# 2013

Very High Energy Phenomena in the Universe

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### XLVIII<sup>th</sup> Rencontres de Moriond

La Thuile, Aosta Valley, Italy – March 9-16, 2013

### 2013 Very High Energy Phenomena in the Universe

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Very High Energy Phenomena in the Universe La Thuile, Aosta Valley Italy March 9-16, 2013

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# Very High Energy Phenomena in the Universe

edited by

Etienne Augé, Jacques Dumarchez and Jean Trân Thanh Vân The XLVIIIth Rencontres de Moriond

### 2013 Very High Energy Phenomena in the Universe

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## 2013 RENCONTRES DE MORIOND

The XLVIIIth Rencontres de Moriond were held in La Thuile, Valle d'Aosta, Italy.

The first meeting took place at Moriond in the French Alps in 1966. There, experimental as well as theoretical physicists not only shared their scientific preoccupations, but also the household chores. The participants in the first meeting were mainly french physicists interested in electromagnetic interactions. In subsequent years, a session on high energy strong interactions was added.

The main purpose of these meetings is to discuss recent developments in contemporary physics and also to promote effective collaboration between experimentalists and theorists in the field of elementary particle physics. By bringing together a relatively small number of participants, the meeting helps develop better human relations as well as more thorough and detailed discussion of the contributions.

Our wish to develop and to experiment with new channels of communication and dialogue, which was the driving force behind the original Moriond meetings, led us to organize a parallel meeting of biologists on Cell Differentiation (1980) and to create the Moriond Astrophysics Meeting (1981). In the same spirit, we started a new series on Condensed Matter physics in January 1994. Meetings between biologists, astrophysicists, condensed matter physicists and high energy physicists are organized to study how the progress in one field can lead to new developments in the others. We trust that these conferences and lively discussions will lead to new analytical methods and new mathematical languages.

The XLVIIIth Rencontres de Moriond in 2013 comprised three physics sessions:

- March 2 9: "Electroweak Interactions and Unified Theories"
- March 9 16: "QCD and High Energy Hadronic Interactions"
- March 9 16: "Very High Energy Phenomena in the Universe"

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It is our sincere hope that a fruitful exchange and an efficient collaboration between the physicists and the astrophysicists will arise from these Rencontres as from previous ones.

E. Augé, J. Dumarchez and J. Trân Thanh Vân

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1. High Energy Cosmic Rays .

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#### COSMIC RAY ACCELERATION

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The origin of the bulk of cosmic rays (CRs) observed at Earth is the topic of a century long investigation, paved with successes and failures. From the energetic point of view, supernova remnants (SNRs) remain the most plausible sources of CRs up to rigidity  $\sim 10^6 - 10^7$  GV. This confidence somehow resulted in the construction of the so-called SNR paradigm: CRs are accelerated through diffusive shock acceleration in SNRs and propagate diffusively in the Galaxy in an energy dependent way. Qualitative confirmation of the SNR acceleration scenario has recently been provided by gamma ray and X-ray observations, although several weak points remain. Here I will summarize some new developments in the theory of particle acceleration in SNRs, with particular emphasis for the non-linear effects that are crucial for the theory in that they represent the dynamical reaction of the accelerated particles on the acceleration in shocks propagating in partially ionized media, with emphasis for the information that one can gather on the origin of CRs from the observations of Balmer lines.

#### 1 Introduction

Understanding the origin of cosmic rays implies an unfolding of several plasma physics processes often operating in a non linear regime. The whole picture is usually made harder to handle by the poor knowledge of the values of environmental parameters (e.g. densities, temperatures, fraction of ionized material). Moreover most observations involve quantities (such as fluxes, chemical composition, anisotropy) measured at Earth that are averages over long (propagation) times and over numerous sources, potentially very different. It is not surprising that a century after the discovery of cosmic rays we are still debating about some aspects of this problem. The purpose of this short review is to provide a view of some aspects of the theory of the origin of CRs that I think are understood and some that are not understood or are poorly understood. I will limit myself to CRs that we think originate inside the Galaxy, though the definition of this transition energy is somehow part of the aspects that need to be discussed.

So far, the only theoretical framework that reached a sufficient level of elaboration to deserve the name "model" is the one based on SNRs as the main sources of the bulk of Galactic CRs. In fact, the lack of a reasonable alternative has elevated the model to the rank of a paradigm. CR acceleration is believed to occur at the forward shock of SNRs through diffusive shock acceleration (DSA). The test particle theory of DSA<sup>1</sup> predicts that the spectrum of accelerated particles is  $N(E) \propto E^{-\gamma}$  with  $\gamma = (r+2)/(r-1)$ , where r is the compression factor at the shock. For typical parameters of SNR shocks,  $r \approx 4$  and  $\gamma \approx 2$ . The propagation of CBs in the Galaxy is usually parametrized through a diffusion coefficient  $D(E) \propto E^{\delta}$ . For nuclei for which spallation is negligible the equilibrium spectrum observed at Earth is  $n(\mathcal{E}) \propto N(\mathcal{E})/\tau_{0/2}(E)$ , where  $\tau_{esc}(E) \sim H^2/D(E) \sim E^{-\delta}$ , where H is the size of the halo of the Galaxy. It follows that  $n(E) \propto E^{-\gamma-\delta}$ . Comparison with observations leads to  $\delta \approx 0.7$  if  $\gamma \approx 2$ . The value  $\delta \approx 0.6 - 0.7$  is also compatible with the low energy observed slope of the B/C ratio. This might look like a self-consistent picture at first sight, but two problems immediately arise: 1) the observed gamma ray spectra in the 1-100 GeV range suggest a steeper CR success, with  $\gamma \sim 2.3 - 2.4^2$ ; 2) A diffusion coefficient  $D(E) \propto E^{0.7}$  would lead to a large scale CR anisotropy much larger than observed<sup>3</sup>. The non-linear theory of DSA (NLDSA, see Ref. <sup>4</sup> for a review) makes these two problems even more severe: the theory accounts for the dynamical reaction of accelerated particles on the shock, which is responsible for the formation of a precursor upstream of the shock. In NLDSA the compression factor felt by accelerated particles becomes a function of energy, which reflects in concave spectra, which turn out to be even harder than  $E^{-2}$  as E > 10 - 100 GeV. As shown in<sup>5</sup>, injection of CRs in SNRs through NLDSA leads to require  $D(E) \propto E^{0.75}$ , that is hardly compatible with the observed large scale anisotropy.

It is clear that the problems of acceleration in the sources and propagation in the ISM are tightly connected with each other and cannot be studied as two independent problems. For instance, the assumption that the diffusion coefficient D(E) is a given function of energy is most likely inappropriate, in that CRs themselves are able to create the scattering centers responsible for their diffusive motion. In turn, the diffusion coefficient affects the CR spectrum observed at Earth. This phenomenon, discussed in Refs. <sup>6,7</sup> might play an important role in understanding features on the CR spectrum recently reported by PAMELA<sup>8</sup> and CREAM<sup>9</sup>.

This paper is organized as follows: in  $\S 2$  I will discuss the implications of the NLDSA in terms of magnetic field amplification and how this might mitigate the spectral problem illustrated above. In  $\S 3$  I will discuss an important recent development in the theory of CR acceleration in SNRs, in connection with the presence of neutral hydrogen in the acceleration region. Some conclusions will be presented in  $\S 4$ .

#### 2 Non linear theory of diffusive shock acceleration and magnetic field amplification

NLDSA describes the process of particle acceleration at collisionless shocks taking into account the CR dynamical reaction on the shock. In some versions of the theory  $^{17,10,11}$  the phenomenon of CR-induced magnetic field amplification and the dynamical reaction of the magnetic field on the background plasma are also included.

The magnetic field can be amplified because of the streaming instability induced by the super-alfvenic motion of CRs in the upstream plasma <sup>12,13,14</sup>. The instability leads to resonant growth of modes with wavenumber  $k \sim 1/r_L$ , where  $r_L$  is the Larmor radius of particles that dominate the particle number at the shock. The waves produced by accelerated particles can also resonantly be absorbed by the same particles thereby leading to their diffusive motion. More recently it was found<sup>16</sup> that non resonant modes may grow much faster than the resonant modes on scales  $k \gg 1/r_L$ . Although this phenomenon may be relevant for magnetic field amolfication, it is not clear whether it may represent the main mechanism for scattering the particles and cause their acceleration at the shock, unless a considerable inverse cascade towards much larger scales occurs.

The amplification of magnetic field due to the streaming of CRs with the shock was first introduced in the theory of NLDSA in Refs.  $^{17,18}$ . Its effect for achieving higher maximum energies was later investigated in Ref.  $^{19}$ . Magnetic field amplification is also needed to explain the narrow X-ray rims detected in virtually all young SNRs (see Ref.  $^{20}$  and references therein



Figure 1: Spatially integrated spectral energy distribution of the Tycho SNR<sup>26</sup>. The curves show the calculated multifrequency spectrum from the radio to the gamma ray band.

## Baselian (End), a con-

#### for a recent review).

Finally the creation of turbulent magnetic field in the shock region might have an important effect in determining the shape of the spectrum. As first emphasized in Ref. <sup>12</sup>, the relevant shock compression factor for particle acceleration is the ratio of velocities of the scattering centers. If the waves are slow in the frame comoving with the plasma, then this is basically the same as the compression factor of plasma speeds. On the other hand, in the non-linear regime, the waves might acquire a substantially higher speed (perhaps of the order of the Alfvén speed calculated in the amplified field). In this case the relevant compression factor may be somewhat smaller and reflect into steeper spectra of accelerated particles  $^{21,22}$ . It is worth recalling that the details of this phenomenon are very model dependent: whether the spectrum becomes harder or softer depends on the helicity of waves, which is hard to predict, especially in a non-linear regime such as the one that is expected close the shock front. In <sup>2,22</sup> the authors assume that wave velocity can be estimated as the Alfvén speed as calculated in the amplified field,  $v_W = \delta B / \sqrt{4\pi\rho}$ , with  $\delta B \gg B_0$ ,  $B_0$  being the pre-existing magnetic field. The situation might be appreciably more complex than that: as discussed in Refs. 14,13,15 the growth rate of the resonant modes excited by CRs in the regime of high CR acceleration efficiency have a phase velocity  $v_{\phi} = \left( \frac{n_{CR}}{n_i} v_s c \right)^{1/2}$ , where  $n_{CR}$  is the density of accelerated particles,  $n_i$  is the ion density,  $v_s$  the shock velocity and c is the speed of light. It is easy to see that  $v_{\phi}$  may easily exceed the Alfvén speed. In this regime the growth rate of the waves also changes.

The simple recipe of Refs. <sup>21,22</sup> was used to calculate the spectrum of CRs at the Earth and it was shown that the required Galactic diffusion coefficient is  $D(E) \propto E^{\bullet,54}$  (see also Ref. <sup>23</sup>), which alleviates but does not solve the anisotropy problem. The finite velocity of the scattering centers was also used in the calculations of the multifrequency spectrum of the Tycho SNR <sup>26</sup>. The results of this calculation are illustrated in Fig. 1 where I show the multifrequency spectrum from the radio band to gamma rays. The relatively steep spectrum in the gamma ray range, that provides a good fit to the data points from Fermi-LAT <sup>24</sup> and Veritas <sup>25</sup>, illustrates well the effect of the velocity of scattering centers (the gamma ray spectrum  $\nu F_{\nu}$  would be roughly flat in the absence of this effect). The predicted strength of the magnetic field reproduces the brightness profile of the non-thermal X-ray emission, as well as the synchrotron spectrum from radio to X-rays. The case of Tycho represents the first convincing instance of a SNR accelerating CRs up to energies of order ~ 500 TeV.

It is worth noticing that the magnetic field amplification as observed in the form of narrow X-ray rims in SNRs might also be the result of purely hydrodynamical processes <sup>27</sup>, as due to the presence of density inhomogeneities upstream that result in vorticity at the shock crossing

and magnetic field amplification due to the wrapping of the eddies downstream. This mechanism operates downstream of the shock and no magnetic field amplification should be expected upstream. This is a very important point in that DSA requires effective scattering of the particles on both sides of the shock and in fact if magnetic field amplification only takes place downstream, no significant increase in the maximum energy should be expected. One noticeable exception to this statement appears if the shock is quasi-perpendicular in which case particle acceleration may proceed through drifts and may in principle be very fast. In this perspective the case of Tycho is especially important, since it is a supernova of Type Ia that exploded in the normal ISM and preferential acceleration at perpendicular shocks should result in a bilateral structure that is quite unlike the spherical appearance of the Tycho SNR.

#### 3 DSA in the presence of neutrals

SNR shocks that develop in the ISM are collisionless, namely their formation is not due to particle-particle scattering but rather to the mediation of electromagnetic instabilities. The thickness of the shock front is expected to be of the order of the Larmor radius of thermal protons behind the shock. Interestingly, even electrons and protons, due to their different masses, are expected to thermalize to different temperatures,  $T_e/T_p \sim m_e/m_p$ , behind the shock. Other collisional and collisionless processes may partially or totally equilibrate electrons and protons downstream. Neutral atoms that cross a collisionless shock do not experience any jump but are coupled to the background plasma through the processes of charge exchange and ionization<sup>28,29</sup>.

The presence of partially ionized material in the acceleration region may profoundly change the way DSA works, mainly because of 1) ion-neutral damping of waves which may stop the growth of CR induced waves and hamper the acceleration process, and because of 2) the dynamical reaction of neutral material in proximity of a collisionless shock front. In addition, the presence of neutral atoms may provide us with a precious diagnostic tool of the acceleration process, as we discuss below.

The dynamical reaction of neutrals on the shock is mainly due to the phenomenon of the neutral return flux (NRF)<sup>31</sup>. The main coupling between neutrals and ions at a collisionless shock is due to charge exchange and ionization, that are activated when the net relative speed between the two components is non-zero. Downstream of a collisionless shock, ions are slowed down and heated up, while neutrals cross the shock and keep their initial velocity. The charge exchange reactions occurring in this situation may eventually produce neutrals moving with large bulk velocity in the direction of the shock and these may recross the shock toward upstream. Charge exchange and ionization with the upstream plasma lead to deposition of energy and momentum of these neutrals upstream, which in turn results in heating of the ionized gas. For shock speed  $\leq 4000$  km/s this NRF considerably changes the structure of the shock and leads to the formation of a shock precursor, similar to the one induced by CRs but in general on a smaller spatial scale. In Ref.<sup>31</sup> the authors showed that the spectrum of test particles accelerated at such shock may visibly deviate from the standard predictions of DSA and account for steeper spectra of accelerated particles. For shocks faster than  $\sim 4000$  km/s, on average a neutral crossing the shock gets ionized before suffering a charge exchange, therefore the NRF is suppressed.

The net effect of the NRF is to heat the plasma in the precursor so that the Mach number of the shock decreases, namely the compression factor gets smaller. Since the spectrum of particles accelerated at the shock depends on the compression factor, the NRF leads to steeper particle spectra. Clearly the effect is the largest for particles diffusing on spatial scales comparable with the scale of the neutral induced precursor. Since the diffusion coefficient is a growing function of energy, the effect of the NRF shows more prominently at lower energies.

As mentioned above, neutral hydrogen atoms in the acceleration region also provide us with an important diagnostics of the acceleration process, through their Balmer emission. The Balmer line emission from hydrogen in the shock region is becoming a powerful tool to measure the CR



Figure 2: FWHM of the broad Balmer line as a function of the CR acceleration efficiency  $\epsilon_{\rm CR}^{33}$ .

acceleration efficiency in SNR shocks<sup>30</sup>. The idea is relatively simple: it is well known that the Balmer line produced by neutrals that suffered charge exchange with hot ions downstream has a width that reflects the temperature of ions, while neutrals that did not suffer charge exchange emit a narrow Balmer line with width ~ 20 km/s, corresponding to the upstream  $T \sim 10^4$  K hydrogen temperature. If CR acceleration is efficient, part of the ram pressure upstream of the shock  $\rho u^2$  is channelled into accelerated particles instead of heating. Therefore the plasma temperature downstream is lower if particle acceleration is efficient and the corresponding broad Balmer line becomes correspondingly narrower. On the other hand, efficient CR acceleration produces a shock precursor upstream that leads the ionized plasma to slow down with respect to neutrals. Therefore charge exchange is also activated upstream and the narrow component of the Balmer line may become broader. As shown in Ref. <sup>32</sup>, for slow enough shocks the NRF also produces a similar effect but it results in the formation of a component of the Balmer line with width intermediate between the broad and the narrow line.

A theory of NLDSA that describes the shock modification as induced by both neutral hydrogen atoms and accelerated particles was recently formulated <sup>33</sup>. The theory describes the neutrals in a kinetic form, which turns out to be of paramount importance for the calculation of the shape of the Balmer line emission, since the distribution function of neutrals is by no means maxwellian. The effects discussed above in qualitative form are clearly observed in the results of the calculations carried out using this theoretical framework. In Fig. 2 I show the width of the broad Balmer line as a function of the acceleration efficiency at a shock with velocity  $V_{sh} = 4000$  km/s. The solid line refers to the case of full equilibration between ions and electrons downstream of the shock, while the dashed line shows the case in which the ratio of electron to ion temperatures is  $\beta_{sown} = 0.01$ . The first point, corresponding to the absence of particle acceleration ( $\epsilon_{CR} = 0$ ) shows the width of the Balmer line at a standard collisionless shock. Higher CR acceleration efficiencies lead to a broad Balmer line narrower by typically a few hundred km/s for  $\epsilon_{CR} \sim 10 - 40\%$ .

The broadening of the narrow component of the Balmer line is more model dependent<sup>33</sup>, in that it depends not only on the CR acceleration efficiency, but also on the maximum momentum of accelerated particles  $p_{max}$  and the level of turbulent heating, namely the fraction  $\eta_{AH}$  of the pressure of Alfvén waves that is transformed into thermal pressure of the plasma upstream. In Fig. 3 I show the FWHM of the narrow line as calculated in Ref.<sup>33</sup>, for  $\eta_{AH} = 0.2$  (left panel) and  $\eta_{AH} = 0.8$  (right panel). The three lines refer to different values of the injection efficiency  $\xi_{inj}$  as indicated (see Ref.<sup>33</sup> for details), which correspond to different acceleration efficiencies. One can see that larger values of the maximum energy lead to a larger effect in



Figure 3: FWHM of the narrow line as a function of the maximum momentum of accelerated protons<sup>33</sup>. The two panels refer to  $\eta_{AH} = 0.2$  and 0.8. The lines refere to different injection parameters  $\xi_{inj} = 3.5$ , 3.7 and 3.8.



Figure 4: FWHM of the broad Balmer line in the absence of CR acceleration and for different electron-ion equilibration levels ( $\beta_{down} = 1$ , solid line and  $\beta_{down} = 0.01$ , dotted line). The data points are the results of Ref.<sup>34</sup> on the SNR 0509-67.5.

terms of broadening of the narrow Balmer line. In all cases the width of the narrow Balmer line in the presence of CR acceleration is appreciably larger than the standard line with width 21 km/s.

The width of the broad Balmer line has been recently measured in two regions of the shock in the SNR 0509-67.5<sup>34</sup>. The FWHM in the two regions are shown in Fig. 4 (data points with error bars) where I also show the FWHM expected according to the calculations of Ref. <sup>33</sup> in the absence of particle acceleration, for the case of full electron-ion equilibration ( $\beta_{down} = 1$ , solid line) and partial equilibration ( $\beta_{down} = 0.01$ , dotted line). The FWHM in the NE rim is affected by a large error and is compatible with the absence of particle acceleration. On the other hand, the SW part of the shock, moving with speed ~ 5000 km/s has a broad Balmer emission with FWHM which is below all predictions obtained in the absence of CR acceleration, thereby imposing a lower limit on the CR acceleration efficiency that has been estimated to be  $\epsilon_{CR} > 0.15^{34}$ . A similar measurement of an anomalous broad Balmer line in the SNR RCW 86 also allowed to impose a limit on the CR acceleration efficiency<sup>35</sup>.

#### 4 Summary

The SNR paradigm for the origin of Galactic CRs appears to have been strengthened by the recent measurements of the gamma ray emission from several remnants, as well as from the observation of bright, thin X-ray rims of non-thermal origin, suggesting that magnetic field may

be substantially amplified at the shock, probably by the same accelerated particles. Moreover, in a few cases, the detection of anomalous widths of Balmer line emission suggests that CR acceleration with efficiency > 10% is taking place at the shock. Despite this body of evidence there are several loose ends in the paradigm: 1) in the cases in which there is reasonable evidence that the gamma ray emission is due to pion decays, the inferred spectra of accelerated particles are appreciably steeper than DSA would suggest, even more so if the non linear version of DSA is used<sup>2</sup>. 2) The steep injection spectra are also required in order to avoid excessive anisotropy in the > TeV energy region<sup>3</sup>. 3) From the theoretical point of view, the details of magnetic field amplification are not fully understood: the CR induced instabilities are forced to operate in the non-linear regime ( $\delta B/B \gg 1$ ), and on many different scales, which makes it difficult to follow the development of these instabilities analytically and even numerically (see Ref. <sup>36</sup> for a review). 4) The simple picture with a power law injection and a power law diffusion in the Galaxy appears to be rather inappropriate to describe nature: several effects make the injection spectrum deviate from a power law, and the spectra observed at Earth show rather puzzling changes of slope <sup>8,9</sup>, that probably indicate some poor understanding of propagation <sup>37,7</sup>.

Most of these issues probably stem from the fact that CRs modify the conditions in which they get accelerated and in which they propagate. These modifications become part of the problem of understanding acceleration and propagation in that non-linear effects become of paramount importance. Spatially resolved images of SNRs in gamma rays, such as the ones expected of CTA, are likely to shed light on some of these problems. Investing in high resolution optical observations of the Balmer lines in selected regions of SNR shocks is also likely to lead to important breakthroughs in the understanding of the connection between CRs and SNRs (see discussion in §3).

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#### **Recent results of Telescope Array experiment**

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The origins of the cosmic rays with energies above  $10^{18}$  eV (UHECRs) have remained a persistent mystery for decades. To study the acceleration mechanism and find the UHECR sources, one must make careful measurements of the energy spectrum, the composition and the arrival directions. Telescope Array (TA) is specifically designed to measure these UHECR properties precisely. TA, located in the west desert of Utah, USA, has collected data over 5 years since 2007. TA consists of a ground array of 507 plastic scintillator detectors spread over an area of 700 m<sup>2</sup>, overlooked by wide-angle fluorescence telescopes placed in three sites on the array boundary. The energy spectrum is determined by using of ground array data. The ankle is around  $10^{18.7}$  eV and there is the second bending point where the UHECR flux starts to decrease. The composition analysis using the longitudinal development measurement shows that proton is dominant above  $10^{18.2}$  eV. Observed arrival direction shows no apparent anisotropy. A low energy extension to TA will add new telescopes and a new high density ground array, providing for cosmic ray observation down to about  $10^{17}$  eV.

#### 1 Introduction

Cosmic rays are highly energetic particles of extraterrestrial origin. The energy of a single particle can reach more than  $10^{20}$  eV (50 joules), which is equivalent to the energy of a baseball (140 g) flying at the speed of 100 km/h (60 mph). Even modern particle accelerators are far from being able to accelerate particles to such enormous energies, leaving cosmic rays as the only source of ultra high energy (UHE - energy above  $10^{18}$  eV) particles. Despite the fact that cosmic ray research is more than a hundred years old, no one can claim to fully understand the nature of this phenomenon.

Due to their extremely small flux especially at the highest energies, the direct observation of cosmic rays is virtually impossible, and all the current knowledge about these particles is gathered from indirect observations through extensive air showers (EASs). Different techniques exist and have been applied successfully to extract information about the energy spectrum, the chemical composition and the anisotropy in the arrival direction of cosmic rays from the properties of EASs. This information helps us to test various astrophysical models of origin, acceleration and propagation of cosmic rays.

#### 2 Telescope Array

The Telescope Array Collaboration was forged by members of the High Resolution Flys Eye (HiRes) and the Akeno Giant Air Shower Array (AGASA) to study Ultra High Energy Cosmic Rays (UHECR). The purpose of Telescope Array is to a) understand the differences between the results of HiRes and AGASA, b) to study the spectrum, composition, and anisotropy of ultra high energy cosmic rays, and c) to study the galactic to extra-galactic transition of cosmic rays.

The collaboration has grown to include groups from the US, Japan, South Korea, Russia, and Belgium. The Telescope Array Observatory is located about 2.5 hours south of Salt Lake City, just west of Delta, Utah USA. The Central Laser Facility (center of the observatory) is located at 39.297° N, 112.909° W and is 1370 m above sea level.

#### 2.1 Fluorescence Detector

The of the Telescope Array consists of 38 fluorescence telescopes (9728 PMTs) located in three stations at the corners of a triangle which is approximately 30 km on each leg. At the two southern sites, Black Rock (BR) and Long Ridge, (LR) new FD telescopes designed specifically for the TA experiment were constructed. Each site houses 12 telescopes with 3m diameter mirrors. Each camera consists of an array of 256 pixels instrumented with Hamamatsu R9508 2-inch diameter photomultiplier tubes (PMTs). Each pixel covers about a 1.1° cone of the sky. The signals from the PMTs are recorded by an FADC operating at 10 MHz. A centralized track finder system is used to look for track-like hit patterns in time coincidence. Once a trigger is activated, 51.2  $\mu$ s (12.8  $\mu$ s before, and 38.4  $\mu$ s after the trigger) of recorded data are read out for every PMT at the site. The northern most FD site at Middle Drum (MD) was constructed from 14 refurbished telescopes from the HiRes-1 site of the High Resolution Flys Eye (HiRes) Experiment. Each of these telescopes has a 2m diameter mirror, and a closed packed array of 1-inch EMI 9974KAFL (telescopes 1-6) and Photonis (formerly Philips) XP3062/FL (telescope 7-14) PMTs. Here each pixel views a  $1.0^{\circ}$  cone of the sky. The time and pulse area information from each channel is readout using traditional TDC and sample-and-hold charge integrator through an ADC. The 14 telescopes trigger individually, with a reduced trigger condition if a neighboring telescope registered a full trigger. Only those telescopes that trigger are read out and data from groups of triggered telescopes within 100 s from one the next are combined as a single event. The use of refurbished HiRes-1 telescopes reduced the cost and construction time of TA, but also allows TA to make a direct comparison to the HiRes experiment.

#### 2.2 Surface Detector

The 507 surface detector (SD) have been deployed 1.2 km separations in Utah desert with covering 700 km<sup>2</sup>. Each surface detector consists of two layers of plastic scintillators. Each layer of scintillator has  $3m^2$  of area and 1.2cm thick. Scintillation light is collected through 104 of 5 m long wave length shifting fibers are laid for each layer. Both ends of the fiber are bundled and connected to a PMT. Installed PMTs were calibrated for relation of high voltage to gain and linearity curve. Scintillators and PMTs are contained in the 1.2 mm thick of stainless box which is mounted under the roof made of 1.2 mm thick of iron. The output signal from PMTs are recorded with a CPU board equipped with 12 bit FADC which is running with 50 MHz of sampling rate. All SD clocks are synchronized by 1pps signal received from a GPS unit (Motorola M12+ on-core module) and run at 50 MHz for 20 nsec time resolution.

#### 3 Latest results

#### 3.1 Primary composition

The longitudinal development of a cosmic ray air shower depends strongly on its primary energy and particle type. The depth in the atmosphere at which the number of particles in the shower reaches a maximum,  $X_{max}$ , is a good indicator of primary particle type. Since an FD observes longitudinal development of air showers, this technique has the advantage over SDs of measuring the energy calorimetrically and being able to determine primary particle type. The mass composition cannot be determined on a shower by shower basis due to fluctuations in development of individual showers, but it can be determined on a statistical basis by comparing the  $X_{max}$ distribution of the data from many showers and the distribution expected from a monte carlo



Figure 1: Left:  $\langle X_{max} \rangle$  distribution above 10<sup>18.2</sup> eV. Right: Primary energy spectrum above 10<sup>18.2</sup> eV.

(MC) simulation. However, it should be noted that the uncertainty of the MC depends strongly on hadron interaction models that have been extrapolated from measured cross sections at much lower energies. As energy increases, the  $X_{max}$  of air showers increase. And at a given energy, the  $X_{max}$  of a light primary particle will be deeper than that of a heavy primary particle. Since the FDs only can see showers in certain geometric regions, the  $X_{max}$  may be either above the field of view (FOV) or below it, or it may be inside the field of view but the FD cannot reconstruct the shower (for instance, the shower may be coming nearlydirectly toward the FD). In these cases one cannot assign an  $X_{max}$  to the shower. This means that the distribution of observed  $X_{max}$ will be different from the expected distribution unless the FD configuration is taken into account in the simulation. In this analysis, the  $X_{max}$  distribution affected by the detector configuration and shower reconstruction biases will be estimated and compared with data to determine UHECR mass composition. The mass composition of UHECR can be determined by data/MC comparison of  $X_{max}$ . However, the MC must reflect the actual detector configuration, atmospheric profile, triggering requirements, etc. of the actual detector. Data was observed in stereo mode from Nov 2007 to Sep 2010. In the right of Fig. 1 the average  $X_{max}$  data is consistent with the prediction expected for protons primaries based on the QGSJET-I hadron interaction model. Moreover, there is no evidence in Fig. 1 of any bend in the variation of average  $X_{max}$ with energy, which suggests that mass composition does not change in this energy region.

#### 3.2 Energy spectrum

Left of Fig. 1 shows the spectrum measured by the TA SD, where the differential flux,  $J(E) = d^4 N(E)/dEdAd\Omega dt$  is multiplied by  $E^3$ , and plotted against  $\log_{10} E$ . This figure is made by the TA SD over approximately four years of observation between May 2008 and May 2012. The ankle structure and the suppression at the highest energies are clearly visible. A fit to a broken power law (BPL) determines the energies of these features. The fit finds the ankle at an energy of  $(4.6 \pm 0.3) \times 10^{18}$  eV and the suppression at  $(5.4 \pm 0.6) \times 10^{19}$  eV. The power exponents for the three regions (below the ankle, between the breaks, and above the suppression) are  $-3.34 \pm 0.04$ ,  $-2.67 \pm 0.03$ , and  $-4.6 \pm 0.6$  respectively. A linear extrapolation of the power law below the suppression predicts 58.6 events above the break; whereas TA observed only 21 events. This difference corresponds to a Poisson probability of  $1.44 \times 10^{-8}$ , or 5.5 standard deviations significance. A related observable,  $E_{12}$ , is the energy at which the integral spectrum falls to 1/2 of its expected value in the absence of the GZK cutoff. Under a wide range of assumptions about the spectrum of extra-galactic sources,  $E_{1/2}$  is predicted to be  $10^{19.72}$  eV for protons<sup>2</sup>. We measure  $\log_{10} E = 19.72 \pm 0.05$ .

This 5.5 standard deviation observation provides independent confirmation of the GZK cutoff observed by HiRes<sup>3</sup>. Furthermore, the energy of the cutoff is consistent with the interpretation that the composition is protonic. The largest source of systematic uncertainty in the spectrum is that of the energy scale. Since the SD energy scale is fixed to that of the TA fluorescence



Figure 2: Autocorrelations in the TA data sets at E > 40 EeV. Left: the number of pairs with angular separations  $\delta$  normalized to the area of the angular bin (data points), compared to the expectation for the uniform distribution (shaded histogram). Right: probability,  $P(\delta)$ , that the excess of pairs with the angular separation less than  $\delta$  occurs as a fluctuation in a uniform distribution. Small  $P(\delta)$  indicates a departure from isotropy

detectors, we take the systematic uncertainty in the SD energy to be 22%, the same as the FD. This propagates into a 37% uncertainty in the flux. We estimate the systematic uncertainty in the aperture calculation by removing the event selection criteria, one by one, and measuring the ratio of the number of events in the data and in the MC. This ratio does not change by more than 3% in any energy bin above  $10^{18.2}$  eV, so we assign this value to be the systematic uncertainty in the aperture.

#### 3.3 Arrival direction

The AGASA experiment reported clustering of UHECR events with E > 40 EeV at the angular scale of  $2.5^{\circ 4}$ . Here we repeat this analysis using the TA data set. The procedure is as follows: for a given angular separation,  $\delta$ , we count the number of pairs of observed events that are separated by an angular distance less than  $\delta$ , thus obtaining the data count. We then generate a large number (typically, 105) of MC event sets each having the same number of events as the real data set. The simulated sets are generated with a uniform distribution according to the TA exposure. In each MC set we count pairs of events in the same way as in the data, which gives the MC count for that set. We then calculate the average MC count for all of the MC sets. This represents the expected number of pairs for the angular scale  $\delta$ , assuming a uniform cosmic ray distribution. For each value of  $\delta$ , we then determine the fraction of simulated sets where the number of pairs is greater than or equal to the number of pairs in the data. This gives the p-value,  $P(\delta)$ , that describes how likely the excess of pairs, if found in the data, is to occur as a result of a fluctuation in a random set. Small values of  $P(\delta)$ , thus indicate a departure from uniformity at the corresponding angular scale. We first perform a blind test of the AGASA claim. Fixing the energy threshold to 40 EeV and the separation angle to  $\delta = 2.5^{\circ}$  we find 0 pairs while 1.5 pairs are expected in the case of a uniform distribution. Therefore, there is no excess of small-scale clusters in the TA data. We next extend the analysis to all angular scales. No significant excess is found. The overall normalization is set in such a way that the expectation in the first bin equals one. The right panels of Fig. 2 show the dependence of the p-value,  $P(\delta)$ , on the separation angle,  $\delta$ , for E > 40 EeV. All present arrival direction analyses are based on the data collected in the period from May 2008 to Sep 2011 of operation by the TA SD.

The Auger collaboration has reported a correlation <sup>5 6</sup> between UHECRs with E > 57 EeV and the nearby (redshift  $z \le 0.018$  or, equivalently, distance d < 75 Mpc) Active Galactic Nuclei (AGNs) from the Veron-Cetty & Veron (VCV) catalog<sup>8</sup>. The greatest correlation was observed at the angle of 3.1°. In the control data set, the number of correlating events was 9 out of 13, which corresponds to about 69% of events. The Auger collaboration has recently updated the



Figure 3: Left: Hammer projection of the TA cosmic ray events with E > 57 EeV and nearby AGNs in the Galactic coordinates. Correlating and non-correlating events are shown by filled red and empty blue circles, respectively. AGNs are represented by black dots. The dashed line shows the boundary of the TA exposure. Right: The number of TA events with E > 57 EeV correlating with VCV AGNs as a function of the total number of events. The expectation according to the original Auger collaboration claim is represented by the blue line together with the 1- and 2-sigma significance bands. The black dashed line shows the expected number of random coincidences.

analysis and found that a smaller fraction of the UHECR events correlates with the same set of AGNs in the latest UHECR data set than in the original one <sup>7</sup>. Out of 55 events with E >55 EeV, 21 were found to correlate with AGNs, which corresponds to a fraction of correlating events equal to 38%. In this section we test the TA data for correlations with AGN. The set of 472 nearby AGNs used by Auger<sup>5</sup> contains 7 objects listed at zero redshift, all in the field of view of TA. Of these 7 objects, two are stars, one is a quasar with unknown redshift, one is a Seyfert 2 galaxy, two are spiral galaxies and one is a dwarf spheroidal galaxy. We exclude these objects from the analysis, which leaves 465 objects in the AGN catalog.

The TA exposure is peaked in the Northern hemisphere, so that the AGNs visible to TA are largely different from those visible to Auger, though there is some overlap. The distribution of nearby AGNs over the sky is not uniform because of the large scale structure and because the VCV catalog is not complete: due to observational bias it tends to contain more objects in the Northern hemisphere. For this reason, a larger fraction of events is expected to correlate with AGNs in the TA data under the assumption that AGNs are sources of the observed UHECRs. Taking into account the distribution of nearby AGNs over the sky and assuming equal AGN luminosities in UHECR, we estimated the correlating fraction will be ~ 73% for TA on the basis of the original Auger collaboration claim, and ~ 43% on the basis of the updated analysis by Auger. The sky map of TA events with E > 57 EeV and nearby AGNs from the VCV catalog is represented in Fig. 3 in Galactic coordinates. The cosmic rays are shown by filled red (correlating events) and empty blue circles. AGNs are shown by black dots.

Fig. 3 shows the number of TA events correlating with AGNs as a function of the total number of events with E > 57 EeV ordered according to arrival time. The black dashed line represents the expected number of random coincidences in case of a uniform distribution calculated via MC simulation. The blue line shows the expected number of correlating events as derived from the original Auger collaboration claim. Shaded regions represent 68% and 95% CL deviations from this expectation calculated by the maximum likelihood method. As is seen from Fig. 3, present TA data are compatible with both isotropic distribution and the AGN hypothesis. In the full TA SD data set, there are 11 correlating events out of 25 total, while the expected number of random coincidences for this total number of events is 5.9. Making use of the binomial distribution with the probability of a single event to correlate  $p_{iso} = 0.24$ , one finds that such an excess has probability of ~ 2% to occur by chance with isotropic distribution of arrival directions.

Even though the sources of UHECRs are not known, their distribution in space at large scales must follow that of the ordinary matter. If UHECRs are not strongly deflected on their way to Earth, their distribution over the sky should correlate with the nearby structures, with



Figure 4: Left: The skymaps of the expected flux at energy thresholds of 10 EeV, 40 EeV, and 57 EeV (from top to bottom) in Galactic coordinates with the TA events superimposed (white dots). The smearing angle is 6<sup>ctrc</sup>. Right: The results of the statistical test for the compatibility between the data and the LSS hypothesis. The three panels correspond to energy thresholds of 10 EeV, 40 EeV, and 57 EeV from top to bottom, as indicated on the plots.

over-densities corresponding to close clusters and underdensities corresponding to voids. To test the compatibility between the observed UHECR distribution over the sky and that expected under the hypothesis that UHECR sources trace matter distribution in the Universe, we employ the method developed by Koers & Tinyakov<sup>9</sup> and used previously in the analysis of the HiRes data<sup>10</sup>. In this method, one first computes the UHECR flux distribution expected under the LSS hypothesis and then compares it to the observed one by the flux sampling test. To calculate the expected flux, we assume that UHECR sources follow the space distribution of galaxies. The simplest way to realize this assumption in practice is to assign each galaxy an equal luminosity in UHECRs. This is a good approximation if the density of the UHECR sources is sufficiently high (so that many sources are present in local structures contributing to the anisotropy).

The contribution of each galaxy to the total flux is then calculated taking into account the distance of the source and the corresponding flux attenuation. Individual contributions are smeared with the Gaussian width  $\theta$ , so that the flux at a given point of the sky is a sum of contributions of all the galaxies within the angular distance of order  $\theta$ . Further details on the flux calculation can be found in References<sup>() [10]</sup>. Fig 4 shows the skymaps of the expected flux at energy thresholds of 10 EeV, 40 EeV, and 57 EeV (top to bottom) and the smearing angle of 6°. The white dots represent the arrival directions of the TA events. Darker regions correspond to higher flux. A band of each color integrates to 1/5 of the total flux. The results of the statistical test for the compatibility between the data and the LSS hypothesis is shown in Fig. 4. The p-values (red points) are shown as a function of the smearing angle  $\theta$ . Low pvalues indicate incompatibility with the LSS model. The horizontal line shows a confidence level of 95%.

#### 4 Near Future Prospects

#### 4.1 Low Energy Extention

The existing experiment was designed with a threshold of  $10^{19}$  eV. While we have been able to extend analysis down to about  $10^{18}$  eV, this is insufficient to fully observe the galactic to extra

galactic transition. In addition, it is optimal to observe cosmic rays from LHC energies through the second knee and up to the GZK cutoff with one well cross-calibrated detector. TALE, the low energy extension to the Telescope Array, is designed to lower the energy threshold to about  $10^{16.5}$  eV. To do this, we are installing an additional 10 telescopes viewing up to 59° in elevation and a new graded array of scintillator detectors. This extension will enable the TA to measure the energy and composition of cosmic rays to much lower energies while cross calibrated with the detectors of the main Telescope Array. By pushing the energy threshold down to  $10^{16.5}$  eV, we hope to sort out the galactic and extra-galactic contributions to the cosmic ray flux. TALE is a hybrid detector which consists of ten additional fluorescence telescopes situated at the MD FD site. These telescopes add to the sky view of the site between 30-57° in elevation. In addition, a graded infill surface array of 105 plastic scintillation counters with variable 400 to 600 m spacing allows for hybrid observation. Together with the original MD FD, this yields a combined sky coverage of 112° in azimuth and 3-57° in elevation for the MD telescope site.

#### 4.2 Octocopter

The optical calibration of the fluorescence telescopes is a significant contribution to the overall uncertainty of energy measurements made by the Pierre Auger and Telescope Array experiments. Some sources of uncertainty, such as the fluorescence yield in air, affect both experiments similarly. However, the optical calibration of the fluorescence telescopes is a source of independent uncertainty. The Pierre Auger and Telescope Array collaborations have taken initial steps to establish a relative end-to-end optical calibration of the fluorescence telescopes. An Octocopter carrying a portable light source has been flown in front of fluorescence telescopes at both Pierre Auger and Telescope Array sites. Laboratory calibration measurements of the light source before and after the flights provide a common baseline for the relative end-to-end calibration. We expect this system will lead to a common photonic calibration for both experiments.

#### 4.3 TA-EUSO project

The TA-EUSO project aims to install a prototype of the JEM-EUSO telescope on BR. The detector consists of one Photo Detector Module (PDM), identical to the 137 present on the JEM-EUSO focal surface. Each PDM is composed by 36 Hamamatsu multi-anode PMTs (64 channels per tube), for a total of 2304 channels. Front-End readout is performed by 36 ASICS, with trigger and readout tasks performed by two FPGA boards that send the data to a CPU and storage system. Two 1.5m diameter Fresnel lenses provide an 8 degrees field-of-view of the telescope. TA-EUSO will be housed in a container located in front of the fluorescence detector of the Telescope Array collaboration, looking in the direction of the ELS (Electron Light Source) and CLF (Central Laser Facility). Aim of the project is to cross-calibrate the response function of the EUSO telescope with the TA fluorescence detector in presence of a shower of known intensity and distribution. An initial run of about six months starting from fall 2012 is foreseen, during which we expect to observe triggered by TA electronics a few cosmic ray events which we low intersect of a longer term program, we are considering to increase the number of PDM and the field of view.

#### 4.4 Radio detection

The Telescope Array Radar (TARA) project will utilize a bistatic radar technique to detect radar echos from the ionization trails of ultra-high energy cosmic rays as they pass through the Earth's atmosphere. This method of observing cosmic rays is unproven, and TARA is the largest and most ambitious attempt yet at detecting UHECR via their radar signature. TARA is co-located with the Telescope Array, the largest cosmic ray observatory in the Northern Hemisphere, which

will provide confirmation of the radar detection of UHECRs via time coincidence. Since mid-2011, TARA has been field testing a low power version of the experiment to gain expertise and study techniques to better utilize the radar method on a much larger scale. In 2013 TARA will begin operations in high power mode using a 40 kW transmitter and a phased array of eight high-gain yagi antennas with a gain of 23 dBi, broadcasting at 54.1 MHz with 100% duty cycle over the TA surface detector array. The effective radiated power will be over 8 MW, continuous. We will also be deploying an enhanced receiver system, making use of a 250 MHz receiver and on-board FPGA to allow smart triggering on signals with a signal-to-noise ratio of -10 to -20 dB. TARA will be the first experiment to attempt to utilize this detection technique at such high power in conjunction with a large cosmic ray detector. If this technique is proven successful, it will allow for very large cosmic ray observatories, which are required to fully probe the ultra high energy regime, to be built much more cheaply and on larger scales than the current generation of fluorescence detectors and surface arrays.

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# Measurement of the energy spectrum of cosmic rays at the highest energies using the Pierre Auger Observatory

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We present the cosmic ray spectra measured with the Pierre Auger Observatory using several methods, all of which rely on fluorescence light measurements to establish the energy of the events. The spectrum obtained with the surface detector for showers with zenith angles below 60° degrees and energies above 3 EeV has been extended to lower energies using showers detected by the fluorescence detector and having at the least one triggered surface station. We also report on an independent spectrum for inclined events with zenith angles from 62° to 80° registered with the surface detector, and on the spectrum for energies above 0.3 EeV obtained with a small region of the array in which the distance between surface stations has been halved. The spectral features are presented in detail and the impact of systematic uncertainties on these features is addressed.

#### 1 Introduction

The Pierre Auger Observatory combines a surface detector (SD) and a fluorescence detector (FD). The SD consists of 1660 water Cherenkov tanks separated by 1500 m covering an area of 3000 km<sup>2</sup> which allows us to sample the electrons, photons and muons in air showers at ground level with a duty cycle of almost 100%. The FD consists of fluorescence telescopes that observe the atmosphere during clear, moonless nights, with a reduced duty cycle of  $\sim 13\%$ . The telescopes are used to measure the longitudinal development of extensive air showers by detecting the fluorescence light emitted by excited nitrogen molecules.

Updated measurements of the cosmic ray spectrum with the Pierre Auger Observatory for ultra high energy cosmic rays are presented here. A precise measurement of the spectral features of the ultra high energy region is of great value for discrimination between different models describing the transition between galactic and extragalactic cosmic rays, the suppression induced by the cosmic ray interaction with the Cosmic Microwave Background and features of the injection spectrum at the sources.

The data are divided into two sets according to zenith angle,  $0^{\circ} < \theta < 60^{\circ}$  (regular) and  $60^{\circ} < \theta < 80^{\circ}$  (inclined), because the latter requires a different reconstruction method. A flux suppression around 50 EeV<sup>*a*</sup> has been established based on measurements of the regular [1] and

 $<sup>^{</sup>a}1 \text{ EeV} = 10^{18} \text{ eV}$ 

inclined SD events [<sup>2</sup>]. A small region of the array  $(24 \text{ km}^2)$  has been instrumented with a higher surface density of particle detectors (infill array) which are separated by 750 m. This small array allows us to extend the spectrum measurement to energies as low as 0.3 EeV compared to the threshold of 3 EeV of the regular array.

An extension to energies down to  $10^{18}$  eV is possible by using events measured simultaneously with FD and at least one SD station (hybrid events). Hybrid measurements and those obtained with the infill array allow us to establish the position and shape of the "ankle" feature where the power law index of the flux changes and the transition between galactic and extragalactic cosmic rays is expected.

#### 2 Spectra obtained with the Surface Detector

Air showers detected by the SD are reconstructed using the signals and trigger times recorded by individual detector stations. Different reconstructions for regular and inclined events are required, due to the different particle distributions for inclined events.

For the analysis of regular events (with  $\theta < 60^{\circ}$ ) the measured signal at 1000 m from the axis, S(1000), is used as an energy estimator after correction for zenith angle variations (partly due to attenuation of the showers). It is obtained by fitting the lateral distribution of the signals recorded at the SD. The energy estimate is based on the calibration of S(1000) with the calorimetric energy from events measured in coincidence with the FD. 64000 events have been recorded above  $3 \times 10^{18}$  eV where the SD efficiency (it is over 95% efficient for regular events) is saturated regardless of the primary mass.

The energy spectrum is based on SD events recorded from 01/01/2004 till 31/12/2010. The exposure is casily calculated by integrating the number of active unit cells of stations over time and has a value of 20905 km<sup>2</sup> · sr · yr in that period. The uncertainty on the derivation of the exposure is ~ 3%, for the SD array. The SD energy resolution varies from 16% at ~ 3 EeV to 13% at ~ 10 EeV. A forward-folding approach is applied to correct the influence of physical and statistical fluctuations on the measurements. These corrections are below 20% in the entire energy range. The corrected spectrum is shown in Fig. 1. It clearly reveals a suppression of the flux at energies above 50 EeV. This is consistent with the spectrum expected for protons interacting with the Cosmic Microwave Background.

Cosmic rays arriving with  $\theta > 60^{\circ}$  induce showers characterized by muon dominance at the ground and a broken circular symmetry in the lateral distribution of particle density, partly due to deflections in the geomagnetic field and partly due to the different trajectories of early and late arriving particles [<sup>3</sup>]. For those reasons, these showers, have to be reconstructed in a separate way from those with  $\theta < 60^{\circ}$ . The energy reconstruction is based on the estimation of the relative muon number N<sub>19</sub> with respect to a reference muon distribution obtained from simulated proton showers at 10<sup>19</sup> eV. The shower core and the N<sub>19</sub> are simultaneously estimated by a maximum likelihood fit of the expected number of muons at each station to the measured signal [<sup>3</sup>]. For inclined showers, the SD energy is obtained by calibrating N<sub>19</sub> with the FD energy of events independently recorded by SD and FD.

The cosmic ray spectrum obtained for the data period from 1/01/2004 to 31/12/2010 is presented in Fig. 2. The exposure for this period is  $5306 \text{ km}^2 \cdot \text{sr} \cdot \text{yr}$ . A correction has been applied to account for the effect of the uncertainty in the energy determination in the binning of the events. The spectrum displays a suppression consistent with that of the regular SD data and is in good agreement with it  $\frac{\rho}{2}$ .

For the infill array, a similar treatment is performed but the estimator chosen is based on the signal at 450 m from the shower axis, S(450) and, in this case, the zenith angle range is reduced to angles below 55°. The exposure between August 2008 and March 2011 amounts to  $26.4 \pm 1.3 \text{ km}^2 \cdot \text{sr} \cdot \text{yr}$  [<sup>5</sup>], and the spectrum reconstruction is in progress [<sup>6</sup>].



Figure 1: Energy spectrum obtained with the regular SD of the Pierre Auger Observatory. Only statistical errors are shown, (68% CL).



Figure 2 Cosmic ray energy spectrum derived from inclined events (black dots), with  $62^{\circ} < \theta < 80^{\circ}$ . It is in agreement with the regular SD spectrum (empty squares). Gray boxes correspond to the systematic uncertainties.

#### 3 Hybrid spectrum

Hybrid events are those detected with the FD which have at least one triggered SD station. Reconstruction of the arrival direction is achieved by fitting the arrival time of the light at each of the triggered FD PMTs and adding the arrival time of the signal of the triggered station with the highest signal. Once the geometry has been established the signals at each PMT can be converted to the light emission at a position in the shower development which provides a measurement of the energy deposited in the atmosphere as the shower develops. A fit of the Gaisser-Hillas function gives the energy of the shower as a calorimetric measurement.

The data period taken into account is from 1/11/2005 till 30/09/2010. Only events that satisfy strict quality cuts are accepted [7]. To avoid a possible bias in the event selection, only showers with geometries that would allow the equivalent observation of all primaries in the range from proton to iron are retained in the data sample.

The exposure of the hybrid mode of the Pierre Auger Observatory has been calculated using a time-dependent Monte Carlo simulation. All the atmospheric measurements as well as monitoring information are considered for the simulation, (more details can be found in [<sup>8</sup>] [<sup>9</sup>]). The uncertainties due to assumptions made in the hadronic interaction models have been estimated to be lower than 2%. The total systematic for the exposure is around 10% (6%) at  $10^{18} \text{ eV}$  ( >  $10^{19} \text{ eV}$ ). The energy spectrum obtained for hybrid events is shown in Fig. 3. The main systematic uncertainty is due to the energy scale, dominated by the uncertainty in the fluorescence yield (further details can be found in [<sup>5</sup>]).

#### 4 Combined energy spectrum

The hybrid energy spectrum has been combined with the regular SD spectrum, using a maximum likelihood method. Since the SD energy estimator is calibrated with hybrid events, the two spectra have the same systematic uncertainty 22%. On the other hand the uncertainties due to the normalization are independent, for the SD we have a 6% and we have a 10% (6%) for the hybrid flux at E=1 EeV (E=10 EeV). These normalization uncertainties are used as additional constraints in the combination process. This combination procedure is used to derive the scale parameters  $k_{SD} = 1.01$  and  $k_{FD} = 0.99$  which have to be applied to the individual spectra in order to match them.

The combined spectrum is shown in Fig. 4, the features of these spectra can be quantified.



Figure 3: Cosmic ray energy spectrum obtained from hybrid data of the Pierre Auger Observatory. Only statistical uncertainties are shown (68% CL).



Figure 4: Combined SD energy spectrum obtained from data of the Pierre Auger Observatory. The spectrum is fitted with power law functions (dotted line) and with power law + smooth functions (solid line),only statistical uncertainties are shown. The energy scale systematic uncertainty is 22%.

Here a parametrization is presented, which consists of three power laws with free breaks between them. The fitted power law has the form:  $J(E) \propto E^{-\gamma_i}$ , where gamma takes the values of  $\gamma_1 = 3.27 \pm 0.02$ ,  $\gamma_2 = 2.68 \pm 0.01$  and  $\gamma_3 = 4.2 \pm 0.1$ .

#### 5 Summary

Four independent measurements of the cosmic ray spectrum have been obtained. They are all in agreement at the 1.5% level. Those obtained for the higher energies, the regular and inclined SD spectra, start respectively at energy thresholds of 3 and 4 EeV. Both provide strong evidence of a suppression of the spectrum at energies above 50 EeV. The spectral index  $\gamma$  is 2.6 ± 0.02 in the energy range 6.3 – 45 EeV.

Spectra obtained with the infill array and the hybrid data start at 0.3 and 1 EeV respectively and have revealed a second feature, the ankle at an energy of 4 EeV. This is an interesting region since it could correspond to the transition between galactic and extragalactic cosmic rays. Although the high energy suppression takes place at the energy at which the GZK cutoff is expected to take place, it cannot be ruled out that it is due to limiting maximum energies that can be achieved in the acceleration sources.

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#### Search for ultra-high energy photons and neutrinos at the Pierre Auger Observatory

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The Pierre Auger Observatory is a hybrid ultra-high energy cosmic rays detector with a large collection area providing a good opportunity to search for photons and neutrinos. Previously published limits on neutrino and photon fluxes using data from the Observatory already provide stringent constraints on top-down models. In this contribution, current results on photon and neutrinos searches will be presented.

#### 1 Introduction

The nature and production mechanism of ultra-high energy cosmic rays (UHECRs) with energies above  $10^{18}$  eV are still unknown. The existence of ultra-high energy photons and neutrinos is expected as all models of UHECRs production predict neutrino and photon fluxes from the decay of charged and neutral pions produced through UHECRs interactions either with background radiation fields (known as cosmogenic or GZK neutrinos) or directly with matter or radiation at their sources. Important fluxes of photons and neutrinos have also been predicted by the so-called "top-down" models and have already been severely constrained by previous photon <sup>2,3</sup> and neutrino<sup>4</sup> searches. The observation of ultra-high energy (UHE) photons and neutrinos would bring important information about the nature and production mechanism of UHECRs as both point back to the production sites and could help to disentangle the origin of the flux cutoff observed above  $10^{19}$  eV, being a signature of the existence of the so-called GZK-cutoff. The Pierre Auger Observatory<sup>1</sup> was designed to study the flux, the composition and the arrival directions of UHECRs with high performance and unchallenged statistics though the detection of the extensive air showers (EAS) they produce within the atmosphere. Though the first role of the Pierre Auger Observatory is to detect UHECRs it has already demonstrated that it has a good sensitivity to UHE photons and neutrinos.

In this contribution, we describe a number of analyses searching for UHE photons and neutrino at the Pierre Auger Observatory. We present the identification criteria used to distinguish



Figure 1: (Left) Scatter plot of  $X_{\text{max}}$  vs  $\log_{10}(S_b)$  for proton (red crosses) and photon (empty blue circles) simulated showers with energy between  $10^{18}$  and  $10^{18.5}$  eV. (Right) Upper limits on the UHE photon flux compared to previous limits from Auger<sup>2,3</sup>, and other experiments<sup>5,6,7</sup> together with predictions from the GZK<sup>8</sup> and top-down models<sup>9</sup>.

neutrino and photon-induced showers from those initiated by UHECRs. Finally, without evidence of UHE photons and neutrinos within the Observatory's data, we present upper bounds to their fluxes.

#### 2 The Pierre Auger Observatory

The Pierre Auger Observatory, located near Malargiie, Argentina, consists of a Surface Detector Array (SD) of 1660 water-Cherenkov stations covering an area of 3000 km<sup>2</sup> arranged in a triangular grid with a 1.5 km step over a nearly flat surface at an altitude of ~ 1440 m asl. The SD is overlooked by the Fluorescence Detector (FD) composed of 27 fluorescence telescopes (FD) deployed over 4 sites. The SD samples the density of secondary particles of the shower at ground level providing data with ~ 100% lifetime, while the FD measures the shower longitudinal development in the atmosphere, working only on clear and moonless nights, corresponding to a ~ 13% duty cycle. Hybrid measurements combining both FD and SD provide data with high quality.

#### 3 Photons

Contrary to nucleon primaries, photons produce EAS mostly through electromagnetic interactions. Therefore, photon showers are expected to reach their maximum  $X_{\text{max}}$  at larger depths and to contain fewer secondary muons. Thus,  $X_{\text{max}}$  measurements provided by FD are key observable to distinguish photons from nucleon primaries. In addition, photons showers produce larger footprints at ground level and larger signals in individual stations. In order to improve the photon-hadron discrimination power, an observable which is sensitive to the size of the footprint and the different amplitudes of the signal in the surface detector has been introduced  $S_b = \sum_i S_i (R_i/R_{ref})^b$  where the sum runs over the triggered stations.  $S_i$  is the recorded signal in the station at distance  $R_i$  from the hybrid reconstructed axis and  $R_{ref}$  is a reference distance equal to 1000 m. The correlation between  $X_{\text{max}}$  and  $S_b$  is shown on Figure 1 (Left) for well reconstructed photon and proton simulated showers for  $E_{\gamma}$  in  $[10^{18}, 10^{18.5}]$  eV. To increase the discrimination power, a Fisher analysis  $^{10}$  based on  $X_{\text{max}}$  and  $S_b$  has been performed using  $\sim$  3000 detailed photon and proton Monte Carlo events. Photon-like events are thus selected by applying an "a priori" cut at 50 % of photon detection efficiency, corresponding to an expected background contamination of about 1% at  $E_{\gamma}$  in  $[10^{18}, 10^{18.5}]$  eV and decreasing with energy. In order to reject misreconstructed profiles, only time periods with cloud-free sky, and with reliable measurement of aerosol attenuation<sup>11</sup> are selected. On the SD side, only events with at

Selection	Earth-skimming	Down-going
	Number of Stations $\geq 3$	Number of Stations $\geq 4$
Inclined	L/W > 5	L/W > 3
	$0.29 \text{ m ns}^{-1} < \langle V \rangle < 0.31 \text{ m ns}^{-1}$	$\langle V \rangle < 0.313 \ {\rm m \ ns^{-1}}$
	$RMS(V) < 0.08 \text{ m ns}^{-1}$	$RMS(V)/\langle V \rangle < 0.08$
Young	ToT fraction $> 0.6$	AoP based Fisher

Table 1: Observables and numerical values of cuts applied to select *inclined* and *young* showers for Earthskimming and downward-going neutrinos. See text for explanation.

least 4 active stations within 2 km from the hybrid reconstructed axis are selected to prevent an underestimation of  $S_b$  due to missing or temporarily deficient detectors.

Applying the method to data from Jan 2005 to Sept 2010, 6, 0, 0, 0 and 0 photon candidates are found for energies above 1, 2, 3, 5 and 10 EeV. This result is consistent with background expectations based purely on a conventional cosmic ray beam with mixed nuclear composition. Upper limits at 95% C.L. on the integral photon flux of  $8.2 \times 10^{-2} \text{ km}^{-2} \text{ sr}^{-1} \text{y}^{-1}$  above 1 EeV and  $2.0 \times 10^{-2} \text{ km}^{-2} \text{ sr}^{-1} \text{y}^{-1}$  above 2, 3, 4 and 10 EeV are derived <sup>12</sup> and shown on figure 1 (Right). Comparing these flux limits to the measured Auger spectrum leads to upper bounds to the photon fraction of about 0.4%, 0.5%, 1.0%, 2.6% and 8.9% for energies above 1, 2, 3, 5 and 10 EeV. Total uncertainties on the flux upper limits are  $\frac{+20\%}{-64\%}$  above 1 EeV and  $\frac{+15\%}{-36\%}$  above 2, 3, 5 and 10 EeV.

#### 4 Neutrinos

With the SD of the Pierre Auger Observatory we can detect and identify UHE neutrinos in the EeV range and above. The main challenge here is to discriminate neutrino induced showers from the large background of nucleonic cosmic ray-induced showers. Protons, heavier nuclei and even photons interact high in the atmosphere while neutrinos, due to their low cross-sections can interact deep in the atmosphere (down-going, DG) or in the earth crust (Earth-skimming, ES). In both cases one can distinguish the signature of neutrino events by looking for very inclined showers produced close to the ground (*i.e.* young showers), exhibiting a significant electromagnetic component at observation level producing signals spread in time over hundreds of nanoseconds in the triggered SD stations. In contrasts, inclined UHECRs showers are dominated by muons at ground level (*i.e.* old showers). Two independent analyses were carried out to search for UHE $\nu$  in the zenith angle ranges 75° <  $\theta$  < 90° (DG analysis) and 90° <  $\theta$  < 96° (ES analyses).

Inclined showers produce an elongated pattern (*footprint*) of triggered stations at the ground. From this pattern we can extract a length L along the arrival direction of the event and a width W perpendicular to it: very inclined events exhibit large values of L/W. In addition, the apparent speed V of the trigger between each pair of stations for an inclined shower is concentrated around the speed of light. Considering young showers selection, the Time Over Threshold (ToT) local trigger (ES analysis) and the ratio between the Area (integrated signal) and the Peak value (AoP, DG analysis) are sensitive to signals spread in time. Within the ES analysis a given percentage of the stations passing the ToT condition is required whilst within the DG analysis a Fisher discriminant method <sup>10</sup> based on the AoP is used. A summary of the sets of cuts used for the selection of neutrino showers is shown on Table 1. Detailed MC simulations of both ES and DG neutrinos were performed to estimate the identification efficiencies and to train the Fisher analysis in combination with real data as a background training sample.

By proceeding to a blind search over the data collected by the SD from 1 Jan 2004 to 31 May 2010, no neutrino candidates were found <sup>13</sup>. Assuming a differential spectrum  $\phi(E_{\nu}) = dN_{\nu}/dE_{\nu} = k \cdot E_{\nu}^{-2}$  for the diffuse flux of UHE $\nu$  and no background, we proceed to place a 90% C.L. upper limit on the integral single flavor neutrino flux of  $k < 3.2 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ 



Figure 2: (Left) Differential and integrated upper limits at 90% C.L. to the diffuse flux of UHE $\nu$ s together with other experiments <sup>16,17</sup> and cosmogenic models <sup>18,19</sup>. (Right) Upper limits (90% C.L.) for the integral flux of neutrinos from a point-like source as a function of source declination.

based on ES neutrinos and  $k < 1.7 \times 10^{-7}$  GeV cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> based on DG neutrinos. These limits, which account for systematic uncertainties using the method from <sup>14</sup>, are represented in Figure 2 (Left) as two horizontal lines. They are valid in the energy range  $1.6 \times 10^{17}$  eV  $\leq E_{\nu} \leq$  $2.0 \times 10^{19}$  eV, where  $\simeq 90\%$  of neutrino events would be detected for a  $E_{\nu}^{-2}$  flux. The 90% C.L. upper limits in differential form (bins of width 0.5 in  $\log_{10} E_{\nu}$ ) are also shown in Figure 2 (Left).

The Pierre Auger Observatory is also sensitive to point-like sources of neutrinos over a broad range of declinations spanning north of  $\delta \sim -65^{\circ}$  and south of  $\delta \sim 55^{\circ}$ . Assuming a differential flux  $F(E_{\nu}) = k_{\rm PS}(\delta) \cdot E_{\nu}^{-2}$  and a 1 : 1 : 1 neutrino flavour ratio, the 90% C.L. upper limit on  $k_{\rm PS}$ for the ES and DG analysis are shown in Figure 2 (Right) as a function of source declination. The exposure to point sources and the corresponding limit derived at each  $\delta$  are evaluated in the same energy region and in a similar way as the diffuse exposure but without integrating over the solid angle<sup>15</sup>. These are the best limits around 1 EeV.

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#### THE NUCLEAR MASS COMPOSITION OF ULTRA HIGH ENERGY COSMIC RAYS WITH THE PIERRE AUGER OBSERVATORY

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The hybrid design of the Pierre Auger Observatory allows the measurement of the mass composition of cosmic rays through several independent methods. The atmospheric depth at which the longitudinal development of an Extensive Air Shower reaches its maximum,  $X_{max}$ , is sensitive to the nuclear mass composition of the primary cosmic ray. The  $X_{max}$  can be measured directly by the Fluorescence Detector (FD), but other composition sensitive variables can be independently evaluated by the Surface Detector (SD). Here are presented the results for the mean value and RMS of  $X_{max}$  distributions for  $E > 10^{18}$  eV. Mass composition results measured by the SD are also shown. All results are compared with the predictions of several hadronic models for different nuclear masses.

#### 1 Introduction

The nuclear mass composition of Ultra High Energy Cosmic Rays (UHECR) is inferred through the detection of Extensive Air Showers (EAS). Since the first interactions in EAS occur at energies more than order of magnitude above those achieved by man-made particle accelerators, the nuclear mass composition can only be interpreted based on high energy hadronic interaction model predictions.

The main engine behind the whole EAS development is the hadronic cascade, consisting mainly of pions. While neutral pions decay almost immediately into photons, generating electromagnetic sub-showers which constitute the bulk of the particles in the EAS, charged pions can either reinteract further in the atmosphere, feeding the hadronic cascade or decay into muons. These muons propagate in nearly straight lines to the ground providing valuable and unique information about the hadronic cascade,<sup>1</sup>. The longitudinal development of the shower can be studied by the fluorescence light emitted by nitrogen air molecules after being excited by the shower electrons. The slant depth at which the longitudinal shower profile reaches its maximum,  $X_{max}$ , reflects the cosmic ray nuclear mass composition since it is sensitive to the cross section of the first interaction, <sup>2,3</sup>. The arrival time structure and particle density at ground are also mass composition sensitive variables, <sup>4,5</sup>.

The Pierre Auger Observatory is located in the Pampa Amarilla site ( $69^{\circ}$  W,  $35^{\circ}$  S, 1400 m a.s.l.) in Argentina. It consists of a Surface Detector Array (SD) with 1660 water-Čerenkov detectors disposed over an area of 3000 km<sup>2</sup> and a Fluorescence Detector (FD) constituted by 27 telescopes, housed at five sites, which overlook the atmosphere above the array. While the

SD registers the time structure and particle densities at ground with very high statistics, the FD makes direct measurements of the longitudinal development of the shower from which the shower energy is measured with high precision. The events detected simultaneously by the FD and the SD are called *hybrid events* and yield better arrival direction resolution  $(0.6^{\circ})$  and energy reconstruction than the events observed by one detector alone, <sup>6</sup>.

We present the Pierre Auger Observatory results for the measurements of cosmic ray composition, namely the depth of the shower maximum, the asymmetry of the signal rise time and the production depth of the muons.

#### 2 The depth of shower maximum of the electromagnetic profile

A detailed description of this analysis is given in <sup>7</sup> and an update, with 80% more statistics, is presented in <sup>8</sup>. The data set consists of hybrid events with  $E > 10^{18}$  eV recorded between December 2004 and September 2010. Quality cuts require that the events are recorded under good atmospheric conditions and with good geometry reconstruction, also that the measured  $X_{max}$  is inside the telescope field of view and its statistical uncertainty is below 40 g/cm<sup>2</sup>. Finally, a Gaisser-Hillas fit is made to the longitudinal profile and events with  $\chi^2/NDF > 2.5$ are rejected. A second set of cuts is further applied in order to remove possible biases regarding the cosmic ray mass composition. From the total of 15979 events passing all the quality cuts, 42% pass the second set of cuts.

The  $X_{max}$  resolution is 20 g/cm<sup>2</sup>, the total systematic in  $\langle X_{max} \rangle$  ranges from 10 g/cm<sup>2</sup> to 13 g/cm<sup>2</sup> with increasing energy. The  $RMS(X_{max})$  resolution goes from 27 g/cm<sup>2</sup> to 18 g/cm<sup>2</sup> with increasing energy and the systematic uncertainty is 5 g/cm<sup>2</sup>. The elongation rate curve  $D_{10} = d \langle X_{max} \rangle / dlogE$  is best described by fitting two slopes with a break at  $log(E/eV) = 18.38^{+0.07}_{-0.17}$ . At low energies the slope is  $D_{10} = 82^{+48}_{-8}$  g/cm<sup>2</sup>/decade and for high energy the slope becomes  $D_{10} = 27^{+3}_{-8}$  g/cm<sup>2</sup>/decade. The  $RMS(X_{max})$  decreases gradually with energy from 55 g/cm<sup>2</sup> to 26 g/cm<sup>2</sup>.

A typical longitudinal profile is shown in figure 1 at the bottom of the left panel and the  $\langle X_{max} \rangle$  and  $RMS(X_{max})$  results are shown in the two bottom plots on the right panel. Data are represented by the black dots and the systematic uncertainty of the measured variables is given by the gray bands. The lines indicate the predictions of several hadronic models for the cases of a pure cosmic ray composition of proton and iron nuclei. If model predictions are correct, the results are compatible with a very light or mixed nuclear mass composition at the lowest energies while at the highest energies a predominance of heavier elements, like CNO, is favored.

#### 3 Risetime Asymmetries

The method, described in detail in <sup>4</sup>, uses the signal risetime  $(t_{1/2})$ , i.e. the time taken for the signal to go from 10% to 50% of the total signal, measured by each SD station. The risetime reflects the stage of the shower development and depends on the distance to the shower maximum, the zenith angle ( $\theta$ ) and the distance to the shower core. For showers in the 30°  $\leq \theta \leq 60^{\circ}$  region, the average risetime depends on the azimuthal angle  $\zeta$ , defined on the shower plane, being given by  $\langle t_{1/2}/r \rangle = a + bcos\zeta$ . b/a is the polar asymmetry amplitude of the signal and varies with  $sec(\theta)$  (Fig. 1 middle image of the left panel). The variable XAsymMax, the value of  $sec(\theta)$  for which b/a is maximum, is sensitive to the primary mass composition. This analysis uses SD events recorded between January 2004 and December 2010 with  $\theta \leq 60^{\circ}$ and  $E > 3.16 \times 10^{18} \text{ eV}$ , <sup>9</sup>. A total of 18581 events were selected. The events are then grouped into bins of energy and  $sec(\theta)$  and the XAsymMax is obtained. The systematic uncertainty in XAsymMax is  $\leq 10\%$ . The XAsymMax results (denoted in the figure by  $\Theta_{max}$ ), are shown


Figure 1: Left panel, top: muon production depth. Middle: average asymmetry in the signal rise-time. Bottom: longitudinal development of energy deposited. Right panel: Results on shower evolution sensitive observables compared with model predictions. The error bars are the statistical uncertainty while systematic uncertainty is represented by the shaded bands.

in the second plot of the right panel. Provided that models give a fair description of ultra-high energy interactions, it can be seen that, as for the  $X_{max}$  measurements, the risetime asymmetry data shows a consistency with a composition of heavier nuclei at higher energies.

## 4 Muon Production Depth (MPD)

As described in <sup>10</sup> the muonic production profile for each event can be reconstructed from the relation between the arrival time delay of muons with respect to the shower front and the point of its production in the atmosphere. Information about the muon arrival time was taken from the signal FADC traces from the SD stations. This analysis uses SD events recorded between January 2004 and December 2010 having  $55^{\circ} \leq \theta \leq 65^{\circ}$  and  $E > 2 \times 10^{19}$  eV, <sup>11</sup>. In order to have a good time resolution of the single muons only stations at a distance of r > 1800 m are selected. In order to avoid SD stations triggered by accidental muons, only stations with a signal larger than three times that of a vertical muon are accepted. The shape of the MPD is well fitted by a Gaisser-Hillas function and the maximum of the muon profile,  $X_{max}^{\mu}$ , is sensitive to the nuclear mass composition, <sup>11</sup>. From the initial set of 417 events, 244 survive all the cuts. The systematic uncertainty of  $\langle X_{max}^{\mu} \rangle$  is 11 g/cm<sup>2</sup>, corresponding to 14% of the proton-iron separation predicted by the models. A muon production depth profile of a real event is shown in figure 1 at the top of the left panel, the  $\langle X_{max}^{\mu} \rangle$  results are depicted at the top of the right panel. It can be seen that the  $X_{max}^{\mu}$  results show the same trend towards a heavier mass composition at higher energies.

# 5 Conclusions

Although all methods presented below are independent to each other and present different systematic uncertainties, the data interpretation yields similar results. Providing that the current models give a fair description of particle interaction at ultra-high energies, the Auger data are consistent with a gradual increase of the average mass composition of cosmic rays at higher energies. However, different interpretations are not excluded given the uncertainties of particle production at the energies of interest.

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# Cosmic ray anisotropies studies at EeV energies with the Pierre Auger Observatory

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We present recent results from cosmic ray anisotropy searches in the EeV energy range with the Pierre Auger Observatory. Methods and results of large scale anisotropy searches in all directions by means of multipolar analysis are presented. Blind searches for EeV neutron galactic point sources performed with the Pierre Auger Observatory data are also discussed.

# 1 Introduction

Measuring the energy of transition at which cosmic rays are no longer of galactic origin but are dominantly extragalactic would be of great help in the understanding of their origin. It is thought that the ankle, a feature in the spectrum at 4 EeV ( $1 \text{ EeV} = 10^{18} \text{ eV}$ ) may be a signature of this transition<sup>1</sup>. At these energies, the deflection of charged particles in the galactic magnetic field prevent us from pointing back to the source of cosmic rays on small angular scales. However, large scale patterns could be imprinted in the flux received on earth if, for instance, the sources are located in the galactic disk. Furthermore, if EeV neutrons are produced along with protons in  $\Delta^+$  resonance with a sufficient flux in galactic sources, they may reach earth before decaying and give rise to an excess in the direction of the source.

The Pierre Auger Observatory is located in the province of Mendoza (latitude  $35.2^{\circ}$  S and longitude  $69.5^{\circ}$  W). It is composed of a Surface Detector (SD), a  $3000 \text{ km}^2$  array of 1660 water-Cherenkov detectors sampling air shower particles at the ground and of 27 telescopes installed on 5 sites, the Fluorescence Detector (FD), that measure shower development in the air by observing fluorescence light. We present here the method and results of a large scale anisotropy<sup>2</sup> search and small scale neutron directional search <sup>3</sup> in Pierre Auger SD data at energies around the ankle.



Figure 1: Left: Right ascension of the dipole direction of the cosmic ray anisotropy under a dipole assumption. Right:  $\beta$  parameter of quadrupole amplitude (see text).

# 2 Large scale anisotropies

For sources located in the galactic disk and for widely accepted assumptions on the galactic magnetic fields, a dipolar anisotropy at a level of few % for heavy primaries, and even larger for light ones, could be imprinted in the flux of cosmic rays up to EeV energies. An extragalactic origin, in contrast, could lead to an almost isotropic distribution of arrival directions on earth. Upper limits of 2% at a 99% C.L. on a dipole component in the equatorial plane have been derived for EeV energies<sup>4</sup>. We present here a search for large scale arrival direction patterns in two dimensions sensitive to a dipole or a quadrupole component, in any direction.

The general method is to expand the cosmic ray flux directions in spherical harmonics. Since the flux observed in any direction is distorted by the coverage function of the Auger observatory, it is critical to control accurately both the coverage function and any systematic uncertainties influencing the counting rate above a fixed energy threshold, especially when searching for anisotropies with relative amplitudes down to % level. Detailed studies can be found in<sup>2</sup>.

#### 2.1 Calculation of the event rate and exposure

The data set analyzed consists of events recorded by the Surface Detector (SD) from 1 January 2004 to 31 December 2011 with zenith angle less than  $55^{\circ}$ . To ensure a good event reconstruction, an event is accepted if all six nearest neighbors of the water-Cherenkov detector with the highest signal were operational at the time of the event.<sup>5</sup>. Due to the steepness of the energy spectrum, any mild bias in the estimate of the shower energy with time or incident angle can lead to significant distortions of the directional event counting rate. To keep these effects under control, the shower energy estimation is performed in two steps. First, the signal recorded by the SD is corrected for atmospheric effects and the distortion due to the geomagnetic field on the charged particles of the air shower. Then the corrected signal is converted into the primary energy using a calibration based on Fluorescence Detector calorimetric studies.

To compute the celestial directional exposure, the array is divided in elemental cells of geometrical aperture  $a_{cell}(\theta) = 1.95 \cos(\theta) \,\mathrm{km}^2$ . The total number of elemental cells is recorded every second so that array growth and dead periods of each detector are accounted for. The small modulations in time imprinted in the event counting rate by experimental effects are accounted for by weighting each event with a factor inversely proportional to the relative variation of the cell number in right ascension. At any time, the effective directional aperture of the SD array is controlled by geometry one and the detection efficiency function  $\epsilon(\theta, \phi, E)$ :

$$\omega(\delta, E) = \sum_{i=1}^{n_{cell}} x^i \int_0^{24h} d\alpha' a_{cell}(\theta(\alpha', \delta)) \times \epsilon(\theta(\alpha', \delta), \phi(\alpha', \delta), E)$$
(1)

where  $x^i$  is the operational time of the cell (i) and  $\alpha' = \alpha - \alpha_0$  is the right ascension referenced to the local sidereal time at the center of the array  $\alpha_0$ . Above 3 EeV the array is fully efficient and below this threshold, the efficiency is calculated empirically. Other effects like the spatial extension of the array during deployment and the small tilt of the array are accounted for in the calculation of exposure.

#### 2.2 Search for large scale pattern

The search for a large scale angular pattern is performed by expanding the arrival direction distribution on spherical harmonic functions:

$$\Phi(\mathbf{n}) = \sum_{l \ge 0} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\mathbf{n}) \text{ where } a_{lm} = \int_{4\pi} \mathrm{d}\Omega \ \Phi(\mathbf{n}) Y_{lm}(\mathbf{n})$$
(2)

Due to the incomplete coverage of the Pierre Auger Observatory in declination angle, the  $a_{lm}$  coefficients cannot be retrieved directly. Instead, we expand the rate i.e. the product of the flux and the coverage :  $\bar{b}_{lm} = \int_{\Delta\Omega} d\Omega \frac{dN(\mathbf{n})}{d\Omega} Y_{lm}(\mathbf{n})$ , where  $\frac{dN(\mathbf{n})}{d\Omega}$  is the distribution of arrival directions of N events. Then, if the multipolar expansion of the angular distribution  $\Phi(\mathbf{n})$  has no higher moments than  $l_{max}$ , the first  $b_{lm}$  coefficients with  $l \leq l_{max}$  are related to the non-vanishing  $a_{lm}$  by a square matrix whose coefficients are fully determined by the coverage function <sup>6</sup>.

A large scale pattern search was performed assuming first a pure dipolar distribution. The dipole amplitude shows no significant deviation from what would be expected from an isotropic flux. However, the dipole direction for all energy bins points to an excess region in the southern hemisphere and its right ascension shows a smooth variation with energy illustrated in Fig. 1 (left). This trend was also observed with first harmonic analysis in right ascension<sup>4</sup> and motivated a prescription aimed at establishing at 99% C.L. whether this consistency in phase is real. Assuming, in a second stage, that the cosmic ray flux is modulated by a quadrupolar pattern in addition to the dipolar one, the flux can be parameterized as :

$$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi} (1 + r\mathbf{d} \cdot \mathbf{n} + \lambda_+ (\mathbf{q}_+ \cdot \mathbf{n})^2 + \lambda_0 (\mathbf{q}_0 \cdot \mathbf{n})^2 + \lambda_+ (\mathbf{q}_- \cdot \mathbf{n})^2)$$
(3)

where r and d are the dipole amplitude and direction and  $\mathbf{q}_+$ ,  $\mathbf{q}_-$ ,  $\mathbf{q}_0$  are three vectors defining the quadrupole orientation with the corresponding amplitudes  $\lambda_+$ ,  $\lambda_-$ ,  $\lambda_0$ . We define the quadrupole amplitude  $\beta \equiv (\lambda_+ - \lambda_-)/(2 + \lambda_+ + \lambda_-)$  which is a measure of maximal anisotropy contrast in the case of a pure quadrupole. Its estimated amplitude is shown in Fig. 1 (right) as a function of energy with the 99% C.L. upper bounds on the quadrupole amplitude that could result from fluctuations of an isotropic distribution being indicated by the dashed lines. Throughout the energy range, no significant evidence for anisotropy was found under the quadrupole assumption.

# 3 Neutron search

Neutron primaries induce air showers indistinguishable from proton ones. However, they are not deflected by magnetic fields and would point back to the sources where they are produced. Their mean travel distance before decaying is  $d = 9.2 \times \frac{E}{(EeV)}[kPc]$  with E the neutron energy. Thus, above 2 EeV, the volume for detectable neutron emitters includes most of the Galaxy. One indication of the presence of neutrons in data would be revealed by an excess in arrival directions within a small angular scale.

A blind search for any excess was performed in a data set of SD events recorded from 1 January 2004 to 30 September 2011 with zenith angles less than  $60^{\circ}$  and with the same quality cuts on reconstruction previously mentioned in section 2. The data set was divided into four energy bins: ([1 - 2] EeV, [2 - 3] EeV,  $E \ge 3$  EeV and  $E \ge 1$  EeV ). The sky was divided into target areas of optimized size according the angular resolution of the Auger SD array. The target size



Figure 2: Left: Li-Ma significance distribution for the energy bin [1 - 2] EeV. Right: Neutron mean flux upper limit averaged over targets in 3° bands of declination for the four energy bins considered in the analysis.

ranges from  $1.36^{\circ}$  for 1-2 EeV to  $0.69^{\circ}$  for  $E \geq 3 \text{ EeV}$ .

To recognize an excess in a target, isotropic distributions were simulated and compared to data. The statistical significance of an excess in a given target was estimated by means of the number of observed events, the number of expected events from an isotropic distribution and the Li-Ma<sup>7</sup> parameter, defined in this analysis as the expected number in the target divided by the number of events in the remainder of the sky. The distribution of Li-Ma significance for one energy bin is shown Fig. 2 (left). In the four scanned energy bins, no deviation from the expectation for an isotropic distribution was revealed. Upper limits on the neutron directional flux, shown Fig. 2 (right), can thus be computed as a function of declination in 3° band. The definition of the upper limit is that of Zech<sup>8</sup> and is discussed in more details in <sup>3</sup>. For  $E \geq 1$  EeV, the median limit in the exposed sky is found to be  $1.14 \times 10^{-2}$  neutron km<sup>-2</sup> year<sup>-1</sup> that corresponds to an energy flux limit of  $8.3 \times 10^{-2}$  eV cm<sup>-2</sup> s<sup>-1</sup>.

## 4 Conclusion

The search for large scale anisotropies at energies from 1 to 10 EeV showed an interesting consistency in the dipole phase, but no significant deviation from isotropy in dipole amplitude or under the quadrupolar assumption. The search for a localized excess at EeV energies and above did not reveal any deviation from isotropy, and upper limits on neutron flux could be established. These results allow us to challenge astrophysical scenarios at EeV energies in which light particles are emitted in all directions by continuous sources in the Galaxy.

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# The isotropy problem of Ultra-high energy cosmic rays: the effects of anisotropic transport

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Time dependent anisotropic transport of ultra-high energy cosmic rays (UHECRs) from pointlike sources in the Galaxy is calculated in various ways. To fully account for the discreteness of UHECR sources in space and time, the Monte Carlo method is used to randomly place sources in the Galaxy and calculate the anisotropy of UHECR flux, given specific realisations of source distribution. We show that reduction in the rate of cross-field transport reduces the anisotropy. However, if the cross-field transport is very small, drift of UHECRs in the Galactic magnetic field (GMF) becomes the dominant contributor to the anisotropy. The surprisingly low anisotropy measured by Auger can be interpreted as intermittency of UHECR sources, without invoking a flat source distribution and/or a high source rate.

# 1 Introduction

It is widely suspected that the abrupt flattening of the cosmic ray (CR) spectrum above 4 EeV, the so-called ankle<sup>1</sup> of the CR spectrum, is due to transition from the Galactic to extragalactic sources. The sources of EeV UHECRs is still an open question. Blast waves from supernova remnants are believed to be unable to accelerate CR protons to energy beyond  $10^{14.5}$  eV<sup>2</sup>, though Jokipii<sup>3</sup> has argued that higher energies may be attainable on equatorial drift trajectories if the magnetic field is sufficiently ordered. As proposed by Levinson and Eichler<sup>4</sup>, GRBs occurring in our Galaxy are possible sources for CRs up to the ankle. Once injected by the sources, propagation of CRs from source to the Earth would depend only on the interaction of CRs with the interstellar medium regardless of the nature of the sources.

Recently Auger collaboration<sup>5</sup> published their measurement of large scale anisotropy in the arrival direction of UHECRs. In a previous paper Pohl and Eichler<sup>6</sup> (henceforth referred to as PE11) showed that the anisotropy predicted by an isotropic diffusion model due to discrete sources in the Galaxy is on average much higher than the measured value. The premises of their model led the authors to conclude that a) the mean free path of the UHECRs is small compared to the proton Larmor radius, or b) intermittency is an important factor and we are living in a rare lull in UHECR production, or c) majority of sub ankle CRs have extragalactic origin. Estimates of anisotropy in several other models<sup>7,8</sup> are also higher than the observed limit for light sub-ankle primaries. We refer to this discrepancy between measured value and theoretical models as the UHECR isotropy problem.

In this paper we consider gyration of CR protons in the GMF which makes their transport anisotropic. We show that reduced cross-field transport significantly reduces the anisotropy of UHECRs compared to the isotropic diffusion model discussed in PE11, and appears to strengthen the case for intermittency as an answer to the isotropy problem. Specifically, the expected anisotropy is higher than observed even for anisotropic diffusion, but the probability is increased that downward fluctuations, either due to lulls in production or due to nearby sources that offset the expected global Galactic anisotropy, will bring the instantaneous anisotropy into accord with observations. We further show that when drift of UHECRs in the GMF is taken into consideration, total anisotropy increases significantly, partially cancelling the reduction due to anisotropic transport.

#### 2 propagation of UHECRs from galactic GRBs: anisotropic diffusion

The turbulent GMF causes UHECRs to scatter and the propagation of charged CRs in the turbulent GMF is governed by the diffusion equation. The turbulence in the GMF is assumed to be isotropic. The regular component of the GMF (directed along the spiral arms), however, breaks the isotropy of diffusion and cross field transport of CRs is reduced<sup>9</sup> due to the gyration of UHECR protons.

We assume the classical scattering limit for the diffusion of charged particles in a magnetic field, that is to say CRs spiral in the regular GMF between instantaneous isotropic scattering events. In this limit, diffusion coefficients parallel and perpendicular to the magnetic field at any given energy are  $D_{\parallel} = c \lambda_{mfp}/3$  and  $D_{\perp} = c \lambda_{mfp}/[3(1 + \lambda_{mfp}^2/r_L^2)]$  respectively <sup>10</sup>, where  $r_L$  is Larmor radius, c is the speed of light, and  $\lambda_{mfp}$  is the mean distance travelled by UHECRs between two subsequent random scattering events. This implies that  $D_{\parallel} \propto 1/D_{\perp}$  (it could be that  $D_{\parallel}$  and  $D_{\perp}$  are weakly correlated due to the complicated magnetic field lines in the Galaxy, so we keep our discussion more general and treat  $D_{\parallel}$  and  $D_{\perp}$  as two independent parameters).

At  $10^{18}$  eV the composition of UHECRs is light, though not necessarily dominated by protons  $^{11,12}$ . Here we assume that UHECRs in the 1-4 EeV energy band is mostly protons. A heavier composition of average nuclear charge Z at energy  $E_Z$  would behave like a proton dominated UHECRs of energy  $E = E_Z/Z$ , and would imply a lower anisotropy than a proton dominated UHECRs at the same energy. As in PE11, we use Larmor radius of protons in 10  $\mu G$  as a scale in this paper.

### 2.1 Anisotropy

The anisotropy in the UHECR intensity arises from the diffusive flux and is given by

$$\begin{split} \delta &= \frac{I_{max} - I_{min}}{I_{max} + I_{min}} &\simeq \left| \lambda_{\perp} \frac{\partial N_{tot}}{\partial \rho} \hat{\rho} + \lambda_{\parallel} \frac{\partial N_{tot}}{\rho \partial \phi} \hat{\phi} \right| / \left( N_{tot} \\ &+ \frac{\lambda_{\perp}^2}{2\rho} \frac{\partial}{\partial \rho} \rho \frac{\partial N_{tot}}{\partial \rho} + \frac{\lambda_{\parallel}^2}{2\rho^2} \frac{\partial^2 N_{tot}}{\partial \phi^2} \right), \end{split}$$
(1)

where  $\lambda_{\parallel} = 3D_{\parallel}/c$ ,  $\lambda_{\perp} = 3D_{\perp}/c$ , and  $N_{tot}$  is the total density of UHECRs after summing the contributions of all GRBs that occurred in recent past.

To fully account for the discreteness of UHECRs sources in space and time, we use the Monte Carlo method to randomly place sources in the Galaxy with the given spatial probability distribution in galactocentric radius,

$$P(\rho_{GC}) = \frac{2\rho_{GC}}{\rho_0^2} \exp\left(-\frac{\rho_{GC}^2}{\rho_0^2}\right) \tag{2}$$

with scale  $\rho_0 = 5$  kpc. This distribution is an approximation to the distribution of baryons and star formation in the Galaxy, which are reasonable proxies for the distribution of GRBs in the Galaxy.

Assuming by way of example that a GRB occurs in the Galaxy in every 1 Myr with the spatial distribution  $P(\rho_{GC})$ , we have plotted in figure 1 the temporal variation in the radial (i.e. galacto-radial) anisotropy for UHECR for three different choices of diffusion parameters; case 1:  $D_{\perp} = D_{\parallel} = cr_L/3$ , case 2:  $2D_{\perp} = D_{\parallel} = cr_L/3$ , and case 3:  $10D_{\perp} = D_{\parallel}/3 = cr_L/3$ . Case 1 is isotropic diffusion with  $\lambda_{mfp} = r_L$ , while in case 2 and 3 mean free path is  $r_L$  and  $3r_L$ 





Figure 1: Temporal variation of the anisotropy and the mean anisotropy are shown for three different choices of diffusion parameters. case 1(red):  $D_{\perp} = D_{\parallel} = cr_L/3$  (isotropic diffusion); case 2(blue):  $2D_{\perp} = D_{\parallel} = cr_L/3$ ; case 3(green): $10D_{\perp} = D_{\parallel}/3 = cr_L/3$ . Dashed lines of corresponding colors indicates the mean anisotropies and the solid lines are the mean anisotropies after adding the contribution from diamagnetic drift (the green dashed line coincides with the blue solid line). The black bar on the right of the figure indicates the measured 99% upper limit by the Auger collaboration.

respectively with  $D_{\parallel}$  and  $D_{\perp}$  consistent with the classical scattering limit. Here the halo size is H = 5 kpc and anisotropies are shown for UHECRs of energy 2.4 EeV. As evident from figure 1, the mean of anisotropy decreases with the decrease in  $D_{\perp}$ .

#### 2.2 Drift in the Galactic Magnetic Field

UHECRs, as a gas of protons of number density N, collectively drift in an inhomogeneous magnetic field **B**. The drift velocity, up to the first order in anisotropy, can be approximated by  $E(\nabla N \times \mathbf{B})/3qNB^2$ , which is also known as diamagnetic drift<sup>13</sup>. For UHECRs of energy several EeV, drift can have non-negligible contribution to the anisotropy. Since the GMF is assumed to be toroidal, drift would produce anisotropy in the direction perpendicular to the Galactic plane, proportional to the radial anisotropy. The mean of total anisotropy after adding UHECRs drift at Earth's location is shown in figure 1 as dashed lines. Drift is not significant for isotropic diffusion, but as the rate of transport in the radial direction decreases $(D_{\perp} \ll cr_L/3)$  drift becomes the dominant contributor to the total anisotropy as compared to the radial anisotropy, implying that the reduction in the cross-field transport can not reduce the anisotropy indefinitely.

# 3 Conclusions

We have calculated the time-dependent transport of UHECRs from a point-like instantaneous GRBs, assuming that the transport rates are different along and across the toroidal GMF (isotropic diffusion, discussed in PE11, being a special case when both are equal). We showed that the regular component of the GMF would make the transport of UHECRs in the Galaxy anisotropic with respect to their sources, which in turn would affect the observed anisotropy of UHECR flux at Earth. Making the diffusion anisotropic bring the UHECRs flux anisotropy down but as the diffusion becomes anisotrpic drift of UHECRs in the GMF contributes significantly to the total anisotropy and must be taken into account. We show that even after adding the drift, the anisotropic diffusion scenario bring the anisotropy down significantly compared to the isotropic diffusion. More specifically, Anisotropy in the 2-4 EeV energy band remains below the observed limit about 40% of the time compared to the 20% in case of isotropic diffusion.

We conclude that anisotropic diffusion combined with the intermittency of the sources enhances the chances of observing the surprisingly low anisotropy as measured by Auger collaboration.

## 4 Acknowledgement

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### Effect of LHC data on Extensive Air Shower Development

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The uncertainty in the prediction of shower observables for different primary particles and energies is currently dominated by differences between hadronic interaction models. Since the end of 2009, LHC data have become available for proton-proton scattering at different energies, extending the reach of collider data. The LHC data on minimum bias measurements has been used to test and improve Monte Carlo generators and these new constrains reduce the uncertainties in air shower predictions. In this contribution, we will show the results of the comparison between the newly available hadronic interaction models EPOS LHC and QGSJETII-04 and LHC data. Implications for air shower simulations will be discussed.

## 1 Introduction

Most of the Astronomy and Astrophysics is done using electromagnetic signals from radio to gamma rays. It gives precious informations on the various objects observed in the Universe and their history. In fact a part of these signals is produced by elementary charged particles like electrons or nuclei which can escape the source and reach the Earth after a long propagation through the (extra)galactic medium. Eventually these charged particles may cross the path of the Earth and enter our field of view: they are cosmic rays. Due to the steeply falling energy spectrum of cosmic rays, direct detection by satellite- or balloon-borne instruments is only possible up to about ~  $10^{14}$  eV. Fortunately, at such high energies, the cascades of secondary particles produced by cosmic rays reach the ground and can be detected in coincidence experiments. The cascades are called extensive air showers (EAS) and are routinely used to make indirect measurements of high energy cosmic rays. The upper limit of the detectable energy is given by the area and exposure time of the detector. For instance, the Pierre Auger Observatory (PAO)<sup>1</sup>, which is currently taking data in Argentina, is designed to detect particles of ~  $10^{20}$  eV for which the flux is less than one particle per km<sup>2</sup> and century.

As a consequence of the indirect character of the measurement, detailed simulations of air showers are needed to extract information on the primary particle from shower observables. Indeed the cascade is initiated by a first hadronic interaction between the initial charged primary cosmic ray and one nucleus from the atmosphere. After their propagation limited by their cross section, the secondary hadronic particles will interact again forming the hadronic cascade which is the skeleton of the EAS. At each hadronic interaction about one third of the energy goes into the  $\pi^0$  which immediately decay into two photons feeding the electromagnetic cascade. After few hadronic generations, more than 90% of the energy of the primary particle is carried by the electromagnetic component of the EAS. Whereas electromagnetic interactions are well understood within perturbative QED, hadronic multi-particle production cannot be calculated within QCD from first principles. Differences in modelling hadronic interactions, which cannot be resolved by current accelerator data, are the main source of uncertainty of air shower predictions<sup>2,3</sup>.

In this article, we will discuss changes in the hadronic model predictions after LHC data and

their consequences on air shower observables. In the first section, we will explain the so-called Heitler model to extract from a simple toy model the main hadronic observables which drive the development of air showers. We will then compare the results of the hadronic interaction models with LHC data for such observables. Finally using detailed Monte Carlo simulations done with CONEX<sup>4</sup>, the new predictions for  $X_{max}$  and for the number of muons will be presented.

### 2 Heitler's Model

To qualitatively describe the dependence of shower development on some basic parameters of particle interaction, decay and production, a very simple toy model can be used. Although initially developed for electromagnetic (EM) showers<sup>5</sup> it can also be applied to hadronic showers<sup>6</sup>.

#### 2.1 Electromagnetic showers

For simplicity, instead of having three particle types  $(\gamma, e^+ \text{ and } e^-)$  like in electromagnetic showers, we will consider only one particle with energy E with only one EM interaction producing two new particles with energy E/2 after a fixed interaction length of  $\lambda_e$ , see Fig. 1.



Figure 1: Schematic view of electromagnetic cascades.

Figure 2: Schematic view of hadronic cascades. Dashed lines represent neutral particles  $(\pi^0)$  and solid lines charged particles  $(\pi^{\pm})$ . Only one charged hadron interaction is shown for each generation.

Denoting with n the number of generations (consecutive interactions), the number of particles at a given depth  $X = n \cdot \lambda_e$  follows from

$$N(X) = 2^n = 2^{X/\lambda_e},\tag{1}$$

with the energy E per particle for a given primary energy  $E_0$  being

$$E(X) = \frac{E_0}{2^{X/\lambda_e}}.$$
(2)

Defining the critical energy  $E_c$  (~ 85 MeV in air) as the energy below which energy loss processes dominate over particle production, one can make the assumption that the shower maximum is reached at a depth at which the energy of the secondary particles reaches  $E_c$ . Then two main shower observables are given by

$$N_{\max} = \frac{E_0}{E_c} \quad \text{and} \quad X^e_{\max}(E_0) \sim \lambda_e \cdot \ln\left(\frac{E_0}{E_c}\right). \tag{3}$$

This simplified picture does not reproduce the detailed behavior of an EM shower, but two important features are well described: the number of particles at shower maximum is proportional to  $E_0$  and the depth of shower maximum depends logarithmically on the primary energy  $E_0$ .

### 2.2 Hadronic showers

Generalizing this idea, a hadronic interaction of a particle with energy E is assumed to produce  $n_{\rm tot}$  new particles with energy  $E/n_{\rm tot}$ , two thirds of which are charged particles  $n_{\rm ch}$  (charged pions) and one third are neutral particles  $n_{\rm neut}$  (neutral pions), as shown Fig. 2. Neutral particles decay immediately into EM particles ( $\pi^0 \rightarrow 2\gamma$ ). After having travelled a distance corresponding to the mean interaction length  $\lambda_{\rm ine}$ , charged particles re-interact with air nuclei if their energy is greater than some typical decay energy  $E_{\rm dec}$ .

#### Shower maximum

Even in an air shower initiated by a hadron, most of the energy is carried by EM particles (~ 90% for n = 6). Hence the depth of shower maximum is given by that of the EM shower component,  $X_{\text{max}}^{e}$ . As the first hadronic interaction produces EM particles of energy ~  $E_0/n_{\text{tot}}$  one gets

$$X_{\max}(E_0) \sim \lambda_{\text{ine}} + X^e_{\max}(E_0/n_{\text{tot}})$$
 (4)

$$\sim \lambda_{\rm ine} + \lambda_e \cdot \ln\left(\frac{E_0}{n_{\rm tot}E_c}\right),\tag{5}$$

where  $\lambda_{\text{ine}}$  is the hadronic interaction length. This simplified expression for the depth of maximum neglects the EM sub-showers initiated by hadrons of later generations. The inclusion of higher hadronic generations does not change the structure of Eq. (5), only the coefficients change (see, for example, <sup>7</sup>).

# Muon component

To keep the picture simple, we assume that all charged hadrons decay into muons when their energy reaches  $E_{\text{dec}}$ . In a real shower, this limit can be seen as the characteristic energy where interaction length and decay length of charged pions are similar (about 150 GeV for pions). By construction, charged particles will reach the energy  $E_{\text{dec}} = \frac{E_0}{(n_{\text{tot}})^n}$  after *n* interactions. Since one muon is produced in the decay of each charged particle, we get

$$N_{\mu} = n_{\rm ch}^n = \left(\frac{E_0}{E_{\rm dec}}\right)^{\alpha},\tag{6}$$

with  $\alpha = \ln n_{\rm ch} / \ln n_{\rm tot} = 1 + \ln R / \ln n_{\rm tot} \approx 0.82 \dots 0.95^7$  where  $R = n_{\rm ch} / n_{\rm tot} < 1$ . The number of muons produced in an air shower depends not only on the primary energy and air density, but also on the total particle multiplicities and in a much more sensitive way<sup>8</sup> of the charged over all particle ratio of hadronic interactions.

