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Multimessenger Sources of Gravitational Waves and High-energy Neutrinos: Science Reach and Analysis Method

B Baret¹, I Bartos^{2,†}, B Bouhou¹, E Chassande-Mottin¹, A Corsi³, I Di Palma⁴, C Donzaud^{1,5}, M Drago⁶, C Finley⁷, G Jones⁸, S Klimenko⁹, A Kouchner¹, S Márka², Z Márka², L Moscoso^{1,*}, M Alessandra Papa⁴, T Pradier¹⁰, G Prodi⁶, P Raffai^{2,11}, V Re¹², J Rollins³, F Salemi^{4,13}, P Sutton⁸, M Tse², V Van Elewyck¹ and G Vedovato¹⁴

¹AstroParticule et Cosmologie (APC), CNRS: UMR7164-IN2P3-Observatoire de Paris-Université Denis Diderot-Paris VII-CEA: DSM/IRFU, France

²Department of Physics, Columbia University, New York, NY 10027, USA

³LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

⁴Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany

⁵Université Paris-sud, Orsay, F-91405, France

⁶INFN, Gruppo Collegato di Trento and Università di Trento, I-38050 Povo, Trento, Italy

⁷Oskar Klein Centre & Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden

⁸Cardiff University, Cardiff CF24 3AA, UK

⁹University of Florida, Gainesville, FL 32611, USA

¹⁰University of Strasbourg & Institut Pluridisciplinaire Hubert Curien, Strasbourg, France

¹¹Eötvös University, Institute of Physics, 1117 Budapest, Hungary

¹²INFN, sezione di Roma Tor Vergata, I-00133 Roma, Italy

¹³Leibniz Universität Hannover, D-30167 Hannover, Germany

¹⁴INFN, Sezione di Padova, I-35131 Padova, Italy

* Deceased

† Corresponding author. Email: ibartos@phys.columbia.edu

Abstract. Sources of gravitational waves are often expected to be observable through several messengers, such as gamma-rays, X-rays, optical, radio, and/or neutrino emission. The simultaneous observation of electromagnetic or neutrino emission with a gravitational-wave signal could be a crucial aspect for the first direct detection of gravitational waves. Furthermore, combining gravitational waves with electromagnetic and neutrino observations will enable the extraction of scientific insight that was hidden from us before. We discuss the method that enables the joint search with the LIGO-Virgo-IceCube-ANTARES global network, as well as its methodology, science reach, and outlook for the next generation of gravitational-wave detectors.

The observation of multimessenger sources of gravitational waves (GWs) and high-energy neutrinos (HENs) is on our doorstep due to recent and near-future development of large-scale observatories. Several GW observatories have been in operation in the past years, including LIGO [1], Virgo [2] and GEO [3]. These detectors will be upgraded to second generation detectors within the next few years. Another advanced GW detector, LCGT [4] in Japan is

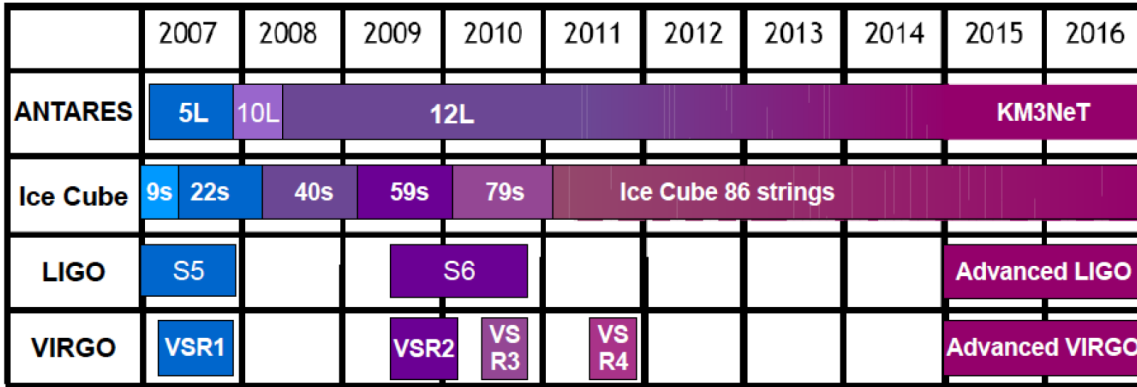


Figure 1. Time chart. Planned data-taking periods for detectors involved in the GW+HEN search.

