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RECENT FINDINGS IN GROUND-BASED GRAVITATIONAL-WAVE DETECTORS

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ABSTRACT. Gravitational-wave astronomy has started less than a decade ago and has already yielded a wealth of fundamental results in astronomy and fundamental physics. We present an overview of the most recent results obtained by the LIGO-Virgo-KAGRA collaboration focusing on how gravitational waves emitted by compact binary coalescences can be used to study the content of the Universe, the standard model of cosmology and test the foundations of general relativity.

1. INTRODUCTION

A century after their prediction by Albert Einstein in his theory of general relativity, gravitational waves have been directly detected for the first time in 2015 by the two Michelson interferometers that form the Laser Interferometer Gravitational-wave Observatory (LIGO). LIGO (Aasi et al., 2015) along with Virgo (Acernese et al., 2015) in Europe and KAGRA (Akutsu et al., 2021) in Japan form an international network of ground-based gravitational-wave detectors that operate jointly to observe the Universe. More precisely they detect in the Herz-kiloHerz regime space-time perturbation generated by the path of gravitational waves through the Earth. Those waves are emitted by the most compact objects, black holes and neutron stars at cosmological distances, and travel at the speed of light without perturbation by the interstellar medium providing unique information about the dynamics of the source and its environment. Many phenomena involving compact objects emit gravitational waves: this is particularly the case when the core of a massive star ending its life starts to collapse forming a neutron star or a black hole. This is also the case of binary systems of two compact objects that coalesce until the final plunge; the orbit shrinks because of the gravitational-wave radiation. The last seconds of these ultra relativistic phenomena are what has been observed so far by the network of gravitational-wave detectors.

As of spring 2024, LIGO and Virgo have observed more than one hundred compact binary mergers including mainly two binary black holes, but also few binary neutron stars and mixed systems black hole - neutron star. As any revolution in science, the observation of the gravitational-wave emission opens many new opportunities: it is a new way to study the content of the Universe and especially to better understand how stellar-mass and intermediate-mass black holes are formed. For the first time general relativity can be tested in strong-field regime. It is interesting to note that a large fraction of alternative theories of general relativity have been ruled out by the discovery of GW170817, the merger of two neutron stars whose prompt electromagnetic counterpart had been observed less than two seconds after by gamma-ray-burst detectors. Thanks to the great sensitivity of the gravitational-wave detectors sources can be detected at cosmological distances and their redshifted properties allow to probe the standard model of cosmology with, for instance, a measure of the Hubble constant. Finally, gravitational waves are also the direct probe to test inflationary theories, as waves emitted during the early times of the Universe travel without any perturbation and form nowadays a stochastic background of primordial gravitational waves. All this requires a network of detectors whose sensitivity is regularly improved. In the next sections we describe the current status of the network, describe the most interesting features of the latest

catalog of gravitational-wave sources released by the LIGO-Virgo-KAGRA collaboration (LVK) and comment on the main results obtained in gravitational-wave astronomy.

2. THE NETWORK OF GRAVITATIONAL-WAVE DETECTORS

The network of ground-based gravitational-wave detectors is formed of two LIGO antennas in the USA, one in Washington State and the other one in Louisiana, the Virgo antenna in Italy and the KAGRA antenna in Japan. With arm lengths of 3 km for Virgo and KAGRA, and 4 km for LIGO, these detectors can measure a relative displacement of the interferometers' arm lengths of 10^{-18} m or smaller. We briefly describe the properties of these Michelson interferometers that can measure disturbances of spacetime created by merging binary neutron star and black holes systems millions to billions of light-years away.

Gravitational waves produce a transverse force on massive objects, a tidal force. Explained via general relativity it is more accurate to say that gravitational waves will deform the fabric of spacetime. Let us imagine a linearly polarized gravitational wave propagating in the z-direction, the fabric of space is stretched due to the strain created by the gravitational wave, but the distortion is not identical in all direction: while during half a period of the wave space is stretched out in one direction, it is squeezed in the orthogonal direction such that if one considers the arms of a Michelson interferometer, their length would be modified in a differential way such that the path of a gravitational wave would be detected as a small phase difference between the light in the two arms. The arms' length difference is directly proportional to the amplitude of the signal that scales inversely with the distance to the source. Because interferometers are sensitive to the amplitude of the signal (and not the square as for the electromagnetic emission), they can detect sources rather far away and an increase of sensitivity by a factor n multiplies the number of sources by a factor n^3 .

