LIGO–Virgo–KAGRA Results and Status of the Current Fourth Observing Run

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1 The LVK Detector Network and Collaboration

It took 100 years from Einstein's prediction of gravitational waves (GWs) to their first detection [3]. Any time-varying mass quadrupole can produce these ripples in spacetime. But we need both extreme astrophysical sources and extremely sensitive detectors to observe this new spectrum of cosmic messengers.

The current global network of laser-interferometric GW detectors consists of two LIGO detectors in the US with 4 km arms [1], the 3 km Virgo detector in Italy [25], the 3 km underground KAGRA in Japan [27] and the 0.6 km GEO600 in Germany [31], mainly used to test new technologies and watch for nearby GW events when the larger detectors are offline. Another 4 km LIGO will be constructed in India [37].

The detectors are operated and their data analyzed by the global LIGO–Virgo–KAGRA collaboration (LVK) with over 2000 members in over 200 groups. The progression of LVK observing runs and sensitivities is shown in Fig. 1.

2 GWs from Compact Binary Coalescences (CBCs)

The first detection of GWs [3] was the GW150914 signal from the merger of a binary black hole (BBH) with component masses $\sim 30\,M_{\odot}$ at a distance ~ 400 Mpc. Found by both matched-filter and unmodelled analysis pipelines, the observed

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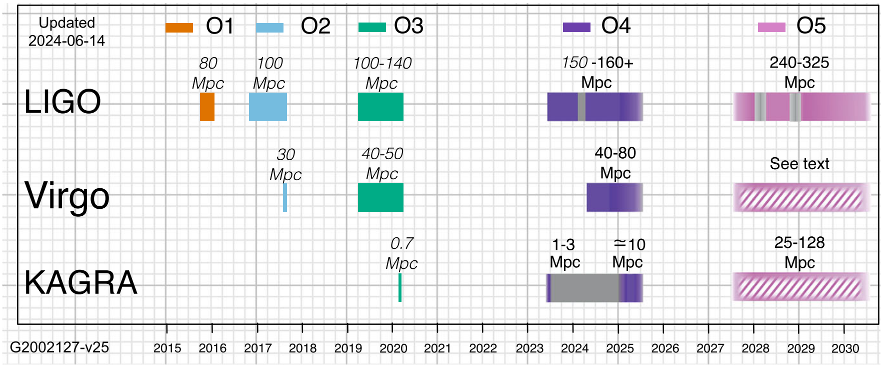

Fig. 1 LVK observing runs so far and plans for the rest of O4 and the future. Sensitivities are summarized as the typical distance at which binary neutron star mergers can be detected. Further updates will be available at https://dcc.ligo.org/G2002127/public/. © 2024, the LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration

waveform closely matches full numerical relativity (NR) solutions of Einstein's equations [2].

Over the first three observing runs of Advanced LIGO, joined by Advanced Virgo since O2 and KAGRA at the end of O3, a total of 90 GW events have been published by the collaboration [9, 13, 20]. Additional events have been reported by external authors (e.g., [34, 40]) from open data provided by the LVK [17, 21]. All come from CBCs, and most from BBHs since heavier objects produce stronger GWs, and hence BBHs can be observed at larger distances. Our current data-based estimates of actual merger rates (per Gpc^3 and year) are 17.9–44 for BBHs, 10–1700 binary neutron stars (BNSs) and 7.8–140 for neutron star—black holes (NSBHs) [22]). The most distant observations reach redshifts of $z \sim 1$.

2.1 BBH Results

Since the GW frequency evolution depends on the source parameters (masses, spins, inclination, sky location), we can extract these parameters through Bayesian inference [39] against large numbers of NR-calibrated model waveforms (see references in [20]). We have found a wide spread of systems consistent with BBHs, recovering an increasingly sharp picture at the population level [22] of their rate and mass distribution. Observed component masses range from a few solar masses up into the intermediate-mass range ($\gtrsim 100\,M_\odot$), touching both of the "mass gaps" often discussed in astrophysics [22]. We have also found such systems with mass ratios from unity to 1:10 and with various spin configurations, though the latter are still difficult to measure precisely at current detector sensitivity. Both mass ratios and spins are useful indicators for astrophysical formation channels [22].

All events so far are well fit by general-relativity waveforms, but the LVK probes alternative theories of gravity through an array of tests yielding increasingly strong constraints [16]: inspiral-merger-ringdown consistency, parametrized tests of GW generation and GW dispersion relation, polarization tests, etc. We are also searching for signatures of gravitational lensing of GWs [15, 23].

2.2 Binaries Including Neutron Stars

The first BNS observation, GW170187 [6], was a revolutionary multimessenger event [7]. Among the many results were a first "standard siren" measurement of the Hubble constant [4, 19], confirmation that the speed of gravity is very close to that of light [5], constraints on the equation of state of nuclear matter at extreme densities [8, 9], and that BNS mergers are a prime source of heavy elements in the Universe [30]. A second BNS event, GW190425, hinted at a surprising population of heavy BNS systems [10, 20]. The set of CBC types observable with the LVK network was completed with the first observation of NSBHs [14, 20].

