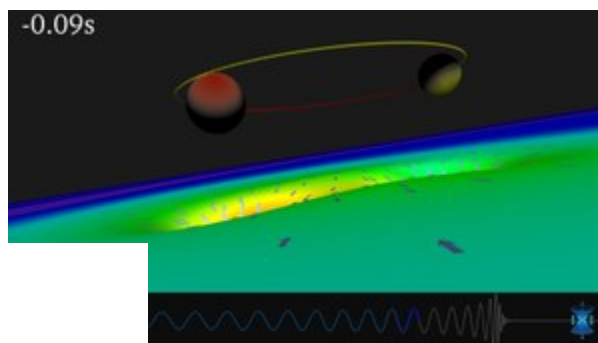


WIKIPEDIA

Gravitational wave

Gravitational waves are disturbances in the curvature of spacetime, generated by accelerated masses, that propagate as waves outward from their source at the speed of light. They were proposed by Henri Poincaré in 1905^[1] and subsequently predicted in 1916^{[2][3]} by Albert Einstein on the basis of his general theory of relativity.^{[4][5]} Gravitational waves transport energy as **gravitational radiation**, a form of radiant energy similar to electromagnetic radiation.^[6] Newton's law of universal gravitation, part of classical mechanics, does not provide for their existence, since that law is predicated on the assumption that physical interactions propagate instantaneously (at infinite speed) – showing one of the ways the methods of classical physics are unable to explain phenomena associated with relativity.



Simulation of the collision of two black holes. In addition to forming deep gravity wells and coalescing into a single larger black hole, gravitational waves will propagate outwards as the black holes spin past each other.

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 2017 Nobel Prize in Physics was subsequently awarded to Rainer Weiss, Kip Thorne and Barry Barish for their role in the direct detection of gravitational waves.

In gravitational-wave astronomy, observations of gravitational waves are used to infer data about the sources of gravitational waves. Sources that can be studied this way include binary star systems composed of white dwarfs, neutron stars,^{[7][8]} and black holes; and events such as supernovae, and the formation of the early universe shortly after the Big Bang.

Contents

Introduction

Speed of gravity

History

Effects of passing

Sources

Binaries

Compact binaries

Black hole binaries

Supernova

Spinning neutron stars

Inflation

Properties and behaviour

Energy, momentum, and angular momentum

Redshifting

Quantum gravity, wave-particle aspects, and graviton

Significance for study of the early universe

Determining direction of travel

Gravitational wave astronomy

Detection

Indirect detection

Difficulties

Negative-mass plasma

Ground-based detectors

Resonant antennas

Interferometers

Einstein@Home

Space-based interferometers

Using pulsar timing arrays

Primordial gravitational wave

LIGO and Virgo observations

In fiction

See also

References

Further reading

Bibliography

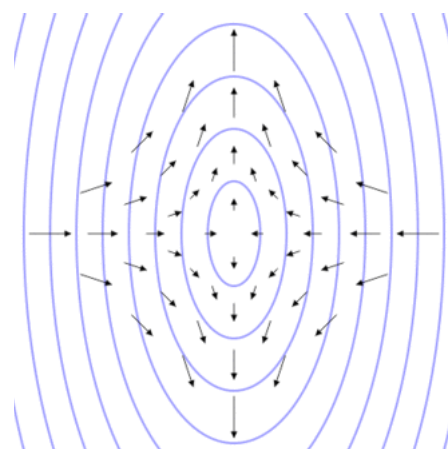
External links

Introduction

In Einstein's general theory of relativity, gravity is treated as a phenomenon resulting from the curvature of spacetime. 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 spacetime will be at the boundary of its volume.^[9] As objects with mass move around in spacetime, the curvature changes to reflect the changed locations of those objects. In certain circumstances, accelerating objects generate changes in this curvature, which 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 spacetime 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.^{[10]:227} Inspiring **binary neutron stars** are predicted to be a powerful source of gravitational waves as they coalesce, due to the very large acceleration of their masses as they **orbit** close to one another. However, due to the astronomical distances to these sources, the effects when measured on Earth are predicted to be very small, having strains of less than 1 part in 10^{20} . Scientists have demonstrated the existence of these waves with ever more 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.^[11] A space based observatory, the **Laser Interferometer Space Antenna**, is currently under development by **ESA**.

Gravitational waves can penetrate regions of space that electromagnetic waves cannot. They allow the observation of the merger of black holes and possibly other exotic objects in the distant Universe. Such systems cannot be observed with more traditional means such as **optical telescopes** or **radio telescopes**, and so **gravitational wave astronomy** gives new insights into the working of the Universe. In particular, 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.^[12] Precise measurements of gravitational waves will also allow scientists to test more thoroughly the general theory of relativity.



Linearly polarised gravitational wave

In principle, gravitational waves could exist at any frequency. However, very low frequency waves would be impossible to detect, and there is no credible source for detectable waves of very high frequency as well. **Stephen Hawking** and **Werner Israel** list different frequency bands for gravitational waves that could plausibly be detected, ranging from 10^{-7} Hz up to 10^{11} Hz.^[13]

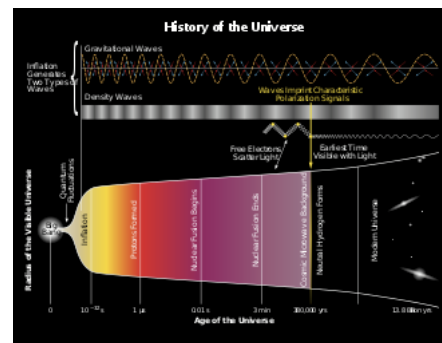
Speed of gravity

The speed of gravitational waves in the **general theory of relativity** is equal to the *speed of light* in a vacuum, *c*.^[14] Within the theory of **special relativity**, the constant *c* is not only about light; instead it is the highest possible speed for any interaction in nature. Formally, *c* is a conversion factor for changing the unit of time to the unit of space.^[15] This makes it the only speed which does not depend either on the motion of an observer or a source of light and / or gravity. Thus, the speed of "light" is also the speed of gravitational waves, and further the speed of any massless particle. Such particles include the **gluon** (carrier of the strong force), the **photons** that make up light (hence carrier of electromagnetic force), and the hypothetical **gravitons** (which are the presumptive field particles associated with gravity; however, an understanding of the graviton, if any exist, requires an as-yet unavailable theory of quantum gravity).

In October 2017, the **LIGO** and **Virgo** detectors received gravitational wave signals within 2 seconds of gamma ray satellites and optical telescopes seeing signals from the same direction. This confirmed that the speed of gravitational waves was the same as the speed of light.^[16]

History

The possibility of gravitational waves was discussed in 1893 by Oliver Heaviside, using the analogy between the inverse-square law in gravitation and electricity.^[20] In 1905, Henri Poincaré proposed gravitational waves, emanating from a body and propagating at the speed of light, as being required by the Lorentz transformations^[21] and suggested that, in analogy to an accelerating electrical charge producing electromagnetic waves, accelerated masses in a relativistic field theory of gravity should produce gravitational waves.^{[22][23]} When Einstein published his general theory of relativity in 1915, he was skeptical of Poincaré's idea since the theory implied there were no "gravitational dipoles". Nonetheless, he still pursued the idea and based on various approximations came to the conclusion there must, in fact, be three types of gravitational waves (dubbed longitudinal–longitudinal, transverse–longitudinal, and transverse–transverse by Hermann Weyl).^[23]



Primordial gravitational waves are hypothesized to arise from cosmic inflation, a faster-than-light expansion just after the Big Bang (2014).^{[17][18][19]}

However, the nature of Einstein's approximations led many (including Einstein himself) to doubt the result. In 1922, Arthur Eddington showed that two of Einstein's types of waves were artifacts of the coordinate system he used, and could be made to propagate at any speed by choosing appropriate coordinates, leading Eddington to jest that they "propagate at the speed of thought".^{[24]:72} This also cast doubt on the physicality of the third (transverse–transverse) type that Eddington showed always propagate at the speed of light regardless of coordinate system. In 1936, Einstein and Nathan Rosen submitted a paper to *Physical Review* in which they claimed gravitational waves could not exist in the full general theory of relativity because any such solution of the field equations would have a singularity. The journal sent their manuscript to be reviewed by Howard P. Robertson, who anonymously reported that the singularities in question were simply the harmless coordinate singularities of the employed cylindrical coordinates. Einstein, who was unfamiliar with the concept of peer review, angrily withdrew the manuscript, never to publish in *Physical Review* again. Nonetheless, his assistant Leopold Infeld, who had been in contact with Robertson, convinced Einstein that the criticism was correct, and the paper was rewritten with the opposite conclusion and published elsewhere.^{[23][24]:79ff} In 1956, Felix Pirani remedied the confusion caused by the use of various coordinate systems by rephrasing the gravitational waves in terms of the manifestly observable Riemann curvature tensor.^[25]

At the time, Pirani's work was overshadowed by the community's focus on a different question: whether gravitational waves could transmit energy. This matter was settled by a thought experiment proposed by Richard Feynman during the first "GR" conference at Chapel Hill in 1957. In short, his argument known as the "sticky bead argument" notes that if one takes a rod with beads then the effect of a passing gravitational wave would be to move the beads along the rod; friction would then produce heat, implying that the passing wave had done work. Shortly after, Hermann Bondi, published a detailed version of the "sticky bead argument".^[23] This later led to a series of articles (1959 to 1989) by Bondi and Pirani that established the existence of plane wave solutions for gravitational waves.^[26]

After the Chapel Hill conference, Joseph Weber started designing and building the first gravitational wave detectors now known as Weber bars. In 1969, Weber claimed to have detected

the first gravitational waves, and by 1970 he was "detecting" signals regularly from the Galactic Center; however, the frequency of detection soon raised doubts on the validity of his observations as the implied rate of energy loss of the Milky Way would drain our galaxy of energy on a timescale much shorter than its inferred age. These doubts were strengthened when, by the mid-1970s, repeated experiments from other groups building their own Weber bars across the globe failed to find any signals, and by the late 1970s general consensus was that Weber's results were spurious.^[23]

In the same period, the first indirect evidence of gravitational waves was discovered. In 1974, Russell Alan Hulse and Joseph Hooton Taylor, Jr. discovered the first binary pulsar, which earned them the 1993 Nobel Prize in Physics.^[27] Pulsar timing observations over the next decade showed a gradual decay of the orbital period of the Hulse–Taylor pulsar that matched the loss of energy and angular momentum in gravitational radiation predicted by general relativity.^{[28][29][23]}

