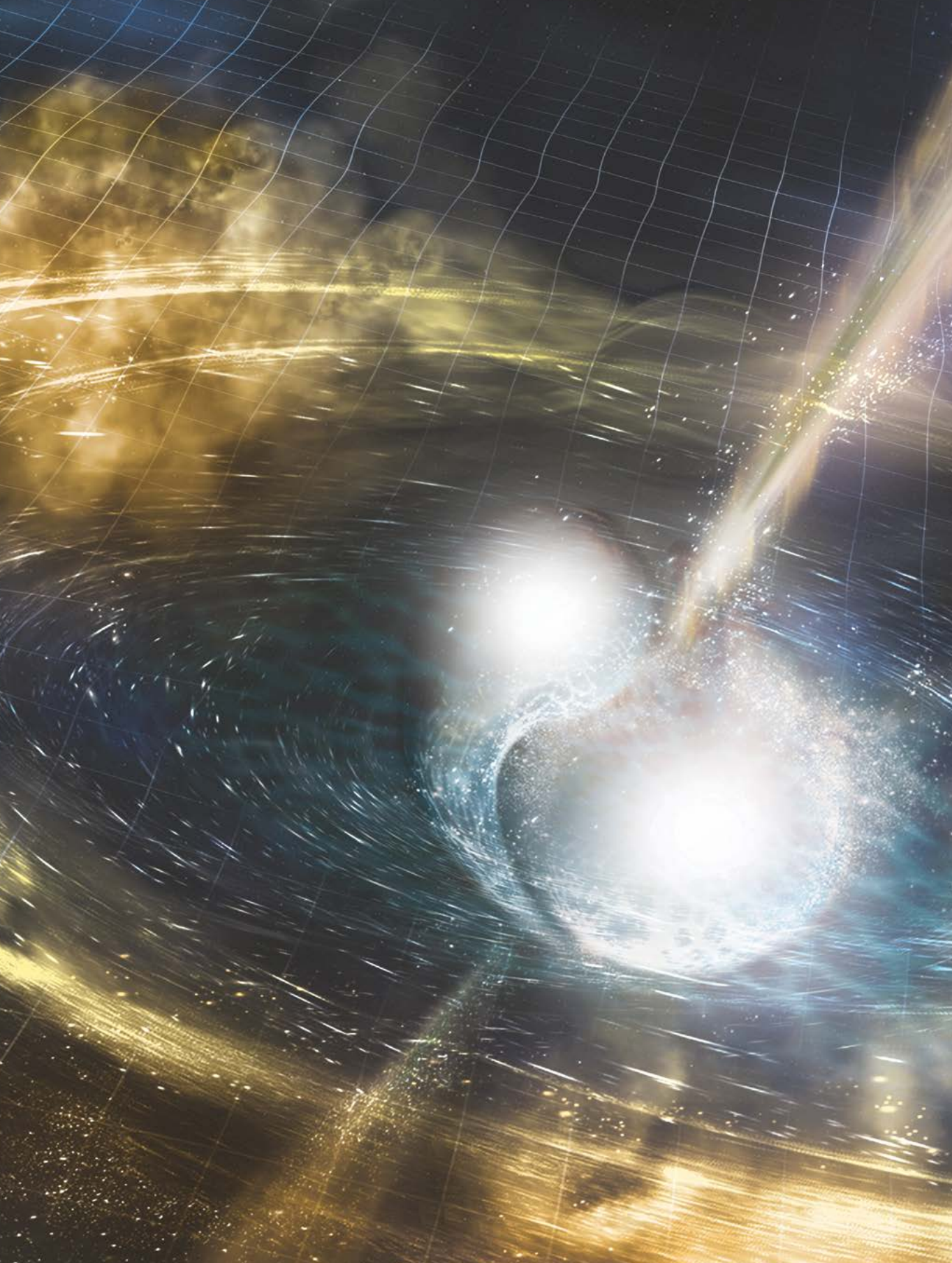




Gravitational waves

Gravitational waves and the birth of a new science

The recent observation of a neutron-star merger in the gravitational and electromagnetic domains opens the era of multi-messenger astronomy and calls for new gravitational-wave observatories to reveal the universe in all its colours.