under construction. LIGO may build a third observatory in India [5] soon after the two US-based detectors. Several HEN observatories are currently in operation, such as IceCube [6], a cubic-kilometer detector at the geographic South Pole, and ANTARES [7] in the Mediterranean sea. ANTARES is being upgraded to a cubic-kilometer detector called KM3NeT in the following years [8]. A third HEN detector operating at the lake Baikal is also planned to be upgraded to a km³ volume [9].

The gravitational-wave – high-energy neutrino (GW+HEN) working group of the LIGO, Virgo, IceCube and ANTARES detectors¹ has been formed to facilitate cooperation and data-sharing between participating institutions. Collaboration is further aided by past and planned coincident data-taking periods, as we show in Figure 1.

The first published result of the GW+HEN working group involved the analysis of the coincident time window within which one can expect the observation of coincident GW and HEN signals from a common source [10]. The analysis focused on gamma-ray bursts (GRBs) as arguably most promising multimessenger sources. The obtained conservative, ~ 500 s long time window took into account processes motivated by current GRB models. The duration of these process was determined based on electromagnetic observational data. The considered processes and their duration are shown in Figure 2.

An important milestone in the work on common GW+HEN sources was the first observational constraint obtained by Bartos *et al.* [11]. They explored the reach of current and planned experiments in constraining the population of multi-messenger sources of GWs and HENs. They derived constraints on the rate of GW and HEN transients based on independent observations by the initial LIGO and Virgo GW detectors and the partially completed IceCube (40-string) HEN detector. Further, they compared the estimated reach of joint GW+HEN searches using advanced GW detectors and the completed km³ IceCube detector to the reach of independent searches using the same detectors. They conclude that, while the main advantage of joint searches is increased sensitivity for the actual detection of sources, joint searches will provide better constraints than independent observations if, upon non-detection they result in an increased exclusion distance by at least a factor $\sim f_b^{1/3}$ compared to independent searches, where f_b is the neutrino beaming angle. The projected population constraint from joint searches with advanced GW and HEN detectors is shown in Figure 5 (right).

As a next important milestone, the baseline analysis has been designed [12] to search for

