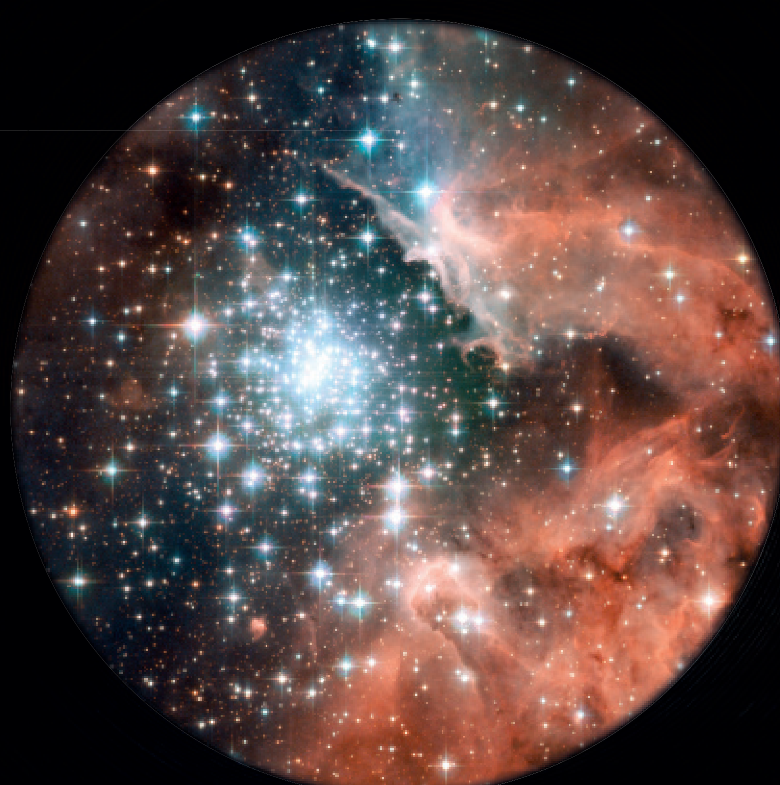
The Ripples in **Space-Time**

Albert Einstein postulated the existence of gravitational waves a century ago in his theory of general relativity, but these distortions in space-time have so far stubbornly resisted direct observation. At the **Max Planck Institute for Gravitational Physics** in Hannover, **Karsten Danzmann** is tracking down this phenomenon with the GEO600 detector.



Puzzling ripples: The cosmos is full of gravitational waves – we need only detect them.

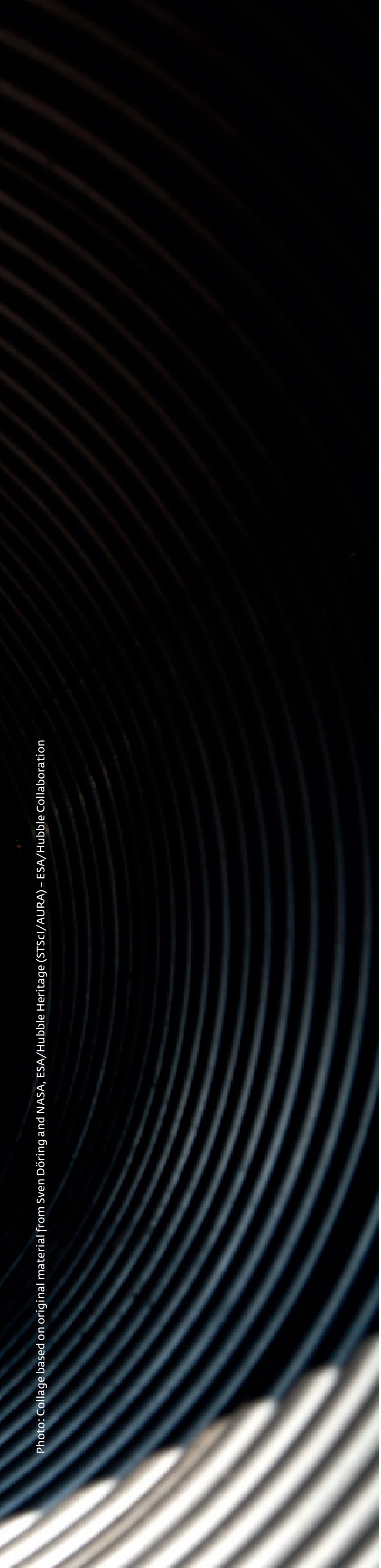


Photo: Collage based on original material from Sven Döring and NASA, ESA/Hubble Heritage (STScI/AURA) – ESA/Hubble Collaboration

TEXT **FELICITAS MOKLER**

On the way to the research campus in Ruthe, some 20 kilometers south of Hannover, the bus carrying the group of visitors squeezes past the hedges lining the narrow farm roads. One last careful manouver and we've managed the left turn onto an even narrower path that brings us to the gravitational wave detector GEO600. On the right, let into the ground, sits a container from which a wide steel pipe extends along the edge of the driveway.

