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Searches for subthreshold sources of Gravitational Waves and High Energy Neutrinos using Advanced LIGO/VIRGO, ICECUBE and ANTARES data

Thierry Pradier[*] [†]
Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
E-mail: thierry.pradier@iphc.cnrs.fr

Marta Colomer [‡]
APC, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris, France
E-mail: mcolomer@apc.in2p3.fr

Bruny Baret
APC, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris, France
E-mail: bruny.baret@apc.in2p3.fr

The ANTARES Collaboration[§]

http://antares.in2p3.fr/Collaboration/index2.html

Astrophysical sources of gravitational waves (GW) can drive relativistic outflows potentially producing high-energy neutrinos (HEN). The results of a search for associated emission of gravitational waves and high-energy neutrinos from astrophysical transients with minimal assumptions using data from Advanced LIGO from its first observing run O1 (2015-2016), and data from the ANTARES and ICECUBE neutrino observatories, are presented, focusing on the ANTARES neutrino selection optmized procedure. Prospects for the second observing run O2 of Advanced LIGO/VIRGO (2016-2017) and the ongoing O3 for improving this neutrino selection procedure will be presented.

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[*]Speaker.

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[‡]*Presenter*

[§]For Collaboration list, see also PoS(ICRC2019) 1177.

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1. Introduction

Gravitational-Wave (GW) astronomy has become in a few years an entirely new branch of astronomy, in tight connection with the "traditional" electromagnetic astronomy. The first (2015-2016) and second (2016-2017) VIRGO/LIGO Observing Runs have permitted the discoveries of multiple Binary Black Hole (BBH) mergers [1], with no electromagnetic counterparts as expected in the most discussed models, whereas the Binary Neutron Stars (BNS) merger GW170817 [2] has confirmed the merger-short GRB connection, through its observations with observatories from radio to gamma-rays. Core-Collapse supernovae (CCSN) GW signals remain to be detected though, a challenging task as the expected signal is poorly known, and thus hard to distinguish from background. The recently started O3 Observing Run has already revealed around 10 BBH, at least one BNS and a probable Neutron Star-Black Hole (NSBH) merger.

In connection with the identification of Cosmic Rays (CR) sources, high-energy neutrinos (HEN) carry information about hadronic acceleration in astrophysical phenomena, such as accreting black holes that can be formed after BBH, BNS or NSBH mergers and CCSN, a large fraction of which may produce relativistic jets. HEN Telescopes thus carry out joint searches with GW and electromagnetic facilities, to search for some common GW+HEN emitters, which would yield valuable information about the collapse/merger-accretion-ejection process, potentially at the origin of CRs.

The IceCube Neutrino Observatory, a gigaton Cherenkov detector located in the ice at the South Pole, has recently revealed the possible link between Blazars and cosmic neutrinos. Operating since 2008, ANTARES is currently the largest high-energy neutrino telescope in the Northern hemisphere [3]. Located in the Mediterranean Sea, 40 km off the Southern coast of France, it is composed of 12 detection lines that detect the Cherenkov light emitted by relativistic upgoing muons, signature of a neutrino interaction close to the detector. After the discovery from ICECUBE of a cosmic neutrino flux of still unknown origin [4] and the multimessenger observation of a flaring blazar in coincidence with a HEN [5], observing campaigns relying both on electromagnetic and multimessenger facilities are decisive to identify the origin of these neutrino events.

No common sources of GWs and high-energy neutrinos have been identified so far. Observational constraints for astrophysical source populations have only been derived using Initial LIGO and VIRGO, and the partially completed ICECUBE and ANTARES detectors [6, 7]. Searches have been carried out for the neutrino counterparts of BBH mergers detected during Advanced LIGO's first [8] and second observing runs [9, 10], and BNS merger GW170817/GRB 170817A [11]. GW+HEN coincidences are a novel way to disentangle signal from background in HEN telescopes, together with HEN follow-ups of multimessenger alerts and multiwavelentgh follow-ups of HEN alerts [12].

