History of gravitational waves

Einstein predicted gravitational waves in 1916

Albert Einstein predicted the existence of gravitational waves in his theory of general relativity. However, the predicted effects of gravitational waves were so small that even Einstein himself thought that gravitational waves would not be observable.

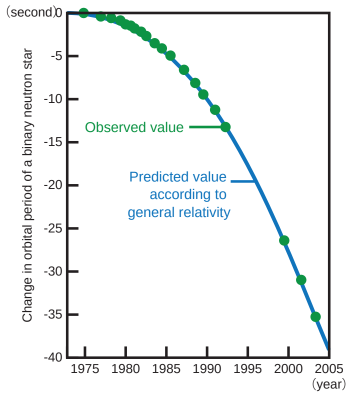
Observation with Weber's resonant bar detector in the 1960s

In 1969, Joseph Weber announced that he had discovered gravitational waves with a detector using a resonant bar. Despite follow-up attempts by a number of scientists, no further detection was successful. Weber's result was probably a false alarm, but many scientists who tried to detect gravitational waves at that time played major roles in later research on gravitational waves using laser interferometry.

Discovery of binary neutron stars by Hulse and Taylor in 1974

Joseph Hulse and Russell Taylor discovered a binary pulsar, which consists of two neutron stars orbiting each other, each only about 20 km in diameter but as massive as the Sun. The orbital period of this binary star gradually reduced year after year. Later research showed that the gradual decay in the orbital period of this pulsar precisely matched the loss of energy due to gravitational radiation predicted by general relativity if the system were emitting gravitational waves.

This was recognized as indirect evidence for the existence of gravitational waves. Hulse and Taylor were awarded the Nobel Prize in Physics in 1993 for their discovery of the first binary pulsar.



1970s: Observation attempts using laser interferometers

After the discovery by Hulse and Taylor, the direct detection of gravitational waves motivated further searches.

In the late 1970s, a number of scientists, including Robert Forward, who had experimented with resonant detectors as a student of Rainer Weiss of the Massachusetts Institute of Technology, and Weiss himself, began using laser interferometers to try to detect gravitational waves. Since then, larger and more sensitive detectors have been built one after another around the world.

1990s: Active research on gravitational waves in Japan

Since the 1990s, research for gravitational wave observation has also accelerated in Japan. After the construction of 20 m to 100 m prototype interferometers, TAMA300 at Mitaka (NAOJ) and CLIO at Kamioka (ICRR) were constructed to improve gravitational wave observation technology and gain experience with interferometers. The KAGRA project was launched in 2010, and tunnel excavation began in 2012.

TAMA300 (c)NAOJ

First detection of gravitational wave at LIGO in 2015

It was announced in February 2016 that Advanced LIGO, a pair of gravitational wave detectors in the US, detected gravitational wave signals that were generated by the merger of two black holes in September 2015.

This was a breakthrough achievement a hundred years after Einstein's prediction, and about fifty years after beginning to try to detect gravitational waves in earnest. For this achievement, the 2017 Nobel Prize in Physics was awarded to three LIGO researchers. Furthermore, a LIGO and Virgo collaboration announced the first-ever detection of gravitational waves originating from the coalescence of a binary neutron star system in 2017. This marked the beginning of multi-messenger astronomy, combining the results of gravitational wave detection with observations from optical telescopes around the world.

KAGRA completed in 2019

In 2019, KAGRA was finally completed. After careful adjustments to enhance the detection of small distortions in space-time, it began its long-awaited observational run on February 25, 2020. In April 2020, KAGRA conducted joint observations with GEO600 in Germany, which belongs to the LIGO group. In May 2023, KAGRA participated in international joint observations with LIGO in the US and Virgo in Europe, and it is currently undergoing further improvements and upgrades to increase its sensitivity.

Photo: Enrico Sacchetti

KAGRA is operated through close collaboration between the core organization, the Institute for Cosmic Ray Research of the University of Tokyo, the National Astronomical Observatory of Japan, and the High Energy Accelerator Research Organization, with the cooperation of researchers from domestic and international research institutes.

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KAGRA Observatory

Institute for Cosmic Ray Research

What are gravitational waves?

