Gravitational Waves: Why and How

Federico Ferrini

1 Introduction

Light travels faster than any other signal, and light radiation has a great chance of manifesting itself. If we cannot reveal it with optical telescopes, then we can use radio telescopes or detectors capable of capturing infrared and ultraviolet light. We have built satellites capturing X-rays and even more intense gamma rays. We collect information by discovering particles that arrive on the Earth's surface with extraordinary violence—cosmic rays—and other ones, very light and very evasive, running almost at the speed of light, neutrinos.

But there is a part of the Universe unattainable by such means of investigation. Indeed both light and particles in their journey can find something that stops and absorbs them and this prevents us from reaching the boundaries of the Universe. Yet there is a traveler without such constraints, who travels at the speed of light and that nothing and no one can stop. Being able to perceive what is beyond the distances reachable by the most powerful gaze is a beautiful challenge and stimulates the imagination.

However, it takes two key ingredients, the first is the theoretical idea that there is a family of signals that goes beyond everything, without getting lost, without camouflaging, without distorting, with a clear and uncontaminated memory. And this idea was given to us by Albert Einstein, always ready to provide us with amazing and visionary ideas, solid as the hardest rock, but ethereal as the lightest and most vibrant dancer. An idea to be verified, as he himself thought, perhaps not verifiable at all [1, 2]. The second ingredient is to understand what the sense is to be used to perceive these signals. Touch allows us to go not far, taste and smell limit our

---

F. Ferrini (✉)
Cherenkov Telescope Array Observatory, Via Piero Gobetti 93/3, 40129 Bologna, Italy
e-mail: federico.ferrini@cta-observatory.org

European Gravitational Observatory in Cascina (2011–2017), Pisa, Italy

M. Streit-Bianchi et al. (eds.), *Advances in Cosmology*,
https://doi.org/10.1007/978-3-031-05625-3_14

range of action. The view is the one that allows us to get to the impenetrable wall—the dark age—but not beyond. So what? There is hearing, which we have not yet considered. Listening to the Universe is what the search for gravitational waves aims to do, listen to its whispers, sighs, the most chilling screams tracing the distribution of the most dramatic collapse phenomena but also the subdued buzz that collects millions of dramatic stories now very distant and so distributed during the expansion of the Universe to make them appear like a sea of fireflies, which, however, instead of emitting light, send sweet sounds.

Why have these gravitational waves not been revealed for about a century; after all they carry a lot of energy on their shoulders and have formidable information potential on very particular astronomical situations. The answer will come in the following, but I can already anticipate that the nature of the gravitational signal is subtle and what the waves combine in their journey from the source to us is very peculiar. This determines the great difficulty of signal detection. Moreover, the measurement of the passage of gravitational waves is the most extreme ever in physics, obscured by the interference of many external causes.

The search for gravitational waves has been the scientific adventure of the twentieth century!

2 The Discovery of the Century: A New Gateway to the Cosmos

If it were a film, we could start telling the story of the search for gravitational waves from the end, or at least from one of the endings at our disposal, of the adventure begun a hundred years ago. The protagonists of this first finale will be the interferometers LIGO Hanford, LIGO Livingston and Virgo and, as the *prima donna*: GW150914. It was detected at 09h50:45 UTC on the 14 September 2015 from binary blackholes merging occurring at about 1.3 billion light-years away. The energy released was enormous $3.0 \pm 0.5\ c^2$ solar masses. [3].

Newspapers around the world have classified the first detection of gravitational waves as “the discovery of the century.” Five arguments justify this statement:

(1) The hundred years since Einstein’s formulation of general relativity and the article in which he predicts the existence of gravitational waves.

(2) The exceptional nature of the discovery that opens a completely new perspective for the investigation of the Universe, comparable to what Galilei did in the seventeenth century the adoption of the telescope instead of the naked eye to aim at the sky. After Galilei it was an interweaving of technological advancement and scientific inventiveness; from then on, the Universe has been studied almost exclusively with the electromagnetic spectrum, in the multiple frequency ranges, from optical to radio, to the X or gamma band, infrared or ultraviolet, but always electromagnetic radiation emitted by stars or similar matter (plus neutrinos). With the discovery of gravitational waves,

we went much further and added a new method of investigation, independent and complementary, and a new sense to perceive the Universe.

(3) The direct view of black holes.

(4) The extraordinary nature of the numbers at stake: duration, energy, frequencies, infinitesimal measures of extraordinary phenomena.

(5) The surprise of what has been observed. Those working in the field expected to see the effect of the collapse of binary neutron star systems, in principle much more frequent than black holes and therefore much more likely as sources.

A century after the formulation of general relativity, nature has manifested itself in its widest generosity and in a few years the Universe will probably appear different from how we have perceived it until today.

3 Why

The concept of “instantaneous remote action” in Newton’s theory could not satisfy Einstein. The causality introduced in its special relativity contrasts with Newton’s formula according to which any object with mass, regardless of its state of motion and the distance at which it is located, instantly exerts the action of gravitational force everywhere.

The paradigm of the force of gravitation as resulting from the action at a distance between two bodies having mass is modified by Einstein’s theory: every single body with mass influences the space–time around it by deforming this “fabric” that fills the universe.

The gravitational force is not transmitted instantaneously at arbitrary distances but as a deformation of space–time and because of the state of motion of the source propagates in a finite time. Gravitational information manifests itself in the form of deformation of space–time at the speed of light.

The fundamental equation of general relativity links the presence of mass (or energy, thanks to their equivalence, again introduced by Einstein: $E = m c^2$) —agent cause—with the deformation of the geometry of space–time—direct consequence.

The equation is in descriptive terms:

Deformation of Geometry = (Coupling Constant) * (presence of mass or energy).

The coupling constant weights the intensity of the effect and is such that within the Solar System the Newtonian formula remains valid.

