Prospectives IN2P3 - GT04 AstroParticle Physics

GWHEN - Gravitational Waves and High Energy Neutrinos, the next multi-messenger connection

T. Pradier [a], Université de Strasbourg/IPHC,
for the APC, CPPM, IPHC, LUPM and Subatech KM3NeT groups

[a] also member of the Virgo Collaboration

Abstract

Ten years ago in 2009 started the Virgo VSR2-3 and Ligo S6 scientific runs, with horizons for compact binaries of the order of 50 Mpc, while IceCube was operating with only 22 of its 86 current strings and ANTARES with its final 12 lines. Gravitational Waves (GW) and High Energy Neutrinos (HEN) were still to be observed. Where will be GW and HEN astronomy in 10 years from now, and in particular the joint GW+HEN searches ?

In 2025 will begin the Observation Run O5 of the GW interferometers Virgo/Ligo, probably together with Ligo India and KAGRA, with a horizon for binaries ranging from 150 Mpc and 300 Mpc. At this time, the KM3NeT HEN telescopes ORCA (GeV neutrinos) and ARCA (TeV-PeV) will be completed, with unprecedented sensitivities for these energy ranges. IceCube foresees the deployment of IceCubeGen2 to reach a sensitivity $\approx 5\times$ ARCA during the next decades. At the same time, the Einstein Telescope (ET), probably 10 times more sensitive than current GW interferometers, will probably come online at the onset of the 2030 decade.

Multi-messenger astronomy, in particular associating GW and HEN (GWHEN), thus have a bright future ahead. This contribution gives some insights on past GWHEN analyses and the possible outcomes of future joint GWHEN studies. This document is a complement of *Multi-Messenger neutrino analyses* [1] for the HEN part, and is also linked to *Real time gravitational waves astronomy* [2] and *Multi-messenger astroparticle physics* [3], for the GW-related part.

Introduction

Since the confirmation of existence of Gravitational Waves (GW) with the detection of GW150914 [4], gravitational astronomy has entered an era of "routine detection". A the time of writing, since the beginning of the O3 Observation Run, more than 20 Black Hole Binaries, and several neutron star binaries and Neutron Star/Black Hole binaries have been announced [5]. In 2017, an electromagnetic (EM) counterpart to the neutron star merger GW170717 detected by Virgo/Ligo (see fig. 1) have been observed throughout the EM spectrum, opening the way to multi-messenger astronomy with GW [6].

In parallel, the IceCube telescope has revealed in 2013 the existence of a diffuse flux of High Energy Neutrinos (HEN) in the TeV-PeV energy range [7] - neutrinos of cosmic origin, emitted by the long-sought sources of Cosmic Rays (CR), in vast majority hadronic. In July 2018, IceCube has announced the detection of the first likely source of HEN, also observed in the EM domain - confirming that the object, the "blazar" TXS 0506+056, is probably a source of CR [8].

But the quest is still long before identifying unequivocally the sources of the detected HEN and hence solving the CR puzzle. To do that HEN telescopes, the existing ANTARES or future KM3NeT telescopes (see fig. 1) have developed a whole system of multi-messenger programs, developed in [1]. After the successfull connection between GW and EM astronomy with GW170817 and between HEN and EM astronomy with TXS 0506 (even if the association is not convincing for many), the **next multi-messenger connection remaining to be revealed is the GW+HEN connection.**

Section 1 : GW+HEN common sources

Common sources of GW and HEN are typically compact objets formed after the collapse of massive stars or the merger of 2 neutron stars/black holes, processes during which the emitted GW can be detected by GW interferometers like Virgo/Ligo or future GW detectors. The resulting object can trigger the formation of a relativistic jet of matter, in which hadronic cosmic rays could be accelerated. The interaction of those cosmic rays with surrounding matter/radiation can in turn produce HEN, which can be detected by current or future HEN telescopes, like KM3NeT telescopes.

Potential GWHEN sources are then gamma-ray bursts-like, either long or short, just like GW170817 was associated to GRB170817A, a short GRB. Some authors have proposed of a potential link between long GRBs and supernovae, suggesting that some "choked" GRBs could exist, which could only be revealed through their GW and/or HEN emissions - e.g. because of a jet too large and too slow to emit any detectable electromagnetic counterpart. These low-luminosity/choked GRBs would be more frequent than traditional GRBs.