This indirect detection of gravitational waves motivated further searches, despite Weber's discredited result. Some groups continued to improve Weber's original concept, while others pursued the detection of gravitational waves using laser interferometers. The idea of using a laser interferometer for this seems to have been floated independently by various people, including M. E. Gertsenshtein and V. I. Pustovoit in 1962,^[30] and Vladimir B. Braginskiĭ in 1966. The first prototypes were developed in the 1970s by Robert L. Forward and Rainer Weiss.^{[31][32]} In the decades that followed, ever more sensitive instruments were constructed, culminating in the construction of GEO600, LIGO, and Virgo.^[23]

After years of producing null results, improved detectors became operational in 2015. On 11 February 2016, the LIGO-Virgo collaborations announced the first observation of gravitational waves,^{[33][34][35][36]} from a signal (dubbed GW150914) detected at 09:50:45 GMT on 14 September 2015 of two black holes with masses of 29 and 36 solar masses merging about 1.3 billion light-years away. During the final fraction of a second of the merger, it released more than 50 times the power of all the stars in the observable universe combined.^[37] The signal increased in frequency from 35 to 250 Hz over 10 cycles (5 orbits) as it rose in strength for a period of 0.2 second.^[34] The mass of the new merged black hole was 62 solar masses. Energy equivalent to three solar masses was emitted as gravitational waves.^[38] The signal was seen by both LIGO detectors in Livingston and Hanford, with a time difference of 7 milliseconds due to the angle between the two detectors and the source. The signal came from the Southern Celestial Hemisphere, in the rough direction of (but much farther away than) the Magellanic Clouds.^[36] The confidence level of this being an observation of gravitational waves was 99.99994%.^[38]

A year earlier, the BICEP2 claimed that they had detected the imprint of gravitational waves in the cosmic microwave background. However, they were later forced to retract this result.^{[17][18][39][40]}

In 2017, the Nobel Prize in Physics was awarded to Rainer Weiss, Kip Thorne and Barry Barish for their role in the detection of gravitational waves.^{[41][42][43]}

Effects of passing

Gravitational waves are constantly passing Earth; however, even the strongest have a minuscule effect and their sources are generally at a great distance. For example, the waves given off by the cataclysmic final merger of GW150914 reached Earth after travelling over a billion light-years, as a ripple in spacetime that changed the length of a 4 km LIGO arm by a thousandth of the width of a

proton, proportionally equivalent to changing the distance to the nearest star outside the Solar System by one hair's width.^[44] This tiny effect from even extreme gravitational waves makes them observable on Earth only with the most sophisticated detectors.

The effects of a passing gravitational wave, in an extremely exaggerated form, can be visualized by imagining a perfectly flat region of spacetime with a group of motionless test particles lying in a plane, e.g. the surface of a computer screen. As a gravitational wave passes through the particles along a line perpendicular to the plane of the particles, i.e. following the observer's line of vision into the screen, the particles will follow the distortion in spacetime, oscillating in a "cruciform" manner, as shown in the animations. The area enclosed by the test particles does not change and there is no motion along the direction of propagation.

The oscillations depicted in the animation are exaggerated for the purpose of discussion – in reality a gravitational wave has a very small amplitude (as formulated in linearized gravity). However, they help illustrate the kind of oscillations associated with gravitational waves as produced by a pair of masses in a circular orbit. In this case the amplitude of the gravitational wave is constant, but its plane of polarization changes or rotates at twice the orbital rate, so the time-varying gravitational wave size, or 'periodic spacetime strain', exhibits a variation as shown in the animation.^[45] If the orbit of the masses is elliptical then the gravitational wave's amplitude also varies with time according to Einstein's quadrupole formula.^[3]

As with other waves, there are a number of characteristics used to describe a gravitational wave:

- **Amplitude:** Usually denoted h , this is the size of the wave – the fraction of stretching or squeezing in the animation. The amplitude shown here is roughly $h = 0.5$ (or 50%). Gravitational waves passing through the Earth are many sextillion times weaker than this – $h \approx 10^{-20}$.
- **Frequency:** Usually denoted f , this is the frequency with which the wave oscillates (1 divided by the amount of time between two successive maximum stretches or squeezes)
- **Wavelength:** Usually denoted λ , this is the distance along the wave between points of maximum stretch or squeeze.
- **Speed:** This is the speed at which a point on the wave (for example, a point of maximum stretch or squeeze) travels. For gravitational waves with small amplitudes, this wave speed is equal to the speed of light (c).

The speed, wavelength, and frequency of a gravitational wave are related by the equation $c = \lambda f$, just like the equation for a light wave. For example, the animations shown here oscillate roughly once every two seconds. This would correspond to a frequency of 0.5 Hz, and a wavelength of about 600 000 km, or 47 times the diameter of the Earth.

In the above example, it is assumed that the wave is linearly polarized with a "plus" polarization, written h_+ . Polarization of a gravitational wave is just like polarization of a light wave except that the polarizations of a gravitational wave are 45 degrees apart, as opposed to 90 degrees. In



The effect of a plus-polarized gravitational wave on a ring of particles



The effect of a cross-polarized gravitational wave on a ring of particles

particular, in a "cross"-polarized gravitational wave, h_x , the effect on the test particles would be basically the same, but rotated by 45 degrees, as shown in the second animation. Just as with light polarization, the polarizations of gravitational waves may also be expressed in terms of circularly polarized waves. Gravitational waves are polarized because of the nature of their source.

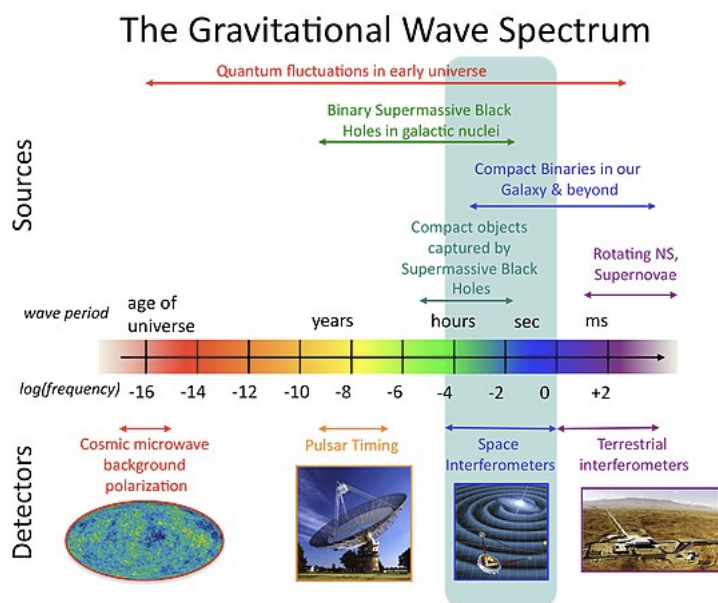
Sources

In general terms, gravitational waves are radiated by objects whose motion involves acceleration and its change, provided that the motion is not perfectly spherically symmetric (like an expanding or contracting sphere) or rotationally symmetric (like a spinning disk or sphere). A simple example of this principle is a spinning dumbbell. If the dumbbell spins around its axis of symmetry, it will not radiate gravitational waves; if it tumbles end over end, as in the case of two planets orbiting each other, it will radiate gravitational waves. The heavier the dumbbell, and the faster it tumbles, the greater is the gravitational radiation it will give off. In an extreme case, such as when the two weights of the dumbbell are massive stars like neutron stars or black holes, orbiting each other quickly, then significant amounts of gravitational radiation would be given off.

Some more detailed examples:

- Two objects orbiting each other, as a planet would orbit the Sun, *will* radiate.
- A spinning non-axisymmetric planetoid – say with a large bump or dimple on the equator – *will* radiate.
- A supernova *will* radiate except in the unlikely event that the explosion is perfectly symmetric.
- An isolated non-spinning solid object moving at a constant velocity *will not* radiate. This can be regarded as a consequence of the principle of conservation of linear momentum.
- A spinning disk *will not* radiate. This can be regarded as a consequence of the principle of conservation of angular momentum. However, it *will* show gravitomagnetic effects.
- A spherically pulsating spherical star (non-zero monopole moment or mass, but zero quadrupole moment) *will not* radiate, in agreement with Birkhoff's theorem.

More technically, the second time derivative of the quadrupole moment (or the l -th time derivative of the l -th multipole moment) of an isolated system's stress–energy tensor must be non-zero in order for it to emit gravitational radiation. This is analogous to the changing dipole moment of



The gravitational wave spectrum with sources and detectors. *Credit: NASA Goddard Space Flight Center^[46]*

charge or current that is necessary for the emission of electromagnetic radiation.

Binaries

Gravitational waves carry energy away from their sources and, in the case of orbiting bodies, this is associated with an in-spiral or decrease in orbit.^{[47][48]} Imagine for example a simple system of two masses – such as the Earth–Sun system – moving slowly compared to the speed of light in circular orbits. Assume that these two masses orbit each other in a circular orbit in the x – y plane. To a good approximation, the masses follow simple Keplerian orbits. However, such an orbit represents a changing quadrupole moment. That is, the system will give off gravitational waves.

