# MULTI-MESSENGER SEARCHES: PAST RESULTS AND FUTURE PROGRAMS

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Second generation gravitational wave (GW) detectors LIGO and Virgo are entering in their operative phase by the end of 2015 and expected to improve past sensitivities by one order of magnitudes by 2019. Transient astrophysical sources as binary compact object coalescence, supernovae or bursting magnetars, are among the most promising targets in the GW frequency range covered by LIGO and Virgo (1 Hz - 10kHz). These sources are well known in the electromagnetic spectrum and are expected to emit neutrinos, thus are ideal test benches for the nascent multi-messenger astrophysics. This review presents some of the main properties of these sources, the results obtained so far from past multi-messenger searches with the first generation GW interferometer observatories, and the programs for the era of the second generation GW observatories.

## 1 Introduction

The two Laser Interferometer Gravitational wave Observatory (LIGO) based in the USA at Livingston, Louisiana, and Hanford, Washington [1], and the Virgo interferometer based in Cascina, Italy [2], are undergoing deep hardware and software upgrade that will increase their GW strain sensitivity by one order of magnitude around the most sensitive frequency (~100 Hz), giving birth to the second generation GW detectors. The nominal sensitivity is expected to be reached by 2019: by that time GW are expected to be detected routinely opening a new era for astronomy in the gravitational wave domain. Transient astrophysical sources such as bursting stars or stars undergoing catastrophic phases, are among the best candidates in the high frequency GW range covered by the advanced LIGO (aLIGO) and Advanced Virgo (1 Hz - 10 kHz).

The most promising transient sources of GWs are binary systems of compact objects, as two neutron stars (NS) or a neutron star and a stellar-mass black hole (BH) or even two BHs. The maximum GW strain is expected to be detected by aLIGO and Advanced Virgo during the final stages of the inspiral phase, just before the merging of the two stars. These systems are often called in the literature as "compact binary coalescence" systems, CBC, or "mergers". The theoretically predicted GW energy from these systems is of the order of $E_{GW} \sim 4.2 \times 10^{-2} M_{\odot} c^2 (\frac{M_{chirp}}{1.22 M_{\odot}})^{5/3} (\frac{f_{max}}{1kHz})^{2/3}$, where $M_{chirp}$ is the chirp mass and $f_{max}$ is the GW frequency at the end of the inspiral phase [3]. The expected waveforms from CBCs are fairly well known and a large number of templates are typically used as "matching filters" in the GW data analysis. Another class of transient GW events that may be observed by the 2nd generation of GW detectors are the core collapsing stars, or core-collapse supernovae (SNII, SNIbc). These astrophysical objects are expected to release a certain amount of GW energy due a supposed degree of asymmetry in the stellar envelope ejection phase. However, the large uncertainties affecting our knowledge on the collapsing phase of these objects makes highly uncertain the GW released energy (for which the present estimates [5,6] range from $10^{-2}$ $M_{\odot}$ $c^2$ to $10^{-8}$ $M_{\odot}$ $c^2$) and, as a consequence, the distance up to which these sources maybe detected is very uncertain too. Another issue for these type of objects it that the waveform is much less defined than for the CBC case. For this reason, burst search methods, largely independent of the waveform, are used. The third class of transient GW sources is populated by rotating NSs with very intense magnetic fields, of the order of $10^{15}$ G (magnetars). Theoretical studies predict that when such stars undergo a starquake, asymmetric strains can temporally alterate the geometry of the star and GW are expected to be produced (see also Dall'Osso proceeding, this volume). The expected amplitude however is highly uncertain, with possible estimates that goes from 2 down to 8 orders of magnitude fainter than for CBC systems [7].

