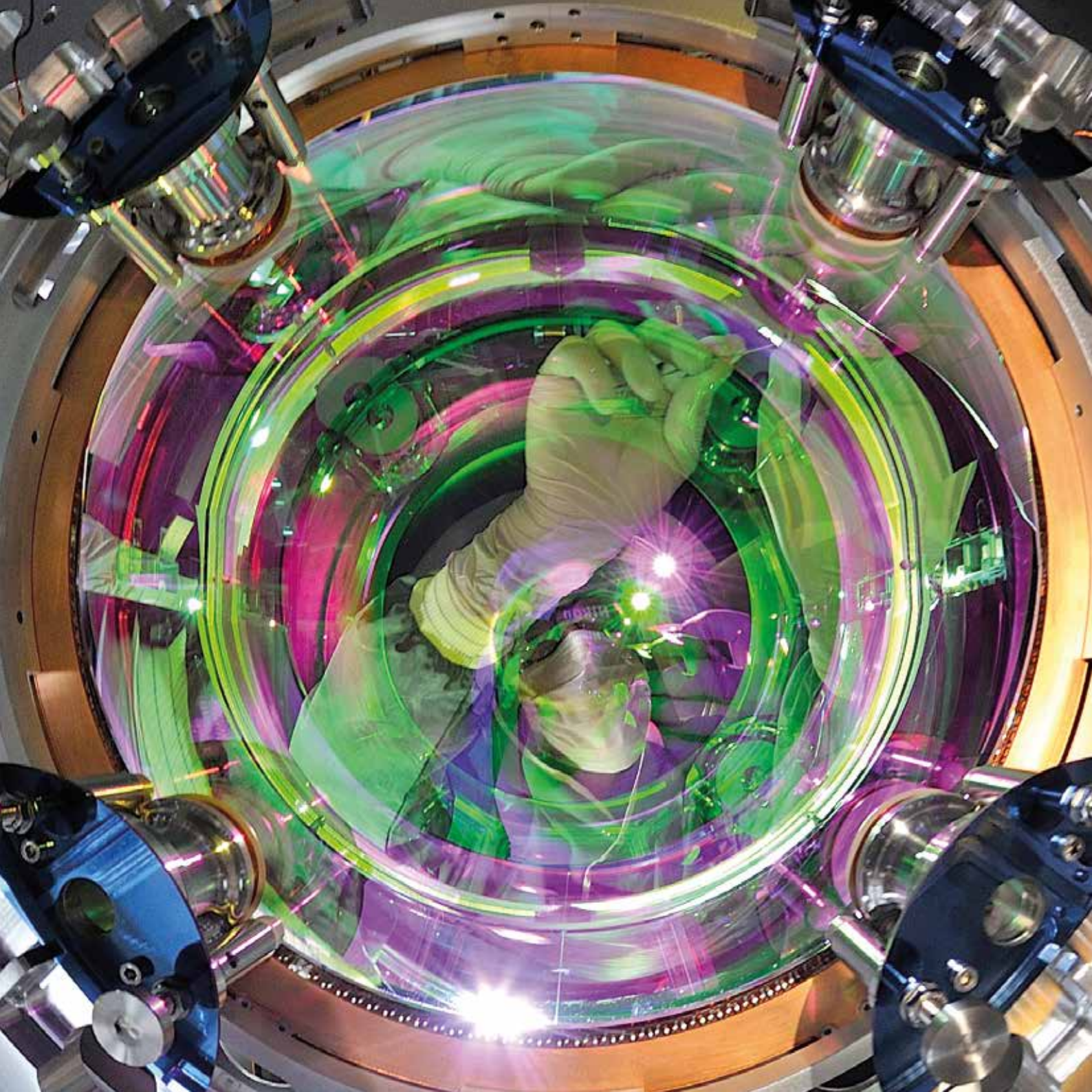
EUROPEAN GRAVITATIONAL OBSERVATORY AND VIRGO

EGO VIRGO



THE CRAZIEST OF UNDERTAKINGS



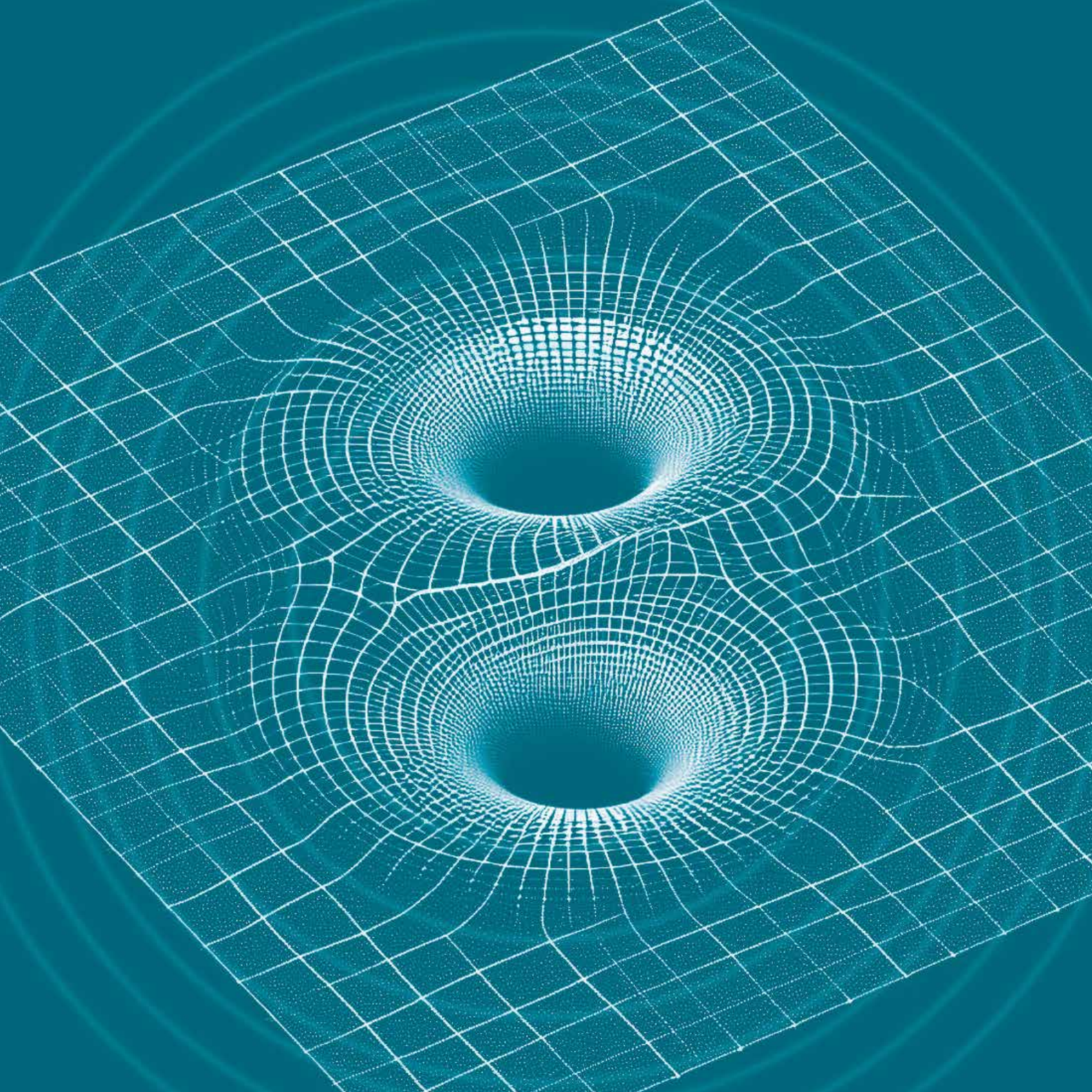
The story of Virgo began in the early 1980s, from the meeting of two visionary physicists: **Adalberto Giazotto**, Italian, and **Alain Brillet**, French. The two joined forces to pursue a common dream: building **a large interferometer to detect gravitational waves**, imperceptible cosmic signals predicted by **Einstein's General Relativity** in the early 1900s.