To the left is an apple orchard. Very fitting – wasn't it also an apple that led to Sir Isaac Newton's realization? According to the legend, an apple is supposed to have fallen onto the head of the scientist one day while he dozed under the tree. This inspired a flash of insight – and Newton's Law of Gravity has since governed the motion of the planets and kept the world on its hinges.

GRAVITATIONAL WAVES STRETCH AND COMPRESS SPACE

Until Albert Einstein introduced his general relativity theory. This states that gravitation is no longer a simple force that acts between two masses – such as the Earth and moon – moving through rigid Euclidean space. Rather, space itself is malleable and dynamic. A mass such as the Sun, for example, curves the space around it. The motion of a second (smaller) mass such as a planet then follows this curvature of space.

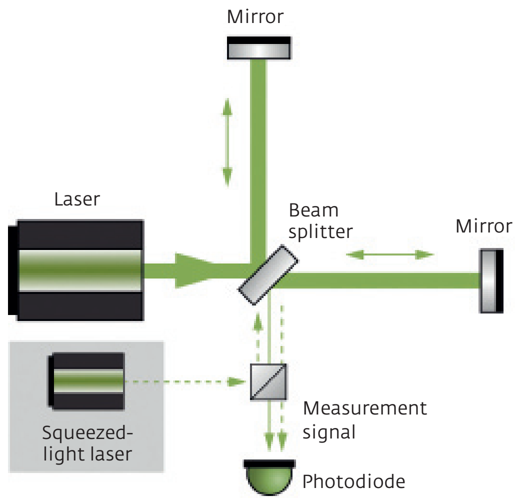
If the local curvature of space changes due to a mass crossing it – at an accelerated speed – then this change propagates as a wave at the speed of light in the structure of space-time. On their journey through the universe, these gravitational waves stretch and compress space perpendicular to their propagation direction. There is extremely little interaction between gravitational waves and matter. Furthermore, their intensity decreases in inverse proportion to the distance from the source. That is why even Einstein himself didn't believe that it would ever be possible to measure the phenomenon that his theory predicts.

HEAVY STAR EXPLOSIONS ARE EXTREMELY RARE

Not so Karsten Danzmann, Director at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) and head of the Institute for Gravitational Physics at Leibniz University in Hannover: "Our technologies are now so sophisticated that we can use GEO600 to measure length differences corresponding to one thousandth the diameter of a proton. Or a similarly small change in the structure of space caused by a passing gravitational wave." A supernova explosion at a distance of less than 28,000 light-years would, according to the theory, distort space by precisely this distance.

So why haven't the physicists managed to capture any gravitational waves yet? "This is because such events as star explosions are extremely rare," explains Danzmann. "We expect such an event to occur, on average, once every 30 years. The last supernova that occurred in our general vicinity was in the Magellanic Cloud in 1987." The researchers might perhaps be able to observe such an event with the detectors available today, but back then, GEO600 and the other detectors didn't exist yet.

The other gravitational wave observatories are the two interferometers of the LIGO experiment, located in Liv-



Crossed paths: In the gravitational wave detector, a laser beam is split at the beam splitter. From there, the two partial beams run perpendicular to one another along the arms of the interferometer. At the ends of the arms, the partial beams are reflected, sent back to the beam splitter and superimposed there to form the signal beam. This then strikes the photodiode. The change in brightness measured by the photodiode is a measure of the relative change in length of the light paths. GEO600 is the first gravitational wave detector in which a squeezed-light laser was recently installed. Fed into the signal beam, this specially prepared light helps dampen the disturbing shot noise.

ingston and Hanford in the US, and Virgo, the French-Italian detector in Cascina, near Pisa. Scientists around the world are collaborating in the field of gravitational wave research. After all, there are major similarities between gravitational waves from space and acoustic signals: although sound can also be perceived with one ear, the direction from which a noise comes can be determined only with two ears. In fact, it takes at least three "ears" to correctly locate gravitational waves.

