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Multi-messenger Observations of a Binary Neutron Star Merger

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On 2017 August 17 the Advanced LIGO and Advanced Virgo detectors observed the merger of a binary neutron star system. The Fermi-GBM and INTEGRAL SPI-ACS instruments independently detected the short Gamma Ray Burst GRB 170817A with a delay of about 1.7 s. The gravitational source was localized within a sky region of about 30 deg^2 and at a luminosity distance of 40 Mpc. The masses of the components were consistent with the known masses of neutron stars. A worldwide observing campaign across the electromagnetic spectrum discovered an optical transient (SSS17a/AT 2017gfo) in the elliptical galaxy NGC 4993. The first optical detection was made less than 11 hours after the merger. The optical and infrared observations in the first days showed the signature of a kilonova. The first X-ray and radio detection of the transient occurred at 9 and 16 days after the merger, respectively. The multi-messenger observations suggest that GW170817 was produced by the merger of two neutron stars in NGC 4993, followed by the short gamma ray burst GRB 170817A and by a kilonova whose emission was powered by the radioactive decay of r-process nuclei synthesized in the ejecta. This review summarizes the initial multi-messenger observations of GW170817.

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PoS(FRAPWS2018)013

1. Introduction

The Advanced LIGO and Advanced Virgo detectors have completed the O2 observing run in August 2017. The majority of detected gravitational events are mergers of binary black holes systems [1], [2], [3], [4], [5], including the events in the recently released GWTC-1 catalog [19].

On 2017 August 17 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo interferometers detected GW170817, the first gravitational signal from the merger of a binary system of neutron stars [6]. The Fermi Gamma-ray Burst Monitor (GBM) and the INTEGRAL spectrometer anticoincidence shield (SPI-ACS) independently detected a short Gamma Ray Burst, GRB 170817A, with a delay of 1.7 s [56], [97], [8]. The gravitational merger GW170817 and the short GRB 170817A were followed by the ultraviolet, optical and near infrared emission of a radioactively powered kilonova and, later, by X-ray and radio emission [7].

The joint observation of a gravitational merger and an electromagnetic counterpart has provided the first evidence that binary neutron star systems are the progenitors of short GRBs (or part of them), that are expected to produce a long duration afterglow whose emission ranges from the radio to the X-rays [52], [86], [87], [84], [37], [47]. The first joint gravitational and gamma ray detection triggered a global multi-wavelength campaign [7]. The photometric and spectroscopic observations of the electromagnetic counterpart are consistent with the scenario of binary neutron star mergers as sites of r-process nucleosynthesis of heavy elements that undergo decay and produce the kilonova transient [72], [67], [81], [35], [36], [104]. The GW170817 merger has allowed to set constraints on the neutron star properties [6], [15], [13], [16]. The event, that is a standard siren [98], has allowed a determination of the Hubble constant independent from the electromagnetic observations [9].

2. The Gravitational Observation

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo interferometers detected the event GW170817 with a combined signal-to-noise ratio of 32.4 and an estimated false alarm rate of less than one per 8.0×10^4 years [6] (Fig. 1). The gravitational source was localized within a sky region of 28 deg^2 and had a luminosity distance of 40^{+8}_{-14} Mpc [6].

The chirp mass estimated from the gravitational signal was $\mathscr{M} = 1.188^{+0.004}_{-0.002}$ $M_\odot$, implying a total mass of the system between 2.72 and 3.29 $M_\odot$ and individual masses ranging from 0.86 to 2.26 $M_\odot$ [6]. The primary and secondary masses have been estimated using both low-spin priors and high-spin priors; in the former case masses are in the ranges 1.36-1.60 $M_\odot$ and 1.17-1.36 $M_\odot$, while in the latter the ranges are 1.36-2.26 $M_\odot$ and 0.86-1.36 $M_\odot$ [6]. The estimated masses are consistent with the known masses of neutron stars in binary systems, but not with the masses of black holes in galactic X-ray binary systems. The observation of the GW170817 merger has allowed to set constraints on the tidal deformability of neutron stars [6]. The properties of the neutron stars involved in GW170817 event are discussed in detail also in [15], [13], [16], [19].

