LIGO, VIRGO, and KAGRA as the international gravitational wave network

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Abstract The first detection of gravitational waves was made by the two LIGO detectors in the United States one hundred years after general relativity was first described by Einstein. Two years later, Virgo joined LIGO in the second advanced gravitational-wave detector observing run. As of May 2021, 50 gravitational-wave events from mergers of binary black-holes or neutron stars have been published by the LIGO-Virgo Collaboration. KAGRA in Japan is part of this international gravitational wave network since April 2020, and joint observations are anticipated in the next observing run. We briefly introduce the LIGO, Virgo and KAGRA detectors and the remarkable results of gravitational-wave observations up to now. The other articles in this handbook provide a comprehensive overview of the subject at this time.

Keywords

Gravitational Wave, LIGO, Virgo, KAGRA, Detector, Observation, Black Hole, Neutron Star

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Introduction

The general theory of relativity was derived by Einstein in 1915 and revolutionised our understanding of gravity. Based on general relativity, Einstein explained the perihelion advance of Mercury, he predicted the bending of light by massive objects and the redshift of light emerging from a gravitational potential, and he showed that gravitational waves should exist and propagate at the speed of light. As physicists grappled with the mathematics of general relativity, some argued that gravitational waves might be a mathematical artifact of how the theory is formulated and not physical phenomena. In 1956, after Einstein's death, Pirani provided a mathematical formulation that demonstrated that the gravitational waves predicted by general relativity carry energy and are thus physical entities. Bergman [1] raised the question whether a binary star system gives rise to gravitational waves that carry energy proportional to the square of the amplitude in his summary of the 1957 Chapel Hill conference without giving any answer. Peters and Matthews subsequently calculated the impact of gravitational-wave emission on a binary system under the assumption that the waves do carry energy [2]. With the discovery of the binary pulsar in 1974, the existence of gravitational waves was indirectly confirmed by demonstrating that the orbit of PSR B1913+16 is shrinking as predicted by Peters and Matthews thus answering Bergman's question in the affirmative. Since then, relativity researchers have made significant progress to understand the theory, to invent experimental measuring devices, to implement simulation techniques, and to construct data analysis methods for the direct detection of gravitational waves.

In the United States, construction of the National Science Foundation's Laser Interferometer Gravitational-wave Observatory (LIGO) was approved in 1990 with the first year of funding in 1991. Civil construction on LIGO facilities at Hanford, Washington and Livingston, Louisiana started in 1994. Each site houses detectors in a pair of 4km long, orthogonal, arms. The first coincident science operations took place in 2002 using the Initial LIGO detectors and the British-German GEO600 detector in Germany [3]. LIGO was envisioned as a facility to house multiple generations of detectors. After a period of scientific data taking interspersed by incremental improvements to the initial LIGO detectors [4], the upgrade to the Advanced LIGO (aLIGO) [5] detectors began in 2010. Advanced LIGO commenced observations in 2015 immediately delivering the first direct detection of gravitational waves [6].

France and Italy realized the laser interferometer Virgo with 3 km arms in the suburbs of Pisa, Italy (construction started in 1996 and was completed in 2003). In 2007, LIGO and Virgo signed an agreement to collaborate on the search for gravitational waves with full data exchange and a joint publication policy. This marked the beginning of operations as LIGO-Virgo network. The Virgo detector was upgraded to a second generation detector through the Advanced Virgo [7] program. The upgrade started at the end of 2011 and Advanced Virgo started joint observation with Advanced LIGO in

August 2017. During the second observing run (O2), the LIGO-Virgo Collaboration reported 8 events including the first detection of a binary neutron star merger [8].

In Japan, the TAMA interferometer with 300 m arms was constructed on the premises of the National Astronomical Observatory of Japan in Mitaka City, Tokyo. TAMA started observations in 1998. Then, following the low-temperature mirror demonstration interferometer CLIO, construction of the KAGRA interferometer with 3 km arms started in 2012 in Kamioka, Gifu, Japan [9]. The implementation of the device was completed in 2019, and KAGRA began joint observations with LIGO and VIRGO in 2020.

As of 2021, the LIGO-Virgo-KAGRA (LVK) Collaboration is working to establish the International Gravitational Wave Network (IGWN) which is conceived as an organization to facilitate coordination among ground-based, gravitational-wave-detector projects across the globe.

This chapter briefly summarizes gravitational-wave observations carried out up to December 2020.

Gravitational Wave Detectors

Basic Concepts

In the 1970s, Rainer Weiss began thinking about building gravitational-wave (GW) detectors using laser interferometers. At the same time, Kip Thorne was studying the theoretical properties of gravitational waves and the astrophysical sources that generate them. Gravitational waves induce a strain in spacetime which is characterized by the change in length per unit length as the waves pass. The strain sensitivity of a laser interferometer gravitational-wave detector is therefore inversely proportional to its arm length. Weiss completed an analysis of the fundamental noise sources impacting these detectors in 1972. Given the weakness of gravitational waves, the instruments would need to have kilometer-scale arms and use a number of tricks to enhance their sensitivity to the waves. Over the next two decades, new ideas led to improved sensitivity of these detectors and the mergers of binary neutron stars and black holes were identified as likely sources. In 1989, the LIGO detectors were proposed to the US National Science Foundation. In Europe, Adalberto Giazotto and Alain Brillet pursued studies on low frequency vibration isolation, lasers and optics which led them to propose the project for a detector in Europe: Virgo. And a group led by James Hough proposed the British-German detector project.

At fixed arm length, the sensitivity of these detectors is limited by noise generated in the measuring instruments. There are many different noise sources, but the sensitive band of the detectors is determined primarily by three types. The first is noise from the light source. Laser interferometric detectors monitor changes in the interference pattern induced by passing gravitational waves. Since the rate at which photons interfere follows a Poisson process, the light fluctuates accordingly. This is photon shot noise. The number of photons collected by the detectors is approximately determined by the power multiplied by the period of the gravitational waves. Thus photon-shot noise limits the sensitivity at high frequencies. It can be reduced by increasing the input power of the laser and by using power recycling to recover the light that would otherwise leave the interferometer through the symmetric output. Even if the entire optical path is evacuated to suppress fluctuations due to refraction, noise will be generated depending on the frequency, intensity, and output beam of the light source. Moreover, as the light-power increases, radiation pressure on the mirrors begins to limit the sensitivity at low frequencies.

