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The new world discovered with the detection of Gravitational Waves

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The detection of gravitational waves from the merger of binary black holes, binary neutron stars, neutron star-black hole binaries has started gravitational astronomy. This contribution reviews the events detected during the first three runs (O1, O2, O3) of Advanced LIGO and Advanced Virgo and the impact of the detections on astrophysics and cosmology.

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1. Introduction

The Advanced LIGO and Advanced Virgo have completed three observing runs and started the fourth run in May 2023. The first direct detection of gravitational waves, the merger of a binary black hole (BBH) system GW150914 [22], occurred during the first observing run O1. The first binary neutron star merger (BNS) GW170817 [23] and of the related electromagnetic counterpart [14, 16] was detected during the second observation run O2. Several binary black hole mergers were detected during the O1, O2 runs, leading to the building of the First Gravitational Wave Transient Catalog GWTC-1 [19]. A large number of mergers, mostly BBH mergers, with a few BNS and NSBH (Neutron Star-Black Hole) mergers, were detected during the O3 run, showing that all combinations of compact objects can undergo merging. The run has produced three catalogs, GWTC-2 [27], GWTC-2.1 [28], GWTC-3 [32], and the detection of some exceptional events that will be discussed below. The cumulative number of detections during the first three observing runs is 90. This paper will focus on the detection of mergers of compact objects; the upper limits on the continuous gravitational radiation from pulsars and on the stochastic background are outside the scope of the paper.

2. The First Detection: GW150914

The merger GW150914 has provided the first direct detection of gravitational waves and the observation of a coalescing binary black holes system [22]. The first detection occurred during the O1 run, that lasted from 2015 September 12 to 2016 January 19. On 2015 September 14 at 09:50:45 UTC the two LIGO interferometers observed a chirp signal sweeping in frequency from 35 to 250 Hz with a peak strain of $\sim 10^{-21}$ (Fig. 1). The merger had a luminosity distance of 440^{+150}_{-170} Mpc [19] and was initially localized within a sky region of 610 deg^2 [9], later narrowed at 182 deg^2 [19].

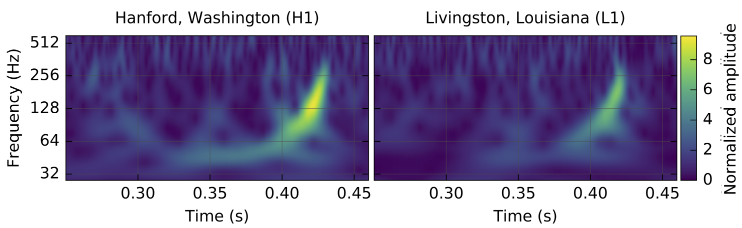

Figure 1: Time-frequency maps of BBH merger GW150914 observed by the LIGO Hanford (H1, left panel) and LIGO Livingston (L1, right panel) interferometers. Adapted from [22].

The masses of the initial black holes were $35.6^{+4.7}_{-3.1}$ and $30.6^{+3.0}_{-4.4}$ $M_\odot$, while the mass of the final black hole was $63.1^{+3.4}_{-3.0}$ $M_\odot$ [19]. The signal evolution was consistent with the merger of a binary black hole system, followed by the damped quasi-normal ringing mode of the final black hole [11].

The merger epoch, sky location and significance were shared with astronomers teams who performed the first follow-up of a gravitational event over the electromagnetic spectrum and with neutrinos [9]. No candidate counterpart was found, with the exception of the Fermi-GBM possible observation of a faint transient (above 50 keV) 0.4 s after the merger epoch [76, 77], see also [109].

The first detection started gravitational astronomy and had a broad range of astrophysical implications [4], showing that heavy stellar mass black holes can be formed, in particular the components of GW150914 formed in a low metallicity environment. The observation of the first gravitational merger constrained the rate of mergers of stellar mass black holes in the range 2-600 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ and the mass of the graviton to be smaller than 1.2×10^{-22} $\mathrm{eV/c^2}$ [11, 22]. The observation of GW150914 allowed to constrain the energy density of the stochastic background from binary black holes [7]. Additional analyses of the GW150914 event have been presented by [5, 6, 10, 34].

