SF2A 2012
S. Boissier, P. de Laverny, N. Nardetto, R. Samadi, D. Valls-Gabaud and H. Wozniak (eds)

GRAVITATIONAL WAVE AND HIGH ENERGY NEUTRINO COINCIDENCES : RESULTS OF THE FIRST ANTARES - VIRGO/LIGO COINCIDENT SEARCH

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Abstract. Sources of gravitational waves (GW) and emitters of high energy neutrinos (HEN) both involve compact objects and matter moving at relativistic speeds. GW emission requires a departure from spherical symmetry, which is the case if clumps of matter are accreted around black holes or neutron stars, and ejected in relativistic jets, where neutrinos are believed to be produced. Both messengers interact weakly with the surrounding matter, hence point directly to the heart of the engines that power these emissions. Coincidences between GW and HEN detectors would then give a unique insight on the physics of the most powerful objects in the Universe.

This contribution describes the results of the first joint GW+HEN search using concomitant data taken with the ANTARES, VIRGO and LIGO detectors in 2007, when ANTARES was operating with 5 of its 12 lines, and VIRGO/LIGO joint runs VSR1/S5 were underway. This search allowed to put the first constraints on the density of possible GW+HEN astrophysical sources.

Keywords: Neutrinos, Gravitational waves, 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 ($\gg$GeV) 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. Becker 2008; Márka 2011; Pradier 2010, for recent reviews). 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 (Aguilar et al. 2011) as well as by the GW interferometers VIRGO (Acernese et al. 2008) and LIGO (Sigg et al. 2008), 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 absence of detection. The combined false alarm rate is indeed severely reduced by the requirement of space-time consistency between both channels. In Section 4, 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 will be published soon (Adrián-Martinez et al. 2012).

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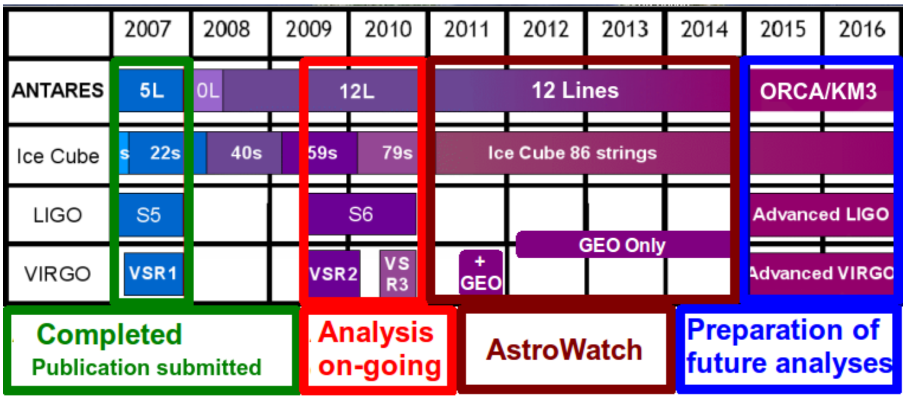

Fig. 1. Time chart of the data-taking periods for the ANTARES, VIRGO and LIGO experiments, indicating the respective upgrades of the detectors (as described in the text). The deployment of the KM3NeT neutrino telescope is expected to last three to four years, during which the detector will be taking data with an increasing number of PMTs before reaching its final configuration (Hernandez-Rey 2009).

2 Astrophysical emitters of gravitational waves and high-energy neutrinos

Potential sources of GWs and HENs are likely to be very energetic and to exhibit bursting activity. For more details, refer to Ando et al. (2012). **Soft Gamma Repeaters (SGRs)** are highly magnetized galactic X-ray pulsars with a soft γ-ray bursting activity. In the popular magnetar model (Thompson & Duncan 1995), the outbursts are caused by star-quakes associated to large-scale rearrangements of the magnetic field. The deformation of the star during the outburst could lead to the emission of GW within range of current interferometric GW detectors (Abadie et al. 2011). Sudden changes in the large magnetic fields would also accelerate protons or nuclei interacting with thermal radiation and generating a flux of HENs (Ioka et al. 2005).

But the most promising class of known extragalactic bursting sources are surely Gamma-Ray Bursts (GRBs), most frequent and better modelled. 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 (Waxman & Bahcall 1997; Rachen & Meszaros 1998; Alvarez-Muniz 2000), although no evidence for GRB neutrinos has been observed yet by IceCube in its 40- (Abbasi et al. 2011) or 59-strings configuration. 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 (Kochanek & Piran 1993; Nakar 2007). **Long-soft GRBs** are most probably induced by "collapsars", i.e. collapses of a massive star into a black hole, with the formation of an accretion disk and a jet that emerges from the stellar envelope (Woosler & Bloom 2008). **Low-luminosity GRBs**, with γ-ray luminosities a few orders of magnitude smaller, are believed to originate from a particularly energetic type Ibc 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 (Razzaque et al. 2004). 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 (Meszaros & Waxman 2001). 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 (Ando & Beacom 2005).

