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The new world discovered with the detection of Gravitational Waves: the era of public alerts

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During the first three observing runs of LIGO/Virgo/KAGRA Collaboration a total of 90 candidate gravitational wave events from the mergers of black hole and neutron stars have been detected. Since then, the O4a run took place and the O4b run is presently ongoing, contributing with the detection of additional mergers. During the runs, all disseminated gravitational events have been the target of multi-messenger follow-up observations, and at the same time, there has been searches of gravitational wave emission from electromagnetic events. The present paper reviews the results of LIGO-Virgo runs with a focus on the runs in the public alert era.

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1. Introduction

The Advanced LIGO and Advanced Virgo have completed three observing runs and begun the fourth run in May 2023. The first observing run O1 produced the first direct detection of gravitational waves from the merger of a binary black hole (BBH) system GW150914 [23]. The second observing run O2 lead to the detection of the first binary neutron star (BNS) merger GW170817 [24] and of its electromagnetic counterpart [14, 17]. The mergers detected during the O1, O2 runs were collected in the First Gravitational Wave Transient Catalog GWTC-1 [20]. During the O3 run a large number of mergers, mostly BBH mergers, with a few BNS and NSBH (Neutron Star-Black Hole) mergers, were detected, demonstrating that all possible combinations of compact objects can undergo merging. The O3 run has produced three catalogs, GWTC-2 [28], GWTC-2.1 [37], GWTC-3 [35], and some exceptional events. The O4 run has so far discovered one exceptional event and increased the statistics of mergers.

The present review is an update of the contribution PoS(MULTIF2023)021, focusing on the detection of merger 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 O1 and O2 Observing Runs

2.1 The First Detection: GW150914

The merger GW150914 is the first direct detection of gravitational waves and the observation of the merging of a binary black hole system [23]. 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 occurred at a luminosity distance of 440^{+150}_{-170} Mpc [20] and was initially localized within a sky region of 610 deg^2 [9], later narrowed at 182 deg^2 [20].

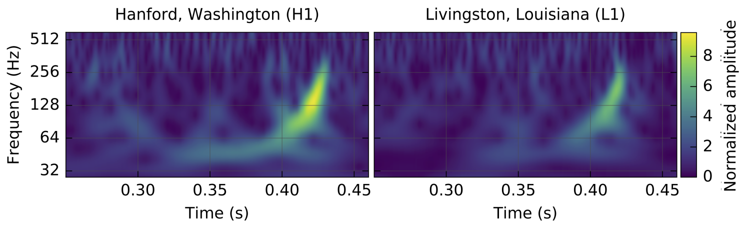

Figure 1: Time-frequency maps of BBH merger GW150914 observed by the LIGO Hanford (H1, left panel) and LIGO Livingston (L1, right panel) interferometers. Adapted from [23].

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 $63.1^{+3.4}_{-3.0}$ $M_\odot$ [20]. The observed signal behaviour 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 whole electromagnetic spectrum and neutrinos [9]. No candidate counterpart was found, with the exception of the Fermi-GBM possible observation (above 50 keV) of a faint transient 0.4 s after the merger epoch [83, 84], see also [118].

The first detection started gravitational astronomy and had several astrophysical implications [4], showing that massive stellar mass black holes can be formed. The observation of GW150914 constrained the rate of mergers of stellar mass black holes in the range 2-600 Gpc^{-3} yr^{-1} and the mass of the graviton to be smaller than 1.2×10^{-22} eV/c^2 [11, 23], constrainimg also 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, 39].

2.2 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 [24] (Fig. 2). The observation with three interferometers narrowed the localization region down to about 28 deg^2 [14]. The luminosity distance of GW170817 was 40^{+8}_{-14} Mpc. 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$_\odot$, were consistent with the known masses of neutron stars in binary systems [24]. The progenitor of GW170817 has been discussed in [18]. 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: all searches yielded negative results [13, 19].