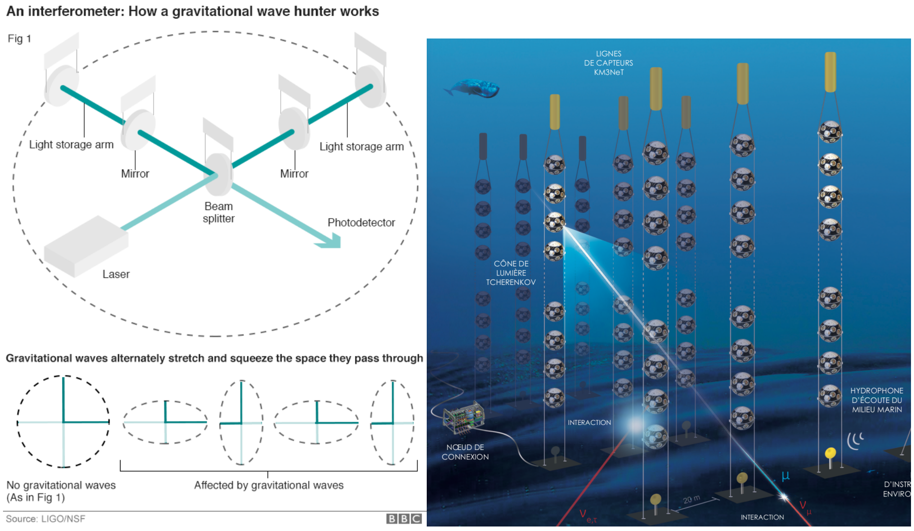

Figure 1: The detectors used for GWHEN - Left: a GW interferometer VIRGO/LIGO. Right: a KM3NeT HEN telescope.

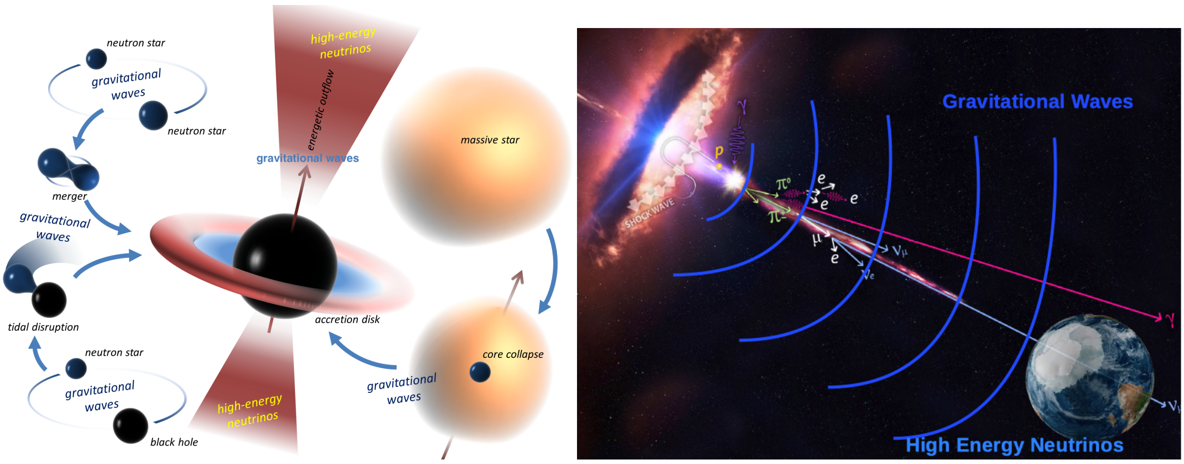

Figure 2: The sources for GWHEN - Left: Formation of a compact object through collapse or merger. Right : Signals from such a resulting object.

