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Multimessenger astronomy with gravitational waves and high-energy neutrinos

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Many of the astrophysical sources and violent phenomena observed in our Universe are potential emitters of gravitational waves and high-energy cosmic radiation, in the form of photons, hadrons, and presumably also neutrinos. Both gravitational waves (GW) and high-energy neutrinos (HEN) are cosmic messengers that may escape very dense media and travel unaffected over cosmological distances, carrying information from the innermost regions of the astrophysical engines (from which photons and charged cosmic rays can barely reach us). For the same reasons, such messengers could also reveal new, hidden sources that have not been observed by conventional photon-based astronomy. Coincident observation of GWs and HENs may thus play a critical role in multimessenger astronomy. This is particularly true at the present time owing to the advent of a new generation of dedicated detectors: the neutrino telescopes IceCube at the South Pole and ANTARES in the Mediterranean Sea, as well as the GW interferometers Virgo in Italy and LIGO in the United States. Starting from 2007, several periods of concomitant data taking involving these detectors have been conducted and more joint datasets are expected with the next generation of advanced detectors planned to be operational by 2015. Combining the informations obtained from these totally independent detectors can provide original ways of constraining the processes at play in the sources, and also help confirming the astrophysical origin of a GW or HEN signal in case of concomitant observation.
Given the complexity of the instruments, a successful joint analysis of this data set will be possible only if the expertise and knowledge of the data is shared between the two communities. This review aims at providing an overview of both theoretical and experimental state-of-the-art and perspectives for such a GW+HEN multimessenger astronomy.

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I. INTRODUCTION

High-energy multimessenger astronomy has entered an exciting era with the development and operation of new detectors offering unprecedented opportunities to observe the universe through all kind of cosmic radiations. In particular, both high-energy ($\gg$GeV) neutrinos (HENs) and gravitational waves (GWs), which have not yet been directly observed from astrophysical sources, are on the waiting list for a first detection (see e.g. Becker (2008); Márka *et al.* (2011) for reviews on these subjects). Contrary to high-energy photons (which are absorbed through interactions in the source and by the photon backgrounds) and charged cosmic rays (which are deflected by ambient magnetic fields), both HENs and GWs can escape from the core of the sources and travel with the speed of light through magnetic fields and matter without being altered. They are therefore expected to provide important information about the processes taking place in the core of the production sites and they could even reveal the existence of sources opaque to hadrons and photons, that would have remained undetected so far.

Many astrophysical sources are expected to produce both GWs and HENs; most of them originate from cataclysmic events. While GWs are linked to the dynamics of the bulk motion of the progenitor, HENs would trace the interactions of accelerated protons (and possibly heavier nuclei) with ambient matter and radiation in and around the source. An overview of the most plausible sources of HENs and GWs is presented in Section II.A of this article, along with relevant references. It includes transient sources like the extra-galactic gamma-ray bursts (GRBs), for which popular progenitor models involve either the collapse of a highly-rotating massive star or the merger of a binary system of compact objects (neutron star/neutron star or black hole/neutron star); both of these scenarios are expected to be associated with the emission of GWs. The presence of accelerated hadrons in the jets emitted by the source would ensure the subsequent production of HENs. Microquasars and magnetars, though less powerful sources, are closer (galactic) and more frequent; they are also considered as possible GW+HEN emitters. Observation-based phenomenological arguments bounding the time delay between the GW and HEN emission in the sources are presented in Section II.B.

The current efforts carried out for the detection of GWs and HENs are described in section III. Concerning the detection of neutrinos, huge ($\sim$km^3) volumes of target material need to be monitored to compensate for the feeble signal expected from the astrophysical sources. Currently operating neutrino telescopes are in-water or in-ice Cherenkov detectors which rely on the construction of 3D arrays of photomultiplier tubes. IceCube (Halzen and Klein (2010); see also `http://icecube.wisc.edu`) is a km^3-scale detector located at the geographic South Pole, while ANTARES(Ageron *et al.* (2011a); see also `http://antares.in2p3.fr`), with an instrumented volume $\sim$ 0.02 km^3, is deployed undersea, 40 km off the French coast and serves as a prototype for a future km^3-scale detector in the Mediterranean. The combination of the two detectors provides full coverage of the sky and partial redundancy.

The direct detection of GWs is performed through the operation of large ($\sim$km long) laser interferometers. The currently operating GW observatories are the two LIGO detectors (Abbott *et al.* (2009a); see also `http://www.ligo.org`) in the USA (one in Livingston, Louisiana, another in Hanford, Washington), Virgo (Accadia *et al.* (2011); see also `http://www.virgo.infn.it`) near Pisa (Italy) and GEO (Grote (2010) ; see also `http://geo600.aei.mpg.de`) near Hanover (Germany). Those instruments form a network of detectors enabling the localisation of astrophysical sources.

While the detection of coincident GW and HEN signals would be a landmark event signing the first observational evidences for both GW and HEN, it is also a way to enhance the sensitivity of the joint detection channel by exploiting the correlation between HEN and GW significances, taking advantage that the two types of detectors have uncorrelated backgrounds. The bottom line of a joint analysis is to ask for the consistency of the detections in time and space. This allows a significant suppression of the background, hence a potential increase of the discovery potential. Section IV starts with laying the basics of the data analysis procedures used in each experiment, including the performance of the detectors, and concentrating on the important aspects connected to GW+HEN searches such as the accuracy of the source sky position reconstruction. Different options for a combined GW+HEN analysis are then presented. Section IV.C describes a method for a HEN-triggered GW search: in this case, the search for GW signals is performed only in parts of the sky defined by neutrino candidate events, and within a time window defined by the observational and phenomenological considerations discussed in Section II.B. Alternatively, comprehensive searches for space-time coincidences between independent lists of neutrino and GW events can also be performed, as illustrated in Section IV.D. In this case, time-coincident signals are tested for correlation using a combined GW+HEN likelihood skymap, as well as additional information on the individual significance of the HEN and GW candidates. This second, more symmetric and comprehensive option requires the existence of two independent analysis chains scanning the whole phase space in search for interesting events.

Preliminary investigations of the feasibility of such searches have been performed by Aso *et al.* (2008) and 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 (e.g. 1/(600 yr) for some realistic parameters). A major challenge for the analysis lies in the combined optimisation of the selection criteria for the different detection techniques. The joint search activities described in this paper are performed in the framework of a dedicated GW+HEN working group involving collaborators from all the previously mentioned experiments. The data-exchange policies are regulated by specific bilateral Memoranda of Understanding.

II. THE SCIENCE CASE FOR MULTIMESSENGER GW+HEN SEARCHES

A. Potential emitters of GW and HEN

1. Gamma-ray bursts

Gamma-ray Bursts (GRBs) are detected as an intense and short-lived flash of gamma-rays with energies ranging from tens of keVs to tens of GeVs. The morphology of their light curves is highly variable and typically exhibits millisecond variability, suggesting very compact sources and relativistic expansion. GRBs are divided into two classes depending on the duration of their prompt gamma-ray emission, which appears to be correlated with the hardness of their spectra and are believed to arise from different progenitors: the short-hard bursts last less than 2 seconds, while the emission of long-soft bursts can last up to tens of minutes.

The BATSE detector, launched in 1991 on board the Compton Gamma-Ray Observatory, was the first mission to accumulate observations on more than a thousand GRBs, establishing the isotropy of their sky distribution and characterizing their light curve and broken power-law spectra (Paciesas *et al.*, 1999). The detection of X-ray and optical counterparts pertaining to the afterglow phase of several GRBs, triggered by the first observation of an X-ray transient emission from GRB970228 by the BeppoSAX satellite (Costa *et al.*, 1997), subsequently confirmed their extragalactic origin by allowing more accurate a localization of the source. Currently operating GRB missions include *Swift* (Gehrels *et al.*, 2004), hosting a wide-field hard X-ray (15 keV - 350 keV) burst alert telescope (BAT) coupled to softer X-ray, ultraviolet and optical telescopes and the Fermi Gamma-Ray Space Telescope (Atwood *et al.*, 2009) which focuses on the high-energy (15 keV - 300 GeV) emission from GRBs.