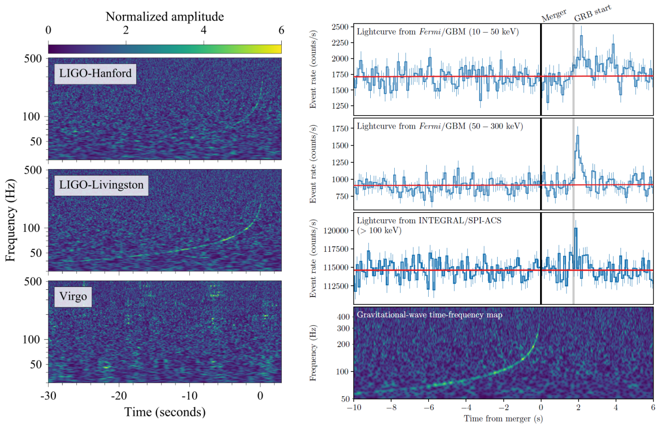

Figure 2: Left panel: time-frequency maps of BNS merger GW170817 observed by the LIGO Hanford (top), LIGO Livingston (center) and Virgo (bottom) interferometers. Right panel: detection of GRB 170817A, associated to GW170817, by the Fermi-GBM (10-50 keV and 50-300 keV) and INTEGRAL SPI-ACS instruments, and the time-frequency map of GW170817. Adapted from [14, 24].

GW170817 is the first gravitational merger with an observed electromagnetic counterpart. The Fermi-GBM observatory detected the short Gamma-Ray Burst GRB 170817A on 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, 191]. The difference in the arrival times of gravitational radiation and gamma-rays was 1.734±0.054 s [112]. No detected gamma-ray excess was detected in the first days after the merger [40, 46, 50, 142, 214].

GW170817/GRB 170817A triggered a multi-messenger follow-up over the electromagnetic spectrum and neutrinos [17]. The optical counterpart of GW170817/GRB 170817A, SS17a/AT 2017gfo, was detected in the elliptical galaxy NGC 4993 10.87 hours after the merging [86, 194] and promptly confirmed [62, 143, 196, 200, 213]. No transient was detected in the images secured before the merger [213]. The gravitational wave luminosity distance was consistent with the known distance of NGC 4993. The extensive ultraviolet, optical and infrared photometric observations has been reviewed by [217], see also individual papers [57, 61–63, 74, 94, 143, 196, 200, 205, 212, 213, 222]. Optical and infrared spectroscopy showed the early emergence of lanthanide features [74, 82, 87, 99, 128, 129, 131, 133, 140, 145, 151, 161, 174, 193, 195, 200, 216]. The prompt photometric and spectroscopic observations could be explained by the kilonova model [67, 70, 89, 100, 138, 141, 155, 160, 167, 168, 201]. The X-ray afterglow emerged 9 days after the merger [101, 119, 149, 191, 198, 206], while the radio afterglow [121] and the optical afterglow [145] appeared after 14 days and 109 days, respectively. In the following months, the optical, X-rays and radio fluxes increased up to a peak and later decreased [52, 73, 90, 98, 108, 111, 119–121, 136, 139, 148, 156–158, 164, 176, 181, 187, 207, 208]. The compilation of optical, radio and X-ray observation presented by [146] showed that the peak occurred at 155 days after the merger epoch (Fig. 3).

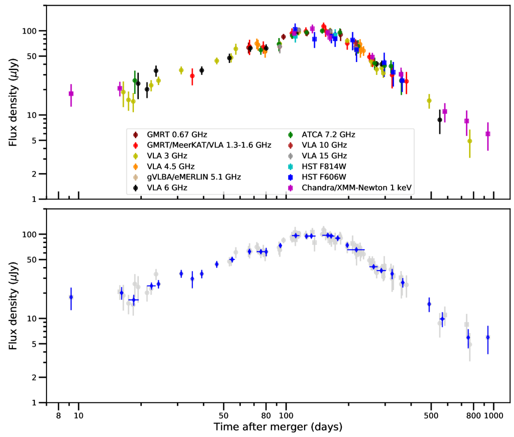

Figure 3: Upper panel: the panchromatic afterglow light curve of GW170817 from +0.5 d to +940 d after the merger, including optical, radio and X-ray data. Lower panel: averaged light curve (blue data points). Credits: http://www.tauceti.caltech.edu/kunal/gw170817/

The electromagnetic follow-up was accompanied by a search for low and high energy neutrinos [48, 51, 66, 122, 173]; all searches were negative both within a time window of ±500 s around the merger epoch and in the first 14 days after the merger.

