Gravitational Waves: An Historical Perspective

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Abstract On September 14, 2015, the Earth was hit by a very brief and extremely weak signal, which was the only trace of a catastrophic cosmic event that took place 1.3 billion light years from our planet. That tiny signal recounted the last whirling moments of the life of a binary system of black holes, before the two bodies—of masses 30 times greater than the mass of the Sun—merged into each other at speeds comparable to the speed of light. Captured by two special experimental devices—the interferometric detectors LIGO in the United States—the radiation of September 14 represents the first gravitational signal ever observed by man and the first confirmation that binary systems of black holes exist. Einstein had predicted the existence of gravitational waves as early as 1916. Nevertheless, their reality as physical entities—and not just mathematical solutions of Einstein's field equations—were still the subject of theoretical discussions in the 1950s, when the first ideas of how to detect them started to develop. Since the first detection in September 2015, an extraordinary new field of cosmic investigation is born: gravitational wave astronomy.

Keywords Gravitational waves · Cosmic event · Binary system · LIGO · Virgo

1 Introduction: An Extremely Ambitious Scientific Challenge

> The following example may help us grasp the magnitude of the task. Imagine this distance: travel around the world 100 billion times (a total of 2400 trillion miles, or one million times the distance to Neptune). Take two points separated by this total distance. Then a strong gravitational wave will briefly change that distance by less than the thickness of a human hair. We have perhaps less than a few tenths of a second to perform this measurement. And

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> we don't know if this infinitesimal event will come next month, next year, or perhaps in 30 years. (Tyson 1991)

With these words, on March 13, 1991, the Bell Laboratories physicist J. Anthony Tyson tried to dissuade the members of the House of Representatives of the United States of America from investing 200 million dollars in the construction of two large new generation detectors for gravitational waves: a pair of twin interferometers with 4 km long arms, called Laser Interferometer Gravitational Observatory (*LIGO*).

Twenty-four years later, on September 14, 2015, the two US interferometric antennae—completed despite their initial detractors—captured a gravitational signal for the first time in history. The signal lasted less than two-tenths of a second and accounted for the measurement of an amazingly small distance variation: 10^{-18} m, i.e. a thousandth part of the diameter of a proton (Abbott et al. 2016).

Skepticism about the possibility of observing gravitational waves was a *fil rouge* running through the entire history of their experimental research. A substantial part of the international scientific community shared a critical attitude already starting from the 1960s, when Joe Weber devised and built the first-generation detectors, the *resonant bars*, at the University of Maryland.

When Weber first proposed the idea of an apparatus capable of vibrating to the passage of gravitational radiation and of measuring the magnitude of the vibration, the very existence of such waves was a theoretical question still debated. Were they purely mathematical entities—an artificial consequence arising from the choice of the coordinates in the field equations of General Relativity—or did they possess a physical and, as such, measurable reality? Not only were the effects of the passage of a gravitational wave so small as to make their measurement seem impossible: it was even doubted that such effects existed.

A Weber *resonant bar* is a metal cylinder suitably suspended to minimize the seismic noise acting on it and isolated as well as possible from environmental disturbances. The cylinder connects to a transducer, which transforms the mechanical vibrations of the resonant bar into amplified and measurable electrical signals. The basic idea of a bar detector recalls a common phenomenon related to sound waves, called "resonance". When a sound of a certain frequency strikes a tambourine, its membrane begins to vibrate. To produce the vibration of the membrane, the frequency of the incoming sound wave must equal the characteristic frequency of the tambourine, i.e. its "resonant frequency".

If a gravitational wave hitting the bar detector spans frequencies including the cylinder resonant frequency, it can cause it to vibrate. If the cylinder is sufficiently isolated from external and spurious disturbances, it should be possible, in principle, to distinguish the vibration induced by the gravitational wave from those due to other causes. It is worthwhile noticing that, however optimized the resonant bar isolation can realistically be, the sought signal is much tinier than external disturbances, and extremely sophisticated data analysis techniques are required to extract the useful signal from the noise.