The current generation of gravitational-wave detectors (named Advanced LIGO, Advanced Virgo and KAGRA) include many features to enhance by many orders of magnitude their sensitivity. First, additional semi-transparent mirrors at the entrance of the arms form Fabry Perot cavities that increase the effective path of the light in the two arms before it gets recombined. With stabilized high-power lasers the interferometer can measure smaller distance displacements and achieve better sensitivity at high frequency. Furthermore more light circulating in the interferometer is possible by adding a mirror at the entrance of the interferometer to recycle the laser power. The interferometer operates such that virtually none of the light exits the interferometer dark port, and the bulk of the light returns towards the laser. However, currently the detectors are not operating with maximal laser power (~ 200 W) because of thermal effects in the optics, but in the current configuration several hundreds of kW are circulating in the Fabry Perot cavities. Figure 1 displays the optical layout of one LIGO detector.

There is one additional modification to the Michelson interferometer that further improves the sensitivity, by enlarging the frequency band range, thanks to another mirror between the beam-splitter and the detection photodiodes forming another Fabry-Perot cavity. This mirror allows the laser beam to acquire additional phase as it sends the light of one arm that contracts to the other one that is expanded. As this process is repeating over and over, signal recycling gives a substantial boost to interferometer sensitivity in a particular range of frequencies, and is implemented in all the main ground based interferometric detectors.

The large number of photons, whose arrival times are random (Poisson statistics) induce large radiation reaction noise (random motion due to transfer of momentum from the photons to the test mass). The low-frequency radiation reaction noise, plus the high frequency shot noise, combine to create the total quantum noise. At high frequencies the shot noise decreases with laser power, while at low frequencies radiation reaction noise increases with the power. One way to reduce quantum noise is to inject quantum states of the light in the interferometer. Squeezed light is a type of

