Gravitational wave observatories

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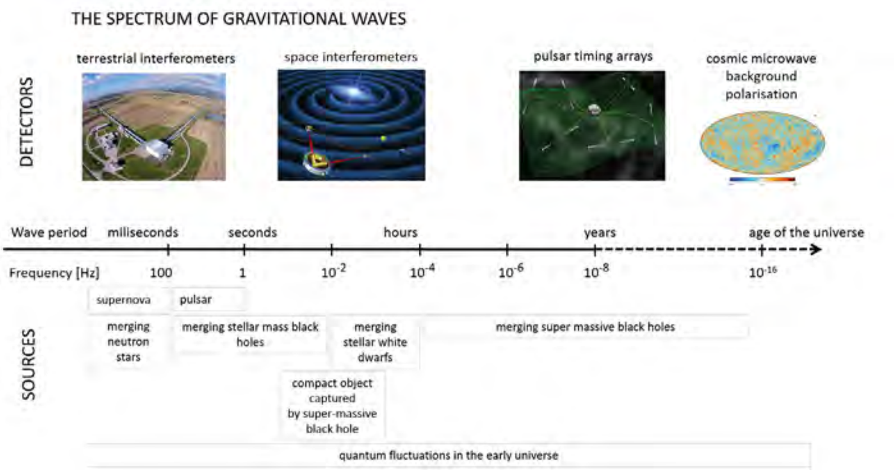
Gravitational waves were first observed on 14 September 2015. To date, a total of about 200 gravitational wave events were recorded by the currently operational terrestrial laser interferometers. The next-generation interferometers, underground and in space, are being prepared. We present short overview.

Gravitational waves are 'ripples' in spacetime travelling at the speed of light. They are caused by some of the most violent and energetic processes in the universe involving massive objects. Examples are massive neutron stars and black holes orbiting each other or collisions of black holes or neutron stars. These processes produce gravitational waves with wavelengths ranging from a few kilometer to larger than the observable universe. The broad spectrum of gravitational waves (Fig. 1) requires observatories ranging from human-made facilities on the ground and in space to galaxy-sized pulsar timing arrays. Details in the cosmic microwave background, the oldest light in the universe, can reveal gravitational waves generated less than 10^{-12} seconds after the big bang.



▲ FIG. 1: Spectrum of gravitational waves.

Operational terrestrial interferometers

Typically, the currently operational terrestrial gravitational wave observatories involve laser interferometers. LIGO in the USA, VIRGO near Pisa, Europe and KARGA in Japan[1] have a L-shape interferometer with two arms with a length of three to four kilometers. An incoming light beam from a laser source is split into two by a semi-reflective mirror. The light path of each beam is folded hundreds of times between large vibration-free suspended mirrors (Fig. 2) at the end and the entrance of the arms, before the beams recombine again at the beam splitter. The recombined beams then travel to the output of the detector, where a photodetector is placed. Here the pattern of interference between the two beams is recorded. Specific interference patterns due to changes in the length of the arms of the interferometer are an indication of a passing gravitational wave. Since 2015, the terrestrial gravitational wave detectors have become important drivers in multi-messenger astronomy. The detection of a gravitational wave event triggers follow-up searches by telescopes in the electro-magnetic domain and neutrino observatories.

The Einstein Telescope

The development of the underground Einstein Telescope is building on the experience of LIGO and VIRGO. The aim is to build an observatory that will be able to observe a volume of the universe about one thousand times larger than that of the current observatories. At a depth of 250 - 300 meters three tunnels with a length of about 10 kilometer will house a triangular interferometer. At each vertex of the triangle a pair of V-shaped interferometers will be installed, together comprising an observatory optimised for the detection of both low and high frequency gravitational waves (Fig. 2).

