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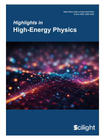

Review

The Age of Gravitational Wave Astronomy

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How To Cite: Marion, F. The Age of Gravitational Wave Astronomy. *Highlights in High-Energy Physics* **2025**, *1*(1), 10. https://doi.org/10.53941/hihep.2025.100010.

Received: 5 April 2025
Revised: 6 May 2025
Accepted: 12 June 2025
Published: 30 June 2025

Abstract: Detecting gravitational waves has been a very long experimental quest, which came to fruition with the second generation of the LIGO and Virgo ground-based interferometric detectors. These groundbreaking instruments have opened a new window on the Universe, revealing cataclysmic astrophysical events. They are spearheading a large-scale endeavor to explore the gravitational-wave spectrum at all frequencies, with rich science cases linked to fundamental physics, astrophysics, cosmology and the physics of the early Universe.

Keywords: gravitational waves; LIGO; Virgo; gravitational-wave astronomy; multi-messenger astronomy

1. Introduction

It feels very appropriate that a conference on the rise of particle physics, taking place at La Sapienza University in Rome, also covered the topics of gravitational waves, as La Sapienza was the home university of Edoardo Amaldi, one of the pioneers of the field. High-energy physics studies the fundamental particles and forces at play in Nature. Gravitation is one of the latter and holds a special place, being weaker than the other interactions by dozens of orders of magnitude and being described by a theoretical framework—Einstein's theory of general relativity—that has no overlap with the quantum field theory modelling the other forces. Although gravitation plays a negligible role when studying particles, due to its extreme weakness, it does play a major role in shaping the distribution of matter in the Universe. It is also intertwined with two major mysteries in modern physics, dark matter and dark energy. This explains why particle physicists make a strong part of the gravitational-wave community, along with astrophysicists, cosmologists and instrumentalists.

General relativity describes gravitation as a geometrical property of a dynamical space-time, summarized in the words of American physicist John Wheeler as "space tells matter how to move and matter tells space how to curve". The dynamics of space-time allows for the possibility of gravitational waves, i.e. ripples in space-time curvature that propagate through space at the speed of light, with their amplitude decreasing with distance. They are transverse waves, their physical effects manifesting in a plane perpendicular to their direction of propagation, where space is elongated and contracted along two orthogonal axes. They can have two independent polarization states, differing by an angle of 45° between their reference axes. Physically their effect is a strain, i.e. their amplitude h corresponds to a rate of elongation or contraction. The longer the distance L between free-floating objects, the larger the distance variation δL induced by gravitational waves ($h = 2\,\delta L/L$), which leads to the need for long-baseline detectors.

Gravitational waves are generated through mass acceleration. High-luminosity emission requires compact and relativistic sources with some asymmetry, so that the mass quadrupole of the system varies strongly with time. These criteria are met in some astrophysical sources and a canonical gravitational-wave source is a system of two compact objects orbiting each other. Although gravitational waves can carry enormous energy, space is so rigid that the resulting strain is very small. The maximum strain experienced on Earth, from the most powerful astrophysical sources, is typically at the level of 10^{-21}, which has made experimental detection an extremely difficult task.

The sources of signals detected so far are indeed compact object binaries, involving stellar-mass black holes or neutron stars, believed to be the remnants of massive stars in both cases. As the compact objects orbit each other, the system emits gravitational waves, which carries energy away and drives the system to smaller and smaller orbits until the objects eventually merge. The associated gravitational-wave signal is very specific and is often referred to as a chirp, because both the frequency and amplitude increase with time until merger. This signature shows up as a typical pattern in a time-frequency plot of the measured strain, as illustrated in Figure 1.