In this contribution, the results of a search for correlations between *substhreshold* GW and HEN events using GW data from Advanced LIGO's first observing run (O1) and HEN data from both ANTARES and ICECUBE are presented [13], emphasizing the ANTARES neutrino selection procedure for *track* events (ν_μ Charged Current interactions). This relies on searches for time and space correlations between HEN detected by ANTARES or ICECUBE and GW candidates of low signal-to-noise ratio. Possible improvements in these selections, that will also be applied to *showers* (ν Neutral Current interactions), to be used for the analysis of VIRGO/LIGO Observing Runs O2/O3, will be developed.

2. Previous searches for particular GW signals

Using ANTARES data, neutrino emissions from GW sources have been searched for during O1 Observing Run, in particular GW150914 and GW151226, with no success [8, 14]. HEN have also been searched for in ANTARES data using 6 BBH GW signals detected during O2, with an optimization such that one event passing the analysis cuts, arriving within $\pm$500s around the time of the alert and located inside the 90% GW probability contour would lead to a 3σ significance, using a data-driven background estimate. These analyses are presented elsewhere at this Conference [10].

On top of searching for HEN counterpart emission of such strong GW events, the search for coincident sub-threshold events, obtained by relaxing data selection quality cuts, can further constrain the joint source population.

3. Joint GW+HEN subthreshold search using O1 data

Advanced LIGO's O1 observing run started on 2015 September 12, and lasted until 2016 January 19. Its sensitivity to GW transients led to the discovery of multiple astrophysical GW signals, briefly described in the previous section. The GW data gathered may contain some *subthreshold* events, which could be associated to neutrino signals that could populate the HEN data sample. The main points of a multimessenger GW+HEN search [13] are outlined in this section.

3.1 GW data and analyses

Data from the 2 Advanced LIGO's detectors in Hanford and Livingston were used to carry out a generic GW transient search for unmodeled and short duration signals. Only GW signal candidates corresponding to a GW false alarm rate (FAR) $\approx$ 1 day^{-1} were considered. Each candidate was characterized by its time and directional probability distribution (skymap) and assigned one of three classifications Ci, with $i = 1,2,3$. Candidates consistent with noise fluctuations often occurring in LIGO-Virgo data were placed into class C1. Those similar in morphology to compact binary mergers were placed in class C3, and all other GW candidates in class C2. A total of 23 signals were identified as C1 and 23 as C2+C3, during the $\approx$ 50 days of coincident data.

C2 and C3 signals were treated separately from C1 signals as the former have a higher probability of being astrophysical. The background distribution of the test statistic (TS) of the GW search was computed separately for these two categories. For a given event, its GW p-value is calculated by comparing the reconstructed TS value to its background distribution in the same category as the event.

To characterize the background distribution of the TS for GW candidates, the same GW search was carried out after applying time shifts between the data from the two LIGO detectors, with time shifts much greater than the travel time of GWs between the LIGO detectors (10 ms), ensuring that no short GW transient appears simultaneously in the data streams of the two detectors (see Figure 1, green frame).

3.2 HEN data and analyses

The IceCube selection procedure is described in details in [13], and this section will focus on the ANTARES selection of HEN candidates, already presented in [15], and summarized below.

In order to optimize the HEN search, a sample of realistic GW events is used [16], which allows to extract a relationship beteween the signal-to-noise ratio ρ (the TS of the GW search) of a signal to the area of 90% confidence region A_{90} for the GW localization, of the form $\log_{10} A_{90} = a \log \rho + b$, used to extrapolate the size of the confidence region to sub-theshold GW events. This size is then convolved with ANTARES visible sky (ANTARES is only sensitive to up-going neutrinos in this analysis), and its local acceptance, to obtain typical sizes ranging from ≈ 500 deg^2 (50% quantile of the distribution of effective sizes, taking into account visibility and acceptance, shown in Figure 2 (left), of GW 90% probability regions) to ≈ 1000 deg^2 (99% quantile).

