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JOINT SEARCHES FOR GRAVITATIONAL WAVES AND HIGH-ENERGY NEUTRINOS WITH THE ANTARES, LIGO AND VIRGO 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 escape very dense media and travel unaffected over cosmological distances. For this reason, they could also reveal new or hidden sources that were not observed by conventional photon astronomy, such as the putative failed GRBs.

After a brief discussion on the plausible common sources of GW and HEN, this constribution presents the strategies for coincident searches of GW and HEN that are currently developed by the ANTARES and VIRGO/LIGO collaborations within the GWHEN working group.

Keywords: multi-messenger astronomy, high-energy neutrinos, gravitational waves

1 Introduction

Astroparticle physics has entered an exciting period with the recent development of experimental techniques that have opened new windows of observation of the cosmic radiation in all its components. In this context, and despite their elusive nature, both high-energy neutrinos (HENs) and gravitational waves (GWs) are now considered as candidate cosmic messengers. Contrarily to high-energy photons (which are absorbed through interactions in the source and with the extragalactic background light) and cosmic rays (which are deflected by ambient magnetic fields, except at the highest energies), both HENs and GWs may indeed escape from dense astrophysical regions and travel over large distances without being absorbed, pointing back to their emitter.

It is expected that many astrophysical sources produce both GWs, originating from the cataclysmic event responsible for the onset of the source, and HENs, as a byproduct of the interactions of accelerated protons (and heavier nuclei) with ambient matter and radiation in the source. Moreover, some classes of astrophysical objects might be completely opaque to hadrons and photons, and observable only through their GW and/or HEN emissions. 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. GW and HEN astronomies will then provide important information on the processes at work in the astrophysical accelerators. The most plausible GW/HEN sources are presented in Section 2, along with relevant references[*].

Common HEN and GW astronomies are also motivated by the advent of a new generation of dedicated experiments. This contribution concentrates on the feasibility of joint GW+HEN searches between the ANTARES neutrino telescope (and its future, km^3-sized, successor KM3NeT) and the GW detectors VIRGO and LIGO (which now form one single experimental collaboration). The detection principle and performances of the instruments are presented in Section 3, while Section 4 proposes some hints at the analysis strategies that will be set up to optimize coincident GW+HEN detection among the three experiments.

The joint search activities described here are performed in the framework of a dedicated GWHEN working group which gathers collaborators from ANTARES, VIRGO and LIGO, with a data-exchange policy regulated by a specific Memorandum of Understanding (signed February, 2010).

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[*] More information can also be obtained on the website of the first Workshop on Gravitational Waves and High-Energy Neutrinos, held in May 2009 in Paris: `http://www.gwhen-2009.org` .

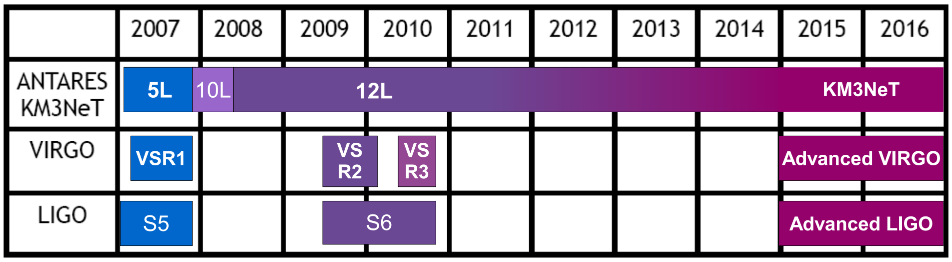

Fig. 1. Time chart of the data-taking periods for the ANTARES, VIRGO and LIGO experiments, indicating the respective upgrades of the detectors (as described in the text). The deployment of the KM3NeT neutrino telescope is expected to last three to four years, during which the detector will be taking data with an increasing number of PMTs before reaching its final configuration (see the KM3NeT TDR 2010).

