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Searches for coincident High Energy Neutrinos and Gravitational Wave Bursts using the ANTARES and VIRGO/LIGO detectors

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Abstract: Cataclysmic cosmic events can be plausible sources of both gravitational waves (GW) and high energy neutrinos (HEN). Both GW and HEN are alternative cosmic messengers that may traverse very dense media and travel unaffected over cosmological distances, carrying information from the innermost regions of the astrophysical engines. Such messengers could also reveal new, hidden sources that have not been observed by conventional photon astronomy. The ANTARES Neutrino Telescope can determine accurately the time and direction of HEN events, and the VIRGO/LIGO network of GW interferometers can provide timing/directional information for GW bursts. Combining these informations obtained from totally independent detectors provide a novel way of constraining the processes at play in the sources, and also help confirming the astrophysical origin of a HEN/GW signal in case of concomitant observation.
This contribution describes the first joint GW+HEN search performed using concomitant data taken with the ANTARES, VIRGO and LIGO detectors in 2007, during the VIRGO VSR1 and LIGO S5 science runs, while ANTARES was operating in a 5-line configuration, approximately half of its final size. No coincident GW/HEN event was observed, which allowed for the first time to place upper limits on the density of joint GW+HEN emitters, which can be compared to the densities of mergers and core-collapse events in the local universe. More stringent limits will be soon available by performing a new and optimized search, described in this contribution, using the data of the full ANTARES telescope in 2009-2010, concomittant with the S6 LIGO science run and VSR2-3 VIRGO science runs, where all the involved interferometers took data with improved sensitivities.

Keywords: high energy neutrinos, gravitational wave bursts, multi-messenger astronomy

1 Introduction

A new generation of detectors offer unprecedented opportunities to observe the universe through all kind of cosmic radiations. In particular, both high-energy (TeV) neutrinos (HEN) and gravitational waves (GW), which have not yet been directly observed from astrophysical sources, are considered as promising tools for the development of a multi-messenger astronomy (see e.g. [1] for a recent review of HEN-related searches). Both HEN and GW can escape from the core of the sources and travel over large distances through magnetic fields and matter without being altered. They are therefore expected to provide important information about the processes taking place in the core of the production sites and they could even reveal the existence of sources opaque to hadrons and photons, that would have remained undetected so far. The detection of coincident signals in both these channels would then be a landmark event and sign the first observational evidence that GW and HEN originate from a common source. The most plausible astrophysical emitters of GW+HEN are presented in Section 2.

The concomitant operation of GW and HEN detectors is summarized in the time chart of Fig. 1. Section 3 briefly describes the detection principles and the performances achieved by the ANTARES neutrino telescope [2] as well as by the GW interferometers VIRGO [3] and LIGO [4], that are currently part of this joint search program. As both types of detectors have completely independant sources of backgrounds, the correlation between HEN and GW significances can also be exploited to enhance the sensitivity of the joint channel, even in the absence of detection. The combined false alarm rate is indeed severely reduced by the requirement of space-time consistency between both channels. In Sections 4 and 5, the strategies being developed for joint GW+HEN searches between ANTARES and the network of GW interferometers using the currently available datasets are presented. The results of the first GWHEN search have recently been published [5].

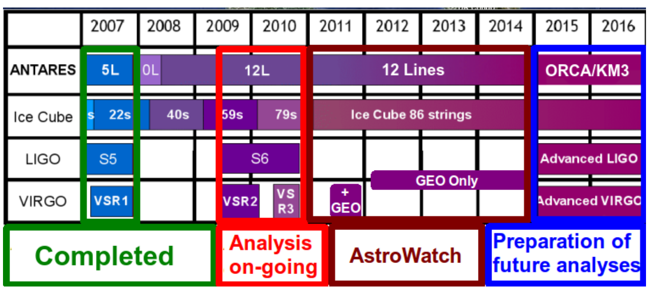

Figure 1: Time chart of the data-taking periods for the ANTARES, VIRGO and LIGO experiments, indicating the respective upgrades of the detectors (as described in the text). The deployment of the KM3NeT neutrino telescope is expected to last three to four years, during which the detector will be taking data with an increasing number of PMTs before reaching its final configuration [6].