The second noise comes from the vibration of the instrumentation arising from heat and gives rise to thermal noise which limits the sensitivity in mid frequencies ($\sim$100 Hz). Up to now, LIGO and Virgo have relied on reducing the internal losses by judicious choices of materials to reduce thermal noise. KAGRA includes a system to cool its mirrors to $\sim$20 K; successful cryogenic operations will further control the thermal noise.

The third noise is seismic vibration. The ground is constantly vibrating due to the unique vibration of the earth itself, and it also vibrates with a great influence on the surrounding environment. Sophisticated vibration isolation systems have been conceived, capable of suppressing the seismic noise by many orders of magnitude, in order to extend the detector bandwidth down to $\sim$ 10 Hz and, at the same time, allowing to control the mirrors at the required level.

There are many more sources of noise that are addressed by the development of new instrumental techniques and by careful design and engineering. Research into better ways to control all of these noise sources is continuing.

Even in stable operations, an interferometer is susceptible to myriad disturbances that can mimic a gravitational wave in a single detector. Moreover, multiple interferometers are required to determine the direction, orientation and distance to a gravitational-wave source, to measure the polarization of gravitational waves, and to maximize the scientific information that can be extracted. Today, LIGO, Virgo and KAGRA operate four detectors in unison and analyze the data together. Table 1, Fig. 1 and Fig. 2 show the locations and their arm orientations of these detectors.

LIGO

The LIGO observatories at Hanford, WA and Livingston, LA were constructed in the 1990s. Each observatory includes two orthogonal, evacuated

Table 1 Geometry of LIGO, Virgo & KAGRA detectors.

Detector	arm length	Latitude	Longitude	X-arm	Y-arm
LIGO Hanford (LHO)	4 km	46°27′19″ N	119°24′28″ W	N 36° W	W 36° S
LIGO Livingston (LLO)	4 km	30°33′46″ N	90°46′27″ W	N 18° S	S 18° E
Virgo	3 km	43°37′53″ N	10°30′16″ E	N 19° E	W 19° N
KAGRA	3 km	36°24′36″ N	137°18′36″ E	E 28.3° N	N 28.3° W

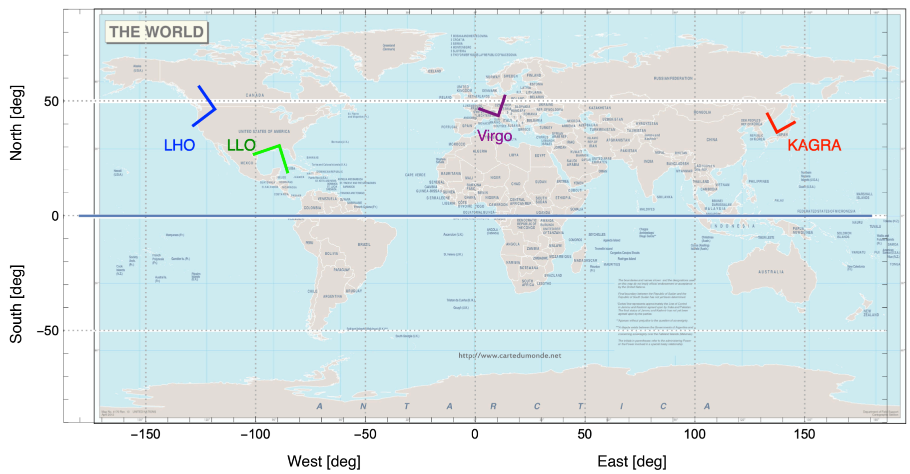

Fig. 1 Location of GW detectors; LHO (LIGO Hanford Observatory), LLO (LIGO Livingston Observatory), Virgo and KAGRA. The size of the arms is drawn exaggeratedly.

arms of 4km in length which house the detectors. The first coincident science operations took place in 2002 using the Initial LIGO detectors and the GEO600 detector in Germany [3]. This was followed from 2002-2010 by a sequence of science runs (S2-S6) that were interleaved between periods of detector improvements. LIGO and Virgo operated their detectors as a network starting with S5. No gravitational-wave signals were identified in the data from those runs.

LIGO was envisioned as a facility to house multiple generations of detectors. The upgrade to the Advanced LIGO (aLIGO) detectors began in 2010 and the aLIGO instruments began operating in 2015 with the first observing run (O1) of the new era starting in September of that year. The LIGO detectors are Michelson laser interferometers with suspended test mass mirrors. The interferometer configuration is modified to enhance their sensitivity to gravitational-wave strain. Resonant cavities in each arm increase the effect of gravitational waves on the phase of the light by ~ 300 times; a power recycling mirror increases the input light power from 20W to 700W on the beam splitter leading to about 100 kW of circulating power in each arm cavity; the bandwith of the coupling to the differential mode is broadened using signal

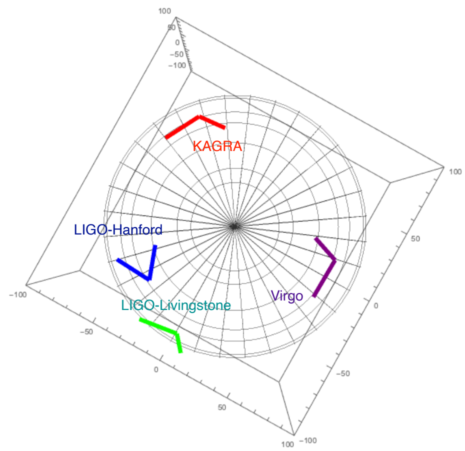

Fig. 2 Orientation of GW detectors on the Earth surface; LHO (LIGO Hanford Observatory), LLO (LIGO Livingston Observatory), Virgo and KAGRA.

recycling; and a Nd:YAG laser with amplitude, frequency and beam geometry stabilization provides light at 1064nm. Together these modifications reduce the impact of photon shot noise on the detection of gravitational waves. The test-mass mirrors are suspended by a quadruple pendulum system in which the final stage supports the mirrors using fused silica fibers. Along with active seismic isolation, seismic noise is suppressed by 10 orders of magnitude above 10Hz. Finally the test masses are 40 kg fused silica substrates with low-loss dielectric coatings providing low-thermal noise. The resulting instruments are $\sim 3-5$ times more sensitive than the initial LIGO instruments at frequencies $100-300$ Hz and more than 10 times more sensitive around 60Hz.