Section 2 : Scientific case for GWHEN

Finding EM Counterparts of GW signals - Fig. 3 shows the GW probability skymap for GW150914, a Binary Black Hole, covering 2% of the sky. For 2 detectors, this skymap consists in a ring on the sky, whereas for 3 detectors, it can still cover up to several hundreds of deg^2. This makes very difficult the identification of a possible EM counterpart, especially in the case of transients, where the signal can have faded by the time telescopes are observing the source location. In comparison, the localization of a HEN is better than 1° for energies above 1 TeV, depending on the topology of the neutrino event. For KM3NeT, the resolutions for tracks and showers will be well below the degree for tracks, reaching a few degrees for showers. The existence of a HEN counterpart would then greatly facilitate the finding of the EM counterpart if it exists, allowing for e.g. host identification and redshift measurement.

In particular, the future upgrades of GW interferometers will make possible the detection of a GW **with one detector only**, which will in turn widen the 90% probability region. In this case, a HEN counterpart, with its sub-degree localization will be crucial to find the possible EM counterpart.

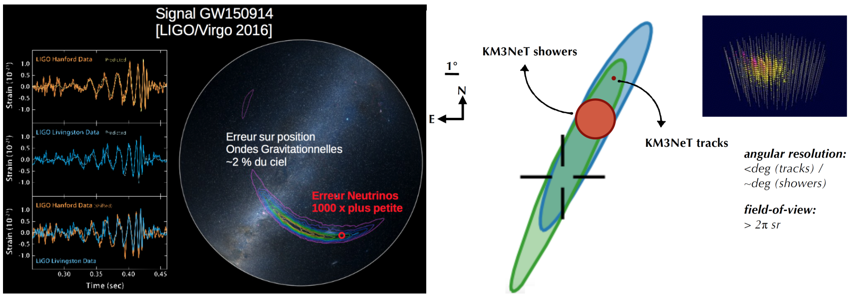

Figure 3: Left : error on GW signal position compared to HEN resolution. Right : Comparison of KM3NeT resolution for tracks and showers compared to the initial GW skymaps for GW170817 with 2 different pipelines.

The origin of Cosmic Rays - GW signals from sources described in Fig. 2 originates from the collapse/merger itself but can also be produced by the acceleration of matter in the relativistic jet [9]. In the case of HEN detected after/during such GW events, a precise study of the source(s), in particular the HEN spectrum, would yield valuable information about the origin of Cosmic Rays - as the HEN are produced by the interaction of hadronic CRs.

Section 3 : Selected results from previous GWHEN searches

"Initial" Detectors (2007 → 2011) - Searches have been performed using data from 2007 to 2011.

The first limits on the density population of GWHEN sources have been put using the S5-VSR1 GW data together with ANTARES data [10], in a dedicated "subthreshold" search, where each HEN was used to perform a triggered GW search. Using S6-VSR2-3 data, an optimised search has been developed, where the HEN strategy was tuned in order to maximize the number of detectable GW+HEN sources [10]. For a given coincidence "false-alarm" rate, an increase of the GW threshold results in a decrease of the HEN horizon, and vice-versa - there is a trade-off to be found between maximal GW efficiency and maximal HEN efficiency, in order for the GW and HEN horizons to be tuned. Such a strategy has been shown to allow for a joint sensitivity comparable to the one obtained with a similar search performed with IceCube, in spite of the reduced size of ANTARES [11]. Using the GW+HEN non-detection, it has also been possible to constrain the HEN jet opening angle to less than 20° for realistic GW emissions (lower than $10^{-2} M_{\odot} c^2$) and HEN emissions consistent with existing models (lower than 10^{52} erg).

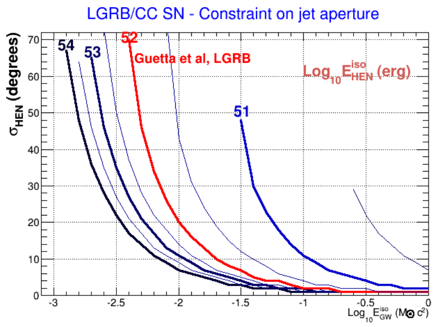

Figure 4: Limits on the jet opening angle for several GW and HEN energies [9].

"Advanced" Detectors (since 2015) - Since the discovery of GW, ANTARES and IceCube have several times associated their data sample to search for HEN emitted during GW events : binary black holes detected during the observation runs O1 and O2 for instance.