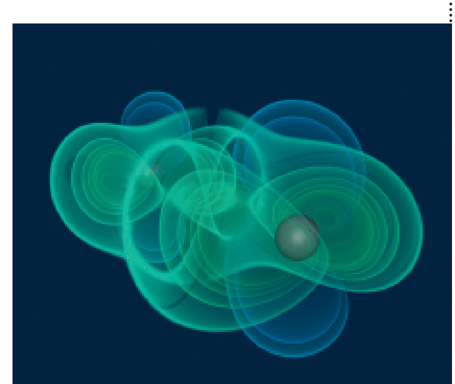
But there are also other reasons why the researchers have multiple detectors tuned into space: only if all measuring instruments independently record the same signal can the scientists be certain that they have measured a gravitational wave. Furthermore, certain properties of a gravitational wave, such as the spatial orientation of its vibration – the polarization – can be determined only when at least three detectors, spread across different positions around the globe, have captured the signal. That is why GEO600, which is operated by the institutes in Hannover in collaboration with British universities such as the University of Glasgow, joined forces with the two American and the Southern European gravitational wave detectors in the LIGO-Virgo Science Collaboration (LVC). Like the other detectors, also GEO600 works on the principle of a Michelson interferometer (see illustration above). It is designed to measure gravitational waves in the frequency range of around 100 hertz up to a few kilohertz.

SOURCES OF WAVES

The first proof – however indirect – of gravitational waves was the achievement of astrophysicists Russell A. Hulse and Joseph H. Taylor, who received the Nobel Prize for their work in 1993. They observed a change in the orbit data of the double-pulsar system PSR B1913+16 over the course of several years. The energy loss in the system as calculated from this data corresponded exactly to the theoretical value of the emission of gravitational waves. This effect has since been confirmed for a number of such binary systems.

Ground-based gravitational wave detectors such as those operated within the LIGO-Virgo Science Collaboration (LVC) are suitable for measuring gravitational waves in the range between a few tens of hertz and a few kilohertz. Among the astrophysical objects that emit gravitational waves at these frequencies are supernova explosions, close binary systems with two neutron stars, and black holes (simulation right) shortly before the two objects merge; but also single neutron stars that rotate somewhat unevenly due to bumps on their surfaces emit gravitational waves.

As paradoxical as it sounds, it is possible to draw conclusions about certain properties of some objects from gravitational waves even when they aren't detected. For a number of pulsars, for instance, the scientists calculated that their shape deviates from a perfect sphere by less than one millionth. Otherwise, with the current measuring sensitivity of the detectors in the LVC collaboration, gravitational waves would have long since had to have been measured directly. FM



Graphic: MPI for Gravitational Physics (top), MPI for Gravitational Physics/ZIB/M. Koppitz/C. Reisswig/L. Rezzolla

Field research: The GEO600 site in Ruthe, near Hannover. In the container-based offices and measuring stations (top) researchers analyze the data they obtain in the 600-meter-long interferometer arms (bottom). Under a protective cover hangs the vacuum tube in which the laser travels between the beam splitter and the end mirror (right).

Photos: MPI for Gravitational Physics – Harald Lück (left, 2), Sven Döring (right)

A laser beam hits a semitransparent mirror, the beam splitter. From there, two coherent light beams run perpendicular to one another along the 600-meter-long interferometer arms in vacuum tubes made of corrugated stainless steel – one at the side of the road, the other located between two fields, in ditches specially dug for this purpose. At the end of the measurement paths, one mirror reflects the light and sends it back to the beam splitter. There, the split beams meet again and are superimposed. The signal beam then strikes a photodiode, which measures the beam intensity.

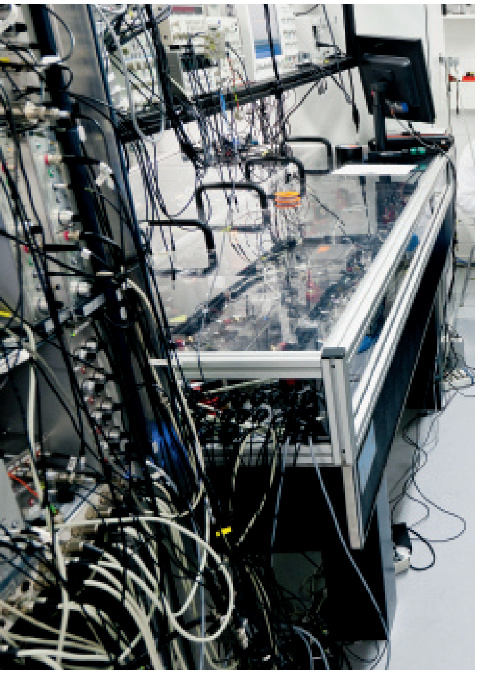
The brightness of the signal beam depends on the wave character of the light. If two wave peaks from the two laser beams coincide, their interference is positive and the signal is particularly bright. If, in contrast, a peak and a valley coincide, the beams cancel each other out. Between peak and valley – the phases of the laser light – are all of the gradients whose coincidence depends on the relative distance the light travels.

