Multimessenger Prospects with Gravitational Waves and Neutrinos after LIGO's First Discovery

To cite this article: Imre Bartos *et al* 2017 *J. Phys.: Conf. Ser.* **888** 012001

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Multimessenger Prospects with Gravitational Waves and Neutrinos after LIGO's First Discovery

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Abstract. The recent observation of gravitational waves unveiled numerous opportunities in astrophysics, as well as in the study the cosmos and the laws of physics. With annually improving detectors, gravitational wave observations are set to rapidly expand in the next years. We briefly introduce the first gravitational-wave detection and its background. We will then outline the status, plans and opportunities in multimessenger observations, in particular with neutrinos, which will broaden our horizon with gravitational waves.

1. Introduction
Soon after its construction ended, Advanced LIGO [1] made the first direct detection of gravitational waves (GWs; [2]). On September 14th, 2015, the LIGO detectors recorded a signal that was soon reconstructed to have come from the merger of two black holes, each with $\sim 30\,\mathrm{M_\odot}$, about 1.3 billion light years away. Not only was this accomplishment the beginning of GW observations that can probe black holes and gravity itself in unprecedented ways; it also started a new chapter for multimessenger astronomy.

Combining information from GW detections with electromagnetic and neutrino observations allows us to gain a fuller understanding of some of the most extreme cosmic processes [3]. GWs are indicative of source dynamics, such as the formation, evolution and interaction of compact objects. Electromagnetic emission contains information on stellar activity and evolution, accretion and dissipation mechanisms. Neutrinos can elucidate the origin and production mechanism of the highest energy cosmic rays, the dissipation processes behind high energy radiation, and the inner properties of cosmic explosions [4, 5, 6].

Similarly to GWs, cosmic neutrino observations are also very recent. The first detection of astrophysical neutrinos was reported only in 1987 from Supernova 1987A [7], and the first discovery of high-energy neutrinos was announced by the IceCube Neutrino Observatory in 2013 [8]. There has been significant progress since this accomplishment in constraining the origin of these observed high-energy neutrinos, however, their source still remains unknown. The solution will likely involve multimessenger observations that enable source or population associations with the neutrinos.

The goal of this paper is to give the reader a brief overview of recent developments and near-future plans in GW astronomy, emphasizing the perspective of multimessenger observation, and in particular neutrino astronomy. This review is based on a non-exhaustive selection of topics, focusing on the most promising GW and multimessenger transients.
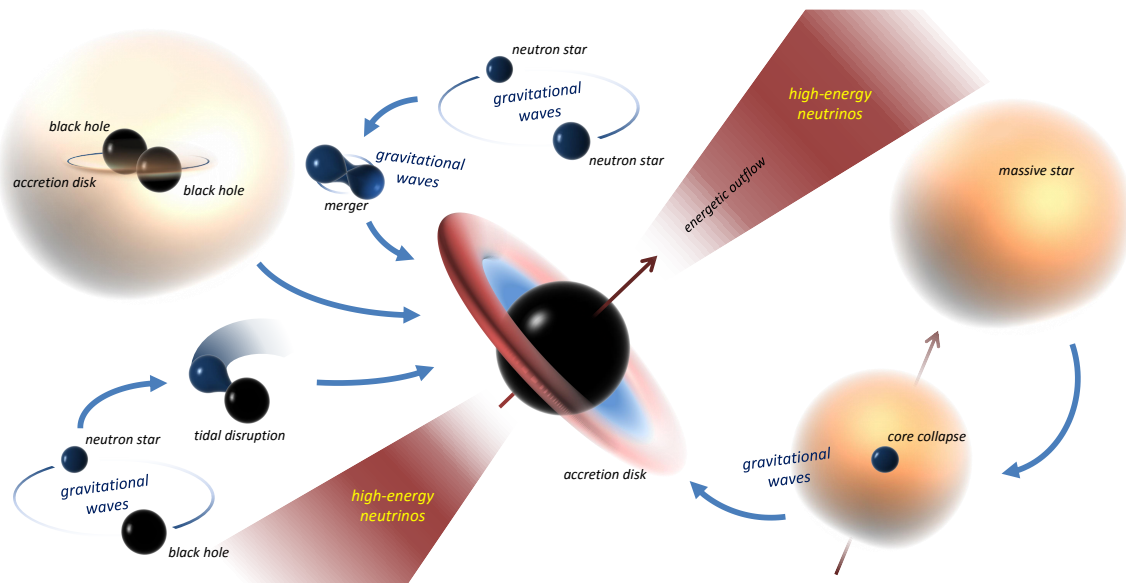
Figure 1. Illustration of multimessenger sources of gravitational waves and high-energy neutrinos.