Both were already conducting research on technologies crucial to the future experiment: laser optics and seismic attenuation. Thus in 1989, on the basis of the preliminary results of their studies, **the National Institute of Nuclear Physics - INFN,** in Italy, and **the Centre national de la recherche scientifique - CNRS**, in France, granted Giazotto and Brillet funding, **kicking off the project of a large European gravitational interferometer, Virgo.** In the same years the Massachusetts Institute of Technlogy (MIT) and the California Institute of Technology (Caltech) were initiating in the United States the design of two similar interferometers, called LIGO.

LIGO and Virgo were the most important gravitational wave research projects ever attempted. They had the support of prestigious international research institutions, however they were looked upon with skepticism by part of the scientific community. The technological challenges associated with the two experiments appeared too ambitious, and the failures of previous experiments, for example those conducted by Joseph Weber in the late 1960s with resonant bars, weighed heavily. Giazotto himself would later say: **"Detecting gravitational waves was the craziest of undertakings."**

pag. 2
An aerial picture of the Virgo interferometer

pag. 4
Virgo scientist working on one of the mirrors of the detector

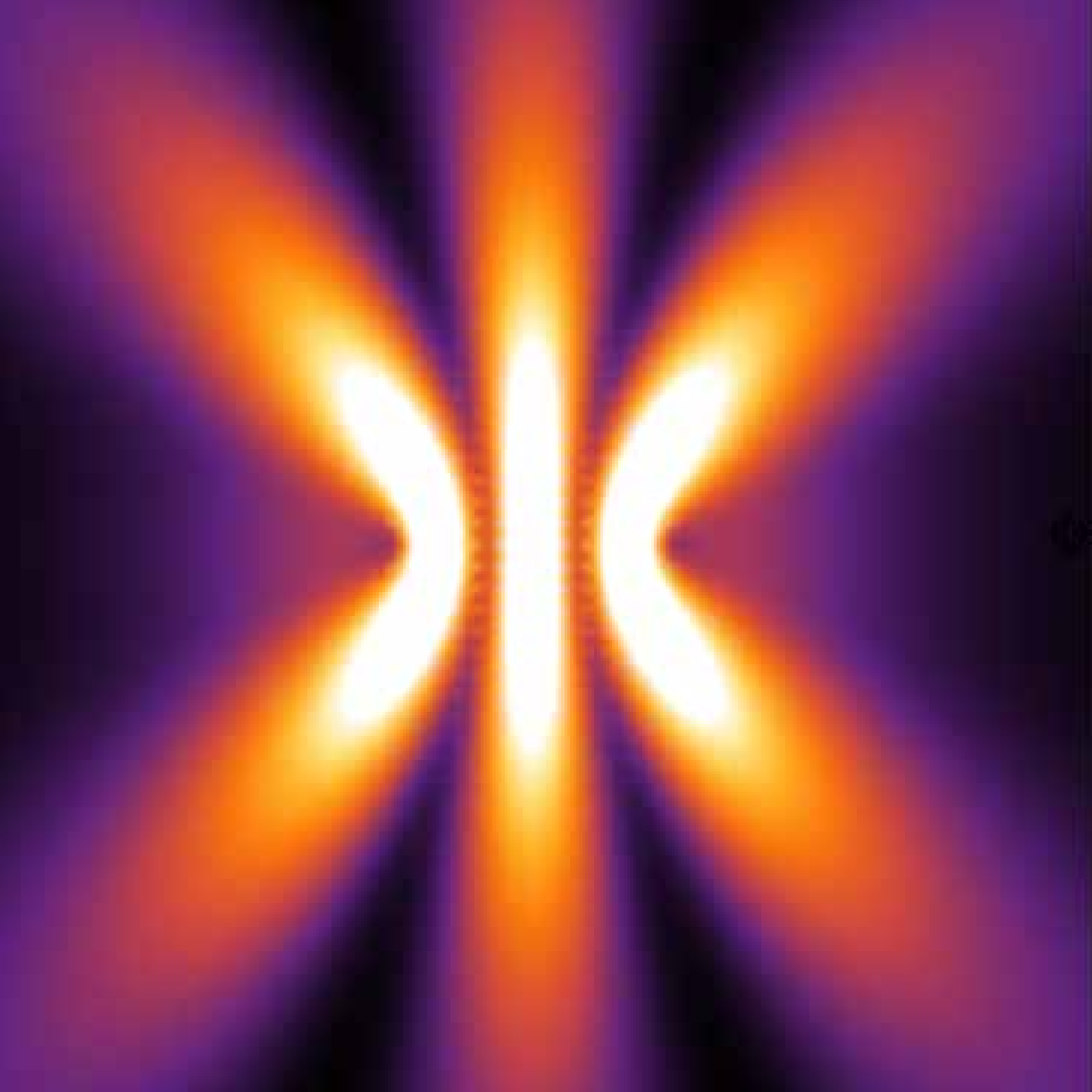


GRAVITATIONAL WAVES

We can imagine gravitational waves as **ripples in the fabric of space-time**, vibrations in the structure of the Universe itself. They propagate by deforming space-time, and thus all objects, for a fraction of a second as they pass through.

