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REVIEW: THE LANDSCAPE OF GRAVITATIONAL WAVE ASTRONOMY

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Abstract. The direct detection of gravitational waves from a binary black hole merger has opened a new window in observational astronomy. The first three observing runs of the LIGO/Virgo ground-based interferometers have produced a broad range of scientific results, including the first observations of a binary neutron star merger and a neutron star-black hole merger. The observations include some exceptional events and other mergers reported in the GWTC-1, GWTC-2, GWTC-2.1, GWTC-3 catalogues, that have allowed tests of general relativity and studies of black hole and neutron star populations. The paper is a concise review of ground-based gravitational wave astronomy and related multi-messenger observations over the electromagnetic spectrum and the neutrino domain. Since the spectrum of gravitational waves extends over a broad frequency range, other techniques for gravitational wave detection outside the sensitivity band of ground-based interferometers will also be discussed.

Keywords: Gravitational waves, black holes, neutron stars.

1. Introduction

The spectrum of gravitational radiation extends over a large frequency interval, ranging from 10^{-10} to 10^4 Hz and includes a broad spectrum of astrophysical sources (Figure 1), requiring the combination of different detection techniques.

The dominant sources in the Very Low Frequency region, below 10^{-5} Hz, are the stochastic background and the radiation of supermassive binaries. The region is explored using pulsar timing techniques [3–5]. The Low Frequency region between 10^{-5} and 0.1 Hz includes the coalescence of both the supermassive black holes and extreme mass ratio systems and the emission of galactic binaries. The frequency band can be observed using space-based interferometers. The High Frequency region, above a few Hz, is being explored with ground-based interferometers and includes several sources:

- stellar mass binary black hole (BBH) mergers,
- binary neutron star (BNS) mergers,
- neutron star/black hole (NSBH) mergers,
- core collapse supernovae,
- pulsars,
- stochastic background of unresolved black holes,
- neutron star binaries.

Ground-based interferometers are strongly affected by seismic noise below a few Hz, while space-based interferometers are limited by optical noise above about 0.1 Hz. Several sources are expected to emit gravitational radiation in this band, among them are intermediate mass black holes (IMBHs, 10^2–10^5 $M_\odot$). The intermediate deci-Hz region between ground- and space-based interferometers will be addressed by space-based interferometers and atom interferometers. The paper is a review of the LIGO/Virgo observations of BBH, BNS, NSBH mergers in the high frequency range (Section 2), the forthcoming space-based interferometers (Section 3), the techniques to fill the intermediate frequency gap (Section 4), and the stochastic background observations with pulsar timing (Section 5).

2. High-frequency gravitational astronomy: Ground-based interferometers

The Advanced LIGO and Advanced Virgo interferometers have performed three complete observing runs, with the fourth run starting in May 2023 and still running at the time of writing. Each run has contributed to progressively uncover new features of the population of black holes and neutrons stars. This section will focus on compact object mergers.

2.1. O1 run: The first detection

The first direct detection of gravitational waves from a binary black hole merger occurred during the first observing run O1 [2]. On 2015 September 14 at 09:50:45 UTC, the Hanford and Livingston LIGO interferometers detected a chirp-like signal sweeping from 35 to 250 Hz from a BBH merger at a luminosity distance of 440^{+150}_{-170} Mpc and localised within 182 deg^2 [2, 6] (Figure 2). Two black holes with masses of $35.6^{+4.7}_{-3.1}$ $M_\odot$, $30.6^{+3.0}_{-4.4}$ $M_\odot$ merged into a final black hole with a mass of $63.1^{+3.4}_{-3.0}$ $M_\odot$. The signal time evolution was consistent with a merger followed by the damped quasi-normal ringing of the final black hole [7]. The first detection triggered several astrophysical investigations [2, 8]: tests of general relativity,