In the standard picture (see e.g. Mészáros and Rees (1993) and the review by Piran (2004)), the mechanism responsible for the enormous energy release ($\sim 10^{50} - 10^{52}$ ergs) and super-Eddington luminosity of GRBs is the dissipation (via internal shocks, magnetic dissipation and/or external shocks) of bulk kinetic or magnetic energy into highly relativistic particles, which are accelerated to a non-thermal energy distribution via the Fermi mechanism in a relativistically expanding fireball ejected by the GRB central engine. The accelerated electrons (and positrons) in the intense magnetic field emit non-thermal photons via synchrotron radiation and inverse Compton scattering.

The canonical fireball phenomenology also promotes GRBs to cosmic ray sources, through Fermi acceleration of hadrons present in the highly boosted astrophysical jet. GRBs are in fact considered as a prime candidate source for the ultra-high-energy cosmic rays (UHECR), observed at energies $E \sim 10^{18} - 10^{20}$ eV, and whose origin and composition is still unknown (Levinson and Eichler, 1993; Vietri, 1995; Waxman, 1995). A detailed discussion of the association between GRBs and UHECRs is beyond the scope of the present colloquium; it can be found in the recent review by Waxman (2011).

Provided that the outflowing jet has a baryonic component, protons will also be shock-accelerated and will undergo interactions with the gamma-rays and/or other protons inside the fireball, producing charged pions and kaons that will subsequently decay into HENs ($\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\overline{\nu}_{\mu} \rightarrow e^{\pm} + \nu_e/\overline{\nu_e} + \nu_{\mu}/\overline{\nu}_{\mu})$[1]. Such neutrinos are emitted in spatial and temporal coincidence with the GRB prompt electromagnetic signal; their energy is typically in the range $\sim$ TeV to PeV. Neutrinos with higher (up to $\sim 10^{10}$ GeV) energy can also be emitted at the beginning of the afterglow phase, when the outflow is decelerated by external shocks with ambient material and the accelerated protons undergo interactions with the matter outside of the jet (Waxman and Bahcall, 2000).

The pick-up of ex-neutrals has also been suggested by Levinson and Eichler (2003) as an alternative model for neutrino production in fireballs. A decaying neutron, or, further downstream, a neutral atom that is ionized, is extremely energetic in the jet frame, and immediately attains an energy of a PeV. The associated neutrinos would come within an order of magnitude of that energy (~ 100 TeV), providing a harder spectrum than the one expected from shock acceleration.

While gamma-ray and HEN emissions from GRBs are related to the mechanisms driving the relativistic outflow, GW emission is closely connected to the central engine and hence to the progenitor of the GRB (although the possibility of gravitational radiation directly from the acceleration of the jets has also been considered by Piran (2002)). Short-hard GRBs are thought to be driven by neutron star–neutron star or neutron star–black hole mergers[2]. Coalescing binaries are expected to emit GWs that are detectable from large distances (Flanagan and Hughes (1998a); Flanagan and Hughes (1998b); Kobayashi and Mészáros (2003)), ~ 15 Mpc with current GW detectors and $\sim$ O(100 Mpc) with Advanced LIGO and Advanced Virgo. These distances coincide with the range where HEN flux is thought to be large enough for detection with current HEN detectors.

Long-soft GRBs are most probably induced by "collapsars", i.e. collapses of a massive star into a black hole, with the formation of an accretion disk and a jet that emerges from the stellar envelope (Woosley and MacFadyen (1999);Woosley and Bloom (2006)). The high rotation rate required to form the accretion disk that powers the GRB allows the production of GW via bar or fragmentation instabilities[3]. Asymmetrically infalling matter produces the burst GW signals not only at the moment of core bounce when the central density exceeds the nuclear density (Kotake *et al.*, 2006; Ott, 2009), but also at the moment of black hole formation, followed by the subsequent ring-down phases (Ott *et al.*, 2011). In addition, general relativistic effects predict the precession of the inner hyperdense accretion disk with the consequent production of GWs (Romero *et al.*, 2010). This GRB population is distributed over cosmological distances so that the associated HEN signal is expected to be faint. Interestingly, Eiroa and Romero (2008) suggested recently that gravitational lensing by supermassive black holes can enhance the chance of HEN detection of nearby and long GRBs. The same lens can act upon the GW since the size of the Einstein ring is far larger than the wavelength of the waves.

Long GRBs include a subclass referred to as "low-luminosity GRBs" (*ll*GRBs), with few orders of magnitude smaller gamma-ray luminosities than conventional GRBs, a smooth single peaked light curve and a soft spectrum. These bursts are associated with particularly energetic type Ibc core-collapse supernovae as observed in GRB 980425/SN 1998bw (Galama *et al.*, 1998; Kulkarni *et al.*, 1998), GRB 031203/SN 2003lw (Malesani *et al.*, 2004; Soderberg *et al.*, 2004b), and GRB 060218/SN 2006aj (Campana *et al.*, 2006; Cobb *et al.*, 2006; Pian *et al.*, 2006; Soderberg *et al.*, 2006). Less luminous than typical long GRBs, these events are (not surprisingly) discovered at smaller distances (SN 1998bw at redshift $z = 0.0085$, about 40 Mpc away from Earth, SN 2003lw at $z = 0.105$, and SN 2006aj at $z = 0.033$). Remarkably, the event rate of *ll*GRBs per unit local volume is more than one order of magnitude larger than that of conventional long GRBs (Coward, 2005; Daigne and Mochkovitch, 2007; Guetta and Della Valle, 2007; Liang *et al.*, 2007; Soderberg *et al.*, 2006), making this source population an interesting target of study also from the GW+HEN point of view (Gupta and Zhang, 2007; Murase *et al.*, 2006; Razzaque *et al.*, 2004; Wang *et al.*, 2007).

Bromberg *et al.* (2011) have recently argued that, given their apparently low power, these *ll*GRBs cannot arise from the regular collapsar model for the time needed for the jet to bore an escape channel through the host envelope would, in most reported cases, exceed their duration. Rather, they may be gamma rays from break-out shocks imparted to the host envelope by jets that themselves fail to emerge ("choked jets")[4]. The smooth light curve and soft spectra of these events are indeed expected from shock breakout (Katz *et al.*, 2010; Nakar and Sari, 2011; Waxman *et al.*, 2007). Other suggested models, which produce smooth, soft emission, include scattering of the gamma rays off an accelerating envelope or wind material (Eichler and Levinson, 1999), or gamma rays that are released from baryon-rich jet material (dirty fireballs) only after some adiabatic loss (Mandal and Eichler, 2010). It has also been suggested that *ll*GRBs are associated with the formation of magnetars rather than black holes, as argued for GRB060218 by Mazzali *et al.* (2006), a scenario that might give rise to somewhat longer GW signals (Corsi and Mészáros, 2009; Piro and Ott, 2011).

Choked Gamma-Ray Bursts, namely events where jets fail to break through the stellar envelope and thus which do not produce a regular prompt GRB, have been hypothesized by various authors[5] and are interesting objects on their own regardless of the

[1] Relevant references on these mechanisms include Eichler (1994), Paczynski and Xu (1994), Waxman and Bahcall (1997), Rachen and Mészáros (1998), Alvarez-Muñiz *et al.* (2000), Mészáros and Waxman (2001), Mészáros and Waxman (2001), Guetta and Granot (2003), Razzaque *et al.* (2003a), Razzaque *et al.* (2003b), Dermer and Atoyan (2003), Guetta *et al.* (2004), Ando and Beacom (2005), Murase and Nagataki (2006), Murase *et al.* (2006).

[2] See Eichler *et al.* (1989); Kochanek and Piran (1993); Nakar (2007); Bloom *et al.* (2007); Lee and Ramirez-Ruiz (2007); Etienne *et al.* (2009).

[3] See Fryer and Woosley (1998); Davies *et al.* (2002); Fryer *et al.* (2002); Kobayashi and Mészáros (2003); Piro and Pfahl (2007).

[4] See MacFadyen *et al.* (2001); Tan *et al.* (2001); Campana *et al.* (2006); Wang *et al.* (2007); Waxman *et al.* (2007); Katz *et al.* (2010); Nakar and Sari (2011).