The three above mentioned classes of sources are well known in the electromagnetic spectrum and are expected to emit high-energy neutrinos (HEN), thus are ideal test benches for the nascent multi-messenger astrophysics. In the coming era of "gravitational astronomy", multi-messenger study will be a main tool to gain insights on the physics of several astrophysical phenomena. Joint GW, electromagnetic (EM) and neutrino observations are expected to provide a wealth of information on the source nature that would be unaccessible from the EM observations alone. For example, both GW and HEN can travel almost unaffected from the region of their production to the observer, while photons are highly scattered before escaping from the innermost regions. Therefore, both GW and HEN can provide crucial information on the processes taking place in the innermost engine of the source [8]. At the same time, the only way to localize and therefore to individuate a GW and/or neutrino emitting source is through multi-wavelength EM observations and, if extra-galactic, this will ultimately enable to identify the hosting galaxy and the distance of the source can thus be estimated accurately by measuring the cosmological redshift of the galaxy spectral line systems. Both accurate position in the sky and distance, in turn, provide useful priors in the GW data analysis parameter space, refining unique information on the bulk motion and the dynamics of the source central regions [9].

This review presents some of the main properties of these three classes of sources in Section 2, the results obtained so far from past multi-messenger searches with the first generation GW interferometer observatories in section 3 while in section 4 the future observational scenario with the advent of the second generation observatories is discussed.

## 2 The electromagnetic and neutrino counterparts of GW transient sources

A key role in multi-messenger astronomy will be played by Gamma-Ray Bursts (GRBs) for which GW and neutrinos are expected to accompany the well known electromagnetic emission. Theoretical models, supported by hydrodynamical relativistic simulations, are generally in agreement by interpreting both long and short GRBs as produced by an accreting stellar mass black hole. However, the central BH is originated through two different channels: from the coalescence of two NSs or a NS and a BH in the case of short GRBs , and from the core collapse of a massive star in the case of long GRBs. This scenario is in line with the experimental properties of GRBs. In particular, the origin of long GRBs from the core collapse of massive stars has been proved by their positional and temporal association with SNIb/c, while for short GRBs there are several indirect evidence as the consistency with older star population than for long GRBs, but the definitive proof will be the coincident detection of GWs. The matter accretion onto the BH is expected to produce relativistic ejecta. Each ejecta, by expanding into the interstellar matter, forms a shock wave that slowly converts the outflow kinetic energy into EM radiation via synchrotron emission [10]. A big conundrum still affecting our knowledge on GRBs is the degree of collimation of their ejecta: this has prevented so far precise burst energetics and event rate estimates that indeed are known unless a factor of $(1 - cos(\theta_{jet}))$. The jet opening angle has been measured only for a small subsample of GRBs with large multi-wavelength data set and known distance and the obtained distribution goes from few degrees up to several tens of degrees [11].

The EM emission from GRBs (both long and short) appears as a bright flash of gamma-rays (form keV up to GeV energy range) of various durations (from less than few seconds for short GRBs up to hundreds of seconds for long GRBs) and it further develops at late times with the "afterglow" emission. Afterglows are thought to be produced when the ejecta starts to decelerate while expanding into the external medium. Afterglow emission peaks after minutes/hours from the burst onset in the X-ray regime (0.1-10 keV), with typical fluxes in the range $10^{-10} - 10^{-12}$ erg $cm^{-2}$ $s^{-1}$ and in the optical and near infrared (NIR), with observed magnitude on average comprised between 15 and 25 mag [12]. After some days, the afterglow emission shifts in the radio frequencies with fluxes typically below the mJy level, up to weeks-months. The flux temporal decay at late time is on average described by power laws with decay index of about -1.5. Photon spectrum is typically non thermal and well represented by synchrotron emission. The EM energies released during the burst, assuming an isotropic geometry (not collimated) is of the order of $10^{52-54}$ erg for long GRBs and on average 2 orders of magnitude less for short GRBs.