Gravitational waves are generated by **the most violent and extreme cosmic phenomena, such as the collisions of black holes and neutron stars,** extremely heavy and dense objects left behind when stars die. Propagating for millions or billions of years in the Cosmos before they reach us, gravitational waves lose most of their energy and thus the effects they generate on Earth, **space-time vibrations, are incredibly tiny, smaller than the size of an atom:** for this reason **revealing their passage seemed to be an impossible challenge!**

Artistic rendition of two black holes merging



THE FOUNDATION

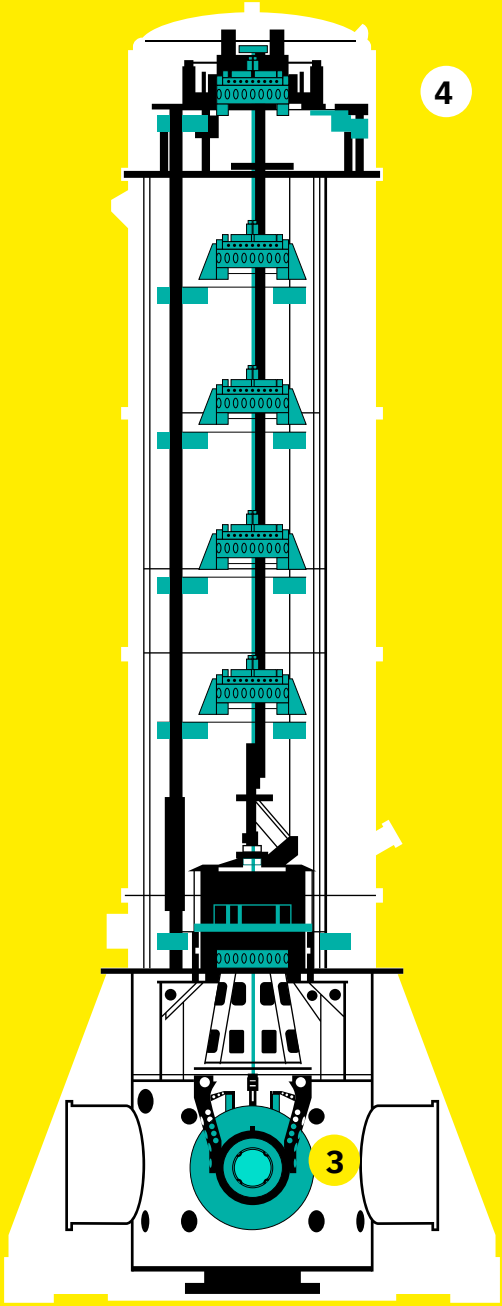


The actual construction of Virgo began in 1996, after the site was selected: a large plain in the countryside near Pisa, in the municipality of Cascina.
The inauguration of the experimental infrastructure on July 23rd 2003, in the presence of ministers from the Italian and French governments and leading members of the international scientific community, **was the culmination of strenuous research and development work on cutting-edge technologies, and of an important institutional and political journey.** In 2000 the European Gravitational Observatory (EGO) was founded, with the mission of managing the research infrastructure's logistical and administrative needs.

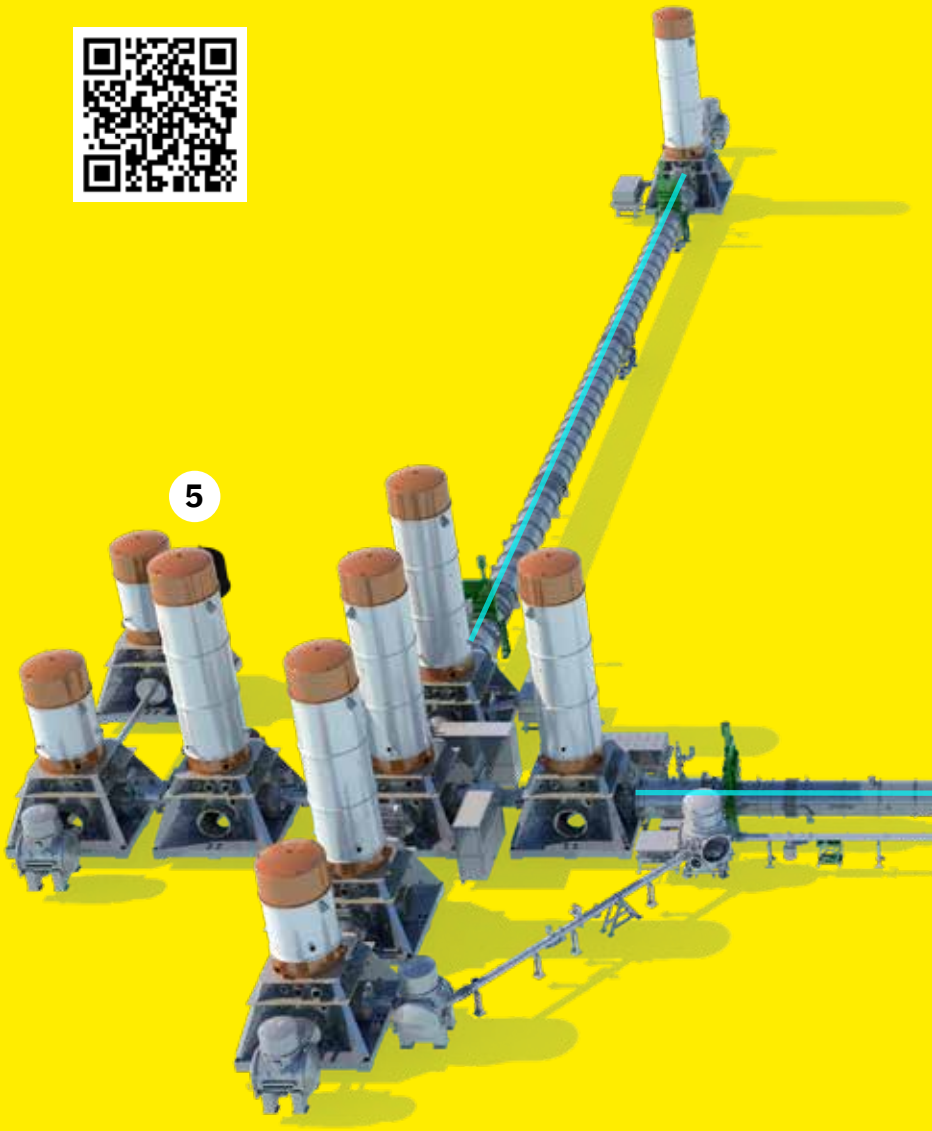
In the same years, also the two LIGO interferometers became operative, but for more than a decade neither Virgo nor the U.S. detectors were able to pick up the long-awaited gravitational signals. The prolonged wait and the uncertainty of the outcome convinced researchers to join forces and create a single global network of interferometers in 2007 so that data could be jointly acquired and analyzed. This network would be joined in 2019 by the Japanese KAGRA detector. The three collaborations together form the LIGO - Virgo - KAGRA International Scientific Collaboration, which now counts nearly 3,000 members.
The EGO consortium, initially French-Italian, has also grown significantly. INFN and CNRS were joined in 2009 by NWO-I (Foundation for Dutch Scientific Research Institutes) as an observer and then in 2022 as an associate member, followed in 2025 by the Belgian research foundations FWO (The Research Foundation - Flanders) and FNRS (Fund for Scientific Research). EGO currently has five funding institutions and four member countries.

pag. 8
Artistic elaboration of a figure of interference of light

pag. 10
The North tunnel of the Virgo detector: on the left the main tube of the interferometer, on the right the squeezing cavity, where the laser is injected to reduce quantum noise.