In theory, the loss of energy through gravitational radiation could eventually drop the Earth into the Sun. However, the total energy of the Earth orbiting the Sun (kinetic energy + gravitational potential energy) is about 1.14×10^{36} joules of which only 200 watts (joules per second) is lost through gravitational radiation, leading to a decay in the orbit by about 1×10^{-15} meters per day or roughly the diameter of a proton. At this rate, it would take the Earth approximately 3×10^{13} times more than the current age of the Universe to spiral onto the Sun. This estimate overlooks the decrease in r over time, but the radius varies only slowly for most of the time and plunges at later stages, as

$$r(t) = r_0 \left(1 - \frac{t}{t_{\text{coalesce}}} \right)^{1/4},$$

with r_0 the initial radius and t_{coalesce} the total time needed to fully coalesce.^[49]

More generally, the rate of orbital decay can be approximated by^[50]

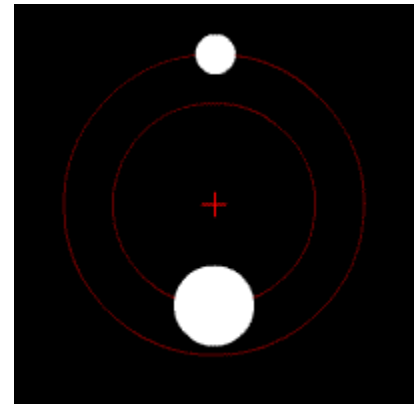
$$\frac{dr}{dt} = -\frac{64}{5} \frac{G^3}{c^5} \frac{(m_1 m_2)(m_1 + m_2)}{r^3},$$

where r is the separation between the bodies, t time, G the gravitational constant, c the speed of light, and m_1 and m_2 the masses of the bodies. This leads to an expected time to merger of^[50]

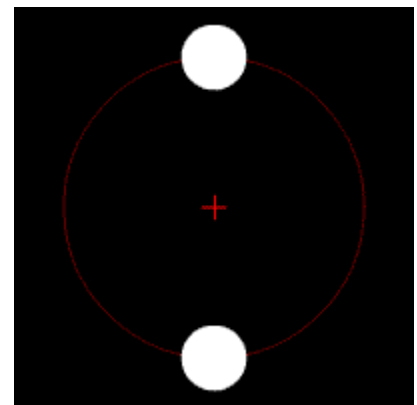
$$t = \frac{5}{256} \frac{c^5}{G^3} \frac{r^4}{(m_1 m_2)(m_1 + m_2)}.$$

Compact binaries

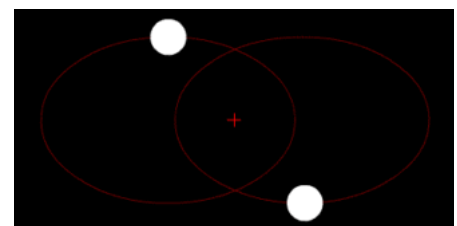
Compact stars like white dwarfs and neutron stars can be constituents of binaries. For example, a



Two stars of dissimilar mass are in circular orbits. Each revolves about their common center of mass (denoted by the small red cross) in a circle with the larger mass having the smaller orbit.



Two stars of similar mass in circular orbits about their center of mass



Two stars of similar mass in highly elliptical orbits about their center of mass

pair of solar mass neutron stars in a circular orbit at a separation of 1.89×10^8 m (189,000 km) has an orbital period of 1,000 seconds, and an expected lifetime of 1.30×10^{13} seconds or about 414,000 years. Such a system could be observed by LISA if it were not too far away. A far greater number of white dwarf binaries exist with orbital periods in this range. White dwarf binaries have masses in the order of the Sun, and diameters in the order of the Earth. They cannot get much closer together than 10,000 km before they will merge and explode in a supernova which would also end the emission of gravitational waves. Until then, their gravitational radiation would be comparable to that of a neutron star binary.

When the orbit of a neutron star binary has decayed to 1.89×10^6 m (1890 km), its remaining lifetime is about 130,000 seconds or 36 hours. The orbital frequency will vary from 1 orbit per second at the start, to 918 orbits per second when the orbit has shrunk to 20 km at merger. The majority of gravitational radiation emitted will be at twice the orbital frequency. Just before merger, the inspiral could be observed by LIGO if such a binary were close enough. LIGO has only a few minutes to observe this merger out of a total orbital lifetime that may have been billions of years. In August 2017, LIGO and Virgo observed the first binary neutron star inspiral in GW170817, and 70 observatories collaborated to detect the electromagnetic counterpart, a kilonova in the galaxy NGC 4993, 40 megaparsecs away, emitting a short gamma ray burst (GRB 170817A) seconds after the merger, followed by a longer optical transient (AT 2017gfo) powered by r-process nuclei. Advanced LIGO detector should be able to detect such events up to 200 megaparsecs away. Within this range of the order 40 events are expected per year.^[52]



Artist's impression of merging neutron stars, a source of gravitational waves^[51]

Black hole binaries

Black hole binaries emit gravitational waves during their in-spiral, merger, and ring-down phases. The largest amplitude of emission occurs during the merger phase, which can be modeled with the techniques of numerical relativity.^{[53][54][55]} The first direct detection of gravitational waves, GW150914, came from the merger of two black holes.

Supernova

A supernova is a transient astronomical event that occurs during the last stellar evolutionary stages of a massive star's life, whose dramatic and catastrophic destruction is marked by one final titanic explosion. This explosion can happen in one of many ways, but in all of them a significant proportion of the matter in the star is blown away into the surrounding space at extremely high velocities (up to 10% of the speed of light). Unless there is perfect spherical symmetry in these explosions (i.e., unless matter is spewed out evenly in all directions), there will be gravitational radiation from the explosion. This is because gravitational waves are generated by a changing quadrupole moment, which can happen only when there is asymmetrical movement of masses. Since the exact mechanism by which supernovae take place is not fully understood, it is not easy to model the gravitational radiation emitted by them.

Spinning neutron stars

As noted above, a mass distribution will emit gravitational radiation only when there is spherically asymmetric motion among the masses. A spinning neutron star will generally emit no gravitational radiation because neutron stars are highly dense objects with a strong gravitational field that keeps them almost perfectly spherical. In some cases, however, there might be slight deformities on the surface called "mountains", which are bumps extending no more than 10 centimeters (4 inches) above the surface,^[56] that make the spinning spherically asymmetric. This gives the star a quadrupole moment that changes with time, and it will emit gravitational waves until the deformities are smoothed out.

Inflation

Many models of the Universe suggest that there was an inflationary epoch in the early history of the Universe when space expanded by a large factor in a very short amount of time. If this expansion was not symmetric in all directions, it may have emitted gravitational radiation detectable today as a gravitational wave background. This background signal is too weak for any currently operational gravitational wave detector to observe, and it is thought it may be decades before such an observation can be made.

Properties and behaviour

Energy, momentum, and angular momentum

Water waves, sound waves, and electromagnetic waves are able to carry energy, momentum, and angular momentum and by doing so they carry those away from the source. Gravitational waves perform the same function. Thus, for example, a binary system loses angular momentum as the two orbiting objects spiral towards each other—the angular momentum is radiated away by gravitational waves.

The waves can also carry off linear momentum, a possibility that has some interesting implications for astrophysics.^[57] After two supermassive black holes coalesce, emission of linear momentum can produce a "kick" with amplitude as large as 4000 km/s. This is fast enough to eject the coalesced black hole completely from its host galaxy. Even if the kick is too small to eject the black hole completely, it can remove it temporarily from the nucleus of the galaxy, after which it will oscillate about the center, eventually coming to rest.^[58] A kicked black hole can also carry a star cluster with it, forming a hyper-compact stellar system.^[59] Or it may carry gas, allowing the recoiling black hole to appear temporarily as a "naked quasar". The quasar SDSS J092712.65+294344.0 is thought to contain a recoiling supermassive black hole.^[60]

Redshifting

Like electromagnetic waves, gravitational waves should exhibit shifting of wavelength and frequency due to the relative velocities of the source and observer (the Doppler effect), but also due to distortions of spacetime, such as cosmic expansion. This is the case even though gravity itself is a cause of distortions of spacetime. Redshifting of gravitational waves is different from redshifting

due to gravity (gravitational redshift).

Quantum gravity, wave-particle aspects, and graviton

In the framework of quantum field theory, the graviton is the name given to a hypothetical elementary particle speculated to be the force carrier that mediates gravity. However the graviton is not yet proven to exist, and no scientific model yet exists that successfully reconciles general relativity, which describes gravity, and the Standard Model, which describes all other fundamental forces. Attempts, such as quantum gravity, have been made, but are not yet accepted.

If such a particle exists, it is expected to be massless (because the gravitational force appears to have unlimited range) and must be a spin-2 boson. It can be shown that any massless spin-2 field would give rise to a force indistinguishable from gravitation, because a massless spin-2 field must couple to (interact with) the stress–energy tensor in the same way that the gravitational field does; therefore if a massless spin-2 particle were ever discovered, it would be likely to be the graviton without further distinction from other massless spin-2 particles.^[61] Such a discovery would unite quantum theory with gravity.^[62]

Significance for study of the early universe

Due to the weakness of the coupling of gravity to matter, gravitational waves experience very little absorption or scattering, even as they travel over astronomical distances. In particular, gravitational waves are expected to be unaffected by the opacity of the very early universe. In these early phases, space had not yet become "transparent", so observations based upon light, radio waves, and other electromagnetic radiation that far back into time are limited or unavailable. Therefore, gravitational waves are expected in principle to have the potential to provide a wealth of observational data about the very early universe.^[63]

Determining direction of travel

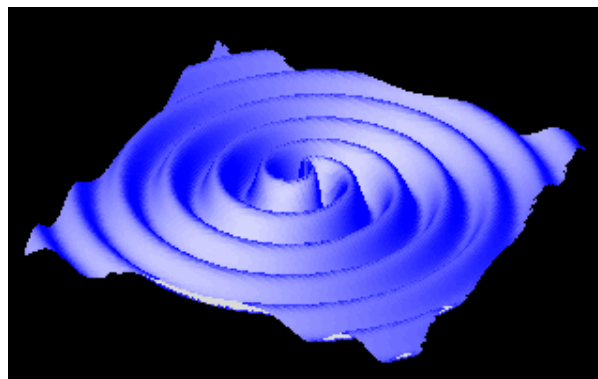
The difficulty in directly detecting gravitational waves, means it is also difficult for a single detector to identify by itself the direction of a source. Therefore, multiple detectors are used, both to distinguish signals from other "noise" by confirming the signal is not of earthly origin, and also to determine direction by means of triangulation. This technique uses the fact that the waves travel at the speed of light and will reach different detectors at different times depending on their source direction. Although the differences in arrival time may be just a few milliseconds, this is sufficient to identify the direction of the origin of the wave with considerable precision.

Only in the case of GW170814 were three detectors operating at the time of the event, therefore, the direction is precisely defined. The detection by all three instruments led to a very accurate estimate of the position of the source, with a 90% credible region of just 60 deg², a factor 20 more accurate than before.^[64]

Gravitational wave astronomy

During the past century, astronomy has been revolutionized by the use of new methods for observing the universe. Astronomical observations were initially made using visible light. Galileo

Galilei pioneered the use of telescopes to enhance these observations. However, visible light is only a small portion of the electromagnetic spectrum, and not all objects in the distant universe shine strongly in this particular band. More information may be found, for example, in radio wavelengths. Using radio telescopes, astronomers have discovered pulsars and quasars, for example. Observations in the microwave band led to the detection of faint imprints of the Big Bang, a discovery Stephen Hawking called the "greatest discovery of the century, if not all time". Similar advances in observations using gamma rays, x-rays, ultraviolet light, and infrared light have also brought new insights to astronomy. As each of these regions of the spectrum has opened, new discoveries have been made that could not have been made otherwise. The astronomy community hopes that the same holds true of gravitational waves.^{[65][66]}



Two-dimensional representation of gravitational waves generated by two neutron stars orbiting each other.