In particular for GW150914, the HEN emission was constrained to be less than 20% of the total energy emitted under the form of GW - limits that depends on the HEN spectrum and declination. For GW170817, a joint study performed by ANTARES, IceCube and the Pierre Auger Observatory constrained the HEN emission from 10^2 to 10^{11} GeV, for prompt or extended emissions [12].
Note that since the Observation Run O3, GW alerts are automatically treated by a dedicated ANTARES software, so that the ANTARES visibility skymap and the potential HEN candidates are known in a matter of seconds after the reception of a GW GCN alert [1].

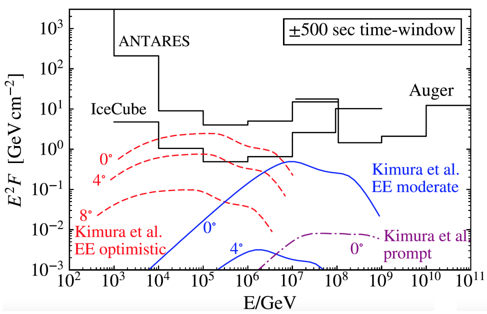

Figure 5: HEN limits for GW170817, in the case of a prompt emission [12].

[1]See for instance this map, which was included in a GCN submitted by ANTARES.

Finally, a search for correlation between HEN candidates from IceCube and ANTARES with "subthreshold" GW candidates was performed using O1 data. This study combines all the available information : GW signal-to-noise ratio, 90% skymap area, energy/direction of HEN, angular resolution, probability of being of astrophysical origin. In this study, the ANTARES time-varying selection criteria which was used improves by 50% the HEN performances. The obtained limits on the density population improves by a factor 100 the previous limits obtained with similar searches, obtained typically for $E_{\mathrm{GW}} = 10^{-2} M_{\odot} c^2$ [13].

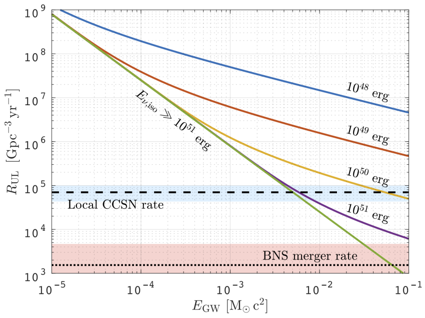

Figure 6: Upper Limits obtained on the rate density of GWHEN sources [13].

Section 4 : GWHEN in 10 years

A complete vision of Accretion/Ejection and the origin of CRs - While allowing for a thorough study of the origin of CRs by the GW+HEN emission of their sources, GWHEN correlations will obviously bring valuable information on the accretion to ejection sequences at work in such objects. In particular :

- Do all collapses induce the formation of a relativistic jet ?
- How often are binary mergers followed by the emission of a relativistic jet ?
- What is the time delay between the collapse/merger (given by the GW signal) and the onset of the HEN emission ?
- How and when CR/HEN are produced in these chains of events ?

Quantum Gravity Phenomenology - There is now a good knowledge of the time sequence of the (low energy) neutrino emission with respect to the GW signal in the case of a core-collapse supernova, which allows for time-of-flight experiments to extract information on the neutrino masses, but not only as the time-delay GW-HEN is an imprint of the underlying cosmology and fundamental physics [14] :

$$\Delta t_{GW-HEN} = \frac{1}{2}\left(\frac{m_\nu c^2}{E_\nu}\right)^2 \int_0^{z_0} \frac{dz}{(1+z)^2 H(z)} - \frac{3}{2}\frac{E_\nu}{E_{\mathrm{QG}}} \int_0^{z_0} \frac{dz(1+z)}{H(z)},$$

with $E_{\text{Quantum Gravity}}$ the quantum gravity (QG) energy scale. In particular for nearby sources $z \ll 1$, $\Delta t^{\mathrm{ms}}_{\text{Quantum Gravity}}(\mathrm{GW}-\nu) \simeq 0.15 \left(\frac{d}{10\ \mathrm{kpc}}\right)\left(\frac{E_\nu}{1\ \mathrm{TeV}}\right)\left(\frac{10^{19}\ \mathrm{GeV}}{E_{\text{Quantum Gravity}}}\right)$, in the Λ-CDM cosmology. Information on Quantum Gravity effects could be extracted from the observation of coincidence GW+HEN signals, provided that a good knowledge of the Accretion/Ejection sequence is acquired.