2 Potential common sources of GW and HEN

Potential sources of GWs and HENs are likely to be very energetic and to exhibit bursting activity. Plausible GW+HEN emission mechanisms include two classes of galactic sources which could be accessible to the present generation of GW interferometers and HEN telescopes. **Microquasars** are believed to be X-ray binaries involving a compact object that accretes matter from a companion star and re-emits it in relativistic jets associated with intense radio (and IR) flares. Such objects could emit GWs during both accretion and ejection phases; and the latter phase could be correlated with a HEN emission provided the jet has a hadronic component (Migliari et al. 2002; Distefano et al. 2002; Pradier 2008). **Soft Gamma Repeaters (SGRs)** are X-ray pulsars with a soft γ-ray bursting activity which, according to the magnetar model (Thompson and Duncan 1995), can be associated with star-quakes. The deformation of the star during the outburst could produce GWs, while HENs could again emerge from hadron-loaded flares (Ioka 2001; Ioka et al. 2005).

Gamma-Ray Bursts (GRBs) are a promising class of extragalactic sources. In the prompt and afterglow phases, HENs ($10^5 - 10^{10}$ GeV) are expected to be produced by accelerated protons in relativistic shocks and several models predict detectable fluxes in km^3-scale detectors (Waxman and Bahcall 1997; Alvarez-Muniz et al. 2000; Rachen and Mészáros 2008). **Short-hard GRBs** are thought to originate from coalescing binaries involving black holes and/or neutron stars; such mergers could emit GWs detectable from relatively large distances, with significant associated HEN fluxes (Nakar 2007). As for the **long-soft GRBs**, the collapsar model is compatible with the emission of a strong burst of GWs during the gravitational collapse of the (rapidly rotating) progenitor star and in the pre-GRB phase; however this population is distributed over cosmological distances so that the associated HEN signal is expected to be faint (Kotake 2006; Ott 2009; Vietri 2008). The subclass of **low-luminosity GRBs**, with γ-ray luminosities a few orders of magnitude smaller, are believed to originate from a particularly energetic, possibly rapidly-rotating and jet-driven population of core-collapse supernovae. They could produce stronger GW signals together with significant high- and low-energy neutrino emission; moreover they are often discovered at shorter distances (Gupta and Zhang 2007). Finally, the **failed GRBs** are thought to be associated with supernovae driven by mildly relativistic, baryon-rich and optically thick jets, so that no γ-rays escape. Such "hidden sources" could be among the most promising emitters of GWs and HENs, as current estimations predict a relatively high occurrence rate in the volume probed by current GW and HEN detectors (Ando and Beacom 2005).

3 The detectors

The **ANTARES** detector (see e.g. Coyle et al. 2010) 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); the respective periods are indicated on the time chart of Fig. 1.

ANTARES detects the Cherenkov radiation emitted by charged leptons (mainly muons, but also electrons

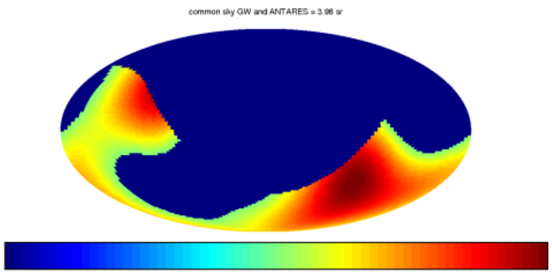

Fig. 2. Instantaneous common sky coverage for VIRGO + LIGO + ANTARES in geocentric coordinates. This map shows the combined antenna pattern for the gravitational wave detector network (above half-maximum), with the simplifying assumption that ANTARES has 100% visibility in its antipodal hemisphere and 0% elsewhere. The colour scale is from 0% (left, blue) to 100% (right, red).

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, as well as to estimate its energy. ANTARES is expected to achieve an unprecedented angular resolution (about 0.3° for neutrinos above 10 TeV) as a result of the good optical properties of sea water (Aguilar et al. 2005).