Gravitational waves have two important and unique properties. First, there is no need for any type of matter to be present nearby in order for the waves to be generated by a binary system of uncharged black holes, which would emit no electromagnetic radiation. Second, gravitational waves can pass through any intervening matter without being scattered significantly. Whereas light from distant stars may be blocked out by interstellar dust, for example, gravitational waves will pass through essentially unimpeded. These two features allow gravitational waves to carry information about astronomical phenomena heretofore never observed by humans.^[63]

The sources of gravitational waves described above are in the low-frequency end of the gravitational-wave spectrum (10^{-7} to 10^5 Hz). An astrophysical source at the high-frequency end of the gravitational-wave spectrum (above 10^5 Hz and probably 10^{10} Hz) generates relic gravitational waves that are theorized to be faint imprints of the Big Bang like the cosmic microwave background.^[67] At these high frequencies it is potentially possible that the sources may be "man made"^[13] that is, gravitational waves generated and detected in the laboratory.^{[68][69]}

A supermassive black hole, created from the merger of the black holes at the center of two merging galaxies detected by the Hubble Space Telescope, is theorized to have been ejected from the merger center by gravitational waves.^{[70][71]}

Detection

Indirect detection

Although the waves from the Earth–Sun system are minuscule, astronomers can point to other sources for which the radiation should be substantial. One important example is the Hulse–Taylor binary – a pair of stars, one of which is a pulsar.^[73] The characteristics of their orbit can be deduced from the Doppler shifting of radio signals given off by the pulsar. Each of the stars is about $1.4 M_{\odot}$ and the size of their orbits is about 1/75 of the Earth–Sun orbit, just a few times larger than the diameter of our own Sun. The combination of greater masses and smaller separation means that the energy given off by the Hulse–Taylor binary will be far greater than the

energy given off by the Earth–Sun system – roughly 10^{22} times as much.

The information about the orbit can be used to predict how much energy (and angular momentum) would be radiated in the form of gravitational waves. As the binary system loses energy, the stars gradually draw closer to each other, and the orbital period decreases. The resulting trajectory of each star is an inspiral, a spiral with decreasing radius. General relativity precisely describes these trajectories; in particular, the energy radiated in gravitational waves determines the rate of decrease in the period, defined as the time interval between successive periastrons (points of closest approach of the two stars). For the Hulse–Taylor pulsar, the predicted current change in radius is about 3 mm per orbit, and the change in the 7.75 hr period is about 2 seconds per year. Following a preliminary observation showing an orbital energy loss consistent with gravitational waves,^[28] careful timing observations by Taylor and Joel Weisberg dramatically confirmed the predicted period decrease to within 10%.^[74] With the improved statistics of more than 30 years of timing data since the pulsar's discovery, the observed change in the orbital period currently matches the prediction from gravitational radiation assumed by general relativity to within 0.2 percent.^[75] In 1993, spurred in part by this indirect detection of gravitational waves, the Nobel Committee awarded the Nobel Prize in Physics to Hulse and Taylor for "the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."^[76] The lifetime of this binary system, from the present to merger is estimated to be a few hundred million years.^[77]

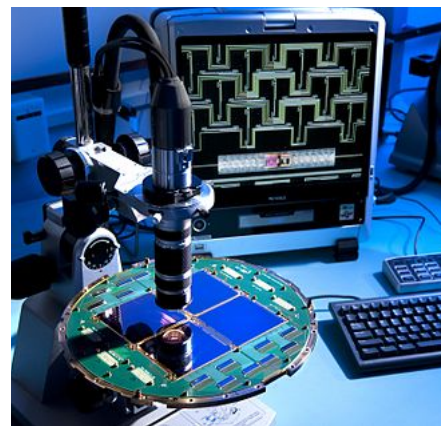
Inspirals are very important sources of gravitational waves. Any time two compact objects (white dwarfs, neutron stars, or black holes) are in close orbits, they send out intense gravitational waves. As they spiral closer to each other, these waves become more intense. At some point they should become so intense that direct detection by their effect on objects on Earth or in space is possible. This direct detection is the goal of several large-scale experiments.^[78]

The only difficulty is that most systems like the Hulse–Taylor binary are so far away. The amplitude of waves given off by the Hulse–Taylor binary at Earth would be roughly $h \approx 10^{-26}$. There are some sources, however, that astrophysicists expect to find that produce much greater amplitudes of $h \approx 10^{-20}$. At least eight other binary pulsars have been discovered.^[79]

Difficulties

Gravitational waves are not easily detectable. When they reach the Earth, they have a small amplitude with strain approximates 10^{-21} , meaning that an extremely sensitive detector is needed, and that other sources of noise can overwhelm the signal.^[80] Gravitational waves are expected to have frequencies $10^{-16} \text{ Hz} < f < 10^4 \text{ Hz}$.^[81]

Negative-mass plasma

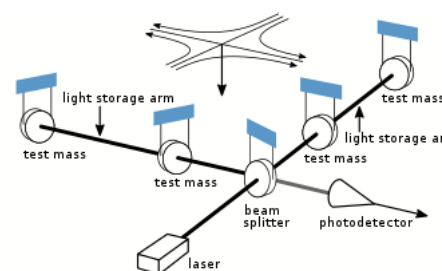


Now disproved evidence allegedly showing gravitational waves in the infant universe was found by the BICEP2 radio telescope. The microscopic examination of the focal plane of the BICEP2 detector is shown here.^{[17][18]} In January 2015, however, the BICEP2 findings were confirmed to be the result of cosmic dust.^[72]

One possible explanation for the difficulties with direct observation of gravitational waves was proposed by cosmologists Saoussen Mbarek and Manu Paranjape after they demonstrated the possible existence of negative mass without violating Einsteinian relativity. Earlier research dismissed the concept due to seemingly violating the energy condition, however Mbarek and Paranjape found that negative matter could still exist in our universe if it was assumed to take the form of a perfect fluid rather than a conventional solid, where negative and positive particles combine in de Sitter space into a sort of plasma. One notable property of this plasma is the ability to absorb gravitational waves, suggesting that difficulties in direct detection might stem from the universe being populated by gravitationally "opaque" clouds of positive-negative plasma which effectively screen the Earth from detecting such waves.^[82]

Ground-based detectors

Though the Hulse–Taylor observations were very important, they give only *indirect* evidence for gravitational waves. A more conclusive observation would be a *direct* measurement of the effect of a passing gravitational wave, which could also provide more information about the system that generated it. Any such direct detection is complicated by the extraordinarily small effect the waves would produce on a detector. The amplitude of a spherical wave will fall off as the inverse of the distance from the source (the $1/R$ term in the formulas for h above). Thus, even waves from extreme systems like merging binary black holes die out to very small amplitudes by the time they reach the Earth. Astrophysicists expect that some gravitational waves passing the Earth may be as large as $h \approx 10^{-20}$, but generally no bigger.^[83]



A schematic diagram of a laser interferometer

Resonant antennas

A simple device theorised to detect the expected wave motion is called a Weber bar – a large, solid bar of metal isolated from outside vibrations. This type of instrument was the first type of gravitational wave detector. Strains in space due to an incident gravitational wave excite the bar's resonant frequency and could thus be amplified to detectable levels. Conceivably, a nearby supernova might be strong enough to be seen without resonant amplification. With this instrument, Joseph Weber claimed to have detected daily signals of gravitational waves. His results, however, were contested in 1974 by physicists Richard Garwin and David Douglass. Modern forms of the Weber bar are still operated, cryogenically cooled, with superconducting quantum interference devices to detect vibration. Weber bars are not sensitive enough to detect anything but extremely powerful gravitational waves.^[84]

MiniGRAIL is a spherical gravitational wave antenna using this principle. It is based at Leiden University, consisting of an exactly machined 1,150 kg sphere cryogenically cooled to 20 millikelvins.^[85] The spherical configuration allows for equal sensitivity in all directions, and is somewhat experimentally simpler than larger linear devices requiring high vacuum. Events are detected by measuring deformation of the detector sphere. MiniGRAIL is highly sensitive in the 2–4 kHz range, suitable for detecting gravitational waves from rotating neutron star instabilities or small black hole mergers.^[86]

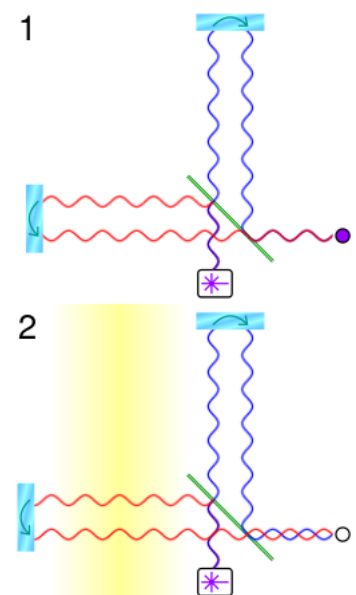
There are currently two detectors focused on the higher end of the gravitational wave spectrum (10^{-7} to 10^5 Hz): one at [University of Birmingham](#), England,^[87] and the other at [INFN Genoa](#), Italy. A third is under development at [Chongqing University](#), China. The Birmingham detector measures changes in the polarization state of a [microwave](#) beam circulating in a closed loop about one meter across. Both detectors are expected to be sensitive to periodic spacetime strains of $h \sim 2 \times 10^{-13} / \sqrt{\text{Hz}}$, given as an [amplitude spectral density](#). The INFN Genoa detector is a resonant antenna consisting of two coupled spherical superconducting harmonic oscillators a few centimeters in diameter. The oscillators are designed to have (when uncoupled) almost equal resonant frequencies. The system is currently expected to have a sensitivity to periodic spacetime strains of $h \sim 2 \times 10^{-17} / \sqrt{\text{Hz}}$, with an expectation to reach a sensitivity of $h \sim 2 \times 10^{-20} / \sqrt{\text{Hz}}$. The Chongqing University detector is planned to detect relic high-frequency gravitational waves with the predicted typical parameters $\sim 10^{11}$ Hz (100 GHz) and $h \sim 10^{-30}$ to 10^{-32} .^[88]

Interferometers

A more sensitive class of detector uses a laser [Michelson interferometer](#) to measure gravitational-wave induced motion between separated 'free' masses.^[89] This allows the masses to be separated by large distances (increasing the signal size); a further advantage is that it is sensitive to a wide range of frequencies (not just those near a resonance as is the case for Weber bars). After years of development the first ground-based interferometers became operational in 2015. Currently, the most sensitive is [LIGO](#) – the Laser Interferometer Gravitational Wave Observatory. LIGO has three detectors: one in [Livingston, Louisiana](#), one at the [Hanford site](#) in [Richland, Washington](#) and a third (formerly installed as a second detector at Hanford) that is planned to be moved to [India](#). Each observatory has two [light storage arms](#) that are 4 kilometers in length. These are at 90 degree angles to each other, with the light passing through 1 m diameter vacuum tubes running the entire 4 kilometers. A passing gravitational wave will slightly stretch one arm as it shortens the other. This is precisely the motion to which an interferometer is most sensitive.

