

Fundamental Physics with Cosmic Gamma Rays

Manel Martinez

IFAE, Edifici Cn, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain

E-mail: martinez@ifae.es

Abstract. The observation of the universe in the VHE gamma ray domain with the new generation of Cherenkov Telescopes is producing new measurements with a direct implication for cosmology. The present results and the future prospects will be discussed.

1. Introduction

VHE Cosmic gamma-ray observation started in 2005 a true revolution in the consolidation of Cherenkov Telescopes as astronomical instruments [1]. After many years of slow development, Imaging Air Cherenkov Telescopes (IACTs) are now in the phase transition from being “high energy experiments” to being “telescopic installations” in the astronomical sense. This fact is motivating an exploding interest in a broad scientific community embracing astrophysics, particle physics and cosmology.

The reason for this phase transition is the big observational step forward occurred within the last years at the quantitative level (increasing up to about 80 the number of detected sources) but also at the qualitative level (producing extremely high quality detections allowing unprecedented detailed studies) due to the start into operation of the Cherenkov Telescopes of the new generation.

Thanks to these instruments, the observational window to study the universe at the highest energies is now wide-open. We are indeed in a golden age for Cherenkov Telescopes and for that reason, this article will concentrate in the discussion of the observations with these instruments.

On the other hand it is clear that modern cosmology has progressed very rapidly during the last decades and, with the help of new instruments and telescopes, the universe history has been traced up to its very early stages, even before galaxies were formed. These exciting and challenging measurements indicate that at present everything we can directly observe in the Universe makes up only a small fraction of its content (altogether less than 5% of the matter-energy content of the universe) and the rest is in the form of unknown Dark Matter (as much as about 25%) and a mysterious kind of substance with negative pressure called Dark Energy (about 70%).

The existence of a very simple “Concordance Cosmological Standard Model” able to fit successfully a broad set of very different measurements based on completely different physics and different instrumental systematic uncertainties with an small set of parameters is probably going to be cataloged as a new scientific revolution for the 21st century. The collection of different sets of experimental data is becoming so compelling that Cosmology is becoming actually Cosmonomy in the sense that precise measurements (with uncertainties at the few

percent level) of the parameters governing the expansion of our universe already exist and will improve even much further in the coming years.

Among the broad spectrum of scientific opportunities offered by the observation of the sky in the VHE gamma ray band with Cherenkov Telescopes there are some which, given the quality of the observations provided by the instruments of the new generation, may have a relevant impact in Fundamental Physics and Cosmology. Discussing them, reviewing its present status and discussing their prospects are the goal of this article.

For that, the outline of this write-up is as follows: in section 2 we will present the status of the indirect search for Dark Matter annihilation into VHE gamma rays discussing the impact of the detailed analyses of the Galactic center observations carried out by H.E.S.S. and MAGIC. In section 3 we will discuss the implications of the studies of the energy spectrum measured in distant Blazars by H.E.S.S. and MAGIC, which allow to place an unexpectedly low upper bound on the density of the Extragalactic Background Light by means of the analysis of the gamma-gamma absorption. As it will be argued, if confirmed this result may open the window for the use of that kind of observations to constrain Dark Energy by using the Optical depth for the VHE gamma rays propagation due to the absorption as a distance estimator in a similar manner as the one used with Supernovae 1a. Section 4 will review the use of light curves showing fast flares of VHE gamma ray sources at cosmological distances to place constraints on the quantum structure of the gravitational vacuum. Finally, section 5 we will give a summary of the present situation and an outlook on the exciting near future.

2. Indirect searches for Dark Matter

Currently, one of the major aims of particle physics is the search for supersymmetric particles. Most of the supersymmetric extensions of the Standard Model of particle physics foresee the existence of a massive stable lightest supersymmetric particle (LSP) which may annihilate in pairs into leptons, quarks or photons.

On the other hand, as has been already mentioned in the introduction, several astrophysics observations agree in predicting that most of the matter in the universe is non-baryonic Dark Matter.

If most of the Dark Matter is in form of Weakly Interacting Massive Particles (WIMP) as the Λ CDM scenarios, favored by most of the observations, presently suggest, a favorite candidate for this Dark Matter is the LSP which in most supersymmetric extensions of the Standard Model is the so-called neutralino, the spin 1/2 supersymmetric partner of the neutral bosons [2]. In that case, Dark Matter may be detected from the neutralino annihilation directly into pairs of VHE gamma rays or into particles and jets which finally produce many VHE gamma rays.

That signal should be proportional to the square of the dark matter density and therefore should mainly come from regions with high dark matter density such as:

- the center of our galaxy,
- dwarf spheroidal satellite galaxies with large mass-to-light ratios,
- subhalo structures,
- microhalos,
- intermediate mass black holes (IMBH)
- local group galaxies and
- globular clusters

for instance.

Out of all the possible target candidates for the indirect detection of Dark Matter through its annihilation into VHE gamma rays the one from which larger flux is expected is the center of our galaxy. The reason is the very high Dark Matter density expected which, as already explained,

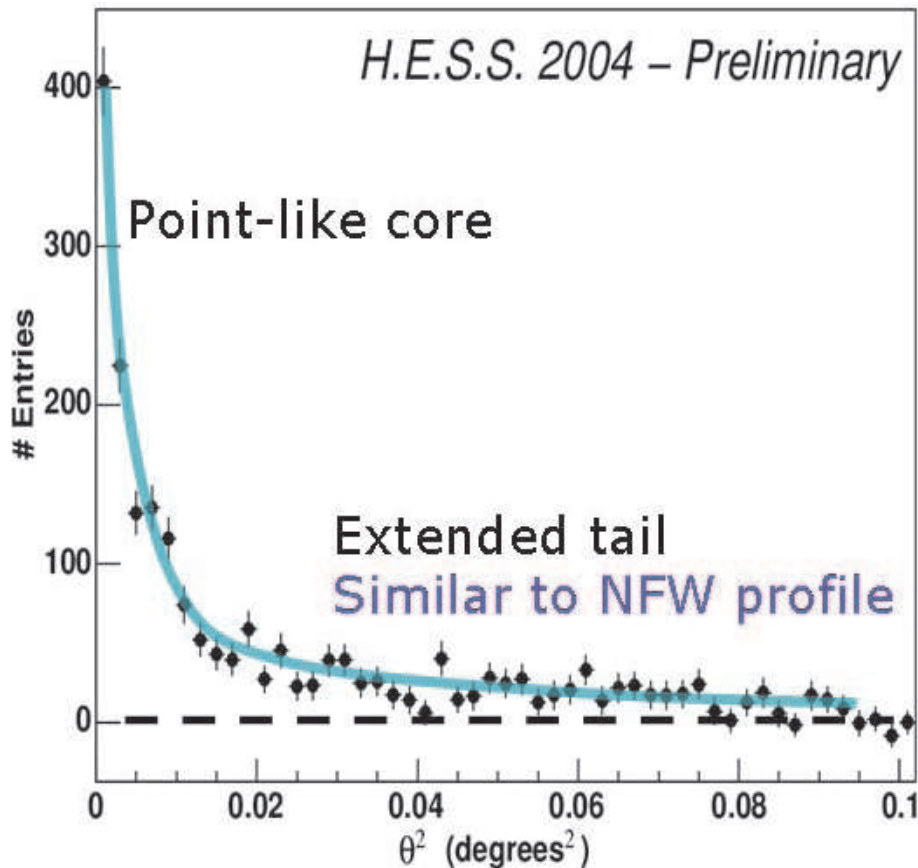


Figure 1. Radial profile of the Galactic Center gamma-ray excess observed in 2004 HESS data.

enters quadratically in the gamma ray flux prediction, and its proximity when compared to other target candidates [3].

The galactic center has been independently observed by H.E.S.S. and MAGIC (in this case at large zenith angle, which implies larger effective area but at a higher energy threshold) providing spectrum measurements in nice agreement, which contradict the measurements previously published by the CANGAROO collaboration.

The signal observed by H.E.S.S. in 2003-2004 was consistent with point-like emission from Sgr A* [4] although it had a slight hint for extension which could be fit with a Navarro-Frenk-White Dark Matter halo profile as can be gleaned from figure 1. In addition, the signal was steady from year to minute scales. The spectrum obtained with the first data taken extended up to energies above 10 TeV and would have required invoking an unnaturally heavy neutralino to explain it.

The final spectrum after analyzing all the accumulated data can be seen in figure 2 which shows that it can be very well fitted by an unbroken power law with index 2.3 from about 150 GeV up to almost 30 TeV. This spectrum is in perfect agreement with the one obtained by the MAGIC collaboration which has observed the Galactic Center at large zenith angles (from 58 to 62 degrees) and hence, with somewhat different systematic uncertainties.