The nature of the merger remnant depends on the masses of the neutron stars and on the equation of state [12], [17], with different possible outcomes: a black hole formed in a prompt collapse, a short lived supramassive or hypermassive neutron star or a stable neutron star. When a black hole is formed, gravitational radiation from the ringdown of normal modes at a few kHz is expected. A

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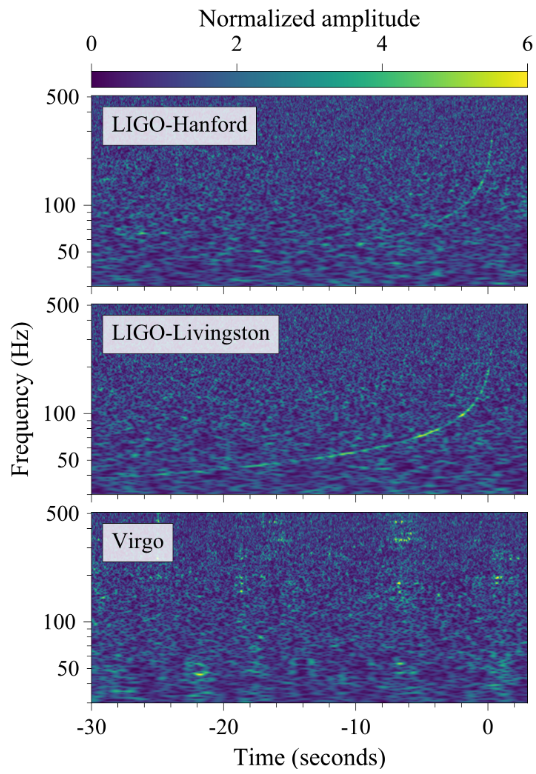

Figure 1: Time-frequency maps of the GW170817 signal in the LIGO-Hanford, LIGO-Livingston and Virgo detectors; adapted from [6]

neutron star remnant could produce gravitational signals with short ($\lesssim$1s) or intermediate ($\lesssim$ 500s) duration. Two searches for short and intermediate duration gravitational signals [12] have found no emission in the frequency band 1-4 kHz from the post merger remnant. A search for longer duration signals, that could be associated to the spin down of a massive magnetar like remnant, found no significant signal [17].

Mergers of binary neutron stars are expected to produce electromagnetic emission over the whole spectrum from material ejected dynamically. The dynamical ejecta are governed by the degree of compactness of the neutron stars. The ejecta mass distribution, in the range 10^{-3} to 10^{-2} $M_{\odot}$, has been estimated using gravitational observations for different equations of state of neutron stars [10]. The combination of the ejecta mass and of the estimated neutron star merger rate (see below) constrain the contribution of binary neutron star mergers to the abundance of Galactic r-process elements: the mergers could explain the abundance if about 10% of the matter ejected from the mergers is converted to r-process elements [10]. The electromagnetic counterpart of GW170817 is located at about 2 kpc from the center of NGC 4993. The progenitor and the second supernova kick during the binary evolution have been constrained by [11].

The detection of GW170817 has produced a revised local coalescence rate of binary neutron star system, 1540^{+3200}_{-1220} Gpc^{-3} yr^{-1} [6]. The estimated merger rate suggests that distant and unresolved systems can produce a significant astrophysical contribution to the stochastic gravitational wave background [14]. The predicted total astrophysical background near 25 Hz is $\Omega_{GW} = 1.8^{+2.7}_{-1.3}$

PoS(FRAPWS2018)013

$\times 10^{-9}$, compared with $1.1^{+1.2}_{-0.7} \times 10^{-9}$ from binary black holes alone [14].

3. The High Energy Counterpart

The Fermi-GBM instrument detected a short Gamma Ray Burst, GRB 170817A, on 2017 August 17 at 12:41:06 UTC, and disseminated the event 14 seconds later [56], [8]. The INTEGRAL instrument detected the event in an off-line analysis triggered by the LIGO-Virgo alert [97], [8]. The gravitational and gamma ray signals are shown in Fig. 2. The difference of the arrival times of the merger and of the GRB signals is 1.734±0.054 s [8].

