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Review

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Review

GW170817: A Short Review of the First Multimessenger Event in Gravitational Astronomy

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Abstract

The first detection of gravitational waves from the binary black merger GW150914 started the era of gravitational astronomy. The observation of the binary neutron star merger GW170817 and of its associated electromagnetic counterpart GRB 170817A started multimessenger gravitational astronomy. This short review discusses the discovery of GW170817 and the follow-up of the electromagnetic counterpart, together with the broad range of results in astrophysics and fundamental physics, including the Gamma-Ray Burst field. The GW170817/GRB 170817A observation showed that binary neutron star mergers can explain at least a fraction of short Gamma-Ray Bursts. The optical and infrared evolution of the associated AT 2017gfo transient showed that binary neutron star mergers are sites of r-process nucleo-synthesis. The combination of gravitational and electromagnetic observations has been used to estimate the Hubble parameter, the speed of gravitational waves, and the equation of state of nuclear matter. The increasing sensitivity of interferometric detectors and the forthcoming operation of third generation detectors will lead to an improved statistics of binary neutron star mergers.

Keywords: gravitational waves; neutron stars; gamma-ray bursts; GW170817

1. Introduction

On 14 September 2015 09:50:45 UTC, at the beginning of the O1 observing run, the two Advanced LIGO interferometers [1] performed the first direct detection of a gravitational wave (GW) from the merger of two black holes (BHs), GW150914 [2], starting gravitational astronomy. The number of detected mergers is steadily increasing; at the end of the O3 run, there were 90 candidates, mostly binary black holes [3]. Historically, the first claimed detection with resonant detectors by [4] was not confirmed by later experiments with improved sensitivities [5].

The O2 observing run (November 2016-August 2017) included the two Advanced LIGO interferometers and Advanced Virgo [6], enabling the first three-detector detection [7]. The GW170817 event on 2017 August 17 during the O2 run was the first observation of a binary neutron star (BNS) merger with gravitational waves [8], accompanied by the detection of a weak short Gamma Ray Burst (sGRB) in spatial coincidence, GRB 170817A [9–11], about 1.7 s after the merger, in the first detection of an electromagnetic counterpart of a gravitational wave event. A multi-messenger follow-up campaign was promptly started [12], discovering an optical/near infrared transient, AT 2017gfo, in the galaxy NGC 4993, at a distance consistent with the luminosity distance of the merger, about 40 Mpc. The transient evolution could be explained with a kilonova [13–17], a transient with a peak luminosity of $\sim 10^{41}$–10^{42} erg s^{-1}, three orders of magnitude brighter than a

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nova. The radiation from a kilonova is produced by the radioactive decay of high mass material produced in r-process nucleo-synthesis.

The physics of BNS mergers has been discussed by several authors [14,18–27]. Binary neutron star mergers and neutron star-black hole (NSBH) mergers had been suggested as possible progenitors of short GRBs [14,28,29], whose duration is smaller than 2 s [29–32]. The classification of GRBs into short and long ones is based on the duration distribution [31,33] and the measured redshifts of the host galaxies [29]. Short GRBs are associated with older stellar populations, with the offsets in their host galaxies suggesting a connection to BNS mergers [34–37]; in addition, there are no supernovae associated with the short GRBs [38–46]. Long GRBs are associated with the collapse of a massive star or collapsar [47–49]. Independently on the duration, all GRBs share some common spectral features, with spectra peaking below MeV energies that could be fit with a broken power law [50], with a few exceptions of spectra at TeV energies [51,52].

The BNS mergers were expected to be accompanied by electromagnetic emission not limited to gamma rays [53,54]. In addition, neutron-rich ejecta from BNS mergers were believed to be a source for r-process nucleo-synthesis [14,15,18,19,53,55–59], whose details had been elusive for a long time. The jet produced in the BNS merger would have to cross the ejecta, which shape its internal structure and the degree of collimation [60–64].

As discussed below, the simultaneous detection of gravitational waves from GW170817/ GRB 170817A was the first in a range of different physics and astrophysics aspects: the first gravitational detection of a binary neutron star merger; the first gravitational event with a detected electromagnetic counterpart; the first detection of a kilonova associated to a binary neutron star merger. Due to the intrinsic multi-messenger nature of GW170817, different names have been used for the electromagnetic counterpart: GRB 170817A for the associated gamma ray radiation burst; IAU name AT 2017gfo for the UV-optical-infrared source; SSS17a [65], DLT17ck [66], EM170817 [67], MASTER OTJ130948.10-232253.3 [68].

The link between BNS mergers and sGRBs, the multi-messenger signature of the event, the occurring of a kilonova and the role of r-processes, the progenitors of merging neutron stars, the type of object that was produced in the merger, and the possibility to estimate the Hubble constant using BNS merger were among the open problems before GW170817. The detection of GW170817 and the associated GRB 170817A provided some answers and constrained theoretical models about the merger and the related electromagnetic counterpart, using gravitational wave information combined with the electromagnetic information. In the following, both kinds of observations will be summarized, together with the information they provided, in particular presenting the electromagnetic observations in each band from radio to gamma-rays. It will be shown that at least a part of short GRBs is associated with binary neutron star mergers. Matter expelled in the merger can involve heavy elements in the rapid neutron capture (r-process) nucleo-synthesis: the prediction of the radioactive decay of heavy elements powering a thermal glow, the kilonova [15,53], was confirmed [69]. The merger produced a structured relativistic jet observed off-axis.

The present paper concisely reviews the first astronomical event with simultaneous observation of gravitational waves and electromagnetic radiation, discussing the gravitational detection and the multi-messenger follow-up. Section 2 is an overview of the gravitational observations, while Section 3 summarizes the early multi-messenger observations; Section 4 presents the evolution of the afterglow; Sections 5 and 6 discuss the impact of GW170817 detection on astrophysics and fundamental physics; and Section 7 presents the open problems and the future prospects.

2. GW170817: The Gravitational Wave Observations

The Advanced LIGO and Advanced Virgo interferometer detected the binary neutron star merger GW170817 on August 17 at 12:41:04 UTC [8] (Figure 1) at a luminosity distance of 40^{+8}_{-14} Mpc, consistent with the distance of the host galaxy NGC 4993 [70–74]. The merger was detected with high significance in the LIGO Hanford and LIGO Livingston interferometers, with a combined signal-to-noise ratio of 32.4 and a false alarm rate smaller than one per 8.0×10^4 years [8], while it was detected with a signal-to-noise ratio of about 2 in the Virgo interferometer, occurring close to the region of null response [8], still providing information about the event localization. Thanks to the presence of three interferometers in the observation network, the 90% localization region was about 28 deg^2 [11], much smaller than the typical regions of hundreds to thousands deg^2, making follow-up observations easier. The gravitational observations showed that both the range of the total mass of GW170817 system, 2.72 to 3.29 $M_\odot$, and of its components, 0.86 to 2.26 $M_\odot$, were consistent with the known masses of neutron stars in binary systems [8].