To identify any gravitational signal drowned in noise, it is necessary to formulate models as accurate as possible of both the various disturbances acting on the detector and the waveforms that we are looking for. At the time of Weber's ambitious proposal, the modeling of gravitational radiation emitted by astrophysical sources was in its infancy. The very definition of the energy carried by the wave was still finding a coherent formulation from a theoretical point of view. These considerations highlight the courage and scientific creativity of Joe Weber, an experimental physicist of singular ability, he brought the scientific debate on the existence of gravitational waves from a theoretical ground to the empirical one.

2 Early Hypothesis About Gravitational Waves

In 1916, just a year after completing his theory of gravitation, Einstein linearized the field equations of General Relativity in the approximation of weak gravitational field. He showed that they admit solutions that propagate through space at the speed of light (Einstein 1916). The result seemed to overcome a controversial assumption underlying Newton's theory of universal gravitation: the fact that gravitational force was considered to act instantaneously between two massive bodies.

Before Einstein, at least two illustrious precursors discussed the hypothesis of the non-instantaneous propagation of the phenomenon of gravity. The first was the French mathematician and astronomer Pierre Simon Laplace (1749–1827). In his treatise *Sur le Principe de la Gravitation Universelle*, published in 1776, among various astronomical issues he addressed the problem of the gradual decrease in the orbital period of the Moon, which was observed over time by taking into consideration the data relating to well-documented eclipses (Laplace 1776).

Laplace pointed out that the slow acceleration of the lunar motion did not seem to follow the law of Newton's universal gravitation. Interestingly, he hypothesized *ad absurdum* that gravity was due to a fluid emanating from the center of gravity at a certain finite speed. The friction between the fluid and the Moon should have caused a gradual decrease of the satellite's orbit (and therefore of its period). However, Laplace calculated that the decrease would occur very quickly and, since this did not correspond to the observations, he argued that the speed of propagation of gravity should have been very large, well exceeding the maximum speed ever measured, i.e. the speed of light. In the limit of infinite speed, in fact, one returns to Newton's assumption, which does not predict a decrease of the orbital radius and period.[1]

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[1] It is worthwhile recalling that Newton himself was unsatisfied by his own assumption, which we may consider motivated by a scientific pragmatism. In a letter addressed to the British philologist and theologian Richard Bentley on February 25, 1962, Newton argued: «It is unconceivable that inanimate brute matter should (without the mediation of something else which is not material) operate upon and affect other matter without mutual contact [...]. That gravity should be innate, inherent, and essential to matter so that one body may act upon another at a distance through a vacuum without the mediation of anything else by and through which their action or force may be conveyed from one to another, is to me so great an absurdity that I believe no man who has in

As underlined by the American physicist Bernard Schutz, one of the leading experts in the field of gravitational wave detection, Laplace was ahead of his time, relating the finite speed of propagation of gravity to the decay of the orbital period, a link that Relativity General would develop successfully only a century and a half later (Schutz 2012).

French was also a second mathematician precursor of Einstein, Henri Poincaré, who took up Laplace's argument in the context of what would become the special theory of relativity and supported the existence of what he called '*ondes gravifiques*' ("ondes" is the French word for "waves"). In a 1905 article Poincaré wrote that for Laplace "the introduction of a finite speed of propagation was the only modification to Newton's law he took into consideration"; this had led him to erroneously conclude that this speed must be, if not infinite, at least much higher than that of light (Poincaré 1905).

According to Poincaré, the classical theory of gravitation needed a much more radical revision, in the light of the recent studies of the Dutch physicist Hendrik Lorentz[2] and his transformation laws (1904), which generalized the principle of Galilean relativity and extended it to electromagnetic phenomena. Poincaré argued that to make gravitational force transform according to the Lorentz transformations in the same way as the electromagnetic forces do (*invariance under Lorentz transformations*), it was necessary to introduce modifications into the law of universal gravitation. One should assume for gravity a finite propagation speed, lower than the speed of light in a vacuum. The latter was in fact postulated in the Lorentz transformations as the maximum achievable by a physical entity.

In analogy to electrodynamics—where accelerated electrically charged particles emit electromagnetic waves—Poincaré hypothesized that massive bodies generate gravitational waves when their distribution of matter in space varies. He suggested that the gravitational radiation takes place at the expense of the energy of the source. Like Laplace, he considered a system made up of two celestial bodies orbiting each other. As the motion proceeds, one can observe the planetary orbit and its period gradually decrease, due to a dissipative process (Poincaré 1908). According to Poincaré, a model of this phenomenon should account for the energy loss related to the emission of gravitational waves.