¹ In order of greatest linear dimension

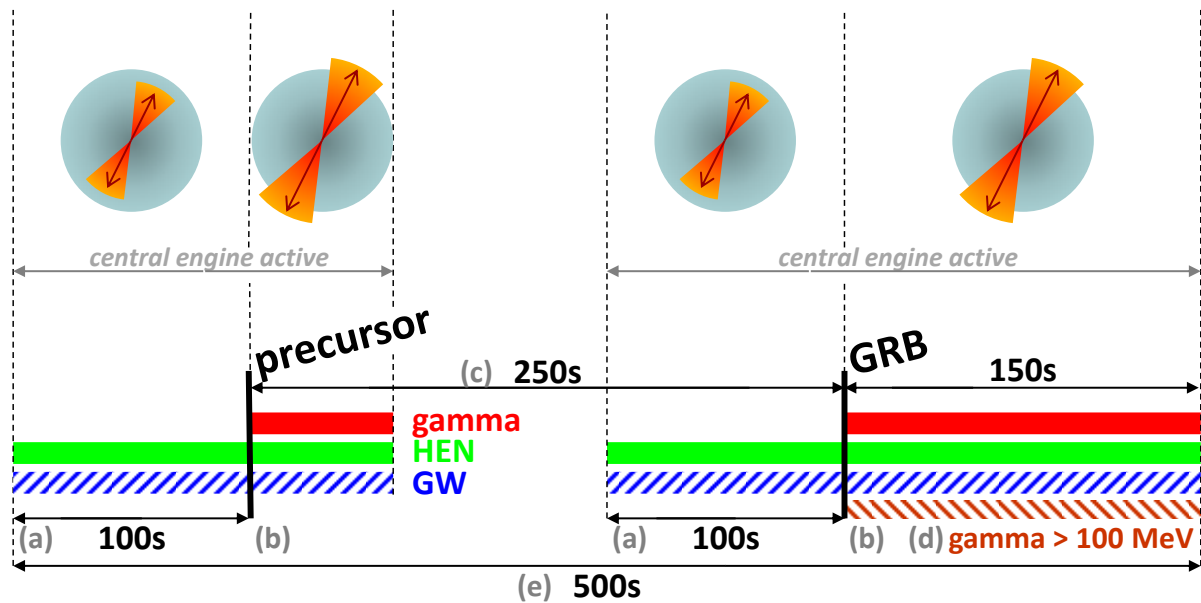


Figure 2. Summary of upper bound of GRB emission process durations taken into account in the total GW+HEN coincidence time window (courtesy of [10]). (a) active central engine before the relativistic jet has broken out of the stellar envelope; (b) active central engine with the relativistic jet broken out of the envelope; (c) delay between the onset of the precursor and the main burst; (d) duration corresponding to 90% of GeV photon emission; (e) time span of central engine activity.

common sources. The baseline joint analysis takes into account the significance of the GW and HEN signals, calculated based on the excess energy in the GW datastream (see e.g. [13]) and the reconstructed neutrino energy and neutrino flux (i.e. number of coincident neutrinos). The analysis also takes into account the directional probability distributions of the GW and HEN signals, as well as the *a priori* source distribution using the observed distribution of blue luminosity in the universe². An example set of spatial probability distributions used by the analysis, as well as their combination, are shown in Figure 3. A parallel search is performed where the blue-luminosity distribution is ignored in order to search for sources not connected to blue luminosity, e.g. galactic sources. The joint search will use the coincidence time window derived by Baret *et al.* [10]. It will consider individual signal candidates, as well as an ensemble of weak, sub-threshold signals that could not be detected individually. In the case of no detection, results will be used to obtain upper limit estimates of multimessenger GW+HEN sources. A schematic flow diagram of the baseline analysis is shown in Figure 4. Projected results for the search using initial LIGO-Virgo detectors (S5/VSR1 science run) with the partial IceCube detector with 22 strings are shown in Figure 5 (left). These upper limit projections were obtained by Baret *et al.* [10] following the calculation of Bartos *et al.* [11], using the different detector parameters.

We are close to the milestone of finishing the first coincident search for GWs and HENs for the initial LIGO-Virgo (S5/VSR1 science runs) and the partial ANTARES detector in its 5-string configuration. The analysis uses the directional distribution and the time of arrival of HENs to trigger a GW follow-up analysis, similar to the analysis used for GW follow-up searches of

² I.e. the analysis assumes that the source distribution follows the blue-luminosity distribution of galaxies.