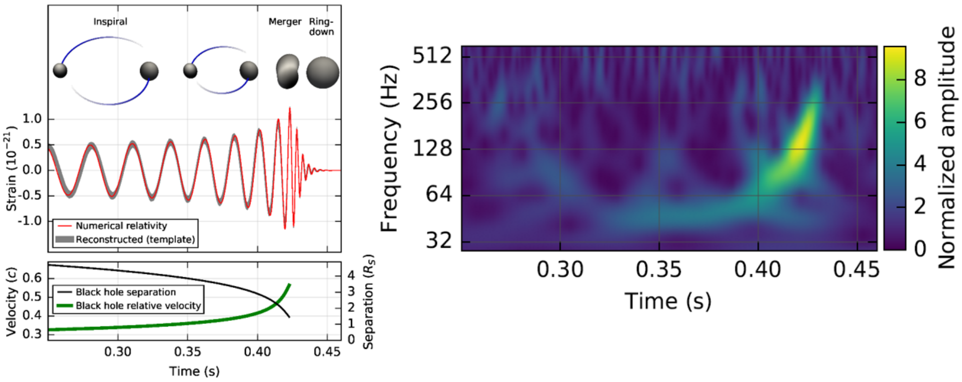

Figure 1. Left : Estimated gravitational-wave strain signal from GW150914 in LIGO Hanford and illustration of the system dynamics. **Right**: Time-frequency representation of the LIGO Livingston data at the time of the GW150914 event [1].

A key feature of the chirp is that the characteristic frequency at merger decreases as the total mass of the system increases and also as the cosmological distance to the source increases (the expansion of the Universe shifting the signal to lower frequencies, similarly to light being redshifted). Ground-based detectors operate at frequencies that make them sensitive to the mergers of neutron stars or stellar-mass black holes (weighing up to a few tens of the mass of the Sun). Sensitivity at lower frequencies is required to capture similar systems at an earlier stage of their evolution (long before merger), to capture systems at much larger distances or to capture much heavier systems involving super-massive black holes. The latter, weighing millions or billions of solar masses, are believed to be present at the center of most galaxies and can emit low-frequency gravitational waves if they are in close binaries.

Overall, gravitational waves are expected to manifest over a broad spectrum covering many orders of magnitude in wavelength and frequency (see Figure 2). Different frequency ranges have different detection techniques. Ground-based interferometers cover the band around 100 Hz. Space interferometry will cover the band around 1 mHz, while pulsar timing arrays cover the low-frequency range at the nHz level, and gravitational waves with periods comparable to the age of the Universe are expected to leave a subtle imprint on the polarization of the cosmic microwave background. The various frequency bands include specific astrophysical sources, with several cases of interest beyond compact binaries. Another speculative but fascinating prospect is the possibility to detect gravitational waves emitted in the very early Universe. There is a discovery potential at all frequencies, which is of great interest to high-energy physicists, the physics of the primordial Universe being largely unknown.