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philosophical matters any competent faculty of thinking can ever fall into it. Gravity must be caused by an agent constantly according to certain laws, but whether this agent be material or immaterial is a question I have left to the consideration of my readers».

[2] In 1902, Lorentz shared the Nobel Prize with Pieter Zeeman, "in recognition of the extraordinary service they rendered by their research into the influence of magnetism upon radiation phenomena".

3 Einstein's Theory of Gravitation and the Weakness of Gravitational Radiation

Less than ten years later, in November 1915, Einstein presented the General Theory of Relativity—a new theory of gravitation—to the Royal Prussian Academy of Sciences. A few months later, as anticipated, he also argued how his field equations—under special approximation conditions—could have solutions in the form of waves (Einstein 1916).

In his second paper on gravitational radiation, published in 1918, Einstein corrected relevant mistakes made in his first work and derived the so-called *quadrupole formula* (Einstein 1918). For large distances from the emitting source, gravitational radiation depends to the first order on variations in the quadrupole moment of the source, unlike electromagnetic radiation, which depends on variations in the dipole moment.[3]

The *quadrupolar nature* of gravitational waves is a consequence of the conservation of the total mass and angular momentum of the system. In practice, the quadrupole dependence implies that a spherically symmetrical body moving or contracting does not emit gravitational waves as far as it maintains its symmetry during the process, since its quadrupole momentum is constant. Conversely, an accelerating electrically charged sphere produces electromagnetic waves. It is a profound difference between gravitational waves and electromagnetic radiation. Looking for a source of gravitational radiation, one should only consider dynamical systems deviating from spherical symmetry, such as the case of two stars orbiting each other.

The quadrupole formula expresses the amplitude of gravitational radiation as a function of the quantities that characterize the source. It shows that the amplitude of the radiation is larger the greater are the mass-energy and the velocity of the radiant system. The amplitude is also inversely proportional to the distance from the source.

Summarizing: gravitational wave sources of greater intensity are to be found among astrophysical systems having relativistic speeds, high mass-energy densities, and a high degree of asymmetry.

Nevertheless, from the first years of their prediction in the framework of General Relativity, it was clear that even considering astrophysical sources of this type, the amplitude of gravitational radiation would be extremely small, as well as the possible effects caused by the passage of such radiation through matter. Measuring such effects was long thought impossible.

The quadrupole term, in fact, contains the factor (G/c^4), which has an extremely modest value, given that the universal gravitational constant G is very small, and the speed of light c is very high. This very small multiplying factor implies that gravitational radiation is extremely weak and interacts very poorly with matter, i.e.

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[3] The amplitude of the gravitational wave is proportional to the second derivative with respect to time of the quadrupole moment Q. G is the universal gravitational constant, c the speed of light, and r the distance from the emitting source. In its turn, the quadrupole moment depends on the geometry and mass distribution of the system.

with nearly no energy dissipation. A gravitational wave can travel through matter keeping its energy virtually intact.

Gravitational radiation interacts very little with matter present in space, as well as with matter specially devised to detect it, such as Weber's resonant bars. Gravitational waves transfer a minimal part of their energy to the detector: while crossing it, they pass practically undisturbed. The effect of their passage is so tiny that it has been unmeasurable for more than half a century.

4 "Do Gravitational Waves Exist?"

The existence and measurability of gravitational waves were for several decades the subject of theoretical debate. Einstein himself questioned the physical reality of waves, in a paper he co-authored with his colleague Nathan Rosen (Einstein and Rosen 1937). The original work had an emblematic title, "Do gravitational waves exist?", and the authors concluded the article giving a negative answer to the question. Indeed, Einstein and Rosen had tried to find exact solutions of the field equations in the form of plane wave, but they had come up against the impossibility of proceeding without introducing singularities in describing the amplitude of the radiation. This result led them to deduce that the field equations did not admit periodic and regular solutions in the form of waves.

This conclusion contrasted with Einstein's early work on the subject and may surprise. Einstein attributed the novel result to the nonlinearity of the field equations. In a coeval letter to the physicist Max Born, he stated:

> Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we have believed up to now. (Kennefick 1996, 2005)

In other words, Einstein argued that the highly nonlinear equations of General Relativity could hide surprises when solutions are calculated using different orders of approximation.