On 14 September 2015, the detectors at LIGO Hanford and LIGO Livingston registered gravitational waves from the merger of a pair of black holes [6] for the first time in history. This first direct observation of gravitational waves took place at the very beginning of O1. The presence of the same signal in both detectors modulo a time and phase shift consistent with their separation and orientation provided compelling evidence that the signal was astrophysical in origin. Careful examination of data from arrays of seismometers, accelerometers, microphones, magnetometers and other environmental sensors was used to rule out an environmental origin. Auxiliary information about the instruments' operational state indicated that they were both in stable operating mode for several hours at the time of the event.

Improvements to the LIGO detectors continue to be interleaved between observing runs. In addition to fixing a number of technical problems, the following significant changes were made between O1 and O3: the injection of squeezed vacuum at 2-3 dB was achieved; a signal recycling mirror with lower transmission was installed; the input power was increased to 40W using an amplifier and tuned mass dampers applied to the test masses to address parametric instabilities at high power; end mirrors were replaced with versions that achieve lower optical losses; and many light baffles were installed to reduce scattered light. The result is an angle averaged binary neutron star range of over 100 Mpc and 125 Mpc for LIGO Hanford and Livingston, respectively, during O3.

Detector improvements have been mapped out by the LIGO Laboratory through the middle of the 2020s. For O4, work is under way to improve stray light control, to introduce a new high power laser amplifier, and to reduce the impact of point absorbers on the test masses.

Additional improvements are expected from early implementation of certain A+ Project [10] upgrades, including adaptive mode-matching and frequency-dependent squeezing. Together these changes should support a BNS range of up to 190 Mpc for O4.

Plans for O5 include installation of large aperture beam splitters and suspension improvements, implementation of a balanced homodyne readout system, and reduction of coating thermal noise via improved test-mass coatings. These changes could bring the detection rate of binary black hole mergers above one per day with commensurate increases in the detection rates of other transients.

VIRGO

Virgo [11] is an interferometric detector of GW located in Cascina, near Pisa, Italy, with an arm length of 3 km. It was funded by CNRS (France) and INFN (Italy). Virgo was designed with a particular attention to the low frequency range: its vibration isolation system, the Superattenuator [12], conceived by A. Giazotto, allows to push the ”wall” of the residual seismic noise down to a few Hz.

The construction of Virgo was completed in 2003 and a long activity of commissioning then started to progressively improve the detector sensitivity. Virgo performed its first science run in 2006.

Since 2000 the detector site is managed by the European Gravitational Observatory, a CNRS-INFN consortium, recently joined by NIKHEF (The Netherlands).

In the years 2011-2017 Virgo underwent a major upgrade through the Advanced Virgo [7] project, approved in December 2009, which allowed to significantly improve its sensitivity. The main features of the upgrade realized before the O2 run were: a larger beam spot on the test masses, heavier test masses (42 kg instead of 21 kg), thermal compensation system to cope with the aberrations on the test masses, improved stray light control, cryopumps at the end of the 3 km tubes.

Advanced Virgo has started taking data on August 1st 2017, joining the two LIGO interferometers in the last part of the O2 run, with a sensitivity corresponding to a BNS inspiral range of ~ 30 Mpc.

Two weeks later Virgo detected its first GW event (GW170814 [13]). The event, also detected by the two LIGO interferometer, was the first triple detection. Three days later the 3 interferometers detected GW170817 [8], the coalescence of a two neutron stars, which marked the start of the multi-messenger astronomy.

Between the end of O2 and the start of O3 Advanced Virgo underwent a phase of further upgrading, with the installation of fused silica suspensions on the test masses and a squeezer [14], and an extensive noise hunting campaign. The BNS inspiral range eventually achieved in the last part of O3 was ~ 60 Mpc. The optical scheme of Advanced Virgo in the O3 configuration is shown in Fig. 3.

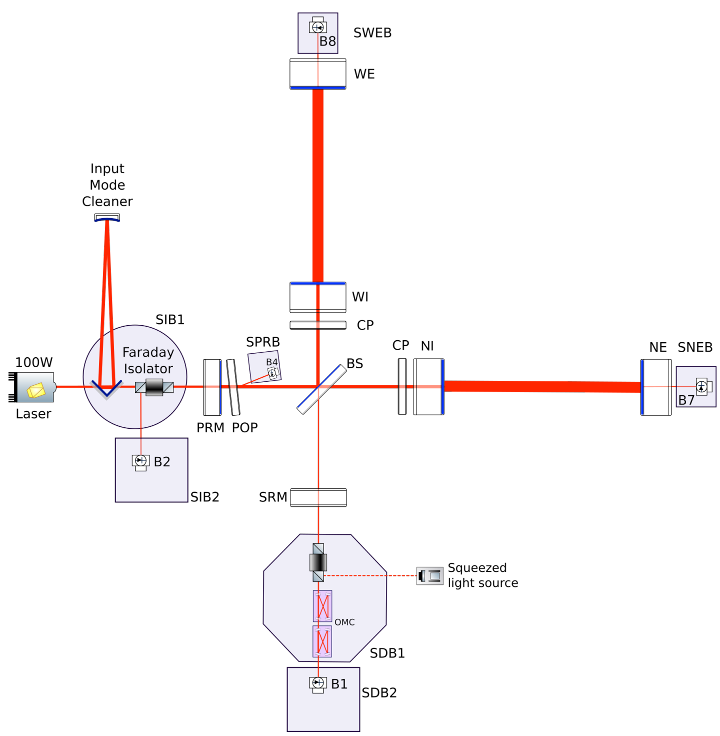

Fig. 3 Optical scheme of the Advanced Virgo detector during the O3 run. NI,WI,NE,WE are the test masses, BS the beam splitter, PRM/SRM the power/signal recycling mirrors, CP the compensation plates, POP the pick-off plate, SIB1/2 the suspended injection benches, SDB1/2 the suspended detection benches, SPRB the suspended power recycling bench, SNEB/SWEB the suspended end benches, whereas B_n are the photodiodes. Courtesy: Virgo Collaboration.

Currently, Virgo is pursuing a 2-phase upgrade named Advanced Virgo+. The main novelties of Phase 1 (before O4) are: a new fiber laser, the signal recycling, the implementation of frequency dependent squeezing, with a the target sensitivity of 90-115 Mpc BNS inspiral range). Between O4 and O5 new mirrors with improved coatings will be installed. The end test masses will have a diameter of 55 cm (instead of 35), allowing to enlarge the beam spot and reduce the thermal noise. The target sensitivity of the Phase 2 configuration is 145-260 Mpc.