This spectrum shape and index are in agreement with the expectations from acceleration mechanisms in standard astrophysical sources and rules out most of the possible interpretations in terms of dark matter annihilation.

Nevertheless, a plausible explanation at that stage was that the signal from the dark matter

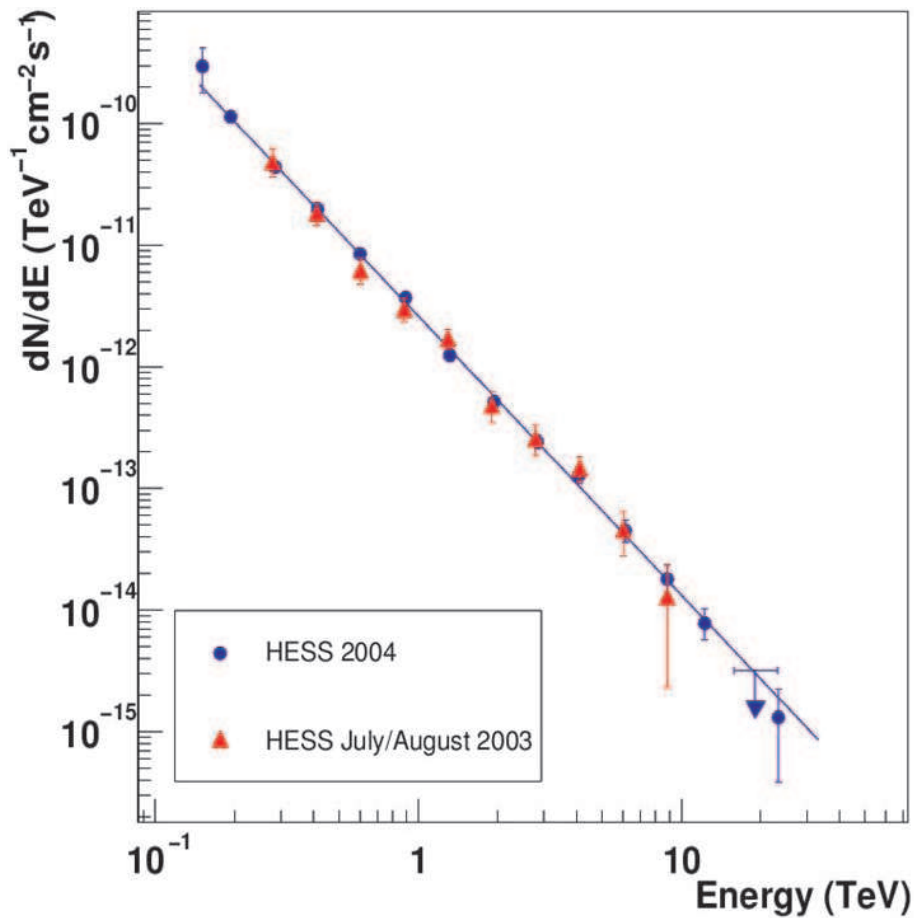


Figure 2. Differential energy spectrum of the Galactic Center gamma-ray excess observed by HESS.

annihilation in the Galactic Center region could be outshined by the VHE gamma ray emission from point-like astrophysical sources in the Galactic Center region which, from observations in many wavelengths is known to be a very busy region with many astrophysics sources and a lot of non-thermal activity.

Following this idea, H.E.S.S. has been able to subtract from a deep exposure the point-like sources (given its point-spread-function) [5] and the observed remaining signal turns out to be in good agreement with the distribution of the molecular gas traced by its CS emission as can be observed in figure 3.

Furthermore, once the molecular clouds have been identified as the origin of the extended emission, the expected gamma ray flux coming from them can be subtracted from the observed flux to see whether the galactic center emission follows actually a point source profile (within the instrument point-spread-function) or follows still a kind of Navarro-Frenk-White Dark Matter halo profile. The answer is shown in figure 4.

Therefore, the high quality data on the Galactic Center obtained in the last few years by H.E.S.S. and MAGIC does not show any evidence of dark matter annihilation signal [6],[7]. In spite of that, it is very difficult to extract any quantitative conclusion of that observation since there are very large uncertainties in the predictions for the expected flux coming from:

- WIMP mass spectrum and couplings which should be known to determine the annihilation probabilities into the different channels. For these quantities, important accelerator and

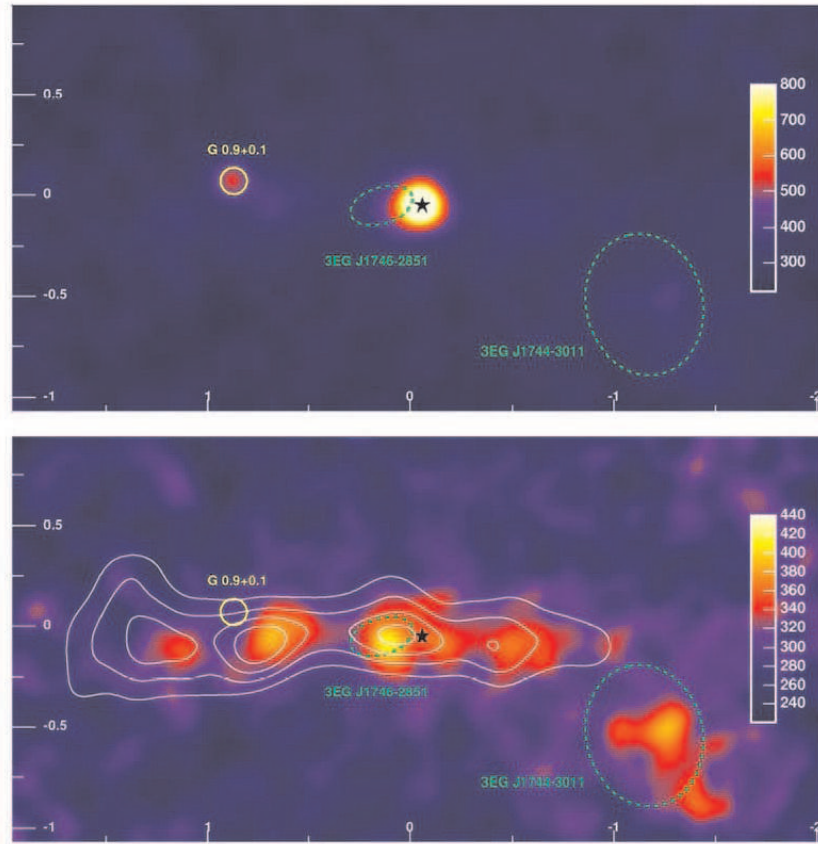


Figure 3. The Galactic Center gamma-ray count map as observed by HESS (upper plot) and after subtracting point-like source contributions (lower plot) showing a clear correlation with the molecular gas traced by its CS emission.

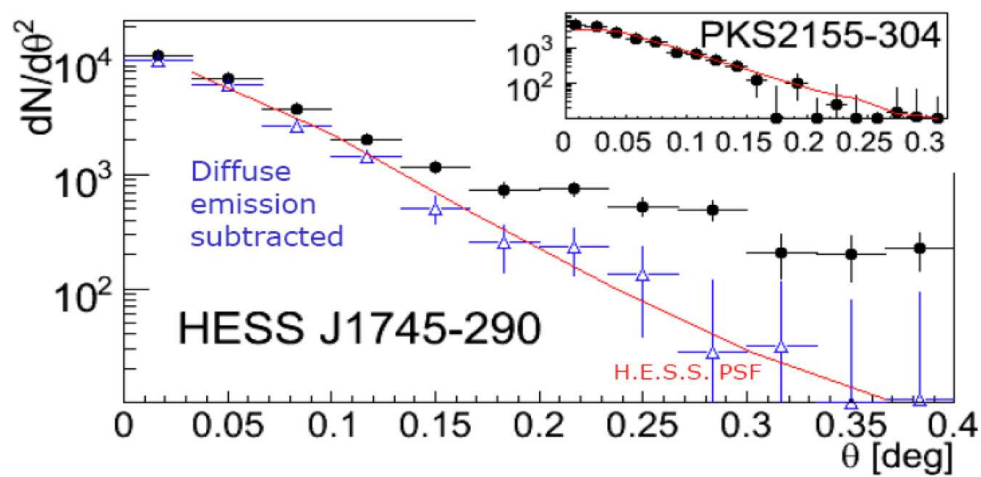


Figure 4. Radial profile of the gamma ray flux measured from the Galactic Center by H.E.S.S. after subtracting the expected contribution for the emission due to the molecular clouds traced by their CS emission. The profile is in excellent agreement with the point-spread-fuction of the H.E.S.S. measurements as independently determined with the observations of the PKS2155 blazar.

relic density constraints exist already but there is still a very broad parameter space open, which make predictions very uncertain. The start of LHC operation in the coming years may narrow down drastically the parameter space and allow for much more precise predictions.