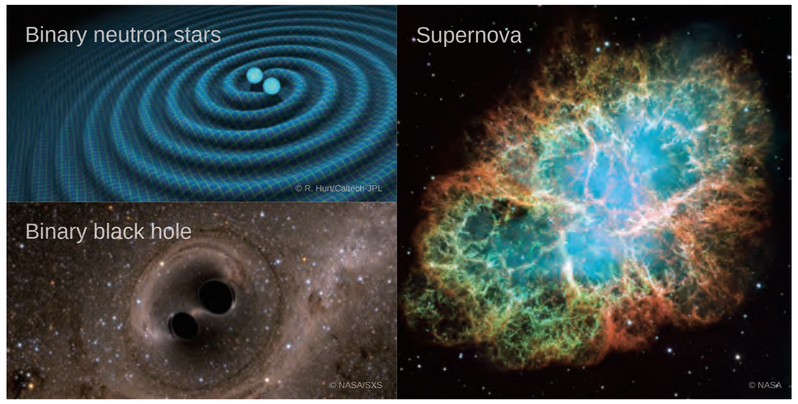
Ripples in space-time, predicted by Einstein in 1916

Gravitational waves were predicted by Albert Einstein's theory of general relativity, published between 1915 and 1916. His theory explained gravity between two objects as caused by the distortion of space created by the mass of the objects. And when such objects move, the distortion created by the movement becomes waves that travel through space at the same speed as light. These gravitational waves are often called "ripples" in space-time.

Astrophysical events generating observable gravitational waves

Heavy objects like stars moving, merging, exploding…

Gravitational waves are created whenever objects with the mass move. In fact, if you move your arms around, you will produce gravitational waves. However, that amplitude is too small to detect with current human technology. Observable gravitational waves are created when heavy objects like stars explode or orbit each other and merge. Some examples of events and phenomena that could cause observable waves are supernovae (the explosion of massive stars, several times more massive than the Sun, at the end of their lives) and neutron stars and black holes orbiting each other and merging. The Big Bang that created the universe also generated gravitational waves.



Detecting gravitational waves

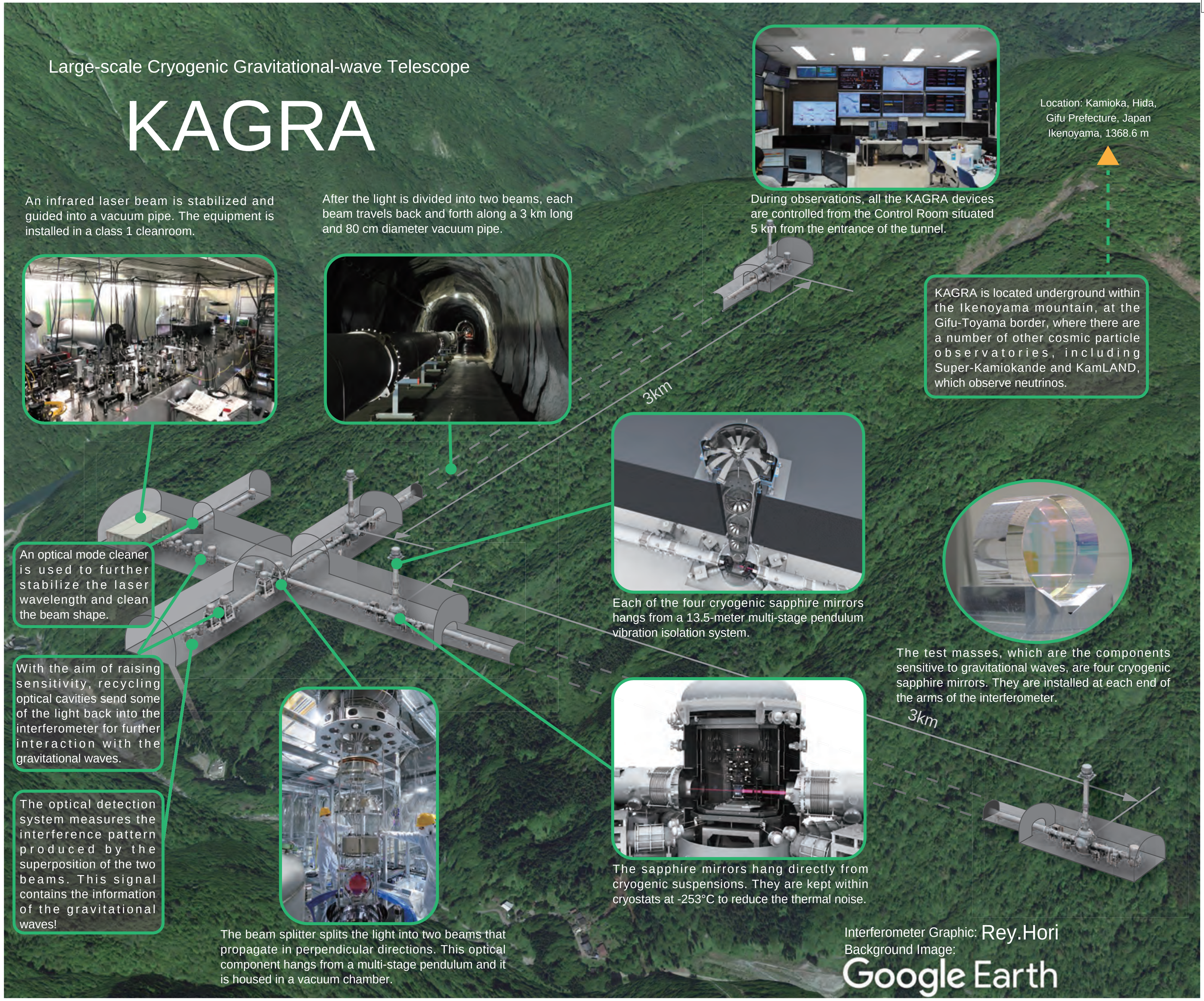
Ripples the size of an atom between the Earth and the Sun