2 Joint GW-HEN astrophysical emitters

Potential sources of GWs and HENs are likely to be very energetic and to exhibit bursting activity. The most promising class of known extragalactic bursting sources are surely Gamma-Ray Bursts (GRBs), most frequent and better modelled - for details on these sources and other possible emitters, refer to [5]. In the prompt and afterglow phases, HEN ($10^5 - 10^{10}$ GeV) are expected to be produced by accelerated protons in relativistic shocks and several models predict detectable fluxes in km^3-scale detectors [7, 8, 9], although no evidence for GRB neutrinos has been observed yet by IceCube 40 [10]. While gamma-ray and HEN emission from GRBs are related to the mechanisms driving the relativistic outflow, GW emissions are closely connected to the central engine and hence to the GRB progenitor. **Short-hard GRBs** are thought to originate from coalescing binaries involving black holes and/or neutron stars; such mergers could emit GW detectable from relatively large distances, with significant associated HEN fluxes [11, 12]. **Long-soft GRBs** are most probably induced by "collapsars", i.e. collapses of massive stars into black holes, with the formation of an accretion disk and a jet that emerges from the stellar envelope [13]. **Low-luminosity GRBs**, with γ-ray luminosities a few orders of magnitude smaller, are believed to originate from particularly energetic Type Ib/c core-collapse supernovae. They could produce stronger GW signals together with significant high- and low-energy neutrino emission; moreover they are more frequent than typical long GRBs and often discovered at shorter distances [14]. Finally, **choked GRBs** are thought to be associated with supernovae driven by mildly relativistic, baryon-rich and optically thick jets, so that no γ-rays escape [15]. Such "hidden sources" could be among the most promising emitters of GW and HEN, as current estimates predict a relatively high occurrence rate in the volume probed by current GW and HEN detectors [16].

3 Detectors and concomittant data taking

The ANTARES detector [2] is the first undersea neutrino telescope; its deployment at a depth of 2475m in the Mediterranean Sea near Toulon was completed in May 2008 [17]. It consists in a three-dimensional array of 885 photomultiplier tubes (PMTs) distributed on 12 lines anchored to the sea bed and connected to the shore through an electro-optical cable. Before reaching this final (12L) setup, ANTARES has been operating in various configurations with increasing number of lines, from one to five (5L) and ten (10L) lines.

ANTARES detects the Cherenkov radiation emitted by charged leptons (mainly muons, but also electrons and taus) induced by cosmic neutrino interactions with matter inside or near the instrumented volume. The knowledge of the timing and amplitude of the light pulses recorded by the PMTs allows to reconstruct the trajectory of the muon and to infer the arrival direction of the incident neutrino. The current reconstruction algorithms achieve an angular resolution (defined as the median angle between the neutrino and the reconstructed muon) of about 0.4° for neutrinos above 10 TeV [18]. The design of ANTARES is optimized for the detection of up-going muons produced by neutrinos which have traversed the Earth and interacted near the detector; its field of view is $\sim 2\pi$ sr for neutrino energies between 100 GeV and 100 TeV. Above this energy, the sky coverage is reduced because of neutrino absorption in the Earth; but it can be partially recovered by looking for horizontal and downward-going neutrinos, which can be more easily identified at these high energies where the background of atmospheric muons and neutrinos is fainter. ANTARES, especially suited for the search of astrophysical point sources, and transients in particular [19], is intended as the first step towards a km^3-sized neutrino telescope in the Mediterranean Sea [6].

The GW detectors VIRGO [3], with one site in Italy, and LIGO (see e.g. [4]), with two sites in the United States, are Michelson-type laser interferometers. They consist of two light storage arms enclosed in vacuum tubes oriented at 90° from each other, able to detect the differential strain in space produced by the GW. Suspended, highly reflective mirrors play the role of test masses. Current detectors are sensitive to relative displacements of the order of 10^{-20} to 10^{-22} Hz$^{-1/2}$. Their detection horizon is about 15 Mpc for standard binary sources.