- The cuspy region of the dark matter density profile, in the vicinity of the central supermassive Black Hole, which remains virtually unknown.
- The background due to astrophysical sources which may be much larger than the Dark Matter annihilation signal making the subtraction very uncertain

Nevertheless, other target candidates, such as Dwarf Spheroidal Satellites of our Galaxy with high mass-to-light ratios which in comparison with the Galactic Center are expected to produce lower fluxes and are more distant, but which may provide cleaner environments with much less astrophysical source backgrounds, are being explored. One of the most promising candidates is Draco, for which by the end of 2005 there was a claim of a highly significant VHE Gamma Ray detection by the CACTUS solar array collaboration [8]. Unfortunately, data taken by MAGIC [9] were in contradiction with that claim, which meanwhile was retired by the CACTUS collaboration while studying in detail systematic effects.

An important step in this search for Dark Matter annihilation signals will be the sky survey catalog which will be produced by Fermi-GLAST in the near future since its unidentified sources may spot dark matter clumps and therefore be prime candidates to study in depth with Cherenkov Telescopes in the quest for dark matter.

In spite of not having observed yet a dark matter signature, it must be stressed that VHE gamma-ray astronomy provides probably the best tool to try to unveil the nature of dark matter since:

- Even if WIMP candidates are found in accelerator experiments such as the LHC, it must be confirmed that they actually constitute the dark matter of our universe and can explain the dark matter distribution detected through gravitational effects at the different structure scales in our Universe.
- Direct searches through nuclear recoil may recognize local halo WIMPs but certainly cannot prove the nature and composition of Dark Matter on the sky.
- Indirect searches using charged particles may detect excesses but not map them into the gravitationally identified density profiles.
- Indirect searches using neutrino telescopes may need many cubic kilometers of instrumented volume to reach the sensitivity attainable to VHE gamma ray installations.
- Indirect searches using gamma satellites such as Fermi-GLAST may have a too limited energy lever arm to pinpoint dark matter spectral features.

Instead, the role of VHE gamma-ray astronomy for Dark Matter studies, even beyond the discovery, is unique since VHE gamma-ray observations provide the only avenue for measuring the dark matter halo profiles and illuminating the role of dark matter in structure formation, that is, probably the only means to develop in the future "Dark Matter astronomy".

3. The Cosmological Gamma Ray Horizon

As it is very well known the intergalactic vacuum is not really empty. There is a sea of photons lying around which constitute the so-called Extragalactic Background Light (EBL). For instance, one can find the well studied Cosmic Microwave Background but there are contributions from any photon energy [10].

The flux of high energy gamma rays that travel through the universe is attenuated by the absorption of gamma rays in the diffuse extragalactic background light through the QED interaction $\gamma_{HE}\gamma_{EBL} \rightarrow f^+f^-$. The cross section for this electromagnetic reaction decreases as

the inverse of the square of the final state fermion mass and hence, the most probable final state is a e^+e^- pair.

Gamma rays of energy E can interact with low-energy photons of energy ϵ from the diffuse EBL over cosmological distance scales. The pair production is expected above the threshold energy condition

$$E\epsilon(1 - \cos\theta) > 2m^2c^4 \quad (1)$$

where θ is the gamma-gamma scattering angle and m the fermion mass.

Therefore, the relevant EBL for the Cherenkov Telescopes is the visible and infra-red background, for which there exists observational data with determinations and bounds of the background spectral energy density (SED) at $z = 0$ for several energies. The determinations come from direct measurements of the EBL density using instruments on satellites whereas the bounds, happen mostly in the infrared part of the EBL and come from extrapolations using galaxy counting. Given the difficulty of observing “cold galaxies” due to the zodiacal light background, they provide just lower limits.

Actually the SED at $z = 0$ is not the end of the story since the EBL evolves with the redshift and the High-energy γ -rays originated at cosmological distances will interact with the EBL at different redshifts. The main contribution to the EBL comes from low-energy photons produced by stars in ordinary galaxies. Therefore either the star formation rate and the star evolution will play an important role to the EBL as a function of redshift determination.

The flux attenuation is a function of the gamma energy E and the redshift z of the gamma ray source and can be parameterised by the Optical depth $\tau(E, z)$, which is defined as the number of e-fold reductions of the observed flux as compared with the initial flux at z . This means that the Optical depth introduces an attenuation factor $\exp[-\tau(E, z)]$ modifying the gamma ray source energy spectrum.

$$\tau(E, z) = \int_0^z dz' c \frac{dt}{dz'} \int_0^2 dx \frac{x}{2} \int_{\frac{2m^2c^4}{Ex(1+z')^2}}^\infty d\epsilon \cdot n(\epsilon, z') \cdot \sigma[2xE\epsilon(1+z')^2] \quad (2)$$

where $n(\epsilon, z')$ is the EBL spectral density at redshift z' , σ the cross-section for $\gamma_{HE}\gamma_{EBL} \rightarrow e^+e^-$ and dt/dz the lookback time.

For any given gamma ray energy, the Gamma Ray Horizon (GRH) is defined as the source redshift for which the Optical depth is $\tau(E, z) = 1$. Therefore, the GRH gives, for each gamma ray energy, the redshift location z of a source for which the intrinsic gamma flux suffers an e-fold decrease when observed on Earth $z = 0$ due to the gamma-gamma absorption.

In practice, the cut-off due to the Optical depth is completely folded with the spectral emission of the gamma source. But on the other hand, the suppression factor in the gamma flux due to the Optical depth depends only (assuming a specific cosmology and spectral EBL density) on the gamma energy and the redshift of the source. Therefore, a common gamma energy spectrum behaviour of a set of different gamma sources at the same redshift is most likely due to the Optical Depth.

To compute the Optical depth using equation 2 there are two quantities which have to be known: on the one hand, the density of the EBL and its redshift dependence, and on the other hand, the cosmological evolution of our universe casted in the lookback time expression.

The direct measurement of the the EBL density in the wavelength range relevant for VHE gamma ray absorption (from $0.1 \mu m$ to $10 \mu m$) is very difficult because of our light-polluted environment, in particular by zodiacal light - sunlight reflected from dust clouds in our solar system. For this reason, the absorption measured by studying the distortion in the energy spectrum of distant sources, has already been widely used to try to bound the EBL density.

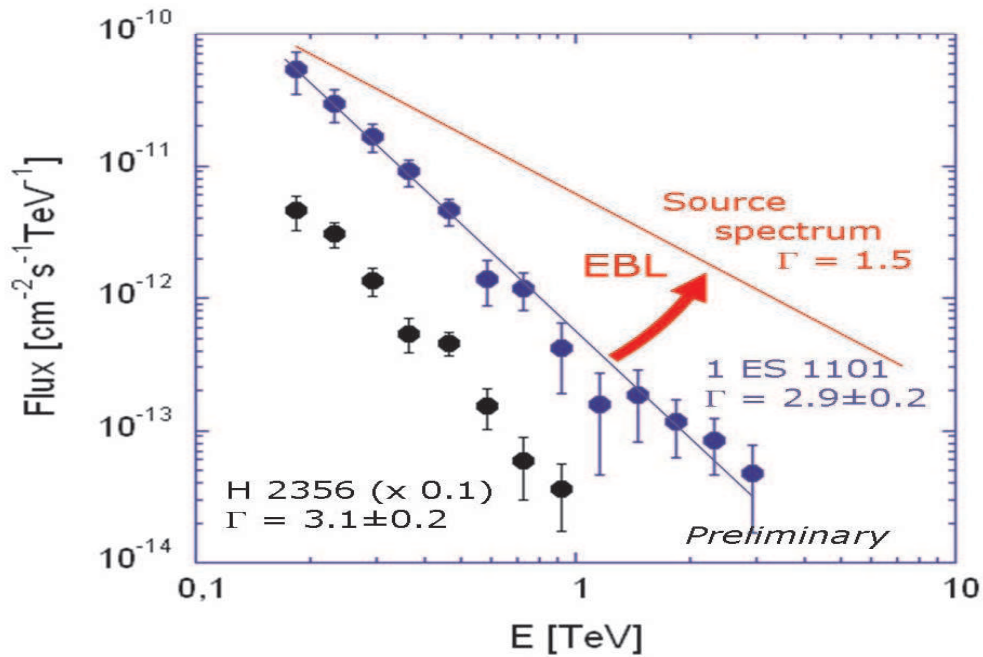


Figure 5. Measured differential energy spectrum of two of the farthest Blazars detected by HESS compared with an intrinsic spectrum of index 1.5.