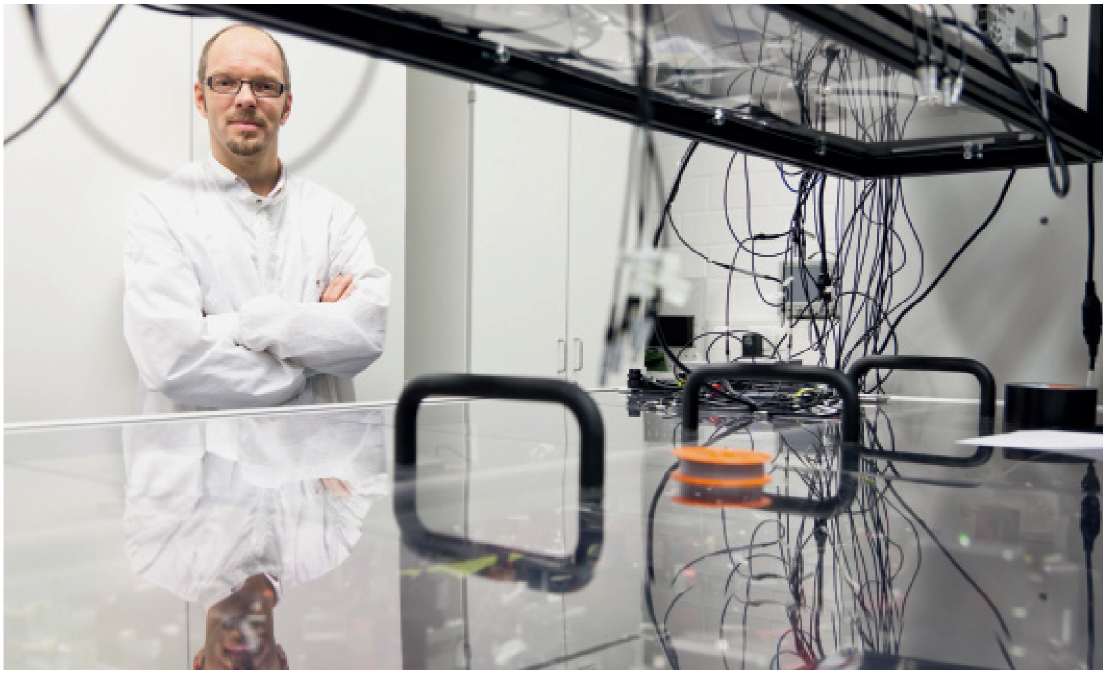
DETECTORS ARE CONTINUALLY UPGRADED IN TURNS

The physicists use this principle of interference to measure very small changes in length. When a gravitational wave passes through the detector, space is stretched and compressed with differing intensities along the two detector arms. This causes the light path of the two laser beams to change relative to one another, and they interfere in a different phase than when at rest. As a result, the photodiode registers a change in brightness.

In principle, the sensitivity of the detectors within the LVC is sufficient to measure gravitational waves of supernovae that explode in our vicinity, within the galaxy. Merging neutron stars or black holes should be visible even in other galaxies of the local group, as these events generate a much stronger signal than a star explosion. They are, however, much more rare. In order to increase the chances of observing a star explosion or a merger of two neutron stars directly, the scientists want to listen even further into space. That is why the detectors of this network are continually upgraded in turns.

GEO600 has always been a trailblazer in this respect. GEO600 has the





shortest measuring distance, with an arm length of 600 meters – LIGO has an arm length of four kilometers, and Virgo three. This means, first, a lower sensitivity for the detector in Ruthe. To compensate for the limitations of the shorter arm length, the physicists in Hannover refined the measuring techniques. The key detector technologies resulting from the GEO600 project are then taken into account in the current renovation phase for the next generation.

THE LASER ITSELF BECOMES AN INTERFERENCE FACTOR

AdvancedLIGO and AdvancedVirgo are expected to increase the measuring sensitivity of the network tenfold. "When the work is completed in a couple of years, we will be able to observe a thousandfold greater volume of the universe. This will simultaneously increase the rate at which we expect to see events," says Karsten Danzmann. "We believe we will get at least a few dozen astrophysically relevant observations per year – in the best case perhaps even a few per day."

BETTER HEARING WITH DISTRIBUTED EARS

The telescope ears in Germany (GEO600), at two locations in the US (LIGO) and at one in Italy (Virgo) form a network to listen for gravitational waves and jointly evaluate the resulting data. The observatories in the US and Italy are now being equipped for the first direct detection and are expected to begin measurements again starting in 2016 – with ten times greater sensitivity.

Previously, the scientists estimated that they would then be able to observe on average 40 merging neutron stars or black holes per year. Now, a study by Bernard F. Schutz, Director at the Golm-based Max Planck Institute for Gravitational Physics (Albert Einstein Institute), shows that, with optimum data analysis, in theory, this rate is even 160 such events per year. However, this can't be achieved with the current spatial arrangement of the detectors. Instead, one measuring instrument is needed on the other side of the globe – an ear on the back of the head, so to speak.