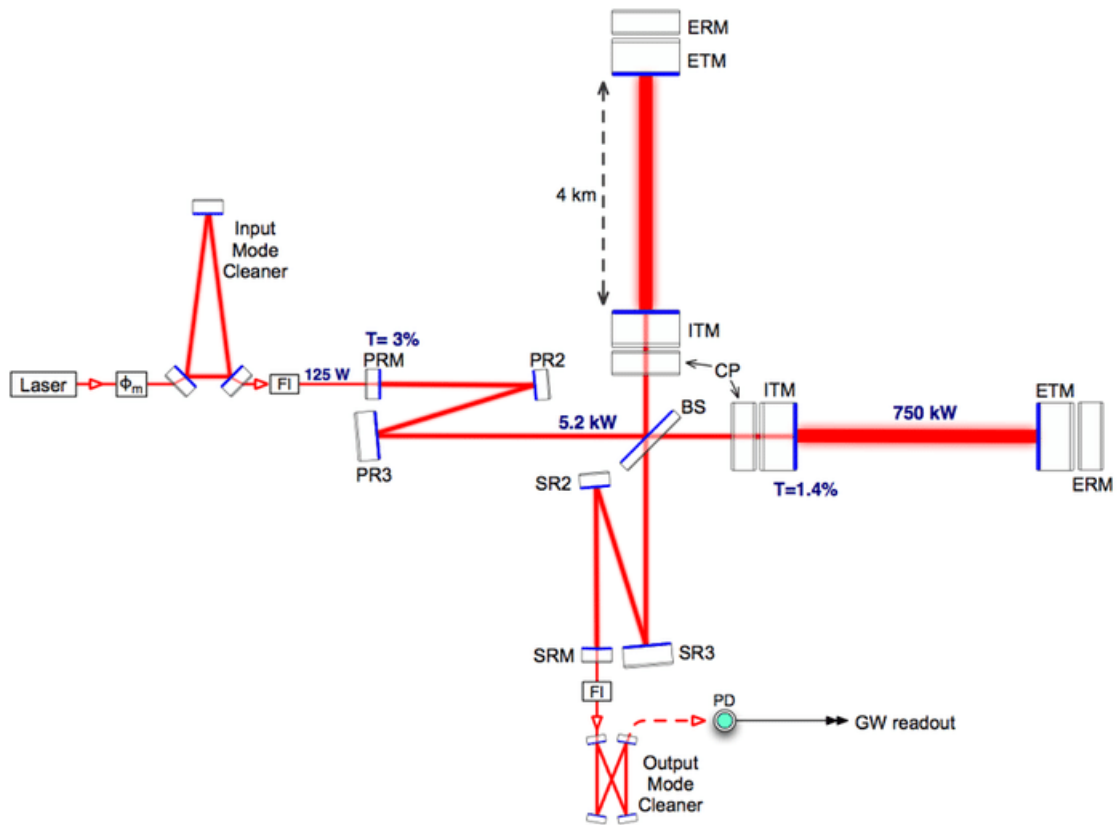


Figure 1: The Advanced LIGO optical layout. Figure from Aasi et al., 2015.

light in which the quantum fluctuations in one of the light's properties, such as its amplitude or phase, are reduced below the standard quantum limit. This reduction of noise was implemented by Advanced LIGO where squeezed light reduced the noise below the shot noise level for frequencies above 50 Hz by as much as 3 dB; Advanced Virgo has also achieved similar results. Advanced LIGO and Advanced Virgo are presently using a method called frequency dependent squeezing to reduce both the shot noise at high frequencies, and the radiation reaction noise at low frequencies. The use of quantum states of light is one of the ways that LIGO, Virgo and KAGRA plan to reduce their noise in the years to come. The other fundamental limiting noise comes from thermal motion of atoms in material that is at room temperature in LIGO and Virgo. The two main thermal noise sources are the wires suspending the mirrors in the last stage of the suspension, and the mirrors themselves, especially the coating material on the mirror surfaces. To reduce the thermal noise, two main ways are investigated: KAGRA sapphire test masses are enclosed into cryostat and cooled down at 20 K. LIGO and Virgo test masses are at room temperature but thermal noise in the wires is reduced by the use of fused silica and better mirror coatings that are in development.

Since 2015, the network of advanced detectors is jointly planning observation with periods for upgrading the detectors to improve their sensitivity as illustrated in Figure 2. During observing runs, data recorded at each observatory are transferred within few a seconds latency to a few computing

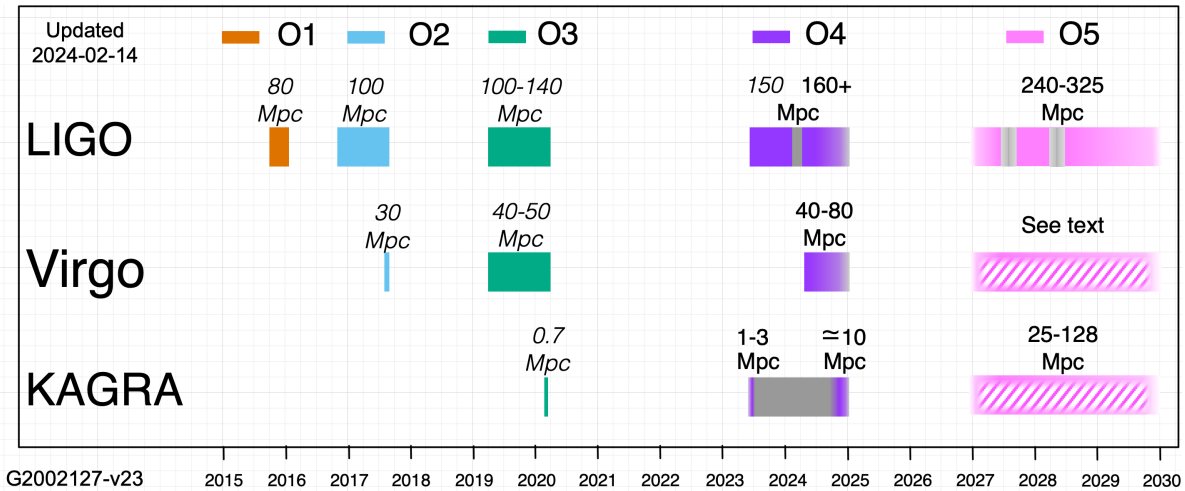


Figure 2: Observing plans of the network of gravitational-wave detectors LIGO, Virgo and KAGRA since 2015. The Virgo detector sensitivity for the fifth observing run O5 is not yet released. Figure from The LIGO-Virgo-KAGRA collaboration, 2024.

