Gravitational Waves and Neutrinos

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We give an overview about the recent detection of gravitational waves by the Advanced LIGO first and second observing runs and by Advanced Virgo, with emphasis on the prospects for multi-messenger astronomy involving neutrino detections.

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1 Introduction

The detection of GW170817 [1], the coincident Gamma Ray Burst (GRB) [2], and the other electro-magnetic counterparts in a wide region of the spectrum from X to radio frequencies [3] marked the historical debut of Gravitational Waves (GWs) on the stage of Multi-messenger Astronomy in the first month of joint activity of the Advanced LIGO [4] and Advanced Virgo detector [5].

Historically, the first extra-solar multi-messenger detection happened with SN1987A [6] and involved a wide spectrum of electromagnetic signals and neutrinos that were detected by Kamiokande II [7], the Irvine-Michigan-Brookhaven Experiment (IBM) [8] and Baksan [9] neutrino observatories with energy $\sim 20$ MeV.

More recently, another multi-messenger transient event involving neutrinos has been detected, namely the extremely-high-energy neutrino event EHE170922A ($\sim$ PeV) [10] by IceCube and consistent detections of gamma ray flares by Fermi-LAT [11] and MAGIC [12] in a window of $\pm 5$ days enabled to identify the source as the active galactic nucleus TXS 0506+056 of the blazar category (i.e. with its relativistic jet directed to Earth producing a characteristic radio emission spectrum), with yet undetermined red-shift. Current interpretation of this astrophysical event is of ultra-high-energy protons producing pions eventually decaying into gamma rays and neutrinos.

In general powerful astrophysical objects, endowed with magnetic field and in the presence of strong astrophysical shocks are capable to accelerate particles to extremely high energy cosmic rays, whose subsequent interaction with radiation and matter can produce electromagnetic waves in an wide frequency range, and high energy neutrinos through decay of mesons.

Neutrinos can reach Earth from the entire cosmos because of their weak interaction with matter (and null interaction with electromagnetic radiation). Even more so for GWs, which can also be originated by the coherent, accelerated motion of astrophysically massive objects. As neutrinos and GWs can travel almost unaltered (apart from cosmological red-shift) from sources to detectors, they represent invaluable messengers to bring a snapshot of the source at their production.

Active searches for joint detections of GW events in coincidence with electromagnetic and neutrino events have received strong momentum by the first detection of GW events from binary black holes GW150914 [13], see [14] for a search of an electromagnetic counterpart and [15] for a neutrino one.

As in this first GW observation, neither neutrinos nor electro-magnetic counterparts have been detected in coincidence with the additional GW events produced by binary black holes coalescences so far observed by LIGO: GW151226 [16], GW170104 [17], GW170608 [18] and by LIGO and Virgo GW170814 [19]: the negative results of searches for coincident neutrino events are reported in [20], [21], [22].

Note that since the decay of a binary black hole pair is very slow, it is not expected
to be surrounded by matter at the time of coalescence, thus preventing the non gravitational messengers to be triggered by these kind of events, although exotic mechanisms to produce multi-messenger signals from binary black hole coalescences have been conceived, see e.g. [23], [24].

Combined searches for transient events by GW and neutrino detectors have been realized in the pre-GW-detection era as well, see e.g. [25] for an early attempt and [26] for a search of GWs in coincidence with neutrino events in a period of joint operations between year 2007 and 2010. Note that the 37 high-energy neutrino events at energies 20 TeV – PeV of cosmic origin observed by IceCube in a 3 year period 2010 and 2013 [27] have no astrophysical association. In particular 2 of the $E > 10^9$ TeV neutrinos were detected during the nominal initial LIGO-Virgo observation periods, however not all of the three GW detectors were operational, thus jeopardizing the possibility to determine interesting limits on joint sources of GWs and high energy neutrinos.

Upper limit rates of combined GW and high energy neutrino ($\gg$ GeV) source population on Initial (Advanced) LIGO-Virgo real (projected) data were computed in [28], with the result of non-detections implying less than $10^0 – \text{few} \times 10^{-2}$ event per Milky Way equivalent galaxy per year for isotropic equivalent energy release in the range $10^{-2} – 10^{-4} M_\odot$ (and upper limits on the event number almost 2 order of magnitude stricter for Advanced LIGO-Virgo).