The measuring sensitivity of a detector network depends on the sensitivity of the individual detectors and their position on the Earth. In his study published in the journal CLASSICAL AND QUANTUM GRAVITY, Schutz shows how this relationship can be characterized for any network using three numbers: the distance from which the gravitational wave source in the sky can be detected by the individual detector; the smallest signal-noise ratio at which a gravitational wave detection is just barely still possible; and the geometric arrangement of the detectors in the network.

"Simply relocating one of the existing LIGO instruments from the US to Australia would increase the detection rate by two- to fourfold," says Schutz. If, as planned, gravitational wave detectors also go into operation in Japan, Australia and India, the researchers will be able to observe around 370 astronomical events each year, and in routine measuring mode, even 500. EM / HOR

Photos: Sven Döring (2)

In Hannover, Karsten Danzmann (center) is tracking down gravitational waves. In the labs, the scientists are working to improve the detector technologies. Roman Schnabel (left) developed the squeezed-light laser source. Benno Willke (right) cleans a laser lens.

The requirements for gravitational wave detectors are so demanding that certain properties of the laser itself are a source of disturbance. This is due to the quantum-mechanical properties of light. When the signal beam reaches the photodiode, the light displays its particle nature: the light quanta pelt down on the photodiode at irregular time intervals like shot pellets. For this reason, experts also refer to these irregularities in the signal as shot noise. If a gravitational wave temporarily generates a similarly weak fluctuation in brightness, it would be only too easily overlooked.

However, the stronger the laser beam is, the lower the impact of the shot noise. This is because a higher photon density means a shorter time interval between the light particles hitting the diode in succession – and there is a decrease in the relative irregularities. A more intense laser source is thus helpful here.

In Hannover, Benno Willke and his working group are developing such lasers with properties that are specially tailored to the requirements of gravitational wave detectors. For this, the Max Planck scientists work closely with the Laser Zentrum Hannover e.V. (LZH). The lasers produced here are marked by high power stability at a well-defined frequency. They operate with Nd:YAG crystals in the infrared at a wavelength of 1,064 nanometers (millionths of a millimeter).

POWER AND FREQUENCY MUST REMAIN STABLE

The power of the laser currently used in GEO600 is 12 watts, but a new 35-watt laser is due to be installed soon. For comparison, a red or green laser pointer for home use operates at a power of less than one milliwatt.

For the search for gravitational waves, the laser power and laser frequency must be constant over time and, at the same time, the spatial beam profile must be particularly symmetrical and stable. But the higher the laser power, the more difficult it becomes, technologically, to produce such a beam profile. In order to reduce the so-called frequency noise, the physicists couple the less stable high-power laser with a lower-power laser that, however, has a more uniform beam. For this, the high-power laser takes on the stability of the weaker laser. In addition, the scientists use control loops to obtain optimum beam quality and a good intensity noise.

In this way, the Max Planck researchers recently produced the first power-stabilized 200-watt laser. They are currently installing it in the LIGO detector in Livingston; two additional light sources of the same design are planned for the detector in Hanford.

Some of the laser technologies developed in gravitational wave research are now being used in industry applications, in slightly modified form. For instance, the amplifier systems modified by neoLASE GmbH can be used for materials processing. neoLASE also took the control electronics and developed, together with the LZH, an application with which the laser systems can now also be controlled from an iPhone.

But 10, 35 or even 200 watts are still not enough for the physicists. “To ensure that we have enough photons available, we even recycle laser light,” says Hartmut Grote. The physicist spends the majority of his working

Photos: Sven Döring (2)

hours at the detector in Ruthe. "We built an additional mirror into the interferometer to create, together with the two end mirrors, a resonator for the laser beam. Trapped in this way, the laser traverses multiple paths in the interferometer and is superimposed on the light that continues to be fed in, until the light power has increased to three kilowatts," says Grote.

The shot noise likewise increases, but to a lesser extent than the average beam intensity. The advantage when searching, for example, for black holes is that the gravitational wave signal stands out better from the background noise. Power recycling was part of the basic configuration of all gravitational wave detectors in the LVC right from the start.

Only at the GEO600 detector is the signal beam likewise amplified. A signal recycling mirror at the detector output reflects the interference beam back to the interferometer, resulting in constructive superimposition of the signal beam and the portion of the laser light containing the gravitational wave signal. This process continues until the signal is amplified tenfold.