A time-dependent selection criterium, based on the quality of the muon track reconstruction, taking into account the time-dependence of the sensitivity of ANTARES, is then determined so that a selected HEN event in a time window of 1000s, in a space angle corresponding to these typical GW-contour regions will yield a significance of 3σ. For the final selection, the value corresponding to the median effective size has been used, which yields a total of 906 selected HEN candidates for ANTARES, for the period covering the entire O1 observation run from Sep 12 2015 to Jan 19 2016, corresponding to a rate of 8 neutrinos/day.

Each HEN candidate is characterized by its detection time, its arrival direction and reconstruction uncertainty, and a probability of being of atmospheric origin based on the number of detected photons, an estimator of the event deposited energy.

3.3 Joint analysis and results

GW and neutrino event candidates were jointly analyzed to search for common sources using a multimessenger search algorithm, which was already followed in previous joint searches [17]; the flow diagram of the joint search algorithm is presented in Figure 1. The significance of GW and neutrino candidates were used independently to quantify the significance of joint events, together with their temporal and directional coincidence. Any neutrino arriving within $\pm$500s of a GW candidate is considered temporally coincident [18], whereas the directional coincidence is the product of the GW skymap and neutrino reconstructed point-spread function. For neutrino candidates in temporal coincidence with GW candidates, a combined statistics X^2 is constructed from the GW p-value, the HEN p-value and the p-value of directional coincidence. The background X^2 distribution is used to evaluate the significance of a joint GW+HEN candidate.

More than 90% of the GW event candidates (42 out of 46) had temporally coincident neutrino candidates found by IceCube, with a total of 195 coincident events out of the ≈ 41000 ICECUBE candidates. No temporally coincident neutrino candidates was found for ANTARES, out of the ≈ 900 neutrino candidates. Both observations are consistent with background expectations. Finally, none of the joint GW+neutrino candidates have sufficiently high significance to consider them a detection. This non-detection during an observation time $T_{\rm obs}$ was used to obtain constraints on the population of GW+HEN sources, $R_{\rm UL}$ evaluated from :

$$N_{\rm GWHEN} = R_{\rm UL} V_{\rm GWHEN} T_{\rm obs} f_b^{-1} \leq 3.9, \tag{3.1}$$

where $f_b^{-1} = (1-\cos\theta_{\rm jet})$ is the neutrino emission's beaming factor for a jet-opening half-angle $\theta_{\rm jet}$, and $V_{\rm GWHEN} = \int_0^\infty 4\pi r^2 P_{\rm GWHEN} dr$, $P_{\rm GWHEN}$ being the joint detection probability. This detection probability depends both on the expected GW amplitude, a function of the distance and total radiated GW energy, and on the average number of detected HEN, a function of the considered HEN telescope and total isotropic-equivalent energy emitted in HEN.

The obtained upper limits, with $f_b = 10$, are shown in Figure 2 (right) ; they scale linearly with f_b, where $f_b \lesssim 10$ for low-luminosity GRBs, and $f_b \approx 10-1000$ for typical long or short GRBs. Considering a given population density for GWHEN emitters, constraints on the jet opening angle could also be extracted. Figure 2 also shows that for neutrino-bright sources ($E_{\nu,\mathrm{iso}} \gg 10^{51}$ erg), R_{UL} scales as expected as $E_{\mathrm{GW}}^{-3/2}$. This O1 search improves previously-published constraints (for $E_{\mathrm{GW}} = 10^{-2} M_{\odot} c^2$, $E_{\nu,\mathrm{iso}} \approx 10^{51}$ erg) from $\approx 10^7$ [6, 23, 19] down to 4×10^4 Gpc^3 yr^{-1}.