2. The First Gravitational Wave Detections

The first GW signal, GW150914, was observed on September 14th, 2015, at the very beginning of Advanced LIGO's first observation period (O1; September 12th, 2015–January 19th, 2016; [2]). It was identified within 3 minutes after arrival by generic GW transient searches working with minimal source assumptions [9]. Subsequently, matched filter-based algorithms also identified the GW event [10], and reconstructed its properties [11].

The properties of GW150914 were somewhat unexpected. While binary black holes were one of the most promising source type, the inferred merger rate [12] exceeded most expectations [13]. Considering the LIGO's full first observing period (O1), the current best estimate on the binary black hole merger rate is $9 - 240 \, \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ [12].

The two masses in GW150914, both at $\sim 30 \, \mathrm{M}_\odot$ (see Table 1), were greater than any stellar mass black hole measured in X-ray binaries [14]. This, nevertheless, is not sufficient to constrain the binary's formation channel. Dynamical formation in dense stellar environments, such as galactic nuclei or globular clusters, isolated binary evolution, or Population III binaries can all plausibly produce the observed merger properties. The large black hole masses suggest that their stellar progenitors were formed in a low-metallicity environment [15]. The data also allowed constraints to be made on the spin of the two black holes in GW150914. Their total weighted spin parallel with the orbital axis was limited to < 0.3. This low orbit-aligned spin is in tension with many of the possible formation channels, for example chemically homogeneous evolution, or if the black holes interact with the gaseous medium left by their stellar progenitors [16]. The spin component that is perpendicular to the orbital axis of the binary is in general difficult to constrain, and no meaningful limits are available for GW150914.

Beyond GW150914, another GW signal, GW151226, was discovered by LIGO on December 26th, 2015. A third possible signal, LVT151012, was identified, although it was not sufficiently significant for claiming discovery [12]. Nevertheless, LVT151012 has 87% probability of being of astrophysical origin, therefore it was examined in detail and was taken into account in GW rate estimates. In the following we describe LVT151012 assuming it is astrophysical.

The gravitational waveforms of both GW151226 and LVT151012 indicate a binary black

event	GW150914	GW151226	LVT151012
signal-to-noise ratio	23.7	13.0	9.7
primary mass $[M_\odot]$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
secondary mass $[M_\odot]$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
orbit-aligned spin	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
luminosity distance [Mpc]	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
redshift	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$

Table 1. Reconstructed parameters for binary black hole mergers and candidates for LIGO's first observing run, O1 [12]. Orbit-aligned spin is defined as the mass-weighted sum of the two black holes's spin in the direction of the orbital axis.

hole merger origin. The reconstructed masses of these two events are, contrary to the case of GW150914, similar to black hole masses observed dynamically in the Milky Way in X-ray binaries (see Table 1). These two events therefore allow for progenitor environments with solar metallicity. Both isolated binary and dynamical formation channels can produce these inferred masses. Nevertheless, GW151226 and LVT151012 are consistent with more extreme mass ratios compared to the essentially equal-mass case of GW150914. A mass ratio $\lesssim 0.5$ is not likely to develop in isolated binaries, and is more consistent with dynamical formation channels [12]. While not very constraining, it is worth noting that the orbital-aligned spin component for GW151226 is moderately positive, and is inconsistent with zero net spin.

The reconstructed luminosity distances of the three binary black hole mergers, up to over 1 Gpc, are indicative of the distance range probed by LIGO (see Table 1), which will grow by a factor of ~ 3 in upcoming observing runs [17].

While neutron stars are a primary target source for earth-based GW and multimessenger observations, no neutron star–neutron star or black hole–neutron star binary has been observed during O1 [18]. This is consistent with our expected source rate. The first such detections are anticipated to occur within the next 1-2 years [17], promising to be of substantial observational and theoretical interest [19, 20, 21].