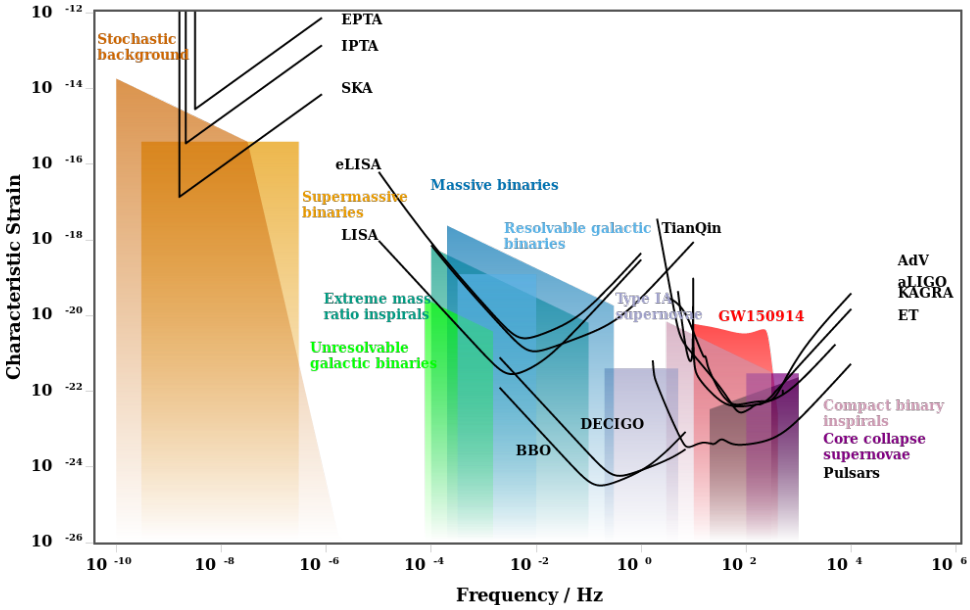


FIGURE 1. The multi-frequency gravitational wave spectrum, built using the tool [1].

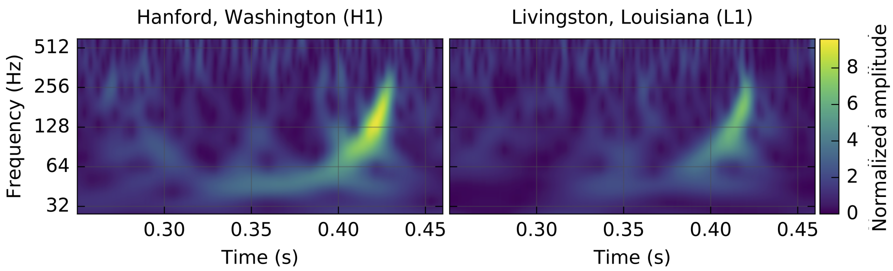


FIGURE 2. Time-frequency maps of BBH merger GW150914 as observed by the LIGO Hanford (H1, left panel) and LIGO Livingston (L1, right panel) instruments. Adapted from [2].

estimation of the BBH merger rate and of the contribution of BBH mergers to the stochastic background, and constraints on the graviton mass.

2.2. O2 run: The first multi-messenger detection

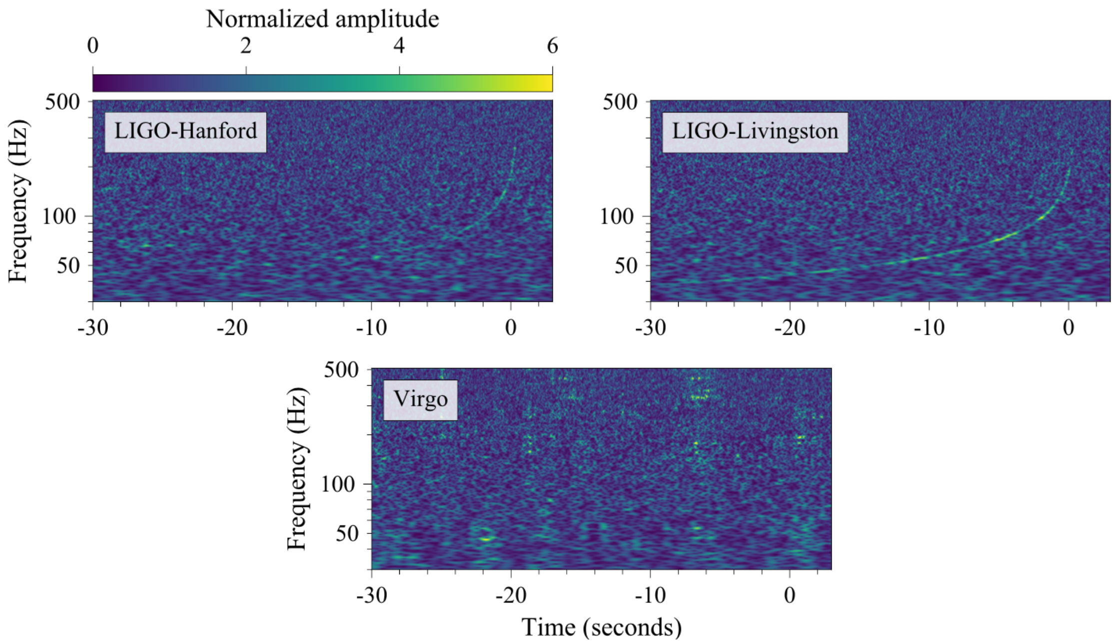
The LIGO/Virgo interferometers detected the binary neutron star merger GW170817 on 2017 August 17 at 12:41:04 UTC [9] at a luminosity distance of 40^{+8}_{-14} Mpc (Figure 3). The component masses ranged from 0.86 to 2.26 $M_\odot$, with a total mass in the interval 2.72 to 3.29 $M_\odot$, consistent with the masses of neutron stars in binary systems [9]. Thanks to the observation with three different interferometers, the event was localised within about 28 deg^2 [10]. GW170817 is the first gravitational merger with a measured electromagnetic counterpart. The Fermi-GBM observatory detected the Gamma-Ray Burst GRB 170817A 1.734 ± 0.054 s after the merger, while INTEGRAL detected it in the offline analysis [10, 11].