It should be kept in mind that the parameters of the model are only effective quantities and are not identical to the respective quantities measured at accelerators. In particular, the approximation of all secondary particles carrying the same energy is only motivated by the fact that it allows us to obtain simple, closed expressions. The well-known leading particle effect, typically quantified by the (in)elasticity of an interaction, can be implemented in the model <sup>6</sup> but will not be considered here.

#### 3 Hadronic Interaction Models and LHC data

It is clear that such a model is only giving a very much over-simplified account of air shower physics. However, the model allows us to qualitatively understand the dependence of many air shower observables on the characteristics of hadronic particle production. Accordingly the parameters of hadron production being most important for air shower development are the



Figure 3: Total and elastic p-p cross section from <sup>18</sup> and LHC measurements by the TOTEM experiment <sup>15</sup> (stars) (left-hand side) and particle density at  $\eta = 0$  for non single diffractive events (NSD) from old experiments and from CMS experiment<sup>19</sup> (stars) as a function of center of mass energy. Simulations are done with EPOS LHC (full line), QGSJETII-04 (dotted line), EPOS 1.99 (dashed line) and QGSJETII-03 (dashed-dotted line).

cross section (or mean free path), the multiplicity of secondary particles of high energy, and the production ratio of neutral to charged particles. Until the start of LHC, these parameters were not well constrained by particle production measurements at accelerators. As a consequence, depending on the assumptions of how to extrapolate existing accelerator data, the predictions of hadronic interaction models differ considerably.

There are several hadronic interaction models commonly used to simulate air showers. Here we will focus on the two high energy models which were updated to take into account LHC data at 7 TeV: QGSJETII-03<sup>9,10</sup> changed into QGSJETII-04<sup>11</sup> and EPOS 1.99<sup>12,13</sup> replaced by EPOS LHC<sup>14</sup>. There is no major change in these models but in addition to some technical improvements, some parameters were changed to reproduce TOTEM<sup>15</sup> cross sections. Both are based on Gribov-Regge multiple scattering, perturbative QCD and string fragmentation. The former versions reproduce accelerator data and even first LHC data reasonably well<sup>16</sup> and Figs. 3 and 4 but predict different extrapolations above  $E_{\rm cms} \sim 1.8$  TeV ( $E_{\rm lab} \sim 10^{15}$  eV) that lead to very different results at high energy<sup>3,17</sup> which can be improved using LHC data.

## 3.1 Cross section

As shown in eq. 5, the cross section is very important for the development of air showers and in particular for the depth of shower maximum. As a consequence, the number of electromagnetic particles at ground is strongly correlated to this observable (if the shower maximum is closer to ground, the number of particles is higher).

The proton-proton scattering total cross section is usually used as an input to fix basic parameters in all hadronic interaction models. Therefore it is very well described by all the models at low energy, where data exist <sup>20</sup>. And then it diverges above 2 TeV center-of-mass (cms) energy because of different model assumptions. As shown on Fig. 3 left-hand side the new point measured by the TOTEM experiment at 7 TeV reduces the difference between the models by a factor of 5 (50 to 10 mb) at the highest energy. In all the figures EPOS LHC is represented by a full (blue) line, QGSJETII-04 by a dotted (red) line, EPOS 1.99 by a dashed (black) line and QGSJETII-03 by a dashed-dotted (green) line.

#### 3.2 Multiplicity

According to eq. 5, the multiplicity plays a similar kind of role as the cross section, but with a weaker dependence (log). On the other hand, the predictions from the models had much larger



Figure 4: Pseudorapidity distribution  $dN/d\eta$  for events with at least one charged particle with  $|\eta| < 1$  (left-hand side) and corresponding multiplicity distribution (right-hand side) for p-p interactions at 7 TeV. Simulations with EPOS LHC (full line), QGSJETII-04 (dotted line), EPOS 1.99 (dashed line) and QGSJETII-03 (dashed-dotted line) are compared to data points from ALICE experiment<sup>22</sup>.

differences for the multiplicity compared to the cross section. As shown Fig. 3 right-hand side, the particle density at mid-rapidity is well reproduced by all the models up to 2 TeV where Tevatron data<sup>21</sup> constrain the results, but at the highest energies (not shown), the difference can be as high as a factor of 10. After re-tuning at 7 TeV to be compatible with CMS data<sup>19</sup> or ALICE data<sup>22</sup> on Fig. 4, the difference is now negligible. On the right-hand side of Fig. 4, we can see that not only the averaged multiplicity had been changed after re-tuning, but the fluctuations are now very similar for QGSJETII-04 and EPOS LHC. This will be important for the fluctuations of the air shower maximum.

So for both cross section and multiplicity, when the models are constrained by LHC data up to 7 TeV, the extrapolation to the highest energy is not so different any more. This will have a strong impact on  $X_{max}$  uncertainty in air shower simulations.

#### 3.3 Baryon production

Another important observable for EAS is the number of muons reaching the ground. Using eq. 6 and the definition of  $\alpha$  and R, it has been shown in<sup>8</sup> that the number of (anti)baryons plays an important role in the value of R especially if we take into account the leading particle effect. As a consequence the number of muons in EAS is sensitive to the number of (anti)baryons produced in the hadronic interactions and it is important to check the production of such particles in LHC data.

Both ALICE <sup>23</sup> and CMS <sup>24</sup> experiments published very nice results on identified spectra used to constrain models used for air shower simulations. As shown in Fig. 5 left-hand side, these data helped a lot to reduce the differences between the models especially because it could resolve an ambiguity on the phase space used to produce some anti-proton over pion ratio with Tevatron data at 1.8 TeV. LHC data are much better defined and can be used to constrain the production of baryon pairs at mid-rapidity (largely dominated by string fragmentation).

It is important to notice that not only (and not all) (anti)baryons are entering in the definition of the ratio R. All particles which do not decay into an electromagnetic particle can play a similar role and keep the energy of the shower into the hadronic channel to produce muons. For instance in QGSJETII-04 the newly introduced  $\rho^0$  resonance as excited state of the pion remnant in pion interactions has a very strong influence on the muon production. Since forward  $\pi^0$ , transferring a lot of energy in the electromagnetic channel, are replaced by particles which decay in charged pions, the energy is kept in the hadronic channel. This is clearly illustrated



Figure 5: Measurement of pion over anti-proton ratio at y = 0 for p-p collisions by ALICE and PHENIX<sup>23</sup> experiments (left-hand side) as a function of center of mass energy and measurement of the  $\pi^0$  longitudinal momentum fraction distribution by NA22 experiment<sup>25,26</sup> (right-hand side) for  $\pi$ -p interactions at 250 GeV lab. Simulations are done with EPOS LHC (full line), QGSJETII-04 (dotted line), EPOS 1.99 (dashed line) and QGSJETII-03 (dashed-dotted line).

by the Fig. 5 right-hand side where we can see that QGSJETII-04 reproduce nicely  $\pi^0$  forward spectra while QGSJETII-03 producing no  $\rho^0$  had too hard  $\pi^0$  spectra. The leading  $\rho^0$ production was already in EPOS 1.99, being one source of difference between the 2 models. On the other hand in EPOS 1.99 another process producing forward (anti)baryons was missing at high energy. As a consequence the reduced rate of (anti)baryons production at mid-rapidity is compensated by more forward (anti)baryons production which is even more important for muon production. Unfortunately there is very little data to constrain this production channel especially in collider experiments. NA61 and LHCf data may help to constrain this process in the future.

## 4 EAS Simulations

Using the air shower simulation package CONEX and the new versions of the high-energy hadronic interaction models, we can get an estimate of the resulting uncertainties. In the following EAS simulation results using EPOS LHC and QGSJETII-04 are presented and compared to former results using QGSJETII-03 and EPOS 1.99.

As shown in Fig. 6 left-hand side, the mean depth of shower maximum,  $X_{max}$ , for proton and iron induced showers simulated with CONEX is still different for EPOS LHC and QGSJETII-04. But now the elongation rate (the slope of the mean  $X_{max}$  as function of the primary energy) is the same in both cases while EPOS 1.99 had an elongation rate larger than QGSJETII-03. The difference between the 2 models is a constant shift of about  $20g/cm^2$  (close to the experimental systematic error in PAO <sup>27</sup>) while before the difference were increasing up to  $50g/cm^2$  at the highest energies

This is very important to study the primary cosmic ray composition. If the models converge to a similar elongation rate, it will allow us to have a more precise idea on possible changes in composition at the "ankle" for instance where the PAO measured a break in the elongation rate of the data.

Concerning the number of muons at ground (for 40° inclined shower at the height of 1500 m), the difference between the new QGSJETII-04 and the old QGSJETII-03 is even more impressive. We can see on Fig. 6 left-hand side that QGSJETII-04 predicts now about the same number of muons than EPOS 1.99 which is about 20% more than QGSJETII-03. It is due to the change in baryon, strangeness and mostly resonance production as described in section 3.3.





Figure 6: Mean X<sub>max</sub> (left-hand side) and mean number of muons at ground divided by the primary energy (right-hand side) for proton and iron induced showers are shown as a function of the primary energy for different high-energy hadronic interaction models, full lines for proton and dashed lines for iron with full triangles for EPOS LHC, open squares for QGSJETII-03, open circles for QGSJETII-04, and full stars for EPOS 1.99. Refs. to the data of mean X<sub>max</sub> can be found in <sup>27</sup> and <sup>28</sup>.

Concerning the predictions of EPOS LHC, the number of muons is very similar to the one in EPOS 1.99 because of the leading baryon production compensating the reduction of (anti)aryon production at mid-rapidity. So, even if the number of muons is much more similar now for the two most recent hadronic models, there is still an uncertainty of about 10% and furthermore the energy spectrum of the muons at ground is different between the models. This is important for the calculation of the missing energy for fluorescence detection. The average energy of the muons is larger in QGSJETII-04 than in EPOS resulting in a slightly larger (1% to 2%) missing energy correction in QGSJETII-04 (same value for EPOS LHC and EPOS 1.99).

# 5 Summary

Using a simple cascade model, it is possible to find the main parameters of hadronic interactions that influence air shower predictions. For the mean depth of shower maximum,  $\langle X_{max} \rangle$ , these parameters are the inelastic cross sections, the secondary particle multiplicity, and the inelasticity (not studied here). Using recent LHC data at 7 TeV it is possible to reduce the uncertainty in the extrapolation of the hadronic interaction models used for EAS simulations. Using pre- and post-LHC versions of the QGSJETII and EPOS models, it has been showed that the difference in multiplicity between these models has been reduced by a factor of 5 at the highest energy, resulting in a very similar elongation rate. There is still a systematic shift in  $X_{max}$  of about  $20g/cm^2$  due to remaining differences in the multiplicity (and elasticity) of the models. This uncertainty is comparable to the experimental uncertainty in the measurement of  $X_{max}$ . As a consequence the interpretation of the data using post-LHC data will be more reliable especially concerning the possible change in mass composition with energy as summarized in <sup>29</sup>.

For the number of muons, the ratio between particles producing hadronic sub-showers and the total number of particles is very important. LHC data are important to constrain (anti)baryon and strangeness production at mid-rapidity. Lower energy data of fixed target experiment are also important to measure forward production of  $\pi^0$  for instance. Taking into account both aspect, the new version of the QGSJETII and EPOS models predict very similar results close to EPOS 1.99 model but with harder spectrum.

The difference between EPOS 1.99 and the preliminary results of EPOS LHC is not very large because most of the changes are taking place at mid-rapidity. This phase space is good to test the physics of the model but is not very important for air shower development. A contrario, large differences between QGSJETII-03 and QGSJETII-04 are observed. With a

larger  $\langle X_{max} \rangle$  the average mass is heavier than before at Auger energies. Since the number of muons increased by about 20% and taking into account this larger average mass, the difference with the number of muons observed by PAO will be reduced significantly.

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# A search for the sources of ultra-high energy cosmic rays<sup>a</sup>

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We investigate whether the arrival direction distribution of the 69 ultra-high energy cosmic rays (UHECRs) detected at the Pierre Auger Observatory (PAO) until December 2009 with energy  $\geq 55$  EeV exhibit the anisotropy expected if they originate in galaxies in the local Universe, using the IRAS-PSCz and 2MASS-6dF galaxy surveys to model the UHECR source distribution. We find that the 69 UHECRs exhibit a stronger correlation with the galaxy distribution than  $\geq 94\%$  of simulated datasets with random arrival directions, but the cross-correlation signal is weaker than in 85% of realisations of UHECRs whose sources are galaxies. The observed cross-correlation signal does exceed that obtained in 50% of realisations if UHE-CRs are deflected by intervening magnetic fields by 5° or more.

# 1 Introduction

The identification of the sources of cosmic rays (CRs) is a challenge due to the presence of magnetic fields (MFs) in the Universe which deflect their trajectories. It is believed that UHECRs with energy above 10 EeV (1 EeV =  $10^{18}$  eV) are extra-Galactic in origin since their gyroradius is too large to be confined by the Galactic MF. It is expected that above ~ 50 EeV protons interact with cosmic microwave background (CMB) photons to produce pions via the GZK process<sup>1</sup>,<sup>2</sup>. All of the 3 largest UHECR observatories to date, namely the High Resolution Fly's Eye (HiRes), PAO and Telescope Array (TA) confirm the existence of a cutoff in the CR spectrum at an energy consistent with the GZK expectation <sup>3</sup>, <sup>4</sup>, <sup>5</sup>.

The power required to accelerate UHECRs can only be found in the brightest extra-galactic objects. The most plausible candidates are Active Galactic Nuclei and Gamma Ray Bursts. The distribution of these sources is correlated with that of galaxies since matter in the Universe is clustered. Due to their prompt interactions with CMB photons, during which they suffer significant energy losses, the propagation of UHECRs above 50 EeV is limited to  $\sim 200$  Mpc. At these scales the universe is not isotropic. At the same time since magnetic deflections are inversely proportional to energy, it is possible that the highest energy CRs point back to their sources within a few degrees. Thus if the distribution of sources of UHECRs and the distribution of galaxies within a few hundred Mpc is expected.

The composition of UHECRs cannot be determined directly since these particles are detected through the shower they produce in the atmosphere. At present there is tension between the results of different experiments at the highest energies. For most of the present analysis we assume proton UHECRs. Proton UHECRs are expected to be deflected by  $\leq 3^{\circ}$  during ~ 100 Mpc of propagation (see <sup>6</sup>, <sup>7</sup> for analytical arguments and numerical simulations) although the strength of intervening MFs is not well known and conflicting results on the deflection experienced by UHECRs exist <sup>8</sup>, <sup>9</sup>.

We derive the local UHECR source distribution from galaxy surveys of the nearby Universe and

<sup>&</sup>lt;sup>a</sup>Based on F. Oikonomou, A. Conolly, F. B. Abdalla, O. Lahav, S. Thomas, D. Waters, E. Waxman, A search for correlation of ultra-high energy cosmic rays with IRAS-PSCz and 2MASS-6dF galaxies, Journal of Cosmology and Astroparticle Physics, In press 2013, arXiv:1207.4043

investigate whether a correlation exists between the UHECR arrival directions and predicted source distribution, taking into account expected magnetic deflections. We assume a flat universe with  $\Omega_M = 0.25$ ,  $\Omega_{\Lambda} = 0.75$  and  $H_o = 70$  km s<sup>-1</sup> Mpc<sup>-1</sup>.

# 2 The dataset

The data used for this analysis are 69 UHECRs with  $E \ge 55$  EeV and zenith angles smaller than 60° detected at the PAO until December 2009<sup>10</sup>. The angular resolution is better than 0.9° for these events<sup>11</sup>. The energy resolution is 15% and there is a 22% systematic uncertainty in the absolute energy scale<sup>12</sup>, <sup>4</sup>.

To model the UHECR source distribution we use two wide field spectroscopic galaxy surveys. The 6dF <sup>13</sup>, which is being used here for the first time in a search for the sources of UHECRs, contains 110,256 galaxies with associated redshifts with median redshift  $\bar{z} = 0.053$  and covers 17000 square degrees of the southern sky (or 86.2% of the instantaneous PAO exposure). We also use the IRAS PSCz catalogue <sup>14</sup>, which covers 84% of the sky and contains 14,677 galaxies with ( $\bar{z} = 0.028$ ). The PSCz is being used here for the first time with the full 69 PAO UHECRs. The two surveys contain objects selected in different wavelength bands and hence they probe complementary large scale structure (LSS).

# 3 Methodology

We derive the expected UHECR source distribution from the galaxy distribution in the two surveys presented above. We consider a model in which the local number density of UHECR sources is comparable to that of galaxies in the local Universe ( $\bar{n}_0 = 10^{-2} \text{ Mpc}^{-3}$ ) and in which individual UHECR sources are faint i.e. each source produces 1 or no events and the probability of a single source producing multiple events is low. Further we assume that all UHECR sources are intrinsically identical.

We mask the galaxies with the declination dependent PAO exposure<sup>15</sup>. We also mask out the galactic plane,  $|b| < 12^{\circ}$  since UHECRs traversing the Galactic MF in the disk might suffer large deflections. We weight the galaxies in each of the surveys by the corresponding selection function<sup>13</sup>, <sup>14</sup>, to correct for the lack of observations with increasing distance due to the flux limit of the surveys.

We weight each source to account for proton energy losses during propagation and flux suppression with distance. The weight for a galaxy at luminosity distance  $r_{\rm L}$ :

$$\omega(r_{\rm L}) = \frac{1}{r_{\rm L}^2} \int_{E'_{\rm f}}^{E_{\rm i,max}} dE_{\rm i} \int_{E'_{\rm f}}^{E_{\rm i}} dE_{\rm f} \left| \frac{\partial P_{\rm p}(r_{\rm L}, E_{\rm i}; E_{\rm f})}{\partial E_{\rm f}} \right| I(E_{\rm i}), \tag{1}$$

where  $P_{\rm p}(r_{\rm L}, E_{\rm i}; E_{\rm f})$  is the probability of a proton arriving on earth with energy  $E_{\rm f}$  if it was emitted with energy  $E_{\rm i}$  by a source at distance  $r_{\rm L}$ . We use the  $P_{\rm p}(r_{\rm L}, E_{\rm i}; E_{\rm f})$  function numerically calculated by <sup>16</sup>. For  $E'_{\rm f}$ , the final energy of the 69 PAO UHECRs, we conservatively adopt the lowest measured energy (55 EeV) present in the PAO dataset. We set  $E_{\rm i,max}$  which is the maximum energy achievable through astrophysical processes to  $10^{21}$  eV. For the injection spectrum we consider a power law with index  $\alpha = 2$ :

$$I(E_{\rm i}) = I_0 E_{\rm i}^{-\alpha} \Theta(E_{\rm i,max} - E_{\rm i}), \qquad (2)$$

where the step function restricts the UHECR energy to below  $E_{i,max}$ .

To compute the cross-correlation between the observed UHECR arrival directions and the predicted source distribution we divide the sky into  $\sim 6^{\circ} \times 6^{\circ}$  equal area bins to average over possible deflections of a few degrees and calculate the statistic  $X^{6}$ :

$$X = \sum_{i} \frac{\left(N_{\mathrm{CR},i} - N_{\mathrm{iso},i}\right) \cdot \left(N_{\mathrm{M},i} - N_{\mathrm{iso},i}\right)}{N_{\mathrm{iso},i}}.$$
(3)

where  $\{i\}$  is the set of angular bins,  $N_{\text{CR},i}$  is the number of observed UHECRs in bin *i*,  $N_{\text{M},i}$  is the number of UHECRs expected in bin *i* if UHECRs originate in sources that follow the predicted source

distribution and  $N_{iso,i}$  the number of UHECRs expected in bin *i* if UHECR sources are isotropically distributed.

# 4 Results

We simulate sets of UHECRs from a distribution of sources that follows that of LSS, as well as sets of UHECRs with random arrival directions, weighted by the PAO exposure and compare the distribution of values of X obtained under the two models to  $X_{Auger}$ , the value of X obtained with the observed PAO UHECRs. In order to avoid any bias of the results due to the arbitrary choice of bin size we vary the bin size in the range  $3.9^{\circ} - 7.3^{\circ}$  to bracket expected UHECR deflections of a few degrees.

In Figure 1 we show the distribution of values of X obtained with 10000 realisations of UHECRs under the two models of source distribution as well as  $X_{Auger}$  separately with the PSCz and the 6dF. The value of  $X_{Auger}$  obtained is higher than for 94% (98%) of isotropic realisations with random arrival directions when cross-correlated with the PSCz (6dF). At the same time  $X_{Auger}$  is lower than in ~ 85% of realisations of UHECRs whose sources are galaxies from either survey. There is an uncertainty of order 10% in the values quoted, due to binning. Qualitatively there is very good agreement between the results obtained with the two different surveys.



Figure 1: Left: The distribution of values of the correlation statistic X in 10000 mock realisations of a set of UHECRs with random arrival directions (dashed histograms) and from a source distribution that follows the PSCz (solid histograms). The black solid line gives the value of X obtained for the observed PAO events ( $X_{Auger}$ ). Right: Same as on the plot on the left but using the 6dF.

We investigate the dependence of the expected cross-correlation signal if UHECR sources trace LSS on the amplitude of the magnetic deflections suffered. If UHECRs are nuclei as some recent experimental data suggest <sup>10</sup>, they will suffer deflections  $\delta_{\text{proton}} \times Z$ . We simulate random magnetic deflections in the range 5° – 20° using a 2 dimensional Gaussian function with width  $\delta$ . The results obtained thus are relevant to protons and Fe nuclei which lose energy at the same rate at the energies we are studying. In Figure 2 we show how the expected cross-correlation signal varies as a function of the average deflection suffered by the simulated UHECRs and compare it to  $X_{Auger}$ . We see that the expected cross-correlation signal drops fast as average deflections increase and that for a set of 69 UHECRs it becomes difficult to distinguish between a distribution of sources that trace LSS and random arrival directions. We also see that the PAO UHECRs are consistent with the mean of a source distribution that traces the galaxy distribution if deflections are ~ 5° or more. With a larger UHECR dataset it will be possible to rule out large deflections if some level of correlation with LSS persists.



Figure 2: Left: The distribution of values of X in 10,000 realisations of UHECRs with random arrival directions (dashed histogram) and from a distribution of sources based on the PSCz (solid histograms) with simulated magnetic deflections. In each solid histogram the UHECRs arrive on earth with a mean position centered at the source's true position and random angular deflections with amplitude  $\delta$  given in the legend. Right: Same as on the plot on the left but using the 6dF.

# 5 Discussion and Conclusions

We have studied the arrival directions of the 69 UHECRs detected by the PAO until December 2009 and examined whether they are consistent with the distribution expected if they originate in luminous extra-Galactic sources and if their trajectories are not significantly deflected by intervening MFs. We find that the observed arrival directions exhibit a stronger correlation with LSS than 94% (98%) of realisations of UHECRs when cross-correlated with the source distribution derived from the PSCz (6dF) catalogue, whereas the exhibit a weaker correlation with LSS than ~ 85% of realisations of UHECRs from either catalogue. The values quoted vary by ~ 10% depending on the size of the angular bins used for the analysis in the range we studied  $(3.9^{\circ} - 7.3^{\circ})$ .

We have also investigated the effect of the largely unknown amplitude of the magnetic deflections on the expected cross-correlation signal and showed that the the correlation statistic for the 69 PAO UHECRs is consistent with the mean of the distribution obtained from mock realisations of UHECRs that originate in galaxies, if magnetic deflections are of order  $5^{\circ}$ .

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# THE LARGE HIGH ALTITUDE AIR SHOWER OBSERVATORY PROJECT

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The Large High Altitude Air Shower Observatory (LHAASO) project will be dedicated to the detection of air showers over a wide energy range with high performances in terms of gamma/hadron discrimination power, with high duty cycle and with a wide field of view. Just below 10 TeV, the sensitivity to gamma-ray sources is expected to reach about 2% of the emission intensity of the Crab nebula, while it is expected to reach  $\simeq 10^{-14}$  TeV cm<sup>-2</sup> s<sup>-1</sup> around 100 TeV, a very interesting energy range for identifying hadronic acceleration in Galactic sources. Meanwhile, this observatory will allow studying cosmic rays from  $\simeq 10$  TeV up to the energies of the knees. This observatory will thus play, in a near future, an important role in astroparticle physics.

The emission of gamma rays in the TeV energy range has been discovered in the last two decades in various types of astrophysical objects, such as pulsar wind nebulas, supernova remnants, X-ray binaries, active galactic nuclei, etc. For some sources, the energy spectra have even been measured to extend up to about 100 TeV. Though most of these energy spectra can be well reproduced with gamma rays produced by accelerated electrons in shock waves, some of them cannot be explained without introducing gamma rays originating from the decay of neutral pions produced consequently to the interaction of high energy protons with low energy ambient photons. This latter mechanism is of considerable interest, since it implies that such gamma-ray sources could be also cosmic-ray sources. Confirming and improving this understanding would be of major importance, since it would allow us to answer to the long lasting question of cosmic ray production.

The Large High Altitude Air Shower Observatory project will be built close to the Shangri-La city (4300 m a.s.l.), in the province of Yunnan in China<sup>1</sup>. It is aimed at searching for cosmic ray sources by the measurement of gamma rays up to 1 PeV, at surveying the whole northern sky for gamma-ray sources above 300 GeV, and at studying cosmic-ray physics from 10 TeV to a few hundreds of PeV. A ground-based array dedicated to the detection of gamma-ray showers at high altitude is an ideal tool to provide an all-sky survey for gamma-ray sources around PeV energies, complementary to imaging Cerenkov telescopes. In addition to the gamma-ray source survey, such an array can also play an essential role for providing a bridge between direct measurements of spectra of individual cosmic ray species at balloon heights and high-energy cosmic ray experiments.

The ground-based detection of very high energy photons and cosmic rays is indirect. For an extensive air shower array, the nature, direction and energy of the primary particles have to be inferred from the detection of the secondary particles of the showers initiated by those primary particles in the upper atmosphere. The unambiguous identification of the nature of the primary particles turns out to be a difficult task, even for distinguishing between photons and cosmic rays. For these reasons, the LHAASO project will be composed of several different



Figure 1: General design of the LHAASO project.

detectors with known techniques allowing a reliable measurement of shower observables. A water Cerenkov detector array (WCDA) composed of 4 ponds of water Cherenkov detectors covering a surface of 90,000 m<sup>2</sup> will allow a continuous survey of the sky at few hundreds of GeV. This is particularly relevant for studying transient and/or variable extragalactic gamma-ray sources, such as gamma-ray bursts and active galactic nuclei respectively. A square kilometer array (KM2A) composed of electron detectors and buried muon detectors will allow the survey of galactic gamma-ray sources around a hundred of TeV with unprecedented sensitivity. A wide field of view Cerenkov telescope array (WFCTA) will allow imaging gamma-ray sources and hybrid measurements of cosmic-ray observables. Finally, a high threshold core detector array (SCDA) will allow shower core measurements. The general design of the observatory is depicted in Fig. 1.

One major challenge for this kind of observatory relies on achieving high performances in gamma ray detection. A flux of photons from a discrete source is expected to cause an excess of events around the direction to the source within the angular resolution of the extensive air shower array. Hence, the search for such excesses is a powerful tool to reveal the presence of very high energy photons over an *overwhelming* background of cosmic rays, background which is highly uniform at the angular resolution scale. For this reason, the sensitivity of any ground-based experiment is generally examined in terms of the flux required in some direction of the sky to reach a 5  $\sigma$  significance in one year for the observed excess. The Crab Nebula is considered in gamma-ray astronomy as a standard candle, so that the sensitivity exemplified in the following refers to this particular gamma-ray source whose flux has been well measured as :

$$\bar{\Phi}_{\sim}^{\rm crab}(E) = 2.86 \ 10^{-11} \ E^{-2.67} \ {\rm cm}^{-2} {\rm s}^{-1} {\rm TeV}^{-1} \tag{1}$$

Using Poisson statistics to calculate the significance of an excess of events observed in the direction of the Crab Nebula, and considering the excess is due exclusively to gamma rays, the significance S is estimated in subtracting the number of expected background events from cosmic rays  $N_{\rm CR}$  to the total number of events observed in the targeted window  $N_{\gamma} + N_{\rm CR}$ , and in normalising this factor by  $\sqrt{N_{\rm CR}}$ . In the absence of any discrimination between photon and cosmic ray-induced showers, this would lead to the simple expression  $S = N_{\gamma}/\sqrt{N_{\rm CR}}$ . However, this factor S can be significantly enhanced for the same observation time by taking profit of the WCDA or KM2A designs aimed at providing well suited observables to obtain a good discrimination power between photon and cosmic ray-induced showers. Denoting by  $\epsilon_{\gamma}$  the efficiency for identifying photon-induced showers and  $\epsilon_{\rm CR}$  the efficiency for identifying cosmic ray-induced showers, sub-samples possibly enriched in gamma rays can be obtained from the



Figure 2: Expected sensitivity to gamma-ray sources of the LHAASO project, compared to other experiments.

initial data set with a total number of events in the target window  $\epsilon_{\gamma}N_{\gamma} + (1 - \epsilon_{\rm CR})N_{\rm CR}$ , the second term coming from the fraction of cosmic rays falsely identified as photons. This leads to the following expression for the significance :

$$S(>E) = \frac{N_{\gamma}(>E)}{\sqrt{N_{\rm CR}(>E)}} Q, \qquad (2)$$

where the conventional notation Q stands for  $\epsilon_{\gamma}/\sqrt{1-\epsilon_{\rm CR}}$ .

For an extensive air shower array with an effective surface of detection for photons  $A_{\text{eff}}^{\gamma}(E,\theta)$ at energy E and zenith angle  $\theta$ , the number of photons detected in an angular target  $\delta\Omega$  around the direction to the Crab source during a one year observation time reads :

$$N_{\gamma}(>E) = n_{1y} \int_{\Delta T} dt \int_{\Delta E} dE \ A_{\text{eff}}^{\gamma}(E,\theta(t)) \ \cos\theta(t) \ \Phi_{\gamma}^{\text{crab}}(E) \ \xi(\delta\Omega), \tag{3}$$

where the time integration is carried out in local sidereal time (expressed in seconds),  $n_{1y}$  is the number of sidereal days in a year, and  $\xi(\delta\Omega)$  stands for the fraction of showers contained in the angular window  $\delta\Omega$ . To optimise the ratio  $N_{\gamma}/\sqrt{N_{\rm CR}}$ , the size of this angular window is chosen to match the angular resolution. Within a sidereal day, the path followed by any source in the sky with equatorial coordinates  $\{\alpha, \delta\}$  as observed from an Earth latitude  $\lambda$  makes the corresponding local angles varying with local sidereal time t in the following way :

$$\theta(t) = \arccos\left[\sin\lambda\sin\delta + \cos\lambda\cos\delta\cos\left(\alpha - 2\pi t/T\right)\right],\tag{4}$$

with T = 86164 s the number of second per sidereal day.

Meanwhile, the number of background events observed in the same target window  $\delta\Omega$  coming from cosmic rays reads as :

$$N_{\rm CR}(>E) = n_{\rm 1y} \int_{\Delta T} dt \int_{\Delta E} dE \ A_{\rm eff}^{\rm CR}(E,\theta(t)) \ \cos\theta(t) \ I_{\rm CR}(E) \ \delta\Omega, \tag{5}$$

with  $A_{\text{CR}}^{\text{CR}}(E,\theta)$  the effective surface of detection for cosmic rays and  $I_{\text{CR}}(E)$  the total intensity of cosmic rays which has been well measured between 1 TeV and 1 PeV as :

$$I_{\rm CR}(E) = 1.43 \ 10^{-5} \ E^{-2.7} \ {\rm cm}^{-2} {\rm s}^{-1} {\rm sr}^{-1} {\rm TeV}^{-1}.$$
 (6)



Figure 3: Construction plan of the LHAASO experiment.

For a source position culminating in the field of view of the extensive air shower array, a high duty cycle is reached in a natural way. The other factors which appear to increase the sensitivity to gamma ray sources are :

- the angular resolution : for a better angular resolution and thus a smaller size of the angular window  $\delta\Omega$ , the number of background events, which is a linear function of  $\delta\Omega$ , is reduced accordingly;
- the largest possible effective surface of detection  $A_{\text{eff}}^{\gamma}(E,\theta)$ ;
- and last but not least, the gamma/hadron discrimination power to get the highest possible Q-factor (which depends on the energy).

End-to-end simulations of the WCDA and KM2A detectors can be found in <sup>2</sup>. With these performances, the expected sensitivity of LHAASO is shown in Fig. 2. Around few hundred GeV, the sensitivity achieved by the WCDA detector will be about 2 % of the emission intensity of the Crab nebula. At higher energies, around a hundred of TeV, the KM2A will allow the same order of sensitivity to be reached. This is particularly relevant for studying the high energy ends of Galactic source spectra, where differences between leptonic or hadronic origins are expected due to the suppression of gamma-ray emission from inverse Compton scattering.

In addition to its high potential for gamma-ray astronomy, the LHAASO project is also expected to provide unprecedented statistics for cosmic ray up to the energies of the knees, with high potential for separating different primary species from each others thanks to accurate electron and muon number measurements, shower maximum development measurements, and high energy fluxes carried by particles near the shower cores. The high expected rates give the opportunity to perform measurements of energy spectra and large-scale anisotropies based on the primary composition. This will allow for further understanding of cosmic ray propagation and production in close sources in the Galaxy.

The funding of the LHAASO project has been approved by the council state of China in early 2013. The construction plan is shown in Fig. 3. International collaboration is foreseen. No doubt that the LHAASO project will play a central role in astroparticle physics in a near future.

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# SPIN OF THE SUPERMASSIVE BLACK HOLE IN THE GALACTIC CENTER

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Supermassive black holes dwell at the centers of nearly all large galaxies, including the Milky Way Galaxy. The quasi-periodic oscillations of the hot plasma spots or clumps orbiting near the black hole contain information on the black hole mass and spin. The promising observational signatures for the measurement of black hole mass and spin are the latitude oscillation frequency of the bright spots in the accretion flow and the frequency of black hole horizon rotation. Both of these frequencies are independent on the accretion model and defined only by the properties of the black hole gravitational field. Interpretation of the known quasi-periodic oscillation data by dint of signal modulation from the hot spots in the accreting plasma reveals the Kerr metric rotation parameter, a=0.64+-0.05, of the supermassive black hole is not a very efficient accelerator of cosmic rays.

In the Galactic center dwells the nearest supermassive black hole with a mass  $M = (4.1 \pm$ 0.4)  $10^6 M_{\odot}$ , measured by the observations of orbital parameters of two serendipitous fast moving stars<sup>1,2</sup>. Meanwhile, the observed quasi-periodic oscillations (QPOs) in the near infra-red and Xrays from the supermassive black hole in the Galactic center Sgr A<sup>\*</sup> contain information on this black hole rotation. The usual interpretation relates QPOs with the resonances in the accretion disks. A weak point of the resonance QPO interpretation is in the ambiguity, related with the dependence on the used accretion model. It seems that the resonance QPO models is applicable to black holes in the Active Galactic Nuclei (AGN) and in the stellar binaries with the high accretion rates. The others two promising approaches for revealing the black hole rotation are the continuum fitting method for the relativistic accretion disk models and the modeling of spectral lines broadening in the accretion flow. Both of these approaches also depend on the used accretion models. Below it is described the alternative QPO interpretation, related with the oscillation frequencies of hot spots in the accretion plasma, which are independent on the accretion model and defined completely by the properties of the black hole gravitational field. The described approach is applicable directly to black holes with a low accretion rate. The supermassive black hole in the Galactic center is the most favorable case. This supermassive black hole is activated from time to time by the episodic accretion of tidally disrupted stars<sup>3</sup>. In the case of the astrophysically interesting thin disk accretion, the black hole will finally spin up to the "canonical" value of the Kerr spin parameter  $a_* = 0.9982$ , i.e. very near to the extremely fast rotating state  $a = 1^4$ .

The geodesic motion of a test particle with mass  $\mu$  (e.g., planets or clumps of hot plasma) in the background gravitational field of the Kerr black hole is completely defined by three integrals of motion<sup>5</sup>: the total particle energy E, the azimuthal component of the angular momentum L and the Carter constant Q, related to the total angular momentum of the particle and non-equatorial motion. It is useful to use the units with G = c = 1 and choose the dimensionless variables and parameters:  $t \Rightarrow t/M$ ,  $r \Rightarrow r/M$ ,  $a \Rightarrow a/M$ ,  $E \Rightarrow E/\mu$ ,  $L \Rightarrow L/(M\mu)$ ,  $Q \Rightarrow Q/(M^2\mu^2)$ . The radius of the black hole event horizon is  $x_h = 1 + \sqrt{1 - a^2}$ .

In Fig. 1 is shown the numerically calculated "plunging" trajectory of the planet infalling into the rotating black hole. The crucial feature of any plunging trajectory is that, by approaching to the black hole horizon,  $x \to x_h$ , the trajectory is quasi-periodically "winding up" with an azimuthal angular velocity  $\Omega_{\phi} = d\varphi/dt$ , tending to the angular velocity of the black hole horizon  $\Omega_h$ , where

$$\Omega_{\rm h} = \frac{d\varphi}{dt}\Big|_{x \to x_h} = \frac{a}{2(1 + \sqrt{1 - \boldsymbol{a}^2})} \frac{1}{M}.$$
(1)

See in the Fig. 1 also the plunging photon trajectory, quasi-periodically "winding up" with the angular velocity  $\Omega_{\phi} \rightarrow \Omega_h$ , by approaching to the black hole event horizon at the southern hemisphere. In result, the angular velocity of the the black hole event horizon  $\Omega_{\phi}$  must be inevitably imprinted to the QPO signal from the accreting black holes. Any source of radiation, e.g., clump of the hot plasma, approaching the event horizon of the rotating black hole will be viewed by the distant observer in a relativistic "synchrotron mode" as the short splashes of radiation, beamed and boosted forwardly into the narrow solid angles<sup>6,7,8,9</sup>, and repeated quasi-periodically with a frequency very near to  $\nu_h = \Omega_h/2\pi$ . The oscillation with  $\Omega_h$  from (1) is a first observational signature for revealing the spin of the supermassive black hole in the Galactic center. The corresponding second signature is related with the QPOs of nonequatorial bound orbits in the accretion flow.



Figure 1: Left panel: the planet trajectory with a total energy E = 0.85, azimuthal angular momentum L = 1.7and Carter constant Q = 1, infalling into the black hole with a spin a = 0.9998 and event horizon radius  $x_h = 1.063$ . The trajectory is "winding up" with the angular velocity  $\Omega_{\phi} \to \Omega_h$ , by approaching to the black hole horizon at the northern hemisphere. Rightpanel: the photon trajectory with an impact parameter b = L/E = 2 and Carter constant Q = 2, infalling into the black hole with a = 0.9998 and  $x_h = 1.063$ . The trajectory is "winding up" with the angular velocity  $\Omega_{\phi} \to \Omega_h$ , by approaching to the black hole horizon at the southern hemisphere. This trajectory corresponds also to the outgoing photon for the black hole with an opposite spin direction.

See in Fig. 2 an example of the numerically calculated bound quasi-periodic orbit, viewed from the black hole north pole and aside, respectively. This is an illustration of the quasi-periodical oscillation of the hot spot or clump of plasma in the accretion flow, which may be used for the determination of the black hole mass and  $spin^{11}$ .

By using relation between the azimuthal and latitudinal angular velocities of the nonequatorial bound orbits,  $\Omega_{\varphi}$  and  $\Omega_{\theta}$ , from<sup>10</sup> and the values for orbital energy E and azimuthal angular momentum L from<sup>12,13</sup> for the test particle at the nonequatorial spherical orbit, it can be calculated from equations of motion the corresponding azimuthal angular velocity at the equatorial plane:

$$\Omega_{\phi,\text{sph}} = \frac{x\sqrt{x^3(3Q - Qx + x^2) + a^2Q^2 - a(x^2 + 3Q)}}{\{x^5 - a^2[x^2 + Q(x + 3)]\}M}.$$
(2)

In the limit  $Q \rightarrow 0$  it follows the angular velocity of the latitudinal oscillation of a near circular orbit in the thin accretion disk:

$$\Omega_{\theta} = \frac{2\pi}{T_{\theta}} = \frac{\sqrt{x^2 - 4ax^{1/2} + 3a^2}}{x(a + x^{3/2})} \frac{1}{M}.$$
(3)





Figure 2: Left panel: the bound quasi-periodic orbit with Q = 2, E = 0.92, L = 1.9, pericenter  $x_p = 1.74$ , apocenter  $x_a = 9.48$  and  $\theta_{max} = 36.3^\circ$ , viewed from the north pole of the black hole with a = 0.9982 and  $x_h = 1.059$ . The orbit is shown thin at the beginning and thick at the ending. Right panel: the same bound quasi-periodic orbit viewed aside, and superimposed onto the thin and opaque accretion disk. Only the parts of the orbit, which are above the accretion disk, may be viewed by the distant observer as QPOs with a frequencies near  $\nu_{\theta} = \Omega_{\theta}/2\pi$ .

This angular velocity describes the latitudinal oscillation of the hot spot or clump of plasma in the thin accretion disk.

It is supposed that the most bright hot spots in the accretion flow are located near the inner edge of the accretion disk, corresponding to the radius of the marginally stable circular orbit<sup>6</sup>,  $x = x_{ms}$ :

$$x_{\rm ms} = 3 + Z_2 - \sqrt{(3 - Z_1)(3 + Z_1 + 2Z_2)},$$
 (4)

where

$$Z_1 = 1 + (1 - a^2)^{1/3} [(1 + a)^{1/3} + (1 - a)^{1/3}]$$
(5)

and  $Z_2 = \sqrt{3a^2 + Z_1^2}$ . See in Fig. ?? the example of the oscillating clump of plasma in the thin accretion disk around the moderately fast rotating black hole. The latitudinal oscillation with an angular velocity  $\Omega_{\theta}$  from (3), estimated at the radius  $x = x_{\rm ms}$ , is the second requested observation signature of the spinning black hole in the Galactic center.

In Fig. 3 are shown two prominent observed QPOs with the mean periods 11.5 and 19 min (filled horizontal stripes), observed<sup>3-5</sup> in the near infra-red and X-rays from the supermassive black hole Sgr A\* with a mass  $M = (4.1 \pm 0.4) 10^6 M_{\odot}$ . Also are shown two characteristic oscillation periods depending only on the black hole spin a:  $T_h$  — is a period of the event horizon rotation from (1), and  $T_{\theta}$  — is a period of the latitudinal oscillation of the hot plasma clump at the near circular orbit in the thin accretion disk with  $\Omega_{\theta}$  from (3). The filled regions correspond to the permissable values of Q and x adjusted with the errors of the observed QPO periods. Note that the values of azimuthal angular velocities  $\Omega_{\varphi}$  of hot spots in the accretion disk would not produce any prominent features in the spectrum of quasi-periodic oscillations.

It is clearly seen in Fig. 3, that the self-consistency of the observed QPO periods with  $T_h$  and  $T_{\theta}$  corresponds to the same value of the black hole spin,  $a = 0.64 \pm 0.05$ . At the same time, the observed 11.5 min QPO period is identified with the latitudinal oscillation period of hot spots  $T_{\theta}$ , and, respectively, the 19 min period is identified with a period of the black hole horizon rotation  $T_h$ . It must be stressed, that this definite spin value is obtained from the over-determined system: two relations for quasi-periods  $T_h$  and  $T_{\theta}$  (under the fixed black hole mass) were used for the determination of only one value of spin a. In other words, two independent QPO frequencies result in the same value of spin parameter a.

The moderate value of spin of the supermassive black hole Sgr A<sup>\*</sup> is quite a natural due to specific conditions in the Galactic center, where the black hole angular momentum is accumulated from the accidentally orientated individual angular momenta of successively accreted stars. Note also that the value of spin parameter  $a = 0.64 \pm 0.05$ , derived here by dint of QPOs, agrees with a corresponding quite independent estimation,  $a \simeq 0 - 0.6$ , from the millimeter VLBI observations



Figure 3: Left panel: near the equatorial orbit of the bright clump of plasma with Q = 0.1, E = 0.91, L = 2.715,  $x_p = 3.85$ ,  $x_a = 5.01$  and  $\theta_{max} = 6.6^{\circ}$ , oscillating in the thin opaque accretion disk around the black hole with a = 0.65,  $x_h = 1.76$  and  $x_{ms} = 3.62$ . Right panel: The observed QPOs with the mean periods 11.5 and 19 min (filled horizontal stripes) from the supermassive black hole Sgr A\* with a mass  $M = (4.1 \pm 0.4) 10^{6} M_{\odot}$ ;  $T_h -$ is a period of the event horizon rotation from (1);  $T_{\theta} = 2\pi/\Omega_{\theta} -$ is a period of the latitudinal oscillation of the hot plasma clump at the near circular orbit in the thin accretion disk with  $\Omega_{\theta}$  from (3). The filled region for  $T_{\theta}$  corresponds to the permissable values of Q and x adjusted with the errors of the observed QPO periods. The self-consistency of the observed QPO periods with  $T_h$  and  $T_{\theta}$  corresponds to the same value of the black hole spin,  $a = 0.64 \pm 0.05$ . Two filled circles correspond to the one sigma deviation from a mean spin value, related with the errors in QPO periods. The 11.5 min QPO period is identified with  $T_{\theta}$ .

of Sgr  $A^{*l4,15}$ . Additionally, the moderate value of the spin indicates, that the nearest to us supermassive black hole is not a very efficient accelerator of cosmic rays.

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# Irradiation of an Accretion Disk by a Jet: Spin Measurements of Black Holes

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X-ray irradiation of an accretion disk around a black hole leads to strong fluorescent reflection features, which are then broadened and distorted by relativistic effects. Analyzing the shape of this reflection spectrum allows to determine the spin of the black hole. Generally, broad reflection features are identified with rapidly spinning black holes. As the shape also depends on the location and size of the irradiating source, we study how different irradiation geometries affect the determination of the spin. We find that broad reflection features are produced only for compact irradiating sources situated close to the black hole. This is the only case where the black hole spin can be determined unambiguously. In all other cases the line shape is narrower, which could either be explained by a low spin or an elongated irradiating source. Hence, for those cases no unique solution for the spin exists and therefore only a lower limit of the spin value can be given.

## 1 Introduction

In Active Galactic Nuclei (AGN) and Galactic Black Holes (GBH) X-rays are emitted very close to the central compact object. Some of this radiation is intercepted by gas in the accretion disk around the black hole, in a process called "X-ray reflection". Because the reflected spectrum comes from the inner parts of the accretion disk, it shows signs of relativistic effects (Fabian et al. 1989)<sup>6</sup>. The strongest X-ray reflection feature observed in these objected is the fluorescent Fe K $\alpha$  line at 6.4 keV. This is the reason why a relativistically distorted line shape could first be seen by analyzing solely this reflection feature (Tanaka et al. 1995<sup>25</sup>; Reynolds at al. 2003<sup>26</sup>; and references therein). In the past decade, such "relativistic lines" have been observed in many GBH (Miller 2007<sup>46</sup>; Duro et al. 2011<sup>5</sup>; Fabian et al. 2012<sup>7</sup>) and AGN (Guainazzi, Bianchi & Dovćiak 2006<sup>2</sup>; Nandra et al. 2007<sup>48</sup>; Patrick et al. 2011<sup>19</sup>) systems. Recently a more selfconsistent approach has been used (see, e.g., Zoghbi et al. 2010<sup>29</sup>; Duro et al. 2011<sup>5</sup>; Fabian et al. 2012<sup>8</sup>; Dauser et al. 2012<sup>3</sup>), where the relativistic effects were applied to the full reflection spectrum. These reflection spectra are calculated by detailed simulations (relionx, Ross & Fabian 2007<sup>22</sup>; xillver, Garcia et al. 2013<sup>11</sup>) and also allow for an ionization of the accretion disk.

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Figure 1: The irradiated intensity I on the accretion disk (left) and the emissivity index  $\epsilon$  (right), which are connected by the relation  $I \propto r^{-\epsilon}$ . Note that for large radii all emissivity profiles converge towards the canonical value of  $r^{-3}$ . We assume that the primary spectrum has a spectral shape  $\propto E^{-\Gamma}$  with  $\Gamma = 2$ , which is a common value for AGN.

# 2 A jet irradiating the accretion disk

The shape of the relativistically distorted line depends on parameters like the black hole spin  $\mathfrak{e}$ , or the inclination of the system. Additionally, also the location and size of the primary source of radiation does affect the line profile. Initially, the idea was that a corona of hot electrons around the inner accretion disk produces the primary radiation by Comptonization of soft disk photons, as this leads to the observed shape in form of a power law (Haardt 1993<sup>13</sup>). In the simplest case, this leads to an intensity irradiating the disk which is proportional to  $r^{-3}$  (Shakura & Sunyaev 1973)<sup>23</sup>. However, in more detailed spectra (e.g., by XMM-Newton) a much steeper emissivity at the inner parts of the disk was found for most sources (e.g., Wilms et al. 2001<sup>28</sup>). Further interpretation of the hard X-ray source may be a the base of a jet or the jet itself, emitted along the rotational axis of the black hole. Such a setup can also describe the power law continuum generally observed in black hole systems (Markoff & Nowak 2004<sup>14</sup>). Moreover the strong light bending effects close to the black are capable in explaining the observed anti-correlation in flux between the direct and the reflected radiation (e.g., Miniutti et al. 2003<sup>17</sup>). Finally, the steep emissivity observed is naturally predicted by the jet base geometry (see, e.g., Fukumura et al. 2007<sup>10</sup>; Wilkins & Fabian 2012<sup>27</sup>; Dauser et al. 2013<sup>2</sup>).

In order to analyze the impact of the jet base geometry, we calculate the irradiation of the disk for different heights of the jet base. The general relativistic calculations used for the following results are presented in more detail in Dauser et al.  $(2013)^2$  and are based on the relline-code (Dauser et al.  $2010)^4$ . Figure 1 shows how the irradiated intensity *I* and the emissivity index  $\epsilon$ , which is defined by  $I \propto r^{-\epsilon}$ , evolves with distance to the black hole and depending on the height of the jet base. Generally one can see that for larger heights of the jet base, there is a growing zone on the accretion disk which gets irradiated by the same intensity ( $\epsilon \approx 0$ ). Using a similar approach, one can also simulate the irradiation of a jet, which is extended along the rotational axis of the black hole. Such an extended jet produces an irradiation profile, which is similar to a jet base at an intermediate height (detailed description and results can be found in Dauser et al. 2013<sup>2</sup>).



Figure 2: (left) Line profiles for high and low spin (a = 0.99 and a = 0) and a compact (point source at  $3r_g$ ) and an extended jet  $(3-100r_g)$ . (right) Simulated 100 ksec XMM-Newton observation for a compact source (a) and an extended jet (b). Figure adapted from Dauser et al. (2013).

# 3 Determining the Spin

The relativistic line profile also depends on the spin of the black hole, as the location of the inner edge of the accretion disk strongly depends on the spin. Namely, for high spin the accretion disk extends to smaller radii. Photons reflected in this additional area are shifted to lower energies due to the strong gravitational redshift and therefore broaden the line shape (see, e.g., Dauser et al.  $2010^4$ ). Hence, we associate broad reflection features with highly spinning black holes (upper panel in Fig. 2). However, this is only true for a compact emission region. Figure 2 also shows that if we allow the primary emission region to be extended, the resulting relativistic line will be narrow, independent of the spin of the black hole. Hence, only for a compact emission region close to a rapidly rotating black hole, a broad line will be observed. Simulations of observations with current X-ray satellites (see Fig. 2, right column) reveal that for a compact emission region we are able to distinguish between low and high spin, while for an extended source there is little difference expected in the spectrum.

# 4 Conclusions

We showed that if we observe a broad emission line, we are in principle able to measure the spin of this object. Such observations also indicate that the emission region of the primary source must be compact and at low height and that the black hole is rapidly rotating. Simulations also revealed that an observation of a narrow relativistic reflection feature alone does not allow to draw firm conclusions on the spin from spectral fitting alone, as such a feature is not sensitive on the spin if produced by an extended primary source. Hence, if we wrongly assume a compact emission region in this case when modeling such data, the wrong spin may be determined. We therefore conclude that in order constrain the spin from a narrow reflection feature, additional information on the geometry of the system are necessary. Such information can be provided by a time lag analysis (so-called "reverberation mapping"), where the time difference between the primary and reflected radiation is measured (see, e.g., Stella 1990<sup>24</sup>; Matt & Perola 1992<sup>15</sup>; Reynolds et al. 1999<sup>21</sup>; Uttley et al. 2011<sup>26</sup>; and references therein). While this reverberation could only be measured for a few sources yet, the large collection area of the next generation of X-ray satcllites (*LOFT*, Feroci et al. 2012<sup>9</sup>; *ATHENA+*, Barcons et al. 2012<sup>1</sup>) will be able to determine the emission geometry for a larger sample of AGN. The new extension of the **relline** mode<sup>‡</sup>, presented in Dauser at al. (2013)<sup>2</sup>, allows to model an extended jet. With this model the uncertainties on the size and the location of the emission region can be estimated directly for the first time by spectral analysis.

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<sup>&</sup>lt;sup>b</sup>download at http://www.sternwarte.uni-erlangen.de/research/relline/

2. Gamma-Ray Astronomy
# INTRODUCTION TO EXTRAGALACTIC SOURCES OF VERY HIGH-ENERGY PHOTONS

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The launch of the Fermi gamma-ray space telescope and the imaging air Cerenkov telescopes H.E.S.S., MAGIC, and VERITAS have substantially transformed our knowledge of gamma-ray sources in the last decade. The extragalactic gamma-ray sky is teeming with blazars, which are active galactic nuclei whose jet is directed at us. Additionally, there are radio galaxies, starburst and spiral galaxies, and gamma-ray bursts, albeit with smaller numbers. Galaxy clusters have not yet been observed in gamma rays. Here, I will introduce the different gamma-ray emission processes and review what they may tell us about these objects and the underlying acceleration mechanisms. Beyond the study of these fascinating objects, TeV gamma rays from blazars probe the integrated star formation history of the universe. Studies of TeV blazar spectra may provide us with insights into intergalactic magnetic fields or alternatively, may lead us to infer the existence of a novel mechanism that heats the intergalactic medium at late times (for redshifts z < 3) and impacts the Lyman- $\alpha$  forest and late-time structure formation. The TeV gamma-ray emission may also allow us to probe fundamental physics such as the structure of space time.

# 1 Introduction

Gamma rays cannot penetrate the Earth's atmosphere to the ground. To directly detect them, we have to go to space, where the Large Area Telescope onboard *Fermi* is currently surveying the entire sky at energies ranging from around 100 MeV to 100 GeV. The upper energy limit is determined by the finite size of the detector, which uses the pair conversion technique to detect gamma rays. However, for a gamma-ray energy above 30 GeV, it is feasible to detect the flash of Cerenkov light that is emitted in the electromagnetic cascade initiated by the gamma ray penetrating the Earth's upper atmosphere. This allows to reconstruct the energy and arrival direction of the original gamma ray and opens a second window to the gamma-ray sky that is employed by the imaging air Cerenkov telescope collaborations H.E.S.S., MAGIC, and VERITAS. Those have to conduct pointed observations of interesting targets. While this allows deeper observations on single objects with better angular resolution, it complicates the characterization of the selection function for population studies. What are the main questions that we can address by observationally probing the extragalactic gamma-ray sky?

- Which objects can we see? Clearly, we can do astronomy in the gamma-ray band and characterize and classify the detected objects into populations. Using multi-frequency constraints, we can then identify the objects with known counterparts at other electromagnetic wavelengths. Gamma-ray emitting objects are active galactic nuclei (blazars, radio galaxies), starburst and spiral galaxies, and gamma-ray bursts.
- What underlying physics can we probe? In practice, gamma-ray emission probes the most extreme physics laboratories of the cosmos. This allows us to assess questions about

the mechanism of particle acceleration and magnetic field amplification, and to study plasma physical processes at conditions that are quite different from those achievable in our laboratories on Earth (e.g., collisionless plasmas, extreme Lorentz factors).

• What fundamental physics can we hope to learn? (1) TeV photons produce electronpositrons pairs upon annihilating with soft photons in the extragalactic background light. This process enables us to probe the integrated star formation history of the universe. (2) It also may provide us with insights into intergalactic magnetic fields (which could be of primordial origin). (3) If the kinetic pair energy can be efficiently dissipated, this may even provide the dominant energy source to the intergalactic medium at late times (for redshifts z < 3) and hence impact the intergalactic medium, the Lyman- $\alpha$  forest and late-time structure formation. (4) Extreme variability at the highest gamma-ray energies may enable us to probe the structure of space time. (5) The gamma-ray energies are well adapted to the weak energy scale, which coincides with the dark matter particle masses in the most popular models since those weakly interacting massive particles would naturally account for the observed relic density if they had thermally decoupled in the early universe. Hence, studies of the physics associated with gamma rays can provide essential clues for our understanding of structure formation, cosmology, and particle physics.

After introducing the different gamma-ray emission processes, I will discuss each object class and the physics that this allows us to probe. This is meant to be a pedagogical introduction rather than a comprehensive review for which the reader is referred to Rieger et al. (2013).

#### 2 Gamma-ray emission processes induced by cosmic rays

Gamma rays carry complementary information to cosmic rays (CRs) and unlike the latter, point back to their origin (except for the ultra-high-energy CRs that perhaps are also little deflected by intervening magnetic fields). We distinguish hadronic processes (as a result of CR protonor ion-initiated interactions) and leptonic processes due to relativistic electrons or positrons. At the heart of all of these emission processes are the acceleration mechanisms that produce a (nonthermal) population of relativistic protons or electrons in first place. Gamma-ray observations can thus give us some constraints on the underlying type of acceleration.

hadronic processes:

leptonic processes:

• pion decay:

$$\mathbf{p} + \mathbf{p} (\mathrm{ion}) \rightarrow \begin{cases} \pi^0 & \rightarrow & \gamma \gamma \\ \pi^{\pm} & \rightarrow & \mathbf{e}^{\pm} + \nu_{\mu} + \bar{\nu}_{\mu} + \overset{(-)}{\nu_{\mathbf{e}}} \end{cases}$$

- photo-meson production:
  - $p(ion) + \gamma \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^{\pm} \rightarrow e^{\pm} + \nu_{\mu} + \bar{\nu}_{\mu} + \bar{\nu}_{e} \end{cases}$
- Bethe-Heitler pair production:

$$p(ion) + \gamma \rightarrow p(ion) + e^+ + e^-$$

The hadronic p-p reaction proceeds if the center-of-momentum energy exceeds the kinetic energy threshold of the pion rest mass (or more precisely the  $\Delta$  resonance through which this reaction proceeds). The latter two hadronic processes require that the gamma-ray energy in the rest system of the proton (ion) exceeds the rest mass of the pion or twice that of the electron, respectively. This can either be achieved by a CR interacting with a soft photon that is Lorentz



- bremsstrahlung:
  - $e^* + p$  (ion)  $\rightarrow e + p$  (ion)  $+ \gamma^*$

 $e^*(p^*) + B \rightarrow e(p) + B + \gamma^*$ 

- - inverse Compton:
    - $e^* + \gamma \rightarrow e + \gamma^*$
  - synchrotron radiation:

boosted to the CR's rest frame or by an energetic gamma ray. The latter could result from either of the *leptonic processes* (shown on the right; a star denotes here an energetic particle).

Inverse Compton emission and synchrotron emission are very similar processes since both describe the interaction of an energetic lepton with a photon. This photon can either be provided by an astrophysical radiation field or is a virtual photon that mediates the electromagnetic interaction of the electron with the magnetic field *B*. Because the synchrotron emissivity of a particle with mass *m* scales with the Thompson cross section,  $\sigma_T \propto m^{-2}$ , protons have to be more energetic by a factor of  $(m_p/m_e)^2$  to produce an emission that is comparable to that of electrons. Finally, (non-)thermal bremsstrahlung emission is caused by the acceleration of a (non-)thermal electron in the Coulomb field of an ion. The gamma-ray spectra resulting from these non-thermal processes are typically power-law spectra that reflect the parent CR (electron or proton) power-law spectra and are convolved with the respective emission spectrum of an individual particle. Changing to a dimensionless integration variable determines the relation between spectral indices of the CR and gamma-ray emission spectra.

## 3 Active galactic nuclei

Active galactic nuclei (AGN) can launch relativistic jets that are powered by accretion onto a central nucleus, presumably a supermassive black hole. The widely accepted AGN standard paradigm provides a unified picture of their emission properties, which depend on the orientation of the AGN relative to the line of sight (Urry *et al.* 1995). There exist two main classes of AGNs that differ in their accretion mode and in the physical processes that dominate the emission.

- Thermal/disk-dominated AGNs. Infalling matter assembles in a thin disk and radiates thermal emission with a range of temperatures. The distributed black-body emission is then Comptonized by a hot corona above the disk that produces power-law X-ray emission, which is a measure of the accretion power of the central object. This class of objects are called QSOs or Seyfert galaxies and make up about 90% of AGNs. They preferentially emit in the optical or X-rays and do not show significant nuclear radio emission. None of these sources have so far been unambiguously detected by *Fermi* or imaging atmospheric Cherenkov telescopes because the Comptonizing electron population is not highly relativistic and emits isotropically, i.e. there is no relativistic beaming effect that boosts the emission.
- Non-thermal/jet-dominated AGNs. Highly energetic electrons that have been accelerated in the relativistic jet interact with the jet magnetic field and emit synchrotron photons that range from the radio to X-ray. The same population of electrons can also Compton up-scatter any seed photon population either provided by the synchrotron emission itself (synchrotron self-Compton scenario) or from some other external radiation field such as ultraviolet (UV) radiation from the accretion disk or the infrared (IR) radiation from the surrounding torus (external Compton scenario). Hence the spectral energy distribution (SED) of these objects shows two distinct peaks. Alternatively, sufficiently energetic proton synchrotron photons can be converted into a pion in the Coulomb field of a proton. The neutral pion decays into gamma rays that trigger an electromagnetic cascade, which produces a spectrum of gamma rays (proton-induced cascades). The luminosity of all these non-thermal emission components probes the jet power of these objects. Observationally, this leads to the class of radio-loud AGNs which can furthermore be subdivided into blazars (with the line of sight intersecting the jet opening angle) and non-aligned non-thermal dominated AGNs.

Blazars can further be subdivided into two main subclasses depending upon their optical spectral properties: flat spectrum radio quasars (FSRQ) and BL Lacs. FSRQs, defined by broad optical emission lines, have SEDs that peak at energies below 1 eV, implying a maximum particle energy



Figure 1: Left. Artist's impression of a super-massive black hole that launches relativistic jets and electromagnetic radiation out to cosmological distances. Blazars are systems where the jet opening angle contains our line of sight, i.e. the jet "points" at us (credit ESA/NASA/AVO/Padovani). Right. Sequence of characteristic blazar SEDs as a function of source luminosity from FSRQ (top curve) to HSP objects (bottom curve, from Donato et al. 2001).

within the jet and limiting the inverse-Compton scattered photons mostly to the soft gamma-ray band. It is presumably for this reason that no continuous TeV component has been detected in an FSRQ (while their flare emission can sometimes reach TeV energies).

In contrast, BL Lacs or Blazars of the BL Lac type (Massaro *et al.* 2009) can be copious TeV emitters. These are very compact radio sources and have a broadband SED similar to that of strong lined blazars but lack the broad emission lines that define those. Depending upon the peak energy in the synchrotron spectrum, which approximately reflects the maximum particle energy within the jet, they are classified as low-, intermediate-, or high-synchrotron peaked BL Lacs, respectively called LSP, ISP, and HSP. While LSPs peak in the far-IR or IR band, they exhibit a flat or inverted X-ray spectrum due to the dominance of the inverse-Compton component (see Fig. 1). The synchrotron component of ISPs peaks in the optical, which moves their inverse-Compton peak into the gamma-ray band of *Fermi*. HSPs are much more powerful particle accelerators, with the synchrotron peak reaching into the UV or, in some cases, the soft X-ray bands. The inverse-Compton peak can then reach TeV energies.

Hard Fermi blazars (defined by a rising energy spectrum,  $E^2 dN/dE$ , in the Fermi band, i.e., HSPs and some ISPs) have a redshift distribution that is peaked at low redshifts extending only up to z = 0.7. This is most likely entirely a flux selection effect; hard blazars are intrinsically less luminous than LSPs and FSRQs, with an observed isotropic-equivalent luminosity range of  $10^{44} - 2 \times 10^{46}$  erg s<sup>-1</sup>, with the highest redshift hard *Fermi* blazars also being among the most luminous objects. There are plausible explanations why hard Fermi blazars should be intrinsically less luminous than FSRQs. Ghisellini et al. (2009) have argued that the physical distinction between FSRQs and hard blazars has its origin in the different accretion regimes of the two classes of objects. Using the gamma-ray luminosity as a proxy for the bolometric luminosity, the boundary between the two subclasses of blazars can be associated with the accretion rate threshold (nearly 1% of the Eddington rate) separating optically thick accretion disks with nearly Eddington accretion rates from radiatively inefficient accretion flows. The spectral separation in hard (BL Lacs) and soft (FSRQs) objects then results from the different radiative cooling suffered by the relativistic electrons in jets propagating into different surrounding media (Ghisellini et al. 2009). Hence in this model, hard Fermi blazars cannot reach higher luminosities than approximately  $2 \times 10^{46} \text{ erg s}^{-1}$  since they are limited by the nature of inefficient accretion flows that power these jets and by the maximum black hole mass,  $\sim 10^{10} M_{\odot}$ .



Figure 2: Left. Stacked spectra of BL Lac objects show an absorption feature that moves to lower energies for increasing redshift (data points, from top to bottom). This confirms that gamma rays are attenuated by annihilating and pair producing on the EBL (dashed curve) and rules out models where all blazars have an intrinsic exponential cutoff and follow the blazar sequence (thin solid, from M. Ackermann *et al.* 2012). Right. Models of the EBL are compared to observational limits on the EBL. The inset shows a compilation of the cosmic star formation rate as inferred from UV,  $H\alpha$ , mid-IR, submillimeter, radio, and  $Ly\alpha$  observations while excluding lower limits (from Dwek & Krennrich 2012).

Despite the tremendous progress in our understanding of properties of the various populations, there are many open questions, including the jet energetics, the mechanisms responsible for jet formation and collimation, the plasma composition (leptonic vs. hadronic), the jet geometry (1-zone vs. spine-layer), or the specific acceleration mechanisms of the jet plasma. Particularly puzzling is the reason for the observed variability of the gamma-ray emission of blazars, which is considerably smaller than the light crossing time of the Schwarzschild horizon in the most extreme cases. TeV "flares" may sign instabilities in the accretion of matter onto the central supermassive black hole or in the jet.

## 4 The impact of TeV blazars on cosmology and structure formation

The light emitted by galaxies and accreting compact objects throughout the history of the universe is encoded in the intensity of the *extragalactic background light* (EBL). Hence it provides an important integral constraint on the star and quasar formation history in the hierarchical model of galaxy assembly. Direct measurements of the EBL are limited by galactic and other foreground emissions. Instead one can infer it indirectly because the universe is opaque to TeV gamma rays, which annihilate and pair produce on the EBL. This implies an absorption feature (the "gamma-ray horizon") in the spectra of gamma-ray blazars. Stacking the spectra of 150 significantly detected BL Lac blazars (0.03 < z < 1.6), the *Fermi* Collaboration showed that the stacked spectrum is unabsorbed for E < 25 GeV. In agreement with the expectation, there is an absorption feature that moves to lower gamma-ray energies for higher source redshifts (propagation distances) due to attenuation of gamma rays by the EBL at optical to UV frequencies (Ackermann *et al.* 2012, see Fig. 2).

The ultra-relativistic pairs of electrons and positrons resulting from TeV photon annihilation on the EBL are commonly assumed to lose energy primarily through inverse Compton scattering with photons of the cosmic microwave background, cascading the original TeV emission a factor of  $\sim 10^3$  down to GeV energies. However, the expected cascaded GeV emission is not seen in the individual spectra of those blazars (Neronov & Vovk 2010). As a putative solution to this problem, *intergalactic magnetic fields* have been hypothesized, which would deflect the pairs out of our line-of-sight to these blazars, diluting the point-source flux into a lower surface brightness "pair halo". A stronger magnetic field implies more deflection and dilution of the GeV point source flux. In this picture, a non-detection of GeV gamma rays suggests a limit on intergalactic magnetic fields of  $B \gtrsim (10^{-17} - 10^{-15}) \mu$ G for a magnetic coherence length of 1 Mpc, where the range covers uncertainties about the time delay of the cascade photons (Taylor *et al.* 2011). Since most of the volume of the universe (and hence a random sight line) is dominated by voids, magnetic fields of these strengths may imply a primordial origin and allow one of these rare glimpses into the early universe.

However, it has been shown recently that there is an even more efficient mechanism that competes with this cascading process. The ultra-relativistic pairs, originating from TeV photon annihilation on the EBL, are propagating trough the intergalactic medium, which can be viewed as two counter-propagating beams that are subject to plasma instabilities. The linear growth rate of the so-called "oblique instability" is larger than the inverse Compton cooling rate of the pairs. If this dominance of the instability growth rate carries over to the regime of nonlinear saturation, this implies a transfer of free kinetic energy of the pairs to the unstable electromagnetic modes in the background plasma, which should eventually be dissipated, heating the intergalactic medium (Broderick et al. 2012, Schlickeiser et al. 2012). Typically, ~ 300yr after the onset of TeV emission, the pair beam density has grown sufficiently for plasma beam instabilities to dominate its evolution, randomize the beam, and potentially suppress the inverse-Compton signal upon which the limits on the intergalactic magnetic fields are based (rendering these limits dubious). In this picture, there are two means to avoid the consequences of plasma beam instabilities during the growth of the pair beam by (1) the sudden appearance of a TeVbright blazar or intrinsically transient sources (e.g., gamma-ray bursts) or (2) for particularly dim sources,  $L \lesssim 10^{42} \,\mathrm{erg \, s^{-1}}$ , for which the pair beam density is too small to support collective plasma behaviour. However, for all luminous TeV blazars detected to date, the presence of these plasma beam instabilities appears unavoidable and suggests the existence of a novel heating mechanism, coined *blazar heating*. It produces an inverted temperature-density relation of the intergalactic medium (Chang et al. 2012) that is in agreement with observations of the Lyman- $\alpha$  forest (Puchwein *et al.* 2012). This also suggests that *blazar heating* can potentially explain the paucity of dwarf galaxies in galactic halos and voids, and the bimodality of central gas entropy values in galaxy clusters (Pfrommer et al. 2012). Detailed comparisons of predictions of blazar heating with *Fermi* observation of blazar statistics (redshift and  $\log N - \log S$  distribution) as well as the isotropic and anisotropy gamma-ray backgrounds have been very successful and supportive of this model (Broderick et al. 2013).

#### 5 Blazar and gamma-ray burst variability probes the structure of space time

Blazar variability shows a complex multi-wavelength behaviour that challenges simple emission models. The H.E.S.S. observation of a giant flare (more than two orders of magnitudes) of PKS 2155-304 shows a variability timescale  $\Delta t_{\rm var} \sim (2-3) \min \sim 0.02 R_s/c$ , where  $R_s/c$  is the light crossing time of the Schwarzschild horizon (Aharonian *et al.* 2008). Causality requires  $R < c\Delta t_{\rm var} \gamma$  and implies a very small emission region and bulk motion with a Lorentz factor  $\gamma > 50$  (Begelmann *et al.* 2008).

Independent of the emission mechanism, the observed variability can also be used to probe the structure of space time and to constrain theories of Quantum Gravity, some of which predict space-time to be "foamy" or discrete at the Planck scale  $l_P = \hbar/(m_P c)$ , where the Planck mass is  $m_P = \sqrt{\hbar c/G}$ . Preserving the O(3) subgroup of SO(3,1), we can parametrize the modified dispersion relation for photons,  $c^2 p^2 = E^2(1 + \xi E/E_{\rm QG} + \eta E^2/E_{\rm QG}^2 + ...)$ , where it is usually assumed that  $E_{\rm QG} \sim m_P c^2 \sim 10^{19}$  GeV and  $\xi = \pm 1$  is a sign ambiguity that is fixed in a given dynamical framework. Assuming that the Hamiltonian equations of motion,  $\dot{x}_i = \partial H/\partial p_i$ , are still valid, this yields  $v = \partial E/\partial p = c(1 - \xi E/E_{\rm QG} + ...)$ . In other words, we obtain



Figure 3: Nearby radio galaxies are emitting in gamma rays. Fermi and H.E.S.S. detected gamma-ray emission from Cen A (left, radio data in orange are overlaid on Fermi data in purple, credit NASA/DOE/Fermi LAT) and M87 (middle, 140 MHz radio data from LOFAR/de Gasperin et al. 2012). Right. Multi-frequency spectrum of M87 indicating the low- (red) and high-flux state (blue) at TeV energies (from Rieger & Aharonian 2012).

an energy-dependent time delay  $\Delta t = \xi(E/E_{\rm QG})(L/c) = 10 \,\mathrm{ms} \,({\rm GeV}/E_{\rm QG})(1 \,{\rm Gpc}/c)$ , where L is the path length of the photon. That is, we can test this by studying propagation of high energy gamma-ray pulses of different energies from cosmological distances (Amelino-Camelia *et al.* 1998).

That test was done with the *Fermi* detection of the early arrival time of the 31 GeV photon of the short gamma-ray burst GRB 090510, implying a conservative bound of  $E_{\rm QG} > 1.2 \times 10^{19}$  GeV (Abdo *et al.* 2009a). The giant flare of PKS 2155-304 observed by H.E.S.S. shows no observable time delay between low- and high-energy photons, thereby implying a bound  $E_{\rm QG} > 2.1 \times 10^{18}$  GeV (Abramowski *et al.* 2011). This starts to constrain an energy-dependent violation of Lorentz invariance (i.e., an energy-dependent speed of light), which is predicted in various models of Quantum Gravity. However, all these analyses make the strong assumption that there is no intrinsic gamma-ray dispersion in the source and that the gamma-ray pulses at different energies are emitted at the same time. To improve upon these constraints, we need a better understanding of the sources and emission mechanisms.

## 6 Radio galaxies and the cluster "cooling flow problem"

Some nearby radio galaxies also emit gamma rays, which may be partly related to the nucleus, the jet, the radio lobes, or CR interactions with the surrounding plasma (see Fig. 3). The closest radio galaxy Centaurus A is at a distance of 3.7 Mpc, often considered as an "AGN under the microscope". *Fermi* observes GeV emission from the giant radio lobes and the core while H.E.S.S. detected TeV emission from the nucleus/inner jet (Abdo *et al.* 2010, Aharonian *et al.* 2009). This triggered ideas that the giant lobes are the sites of high-energy particle acceleration and production of ultra-high-energy cosmic rays (Hardcastle *et al.* 2009).

At the end of the momentum-driven phase, relativistic jet particles inflate radio-emitting lobes and do pressure-volume work on the ambient intra-group and -cluster medium. According to the current paradigm, the buoyantly rising lobes either do mechanical work on the surroundings (which gets dissipated through shocks or a turbulent cascade) or they release CRs into the intracluster medium. Those stream at the Alfvén velocity with respect to the plasma rest frame and heat the surrounding thermal plasma (Loewenstein *et al.* 1991). This "AGN feedback" balances radiative cooling and solves the cluster "cooling flow problem" at low redshifts,  $z \leq 1$  (McNamara & Nulsen 2012). What can gamma-ray observations add to this picture?

*Fermi* and H.E.S.S. discovered gamma-ray emission from the radio galaxy M87 (Abdo *et al.* 2009b, Abramowski *et al.* 2012), the central galaxy of the Virgo cluster, our closest galaxy cluster at a distance of 17 Mpc. While the TeV emission in the high state is likely connected to the emission from the nucleus/jet, there is the possibility that the low emission state traces pion-decay gamma rays from the Virgo cool-core region as implied by the spectral similarity



Figure 4: The nearby starburst galaxies M82 (Acciari *et al.* 2009) and NGC 253 (Acero *et al.* 2009) emit TeV gamma rays. We contrast gamma-ray significance maps to optical images of these galaxies.

to LOFAR radio data (see Fig. 3). In this picture, the gamma-ray emission can be used to normalize the CR-induced heating rate, which balances that of radiative cooling *on average* at each radius, thereby suggesting a solution to the "cooling flow problem" in the Virgo cluster (Pfrommer 2013). This model would predict the gamma-ray emission in the low state to be steady and slightly extended, which is testable with current observations.

## 7 Starburst and spiral galaxies

M82 and NGC 253 are TeV gamma-ray emitting starburst galaxies (Acciari *et al.* 2009, Acero *et al.* 2009), both at a distance of ~ 3 Mpc (see Fig. 4). *Fermi* confirmed the gamma-ray emission in those objects and increased the sample of starburst galaxies by two more objects (NGC 4945, NGC 1068) although those are composite starburst/Seyfert 2 systems, which makes it challenging to disentangle the pure starburst component (Lenain *et al.* 2010). Their star formation rate (in a compact region) is larger than that of the Milky Way. In the emerging picture, supernova remnants, associated with star formation regions, can energize CR protons through diffusive shock acceleration. Hadronic interactions of those CR protons with the ambient dense gas produce pion-decay gamma rays. In the starburst region, there is dense interstellar gas, with (n) ~ 250 cm<sup>-3</sup>, which yields a hadronic interaction time that is of order the diffusive escape time,  $t_{\rm pp} \sim t_{\rm esc}$ . Hence we are approaching the calorimetric limit.

The large magnetic field strengths and high densities should also give rise to efficient leptonic emission. In fact, the tight far infrared (FIR)-radio correlation implies universal conversion of the star formation rate to the CR- and the synchrotron luminosities. Provided the picture of gamma-ray emission is correct, this also would imply a FIR-gamma-ray correlation. The local four spiral galaxies (Milky Way, SMC, LMC, M31) show indeed gamma-ray luminosities, which fall on the locus of the FIR-gamma-ray correlation defined by the starburst galaxies. However, to fully establish this picture, the AGN contribution to the observed gamma-ray emission of starburst galaxies needs to be carefully quantified. Moreover, the possible counterexamples to this relation, i.e., upper limits on the gamma-ray emission of some galaxies that fall also within the implied relation (IC342, NGC 6946), need to be understood. While their upper limits are still compatible with the scatter around the relation, tighter limits will either strengthen the tension or lead to a detection, thereby confirming the existence of a FIR-gamma-ray correlation.



Figure 5: Expected gamma-ray emission in a cosmological hydrodynamical simulation of a galaxy cluster. The surface brightness emission (*left*) and spectral index map,  $\Gamma_{100MeV}^{1.GeV}$ , (*middle*) is dominated in the center by pion decay and outside the virial radius (of 2.4 Mpc) by primary inverse Compton (pIC) emission from shock-accelerated relativistic electrons. The total CR proton spectrum shows a universal shape across clusters (*top right*) that is inherited by the pion decay and secondary IC emission following hadronic p-p interactions (*bottom right*). The pIC emission only has a small contribution to the total emission for E > 30 MeV (from Pinzke & Pfrommer 2010).

## 8 Galaxy clusters

Despite many efforts in the recent years, no cluster-wide gamma-ray emission has been detected so far (Ackermann *et al.* 2010). The observed radio halo and relic emission on cluster scales (1-3 Mpc) proves the existence of CR electrons and magnetic fields that permeate the cluster volumes and suggests that clusters also emit diffuse gamma rays. Cosmological hydrodynamical simulations of galaxy cluster with self-consistent CR physics show that the normalized CR spectrum has a universal concave shape across clusters (Pinzke & Pfrommer 2010). During the hierarchical assembly, every fluid element experienced on average the same history of shock strengths, which is responsible for shaping the CR spectrum. As a result, the gamma-ray signal is expected to be dominated by pion decay, but other possibilities exist, such as inverse Compton emission from electrons that have been accelerated at structure formation shock waves (see Fig. 5).

Non-observations of gamma rays from the Perseus and Coma clusters constrain the CRto-thermal pressure to  $P_{\rm CR}/P_{\rm th} < 1.7\%$  in those clusters (Aleksic *et al.* 2012, Arlen *et al.* 2012). This immediately implies that hydrostatic cluster masses are not significantly biased by CRs—an important result if cluster populations are to be used for determining cosmological parameters. A comparison to hydrodynamical cluster simulations constrains the maximum acceleration efficiency at formation shock on average to < 50%. Provided the (*high-frequency*) radio halo emission is produced by secondary electrons from CRp-p interactions, this allows us to place limits on the central cluster magnetic fields of  $> (4 - 9) \mu G$  (Perseus) and  $> (2 - 5) \mu G$ (Coma), which are below the limits obtained from Faraday rotation measure studies (Aleksic *et al.* 2012, Arlen *et al.* 2012). However, these limits on magnetic fields are in conflict with Faraday rotation data for the *low-frequency* radio halo emission in Coma, arguing for a leptonic origin of (at least) the external halo at these frequencies (Brunetti *et al.* 2011).

#### 9 Conclusions

The non-thermal universe revealed by high-energy radiation provides not only deep insights into high-energy astrophysics and plasma processes that are not accessible in our laboratories on Earth but also new probes of fundamental physics, cosmology, and structure formation. With the successful *Fermi* telescope and the imaging air Cerenkov collaborations H.E.S.S., MAGIC, and VERITAS, we are currently entering a fascinating era that is complemented by multifrequency experiments. As a result of this, there is no shortage of new discoveries and puzzles to solve. In tackling those, we should not be afraid of employing new ideas and theories, some of which may later need to be refined. In doing so, we should mind the unseen (dark matter, galaxy clusters, ...). What can it teach us? Does it conflict with our previous models of particle acceleration and/or transport? To proceed, a precise and accurate measurement of the isotropic and anisotropic extragalactic gamma-ray background is critical for constraining the luminosity evolution of various populations by their maximally allowed contribution to the respective backgrounds. I will end this introduction by a quote of Louis Pasteur stating that "in the fields of observation chance favors only the prepared mind"!

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## PROPAGATION OF HIGH-ENERGY PHOTONS

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Spectrum and timing characteristics of high-energy and very-high energy  $\gamma$ -ray signal from astronomical sources could be significantly modified during propagation through matter and radiation environments of the sources, their host galaxies and the intergalactic medium. Interactions of  $\gamma$ -rays during propagation from the source to the Earth initiate development of electromagnetic cascades along the path of the  $\gamma$ -ray beam. Secondary  $\gamma$ -ray emission from these cascades is detectable either as a separate component or as an integral part of the source signal. Study of the properties of the cascade emission signal could be used to probe the physical conditions in the medium through which  $\gamma$ -rays propagate. An example of such probe is the possibility of the measurement of weakest magnetic fields in the intergalactic medium using the  $\gamma$ -ray signal from distant active galactic nuclei.

#### 1 Relevant interaction channels

The highest energy  $\gamma$ -rays produced by particles accelerated in different types of astronomical sources do not propagate freely from their production site up to the telescope on Earth. Their energy is typically high-enough to initiate production of secondary particles in interactions with photons electrons and/or atomic nuclei.

In the astrophysical context, the dominant interaction channel of high-energy  $\gamma$ -rays is gamma-gamma pair production. A  $\gamma$ -ray with energy  $E_{\gamma}$  will interact with a another photon of energy  $\epsilon$  if its energy if above the threshold  $E_{\gamma\gamma\rightarrow e^+e^-} = (m_ec^2)^2/\epsilon$ . For a  $\gamma$ -ray propagating through an isotropic soft photons field, the scattering angle averaged cross-section of the  $\gamma\gamma$  pair production reaches a maximum at the energy  $E_{max \ \sigma} \simeq 4E_{\gamma\gamma\rightarrow e^+e^-} \simeq 4(m_ec^2)^2/\epsilon = 1 [\epsilon/1 \text{ eV}]^{-1}$  TeV where it reaches the value  $\sigma_{max}, \gamma\gamma\rightarrow e^+e^- \simeq 1.3 \times 10^{-25} \text{ cm}^{-21}$ . At the energies  $E_{\gamma} \gg E_{max \ \sigma}$ , the  $\gamma\gamma$  pair production cross-section, which is a function of  $s = E_{\gamma}\epsilon/(m_ec^2)^2$ ) decreases asymptotically as  $E_{\gamma}^{-1} \ln(E_{\gamma})$  (for a fixed  $\epsilon$ ), see Fig. 1. If the spectrum of the soft photon background with the density  $n_{ph}$  is sharply peaked at a

If the spectrum of the soft photon background with the density  $n_{ph}$  is sharply peaked at a particular energy, the energy-dependent mean free path of  $\gamma$ -rays through the soft photon background could be estimated as  $\lambda_{\gamma\gamma \to e^+e^-} \simeq (\sigma_{max, \gamma\gamma \to e^+e^-} n_{ph})^{-1} \simeq 7 [n_{ph}/400 \text{ cm}^{-3}]^{-1}$  kpc. In the last equation we have taken, for a reference, the number density of photons of the Cosmic Microwave Background (CMB), which have the average energy  $\epsilon \simeq 3T \simeq 10^{-3}(T/2.7 \text{ K}) \text{ eV}$  and, therefore, interact most efficiently with the  $\gamma$ -rays of the energies  $E_{max \sigma} \simeq 1$  PeV.

Comparing the estimate of the mean free path with the typical sizes of the Milky Way type galaxies,  $R_{galaxy} \sim 10$  kpc, one could see that e.g. PeV  $\gamma$ -rays produced in astronomical sources in galaxies other than our own Milky Way would not be able to reach telescope and be detected on the Earth. Even for the sources in the central part of our own Galaxy (distance range  $R_{GC} \simeq 8$  kpc, PeV  $\gamma$ -rays produced by Galactic "PeVatrons" would be absorbed on the way from the source to the Earth.



Figure 1: Cross-sections of interactions of gamma-rays with photons and matter. Solid blue line shows the Compton scattering cross-section. Solid black line is for the  $\gamma\gamma$  pair production. Dashed black line is for the double-pair production cross-section. Dotted blue line it the Bethe-Heitler pair production cross-section, dashed blue line is the triple pair production cross-section.

Decrease of the  $\gamma\gamma$  pair production crosssection at the energies much above  $E_{max \sigma}$ leads to the increase of the  $\gamma$ -ray mean free path, so that not only low-energy  $\gamma$ -rays, but also  $\gamma$ -rays with energies much higher than of the energies much higher than PeV could be observed from sources throughout the Milky Way galaxy. At the energies  $E_{\gamma} \gtrsim 10^6 E_{max \sigma}$ , the gamma-gamma pair production cross section decreases by some four orders of magnitude. Above this energy, the dominant interaction channel is double pair production, which has an energy-independent cross-section much above the pair production threshold, see Fig. 1. The double pair production channel could hardly be of astrophysical importance because  $\gamma$ -rays with energies some  $10^6$  times higher than the threshold energy of single pair production for a

particular target photon field, e.g. CMB, would mainly interact via single pair production with abundant lower energy (e.g. radio) photons.

Another obstacle for high-energy  $\gamma$ -rays is medium of protons and electrons.  $\gamma$ -rays with energies above the pair production threshold  $E_{\gamma H \to H + e^+ e^-} \simeq 2m_ec^2$  could produce pairs interacting with Coulomb field of atomic nuclei (mostly hydrogen and helium in astrophysical conditions), as well as with the bound and free electrons<sup>1</sup>. In spite of the fact that the cross-section of this process is suppressed (compared to the Thomson cross-section) by the fine structure constant  $\alpha$ , logarithmic growth of the cross-section with energy makes the process important at the energies much above the threshold. The asymptotic value of the pair production cross section is  $\sigma_{max,\gamma H \to H + e^+e^-} \simeq 30\alpha r_e^2 \simeq 2 \times 10^{-26}$  cm<sup>2</sup>. From Fig. 1 one could see that the pair production starts to dominate over Compton scattering as soon as the energy of  $\gamma$ -rays rises to about 300 MeV. The pair production in the Coulomb field of high-Z nuclei is used for detection of high-energy  $\gamma$ -rays by Fermi space  $\gamma$ -ray telescope <sup>2</sup>; pair production in the atmosphere is used for detection of TeV  $\gamma$ -rays by Cherenkov telescopes <sup>1</sup>.

#### 2 Interactions inside gamma-ray sources

#### 2.1 Pulsars

The most commonly known example of attenuation of the  $\gamma$ -ray flux by the pair production effect is that of the pulsed emission from pulsars. In this case, particles accelerated in the vacuum gap(s) in pulsar magnetosphere produce curvature and/or inverse Compton  $\gamma$ -ray emission. This emission is directly observable in telescopes like Fermi Large Area Telescope (LAT) in 0.1-100 GeV energy band and at higher energies by the Cherenkov telescopes like MAGIC, and VERITAS<sup>3,4,5</sup>. Pulsed emission coming from the "outer" vacuum gap in the magnetosphere is cut-off at the highest energy because of the onset of pair production on lower energy photons<sup>6</sup>.

Taking Crab pulsar as an example, one could estimate the energy dependent density of photons in the outer magnetosphere, close to the "light cylinder" at the distance  $R_{lc} = cP \simeq 10^8 [P/33 \text{ ms}] \text{ cm}$  (P is the rotation period of the neutron star). The spectral energy distribution of the pulsed emission from Crab peaks in the keV-MeV energy range at the level of  $F \sim 10^{-9} \text{ erg/(cm}^2 \text{s})$ , see Fig. 2. Assuming that all the pulsed emission comes from inside of the light cylinder, one finds that the X-ray photon density within the light cylinder is  $n_{ph} \simeq F(d/R_{lc})^2/\epsilon \simeq 10^{17} \text{ cm}^{-3}$ , where  $d \simeq 2 \text{ kpc}$  is the distance to the source. The mean free path of  $\gamma$ -rays is  $\lambda_{\gamma\gamma\to e^+e^-} \sim 10^8 \text{ cm}$  for the  $\gamma$ -rays with energies  $E_{max \ \sigma} \simeq 1[\epsilon/1 \text{ keV}]^{-1}$  GeV. The

optical depth for  $\gamma$ -rays escaping from the interior of the light cylinder is  $\tau = R_{lc}/\lambda_{\gamma\gamma \to e^+e^-}$ and the escaping  $\gamma$ -ray flux is suppressed as  $\exp(-\tau)$  by the pair production. The suppression of the spectrum above  $\sim 1$  GeV energy, seen in Fig. 2 could, therefore, be due to the effect of absorption of  $\gamma$ -rays during their propagation through the X-ray photon background in the source. Absorption of the escaping  $\gamma$ -rays due to the pair production on the lower energy (optical-to-X-ray) pulsed emission could also explain the observed shape of the  $\gamma$ -ray spectrum. Indeed, the density of the soft X-ray photons increases with the decrease of energy as  $\epsilon^{-0.5}$ (see Fig. 2). As a consequence, the mean free path of the  $\gamma$ -rays decreases with energy as  $\lambda_{\gamma\gamma \to e^+e^-} \sim E^{-0.5}$  and the optical depth increases as  $\tau \sim E^{0.5}$ . The suppression of the  $\gamma$ -ray flux is then  $\exp(-\tau) \sim \exp(-E^{0.5})$ . This is consistent with the observed decrease of the flux of the pulsed emission from Crab at the highest energies, up to several hundred GeV, see Fig. 2.



Figure 2: Spectrum of pulsed emission from Crab pulsar. High-energy suppression of the flux due to pair production is shown by the grey band. Arrows with energy marks show the typical energies of soft photons with which  $\gamma$ -rays interact. Optical-to- $\gamma$ -ray data (blue) are from Ref. 8. Fermi GeV (red) are from Ref. 9. TeV data are from Refs. 4,5.

A self-consistent model of the emergent pulsed emission spectrum should take into account emission from the secondary  $e^+e^-$  pairs produced in result of the absorption of the  $\gamma$ -rays. Taking into account that the magnetic field in he region around the light cylinder is about  $10^{12} (R_{lc}/R_*)^{-3}$  G  $\simeq 10^6$  G ( $R_* \simeq 10$  km is the radius of the neutron star), one finds that the pairs of the energies 1-100 GeV produce synchrotron emission in the 10 keV-10 MeV energy range and contribute to the "bump" in the pulsed emission spectrum in this energy range.

#### 2.2 Gamma-ray binaries

In isolated pulsars, high density of soft photons in the magnetosphere is the only obstacle for escaping  $\gamma$ -rays.  $\gamma$ -rays produced further away

from the neutron star, in the pulsar wind nebula could escape without absorption, even if their energy is much higher, in the TeV range. This is not so if the pulsar is a member of a binary system with a bright massive star driving strong stellar wind. In this case high energy particles from relativistic pulsar wind interact with the massive star wind and form a compact version of the pulsar wind nebulae <sup>10,12</sup>. Although such systems are rare, several are known in the Galaxy, with PSR B1259-63<sup>11</sup> being the prototypical example.

The massive star in the binary produces a wind, which could be dense close to the stellar surface,  $n_w = \dot{M}/(4\pi d^2 m_p v_{wind}) \simeq 10^{13} \left[ \dot{M}/10^{-5} M_\odot/yr \right] \left[ v_{wind}/(10^7 \text{ cm/s}) \right]^{-1} \left[ d/10 R_\odot \right]^{-2} \text{ cm}^{-3}$ . Here  $v_{wind}$  is the wind velocity,  $\dot{M}$  is the mass loss rate. Similarly dense is the radiation field:  $n_{ph} = L_*/(4\pi d^2\epsilon c) \simeq 10^{13} \left[ L_*/10^{38} \text{ erg/s} \right] [\epsilon/10 \text{ eV}]^{-1} \left[ d/10 R_\odot \right]^{-2} \text{ cm}^{-3}$  where  $L_*$  is the star's luminosity. Calculating the mean free path of the  $\gamma$ -rays created in the system, one finds that the  $\gamma$ -ray mean free path with respect to the gamma-gamma pair production,  $\lambda_{\gamma\gamma\rightarrow e^+e^-} \sim 10^{12} [n_{ph}/10^{13} \text{ cm}]^{-1}$  cm, or even with respect to the Bethe-Heitler pair production  $\lambda_{\gamma H\rightarrow H+e^+e^-} \sim 10^{12.5} [n_w/10^{13} \text{ cm}]^{-1}$  cm, could be shorter than the characteristic distance scales in the system (e.g. the binary separation distance) if the binary is compact enough,  $d \sim 10^{12}$  cm. This is the case for some known  $\gamma$ -ray binary systems such as LSI +61 303^{13} or LS 5039^{14}.

The probability of interaction of high-energy  $\gamma$ -rays is enhanced if they are emitted in the direction of the massive star, so that they have to fly by the star before escaping from the system. This geometrical effect acts in the same way both on the  $\gamma$ -rays and on electrons/positrons, so that the probability of interaction of high-energy electrons flying in the direction of the massive star is enhanced, compared to the probability of interactions for electrons running away from the star. Higher probability of interaction of high-energy electrons leads to the increase of

production rate of high-energy photons, via inverse Compton scattering on the soft (usually UV band) photons emitted by the star.

The overall effect of the increase of the production rate of high-energy  $\gamma$ -rays accompanied by the increase of the absorption, results in a "rotating hollow cone" type anisotropy of  $\gamma$ -ray emission<sup>29</sup>. The cone axis is along the direction from the pulsar toward the massive star, because this is the direction in which the production rate of  $\gamma$ -rays is highest. The interior of the cone is empty because  $\gamma$ -rays are absorbed by the UV radiation in vicinity of the star.

Similarly to the case of pulsars, the effect of the pair production is not limited to the suppression of the  $\gamma$ -ray flux from the source. The  $e^+e^-$  pairs injected by the pair production will produce secondary synchrotron / Bremssrahlung / inverse Compton emission, so that a self-consistent model of the source spectral



Figure 3: Spectra of the  $\gamma$ -ray binary LS 5039 in different orbital phases: superior conjunction (highest absorption of  $\gamma$ -rays) in light blue and inferior conjunction (no  $\gamma\gamma$  absorption). Grey band shows possible modification of the spectrum due to the pair production. due to pair production on the photon field of companion star.

and timing properties should include a calculation of the full electromagnetic cascade<sup>32</sup>. The extended nature of the emission from the electromagnetic cascade might be responsible for the fact that no pronounced absorption is observed in the spectra of known $\gamma$ -ray binaries (Fig. 3).

#### 2.3 Blazars and radio galaxies

Similarly to pulsars and gamma-ray binaries, escape of the highest energy  $\gamma$ -rays from the environment of radio loud active galactic nuclei (AGN) is also hindered by the effects of the pair production, which is, obviously, strongest in the environment of the AGN central engine, the supermassive black hole. Let us consider as an example the environment of the central engine of Fanaroff-Riley type I radio galaxies and their beamed versions, BL Lac type objects.

In these sources are characterized by moderate intrinsic luminosities which are several orders below the Eddington limit. In such situation the accretion proceeds via a Radiatively Inefficient Accretion Flow (RIAF) with radial velocity, similarly to spherically symmetrical Bondi accretion, close to the free fall velocity  $v_{ff} = \sqrt{GM/2r}$  so that the radial density profile of the accretion flow is  $\rho(r) = \dot{M}/4\pi r^2 v_{ff} \sim r^{-3/2}$ , where  $\dot{M}$  is the accretion rate. The density close to the black hole could be estimated if the density of the interstellar medium at the accretion radius is known. Assuming that the temperature of the interstellar medium is  $T_{ISM} \sim 0.1$  keV, one finds the accretion radius of the order of  $R_{acc} \sim 30$  pc from the relation  $GM/R_{acc} \sim T_{ISM}/m_pc^2$  for a black hole of the mass  $M \sim 10^8 M_{\odot}$ . If the density of the interstellar medium on this distance scale is  $n_{\infty} \sim 10 - 10^3$  cm<sup>-3</sup>, close to the black hole the density is  $n_{RIAF} \sim n_{\infty} \left( R_{acc}/GM \right)^{3/2} \sim$  $10^{11} \div 10^{13}$  cm<sup>-3</sup>. The density of soft photons (synchrotron emission from the accretion flow electrons, in the infrared-optical energy band) could be estimated from the known luminosity L of the accretion flow as  $n_{ph} \simeq L/(4\pi (10GM)^2 c\epsilon) \simeq 10^{13} [L/10^{42} \text{ erg/s}] [M/10^8 M_{\odot}]^{-2} [\epsilon/1 \text{ eV}]^{-1}$ Estimating the mean free path of high-energy  $\gamma$ -rays with respect to the gamma-gamma and Bethe-Heitler pair production one finds that the latter could hardly be important due to the low density of the accretion flow. At the same time the  $\gamma\gamma$  pair production could significantly attenuate the  $\gamma$ -ray emission power at the energies above  $E_{max \sigma} \simeq 1 [\epsilon/1 \text{ eV}]^{-1}$  TeV <sup>16,17</sup>.

As an example let's consider the escape of the highest energy photons from the nearby radio galaxy M87, which is known to be a TeV  $\gamma$ -ray source<sup>18</sup>. It hosts one of the most massive black holes with  $M \simeq 3 \times 10^9 M_{\odot}^{-19}$ , which has largely sub-Eddington luminosity of the order of  $L \sim 10^{42}$ erg/s dominated by emission in the infrared band. The density of the infrared photons



with energies in the  $\epsilon \sim 0.1$  eV energy range is then  $n_{ph} \sim 10^{12}$  cm so that the mean free path of the  $\gamma$ -rays with energies  $E_{max \sigma} \sim 10$  TeV is  $\lambda_{\gamma\gamma \rightarrow e^+e^-} \sim 10^{13}$  cm, if the size of the infrared source is just about 10 gravitational radii. Fast variability of the TeV emission from this source indicates that TeV  $\gamma$ -rays originate right from the vicinity of the black hole<sup>18</sup>, i.e. from the region of the size no much larger than  $R_{BH} \sim 2GM/c^2 \sim 10^{15}$  cm. At the same time, multi-TeV  $\gamma$ -rays could interact with the infrared photons before the escape. This might lead to a strong suppression of the flux by the pair production, similarly to what is observed in the pulsars (see above). As it is clear from Fig. 4, no such suppression is observed at the energies up to 20 TeV. Non-observation of such suppression imposes a lower bound on the extent of the infrared source, which is about 50 times the Schwarzschild radius of the supermassive black hole in M87<sup>16</sup>.