KAGRA

Comparing to LIGO and VIRGO, KAGRA is technologically unique in two ways. [9, 15]. First, it is located in an underground site in order to reduce seismic noise. In addition, KAGRA's test masses are sapphire mirrors that are designed to be operated at cryogenic temperatures ($\sim$20 K) in order to reduce thermal noise. KAGRA is designed as a resonant sideband extraction (RSE) interferometer, and quantum non-demolition techniques are planned to be applied to beat the standard quantum limit of displacement measurements. As a result, KAGRA is expected to reach an equivalent sensitivity to those of Advanced LIGO/Virgo; $2 \times 10^{-24}/\sqrt{\mathrm{Hz}}$ at 100 Hz. The designed sensitivity is 140 Mpc in BNS range.

In Japan, plans to construct interferometric gravitational wave detectors started in the 1980s. After the comparisons of a 100-m delay-line Michelson interferometer (TENKO-100) at the Institute of Space and Astronautical Science (ISAS) and a 20-m Fabry-Perot Michelson interferometer at the National Astronomical Observatory of Japan (NAOJ), Japanese decided to construct a 300-m Fabry-Perot Michelson interferometer, called TAMA at NAOJ, which was successfully operated for more than 1000 hours in 2001. However, since NAOJ is in a suburb of Tokyo, significant seismic noise due to human activities was inevitable below 100 Hz. In order to overcome the large seismic noise, it was decided to put a planned future interferometer underground.

Although various experiments showcased the possible scientific achievements of the project and the plausibility of fundamental technologies, the proposal for developing a km-scale cryogenic detector took years to be formally approved in Japan. This was mainly due to the fact that there was no gravitational wave detection reported in 2000s, and thus it was judged to be too expensive and too risky.

The project (named LCGT; Large-scale Cryogenic Gravitational wave Telescope) was finally approved in 2010 for construction, and the excavation of the tunnels in Kamioka began in 2012 and finished in early 2014. During the construction, LCGT was given its nickname, KAGRA, chosen from a public naming contest. The name KAGRA is taken from KAmioka (the location) plus GRAvity; the Japanese word kagura reminds a type of traditional sacred dance accompanied by music dedicated to gods.

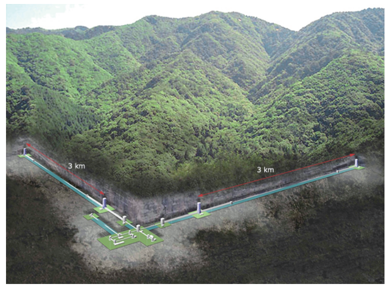

Fig. 4 Concept image of KAGRA: a 3-km cryogenic interferometer inside Ikenoyama mountain in Kamioka, Gifu, Japan. Courtesy: KAGRA Observatory, ICRR, The University of Tokyo.

KAGRA is constructed in Kamioka, Gifu, Japan, which is located 220 km northwest of Tokyo (Fig. 4). Kamioka also hosts the neutrino detectors, Super-Kamiokande and KamLAND, which share the area with KAGRA. All the operations of KAGRA are controlled remotely from the office 5 km apart from the site.

The installations of the principal instruments, such as sapphire mirrors, large suspensions (Fig. 6), and cryogenic instruments were completed in the summer of 2019. Meanwhile two engineering runs were performed in April 2016 (as iKAGRA operation)[16] and April 2018 (bKAGRA phase-1 operation)[17]. In the latter, the performance of the large vibration isolation systems and cryogenic technology (down to 20 K) were demonstrated.

From the summer 2019, the commissioning of the detector was initiated. This continued until March 2020, when the sensitivity got over 1 Mpc in BNS range with power-recycling technique, and KAGRA joined the international GW network.

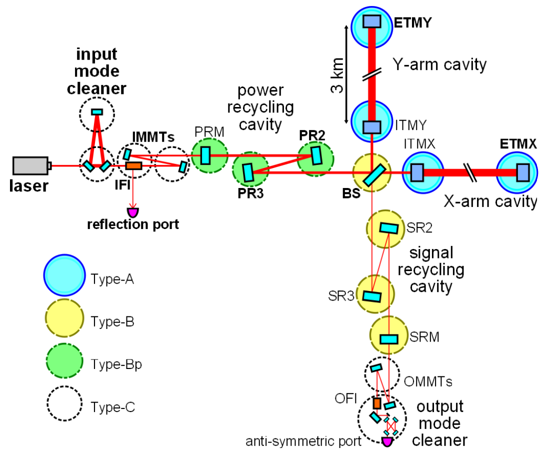

Fig. 5 Schematic image of the KAGRA interferometer. All the mirrors shown are suspended inside the vacuum tanks with four types of vibration isolation systems (Type-A, B, Bp, and C). IMMT/OMMT: input/output mode-matching telescope, IFI/OFI: input/output Faraday isolator, BS: beam splitter, PRM/SRM: the power/signal recycling mirrors, ITMX/ITMY: initial test masses, ETMX/ETMY end test masses. (Figure from [17]).

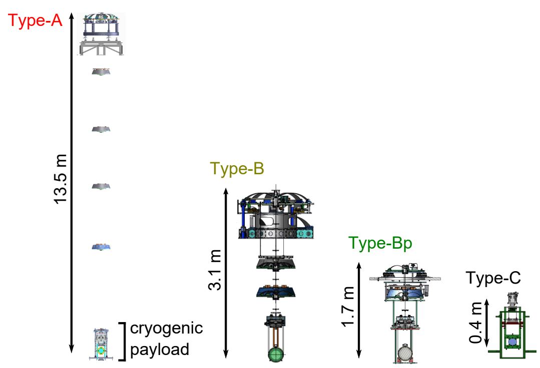

Fig. 6 Four types of KAGRA mirror suspension system. Type-A system is for the four main mirrors (ITMs and ETMs). Type-B system is for beam splitter and signal recycling mirrors. Type-Bp system is for power recycling mirrors. Type-C system is used for other auxiliary mirrors. Type-A has the hight of 14 m, of which top is located in the higher layer of the tunnel. (Figure from [17]).

International Gravitational-Wave Network (IGWN)

It was understood early in the development of interferometric gravitational-wave detectors that establishing confidence that a minute strain originated from a passing gravitational-wave signal would require its observation in more than one detector. Even in stable operations, an interferometer is susceptible to myriad disturbances that can mimic a gravitational wave in a single detector. It is also extremely difficult to measure the background in a single detector since we cannot shield the effect of gravitational waves. Data that is time-shifted between multiple detectors is used to go off-source and estimate the background in a multi-detector analysis. Moreover, multiple interferometers are required to determine the direction, orientation and distance to a gravitational-wave source, to measure the polarization of gravitational waves, and to maximize the scientific information that can be extracted. In short, having more detectors is better.

