GRAVITATIONAL WAVES

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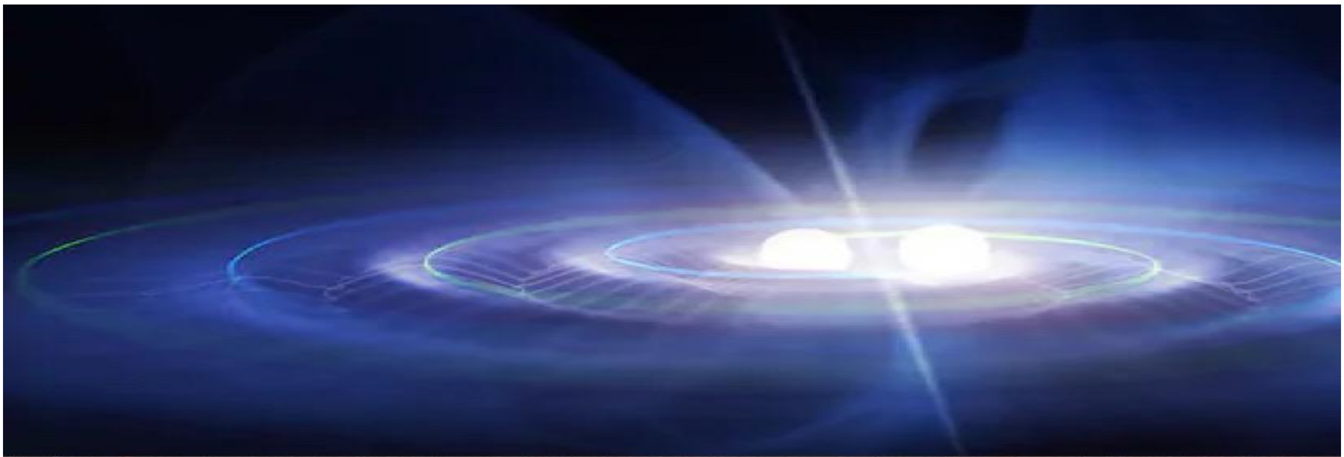
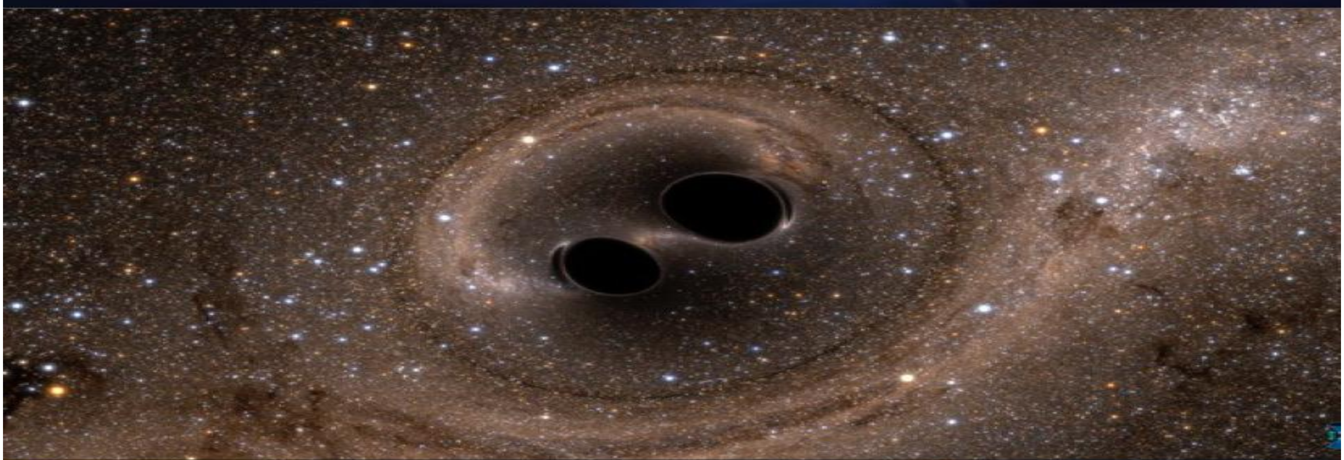
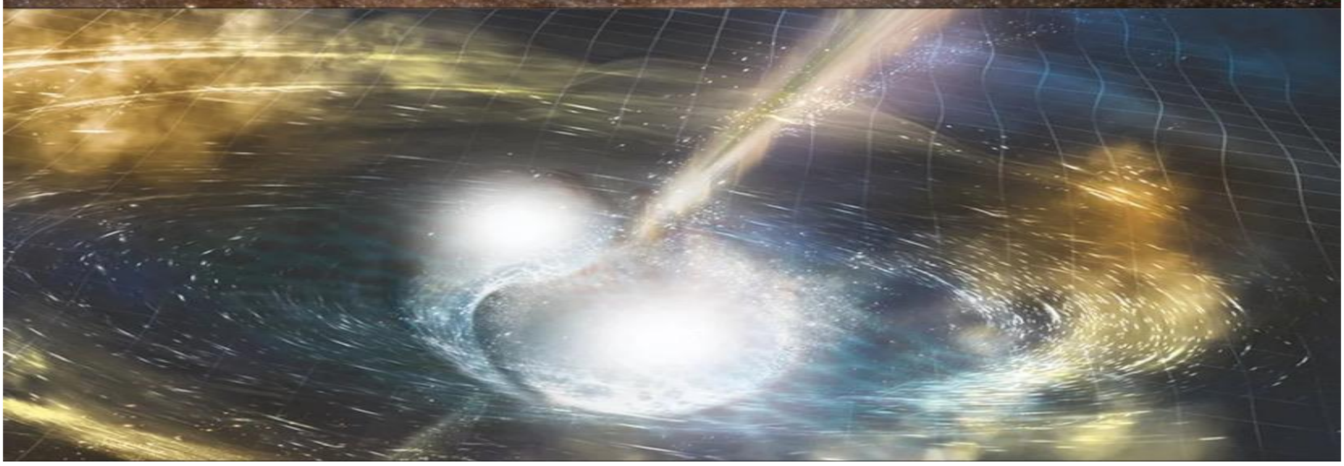
A gravitational wave is a ripple in the fabric of space and time. If you imagine space as a giant, tightly-pulled sheet of rubber and imagine objects with mass, like planets and stars, are objects placed on top of the sheet, then you can understand how these objects create “distortions” in the space around them, like “a bowling ball on a trampoline” as they put it. In this report, that summarizes the results of our research, we will try to clarify what are gravitational waves and we hope you will learn something about our topic.