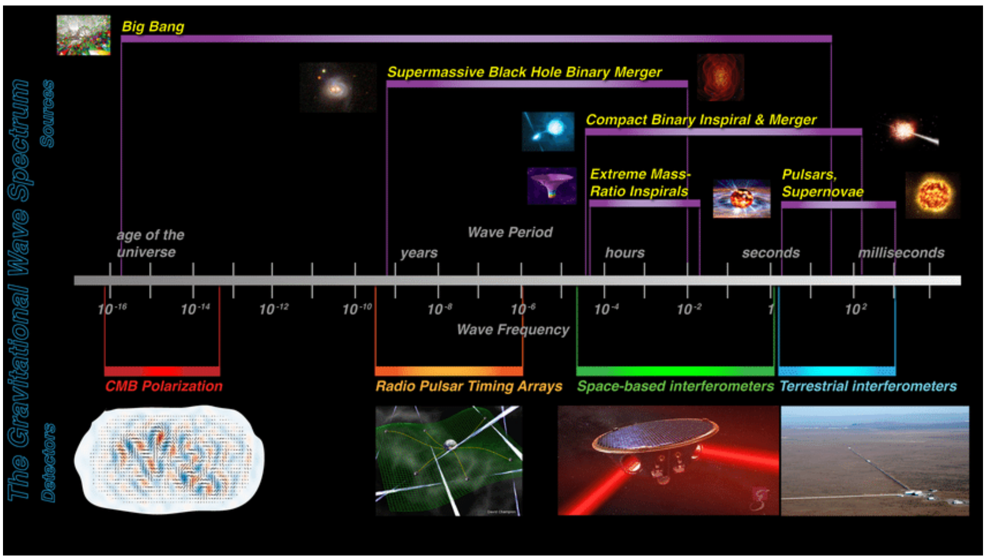

Figure 2. The gravitational-wave spectrum, highlighting detection techniques and various sources of interest. Figure courtesy of NASA/J. I. Thorpe.

2. Detecting Gravitational Waves

Einstein's theoretical prediction of gravitational waves dates back to 1916, but the experimental efforts toward detection only started in the 60', when Joe Weber built the first resonant-mass detectors in the US. Sophisticated versions of such detectors were developed and operated for several decades around the world. In the 70', interferometers were proposed as an alternative detection method, and Ray Weiss produced the first realistic study of an interferometric detector. The 80' brought observational confirmation of gravitational waves, through the orbital decay of the PSR 1913+16 binary, where a pulsar orbits another neutron star in a system losing energy in perfect agreement to general relativity's prediction based on gravitational-wave emission [2]. This confirmation prompted the design of large-scale interferometers—this was the beginning of the LIGO project in the US and of Virgo in Europe (the latter driven by Adalberto Giazotto and Alain Brillet). The 90' were decisive in that the funding agencies decided to build the first generation of LIGO and Virgo, initial detectors meant to evolve.

The first-generation detectors became operational in the noughties and demonstrated that it was possible to reach a level of sensitivity making gravitational-wave detection a possibility, even though they were not quite sensitive enough for a detection. They paved the way with the first science observations and the agreement of the various detectors to form a network, share their data and analyze them together. Success came in the following decade with the second-generation detectors, which had been upgraded to their so-called 'advanced' configurations. The discovery was made in 2015 with the two LIGO detectors and was celebrated by the 2017 Nobel Prize awarded to Barry Barish, Kip Thorne and Ray Weiss.

The past decade has been very successful—with the fields of gravitational-wave astronomy and multi-messenger astronomy on the rise—but in many ways, this is only the beginning. A new generation of interferometers is already being designed and other wavelengths are targeted as well, so that in the future it will be possible to observe the Universe in depth with gravitational waves, across a broad spectrum. There are currently four long-baseline, ground-based interferometric detectors around the world: the two LIGO detectors [3] in the US (at the Hanford and Livingston sites), Virgo [4] in Italy, and KAGRA [5] in Japan gearing up to join observations. The basic principle is that of a Michelson interferometer with suspended mirrors serving as test masses. As a gravitational wave passes through the plane of the interferometer, one arm gets longer as the other arm gets shorter and vice versa, which changes the interference pattern at the output port and modifies the output power in a measurable way. The principle is simple, but the target is to measure strains at the level of 10^{-21} at best. With arms that are 3 (in Virgo and KAGRA) or 4 (in LIGO) kilometers long, this translates into variations in the arm length at the level of 10^{-18} m, which is 12 orders of magnitude smaller than the laser wavelength of 1 μm. The change in the interference pattern is therefore tiny and extreme care is needed so that it is not buried in noise.

The optical configuration is actually more complex than that of a Michelson interferometer, with the addition of mirrors to form Fabry-Perot cavities in the arms, as well as power and signal recycling cavities (see Figure 3). The purpose of these cavities is to amplify the gravitational-wave signal and minimize sensing noise. On top of this, the detectors need a whole range of advanced technologies to reach good sensitivity. They need powerful and extremely stable laser sources, as well as high levels of vacuum to propagate the laser beams and host the mirrors. The mirrors themselves need to be near perfect, so that they can reflect the light beams thousands of times without disturbing them. They need to be seismically isolated, as typical ground motion is orders of magnitude larger than the 10^{-18} m target. They also need to be suspended in a way that minimizes thermal noise.