Even with such long arms, the strongest gravitational waves will only change the distance between the ends of the arms by at most roughly 10^{-18} m. LIGO should be able to detect gravitational waves as small as $h \sim 5 \times 10^{-22}$. Upgrades to LIGO and [Virgo](#) should increase the sensitivity still further. Another highly sensitive interferometer, [KAGRA](#), which is located in the [Kamioka Observatory](#) in Japan, is in operation since February 2020. A key point is that a tenfold increase in sensitivity (radius of 'reach') increases the volume of space accessible to the instrument by one thousand times. This increases the rate at which detectable signals might be seen from one per tens of years of observation, to tens per year.^[90]

Interferometric detectors are limited at high frequencies by [shot noise](#), which occurs because the lasers produce photons randomly; one analogy is to rainfall – the rate of rainfall, like the laser intensity, is



Simplified operation of a gravitational wave observatory

Figure 1: A beamsplitter (green line) splits coherent light (from the white box) into two beams which reflect off the mirrors (cyan oblongs); only one outgoing and reflected beam in each arm is shown, and separated for clarity. The reflected beams recombine and an interference pattern is detected (purple circle).

Figure 2: A gravitational wave passing over the left arm (yellow) changes its length and thus the interference pattern.

measurable, but the raindrops, like photons, fall at random times, causing fluctuations around the average value. This leads to noise at the output of the detector, much like radio static. In addition, for sufficiently high laser power, the random momentum transferred to the test masses by the laser photons shakes the mirrors, masking signals of low frequencies. Thermal noise (e.g., Brownian motion) is another limit to sensitivity. In addition to these 'stationary' (constant) noise sources, all ground-based detectors are also limited at low frequencies by seismic noise and other forms of environmental vibration, and other 'non-stationary' noise sources; creaks in mechanical structures, lightning or other large electrical disturbances, etc. may also create noise masking an event or may even imitate an event. All these must be taken into account and excluded by analysis before detection may be considered a true gravitational wave event.

Einstein@Home

The simplest gravitational waves are those with constant frequency. The waves given off by a spinning, non-axisymmetric neutron star would be approximately monochromatic: a pure tone in acoustics. Unlike signals from supernovae or binary black holes, these signals evolve little in amplitude or frequency over the period it would be observed by ground-based detectors. However, there would be some change in the measured signal, because of Doppler shifting caused by the motion of the Earth. Despite the signals being simple, detection is extremely computationally expensive, because of the long stretches of data that must be analysed.

The Einstein@Home project is a distributed computing project similar to SETI@home intended to detect this type of gravitational wave. By taking data from LIGO and GEO, and sending it out in little pieces to thousands of volunteers for parallel analysis on their home computers, Einstein@Home can sift through the data far more quickly than would be possible otherwise.^[91]

Space-based interferometers

Space-based interferometers, such as LISA and DECIGO, are also being developed. LISA's design calls for three test masses forming an equilateral triangle, with lasers from each spacecraft to each other spacecraft forming two independent interferometers. LISA is planned to occupy a solar orbit trailing the Earth, with each arm of the triangle being five million kilometers. This puts the detector in an excellent vacuum far from Earth-based sources of noise, though it will still be susceptible to heat, shot noise, and artifacts caused by cosmic rays and solar wind.

Using pulsar timing arrays

Pulsars are rapidly rotating stars. A pulsar emits beams of radio waves that, like lighthouse beams, sweep through the sky as the pulsar rotates. The signal from a pulsar can be detected by radio telescopes as a series of regularly spaced pulses, essentially like the ticks of a clock. GWs affect the time it takes the pulses to travel from the pulsar to a telescope on Earth. A pulsar timing array uses millisecond pulsars to seek out perturbations due to GWs in measurements of the time of arrival of pulses to a telescope, in other words, to look for deviations in the clock ticks. To detect GWs, pulsar timing arrays search for a distinct pattern of correlation and anti-correlation between the time of arrival of pulses from several pulsars.^[92] Although pulsar pulses travel through space for hundreds or thousands of years to reach us, pulsar timing arrays are sensitive to perturbations in their travel time of much less than a millionth of a second.

The principal source of GWs to which pulsar timing arrays are sensitive are super-massive black hole binaries, that form from the collision of galaxies.^[93] In addition to individual binary systems, pulsar timing arrays are sensitive to a stochastic background of GWs made from the sum of GWs from many galaxy mergers. Other potential signal sources include cosmic strings and the primordial background of GWs from cosmic inflation.

Globally there are three active pulsar timing array projects. The North American Nanohertz Observatory for Gravitational Waves uses data collected by the Arecibo Radio Telescope and Green Bank Telescope. The Australian Parkes Pulsar Timing Array uses data from the Parkes radio-telescope. The European Pulsar Timing Array uses data from the four largest telescopes in Europe: the Lovell Telescope, the Westerbork Synthesis Radio Telescope, the Effelsberg Telescope and the Nancay Radio Telescope. These three groups also collaborate under the title of the International Pulsar Timing Array project.^[94]

Primordial gravitational wave

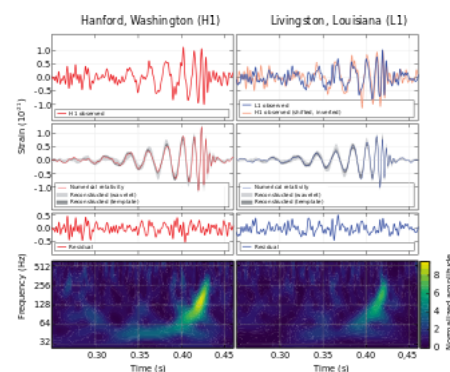
Primordial gravitational waves are gravitational waves observed in the cosmic microwave background. They were allegedly detected by the BICEP2 instrument, an announcement made on 17 March 2014, which was withdrawn on 30 January 2015 ("the signal can be entirely attributed to dust in the Milky Way"^[72]).

LIGO and Virgo observations

On 11 February 2016, the LIGO collaboration announced the first observation of gravitational waves, from a signal detected at 09:50:45 GMT on 14 September 2015^[33] of two black holes with masses of 29 and 36 solar masses merging about 1.3 billion light-years away. During the final fraction of a second of the merger, it released more than 50 times the power of all the stars in the observable universe combined.^[95] The signal increased in frequency from 35 to 250 Hz over 10 cycles (5 orbits) as it rose in strength for a period of 0.2 second.^[34] The mass of the new merged black hole was 62 solar masses. Energy equivalent to three solar masses was emitted as gravitational waves.^[38] The signal was seen by both LIGO detectors in Livingston and Hanford, with a time difference of 7 milliseconds due to the angle between the two detectors and the source. The signal came from the Southern Celestial Hemisphere, in the rough direction of (but much further away than) the Magellanic Clouds.^[36] The gravitational waves was observed in the region more than 5 sigma^[96] (in other words, 99.99997% chances of showing/getting the same result), the probability of finding enough to have been assessed/considered as the evidence/proof in a experiment of statistical physics.^[97]

Since then LIGO and Virgo have reported more gravitational wave observations from merging black hole binaries.

On 16 October 2017, the LIGO and Virgo collaborations announced the first-ever detection of



LIGO measurement of the gravitational waves at the Hanford (left) and Livingston (right) detectors, compared to the theoretical predicted values.

gravitational waves originating from the coalescence of a binary neutron star system. The observation of the [GW170817](#) transient, which occurred on 17 August 2017, allowed for constraining the masses of the neutron stars involved between 0.86 and 2.26 solar masses. Further analysis allowed a greater restriction of the mass values to the interval 1.17–1.60 solar masses, with the total system mass measured to be 2.73–2.78 solar masses. The inclusion of the Virgo detector in the observation effort allowed for an improvement of the localization of the source by a factor of 10. This in turn facilitated the electromagnetic follow-up of the event. In contrast to the case of binary black hole mergers, binary neutron star mergers were expected to yield an electromagnetic counterpart, that is, a light signal associated with the event. A gamma-ray burst ([GRB 170817A](#)) was detected by the [Fermi Gamma-ray Space Telescope](#), occurring 1.7 seconds after the gravitational wave transient. The signal, originating near the galaxy [NGC 4993](#), was associated with the neutron star merger. This was corroborated by the electromagnetic follow-up of the event ([AT 2017gfo](#)), involving 70 telescopes and observatories and yielding observations over a large region of the electromagnetic spectrum which further confirmed the neutron star nature of the merged objects and the associated [kilonova](#).^{[98][99]}

In fiction

An episode of the 1962 Russian science-fiction novel *Space Apprentice* by [Arkady and Boris Strugatsky](#) shows the experiment monitoring the propagation of gravitational waves at the expense of annihilating a chunk of asteroid [15 Eunomia](#) the size of [Mount Everest](#).^[100]

In [Stanislaw Lem's](#) 1986 novel *Fiasco*, a "gravity gun" or "gracer" (gravity amplification by collimated emission of resonance) is used to reshape a collapsar, so that the protagonists can exploit the extreme relativistic effects and make an interstellar journey.

In [Greg Egan's](#) 1997 novel *Diaspora*, the analysis of a gravitational wave signal from the inspiral of a nearby binary neutron star reveals that its collision and merger is imminent, implying a large gamma-ray burst is going to impact the Earth.

In [Liu Cixin's](#) 2006 *Remembrance of Earth's Past* series, gravitational waves are used as an interstellar broadcast signal, which serves as a central plot point in the conflict between civilizations within the galaxy.