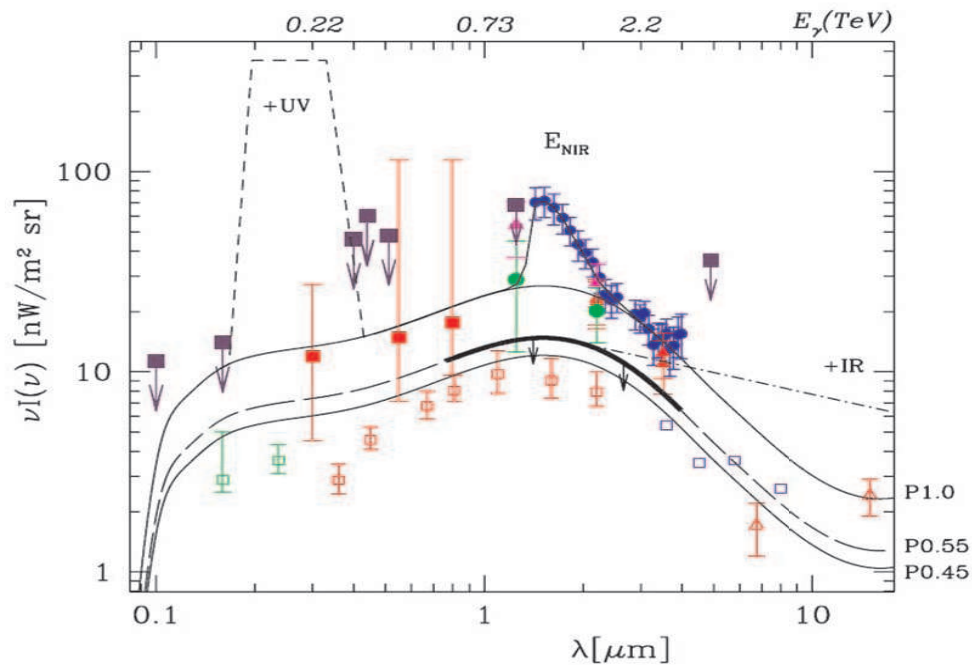


Figure 6. Direct measurements, upper and lower limits and different possible scenarios explored by the HESS collaboration for the modelization of the Extragalactic Background Light spectrum in the wavelength range relevant for VHE gamma-ray astronomy. A meaningful deconvolution of the HESS Blazar spectra requires an EBL density which is at most about a factor two smaller than the Primack et al. prediction, almost saturates the lower limits from galaxy counts and therefore is almost consistent with a resolved EBL scenario (see text).

H.E.S.S. and MAGIC have observed VHE gamma rays from few relatively distant active galaxies. In the case of H.E.S.S. two objects, identified as the Blazars H2356-309 and 1ES1101-232 at redshifts of $z = 0.165$ and 0.186 respectively, have been detected. The multiwavelength observations of Blazars as well as theoretical shock acceleration models in jets have serious difficulties to predict intrinsic gamma ray spectral energy slopes harder than $\Gamma = 1.5$ ¹ while the observed slope for these two sources and for the 1ES1218+304 Blazar at redshift $z = 0.182$ discovered by MAGIC are unexpectedly very hard, of about $\Gamma \approx 3$ as can be seen in figure 5. The observation of such hard spectra hints to a universe more transparent to VHE gamma rays than what was expected based on the direct measurements and the model predictions of the EBL density.

Actually, using these spectra and the energy dependence of the Optical depth through electron-positron pair production which can be obtained from equation 2, the H.E.S.S. collaboration has been able to set a firm upper limit on the absorption of gamma ray and hence on the amount of extragalactic background light [11].

This limit is sensibly less than - and hence in conflict with - the values derived by direct measurements of the extragalactic background light as can be seen in figure 6. Furthermore, being only about a factor of ~ 1.5 above the lower limit given by direct observation of galaxies by the Hubble Space Telescope, the H.E.S.S. observations seriously limit the possible contribution from sources other than galaxies. This is in good agreement with recent theoretical calculations and arguments against a strong extragalactic background from first-generation stars. This is bad news for the attempts at direct detection of the glow of these population III stars but the H.E.S.S. results expand the horizon of the gamma-ray universe, allowing Cherenkov telescopes to detect many other remote active galaxies.

Recently, MAGIC was able to observe VHE gamma ray emission from 3C279, a quasar at $z=0.536$ and therefore the most distant source ever detected in the VHE gamma ray domain [12]. The analysis of the spectrum measured constrains even further the existence of an unresolved EBL component as can be seen in figure 7.

If the upper bounds on the EBL density from MAGIC and H.E.S.S. are further established, and taking into account that the correction of any possible observational biases in the galaxy count contribution to the EBL would very likely increase the lower bound, narrowing even further the distance between that lower bound and the H.E.S.S. upper bound, one may think that the EBL density in the relevant region for VHE gamma ray astronomy might be basically resolved as the sum of the contributions from the light of all the galaxies observed as point-like sources. Since there are many deep-exposure large astronomical surveys in operation and proposed for the coming years cartographing the galaxies in big volumes of the visible universe, it may be then possible to get a rather accurate determination of the EBL density as a function of redshift in the wavelength region relevant for VHE gamma ray astronomy.

In that case, the only missing information in equation 2 would be the lookback time, and then the measurement of the Optical depth using the distant Blazar spectrum absorption could be turned upside down and used to try to measure the Cosmological Parameters instead of the EBL density.

The idea would be using the spectrum absorption due to the interaction with the EBL to compute the "absorption distance" and use it as a distance estimator, in a similar way as the observed luminosity of Supernovae 1a is used, assuming they behave as standard candles, to compute the "luminosity distance" and use it as a distance estimator. Both distance estimators have different redshift dependence and can be considered as complementary since they use very different targets (active galaxies versus Supernovae), with very different assumptions (universal

¹ Nevertheless, it should be pointed out that this assumption could be relaxed in case of significant absorption of gamma rays at the source, for instance with the optical radiation from the accretion disk or scattered along the jet, which could produce an spectral index harder than 1.5

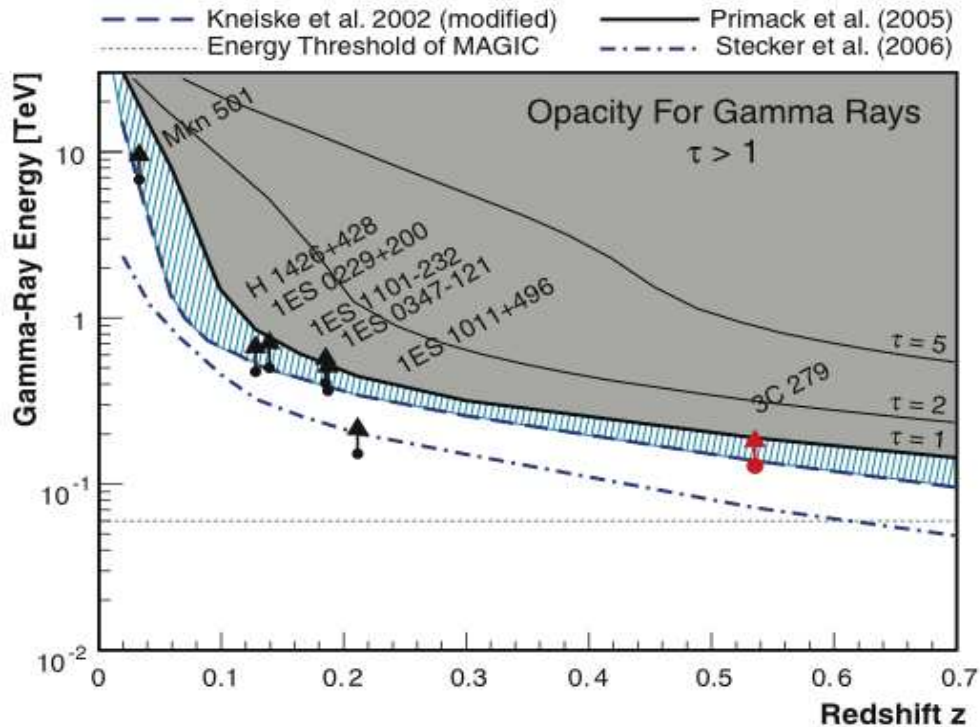


Figure 7. The Gamma Ray Horizon as predicted by different EBL models and as inferred from the observation of AGNs at different redshifts. The MAGIC observation of 3C279 extends the constraints on the EBL density up to the largest redshifts ($z=0.536$) observed so far in the VHE gamma ray domain.