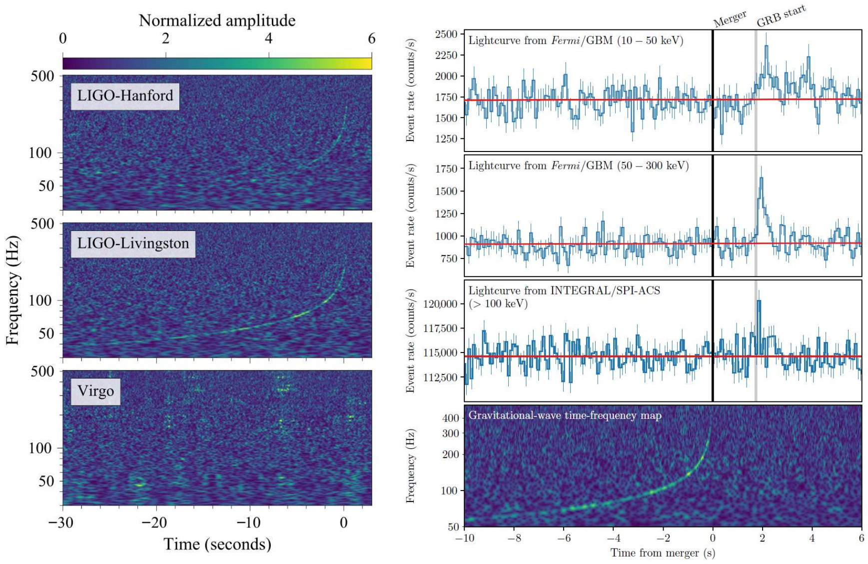

Figure 1. Left panel: time–frequency maps of BNS merger GW170817 observed by the LIGO Hanford (top), LIGO Livingston (center) and Virgo (bottom) detectors. Right panel: detection of GRB 170817A, associated with GW170817, by the Fermi-GBM (10–50 keV and 50–300 keV) and INTEGRAL SPI-ACS instruments, and the time–frequency map of GW170817. Adapted from [8,11].

The Fermi-GBM observatory detected the short Gamma-Ray Burst GRB 170817A 1.734 ± 0.054 s later [9]. The INTEGRAL SPI-ACS instrument detected the merger in an off-line analysis after the LIGO-Virgo alert [10]. The prompt electromagnetic observations during the first days after the merger will be briefly summarized here for completeness and will be discussed in detail below. The optical counterpart of GW170817/GRB 170817A, AT 2017gfo, was detected in the elliptical galaxy NGC 4993 10.87 h after the merging by the One-Meter Two-Hemispheres collaboration using the Swope telescope [65,75] and confirmed in the following hours [66,68,76–78]. No transient was visible in the images secured four months before the merger [66]. No X-ray or radio counterpart was detected during the first week after the merger [10,79–83]. The X-ray and radio afterglows emerged 9 days [84] and 16 days [81] after the merger. The multi-messenger observations around the epoch and the first days after the GW170817 merger have been reported by [12]. The multi-messenger observations have been instrumental in refining the GW170817 properties, combined with an improved calibration [85], leading to a primary mass m_1 in the range (1.36, 1.89) $M_\odot$ and a secondary mass m_2 in the range (1.00, 1.36) $M_\odot$, with a total mass of $2.77^{+0.22}_{-0.05}$ $M_\odot$ when using a high-spin prior ($\chi \leq 0.7$); a low-spin prior ($\chi \leq 0.05$) leads to a primary mass m_1 in the range (1.36, 1.60) $M_\odot$, a secondary mass m_2 in the (1.16, 1.36) $M_\odot$, and a total mass of $2.73^{+0.04}_{-0.01}$ $M_\odot$ [85]. The detection of electromagnetic radiation, together with the mass range of primary and secondary, suggests that at least one of the compact objects was a neutron star. The GW170817 event has been included in the GWTC-1 catalog, leading to $m_1 = 1.46^{+0.12}_{-0.10}$ $M_\odot$, $m_2 = 1.27^{+0.09}_{-0.09}$ $M_\odot$, a distance of 40^{+7}_{-15} Mpc, and a localization region of 16 deg^2 [86]. The detection of GW170817 enabled estimating a merger rate of 1540^{+3200}_{-1220} Gpc^{-3} yr^{-1} and setting limits on the stochastic gravitational wave background [87].

The final product of the merger, the remnant, could be either a neutron star or a black hole; a massive neutron star can also collapse into a black hole [88,89]. The search for post-merger gravitational emission in GW170817 was performed in the kHz region, both on short (sub-second) or intermediate ($\leq$500 s) timescales, with negative results [90,91]. The gravitational observations are consistent with final scenarios ranging from prompt collapse to long-lived or stable remnants [92]. A hypermassive neutron star collapsing into a black hole within one second is favored compared to the prompt collapse to a black hole [93–100]. No evidence for accretion onto a black hole or for spin down of a neutron star has been found [101].

The proximity and the accurate sky localization of GW170817/GRB 170817A have been instrumental for the detection of the electromagnetic counterpart. The number of detected mergers steeply increased during the O3 run (1 April 2019–1 October 2019 and 1 November 2019–27 March 2020), leading to the detection of a total of 90 candidates [3], but so far no other electromagnetic counterpart of a binary neutron star merger or of a neutron star–black hole merger has been detected. A second binary neutron star merger, GW190425, was detected during the O3 run [102], with component masses of $2.1^{+0.5}_{-0.4}$ $M_\odot$ and $1.3^{+0.3}_{-0.2}$ $M_\odot$ [103], consistent with components being neutron stars, and a total mass, $3.4^{+0.3}_{-0.1}$ $M_\odot$ [103], exceeding both the total mass of the most massive Galactic binary pulsar, 2.89 $M_\odot$ [104], and the total mass of GW170817, about 2.7 $M_\odot$. For completeness, some Equations of State (EoS) allow neutron star masses as large as 3 $M_\odot$ [105–107]. Compared to GW170817, the sky localization of GW190425, 8700 deg^2, and the luminosity distance, $0.15^{+0.08}_{-0.06}$ Gpc, were both much worse. The follow-up campaign [108–127] did not find any counterpart. However, the Anti-Coincidence Shield (ACS) of the SPI gamma-ray spectrometer of INTEGRAL detected the faint Gamma Ray Burst GRB 190425, with a light curve showing a behavior similar to the behavior of GW170817/GRB 170817A [128], but the observation was not confirmed by Fermi-GBM [129]. The Canadian Hydrogen Intensity Mapping Experiment (CHIME) detected a Fast Radio Burst, FRB 20190425A, within the localization region of GW190425 about 2.5 h after the merger [130], with a single galaxy, UGC 10667, consistent with the positions of both the gravitational and radio events [131]. The possible association of the FRB and the merger was ruled out [127], due to the non observation of a bright kilonova. Another reason why the GW190425-FRB 20190425A association is disfavored is the low dispersion measure observed in the FRB [132]. In addition, two neutron star-black hole mergers, with possible electromagnetic emission, have been detected, GW200105 and GW200115 [133], without the detection of any counterpart.

3. GW170817/GRB 170817A/AT 2017gfo/SSS17a: The Early Electromagnetic and Neutrino Follow-Up

The detection of GW170817 and the associated GRB 170817A triggered a worldwide multi-messenger follow-up campaign [12]. The multi-messenger observations of GW170817 and their implications have been extensively reviewed by [134–137].