The most recent versions of LIGO and Virgo also implement sophisticated techniques to reduce quantum noise, which comes in two ways. Photons arrive in a random way on the photodetector, which results in power fluctuations—this is shot noise, which decreases with laser power. In addition, fluctuations of photons reflecting from a suspended mirror cause random mirror motion—this is radiation pressure noise, which increases with laser power. Both therefore cannot be reduced at the same time, unless a technique called frequency-dependent squeezing is employed.

LIGO, Virgo and KAGRA operate as a network, for several reasons. One of them is that when searching for rare and weak signals, redundancy helps discriminate signals from noise. The main reason however is that more than one detector is needed to infer where a signal is coming from. A given detector is not very directional but has instead a broad antenna pattern showing a modest dependence of the wave-detector coupling on the source direction (except for blind spots along the bisector of the interferometer arms). Therefore, locating a source on the sky requires comparing the signals received in different detectors, primarily in terms of their arrival times, and performing triangulation. This is crucial to get a chance to know the full astrophysical context of an event.

The performance of detectors is characterized by their sensitivity curves, which give the level of noise as a function of frequency, over a frequency band that goes roughly from 10 Hz to 10 kHz for ground-based interferometers. They result from a mixture of fundamental and environmental noise sources, as well as many technical noise sources. They are improved on iteratively, through commissioning work and upgrades to the detectors. The sensitivity curve can be compared to the expected spectrum of a signal to estimate the signal-to-noise (SNR) ratio. Using by convention the signal of a 1.4 + 1.4 $M_\odot$ binary neutron star (BNS) merger, the sensitivity curve can be summarized into a figure of merit called the BNS range, giving the typical distance where such a merger can be detected with an SNR of 8. This figure of merit has doubled over the past decade. The Advanced LIGO detectors started with a BNS range around 80 Mpc back in their first observing run (O1) in 2015. It is now around 160 Mpc. A factor 2 on the reach of the detectors means a factor 8 on the volume probed, and consequently on the rate of detections. The latter has indeed increased with sensitivity improvement, up to a level of a couple per week of observing time in the on-going fourth observing run (O4). The current tally of confirmed detections and detection candidates is approaching 300.

The detectors are currently in the third part of the O4 run and are preparing the upgrades coming next, in view of the O5 run. Beyond O5, there are plans for an "ultimate" set of upgrades, to improve the sensitivities to the limits imposed by the current infrastructures; these are the A$\sharp$ concept for LIGO and the Virgo_nEXT concept for Virgo. Pushing further will require a new generation of instruments, built in new infrastructures, which is the purpose of the Cosmic Explorer project in the US and the Einstein Telescope in Europe.

