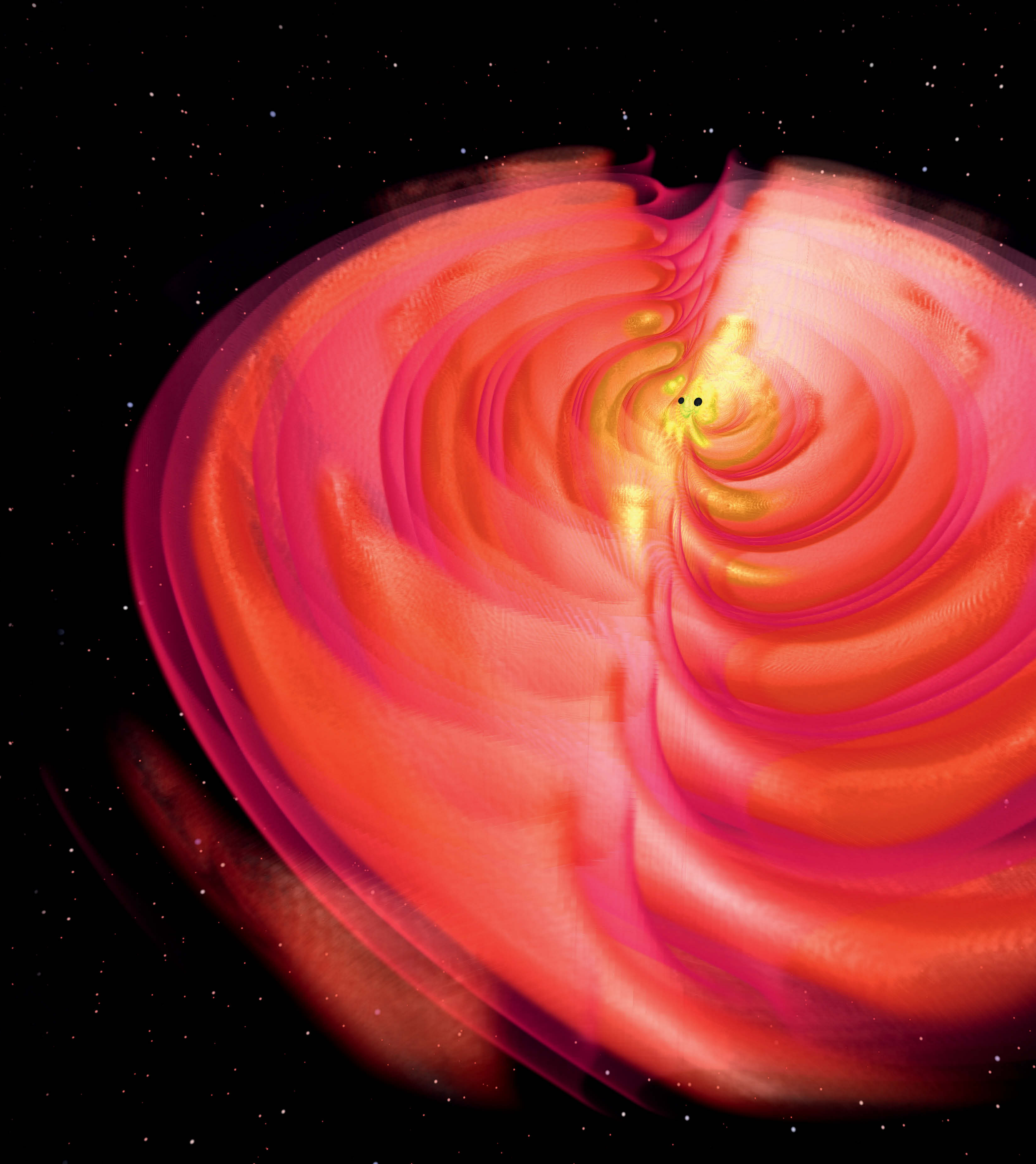
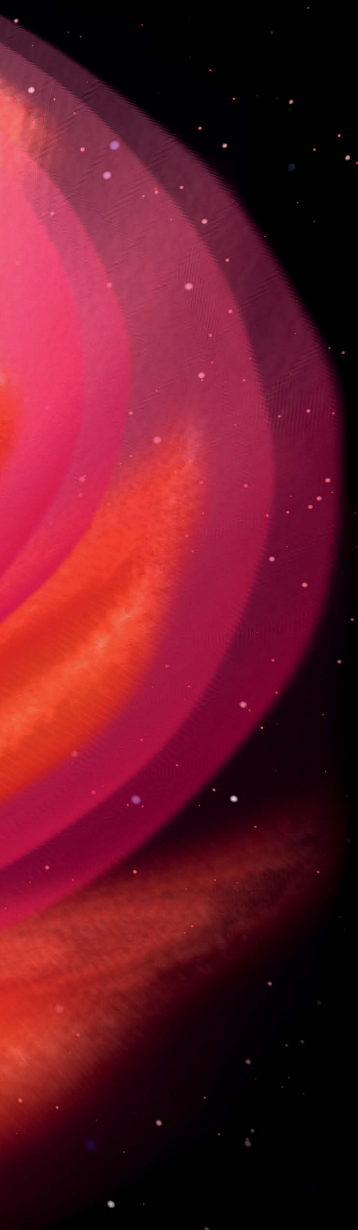