The Einstein formula is hence:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$T_{\mu\nu}$ contains all the information related to the presence and distribution of mass/energy,

$G_{\mu\nu}$ describes the deformation of the four-dimensional geometry,

$G = 6{,}67\ 10^{-11}\ m^3/kg\ s^2$ is the universal gravitation constant as defined by Newton, the one which determine the gravitational effects also on the Earth surface, c is the speed of light equal to $3 \cdot 10^8$ m/s.

The coefficient has the value of about $2 \cdot 10^{-43}$, a dramatic small number; the lattice of space–time turns out to be very rigid, with a very low elasticity.

Due to the coupling constant, we can immediately deduce that a mass or a concentration of very large energy is necessary to be able to cause changes in the geometry, capable of canceling the attenuation effect that comes from the coefficient.

And here Einstein again amazes; he deduced three effects from his general relativity theory that have been fully verified by astronomy in the decades following their formulation:

(1) Precession of the Mercury orbit of a value about twice as much as Newton's gravitational physics could justify.
(2) Gravitational shift towards red, made evident for example in the observation of the slowdown of clocks immersed in the gravitational field with respect to an external observer.
(3) Gravitational lensing effect, for which even the Sun can deflect light, and for which from the Earth you can receive the light emitted by distant stars, physically hidden from our direct vision by the solar sphere that is on the direct path between us and the star.

Having at his disposal the mathematical formulation that fully satisfied his conception of gravitation, Einstein tried his hand at finding solutions to the same equations, an extremely difficult task due to the complexity. It is in fact a system of equations coupled with non-linear terms, impossible to solve in the general case with analytic solutions. This is not uncommon in physics, indeed unfortunately it is often the rule, so only by making use of powerful electronic computers and settling for approximate solutions can we determine particular solutions of the general equations.

Einstein then sought a solution that could be calculated in the simplified situation, which results from being very far from the area where the mass is concentrated, in order to approximate the effects on the curvature of space–time and be allowed to treat these effects as a small perturbation of empty space–time, free of masses.

This fundamental simplification allowed him to determine the reduced equation that the small perturbation must satisfy; the resulting equation is identical to the one describing the propagation of electromagnetic waves. He determined the solution of this equation: gravitational wave, ripple of space–time generated by a system of high concentration of mass/energy at distances large from the size of the area surrounding the source.

This is Einstein's fourth deduction from his equation for gravitation and unlike the others it took almost a hundred years to be verified experimentally, thus allowing to dissolve the last residual doubt about the validity of Einstein's theory.

4 How

Gravitational waves are not "material" waves such as pressure waves characteristic of sound phenomena whereby the thrust of the initial fluid medium is transmitted with compressions and rarefactions in matter. Nor are these waves like electromagnetic ones. Gravitational waves are connatural to space–time, to this lattice permeating the universe and therefore can only generate effects on space–time itself, they do not move material bodies in their travel, bodies do not undergo accelerations; the waves cause a modification on the immaterial lattice of distances and times: they dilate the spatial dimensions in one of the two directions perpendicular to the propagation and shorten the distances in the other alternately in the succession of the cyclic perturbation.

The signature in space–time generated by the passage of a gravitational wave is therefore the fundamental characteristic that allows us to identify the phenomenon: the waves are not absorbed by any material and cross unscathed Earth, planets, stars, galaxies except for the effect of the reduction of the intensity inversely proportional to distance. The intrinsic reasons for the complexity of detection are:

(1) The peculiarity and rarity of the sources: Binary systems of neutron stars and/or black holes are infrequent and therefore one must be able to cover a large volume of the universe to have a non-negligible probability of capturing one.
(2) The weakness of the signals generated at great distances from the Earth.
(3) The lack of interaction with standard physical detection systems.

All these complexities have contributed to the need for adventurous and reckless exploration along unknown roads.

In the sixties, the American physicist John Weber devised a simple and refined system at the same time: a large suspended and insulated aluminum cylinder could act as an antenna; the oscillations induced by the passage of gravitational waves would have been measured thanks to the piezoelectric effect. The large bar in the beginning would resonate at its own frequency, about 1.000 Hz, due to the release of the energy of the waves emitted by some galactic supernova; the coincidence of the signals recorded by two antennas placed in distant sites would mark the passage of the wave [4, 5].

Too many internal noises, mainly thermal and external, made the system not very sensitive, and other researchers tried to improve and develop Weber's original idea in much more complex forms. Among these was the contribution of Edoardo Amaldi and his collaborators, who built various cryogenic antennas; the cooling to almost absolute zero allowed to significantly reduce the intrinsic noises of the bar [6, 7]. No signals were found during this phase, but in Italy the nucleus of the scientific community was created that would later lead to the realization of Virgo [8–10].

The optical interferometer is an instrument used in physics since the last decades of the nineteenth century. Michelson and Morley [11] measured the speed of light in different frames of reference, a key experiment for Einstein's special relativity.

The equipment measures the difference in length in two perpendicular directions through light. A light source sends a beam on a partially reflective mirror placed at an angle of 45° to the incident beam, the beam splitter. The transmitted light continues in a straight line towards a mirror, the reflected light goes towards an identical mirror placed in an orthogonal direction. The light rays are reflected from the mirrors and recombine on the semi-transparent mirror; the two overlap and hit a screen, in a direction orthogonal to that of the initial beam. The screen is a sensitive light meter and receives the sum of the two light beams whose waves interfere by adding up or erasing, depending on the difference in distance traveled on their way. In general, the adjustment of the optical system is such that, in case of absolute quiet, the two light beams are perfectly erased, and no light appears on the screen. When one of the mirrors moves, the distances traveled vary and a light signal begins to appear on the screen that is affected by the difference in optical path in the two perpendicular arms. In our experiment it is not important to measure the precise distance traveled, but to be able to have evidence of a variation that occurred in the two directions, which is precisely what is expected to happen during the transit of gravitational waves.

The interferometer is immediately much more promising than the bars by its very nature: the variation of light is extraordinarily easier to measure than an infinitesimal mechanical variation. There is also a much more important potential of principle: the bar is limited to revealing only the resonance frequency, the interferometer can trace a wide spectrum of frequencies, limited only by intrinsic or surrounding noises.