EBL versus "standard candle") and with very different systematic uncertainties.

A study of the viability of such an approach was conducted few years ago [13],[14]. In that work the sensitivity of the measurement of the Gamma Ray Horizon with respect to the cosmological parameters was studied showing that indeed there was a sizable dependence which, assuming the EBL density known, could allow for meaningful constraints in the cosmology. Moreover, a reasonable simulation of the gamma ray horizon measurement as it could eventually be obtained from about 20 EGRET sources extrapolating the measured spectra was performed. By assuming reasonable observation periods and taking only statistical uncertainties into account, the constraints in the Ω_m v.s Ω_Λ plane predicted are the ones shown in figure 8 which were improving the Supernovae constraints existing at that time by a factor ~ 2 . That work included as well a discussion on the possible systematic uncertainties from experimental and theoretical origin concluding the the uncertainty in the actual EBL density could be the dominant one although some strategies to try to squeeze it were also proposed.

Summarizing, there are two implications of the H.E.S.S. and MAGIC results, namely:

- on the one hand, the universe is more transparent to gamma rays than expected and therefore the redshift reach of Cherenkov Telescopes should be substantially larger than anticipated allowing to observe much more distant extragalactic sources,
- on the other hand, the EBL density in the wavelength region relevant for the VHE gamma ray absorption might be actually resolved and hence the EBL density could be directly measured by surveys performing deep and detailed galaxy count

If these implications are confirmed, the study of the absorption in the energy spectrum of extragalactic VHE gamma rays at different redshifts may provide a competitive complementary

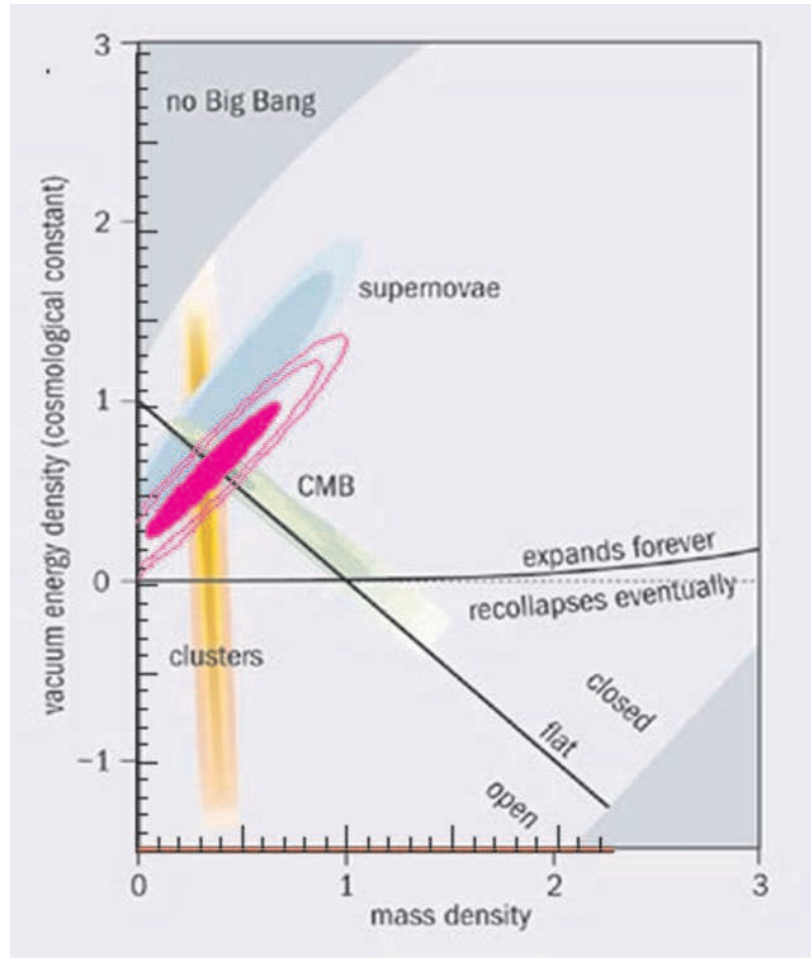


Figure 8. The solid purple contour shows the 68% c.l. area constraint in the Ω_m v.s Ω_Λ plane coming from a simulation of the gamma ray horizon as could be eventually measured in 20 EGRET AGN extrapolated to the energy range covered by Cherenkov Telescopes. That contour, obtained in 2004 and which takes into account only statistical uncertainties, was at that time improving by a factor 2 the one from the Supernovae visible in blue in the figure.

technique for the determination of the parameters with govern the expansion of our universe and specifically, may help in constraining Dark Energy.

4. Tests of the invariance of the speed of light

Any quantum theory of gravitation introduces quantum fluctuations at the Planck scale ($E_P \approx 10^{19}$ GeV or correspondingly $L_P \approx 10^{33}$ cm), which would induce a deformed dispersion relation for photons of the form [15]:

$$p^2 c^2 = E^2 [1 + f(E/E_{QG})] \quad (3)$$

where E is the photon energy, E_{QG} an effective quantum gravity energy scale (which might be as large as the Planck scale) and f is a model-dependent function of the ratio E/E_{QG} , p is the photon momentum and c is the velocity of light. At small energies $E \ll E_{QG}$ a series expansion of the dispersion relation can be made:

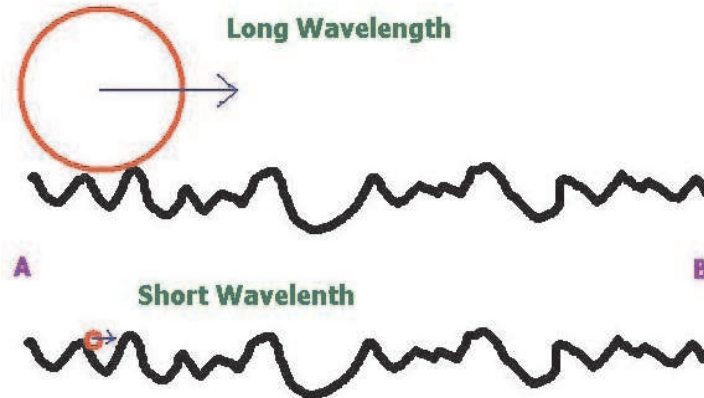


Figure 9. Sketch of the relation between the foamy structure of geodesics in gravitational vacuum at small distances as predicted in Quantum Gravity scenarios and the existence of an energy dispersion relation of the speed of light in vacuum.

$$p^2 c^2 = E^2 [1 + \xi E/E_{QG} + O(E^2/E_{QG}^2)] \quad (4)$$

where $\xi = \pm 1$ is a sign ambiguity which is fixed in the given theory. Equation 4 leads then to energy-dependent velocities of the photon:

$$v = \frac{\partial E}{\partial p} \approx c(1 - \xi \frac{E}{E_{QG}}) \quad (5)$$

Gamma rays travelling cosmological distances should therefore encounter a "vacuum" energy dispersion $\delta v \sim E/E_{QG}$, violating Lorentz invariance. A gamma ray signal of observed energy E_γ should acquire a time delay with respect to the Lorentz-invariant case, after having travelled a distance L (redshift z) [16]:

$$\Delta t \approx \xi \frac{E}{E_{QG}} \int_0^z (1+z) \frac{dl}{dz} dz \xrightarrow{z \ll 1} \xi \frac{E}{E_{QG}} \frac{L}{c} \quad (6)$$

Figure 9 sketches conceptually the relation between the foamy structure of geodesics in gravitational vacuum at small distances as predicted in Quantum Gravity scenarios and the existence of an energy dispersion relation of the speed of light in vacuum.

Gamma rays of different energies being emitted simultaneously should thus reach an observer at different times. In order to use equation 6 to test E_{QG} , a rapidly varying signal is required with typical time intervals δt smaller than the time delay Δt due to the quantum gravity effect and observed simultaneously at two different energies at least.

Gamma ray telescopes are specially well suited to measure this effect since they study photons of the the highest energies, they study sources at cosmological distances such as Blazars and Gamma Ray Bursts, and these sources provide natural time stamps since they are either flaring or transient. The light curves of these fast flares can be recorded and studied in detail thanks to the the huge effective areas of these telescopes.