2.3 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 [20]. The candidate events were selected using three search pipelines: the matched filtering searches using relativistic waveform models, PyCBC [163, 211] and GstLAL [154, 188], and the unmodelled search for excess noise from short duration bursts, coherent WaveBurst (cWB) [137]. 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% [102]. During run O1, the BBH mergers GW150914 [23], GW151226 [8] and GW151012 have been observed. During run O2, three binary black hole mergers had been published before GWTC-1 catalog, GW170104 [22], GW170608 [15], and GW170814 [16], one BNS merger GW170817 [14, 191]. The GWTC-1 analysis recovered some additional BBH mergers: GW170729, GW170809, GW170818 and GW170823.

3. The O3 Run: the Era of Public Alerts Starts

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 alerts became public and were disseminated on time scales of the order of minutes using the Gamma-Ray Coordinate Network GCN [1]. The O3 run produced a remarkable improvement in the statistics of gravitational wave detections, one order of magnitude larger than the combined statistics of O1 and O2 runs (Fig. 4).

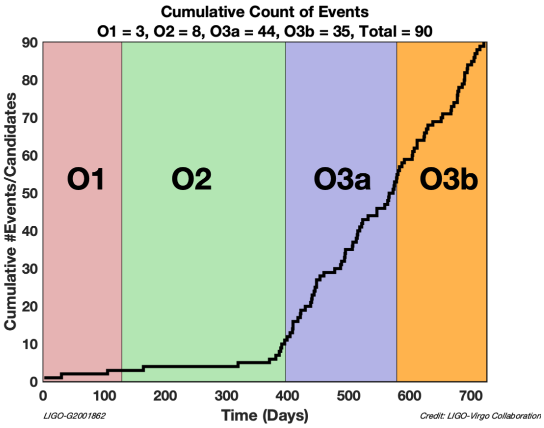

Figure 4: Cumulative counts of events in the O1, O2, O3 runs; the thin vertical lines mark the end of O1, O2, O3a runs (start and end dates of observing runs can be found in the text). Credits: LVK Collaboration, https://dcc.ligo.org/LIGO-G2102395/public

The standard measure of sensitivity is the BNS inspiral range, the average distance at which a 1.4 $M_\odot$ + 1.4 $M_\odot$ BNS can be detected with a signal-to-noise ratio (SNR) of 8 [54, 80, 105]. During O3b observations, the median BNS inspiral ranges for LIGO Livingston, LIGO Hanford, and Virgo were 133, 115, and 51 Mpc, respectively.

The mergers observed during O3 have been reported in some discovery papers and in the GWTC-2 [28], GWTC-2.1 [37] catalogs for O3a run and GWTC-3 [35] catalog for O3b run. The O3 catalogs introduced the full gravitational naming with the UTC time appended after an underscore to the GWyymmdd prefix including the date.

3.1 The O3 Catalogs: GWTC-2, GWTC-2.1, GWTC-3

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

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

of two per year [28]. The GWTC-2.1 catalogs included a deeper list of candidates with a FAR threshold of two per day [37]; a subset of 44 candidates has a probability of astrophysical origin $p_{astro} > 0.5$, among them 36 candidates previously reported in the GWTC-2 catalog. The p_{astro} parameter is a Bayesian odds comparing the astrophysical and terrestrial hypothesis, using the signal rate and the noise rate to estimate the event significance [102, 127]. The GWTC-3 catalog contains 35 candidates with a probability of astrophysical origin $p_{astro} > 0.5$ [35], 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 covers an order of magnitude, ranging from about 14 $M_\odot$ to about 150 $M_\odot$.