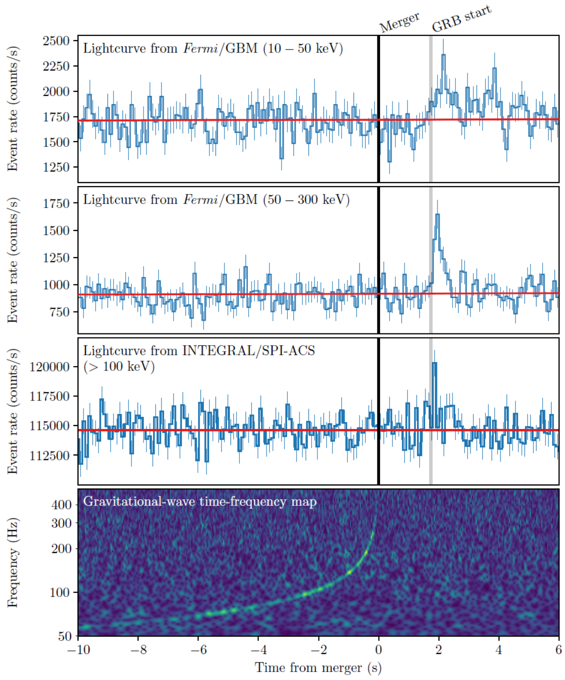

Figure 2: Joint detection of GW170817 and GRB 170817A. From top to bottom: Fermi-GBM light curve for GRB 170817A between 10 and 50 keV; the same as above but in the 50 to 300 keV energy range; INTEGRAL SPI-ACS light curve above 100 keV; time-frequency map of GW170817 gravitational signal; adapted from [8]

The burst duration of GRB 170817A estimated by Fermi-GBM is T_{90} = 2.0±0.55 s (interval over which 90% of the fluence in the range 50-300 keV is accumulated), suggesting its classification as a short Gamma Ray Burst [56], [7]. The fluence over the T_{90} interval was (2.8±0.2) $\times 10^{-7}$ erg cm^{-2} (10-1000 keV) [56]. The burst had two components, a main pulse with a Comptonized spectrum and a tail with a softer black body spectrum [56]. GRB 170817A was more than three orders of magnitude fainter than the typical short Gamma Ray Bursts [8]. The low brightness has been discussed by different models. In scenarios that do not involve the formation of a jet, the isotropic fireball expands preceding the kilonova ejecta [95]. In models involving a jet [90], [64], [63], [107], [69], [8], the low luminosity of the GRB is explained either by a uniform jet with a small bulk Lorentz factor observed at large angles or a structured jet or a mildly relativistic isotropic cocoon with a chocked jet.

PoS(FRAPWS2018)013

The gamma ray follow-up did not detect a signal excess around or within the first days after the merger, but set upper limits in different energy regions: Insight-HXMT (0.2-5 MeV) [73]; CALET (above 1 GeV) [23]; AGILE (above 30 MeV) [111]; ASTROSAT (30-200 keV) [34] ; Fermi-LAT (0.1-1 GeV) [24]; HESS (270 GeV-8.55 TeV) [20]; HAWC (above 40 TeV) [79].

The sky localization of GW170817 by the three interferometers within about 30 deg^2 was instrumental in the search of electromagnetic counterpart. The alert started an extensive multi-messenger observing campaign [7]. The gravitational observation provided a distance estimate of 40 Mpc. The list of candidate host galaxies in the gravitational error box was narrowed to 54 by [43]. The sky localization of GW170817 is shown in Fig. 3.

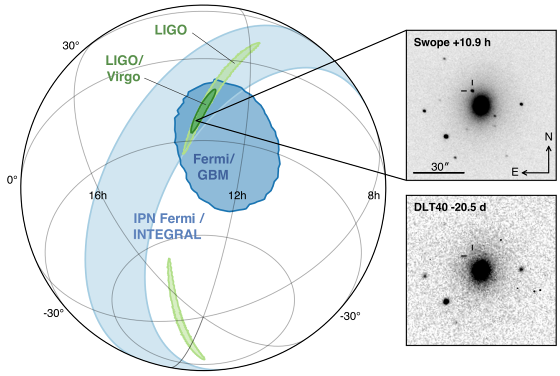

Figure 3: Sky localization of the gravitational, gamma-ray and optical signals off GW170817. Left: LIGO (light green), LIGO-Virgo (dark green), Fermi and INTEGRAL triangulation (light blue) and Fermi GBM (dark blue) localization; Right: localization of the host galaxy NGC 4993 by 1M2H Collaboration at 10.9 hours after the merger and the DLT40 pre-discovery image; adapted from [7]