Before going into more details on the technical characteristics and the struggles we had to overcome to arrive at the brilliant result for which the Nobel prize has been awarded in 2017 it is good to remind the reader that a good summary of the various steps from conception, proposal and realisation are reported in LIGO History and Virgo History as described in their respective web sites (see references for the link).

The first studies of the 70s, followed by some prototypes of reduced dimensions (arms 30–40 m long in Garching near Munich and Pasadena in California), were the guide of large-scale projects (arms of the order of a few kilometers) that began to be conceived starting from the mid-80s. In the 90s the National Science Foundation, in the United States, the Italian National Institute of Nuclear Physics and the French Centre National de la Recherche Scientifique in Europe, accepted respectively the proposal of the LIGO collaboration and the Virgo collaboration. In Hanford, near Seattle, and in Livingston, not far from New Orleans, the construction of the two American interferometers began and in Cascina in the province of Pisa that of the Italian-French interferometer. Interferometers came into operation in 2000 in the United States and in 2003 in Italy, since 2007 they worked jointly.

The feasibility of the projects had been demonstrated by 2012 and the infrastructures capacities to host the interferometers have been built up (Figs. 1, 2, 3 and 4).

The sensitivity was not enough to achieve the objective. The amplitude of the signal of a gravitational wave coming from the collapse of a binary system of neutron stars arriving from the next cluster of galaxies of Virgo from the Einstein theory can be evaluated to be h $\approx 10^{-21}$.

The distance between two mirrors in the interferometer when the wave of such amplitude is passing by is $\Delta L \approx h L$, where L is the distance between the two mirrors and ΔL is the displacement to be measured. On the earth's surface we can

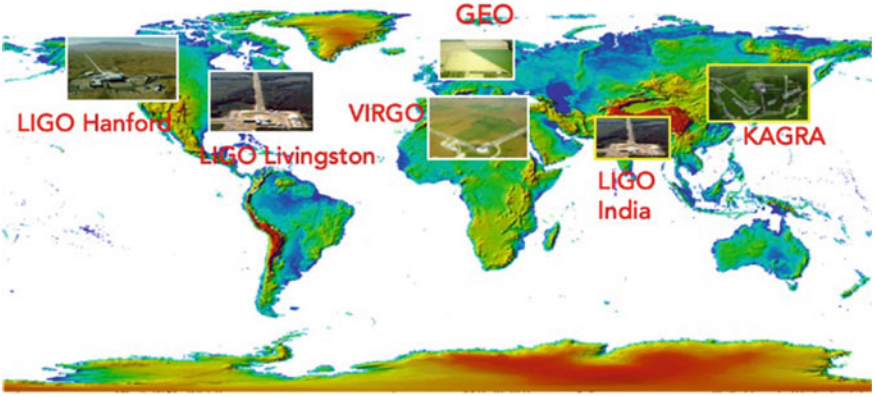

Fig. 1 The Gravitational Waves Observatories in a World-wide Collaboration (Credits The LIGO/Virgo Collaboration)

Fig. 2 Aerial vue of Virgo site (Credits The Virgo Collaboration/N.Baldocchi)

imagine keeping the two mirrors away from each other at distances of the order of the kilometer, so $L \approx 10^3$ m hence: $\Delta L \approx 10^{-18}$ m.

The displacement that the mirror undergoes is equivalent to varying the size of an atom the Earth-Sun distance.

Fig. 3 Aerial vue of LIGO-Livingston site (Credits The LIGO Collaboration) https://www.ligo.caltech.edu/system/avm_image_sqls/binaries/30/jpg_original/ligo-livingston-aerial-02.jpg?1447107179

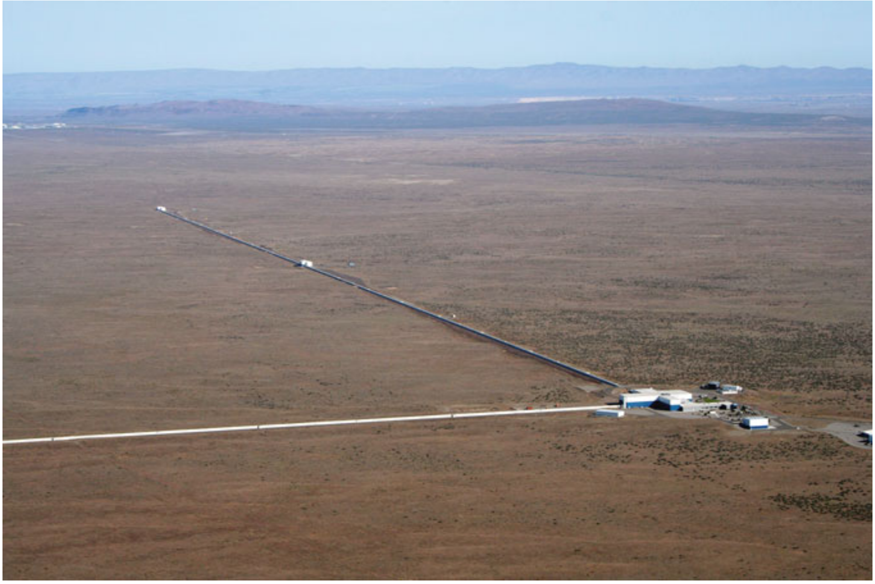

Fig. 4 Aerial vue of LIGO-Hanford site (Credits the LIGO Collaboration) https://www.ligo.caltech.edu/system/avm_image_sqls/binaries/32/jpg_original/ligo-hanford-aerial-04.jpg?1447108890

4.1 An Endless Struggle

4.1.1 Signal Stabilization

The first consideration arising is that the laser must be as stable as possible otherwise its variations could overlap with the optical path difference. The lasers on the market do not have the quality that serves the experiment, in fact they have a possible tolerance of the order of one part in a million, laughing matter compared to the experimental requests at stake. Physicists and engineers of optical groups starting from the best available lasers modify them and create a signal and frequency stabilization system that recreates the output signal from the laser bench, so that it can be injected into the interferometer with the ideal conditions that are required.