[5] See e.g. Eichler and Levinson (1999); Mészáros and Waxman (2001); Ando and Beacom (2005)

question whether they produce *ll*GRBs or not. In fact, late-time radio emission of some type Ic supernovae indeed suggests the presence of mildly relativistic outflow (Granot and Ramirez-Ruiz, 2004; Mazzali *et al.*, 2005; Soderberg *et al.*, 2004a, 2010) that may indicate the activity of a jet in these cases.

The expected overall energy budget of choked jets is large and comparable to the one observed in regular GRBs. Note that if indeed a choked jet produces a *ll*GRB via shock breakout, the prompt γ-rays involve only a small fraction of the total energy (Bromberg *et al.*, 2011; Nakar and Sari, 2011). These choked jets could be, therefore, promising emitters of GWs and HENs[6], as current estimations predict potentially observable levels of signal as well as a relatively high occurrence rate in the volume probed by current GW and HEN detectors. An ejecta at 10 Mpc with kinetic energy of 3×10^{51} erg and Lorentz factor of 3 would e.g. generate ∼30 neutrino events detected in a km^3 detector (Ando and Beacom, 2005). The production of HEN is closely related to the efficiency of proton acceleration inside the jet, an issue which is still debated considering that the relevant shocks in these choked GRBs are expected be radiation-dominated (Levinson and Bromberg, 2008). In this context, HEN and GW could play a crucial role in revealing the properties of these elusive sources whose detection through conventional astronomical telescopes appears to be highly challenging.

Alternatively, and provided that the emission mechanisms are sufficiently well known, a precise measurement of the time delay between electromagnetic, HEN and GW signals coming from a very distant source could also probe quantum-gravity effects such as a violation of the Lorentz invariance (Alfaro *et al.*, 2000; Amelino-Camelia, 2003; Choubey and King, 2003; Jacob and Piran, 2007) or set constraints on dark energy models(Choubey and King, 2003). GRBs appear as good candidates, *albeit* quite challenging (Gonzalez-Garcia and Halzen, 2007), for such time-of-flight studies.

2. Galactic sources

Soft gamma-ray repeaters (SGRs) are X-ray pulsars which have quiescent soft (2-10 keV) periodic X-ray emissions with periods ranging from 5 to 10 s. They exhibit repetitive erratic bursting episodes lasting a few hours each and composed of numerous very short ($\sim$ ms) pulses. Every once in a while they emit a giant flare in which a short (< 0.5 sec) spike of harder radiation is observed; such flares can reach peak luminosities of $\sim 10^{47}$ erg/s, in X-rays and γ-rays. A handful of SGR sources are known, most of them in the Milky Way and one in the Large Magellanic Cloud. Their population has been increasing in the last years, thanks to more sensitive instruments and better monitoring[7]. Three of them have had hard spectrum ($\sim$ MeV energy) giant flares: one with a luminosity of 10^{40} J/s, the two others being two orders of magnitude weaker.

The favoured *magnetar* model for these objects is a neutron star with a huge magnetic field $B \gtrsim 10^{15}$ G (Duncan and Thompson, 1992; Thompson and Duncan, 1995, 1996), which is subject to star-quakes that are thought to fracture the rigid crust, causing outbursts. The giant flares result from the formation and dissipation of strong localized currents due to magnetic field rearrangements associated with the quakes, and liberate a high flux of X- and γ-rays. Sudden changes in the large magnetic fields would accelerate protons or nuclei that produce neutral and charged pions in interactions with thermal radiation. These hadrons would subsequently decay into TeV or even PeV energies γ-rays and neutrinos (Halzen *et al.*, 2005; Ioka *et al.*, 2005), making flares from SGRs potential sources of HENs. An alternative model involving a large scale rearrangement of the magnetic field has also been proposed by Eichler (2003), which allows for huge energy releases, and detectable HEN fluxes from Galactic magnetars even for relatively small HEN efficiencies.

During the crustal disruption, a fraction of the initial magnetic energy is annihilated and released as photons, and the stored elastic energy is also converted into shear vibrations. SGR flares should excite to some extent the fundamental or f-modes of the star, which radiate GW with damping times of $\sim$ 200 ms (de Freitas Pacheco, 1998; Gualtieri *et al.*, 2004; Lindblom and Detweiler, 1983). These timescales are shorter than other relevant ones, except for the Alfvén-wave crossing time of the star, to which they are comparable. If much of the flare energy goes into exciting the f-modes, they might emit GW energy exceeding the emitted EM energy. While detailed predictions about the GW amplitude are difficult to obtain, Corsi and Owen (2011) estimated that the maximum GW energy is of the order of magnitude of 10^{48} erg 10^{49} erg. For sources at a distance of 1 kpc from Earth such as the recently discovered SGR0501+4516, this emission level place the expected amplitudes within range of current interferometric GW detectors (Abadie *et al.*, 2011b). However, if the fraction of flare energy that goes into exciting the f-mode is small, a detection of GWs from f-modes may be difficult (Levin and van Hoven, 2011; Zink *et al.*, 2011). On the other hand, lower frequency modes may be excited. For example, torsional modes ($\sim$ 100 Hz) have been suggested to couple well to flares (Levin and van Hoven, 2011; Zink *et al.*, 2011). The viability of low-frequency modes for potential GW observations is uncertain and a topic of ongoing investigations (Kashiyama and Ioka, 2011; Levin and van Hoven, 2011; Zink *et al.*, 2011, e.g.).

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[6] See Eichler and Levinson (1999);Mészáros and Waxman (2001); Ando and Beacom (2005); Koers and Wijers (2007); Horiuchi and Ando (2008).

[7] See e.g. Hurley *et al.* (1999a); Hurley *et al.* (1999b); Cline *et al.* (2000); Kulkarni *et al.* (2003); Palmer *et al.* (2005); Mereghetti (2008); Aptekar *et al.* (2009); Hurley (2010); Göğüş *et al.* (2010); Kaneko *et al.* (2010); van der Horst *et al.* (2010).

Microquasars (MQs) are galactic jet sources associated with some classes of X-ray binaries involving both neutron stars and black hole candidates. During active states, the X-ray flux and spectrum can vary substantially, with a total luminosity that often exceeds the Eddington limit. A considerable fraction of the liberated accretion energy appears to be released in the jets of the microquasar, giving rise to intense radio and IR flares (Mirabel *et al.*, 1998). Radio monitoring of X-ray transients has revealed superluminal motions in some objects, indicating that the jets are relativistic, with $\Gamma \sim 1 - 10$. The duration of major ejection events is typically of the order of days, while that of less powerful flares is correspondingly shorter (minutes to hours). The correlation between the X-ray and synchrotron emissions clearly indicates a connection between the accretion process and the jet activity. Whether radio and IR outbursts represent actual ejection of blobs of plasma or, alternatively, formation of internal shocks in a quasi-steady jet is unclear. In any case, since the overall time scale of outbursts is much longer than the dynamical time of the compact object (milliseconds), it is likely that shocks will continuously form during the ejection event.

The content of jets in microquasars remains an open issue. A possible diagnosis of e-p jets is the presence of Doppler-shifted spectral lines, such as the Hα line seen in SS433. Taking the example of LS 5039, Aharonian *et al.* (2006) and Aiello *et al.* (2007) have argued in favor of a hadronic origin of TeV photons, especially if produced within the binary system. In the case of windy microquasars in particular, hadronic interactions seem to be unavoidable (Romero *et al.*, 2003). The detected γ-rays should then be accompanied by a flux of high energy neutrinos emerging from the decays of $\pi^{\pm}$ mesons produced in pp and/or pγ interactions (Distefano *et al.*, 2002; Romero and Vila, 2008; Vila and Romero, 2010). The flux of TeV neutrinos, which can be estimated on the basis of the detected TeV γ-ray flux, taking into account the internal $\gamma\gamma \to e^+e^-$ absorption, depends significantly on the location of the γ-ray production region. HESS/EGRET data agree well with a production of γ (and neutrinos) at the base of the jet, very close to the onset of the acceleration phase. Reynoso and Romero (2009) however pointed out that the effect of strong magnetic fields can attenuate the neutrino signal through the cooling of charged pions and muons. The detectability by Ice Cube, ANTARES and other future km^3-scale telescopes strongly depends on the high-energy cutoff in the spectrum of parent protons. Romero and Vila (2008) also remarked that internal absorption in the inner jets of MQs can suppress high-energy gamma-ray emission leading to “dark” neutrino sources.