Einstein and Rosen's paper was sent for publication in the American scientific journal *Physical Review*. According to the peer review system—a practice, which, in its modern form, was gradually establishing itself internationally—the editor sent a copy to a secret referee (an expert in the field able to evaluate and comment on the correctness of the scientific content). The latter found an error that invalidated the result and reported it to the editor, who sent the work back to the illustrious sender with the request to consider the observations of the anonymous referee. Einstein reacted very negatively. In his response letter, he addressed the editor:

> Dear Sir,
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> We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the—in any case

> erroneous—comments of your anonymous expert. On the basis of this incident I prefer to publish the paper elsewhere. (Kennefick 1996, 2005)

Later, Einstein re-thought his work in collaboration with his Polish colleague Leopold Infeld. Together, they corrected the calculations, changing the conclusions of the article and publishing the new version in the *Journal of the Franklin Institute* in Philadelphia (Kennefick 2007). Although he acknowledged the error, Einstein never again approached *Physical Review* for publication of his work. As unveiled later, the anonymous referee was the well-known American cosmologist and relativist Howard Percy Robertson.

The debate on the existence of gravitational waves, on the calculation of the energy they carry, and on the effects of their passage through matter was greatly enriched during that lively scientific period that physics historians call the Renaissance of General Relativity.[4] Between the 1950s and 1960s, thanks to the contributions of theorists such as Herman Bondi, Felix Pirani, Richard Feynman, Subrahmanyan Chandrasekar, and John Wheeler, these issues were approached with new vigor (Weber 1969). However, it was certainly the experimental work by Joe Weber that gave the greatest impetus to research on gravitational radiation.

5 Claimed Evidence for Discovery

On June 16, 1969, the scientific journal *Physical Review Letters* published an article with the triumphal title "Evidence for discovery of gravitational radiation", signed by Weber (1969). He reported the analysis of coincident signals from six room-temperature bar detectors, one located in the Argonne National Laboratory (near Chicago) and five in the physics department of the University of Maryland, where Weber was a professor. The devices showed some coincident peaks in the data collected during the first months of the year, which exceeded the threshold value established for detection. The fact that the Argonne bar was located about 1000 km away from the others appeared to support the idea that the observed coincidences had a common cosmic cause. The article began with the following words:

> The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.

Having several detectors placed at a certain distance from each other and operating in coincidence is a fundamental requirement in the search for gravitational waves. If two or more detectors are far from each other, the noises acting on the bars will be largely uncorrelated. A gravitational wave from an astrophysical source will hit the detectors almost simultaneously, inducing a characteristic vibration. The probability

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[4] For a description of the Renaissance of General Relativity, see Blum et al. (2015), Blum et al. (2020).

of having spurious coincidences decreases as the number of detectors increases. In principle, the coincidence analysis of the data allows identifying by comparison the spurious and uncontrollable local noises affecting the individual devices.

Following Weber's 1969 paper, several researchers around the world set up similar experiments in their laboratories. Nevertheless, none of them confirmed the results obtained by the father of the bar detectors. Even experiments carried out with devices that were more sensitive and using more sophisticated data analyzes were unable to highlight significant coincidences.

One of these first-generation experiments (resonant bars at room temperature) was set up in Italy, in Frascati, in the laboratories of the newborn European Space Research Institute.[5] In 1969, the German electronics engineer Karl Maischberger and the Italian physicist Donato Bramanti began to build a Weber resonant bar, stimulated by the theoretical physicist and relativist Bruno Bertotti (La Rana and Milano 2016). They soon came into contact with another research group that had begun a similar experiment in Munich, under the leadership of Heinz Billing, one of the pioneers of computing and data archiving systems. A collaboration took place to operate the two detectors in coincidence; the Frascati-Munich experiment was the first international collaboration for the detection of gravitational waves. At the time of room-temperature resonant bars, it provided the strongest evidence against the validity of Weber's results. The sensitivity achieved by the devices of the two groups was higher than that of the Weber bars, but after about 350 days of coincident operation, no significant event was observed.