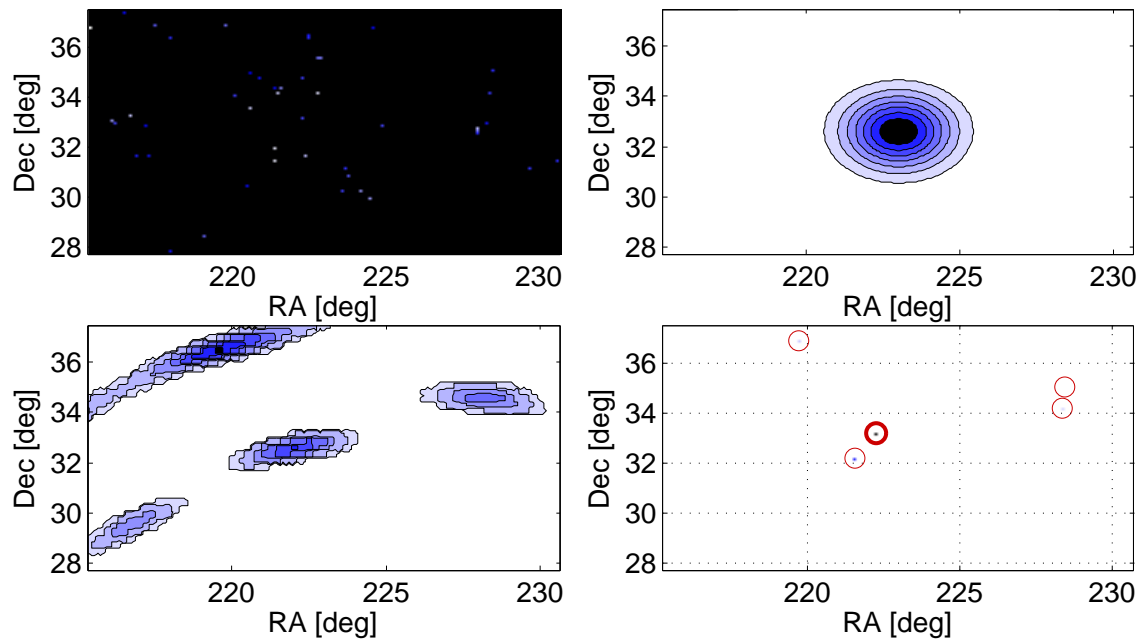


Figure 3. Example likelihood distributions as parts of the joint likelihood ratio: weighted galaxy distribution (upper left), HEN directional probability distribution function (PDF) (upper right), GW PDF (lower left) and joint PDF (lower right), all shown in arbitrary units. On the joint PDF plot, every galaxy for which the joint PDF is non-zero is circled for visibility. Courtesy of [12].

GRBs (e.g. [14]). The search uses the conservative coincidence time window of 500 s of Baret *et al.* [10]. There are ~ 200 neutrino triggers from ANTARES, most of which are detected by digital optical modules (DOMs) on two strings, while 13 neutrinos are detected by DOMs on three strings. The detailed method and the first scientific results will be published soon.

One can consider specific source emission models to interpret the reach of the projected population upper limits [12]. Taking two typical HEN emission models, Figure 6 shows the corresponding population upper limits as functions of GW emission.

The first observational results and projected population estimates indicate that multimessenger searches for gravitational waves and high-energy neutrinos will be an exciting and fruitful field in the near future.