On 14 September 2015, the world changed for those of us who had spent years preparing for the day when we would detect gravitational waves. Our overarching goal was to directly detect gravitational radiation, finally confirming a prediction made by Albert Einstein in 1916. A year after he had published his theory of general relativity, Einstein predicted the existence of gravitational waves in analogy to electromagnetic waves (i.e. photons) that propagate through space from accelerating electric charges. Gravitational waves are produced by astrophysical accelerations of massive objects, but travel through space as oscillations of space–time itself.

It took 40 years before the theoretical community agreed that gravitational waves are real and an integral part of general relativity. At that point, proving they exist became an experimental problem and experiments using large bars of aluminium were instrumented to detect a tiny change in shape from the passage of a gravitational wave. Following a vigorous worldwide R&D programme, a potentially more sensitive technique – suspended-mass interferometry – has superseded resonant-bar detectors. There was limited theoretical guidance regarding what sensitivity would be required to achieve detections from known astrophysical sources. But various estimates indicated that a strain ▷

An illustration of two merging neutron stars, as recently detected by LIGO–Virgo, during which bursts of gamma rays are emitted just seconds after the gravitational waves, along with swirling clouds of material including gold and other heavy metals. (Image credit: NSF/LIGO/Sonoma State University/A Simonnet.)

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sensitivity $\Delta L/L$ of approximately 10^{-21} caused by the passage of a gravitational wave would be needed to detect known sources such as binary compact objects (binary black-hole mergers, binary neutron-star systems or binary black-hole neutron-star systems). That's roughly equivalent to measuring the Earth–Sun separation to a precision of the proton radius.

The US National Science Foundation approved the construction of the Laser Interferometer Gravitational-Wave Observatory (LIGO) in 1994 at two locations: Hanford in Washington state and Livingston in Louisiana, 3000 km away. At that time, there was a network of cryogenic resonant-bar detectors spread around the world, including one at CERN, but suspended-mass interferometers have the advantage of broadband frequency acceptance (basically the audio band, 10–10,000 Hz) and a factor-1000 longer arms, making it feasible to measure a smaller $\Delta L/L$. Earth-based detectors are sensitive to the most violent events in the universe, such as the merger of compact objects, supernovae and gamma-ray bursts. The detailed interferometric concept and innovations had already been demonstrated during the 1980s and 1990s in a 30 m prototype in Garching, Germany, and a 40 m prototype at Caltech in the US. Nevertheless, these prototype interferometers were at least four orders of magnitude away from the target sensitivity.

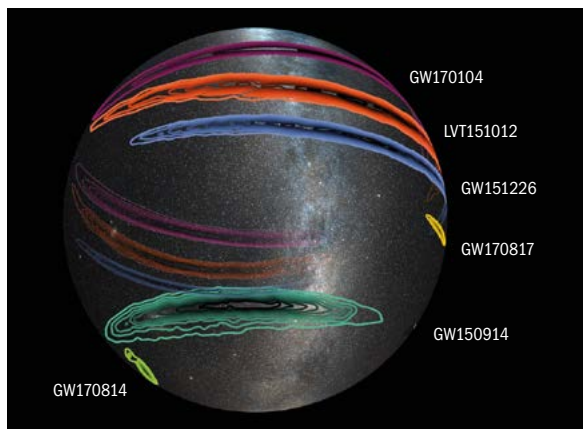
Strategic planning

We built a flexible technical infrastructure for LIGO such that it could accommodate a future major upgrade (Advanced LIGO) without rebuilding too much infrastructure. Initial LIGO had mostly used demonstrated technologies to assure technical success, despite the large extrapolation from the prototype interferometers. After completing Initial LIGO construction in about 2000, we undertook an ambitious R&D programme for Advanced LIGO. Over a period of about 10 years, we performed six observational runs with Initial LIGO, each time searching for gravitational waves with improved sensitivity. Between each run, we made improvements, ran again, and eventually reached our Initial LIGO design sensitivity. But, unfortunately, we failed to detect gravitational waves.