Two kinds of processes could lead to detectable GW signals from MQs. First, the matter accreted around the central object could fall into it, and, provided that the process is fast enough, trigger the resonance of normal modes in the central object as described by Price (1972) and Nagar *et al.* (2007). This would typically result in a damped sine signal, which could continue during the ejection phase. Second, the acceleration of the matter in the jet is the origin of a short GW burst. For both signals, the amplitude depends critically on the accreted/ejected mass. The time-lag between the two processes is unknown, and could range from ms up to several days.

B. Bounds on the GW+HEN time delay

The possible time delay between the arrival of GWs and HENs from a given source defines the coincidence time window to apply in a multimessenger search algorithm. This window should not be too small, which could lead to the exclusion of potential emission mechanisms, nor too large, which would decrease the detection sensitivity by including non-physical coincidences. Upon detection, the difference between the times of arrival of GW and HEN signals can give us important clues of the emission mechanism. For instance detecting a HEN prior to a GW signal may indicate that the strongest GW emission from the source is not connected to the onset of the activity of the central engine that one might expect from core-collapse models.

Baret *et al.* (2011a) used model-motivated comparisons with GRB observations to derive a conservative coincidence time window for joint GW+HEN searches. Various GRB emission processes were considered, assuming that GW and HEN emission are connected to the activity of the central engine. Considered processes include prompt gamma-ray emission of GRBs, with a duration upper limit ($\sim$ 150 s) based on BATSE observations (Paciesas *et al.*, 1999), as well as GRB precursor activity, with an upper limit on the time difference (as compared to the onset of the main burst) of $\sim$ 250 s, following the analysis of Burlon *et al.* (2009). Further processes considered include precursor neutrino emission, as well as $\gtrsim$ 100 MeV photon emission from some GRBs, as detected by Fermi LAT (Atwood *et al.*, 2009). The authors conclude that GW and HEN signals are likely to arrive within a time window of $\pm$ 500 s, as illustrated in Figure 1.

The time-delay between HENs and GWs could be much smaller for binary mergers which are often mentioned as the possible progenitor of short-hard GRBs. The amount of accreted/ejected matter involved in such case is very small, and the outflowing matter can expand unhindered, adding almost nothing to the time delay. A semi-analytical description of the final stage of such merger indicates that most of the matter is accreted within 1 second (Davies *et al.*, 2005), and numerical simulations on the mass transfer suggest time scales of milliseconds (Shibata and Taniguchi, 2008) to few seconds maximum (Faber *et al.*, 2006). Therefore, the GW signal is expected to arrive very close to HENs. A window of $[-5, +1]$ seconds around the trigger time, as used for (short) GRB-GW searches (Abadie *et al.*, 2010c; Abbott *et al.*, 2008), seems reasonable. More details on the justification on this window can be found in (Dietz *et al.*, 2011).

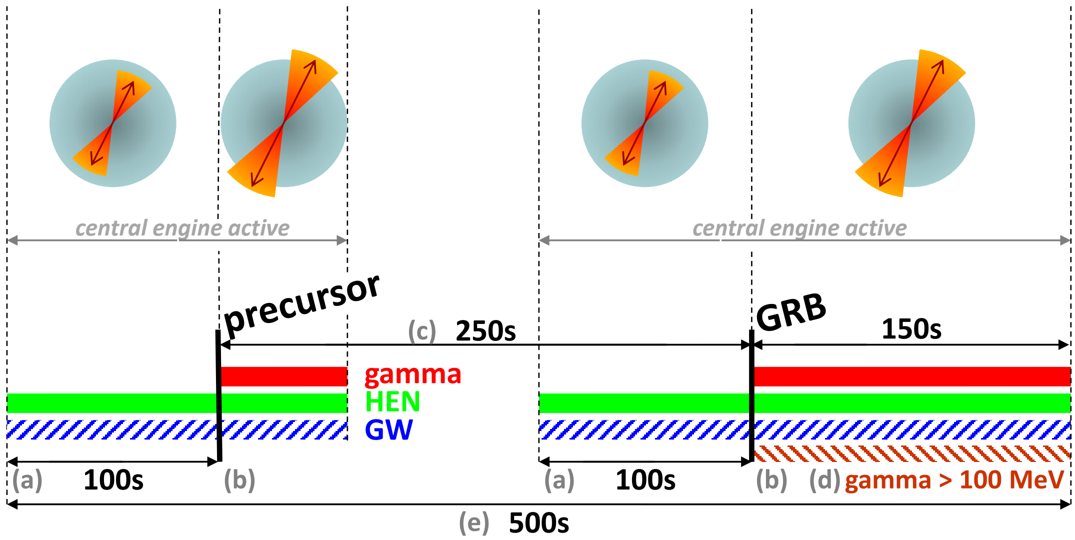

FIG. 1 Summary of the upper bounds on the duration of GRB emission processes taken into account in the total GW+HEN coincidence time window. (a) active central engine before the relativistic jet has broken out of the stellar envelope; (b) active central engine with the relativistic jet broken out of 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. The top of the figure shows a schematic drawing of a plausible emission scenario. Figure taken from Baret *et al.* (2011a).

III. GW AND HEN DETECTION: STATUS AND PROSPECTS

A. Interferometric Gravitational Wave detectors

The first generation of interferometric GW detectors includes a total of six large-scale instruments. The US-based Laser Interferometer Gravitational-Wave Observatory (LIGO) (Abbott *et al.*, 2009a) comprises three kilometric-scale instruments located in Livingston, Louisiana and Hanford, Washington (the latter hosting two interferometers in the same vacuum enclosure). The French-Italian project Virgo (Accadia *et al.*, 2011) has one instrument of the same class located in Cascina near Pisa, Italy. This set of kilometer-scale instruments is complemented by a couple of detectors with more modest dimensions (several hundreds of meters): GEO (Grote, 2010), a German-British detector in operation near Hanover, Germany and the Japanese prototype CLIO (Agatsuma *et al.*, 2010) located in the Kamioka mine.

Despite major differences in the technologies in use, all those instruments measure gravitational waves through the same principle. They all sense the strain that a passing GW exerts on space-time by monitoring the differential length $\delta\ell$ of the optical path followed by two laser beams propagating along orthogonal directions. Measurement noises (mainly the thermal noise due to the Brownian agitation of the atoms constitutive of the main optics and the shot noise due to the quantum nature of light) can be reduced to reach the level of $h \equiv \delta\ell/L \sim 10^{-21}$, where h is the GW amplitude and L is the total optical path length. This best sensitivity is achieved in a frequency band ranging from ~ 100 Hz to 1 kHz approximately (see Figure 3) and it approaches the theoretical expectations from the astrophysical sources presented earlier.

The detectors have conducted several campaigns of joint data taking ("science runs"), as illustrated in Figure 2. These data have been searched for a broad range of GW signatures. Those signatures are either from short transient sources associated with very energetic cataclysmic events like mergers of neutron star and/or black hole binaries, or either from long-lived permanent sources such as deformed neutron stars or stochastic backgrounds resulting from the superposition of many unresolved sources. No gravitational wave have been detected so far. Interesting upper limits were placed on the GW strain amplitude from the targeted sources. We will focus here on the first category (transients) since it pertains to the main interest of this paper.