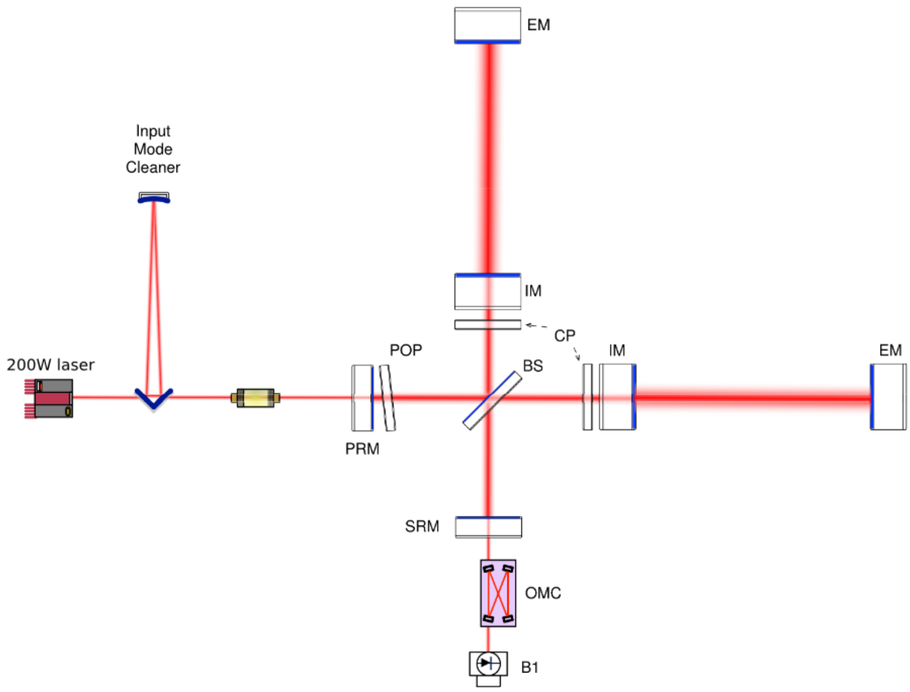

Figure 3. Simplified optical layout of the Advanced Virgo interferometer. Each of the long cavities in the arms is formed by an input mirror (IM) and an end mirror (EM). The recycling cavities are formed by the power-recycling mirror (PRM) or the signal-recycling mirror (SRM) and the two input mirrors [4].

3. Searching for Gravitational-Wave Signals

It is common practice in the LIGO-Virgo-KAGRA (LVK) collaboration to classify gravitational-wave sources both according to whether they produce transient or persistent signals and according to whether the expected waveform is known or not. Compact binary coalescences are not the only possible sources of transient signals, a category that also includes the generic class of "bursts", which are mostly unmodeled transients. On the persistent signal side, LVK data are searched for continuous waves from spinning neutron stars, and for gravitational-wave stochastic backgrounds produced by unresolved sources.

Compact binary coalescences are the only class of events detected to date. It is a prime case where the expected signal is known, as waveforms can be computed accurately, solving general relativity's equations both analytically and numerically. This allows using matched filtering, namely cross-correlating the data with the expected signal – called a template – giving different weights to different frequencies to take the sensitivity curve into account. The output of the matched filter will peak when the signal is indeed present in the data. The binary system parameters are not known a priori, though, which requires trying many templates to cover the parameter space of interest.

The case of generic transients, what we call bursts, is more difficult. They include many possible astrophysical events. A primary target is the gravitational-wave signal emitted during a core-collapse supernova, as it would be

https://doi.org/10.53941/hihep.2025.100010

a powerful tool to understand the dynamics of the collapse. Other targets include the post-merger signal after a binary coalescence, instabilities in neutron stars, or a signal associated with long Gamma-ray bursts. The signals are typically poorly modeled, which requires a robust search strategy. This involves looking—in the time-frequency space—for excess power that is coherent in multiple detectors, meaning that the signal amplitudes and phases are consistent with a single sky location.

A primary target for persistent signals is spinning neutron stars, which are expected to emit gravitational waves if they are not symmetric around their rotation axis. There are many neutron stars in our own Galaxy, and detecting such a signal would be a way to probe their structure. The strength of the signal depends on how elliptical the neutron star can be, which is unknown. The signal is likely to be very small, but it can be integrated over a long time to increase the SNR. It is a search that is computationally limited, though, as the signal needs to be tracked coherently, and although the signal itself is quasi-monochromatic, the time-varying Doppler shift arising from the motion of the Earth-based detector relative to the source needs to be taken into account. This amounts to scanning an enormous parameter space, which cannot be done in practice and requires trade-offs. A fully coherent search is possible if the target is a known pulsar where both the sky position and the signal frequency are known a priori, but a semi-coherent search is the way to go if conducting an all-sky search where no parameters are known a priori.