Much stronger absorption is expected for  $\gamma$ -rays which are produced in the central engines of bright quasars accreting at Eddington rate. The luminosity of the accretion flows (accretion disks) there reaches some  $L_{Edd} \simeq 10^{45} [M/10^7 M_{\odot}]$  erg/s produced in the regions of the size about several Schwarzschild radii  $R \sim (several)R_{BH} \sim$  $10^{13} [M/10^7 M_{\odot} \text{ cm.}]$ This provides soft photon density  $n_{ph} \simeq L/(4\pi R^2 c\epsilon)$  $10^{18} [M/10M_{\odot}]^{-1} [\epsilon/10 \text{ eV}]^{-1} \text{ cm}^{-3}$ , where we have assumed characteristic energies of photons in the accretion flow in the UV range, as expected for the AGN accretion disks. Comparing the mean free path of  $\gamma$ -rays with energies  $E_{max \sigma} \simeq 0.1 [\epsilon/10 \text{ eV}]^{-1}$  TeV with the size of the central engine, we find that the op-



Figure 4: Fermi (GeV) and HESS (TeV) spectrum of radio galaxy M87.TeV band data are from Ref. 18. GeV data are the spectrum extracted from 4.5 yr exposure with Fermi/LAT. Grey band shows the expected effect of absorption  $\gamma$ -rays due to the pair production.

tical depth for the  $\gamma$ -rays might reach some  $\tau = R/\lambda_{\gamma\gamma\rightarrow e^+e^-} \sim 10^5$ , so that the escape of  $\gamma$ -rays with energies in the 100 GeV range is completely blocked. The spectrum of soft photons in the accretion disk at the energies above 10 eV is exponentially decreasing, so that the optical depth drops quickly and GeV  $\gamma$ -rays could freely escape from the vicinity of the accretion disk. In fact, the brightest blazars/quasars are commonly observed in the GeV band, but never in the Very-High-Energy band above 100 GeV. In spite of better transparency of the accretion flow to sub-100 GeV  $\gamma$ -rays, it is still not clear a-priori if such  $\gamma$ -rays could escape from the system, if they are produced in a compact region near the footprint of the AGN jet, because, similarly to pulsar wind nebulae, they would interact with lower energy synchrotron photons and also with the X-ray emission from "coronae" surrounding the accretion disk<sup>20</sup>.

## 2.4 Large scale jets

In the case of M87 and other radio galaxies the observed highest energy  $\gamma$ -rays escape not along the direction of the jet. At the same time, there are surely  $\gamma$ -rays which are emitted by the central engine region in the direction of the jet. Unless the source belongs to the "blazar" class (radio galaxies and quasars with jets aligned along the line of sight), these  $\gamma$ -rays are not directly observable. The highest energy photons propagating through the jet suffer significant absorption and/or re-processing by electromagnetic cascade developing in the jet<sup>21,22</sup>.

As an example, I take the same source M87, but this time consider propagation of the 10-100 TeV  $\gamma$ -rays emitted in the direction of the large scale jet. The spectrum of  $\gamma$ -rays propagating from the central engine through the jet is assumed to have a power law shape  $dN_{\gamma}/dE \sim E^{-\Gamma}$ .

Due to its proximity, the structure of the large scale jet of M87 is known in great details<sup>23</sup>. The spectrum and morphology of soft photon emission (synchrotron emission from high-energy electrons) is known at every position along the jet, from radio to X-ray band. This knowledge

could be used to derive the density of soft photons in the jet as a function photon energy and of the distance from the AGN core. An example of such calculation is shown in Fig. 5 (top panel for a decade-wide energy band centred at  $\epsilon \simeq 0.01$  eV.

Soft photons with energies around 0.01 eV interact most efficiently with  $\gamma$ -rays of the energies  $E \sim 20 - 100$  TeV. Comparing the mean free path of those  $\gamma$ -rays with respect to the pair production,  $\lambda_{\gamma\gamma\rightarrow e^+e^-} \sim 10[n_{ph}/10^2 \text{ cm}^{-3}]$  kpc with the length scale of the M87 jet  $d_{jet} \sim 10$  kpc, one finds that the highest energy  $\gamma$ -rays are absorbed in the jet.

As a result of this absorption,  $e^+e^-$  pairs with energies comparable to the energies of the primary  $\gamma$ -rays are injected all along the jet length. In the particular example of 20 – 100 TeV  $\gamma$ -rays interacting with  $\epsilon \sim 0.01$  eV synchrotron photons in the jet, pairs of the energies 10-100 TeV are injected all along the jet length. The injection rate varies along the jet, depending on the local density of the soft photon field and on the residual power of the primary  $\gamma$ -ray beam.

Knowing the density of the soft photon background as a function of the distance along the jet it is straightforward to calculate the rate of injection of 10-100 TeV  $e^+e^-$  pairs as a function of the distance from the core. The result



Figure 5: Top: density of synchrotron photons of the energy  $\epsilon \sim 0.01$  eV in the jet of M87 as a function of the distance from the core. Bottom: injection rate of 100 TeV electron-positron pairs responsible for the X-ray emission from the jet (solid), compared to the observed X-ray brightness profile of the M87 jet (dashed, Ref. 23).

is shown in the bottom panel of Fig. 5. The  $e^+e^-$  pairs injected in result of the pair production release their energy on a relatively short time scale in the form of X-ray synchrotron radiation. Contrary to the primary  $\gamma$ -ray beam, the X-ray synchrotron emission from the secondary pairs is isotropic, because the trajectories of electrons and positrons are isotropized by the magnetic field present in the jet. Indeed, taking a typical estimate of the jet's magnetic field  $B \sim 10^{-5}$  G, one finds that the gyroradius of electrons/positrons with energy in the 100 TeV range is less than 0.1 pc, so that the directions of propagation of the pairs are randomised on the time scales shorter than a year. The synchrotron cooling time is  $t_s \simeq 10^3 [B/10 \ \mu \text{G}]^{-2} [E_e/100 \ \text{TeV}]^{-1}$  yr. This means that the synchrotron emission from the pairs is isotropic.

X-ray synchrotron emission from the pairs provides a contribution to the overall X-ray luminosity of the jet. For comparison, the bottom panel of Fig. 5 shows the observed X-ray brightness profile of the jet. It is remarkably close to the profile of the injection rate of  $e^+e^-$  pairs by the gamma-gamma pair production process. This points to a possibility that , in fact, all the 100 TeV electrons present in the jet are injected by the pair production, rather than are accelerated in the jet, e.g. via shock acceleration mechanism in the jet knots.

Similar process of gamma-gamma pair production should also take place on shorter distance scales, in the parsec and sub-parsec scale jet and, perhaps at the jet footprint near the super-massive black hole. However, in this case the straightforward calculations presented above for the case of M87 are not possible because our knowledge of the geometry of the system, as well as of the space-dependent spectra of the soft photon background are very limited. Because of this limitation, typical model calculations of the blazar spectra are based on the "synchrotron – inverse Compton" (synchrotron-self-Compton, synchrotron-external-Compton) models<sup>24</sup>, in which a requirement of the absence of the pair production by the escaping highest energy  $\gamma$ -rays is imposed. Such a requirement would naturally arise also in the full calculation with account

of the gamma-gamma pair production induced electromagnetic cascade, because the cascade development channels all the power to the particles (gamma-rays and electrons/positrons) with energies below the pair production threshold.

## 2.5 Source host galaxy

Further attenuation of the  $\gamma$ -ray beam from distant sources happens in the source host galaxy. The spectrum of soft photon emission from galaxies usually consists of two components: collective emission from stars, concentrated in the infrared – visible – UV energy band peaked in the  $\epsilon \sim 1 \text{ eV}$  energy range and the far infrared emission ( $\epsilon \sim 10^{-2} \text{ eV}$ ) produced by dust. Taking Milky Way as a reference, one could estimate the density of the soft photon background as  $n_{ph} \sim L_{gal}/(4\pi R_{gal}^2 c\epsilon) \simeq 20 \left[L_{gal}/10^{44} \text{ erg/s}\right] [R_{gal}/10 \text{ kpc}]^{-2} [\epsilon/0.01 \text{ eV}]^{-1}$ .

Presence of these soft photon backgrounds leads to a slight suppression of the  $\gamma$ -ray flux in the TeV and 100 TeV energy band. In the 100 TeV band the optical depth of a galaxy is estimated as  $\tau_{gal} \sim R_{gal}\sigma_{\gamma\gamma}n_{ph} \sim 0.1$  for a Milky Way type galaxy. However, bright elliptical galaxies, like e.g. the CD galaxies of galaxy clusters (citing agin M87 as an example) could provide an optical depth  $\tau_{gal} \sim 1$  for  $E \sim 100 \text{ TeV} \gamma$ -rays<sup>16</sup>. This is illustrated in Fig. 4, where the light grey shading shows the effect of absorption of the  $\gamma$ -ray flux by the soft photon background in the M87 galaxy. As it is mentioned in Section 1. The flux above 100 TeV is completely suppressed already on galaxy scale propagation lengths, because of the pair production on CMB.

#### 3 Interactions during propagation in the intergalactic medium

Collective emission from stars and dust in all the galaxies creates diffuse radiation field known under collective name of "Extragalactic Background Light", EBL<sup>25</sup>.  $\gamma$ -rays escaping from the soft photon field of the source host galaxy continue to interact with the soft photon fields during their propagation through the intergalactic medium from the source to the Earth. Taking into account that the energy density of the EBL in the 0.01-1 eV energy range is about  $(1-4) \times 10^{-4} \text{ eV/cm}^3$ , one finds that the mean free path of  $\gamma$ -rays with energies in the  $E \sim 0.1 - 100 \text{ TeV}$  range varies as  $\lambda_{\gamma\gamma \to e^+e^-} \simeq 100 [E/10 \text{ TeV}]^{-1} \text{ Mpc}.$ 

The effect of attenuation of the  $\gamma$ -ray flux



Figure 6: Spectrum of direct and cascade emission from a blazar 1ES 0229+200. From Ref. 30

by the pair production on EBL is routinely observed in the spectra of the extragalactic sources observed in the 0.1-10 TeV energy range by HESS, MAGIC and VERITAS. An example could be found in Fig. 6 where the spectrum of 1ES  $0229+200^{26}$  is shown. The grey band in this image shows the difference between the intrinsic and observed spectrum of the source.

Pair production on EBL results in injection of  $e^+e^-$  pairs in the intergalactic medium. These pairs loose their energy via inverse Compton scattering of the Cosmic Microwave Background (CMB) photons. As a result, they generate secondary  $\gamma$ -ray emission along the primary beam. The energies of the IC photons are  $E \simeq 1[E_e/1 \text{ TeV}]^2$  GeV, where  $E_e$  is the energy electron/positron. This secondary "cascade" emission could be observed by  $\gamma$ -ray telescopes<sup>27,28,29</sup>.

The cascade emission has a different observational appearance, compared to the primary point source. The difference is not only in the spectral characteristics, but also in the timing and imaging properties. This difference stems from the fact that trajectories of the pairs are deflected by magnetic fields present in the intergalactic medium. The primary  $\gamma$ -ray beam is usually collimated within several degrees opening angle, because of relativistic beaming of the signal from blazars. If the deflections of  $e^+e^-$  pairs by magnetic field during the inverse Compton cooling time are less than several degrees, the secondary emission is also concentrated within a several-degrees cone, so that the flux of the secondary emission detected on Earth is comparable to the primary  $\gamma$ -ray flux at higher energies.

Otherwise, if the magnetic field is strong enough, the secondary emission is emitted within a wider cone or it is completely isotropized. This leads to suppression of the secondary  $\gamma$ -ray flux. Difference in the travel path between the primary  $\gamma$ -rays and "primary  $\gamma$ -rays – electron/positron – secondary  $\gamma$ -ray" path leads also to a time delay of the cascade signal. If the time delay is much longer than the period of activity of the source, the cascade flux might also be suppressed compared to the direct souce flux. This is illustrated in Fig. 6, which shows several model calculations of suppression of the cascade emission in the presence of magnetic fields of different strength<sup>30</sup>. Non-detection of the cascade emission by Fermi  $\gamma$ -ray telescope in 1-100 GeV band imposes a lower bound on magnetic field in the intergalactic medium, see <sup>31</sup> for a review.

To summarise, propagation of high-energy  $\gamma$ -rays through matter and radiation fields in astrophysical conditions provides a range of intersting observable phenomena and a set of diagnostics tools for the medium through which  $\gamma$ -rays propagate.

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## Highlights from VERITAS Extragalactic Observations

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VERITAS is an array of four 12-m imaging Cherenkov telescopes, sensitive to gamma rays in the energy range from  $\sim 100$  GeV to  $\sim 50$  TeV. VERITAS dedicates roughly half of its total observing time to extragalactic targets. We present recent highlights from our blazar discovery and long-term monitoring programs, together with results on selected non-blazar targets. Key scientific goals include source modeling and setting limits on the extragalactic background light. We alsoshow the impact of the newly upgraded VERITAS camera on blazar observations, and we present some recent detections with data taken after the completion of the upgrade in summer 2012.

# 1 Introduction

VERITAS has been in full operation since 2007, taking roughly 1000 hours of data per year. About half of that observation time is used to study extragalactic targets. A range of observing strategies is used to discover new very high energy (VHE; E > 100 GeV) sources, obtain deep observations while monitoring known sources, and gather multiwavelength observations for modeling emission mechanisms.

Blazars, the most numerous type of source detected at VHE, are a subclass of active galactic nuclei (AGNs) in which a relativistic jet is oriented within a few degrees of our line of sight<sup>1</sup>. The broadband emission is generally thought to be from relativistic electrons, accelerated in the jet, emitting synchrotron from radio to X-ray and inverse-Compton scattering radiation up to gamma rays. The emission is highly beamed towards the observer.

Besides blazars, extragalactic targets include radio galaxies and starburst galaxies. Using observations of all these objects, we aim to accomplish far-ranging goals. We would like to understand characteristics of supermassive black holes, such as how they launch relativistic jets, the sorts of environments they are found in, and how they evolve with time. A wide variety of topics in fundamental physics can be addressed, such as searches for dark matter, axion-like particles, and Lorentz-invariance violation. Gamma-ray emission from blazars can also be used to probe the intensity of the extragalactic background light (EBL) and the magnitude of intergalactic magnetic fields, contributing to our understanding of cosmology.

The ability of VERITAS to achieve these goals has been helped by several upgrades over the years. In 2009, one of the telescopes was relocated, increasing the sensitivity by  $\sim 30\%$ . An upgrade to the camera-level topological trigger was performed in 2011, allowing triggering on shorter timescales and removing spurious events. Finally, an upgrade to the VERITAS camera was performed during the summer of 2012, replacing the old Photonis XP2970 photomultiplier tubes (PMTs) of the cameras with new super-bialkali PMTs (Hamamatsu R10560-100-20). The new PMTs have a faster pulse profile and a 35% higher quantum efficiency resulting in a lower energy threshold for the array.

## 2 Highlights from the Extragalactic Science Program

**M 82** is a prototypical starburst galaxy, located at a distance of about 3.7 Mpc. Tidal interactions with nearby M 81 have triggered intense star-formation activity in the innermost ~1000 light years <sup>2,3</sup>. The star-formation rate is approximately 10 times that of our own Milky Way galaxy, leading to a supernova rate of 0.1 to 0.3 per year<sup>4,5</sup>. Supernova remnants (SNRs) produce shock fronts that are known to accelerate electrons to relativistic energies, and it is likely that these shock fronts accelerate hadronic cosmic rays as well. Observations of intense radiosynchrotron emission imply cosmic-ray fluxes up to two orders of magnitude higher than in the Milky Way<sup>6</sup>. Models of VHE gamma-ray emission contain an electronic component but are dominated by hadronic cosmic-ray interactions with interstellar material, producing  $\pi^0$ , which decay into gamma rays. Another possibility is for ambient X-rays to be inverse-Compton scattered to VHE by cosmic-ray electrons.

VERITAS observed M 82 for 137 hours (after quality selection) between January 2008 and April 2009. An excess of 91 events was detected above 700 GeV, yielding a significance of 4.8 standard deviations ( $\sigma$ ). The energy threshold is higher than typical VERITAS observations, owing the high average zenith angle of 39°. The VHE spectrum is well described by a power law with index  $\Gamma = 2.5 \pm 0.6_{\text{stat}} \pm 0.2_{\text{sys}}$ , and the flux is in agreement with hadronic predictions<sup>7</sup>.

M 87 is the brightest VHE radio galaxy and the only one currently detected by VERITAS. This giant radio galaxy presents a rare opportunity both because its jet is oriented  $\sim 20^{\circ}$  from our line of sight and because of its proximity to us. Being located in the center of the Virgo cluster at a distance of just  $\sim 16$  Mpc, the relativistic jet is resolvable in the radio, optical, and X-ray bands.

M 87 was discovered in VHE gamma rays with marginal significance by HEGRA<sup>8</sup>, but has since been detected by HESS<sup>9</sup>, VERITAS<sup>10</sup>, and MAGIC<sup>11</sup>. The extensive VHE observations have shown that the source is quite variable, which is also true at lower energies.

Multiple flaring episodes were detected during a VERITAS-coordinated observing campaign in 2008. Contemporaneous Chandra X-ray and VLBA radio observations were made in an effort to constrain the emission region. While the core was bright, the innermost knot in the jet (HST-1) was found to be in a low state. Progressive brightening of the core flux was seen in radio following a VHE flare. This points to the core as the most likely region for VHE emission, rather than acceleration sites further out in the jet<sup>12</sup>.

**BL Lacertae**, the eponym of the BL Lac subclass of blazars, is located at z = 0.069. A low-frequency-peaked BL Lac (LBL) object, it has been detected only sporadically in VHE gamma rays during flaring events. VERITAS began more frequent monitoring of this source in June 2011 after observations by *Fermi* LAT and AGILE pointed to an enhanced state.

VERITAS detected a bright flare of ~125% Crab units on 2011 June 28. The spectrum is fitted by a power law with index  $\Gamma = 3.8 \pm 0.3$ , consistent with an earlier MAGIC detection when the source was in a lower state. Although the rising edge of the flare was missed, the brief 34.6-minute exposure allowed the falling edge of the flare to be fitted by an exponential decay with time constant  $\tau = 13 \pm 4$  minutes. This is the first time such rapid variability has been observed in an LBL, constraining the emission region to be quite small, probably near the black hole as opposed to further out in the jet. The VHE flare appears to be associated with the emergence of a new radio knot from the radio core, identifiable by its polarization angle. A strong radio flare four months after the VHE flare could also be linked to the VHE flare, emerging later only as the emission region becomes optically thin to radio waves. In any case, the rapid variability and multiwavelength data pose a serious challenge to our theoretical understanding of gamma-ray production in blazars<sup>13</sup>.

**3C66A and W Comae** are in a rare class of VHE blazars. The spectral energy distribution (SED) from blazars has two peaks. Most blazars detected in VHE are high-frequency-peaked BL Lacs (HBL) where the synchrotron emission peaks beyond  $10^{15}$  Hz. The few low- and intermediate-frequency-peaked BL Lacs (IBLs) are mainly detected during flaring states. Over-

all, LBLs are more powerful and more luminous than HBLs. Jet alignment is one possible explanation for shifts in the observed peak frequency. Other scenarios involve accretion rate differences<sup>14</sup>.

Since blazar spectra have been observed to harden during flaring states, we need to obtain low-state detections of LBLs and IBLs to construct unbiased SEDs. Only with low-state detections can we accurately explore relations between the low- and high-frequency peaks of blazar SEDs. Recently, VERITAS was able to accumulate enough observation time to detect two IBLs, W Comae and 3C66A, in states where the flux is about five times lower than that observed in flares. Detailed multiwavelength analysis on these data is underway.

**1ES 1440+122** is a BL Lac at z = 0.163. The object was discovered by VERITAS at a significance level of 5.5  $\sigma$  during the 2008–2010 observing seasons. Combining data from Swift X-rays, *Fermi*-LAT high-energy gamma rays, and VERITAS VHE gamma rays, SEDs were fitted to find optimal jet parameters for synchrotron self-Compton, external-Compton, and hadronic models. All models reproduce the data well, resulting in jet parameters in line with other BL Lacs. An external radiation field appears to be required to get close to equipartition between the relativistic electron population and the magnetic field.

1ES 1440+122 was originally classified as an IBL<sup>15</sup> or a borderline HBL. The VERITAS observations and multiwavelength modeling efforts argue for a firm classification as a HBL, with the synchrotron emission peaking around  $10^{17}$  Hz.

**PG 1553+113** is an HBL with unknown redshift. The redshift does have a firm lower limit of  $z > 0.40^{16}$ , making it one of the most distant VHE-detected blazars. It has a hard spectrum as seen by the *Fermi*LAT ( $\Gamma_{\text{LAT}} = 1.67 \pm 0.022^{17}$ . This hard spectrum for lower-energy gamma rays stands in contrast to the very soft spectrum observed at VHE ( $\Gamma_{\text{VHE}} = 4.3 \pm 0.1$ ) where attenuation on extragalactic background light (EBL) is clearly evident.

VERITAS performed deep observations of PG 1553+113, accumulating 80 hours of qualityselected data between 2010 and 2012 and resulting in the highest VHE signal-to-noise spectrum yet. The time-averaged flux during this period corresponds to 6.9% of the Crab Nebula flux above 160 GeV during this period. There is evidence for long-term variability in the flux, which reached as high as 18.3% of the Crab Nebula flux above 160 GeV.

The gamma-ray spectrum of PG 1553+113 measured by VERITAS can be used to constrain the source distance by excluding redshifts that would produce an EBL-corrected spectrum with an upturn towards higher energies, a feature not observed in any other VHE blazar. Using a minimal EBL model to obtain the intrinsic gamma-ray spectrum, an upper limit of z < 0.62can be derived.

**1ES 0647+250** is the first of two new VERITAS detections during the 2012–2013 season. **1ES 0647+250** was previously detected by MAGIC in 2011 and was reported to have an integrated flux of 3% of the Crab Nebula flux<sup>18</sup>. The redshift is not well measured spectroscopically but three imaging redshift estimates are available:  $z = 0.45 \pm 0.08^{19}$ ,  $z = 0.41 \pm 0.06^{20}$ , and  $z > 0.49^{21}$ .

The source was selected as a VHE candidate on the basis of its radio, optical, and X-ray properties<sup>22</sup>, and also because of the hard high-energy gamma-ray spectrum from the *Fermi* LAT ( $\Gamma_{\text{LAT}} = 1.59 \pm 0.08$ ). VERITAS began observing the source during partial moonlight with raised trigger thresholds. After noting a possible enhanced state compared to previous observations, a target-of-opportunity program was initiated to get 10.9 hours of dark time, yielding a detection with a significance of 6.2  $\sigma$  and with a flux of 2.9% Crab units >140 GeV, in close agreement with the MAGIC detection. Multiwavelength data were collected and analysis is ongoing.

**1ES 1011+496** was observed to be in a higher-than-normal state on the same night as 1ES 0647+250 was first noticed. Target-of-opportunity observations collected 10.4 hours of quality-selected data, yielding an 8.5  $\sigma$  detection. This was also the first time VERITAS detected the source. The flux above 150 GeV was observed to be 6.3% Crab units, in rough agreement with the MAGIC-reported flux of 7% Crab units above 200 GeV<sup>23</sup>. Multiwavelength data were

collected and analysis is ongoing.

## 3 Conclusions

Extragalactic observations are a large component ( $\sim$ 50%) of the VERITAS observing program. The long-term plan includes both monitoring of known sources and discovery observations although in the last season the emphasis has shifted towards building up deep observations of known sources ( $\sim$ 70% of the time). Even so, with the upgrade of the PMTs in the camera and monitoring of candidate sources during partial moonlight time, we were able to confirm two previous MAGIC detections for the first time. In conjunction with VHE data collection, we have programs in place to exploit multiwavelength data in order to derive the maximum science output.

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## Diffuse $\gamma$ -ray emission from misaligned active galactic nuclei

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#### Abstract

We calculate the diffuse  $\gamma$ -ray emission due to the population of misaligned AGN (MAGN) unresolved by the Large Area Telescope (LAT) on the *Fermi* Gamma-ray Space Telescope (*Fermi*). A correlation between the  $\gamma$ -ray luminosity and the radio-core luminosity is established and demonstrated to be physical by statistical tests, as well as compatible with upper limits based on *Fermi*-LAT data for a large sample of radio-loud MAGN. We constrain the derived  $\gamma$ -ray luminosity function by means of the source count distribution of the MAGN detected by the *Fermi*-LAT. We finally estimate the diffuse  $\gamma$ -ray flux due to the whole MAGN population which ranges from 10% up to nearly the entire measured Isotropic Gamma-Ray Background (IGRB). We evaluate also the room left to galactic DM at high latitudes (> 10°), by taking into account the results on the MAGN together with the other significant galactic and extragalactic  $\gamma$ -rays emitting sources.

# 1 The correlation between $\gamma$ -ray and radio luminosity

The *Fermi*-LAT has measured the Isotropic Gamma-Ray Background (IGRB) with very good accuracy from 200 MeV to 100 GeV (A. A. Abdo et al. <sup>1</sup>). However the nature of the IGRB is still an open problem in astrophysics. Blazars, high luminosity Active Galactic Nuclei (AGN) whose jets are oriented along the lines-of-sight (l.o.s.), may contribute to 20%-30% of the IGRB (A. A. Abdo et al. <sup>4</sup>). AGN with axes misaligned with respect to the line-of-sight (hereafter MAGN) have weaker luminosities but are expected to be more numerous than blazars. It is expected that a non-negligible contribution to the IGRB might be attributable to the unresolved MAGN population. The aim of this contribution is the estimation of the  $\gamma$ -ray diffuse emission produced by the cosmological population of MAGN. For any details we referer to Di Mauro et al. <sup>2</sup>.

The bulk of the  $\gamma$ -ray radiation from AGN is generated via synchrotron self-Compton (SSC) or external inverse Compton (EC) scatterings in the central region of the source, the core. In the absence of predictions for the  $\gamma$ -ray luminosity function, we follow a phenomenological approach to relate the source  $\gamma$ -ray luminosity to the radio luminosity of the source core. The latter is phenomenologically much better established, given the high number of detected MAGN in the



Figure 1: On the left panel we display the observed  $\gamma$ -ray luminosity vs radio core luminosity at 5 GHz for our MAGN sample, the right panel shows upper limits on a sample of *Fermi*-LAT undetected radio-loud MAGN.

radio frequencies. In the first and the second catalogs of LAT AGN sources (A. A. Abdo et al. <sup>5</sup> and M. Ackermann et al. <sup>6</sup>) *Fermi*-LAT has reported the detection of 15 MAGN. In Fig. 1 (left) we plot the core radio and  $\gamma$  luminosities for 12 selected MAGN. The derived correlation between  $L_{r,\text{core}}$  and  $L_{\gamma}$ :

$$\log (L_{\gamma}) = 2.00 \pm 0.98 + (1.008 \pm 0.025) \log (L_{r,core}^{5GHz})$$
(1)

is shown as a solid line and the relevant  $1\sigma$  error band as a shaded area. The correlation could be biased by distance effects and flux-limited samples therefore we have tested its strength via a Spearman rank-order and a modified Kendall rank correlation test. We can exclude the correlation happening by chance at the 95% C. L. In order to test the robustness of the core radio  $\gamma$ -ray luminosity correlation we derive 95% C.L.  $\gamma$ -ray upper limits for a sample of *Fermi*-LAT undetected radio-loud MAGN. The result in Fig. 1 indicates that upper limits are consistent with the correlation in Eq. 1 within its uncertainty band (see Di Mauro et al. <sup>2</sup> for details).

#### 2 The $\gamma$ -ray luminosity function and the source count distribution

The calculation of the diffuse emission from unresolved (*i.e.* not detected by the *Fermi*-LAT) MAGN relies on the  $\gamma$ -ray luminosity function (GLF) for that specific population. We derive the GLF from the radio luminosity function (RLF) by exploiting the correlation between radio and  $\gamma$ -ray luminosities. We assume that  $N_{\gamma} = k N_r$ , where the normalization k takes into account our ignorance of the number of radio-loud MAGN emitting in  $\gamma$ -rays. Therefore the GLF is defined through a RLF by:

$$\rho_{\gamma}(L_{\gamma}, z) = k \ \rho_{r, \text{core}}(L_{r, \text{core}}^{\text{5GHz}}(L_{\gamma}), z) \frac{d \log L_{r, \text{core}}^{\text{5GHz}}(L_{\gamma})}{d \log L_{\gamma}}, \tag{2}$$

where  $\rho_{r,\text{core}}$  refers to the radio luminosity function of the cores of the MAGN. We use the total RLF derived in C. J. Willott et al.<sup>9</sup> (Model C with  $\Omega_M=0$ ) and obtain the core RLF through the link between total and core radio luminosities as in L. Lara et al.<sup>8</sup>.

An important observable for the correctness of our method is provided by the source count distribution of MAGN, i.e. the cumulative number of sources  $N(>F_{\gamma})$  detected above a threshold flux  $F_{\gamma}$  defined as:

$$N_{\rm th}(>F_{\gamma}) = 4\pi \int_{3.5}^{1.0} \frac{dN}{d\Gamma} d\Gamma \int_0^6 \frac{d^2 V}{dz d\Omega} \int_{L_{\gamma}(F_{\gamma,z},\Gamma)}^{10^{50} {\rm erg/s}} \frac{dL_{\gamma}}{L_{\gamma} \ln(10)} \rho_{\gamma}(L_{\gamma},z,\Gamma).$$

The spectral index distribution,  $dN/d\Gamma$ , is assumed to be gaussian in analogy with blazars (A. A. Abdo et al. <sup>4</sup>). Fig. 2 (left) shows the theoretical  $N_{\rm th}(>F_{\gamma})$ , with different bands of



Figure 2: On the left panel we show  $N_{\text{th}}(> F_{\gamma})$  and on the right the diffuse  $\gamma$ -ray flux due to the MAGN with different bands of uncertainty, overlaid with the experimental data.

uncertainty, overlaid with the experimental source count distribution (see Di Mauro et al. <sup>2</sup> for details). It is remarkable that the uncertainty bands are in good agreement with the *Fermi*-LAT data, supporting the validity of our procedure. We stress also that the theoretical source count distribution predicts a large number of MAGN at very low fluxes and this fact may lead to a significant  $\gamma$ -ray diffuse emission.

## 3 The diffuse $\gamma$ -ray emission from MAGN

The diffuse  $\gamma$ -ray flux due to the whole population of MAGN may be estimated as follows:

$$\frac{d^2 F(\epsilon)}{d\epsilon d\Omega} = \int_{1.0}^{3.5} d\Gamma \frac{dN}{d\Gamma} \int_0^6 \frac{d^2 V}{dz d\Omega} \int_{10^{41} \mathrm{erg/s}}^{10^{50} \mathrm{erg/s}} \frac{dF_{\gamma}}{d\epsilon} \frac{dL_{\gamma}}{L_{\gamma} \ln(10)} \rho_{\gamma}(L_{\gamma}, z) (1 - \omega(F_{\gamma})) \exp\left(-\tau_{\gamma, \gamma}(\epsilon, z)\right).$$

The term  $\omega(F_{\gamma,i})$  is the detection efficiency of the *Fermi*-LAT,  $dF_{\gamma}/d\epsilon$  is the intrinsic photon flux at energy  $\epsilon$  and  $\tau_{\gamma,\gamma}$  is the optical depth of  $\gamma$  rays ( $\epsilon > 20$  GeV) propagating in the Universe and absorbed by the interaction with the extragalactic background light (EBL). Fig. 2 (right) shows the diffuse  $\gamma$ -ray flux due to the MAGN population with the relevant uncertainty band, which is nearly a factor of ten wide, as a function of  $\gamma$ -ray energy and along with the *Fermi*-LAT data for the IGRB (A. A. Abdo et al<sup>-1</sup>). The effect of EBL absorption is clear from the softening of the flux above 50 GeV. At all *Fermi*-LAT energies, the best fit MAGN contribution is 20%-30% of the measured IGRB flux. The intensity from MAGN integrated above 100 MeV is  $9.83 \cdot 10^{-7}/2.61 \cdot 10^{-6}/8.56 \cdot 10^{-6}$  photons cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>, when considering the lower/best fit/upper curve of the uncertainty band. These numbers represent 9.5%/25%/83% of the IGRB, respectively. The analogous calculation for the two blazar populations of BL Lacs and FSRQs and for star-forming galaxies (SF) gives respectively  $7.83^{+1.09}_{-1.07}$  photons cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> ( $\sim 8\%$ ) of the IGRB),  $9.66^{+1.67}_{-1.09}10^{-7}$  photons cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> ( $\sim 10\%$ ) and  $8.19^{+7.31}_{-3.89} \cdot 10^{-7}$  photons cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> ( $\sim 8\%$ ) (see F. Calore et al. <sup>7</sup> and refs. therein).

#### 4 Constraints on Dark Matter annihilation into $\gamma$ -rays

The self-annihilation of DM pairs in the haloes of galaxies may give birth, among other species, to  $\gamma$ -rays. We have calculated the direct (prompt emission) and indirect production (through Inverse Compton scattering), of  $\gamma$ -rays produced by WIMP pair annihilation in the halo of our Galaxy. We considered a Burkert DM profile for latitudes  $|b| > 10^{\circ}$  with a local DM density of  $\rho(r = r_{\odot}) = 0.4$  GeV cm<sup>-3</sup> and  $r_{\odot}$ =8.33 kpc. In Fig. 4 we display the upper bounds on the DM annihilation cross section averaged on the velocity distribution  $\langle \sigma v \rangle$  for annihilation channels into  $b\bar{b}$  (left) and  $e^+e^-$  (right). In order to appreciate how the uncertainty on the MAGN flux



Figure 3: Upper limits to  $\langle \sigma v \rangle$  into  $\gamma$ -rays from  $b\bar{b}$  (left) and  $e^+e^-$ (right). The MAGN flux is varied from the minimum predicted value (red upper curve), to its best fit (cyan), to 60% (green) and 65% (orange, bottom curve) of the predicted maximum level. Pink dashed lines illustrate the uncertainty on the DM local density.

prediction affects the bounds on  $\langle \sigma v \rangle$ , we have fixed the diffuse contribution from BL Lacs, FSRQs, SF galaxies and millisecond pulsar (MSPs) at their best fit values and varied the level of the MAGN flux from its minimal predicted value up to 60% and 65% of the maximum flux estimated. Were the MAGN contribute about 60%-65% of the predicted maximal flux, the constraints on  $\langle \sigma v \rangle$  would be set below the thermal decoupling cross section  $2 \cdot 10^{-26}$  cm<sup>3</sup>/s expected for a generic WIMP DM candidate, depending on the mass of the DM particle and on the annihilation channels (see Calore et al. <sup>3</sup> for details).

## 5 Conclusions

We have calculated the  $\gamma$ -ray flux from the MAGN cosmological population. We have first established the existence (at 95% C.L.) of a correlation between the radio core and the  $\gamma$ -ray luminosities of the MAGN detected by the *Fermi*-LAT. We then used this correlation to infer the  $\gamma$ -ray luminosity function from a well established radio luminosity function, and further tested the former against the MAGN count distribution measured by the *Fermi*-LAT. Using our  $\gamma$ -ray luminosity function, and after taking into account  $\gamma$ -ray absorption from EBL, we have predicted the diffuse  $\gamma$ -ray flux due to MAGN and estimated an uncertainty band of about a factor ten. The best fit to the MAGN diffuse  $\gamma$ -ray emission is 20%-30% of the measured IGRB flux. Moreover we have found that the cosmological population of faint and numerous MAGN, when added to the contribution from other sources (*i.e.* blazars, SF galaxies, MSPs), could entirely explain the observed IGRB. We have demonstrated that this scenario would leave very little room to more exotic sources, such as DM in the halo of our Galaxy.

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# MEASURING NON-THERMAL PRESSURE IN GALAXY CLUSTERS: FROM SKA TO CTA

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The atmospheres of clusters of galaxies are repositories of the cosmic history of thermal and non-thermal plasma, but the amount of their pressure ratio is still under debate. We present here a new estimate of the non-thermal to thermal pressure ratio  $X = P_{non-th}/P_{th}$  in galaxy clusters hosting radio halos that are selected from the Planck survey. Our results indicate that this pressure ratio evolves with the cluster X-ray luminosity as  $\sim L_X^{-0.81}$  in order to reproduce the correlation between the total Compton parameter  $Y_{SZ}$  and the X-ray luminosity  $L_X$  of the largest (so far) sample of galaxy clusters with combined radio, SZ and X-ray data.

## 1 Radio Halos in galaxy clusters

The origin of radio halos (RHs) in galaxy clusters is a long-standing but still open problem. Various scenarios have been proposed that refer to primary electron models, re-acceleration models, secondary electron models, Dark Matter annihilation models and also geometrical projection effect models. Each of these models has both interesting and contradictory aspects, but each one relies on the presence of a population of relativistic electrons (and positrons) and of a largescale magnetic field that are spatially distributed in the cluster atmosphere. The presence of RHs in clusters requires then an additional non-thermal pressure (energy density) component in addition to the thermal pressure (energy density) provided by the intra cluster medium (ICM). Galaxy clusters hosting RHs show a correlation between their radio power measured at 1.4 GHz  $P_{1.4}$  due to synchrotron emission, and their X-ray luminosity  $L_X$  due to thermal bremsstrahlung emission (see, e.g., Colafrancesco 1999, Feretti et al. 2012). Such a correlation links the nonthermal particle and magnetic field energy density (pressure), related to the synchrotron radio luminosity  $P_{1.4} \propto P_{non-th} U_B^{(\alpha+1)/4}$  (where  $\alpha$  is the slope of a power-law electron spectrum  $n_{e,rel} \sim E^{-\alpha}$ ), with the thermal pressure  $P_{th}$  of the ICM, related to the thermal bremsstrahlung X-ray emission given by  $L_X \propto n_e^2 T^{1/2} \sim P_{th} t_{cool}^{-1}$ , where  $P_{th} \propto n_e T$  and  $t_{cool} \propto T^{1/2} n_e^{-1}$ . An analogous correlation has been found (see, e.g., Basu 2012) between  $P_{1.4}$  and the integrated Compton parameter  $Y_{SZ}$  due to the SZ effect (SZE) produced by Inverse Compton Scattering of CMB photons off the electron populations that are residing in the cluster atmosphere (see

Colafrancesco et al. 2003 for details, and Colafrancesco 2012 for a recent review). The Compton parameter  $Y_{SZ} \propto \int d\ell P_{tot}$  is proportional to the total particle pressure (energy density) provided by all the electron populations in the clusters atmosphere (see Colafrancesco et al. 2003). Therefore, the  $P_{1.4} - Y_{SZ}$  correlation links the non-thermal particle and B-field pressures, as measured by  $P_{1.4}$ , with the total particle pressure  $P_{tot}$ , as measured by  $Y_{SZ}$ . For the sake of generality we write here the total particle pressure  $P_{tot} = P_{th} + P_{non-th} = P_{th}(1 + X)$  where  $X \equiv P_{non-th}/P_{th}$ . The correlated X-ray, SZE and radio emission from RH clusters, as shown by the  $P_{1.4} - L_X$  and  $P_{1.4} - Y_{SZ}$  relations, indicate that RH clusters must also exhibit a relation between the thermal ICM pressure  $P_{th}$  and the non-thermal particle pressure  $P_{non-th}$  that can be hence constrained by observations. It is possible to measure the relation between  $P_{non-th}$  and  $P_{th}$  using the correlation between the Compton parameter  $Y_{SZ}$  and the X-ray bolometric luminosity  $L_X$  shown by the same data. A power-law correlation  $Y_{SZ}D_A^2 = cL_X^m$  provides best fit values of  $m = 0.88 \pm 0.05$  and  $Logc = -44.04 \pm 2.49$  (here  $D_A$  is the angular diameter distance).

# 2 Measuring $P_{non-th}$

The characteristic quantities that describe the galaxy cluster structure are defined in a simple self-similar model (see, e.g., Arnaud et al. 2010), and we use in the following this theoretical paradigm to study the  $Y_{SZ} - L_X$  correlation (see Colafrancesco et al. 2013, for further details). Under a  $\beta$ -model gas density profile assumption, the spherical integrated Compton parameter and the X-ray luminosity within the radius  $R_{500}$  can be written as

$$Y_{sph,R500}E(z)^{-4} = (1+X)\frac{8\pi^2}{3}\frac{\sigma}{m_e c^2} \times G\mu m_p 500\rho_c n_{e0,g}\lambda^3 R_{500}^5 V_1(\lambda)$$
(1)

 $\operatorname{and}$ 

$$L_X E(z)^{-5} = 4\pi C_2 \left(\frac{2\pi}{3k_B} G\mu m_p 500\rho_c\right)^{\frac{1}{2}} \times n_{e0,g}^2 \lambda^3 R_{500}^4 W_1(\lambda) , \qquad (2)$$

where

$$V_1(\lambda) = \int_0^{\frac{1}{\lambda}} \left( 1 + u^2 \right)^{-\frac{3\beta}{2}} u^2 du$$
 (3)

and

$$W_1(\lambda) = \int_0^{\frac{1}{\lambda}} \left(1 + u^2\right)^{-3\beta} u^2 du , \qquad (4)$$

and the constant  $C_2 = 1.728 \times 10^{-40} W s^{-1} K^{-1/2} m^3 \cdot \bar{g}$ , where  $\bar{g}$  is the average Gaunt factor. The theoretical prediction for a constant value of X is shown in Fig.1 together with the best-fit correlation of the data. We stress that the theoretical curve calculated under these assumptions is sensitively steeper than the power-law best-fit to the data. This is the result of having assumed a constant value of X for all cluster X-ray luminosities in our model. A dccrcasing value of Xwith the X-ray luminosity (or with the Compton parameter) as  $X \sim L_X^{-\xi}$  can alleviate the problem providing a better agreement between the cluster formation scenario and the nonthermal phenomena in RH clusters. In order to consider this effect, we compute the value of X for each individual cluster in our sample by using the relationship between the Compton parameter and the X-ray bolometric luminosity given above. Fig.1 shows also the correlation of the values of X with both the Compton parameter and with the bolometric X-ray luminosity of each cluster. The data and our estimate for X show that there is a clear decreasing trend of the pressure ratio X with the cluster X-ray luminosity indicating that low- $L_X$  (mass) cluster hosting RHs require a larger ratio of the non-thermal to thermal pressure ratio. We fit the  $X - L_X$  relation in Fig.1 by assuming a power-law form  $X = Q \cdot L_X^{-\xi}$  and we obtain best fit values of  $\xi = 0.81 \pm 0.30$  and  $LogQ = 36.45 \pm 13.25$ . The best fit curve with these parameters is also shown in Fig.1. We then calculate our theoretical prediction for the  $Y_{sph,B500} - L_X$  relation



Figure 1: Left. The best fit line (solid blue) together with the associated uncertainties in the slope and intercept (dashed cyan) and the theoretical expectation (solid red) for the  $Y_{sph,R500} - L_X$  relation. The best-fit value of X is  $0.43 \pm 0.14$  for the case of on isothermal  $\beta$ -model with a core radius of  $r_c = 0.25R_{500}$  and  $\beta = 2/3$ . Center. The behavior of the pressure ratio X as a function of the cluster X-ray bolometric luminosity for the cluster sample. The best fit curve  $X \sim L_X^{-0.81}$  is also shown by the red solid line. Right. The best fit line (solid blue) together with the associated uncertainties in the slope and intercept (dashed cyan) and the theoretical expectation (solid red urve). The relation  $X \sim L_x^{-0.81}$  has been used in the teoretical prediction shown by the red solid curve

using the previous  $X \propto L_{\chi}^{-\xi}$  relation and we find indeed a much better agreement of the cluster formation model with the available data for our sample of RH clusters (see Fig.1). This result shows that the existence of a non-thermal pressure in RH clusters with a ratio  $X = P_{non-th}/P_{th}$ that decreases with cluster X-ray luminosity (or mass) is able to recover the consistency between the theoretical model for cluster formation and the presence of RHs in clusters.

#### 3 Consequences for the high-E emission of galaxy clusters

Our results indicate the presence of a considerable non-thermal pressure provided by the nonthermal electrons (and positrons): this is the minimal particle energy density requirement because it has been derived from SZE measurements (i.e. by Compton scattering of CMB photons off high-energy electrons, and positrons). For a complete understanding of the overall cluster pressure structure one should also consider the additional contribution of non-thermal proton that is higher than the electron one since protons loose energy on a much longer time scale. A full understanding of the proton energy density (pressure) in cluster atmospheres could be obtained by future gamma-ray observations (or limits) of these galaxy clusters with RHs because the gamma-ray emission could possibly be produced by  $\pi^0 \rightarrow \gamma + \gamma$  decays where the neutral pions  $\pi^0$  are the messengers of the presence of hadrons (protons) in cluster atmospheres (see, e.g., Colafrancesco & Blasi 1998, Colafrancesco & Marchegiani 2008 and references therein). We show here in Fig.2 the predictions for the radio and  $\gamma$ -ray emission from a specific cluster A2163, which has a value X = 0.105. It is clear that the next coming high-sensitivity observations with SKA in the radio and with CTA in the  $\gamma$ -ray domains will be able to determine both the value of  $P_{non-th}$  from and the value of the cluster B-field, and then set crucial constraints on the main scenario for the origin of the high-E particles residing in the cluster atmospheres.

We conclude that the combination of observations on RH clusters at different wavelengths (radio, mm., X-rays and  $\gamma$ -rays) is able to provide physical constraints on the non-thermal particle content of galaxy clusters. This is possible by combining the relevant parameters carrying information on the non-thermal (i.e. the total Compton parameter) and thermal (i.e. the X-ray bremsstrahlung luminosity) pressure components residing in the cluster atmosphere. The next generation radio (e.g. SKA and its precursors, like MeerKAT), mm. (e.g. Millimetron, and in general mm. experiment with spatially-resolved spectroscopic capabilities) X-ray, and  $\gamma$ -ray



Figure 2: Predictions for the radio (left) and gamma-ray (right) emission for A2163, with a value X = 0.105, are shown for primary electrons (upper panels) and secondary electrons (lower panels).

(HESS-II and CTA) instruments will definitely shed light on the origin of radio halos in galaxy clusters and on their cosmological evolution.

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# CHARTING THE TEV MILKY WAY: H.E.S.S. GALACTIC PLANE SURVEY MAPS, CATALOG AND SOURCE POPULATIONS

#### S. CARRIGAN<sup>1</sup>, F. BRUN<sup>1</sup>, R.C.G. CHAVES<sup>2,1</sup>, C. DEIL<sup>1</sup>, H. GAST<sup>3,1</sup> AND V. MARANDON<sup>1</sup> FOR THE H.E.S.S. COLLABORATION

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Very-high-energy (VHE, E>100 GeV)  $\gamma$ -rays provide a unique view of the non-thermal universe, tracing the most violent and energetic phenomena at work inside our Galaxy and beyond. The latest results of the H.E.S.S. Galactic Plane Survey (HGPS) undertaken by the High Energy Stereoscopic System (H.E.S.S.), an array of four imaging atmospheric Cherenkov telescopes located in Namibia, are described here. The HGPS aims at the detection of cosmic accelerators with environments suitable for the production of photons at the highest energies and has led to the discovery of an unexpectedly large and diverse population of over 60 sources of TeV gamma rays within its current range of 1 = 250 to 65 degrees in longitude and |b| < 3.5 degrees in latitude. The data set of the HGPS comprises 2800 hours of high-quality data, taken in the years 2004 to 2013. The sensitivity for the detection of point-like sources, assuming a power-law spectrum with a spectral index of 2.3 at a statistical significance of 5  $\sigma$ , is now at the level of 2% Crab or better in the core HGPS region. The latest maps of the inner Galaxy at TeV energies are shown alongside an introduction to the first H.E.S.S. Galactic Plane Survey catalog. Finally, in addition to an overview of the H.E.S.S. Galactic sources population a few remarkable, recently discovered sources will be highlighted.

## 1 Introduction

The superior sensitivity of the latest generation of imaging atmospheric Cherenkov telescopes such as H.E.S.S.<sup>1</sup>, MAGIC<sup>2</sup>, and VERITAS<sup>3</sup>, has resulted in the discovery of numerous VHE  $\gamma$ -ray sources, and currently more than 140 sources are listed in the online TeV  $\gamma$ -ray catalogue TeVCat<sup>*a*</sup>. The High Energy Stereoscopic System (H.E.S.S.) in particular is ideally suited for undertaking a deep survey of our Galaxy, due to its high sensitivity, comparatively large field-ofview of  $5^{\circ}$ , and its angular resolution of  $\sim 0.1^{\circ}$ . Its location in the Khomas highlands of Namibia allows it a prime view of the inner Galaxy. Here we report on the status and latest results of the H.E.S.S. Galactic Plane Survey (HGPS), the deepest and most comprehensive survey of the inner Galaxy undertaken in VHE  $\gamma$ -rays so far. The latest maps are shown, alongside advanced methods for the suppression of cosmic-ray induced background. The construction of a software framework to detect and model sources of VHE  $\gamma$ -rays in the survey data set is introduced. The VHE  $\gamma$ -ray source population in our Galaxy is dominated by objects that are linked to the final stages in stellar evolution, namely pulsar wind nebulae (PWNe) and supernova remnants (SNRs). For nearly a third of the sources, however, no plausible counterpart at other energies has been found yet, or the physical origin of the detected emission remains unclear. A snap shot of our current understanding of the H.E.S.S. source population on the Galactic plane is shown,

<sup>&</sup>lt;sup>a</sup>http://tevcat.uchicago.edu/



Figure 1: Illustration of the different background estimation methods for image and spectral analysis, as well as the challenges the high density of extended sources in the inner Galaxy poses. Exclusion regions (see Section 2 for details) are shown as grey areas. The field-of-view of 2° radius is illustrated as green solid circles. Left panel: The adaptive ring background technique. Right panel: The reflected region background technique.

as well as a few interesting examples of recent sources.

#### 2 Maps

In the HGPS, the inner Galaxy has been systematically raster scanned using observation positions with overlapping fields-of-view, with the main goal of discovering new VHE  $\gamma$ -ray sources and enabling population studies of Galactic source classes as a consequence. Advanced analysis techniques for background suppression  $^{4,5,6,7}$  play a very important role in the data analysis. After calibration and quality selection, a multi-variate analysis technique <sup>4</sup> based on extensive air shower and image shape parameters is used to discriminate  $\gamma$ -ray-like events from cosmicray-induced showers. A minimum image amplitude of 160 photoelectrons is required.

To generate maps, the remaining background is estimated locally by the ring background technique<sup>8</sup>, where for each trial source position (red filled circles) in the field-of-view (of  $2^{\circ}$ radius, green circle) the background is estimated from a ring centered on this position (blue shaded circles), as shown in the left panel of Figure 1. Regions on the sky containing known VHE  $\gamma$ -ray sources (grey areas) are excluded from background estimation. These exclusion regions are automatically generated from significance maps which are smoothed with a top-hat function with radii of 0.1°, 0.2° and 0.4°, by thresholding them at the level of  $5\sigma$  and dilating each excluded pixel by a further  $0.1^{\circ}$  (small exclusion regions, dark grey) or  $0.3^{\circ}$  (large exclusion regions, light grey). For the *small* exclusion regions, the resulting maps for  $0.1^{\circ}$  and  $0.2^{\circ}$  radius are added, excluding all significant emission from the background but cutting quite close to the edges of sources. For the *large* exclusion regions, the resulting maps for  $0.1^{\circ}$ ,  $0.2^{\circ}$  and  $0.4^{\circ}$ radius are added, cutting away more of any emission that is possibly extending into the area for background estimation. The resulting *large* exclusion regions, used for the production of maps, turn out to cover areas of the sky that are comparatively large on the scale of the size of the field-of-view. Therefore, as illustrated in the left panel of Figure 1, the ring radius is adaptively enlarged when a large fraction of the ring area overlaps with an excluded region, until an appropriate ring of the same thickness is reached. The statistically significant value for each position is then calculated<sup>9</sup>, by summing the candidate events within a fixed and predefined

correlation radius, e.g.  $0.1^{\circ}$  (suitable for point-like sources), and comparing to the estimated background level at that position. Figure 5 shows the latest significance map obtained for the survey region.

Figure 6 depicts the current sensitivity to VHE  $\gamma$ -ray sources, as an example for point-like sources emitting a power-law spectrum with index 2.3 and located at a Galactic latitude of b =  $-0.3^{\circ}$ , the approximate average among known Galactic sources. The sensitivity is below 2% Crab for practically all of the longitude range  $l = 283^{\circ}$  to 59° at this latitude. This can also be seen in a slice of this map, shown in Figure 4.

## 3 Source catalog

Using the H.E.S.S. survey maps as input, we have implemented a pipeline to generate a source catalog, which will be published alongside with the maps. The aim is to have detection criteria as well as morphological and spectral analysis as uniform as possible, to make this source catalog useful for the astronomical community to compare to data from other wavelengths, e.g. Fermi<sup>b</sup> or HAWK<sup>c</sup>, for radio or X-ray data, as well as Galactic source population studies and diffuse emission measurements.

To construct the catalog, we use a likelihood fit of the H.E.S.S. counts map taking the exposure and point spread function as well as the estimated background into account. To acknowledge the fact that most sources in the H.E.S.S. Galactic plane survey region have been found to be extended, we are producing an extended source catalog by modelling the excess as the superposition of symmetric Gauss-shaped sources. The Gauss shape is not physically motivated, it was chosen as one commonly used empirical shape in the absence of an expected source morphology model. Figure 2 displays the fitting process. In the left panel a significance map of the Kookaburra region and HESS J1427-608 is shown, while the middle and right panel show a 2 sources model and 3 sources fit model, respectively, alongside with their resulting residual maps. The 3 sources solution, i.e. the Kookaburra region splitting up into the two sources HESS J1420-607 and HESS J1418-609, is significantly better. Indeed it is believed that the emission from HESS J1420-607 and HESS J1418-609 is produced by two different, large-offset PWNe, K3 powered by the high-spin down pulsar PSR J1420-6048 in case of HESS J1420-607, and the Rabbit or R2, in case of HESS J1418-609<sup>14</sup>. The third source, HESS J1427-607, is slightly extended and so far could not be identified with a counterpart such as an SNR or PWN<sup>15</sup>.

For H.E.S.S. the background is dominated by the small fraction of hadronic air showers that cannot be distinguished from gamma-ray-induced air showers. After source detection and subsequent estimation of source position and extension, for each catalog source a circular source region containing most of the emission according to the best-fit source model excess map is chosen, and the spectral analysis is run independently of the maps. The measurement of spectra is done by using the *reflected background method*<sup>8</sup> (see right panel of Figure 1). In this method, multiple background regions (OFF regions, blue filled circles) arranged in a circle are used for each trial source position (ON region, red filled circle), where each OFF region has the same size and shape as the ON region and an equal offset to the observation, or pointing, position. Due to the equal offset of ON and OFF regions from the pointing direction of the system, no radial acceptance correction is required with this method, making it ideal for spectral analysis. Figure 1 also illustrates the motivation behind using two different sets of exclusion regions, as the *large* exclusion regions can be too large to allow for spectral extraction in many cases, and the *small* exclusion regions are used instead.

The difficult part about the catalog construction is the high source density in the inner Galaxy. There are several regions of multi-degree-scale excess along the Galactic plane where

<sup>&</sup>lt;sup>b</sup>http://fermi.gsfc.nasa.gov

<sup>&</sup>lt;sup>c</sup>http://www.hawc-observatory.org



Figure 2: Iterative process of the source fitting in the *Kookaburra* region. Significance map (left) and model and residual images (small pictures on the right). It can be seen that the 3-source solution leaves a flat residual map and is therefore preferred.

it is not obvious how to best represent them in an extended source catalog. Therefore we are investigating e.g. adding a criterion to the catalog construction method that prevents large and bright sources from decomposing into multiple, strongly overlapping components.

#### 4 Galactic source population and recent discoveries

To date, 67 sources are listed in the catalog of published H.E.S.S. sources<sup>d</sup>. Figure 3 shows a pie chart of the H.E.S.S. Galactic source population, status February 2013, where the source classification is taken from TeVCat<sup>e</sup>. While the largest source class are pulsar wind nebulae (PWN, orange), followed by supernova remnants, either interacting with a molecular cloud (SNR MC, yellow) or exhibiting emission from their shell (SNR Shell, light green), there are to date only a few massive stellar clusters (dark red) and binary systems (light blue) identified as H.E.S.S. sources. A large part of the H.E.S.S. source population remains ambiguous, therefore Unidentified (dark blue). It should be noted that with further multi-wavelength data the distribution of this chart will likely change, not only will sources migrate from being unidentified to another source class, but in some cases possibly even between the defined source classes. Therefore this chart represents our knowledge at this point in time.

An example of a previously unidentified source that has now been identified as a PWN is **HESS J1303–631**, which was the first source classed as unidentified for H.E.S.S. Significant energy-dependent morphology of this source, as well as the identification of an associated X-ray PWN from XMM-Newton observations enable identification of the VHE source as an evolved PWN associated with the pulsar PSR J1301–6305<sup>10</sup>.

**W49B** is an SNR interacting with a molecular cloud, located in the W49 region. W49B has one of the highest surface brightnesses in radio of all the SNRs of this class in our Galaxy and is one of the brightest ejecta-dominated SNRs in X-rays. Infrared observations evidenced that W49B is interacting with molecular clouds and Fermi reported the detection of a coincident bright, high-energy  $\gamma$ -ray source<sup>11</sup>. H.E.S.S. detected significant emission from the W49 region, compatible with VHE emission from the SNR W49B<sup>12</sup>. The position of the emission is compatible with the brightest part of the radio emission from the SNR as well as with the GeV emission. Energy spectra in the GeV and TeV bands are in very good agreement. Given the

<sup>&</sup>lt;sup>d</sup>http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/ <sup>e</sup>http://tevcat.uchicago.edu/





Figure 3: Galactic H.E.S.S. sources, status February 2013, classifications taken from TeVCat. Pulsar wind nebulae (PWN, orange) are the largest source class with ~35%, followed by supernova remnants, either interacting with a molecular cloud (SNR MC, yellow, ~13%) or exhibiting emission from their shell (SNR Shell, light green, ~8%). Besides a few massive stellar clusters (dark red, ~6%) and some binary systems (light blue, ~4%) a large part of the H.E.S.S. source population remains unidentified (dark blue, ~31%). 'Other' (dark green) comprises the globular cluster Terzan 5 and the high-frequency peaked BL Lac object HESS J1943+213.

very high GeV luminosity, the GeV-TeV connection, and the fact that the SNR is interacting with a dense molecular cloud, a hadronic emission scenario is favored in the case of W49B.

Finally, **HESS J1641–463** is an example for a source that remains unidentified, despite of the existence of multi-wavelength data <sup>13</sup>. It is found within the bounds of a radio SNR, however, the existing X-ray observations do not provide additional support to this scenario due to the lack of detection of an extended X-ray feature at the position of HESS J1641–463. In addition, the larger extension of the SNR G338.5+0.1 as compared to the H.E.S.S. source, and the relatively old age of the SNR inferred from its physical size suggests that the emission might not be necessarily connected with the SNR but rather with a PWN at its center, driven by an yet undetected pulsar. Due to its small size, compatible with a point-like source for H.E.S.S., the possibility that HESS J1641–463 is a binary system cannot be excluded.

## 5 Outlook

After nearly a decade of observing the Southern sky, H.E.S.S. is ending its surveying program of the Galactic Plane. With the additional, much larger fifth Cherenkov telesope in the centre of the H.E.S.S. array, H.E.S.S. is entering phase II and will concentrate on deeper observations with improved sensitivity and angular resolution. Here we have shown the latest results of the HGPS and an overview over the H.E.S.S. Galactic source population. We aim to present the entire data set of the HGPS, in the form of maps and a catalog, and to make it accessible to astronomers. With this large data set, population studies in the VHE range become possible for the first time.



Figure 4: Profile of the sensitivity map (refer to Figure 6) for  $b=-0.3^{\circ}$ .

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Figure 5: Significance map for the H.E.S.S. Galactic Plane Survey. The pre-trials significance for a correlation radius of 0.1 deg is shown. The colour transition from blue to red corresponds to  $\sim 5\sigma$  post-trials significance. The significance has been calculated for regions on the sky where the sensitivity of H.E.S.S. for point sources ( $5\sigma$  pre-trials, and assuming the spectral shape of a power law with index 2.3) is better than 10 % Crab. Identifiers for sources that have been described in publications or announced at conferences are included.



Figure 6: Sensitivity of H.E.S.S. to point-like  $\gamma$ -ray sources with an assumed spectral index of 2.3, for a detection level of  $5\sigma$  pre-trial. The sensitivity is expressed as an integral flux above 1 TeV in units of  $2.26 \cdot 10^{-9} \text{ m}^{-2} \text{ s}^{-1}$ , which amounts to 1% of the Crab integral flux above 1 TeV.

#### Supernova remnants and molecular clouds

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The search for the origin of galactic cosmic rays cannot be led directly as charged particles scatter on magnetic perturbations inside our Galaxy. Neutral particles such as high or very high energy gamma-rays, produced by interacting high energy charged particles, can be effectively used to search for acceleration sites. Large matter concentrations such as molecular clouds in the vicinity of potential accelerators are very interesting probes for accelerated hadrons. The interest of supernova remnant associated with molecular clouds in order to confirm the standard paradigm of the origin of galactic cosmic-rays is presented here.

#### 1 The standard paradigm of the origin of galactic cosmic rays

The origin of Galactic cosmic rays (CRs) is a long standing question, since their discovery more than 100 years ago in 1912 by Victor Hess. It is commonly believed that supernova remnants (SNRs) are the main particle accelerators in the Galaxy. Diffusive shock acceleration mechanism in the associated strong shock could accelerate particle efficiently up to  $10^{15}$  eV (for a review see e.g. <sup>1</sup>). A conversion efficiency of 10% of the kinetic energy of the Galactic SNRs into CRs can explain the observed flux at Earth (taken to be typical of the Galaxy). Even if the connection between supernovae and cosmic rays has been proposed a short time after the discovery of cosmic rays in 1934 by Baade and Zwicky<sup>2</sup>, the definitive confirmation is still missing.

In the last decade, the proof that high energy particles are efficiently accelerated has been brought by very high energy (VHE, E > 100 GeV) gamma-ray telescopes. A VHE gammaray emission has been detected toward several shell-type SNRs with H.E.S.S., MAGIC and VERITAS. The emission of such non thermal energetic photons can only occur through the interaction of high energy charged particles. It confirms that these objects accelerate particles up to at least 10 TeV<sup>34</sup>. However, TeV measurements alone do not allow to disentangle between a hadronic or a leptonic origin of the gamma-rays and thus the confirmation that hadronic cosmic rays are accelerated by SNRs is still missing.

More recently, the high energy gamma-ray space telescopes Fermi-LAT and AGILE have completed the picture of those objects. A GeV gamma-ray emission has been detected towards several shell-type SNRs. Amongst them are two remnants already detected at TeV energies: Tycho<sup>5</sup> and RX J1713.7-3946<sup>6</sup>. Whereas in the first case the spectral energy distribution clearly favors a hadronic origin, in the latter a leptonic scenario seems preferred. In general, even if the gamma-ray measurements indicate that hadronic gamma-ray seems effectively accelerated inside supernova remnants, it seems difficult to completely confirm that SNRs are responsible for the bulk of cosmic rays. Another pending question concerns the highest energies. Diffusive shock acceleration mechanism predicts that the accelerated particles could reach PeV energies into strong shocks. However, no gamma-ray emission produced by such energetic particles has been detected, leading to the conclusion that either no such energies have been reached, or these particles have already escaped the acceleration site. Given the age of the observed SNRs, the latter hypothesis is expected.

### 2 Molecular clouds and the origin of cosmic rays

The ingredients for a leptonic gamma-ray emission are naturally present in supernova remnants. A population of accelerated electrons will naturally produce high energy photons through Inverse Compton diffusion on the CMB photons, even without additional photon field target. On the contrary, a gamma-ray emission from a population of hadrons needs a consequent target density to produce a detectable gamma-ray signal. A supernova remnant evolving into a low density medium may not have enough target matter in its surrounding to be observed with current telescopes. The lake of detection of hadronic gamma-ray from some supernova remnant could be thus due to the low density medium surrounding the remnant.

In order to confirm that supernova remnant are efficient hadrons accelerator, a good strategy would be to look at remnants close to a large concentration of matter<sup>7</sup>. Such kind of association are frequent in our Galaxy. Most of the neutral matter is concentrated into dense molecular clouds, in which up to  $10^5$  solar masses can be confined with densities up to  $10^6$  particles per cm<sup>3</sup>. Such massive clouds frequently host star forming regions with massive stars that gives birth to supernova. This childhood link between supernova remnants and molecular clouds explains why the association is frequently expected <sup>8</sup>.

However, the detection of such associations is difficult to assess. The distance to molecular clouds is pretty accurate thanks to radio or millimetric line doppler effect, but is much difficult to evaluate in the case of supernova remnants. To search for physical associations, the presence of 1720 MHz OH masers is a very helpful indicator. This maser is emitted within shocked dense region as the line inversion can occur only through collisional pumping in low temperature clouds <sup>9</sup>. The detection of this maser undoubtedly indicates that a shock wave propagates through the cloud and thus that the cloud is physically associated with the remnant. Over 10% of the known supernova remnants are OH masers emitting, indicating that a physical association is very frequent. These remnants appears to be very promising target to search for a population of accelerated hadrons. A recent study summarized the detection of GeV or TeV gamma-ray emission towards these remnants and showed that a significant fraction of the know interacting remnant are gamma-ray emitters <sup>10</sup>. Around 10% of the know supernova remnants, all showing evidences of interaction with a dense cloud (either OH masers or radio line broadening) emit gamma-rays, whereas another 10% that could be interacting are also emitters.

It should be kept in mind that there are some caveats related to such associations when looking at particle acceleration. First the presence of dense matter slowing down the propagation of the shock wave may have an impact on the acceleration efficiency. Moreover, this maser line is observed when a slow shock propagate through the cloud, meaning that the remnant is already in an advanced stage of its evolution. The particles with the highest energies have very probably escaped the remnant at this stage. These two caveats add to the fact that the morphology of the remnant is most of the time unusual due to the propagation into an inhomogeneous medium. These supernova are thus probably not the best candidates to compare to theoretical models.

# 3 The gamma-ray picture: from GeV to TeV

In the last five years, this class of gamma-ray source has grown-up very rapidly, mainly thanks to the observations of the GeV instruments Fermi-LAT and Agile. Only a bunch of TeV detections by H.E.S.S., MAGIC or VERITAS were known four years ago: W28, IC443, CTB 37A, W51,



Figure 1: The GeV-TeV picture of the W28 field. The position of the supernova remnant is indicated by a white or green circle. Left: The VHE gamma-ray excess map seen by HESS. Middle: The HE gamma-ray excess contours from Agile in black over-imposed on the H.E.S.S. excess map. Right: The HE gamma-ray excess map from Fermi-LAT with the H.E.S.S. excess contours overlaid as black lines.

G359.1-0.5  $^{11}$ . Fermi or Agile have confirmed that these are also emitting in the GeV range. Several other GeV emissions have been detected since then. As well, several other TeV emissions have been discovered toward interacting SNRs.

The brightness of these sources in the GeV range put a strong constraint on the origin of the gamma-ray emission. Even if a leptonic origin of the gamma-ray emission cannot be completely ruled out for all of these gamma-ray emission, a hadronic origin is much more favored by their spectral energy distribution. In most of the case the position of the gamma-ray emission is well correlated with the presence of the molecular clouds, making the hadronic interpretation even more convincing.

## 3.1 The case of W28

The W28 complex is a well known case of supernova remnant interacting with a molecular cloud. Figure 1 *left* is the VHE gamma-ray excess map of the W28 field observed by HESS<sup>12</sup>. Two sources are detected: at the northeastern boundary of the remnant, HESS J1801-233, and to the South, HESS J1801-240 (possibly divided into three components, A, B and C). The W 28 SNR is interacting along its northern and northeastern boundaries with molecular clouds visible within NANTEN observations in the  $CO(J=1-\rightarrow 0)$  line. NANTEN observations showed also the presence of a dense molecular cloud coincident with the southern gamma-ray excess. The doppler effect of the CO line showes that this cloud lies also in the vicinity of the remnant, even not being physically associated.

The GeV view of the remnant has been published by Agile<sup>14</sup> and Fermi-LAT<sup>13</sup> in 2010. Figure 1 *middle* represents the HE gamma-ray excess map contours from Agile over imposed on the HESS VHE gamma-ray map. Figure 1 *right* is the HE gamma-ray excess map from Fermi-LAT with the HESS contours over-imposed. The GeV emission appears quite nicely correlated with the TeV emission. Both the northern and the southern TeV excesses have a counterpart at lower energies. The coincidence between these gamma-ray emission and the molecular clouds argues in favor of a hadronic origin of the photons. The spectral energy distribution favors also a hadronic origin.

It should noted that the three hotspots of the southern TeV excess are not all detected at GeV energies. Only one of the hotspots associated with the southern molecular clouds (region A and B on figure 1 *left*) is detected. Moreover, the brightness ratio between the two parts is different in the two energy band. While the northern excess is the fainter in the HESS map, the southern is the fainter in the GeV maps. This different brightness ratio as well as the lake of



Figure 2: Left: GeV to TeV energy spectral distribution of the gamma-ray emission detected by AGILE and HESS toward the W28 field. The black and red lines correspond respectively to the northern and southern excess. Right: Spectral energy distribution of the SNRs W44 and IC 443. The dashed lines are hadronic model over-imposed on the spectra measured by Fermi-LAT. The solid lines show the hadron spectra corresponding to the gamma-ray model.

detection in the A region can be explain by diffusion effects. W28 is a prototype to test the effect of particle escaping the remnant when they are not anymore confined in the acceleration zone. Only the northern cloud is in the immediate vicinity of the shock, although the southern cloud is more distant and thus particle interacting into this cloud have already escaped the remnant. The propagation effect is visible on figure 2 *left* showing the measurement from Agile combined with the one obtained by HESS and a model of accelerated particle propagation outside the remnant. The spectral energy distribution of the southern source is visible in red. The peak in the distribution is shifted toward the highest energy compared to the blck one describing the northern cloud. It showes that the lowest energy particles did not reached the cloud yet and that they are still confined into the shock.

#### 3.2 The pion decay signature

Recently, the Fermi-LAT collaboration has reported the detection of a pion decay signature in the gamma-ray spectrum of two interacting SNRs: IC 443 and W44<sup>15</sup>. Figure 2 *right* showes the spectral points obtained by Fermi compared to a hadronic model (dotted lines). The solid lines indicate the original particle energy spectra that produced the modeled gamma-ray spectra. The very precise measurement of these strong GeV gamma-ray sources, combined with an improved data treatment reducing the energy threshold, helped to detect the pion decay spectral feature above a few tens of MeV. Here also a leptonic origin of the gamma-ray cannot be excluded but this scenario cannot easily reproduce the spectra without adding ad hoc features in the electron spectrum.

#### 3.3 Common pictures

The number of detected sources, either at GeV and/or TeV energies, is now larger than ten and several common features appear. All these sources are bright GeV emitters with a spectral index in the GeV index close to 2, whereas in the TeV range, these sources are much fainter with a softer spectral index. This steepening of the spectra implies the presence of a spectral break in between that arrises around a few GeV. These recent detections triggered a lot of attempts to model the gamma-ray emission from those objects. Modeling the case of interacting supernova remnants needs to take into account the diffusion of accelerated particles around the remnant. It has been shown that the spectral break can be reproduced taking into account the finite volume of the cloud and the diffusion of particle within the cloud <sup>16</sup>. The low energy part of the spectra



Figure 3: Left: GeV to TeV energy spectral distribution of the emission detected toward the W51 region. The solid lines are hadronic models reproducing the data with three different energy cuts of the particle spectrum considered. The dashed lines correspond to the associated neutrino flux. Right: Integrated neutrino flux as a function of the threshold energy detected by an IceCube-like detector in one year. The dotted and dashed lines corresponds to three particle spectrum cut-offs considered and are compared to the red solid line representing the number of atmospheric neutrinos detected during the same period.

is dominated by still confined particles which follow a spectral shape compatible with diffusive shock acceleration model. At high energy, the particles are not confined in the acceleration zone and are diffusing into the cloud that could extend further than the shock region. This diffusion is responsible for the energy break that arises around a few GeV.

# 4 Other view angles for interacting SNRs

# 4.1 Neutrinos

A definitive answer concerning the origin of the detected gamma-rays could come from the detection of associated neutrinos. The gamma-rays are produced when  $\pi^0$  produced in hadronic inelastic interaction decay into photon pairs. These  $\pi^0$  are produced with associated  $\pi^{\pm}$  that decay producing neutrinos. The detection of neutrinos from supernova remnants would thus confirm unambiguously the presence of accelerated hadrons. Unfortunately, the effective area of current neutrino detectors such as Antares, IceCube or the future network Km3Net is too limited to be sensitive to the low neutrinos flux induced by interacting SNRs. Figure 3 left showes the expected neutrino fluxes from the SNR W51C<sup>17</sup>. The neutrino spectrum follows the same shape as the gamma-ray spectrum. The soft gamma-ray spectrum observed in the TeV range for most of the interacting SNRs leads to a soft neutrinos in one year. Even in the most favorable case with no energy cut-off below a few tens of TeV, the expected number of neutrinos is less than one per year (of the order of 1 per year for some remnants) with an atmospheric background event number at the same level in the most favorable case.

## 4.2 Low energy cosmic rays and molecular clouds

Not only the highest energy particles interact within molecular clouds. The lowest energy particles, much more abundant, have also an impact inside the clouds. They are more effective in ionizing the interstellar gas. This induced ionization has an impact on the cloud chemistry and can lead to visible effect. The enhanced ionization rate within interacting molecular clouds could be thus helpful to bring additional indication of the presence of accelerated particle. Recently, several studies has been led towards the known interacting remnants IC 443<sup>18</sup> and W51C<sup>19</sup>. These millimetric observations pointed at several species which abundance ratio are directly

proportional to the ionization rate inside the cloud. They showed that the ionization rate is larger by a factor 100 inside these clouds compared to clouds without accelerator nearby. It confirms that at least low energy particles are freshly accelerated by the SNRs and brings an additional confirmation that the observed gamma-rays from these clouds are originated in higher energy hadronic particle interactions.

# 5 Summary and perspectives

The class of interacting SNRs is a new field in rapid expansion. In the last five years, a lot of new candidates have been discovered, either at GeV or TeV energies. Individually these detections cannot be attributed undoubtedly to hadron particles interacting within the cloud. However, the accumulation of indications and the improvement in the spectral description of these emissions provide evidence that cosmic rays protons are effectively accelerated by supernova remnants.

Due to the rapidly falling spectra in the TeV band, current VHE observations do not have the same precision level brought in the GeV band by Fermi-LAT. In particular, the question of the highest energies, whether SNRs can accelerate particle up to the knee can be hardly solved with current detectors. The future VHE gamma-ray observatory CTA will bring a factor 10 in sensitivity and around a factor 5 in angular resolution compared to current telescopes. Observations with CTA of interacting SNRs will probably improve the measurement in the TeV range in the same order as Fermi-LAT did in the GeV band. More detections could be expected and the improved sensitivity and resolution will help disentangling between the different scenario.

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# SUPERNOVA REMNANTS INTERACTING WITH MOLECULAR CLOUDS AS SEEN WITH H.E.S.S.

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About 30 Galactic supernova remnants (SNRs) are thought to be physically associated with molecular clouds (MCs). These systems are prime  $\gamma$ -ray source candidates as the accelerated particles from shock fronts collide with the surrounding high-density medium thus emitting gamma-rays through hadronic interactions. However only a handful of such interacting SNRs are detected at TeV energies. We report the current status of the High Energy Stereoscopic System (H.E.S.S.) observations towards these SNR-MC systems, with a particular emphasis on the latest results.

# 1 Introduction

Since the 1930s' <sup>23</sup>, supernova remnants (SNRs) remain the most probable sources of Galactic cosmic rays (CRs). Through the diffusive shock acceleration and subsequent magnetic field amplification mechanisms, particles can be accelerated up to the knee at the SNR shock surface. However despite several decades of multi-wavelength observations no compelling *direct* evidence in favor of efficient CR acceleration in SNRs has been observed yet. The interaction of protons and nuclei accelerated at the SNR shock with the interstellar/circumstellar medium (ISM/CSM) is accompanied by the emission of high/very-high energy (HE/VHE)  $\gamma$ -rays resulting of the decay of neutral pions. Such hadronic interactions are tracers of the amount of protons accelerated at the SNR shock. Hence SNRs interacting with dense interstellar material such as molecular clouds (MCs) are prime targets to test the SNR paradigm. Inverse Compton scattering of accelerated leptons off the different seed photon fields or non-thermal bremsstrahlung on ambiant nuclei can also give rise to  $\gamma$ -ray emission. These three mechanisms lead to different photon spectral shape in the GeV-TeV energy range. One can identify the  $\gamma$ -ray production process by using joint observations from imaging atmospheric Cherenkov telescopes (IACTs) such as the H.E.S.S., MAGIC, VERITAS experiments as well as the Fermi-LAT and AGILE telescopes.

The H.E.S.S. array detects  $\gamma$ -rays above an energy threshold of  $\sim 100 \,\text{GeV}$ . The primary particle direction and energy are reconstructed with an energy resolution of  $\sim 15\%$  and an angular resolution of  $\sim 0.1^{\circ}$ . About 50 H.E.S.S. sources are coincident with a Galactic SNR (from the Green's catalogue), among which 3 are firmly associated with a SNR-MC system (W51C  $^{26,21}$ . W49B<sup>24</sup>, W28<sup>17</sup>) and 5 with the SNR shell emission itself (Vela Jr<sup>14</sup>, HESS J1731-347<sup>15</sup>, RCW 86<sup>19</sup>, RX J1713.7-3946<sup>16</sup>, SN 1006<sup>11</sup>). The other sources are either associated with a pulsar wind nebula (PWN) emission or without any clear counterpart. 1720 MHz OH masers are reliable indicators of a physical interaction between a SNR and a MC but other tracers like molecular (CO, CS...) line broadening or specific infrared line emissions can also be used to probe SNR-MC shocks (see B. Jiang's list of Galactic SNRs interacting with MCs at http: //astronomy.nju.edu.cn/~bjiang/SNR\_MC.htm).

In the following, the association of recently detected H.E.S.S. sources with SNR-MC interactions will be discussed in the light of their multi-wavelength counterparts and their spectral energy distribution modeling. Different SNR types detected in the  $\gamma$ -ray domain will be compared in order to emphasize some trends between isolated and MC-interacting SNRs.

#### 2 H.E.S.S. sources possibly associated with a SNR-MC shock

# 2.1 H.E.S.S. sources coincident with a SNR, a MC and OH masers

HESS J1804–216<sup>13,20</sup> is a bright  $\gamma$ -ray source with an extension of 22' and coincident with the massive star forming region W30. This complex contains several HII regions, the evolved SNR G8.7–0.1, the pulsar PSR J1803–2137 and the PWN G8.40+0.15. The presence of a MC and the detection of an OH (1720 MHz) maser <sup>29</sup> on the eastern edge of the remnant confirm the interaction of the SNR with the MC. However the TeV emission does not match with any known object: the angular distance from the SNR G8.7–0.1 and from the PSR is of about ~0.2-0.3° and the size of the coincident PWN (2') is much smaller than the TeV emission. While the required energy budgets do not discard any of the SNR-MC shock and PWN scenarios, such offsets make the association unclear.

HESS J1714–385<sup>18</sup> is coincident with the SNR G348.5+0.1 (also called CTB 37A) which is interacting with three molecular clouds as shown by the detection of several 1720 MHz OH masers in different locations in the SNR<sup>27</sup>. A slightly extended non-thermal X-ray source CXOU J171419.8–383023 which could be a PWN is detected in the north-western part of the remnant. However no associated pulsar is detected. On the one hand a PSR-PWN scenario is not ruled out by the estimated spin-down luminosity of a potential pulsar powering the nebula. On the other hand the derived CR energetics in the SNR-MC scenario are reasonable. Despite the slight extent of the TeV source, no detailed morphological study can be carried out for such a weak TeV source. Therefore, two possible scenarios remain to explain the HESS J1714–385 emission.

#### 2.2 H.E.S.S. sources coincident with a SNR and a MC

The two TeV sources HESS J1834–087 and HESS J1640–465, both coincident with known SNRs and discovered in the H.E.S.S. Galactic Plane survey <sup>13</sup> have been followed up until 2012. The analysis of a larger amount of data led to more detailed morphological and spectral studies and resulted in the discovery of two new H.E.S.S. sources also coincident with SNRs: HESS J1832–093 nearby HESS J1834–087 and HESS J1641–463 close to HESS J1640–465.

HESS J1834–087<sup>36</sup> is a bright and extended VHE emission coincident with the SNR W41. The morphological analysis of the source results in the identification of two components: a TeV pointlike component coincident with the central compact object (CCO) CXOU J183434.9–084443<sup>37</sup> which does not show any pulsation, and a surrounding TeV extended component with an extension of ~0.17°. In addition to detecting a CCO in the center of the remnant, X-ray observations revealed a PWN candidate in the form of non-thermal diffuse emission surrounding the X-ray compact source. The TeV source is marginally coincident with <sup>12</sup>CO<sup>25</sup> and <sup>13</sup>CO<sup>30</sup> line emissions. The analysis of 47 months Fermi-LAT data results in the detection of an extended GeV source coincident with HESS J1834–087, with a power law spectrum of index ~2.15. The two TeV components are well described by power laws with softer spectral indices ( $\Gamma \geq 2.6$ ). A PWN scenario alone can not explain the combined spectrum of the extended GeV and TeV components. A SNR-MC scenario would imply a spectral break at ~100 GeV to accomodate it. A break at a few GeV is observed in the spectra of several SNRs interacting with MCs (W51C<sup>1</sup>, W49B <sup>2</sup>, W28<sup>3</sup>, IC443<sup>8,6</sup>, W44<sup>4</sup>) and can be explained by the damping of Alfvén waves due to the

presence of neutrals in the dense surrounding medium<sup>35</sup>. However it would be the first detection of a spectral break at so high energies. Assuming such a break, the combination of a PWN and SNR-MC scenarios could explain the Fermi-LAT and H.E.S.S. spectra.

HESS J1832–093<sup>32</sup> is a point-like source located  $0.5^{\circ}$  from W41 and spatially coincident with the western radio rim of the SNR G22.7–0.2. Nor the age, neither the distance of this SNR are known. An X-ray point-like source is detected 1' away from the H.E.S.S. source and no GeV counterpart is observed <sup>38</sup>. From <sup>13</sup>CO observation <sup>30</sup> two clouds are detected towards the TeV emission and could be interacting with G22.7–0.2. The CRs energy budget resulting from such a SNR-MC scenario is reasonable however no tracer of a SNR-MC shock has been detected so far.

HESS J1640–465 is an extended  $\gamma$ -ray source coincident with the northern part of the G338.3– 0.0 SNR shell. This distant SNR (~10 kpc) is coincident with the southern part of a giant HII region G338.4+0.1 and is located nearby the stellar cluster Mc81. Fermi-LAT observations revealed a GeV counterpart to HESS J1640–465. A compact and extended X-ray sources <sup>33,40</sup> are detected close to the center of the remnant and are compatible with the VHE emission but no pulsation has been detected. The latter source was suggested to be a potential pulsar and HESS J1640–465 was first interpreted as the associated PWN. The new H.E.S.S. results reveal that the TeV spectrum (I'=2.15) connects smoothly with the Fermi-LAT power-law spectrum of index ~2.3. This differs significantly from the previous HE spectral energy distribution and suggest that at least part of the TeV emission is likely of hadronic origin. The estimated product of total energy in protons and average target gas density from 1 GeV to 20 TeV is  $W_p \cdot n_H \approx$  $4 \cdot 10^{52} (\frac{d}{10 \, \text{kpc}}) \, \text{erg cm}^{-3}$ .

HESS J1641–463<sup>39</sup> is coincident with the SNR G338.5+0.1 and located ~0.25° from HESS J1640–465. This SNR is at ~11 kpc<sup>31</sup> and the giant HII region G338.4+0.1 lying between the two SNRs G338.5+0.1 and G338.3–0.0 seems to connect them. No other counterpart is found to be compatible with HESS J1641–463. The spectral analysis reveals a hard power-law shape ( $\Gamma \sim 2$ ), which explains why the distinction between the two TeV sources HESS J1640–465 and HESS J1641–463 becomes more evident above a few TeVs.

# 3 Features of isolated and MC interacting SNRs



Figure 1: Left: Integrated flux on the 1-100 GeV energy range versus integrated flux on the 1-100 TeV energy range for SNRs interacting with MCs (full red squares), isolated SNRs (empty blue squares) and SNRs possibly interacting with MCs (black dots). The vertical dashed line represent 1% of the Crab flux. Right: Ratio of the 1-100 GeV over 1-100 TeV integrated fluxes versus the SNR age (same legend as for the left panel).

Fig.1 shows the integrated 1-100 GeV flux versus the integrated 1-100 TeV flux (left) and the

integrated flux ratio  $I_{1-100 \, GeV}/I_{1-100 TeV}$  versus the SNR age (right) for different SNR types. HE-VHE sources associated with SNR-MC systems (W51C, W28N, W49B, IC443) have an integrated GeV flux much higher than the integrated TeV flux:  $I_{GeV}/I_{TeV} = 5 \cdot 10^4 - 3 \cdot 10^5$ . This confirms that SNRs interacting with MCs are luminous GeV and weak TeV sources.

The  $\gamma$ -ray emitting isolated SNRs (Vela Jr <sup>14,41</sup>, HESS J1731–347 <sup>15</sup>, RCW 86 <sup>19,34</sup>, RX J1713.7–3946 <sup>16,7</sup>, SN1006 <sup>11,22</sup>, Tycho <sup>10,28</sup>, Cas A <sup>9,5</sup>) are all young SNRs (Vela Jr is  $3000 \pm 1300$  yr old, but note that the age of HESS 1731–347 is weakly constrained). The SN 1006 upper limit (UL) on the 1-100 GeV flux was derived by Araya & Frutos (2012) <sup>22</sup> assuming a point-like source at the position of SN 1006. The RCW 86 UL is extracted from Lemoine-Goumard et al. (2012) <sup>34</sup>. For HESS J1731–347 and HESS J1832–093, the flux of the closest Fermi detection is used as an UL (2FGL J1730.5–3350 and 2FGL J1827.4–0846 respectively). The value of the GeV-TeV integrated flux ratio for isolated SNRs is much lower than for SNR-MC systems ( $I_{GeV}/I_{TeV} \leq 6 \cdot 10^3$ ) and characterizes hard GeV and strong TeV sources. Some evident differences appear between the MC-interacting and isolated SNRs.

The inauguration of the fifth H.E.S.S. telescope last summer marks an encouraging step forward to disentangle features of confused sources, thanks to its improved sensitivity and resolution. The expected lower energy threshold of the instrument ( $E \ge 10 \text{ GeV}$ ) is a crucial tool for SNRs detected at GeV energies but not seen at TeV energies like W44. The detection of this strong GeV source resulting from the interaction of a SNR with a MC is still missing at VHE suggesting a cutoff or a break at a few ~ 10 GeV.

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#### Hadronic emission in middle-aged SNRs

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Recent gamma-rays observations of Supernova Remnants revealed the existence of a class of objects characterized by an age older than some thousands of years, interacting with massive molecular clouds and with a soft spectral energy distribution peaked at some hundreds of MeV.

This class includes the well known SNRs W44, IC 443, W28, W51C and others. Here we present the AGILE observations of this class of SNRs in the band 50 MeV - 10 GeV. The observations in this range (especially in the lowest part, 50-100 MeV) are crucial in constraining the emission models of these objects and can be used to study the diffusion of particles in the ISM around the source.

Probably the most relevant object in this class is SNR W44, for which, combining gamma-rays and radio observations, we demonstrated that lepton-dominated models fail to explain simultaneously the well-constrained multiwavelenght spectrum, leading to the first unambiguous evidence of gamma-rays emission from neutral-pions decay in a SNR.

# 1 SNRs in gamma-rays

Recent gamma-rays observations of supernova remnants have shown that SNRs can be divided in two classes, on the basis of their spectrum, age, morphology and ambient medium. We can then define the two classes following these criteria: *Class 1* objects, are young shell-like SNRs (with age between few hundreds and few thousands of years), expanding in a relatively low density medium, with gamma emission morphology typically very nicely correlated with the radio (and often X-rays) shell. *Class 2* objects, are mixed-morphology middle-aged SNRs (thousands or tens of thousands years) are objects, interacting with giant molecular clouds and with a gamma morphology that correlates with the molecular clouds better than with the radio shell.

Figure 1 shows, for some member of the two classes, their intrinsic luminosity as a function of age (ages and distances were taken by literature). The Class 2 objects are characterized by an higher luminosity likely due to the higher density of the medium.

The distribution of ages seems to suggests that the phenomenon that give rise to the first class of SNRs lasts on shorter timescales (thousands of years instead of tens of thousands of years). Moreover the higher intrinsic luminosity and the older ages of Class 2 SNRs implies that the fraction of gamma-rays emitting SNRs is much lower for class 2 objects.



Figure 1: Gamma-Rays luminosity (E>100 MeV) as a function of age (ages and distances were taken by literature) for some Class 1 and Class 2 objects (see text).

# 2 The SNR W44

W44 is a middle-aged SNR ( 20000 years) expanding in a dense and very inhomogeneous medium. There is evidence of interaction with the surrounding molecular clouds This object is source of intense non-thermal emission in both radio band (which has been measured over the frequency range 10 MHz - 10 GHz) and gamma-rays band (from 50 MeV to 50 Gev). It is extended approximately 0.5 degrees corresponding to about 30 pc if a distance of 3 kpc is assumed. For these features the supernova remnants W44 is an ideal laboratory for understanding the mechanisms of the gamma-rays emission in SNRs

The radio spectrum of W44<sup>1</sup> is well represented by power-law with a spectral index of  $-0.37\pm0.02$  over a frequency range spanning more than three orders of magnitude. If interpreted as synchrotron emission from relativistic electrons, it corresponds to a distribution of particles with slope -1.74 in the energy range 300 MeV - 10 GeV if a magnetic field of 10  $\mu$ G is assumed, or 100 MeV - 3 GeV for a magnetic field of 100  $\mu$ G.

# 2.1 The gamma-rays spectrum of W44

The gamma-rays detectors on board of Fermi<sup>4</sup> and  $AGILE^{6}$  were able to measure the spectrum of W44 in the energy range 50 MeV - 50 GeV. These observations allowed to characterize the gamma-rays spectrum of W44 in a very accurate way. As shown in figure 2 this spectrum is characterized by a wide bump at energies of about 700-800 MeV. This spectral shape leads to remarkable insights on the population of gammarays-emitting particles.

- A single population of electrons cannot fit simultaneously the Gamma-rays and radio spectra. While gamma-rays emission from neutral pion decay can fit very nicely the spectrum. This was the first direc evidence of accelerated protons in a supernova remnant.
- The gamma-rays spectrum is very soft for energies greater than 1 GeV. This in turn



Figure 2: Gamma-rays spectrum of W44 as seen by AGILE (data points in green) and Fermi (orange).

implies that the protons distributions must be very hard (an index of 3.5) for energies greater than few GeV up to 50 GeV.

• A simple power-law overestimate the flux in the low energy part of the spectrum. This implies that the distribution of protons is strongly suppressed below few GeV.

# 3 SNR W28

W28 is a mixed morphology SNR with an age of more than 35 000 years located at a distance of about 1.9 kpc. A system of massive molecular clouds is associated to the SNR as revealed by the CO  $(J = 0 \rightarrow 1)$  observation carried by the NANTEN telescope <sup>2</sup>. Two main peaks in the molecular hydrogen distribution can be seen at R.A., dec = 270.4, -23.4 (cloud N) and at R.A., dec = 270.2, -24.1 (cloud S, see fig. 3)

The molecular clouds distribution correlates nicely with the gamma rays observations in both the TeV energy band <sup>3</sup> and in the E > 400 MeV energy band observed by AGILE. However the ratio between the TeV and the multi-MeV emission is significantly different for the cloud N and the cloud S. In the right panel of figure 3 the gamma-ray spectra for the two clouds are shown.

The interpretative scenario proposed in <sup>5</sup> assumes that the N cloud is closer to the CR acceleration site than the S cloud. If protons diffuse in the interstellar medium with a diffusion coefficient given by  $D(E) = D_0 E^{0.5}$  the resulting proton energy spectrum is suppressed below a threshold energy  $E_t \sim R^4 t^{-2}$  where R is the distance from the acceleration site and t the age of the SNR. Figure 3 shows also the gamma-rays spectra produced by protons (through neutral pion decay) interacting with the cloud N and S assuming respectively R = 9 and 4 pc.

This scenario can explain also the morphology of the gamma-rays emission seen at different energies ranges. Assuming that CR are accelerated in a spherical region (indicated by the blue circle) we evaluated the tridimensional distribution of cosmic rays N(r,E,t) around the SNR as a function of the particle energy and SNR age solving the diffusion equation :

$$\frac{dN(r, E, t)}{dt} = D(E) \nabla^2 N + \frac{\partial}{\partial E} \left[ b(E)N \right] + Q(E)$$



Figure 3: Left: AGILE counts map for the W28. The blue circles indicate the location of the supernova remnant W28, the black contours show the CO intensity emission. Right:Combined AGILE and HESS gamma-ray photon spectra for cloud N (black) and cloud S (red). The curves represent the gamma-ray spectra estimated (accordling to the model presented in the text) for the two clouds.

where b(E) represents the energy losses, and assuming that the cosmic rays were injected impulsively with a spectrum  $Q(E) \sim E^{-2.2}$ . Black countours shows the distribution of targets (molecular hydrogen) as derived by the observations of the NANTEN telescope.

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# Recent MAGIC results on Galactic sources of VHE gamma-rays

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The two MAGIC Imaging Atmospheric Cherenkov Telescopes (IACTs), situated on the Canary island of La Palma, provide a window into the very high energy (VHE) gamma-ray Northern sky. With a low threshold of 50 GeV in its standard trigger operating mode, MAGIC can bridge the gap in energy between satellite and ground-based measurements. Discussed here are observational highlights from the MAGIC Galactic source programme, including the morphology studies of SNR W51, the detection Crab pulsar at energies up to 400 GeV, together with results from compact binary systems.

# 1 Introduction

MAGIC is a system of two Imaging Atmospheric Cherenkov Telescopes (IACTs) located on the Canary Island of La Palma. The system has been operating in stereoscopic mode since autumn 2009, while prior to this, MAGIC comprised a single IACT that began taking data in 2004. MAGIC achieves a low trigger threshold of 50 GeV and its sensitivity to point-like sources above 290 GeV is 0.8 Crab units (C.U.) in 50 hours (Aleksić *et al.*<sup>1</sup>). Here we outline some key MAGIC results obtained from recent observations of Galactic sources of VHE gamma-rays.

# 2 The Crab Pulsar and Nebula

The Crab pulsar and it pulsar wind nebula (PWN) are among the best studied astrophysical systems, with extensive measurements made across the electromagnetic spectrum, ranging from radio to TeV gamma-rays. It was not until 2008, however, that pulsed gamma-ray emission above 25 GeV was discovered from the Crab pulsar (Aliu et al.<sup>2</sup>). This ruled out the polar cap (PC) class of models since the emission had to come from the outer regions of the pulsar magnetosphere. Other important measurements followed, with the detection by VERITAS (Aliu et al.<sup>2</sup>) and MAGIC (Aleksić et al.<sup>4,5</sup>) of pulsed emission from 25 up to 400 GeV. The resulting spectra (summarized in Fig. 1) excluded an expoential cutoff in the spectrum at a few GeV and in so doing, challenged existing models. Our phase-resolved spectra, along with those obtained by Fermi-LAT (Abdo  $et \ al.^8$ ) represent the first such measurement between 100 MeV and 400 GeV. We interpreted these data through an extension of the outer gap (OG) model (Aleksić et  $al.^{5}$ ), where the emission results from magnetospheric cascades of secondary and tertiary  $e^{\pm}$ pairs that emit gama-rays via inverse compton (IC) scattering on IR-UV photons. Iterestingly, the model predicts a power law component that extends to higher energies. We intend to use new and archival MAGIC data to search for such pulsed emission above 400 GeV and to improve the precision of our measurements in the low energy regime.

MAGIC has also measured the spectrum of the Crab Nebula using 49 hours of stereoscopic data taken from 2009 to 2011. The spectrum, which ranges between energies of 50 GeV and 45  $\,$ 



Figure 1: Crab Pulsar phase-averaged (P1+P1) SEDs (left), and those of the individual peaks (right), taken from Aleksić et al. <sup>5</sup>. The yellow diamonds, squares and circles indicate the Crab pulsar SED measured from Fermi-LAT (Aleksić et al. <sup>4</sup>) MAGIC monoscopic (Aleksić et al. <sup>4</sup>) and MAGIC stereoscopic (Aleksić et al. <sup>5</sup>) data respectively, and obtained using EGRET peak interval definitions (Fierro et al. <sup>6</sup>). The red squares indicate the MAGIC-Stereo spectra obtained using the peak interval definitions in Aleksić et al. <sup>5</sup>. The light blue points indicate the VERITAS measurement, using the peak interval definitions in Aleksić et al. <sup>5</sup>. For comparison we show the Crab Nebula SED measured by MAGIC and Fermi-LAT (excluding the pulsed emission component) as the green circles and squares, respectively. The solid line represents the model presented in Aleksić et al. <sup>5</sup>, which includes inter-pulse emission. The displayed systematic error of the MAGIC-stereo measurement indicates a  $\pm 17\%$ unceratinty in the energy scale and a  $\pm 19\%$  uncertainty in the flux.

TeV, may be described by a variable power law:  $\frac{d\mathbf{N}}{d\mathbf{E}dtd\mathbf{A}} = f_0 \frac{E}{1\text{TeV}} e^{-\alpha + b \cdot \log 10} \frac{E}{1\text{TeV}} \text{TeV}^{-1} \text{cm}^2 \text{s}^{-1}$ with  $f_0 = (3.27 \pm 0.03_{stat}) \times 10^{-11}$ ,  $\alpha = 2.40 \pm 0.01_{stat}$ , and  $\mathbf{b} = -0.15 \pm 0.01_{stat}$  (Zanin *et al.*<sup>7</sup>). The statistical errors are small (around 5% below 100 GeV) compared to the systematic errors, which we estimate as 15% uncertainties in the flux normalization and energy scale, and a  $\pm 0.15$  uncertainty in the spectral index. Combining our data with those of Fermi-LAT (Abdo *et al.*<sup>8</sup>) has provided the most precise measure to date of the IC peak:  $59 \pm 6_{stat} \pm 10_{stat}$  GeV.

We conducted observations of the Crab Nebula during MeV flare of September 2010 (Tavani et al.<sup>9</sup>, Abdo et al.<sup>10</sup>) and found our daily lightcurve above 300 GeV to be constant within systematic uncertainties. Under strong moonlight conditions we also observed during the first peak (April 12–14) of the Fermi-LAT flare of April 2011 (Buehler et al.<sup>11</sup>), finding no significant change in the flux between 0.7 - 10 TeV (Zanin et al.<sup>7</sup>).