We then undertook a major upgrade to Advanced LIGO, which had the goal of improving the sensitivity over Initial LIGO by at least a factor of 10 over the entire frequency range. To accomplish this, we developed a more powerful NdYAG laser system to reduce shot noise at high frequencies, a multiple suspension system and larger test masses to reduce thermal noise in the middle frequencies, and introduced active seismic isolation, which reduced seismic noise at frequencies of around 40 Hz by a factor of 100 (CERN Courier January/February 2017 p34). This was the key to our discovery of our first 30 solar-mass binary black-hole mergers,

which are concentrated at low frequencies, two years ago. The increased sensitivity to such events had expanded the volume of the universe searched by a factor of up to 10^6 , enabling a binary black-hole-merger detection coincidence within 6 ms between the Livingston and Hanford sites.

Then, on 17 August, we really hit the jackpot.



LIGO/Virgo/NASA/J. Singer (Milky Way image: Axel Mellinger)

Sky localisations of gravitational-wave signals detected by LIGO beginning in 2015 (GW150914, LVT150102, GW151226, GW170104) and, more recently, by the LIGO–Virgo network (GW170814, GW170817). The latter illustrate the improvement in localising the source thanks to the additional detector.

We recorded the last 0.2 seconds of this astrophysical collision: the final merger; coalescence; and “ring-down” phase, constituting the first direct observation of gravitational waves. The waveform was accurately matched by numerical-relativity calculations with a signal-to-noise ratio of 24:1 and a statistical probability easily exceeding 5σ . Beyond confirming Einstein’s prediction, this event represented the first direct observation of black holes, and established that stellar black holes exist in binary systems and that they merge within the lifetime of the universe (CERN Courier January/February 2017 p16). Surprisingly, the two black holes were each about 30 times the mass of the Sun – much heavier than expectations from astrophysics.