The small localisation region was instrumental for the extensive electromagnetic and neutrino follow-up of the event and the search for the host galaxy [12]. The optical counterpart was first detected 10.87 hours after the merger in the galaxy NGC 4993 [13]. Spectroscopic observations showed the early appearance of lanthanide features [14–29], as predicted by the kilonova model [30–40]. The X-ray afterglow appeared 9 days after the merger [41–45], followed by the radio afterglow after 14 days [46] and by the optical afterglow after 109 days [47]. In the later evolution, the optical, X-rays and radio fluxes reached a maximum 155 days after the merger before decreasing. The evolution of optical, radio and X-ray observations has been reviewed by [48] (Figure 4).

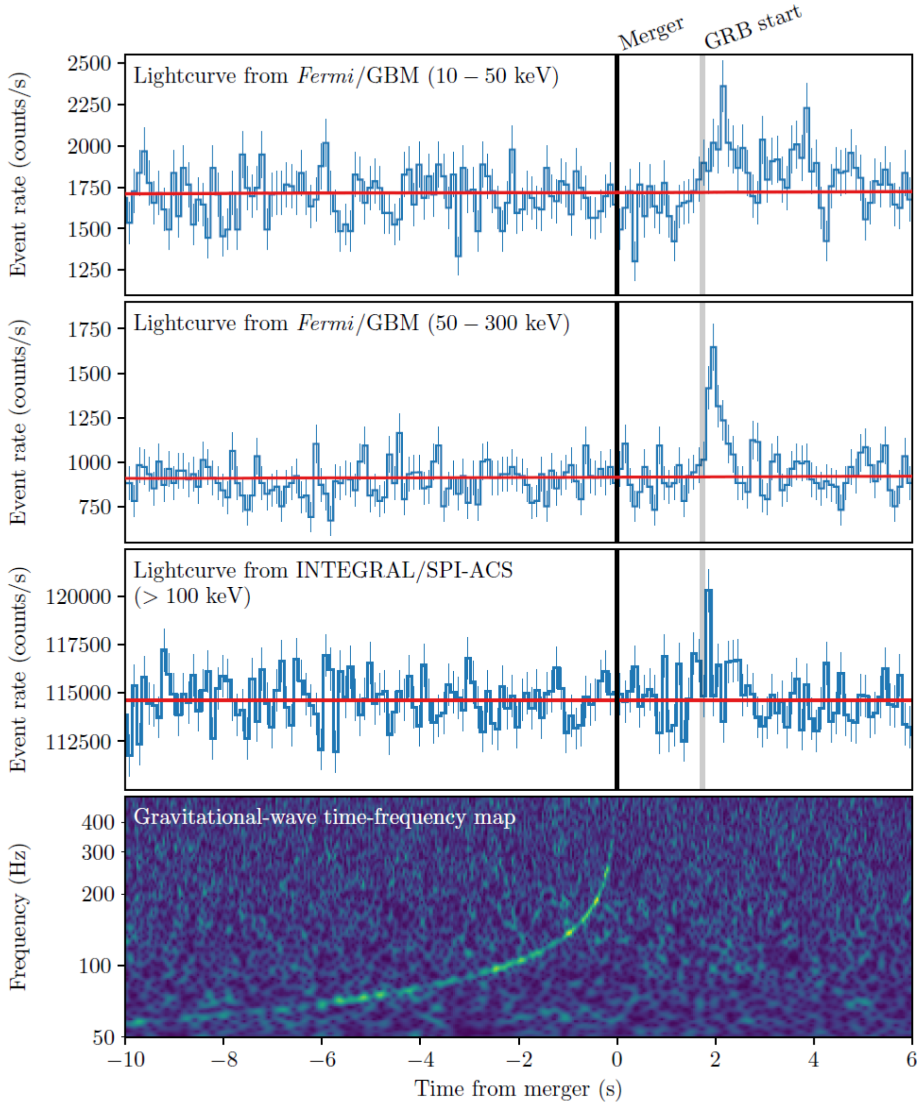
The simultaneous observation of the GW170817 merger with its associated electromagnetic counterpart allowed the first standard candle measurement [50] of the Hubble parameter H_0 [51]. There is tension between the estimates of the Hubble parameter from the Cosmic Microwave Background (CMB) [52], $67.74 \pm 0.46\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, and from type Ia supernovae [53], $73.24 \pm 1.74\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The independent GW170817 estimation, $70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [51], is broadly consistent with both electromagnetic estimations.