Cosmic collision: The first gravitational waves ever observed originated from two merging black holes around 1.3 billion light-years from Earth. Researchers at the Max Planck Institute for Gravitational Physics simulated the scenario on the computer.



Numerical-relativistic simulation: S. Ossokine, A. Buonanno (Max Planck Institute for Gravitational Physics)/scientific visualization: W. Benger (Airborne Hydro Mapping GmbH)

The Quaking **Cosmos**

Albert Einstein was right: gravitational waves really do exist. They were detected on September 14, 2015. This, on the other hand, would have surprised Einstein, as he believed they were too weak to ever be measured. The researchers were therefore all the more delighted – particularly those at the **Max Planck Institute for Gravitational Physics**, which played a major role in the discovery.

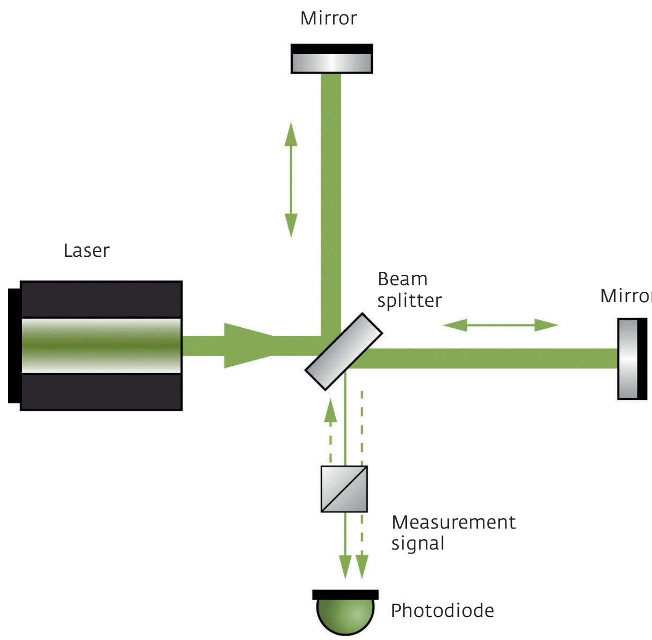
TEXT **HELMUT HORNUNG**

On that memorable Monday in September 2015, the clock in Hanover stood at 11:51 a.m. when Marco Drago at the Max Planck Institute for Gravitational Physics first saw the signal. For around a quarter of a second, the gravitational wave rippled through two detectors known as Advanced LIGO. The installations are located thousands of kilometers away in the US, one in Hanford, Washington, the other in Livingston, Louisiana.

Drago initially thought the signal had been slipped in deliberately to test the scientists' response, as has happened many a time in the past. But Advanced LIGO wasn't even in regular operation yet, so Drago informed his colleague Andy Lundgren. Both agreed: the curve looked perfect; the signal appeared to be real. The Max Planck researchers had an inkling that they had just become witnesses to a historic moment.

The discovery represents the current pinnacle of the history of gravitation – the general theory of relativity has now passed its final test with flying colors. In addition, the measurement opens up a new window of observation, as almost 99 percent of the universe is in the dark – that is, it doesn't emit any electromagnetic radiation. With gravitational waves, in contrast, it will be possible for the first time to investigate cosmic objects such as black holes in detail. And in the future, the researchers will even be able to "hear" almost as far back as the Big Bang.