3. The First Merger with an Electromagnetic Counterpart: GW170817

The Advanced LIGO and Advanced Virgo interferometer detected the binary neutron star merger GW170817 on August 17 at 12:41:04 UTC [23] (Fig. 2). The luminosity distance of GW170817 was 40^{+8}_{-14} Mpc. The observation of the merger with three interferometers narrowed the localization region down to about 28 deg^2 [14]. The ranges of the total mass of the system, 2.72 to 3.29 $M_\odot$, and of the components, 0.86 to 2.26 $M_\odot$, was consistent with the known masses of neutron stars in binary systems [23]. The progenitor of GW170817 has been discussed in [17]. The merger remnant could be either a neutron star or a black hole, that could show gravitational wave emission in the kHz region with short (sub-second) or intermediate ($\leq$ 500 s) duration, but all searches yielded negative results [13, 18].

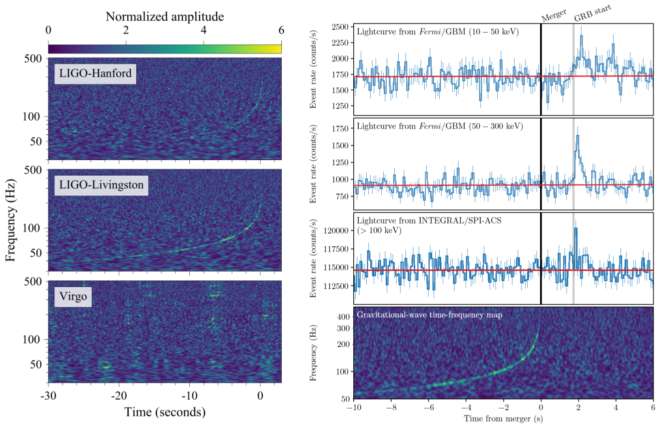

Figure 2: Left panel: time-frequency maps of BNS merger GW170817 observed by the LIGO Hanford (top), LIGO Livingston (center) and Virgo (bottom) interferometers. Right panel: detection of GRB 170817A, associated to GW170817, by the Fermi-GBM (10-50 keV and 50-300 keV) and INTEGRAL SPI-ACS instruments, and the time-frequency map of GW170817. Adapted from [14, 23].

GW170817 is the first merger with an observed electromagnetic counterpart. The Fermi-GBM observatory detected the short Gamma-Ray Burst GRB 170817A on August 17 at 12:41:06 UTC. The INTEGRAL observatory detected the merger in an off-line analysis after the LIGO-Virgo alert [14, 181]. The difference in the arrival times of gravitational radiation and gamma-rays was 1.734±0.054 s [103]. There was no detected gamma-ray excess in the first days after the merger [35, 41, 45, 133, 204].

GW170817/GRB 170817A triggered an extensive multi-messenger follow-up over the electromagnetic spectrum and neutrinos [16]. The optical counterpart of GW170817/GRB 170817A, SS17a/AT 2017gfo, was detected in the elliptical galaxy NGC 4993 10.87 hours after the merging

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[79, 184] and confirmed in the following hours [56, 134, 186, 190, 203]; no transient was visible in the images secured before the merger [203]. The gravitational wave luminosity distance was consistent with the known distance of NGC 4993. The extensive ultraviolet, optical and infrared photometric observations has been summarized and discussed by [207], see also individual papers [51, 55–57, 68, 87, 134, 186, 190, 195, 202, 203, 212]. Optical and infrared spectroscopy showed the early emergence of lanthanide features [68, 75, 80, 92, 119, 120, 122, 124, 131, 136, 142, 152, 165, 183, 185, 190, 206]. The prompt photometric and spectroscopic observations could be explained by the kilonova model [61, 64, 82, 93, 129, 132, 146, 151, 158, 159, 191]. On the other hand, the afterglow of GW170817 evolved over longer time scales. The X-ray afterglow emerged 9 days after the merger [94, 110, 140, 181, 188, 196], while the radio afterglow [112] and the optical afterglow [136] appeared after 14 days and 109 days, respectively. In the following months, the optical, X-rays and radio fluxes increased achieving a peak and later decreasing [47, 67, 83, 91, 99, 102, 110–112, 127, 130, 139, 147–149, 155, 167, 171, 177, 197, 198]. The compilation of optical, radio and X-ray observation presented by [137] showed that the peak occurred at 155 days after the merger epoch (Fig. 3).

