GRAVITATIONAL-WAVE ASTRONOMY: A CENTURY AFTER EINSTEIN, AND TEN YEARS AFTER THE FIRST DETECTION

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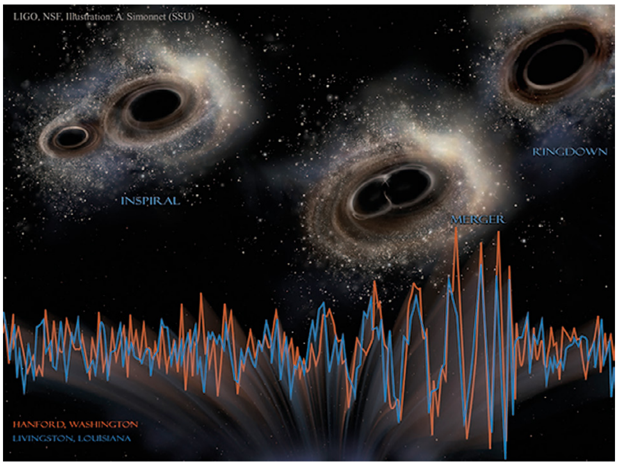

Since Einstein's 1916 prediction, gravitational-wave astronomy has evolved into a mature observational science. After early conceptual debates and bar-detector attempts, kilometer-scale laser interferometers LIGO achieved the first detection in 2015 (GW150914), opening a new window for astronomy and enabling new tests of general relativity.

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With Virgo joining in 2017, the LIGO and Virgo detectors and about 70 telescopes all around the world allowed the first multi-messenger event (GW170817), tightly constraining the speed of gravity, revealing r-process nucleosynthesis in a kilonova, and introducing "standard siren" cosmology. By September 2025 the network, including now also the Japanese KAGRA, has reported nearly 300 candidate gravitational-wave sources (more than 200 published), enabling population studies of black-hole masses and spins, evidences of intermediate-mass black holes, and mixed systems. Here we review the historical developments, key technological milestones, and science highlights.

On September 14, 2025, we have celebrated the tenth anniversary of the first detection of gravitational waves (the event called GW150914). Predicted by Albert Einstein in 1916 through the linearization of his general relativity field equations, these waves are oscillations of spacetime geometry that propagate at the speed of light and are emitted by the acceleration of asymmetric compact systems—such as a binary black hole system. Gravitational waves had a difficult beginning: Einstein himself, in his 1916 article, wrote that in all possible situations, their amplitude would be practically zero [1]. He was clearly aware of the challenge of deforming spacetime, a medium that is elastic yet extremely rigid, and even more, of making it vibrate. Of course, in 1916 the existence of compact objects like black holes and neutron stars was not yet known, and the idea of massive bodies like the Sun rotating near the speed of light with the density of atomic nuclei would have seemed like fantasy. In 1936, Einstein denied the existence of gravitational waves, unable to identify them as exact solutions to his equations. Fortunately, the article, written with Nathan Rosen, known for both the EPR paradox and the *Einstein–Rosen bridges*, was never published, since a reviewer identified an inconsistency. Shortly thereafter, Einstein and Rosen corrected the error and published a different conclusion [2]. Yet, a fundamental question remained: even if such waves exist mathematically, can they be detected? Do they possess a physical reality? Can they deposit energy in a detector? This dilemma persisted until 1957, at the famous Chapel Hill conference, where some of the leading researchers in relativity concluded that the passage of gravitational waves would indeed modify the distance between free-falling test masses, and that if these masses were coupled to a dissipative element, the passage of the wave would generate heat [3].

From Weber's bars to interferometry

At the beginning of the 1960s, the experimental quest began. The first attempt to detect gravitational waves was carried out by the American physicist Joseph Weber, who introduced resonant bars: metallic cylinders designed to oscillate at their resonant frequency when traversed by a gravitational wave. In 1969, Weber went as far as to claim the detection of several signals, which might have originated from galactic supernovae [4]. However, it soon became clear that the recorded signals were too intense to be attributed to gravitational waves. Despite this, Weber had the merit of launching