See also

- 2017 Nobel Prize in Physics, which was awarded to three individual physicists for their role in the discovery of and testing for the waves
- [Anti-gravity](#)
- [Artificial gravity](#)
- [First observation of gravitational waves](#)
- [Gravitational plane wave](#)
- [Gravitational field](#)
- [Gravitational-wave astronomy](#)
- [Gravitational wave background](#)
- [Gravitational-wave observatory](#)
- [Gravitomagnetism](#)
- [Graviton \(and Gravitational wave observation § Gravitons\)](#)
- [Hawking radiation](#), for gravitationally induced electromagnetic radiation from black holes
- [HM Cancri](#)
- [LISA](#), [DECIGO](#) and [BBO](#) – Proposed space-based detectors

- [LIGO](#), [Virgo interferometer](#), [GEO600](#), [KAGRA](#), and [TAMA 300](#) – Ground-based gravitational-wave detectors
- [Linearized gravity](#)
- [Peres metric](#)
- [pp-wave spacetime](#), for an important class of exact solutions modelling gravitational radiation
- [PSR B1913+16](#), the first [binary pulsar](#) discovered and the first experimental evidence for the existence of gravitational waves.
- [Spin-flip](#), a consequence of gravitational wave emission from binary [supermassive black holes](#)
- [Sticky bead argument](#), for a physical way to see that gravitational radiation should carry energy
- [Tidal force](#)

References

1. http://www.academie-sciences.fr/pdf/dossiers/Poincare/Poincare_pdf/Poincare_CR1905.pdf
2. Einstein, A (June 1916). "Näherungsweise Integration der Feldgleichungen der Gravitation" (https://web.archive.org/web/20160115224321/http://einstein-annalen.mpiwg-berlin.mpg.de/related_texts/sitzungsberichte). *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften Berlin*. part 1: 688–696. Bibcode:1916SPAW.....688E (<https://ui.adsabs.harvard.edu/abs/1916SPAW.....688E>). Archived from the original (http://einstein-annalen.mpiwg-berlin.mpg.de/related_texts/sitzungsberichte) on 2016-01-15. Retrieved 2014-11-15.
3. Einstein, A (1918). "Über Gravitationswellen" (https://web.archive.org/web/20160115224321/http://einstein-annalen.mpiwg-berlin.mpg.de/related_texts/sitzungsberichte). *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften Berlin*. part 1: 154–167. Bibcode:1918SPAW.....154E (<https://ui.adsabs.harvard.edu/abs/1918SPAW.....154E>). Archived from the original (http://einstein-annalen.mpiwg-berlin.mpg.de/related_texts/sitzungsberichte) on 2016-01-15. Retrieved 2014-11-15.
4. Finley, Dave. "Einstein's gravity theory passes toughest test yet: Bizarre binary star system pushes study of relativity to new limits" (<http://phys.org/news/2013-04-einstein-gravity-theory-to-ughest-bizarre.html>). Phys.Org.
5. The Detection of Gravitational Waves using LIGO, B. Barish (<http://www.dpf99.library.ucla.edu/session14/barish1412.pdf>) Archived (<https://web.archive.org/web/20160303205650/http://www.dpf99.library.ucla.edu/session14/barish1412.pdf>) 2016-03-03 at the [Wayback Machine](#)
6. Einstein, Albert; Rosen, Nathan (January 1937). "On gravitational waves". *Journal of the Franklin Institute*. **223** (1): 43–54. Bibcode:1937FrInJ.223...43E (<https://ui.adsabs.harvard.edu/abs/1937FrInJ.223...43E>). doi:10.1016/S0016-0032(37)90583-0 (<https://doi.org/10.1016%2FS0016-0032%2837%2990583-0>).
7. Chang, Kenneth (29 June 2021). "A Black Hole Feasted on a Neutron Star. 10 Days Later, It Happened Again - Astronomers had long suspected that collisions between black holes and dead stars occurred, but they had no evidence until a pair of recent detections" (<https://www.nytimes.com/2021/06/29/science/black-holes.html>). *The New York Times*. Retrieved 29 June 2021.

8. Abbott, R.; et al. (29 June 2021). "Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences" (<https://iopscience.iop.org/article/10.3847/2041-8213/ac082e>). *The Astrophysical Journal Letters*. **915** (1): L5. arXiv:2106.15163 (<https://arxiv.org/abs/2106.15163>). Bibcode:2021ApJ...915L...5A (<https://ui.adsabs.harvard.edu/abs/2021ApJ...915L...5A>). doi:10.3847/2041-8213/ac082e (<https://doi.org/10.3847/2041-8213/ac082e>). S2CID 235670241 (<https://api.semanticscholar.org/CorpusID:235670241>). Retrieved 29 June 2021.
9. "First Second of the Big Bang". *How The Universe Works 3*. 2014. Discovery Science.
10. Bernard Schutz (14 May 2009). *A First Course in General Relativity* (https://archive.org/details/irstcourseingen00bern_0). Cambridge University Press. ISBN 978-0-521-88705-2.
11. LIGO Scientific Collaboration; Virgo Collaboration (2012). "Search for Gravitational Waves from Low Mass Compact Binary Coalescence in LIGO's Sixth Science Run and Virgo's Science Runs 2 and 3". *Physical Review D*. **85** (8): 082002. arXiv:1111.7314 (<https://arxiv.org/abs/1111.7314>). Bibcode:2012PhRvD..85h2002A (<https://ui.adsabs.harvard.edu/abs/2012PhRvD..85h2002A>). doi:10.1103/PhysRevD.85.082002 (<https://doi.org/10.1103/PhysRevD.85.082002>). S2CID 6842810 (<https://api.semanticscholar.org/CorpusID:6842810>).
12. Krauss, LM; Dodelson, S; Meyer, S (2010). "Primordial Gravitational Waves and Cosmology". *Science*. **328** (5981): 989–992. arXiv:1004.2504 (<https://arxiv.org/abs/1004.2504>). Bibcode:2010Sci...328..989K (<https://ui.adsabs.harvard.edu/abs/2010Sci...328..989K>). doi:10.1126/science.1179541 (<https://doi.org/10.1126/science.1179541>). PMID 20489015 (<https://pubmed.ncbi.nlm.nih.gov/20489015>). S2CID 11804455 (<https://api.semanticscholar.org/CorpusID:11804455>).
13. Hawking, S. W.; Israel, W. (1979). *General Relativity: An Einstein Centenary Survey* (<https://books.google.com/books?id=pxA4AAAAIAAJ&pg=PA98>). Cambridge: Cambridge University Press. p. 98. ISBN 978-0-521-22285-3.
14. Hartle, J.B. (2003). *Gravity: An introduction to Einstein's General Relativity* (<https://archive.org/details/specialrelativit0000chan/page/332>). Addison-Wesley. p. 332. ISBN 978-981-02-2749-4.
15. Taylor, Edwin F.; Wheeler, John Archibald (1991). *Spacetime Physics* (2nd ed.). p. 12.
16. "GW170817 Press Release" (<https://www.ligo.caltech.edu/page/press-release-gw170817>). *LIGO Lab – Caltech*.
17. Staff (17 March 2014). "BICEP2 2014 Results Release" (<http://bicepkeck.org>). *National Science Foundation*. Retrieved 18 March 2014.
18. Clavin, Whitney (17 March 2014). "NASA Technology Views Birth of the Universe" (<http://www.jpl.nasa.gov/news/news.php?release=2014-082>). NASA. Retrieved 17 March 2014.
19. Overbye, Dennis (17 March 2014). "Detection of Waves in Space Buttresses Landmark Theory of Big Bang" (<https://www.nytimes.com/2014/03/18/science/space/detection-of-waves-in-space-buttresses-landmark-theory-of-big-bang.html>). *New York Times*. Retrieved 17 March 2014.
20. Heaviside O. A gravitational and electromagnetic analogy, *Electromagnetic Theory*, 1893, vol.1 455–466 Appendix B
21. (PDF) (http://www.academie-sciences.fr/pdf/dossiers/Poincare/Poincare_pdf/Poincare_CR1905.pdf) Membres de l'Académie des sciences depuis sa création : Henri Poincaré. Sur la dynamique de l' electron. Note de H. Poincaré. C.R. T.140 (1905) 1504–1508.
22. "page 1507" (http://www.academie-sciences.fr/pdf/dossiers/Poincare/Poincare_pdf/Poincare_CR1905.pdf) (PDF).

23. Cervantes-Cota, J.L.; Galindo-Uribarri, S.; Smoot, G.F. (2016). "A Brief History of Gravitational Waves" (<https://doi.org/10.3390%2Funiverse2030022>). *Universe*. **2** (3): 22. arXiv:1609.09400 (<https://arxiv.org/abs/1609.09400>). Bibcode:2016Univ...2...22C (<https://ui.adsabs.harvard.edu/abs/2016Univ...2...22C>). doi:10.3390/universe2030022 (<https://doi.org/10.3390%2Funiverse2030022>). S2CID 2187981 (<https://api.semanticscholar.org/CorpusID:2187981>).
24. Daniel Kennefick (29 March 2016). *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves*. Princeton University Press. ISBN 978-1-4008-8274-8.
25. Pirani, Felix (1956), "On the physical significance of the Riemann tensor", *Acta Physica Polonica*, **15**: 389–405, Bibcode:1956AcPP...15..389P (<https://ui.adsabs.harvard.edu/abs/1956AcPP...15..389P>)
26. David Robinson, Gravitation and general relativity at King's College London, *European Physical Journal H* 44, pp 181–270 (2019)
27. Nobel Prize Award (1993) Press Release (<https://www.nobelprize.org/prizes/physics/1993/press-release/>) The Royal Swedish Academy of Sciences.
28. Taylor, J. H.; Fowler, L. A.; McCulloch, P. M. (1979). "Overall measurements of relativistic effects in the binary pulsar PSR 1913 + 16". *Nature*. **277**: 437–440. Bibcode:1982ApJ...253..908T (<https://ui.adsabs.harvard.edu/abs/1982ApJ...253..908T>). doi:10.1086/159690 (<https://doi.org/10.1086%2F159690>).
29. Taylor, J.; Weisberg, J.M. (1979). "A New Test of General Relativity: Gravitational Radiation and the Binary Pulsar PSR 1913+16". *Astrophysical Journal*. **253** (5696): 908–920. Bibcode:1979Natur.277..437T (<https://ui.adsabs.harvard.edu/abs/1979Natur.277..437T>). doi:10.1038/277437a0 (<https://doi.org/10.1038%2F277437a0>). S2CID 22984747 (<https://api.semanticscholar.org/CorpusID:22984747>).
30. Gertsenshtein, M. E.; Pustovoit, V. I. (1962). "On the detection of low frequency gravitational waves". *JETP*. **43**: 605–607.
31. Cho, Adrian (Oct. 3, 2017). "Ripples in space: U.S. trio wins physics Nobel for discovery of gravitational waves (<https://www.sciencemag.org/news/2017/10/ripples-space-us-trio-wins-physics-nobel-discovery-gravitational-waves>)," *Science*. Retrieved 20 May 2019.
32. Cervantes-Cota, Jorge L., Galindo-Uribarri, Salvador, and Smoot, George F. (2016). "A Brief History of Gravitational Waves (<https://arxiv.org/abs/1609.09400>)," *Universe*, 2, no. 3, 22. Retrieved 20 May 2019.
33. "Gravitational waves from black holes detected" (<https://www.bbc.co.uk/news/science-environment-35524440>). *BBC News*. 11 February 2016.
34. Abbott BP, et al. (LIGO Scientific Collaboration and Virgo Collaboration) (2016). "Observation of Gravitational Waves from a Binary Black Hole Merger". *Physical Review Letters*. **116** (6): 061102. arXiv:1602.03837 (<https://arxiv.org/abs/1602.03837>). Bibcode:2016PhRvL.116f1102A (<https://ui.adsabs.harvard.edu/abs/2016PhRvL.116f1102A>). doi:10.1103/PhysRevLett.116.061102 (<https://doi.org/10.1103%2FPhysRevLett.116.061102>). PMID 26918975 (<https://pubmed.ncbi.nlm.nih.gov/26918975>). S2CID 124959784 (<https://api.semanticscholar.org/CorpusID:124959784>).
35. "Gravitational waves detected 100 years after Einstein's prediction | NSF - National Science Foundation" (https://www.nsf.gov/news/news_summ.jsp?cntn_id=137628). *www.nsf.gov*. Retrieved 2016-02-11.
36. Castelvechi, Davide; Witze, Witze (11 February 2016). "Einstein's gravitational waves found at last" (<http://www.nature.com/news/einstein-s-gravitational-waves-found-at-last-1.19361>). *Nature News*. doi:10.1038/nature.2016.19361 (<https://doi.org/10.1038%2Fnature.2016.19361>). S2CID 182916902 (<https://api.semanticscholar.org/CorpusID:182916902>). Retrieved 2016-02-11.