The outline of this short paper is the following: in sec. 2 we give an overview of standard, non-exotic sources for a joint GW-neutrino detection and in sec. 3 we summarize the salient features of the sources that are imprinted in a GW observations and the prospect for future detections. We conclude in sec. 4 with an outlook of future combined detection of GWs and neutrinos.

## 2 Potential sources for coincident neutrino and gravitational detections

Main candidates for a future detection of GWs and neutrinos are GRBs from core collapse supernova and compact coalescing binaries involving at least one non-black hole object.

The duration distribution of GRBs shows a clear bi-modality, enabling the distinction between short ($\lesssim 2$ sec) and long ones ($\gtrsim 2$ sec), both being distributed isotropically in the sky supporting a cosmological origin and the former being preferentially harder than the latter, see e.g. [29].

Short GRBs were widely believed to originate from coalescing binaries involving at least one neutron star already before GW170817 detection, model that this observation has confirmed. Neutrino emission models cannot exceed (per flavor) fluence
\[ F \simeq \text{few} \times \left( \frac{E}{\text{GeV}} \right)^{-2} \left( \frac{d}{40 \text{ Mpc}} \right)^{-2} \text{GeV}^{-1}\text{cm}^{-2} , \]  

(1)

for the most optimistic choice of parameters [31] (and on-axis view, for a ±500 sec window around trigger time), with maximal neutrino energy expected between 100 TeV and 10 PeV, and neutrinos can be emitted within minutes of the GRB since they are associated with both prompt and extended emission of gamma rays. Even more stringent fluence upper limit applies if a millisecond, rapidly spinning, highly magnetized neutron star (magnetar) is created by the binary neutron star merger, which can emit over a longer time span (weeks) [32] (and for which maximal neutrino energy can exceed 100 PeV). In the case of maximal fluence, this limit is scraping the bottom of the upper limit set by the ANTARES, IceCube and Auger non-observation of a neutrino counterpart of GW170817 [30], which were able constrain the neutrino fluence in the 100 GeV – 10^5 PeV energy window, with GW170817 having origin in a galaxy at a distance of 40 Mpc from Earth.

Neutrino flux can also be modulated by the viewing angle, with fluxes decreasing rapidly when the observation angle exceeds the opening angle of the jet.

The energy released in GWS by short GRB events originated by coalescing binaries can extend up to 10^{-2} M_\odot, from which GW spectral amplitude \( h_s \) can be computed:

\[ h_s \simeq 10^{-21} \text{Hz}^{-1/2} \left( \frac{E}{10^{-2} M_\odot} \right)^{1/2} \left( \frac{f_{GW}}{1 \text{kHz}} \right)^{-1} \left( \frac{D}{1 \text{Mpc}} \right)^{-1} , \]  

(2)

allowing a detection up to \( O(100) \) Mpc given the noise level of Advanced interferometer that have reached sensitivity \( h_s \simeq \text{few} \times 10^{-23} \text{ Hz}^{-1/2} \) in the frequency range between 100 Hz and 1 kHz.

Pre-GW detection era results tried to dig into GW data to search for signals in coincidence with both and long GRBs [33], with the result that no association could be made, with closest GRB considered being at a distance \( \sim 150 \) Mpc (corresponding to red-shift \( z \simeq 0.05 \)).

Long GRBs are instead thought to be originated by the core-collapse of massive (few \( \times 10 M_\odot \)) stars [34] and their isotropically equivalent luminosities can range between \( 10^{51} \) and \( 10^{53} \) erg/sec. According to the collapsar model long GRBs are triggered by the core-collapse explosion of a stripped-envelope massive star, after which powerful jets of matter plow through the collapsing star along the spin-axis, eventually matter flows towards a newly formed black hole or magnetar reaching relativistic speeds, and producing GRBs.

High energy neutrinos (\( \gg \) GeV) can be produced before the jet outflows and their production can still be active during the afterglow, so that no clear prediction can

\[ \int_{-\infty}^{\infty} dt h^2_+(t) + h^2_\times(t). \]
be made for their arrival time. Neutrino fluxes for energies in the range 100 GeV to 100 TeV can be estimated to be around $100 \times (d/10 \text{Mpc})^{-2}$ events at a distance $d$ (for a km-scale water- or ice-Cherenkov detector)\cite{35}, where value at least $O(10)$ are phenomenologically interesting.

Long GRBs can are further divided on observational basis into low-luminosity core collapse supernovae, engine-driven core collapse supernovae, standard low-luminosity GRBs with core-collapse supernovae, and canonical long GRBs, with considerable uncertainty in estimates for neutrino fluxes.