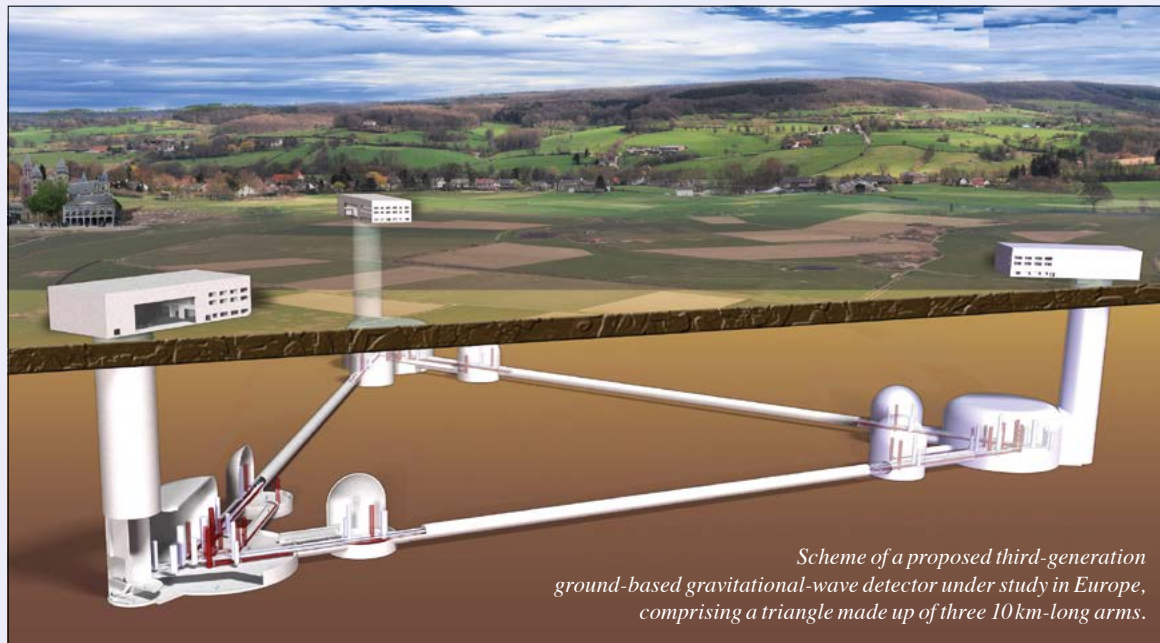
Run 2 surprises

Similar to Initial LIGO, we plan to reach Advanced LIGO design sensitivity in steps. After completion of the four-month-long first data run (called O1) in January 2016, we improved the interferometer at the Livingston site from 60 Mpc to 100 Mpc for binary neutron-star mergers, but fell somewhat short in Hanford due to some technical issues, which we decided to fix after LIGO’s second observational run (O2). We have now reported a total of four black-hole-merger events and are beginning to determine characteristics such as mass distributions and spin alignments that will help distinguish between the different possibilities for the origin of such heavy black holes. The leading ideas are that they originate in low-metallicity parts of the universe, were produced in dense clusters, or are primordial. They might even constitute some of the dark matter.

Advanced LIGO’s O2 run ended in August this year. Although it seemed almost impossible that it could be as exciting as O1, several more black-hole binary mergers have been reported, including one after the Virgo interferometer in Italy joined O2 in August and dramatically improved our ability to locate the direction of the source. In addition, the orientation of Virgo relative to the two LIGO interferometers enabled the first information on the polarisation of ▸

CERN LIGO–Virgo meeting weighs up 3G gravitational-wave detectors

Max Planck Institute for Gravitational Physics



Scheme of a proposed third-generation ground-based gravitational-wave detector under study in Europe, comprising a triangle made up of three 10 km-long arms.

Similar to particle physicists, gravitational-wave scientists are contemplating major upgrades to present facilities and developing concepts for next-generation observatories. Present-generation (G2) gravitational-wave detectors – LIGO in Hanford, Livingston and India, Virgo in Italy, GEO600 in Germany and KAGRA in Japan – are in different stages of development and have different capabilities (see main text), but all are making technical improvements to better exploit the science potential from gravitational waves over the coming years. As the network develops, the more accurate location information will enable the long-time dream of studying the same astrophysical event with gravitational waves and their electromagnetic and neutrino counterpart signals.

The case for making future, more sensitive next-generation gravitational-wave detectors is becoming very strong, and technological R&D and design efforts for 3G gravitational detectors may have interesting overlaps with both CERN capabilities and future directions. The 3G concepts have many challenging new features, including: making longer arms; going underground; incorporating squeezed quantum states; developing lower thermal-noise coatings; developing low-noise cryogenics; implementing Newtonian noise cancellation; incorporating adaptive controls; new computing capabilities and strategies; and new data-analysis methods.

In late August, coinciding with the end of the second Advanced LIGO observational run, CERN hosted a LIGO–Virgo collaboration meeting. On the final day, a joint meeting between LIGO–Virgo and CERN explored possible synergies between the two fields. It provided strong motivation for next-generation facilities in both particle and gravitational physics and revealed intriguing overlaps between them. On a practical level, the event identified issues facing both communities, such as geology and survey, vacuum and cryogenics, control systems, computing and governance.

The time for R&D, construction and commissioning is expected to be around a decade, with problems near to intractable. It is planned to use cryogenics to bring mirrors to the temperature of a few kelvin. The mirrors themselves are coated using ion beams for deposition, to obtain a controlled reflectivity that must be uniform over areas 1 m in diameter. These mirrors work in an ultra-high vacuum, and residual gas-density fluctuations must be minimal along a vacuum cavity of several tens of kilometres, which will be the approximate footprint of the 3G scientific infrastructure.