The first concomitant data-taking phase with the whole VIRGO/LIGO network VSR1/S5 was carried out in 2007, while ANTARES was operating in 5L configuration (see Fig. 1). A second data-taking phase was conducted between mid-2009 and end 2010 with upgraded detectors, S6/VSR2 and VSR3, in coincidence with the operation of ANTARES 12L (see section 5). Another major upgrade for both classes of detectors is scheduled for the upcoming decade: the Advanced VIRGO/Advanced LIGO and KM3NeT projects should gain a factor of 10 in sensitivities with respect to the presently operating instruments. The VIRGO/LIGO network monitors a good fraction of the sky in common with ANTARES: the instantaneous overlap of visibility maps is about 4 sr, or $\sim 30\%$ of the sky [20].

4 First joint GW+HEN search

GW interferometers and HEN telescopes share the challenge to look for faint and rare signals on top of abundant noise or background events. Preliminary studies on the feasibility of such searches [20, 21] indicated that, even if the constituent observatories provide several triggers a day, the false alarm rate for the combined detector network can be kept at a very low level (e.g. $\sim$1/600 yr^{-1} in [21]).

4.1 Coincidence Time Window

An important ingredient of these searches is the definition of an appropriate coincidence time window between HEN and GW signals hypothetically arriving from the same astrophysical source. A case study that considered the duration of different emission processes in long GRBs, based on BATSE, Swift and Fermi observations, allowed to derive a conservative upper bound $t_{GW} - t_{HEN} \in [-500s, +500s]$ on this time window [22]. For short GRBs, this time-delay could be as small as a few seconds. For other sources, this delay is poorly constrained.

4.2 Analysis Strategy

The strategy chosen for the 2007 search consists in an event-per-event search for a GW signal correlating in space and time with a given HEN event considered as an external trigger. Such a search is rather straightforward to implement as it allows to make use of existing analysis pipelines developed e.g. for GRB searches. It has been applied to the concomitant set of data taken between January 27 and September 30, 2007 with ANTARES 5L-VSR1/S5. Such a triggered GW search has been proven to be more efficient than a classical all-sky analysis, because of the knowledge of the direction and time of arrival of the signal. More details on this analysis can be found in [5].

The ANTARES 5L data were filtered according to quality requirements similar to those selecting the well-reconstructed events that are used for the standalone searches for HEN point sources. The list of candidate HEN includes their arrival time, direction on the sky, and an event-by-event estimation of the angular accuracy, which serves to define the angular search window for the GW search. For the purpose of this joint search, the angular accuracy is defined as the 90% quantile (and not the median) of the distribution of the error on the reconstructed neutrino direction, obtained from Monte Carlo studies. The on-source time window defined in Section 4.1.

The list of HEN triggers is then transmitted to the X-pipeline, an algorithm which performs coherent searches for unmodelled bursts of GWs on the combined stream of data coming from all active interferometers (ITFs). The background estimation and the optimization of the selection strategy are performed using time-shifted data from the off-source region in order to avoid contamination by a potential GW signal. Once the search parameters are tuned, the analysis is applied to the on-source data set. If a coincident event is found, its significance is obtained by comparing to the distribution of accidental events obtained with Monte-Carlo simulations using time-shifted data streams from the off-source region ; this is particularly efficient to look for strong signals but one can also look for an accumulation of weakest signals, by performing a dedicated statistical test, as will be shown later.

4.3 HEN events and error box for GW search

The HEN candidates have been selected using the BBFit reconstruction [5]. A total of 414 events, among which 198 reconstructed with 2 lines, with 2 azimuthal possible solutions, and 18 more energetic events reconstructed with more than 2 lines (with a unique solution), were selected. Finally, when taking into account the fact that 2 or more ITFs are needed in order to reconstruct a possible GW arrival direction on the sky, 144 2-line events and 14 3-line events were analyzed for a possible GW counterpart.

The angular accuracy with which the HEN arrival direction is reconstruted depends on the energy of the event and its direction. The space-angle error distribution between the true neutrino direction and the reconstructed muon direction has been parametrized using a log-normal law in intervals of declination and energy. The parameters of the function has been used in the GW analysis to estimate the consistency of a reconstructed signal with the HEN arrival direction. This is the 90% quantile of this distribution which is used as a angular window for the GW search, seen in Figure 2.