### 3 The W51 region

The medium-age (30 kyr) supernova remnant (SNR) W51C is located at a distance of around 5.5 kpc and in the vicinity of star forming regions W51A and W51B. PWN candidate CXO J192318.5+140305 may also be associated with the SNR (Koo *et al.*<sup>14</sup>). The high cosmic ray ioinzation rate of the region (Ceccarelli *et al.*<sup>15</sup>), together with the detection of gamma-ray emission by H.E.S.S. (Fiasson *et al.*<sup>16</sup>) and Fermi-LAT (Abdo *et al.*<sup>17</sup>), made the W51 complex a promising target in which to study cosmic ray (CR) acceleration by an SNR. MAGIC observed W51 during 2010-2011, detecting the source with a significance of 11 $\sigma$  in 53 hours (Aleksić *et al.*<sup>18</sup>), finding it to be extended with respect to our PSF and that its spectrum was compatible with a power law with an index of 2.58 ± 0.07<sub>stat</sub> ±0.22<sub>stat</sub>. This spectrum was in agreement with that measured by Fermi-LAT, resulting in a broadband spectrum from 10 GeV to 5 TeV that is described by a single power law. MAGIC also mapped the source energy-dependent



Figure 2: MAGIC gamma-ray flux maps in arbitrary units (a.u.) for events with energy between 300 GeV to 1 TeV (top maps), and above 1 TeV (bottom maps), taken from Aleksić *et al.*<sup>18</sup>. Overlaid in cyan are test statistic (TS) value contours in steps of 1, starting at 3. Also shown is the instrumental point spread flunction (PSF) after smearing. The pink contour indicates the 3 events above 1 GeV contour from Fermi-LAT. The PWN candidate position (Koo *et al.*<sup>14</sup>) is indicated by the blue diamond. The green contours in the maps on the left indicate  ${}^{13}CO(J = 1 \rightarrow 0)$  molecular line emission from the GRS (Jackson *et al.*<sup>19</sup>), for velocities  $63 - 72 \text{ kms}^{-1}$ . The green contours in the maps on the right represent the 21 cm continuum emission (Koo & Moon. <sup>12</sup>). The red dashed ellipse shows the position of Shocked atomic and molecular gas (Koo & Moon. <sup>13</sup>), the black corss shows the position of OH maser emission (Green *et al.*<sup>20</sup>).

morphology, which is shown in Fig. 2 together with multi-wavelength data. The peak VHE emission coincides with the region of shocked molecular and atomic gas, while there is a South-Eastern tail toward the PWN, which appears more prominent above at higher energies. Given the lack of molecular gas around the PWN, the possibility of two distinct gamma-ray sources exists, however the event statistics were insufficient to prove this. The region around the PWN was found to account for only around 20% of the VHE emission across the energy range covered by MAGIC, so we consider a common origin when modeling the emission. We applied a simple hadronic 1-zone model to W51, which predicts that around 16% of the explosion energy goes into CR kinetic energy. We found that simple leptonic models failed to adequately describe the data, in agreement with the findings of Abdo *et al.*<sup>17</sup>. Furthermore, the morphology suggests that the bulk of the VHE gamma-ray emission stems from the interaction region between W51C and the molecular cloud. These findings may be interpreted as evidence of ongoing hadronic acceleration in the interaction of an SNR with surrounding clouds. A detailed discussion can be found in Aleksić *et al.*<sup>18</sup>.

# 4 Binaries

Only four binary systems, which consist of a compact object and a companion star, are currently known to emit in TeV gamma-rays. Depending in the nature of the compact object, the VHE emission is thought to stem from the pulsar wind in the case of a neuron star, or from accretiondirven jets in the case of a black hole. The LS I+61°303 system, which has a period of 26.5 days and consists of a Be star and compact object of unknown nature, was discovered by MAGIC in 2006 (Albert *et al.*<sup>21</sup>). The flux during 2005 - 2007 was modulated (Albert *et al.*<sup>22</sup>) and X-ray/TeV correlation was found in the orbital profile variability (Anderhub *et al.*<sup>23</sup>). During 2007-2008 the system changed to a low state, and in 2009 the flux at the expected peak orbital phase interval (0.6-0.7) was almost an order of magnitude lower than in previous measurements. Despite this, no spectral variability was detected. Based on these findings we conclude that the change in flux cannot only be due to increased gamma-ray abosorption within the photon field of the companion star (Aleksić *et al.*<sup>24</sup>).

MAGIC has also monitored the new binay HESS J0632 + 057 from October 2010 to March 2011. The source, which has an orbital period of 321 days, was detected with  $6.5\sigma$  significance during an X-ray outburst in February 2011, roughly 100 days after its periastron passage (Aleksić *et al.*<sup>25</sup>). This led us to conclude that the source exhibits VHE variability timescales on the order of one to two months, and this may be linked to the periodic X-ray outbursts. We also measured the source spectrum down to 140 GeV, finding no indication of a turnover at low energies.

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# **VHE Galactic Highlights from VERITAS**

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The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is a major groundbased gamma ray observatory, able to detect very high energy (VHE) gamma rays with energies from 100 GeV up to 30 TeV. We report on recent Galactic results and discoveries made by the VERITAS Collaboration. Topics include the discovery of VHE emission from the supernova remnants Tycho and CTA 1, the substantially improved view of the gamma ray emission from the binary system LS I +61°303, and the remarkable discovery of VHE emission from the Crab pulsar.

### 1 Introduction

VERITAS is an array of four 12m imaging atmospheric Cherenkov telescopes located at the Fred Lawrence Whipple Observatory in southern Arizona. Each telescope is equipped with a  $3.5^{\circ}$  field of view. The instrument operates in the energy range of 100 GeV - 30 TeV with an energy resolution of 15-25%. Combined with an angular resolution of  $0.1^{\circ}$ , it enables the detection of 1% of the Crab Nebula flux in approximately 25 hours. During the summer of 2012, VERITAS underwent a focal plane upgrade and new photomultiplier tubes increase the light yield by 35%. For more details on the VERITAS instrument and analysis techniques, please refer to Holder *et al.*<sup>1112</sup>.

Approximately 40% of the VERITAS program of observations is dedicated to the study of Galactic gamma ray sources and source candidates. This focus has resulted in the detection by VERITAS of 17 sources listed in Table 1. Here we summarize these results including observations of supernova remnants (SNR), pulsar, pulsar wind nebula (PWN) and binary system. Modeling of such sources in conjunction with multiwavelength campaigns enables the identification of possible acceleration mechanisms.

#### 2 Crab Pulsar

One of the most powerful pulsars in gamma rays is the Crab pulsar, PSR J0534+220, which is the remnant of a historical supernova observed in 1054 A.D. It is located at a distance of 6500 light years, and has a rotation period of 33 ms, a spin-down power of  $4.6 \times 10^{38}$  erg.s<sup>-1</sup> and a surface magnetic field of  $3.78 \times 10^{12}$  G. It has been routinely used as a standard candle in energies from X-ray to TeV.

Within the corotating magnetosphere, charged particles are accelerated to relativistic energies and emit nonthermal radiation from radio waves through gamma rays. In general, gamma ray pulsars exhibit a break in the spectrum between a few hundred MeV and a few GeV. Mapping the cut-off can help to constrain the geometry of the acceleration region, the gamma ray radiation mechanisms and the attenuation of gamma rays. Based on previous measurements and present theoretical understanding, the dominant gamma ray emission mechanism is curvature 

 Table 1:
 Galactic sources of TeV gamma ray emission detected by VERITAS. Some of the designations are definitive; we list here the most likely counterpart. The unidentified sources (UID) are presumed to be Galactic due to their location in the Galactic plane or their angular extent.

Source name	Class
Crab Nebula	PWN
Crab pulsar	Pulsar
LSI+61°303	Binary
HESS J0632+057	Binary
IC 443	SNR
Cas A	SNR
G106.3 + 2.7	SNR/PWN
G54.1+0.3	PWN
HESS J1857+026	PWN?
CTB 87	PWN
MGRO J1908+06	PWN?
TeV J2032+4130	PWN?
Galactic Centre	UID
VER J2019+407	UID
Cyg OB1 TeV complex	UID



Figure 1: VERITAS pulse profile of the Crab pulsar at energy > 120 GeV. The pulse profile is shown twice for clarity. The dashed horizontal line shows the background level estimated from data in the phase region between 0.43 and 0.94. The vertical lines mark the best-fit peak positions in the VERITAS data.

radiation. It is also widely believed that the shape of the spectral break is best described by an exponential cut-off. Following 130 hours of observations, VERITAS identified pulsed emission from the Crab pulsar, obtaining a signal above 100 GeV at the  $10.7\sigma$  level. Figure 1 shows the phase-folded pulse profile. The main pulse peak is observed close to phase 0.0, with an inter-pulse at 0.4. A combined fit to the pulsed Fermi-LAT<sup>2</sup> and VERITAS data is not well described by an exponential cut-off, but the data are well fitted by a broken power law of the form  $dN/dE = A \times (E/4 \text{ GeV})^{\alpha}/[1 + (E/4 \text{ GeV})^{(\alpha-\beta)}]$  where  $A = 1.45 \times 10^{-5} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ ,  $\alpha = 1.96$  and  $\beta = -3.52$ . The above fit has a  $\chi^2$  of 13.5 for 15 degrees of freedom, while an exponential cut-off predicted by curvature radiation has a value of 66.8 for 16 degrees of freedom. It is therefore unlikely that curvature radiation is the dominant production mechanism of the observed gamma ray emission above 100 GeV. Two possible interpretations are that either the entire gamma ray production is dominated by one emission mechanism different from curvature radiation or that a second mechanism becomes dominant above the spectral break energy.



#### 3 Pulsar Wind Nebulae and Supernova Remnants: CTA 1 and Tycho

CTA 1 is a composite supernova remnant (SNR), with a shell-type structure of diameter  $1.8^{\circ}$  in the radio band and a center-filled morphology in X-rays corresponding to a PWN<sup>13</sup>. A nearby Fermi-LAT pulsar was discovered in 2008 with a period of 316 ms and a spin-down luminosity of  $4.5 \times 10^{35}$  erg.s<sup>-1</sup>. The presence of both a bright PWN and a SNR shell interacting with the ambient interstellar medium makes CTA 1 a prime candidate for VHE gamma ray observations. VERITAS observed CTA 1 for 41 hours resulting in a  $6.5 \sigma$  post-trials excess discovery<sup>6</sup>. The spectrum is well described by a power law with an index of  $2.2\pm0.2_{\rm stat}\pm0.3_{\rm sys}$  and normalization at 1 TeV of  $9.1\pm1.3_{\rm stat}\pm1.7_{\rm sys}\times10^{-14}$  TeV<sup>-1</sup>cm<sup>-2</sup>s<sup>-1</sup>. Integrated above 1 TeV, the flux corresponds to ~ 4% of the steady TeV gamma ray emission from the Crab Nebula.

A comparison with the TeV and X-ray properties of other PWN supports the conclusion that the CTA 1 emission has the same origin and strongly suggests a PWN scenario for the TeV emission.

The remnant of Tycho's supernova is a young among Galactic SNRs (441 years). It shows a distinct shell-like morphology in radio <sup>8</sup> and strong nonthermal X-ray emission concentrated in the SNR rim. It has long been considered a good candidate for demonstrating hadronic acceleration. VERITAS observations <sup>4</sup> performed between 2008 and 2010 reveal one of the weakest sources yet detected in TeV gamma rays (0.9% of the Crab Nebula flux). The source spectrum is relatively hard, with a differential source spectral index of  $\Gamma = 1.95 \pm 0.51_{stat} \pm 0.30_{sys}$ . The VERITAS source name for this object is VER J0025+641.

The Fermi-LAT<sup>9</sup> reports the detection of Tycho from gamma ray energies of 100 GeV all the way down to 400 MeV. The broadband spectral energy distribution can be adequately fit by both leptonic and hadronic acceleration models. Clear identification of the  $\pi^{\circ}$ -decay cut-off below  $E = m_{\pi^{\circ}}/2$  in the photon spectrum (Figure 2) would support the hypothesis of an SNR origin of the Galactic cosmic rays.

# 4 Binaries: LS I +61°303

Gamma ray binaries constitute one of the least numerous class types of VHE sources. Their nonthermal emission is difficult to study at the highest energies due to their inherent periodicity, and the nature of the gamma ray emission is therefore still a matter of debate. Two models have been proposed: the pulsar wind model, in which accelarated particles from a pulsar interact with UV photons from the host star, and the microquasar model, in which jets are produced by matter accreting onto a compact object.

The high-mass X-ray binary LS I  $+61^{\circ}303$  consists of a massive star and a compact object of unknown nature (neutron star or black hole). Optical observations show that the compact object orbits the star every 26.5 days in a close orbit, characterized by a semimajor axis of only a few stellar radii <sup>10</sup>.

In the GeV band, Fermi-LAT observations of LS I +61°303 show that the gamma ray emission at energies about 30 MeV is modulated at the orbital period<sup>1</sup>. The spectrum showed an exponential cutoff at  $6.3 \pm 1.1_{stat} \pm 0.4_{sys}$  GeV and a photon index of  $\Gamma = 2.21 \pm 0.04_{stat} \pm 0.06_{sys}$ . In the VHE range, LS I +61°303 was detected in 2006-2007 by ground-based gamma ray observatories, with emission peaking around apastron<sup>3</sup>. Subsequent observations in 2008-2010<sup>5</sup> showed no evidence for emission during the previously detected phases; instead, the source was only detected (at a lower TeV flux) near the periastron passage of a single orbit.

VERITAS observations taken in 2011-2012 detected LS I  $+61^{\circ}303$  on a nightly timescale during orbital phases of 0.5-0.8, and did not show a significant correlation with the observed emission in the X-ray or MeV-GeV regime. The combination of the differential energy spectra obtained by both Fermi-LAT and VERITAS during the same period reveals a gap in emission in the 1-200 GeV range, see Figure 4. Since most models used to explain the emission from



SNR together with models for the various emission com- ergy distributions for LS I  $+61^{\circ}303$  during December ponents dominated by leptonic (dashed blue line) or 2011 - February 2012. The system exhibits a sharp hadronic processes (red and green lines, and blue dot cut-off around a few GeV, typical of known Fermi-LAT dashed line) in the gamma ray band. Hadronic models pulsars; however, despite many extensive searches, no fit the data just as well as the leptonic model. How- evidence for pulsed emission from this system has been ever they are quite different at low energies with the hadronic flux exhibiting a  $\pi^{\circ}$ -decay cut-off below few hundred MeV.

Figure 2: The spectral energy distribution of Tycho's Figure 3: The VERITAS and Fermi-LAT spectral endetected at radio, X-ray or GeV energies.

this source typically utilize a single population of particles to explain MeV-TeV emission, this emission gap provides strong constraints on the gamma ray radiation mechanisms.

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## TeV gamma rays from galactic supernova remnants

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Several supernova remnants have been detected in gamma rays, as expected in the hypothesis where they would be the sources of galactic cosmic rays. However, these detections do not constitute a conclusive proof that they are the source of galactic cosmic rays. Indeed, such gamma rays can be produced either by proton-proton interactions of hadronic cosmic rays in the ambient gas, or by inverse Compton scattering of electrons on soft photons. By means of a Monte Carlo we simulated the location and time of supernova explosions in the Galaxy. We computed the expected gamma-ray emission from each supernova remnant under the hypothesis that these objects are the sources of cosmic rays. We then estimated the number of remnants that one is expected to detect in the HESS survey of the galactic plane. A substantial agreement is found with data. This provides a consistency check for the supernova remnant paradigm for the origin of galactic cosmic rays.

Supernova remnants (SNRs) are believed to accelerate galactic Cosmic Rays (CRs) up to the knee (~4 PeV) and beyond via diffusive shock acceleration (see e.g. <sup>1</sup> for a review). Although this is a very popular idea, an unambiguous evidence to proof (or refute) this hypothesis is still missing. The detection of a number of SNRs in TeV gamma rays (see e.g. <sup>2</sup>) is encouraging, since gamma rays are expected to be produced in hadronic interactions between the accelerated CRs and the ambient gas swept us by the shock. However, it still does not constitute a conclusive proof since a competing leptonic process, namely, inverse Compton scattering of high energy electrons on soft photons may also explain these observations. For example, the gamma ray emission detected from the historical SNR Tycho has most likely an hadronic origin <sup>3,4</sup>, while the emission from the SNR RX J1713.7-3946 <sup>5,6</sup> is most likely leptonic. For most of the other SNRs detected in gamma rays the situation is less clear. The accumulation of data, and the detection of new SNRs will help to understand the relative importance of those two mechanisms.

During its extended survey of the galactic plane, the Cherenkov telescope HESS has detected a few sources that are now clearly considered to be SNRs (the list includes for example RXJ 1713, RXJ1731, RCW86, W41, and W49B). Other less firm identifications with SNRs have been proposed (see e.g. <sup>7</sup>). Moreover, since a large fraction of TeV sources is still unidentified, the number of gamma-ray SNRs might be, in principle, significantly larger.

Using Monte Carlo methods, it is possible to simulate the location and time of the supernova explosions in the Galaxy and to compute the expected gamma-ray emission from each remnant, under the assumption that SNRs indeed are the sources of CRs. This allows to predict the number of SNRs that one is expected to detect during the HESS extended survey of the galactic plane. Other quantities can be estimated from the simulation, like the average angular size of the detected SNRs, their typical age, and distance. By comparing these predictions with the data from the HESS scan of the galactic disc one can obtain a consistency check for the SNR paradigm for the origin of galactic CRs.

# 1 Method

We developed a Monte Carlo code to simulate the position and the time of the explosion of supernovae in the Galaxy. We follow the spatial distribution given by <sup>9</sup> and we assume that 3 supernovae explode each century in the Milky Way. Such a rate, combined with the measurement of the total CR power in the Galaxy<sup>10</sup>, provides us with an estimate of the average CR acceleration efficiency at SNR shocks. The time evolution of the SNR radius and shock velocity can be determined from the knowledge of the gas density at the simulated position of the explosion. The gas density distribution are taken from <sup>11,12</sup>.

In order to describe the acceleration of particles at SNRs, we rely on the approach developed in <sup>13</sup>. The spectrum of accelerated particles at the shock is assumed to be a pure power law  $f_0(p) \propto p^{-\alpha}$  (where  $\alpha$  is larger than 4, to be consistent with CR data) and the spatial distribution of CR protons inside the SNR is computed at any time by solving the CR transport equation (for details see<sup>13</sup>). The maximum energy for accelerated protons is determined by equating the particles' diffusion length with a fraction of the SNR radius <sup>13</sup>, assuming that particle diffusion proceeds in the Bohm regime. The magnetic fields downstream of the shock is parametrized following <sup>14</sup>, who assumed that a fraction ( $\approx 3.5\%$ ) of the dynamical pressure of the shock is converted into magnetic energy <sup>15</sup>. The spectrum of CR electrons is also computed, by assuming that at low ( $\sim 1 \text{ GeV}$ ) energies the ratio between electrons and protons is a free parameter  $K_{ep}$ . A break appears in the electron spectrum roughly at the energy at which synchrotron losses equates the age of the SNR, while the maximum energy for electrons is computed by equating the acceleration time with the synchrotron loss time.

Once the spectra and spatial distribution of CR protons and electrons are known, the gamma ray emission from the SNR can be estimated. The contributions from both proton–proton interactions  $^{16}$  and inverse Compton scattering of electrons  $^{17}$  are taken into account.

The expected gamma–ray emission from each SNR is then compared with the sensitivity of the H.E.S.S. telescope<sup>18</sup>. Here we focus our attention on the region of galactic longitude  $|l| < 40^{\circ}$  in galactic longitude and  $|b| < 3^{\circ}$ , in which the sensitivity of H.E.S.S. for point sources is quite homogeneous and always at the level of at least  $\approx 1.5\%$  of the Crab level<sup>19</sup>. The sensitivity for extended sources has been degraded by a factor of  $\vartheta_s/\vartheta_{PSF}$ , where  $\vartheta_s$  is the source apparent size and  $\vartheta_{PSF} \approx 0.1^{\circ}$  is the angular resolution of H.E.S.S.

We ran 1000 Monte Carlo realizations of the supernova explosions in the Galaxy and computed the number of sources above 1 TeV expected to be detected by H.E.S.S. within the region in exam.

# 2 Results and conclusions

Our results are shown in Fig. 1. In the top panel, the mean number of expected detection is plotted as a function of the spectral slope  $\alpha$  of accelerated CRs. The black and red lines refer to values of the electron-to-proton ratio of  $K_{ep} = 10^{-5}$  and  $K_{ep} = 10^{-2}$ , respectively. It can be seen from Fig. 1 that for steep particle spectra ( $\alpha$ =4.4) the expected number of

It can be seen from Fig. 1 that for steep particle spectra ( $\alpha$ =4.4) the expected number of detections is  $\approx 5$  and 7 for  $K_{ep} = 10^{-5}$  and  $10^{-2}$ , respectively. These numbers progressively increase if harder and harder spectra are considered, and for  $\alpha = 4.1$  we found, for two values of  $K_{ep} \approx 17$  and 22 detections. These numbers are comparable, or larger than the most optimistic estimate for the actual number of SNRs detected by H.E.S.S. in the region. This suggests that steep spectra are consistent with observations, while  $\alpha$  close to 4 (the standard prediction of test-particle first order Fermi acceleration) would imply an unreasonably high number of detections. This finding is in agreement with both gamma-ray observations of some individuals

All the other panels of Fig. 1 refer to the case  $K_{ep} = 10^{-2}$ , and show the median and maximum values of the following quantities (top to bottom): distance, age, and apparent angular size of the SNRs that should have been detected by H.E.S.S. in the region we are considering. Thick red lines show the median values for all those SNRs (dashed lines) and for spatially resolved



Figure 1: The top panel shows the expected number of SNRs detectable by H.E.S.S. in the region of coordinates  $|l| < 40^{\circ}$  and  $|b| < 3^{\circ}$  as a function of the spectral slope  $\alpha$  of accelerated particles. Black and red lines correspond to  $K_{ep} = 10^{-5}$  and  $10^{-2}$ , respectively. The other panels (top to bottom) show, for the case  $K_{ep} = 10^{-2}$  the distance, age, and angular size of the detected SNRs. Median values of these quantities are shown for all SNRs and for spatially resolved ones with a solid and dashed thick line, respectively. The thin dashed lines represent the maximum value for these quantities (averaged over the Monte Carlo realizations). In the bottom panel the fraction of point–like sources is also shown as a black dotted line.

ones (solid lines), i.e., with an angular size larger than  $\approx 0.1^{\circ}$ . The thin dashed lines show the maximum value for these quantities, averaged over the number of Monte Carlo realizations.

The median distance of detected SNRs lays, for all the values of the spectral slope  $\alpha$ , in the range 5 kpc < d < 10 kpc, which means that in the majority of the cases the detected SNRs are closer than the galactic centre. The median distance is slightly smaller ( $d \approx 5$  kpc) if only resolved sources are considered, as expected given the worse instrument sensitivity in detecting extended sources, and given that it is easier to resolve nearby sources. On the other hand, the maximum distance up to which SNRs are detected – a sort of horizon for the detection of SNRs is  $\approx 15$  kpc for hard particle spectra ( $\alpha \approx 4$ ) and decreases gradually for steeper and steeper spectra reaching a value of  $\approx 10$  kpc for  $\alpha = 4.4$ .

The predicted median age of the SNRs detectable by H.E.S.S. is quite insensitive to the value of  $\alpha$ , and is of the order of  $\leq 5$  kyr. This slightly increase to  $\geq 5$  kyr if only resolved SNRs are considered. This is expected, given that older SNRs are obviously larger than younger ones. Also in this case, the maximum age of the detected SNRs is predicted to decrease from  $\approx 20$  kyr to  $\approx 12$  kyr when the spectral slope of accelerated CRs goes from  $\alpha = 4.1$  to 4.4.

Finally, the predicted fraction of point–like SNRs is in the range  $\approx 0.4...0.6$ , as indicated by the black dotted line in the bottom panel of Fig. 1. Amongst extended sources, the expected median angular size is  $\approx 0.2^{\circ}$ , while the largest detectable sources have a size of  $\approx 1...1.2^{\circ}$ . All these quantities are quite insensitive to the value chosen for  $\alpha$ .

Though a rigorous comparison between our predictions and available data is not easy, a qualitative agreement between data and predictions exists. Our expectations for the selected region of the H.E.S.S. scan seem to reproduce correctly the actual number of detections and the typical distances, ages, and apparent sizes of the gamma-ray bright SNRs (RXJ 1713.7-3946, J1731-347, CTB 37B).

All these facts are encouraging and provide additional support to the consistency of the SNR paradigm for the origin of CRs. A summary of this study and discussions for other scenarios can be found in a paper  $^{20}$ .

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## THE DISCOVERY OF A POPULATION OF $\gamma$ -RAY NOVAE

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Novae have long been expected to be sources of emission at several MeV from the decay of radioactive elements in the novae ejecta, however, they were not anticipated to be sources of continuum emission in the GeV energy domain. In March 2010 the Large Area Telescope (LAT) on-board the *Fermi Gamma-ray Space Telescope* discovered for the first time >100 MeV gamma-ray emission from a nova within our galaxy, V407 Cyg. The high-energy spectrum and light curve was explained as a consequence of shock acceleration in the nova shell as it interacts with the local ambient medium. While this was an exciting and important discovery it was suspected that the necessary conditions for high-energy emission from novae would be rare. In June 2012 the LAT detected two new transient sources that have been associated with classical novae observed in the optical, Nova Sco 2012 and Nova Mon 2012. We report on the observational properties of the population of gamma-ray novae, their similarities and differences and the emission processes that generate the high energy radiation in these systems.

## 1 Introduction

Novae have been observed by astronomers for thousands of years although it is only in more modern times that the processes behind these cosmic eruptions has become clear. Classical novae (CNe) are a subset of cataclysmic variables, binary systems that host a white dwarf (WD) that accretes material from the secondary star. In the vast majority of these systems the orbital period ranges between  $\sim 1.4-8$  hours and the secondary star is a low mass, main sequence star; there are a few longer period systems in which for the secondary star to fill its Roche Lobe it has to have evolved off the main sequence<sup>1</sup>.

The WD accretes material off the secondary star building up H-rich material on its surface. Once sufficient material has accumulated for the critical pressure/temperature to be achieved at the base of the accreted envelope then a thermonuclear runaway explosion is triggered producing a CN event. The outburst increases the luminosity to  $L\sim 10^4 L_{\odot}$  and large amounts of mass are ejected at high velocities<sup>1</sup>, typically  $M_{ejecta} \sim 10^{-5} - 10^{-4} M_{\odot}$  and  $v_{ejecta} \sim 10^2 - 10^3 \text{ km s}^{-1}$ . The inter-outburst period of CN explosions is believed to be  $\sim 10^3 - 10^4$  years.

Conversely, recurrent novae (RNe) have inter burst timescales of the order of decades. Only ten such systems have been identified within our Galaxy and are broken into three subclasses: RS Oph/T Crb systems with long orbital periods (~100s days) and red giant donors with heavy winds; U Sco systems are characterised by containing a more evolved main sequence or sub-giant secondary with orbital periods of order a day and extremely high ejection velocities; T Pyx are



Figure 1: Fermi-LAT 1-day binned (> 100 MeV) light curves of the three detected  $\gamma$ -ray novae. The start dates indicate the i $\gamma$ -ray onset and are from top to bottom, 2012 June 9, 2012 June 15, and 2010 March 10. Detections with  $\geq 3\sigma$  significances are the points with flux error bars shown in black, while data with 2-3 $\sigma$  significances are shown in gray; upper limits are shown for points with  $< 2\sigma$  significances.

short orbital period systems that show slower optical decays than the other RNe.

MeV  $\gamma$ -ray line emission has long been predicted from novae as a consequence of the decay of radioactive elements produced in the nova explosion<sup>2</sup>, however, prior to the discovery of GeV emission from V407 Cyg by the *Fermi* Large Area Telescope (LAT) in 2010<sup>3</sup> there had been no predictions of continuum emission at such high energies.

### 2 V407 Cyg: The first $\gamma$ -ray nova

On 11 March 2010 Japanese amateur astronomers reported the discovery of a new  $8^{th}$  magnitude nova in the Cygnus constellation<sup>4</sup>. The nova was identified as originating from the known symbiotic binary, V407 Cyg. This systems comprises of a hot WD accreting from a Mira-type variable red giant and consequently the WD is embedded in a particularly dusty environment generated by the heavy wind of the donor star.

The discovery of a classical nova event in this system was completely unexpected compounded by the unexpected discovery of  $\gamma$ -ray emission above 100 MeV from the nova by the LAT<sup>5,3</sup>. The  $\gamma$ -rays were detectable for approximately two weeks after the optical nova onset with an average spectral energy distribution in the form of a power law with an exponential cutoff and flux above 100 MeV of  $4.4 \times 10^{-7}$  ph cm<sup>-2</sup> s<sup>-1</sup>. The onset of  $\gamma$ -ray emission was consistent with the optical onset. The  $\gamma$ -ray light curve of the 2010 V407 Cyg eruption is shown

Table 1: A comparison of some of the properties of V407 Cyg, Nova Sco 2012 and Nova Mon 2012.			
System	V407 $\overline{\text{Cyg}^3}$	Nova Sco 2012 <sup>11,12</sup>	Nova Mon 2012 <sup>15,17</sup>
Optical companion	Mira-type red giant	?	K Dwarf?
Distance	$2.7 \ \mathrm{kpc}$	$\sim$ 4–5 kpc	$3.6  \mathrm{kpc}$
Nova spectral class	He/N	Fe-II	Neon nova: ONe WD
Speed class	Very fast	Fast/moderately fast	Fast?
	$t_2 \sim 5.9 \text{ days}$	$t_2 \sim 25 \text{ days}$	?
$\gamma$ -ray spectrum	Cutoff power law	Power law	Power law
$\gamma$ -ray duration	$\sim 16 \text{ days}$	$\sim 12 \text{ days}$	$\sim \!\! 12 \text{ days}$
Optical/ $\gamma$ -ray delay	<3 days	$\sim 14 \text{ days}$	?
Peak $\gamma$ -ray flux	$\sim 1.4$	$\sim 1.3$	$\sim 1.4$
$\times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$			

in the lower panel of Figure 1.

The  $\gamma$ -ray emission was explained by the nova ejecta shell expanding outwards and colliding with the stellar wind of the red giant companion and forming a shock front where particles could be accelerated to high energies. The line connecting the WD with the donor star contains the largest local density enhancement attributable to the red giant wind in which the nova shell can sweep up material in a fashion similar to what is ascribed in supernova explosion models. Taking the estimated parameters of the system (wind density, ejecta velocity, etc...) and the measured spectral energy distribution, it was shown that this model could feasibly produce  $\gamma$ -ray emission through the decay of neutral pions produced in proton collisions or inverse Compton (IC) scattering off accelerated electrons<sup>3</sup>. More detailed modelling of the environment has suggested that leptonic processes may be dominant<sup>6</sup>. The direct link between the dense local wind environment and the  $\gamma$ -ray production mechanism and the rarity of symbiotic and RS Oph type RNe systems led to the suggestion that ' $\gamma$ -ray' novae would be exceptionally rare events<sup>7</sup>.

#### A new Galactic transient: Fermi J1750-3243 3

From 16–30 June 2012 Fermi identified a new  $\gamma$ -ray source, Fermi J1750–3243, that was not consistent with any of the known 2FGL catalog sources<sup>8</sup>. This new source was localised to RA = 267.727°, Dec =  $-32.720^{\circ}$  with a 95% error radius of  $0.122^{\circ 9}$ . The location of the new LAT transient was consistent with the report of a newly discovered optical nova, MOA 2012 BLG-320 (Nova Sco 2012) which had entered into optical outburst between June 1.77-2.15 2012 when it brightened dramatically in the I band from  $17^{th}$  magnitude to  $11^{th}$  magnitude <sup>10</sup>. Subsequent IR spectral observations on June 17.879 indicated that it was an Fe-II nova event with an ejecta velocity of ~2,200 km s<sup>-1</sup> <sup>11</sup>. It appeared that *Fermi* had discovered another ' $\gamma$ -ray nova'. However this system appeared to more like traditional CNe systems with no indication of a dense stellar environment and it's behaviour at other wavelengths was quite different to that observed in V407 Cyg<sup>12</sup>.

#### Nova Mon 2012: A nova first discovered in $\gamma$ -rays 4

On 22 June 2012 another new unidentified  $\gamma$ -ray source was detected by the LAT, Fermi  $J0639+058^{13}$ ; proximity to the Sun prohibited follow-up observations at other wavelengths. In August 2012 a late-stage optical nova, Nova Mon 2012, was discovered within the LAT error circle<sup>14</sup>. The first optical spectra were taken approximately 55 days after the  $\gamma$ -ray peak and identified the WD as being a member of the ONe class<sup>15</sup> i.e. the more massive class of WDs. This system has also been associated with the more common CNe systems and has been identified as having a tight binary orbital period of  $\sim 7.1$  hours<sup>16</sup>.

# 5 Summary

The *Fermi*-LAT light curves of all three novae are shown in Figure 1 and can be seen to be remarkably similar. However, as demonstrated by the summary of some their more general multi-wavelength characteristics in Table 1 there are also a number of distinct differences. Most notable is that the two 2012 novae appear to be CNe in the traditional sense and so the  $\gamma$ -ray production mechanism invoked to explain the cmission in V407 Cyg cannot be applied suggesting that there is another mechanism in action in these systems. This raises the potential for many other CNe and RNe to be  $\gamma$ -ray bright, although it is equally evident that numerous other optically detected CNe have not been reported by that LAT. Only with further study and analysis will we be able to identify the  $\gamma$ -ray production channels and determine what fraction of the Galactic novae population are capable of producing emission at these high energies.

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# Survey of the Milky Way in hard X-rays

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Results of the study of persistent high mass X-ray binaries (HMXBs) in the Milky Way, obtained from the deep INTEGRAL Galactic plane survey, are presented. We show that the spatial density distribution of HMXBs correlates well with the star formation rate distribution in the Galaxy. The vertical distribution of HMXBs has a scale-height  $h \simeq 90$  pc, that is somewhat larger than the distribution of young stars in the Galaxy. The luminosity function of wind-fed persistent HMXBs with accreting neutron stars can be described by a broken power law. Using this luminosity function estimations of number of X-ray HMXBs in future surveys with the better sensitivity are obtained.

#### Introduction 1

The study of populations of sources is the only way to understand processes of a formation and evolution of stars and binary systems due to their low rates (typical timescales of  $> 10^6$ yr). Properties of an ensemble of sources at different stages of their evolution do have characteristics which can be measured and compared with predictions of different models. In spite of the observational progress connected with advances in the sensitivity and angular resolution of current X-ray telescopes, only the study of populations of different binary systems in our Galaxy can give answers to the questions about their formation and evolution. But to conduct such studies one need to construct an unbiased sample of X-ray binaries in the Galaxy, that was practically impossible earlier. A systematic survey of the Galaxy in 2003-2011 with the INTEGRAL observatory  $^{1}$  in the hard X-ray energy range (> 17 keV) allowed us for the first time to perform virtually unbiased by influence of the interstellar photo-absorption and narrow field of view search for X-ray binaries in the Milky Way with an unprecedented sensitivity (up to 0.3 mCrab in the 17-60 keV energy band<sup>2</sup>.

Results of our study of persistent high mass X-ray binaries in our Galaxy are presented briefly below (all details as well as description of the model for describing general properties of HMXBs and flaring activity of supergiant fast X-ra transients, SFXT, can be found in our recent paper<sup>3</sup>). We use the most sensitive at the moment flux-limited sample of non-transient high mass X-ray binaries in our Galaxy to establish and understand general properties of this population. The sensitivity of our survey is typically  $10^{-11}$  erg s<sup>-1</sup> cm<sup>-2</sup> in the 17-60 keV energy band, which ensures the detection of sources with luminosities  $> 10^{35}$  erg s<sup>-1</sup> within a half of the Galaxy (< 9 kpc from the Sun) and >  $5 \times 10^{35}$  erg s<sup>-1</sup> over the whole Galaxy (< 20 kpc from the Sun).

Table 1: Best fit parameters of the luminosity function of HMXBs and their spatial density distribution

Parameter	Value and $1\sigma$ error
$\alpha_1$	$1.40 \pm 0.13 (\text{stat.}) \pm 0.06 (\text{syst.})$
$\alpha_2$	> 2.2
$L_{\star}, 10^{36}  {\rm erg  s^{-1}}$	$2.5^{+2.7}_{-1.3}$ (stat.) $\pm 1.0$ (syst.)
$R_{g}$ , kpc	$N(L>10^{35}~{ m erg~s^{-1}})~{ m kpc^{-2}}$
0-2	$0.0 \pm 0.05 (\text{syst.})$
2-5	$0.11^{+0.05}_{-0.04}$ (stat.) $\pm 0.02$ (syst.)
5-8	$0.13^{+0.04}_{-0.03}(\mathrm{stat.}) {\pm} 0.01(\mathrm{syst.})$
8-11	$(3.8^{+2.1}_{-1.2}) \times 10^{-2}$ (stat.) $\pm 6.5 \times 10^{-3}$ (syst.)
11-14	$(6.2^{+7.2}_{-4.3}) \times 10^{-3}$ (stat.) $\pm 4.8 \times 10^{-3}$ (syst.)

### 2 Sample

During the INTEGRAL Galactic plane survey 75 HMXBs with a confirmed nature and 33 sources of an unknown one were detected at latitudes  $|b| < 5^{\circ}$ . To construct a flux limited sample we applied several criteria: exclude transient sources; raise the flux limit of the survey up to 0.7 mCrab in the inner part of the Galaxy and 1.5 mCrab in the outer one; exclude from the sample sources with a peculiar nature (HMXBs harboring black holes and  $\gamma$ -loud binaries). As a result a final flux limited sample contains 37 persistent HMXBs with neutron stars accreting from the stellar wind. This sample was used in the sequel to study general properties of the HMXBs population.

# 3 Luminosity function and spatial distribution of wind-fed HMXBs

To construct the luminosity function using our sample we have limited ourself by an axially symmetric distribution of HMXBs in the Galaxy<sup>3</sup>. We have divided the Galaxy into annuli with radii  $R_{\rm g} < 2$  kpc, 2-5 kpc, 5-8 kpc, 8-11 kpc, 11-14 kpc from the center (the distance from the Sun to the Galactic center is expected to be 8.5 kpc).

We assume that:

- the surface density of HMXBs  $(src/kpc^{-2})$  is constant within each annulus;
- shape of the luminosity function and its parameters are the same for all annuli.

A minimization of the Cash-statistics<sup>4</sup> gives us best fit parameters of the luminosity function and its normalization in each annulus. We have adopted a simple broken power law shape of the luminosity function with slopes  $\alpha_1$  and  $\alpha_2$  below and above the break at the luminosity  $L_*$ :

$$\frac{dN}{dL} = \begin{cases} A_j (L/L_*)^{-\alpha_1} & \text{if } L < L_* \\ A_j (L/L_*)^{-\alpha_2} & \text{if } L > L_* \end{cases}$$
(1)

where  $A_j$  – normalization of the luminosity function in each annulus j. Best fit parameters of this model with uncertainties are presented in Table 1 and Fig.1 (see<sup>3</sup> for details).

The obtained luminosity function of wind-fed HMXBs demonstrates a break, or at least a curvature (see Fig.2, left panel). From a purely statistical point of view the statistical significance of the break is about  $2\sigma$ , that can be interpreted as a possible indication of its presence. But it should be noted additionally, that evidences for some flattening of the HMXBs luminosity function was mentioned earlier<sup>5,6</sup>. Thus it is likely that its gradual flattening is real.

A comparison of the obtained HMXBs surface densities with the star formation surface densities taken from papers <sup>7,8,9</sup> shows their very good correlation:  $N(HMXB, L_x > 10^{35} \text{erg s}^{-1})/$ 



Figure 1: (*left panel*) Surface density of HMXBs in the Galaxy (the darker color of the annulus corresponds to the higher surface density of HMXBs). Black dotted and dashed curves show areas of the Galaxy, within which the INTEGRAL Galactic survey detects all sources with luminosities >  $10^{35.5}$  erg s<sup>-1</sup> and >  $10^{35}$  erg s<sup>-1</sup>, respectively. Blue points indicate positions of HMXBs from our sample. All distances are in kpc. (*right panel*) HMXBs surface density (histogram, right axis) and star formation rate surface density (left axis) dependencies on the galactocentric distance. Star formation rates are presented by their upper and lower bounds (solid curves).

 $\rm kpc^2\approx 5.5\times 10^{-2}~SFR/SFR_{\odot}$  (see Fig.1, right panel), here  $SFR_{\odot}$  is the surface density of the star formation rate near the Sun.

We have fitted also a vertical distribution of HMXBs and found that its scale-height is about  $\simeq 90$  pc both with using a simple exponential model of HMXBs volume density and a model of a self-gravitating isothermal disk. This value is somewhat smaller than that presented in earlier papers <sup>10</sup>, likely due to the higher completeness and uniformity of our sample.

It is important to note that the scale-height of the HMXBs distribution is larger than the one of the distribution of massive stars in the Galaxy, like OB associations, WR stars, open clusters. If we will assume that HMXBs receive their systemic velocity during supernova explosions, we can roughly estimate the kinematic age of HMXBs after the supernova explosion. Adopting the value  $\sim 50-90 \text{ km } s^{-1}$  of the systemic velocity as a typical value for HMXBs<sup>11</sup> we can obtain their kinematic age,  $\tau \simeq 50 \text{ pc}/(50-90) \text{ km } s^{-1} \simeq 0.5-1 \text{ Myr}.$ 

## 4 Future surveys

A general understanding of the luminosity function of HMXBs and their Galaxy-wide distribution provides us a possibility to make predictions of a number of persistent sources at fainter fluxes.

The expected number of HMXBs in flux limited surveys of the Galactic plane is shown in Fig.2 (right panel) in line with ones for active galactic nuclei (AGNs) and CVs. A number-flux function of AGNs was taken from <sup>12</sup>, a number-flux function of cataclysmic variables was calculated using the parametrization from <sup>13</sup>. It is clear that the number of CVs and AGNs begin to dominate over HMXBs at fluxes below  $\sim 10^{-12}$  erg s<sup>-1</sup> cm<sup>-2</sup>, which will be achieved with the new generation of hard X-ray telescopes like NuSTAR <sup>14</sup> and Astro-H <sup>15</sup>. Small fields of view of these instruments will limit the detection rate of HMXBs. In order to increase the number of known persistent HMXBs in the Galaxy (mainly due to low luminosity sources) one need to use large survey missions like Spectrum-RG <sup>16</sup>.



Figure 2: (*left panel*) Luminosity function of the wind fed accreting HMXBs in the Galaxy. Dashed red curve shows the best fit model with parameters from Table 1. (*right panel*) Surface density of HMXBs in the direction to the Norma and Scutum regions in the Galactic plane (gray areas). Lines show predictions of numbers of different types of sources in these areas: AGNs (dashed line), CVs (dotted line) and HMXBs (solid lines). Predictions of a number of HMXBs at faint fluxes were done using two types of their luminosity function with different slopes.

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# Fundamental Physics with Imaging Atmospheric Cherenkov Telescopes

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Ground-based gamma-ray astronomy experienced a major boost with the advent of the present generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) in the past decade. Photons of energies  $\gtrsim 0.1$  TeV are a very useful tool in the study of several fundamental physics topics, which have become an important part of the research program of all major IACTs. A review of some recent results in the field is presented.

# 1 Introduction

Imaging Atmospheric Cherenkov Telescopes (IACTs) are currently the most sensitive instruments for the observation of the Universe in the Very High Energy band of the electromagnetic spectrum (VHE,  $E_{\gamma} \sim 0.1$  - 100 TeV). There are now three major IACT arrays in operation: H.E.S.S. in Namibia, MAGIC in the Canary island of La Palma, and VERITAS in Arizona (see<sup>1</sup> for a recent review of the field). Typical performance parameters of the current generation of IACTs are an energy threshold between  $\simeq 20$  and 100 GeV, an angular resolution O(0.1°), an energy resolution of  $\simeq 15\%$  (both of them energy-dependent), and an integral flux sensitivity for point-like sources of about 1% of the Crab Nebula flux (or  $\simeq 1.2 \times 10^{-12} \ cm^{-2} s^{-1}$  above 300 GeV) in 25 hours of observation. The projected *Cherenkov Telescope Array* (CTA<sup>2</sup>) is expected to provide, by the end of this decade, an order of magnitude improvement in sensitivity over existing facilities.

Several topics related to fundamental physics can be addressed with IACTs; here we review the results obtained in the past few years in three of these areas: tests of the invariance of the speed of light, the search for gamma rays from dark matter annihilation, and the search for signatures of the existence of axion-like particles. The fundamental physics prospects for CTA are presented elsewhere in these proceedings<sup>3</sup>.

# 2 Testing the invariance of the speed of light

Some quantum gravity (QG) theories predict violation of Lorentz invariance (LIV) which, among other consequences, could result in an energy dependence of the speed of light<sup>4</sup>. This effect would be suppressed by some large QG energy scale, of the order of the Planck mass  $m_P$  (or below, in some models), so that the speed of light as a function of energy would behave as  $v(E) = c (1 \pm E/M_{QG1} \pm (E/M_{QG2})^2 \pm ...)$ . The observations with IACTs of rapidly varying VHE emission from active galactic nuclei (with flux-doubling timescales down to few minutes) in a wide -O(TeV)- energy range, have not produced to date any convincing evidence <sup>a</sup> of

<sup>&</sup>lt;sup>a</sup>MAGIC reported<sup> $\delta$ </sup> a small hint of energy-dependent time shift in the light curve of Mrk 501; it has to be noted that such delays, if confirmed, may also have less exotic explanations.

this phenomenon<sup>6,7</sup>, but have been used to set constraints on the values of  $M_{QG1}$  and  $M_{QG2}$ , for the cases of dominating linear and quadratic term respectively. The best current limits, from H.E.S.S. observations of the blazar PKS 2155-304, are  $M_{QG1} > 0.172~m_P$  and  $M_{QG2} >$  $5.2 \times 10^{-9} m_P$ . The latter, though far from the Planck scale, is the most constraining limit on the quadratic term obtained by any technique, thanks to the long *lever arm* in energy provided by IACTs. For the linear term, the Fermi-LAT limits from the observation of Gamma-Ray Bursts  $(GRBs)^{8,9}$  are the most constraining ones  $(M_{QG1} > 1.2 m_P)$ . Since the relevant observable is the accumulated photon delay upon arrival on Earth, very distant sources are the best candidates for LIV tests; unfortunately, the *horizon* for IACTs is limited by the non-perfect transparency of the Universe to VHE radiation (see  $\S4.1$ ). This, together with the limited field of view (FoV) of IACTs, makes the detection of GRBs in the VHE range a challenging task - yet to be accomplished. A promising alternative<sup>10</sup> for LIV searches is the observation of pulsars, after the detection by VERITAS<sup>11</sup> and MAGIC<sup>12</sup> of a power-law tail in the VHE emission of the Crab pulsar. The smaller distance would be compensated by the fast variability ( $\sim$ ms), which allows a more precise measurement of possible delays, and by the possibility of accumulating long observation times (limited in all other cases by the duration of the flaring states).

### 3 Indirect dark matter searches

Weakly Interacting Massive Particles (WIMPs), with masses in the GeV - TeV range are promising dark matter (DM) candidates, on the grounds of the so-called WIMP miracle<sup>13</sup>, i.e. the fact that, for a weak-scale annihilation cross-section, their present relic abundance could roughly account for the DM density inferred from cosmological observations. WIMPs are part of various extensions of the standard model (SM) of particle physics (e.g. supersymmetric models), and, upon annihilating into SM particles, are expected to produce gamma-rays mostly via  $\pi^0$ -decay and final state radiation. The resulting gamma-ray continuum spectrum would extend up to the DM particle mass, and hence can reach the IACT energy band for  $m_{DM}$  in the order of hundreds of GeV or above. In this type of search, a drawback of IACTs with respect to the lower-energy, space-borne telescopes, is their limited FoV, which enforces the a-priori selection of few DM targets, and limits (through competition for observation time with other programs) the exposure that can be accumulated on them. In the case of annihilating DM, the most relevant parameter of a candidate source is the volume integral, along the line of sight, of the squared DM density over distance squared, often called *astrophysical factor*, which enters linearly in the computation of the expected gamma-ray flux. Other desirable features are an angular extension well below the telescope FoV, to facilitate evaluation of the background due to cosmic-ray initiated air showers, and the lack of nearby conventional astrophysical gamma-ray sources.

## 3.1 Limits from dwarf spheroidal galaxies

The above wish list has made of dwarf spheroidal galaxies orbiting our own galaxy the most popular targets for indirect DM searches with IACTs. All three major IACT arrays have conducted observational campaigns on several of these objects, and no significant excess of gamma rays has been observed from any of them (for the most recent results, see refs.<sup>14,15,16</sup>). Flux upper limits can be transformed into an upper limit in the velocity-averaged DM annihilation cross section,  $\langle \sigma_{ann} v \rangle$ , for a given energy-dependent gamma-ray yield per annihilation  $dN_{\gamma}/dE(E)$ . The latter is the result, in a specific particle physics model (e.g. a given realization of supersymmetry), of the sum of all possible annihilation channels. Alternatively, one can assume 100% annihilation into a single channel, e.g.  $xx \rightarrow b\bar{b}$ , and hence obtain upper limits on  $\langle \sigma_{ann} v \rangle$  for that specific channel. Even for the channels with highest gamma-ray yield in the VHE range, the current IACT limits from dwarf spheroidal observations are two to three orders of magnitude above the expected  $\langle \sigma_{ann} v \rangle \lesssim 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$  for thermally produced DM (see left panel of fig. 1). It must be noted that the estimated astrophysical factors, that are needed to translate observa-



Figure 1: Left pad: compilation by Conrad <sup>22</sup> of various limits on  $\langle \sigma_{ann} v \rangle$  by IACTs compared to the stacked analysis of 24 months of Fermi-LAT observations of 10 dwarf spheroidal galaxies <sup>19</sup>. Pure  $b\bar{b}$  or  $b\bar{b}$ -dominated annihilation channel is assumed. The squares show models of phenomenological Minimal Supersymmetry, red ones being those assuming thermal DM production and with relic density consistent with WMAP measurements<sup>20</sup>. Right pad: Milky Way DM profiles used in the H.E.S.S. search for an annihilation signal from the galactic halo<sup>21</sup>, and definition of the signal and background regions.

tions into DM constraints, have quite large statistical and systematic uncertainties, which on one hand undermines the robustness of the limits, but on the other may be used to argue for the continuation of the observations, in the hope that detection might be closer than expected. The same can be said of possible *boosts* of the gamma-ray flux induced by particle physics effects, like additional contributions from internal *bremsstrahlung*<sup>17</sup> or the *Sommerfeld enhancement*<sup>18</sup> of the cross section, in models where DM particles have long-range interactions besides gravity.

# 3.2 Limits from observations of the galactic halo

Flux-wise, the center of our own galaxy should be, for observers on Earth, the brightest source of gamma rays from DM annihilation. However, the presence of astrophysical gamma-ray backgrounds (diffuse emission from cosmic ray interactions and a strong source coincident with the position of the central black hole Sgr  $A^*$ ) makes this a challenging region in the search for DM annihilation. The situation improves as one gets away from the galactic center, but then IACTs face the problems associated to the determination of the background in the search for a faint diffuse gamma-ray excess which spans (and hardly varies across) the whole FoV of the telescopes. Instead of trying to set a limit on the absolute DM annihilation flux in this central part of the galactic halo, the H.E.S.S. collaboration <sup>21</sup> looked for systematic differences between the diffuse background rates (after masking all known astrophysical sources) in two different ranges of galactocentric distance (see fig. 1, right), with a careful selection of the signal and background regions to ensure that they were completely equivalent in terms of instrumental gamma-ray acceptance. In 112 hours of live time, no significant excess was found in the signal region. Under the assumption that the galactic DM halo follows a Navarro-Frenk-White or an Einasto profile, the resulting limits (fig. 1, right) on  $\langle \sigma_{ann} v \rangle$  are the best obtained by IACTs to date, and are just one order of magnitude away from constraining the relevant part of the WIMP parameter space. Note however that the 2-year Fermi-LAT observations of dwarf spheroidals<sup>19</sup> provide the best constraints up to DM masses as high as 1 TeV (thanks to its large FoV and duty cycle, Fermi-LAT achieves much higher exposure than IACTs; besides, most of the annihilation photons would be emitted at energies well below the DM particle mass, within Fermi-LAT's range). The H.E.S.S. galactic halo observations were also used recently  $^{23}$  to set limits on DM annihilation lines or other narrow spectral features in the energy range 0.5 - 25 TeV.

Clusters of galaxies have also been targeted by IACTs<sup>24,25,26</sup>, but currently provide weaker DM constraints than either dwarf spheroidals or the galactic halo, with the additional complication of potential gamma-ray *contamination* from active galaxies in the cluster and from

### 4 Search for axion-like particles

Axion-Like Particles (ALPs) are hypothetical spin-0 bosons with a 2-photon interaction vertex. They are a generalization of the axion which would result from the spontaneous breaking of the Peccei-Quinn symmetry postulated to solve the strong CP problem<sup>27</sup>. ALPs can convert into photons and vice-versa in the presence of an electric or magnetic field (Primakoff effect), a process which could enable the direct detection of ALPs in experiments like CAST <sup>28</sup> and ADMX <sup>29</sup>. The existence of ALPs could also affect the propagation of photons over cosmological distances. They were once invoked as an alternative explanation for the dimming of type Ia supernovae without resorting to cosmological acceleration<sup>30</sup>, as well as to account for the observation, by the AGASA experiment, of an excess of cosmic rays of energies above the GZK cutoff<sup>31</sup>. In the latter case, super-GZK events were assumed to be ultra-high energy photons which convert to ALPs through interaction with intergalactic magnetic fields, thus evade suppression via e<sup>+</sup>e<sup>-</sup> pair-production against the extragalactic radio background, and finally convert back to photons in the vicinity of the Earth. However appealing, this solution was rendered unnecessary when newer data from HiRes<sup>32</sup> and the Pierre Auger Observatory<sup>33</sup> showed the presence of the expected GZK suppression in the cosmic ray spectrum. But the idea that ALPs could play an important role in photon propagation in the Universe would soon revive in the context of VHE astronomy.

# 4.1 VHE gamma-ray propagation

Propagation of VHE photons over intergalactic distances is hindered by the presence of the so-called Extragalactic Background Light (EBL), an ubiquitous radiation in the UV to IR wavelength range, which results from the thermal emission by stars and dust in galaxies throughout the history of the Universe. For center-of-momentum energies above 2  $m_{e}$ , VHE and EBL photons can interact to produce  $e^+e^-$  pairs, a process which induces an energy-dependent depletion of the VHE gamma-ray flux from distant sources. The flux suppression increases with the gamma-ray energy, and sets a limit to the size of the Universe observable in the VHE range, often referred to as the "gamma-ray horizon".

Direct measurements of the EBL are challenging due to the strong foreground emission, mainly from zodiacal light. Robust lower limits have been derived by integrating the contribution of resolved galaxies in deep-field optical and infrared observations<sup>34,35</sup>. Upper limits to the EBL density were derived from IACT observations (see e.g.<sup>36</sup>), under the assumption that the intrinsic VHE spectra of BL Lac sources and other blazars should have shapes allowed by the gamma-ray emission models, e.g. should not be much harder than  $dF/dE \propto E^{-1.5}$ , and should become softer as energy increases. There were also claims<sup>40,41,42</sup> that some VHE spectra were violating these constraints (or at least *in tension* with them), even when the lowest possible EBL density was assumed in order to derive the intrinsic spectra from the observations. Axion-Like Particles were then proposed as a possible explanation of these anomalies (see §4.2).

The first actual indirect measurements (not upper limits) of the EBL density using gammaray observations were published independently by the Fermi-LAT <sup>37</sup> and H.E.S.S.<sup>38</sup> collaborations in 2012. In both cases, a number of gamma-ray spectra were combined, using certain assumptions on the intrinsic spectral shapes, to build a single likelihood which was maximized to obtain the most likely scaling factor for the optical depth  $\tau(E, z)$ , whose energy- and redshift dependence was taken from the Franceschini '08 EBL model <sup>39</sup> - FR08 in the following. These works concluded that, within uncertainties, the EBL density at UV - near IR frequencies was compatible with that of FR08 and other similar models, and less than  $\simeq 50\%$  above the lower limits from galaxy counts.

## 4.2 Propagation anomalies and ALPs

There have been several works  ${}^{40,41,42}$  claiming that VHE observations of some sources indicate that the Universe is more transparent to gamma-rays than expected from "low EBL" models like FR08 and others, in a sort of revival of the TeV-IR crisis<sup>43</sup> triggered by the 1997 observations of Markarian 501 by the HEGRA array of Cherenkov telescopes 44,45. The most recent of these claims, by Meyer et  $al^{46,47}$ , makes use of a sample of 50 VHE gamma-ray AGN spectra from the current and previous generation of IACTs, and studies how the spectral points in the opticallythick regime (i.e. those affected by significant absorption in the EBL) deviate from the fluxes expected under some reasonable assumptions on the EBL density and on the intrinsic spectral shape of the gamma-ray emission. The authors find that, using the best-fit EBL density from H.E.S.S. <sup>38</sup> ( $\tau \simeq 1.3 \times \tau_{FR08}$ ), the spectral points at  $\tau > 2$  are in average above the expectation, i.e. they show a smaller flux suppression than anticipated (see fig. 2). This excess seems to be correlated with the optical depth  $\tau(E, z)$ , and not with the energy of the spectral points, hence suggesting the anomaly is related to propagation, rather than being related to the intrinsic source spectra. The statistical significance of the anomaly is 3.5 standard deviations <sup>47</sup>. They term this effect "pair production anomaly", and speculate that it might be due to conversion of gamma rays into (EBL-immune) axion-like particles and vice versa in the magnetic fields traversed by the radiation.



Figure 2: Relative residuals of measured VHE fluxes with respect to the expectations for reasonable intrinsic spectra and for the EBL density favoured by H.E.S.S. observations (taken from <sup>47</sup>). The horizontal axis indicates the optical depth for  $\gamma\gamma \rightarrow e^+e^-$ . Spectral points in the  $\tau > 2$  regime lie in average above the expectations.

Under that assumption, they present in a separate paper <sup>48</sup> lower limits to the photon -ALP coupling constant  $g_{a\gamma}$  as a function of the ALP mass. Since the conversion of photons into ALPs depends on the magnetic fields in the space between the source and the observer, several different scenarios were considered for the source, its environment and the intergalactic magnetic field. Conversions in the galactic magnetic field were also included in the framework. For each of the B-field scenarios and scanned ALP masses, the minimum value of  $g_{a\gamma}$  to reproduce the observed anomaly was computed (fig. 3). Although this is presented as a lower limit to  $g_{a\gamma}$ , this is certainly not a "limit" in the same sense as the upper limits from direct axion searches. The existence of ALPs with lower coupling constants, or even the non-existence of ALPs, is not forbidden by these observations. What fig. 3 really shows is the region of the parameter space in which ALPs would be a viable explanation for the pair production anomaly.

It must be remarked that the statistical significance of the *pair production anomaly* is just 3.5  $\sigma$ , and besides, there are a number of possible systematic effects which may be contributing to it. For example, in steep spectra, there is a significant spill-over of events towards larger energies, given the limited energy resolution of the IACT technique ( $\Delta E/E \simeq 15\%$ ). The correction of



Figure 3: ALP parameter space (coupling constant vs. mass) from  $Meyer \ et \ al^{48}$ , showing in different shades of blue the regions in which ALPs might account for the so-called *pair production anomaly*, under different assumptions on the intervening magnetic fields.

this effect requires a good matching of the data and the Monte Carlo (MC) simulations used in the calculation of the instrument response (something difficult to achieve, given the crucial role of the atmosphere in the IACT technique). Since energy reconstruction is trained on MC, any mismatch will likely result in worse energy resolution in the real data as compared to the simulations, hence in larger event spill-over in the data, which will not be fully corrected by the simulation-based response function. Another problem comes from the fact that the highestenergy points of VHE spectra are naturally biased towards higher fluxes: for an average flux slightly below the instrument sensitivity, positive fluctuations, of the signal or of the background, will make the point to become part of the measured spectrum, and the estimated flux will then have a positive bias. The corresponding negative fluctuations, on the contrary, would not be present in the spectra. The authors of the first paper <sup>46</sup> discuss these sources of systematics and conclude that in the worst case they would reduce the significance of the anomaly from 4.2  $\sigma$  to 2.6  $\sigma^{b}$ .

On the other hand, in the 17 high-quality VHE spectra from 7 sources used by the H.E.S.S. collaboration in the measurement of the EBL density, there seems to be no hint of anomalies for any of the spectral points, even at large optical depths (see fig. 4). It might be argued, indeed, that the high- $\tau$  points enter the fit, but the energy- and redshift dependence of  $\tau$  are fixed to those of the FR08 model, so anomalous high- $\tau$  points could not possibly pull the fit without worsening the agreement at lower  $\tau$ . As mentioned above, the best-fit normalization, within uncertainties, is perfectly compatible with the FR08 value. Since the hypothesized ALP-gamma mixing would depend on the magnetic field structure between source and observer <sup>49</sup>, it is just possible that for those particular sources, by chance, the net effect of the ALPs is negligible. A plausible alternative to reconcile both results without ALPs is to blame the anomaly fully on experimental systematics which may be absent in high-quality spectra like those used in the H.E.S.S. EBL measurement.

Another recent work in which ALPs are proposed as a solution for an observed anomaly in VHE data is the paper <sup>53</sup> by Tavecchio *et al*, which addresses the difficulties in modelling the observations by MAGIC <sup>54</sup> of the quasar PKS 1222+216. The fast variability of this object indicates a compact emission region close to the central engine, i.e. in a very  $\gamma$ -ray opaque environment, due to photon-photon interaction in the dense UV fields originated in the broad

<sup>&</sup>lt;sup>b</sup>In the 2012 paper by Horns and Meyer<sup>46</sup> the so-called "minimal EBL model" was used, and the significance of the anomaly was 4.2  $\sigma$ . For the updated 3.5  $\sigma$  result<sup>47</sup>, using the scaled FR08 EBL, the effect of systematics is not reported, but assuming it to be similar, it would bring the significance down to around 2  $\sigma$ .





Figure 4: Transmission factor vs. gamma-ray energy for the best joint likelihood fit of EBL density and intrinsic spectra of a sample of very high quality H.E.S.S. observations of bright blazars. Adapted from <sup>38</sup>. Three ranges of redshift are shown separately. Even for optical depth  $\tau > 3$  (transmission < 0.05) the data (points with error bars) do not seem to be systematically above the expectations (solid lines and shaded regions).

line region. While ALPs are, once again, a possible way to reduce the optical depth and hence explain the observations, alternative models exist (see discussion  $in^{53}$ ) which do not require new physics.

## 4.3 Spectral irregularities as a signature of photon - ALP mixing

It has been noted <sup>49,50,51</sup> that, due to the turbulent nature of the intergalactic magnetic fields (IGMF), the effects of ALPs on gamma-ray propagation, and in particular, the possible reduction of the EBL-induced flux suppression, will depend on the detailed magnetic field structure along the beam path, and will be impossible to predict for a single source. Even under the assumption of a certain IGMF intensity (or spectrum of intensities) and coherence length, only the average effect on a large number of sources can be predicted for a given ALP scenario. Wouters et al<sup>51</sup> propose an alternative method which can be applied to individual VHE spectra, namely to look for spectral *irregularities* resulting for the strong energy dependence of the ALP- $\rightarrow \gamma$  conversion probability in the so-called *weak mixing regime*, at energies close to the threshold of the process. This method has already been applied by the H.E.S.S. collaboration, and results are presented elsewhere in these proceedings <sup>52</sup>.

#### 5 Conclusions

With the current generation of IACTs, astronomy in the VHE band has reached its maturity, and is providing a wealth of data which allow to address, besides the traditional topics of highenergy astrophysics, a number of questions in the field of Fundamental Physics. Despite some interesting hints, no evidence for new phenomena has been found to date. Nonetheless, IACTs are already providing competitive constraints which foster the hopes set in the next-generation ground-based gamma-ray telescope,  $CTA^{55}$ .

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# CONSTRAINTS ON AXION-LIKE PARTICLES FROM $\gamma\text{-}\mathbf{RAY}$ ASTRONOMY WITH H.E.S.S.

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#### Abstract

Pseudoscalar particles like axion-like particles generically couple to two photons, giving rise to the possibility of oscillations with photons in an external magnetic field. These oscillations could lead to measurable imprints in the electromagnetic spectrum of astrophysical sources if the coupling to photons is strong enough. One possible signature is the presence of irregularities in a limited energy range of the spectrum. In this study, anomalous irregularities are searched for in the spectrum of the bright extragalactic TeV emitter PKS 2155-304 as measured by H.E.S.S. to put constraints on the coupling of light spin 0 particles to photons.

# 1 Introduction

Pseudoscalar particles are predicted in many extension of the Standard Model. A well-known example is the axion, which is the pseudo Nambu-Goldstone boson associated to the breaking of the U(1) symmetry introduced by Peccei and Quinn to solve the strong CP problem<sup>1</sup>. Strong constraints on the energy scale of the breaking of the symmetry are obtained by astrophysical observations<sup>2</sup>, implying that the mass of the axion should be lower than 1 eV. A generic property of pseudoscalar particles is their coupling to the electromagnetic field via a two-photon vertex. In the specific case of the axion, the coupling to photons is predicted to scale with its mass. However, more general low mass pseudoscalars with coupling and mass unrelated are expected from other exotic models<sup>3</sup>. Such particles are called axion-like particles (ALPs) and couple electromagnetically in the same way axions do.

The coupling of ALPs to two photons enables oscillations between photons and ALPs in an external magnetic field <sup>4</sup>. In  $\gamma$ -ray astronomy, these oscillations are sometimes considered as a possible mechanism responsible for the potential reduction of the opacity of the universe to TeV photons <sup>5</sup>. However, in ref. 6, a new signature of ALPs in the energy spectrum of bright  $\gamma$ -ray sources has been proposed. Because of the turbulent nature of the astrophysical magnetic fields crossed by the photon beam of a  $\gamma$ -ray emitter, the observed spectrum can be affected by strong irregularities in a limited energy range. These irregularities are expected around the critical energy  $E_c = m^2/(2g_{\gamma a}B)$  above which the strong mixing regime is attained, where *m* is the ALP mass,  $g_{\gamma a}$  the coupling constant and *B* the magnetic field strength. Fig. 1 shows an example of such irregularity pattern (upper panel), and the same pattern smeared by the energy resolution of approximately 15 % of H.E.S.S. (lower panel). Here, the initial photon beam is taken unpolarized and the survival photon probability cannot be lower than 1/2. The survival probability is computed using the matrix density formalism described in 7. For magnetic fields at the  $\mu$ G level typical of galaxy clusters and a coupling constant  $g_{\gamma a} = 10^{-10}$  GeV<sup>-1</sup> close to the upper limit set by the



Figure 1: Transfer function for  $\gamma$ -rays mixing with ALPs in a galaxy cluster magnetic field (see text for details). Top panel : raw function. Bottom panel : Same function smeared with the energy resolution and bias of H.E.S.S.

Figure 2: Time-averaged energy spectrum of PKS 2155-304 (black points) for the dataset used in the analysis. Top panel : the blue line is the best fit of a curved power-law with EBL absorption to the data. Bottom panel : relative residuals of the fit normalized to the errors.

CAST experiment<sup>8</sup>,  $E_c$  is of order of 1 TeV for ALP masses of a few tens of neV. This means that the sensitivity of H.E.S.S. to ALPs lies in a limited range of mass between 10 neV and 100 neV. In the following, irregularities are searched for in the energy spectrum of the bright TeV blazar PKS 2155-304 measured by H.E.S.S<sup>9</sup>.

# 2 Magnetic fields on the line of sight

PKS 2155-304 is a BL Lac object situated at redshift z = 0.116 that is a powerful TeV emitter. This source is chosen here for two reasons. First, it has been extensively observed by H.E.S.S. and the high statistics available makes a precise determination of the spectrum possible <sup>10</sup>. Second, a small galaxy cluster of radius 372 kpc is observed around this source <sup>11</sup>, meaning that a magnetic field in the vicinity of the source is expected. The magnetic field in the galaxy cluster surrounding PKS 2155-304 is not measured. Usually, Faraday rotation measurements enable to probe the structure of the magnetic field in similar galaxy clusters, hosting FR I radio galaxies (believed to be the parent population of BL Lac objects) <sup>12</sup>. These studies report evidence for magnetic fields of the order of a few  $\mu$ G and turbulence in agreement with a Kolmogorov turbulence on scales as large as 10 kpc. In the following, a conservative value of 1  $\mu$ G is assumed for the magnetic field strength and a Kolmogorov power spectrum on scales between 1 and 10 kpc describes the turbulence.

Conversion of photons from PKS 2155-304 in the intergalactic magnetic field (IGMF) can also be considered. The IGMF is subject to large uncertainties and no measurement of its strength has been possible so far. The range of possible values is experimentally constrained between  $10^{-16}$  G and 1 nG. In the following, a value of 1 nG is assumed for the IGMF strength to derive the ALP exclusions. This means that they are deduced from the most optimistic model. The shape of the turbulence power spectrum is not clear too. A Kolmogorov power-law may not be relevant for the description of the IGMF turbulence. A single turbulent scale of 1 Mpc is assumed to simulate the conversion in the IGMF. Conversion inside the source itself, within the jet or radio lobes is not considered here because of the very uncertain nature of the magnetic fields.



# 3 H.E.S.S. Observations of PKS 2155-304

PKS 2155-304 has been observed by the H.E.S.S. phase I array of four imaging atmospheric Cherenkov telescopes that observe the  $\gamma$ -ray sky above a few hundreds of GeV<sup>13</sup>. Observations of PKS 2155-304 with H.E.S.S. during the flare of July 2006 are selected for the spectral analysis, for a total live-time of 13 hours. Data taken during the flare of July 2006 are selected in order to minimize possible bias in the spectrum reconstruction coming from mis-subtracted background that could mimic ALP patterns. During the high state, observations of the source are almost background free. The spectrum of the 45505  $\gamma$ -ray candidates is shown on Fig. 2. It is well-modeled by a curved power-law convolved by absorption on the EBL  $(dN/dE \propto (E/1\text{TeV})^{-\alpha-\beta\log(E/1\text{TeV})}e^{-\tau_{\gamma\gamma}(E)})$  with  $\alpha = 3.18 \pm 0.03_{\text{stat}} \pm 0.2_{\text{syst}}$ ,  $\beta = 0.32 \pm 0.02_{\text{stat}} \pm 0.05_{\text{syst}}$  and  $\tau_{\gamma\gamma}$  is the optical depth from the EBL model of Kneiske & Dole<sup>14</sup>. No significant irregularities appear in the spectrum so that it is used to constrain the coupling of ALPs to photons.

# 4 Method and results

A natural method to constrain the value of  $g_{\gamma a}$  would be to fit a spectral shape expected from  $\gamma$ -ALP oscillations on the spectrum measured by H.E.S.S. Here, the intrinsic spectrum of the source is not known, so that this method would have to rely on an assumption for the spectral shape that may be wrong. In this case, the limits deduced would be biased and could be optimistically too constraining. To bypass this issue, an estimator of the irregularities in the spectrum is used that does not make the assumption of a spectral shape. It is based on the assumption that the spectrum is log-linear on scale of three bins, which is justified in the context of the astrophysical processes involved. In each group of three consecutive bins, the level of irregularity is quantified by the deviation of the middle bin from the power-law defined by the side bins, taking all errors and correlations into account. The deviations are quadratically summed over all the groups of three consecutive bins to form the estimator  $\mathcal{I}$  of irregularities in the spectrum. The value of  $\mathcal{I}$  may depends on the binning of the spectrum. To estimate the uncertainty on  $\mathcal{I}$ , the binning is modified in size and position, which induce small variations of  $\mathcal{I}$  due to the reshuffling of some events. The average and root mean square of  $\mathcal{I}$  when varying the binning is  $\mathcal{I} = 4.10 \pm 0.65$ . The value of 4.75 is conservatively assumed in the following to obtain the constraints.

In order to estimate the level of irregularities induced by ALPs that can be accommodated by the H.E.S.S. spectrum, simulations of spectra that would be observed for various ALP parameters are performed. The exact turbulent configuration of the magnetic field is unknown so that the simulations are repeated for different realizations of the magnetic field. For one parameter set, the ensemble of all the  $\mathcal{I}$  measured on simulated spectra for different realizations of the magnetic field constitutes the PDF of  $\mathcal{I}$ . An example of such PDF is shown on Fig.3 for conversion in the galaxy cluster magnetic field and two values of the coupling strength,  $g_{\gamma a} = 0.5 \times 10^{-11} \text{GeV}^{-1}$ and  $g_{\gamma a} = \times 10^{-10} \text{GeV}^{-1}$ . If the measured value of  $\mathcal{I}$  is excluded by the PDF at a one-sided 95% probability, the parameters are excluded. In the case of Fig. 3, the second value for  $g_{\gamma a}$  is excluded while the first one is not.

The constraints obtained with this method for conversion in the galaxy cluster and in the IGMF are shown on Fig. 4. For the conversion in the galaxy cluster magnetic field, a conservative strength of 1  $\mu$ G is assumed so that the constraints derived are considered as safe and robust. Conversely, for the IGMF, an optimistic value of 1 nG is used and this limit is shown as an indication of the H.E.S.S. sensitivity with values usually assumed in the literature. The CAST limit is also shown on the plot. The H.E.S.S. exclusions improve the CAST limit in a restricted range of mass around a few tens of neV. H.E.S.S. is sensitive in a restricted mass range because the irregularities are expected in a limited energy range around the critical energy that defines the energy above which  $\gamma$ -ALP oscillations are possible. The range of energy that H.E.S.S. is sensitive to thus translates in



Figure 3: Predicted probability density functions of irregularity reconstructed with the fluctuation estimator for two ALP parameter sets. The vertical band correspond to measurements in the data with different bin sizes and the dashed line is the value used to set the limits.



Figure 4: H.E.S.S. exclusion limits on the ALP parameters  $g_{\gamma a}$  and m. The blue dashed region on the left is obtained considering  $\gamma$ -ALP mixing in the IGMF with in an optimistic scenario with a 1 nG strength. The green dashed region on the right is obtained considering  $\gamma$ -ALP mixing in the galaxy cluster of PSK 2155-304.

a range of mass that can be probed. The limits that are shown on Fig. 4 are valid for any kind of scalar or pseudoscalar particles that couple to photons. The exclusion obtained with H.E.S.S. are the first exclusions on ALPs from  $\gamma$ -ray astronomy. In the future, observations including the fifth telescope of H.E.S.S. would lower the energy threshold of the spectral analysis and then enlarge the accessible mass range.

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# PROBING LORENTZ INVARIANCE IN COSMOLOGY

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We discuss the possibility to test Lorentz invariance violations with cosmological observations. The main observable effect of Lorentz violations is a modification of particles dispersion relation. In the case of photons, a much studied possibility is that the phase velocity depends on their helicity. This produces a rotation of the linear polarization vector during photons propagation (in vacuo birefringence). We report the constraints on this kind of effects coming from Cosmic Microwave Background observations, discussing also the possibility to study direction-dependent effects and to improve constraints through an energy dependence study. We comment on the issue of comparing cosmological results with the ones coming from astrophysical observations. This report is based on work done by the author and collaborators 1,2,3,4.

# 1 Introduction

Violations of Lorentz invariance are expected to emerge in a variety of Quantum Gravity frameworks. A heuristic motivation is the fact that combining the three main fundamental constants of gravitational and quantum physics, *i.e.* the Newton constant G, the speed of light c and the Planck constant  $\hbar$ , another constant can be obtained, the Planck energy  $E_P \equiv \sqrt{\frac{\hbar c^5}{G}} \sim 10^{28} eV$ . Because of its construction, this is the scale at which Quantum Gravity effects are expected to be dominant. Of course, invariance of physics under Lorentz transformations is not compatible with the presence of a constant energy scale, so its existence leads to question the reliability of Lorentz symmetries in the description of physics at scales close to  $E_P$ .

The most studied phenomenological consequence of Lorentz violations is the modification of particles energy-momentum dispersion relations<sup>5</sup>, with corrections to the special relativistic expression which are governed by the Planck scale. In the high-energy regime, to the first order in  $\frac{1}{E_{P}}$ , the modified dispersion relation for photons takes the form

$$E \simeq p + \frac{\eta}{E_P} p^2, \tag{1}$$

where  $\eta$  is a dimensionless parameter governing the amplitude of the correction. It has been studied also the case <sup>5,6</sup> in which opposite-helicity states behave differently, obeying dispersion relations:

$$E_{\pm} \simeq p \pm \frac{\eta_*}{E_P} p^2. \tag{2}$$

Since in this case the two helicity states of the electromagnetic waves have different phase velocity, linearly polarized monochromatic radiation rotates its polarization vector during propagation. This behavior is known as *in-vacuo* birefringence, due to its similarity with the birefringence effects observed when light propagates in materials with chiral molecules. For linearly

polarized radiation with energy p propagating for a time T, the amount of polarization rotation is given by:

$$\alpha(T) = 2\frac{\eta_*}{E_P} p^2 T. \tag{3}$$

Note that the amount of rotation increases linearly with propagation time T and quadratically with the photons energy p.

A more formal way to introduce modified dispersion relations exploits an effective field theory framework, describing the remnants of Planck-scale phenomena on low energy physics through the addition of non-renormalizable operators to the Standard Model Lagrangian, with coupling constants given by the dimensionally appropriate power of the Planck energy. It is then possible, for example, to build a theory for Electrodynamics which is explicitly Lorenz breaking through the introduction of a coupling of the energy-momentum tensor to some fixed four-vector. The lowest order correction of this kind is the one first proposed by Myers and Pospelov<sup>7</sup>, and is such that the electromagnetic Lagrangian reads:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2E_P} n^{\alpha} F_{\alpha\delta} n^{\sigma} \partial_{\sigma} (n_{\beta} \varepsilon^{\delta \delta \gamma \lambda} F_{\gamma \lambda}) \tag{4}$$

where  $n^{\alpha}$  is the symmetry-breaking four-vector.

For convenience a simplified version of the model is usually studied, in which the four-vector  $n^{\alpha}$  has the spatial components set to zero  $(n_{\alpha} = \{n_0, 0, 0, 0\})$ . In this case, the Lagrangian density takes the form:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\xi}{2E_P}F_{0j}\varepsilon^{jkl}\partial_0F_{kl}$$
(5)

where  $\xi \equiv (n_0)^3$  is the parameter governing the amplitude of non-standard effects so that its ratio with  $E_P$  sets the scale at which new phenomena are originating.

It can be shown<sup>2</sup> that this Lagrangian leads to a modified photon dispersion relation of the kind of (2) with  $\eta_* = \xi$ , producing a birefringent behavior during photon propagation. In the more general case, with the spatial components of  $n^{\alpha}$  different from zero, the amount of polarization rotation  $\alpha$  depends on the propagation direction, and we have:

$$\alpha(\theta,\phi) = T \frac{|\vec{p}|^2}{E_P} \left( n_0 - |\vec{n}| \left( \sin\theta \sin\theta_n \cos(\phi - \phi_n) + \cos\theta \cos\theta_n \right) \right)^3.$$
(6)

Here  $\theta$  and  $\phi$  indicate the observation direction,  $\{\theta_n, \phi_n\}$  is the direction pointed out by the spatial part of  $n^{\alpha}$ .

Cosmic Microwave Background radiation is well suited to test this kind of phenomenon, since it is partially linearly polarized and it is detected after an ultra-long propagation time, which works as an amplifier of the anomalous effect of polarization rotation. In this case, due to energy redshift produced by the Universe expansion, the quadratic energy factor in (6) and (2) has to be corrected. Given  $H_0$  as the value of the Hubble constant,  $\Omega_m$  and  $\Omega_{\Lambda}$  as, respectively, the matter and dark energy densities in a standard  $\Lambda$ CDM cosmological model, we have :

$$\Gamma p^2 \to \frac{p_0^2}{H_0} \int_0^z \frac{(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz' \tag{7}$$

In this formula  $p_0$  is the energy of radiation measured today, and z is the redshift at which radiation started propagating ( $z \sim 1100$  for CMB).

Expanding the polarization pattern of CMB on the sky in spherical harmonics it is possible to separate the modes with different properties under parity transformations (the so-called "electric", E, and "magnetic", B, modes of polarization). Due to parity invariance of the original polarization pattern, we would expect to see only parity-even modes (the "electric" ones). Parityodd modes are produced instead from the parity-even ones if a rotation of polarization occurs.

Experiment	Energy channels (GHz)	$\alpha \pm stat(\pm syst)$ (deg)	Reference
WMAP7	41+61+94	$-0.9 \pm 1.4 \pm 1.5$	8
BOOM03	145	$-4.3 \pm 4.1$ (systematic error included)	9
QUAD	100	$-1.89 \pm 2.24 \pm 0.5$	10
QUAD	150	$0.83 \pm 0.94 \pm 0.5$	10
BICEP	100 + 150	$-2.60 \pm 1.02 \pm 0.7$	11

So, looking at the B modes, and studying their correlation with the E ones and with the CMB temperature anisotropies, it is possible to estimate the amount of birefringence effect, if present. <sup>a</sup>

Current estimates on the birefringence angle, in the case in which the polarization angle does not depend on the observation direction  $(n_{\alpha} = \{n_0, 0, 0, 0\})$  are provided in table 1.

By performing a fit on these data to test quadratic energy dependence it is possible to derive the following constraint for the  $\xi$  parameter appearing in the isotropic Lagrangian of equation (5)<sup>4</sup>:

$$-0.44 < \xi < 0$$
 (8)

at 68% confidence level. We also provide the constraint deduced excluding the QUAD 150 GHz datum, as its reliability has been questioned by several authors<sup>4,11</sup>. In this case we find:

$$-1.21 < \xi < -0.53 \tag{9}$$

at 68% confidence level.

Comparing the goodness of this fit with the one of fits testing other kind of energy dependence it is also possible to discriminate among different effects leading to the same kind of CMB crosscorrelation spectra<sup>4</sup> (just to mention one, a systematic error induced by a miscalibration of the polarimeters would show up as an energy-independent rotation<sup>9</sup>). It is intriguing that presently available data seem to follow quite well the quadratic energy dependence expected from a Planckscale-induced Lorentz violation (see figure 1). However more information, expected to come from the PLANCK satellite, is needed before drawing more robust conclusions.



Figure 1: Constraints on birefringence angle coming from different experiments, as a function of each experiment's measured energy. The (dashed) blue line is the best fit curve obtained including the QUAD 150 GHz channel (blue point), while the thick black line is the one not including it. The thin black line marks the zero.

We have shown that present CMB polarization data provide sensitivity to the Planck scale birefringence parameter  $\xi$  of order 10<sup>-1</sup>. Now we want to comment about the possibility of

<sup>&</sup>lt;sup>a</sup>If the symmetry breaking vector has only a non-zero time component, so that the amount of rotation is uniform over the sky, it is sufficient to analyze the full sky correlation power spectra, and the analysis is quite straightforward. In the more general case of non-isotropic effect, it is necessary a more careful analysis, which requires a very high signal-to-noise ratio of the polarization data<sup>3</sup>. These constraint are not yet available.

testing the same kind of effect using astrophysical observations. The method that has shown to be the most effective until now is to compare linear polarization direction of radiation coming from Gamma Ray Burst sources in different energy ranges. Exploiting the quadratic energy dependence of the amount of polarization rotation it is possible to constrain  $\xi$  through:

$$|\alpha(p_1) - \alpha(p_2)| = \xi \frac{|p_1^2 - p_2^2|T}{E_P}$$
(10)

A measurement performed by the INTEGRAL team allowed to set  $^{12} |\xi| < 1.1 \cdot 10^{-14}$ . So apparently analyses exploiting astrophysical sources are able to put much more stringent constraints than cosmological observations. But the task of comparing astrophysical and cosmological limits is not so trivial, since they refer to different reference frames and  $\xi$  is actually related to the time component of a four vector (the limit of  $10^{-14}$  on  $\xi$  translates into an upper limit of  $5 \cdot 10^{-4}$ on  $|n_0|$ ). One could have  $n_{\alpha} = (0, 1, 1, 1)$  in some reference frame, but then, in another reference frame moving with velocity  $\beta = 10^{-3}$  with respect to the first one, one would have  $n_0$  of order  $10^{-3}$ . And this value for  $\beta$  is of the same order of magnitude as the relative velocity between CMB reference frame and our galactic cluster reference frame. So it is clear the importance on putting bounds all the four components of  $n_{\alpha}$ . But from the general spatial dependence of  $\alpha$ , equation (6), we see that, if  $n_{\alpha}$  is space-like, there are some propagation directions for the photons, in which they behave classically. So using point-like astrophysical sources to constrain Lorentz violations induced by the Lagrangian (4) can be misleading. One would need to do some statistical analysis of the information coming from many sources (which is not presently available) and combine it with the information on the state of motion of these sources with respect to some fixed reference frame, like the one of CMB, which is also very difficult to obtain. We hope for this kind of analysis to be feasible (and actually done) in the nearby future.

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#### STATUS OF THE MACE TELESCOPE

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The MACE telescope with a light collector diameter of 21 m, is being set up at the high altitude astronomy site at Hanle (4200m asl) in India, to explore the gamma-ray sky in the tens of GeV energy range. The imaging camera of the telescope comprises 1088 pixels with an uniform pixel resolution of  $0.12^{\circ}$  and covers a total field-of-view of  $4.3^{\circ} \times 4.0^{\circ}$ . In order to achieve a low energy trigger threshold of less than 30 GeV, a two level trigger scheme has been designed for the telescope. The present status of the MACE telescope and particularly the basic design concept of its trigger system along with its performance evaluation in terms of threshold energy and trigger rate estimates based on Monte Carlo data are presented in this paper.

# 1 Introduction

Gamma rays in the energy range more than few tens of GeV reaching the Earth are produced by cosmic particle accelerators such as supermassive black holes, supernovae, pulsars, binary stars, etc. These photons therefore carry information about very high energy phenomenon occuring in the Universe. As high-energy gamma rays are secondary products of these cosmic acceleration processes, gamma ray telescopes allow us to study these high-energy sources. The current generation of imaging atmospheric Cherenkov telescopes (IACT) has increased the number of known GeV/TeV astrophysical sources to more than 150. The Himalyan Gamma Ray Observatory (HiGRO) is the highest altitude ground based gamma ray observatory using the atmospheric Cherenkov technique, located at Hanle ( $32.8^{\circ} N$ ,  $78.9^{\circ} E$ ,  $4200m \, asl$ ) in the Ladakh region of Himalayas, in Northern India. High Altitude GAmma Ray (HAGAR) telescope which is a wavefront sampling array of seven telescopes each with 7 para-axially mounted mirrors of 0.9m diameter, has been in operation there since 2008 as the first phase of the HiGRO. The MACE (Major Atmospheric Cherenkov Experiment) telescope which is currently being setup there will explore the gamma ray sky at energies down to  $30 \, GeV$ .



Figure 1: Camera of the MACE telescope: left figure depicts the pixel and CIM layout and the figure on the right side depicts the design concept of the trigger system

# 2 Telescope description

The 155 ton MACE telescope follows a track and wheel design and is supported on 6 wheels of 60 cm diameter which move on a 27 m diameter track. The 21 m diameter light collector of the telescope is made up of honeycomb based spherical Aluminium mirror facets (size  $50cm \times 50cm$ ) which have been manufactured within the country. They have graded focal length between 25.1m and 26.2m and produce an on-axis spot size of 14mm diameter. The imaging camera of the telescope comprises 1088 pixels covering a total field-of-view of  $4.3^{\circ} \times 4.0^{\circ}$  with a trigger field-of-view of  $2.6^{\circ} \times 3.0^{\circ}$  shown in Fig 1(left). The signal processing and data acquisition electronics is housed in the camera shell. The imaging camera follows a modular design with 16 pixels forming a Camera Integrated Module (CIM) complete with its signal processing and digitization electronics. The data from all the 68 modules are integrated in a data concentrator before being sent to archiving and display systems located in the control room.

## 2.1 Trigger algorithm of the MACE telescope

The trigger logic for the MACE telescope has been designed as a two level scheme. The first level trigger (FLT) is generated within the 16 pixels of a CIM based on N nearest neighbour (N=3,4,,5,6) pixels (presently being optimized for 4 nearest neighbour i.e. 4NN close cluster configuration) within a coincidence gate window of 5 ns while the second level trigger (SLT) is generated by combining the first level triggers from neighbouring CIMs for a coincidence gate window of 10 ns. The basic trigger design of the MACE camera is shown in Fig 1(right). FLT reduces the number of signals from 16 (discriminated output from individual PMT) to 4 and sends the trigger information out of a CIM through 4 logical lines carrying the status of FULL and BORDER triggers without any side information i.e. which side of the CIM has generated the BORDER trigger, resulting in large number of accidental triggers. First level BORDER triggers as shown in Fig 1(right), are combined with the BORDER triggers of neighbouring CIMs in such



Figure 2: Chance trigger rate as a function of single channel rate.



Figure 3: Effective areas and differential rates for gamma-rays and protons for (4NN, 7pe) configuration.

a manner that a cluster of N pixels (4 in the present case) configuration can be formed. In the process of combining trigger information among all the CIMs within the trigger region of inner 576 pixels (36 CIMs), a large number of unwanted combinations also contribute to the chance trigger rate. The total chance rate as a function of single channel rate (SCR) is shown in Fig 2 by line (5). The hardware implementation of the trigger logic is based on complex programmable logic devices (CPLD) and therefore is capable of performing trigger analysis based on the Hit Pattern i.e. information of triggered pixels. The Hit Pattern recorded by the data acquisition system of the telescope is passed on to the SLT hardware which performs trigger analysis and identifies side information of BORDER events. This information can be used to discard the unwanted triggers with a processing delay of ~ 2  $\mu s$  (negligible as compared to the event acquisition time of ~ 350  $\mu s$ ). After removing the contribution from unwanted combinations, the resulting chance rate has been shown in Fig 2 by line (4). In this design, we consider the overlap only up to two CIM modules and retain nearly 92% combinations.

The trigger efficiency has been obtained for both gamma-ray and cosmic-ray proton showers using a framework developed for the MACE camera which provides the trigger efficiency as per



Figure 4: MACE telescope being assembled at Hyderabad.

the actual hardware implementation. This framework can be programmed for various trigger multiplicities and single pixel thresholds. Nearly  $10^5$  showers have been generated for gammarays of energies between 10 and 190 GeV and up to core distance of  $250 \, m$ . Similarly a database of  $10^6$  events has been generated for proton events. Using these simulated showers, we have estimated the effective collection area, trigger threshold and trigger rates for the MACE telescope for both type of primaries, which are shown in Fig 3. For gamma-rays, the trigger threshold varies from 16 GeV to  $30 \, GeV$  while triggers rates vary from 8.0 to  $1.5 \, Hz$  by changing the single pixel threshold from 5 to  $10 \, pe$ . We have also estimated these two parameters of the telescope for cosmic ray protons for a single pixel threshold value of 7 pe. For 4NN, 7pe configuration the (trigger threshold, trigger rate) values for gamma-ray and protons are found to be  $(21 \, GeV,$  $3.4 \, Hz)$  and  $(140 \, GeV, 185 \, Hz)$  respectively.

#### 2.2 Present status of the telescope

As shown in Fig 4, the structural elements of the telescope are presently being assembled at the manufacturer's facility in Hyderabad. The drive system tests are likely to be started soon after installing 10-20 mirror panels on the space frame of the telescope. The modular data acquisition hardware and software is at an advanced stage of prototyping. After detailed testing the telescope is planned to be shifted to Hanle in early 2014 and we expect the first engineering runs to commence at Hanle by the end of 2014.

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# THE ASTRI PROJECT: A MINI ARRAY OF DUAL-MIRROR SMALL CHERENKOV TELESCOPES FOR CTA

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which aims to develop an end-to-end prototype of the CTA small-size telescope. The proposed design is characterized by a dual-mirror Schwarzschild-Couder configuration and a camera based on Silicon photo-multipliers, two challenging but innovative technological solutions which will be adopted for the first time on a Cherenkov telescope. Here we describe the current status of the project, the expected performance and the possibility to realize a mini-array composed by a few small-size telescopes, which shall be placed at the final CTA Southern Site.

# 1 The ASTRI project

ASTRI ('Astrofisica con Specchi a Tecnologia Replicante Italiana') is a flagship project of the Italian Ministry of Education, University and Research, which, under the leadership of the Italian National Institute of Astrophysics (INAF), aims to develop the 'replica' technology for mirrors and sensors for very-high energy (VHE) astrophysics. It is strictly linked to the Cherenkov Telescope Array (CTA, Actis et al. 2011<sup>1</sup>), since it is currently developing an end-to-end prototype of the Small-Size scale Telescope (SST) with wide field of view, aimed to observe the highest energy range (E ~ 1-100 TeV) investigated by CTA.



Figure 1: Layout of the ASTRI prototype (left panel) and of its camera (upper right panel) with lid opening. The lower right panel shows how a Cherenkov event would be seen by the ASTRI camera (see text for details).

The ASTRI prototype is characterized by two special features (Fiorini et al.  $2012^{2}$ ): the optical system is designed in a dual-mirror configuration (SST-2M); the camera is formed by an array of Silicon photo-multipliers. The ASTRI SST-2M prototype is currently under construction and it will be tested on field: it is scheduled to start acquisition in 2014.

Beside the prototype, the ASTRI project aims to realize, in collaboration with CTA international partners, a mini-array of SST-2M telescopes. Among them, at least three ASTRI SST-2M telescopes are foreseen; they shall constitute, starting operation in 2016, the first seed of the CTA Observatory at its Southern site.

# 2 The ASTRI prototype

The ASTRI SST-2M, for the first time for a Cherenkov telescope, will adopt a dual-mirror Schwarzschild-Couder (SC) optical design (Vassiliev et al. 2007<sup>3</sup>), which is characterized by a wide field of view (FoV =  $9.6^{\circ}$  in diameter) and a compact optical configuration (f-number f/0.5). In this way it will be possible to use a light and compact camera based on Silicon photo-multipliers, with a logical pixel size of 6.2 mm × 6.2 mm, corresponding to an angular size of  $0.17^{\circ}$ . Figure 1 (left panel) shows the telescope layout, whose mount exploits the classical altazimuthal configuration, and which is fully compliant with the CTA requirements for the SST array. The ASTRI SST-2M prototype will be placed at Serra La Nave, on the Etna Mountain near Catania, at the INAF 'M.G. Fracastoro' observing station 1735 m a.s.l. (Maccarone 2011<sup>4</sup>); it will begin data acquisition in 2014.

**The Optical Design.** The proposed layout (Canestrari et al. 2011<sup>5</sup>) is characterized by a widefield aplanatic optical configuration: it is composed by a segmented primary mirror made of three different types of segments, a concave secondary mirror, and a convex focal surface. The design

has been optimized in order to ensure, over the entire FoV, a light concentration higher than 80 % within the angular size of the pixels. The telescope design is compact, since the primary mirror (M1) and the secondary mirror (M2) have a diameter of 4.3 m and 1.8 m, respectively, and the primary-to-secondary distance is 3 m. The SC optical design has an f-number f/0.5, a plate scale of 37.5 mm/°, a logical pixel size of approximately  $0.17^{\circ}$ , an equivalent focal length of 2150 mm and a FoV of 9.6° in diameter. The mean value of the active area is ~ 6.5 m<sup>2</sup>, which takes into account the segmentation of M1, the obscuration of M2, the obscuration of the camera, the reflectivity of the optical surfaces (as a function of the wavelength and incident angle), the losses due to the protection window of the camera and the efficiency of the silicon detectors as function of the incident angles (ranging from 25° to 72°).

The Mirrors. The primary mirror is composed by 18 hexagonal segments, with an aperture of 849 mm face-to-face; the central segment is not used because it is completely obstructed by the secondary mirror. According to their distance from the optical axis, there are three different types of segments, each having a specific surface profile. In order to perform the correction of the tilt misplacements, each segment will be equipped with a triangular frame with two actuators and one fixed point. The secondary mirror is monolithic and has a curvature radius of 2200 mm and a diameter of 1800 mm. It will be equipped with three actuators, where the third actuator will provide the piston/focus adjustment for the entire optical system. For both the segments of the primary mirror and the secondary mirror the reflecting surface is obtained with a Vapor Deposition of a multilayer of pure dielectric material, a technology approach developed at the INAF Brera observatory.

The Camera. The SC optical configuration allows us to design a compact and light camera. Currently, the ASTRI camera has a dimension of about 500 mm  $\times$  500 mm  $\times$  500 mm, including the mechanics and the interface with the telescope structure, for a total weight of  $\sim$  50 kg. Such small detection surface, in turn, requires a spatial segmentation of a few square millimeters to be compliant with the imaging resolving angular size. In addition, the light sensor shall offer a high photon detection sensitivity in the wavelength range between 300 and 700 nm and a fast temporal response. In order to be compliant with these requirements, we selected the Hamamatsu Silicon Photomultiplier (SiPM) S11828-3344M (Hamamatsu 2011 <sup>6</sup>). The 'unit' provided by the manufacturer is the physical aggregation of  $4 \times 4$  pixels ( $3 \text{ mm} \times 3 \text{ mm}$  each pixel), while the logical aggregation of  $2 \times 2$  pixels is a 'logical pixel'; its size of  $6.2 \text{ mm} \times 6.2 \text{ mm}$  corresponds to  $0.17^{\circ}$ . In order to cover the full FoV, we adopt a modular approach: we aggregate  $4 \times 4$  units in a Photon Detection Module (PDM) and, then, use 37 PDMs to cover the full FOV. The advantage of this design is that each PDM is physically independent of the others, allowing maintenance of small portions of the camera. To fit the curvature of the focal surface, each PDM is appropriately tilted with respect to the optical axis.

The camera is equipped with a light-tight two-petal lid (Figure 1, upper right) in order to prevent accidental sunlight exposure of its SiPM detectors. Eventually, Figure 1 (lower right panel) shows how the ASTRI camera would 'see' a Cherenkov event; the example refers to an on-axis simulated event for a primary gamma-ray with 10 TeV energy, a core distance of about 143 m, and embedded in a night-sky background of  $1.9 \times 10^{-12}$  photons m<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>; the color table indicates the number of photoelectrons registered in each logical pixel.

The Prototype Expected Performance. Although the ASTRI prototype will mainly be a technological prototype, it should be able to perform also scientific observations. Based on the foreseen maximum sensitivity, a source flux of 1 Crab at E > 2 TeV should be detectable at 5  $\sigma$  confidence level in some hours, while a few tens of hours should be necessary to obtain a comparable detection at E > 10 TeV (Vallania et al. 2012<sup>7</sup>). In this way we would obtain the first Crab observations with a Cherenkov telescope adopting a Schwarschild-Couder optical design and a SiPM camera. Figure 2 (left panel) shows the expected ASTRI prototype sensitivity (yellow stars, computed at 5  $\sigma$  confidence level and 50 hr of observation) compared to those of Fermi-LAT (for one-year integration) and of a few Image Atmospheric Cherenkov Telescopes.



Figure 2: Expected sensitivity as a function of the energy for the ASTRI SST-2M prototype (*left panel*, yellow stars) and mini-array (right panel, green lines), computed at 5  $\sigma$  and 50 hr of observation.

#### 3 The ASTRI SST-2M Mini-Array

The ASTRI Project aims to realize also a mini-array of a few SST-2M telescopes, which shall be placed at the CTA Southern Site and start operations in 2016. Preliminary Monte Carlo simulations (Di Pierro et al.  $2012^8$ ) yield an improvement in sensitivity that, for 7 telescopes at an optimized distance of 250-300 m, could be a factor 1.5 at 10 TeV w.r.t. H.E.S.S. (Figure 2, right panel). The ASTRI SST-2M mini-array will be able to study in great detail sources with a flux of a few  $10^{-12}$  erg cm<sup>-2</sup> s<sup>-1</sup> at 10 TeV, with an angular resolution of a few arcmin and an energy resolution of about 10-15 %. Moreover, thanks to the array approach, it will be possible to verify the wide FoV performance to detect very high energy showers with the core located at a distance up to 500 m, to compare the mini-array performance with the Monte Carlo expectations (by means of deep observations of few selected targets), and to perform the first CTA science, with its first solid detections during the first year of operation.

The Mini-array will observe prominent sources such as extreme blazars (1ES 0229+200), nearby well-known BL Lac objects (MKN 421 and MKN 501) and radio-galaxies, galactic pulsar wind nebulae (Crab Nebula, Vela-X), supernovae remnants (Vela-junior, RX J1713.7-3946) and microquasars (LS 5039), as well as the Galactic Center. In this way it will be possible to investigate the electron acceleration and cooling, to study the relativistic and non relativistic shocks, to search for cosmic-ray (CR) Pevatrons, to study the CR propagation and the impact of the extragalactic background light on the spectra of the nearby sources.