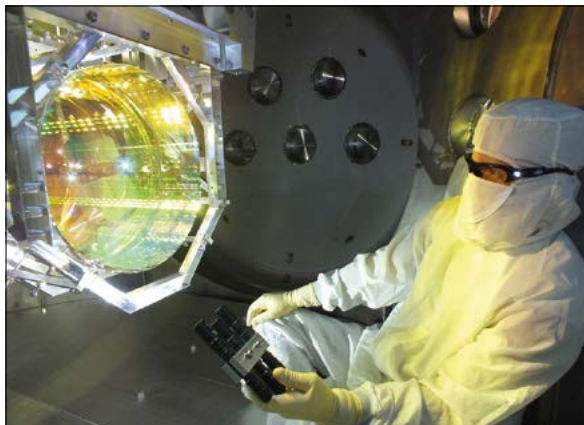
Data storage and analysis is another challenge for both gravitational and particle physicists. Unlike the large experiments at the LHC, which count or measure energy deposition in millions of pixels at the detector level, interferometers continuously sample signals from hundreds of channels, generating a large amount of data consisting of waveforms. Data storage and analysis places major demands on the computing infrastructure, and analysis of the first gravitational events called for the GRID infrastructure.

Interferometers have to be kept on an accurately controlled working point, with mirrors used for gravitational-wave detection positioned and oriented using a feedback control system, without introducing additional noise. Sensors and actuators are different in particle accelerators but the control techniques are similar.

Comparisons of the science capabilities, costs and technical feasibility for the next generation of gravitational-wave observatories are under active discussion, as is the question of how many 3G detectors will be needed worldwide and how similar or different they need be. Finally, there were discussions of how to form and structure a worldwide collaboration for the 3G detectors and how to manage such an ambitious project – similar to the challenge of building the next big particle-physics project after the LHC.

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Matt Heintze/Catech/MIT/LIGO Lab



Inspecting LIGO's optics for contaminants.

the gravitational waves. Together with other measurements, this allowed us to limit the existence of an additional tensor term in general relativity and showed that the LIGO–Virgo event is consistent with the predicted two-state polarisation picture.

Then, on 17 August, we really hit the jackpot: our interferometers detected a neutron-star binary merger for the first time. We observed a coincidence signal in both LIGO and Virgo that had strikingly different properties from the black-hole binary mergers we had spotted earlier. Like those, this event entered our detector at low frequencies and propagated to higher frequencies, but lasted much longer (around 100 s) and reached much higher frequencies. This is because the masses in the binary system were much lower and, in fact, are consistent with being neutron stars. A neutron star results from the collapse of a star into a compact object of between 1.1–1.6 solar masses. We have identified our event as the merger of two neutron stars, each about the size of Geneva, but having several hundred thousand times the mass of the Earth.

As we accumulate more events and improve our ability to record their waveforms, we look forward to studying nuclear physics under these extreme conditions. This latest event was the first observed gravitational-wave transient phenomenon also to have electromagnetic counterparts, representing multi-messenger astronomy. Combining the LIGO and Virgo signals, the source of the event was narrowed down to a location in the sky of about 28 square degrees, and it was soon recognised that the Fermi satellite had detected a gamma-ray burst shortly afterwards in the same region. A large and varied number of astronomical observations followed. The combined set of observations has resulted

An ultimate goal is to use gravitational waves to study the Big Bang itself.

in an impressive array of new science and papers on gamma-ray bursts, kilonovae, gravitational-wave measurements of the Hubble constant, and more. The result even supports the idea that binary neutron-star collisions are responsible for the very heavy elements, such as platinum and gold.



Virgo Collaboration

Virgo, located near Pisa in Italy, has arms that are 3 km long and was the first detector in Europe – and the third ever – to register a passing gravitational wave.