All the afterglows observed so far were associated with a prompt gamma-ray emission, that is, with a GRB ejecta collimated towards the Earth. However, a non-negligible EM afterglow emission is expected also from GRBs "off-axis" (i.e. not pointing towards the Earth). In particular, both for short and long GRBs, off-axis afterglow emission (also called "orphan afterglow" because no gamma-ray burst is anticipating it) will enter in the observer line of sight when the ejecta starts to spread laterally as it decelerates and expands into the interstellar medium. Off-axis afterglow emission is fainter and peaks at later times than the "on-axis" counterpart. So far, only in one case a possible "orphan afterglow" has been detected with the Palomar Transient Factor Telescope (PTF). However, the detected source (PTF11agg) showed multi-wavelength properties more typical of an "on-axis" afterglow and its origin is still debated [13].

Coalescing NS-NS systems are theoretically predicted to isotropically eject a small quantity of neutron rich matter, the radioactive decay of which produces optical/NIR transients ("kilonova") with typical thermal spectrum [14]. The peak of kilonova emission is predicted at 1 to few days after the merger. Interestingly, the main kilonova emission may be preceded by a moderately bright precursor in the U-band few hours after the merging that can potentially better mark the time of the associated GW event [15]. So far only one possible evidence of a kilonova was found for the short GRB 130604B for which a detection about one week after the burst was found to be inconsistent with the expected optical/NIR afterglow fluxes at the same epoch [16]. It is thought that the small detection rate of kilonova so far, is mainly due to its intrinsic faintness that is likely dominated by the afterglow emission for on-axis GRBs.

Core-collapse SNe are typically detected in the electromagnetic spectrum at optical frequencies after tens of days from the collapse. Only in very few cases, an early "SN shock break-out" (SBO) was observed in X-rays and UV-optical wavelengths, marking the very first leak of radiation from a collapsing star experiencing its SN phase [17,18]. Despite its challenging detection, SBO emission is extremely important to mark the time of explosion since it is expected after much shorter time (few hours on average) than the typical optical signature weeks later.

Events such as X-ray flares and bursts from neutron stars are well known phenomena [19] that go under the name of Soft Gamma Repeters (SGR) and Anomalous X-ray Pulsars (AXP). In particular, SGRs were discovered in 1979 as transient sources of hard X-ray bursts and giant flares, while AXPs were identified in late '90s as a class of persistent X-ray pulsars with no evidence of binary companion and with an X-ray luminosity much higher than the expected luminosity from magnetic dipole radiation only. Today, both SGRs and AXPs are largely believed to be associated to a single astrophysical source, that is a highly magnetized neutron star (magnetar), experiencing starquakes and consequent crust disruption. Magnetars emission is characterized by a persistent X-ray emission with luminosity $L_x = 10^{35-36}$ erg $s^{-1}$ (in the 0.2-200 keV energy range) and episodic short bursts of duration of about 0.1-1 s of soft gamma-rays (thermal peak energy at KT=30-40 keV and luminosity of $L_x = 10^{39-41}$ erg $s^{-1}$). In very few cases (3 over 30 years so far) giant flares are emitted by these objects whith an X-ray luminosity that can reach values of $L_x > 10^{44}$ erg $s^{-1}$ and an X-ray released energy of the order of $10^{46}$ erg.

The above mentioned astrophysical sources, and in particular GRBs, are expected to produce relativistic outflows in which hadrons are accelerated and produce high-energy neutrinos by interacting with the surrounding medium and radiation. MeV neutrinos have been detected with SuperKamiokande and the IMB neutrino detectors on 23 February 1987 several hours before the otpical discovery of the supernova SN 1987A in the Large Magellanic Cloud [20,21]. These observations confirmed not only the expected neutrino emission from ccSNe, but also revealed the huge

Table 1: Initial LIGO and Virgo past science runs during which multi-messenger searches were performed.

| LIGO | Virgo | |
|---|---|---|
| S5: Nov 2005-Aug 2007 | VSR1: May 2007-Oct 2007 | |
| S6: Jun 2009-Oct 2010 | VSR2: Jul 2009-Jan 2010 | "Winter run" 29 Dec 2009-7 Jan 2010 |
| | VSR3: Aug 2010-Oct 2010 | "Autumn run" 16 Sept 2010-3 Oct 2010 |

importance of neutrino detection in the multi-messenger astronomy since it can better mark the time of GW emission. However, in no other case of cosmic neutrino detection an astrophysical source could be associated.