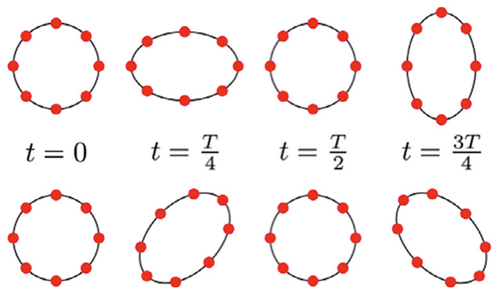
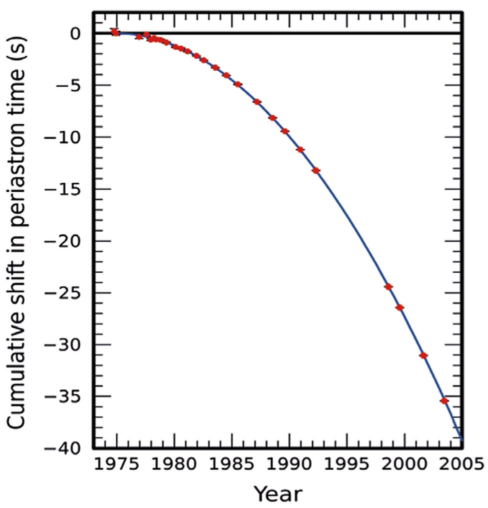


Figure 1. a system of freely falling masses when a gravitational-waves passes through the plan of the page.

the experimental efforts and introducing a fundamental idea: that of coincident detection using instruments separated by large distances, in order to exclude local noise sources, such as seismic activity, electrical glitches, or transient mechanical or electronic disturbances specific to individual instruments. During the same period, two Russian physicists, M. E. Gertsenshtein and V. I. Pustovoit, understood that the Michelson interferometer, the same instrument for which Albert Abraham Michelson received the Nobel Prize in 1907, had the right characteristics for detecting gravitational waves. In 1972, Rainer Weiss, a young physics professor at MIT in Boston, conducted a detailed analysis

Figure 2. Evidence of orbital decay of PSR B1913+16
Source : https://en.wikipedia.org/wiki/Hulse–Taylor_pulsar



of the noise sources limiting the sensitivity of such an instrument, and proposed a conceptual scheme for a gravitational-wave detector. This would become one of the foundational ideas that led to LIGO and Virgo. The document, about thirty pages long, was not formally published at the time, but remained an internal MIT report [5]. Also for this work, Weiss would later be awarded the Nobel Prize in Physics, together with Kip Thorne and Barry Barish, for their decisive contributions to LIGO. In parallel, neutron stars were being discovered in the form of pulsars, by Jocelyn Bell Burnell. At the same time, the first black hole candidates began to emerge from X-ray astronomy. The invention of the laser in 1960 opened the way for the first prototypes of laser interferometers. One of the earliest was developed by Robert Forward in Malibu: although its sensitivity was ten orders of magnitude worse than that of today's LIGO and Virgo, it represented a crucial first step toward interferometric detection of gravitational waves [6].

Binary pulsars and the proof of the gravitational-wave existence

In 1974, two American radio astronomers, Russell Hulse and Joseph Taylor, discovered the binary pulsar PSR B1913+16, a system composed of two compact objects, one of which is a pulsar. The presence of the pulsar - a highly precise cosmic clock - allowed for extremely accurate orbital measurements and made it possible to test general relativity in strong-field conditions. This discovery earned the two scientists the 1993 Nobel Prize in Physics. Observations of the system over several years showed that the orbital period was decreasing over time, in spectacular agreement with ●●●

the theoretical predictions of gravitational-wave emission. This provided the first confirmation of the existence of gravitational waves, as predicted by Einstein's theory [7].