The first joint LIGO-Virgo science run, labelled S5 for LIGO and VSR1 for Virgo, provided $T = 270$ days of observing time (Abadie *et al.*, 2010a). The upper limit (at 50% confidence level) on the GW strain obtained from an all-sky all-time search is slightly below $h_{rss} \lesssim 5 \times 10^{-22}$ Hz$^{-1/2}$ for waveform frequency at about 200 Hz, where the bound is on the root-square-sum amplitude $h_{rss}^2 \equiv \int dt\ h_+^2(t) + h_\times^2(t)$ of the two GW polarizations, h_+ and $h_\times$, at Earth. Note that the exact result depends on the assumed GW model (the generic choice considered here are sine Gaussian waveforms of various central frequencies). Assuming a linearly polarized wave and averaging over the inclination of the source, this strain limit corresponds to a GW burst energy of $10^{-8} M_\odot c^2$ for a source at Galactic distance of 10 kpc, and $5 \times 10^{-2} M_\odot c^2$ for a source located in the Virgo cluster

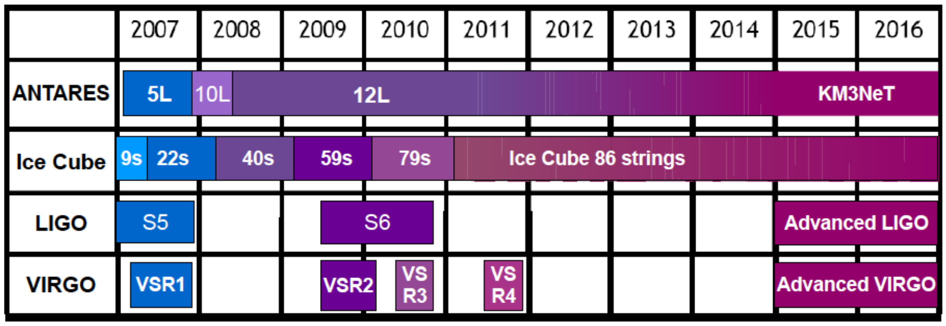

FIG. 2 Time chart of the data-taking periods for the ANTARES (and KM3NeT), IceCube, LIGO and Virgo experiments, indicating the respective (achieved or planned) upgrades of the detectors. The IceCube detector is now complete and will be operating for at least another 5 years, with possible upgrades in the meantime. The deployment of the KM3NeT neutrino telescope, which will take place in parallel with the operation of ANTARES, is expected to last three to four years, possibly starting in 2014. The detector will be taking data with an increasing number of PMTs before reaching its final configuration. A larger-scale upgrade to the next generation of GW interferometers (Advanced LIGO and Virgo) is ongoing and data taking should start again around 2015.

(at a distance of 15 Mpc). Those estimates are comparable to the expected GW-radiated energy from core-collapses and mergers of stellar-mass compact objects respectively. The same data, when searched specifically for inspiraling binaries of neutron stars, led to an upper limit on the rate of such astrophysical events of $\mathcal{R}_{90\%} = 8.7 \times 10^{-3}\mathrm{yr}^{-1} L_{10}^{-1}$ (Abadie *et al.*, 2010d) which is still one order of magnitude larger than the rate estimate obtained from population models. (Abadie *et al.*, 2010b).

Specific efforts aim at developing analyses of the GW observations jointly with other cosmic messengers, for instance high-energy photons from (short and long) GRBs (see e.g. Abbott *et al.* (2010), Abadie *et al.* (2010c) and references therein) and SGRs (see e.g. Abadie *et al.* (2011b) and references therein).. The GW+HEN program of interest here is one of those. It is also worth mentioning here the electromagnetic observation follow-up program of candidate GW triggers performed recently during the last joint LIGO-Virgo data taking and described in (Abadie *et al.*, 2011a). This program involved a range of robotic telescopes including the Liverpool Telescope, the Palomar Transient Factory, Pi of the Sky, QUEST, ROTSE, SkyMapper, TAROT and the Zadko Telescope observing the sky in the optical band, the *Swift* satellite with X-ray and UV/Optical telescopes and the radio interferometer *LOFAR*.

The next generation of GW instruments is under way and expected around 2015. Source population models imply (Abadie *et al.*, 2010b) that direct detection of gravitational waves can be achieved within the next decade by such advanced ground-based GW detectors: Advanced LIGO in the USA (Harry (2010); see also `http://www.ligo.caltech.edu/advLIGO/`), Advanced VIRGO in Italy (Acernese *et al.* (2010); see also `http://wwwcascina.virgo.infn.it/advirgo/`) and LCGT in Japan (Kuroda, 2010). These detectors shall offer a tenfold sensitivity increase over the initial detectors around 100Hz and their frequency range will enable operation down to the pristine 10Hz regime. Observation-based models predict e.g. a detectable rate for binary neutron star coalescence between about 0.4 to 400 events annually (Abadie *et al.*, 2010b).

For more details on direct detection of gravitational waves and its implications to astrophysics and cosmology, we refer the reader to Sathyaprakash and Schutz (2009).

B. High-energy neutrino telescopes

Given the very weak neutrino cross section and the typical astrophysical spectra falling as a power-law at high energies, HEN astronomy requires instrumenting huge (~ 1 km^3) volumes of target material. The concept of neutrino telescopes appeared in 1961 when M.A. Markov proposed to use the water of deep lakes or the sea to detect the secondary muons created in the charged-current interaction of HEN with nuclei. The Cherenkov light emitted by the muon in a transparent medium can be used to infer the arrival direction of the neutrino (Markov and Zheleznykh, 1961). This detection principle takes advantage of the fact that the muon track can be several kilometers long, thus enhancing the effective volume of the detector. Such neutrino telescopes have been built in the form of three-dimensional arrays of photomultiplier tubes (PMTs) embedded in pressure-proof glass spheres arranged on vertical cable strings, with an inter-storey spacing of a few tens of meters and an inter-string distance up to about 100 meters. 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.

These detectors have to cope with a large background of high-energy muons from the air showers generated by the interaction of high-energy cosmic rays with the atmosphere. They are therefore installed beneath thousands of meters of water-equivalent shielding, restricting the possible sites to deep lakes, the deep sea, or the south pole glacier. Even with this shielding, the rate of atmospheric muons is several orders of magnitude above the rate of neutrinos created in the cosmic-ray interactions in the atmosphere. To further reduce this background, such detectors are optimized to detect up-going muons produced by neutrinos which have traversed the Earth (which acts as a shield against all other particles). The field of view of neutrino telescopes is therefore 2π sr for neutrino energies 100 GeV $\leq E_\nu \leq$ 100 TeV; a detector placed in the southern hemisphere will observe the northern sky and conversely. Above this energy, the sky coverage is reduced because of neutrino absorption in the Earth; but it can be partially recovered by looking for horizontal and downward-going neutrinos, which can be more easily separated from the background of atmospheric muons because of their much higher energy.

Three neutrino telescopes are currently operating worldwide. The most advanced one is IceCube (Halzen and Klein, 2010), which has recently achieved its final configuration with 86 strings, instrumenting one km^3 of South pole ice at depths between 1500 m and 2500 m. Results from the 40-string configuration (IC40) have been published and data from IC59 are currently under analysis.Another neutrino telescope has been operating for some years in Lake Baikal (Aynutdinov *et al.*, 2011) in a much smaller configuration; it has recently deployed 3 prototype strings for a km3-scale detector. Finally, ANTARES (Ageron *et al.*, 2011a) is a neutrino telescope deployed at depths from 2000 m to 2500 m in the Mediterranean Sea, near Toulon (France); it is operating in its complete, 12-line configuration since mid-2008. ANTARES has been joined by the two prototype projects NEMO (Taiuti, 2011) and NESTOR (Rapidis, 2009) in forming the European Consortium KM3NeT which aims at the construction of a km^3-scale telescope in the Mediterranean, whose operation could start in 2014 (Katz, 2011). This second kilometer-scale project would allow an all-sky coverage, and in particular the monitoring of a large fraction of the Galactic Plane, which contains many potential sources. An interesting characteristic of these detectors is the ability to take data during the construction phase; each data taking configuration is labelled by the number of functioning detector lines (or strings). Detector performance, as measured by e.g. effective area and pointing accuracy, then improves as new lines are added. The time chart in Figure 2 presents the different phases of operation of the IceCube and ANTARES telescopes from 2007 on.