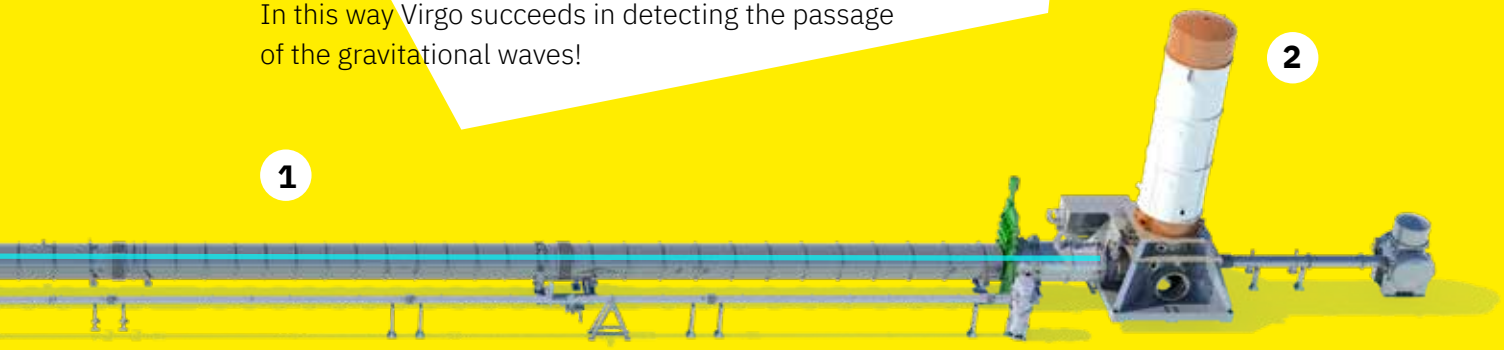
watch
the animation

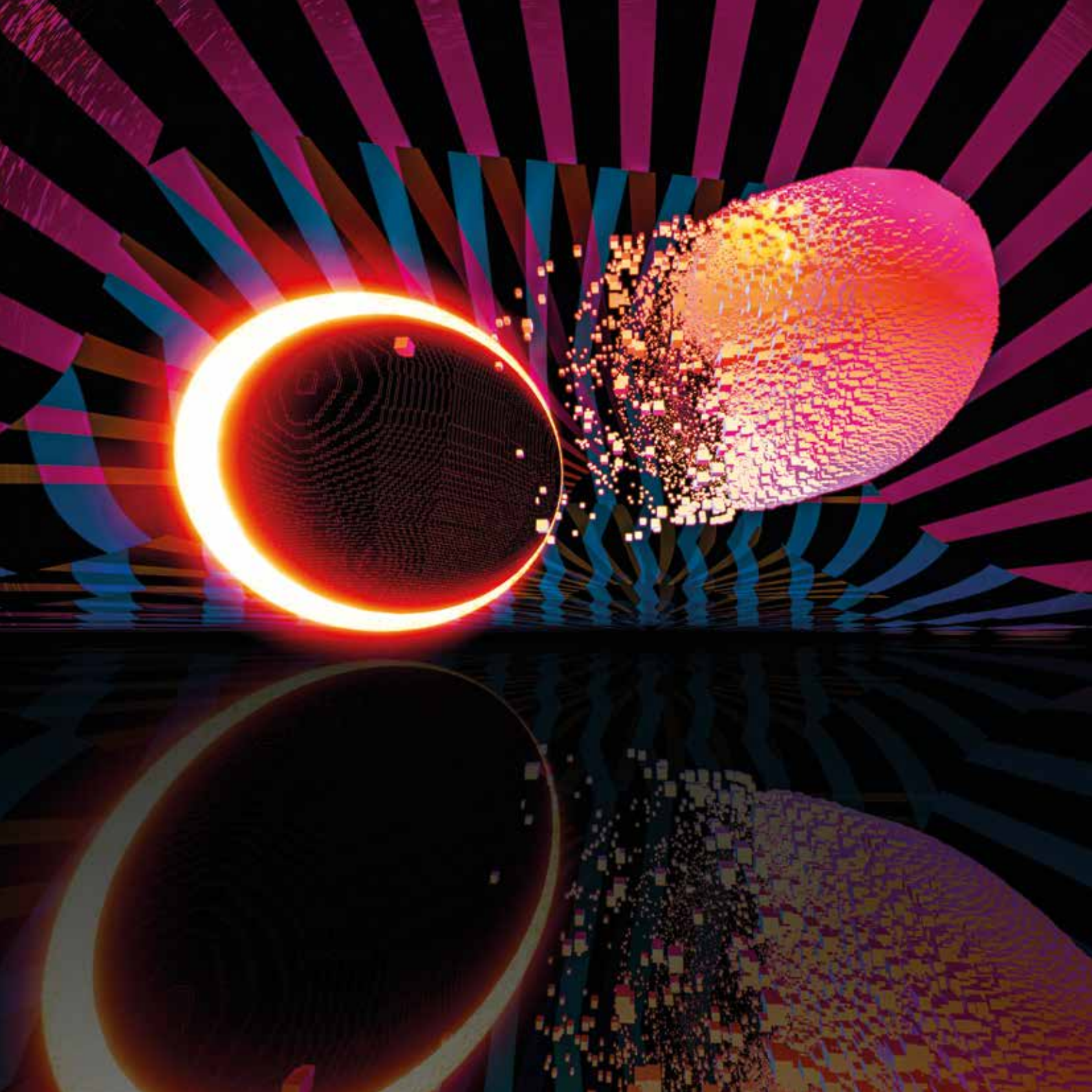


INTER FERO METER

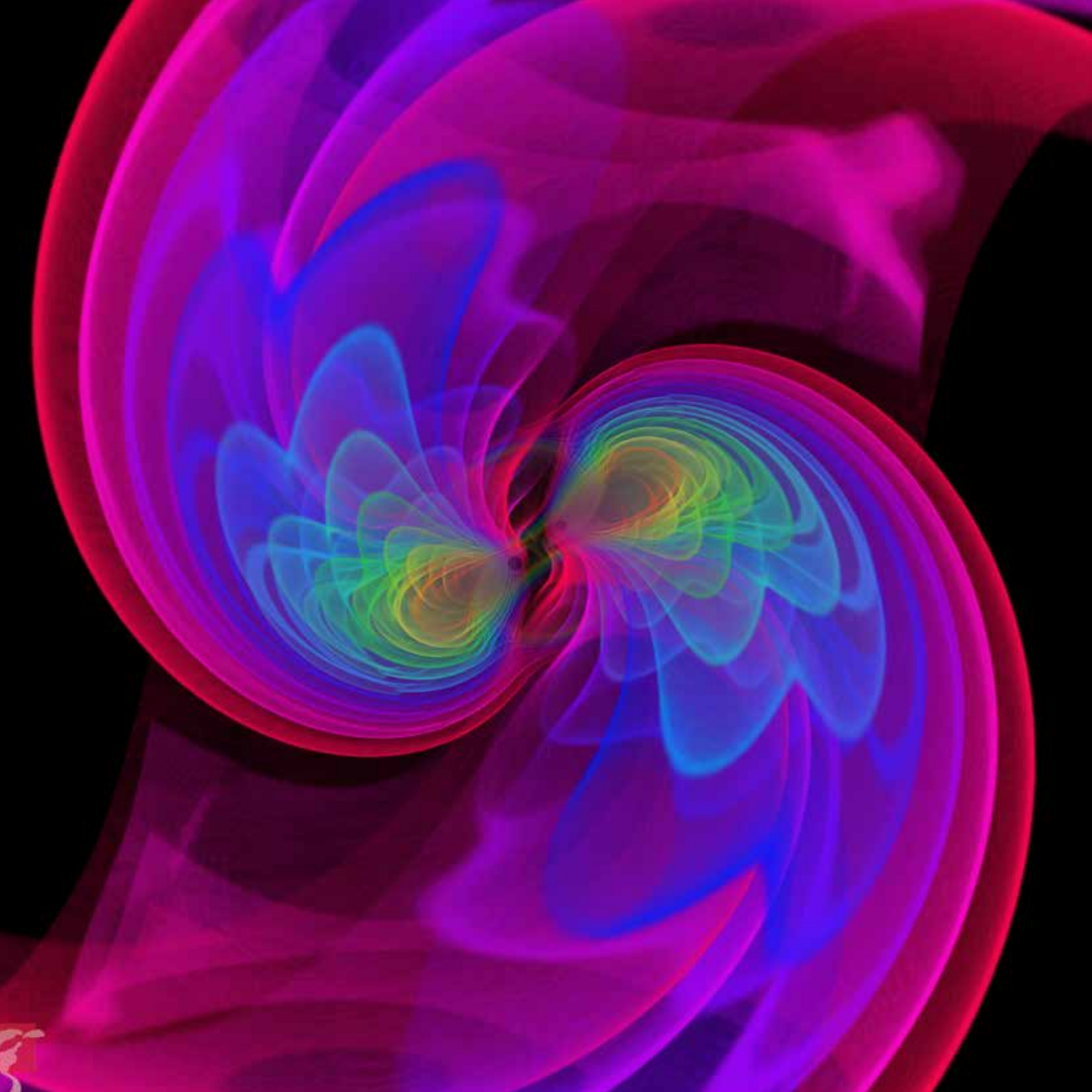
To reveal the passage of these imperceptible oscillations of space-time, **Virgo uses the interference of two laser beams, which propagate, in ultra-high vacuum, along two perpendicular 3-kilometer arms**(1)**.** At their ends, **inside 11-meter-high vacuum bells**(2)**, two super-reflective, flat mirrors**(3) **are suspended by very thin glass fibers from large earthquake-proof shock absorbers**(4), which keep them perfectly still.
The mirrors reflect laser beams, which rejoin at the intersection of the arms(5), producing a peculiar interference pattern.

As a gravitational wave passes through, the arms are deformed for a fraction of a second, one becoming longer and one shorter by an amount equal to one thousandth of the diameter of a proton (or one millionth of a billionth of a millimeter). This changes the path length of the two lasers, and thus changes the interference pattern. In this way Virgo succeeds in detecting the passage of the gravitational waves!





A NEW ASTRONOMY



The discovery of gravitational waves, announced in February 2016 by the Scientific Collaborations of LIGO and Virgo is a milestone in the history of Astronomy and has triggered a scientific revolution, which many consider comparable to that achieved by Galileo with his telescope. Beyond the confirmation of Einstein's prediction, **the ability to detect gravitational waves has indeed given us a new way, a new 'sense', to listen to the most remote cosmic signals.** It has allowed us, for example, to obtain new information about black holes, their masses, their distribution and the way they form, illuminating a cosmic landscape we did not know. Moreover, in 2017, the discovery earned LIGO scientists Rainer Weiss, Barry Barish and Kip Thorne the Nobel Prize.

Virgo, mentioned in the motivation for the prize, had not participated experimentally in the detection of the first gravitational signal, which took place in September 2015, but participated in the analysis of the data. Two years later, however, it would make a decisive contribution to another major milestone.