A particular interesting case for joing GW and neutrino detection are the so called "low-luminosity GRB" (or "chocked GRBs"). These are a small subset of long GRBs that show fainter and typically softer emission during the burst. The spatial distribution of low luminosity GRBs is on average skewed towards nearby distances with respect to long GRBs. It has been suggested that the peculiar low luminosity of this type of long GRBs is due to mildly relativistic outflows that nearly fail to cross the stellar envelope, thus producing fainter EM emission [22].

## 3 Results from multi-messenger past searches

In this section, some of the results from past multi-messenger searches during the LIGO and Virgo observational runs performed before their upgrade are summarized together with their literature references. Table 1 shows the temporal windows during which LIGO and Virgo performed their past science runs. During LS6 and VSR2 and VSR3 epochs, GW candidate triggers were released to the astronomical facilities that signed the Memorandum of Understanding (MoU) at that time. These were typically large field of view (FOV) optical telescopes (see next section). The candidate triggers were the most significant events of the science runs, but they were low signal to noise ratio events with amplitude corresponding to high False Alarm Rate (FAR). For GRBs and flares from NS that happened during these epochs, off-line GW data analysis was also performed using as priors the time and the sky localization of the astrophysical event.

In the following we summarize some of the results from coincident GW plus electromagnetic (EM) and neutrinos searches during initial LIGO and Virgo science runs. Note that the detector sensitivities during LS6 and VSR3 corresponded to a maximum distance of $D_h = 40, 80, 90$ Mpc for a NS-NS, NS-BH of and BH-BH systems, respectively[a], by assuming 1.35 $M_\odot$ for NS mass and 5.0 $M_\odot$ for BH mass [23].

### *3.1 From GW candidate event triggers to EM follow-up*

An important issue in the search for multi-messenger counterpart of GW candidate events is the fact that GW observatories are non-imaging detectors. Localization of GW source is based on the triangulation method, that is, on the temporal delay of a GW detection between two or more detectors due to the finite travel velocity of GW. Thus, to localize a GW source, multiple detector network is needed. Localization uncertainty is driven by: 1) amplitude of the signal; 2) time delay between detectors. Therefore, localization strongly benefits of detector network with similar sensitivities and far apart one with the other. For example, the sky localization precision for the second generation GW detectors with the advent of LIGO India[24] and KAGRA[25] in addition to the aLIGO and Advanced Virgo, is expected to improve of about one order of magnitude the present values (see next section). At the time of the first-generation LIGO and Virgo science runs, the achieved localization precision was not better than hundreds of square degrees.

[a] where with $D_h$ we indicate the horizon distance, that is the maximum distance at which a binary system can be detected in optimal condition (e.g. face-on and at a position in the sky that maximizes the GW detector sensitivity)

During the so called "Winter run" and "Autumn run" observational periods of LIGO and Virgo (see Tab.1), 8 GW trigger alerts were sent to the MoU partners and a multi-wavelength follow-up observational campaign was performed for each trigger. The FAR of these events ranged from 4.5 to 0.02 per day. At that time, the activated large field of view (FOV) facilities were the optical telescopes QUEST, TAROT, ROTSE, PTF, Liverpool-SkyCamZ and Pi Of The Sky and the radio telescope array LOFAR. Small FOV optical telescopes also were pointed, namely Zadko, Liverpool-RATCam, and the UV-Optical (UVOT) and X-ray (XRT) Telescopes on board the Swift satellite.

For each trigger, the date and time of the event, the FAR associated with that event, and the sky probability map, were provided to the astronomers. Several exposures were taken with large FOV telescopes in order to cover the sky regions with maximum probability to detect a GW source indicated by the probability skymaps obtained from GW data analysis and prioritized taking into account of the galaxies within the GW detectors range.