But what exactly are these waves from outer space? The roots of modern gravitational research lie in Switzerland. There, in 1907, a "technical expert second class" at the patent office in Berne was giving some intense thought to gravity: Albert Einstein. He simulated gravity using acceleration, since acceleration also generates forces



Left 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.

Right Field research: One of Advanced LIGO's detectors, which stretches out its four-kilometer arms in Livingston, Louisiana. Its heart is the building in the center that houses the laser system. The second, practically identical LIGO detector is located in Hanford, Washington, some 3,000 kilometers away.

as occur, for instance, in a rapidly accelerating elevator. If the elevator car were soundproof and lightproof, the passengers might think that terrestrial gravity had suddenly increased.

EARTH BENDS SPACE AS IT ORBITS THE SUN

The realization that gravitation is at least partially a question of one's system of reference led Albert Einstein to the revolutionary ideas he presented in his general theory of relativity in the fall of 1915, after eight years of work. It was ultimately a field theory. It states that the accelerated motion of masses leads to perturbations that move through space at the speed of light – gravitational waves.

If you jump up and down on a trampoline, for example, you lose energy and generate these waves in space-time. They are immeasurably small, because a human being has a low mass and jumps relatively slowly. Space, on the other hand, contains very large masses – and even a trampoline: space-time. Everything is in motion here, as not a single celestial body remains at rest in one place. Earth bends space as it orbits the Sun, radiating gravitational waves with a power of 200 watts. But even these gravitational waves are still too weak to be tracked down with a detector.

Fortunately, there are also much stronger tremors of space-time in the universe: when two neutron stars or black holes orbit each other extremely quickly, or even collide with each other. Or when a massive star explodes as a supernova. Such cosmic events generate gravitational waves with an energy of around 10^{45} watts.

Gravitational waves change the separation between the objects in space perpendicularly to the direction of propagation. This is extremely difficult to measure, which is why Albert Einstein thought it would be impossible to detect them. And yet scientists have come up with instruments that have now succeeded in doing just that. The first-generation instruments of the 1960s consisted of aluminum cylinders weighing many tons and equipped with sensitive sensors. Pulses of gravitational waves should have caused them to oscillate like the clapper of a bell. But despite sophisticated amplifiers, these resonance detectors produced no results.

The researchers thus designed receivers that were even more sensitive, known as laser interferometers. Here, a laser beam impinges on a beam splitter, where it is split into two beams; one continues on in a straight line while the other is deflected to the side. At the end of each path is a mirror that reflects the light back to the beam splitter. This mirror now deflects the beams in such a way that they are superimposed on each other – that is, they interfere – and strike a photodiode.

WAVE CREST MEETS WAVE TROUGH

In the case of unperturbed measurement paths, the light waves arriving at the photodiode oscillate not in phase, but out of phase: wave crest meets wave trough, the light waves extinguish each other. If a gravitational wave perturbs the system and thus changes the measurement paths, the light waves lose the beat. The receiver no longer remains dark – a signal appears.

In 1975 a group working with Heinz Billing at the Max Planck Institute for Physics and Astrophysics built the prototype of such an interferometer with a

Graphic: MPI for Gravitational Physics

Photo: Caltech/LIGO Laboratory

path length of 3 meters; in 1983 they built one with a 30-meter path length. The foundations were thus laid for all subsequent installations of this type. The scientists have developed innovative technologies – for instance for the suspension of the mirrors or to stabilize the laser – particularly for the GEO600 detector, which has been stretching out its 600-meter arms in a field near Hanover since the mid-1990s.

"Seen in this light, Advanced LIGO is our detector as well," said Karsten Danzmann on February 11 in Hanover, on the occasion of the official announcement of the discovery. After all, the two structurally similar facilities in the US are full of technical know-how from Danzmann's team. When they detected the tremor in space-time, the length of the laser paths, each four kilometers long and arranged perpendicular to each other, had changed by only a tiny fraction of the diameter of an atom.

In order to discover the gravitational wave signals in the pile of data, the researchers had to know what they were looking for in the first place. The researchers in Bruce Allen's department in Hanover are therefore working on programs to see and analyze the signals. And Alessandra Buonanno's group in Potsdam-Golm developed the models they use to better understand the sources of the waves.