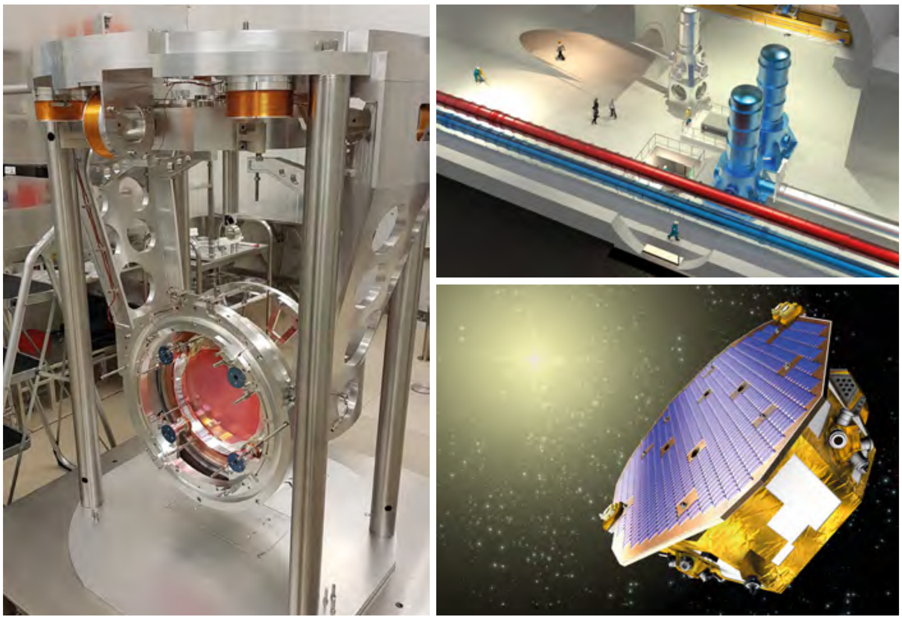
Currently, two projects are conducted to find the best location for the telescope. One is in the Euregio Meuse-Rhine, where Belgium, Germany and The Netherlands meet, the other is on Sardinia, Italy[2]. Recently, an alternative proposal has been issued to build detectors at both locations – one in Euregio Meus-Rhine and one on Sardina, about 1000 kilometers apart, each with L-shaped interferometers with arms lengths of about 15 kilometers instead of the single triangular one with smaller arms. The alternative configuration could lead to two to three times more events than with the triangle and could improve the pointing resolution of the telescope. On the other hand, the triangular configuration might perform better in analysing noise and thus better distinguish a gravitational wave event. No decisions have been taken yet. The Einstein telescope should become operational by 2035.

The LISA telescope

To detect gravitational waves with a wave length larger than the Earth's diameter it is necessary to go to space. In space, the LISA interferometer[3] will form an equilateral

[1] https://www.ligo.caltech.edu, https://www.virgo-gw.eu, https://gwcenter.icrr.u-tokyo.ac.jp/en
[2] https://www.einsteintelescope-emr.eu/en/ and https://www.einstein-telescope.it/en/home-en
[3] https://lisa.nasa.gov/index.html

triangle with millions kilometers long 'arms', thus forming a gigantic interferometer with a spacecraft (Fig. 2) at each vertex. The triangle will trail tens of millions kilometer behind the Earth. The spacecraft will send laser beams back and forth between each other. Such an interferometer in space will be able to measure gravitational waves in a lower frequency domain than the terrestrial ones (Fig. 1). The LISA pathfinder demonstrated successfully the concept of full LISA. It was operational between December 2015 and July 2017. The launch of LISA is expected in 2035.



▲ FIG. 2: Left: suspended mirror of VIRGO, © EGO/VIRGO; Top right: artist's impression of the interiors of the Einstein Telescope by Marco Kraan, Nikhef; Bottom right: impression of the spacecraft of the LISA pathfinder, © ESA.

Pulsar Timing Arrays

For the detection of gravitational waves with even larger wavelengths an array of millisecond pulsars can be used to form a galactic-size gravitational wave detector. Millisecond pulsars are rapidly rotating neutron stars that emit radio waves from their magnetic poles. The radio waves are observed on Earth as a string of pulses. Since the rotation periods of the pulsars are very stable, the arrival times of the pulses are very regular. Disturbances of the pattern might indicate the passage of a gravitational wave. The pulsars in an Pulsar Timing Array (PTA) are observed in different directions by a network of radio telescopes. Several PTAs with collaborating radio telescopes are active, among them the European PTA, which in 2023 together with other PTAs reported evidence for ultra-low-frequency gravitational waves. ■

[3] https://lisa.nasa.gov/index.html

[4] https://www.epta.eu.org