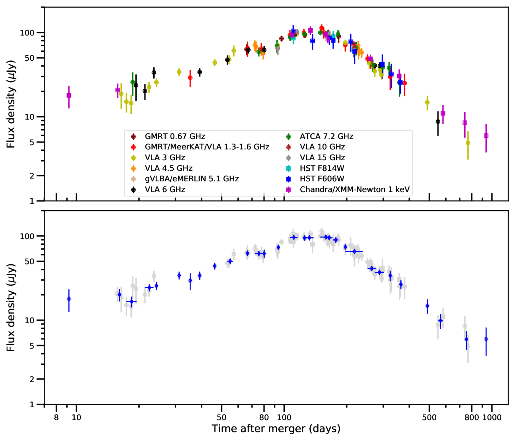

Figure 3: Upper panel: the panchromatic afterglow light curve of GW170817 from +0.5 d to +940 d after the merger, including optical, radio and X-ray data. Lower panel: averaged light curve (blue data points). Credits: http://www.tauceti.caltech.edu/kunal/gw170817/

The electromagnetic follow-up was accompanied by low and high neutrino observations [43, 46, 60, 113, 164]; searches were negative both in a time window of ±500 s around the merger epoch and in the first 14 days after the merger.

4. The GWTC-1 Catalog

The First Gravitational Wave Transient Catalog, GWTC-1, includes 11 confident gravitational wave detections (10 BBHs and one BNS merger) from compact binary mergers during the O1, O2 observing runs [19]. The candidate events were selected using three search pipelines; two matched filtering searches using relativistic waveform models, PyCBC [154, 201] and GstLAL [145, 178], and one unmodelled search for excess noise from short duration bursts, coherent WaveBurst (cWB) [128]. The threshold for event selection was a False Alarm Rate (FAR) of 1 per 30 days in at least one of the matched filter searches. The *confident event* designation was assigned to events with probability of astrophysical origin in either matched filter search above 50%, the *marginal event* designation to the other events [95]. During run O1, the BBH mergers GW150914 [22], GW151226 [8] and GW151012 have been observed. During run O2, three binary black hole mergers had been published before GWTC-1 catalog, GW170104 [21], GW170608 [3], and GW170814 [15], and the BNS merger GW170817 [14, 181]. The GWTC-1 analysis recovered some additional BBH mergers: GW170729, GW170809, GW170818 and GW170823.

5. The O3 Run

The O3 run was split into the O3a run, from 2019 April 1 to 2019 October 1, and the O3b run, from 2018 November 1 to 2020 March 27. During O3 run, the gravitational wave alert became public. The gravitational wave candidates were archived in the Gravitational Wave Candidate Event Database GraceDb *. The alerts were distributed using the Gamma-Ray Coordinate Network GCN †. Run O3 produced an improvement in the statistics of gravitational wave detections, almost one order of magnitude larger than the combined count of O1 and O2 runs (Fig. 4).

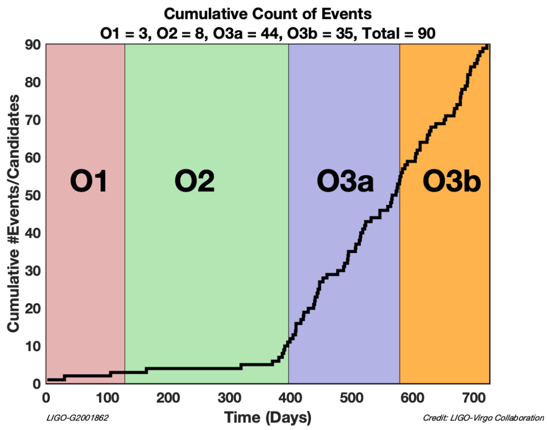

Figure 4: Cumulative counts of events in the O1, O2, O3 runs; the thin vertical lines mark the end of O1, O2, O3a runs (start and end dates of observing runs can be found in the text). Credits: LVK Collaboration, https://dcc.ligo.org/LIGO-G2102395/public

The merger observed during O3 have been reported in some discovery papers and in the GWTC-2 [27], GWTC-2.1 [28] catalogs for O3a and GWTC-3 [32] catalog for O3b. The O3 catalogs introduced the full gravitational naming appending the UTC time after an underscore to the GWyymmdd date naming analogous to GRB naming.