The signal detected on September 14, 2015 told of the merger of two black holes with 29 and 36 solar masses, 1.3 billion light-years away from Earth. The close interplay of experiment, simulations, analytical calculations and data analysis allows the scientists to illuminate the dark corners of the universe. The ripples in space-time will shed light on the astronomy of the future. ◂

"The signal caught our eye immediately"

The discovery of gravitational waves on September 14, 2015 was the crowning moment of a search that had lasted decades and employed ingenious methods. The **Max Planck Institute for Gravitational Physics**, with its branches in Potsdam-Golm and Hanover, played a crucial role in this success. There, researchers are working not only on innovative technologies, but also on theoretical models, virtual simulations and data analysis. We discussed this work and the importance and consequences of the discovery with Directors **Bruce Allen**, **Alessandra Buonanno** and **Karsten Danzmann**.

Mr. Allen, Ms. Buonanno, Mr. Danzmann: As members of an international network of gravitational wave detectors, the LIGO Virgo collaboration, you and the staff at your institute played a significant role in the very first measurement of gravitational waves. Congratulations!

All three: Thank you!

Did you expect to make the discovery at this point in time?

Karsten Danzmann: No, not at all. It was a complete surprise. In mid-September 2015, the American LIGO detectors – designed along the lines of a Michelson interferometer like our GEO600 detector – were still only in test mode after undergoing a rather long upgrade phase. The plan was for the scientific measuring operation to begin a few days later. The scientists were still checking whether the instruments were working as planned. They were indeed. But that they were operating so well and would be able to receive a gravitational wave signal right at the start – nobody expected that.

Bruce Allen: The signal arrived late in the morning of September 14, 2015 Central European Time. It was night time in the US and our colleagues there were asleep. So it was two members of the Max Planck Institute for Gravitational Physics who were the first to see it on their monitors a few minutes after the detectors had been triggered. They analyzed the data for several hours and then sent an initial e-mail to the collaboration. We couldn't believe it at first, especially since the signal was so strong and looked so perfect that we first asked ourselves whether it was actually real.

Karsten Danzmann: It must be said here that we regularly simulate the impact of gravitational waves on the detectors for test purposes. This allows us to test the operability of the instruments, and also to check the detection chain and establish that the scientists are working independently of each other.

Bruce Allen: In the first few weeks after the discovery, we actually did have concerns that someone might have mistakenly injected an artificial signal or forgotten to tell us about it. We expended a lot of effort to rule out this possibility. In the end, however, it was clear that the signal originated from outer space. We had become witnesses to the fact that, in a distant galaxy, two black holes had collapsed into one another!

What does such a signal look like?

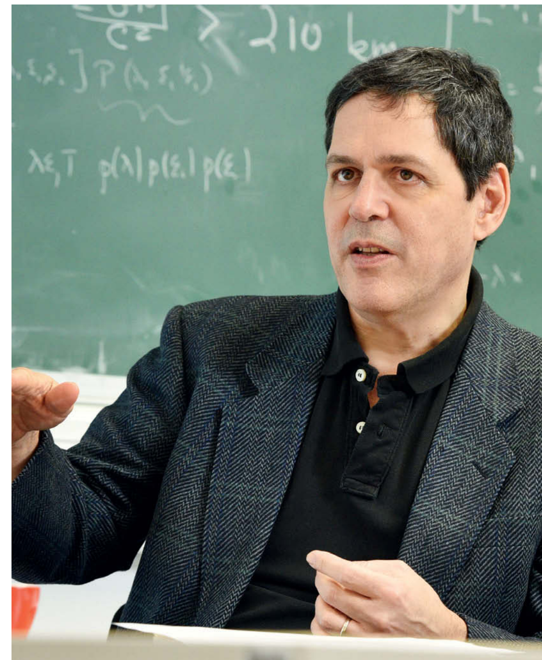
Alessandra Buonanno: The signal swept through the LIGO detectors for around a quarter of a second. It looked remarkably simple! A sine wave of about 10 to 15 cycles whose amplitude first grew, then reached its maximum and eventually died out. In the meantime, its frequency increased more and more until it reached a constant value. This characteristic signal can be explained as follows: As the two black holes orbit each other, they lose energy because of gravitational wave emission. Therefore, they come closer and closer until they collide with each other and merge. This forms a more massive black hole that then rings like a bell for a little while before settling down. Before merger, the signal's frequency is proportional to the orbital frequency, and its amplitude to the characteristic velocity of the binary star, which is almost the speed of light during the last stages of the evolution. Once the new black hole forms, it rings down, emitting gravitational waves at a constant frequency.