In recognition of these facts and with the goal of establishing a long-term collaborative relationship, LIGO and Virgo first established an agreement in 2007 to work together to detect gravitational waves and use them as physical and astronomical probes. A key demonstration of the importance and success of this collaboration was the identification of GW170817 and its associated optical counterpart.

In 2019, the agreement was revised to include KAGRA and the LIGO-Virgo-KAGRA Collaboration now carries out its observational science program in unison, coordinating observing runs, and jointly planning and carrying out analyses. The LIGO-India detector, currently under construction in Maharastra, India is expected to join the network in the late 2020s.

With the transition to routine astronomical operations, LIGO-Virgo-KAGRA have established are establishing the International Gravitational Wave Network (IGWN) to coordinate multiple facets of the research, development, construction and operations of earth-based gravitational-wave detectors. As an initial step towards establishing an IGWN organization, the LIGO-Virgo-KAGRA computing and software development activities have been formulating a unified plan to provide the infrastructure and resources needed to maximize the scientific impact of the network. We envision IGWN as providing a structure in which to work together on common problems, to share infrastructure, to synchronize observation runs, and to collaborate on acquiring and analyzing data. IGWN also provides a common interface with other astronomy and physics communities and supports open access to gravitational-wave data and tools through the Gravitational-Wave Open Science Center (GWOSC). Interested readers can find more information using the links provided in Table 2.

Table 2 List of webpages. GraceDB (Gravitational-Wave Candidate Event Database) provides information about candidate GW events. GWOSC (GW Open Science Center) provides data from gravitational-wave observatories, along with access to tutorials and software tools.

	URL
LIGO	www.ligo.org
Virgo	www.virgo-gw.eu
KAGRA	gwcenter.icrr.u-tokyo.ac.jp/en/
GraceDB	gracedb.ligo.org
GWOSC	www.gw-openscience.org

Observing Runs

The first observation run (O1) of Advanced LIGO started in September 2015 and lasted for four months. After a break to further improve the detectors, Advanced LIGO started the second observing run (O2) in November 2016. Advanced Virgo joined O2 in August 2017 and the run concluded after 9 months and many spectacular discoveries. The most recent observing run (O3) started on 1 April 2019 with both LIGO and Virgo operating and was planned for a year. Due to COVID-19, LIGO and Virgo O3 operations were interrupted at the end of March 2020 just as KAGRA was preparing to join the run. KAGRA started operating in April 2020, joining GEO600 which was operating as "Astrowatch" with the sensitivity ~ 1 Mpc. Coincident GEO600 and KAGRA data is being analyzed as a part of O3b. Table 3 and Fig. 7 show the list of observing runs and its period.

Table 3 List of Observing Period

Obs. Runs	Advanced LIGO	Advanced Virgo	KAGRA
O1	Sep 12, 2015 to Jan 19, 2016	–	–
O2	Nov 30, 2016 to Aug 25, 2017	Aug 1, 2017 to Aug 25, 2017	–
O3a	Apr 1, 2019 to Sep 30 2019	Apr 1, 2019 to Sep 30, 2019	–
O3b	Nov 1, 2019 to Mar 27 2020	Nov 1, 2019 to Mar 27, 2020	
O3GK	–	–	Apr 7, 2020 to Apr 21, 2020

Observational Science Highlights

Since the beginning of observations with the advanced detectors in 2015, gravitational-wave astronomy has yielded many remarkable results.

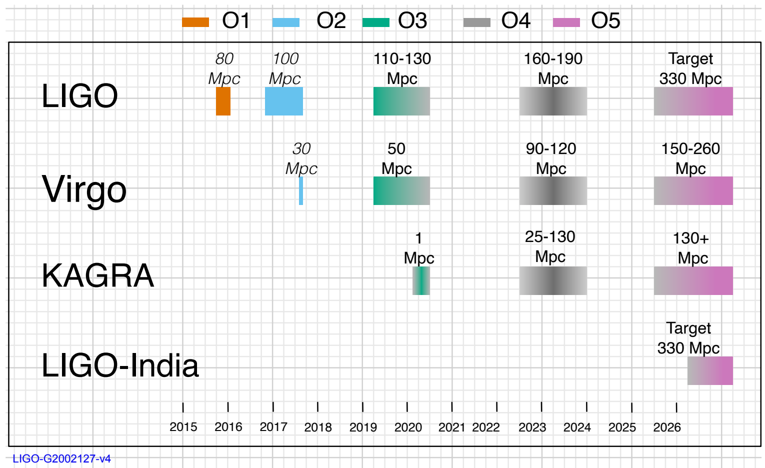

Fig. 7 Timeline table of Observing Runs up to O3b together with the sensitivities of the detectors in binary NS range, and future plans of Observing Runs. The planned start of O4 is in the middle of 2022. [10]

Observing Run 1 (O1)

On 14 September 2015, the LIGO detectors at Hanford and Livingston registered gravitational waves from the merger of a pair of black holes [18] for the first time in human history. This first direct detection of gravitational waves took place as the LIGO Scientific Collaboration was closing out the engineering run that preceded O1. Detailed analysis of the data around this event revealed the following:

- GW150914[18] was the first detection of gravitational waves from a BBH merger. The masses of the pre-merger components are measured to be 30 $M_\odot$ and 36 $M_\odot$ ($M_\odot$: mass of the Sun), and the final remnant mass is 62 $M_\odot$. The luminosity distance to the source is approximately 400 Mpc. In addition to being the first direct measurement of gravitational waves, this event was also the first confirmed observation of a stellar-mass black-hole binary, and the first direct measurement of black holes of this mass.

The first detection was announced publicly on February 11, 2016 making headline news around the world. For the scientific community, the observation also brought a wealth of new results. The rate of BBH mergers similar to GW150914 was estimated to be $2-600\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ providing the first ever lower bound on the merger rate [19]. The observation enabled tests of general relativity via the dynamics of gravitational waves generated in the regime of strong field gravity alone [20]. The discovery also opened new research directions in astrophysics [21].

The first observing run (O1) lasted just over 4 calendar months and resulted in two additional detections [22]. GW151226 was identified in low-latency analysis of the data for BBH signals; it was a lower mass binary resulting in a final black hole of about 20 $M_\odot$. A third BBH signal LVT151012, with lower significance in the initial searches, was also identified.