Going deeper

Much has happened since our first detection, and this portends well for the future of this new field. Both LIGO and Virgo entered into a 15 month shutdown at the end of August to further improve noise levels and raise their laser power. At present, Advanced LIGO is about a factor of two below its design goal (corresponding to a factor of eight in event rates). We anticipate reaching design sensitivity by about 2020, after which the KAGRA interferometer in Japan will join us. A third LIGO interferometer (LIGO-India) is also scheduled for operation in around 2025. These observatories will constitute a network offering good global coverage and will accumulate a large sample of binary merger events, achieve improved pointing accuracy for multi-messenger astronomy, and hopefully will observe other sources of gravitational waves. This will not be the end of the story. Beyond the funded programme, we are developing technologies to improve our instruments beyond Advanced LIGO, including improved optical coatings and cryogenic test masses.

In the longer range, concepts and designs already exist for next-generation interferometers, having typically 10 times better sensitivity than will be achieved in Advanced LIGO and Virgo (see panel on previous page). In Europe, a mature concept called the Einstein Telescope is an underground interferometer facility in a triangular configuration (see panel on previous page), and in the US a very long (approximately 40 km) LIGO-like interferometer is under study. The science case for such next-generation devices is being developed through the Gravitational Wave International Committee (GWIC), which is the gravitational-wave field's equivalent to the International Committee for Future Accelerators (ICFA) in particle physics. Although the science case appears very strong scientifically and technical solutions seem feasible, these are still very early days and many questions must be resolved before a new generation of detectors is proposed.

To fully exploit the new field of gravitational-wave science, we must go beyond ground-based detectors and into the pristine seismic environment of space, where different gravitational-wave sources will become accessible. As described earlier, the lowest frequencies accessible by Earth-based observatories are about 10 Hz. The Laser Interferometer Space Antenna (LISA), a

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European Space Agency project scheduled for launch in the early 2030s, was approved earlier this year and will cover frequencies around 10^{-1} – 10^{-4} Hz. LISA will consist of three satellites separated by 2.5×10^6 km in a triangular configuration and a heliocentric orbit, with light travelling continually along each arm to monitor the satellite separations for deviations from a passing gravitational wave. A test mission, LISA Pathfinder, was recently flown and demonstrated the key performance requirements for LISA in space (CERN Courier January/February 2017 p37).

Meanwhile, pulsar-timing arrays are being implemented to monitor signals from millisecond pulsars, with the goal of detecting low-frequency gravitational waves by studying correlations between pulsar arrival times. The sensitivity range of this technique is 10^{-6} – 10^{-9} Hz, where gravitational waves from massive black-hole binaries in the centres of merging galaxies with periods of months to years could be studied.

An ultimate goal is to study the Big Bang itself. Gravitational waves are not absorbed as they propagate and could potentially probe back to the very earliest times, while photons only take us to within 300,000 or so years after the Big Bang. However, we do not yet have detectors sensitive enough to detect early-universe signals. The imprint also of gravitational waves on the cosmic microwave background has been pursued by the Bicep2 experiment, but background issues so far mask a possible signal.

Although gravitational-wave science is clearly in its infancy, we have already learnt an enormous amount and numerous exciting opportunities lie ahead. These vary from testing general relativity in the strong-field limit to carrying out multi-messenger gravitational-wave astronomy over a wide range of frequencies – as demonstrated by the most recent and stunning observation of a neutron-star merger. Since Galileo first looked into a telescope and saw the moons of Jupiter, we have learnt a huge amount about the universe through modern-day electromagnetic astronomy. Now, we are beginning to look at the universe with a new probe and it does not seem to be much of a stretch to anticipate a rich new era of gravitational-wave science.

● **Barry Barish**, the author of this feature, shared the 2017 Nobel Prize in Physics with Kip Thorne and Rainer Weiss for the discovery of gravitational waves (CERN Courier November 2017 p37).

Résumé

Les ondes gravitationnelles et la naissance d'une nouvelle science

L'observation récente de la fusion d'étoiles à neutrons par les détecteurs d'ondes gravitationnelles LIGO et Virgo, combinée aux mesures électromagnétiques correspondantes, marque le début de l'ère de l'astronomie combinant différentes méthodes. Pour faire avancer au mieux la science des ondes gravitationnelles, de nouveaux observatoires équipés d'interféromètres sont nécessaires. En plus des extensions et des améliorations de LIGO et de Virgo, la communauté élabore des projets pour les détecteurs de la prochaine génération, à la fois sous terre et dans l'espace. Barry Barish, co-lauréat du prix Nobel de physique pour la découverte des ondes gravitationnelles, évoque dans cet article ce qui s'est passé jusqu'ici et ce qui nous attend.