3 Detectors and concomittant data taking

The Antares detector (Aguilar et al. 2011) is the first undersea neutrino telescope; its deployment at a depth of 2475m in the Mediterranean Sea near Toulon was completed in May 2008. It consists in a three-dimensional array of 884 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).

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 (Adrián-Martinez et al. 2011). 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 $\sim 2\pi\,\mathrm{sr}$ for neutrino energies 100 GeV $\lesssim E_\nu \lesssim$ 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 (Ageron et al. 2012), is intended as the first step towards a km^3-sized neutrino telescope in the Mediterranean Sea (Hernandez-Rey 2009).

The GW detectors VIRGO (Acernese et al. 2008), with one site in Italy, and LIGO (see e.g. (Sigg et al. 2008)), 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. Suspended, highly reflective mirrors play the role of test masses. Current detectors are sensitive to relative displacements (hence GW amplitude) 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 on 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. 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 ($\sim$ 30% of the sky) (Pradier 2009).

4 First joint GW+HEN search using ANTARES data in 2007

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 (Aso et al. 2008; Pradier 2009) 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 ($\sim$1/(600 yr)).

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 (Baret et al. 2011). 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.

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 (see Adrián-Martinez et al. 2012, for more details). 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 error distribution on the reconstructed neutrino direction, obtained from Monte Carlo studies. The on-source time window is taken to be $[-500s, +500s]$ around the neutrino arrival time.

The list of HEN triggers is then transmitted to the X-pipeline (Sutton et al. 2010), 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 with 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 candidates and error box for the GW search

The HEN candidates have been selected using the BBFit reconstruction (Adrián-Martinez et al. 2012). 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, 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, see Figure 2.

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, see Figure 2.

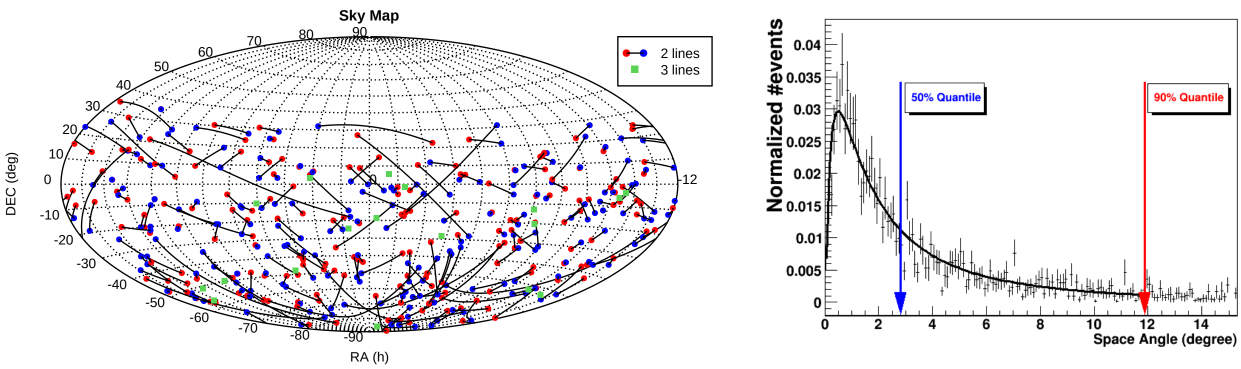

Fig. 2. Left: Skymap in equatorial coordinates of the 2-line and 3-line HEN events, selected in 2007 ANTARES data for the search. **Right:** Space angle error between the true neutrino direction and the reconstructed muon direction, together with the log-normal parametrization.

4.4 The GW search and its results

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 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, as can be seen in Figure 3 (for the low-frequency search only). 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%.

5 Astrophysical interpretation of the search

The non-observation of a GW+HEN coincidence during the $\sim$ 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 $\sim$ 10 Mpc for mergers, and $\sim$ 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.