Since no significant excess has been found yet in the data of any of these detectors, limits have been set both for point sources (Abbasi *et al.*, 2011d; Adrian-Martinez *et al.*, 2011a) and for the diffuse all-sky flux expected from the large-scale distribution of sources which are individually too faint to resolve (Abbasi *et al.*, 2011a; Aguilar *et al.*, 2011). The latest results of searches for point-like sources of high energy neutrinos are presented in Figure 3. A wide variety of generic and specialized searches are also performed on the neutrino data, many of which make use of time-dependent observations from photon experiments. Recent searches have been performed e.g. for neutrinos from flares from active galactic nuclei (Abbasi *et al.*, 2012; Adrian-Martinez *et al.*, 2011b) and from GRBs (Abbasi *et al.*, 2011c). In the latter case, upper limits have already begun to constrain models in which UHECRs are predominantly protons that are accelerated in GRBs. Similar constraints are expected to come from the limits on the diffuse all-sky neutrino flux, as pointed out in Ahlers *et al.* (2011)).

Additionally, the near-simultaneous arrival of two or more neutrinos from the same direction could indicate that a highly energetic burst has occurred. If this is detected in real-time, then neutrino telescopes can be used as triggers for optical, x-ray, and gamma-ray follow-ups. IceCube and ANTARES currently have alert programs established or in development with e.g. fast optical telescope networks like ROTSE and TAROT, gamma-ray telescopes such as Swift, Fermi, MAGIC, and VERITAS (Ageron *et al.*, 2011b; Franckowiak *et al.*, 2009; Van Elewyck, 2011). “All-sky” instruments like neutrino telescopes and GW detectors thus provide an opportunity to alert pointing instruments before or while an astronomical event occurs. At the same time another advantage, which is the focus of this article, is that they can perform more powerful joint searches for bursts in a completely offline way after the data has been recorded.

It should be noted that an analogous possibility exists for much lower energy neutrinos. Because the PMT dark noise rate is particularly low in ice, the IceCube detector has sensitivity to sudden fluxes of MeV neutrinos which lead to collective rise in the PMT rates. Nearby supernova up to 50 kpc can be detected this way. IceCube is therefore part of the SuperNova Early Warning System (SNEWS), sending real-time triggers when the collective PMT rate passes a given threshold (Abbasi *et al.*, 2011b; Kowarik *et al.*, 2009). As with high energy neutrino data, an offline analysis with other all-sky instruments, like GW detectors, is also possible. While the MeV neutrino signal does not provide any directional information, the time-coincidence search would allow exploring the data below the higher threshold required for SNEWS.

More information on the experimental aspects and physics reach of high-energy neutrino astronomy can be found in recent reviews by Chiarusi and Spurio (2010), Anchordoqui and Montaruli (2010) and Baret and Van Elewyck (2011)).

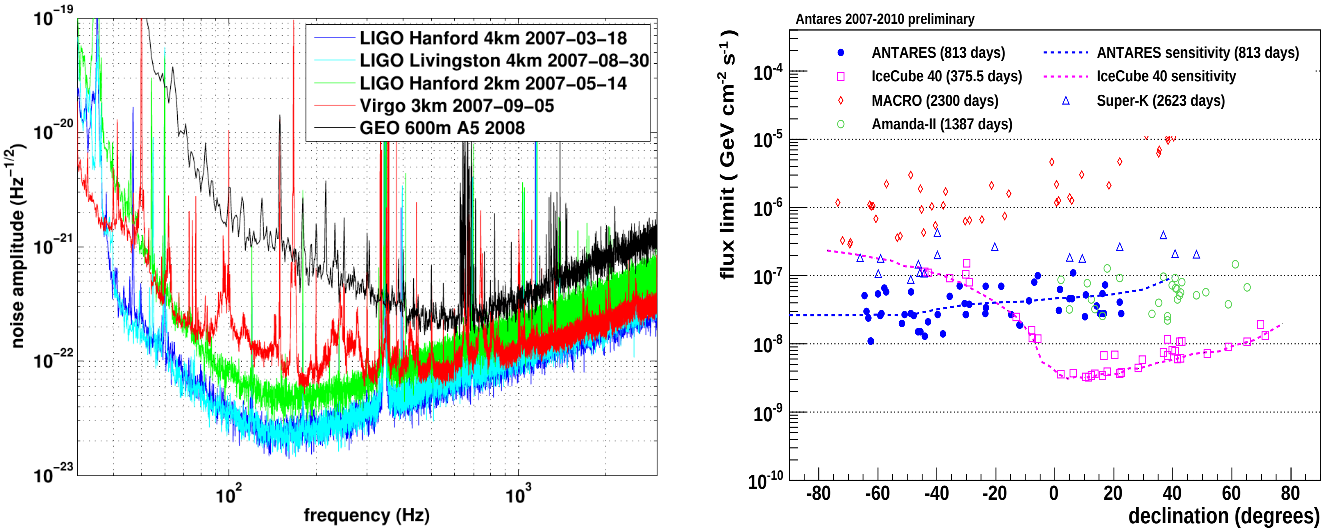

FIG. 3 **Left:** Best detector noise spectra from the LIGO and Virgo associated with the S5/VSR1 data set (2007) along with that of GEO (2008). This figure is taken from (Abadie *et al.*, 2011b). **Right:** Current experimental sensitivities to differential cosmic neutrino flux $E^{-2}\frac{dN}{dE}$ (solid lines) and limits (points) in function of declination for time-integrated searches of point-like sources. The figure shows the results of AMANDA-II (Abbasi *et al.*, 2009) and its successor IceCube, in its 40-string configuration (Abbasi *et al.*, 2011d), as well as those of ANTARES; also displayed are the limits from the MACRO (Ambrosio *et al.*, 2001) and Super-Kamiokande (Thrane *et al.*, 2009) experiments, which are not principally devoted to neutrino astronomy. Figure taken from Adrian-Martinez *et al.* (2011a).

IV. PERSPECTIVES FOR THE JOINT DATA ANALYSIS

A. GW data analysis

Most ongoing searches for unmodelled GW bursts are based on *coherent excess power* methods[8]. These combine the data streams from multiple detectors, taking into account the antenna response and noise level of each detector so as to maximise the signal-to-noise ratio (SNR) of a burst from a given sky direction. The combined data are used to produce a time-frequency map of the excess power (equivalently, the SNR), which is then scanned for transient excursions (or *events*) that may be GW signals. Each event is characterised by a measure of significance, based on energy and/or correlation between detectors, as well as its time-frequency properties.

Besides the search for unmodelled bursts of GWs, templated searches are also ongoing, looking for signals with known waveforms. These searches focus on signals from the coalescence of two compact objects, e.g. two neutron stars or a neutron star and a black hole, which are the prime progenitor candidates for short-hard GRBs. Several triggered searches for such coalescence signals have been done in the past (Abadie *et al.*, 2010c; Abbott *et al.*, 2008), or are ongoing with recent LIGO/Virgo data. As the time and the sky directions are known, a more sensitive search can be conducted compared to all-sky searches (Abbott *et al.* (2009c); Abbott *et al.* (2009b)). As the waveforms of such signals are known to post-Newtonian order (Blanchet, 2002; Buonanno *et al.*, 2007), matched-filter algorithms (Allen *et al.*, 2005) are used to analyze the data in a coherent way (Harry and Fairhurst, 2011). Each event is primarily characterized by its mass and its coalescence time.

For the current and upcoming generation of ground-based GW detectors, signals are expected to be low SNR and infrequent. The identification of these weak signals is confounded by the presence of “glitches”: non-Gaussian fluctuations in the background noise. Glitches are produced by a variety of environmental and instrumental processes, such as local seismic noise or saturations in feedback control systems. Since glitches occasionally occur nearly simultaneously in separate detectors by chance, they can mimic a GW signal (Blackburn *et al.*, 2008). To discriminate between true signals and noise, consistency tests based on the correlations between the detectors are applied to the events. For example, certain “null” combinations of the data streams will cancel a GW signal, but not background glitches. The energy in the null stream may be used to reject or down-weight events not consistent with a gravitational wave. Such tests depend critically on having several independent detectors of comparable sensitivity.