Nevertheless, since possible energy-dependent time delays observed in a specific source could have an astrophysical origin and be produced either in the emission process or during the propagation of the photons thorough space for that specific region of the sky [17], a sinequanon condition to make a claim of observation of a Quantum Gravity effect should be the observation of delays in a sample of sources distributed across different regions in the sky and located within

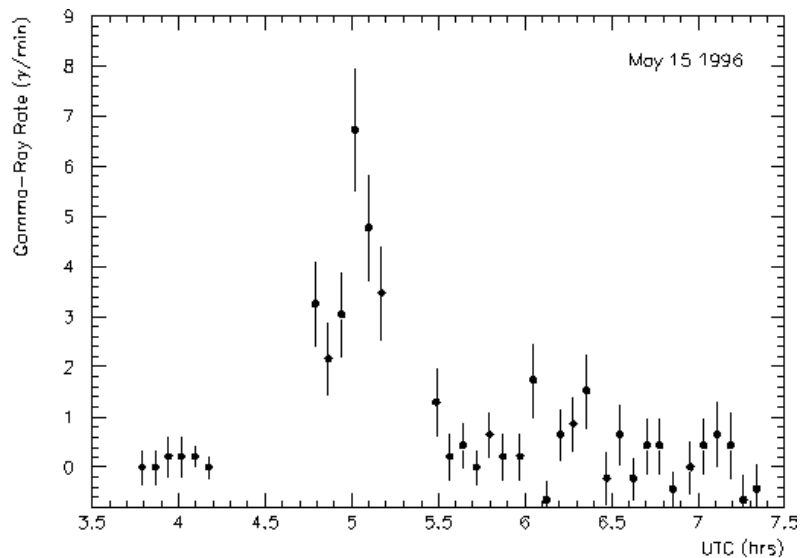


Figure 10. Light curve of the Mkn 421 flare in VHE Gamma Rays observed by WHIPPLE in 1999.

a broad range of distances, which should nevertheless adjust the simple mathematical relation casted in equation 6.

The use of this concept in VHE observations was pioneered by the WHIPPLE collaboration which in 1999, published [18] a first bound on E_{QG} , obtained with that technique using a flare of the blazar Mrk 421 ($z = 0.031$) which was very fast ($\delta t \approx 280s$ as can be seen in the lightcurve of figure 10) and was observed up to a gamma ray energy of 2 TeV. The analysis of that flare allowed the WHIPPLE collaboration to place a constraint of

$$E_{QG}/\xi > 4 \times 10^{16} \text{ GeV}$$

at 95% confidence level for the linear term, the best limit until the new generation of IACTs came on stage.

More recently, the MAGIC collaboration published the analysis of two huge flares from the blazar Mrk 501 ($z=0.034$) [19] (see figure 11). One of these flares was even faster and with a much larger amount of gamma rays recorded than the one observed by WHIPPLE, allowing a broader and more detailed energy spectrum and therefore, a much better determination of the arrival delay as a function of the gamma ray energy [12].

Actually, the detailed analysis of that flare performed with two new independent approaches which make full use of the gamma information without binning the data, showed an increasing arrival delay with energy [20], [21] which, if interpreted as due to linear quantum gravity effects, would correspond to an effective Quantum Gravity scale of

$$E_{QG}/\xi = 0.47(+0.31 - 0.13) \times 10^{18} \text{ GeV}$$

and, in the case of a vanishing linear term, would correspond to an effective Quantum Gravity scale in the quadratic term of

$$E_{QG}/\xi_2 = 0.61(+0.49 - 0.14) \times 10^{11} \text{ GeV}$$

Nevertheless since, as we've already mentioned, it cannot be discarded that that delay could have been produced at the source due to the dynamics of the particle acceleration mechanism,

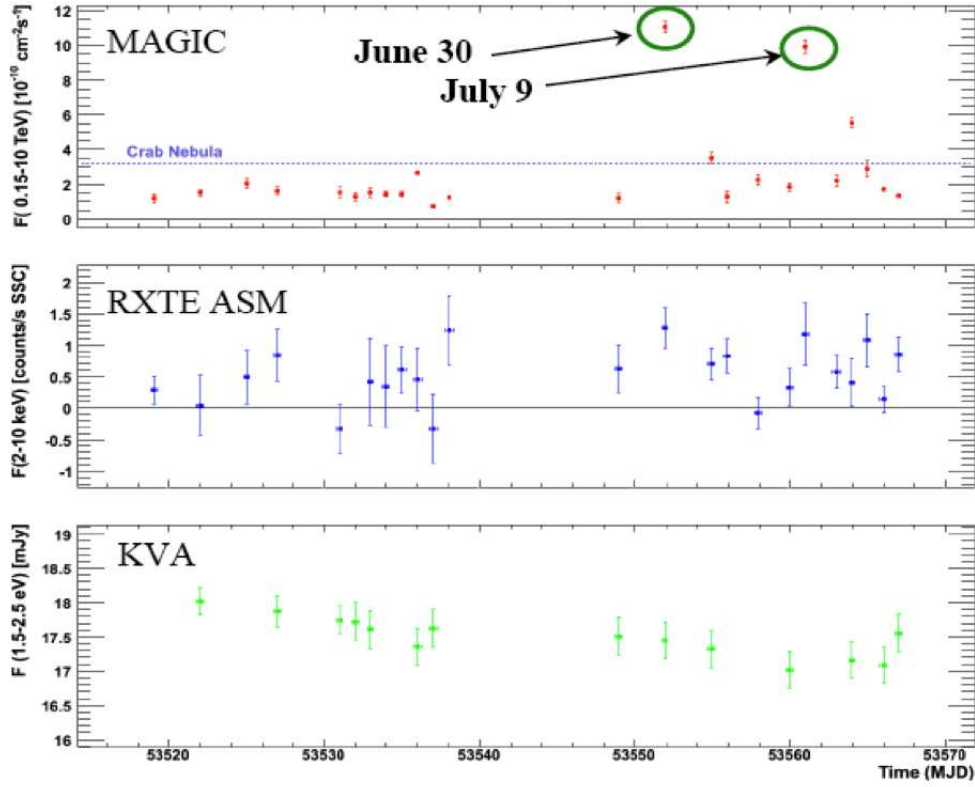


Figure 11. Large Mkn 501 flares recorded by MAGIC in 2005

one can use the data to place a limit in the effective Quantum Gravity scale of

$$E_{QG}/\xi > 0.26 \times 10^{18} \text{ GeV}$$

at 95% confidence level for the linear term and even, in case of a vanishing linear term,

$$E_{QG}/\xi_2 > 0.27 \times 10^{11} \text{ GeV}$$

at 95% confidence level for the quadratic term.

In order to disentangle propagation delays from source-intrinsic delays the simplest strategy is to observe sources at different redshifts and check that the delay is proportional to the distance. It turns out that the H.E.S.S. collaboration recorded in 2006 a huge flare of the PKS 2155 blazar ($z=0.116$) [22]. Since the source is different from the one observed by MAGIC and, moreover, its redshift is about three times larger, in principle the analysis of that flare could allow to disentangle the reason for the MAGIC observed delay. In fact, that flare was so intense that produced the largest flux ever recorded in the VHE gamma ray domain and, in addition, it showed a very complex structure with very fast-changing fluxes [13]. The analysis of that flare showed no significative energy-dependent delay and has allowed the H.E.S.S. collaboration to place a limit in the effective Quantum Gravity scale of

$$E_{QG}/\xi > 0.6 \times 10^{18} \text{ GeV}$$

at 95% confidence level for the linear term [23] which, although constitutes the best limit for the linear term, does not contradict yet with enough significance the interpretation for the delay observed by MAGIC as due to Quantum Gravity effects.