37. "This collision was 50 times more powerful than all the stars in the universe combined" (<http://www.techinsider.io/black-hole-collision-energy-50-times-universe-2016-2>).
38. Scoles, Sarah (2016-02-11). "LIGO's First-Ever Detection of Gravitational Waves Opens a New Window on the Universe" (<https://www.wired.com/2016/02/scientists-spot-the-gravity-waves-th-at-flex-the-universe/>). *Wired*.
39. Clara Moskowitz (17 March 2014). "Gravity Waves from Big Bang Detected" (<http://www.scientificamerican.com/article/gravity-waves-cmb-b-mode-polarization/>). *Scientific American*. Retrieved 21 March 2016.
40. Ian Sample (2014-06-04). "Gravitational waves turn to dust after claims of flawed analysis" (<https://www.theguardian.com/science/2014/jun/04/gravitational-wave-discovery-dust-big-bang-inflation>). *the Guardian*.
41. Rincon, Paul; Amos, Jonathan (3 October 2017). "Einstein's waves win Nobel Prize" (<https://www.bbc.co.uk/news/science-environment-41476648>). *BBC News*. Retrieved 3 October 2017.
42. Overbye, Dennis (3 October 2017). "2017 Nobel Prize in Physics Awarded to LIGO Black Hole Researchers" (<https://www.nytimes.com/2017/10/03/science/nobel-prize-physics.html>). *The New York Times*. Retrieved 3 October 2017.
43. Kaiser, David (3 October 2017). "Learning from Gravitational Waves" (<https://www.nytimes.com/2017/10/03/opinion/gravitational-waves-ligo-funding.html>). *The New York Times*. Retrieved 3 October 2017.
44. LIGO press conference 11 February 2016
45. Landau, L. D.; Lifshitz, E. M. (1975). *The Classical Theory of Fields* (<https://books.google.com/books?id=X18PF4oKyrUC&pg=PA356>) (Fourth Revised English ed.). Pergamon Press. pp. 356–357. ISBN 978-0-08-025072-4.
46. "Gravitational Astrophysics Laboratory" (<http://science.gsfc.nasa.gov/663/research/index.html>). *science.gsfc.nasa.gov*. Retrieved 20 September 2016.
47. Peters, P.; Mathews, J. (1963). "Gravitational Radiation from Point Masses in a Keplerian Orbit". *Physical Review*. **131** (1): 435–440. Bibcode:1963PhRv..131..435P (<https://ui.adsabs.harvard.edu/abs/1963PhRv..131..435P>). doi:10.1103/PhysRev.131.435 (<https://doi.org/10.1103%2FPhysRev.131.435>).
48. Peters, P. (1964). "Gravitational Radiation and the Motion of Two Point Masses" (https://thesis.library.caltech.edu/4296/1/Peters_pc_1964.pdf) (PDF). *Physical Review*. **136** (4B): B1224–B1232. Bibcode:1964PhRv..136.1224P (<https://ui.adsabs.harvard.edu/abs/1964PhRv..136.1224P>). doi:10.1103/PhysRev.136.B1224 (<https://doi.org/10.1103%2FPhysRev.136.B1224>).
49. Maggiore, Michele (2007). *Gravitational waves : Volume 1, Theory and experiments*. Oxford University Press. Oxford: Oxford University Press. ISBN 978-0-19-152474-5. OCLC 319064125 (<https://www.worldcat.org/oclc/319064125>).
50. (PDF). 29 January 2016 <https://web.archive.org/web/20160129142844/http://www.eftaylor.com/exploringblackholes/GravWaves150909v1.pdf> (<https://web.archive.org/web/20160129142844/http://www.eftaylor.com/exploringblackholes/GravWaves150909v1.pdf>). Archived from the original (<http://www.eftaylor.com/exploringblackholes/GravWaves150909v1.pdf>) (PDF) on 29 January 2016. {{cite web}}: Missing or empty |title= (help)
51. "ESO Telescopes Observe First Light from Gravitational Wave Source – Merging neutron stars scatter gold and platinum into space" (<https://www.eso.org/public/news/eso1733/>). *www.eso.org*. Retrieved 18 October 2017.
52. *LIGO Scientific Collaboration – FAQ; section: "Do we expect LIGO's advanced detectors to make a discovery, then?" and "What's so different about LIGO's advanced detectors?"* (<http://ligo.org/science/faq.php>), retrieved 14 February 2016

53. Pretorius, Frans (2005). "Evolution of Binary Black-Hole Spacetimes". *Physical Review Letters*. **95** (12): 121101. arXiv:gr-qc/0507014 (https://arxiv.org/abs/gr-qc/0507014). Bibcode:2005PhRvL..9511101P (https://ui.adsabs.harvard.edu/abs/2005PhRvL..9511101P). doi:10.1103/PhysRevLett.95.121101 (https://doi.org/10.1103%2FPhysRevLett.95.121101). ISSN 0031-9007 (https://www.worldcat.org/issn/0031-9007). PMID 16197061 (https://pubmed.ncbi.nlm.nih.gov/16197061). S2CID 24225193 (https://api.semanticscholar.org/CorpusID:24225193).
54. Campanelli, M.; Lousto, C. O.; Marronetti, P.; Zlochower, Y. (2006). "Accurate Evolutions of Orbiting Black-Hole Binaries without Excision". *Physical Review Letters*. **96** (11): 111101. arXiv:gr-qc/0511048 (https://arxiv.org/abs/gr-qc/0511048). Bibcode:2006PhRvL..96k1101C (https://ui.adsabs.harvard.edu/abs/2006PhRvL..96k1101C). doi:10.1103/PhysRevLett.96.111101 (https://doi.org/10.1103%2FPhysRevLett.96.111101). ISSN 0031-9007 (https://www.worldcat.org/issn/0031-9007). PMID 16605808 (https://pubmed.ncbi.nlm.nih.gov/16605808). S2CID 5954627 (https://api.semanticscholar.org/CorpusID:5954627).
55. Baker, John G.; Centrella, Joan; Choi, Dae-Il; Koppitz, Michael; van Meter, James (2006). "Gravitational-Wave Extraction from an Inspiring Configuration of Merging Black Holes". *Physical Review Letters*. **96** (11): 111102. arXiv:gr-qc/0511103 (https://arxiv.org/abs/gr-qc/0511103). Bibcode:2006PhRvL..96k1102B (https://ui.adsabs.harvard.edu/abs/2006PhRvL..96k1102B). doi:10.1103/PhysRevLett.96.111102 (https://doi.org/10.1103%2FPhysRevLett.96.111102). ISSN 0031-9007 (https://www.worldcat.org/issn/0031-9007). PMID 16605809 (https://pubmed.ncbi.nlm.nih.gov/16605809). S2CID 23409406 (https://api.semanticscholar.org/CorpusID:23409406).
56. "Neutron Star Crust Is Stronger than Steel" (http://www.space.com/6682-neutron-star-crust-stronger-steel.html). *Space.com*. 18 May 2009. Retrieved 2016-07-01.
57. Merritt, D.; et al. (May 2004). "Consequences of Gravitational Wave Recoil". *The Astrophysical Journal Letters*. **607** (1): L9–L12. arXiv:astro-ph/0402057 (https://arxiv.org/abs/astro-ph/0402057). Bibcode:2004ApJ...607L...9M (https://ui.adsabs.harvard.edu/abs/2004ApJ...607L...9M). doi:10.1086/421551 (https://doi.org/10.1086%2F421551). S2CID 15404149 (https://api.semanticscholar.org/CorpusID:15404149).
58. Gualandris A, Merritt D, et al. (May 2008). "Ejection of Supermassive Black Holes from Galaxy Cores". *The Astrophysical Journal*. **678** (2): 780–797. arXiv:0708.0771 (https://arxiv.org/abs/0708.0771). Bibcode:2008ApJ...678..780G (https://ui.adsabs.harvard.edu/abs/2008ApJ...678..780G). doi:10.1086/586877 (https://doi.org/10.1086%2F586877). S2CID 14314439 (https://api.semanticscholar.org/CorpusID:14314439).
59. Merritt, D.; Schnittman, J. D.; Komossa, S. (2009). "Hypercompact Stellar Systems Around Recoiling Supermassive Black Holes". *The Astrophysical Journal*. **699** (2): 1690–1710. arXiv:0809.5046 (https://arxiv.org/abs/0809.5046). Bibcode:2009ApJ...699.1690M (https://ui.adsabs.harvard.edu/abs/2009ApJ...699.1690M). doi:10.1088/0004-637X/699/2/1690 (https://doi.org/10.1088%2F0004-637X%2F699%2F2%2F1690). S2CID 17260029 (https://api.semanticscholar.org/CorpusID:17260029).
60. Komossa, S.; Zhou, H.; Lu, H. (May 2008). "A Recoiling Supermassive Black Hole in the Quasar SDSS J092712.65+294344.0?". *The Astrophysical Journal*. **678** (2): L81–L84. arXiv:0804.4585 (https://arxiv.org/abs/0804.4585). Bibcode:2008ApJ...678L..81K (https://ui.adsabs.harvard.edu/abs/2008ApJ...678L..81K). doi:10.1086/588656 (https://doi.org/10.1086%2F588656). S2CID 6860884 (https://api.semanticscholar.org/CorpusID:6860884).
61. For a comparison of the geometric derivation and the (non-geometric) spin-2 field derivation of general relativity, refer to box 18.1 (and also 17.2.5) of Misner, C. W.; Thorne, K. S.; Wheeler, J. A. (1973). *Gravitation*. W. H. Freeman. ISBN 978-0-7167-0344-0.