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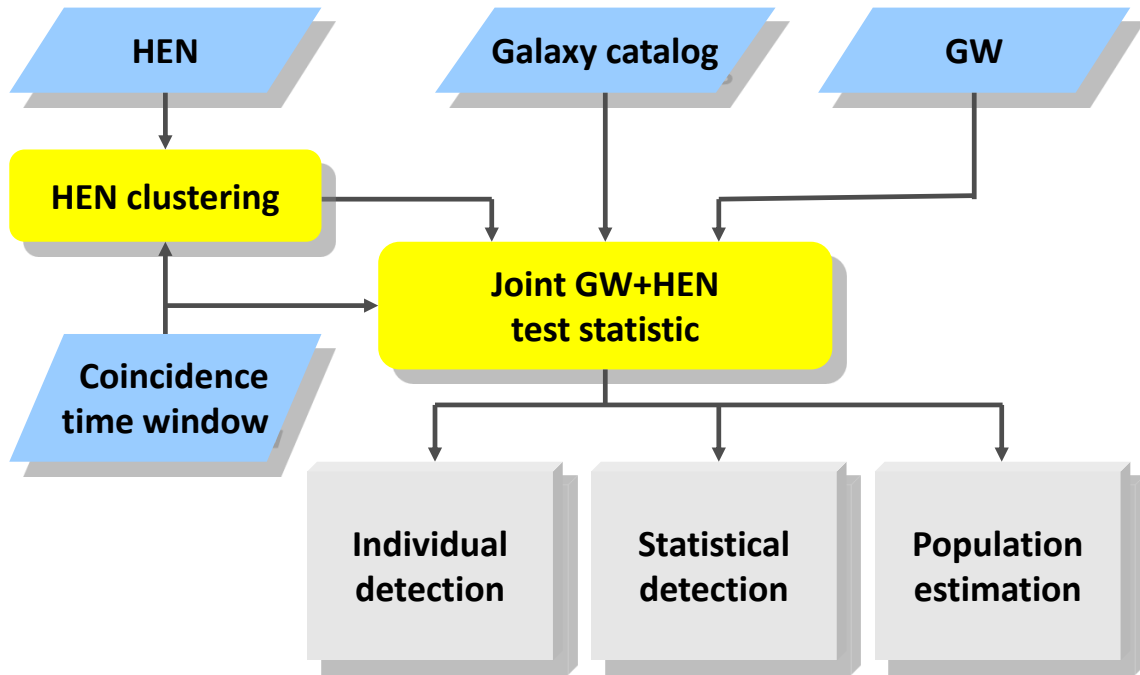


Figure 4. Schematic flow diagram of the baseline joint GW+HEN search pipeline [12]. This pipeline is used for the search with initial LIGO-Virgo (S5/VSR1) + IceCube (22 strings).

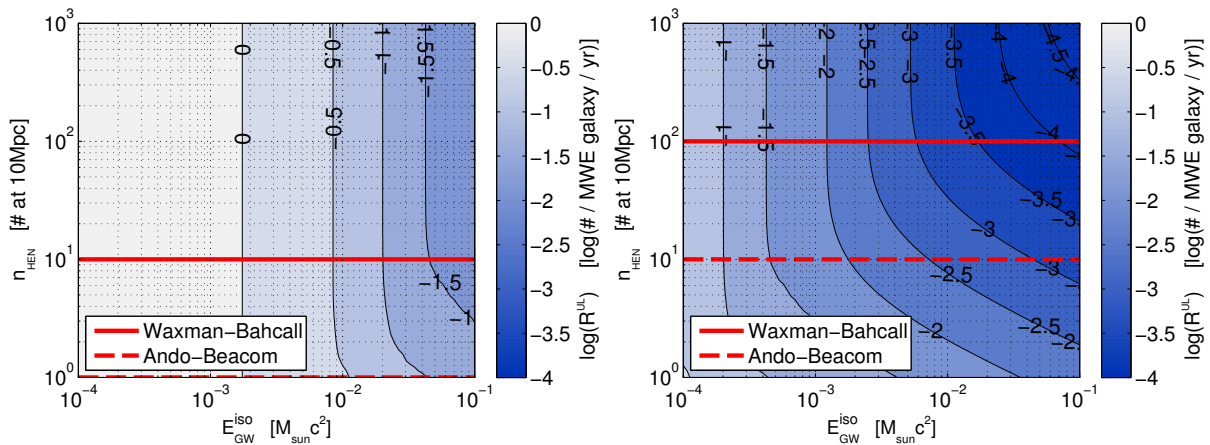


Figure 5. Expected GW+HEN source population upper limits for IceCube-22 coincident with initial LIGO-Virgo (left; courtesy of [12]) and IceCube-86 coincident with advanced the LIGO-Virgo detectors (right; courtesy of [15]), with one year of coincident measurement time. The results take into account the blue luminosity-weighted galaxy distribution. The x-axis represents the GW energy output of a standard source. The y-axis represents the number of detected neutrinos from a standard source at 10 Mpc. The color scale shows the obtained source rate upper limit R^{UL} in logarithmic units of number of sources per (Milky Way equivalent) galaxy per year. On both plots, the two horizontal lines (scaled for detector sensitivity) show the Waxman-Bahcall emission model [16] (higher) and the HEN emission model of Ando and Beacom [17] for reverse shocks in mildly relativistic supernova jets / choked GRBs (lower).