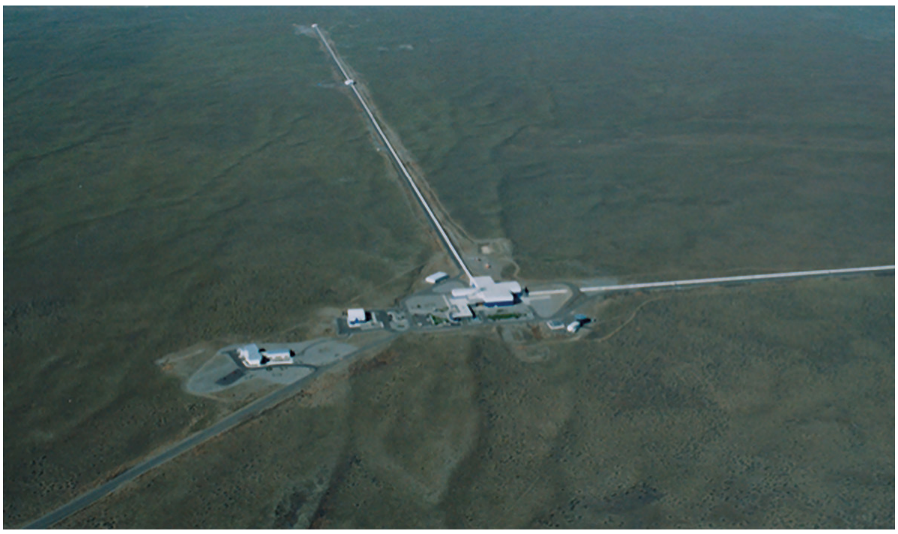
The birth of large interferometers

In the 1980s, large-scale projects were proposed: two detectors in the United States (to enable coincidence detection), which would become LIGO, and a third near Pisa (Italy), Virgo, the result of a Franco-Italian collaboration that has since grown into a broader European effort. Meanwhile, other experimental prototypes and key technological developments emerged: vibration isolation systems to isolate the test masses from the seismic noise and create an almost "free fall" condition in the frequency region of interest, improvements in lasers, mirror coatings and a deeper understanding of fundamental noise sources. Particular attention was devoted to quantum noise (including *squeezing*, following the early works of Carlton Caves in the 1980s [8] and Brownian thermal noise, studied by Peter Saulson [9] and others). France played a crucial role in several of these technological developments, especially in laser stabilization, mirror coatings, optical metrology, and interferometric simulations, contributions that remain essential today.

The commissioning and the "single machine"

At the beginning of the new millennium, LIGO and Virgo were "switched on", and the long and arduous *commissioning* phase began: the period between the end of detector integration and the start of scientific data-taking. The goal was to bring the detector into its operational regime and begin the systematic identification and mitigation of noise sources. Although theoretical models had driven the design of these instruments, their originality - and the extreme displacement sensitivity required, of the order of 10^{-18} meters - meant that several noise sources, their coupling mechanisms, and their mitigation strategy had to be studied experimentally and *in situ*. Furthermore, their target sensitivity lies in a frequency range around 100 Hz, a region relatively new for precision metrology, where a dense "forest" of noise sources, including environmental, technical, and control-related noise, makes detection even more challenging. The first-generation versions of LIGO and Virgo did not succeed in detecting gravitational waves. Around 2011, both detectors were upgraded to their second-generation configurations: *Advanced Virgo* and *Advanced LIGO* [10,11]. This meant replacing mirrors, lasers, suspending optical benches and improving vibration isolation. Meanwhile, an important political development had occurred: LIGO and Virgo had signed a data-sharing and joint-publication agreement. Since 2007, they have effectively operated as a single global observatory, a "single machine", capable of triangulating and localizing sources. In fact, unlike telescopes, LIGO and Virgo are non-directional: they observe the entire sky, continuously. In order to pinpoint a source, one must compare the arrival times of the gravitational-wave signal at least of three detectors. Beyond being a great scientific and technical adventure, the detection of gravitational waves has also proven to be a visionary exercise in international cooperation.

Figure 3. LIGO Hanford interferometer. Source : https://www.ligo.caltech.edu/image/ligo20150731er



GW150914: The Birth of Gravitational-Wave Astronomy

In 2015, the first observing run of LIGO began. Virgo, due to a two-year historical delay from the time of its funding, was not yet ready. Just two days after the start of the data taking, LIGO observed a signal, lasting a fraction of a second, in coincidence between its two detectors. The event was interpreted as the merger of two black holes, each of approximately 30 solar masses, located at a distance of about 1.3 billion light-years. The signal was unmistakable, although for reasons of caution, it took the scientific community five months to finalize the analysis and announce the discovery.