Standard Sirens and Cosmology - In a binary inspiral, the rate of change of the frequency of the GW signal depends mostly on one parameter, the *chirp* mass, a combination of the 2 stars masses. The observation of a GW signal thus yields the chirp mass. By using several detectors with different orientations, the inclination angle of the binary can be determined. With these 2 parameters measured, the waves' amplitude yield the distance to the source - see fig. 7.

Binary inspirals thus act as a GW-analogue of a standard candle, hence the term "standard siren" (using an analogy between sound and GW signal). In the case of an electromagnetic counterpart to the GW, a measurement of the spectrum of an associated host galaxy determines the redshift to the source. Finally, H_0 can be extracted using $cz = H_0 D$, with z measured thanks to the counterpart, and D from the GW observation. Note that the HEN counterpart can help identifying the host galaxy and hence facilitate the redshift measurement. Such Standard Sirens can also yield constraints on the Dark Energy Equation of State [15, 16].

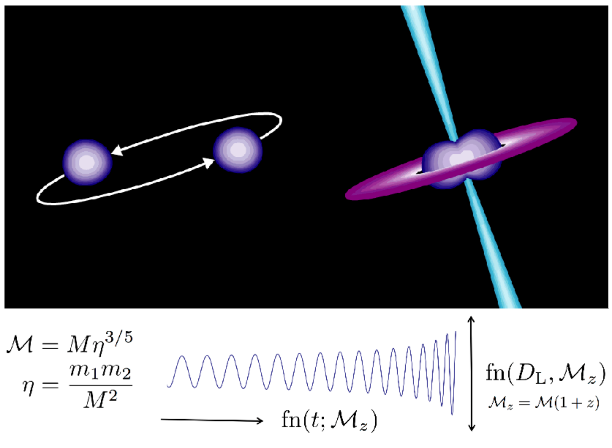

Figure 7: The GW signal of a BNS merger - the characteristic signal depends on the chirp mass and redshift, which is needed to extract the distance to the source.

Conclusions

During the decades 2020-2030 and beyond, the KM3NeT telescopes and other HEN telescopes will be observing the HEN sky from GeV to PeV energies (and even beyond with downgoing events), while Virgo/Ligo, and possibly ET, will have enlarged the already impressive GW horizon. Correlations of GW and HEN signal will probably become *routine* multi-messenger observations, and could have important consequences ranging from **astrophysics** (origin of hadronic cosmic rays, understanding of the collapse/merger to ejection sequence in compact objects), to **cosmology** (Hubble constant, Dark Energy) and **fundamental physics** (Quantum Gravity).

References

[1] D. Dornic for the KM3NeT groups **Multi-messenger neutrino analyses**, these Prospectives

[2] B. Mours et al., **Real time gravitational waves astronomy**, these Prospectives

[3] N. Leroy et al., **Multi-messenger astroparticle physics**, these Prospectives

[4] Ligo Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 116, 061102 (2016)

[5] GraceDB GW Public Alerts from Ligo-Virgo

[6] Ligo Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 119, 161101 (2017) ; Abbott et al. Astrophys. J. Lett. 848, L12 (2017)

[7] e.g. Aartsen et al. Physical Review Letters 113 (2014) 101101

[8] IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403, Science 361, eaat1378 (2018)

[9] T. Pradier, *Habilitation à Diriger des Recherches*, Université de Strasbourg (2015)

[10] e.g. Albert et al. - Astrophys. J. Lett. 850, L35 (2017) ; see also T. Pradier NIM A 602, Issue 1 (2009) 268-274 ; Antares Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration, JCAP 06 (2013) 006

[11] B. Baret VLVNT2018

[12] Antares Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration, Phys. Rev. D 93, 122010 (2016)

[13] Antares Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration, Astrophys.J. 870 (2019) no.2, 134

[14] S. Choubey, S. E. King, Phys. Rev. D, 67 (2003) 073005.

[15] Abbott et al. Nature 551, 85 (2017) ; see also Abbott et al. submitted to ApJ (2019)

[16] e.g. X. Zhang, Sci. China-Phys. Mech. Astron. 62, 110431 (2019) ; M. Du et al., Phys. Rev. D 100, 043535 (2019)