Despite the lack of confirmation from all the experiments of the following decades, Weber remained steadfast in the belief that he had detected the first gravitational signal and continued to support his scientific reasons until his death, in 2000.

The march toward the first direct detection of gravitational waves has been long, arduous, and studded with failures, false alarms, illusions, and clashes within the international scientific community.[6] Like Weber, other pioneers in the field risked or even dented their scientific credibility along the way, claiming in good faith that they had detected a signal, which, however, never found confirmation in the results of subsequent experiments, including those obtained by second-generation detectors: *cryogenic resonant bars*, bars cooled down to a temperature of a few kelvins, to remove thermal noise.

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[5] ESRIN was born in 1968 as an offshoot of the *European Space Research Organization* (ESRO), directed by Herman Bondi, one of the theoretical physicists contributing to the lively scientific debate on gravitational waves started during the so-called Renaissance of General Relativity. ESRO was a brand-new institution, founded just four years earlier. In the 1970s, it would merge with the European Launcher Development Organization to form ESA, the *European Space Agency*. The idea of ESRO, the first European space research centre, had originally been stimulated by Edoardo Amaldi, one of the founding fathers of the Conseil Européen pour la Recherche Nucléaire (CERN), the first European laboratory born in Geneva in the early 1950s. In Amaldi's view, ESRO should have been modeled on the principles of CERN.

[6] This bumpy and emblematic path has been studied and analyzed for several decades by the English science sociologist Harry Collins, who has been collecting a huge number of documents and testimonies from researchers involved in one of the most ambitious scientific enterprises of all time. See Collins (2004).

Fig. 1 Edoardo Amaldi and Guido Pizzella, in a picture taken in 1983 by Emilio Segrè (Courtesy of Guido Pizzella)

6 On the Italian Side

Also the second international collaboration for the detection of gravitational waves was born in Italy, around the same time as the Frascati-Munich experiment and a short distance away, at the University of Rome.

Between 1970 and 1971, Edoardo Amaldi[7] and his young collaborator Guido Pizzella (Fig. 1) established agreements with two teams in the United States: the Stanford University team, led by William Fairbank and the one led by William Hamilton at Louisiana State University. The collaboration involved the construction of three cryogenic gravitational antennae, to be operated in coincidence in the three different laboratories.

During the 1960s, Edoardo Amaldi had attempted more than once at establishing a research activity on gravitational waves in Rome. His interest in experiments on gravity had begun in the late 1950s, in the wake of the renaissance of General Relativity and had grown with the flourishing of relativistic astrophysics in the following years (La Rana and Bonolis 2018; Bonolis et al. 2018; La Rana 2022). His program could only materialize thanks to the return from the United States of the young Guido Pizzella, who became to all intents and purposes the leader of the new research activity.

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[7] At the time, Edoardo Amaldi was about 60 years old and represented the greatest scientific personality on the Italian scene. A pupil and collaborator of Enrico Fermi, he had been part of the glorious group of boys from via Panisperna, contributing to the discovery of radioactivity induced by slow neutrons. The only researcher of that group to remain in Italy during and after the war years, he became one of the most active promoters of the reconstruction of science in Italy and in Europe.

The development of the technologies needed to bring an aluminum bar weighing several tons to temperatures close to absolute zero took some time. The construction of the Roman antenna was completed during the 1980s at CERN, after an initial development period at the SNAM-Progetti laboratories in Monterotondo.[8] *Explorer*, as the detector came to be called, was the first cryogenic antenna to achieve the design sensitivity and stability needed to operate over long periods. Explorer's aluminum cylinder weighed 2300 kg, was 3 m long, with a diameter of 60 cm, and was cooled by liquid helium to a temperature of 2.6 K. As for all bar detectors, its resonant frequency hovered around 1 kHz.

The decision to build the bars resonating around 1 kHz was motivated on one side by practical reasons, on the other by the type of gravitational radiation source one aimed at detecting. For several years, the best candidate had seemed to be a supernova explosion. The gravitational signals expected from an astrophysical event of this type had peak frequencies of the order of the kilohertz. The bars were then optimized to resonate at the frequencies expected for gravitational radiation emitted by a supernova event.