3.1. High Energy Observations

The detection of gamma rays by Fermi-GBM [9] and INTEGRAL SPI-ACS [10] at about 1.7 s after the GW170817 merger [11] and in spatial coincidence has a probability of chance coincidence of 5×10^{-8} [11]. The GRB 170817A signal consists of a fast rising peak of about 0.5 s in both Fermi-GBM [9] and INTEGRAL SPI-ACS [10], followed by a slow tail with a duration of about 2 s [9,10]. The spectrum of the peak can be fitted by a power law with an exponential cut-off point and peak energy $E_{peak} = 185 \pm 62$ keV [9,11]. The softer tail emission can be fitted by a black body with a temperature of 10.3 ± 1.5 keV [9,11]. The peak luminosity, $L_{peak,iso} = (1.4 \pm 0.5) \times 10^{47}$ erg s^{-1}, and the isotropic equivalent energy $E_{\gamma,iso} = (4.8 \pm 0.9) \times 10^{46}$ erg [138], suggest that GRB 170817A is fainter and less energetic than cosmological sGRBs [139–143] (Figure 2). The existence of close sub-luminous SGRB populations had been previously suggested by [144,145].

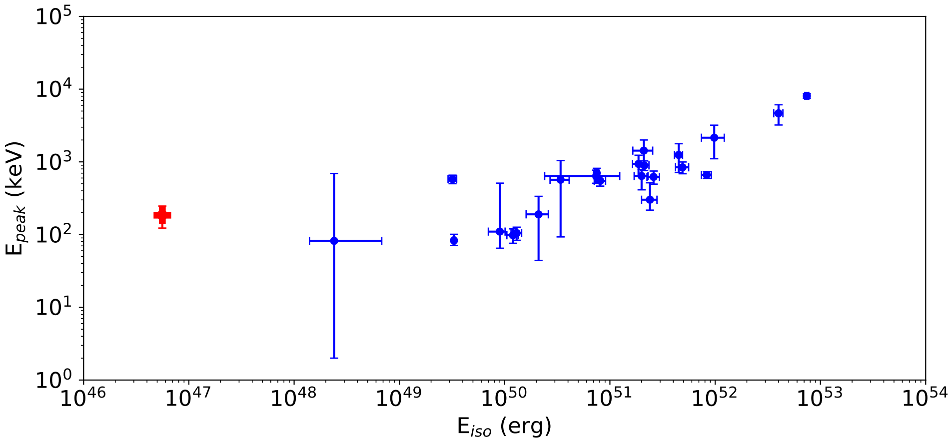

Figure 2. Peak energy E_{peak} versus isotropic equivalent energy $E_{\gamma,iso}$ for GRB 170817A (red cross) and a selection of short GRBs from [138] (blue filled circles.)

The faintness of GRB 170817A can be explained by assuming that it is observed off-axis. Gravitational observations alone constrain the angle of inclination θ_{JN} between the total angular momentum of the system and the line of sight to $\cos\theta_{JN} \leq -0.54$ [8,9].

GRB 170817A is a special example of a sub-luminous short GRB with known distance. It has been estimated that it could be detectable by GBM up to a distance of 65 Mpc, much closer than the majority of sGRBs with known redshift [9,11,146]; the closest sGRB with an identified host prior to GRB 170817A was GRB 111020A at 81 Mpc, showing E_{iso} of about 10^{46} erg, similar to GRB 170817A [147]. Probably short GRBs with luminosities between GRB 170817A value and the value of other GRBs with known redshift were detected, but not identified [146]. Up-to-date reviews of GRBs have been published by [148,149] in this Special Issue.

After the prompt emission of the GRB, there was no detected gamma-ray excess in the energy range from MeV to TeV in the first days after the merger, according to the observations by Insight-HXMT [150], AGILE [151], CALET [152], Fermi-LAT [153], and H.E.S.S. [154].

3.2. Ultraviolet, Optical, and Infrared Observations

The optical counterpart of GW170817/GRB 170817A, SS17a/AT 2017gfo, was detected in the elliptical galaxy NGC 4993 10.87 h after the merging by the One Meter Two Hemisphere collaboration [65] and confirmed in the following hours by DLT40 [66], VISTA [76], MASTER [68], DECam [77], and Las Cumbres [78]. No optical transient was detected in the archival images secured before the merger [66]. The extensive ultraviolet, optical, and infrared photometric observations have been collected and reviewed by [155], see also individual papers [65–68,76–79,84,156–169]. The light curve of AT 2017gfo in different photometric bands covering the first month after the merger, built using the data reported by [155], is reported in Figure 3. The UV and bluer bands showed a faster decline compared to the redder ones [75,79,155,161]. The infrared K_s band peaked at about 3.5 days [65,67,77,157,160,164,166].

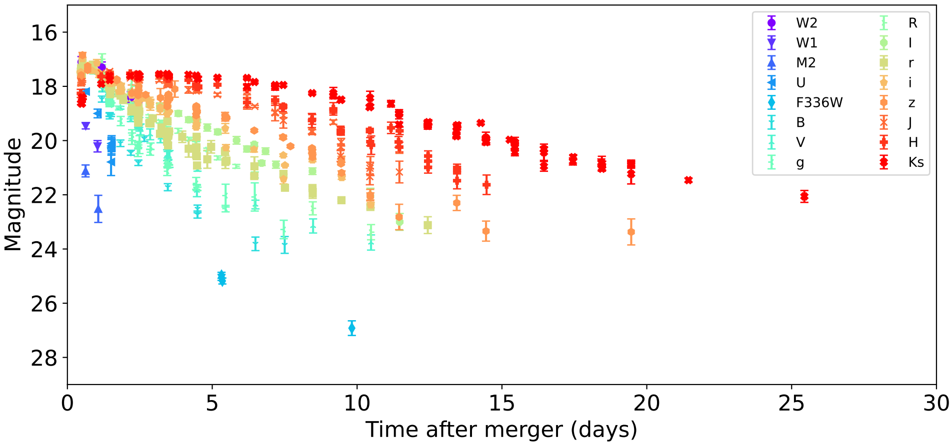

Figure 3. Light curves of AT 2017gfo for a selection of photometric bands: the Swift/UVOT W2, W1, M2; Johnson-Cousins U, B, V, R, I; SDSS g, r, i, z; HST WFPC2 F336W; infrared J, H, K_s. Data credits: [155].

Optical and infrared spectroscopy started at +0.5 d and +1.5 d, respectively [66,67,69,76,84,156,160,161,164,166,170–177]. The optical spectra secured during the first week showed a dominant blue component without any particular feature [66,67,69,76,84,156,160,161,164,166,170–177]. Later the peak of the spectrum moved towards the infrared [66,76,84,164,166,172,175–177], with persistent broad features that could be associated with the presence of lanthanide elements [67,76,84,164,166,170]. The Spectral Energy Distribution during the first days was a blackbody. During the first week the transient showed a red color, with a blackbody temperature 2500 K, that had been previously predicted by [57]; the presence of dust was excluded [178]. A set of spectra of AT 2017gfo secured by [176] is presented in Figure 4.