centers as they need to be coherently analyzed. Several pipelines are searching for compact binary coalescence of binary black holes, binary neutron stars and mixed systems as well as any coherent short duration (up to few seconds) transient signals. Gravitational-wave sources are detected and public alerts are generated and published over the Global Coordinate Network system with a latency of a few tens of seconds. These alerts provide information about the nature of the source, the probability the event could be due to noise, its most likely 3D location and some indication about a possible electromagnetic counterpart. This latter information is important for the follow-up by world-wide large instruments that search for an electromagnetic counterpart to a gravitational-wave signal, such as GW170817 (Abbott et al., 2017a), the first binary neutron star discovered thanks to its gravitational-wave emission as well as the prompt gamma emission that quickly followed. The afterglow emission of the kilonova has been detected 11 hours after by 1–m class telescopes (Abbott et al., 2017b).

The next important step are the offline searches that target not only transient gravitational-wave signals but also gravitational-wave continuous signals from isolated neutron stars and the stochastic gravitational-wave background resulting from the built-up of all gravitational-wave emission. These searches benefit from improved background rejection (many artefacts are present in the data) and better data calibration. Their sensitivity is improved compared to the low-latency signal detection searches and more refined information about the source parameters are determined.

For well modeled signals such compact binary coalescence all source parameters are estimated using Bayesian inference methods (Christensen and Meyer, 2022). This includes the individual masses and spins, the sky position, the luminosity distance, the polarization and inclination angles, the time and phase of coalescence. For non-compact binary sources, waveform reconstruction assuming generic waveform models is performed (Cornish and Littenberg, 2015).

The proprieties of all the gravitational-wave sources that are considered confidently detected are reported in a catalogue of gravitational-wave sources. The catalogue is regularly updated as explained in the next section. Because gravitational-wave detectors' improvements are challenging, it happens that not all four detectors of the network are observing during official observation runs. This has been for instance the case for KAGRA which joined the third observing run (O3) after LIGO and Virgo had to shutdown earlier than foreseen because of the pandemic in 2020. This is also the case of Virgo that could not join the first part of the fourth observation run (O4) because

its sensitivity and stability were not good enough compared to the LIGO detectors. Despite the fact that the accuracy of the source parameters estimation increases with the number of observing antennas (this is especially the case of the source sky localization), it is possible to detect confidently sources with one or two detectors.

2. THE GWTC-3 CATALOGUE

The third Gravitational-Wave Transient Catalog (GWTC-3) describes sources detected with Advanced LIGO and Advanced Virgo up to the end of their third observing run (O3). It includes all events from previous released catalogs (Abbott et al., 2023a). In total GWTC-3 contains 90 confident detections among which 35 new compact binary coalescences observed during the second half of O3 run between November 2019 and March 2020 by at least one search algorithms with a probability of astrophysical origin $p_{astro} > 0.5$. Of these, 18 were previously reported as low-latency public alerts, and 17 were found offline.

2.1 Population studies

Based upon estimates for the component masses, all sources are consistent with gravitational-wave signals from binary black holes or neutron star–black hole binaries, and none from binary neutron stars, which means that GW170817 and GW190425 are the only identified binary neutron stars mergers. The range of inferred component masses is similar to that found with previous catalogs, but the new candidates include the first confident observations of neutron star–black hole binaries GW200125 and GW200115. Overall, the number of detected events scales with the detectors’ network sensitivity increase and the observation duration: 3 detections during the first observing run (O1), 11 in GWTC-1 catalogue after the second observing run (O2), 55 in GWTC-2.1 after the end of the first part of O3 and finally 90 at the end of O3. Some of the source parameters are accurately estimated; this is the case for the chirp mass ($\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$ where m_1 and m_2 are the primary and secondary component mass). This is not the case for the individual spins which have often very wide posterior distributions. What is slightly better measured is χ_{eff} the mass-weighted spin projections onto the orbital angular momentum and the precession spin χ_p that quantifies the orbital precession of the binary. The chirp mass as function of the effective spin of the binary is given in Figure 3. Among the sources in GWTC-3, few have interesting features:

- GW190425 is likely the result of the merger of two neutron stars with components masses of $\sim 1.7 M_\odot$ and $\sim 1.5 M_\odot$ (Abbott et al., 2020a). Contrary to GW170817 no electromagnetic counterpart has been observed for this event. The prompt gamma-ray emission is collimated and only a small fraction of gamma-ray burst are detected. The isotropic afterglow emission has been missed because of the distance (156 Mpc) and the poor sky localization (8200 deg^2). This event was observed by only one LIGO detector. This shows the difficulty of multi-messenger astronomy and the importance of having a network of several detectors observing at the same time. One noteworthy aspect of GW190425 is the high mass of the resulting object after the neutron star merger. The total mass of the system is $\sim 3.4 M_\odot$, making the remnant object more massive than most known neutron stars.
- GW190814 components mass ($\sim 23.3 M_\odot$ and $\sim 2.6 M_\odot$) makes the system the most unequal mass ratio yet measured with gravitational waves and its secondary component is either the lightest black hole or the heaviest neutron star ever discovered in a double compact-object system (Abbott et al., 2020b). It might also be the first observed merger of a black hole with a neutron star.
- GW190521 is the most massive binary black hole merger ever observed with a gravitational-wave signal consistent with the merger of two black holes with masses of $\sim 85 M_\odot$ and

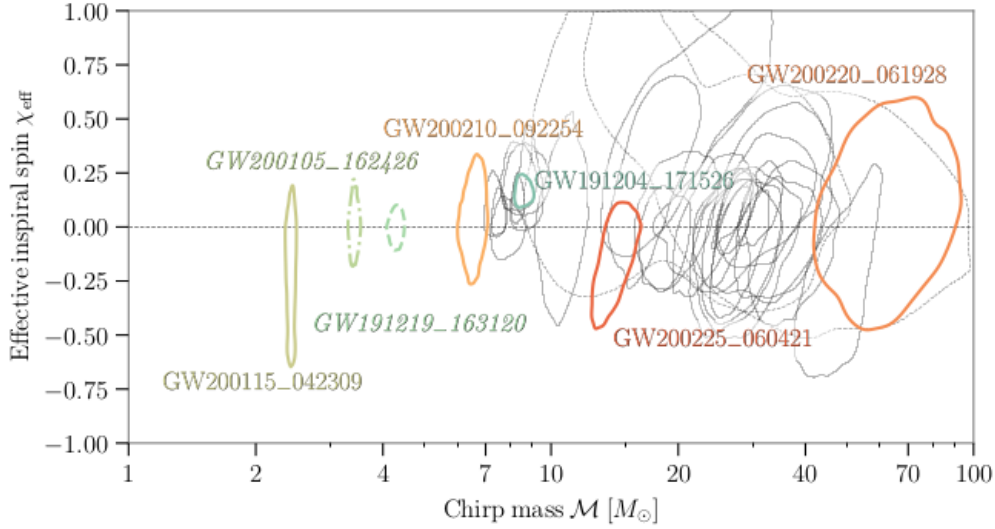


Figure 3: Credible-region contours (90%) in the plane of chirp mass \mathcal{M} and effective spin χ_{eff} for the 35 newest candidates of the GWTC-3 catalog. Figure from Abbott et al., 2023a.

$\sim 66 M_{\odot}$ at 90 % confidence level (Abbott et al., 2020c). What makes it very particular is the fact that the primary black hole mass lies within the gap produced by pulsational pair-instability supernova processes (PPIS), and has only a 0.3% probability of being below $65 M_{\odot}$ which is the lower bound of the PPIS mass gap. The remnant object with a mass of $\sim 142 M_{\odot}$ can be considered an intermediate mass black hole, the first evidence of their existence.

- Two neutron star - black hole mergers have been reported in GWTC-3. The source of GW200105 has component masses $\sim 8.9 M_{\odot}$ and $\sim 1.9 M_{\odot}$, whereas the source of GW200115 has component masses $\sim 5.7 M_{\odot}$ and $\sim 1.5 M_{\odot}$. Despite their large value, the secondary's mass is below the maximal mass of a neutron star with a high probability. After many binary black hole mergers, GW170817 and GW190425, the first observation of mixed systems completes the family of compact object binary systems (Abbott et al., 2021).