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# THE CHERENKOV TELESCOPE ARRAY

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The Cherenkov Telescope Array (CTA) is a next-generation observatory proposed for very high-energy gamma rays aiming to achieve complete sky coverage, improve sensitivity by about an order of magnitude over current imaging air Cherenkov telescopes (IACTs), cover an energy range of about four decades (from a few tens of GeV to above 100 TeV), and to enhance angular and energy resolutions. CTA will have a large discovery potential in key areas of astronomy, astrophysics and fundamental physics research. These include the study of the origin of cosmic rays and their impact on the constituents of the universe, the investigation of the nature and variety of black hole particle accelerators, and enquiries into the ultimate properties of matter and physics beyond the Standard Model.

#### 1 CTA concept and project

Current IACT instruments and air shower experiments have produced a wealth of exciting results and have demonstrated that very high energy (VHE) phenomena are ubiquitous throughout the universe raising the need of a new generation instrument for a deeper understanding of the underlying phenomena. The mature technology of current Cherenkov telescopes and the high quality of their data open the perspective to build up CTA, a new and highly reliable infrastructure consisting of  $O(10^2)$  telescopes of three different sizes, covering an energy range from a few tens of GeV to above 100 TeV and located at two sites in the northern and the southern hemispheres to achieve full-sky coverage.

A formal international collaboration has been set up, which has now over 1000 members from 27 countries from Europe, Asia, Africa and North and South America. In 2010 the CTA Consortium completed a Design Study [Actis et al.<sup>1</sup>] and started a three-year Preparatory Phase which should lead to production readiness of CTA in 2014. The CTA Consortium aims to build a next-generation system with unprecedented sensitivity, spectral coverage, and angular, energy and timing resolutions; and that it will be operated as a true observatory open to the wider scientific community and providing support for easy access and analysis of data.

CTA will be composed of three classes of telescopes: the Large Size Telescopes (LSTs) for the lowest energies, the medium ones (MSTs) for the core energy range and many small ones



Figure 1: Summary of the three classes (large, medium, small sizes) telescopes parameters and examples of current designs under investigation and optimisation through prototyping phases.

(SSTs) for the highest energies (figure 1). For sensitivity at the highest energies, CTA requires a collection area of the order of  $10 \text{ km}^2$  which means spreading numerous telescopes over a substantial area. The CTA Consortium is leading an important R&D and prototyping phase aiming to finalise the best design of the telescopes and define the technical implementation details. The light collection capability (i.e. the product of mirror area and the photon collection and detection efficiencies), the field-of-view (FoV), and the camera pixel size, which limits the size of image features which can be resolved, are the main figures of merit characterising the performance of a single Cherenkov telescope. Intensive technical developments in mechanics are being carried out for the: LST, for which the rapid re-pointing for GRB follow-up motivates the choice of a light-weight structure of stiff carbon tubes holding a 23 m diameter reflector [Deleglise et al.<sup>2</sup>], and for the MST and SST in their dual-mirror Schwarzschild-Couder (SC) optical design option with small camera and pixel size, requiring high mechanical stability of the order of few  $\mu$ m. The electronics for signal capture and triggering should provide a bandwidth matched to the length of Cherenkov pulses (of a few nanoseconds). The performance of an array is also dependent on the triggering strategy. Cherenkov emission from air showers has to be separated in real time from the high flux of night sky background photons, based on individual images and the combination of images from several telescopes. Characterisation of new generation photo-sensors, i.e. the Silicon-PM potentially providing higher photo-detection efficiency and reduced single-pixel size (Shayduk et al.<sup>3</sup>, Teshima et al.<sup>4</sup>], together with corresponding front-end electronics design are other important and promising development paths followed in every class of telescope sub-project. Figure 1 shows the design of the three classes of telescopes currently under investigation and a summary of main current design parameters. It is worth recalling that the large number of telescopes, warranted to ensure a higher sensitivity than current instruments, will also enable independent operations of sub-arrays which can be pointed at either one source or multiple directions to cover a larger area of the sky.

Determining the arrangement and characteristics of the CTA telescopes in the southern and northern arrays is a complex optimisation problem, requiring a balance of cost against performance in different bands of the spectrum. Figure 2 illustrates the current achievable sensitivity by the southern array (and the contribution to it by the three classes of telescopes sub-arrays) according to the Monte Carlo (MC) simulation study of a potential baseline layout [Bernlöhr et al.<sup>5</sup>]. While at TeV and tens of TeVs energies, background and area extension are respectively the major limiting factors, at lower energy where a core of four LSTs will operate



Figure 2: Differential sensitivity (in units of the energy-dependent flux of the Crab nebula) for array I: 4 LSTs, 23 MSTs and 32 SSTs telescopes (50 h, 5  $\sigma$ , 5% background, 10 events, alpha=0.2).

the systematic effects of the gamma-rays shower evolution are the main constraints. Further expected performance are the angular resolution from  $0.3^{\circ}$  to  $0.02^{\circ}$  and the energy resolution from 25% to 5% depending on the energy domain [Hinton et al.<sup>6</sup>].

## 2 CTA science cases

CTA will have a large discovery potential in research areas including among others the study of the origin of cosmic rays and their impact on the constituents of the universe, the investigation of the nature and variety of black hole particle accelerators, and enquiries into the ultimate properties of matter and physics beyond the Standard Model, e.g by searching for dark matter and the effects of quantum gravity. With its expected performance CTA opens the path to two major and unique (in the sense that no other instrument has a similar ability in the same energy regime) scientific goals at gamma-ray energies: producing the deepest surveys of the sky (with unprecedented angular and energy resolution, and energy coverage); performing the first sensitive observation of short timescale phenomenology. About the latter, the optimisation of CTA (LST sub-array) particularly in the overlapping energy range 10-100 GeV has taken into account competition and complementarity with Fermi. A first in-depth comparison by Funk et al<sup>7</sup> of the two sensitivities shows that CTA will perform better thanks to its higher sensitivity although the Fermi-LAT obviously has a huge advantage in terms of field of view. For short-term phenomena (order of minutes) CTA will perform orders of magnitude better than the Fermi-LAT. In the following some examples of selected key science questions addressed by CTA are discussed as well as the critical requirements set-up by them are recalled. For a more complete view on more physics topics see Hinton et al.<sup>6</sup>.

## 2.1 Cosmic-rays origin: population studies of supernova remnants

The expected impact of future observations with CTA for cosmic ray studies relies on its improved sensitivity aiming to increase significantly the number of detected sources making possible population studies of sources like PWNe, SNRs, and molecular clouds. Being able to detect such objects up to the other side of the Galaxy, CTA is expected to provide hundreds of sources and in particular a sample of several tens of TeV-bright young SNRs.

CTA will enable a statistical analysis of the SNR properties in gamma rays through dedicated population studies [Acero et al.<sup>8</sup>]. Only for 5 of the SNRs, that have been detected in TeV gamma rays, their morphology was resolved and they exhibit a clear shell-like morphology: RX J1713.7-3946, Vela Junior, RCW 86 1, SN 1006, and HESS J1731-347. Extrapolating their luminosities



Figure 3: Left: simulated distribution of Galactic SNRs. The Sun and the Galactic centre are depicted by the red cross and the black dot, respectively. Middle: Fraction of SNRs visible as a function of distance from Earth (dashed line). Right: same as middle but with the CTA PSF improved by a factor of 2.

as representative of the whole class of SNRs starting from the CTA expected sensitivity one can derive the horizon of detectability: the maximum distance at which a generic SNR would be detected. From the knowledge of the spatial distribution of supernovae in the Galaxy (also simulated in figure 3-left panel), their explosion rate, and the duration of the TeV emission (believed to last a few thousand years) we can obtain the prediction for the number of objects detectable by CTA. Monte Carlo simulations study considering the angular resolution of CTA as a function of size and distance of the sources have been conducted [Acero et al.<sup>8</sup>]. The results enable to estimate (in absence of prior detection of shell-like morphology in other wavelengths, e.g. radio) the CTA horizon of resolvability, defined as the maximum distance up to which the shell of an SNR can be spatially resolved and distinguished from a simple Gaussian shape. In the middle and right panels of figure 3 the fraction of SNRs located within a given distance from the Sun and visible with zenith angle  $<45^\circ\!,$  from the CTA southern hemisphere array, is plotted as a dashed line. The horizon of detectability and of resolvability have been computed for three TeV-bright shell type SNRs: Vela Jr (circles), RCW 86 (downward triangles), and RX J1713 (upward triangles). The horizon of resolvability is indicated with the filled symbols and is defined as the distance up to which the shell-like morphology of those objects would be significantly identified by CTA and favoured at  $3\sigma$  over the uniform sphere model. The horizon of detectability is indicated by the open symbols and indicates the maximum distance up to which the three SNRs would be detectable by CTA with a peak significance of  $5\sigma$ , regardless of their morphology. The two horizons have been defined after simulating 100 SNR images per distance bin for an observing time of 20 hours. Different colours refer to three different configurations of the array. If it is assumed that an SNR is bright in TeV gamma rays for  $\sim 3000$ yr (this is approximately the age of Vela Jr), and we recall that  $\sim 2.8$  supernovae are expected to explode each century in the Galaxy, one can infer that the number of SNRs currently emitting TeV gamma rays is  $\sim 80$ . One can then use the results from figure 3 to infer the number of SNRs detectable (or resolvable) by CTA. The difference between the middle and the right panel is in the PSF that has been assumed in the calculations.

The CTA improved sensitivity over a large energy range will increase greatly the quality of spectral studies. This will possibly enable the detection of cutoffs or breaks in gamma ray spectra of SNRs, which combined with a competitive angular resolution (e.g. if a goal PSF of about 1 arcmin at 10 TeV is achieved) will also constrain the width of the TeV-counterpart filaments in several energy bands compared to those measured in X-rays. Such spectro-imaging studies could shed light on the nature (leptonic or hadronic) of the VHE emission.

The spectral sensitivity at the highest energies would make it possible the search also for



Figure 4: Simulation of CTA measurement of quiescent spectrum of PKS 2155-304 (z=0.116): distinguishing different levels of EBL attenuation effect (see description in the text).

Pevatron candidate within this galactic population. A >  $3\sigma$  excess reachable after 8-10 hours would be followed by deeper observation for discovery confirmation.

# 2.2 Extragalactic population studies, black holes and star formation history

Thanks to the past and current IACT systems, more than 45 Active Galactic Nuclei (AGN), spread in redshifts from z = 0.0018 to z = 0.536, have been identified in the VHE band; the majority of these sources belonging to the blazar class (presenting continuum emission by a relativistic jet closely aligned with the line of sight). An other class of AGN TeV emitters, more recently detected, are radiogalaxies (e.g. M87 and Cen A). Although these observations already challenge current theories of particle acceleration, to better understand a possible AGN unification scheme, a large statistical population study is demanded and CTA will provide it with hundreds of AGN to be detected. CTA will offer: a large dynamic range well above 10 000 for the studies of bright VHE flaring epochs; sub-minute timing resolution to catch AGN micro-variability; 10% to 15% energy resolution and four orders in magnitude of energy range. These are all crucial figures of merit of CTA to contribute to answer open questions on AGN physics such as the nature of black hole magnetosphere, the formation of jets and the acceleration of particles, the total energy budget, or the prime origins of variability. CTA is expected to firmly detects and studies quiescent stationary VHE states between bright flares of blazars and AGN, consequently leading, through comparison within a larger population, to clarify the validity of the so-called blazar sequence or other tentative unifying scheme [Sol et  $al^{10}$ . A crucial role is expected in this context by the LSTs which, enabling the detection at E>30 GeV, would make possible to detect extragalactic objects at different redshifts, it will therefore clarify the actual distribution of observed photon spectral index versus redshift and to study evolutionary effects at VHE, at least for the blazar class. Furthermore, observing over a large spectral range up to several tens of TeV with a good spectral resolution will make it possible to find out whether the observed cut-offs in the blazar spectra are intrinsic to the source or are induced by the effect of Extragalactic Background Light (EBL) absorption, and to analyze the maximal energies at which particles are accelerated. Meanwhile as already experimented by current telescopes, it would be possible to further indirectly constrain the EBL density and infer the star formation history (SFR), one of the fundamental quantities of cosmology and which is closely linked to structure and galaxy formation. Up to a redshift of 1 to 2 the star formation rate is reasonably well measured (spread of 20-50%). At higher redshifts, data are rare and mostly lower limits are provided. To accurately model the intrinsic parameters of distant sources one requires a simultaneous measurement of the EBL attenuation (at high energies), together with the unattenuated intrinsic spectrum (at the lowest energies). Results of MC simulation study on the capability of CTA are shown in figure 4 where an example of simulated spectra for different EBL densities is proposed [Mazin et al.<sup>11</sup>]. The base spectrum assumed is the quiescence state spectrum of PKS 2155-304. The measured spectrum (grey markers), the simulated spectra for different level of the EBL density (black markers) and the corresponding assumed intrinsic spectra (black lines) are illustrated together; the source spectrum in the GeV energy range as measured by Fermi-LAT is also shown (purple butterfly), and the energy ranges, which are used to determine the slope of the simulated spectrum at low (light red) and high (blue) energies. The CTA high sensitivity in the energy range between 20 and 100 GeV would make possible to sample directly parts of the energy spectrum of a source, which are not affected by the EBL attenuation (red-band in figure 4-middle panel). With the difference between the measured spectrum in the unabsorbed part of the VHE spectrum and in the absorbed part of the spectrum (blue-band in figure 4-middle panel), especially if studied for several sources with good statistics, the strength of the EBL can be derived. Figure 4-right panel shows the measured spectral index of the blazar from the fit of a power law to the low (red) and high (blue) energy range versus the scaling factor of the EBL model. The colour shaded bands denote the error on the spectral index from the fit (RMS of the spectral index distribution). Black crosses mark the intrinsic spectral index that has been utilised. One can notice from these results the level of precision of spectral measurements expected from CTA.

The guaranteed science cases indirectly related to the AGN population study and EBL attenuation measurements concern: reducing uncertainties of the cosmic star formation rate (SFR), traced by the EBL, at higher redshifts; constraining cosmological models and measure the Hubble parameter and cosmological densities though universalising of blazars spectra versus redshifts; probing the properties of early stars and galaxies in the epoch of reionization, by upper limits on the EBL density from spectral cutoffs in sources at very high redshifts (z > 5), feasible for Gamma Ray Bursts (GRBs) with CTA. A common expectation is that only GRBs will provide high enough gamma-ray luminosity to detect a source located at high redshifts (z > 2): GRB 080916C was the brightest GRB observed by the Fermi/LAT so far. The probability that GRBs with sufficiently high flux will be observed by CTA within its life time has been addressed by several authors finding that CTA, thanks to its low energy threshold of 20-30 GeV and the rapid slewing motion of the LSTs (180° maximum in 20 s) would be able to detect 0.1-0.2 GRBs per year during the prompt phase and about 1 per year in the afterglow phase.

Simulated energy spectrum of GRB 080916C (z = 4.3) if measured with CTA is shown in figure 5-left panel assuming EBL from Dominguez et al.<sup>14</sup>. The duration of the measurement is 45 s as measured with Fermi/LAT. A clear detection can be made and spectral shape can be measured from 30 GeV to 100 GeV. Starting from an assumed source flux of dN/dE =  $1.4 \times 10^{-7} (E/TeV)^{-1.85} cm^{-2} s^{-1} TeV^{-1}$  and simulating the CTA spectral measurement after exposure time of 20 s, the EBL models of Inoue et al.<sup>12</sup> (blue) and Kneiske et al.<sup>13</sup> best – fit (red) can be compared. Due to the lower absorption in case of the EBL model of Inoue et al. the spectral shape of the GRB emission can be measured much better.

It has been suggested that Quantum Gravity effects may induce time delays between photons with different energies travelling over large distances due to a non-trivial refractive index of the vacuum. The observation of very distant, strong flaring blazars will provide the strongest constraints of Lorentz Invariance Violation compared to the current generation of IACTs. In order to constrain LIV effects CTA is required to have very good timing capability: for observations of Mrk 421 (z = 0.03) with a sensitivity of  $10^{-11}$  erg cm<sup>-2</sup> s<sup>-1</sup> for E > 10 TeV photons (30 min obs. at 10 TeV), Planck scale effects would be expected to induce a time delay of ~ 1 s/TeV. This means that CTA needs to resolve flare features of ~ 30 s duration. Higher redshift sources will benefit from the lower energy threshold of CTA [Moralejo<sup>15</sup>].

On the other hand, axions, which are a proposed solution to the strong-CP problem of QCD (or ALPs in general), are also valid candidates to constitute a part or all of CDM. They are expected to convert into photons (and vice versa) in the presence of magnetic fields. In the case of a very distant AGN, the ALP/photon can cause either attenuation or enhancement of the photon flux (in competition with the EBL absorption), depending on the ALP mass [Moralejd<sup>5</sup>].



Figure 5: Left) 45 s observation of a bright burst at z=4.3; spectrum determination possible between 50 and 100 GeV (intrinsic spectrum extrapolated from Fermi-LAT). Right) 20 s interval (harder spectrum, higher flux, from Fermi-LAT) allows to distinguish different EBL models.

## 2.3 Dark Matter

A large number of observations from Galactic to cosmological scales support the explanation that Dark Matter (DM) would be composed by a new type of particle although its nature remains unknown. The proposal of Weakly Interacting Massive Particle (WIMP) predicted by theories beyond the Standard Model of particle physics provides a relic abundance accounting for the inferred amount of DM. The WIMP search is conducted in three ways: by particle production at the LHC, probing the theories of Standard Model extension; by searching for nuclear recoils signals experiments, probing the WIMP scattering cross section; by indirect search looking for a signal in secondary products of WIMP annihilation or decay, probing the annihilation cross section.

Joint observations and complementary investigations along the three different approaches work together to better constrain model parameters. In particular the indirect search conducted through different channels: neutrinos, antimatter cosmic-rays and gamma rays and the overlap of experimental observations can increase confidence in the interpretation of signals, especially because of poorly understood astrophysical backgrounds.

These considerations apply in particular to the gamma-ray based indirect searches for dark matter. Potential spectral signatures in gamma-rays can be classified in mainly strong spectral features and ambiguous signals. The first class is due, for instance, to direct annihilations into  $\gamma\gamma$  or  $Z\gamma$  producing a sharp line spectrum with a photon energy depending on the WIMP mass (in the SUSY neutralino hypothesis). Unfortunately, these processes are loop-suppressed and therefore very rare. In some extent more ambiguous are signals due to continuum emission from pion decay resulting from the WIMPS annihilations in pairs of leptons or quarks. The number of gamma rays finally originated by WIMP annihilation depends on the DM density along the line of sight of the observer. This motivates a number of promising targets for indirect DM searches, namely those with known density enhancements, foremost the Galactic Centre and close-by dwarf galaxies and galaxy clusters. More specifically, assuming the  $\Lambda$ CDM cosmological model, the hierarchical collapse of small over-densities are formed by DM structures which may also host smaller satellite structures and it has been proposed that dwarf spheroidal galaxies may have formed within some of these sub-halos hosted in the larger Milky Way dark matter halo.

By observing the region around the Galactic Centre, and by adopting dedicated observational strategies [Doro et al.<sup>16</sup>], CTA will reach the canonical velocity-averaged annihilation cross-section of  $\sim 3 \times 10^{-26}$  cm<sup>3</sup> s<sup>-1</sup> in only 100 h observation DM mass above 300 GeV. This will be the first time for ground-based IACTs to reach this sensitivity level. Together with the constraints from Fermi-LAT for DM lighter than a few hundred GeV, this can seriously constrain the WIMP paradigm for CDM in case of no detection. Models with a large photon



Figure 6: Dwarf spheroidal galaxies are interesting objects for DM search but not the strongest science case for CTA. Galactic halo and (ex. Fornax) galaxy cluster are more promising.

yield from DM annihilation will be constrained to even smaller cross-sections. In conclusion, the WIMP scenario, either through detection or non-detection will be significantly affected by the first years of operation of CTA. Overall, the CTA prospects for detection of the expected dark matter annihilation signal are best for the Galactic halo, followed by galaxy clusters and then dwarf spheroidal galaxies. Comparison of exclusion curves of Fermi-LAT in 24 months and expected for 10 years (rescaled with the square root of time) are shown in figure 6 [Doro et al.<sup>16</sup>]. The exclusion curves for the various targets studied in this contribution are also reported for the bb-annihilation channel: for the dwarf satellite galaxy Segue 1 (green curve), for the Fornax galaxy cluster in case only DM-induced gamma-rays are considered (blue line) and for the ring-method of observation of the Galactic Centre vicinities.

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3. Dark Matter

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Search for Dark Matter in the sky with the Fermi Large Area Telescope

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## Abstract

Can we learn about New Physics with astronomical and astro-particle data? Since its launch in 2008, the Large Area Telescope, onboard of the Fermi Gamma-ray Space Telescope, has detected the largest amount of gamma rays in the 20 MeV - 300 GeV energy range and electrons + positrons in the 7 GeV- 1 TeV range. These impressive statistics allow one to perform a very sensitive indirect experimental search for dark matter. We will present the latest results on these searches and the comparison with LHC searches.

# 1 Introduction

The Fermi Observatory carries two instruments on-board: the Gamma-ray Burst Monitor  $(\text{GBM})^1$  and the Large Area Telescope  $(\text{LAT})^2$ . The LAT is a pair conversion telescope for photons above 20 MeV up to a few hundreds of GeV. The field of view is ~2.4 sr and LAT observes the entire sky every ~ 3 hours (2 orbits). These features make the LAT a great instrument for dark matter (DM) searches. The operation of the instrument through the first three years of the mission was smooth at a level which is probably beyond the more optimistic pre- launch expectations. The LAT has been collecting science data for more than 99% of the time spent outside the South Atlantic Anomaly (SAA). The remaining tiny fractional down-time accounts for both hardware issues and detector calibrations <sup>3,4</sup>.

More than 650 million gamma-ray candidates (i.e. events passing the background rejection selection) were made public and distributed to the Community through the Fermi Science Support Center (FSSC)<sup>*b*</sup>.

Over the first three years of mission the LAT collaboration has put a considerable effort toward a better understanding of the instrument and of the environment in which it operates. In addition to that a continuous effort was made to in order to make the advances public as soon as possible. In August 2011 the first new event classification (Pass 7) since launch was released, along with the corresponding Instrument Response Functions ( and a release of a new event class 'Pass 7 reprocessed' is planned for the near future). Compared with the pre-launch (Pass 6) classification, it features a greater and more uniform exposure, with a significance enhancement in acceptance below 100 MeV.

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<sup>&</sup>lt;sup>b</sup>The FSSC is available at http://fermi.gsfc.nasa.gov/ssc



Figure 1: Sky map of the energy flux derived from 24 months of observation. The image shows  $\gamma$ -ray energy flux for energies between 100 MeV and 10 GeV, in units of  $10^{-7}$  erg cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>.

## 2 The Second Fermi-LAT catalog

The high-energy gamma-ray sky is dominated by diffuse emission: more than 70% of the photons detected by the LAT are produced in the interstellar space of our Galaxy by interactions of high-energy cosmic rays with matter and low-energy radiation fields. An additional diffuse component with an almost-isotropic distribution (and therefore thought to be extragalactic in origin) accounts for another significant fraction of the LAT photon sample. The rest consists of various different types of point-like or extended sources: Active Galactic Nuclei (AGN) and normal galaxies, pulsars and their relativistic wind nebulae, globular clusters, binary systems, shock-waves remaining from supernova explosions and nearby solar-system bodies like the Sun and the Moon.

The Second Fermi-LAT catalog  $(2FGL)^5$  is the deepest catalog ever produced in the energy band between 100 MeV and 100 GeV. Compared to the First Fermi-LAT  $(1FGL)^6$ , it features several significant improvements: it is based on data from 24 (vs. 11) months of observation and makes use of the new Pass 7 event selection. The energy flux map is shown in figure 1. It is interesting to note that 127 sources are firmly identified, based either on periodic variability (e.g. pulsars) or on spatial morphology or on correlated variability. In addition to that 1170 are reliably associated with sources known at other wavelengths, while 576 (i.e. 31% of the total number of entries in the catalog) are still unassociated. In addition, the first catalog of high energy sources<sup>7</sup> as well as the first SNR catalog are in preparation<sup>8</sup>.

#### 3 Indirect Dark Matter searches

One of the major open issues in our understanding of the Universe is the existence of an extremely-weakly interacting form of matter, the Dark Matter (DM), supported by a wide range of observations including large scale structures, the cosmic microwave background and the isotopic abundances resulting from the primordial nucleosynthesis. Complementary to direct searches being carried out in underground facilities and at accelerators, the indirect search for DM is one of the main items in the broad Fermi Science menu. The word indirect denotes here the search for signatures of Weakly Interactive Massive Particle (WIMP) annihilation or decay processes through the final products (gamma-rays, electrons and positrons, antiprotons) of such processes. Among many other ground-based and space-borne instruments, the LAT plays a prominent role in this search through a variety of distinct search targets: gamma-ray lines,


Figure 2: Derived 95% C.L. upper limits on WIMP annihilation cross sections in the Milky Way halo, for the muon (*left*) and tau (*right*) annihilation channels.

Galactic and isotropic diffuse gamma-ray emission, dwarf satellites, CR electrons and positrons.

## 3.1 Galactic center

The Galactic center (GC) is expected to be the strongest source of  $\gamma$ -rays from DM annihilation, due to its coincidence with the cusped part of the DM halo density profile<sup>9,10,11</sup>. A preliminary analysis of the data, taken during the first 11 months of the Fermi satellite operations is presented in <sup>12,13</sup>.

The diffuse gamma-ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models<sup>12,13</sup>. Improved modeling of the Galactic diffuse model as well as the potential contribution from other astrophysical sources (for instance unresolved point sources) could provide a better description of the data. Analyses are underway to investigate these possibilities.

# 3.2 Galactic halo

In order to minimize uncertainties connected with the region of the Galactic Center, analysis <sup>14</sup> considered a region of interest consisting of two off-plane rectangles ( $5^0 \leq |b| \leq 15^0$  and  $|l| \leq 80^0$ ) and searched for continuum emission from dark matter annihilation or decay in the smooth Galactic dark matter halo. They considered two approaches: a more conservative one in which limits were set on DM models assuming that all gamma ray emission in that region might come from dark matter (i.e. no astrophysical signal is modeled and subtracted). In a second approach, dark matter source and astrophysical emission was fit simultaneously to the data, marginalizing over several relevant parameters of the astrophysical emission. As no robust signal of DM emission is found, DM limits are set.

These limits are particularly strong on leptonic DM channels, which are hard to constrain in most other probes (notably in the analysis of the dwarf Galaxies, described below). This analysis strongly challenges DM interpretation<sup>15</sup> of the positron rise, observed by PAMELA<sup>16</sup> and Fermi LAT<sup>17,18</sup> (see figure 2).

# 3.3 Dwarf galaxies

Dwarf satellites of the Milky Way are among the cleanest targets for indirect dark matter searches in gamma-rays. They are systems with a very large mass/luminosity ratio (i.e. systems which are largely DM dominated). The LAT detected no significant emission from any of such systems and the upper limits on the  $\gamma$ -ray flux allowed us to put very stringent constraints on the parameter space of well motivated WIMP models<sup>19</sup>.



Figure 3: Left: Derived 95% C.L. upper limits on WIMP annihilation cross sections for different channels. Right: Predicted 95% C.L. upper limits on WIMP annihilation cross sections in 10 years for bbar channel.

A combined likelihood analysis of the 10 most promising dwarf galaxies, based on 24 months of data and pushing the limits below the thermal WIMP cross section for low DM masses (below a few tens of GeV), has been recently performed<sup>20</sup>. The main advantages of the combined likelihood are that the analysis can be individually optimized and that combined limits are more robust under individual background fluctuations and under individual astrophysical modelling uncertainties than individual limits. The derived 95% C.L. upper limits on WIMP annihilation cross sections for different channels are shown in figure 3 (left). The most generic cross section (~  $3 \cdot 10^{-26} cm^3 s^{-1}$  for a purely s-wave cross section) is plotted as a reference. These results are obtained for NFW profiles<sup>21</sup> but for cored dark matter profile the J-factors for most of the dSphs would either increase or not change much so these results includes J-factor uncertainties<sup>20</sup>.

With the present data we are able to rule out large parts of the parameter space where the thermal relic density is below the observed cosmological dark matter density and WIMPs are dominantly produced non-thermally, e.g. in models where supersymmetry breaking occurs via anomaly mediation for the MSSM model, updated from <sup>19</sup>).

Future improvements (apart from increased amount of data) will include an improved event selection with a larger effective area and photon energy range, and the inclusion of more satellite galaxies. In figure 3 (right) are shown the predicted upper limits in the hypothesis of 10 years of data instead of 2; 30 dSphs instead of ten (supposing that the new optical surveys will find new dSph); spatial extension analysis (source extension increases the signal region at high energy  $E \geq 10 \ GeV$ ,  $M \geq 200 \ GeV$ ).

Other complementary limits were obtained with the search of possible anisotropies generated by the DM halo substructures  $^{22}$ , the search for Dark Matter Satellites  $^{23}$  and a search for high-energy cosmic-ray electrons from the Sun  $^{24}$ .

#### 3.4 Gamma-ray lines

A line at the WIMP mass, due to the  $2\gamma$  production channel, could be observed as a feature in the astrophysical source spectrum<sup>11</sup>. Such an observation would be a "smoking gun" for WIMP DM as it is difficult to explain by a process other than WIMP annihilation or decay and the presence of a feature due to annihilation into  $\gamma Z$  in addition would be even more convincing. No significant evidence of gamma-ray line(s) has been found in the first two years of data from 7 to 200 GeV<sup>25</sup> (see also<sup>26</sup>).

Recently, the claim of an indication of line emission in Fermi-LAT data  $^{27,28}$  has drawn considerable attention. Using an analysis technique similar to  $^{26}$ , but doubling the amount of



Figure 4: Dark matter annihilation 95% CL cross section upper limits into  $\gamma\gamma$  for the Einasto profile for a circular region of interest (ROI) with a radius  $R_{GC} = 16^{\circ}$  centered on the GC with  $|b| < 5^{\circ}$  and  $|l| > 6^{\circ}$  masked.

data as well as optimizing the region of interest for signal over square-root of background, <sup>27</sup> found a (trial corrected) 3.2  $\sigma$  significant excess at a mass of ~ 130 GeV that, if interpreted as a signal would amount to a cross-section of about  $\langle \sigma v \rangle \sim 10^{-27} cm^3 s^{-1}$ .

The signal is found to be concentrated on the Galactic Centre with a spatial distribution consistent with an Einasto profile<sup>29</sup>. This is marginally compatible with the upper limit presented in <sup>25</sup>. In the analysis of the 4 year data the Fermi LAT team has improved over the two year paper in three important aspects: i) the search was performed in five regions of interest optimized for DM search under five different assumptions on the morphology of the DM signal, ii) new improved data set (pass 7 reprocessed) was used, as it corrects for loss in calorimeter light yield due to radiation damage during the four years of the Fermi mission and iii) point spread function (PDF) was improved by adding a 2nd dimension to the previously used triple Gaussian PDF model, leading to a so called '2D' PDF (such procedure is shown to increase the sensitivity to a line detection by 15%). In that analysis<sup>30</sup> no globally significant lines have been fond and new limits to this DM annihilation channel were set (see figure 4). In a close inspection of the 130 GeV feature it was found that indeed there exist a 135 GeV signal at  $4.01\sigma$  local significance, when a '1D' PSF and old data sets were used (consistently with what <sup>27,28</sup> have found). However, the significance drops to  $3.35\sigma$  (local, or  $\leq 2\sigma$  global significance once trials factors are taken into account). In addition, a weaker signal is found at the same energy in the control sample (in the Earth limb), which might point to a systematics effectpresent in this data set. In order to examine this possibility weekly observations of the Limb are scheduled, and a better understanding of a nature of the excess in the control sample should be available soon.

A new version of the event-level reconstruction and analysis framework (called Pass 8) is foreseen soon from the Fermi LAT collaboration. With this new analysis software we should increase the efficiency of the instrument at high energy and have a data set based on independent event analysis thus gaining a better control of the systematic effects.

#### 3.5 The Cosmic Ray Electron spectrum

The experimental information available on the Cosmic Ray Electron (CRE) spectrum has been dramatically expanded with a high precision measurement of the electron spectrum from 7 GeV



Figure 5: Positron fraction measured by the Fermi LAT and by other experiments <sup>31,32,16</sup>. The Fermi statistical uncertainty is shown with error bars and the total (statistical plus systematic uncertainty) is shown as a shaded band.

to 1 TeV by the Fermi LAT<sup>17,18</sup>. The spectrum shows no prominent spectral features and it is significantly harder than that inferred from several previous experiments.

Recently the Fermi-LAT collaboration performed a direct measurement of the absolute  $e^+$  and  $e^-$  spectra, and of their fraction <sup>33</sup>. As the Fermi-LAT does not carry a magnet, analysis took advantage of the fact that due to its magnetic field, the Earth casts a shadow in electron or positron fluxes in precisely determined regions. As a result, this measurement confirmed a rise of the positron fraction observed by PAMELA, between 20 and 100 GeV and determine for the first time that it continues to rise between 100 and 200 GeV (see figure 5).

These measurements show that a new component of  $e^+$  and  $e^-$  are needed with a peak at  $\sim 1$  TeV. The temptation to claim the discovery of dark matter from detection of electrons and positrons from annihilation of dark matter particles is strong but there are competing astrophysical sources, such as pulsars, that can give a strong flux of primary positrons and electrons (see <sup>15</sup> and references therein). At energies between 100 GeV and 1 TeV the electron flux reaching the Earth may be the sum of an almost homogeneous and isotropic component produced by Galactic supernova remnants and the local contribution of a few pulsars with the latter expected to contribute more and more significantly as the energy increases. If a single nearby pulsar give the dominant contribution to the extra component a large anisotropy and a small bumpiness should be expected; if several pulsars contribute the opposite scenario is expected.

So far no positive detection of CRE anisotropy was reported by the Fermi-LAT collaboration, but some stringent upper limits were published  $^{34}$  the pulsar scenario is still compatible with these upper limits.

After the conference the AMS-02 collaboration presented the result on the positron fraction  $^{35}$  that confim the positron ratio rise observed by PAMELA and Fermi and extend it up to 350 GeV.

Forthcoming measurements from AMS-02 and CALET are expected to reduce drastically the uncertainties on the propagation parameters by providing more accurate measurements of the spectra of the nuclear components of CR. Fermi-LAT and those experiments are also expected to provide more accurate measurements of the CRE spectrum and anisotropy looking for features which may give a clue of the nature of the extra component.



# 4 Conclusions

Fermi turned four years in orbit on June, 2012, and it is definitely living up to its expectations in terms of scientific results delivered to the community. The mission is planned to continue at least four more years (likely more) with many remaining opportunities for discoveries.

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# DARK MATTER AND FUNDAMENTAL PHYSICS WITH THE CHERENKOV TELESCOPE ARRAY

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The Cherenkov Telescope Array (CTA) is a project for a next-generation observatory for veryhigh-energy (GeV-TeV)  $\gamma$ -ray astronomy. Several tens of telescopes of two to three different sizes will be distributed over a large area to allow for an improved sensitivity up to a factor ten better than current instruments, like H.E.S.S, MAGIC and VERITAS, an energy coverage from a few tens of GeV to several tens of TeV and a field of view of up to 10 degrees. Prospects for cold dark matter searches following different observational strategies are investigated: in dwarf satellite galaxies of the Milky Way, in the region close to the Galactic Centre, and in clusters of galaxies. Searches for axion-like particles and tests of Lorentz invariance using long-lasting flares from distant sources are also presented.

# 1 Introduction

The Cherenkov Telescope Array (CTA) <sup>i</sup> will be the next-generation very-high-energy  $\gamma$ -ray observatory operating in the GeV-TeV regime in the framework of a worldwide, international collaboration. Compared to the current generation of Imaging Atmospheric Cherenkov Telescopes (IACT) *e.g.* H.E.S.S., MAGIC and VERITAS<sup>*a*</sup>, CTA is aimed to significantly improve the overall performances of the currently operating IACTs: (i) an order of magnitude in sensitivity in the 100 GeV - 10 TeV energy range; (ii) an extension of the current sensitivity to a few tens of GeV to a few hundred of TeV; (iii) a factor of two to three better in angular resolution. This will be achieved by deploying several tens of telescopes of two-to-three different sizes over an area of several square km. CTA will be operated as an open observatory, with improved data dissemination among the world-wide scientific community and a substantial fraction of the total observation time devoted to guest proposals.

Among the key science drivers of CTA are the study of the origin of cosmic rays and their impact on the constituents of the Universe, the exploration of the nature and variety of black hole particle accelerators, and the examination of the ultimate nature of matter and of physics beyond

<sup>&</sup>lt;sup>a</sup>www.mpi-hd.mpg.de/hfm/HESS/, wwwmagic. mppmu.mpg.de/ and veritas.sao.arizona.edu/, respectively

the Standard Model. The CTA prospects for fundamental physics discussed here are the search for cold dark matter and axion-like particles, and the sensitivity to possible violation of Lorentz Invariance by quantum gravity effects. Realistic estimates of the prospects are presented using the most up-to-date performance files for the CTA proposed arrays and analysis algorithms<sup>+</sup>.

# 2 Dark Matter particle searches

A major question of comptemporary physics is the nature of dark matter (DM). A large number of astrophysical and cosmological datasets shows that most of the matter in the Universe is composed of DM. Its gravitational effects have been observed on all spatial scales ranging from the inner kiloparsecs of galaxies up to cosmological scales. Also, large scale structure formation requires the dominant component of the matter to be cold DM. One of the most popular scenarios for particle DM is that of Weakly Interacting Massive Particles which includes numerous nonbaryonic candidates with masses typically between a few tens of GeV and a few tens of TeV and annihilation cross-section set by weak interactions. WIMPs can annihilate into Standard Model particles, and have hadrons or leptons in the final annihilation products. From cosmic DM annihilations, one can thus expect emission of neutrinos, charged cosmic rays, multi-frequency electromagnetic radiation from charged products, and prompt  $\gamma$ -rays. The detection of these final state particles can help to identify DM.  $\gamma$ -rays are not deflected by cosmic magnetic fields, and thus trace back to their origin. Therefore, observation of a  $\gamma$ -ray signal from cosmic targets where DM is expected could prove conclusive about its nature.

In the context of  $\gamma$ -ray astronomy, the differential flux of  $\gamma$ -rays from within a solid angle  $\Delta\Omega$  around a given astronomical target where DM is expected, can be written as:

$$\frac{\mathrm{d}\Phi(\Delta\Omega, E_{\gamma})}{\mathrm{d}E_{\gamma}} = \mathrm{B}_{\mathrm{F}} \times \frac{1}{4\pi} \underbrace{\frac{\sigma v}{2m_{\mathrm{DM}}^2} \sum_{i} \mathrm{BR}_{i} \frac{\mathrm{d}N_{\gamma}^{i}}{\mathrm{d}E_{\gamma}}}_{Particle Physics} \times \underbrace{\widetilde{J}(\Delta\Omega)}_{Astrophysics}, \tag{1}$$

where  $\sigma_{ann}v$  is the velocity-weighted annihilation cross-section,  $\sum_i BR_i dN_{\gamma}^i/dE_{\gamma}$  is the photon flux per annihilation summed over all the possible annihilation channels i with branching ratios  $BR_i$ , and  $m_{DM}$  is the mass of the DM particle. The 'astrophysical factor'  $\tilde{J}$  is the integral over the line of sight (los) of the squared DM density and over the integration solid angle  $\Delta\Omega$ :  $J = \int_{\Delta\Omega} d\Omega \int_{\log} ds \, \rho^2(s,\Omega)$ . The remaining term B<sub>F</sub> in Eq. (1) is the so-called *boost factor* which stands for intrinsic flux contributions that are not accounted for directly in the formula. Promising targets to look for a DM annihilation detection include dwarf galaxy satellites of the Milky Way, nearby galaxy clusters and the Galactic halo. Figure 1 shows the CTA sensitivity on the velocity-averaged annihilation cross section versus the DM particle mass. On the left-hand side, the sensitivity is shown towards the classical dwarf galaxies Sculptor and Ursa Minor, and for the ultra-faint dwarf galaxy Segue 1, assuming no boost factor. The center and right plots shows the sensitivity towards the Fornax galaxy cluster and the Galactic halo, respectively. The sensitivity towards the Fornax cluster is competitive with those obtained from dwarf galaxies. The best sensitivity is for annihilation signatures in the Galactic halo, where the DM density is expected to be known with much higher precision than in the Galactic Centre itself or in (ultra-faint) dSphs or galaxy clusters. By adopting dedicated observational strategies of the region close to the Galactic Centre<sup>4,3</sup>, CTA has the potential to reach the thermal annihilation cross-section expected from thermally-produced DM of  $10^{-26}$  cm<sup>3</sup>s<sup>-1</sup>.

# 3 Axion-like-particle searches

Axions were first proposed in the 1970s as a by-product of the Peccei-Quinn solution of the strong-CP problem in QCD  $^5$  An interesting property of axions, or more generically, Axion-Like



Figure 1: CTA sensitivities on the velocity-averaged annihilation cross section versus the WIMP mass for 100 hours observation and the CTA candidate arrays E, and B when explicitely mentioned. Left: Towards the dwarf galaxies Sculptor, Ursa Minor and Segue 1, for  $\Delta\Omega = 10^{-5}$  sr assuming 100% branching ratio into  $b\bar{b}$  (for Segue 1 also into  $\tau^+\tau^-$  and  $\mu^+\mu^-$ ). Center: Towards Fornax galaxy cluster for various integration angles, a DM particle annihilating into  $b\bar{b}$  and a subhalo boost factor B<sub>F</sub> of 580. The shaded regions indicate the 1 $\sigma$  standard deviation among 10 different simulations. Right: For the Galactic halo assuming 100% branching ratio into  $b\bar{b}$ ,  $\tau^+\tau^-$  and  $\mu^+\mu^-$ . The natural value for the annihilation cross section for thermally-produced DM particles at  $3 \times 10^{-26} \, {\rm cm}^3 {\rm s}^{-1}$  is shown (black line).

Particles (ALPs<sup>b</sup>, is that they are expected to convert into photons (and vice versa) in the presence of magnetic elds. The photon/ALP mixing could distort the spectra of  $\gamma$ -ray sources, such as Active Galactic Nuclei (AGN) or galactic sources, in the TeV range.

Whether the photon/ALP conversion occurs at the source, in the intergalactic magnetic field or near the Earth, the intrinsic source can be attenuated or recovered (see righ-hand side of Fig. 2). The Extragalactic Background Light (EBL) also plays a crucial role, its main effect is an additional attenuation of the photon flux (especially at energies above about 100 GeV).



Figure 2: Left: Photon/ALP conversions that can occur in the emission from a cosmological source.  $\gamma$  and a symbols represent  $\gamma$ -ray photons and ALPs respectively. Main physical scenarios are shown<sup>6</sup>. Right: Simulation of a 5 h CTA observation of a PKS 1222+21 flare 5 times more intense than the one recorded by MAGIC<sup>7</sup>. In black, energy bins used for the fit (those with a signal exceeding three times the RMS of the background, and a minimum of 10 cxcess events). Excluded points are displayed in grey. The estimated intrinsic differential energy spectrum (after correcting for the EBL effect) shows a boost at high energies due to photon/ALP mixing. The IGMF strength is assumed to be 0.1 nG, and ALP parameters result in  $E_{crit} = m_{a,eff}^2/(2g_{\alpha\gamma}B) = 200$  GeV. From Ref.<sup>3</sup>.

Depending on distance, IGMF and the EBL model considered, a flux enhancement at Earth is possible because ALPs travel unimpeded through the EBL, and a fraction of them can convert back into photons before reaching the observer<sup>3</sup>. Figure 2 (right) shows the observed spectrum of PKS 1222+21 are, after de-absorption of the EBL effect, for 5 hour observation with CTA. A clear hardening of the spectral index is visible showing the characteristic scale energy ( $E_{crit}$ )

<sup>&</sup>lt;sup>b</sup>Unlike axions, the mass and the coupling constant of ALPs are not related to each other.

that can be probed with CTA. Similar flaring AGNs will be followed up by CTA making the field of ALP searches very promising.

# 4 Test of Lorentz invariance symmetry

Lorentz invariance is a fundamental symmetry in modern physics. Several models in the context of quantum gravity have predicted a possible energy dependence of the speed of light in the vacuum. Amelino-Camelia et al.<sup>8</sup> proposed that this can be parameterised by a Taylor expansion of the usual dispersion relation :  $c^2p^2 = E^2 \left[1 \pm \xi_1(E/E_{\rm Pl}) \pm \xi_2(E/E_{\rm Pl})^2 \pm ...\right]$ , where the value of the coefficients  $\xi_{\alpha}$  is given by the model of quantum gravity. Observation of  $\gamma$ -ray flares from far distant objects like AGNs or  $\gamma$ -ray bursts, may allow to detect the time-delay between photons of different energies not caused by intrinsic source mechanisms. The measurement of a possible time lag in two energy bands allows to determine the linear and quadratic terms in the dispersion relation. Figure 3 shows the integral numbers of photons and the flare timescale for representative AGN to test LIV signatures at the Planck scale in AGN flares for various CTA candidate arrays. For PKS 2155-304, CTA would need features on the timescale of 120 s to test Planck scale effects, which is still a factor of a few faster than the rising and falling timescales of the  $\sim$ 7 Crab flares observed to date <sup>10</sup>.



Figure 3: Integral number of events above a given energy, expected for various array configurations for simulated flares, for N(> 10 TeV) = 10 photons. Each panel is accumulated for the appropriate flare timescale required to be able to determine if Planck scale quantum gravity induced LIV is present. The left panel is for a 10 Crab Mrk 421 flare<sup>6</sup> if it lasted for 30 s duration. The right panel is PKS 2155-304 similarly at its high level<sup>10</sup>, but 120 s duration. From Ref.<sup>6</sup>.

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# INDIRECT DETECTION OF DARK MATTER WITH THE ANTARES NEUTRINO TELESCOPE

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Indirect search for Dark Matter trapped inside celestial bodies is one of the main physics goals of neutrino telescopes. The analysis performed with the data recorded by ANTARES in 2007 and 2008 to detect the flux of neutrinos originating from Dark Matter inside the Sun is reviewed. The obtained limits on the neutrino flux and on the WIMP-nucleon cross-sections are presented and compared to other existing limits from direct and indirect detection experiments as well as predictions from SUSY models such as the CMSSM and the more phenomenological MSSM-7 model.

# 1 Introduction

The most popular paradigm of modern cosmology considers the Dark Matter as a population of stable weakly interacting massive particles (WIMPs) relic from the Big Bang, although not yet discovered. Those particles would gravitationally accumulate in the core of massive celestial bodies such as stars or to a lesser extend planets, where they could self-annihilate into ordinary matter and eventually produce significant high energy neutrino fluxes. Indirect search for Dark Matter looking at such neutrino signals coming from the core of the Sun, the Earth or the Galactic Centre is thus one of the main physics goals of neutrino telescopes.

# 2 The ANTARES neutrino telescope

The ANTARES detector  $^{1}$  is the first undersea neutrino telescope and the largest one of the Northern hemisphere. It is composed of 12 mooring lines, each holding 75 photomultipliers distributed on 25 storeys (the titanium structure holding a triplet of photodetectors), installed at a depth of about 2500 metres off shore of the Provencal coast of France, in order to form a 3D-matrix of  $\sim 900$  photodetectors. The main goal of the experiment is to look for the Cherenkov light induced by high energy muons during their travel in the sea water throughout the detector. The trajectory of the muon track is reconstructed from the detection time of the Cherenkov photons as well as from the positions of the photodetectors. An indirect search for neutrinos can then be performed by selecting upward-going muons produced by neutrinos which have passed through the entire Earth and interacted in the vicinity of the detector. The direction of the incoming neutrino, being almost collinear with the secondary muon, can then be determined with an accuracy reaching  $0.2^{\circ}$  for high energy neutrinos above 10 TeV. Due to its size and the spacing of the photomultipliers, the ANTARES detector has a low energy threshold of  $\sim 20$  GeV for reconstructed neutrinos and an effective area of  $\sim 10^{-3}$  m<sup>2</sup> for neutrinos with an energy of 500 GeV. The effective area increases strongly with the neutrino energy and reaches  $\sim 1 \text{ m}^2$  for PeV energy neutrinos. Its location in the Northern hemisphere makes it complementary in sky coverage with the South Pole neutrino telescope IceCube. In addition, a large fraction of the full sky can be observed with ANTARES thanks to the rotation of the Earth, including the central part of the Galaxy which is believed to be the host of many high energy phenomena.

The building of the ANTARES detector started in 2006 with the installation and the operation of the first line, and was completed in May 2008. The analysis presented here is based on the data recorded in 2007 with a 5-line detector and in 2008 with a 9-to-12-line detector. The event reconstruction is performed by a  $\chi^2$  fit of the photodetector hit times as a function of their positions assuming that the light originates from the Cherenkov cone of a muon track passing though the detector<sup>2</sup>. Although the photomultipliers point at 45° downwards, the vast majority of reconstructed events are due to down-going atmospheric muons. The neutrino candidates are obtained by looking for upward-going tracks selected by a set of quality cuts on the reconstruction parameters in order to reject the background of badly reconstructed down-going atmospheric muons. After selection, the event sample contains about 1000 neutrino candidates recorded in ~295 effective days of data taking.

# 3 Indirect search of Dark Matter annihilations in the Sun with ANTARES

A search for neutrinos produced by Dark Matter annihilations into the Sun has been carried out in the data sample collected by ANTARES in 2007 and 2008<sup>3</sup>. The analysis is based on a binned search strategy looking for an excess of neutrino events in a cone centered towards the direction of the Sun over the background of atmospheric neutrinos. Although a good agreement in the number and the distribution of events between data and Monte Carlo simulation is observed after selection, the background coming from atmospheric muon and atmospheric neutrino events has been estimated directly from the data sample by scrambling the recorded time of the events in order to generate a fake Sun. This allows to suppress the systematic errors coming from the uncertainties on the fluxes of atmospheric muon and neutrino events.

The estimation of the neutrino signal induced by Dark Matter annihilations in the core of the Sun has been estimated by using the WIMPSIM package <sup>4</sup> which generates the neutrino spectrum originating from the annihilations in the model independent way. For a given neutrino mass, this Monte Carlo simulation program calculates the capture rate and the annihilation rate in the Sun at equilibrium and generates the neutrino spectrum resulting from all possible self-annihilation channels. The propagation of the neutrinos within the Sun and in vacuum up to the Earth is simulated taking into account neutrino interactions and regeneration of the tau leptons in the Sun medium, as well as neutrino oscillations in a full three-flavour framework.

The sensitivity to Dark Matter signal has been estimated in a model independent way by considering an extreme "soft" neutrino spectrum corresponding to self-annihilations into bquarks and a "hard" neutrino spectrum corresponding to self-annihilations into W/Z boson pairs or tau leptons. These channels are well representative of a WIMP in the form of neutralinos in the framework of Minimal Supersymmetric extensions of the Standard Model (MSSM). A full sensitivity study has been performed for 17 different values of the WIMP mass ranging from 10 GeV to 10 TeV.

For a WIMP with a given mass and a given neutrino annihilation spectrum, the number of signal events is obtained by convoluting the neutrino flux with the detector efficiency, the socalled effective area, determined for a given set of the selection parameters, mainly the values of the track fit quality parameter and of the half-opening angle of the search cone around the Sun. The sensitivity to a given WIMP model is thus derived as the ratio between the average upper limit on the number of background events estimated from the scrambled data, considering a Poisson statistics in the Feldman-Cousins approach <sup>5</sup>, and the number of signal events predicted for the corresponding WIMP mass and annihilation spectrum, and for the lifetime of the data taking. Following the Model Rejection Factor (MRF) technique <sup>6</sup>, the values of the cuts on the track fit quality parameter and on the half-cone opening angle are optimized for each considered



Figure 1: Left: Observed number of events in the data collected by ANTARES in 2007-2008 as a function of the angular separation between the direction of the event track and the Sun position compared to the background distribution estimated from scrambled data. Right: Upper limits on the muon neutrino plus anti-neutrino flux coming from the Sun as a function of the WIMP mass obtained by ANTARES for the considered self-annihilation channels.

model in order to minimize the sensitivity. The optimization leads to a selection cone around the Sun of  $3^{\circ}-5^{\circ}$  of half-opening angle for the various models corresponding to about 1-3 events of background inside the cone.

# 4 Results and perspectives

Figure 1 (left) shows the differential distribution of the observed number of selected events in the data recorded by ANTARES in 2007-2008 as a function of the angular separation between the direction of the event track and the position of the Sun at the time of the event. As illustrated, no excess in the direction of the Sun has been observed with respect to the distribution of the expected background due to atmospheric neutrino and atmospheric muon events estimated from scrambled data. This allowed to derive upper limits on the flux of muon neutrino plus anti-neutrino flux coming from the Sun and resulting from self-annihilations of Dark Matter particles in the core of the Sun<sup>3</sup>. Figure 1 (right) show such limits as a function of the WIMP mass for the considered "soft" and "hard" annihilation channels assuming a 100% branching ratio in that channel. Given its soft energy spectrum, the channel  $b\bar{b}$  yields the weakest limit, while the others  $(W^+W^-, \tau^+\tau^-)$  are the most stringent.

This neutrino flux, related to the annihilation rate of Dark Matter into the Sun, can also be related to the capture rate of the WIMPs by elastic scattering, and thus to the scattering cross-sections of the WIMPs on protons, with the reasonable hypothesis of equilibrium between the WIMP capture and self-annihilation rates in the Sun. Figure 2 presents the corresponding upper limits on the spin-dependent (SD) and spin-independent (SI) WIMP-proton cross-sections as a function of the WIMP mass, which can be derived from the limits on the neutrino flux coming from the Sun obtained by ANTARES. Individual limits on the SD and SI components of the cross-sections are derived assuming that one or the other is dominant. The latest and most stringent limits from other indirect and direct detection experiments are also shown. The predictions of the phenomenological MSSM-7 model, obtained with an adaptative grid scan of its parameter space performed with the DarkSUSY program<sup>7</sup> and taking into account the latest constraints for various observables from accelerator-based experiments and in particular the recent measurement of the Higgs boson mass, are also presented for comparison. A similar analysis of the parameter space of the more constraint CMSSM has also been performed and compared to our limits<sup>3</sup>. These analyses demonstrates the complementarity as well as the great sensitivity of neutrino telescopes with respect to direct detection experiments in the hunting quest for the Dark Matter of the Universe. In particular, ANTARES and IceCube are now



Figure 2: Upper limits on the spin-dependent (left) and spin-independent (right) WIMP-proton cross sections as a function of the WIMP mass obtained by ANTARES for the considered self-annihilation channels, compared to the results of other indirect and direct search experiments. The predictions of a grid scan of the MSSM-7 model are also presented for comparison.

starting to probe interesting regions of the parameter space of SUSY models.

Thanks to the data taking performed since 2008 with a complete detector, ANTARES has now accumulated more than 7000 neutrinos corresponding to about seven times the statistics used in the analysis presented here. In addition, studies are being performed to further improve the sensitivity of such analysis by using an energy estimator in order to obtain a better selection of the Dark Matter neutrino signal events with respect to the atmospheric neutrino background, or by using alternative event reconstruction algorithms with better performances for low energy events. Another improvement comes from the inclusion in the analysis of the events reconstructed on a single detector line which were rejected by the standard analysis presented above in a first place, since the azimuth angle of the reconstructed track cannot be determined for such events. A similar analysis can anyway be followed by constraining the zenith angle of the track to be close to the one of the Sun while integrating over the whole azimuth band. A major improvement of the analysis sensitivity is then observed for low mass WIMPs ( $M_{WIMP} < 120$  GeV) for which low energy neutrino events reconstructed on a single detector line are dominant. Preliminary studies of this improved analysis looking for neutrino produced by annihilation of Dark Matter inside the Sun performed on the ANTARES data set collected between 2007 and 2010 show an improvement of almost a factor 10 on the sensitivity to the WIMP-proton cross-sections with respect to the present limits of ANTARES. In addition, other potential Dark Matter sources such as the Earth, the Galactic Centre and Dwarf Spheroidal galaxies are being studied in the Collaboration by dedicated analyses. The hunt for Dark Matter with ANTARES is therefore only starting and the near future will certainly be exciting.

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## Spiral galaxies without nonbaryonic Dark Matter?

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We report on a number of galaxies whose rotation could be accounted for without non-baryonic dark matter. In the framework of axi-symmetric global thin disk model this is possible for galaxies NGC 7793, NGC 1365, NGC 6946, NGC 4736, UGC 6446 and for the Milky Way, NGC 891, NGC 2403, NGC 4559, NGC 4302, NGC 5775. For the latter 6 galaxies (including Milky Way) the measurements of the vertical gradient of rotation are available and can be compared with the values predicted in the disk model. Our preliminary results may suggest that the problem of missing mass in spiral galaxies is not so severe as expected so far.

# 1 Introduction

Customary approach to modeling of rotation curves assumes that spiral galaxies consist of three main baryonic subsystems: the central bulge, the disk and a halo of stars, satellite compact objects and gas, all three components immersed in a spheroidal non-baryonic dark halo. The dynamics is dominated by the non-baryonic component.<sup>1</sup> The luminous and nonluminous baryonic matter comprises only 20% of the total mass in galaxies which, for example, can be inferred from analyzing radial motions of luminous external compact halo objects like in the Milky Way galaxy<sup>2</sup> (when a non-baryonic halo model is assumed, although a recent result in a different approach suggests that Galaxy mass can be much lower<sup>3</sup> [and references therein]). However, not all observational facts are consistent with this picture. In this paper we report recent results concerning our study of galaxies in the framework of a global thin disk model, assuming gross mass distribution to form a flattened structure resembling a disk rather than a spheroid. This approach leads to physically viable results. We obtain low mass-to-light ratios with column mass density overlapping with the measured amount of gas at the galactic outskirts. In this model we also obtain correct values for the vertical gradient of the azimuthal component of rotation.

# 2 Thin disk model

The source of the gravitational potential in the framework of global disk model is approximated by a substitute axi-symmetric column mass density forming a thin disk in the mid-plane. The rotation law on circular concentric orbits of the disk is identified with the observed galactic rotation curve. There is a unique relation between the rotation law v(r) and the surface mass distribution  $\sigma(r)$  and the inverse relation, given by the following mutually invertible integral transforms derived in  $^4$  that can be simplified to  $^5$ 

$$\sigma(r) = \frac{1}{2\pi^2 G} \int_0^\infty \left[ \frac{K(\kappa(x))}{1+x} - \frac{E(\kappa(x))}{1-x} \right] \frac{v^2(r\,x)}{r\,x} \,\mathrm{d}x, \qquad \kappa(x) = \frac{2\sqrt{x}}{1+x}, \tag{1}$$

$$\frac{v^2(r)}{r} = 2G \int_0^\infty \left[ \frac{K(\kappa(x))}{1+x} + \frac{E(\kappa(x))}{1-x} \right] \sigma(r\,x) \, x \, \mathrm{d}x,\tag{2}$$

where E and K are complete elliptic integrals defined in<sup>6</sup>. In studying galaxies with the help of above formulae, it is assumed that a galaxy is a flattened disk-like object rather than spheroidal and that the motion of matter is predominantly circular.

It is important to stress that mass density  $\sigma(r)$  cannot be uniquely determined from the measured part of rotation curve, since  $\sigma(r)$  involves integration of the rotation law also beyond the range of radii covered by the measurements and regions where matter is present (note also, that the rotation at a given radius depends also on the mass distribution beyond that radius, which is a qualitative difference between spheroidal and flattened systems). One of the consequences is that the predicted mass density falls off rapidly close to the end point of rotation data due to cutting off the integration. This and other 'cutoff' effects were discussed and illustrated in detail in <sup>4</sup>, where it was also given an argument showing that despite this non-uniqueness, the mass distribution can be determined from rotation with a satisfactory accuracy in an internal part of a region covered by the rotation data.

To bypass the cutoff effect or reduce it, some additional data complementary to the rotation data are indispensable. To this end a radio measurements of the gas amount (like hydrogen) can be used. These measurements provide the lower limit for the mass density at larger radii. All the data can be made self-consistent and provide a global mass distribution by means of iterations, so that the density of dynamical mass inferred from the rotation curve at lower radii with the help of integral (1) continuously overlaps with the mass density of gas at larger radii. In effect, the global mass density after substitution to (2) gives correct rotation curve. An example of such an iteration scheme we described in <sup>7</sup> for galaxy NGC 4736. Based on such obtained column mass density supplemented with the luminosity measurements, the local mass-to light ratio can be inferred (not assumed) and it turns out to be a variable function of the distance in the disk, see Fig.1. A similar procedure can be repeated for various other spiral galaxies. The



Figure 1:<sup>8</sup> Results for galaxy NGC 4736. a) Rotation curve: THINGS measurements [solid circles]<sup>12</sup>, the model [solid line], and comparison with a high resolution rotation curve<sup>3</sup>. b) the model global surface mass density [solid line], surface mass density of H1+He (open circles]; and the surface brightness: B-band [solid squares], V-band [solid triangles], I-band [solid circles]<sup>14</sup>; c) mass-to-light ratio profile (H1+He excluded).

example results are summarized in Tab.1. It is seen that the mass-to-light ratio is low, indicating that the luminous mass suffices to account for the rotation data and that there is no need for invoking other forms of matter.

name	NGC 7793			NGC 1365			NGC 6946			NGC 4736	UGC 6446
distance [Mpc]	3.38 <sup>A</sup>			18.6 <sup>L</sup>			$6.0^{-M}$			4.7 P	18.6 G
morph. type	SAd <sup>A</sup>			SBb $^{B}$			SAbc $^{B}$			Sab $^{B}$	$\operatorname{Sd} G$
$L_B [10^{10} L_{\odot}]$	$0.3$ $^{K}$			9.81 <sup>E</sup>			1.64 <sup>H</sup>			1.3 <sup>S</sup>	0.218 J
$M_{H+He} [10^{10} M_{\odot}]$	$0.12^{-A}$			2.36 <sup>E</sup>			$0.97^{-M}$		$0.067 \ ^{T}$	$0.434 \ ^{G}$	
$M_{H_2} \left[ 10^{10} M_{\odot} \right]$	-			-			$0.45^{-J}$			-	-
rotation curve	$HI^{A}$	$HI + H_{\alpha}O$	THINGS <sup>P</sup>	В	L		R	Μ	P	THINGS	G
$M_{Gal} [10^{10} M_{\odot}]$	1	1.02	1	33.4	30.9	31.9	7.14	8.55	11.5	2.68	1.5
$M_{Gal}/L_B$	3.33	3.4	3.33	3.4	3.15	3.25	4.35	5.21	7.01	2.06	6.88
$\frac{M_{Gal}-M_{gas}}{L_B}$	2.93	3	2.93	3.16	2.91	3.01	3.49	4.35	6.15	2.01	4.89

Table 1:<sup>8</sup> The results obtained in the framework of thin disk model for several galaxies using measurements data from:  $A^{15}$ ,  $B^{13}$ ,  $D^{16}$ ,  $E^{17}$ ,  $F^{18}$ ,  $G^{19}$ ,  $H^{20}$ ,  $I^{21}$ ,  $J^{22}$ ,  $K^{23}$ ,  $L^{24}$ ,  $M^{25}$ ,  $O^{11}$ ,  $P^{12}$ ,  $R^{26}$ ,  $S^{14}$ ,  $T^{27}$ 



Figure 2: <sup>9</sup> Galaxy NGC 4559. [Left]: disc rotation curve (solid circles) and the anomalous gas rotation curve above the disk (open circles), both from <sup>28</sup>. The solid lines are rotation curves predicted by our model at various heights above the mid-plane at z = 0.6, 1.2, 1.8, 2.4, 3.0 and 3.6 kpc. The dashed line is the rotation curve predicted at z = 4 kpc; [Right]: the azimuthal velocity as a function of the vertical distance from the mid-plane. The points represent the velocity values averaged over the interval  $r \in (2.5, 6)$  kpc, the bars show the standard deviation in this interval.

#### 3 The vertical gradient of rotation

Thanks to the constantly improving quality of measurements, it has become possible to determine the vertical structure of the rotation above the galactic disc. This enables to test models of mass distribution in spiral galaxies more accurately. In the thin disk model framework discussed above one can relate the column mass density to the vertical structure of the azimuthal component of rotation  $v_{\phi}(r, z)$ , assuming the approximation of quasi-circular orbits above the mid-plane z = 0. Then, as we showed in <sup>10</sup>,

$$v_{\phi}^{2}(r,z) = \int_{0}^{\infty} \mathrm{d}\chi \frac{2G\sigma(\chi)\,\chi}{\sqrt{(r+\chi)^{2}+z^{2}}} \left[ K(k) - \frac{\chi^{2}-r^{2}+z^{2}}{(\chi-r)^{2}+z^{2}} E(k) \right], \qquad k = \sqrt{\frac{4\chi\,r}{(r+\chi)^{2}+z^{2}}},$$

where  $\sigma(r)$  is assumed to have been determined by iterations. The results for the predicted behaviour of the vertical gradient  $\partial_z v_{\phi}(r, z)$  is shown in Fig.2 and Tab.2. The simple model gives high gradient values consistently with the measurements.

# 4 Summary

The results shortly reported in this work for a sample of galaxies (Milky Way, NGC 891, 1365, 2403, 4302, 4559, 4736, 5775, 6946, 7793 and UGC 6446) suggest in the framework of Newtonian gravitation that one can describe spiral galaxies consistently with the measurements and without invoking large amounts of unseen (non-baryonic) dark matter. For several galaxies it was also

name	Milky Way	NGC 891	NGC 2403	NGC 4559	NGC 4302	NGC 5775
distance [Mpc]		9.5	3.24	9.7	16.8	24.8
mass $\left[10^{10}M_{\odot}\right]$	14.5		5.22	4.82	5.05	9.65
$\partial_z v_{\phi}$ observed $\left[\frac{km}{s \cdot kpc}\right]$	$-22 \pm 6$	-17.5 ±5.9	-12	-10	$-31 \pm 19.8$	-8 ±4
z- segment [kpc]	(0.02, 0.1)	(1.2, 4.8)	(0.4, 2.4)	(0.2, 4)	(0.4, 2.4)	(1.2, 3.6)
r- segment [kpc]	(3, 8)	(4.02, 7.03)	(4.02, 7.03)	(1.3, 19.7)	(2.5, 6)	(0, 12)
$\partial_z v_{\phi}$ predicted $\left[\frac{km}{s \cdot kpc}\right]$	$-21.3 \pm 4.2$	-19.9 ±3	$-10 \pm 4$	-7.2 $\pm$ 2,4	$-22.7 \pm 8.4$	$-12 \pm 4.3$

Table 2:9 <sup>10</sup> The vertical gradient of rotation in the framework of thin disk model for several galaxies

possible to compare with a good result the predictions of the disk model with the measured large values of the vertical gradient of rotation.

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# Dark Radiation Constraints on Mixed Axion/Neutralino Dark Matter

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Recent analyses of WMAP9 data show that the effective numer of neutrinos contributing to the cosmic expansion is consistent with the Standard Model. Additional relativistic degrees of freedom at the time of matter-radiation decoupling are bounded from above by  $\Delta N_{eff} \lesssim 1.6$  at 95% CL. We consider the mixed axion/neutralino cold dark matter scenario which arises in *R*-parity conserving supersymmetric (SUSY) models wherein the strong CP problem is solved by hadronic axions with a concommitant  $axion(a)/saxion(\hat{a})$  supermultiplet. We show that the above bound on  $\Delta N_{eff}$  is automatically satisfied if saxions are mainly thermally produced and  $m_{LSP} < m_{\tilde{a}} \lesssim m_s$ . However if the dominant mechanism of saxion production is through coherent oscillations, the WMAP9 data provides an upper bound on the Peccei-Quinn breaking scale.

## 1 Introduction

The recent discovery of a Higgs-like boson with mass  $m_h \simeq 125$  GeV at the CERN LHC is an outstanding accomplishment <sup>1,2</sup>, and seemingly provides the last of the matter states encompassed within the Standard Model of particle physics. However, if indeed the new boson turns out to be spin-0, then it raises a conundrum: how is it that fundamental scalar particles can exist at or around the weak scale when their masses are quadratically divergent? The well-known solution is to extend the model to include weak scale supersymmetry. One of the additional virtues of the Minimal Supersymmetric Standard Model (MSSM) is that it includes several candidates for particle dark matter. In *R*-parity-conserving theories, it is common to conjecture the lightest neutralino  $\tilde{Z}_1$  as CDM<sup>3</sup>.

A distinct fine-tuning problem arises in the QCD sector of the Standard Model, which is only consistent with data if the strong CP-violating phase ( $\theta_{CP}$ ) is extremely small:

$$\theta_{CP} \stackrel{<}{\sim} 10^{-10} \tag{1}$$

A possible solution invokes the Peccei-Quinn (PQ) mechanism, which implies the existence of a pseudo-Goldstone boson, known as the axion<sup>4</sup>. Although its mass is predicted to be slight, the axion is still an excellent CDM candidate if produced through coherent oscillations. In moving towards realistic models, it should be fruitful to incorporate simultaneously solutions to both the gauge hierarchy problem and the strong CP problem <sup>5</sup>. In supersymmetric axion models, labelled here as the Peccei-Quinn-augmented MSSM or PQMSSM, the axion necessarily occurs as an element of an axion supermultiplet

$$\hat{a} = \frac{s+ia}{\sqrt{2}} + i\sqrt{2}\bar{\theta}\bar{a}_L + i\bar{\theta}\theta_L \mathcal{F}_a,\tag{2}$$

in 4-component spinor notation<sup>6</sup>. Here, we also introduce the *R*-parity-even scalar saxion field s and the *R*-parity-odd spin-1/2 axion field  $\tilde{a}$ . In gravity-mediation (as assumed in this paper) the saxion is expected to gain mass  $m_s \sim m_{3/2}$ , where  $m_{3/2}$  is the gravitino mass. On the other hand, the axino mass can range from keV to  $m_{3/2}$  <sup>7,8</sup>. Here we always assume  $m_{\tilde{a}} \sim m_{3/2}$ , so the lightest suspersymmetric particle (LSP) is the neutralino. The axion, saxion and axino couplings to matter are all suppressed by the PQ breaking scale  $f_{\bullet}$ . In the PQMSSM with a neutralino LSP ( $m_{\tilde{a}} \sim m_{3/2}$ ), one expects dark matter to be comprised of an axion-neutralino admixture <sup>9,10,11</sup>. In spite of their suppressed couplings to matter, both the axino and saxion can play huge roles in dark matter production rates in the early universe.

The interactions of saxions with axions can be obtained from <sup>12</sup>

$$\mathcal{L} \ni \left(1 + \frac{\sqrt{2\xi}}{v_{PQ}}s\right) \left[\frac{1}{2}(\partial_{\mu}a)^2 + \frac{1}{2}(\partial_{\mu}s)^2\right] + \cdots$$
(3)

where  $\xi = \sum_i q_i^3 v_i^2 / v_{PQ}^2$ ,  $q_i$  is the PQ charge of various PQ multiplets,  $v_i$  are their vevs after PQ symmetry breaking and  $v_{PQ} = \sqrt{\sum_i v_i^2 q_i^2} = f_a / \sqrt{2}$ . In some simple models,  $\xi$  can be small or even zero, while in others it can be as high as unity <sup>7</sup>. In particular, for  $\xi \gtrsim 0.05$ , the decay  $s \to aa$  can dominate, giving rise to a population of relativistic axions which forms the so-called *dark radiation*.

The population of weakly interacting relativistic degrees of freedom is parametrized by the number of effective neutrinos  $(N_{eff})$ , which is ~ 3 in the Standard Model, corresponding to the three neutrino flavors. Recently the WMAP9 evaluation of cosmological data <sup>13</sup> extracts  $N_{eff} = 3.84 \pm 0.40$  from a combination of  $WMAP + eCMB + BAO + H_0$  data. Thus, it seems there is no pressing need for additional relativistic species beyond photons and the three SM neutrinos and the measured value of  $N_{eff}$  provides a strong bound on parameter space of models like the PQMSSM, which necessarily contains a component of dark radiation. For the purpose of this paper, we will invoke a conservative constraint of

$$\Delta N_{eff} \equiv N_{eff} - N_{eff}^{SM} < 1.6 . \tag{4}$$

Higher values of  $\Delta N_{eff}$  are excluded at 95% CL (or more) by any of the current CMB analysis.

In this paper we discuss the impact of the WMAP9 constraint on the PQMSSM parameter space, assuming  $m_{\tilde{a}} \sim m_{3/2}$ , so the neutralino is the LSP. While the decay  $s \rightarrow aa$  may lead to a relativistic component of dark matter which is strongly constrained by  $\Delta N_{eff} < 1.6$ , it may also diminish the saxion entropy dilution effect which is large when  $s \rightarrow gg$  dominates instead. As seen in Fig. 1, unless  $\xi \ll 1$ , saxions mainly decay to axions. When computing the abundance of relativistic axions at late times ( $T \ll 1$  MeV), two competing effects must be taken into consideration: axion injection from saxion decays and entropy injection from both saxion ( $s \rightarrow gg, \tilde{g}\tilde{g}$ ) and axino decays. While the former enhances the amount of dark radiation, the latter dilutes it. Thus, in the case of entropy dilution:

$$\Delta N_{eff} = \frac{1}{r} \frac{\rho_a(T)}{\rho_\nu(T)} = \frac{1}{r} \frac{\rho_a(T)}{T^4} \frac{120}{7\pi^2} \left(\frac{11}{4}\right)^{4/3} \tag{5}$$

where r is the entropy dilution factor. The above expression must be computed at  $T \sim eV$ , which are the temperatures to which the CMB is sensitive.

As mentioned before, axions can be both thermally and non-thermally produced in the early universe, so  $\rho_a$  receives contributions from thermal production of axions and thermal and coherent production of saxions, followed by  $s \rightarrow aa$  decays. It can be shown that thermal production of axions only gives subdominant contributions to  $\Delta N_{eff}$  and will be neglected from here on. Thus the axion energy density after saxion decays is:

$$\rho_a(T) = BR(s \to aa) \left(\frac{g_{*S}(T)}{g_{*S}(T_D)}\right)^{4/3} \left(\frac{T}{T_D}\right)^4 \rho_s(T_D) \tag{6}$$



Figure 1: Saxion branching fractions  $s \to gg$  (red),  $s \to \tilde{g}\tilde{g}$  (green),  $s \to aa$  (dark blue) and  $s \to \tilde{a}\tilde{a}$  (light blue) versus  $m_s$  for  $m_{\tilde{a}} = 0.5$  TeV and  $m_{\tilde{g}} = 1.6$  TeV. We take  $\xi = 0.01$  (dashed) and 1 (solid).

where  $T_D$  is the saxion decay temperature. In the above expression we do not include the possibility of entropy dilution of  $\rho_a$ , since this is accounted for by the dilution factor r in Eq. 5. Using

$$\rho_s(T_D) = m_s Y_s s(T_D) \text{ and } g_{*S}(T \sim eV) = 3.9,$$
(7)

where  $s(T) = 2\pi^2 g_{*S}(T)T^3/45$  is the entropy density and combining Eqs. 5 and 6, we obtain:

$$\Delta N_{eff} \simeq 18.02 \frac{1}{r} BR(s \to aa) g_{*S}(T_D)^{-1/3} \frac{m_s Y_s}{T_D}$$
(8)

In the above expression  $Y_s$  is the saxion yield and in general receives contributions from thermal and coherent oscillation production of saxions. The thermal production of saxions (in super-symmetric axion models) was calculated in Ref.<sup>14</sup> and is given by (assuming out-of-equilibrium production):

$$Y_s^{TP} m_s = \frac{\rho_s^{TP}}{s} \simeq 1.33 \times 10^{-5} g_s^6 \ln\left(\frac{1.01}{g_s}\right) \left(\frac{10^{12} \text{ GeV}}{f_a}\right)^2 \left(\frac{T_R}{10^8 \text{ GeV}}\right) m_s.$$
(9)

where  $T_R$  is the reheat temperature and  $g_s$  the strong coupling constant. The contribution from coherent oscillations gives:

$$Y_s^{CO} m_s = \frac{\rho_s^{CO}}{s} \simeq 1.9 \times 10^{-5} \text{ GeV} \frac{\min[T_R, T_s]}{10^8 \text{ GeV}} \left(\frac{s_0}{10^{12} \text{ GeV}}\right)^2$$
(10)

where  $T_s$  is the temperature at which saxions start to oscillate, given by  $3H(T_s) = m_s$ . In the above expression,  $s_0$  is the initial saxion field amplitude and depends on the UV details of the model and the inflation dynamics. Natural scales for  $s_0$  are usually taken to be of order the PQ breaking scale  $f_a$  or the reduced Planck mass  $M_P$ <sup>15</sup>.

Using the expressions presented above, we can compute the amount of dark radiation in PQMSSM models. In most cases,  $\Delta N_{eff}$  is dominated either by  $Y_s^{CO}$  or  $Y_s^{TP}$ , so it is interesting to separately discuss each of these scenarios.

# 2 $\Delta N_{eff}$ from Thermal Production

Here we assume that saxions are mostly thermally produced, so  $Y_s^{TP} \gg Y_s^{CO}$ . This happens for large  $T_R$  and/or small  $s_0$ . In this case, Eq. 8 becomes:

$$\Delta N_{eff} \simeq 18.02 \frac{1}{r} BR(s \to aa) g_{*S} (T_D)^{-1/3} \frac{m_s Y_s^{TP}}{T_D}.$$
(11)

We also assume that  $\xi \sim 1$ , so saxion decays to gluons and gluinos are suppressed (see Fig. 1). In this case, entropy injection is dominated by axino decays, so that

$$r \simeq \max\left[1, \frac{4}{3} \frac{m_{\tilde{a}} Y_{\tilde{a}}^{TP}}{T_{D}^{\tilde{a}}}\right],\tag{12}$$

Using Eqs. 11, 12, and 9, it can be shown that  $\Delta N_{eff}$  satisfies:

$$\Delta N_{eff} \le (0.09 - 0.19) \sqrt{\frac{m_{\tilde{a}}}{m_s}} \tag{13}$$

where we have used  $g_{*S}(T_D), g_{*S}(T_D^{\circ}) = 10-100$ . Although the above result is an approximation, we point out that it is a conservative upper bound on  $\Delta N_{eff}$ , since the upper bound is stronger in regions of parameter space where r < 1. We also point out that although the above bound is quite general and independent of all other PQ parameters, it is only valid for *thermal production* of saxions. The result from Eq. 13 shows that in order to violate the WMAP9 constraint on dark radiation ( $\Delta N_{eff} < 1.6$ ), the axino needs to be at least one order of magnitude heavier than the saxion. This is hard to achieve on most supersymmetric PQ models, where typically  $m_{\tilde{a}} \leq m_{3/2} \sim m_s^8$ . Therefore, we conclude that the WMAP9 constraint on  $\Delta N_{eff}$  can be easily accomodated in the PQMSSM if saxions are mainly thermally produced. In the following we discuss the case in which saxion production is dominated by its coherent oscillation component.

## 3 $\Delta N_{eff}$ from Coherent Oscillations

As shown in the previous section, the contribution to  $\Delta N_{eff}$  from thermal production of axions and saxions is suppressed unless  $m_{\bar{a}} \gg m_s$ . In this section, we assume  $m_{\bar{a}} \leq m_s$ , so the thermal production is negligible and the relic density of relativistic axions is dominated by coherent production of saxions and their decay. Furthermore, we assume that  $Y_{\bar{a}} \ll Y_s^{CO}$ , so that we can neglect entropy injection from axions. Under these assumptions we have:

$$\Delta N_{eff} \simeq 18.02 \frac{1}{r} BR(s \to aa) g_{*S} (T_D)^{-1/3} \frac{m_s Y_s^{CO}}{T_D}$$
(14)

and

 $r \simeq \max\left[1, \frac{4}{3}R(s \to X)\frac{m_s Y_s^{CO}}{T_D}\right].$ (15)

where  $R(s \rightarrow X) = 1 - BR(s \rightarrow aa)$ .

The impact of the WMAP9 constraints on the PQ parameter space for  $\xi = 1$  is summarized in Fig. 2, where we show the excluded region in the  $f_a$ - $m_s$  plane for different values of  $T_R$  and  $s_0$ . As we can see, the constraint  $\Delta N_{eff} < 1.6$  imposes an upper bound on  $f_a$ , which strongly depends on the value of  $s_0$ , since this parameter controls the amplitude of saxion coherent oscillations. On the other hand, the bound is independent of the misalignment angle  $\theta_i$  and is not related to the traditional upper bound on  $f_a$  ( $\lesssim 10^{12}$  GeV) coming from the overclosure of the universe from CO production of axions in non-SUSY models.



Figure 2: Dark radiation bounds on the  $f_a$ - $m_s$  plane for  $s_0 = f_a$  (left) and  $s_0 = M_P/100$  (right). The region above the solid red (blue) line has  $\Delta N_{eff} > 1.6$  for  $T_R = 10^{10}$  GeV ( $T_R = 10^6$  GeV). The curves assume  $m_s < 2m_{\tilde{a}}$ , only include the contribution from CO saxions and were obtained using Eq. 14 and  $\xi = 1$ .

#### 4 Conclusions

In this paper, we have presented the impact of the CMB constraints on dark radiation for the mixed neutralino/axion dark matter scenario. We discussed the case of large  $\xi$  ( $\gtrsim 0.05$ ) where saxion decays to *aa* is dominant. In the present case,  $s \rightarrow aa$  may contribute to dark radiation with a contribution parametrized as  $\Delta N_{eff}$ , the non-standard contribution to the number of effective neutrinos.

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#### Magnetic monopoles at the LHC and in the Cosmos

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The magnetic monopole was postulated in 1931 by Dirac to explain electric charge quantisation. Searches for pair-produced monopoles are performed at accelerator facilities whenever a new energy regime is made available. In addition, monopoles with masses too high to be accessible at colliders would still have been produced in the early Universe and such relics can be searched for either in flight or trapped in matter. Here we discuss recent results and future prospects for direct monopole detection at the LHC and in bulk matter searches, with emphasis on the complementarity between the various techniques. Significant improvements of the results from the ATLAS experiment are expected with the development of new triggers. Dedicated LHC experiments will allow to probe wider ranges of monopole charges and masses: the MoEDAL experiment using both nuclear-track detectors and absorbing arrays, and searches for trapped monopoles in accelerator material. Finally, it is highlighted how the first search for monopoles bound to matter in the Earth's interior and by extension in the primary material that formed the Solar System.

# 1 Introduction

One example of a well-motivated particle whose discovery would be of great significance to modern physics is the magnetic monopole – a particle carrying a positive or negative magnetic charge in analogy to the electric charge carried by an electron. The monopole was postulated by Dirac in 1931 to explain electric charge quantisation<sup>1</sup> and was shown by 't Hooft and Polyakov in 1974 to be an essential ingredient in grand-unification theories<sup>2</sup>. It follows from Dirac's argument that monopoles should carry a magnetic charge equal to a multiple of a fundamental unit referred to as the Dirac charge. The Dirac charge is equivalent to 68.5 electron charges in terms of ionisation energy loss at high velocities; monopoles are thus expected to manifest themselves as very highly ionising particles.

Searches for direct monopole production have been performed each time an accelerator of a new type or surpassing power has been operated, including the CERN Large Electron-Positron (LEP) collider and the Tevatron proton-antiproton collider at Fermilab, where isolated monopoles carrying one Dirac charge were excluded up to masses of the order of 400 GeV<sup>3,4,5,6</sup>. Much higher masses (up to 4000 GeV) can be probed at the LHC. It has been pointed out that, to be effective, LHC searches for monopoles should use several complementary techniques <sup>7</sup>, including the ATLAS general-purpose experiment, the dedicated MoEDAL experiment, and trapping experiments. As discussed below, such a wide programme of searches has already started.

There are no theoretical constraints on the mass a monopole should carry. The monopole mass can be as high as  $10^{16}$  GeV in grand unification theories. Monopoles with masses above the LHC collision energy could only be produced in high-energy cosmic events, e.g. during the

inflation phase of the early Universe<sup>8</sup>. Monopoles would be stable and could still be around us today. Even though there are presently no adequate models that describe to which extent relic monopoles would be present in cosmic rays or have accumulated inside astronomical bodies, fluxes and abundances can be constrained by experiments. Monopoles in flight have been sought with array detectors. These set tight constraints on the flux of cosmic monopoles incident on Earth <sup>9,10,11,12,13,14,15,16</sup> (only the most recent results are given here; see <sup>17</sup> for a complete list). Trapped monopoles have been sought in hundreds of kilograms of samples from the Earth's crust<sup>18,19</sup>, in rocks from the Moon's surface<sup>20</sup>, and in meteorites<sup>19</sup>. One of the great advantages with meteoritic samples is the possibility that they contain so-called "stellar" monopoles, i.e., monopoles would have sunk to the cores of large astronomical bodies such as the Earth and the Moon while they were still molten. However, the Earth's magnetic field is expected to cause the migration of such monopoles along the Earth's magnetic axis. A novel search for stellar monopoles performed recently in polar volcanic rock samples<sup>21</sup> is presented below.

## 2 Monopole searches at the LHC

Three complementary techniques have been proposed to probe monopole production at the LHC in the most thorough possible way<sup>7</sup>: in-flight detection in general-purpose detectors, in-flight detection using nuclear-track detectors, and the detection of stopped monopoles in matter with the induction technique. Only direct monopole detection is considered here. A recent discussion of indirect signatures at the LHC can be found e.g. in Ref.<sup>22</sup>.

#### 2.1 Monopoles in the ATLAS detector

The ATLAS collaboration performed pioneering highly-ionising particle searches with 7 TeV proton-proton collision data, which already largely surpass the LEP and Tevatron results  $^{23,24}$ . ATLAS plans to extend the search with 8 TeV and 14 TeV data.

A monopole event in the ATLAS detector would be rather striking, with a large number of high-threshold hits in the transition radiation tracker (TRT) and a very localised energy deposition in the electromagnetic (EM) calorimeter. These two independent features are powerful discriminants against backgrounds  $^{23,24}$ . This is assuming, however, that the monopole penetrates all the way to the EM calorimeter. Current level-1 triggers used for collision runs in ATLAS are only sensitive to monopoles which do not range out before entering the EM calorimeter because they rely on either a calorimeter energy deposition or a track in the muon system. For a monopole with the Dirac charge, this corresponds to kinetic energies above  $200 \text{ GeV}^7$ . Moreover, standard electron and photon triggers at level-2 require energy deposition in the second EM calorimeter layer and have transverse energy thresholds exceeding 60 GeV for the data taken in 2011–2012. These two conditions increase the minimum kinetic energy required for a Dirac monopole to 500 GeV<sup>24</sup>, severely limiting the search acceptance. Therefore, a dedicated level-2 trigger algorithm was developed. This new trigger does not require calorimeter energy deposition beyond level-1 (without second layer requirement and with an 18 GeV threshold) and discriminates on the TRT hit energy to keep the rate under control. This reduces the minimum monopole energy for a fully efficient trigger to 300 GeV. This trigger was enabled in September 2012 and collected 7.1  $fb^{-1}$  of 8 TeV collision data. The analysis of these data will result in the strongest LHC constraints on the production of long-lived massive particles with electric charge up to 100 times the electron charge or magnetic charge up to twice the Dirac charge.

#### 2.2 Trapped monopoles in accelerator material

Magnetic monopoles which would stop in material around collision points without being seen by sensitive detectors would not necessarily be lost. Stopped monopoles are expected to bind to

nuclei<sup>25</sup> and thus remain trapped in matter. After the run is finished, the material can be taken apart and probed for monopoles with the so-called induction technique, seeking for a persistent current after passage of the samples through a superconducting coil. This kind of search was performed with beam pipes and detector material at the Tevatron and HERA colliders  $^{26,27,28}$ . Monopoles need only to traverse vacuum before they reach the beam pipe. Beam-pipe searches would therefore allow to probe magnetic charge ranges which extend well beyond the reach of other detectors <sup>7</sup>.

Superconducting magnetometer tests recently performed at the Laboratory of Natural Magnetism at ETH Zurich with calibration devices and obsolete LHC accelerator parts near the CMS interaction region demonstrated that such a search is indeed feasible <sup>29</sup>. One attractive possibility is to search for monopoles trapped in the central sections of the beryllium beam pipes of the ATLAS and CMS experiments. These beam pipes were exposed to the products of high-energy collisions between 2010 and the end of 2012. They are being replaced and will become available for processing into suitable samples as soon as the performance of the new beam pipes is demonstrated, which is foreseen to happen in 2016 – 2017. This is the only experiment which can efficiently probe monopoles with magnetic charge higher than nine times the Dirac charge<sup>7</sup>.

# 2.3 Monopoles in the MoEDAL detector

The MoEDAL experiment<sup>30</sup> consists of detector arrays made of thin plastic foils called nuclear track detectors <sup>31</sup> to be exposed to collision products around the LHCb interaction point. After exposure, the nuclear track detectors are removed, etched by a chemical process, and scanned to search for the typical fingerprint a highly-ionising particle would leave behind while traversing the plastic. There are several advantages with such a method: the amount of material between the interaction point and the detectors is typically less than in a general-purpose detector, providing sensitivity to higher charges; the detectors are specifically designed to detect highly-ionising particles in a robust manner and can be calibrated with ion beams; and there are no timing constraints, providing sensitivity to low particle velocities and thus high masses.

The recent addition of the Magnetic Monopole Trapper (MMT) enhances the sensitivity and redundancy of the MoEDAL experiment. The MMT consists of an absorbing array made of aluminum. Monopoles which would range out and stop within the array would be detectable with the induction technique. The analysis of magnetometer data is relatively fast and straightforward compared to the complex ATLAS detector or the MoEDAL nuclear track detectors. Due to its bulk and weight, the MMT subdetector can only cover a limited solid angle and has therefore a lower acceptance than the rest of MoEDAL; however, the MMT has the three attractive advantages of simplicity, speed of result delivery, and complementarity. A test array comprising 198 aluminium rods of 60 cm length and 2.5 cm diameter was deployed in September 2012 and is expected to yield its first results in 2013. With limited sensitivity, this first MMT run allows to probe monopoles carrying a magnetic charge larger than the Dirac charge (up to 4 times the Dirac charge) for the first time at the LHC. The full array to be deployed in 2014 will be thicker and will cover more solid angle. This experiment will result in the first monopole search in 14 TeV proton-proton collisions and has the potential to procure a robust and independent cross-check of a discovery as well as a unique measurement of the magnetic properties of a monopole.

## 3 Primordial monopole searches

Recent searches for monopoles trapped in bulk matter have focused on stellar monopoles, which were missed by previous searches which used samples from the crusts of the Earth and the Moon. Accessible samples which could contain stellar monopoles include meteorites and polar volcanic rocks.

#### 3.1 Monopoles in meteorites

The most extensive meteorite search to date was performed in 1995<sup>19</sup>. It sets a limit on the monopole density in meteoritic material of less than  $2.1 \cdot 10^{-5}$ /gram at 90% confidence level. The study analysed 112 kg of meteorites, among which ~ 100 kg are chondrites and can thus be assumed to consist of undifferentiated material from the primary solar nebula.

#### 3.2 Monopoles in polar volcanic rocks

Stellar monopoles inside the Earth would tend to accumulate at a point along the magnetic axis where the downwards gravitational force is equal to the upwards force exerted by the Earth's magnetic field. An equilibrium above the core-mantle boundary for a monopole with the Dirac charge corresponds to the condition that the mass should be less than  $4 \cdot 10^{14}$  GeV. From this point, the solid mantle convection would be expected to slowly bring up monopoles to the surface. Over geologic time, monopoles would thus accumulate in the mantle beneath the geomagnetic poles for a wide range of masses and charges.

These considerations motivated a novel search which probed 23.4 kg of polar volcanic rock samples  $^{21}$  with the superconducting magnetometer in Zurich. This represents 4-5 times less material than used in the meteorite search. However, for monopole mass and charge satisfying the criterion for a position above the core-mantle boundary, this difference is compensated for by an increase in monopole concentration of roughly a factor 6 in polar mantle-derived rocks. It results that, in a simple model, a limit of  $1.6 \cdot 10^{-5}$ /gram can be set in the matter averaged over the whole Earth. This is slightly better than the limit from the meteorite search.

#### 4 Conclusions

A wide programme of searches for magnetic monopoles at the LHC has started. The production of monopoles of any charge and mass can be probed efficiently by combining the use of special triggers in the ATLAS general-purpose detector, the analysis of obsolete accelerator material, and the use of dedicated MoEDAL array detectors.

The polar volcanic rock search provides a novel probe of stellar monopoles in the Solar System. One can think of two ways in which these results could be further improved in the future: by analysing large (> 100 kg) amounts of meteorites and polar rocks with a high-efficiency magnetometer, or by gaining access to new types of samples such as asteroid and comet fragments.

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# LATEST RESULTS FROM THE XENON PROGRAM

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The XENON100 experiment is the current phase of the XENON direct dark matter search program, and uses a xenon dual phase time-projection chamber. The results reported here correspond to the 224.6 live days of data taken from March 2011 to April 2012. This new science run has yielded no evidence of any dark matter interaction, but lowered the sensitivity limits to an unexplored region. In addition to these results, some post-unblinding analysis on the same data are also presented here, completed by a brief description of the current status of next phase of the XENON program, the XENON1T detector.

## 1 Introduction

Many astronomical and cosmological observations, recently confirmed by Planck's latest measurement <sup>1</sup>, indicate that about 26% of the content of the Universe is made by Dark Matter. Among all candidates to describe the Dark Matter, the most favorite one has the generic name of Weakly Interacting Massive Particle (WIMP)<sup>2</sup>.

The XENON program is a phased approach to achieve the direct detection of WIMP by using an underground time projection chamber (TPC) with ultra-pure liquid xenon (LXe) as both target and detection medium. The current phase of the program is the XENON100 detector<sup>3</sup>, which has been taking data at the Gran Sasso National Laboratory (LNGS), in Italy, since 2008.

#### 2 The XENON100 experiment

The XENON100 detector is a cylindrical two-phase (liquid and gas) Time Projection Chamber (TPC) filled with 62 kg of LXe as target mass, and surrounded by 99 kg additional LXe as an active scintillator veto, optically separated from the target by PTFE panels. The TPC and the veto are mounted in a double-walled stainless-steel cryostat, enclosed by a passive shield made from OFHC copper, polyethylene, lead and water/polyethylene. The shield is continuously purged with boil-off N<sub>2</sub> gas in order to suppress radon background. For more details about the detector, please refer to the dedicate paper<sup>3</sup>.

An interaction within the active volume of the detector creates ionization electrons and prompt scintillation photons. A part of the released electrons escapes to recombination and drifts towards the gas phase thanks to a constant electric field at 0.53 kV/cm. Close to the interface, electrons are accelerated by a stronger field and extracted into the gaseous phase, where they generate proportional scintillation light. Two arrays of photomultiplier tubes (PMTs), one in the liquid and one in the gas, detect the prompt scintillation (S1) and the delayed secondary scintillation signal (S2). Thanks to the concentric organization of the top array, the detector allows the reconstruction of the (x;y) position of the interaction inside LXe with a resolution < 3

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mm  $(1\sigma)$  by using the light hitpattern on PMTs. In the same time, the z coordinate is evaluated with a resolution of 0.3 mm  $(1\sigma)$  thanks to the time difference between the both signals. By taking advantages to this very good three dimensional position reconstruction, and considering the self-shielding capability of the LXe, one can reject the majority of background from the detector itself thanks to fiducialization. Then, the ratio between light from S1 and S2 allows the discrimination between nuclear recoil (NR) induced by neutron or WIMP interaction, and electronic recoils (ER) induced by  $\beta$  or  $\gamma$ . Finally, the multiple scattering rejection, corresponding to the rejection of events with more than one identified S2 allows the discrimination of WIMP signal from neutron background.

More informations about the general methods developed so far by the XENON Collaboration for the XENON100 data are reported in a dedicated paper<sup>4</sup>, that is focussed on the first science run (2010).

# 2.1 Improvements with the new run

The second XENON100 science run presented here consists in 224.6 live days of data that have been continuously taken over more than one year, from March 2011 to April 2012, with excellent detector performance and stability. Compared to the data from the previous science run, the new dark matter search is characterized by crucial improvements<sup>5</sup>:

The main one consists of the increase of the time exposure. Indeed, besides three interruptions due to equipment maintenance, the dark matter data wcrc acquired continuously over 13 month, and were interrupted only for regular calibration with different sources. A final selection was done in order to remove periods with increased electronic noise or very localized light emission in the xy-plane, or also with too much fluctuation from the average of the experimental parameters like the inner temperature or pressure. In parallel, the calibration statistic was also strongly improved, with about 35 times more data for ER calibration than for dark matter search in the considered recoil energy range, by using <sup>60</sup>Co and <sup>232</sup>Th sources, but also with two NR calibration runs with <sup>241</sup>AmBe source that were taken at the beginning and at the end of the run.

In addition to this improvement, the LXe intrinsic background from  $^{85}$ Kr was also reduced thanks to a dedicated cryogenic distillation run prior to the science run. This has led to a  $^{nat}$ Kr concentration lowered down to  $19\pm4$  ppt, with stable value regularly measured during the run. The reduction of the Kr level is a critical point, since it could not be reduced by fiduzialization because of its unallocated distribution inside the LXe, but also since the sensitivity of the previous science run was limited due to an accidental leak that led to very high Kr level.

This science run corresponds also to an improvement of the electronic conditions, with a modified hardware trigger focused on the S2 signal, leading to a trigger efficiency above 99% for S2 signals higher than 150 photo-electrons (PE, corresponding to about ten electrons extracted in the gaseous phase). This contributed also to improve the detector ability to trigger on smaller signals, leading to virtually no loss of events in the considered recoil energy region.

Another improvement consists in a better 3-dimensionally position reconstruction correction of the both signals by taking into account the non-uniform light collection with the two PMTs arrays, but also on a reduction of the attenuation of the charge signal because of residual impurities in the LXe. The concentration of this latest was monitored all along the run by taking regular <sup>137</sup>Cs calibrations in order to measure the evolution of the electron lifetime during the run. For this science run, this lifetime increased from 374  $\mu$ s to 611  $\mu$ s, with an average of  $\tau_e = 514 \ \mu$ s, which corresponds to a level of electronegative impurities of about 1 ppb O<sub>2</sub>-equivalent. As a comparison, the electron lifetime increased linearly from 230  $\mu$ s to 380  $\mu$ s in the previous run <sup>4</sup>.

Finally, the last improvement concerns the fiducial volume reduced here to 34 kg of LXe, determined by maximizing the sensitivity of this run given the accessible ER background above the blinding cut.



Figure 1: Space parameter indicating the search for WIMPs. (right) New result on spin-independent WIMPnucleon scattering from XENON100

Thanks to all those improvements, the both calibration data, ER and NR, provided respectively an expected background for the whole science run at 0.79  $\pm$  0.16 event and 0.17  $^{+0.12}_{-0.07}$  event, corresponding to a total expected background at 1.0  $\pm$  0.2 event for the whole science run, in the [6.6-30.5] keV/c<sup>2</sup> deposited energy range.

## 2.2 XENON100 latest results

During all the run, a blinding procedure was applied to dark matter search data, consisting in hiding the [2-100] PE part for the SI signal, and keeping free only the 90% of the upper part of the ER band, masking more than 90% of the signal region (NR band). The analysis of the results was done by using the Profile Likelihood (PL) method, as it was the case for the first science run to set WIMP SI cross-section limits  $^{4,6}$ . For this analysis, a region of interest was defined by restricting the S1 signal in the [3-30] PE energy range, and by keeping the 97% upper quantile of the NR band. No excess on the expected background was founded there.

As a cross-check, a benchmark region, defined with the S1 signal in the [3-20] PE energy range, the 97% upper quantile of the NR band and the region below the 99.75% rejection line for ER was used. After the unblinding, two events were observed in this region, expected  $1.0 \pm 0.2$  event, as illustrate in Figure 1 (left).