A MIRROR THAT SWALLOWS PRACTICALLY NO LIGHT

The previously used signal recycling mirror permitted amplification of only limited frequency ranges, for instance around 500 hertz or 1 kilohertz, depending on the position of the mirror. The replacement mirror now in use in GEO600 exhibits a lower reflectivity, but overall, it amplifies the signal beam for a broader frequency range without having to adjust the mirror position. "It is due to this technique, among other things, that GEO600 is currently able to measure at high frequencies with similar sensitivity as Virgo despite the shorter arm length," explains Hartmut Grote. It is also planned to use this method in the next generation of gravitational wave detectors in LIGO and Virgo.

It is also important to use top-quality material for the mirror in order to eliminate, as far as possible, many sources of interference. For this reason, a glass substrate named Suprasil 311SV was created specifically for the mirrors in the GEO600 and Virgo interferometers. This quartz glass is marked by a particularly low absorption coefficient – a property that is crucial especially for the beam-splitter mirror. If possible, the mirror should not absorb any light at all when a laser beam passes it or is reflected. With the substrate from Heraeus, this is successfully achieved to less than 1 ppm (parts per million) per centimeter.

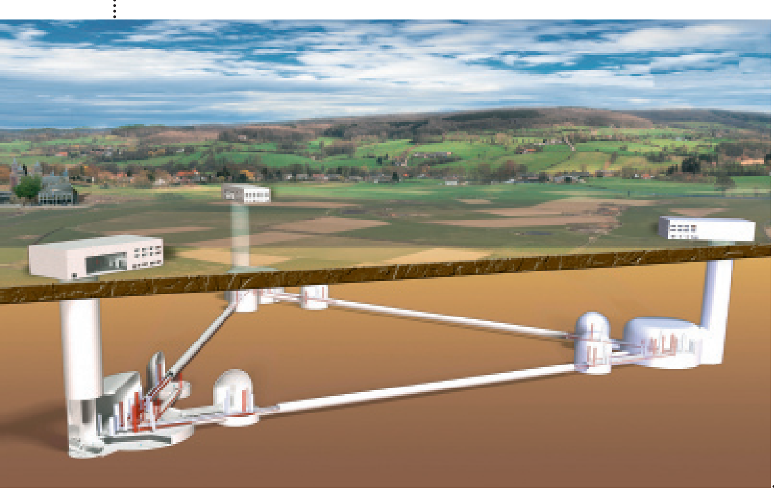
ET PAVES THE WAY INTO THE HIDDEN UNIVERSE

The Einstein telescope (ET) is a community project of eight European research institutes headed up by the European Gravitational Observatory (EGO).

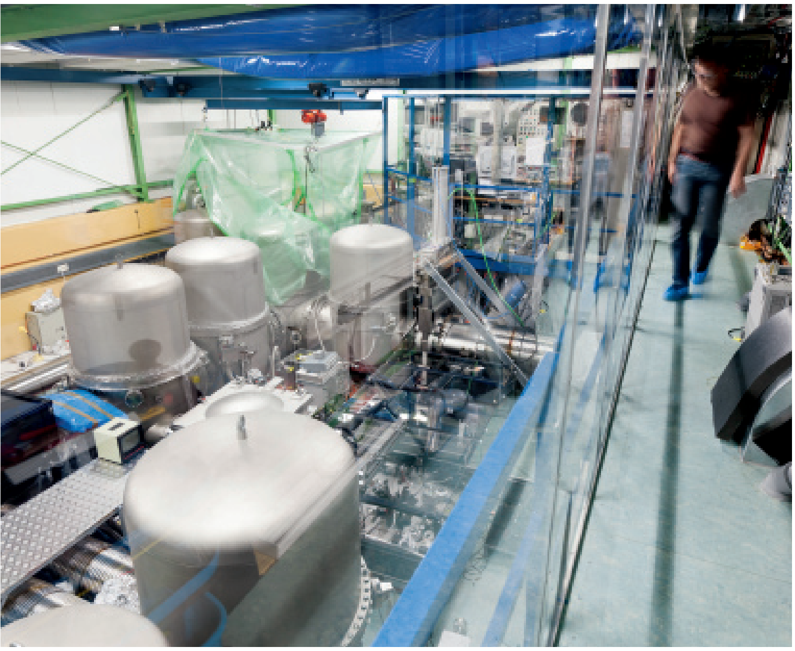
ET is planned as a third-generation gravitational wave detector and is expected to measure with 100 times greater sensitivity than first-generation instruments. Just as with the first two detector generations, tiny changes in length – far less than the diameter of an atomic nucleus – will be measured in two connected, several-kilometer-long interferometer arms.