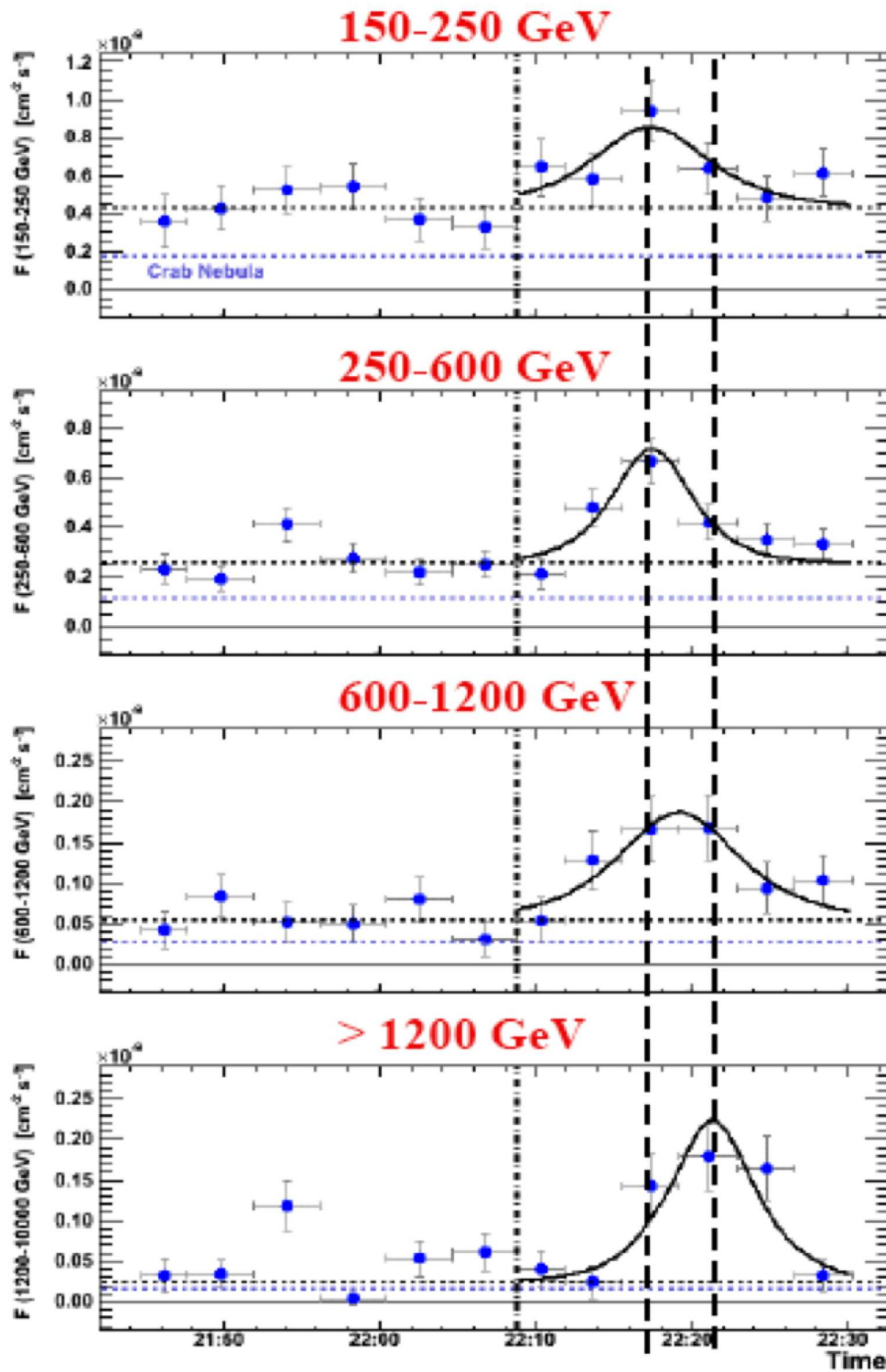


Figure 12. Light curve of the Mkn 501 flare recorded by MAGIC in July 2005 shown in four energy bands. An increasing arrival delay with energy can be seen by eye.

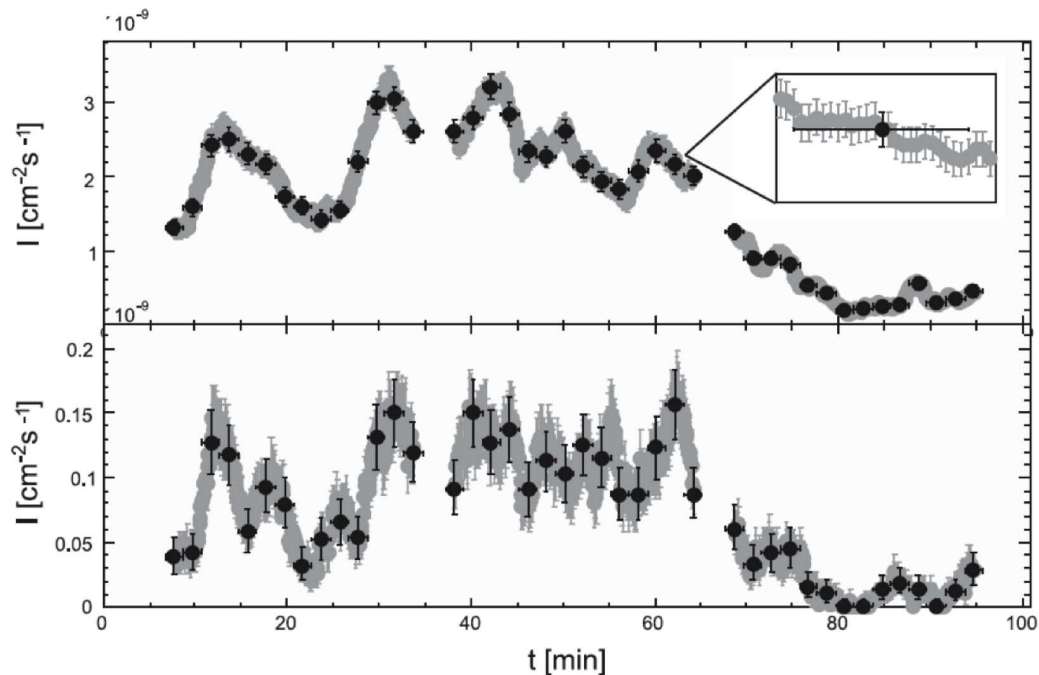


Figure 13. Light curve of the huge PKS2155 flare recorded by H.E.S.S. in 2006 shown in two energy bands: from 200-800 GeV in the upper plot and above 800 GeV in the lower one.

While this manuscript was being elaborated, the Fermi-GLAST collaboration published [24] the detection of GRB080916C, a Gamma Ray Burst at $z = 4.35 \pm 0.15$ and with an observed spectrum extending up to about 13 GeV, in which they observe an increasing arrival delay with energy qualitatively similar to the one measured by MAGIC. A very conservative preliminary analysis of the data allows already to place a limit in the effective Quantum Gravity scale of

$$E_{QG}/\xi > 1.55 \times 10^{18} \text{ GeV}$$

at 95% confidence level for the linear term and in case of a vanishing linear term,

$$E_{QG}/\xi_2 > 9.66 \times 10^9 \text{ GeV}$$

at 95% confidence level for the quadratic term. Given the huge distance to the source, the limit for the linear term is, so far, the most stringent one ever obtained and excludes beyond two standard deviations the interpretation of the delay observed by MAGIC as due to quantum gravity effects. On the other hand, given the limited maximum energy of the gamma rays detected, the limit for the quadratic term is almost one order of magnitude worse than the MAGIC one and therefore does not exclude the interpretation of the MAGIC delay being due to a second order quantum gravity effect.

At any rate, a detailed analysis of the data allowing a comparison between the intriguing delay observed in GRB080916C (and apparently also in other GBRs recorded by Fermi) and the one observed in Markarian 501 by MAGIC may shed some light on the actual origin of such delays.

5. Summary and outlook

The new generation of Cherenkov Telescopes has allowed a quantitative and qualitative step in VHE gamma ray astronomy which has open a new window in the use of these measurements for measurements with implications in Fundamental Physics and Cosmology.

First, detailed studies of the VHE gamma rays coming from the Milky Way Center region have shown no hint for signals of dark matter annihilation into gamma rays. The same is true for the observation of Dwarf Spheroidal Satellites and the search of gamma emission from IMBH candidates. Although these results do not place by themselves strong constraints on dark matter models or Supersymmetric dark matter theoretical candidates such as neutralinos, it shows that, given the fact that the Galactic Center and the Dwarf Spheroidal Satellites were the prime target candidates, the indirect detection of dark matter signatures through gamma rays might be a rather challenging enterprise.

Nevertheless, given the fact that even if neutralinos are found at accelerators it must be proven that they are the dark matter constituents and that IACTs are anyway the best tools for providing this connection, the search for gamma rays from regions of high dark matter concentration should keep been one of the prime scientific objectives of IACTs and may receive a clear help from gamma rays surveys as the one that will be provided by Fermi-GLAST.

Second, the analysis of the VHE gamma ray absorption by the Extragalactic Background Light by measuring the energy spectra of distant Blazars by H.E.S.S. and MAGIC seems to indicate an EBL density sensibly smaller than the one predicted by direct measurement and different theoretical modelizations and that has two implications:

- on the one hand, the universe is more transparent to gamma rays than expected and therefore the redshift reach of Cherenkov Telescopes should be substantially larger than anticipated allowing to observe much more distant extragalactic sources,
- on the other hand, the EBL density in the wavelength region relevant for the VHE gamma ray absorption might be actually resolved and hence the EBL density could be directly measured by surveys performing deep and detailed galaxy count.