Another interesting sources for joint detection of GWs and neutrinos are magnetars which represent the best model to explain soft gamma repeaters and anomalous X-ray pulsars, which display repeated outburst of short duration ($\sim 0.1$ sec) with peak luminosity of $\sim 10^{42}$ erg/sec, thus much less luminous than GRBs (even though some rare SGR have reached luminosities of $10^{47}$ erg/sec\cite{36, 37}). LIGO/Virgo have already searched in 2008-2010 data for signals in coincidence with galactic soft gamma repeaters, with negative results\cite{38}.

3 Gravitational Wave detector physics

Advanced LIGO and advanced Virgo GW detectors are Michelson interferometer with Fabri-Perot cavities which represent the most precise ruler ever made: by measuring the differential variation of the interferometer’s arms they can monitor the passage of a GWs in the frequency range from few tens of Hz to roughly 1 kHz. Because of the frequency range interferometric GW detectors are sensitive only to binary coalescence of compact objects, thus small enough ($\sim 10 - 100$ km) that can achieve such high orbital frequencies. Interferometers respond linearly to the GW strain by measuring the difference in optical path with the result of being mild directional detectors, as they can detect only GWs that do not alter symetrically the two end mirrors.

GWs have 2 polarizations, conventionally called $h_+$ and $h_\times$ and each detector is sensitive to only one linear combination of them, the coefficients of proportionalitys between detector output and $h_+, h_\times$ being the pattern functions $F_+, F_\times$, see fig. 1 for the values of the LIGO and Virgo pattern functions at the time of GW170817.

For un-modeled events LIGO and Virgo search for excess noise but for coalescing binaries accurate theoretical models exist enabling to correlate observational data with pre-computed templates.

One important quantitative detail is that because of the quadrupolar nature of the source the two polarization are affected in a specific way by the relative orientation of the binary orbital plane and the observation direction. Denoting such angle by $\iota$ one has

$$
\begin{align*}
h_+ &\propto \frac{1 + \cos^2 \iota}{2}, \\
h_\times &\propto \cos \iota,
\end{align*}
$$

\text{(3)}
introducing a degeneracy between $\iota$ and the source-observer distance to which the GW amplitude is inversely proportional: stronger signals could equally well be closer and misaligned or farther and better aligned, with the latter possibility favoured a priori because at a larger distance more volume is available, hence more possible sources [39].

GWs can be localized with reasonable accuracy (e.g. the 90% credible region of GW170817 which happened at 40 Mpc from Earth and was observed by 3 detectors, measured 28 degree squared, with lower precision expected for fainter objects) by short-circuiting the data of the time of arrival (triangulation) and the information from the signal amplitudes and phases across the detector network [40], with the result shown in fig.2 for GW170817, where the GRB [3] and optical [41] localizations are also shown.

Source-detector orientation also matters for neutrino observatories as for e.g. surface neutrino detectors like Auger have the optimal condition represented by high-
energy ($\gg 100$ TeV) showers created close to the detector by neutrinos with earth-grazing incidence, see fig. 3 for the neutrino detector orientation with respect to GW170817. In-ice (like IceCube) and in-water (like ANTARES) detectors can take advantage of earth shield for up-going neutrino (however Earth stop being transparent at $E > 10$ PeV) or look preferably at sufficiently high energy ($> 100$ TeV) to kill the background of penetrating muons from cosmic ray showers.

4 Conclusions

The study of transient sources, which involve compact objects and ultra-violent phenomena (such as gamma-ray bursts and magnetars) is a very active, promising and new field of research in astronomy. Neutrino and gravitational waves have their own specific characteristics making them unique messengers from the most energetic astrophysical events, beside carrying invaluable information on the fundamental structure of matter and interactions.

Detectors sensitivities are expected to improve in the coming years, pushing for a perseverant effort in the coordination for a joint detection, possibly solving in the future the puzzle of the still unexplained origin of the extremely high energy neutrino events ($\sim$ PeV) [12], which could be the first indication of an astrophysical neutrino flux, and allowing another insightful messenger to carry information about astrophysical sources.
Figure 3: Location of neutrino experiments and line dividing up/down directions. Also reported are the position of GW170817 at emission (black circle) and at the time of the first optical detection (red circle), 10.87h afterwards, by the One-Meter Two-Hemisphere (1M2H) team with the 1 m Swope telescope at Las Campanas Observatory in Chile. Adapted from [30].

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