The data acquisition system of ANTARES is based on the “all-data-to-shore” concept, which allows to operate different physics triggers to the same data in parallel. Satellites looking for GRBs can also trigger the detector in real time via the GCN (Gamma-Ray Burst Coordinate Network) alert system. About 60s of buffered raw data are then written on disk and kept for offline analysis (Bouwhuis et al. 2009). Since last year, ANTARES has also implemented the possibility to trigger an optical telescope network on the basis of “golden” neutrino events selected by a fast, online reconstruction procedure. This program is described by D. Dornic (for the ANTARES Coll.) elsewhere in these Proceedings. The possibility to extend it to other instruments in different wavelength domains (such as the gamma-ray telescope FERMI) is also under study. All these characteristics make the ANTARES detector especially suited for the search of astrophysical point sources, and transients in particular. ANTARES is intended as the first step towards a km^3-sized neutrino telescope in the Mediterranean Sea, currently under R&D in the framework of the KM3NeT Consortium (see the KM3NeT TDR 2010).

The GW detectors **VIRGO** (see e.g. Acernese et al. 2008), with one site in Italy, and **LIGO** (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} $\mathrm{Hz}^{-1/2}$. Their current detection horizon is about 15 Mpc for standard binary sources.

Early in 2007, both experiments joined their efforts and agreed on full data exchange starting from the concomitant data-taking phase during 2007 (VSR1/S5), which partially coincided with the ANTARES 5L configuration. A second data-taking phase has started mid-2009 with upgraded detectors VIRGO+ and eLIGO, corresponding to a gain of a factor 2 (at least) in sensitivity (Accadia et al. 2010), and in coincidence with the operation of ANTARES 12L. The current LIGO and Virgo science runs (L6/VSR3) will stop by the end of 2010 to open the way to the development of the next generation of detectors: Advanced VIRGO and Advanced LIGO, to be operational by 2015 with an expected sensitivity $\sim$10 times better than the current instruments (Harry et al. 2010). As can be seen from Figure 2, the VIRGO/LIGO network monitors a good fraction of the sky in common with ANTARES: the instantaneous overlap of visibility maps is about 4 sr ($\sim$ 30% of the sky).

4 Outlook on the analysis strategies

GW interferometers and HEN telescopes share the challenge to look for faint and rare signals on top of abundant noise or background events. The GW+HEN search methodology involves the combination of GW/HEN candidate event lists, with the advantage of significantly lowering the rate of accidental coincidences.

Two strategies are currently under study. The first one consists in an event-per-event search for a GW signal correlating in space and time with a given neutrino event considered as an external trigger; it makes use of existing analysis pipelines developed e.g. for GRB searches. Alternatively, comprehensive searches for time-coincidences between independent lists of neutrino and GW events can also be performed, followed by a test of spatial correlation using the combined GW/HEN likelihood skymap. This second, more symmetrical, option requires the existence of two independent analysis chains scanning the whole phase space in search for interesting events. In both cases an astrophysically motivated (and possibly source- or model-dependent), time interval is used to define the coincidence window. 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 (and scrambled real neutrino event lists when needed).

Preliminary investigations of the feasibility of such searches have already been performed (Aso et al. 2008; Pradier 2009) and indicate that, even if the constituent observatories provide several triggers a day, the false alarm rate for the combined detector network can be maintained at a very low level (1/600 yr). A major issue for the analysis lies in the combined optimisation of the selection criteria for the different detection techniques.

5 Conclusions

A joint GW+HEN analysis program could significantly expand the scientific reach of both GW interferometers and HEN telescopes. The robust background rejection arising from the combination of two totally independent sets of data results in an increased sensitivity and the possible recovery of cosmic signals. The observation of coincident triggers would provide strong evidence for the existence of common sources. Beyond the benefit of a potential high-confidence discovery, coincident GW/HEN (non-)observation shall play a critical role in our understanding of the most energetic sources of cosmic radiation and in constraining existing models. They could also reveal new, "hidden" sources unobserved so far by conventional photon astronomy.

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