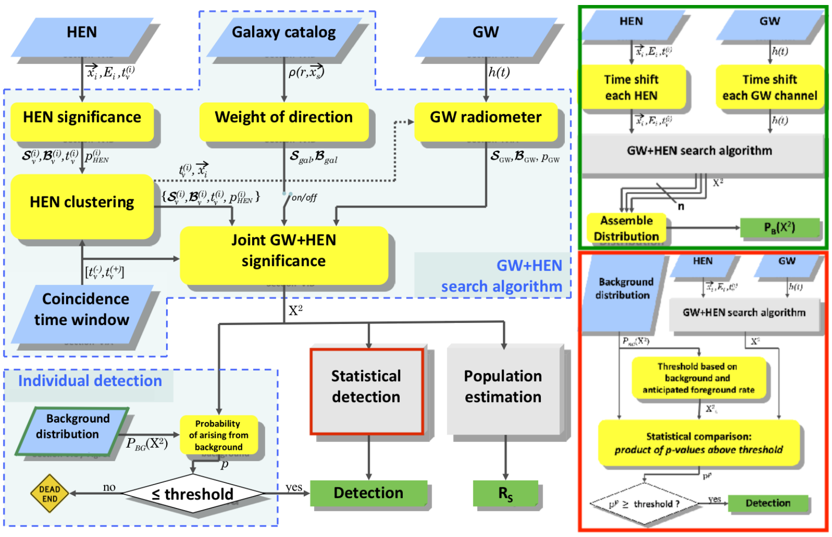

Figure 1: Flow diagram of the joint GW+HEN search algorithm. Green frame : details on the calculation of the background distribution. Red frame : details on statistical detection of multiple GW+HEN sources [17].

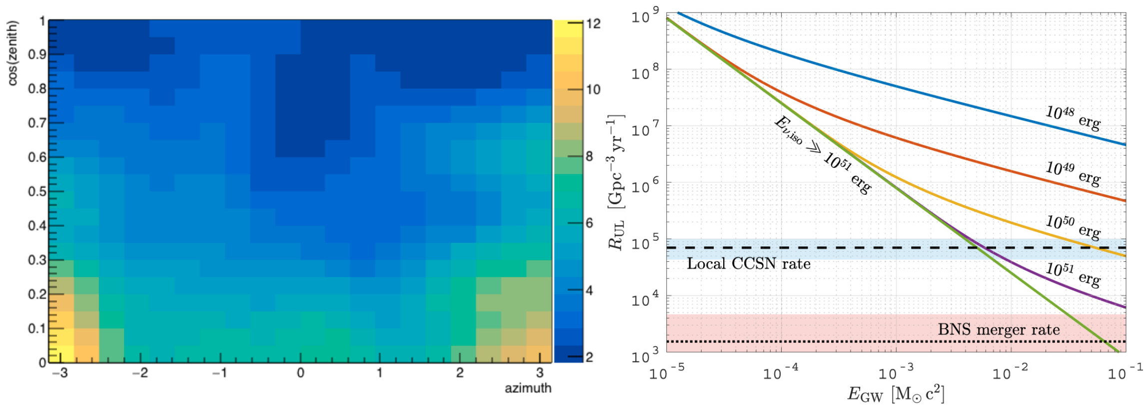

Figure 2: Left : ANTARES local acceptance, as the number of reconstructed events wrt direction. Right : Upper limits for the rate density of GW+HEN sources as functions of the GW radiated energy, for different values of the HEN energy, with $f_b = 10$ [13]. The local rate of CCSN [13] and BNS mergers [2] are also represented. The derived limits are only constraining (= below the CCSN rate) in the strong-emission regime.

4. Planned and possible improvements for O2 and O3 periods

The Advanced LIGO detectors took data between Nov 30th 2016 and August 25th, whereas VIRGO joined O2 starting from August 1st, and led in particular to the discovery of GW170817 related to GRB170817A (see section 2). The O3 Observing Run started in April 2019, and is still ongoing. Figure 3 (left) shows the typical planned sensitivities for O2 and O3 [20]. For O2, the ANTARES original procedure will also be applied to *shower* events and not only to tracks, which will lead to about 200 shower events selected for ≈ 2000 track events for the sole O2 period, to be compared with ≈ 8000 tracks and ≈ 200 showers selected in the recent ANTARES Point Source search [21]. Several possibilities exist to optimize such a joint search.