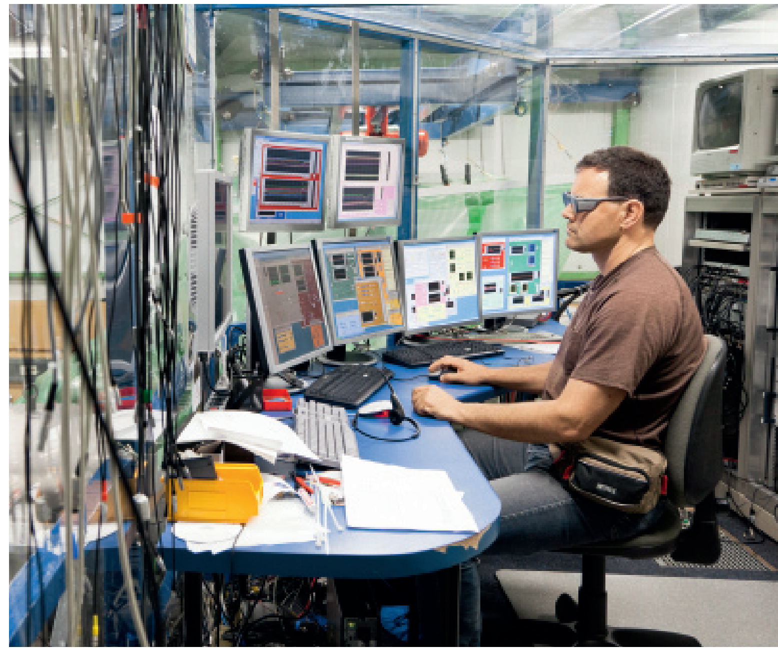
"We decided to investigate possibilities for the construction of a new generation of more sensitive observatories. After three years of work by more than 200 scientists from Europe and around the world, we can now present the draft study for the Einstein telescope. This paves the way to the discovery of previously hidden regions of the universe," says Harald Lück, deputy scientific coordinator of the ET study and researcher at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute/AEI) in Hannover.

The study, which was presented at the European Gravitational Observatory (EGO) in Pisa in late May, states the scientific aims of the ET, the planned design and technology of the detectors, and the estimated construction time and costs. ET will be extremely sensitive because it is to be built underground at a depth of 100 to 200 meters. This will significantly reduce measurement uncertainty and interference caused by seismic movements. ET will therefore be very sensitive also at low frequencies – between 1 and 100 hertz. The researchers aim to use the detector to observe the entire spectrum of gravitational wave frequencies that can be measured on the Earth. MM



Graphic: Albert Einstein Institute Hannover





The laser and mirror are housed in the vacuum tanks (left). The physicists (here Harald Lück) monitor the detector settings and the signal beam on the screens.

This is important because absorbed light heats up the glass at the site of passage according to its intensity. The refractive properties of the mirrors, in turn, change with the temperature. Since the laser beam is more intense at the center than at the edge, the mirror heats up more in the center than in the outer regions. This temperature difference acts like a thermal lens, distorting the entire optics and affecting the measurement.

WELL-BALANCED BY PENDULUMS

For the end mirror of the interferometer, in turn, the reflection properties can't be good enough. To optimize them, the quartz glass surface is provided with an extra mirror layer. If sunlight from the atmosphere hits a windowpane perpendicularly, it doesn't pass through the glass completely. A small portion, about 4 percent, is reflected. Wafer-thin, alternating layers of silicon dioxide (SiO_2) and tantalum(V) oxide (Ta_2O_5) with different refractive indices applied to the interferometer mirror have the same effect for a laser beam. Altogether, between 23 and 28 such double-layers are required to obtain an optimum reflection (99.998 percent).

A number of disturbing influences that still have to be considered are seismic in origin. They are especially troublesome when making measurements at low frequencies below 100 hertz. To reduce them to a reasonable extent, scientists at the University of Glasgow developed a special pendulum suspension for GEO600.

A simply suspended pendulum oscillates easily below its resonance frequency. It's easy to try this yourself: a heavy object – such as a stone – tied to a string, and you have a pendulum. Input energy into the pendulum by moving the upper end of the string back and forth, slowly at first, and it will begin to sway rhythmically. The pendulum will have the largest amplitude when it is pushed in time with its natural frequency. If, in contrast, the rate of the energy input is above the resonant frequency, the pendulum will move only weakly or not at all. If multiple pendulums are suspended one above the other, it will be possible to stimulate them practically only at the resonant frequencies of the combination.

The detector mirrors are thus also suspended as multiple pendulums in order to minimize seismic interference across the broadest possible spectrum. The end mirrors of the GEO600 detector, for instance, are arranged in a triple suspension for this reason. The mechanical filter effect of the pendulums makes it possible to passively reduce disturbing seismic influences by as many as nine orders of magnitude. Directly behind this is a second triple pendulum whose components target the corresponding mass of the mirror suspension through electromagnetic and electrostatic forces. These actuators, as they are called, help to actively dampen the remaining disturbances, whether internal or produced at resonant frequencies.