Initial hopes dashed, supernova explosions have given way to more promising sources: binary systems made up of very dense and compact objects such as neutron stars or black holes, which spiral around a common center of mass, until they merge into one body. During the last instants preceding the collision (*coalescence phase of the binary system*) and during the collision itself (*merger phase*), the system radiates an enormous amount of energy in the form of gravitational waves, rapidly changing in frequency and amplitude. The frequencies of the radiation vary according to the value of the masses involved and can go from mHz to tens of Hz.

Since a bar detector is sensitive in a very narrow band of frequencies, centered around its resonance frequency, this kind of device is not suitable for detecting and following the signals emitted by coalescent binary systems, whose amplitude and frequency grow over time. This is where interferometric detectors come into play. Interferometric antennae are third-generation detectors and can achieve high sensitivity over a wide frequency range.

7 Indirect Evidences of the Existence of Gravitational Waves

After the many unfulfilled hopes of the 1970s, a remarkable discovery in astrophysics gave new impetus to the search for gravitational waves.

In 1974, the astronomers Russell Hulse and Joseph Taylor discovered the first binary system composed of a neutron star and a radio pulsar (the system PSR B1913 + 16) (Hulse and Taylor 1975). The radio signal emitted by the pulsar and observed

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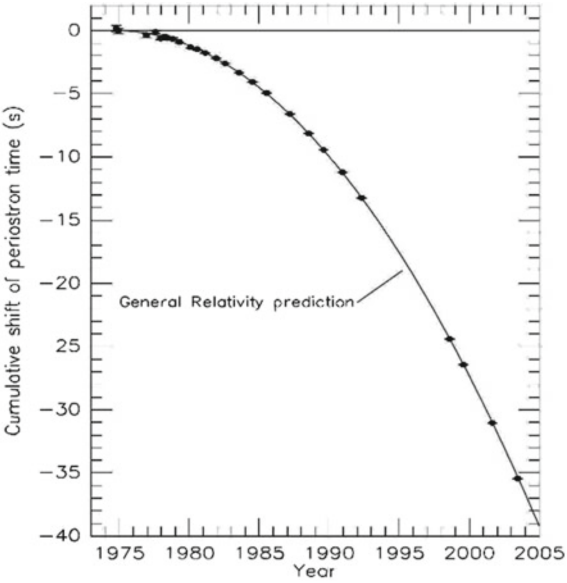
[8] The SNAM-Progetti laboratories in Monterotondo were part of the ENI Group and were expressly dedicated to fundamental research. Its director was Giorgio Careri, a low-temperature physicist at the University of Rome.

Fig. 2 Decrease in the orbital period of the binary system PSR B1913 + 16 during about 30 years of observations, starting from the discovery of the system in 1974. The dots represent the results of the measurements, while the solid line indicates the theoretical orbital decay curve predicted by General Relativity for the emission of gravitational waves by a binary system (Weisberg and Taylor 2005)



at regular time intervals from the Earth made it possible to precisely calculate the orbital period of the system and measure its evolution over the years. Such a binary constituted, as Hulse argumented in his Nobel Lecture, an extraordinary astrophysical laboratory for testing the theory of General Relativity (Hulse 1993).

In 1982, after a few years of observations, Taylor and Joel Weisberg were able to verify that the orbital period decreased progressively over time, following with very high precision the curve predicted by gravitational wave emission models in the framework of General Relativity (Fig. 2).

The issue, which had been addressed prematurely by Laplace and Poincaré, had finally found a coherent explanation supported by accurate astrophysical observations. While the two stars of PSR B1913 + 16 rotate around their common center of mass, the system loses energy by the emission of gravitational waves. The latter propagate at the speed of light, while the orbits of the two celestial bodies shrink more and more, and their orbital period decreases.[9]

In receiving the Nobel Prize together with Hulse in 1993, Taylor explained:

> The clock-comparison experiment for PSR 1913 + 16 thus provides direct experimental proof that changes in gravity propagate at the speed of light, thereby creating a dissipative mechanism in an orbiting system. It necessarily follows that gravitational radiation exists and has a quadrupolar nature. (Taylor 1993)

However, this wonderful scientific achievement was still an indirect confirmation of the existence of the waves, made by observing the orbital motion of the stars. It was not a direct measurement of their effects, made through a detection device.

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[9] For the conservation of angular momentum.