Stochastic gravitational-wave backgrounds can be of two kinds. Astrophysical backgrounds are expected to arise from the superposition of many unresolved sources; examples could be pulsars in our Galaxy or binary mergers too far away to be resolved. Their detection would complement individual source detection. Even more fascinating is the second kind, backgrounds arising from gravitational waves produced in the primordial Universe. The physics of the latter is largely unknown and there are various speculative models for gravitational waves generated during inflation, during phase transitions, by topological defects, etc. The mechanisms typically involve energy scales way beyond what can be reached in particle colliders, therefore offering a unique discovery potential. Stochastic backgrounds would basically show up in the data as extra noise, but noise that is correlated across detectors and shows a signature spectrum. The search method is similar to the matched filtering we use for compact binary coalescences, but using the data stream of one detector as a template for another detector.

4. Highlights of Gravitational-Wave Science

The hundreds of events detected so far have led to a rich variety of results. The science relies on measuring the source properties by analyzing the detailed features of the signal, which depends on the parameters of the system, both the intrinsic parameters that drive the dynamics, like the component masses and spins, and the extrinsic parameters, like distance and sky location. This parameter estimation is done through Bayesian analysis. Results are then derived in terms of astrophysics, fundamental physics or cosmology, based either on some individual events or on a statistical analysis of the sample of events.

With event names based on the date they were detected, GW150914 was the discovery event, detected on 14 September 2015 [1]. It was the merger of two black holes weighing about 30 solar masses ($M_\odot$) each, which was surprisingly heavier than the black holes previously known in our Galaxy. Though unique is that it was the first ever detected, the event later turned out to be quite typical. Our sample of detected events is indeed dominated by binary black hole mergers, most of them with roughly equal masses—asymmetric systems are rarer (see Figure 4).

GW170817 [6] was the first binary neutron star merger, a strong signal with a well-localized source, as it was one of the first events observed at a time when three detectors were online (LIGO Hanford, LIGO Livingston and Virgo). What made this event particularly remarkable is that it was immediately followed by a short Gamma-ray burst—a flash emitted by an outflow of relativistic particles—and was later followed by a kilonova, the light emitted by the matter ejected during the collision, which is a site of rapid nucleosynthesis, heated by radioactivity. For astrophysics, GW170817 therefore confirmed that BNS mergers are linked to short Gamma-ray bursts and to kilonovae, and that kilonovae are a site of heavy elements production. BNS mergers are also crucial for fundamental physics, as they are a laboratory to study the structure of matter at the extreme densities found in neutron stars. GW170817 and the almost simultaneous Gamma-ray burst confirmed to an excellent precision that gravitational waves and light propagate at the same speed. The event also illustrated the potential that BNS mergers have for cosmology, in measuring the current rate of expansion of the Universe.

GW190521 [7] is another remarkable event for several reasons; one being that its remnant—the black hole formed by the merger—has a mass close to 150 $M_\odot$, which falls in the intermediate-mass range between stellar-mass black holes and super-massive black holes. This is a range where hardly any black holes are known yet some are expected, if the lighter black holes are seeds to form the heavier ones.

Beyond the features of individual events, looking at the sample of detections [8] as a whole allows addressing a broad range of questions. It provides measurements of how often mergers occur and of the merger rate per binary type—mergers have now been observed from three types of systems: pairs of black holes, pairs of neutron stars, and mixed systems with a black hole and a neutron star. Moreover, as the sample keeps growing and includes sources at further distance, it becomes possible to study how the merger rate evolves with redshift and therefore with cosmic time.