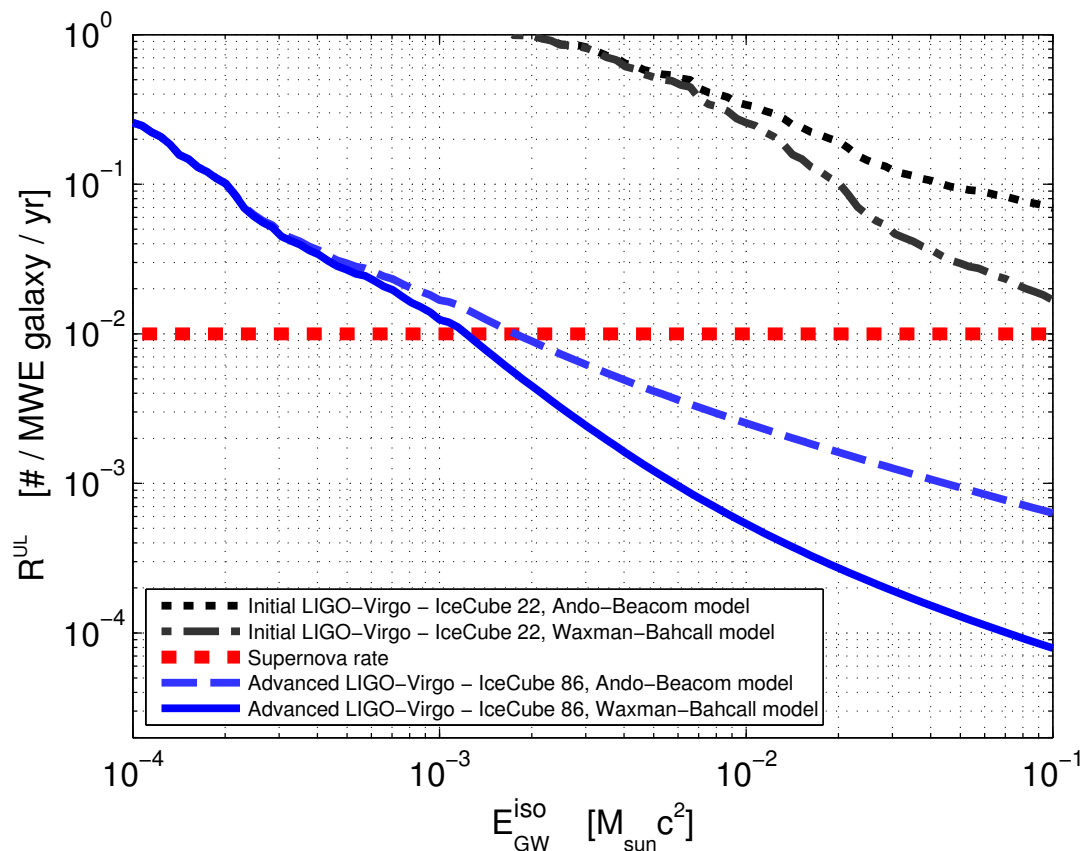


Figure 6. Expected GW+HEN source population upper limits for anticipated HEN emission from two emission models, as functions of isotropic-equivalent GW emission energy E_{GW}^{iso} (courtesy of [12]). Results are shown both for measurements with the initial LIGO-Virgo detectors and the IceCube-22 detector (dashed line), as well as for the advanced LIGO-Virgo detectors and the IceCube-86 detector (solid line), both with one year of coincident measurement time. For comparison, the galactic supernova rate is shown (dotted line).

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