No credible EM counterparts for any of the GW triggers was found. Several papers describe in details the results from the observational campaigns with optical facitilies [26,27], with Swift-XRT and UVOT [28], and at the radio wavelengths [29].

Interestingly, during the "Autumn run", one of the GW triggers was labelled as "Big Dog" due to the low FAR with which it was associated (FAR $< 0.01$). However, this event resulted to be a blind injection, that is a simulated signal secretly added to the data to test the end- to-end system. The "Big Dog" injection was not announced until a full analysis has been performed and approved, results gathered in a paper and presented at the LIGO-Virgo meeting on 14th March 2011.

### *3.2 From EM to GW using GRBs*

Using Gamma Ray Bursts as indicators in terms of time and position in the sky, GW signals have been searched at the epoch of 196 long GRBs and 27 short GRBs detected with the high energy satellite network (IPN) during the LIGO-Virgo science run periods quoted in Table 1. Almost all the GRBs were at unknown distances. Indeed, for IPN-discovered GRBs, the time delay in announcing the discovery of a GRB, that is a function of the downlink times of the various missions and the computational time to produce an error-box, is of the order of several hours up to days from the trigger. Such time delays, typically prevent the possibility to detect the GRB afterglow counterpart in the degree-scale sky IPN error boxes, since the emission has already faded below the detection threshold. For all the analyzed IPN GRBs, no significant coincident GW event was found. From the lack of any coincident GW event, the 90 % confidence level lower limits on the distance of each GRB ("exclusion distance") were computed. The obtained values (median exclusion distance) range from 12 to 22 Mpc for short GRBs by assuming face-on NS-NS and a NH-BH system waveforms, respectively, and from 4.9 Mpc to 13 Mpc for long GRBs by assuming unmodeled waveform at 150 Hz and 300 Hz, respectively [30].

During LS5 and VSR1 science runs, GW data around the time[b] of the burst onset of 22 short GRBs were analyzed. The search for GW signals did not make any assumption on the GW polarization and expected signals from binary coalescence systems. From the lack of any significant detection, the presence of a NS-BH or NS-NS progenitor for these short GRBs was excluded at 90% confidence within a distance of 6.7 Mpc and 3.3 Mpc, respectively [43]. In the same GW data set a similar search was performed [4] by looking for GW bursts associated with 137 long and short GRBs. This time, a circularly polarized 1-s long waveform at the detector most sensitive frequencies (about 150 Hz) was assumed. Exclusion distances for each GRB were computed by assuming that 0.01 $M_{\odot}$ is converted into isotropically emitted gravitational waves, finding a median of 12 Mpc. With the same assumption on GW emitted energies around the most sensitive frequencies, LS6 and VSR2 and VSR3 GW data were analyzed in coincidence with 154 GRBs detected mostly with Swift and Fermi [26]. Two search methods were applied: one based on unmodeled GW and the other assuming a NS-NS or NS-BH expected waveforms. Computed median exclusion distance for all bursts was 17 Mpc, while for short GRBs, assuming a NS-NS or NS-BH progenitor, computed values were 16 Mpc and 28 Mpc, respectively. Finally, using data from LS5 and long GRB triggers from Swift,

[b] within -5 and +1 s from the burst trigger time

a search for unmodeled long-lived (10-1000 s) GW transients was performed [41] and an exclusion distance was obtained at 33 Mpc.

All the exclusion distance values obtained in the above described searches, are well below the typical GRB distances. Indeed, the average distance of short GRBs for which the cosmological reshift has been measured, that is for about 20 short GRBs so far, is z=0.5 (3 Gpc) and the most nearby short GRB is at 500 Mpc (Fig.1). Long GRBs have an average redshift around 2.2 although the most nearby (GRB 980425) is at 40 Mpc, a distance within the range of the second-generation GW detectors. Thus, in general, the lack of any GW signal coincident with a GRB is consistent with the observed low rate of these events in the local Universe.