3. Multimessenger Sources

The most promising GW emission is related to compact stellar remnants. The merger of binary black holes, binary neutron stars or black hole-neutron star binaries are abundant GW sources and will likely make up the majority of detections [17]. Stellar core collapse with a rapidly rotating core may also be a significant GW emitter [19, 22, 23], while slower rotating cores may be detectable at closer distances [24]. If the core collapse results in a protoneutron star, fallback accretion can significantly increase the angular momentum thus resulting in increased GW production, improving detection prospects [25]. Other GW sources include rotating neutron stars [26], and plausibly magnetar flares [27, 28, 29].

Observable neutrino emission can be produced in two distinct ways. In stellar core collapse, the formation of a neutron core releases a large number of thermal neutrinos, which carry away $\sim 10\%$ of the star's rest mass. Despite this extremely high flux, its observation is feasible only for nearby ($\lesssim 1$ Mpc) events, due to the neutrinos' small cross section at MeV energies [30].

More easily detectable, high-energy ($\gg$ GeV) neutrinos can be produced in non-thermal, dissipative processes, such as relativistic outflows or shocks in supernova remnants. Protons accelerated in these processes undergo photohadronic interaction [31] or nuclear collisions [32], producing high-energy neutrinos and gamma radiation.

Accreting black holes are typically responsible for driving relativistic outflows. GW sources

that result in a black hole-accretion disk system can therefore also produce high-energy neutrinos (see illustration in Fig. 1). Binary neutron star and neutron star black hole mergers, as well as stellar core collapse with a rapidly rotating core, are such systems. They are the likely progenitors of gamma-ray bursts (GRBs), which are observational evidence for non-thermal dissipation [33].

Binary black hole mergers are typically not expected to experience sufficient mass accretion for detectable emission. Nevertheless, in some scenarios the black holes may be embedded in a dense, gaseous environment that can result in strong electromagnetic, and possibly neutrino emission. Such a scenario can occur in active galactic nuclei (AGNs). Galactic nuclei are expected to harbor a large number, potentially tens of thousands of stellar mass black holes, which migrate to within the innermost parsec via mass segregation [34, 35]. In active galaxies, a large gas inflow is present that feeds the central supermassive black hole through a dense accretion disk. Stellar mass black hole binaries in the nucleus will migrate into this accretion disk, in which they rapidly merge due to dynamical friction caused by the gas [36]. The inspiralling black holes experience an enhanced accretion compared to single black holes. The resulting mini-accretion disks around the stellar mass black holes can drive relativistic outflows, and may produce observable high energy and neutrino emission.

4. Gravitational Wave Detectors

The Advanced LIGO observatories [1] began their operations in 2015 at a sensitivity that is approximately 3 times below their design sensitivity. They will be upgraded roughly annually in the following few years until they reach their design sensitivity around 2019 [17]. A European detector, Advanced Virgo [37], in Italy is expected to begin observations during LIGO's second observing run in 2017 [17]. Similarly to LIGO, Virgo will also annually improve its sensitivity until it reaches its design specifications at the end of the decade. Another detector, KAGRA [38], is currently being constructed in Japan, using novel cryogenic technology. For the first time for large scale GW instruments, but pointing towards the future, KAGRA is being built underground, where seismic activity is significantly reduced. Finally, LIGO is planning to construct a third facility in India [39], with identical instrumentation to the other two detectors. Construction is planned to commence shortly, with expected completion early next decade [17].

An increased number of GW detectors comes with multiple, significant advantages. First, with an improved signal to noise ratio, more detectors means higher sensitivity and more uniform spacial coverage. Second, since direction reconstruction is primarily done using triangulation between the detectors, more, distant detectors can significantly reduce GW localization uncertainty, greatly helping electromagnetic follow-up efforts. And third, GW detectors regularly experience downtime, a larger number of detectors can therefore significantly improve the duty cycle of the detector network.

5. Multimessenger Observation Campaigns

With the onset of GW observations, there has been a significant effort to search for electromagnetic and neutrino emission from GW sources [40]. Started during the operation of initial LIGO and Virgo [41, 42], electromagnetic follow-up efforts now include a large number of partner observatories from radio to gamma-ray [20]. A significant number of these detectors searched for counterparts of the first observed GW, GW150914 [20].