On August 17th 2017, the two interferometers LIGO and Virgo identified for the first time the gravitational signal of a very special cosmic event: the merger of two neutron stars.
In these collisions signals of a completely different nature are generated in addition to gravitational waves: radio waves, visible light, X-rays, gamma rays...
On that day, the triangulation of the three gravitational detectors made it possible to identify the direction of the astrophysical source and to perform, for the first time, a coordinated observation of the same cosmic phenomenon by more than 70 telescopes on the planet and satellites. Thus began what scientists call the Multimessenger Astronomy era.

pag. 14
Artist's visualization of a merger between a black hole and a neutron star.

pag. 16
Numerical simulation of black-hole binary merger GW150914



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Universidade de Coimbra

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Gravitational Wave Science Center, UniGe

INTERNATIONAL NETWORKS

An international community of around 1000 members, from 160 institutions in 17 countries is committed to operate the Virgo gravitational wave detector, hosted by the European Gravitational Observatory in Cascina (PI), and to analyze the data it produces. The members of the collaboration cover a wide variety of roles, **including physicists, mathematicians, engineers and technicians.**

Scientists of the Virgo Collaboration work together with scientists from LIGO and KAGRA to form the LIGO-Virgo-KAGRA Collaboration (LVK). This is a global network of scientists collaborating on the operation of the four biggest gravitational wave detectors currently existing in the world and the production of coordinated scientific results. Also GEO600, a smaller gravitational wave detector in Germany, contributes to the scientific and technological achievements of the international network, hosting crucial R&D activities.



LISTENING TO THE ENVIRONMENT



To detect gravitational waves, deformations of space-time smaller than the size of an atom, EGO and Virgo scientists had to make use of state-of-the-art technologies, many of which were developed for the first time for this purpose.