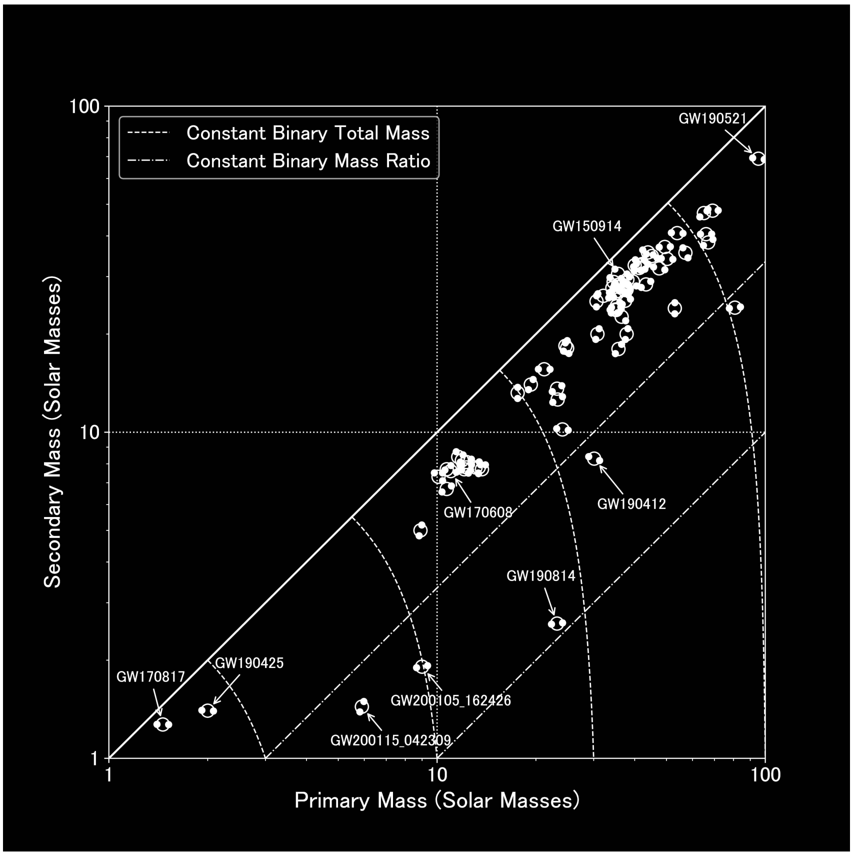

Figure 4. The sample of binary systems observed in the LIGO-Virgo O1, O2 and O3 observing runs and used to characterize the population of sources, shown in the component mass space. Figure courtesy of LIGO-Virgo-KAGRA Collaboration/IGFAE/Thomas Dent.

Inferring the mass distribution of the compact objects involved in merging binaries helps shed light on a number of astrophysical open questions: What is the maximum mass for neutron stars? What is the minimum mass for black holes born from stars? Is there a gap between the two? Although difficult, it is also interesting to measure how fast those compact objects are spinning, as this might be a key to understand not only their formation but also how the binaries themselves were formed, with two main scenarios: either the stars co-evolved in a pre-existing binary, or the binary was formed dynamically after the stars had become compact remnants.

An aspect that is of major interest to particle physicists is to understand how the strong nuclear force behaves in neutron stars, where matter reaches extreme densities, higher than in atomic nuclei, and the structure is unknown. Depending on their structure, neutron stars will be more or less deformable, leading to stronger or weaker tidal effects during the late inspiral of the binary. Tidal effects are expected to leave a subtle imprint on the gravitational-wave signal, which can only be constrained today but will be measurable in hundreds of events with the next generation of detectors. One can also explore if the compact objects involved in mergers are actually neutron stars or ordinary black holes, or if they could be exotic objects, and look for signatures of dark matter.

Another major application is cosmology, with the prospect of measuring the expansion rate of the Universe using compact binary coalescences as standard candles, i.e. the source distance can be inferred from the gravitational wave signal. The redshift cannot, but GW170817 gave a proof of concept that an electromagnetic counterpart can point to the host galaxy, whose redshift can be used to measure the Hubble constant. The measurement was only at the $\sim$15% level but the prospect of reaching a precise measurement is exciting, given that the main methods to measure the Hubble constant disagree with each other, creating tension in the standard model of cosmology.