6. The O3 Catalogs: GWTC-2, GWTC-2.1, GWTC-3

The three catalogs have adopted different criteria for event selection. The GWTC-2 catalog included 39 detections (26 reported as public alerts) during the O3a run, with a FAR threshold

*https://gracedb.ligo.org
†https://gcn.gsfc.nasa.gov/

of two per year [27]. The GWTC-2.1 catalogs included a deeper list of candidates with a FAR threshold of two per day [28]; a subset of 44 candidates has a probability of astrophysical origin $p_{astro} > 0.5$, amomg them 36 candidates previously reported in the GWTC-2 catalog. The p_{astro} is a Bayesian odds comparing the astrophysical and terrestrial hypothesis, using the signal rate and the noise rate to estimate the event significance [95, 118], The GWTC-3 catalog contains 35 candidates with a probability of astrophysical origin $p_{astro} > 0.5$ [32], among them 18 candidates previously reported in low latency searches. The population of mergers detected during the O3a and O3b runs is summarized in Fig. 5, where the credible region contours are showed in the plane of mass ratio $q = m_2/m_1$ versus the total mass M. The majority of detected events are BBH mergers, whose total mass spans an order of magnitude, ranging from about 14 $M_\odot$ to about 150 $M_\odot$.

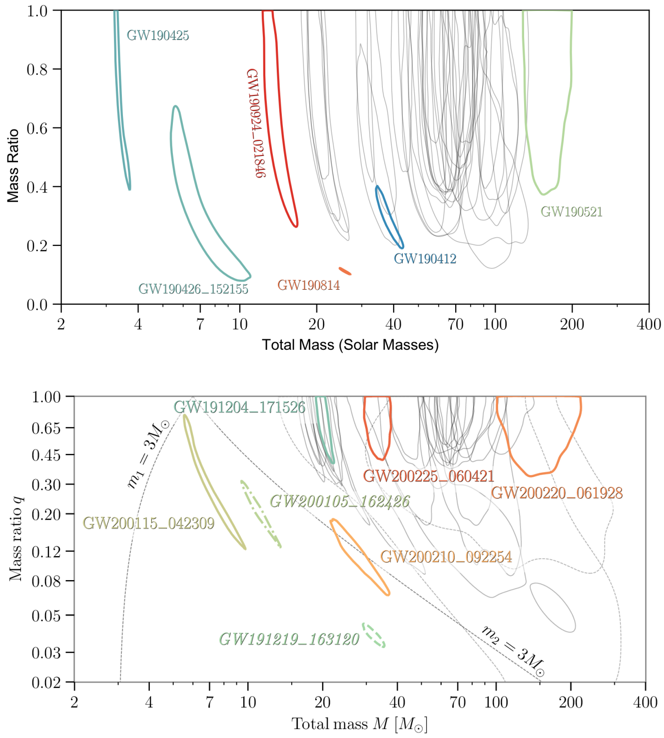

Figure 5: Top: credible region 90% contours for all O3a candidates in the plane of mass ratio q and total mass M; mergers GW190412, GW190425, GW190521, GW190814 (discussed in the text), candidate NSBH merger GW190426_152155 and the lightest BBH system GW190924_021846 are highlighted. Adapted from [27]. Bottom: credible region 90% contours for all O3b candidates with $p_{astro} > 0.5$ and for GW200105 in the plane of mass ratio q and total mass M. Highlighted candidates include the NSBH mergers GW200105, GW200115 (discussed in the text), GW191219_163120, the low mass BBH/NSBH system GW200210_092254, the heaviest system GW200220_061928, the systems GW200225_060421 and GW191204_171526 with negative and positive effective spins. Adapted from [32]

7. Exceptional Events in O3

During the O3 run some exceptional BBH events with components having non comparable masses, and a second BNS merger, have been observed. The exceptional events will be discussed below.