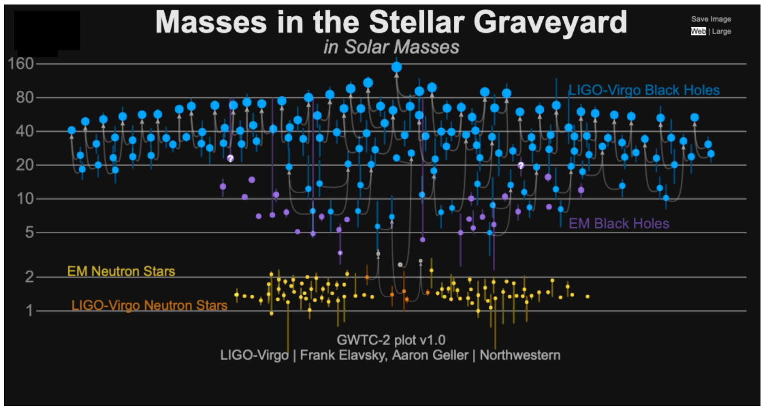

Fig. 8 Results after O3a (Apr.1/2019 - Sep.30/2019). GWTC-2 (released on Oct. 28, 2020) has 46 BBHs, 2 BNS, and 2 unknown companion binary with BH. The graphic shows BHs (blue), NSs (orange), and compact objects of uncertain nature (gray). (Credit: LIGO Virgo Collaboration / Frank Elavsky, Aaron Geller / Northwestern University)

Observing Run 2 (O2)

The second observing run (O2) started with LIGO's two detectors in November, 2016. Virgo joined O2 from July 2017. In the single month of August 2017, the three detector LIGO-Virgo network detected gravitational waves from 4 BBH mergers and the BNS merger GW170817. The localization of GW170817 using information from all three detectors enabled the discover of an optical counterpart in NGC4993 leading to an unprecedented follow-up effort by astronomers around the globe.

Notable detections during O2 include:

- GW170814: The first gravitational-wave signal measured by the three-detector network came from a binary black hole merger.
- GW170817 [8, 23]: The first gravitational-wave signal measured from a BNS merger – and also the first event also observed in light, by dozens of telescopes across the entire electromagnetic spectrum. This event is widely considered the beginning of the modern era of multi-messenger astronomy.

The first Gravitational-Wave Transient Catalog (GWTC-1) [24] was released on Dec.3, 2018 and includes 10 BBH mergers and 1 BNS merger.

Observing run 3 - the first 6 months (O3a)

The LIGO-Virgo Collaboration started observing run 3 (O3) on April 1, 2019, with the sensitivity 120-130 Mpc (LIGO) and 50 Mpc (Virgo) in BNS range. They took a one-month commissioning break in October 2019 designating the first six months of observations as O3a.

From the start of O3a, event alerts were publicly distributed within minutes of data acquisition. The events were available via GraceDB (Gravitational-Wave Candidate Event Database) including estimates of the false alarm rate for the event, localization of the source, probability that the signal was astrophysical, and the likelihood that source included a neutron star in the case of mergers. By the end of O3, these alerts were automatically distributed within about 10 minutes with updated information provided within hours or when available.

As of May 2021, the second Gravitational-wave Transient Catalog (GWTC-2) [25] has been released including events from O3a This includes 46 BBHs, 2 BNSs, and two other binaries for which may be BBH or NSBH. Fig. 8 shows the mass posteriors for events in GWTC-2. Notable events from O3 include:

- GW190412: The first BBH with definitively asymmetric component masses, which also shows evidence for higher harmonics in its waveform.
- GW190425: The second GW event consistent with a BNS, following GW170817.
- GW190426_152155: A low-mass event consistent with either an NSBH or BBH.
- GW190514_065416: A BBH with the smallest effective aligned spin of all O3a events.
- GW190517_055101: A BBH with the largest effective aligned spin of all O3a events.
- GW190521: A BBH with total mass over 150 $M_\odot$, the first evidence of the intermediate mass BH (over 100 $M_\odot$, and less than the super-massive BH $\sim 10^4\ M_\odot$).
- GW190814: A highly asymmetric system, corresponding to the merger of a 23 $M_\odot$ BH with a 2.6 $M_\odot$ compact object, making the latter either the lightest BH or heaviest NS observed in a compact binary.
- GW190924_021846: The lowest-mass BBH, with both BHs exceeding 3 $M_\odot$.

GWTC-2 was released together with companion papers analyzing the population properties [26] and using the events to test general relativity [27].

As we see in Fig. 9, the number of detected events is monotonically increasing according to the effective BNS spacetime volume VT surveyed; VT is defined by the spatial sensitive volume of the search integrated over time. Intuitively, this is the average spatial sensitive volume of the second-most sensitive detector in the network multiplied by the live-time of the that network configuration. Fig. 10 shows 90% credible region of mass M and mass ratio q for all candidate events.

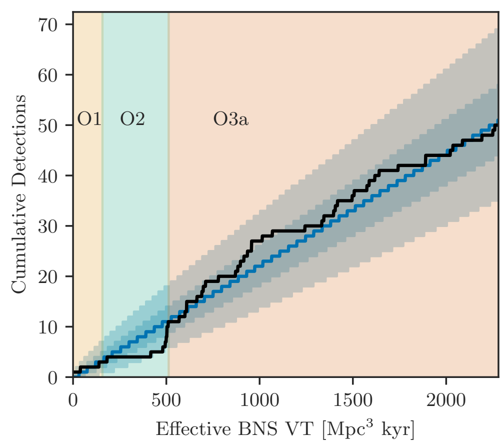

Fig. 9 The number of compact binary coalescence detections versus the effective volume-time to which the gravitational wave network is sensitive to BNS coalescences. Fig. 1 from the GWTC-2 paper [25].

Using the events in GWTC-2, we estimate merger rates for BBH to be $\mathscr{R}_{\rm BBH} = 23.9^{+14.9}_{-8.6}\,{\rm Gpc}^{-3}{\rm yr}^{-1}$, and for BNS to be $\mathscr{R}_{\rm BNS} = 320^{+490}_{-240}\,{\rm Gpc}^{-3}{\rm yr}^{-1}$. The primary mass distribution of BH is not well-described as a simple power-law model, but with additional single peak around $37M_\odot$. The minimum mass of black holes in BBH systems is constrained to be $M_{\rm min} < 6.6M_\odot$. There are a couple of events with masses in the range 2–5 $M_\odot$ for which it has not been possible to determine if they are black holes or neutron stars. There is evidence of spin-induced, general relativistic precession of the orbital plane and examples of component spin that is anti-aligned with respect to the orbital angular momentum of the binary. The latter suggests the dynamical formation of the binary. There is no evidence of violation of general relativity.