2.3. O3 run: Peculiar mergers

While during the O1 and O2 runs, BBH mergers with components having close masses have been detected, during the O3 run, several detected BBH mergers had components with asymmetric masses. In addition,

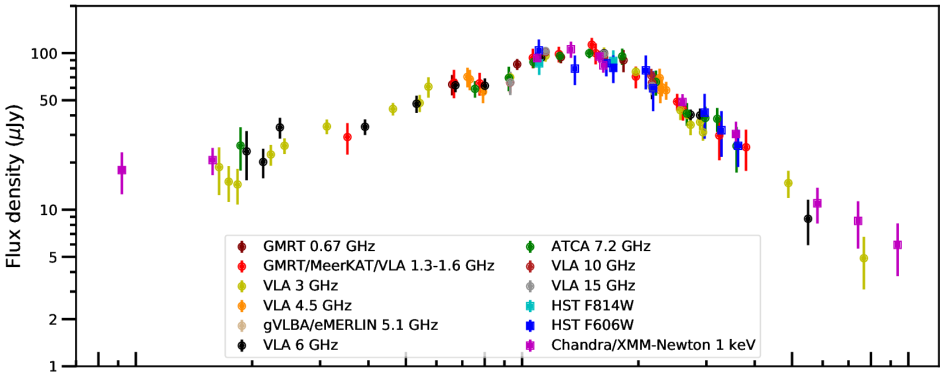


(a). Time-frequency maps of BNS merger GW170817 observed by the LIGO Hanford, LIGO Livingston and Virgo instruments.

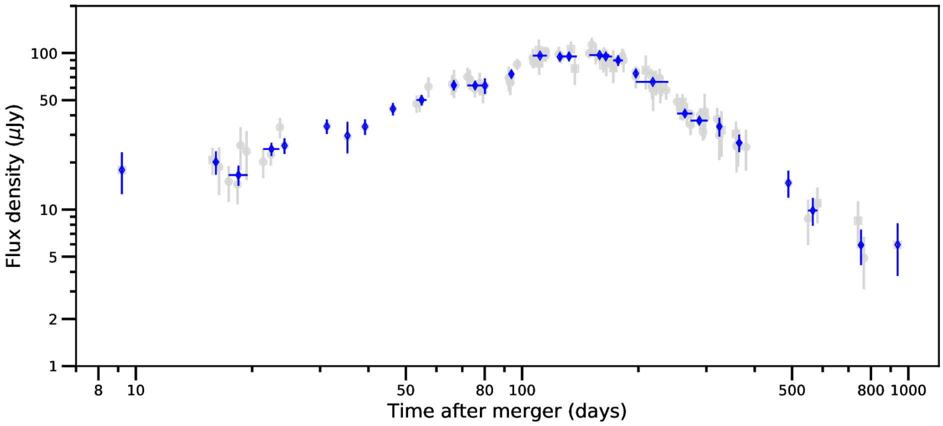


(b). Observation of GRB 170817A, associated to GW170817, by the Fermi-GBM (10–50 keV and 50–300 keV), and INTEGRAL SPI-ACS instruments, and the time-frequency map of GW170817.

Figure 3. Gravitational (A) and gamma-ray (B) signals of GW170817/GRB 170817A. Adapted from [9, 10].



(A). The panchromatic (optical, radio and X-rays) afterglow light curve of GW170817 from +0.5 d to +940 d after the merger.



(B). Averaged light curve (blue data points).

FIGURE 4. Evolution of GW170817 afterglow [49].