4. The Ultraviolet, Optical and Infrared Observations

The first detection of an optical transient, SSS17a, also designated as AT 2017gfo, was performed at 23:33 UTC (10.87 hours after the event) by the One-Meter, Two-Hemisphere (1M2H) group with the 1m Swope telescope, Las Campanas, Chile [45], [100], that discovered a new optical source in the elliptical galaxy NGC 4993, whose distance was consistent with the gravitational luminosity distance. The transient was independently observed by other instruments: DLT40 at 11.08 hr after the event [110], VISTA at 11.24 hr [105], MASTER at 11.31 hr [74], DECam at 11.40 hr [102], Las Cumbres at 11.57 hr [29]. The source was not present in DLT40 archival images secured a few weeks before the merger [110]. A network of ground and space based instruments participated to the electromagnetic follow-up of the event in the following weeks [7], allowing the association of the transient AT 2017gfo with the gravitational event GW170817. The optical counterpart has been monitored by a large number of ground and space based facilities with apertures ranging from half a meter to ten meters [7]. The light curves of GW170817/GRB 170817A/AT 2017gfo in different photometric bands during the first month after the merger are reported in Fig. 4. Several observatories have performed optical photometric observations during the decline: SALT [39], Subaru [106], RATIR [57], TOROS [49], Las Cumbres [30], Australian

PoS(FRAPWS2018)013

facilities [28], J-GEM [109], DLT-40 [113]. A compilation of published ultraviolet, optical, and infrared photometric data of GW170817/GRB 170817A/AT 2017gfo has been presented by [31].

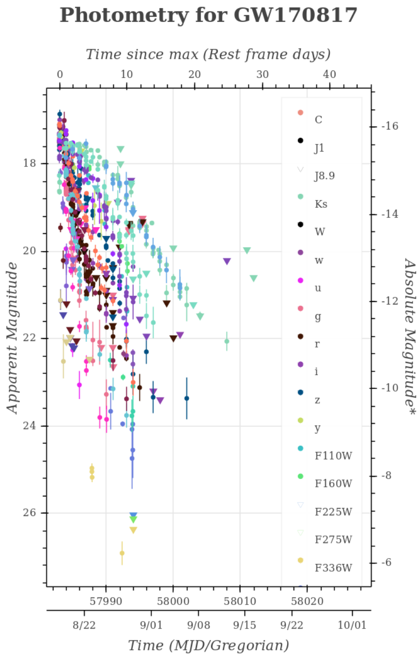

Figure 4: Light curve of GW170817 in different photometric bands in the first month after the merger; data from https://kilonova.space/kne/GW170817/

The first spectrum with the Magellan telescope at 11.6 hours after the merger showed a featureless blue (black body temperature 11000 K) continuum [99]. The spectra acquired during the first days after the merger by [99], [39], [80], [90], [75], [85] [63], [62], [65], [30], [46], [101], [51], [107], [71], [105], [42] showed a rapid fading of the blue spectrum and no features, ruling out the possibility that AT 2017gfo could be a young supernova. The spectral energy distribution shifted from the optical to the infrared with the emergence of broad features consistent with the production of lanthanides in the ejecta. The evolution of the spectral energy distribution was in agreement with the predictions of the kilonova model [81]. A compilation of spectroscopic observations during the first ten days after the merger is shown in Fig. 5. The analysis of the kilonova light curves by [112] suggested the presence of three components: a blue and fast lanthanide poor component, an intermediate opacity component and a red and slower lanthanide rich component.

The detection of the binary neutron star merger triggered new observations of the host galaxy, NGC 4993. The environment of the galaxy was studied by [88], [61], [71], [55], [38]. After the GW170817 event, the distance of NGC 4993 has been re-determined using different methods: heliocentric redshift and Fundamental Plane of galaxies (combined 41.0±3.1 Mpc) [60], surface brightness fluctuations (40.7±1.4±1.9 Mpc) [40], Globular Cluster Luminosity Function (41.65±3.00 Mpc) [70], fundamental plane (37.7±8.7 Mpc) [61].