One of the observatories, the Gamma-ray Burst Monitor onboard the Fermi satellite, reported a possible GRB counterpart observed $0.4\,$s after the merger of GW150914 [43]. The event was consistent with a weak short GRB. At the same time, the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) detected no gamma-ray emission, constraining the astrophysical origin of the Fermi-GBM signal for typical hard spectra or spectra without a break

[44]. Some authors also questioned the Fermi-GBM data analysis applied for this detection, and suggested that there may be no significant counterpart [45].

Electromagnetic follow-up observations are poised to further expand in scope, with more electromagnetic counterparts falling within reach, and with new, large scale instruments joining the effort. For example, the Cherenkov Telescope Array (CTA; [46]), a network of telescopes with unprecedented sensitivity to GeV-TeV gamma-rays, will be well suited to search for high-energy photons from GRB-type emission likely produced by binary neutron star mergers [47]. Another near future observatory, the James Webb Space Telescope, will provide the most sensitive near-infrared observation capability to date, promising to efficiently identify kilonova emission, also from binary neutron star mergers [48].

Due to the limited GW sky localization, electromagnetic searches will greatly benefit from constraints on the possible source directions. One such constraints can come from potential source catalogs, such as galaxy catalogs. Follow-up observations can target a set of galaxies within the GW sky area, largely decreasing the number of false positives, and mitigating the needed telescope time. Unfortunately, galaxy catalogs are currently largely incomplete beyond $\sim 100 \deg^2$, while the relevant distance range for GW observations is $\gtrsim 200\,\mathrm{Mpc}$ when considering compact binary mergers. This incompleteness can be remedied, even with limited observational resources, if one surveys galaxies only within the GW localization, as opposed to over the whole sky. For electromagnetic counterparts that last for a few days, such as kilonova emission, there is sufficient time following the detection of a GW to assemble such catalogs with meter class or larger telescopes [49].

As we will see below, another possibility to significantly improve source localization for electromagnetic follow-up searches is the coincident detection of high-energy neutrinos.

5.1. Joint Gravitational wave + Neutrino Searches
Searching for high-energy neutrinos from GW sources can probe the connection between compact object dynamics and particle acceleration, and can increase search sensitivity. Further, a joint GW+neutrino observation could rapidly provide a sub-1 $\deg^2$ directional accuracy for muon neutrinos, aiding electromagnetic follow-up observations. Even high-energy electron- and tau-neutrinos for which the reconstruction precision is $\sim 15°$, using their directional information and precise timing, can be beneficial. Additionally, for hidden neutrino sources that are opaque to gamma-rays [50], GWs may be the only detectable counterpart that can help identify the source and its properties.

Joint GW+neutrino searches started with initial GW detectors. These searches adopted a $\pm 500\,\mathrm{s}$ time window for temporal coincidence, building on the observed time frame of high energy emission from GRBs [51], and most of them were based on the same baseline GW+neutrino search technique [52]. The first observational constraints for joint sources were derived using initial LIGO-Virgo measurements and the partially completed IceCube detector [53], which was soon followed by searches with ANTARES [54] and IceCube [55]. Most recently, high-energy neutrino searches were carried out for the first GW detection, GW150914, with the ANTARES and IceCube detectors [21] and the Pierre Auger Observatory [56], while the KamLAND detector [57] and IceCube [21] searched for MeV neutrino counterpart. No significant temporally and directionally coincident neutrinos were found by these searches.

6. Conclusion and Future Direction
LIGO's discovery of a binary black hole merger set the beginning of gravitational wave astrophysics, and opened a new chapter in multimessenger search efforts. It also signaled that even the near future may see a large number of interesting detections. With the increasing sensitivity and number of GW detectors, and with the large scale organization of GW, electromagnetic and neutrino observations, we can soon expect a boom in multimessenger

detections and their effect on our understanding of cosmic processes. It remains to be seen whether the most populous source type, binary black hole mergers, will exhibit detectable electromagnetic and/or neutrino emission. There are plausible evolutionary channels, and a joint detection would greatly expand our knowledge of the formation and environment of binary black holes.

To maximize the scientific impact of multimessenger observations, we will need to remove the barriers from rapid data reduction and sharing, and facilitate the joint analysis of more than two messengers.

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