In addition to this, the exclusion limit for the SI WIMP nucleon cross section  $\sigma_{\chi}$  was calculated with 90% confidence level, using standard assumptions of the Dark Matter halo<sup>5</sup>. The expected sensitivity of this dataset in the absence of any signal is shown in Figure 1 (right). The new limit is represented by the thick blue line. This new result corresponds to the most stringent limit in the whole energy range for WIMP masses (showed up to 10 GeV/c<sup>2</sup>), except the region below 8 GeV/c<sup>2</sup> where the best limit still belongs to the low mass analysis from XENON10. The lowest value for the SI cross-section is obtained for  $m_{\chi} = 55 \text{ GeV/c}^2$  with  $\sigma_{\chi} = 2.0 \times 10^{-45} \text{ cm}^2$ . The new XENON100 result continues to challenge the interpretation of the DAMA<sup>7</sup>, CoGeNT<sup>8</sup>, and CRESST-II <sup>9</sup> results as being due to scalar WIMP-nucleon interactions.

One of the advantages of using xenon as detector medium is to allow both SI and SD analysis. For this latter, only the <sup>129</sup>Xe and <sup>131</sup>Xe isotopes were considered, since they have both one unpaired neutron, and since they represent about the half of the <sup>nat</sup>Xe in term of abundance. As for the SI analysis, the PL method was applied, using the same datasets and event selection. The final result was obtained using the new nuclear model from Menendez et  $al^{10}$ . The resulting XENON100 limits yields to the most stringent limit for  $m_{\chi} > 6 \text{ GeV}/c^2$  for neutron coupling, with the lowest limit at  $\sigma_{\chi} = 3.5 \cdot 10^{-40} \text{ cm}^2$  for  $m_{\chi} = 45 \text{ GeV}/c^2$ , see Figure 2 (left), and to weaker values for proton coupling because of an even number of proton for the xenon atom as shown on Figure 2 (right). Please refer to the dedicate paper <sup>11</sup> for more details.

In addition to this, the XENON100 detector provides also some other interesting results

Figure 2: (left) New results on WIMP-neutron (left) and WIMP-proton (right) scattering from XENON100.



that have been published, or will come in the future, focused for example on simulation/data comparison for NR response<sup>12</sup>, or on NR background in XENON100, but also on single electron charge signal or on  $\gamma$  background annual modulation. The detector is still taking data with a new run that has recently started.

#### 3 The XENON1T experiment

In parallel, the Collaboration has designed the next generation Dark Matter detector, XENON1T, which consists in a 1 m drift TPC, with 1 ton of LXe as fiducial volume (2.4 tons in total), surrounded by a 10 m water shield muon veto. Thanks to this and to a careful material selection, the background would be reduced by a factor 100, allowing to explore deeper region than current detectors. The construction will start around this summer, with the aim to start a first science run in 2015, with a sensitivity goal at  $2 \cdot 10^{-47}$  cm<sup>2</sup> after two years of data taking.

Scaling up the detector size also requires an increase in the size of the infrastructures needed to store and handle the xenon. One key aspect is how to store the xenon when it is not inside the TPC. For this purpose, the Collaboration has designed a special storage system, called  $\text{ReStoX}^{13}$  (Recovery and Storage of Xenon), consisting in a cryogenic sphere with an inner cooling and purification system able to keep about 3.6 tons of xenon, in the liquid or in the gas phase.

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## RECENT RESULTS FROM XMASS

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The XMASS project aims to detect dark matter, pp and <sup>7</sup>Be solar neutrinos, and neutrino-less double beta decay using ultra pure liquid xenon. Recent results from the XMASS experiment which employs 835 kg of xenon as an active target are presented.

# 1 Introduction

The XMASS project <sup>1</sup> aims to detect dark matter, pp and <sup>7</sup>Be solar neutrinos, and neutrino-less double beta decay using ultra pure liquid xenon. Advantages of using liquid xenon as a target material are its large amount of scintillation light (42,000 photons/MeV), and its "self-shielding" ability, i.e., owing to its large atomic mass (Z = 54) and high density (~2.9 g/cm<sup>3</sup>), incoming gammas can be absorbed in a short distance from the detector surface, and hence liquid xenon itself acts as a shield for external gamma backgrounds. As the first phase, construction of the detector pursuing dark matter detection was started in April 2007 and completed in September 2010. After installation of purified xenon, commissioning runs were conducted from December 2010 until June 2012. In this paper, recent results and future prospects of XMASS are presented.

#### 2 Experimental setup

The XMASS detector <sup>2</sup> is located underground (2,700 m water equivalent) in the Kamioka Observatory in Japan. Figure 1 shows a schematic drawing of the detector. It is a single phase liquid xenon scintillator detector containing 835 kg of liquid xenon in an active region. The volume is viewed by 630 hexagonal and 12 cylindrical Hamamatsu R10789 photomultiplier tubes (PMTs) arranged on an 80 cm diameter pentakis-dodecahedron support structure. A total photocathod coverage of 62.4% is achieved. In order to shield the liquid xenon detector from external gammas, neutrons, and muon-induced backgrounds, the copper vessel is placed at the center of a  $\phi 10 \text{ m} \times 11 \text{ m}$  cylindrical tank filled with pure water. The water tank is equipped with 72 Hamamatsu R3600 20-inch PMTs to provide both an active muon veto and passive shielding against these backgrounds. The liquid xenon and water Cherenkov detectors are hence called an Inner Detector (ID) and an Outer Detector (OD), respectively.

Signals from each PMT are fed into ADCs and TDCs. For each PMT channel the discriminator threshold is set to 0.2 photoelectron (p.e.) equivalent. When the number of hit PMTs in ID within a 200 ns window exceeds a certain threshold, an ID trigger is issued. In the same manner, an OD trigger is generated. A global trigger is asserted by either of them to initiate



Figure 1: Schematic drawing of the XMASS detector.

data acquisition for each event. Typical trigger rates for ID and OD are  $\sim 4$  Hz and  $\sim 7$  Hz, respectively.

Energy and position reconstruction calibrations are performed at several energies and positions along the central vertical axis (z-axis) using radioactive sources ( $^{55}$ Fc,  $^{57}$ Co,  $^{109}$ Cd,  $^{137}$ Cs, and  $^{241}$ Am). Using 122 keV gammas from the  $^{57}$ Co calibration source placed at the center of the detector, the xenon light yield was measured to be 14.7 p.e./keVee. Since the 5.9 keV X-ray from  $^{55}$ Fe is the lowest energy calibration point, the response at lower energies is extrapolated using a linear fit through all calibration energies.

# 3 Light WIMP search

Weakly Interacting Massive Particles (WIMPs), the most possible dark matter candidates, can be detected directly through observation of nuclear recoils produced in their elastic scattering interactions with detector nuclei. Although many theories of physics beyond the Standard Model predict WIMPs with mass larger than 100 GeV, some experiments indicate a possible WIMP signal with a lighter mass of ~10 GeV<sup>3,4,5</sup>.

The XMASS Collaboration has performed a search for low mass WIMPs  $^{6}$ . The data set used for this analysis, corresponding to 6.70 days of livetime, was taken in February 2012 with a low trigger threshold of four PMT hits in ID. A sequence of data reduction is applied to remove events caused by the tail of the scintillation light distribution after energetic events; (1) events triggered only with the liquid xenon detector are selected, (2) events that occurred within 10 ms of the previous event are rejected, and (3) events whose timing distribution has an RMS greater than 100 ns are removed. An additional cut is applied to remove Cherenkov events originated from  ${}^{40}$ K contamination in the PMT photocathodes; events with more than 60% of their PMT hits occurring within the first 20 ns of the event window are removed as Cherenkov-like. The observed spectrum does not have any prominent feature which suggests positive evidence of WIMP signals over background. In order to set a conservative upper bound on the spin-independent WIMP-nucleon cross section, the cross section is adjusted until the expected event rate in XMASS does not exceed the observed one in any energy bin above the analysis threshold. The analysis threshold is chosen as the energy at which the trigger efficiency is greater than 50% for 5 GeV WIMPs and corresponds to 0.3 keVee. Figure 2 shows the resulting 90% confidence level (C.L.) limit derived from this procedure. Systematic uncertainties in the energy scale, and the trigger and selection efficiencies are taken into account. The impact of the uncertainty from the scintillation efficiency,  $\mathcal{L}_{\text{eff}}$ , is large in this analysis, so its effect on the limit is shown separately in the figure. Without discriminating between nuclear-recoil and electronic




Figure 2: Spin-independent WIMP-nucleon cross section as a function of WIMP mass.

Figure 3: Limits on the axion-electron coupling constant  $(g_{ace})$  as a function of axion mass.

events, XMASS sets an upper limit on the WIMP-nucleon cross section for WIMPs with masses below 20 GeV and excludes part of the parameter space allowed by other experiments.

#### 4 Axion search

Axion is a hypothetical particle which is invented for solving the CP problem in the strong interactions. The particle would be produced in the sun through various mechanisms; in this paper, we focus on Compton scattering of photons on electrons,  $e+\gamma \rightarrow e+a$ , and bremsstrahlung of axions from electrons,  $e+Z \rightarrow e+a+Z^7$ . In the liquid xenon detector, axions can be detected through the axio-electric effect, which is an analog of the photo-electric effect.

In order to search for solar axion in XMASS, the same data set as used for light WIMPs search is analyzed <sup>8</sup>. No prominent feature which suggests a positive evidence of axion signals over background is observed. Hence, by adopting a criteria that the expected signal cannot be larger than the observed spectrum at 90% C.L., upper limits on the axion-electron coupling constant,  $g_{aee}$ , are derived. Figure 3 shows a summary of the upper limits on  $g_{aee}$ . The best direct experimental limit on  $g_{aee}$  is obtained, and the limit is close to the one obtained theoretically based on the consistency between the observed and expected solar neutrino fluxes.

# 5 Understanding backgrounds

It is important to understand background contamination in order to look for positive evidences of signals. The most backgrounds after the standard selection mentioned above were originally considered to be gammas emitted from radioactive contaminations in PMTs. However, studies of the origin of the background reveals that most of it originates from the inner surface of the detector. Aluminum sealing parts for the PMT, which are faced to liquid xenon, have contaminations of  $^{238}$ U and  $^{210}$ Pb, confirmed by a measurement with a high purity germanium detector. The inner surface of the PMT support structure is contaminated by  $^{210}$ Pb, indicated by a measurement of alphas in the detector. Figure 4 shows the observed energy spectrum overlaid with simulated spectrum based on the measured activities. Though backgrounds are identified above 5 keV, origins of events below 5 keV are not completely understood. Contamination of  $^{14}$ C in the GORE-TEX<sup>®</sup> sheets between the PMTs and the support structure may explain a fraction of the events. Light leaks through this material are also suspect.



Figure 4: Observed energy spectrum overlaid with simulated background spectrum.



Figure 5: Projected sensitivity of XMASS-1.5 to spin-independent WIMP-nucleon scattering.

# 6 Outlook

The XMASS Collaboration are working on modifications to the inner surface of XMASS, especially around the PMTs, to improve the detector performance. Data-taking will be resumed in summer 2013. By selecting fiducial volume events using an event reconstruction, more sensitive searches are expected to be done. Further discrimination of surface background using hits' timing information is also underway. As a further next step, the XMASS detector will be upgraded to contain total liquid xenon mass of 5 tons (1 ton fiducial mass), which is called XMASS-1.5. The projected sensitivity to spin-independent WIMP-nucleon scattering is shown in Figure 5.

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#### Underground Commissioning of LUX

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LUX is a dual-phase xenon TPC designed for the direct detection of dark matter. Using 370 kg of xenon, LUX is capable of setting a WIMP-nucleon cross section limit at  $2 \times 10^{-46}$  cm<sup>2</sup> after 300 days of running. LUX will surpass all existing dark matter limits for WIMP masses above 10 GeV within weeks of beginning its science run. Following a successful six month surface run, the detector has recently been deployed underground, and we expect completed commission in the near future. Updates on status and results are provided.

## 1 Introduction

Evidence in favor of a mass component of the universe that is uncoupled from the generation of electromagnetic radiation has been accumulating for 80 years<sup>1</sup>. It is known that non-baryonic dark matter makes up a majority of the mass density of the universe<sup>2</sup>. Observational evidence is plentiful and includes galaxy cluster rotation profiles that suggest large, extended mass distributions that conflict with the mass distribution of the largest known mass contributor, intergalactic gas. A weakly interacting massive particle (WIMP) can be constructed in a number of models<sup>3</sup> as a heavy dark matter candidate that would interact with baryonic matter via nuclear scattering<sup>4</sup>.

## 2 Operating Principle

The Large Underground Xenon Experiment (LUX) has deployed a dual phase xenon time projection chamber for direct detection of dark matter. Liquid xenon's density makes it a very attractive target for direct dark matter searches. The LUX detector contains 370 kg of liquid xenon with 300 kg in the active region where signal can be extracted. To illustrate our event topology, an event schematic in LUX is shown in Figure 1. Energy depositions are partitioned in to scintillation light and ionization. Immediate partial recombination of the ionization signal with Xe ions can occur leading to additional scintillation. The scintillation signal (S1 signal) is prompt and collected in timescales on the order of 100 ns.

An electric field is established from the top of the gaseous xenon to the bottom of the liquid xenon space. Ionized electrons are slowly drifted to the liquid surface where electron extraction occurs. Electrons enter into the gaseous region where acceleration in the electric field causes electroluminescence, creating additional scintillation light in the timespan of microseconds. This delayed ionization signal (S2 signal) is separated in time from the S1 signal proportional to the depth of the energy deposition, and measurement of the time difference allows realization of the z location of the event. The S2 signal provides (x,y) information thus permitting full three-dimensional position reconstruction.



Figure 1: Event schematic in the LUX detector. An energy deposition causes ionization and prompt light (S1). An applied electric field drifts ionization electrons to the gas gap where extraction occurs and electroluminescence creates a delayed light signal (S2). The size of the S2 is proportional to the charge that reached the surface, and the time separation is proportional to the depth of the energy deposition in the liquid xenon.

# 3 The Detector

The details of the detector are described in greater detail elsewhere  $^5$ . An inner and outer cryostat constructed from low-background titanium<sup>6</sup> house the internals of the experiment. Internal support structures that are not load-bearing are machined oxygen-free high thermal conductivity copper.

LUX is instrumented with 122 low-background Hamamatsu R8778 PMTs<sup>7</sup>. The 2" tubes have a measured quantum efficiency ~33% and are separated in to two banks of 61 tubes. The upper bank reconstructs (x,y) position based on the hit pattern of the S2 signal in gaseous xenon while the bottom array is located in liquid xenon and benefits from enhanced light collection for the primary scintillation signal providing improved energy reconstruction.

The electric field is separated into multiple field regions by a collection of four wire grids and one wire mesh. Near the top and bottom PMT banks, reverse biased grids create electromagnetic shields to prevent charge collection from occurring around the photosensors. The cathode grid at the bottom of the active region delivers a large negative voltage that establishes a drift field across the bulk of the detector. A gate grid just below the liquid surface marks the end of the drift field and the beginning of the extraction field. A large positive voltage applied to the anode mesh in the gas phase, together with the gate grid, create (over a distance of 1 cm) a large extraction field for removing electrons from the liquid.

### 4 Surface Run

The LUX detector was deployed in a surface laboratory at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA, for an above ground run while final excavation and construction of the underground laboratory concluded. The surface laboratory was meant to mimic the underground environment to achieve as similar installation and operating conditions as possible. The same detector stand, the same **w**ansportation structures, and the same style of cleanroom served as excellent tools to perfect underground deployment. The only significant difference between the surface laboratory and the underground facility was a diminished surface water tank (3 m diameter) versus the subterranean tank (8 m diameter). Without the rock overburden of the underground lab, the surface run had significantly higher background rates than are allowable for any rare event dark matter search. The surface water tank provide observable particle flux moderation but did not provide anything similar to operating deep underground.

The surface run began on September 1, 2011 and ended February 14, 2012 after over 100 days of cryogenic detector operation. The LUX surface run accomplished all set goals and demonstrated all





Figure 2: Measurement of the 204  $\pm$  6  $\mu$ s drift time (left) and reconstruction of x,y event locations using the Mercury reconstruction algorithm (right).

subsystems are capable of performing at or beyond operational goals<sup>8</sup>, with the exception of a single lose fitting that partially compromised our circulation path.

### 4.1 Surface Results

The xenon purification system achieved an electron lifetime of  $204 \pm 6 \mu s$  while purifying at 35 slpm, as shown in Figure 2 (left). This rate is equal to 300 kg/day (a majority of the LUX mass). We achieved >98% heat exchanger efficiency (<5 W heat load). The light collection measurements indicated 8 phe/keVee (>4 phe/keVee) at the center of the detector with zero field (field-adjusted, scaled to 122 keV) with lower bounds on PTFE reflectivity of >95% and a photoabsorption length of >5 m.

LUX implemented the Mercury position reconstruction algorithm<sup>9</sup> which uses a maximum likelihood analysis of measured phototube light response functions and the measured intensity of the S2 signal in each PMT to estimate the (x,y) location of an event. Figure 2 (right) shows the dodecagonal silhouette of the PTFE walls of the interior of LUX as well as the clear orientation of the thin gate grid wires that create the electron extraction field just below the liquid surface. The 5 mm spacing of the gate grid wires provide a relative indication of the performance of the reconstruction.

In addition, using the coincident decay of the 3.3 MeV  $\beta^-$  and then the 7.7 MeV  $\alpha$  radiation from decay chain <sup>214</sup>Bi  $\rightarrow$  <sup>214</sup>Po  $\rightarrow$  <sup>210</sup>Pb, our reconstruction technique has shown to reconstruct with a resolution of ~7 mm in each of the x and y directions. Although these are significantly higher energies than the dark matter energy window, a lower photomultiplier gain was required for surface running to prevent possible photocathode degradation due to large and continuous S2 signals from cosmic ray backgrounds, thus allowing the comparison of high energy, low gain S2 reconstruction to projected low energy, high gain S2 reconstruction.

### 5 Commissioning

Following the successful operation on the surface, we emptied the detector of xenon and transported the LUX detector 1480 m (4300 m.w.e) underground. The process of transporting a fully instrumented detector and attached breakout systems began on July 11, 2012. Two days of meticulous adjustments and translations culminated with LUX in the new Davis Laboratory ready for deployment. Unpacking and installation proceeded until September 2012. In October, the water tank was filled (Figure 3) and the detector began collecting vacuum Čerenkov data. With the introduction of gaseous xenon in December 2012, LUX began a stabilization and purification period to better understand run conditions and



Figure 3: The LUX detector situated in the filled 8 m by 6 m water tank. Installation occurred while the tank was empty of water and personnel. A portion of the detector stand is visible on the left, with the outer cryostat of the detector on the right.

parameterize operating behaviors underground.

#### 6 Outlook

The LUX detector was successfully deployed and is ramping up for a preliminary dark matter run in 2013. The detector is currently operating underground, and is circulating and purifying liquid xenon at SURF. Calibrations are underway to improve our understanding of the detector response in a quiet, underground environment. After full detector commission is finished and all subsystems have been operationally verified, we will begin a 60 day WIMP dark matter run with results expected by the end of the year.

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### DIRECTIONAL DARK MATTER DETECTION

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The hypothesis of the existence of non-baryonic dark matter in our galactic halo is supported by all astrophysical observations performed from cosmological to local scales. The direct detection of an elastic collision with a target nucleus of a weakly interacting massive particle (WIMP), the most accepted candidate for such a matter, has to be discriminated from those produced by neutrons. The only non-ambiguous signature to be able to discriminate the WIMP events from background is to correlate those elastic collisions in the detector with the relative motion of our Solar system with respect to the galactic halo. It is the measurement of the direction in 3D of nuclear recoil tracks of a few tens of keV what is called directional detection. The directional detection opens a new field in cosmology bringing the possibility to build a map of nuclear recoils exploring the galactic halo and giving access to a particle characterization of dark matter. Many experiments all around the world try to demonstrate the ability to get this signature. This short and inevitably incomplete review will summarize the techniques and status of the most important experiments running in an underground site;, DRIFT, DMTPC, NEWAGE, Nuclear Emulsions and MIMAC.

# 1 Introduction

Cosmological and astrophysical observations converge to a standard cosmological model requiring a new kind of particle to explain a large amount of non-baryonic dark matter, being one of the most favorable candidates a stable weakly interacting massive particle (WIMP). In the context of direct detection of these new particles an alternative, complementary and in any case needed strategy is the development of detectors providing an unambiguous positive WIMP signal. Indeed, directional detection gives a new degree of freedom to reject neutrons, the particles that produce the same expected signal from the nuclear recoil energy. This can be achieved by searching for a correlation of the WIMP signal with the solar motion around the galactic center, observed as a direction dependence of the WIMP stream<sup>12</sup>, coming from  $(1 = 90^{\circ}, b = 0^{\circ})$  in galactic coordinates, which happens to be roughly in the direction of the constellation Cygnus. The background events, coming from gamma rays and neutrons produced in the atmosphere or in the rock should follow the rotation of Earth isotropic in galactic coordinates and very different with respect to the Cygnus direction. A dedicated statistical study with simulated data analysis has shown that even a low-exposure, directional detector could allow a high significance discovery of galactic Dark Matter even with a sizeable background contamination<sup>3</sup> or to a robust and competitive exclusion curve<sup>4</sup>, depending on the value of the unknown WIMP-nucleon cross section. In<sup>5</sup>, a study has been performed on the capability of directional detectors to probe neutralino dark matter in the Minimal Supersymmetric Standard Model and the Next-to-Minimal Supersymmetric Standard Model with parameters defined at the weak scale. It shows that directional detectors at a scale of 50  $\mathrm{m}^3$  will probe spin dependent dark matter scattering on nucleons that are beyond the reach of current most spin independent sensitive detectors being the scalar and axial cross section not correlated. The very weak correlation between the neutralino-nucleon scalar cross section and the axial one, as it was shown, in 2005 by E. Moulin et al. <sup>6</sup>and more recently by D. Albornoz et al<sup>5</sup>, makes this research, at the same time, complementary to the massive target experiments.



Figure 1: (Left) Proton-neutralino spin dependent elastic scattering cross section versus the neutralino mass with the exclusion and discovery projections for a 30 kg.year MIMAC detector. Points correspond to MSSM configuration allowed by collider and cosmological constraints. In blue safe points and in yellow points excluded by either XENON100 or Fermi-LAT. Figure from [19]. (Centre) The result of a maximum likelihood analysis of the map shown in (Right) giving the correct number of Wimp events (=S/(S+B) 0.5) and the directionality in galactic coordinates (=900, b=00). (Right) The map made with 100 events assuming the neutron background at the same level than the signal (S/B=1) that means 50 Wimp events and 50 of background.

The main interest of the directional detection is based on the fact that the WIMP angular distribution is pointing towards the Cygnus constellation while the background one is isotropic. The right panel of figure 1 presents a typical recoil distribution observed by a directional detector: 100 WIMP-induced events and 100 background events generated isotropically. For an elastic axial cross-section on nucleon  $\sigma_n = 1.5 \times 10^{-3}$  pb and a 100 GeV.c<sup>-2</sup> WIMP mass, this corresponds to an exposure of  $\sim 1.6 \times 10^3$  kg.day in CF<sub>4</sub>, as discussed in ref.<sup>3</sup>. Low resolution maps are used in this case  $(N_{\text{pixels}} = 768)$  which is sufficient for the low angular resolution,  $\sim 15^{\circ}$  (FWHM), expected for this type of detector. In this case, 3D read-out and sense recognition are considered, while background rejection is based on electron/recoil discrimination by track length and energy selection <sup>7</sup>. It is not straightforward to conclude from the recoil map of figure 1 (right) that it does contain a fraction of WIMP events pointing towards the direction of the solar motion. To extract information from this example of a measured map, a likelihood analysis has been developed. The likelihood value is estimated using a binned map of the overall sky with Poisson statistics, as shown in <sup>3</sup>. This is a four parameter likelihood analysis with  $m_{\chi}$ ,  $\lambda = S/(B+S)$  the WIMP fraction (B is the background spatial distribution taken as isotropic and S is the WIMP-induced recoil distribution) and the coordinates  $(\ell, b)$  referring to the maximum of the WIMP event angular distribution.

The result of this map-based likelihood method is that the main recoil direction is recovered and it is pointing towards ( $\ell = 95^{\circ} \pm 10^{\circ}, b = -6^{\circ} \pm 10^{\circ}$ ) at 68 % CL, corresponding to a non-ambiguous detection of particles from the galactic halo. This is indeed the discovery proof of this detection strategy (centre panel of fig. 2)<sup>3</sup>. Furthermore, the method allows to constrain the WIMP fraction in the observed recoil map leading to a constraint in the ( $\sigma_n, m_{\chi}$ ) plane (left panel of fig. 2). As emphasized in ref.<sup>3</sup>, a directional detector could allow for a high significance discovery of galactic Dark Matter even with a sizeable background contamination. For very low exposures, competitive exclusion limits may also be imposed <sup>4</sup>. We have recently shown by a Markov Chain Monte Carlo analysis<sup>8</sup> that the directionality opens the way to characterize also the dark matter particle mass describing at the same time our galactic halo, as shown in fig. 2.

A gas TPC can aim at achieving measurement of the direction of WIMP-induced nuclear



Figure 2: Marginalized distributions (diagonal) and 2D correlations (off-diagonal) plots of the 7 parameters from the analysis of simulated data in the case of an isothermal halo with a WIMP mass of 50 GeV.c-2 and a WIMP-nucleon cross section n = 103 pb, see<sup>8</sup> for more details

recoils. After a WIMP collision, the nuclei recoils with typical energies of 1-100 keV, travel distances of the order of few 100 amstrongs in solids, while in gases this distance can be up to the mm scale, depending on the type and pressure of the gas. Many projects over the world, DRIFT (USA, UK), DM-TPC (USA), Newage (Kyoto -Japan) , Nuclear Emulsions (Japan) and MIMAC (France), try to achieve the goals proposed for directional detection using different techniques. These efforts have been summarized at the status of 2009, in a collective work<sup>9</sup> and in June 2011, the third international workshop on directional dark matter detection CYGNUS 2011 was held at Aussois (France) and the proceedings were edited <sup>10</sup>. A brief and inevitably incomplete description of the most important projects will be done in the following sections.

### 2 DRIFT

The Directional Recoil Information From Tracks (DRIFT) dark matter collaboration at Boulby has, since 2001, pioneered construction and operation underground of low background directional TPCs at the 1 m<sup>3</sup> scale with Multi-wire Proportional Counter (MWPC) readout using negative ion (NITPC) CS<sub>2</sub> gas to suppress diffusion without magnetic fields.<sup>11</sup> The NITPC concept, as demonstrated first in DRIFT I, allows larger drift distances (> 50 cm) than is feasible with conventional gases like CF<sub>4</sub>, thereby reducing the required readout area and hence cost <sup>12</sup>. Operation with 1 m<sup>2</sup> MWPC readout planes allows the study of realistic size detectors underground with near-conventional technology.

In DRIFT, the ionization generated from recoil events (mainly S recoils) goes to create tracks of  $CS_2$  negative ions. Under the influence of an applied electric field, the negative ions drift to one of the two back-to-back MWPC planes for readout. The MWPCs include two orthogonal layers (x and y) of 512 20 micron wires with 2 mm spacing. Wires are grouped to reduce the number of readout channels. Reconstruction is feasible in 3D using timing information for the z direction (perpendicular to the x-y plane of wires). Additional R&D is underway to allow absolute z positioning, though some z positioning is feasible already through pulse shape analysis. Calibration is undertaken typically every 6 hours using internal <sup>55</sup>Fe sources (one for each MWPC) that are shielded by an automated shutter system when not in use.

The Boulby program, particularly with the second generation  $1 \text{ m}^3$  scale DRIFT IIa-d experiments since 2006 (see Fig. 3 and  $1^2$ ), has recently made progress on the practical understanding of all background types for directional TPCs operated underground, on scale-up issues such as safety and backgrounds, and on directional sensitivity, for instance demonstrating for the first time sensitivity to recoil direction sense (head-tail discrimination) at low energy (47 keV S recoil).<sup>13</sup>

Recently, very important improvements have been done on the radon progeny events reduction and on space fiducialization from minority charge carriers.



Figure 3: DRIFT IIb detector at Boulby mine. Two back-to-back TPCs each with a 50 cm drift distance, share a common vertical central cathode. Readout is done with two 3-layer MWPCs with 2 mm wire spacing. Operation is with negative ion CS<sub>2</sub> gas at 40 Torr (170 g target mass)<sup>12</sup>

## 3 DMTPC

The Dark Matter Time Projection Chamber (DMTPC) collaboration has developed and operated a 10-liter gas-based directional dark matter detector. The current instrument consists of a dual TPC, filled with CF<sub>4</sub> gas at ~75 Torr. Proportional scintillation from the avalanches is read out with two CCD cameras. The charge on the TPC anode is also measured. With this instrument, DMTPC has demonstrated head-tail sensitivity for neutron-induced recoils above 100 keV, and an angular resolution for track reconstruction of 15° at 100 keV. A detector is running underground at the Waste Isolation Pilot Plant (WIPP) at a depth of 1600 meters water equivalent.

The 10-liter DMTPC detector is shown in Fig. 4. The dual-TPC is housed inside a stainless steel vacuum vessel. The drift region is defined by a woven mesh cathode, typically at a potential of -5 kV, separated from a wire mesh (28  $\mu$ m wire, 256  $\mu$ m pitch) ground grid 20 cm away. The vertical drift field is kept uniform to within 1% by stainless steel field-shaping rings spaced 1 cm apart. An amplification region is formed between the ground grid and a copper-clad G10 anode plane (at 720 V) which are separated from each other by 500  $\mu$ m using resistive spacers (currently fishing line). A charge amplifier connected to the anode measures the ionization generated by a particle moving through the detector. A CCD camera images the proportional scintillation light generated in the amplification region. The CCD camera and readout electronics are located outside of the vacuum vessel. The mesh-based amplification region allows for two-dimensional images of charged particle tracks.

With a CF<sub>4</sub> pressure of 75 Torr, gas gains of approximately  $10^5$  are routinely achieved with minimal sparking. The energy resolution of the charge readout is 10% at 5.9 keV (measured with an  $^{55}$ Fe source), and is 15% at 50 keV for the CCD readout (measured with an alpha source). Since the stopping d E/dx in the detector is much smaller for electrons than for nuclear recoils, the surface brightness of an electron track is dimmer, and electron tracks are easily distinguished from nuclear recoils. The gamma rejection of the detector was measured to be >  $10^6$  using an 8  $\mu$ Ci  $^{137}$ Cs source<sup>14</sup>. For more details on background studies, see  $^{15}$ .

A program is underway to achieve full volume fiducialization by measuring the z-coordinate of an interaction in the TPC. This can be achieved through the detection of primary scintillation light or from an analysis of the charge pulse profile on the cathode. Techniques to reconstruct the third dimension of tracks ( $\Delta z$ ) from the charge or PMT signal at the amplification region are also under development. In addition, a cubic meter detector design was done and its construction recently funded.





Figure 4: (left) Photograph of the 10-liter DMTPC detector with an image of the dual TPC overlaid to provide an artificial glimpse inside the vacuum vessel. The CCD cameras (top and bottom) each image an amplification region. The stack of stainless steel field shaping rings condition the drift fields. (right) A schematic representation of a WIMP-nucleus elastic scattering event in the detector.

### 4 NEWAGE

NEWAGE (NEw generation WIMP-search With an Advanced Gaseous tracking device Experiment) is a direction-sensitive dark matter search experiment with a gaseous micro-time-projection chamber ( $\mu$ -TPC) that began detector R&D in 2003, and published the first direction-sensitive dark matter limits in 2007 (see <sup>16</sup>.

The NEWAGE collaboration has been studying the detector background in the Kamioka Underground Observatory since  $2007^{17}$  and important improvements on radon filtration and discrimination have been done.

The NEWAGE-0.3a detector, the first version of the  $(0.3m)^3$ -class prototypes, is a gaseous  $\mu$ -TPC filled with CF<sub>4</sub> gas at 152 Torr. The effective volume and the target mass are 20 × 25 × 31 cm<sup>3</sup> and 0.0115 kg, respectively. For details of the detector system and performance studies, see<sup>17</sup>. A picture of the NEWAGE-0.3a detector is shown in Fig. 5. The NEWAGE-0.3a detector is read out by a 30.7 × 30.7 cm<sup>2</sup>  $\mu$ -PIC. A  $\mu$ -PIC is one of the several types of micro-patterned gaseous detectors. By orthogonally-formed readout strips with a pitch of 400  $\mu$ m, the  $\mu$ -PIC can generate two-dimensional images. A design of 1 m<sup>3</sup> detector is underway.

### 5 Nuclear Emulsions

Nuclear emulsions allow for both tracking resolution and large target mass, which has great potential for directional dark matter detection. Emulsions are photographic films composed of AgBr and gelatin that can be used as 3D tracking detectors with  $\sim 1 \ \mu m$  resolution. Nuclear emulsions may be useful in a directional dark matter search if they can detect the nuclear recoil tracks from WIMP interactions with sufficient accuracy.

The high density ( $\sim 3 \text{ g/cm}^3$ ) of emulsions, and extremely high resolution are the strongest points. From SRIM simulations, the expected range of a WIMP-induced nuclear recoil track is of the order of 100 nm. However, it is difficult to detect nuclear recoil tracks in standard emulsions because the maximum resolution is about 1  $\mu$ m. Therefore, it has developed a new



Figure 5: Picture of the NEWAGE-0.3a detector.



Figure 6: Electron microscope image of standard emulsion (left) and NIT emulsion (right)

11 grains/µm

2.3 grains/µm

high-resolution nuclear emulsion, called the "Nano Imaging Tracker" (NIT).<sup>18</sup> In the NIT, the AgBr crystal size is 40±9 nm and the density is 2.8 g/cm<sup>3</sup>. The density of AgBr that an incoming particle can penetrate is 11 AgBr/µm (Fig. 6). When one considers a dark matter search, it is not realistic to use an electron microscope to scan a large volume of emulsions. Furthermore, nuclear recoil tracks which are less than 1 µm long (smaller than the optical resolution) cannot be identified as tracks by an optical microscope. To resolve this problem, a method was developed to expand the tracks.

Nuclear recoil tracks consist of grains spanning roughly 100 nm. If the emulsion is then expanded, the inter-grain spacing grows and the track length is expanded to several  $\mu$ m. With this technique, nuclear recoil tracks may be identified by an optical microscope. It has been used a pH-controlled chemical treatment to expand the emulsion. As a result, tracks from Kr ions with E > 200 keV attained lengths of several  $\mu$ m, and could be recognized as tracks by an optical microscope. Such tracks could be distinguished from random noise (fog) because the fog consists of single grain events. The angular resolution of the original state for NIT is about 12 degrees or better. However, the angular resolution is expected to be about 45 degrees



with the expansion technique. In practice, if the expansion technique is used, two or more NIT emulsion detectors should be mounted in the directions horizontal and vertical to Cygnus on an equatorial telescope.

### 6 MIMAC

The MIMAC (MIcro-tpc MAtrix of Chambers) project <sup>19</sup>, started in 2003, has recently built a bi-chamber prototype consisting of two chambers of (10 cm x 10 cm x 25 cm) with a common cathode, which is the elementary module of the future large matrix. The purpose of this prototype is to show the ionization and track measurement performances needed to achieve the directional detection strategy. The primary electron-ion pairs produced by a nuclear recoil in one chamber of the matrix are detected by driving the electrons to the grid of a bulk micromegas <sup>24</sup> and producing the avalanche in a very thin gap (256 $\mu$ m).



Figure 7: (Left): The anode is read every 20 ns and knowing the drift velocity of primary electrons the 3D track can be reconstructed from the consecutive number of images defining the event. (Right): A picture of the MIMAC bi-chamber detector installed at Modane in June 2012

As schematically shown on figure 7, the electrons are collected towards the grid in the drift space and are multiplied by avalanche to the pixellized anode thus allowing to get information on X and Y coordinates. To have access to the X and Y coordinates a bulk micromegas<sup>24</sup> with a 10 by 10 cm active area, segmented in pixels with a pitch of 424  $\mu$ m was used as 2D readout <sup>21</sup>. In order to reconstruct the third coordinate Z of the points of the recoil track, the LPSC developed a self-triggered electronics able to perform the anode sampling at a frequency of 50 MHz. This includes a dedicated 64 channels ASIC<sup>22</sup> associated to a DAQ<sup>23</sup>.

In order to get the total recoil energy we need to know the ionization quenching factor (IQF) of the nuclear recoil in the gas used. The MIMAC team has developed at the LPSC a dedicated experimental facility to measure such IQF. A precise assessment of the available ionization energy has been performed in <sup>4</sup>He + 5%C<sub>4</sub>H<sub>10</sub> mixture within the dark matter energy range (between 1 and 50 keV) by a measurement of the IQF <sup>25 26</sup>. For a given energy, an electron track in a low pressure micro-TPC is an order of magnitude longer and showing more straggling than a recoil one. It opens the possibility to discriminate electrons from nuclei recoils by using both energy and track information, as it was shown in <sup>19</sup> and <sup>20</sup>.

In June 2012, we have installed the bi-chamber module, at the Underground Laboratory of Modane (LSM). In order to characterize the total background of our detector at Modane, we worked without any shielding. Besides the very good stability of the calibration validating the gas circulation, one of the most interesting facts observed during this first run was the measurement for the first time of 3D tracks of nuclear recoils in the range of 30 keV in ionization. The 10 cm by 10 cm micromegas coupled to the MIMAC electronics running the 512 channels per chamber and working at high gain and without any problem during a long period of time (4 months in our first run at Modane), is in fact the validation of the feasibility of a large TPC for directional detection. As an illustration of the high quality of data obtained at Modane, we show on fig.8 a very interesting recoil event of 34 keV in ionization. For more details on the



Figure 8: A 3D recoil track measured at 34 keV in ionization: On the left, the X-Y plane of the anode showing the intersections of the strips fired. On the centre, the X projection as a function of time, every 20 ns. On the right, the same but for the Y projection

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# COUPP: BUBBLE CHAMBERS FOR DARK MATTER DETECTION

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COUPP uses bubble chambers filled with  $CF_3I$  to search for spin-dependent WIMP-proton and spin-independent WIMP-nucleon interactions. The target material is in a mild superheated state and rendered insensitive to electromagnetic interactions by a suitable choice of the pressure and temperature. Particles crossing the CF<sub>3</sub>I can interact with nuclei and produce bubbles. The images of the bubbles as well as their acoustic signal are recorded by two cameras and piezo-acoustic transducers, respectively. The acoustic discrimination efficiency between alphas and neutrons has been measured to be better than 99%. Results from two physics runs at SNOLAB showed an improvement in alpha discrimination and in sensitivity compared to

# 1 Introduction

a previous run at Fermilab.

COUPP, the Chicagoland Observatory for Underground Particle Physics, makes use of bubble chambers to search for dark matter. The nucleation of bubbles is induced by single nuclear recoils due to WIMP-nucleon elastic scattering, neutron interactions or alpha decays. When the thermodynamic parameters (pressure and temperature) are appropriately tuned, nucleations by electromagnetic radiation can be suppressed at the level of  $10^{-101}$ .

The COUPP bubble chambers consist of synthetic fused silica jars filled with  $CF_3I$  as the target material and ultra pure water as a buffer. The system is enclosed in a stainless steel pressure vessel filled with an hydraulic fluid, propylene glycol, and connected to a pressure control unit. A more detailed description of the apparatus as well as the data analysis can be found elsewhere<sup>2</sup>.

Two bubble chambers have been operated deep underground at SNOLAB. COUPP4 (Fig. 2) was installed in the summer of 2010, acquiring data in two physics runs. The first physics run from September 2010 to August 2011 accumulated 553 kg-days of livetime with 4.048 kg of CF<sub>3</sub>I, and the results have already been reported <sup>2</sup>. The second physics run from May to November 2012 accumulated 499 kg-days with 4.052 kg of CF<sub>3</sub>I, and the results are reported here.

COUPP60 (Fig. 4) was installed from May 2012 to May 2013 and is currently under commissioning, with the expected start of data taking in mid June 2013. The detector has registered the first events, with an active mass of 36.8 kg of CF<sub>3</sub>I.

# 2 Results

Results from the first physics run at SNOLAB reported by the COUPP collaboration in 2012 pointed to at least one unknown background that produced 20 single and 3 multiple bubble



Figure 1: Three bubble event in COUPP4. Neutrons may produce more than one bubble due to the 15 cm mean free path in  $CF_3I$ . The ratio of singles to multiples in COUPP4 is 3:1. The fused silica jar with  $CF_3I$  and water buffer on top (interior), as well as propylene glycol and the piezoelectric acoustic transducers on top (exterior) can be observed.

events during a total exposure of 553 kg-days distributed over three different bubble nucleation thresholds. A screening campaign of several components in the detector led to two possible sources for five single nuclear recoils observed: four lead zirconate piezoelectric acoustic transducers epoxied on top (exterior) of the jar and four borosilicate glass viewports of the stainless steel pressure vessel. These components were replaced, using radioactively cleaner materials and a second physics run started on May 2012.

The results of the second physics run indicated no reduction in the backgrounds observed, as 16 single and 2 multiple bubble events were observed during a total exposure of 499 kg-days distributed over two different bubble nucleation thresholds. The physics run ended due to failures in the hydraulic system and piezoelectric acoustic transducers.

Table 1 summarizes the events observed during the two physics runs of COUPP4 at SNOLAB. The total single bubble event rate in the 2012 run is 0.0301 cts/kg/day at 34 C, to be compared with 0.026 cts/kg/day in the 2010-2011 run, and including all thresholds the total rate of multiple bubble events is 0.004 cts/kg/day in 2012 to be compared with 0.005 cts/kg/day in 2010-2011.

Table 1: Nuclear recoil events observed in COUPP4 during two physics runs at SNOLAB in 2010-2011 and 2012.

Run	201	12	2 2010-2011		1	
Exposure (kg-day)	553			499		
Threshold (keV)	16.3	8.1	15.5	11.0	7.8	
Single bubbles	8	8	8	6	6	
Multiple bubbles	0	2	1	2	0	

A second screening campaign took place using inductively coupled plasma mass spectrometry (ICP-MS) to assay several components such as the stainless steel pressure vessel and the water filled polypropylene tanks. The assay results haven't been completed at the time these proceedings are being written.

The exclusion plots for spin-independent WIMP-nucleon and spin-dependent WIMP-proton cross sections are shown in Figure 3 for the two COUPP4 physics runs at SNOLAB. As in the





Figure 2: COUPP4 detector in the J-drift at SNOLAB



Figure 3: 90% C.L. limits for spin-independent WIMP-nucleon (left) and spin-dependent WIMP-proton (right) elastic scattering. The dark blue line shows the exclusion limits for the 2012 run assuming an exponential efficiency model. The light blue band represents the systematic uncertainty in the bubble nucleation efficiency of fluorine recoils for the first physics run published in 2012, where the upper boundary assumes an exponential efficiency model and the lower boundary a flat efficiency model, as described in E. Behnke *et al.* 

results previously reported for the first physics run in 2010-2011<sup>2</sup>, no background subtraction has been attempted for the 2012 data. The 90% C.L. limits are therefore based on treating all nuclear recoil events as dark matter candidates. The calculations assume the standard halo parameterization<sup>3</sup>, with  $\rho_D = 0.3 \text{ GeV c}^{-2} \text{ cm}^{-3}$ ,  $v_{esc} = 544 \text{ km/s}$ ,  $v_E = 244 \text{ km/s}$ ,  $v_0 = 230 \text{ km/s}$ , and the spin-dependent parameters from the compilation in Tovey *et al*<sup>4</sup>.

# 3 Future of COUPP detectors

The COUPP collaboration has decided to decommission the existing COUPP4 detector. COUPP4 was able to prove that a bubble chamber can be operated deep underground and demonstrated excellent acoustic discrimination. It has set the best spin-dependent WIMP-proton cross section limits for direct searches and the lessons learned will be used to continue improving the programme for dark matter searches using bubble chambers.

Current efforts are focused towards a physics run of COUPP60 at SNOLAB, running initially with 36.8 kg of CF<sub>3</sub>I and potentially twice that by the end of the year (Fig. 4). COUPP also plans to operate an upgraded COUPP4 prototype, currently dubbed COUPP4-lite, using 2 liters

of  $C_3F_8$  in order to target low WIMP masses and spin-dependent interactions. This detector could reach a sensitivity of  $10^{-42}$  cm<sup>2</sup> for WIMP masses around 10 GeV in three months running at SNOLAB, being in a position to confirm or refute recent results claiming evidence for light WIMPs<sup>5</sup>. The infrastructure will consist of a new acrylic pressure vessel, as well as an upgraded hydraulic control. COUPP4-lite will be placed in the same location as the original COUPP4 at SNOLAB, and will make use of the same water filled polypropylene tanks as shielding. The data acquisition will remain similar to the previous efforts with CF<sub>3</sub>I.

The COUPP collaboration has recently merged with PICASSO in order to pursue a 500kg superheated detector at SNOLAB by 2015, and COUPP4-lite will be the first COUPP-PICASSO joined effort.



Figure 4: COUPP60 detector in the ladder labs at SNOLAB

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#### Dark Matter directional detection with MIMAC

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Directional detection is a promising direct Dark Matter (DM) search strategy. The angular distribution of the nuclear recoil tracks from WIMP events should present an anisotropy in galactic coordinates. This strategy requires both a measurement of the recoil energy with a threshold of about 5 keV and 3D recoil tracks down to few millimeters.

The MIMAC project, based on a  $\mu$ -TPC matrix, with  $CF_4$  and  $CHF_3$ , is being developed. In June 2012, a bi-chamber prototype was installed at the LSM (Laboratoire Souterrain de Modane). A preliminary analysis of the first four months data taking allowed, for the first time, the observation of recoils from the <sup>222</sup>Rn progeny.

# 1 Introduction: Directional detection

Dark Matter (DM) directional detection is based on the idea that the angular distribution of WIMP (Weakly Interacting Massive Particle) momentum directions should present an anisotropy in galactic coordinates <sup>1</sup>. This anisotropy is due to the relative motion of the solar system with respect to the cold galactic DM halo. Thus, the angular distribution of recoils produced by scattering of WIMPs on nuclei should present an anisotropy pointing towards the constellation Cygnus. Background events are instead isotropically distributed in Galactic coordinates. Using a profile likelihood analysis <sup>2</sup> it has been shown that it is possible to extract a DM signal from background events. As other directional detection experiments<sup>3</sup>, the aim of the MIMAC project is the measurement of nuclear recoil energy and angular distribution to search for this signature.

# 2 MIMAC detection strategy

The MIMAC detector is a low pressure  $\mu$ -TPC (Time Projection Chamber). When charged particles pass through the gas detector (e.g. CF<sub>4</sub>), they lose a part of their energy by ionization,

creating pairs of electrons and ions. These electrons are drifted to the grid by an electric field  $(E_{\rm drift} \sim 200 {\rm V.cm^{-1}})$ . Finally, after passing through the grid, these electrons are amplified by avalanche with a high electric field  $(E_{\rm aval} \sim 30 \, {\rm kV.cm^{-1}})$  reaching the pixelized anode. Fig. 1 right shows a small part of a  $10 \times 10 \, {\rm cm^2}$  pixelized micromegas<sup>4</sup> each pixel being 200 µm wide. By coupling a micro-pattern detector, such as a micromegas, with a fast and self-triggered electronics<sup>5</sup>, we are able to sample the 512 channels of the anode at 50 MHz. Fig. 1 left illustrates the ionization energy deposition, the charge collection and the sampling of a recoil track every 20 ns. The energy released by ionization is measured by a charges integrator (flash-ADC) connected to the grid. Knowing the drift velocity, nearly 20 µm/ns, which is also measurable with this setup <sup>6</sup>, a 3D track can then be reconstructed <sup>7</sup>.



Figure 1: Left: Scheme representing a nuclear recoil produced in the active volume of the detector and the sampling of the pixelized anode at 50 MHz of collected charges. Right: A picture of a small part of the micromegas pixels designed by IRFU Saclay (France) showing the 200 µm wide pixels.

### 3 MIMAC bi-chamber prototype at the Laboratoire Souterrain de Modane

The bi-chamber module shown in Fig. 2 left, is composed of two mirrored detectors sharing the same cathode. The prototype active volume ( $V \sim 5.8 \,\mathrm{L}$ ) is filled with the following gas mixture : 70 % CF<sub>4</sub> + 28 % CHF<sub>3</sub> + 2 % C<sub>4</sub>H<sub>10</sub> at a pressure of 50 mbar. The MIMAC bi-chamber prototype was installed at the Laboratoire Souterrain de Modane (LSM) in June 2012 for four months of data taking in an underground laboratory. By means of an X-ray generator, the detector has been weekly calibrated with fluorescence photons from metal foils. The gas circulation system includes a buffer volume, an oxygen filter, a dry pump and a pressure regulator. It allows to keep the gas quality stable in a closed circuit. Indeed, the presence of impurities and O<sub>2</sub> must be controlled to to prevent gain and resolution degradation of the detector.

Fig. 2 right shows the slope coefficient of a linear calibration as a function of time, highlighting the gain stability during this data taking period.



Figure 2: Left: The bi-chamber prototype at the Laboratoire Souterrain de Modane in June 2012. The bi-chamber module is identified in red and the buffer volume in blue. Right: The slope coefficient of a linear calibration as a function of time in keV/ADC-Channel. Each measurement has its error bar.

### 4 Preliminary analysis of the first months of data taking

The first available data set of the bi-chamber prototype was started on July 5<sup>th</sup> and finished on October 12<sup>th</sup> 2012. The measured total event rate of tracks with a 2 keV threshold was  $5.6 \pm 0.4$  evts/min without any cuts. We performed a first data analysis that allowed us to obtain 3D-track events with an energy spectrum shown on Fig. 3 left. In this spectrum, we can clearly identify two peaks at  $32.4 \pm 0.1$  and  $44 \pm 0.3$  keV, and a flat distribution above 60 keV.

Fig. 3 right shows the event rate of  $\alpha$ -particles (Flash-ADC saturation above 120 keV) and of events with energies between 20 and 60 keV selected by this analysis. These event rates remained constant until October 3<sup>rd</sup>, when the gas circulation was stopped to isolate the bi-chamber from the gas circulation system. We can observe an exponential reduction of the event rates which fit with the <sup>222</sup>Rn half-life ( $T_{1/2} = 3.8$  days). It signs a pollution of the gas mixture by Radon isotopes contained in the circulation gas system originating from <sup>238</sup>U and <sup>232</sup>Th chains. The exponential decrease being dominated by the half-life of the <sup>222</sup>Rn, hence, the contribution from the decay of <sup>220</sup>Rn may be neglected in a first order approximation. The absence of <sup>220</sup>Rn could be explained by its short half-life ( $T_{1/2} = 55$  s) preventing it to reach the active volume. Indeed, the time required for <sup>220</sup>Rn to reach the active volume of the chamber passing through the circulation circuit is at least one order of magnitude longer than its half-life.



Figure 3: Left: The energy spectrum obtained after a preliminary analysis between 20 and 120 keV. Right: The event rates of  $\alpha$ -particles (orange dots) and obtained with this analysis with 20 < E < 60 keV (blue dots). The dashed orange line indicate the shutdown of the gas circulation system, on October 3<sup>rd</sup>, 2012.

As shown in Tab. 1, the seven  $\alpha$ -particles from the decay of <sup>222</sup>Rn and <sup>220</sup>Rn descendants, called Radons progeny, are emitted with kinetic energies  $E_{\alpha}^{kin}$  ranging from 5.5 to 8.8 MeV. A simulation showed that these  $\alpha$ -particles can pass through the 24 µm cathode to reach the other chamber even if the decay is produced in the gas volume. The simulated energy spectrum of the  $\alpha$ -particles reaching the other chamber was flat from 0 to 120 keV (our ionization energy dynamic range). In addition, if the decays occur at the cathode surface and if the  $\alpha$ -particles are absorbed in the matter, only the recoils of the daughter nuclei will be detected. The recoils of the daughter nuclei from the Radons progeny are emitted, as shown on Tab. 1, with kinetic energies from 100 to 170 keV.

There is a difference between the kinetic energy of an ion  $E_{recoil}^{kin}$  and the energy released by ionization  $E_{recoil}^{ioni}$ . The Ionization Quenching Factor (*IQF*) is defined as the ratio between the ionization energy released by a recoil and the ionization energy released by an electron at the same kinetic energy. Taking into account the *IQF* correction from SRIM<sup>9</sup>, the recoils from <sup>222</sup>Rn and <sup>220</sup>Rn progeny would be detected with ionization energies from 38 to 70 keV. It was shown that SRIM must overestimates the *IQF* roughly by 20 % at such recoil energies<sup>8</sup>. Thus, the measured ionization energies should be lowered by 20 % with respect to the values on the Tab. 1.

In conclusion, the 3D-track events associated to the energy spectrum shown on Fig. 3 left

Parent	$E_{\alpha}^{kin}$ [MeV]	Daughter	$E_{recoil}^{kin}$ [keV]	<i>IQF</i> [%]	$E_{recoil}^{ioni}$ [keV]			
From <sup>222</sup> Rn								
$^{222}$ Rn	5.489	$^{218}$ Po	100.8	37.93	38.23			
<sup>218</sup> Po	6.002	<sup>214</sup> Pb	112.3	39.10	43.90			
<sup>214</sup> Po	7.687	$^{210}$ Pb	146.5	40.12	58.78			
From <sup>220</sup> Rn								
<sup>220</sup> Rn	6.288	<sup>216</sup> Po	116.5	39.0	45.4			
<sup>216</sup> Po	6.778	<sup>212</sup> Pb	128.0	39.1	50.0			
$^{212}$ Po	8.785	$^{208}$ Pb	169.1	41.3	69.8			
<sup>212</sup> Bi	6.090	<sup>208</sup> Tl	117.2	39.0	45.7			

Table 1: This table details the  $\alpha$ -decays from <sup>222</sup>Rn and <sup>220</sup>Rn progeny, the kinetic energies  $E_{\alpha}^{kin}$  of the emitted  $\alpha$ -particles and the kinetic  $E_{recoil}^{kin}$  and ionization  $E_{recoil}^{toni}$  energies of the emitted daughter nuclei. The IQF was estimated with SRIM.

come from the  $^{222}$ Rn progeny in the detector. Indeed, taking into account the *IQF* overestimation, the energy range of the recoils from the  $^{222}$ Rn progeny would fit the spectrum. The identification of the contribution for each nuclear recoil from the  $^{222}$ Rn progeny will be studied in a future paper.

For directional detection it is important to discriminate Radon progeny events from WIMP like events. This discrimination should be possible by using the time and spatial coincidence between the two chambers. For these events, we expect one recoil event in one of the chambers and one recoil event in the other one. For this data taking, the time synchronization of the chambers was not available. The study of the coincidences between the two chambers will be performed with a new 12 µm cathode for the next data taking period.

### 5 Conclusions and Perspectives

The MIMAC bi-chamber prototype was installed at the LSM in June 2012. A preliminary analysis of the first data set allowed us to observe, for the first time, the 3D-track and energy of recoils from the  $^{222}$ Rn progeny. At present, only the  $\alpha$  particle spectrum from  $^{222}$ Rn progeny was measured <sup>10</sup>. This kind of measurement shows the potential of the MIMAC experiment for 3D recoil track measurements at low ionization energy. Moreover, using the time correlation between the two chambers of the bi-chamber module, we should be able to discriminate these events.

The next step of the MIMAC project will be the development of the MIMAC  $1 \text{ m}^3$ . This detector will be the demonstrator for a large TPC devoted to DM directional search.

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# DEEP UNDERGROUND ASTROPARTICLE PHYSICS AT SNOLAB

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SNOLAB is a world class facility located 2km underground near Sudbury Ontario. The experimental programme is focused on dark matter search and neutrino physics. Currently running experiments are COUPP60, DAMIC, HALO and PICASSO, while experiments under construction are SNO+, DEAP-3600 and MiniCLEAN. SNOLAB is becoming a leading facility in experimental Astroparticle Physics by providing infrastructure and support within a clean environment to avoid contamination. The current status of the science programme is presented in this letter.

# 1 Introduction

The SNOLAB international facility was developed from the SNO experiment for deep underground science with a programme focused on experimental Astroparticle Physics, specifically for the search of dark matter and the study of neutrino properties. The laboratory is located in the Vale Creighton mine near Sudbury Ontario, 2km underground to shield experiments from cosmic rays and operated in a clean environment better than class 2000.

## 2 Dark matter programme

Currently running experiments are COUPP60, DAMIC and PICASSO, while DEAP3600 and MiniCLEAN are under construction, moreover SuperCDMS will be deployed in the short term. Other experiments, such as COUPP4 and DEAP-1 were prototypes successfully deployed and operated that improved the next generation of detectors at SNOLAB. A summary is presented below for this extensive programme where experiments are using noble gases, superheated liquids, and solid-state detectors to search for dark matter interactions sensitive to spin-dependent and/or spin-independent WIMP-nucleon cross sections.

## 2.1 COUPP

COUPP, the Chicagoland Observatory for Underground Particle Physics, uses bubble chambers filled with  $CF_3I$ , a material sensitive to spin-dependent and spin-independent WIMP-nucleon interactions. The target material is in a superheated state insensitive to electromagnetic interactions. Particles crossing the  $CF_3I$  deposit energy, evaporating a small amount of material, which leads to the production of bubbles that are recorded by two cameras. Additionally, piezo-electric transducers register the acoustic signal and allow discrimination between alphas and neutrons with more than 99% efficiency. Results from the first physics run at SNOLAB with a



Figure 1: COUPP4 experiment during the 2010-2011 run in the J drift (lcft) and COUPP60 currently under commissioning in the ladder labs (right)

4 kg detector were published in  $2012^{\text{i}}$  setting best limits for spin dependent WIMP-proton cross sections for direct detection. A 37 kg detector is under commissioning, expecting to start data taking in the beginning of June 2013.

# 2.2 PICASSO

PICASSO, the Project In CAnada to Search for Supersymmetric Objects, uses  $C_4F_10$  in the form of superheated droplets suspended in an inactive polymerized gel matrix sensitive to spindependent interactions. The nuclear recoils produce a phase transition, generating an acoustic signal that is recorded by piezo acoustic transducers used to discriminate alpha decays from neutron interactions. This technique allows to achieve a low threshold of 2 keV for nuclear recoil events. The current phase of the experiment is located in the ladder labs and has 32 detectors running for a total active mass of 2.6 kg.

#### 2.3 DAMIC

DAMIC, DArk Matter In CCDs, looks for dark matter with charge-coupled devices by detecting the nuclear recoils in silicon. The extremely low electronic readout noise on the CCDs allows to set a very low threshold of approximately 40 eVee. The experiment is located in the J drift and uses ten 250 microns-thick CCDs, which are fabricated in high resistivity silicon and can be fully depleted at low voltages. DAMIC has an active mass of 10 grams and was deployed underground in November 2012.



Figure 2: DAMIC detector located in the J drift (left) and one of the 32 PICASSO modules used for dark matter search (right)

# 2.4 DEAP

DEAP-1, Dark matter Experiment with Argon and Pulse-shape discrimination, was a prototype with 7 kg of liquid argon sensitive to spin-independent interactions. The detector consisted of an acrylic chamber filled with liquid argon, and two photomultipliers. The principle of operation is to detect the scintillation light produced by the argon atoms due to WIMP scatterings. Pulse-shape discrimination is used to discriminate electromagnetic interactions from nuclear recoils. DEAP-1 is part of the DEAP/CLEAN program at SNOLAB for dark matter searches using cryogenic noble gases, and was used to understand backgrounds for a larger-scale experiment, DEAP-3600<sup>3</sup>. DEAP-3600 is in construction and expected to start collecting data in 2014. It will consist of an acrylic vessel filled with 3,600 kg of liquid argon (1,000 kg fiducial mass) and 255 photomultipliers, using the same principle as DEAP-1, pulse-shape discrimination, to distinguish electromagnetic interactions from nuclear recoils. The experiment will be sensitive to spin-independent WIMP-nucleon interactions with a cross-section of the order of  $10^{-46}$  cm<sup>2</sup>.

## 2.5 MiniCLEAN

MiniCLEAN will have 500 kg (150 kg fiducial) of cryogenic liquid, interchangeable between argon and neon to study the response to signal and backgrounds in these two media, also reducing background by the technique of pulse-shape discrimination. The experiment will consist of a stainless steel vessel with 92 photomultipliers and it is currently under construction. Mini-CLEAN will have a sensitivity to spin-independent WIMP-nuclear scattering cross-sections of the order of  $10^{-45}$  cm<sup>2</sup>.



Figure 3: DEAP-1 prototype in the J drift (left), DEAP-3600 acrylic vessel sitting underground after machining of the light guides (center) and MiniCLEAN detector while being assembled in the cryopit

#### 3 Neutrino physics programme

Experiments to study neutrino properties are SNO+, under construction, and HALO, fully operational. SNO+ is a multipurpose neutrino experiment, aiming to detect low energy solar, supernova, reactor and geo neutrinos, as well as double beta decay, and HALO is a dedicated supernova detector. Other experiments have requested space such as EXO and COBRA for double beta decay. The current status of the neutrino physics programme is summarized below.

## 3.1 SNO+

The SNO+ detector is the successor of the SNO experiment, replacing the 1,000 tons of heavy water by about 780 tons of Linear Alkyl Benzene (LAB) liquid scintillator, while maintaining and improving on the low backgrounds achieved in SNO. The SNO+ programme is divided into three phases. The acrylic vessel will be filled initially with ultra pure water in 2013 to search for nucleon decay. Once the detector is filled with liquid scintillator, it will search for neutrinoless double beta decay by dissolving Neodymium or Tellurium; and afterwards, following the Nd or



Figure 4: SNO+ acrylic vessel with the hold down system rope in place on the exterior (left) and front section of the HALO detector during commissioning phase (right)

Te removal, it will aim to detect pep and CNO solar neutrinos, reactor and geo anti-neutrinos, as well as supernova monitoring.

# 3.2 HALO

The HALO experiment reuses the SNO <sup>3</sup>He proportional counters, and 80 tons of lcad from a decommissioned cosmic ray observatory. HALO is a dedicated supernova detector, where the lead is the neutrino target that leads to the production of neutrons detected by the proportional counters. HALO will be part of the SuperNova Early Warning System (SNEWS). HALO is fully operational since early 2012 with most of the shielding in place.

## 4 Final remarks

The rich physics program at SNOLAB is making important contributions to experimental research in Astroparticle Physics, specifically for dark matter search and neutrino physics. SNO-LAB is becoming one of the leading facilities in experimental research in Astroparticle Physics not only for its depth, but also for the clean environment and highly specialized support and infrastructure.

#### Acknowledgments

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4. Neutrinos

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#### The IceCube Neutrino Observatory: Status and Recent Results

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The IceCube Neutrino Observatory is a cubic-kilometer Cherenkov telescope located at the geographic South Pole. Its main component consists of an in-ice array of digital optical modules that monitor the Antarctic glacier for Cherenkov light emission from secondary particles produced in high-energy neutrino interactions. In IceCube's center the low-energy extension DeepCore uses a denser instrumentation in particularly clear ice. The in-ice array is supplemented by the square-kilometer cosmic ray surface detector IceTop. The individual and combined results of these sub-detectors and the unique geographical location allows for a wide scientific program beyond neutrino astronomy. I will summarize the present status and highlight recent results.

#### 1 Introduction

High-energy neutrino astronomy is based on a simple expectation. From the existence of highenergy cosmic rays (CRs) we can deduce that hadronic interactions with matter or radiation somewhere between the sources of CRs and Earth will create neutrinos via the decay of highenergy secondary mesons and leptons. The Universe is mostly transparent to neutrinos and the observable flux is simply proportional to the neutrino production rate corrected for flavor oscillation effects. In fact, a "proof of concept" is the observation of atmospheric neutrinos produced in CR air showers – though this is probably the least interesting realization of neutrino production from an astronomical point of view.

As usual, the devil is in the detail: being an efficient cosmic ray accelerator requires that CR interactions within the sources are sufficiently rare. If there was a large neutrino "energy leak", the CR accelerator would be doomed. This principle also holds once the cosmic ray escaped the source environment. Here, the energy density of neutrinos is directly limited by the observed flux of high-energy cosmic rays. The observed energy density of cosmic rays is thus also a measure for the absolute flux of neutrinos that we can expect on Earth. Since the energy per decade of the cosmic ray flux is falling as  $\sim 1/E$ , the observable flux of high-energy neutrinos is correspondingly small. A typical benchmark density for extra-galactic neutrino sources is at the level of  $10^{-20}$  erg/cm<sup>3</sup> – equivalent to about one cosmic PeV neutrino per day passing a football field.

This is not the only challenge. The rate of, say, PeV neutrino interactions via deep inelastic scattering is only of the order of one event per year and cubic-kilometer of matter. Fortunately, these very rare events have a high multiplicity of secondary energetic particles and have a good chance to be observable via multiple experimental techniques. One possibility is to look for the Cherenkov radiation of secondary charged leptons in optically transparent media. The experimental method has been successfully applied in Lake Baikal<sup>1</sup>, the Mediterranean (ANTARES<sup>2</sup>)

<sup>&</sup>lt;sup>a</sup>for a full author list see: http://icecube.wisc.edu/collaboration/authors/current.

or the Antarctic glacier (AMANDA  $^3$  and IceCube). In the following I am going to present the status and highlight recent results of the IceCube Observatory.

### 2 The IceCube Neutrino Observatory

The IceCube Neutrino Observatory is located at the geographic South Pole. It consists of three components that are illustrated in the left plot of Fig. 1. The main component is the IceCube Cherenkov telescope denoted as "IceCube Array" in the plot. It consists of 86 read-out cables ("strings"), each with a length of about 2.5 km carrying 60 digital optical modules (DOMs) along the last one kilometer just above the bedrock. The positions of the strings follow a triangular grid with a baseline of about 125 m except for eight "DeepCore" strings in the center of IceCube (shown as small dots in the right sketch of Fig. 1). The DOMs on these strings are placed in a particularly clear part of the Glacier and serve as a low energy neutrino extension for IceCube.

High-energy neutrino interactions in ice are dominated by deep-inelastic scattering with nuclei via parton-level charged and neutral current interactions. Anti-electron neutrinos may also undergo resonant charged current interactions with in-ice electrons. This narrow Glashow-resonance dominates the anti-electron neutrino cross section at neutrino energies of 6.4 PeV, corresponding to the mass of the W-boson in the center of mass system. Neutral current interactions of all neutrino flavors produce nearly spherical "cascade" events of secondary charged particles from the break-up and subsequent fragmentation of the hit nuclei. Charged current interactions also produce a high-energy lepton in its first interactions that triggers either an immediate (electron) or possibly delayed (tau) cascade as well as "tracks" from energy losses of muons in ice along their trajectory.

Each DOM consists of a spherical glass pressure vessel with a diameter of 35cm that contains a photo-multiplier tube (PMT) and electronics performing a complex list of autonomous triggering, analysis and filtering tasks. On trigger the analog waveform is digitized into 128 bins with a 3.3 ns time-width (equivalent to one meter of light propagation) and with a coarser binning covering 6.4  $\mu$ s (or 1.9 km equivalent). The temporal and spatial information collected in all DOMs in combination with the ice properties w.r.t. photon absorption and diffusion before detection <sup>4</sup> is used for neutrino event classification, their direction and deposited energy. The dominating background consists of muon bundles of atmospheric showers that reach down into IceCube and trigger the detector at a rate of a few kilo-Hertz.

The in-ice Cherenkov array is supplemented by a surface array "IceTop" of water Cherenkov tanks that trigger on the extended electromagnetic component of atmospheric showers. It consists of 81 stations that mostly follow the same triangular pattern as the in-ice string setup and cover about one square-kilometer. Each station consists of a pair of two meter wide cylindrical tanks filled with 0.9 m of ice and placed at a relative distance of about 10 m. Each tank contains two standard IceCube DOMs that are operating at different PMT gains to cover a wider dynamic range.

The average atmospheric overburden at the South Pole is about  $680 \text{ g/cm}^3$ , corresponding to the altitude of 2.8 km above sea level. The size and altitude of IceTop as well as the stable atmospheric conditions over periods of days are excellent conditions to study the CR spectrum in the knee region of PeV CRs. IceTop can also serve as a veto for atmospheric shower activity for astrophysical neutrino searches. However, the benefits of the sub-detectors are mutual. For instance, muon bundles observed in coincidence with shower can be utilized for CR composition studies.

The construction phase of the observatory took place over a period of seven years starting in 2004. The right plot of Fig. 1 shows an areal view indicating the strings that were present from previous seasons (gray dots) and those strings that were added in the corresponding season (colored dots). DeepCore strings are show as smaller dots. Data taking of each string and IceTop station (not shown in plot) started soon after deployment. Hence, every construction stage of



Figure 1: Left panel: A sketch of the IceCube observatory showing its subcomponents "IceCube", "IceTop" and "DeepCore". Right panel: The deployment history of the IceCube array. Large and small circles show regular and DeepCore strings, respectively. We also show the deployment status of IceTop at the end of each season.

the observatory corresponds to an autonomous detector (operating for about one year) denoted by the number of total strings and stations present. This is indicated below the sketches in the right plot of Fig. 1. The final "IC-86/IT-81" configuration has been operating since early 2011 collecting data for more than two years now.

The individual and combined observations with IceCube, DeepCore and IceTop together with the unique geographical location allow for a wide scientific program. In the following I am going to present recent results from the search of point-like and diffuse astrophysical neutrino sources and measurements of the background of atmospheric neutrinos. A recent scientific highlight is the detection of two PeV neutrino candidates that lie well above the expected atmospheric background as well as the observation of the cosmic ray flux, composition and anisotropies with IceCube and IceTop.

# 3 Atmospheric Neutrinos

The flux of atmospheric neutrinos is a result of CR interactions in the upper atmosphere and subsequent decay of mesons. The shape of the energy spectrum is a result of the competition of the decay of mesons against hadronic interactions (see e.g. Ref. <sup>5</sup>). Long-lived pions and kaons are more likely to interact than to decay. Since the life-time increases linear with energy while the interaction length remains approximately constant the resulting spectrum is about one order of magnitude steeper than the CR spectrum. Hence, this "conventional" atmospheric neutrino flux follows approximately  $E^{-3.7}$ . Since the atmospheric depth depends on zenith angle this atmospheric component is not completely isotropic since more horizontal showers have more time to develop.

The same line of arguments also apply to the much rarer charmed mesons produced in the first few interactions of the CR showers. However, due to their very short life-time they tend to decay rather than interact unless at extremely high energies. This decay-dominated "prompt" atmospheric component follows a harder spectrum proportional to the initial flux of CRs,  $E^{-2.7}$ , and is expected to be isotropic (neglecting oscillation). Thus, even though initial charm production is low the prompt spectrum may eventually dominate over the conventional. The crossover of the spectra depends on the relative production rate, which are affected by theoretical uncertainties of perturbative QCD calculations<sup>6</sup>. The production channel depend on parton-level of gluons and quarks at small Bjoerken-x and predictions rely on model-dependent extrapolations of available collider data. On the other hand, neutrino observatories would provide a



Figure 2: Left panel: A summary plot of the atmospheric neutrino spectrum and limits on astrophysical neutrino fluxes collected from IceCube<sup>7,8,10</sup> and previous experiments (see Ref.<sup>10</sup> for references). Right panel: (From Ref.<sup>13</sup>) Preliminary sensitivity (blue solid lines) and discovery potential (blue dashed lines) for the combined IC-40/59/79 search of point-sources with an E<sup>-2</sup>-spectrum as function of declination. The blue circles show upper flux limits on a source catalog. Also shown are ANTARES sensitivity and upper limits<sup>14</sup>.

viable experimental input for hadronic interaction models by a detection of this prompt neutrino component. There are also other ways of testing the shower physics of the first interaction of very-high energy particles, for instance, by the study of the lateral distribution of muons with high transversal momentum  $^{9}$ .

The left plot of Fig. 2 shows recent measurements of IceCube of the atmospheric muon and electron neutrino spectrum. The spectrum is dominated by muon neutrinos (and antineutrinos) at all energies. The fraction of electron neutrinos neutrinos is about 50% at GeV energies dominated by pion decay but decreases at higher energies depending on the branching ratio of kaon decays. The atmospheric muon neutrino component observed by IC-40 is in overall good agreement with previous observations of Super-K, Fréjus and AMANDA also indicated in the plot (see Ref.<sup>10</sup> for references). Recently, the atmospheric electron neutrino component could be inferred from a combined study with DeepCore (DC) and IC-79 shown as the green data points<sup>10</sup>. This is the first measurement of this spectrum in the 10 GeV to 10 TeV region. The over-all data is in good agreement with the predicted conventional muon and electron neutrino flux of Ref.<sup>11,12</sup> shown as blue and red lines, respectively. Also shown as a magenta band is the expected range of the prompt component from Ref.<sup>6</sup>.

# 4 Astrophysical Neutrinos

For IceCube the signal-to-background ratio of atmospheric neutrinos in the southern sky w.r.t. down-going CR muons is about one in a million. Any search for astrophysical neutrino fluxes in the same part of the sky has to face the same background. In the northern hemisphere the nearly-isotropic and steady flux of atmospheric neutrinos is itself the main background. However, as indicated in the left plot of Fig. 2 the spectrum of atmospheric neutrinos and similarly atmospheric muons is steeply falling in energy. Hence, the sensitivity to astrophysical neutrino sources across the sky increases drastically for high energy neutrino emission. In addition, a known time-profile and location of a candidate neutrino source can help to further reduce the background.

The right panel of Fig. 2 shows the preliminary sensitivity (blue solid line) and discovery potential (blue dashed line) of a search for neutrino point-sources in the combined IC-40/59/79

data collected from April 2008 to May 2011 in terms of declination  $\delta$  with  $\sin \delta > 0$  below the horizon <sup>13</sup>. The search used an un-binned maximum likelihood method for a given direction in the sky to determine a pre-trial *p*-value for an event excess above background estimated by right-ascension scrambling of the data. This is then trial-corrected by the number of background samples that have a higher pre-trial *p*-value. No significant excess was observed; the hot-spot post-trial probability is about 57%. The blue circles shows the 90% C.L. upper limit of the flux from a list of candidate sources.

Note that this plot assumes an  $E^{-2}$ -spectrum of the source without cutoff. In this case IceCube's point-source sensitivity can become compatible to or even better than ANTARES for the southern hemisphere (sin  $\delta < 0$ ) dominated by atmospheric muons. The corresponding sensitivity of ANTARES search over a four-year period is shown as a red solid line in the plot with upper limits on the flux of individual sources shown as red triangles <sup>14</sup>. Again, a crucial assumption here is that the energy cut-off of the spectrum is sufficiently large to overcome the large CR muon background (see also Ref. <sup>15</sup> in these proceedings).

Background reduction can also proceed via the search of neutrinos in coincidence with observed bursts or flares of sources. One of the best-studied neutrino source candidates are gamma-ray bursts (GRBs) that are observed with an average rate of about one per day. Being cosmological sources the distribution of GRBs is uniform across the sky. In the so-called "fire-ball" model of GRBs an emission of TeV to PeV neutrinos is expected in coincidence with the burst if UHE CR protons are also present in the fireball environment <sup>16</sup>. A recent analysis of the combined IC-40/59 data showed no evidence of neutrino emission in spatial and temporal coincidence with known GRBs of this epoch while about five events where expected <sup>17</sup>. This allows to constrain the allowed parameter space of the fireball model. Other time-dependent source studies with IceCube are neutrino flares from active galactic nuclei (see Ref. <sup>18</sup> in these proceedings).

One of the main scientific goals of IceCube is the study of diffuse neutrino fluxes that are associated with the extra-galactic sources of ultra-high energy (UHE) cosmic rays. These neutrinos might either be produced in the sources themselves while CRs are accelerated or via interactions with the cosmic background radiation. From the observed power in UHE CRs one can infer an upper bolometric limit on the associated neutrino flux<sup>19</sup>. This limit is indicated as a black dashed horizontal line in the left plot of Fig. 2. The preliminary upper limit of IC-59 on diffuse flux of high-energy muon neutrinos is indicated as the blue solid line in the same plots<sup>20</sup>. It shows IceCube's potential to test the source of UHE CRs beyond these indirect limits using bolometric arguments.

Ultra-high energy cosmic rays have to propagate over cosmological distance until they reach Earth. On these scales even feeble hadronic interactions with cosmic radiation backgrounds become important <sup>21,22,23</sup>. In particular, cosmogenic neutrinos produced via interactions of UHE CR protons with the cosmic microwave background are in reach of IceCube's sensitivity. The predicted fluxes have typically a broad energy spectrum in the EeV region. The corresponding event signatures in IceCube correspond to very bright events with a background dominated by atmospheric muons. Hence, the extremely-high energy (EHE) neutrino search optimizes the search window for the reconstructed zenith angle and number of photo-electrons as a measure of brightness.

In the most recent IC-79/86 analysis no events consistent with this EHE cosmogenic neutrino flux were found (see Ref. <sup>24</sup> in these proceedings). However, after unblinding of the data two PeV background cascades at the edge of the search region were observed <sup>25</sup>. The energies of these cascades have been analyzed in detail post-unblinding and lie at  $1.04 \pm 0.16$  PeV and  $1.14 \pm 0.17$  PeV, respectively. The chance that these events are pure atmospheric background is  $2.9 \times 10^{-3}$  corresponding to an  $2.8\sigma$  excess. Further studies on the initial neutrino direction as well as a dedicated search for high-energy starting events in IceCube similar to these background events are underway.



Figure 3: Left panel: The preliminary significance maps of the CR anisotropy inferred from in-ice muon bundles in IC-79. Results are shown for median CR energies of 40 TeV (top), 126 TeV (middle) and 400 TeV (bottom). Right panel: The preliminary cosmic ray spectrum of IT-73 (from Ref. <sup>27</sup>). Results are shown assuming an all-proton spectrum (blue triangles) and all-iron (red inverted triangles). The inferred spectra are consistent with previous results of IT-26 <sup>26</sup> (magenta stars and green crosses) and combined spectral and composition study with IT-40/IC-40<sup>28</sup> (brown diamands). Also shown are the respective systematic uncertainties as shaded bands.

### 5 Cosmic Rays

The IceTop surface array has an average atmospheric overburden of 680 g/cm<sup>2</sup>. This is close to the shower maximum of protons in the PeV-EeV energy region. Energy uncertainties of the CR spectrum in the knee region due to shower-to-shower fluctuations are hence minimized in IceTop measurements. The relation between CR shower size and energy depend on the initial mass and zenith angle. Cosmic ray composition models can hence be tested via an unfolding of the spectrum in cos-zenith-angle bins of constant size (and hence constant  $\Delta\Omega$ ). The unfolded spectra are expected to be independent on zenith angle since the initial flux of CRs is expected to be isotropic.

This method was first applied to IT-26 data showing good agreement of spectra assuming an all-pure proton or a simple two-component model <sup>26</sup>. This result is shown in right panel of Fig. 3 (from Ref.<sup>27</sup>). Additional information on composition is carried by in-ice muon bundles in coincidence with the electromagnetic component seen with IceTop. For the IT-40 CR analysis the combined IT-40/IC-40 data was used to infer the energy and mass composition <sup>28</sup>. The result of the cosmic ray spectrum is shown in the plot as diamonds.

In the right panel of Fig. 2 we also show preliminary results from the analysis of the IT-73 data assuming all-proton and all-iron composition as extreme cases. These spectra and the previously published results show the characteristic knee feature at about 4 PeV. For the IT-26 mixed proton-iron composition the spectral index above the knee is about -3.1. Interestingly, the spectrum also indicates a flattening above about 20 PeV with a spectral index of -2.9. This feature is also present for different composition assumptions and preliminary IT-73 results, as shown in the plot, and could be the result of a transition between different source populations and/or properties of the interstellar medium on CR propagation (see *e.g.* Ref. <sup>29</sup>).

Possibly one of the most interesting results of cosmic ray studies with IceCube and IceTop is the observation of significant CR anisotropies at the per-mille level  $^{30,31,32}$ . These were the first CR anisotropy studies in the southern hemisphere. A great advantage of IceCube's location at the South Pole is the stable atmospheric conditions over periods of days. As the Earth rotates over 24 hours each direction in the Galactic reference system sweeps out a circle on the sky at

constant zenith angle. Simple integration the CR counts over a 24h period hence averages out the intrinsic azimuthal anisotropy of IceCube or IceTop.

The left panel of Fig. 3 shows the significance map  $^{33}$  of the anisotropy with median energies of 40 TeV (top), 126 TeV (middle) and 400 TeV (bottom) with a 20 degree smoothing scale inferred by the high-statistics "background" of in-ice CR muon bundles with IC-79. Positive and negative significance indicate an excess and deficit above the mean background level, respectively. At 40 TeV the anisotropy is dominated by large angular scales of more than  $60^{\circ}$  (dipole and quadrupole). However, the map at this energy scale shows also significant anisotropies at smaller amplitudes at a few ten degrees  $^{32}$ . The overall anisotropy pattern shows also significant large scale structures at 126 TeV and 400 TeV as shown in the left panel of Fig. 3. However, the location changes across the sky and it appears that there is an interchange between excesses and deficits from 40 TeV to 400 TeV. The pattern seems to persist to higher energies of PeV though with smaller significance.

The origin of these anisotropy is unknown. A dipole anisotropy is expected from the relative motion of the Earth w.r.t. to the system where Galactic CRs are isotropic – the Compton-Getting effect<sup>34</sup>. The diffusion of Galactic CRs in the interstellar environment is also expected to produce a dipole feature itself (see *e.g.* Ref. <sup>35</sup>) oriented in a weighted direction of the corresponding sources. Its strength should depend on the diffusion coefficient, *i.e.* the mean free path of diffusive isotropization and should reflect its energy dependence. Unfortunately, due to the partial sky coverage of IceCube and IceTop and the limited statistics and energy resolution the orientation and size of the low multipole features are hard to disentangle. Small scale anisotropies might be an effect of the local realization of the turbulent magnetic field structure within a mean free path <sup>36</sup>.

At 40 TeV the anisotropy pattern can be compared with measurements at similar energy with Milagro, Super-K, Tibet AS $\gamma$ , ARGO-YBJ or EAS-TOP in the northern hemisphere (see Ref. <sup>32</sup> for references). Though statistics in the overlap region is limited, the overall structure seems to be consistent with a smooth continuation across declination bands into the northern sky. Cosmic ray anisotropies has also been studied with air shower data observed with IceTop<sup>37</sup>. An advantage of IceTop is the better energy reconstruction of the primary CR shower for the study of the energy dependence of the anisotropy. The trade-off is a lower event statistics. Preliminary results of a study of data collected between May 2009 and May 2012 (IT-59/73/81) show anisotropy pattern at 400 TeV and 2 PeV that are consistent with IceCube's previous findings.

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### **Recent Results from the ANTARES Neutrino Telescope**

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The ANTARES experiment is currently the largest underwater neutrino telescope. It is taking high quality data since 2007 and aims to detect high energy neutrinos that are expected from the acceleration of cosmic rays from astrophysical sources. We will review the status of the detector and present several analyses carried out on atmospheric muons and neutrinos. For example we will show the latest results from searches for neutrinos from steady cosmic pointlike sources, for neutrinos from Fermi Bubbles, for neutrinos from Dark Matter in the Sun and the measurement of atmospheric neutrino oscillation parameters.

## 1 Introduction

The discovery of high energy cosmic rays which collide with the Earth's atmosphere is known since 100 years, but their astrophysical origin and their acceleration to such high energies is still unclear. The observation of these cosmic rays is a strong argument for the existence of high energy neutrinos from the cosmos. Such cosmic neutrinos are expected to be emitted along with gamma-rays by astrophysical sources in processes involving the interaction of accelerated hadrons and the subsequent production and decay of pions and kaons.

The advantage of using neutrinos with respect to cosmic particles like protons and photons is that they are not deflected by magnetic fields and are weakly interacting. The neutrinos point directly back to the source of emission and can provide information about the source.

The disadvantage to detecting neutrinos is their extremely small interaction probability. A very large amount of matter is needed to have some interacting neutrinos. The flux of high energy cosmic neutrinos can be estimated from the observation of the rate of high energy cosmic rays. Theoretical calculations show that a detector of the size of about a cubic kilometer is needed to discover high energy cosmic neutrinos.

A cost effective way to detect high energies neutrinos is to use detector material found in nature, like water and ice. The detector material has to be equipped by a three dimensional array of light sensors, so that muon neutrinos are identified by the muons that are produced in charged current interactions. These muons are detected by measuring the Cerenkov light which they emit when charged particles move faster than the speed of light in the detector material. The knowledge of the timing of the Cerenkov light recorded by the light sensors allows to reconstruct the trajectory of the muon and so to infer the arrival direction of the incident neutrino. This technique is used in large-scale Cerenkov detectors like IceCube <sup>1</sup> and ANTARES <sup>2</sup> which are currently looking for high-energy (~TeV and beyond) cosmic neutrinos.



Figure 1: Left: The reconstructed zenith angle data distribution of selected events compared to the Monte Carlo distribution for atmospheric neutrino and muon background. Right: Skymap in equatorial coordinates of the 51 neutrino candidate sources (blue squares) and the 11 most promising gravitational lensing systems (black circles). The ANTARES visibility is also shown.

# 2 ANTARES Neutrino Telescope

The ANTARES detector is taking data since the first lines were deployed in 2007. It is located in the Mediterranean Sea, 40 km off the French coast at 42°50′N, 6°10′E. The detector consists of twelve vertical lines equipped with 885 photomultipliers (PMTs) in total, installed at a depth of about 2.5 km. The distance between adjacent lines is of the order of about 70 m. Each line is equipped with up to 25 triplets of PMTs spaced vertically by 14.5 m. The PMTs are oriented with their axis pointing downwards at 45° from the vertical. The instrumented detector volume is about 0.02 km<sup>3</sup>. The design of ANTARES is optimized for the detection of upward going muons produced by neutrinos which have traversed the Earth, in order to limit the background from downward going atmospheric muons. The instantaneous field of view is  $2\pi$  sr for neutrino energies between 10 GeV and 100 TeV, due to selection of upgoing events. Further details on the detector can be found elsewhere<sup>2</sup>.

# 3 Cosmic Point-Like Neutrino Sources

The main goal of the ANTARES neutrino telescope is the observation of neutrinos of cosmic origin in the Southern sky. The main physical background to identify cosmic neutrinos are atmospheric muons and upward going atmospheric neutrinos. The atmospheric muons are produced in the upper atmosphere by the interaction of cosmic rays and can reach the apparatus despite the shielding provided by 2 km of water. Figure 1 left shows a comparison of the zenith angle distribution between data and Monte Carlo simulation. It can be seen that the flux of atmospheric muons is several order of magnitude larger than that of atmospheric neutrinos and that there is a good agreement between data and the Monte Carlo simulation.

The collaboration has developed several strategies to search in its data either for diffuse<sup>3</sup> or point-like<sup>4,5</sup> cosmic neutrino sources, possibly in association with other cosmic messengers such as gamma-rays<sup>6,7</sup> or gravitational waves<sup>8</sup>. Clustering of neutrino arrival directions can provide hints for their astrophysical origin. In the search of cosmic neutrino point sources, upward going events have been selected in order to reject atmospheric muons. Additional cuts on the quality of the muon track reconstruction have been applied in order to eliminate events that correspond to downward going atmospheric muons which are misreconstructed as upward going. Most of





Figure 2 Left: Probability for a 3 (red lines) and 5 (blue lines) sigma discovery as a function of the mean number of signal events. The dashed lines show the case where the number of hits information is used as an energy estimator in the likelihood, whereas for the solid lines no energy information is used. Right: Upper limits (at 90% C.L.) on the  $E^{-2}$  neutrino flux from the 62 selected candidate sources as well as the sensitivity as function of the declination. Also shown are the results from other experiments.

the remaining events are atmospheric muon neutrinos which constitute an irreducible diffuse background for cosmic neutrino searches. The 2007-2010 data contain around 3000 neutrino candidates with a predicted atmospheric muon neutrino purity of around 85%. The estimated angular resolution is  $0.5\pm0.1$  degrees.

The selection criteria are optimized to search for  $E^{-2}$  neutrino flux from point-like astrophysical sources, following two different strategies: a full sky search and a search in the direction of particularly interesting neutrino candidate sources. The selection of these sources is either based on the intensity of their gamma-ray emission as observed by Fermi<sup>9</sup> and HESS <sup>10</sup> or based on strong gravitational lensed sources with large magnification.

The motivation to select lensed sources is that neutrino fluxes as photon fluxes can be enhanced by the gravitational lensing effect, which could allow to observe sources otherwise below the detection threshold. Neutrinos (contrary to photons) are not absorbed by the gravitational lens. Therefore, sources with a moderate observed gamma-ray flux could be interesting candidates for neutrino telescopes. Figure 1 right shows the skymap in equatorial coordinates with the ANTARES visibility of the 51 neutrino candidate sources with strong gamma-ray emission and the 11 most promising strong gravitationally lensed sources.

The cosmic point source search has been performed using an unbinned maximum likelihood method <sup>5</sup>. This method uses the information of the event direction and, since the cosmic sources are expected to have a much harder spectra than atmospheric neutrinos, the number of hits produced by the track. Figure 2 left shows how the introduction of an energy estimator like the number of hits increases the discovery potential about 25% in comparison without using such an information. For each source, the position of the cluster is fixed at the direction of the source and the likelihood function is maximized with respect to the number of signal events. In the absence of a significant excess of neutrinos above an expected background, an upper limit on the neutrino flux is calculated.

A full sky point source search based on the above mentioned algorithm has not revealed a significant excess for any direction. The most significant cluster of events in the full sky search, with a post-trial *p*-value of 2.6%, which is equivalent to  $2.2\sigma$ , corresponds to the location of  $(\alpha, \delta) = (-46.5^{\circ}, 65.0^{\circ})$ . No significant excess has been found also in the dedicated search from the list of 11 lensed and 51 gamma-rays selected neutrino source candidates. The obtained neutrino flux limits of these selected directions are plotted as function of declination in Figure 2



Figure 3: Left: Muon event rate as a function of the shower multiplicity for data (points) and the Corsika simulation (line). The systematic error for the simulation is given by the height of the gray bands. Only statistical errors are shown for the data points. Right: Upper limits (at 90% C.L.) on the  $E^{-2}$  neutrino flux from the Fermi Bubbles for different cutoffs: no cutoff (black), 500 TeV (red), 100 TeV (green), 50 TeV (blue) are shown together with theoretical predictions in case of pure hadronic model (dashed lines).

right, where for comparison the limits set by other neutrino experiments is also shown.

#### 4 Electromagnetic Showers along Muon Tracks

Even if the primary aim of ANTARES is the detection of high energy cosmic neutrinos, the detector measures mainly downward going muons. These muons are the decay products of cosmic ray collisions in the Earth's atmosphere. Atmospheric muon data have been used for several analyses <sup>11,12,13</sup>, in particular the collaboration investigated the sensitivity of the composition of cosmic rays through the downward going muon flux <sup>14</sup>. Several observational parameters are combined to estimate the relative contribution of light and heavy cosmic rays. One of these parameters is the number of electromagnetic showers along muon tracks.

Catastrophic energy losses appear occasionally, when a high energy muon ( $\sim 1 \text{ TeV}$ ) traverses the water. These energy losses are characterized by discrete bursts of Cerenkov light originating mostly from pair production and bremsstrahlung (electromagnetic showers). A shower identification algorithm <sup>15,16</sup> is used to identify the excess of photons above the continuous baseline of photons emitted by a minimum-ionizing muon. With this method downward going muons with energies up to 100 TeV have been analysed.

The muon event rate as a function of the number of identified showers is plotted in Figure 3 left. The distribution shows the results for data and a Corsika based simulation. As can be seen, about 5% of the selected muon tracks have at least one well identified shower. Also shown is the systematic uncertainty for the simulation, where the largest systematic errors arises from uncertainties on the PMT angular acceptance and absorption length.

# 5 Fermi Bubbles

The Fermi Satellite has revealed an excess of gamma-rays in an extended pair of bilateral bubbles above and below our Galactic Center. These so called Fermi Bubbles (FB) cover about 0.8 sr of the sky, have sharp edges, are relative constant in intensity and have a flat  $E^{-2}$  spectrum between 1 and 100 GeV.

It has been proposed that FB are seen due to cosmic ray interactions with the interstellar medium, which produce pions. In this scenario gamma rays and high-energy neutrino emission



Figure 4: Left: The number of observed neutrinos (black triangles) and expected background events (solid blue line) as a function of the search cone radius around the Sun. A  $1\sigma$  Poisson uncertainty is shown for each data point. Right: 90% C.L. upper limit on the muon flux as a function of the WIMP mass for three self-annihilation channels  $b\bar{b}$  (dotted line),  $W^+W^-$  (solid line) and  $\tau^+\tau^-$ (dashed line). The results from Super-Kamiokande (in blue) and IceCube (in green) are also shown.

are expected with a similar flux from the pions decay.

ANTARES has an excellent visibility to the FB and therefore a dedicated search for an excess of neutrinos in the region of FB has been performed <sup>17</sup>. This analysis compares the rate of observed neutrino events in the region of the FB to that observed excluding the FB region. The of source FB region is equivalent in size and has in average the same detector efficiency as the FB region. The analyzed 2008-2011 data reveal 16 neutrino events inside the FB region. Estimations from outside the FB region predicts 11 neutrino events. These results are compatible with no signal and limits are placed on the fluxes of neutrinos for various assumptions on the energy cutoff at the source. Figure 3 right shows the upper limits and compares it to expected signal for optimistic models<sup>18</sup>. It can be seen that the calculated upper limits are within a factor 3 above the expected signal.

## 6 Dark Matter

The indirect search for dark matter in the universe is one further goal of ANTARES<sup>19</sup>. The weakly interactive massive particles could be gravitationally trapped in the center of the Sun. After the self-annihilation process of these weakly interactive massive particles neutrinos can be created.

Using the data recorded during 2007 and 2008, a search for high energy neutrinos coming from the direction of the Sun has been performed. The neutrino selection criteria have been chosen to maximize a possible neutrino signal. Decay channels leading to both hard  $(W^+W^-, \tau^+\tau^-)$  and soft  $(b\bar{b})$  flux spectra are considered. The expected background is estimated from the data by scrambling the direction of the observed neutrino candidates. The number of events in a search cone around the Sun is shown in Figure 4 left as a function of the search cone radius. It can be seen that the number of observed neutrino candidates is in good agreement with the background expectations. As there is no evidence for a flux of neutrinos from the Sun, upper limits on the muon flux are set and are presented in Figure 4 right. For comparison the limits from the other experiments such as IceCube<sup>20</sup> and Super-Kamiokande<sup>21</sup> are also shown. By improving the event selection and including data already available the analysis can be improved by around an order of magnitude.



Figure 5: Left: Arrival time as a function of the distance between the LED ( $\lambda = 469$  nm) and the PMT. The solid line corresponds to a fit of a linear function to the data. Right: Index of refraction corresponding to the group velocity of light as a function of the wavelength. The gray band shows the systematic uncertainty. The two solid lines correspond to a parametrization of the index of refraction evaluated at a pressure of 200 atm (lower line) and 240 atm (upper line).

## 7 Velocity of Light in Water

Charged particles crossing sea water induce the emission of Cerenkov light whenever the condition  $\beta > 1/n_p$  is fulfilled, where  $\beta$  is the speed of the particle relative to the speed of light in vacuum and  $n_p$  is the phase refractive index. The Cerenkov photons are emitted at an angle with respect to the particle track given by  $\cos \theta_c = \frac{1}{\beta n_p}$ . The individual photons then travel in the medium at the group velocity. Both the phase and group refractive indices depend on the wavelength of the photons and has the effect of making the emission angle and the speed of light wavelength dependent. Good knowledge of this wavelength dependence enables to reach the optimal performance of the detector.

The velocity of light has been measured using a set of pulsed light sources (LEDs emitting at different wavelengths) distributed throughout the detector illuminating the PMTs through the water<sup>22</sup>. In special calibration data runs the emission time and the position of the isotropic light flash, as well as the arrival time and the position when the light reaches the PMTs are recorded. Figure 5 left shows the arrival time as a function of the distance between the LED and the different PMTs. The slope of a linear fit to the arrival time versus distance gives the inverse of the light velocity. The refractive index has been measured at eight different wavelengths between 385 nm and 532 nm. This refractive index with its systematic errors are shown in Figure 5 right. Also shown is the parametric formula of the refractive index. The measurements are in agreement with the parametrization of the group refractive index.

### 8 Atmospheric Neutrino Oscillations

ANTARES is also sensitive to neutrino oscillation parameters through the disappearance of  $atmospheric muon neutrinos^{23}$ .

Neutrino oscillation are commonly described in terms of L/E, where L the oscillation path length and E is the neutrino energy. For upward going neutrinos crossing the Earth the travel distance L is translated to  $D \cos \theta$  where D is the Earth diameter and  $\theta$  the zenith angle. Within the two-flavour approximation, the  $\nu_{\mu}$  survival probability can be written as



Figure 6: Left: The fraction of events as a function of the  $E_R/\cos\theta_R$  distribution. Black crosses are data with statistical uncertainties, the blue histogram shows the non-oscillation hypothesis and the red histogram shows the result of the best fit. Right: 68% and 90% C.L. contours (solid and dashed red lines) of the neutrino oscillation parameters as derived from the fit of the  $E_R/\cos\theta_R$  distribution. The best fit point is indicated by the triangle. For comparison the solid filled regions show results at 68% C.L. from K2K (green), MINOS (blue) and Super-Kamiokande (magenta).

$$P(\nu_{\mu} \to \nu_{\mu}) = 1 - \sin^2 2\theta_{23} \cdot \sin^2(1.27 \triangle m_{23}^2 \frac{L}{E_{\nu}}) = 1 - \sin^2 2\theta_{23} \cdot \sin^2(16200 \triangle m_{23}^2 \frac{\cos \theta}{E_{\nu}}),$$

where  $\theta_{23}$  is the mixing angle and  $\triangle m_{23}^2$  is the squared mass difference of the mass eigenstates (with L in km,  $E_{\nu}$  in GeV and  $\triangle m_{23}^2$  in eV<sup>2</sup>). The survival probability P depends only on the two oscillation parameters,  $sin^2 2\theta_{23}$  and  $\triangle m_{23}^2$ , which determine the behavior for the atmospheric neutrino oscillations.

Taking the recent results from the MINOS experiment <sup>24</sup>, the first minimum in the muon neutrino survival probability ( $P(\nu_{\mu} \rightarrow \nu_{\mu}) = 0$ ) occurs for vertical upward going neutrinos at about 24 GeV. Muons induced by a 24 GeV neutrino travel in average around 120 m in sea water. The detector has PMTs spaced vertically by 14.5 m so that this energy range can be reached for events detected on one single line.

The reconstructed flight path through the Earth is reconstructed through zenith angle  $\theta_R$ , which is estimated from a muon track fit <sup>25</sup>. Whereas the neutrino energy  $E_R$  is estimated from the observed muon range in the detector. Figure 6 left shows event rate of the the measured variable  $E_R/\cos\theta_R$  for a data sample from 2007 to 2010 with a total live time of 863 days. The neutrino oscillations causes a clear event suppression for  $E_R/\cos\theta_R < 60 \text{GeV}$  with a clean sample of atmospheric neutrinos with energies as low as 20 GeV. The parameters of the atmospheric neutrino oscillations are extracted by fitting the event rate as a function  $E_R/\cos\theta_R$  and is plotted as a red curve in Figure 6 left with values  $\Delta m_{23}^2 = 3.1 \cdot 10^{-3} eV^2$  and  $\sin^2 2\theta_{23} = 1$ .

This measurement is converted into limits of the oscillation parameters and is shown in Figure 6 right. If maximum mixing is imposed  $(sin^22\theta_{23} = 1)$  the values of  $\triangle m_{23}^2$  is  $\triangle m_{23}^2 = (3.1 \pm 0.9) \cdot 10^{-3} eV^2$ . This measurement is in good agreement with the world average measurements. Although the results are not competitive with dedicated experiments, the ANTARES detector demonstrates the capability to measure atmospheric neutrino oscillation parameters and to detect and measure energies as low as 20 GeV.

### 9 Conclusion

ANTARES has been taking data since the first lines were deployed in 2007. With these data a broad physics program is underway producing competitive results. Unfortunately ANTARES has still not seen any cosmic neutrinos.