The above is a prime example of what we call "noise hunting" because all in all the goal is to remove the intrinsic fluctuations, the noise that the optical signal would carry with it if it were not made pure and very stable.

4.1.2 The Removal of Obstacles

It is also necessary that the light beam does not encounter any obstacles in its path. A speck of dust or a simple molecule would cause the phenomenon known in optics with the name of light *diffusion;* a phenomenon very beautiful to see (it is thanks to the diffusion of sunlight on the upper layers of the atmosphere that the sky appears blue) but harmful to the measurement we want to make and that is already in itself almost impossible to achieve.

The condition of absence of diffusion and scattering of laser light can be satisfied if the beam travels in total vacuum, in the absolute lack of molecules and atoms along its path. This would be the ideal condition, to which we try to get as close as possible by creating the emptiest volume that exists on the earth's surface. In the Virgo Tunnel a volume of 7.000 m^3 is maintained under super high vacuum conditions with a complex system of vacuum pumps (Fig. 5).

The special steel tubes underwent a long and complex treatment which freed their inner walls from the gaseous molecules enclosed in the metal structure. The surfaces of metals naturally capture the molecules that make up the air and trap some of them in their metal lattice. By properly "cooking" the tube sections at high temperatures (400 degrees) and for a sufficiently long time (two weeks) it is actually possible to release the gaseous content, significantly reducing the risk that in the phase of very high vacuum the molecules initially trapped in the metal find it more attractive to migrate to the available empty space, making the work of the pumps much less effective.

The risk of the presence of heavy molecules—for example water, which can be introduced by human bodies even if protected by adequate clothing, or methane, present in the air that returns to the circulation at the time of maintenance operations—which with their relatively large size could disturb the passage of the laser beam,

Fig. 5 The 3 km vacuum tube inside the Virgo North galler (Credits The Virgo Collaboration)

must also be reduced. To this end, a very sophisticated system has been conceived: in four regions of about three meters in size, at the beginning and at the end of the two tunnels, the so-called cryotraps are placed, areas maintained at very cold temperatures thanks to a constant flow of liquid nitrogen, so that the inner face of the pipe has a temperature of about 190° below zero. The heavy molecules are slowed down in their chaotic motion and captured by the inner walls, so as to free their cumbersome presence the path of laser light in the tunnel. Just to give some numbers: the pressure inside the tube is one thousandth of a billionth of an atmosphere (10^{-12} atm).

4.1.3 The Characterization of Optical Components

The material chosen for the optical components is silicon (SiO_2), quartz, 100% pure. It is now very clear to you that we want perfection not for hysteria, but for real experimental needs: the presence of impurities, even very modest and in practice invisible to a standard analysis, produce disturbances on the path of the laser beam causing loss of coherence, diffraction and, if on the surface, aberration.

There are two categories of optical components: the hundreds of lenses, prisms, mirrors of diameters up to 15 cm and the dozen of large lenses and mirrors of diameter equal to or greater than 40 cm and thickness from 15 to 35 cm. For the former ones, there are specialized companies on the market capable of supplying us with these materials in appreciably satisfactory conditions. When the dimensions become significantly larger and the required glass weighs more than 40 kg, the number of highly specialized suppliers is greatly reduced: only three companies worldwide—one in Europe, one in the United States and the third one in Australia—are able to produce the most pure material of the required size. The production of a single

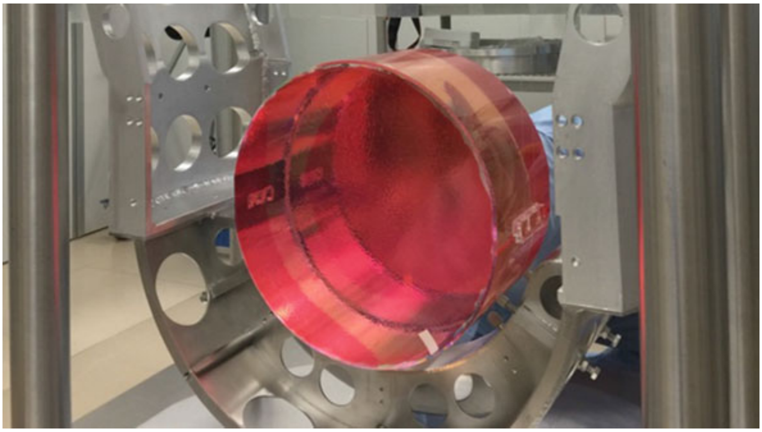

Fig. 6 One of the Virgo mirrors (Credits The Virgo Collaboration/M.Perciballi)

substrate, which will then become a lens or mirror, takes several months, because, even starting from pure material, the cooling times must be very slow, so as not to create microstructures that would then turn out to be critical for the optical quality and the same stability of the sample.

The blocks of super pure glass (at 99.9999%) have, depending on the position where they are to be inserted, perfectly flat surfaces or a spherical curvature; this curvature is calculated through simulations of the overall optical system and results as the portion of a sphere with a radius of about a kilometer and a half, with an accuracy of the order of a few centimeters, to identify with great precision the central part on which the laser beam is engraved (Fig. 6).

At the beginning of its journey in the interferometer, immediately after the complex initial "cleaning", the laser beam is very thin, just a thread of light energy in the infrared that seeks its way to the mirrors at the end of the long arms. Here another brilliant idea intervenes; we have already observed that the longer the path covered by the beam, the better the sensitivity of the instrument will be. The length of the arms is limited by external conditions, for example roads and houses in the Cascina countryside, and, perhaps even more, by financial limitations: an extra kilometer for each arm costs about 20 million euros between infrastructure works and the cost of extending the vacuum system. To overcome this problem, physicists forced the beam to "bounce" numerous times inside each individual arm, practically lengthening the distance traveled. To create this optical cavity, an additional mirror was inserted at the beginning of the arm, with the curved face facing the end of the arm, where the beam is awaited by an identical symmetrically curved mirror. The light thus circulates between the two mirrors several times, obtaining two effects: lengthen the optical path and intensify the beam, which acquires a diameter of about ten centimeters. The amount of light energy inside the vacuum tube becomes significantly higher: in the presence of a laser with a power of 125 W, at the entrance of the central part of the interferometer the beam has a power of 4.9 kW. With the creation of resonant cavities, the circulating power rises to 650 kW [12].