4.4 Results of the GW search

A low-frequency search, with a cut-off frequency at 500 Hz, was performed for all the HEN events. An additional high-frequency search up to 2kHz, more time-consuming, was performed for the 3 line events, more energetic and more likely to be of astrophysical origin.

No GW candidate was observed. This allowed to extract GW exclusion distances for typical signal scenarios. For binary merger signals, expected in the case of short GRBs, the null observation means that no merger of this type

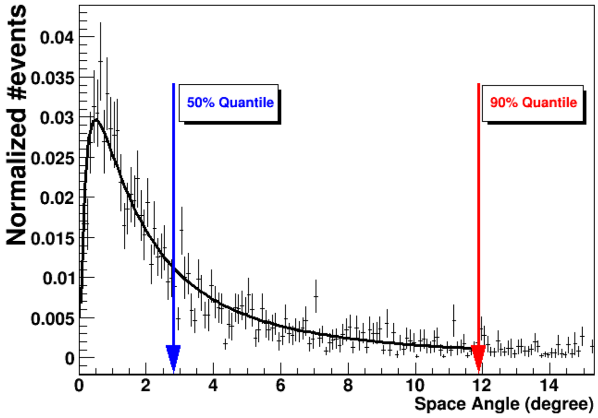

Figure 2: Space angle error between the true neutrino direction and the reconstructed muon direction, together with the log-normal parametrization.

has occured within ~ 10 Mpc. The exclusion distances obtained are similar for collapse-like signals, which are to be expected in the case of long GRBs for instance.

A binomial test has been performed to look for an accumulation of weak GW signals. Its results are negative for both the low and high frequency searches - the post-trial significance of the largest deviation from the null hypothesis is 66%.

4.5 Astrophysical interpretation of the search

The non-observation of a GW+HEN coincidence during the ~ 100 days of concomittant data taking allows to set that the actual number of coincidences verified $N_{\rm GWHEN} = \rho_{\rm GWHEN} V_{\rm GWHEN} T_{\rm obs} \leq 2.3$ at the 90% confidence level. Here $\rho_{\rm GWHEN}$ is the density of objects aimed at with the present analysis, typically the collapse or coalescence of compacts stars, GW emitters, followed by a jet, in which HEN are produced, in the local universe. This is a novel way to test the non-constrained gravitational origin of astrophysical jets formation.

$V_{\rm GWHEN}$ is the effective volume of universe probed by the search, which depends on the horizon of the involved experiments for typical signals. The GW horizon has been estimated to be ~ 10 Mpc for mergers, and ~ 20 Mpc for collapses. The HEN horizons are weaker for the ANTARES 5 line detector, of the order of 5 Mpc for mergers (computed using typical short GRB models), and 10 Mpc for long GRBs. The variation of the detection efficiencies of both experiments with distance have to be taken into account to have a realistic estimate of the effective volume.

Converting the null observation into a density yields a limit ranging from 10^{-2} Mpc^{-3}.yr^{-1} for short GRB-like signals down to 10^{-3} Mpc^{-3}.yr^{-1} for long GRB-like emissions. The comparisons with existing estimates of occurence rates for short/long GRBs or other objects of interest is made in Figure 3.

5 Joint Analysis using 2009-2010 data

Data taken with the 9-12 lines ANTARES detector in 2009-2010, concomitant with the VIRGO VSR2 and LIGO S6 joint runs, with GW upgraded detectors, yield 129 days of joint operations to be analyzed. A new HEN reconstruc-

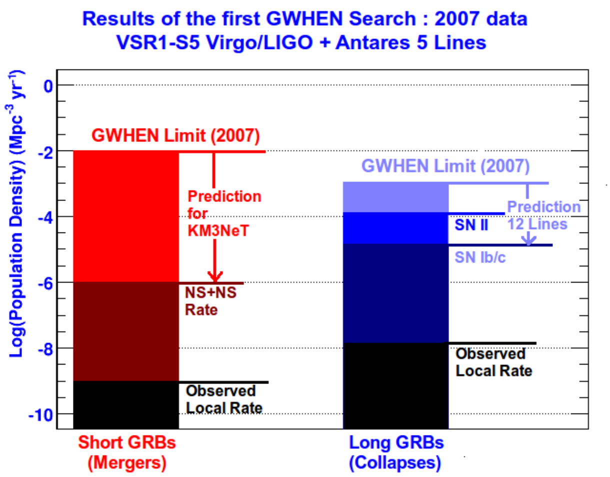

Figure 3: GWHEN 2007 astrophysical limits are compared with local short/long GRB rates, merger rates, and SN II and SN Ib/c rates. Also shown are the potential reach of ongoing or future analyses.