The gravitational observations alone set a constrain the viewing angle of the system to be below 55 degrees [6]. The combination of the gravitational wave measurements with the redshift of the host galaxy NGC 4993 and the Hubble constant measurement by the Dark Energy Survey

PoS(FRAPWS2018)013

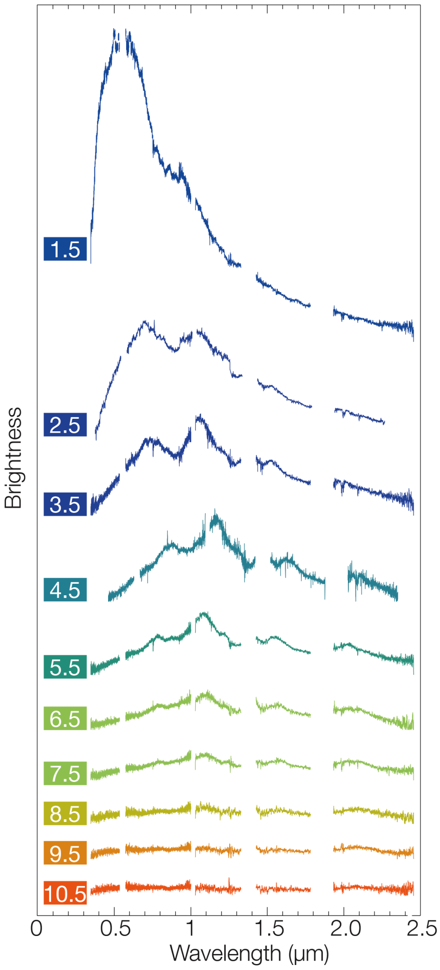

Figure 5: Spectra of GW170817 in the first days after the merger. Image credit: ESO/E. Pian et al./S. Smartt & ePESSTO

constrain the inclination to be smaller than 28 degrees [76].

5. The X-ray and Radio Observations

The first X-ray observations of GW170817 failed to detect the counterpart. Upper limits were set by MAXI (2-10 keV) at +0.19 days after the merger [103], AGILE (18-60 keV) at +0.53 days [111], Chandra at +2.2 days [77], INTEGRAL JEM-X at +6 days [97]. The X-ray afterglow was discovered at 9 days after the merger (2017 Aug 26) in Chandra observations by [107]. Chandra observations at about 15 days after the merger by [107], [58] showed a rising emission, in contrast with the fading of standard GRB afterglows. X-ray observations with Swift and NuSTAR in the first days showed a rapid UV fading and set limits on the X-ray counterpart [53]. The radio afterglow was detected at 3 and 6 GHz with the VLA on September 2, 16 days after the merger [59], with a flux increase in the following weeks [59], [82]. The brightness rising was confirmed by X-rays, optical and radio observations [48], [75], [78], [108], [82], [66], [94]. The early multiwavelength observations of GW170817 has been used by [91] to model the prompt high energy emission. The

PoS(FRAPWS2018)013

initial brightening was followed by a turnover in the radio and X-rays light curves at about 149-170 days and by a decline [94], [48], [78], [92], [83], [50], [26]. Limits on the magnetic field of the shocked ejecta has been set by the polarimetric observations by [44]. The afterglow evolution ruled out the uniform jet model, being consistent with an off-axis structured jet [107], [69] or a cocoon with energy injection [82], [108].

6. The Neutrino Follow-up

The ANTARES, IceCube, and Pierre Auger Observatories searched for high-energy neutrinos from GW170817 in the GeV-EeV energy range [25]. No high energy neutrinos and no MeV neutrinos were detected within $\pm$500 s around the merger time at the source position and in the 14 days after the merger. The Super-Kamiokande Observatory searched for neutrino events in the energy range from 3.5 MeV to about 100 PeV within a time window of $\pm$500 s around the GW170817 detection time and during a 14 days interval after the detection, without observing any neutrino event in either time window [21]. A search for high energy neutrino (from TeV to 100 PeV) with the Baikal-GVD telescope, yielded no neutrino coincident with the source within $\pm$500 s around the merger time and during a 14 day period after the merger was detected [32]. The search for neutrinos and antineutrinos (above 1 GeV) with the Baksan Underground Scintillation Telescope did not find any event in the interval of 500 s around the merger time [89].

7. Fundamental Physics and Cosmology with Gravitational Waves

GW170817 has allowed to probe the strong field dynamics of compact binaries and to test and set constraints on several aspects of General Relativity [18]: deviations from General Relativity in the Post Newtonian dynamics in the inspiral phase; anomalous dispersion during gravitational wave propagation; violation of the local Lorentz Invariance; number of large extra spatial dimensions; alternative polarization states of gravitational waves.