a second BNS merger and the first NSBH mergers have been observed, showing that all combinations of compact objects can undergo merging. The event alerts during the O3 run were public, triggering extensive multi-messenger follow-ups of mergers, producing more than 150 papers [54]. Besides a few exceptions described below, there is no confirmed electromagnetic or neutrino counterpart. The BBH merger GW190412 [55] had components with largely asymmetric masses, $27.7^{+6.0}_{-6.0}\,\mathrm{M}_\odot$ and $9.0^{+2.0}_{-1.4}\,\mathrm{M}_\odot$ [56], being the first BBH merger where gravitational radiation from higher multipole orders [57] has been detected. GW190425 is the second BNS detected merger [58], with component masses of $2.1^{+0.5}_{-0.4}\,\mathrm{M}_\odot$ and $1.3^{+0.3}_{-0.2}\,\mathrm{M}_\odot$ [56], as expected for neutron stars. The total mass of $3.4^{+0.3}_{-0.1}\,\mathrm{M}_\odot$ [56] is larger than both the total mass of GW170817, $2.7\,\mathrm{M}_\odot$, and the total mass of the heaviest Galactic binary pulsar, $2.89\,\mathrm{M}_\odot$ [59]. The sky localisation of GW190425 was worse than that of GW170817, 8 700 deg^2, and the luminosity distance was $0.15^{+0.08}_{-0.06}$ Gpc, larger than the distance of GW170817. Despite the extensive follow-up campaign, there is no evidence for an electromagnetic or neutrino counterpart in association to GW 190425, with the exception of the weak Gamma Ray Burst GRB 190425 detected by the Anti-Coincidence Shield (ACS) of the SPI gamma-ray spectrometer of INTEGRAL [60], not confirmed by Fermi-GBM [61]. The BBH merger GW190521 [62] had components with masses of $98.4^{+33.6}_{-21.7}\,\mathrm{M}_\odot$ and $57.2^{+27.1}_{-30.1}\,\mathrm{M}_\odot$, producing a final black hole with a mass of $153.1^{+42.2}_{-16.2}\,\mathrm{M}_\odot$ [56], in the predicted range for Intermediate Mass Black Holes (IMBHs, 10^2 to $10^5\,\mathrm{M}_\odot$) [63]. The heaviest component of GW190521 shows a mass in the Pair-Instability Supernova mass gap [64]. The massive initial black holes suggest hierarchical mergers in the disk of an Active Galactic Nucleus (AGN) [65, 66], an environment predicted to show an excess of eccentric mergers [67]. The observed signal has been discussed as the possible evidence for non null eccentricity [68–70] and for quasi-circular orbits and presence of higher order modes [71], see also [72]. The GW190521 merger had a luminosity distance of $3.31^{+2.79}_{-1.80}$ Gpc (corresponding to a redshift of $0.56^{+0.36}_{-0.27}$) and was localised within a region of about 1 000 deg^2 [56]. No electromagnetic or neutrino counterpart was detected in the follow-up around the epoch of the merger, but the Zwycki Transient Facility detected the transient ZTF19abanrhr 34 days after the merger, as the flare of AGN J124942.3+344929 at a redshift of 0.438, suggesting its association with GW190521 [73]. The flare could have been produced by a kicked BBH merger with a total mass of about $100\,\mathrm{M}_\odot$ occurring in the accretion disk of the AGN [73–75]. However, the association of GW190521 with ZTF19abanrhr has been disputed [76–78]. GW190814 [79] was the merger of a black hole with a mass of $23.3^{+1.4}_{-1.4}\,M_\odot$ and a compact object with a mass of $2.6^{+0.1}_{-0.1}\,M_\odot$ [56]. The nature of the secondary component is ambiguous, since it could be either the heaviest neutron star or the lighter black hole found in a compact binary [79]. The most massive Galactic neutron star, PSR J0952-0607, has a mass of $2.35 \pm 0.17\,M_\odot$ [80], while GW170817 set an upper limit of $2.4\,M_\odot$ [9]. Larger masses up to about $3\,M_\odot$ are, however, allowed by some Equations of State [81–83]. GW200105 and GW200115 are the first detected NSBH mergers [84], for which electromagnetic emission was expected [37]. The large luminosity distances of the mergers ($0.27^{+0.12}_{-0.11}$ Gpc for GW200105 and $0.29^{+0.15}_{-0.10}$ Gpc for GW200115) and the area of the sky localisation regions (9 600 deg^2 for GW200105, 720 deg^2 for GW200115) [54], made counterpart detection difficult. The component masses, $m_1 = 9.1^{+1.7}_{-1.7}\,M_\odot$ and $m_2 = 1.91^{+0.33}_{-0.24}\,M_\odot$ for GW200105, and $m_1 = 5.9^{+2.0}_{-2.5}\,M_\odot$ and $m_2 = 1.44^{+0.85}_{-0.28}\,M_\odot$ for GW200115 [54], are consistent with masses of black holes and neutron stars, respectively, for both mergers.

2.4. Growing statistics: The catalogues

In addition to the exceptional events discussed above, several mergers were detected during the O1, O2, O3 runs, leading to several catalogues. The First Gravitational Wave Transient Catalog GWTC-1 [6] collected the mergers observed during the O1-O2 runs. An increased number of mergers, mostly BBH mergers, together with a few BNS and NSBH mergers, were detected during the O3 run, leading to three catalogues: GWTC-2 [85] and GWTC-2.1 [56] for O3a run, GWTC-3 [54] for O3b run. The cumulative number of detections during the first three observing runs is 90, with the O3 run contributing with a statistic almost an order of magnitude larger than the combination of O1-O2 (Figure 5).

The three catalogues have adopted separate criteria to select events for the inclusion. The GWTC-2 catalogue includes 39 detections (26 reported as public alerts), using a False Alarm rate (FAR) threshold of two per year [85]. The GWTC-2.1 catalogue performed a deeper search with a FAR threshold of two per day [56], including a subset of 44 candidates having a probability of astrophysical origin $p_{\mathrm{astro}} > 0.5$ (36 candidates previously included in the GWTC-2 catalogue). The p_{astro} parameter is a Bayesian odds comparing the astrophysical and terrestrial origin hypothesis, combining the information about the signal rate and the noise rate to estimate the event significance [86, 87], The GWTC-3 catalogue includes 35 candidates with a probability of astrophysical origin $p_{\mathrm{astro}} > 0.5$ [54], among them 18 candidates previously reported in low latency searches.