One of the most extreme and fascinating technological challenges is **to discriminate gravitational signals from all possible 'noises' generated by the environment or by human beings:** atmospheric phenomena, seismic ground vibrations, waves in the nearby sea, road traffic, wind turbines, helicopters or airplanes.... This is why EGO contains and operates the largest volume of ultra-high vacuum in Europe (the third in the world), to isolate the laser and the other components of the experiment. The latter, and in particular the mirrors, are suspended from large seismic dampers, multiple pendulum towers 11 meters high, which are another another core technology of Virgo.

Nonetheless, some faint noises can get past the sophisticated isolation systems and reach the interferometer, so constant environmental monitoring is in place, allowing, through intelligent algorithms, to identify and subtract spurious signals from the detector output in real time.
Virgo therefore is not only observing the deep universe, but is also **a very sensitive ear listening to the environment, recording information that in the future could help us study the Earth, the sea or the climate.**

pag. 20
The north arm of the Virgo interferometer

pag. 22
The west arm of the Virgo interferometer, and the end building of the mode cleaner cavity, which cleans the laser before it enters the interferometer

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DATA

In one year of observations Virgo collects over 1 PB of data, equivalent to 150 computers streaming a film simultaneously. This is not only the output of the detector, but also a huge amount of what is called “auxiliary data.” At all times Virgo monitors its surroundings (seismic activity, human activity, wind, thunderstorms, sea waves...) so that **scientists can get an accurate picture of the environmental conditions at the time of gravitational signal detections**.

When a gravitational wave reaches Virgo the first identification is made by an automatic algorithm, which recognises the possible signal in the data. This produces an alert: a team of scientists is immediately activated and within minutes they assess the reliability of the detection. If it is considered valid, **an approximate location of the event that generated the gravitational signal is communicated to a global network of telescopes on Earth and in space.** The aim is to hunt down other signals of a different nature (mainly electromagnetic) emitted by the same cosmic event, as was already the case in the famous multi-messenger observation of August 17th 2017.

Text file of the data collected by the Virgo detector



VACUUM, LIGHT AND MIRRORS


Frigerio

Virgo's towers, where the mirrors and their superattenuators are located, are in a state known as ultra-high vacuum, **the closest thing to an absolute vacuum existing on Earth, with a residual pressure of about 10^{-9} millibars, similar to that of deep space.** This arduous technological feat makes it possible to prevent dust contamination from ruining Virgo's delicate components, and to ensure that the path of the laser light is not deflected by the presence of air and other particles.

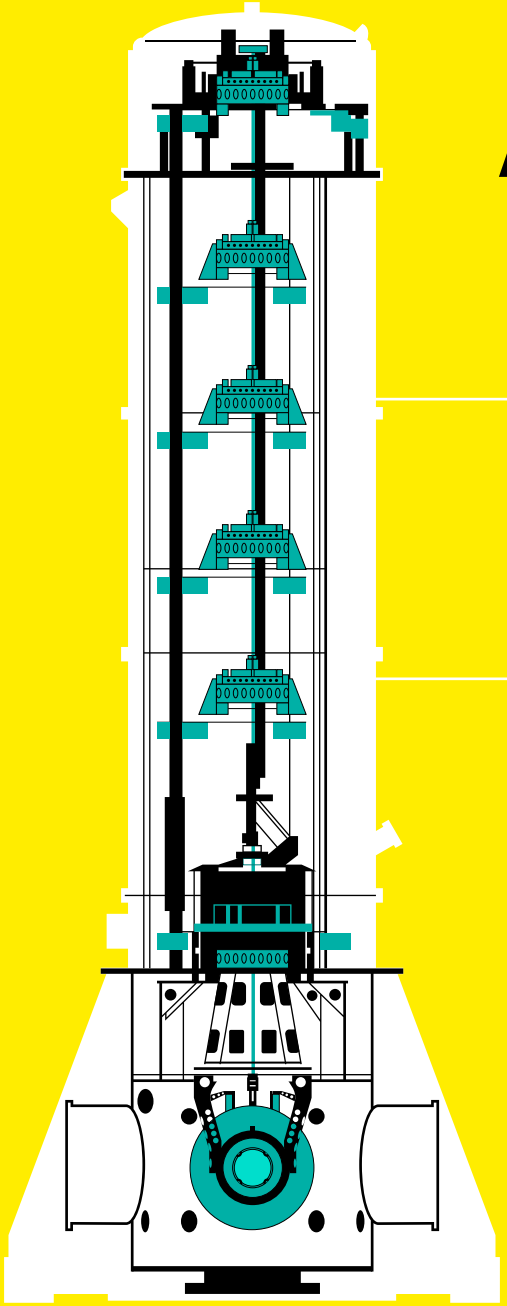
Superattenuators are a sophisticated technology, specially designed and manufactured by Virgo researchers, with which it is possible to attenuate by more than a trillion times all the vibrations that could reach the detector mirrors. They consist of a **long chain of pendula and a series of active sensors and controls regulated by a sophisticated electronic system.** Suspended from these extraordinary and extremely sensitive attenuators by means of very thin glass fibres are the ultra-flat mirrors on which the laser is reflected. To minimise any mechanical dissipation, the fibres, less than half a millimetre thick, are made of the same material used for the mirror substrates, fused silica. Making them and suspending the mirrors requires sophisticated technology.

Finally, the detector mirrors are unique objects built (also for LIGO) in a Virgo laboratory in Lyon, France. Designed to reflect the laser's infrared light, they are transparent to visible light.
They are cylinders of the purest quartz weighing 42 kg, to which a 7 µm (0.0007 cm) coating is applied to reflect 99.9999% of the light. To prevent the light beam from being scattered, the surface of the mirror must be perfectly flat with a precision to the level of a dozen atoms.

pag. 26
Virgo scientist working on the mirror of the mode cleaner cavity, which cleans the laser before it enters the interferometer

pag. 28
Two researchers in Virgo's central building, where you can find most of the ultra-high-vacuum towers hosting the mirrors and superattenuators of Virgo

TECHNOLOGICAL ACHIEVEMENTS

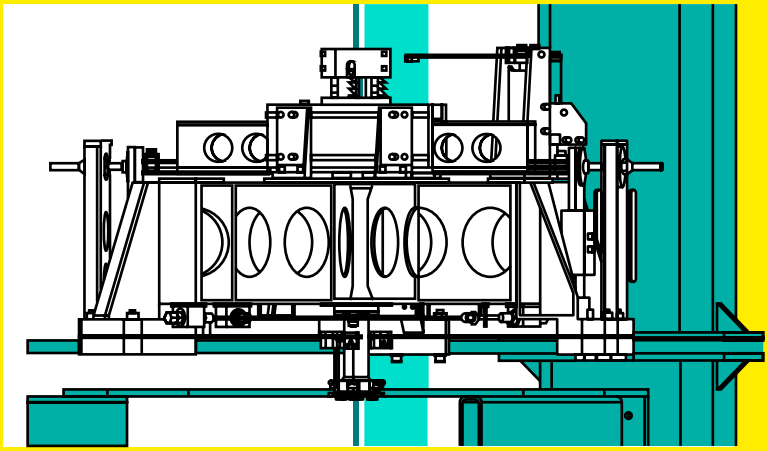


Superattenuators and noise reduction

Suspensions attenuation:	**a factor of 10^{12}**
No. of environmental sensors:	**over 1,000**