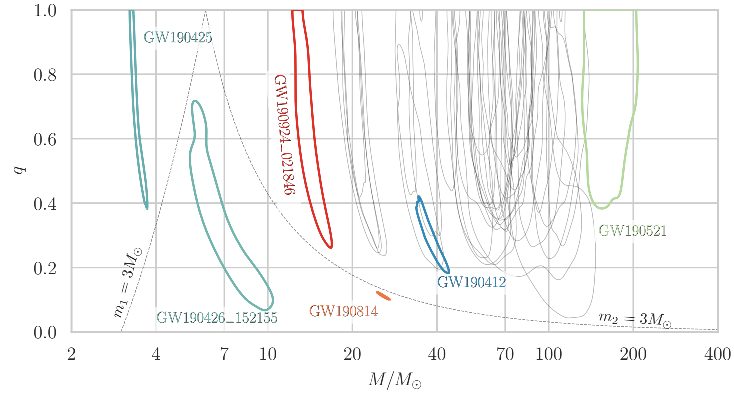

Fig. 10 Credible region contours for all condidate events in the plane of total mass M and mass ratio q. Each contour represents the 90% credible region for a different event. Fig. 6 from the GWTC-2 paper [25].

Outlook

The direct measurement of gravitational waves in 2015 established gravitational-wave detectors as powerful new tools for exploring the Universe. When combined with electromagnetic telescopes and particle detectors, they extend our view into the nature of gamma-ray bursts, neutron star structure, and cosmology.

Over the next 5 years, the sensitivity of the LIGO-Virgo-KAGRA network should improve by up to 2-3 times in amplitude sensitivity over O3 [10]. That will bring the detection rate of compact binary mergers close to 1 per day with signal-to-noise of the most significant candidates in the 50-100 range. The majority of these detections will involve binary black hole mergers providing a rapidly increasing sample with which to study the properties and mechanisms of binary black hole formation. Moreover, the reduced statistical uncertainty on measured parameters of the loudest events will enable more stringent tests of general relativity in the context of binary black hole mergers.

While GW170817 is the only binary neutron star merger observed both in gravitational and electromagnetic waves to date, early identification of gravitational-wave transients and distribution of alerts about them is a high priority for the community. By the end of O3, the LVK was publicly releasing alerts within minutes of data acquisition for compact binary mergers of all sorts. Unfortunately, the candidates thought most likely to contain a neutron star were not well localized during O3 making the identification of electromagnetic counterparts extremely challenging, and no high-confidence associations were found. It was gratifying to see improved coordination of follow-up observations across the community: this bodes well for future runs.

Moreover, an improved alert system was deployed and shown to be capable of identifying coalescing neutron-star systems and alerting the broader community from seconds to minutes before merger [28, 29]. As the sensitivity of the IGWN detectors improves and the number of useful baselines grows, transient events will be better localized. Improving the sensitivity of all detectors operating in the network is the best way to improve the likelihood of identifying the electromagnetic counterpart of gravitational-wave sources. We look forward to the identification of multi-messenger sources becoming more routine over the course of the decade.

While it is appropriate at this time to emphasize the breakthroughs associated with the observations of compact binary mergers over the past years and the opportunities that increased detection rate affords, the gravitational-wave discovery space remains largely untapped beyond compact binaries. Searches for a gravitational-wave stochastic background have constrained the dimensionless energy density $\Omega_{\mathrm{GW}} \leq 5.8 \times 10^{-9}$ at the 95% credible level for a flat (frequency-independent) GWB [30]. Searches for gravitational waves from spinning neutron stars in our Galaxy continue to set tighter limits on gravitational-wave emission from known pulsars and from as yet unidentified sources [31, 32, 33, 34]. The possibility of detecting gravitational waves hypothesized sources such as cosmic strings [35], dark matter [36], supernovae [37], or as yet unknown astrophysical sources or events is tantalizing.

As we enter a new decade, physicists and astronomers are considering the future paths for gravitational-wave detectors. The LIGO-Virgo-KAGRA Collaboration ~~have established~~are establishing the International Gravitational Wave Network (IGWN) which is conceived as an organization to facilitate coordination among gravitational-wave detector projects across the globe. The initial effort is being invested in establishing a unified computing plan under the IGWN umbrella to introduce efficiencies by sharing common infrastructure and tools.

The A+ and AdV+ projects involve significant upgrades to the detectors in the LIGO and Virgo facilities that will be completed for O5 which is anticipated to start around 2025. Both LIGO and Virgo have initiated studies to consider options for upgrades in the existing facilities that would dovetail with the constructions and operations of next generation facilities. The LIGO-India [38] project is also under way and should join the international network ~~in the middle~~toward the end of the decade.

Work has continued to ramp up on next generation facilities featuring detectors with arm lengths of 10km to 40km that could begin operations in the early to mid-2030s. Einstein Telescope [39] is being pursued in Europe as an underground facility to house multiple detectors in triangular configuration. Cosmic Explorer [40, 41] is being pursued in the US as an above ground facility with interferometers at different locations. Specialized detectors, such as the Australian NEMO [42], are also being proposed to pursue specific science goals.

With the successes of the past decade and the possibilities of future observations and facilities, the dream of gravitational-wave astronomy is now reality.

References

[1] P. G. Bergmann. Summary of the Chapel Hill Conference. Rev. Mod. Phys., 29:352–354, Jul. 1957.

[2] P. C. Peters and J. Mathews. Gravitational Radiation from Point Masses in a Keplerian Orbit. Phys. Rev., 131:435–440, Jul. 1963.

[3] B. Abbott et al. Detector description and performance for the first coincidence observations between LIGO and GEO. Nuclear Instruments Methods Phys. Research Sec. A, 517(1):154–179, 2004.

[4] B. P. Abbott and et al. (LIGO Scientific Collaboration). LIGO: The Laser interferometer gravitational-wave observatory. Rept. Prog. Phys., 72:076901, 2009.

[5] J. Aasi and et al. (LIGO Scientific Collaboration). Advanced LIGO. Class. Quant. Grav., 32:074001, 2015.