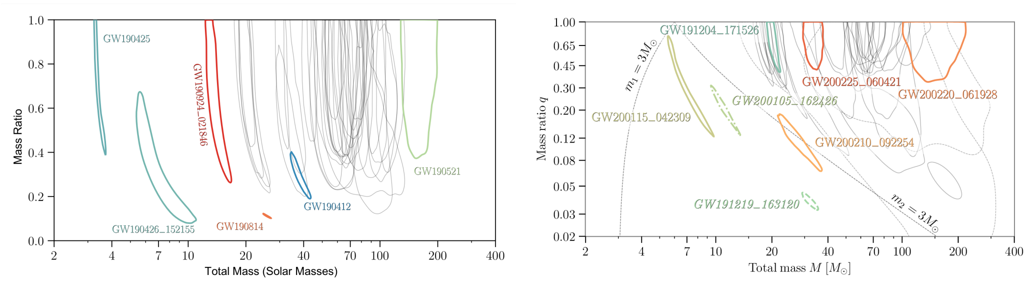

Figure 5: Left: credible region 90% contours for all O3a candidates in the plane of mass ratio q and total mass M; mergers GW190412, GW190425, GW190521, GW190814 (discussed in the text), candidate NSBH merger GW190426_152155 and the lightest BBH system GW190924_021846 are highlighted. Adapted from [28]. Right: 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 [35]

3.2 Exceptional Events in O3

During the O3 run various exceptional events have been detected: some BBH mergers with components having non comparable masses, a second BNS merger, the first Neutron Star-Black Hole (NSBH) merger. The exceptional events will be discussed below.

3.2.1 GW190412

The GW190412 BBH merger [25] involved components with asymmetric masses, $27.7^{+6.0}_{-6.0}$ $M_\odot$ and $9.0^{+2.0}_{-1.4}$ $M_\odot$ [37]. GW190412 is the first BBH merger where gravitational emission from higher orders in the multipole expansion of GW radiation [204] have been detected, as expected for system with asymmetric mass ratios (see also GW190814 below). The follow-up of GW190412 did not find any counterpart [2, 42, 43, 60, 69, 76, 114, 125, 135, 165, 169, 182, 190].

3.2.2 GW190425

GW190425 is the second BNS detected merger after GW170817 [21], with component masses, $2.1^{+0.5}_{-0.4}$ $M_\odot$ and $1.3^{+0.3}_{-0.2}$ $M_\odot$ [37], consistent with neutron stars as individual components. The total mass, $3.4^{+0.3}_{-0.1}$ $M_\odot$ [37], 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 $M_\odot$ [103]. The luminosity distance of GW190425 was $0.15^{+0.08}_{-0.06}$ Gpc, larger than the distance of GW170817, 40^{+8}_{-14} Mpc, and the sky localization, 8700 deg^2, was poorer than that of GW170817, 28 deg^2. The classification of the event as a BNS merger started an intensive follow-up campaign that produced more than one hundred circulars, but no evidence for an electromagnetic or neutrino counterpart could be found [2, 42, 43, 60, 69, 72, 76, 78, 85, 91, 114, 124, 125, 130, 144, 165, 169, 182, 190]. The possible exception is the weak Gamma Ray Burst GRB 190425 detected by the Anti-Coincidence Shield (ACS) of the SPI gamma-ray spectrometer of INTEGRAL [177], that was not confirmed by Fermi-GBM [75].

3.2.3 GW190521

The BBH merger GW190521 [26] 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 $153.1^{+42.2}_{-16.2}$ $M_\odot$ [37], within the expected range of Intermediate Mass Black Holes (IMBHs, 10^2 to 10^5 $M_\odot$ [117]. The heaviest component of GW190521 has a mass in the pair-instability supernova mass gap [219]. The large mass of both merging black holes suggests hierarchical mergers in the disk of an Active Galactic Nucleus (AGN) [199, 221], an environment predicted to produce an excess of eccentric mergers [189]. While evidence for non null eccentricity has been suggested [109, 110, 185], the gravitational signal has also been explained by involving quasi-circular orbits and higher order modes [126]. A multimode ringdown spectrum, suggesting progenitor components with unequal masses, has been detected by [77]. The GW190521 merger occurred at 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 [37]. No electromagnetic or neutrino counterpart was detected during the prompt follow-up [2, 42, 43, 59, 69, 76, 114, 125, 165, 169, 171, 175, 182, 190]. The Zwicky 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 [115], 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 [115]. The association of GW190521 with ZTF19abanrhr has been disputed by other authors [65, 92, 170]. The merging of compact objects in the disk of AGNs has been discussed by [68, 152].