While the processes that generate gravitational waves are extremely violent and destructive, by the time the waves reach Earth they are thousands of billions of times smaller. In fact, the amount of space-time distortion that KAGRA is trying to detect is roughly the size of an atom of hydrogen (0.0000000001m) seen from the distance between the Earth and the Sun (which are separated by 150,000,000 km).

Laser interferometer detecting small distortions

How does KAGRA detect such small distortions? KAGRA is a 3 km L-shaped laser interferometer, which runs a laser beam back and forth between mirrors at the opposite ends of the arms to measure the length difference between the two orthogonal directions. The gravitational wave telescope is a huge and precise "measuring stick".

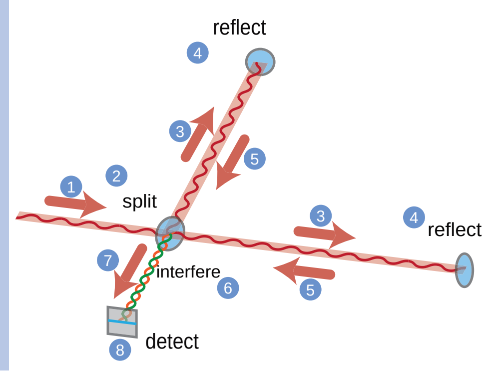
KAGRA has taken various measures to detect the slightest distortions. Each of the mirrors that reflect the laser beam is suspended from a pendulum called a vibration isolation system to keep it away from vibrations in the ground. Also, in order to reduce disturbance from seismic activity, the KAGRA interferometer was constructed underground, within purpose-built tunnels. In addition, the mirrors are cooled to minus 253 degrees Celsius in cryostats to reduce thermal noise. The entire device is placed in a vacuum chamber to prevent the laser beam from being scattered or shaken by the air. Various other devices are also incorporated to increase the system's sensitivity.

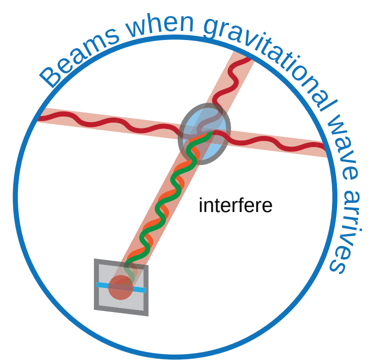


How a Laser Interferometer Works

1. Incident laser beam.
2. With a beam splitter, the laser is split into two beams, traveling in perpendicular directions.
3. The beams propagate along the arms.
4. At the end of the arms, the beams are reflected by mirrors.
5. The beams propagate back to the beam splitter.
6. At the beam splitter, the two beams recombine and produce interference.
7. The combined beam is sent to a detector.
8. The intensity of the interference pattern is measured by the detector.

Beams in normal state





As suggested in the figure on the left, light is an undulatory phenomenon. The dark red lines represent the changing amplitudes of the electric fields as the two beams propagate along the arms.

After the beams recombine at the beam splitter, in the absence of gravitational waves, the maxima of one wave and the minima of the other coincide, canceling each other and producing no signal at the output. However, when gravitational waves pass through, they change the distance traveled by the beam along the arms, causing the maxima and the minima away from each other. Under these new conditions, the fields fail to cancel and a signal appears at the output.