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.

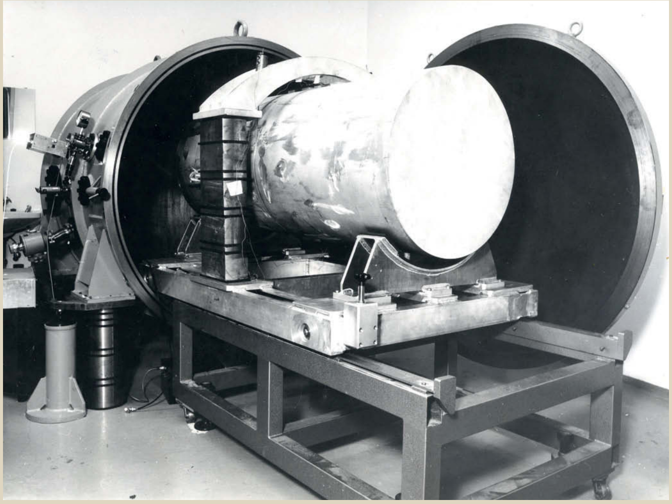
Born in 1919 in New Jersey, the researcher at the University of Maryland has an idea for a simple experiment: he suspends an incredibly heavy aluminum cylinder – 1.5 meters long and 60 centimeters across – in a steel wire loop and attaches piezo sensors to its middle to register oscillations. The whole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

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.

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.

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.