In this proceeding there was not enough room to discuss other topics which were illustrated at the Rencontres de Moriond, such as the atmospheric muon <sup>11</sup> and neutrino fluxes <sup>3</sup>, the time calibration system <sup>26</sup>, the acoustic neutrino detection system <sup>27</sup>, the search for relativistic magnetic monopoles <sup>28</sup>, the searches for nuclearites <sup>29</sup> and the correlation of neutrinos with gravitational waves <sup>8</sup>, for which the reader is referred to elsewhere.

Neutrino telescopes are starting to open up a new window in the sky exploring new territory and they will hopefully reveal new unknown phenomena and help answer open questions.

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# A SEARCH FOR EXTREMELY HIGH ENERGY COSMOGENIC NEUTRINOS WITH ICECUBE

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Extremely high energy cosmogenic neutrinos were searched for with the IceCube data taken from May, 2010 to May, 2012. Two neutrino-induced events with energies of approximately 1 PeV were observed. Small probability of the event energies being above 10<sup>9</sup> GeV and the large effective area for neutrino detection led to the most stringent upper limit for the extremely high energy cosmogenic neutrinos. Strong cosmological evolutions of the highest energy cosmic ray sources such as AGNs associated with radio-loud jets are disfavored with the current IceCube observation.

# 1 Introduction

One of the most mysterious astrophysical puzzles is the origin of the extremely high energy cosmic rays (EHECRs). The answer has been longed for since the first detection. EHECRs above  $5 \times 10^{10}$  GeV inevitably interact with cosmic microwave background photons while traveling to the Earth from a source, and produce extremely high energy (EHE) cosmogenic neutrinos with energies of  $\sim 10^9$  GeV. Since such neutrinos rarely interact with materials in space, they can preserve information about the generation. Therefore, the detection of such neutrinos can give an insight on the long standing puzzle of the EHECR origin.

The construction of the IceCube Neutrino Observatory at the South Pole was completed in December 2010. The IceCube detector consists of approximately 5,000 optical modules (DOMs) deployed in the glacial ice between 1.5-2.5 km from the surface, detecting Cherenkov light from secondary particles resulting from a neutrino interaction. The large detector volume of 1 km<sup>3</sup> enables us to observe rare EHE cosmogenic neutrinos. A search for EHE cosmogenic neutrinos were performed with the IceCube data taken May, 2010 to May, 2012.

# 2 The search for extremely high energy cosmogenic neutrinos

There are two main backgrounds for the high energy cosmogenic neutrino search: atmospheric muons and neutrinos generated in air showers. Since the energy spectra of the atmospheric muons and neutrinos are vcry steep with the index of  $\sim$ -3.7, the cosmogenic neutrino signals exceed the background at high energy. The atmospheric muons overwhelmingly come from the vertical direction at the IceCube depth due to the thicker Earth shield at horizontal direction. On the other hand, high energy cosmogenic neutrinos come from mainly horizontal direction because high energy neutrinos above 1 PeV can not penetrate the Earth due to increased neutrino cross section. Those energy and zenith angle information is used to separate cosmogenic neutrino signals from the background.

<sup>\*</sup>http://icecube.wisc.edu/collaboration/authors/current



Figure 1: Event number distributions on the plane of NPE and cosine of reconstructed zenith angle  $(\cos \theta)$  for IC79. The experimental test data are shown in left panels with the livetime of 33.4 days. The atmospheric muon (middle left panels), and the conventional atmospheric neutrino and prompt atmospheric neutrino background (middle right panels), and signal cosmogenic neutrino model Monte Carlo simulations (right panels) are also shown. The solid lines in each panel indicate the final selection criteria. The distributions for IC86 are similar and the selection criteria were also determined similarly.

Observation data from May, 2010 to May, 2011 were taken with the partial detector of 90% completed detectors with 79 strings configuration (IC79), and data from May, 2011 to May, 2012 were taken for the first time with the fully completed detector with 86 strings configuration (IC86). The livetimes are 319.2 days for IC79 and 350.9 days for IC86 respectively. Atmospheric muons were simulated by an air shower simulation CORSIKA <sup>1</sup> with a pure iron primary cosmic-ray composition in order to be conservative. Atmospheric neutrinos were simulated with the ANIS package <sup>2</sup> by taking into account the spectral index change at the knee of the cosmic ray spectrum. The prompt atmospheric neutrinos were also simulated with a flux predicted by Enberg et al. <sup>3</sup> which is based on perturbative-QCD as our standard flux. High energy cosmogenic neutrinos were generated with JULIET package <sup>4</sup> in order to represent variety of cosmogenic neutrino models with appropriate flux weights.

We found total number of photo-electrons (NPE) for each event measured by all DOMs has a good correlation with an energy of an event, therefore, NPE information is used to indicate the event energy. Zenith angles are reconstructed by  $SPE^5$  for IC79 and improved linefit<sup>6</sup> for IC86. This analysis employed an blind analysis technique by using only test samples of approximately 10% of whole data. This test data was only used to check the validity of the Monte-Carlo (MC) data we used. The NPE and reconstructed zenith angle distributions were checked to reasonably agree between the observed data and MC data. The final selection criteria were determined on NPE and zenith angle plane as shown in Fig. 1 by using only MC data.

## 3 Results

Two events were found after unblinding the observation data with applying the selection criteria <sup>7</sup>. Observed events are perfectly spherical, indicating the events are cascades generated by either electron neutrinos with charged current interactions or any flavor of neutrinos with neutral current interactions. The expected number of background events above the selection criteria in the livetime of 615.9 days excluding the test data is  $0.082 \pm 0.004$  (stat.)  $^{+0.041}_{-0.057}$  (syst.) with the nominal prompt atmospheric neutrinos<sup>3</sup>. The p-value of observing two events for the background hypothesis is  $2.9 \times 10^{-3}$  equivalent to a  $2.8\sigma$  standard deviation. The deposited cascade energies of two events are estimated as  $1.04 \pm 0.16$  and  $1.14 \pm 0.17$  PeV including the systematic errors mainly from the absolute DOM sensitivity and the optical properties of the ice. The deposited energy is exactly same as the incoming neutrino energy in case of an electron neutrino with a charged current interaction. The incoming neutrino energy is transferred to the cascade. Since we are not able to distinguish the type of neutrino interactions, the incoming energies were evaluated with a form of probability density function (PDF) by taking into account the interaction channels as well as the energy resolution of an event reconstruction. The

u Model	$P_{\mathbf{E}}$	Event Rate	$P_{\rm rate}$	p-value
Yoshida and Teshima <sup>9</sup> , $m = 4.0, z_{max} = 4.0$	0.077	2.8	0.55	0.18
Ahlers <i>et al.</i> <sup>8</sup> , $m = 4.6, z_{max} = 2.0$ , ("the best fit")	0.075	2.1	0.73	0.21
Kotera <i>et al.</i> <sup>10</sup> , GRB	0.052	1.1	0.42	0.10
Kotera <i>et al.</i> <sup>10</sup> , Fanaroff-Riley type II	0.039	5.9	0.038	0.011

Table 1:  $P_{\rm E}$ , Expected number of events,  $P_{\rm rate}$  from several cosmogenic neutrino models and the resultant p-value for consistency with this observation.

$\nu$ Model	Event rate above 100 PeV	p-value
Yoshida and Teshima <sup>9</sup> , $m = 4.0, z_{max} = 4.0$	2.6	0.16
Kalashev et al. <sup>13</sup> , $m = 5.0, z_{max} = 3.0$	4.0	0.048
Yoshida and Ishihara <sup>14</sup> , $m = 5.0, z_{max} = 2.0$	2.0	0.30
Ahlers <i>et al.</i> <sup>8</sup> , $m = 4.6, z_{max} = 2.0$ ("the best fit")	2.0	0.30
Ahlers <i>et al.</i> <sup>8</sup> , ("the maximal flux")	4.1	0.045
Kotera <i>et al.</i> <sup>10</sup> , GRB	0.63	0.64
Kotera <i>et al.</i> <sup>10</sup> , SFR	0.60	0.65
Kotera <i>et al.</i> <sup>10</sup> , Fanaroff-Riley type II	3.8	0.023
Top-down 1 <sup>15</sup> , SUSY	21	$\leq 0.0020$
Top-down 2 <sup>15</sup> , GUT	5.0	0.021

Table 2: Expected number of events from several neutrino models and the p-value for consistency with the present observation in energy range above 100 PeV.

estimated 90% C.L. energy ranges of the incoming neutrinos at the Earth's surface are 0.81 - 7.6 PeV and 0.93 - 8.9 PeV with a  $E^{-2}$  spectrum, and 0.98 - 500 PeV and 1.1 - 520 PeV with a standard cosmogenic neutrino flux<sup>8</sup>.

We examined EHE cosmogenic neutrino models to see whether they account for the present observations. In order to set the best limit, the IC40<sup>11</sup> results were also used hereafter, where no event was found beyond the selection criteria. The IC40 exposure increases the observation exposure by  $\sim 30\%$  from the IC79 and IC86 exposure. Firstly, whether a cosmogenic neutrino model explains the two PeV cascade event observation was investigated by using the neutrino energy distribution and event rate with the Fisher's method. A statistical significance is calculated by the following test statistic:  $x_{\rm F}^2 = -2 \ln(P_{\rm E}) - 2 \ln(P_{\rm rate})$ , where  $P_{\rm E}$  represents a p-value based on energies of the two observed events and the energy distribution predicted by a given model by using the Kolmogorov-Smirnov test, and  $P_{\rm rate}$  is a p-value based on the event rate. The energy distributions at the Earth's surface by the PDFs were then taken into account for the  $P_{\rm F}$ calculation. Table 1 summarizes the results. All the models in the table assume the cosmic ray primaries to be protons. Although the results are not conclusive due to the limitted statistics, the models are disfavored to explain the present two cascade event observation. Secondly, in order to give an insight to the EHECR origin, several cosmogenic neutrino models are tested based on the event rate above 100 PeV. In order to constrain those models, the model rejection factor <sup>12</sup> approach was used. The model rejection factor is written with  $R_{\text{MRF}} = N_{100(1-\alpha)\%}/\mu_{\nu}$ where  $N_{100(1-\alpha)\%}$  is the upper limit of number of events at  $100(1-\alpha)\%$  C.L. and  $\mu_{\nu}$  is the neutrino signal rate above 100 PeV. In this approach a model with  $R_{\rm MRF}$  below unity is rejected at  $100(1-\alpha)\%$  C.L. The upper limit is calculated with using the energy PDFs in order to include the effect of the two event observation. The resultant p-values are summarized in Table 2. The results indicate that strongly evolved sources such as m >> 4 are not responsible for the EHECR origin. The Fanaroff-Riley type II (FR-II) radio galaxies belong to this category, though it was one of the promising candidate for the origin.

The quasi-differential model independent 90% C.L upper limit on neutrino fluxes normalized by energy decade is shown in Fig. 2. The limit were derived by the similar method performed in



Figure 2: All flavor neutrino flux differential upper limit from the present IceCube EHE analysis including the IceCube exposure from the previously published result (IC40) (bold solid line). The systematic errors are included. Various model predictions (assuming primary protons) are shown for comparison; Engel *et al.*<sup>16</sup>, Kotera *et al.*<sup>10</sup>, Ahlers *et al.*<sup>8</sup>, Yoshida *et al.*<sup>9</sup> The model-independent differential upper limits by other experiments are also shown.

previous analyses  $^{6,11}$  except we took the two event observation into account by using the PDFs. This is the most stringent limit in the EeV regime obtained to date.

### 4 Summary

We have searched for EHE cosmogenic neutrinos in order to shed light on the EHECR origin. We found two cascade events whose energies are both approximately PeV. High energy cosmogenic neutrino models disfavors the two event observation. We also constrained cosmogenic models based on the observations. One of the promising candidates for the EHECR origin, FR-II, was rejected with more than 95% C.L. by our observation. Data taken with the fully completed detector is ongoing, and will further enhance the IceCube sensitivity for the EHE neutrino search.

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# UPDATED LIMITS ON DIFFUSE FLUXES OF COSMIC NEUTRINOS WITH 2008-2011 ANTARES DATA

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The ANTARES neutrino telescope detects the Cherenkov radiation emitted along the path of charged particles produced in neutrino interactions. ANTARES is sensitive to all flavors even though it is optimized for muon neutrinos. Several algorithms estimating the deposited energy in the active volume of the detector have been developed and applied to the reconstruction of the primary neutrino energy – this allows to improve the search for a diffuse flux of astrophysical neutrinos. The search for a diffuse flux of cosmic neutrinos at very high energies ( $E_{\nu} > 30$  TeV) is updated using 4 years of data with the full detector.

# 1 ANTARES and Diffuse Cosmic Neutrinos

The ANTARES neutrino telescope <sup>1</sup> is taking data in its final configuration since 2008, see Fig. 1 (left). The main physics subject is the search for cosmic sources of neutrinos, even though several results have been obtained in other topics, e.g. neutrino oscillations, searches for dark matter and exotics (monopoles, nuclearites), oceanography and marine biology <sup>2</sup>.

An update of the analysis on the search for a diffuse flux of cosmic neutrinos<sup>3</sup> with two years of data is presented. Two years more of data are added to the measurement. In the meanwhile, our knowledge of the detector has improved and better Monte Carlo (MC) simulations have been made available, allowing to use a larger data fraction for analyses, with less requirements on the data quality. The equivalent live-time is 885 days now, about a factor three larger than for previous analysis.

An isotropic diffuse flux of neutrinos generated by extragalactic sources in the Universe is expected. Atmospheric neutrinos with an energy spectrum  $\propto E_{\nu}^{-3.7}$  represent an irreducible background in the search for a diffuse flux of cosmic  $\nu$  and the signal might be seen as an excess in the high energy region of the spectrum. A harder spectrum, proportional to  $E^{-2}$ , is expected for  $\nu$  of astrophysical origin; above an unknown value of the critical energy  $E_{\nu}^{c}$  (which depends on the absolute normalization of the cosmic  $\nu$  flux) astrophysical neutrinos should exceed those of atmospheric origin. The discrimination can be done on the basis of the visible energy of muons generated by neutrinos. In the following we refer to  $\nu_{\mu}$  and  $\bar{\nu}_{\mu}$  as "muon neutrinos", because the sign of the charged muon is indistinguishable.

IceCube results on the search for diffuse neutrinos using IC59 data  $^4$  show no significant excess with respect to the background expectations, hence an upper limit at 90% confidence level was derived:

$$E^2 \Phi_{\nu_{\mu}} = 1.44 \cdot 10^{-8} \text{ GeV } \text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$
 (1)

The IC59 sensitivity to diffuse fluxes is a factor two lower than the limit. Even if this result



Figure 1: Left: A schematic view of ANTARES. Right: Data and MC events with an equivalent live-time of 885 days as a function of  $\Lambda$ , selected with  $\theta > 90^\circ$ ,  $\beta < 0.5$ ,  $N_{hit} > 35$ .  $\Lambda$  is negative and takes values closer to zero for well reconstructed tracks. Red represents atmospheric muons, blue the conventional atmospheric neutrinos, green the cosmic signal  $\Phi_{test} \propto E^{-2}$ , points are data. The cut at  $\Lambda > 4.9$  (pink vertical line) is adjusted according to an exponential fit of the muon distribution that reduces the muon background to 0.15% (1.3  $\mu$ ) of the total.

is statistically compatible with zero at 1.8  $\sigma$ , there is a soft indication of the presence of high energy astrophysical neutrinos.

A test  $\nu_{\mu}$  signal with a flux proportional to  $E^{-2}$  and normalized at

$$E^2 \Phi_{test} = 10^{-8} \text{ GeV } \text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$
(2)

is used in this analysis. The normalization is arbitrary and does not affect the result of the following cut optimization. The entire procedure and the optimization of all the cuts was done using only the 10% of available data (blind analysis) and the full MC set, in order to avoid any bias.

Down-going atmospheric muons reconstructed as up-going can mimic high-energy neutrino induced muons. In fact, atmospheric muons reach the detector in "bundles" of particles with a large multiplicity. The main effect is the production of a large amount of hits on the PhotoMultiplier Tubes (PMTs) – the signature of high energy events. A cut on the quality of reconstructed tracks is defined to keep under control the atmospheric muon background.

The algorithm that reconstructs the muon direction <sup>5</sup> uses as input the time and position information of hits produced by the photons recorded by the PMTs, and gives as output the direction of the muon (zenith and azimuth), a quality parameter ( $\Lambda$ ), the estimation of the angular resolution ( $\beta$ ), and the number of hits correlated with the track ( $N_{hit}$ ). An a priori cut on the reconstructed zenith angle is applied ( $\theta > 90^{\circ}$ ). A combined cut on the three parameters given by the reconstruction algorithm ( $\Lambda$ ,  $\beta$ ,  $N_{hit}$ ) has been optimized to reduce the muon background maximizing the total number of signal events.

First level cuts are defined as the combination of:

$$\Lambda > -4.9, \quad \beta < 0.5, \quad N_{hit} > 35. \tag{3}$$

Due to the reduced statistics in the muon MC sample (one third of the equivalent live-time in data) the cut on  $\Lambda$  is adjusted according to the fit shown in Fig. 1 (right). The first level cuts allow to reduce the muon background at the level of 1.3 event (885 days).

After the cuts of eq. 3 the prevailing background for cosmic neutrinos is due to atmospheric neutrinos, which are expected to dominate below the critical energy  $E_{\nu}^{c}$ . The neutrino energy cannot be directly measured and the neutrino induced muons are observed in a limited interval of their range, due to the limited size of ANTARES. An estimate of the muon energy can be



Figure 2: Left: Inverse cumulative distributions of data (crosses) and Monte Carlo as a function of the energy estimator  $\rho$ . The blue histogram represents the atmospheric Bartol  $\nu_{\mu}$  normalized to the total number of data events, without any prompt contributions; the green histogram the cosmic neutrinos with the test flux of eq. 2; the pink vertical line shows the position of the cut which minimizes the MRF. Right: Distribution of atmospheric and signal  $\nu_{\mu}$  as a function of the true energy obtained from MC, before and after the energy cut log  $\rho > 3.1$ . The region that contains the 90% of signal is highlighted.

done through the measurement of some observables related with the muon energy loss in water. In fact, at energies higher than ~ 500 GeV, the energy loss is proportional to the energy of the muon. An energy estimator<sup>6</sup>,  $\rho$ , is defined through an approximation of the total muon energy deposited in the detector along its path,  $\Delta E/\Delta x \propto \rho(Q_i, \vec{x}, L_\mu, \epsilon)$ , and it is a function of the total number of photoelectrons recorded by PMTs  $(Q_i)$ , the reconstructed muon direction  $(\vec{x})$ , the geometrical track length within the sensitive volume  $(L_\mu)$ , and the detector efficiency  $(\epsilon)$ .

The atmospheric neutrinos are simulated according to the conventional "Bartol" flux<sup>7</sup>, while the signal is taken assuming the flux of eq. 2. The inverse cumulative distributions of expected neutrinos as a function of  $\log \rho$  is shown in Fig. 2 (left). The energy estimator  $\rho$  is used in the Model Rejection Factor (MRF) procedure<sup>8</sup> to define the cut which gives the best sensitivity. The MRF as a function of  $\rho$  was computed through pseudo-experiments using the Feldman&Cousins statistics<sup>9</sup> at 90% confidence level. The minimum occurs selecting events with  $\log \rho > 3.1$  and corresponds to a sensitivity:

$$\Phi_{sens} = 3.0 \cdot 10^{-8} E^{-2} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$
(4)

# 2 Results

Applying the first level cuts to the data sample, the conventional atmospheric neutrinos from MC simulations show a 27% deficit with respect to the observed data events. This is well within the systematic uncertainties on the theoretical expectation at these energies; the  $\nu$  background is then normalized to the data. After normalization, 7.9 atmospheric events are expected for  $\log \rho > 3.1$ , and 1.8 signal events from the test flux (eq. 2).

After unblinding the high energy region, 7 neutrino events are found in the full data sample. Fig. 2 (left) shows the inverse cumulative distribution as a function of the energy estimator  $\rho$  for data and MC. The pink line at log  $\rho = 3.1$  shows the cut value which minimizes the MRF.

The effects of systematics is considered in the calculation of the upper limit. The evaluation of the systematic errors on the background is taken from the normalization factor applied to Monte Carlo, giving a  $\pm 27\%$  effect on the predicted 7.9 events. This factor includes the systematics about the knowledge of the detector plus theoretical uncertainties on the conventional neutrino flux. Concerning the signal, an assumption is done on the flux shape and the absolute normalization does not influence the resulting upper limit. The variation in the number of



Figure 3: Left: The ANTARES 08-11 upper limit is compared with limits from other experiments and theoretical models. The gray band represents the conventional Bartol flux from vertical to horizontal events. Right: The upper limit on diffuse fluxes and the unfolded atmospheric neutrino energy spectrum are shown for comparison in the same picture, together with the expectations from the Bartol flux.

expected signal events depends on the detector efficiencies only. Some critical parameters were changed in the MC simulations to evaluate the signal expectations: absorption length of light in water ( $\pm 10\%$ ), PMT quantum efficiency ( $\pm 10\%$ ), PMT angular acceptance. The effect of the systematic uncertainties is to change the expected 1.8 signal events by  $\pm 14\%$ .

Using the method described in Conrad *et al.*<sup>10</sup>, the upper limit at 90% confidence level is:

$$E^2 \Phi_{90\%} = 3.2 \cdot 10^{-8} \text{ GeV } \text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$
(5)

The central 90% of the signal is found in the neutrino energy range from 45 TeV to 6.3 PeV – see Fig. 2 (right). The interval is the region containing 90% of the signal from MC simulations.

### 3 Conclusions

ANTARES data taken in the years 2008-2011 were analyzed to search for a diffuse cosmic neutrino signal. The whole period corresponds to 855 days of equivalent live-time. Using an estimator of the muon energy loss in sea water, no excess of events is found with respect to the atmospheric neutrino flux hence an upper limit at 90% c.l. is obtained. This result is compared with other experiments and theoretical expectations in Fig. 3 (left) – see<sup>3</sup> for references. The same data set was analyzed to unfold the atmospheric neutrino energy spectrum <sup>11</sup>; Fig. 3 (right) shows the combination of both results together with the conventional Bartol flux.

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# SEARCH FOR NEUTRINO FLARES FROM ACTIVE GALACTIC NUCLEI WITH THE ICECUBE DETECTOR

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The IceCube neutrino telescope is designed to detect neutrinos in the energy range from O(10 GeV) up to the EeV scale. One of its primary goals is the observation of high-energy neutrinos that may be connected with cosmic-ray acceleration and propagation. In this context, we describe a set of strategies to search for localized, point-like neutrino sources, focusing on selected Active Galactic Nuclei (AGN). These strategies exploit the extreme variability in AGN electromagnetic emissions to look for correlated neutrino events.

### 1 Introduction

The origin of cosmic rays, especially at primary energies above  $E \sim 10^{18}$  eV, remains the subject of intense research more than 100 years since their discovery<sup>1</sup>. Active Galactic Nuclei (AGN), in particular Flat Spectrum Radio Quasars (FSRQs) and BL-Lacs, are believed to satisfy the necessary conditions to emit charged particles at such high energies<sup>2</sup>. Within the context of hadronic models, neutrinos should be produced in interactions of these particles inside the AGN jet<sup>3,4</sup>. One of the aims of the IceCube neutrino observatory is to be sensitive to this high energy neutrino flux<sup>5</sup>.

In order to distinguish astrophysical neutrino signal events from background events generated in the atmosphere (neutrinos and muons) energy and direction reconstructions have been used in several searches of localized excesses (time-integrated methods<sup>6</sup>). An additional way to assess signal-background discrimination is the use of time information to reduce the effective background<sup>7,8</sup>. AGNs are known to show time variability (flares) at different wavelengths and in different time scales<sup>9</sup>. The associated neutrino emission may exhibit the same kind of variability and this is used to improve the detection probability with respect to time-independent searches. Here we briefly describe the different time-dependent methods designed to search for such neutrino flares, particularly from AGNs, using IceCube data.

## 2 Time-integrated searches

In this section we describe the unbinned likelihood method for time-integrated searches in Ice-Cube. This approach is an standard tool for IceCube point source searches and is documented in detail elsewhere<sup>6,10</sup>. An astrophysical neutrino point source signal is expected to manifest in the data as a clustering of events in space which have a different energy spectral index ( $\gamma_s$ ) than the atmospheric neutrino and muon spectra<sup>5</sup>. Time-integrated searches are based on a likelihood constructed with background and signal probability density functions (PDFs) evaluated for each event *i* of the data sample. The PDFs depend on the reconstructed direction and

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Figure 1: (Left) Discovery potential and sensitivity of the untriggered search as function of the Gaussian PDF with width  $\sigma_w$ . The dashed lines correspond to the time-integrated analysis. (Right) Distribution of  $\log_{10}$ (pretrial p-values) in sky-map (equatorial coordinates (J2000)) for the all-sky untriggered search. The dotted line indicates the galactic plane

energy<sup>6</sup>. The signal PDF  $(S_i(\gamma_s) = S_i^{\text{Space}} S_i^{\text{Energy}}(\gamma_s))$  is calculated from simulations and the background PDF  $(B_i = B_i^{\text{Space}} B_i^{\text{Energy}})$  is constructed directly from data. The likelihood to be maximized is defined as a linear combination of these PDFs,  $\mathcal{L}(n_s, \gamma_s)$ , where  $n_s$  (the number of signal events over the background) and  $\gamma_s$  (the signal spectral index) are free parameters. The final significance is calculated from the likelihood ratio between the best fit  $(\hat{n}_s)$  and the null  $(n_s = 0)$  hypothesis. Results obtained with 3 years of IceCube data are described in Ref.<sup>5</sup>.

## 3 Time-dependent searches

The variability in AGN electromagnetic emission may be exploited to further reduce the atmospheric background. For this purpose, additional PDFs dependent on the event time  $t_i$  are included in the likelihood. Each of the methods briefly described below compare the data to a signal hypothesis,  $S_i^{\text{Time}}(t_i)$ . The assumed PDF characterizes the temporal behavior of the potential source in a different way to assess several possible scenarios. The background PDF is assumed to be flat in time, *i.e.*  $B_i^{\text{Time}}(t_i) = 1/\Delta T_{Data}$ , where  $\Delta T_{Data}$  is the data livetime.

3.1 Untriggered search<sup>7,11,12</sup>: This analysis aims to find a significant set of events clustered in time at any point in the sky. The data corresponds to the 79-string configuration of IceCube (IC79)<sup>5</sup>. The time PDF is defined as a Gaussian function, with centroid ( $\mu$ ) and width ( $\sigma_w$ ) as free parameters in the likelihood maximization. The method is sensitive to a wide region of flare durations (see Figure 1 (*Left*)) that do not necessarily have an electromagnetic counterpart. In principle short bursts may be discovered at a 5 $\sigma$  level with approximately 3 events if they occur close in time. The method is more sensitive than time-integrated searches for flares with  $\sigma_w \lesssim 100$  days). Figure 1 (*Right*) shows the significance sky map resulting from this test. The most significant location has a post-trial p-value of 0.66, which is compatible with expected background fluctuations. An all-sky search implies a large trial factor that is reduced by selecting a list of promising AGN candidates, as described next.

3.2 Triggered search<sup>11,12</sup>: The signal hypothesis in this kind of search takes into account information extracted from  $\gamma$ -ray measurements in the GeV band for a set of selected AGNs. The  $\gamma$ -ray light curves from the Fermi LAT are interpolated to define the time PDFs of the associated neutrinos. A small time delay, up to 0.5 days in absolute value, is introduced as a free parameter. The Fermi LAT provides data to implement this test using accumulated light curves of 3 years for a subset of the selected AGN. The largest significance was observed for the Seyfert galaxy NGC 1275 with a post-trial p-value of 0.95.





Figure 2: (*Left*) Discovery potential for the multiflare and multiflare-stacking searches as function of the flare activity time,  $\Delta T(M)$ . The signal hypothesis is a double-flare defined in the upper left corner. (*Right*) Fluence upper limits obtained with the multi-flare method for the selected AGNs (open squares and circles). The black triangles are the upper limits obtained with a time-clustering algorithm<sup>8</sup> applied to IceCube data in its 40-string configuration<sup>11</sup>.

3.3 Multiflare search<sup>13,14</sup>: The multiflare analysis is a method designed to be sensitive to several neutrino flares separated in time with only a weak dependence on  $\gamma$ -ray or other wavelength measurements. The time PDF in this case is a sum of box PDFs with variable separation in time constructed from data. This approach has the advantage of considering a scenario where neutrino flares do not have a one to one correlation with high  $\gamma$ -ray states permitting larger time delays or different durations, as discussed in some emission models<sup>15,16</sup>. However the search is restricted to a time window of ~80 days since the significance of the multiflare signal decreases with its length.

As an illustrative example, two neutrino flares separated in time (double-flare) are considered as a signal hypothesis. A double-flare may not be observed by the untriggered search because the Gaussian time structure is not valid for large time gaps between the individual flares. As shown in Figure 2 (*Left*) the discovery potential is approximately constant over different time scales (see the sub-figure and the black curves) for all the FSRQs tested (dashed lines). It is also shown that the multiflare discovery potential is better than the time integrated search (labeled solid line) for the range of flare activity times tested in this example.

The multi-flare method is applied to list of promising AGN selected using data of the second Fermi catalog following a criteria based on several theoretical models<sup>14</sup>. The search time window for each AGN is defined by looking for photon flares in the IC79 period reported in astronomer telegrams or other relevant references. The post-trial p-value for the most significant AGN (PKS 1830-211) is 0.93. Fluence upper limits for the most significant time window for each source are shown in Figure 2 (*Right*). The upper limit depends on the declination since the sensitivity is different for the energy ranges accessible in each part of the sky<sup>17</sup>.

3.4 Multiflare stacking search: An extension of the multiflare method was developed to consider several flaring sources that belong to a particular AGN category (FSRQs or BL-Lacs) in a single statistical test. The multiflare stacking search is the time-dependent equivalent of the stacking analysis shown in previous time-integrated analyses. The advantage of this approach is that

Table 1: Results of the multiflare stacking searches.

Category	# AGNs	p-value
BL-Lacs	6	0.91
FSRQs (Northern Hemisphere)	5	0.98
FSRQs (Southern Hemisphere)	7	0.16

although the flux required for discovery increases, each source in a considered category may contribute with less flux to achieve an overall 5 $\sigma$  detection than if individually analyzed. This is shown in the example in Figure 2 (*Left*) comparing the dashed lines (multiflare analysis of each one of the 5 considered sources) with the solid lines (stacking the 5 sources). The stacking categories are also defined dependent on the source location since IceCube has higher sensitivity to PeV-EeV energies in the southern hemisphere<sup>17</sup> (see Table 1). The most significant category is the set of FSRQs located in the southern hemisphere with a post-trial p-value of 0.16.

3.5 Neutrino Triggered Target of Opportunity<sup>18</sup>: The methods discussed so far were performed in "offline mode." Once the raw data is taken, additional procedures in the analysis are required, including direction and energy reconstructions, selection of well reconstructed events, background reduction, and the implementation of the statistical test. There is specific interest in simulataneous measurements of  $\gamma$ -rays and neutrinos. A dedicated event selection and analysis have been implemented in recent years to take into account the timing properties of neutrino events and select promising periods in real time. Given pre-defined significance thresholds, alerts are sent from IceCube to partner Imaging Air Cherenkov Telescopes (IACTs) in real time such that follow-up measurements of a source in a list of selected AGNs may be performed.

### 4 Summary

Evaluating the time domain is an effective way to help distinguish astrophysical neutrino events from background events in neutrino telescopes. The IceCube collaboration has developed several time-dependent search methods that are sensitive to different scenarios of neutrino flares. These methods have been applied in the search for neutrinos produced in AGNs. Improvements in the performance of several of the methods described will be implemented in future IceCube analyses to enhance the probability of finding astrophysical high energy neutrinos.

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# SEARCH OF A NEUTRINO SIGNAL WITH THE ANTARES TELESCOPE BASED ON MULTI-MESSENGER ANALYSIS

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ANTARES is currently the largest neutrino telescope operating in the Northern Hemisphere, aiming at the detection of high-energy neutrinos from astrophysical sources. Such observations would provide important clues about the processes at work in those sources, and possibly help solve the puzzle of ultra-high energy cosmic rays. In this context, The ANTARES Collaboration is developing several programs to improve its capabilities of revealing possible spatial and/or temporal correlations of neutrinos with other cosmic messengers: photons, cosmic rays and gravitational waves.

# 1 Introduction

Neutrinos are unique messengers to study the high-energy universe as they are neutral and stable, interact weakly and therefore travel directly from their point of creation to the Earth without absorption. Neutrinos could play an important role in understanding the mechanisms of cosmic ray acceleration and their detection from a cosmic source would be a direct evidence of the presence of hadronic acceleration. The production of high-energy neutrinos has been proposed for several kinds of astrophysical sources, such as active galactic nuclei (AGN), gamma-ray bursters (GRB), supernova remnants and microquasars, in which the acceleration of hadrons may occur (see Ref.<sup>1</sup>).

The ANTARES Collaboration has constructed a neutrino telescope  $^2$  at a depth of about 2475 meters, offshore Toulon, France. Neutrinos are detected by photomultiplier tubes (PMTs), housed in pressure resistant glass spheres, which are arranged on 12 detection lines. Each line accommodates up to 25 triplets of PMTs, located between 100 and 450 m above the sea bed. On shore, a computer farm runs a set of trigger algorithms to identify events containing Cherenkov light from high energy muons within the data stream, which otherwise consists mostly of signals from radioactive decay and bioluminescence. In 2007, the first 5 detector lines became operational, followed, in May 2008, by the completion of the full 12-line detector.

Most of the analyses described here use a muon track reconstruction algorithm based on Ref.<sup>3</sup>). The angular resolution (i.e. the median angle between the neutrino and the reconstructed muon) was found to be  $0.4\pm0.1$  (sys) degrees for the detector with all 12 lines operational<sup>4</sup>.

# 2 Time-Dependent Point Source Search

By design, neutrino telescopes constantly monitor at least one complete hemisphere of the sky and are thus well set to detect neutrinos produced in transient astrophysical sources. The flux of HE neutrinos from transient sources is lower than the one expected from steady sources, but the background originating from Earth's atmosphere can be dramatically reduced by requiring a directional and temporal coincidence with the direction and time of the astrophysical phenomena detected by a satellite. These studies are applied to GRBs, AGNs or microquasars while observed in high flaring activities.

Blazars are particularly interesting as potential neutrino point sources as their enormous energy output in the form of electromagnetic radiation and their relativistic outflow of collimated streams of matter make them good candidate sources of high-energy cosmic rays. As a consequence, neutrinos and gamma-rays may be produced in interactions of accelerated hadrons with intense ambient photon fields or matter. The gamma-ray light curves of blazars measured by the LAT instrument on-board the Fermi satellite reveal important time variability on a timescale of hours up to several weeks, with high-state intensities mostly several times larger than the typical flux of the source in its quiescent state. Assuming a hadronic origin of the observed gamma-rays, it is assumed in the following that the observed time-variable gamma-ray fluxes and the expected associated neutrino fluxes are proportional. Therefore, high states of gamma-ray activity in a source are used to define time windows for the neutrino search from this source.

The algorithm for a point source search with time dependence factorizes the probability of a given event to be signal or background into a directional and a time component. The probability density function describing the background contribution is derived from data using the observed declination distribution of the selected neutrino candidate events and the time distribution of all reconstructed muons. The probability density for the signal is described by the telescope's point spread function and by the gamma-ray light curve of the source under inspection. Using a method that maximizes the likelihood ratio of signal and background, it has been shown (Ref.<sup>6</sup> for details) that the discovery potential of the telescope improves at least by a factor of 2-3 for flare durations shorter than a day compared to the time integrated point-source analysis.



Figure 1: Gamma-ray light curve (dots) of the blazar 3C279 measured by the LAT instrument onboard the Fermi satellite above 100 MeV. The blue histogram indicated the high state periods. The dashed line (green) corresponds to the fitted baseline. The red histogram displays the time of the associated ANTARES neutrino event.

The ANTARES data used in this first coincidence search corresponds to the period from September 6th to December 31st, 2008 (effective live time of 60.8 days). This time-dependent analysis has been applied to bright and variable blazars reported in the first year Fermi LAT catalogue<sup>5</sup>. The resulting list includes six Flat Spectrum Radio Quasars (PKS0208-512, PKS0454-234, 3C273, 3C279, PKS1510-089, 3C454.3)) and four BL Lacs (AO235+164, OJ287, WComae, PKS2155-304). The most significant source is the blazar 3C279, which has a pre-trial p-value of 1 %. The unbinned method described above finds one high-energy neutrino event located at 0.6° from the source location during a large flare in November 2008. Figure 1 shows the

time distribution of the Fermi gamma-ray light curve of 3C279 and the time of the coincident neutrino event<sup>6</sup>. The error estimate on the reconstructed direction, derived from the maximum-likelihood track fit, is  $0.3^{\circ}$ . The final probability, after the trial correction to find a signal at least as significant as the one observed amounts to 10 %, compatible with the background hypothesis.

The time-dependent point source search has also been performed with a list of six microquasars with X-ray or gamma-ray outbursts in the 2007-2010 satellite data (RXTE/ASM, Swift/BAT and Fermi/LAT)<sup>7</sup>. The list includes Cir X-1, GX339-4, IGR J17091-3624, Cyg X-1, Cyg X-3. No significant excess of neutrino events in spatial and time coincidence with the flares was found. The inferred limits on the neutrino flux are close to predictions <sup>8</sup> which may be reached by ANTARES in the following years, in particular for GX339-4 and Cyg X-3.

#### 3 TAToO: optical follow-up of neutrino alerts

The above mentioned studies are triggered searches based on external alerts. Reversely, ANTARES can also send alerts thanks to the ability of its data acquisition system to rapidly filter and reconstruct events in real-time<sup>9</sup>. The main advantage of this program is that no hypothesis is required on the nature of the source, only that it produces neutrino and photons. In this context, the 2  $\pi$  instantaneous sky coverage and the high duty cycle of the detector are relevant assets. Alerts consist either on doublets occurring within 15 minutes and separated by  $3^{o}$  or on HE events (typically above 5 TeV). Recenty, a third criterion has been implemented: events closer than  $0.3^{\circ}$  from a local galaxy (within 20 Mpc) generate an alert as well. Depending on the neutrino trigger settings, the alert are sent at a rate of about twice per month. With this system, ANTARES is able to send alerts in few seconds ( $\approx 3-5$  s) after the detection of the neutrinos. The optical follow-up is performed by the two 25 cm robotic telescopes of TAROT<sup>10</sup> and the four 45 cm telescopes of ROTSE -III<sup>11</sup>. The main advantages of these instruments are the large field of view of about 2 x 2 square degrees and their very fast positioning time (less than 10s). Recently, the follow-up has been extended to the 1 m ZADKO telescope <sup>12</sup> located in Australia. Thanks to the location of the ANTARES telescope in the Northern hemisphere (42.79 degrees latitude), all the seven telescopes are used for the follow-up program. With the current settings, the connected telescopes can start taking images with a latency of the order of about 20 s with respect to the neutrino event including the telescope slewing. To be sensitive to all astrophysical transient phenomena, the observation strategy is composed of a real-time observation followed by few observations during the following month  $^9$ .

Curently, two offline analysis pipelines are used: the ROTSE automated pipeline<sup>13</sup> and one specially adapted to the TAROT and ROTSE image quality based on the Poloka<sup>14</sup> program originally developped for the supernovae search in the SuperNova Legacy Survey (SNLS) project. This off-line program is composed of three main steps: astrometric and photometric calibration, subtraction of each image and a reference one and light curve determination for each variable candidates. The photometry is done using <sup>15</sup>.

The results of the analysis of the data taking from 01/01/2010 to 31/12/2012 is presented. During this period a total of 83 alerts were successfully sent to the telescopes, 65 of which benefit from at least 3 observations. For the remaining 18 alerts were not followed because of the telescope maintenance or due to the Sun position too close to the alert direction. Only 12 alerts had a good quality follow-up within less than one day (i.e. prompt follow-up). The lack of prompt observations is due to the telescopes observing efficiency upon the reception of the alert. The minimum delay between the neutrino detection and the first image is around 20 s. No object has been found for which the light curve is compatible with a fast time decreasing signal. The limitation is most probably due to the sensitivity of the telescope and atmospheric conditions during the observation, which reduce the limiting magnitude. We define the limiting magnitude as the mean value of sources extracted at a Signal-to-Noise Ratio (SNR) of 5. Table 1 shows the obtained limits along with the delay of the first image acquisition with respect to the neutrino detection.

Alert	Time delay	Limiting magnitude	Galactic extinction
	(days)	(R mag) Prelim	(mag)
ANT100123	0.64	12.0	0.2
ANT100302	1.01	15.7	0.2
ANT100725	8.7e-4	14.5	0.3
ANT100922	4.7e-2	14.0	0.5
ANT101211	0.50	15.1	0.1
ANT110409	3.0e-3	18.1	6.7
ANT110529	5.2e-3	15.6	1.2
ANT110613	7.8e-4	17.0	2.3
ANT120730	2.4e-4	17.6	0.4
ANT120907	2.9e-4	16.9	0.2
ANT121010	2.8e-4	18.6	0.1
ANT121206	3.1 e-4	16.9	1.3

Table 1: Magnitude limits in R-band (5 $\sigma$ threshold) for the	e neutrino alerts. The second column indicates the time
delay between the first image and the neutrino detection	. An estimate of the Galactic extinction is indicated.

### 4 Conclusion

The ANTARES neutrino telescope is the first and only deep sea neutrino telescope currently in operation. It has been continuously monitoring the Southern Sky with unprecedented sensitivity (in particular to the TeV sources of the central region of our Galaxy) since the deployment of the first detection lines in 2007. Several searches for neutrinos of astrophysical origin have been performed, including a rich multi-messenger program.

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5. GRBs .

Swift results on Gamma-Ray Bursts

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### 1 Gamma-Ray Bursts

Gamma-Ray Bursts (GRBs) are brief end extremely bright explosive events. Their typical prompt phase has an energy content of ~  $10^{51}$  erg and lasts less than 100 seconds, making them the most powerful objects in the whole  $\gamma$ -ray sky (sometimes producing direct flows of relativistic matter with kinetic luminosities  $\geq 10^{53}$  erg s<sup>-1</sup>) for the time interval of their duration (T<sub>90</sub>). There is not a standard prompt  $\gamma$ -ray light curve and the distribution of T<sub>90</sub> displays a double peak (Fig. 1; from<sup>1</sup>), naturally dividing GRBs in two separated classes: a) *short bursts* (SGRBs) for which the typical duration is less than 2 s and b) *long bursts* (LGRBs) for which the duration is longer than 2 s. This separation is not so sharp and both classes shows a broad tail, to longer and shorter bursts respectively, in their distributions: therefore for SGRBs we might have  $10^{-2} < T_{90} < 10^2$  s and for LGRBs we might have  $1 < T_{90} < 10^3$  s. This difference, together with different temporal and spectral properties, points to a different origin mechanism for these two classes: the merger of two compact objects seems to be a better explanation for SGRBs, whereas the collapse of fast rotating massive stars seems to explain in a better way the observed properties of LGRBs.

From an observational point of view, the prompt  $\gamma$ -ray emission is followed by a long lasting (from few seconds up to weeks after the burst) afterglow emission that can be detected at longer wavelengths, from X-rays, through ultraviolet, optical, infrared up to radio wavelengths. The detection of the afterglow emission at all wavelengths<sup>2,3,4,5,6</sup> confirmed the extragalactic origin of GRBs and motivated the building of the first dedicated multi-wavelength observatory for GRBs astronomy: Swift<sup>7</sup>

# 2 The Swift mission

The *Swift* satellite <sup>7</sup> has three instruments (see Fig. 2, left panel): the Burst Alert Telescope  $(BAT^{8})$ , the X-Ray Telescope  $(XRT^{9})$  and the UV-Optical Telescope  $(UVOT^{10})$ . The BAT



Figure 1: Left:  $T_{90}$  distribution for SGRBs (blue) and LGRBs (red) as observed in the GRBs BATSE sample. On the top panel the difference between the observed peak energy ( $E_p$ ) of the two classes is shown [From <sup>1</sup>]. Right: prompt  $\gamma$ -ray light curves of the first 8 GRBs observed by the Swift telescope (from the official Swift archive: http://heasarc.gsfc.nasa.gov/docs/swift/archive/grb\_table/).

operates in the 15-150 keV energy band and has a field of view of two steradians; it detects GRBs and locate them with a centroid accuracy of few arcmin. These positions are delivered immediately to the community while the spacecraft repoint the XRT and the UVOT at the event. The XRT operates in the 0.2-10 keV energy band, has a field of view of  $23.6' \times 23.6'$  and a centroid accuracy of few arcsec; the UVOT is a 30-cm telescope that operates with six filters (in the 170-600 nm wavelength range), has a field of view of  $17' \times 17'$  and a centroid accuracy of less than one arcsec. If a more accurate position with respect to the BAT detection is found by XRT and UVOT the science community is alerted of the improved position, allowing fast multi-wavelengths follow-up observations from ground-based facilities. There are plenty of ground-based telescopes of all sizes, many of them react automatically to triggers delivered by *Swift*, that participate to the multi-wavelengths study of these events, following the decaying light curves, measuring the redshifts and observing their host galaxies.

Table 1: GRBs statistics for the Swift satellite. Updated to May 15, 2013.

Total Number of GRBs detected	764
with XRT observations	$652 (\sim 85.3\%)$
with XRT detection	$591~(\sim 90.6\%)$
with UVOT observations	647 (~84.6%)
with UVOT detection	$243 ~(\sim 37.6\%)$
with ground detection	422 (~55.3%)
with redhsift $(z)$	246 (~32.2%)

As of 15 May 2013, BAT has detected 764 GRBs (at an average rate of ~ 2 GRB per week, Tab. 1). XRT and UVOT, when not limited by observing constrains, promptly observed ~ 85% of the total number of detected events. For the majority of these GRBs the X-ray afterglow was detected by XRT (~90.6%) and the optical counterpart was observed by UVOT for ~40% of the cases. There are 246 *Swift* GRBs with redshift (more than 30% of the total), compared with

41 redshifts found before the advent of *Swift*. A comparison between the redshift distributions of *Swift* and pre-*Swift* LGRBs is shown in Fig. 2; the z-distribution seems to roughly follow the co-moving volume of the Universe<sup>11,12</sup>.



Figure 2: Left Swift spacecraft and instruments. Right: redshift distribution z and look-back time  $(t_{LB})$  of the Swift LGRBs. Swift GRBs are shown in blue, the pre-Swift GRBs in yellow and the co-moving volume of the Universe with the red curve [From <sup>11,12</sup>].

## 3 Swift highlights

### 3.1 High-z GRBs

In the Swift-era 9 events with z > 5 have been found: Four of them with photometric identification of the redshift (GRB 050502B, z=5.2<sup>13</sup>; GRB 050814, z=5.3<sup>14</sup>; GRB 071025, z=5.2<sup>15</sup>; GRB 090429B, z=9.4<sup>16</sup>) and five with spectroscopic confirmation (GRB 050904, z=6.29<sup>17</sup>; GRB 060522,  $z=5.11^{18}$ ; GRB 060927,  $z=5.47^{19}$ ; GRB 080913,  $z=6.69^{20}$ ; GRB 090423,  $z=8.2^{21,22}$ ). For these events Swift arcsec position enabled intense follow-up observations and ground spectroscopy. The study of high-z GRBs is a strong tool to investigate the star formation rate, re-ionization epochs and the cosmic chemical evolution<sup>23,24</sup> (see Fig. 3). In particular these studies show that the dumped Lyman- $\alpha$  systems (GRB-DLAs) metallicity is on average 5 times larger than what observed in quasars (QSO-DLAs)<sup>23</sup> with no evidence for a strong peak in the star formation rate versus  $z^{24}$ .

### 3.2 Outstanding events

Since 20 November 2004 *Swift* has detected several outstanding events. The most notable is certainly GRB 080319B, the so-called "naked-eye" burst due to its extraordinary brightness (peak visual brightness of 5.6 mag), for which optical observations started less than 10 s from the BAT detection. The multi-wavelengths coverage of the light curve from the very early stages provided diagnostics within seconds of its formation. showing how the prompt emission came from a single physical region, with an extremely relativistic outflow that propagated within the narrow inner core of a two-component jet. GRB 080319B was so luminous that such an event could be detected in gamma rays by BAT out to  $z \sim 11$ , while the in *K*-band this source would have been easily detected with small-class telescopes up to  $z \sim 17$  (Fig. 4, left panel, from <sup>26</sup>).



Figure 3: Left: Redshift evolution of the metallicity relative to solar values, for nine GRB-DLAs (blue circles) and QSO-DLAs (squares) [Adapted from <sup>23</sup>]. Right: Cosmic star formation history; bias corrected Swift-GRBs rates (diamonds) show evidence for a flat behaviour with respect to the redshifts [Adapted from <sup>24</sup>].

Another notable event is GRB 050724: it has been the first ever *Swift* short/hard GRB with an optical counterpart. The steep decay observed in its optical light curve did not result from jetted emission, but was due to the large X-ray flare which was contributing to the optical band as well. This interpretation has important consequences in terms of the energetics for the class of SGRBs, showing that the short GRBs luminosity function is quite broad  $^{27}$ .



Figure 4: Left: Absolute magnitude ( $M_r$ ) vs. time of GRB 080319B (red circles) compared with other bright object; SN2006gy (blue triangles), GRB 990123 (yellow stars) and GRB 050904 (green squares). The most luminous known quasar is shown with a dashed horizontal line [From <sup>26</sup>]. Right: X-ray, optical and radio light curves of the afterglow of GRB 050724 [From <sup>27</sup>].

## 3.3 Unexpected transients

Some events triggered BAT as normal GRBs do. However subsequent multi-wavelength analysis revealed the unexpected nature of such particular events. This was the case of Swift J1644+57 and GRB 101225A.

Swift J1644+57 showed intense flares activity in the  $\gamma$ -ray during the first 3 days from the trigger, mimicked by the emission in the X-ray band, followed by an highly variable light curve in the X-ray band that has been gradually fading since <sup>28</sup> (Fig. 5, left panel). This source was not previously detected at any wavelength, it was not present in any sky catalogues and it was unlike any previously discovered extragalactic X-ray transient. The collected data suggest that what seen in the  $\gamma$  and X-ray bands was the onset of relativistic jet activity from a supermassive black hole, due to the tidal disruption of a star falling into a supermassive black hole <sup>28</sup>.



Figure 5: Left: X-ray light curve of Swift J1644+57: a relativistic jet from a star torn apart by a black hole. Right: X-ray, optical and UV light curves of GRB 101225A [From <sup>29</sup>].

GRB 101225A is a well discussed event, for which a firm conclusion about its nature has not yet been found. One interpretation of the data suggested the possibility of a Galactic origin of this event, being a tidal disruption event, consequence of the falling of a minor body (comet-like) into a neutron star<sup>29</sup>. An alternative interpretation suggested a GRB nature of the event with the possible association with a supernova at a redshift  $z=0.3^{30}$ . Not even the detection of the galaxy possibly associated with the event (at a redshift  $z\sim0.85$ , not Galactic but quite different from 0.3) did solve unarguably the quandary between the two proposed interpretation<sup>31</sup>.

### 4 Summary and future prospects

In its 8.5 yrs of life the *Swift* satellite has proved to be a world's premier GRBs observatory. With the discovery of several high-z sources, *Swift* highlighted the LGRBs potential of being beacons from the distant past, as unique probes for SFR, re-ionization and cosmic chemical evolution. At the same time the rapid identification with good accuracy of SGRBs X-ray and optical afterglows allowed the investigation of the nature of this class of events (NS-NS merger) and their host galaxies more in details. The time domain sampling and wavelength coverage of *Swift* is unique, allowing outstanding science results not only on LGRBs and SGRBs, but also for Soft-Gamma Repeters, flare stars, Galactic transients, Blazars, X-ray transients and Supernovae. For the latter, thanks to *Swift*, it has been possible to discover the shock break out of SNe in the X-ray band and accumulate data in the UV band that are critical for cosmology applications of SNe. Last but not least, the versatility of the instrumentation has allowed, and will continue to do so in the near future, the discovery of more usual and unusual transient events.

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# GAMMA-RAY BURST OBSERVATIONS WITH FERMI

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After more than four years of science operation, the Large Area Telescope (LAT) onboard the *Fermi* Gamma-Ray Space Telescope has detected emission from more than 35 Gamma-Ray Bursts (GRBs) at energies ranging from 20 MeV up to tens of GeV. We give an overview of these observations, focusing on the 3-year LAT GRB catalog and presenting the common properties in GRB temporal and spectral behavior at high energies. We also highlight the unique characteristics of some individual bursts. The main physical implications of these results are discussed, along with open questions regarding GRB modeling in their prompt and temporally-extended emission phases.

# 1 Introduction

The *Fermi* Large Area Telescope<sup>11</sup> (LAT) is a pair-conversion detector of high-energy gamma rays of energies ranging from 20 MeV to more than 300 GeV. Since the launch in June 2008, it has been operating in synergy with the Gamma-ray Burst Monitor<sup>22</sup> (GBM), which covers the entire unocculted sky and is designed for gamma-ray transients' detection and spectroscopy between 8 keV and 40 MeV.

This review covers the LAT observational results, focusing on recent populations studies and on GRB common properties at high energies. In section 2, we present what has been seen with the LAT in 3 years of operations, highlighting results from the first LAT GRB catalog. In section 3, we discuss the LAT GRB rate and examine the LAT non-detections of GBM bright GRBs. Whereas about half of the GBM GRBs occur in the LAT field of view (FoV), we investigated why only ~8% are detected with the LAT above 100 MeV. We give our conclusions and some perspective in section 4.

# 2 The First LAT Gamma-Ray Burst Catalog

The first LAT GRB catalog, which is presented in detail in Ref.  $^{18}$ , is a systematic study of GRBs at high energies (>20 MeV), covering a 3-year period starting from the beginning of the nominal *Fermi* science operations in August 2008. It aims at characterizing GRB temporal and spectral properties at high energies, including tabulated GRB parameters along with details on the analysis methodology and tools and their caveats. In the following, we describe some of the ingredients necessary to this work and present selected results.



Figure 1: LAT Low-Energy (LLE) light curves of GRB 090227B (left) and GRB 080916C (right).

## 2.1 Ingredients for GRB Analysis with the LAT

*Fermi* was designed with the capability to repoint in the direction of a bright GRB and keep its position near the centre of the LAT FoV for several hours, subject to Earth-limb constraints. This repointing occurs autonomously in response to requests from the GBM or the LAT, with adjustable brightness thresholds. Each Autonomous Repoint Request (ARR) causes rapid variations of the source off-axis angle in the LAT FoV, making the estimate of the background quite challenging<sup>*a*</sup>. In particular, the usual background-estimation method which consists of extrapolating fits of the event rate before the burst (or interpolating from fits to pre- and post-burst time intervals) provides wrong estimates in the case of ARRs. For the analyses included in the LAT GRB catalog, we instead make use of the background-estimation tool developed by the LAT collaboration and described in detail in Ref.<sup>1</sup>. This tool works in any observational conditions and provides estimates with 10-15% accuracy.

Another important ingredient for GRB studies is the use of the "LAT Low-Energy" (LLE) event  $class^{25}$ . In the catalog work, most GRBs are detected by performing an unbinned likelihood analysis based on the standard event selection (the so-called "transient"-class events) above 100 MeV. However, some GRBs are too weak or at too high off-axis angles (>70°) to be significantly detected. In order to recover significant signal in these situations, we introduced the LLE event class, which corresponds to relaxed event selection criteria. It provides significantly higher effective area at tens-of-MeV energies and at larger off-axis angles (Fig. 1, left) and, for the bright GRBs, the needed statistics to study the temporal properties at low energies in the LAT (Fig. 1, right).

## 2.2 Temporal and Spectral Properties

Whereas the GBM detects ~250 GRBs per year <sup>24</sup> (half of them occuring in the LAT FoV), the LAT detected 35 GRBs in 3 years of operations. This includes 30 long and 5 short GRBs, and 7 "LLE-only" GRBs. Approximately half of these detections benefited from more accurate follow-up localizations by Swift and ground-based observatories. In this sample, 10 redshift measurements are available, ranging from z=0.74 (GRB 090328) to z=4.35 (GRB 080916C).

The GRB emission detected by the LAT above 100 MeV is systematically delayed with respect to the emission observed with the GBM at hundreds-of-keV energies (Fig. 2, left), and it lasts systematically longer (Fig. 2, right). Joint spectral fits using GBM and LAT data recorded during the GBM  $T_{90}$  were possible for 30 LAT-detected GRBs and showed that the commonly used Band function<sup>14</sup> does not capture all spectral characteristics. While this phenomenological

 $<sup>^{</sup>a}$ Another consequence is the huge variation of the LAT exposure, which strongly modulates the observed light curves in detected count space.





Figure 2: Onset time (T<sub>05</sub>, left) and duration (T<sub>90</sub>, right) of the GRB emission observed by the GBM (50-300 keV) and the LAT (>100 MeV). Filled circles indicate long GRBs, and open circles short GRBs.

shape alone can reproduce the spectrum of 21 GRBs in this sample, all other spectra but two (for which a logarithmic parabola alone is preferred) are best fitted using either an additional power-law component (6 GRBs<sup>b</sup>) and/or an exponential cutoff (2 GRBs) at high energies. Apart from the functional shapes examined in the LAT GRB catalog analysis, a couple of GRBs (e.g., GRB 110721A<sup>13</sup>) also show deviations from the Band function in the sub-100 MeV energy domain. This low-energy thermal component has been interpreted as the fireball photospheric emission and is thoroughly addressed in Ref.<sup>23</sup>. As for instance discussed in Ref.<sup>26</sup>, understanding the GRB spectral diversity as revealed by *Fermi* will require detailed broad-band physical modeling in the future.

The origin of the high-energy emission seen in the LAT at later times is less unclear, as the LAT flux above 100 MeV decays smoothly after the end of the low-energy prompt emission (Fig. 3, left). In particular, no obvious pattern is seen in the spectral evolution, and the photon spectral index is close to -2. Such a decay phase is consistent with an afterglow origin of the high-energy emission. Specifically, the observed light curves are well described by a power law in all but three cases, for which a broken power law is preferred (Fig. 3, right). The significance of the breaks corresponds to a chance probability of less than  $10^{-3}$ . In these cases (GRBs 090510, 090902B and 090926A), the time of the break is observed after the end of the low-energy emission, as measured by the GBM T<sub>90</sub>. If we define a late time decay index  $\alpha_L$  as the index measured after the break for these GRBs, and the index of the power law for the light curves which are best fitted by a simple power law, we find that  $\alpha_L \simeq -1$ . This value is expected from the standard afterglow model for an adiabatic expansion of the fireball in a constant density environment. Note that a radiative expansion would predict a decay index of  $10/7^{19}$ , which is not observed. The initial steep decay phase observed in the light curves of GRBs 090510, 090902B and 090926A (Fig. 3, right) might be due to a transition from the prompt emission phase to the phase dominated by the early afterglow emission.

The afterglow of GRB 090510 and GRB 110731A was observed by Swift and other instruments when the high-energy emission was still detectable by the LAT. A broad-band study, from optical wavelengths to gamma rays, showed that the emission is compatible with being

<sup>&</sup>lt;sup>b</sup>Including GRB 080916C, for which this detection was made possible thanks to the improvements in estimating the background and the instrument responses with respect to the initial analysis<sup>2</sup>.



Figure 3: (Left) Decay of the luminosity with time measured in the rest frame for all the LAT GRBs with detected extended emission. (Right) Same quantity, for 3 GRBs with a significant time break detected. Dashed-dotted lines are the best fits of a broken power law to each light curve, while dashed crosses are the luminosities before the peak times (not used in the fits).

from external shock origin  $^{17,10}$ . In one other case, GRB 100728A, high-energy emission was detected by the LAT in correspondence with and around an X-ray flare, which was successfully modeled from X-ray to gamma-ray energies as emission from internal shocks<sup>6</sup>.

# 2.3 Fluences and Energetics

Fig. 4 (left) compares the fluence of the LAT GRBs in the GBM energy range and within the GBM  $T_{90}$  with the entire GBM spectral catalog sample <sup>20</sup>. Not surprisingly, the GRBs detected by the LAT are found to be among the GBM brightest GRBs<sup>c</sup>. In addition, remarkable properties of GRBs were discovered with the LAT at high energies. Firstly, whereas the fluence in the LAT energy range is  $\approx 10\%$  of the fluence in the GBM energy range for long GRBs, short GRBs have a larger fluence ratio (Fig. 4, right). Although this result certainly requires more GRB statistics to be firmly confirmed, it already suggests different energy outputs above 100 MeV from GRBs depending on their progenitors. Secondly, some evidence of a class of hyper-energetic GRBs was found, with four exceptionally bright events (GRBs 080916C, 090510, 090902B and 090926A)<sup>2,7,3,8</sup>. This important result can not be simply explained by the proximity of these GRBs, as their redshifts are distributed from 0.90 to 4.35.

Fig. 5 (left) compares the isotropic equivalent energy (from 1 keV to 10 MeV during the GBM  $T_{90}$ ) of the 10 LAT GRBs with measured redshifts with the samples of GBM  $^{20}$  and Swift  $^{16}$  GRBs. It shows that the LAT GRBs are among the most (intrinsically and observationally) energetic GRBs (GRB 090510 being the most energetic short one), with no particular trend in redshift with respect to the GBM and Swift samples. The right panel in the same figure shows that the rest-frame emission from these GRBs can frequently reach several tens-of-GeV energies, which is a very good sign for the detection prospects of future very high-energy observatories such as the High Altitude Water Cherenkov experiment  $^{27}$  and the Cherenkov Telescope Array  $^{21}$ . These high-energy photons were extensively used to set different kinds of constraints. First of all, they provided lower limits on the mean Lorentz factor  $\Gamma$  of the GRB jets through compactness arguments (Fig. 6, right), and helped to demonstrate that both long and short GRBs can have high outflow rapidity  $^{2.7,3.8}$ , a key result for GRB modeling (see also section 3). Secondly,

 $<sup>^</sup>c\!\mathrm{Note}$  that selection effects due to ARRs should be investigated though.


Figure 4: (Left) Fluence in the GBM energy range and within the GBM  $T_{90}$ , for the entire sample in the GBM spectral catalog and for the LAT GRBs only. (Right) Comparison of the LAT GRB fluences, computed in the GBM and LAT respective energy ranges and  $T_{90}$ 's. Filled circles indicate long GRBs, and open circles short GRBs.

high-energy gamma rays can be absorbed by the Extragalatic Background Light (EBL) when travelling from the emitting region to the observer. Only photons with energies above ~10 GeV suffer from pair creation on the EBL, and they can be used to probe this cosmic diffuse radiation field as a function of redshift in the optical-UV range<sup>5</sup>. Finally, the LAT observations of >10 GeV photons from bright GRBs also provided the best lower limits on the energy scale at which postulated quantum-gravity effects create violations of Lorentz invariance. These constraints strongly disfavour models which predict a linear variation of the speed of light with photon energy below the Planck energy scale (i.e., <1.22 \times 10<sup>19</sup> GeV)<sup>4,28</sup>.

### 3 Non-Detections of GBM Bright GRBs and LAT GRB Rate

Whereas ~9.3 GRBs with more than 10 photons above 100 MeV were expected per year from pre-launch estimates <sup>15</sup>, a mean LAT GRB rate of ~6.3 GRBs per year is obtained from the first LAT GRB catalog, based on the number of photons predicted by the likelihood analysis within the LAT  $T_{90}$  (Fig. 6, left). In spite of different systematic uncertainties arising in these analyses <sup>d</sup>, the lack of LAT GRB detections raises the question whether the high-energy emission is suppressed and if spectral cutoffs are more common than anticipated, similarly to the attenuated spectrum of GRB 090926A<sup>8</sup>.

In order to investigate this question, we estimated the fraction of GBM GRBs that should have been detected by the LAT. In the analysis presented in Ref.<sup>9</sup>, we examined a sample of 30 GBM bright and hard GRBs, with >70 counts/s in the BGO detectors and with a good measurement of the high-energy slope  $\beta$  of the Band spectrum ( $\Delta\beta < 0.5$ ). Comparing upper limits on the LAT flux (0.1-10 GeV) over the GBM T<sub>90</sub> with predictions from the extrapolation of the spectral fits to GBM data, we found that ~50% (15 GRBs) should have been detected by the LAT. In a second step, we included the LAT data ("transient"-class events) above 100

<sup>&</sup>lt;sup>d</sup>For instance, the extrapolations from the BATSE energy range to the LAT energy range as performed in Ref. <sup>15</sup> are uncertain due to the large lever arm and to errors on the high-energy spectral slope  $\beta$ . Moreover, these past estimates used simple detection thresholds and idealized backgrounds.



Figure 5: (Left) Isotropic equivalent energy from 1 keV to 10 MeV during the GBM T<sub>90</sub>. The 10 LAT GRBs with measured redshifts are compared with the samples of GBM and Swift GRBs. (Right) Rest-frame energy of the highest-energy photons from the GRBs detected by the LAT.

MeV in the spectral fits, which yielded considerably softer  $\beta$  values and decreased this fraction down to ~23%. Finally, we repeated the GBM-LAT joint fits, adding a spectal softening in the model between the GBM/BGO and the LAT energy ranges. This modification to the spectrum improved the fits significantly for 20% of the GRBs (6 out of 30), implying that a degree of spectral softening is required to explain their LAT non-detection. The rest 80% of the GRBs remained statistically consistent with a softer  $\beta$ . It is interesting to note that these 6 GRBs have the smallest  $\Delta\beta$  values (and no other particular characteristic), indicating that only a very accurate spectroscopy is sensitive to this spectral feature. Assuming that the softening is due to internal opacity effects, we finally set upper limits on the jet mean Lorentz factors of the 6 GRBs, assuming a (conservative) 100 ms variability time scale. The comparison of these limits to other estimates obtained for the 4 LAT brightest GRBs (Fig. 6, right) indicates a relatively broad range of possible  $\Gamma$  values among *Fermi* GRBs.

## 4 Conclusions and Perspective

The GBM and LAT instruments onboard the *Fermi* space observatory have jointly detected the keV-MeV-GeV emission from a large sample of GRBs. The first LAT GRB catalog <sup>18</sup> will certainly be a valuable tool for future theoretical research and a useful informational resource for scientists who wish to analyze LAT GRB data. The LAT detected 35 GRBs in the first 3 years of *Fermi* operations, by means of the standard likelihood technique above 100 MeV and/or using the new LAT Low-Energy (LLE) event class. A population study indicates (or confirms) interesting patterns, like the delayed onset and the temporal extension of GRB emission observed in the LAT above 100 MeV with respect to the emission detected by the GBM at lower energies. Emergent groups are also observed: LAT GRBs are among the brightest and most energetic GBM GRBs, and the evidence of a class of hyper-energetic GRBs is growing.

Before *Fermi*, the phenomenological Band function provided the standard picture of GRB spectra during their prompt emission phase. A so-called "Band model crisis" has been prompted by *Fermi*, which revealed the diversity and complexity in GRB spectra, calling for a better broadband modeling, opening new questions and triggering new theoretical developments. The origin



Figure 6: (Left) Comparison between the observed yearly rate of LAT GRB detections (red lines) to the pre-launch expectations (black lines) for an energy threshold of 100 MeV. The dashed black line corresponds to an input distribution from which hard bursts have been removed. The red lines indicate the observed number of GRBs as a function of the number of events predicted by the best-fit model in the likelihood analysis. The hatched regions correspond to the statistical uncertainties assuming Poisson fluctuations. (Right) Upper limits  $\Gamma_{\rm max}$  on the jet mean Lorentz factors for the 6 GRBs exhibiting a spectral softening. We only know the redshift for GRB 091127 (brown triangle), so we set  $\Gamma_{\rm max}(z)$  for the rest: GRBs 080925, 081207, 090131, 090528B, and 100724B (brown curves). Lower limits  $\Gamma_{\rm min}$  (GRBs 080916C, 090510, 090902B) and measurements (GRB 090926A) for LAT bright GRBs are superimposed (blue triangles and point). The target photon field for  $\gamma\gamma$  absorption is assumed uniform, isotropic and time-independent, but the error bar for GRB 090926A accounts for different models, illustrating the overall scaling that could be applied to the entire figure.

of the delayed onset of GRB emission observed in the LAT above 100 MeV remains unclear. At late times, the high-energy emission is consistent with the canonical afterglow model if considering an adiabatic fireball. Better time-resolved spectroscopic studies during the prompt emission phase and during the transition to the early afterglow phase will thus be crucial in order to discriminate between the existing models (leptonic vs. hadronic, internal vs. external shocks) which are commonly invoked to explain the GRB temporal and spectral properties at high energies.

Fewer GRBs are detected by the LAT than would be expected by extrapolating BATSE or GBM spectra. The need for an overall softer spectrum or for high-energy cutoffs in GRB spectra at MeV energies is confirmed (~20% in the sample examined). Assuming that this spectral softening arises from internal opacity effects, the range of values for the mean Lorentz factors  $\Gamma$  of *Fermi* GRB jets is found to be broader than those derived only from the LAT bright GRBs. More LAT GRBs will certainly help to understand these spectral properties and to shed light on the LAT GRBs rate. The LLE data fill the gap between the GBM and the LAT energy ranges and have been publicly released at the *Fermi* Science Support Center <sup>e</sup>. Whereas the standard "transient" event selection runs out of effective area below ~100 MeV, the LLE event selection provides plenty of statistics to probe GRB spectral cutoffs in the tens-of-MeV-energy region. Major improvements of the standard analysis are also expected from the future "Pass 8" data, which correspond to a radical revision of the LAT event-level analysis based on the experience gained in the prime phase of the mission. In particular, these improvements include an increased effective area (2-3 times larger than "Pass 7" at 100 MeV) and an extension of the energy reach for the photon analysis below 100 MeV in the future <sup>12</sup>.

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 $<sup>{}^{</sup>e} {\tt http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermille.html}$ 

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# Models and possible progenitors of gamma-ray bursts at the test field of the observations

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During the last 15 years, a standard paradigm has emerged to explain both the progenitor nature and the observed radiations of gamma-ray bursts. In this work we show three GRBs for which the standard paradigm could be tested with high statistics due to their exceptional spectral and temporal coverage. While GRB 1112095 represents a very good example of the standard scenario, GRB 090102 and GRB 111209A do not fit into the standard paradigm.

# 1 Introduction

With the discovery that Gamma-Ray Bursts (GRBs) are cosmological events<sup>1</sup>, a common picture has emerged to explain these events. There are two classes of GRBs: short and long events, separated by the canonical duration value of  $T_{90} = 2 \text{ s}^2$ . Short events are thought to originate from the merging of a binary system of compact objects <sup>3</sup>, even if some magnetar formation models can also explain the observations <sup>4</sup>. Long events are associated with the death of a certain kind of Wolf-Rayet stars in a cataclysmic collapse of the core, the collapsar model <sup>5</sup>. Several pieces of evidence have confirmed the collapsar model: observation of stellar winds around the progenitors <sup>6,7</sup>, association of type Ib/c supernovae<sup>8</sup>,...

Independently on the progenitor nature, a fireball, collimated within a jet and with a Lorentz factor of the order of several hundreds, is produced  $^{9,10,11}$ . The fireball is responsible of the observed radiation through three different classes of shocks: internal shocks (the origin of the prompt phase), external shocks (responsible of the afterglow), and the reverse shock (that cause a rebrightening at low energy) as explained in details in the review of  $^{12}$ . A good example can be seen in Fig. 1 where the light curve of GRB 110205A is shown. This burst is the archetypal event that fit the fireball model, displaying all the components well separated in time. More details on this burst can be found in Gendre *et al.* 2012<sup>13</sup>.

# 2 An example of "non-fitting" burst: GRB 090102

One of the best example of burst that cannot be fitted by the fireball model is GRB 090102. This work has been presented in Gendre *et al.* 2010<sup>14</sup>, and can be summarized as follow. In X-rays, it presents a very smooth light curve with no hint of a temporal break. In the optical, the light curve presents a steep-flat behavior, with a break time at  $\sim 1$  ks after the burst. When taken alone, each of the observation band results can be explained by the standard model. In



Figure 1: Optical light curve of GRB 110205A, extracted from Gendre *et al.* 2012. All the components of the fireball model are clearly seen.

X-ray, this is a typical afterglow expanding in the interstellar medium. In optical, the data could be interpreted as either due to a termination shock, locating the end of the free-wind bubble at the position of the optical break; or as a normal fireball expanding in an ISM, with a reverse shock present at an early time (before the break time). However, once combined together, the flux levels are not compatible between the optical and X-ray band. The cannonball model <sup>15</sup> can partly reproduce the data. It appears clear, however, that in order to explain the broad-band emission, some fine-tuning of this model is mandatory, likewise for the fireball model. Another very good example of "non-fitting" burst is GRB 061126 that also feature an unusual afterglow, and again a non standard model has been proposed for explaining this event <sup>16</sup>.

# 3 Peculiar progenitor: the case of GRB 111209A

We now turn our focus to GRB 111209A, a very peculiar event. It was discovered by the Swift satellite, producing two triggers of the Burst Alert Telescope, and also followed by Konus-Wind. As shown by a re-analysis on ground, the burst started about 5400 seconds before  $T_0$ , and lasted in gamma-ray about 15 000 seconds. In X-ray, the start of the steep decline is supposed to be the true end of the prompt phase<sup>17</sup>: taking this stop time we reached a total duration for this event of more than 25 000 seconds<sup>18</sup>. Browsing all available archives and catalog of GRBs, it was impossible to find another burst with such a large duration. Because this burst occurred at a redshift of  $z = 0.677^{19}$ , its intrinsic duration is larger than 10 000 seconds, making it the first ultra-long burst studied. Its light curve is displayed in Fig. 2.

The origin of this event is not clear. As one can clearly see in Fig. 3, it is very different from normal long GRBs. It presents a thermal component at the start of the XRT observation. Two super long GRBs (GRB 060218, z = 0.033, and GRB 100316D, z = 0.059) were associated with a supernova shock breakout <sup>20,21</sup>, and presented a strong thermal component. However



Figure 2: Light curve of GRB 111209A. We present the high energy, X-ray and optical light curves.

the thermal component for GRB 111209A disappears very soon, and most of the prompt phase is free of thermal emission. Moreover, there is no clear evidence of any SN emission. We can therefore discard this hypothesis, and test unusual progenitors.

The main difficulty in explaining the nature of the progenitor of GRB 111209A is its duration. In  $^{18}$  we discuss how a magnetar model cannot reproduce the energetics and spectral characteristics. The most probable scenario is a single supergiant star with low metallicity. The hypothesized progenitors of long duration GRBs are Wolf-Rayet stars (stars with the outer layers expelled during stellar evolution). When these layers are still present, as in low metallicity super-giant stars with weak stellar winds, the stellar envelope may fall-back and accretion can fuel the central engine for a much longer time. In this scenario, blue super-giant stars can produce GRBs with prompt emission lasting about 10<sup>4</sup> seconds  $^{23}$ .

The afterglow analysis uses the observations of XMM-Newton and Swift in the X-ray, TAROT and GROND in the optical, and ACTA data in radio. From the optical-to-gamma-ray prompt spectral energy distribution we find evidence of dust extinction of the order of  $A_V \sim 0.3 - 1.5$  mag in the rest frame of the GRB, depending on the assumed spectral continuum, that however is not confirmed during the afterglow emission. We find that our results point against a low metallicity environment possibly challenging the low-metallicity progenitor solution. Despite the unusual progenitor nature, the standard fireball model can fit the afterglow data.

## 4 Conclusion

We have presented several cases that does not follow the standard paradigms of GRBs. These cases show that not all GRBs can be explained using the standard fireball, and that not all long GRBs are due to the same kind of progenitor. We have also shown that an unusual progenitor



Figure 3: Position of GRB 111209A (red triangle) in the fluence-duration plane, compared to normal long GRBs (green stars), tidal disruption events (black diamond), supernovae shock breakouts (blue square), and unknown very long events (blue circles).

does not imply an unusual afterglow. The exact explanation of GRBs is still not clearly set, and further works are still needed.

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# EXPLOSIONS OF VERY MASSIVE STARS AND THE ROLE OF HYDRODYNAMICAL INSTABILITIES

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Modern theoretical models predict that massive stars with masses within the 100–250  $M_{\odot}$  range can produce pair-instability supernovae (PISNe). Since the first stars of the Universe are believed to be very massive, these supernovae should play a significant role in the early stages of its history. But these stars represent the last unobserved population, owing to detection limits of current telescopes. We present an analysis of pair-instability supernovae explosions using various numerical codes. We discuss a possible connection of PISNe with gamma-ray bursts (GRBs) and explanation of some properties of GRB in this framework.

# 1 Introduction

The first generation of stars in the Universe, so called Population III stars (Pop III), was formed hundreds of millions of years after the Big Bang. Today we do not have direct observations of how the primordial stars were formed. But certainly, the new generation of instruments will give us an opportunity to test theoretical ideas about the formation of the first stars.

Among these first-generation stars, an important role was played by massive stars. As shown by many numerical simulations,<sup>1,2,3</sup> these very massive stars could end their life either by producing pair-instability supernovae (PISNe), leaving no remnant, or by collapse to a black hole. In the case of PISNe, the energy release is tremendous and could possibly be seen with new telescopes (James Webb Space Telescope, European Extremely Large Telescope).

Gamma-Ray Bursts (GRBs) are very high energetic flashes of gamma emission that last for a few seconds and come from cosmological distances. Although they are already known from 1960s and several models of this phenomenon were proposed,  $^{4,5}$  but until now there is no definite answer on the question "Which objects are the sources of GRBs?". Recently a new interpretation of GRBs as pair-instability supernovae explosions was proposed by Chardonnet et al.<sup>6</sup>

In this work we present an analysis of the PISN explosion. We present the results of onedimensional simulations and analysis of the fate of a star depending on physical conditions. We also present 2D simulations of PISN explosion based on the idea of non-uniform explosion. We discuss possible explanation of some features of GRBs in the case if they can be produced by PISNe.





Figure 1: Fate of a star depending on its mass,  $M_c$ , and binding energy,  $E_{bind}$ . Explosion is marked by diamonds and collapse is marked by circles.

Figure 2: Comparison of the maximum temperature,  $T_{mex}$ , and total nuclear energy release,  $E_{nuc}$ , (shown with stars) with the peak energy,  $E_{p}$ , and isotropic equivalent energy,  $E_{iso}$ , of Swift GRBs.

#### 2 Numerical approach

To investigate the behavior of pair-unstable stars, we performed various hydrodynamical simulations. With the one-dimensional (1D) Lagrangian code, we studied the fate of oxygen cores depending on mass and initial configuration. To study the last stage of explosion when shockwave propagates outward, we applied a two-dimensional (2D) code. There are a few recent modelizations of PISNe in 2D.<sup>7,8</sup> In both cases a modern astrophysical code, CASTRO, has been used. To investigate the influence of hydrodynamical solvers we applied our own numerical code based on the Piecewise Parabolic Method on a Local stencil (PPML).<sup>9,10</sup>

### 2.1 Modelization in 1D

We performed the hydrodynamical simulations for the several models of stars with different masses of the core  $M_c$ . We considered only the cores, initial composition was assumed to be pure oxygen. Initial configurations were computed from the hydrostatic equilibrium condition with the polytropic index  $\gamma = 4/3$ . For each core having mass  $M_c$ , we built several configurations by choosing different values of central density,  $\rho_c$ . This allowed us to consider models with different values of binding energy,  $E_{bind}$ . Thermodynamical quantities at the center that we chose and values of binding energy are very close to the results of evolutionary calculations.<sup>3</sup>

For the 1D computations we developed a numerical code based on the standard Lagrangian approach.<sup>11</sup> The equation of state that we used takes into account the birth of electron–positron pairs.<sup>12</sup> Energy release from nuclear burning and neutrino losses were taken into account. Nuclear burning was followed by  $\alpha$ -chain of reactions up to <sup>56</sup>Ni.

An important fact was established that the fate of the core depends on the value of initial binding energy  $E_{bind}$ . The critical value of  $E_{bind}$  depends on the mass of the core  $M_c$ . Two regions could be seen clearly on  $M_c$ - $E_{bind}$  diagram (Fig. 1). This behavior could be explained by the fact that models with lower  $E_{bind}$  (higher absolute value of  $E_{bind}$ ) gain higher kinetic energy to the moment of oxygen ignition and proceeds faster to Fe-He transition zone (photodissociation). Thus outer layers of the core have not enough time to bounce and expand. Therefore the pressure on the central part couldn't be reduced. Photodissociation dramatically drops down the pressure in the center and the core collapses. The critical value of  $E_{bind}$  tends to zero with growth of  $M_c$ . Taking into account that for a stable non-rotating configuration the binding energy should be negative, we can propose the mass limit for the explosion of non-rotating oxygen core at value about 110  $M_{\odot}$ . This value is in a good agreement with results of the previous works. <sup>13,14</sup>

An interesting correlation has been found for the models that explode: value of total nuclear



Figure 3: SN model with multi-core ignition for the moment t = 28 sec. Logarithm of density (a) is shown in the units of  $\rho_c = 2.65 \times 10^5$  g/cm<sup>3</sup>. Temperature (b) is shown in the units of  $T_c = 2.36 \times 10^9$  K.

energy release,  $E_{nuc}$ , increases with maximum temperature  $T_{max}$  at the center (Fig. 2). If we consider PISN as a source of GRB then in the case of the total disruption of a star hot matter of the core could be ejected outside. Energy gathered from nuclear burning will be emitted by electromagnetic radiation with the same characteristic energies as the temperature of the matter. The efficiency of the transformation of the nuclear energy into the emission should be high, since there are no intermediate processes of transformation and redistribution of energy. Assuming that the progenitor of GRB is a pair-instability explosion of a very massive star, it is natural to associate the peak energy  $E_p$  with the maximum temperature,  $T_{max}$ , and the total isotropic energy,  $E_{iso}$ , with the nuclear energy release  $E_{nuc}$ . It is seen from Fig. 2 that computed values and observational data of GRBs <sup>15</sup> are in a good agreement.

#### 2.2 Numerical explosion in multi-D

To study the role of hydrodynamical instabilities on the process of explosion we performed 2D computations. Hydrodynamic simulations were performed with numerical code based on the Piecewise Parabolic Method on a Local stencil (PPML).<sup>9,10</sup>

We chose simplified physical model of explosion, neglecting the energy release from nuclear reactions and gravity changes. The main goal was to obtain the principal possibility of the total disruption of the stellar core to many fragments in the case of very massive progenitor. We investigated a Pop III star with 100  $M_{\odot}$  oxygen core assuming rotational symmetry. As in 1D case we used polytropic model of a star with index  $\gamma = 4/3$ .

The explosion was simulated by deposition of thermal energy in central region. The energy was inserted by the series of 10 ignition bubbles at the moment of t = 0 sec. All of the bubbles had different energy values and sizes distributed in a stochastic way. The total energy deposited was  $E = 5 \times 10^{52}$  ergs. This nonuniformity could present some inhomogeneities in the core that occur prior to explosion. Nuclear burning in the center of a star could cause the development of large-scale convection. <sup>16</sup> If convection occurs prior to the moment of pair-instability, the contraction and explosion could be non-symmetrical. Inhomogeneities in temperature and density could lead to the occurrence of ignition spots in the core.

The results of the computations are presented in Fig. 3. It shows the density and the temperature for the moment t = 28 sec. The shock, produced by the explosion, is split on 2 fronts propagating through the rarefied matter and heating it. In the central part of the core there is a region with Rayleigh-Taylor instability. The radius at which this instability occurs is very close to the value obtained by Chen et al.<sup>7</sup> Many spots of hot matter appears behind the shockwave. This could lead to the disruption of the star in many fragments. As a result the

light curves of such supernova could be very complex, which could be a possible explanation of time-variability of GRBs.

## 3 Discussions and conclusions

We presented our analysis of PISN explosion. Results of 1D simulations are in a good agreement with previous works. We proposed the initial binding energy of a star as the criteria of its subsequent fate. An interesting correlation between total nuclear energy release and maximum temperature has been found which could be a key to understanding the Amati correlation.

We performed also the 2D numerical simulations. We proposed multi-core ignition scenario to explore non-uniform PISN explosion. This could be an "exotic scenario", but if the explosion is non-uniform it could change the light curve, chemical production and also the spectrum.

Another key question of PISN explosion phenomena is the role of envelope. In order to explain properly GRB with PISN the envelope of a pre-supernova must be removed in a certain way. Woosley et al.<sup>17</sup> proposed the idea that quite small pulsation of pair-unstable star could eject the envelop. Non-uniform explosion of a star without envelope could produce light curve that is different from typical plateau-type, having very complex behavior, typical for GRBs.

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# FERMI OBSERVATIONS OF THE JET PHOTOSPHERE IN GAMMA RAY BURSTS

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Fermi Gamma Ray Space Telescope observations of the prompt emission in gamma-ray bursts have shown that several components can be present in the spectrum. The physical source for one such feature is likely emission from a jet photosphere. The detailed *Fermi* observations regarding the behaviour of the photosphere show that it plays a significant role in the formation of the spectrum in several strong bursts. In particular, the identification of the photospheric component is important in order to correctly interpret the emission. Moreover the observations of the thermal spectra broadening in one of the *Fermi* bursts support the models of geometrical and physical processes that can broaden the photospheric spectrum from a relativistic outflow. These same processes can therefore explain the non-thermal spectra seen in many bursts.

# 1 Introduction

Gamma ray bursts (GRBs) are cosmological flashes whose prompt emission, lasting for 0.01-100s, is in the gamma ray band. Their late emission lasting for thousands of seconds, can be detected at lower energy ranges like optical and radio. One or two GRBs per day are typically observed, but their origin and the particle acceleration mechanisms involved still remain unknown. The favourite hypothesis on their origin is the collapse of a supermassive star, while there is no leading hypothesis for the acceleration mechanisms involved in the outflow responsible for the prompt emission.

In the fireball model the gravitational potential energy of the core collapse of a supermassive star can be extracted in a short timescale to form an unstable relativistic outflow with a bulk Lorentz factor  $\Gamma \sim 100$  to 1000. The initial gravitational energy can be transformed into kinetic energy (e.g. Mészáros & Rees 1993<sup>13</sup>) of the plasma that further creates the jet emerging from the star envelope. As the initial fireball cools and becomes transparent, thermal, photospheric emission is expected to be emitted. Furthermore, these outflows naturally lead to dissipation processes, such as shocks or magnetic reconnection. The dissipated energy accelerates leptons to high energies, and these then radiate synchrotron and inverse Compton radiation. The process of conversion of the internal or kinetic energy of the shells, which is carried mainly by protons (and/or the magnetic field), to the electrons which are the radiating agents, is most uncertain. This emission constitutes the prompt phase radiation, a flash of gamma-rays lasting from a fraction of a second to a few minutes.

Since their discovery about 40 years ago many missions have been dedicated to the GRBs and in particular to understand the emission mechanisms involved in the prompt emission phase, but not yet a clear unique picture has emerged from the observations. The spectrum of the prompt is commonly thought to be non-thermal and modeled with a form function proposed by Band et al. 1993 <sup>4</sup> consisting of two power laws smoothly joint together. In some cases this function has found to be in agreement with the spectrum produced by synchrotron emission from an electron population in fast cooling regime whose energy distribution is a power law (e.g. Tavani 1996<sup>22</sup>). On the contrary most of the observed spectra fitted with the Band function have a low energy index (commonly called  $\alpha$ ) steeper than the slopes allowed by the optically-thin synchrotron or synchrotron self-Compton model predictions. Moreover the outflow internal shocks that produce the synchrotron emission are demonstrated to be too inefficient to provide the observed energy release and the correlation between the peak energy and the luminosity (Ramirez-Ruiz & Lloyd-Ronning 2002<sup>18</sup>). On the other hand the original fireball model of gamma-ray bursts predicts a strong photospheric component during the prompt phase (Goodman 1986<sup>8</sup>, Paczyński 1986<sup>16</sup>). The very high optical depth to scattering expected near the base of the flow implies that, regardless of the exact nature of the emission process, the resulting spectrum thermalises and is observed as a Planck spectrum. In this same frame also a possible softening of the low energy spectral index, due to geometrical effects, has been proposed (Paczyński 1986<sup>16</sup>).

An hybrid model has been proposed by Mészáros & Rees 2000<sup>14</sup> where an dditional opticallythick thermal (blackbody) component that may contribute to the observed non-thermal spectrum. The observed spectrum and its evolution would be the result of super imposed emissions coming from two different emission regions of the outflow. This model explains not only the hard spectral slopes but also the observed spectral correlation between peak energy and luminosity and therefore the high radiative efficiency required to produce such spectra.

# 2 The BATSE Era

The photospheric component was first seen in the BATSE data covering the 25-2000 keV energy range. Several GRB spectra could be equally well or better described by a Plank function together with a power law component respect to the commonly used Band function<sup>19</sup>. The evolution of the thermal component throughout the duration of the burst was observed to have a common behaviour in the studied bursts. The black body temperature evolution follows a broken power law while the normalization of the Plank component follows a power law. As can be seen in fig.1 the normalization parameter increases with time, while the temperature parameter decreases down to an undetectable level.



Figure 1: Example of a BATSE detected burst spectrum compatible with photospheric emission (left). The temperature (centre) and the normalization (right) evolutions show the typical behaviour of this type of bursts.

#### 3 The Fermi Era

The *Fermi* telescope, launched in May 2008, has a larger energy coverage for the GRB than BASTE. The two experiments onboard *Fermi*, namely the Gamma ray Burst Monitor (GBM  $^{12}$ ) and the Large Area Telescope (LAT  $^2$ ), provide an uninterrupted detection energy range

from 8 keV to 200 GeV. Many new GRB proprieties have been discovered by the *Fermi* team in these years, like the delay onset of emission > 100 MeV or the presence of a spectral extra component that accounts for the high energy emission in some GRBs. The thermal component already seen in the BATSE bursts is confirmed by the *Fermi* observations and the wider energy coverage allows to further investigate the higher energy part of the spectra modeled by a power law in the BATSE data.



Figure 2: Time-integrated spectrum of GRB110721A fitted with a Band function combined with a Planck function (left). The upper panel shows the model spectrum in  $\nu F \nu$  representation, the middle panel the count spectrum and the lower panel the residuals of the fit. The temporal evolution of the black body temperature is shown in the top right panel and the evolution of its normalization in the bottom right panel. In the top panel, filled circles indicate a > 5 $\sigma$  significance of the blackbody, open circles a 3 $\sigma$  significance. The smaller points in both panels are from fits using a high time resolution, which lowers the significance of the component.

## 3.1 The double-humped spectrum

The cases of GRB090820A (Burgess et al.<sup>5</sup>) and GRB100924B (Guiriec et al.<sup>9</sup>) proposed a "double humped" spectrum where together with the Plank function there is an additional spectral component that peaks at higher energy and is generally shaped like a Band function up to 10 MeV. This type of GRB has been recently confirmed by the GRB110721A that was detected by the GBM and LAT detectors. In this case Axelsson et al.<sup>3</sup> found that the second component peaks at  $15.2 \pm 1.3$  MeV at the beginning of the burst and declines like a power law with index  $-1.22 \pm 0.13$  as a function of time. The temporal evolution of the temperature and the normalization of the Plank function follow the same pattern found in the BATSE bursts: a broken power law and a power law respectively (see fig.2).



Figure 3: Photospheric emission spectrum of GRB090902B at early time (left pannel). Broadening of the spectrum at later times (center) and temporal evolution of the temperature in the first epoch (right).

### 3.2 The photospheric dominated spectrum

Among the almost 40 bursts detected by both the GBM and the LAT detectors, some exhibit the double humped spectral behaviour while others do not. In particular GRB090902B shows a dominant photospheric component but no Band-like one. The high energy emission seen in this bursts is well described from Abdo et al.<sup>1</sup> by a power law that extends throughout all the spectrum from 8 keV.

A further study of this burst from Ryde et al.<sup>20</sup> with finer resolved time bins divides the emission in two epochs: from 0.0s to 12.5s and from 12.5s to 25s. In the first epoch the spectral photospheric component is very narrow,  $\alpha \sim 0.3$  and  $\beta \sim -4$  (see fig. 3 first panel). The measured value of  $\alpha$  has been demonstrated by Ryde et al.<sup>21</sup> to be highly incompatible with the typical  $\alpha = -1.5$  in the case of synchrotron emission from fast cooling electrons in a optically thin region. The second epoch instead is characterised by a broadening of the peaked emission towards a spectral shape that more resembles the commonly seen wide spectra (see fig. 3 middle panel).

The identification of the clear photospheric component in the early time bins provides the opportunity to follow the evolution of the physical conditions of the outflow, in particular the radius of the photosphere and the bulk Lorentz factor that seem to increase at later times. In this case the temporal evolution of the black body temperature (see fig. 3 last panel) is not described by a broken power law as seen in the double humped spectra, suggesting different environmental conditions at the emission site.

## 4 Modification of the Plank function in photospheric emission

GRB090902B gave a solid observational contribution to the debate of the spectral shape of the photospheric emission. The possible modification of the Plank function under particular emission conditions or geometrical effects was already hypothesized to explain Band-like spectra.

In the case of subphotospheric emission several different mechanisms for the energy dissipation below the photosphere can intervene to modify the original Plank function. Among those magnetic reconnection (Giannios  $2008^7$ ), internal shocks (Ioka  $2010^{10}$ ) or collisional dissipation (Beloborodov  $2010^5$ ). Or if the amount of dissipation and parameters of the outflow are varied, it is possible to produce a wide range of spectral shapes by such subphotospheric energy release (Peer et al.  $2006^{17}$ , Nymark et al.  $2011^{15}$ ) more complex than the pure Band function.

Purely geometrical effects can also broaden the spectrum by making the  $\alpha$  value range between -1 and 0.4 as shown by Lundman et al.<sup>11</sup>. They use a combination of analytical modeling and numerical simulations to describe the energy spectra of the GRB outflow as a function of the viewing angle in the case of a narrow jet. In the case of a wider jet the spectral broadening is present only if the viewing angle is close to the jet opening angle.

### 5 Summary

The advent of the *Fermi* telescope brought a deeper understanding of the GRB spectra. Important results, already outlined by the BATSE data, on the emission processes involved in the outflow have been confirmed and expanded. A recurring double humped spectral shape in the *Fermi* GRBs is suggesting that the presence of the photospheric emission is more common than previously thought. By connecting the Plank function component to the jet photosphere we can study the radius of the photosphere and the bulk Lorenz factor of the emitting region. Furthermore the identification of the main spectral component of GRB090902B with the emission from the photosphere allows the study of the broadening of the Plank function. Several mechanisms can account for this modification of the Plank function from dissipative processes to geometrical effect of the jet viewing angle. Including a photospheric component is thus a first step to understanding the physical origin of GRB prompt emission - something which the Band function cannot provide.

## Acknowledgments

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## GRB SPECTRA BEYOND THE STANDARD MODEL

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I discuss successes and issues for the GRB spectral 'standard model': the Band function. In light of the observation of an additional hard power law component in some bursts as well as the evidence that many spectra exhibit a photospheric component, I will show how burst spectroscopy is being forced into new directions. One recent development, which is work done by J. Michael Burgess at UAH, involves directly fitting physical models to the data.

# 1 The Standard Model: Band '93

In the beginning, Apollo (16) went to the Moon. Apollo sought the Cosmic Fire (GRB). Apollo brought the Cosmic Fire back to Man. Apollo saw that it was good; Man saw that it was Band<sup>1</sup>. That is, one of the first published spectra of a bright GRB had as its spectral function a smoothly broken power law. David Band<sup>2</sup> codified it as the unique function that consists of two asymptotic power laws where both the function and its first derivative are continuous:

$$f(E) = A\left(\frac{E}{100 \text{ keV}}\right)^{\alpha} \exp\left(\frac{-E\left(2+\alpha\right)}{E_{\text{peak}}}\right)$$
  
if  $E < \frac{(\alpha-\beta)}{(2+\alpha)} \frac{E_{\text{peak}}}{\equiv} E_{\text{break}},$   
and  $f(E) = A\left[\frac{(\alpha-\beta)}{(2+\alpha)} \frac{E_{\text{peak}}}{100 \text{ keV}}\right]^{(\alpha-\beta)} \exp\left(\beta-\alpha\right) \left(\frac{E}{100 \text{ keV}}\right)^{\beta}$   
if  $E \ge \frac{(\alpha-\beta)}{(2+\alpha)} \frac{E_{\text{peak}}}{(2+\alpha)}.$  (1)

This is usually parametrized in terms of the energy at the peak of photon power density  $(\nu F_{\nu})$  distribution:  $E_{\text{peak}}$ . The definition requires that the high energy power law index  $\beta < 2$ , in order for a peak to exist. Although the function is completely empirical, it is flexible enough to mimic optically-thin thermal Bremsstrahlung, optically-thin synchrotron and blackbody spectra, each in the appropriate limit of the parameters.

Several spectral catalogs have been compiled from the fitted spectral shape parameters of the Band function:  $\alpha$ ,  $\beta$ , &  $E_{\text{pcak}}^{3,4}$ . For example, 'The BATSE 5B Gamma-Ray Burst Spectroscopy Catalog' (Goldstein et al., submitted) compiles the spectral fit parameters from 2145 bursts observed over the entire lifetime of BATSE. Two spectra are derived from each burst: the 2s peak flux interval and the time-averaged fluence. In addition, several functions, including Band, are fitted to each spectrum, and statistical estimates are made to determine which function provides the best fit to the data. In general, the lower fluence spectra do not provide enough counts even to determine an  $E_{\text{peak}}$ , which is why only 2000 out of the total 2145 fluence spectra have a peak energy as a best fit function parameter. Still, even in this extended burst selection, the predominant fitted values for this parameter are distributed roughly as a Gaussian in log energy, with a peak near 200 keV, as they do for the bright burst catalog<sup>3</sup>. Compared with the bright sample, the inclusion of weaker bursts seems to add values on the higher energy wing of the overall distribution. Although the Band function provides acceptable fits to GRB spectra, the interpretation of the fitted parameters in terms of physical emission models raises some issues.

The low-energy power law index ( $\alpha$ ) from the Band function (Eq. 1) could be seen as proxy for the low-energy behavior of optically-thin synchrotron emission, which is one possibility for the prompt emission of GRBs. When we examine the distribution of the fitted values for  $\alpha$ , we see that it is again roughly Gaussian in shape, with a peak very close to an index of -1, which is not expected from any emission model<sup>3</sup>. What is worse, are the two 'death lines' limiting regular and fast cooling synchrotron to values > -2/3 and > -3/2, respectively<sup>5,7</sup>. That the majority of GRBs have spectra that violate fast-cooling emission remains a serious open issue, since it should dominate under conditions likely in the prompt emission.

An issue of a different kind exists for the Band high-energy power law parameter. Relativistic shock simulations tend to show universal power-law index for the accelerated electrons, on the order of  $p = 2.4^8$ . Assuming that the photon spectrum reflects this, we expect the high-energy power law photon index to be constant at (p+2)/2 = 2.2. There are several bright bursts that clearly demonstrate that the power law index changes with great significance. For bright bursts in general, the change is typically -0.6 over the duration of the burst<sup>6</sup>. This poses a problem for the interpretation of the prompt emission in terms of relativistic shocks.

#### 2 New Features

So far, we have the impression that the prompt emission of GRBs is rather simple. However, there are several observations that demonstrate that burst spectra can be quite complex. Indeed, these observations challenge our basic assumptions of jet physics, while at the same time, they open the door to solving some of the issues already covered above.

First of all, there is evidence for an extra high-energy power law spectral component, as first shown by Gonzalez et al.  $(2003)^9$ . In joint fits performed with BATSE and the EGRET-TASC calorimeter, a high-energy excess was discovered in the light curve of one burst, GRB941017. Fitting time-resolved spectra reveals a very hard (-1 power law index) component that persists for 200 s, long after the BATSE emission has quit, and is not an extrapolation of the BATSE  $\beta$  power law into the TASC energy range, but clearly an extra component.