The properties of the mergers detected during the O3a and O3b runs are summarised in Figure 6, the plane of mass ratio $q = \frac{m_2}{m_1}$ versus the total mass M.

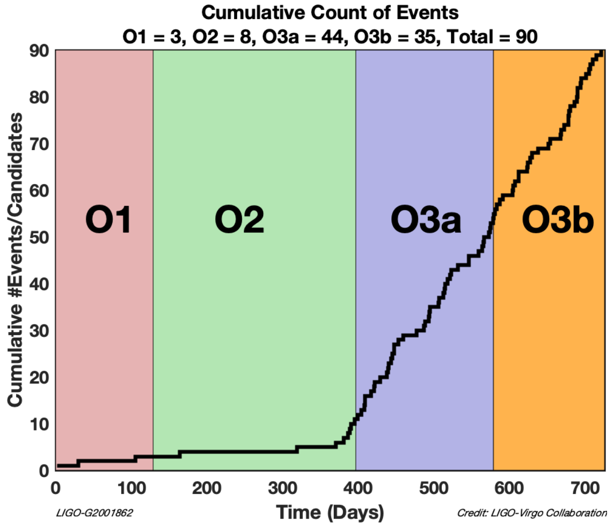


Figure 5. Cumulative counts of events in the O1, O2, O3 runs; the vertical lines mark the end of O1, O2, O3a runs [88].

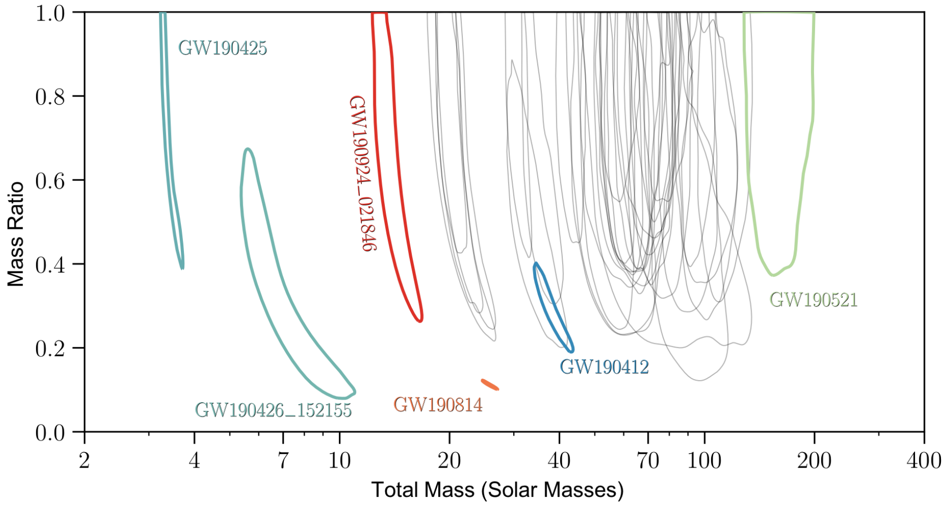
The majority of the detected mergers are BBH mergers, with a total mass extending over an order of magnitude, ranging from about $14\,M_\odot$ to about $150\,M_\odot$.

2.5. Astrophysical and cosmological implications

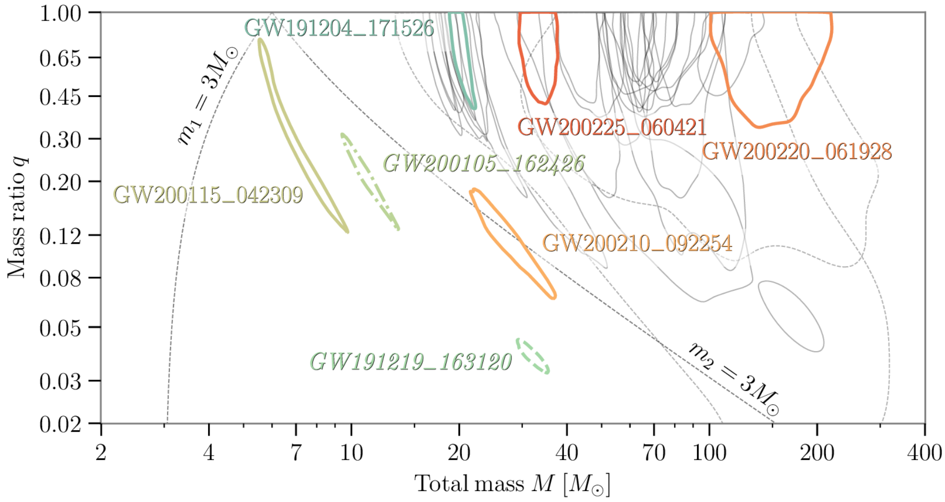
The detected mergers have allowed to perform tests of general relativity in the strong field regime, showing that there is no evidence for physics beyond general relativity [89]. Tests include the consistency of the spin-induced quadrupole moments of BBH components with those of Kerr black holes, the consistency of the final mass and final spin values estimated from the pre-merger and post-merger evolutionary phases, the behaviour of the remnant black holes, the consistency of post-Newtonian coefficients with predictions, the lack of dispersion of gravitational waves, the non-observation of non-standard polarisation modes or post-merger echos [89]. The observations have also set an upper limit on the mass of the graviton at 1.27×10^{-23} eV c^{-2} [89].