Barry C Barish, LIGO Laboratory, California Institute of Technology.

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Tailor-made positioning solution for nanotomography: mechanical system approaches limit of technical feasibility

At the X-ray light source PETRA III at the DESY research center (German Electron Synchrotron) in Hamburg, Germany, the Helmholtz-Zentrum Geesthacht - Center for Materials and Coastal Research (HZG) operates the Imaging Beamline P05, which includes two experimental hutches, one for nanotomography and one for microtomography. In the nanotomography hutch, X-ray optics for three-dimensional micrographs with resolutions around 100 nm are used. The setup also includes microscopy optics for visible light, used for further magnification of the X-ray micrographs and their transfer to a camera.

With the aim to carry out as many different experiments as possible, the HZG provides two different X-ray optics configurations: An imaging setup, in which the sample is positioned in front of the objective optics, and a cone-beam setup, in which the sample is placed in the diverging beam behind the optics. In both cases, high mechanical stability and precision positioning are essential in order to obtain micrographs of high quality.

However, thanks to the close cooperation of the clients with the engineers and developers from PI (Physik Instrumente), this complex task could be solved in a practice-oriented manner.

A particular challenge was how to configure the control, which was based on an industrial controller. The challenge consisted in controlling almost 50 axes independently of one another while ensuring collision protection. The entire system was finally integrated into the TANGO interface customary for beamlines.

The Base: Granite Platform Supported by Air Bearings

To minimize the effect of vibrations and securely fasten the individual components and stabilize them, relative to one another, a granite base 6.8 m in length forms the basis of the instrument. Another four moving granite platforms driven by linear motors are arranged on this base on air bearings. This makes it possible to position all components with high speed and precision: The sample stage, the X-ray optics, and the detector. The substructure itself, which weighs several tons, is also mounted on air bearings. This allows the entire assembly to be moved out of the



The Z lifting stage performs the height adjustment, tilt correction, and orthogonal alignment, relative to the beam (image: PI / HZG)

X-ray beam with minimal effort when the second experimental station is to be used, while maintaining a stable position as soon as the air flow is switched off.

Complex Sequences during Sample Positioning

The basis of sample positioning is a horizontal positioning unit which moves the sample stage into the beam. It has a travel range of 20 mm, can be subjected to a load of 300 kg and works with a repeatability of 30 nm.

This displacement unit is equipped with three lifting elements which perform the height adjustment, tilt correction, and orthogonal alignment, relative to the beam. It is based on three identical, symmetrically arranged, and position-controlled stepper motors, combined with worm gears and spindle drives. Mounted on this Z stage is an air-bearing supported rotation stage. In developing this stage, the designers had to go push the limits of technical feasibility: What was required was a really "pure" rotary motion of the sample with minimal wobble, radial runout or eccentricity. Only in this case can sharp pictures over 360 degrees be made which all refer to the same volume element and can all be clearly assigned when reconstructing the picture. This is why the rotation stage, which rotates at a velocity of $36^\circ/\text{s}$, works with flatness deviations of less than 100 nm at a resolution of 0.5 μrad .

The air bearing does not produce any friction, which over time would lead to a deterioration of these values.

Parallel Kinematics for the Sample Holder and the Optics

The actual sample holder is located in the aperture of the rotation stage on the moving platform of a six-axis parallel kinematic system. The samples are positioned with six degrees of freedom. Essential features are the freely selectable pivot point of the parallel-kinematic system and its high stiffness. A six-axis parallel-kinematic system of this type is also used for the positioning of the optics. In nanotomography, which allows three-dimensional micrographs with resolutions below 100 nm, this machine is used to align compound refractive lenses (CRL) in the beam with high precision.

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