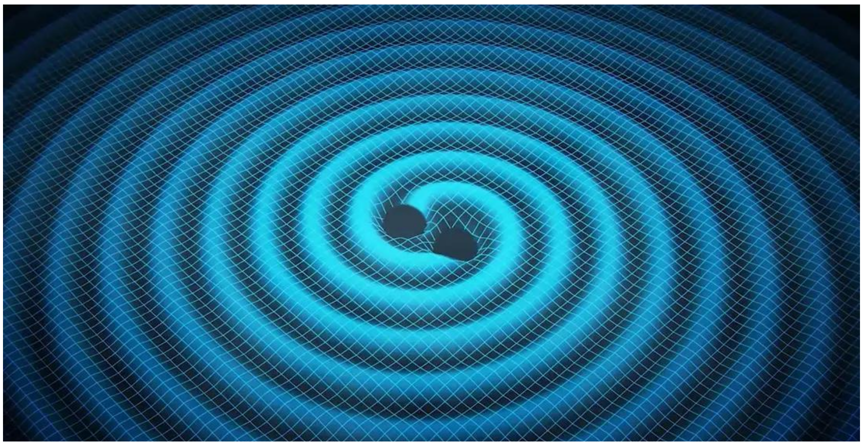


Definition and history of gravitational waves

Gravitational waves are disturbances in the curvature of space-time, generated by accelerated masses, that propagate as waves outward from their source at the speed of light. Gravitational waves transport energy as gravitational radiation, a form of radiant energy similar to electromagnetic radiation.

They were proposed by Henri Poincaré in 1905 and subsequently predicted in 1916 by Albert Einstein on the basis of his general theory of relativity.

In Einstein's general theory of relativity, gravity is treated as a phenomenon resulting from the curvature of space-time. This curvature is caused by the presence of mass. Generally, the more mass that is contained within a given volume of space, the greater the curvature of space-time will be at the boundary of its volume. As objects with mass move around in space-time, the curvature changes to reflect the changed locations of those objects. In these circumstances, when accelerating objects change this curvature, they propagate outwards at the speed of light in a wave-like manner. These propagating phenomena are known as gravitational waves. As a gravitational wave passes an observer, that observer will find space-time distorted by the effects of strain. Distances between objects increase and decrease rhythmically as the wave passes, at a frequency equal to that of the wave. The magnitude of this effect decreases in proportion to the inverse distance from the source.