GW190814, GW190425 and few others events seem to indicate that the hypothetical mass gap between the heaviest neutron stars ($\sim 2.5 M_{\odot}$) and the lightest black holes ($\sim 5 M_{\odot}$ due to matter fallback accretion onto the newborn black hole) does not exist when all factors such as star's initial mass, rotation, and metallicity are considered (de Sá, 2022). With GW190521 and few other massive mergers, gravitational-wave observation seem also to indicate that the other mass gap between ~ 65 and $\sim 130 M_{\odot}$ is maybe populated by few massive black holes. However GW190521 itself has not permit to conclude if the primary component is the remnant of the collapse of a massive star at the end of its life or the result of a merger of two lighter black holes. In the latter case, this would mean that we have observed the merger of second generation black holes, the first hints of the hierarchical merger process that is privileged to explain how intermediate and super-massive black holes are created. A precise measurement of the component spins would help to estimate the fraction of mergers that are formed from an isolated system of massive stars that overcome a collapse into a black hole. For these systems one expects that the components have aligned their spin. In the case of a dynamical binary black hole formation in dense environment one could expect misaligned spins and thus orbits with precession. The large majority of GWTC-3 mergers do not show any precession. GW200129 is the only merger for which the spin component

in the orbital plane χ_p is not null at 90% confidence level.

The merger rate of the three families of binary systems is more and more precisely measured and the population of binary black hole merger shows that the rate as function of the redshift follows roughly the star formation rate redshift dependence. The primary component mass distribution of the GWTC-3 population is displayed in Figure 4.

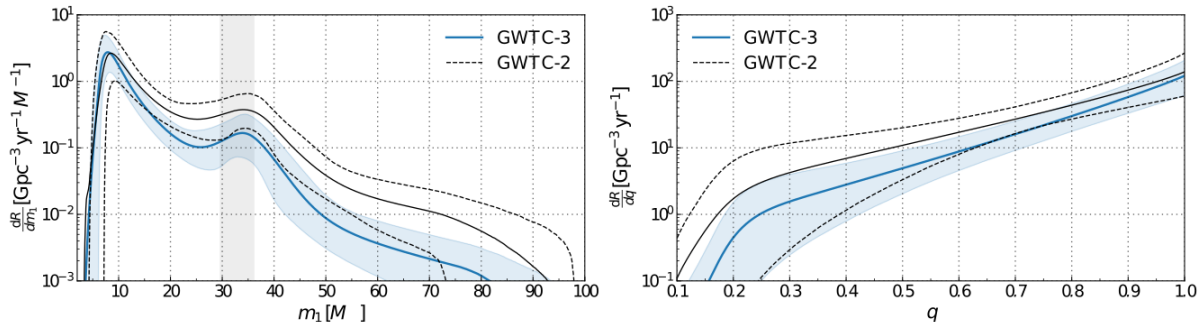


Figure 4: Merger rate as function of primary mass (left) or mass ratio (right) obtained from the GWTC-3 catalog. The solid blue curve shows the posterior population distribution with the shaded region showing the 90% credible interval. The black solid and dashed lines corresponds to the GWTC-2 catalog. Figure from Abbott et al., 2023b.

2.2 Cosmology with gravitational waves

The Hubble constant (H_0) represents the current rate of expansion of the Universe. Gravitational waves can provide a unique and independent way to measure the Hubble constant. The approach involves using standard sirens, which are astrophysical events that emit both gravitational waves and electromagnetic radiation, such as binary neutron star mergers or binary black hole mergers.