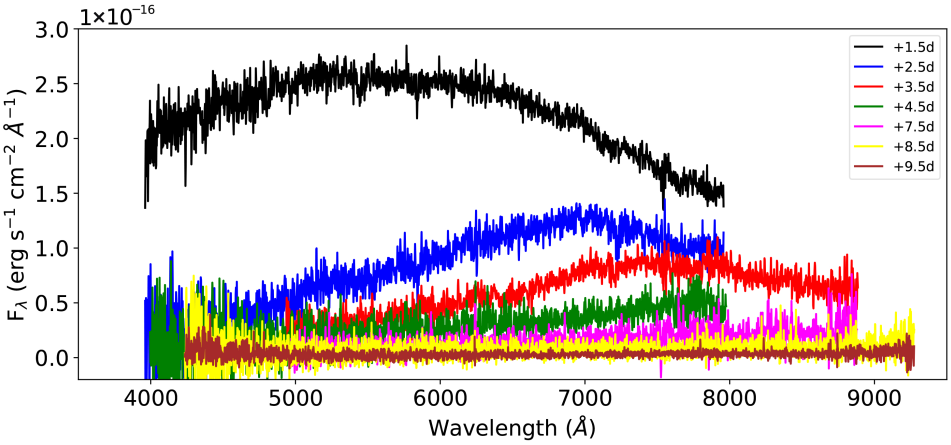

Figure 4. Spectra of AT 2017gfo in the first days after the merger; data from [176], available at https://kilonova.org/data (accessed on 1 January 2025).

The initial spectra of AT 2017gfo were featureless and with a strong blue component [177]; later spectra showed a peak progressively shifting towards the infrared and the development of broad features related to expansion velocities in the range 0.1 to 0.3 c [76,84,164,166,170,175–177]. The spectra did not show any feature typical of supernovae. The prompt photometric and spectroscopic observations can be explained by the kilonova model [14,29,32,56,59,179–184]. The brightness of AT 2017gfo can be explained by astrophysical r-processes, that produce a typical abundance pattern with peaks at high atomic masses [185]. The early spectra can be fitted by a kilonova model including lanthanides, confirming that the ejecta were composed of r-process material, whose radioactive decay powered the optical and infrared luminosity [66,67,69,76–78,155,160,161,164,166,176]. The estimated amount of r-process-enriched material in the merger ejecta was about 0.05 $M_{\odot}$, with a speed of 0.1 to 0.3 c [64,66,67,69,76–78,155,160,161,164,166,170,172,176,177,186,187]. Combining the above mass with the estimated rate of BNS mergers suggests binary neutron star mergers as the main or only source of r-process elements [155,188].

The detection of UV [79] and blue emission with a color temperature in the range 7000 to 11,000 K [177] in the early stages, together with a steeply declining optical emission, could seem to be in contrast with the lanthanide red pattern. The timescale of the expansion of lanthanide-rich ejecta, with an opacity 10^2 cm^2 g^{-1}, is of the order of one week in a red kilonova [56,189,190], while lanthanide-poor ejecta have a smaller opacity (≤ 1 cm^2 g^{-1}) and lead to a blue kilonova with a temperature of $\sim$10,000 K within two days after the merger [191] In principle, the merger ejecta can contain a spread in the fraction of lanthanides, and the blue and red kilonovae are not mutually exclusive, assuming the presence of a fraction of blue ejecta [155,160,161,175–177]. A model including only a blue kilonova underestimates infrared emission and is affected by line blanketing [69]. The blue emission has been explained by considering cocoon emission [64,67,187], considering the cooling of the energy released by the jet in the early stages and the Doppler boosted emission of the cocoon material, a model favored over the shock heating of the ejecta around the remnant [187]. Post merger winds can explain the composition and the high mass of ejecta [191–194] against the low mass resulting in shock-heated lanthanide-poor ejecta [21,22,24,195].

According to the predictions of the kilonova model [59,196], the jet from the merger was expected to interact with the above outflow during the way to breakout, ending either as a full developed jet or as a choked jet [60–62,64,196–200]. Energy dissipation occurred through a wide-angle outflow blending jet and ejecta, the cocoon, or in large angle jet wings around the central core [62].

The intrinsic asymmetry in the ejecta of BNS mergers can in principle produce a detectable optical polarization, at least when blue emission is dominating. The optical polarization of AT 2027gfo has been measured at five epochs [201], with a single detection of a polarization of P = (0.50 ± 0.07)% at the first epoch, 1.46 days after merger, and upper limits at +2.45, 3.47, +5.46, +9.48 d. The propagation in the interstellar medium was the main contributor, with the intrinsic polarization estimated to be below 0.18% [202].

3.3. Radio and X-Ray Observations

Radio and X-ray observations of GRB afterglows are relevant to constrain the energy and the geometry of the outflow and the environment properties [64,196,203–205].

After several non detections during the first week, the synchrotron afterglow emerged 9 days after the merger in the X-rays [10,79,82–84,206] and 14 days after in the radio [81]. The optical afterglow emerged 109 days after [174].

3.4. Neutrino Observations

Searches for neutrinos associated with GW170817 were performed by different observatories over a broad energy range: 10^{11}–10^{13} eV in ANTARES, IceCube, AUGER [207]; 3.5 MeV–100 PeV in SuperKamiokande [208]; 1 TeV–100 PeV in Baikal-GVD [209]; above 5 MeV in LVD [210]; above 21 MeV in Baksan [211]. All searches were negative, both using a time window of ±500 s around the merger epoch and in the 14 days after the merger. Early neutrino emission associated with the prompt gamma-ray emission would be related to hadronic mechanisms, while long-lived emission of energetic neutrinos would be consistent with a either a long-lived remnant or a stable remnant, like a magnetar [212].

3.5. The Host Galaxy and the Progenitor

The GW170817 was localized in the early type galaxy NGC 4993 at a projected distance of about 2 kpc from the galaxy center [213], a value consistent with the offset of sGRBs in other galaxies [29,37,214]. The detection of GW170817/GRB 170817A triggered extensive investigations of the environment and the distance of the host galaxy NGC 4993 [73,173,215,216]. NGC 4993 shows a bulge component, concentric shells and dust lanes, hosting an old stellar population with a low Star Formation Rate [217]. The distance of NGC 4993 has been measured after GW170817 using four different methods: heliocentric redshift and Fundamental Plane of galaxies (combined 41.0 ± 3.1 Mpc) [72], fundamental plane (37.7 ± 8.7 Mpc) [73], surface brightness fluctuations (40.7 ± 1.4 ± 1.9 Mpc) [71], Globular Cluster Luminosity Function (41.65 ± 3.00 Mpc) [74].

The formation of close binaries with two neutron stars undergoing merging within a Hubble time involves mass-transfer stages and two core-collapse supernova (SN) explosions [218–220]. The supernova explosions are expected to involve an asymmetric collapse, either from an anisotropic explosion or neutrino emission [221–223], with the remnant being imparted a kick speed of the order of some hundreds km s^{-1} [224–229].

Gravitational observations alone constrained the viewing angle of GW170817 to be below 55 deg, due to the inclination–distance degeneracy [8]. The degeneracy can be broken using an independent distance measurement, combining the recession velocity of the host galaxy NGC 4993 with the value of the Hubble constant H_0 estimated by DES, leading to an inclination angle between the orbital angular momentum of the binary and the line of sight smaller than 28 deg [230].