A general gravitational wave

The first indirect evidence for the existence of gravitational waves came from the observed orbital decay of the Hulse –Taylor binary pulsar, which matched the decay predicted by general relativity as energy is lost to gravitational radiation. In 1993, Russell A. Hulse and Joseph Hooton Taylor Jr. received the Nobel Prize in Physics for this discovery.

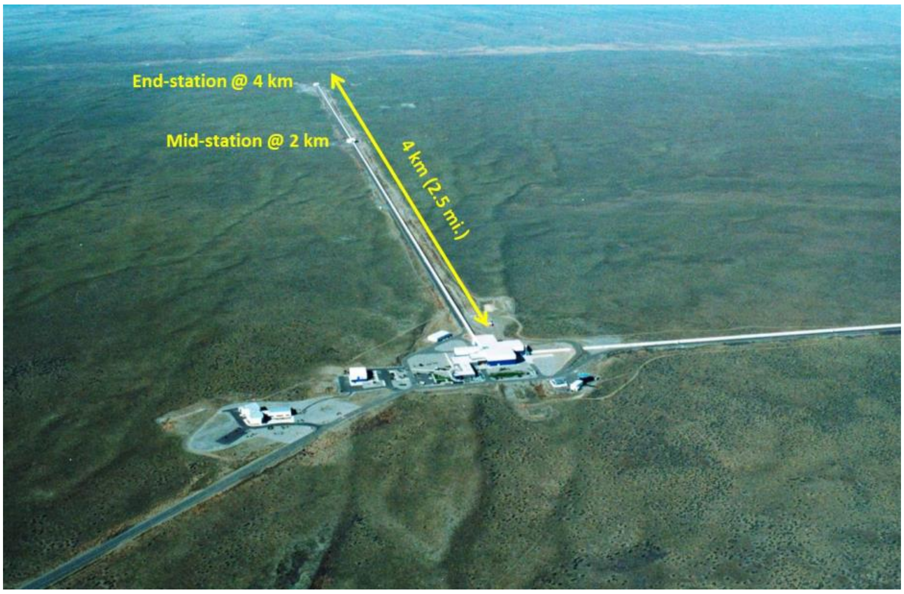
The first direct observation of gravitational waves was not made until 2015, when a signal generated by the merger of two black holes was received by the LIGO gravitational wave detectors in Livingston and in Hanford.

The two physicians Russell A. Hulse and Joseph Hooton Taylor Jr

Facilities

Scientists have demonstrated the existence of these waves using increasingly sensitive detectors. The most sensitive detector accomplished the task possessing a sensitivity measurement of about one part in 5×10^{22} (as of 2012) provided by the LIGO and VIRGO observatories. A space based observatory, the Laser Interferometer Space Antenna, is currently under development by ESA.

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a large-scale physics experiment and observatory to detect cosmic gravitational waves and to develop gravitational- wave observations as an astronomical tool. Two large observatories were built in the United States with the aim of detecting gravitational waves by laser interferometry. These observatories use mirrors spaced four kilometers apart which are capable of detecting a change of less than one ten-thousandth the charge diameter of a proton. LIGO is the largest and most ambitious project ever funded by the NSF. In 2017, the Nobel Prize in Physics was awarded to Rainer Weiss, Kip Thorne and Barry C. Barish "for decisive contributions to the LIGO detector and the observation of gravitational waves".



The LIGO concept built upon early work by many scientists to test a component of Albert Einstein's theory of general relativity, the existence of gravitational waves. Starting in the 1960s, American scientists including Joseph Weber, as well as Soviet scientists Mikhail Gertsenshtein and Vladislav Pustovoit, conceived of basic ideas and prototypes of laser interferometry, and in 1967 Rainer Weiss of MIT published an analysis of interferometer use and initiated the construction of a prototype with military funding, but it was terminated before it could become operational. Starting in 1968, Kip Thorne initiated theoretical efforts on gravitational waves and their sources at Caltech, and was convinced that gravitational wave detection would eventually succeed.