After about 400 round trips the beam exits and returns to the recombination and measurement zone. A further prolongation of the coming and going would lead to the creation of consistent circulations of light with multiple frequencies than the one we have so well stabilized, and this would damage the definition of the signal. The increase in energy inside the pipe has two effects that we must counteract. The first is the heating effect induced by light radiation on the mirrors: glass, like all materials, if heated, expands and in our mirrors this involves a variation in the radius of curvature. Alas if we gain on one side and lose on the other! We do not dramatize: with an extremely sophisticated system of control of the surface of the mirrors, we calculate in real time their curvature and where necessary we intervene with a fully automated system that injects light from some auxiliary lasers placed near each mirror to bring the surface back to the ideal curvature, heating the vitreous material in appropriate places. It really sounds like science fiction, but it works!

The second effect, caused by the intensification of the beam, is to exert an important pressure on the mirrors themselves, moving them slightly. Light has a dual nature: wave and particle coexist in its properties, and this has been known since the early twentieth century; curiously it is precisely for the interpretation of the photoelectric effect in which the dual nature of light has a crucial role, that Einstein received the Nobel Prize, and not for the theory of relativity! In our beam these properties coexist and photons hitting the mirrors, transfer their momentum. If the surface is rigidly blocked, no variation is observed, but if the surface is free, it will move: so our mirrors move affected by the collective effect of the beam, populated by many photons, as if they were subjected to a total pressure, the radiation pressure. Obviously, a complex control system corrects this effect, well calculable with beam modelling (Fig. 7).

A further consequence of the passage of the beam of substantial dimensions in the optical system is the presence of diffused light. Some photons, due to slight fluctuations of the optical path, leave the parallelism of the beam and can go along trajectories that lead it to bounce on the inner walls of the vacuum tube. A sophisticated system of absorbent rings distributed in the tube and near the main mirrors captures these unruly photons and reduces as much as possible the annoying diffused light that results.

So far, we had to deal with the conditions that we must impose on the quality of the materials that make up the optical components, but we have not yet talked about their surface. A surface defect is equivalent to a noise on the signal and therefore makes it impossible to carry out our measurement. The surfaces of lenses and mirrors must be perfectly smooth and, depending on their use in the optical path, perfectly transparent or perfectly reflective. It is a matter of creating of a perfectly reflective layer for the laser frequency. If for small optical components these characteristics are obtained in a standard way and with performance acceptable by various industries, for large diameter glass there are only two companies capable of standardizing the surface but not of creating a perfectly reflective layer. The only possible solution was to create an ad hoc laboratory, building the appropriate machinery for the treatment of large surfaces, to satisfy scientific requests. The *Laboratoire des Materiaux Avancés*

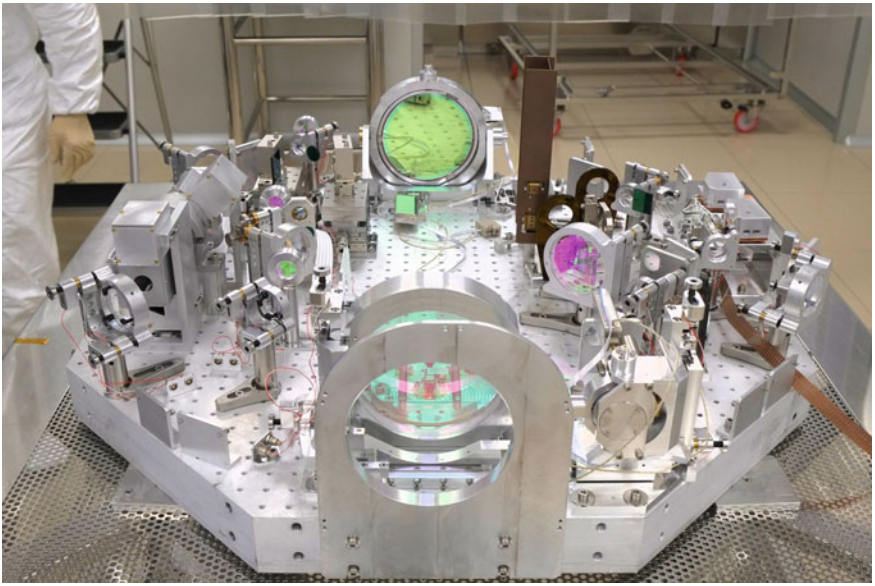

Fig. 7 One of the Virgo optical benches (Credits The Virgo Collaboration/LAPP)

(LMA) in Lyon has been created and the surfaces of large mirrors are coated with combinations of heavy metal oxides with an accuracy of half a nanometer. The laboratory works so well that he was entrusted with the preparation of all the mirrors of the large interferometers, the two LIGO, Virgo and the Japanese KAGRA.

For a complete technical overview with the most recent updates the specialists might consult The Virgo Physics Book: OPTICS and related TOPICS [13].

4.1.4 Suspension and Isolation of Mirrors

The purpose of the interferometer is to measure variations in distances and therefore the position of the mirrors must be known with the utmost precision and must remain immutable all the time, except when gravitational waves pass. In fact, it is the mirrors that determine the lengths of the optical paths traveled by light and modified by the passage of the wave.

Naively you could think of blocking every mirror on a very rigid table well anchored to the ground, but we would be in huge trouble: the earth's surface never stands still, it is subject to a continuous and annoying micro seismicity that generates in the mirrors anchored to it displacements ten billion times greater than the displacement induced by gravitational waves. A deafening noise for our poor measures!