Finally, gravitational waves are a unique tool to test general relativity. GW170817 has already provided tight constraints that gravitational waves and light not only travel at the same speed but also are affected by gravitational potentials in the same way. Still regarding the propagation of gravitational waves, one can look for signs of dispersion, i.e. different frequencies travelling at slightly different speeds. Thinking of gravitation in a framework similar to the other interactions, it would be mediated by a particle, called the graviton. Even though our detectors sense waves, not gravitons, the graviton mass can be constrained as a non-zero mass would result in dispersion in the signal. With no observational evidence for the latter, the mass of the hypothetical graviton is constrained to be less than 10^{-23} eV. One can test if gravitational-wave signals are consistent with two independent polarizations and, more generally, if the waveforms are consistent with general relativity predictions, in an extreme regime of space-time dynamics. An important test is to check if black holes behave as predicted by general relativity. Binary mergers leave behind a remnant black hole that reach the quiescent state by emitting a set of damped sinusoids, whose frequencies and damping times depend only on the black hole mass and spin, according to general relativity. Doing precise spectroscopy of those black hole ringdowns will allow testing this 'no-hair' prediction.

5. Outlook

In the future, gravitational-wave astronomy is going to evolve towards a multi-wavelength and multi-messenger landscape. As parts of the gravitational spectrum are opened or explored with improved sensitivity, new astrophysical sources will be revealed, and possibly gravitational-wave backgrounds of cosmological origin, which would be a major breakthrough.

On Earth, there are plans for a new generation of detectors, in new infrastructures that would provide baselines up to an order of magnitude longer. Europe has the Einstein Telescope project, designed as an underground triangle with 10 km sides, while the US have the Cosmic Explorer project, with one or two 40 km L-shaped detectors on the ground. The long baseline will make a major difference in the volume probed. Current detectors are only skimming the surface whereas future detectors will essentially probe the whole population of merging binaries, far into the past of the Universe, and will likely reveal novel types of gravitational-wave sources.

Current detectors are very sensitive and can measure very weak signals, but they do not measure them with high precision, as the recorded signal-to-noise ratio remains modest. SNRs will reach hundreds and thousands for nearby sources in Cosmic Explorer and Einstein Telescope, which will also provide a much larger sample of events and, with a bandwidth extended at low frequencies, more precise parameter estimation. The next generation will therefore bring us into the high-statistics, high-precision regime that has made the success of high-energy physics. Moreover, a sizeable subset of the sample will be multi-messenger events, which enable so much science.

Other observational windows are already opening at lower frequencies. Pulsar-timing arrays are like Galactic-scale detectors. Pulsars are excellent clocks, with their radio emission periodically received on Earth like a rotating lighthouse, with a stability at the level of ~ 100 ns for the most stable of them. With the Earth and pulsars in free fall, monitoring the arrival times of radio pulses is sensitive to perturbations in the metric due to gravitational waves passing through the Galaxy, which affect the arrival times from different pulsars in a correlated way. This is sensitive to frequencies around the nHz and allows probing a stochastic background of gravitational waves emitted by close binaries of super-massive black holes. The various pulsar-timing arrays in the US, Australia and Europe are indeed seeing growing evidence of such a signal in their data [9–12]. If confirmed, this will provide a new handle on the growth of massive black holes and the evolution of galaxies.

The frequency band around the mHz is expected to open in about a decade from now, when the LISA mission [13] of the European Space Agency (with contributions from NASA) will be launched. LISA will perform interferometry in space between three satellites separated by 2.5 million kilometers. The mission will probe a diversity of compact-object binaries: light systems long before they merge (revealing the population of binary stars in our Galaxy); massive black hole binaries as they merge, at all cosmic times; extreme-mass ratio inspirals, where a stellar-mass black-hole orbits a massive black hole (the complex gravitational-wave signal offering a map of space-time around the massive object).

With the detection of gravitational waves, a new field of physics is born, which relies on incredibly sensitive detectors. This age of gravitational-wave astronomy brings a wealth of science within reach, but fulfilling this potential will need a new generation of instruments. Plans exist but will also need a new generation of physicists to make them a reality. It is a must, as gravitational waves are a goldmine for a very broad community sitting at the crossroads of fundamental physics, cosmology and astrophysics.

Conflicts of Interest

The author declares no conflict of interest.

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