7.1 GW190412

The GW190412 BBH merger [24] involved components with largely asymmetric masses, $27.7^{+6.0}_{-6.0}$ $M_\odot$ and $9.0^{+2.0}_{-1.4}$ $M_\odot$ [28]. GW190412 is the first BBH merger where gravitational emission from higher orders in the multipole expansion of GW radiation [194] have been detected. Higher order modes, beyond quadrupole, are needed in system with asymmetric mass ratios, as GW190412 and GW190814 (see below). The follow-up of GW190412 did not find any counterpart [1, 37, 38, 54, 63, 70, 105, 116, 126, 156, 160, 172, 180].

7.2 GW190425

GW190425 is the second BNS detected merger after GW170817 [20]. The component masses, $2.1^{+0.5}_{-0.4}$ $M_\odot$ and $1.3^{+0.3}_{-0.2}$ $M_\odot$ [28], are consistent with neutron stars as individual components. The total mass, $3.4^{+0.3}_{-0.1}$ $M_\odot$ [28], is larger than the total mass of GW170817, 2.7 $M_\odot$, and the total mass of the most massive Galactic binary pulsar, 2.89 $M_\odot$ [96]. The luminosity distance of GW190425 was $0.15^{+0.08}_{-0.06}$ Gpc, larger than the distance of GW170817, 40^{+8}_{-14} Mpc. In addition, the sky localization of GW190425, 8700 deg^2, was poorer than that of GW170817, 28 deg^2. The classification of the event as a BNS merger triggered a follow-up campaign that included also more than one hundred circulars. There is no evidence for an electromagnetic or neutrino counterpart in association to GW 190425 [1, 37, 38, 54, 63, 66, 70, 72, 78, 84, 105, 115, 116, 121, 135, 156, 160, 172, 180]. There is an exception, since a weak Gamma Ray Burst, GRB 190425, was detected by the Anti-Coincidence Shield (ACS) of the SPI gamma-ray spectrometer of INTEGRAL [168], but it was not confirmed by Fermi-GBM [69]. The time profile of GRB 190425 was similar to the profile of GW170817 [168].

7.3 GW190521

The BBH merger GW190521 [25] involved components with masses of $98.4^{+33.6}_{-21.7}$ $M_\odot$ and $57.2^{+27.1}_{-30.1}$ $M_\odot$ that produced a final black hole with a mass $153.1^{+42.2}_{-16.2}$ $M_\odot$ [28], in the expected range expected for Intermediate Mass Black Holes (IMBHs, 10^2 to 10^5 $M_\odot$ [108]. In addition, the heaviest component of GW190521 has a mass in the Pair-Instability Supernova mass gap [209]. The large mass of both initial black holes points to hierarchical mergers in the disk of an Active Galactic Nucleus (AGN) [189, 211], an environment that is expected to produce an excess of eccentric mergers [179]. While evidence for non null eccentricity has been suggested [100, 101, 175], the gravitational signal has also been explained by quasi-circular orbits and higher order modes [117]. A multimode ringdown spectrum, suggesting progenitor components with unequal masses, has been detected by [71]. 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 localized within a region of 1000 deg^2 [28]. No electromagnetic or neutrino counterpart was detected during the follow-up [1, 37, 38, 53, 63, 70, 105, 116, 156, 160, 162, 166, 172, 180]. The Zwycki Transient Facility detected the transient ZTF19abanrhr 34 days after the merger, the flare of AGN J124942.3+344929 (redshift 0.438), that was associated with GW190521 merger [106], making it the first candidate electromagnetic counterpart of a binary black hole merger. The flare could be explained by a kicked binary black hole merger with a total mass of about 100 $M_\odot$ occurring in the accretion disk of the AGN, with a new flare predicted in about 1.6 years [106]. The association of GW190521 with ZTF19abanrhr has been disputed by other authors [59, 85, 161]. The physics of merging of compact objects in the disk of AGNs has been discussed by [62, 143].