Two interesting cases where the two short GRBs 070201 and 051103 for which the distances could be inferred by their positional coincidence with two known galaxies. For GRB 070201, the IPN sky error box was found to overlap with Andromeda galaxy[31] at 770 kpc. For the short GRB 051103, the IPN sky error box overlaps [32] with M81 at 3.6 Mpc. If these two short GRBs were associated with a NS-NS or NS-BH binary system progenitor, at such distances GWs should had been detected confidently. The lack of any GW counterpart may imply a different nature of these two sources, possibly associated with two Soft Gamma Repeters. Indeed, the energetics of these two bursts, in terms of isotropically-equivalent released energy in the keV-MeV photon range, are $E_{iso} \sim 10^{45}$ erg and $E_{iso} \sim 10^{46}$ erg for GRB 070201 and 051103 respectively, that is, 2 to 3 orders of magnitude lower than the typical $E_{iso}$ inferred for short GRBs, thus supporting the SGR hypothesis. Another possibility is that these short GRBs are indeed much further away and just by chance their positions, that is the IPN degree-level error boxes, coincide with the two nearby large galaxies.

### *3.3 From EM to GW using flaring NSs*

During the period between November 2006 and June 2009 (science runs S5 and VSR1), 5 SGRs and one AXP phenomena were observed from 6 NSs in their bursting and flaring phase, with a total of 1279 electromagnetic triggers. Using the position and the epoch of the main X-ray activity of each source as priors for the analysis, GW data were analyzed by testing 12 different waveforms for each source[33]. From the lack of any signal, stringent 90% model-dependent upper limits on the GW energy $E_{GW}$ released during each event were obtained. The most stringent model dependent $E_{GW}$ value of $< 3 \times 10^{44}$ erg was obtained for the newly discovered SGR0501+4516 at the closeby distance of $d < 1$ kpc, that is one order of magnitude closer than other discovered magnetars. For this source, $E_{GW} < 3 \times 10^{44}$ erg, that is about one order of magnitude lower than past SGR upper limits. More interestingly, for the first time GW energy upper limits are almost comparable with electromagnetic energies from giant flares.

### *3.4 Neutrinos and GW coincident searches*

Neutrino detectors, as the GW detectors, are "all-sky" observatories and cannot provide accurate localization. However, the time of neutrino detection can provide an optimal constraint for GW search since neutrino emission is expected to be nearly simultaneous to GW. Therefore, search for coincident signals from LIGO and Virgo and the two high energy neutrino detectors IceCube, a cubic-kilometer detector at the South Pole [34], and ANTARES in the Mediterranean sea [35], were performed during the epochs quoted in Table 1. ANTARES is more sensitive to TeV neutrinos while IceCube can detect also MeV neutrinos. Details on the state of the neutrino detectors at that time and on the performed data acquisition and data analysis have been published in the literature for IceCube observations [42], and for ANTARES observations [36] (see also Baret proceeding, this volume).

No temporally coincident detection was found. Assuming the most favorable case of a release of energy of $E_{GW} = 0.01\ M_{\odot}c^2$ and a neutrino released energy of $E_\nu = 10^{51}$ erg, source rate upper limit was estimated as $R < 1.6 \times 10^{-2}$ Mpc$^{-3}$ yr$^{-1}$. This value is still too high with respect to astrophysical expected rates and could not constrain any current astrophysical model.

## 4 Future programs

Second generation of GW detectors will start taking data by Fall 2015 with the two aLIGO at Hanford and Livingston (HL and LL), and by 2016 with the network formed by HL and LL plus Advanced Virgo in Italy. During the next three years, thus up to 2019, the instrumental sensitivities will gradually improve eventually reaching their nominal values.