The large number of detected mergers has been used to investigate the properties of black holes and neutron star populations [90]. The mass distribution of primary black holes can be explained with a power law with superposed peaks at about 10, 35, and possibly $18\,M_\odot$. The mass distribution of neutron stars suggests a single peaked distribution with a higher mass support, with respect to the double peaked distribution of Galactic systems; however, the extragalactic population observed in gravitational observations could be different from the Galactic population. The catalogues have provided updated estimations of the merger rates: 10–1 700 Gpc^{-3} yr^{-1} for BNS, 7.8–140 Gpc^{-3} yr^{-1} for NSBH, 17.9–44 Gpc^{-3} yr^{-1} for BBH at the fiducial redshift $z = 0.2$ [90].

The investigation of the cosmic expansion requires an independent measure of the source redshift, a quan-



(A). Credible region 90 % contours for all O3a candidates in the plane of mass ratio q and total mass M; exceptional mergers GW190412, GW190425, GW190521, GW190814 (discussed in the text), the candidate NSBH merger GW190426_152155 and the lightest BBH system GW190924_021846 are highlighted. Adapted from [85].



(B). Credible region 90 % contours for all O3b candidates with $p_{\mathrm{astro}} > 0.5$ and for GW200105 in the plane of mass ratio q and total mass M. The highlighted candidates include the NSBH mergers GW200105, GW200115 (discussed in the text), GW191219_163120, the low mass BBH/NSBH system GW200210_092254, the most massive GW200220_061928, the systems GW200225_060421 and GW191204_171526 with negative and positive effective spins. Adapted from [54].

FIGURE 6. Mass ratio versus total mass for O3a, O3b candidates.

tity degenerate with the source masses in gravitational observations. While the redshift of the merger host galaxy can be estimated when a confirmed electromagnetic counterpart is detected, when counterpart is missing, it is necessary to use statistical methods, such as the statistical estimation using galaxy catalogues [50], the comparison of the redshifted mass distribution with a source mass distribution [91], the source redshift distribution [92], and the spatial clustering between gravitational sources and galaxies [93]. The Hubble parameter has been estimated using 47 mergers of GWTC-3 catalogue (42 BBHs, 2 BNSs, 2 NSBHs and GW190814) with two approaches [94], excluding [95] and including [96] the information from galaxy catalogs. The joint fit of the cosmological parameters with the BBH population produced $H_0 = 68^{+12}_{-7}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ in combination with the GW170817 H_0 estimation, and $H_0 = 50^{+37}_{-30}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ when using only the BBHs merger. The association of each merger event with a candidate galaxy in the GLADE+ catalogue [97] yielded $H_0 = 68^{+8}_{-6}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2.6. FUTURE INSTRUMENTS

The long-term vision for the third generation interferometers foresees longer arm lengths, operating underground to reduce seismic and Newtonian noise for accessing lower frequencies, and cryogenic operation to reduce thermal noise (Figure 7). The KAGRA interferometer currently in operations is a sec-

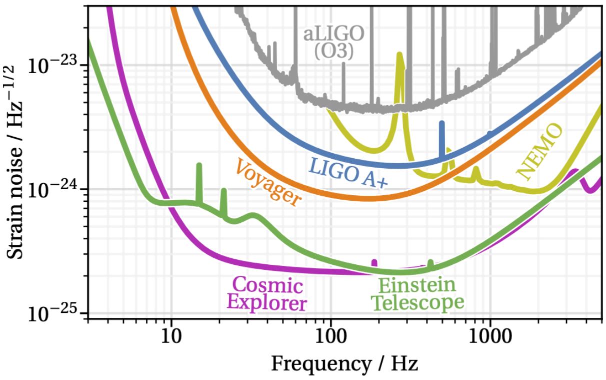


Figure 7. Amplitude spectrum of interferometer noise as a function of frequency for Cosmic Explorer (CE), O3 run and upgraded (A+) sensitivities of Advanced LIGO, LIGO Voyager, NEMO, and the Einstein Telescope (ET) [98].

ond generation interferometer with third generation technologies, being located underground and using cryogenic operation [99]. The 2.5-generation of gravitational observatories will include LIGO Voyager [100] and the Neutron Star Extreme Matter Observatory (NEMO) [101], expected to start observations in the late 2020s and early 2030s, with an improvement in sensitivity by a factor of about 5 over the second generation detectors.