The lowest frequencies up to 1 hertz are suppressed at the topmost pendulum component, frequencies below 10 hertz at the middle component, and interference up to 100 hertz directly at the mirror. In this way, the mirror is brought into its working position and kept still there. Nevertheless, the gravitational wave detector is not safe from earthquakes registering more than six on the Richter scale, no matter where on the planet they occur. Then it is jolted out of alignment, and the mirrors have to be fine tuned again. But it takes only a few minutes until GEO600 is able to listen into space again. A total of 260 control loops align the mirror, hold it in position and dampen external vibrations.

In addition, the mirrors in the pendulum are suspended particularly friction-free. The mirrors and middle pen-

Photos: Sven Döring (2)

Glimpse into the future: Harald Lück (left) and Hartmut Grote anxiously await the discovery of the first gravitational wave.

dulum weight aren't hung on a fine steel wire, for example, but instead on a thin thread made of quartz glass. What is special about this material is that it has a much lower frictional resistance than steel. Furthermore, the glass fiber is directly (monolithically) connected with the mirror and the second pendulum weight, so there is no friction at these two points of contact. This is advantageous for the measurements with GEO600 because lower friction causes fewer disturbances, resulting in more refined measurements.

These quartz glass fibers were specially developed by scientists at the University of Glasgow for the mirror suspension in gravitational wave detectors. This technology has already been in use in GEO600 for ten years, and was also recently installed in Virgo.

The gravitational wave detectors now measure with such precision that, particularly with high-frequency signals of a few hundred hertz, the shot noise is especially disturbing. At these frequencies, even a high-power laser or power recycling is not sufficient to filter a potential signal from space out of the background noise. Roman Schnabel in Hannover is focusing on such measurements at the quantum limit. He and his working group developed a laser source that produces particularly low-noise light.

The quantum physicists use photons from so-called non-linear crystals to line up the recalcitrant photons of a laser beam at more uniform intervals, "squeezing" them into a neat line.

Such crystals have a special optical property: in the excited state, they are able to take up and emit photons that have exactly half the energy of the light quanta required for excitation. To conserve energy, however, a non-linear crystal always absorbs two of the low-energy photons. In order to "store" them, it converts them into a higher-energy photon of its excitation frequency. Then two light quanta of the longer wavelength are again available for the emission.

Periodically poled potassium titanyl phosphate (KTP) – the scientific name of the crystal – is what Roman Schnabel uses in his "squeezed-light laser." The atoms in this crystal can be excited with green light of a wavelength of 532 nanometers. But the emitted laser light can also have double that wavelength (1,064 nanometers). That is precisely the wavelength of the laser that is circulating in GEO600.

RESEARCHERS EVEN OUT IRREGULARITIES

The photons emitted with low energy always occur in pairs and quantum-mechanically entangled. "Here, we are using an effect that quantum theory predicts, but that can't be illustrated in any way," explains Schnabel. "We superimpose the photon pairs from our crystal with the normal laser light in GEO600." This interference is noticeable thus: Whenever, as a result of quantum noise, there are too few photons in the beam, constructive interference occurs. When there are too many, the excess photons are eliminated. "Surprisingly, this works, although the quantum noise is really random," says Schnabel. In this way, it is possible to even out the quantum-physics-induced irregularities in a laser beam. This may soon make it possible to double the measuring precision of gravitational wave detectors.

Whether the researchers themselves bring about advances in the measuring technologies, or whether they manage to further outsmart the laws of nature – either way, it remains exciting. And if the theorists' calculations are correct, gravitational waves may soon be trapped in the nets of Earth-bound scientists. ◂

GLOSSARY

Euclidean space
Well into the late 19th century, it was assumed that Euclidean space describes the "space in our view" and thus the physical space that surrounds us. However, not least Albert Einstein (1879 to 1955) developed, in his relativity theory, a space concept that differs from Euclidean space with respect to mathematics.

Laser
Laser stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Amplification in a resonator, such as a crystal, is achieved by inputting energy, causing more electrons to populate a higher-energy state than a lower-energy one (population inversion). Through stimulation, the electrons finally fall back to their starting level and produce light. The reflection in the resonator amplifies this light emission like a cascade.

Newton's Law of Gravity
This law, published by Isaac Newton (1643 to 1727) in his work *Philosophiae Naturalis Principia Mathematica* in 1686, states that every mass point exerts on every other mass point a force that is directed along the line connecting the mass points. The amount of this gravitational force is proportional to the product of the two masses and inversely proportional to the square of the distance between the two masses.

Photo: Sven Döring