4.1 Optimizing the number of detectable sources

As presented in [22, 23], the selection applied on HEN and GW data can be tuned to maximize the number $\mathscr{N}_{\rm GWHEN}$ of detectable sources emitting both GW and HEN while keeping the instantaneous false alarm probability constant, e.g. below 2.7×10^{-3}, for a 3σ significance. For isotropically-distributed identical sources emitting $E_{\rm GW}$ in GW and $E_{\nu,\rm iso}$ in HEN, $\mathscr{N}_{\rm GWHEN}$ can be evaluated :

$$\mathscr{N}_{\rm GWHEN} \propto \frac{\varepsilon_{\rm HEN}}{\rho_{\rm GW}}, \qquad (4.1)$$

where $\varepsilon_{\rm HEN}$ is the signal efficiency of the HEN selection procedure, and $\rho_{\rm GW}$ the threshold signal-to-noise ratio of the GW analysis. Such a procedure takes advantage of the low coincident background to enhance the detector sensitivity, and has been shown to improve the limits on $E_{\nu,\rm iso}$ for realistic GW energies $E_{\rm GW} < 10^{-2} M_\odot c^2$ [23].

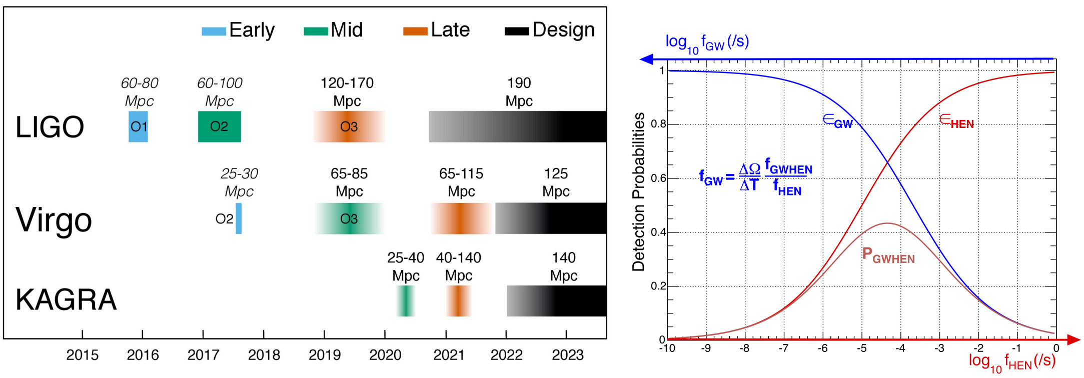

Figure 3: Left : Planned sensitivity evolution and observing runs of the Advanced LIGO, Advanced VIRGO and KAGRA detectors over the coming years, in terms of BNS detection distance [20]. Right : Principle of an optimized GWHEN analysis, where the GW and HEN selections are jointly tuned according to an overall false-alarm rate $f_{\rm GWHEN}$, to maximize the coincident detection probability $P_{\rm GWHEN}$.

4.2 Optimizing the showers/tracks ratio of the HEN sample

As shown in Figure 3 (right), a GWHEN optimized analysis relies on the joint tuning of GW and HEN selections (depending on false-alarm rates $f_{\rm GW}, f_{\rm HEN}$) with respect to a given coincident false-alarm probability f_{GWHEN}, for a coincidence time window ΔT and an angular coincidence window $\Delta\Omega$. The GW and HEN detection efficiencies are thus dependent on each other, and the joint detection probability P_{GWHEN} can be maximized - this is equivalent to optimizing the number of detectable sources as presented in Section 4.1.

This procedure can be applied to a sample of tracks or showers, or to a mixed sample. In particular, the showers/tracks content of the final sample can be further optimized. At the trigger level, $N_{\text{Tracks}} \approx 3 \times N_{\text{Showers}}$, a ratio which is later changed by factors such as the detector efficiency or the reconstruction performances. Furthermore, showers suffer from a poorer angular resolution than tracks, and the signal efficiency of the shower and track reconstruction are different ; a trade-off can be found in the fraction of showers/tracks of the final HEN sample used in the joint analysis.