3.2.4 GW190814

The GW190814 merger [27] involved a black hole with a mass of $23.3^{+1.4}_{-1.4}$ $M_\odot$ and a compact object with a mass of $2.6^{+0.1}_{-0.1}$ $M_\odot$ [37]. The merger was localized within 22 deg^2 at a distance of $0.23^{+0.04}_{-0.05}$ Gpc [37]. The secondary component could be either the most massive neutron star or the least massive black hole observed in a compact binary [27]. The heaviest Galactic neutron star, PSR J0952-0607, has a mass of 2.35±0.17 $M_\odot$ [184], while GW170817 set an upper limit of 2.4 $M_\odot$ [24], however masses up to about 3 $M_\odot$ are allowed by some equations of state [159, 186, 202]. No electromagnetic or neutrino counterpart was found [43, 45, 53, 58, 59, 69, 76, 78, 93, 97, 113, 114, 130, 134, 165, 182, 190, 203, 209, 215, 218].

3.2.5 GW200105 and GW200115

GW200105 and GW200115 are the first detected NSBH mergers [29], that could potentially show electromagnetic emission [70]. The luminosity distances of both mergers were large ($0.27^{+0.12}_{-0.11}$ Gpc for GW200105 and $0.29^{+0.15}_{-0.10}$ Gpc for GW200115), as the sky localization regions were poorly constrained (9600 deg^2 for GW200105, 720 deg^2 for GW200115) [35], 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 [35]. 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 [35]. The formation of NSBH systems can be explained by different mechanisms [147], 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 targets of electromagnetic and neutrino follow-up [2, 43, 56, 59, 64, 69, 91, 130, 165, 169, 171, 182], without any detected counterpart.

3.3 Multi-Messenger Searches in O3

The follow-up involved more than one hundred teams and covered the whole electromagnetic spectrum and neutrinos. Optical and infrared photometry has been both targeted to single mergers of interest containing one or two neutron stars, and to systematic observations of the majority of candidates [45, 55, 59, 60, 69, 78, 91, 114, 135, 144, 171, 190]. No optical or infrared counterpart was found for any merger, with the possible exception of GW190521 (Subsection 3.2.3). The negative observations of kilonova candidates in the follow-up discussed above and in targeted searches [179] has been used by [130] to set constrains on the kilonova luminosity function. The follow-up in the radio domain has been mostly devoted to events with one neutron star at least [71, 72, 96, 97], without any counterpart detected. The coverage with X-ray and Gamma-rays extended from keV to TeV energies, without any counterpart detection [41, 47, 64, 76, 107, 132, 165, 169, 175, 182], with the possible exception of GW190425 (Subsection 3.2.2). The neutrino observatories involved in the follow-up covered an energy region extending from MeV to PeV, but no signal excess was found [2, 3, 43, 44, 125, 172, 210].

In addition to the follow-up, coincidences between gravitational events and/or a variety of high energy events have been investigated. The systematic search for gravitational waves associated with Gamma-Ray Bursts detected by Fermi and Swift during the O3a and O3b runs did not find any association [30, 33]. No gravitational signal was found in association neither to Fast Radio Bursts detected by CHIME/FRB during O3a [32], nor to magnetar bursts during O3 [38]. In addition, the joint Fermi-GBM and Swift-BAT Analysis [106] and the Swift-BAT GUANO follow-up [178] of gravitational candidates during O3 run were negative. The search for coincident optical, high energy candidates in Swift observations and gravitational candidates was negative [132]. Precursors of Gamma-ray burst associated to BNS mergers could show time modulation, as recently observed in GRB 211211A [153, 180, 220], but the search in Fermi-GBM data during O2 and O3 runs was negative [197].