4. The Afterglow

The evolution of GRBs shows a rich pattern of features, including plateaus. Kilonovae are not necessarily associated with short GRBs but have also been observed for long GRBs [231] (a list can be found at the beginning of Section 6). The boundary between the two classes, the duration of 2 s, has been criticized and could be as low as 0.65–0.8 s [232,233]. There are several correlations related to GRBs and their afterglows that can shed light on the nature of GRB 170817A-like events. The Amati relation correlates the estimated total isotropic energies and the GRB redshift [234], see also [142]. The luminosity–time and luminosity–luminosity correlations for the prompt, plateau, and afterglow of Gamma Ray Bursts has been extensively addressed in the Dainotti relations [235–252]. The two dimensional correlation between the X-ray luminosity at the end of the plateau phase L_X and the rest frame duration of the plateau T^*_X [235,236] was further extended with the addition of the high energy 1 s peak luminosity of the prompt phase L_{peak}, establishing the Dainotti relation [242,243]. A three-dimensional correlation for different classes of GRBs was presented in [246]. Using all GRBs with known redshifts detected by the Swift, Fermi, and ground-based optical telescopes, a new relation between the X-ray luminosity at the end of the plateau phase L_X, the time at the end of the X-ray plateau T^*_X, and the corresponding optical luminosity L_{opt} has been proposed in [252]; using the peak luminosity measured by Fermi-GBM decreased the scatter compared to the correlation obtained for Swift measurements of the corresponding luminosity. A classification of GRBs into the merger and collapsar families had been previously proposed by [253], using the duration, the association with a supernova, the features of the host galaxy, and the environment. Their E_{peak}–E_{iso} diagram, where E_{peak} is the rest frame peak energy and E_{iso} the isotropic equivalent energy emitted during the prompt phase [254], shows separate clustering of the two families. The work by [252] finds that the E_{peak}–E_{iso} diagram of GRBs observed by Fermi shows two evident clusters of data, long GRBs (collapsar origin) following the Amati correlation with $E_{iso} > 10^{52}$ erg and $T_{90} > 2$ s and short GRBs (merger origin) above the former cluster and with smaller values of E_{iso}. Following the suggestion of the correlation of the L_X-T^*_X relation residuals with the slope of the plateau by [255] and the energy hardness parameter EH, the rescaled residual of the Amati correlation, by [256], the authors of [252] defined the Plateau Shift parameter PS, the residual of the 3D Dainotti relation, whose numerical coefficients were obtained by fitting the parameters for 61 long GRBs. The observed and predicted Dainotti relation are reported in Figure 5. The majority of sources with greatly overestimated values of $\log_{10} L_{X,th}$, i.e., under the correlation plane, lie in the region of merger events. A group of sources with a small energy hardness parameter lies significantly under the plane of correlation. Several short GRBs cluster at about 2 dex below the Dainotti relation for long GRBs, but some are about 1 dex below and could be produced by neutron star–black hole mergers. GRB 170817A appears as an outlier of both collapsars and mergers, due to the lack of low-luminosity short GRBs in the sample.

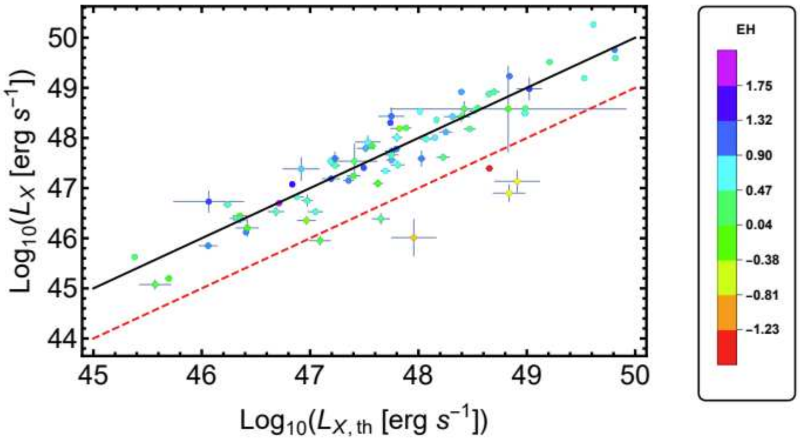

Figure 5. Observed vs. predicted Dainotti relation $\log_{10} L_X$ values, with the EH parameter marked by color; the dashed red line marks the 1 dex offset from the equality line. Image credits: [252].

The Energy Hardness–Plateau Shift diagram shows a clearly defined cluster of points with $-0.7 > \text{PS} > 0.7$ and $-0.7 > \text{EH} > 0.7$, all with $T_{90} > 1$s, surrounded by sparse bursts with $T_{90} < 2$ s; all GRBs falling significantly under the plane of $\log_{10} L_X$-$\log_{10} T^*_X$-$\log_{10} L_{peak}$ correlation ($\text{PS} < -1$) belong to the merger family. Prompted by closure relationships supporting the energy injection scenario in opposition to the jet ejection and cooling scenario [257], the authors suggested a new model for the GRB plateau based on the Blandford–Znajek mechanism [258], the energy extraction from a quickly rotating black hole via spin down, against the magnetar based model [259]. The model explains several observed features and predicts the plateau luminosity–time anti-correlation [252]. Future gravitational observations may have the potential to discriminate between black hole and magnetar models [260].

The afterglow of GW170817 evolved over long time scales, with the optical, X-ray, and radio fluxes achieving a peak at about 155 days after the merger and slowly declining later [81,82,101,174,206,217,261–280]. The compilation of optical, radio, and X-ray observations during the first thousand days has been presented by [281]. The afterglow evolution shows that the peak occurred at 155 ± 4 days after the merger epoch (Figure 6); the rising and declining parts of the light curve behave as $t^{-0.86 \pm 0.04}$ and $t^{1.92 \pm 0.12}$, respectively [281].

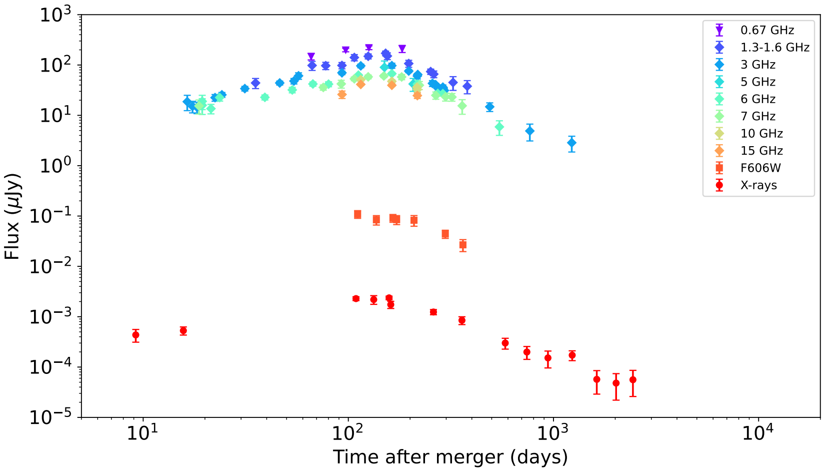

Figure 6. The afterglow light curve of GW170817 in different bands (radio: 0.67, 1.3–1.6, 3, 5, 6, 7, 10, 15 Ghz; optical data: HST F606W band; X-rays: Chandra, XMM-Newton) covering from +0.5 d to +2440 d after the merger; upper limits not reported. Data credits: [277–279,281–283], updated data available at https://github.com/kmooley/GW170817/tree/main (accessed on 1 January 2025).