Bruce Allen: I didn't expect that the very first detection would enable us to deduce the event so directly from the waveform. I had assumed that the first detections would be much weaker and that we would need our analysis programs to fish them out of the data. And also that it would be difficult to understand what is really happening there. The fact that it stands out so clearly in the raw data, and is even visible to the human eye, is remarkable.

Even though the gravitational wave signal in this case is obviously easy to see with the naked eye, it is imperative to undertake a sound data analysis. How is this done and what role does the Max Planck Institute for Gravitational Physics play in it?

Karsten Danzmann: While the detectors are running, the measurement data is automatically trawled continuously for signals. If something is found, the scientists are notified by e-mail.

Bruce Allen: The foundations for the algorithm that detected the latest signal were laid by colleagues at the University of Florida. This algorithm searches the LIGO detectors for a deflection at the same frequencies so that the events in both detectors match. In our working group we have spent years developing and improving this code in order to specifically filter out from the data the signals from binary systems with black holes of moderate mass. These improvements were one of the reasons that the latest event was discovered. And as far as the algorithm for the precision analysis applied after the detection is concerned, the colleagues at our institute belong to one of only two groups of experts in the world.



Bruce Allen

Photo: Frank Vinken

» Toward the end of the next measuring period we will have around 20 such detections.

Where are the calculations done?

Bruce Allen: Most of them are done on the ATLAS computer cluster here in Hanover. It has roughly the same capacity as the rest of the collaboration together has available.

Karsten Danzmann: After excluding all other external perturbations including, for instance, earthquakes, the signal is compared with synthetically generated waveforms. This is how we determine the properties of the astrophysical source emitting the gravitational waves.

How are those wave signals modeled and implemented in your search?

Alessandra Buonanno: First we developed sophisticated, analytical approximations to describe the two-body dynamics and gravitational radiation during the phase in which two black holes come ever closer to each other. Then we used the re-

Alessandra Buonanno

And afterwards, you can say precisely what the system you found really looks like?

Alessandra Buonanno: Having identified the signal in the data, we used our waveform models to run follow-up analyses and infer the astrophysical properties of the source. We found that the binary system was composed of two black holes that had 36 and 29 solar masses, respectively. The two black holes merged into a single, rotating black hole with a mass of around 62 times the mass of the Sun. The binary system was 1.3 billion light-years away. Furthermore, the signal was quite loud, making it possible to also use our waveform models to look for violations of Einstein's general theory of relativity. No deviations were found!

» Having identified the signal in the data, we used our waveform models to run follow-up analyses and infer the astrophysical properties of the source.

sults of numerical-relativity simulations of binary black holes to model the merger and ring-down signal. It is not possible to employ only numerical-relativity waveforms in searches and follow-up analyses because it takes one month or more to simulate the last 15 orbits of a binary black hole coalescence. The waveform models we have developed were also implemented and employed in the continuing search for binary coalescences in the LIGO data. This search observed the black hole merger known as GW150914 with sufficient significance to be confident in the detection.

Apart from the signal strength, was this system a surprise in any other way?

Alessandra Buonanno: We didn't know if black holes exceeding 20 solar masses existed, but we did know that if they existed, they would be the strongest gravitational wave sources for LIGO. They proved to be the golden sources we always dreamed of! Because with such massive binary black holes, the merger signal lies in the detector's sweet spot – its most sensitive region – and it is at merger that the signal is strongest.

Which frequencies are these?

Karsten Danzmann: Between 60 and 250 hertz. In this range, the LIGO detectors are now almost ten times as sensitive as before the upgrade. Incidentally, this is something we are particularly delighted about: almost all the developments that have made Advanced LIGO so much more sensitive were developed or tested out at GEO600. At higher frequencies where we expect the signals from two merging neutron stars, for example, the instruments are currently a factor of three better than before. However, this is expected to be increased to a factor of ten in the coming months. The dominance of seismic effects is too great at very low frequencies. In the future, however, this gap will be closed by the VIRGO detector in Italy, which is also a member of our network. Its technology is also currently being modernized and is set to resume operation next year.