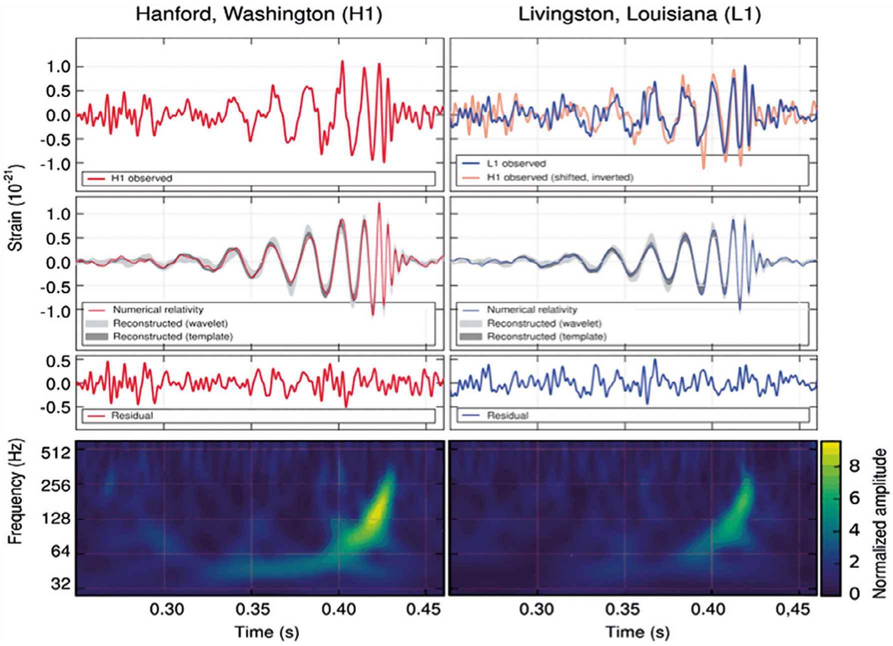


Figure 4. GW150914, the first gravitational-wave detection
Source : https://en.wikipedia.org/wiki/First_observation_of_gravitational_waves

The detection was published by the LIGO and Virgo Collaborations, comprising more than a thousand scientists. With that detection (GW150914) gravitational-wave astronomy officially began [12]. This first signal not only enabled the first direct detection of gravitational waves, but also demonstrated that black holes can exist in binary systems and can merge within the age of the Universe. Moreover, general relativity was tested in a completely new regime: that of strong gravitational fields. The detected waveform was compared to a combination of analytical models (valid especially during the inspiral phase) and numerical simulations (necessary during the merger and ringdown phases). If general relativity had been incorrect, the orbital dynamics of the objects, and therefore the emitted waveform, would have differed. But the match was remarkably precise.

Virgo joins LIGO: The era of multi-messenger astronomy

In 2017, Virgo officially joined LIGO in the second observing run (O2). On August 14, the first triple detection - with signals observed by both LIGO detectors and Virgo - was recorded: a binary black hole merger (GW170814) [13]. This event marked a fundamental step forward, demonstrating the power of triangulation in improving the sky localization of gravitational-wave sources. Just three days later, on August 17, the gravitational-wave community observed a truly historic event: GW170817, the first detection of a binary neutron star merger [14]. The gravitational-wave signal was emitted first, followed 1.7 seconds later by a short gamma-ray burst detected by NASA's *Fermi* and ESA's INTEGRAL satellites. The combined observation enabled an extremely precise •••

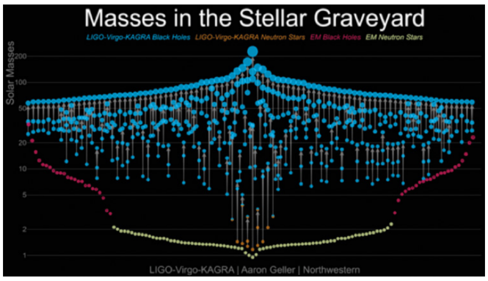


Figure 6. Gravitational-wave sources detected by the LIGO-Virgo-KAGRA (GWTC4.0 catalog) Source: https://www.ligo.caltech.edu/news/ligo20250826

measurement of the speed of gravitational waves: their velocity matches that of light to within one part in 10^{15}, ruling out a wide class of modified gravity theories that had been proposed to explain dark energy. Thanks to the localization capabilities of the Virgo-LIGO network, about 70 telescopes around the globe, spanning almost the entire electromagnetic spectrum, were able to quickly point toward the source, located in the galaxy NGC 4993, about 130 million light-years away. Among them was the Hubble Space Telescope. This coordinated effort led to the discovery of an optical transient, the so-called *kilonova*, produced by nuclear reactions following the merger of the two neutron stars. The spectral and photometric analysis of the kilonova light confirmed the presence of heavy elements (such as gold, platinum, and lanthanides), thus validating the long-standing hypothesis that such mergers are key sites for r-process nucleosynthesis [15]. Moreover, this joint detection enabled a new method to measure the Hubble constant, by combining the gravitational-wave luminosity distance with the electromagnetic redshift of the host galaxy. This so called *standard-siren* approach provides a completely independent way from those using Type Ia supernovae or the cosmic microwave background, and is therefore essential in addressing the ongoing Hubble tension [16].