The X-ray and radio data secured one year [275] and about one thousand days after merger [277] supported the evolution of a structured jet and the energy injection by a long-lived central engine. The observations secured 3.5 years after the merger showed a long lasting signal not predicted by the previous jet models [278]. An excess of X-ray emissions was observed 1234 days after the merger, a deviation from the afterglow behavior at earlier times [284], with no detectable 3 GHz radio emission. The observations were consistent with the emerging of a new component [284] and the presence of a high velocity tail in the merger ejecta, which is not consistent the prompt collapse of the merger remnant into a black hole [284]. The radio observations at about 1200 days after the merger did not find any evidence for a late radio re-brightening [285], in contrast to the excess observed at X-ray wavelengths at the same epoch [284]. The observations agree with the predictions from the after-peak decay of the radio afterglow of the GW170817 structured jet [285], suggesting an energy–speed distribution of the kilonova ejecta with an index of about 5 [285]. The possibility of explaining the reported excess flux with a boosted fireball jet model has been proposed by [286]: the excess could coincide with the emission from a counter-jet, but its apparent motion did not match the observed apparent motion measured in the VLBI observations described below [270]. The object is still detectable in deep Chandra observations 7 years after the merger [280]. There is no significant evidence for any new afterglow component, and the light curve decline is shallower than the predictions of synchrotron afterglow jet models with lateral broadening, pointing to an additional energy injection at late epochs [283].

The Very Long Baseline Interferometry (VLBI) observation of the electromagnetic afterglow of GW170817 revealed the presence of a collimated jet [270]. The compact radio source associated with GW170817 exhibits apparent super-luminal motion with $\beta = 4.1 \pm 0.5$ in the observations between 75 days and 230 days after merger, breaking the degeneracy between the choked-jet and successful-jet cocoon models; the late emission was probably dominated by a strongly collimated jet (opening angle less than 5 deg) observed from a viewing angle of about 20 deg. The apparent size of the source has been constrained to be below 2.5 mas in the observations secured at 270 days after the merger [265].

Late infrared observations with Spitzer secured at +43 and +74 days after the merger at 3.6 and 4.5 µm detected the transient at both epochs at 4.5 µm but not at 3.6 µm; the 4.5 µm fluxes were larger than the estimated afterglow contribution [171,287]. There is evidence that the flux decrease between the two epochs is explained by the second and third peaks of r-process elements in the merger ejecta [171], see also [288]. Optical observations secured from 109 to 170 days after merger were consistent with the spectral index in the afterglow light curve [282].

The combination of optical, radio, and X-ray observation of the jet afterglow up to 3.5 years after the merger has provided a measure of the viewing angle of the binary, $30.4^{+2.9}_{-1.7}$ deg [289].

In the early stages of the afterglow, during the first week, there were no radio or X-ray detections, suggesting that the jet and the line of sight were misaligned. The X-ray and radio observations during the initial rise ruled out both a standard on-axis sGRB and a top-hat off-axis jet [79,81,82,84,174,200,206,261,268,273,290]. The jet structure was weakly constrained by the early afterglow data, not ruling out the presence of slower material within a broader angle [64,265,268,272,276,291,292]. The afterglow emission is consistent with a mildly relativistic wide-angle outflow [64,265,268,272,276,291,292], with a cocoon formed in the interaction between the jet and ejecta [64,290].

5. Impact on Astrophysics and Cosmology

The GW170817/GRB 170817A discovery has triggered a large number of investigations into the properties of neutron stars, tests of General Relativity, estimates of the Hubble constant, and constraints on alternative models of gravity; some of them will be discussed below.

5.1. Neutron Stars Properties

The compact objects undergoing merging in the GW170817 event are neutron stars instead of the more common merging binary black holes. While the early waveform is governed by the chirp mass and later by the mass ratio of the components [293], the properties of the merging objects become more relevant when the object separation is approaching their size [294–296]. The key parameter to assess the compactness of the binary components is the dimensionless tidal deformability $\tilde{\Lambda}$, which depends on both the mass and the radius of the neutron star, i.e., on its Equation of State (EoS), and is null for a black hole [294,297–304]. The tidal effect was predicted to be observable above about 600 Hz [300,305–314]. The tidal deformability has been investigated by allowing the deformabilities Λ_1, Λ_2 of the high and low mass components to vary independently and comparing them with the predictions of a set of Equations of State [105,315–318], see also [319] for parametrization, that support masses of $2.01 \pm 0.01\ M_\odot$. Gravitational observations disfavor EoSs predicting less compact neutron stars, in agreement with the constraint on radius provided by the X-ray observations [320–324]. The gravitational wave phase is governed by the parameter [296,308]:

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}. \tag{1}$$

Gravitational observations alone constrain the tidal deformabilities Λ_1, Λ_2 of the binary components [8], with additional information provided by the associated electromagnetic emission. A first estimation with minimal assumptions about the nature of the merging objects, produced a mass weighted tidal deformability parameter of the system as $\tilde{\Lambda} \in (0, 630)$ for large component spins ($\chi \leq 0.89$) and 300^{+420}_{-230} for low magnitude spins [85], ruling out some of the stiffest EoSs. An additional estimation was performed under the assumption that both merging bodies were neutron stars sharing the same EoS [325], getting a tidal deformability of 190^{+300}_{-120} for a standard EoS, suggesting that softer EoSs are favored over stiff EoSs. Gravitational data combined with EoS unsensitive relations between neutron star properties lead to the estimates of the radii of the heavier and lighter neutron stars as $R_1 = 10.8^{+2.0}_{-1.7}$ km and $R_2 = 10.7^{+2.1}_{-1.5}$ km. Allowing the EoS to support neutron star masses larger than 1.97 $M_\odot$, consistent with electromagnetic observations, yielded the stronger constrains $R_1 = 11.9^{+1.4}_{-1.4}$ km, $R_2 = 11.9^{+1.4}_{-1.4}$ km [325]. Other authors have set lower limits on the mass weighted deformability parameter of the system, $\tilde{\Lambda} \geq 300$ [326,327].

The gravitational observations of GW170817 alone constrain the maximum neutron star mass to be 2.17 $M_\odot$. However several neutron stars have masses larger than 2 $M_\odot$: PSR J0348+0432 ($M = 2.01^{+0.04}_{-0.04}$ $M_\odot$) [328]; PSR J0740+6620 ($M = 2.072^{+0.067}_{-0.066}$ $M_\odot$) [329]; PSR J0952-0607 ($M = 2.35^{+0.17}_{-0.17}$ $M_\odot$) [330], the most massive to date. The gravitational constraints have been combined with electromagnetic observations to estimate a broad range of maximum masses: 2.17 $M_\odot$ [93]; 2.15–2.25 $M_\odot$ [95]; 2.16–2.28 $M_\odot$ [331]; 2.01 ± 0.04 to $2.16^{+0.17}_{-0.15}$ $M_\odot$ [96]; $2.25^{+0.08}_{-0.07}$ $M_\odot$ [332]; 2.49–2.52 $M_\odot$ [333].