Given the smallness of the expected signal—let's remember that the typical variation is of the order of 10^{-18} m, a billionth of a billionth of a meter—the ideal condition would be to have the mirrors suspended in the void, without bonds and isolated from everything, free to hear the gravitational rustle and react only to it. Not yet having available mechanisms of levitation of objects of about forty kilograms, we must resort to a system of mechanical suspension, isolating them from external disorders.

This is one of the most complex and difficult problems to solve, to which Adalberto Giazotto, Virgo's father, has managed to give an elegant and very effective solution, devising a brilliant system to super-cushion the vibrations of the ground. Three metal columns 10 m high are fixed to a base on the ground and at the top support a platform, in the center of which are suspended in sequence seven oscillating bodies connected to each other by sections of steel cable, a sequential series of pendulums. Each of these massive objects, called filters, has a cylindrical shape, a diameter of about 70 cm, a height of about 40 cm and a weight varying between 30 and 100 kg, depending on the metal structure and the instrumentation that characterizes it. Each component behaves like a pendulum, capable of swinging in horizontal directions but also of moving along the vertical; each filter therefore has three degrees of freedom.

Twelve blades of special steel are inserted in the lower part of each filter capable of dampening the vibrations coming from the upper layers by a factor of one hundred; in the center of the filter are inserted magnets that, touching each other, couple their appropriately oriented magnetic fields and act as a brake for the vertical oscillations of the system, contributing to the effectiveness of the reduction of external disturbances (Fig. 8).

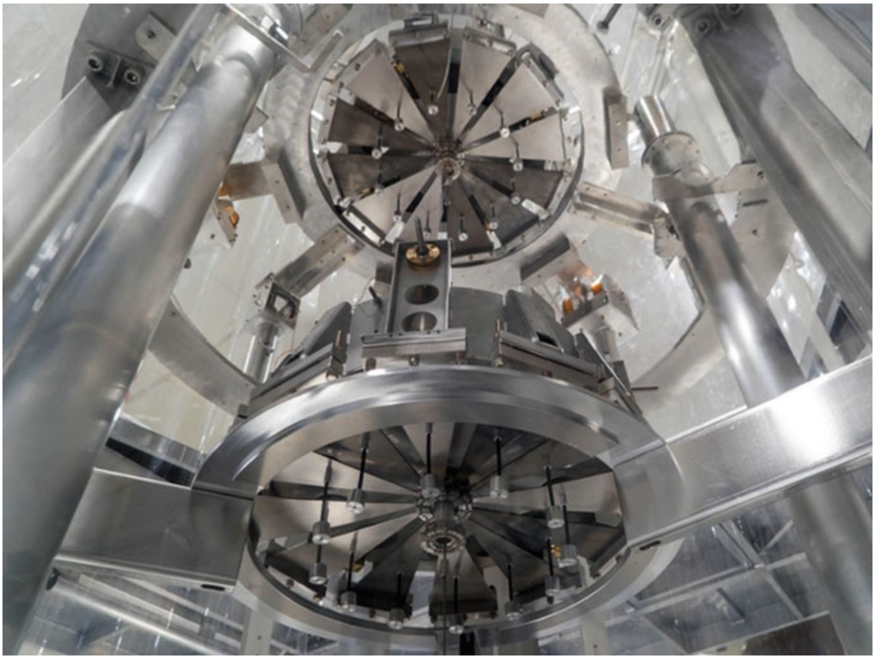

Fig. 8 Virgo Superattenuator (Credits G. Raffaelli/Sonic Somatic)

The last stage of the chain consists of a metal structure reminiscent of the system of wooden sticks used to command the puppets, governed and in their funny movements by a barbell to which they are attached and with light cords. By analogy, the block in which sophisticated magnetic control systems are inserted that allow the mirror to be oriented, in such a way that the alignment of the centers of the mirrors is perfectly in line with the laser beam, is called a *marionette.*

It remains to clarify the way in which the mirror is connected to the marionette. In the first phase of the experiments, thin steel wires were used which, passing under the mirrors, allowed them to be suspended with tranquility and safety, even considering their weight, of the order of 40 kg. The suspension system and the positioning through the marionette are optimally recorded when the towers of the attenuator-mirror complex are in the air, in the absence of the laser beam, to allow the experts to act even physically on the various components. After vacuuming and sending the laser beam on the mirrors, a further adjustment is necessary, through the complex electronic control system designed ad *hoc;* this is necessary due to the temperature variation determined by the presence of the beam. During prolonged phases of operation that can last months, the temperature variations of the external environment modify the internal thermal conditions affecting the materials inside the instrument. Each material, as the temperature changes, undergoes deformations, different depending on the nature of the substance, in particular the responses of steel and glass are quite different. Consequently, to improve the behavior of the mirror-marionette system, it was decided to support the mirrors with delicate quartz threads, hooked to the side walls of the mirrors themselves, excluding any other material than glass. It is not easy at all: just think that each mirror weighs more than forty kilograms and the four quartz fibers that support it have a diameter of a few millimeters!

In conclusion, each suspension tower of the mirrors has seven filters in series, plus three oscillating arms that support everything and help dampen the micro-seismic vibrations of the ground, so that the eleven-meter-high complex produces a reduction in seismic noise of one million billion times, 10^{-15} guaranteeing the mirror an effective isolation from the motions of the ground below [14].

What if there is an earthquake? The answer is simple: we measure its effects thanks to the consequences on the position of the mirrors. The complex attenuation systems could promise interesting applications for understanding seismic motions.