While for SNe the expected range distance[c] for GW detection is of the order of a few to a few dozens of Mpc and for bursting NSs possible detections outside our galaxy is predicted only in the most closeby neighborhood, CBC systems are expected to be detected up to 200 Mpc for NS-NS, 400 Mpc for NS-BH and 900 Mpc for BH-BH. Within such distances, the astrophysical rate density estimated for CBC systems, despite large uncertainties, are consistent with a highly plausible detection [37,38].

For simultaneous GW and EM plus possibly neutrino detection from short GRBs, the binary system is expected to be face-on. In this configuration, by averaging over all the possible positions in the sky where one can find the source, the range distance of GW detectors increases by a factor of about 1.5, thus reaching values of 300 Mpc for NS-NS and 750 Mpc for NS-BH systems. Within such distances, for an "all-sky" instrument (not limited by its field of view) and by assuming that all short GRB emit GW that can be detected by AdvLIGO and AdvVirgo, if all short GRBs were NS-NS, the expected GRB-GW rate is of 0.1-2 $yr^{-1}$ and 0.4-15 $yr^{-1}$ if they all were NS-BH [39].

The GW interferometer KAGRA, in Japan, is expected to start taking data by 2018, and the other planned GW interferometer LIGO India, by 2022. The 5 GW detector network will provide significant improvements in sky localization, reaching values down to few degrees sky ellipse regions [40,41], that is a factor of more than 10 more precise than the present localization uncertainties. Within such sky errorbox it will be possible to perform transient search with much larger chances of detection than in the past searches. Follow-up campaigns of GW triggers by aLIGO and Advanced Virgo will be performed by more than 150 observatories from 19 countries who signed the LIGO and Virgo Collaboration MoU[d] (more than 10 times the MoU partners during the last science run), covering the the entire EM spectrum from radio to gamma-rays. "External trigger" as GRBs will be provided by the Swift and Fermi satellites for which operative life-time has been guaranteed[e] up to 2016 and it has been proposed for extension up to 2018 (possible further extensions up to 2020 and beyond are expected). In addition, the GRB dedicated mission SVOM [44] is expected to be launched for 2021, that is when the 5 detectors network will be in operation.

Starting from then end of 2017, neutrino detections will be performed by the IceCube detector in its final configuration and by the KM3neT, an evolution of ANTARES into a multi-cubic-kilometer detector. The expected detection of GeV up to PeV neutrinos as well as MeV ones from IceCube from several sources of GWs will ensure this important piece of information in the multi-messenger astronomy [8].

## 5 Summary

By 2019 the second generation GW detectors will reach their nominal sensitivity and by that time GWs detection is largely plausible. Best astrophysical candidates of high frequency GW (1Hz-10kHz) are the following transient sources: 1) coalescing binary systems of compact objects (Short GRBs); 2) core collapsing rotating stars (SNe, Long GRBs); 3) bursting/flaring magnetars (AXPs and SGRs). These sources are well known in the EM spectrum and neutrinos emission is also expected, therefore are ideal targets for multi-messenger studies. Past results from multi-messenger searches provided upper limits on the energetics in GW and source rate density still consistent

[c]"range" is the maximum distance up to which one can detected the source, averaged over all the possible positions in the sky of the source (in terms of latitude and longitude) and over all the possible orientations of the system from which the GW amplitude depends (e.g. from a face-on case, where the maximum GW strain is expected, to a edge-on case)

[d]The list of MoU partners is published at `https://gw-astronomy.org/wiki/LV_EM/PublicParticipatingGroups`

[e]`http://swift.gsfc.nasa.gov/news/2014/sr_review.html`

with current astrophysical models. According to theoretical modelling of ccSNe and flaring NSs, the strain sensitivity of the second generation GW detectors may be enough to enable a detection of nearby sources in the next years. At the same time, the probed distances for CBC systems will contain a number of sources consistent with a significant GW detection rate. The constantly improving localization capabilities of GW detectors network will enable the $> 150$ MoU partners to ensure EM counterpart detection and monitoring of the newly discovered GW sources.


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