5.2. Cosmology with GW170817/GRB 170817A

Binary neutron star mergers are standard sirens for the determination of Hubble parameter H_0 [334], since they do not depend on the astronomical distance ladder, providing in principle a tool to resolve the tension between the Planck measurements [335] and the Cepheid/SN Ia measurements [336]. The topic is addressed in more detail in a companion paper of this Special Issue and will be briefly summarized here [337]. The Hubble constant tension has been extensively addressed by [242,243,245,246,249–251,338–361].

The joint observation of GW170817 and of its associated counterpart, GRB 170817A/AT 2017gfo, provided the first standard siren for estimating the absolute distance using gravitational information only. The measurement of the Hubble constant combined the distance to the source estimated purely from the gravitational wave signal with the recession velocity estimated in the electromagnetic domain [362]. In this approach, the cosmic distance ladder is not necessary, since the gravitational observations directly provide the luminosity distance. The estimated Hubble constant was 70^{+12}_{-8} km s^{-1} Mpc^{-1} [362], consistent with electromagnetic estimates [363,364] but completely independent from them. The uncertainty on H_0 is mainly caused by the degeneracy between the luminosity distance and inclination angle of the binary system [362,365].

5.3. Tests of General Relativity

The measured delay between gravitational radiation and gamma rays, about 1.74 ± 0.05 s, constrained the fractional difference between the speed of light and the speed of gravity to be in the range -3×10^{-15} to 7×10^{-16} times the speed of light [11]. The GW170817 merger allowed the testing of strong-field dynamics of compact binaries in presence of matter [366]. A set of bounds were set on a variety of processes: dipole radiation and possible deviations from General Relativity in the post-Newtonian coefficients governing the inspiral stage; modified dispersion of gravitational waves; effects due to large extra dimensions; polarization content [366]. All performed tests are consistent with General Relativity [366]. The constraints on alternative models of gravity will be discussed below.

6. Discussion

GW170817/GRB 170817A/AT 2017gfo is the first and so far unique kilonova detected with gravitational waves and is associated with a short GRB. Kilonovae can be identified also in electromagnetic observations in association with Gamma Ray Bursts, as GRB 130603B [45,184], GRB 050709 [367], GRB 060614 [368,369], GRB 070707 [370], GRB 080503 [371,372], GRB 150101B [373], GRB 181019A [374], GRB 211211A [375], and GRB 230307A [376,377]. While GRB 170817A is a short Gamma Ray Burst, the last three bursts show a short pulse followed by a longer (tens of seconds) tail, with a possible extended emission [378], blurring the traditional classes of short and long GRBs.

The rate of short GRBs is about 1000 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ [379], consistent with the BNS merger rate merger rate of $1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ after GW170817 [85] and the range 10 to 1700 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ estimated from the GWTC-3 catalog [380], but higher than the NSBH merger by about one order of magnitude [381,382], suggesting that the NSBH contribution should be very small. The progenitors of low redshift short GRBs have been investigated by [383]. It is expected that formation rate (FR) of long GRBs should be similar to the cosmic star formation rate (SFR), while that of short GRBs is expected to be delayed relative to the star formation rate, as supported by the localization of some long GRBs in or close to star forming regions in the host galaxies and the larger distance of short GRBs from the same regions [383]. The formation rate for long GRBs is significantly larger than SFR at low redshift and close to the FR of short GRBs. The low redshift long GRBs 211211A and 230307A with associated kilonovae do not necessarily have a collapsar origin. About $(60 \pm 5)\%$ of long GRBs with low redshift could have compact star merger as progenitors, thereby increasing the expected rate of the gravitational and kilonova detections [383].

Additional searches for kilonovae have been performed by optical and infrared surveys without triggers from gravitational waves or GRBs [113,384–388]. Only one object, PS17cke, has been identified a potential kilonova candidate [387]. The rate of kilonovae with luminosity similar to that of AT 2017gfo has been estimated to be $<4029\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ [385], with the caveat that some kilonovae could be fainter than that associated with GW170817.

The detection of GW170817/GRB 170817A/AT 2017gfo and its association with a binary neutron star merger has been discussed by several authors. The possibility of GW170817 being produced by different combinations of neutron stars and white dwarfs has been addressed by [389], who investigated GRB 090510 (BNS merger producing a black hole), GRB 130603B (BNS merger producing a massive neutron star with an associated kilonova), GRB 060614 (white dwarf-neutron star merger producing a massive neutron star with an associated kilonova), and GRB 170817A as a white dwarf-white dwarf merger producing a massive white dwarf with an associated transient emissions. The authors concluded that none of the above systems could support the association and that the association of GRB 170817A with AT 2017gfo suggests a new subclass of GRBs [389].

The delay between gravitational radiation and gamma rays, about 1.74 ± 0.05 s, is dominated by the propagation time of the jet to the gamma-ray production site [390]. An alternative explanation for the time delay between GRB 170817A and GW170817 has been proposed by [391], who suggested that the delay is incompatible with emission from an off-axis relativistic jet, while the prompt emission and the later X-ray and radio observations can fit a giant flare scenario, with a relativistic outflow driven by the intense magnetic field produced by magneto-hydrodynamic amplification. The delay between the gravitational and the GRB signal has been used to set an upper limit on the prompt GRB emission radius [94] and on the possible violations of the Weak Equivalence Principle [392,393]. Different models predicted lags in excess of 10 s, see e.g., [394,395], or the arrival of photons before the merger [396]. At the epoch of detection, some models allowed for time lags above one thousand years [397,398].

The observation of GW170817 has been used to constrain modified theories of gravity (extensive reviews by [399,400]). While in General Relativity the gravitational wave speed is the same as the speed of light, investigations into dark matter and dark energy suggest the possibility that gravity could deviate from General Relativity, at least in some regimes. In particular, some models predict different arrival times of the simultaneously emitted gravitational and photon signals. Among them, the Dark Matter Emulators remove the need for dark matter [401], by having ordinary particles coupling to a different metric from that of gravitational waves. In these models, the time delay between gravitational waves and photons from the same astrophysical source can be appreciable [402]. The joint detection of gravitational and electromagnetic signals has ruled out the class of Dark Matter Emulators [392,393]. The constraints set by GW170817 event and its electromagnetic counterparts have been discussed in the context of different gravity models, e.g., Horndeski, Modified Gravity (MOG), Einstein-Gauss-Bonnet, scalar-tensor [403–406]. The close values of the speed of gravitational waves and of light in GW170817/GRB 170817A have constrained some dark energy models [407–409].