3.4 Gravitational Wave Mergers: Astrophysical and Cosmological Implications

The detected gravitational mergers have been used for a range of investigations in astrophysics and cosmology.

The populations of black holes and neutron stars have 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) [36]. The mass distribution of primary black holes can be explained by a power law with significant features at about 10 and 35 $M_\odot$ and possiblly also at about 18 $M_\odot$ [36]. The mass distribution of neutron stars observed in gravitational mergers favors a distribution with more support at high masses compared to the double peaked distribution of Galactic pulsars detected in radio or X-rays [36]. The maximum neutron star mass in the gravitational sample is in the range 1.8 to 2.3 $M_\odot$, consistent with pulsar observations, but the extra-galactic population producing the detected mergers could be distinct from the Galactic population. The updated 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 [36].

The mergers has been used for testing General Relativity in the strong field regime, finding no evidence for physics beyond General Relativity [31]. The tests include: consistency of post-Newtonian coefficients 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 [31]. The upper limit on the mass of the graviton has been constrained as 1.27×10^{-23} eV/c^2 [31].

Gravitational waves can provide an estimation of the Hubble parameter independent from the electromagnetic estimates. Presently, there is tension between the values of the Hubble parameter H_0 obtained using observations from the Cosmic Microwave Background (CMB) [49] and observations from Cepheids and type Ia supernovae [183]. 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 detection of the gravitational waves from the BNS merger GW170817 [24] and of the associated EM emission [14] provided the first standard siren measurement [192] of the Hubble parameter [12], $70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}. The redshift of the host galaxy can be estimated in presence of a confirmed electromagnetic counterpart [79, 104, 123, 162, 192], but when a counterpart is missing statistical methods are used, including: redshift estimation using galaxy catalogs [192]; comparison of the redshifted mass distribution with a source mass distribution [81]; source redshift distribution [95]; spatial clustering between gravitational sources and galaxies [166]. The Hubble parameter has been estimated using 47 mergers of GWTC-3 catalog (42 BBHs, 2 BNSs, 2 NSBHs and GW190814) [34], and both excluding [150] or including [116] 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 BBHs merger only. The association of each merger event with a candidate galaxy in the GLADE+ catalog [88] produced $H_0 = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}.

4. The O4 Run

4.1 O4a

The O4a run occurred from May 2023 to January 2024, with both LIGO interferometers (Hanford and Livingston) in observing mode. The sensitivity to a BNS merger, reported in Fig. 6, shows an increase in the detection range of the LIGO interferometer compared to O3 run, when the median ranges for LIGO Livingston and LIGO Hanford were 133 and 115 Mpc respectively.

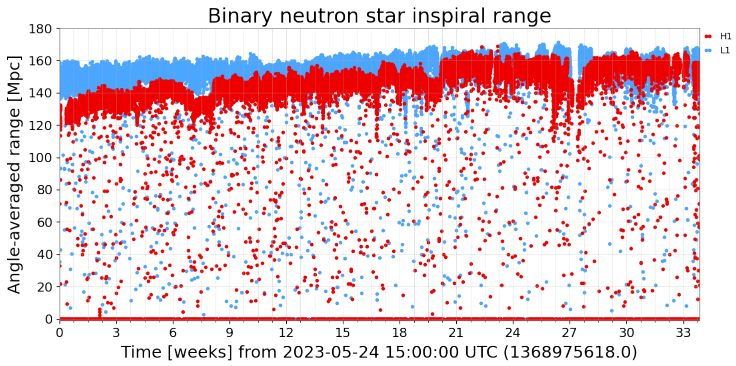

Figure 6: Sensitivity to a BNS merger in O4a (https://gwosc.org/detector_status/O4a/)

The cumulative number of significant detections (non retracted event candidates identified by online pipelines) during all observing runs is reported in Fig. 7. During O4a run, there were 81 significant detection candidates (92 total, 11 retracted) and 1610 low significance selection candidates. The statistics of significant candidates during O4a is comparable with the statistics of all previous runs combined.