Third generation observatories aim to improve the sensitivity by one order of magnitude compared to the second generation ones. The Einstein Telescope will be a single-site observatory with 10 km long arms located at about 200 to 300 m underground and cryogenic operation (10 to 20 K) [102]; observations are expected to start by 2035. Cosmic Explorer will be an L-shaped interferometer with an arm length of 40 km, with a further upgrade to the cryogenic operation [103].

3. Low frequency gravitational astronomy: Space-based interferometers

The initial LISA interferometer design was a configuration of three spacecrafts in heliocentric orbit lagging the Earth with an arm length of 5×10^6 km [104], later switched to eLISA, with a shorter arm length [105, 106]. The new LISA design, scheduled for launch in 2034, will have three arms between three identical spacecrafts in a triangle-shaped formation, separated by 2.5×10^6 km. The spacecraft constellation will orbit the Sun in a configuration centred in the ecliptic plane and trailing the Earth by about 20 deg, while the triangle plane will be tilted by 60 deg with respect to the ecliptic. The observatory will measure both gravitational polarizations at the same time in the frequency band from about 10^{-5} Hz to about 10^{-1} Hz [106]. The spacecrafts will contain free-falling test masses and will be always centred on the masses, that will be the end points of the optical length. The standard Michelson interferometer configuration of ground-based interferometers is not viable in LISA due to the large distance between spacecrafts, thus the lasers will be used in a transponder mode, where the laser at the receiving station will be phase-locked to the incident beam and will send back a replicated beam. Each LISA arm will host two transponders, using the Time-Delay Interferometry technique to build a virtual interferometer in the post-processing phase [107]. The LISA Pathfinder (LPF) mission has successfully demonstrated the LISA concept testing the key technologies, placing two test masses in free fall, unperturbed by other stray forces at a level more than five times better than the original specifications [108–110]. Taiji, to be launched in 2033, will be in a heliocentric orbit ahead of the Earth by about 18–20 deg, with the spacecrafts at a distance of 3×10^6 km, covering the range between 10^{-4}–0.1 Hz [111]. TianQin, scheduled for launch in 2035, will use a three-spacecraft configuration on almost identical geocentric orbits with semi-major axis of about 10^5 km forming an equilateral triangle [112]; the geocentric orbits will allow easier access for launch and operation. TianQin will bridge the gap region between LISA and DECIGO, described below.

The space-based interferometers will provide access to low-frequency Galactic and extragalactic sources: compact Galactic binaries; coalescing massive black holes (MBHs) throughout the Universe; extreme mass ratio inspirals [105].

4. Filling the gap

The gap region between the high-frequency limit of space-based interferometers and the low-frequency limit of ground-based interferometers, spanning 10^{-2} to a few Hz, will be addressed by two techniques.

The Deci-Hertz Interferometer Gravitational Wave Observatory (DECIGO) will be a space based interferometer sensitive in a frequency band from 0.1 Hz to 10 Hz [113, 114] similar to the instruments described above. DECIGO will consist of four clusters of observatories in heliocentric orbit, each cluster composed of three spacecrafts forming three Michelson interferometers with an arm length of 1 000 km. The science reach of DECIGO includes the observation of BNS coalescences, the measurement of the universe expansion, and the detection of gravitational waves from primordial black holes [113].

A completely different approach will use interferometry, but with matter waves instead of radiation [115]. Several atom interferometers with arm lengths from hundreds to thousands metres are being constructed or in the planning stage [116]: MAGIS [117], AION [118], MIGA [119], ELGAR [120], ZAIGA [121], all ground-based, and the space-based experiment AEDGE [122]. Atom interferometer have a strong potential for the detection of gravitational waves from the merger of intermediate mass black holes, cosmic strings, phase transitions in the early universe, and the memory effect from neutrinos from supernovae [116].

5. Very low frequency gravitational astronomy: Pulsar timing

Pulsar timing arrays (PTAs) aim to detect low frequency gravitational waves by monitoring a collection of millisecond radio pulsars [123]. An incident gravitational wave produces shifts in the arrival times of radio pulses – that are correlated between pairs of pulsars in the Helling-Downs (HD) correlations [124]. The most likely sources are ensembles of supermassive black hole binaries [125] producing a stochastic gravitational wave background. Recently, NANOGrav [126], EPTA+InPTA [127], and PPTA [128] have reported evidence of an HD correlated background with difference levels of significance. The background amplitude and spectrum are consistent with the expectations from a population of supermassive black hole binaries.

6. Conclusion

The landscape of gravitational astronomy is very rich. To date, there have been several detections of BBHs, BNSs, and NSBHs systems by the ground-based interferometers and there is evidence for the stochastic background at very low frequency via pulsar timing. The next few years will witness the development of new techniques and the start of observations with new instruments, with a broad astrophysical and cosmological reach.

Acknowledgements

Acknowledgements at `https://dcc.ligo.org/P2100218`.

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