[6] B. P. Abbott, others (LIGO Scientific Collaboration, and Virgo Collaboration). Observation of Gravitational Waves from a Binary Black Hole Merger. Phys. Rev. Lett., 116(6):061102, 2016.

[7] F. Acernese and et al. (Virgo Collaboration). Advanced Virgo: a second-generation interferometric gravitational wave detector. Class. Quant. Grav., 32(2):024001, 2015.

[8] B. P. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration). GW170817: Observation of gravitational waves from a binary neutron star inspiral. Phys. Rev. Lett., 119:161101, Oct. 2017.

[9] T. Akutsu, et al. (KAGRA Collaboration). KAGRA: 2.5 generation interferometric gravitational wave detector. Nature Astro., 3:35, Jan. 2019.

[10] B. P. Abbott, others (KAGRA Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration). Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA. Liv. Rev. Relativ., 23, Sep. 2020.

[11] T. Accadia, et al. (Virgo Collaboration). Virgo: a laser interferometer to detect gravitational waves. Journal of Instrumentation, 7:3012, 2012.

[12] S. Braccini et al. Measurement of the seismic attenuation performance of the VIRGO Superattenuator. Astropart. Phys., 23:557, 2005.

[13] B. P. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration). GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence. Phys. Rev. Lett., 119:141101, 2017.

[14] F. Acernese, et al. (Virgo Collaboration). Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light. Phys. Rev. Lett., 123:231108, 2019.

[15] T. Akutsu, et al. (KAGRA Collaboration). Overview of KAGRA: Detector design and construction history. Prog. Theor. Exp. Phys., 2021:05A101, May 2021.

[16] T. Akutsu, et al. (KAGRA Collaboration). Construction of KAGRA: an Underground Gravitational Wave Observatory. Prog. Theor. Exp. Phys., 1:013F01, Aug. 2018.

[17] T. Akutsu, et al. (KAGRA Collaboration). First cryogenic test operation of underground km-scale gravitational-wave observatory KAGRA. Class. Quant. Grav., 36:165008, Jul. 2019.

[18] B. P. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration). GW150914: The advanced LIGO detectors in the era of first discoveries. Phys. Rev. Lett., 116:131103, Mar 2016.

[19] B. P. Abbott, et al. (LIGO Scientific Collaboration, and Virgo Collaboration). The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914. Astrophys. J. Lett., 833(1):L1, 2016.

[20] B. P. Abbott, et al. (LIGO Scientific Collaboration, and Virgo Collaboration). Tests of general relativity with GW150914. Phys. Rev. Lett., 116(22):221101, 2016. [Erratum: Phys.Rev.Lett. 121, 129902 (2018)].

[21] B. P. Abbott, et al. (LIGO Scientific Collaboration, and Virgo Collaboration). Astrophysical Implications of the Binary Black-Hole Merger GW150914. Astrophys. J. Lett., 818(2):L22, 2016.

[22] B. P. Abbott, et al. (LIGO Scientific Collaboration, and Virgo Collaboration). Binary Black Hole Mergers in the first Advanced LIGO Observing Run. Phys. Rev. X, 6(4):041015, 2016. [Erratum: Phys.Rev.X 8, 039903 (2018)].

[23] B. P. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration, with other astronomical observatories). Multi-messenger observations of a binary neutron star merger. Astrophys. J. Lett., 848:L12, Oct. 2017.

[24] B. P. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration). GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs. Phys. Rev. X, 9:031040, Sep. 2019.

[25] R. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration). GWTC-2: Compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run. Phys. Rev. X, 11:021053, Jun. 2021.

[26] R. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration). Population properties of compact objects from the second LIGO-Virgo gravitational-wave transient catalog. Astrophys. J. Lett., 913:7, May 2021.

[27] R. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration). Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog. Phys. Rev. D, 103:122002, Jun. 2021.

[28] S. Sachdev et al. An Early-warning System for Electromagnetic Follow-up of Gravitational-wave Events. Astrophys. J. Lett., 905(2):L25, 2020.

[29] R. Magee et al. First demonstration of early warning gravitational wave alerts. Astrophys. J. Lett., 910(2):L21, 2021.

[30] R. Abbott, et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration). Upper Limits on the Isotropic Gravitational-Wave Background from Advanced LIGO's and Advanced Virgo's Third Observing Run. arXiv:2101.12130, Jan. 2021.

[31] R. Abbott, et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration). Searches for continuous gravitational waves from young supernova remnants in the early third observing run of Advanced LIGO and Virgo. arXiv:2105.11641, May 2021.

[32] R. Abbott, et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration). Constraints from LIGO O3 data on gravitational-wave emission due to r-modes in the glitching pulsar PSR J0537-6910. arXiv:2104.14417, Apr. 2021.

[33] R. Abbott, et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration). Diving below the spin-down limit: Constraints on gravitational waves from the energetic young pulsar PSR J0537-6910. Astrophys. J. Lett., 913, May 2021.

[34] R. Abbott, et al. (LIGO Scientific Collaboration, and Virgo Collaboration). All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems. Phys. Rev. D, 103(6):064017, 2021.

[35] R. Abbott, et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration). Constraints on cosmic strings using data from the third Advanced LIGO-Virgo observing run. Phys. Rev. Lett., 126:241102, Jun. 2021.

[36] R. Abbott, et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration). Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run. arXiv:2105.13085, May 2021.

[37] B. P. Abbott, et al. (LIGO Scientific Collaboration, and Virgo Collaboration). Optically targeted search for gravitational waves emitted by core-collapse supernovae during the first and second observing runs of advanced LIGO and advanced Virgo. Phys. Rev. D, 101(8):084002, 2020.

[38] M. Saleem et al. The Science Case for LIGO-India. arXiv:2105.01716, May 2021.

[39] M. Punturo et al. The Einstein Telescope: A third-generation gravitational wave observatory. Class. Quant. Grav., 27:194002, 2010.

[40] D. Reitze et al. Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO. arXiv:1907.04833, Jul. 2019.

[41] B. P. Abbott and et al. (LIGO Scientific Collaboration). Exploring the Sensitivity of Next Generation Gravitational Wave Detectors. Class. Quant. Grav., 34(4):044001, 2017.

[42] K. Ackley et al. Neutron star extreme matter observatory: A kilohertz-band gravitational-wave detector in the global network. Publications of the Astronomical Society of Australia, 37:e047, 2020.