3 Beyond Binaries: Other GW Sources in the LVK Band

3.1 GW Bursts

While CBCs are well-modelled signals for which matched filtering is the standard approach, other sources of short GW transients ("bursts") are less well understood: core-collapse supernovae, magnetars, accretion disk instabilities, highly eccentric BBHs, cosmic strings, etc. Burst searches use more generic methods, often based on empirical models such as wavelets or sine-Gaussians or pattern recognition in time-frequency GW spectrograms. See [11, 12] for recent LVK all-sky burst searches, and references therein for physical scenarios and analysis methods. No detections of any signals beyond CBCs have been made so far, but even non-detections can yield interesting physical constraints, e.g., on galactic supernovae or on magnetars vs. BNS as sources for nearby gamma-ray bursts.

3.2 Continuous GWs

By contrast, long-duration persistent GWs can also be emitted by a number of sources, especially spinning non-axisymmetrically deformed neutron stars. They produce very weak GW strains but stay observable for years, with great promise for multi-messenger astronomy and as probes of nuclear physics at extreme densities. For a review of the physics, computationally very challenging search methods and the non-detection upper limits results obtained so far, see [36]. CW search methods are also used for direct and indirect dark matter detection with GW detectors; see Sect. 5.

3.3 Stochastic GW Backgrounds

GW detectors could uncover two types of stochastic backgrounds in the Universe: astrophysical backgrounds from the overlap of faint, unresolved CBCs and other sources or cosmological backgrounds from early-universe physics: inflationary tensor modes, phase transitions, etc. For recent reviews see [35, 38]. Complementary to LVK searches, in 2023 pulsar timing array experiments have found first evidence for such backgrounds at much lower (nHz) frequencies [26].

4 The Present: The O4 Run

The O4 run started on 27 May 2023, with sensitivity of the LIGO detectors further improved over O3. Virgo rejoined after a commissioning break between the O4a and O4b periods and KAGRA plans to participate again later in O4b, which will run into 2025. For detector status see gwosc.org/detector_status/O4a/.

Public alerts from low-latency data analysis are available via gracedb.ligo.org. News in O4 include alerts for marginal candidates (to enable deep multimessenger coincidence searches) and BNS pre-merger alerts. The accumulation of detections from O1–O3 and O4a candidates is shown in Fig. 2. When ACHEP2023 was held

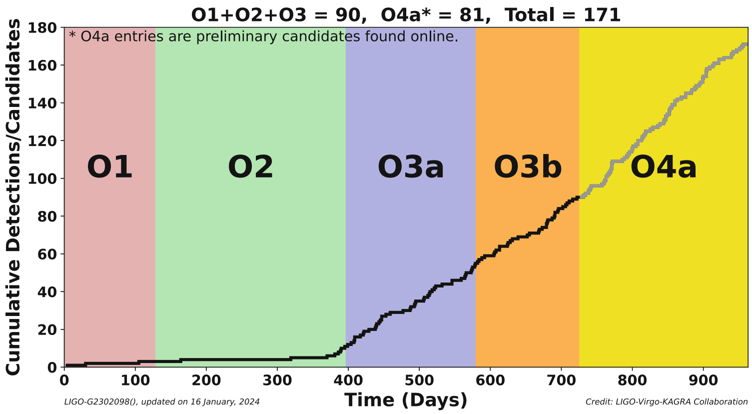

Fig. 2 GW detections published by the LVK from the O1–O3 runs [20, 24] and O4a candidates up to 2024-01-16, released to the public via gracedb.ligo.org. ©2024, the LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration

in October 2023, there were 55 significant candidates from O4a; and by the time of the final version of this proceedings papers in June 2024, the number from O4a+b had grown to over 100. CBC catalog updates from O4 and further search results for bursts, CWs, stochastic backgrounds, etc. will be published by the LVK in due course, and O4 data will be made public via gwosc.org.

5 GWs, High-Energy Physics and New Physics

Of particular interest to the HEP community are the many avenues for exploring fundamental physics with GWs. These include the already mentioned tests of theories of gravity [16] and GWs as a new probe for cosmography [4, 19], the early Universe [33], and nuclear matter at extreme densities [8, 36]. LVK data can also be used to look for exotic compact objects [29], primordial BHs [32] and particulate dark matter—via indirect detection (GWs from annihilating boson clouds [28]) or direct detection of interactions with the detector hardware [18]. And multi-messenger astronomy [7] includes GWs and traditional photonic astronomy together with high-energy astroparticle observatories (gamma-ray, TeV and neutrino detectors). The HEP and GW communities also have notable overlap in data analysis techniques, computing infrastructure, instrumentation, the planning of large-scale facilities, as well as potential synergies in global community building and outreach strategies.

6 Conclusions

Through decades of work and with the expertise of a global community, GW astrophysics became reality. With 90 published detections from the first three observing runs and almost as many new candidates already from the ongoing O4 run, the LVK is obtaining unprecedented insights into the physics, populations and evolutionary history of compact objects in our Universe. Many other science targets are within reach as the global detector network is growing and continuing to improve its sensitivity, and future GW detectors will further push cosmic frontiers.

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