The observation of a gravitational event with an electromagnetic counterpart has opened the possibility of cosmology with gravitational wave observations. The joint observation of gravitational and electromagnetic emission in GW170817 has constrained some models that predict a different speed for light and gravitational waves [8]. The delay of the gamma ray signal with respect to the gravitational event has enabled to constrain the fractional difference between the speed of light and the speed of gravity between -3×10^{-15} and $+7\times10^{-16}$, in agreement with the predictions of General Relativity [8]. The constraint on the gravitational wave speed has ruled out or set strong constraints on some classes of modified gravity or dark energy models (see e.g. [27], [33], [68], [96]).

GW170817 is a standard siren, the gravitational counterpart of the standard candle, as proposed by [98]. Combining the distance estimated using gravitational waves and the velocity of the optical counterpart it is possible to directly measure the Hubble constant H_0 [98]. The value of the Hubble constant measured with the Cepheid variables, 73.48$\pm$1.66 km s^{-1} Mpc^{-1} [93], is in tension with the value measured using CMB observations, 67.8$\pm$0.9 km s^{-1} Mpc^{-1} [22]. The distance inferred from gravitational observations alone does not depend on any of the two methods. The value of the Hubble constant, 70^{+12}_{-8} km s Mpc^{-1}, has been determined by combining the

PoS(FRAPWS2018)013

distance value estimated by the gravitational signal with the recession velocity of the host galaxy NGC 4993 [9] (Fig. 6).

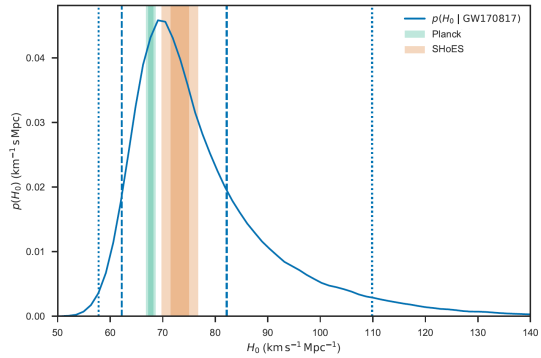

Figure 6: Relative probability of different values of Hubble constant estimated in [9] (solid blue curve), with limits of 68.3% and 95.4% credible intervals (dashed and dotted blue vertical lines); range of values inferred from CMB data by the Planck satellite (green band); range of values inferred from the SHoES analysis of Cepheids and type Ia supernovae (orange band). Adapted from [9]

The precision on the Hubble constant is expected to improve in the future with the collection of a larger number of events, at the level of 2% in five years and of 1% in ten years [41]. The possibility of measuring the Hubble constant with a statistical analysis of events without electromagnetic counterpart has been discussed by [54], considering the galaxies within the event localization region and combining the redshift of the contained galaxies with the gravitational estimated distance.

8. Conclusions

The detection of the gravitational event GW170817 from the merger of two neutron stars in NGC 4993 was followed by the detection of the sub-luminous short Gamma Ray Burst GRB 170817A within 1.7 s. The association of the GRB with the gravitational detection confirmed that at least some sGRB are associated to binary neutron star mergers. The detection of the gamma rays after the gravitational signals has bounded the speed of gravity to the speed of light within a fractional difference of 10^{-15}-10^{-16}. The electromagnetic follow-up showed that the merger was followed by a kilonova with lanthanide rich ejecta. X-ray and radio afterglows appeared 9 and 16 days after the merger, respectively. The GW170817 event constrained the tidal deformability of neutron stars and provided the first estimation of the Hubble constant outside the electromagnetic domain. The worldwide observation campaign of GW170817 with gravitational waves, neutrinos and over the electromagnetic spectrum marks the beginning of multi-messenger astronomy.

The third LIGO-Virgo observing run (O3) started on April 1, 2019 and new binary neutron star mergers are expected. The LIGO-Virgo alerts in O3 are public. The gravitational candidates are found in the Gravitational Wave Candidate Event Database GraceDb, [1], while the alerts are distributed over the Gamma-Ray Coordinate Network GCN [2].

[1]https://gracedb.ligo.org

[2]https://gcn.gsfc.nasa.gov/

PoS(FRAPWS2018)013

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PoS(FRAPWS2018)013

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PoS(FRAPWS2018)013