And what is the situation with GEO600 in Ruthe near Hanover?

Karsten Danzmann: It's smaller, so it's not sensitive enough for such signals at low frequencies. Its strength lies at higher frequencies. But the main thing we have here is decades of tradition in developing technologies. All innovations that have had their origins here can now be found in the other detectors in the network; they include special systems for suspending mirrors, and also the laser technology and the optical layout of the interferometer in general. We provided the hardware for the pre-stabilized laser systems used with Advanced LIGO. Advanced LIGO is our detector as well!

The discovery has shown that the calculation that the new measurement sensitivity of the detectors would finally enable us to mea-

Photo: Sven Döring

» We suddenly have a new tool at our disposal with which to study the dark side of the universe.

Karsten Danzmann

sure gravitational waves directly proved to be correct – and even earlier than was hoped for. What further developments and observations do you expect in the near future?

Bruce Allen: In the immediate future it could become particularly exciting. We have now observed one system very well. I estimate that during the next six months of scientific operation following a further, brief update phase over the course of the year, we will see a system like this every three or four days. Toward the end of the next measuring period we will have around 20 such detections. We will be able to see what the mass spectrum of such systems is. And we will learn something about the evolution of such systems, because some of them will be close while others are more distant, which means they formed at an earlier point in time. This will tell us something about the proportion of heavy elements in the universe during the various eras, for example, because this has a considerable impact on the formation rate of massive stars and black holes in particular. And then we naturally hope to also find all the other types of sources that are to be expected – the merger of two neutron stars or combinations of a neutron star and a black hole.

What does the discovery mean for physics in the broader sense?

Karsten Danzmann: I think it has enormous significance for physics and astronomy. Not so much because gravitational waves have finally been detected – nobody doubted they would be! But because gravitational wave astronomy has now become mainstream astronomy. We suddenly have a new tool at our disposal with which to study the dark side of the universe. We have to realize that more than 99 percent of space emits no light and no electromagnetic radiation. All we know about this part at the moment is that it is subject to gravitation. The great hope now is that it will be possible to investigate it.

Bruce Allen: But first and foremost we have shown that we can measure gravitational waves directly. We can now use this to do research. And we are now in a position to test the general theory of relativity in strong gravitational fields. Until now, it has proved primarily that Einstein's theory is completely correct. So I don't think this will tell us something fundamentally new about physics that we don't already know. But we have a wonderful method for checking these laws.

Alessandra Buonanno: It is such an enormous discovery that it is difficult to immediately anticipate all the repercussions for gravitation, fundamental physics and astrophysics, but its echoes will be reverberating in those fields for many, many years. And it's fantastic that the announcement takes place shortly after the 100-year anniversary of Einstein's publication of the paper in which he predicted the existence of gravitational waves! We now have a new tool to probe the universe and unveil its dark, most extreme side. We have discovered that stellar-mass black holes exist, that they exist in pairs – that is, in binary systems – and that they can be quite massive. And yes, the observation of binary black hole mergers provides us with the remarkable opportunity to see how gravity operates at such extreme conditions and test whether Einstein's general theory of relativity still holds. So far, so good!

Bruce Allen: I also think back to the centenary anniversary of the general theory of relativity, which we celebrated in autumn 2015 in Berlin: because even Einstein himself didn't believe that it would ever be possible to measure gravitational waves, since they are so weak. Nor did he believe in black holes. We have shown that he was wrong on both counts. But I don't think this would have bothered him. I think he would have been delighted! ◂

Interview: Felicitas Mokler

Photo: Frank Vinken

The Search for the **Gentle Tremble**

Gravitational waves are some of the most spectacular predictions of the 1915 general theory of relativity. However, it wasn't until half a century later that physicist Joseph Weber attempted to track them down. In the early 1970s, **Max Planck scientists** also began working in this research field, and developed second-generation detectors. The groundwork laid by these pioneers meant the waves in space-time ceased to be just figments of the imagination: in September 2015 they were finally detected.

TEXT **HELMUT HORNUNG**

Albert Einstein is beset by doubt: it will never be possible to detect gravitational waves – the tremble in space-time is simply too weak! Yet it was he himself who had postulated their existence, which follows from the general theory of relativity he put forward in November 1915. A short time later, in 1916 and again in 1918, he devotes a paper to this phenomenon.