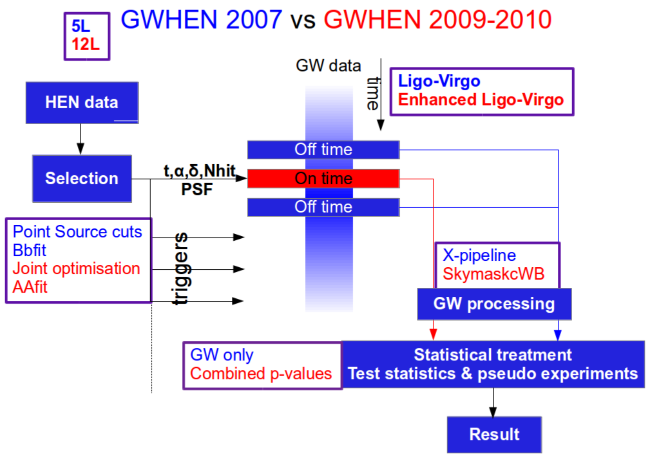

Figure 4: Strategy of the 2009-2010 ANTARES-VIRGO/LIGO joint search compared to the 2007 analysis. A new HEN reconstruction method has been used, with improved angular resolution, and a new GW software, suited for joint simulations, has been developed for the search.

tion algorithm has been used to reduce the HEN angular error [18]. A different GW software [23] has also been developed specifically for this search to perform joint simulations - a necessary step to optmize the joint analysis. The need for such an optimization can be understood with the following arguments, already discussed in [20] : the false-coincidence rate of the GW+HEN search indeed depends on the individual false-alarm rates $f_{\rm HEN}$ and $f_{\rm GW}$. For instance, if $f_{\rm HEN}$ is high, because of loose selection cuts to obtain a high HEN detection efficiency, $f_{\rm GW}$ has to be reduced to conserve the same significance in case of a detection, reducing the joint GWHEN detection figure of merit defined as :

$$\eta_{\rm GWHEN} = \frac{\varepsilon_{\rm HEN}}{\rho_{\rm GW}} \tag{1}$$

Here $\varepsilon_{\rm HEN}$ represents the HEN efficiency, which depends on the selection cuts, and $\rho_{\rm GW}$ stands for the threshold signal-to-noise ratio in the GW detection process. Reciprocally, if the HEN selection criteria are too tight, resulting in a low number of selected HEN events, the HEN detection horizon is dramatically reduced, resulting in a smaller $\eta_{\rm GWHEN}$, even if the GW search is more powerful because of the lower allowed thresholds. Of course, this optimization depends on the, e.g., HEN spectrum index, and the GW assumed signals. This optimization has been performed to find the optimal HEN selection cuts. Figure 4 shows a summary of the differences between this new ANTARES-VIRGO/LIGO search with respect to the one presented in Section 4.

According to preliminary estimates, the enhanced sensitivity of the GW interferometers, combined with the increased joint live time and the improvement of a factor 3 in the ANTARES effective area above 100 TeV should result in an increase by a factor 5 of the volume of universe probed by the joint search : this ongoing search could be able to constrain for the first time the fraction of star collapses followed by the ejection of a hadronic jet.

6 Conclusions

These pioneering GW+HEN searches, developed in [5] and [24], opens the way towards a new multi-messenger astronomy. Beyond the benefit of a potential high-confidence discovery, future analyses, particularly the one involving a km^3 HEN telescope [6] and advanced interferometers [25], could be able to constrain the density of joint sources down to astrophysically-meaningful levels - hence contrain for the first time the fraction of binary mergers followed by the emission of a relativistic jet.

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