Going into more details, the coincident false-alarm probability in a time-window $\Delta\tau$ and GW 90% probability region $\Delta\Omega_{\text{GW}}$ which depends on the threshold signal-to-noise ratio ρ_{GW}, can be written as, with $N_{\text{T}} = N_{\text{Tracks}}$ and $N_{\text{S}} = N_{\text{Showers}}$:

$$f_{\text{GWHEN}} = f_{\text{GW}} \times f_{\text{HEN}} \times \Delta\tau \times f_{\Omega}, \tag{4.2}$$

where $f_{\text{HEN}} = \frac{N_{\text{T}} f_T + N_{\text{T}} f_S}{N_{\text{T}} + N_{\text{S}}}$ is a combination of tracks and showers efficiencies, which depend on the corresponding selection parameters. The angular term f_{Ω} is a linear mixture of the spatial term for tracks $\Delta\Omega_T$ and for showers $\Delta\Omega_S$, with typically $\Delta\Omega_S \gg \Delta\Omega_T$. With a fraction x_s of showers with respect to tracks, the combined angular term reads :

$$f_{\Omega} = \frac{1}{\Delta\Omega_{\text{GW}}} \frac{\Delta\Omega_T + x\Delta\Omega_S}{(1+x_s)}. \tag{4.3}$$

A possible improvements for future joint searches would then consist in optimizing the GWHEN figure-of-merit 4.1 with respect to the fraction x_s : this would ensure that all the available information about the neutrino reconstruction, in particular the differences of the shower and track channels, are fully taken into account.

5. Conclusions & Perspectives

Searching in data recorded by the ANTARES and ICECUBE Neutrino Telescopes concomitant with LIGO Observation Run O1, no neutrino emission associated with the GW event candidates was found. These GW signals can correspond to BBH mergers, in which case HEN and/or electromagnetic emission can be expected in the case of significant gas accretion, which would trigger an energetic outflow. They can of course origin from distant BNS or NSBH mergers, or from CCSN, for which the creation of possible relativistic jets producing HEN emission is poorly understood. In particular, HEN emission can be enhanced for sub-photospheric dissipation processes, in which the observable gamma-ray flux is reduced by absorption. Such spurious HEN signals, difficult to associate to any electromagnetic counterpart, would be buried in the atmospheric background of the HEN telescope. Such joint GW+HEN analyses are a novel way to reveal the signals both in the GW and HEN detectors.

For GWHEN source rate densities $< 10^5$ Gpc^{-3}yr^{-1} (below the local CCSN rate), the limits obtained are constraining in the strong-emission regime corresponding to $E_{\text{GW}} \gtrsim 10^{-2} M_{\odot} c^2$ and $E_{\nu,\text{iso}} \gtrsim 10^{51}$erg, a neutrino brightness that would only be possible for BNS mergers.

The typical GW sensitivity during O2 was increased with respect to O1, and saw the addition of VIRGO, improving the GW localization, which will decrease the global coincidence rate for the joint search for each event. For the ongoing O3, the planned improvement in detection distance could reach a factor 2, increasing considerably the volume of universe probed by joint GW+HEN analyses. ANTARES is still in operation until 2020, soon to be superseded by the KM3NeT telescopes, ORCA, for GeV neutrinos, and ARCA, for TeV-PeV neutrinos, under construction and deployment [3]. In particular, the combination of the fully completed ORCA and ARCA data at the horizon 2023-5, when Advanced VIRGO and Advanced LIGO will have reached their design sensitivity, with a BNS range of 150 to 200 Mpc (see Figure 3), will allow to probe the sky for GeV to PeV neutrino emissions, and possibly reveal the tight connection between merger/collapse events and accretion/ejection processes at the origin of cosmic rays.

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