Therefore, if the MAGIC and H.E.S.S. results are further confirmed, the study of the absorption in the energy spectrum of extragalactic VHE gamma rays at different redshifts may provide a competitive complementary technique for the determination of the parameters which govern the expansion of our universe and specifically, may help in constraining dark energy.

Finally, fast flares recorded by telescopes of the new generation, such as the ones studied by the MAGIC and H.E.S.S. collaborations have allowed to place strong constraints on the quantum structure of the gravitational vacuum reaching effective scales on the order of the Planck mass.

But this is not the end of the story. The spectacular astrophysics results from current Cherenkov instruments have generated considerable interest in both the astrophysics and particle physics communities and have spawned the urgent wish for a next-generation, more sensitive and more flexible facility, able to serve a large community of users.

The answer of the whole European VHE gamma ray community together to this wish is the “Cherenkov Telescope Array” (CTA) [25]. CTA will be an advanced facility for ground based very-high-energy gamma ray astronomy, based on the observation of Cherenkov radiation. It builds on the mastering of the Imaging Atmospheric Cherenkov Telescope technique developed by the H.E.S.S. and MAGIC installations. From the successes of H.E.S.S. it exploits the concept of telescope arrays and stereoscopic analysis for improving the current sensitivity by one order of magnitude. From the success of MAGIC it exploits the use of large telescopes to attain the lowest possible threshold. Both approaches have proven to be extremely successful for gamma rays of energies above few tens of GeV and have wide-open a new window in astronomy: the detailed study of the universe at the largest energies to study the most extreme astrophysical phenomena and fundamental physics.

The main wishes of the European VHE gamma ray community to be fulfilled by CTA are (see figure 14):

- A wide energy coverage: four decades, from some 10 GeV to beyond 100 TeV

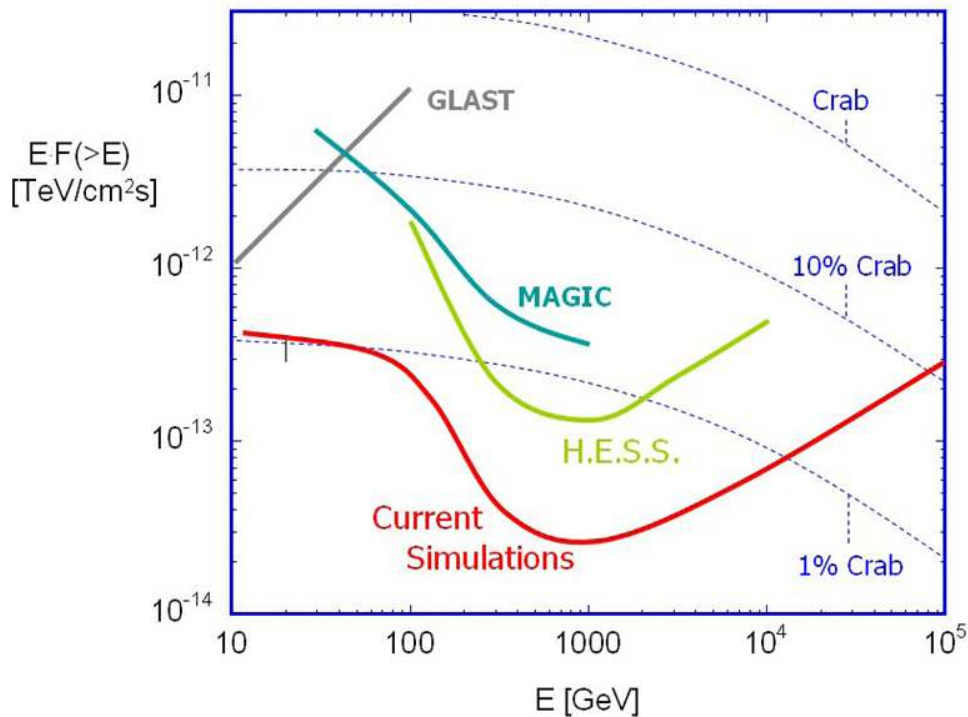


Figure 14. The goal sensitivity of the CTA installation.

- A sensitivity at least one order of magnitude better than any existing installation: better than 1 mCrab at the intermediate energies.
- Two observatories, operated under a common framework, for all-sky monitoring capability: a northern observatory with emphasis on extragalactic studies and a southern one mainly for galactic studies.

With these goals in mind, the CTA installation such have the following features:

- High sensitivity at TeV energies (above a factor 10) and therefore deeper observations and the discovery of many more sources.
- High detection area and therefore higher detection rates, which shall allow a much better study of transient phenomena.
- Improved angular resolution which shall enable better morphology analysis and therefore better study of the structure of extended sources.
- Low threshold (some 10 GeV) which shall be instrumental for the detailed study of Pulsars, distant AGN, source mechanisms and to provide a good overlap with the energy region covered by Fermi-GLAST.
- High energy reach (PeV and beyond) which shall allow the precise determination of the cut-off region of Galactic accelerators and an overlap with the survey at TeV energies performed by future surface detector arrays such as HAWC.
- Wide field of view which should allow the detailed study of extended sources and the realisation of high sensitivity and wide energy band surveys.

Reaching such features will require building observatories consisting in an array of several tens of Cherenkov Telescopes probably of two or three different sizes: few large telescopes in

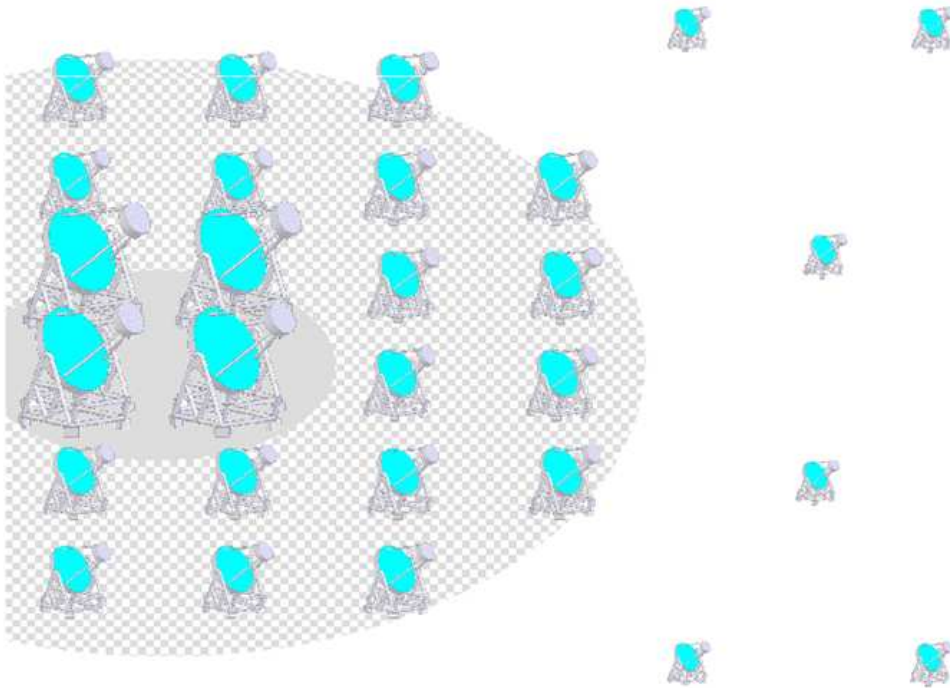


Figure 15. An sketch of the possible layout of one of the CTA sites (not to scale).

a compact configuration for the lowest threshold, few tens of mid-size telescopes for the high-sensitivity intermediate-energy region, several tens of small telescopes spread in a large area for the for the highest energies (see figure 15). Actually, the present results obtained from Monte Carlo simulations validated with H.E.S.S. and MAGIC data suggest that such a system will probably consist of about 50 to 100 telescopes with a total of about 100 000 to 200 000 electronics channels and $O(10\,000)$ m^2 total mirror area with a total cost estimate of $O(150)$ MegaEuros.

CTA may discover and study in detail the spatial structure, light curve and energy spectra of around thousand sources and, given the fast variability of many VHE gamma ray sources, shall be in operation while Fermi-GLAST is still active since both installations nicely complement each other. Operational overlap with the Fermi satellite mission will provide seamless coverage of 20 octaves of the spectrum.

The CTA (Cherenkov Telescope Array) consortium is meeting the challenge of designing an installation fulfilling the above goals in a Design Study that had its kick-off beginning of 2008 and which aims to result in 2010-2011 in the commissioning of a prototype telescope(s) that meet the requirements explained. Implementation of the array could start after first verifications with these prototypes.

Acknowledgments

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