4.1.5 Anthropic Noise

Another problem to be addressed concerns vibrations not due to natural causes but due to human activities, the so-called anthropogenic noise. There are indeed numerous sources capable of generating disturbances to the equipment, which are not always easy to list. Among those well-defined I cite as examples the car traffic, in particular the passage of heavy vehicles, the presence of planes and helicopters that fly over the buildings that house the instrumentation, the rotation of the wind turbines, the presence of quarries and other industrial installations that generate vibrations by crushing and compaction of material. Each of these activities generates superficial or deep vibrations which distort the measurement process. For example, wind turbines cause low-frequency waves that the rigid layers in the subsoil transmit to the towers that suspend the mirrors, creating a noise around 5 Hz.

4.1.6 Other Sources of Noise

There are other complex sources of noise that limit the performance of the interferometer, and that are related to the intrinsic nature of the electronic equipment that allows us to collect signals: the noise due to the thermal agitation of the conduction electrons and the granular noise due to the corpuscular—quantum—nature of the electrons themselves. They are highly technological noises that we can only fight up to a certain point; one way to protect ourselves is to increase the power of the laser as much as possible, so the effects of fluctuation due to the quantum nature are relatively weaker and the situation improves. Unfortunately, increasing the power of the laser involves risks such as the control of the thermal situation of the mirrors, and therefore it is necessary to find a compromise, an acceptable cocktail in order to guarantee an adequate and stable sensitivity to our instrumentation.

It is important to know on which frequency ranges the various sources of noise exert their influence; with theoretical reasoning and with tests and experimental attempts we have understood that seismic effects limit sensitivity in areas of frequency below 2–3 Hz, thermal effects are the most important in areas between 10 and 300 Hz, while quantum electronic effects are the reason for maximum concern above 300 Hz. The brilliant solutions put in place over the years to limit damage are currently ineffective below 5 Hz and above 1.000 Hz; this is the frequency range in which the detectors placed on the Earth's surface have the best sensitivity range. Consequently, we can identify which astronomical sources are candidates to be recognized in this range. Our ideal candidates as gravitational wave generators will be those systems that emit gravitational waves with effectiveness in the frequency range in which our detectors show the maximum sensitivity—between 30 and 500 Hz—: that is, supernovae, binary systems of neutron stars and binary systems of black holes with masses up to about 100 times the mass of the Sun. The rest of the astronomical emitters for now escapes our hunt.

At the end of this listing of the relentless struggle aimed at bringing out of a sea of multiple noises the faint voice of gravitational waves, I quote some "curious" effects that have a disturbing role, in some cases systematic, and for which ad *hoc* solutions have been found. Both marine and terrestrial tides induced by the motion of revolution of the Moon around the Earth have a well-regular and well-known course; they obviously cause shifts of the mirrors that can be corrected equally systematically with an appropriate system of corrections installed on the platforms placed at the top of the columns of super-attenuators: the positioning of the whole chain is modified to cancel the effect of the tides.

The curvature of the Earth, already 3 km away, causes a lack of parallelism between the vertical directions of the mirrors: they point towards the center of the Earth, due to the local acceleration of gravity, and the faces are not correctly aligned. So, the system at the top of the column of filters must also think about this, to put them back well aligned so as not to make the incident beam wander.

Even non-systematic environmental phenomena, but linked to local weather variations, affect the stability of the very delicate system: intense winds with their vibrations on the external walls of the buildings and the tunnel that contains the ultra-high vacuum pipe, as well as the very intense wave motion on the seashore about a few kilometers from the Virgo infrastructure transmitted through the ground, they can even lose alignment and force operators to spend a few hours resetting the system to recover the laser beam that no longer sees the center of the mirrors. It is therefore understandable why the long blue tube is not flanked by an elegant row of cypresses that would be perfectly suited to the Tuscan landscape but could cause boring vibrations to the mechanical system of the interferometer.

5 GW150914 and GW170817

Increasing the sensitivity by ten times means increasing the distance by ten times and the spherical volume to investigate one thousand times; this was achieved with the second generation of interferometers in operation since 2015; thanks to that the statistical expectation was confirmed and it was possible to discover gravitational waves.

September 14, 2015: a binary black holes system released the first even detected gravitational wave signal.

August 17, 2017: a binary neutron stars system released the first gravitational wave signal correlated to a spectacular series of electromagnetic signals, from gamma-rays observed 1, 7s after the arrival of the gravitational wave, followed by optical and infrared observations.

Since then, the two LIGOS and Virgo have been harvesting tens and tens of events, creating a rich collection of cases, significantly enriching the knowledge of the violent Universe. The Japanese interferometer KAGRA then joined them and now we have a network of instrument ready to systematically study the GW sky.

On January 5 2020 **GW200105** and on January 15, 2020 **GW200115** the merging of black hole with neutron star have been detected and the article *Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences* published on the 29 of June 2021 [15]. From this observation and quoting the LIGO Web site announcement: *Having confidently observed two examples of gravitational waves from black holes merging with neutron stars, researchers now estimate that, within one billion light-years of Earth, roughly one such merger happens per month.*

“The detector groups at LIGO, Virgo, and KAGRA are improving their detectors in preparation for the next observing run scheduled to begin in summer 2022,” says Brady. *“With the improved sensitivity, we hope to detect merger waves up to once per day and to better measure the properties of black holes and super-dense matter that makes up neutron stars.”* (https://www.ligo.caltech.edu/news/ligo20210629*)* (Fig. 8).

Up to december 2021, 90 gravitational waves have been detected by the global three interferometer network LIGO, Virgo, KAGRA. (see LIGO, Virgo and KAGRA web sites).

6 Arts and Science

Now it is a widely diffuse communication tool, but indeed it was in 2011 that we started at the European Gravitational Observatory, the house of Virgo, to create Arts & Science events. It is evident the "spiritual" connection between these two creative manifestations of humanity, and we promoted a series of events, such as artistic exhibitions and theater events that accompanied our scientific progress during those complex and exciting years. It has been a direct way to communicate to the enthusiasm and the expectations to the public, that very faithfully, from the youngest children to the mature public, followed our events, asking for more performances. The first art work organized at EGO were the "Big Bang" monologue by Lucilla Giagnoni, the concert "La Musica e l'Universo" with the Quartetto Elisa who among other pieces of music executed a perfect version of the Quartetto in Do maggiore KV 465 "Dissonanze" by W.A. Mozart, the piece "Copenhagen" by M. Frayn adapted to a young public by the Teatri della Resistenza, the monologue "Marie Curie" by the Teatri della Resistenza and the piece "The Physicists" by F. Durrenmatt played by a group of scientists from La Sapienza University of Rome. After we opened this door, further activities continued in the years.