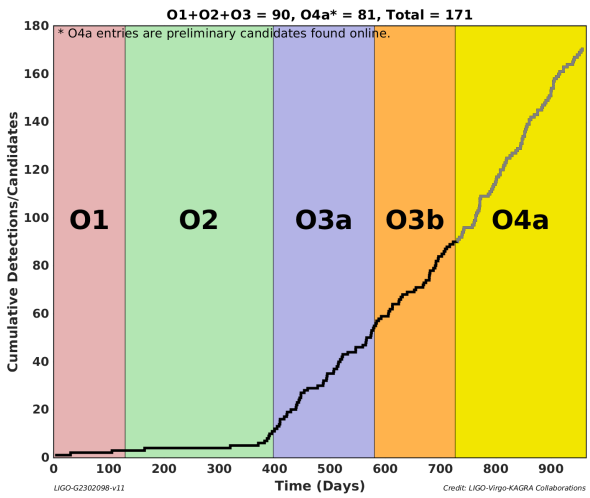

Figure 7: Cumulative detections in the O1+O2+O3a+O4 runs (Credits: https://dcc.ligo.org/LIGO-G2302098)

GCN circulars have reported candidate counterparts for several candidate mergers, but without any confirmed association. The first exceptional event detected in O4a, GW230529 [1], had a primary with a mass between 2.5 and 4.5 $M_\odot$, larger than the expected range for neutron stars and smaller than the expected range for black holes, and a secondary with a mass between 1.2 and 2.0 $M_\odot$, almost certainly a neutron star. GW230529 is the first detected merger with a primary component lying in the mass gap distribution of compact objects between massive neutron stars and lightest black holes, ranging from 3 $M_\odot$ to 5 $M_\odot$. The observation of GW190814 had previously suggested the existence of objects in the mass gap. During the O4a run the KAGRA interferometer joined for one month.

4.2 O4b

The O4b run started in April 2024 and is ongoing at the moment of writing, expected to end in 2025. LIGO Hanford has a BNS range of about 155-160 Mpc and a duty cycle of around 70%, while LIGO Livingston has a BNS range of 170-180 Mpc and a duty cycle of 77%. Virgo joined the O4b observations, with a 50-55 Mpc BNS range and a duty cycle above 80%. KAGRA is recovering from the Noto earthquake occurring on 1 January 2024, planning to join observations before the end of O4 with a sensitivity of about 10 Mpc. The BNS range for O4b so far is reported in Fig. 8.

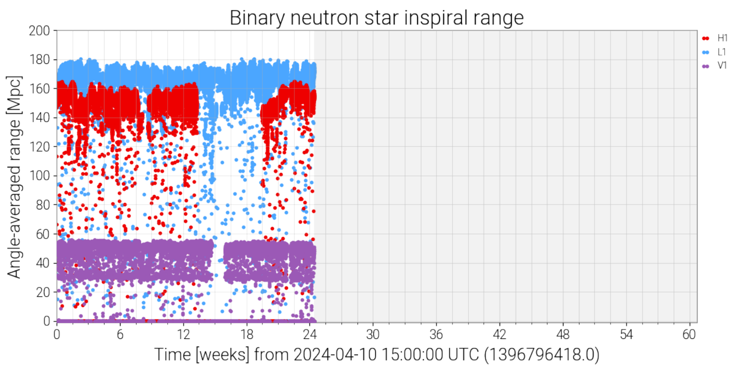

Figure 8: Sensitivity to a BNS merger in O4b (https://gwosc.org/detector_status/O4b/)

5. Conclusions

During the O3 run a large number of mergers have been observed, among them the first observations of NSBH mergers, achieving a total number of 90 events including the previous runs. The gravitational events have been the target of electromagnetic and neutrino follow-ups, without 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. The O4 run has greatly improved the statistics of detections, including the first detected merger with a primary component lying in the mass gap.

6. Acknowledgements

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

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PoS(GOLDEN2023)042

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