The results of Hulse, Taylor, and Weisberg greatly contributed to convincing the funding agencies to finance very expensive projects for large third-generation detectors. In the early 1990s, the US National Science Foundation gave the green light to the construction of the twin interferometers LIGO, while the Italian *National Institute of Nuclear Physics* (INFN) and the French *Center National de la Recherche Scientifique* (CNRS) signed the agreement to build Virgo (Fig. 3) (La Rana 2020).

Fig. 3 Virgo interferometer (3 km arm length), located in Cascina, close to Pisa (Italy)(Courtesy of the Virgo Collaboration). The working principle of interferometric gravitational wave detectors is based on a special physical effect. A gravitational wave that hits two small test masses floating in space—i.e. subject to gravity alone or, in other terms, in *free fall*—produces a periodic contraction and expansion of their distance. To detect a gravitational wave, it is thus necessary to measure a distance variation between two test masses. This distance variation is extremely small and evolves over time with a characteristic trend, depending on the type of source that radiated the wave. In an interferometric detector, the test masses consist of mirrors located at each end of the orthogonal arms of the antenna. Along each arm of Virgo, the mirrors are 3 km apart, while in the two LIGO they are 4 km apart. Each mirror is suspended in a vacuum chamber through a very sophisticated noise attenuation system, capable of isolating the mirror from external disturbances, so to achieve a condition as close as possible to free fall along the two perpendicular directions of the interferometer. A laser beam is split in two orthogonal beams by a beam-splitter; the beams then travel along the two arms of the antenna, and are reflected multiple times between the suspended mirrors of each arm. After these multiple reflections, the two beams finally recombine at the output in a single beam, which is detected by a sensor. Variations in the distance between the mirrors cause a phase shift between the two interfering beams and this phase shift is measured by the sensor. From the measurement of the phase shift of the two beams, one can measure the variation of the distance between the mirrors. (Courtesy of the Virgo Collaboration)

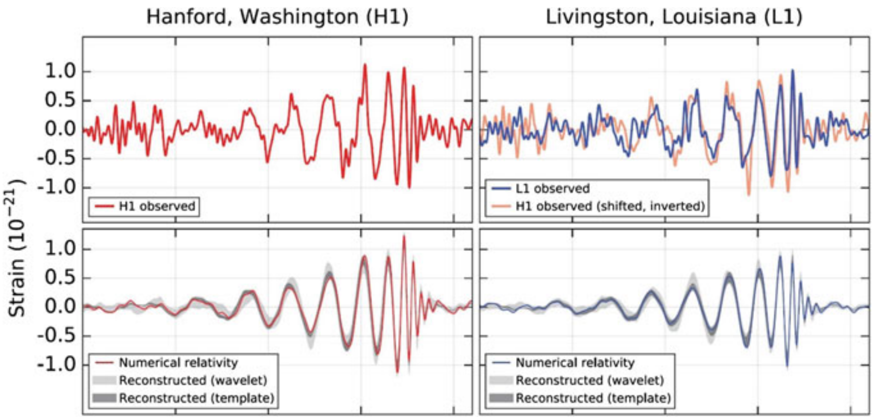

Fig. 4 Signals captured by the two LIGOs and analyzed by the LIGO-Virgo collaboration. The ordinate axis shows the ratio between the measured gravitational signal h (i.e., the distance variation between the interferometer mirrors) and the arm length of the interferometer. ($l = 4$ km for both LIGO detectors). The order of magnitude of the measured distance variations is: $10^{-21} \times 10^{3}$ m $= 10^{-18}$ m. To compare the two amplitudes, the Hanford signal was shifted in time by 6.9 ms, corresponding to the time interval between the detection of the signal at Hanford and the detection at Livingston (due to the finiteness of the wave propagation velocity). The sign of the signal has also been inverted, due to the opposite orientation of the arms of the Hanford interferometer with respect to that of Livingston (Courtesy of the LIGO-Virgo Collaboration)

8 The First Detection

On February 11, 2016—about one hundred years after the first prediction made by Einstein—the physicists of the LIGO-Virgo international collaboration announced to the world the first direct detection of a gravitational wave. Of the three large third-generation detectors existing in the world, only the two American antennae were in operation on September 14, 2015. On that date, a particularly intense gravitational signal hit the Earth, causing a measurable vibration in the LIGO interferometers.