Virgo is a large interferometer, built for detecting gravitational waves.
It has been designed and built by the collaboration between the French “Centre National de la Recherche Scientifique (CNRS)” and the Italian “Istituto Nazionale di Fisica Nucleare (INFN)”; now it involves an international collaboration of French, Italian, Dutch, Polish and Hungarian scientists.
Virgo is located in Italy, in Cascina, near the city of Pisa, on the site of the European Gravitational Observatory (EGO). Virgo works together with Ligo and they have given birth to a collaboration for the analysis of data, making a single large observatory, which extends from Europe to Pacific.
Virgo is made up of two twin arms, 3 kilometers long each. The light source is a laser, which is divided into two beams by a beam splitter, tilted by 45 degrees. In this way the two beams propagate in the two arms, which are set perpendicular to each other. In particular the beams circulate under ultra-high vacuum, indeed Virgo is the largest ultra-high vacuum system in Europe. At the end of each arm the beams are reflected by high quality mirrors; making them traveling back and forth hundreds of time, virtually extending the arms up to 300 kilometers long.

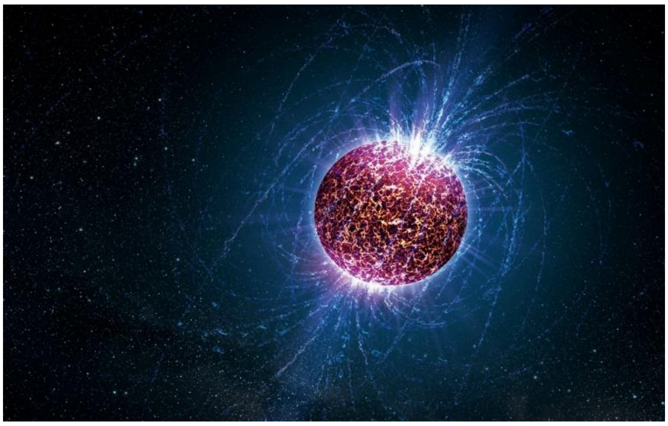
When the two beams come together again, recombining in the beam splitter, an interference pattern is produced and detected by a photo-diode. At that point if a gravitational wave passes through the interferometer, it is caused a variation in the length of the arms: one becomes shorter, while the other becomes longer. Virgo can detect very small variations, of the size of one billionth of the diameter of an atom; indeed it is an extremely sensitive tool and it is also able to detect gravitational waves from 10Hz to 10000 Hz.

Sources and types of gravitational waves

LIGO scientists have defined four categories of gravitational waves, according to the various sources generating them: Continuous, Compact Binary Inspiral, Stochastic and Burst. Each of these gives birth to a peculiar, unique or characteristic set of signal.
It is thought that **Continuous gravitational waves** are produced by a single spinning massive object, such as a neutron star.
A neutron star is a type of star which is very old, since it has cooled down and stopped nuclear fusion reactions. It forms when the gravity pulls the star down on itself and its electrons and protons

are compressed together, thus leaving just neutrons. The star is then held up against gravity by the so-called neutron degeneracy pressure, according to which no two neutrons can be in the same place at the same time.

So any bumps on or imperfections in the spherical shape of this star will generate gravitational waves as it spins. If the spin-rate of the star stays constant, the gravitational waves it emits will be constant, too. That means the gravitational wave continuously has the same frequency and amplitude. That's why these are called “Continuous Gravitational Waves”. Actually, these gravitational waves haven't been detected yet, but researchers have created simulations of what an arriving continuous gravitational wave would sound like if its signal was converted into a sound. Here is the link, in case you were curious to hear what the gravitational waves from a spinning neutron star would "sound" like.



The next class of gravitational waves LIGO and VIRGO hunts for is **Compact Binary Inspiral waves**, which are generated by orbiting pairs of massive and compact objects, such as white dwarf stars, black holes and neutron stars. More specifically, three categories of compact binary systems exists:

- Binary Neutron Star
- Binary Black Hole
- Neutron Star – Black Hole Binary

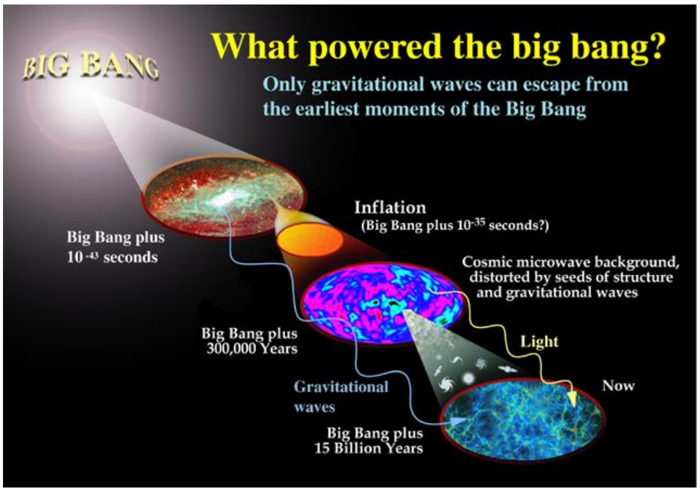
Each of these pairs gives birth to a unique pattern of gravitational waves, but the mechanism is exactly the same and it's called inspiral. Inspiral occurs when pairs of dense compact objects revolve around each other. While orbiting, they emit gravitational waves, carrying away some of the system's orbital energy. Consequently, over millions of years, the objects gradually orbit closer and closer together, which causes them to even orbit faster, thus emitting stronger waves.

So, the objects of the system are locked in this runaway accelerating spiraling process. Given that, the sequence of generating gravitational waves and orbiting closer and closer inevitably ends with the collision of the objects. These objects had been orbiting each other for billions of years; LIGO and VIRGO capture the last fraction of a second or few seconds of that lifetime together.

The masses of the objects involved determine how long they emit detectable gravitational waves. Heavy objects, like black holes, move through their final inspiral phase much more rapidly than lighter objects, like neutron stars. This means that black-hole merger signals are much shorter than neutron star merger signals, and the differences are quite striking. For example, the first pair of merging black holes that LIGO detected produced a signal just two-tenths of a second long. In contrast, the first neutron star merger LIGO detected in August 2017 generated a signal over 100 seconds long. So far, Compact Binary Inspiral gravitational waves, from collision of two black holes or two neutron stars, are the only ones that LIGO and VIRGO have been able to detect, since the first discovery on 14th September 2015.

Two types of compact binary inspiral waves: the first originated by two stars of neutron and the second by two black holes

Stochastic gravitational waves are the relic gravitational waves of the early evolution of the universe, which derive from a large number of random and independent events that combine to create a background of cosmic gravitational waves. Astronomers predict that there are so few significant sources of continuous or binary inspirational gravitational waves in the Universe that LIGO doesn't care about the possibility that more than one pass from Earth at once can be neglected in the analysis of Ligo data. However, it is assumed that many small gravitational waves pass continuously from all over the Universe and are mixed together randomly. These small waves from every direction make up what is called a "Stochastic Signal", since you have a random pattern that can be analyzed statistically, but not accurately predicted. Although these are the smallest and most difficult gravitational waves to detect, it is possible that at least some of this stochastic signal could have come from the Big Bang. Detecting this kind of waves would allow us to see further back in the history of the Universe than ever before. Recent observations of gravitational waves by Advanced LIGO and Advanced Virgo detectors imply that there is also a stochastic background that has been created by the fusion of binary black holes and binary neutron stars throughout universe history.
As far as the sound is concerned, these gravitational waves would produce a continuous noise (very similar to static noise) that will be the same from every part of the sky.



Then, we can focus on another kind of gravitational waves, that are "**burst gravitational waves**", whose search is really a search unpredictable, since LIGO has yet to detect them and there are many unknowns about it. Probably, physical knowledge is still not enough in order to predict how gravitational waves will appear from that source. To search for these gravitational waves, we cannot assume that they assume that they will have well-defined properties such as those of continuous and compact binary inspiratory waves. For these types of gravitational waves, scientists must recognize a pattern of signal even when such a pattern has not been modeled (as we think a signal may appear) before. Although this makes it difficult to search for exploded gravitational waves, detecting them has the greatest potential to reveal information revolutionaries of the universe. The gravitational waves burst from unknown or unexpected sources of short duration: they are the gravitational waves that collide in the night. Whenever humans looked at the universe with telescopes to look at visible light, radio waves, or gamma ray detectors to view gamma rays, they found things that were unexpected and revolutionized our understanding of the universe. Therefore, in there are hypotheses that some systems such as supernovae or gamma-ray bursts may produce gravitational waves, but too little is known about the details of these systems to anticipate the shape these waves will take. As for the sound, gravitational waves should produce are "pops" and "crackles" (it is difficult to say since very little can be assumed of their origin).

Conclusion

Gravitational waves could be of interest to cosmologists as they offer a possible way of observing the very early Universe. This is not possible with conventional astronomy, since before recombination the Universe was opaque to electromagnetic radiation. Precise measurements of gravitational waves will also allow scientists to test more thoroughly the general theory of relativity.

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