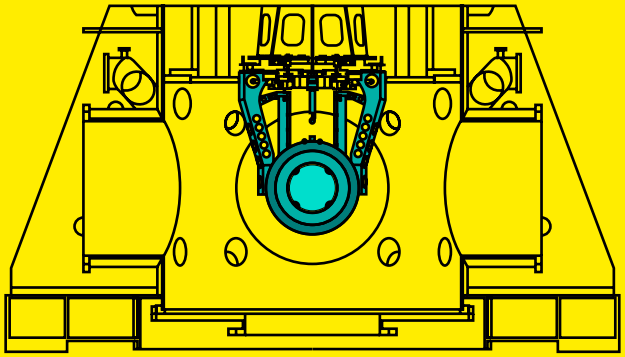
Vacuum

Volume:	**7000 m^3**
Area:	**23000 m^2**
Level:	**up to 10^{-9} millibars**
No. of pumping stations:	**30**



Mirrors

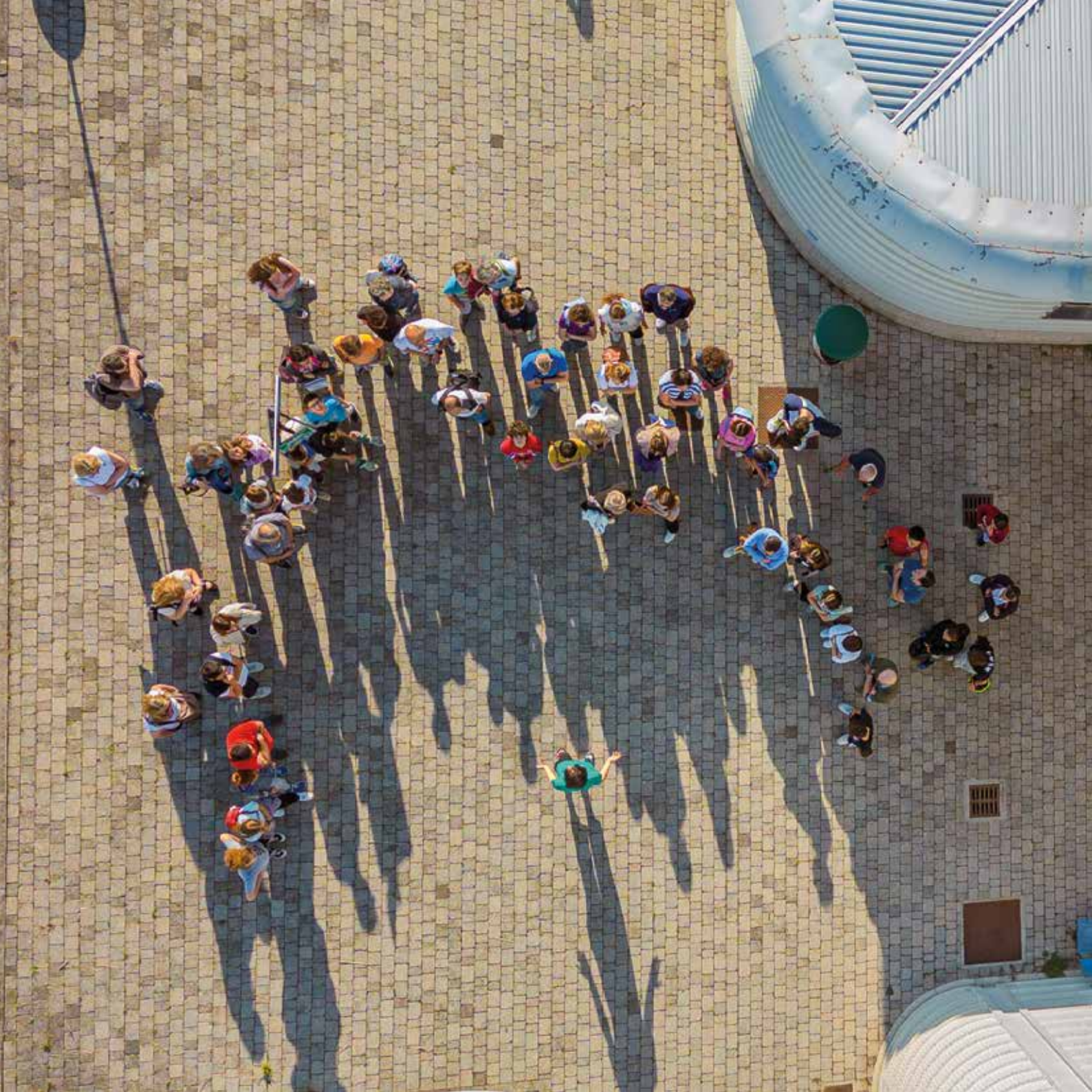
weight: **40 kg**
diameter: **35 cm**
surface distortion: **0.01 micron**
percentage
of reflected light: **99.9999%**
glass fibre thickness: **0.4 mm**