Gravitational-wave observations of the merger of two compact objects provide an estimate of the mass and spins of the binary component as well as the luminosity distance to the source. When the compact binary involves a neutron star, electromagnetic radiation, such as gamma-ray burst followed by a kilonova, is emitted. The joint detection of gravitational waves and electromagnetic signals allows for a more precise determination of the source's location in the sky. This helps to determine with small/medium field of view telescopes the host galaxy. Spectrometer measurements can then determine the redshift of the host galaxy. By combining the distance to the source, the redshift, and the speed of light, one can calculate the Hubble constant using the Hubble law: $H_0 = v/d$, where H_0 is the Hubble constant, v is the velocity (determined from the redshift), and d is the distance. This standard sirens method has been used to estimate the Hubble constant with gravitational-wave measurements of GW170817 ($70.0^{+12.0}_{-8.0}$ $\text{kms}^{-1}\text{Mpc}^{-1}$) (Abbott et al., 2017c). Besides, an accurate measurement of the Hubble constant from standard siren GW cosmology also requires a robust peculiar velocity correction of the redshift of the host galaxy. For sources without an electromagnetic counterpart, such as binary black hole mergers (dark standard sirens), alternative techniques to infer the source redshift are considered (Abbott et al., 2023c): the first method include comparing the redshifted mass distribution to an astrophysically-motivated source mass distribution to extract the redshift. The second method associates each binary black hole merger with its probable host galaxy in the catalog GLADE+, statistically marginalizing over the redshifts of each event's potential hosts. Both methods have shortcomings and are impacted by assumptions either about the binary black hole source mass distribution or are affected by the rather large error box in the sky of the source location. This makes most of the binary black hole

sources, except the well-located source GW190814, rather uninformative about H_0 .

Using gravitational waves to measure the Hubble constant with standard sirens or the dark sirens (binary black hole mergers) provides a direct and independent method that complements other cosmological measurements. This approach is not affected by the same systematic uncertainties as some traditional methods (e.g., those based on the cosmic microwave background or type Ia supernova), making it valuable for improving the precision of our understanding of the current expansion rate of the Universe. The comparison of the different methods is given in Figure 5.

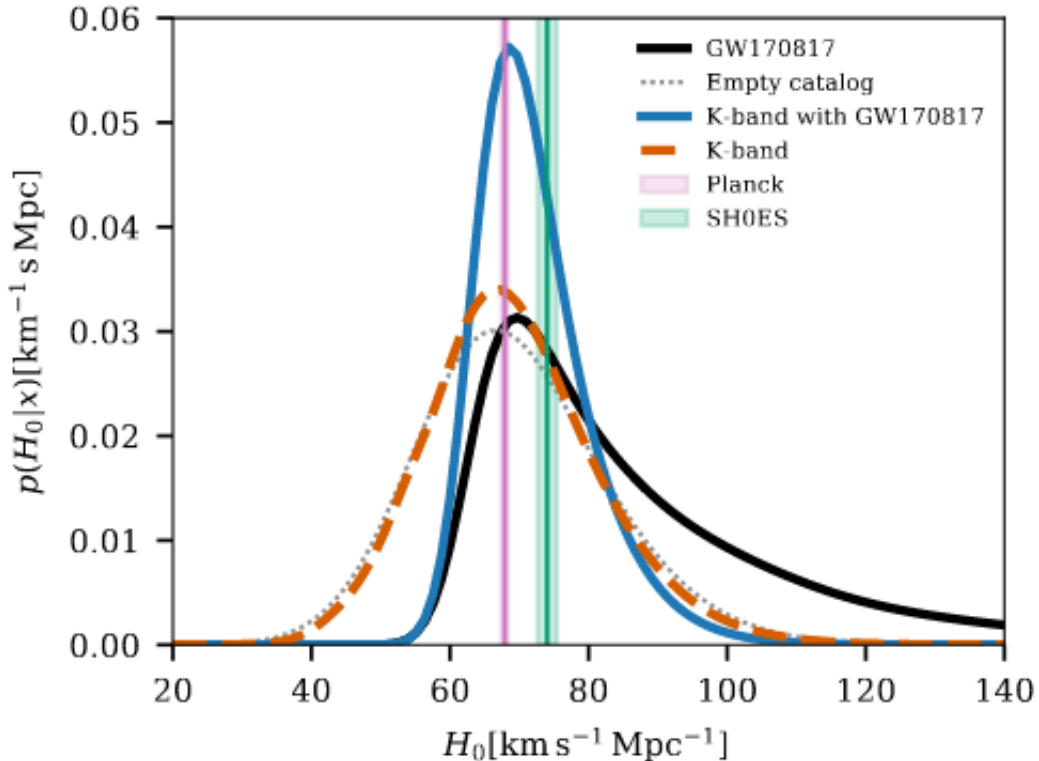


Figure 5: Hubble constant posterior for several cases: posterior obtained using all dark sirens without any galaxy catalog information and fixing the BBH population model (gray dotted line), posterior using all dark sirens with GLADE+ K-band galaxy catalog information and fixed population assumptions (orange dotted line). Posterior using GW170817 (black line). In blue, posterior combining all previous posteriors. The pink and green shaded areas identify the 68% confidence interval constraints on H_0 inferred from the CMB anisotropies and in the local Universe from type Ia supernovae. Figure from Abbott et al., 2023c.