The correlation between detectors is also critical to determining the incident direction of the candidate signal. GW detectors

[8] See for example Guersel and Tinto (1989); Flanagan and Hughes (1998b); Anderson *et al.* (2001); Mohanty *et al.* (2006); Rakhmanov (2006); Chatterji *et al.* (2006); Summerscales *et al.* (2008); Klimenko *et al.* (2008).

are non-imaging instruments with a nearly omnidirectional response. Source localization therefore requires multiple detectors, in order to use the measured time delay between detectors as well as the amplitude of the measured signal in each detector to triangulate a sky location. Several methods of localisation have been investigated[9]. Fairhurst (2009) gives the following approximation for the timing accuracy of a GW signal: $\sigma_t \sim (2\pi\sigma_f\rho)^{-1}$, where σ_f is the effective bandwidth of the source and ρ is the SNR. For nominal values $\sigma_f = 100$ Hz and $\rho = 8$, timing accuracies are on the order of 0.1 ms. This can be compared to the light travel time between detectors, 10 – 30 ms for the LIGO-Virgo network. For example, for a binary coalescence signal at the threshold of detectability, Fairhurst (2009) estimates a best-case localization of 20 deg^2 (90% containment), and a typical localization of twice this. Additional constraints provided by other instruments with a better angular accuracy such as HEN telescopes can therefore significantly help improving the source localization.

B. HEN data analysis

The searches for astrophysical point-sources of HEN rely principally on charged-current interactions of muon neutrinos: at the energies probed by neutrino telescopes, the outgoing muon can travel from hundreds of meters up to many kilometers, and the direction of the muon is nearly collinear with the original direction of the neutrino. Cherenkov photons propagating from the track are detected by the array of photo-multiplier tubes, and the relative timing of the photon hits is used to reconstruct the muon direction. The angular resolution is limited by the number of hits detected and by any distortions in the photon arrival times due to scattering in the water or ice. Higher energy muons are generally better reconstructed, since they travel farther, providing a longer lever arm for reconstruction, and since more photons are emitted in stochastic energy losses along the path.

The track reconstruction principle is to maximize the likelihood of time residuals of photon hits. At the reconstruction level, the rate of downgoing atmospheric muons (from cosmic ray showers above the detector) misreconstructed as upgoing tracks is still several orders of magnitude larger than the rate of genuine upgoing muons events that come from atmospheric neutrinos originating in the opposite hemisphere and traversing the Earth. This background of misreconstructed tracks can be reduced to about a few percent of the bulk of upgoing atmospheric neutrinos by applying quality cuts e.g. on the likelihood of the track. The angular resolution above 10 TeV is essentially determined by the scattering length of light in the medium, yielding a median error angle on the neutrino direction of about 0.1° in the deep sea and 0.5° in the South Pole glacier for telescopes of km^3-scale size.

The energy of the incoming neutrino is estimated on basis of the amount of Cherenkov light detected from the muon track. The simplest estimator is in fact the total number of photon hits detected from the track. Given that only a fraction of the muon track is contained in the instrumented volume, the resolution is intrinsically limited and is usually a lower bound, since a muon from a high energy neutrino interaction many kilometers away will lose a large fraction of its energy before reaching the detector. On the other hand, the observation of a large number of photons from a track unequivocally signs a high-energy event. Therefore energy estimation can still be used to distinguish cosmic neutrinos from atmospheric ones, because the atmospheric spectrum is known to fall steeply with energy ($\sim E^{-3.7}$) whereas cosmic fluxes can be much harder with a typical E^{-2} spectrum extending to PeV energies.

At energies well above a TeV, up-going tracks are generally straightforward to separate from the misreconstructed muon background. At lower energies, the smaller number of photon hits makes it increasingly difficult to perform this separation. Steady point source searches often place less emphasis on this low-energy range, because the steepness of the atmospheric neutrino background means that even if a high purity neutrino sample is obtained, the low energy region is dominated by the pile-up of atmospheric neutrinos. However, on very short time scales such as $\sim$second-long bursts, even the atmospheric neutrino background is small. This means that more powerful event selection methods, for instance machine learning algorithms like boosted decision trees, can be used to separate lower energy neutrino events from the mis-reconstructed muon background. The development of these techniques will play an important role in searches for objects like choked GRBs, where the neutrino energies may be at $\sim$TeV and below.

C. HEN-triggered GW searches

One of the simplest GW+HEN coincidence searches that may be performed would search the GW data around the neutrino arrival time in the estimated direction of the neutrino candidate. Thanks to the reduction in the volume of analyzed data, such triggered GW searches can be run with a lower event detection threshold than an un-triggered search, leading to a higher detection probability at a fixed false alarm probability and better limits in the absence of detection. Similarly, the *a priori* knowledge of

[9] See e. g. Guersel and Tinto (1989); Wen and Schutz (2005); Cavalier *et al.* (2006); Rakhmanov (2006); Acernese *et al.* (2007); Searle *et al.* (2008); Searle *et al.* (2009); Wen *et al.* (2008); Markowitz *et al.* (2008); Fairhurst (2009); Wen and Chen (2010).

the source direction allows for searching only a small part of the sky and veto candidate events seen in multiple detectors at times not consistent with the expected GW arrival time difference. In fact, the number of accidental coincidences between GW detectors decreases with the size of the search time window. Thus, the use of an external trigger can be a very effective tool for a successful search of GW signals.

Such a search can be performed using various techniques such as the X-Pipeline (Sutton *et al.*, 2010) and STAMP (Thrane *et al.*, 2011). The X-Pipeline is a semi-coherent technique that has been used to perform searches for GWs in association with GRBs (Abbott *et al.*, 2010). It is a software package designed for autonomous searches for unmodelled GW Bursts (GWB). It targets GWBs associated with external astrophysical "triggers "such as GRBs or neutrinos. It performs a coherent analysis of data from arbitrary networks of GW detectors, while being robust against noise-induced glitches. This allows the analysis of each external trigger to be optimized independently, based on background noise characteristics and detector performance at the time of the trigger, maximizing the search sensitivity and the chances of making a detection. The pipeline also accounts for effects of uncertainties in the results such as those due to calibration amplitude, phase, and timing.

Stochastic Transient Analysis Multi-detector Pipeline (STAMP) is a cross- correlation-based algorithm that looks for structures due to GWs in cross-power frequency-time maps. Cross-power maps are produced by cross-correlating strain data from two spatially separated GW detectors after applying a filter function. By choosing a proper filter function, STAMP can search for a GW signal from a particular direction in the sky. Due to its cross-correlation approach, STAMP mitigates noise glitches due to environmental factors. In STAMP, the SNR of any GW signal will increase as $\sqrt{T}$ where T is the duration of the signal. This makes STAMP suitable for GW signals with duration of tens of seconds to weeks while X-Pipeline is more commonly applied to signals with duration of second or less.

In this context, a neutrino source will be characterised by a set of inputs for the search algorithms: its sky position, as given by the direction of the reconstructed muon track in the neutrino telescope, the associated (and possibly direction-dependent) point-spread function of the detector, the neutrino arrival time, which defines the trigger time t_0, and the range of possible time delays (positive and negative) Δt between the neutrino signal and the associated GW signal, which is astrophysically motivated, as discussed in Section II.B. The latter quantity is referred to as the *on-source* window for the neutrino; this is the time interval which is searched for GW candidate signals.

A crucial part of the procedure is the estimation of the background distributions, which is performed on the data pertaining to an *off-source* time window, typically covering about 1.5 hours around the neutrino time trigger and excluding the on-source interval. This strategy ensures that the background does not contain any signal associated with the neutrino event but has similar statistical features as the data searched in association with the neutrino. This time range is limited enough so that the detectors should be in a similar state of operation as during the neutrino on-source interval, but long enough to provide off-source segments for estimating the background. A schematic flowchart of this analysis strategy is presented in Figure 4.

Such an analysis with the X-Pipeline is currently being performed using as external triggers a list of ANTARES neutrino candidates obtained during the data taking period from February to September 2007, in coincidence with S5 and VSR1, and considering a symmetric on-source window of $t_0 \pm \Delta t$, with $\Delta t = 500$ s consistently with the discussion in Sec. II.B. A similar analysis using STAMP is in preparation.