Laser

Power in the arms:
approx. 90kW

equivalent
km travelled
by a photon: **900 km**



ENGAGING COMMUNITIES



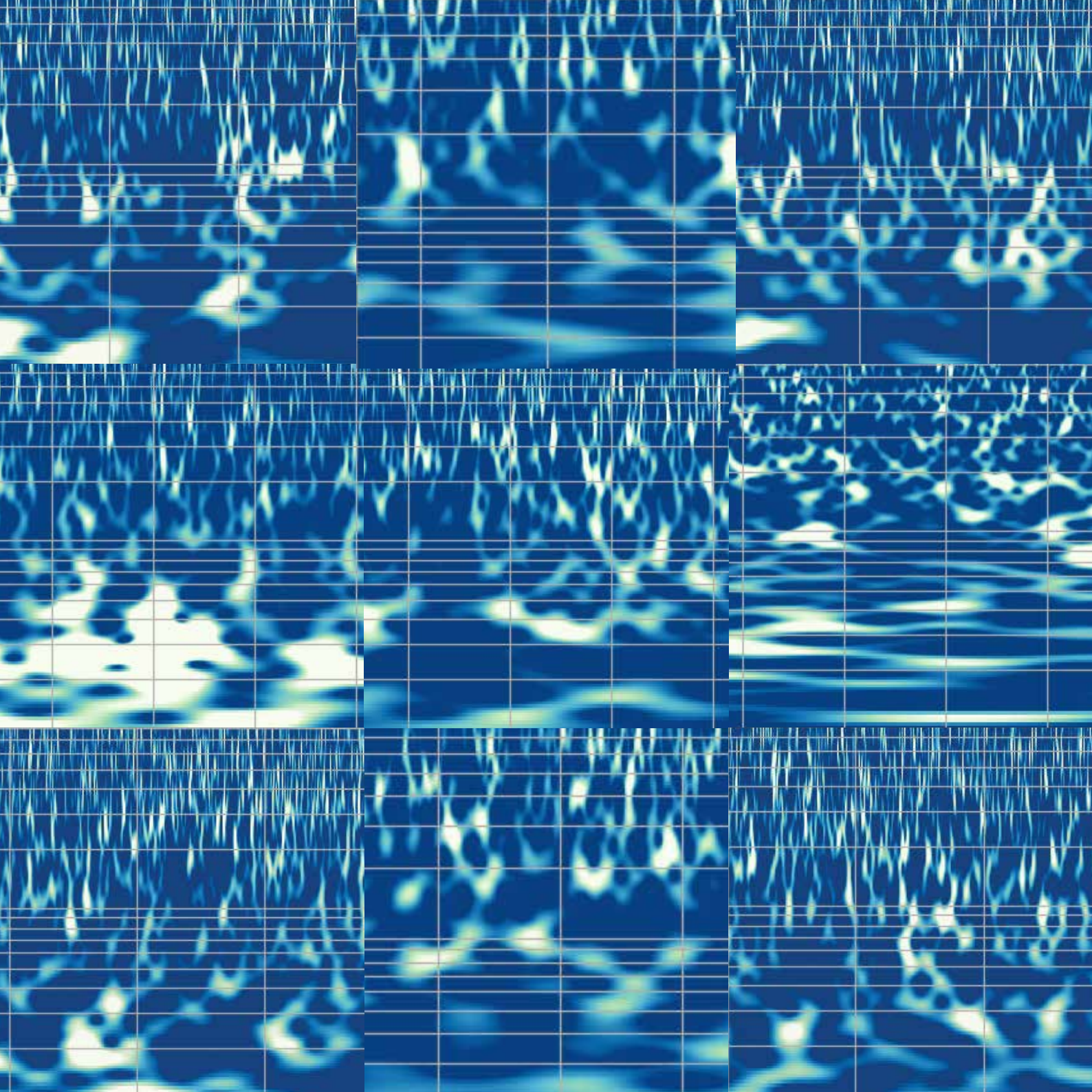
The European Gravitational Observatory and the Virgo Collaboration are constantly engaged in initiatives aimed at the general public on a local, national and international scale. The experiment is accessible to the public regularly twice a week and has become in recent years **one of the main destinations for science tourism in Italy, reaching over 10,000 visitors a year from all over the world.**

A privileged channel of communication is with young people, students of all ages and schools, who come to visit or encounter Virgo's research in conference-shows, exhibitions or cultural festivals.
In these contexts, in order to involve all kinds of audiences, EGO has created **interactive and multimedia installations, role-playing games, and even a van,** which tours Europe, bringing the story of gravitational waves to the streets, as well as to the most peripheral neighbourhoods: the Big Bang Machine.

Another avenue that we have explored to tell the story of science is that of dialogue, and sometimes a real fusion, with art.
Numerous artists, including internationally renowned ones, have been inspired by the magic of gravitational waves: Virgo has been the protagonist of major art exhibitions, land art works, musical elaborations, theatrical performances and much more.

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A group of visitors during the EGO Open Day

pag. 34
Giulia Perelli and Amedeo Balbi during the event 'The Hidden Music of the Universe' at EGO, July 2025



Discover GWitchHunters:

SCIENCE FOR ALL

Everyone, even those with no scientific background, can contribute to the search for gravitational waves. In fact, a few years ago EGO and Virgo launched a citizen science programme, which allows all enthusiasts, thanks to an online app (GWitchHunters), **to help scientists isolate gravitational signals from external or interferometer-generated disturbances (so-called glitches)**.
After a short online training session, people of all ages can help to erase annoying 'noise' from Virgo's data that could mask the wave signal, like real scientists.

Another way in which we are enabling more and more people to access Virgo's data is through sonification, its transformation into sound. Thanks to this process we can hear, for example, a sound that represents the echo of black hole mergers that took place millions or billions of light years away from Earth. **Sonification not only gives us the experience of listening to cosmic signals, but also allows blind people access to scientific data.** Moreover, it can become an additional tool for analysing signals, which could help us to grasp aspects and details hidden in the data displayed on a screen. In the future, therefore, even the hunt for 'noises' that disturb the interferometer may become more auditory than visual.

pag. 36
A visual display of Virgo detector glitches, as they appear in the citizen science app Gwitchunters




THE
FUTURE



The era of gravitational astronomy has just begun, and there are countless questions that could be answered. **We only know about 5% of the matter in the universe; the remaining portion is composed of dark matter and dark energy, the nature of which is completely unknown.** Studying black holes and finding out what happens during the most violent events in the cosmos will provide us with valuable information to investigate these and other mysterious puzzles.

While the LIGO, Virgo and KAGRA detectors will continue to be improved to the limits of their sensitivity, work has already begun on the design and construction of their descendants, the third-generation gravitational wave interferometers. The one to be built in Europe will be called the Einstein Telescope (ET), in honor of the physicist who first theorized the existence of gravitational waves.

ET will have arms about five times longer than Virgo's, it will be built underground to minimize disturbances from environmental noise, and it will be able to take advantage of even more innovative technologies, thanks to years of research and experience gained with existing detectors. This will enable it to reach levels of sensitivity now unthinkable, observe increasingly faint and distant signals, and even **listen to the gravitational echo of the origin itself of the Universe, the Big Bang.**
The most 'silent' and already naturally empty place for a large gravitational interferometer, however, is space. Therefore, **the mission of the European Space Agency LISA (Laser Interferometer Space Antenna) will be a gigantic, triangular-shaped space detector**. Laser light will travel in the vacuum of space between its vertices, that are orbiting around the sun at a distance of 2.5 million kilometres from each other.

pag. 38
Virgo scientists in the control room of the detector

pag. 40
The west arm of the Virgo interferometer (right), and the tunnel of the mode cleaner cavity (left), which cleans the laser before it enters the interferometer

pag. 42-43
EGO and Virgo scientists dressed as they would to enter the ultra-high vacuum towers or the clean rooms of Virgo





EGO EUROPEAN GRAVITATIONAL OBSERVATORY VIRGO

The European Gravitational Observatory is a consortium of:

INFN Istituto Nazionale di Fisica Nucleare · cnrs · NWO · fwo · fnrs FREEDOM OF RESEARCH

Virgo is part of the LIGO-Virgo-KAGRA Collaboration

LIGO VIRGO KAGRA

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