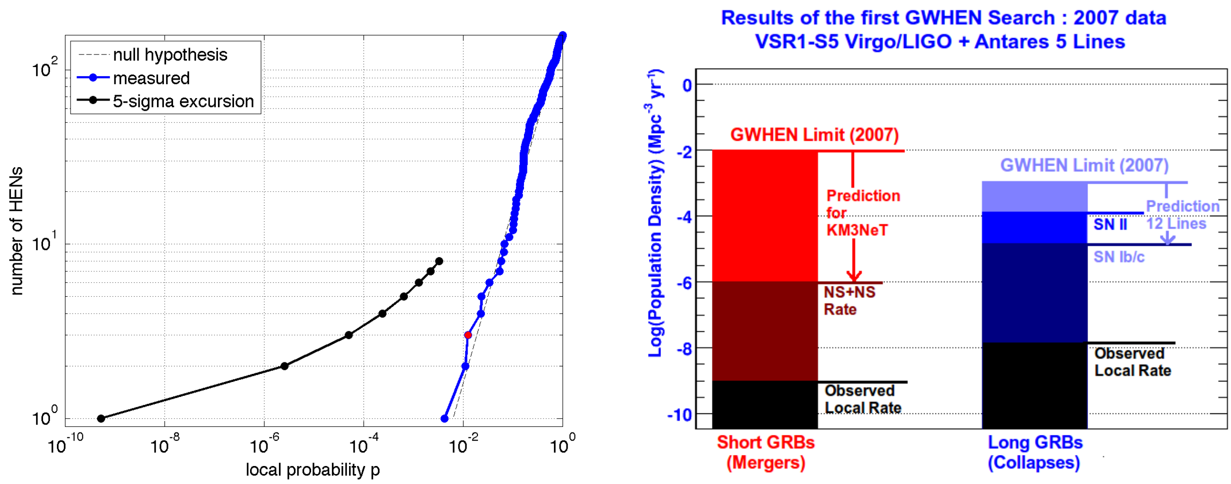

Fig. 3. Left: Binomial test which shows the probability to get $N_{\rm HEN}$ GW signals with a p-value higher than p. The black dots shows the number of GW+HEN associations needed to reach a 5σ significance. **Right:** GWHEN 2007 astrophysical limits are compared with local short/long GRB rates, merger rates (for short GRB-like sources), and SN II and SN Ib/c rates (for long GRB-like models). Also shown are the potential reach of future analyses.

6 Future analyses and conclusions

The analysis of the data taken with the full 12 lines of the ANTARES detector in 2009-2010, concomittant with the VIRGO VSR2 and LIGO S6 joint run, with GW upgraded detectors, has now started. A new HEN reconstruction algorithm has been used in order to reduce the HEN angular error. Moreover, a new GW software has been used which allows to perform joint simulations in order to optmize the joint analysis. The false-coincidence rate of the GW+HEN search depends on the individual false-alarm rates $f_{\rm HEN}$, $f_{\rm GW}$: for instance, if $f_{\rm HEN}$ is high, because of loose selection cuts, $f_{\rm GW}$ has to be reduced to conserve the same significance in case of a detection. Of course, this optimization strongly depends on the, e.g., HEN spectrum index, and the GW assumed signals. This optimization is currently underway to find the optimal HEN selection cuts. This search could be able to constrain for the first time of fraction of star collapses followed by the ejection of a hadronic jet (see Figure 3).

This first pioneering GW+HEN search, developed in Adrián-Martinez et al. (2012), 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 (Hernandez-Rey 2009) and advanced interferometers (Harry et al. 2010), 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, as shown in Figure 3.

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The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory, the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector, and the Italian Istituto Nazionale di Fisica Nucleare and the French Centre National de la Recherche Scientique for the construction and operation of the Virgo detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the International Science Linkages program of the Commonwealth of Australia, the Council of Scientic and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Educacion y Ciencia, the Conselleria d'Economia Hisenda i Innovacion of the Govern de les Illes Baleares, the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientic Research, the Polish Ministry of Science and Higher Education, the FOCUS Programme of Foundation for Polish Science, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, The National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation. The authors also acknowledge the financial support of the funding agencies for the construction and operation of the ANTARES neutrino telescope: Centre National de la Recherche Scientique (CNRS), Commissariat à l'Énergie atomique et aux énergies alternatives (CEA), Agence National de la Recherche (ANR), Commission Européenne (FEDER fund and Marie Curie Program), Région Alsace (contrat CPER), Région Provence-Alpes-Côte d'Azur, Département du Var and Ville de La Seyne-sur-Mer, France; Bundesministerium fur Bildung und Forschung (BMBF), Germany; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Stichting voor Fundamenteel Onderzoek der Materie (FOM), Nederlandse organisatie voor Wetenschappelijk Onderzoek (NWO), the Netherlands; Council of the President of the Russian Federation for young scientists and leading scientic schools supporting grants, Russia; National Authority for Scientic Research (ANCS), Romania; Ministerio de Ciencia e Innovacion (MICINN), Prometeo of Generalitat Valenciana (GVA) and Multi-Dark, Spain. They also acknowledge the technical support of Ifremer, AIM and Foselev Marine for the sea operation and the CC-IN2P3 for the computing facilities.

This work has received support from the **Groupement de Recherche Phénomènes Cosmiques de Haute Energie**.