Two decades later, he suddenly has a change of heart: "I have been working with a young colleague [Nathan Rosen] and we have come to the interesting conclusion that gravitational waves do not exist," Einstein writes to his colleague Max Born. In 1936, he submits a manuscript to the renowned journal Physical Review; it is returned to the author by a reviewer who considers it to be unsuitable. Albert Einstein is fuming about this embarrassment, but must concede that his argumentation is indeed flawed. His doubts were unfounded.

And the physics world? It barely pays any heed to gravitational waves. The same applies to the general theory of relativity overall, which has been eking out a rather miserable existence since the 1920s. It is only after Einstein's death in 1955 that people begin to take an interest in it. Astrophysicists are now starting to turn their sights toward black holes and quasars, exotic objects that can't be explained without Einstein's equations. This renaissance of relativity ultimately benefits gravitational waves, too, which strike a chord with at least one physicist: Joseph Weber.

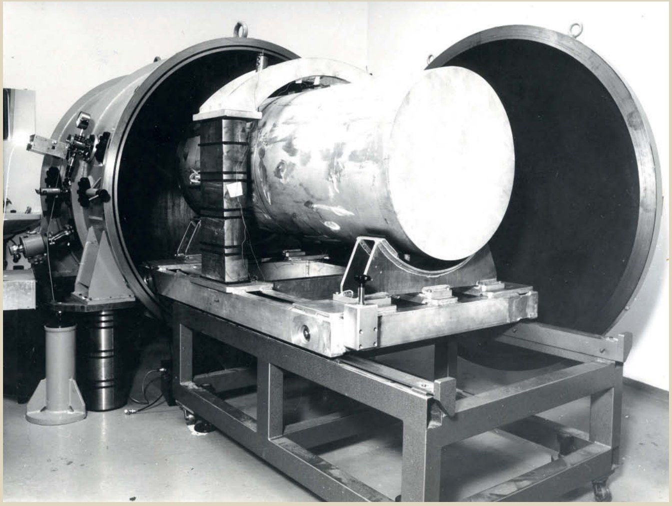
Born in 1919 in New Jersey, the researcher at the University of Maryland has an idea for a simple experiment: he suspends an incredibly heavy aluminum cylinder – 1.5 meters long and 60 centimeters across – in a steel wire loop and attaches piezo sensors to its middle to register oscillations. The whole test rig is housed in a vacuum chamber.

But why can gravitational waves cause a solid metal cylinder to tremble? Because they stretch and compress space perpendicularly to their direction of propagation. Let's imagine that gravitational waves impinge on a spherical balloon: within a matter of milliseconds, they would first deform it into the shape of an egg and then elongate it into the shape of a sausage.

Weber thinks gravitational waves originate primarily from cosmic catastrophes within our Milky Way – a supernova, for instance. This is when a star explodes and ejects great amounts of mass into space at the same time as its inner regions are collapsing in on themselves. What remains is a neutron star or a black hole. We now know that these objects themselves can also generate gravitational waves – whenever they are formed in pairs on close orbits and merge with each other. The waves registered in September 2015 originated from this type of event: two black holes with a mass of around 29 and 36 solar masses each that merged with one another in a galaxy approximately 1.3 billion light-years away.

The reach of Weber's cylinder extends only to a small region within our Milky Way. It is unlikely that a supernova will explode here, especially since there are thought to be only two to four such events per century in the entire galaxy. Nevertheless, Joseph Weber reports success in 1969. His detectors in Maryland and at Argonne National Laboratory 1,000 kilometers away are said to have actually registered gravitational waves, and even several per week!

Other scientists remain skeptical, including those at the Max Planck Institute for Physics and Astrophysics in Munich. In 1970, this becomes the birthplace of gravitational wave research in



Weighty experiment: In the early 1970s, Max Planck researchers used a massive aluminum cylinder like the one shown here in their search for gravitational waves.

Photo: MPG archive

Germany. "We decided back then to repeat Weber's experiment as precisely as we could with refined technology and sophisticated data processing," remembers Walter Winkler, one of the ambitious Max Planck researchers. The group working with Heinz Billing builds the world's most sensitive cylinder detectors in Munich and in Frascati, Italy. They are capable of registering changes in length of 10^{-15} centimeters. The experiments run from 1972 until 1975. The result: nothing!