To analyze the collected data and identify beyond any doubt the nature of the signal, it took several months of feverish work by the approximately 1000 researchers of the LIGO-Virgo collaboration.

The measured signal has a characteristic trend, as can be seen from Fig. 4 (Abbott et al. 2016).

In the very first fractions of a second, the frequency and amplitude grow rapidly over time. Making an analogy with sound waves, the shape of this gravitational signal resembles the *chirp* made by some birds. Birds' chirp is an acoustic signal in which frequency and amplitude increase rapidly in time. The *chirping pattern* characterizes the gravitational signal emitted by a binary system in the final phase of its life, just before the merger.[10] The two celestial bodies spiral around each other faster and

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[10] It is worthwhile noticing that the sound waves that our ears perceive have frequencies in the range of 20 Hz–20 kHz. Detectable gravitational waves have frequencies from 10 kHz dow.: There

faster, emitting a gravitational wave that has an instantaneous frequency equal to twice the orbital instantaneous frequency. In the observed signal, the frequency of the radiation increases from 35 to 250 Hz in less than two-tenths of a second.

The signal captured by LIGO was emitted 1.3 billion years ago by a system of two black holes, which were rotating around each other at half the speed of light, in their last two-tenths of a second before they merged. Once the final black hole is formed and a spherical symmetry is reached, the signal rapidly goes to zero: the gravitational emission ceases.

Based on the shape of the detected signal and the theoretical models calculated within the theory of General Relativity, it was possible to establish that the two original black holes had masses equal to 29 and 36 solar masses, concentrated in two spheres with a smaller diameter at 200 km. Moving at an astonishing speed, they merged to form a final black hole of 62 solar masses. The missing three solar masses were emitted in the form of gravitational radiation energy.

9 Cosmic Messengers and a New Era of Astronomy

Gravitational waves can pass almost undisturbed through huge amounts of matter, giving up an infinitesimal part of their energy along the way, as if they were traveling through empty spaces. This feature that hid them from observation for more than 50 years is also the reason for their enormous interest in astrophysics and cosmology. By interacting so feebly with matter, they can travel enormous distances without losing information about the sources that generated them. Ultimately, they are very precious messengers which may come from extremely remote astrophysical objects.

Gravitational waves are providing completely new and complementary information with respect to electromagnetic waves. They are particularly precious for studying those phenomena, which have no electromagnetic counterpart, such as, for example, binary systems of black holes. Suffices to say that the first gravitational signal observed was also the first direct proof of the existence of black holes and the very first observation of a binary system made up of these monsters of the cosmos.[11]

In August 2017, a new exciting and unprecedented event has seen LIGO and Virgo as protagonists. The three interferometric antennae detected the first gravitational signal radiated from a collision between two neutron stars (Abbott et al. 2017). About 2 s later, a gamma-ray signal was observed by the space telescopes Integral—the ESA's International Gamma-Ray Astrophysics Laboratory—and the Fermi Gamma-ray Space Telescope, run by NASA. Alerted by LIGO and Virgo, the astrophysical community started an epical search. In the following hours, tens of ground-based and

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is therefore an overlap of frequency ranges, which means that sound simulations of gravitational radiation provide a natural way for physicists to "sense" gravitational waves (analogously, a false-color photo highlights the X-ray emitted by an astrophysical source).

[11] For more details about black holes and their detection, see in this volume the chapter: Gravitational Waves and Black Holes by MariaFelicia DeLaurentis and Paolo Pani.

space-based telescopes began to scan a special patch in the sky identified by Virgo and LIGO, to single out the electromagnetic source of such a special gravitational wave signal. The source was identified about ten hours later: a luminous spot in the Hydra constellation, which was not there before. In the galaxy NGC4939, at about 130 million light-years from the Earth, two neutron stars weighing about one solar mass each had merged, radiating not only gravitational waves, but also all kinds of visible and invisible electromagnetic waves. The *kilonova* was the first astrophysical event to be observed both through its electromagnetic and gravitational emission. A new era of multi-messenger astronomy was thus inaugurated, which now includes, alongside electromagnetic waves and neutrinos, also the precious messengers of gravity.

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