Technological advancements and the rise of compact objects population studies

Around 2018, one of the most significant upgrades was introduced into the detectors: the implementation of squeezed vacuum states of light. This technique, originally theorized in the early 1980s by Carlton Caves, reduces quantum noise, particularly at high frequencies, by manipulating vacuum fluctuations. The application of squeezed light marked the beginning of a new generation of quantum-enhanced gravitational-wave detectors [17]. In 2019, data-taking resumed for the third observing run (O3). Between 2019 and early 2020, before the interruption caused by the COVID pandemic, nearly 100 gravitational-wave sources were detected. This volume of events allowed the community not only to highlight exceptional signals, but also to begin conducting population studies. By combining the properties of multiple sources, researchers could derive statistical distributions of mass and spin for observed black holes and begin investigating whether these distributions are consistent with theoretical predictions. For example, the third gravitational-wave transient catalog (GWTC-3), published in 2021, revealed an excess of black-hole with masses near 35 solar masses, raising questions about their mechanism of formation [18]. These studies opened the door to a statistical astronomy of compact objects, no longer focused solely on rare or spectacular events, but on the global structure and demographics of the gravitational-wave sky.

Toward a global network: new detectors, KAGRA and the O4 data taking

After 2020, the detectors underwent further changes. In particular, LIGO managed to increase its power and implemented a specific form of squeezing, called *frequency-dependent squeezing*. Virgo introduced the so-called *signal recycling* mirror (already present in LIGO), with the aim of enhancing the detector's bandwidth, and the optimization of this configuration is still underway. Meanwhile, in 2023, data collection resumed with a fourth observing run (O4) involving the international network of terrestrial interferometric detectors, currently known as LVK (LIGO–Virgo–KAGRA), and soon to be called IGWN,

Figure 5. Virgo, source: https://www.ligo.caltech.edu/image/ligo20170927b

the *International Gravitational-Wave Network*. Virgo joined the the data taking in 2024 and the Japanese detector KAGRA, located underground and designed to operate at cryogenic temperatures, joined the run despite a sensitivity still insufficient for full scientific contribution. However, it continues to make steady progress, and will become the first cryogenic interferometer once fully operational. A fifth detector, LIGO-India, is currently under construction as a collaboration between the United States (providing instrumentation) and India (providing infrastructure such as the vacuum tubes and site). Once completed, it will significantly improve the localization accuracy of the network. Since the beginning of O4, more than 200 candidate events have been identified (by rapid search algorithms), mainly binary black hole mergers, with a detection rate of approximately 2–3 per week. The full analyses are forthcoming, but some "exceptional" systems have already been identified, including a merger that produced a final black hole of about 200 solar masses, in the intermediate-mass black hole region. These events are of great interest, not only because they expand the *taxonomy* of astrophysical objects, but also because they challenge formation theories. In particular, at least one of the black holes observed in the GW231113 event (23 November 2023) appears to lie within the "mass gap" between 60 and 130 solar masses, where no black hole remnants are expected due to pair-instability supernova.

Ten Years of Gravitational-Wave Astronomy

Ten years after the first detection (GW150914), the global detector network has observed nearly 300 candidates gravitational-wave sources, including about 200 published events at the time of writing (September 2025, see [19]). This corresponds to mainly black holes mergers, while two confirmed neutron star mergers and a few mixed events (black hole + neutron star) have been identified.

Thanks to the LIGO–Virgo–KAGRA collaboration, new astrophysical windows have been opened. Gravitational-waves allow us to:

- Perform tests of general relativity
- Address key cosmological questions such as the value of the Hubble constant
- Explore the mass distribution and formation pathways of black holes
- Probe the interior structure of neutron stars
- Localize transient for rapid electromagnetic follow-up

While advanced data analysis techniques, play a crucial role in improving detection efficiency, the future of gravitational-wave science fundamentally depends mainly on instrumental progress: better mirrors, more powerful lasers, improved isolation systems, more sophisticated squeezing schemes—and crucially, sensitivity at lower frequencies (down to 10 Hz or even below), where technical and environmental noise sources are most challenging. Many R&D efforts around the world are now focused on preparing upgrades to LIGO and Virgo in the 2030s, and on the next-generation observatories: the Einstein Telescope (ET) in Europe and Cosmic Explorer (CE) in the United States. These facilities, currently under study, are designed to have much longer arms and are therefore far more sensitive.

So, happy 10th birthday GW150914, and happy birthday to LIGO, Virgo, and KAGRA. Looking forward to new surprises and to a new sky made by spacetime vibrations.

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