2.3 Testing general relativity

As already mentioned, gravitational-wave observations provide a unique opportunity to test and confirm various aspects of the theory of general relativity under extreme conditions. Some of the main tests of general relativity facilitated by gravitational waves include:

- **Waveform Consistency:** One of the primary tests involves comparing the observed gravitational waveforms with the predictions of general relativity. Any deviations in the waveform could indicate the presence of alternative theories of gravity or additional phenomena not accounted for in general relativity.

- Speed of Gravitational Waves: general relativity predicts that gravitational waves propagate at the speed of light. By precisely measuring the arrival times of gravitational waves at different detectors, scientists can test this prediction and constrain potential deviations from the speed of light.
- Polarization of gravitational waves: gravitational waves can have different polarizations, and the patterns of these polarizations are dictated by general relativity. Observations of gravitational-wave polarization can provide additional confirmation of the theory.
- Mass and spin measurements: gravitational-wave signals from binary black hole or neutron star mergers contain information about the masses and spins of the involved objects. Comparing these measurements with the predictions of general relativity allows to test the theory in strong-field environments.
- No-hair theorem: The no-hair theorem in general relativity suggests that the observable properties of a black hole are determined solely by its mass, its spin and its charge. Gravitational-wave observations help test and confirm this theorem by providing precise measurements of the events' properties.

By subjecting general relativity to tests in environments with strong gravitational fields and dynamics, gravitational-wave astronomy contributes to the understanding of gravity and provides an opportunity to discover potential deviations from Einstein's theory. So far, the observations have been consistent with general relativity (Abbott et al., 2023d).

3. CONCLUSION

Gravitational-wave detections have provided valuable insights into the population of black holes, revealing information about their masses, spins, and the nature of their mergers. Many observations have already changed our description of the content of the Universe. Gravitational-wave observations have helped establish a mass spectrum for black holes. Prior to these detections, the masses of stellar-mass black holes were only indirectly inferred. We now know the mass spectrum is more complex and there might be a continuum between neutron star and the lightest black hole as well as no mass gap between 65 and 130 M_{\odot} . Gravitational-wave signals also carry information about the spins of the merging black holes. The analysis of these spins provides insights into the formation and evolution of binary systems, as well as the dynamics of massive stellar collapse. Gravitational-wave events have provided constraints on the possible formation scenarios for binary black hole systems. For example, they have contributed to our understanding of the role of common envelope evolution, metallicity, the stability of massive binary systems, and the importance of dynamical interactions in dense stellar environments. Gravitational-wave observations have implications for cosmology, as they provide a new tool for measuring distances to merging black hole systems and testing the expansion of the Universe. Finally they are a unique probe to test general relativity in a strong field regime.

So far only compact binary mergers have been detected. Yet, other sources of gravitational waves are possible: core collapse supernovae, pulsars, neutron star binary systems, newly formed black holes, or even early Universe inflation. The observation of these types of events would be extremely significant for contributing to knowledge in astrophysics and cosmology. Gravitational waves from the Big Bang would provide unique information of the Universe at its earliest moments. Observations of core-collapse supernovae will yield a gravitational snapshot of these extreme cataclysmic events. Pulsars are neutron stars that can spin on their axes at frequencies up to hundreds of herz, and the signals (due to a slight non-spherical shape) from these objects will help to decipher their characteristics and aid in studying ultra-dense nuclear matter.

To continue observing new sources of gravitational waves we need a performant network of detectors. Increasing the sensitivity of ground based detectors turns out to be extremely challenging. It is expected that the LIGO-Virgo-KAGRA network be joined by another detector in India before the end of the decade. In the longer term, the space-mission LISA, whose launch is planned in 2035, will complement ground-based gravitational-wave detectors in the milliHertz regime.

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