D. Baseline search with HEN and GW candidate lists

Joint GW and HEN multimessenger searches provide another interesting perspective for data analysis compared to more traditional externally triggered searches, e.g., with electromagnetic (EM) GRB observations. While EM observations of GRBs allow for searches for GW or HEN signals from a precisely determined time and direction, the joint search for GW and HEN signals with no EM counterpart relies on the combination of significance and directional probability distribution from these two messengers (Baret *et al.*, 2011b). In such a case, the possibility that multiple neutrinos are detected from the same astrophysical source can also be considered, e.g. if several neutrino candidates happen to fall within a predefined space-time window.

Similarly to how multiple GW detectors are effective in rejecting "glitches" from the non-Gaussian background noise by requiring the coincident occurrence of an astrophysical signal in spatially separated GW detectors, requiring spatial and temporal coincidence from GW and HEN signal candidates can highly reduce false alarm rate (Aso *et al.*, 2008).

Due to the uncertainty of directional reconstruction, especially for GWs, one can also enhance background rejection by using the expected source distribution in the nearby universe. Such distribution can be based on the distribution of nearby galaxies and their weight. The density of at least some GW+HEN sources can be connected to the blue luminosity of galaxies (Phinney, 1991; White *et al.*, 2011), while source density can also depend on the type of the galaxy (de Freitas Pacheco and et al., 2006; O'Shaughnessy *et al.*, 2010).

The search for joint GW+HEN signal candidates can be aimed for detecting a single astrophysical signal with high-enough significance to claim detection. Another possibility is to aim for a set of weaker signals that could not be detected individually, but their joint distribution differentiates them from the background. Such a technique has been used in various searches for GWs;

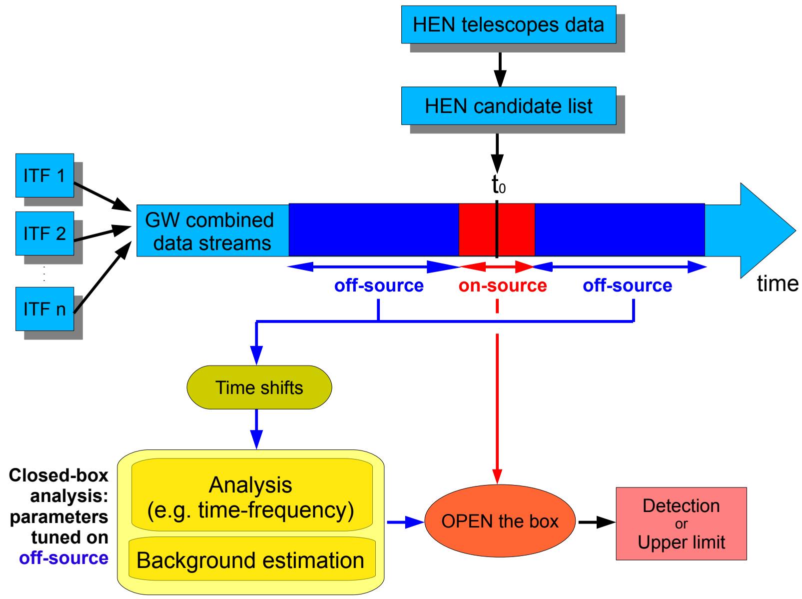

FIG. 4 Schematic flow diagram of a HEN-triggered search for GWs. Each neutrino candidate (with its time and directional information) provided by a HEN telescope acts as an external trigger for the X-pipeline, which searches the combined GW data flow from all active interferometers (ITFs) for a possible concomitant signal. The size of the spatial search window is related to the angular accuracy associated to each HEN candidate. The background estimation and the optimization of the selection strategy are performed using time-shifted data from the off-source region in order to avoid contamination by a potential GW signal. Once the search parameters are tuned, the box is open and the analysis is applied to the on-source data set.

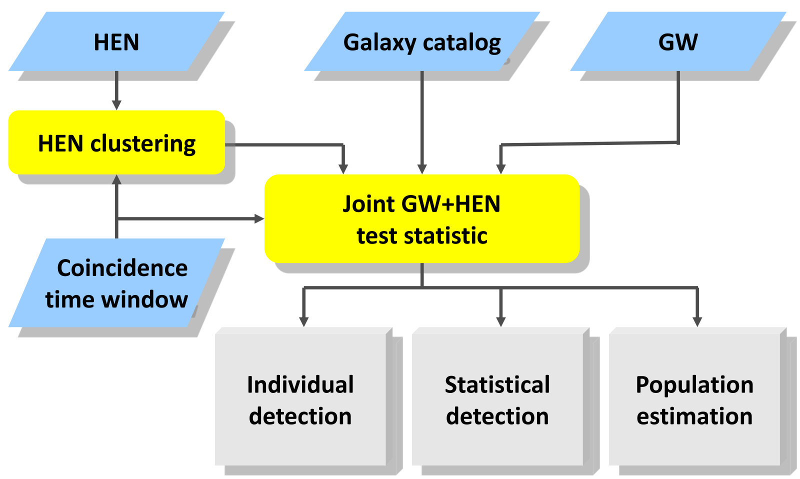

FIG. 5 Schematic flow diagram of a joint GW+HEN search pipeline. The inputs of the pipeline are, besides data from HEN and GW detectors, the astrophysical source distribution from a galaxy catalog, as well as the coincidence time window used for the search. Spatially and temporally coincident neutrinos can be clustered, that can potentially greatly increase a significance, and decrease the false alarm rate, of a coincident GW+HEN signal. Combining these information in a joint test statistic, one can evaluate the results to look for individual or statistical detection of signal candidates. Upon non-detection, the results can be used to determine an upper limit on the source population.

see e.g. Abbott *et al.* (2010).

A schematic flow diagram of a joint search algorithm is shown in Figure 5.

V. CONCLUSIONS

Astrophysical targets of GW and HEN searches include gamma-ray bursts, soft-gamma repeaters, supernovae, and other intriguing transients. Such sources are often expected to be observable through electromagnetic messengers, such as gamma-rays, X-rays, optical and radio waves. Some of these channels are already being used both in searches for GWs with the LIGO-GEO-Virgo interferometer network, and in searches for HEN with the current neutrino telescopes ANTARES and IceCube. However, many of the emission models for these astrophysical objects have so far been indistinguishable by electromagnetic observations, and some sources such as choked GRBs are even expected to have little or no detectable electromagnetic counterparts. The combination of two weakly interacting messengers, GWs and HENs, therefore provides a new and exciting opportunity for multimessenger searches with different challenges and outcomes from observations using electromagnetic counterparts.

Such 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, some of which having possibly remained unobserved so far by conventional photon astronomy. Information on the progenitor, such as trigger time, direction and expected frequency range, can also enhance our ability to identify GW signatures or astrophysical HENs with significances close to the noise floor of the detectors.

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. Upon detection, the relative times of arrival or relative flux of the different signals can indicate important properties of the central engine; on the other hand, the absence of coincident signal can constrain the joint parameter space of the source. In the promising case of GRBs, the outcome of a joint GW+HEN search could *e. g.* improve our understanding of the details of astrophysical processes connecting the gravitational collapse/merger of compact objects to black-hole formation as well as to the formation of fireballs.

Several periods of concurrent observations with GW and HEN detectors have already taken place and the corresponding data are being scrutinized for coincident GW+HEN signals. Future schedules involving next-generation detectors with a significantly increased sensitivity (such as KM3NeT and the Advanced LIGO/Advanced Virgo projects) are likely to coincide as well. Studies are ongoing to explore the reach of current and planned experiments in constraining the population of multimessenger sources of GWs and HENs, with or without electromagnetic counterpart (Bartos *et al.*, 2011; Chassande-Mottin *et al.*, 2011). Constraints on the rate of GW and HEN transients can be derived using the independent observations already available from the current generation of detectors. On this basis, Bartos *et al.* (2011) estimated the reach of joint GW+HEN searches using advanced GW detectors and the completed IC86 detector, showing that searches undertaken by advanced detectors are indeed likely to be capable of detecting, constraining or excluding several existing astrophysical models within one year of observation.

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