7 Conclusion

"The GW community has a roadmap", stated Giovanni Losurdo, Virgo spokesperson and one of the authors of the Nature published paper [16].

"*An extraordinary science plan for the next two decades: a variety of existing and planned projects, which promise to continue the scientific revolution that began with the discovery of gravitational waves five years ago. Nature has published this roadmap, noting once again the increasing attention of the wider scientific community to this field. In the paper, we list a number of fundamental questions to be addressed through GW observations, which represent an extremely ambitious scientific programme, able to dramatically widen our knowledge of the cosmos.*" (Virgo web site).

In the first two decades of the millennium, we have done a fundamental step forward in the knowledge of the Universe. While the network of actual interferometers is producing almost every week a new contribution to the patchwork of the gravitational Universe, next generation interferometers are under preparation: LISA in the space, Einstein Telescope and Cosmic Explorer on Earth. These future observatories, if realized, with enlarge the horizon to which Gravitational Waves can be detected toward the very high redshift values and will extend the frequency range of potential observations, till the low frequency region that is going to be the domain to be explored by the space project LISA, that will magnificently complement the ground earth observatories.

Furthermore, gamma ray instrumentation is going to be improved by order of magnitude to be ready to work in symbiosis and to produce a holistic vision of the extreme astronomical phenomena, via the creation of the Cherenkov Telescope Array Observatory. With more than 100 telescopes on two sites located in the Northern and Southern hemisphere, the Observatory will allow to investigate electromagnetic signals produced at energies inaccessible to currently accelerators and will help scientists to unveil the behavior of ultra-relativistic particles as well provide fundamental information about the dark matter. I had the privilege to be first involved in Gravitational Waves and then into gamma-ray particle-astrophysics, probably the most exciting aspects of modern physics.

Unexpected physics is behind the corner!

Post Scriptum: If you want to know more, many books, documentary, educational videos also intended for non-experts are available in several languages.

A Brief History of LIGO.

https://www.ligo.caltech.edu/system/media_files/binaries/313/original/LIGOHistory.pdf

Virgo History https://www.ego-gw.it/history/

https://www.ligo.caltech.edu/

https://www.virgo-gw.eu/

https://gwcenter.icrr.u-tokyo.ac.jp/en/

https://www.cta-observatory.org

References

1. A. Einstein Naherungsweise Integration der Feldgleichungen der Gravitation. Königlich Preußische Akademie der Wissenschaften (Berlin). Sitzungsberichte, pp. 688–696 (1916)
2. A. Einstein Über Gravitationswellen. Königlich Preußische Akademie der Wissenschaften (Berlin). Sitzungsberichte, pp. 154–167 (1918)
3. B.P. Abbott et al., Ligo scientific collaboration and Virgo collaboration: observation of gravitational waves from binary black hole merger. Phys. Rev. Lett. **11**(16), 061102 (2016). Published 11 February 2016
4. J. Weber, Gravitational radiation. Phys. Rev. Lett. **18**, 498 (1967)
5. J. Weber, Gravitational-wave detector events. Phys. Rev. Lett. **20**, 1307 (1968)
6. E. Amaldi et al., Initial operation of the M = 390 kg cryogenic gravitational-wave antenna. Il Nuovo Cimento C **1**, 497–509 (1978). https://doi.org/10.1007/BF02510108
7. E. Amaldi et al., Measurements with a small (M = 24,4 kg) cryogenic gravitational-wave antenna at T=1,5 K. Il Nuovo Cimento 07–08 **1**(4), 341–359 (1978). https://doi.org/10.1007/bf02525046
8. E. Amaldi et al., Preliminary results on the operation of a 2270 kg cryogenic gravitational wave antenna with a resonant capacitive transducer and a D.C. squid amplifier. Nuovo Cimento C **9**, 829–845 (1986). https://doi.org/10.1007/BF02558082

9. E. Amaldi et al., Sensitivity of the Roma gravitational wave experiment with the explorer cryogenic resonant antenna operating at 2 K. Europhys. Lett. **12**(1), 5 (2007). https://doi.org/10.1209/0295-5075/12/1/002
10. T. Accadia et al., Virgo: a laser interferometer to detect gravitational waves. Journal of Instrumentation **7**(3), 1–119 (2012). JINST 7 P03012 https://iopscience.iop.org/article/https://doi.org/10.1088/1748-0221/7/03/P03012
11. A.A. Michelson, E.W. Morley, On the relative motion of the earth and the luminiferous ether. Am. J. Sci. **34**(203), 333–345 (1887). https://doi.org/10.1007/bf0252504610.2475/ajs.s3-34.203.33
12. F. Acernese et al., Measurement of the optical parameters of the Virgo interferometer. Appl. Opt. **46**, 3466–3484 (2007). http://hal.in2p3.fr/in2p3-00113562
13. V.Y. Vinet, The virgo physics book : OPTICS and related TOPICS (2020)ss. 1–456 First release Feb. 2001. last update September 9, 2020.
14. S. Braccini et al., An improvement in the VIRGO super attenuator for interferometric detection of gravitational waves: the use of a magnetic antispring (1993)
15. R. Abbott, T.D. Abbott, S. Abraham et al., Observation of gravitational waves from two neutron star-black hole coalescences. Astrophys. J. Lett. **915**(L5), 1–24 (2021). https://doi.org/10.1007/bf0252504610.3847/2041-82131/ac082e
16. M. Bailes et al., Gravitational/wave physics and astronomy in the 2020s and 2030s. Nat. Rev. Phys. **3**, 344–366 (2021)