7.4 GW190814

The GW190814 merger [26] involved a black hole with a mass of $23.3^{+1.4}_{-1.4}$ $M_\odot$ and a compact object with a mass of $2.6^{+0.1}_{-0.1}$ $M_\odot$ [28]. The merger was localized within 22 deg^2 at a distance of $0.23^{+0.04}_{-0.05}$ Gpc [28]. The secondary component could be either the most massive neutron star or the least massive black hole found in a compact binary [26]. The heaviest Galactic neutron star, PSR J0952-0607, has a mass of 2.35±0.17 $M_\odot$ [174], while GW170817 set an upper limit of 2.4 $M_\odot$ [23], however masses up to about 3 $M_\odot$ are allowed by some Equations of State [150, 176, 192]. No electromagnetic or neutrino counterpart was found [38, 40, 48, 52, 53, 63, 70, 72, 86, 90, 104, 105, 121, 125, 156, 172, 180, 193, 199, 205, 208].

7.5 GW200105 and GW200115

GW200105 and GW200115 are the first detected NSBH mergers [29], that could potentially show electromagnetic emission [64]. However, the luminosity distances of the mergers were very large ($0.27^{+0.12}_{-0.11}$ Gpc for GW200105 and $0.29^{+0.15}_{-0.10}$ Gpc for GW200115), as the size of sky localization regions (9600 deg^2 for GW200105, 720 deg^2 for GW200115) [32], making detection of electromagnetic radiation less likely. The component masses were $m_1 = 9.1^{+1.7}_{-1.7}$ $M_\odot$ 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 [32]. In both mergers the mass of primaries and of secondaries are consistent with masses of black holes and neutron stars, respectively. The NSBH merger GW200105 was classified as a marginal event in the GWTC-3 catalog due to its low p_{astro} value [32]. The formation of NSBH systems can be explained by different mechanisms [138], via supernova explosions in a binary star leading to a black hole and a neutron star or via independent formation of a black hole and a neutron star that later join into a binary system. GW200105 and GW200115 have been the target of an extensive electromagnetic and neutrino follow-up [1, 38, 50, 53, 58, 63, 84, 121, 156, 160, 162, 172], without any detected counterpart.

8. The Era of Public Alerts: Multi-Messenger Searches for Electromagnetic Counterparts in O3

During the O3 run, the alerts for gravitational candidates found by low-latency searches became public. The follow-up involved more than one hundred teams and covered the whole electromagnetic spectrum and neutrinos.

8.1 Optical and Infrared Follow-up

Large efforts have been devoted to the optical and infrared observations to measure the light curves and the spectra of possible counterparts with a combination of photometric and spectroscopic techniques. In addition to observations targeted to single mergers of interest containing one or two neutron stars, several collaborations performed systematic observations of the majority of candidates

[40, 49, 53, 54, 63, 72, 84, 105, 126, 135, 162, 180]. No optical or infrared counterpart was found for any merger, with the possible exception of GW190521 (Subsection 7.3). The negative observations of kilonova candidates in the follow-up discussed above and in targeted searches [169] has been used by [121] to set constrains on the kilonova luminosity function.

8.2 Radio Follow-up

The follow-up in the radio domain has been mostly devoted to events with one neutron star at least [65, 66, 89, 90], without any counterpart detected.

8.3 High Energy Follow-up: X-ray and Gamma-rays

The coverage of the high energy region extended from keV to TeV energies, without detecting any counterpart [36, 42, 58, 70, 98, 123, 156, 160, 166, 172], with the possible exception of GW190425 (Subsection 7.2). The search for coincident optical, high energy candidates in Swift observations and gravitational candidates was negative [123]. Precursors of Gamma-ray burst associated to BNS mergers could show time modulation, as recently observed in GRB 211211A [144, 170, 210]; the search in Fermi-GBM data during O2 and O3 runs was negative [187].

8.4 Neutrino Follow-up

The neutrino observatories involved in the follow-up covered an energy region extending from MeV to PeV, but no signal excess was found [1, 2, 38, 39, 116, 163, 200].

9. Gravitational Wave Astronomy and Astrophysical and Cosmological Implications

The statistics of mergers has allowed to perform a variety of investigations covering various fields of astrophysics and cosmology.