As mentioned in Piron's review of the Fermi-LAT observations of GRBs (elsewhere in this volume), this extra, hard component seems to be a fairly common feature of the bursts that are visible in the LAT. The extended temporal emission has also been observed several times. The extra power law component challenges our understanding of burst emission in several ways. The -1 power law can not persist to much higher energies, as the power emitted goes up quickly, to the point where infinite energy would be required. The timing of this spectral component is also suspect: its light curve does not mimic that of the BATSE data, rather it rises from nothing and persists at a constant flux. This seems to rule out an Inverse Compton nature for

the extra component, if the BATSE gamma ray light curve were providing the seed photons for upscattering.

Ryde et al. (2006)<sup>10</sup> examined archival BATSE spectral data and found that an alternative spectral function composed of the sum of a blackbody (BB) and power law (PL) resulted in adequate fits to a surprising number of spectra. This photospheric model is reviewed elsewhere in this volume by Moretti. Here, I would like to address the question, 'Given that the Band function is so successful, why does this new function work at all?'. GRB spectra with sufficient statistics for spectral analysis (45 $\sigma$ ) typically allow only 4 free parameters for fitting, as with the Band GRB function. However, the BB + PL function also has 4 free parameters, thus there is the same freedom to accomodate the data. However one might accept the interpretation, such a model does open up some interesting possibilities. Given that the BB low-energy portion is so steep (+1 index), the sum of that with the fitted PL should result in an overall spectrum that mimics nearly any PL index < +1. The sum of tow PL is not a PL, however, so we must assume that the data are accommodating enough, given the detector resolution, that it can be fit by a single PL, as with the Band  $\alpha$ . That does not say why the Band parameter clusters around -1, but it does address the two 'lines of death'. Finally, on the Wien side of the BB, the spectrum resulting from the roll-off and the high-energy portion of the PL could, given the poor statistics at high energies, mimic a single PL index, such as the Band  $\beta$ . In fact, changing the normalization between the two components over time could account for the observed change in  $\beta$ .

# 3 Next Steps

Motivated by Baring and Braby  $(2004)^{11}$ , Burgess et al.  $(2011)^{12}$  began fitting spectra with numerically integrated synchrotron emission from parametrized electron distributions. The electron distributions are 'life-like': Fermi shock accelerated PL from a thermal (relativistic Maxwellian) reservoir or fast cooling broken PL. Fitting is done to the electron distribution, then numerically convolved with the synchrotron emissivity kernel; this has been too numerically intensive until recently. Adding a photospheric component, we find that its evolution is more tightly constrained and kT better determined than can be found with BB + Band. we can use this to better probe the independence (or correlation) of each component, using fewer free parameters than with the Band GRB function.

The left hand of Figure 1 shows the typical electron distribution function that is fitted, via its convolution with the synchrotron kernel, to the spectral data, At the low energy end, it is expected to be dominated by a thermal Maxwellian, characterized by a thermal energy  $\gamma_{\text{th}}$ . All of the electrons above the peak in the distribution are assumed to have been accelerated into a power law with index  $\delta$ , down to a minimum energy  $\gamma_{\min}$ . In the saturated case<sup>13</sup>, backed by relativistic PIC simulations<sup>11</sup>, we have fixed the parameters such that  $\gamma_{\min} = 3 \gamma_{\text{th}}$  and the normalizations match at  $\gamma_{\min}$ . The left hand side of Figure 1 shows the resulting electron distribution, with the various parameters indicated. A typical sequence of time-resolved spectral fits are shown in the right side of Figure 1 for GRB081224A, which in this case also includes an evolving photospheric component. In our study, such models have resulted in acceptable goodness of fit values, indicating that physical models can be applied directly to burst data. Much work has yet to be done, since the optically-thin synchrotron model is only one of several that need to be investigated.

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Figure 1: *left*: A typical electron distribution function, with relevant parameters indicated. *right*: A sequence of spectral fits for GRB 081224A, as a function of time (light grey to dark grey). The photospheric and synchrotron components have been separated out.

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# New constraints on primordial black holes abundance from femtolensing of gamma-ray bursts

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The abundance of primordial black holes is currently significantly constrained in a wide range of masses. The weakest limits are established for the small mass objects, where the small intensity of the associated physical phenomenon provides a challenge for current experiments. We used gamma-ray bursts with known redshifts detected by the Fermi Gamma-ray Burst Monitor to search for the femtolensing effects caused by compact objects. The lack of femtolensing detection in the data provides new evidence that primordial black holes in the mass range  $10^{17} - 10^{20}$  g do not constitute a major fraction of dark matter.

## 1 Introduction

Dark matter is one of the most challenging open problems in cosmology or particle physics. An idea that the missing matter may consist of compact astrophysical objects was first proposed in the 1970s [1]. An example of such compact objects are primordial black holes (PBHs) created in the very early Universe from matter density perturbations. Recent advances in experimental astrophysics, especially the launch of the FERMI satellite with its unprecedented sensitivity, has revived the interest in PBH physics [2].

Here, we present the results of a femtolensing search performed on the spectra of GRBs with known redshifts detected by the Gamma-ray Burst Monitor (GBM) on board the FERMI satellite [3]. We describe the optical depth derivation based on simulations applied to each burst individually. The sensitivity of the GBM to the femtolensing detection is also calculated.

# 2 Femtolensing

One of the most promising ways to search for PBHs is to look for lensing effects caused by these compact objects. Since the Schwarzschild radius of a PBH is comparable to the photon wavelength, the wave nature of electromagnetic radiation has to be taken into account. In such a case, the lensing caused by PBHs introduces an interferometry pattern in the energy spectrum of the lensed object [4]. This effect is called 'femtolensing' [5] due to the  $\sim 10^{-15}$  arcseconds angular distance between the images of a source lensed by a  $10^{18}$ g lens.Gould (1992) [5] first suggested that the femtolensing of GRBs at cosmological distances could be used to search for dark matter objects in the  $10^{17} - 10^{20}$ g mass range.

## 2.1 Magnification and spectral pattern

Consider the lensing of a GRB event by a compact object. In the case of a point source, the amplitude contributed by the  $r_\pm$  images is

$$A_{\pm} \propto rac{\exp(i\phi_{\pm})}{\sqrt{|1 - rac{r_{E}^{+}}{r_{\pm}^{+}}|}}$$
 (1)

The magnification  $A^2$  is obtained by summing the amplitudes (1) and squaring, which gives

$$A^{2} = |A_{+} + A_{-}|^{2} = \frac{1}{1 - \frac{r_{E}^{4}}{r_{+}^{4}}} + \frac{1}{1 - \frac{r_{E}^{4}}{r_{-}^{4}}} + \frac{2\cos(\Delta\phi)}{\sqrt{|1 - \frac{r_{E}^{4}}{r_{+}^{4}}|}\sqrt{|1 - \frac{r_{E}^{4}}{r_{-}^{4}}|}},$$
(2)

where  $r_E$  is the Einstein radius,  $r_+$  and  $r_-$  are the distances between the lens and first and second image, respectively. Equation (2) indicates that the magnification depends on the phase. When the two lights paths are not temporally coherent equation (2) is reduced to the two first components.

In the case of femtolensing, the phase shift between the two images is:

$$\Delta \phi = \frac{E \,\delta t}{\hbar},\tag{3}$$

where E is the energy of the photon. The energy dependent magnification produces fringes in the energy spectrum of the lensed object.

#### 2.2 Lensing probability

The optical depth  $\tau$  for lensing by compact objects is calculated according to the formalism described in Fukugita et al. (1992) [6]. The cosmological parameters used in the calculation are:  $\Omega_M = 0.3$  and  $\Omega_{\Lambda} = 0.7$ . When  $\tau \ll 1$ , the lensing probability p is given by  $p = \tau \sigma$  where  $\sigma$  is the "lensing cross-section" (see Chap. 11 of [7]).

In this analysis, the cross-section is defined in the following way. Fringes are searched in the spectra of GRBs. These fringes are detectable only for certain positions  $r_S$  of the source. The maximum and minimum position of  $r_S$ , in units of  $r_E$  are noted  $r_{S,min}$  and  $r_{S,max}$ . They are found by simulation and depend on the GRB redshift and luminosity. The femtolensing "cross-section" is then simply

$$\sigma = r_{S,max}^2 - r_{S,min}^2 \,. \tag{4}$$

The lensing probability does not depend on the individual masses of lenses, but only on the density of compact objects  $\Omega_{CO}$ .

### 3 Data analysis

In our analysis, we use a sample of GRBs detected by GBM with known redshifts. The initial sample consisted of 32 bursts taken from Gruber et al. (2011) [8]. Data were analyzed with the RMfit version 33pr7 program. The observed data is a convolution of the GRB photon spectrum with an instrument response function. For each detector with sufficient data, the background was subtracted and the counts spectrum of the first ten seconds of the burst (or less if the burst was shorter) was extracted.

## 3.1 Simulations

The detectability of spectral fringes has been studied with simulated signals. The detectability first depends on the luminosity and redshift of the bursts, and second on the detector's energy resolution and data quality. The sensitivity of the GBM to the lens mass M depends strongly also on the energy range and resolution of the GBM detectors. When small masses are considered, the pattern of spectral fringes appears outside of the energy range. The large masses produce fringes with hardly detectable amplitudes and periods smaller than the energy bin size.

Because the data quality and the background are not easily simulated, the detectability estimation is performed on real data. For a given observed GRB, the femtolensing signal depends thus only on 2 parameters: the lens mass M and the source position in the lens plane  $r_S$ . The data are then processed as follows:

- 1. The magnification (equation 2) as a function of the energy is calculated for the given lens mass M and position of the source  $r_S$ .
- 2. This magnification is then convolved with the instrumental resolution matrix to obtain magnification factors for each channel of the detector.
- 3. The spectral signal is extracted from the data by subtracting the background. It is then multiplied by the corrected magnification.
- 4. The background is added back.

Figure 1 shows the maximum and minimum detectable  $r_S$  for different lens masses. The maximum difference between  $r_{S,max}$  and  $r_{S,min}$  is at  $M = 1 \times 10^{18}$  g. The largest femtolensing cross-section occurs for this mass.

## 4 Results

As explained in section 2.2, the lensing probability for each burst depends on the lens mass and on the  $r_{S,min}$  and  $r_{S,max}$  values. Since the sensitivity of GBM to femtolensing is maximal for lens masses of  $\sim 1 \times 10^{18}$  g (see figure 1), the values of  $r_{S,min}$  and  $r_{S,max}$  for each event were first determined at a mass  $M = 1 \times 10^{18}$  g by simulation. The lensing probability is then calculated for both the FRLW and Dyer & Roeder cosmological models using the redshift of each burst, the most probable lens position and the values of  $r_{S,min}$  and  $r_{S,max}$  for the mass  $M = 1 \times 10^{18}$  g. The number of expected lensed bursts in the sample is the sum of the lensing probabilities. It depends linearly on  $\Omega_{CO}$ .

Since no femtolensing is observed, the number of expected events should be less than 3 at 95% confidence level (C.L.). The constraints on the density of compact objects  $\Omega_{CO}$  is derived to be less than 4% at 95% C.L for both cosmological models.

# 5 Discussion and conclusions

In the mass range below  $5 \times 10^{14}$  g,  $\Omega_{CO}$  is constrained by PBH evaporation. Above the femtolensing range, the constraints come from microlensing. It is stated in [9] that the compact objects abundance in the mass range  $10^{16}$  g  $< M_{BH} < 10^{26}$  g was virtually unconstrained. Indeed, the only published limits were given by just one group ([10]). The limits are shown on figure 2 as GRB femto and pico. Their limits were based on a sample of 117 bright bursts detected by the BATSE satellite. The bursts were searched for spectral features by Briggs et al. (1998) [11]. The constraints reported by Marani et al. (1999) [10] are  $\Omega_{CO} < 0.2$  if the average distance to the GRBs is  $z_{GRB} \sim 1$  or  $\Omega_{CO} < 0.1$  if  $z_{GRB} \sim 2$ .

The FERMI satellite was launched three and a half years ago. Since then, almost 1000 of GRB were observed with the GBM detector. In many cases data quality is good enough to



Figure 1: Minimum and maximum detectable  $r_S/r_E$  as Figure 2: Constraints on the fraction of compact objects a function of the lens mass for GRB 090424592. of different masses. Figure credited from [2]

reconstruct time-resolved spectra. This unique feature is exploited in our femtolensing search by selecting the first few seconds of a burst in data analysis.

Limits from the present analysis were obtained by selecting only those bursts with known redshifts in the GBM data. This reduces the data sample to only 20 bursts. The constraints on  $\Omega_{CO}$  obtained at the 95% C.L. are shown on figure. 2. These constraints improve the existing constraints by a factor of 4 in the mass range  $10^{17} - 10^{20}$  g.

After ten years of operation, the GBM detector should collect over 2500 bursts. Only a few of the bursts, say 100, will have a measured redshift and sufficient spectral coverage. By applying the methods described in this thesis, the limits will improve by a factor of 5 reaching a sensitivity to density of compact objects down to the 1% level.

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#### Gamma-Ray Bursts as Cosmological Probes

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To use the luminous GRB and afterglow emission as messengers from the early Universe has been advocated ever since the discovery of the cosmological nature of the GRB phenomenon in the late nineties. It took, however, until the advent of *Swift* to detect high-redshift GRBs in significant numbers, and to provide the localization capabilities to enable statistical samples of GRBs free of selection biases and complete in redshift. I will review the progress of the field in the last four years, with an emphasize on new results derived from sample studies and their implications for the nature of GRBs and their host galaxies.

## 1 Introduction

Because long gamma-ray bursts (GRBs) are tightly linked to core-collapse SNe<sup>1,2,3</sup>, GRBs, their afterglows and host galaxies offer a unique opportunity to probe the interstellar medium and the environments where stars form throughout the observable Universe. The highest GRB redshifts measured to date are  $z = 8.2^{4,5}$  for GRB 090423 via spectrosocpy and  $z_{\rm phot} \sim 9.4^{\circ}$  for GRB 090429B through photometry. GRBs and their afterglows are intrinsically luminous and occasionally outshine even the most energetic QSO by a factor of 1000. In addition, their  $\gamma$ - and X-ray signatures are largely unaffected by dust and fade quickly, leaving an uncontaminated view of their host. GRBs therefore pinpoint regions of star-formation irrespective of host luminosity, redshift and dust obscuration. In particular at the highest redshifts, where detailed galaxy observations become challenging, GRBs provide means to measure direct absorption metallicities, constrain the star-formation history and cosmic chemical evolution of the Universe completely independently and complementary to deep galaxy or QSO surveys.

The most significant trend in the recent years in GRB afterglow studies has been the transition from the detailed investigation of individual events to a more statistical analysis of representative samples. This has been facilitated by the exquisite detection and localization capabilities of *Swift*, which allowed efficient ground-based observation for a large number of GRBs. Different groups with different selection methods and follow-up strategies have published large (number counts up to  $\sim 50 - 100$ ) samples of GRBs, afterglows and/or hosts in the recent years<sup>7,8,9,10,11,12</sup>. These samples allow for the first time to study optical/NIR afterglows and host properties systematically, while at the same time limiting inherent uncertainties because of selection biases.

The aim of this review is to provide a short overview over recent results. The limited time and space implies that, within this broad field, I am only able to cover individual aspects briefly, and limit the discussion to a very subjective and biased selection of recent results. For more extensive information, I refer to reviews by J. Fynbo *et al.*<sup>13</sup>, P. Petitjean & S. Vergan<sup>14</sup>, or E. Levesque<sup>15</sup>, and the references given throughout this manuscript.



Figure 1: Each postage stamp shows the 2d-spectrum of a GRB host at the wavelength of a strong emission line as observed with X-shooter. Each row belongs to a single GRB host, while each column shows a strong emission line. Taken from the work of Krühler *et al.* (2012).

## 2 GRB redshifts

Central to the physical interpretation of both the high-energy and afterglow emission is obviously an accurate determination of the GRB's cosmological redshift. Conventionally, this measurement is done with low-resolution spectroscopy of the optical afterglow on large ground-based telescopes<sup>9</sup>. The most robust redshift determination is available from the detection of fine-structure lines of metals, such as Fe II\* or Ni II\*, that are excited by the afterglow emission<sup>16</sup>. Accurate redshift measurements also come from the absorption of metals in the ground state, both from low- (e.g., Mg II, Al II, Fe II) and high-ionization species (e.g., C IV, Si IV), and less accurately from the (in most cases) damped Ly $\alpha$  transition at z > 1.7. The strong Ly $\alpha$  and Lyman-limit breaks, as well as the simple continuum yield also robust photometric redshifts over a large redshift range<sup>17</sup>. The photo-*z*'s are very reliable because of the transient nature of afterglows. There is hence no ambiguity in the continuum spectrum. In particular at the highest redshifts, photometry provides a reliable tool to estimate the distance even in the absence of spectroscopy<sup>18,6</sup>, or to preselect interesting events for deep follow-up observations<sup>19</sup>.



Figure 2: The redshift distribution of the TOUGH survey, before (left panel (a)) and after (right panel (b)) the inclusion of GRB host redshifts. The dashed vertical lines denotes the median redshift of the respective distribution(z = 2.35 for panel (a), z = 2.14 for panel (b)). Taken from the work of Hjorth *et al.* (2013).

The excellent localization accuracy<sup>20</sup> of *Swift*/XRT also allows a redshift determination once the afterglow had faded, i.e, a measurement that does not need to be performed within the first hours after the GRB trigger. Given a sufficiently accurate position (< 2"), a deep image of the GRB field taken at a sufficiently late time provides in many cases a statistical identification between the GRB and its host galaxy<sup>21,22</sup>. Once the putative host galaxy is identified, a spectrum of the host galaxy often reveals emission lines from forbidden ([O II], [O III]) or Balmer (H $\beta$ , H $\alpha$ ) transitions (Figure 1). These kind of redshift determinations have become very efficient only recently through the advent of X-shooter, a second generation instrument at ESO's VLT. With its broad wavelength coverage, it can detect emission lines successfully in a wide redshift galaxies<sup>23</sup>. In particular in cases



where the optical afterglow emission is dust-attenuated below the sensitivity limits of absorption line spectroscopy, host spectroscopy now proves fundamental for building GRB, afterglow and host samples of extremely high redshift completeness (see Figure 2).

## 3 GRBs at the highest redshifts

The huge luminosities emitted in both  $\gamma$ -rays and in the optical/NIR wavelength range make GRBs in principle detectable to  $z \sim 20$  with state-of-the-art technology. Complementary to the identification of drop-out galaxies in the deep Hubble fields, or Ly $\alpha$  emitters in narrow-band surveys, GRBs offer a route for identifying very high-z objects. Noteworthy examples from the recent years are GRB 080913 at  $z = 6.7^{19}$ , GRB 090423 at  $z = 8.2^{4.5}$ , and GRB 090429B at  $z_{\text{phot}} \sim 9.4^{6}$ .

These GRBs clearly show that massive stars were dying in very early phases of the Universe. They also illustrate the potential of similar observations. It is feasible with GRBs to accurately pinpoint the first galaxies independent of their intrinsic luminosity, trace the star-formation rate deep into the era of re-ionization and use the bright afterglow to study the evolution of metal-abundance in the Universe up to very high-redshifts.

The very high redshift GRBs studied until now are intriguingly not very different from their lower redshift counterparts in terms of their physical properties. Both, prompt  $\gamma$ -rays emission and X-ray/NIR afterglow are remarkably similar to many GRBs/afterglows observed at much lower redshift. This suggests that the progenitors of the very high redshift GRBs observed to date are not very massive population III stars, but are more similar to the commonly-detected GRBs at lower redshift and explode in broadly similar physical environments.

#### 4 GRBs as probes of dust



Figure 3: The spectral energy distribution of the afterglow of GRB 070802 with the presence of a 2175 Å dust feature and  $A_V \sim 1$  at z = 2.45. Taken from the work of Krühler *et al.* (2008).

Afterglows are intrinsically extremely luminous, and their continuum is simple synchrotron emission and can be constrained over large regions of the electromagnetic spectrum. This allows a direct measurement of the dust extinction properties from intermediate up to very high redshifts. Afterglow data hence provide direct and detailed insights into the wavelength dependence of dust absorption and thus its properties at redshifts that are not easily accessible by other means.

GRB afterglows, for example, have facilitated the detection of the 2175 Å dust feature (Figure 3) at the highest redshifts to date<sup>24,25,26</sup>, and provided evidence for supernova-synthesized dust at  $z \sim 5^{27}$ . Extending similar analysis to a larger number of events, the distribution of visual extinctions  $A_V$  for a highly complete sample of afterglows was measured for the first time:  $\sim 1/2$ 

of the Swift GRBs shows  $A_V < 0.2 \text{ mag}$ ,  $\approx 30\%$  have  $0.2 \text{ mag} < A_V < 1 \text{ mag}$ , but also  $\sim 20\%$  of all Swift GRB are located behind large dust columns with  $A_V > 1 \text{ mag}^{10,28}$ . Similarly, detailed studies of the dust extinction curves in star-forming galaxies are possible using GRB afterglows<sup>29,30</sup>.

## 5 GRBs as probes of star-formation

The association between GRBs and the death of very massive stars has immediately lead to the suggestion to connect and trace the cosmic star-formation rate (SFR) with GRBs out to redshifts of  $z \sim 8$  and possibly beyond<sup>\$1</sup>. As an example, I show the cumulative redshift distribution of the The Optically Unbiased GRB Host (TOUGH) survey overplotted with different illustrative models in Figure 4. To empirically tie the GRB rate ( $\rho_{\text{GRB}}$ ) to the overall SFR, both quantities are typically related at lower redshift via a power-law index  $\alpha$  in a way that  $\rho_{\text{GRB}}(z) = (1 + z)^{\alpha} \times \text{SFR}(z)$ . With  $\alpha$  derived from low-redshift data, simple GRB number counts at high redshift bins then directly provide SFR(z).



Figure 4: Cumulative redshift distribution of the The Oopticall Unbiased GRB Host (TOUGH) survey (thick solid line) from Jakobsson *et al.* (2012). Dotted and dashed curves are the expected distributions using different parameterizations of the SFR. The shaded and hatched regions illustrate conservative sampling and systematic errors on the thick solid line, respectively. For details of the different models, please see Jakobsson *et al.* (2012).

Despite the fact that GRBs are very closely linked to active star-formation, there are a number of severe difficulties in this in principle rather straight-forward procedure. GRBs are a rare endpoint of stellar evolution, and their production rate is likely subject to environmental effects: Metallicity thresholds or dependencies or a varying GRB luminosity functions are expected to shape the detailed appearance of the redshift dependent relation between GRB rate and SFR. Furthermore, evolving initial stellar mass functions as well as biases in the GRB sample selection<sup>22</sup> could play an important role. These reasons complicate the analysis so that a consensus on the redshift dependency between SFR and GRB rate has not been reached in the recent literature and remains the subject of lively debate<sup>12,33,34,35,36,37</sup>. Current estimates for  $\alpha$  range between  $\alpha = 0$  (a nonevolving, direct proportionality between GRB rate and SFR), to  $\alpha \sim 1.5$ . For more details, I refer to the aforementioned references or the contribution from Coward and collaborators in this conference.

## 6 GRBs as probes of star-forming galaxies

An alternative and independent way of shedding light on the relation between star-formation and GRBs as well as the progenitors of GRBs is by studying their host galaxies. A fundamental limit of previously available GRB host galaxy samples is the incompleteness which arises from the non-detection of the optical afterglow of a GRB because of dust obscuration. Accurate positions from afterglow observations are necessary to be able to unambiguously associate galaxies with GRBs.



The lack of optical afterglows for GRBs therefore creates a systematic bias against the host galaxies of dusty GRBs in previous studies. Thanks to the accurate positions from X-ray data, and new follow-up instruments operating in the less-attenuated NIR wavelength range, this bias can now be removed.



Figure 5: Distributions of stellar mass (upper panel) and luminosity (lower panel) for GRB host galaxies selected through bright (grey data) and dust-extinguished afterglows (blue data). The redshift distribution of both samples has a mean of  $z \sim 1.5$ . Dust-extinguished afterglows have on average more massive and more luminous hosts. Taken from the work of Krühler *et al.* (2011).

The host galaxies of optically bright afterglows are quite exclusively blue, low-mass, lowluminosity galaxies with elevated star-formation rate and limited chemical enrichment<sup>38,39,40</sup>. This has been interpreted as support for a limited chemical evolution of the GRB progenitor, in line with the leading Collapsar model for GRB formation that predicts generally low metallicity for GRB progenitors.

Newly found host galaxies of the dustiest GRBs are, however, on average more luminous, redder, more massive and evolved (see Figure 5) than the hosts of non-extinguished afterglows<sup>11,41,42</sup>. Spectroscopically, a small number of hosts with gas-phase metallicity above half the solar value were identified<sup>43,44</sup>, which directly violate a proposed cut-off in GRB host metallicity. In addition, there is also no correlation between isotropic-equivalent energy release in  $\gamma$ -rays of GRBs and host metallicity<sup>45</sup>.

This newly found population of massive and metal-rich GRB-selected galaxies raises questions about our understanding of GRB hosts and progenitor models. GRBs can apparently form in galaxies of all metallicities, and the relation between GRBs, their energy release and host metallicity is still far from being understood. A better understanding of the chemical environments in which GRBs form at z < 3 would add confidence to the implications of studies of GRB hosts and their use of SFR tracers at higher redshift.

It is thus now clear that GRBs occur in all type of star-forming environments from lowluminosity dwarf galaxies to ultra-luminous infrared galaxies. Whether they do so in proportionality to the fraction of star-formation within these very same environments is still an somewhat open question. Very recent studies<sup>46</sup>, that include a large number of galaxies hosting dust-extinguished afterglows, still indicate a deficiency of GRBs in high-mass galaxies at z < 1.5. This can be interpreted as due to a metallicity dependence of the GRB rate. Only future observations and analysis will show whether this trend confirms, how it evolves with redshifts, and whether metallicity and its evolution with cosmic time is responsible for this trend. Statistically significant and carefully selected samples, such as TOUGH<sup>11,23,35,47,48</sup>, will play a key role in this endeavor (see Figure 6).

Independent on the exact relation between GRBs and star-formation, long GRBs always pinpoint galaxies. This is particularly interesting at the highest redshifts, because it alleviates the problem of redshift measurement for these very faint galaxies: the redshift is known from afterglow



Figure 6: Results from the TOUGH survey. The panels show from left to right: *R*-band host magnitudes in the Vega system,  $K_s$ -band magnitudes (Vega),  $R - K_s$  colors, and Lyman $\alpha$  fluxes and upper limits in units of  $10^{-18} \,\mathrm{erg cm^{-2} \, s^{-1}}$ . TOUGH is a homogeneous and optically unbiased survey of 69 *Swift* GRB hosts with a redshift completeness of currently ~85%. Taken from the work of Hjorth *et al.* (2012).

data. Deep optical/NIR follow-up observations however did not reveal significant galaxy emission underlying the position of any z > 5 GRB so far<sup>49,50</sup>. These non-detections, even with very deep HST observations, put strong contraints on the star-formation rate within these host galaxies (typically SFR < 4M<sub> $\odot$ </sub> yr<sup>-1</sup> for individual galaxies<sup>49</sup>). As an ensemble (mean SFR < 0.2M<sub> $\odot$ </sub> yr<sup>-1</sup> per galaxy<sup>49</sup>), they provide evidence for a steep galaxy luminosity function at high redshift, implying that a large fraction of the star-formation at  $z \sim 7$  is undetected in even the deepest HST surveys<sup>49</sup>.

### 7 GRBs as probes of cosmic chemical enrichment



Figure 7: Distribution of H1 column densities in different absorbers. Black lines are QSO-DLAs re-normalized to the number of GRB-DLAs, and red lines show GRB-selected absorbers. The vertical dashed line shows the limit above which absorbers are typically considered DLAs. Clearly, the distribution of hydrogen column densities of GRB-DLAs peaks at a much higher value than the one for QSO-DLAs. Taken from Fynbo *et al.* (2009).

The bright optical afterglow of GRBs is a powerful probe of the inter-stellar medium (ISM) in the GRBs host galaxy<sup>51,52</sup>. Optical afterglow spectra often show the presence of large amounts of neutral gas, so-called damped Lyman $\alpha$  (DLA) systems (Figure 7), with a column density of neutral hydrogen  $\log(N(\text{H I})/\text{cm}^{-2}) > 20.3$ . The rest-frame UV wavelength range (redshifted into the visible above  $z \sim 2$ ) contains a plethora of line-transitions of hydrogen and metals in various states. GRB afterglow spectra can thus be used to obtain fundamental information about the chemical, ionization and excitation state of the various components of the ISM in the GRB host galaxy.

The excited metal lines are, for example, used to robustly model the distance between the GRB and the bulk of the metal column density, and in most cases distances of several hundred parsecs are inferret  $e^{16,53,54}$ . Most of the neutral gas seen in absorption in GRB afterglow spectra is thus neither related to the immediate environment of the GRB progenitor, nor to its birth cloud.

The physical environments probed by GRB-DLAs are diverse. They have metallicities between roughly 1/100 up the solar value<sup>53,55,56,57</sup>, with a median of around  $0.1 \times Z_{\odot}$  and visual extinctions between  $A_V \sim 0$  mag and  $A_V > 5$  mag. The column densities of gas (see Figure 7) and metals are typically much higher than what is observed in DLAs along QSO sightlines<sup>9,51</sup>, a direct manifestation of the physical location of GRB-DLAs deep within the GRB host galaxies: while GRB sightlines probe a sightline to a region of star-formation in its host, QSO-DLAs are selected based on the H I cross section of a random sightline through a galaxy.

Similarly, the relative abundance of refractory elements is often much higher than the average value in QSO-DLAs<sup>51</sup>. This is generally interpreted as a strong evidence for dust depletion of e.g., iron, chromium or nickel. A large fraction (90% or even above) of the abundance of these elements can thus be locked up into dust grains in GRB-DLAs. Also molecular gas (H<sub>2</sub> and CO), that was long elusive in GRB-DLAs, is now detected for a few events<sup>55,58</sup>. Figure 8 shows the afterglow spectrum of GRB 120815A illustrating the detection of molecular hydrogen in a GRB-DLA.

GRB-DLAs thus allow us to study the cosmic chemical evolution in the center of star-forming galaxies up to redshifts of  $z \sim 5$ , and possibly above (suitable targets provided). They hence characterize star-formation, metallicity, dust abundance, dust properties and molecular content over cosmic time in a way that is currently not possible by other means.



Figure 8: The spectrum of the afterglow of GRB 120815A at z = 2.36. The grey lines show the data, the black lines the error spectrum and the red-lines show a model fit of the absorption signatures of molecular hydrogen in the Lyman-Werner bands as well as neutral hydrogen to the data. Note the strong DLA with at  $\log(N(\text{H}_{\rm I})/\text{cm}^{-2}) =$ 21.95 centered around 4080 Å. Brown labels and lines show the position of absorption lines often observed along GRB sightlines. Taken from the work of Krihler *et al.* (2013).

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# The Swift Gamma-Ray Burst redshift distribution: selection biases or rate evolution at high-z?

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We employ realistic constraints on selection effects to model the Gamma-Ray Burst (GRB) redshift distribution using *Swift* triggered redshift samples acquired from optical afterglows and the TOUGH survey. Models for the Malmquist bias, redshift desert, and the fraction of afterglows missing because of host galaxy dust extinction, are used to show how the "true" GRB redshift distribution is distorted to its presently observed biased distribution. Our analysis, which accounts for the missing fraction of redshifts in the two data subsets, shows that a combination of selection effects (both instrumental and astrophysical) can describe the observed GRB redshift distribution. The observed distribution supports the case for dust extinction as the dominant astrophysical selection effect that shapes the redshift distribution.

# 1 Introduction

In this study, we use realistic constraints and models for redshift dependant selection biases, combined with GRB OA luminosities, to show how selection effects distort the "trure" spatial distribution to its presently observed distribution. We employ two subsets of GRB redshifts. The first, Howell & Coward (2013)<sup>1</sup>, hereafter HC, uses 141 *Swift* triggered spectroscopic absorption redshifts from OAs up to Oct 2012.<sup>a</sup>. The second, less biased but smaller sample, uses a subset of 58 redshifts from the TOUGH (The Optically Unbiased GRB Host) survey<sup>2</sup>. By accounting for selection effects, we investigate if the observed GRB redshift distribution is compatible with GRB rate evolution tracking the global star formation rate.

# 1.1 GRB optical selection effects

We define gamma ray burst (GRB) optical afterglow (OA) selection effects as the combination of sensitivity limited optical follow-up and phenomena, astrophysical and instrumental, that reduce the detection probability of an OA. Some of the more widely understood effects are discussed

<sup>&</sup>lt;sup>a</sup>GRB redshift sample is a subset taken from GCN circulars and http://www.mpe.mpg.de/~jcg/grbgen.html

by Fynbo et al.<sup>3</sup> in detail. Optical biases have reduced the fraction of *Swift* triggered OAs, and have introduced a selection towards detecting the brightest OAs, hence the more nearby bursts. Additionally, there are biases that distort the redshift distribution over certain redshift ranges (see e.g.  $^{4,5}$ ). See Coward et al.<sup>6</sup> for a complete description:

1. Malmquist bias: This bias arises because the telescopes and instruments acquiring OA absorption spectra (and photometry) are limited by sensitivity. In reality, the instruments acquiring redshifts are biased to sampling the bright end of the OA luminosity function. To account for this bias, it is necessary to have some knowledge of OA luminosity function (which is uncertain especially at the faint end), and an estimate of the average sensitivity limit of the instruments. This is the most fundamental bias that encompasses all flux limited detection and is the basis for modelling a selection function for OA/redshift measurement.

Kann et al. (2010)<sup>7</sup> find a weak correlation between  $E_{\rm iso}$  and  $L_{\rm opt}$  with a Kendall rank correlation coefficient of 0.29 for the subset of GRBs used in this study to estimate an optical LF. The key question is: how does this correlation affect the Malmquist bias? Firstly consider the effect if  $E_{\rm iso}$  and  $L_{\rm opt}$  are uncorrelated. This implies that a high  $E_{\rm iso}$  (that will be preferentially detected by *Swift*) could be associated with equal probability with either a low or high luminosity optical afterglow. This scenario implies that detection of the OA is independent of the high energy luminosity. Alternatively, observation suggests a high  $E_{\rm iso}$  preferentially selects a high optical luminosity. This implies that the Malmquist bias will be reduced at high-z, because it is the high  $E_{\rm iso}$  bursts that are preferentially seen at large-z. These bursts will also be more optically luminous, so that redshift measurement will be more probable.

- 2. Redshift desert: The so-called redshift desert is a region in redshift (1.4 < z < 2.5) where it is difficult to measure absorption and emission spectra. As redshift increases beyond  $z \sim 1$ , the main spectral features become harder to recognize as they enter a wavelength region where the sensitivity of CCDs starts to drop and sky brightness increases. Beyond  $z \sim 1.4$ , the spectral features move beyond 1  $\mu$ m, i.e., into the near-IR. In the case of actively starforming galaxies at z > 1.4, these are several narrow absorption lines over the UV continuum, most of which originate in the ISM of these galaxies.
- 3. Different redshift measurement techniques: Historically, because of the deficiency in pre-Swift ground-based follow-up of GRBs, there was a strong bias for imaging the brightest bursts. Because the brightest bursts are predominantly nearby, a significant fraction of the first GRB redshifts were obtained by emission spectroscopy of the host galaxy. In the Swift era (from 2005 onwards), an optical afterglow (OA) is usually required to measure a redshift. For most high-z GRBs, this is achieved by absorption spectroscopy of the GRB afterglow. The host galaxies are usually too faint to make a significant contribution to the spectra. Most GRB spectroscopic redshifts are acquired by large aperture ground based telescopes, including VLT, Gemini-S-N, Keck and Lick (see <sup>3</sup> for a more complete list along with specific spectroscopy instruments). The measurement of a GRB redshift depends strongly on the limiting sensitivity and spectral coverage of the spectroscopic system. This bias is expected to manifest at high-z, where the optically brightest OAs are near the limiting sensitivity of the telescope.
- 4. Host galaxy extinction: There has been growing evidence that dark bursts are obscured in their host galaxies e.g.<sup>8,9</sup>. These studies generally show that GRBs originating in very red host galaxies always show some evidence of dust extinction in their afterglows. Also a significant fraction of dark burst hosts have extinction columns with  $A_V \sim 1$  mag, and


Figure 1: The *Swift* mean redshift uncertainty bound plotted over the duration of the mission. It is clear there is a drift in the mean redshift over time, a consequence of different priorities and instruments contributing to redshift acquisition. The *jump* observed in 2009 is a result of GRBs 090423 and 090429B, with redshifts of z = 8.26 (NIR spectroscopic) and z = 9.2 (photometric) respectively.

some as high as  $A_V = 2 - 6 \text{ mag}^9$ .

## 2 GRB redshift distribution model with selection effects

The dominant GRB redshift distribution biases discussed above are represented as the product of independent dimensionless selection functions that are unity for a 100% selection probability (see Coward et al.  $^{6}$ ):

- 1.  $\psi_{\text{Obs}}$  number dropouts from mostly non-redshift dependant biases, which are different depending on the selection criteria for the sample. We assume that the TOUGH sample is relatively free of instrumental biases, but about 20% of the HC sample is affected by instrumental biases.
- 2.  $\psi_{\text{Swift}}(z)$  the limited sensitivity of *Swift* to trigger on GRBs.
- 3.  $\psi_{M}(z)$  the limited sensitivity of instruments to measure a redshift from the GRB OA.
- 4.  $\psi_{\text{Desert}}(z)$  number dropouts from the redshift desert.
- 5.  $\psi_{\text{Dust}}(z)$  number dropouts from host galaxy dust extinction.

The GRB redshift probability distribution function, that includes the above selection effects, can be expressed as:

$$P(z) = N_p \frac{dV(z)}{dz} \frac{e(z)}{(1+z)} \psi_{\text{Swift}}(z) \psi_{\text{Obs}} \psi_{\text{M}}(z) \psi_{\text{Desert}}(z) \psi_{\text{Dust}}(z)$$
(1)

where N is a normalization constant. The volume element, dV/dz, is calculated using a flat- $\Lambda$  cosmology with  $H_0 = 71$  km s<sup>-1</sup> Mpc<sup>-1</sup>,  $\Omega_M = 0.3$  and  $\Omega_{\Lambda} = 0.7$ , and we fix  $\psi_{\text{Obs}} \approx 0.5$  (see the selection effects listed above). The function e(z) is the dimensionless source rate density evolution function (scaled so that e(0) = 1). We assume that e(z) tracks the star formation rate history (See Coward et al. <sup>6</sup> for a full description of the model):



Figure 2: Left: The redshift distributions for models with and without optical selection effects, and the relative distribution of the HC sample. The optimal models, defined as having both high K-S probabilities and small fractional errors, are Models which includes selection effects, a GRB rate evolution at z = 10 similar to that of z = 1, and either including or excluding a Malmquist bias correction. The least optimal model excludes selection effects. Right: Same as the left figure but using the TOUGH redshift distribution. Both the HC and TOUGH data require the same optimal models that include selection effects.

## 3 Summary

Fig. 2 plots the observed redshift distribution, with the optimal model (that includes selection effects), and for comparison the expected distribution that would be observed if all optical selection effects were removed. In summary, our analysis suggests that a combination of selection effects (both instrumental and astrophysical) can adequately describe the observed redshift distribution. Furthermore the observed distribution is compatible with a rate evolution that tracks the evolving SFR. We show that the TOUGH selection and a subset of absorption redshifts (the HC sub-sample) are compatible and both support the case for dust extinction as the dominant astrophysical selection effect that shapes the redshift distribution.

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## GRAVITATIONAL WAVES ASSOCIATED WITH GAMMA RAY BURSTS

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The proposed progenitors of gamma-ray bursts, the coalescences of neutron stars or of a neutron star and a black hole, as well as extreme cases of stellar collapse, are expected to emit large amounts of gravitational waves. I discuss the phenomenology of these progenitors from the point of view of gravitational wave emission, and describe two search methods targeting each source scenario. I review the results of these searches in data acquired by the LIGO and Virgo network of gravitational wave detectors, in years 2005-2010, and discuss prospects of observations in the era of Advanced LIGO and Virgo, c. 2015+.

## 1 Introduction

Gravitational waves are one of the early predictions of Einstein's theory of general relativity <sup>1</sup>. They are transverse space-time deformations that propagate at the speed of light and are emitted by accelerated masses. The first direct detection attempts started in the sixties with resonant bar detectors <sup>2</sup>, and the most sensitive instruments operated to date are kilometer scale interferometric detectors: LIGO <sup>3</sup>, Virgo <sup>4</sup> and GEO 600 <sup>5</sup>. In the mean time indirect observation of gravitational wave emission has been obtained thanks to the discovery of a binary pulsar system <sup>6</sup>. As the observed energy loss of the binary system (orbital period decrease) follows the predicted gravitationally radiated energy with a precision of order  $10^{-37}$ .

Gamma-ray bursts (GRBs) are one of the most violent event observed in the universe. The observed GRBs correspond to an emission of of  $\sim 10^{51}$  erg over a fraction of a second to a few dozen seconds. These bursts are observationally classified into two groups<sup>8</sup>:

- short GRBs with typical duration of 2 seconds or less
- long GRBs with typical duration of 2 seconds or more, and a softer spectrum (lower energy peak emission) than short GRBs.

Both types of GRBs are of extra-galactic origin. Short GRBs are thought to be produced by the coalescence of a neutron star with another neutron star or a black hole  $^{9,10,11,12}$ , and long GRBs are due to the collapse of massive rapidly rotating stars  $^{13,14}$ .

Both GRB scenarios should produce large amount of gravitational waves. Hence, several analysis have been performed within the LIGO and Virgo collaborations searching for gravitational waves associated with GRBs <sup>15,16,17,18,19,20,21</sup>. In section 2 gravitational wave properties and detectors are introduced. Section 3 discusses the GRB astrophysics relevant to gravitational wave followup observation. Section 4 presents search methods and results from the LIGO and Virgo collaborations for these followups. Prospects from future observations in the next 5-10 years are given in section 5.



Figure 1: Superposed evolution of a binary neutron star system and the effect at Earth of the produced gravitational wave. The rotation is around the z axis, and  $\psi$  is the orbital phase. A circle of free test masses (red) is deformed into an ellipse by the passing gravitational wave. When the binary system is seen face-on (top part) the deformation ellipse is rotating rigidly with the binary system – the gravitational wave is circularly polarized. For the same system seen edge-on (bottom part), the projection of the quadrupolar momentum shows just two masses going back and forth, hence the gravitationally is linearly polarized, with the axis of the deformation ellipse fixed.

## 2 Gravitational Waves

#### 2.1 Properties

Gravitational waves are transverse deformation of space-time that propagate at the speed of light, where the space-time metric  $g_{\mu\nu}$  can be decomposed into a stationary background metric  $\eta_{\mu\nu}$  and a propagating perturbation  $h_{\mu\nu}$ 

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \tag{1}$$

There are two polarizations, their affect the plane orthogonal to the direction of propagation. In that plane a gravitational wave squeezes distances in one direction, and stretches distances in the orthogonal direction. The two polarization correspond to the same effect, with the squeezing/stretching effect rotated by 45 degrees, hence they are usually called "+" (plus) and " $\times$ " (cross) polarizations.

For almost all astrophysical emission scenarios the dominant gravitational wave emission mode can be well described in the far field and slow moving source approximation. The resulting space perturbation by the gravitational wave  $h_{jk}^{TT}$  in the transverse-traceless coordinates can then be directly related to the source mass quadrupolar momentum  $I_{mn}$  as

$$h_{jk}^{TT}(t) = \frac{2G}{rc^4} \underbrace{P_{jkmn}}_{1/\text{distance}} \underbrace{\ddot{I}^{mn}(t-r/c)}_{\text{projection quadrupolar moment}},$$
(2)

where  $P_{jkmn}$  is a projection matrix from the source frame to the gravitational wave frame and r is the distance between the observer and the source. The connection between mass quadrupole evolution and gravitational wave polarization is illustrated in figure 1 for a binary neutron star system. For a binary system seen face-on the gravitational wave is circularly polarized, whereas for a system seen edge-on the wave is linearly polarized.

#### 2.2 Detectors

Interferometric gravitational wave detectors are based on the Michelson interferometer, with pendulum suspended mirrors such that they can be considered as free masses above the pendulum frequency in the horizontal plane. A plus polarized gravitational wave arriving from directly



Figure 2: Typical sensitivity of LIGO and Virgo detectors during the 2009-2010 science run, data taken from <sup>26</sup>

above (or below) the detector causes one arm of the interferometer to stretch while the other arm is shrunk. As a consequence the amount of light at the output of the interferometer is changed.

During the latest 2009-2010 joint run two LIGO<sup>3</sup> detector and the Virgo<sup>4</sup> detector achieved a gravitational wave strain sensitivity of a few  $\times 10^{-23} 1/\sqrt{\text{Hz}}$ , in a band from a few dozen Hz to a few kHz (see figure 2). This sensitivity corresponds to a typical detection horizon distance for a binary neutron star systems of ~ 40 Mpc for LIGO detectors and ~ 20 Mpc for Virgo. At high frequency the sensitivity is limited by photon shot noise, at intermediate frequency by thermal noise of the optics, and at low frequency by seismic noise (ground motion).

The second generation of gravitational wave detectors is under construction, with three advanced LIGO detectors  $^{22}$  two of them located in the USA and possibly one in India, and advanced Virgo  $^{23}$  located in Italy. A fifth kilometer scale detector, KAGRA  $^{24}$ , is also in construction underground in Japan. For all of these detectors the goal is to improve the sensitivity by a factor 10 compared to the sensitivity achieved by LIGO and Virgo, and decrease the lower bound of the sensitive band down to 10 Hz. These detectors should start taking science data in 2015, with a complete 5 detector network in 2020  $^{25}$ .

## 3 Gamma-ray bursts

## 3.1 Short GRBs

Short GRBs are thought to be produced by the coalescence of a neutron star with another neutron star or a black hole. The gravitational wave produced by the inspiral part of the coalescence can be precisely computed by perturbative expansion of Einstein's equations. The compact objects merger itself and the subsequent remanent object ringdown cannot be precisely modeled, as the equation of state of neutron star matter is not known. However, the emission of these latter two stages will have a 10 times lower contribution to the signal observed by gravitational detectors, as it will be buried in the shot noise at a few kHz. Hence, a gravitational search can be performed using matched filtering with inspiral templates, without significant loss in sensitivity.



Figure 3: Cartoon of the various scenarios that can lead from a massive star to a GRB central engine.

Once the two compact objects merge, the central engine that produce the GRB needs to be formed. It is thought to be composed of a black hole surrounded by a massive dense torus, and this system should be formed on a viscous time scale within less than 1 second. The gamma-ray emission is produced at large distance within the collimated relativistic jet ejected by the central engine. However, for an observer within the emission cone of the jet, the propagation time delay is compressed by the Lorentz factor squared, and is at most as large as the GRB variability scale.

Hence the gamma-rays should arrive up to a few seconds after the end of the gravitational wave inspiral signal. Given that the relativistic jet is collimated around the rotation axis, thebinary system has to be face-on and the gravitational waves will be circularly polarized. The polarization remain mostly circular even up to inclination angles as large as 60 degrees.

### 3.2 Long GRBs

Long GRBs are thought to be due to the collapse of massive rapidly rotating stars  $^{13,14}$ . The details of the collapse are not known, given that it requires 3D simulations and proper neutrino transport. The general picture is depicted in figure 3. The star collapses to a hot proto-neutron-star and a stalled accretion shock. This accretion shock may be revived by neutrino heating and some instability to produce a supernova, ending with central engine composed of a highly magnetized neutron star, or a black hole surrounded by an accretion torus. Or the revival of the shock fails, and a black hole – accretion torus system is directly produced <sup>27</sup>.

In these scenarios large amounts of gravitational wave might be produced at the protoneutron-star stage and at the black hole with accretion torus stage:

- **Proto-neutron-star** Given the high amount of rotation, a bar mode instability might develop in the star and produce gravitational waves<sup>28,29</sup> or in even more extreme scenarios the neutron star might fragment into several pieces which produce gravitational wave by spiraling around each other <sup>30,31</sup>.
- **Black hole and accretion disk** Similarly to the previous case rotational instabilities might lead to fragmentation in the accretion torus, with clumps of matter spiraling around the black hole<sup>32</sup>. Or more directly a misalignment of the black hole spin and torus axis, leads to precession of the disk<sup>33</sup>.

All these analytical scenarios correspond to the emission by a rotating quadrupole, that is circularly polarized gravitational waves emitted along the rotation axis. The amount of energy emitted could be as large as  $10^{-2} \, M_\odot c^2 \sim 10^{52}$  erg, but may be orders of magnitude lower. There are many other gravitational wave scenarios for a stellar collapse, but none of them can be seen at extra-galactic distances<sup>34,35</sup>, even by second generation gravitational wave detectors.

For long GRBs an important question is the relative timing between the arrival of gravitational waves and gamma-rays. The formation of the black hole – accretion torus system can be delayed up to 100 seconds after the collapse; then the jet needs to plow at sub-relativistic

speed through the envelope of the star, which also causes up to 100 seconds delay; finally the gamma-rays are produce at large distance, which for an on axis observer is delayed by up to the GRB variability time scale that is at most 100 seconds. In total the gravitational wave arrival may precede by up to few hundred seconds the gamma-rays.

## 4 Results

The LIGO and Virgo collaborations have performed followup of GRBs since the early science runs<sup>15,16,17,18,19,20,21</sup>. For the latest 2009-2010 data two search techniques were applied <sup>36</sup>, which target the two progenitor models of GRBs.

A coherent matched filtering algorithm  $^{37}$  is applied for data corresponding to short GRBs. This assumes that gravitational waves will follow an inspiral waveform as predicted for binary coalescence. The search is performed with the inspiral ending in a tight time window of [-5, 1]s, as only a small delay is expected for the gamma-ray arrival.

A coherent unmodeled burst search  $^{38,39}$  is performed for all GRBs. This search is wide in scope without any particular assumption on the gravitational waveform, but with an assumption of circular polarization. It is about a factor 2 less sensitive to binary coalescence than the targeted matched filtered search. It uses a wide time window of [-600, 60] s, as gravitational wave may precede the long GRB by a large amount.

During the 2009-2010 science run about 400 GRBs have been detected and circulated through the gamma-ray burst coordinate network (GCN  $^{40}$ ) or published in the Swift and Fermi satellite databases. Data from at least two gravitational wave detectors were available for 154 of these GRBs, out of which 26 were deemed short. The criteria for short are rather lenient: duration of less than 4 second, or a short spike at the start of the light curve to account for short GRB extended emission. The selection criteria are lenient because sample completeness is much more important than purity for detection prospects. No significant signal was found, and the typical distance lower limits are between 7 Mpc and 28 Mpc depending on which gravitational wave emission model is assumed  $^{36}$ .

In general these limits are not particularly interesting. However, for two cases during the 2005-2007 science run, interesting astrophysical limits were claimed. GRB 051103 and GRB 070201 were both localized by the Inter Planetary Network <sup>41</sup>, and the error box intersect nearby galaxies, respectively M81 and Andromeda. In both cases the lack of inspiral signal in LIGO data excludes a scenario of binary coalescence within these galaxies. Two scenarios remain viable: a binary coalescence in a galaxy behind M81 or Andromeda, or SGR giant flare within these galaxies <sup>18,19</sup>.

## 5 Prospects

Most of the lower limits on distances given by LIGO and Virgo are not particularly interesting for GRB science. A good way of visualizing this is to combine the individual distance lower limits for each analyzed GRB into a global distance distribution exclusion. This exclusion shown in figure 4 illustrates that no detection was expected with available data, but shows good prospects of detection for second generation detectors. Especially for short GRBs where the gravitational wave amplitude is known. Either several detections are expected or the exclusion of the binary coalescence model for short GRBs. For long GRBs, it is plausible that the emitted gravitational wave energy is much smaller than  $10^{-2} \,\mathrm{M_{\odot}c^2}$ , hence detection remains uncertain.

A single detection associated with a short GRB would confirm the binary coalescence model. It would also allow us to measure the speed of gravitational waves relative to the speed of light with a precision of order  $10^{-16}$ . A larger sample of signals would allow us to measure statistically the typical opening angle of GRB jets, by comparing the number of gravitational wave detections with and without associated GRB, as gravitational wave emission is not beamed. It would also



Figure 4: GRB distance distribution exclusions and extrapolation to second generation detectors. On the left pane the exclusion for long GRBs is shown, assuming that each GRB produces a gravitational wave burst at 150 Hz carrying  $10^{-2} M_{\odot}c^2$  of energy. On the right pane the exclusion for short GRBs is shown, assuming that all short GRB are due to binary neutron star coalescence, or to neutron star black hole coalescence. These are compared to their respective red-shift distributions. Extrapolation to several years of second generation detectors operation are shown as dashed lines. Figures take from <sup>36</sup>

enable a measure of the Hubble's constant with a precision of  $\sim 10\%$ <sup>42</sup>. This measure would be completely independent from the distance ladder used in other measurements of the Hubble's constant.

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## Search for High Energy GRB Neutrino Emission with ANTARES

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ANTARES is the largest high-energy neutrino telescope on the Northern Hemisphere. A search for neutrinos in coincidence with gamma-ray bursts using ANTARES data from 2008 to 2011 is presented here. An extended maximum likelihood ratio search was employed to optimise the discovery potential for a neutrino signal as predicted by the numerical NeuCosmA model. No significant excess was found, so 90% confidence upper limits on the fluxes as expected from analytically approximated neutrino-emission models as well as on up-to-date numerical predictions were placed.

## 1 Introduction

The ANTARES neutrino telescope [1] is located in the Mediterranean Sea at a depth of 2.4 km. The detector consists of 12 vertical strings, separated from each other by a typical distance of 70 m. Each string is anchored to the seabed and held upright by a buoy at the top; over a length of 350 m, it is equipped with 25 triplets of photo multiplier tubes (PMTs), building a 3-dimensional array of 885 PMTs in total. The instrumented volume is  $\sim 0.02 \text{ km}^3$ .

The main scientific purpose of ANTARES is the search for astrophysical neutrinos, which are detected via their charged-current interaction in Earth and the subsequent Cherenkov emission of the secondary charged lepton in the water of the Mediterranean Sea. Gamma-ray bursts (GRBs) are suitable cosmic candidate sources for neutrino telescopes, as they are thought to accelerate not only electrons — leading to the observed gamma rays — but also protons, which would yield the emission of high-energy neutrinos.

In the prevailing fireball model for gamma-ray bursts as proposed for example by Mészáros and Rees [2], the observed electromagnetic radiation is explained by synchrotron radiation and subsequent inverse Compton scattering of relativistic shock-accelerated electrons [3, 4]. If protons were also accelerated in the shock outflow, high-energy neutrinos would accompany the electromagnetic signal of the burst [5]. The detection of GRB neutrinos would be unambiguous proof for hadronic acceleration in cosmic sources and could also serve to explain the origin of the cosmic-ray flux at ultra-high energies.

For the analysis presented in the following, we utilise ANTARES data from the end of 2007 to 2011. The total integrated live-time of the data in coincidence with the selected sample of 296 GRBs is 6.55 hours. For a more detailed description of the analysis scheme, see [6].

## 2 Analysis

#### 2.1 GRB Parameters and Selection

The parameters needed for the search and the simulation of expected neutrino fluxes are primarily obtained from different gamma-ray burst catalogues provided by the instruments *Swift*  [7] and Fermi GBM [8, 9]. It is then completed using a table supplied by the IceCube collaboration [10], which is created by parsing the Gamma-ray Coordinates Network notices. In case a parameter could not be measured, standard values as given in [10] are used to calculate the spectra.

For the final sample, gamma-ray bursts are excluded when neither spectral nor fluence information was available and when no duration was given. Short GRBs are also discarded since this class is much less understood. In addition we require both that the GRBs were located below the local horizon for ANTARES and that the detector was taking reliable physics data during the burst. Eventually, 296 bursts were selected. Their distribution on the sky is shown in Fig. 1.



Figure 1: Left: Sky distribution of the selected 296 gamma-ray bursts in equatorial coordinates. The photon fluence of each burst is indicated by the colours. The ANTARES detector is sensitive to both Southern and Northern Hemispheres up to a declination of  $47^{\circ}$ , with an instantaneous field of view of  $2\pi$ . Right: Individual neutrino spectra of the 296 GRBs. Blue lines show the expectations due to the analytical model [12], whereas red lines show the NeuCosmA predictions [11], respectively. Thick lines show the sum of all individual spectra.

#### 2.2 Gamma-Ray Burst Neutrino Emission

The expected neutrino fluxes from gamma-ray bursts are usually derived from the spectrum of the Fermi-accelerated protons and the measured photon spectrum. Different models have been developed to calculate the neutrino flux from photohadronic interactions; up-to-date models like NeuCosmA [see 11, and references therein] feature detailed numerical simulations of the underlying processes. The analysis presented here relies on the prediction made by this model. Figure 1 shows the spectra for the numerical NeuCosmA model in comparison to the widely-used analytical approximation [12], which overestimates for instance the pion production efficiency [11].

#### 2.3 Signal and Background Probability Density Functions

For each gamma-ray burst, signal neutrino events according to the expected NeuCosmA fluxes are simulated with high statistics and then reconstructed in order to compute the detector's acceptance and the spread of events around the actual burst's direction. This distribution yields the signal probability density function (PDF) labelled  $S(\delta)$ , where  $\delta$  represents the space angle between the reconstructed event direction and the GRB's coordinates.

The background PDF  $\mathcal{B}(\delta)$  is considered to be flat within a 10° search cone around each burst position. In order to estimate the expected mean number of background events  $\mu_b$  for each burst as realistically as possible, real reconstructed data events are used. However, as the number of upgoing events is very low (~4 per day, see [13]), large time periods are needed to yield enough statistics, which in turn requires averaging over different detector conditions (in particular due to seasonal variations of the optical background). To compensate for this, we

<sup>&</sup>lt;sup>a</sup>GCN: gcn.gsfc.nasa.gov/gcn3\_archive.html

first estimate the average reconstructed event rate in the GRB's direction using data from the whole late-2007 to 2011 period, then adjust it for varying detector conditions.

The reconstruction algorithm returns the track fit quality parameter  $\Lambda$ ; a cut on this parameter selects well-reconstructed events and is later on used to optimise the analysis. Both  $\mathcal{S}(\delta)$  and  $\mathcal{B}(\delta)$  depend on the final choice of the cut on  $\Lambda$ .

## 2.4 Search Optimisation

Pseudo-experiments are generated that randomly draw signal and background events i with space angle  $\delta_i$  from the normalised PDFs  $\mathcal{B}(\delta)$  and  $\mathcal{S}(\delta)$  corresponding to each  $\Lambda$  cut. For each pseudo-experiment with  $n_{\text{tot}}$  events, the test statistic Q is calculated:

$$Q = \max_{\mu'_{\rm s} \in [0, n_{\rm tot}]} \left( \sum_{i=1}^{n_{\rm tot}} \log \frac{\mu'_{\rm s} \cdot \mathcal{S}(\delta_i) + \mu_{\rm b} \cdot \mathcal{B}(\delta_i)}{\mu_{\rm b} \cdot \mathcal{B}(\delta_i)} - (\mu'_{\rm s} + \mu_{\rm b}) \right). \tag{1}$$

This is the so-called Extended Maximum Likelihood Ratio [14] with an a-priori knowledge of the expected number of background events  $\mu_{\rm b}$ . Larger values of Q indicate that the measurement is more compatible with the signal hypothesis.

The distributions of the test statistic for different numbers of injected events are used to evaluate the model discovery potential  $\mathcal{MDP}$  for a given number of expected signal events  $\mu_s$  as predicted by the NeuCosmA model. The cut on the quality parameter  $\Lambda$  is then chosen as that which maximises the  $\mathcal{MDP}$ . Figure 2 shows the  $\mathcal{MDP}(\mu_s)$  using PDFs of GRB110918 for  $3\sigma$ ,  $4\sigma$  and  $5\sigma$  for arbitrary numbers of expected signal events.

### 3 Results

Using the strategy outlined above, we analysed ANTARES data from the end of 2007 to 2011 searching for neutrino events in coincidence with the selected gamma-ray bursts and within  $10^{\circ}$  around each. No data events passed the event selection cuts within the accumulated search duration of 6.55 hours. Hence, the measured Q-value is zero.

In total, 0.06 signal events were predicted from the NeuCosmA model (0.5 from the analytical model) against a background of 0.05 events. The 90% C.L. upper limit on the signal can be set to 2.3 events, thus limits can be placed on the cumulative flux of the whole sample as shown in Fig. 2.

Limits from previous analyses are also shown: The ANTARES limit [16] from the construction phase of the detector in 2007 as well as the IceCube limit [15] using the IC40 and IC59 detector configurations used the analytical model predictions. The right-hand axis of Fig. 2 (b) shows how the limits on the individual samples translate into a limit on the inferred quasi-diffuse flux, assuming that the selections represent average burst distributions and that the annual rate of long bursts is 667 per year.

We have presented the first analysis that relies on up-to-date numerical simulations of neutrino emission from GRBs. It has been shown that the expected fluxes are one magnitude lower than predicted by prevailing analytical approaches [e.g. 12]. Hence, existing limits have not put any constraints on realistic neutrino emission models; i.e. the fireball paradigm has not yet been probed by neutrino telescopes. Nevertheless, the collection of more and more data with active experiments as well as planned neutrino telescopes like KM3NeT will certainly allow to probe the widely-established fireball paradigm in the near future.

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Figure 2: Left: Model Discovery Potential versus any mean number of expected signal events  $\mu_{\rm s}$  for  $3\sigma$  (red solid line),  $4\sigma$  (black dotted) and  $5\sigma$  significance (blue dashed), with PDFs for GRB110918 and  $\Lambda > -5.5$ . Right: Solid lines: sum of the 296 individual gamma-ray burst neutrino spectra used in this analysis, for the analytical model in blue and the NeuCosmA model in red. Dashed lines show the limits on these fluxes. The IceCube IC40+59 limit [15] on the neutrino emission from 300 GRBs and the first ANTARES limit from its construction phase in 2007 using 40 GRBs [16] are also shown in black (dashed) and grey (dash-dotted), respectively.

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# THE SPECTRUM OF COSMIC RAY ELECTRONS AND POSITRONS MEASURED BY THE PAMELA EXPERIMENT: A REAL PROBLEM STILL SEEKING A SOLUTION

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The Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) has now provided a very accurate measurement of the spectrum of cosmic-ray electrons and positrons. These results are consistent with a single power-law, but visually they suggest an excess emission from about 100 GeV to 1 TeV, which leads to the emergence of a debate about the existence and the source of this excess: Could come from nearby pulsars or dark-matter annihilation? We do not know, each one has its reasons. In this work we will try to study this controversy by clarifying this spectrum using the GALPROP code.

## 1 Introduction

Knowledge of the primary cosmic ray electron spectrum near the earth  $\leq 1$ kpc allows us to understand several astrophysical problems. In fact, the first hint for the existence of this type of rays in our Galaxy (*MilkyWay*)came from the interpretation in 1950 of the non-thermal radio noise<sup>1</sup>. The first direct observation of primary cosmic ray electrons was made in 1960<sup>2,3</sup>, in the energy ranges of 100 MeV to several TeV. Since then, the electron spectrum has been extensively investigated.

Before 2008, the high-energy electron spectrum  $E_e \geq 10$  GeV was measured by balloon borne experiments <sup>4</sup> and by a single space mission AMS-01 <sup>5</sup>. To date, we have at hand data from new instruments, such as Pamela <sup>6</sup>, Fermi <sup>7</sup>, H.E.S.S<sup>8</sup>, and ATIC <sup>9</sup>. These measurements represent a unique probe for studying the origin and diffusive propagation of high energy cosmic-ray electrons in the interstellar medium within the GeVTeV energy range, as well as for constrain current models of the observed Galactic diffuse gamma-ray emission <sup>10</sup> such as the cosmic ray propagation package GALPROP <sup>11</sup>.

In this work, we explore the possibility of interpreting the aforementioned data sets concerning the electrons spectrum by a model with reacceleration for the production and propagation of positrons and electrons in the Galaxy. In this framework, we start with obtaining a set of propagation parameters which reproduce the cosmic-ray B/C ratio, then we perform the calculation of the spectra of positrons and electrons using the GALPROP code. we compare with recent observations reported by ATIC, Fermi, HESS, and other experiments.

### 2 Results and discussion

In this study, we have chosen the diffusion reacceleration model, which has been used in a number of studies utilizing the GALPROP code. This model is two dimensional (2D) with cylindrical symmetry in the Galaxy, and the basic coordinates are (R, z, p) where R is Galactocentric radius, z the distance from the Galactic plane and p the total particle momentum. The propagation region is bounded by  $R_h = 30$  kpc and vertical boundaries (halo size )  $Z = z_h$ . The spatial diffusion coefficient is given by <sup>12</sup>:

$$D_{xx} = \beta D_0 \left(\frac{\rho}{\rho_0}\right)^{\circ} \tag{1}$$

Where  $D_0 = 5.5 \times 10^{28} sm^2 s^{-1}$  is a free normalization at the fixed rigidity, $\rho_0 = 4GV$ . The power-law index is  $\delta = 1/3$  for Kolmogorov diffusion. The main free parameter in this relation is the Alfven speed  $v_0 = 30 km/s$ . The injection spectrum of nucleons is assumed to be a power law in momentum,  $q(p) \propto p^{\gamma_0}$  the value of  $\gamma = 2.4$  can vary with species.



Figure 1: The left panel show B/C ratio which is computed by our model given above and compared with experimental data. The electron  $(e^+ + e^-)$  spectrum is shown for the same model in *center panel* and the corresponding positron fraction  $(e^+/(e^+ + e^-))$  curve computed under the same conditions is shown in the *Right panel* and compared with experimental data.

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#### Shear Boundary Layer (SBL) acceleration and radiation mechanism in blazars

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We present results of particle-in-cell (PIC) simulations of relativistic shear layers in both electron-proton and electron-positron jets. In our simulations, transverse magnetic fields can be self-generated at the shear boundary layers by initially un-magnetized shear flows and relativistic particles are energized by charge separation and electromagnetic turbulence. We found that the shear boundary layer is unstable to both longitudinal and transverses modes in the case of electron-positron jets. In the electron-proton case, the shear-layer reaches a steady quasi-equilibrium with well ordered magnetic fields.

# 1 Model setup and evolution f particle energy

There is evidence that suggests that the jets in blazars have at least two main components: outer jets which include mildly relativistic particles carry most of the kinetic energy of the jets and inner jets which include highly relativistic particles carry the most angular momentum in the jets (Tchekhovskoy et al. 2008, McKinney & Blandford 2009). While in the past few years, research has mostly focused on shock formation and dissipation in jets in order to understand the conversion of the outflow energy into electromagnetic turbulence and high energy particles and photons, another important aspect are the boundary layers of shear flows (Liang et al. 2013a,b). Here, we persent PIC simulation results of relativistic SBL in non-magnetized plasma, using the 2.5D (2D space, 3-momenta) ZOHAR code (Birdsall & Langdon 1991) with time steps  $\Delta t = 0.1/\omega_e$ , where  $\omega_e$  is electron plasma frequency, using a  $1024 \times 2048$  grid with ~ 10<sup>8</sup> particles. The initial conditions for our simulations are illustrated in figure 1. The simulations are performed in a reference frame in which the inner spine and the outer sheath are counter-streaming with equal, but opposite velocities. Both plasmas are assumed to be initially cool and unmagnetized. Ion-to-electron mass ratios of  $m_i/m_e = 1$  ( electron-positron plasma) and  $m_i/m_e = 1836$  (electron-proton plasma) have been simulated.







Figure 1: Model setup for simulations of shear layers in radially stratified relativistic jet



Figure 3: Evolution of particle energy and field energy in the  $e^-e^+$  case

The jet axis defines the x axis, the y axis is oriented in the radial direction (across the shear layer), while the z axis extends along the shear layer. The cell size for the simulations is set equal to the plasma skin depth,  $\Delta x = c/\omega_e$ . Doubly-periodic boundary conditions are imposed in the x and y directions. Figures 2 and 3 illustrate the evolution of particle and field energy in the  $e^-p$  SBL run versus the  $e^-e^+$  run with  $P_x/mc = \pm 15$ . In the  $e^-p$  SBL, the electron energy reaches equipartition with the ion energy and the field energy reaches only~ 0.11 of the total energy. In the  $e^-e^+$  case, the field energy reaches 0.15 of the total energy before falling to 0.05.

#### 2 Magnetic field generation and synchrotron radiation

Figures 4 and 5 illustrate the self-generated magnetic field  $B_z$  in the case of a run for an  $e^-p$  plasma and  $e^-e^+$  plasma with  $p_x/mc = \pm 15$ . Blue and red denote opposite polarities. In the  $e^-p$  case, the B-field has the same polarity on both sides of the shear boundary layer because electrons have small gyro-radii and are fluid like while the ion drift is unperturbed due to inertia. In the  $e^-e^+$  case, the B-fields form vertical paterns with alternating polarities. Figure 6 illustrates the synchrotron radiation from the thermal distribution of quasi- electrons in the  $e^-p$  case, for sample values of B fileds, corresponding to SBLs with  $p_x/mc = \pm 15$  and  $p_x/mc = \pm 5$  respectively, which can be well approximated by a function  $F_{\nu} \sim \nu \exp(-(\nu/\nu_c)^{1/3})$ , where  $\nu_c = (KT/mc^2)^2 eB/(4.5mc)$  (Petrosian 1981). We plot the cases  $p_x/mc = \pm 15$  and  $p_x/mc = \pm 5$  with different average magnetic filed values.





Figure 6: Synchrotron radiation from a thermal distribution of an  $e^-p$  plasma from SBL, with peak frequency rep-Figure 5: Magnetic fields  $B_z$  for an resentative of high-frequency peaked

Figure 4: Magnetic fields  $B_z$  for an  $e^-p$ plasma of Fig. 1.

 $e^-e^+$  plasma of Fig. 1.

blazars (green) and low-frequency peaked blazars (blue).

Because the particles are accelerated perpendicular to  $B_z$ , they emit Synchrotron radiation efficiently. For a higher value of the magnetic field and shear momentum, the synchrotron peak frequency shifts towards a higher value.

#### 3 Summary

Our PIC simulations have shown that the magnetic field generated and electron distribution by  $e^{-p}$ SBLs are different from the  $e^-e^+$  SBLs. In the  $e^-p$  SBLs, the global field energy reaches ~ 0.11 of the initial ion drift energy. In  $e^-e^+$  case, the field energy reaches 0.15 of the total energy before falling to 0.05. We found that the shear boundary layer is unstable to both longitudinal and transverses modes in the case of  $e^-e^+$  jets. In  $e^-p$  case, the shear-layer reaches a steady quasi-equilibrium with well ordered magnetic fields. The synchrotron radiation from a thermal distribution of an  $e^-p$  plasma shows that for a higher value of the magnetic field and momentum, the synchrotron peak frequency shifts towards a higher value as one would expect.

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# GRAVITATIONAL LENS SYSTEM B0218+357: CONSTRAINTS ON LENS MODEL AND HUBBLE CONSTANT

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The possibility to use observations of lensed relativistic jets on very small angular scales to construct proper models of spiral lens galaxies and to independently determine the Hubble constant is considered. On the example of the system B0218+357 it is shown that there exists a great choice of model parameters adequately reproducing its observed large-scale properties but leading to a significant spread in the Hubble constant. The jet image position angle is suggested as an additional parameter that allows the range of models under consideration to be limited. It is shown that the models for which the jet image position angles differ by at least 40° can be distinguished between themselves during observations on very small angular scales. Observations with the space interferometer RadioAstron-Earth is proposed to determine the jet orientation.

Gravitational lens observations make it possible to estimate the most important cosmological parameter, the Hubble constant, if the surface density distribution of the lens, time delay between source images, the relative position of the lens and the source are known. The source B0218+357  $(z = 0.96^{1})$  with a large-scale jet is a "gold lens" for the aforesaid goal because the time delay between the two compact core images has been measured with a good accuracy <sup>2</sup>, and there is no gravitational field distortion from nearby sources. But at the same time there is a significant uncertainty in determining the relative position of the lens (spiral galaxy) and the source<sup>4</sup>, which cannot be measure with present-day optic and infrared instruments due to a small angular separation of them. Therefore it is necessary to construct an accurate model of the system to evaluate the Hubble constant. It was shown that there exists a fairly wide choice of model parameters adequately reproducing the large scale observed properties of B0218+357 (the intensity ratio of images A and B for the compact source  $I_A/I_B \simeq (3.1 - 3.7)$ , the image separation  $d \simeq 335$  milliarcseconds (mas), the position angle of the large-scale jet) but leading to a significant spread in the Hubble constant<sup>5</sup>. Furthermore the ring-like structure (see Fig.1, left panel) observed in the radio band and produced by the lensing of the large-scale jet appears only for a limited set of model parameters and jet directions (see, e.g., Larchenkova et al.<sup>6</sup>). However even for this limited set of parameter the spread in the estimates of the Hubble constant is still significant. Here we propose to observe the jet image position angle on scales of tens of microarcseconds ( $\mu$ as) and use it as an additional parameter to restrict models remaining after the large-scale analysis. The main idea of the proposition is that the lensed jet images of source B0218+357 retain its proper geometric shape on scales of tens of  $\mu$ as.

According to the VLBA survey of extragalactic sources at 15 GHz the correlated flux density for B0218+357 does not decrease to zero even at the maximum projected baseline of this ground-based interferometer ( $440 \times 10^6$  wavelengths) but is about 250 mJy<sup>7</sup>. At 5 GHz the components may be more extended, but we know that they are still visible well at 8.4 GHz<sup>2</sup>.

Thus, observations of this source with a long baseline space interferometer are reasoned from a viewpoint of determining the structure and the direction of the relativistic jet at very small angular distances from the nozzle (the ejector of relativistic particles).



Figure 1: Left: VLA 15 GHz radio map of B0218+357 from paper<sup>2</sup>. Clearly visible are the two compact cores (A to the right), the Einstein ring and non-lensed large-scale radio jet to the south. Middle: The initial phase ( $30 \ \mu s$ ) of the relativistic jet emerging from image A for the three different position angles (see details in Larchenkova et al. <sup>5</sup>). Right: The visibility function for the four sets of model parameters with position angles corresponding middle panel with projected baselines of the space VLBI Mission RadioAstron with the Effelsberg, Arecibo and Evpatoria radiotelescopes at 5 GHz (gray areas) in January 2014. The typical uncertainties of measurements with RadioAstron are shown by vertical lines.

Fig.1 (right panel) shows the visibility function for four sets of model parameters with different position angles (Fig.1, middle panel) of the jet emerging from the brighter compact core image (image A) in January 2014 (see details in Larchenkova et al.<sup>5</sup>). The gray area corresponds to the projected baselines of the space VLBI Mission RadioAstron (RA) with Effelsberg, Arecibo and Evptoria radiotelescopes at 5 GHz. From this figure it is clearly seen, that the possibility to distinguish one model from the other will depend on the signal-to-noise ratio. Taking into account the current RA detection threshold (~7 $\sigma$ ), the models for which the jet image position angles differ by at least 40° can be distinguished between themselves. It is necessary to note that a probable non-uniformity of the intensity distribution along the jet (e.g., a presence of knots) practically have not an effect on this conclusion.

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# HIDDEN MASS BOSON MEDIUM AS REAL DARK MATTER WITH THEORETICAL BACKGROUND AND PRACTICAL APPLICATIONS

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Hidden Mass Boson (HMB) medium as real Dark Matter (DM) is considered. This DM model bases on the Newtonian approach of gaseous compressible substance. For confirmation of our simulation we present the special experimental results on the temperature dependence for propagation velocity of electromagnetic fronts, additional detail explanation of the Hooke law, the Dulong–Petit law, the thermal expansion law, the Stephan-Boltzmann radiation low and some astrophysics problems (cosmic jets, gamma-ray bursts with their afterglows and oth.). Theoretical part of our study contains some main physical principles, the dimensional analysis, thermodynamically compatible conservation laws, nonlinear thermal radiation modeling and exact solutions.

Coming back from the positions of modern experimental data to fundamental ideas of early XX century theoretical physics (first of all, works by M. Planck, A. Einstein and L. de Broglie) allows us to indicate rather motivated solution of some mysterious problems of the present-day physics. A typical example here can serve a correlation linking energy E with mass value m, frequency v and temperature T

$$E = mc^2 = hv \approx kT,\tag{1}$$

where c - light velocity, h and k- the Planck and Boltzmann constants. The last approximate equality in (1) follows from Planck's distribution in vicinities of maximum radiation density distribution of absolutely black body and presents itself Wien's displacement law.

In the first half of XX century the temperature in cosmic vacuum was considered equal zero (T=0) that due to relation (1) matched mass value m=0 (mass absence in free space of cosmos). However finding in the second half of XX century of a final not zero temperature in cosmic vacuum (cosmic microwave background radiation - CMBR) T=2.725 K allows us by means of relation (1) to define vacuum particle mass  $m \approx kT/c^2$ . The presence of these massive particles in physical vacuum was specified in [1,2], and [3-5] it was identified with massive particles of Dark Matter (DM). Subsequently, in [6-8] this particle was named Hidden Mass Boson - HMB (in analogy with the known of Higgs Boson). To be short, we change the virtual Planck resonators in his derivation of the formula for absolutely black body radiation density by real (massive) particles.

Another important effect of correlation (1) under m = const is the presence for typical velocity c the dependency on temperature  $c \approx \sqrt{kT/m}$ . Thereby, electromagnetic waves velocity in vacuum should not be a universal constant. This conclusion requires more detailed explanation.

Validity of fundamental correlation (1) brings about the necessity to introduce for physical vacuum a classical elastic medium model, which should consider the existence of two typical distortion propagation velocities  $c_0$  and  $c_1$ : velocity  $c_0$  - for longitudinal (potential) distortions - waves of compression - depression (without particles rotation) and velocity  $c_1$  - for transverse (solenoid) distortions - waves of shift (without volume change). Herewith, using the classical Poisson approach for elastic medium we should write down intensities of electric field  $\overline{E}$  and magnetic field  $\overline{H}$  in linear approach as sums of potential and solenoid components

$$\overline{E} = \operatorname{grad} \varphi + \operatorname{rot}\overline{A}, \quad \overline{H} = \operatorname{grad} \psi + \operatorname{rot}\overline{B}.$$
<sup>(2)</sup>

A further effect of correlations (1) and (2) for electromagnetic distortions is an extended writing of the Maxwell system of electrodynamics equations [7-9] providing for presence of longitudinal waves (for free space without concentrated charges and currents)

$$\frac{\partial E}{\partial t} - c_1 rot \overline{H} + c_0 gradp = 0; \quad \frac{\partial p}{\partial t} + c_0 div \overline{E} = 0,$$

$$\frac{\partial \overline{H}}{\partial t} + c_1 rot \overline{E} + c_0 gradq = 0; \quad \frac{\partial q}{\partial t} + c_0 div \overline{H} = 0.$$
(3)

Relations (3) incorporate scalar fields p and q presenting fields of "force lines density" (Faraday field lines) of electric and magnetic fields. One can easily show [7] that scalar potentials  $\varphi$  and  $\psi$  in (2) and scalar fields p and q in (3) satisfy the d'Alembert wave equations with typical velocity  $c_0$  for longitudinal (potential) distortions and vector potentials A and B satisfy the d'Alembert wave equations with typical velocity  $c_1$  for transverse (solenoid) distortions. Thereby, finding the final temperature in physical vacuum should result in a finite mass of vacuum particle and existence of longitudinal components of electromagnetic field.

Hereinafter the report justifies the equation of physical vacuum state p = nkT (*n* - DM particles concentration) and HMB structure in the form of classical dipole with characteristic charge value of the  $q \approx 10^{-28}$  C. The presence of characteristic charge under the given particles concentration allows us to define the Debye screening radius and build a unified theory of chemical linkages, electromagnetic, weak and strong interactions [9]. By that the main role plays the Debye screen radius of electron and proton charges.

As confirmation of our DM modeling we present the special experimental results on the temperature dependence for electromagnetic front and disturbances velocities [8-10], additional detail explanations of the Hooke, the Dulong – Petit, the thermal expansion and the Stephan – Boltzmann radiation laws and astrophysics problems (cosmic jets, gamma-ray bursts with their afterglows) [9]. The theoretical part of our study contains the dimensional analysis [6-8], thermodynamically compatible conservation laws [5], nonlinear thermal radiation modeling and exact solutions [11]. We demonstrate also practical application of this simulation for air breathing engines design. The talk shows typical results for turbojet engines and their components [5-9].

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# IF A MACHIAN RELATIONSHIP EXISTS BETWEEN GRAVITONS AND GRAVITINOS, WHAT DOES SUCH A RELATIONSHIP IMPLY AS TO SCALE FACTOR AND QUINTESSENCE EVOLUTION AND THE EVOLUTION OF DM?

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We investigate the relationship between gravitons and gravitinos with a revision of SUSY assuming a massive graviton, this leads to an entropy value for the electroweak era. Further consequences including the value of the weak fermi scale occur naturally.

## 1 Introduction

We start off with the following mass scales, using <sup>1</sup> as a guide while using <sup>2</sup> as well. This leads to the following mass scales<sup>1</sup> as given by  $M_X \ge 10^{15}$ GeV-grand unification scale, then  $M_W \ge 2$ GeV,  $M_S$ -super symmetry scale, and  $M_P$  as a Planck mass value. From here, Salvoy<sup>1</sup> gives a preliminary value for the gravitino of  $m_{3/2} \approx \frac{M_S^2}{\sqrt{3}M_P} = \frac{M_W M_X}{\lambda^2 M_P}$ , which can have a mass as high as a 1 or more TeV, although we will use a different scaling value to fill in our subsequent tables. The coefficient  $\lambda$  is roughly a measure of how closely the gravitino can couple to matter fields, which is relevant as to the electroweak regime. This will be used to make an estimate <sup>2</sup> as to relevant graviton to gravitino mass values. That is, we relate this synthesis of gravitino to massive gravitons <sup>2</sup> to a machian relationship, which will be developed in the body of our text.

# 2 Forming $m_{3/2}$ for a Gravitino and Linking It to Massive Graviton Contributions in the Electroweak Era: For the Machian Relationship

The idea was to mix results in  $^1$  with

$$\begin{aligned} M_{\rm electroweak} &= N_{\rm electroweak} \cdot m_{3/2} = N_{\rm electroweak} \times 10^{38} \cdot m_{\rm gravitino} \\ &= N_{\rm today} \cdot m_{\rm graviton} \approx 10^{88} \cdot m_{\rm graviton}. \end{aligned}$$
 (1)

Then the electroweak regime would have an entropy value of (1), whereas  $m_{3/2}$  is a gravitino mass value. With (2) below being the initial entropy value in the electroweak regime, which grows to  $10^{88}$  today. That is,

$$N_{\text{electroweak}} \sim 10^{50}$$
. (2)

The first and second equations form our Machian relationship for linking massive gravitons to SUSY gravitinos This would lead to, say,

$$\sum m_{\rm Bosons} - \sum m_{\rm Fermions} = 0. \tag{3}$$

$M_{\mathrm{Planck}}$	$M_{ m TeV}pprox M_{ m DM}pprox M_{ m Gravitino}$	$M_{\rm DE}$	$M_{ m Graviton}$
$10^{-8} \text{ kg} \sim 10^{16} \text{ TeV}$	$10^{-24} \text{ kg} = 10^{12} \text{ eV}$	$10^{-16}M_{\rm DM}$	$10^{-65} { m ~kg}$

#### 3 Conclusion for Forming the Machian Relationship, Reviewed

We can make an argument that a "massive" graviton is formed due to a Lorentz violation, and that due in part to the argument made by Bjorker<sup>3</sup> in his "Zeldovitch relationship." That is,

$$\frac{4\pi \cdot \gamma \cdot \rho_A}{\sqrt{1+\gamma^2}} \approx 10^{-60} M_{\text{Planck}} \approx [\Delta_{QCD}]^3.$$
<sup>(4)</sup>

Here, we have that the Lorentz-violating term has a magnitude due to

$$b_{\mu} = \frac{\eta_{\mu} \cdot 2\pi \rho_A \gamma}{M_{\text{Planck}} \cdot (1 + \gamma^2)} \le 10^{-33} \text{ eV.}$$
(5)

This assumes that there is a Lorentz-violating Lagrangian term of <sup>3</sup>

$$L_{\text{Lorentz-Violation}} \approx b_{\mu} \psi \gamma^{\mu} \gamma_5 \psi.$$
 (6)

The assertion being asked is if the formation of the Lorentz-violating Lagrangian term in (5) would be necessary for conditions (1) and (2) to form, which among other thigns is that the mass of a gravitino is  $\approx 10^{+41} M_{\text{Graviton}}$ , whereas the  $M_{\text{DE}}$  is about  $10^{-16} M_{\text{DM}}$ . The masses alone argue as to a coherent bunching of gravitons to represent DE, in line with string theory, but the real action will be to perhaps link  $\Lambda_{\text{EW}}$  in its initial configuration with a) DM initial creation, at about the electroweak regime, b) possibly by Machian physics make an interrelationship between DM and DE as through the rise  $\Lambda_{\text{EW}}$  of as outlined below in (7). The more general situation may arise due to a Casmir type force between the IR and UV Randal-Sundrum model branes with the DE transmitted to our present universe. Partly because Casimir energy = vacuum energy, which may be the easiest way to generate dark energy. Here the overall density value due to a scale factor of  $a(t) \propto \frac{\text{const}}{\rho} \approx \exp(H \cdot t) \Rightarrow \rho \propto \Lambda \sim \exp(-H \cdot t)$ .

$$\rho.|_{\text{Today}} \sim \frac{\Lambda_{\text{EW}}}{8\pi} \exp(-H_{\text{EW}} \cdot t|_{\text{Today}}) \iff \Lambda_{\text{Today}} \sim \Lambda_{\text{EW}} \exp(-H_{\text{EW}} \cdot t|_{\text{Today}})$$
(7)

And  $\Lambda_{\rm EW} \ 10^{-38} - 10^{-40}$  or more to the tiny present  $\Lambda_{\rm Today}$  for vacuum energy, assuming  $\Lambda_{\rm Today} \sim \Lambda_{\rm EW} \exp(-H_{\rm EW} \cdot t|_{\rm Today})$  and this leading to Salvoy<sup>1</sup> if M is the total mass affected by the Machian relationship as is given in the cubic equation

$$(a \cdot r)^3 - \frac{E}{(\beta + H)^2} \cdot (a \cdot r) - \frac{M}{(\beta + H)^2} = 0.$$
 (8)

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## THERMAL DEATH OF THE CHELYABINSK METEOR WITH ENERGY NEARLY 500 KILOTONNES

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The paper considers physical features of thermal explosion - detonation combustion mode of the Chelyabinsk and the Tunguska meteors. A plasma dynamic model of detonation wave propagation in ionizing gaseous and intensively evaporating solid media is constructed. The thermal radiation plays one of the main roles in considered high temperature burning process. Additional experimental results (measured speeds of detonation waves in various explosives) are given with the purpose of validation of the proposed model.

## 1 Introduction

The destroying meteor from the last 100 years blasted above the Chelyabinsk region in Russia on 15 February 2013. It is the largest known object to have entered Earth's atmosphere since the 1908 Tunguska event which destroyed a wide, remote forest area of Siberia. The Chelyabinsk meteor was a typical chondrite a stony meteor with low iron content. The meteor was near 17 meters across and weight nearly 10,000 tons. The analysis reveals that the meteor first became visible around 90 kilometers above ground at an estimated speed of 18 km/s, approximately 50 times the speed of sound. At a height of nearly 25 kilometers, it exploded damaging thousands of homes and injuring more than 1,500 people in and around Chelyabinsk. The explosion generated a bright flash, producing many small fragmentary meteorites and a powerful shock wave. The explosive energy was nearly 500 kilotons (in the TNT equivalent). One of main real explanation is a thermal explosion with detonation burning process. We consider the main stages of a meteor detonation: very high temperature and pressure in head shock layer (near leading blunt body edge); intensive radiation heat in detonation medium (a stony meteor); very fast evaporation and ionization processes (from leading blunt edge); plasma soliton formation, which determines detonation wave propagation.

## 2 Ion-sonic soliton generation in a head shock layer

Strong shock waves with velocities of more than 1 km/s are usually accompanied by chemical reactions, intensive radiation, photo excitement and ionization. Plasma, which is formed in this processes, generates an ion-sonic soliton package  $^{1,2,3,4,5}$  and accelerates the shock wave front  $^{6,7,8}$ . Highly ionized soliton package is an internal source for fast chemical reactions in a mixture. For this action to proceed, the large mono energetic electron group should be formed in a detonation medium. This group forms from the collisions of the second kind with excited atoms.

There is a critical value of the ionic Mach-number  $M_i \approx 1.6$  ( $M_i = C/V_{is'}$  where C is speed of a shock wave,  $V_{is} = \sqrt{T_e/m_j}$  is velocity of an ionic sound). On the condition  $1 < M_i \le$  1.6 the plasma fluid dynamic equations have a soliton solution  $^{9,10,11,12}$ . As the results we can consider both soliton and shock wave velocities. Figure 1 and 2 demonstrate the examples of this nonlinear plasma effect influence on a shock wave<sup>7</sup> (photo of F. Shugaev).





Figure 1: Interferogram of a shock wave in xenon;  $M=25, M_{\rm i}=1.5; 1$  the front of head shock wave, 2 the front of ion-acoustic wave in precursor.

Figure 2: Interferogram of a shock wave in xenon; collapse of a shock wave at M=27.1;  $M_i$  1.6

At motion of a supersonic body in molecular gas there are two areas with a sharp change of fields. It is area of the front of a shock wave where there is a photo-ionization and excitation, and a relaxation zone in which there is the collapse of shock waves. Here after decomposition of working gas there are reactions leading to ionization of products of decomposition and emergence of new groups of fast electrons. Near the front of the bow shock and in relaxation zone in areas of resonance the ion-acoustic soliton bunches are forming. The ionization coefficient sharply increases in these bunches and approaches to value  $\alpha = 1$ . Complex structure of the bunch of strongly ionized plasma is formed  $^{6}$ . In a highly ionized plasma bunch there is non-linear interaction of the charged and neutral components. A result of this interaction is a change in the structure of the shock wave. The amplitude of the ion-acoustic bunch rapidly increases with approach the ion-acoustic Mach number to the value of M  $\approx 1.6$ . Further there is a collapse of a soliton bunch and restoration of a wave structure. Processes in molecular gases are more complex due to plasma reactions, dissociation and multicomponent ion composition. The phase velocity of ion-acoustic bunch is determined by the electron temperature and depends on a type of function of distribution of electrons on energy. At movement of an ionizing shock wave function of distribution of electrons on energy is formed in plasma reactions in collisions of excited to a resonant or metastable level of atoms and molecules, as well as collisions of the second kind. Near the front of a shock wave there are groups of electrons with the various energies. Each of these formations has its own electron temperature. Thus, in plasma in area of a shock wave the set of ionic sound speeds exists and the ionic Mach - number of a shock wave can reach critical values  $M_i \approx 1.6$  repeatedly.

## 3 Soliton bunch in air plasma

Researches of shock wave propagation in the air plasma represent great practical interest. Nonlinear interactions in dynamic plasma get better understanding of detonation physics. Here we consider more detail decomposition of nitrogen and oxygen.

**Nitrogen.** Two basic kinds of ions of  $N_2^+$  and  $N^+$  are formed at propagation of a strong shock wave in nitrogen. Five groups of the fast electrons with energy of 1,8eV; 2eV; 6,06eV; 6,2eV, 10,3 eV will be formed in result of collisions of atoms and molecules exited on metastable or resonant levels, and also of collisions of the second kind

- 1. N\* (10,3 eV) +N\*(10,3 eV)  $\rightarrow$  N<sup>+</sup> + N + e (6,06 eV)
- 2. N\* (10,3 eV) + e (6,06 eV)  $\rightarrow$  N^+ + e (1,82eV) + e (~0eV)
  - 344

3.  $N_{2}^{*}(6,2 \text{ eV}) + e (\sim 0 \text{ eV}) \rightarrow N_{2} + e (6,2 \text{ eV})$ 4.  $N^{*}(10,3 \text{ eV}) + e (6,2 \text{ eV}) \rightarrow N^{+} + e (2 \text{ eV}) + e (\sim 0 \text{ eV})$ 5.  $N^{*}(10,3 \text{ eV}) + e (\sim 0 \text{ eV}) \rightarrow N + e (10,3 \text{ eV})$ 

Each kind of a nitrogen ion can form five resonances. Ten ranges in which there is the ion-acoustic bunch can exist in result of these reactions in nitrogen when  $1_i M_i$  [1,6. In area of a shock front formation of a bunch and instability of flow can be observed in the ranges of speeds: 1) 2,5 4,05; 2) 2,6 - 4,25; 3) 4,6 - 7,3; 4) 4,8 - 7,7; 5) 5,9 - 9,6 km/s (ion N<sub>2</sub><sup>+</sup>). Instability of flow can be observed also in a range of speeds: 6) 3,5 - 5,6; 7) 3,7 - 6; 8) 6,4 - 10,2; 9) 6,75 - 10,8; 10) 8,4 13,7 km/s ( ion N<sup>+</sup>).

We have no enough experimental data on instability of shock front. The strong instability of fronts is displayed at the end of resonant range in narrow region of speeds  $\Delta V \sim 100$  m/s. The experiments are rather consuming. Besides, ranges of existence of ion-sound solitons are overlapped that also complicates their identification. A distortion and collapse of a shock front in experiments in a shock tube at speed a shock wave of V=6,2 - 7,3 km/s (range N<sup>Q</sup>3) was observed. In experiments in shock tube at speed of V = 6,6 km/s the formation of an internal shock wave (ion-acoustic) was also observed. In this area the ranges N<sup>Q</sup>N<sup>Q</sup> 3, 4, 6, 7, 8 are overlapped. The most significant destruction of shock wave front occurred also at speed V = 4 km/s, that corresponds to the end of range N<sup>Q</sup>1. A front of a shock wave was demolished at speed of V=4 km/s and V=7,3 km/s (ranges N<sup>Q</sup>N<sup>Q</sup> 2,3). Experimental results correspond well enough to calculated ranges.

**Oxygen**. Similarly in the field of a shock wave in oxygen two types of ions and nine main groups of electrons  $^{7}$  are formed. For example groups of electrons with energy 3,3; 4,7; 5,8; 7,9; 9,15; 9,52 eV are formed. As a result in area of a shock wave high-ionized soliton bunches arise at the corresponding speeds 5; 6; 7; 8,5; 9,4; 11; 12 km/s, which get to value of ionic Mach  $M_i =$ 1,6. These soliton bunches have a super-high temperature from 60,000 to 110000 K (Te  $\approx$  Tg, see below). At movement of a shock wave in oxygen instability can be observed in plasma for overlapping speed ranges up to 12 km/sec. Experiments in oxygen are technically difficult and practically are absent. Bloating front in oxygen was observed at speed of 3.9 km/s [6]. These results correspond to the maximum amplitude of a soliton bunch at the end of the calculated range of 2,5 4 km/s<sup>7</sup>. At high speeds of a shock wave decomposition of molecular gas happens at a great distance before the front. For example in carbon dioxide soliton bunches with atomic ions observed in area of the front even at speeds of V > 3-4 km/s  $^{7}$ . Thus at the propagation of the shock wave or hypersonic body in air mixture huge quantities of high-speed ranges with high-temperature soliton bunches exist. These bunches are formed by different ions and exist in a wide range of speeds from 4 to 12 km/s. In dense plasma at atmospheric pressure, in front of the bow shock the collisions have a predominant role. Therefore the resulting quasi-steady state must be described by the same laws that describe the plasma in a state of thermodynamic equilibrium. Thus it can be assumed that fully ionized plasma in area of soliton bunch exists in a state of local thermodynamic equilibrium. In this area approximately equality of temperatures of electrons and heavy plasma components Te  $\approx$  Tg is realized. Table 1 shows some examples of bunches and shows the temperature of medium in these bunches. Designation of bunch  $[N^* (10,3 \text{ ev}), N^+]$  indicates that it is due to a group of electrons formed from the metastable term  $N^*$  (10,3 eV), and ion  $N^+$ . These results demonstrate that in local areas near hypersonic body equilibrium temperature can reach values of 120000 K. At such temperatures there is a decomposition, evaporation and ionization of the most refractory component of a material of a body. The spatial scale of the observed ion-acoustic perturbations can reach of meters. The length of the plasma precursor in front of the meteor body can reach tens or hundreds of meters.

Table 1: The equilibrium temperatures of plasma in the soliton bunch

Soliton bunch	Body velocity, km/s	Temperature in a bunch, K; $TE \approx Tg$
N* (10,3 ev), N <sup>+</sup>	13,3,	120 000
$N^*$ (10,3 ev), $N_2^+$	9,5	120 000
O* (9,15 ev), O+	11,9	106 000
O* (9,52 ev), O <sup>+</sup>	12,2	110 000
$N_2^*$ (6,2 ev), $N_2^+$	7,5	75 000
$N_2^*$ (6,2 ev), $O_2^+$	7	75 00
$e (2 ev), N_2^+$	4,25	23 000

## 4 Structure of meteor shock layer soliton bunch.

Destruction of a bow shock wave in formation zone of soliton bunch is shown in figure 3 before cylindrical model in freon. The gas dissociation behind the front occurs in area of temperature increase of heavy components in soliton bunches. In the shadow photography for a short interval of time we can see "a mask" of a soliton bunch. Source of an ionic sound is both a shock wave and a double layer near a body surface. Therefore soliton bunch can appear both before the front in a precursor and behind the front near a surface of a body. In figure 3 behind a shock wave in area of high optical density there is "a mask" of soliton bunch. It is visible that this "mask" in the form of perturbation behind the front represents system of the separate spots on lines, parallel to the front of a bow shock wave. Some such lines structures are visible. The soliton structure represents set of separate spots and reminds the structure of separate filament in microwave discharge. Thus the ion-acoustic soliton bunch represents a special type of the dynamic resonant discharge. Properties of this discharge determine its gas dynamic characteristics.



Figure 3: Soliton bunch in the bow shock;  $CF_4$ , M=9.9;  $M_i=1.5$ ,  $T_e \approx 2.8$  eV (photo V. Maslennikov)

The meteor body at entering into the atmosphere generates the head shock wave with very high temperature (table 1). Here in area of significant gradient of fields the high-temperature the ion-acoustic soliton bunches also exists. In area of these bunches there is an evaporation and decomposition even most refractory compounds of meteorite material. Additional bunches are formed by the metastable and resonance terms of the elements of the body material. Thus at meteorite movement in atmosphere the plasma column of the various substances evaporated and dissociated at ultrahigh temperatures of the solitonic discharge is formed. In soliton bunches at critical values of ionic Mach - number  $1 < M_i < 1,6$  the process of detonation combustion begins. About 18% of the material of the meteorite was silicon. We get detonation burning mode for silicon in oxygen and nitrogen with reactions

$$3Si + 2N_2 = Si_3N_4$$
;  $Si + O_2 = SiO_2$ 

The oxidizing agent may serve as oxygen, or nitrogen. If energy is allocated enough, an ion-

acoustic shock wave can be formed also. At the formation of a soliton bunch and ion-acoustic shock waves arising double shock-wave structure is accelerated. It can be accelerated to the maximum phase speed of soliton bunch. For example, the maximum phase speed of a bunch  $[NO^* (4,7eV), C^+]$  is 10 km/s. For the bunch  $[N_2^* (6,2eV), Si^+]$  maximum phase velocity is V= 7.3 km/s. For the bunch  $[Mg^{*}(4,34eV), Si^{+}]$  maximum phase velocity is 6.2 km/s. Thus the ion-acoustic model of detonation combustion in general can logically explain the basic processes observed at falling of large meteor bodies, such as Chelyabinsk or the Tunguska meteors. Our comparison shows that the phase velocities of the soliton bunches in the field of a shock wave front coincide with the detonation velocities in considered explosives such as nitro compounds. From the point of view of plasma nonlinear ionic-sound model the detonation stops, when the velocity of a detonation wave passes the critical value for soliton velocity  $C \approx 1.6 V_{is}$ , at which soliton bunch collapses and shock wave structure is destroyed. This physical mechanism determines the velocity of a detonation in gas mixtures and in condensed explosives. Proposed model describes the main physical stages of detonation wave propagation: the outstripping radiation heat of detonation medium with ionization process and ion-sonic soliton formation, which determines the detonation wave velocity.

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