The Weber detectors fall out of fashion – and make room for a new method: interferometry. This idea originally came from German-American physicist Albert A. Michelson. In 1881, he wanted to use such an instrument in Potsdam to measure the speed of the Earth relative to what was then thought to be the ether. Ninety years later, Philip Chapman, Robert Forward and Rainer Weiss suggest using this type of instrument as a detector for gravitational waves. The light source is to be a laser. But a lack of money prevents the three US researchers from getting any further.

Once again, the group from the Max Planck Institute for Physics and Astrophysics comes onto the scene. They are the only people in the world to begin working with this new technology. Its principle is simple: a laser beam impinges on a beam splitter, where it is split into two beams; one continues on in a straight line while the other is deflected to the side. At the end of each path is a mirror that reflects the light back to the beam splitter.

GEO, November 1985

» Researchers at the Max Planck Institute of Quantum Optics in Garching aim to use a three-by-three kilometer "antenna" to detect gravitational waves from distant galaxies.

This mirror now deflects the beams such that they are superimposed on each other – that is, they interfere. However, the light waves arriving at a photodiode oscillate not in phase, but out of phase: wave crest meets wave trough – the light waves extinguish each other. If a gravitational wave runs through the system, it compresses and elongates space, thus changing the measurement paths. The light waves are no longer out of phase. The receiver no longer remains dark – a signal appears.

In 1975, the researchers in Munich – working with Heinz Billing are Walter Winkler, Albrecht Rüdiger, Roland Schilling, Lise Schnupp and Karl Maischberger – build a prototype with an arm length of 3 meters. The light of a 3-watt argon laser is reflected 150 times. But this second-generation detector also has its problems: the frequency of the laser light must be extremely stable, and its basic power is too weak. Moreover, fluctuations in the geometry of the beam lead to undesired error signals and allow tremors to shake the mirrors.

To reduce all these unwanted effects, the physicists develop innovative technologies that no modern gravitational wave trap can now do without. From 1983 onward, they continue their pioneering work with a second prototype with 30-meter arm length. This is really short, because in the thousandth of a second that it takes a gravitational wave to traverse the measurement path, the light covers 300 kilometers. The laser beam would therefore have to be en route over the same length in order to observe the wave completely. The researchers avail themselves of a trick they call "delay line," which consists in "folding" the beam path and reflecting the beam backwards and forwards between the mirrors many times, as described above.

New technology: Lasers form the heart of the second generation of detectors. Here, Walter Winkler (background left) and Karl Maischberger are working on the prototype of such an interferometer in 1977.

Photo: MPG archive

Nevertheless, the longer the measurement path, the better. "So in 1985, we submitted an application to build a detector with an arm length of 3 kilometers," says Walter Winkler. "But in Germany there was no interest at all in the project, so it wasn't approved." A British group suffers the same fate. It had been undertaking similar research since 1977 at the University of Glasgow and had built a detector with 10-meter arm length in 1980. In 1986, the Scottish application for a large interferometer fell on deaf ears.

But similar fates bring people together, so three years later, the two teams decide to collaborate. Only a short time later, they submit joint plans for a detector to be built in the Harz Mountains in Germany, again without success. The breakthrough finally comes in 1994: the construction of a German-British detector with each arm measuring 600 meters finally becomes reality just outside Hanover. "Herbert Welling from the University of Hanover managed to convince his colleagues to bring the installation to Lower Saxony," says Winkler.

Karsten Danzmann, then Group Leader in Garching and now Director at the Max Planck Institute for Gravitational Physics, is appointed and given funding by the Federal State of Lower Saxony, the university and the Volkswagen Foundation. With not much money but a lot of hard work – also by the British colleagues – the researchers get the project off the ground.

The first groundbreaking ceremony is held on September 4, 1995. Since 2002, the detector has been operated by the Center for Gravitational Physics, of which the Max Planck Institute is a member, together with Leibniz Universität Hannover and Glasgow and Cardiff Universities. The facility serves primarily as a test laboratory for technologies that are incorporated in other detectors all over the world. Even David Shoemaker, leader of the Advanced LIGO project, was a member of the Max Planck Group for a while. This American facility with German technology is now the first to have measured gravitational waves and crowned the decades-long search for the gentle tremble from space.