9.1 Black Hole and Neutron Star Populations

The population of black holes and neutron stars has been investigated using a set of 74 compact binary mergers detected up to the end of O3b run (70 BBH, two BNS and two NSBH mergers) [33]. The mass distribution of primary black holes can be explained with a power law with significant peaks at about 10 and about 35 $M_\odot$ and another possible peak at about 18 $M_\odot$ [33]. The mass distribution of neutron stars observed in gravitational mergers favors a single peaked distribution, with more support at high masses compared to the double peaked distribution of Galactic pulsars detected in radio or X-rays [33]. The maximum neutron star mass in the gravitational sample is in the interval 1.8 to 2.3 $M_\odot$, consistent with pulsar observations. The extra-galactic population producing the detected gravitational waves could be distinct from the Galactic population that is observed as pulsars.

The estimated merger rates of compact objects are 10-1700 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 [33].

9.2 Tests of General Relativity

The sample of mergers has been used for testing General Relativity in the strong field regime, showing that there is no evidence for physics beyond General Relativity [30]. The tests include: consistency of post-Newtonian coefficients are consistent with GR predictions consistency of the spin-induced quadrupole moments of BBH components with those of Kerr black holes; consistency of the final mass and final spin values estimated from the pre-merger and post-merger parts; behaviour of the remnant black holes; no evidence for dispersion of gravitational waves, non standard polarization modes, post-merger echos [30]. The upper limit on the mass of the graviton has been constrained as 1.27×10^{-23} eV/c^2 [30].

9.3 Standard Siren Measurements of the Hubble Parameter

There is tension between the values of the Hubble parameter H_0 obtained using data from the Cosmic Microwave Background (CMB) assuming a standard cosmological model [44] and data from Cepheids and type Ia supernovae [173]. The detection of the gravitational waves from the BNS merger GW170817 [23] and of the associated EM emission [14] provided the first standard siren measurement [182] of the Hubble parameter [12], $70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}. In general, the investigation of the cosmic expansion demands an independent measure of the source redshift, that in the gravitational observations is degenerate with the source masses. The redshift of the host galaxy can be estimated in presence of a confirmed electromagnetic counterpart [73, 97, 114, 153, 182]. When the counterpart is missing, it is necessary to rely on statistical methods, among them: statistical redshift estimation using galaxy catalogs [182]; comparing the redshifted mass distribution with a source mass distribution [74]; source redshift distribution [88]; spatial clustering between gravitational sources and galaxies [157]. The Hubble parameter has been estimated using 47 mergers of GWTC-3 catalog (42 BBHs, 2 BNSs, 2 NSBHs and GW190814) [31], both excluding [141] or including [107] the information of galaxy catalogs. The joint fit of the cosmological parameters with the BBH population yielded $H_0 = 68^{+12}_{-7}$ km s^{-1} Mpc^{-1} when combined with the GW170817 H_0 estimation, and $H_0 = 50^{+37}_{-30}$ km s^{-1} Mpc^{-1} when using the 42 BBHs merger only. The association of each merger event with a candidate galaxy in the GLADE+ catalog [81] produced $H_0 = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}.

10. The O4 Run

The O4a run started in May 2023, with improved sensitivity, and will last until mid January 2024. The LIGO Hanford and Livingston interferometers are observing with BNS ranges between 140 and 170 Mpc. The Virgo interferometer has achieved a BNS range greater than 45 Mpc and optimizing the operation for in view of the start of O4b run on 27 March 2024.

As of December 2023, more than 180 candidates have been disseminated via GCN, with related circulars accounting for about 25% of the total GCN traffic. As of December 2023, there are more than 10 events with electromagnetic/neutrino candidate counterparts.

11. Conclusions

During the O3 run a large number mergers have been observed, including the first observations of NSBH mergers, achieving a total number of 90 events including the previous runs. The gravitational events has been the subject electromagnetic and neutrino follow-ups, without the detection of any confirmed counterpart. The improved statistics has allowed a large number of tests and has improved the knowledge of the populations of black holes and neutron stars.

12. Acknowledgements

Acknowledgements may be found in https://tds.virgo-gw.eu/?content=3&r=19511

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