7. Conclusions and Future Prospects

The rates for joint gravitational and electromagnetic detections for binary neutron star mergers are a field of active investigation, given that, to date, GW170817 is the only detection. The recent estimate based on the mergers in the GWTC-3 catalog predicts a merger rate of 10 $\text{Gpc}^{-3}\ \text{yr}^{-1}$ to 1700 $\text{Gpc}^{-3}\ \text{yr}^{-1}$ [380]. The estimated rate of joint detections in the near future is smaller than one per year [410]. The third generation detectors, Einstein Telescope [411] and Cosmic Explorer [412], will improve the sensitivity by one order of magnitude, with an increase in the statistics of BNS mergers.

A list of open questions and issues about GW170817/GRB 170817A include different aspects of the mergers and of the aftermath.

- The impact of GW170817 on the EoSs and on the maximum mass of neutron stars has been extensively reviewed by [413–415], see also [93,327,416–424]. The gravitational observations have also been discussed in combination with X-ray observations by Neutron Star Interior Composition Explorer (NICER) and X-ray Multi-Mirror (XMM-Newton) [425–430]. It has been suggested that about 10 joint gravitational and electromagnetic detections can constrain the maximum mass and the characteristic radius to the several percent level [431].
- The first optical detection of AT 2027gfo occurred 10.87 h after the merger [65,75]. Early observations with high cadence can allow exploring the evolution and presence of different components. The relevance of high cadence early optical and ultraviolet observations (in the first hours after the merger) has been discussed by [157], pointing to the possible interpretation of the early blue emission and the decline with different models. The missing constraints on the ultraviolet flux during the first hours after merger are consistent with different cooling mechanisms [157].
- The late afterglow of the event is of great interest, since it can show the presence of excess X-ray radiation. In addition, the sensitivity of present optical and infrared observations does not allow following the related afterglows over long times. The facilities over different electromagnetic bands to monitor the afterglow have been reviewed by [432].
- The merger remnant could be either a black hole or a neutron star, that, when massive, can collapse into a black hole [88,89,433–439]. The high frequency search for post-merger gravitational emission in GW170817 at short (sub-second) or intermediate ($\leq$500 s) targeting massive neutron stars [90,91] was negative and was consistent with different final scenarios [92]. The nature of the remnant merger produces signatures

also in the merger counterpart, involving the properties of the ejecta, the kilonova photometric evolution, and the presence of a jet [21,95,199]. While a hypermassive neutron star collapsing into a black hole within one second is favored compared to the prompt collapse to a black hole [93–100], the direct collapse into a black hole cannot be ruled out, since the expected black hole ringdown is below the sensitivity threshold of present interferometers [90].

- The GW170817 detection has established binary neutron star mergers as sites for r-process and contributors to Galactic nucleosynthesis [188]. The role of binary neutron star mergers will be refined with additional detections. Collapsars have been suggested as a source of r-process elements; although these systems are less common than binary neutron star mergers, the lower rate could be compensated by the larger amount of material ejected per event [440].
- Searches for neutrinos associated with GW170817 were performed by different observatories from MeV to EeV by ANTARES, IceCube, AUGER, SuperKamiokande, Baikal-GVD, LVD, and Baksan [207–211] with a time window of ±500 s around the merger epoch and in the 14 days after the merger: all searches were negative. The observation of long-lasting emission of energetic neutrinos could shed light on the nature of the remnant, either a long-lived remnant or a stable remnant, such a magnetar [212]. In addition to the single events, populations of binary neutron star mergers have been suggested as production sites of high-energy neutrinos contributing to the predicted diffuse neutrino flux, as presented by [441].

All the open questions above demand an improvement in both the LIGO/Virgo/KAGRA sensitivity and in the limiting magnitude/minimum detectable flux of the electromagnetic instruments.

The nominal range detection of BNS systems by the end of the O4 run is above 150–160 Mpc for LIGO, 50–80 Mpc for Virgo, and 10 Mpc for KAGRA is reported in Figure 7, with a large improvement expected in the O5 run (https://observing.docs.ligo.org/plan/, accessed on 1 February 2025).

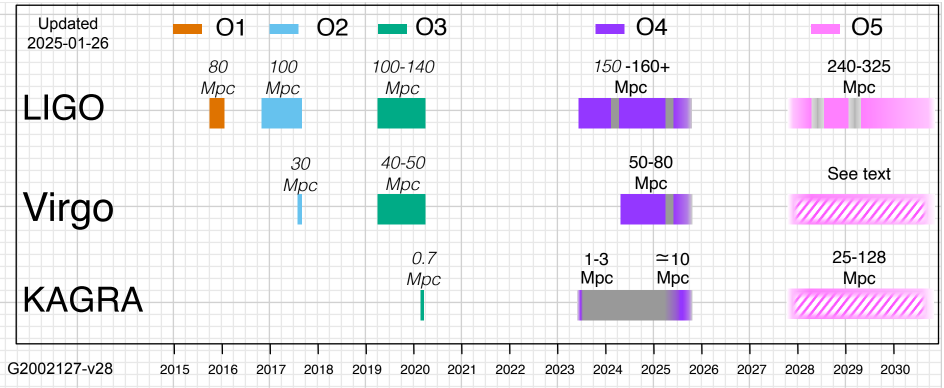

Figure 7. The evolution of achieved and planned sensitivity of LIGO, Virgo, and KAGRA interferometers during the observing runs. Credits: https://dcc.ligo.org/LIGO-G2002127/public (accessed on 1 February 2025).

Identifying a transient as a kilonova is made difficult by the combination of two factors, the time scale of the decline, a few days, and the localization region of hundreds to thousands or deg^2, which contains a large number of unrelated transients. The breakthrough results with GW170817 were possible due to the close distance of the source, about 40 Mpc, and the small localization region, smaller than 30 deg^2, with a short list of 54 galaxies obtained by cross-matching a galaxy catalog with the localization volume of the merger. The search for candidate host galaxies of similar events at large distance will have to deal with the galaxy catalog completeness: for example, GLADE+ is complete up to a luminosity distance of 47^{+4}_{-2} Mpc [442]. While the nature of AT 2027gfo as a kilonova has been recognized by spectroscopic observations, high cadence multi-band photometry can allow the identification of faint systems, using their fast evolution and peculiar color. The present instruments of all sky surveys have photometric depths not exceeding about 20 magnitudes. The image depth of the reference images by sky surveys such as DESI Legacy Imaging Survey [443] and PanSTARRS [444] is not uniform over the sky, leading to possible spurious detections. The forthcoming large telescope facilities will offer wide field imaging to tackle the large localization regions and will have large apertures, to increase the limiting magnitude of observations. The 6.5 m Vera C. Rubin Telescope will be equipped with a 9.6 deg^2 camera and ugrizy filters, with a limiting magnitude $r \sim 24$ with 30 s exposure [445], observing each field every three days. The Nancy Grace Roman Space Telescope will cover the optical and the near infrared regions, with a field of view of 0.281 deg^2 and a resolution of 0.1 arcsec/pixel [446].

The synergy between gravitational observatories and electromagnetic neutrino observatories involved some thousands of astronomers, leading to the first gravitational detection of a binary neutron star merger, the first gravitational event with an associated electromagnetic counterpart and the first detection of a kilonova.

Although GW170817GRB 170817A/AT 2017gfo is so far the only binary neutron star event with an electromagnetic counterpart, the searches for similar events and the related modeling are a blossoming field, in view of the O4 run presently ongoing and the future O5 run.

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