62. Lightman, A. P.; Press, W. H.; Price, R. H.; Teukolsky, S. A. (1975). "Problem 12.16". *Problem book in Relativity and Gravitation*. Princeton University Press. ISBN 978-0-691-08162-5.
63. Mack, Katie (2017-06-12). "Black Holes, Cosmic Collisions and the Rippling of Spacetime" (<https://blogs.scientificamerican.com/observations/black-holes-cosmic-collisions-and-the-rippling-of-spacetime/>). *Scientific American (blogs)*.
64. Update on Gravitational Wave Science from the LIGO-Virgo Scientific Collaborations (<https://www.youtube.com/watch?v=xR6d8V5oh0o>) (Video of the press conference), retrieved 27 September 2017
65. Gough, Evan (11 February 2016). "Gravitational Waves Discovered: A New Window on the Universe" (<https://www.universetoday.com/127351/gravitational-waves-discovered-a-new-window-on-the-universe/>). *Universe Today*. Retrieved 30 March 2021.
66. Berry, Christopher (14 May 2015). "Listening to the gravitational universe: what can't we see?" (<https://unibirmingham.tumblr.com/post/118939268978/listening-to-the-gravitational-universe-what>). *University of Birmingham*. University of Birmingham. Retrieved 29 November 2015.
67. Grishchuk, L. P. (1976). "Primordial Gravitons and the Possibility of Their Observation". *Sov. Phys. JETP Lett.* **23** (6): 293–296. Bibcode:1976ZhPmR..23..326G (<https://ui.adsabs.harvard.edu/abs/1976ZhPmR..23..326G>). PACS numbers: 04.30. + x, 04.90. + e
68. Braginsky, V. B., Rudenko and Valentin, N. Section 7: "Generation of gravitational waves in the laboratory", *Physics Report* (Review section of *Physics Letters*), 46, No. 5. 165–200, (1978).
69. Li, Fangyu, Baker, R. M L, Jr., and Woods, R. C., "Piezoelectric-Crystal-Resonator High-Frequency Gravitational Wave Generation and Synchro-Resonance Detection", in the proceedings of *Space Technology and Applications International Forum (STAIF-2006)*, edited by M.S. El-Genk, *AIP Conference Proceedings*, Melville NY 813: 2006.
70. Wall, SPACE.com, Mike. "Gravitational Waves Send Supermassive Black Hole Flying" (https://www.scientificamerican.com/article/gravitational-waves-send-supermassive-black-hole-flying/?WT.mc_id=SA_FB_SPC_NEWS). *Scientific American*. Retrieved 2017-03-27.
71. Chiaberge, M.; Ely, J. C.; Meyer, E. T.; Georganopoulos, M.; Marinucci, A.; Bianchi, S.; Tremblay, G. R.; Hilbert, B.; Kotyla, J. P. (2016-11-16). "The puzzling case of the radio-loud QSO 3C 186: a gravitational wave recoiling black hole in a young radio source?". *Astronomy & Astrophysics*. **600**: A57. arXiv:1611.05501 (<https://arxiv.org/abs/1611.05501>). Bibcode:2017A&A...600A..57C (<https://ui.adsabs.harvard.edu/abs/2017A&A...600A..57C>). doi:10.1051/0004-6361/201629522 (<https://doi.org/10.1051%2F0004-6361%2F201629522>). S2CID 27351189 (<https://api.semanticscholar.org/CorpusID:27351189>).
72. Cowen, Ron (2015-01-30). "Gravitational waves discovery now officially dead". *nature*. doi:10.1038/nature.2015.16830 (<https://doi.org/10.1038%2Fnature.2015.16830>).
73. The LIGO Scientific Collaboration; the Virgo Collaboration (2004). "Relativistic Binary Pulsar B1913+16: Thirty Years of Observations and Analysis". *Binary Radio Pulsars*. **328**: 25. arXiv:astro-ph/0407149 (<https://arxiv.org/abs/astro-ph/0407149>). Bibcode:2005ASPC..328...25W (<https://ui.adsabs.harvard.edu/abs/2005ASPC..328...25W>).
74. Taylor, J. H.; Weisberg, J. M. (1979). "A New Test of General Relativity: Gravitational Radiation and the Binary Pulsar PSR 1913+16". *Astrophysical Journal*. **253** (5696): 908–920. Bibcode:1979Natur.277..437T (<https://ui.adsabs.harvard.edu/abs/1979Natur.277..437T>). doi:10.1038/277437a0 (<https://doi.org/10.1038%2F277437a0>). S2CID 22984747 (<https://api.semanticscholar.org/CorpusID:22984747>).

75. Huang, Y.; Weisberg, J. M. (2016). "Relativistic Measurements from Timing the Binary Pulsar PSR B1913+16". *Astrophysical Journal*. **829** (1): 55. arXiv:1606.02744 (<https://arxiv.org/abs/1606.02744>). Bibcode:2016ApJ...829...55W (<https://ui.adsabs.harvard.edu/abs/2016ApJ...829...55W>). doi:10.3847/0004-637X/829/1/55 (<https://doi.org/10.3847%2F0004-637X%2F829%2F1%2F55>). S2CID 119283147 (<https://api.semanticscholar.org/CorpusID:119283147>).
76. "Nobel Prizes and Laureates – NobelPrize.org" (http://www.nobelprize.org/nobel_prizes/physics/laureates/1993/). *NobelPrize.org*.
77. Damour, Thibault (2015). "1974: the discovery of the first binary pulsar". *Classical and Quantum Gravity*. **32** (12): 124009. arXiv:1411.3930 (<https://arxiv.org/abs/1411.3930>). Bibcode:2015CQGra..32l4009D (<https://ui.adsabs.harvard.edu/abs/2015CQGra..32l4009D>). doi:10.1088/0264-9381/32/12/124009 (<https://doi.org/10.1088%2F0264-9381%2F32%2F12%2F124009>). S2CID 118307286 (<https://api.semanticscholar.org/CorpusID:118307286>).
78. Crashing Black Holes (<http://calteches.library.caltech.edu/4298/1/BlackHoles.pdf>)
79. Binary and Millisecond Pulsars (<http://relativity.livingreviews.org/Articles/lrr-2005-7/download/lrr-2005-7Color.pdf>) Archived (<https://web.archive.org/web/20120301210516/http://relativity.livingreviews.org/Articles/lrr-2005-7/download/lrr-2005-7Color.pdf>) 2012-03-01 at the [Wayback Machine](#)
80. "Noise and Sensitivity" (http://www.gwoptics.org/ebook/sensitivity_noise.php). *gwoptics: Gravitational wave E-book*. University of Birmingham. Retrieved 10 December 2015.
81. Thorne, Kip S. (1995). "Gravitational Waves" (<https://archive.org/details/arxiv-gr-qc/9506086>). *Particle and Nuclear Astrophysics and Cosmology in the Next Millenium*: 160. arXiv:gr-qc/9506086 (<https://arxiv.org/abs/gr-qc/9506086>). Bibcode:1995pnac.conf..160T (<https://ui.adsabs.harvard.edu/abs/1995pnac.conf..160T>).
82. Mbarek, Saoussen; Paranjape, Manu (2014). "Negative Mass Bubbles in De Sitter Spacetime". *Phys. Rev. D*. **90** (10): 101502. arXiv:1407.1457 (<https://arxiv.org/abs/1407.1457>). Bibcode:2014PhRvD..90j1502M (<https://ui.adsabs.harvard.edu/abs/2014PhRvD..90j1502M>). doi:10.1103/PhysRevD.90.101502 (<https://doi.org/10.1103%2FPhysRevD.90.101502>). S2CID 119167780 (<https://api.semanticscholar.org/CorpusID:119167780>).
83. Blair DG, ed. (1991). *The detection of gravitational waves*. Cambridge University Press.
84. For a review of early experiments using Weber bars, see Levine, J. (April 2004). "Early Gravity-Wave Detection Experiments, 1960–1975". *Physics in Perspective*. **6** (1): 42–75. Bibcode:2004PhP....6...42L (<https://ui.adsabs.harvard.edu/abs/2004PhP....6...42L>). doi:10.1007/s00016-003-0179-6 (<https://doi.org/10.1007%2Fs00016-003-0179-6>). S2CID 76657516 (<https://api.semanticscholar.org/CorpusID:76657516>).
85. De Waard, A.; Gottardi, L.; Frossati, G. (2006). "MiniGRAIL, the first spherical gravitational wave detector" (<http://www.minigrail.nl/AboutMiniGRAIL/AboutMiniGRAIL-index.html>). *Recent Developments in Gravitational Physics*: 415. Bibcode:2006rdgp.conf..415D (<https://ui.adsabs.harvard.edu/abs/2006rdgp.conf..415D>).
86. de Waard, Arlette; Luciano Gottardi; Giorgio Frossati (July 2000). *Spherical Gravitational Wave Detectors: cooling and quality factor of a small CuAl6% sphere*. Marcel Grossmann meeting on General Relativity. Rome, Italy: World Scientific Publishing Co. Pte. Ltd. (published December 2002). pp. 1899–1901. Bibcode:2002nmgm.meet.1899D (<https://ui.adsabs.harvard.edu/abs/2002nmgm.meet.1899D>). doi:10.1142/9789812777386_0420 (https://doi.org/10.1142%2F9789812777386_0420). ISBN 9789812777386.
87. Cruise, Mike. "Research Interests" (<http://www.sr.bham.ac.uk/~amc/research/>). *Astrophysics & Space Research Group*. University of Birmingham. Retrieved 29 November 2015.

88. High Frequency Relic Gravitational Waves (<http://www.docfoc.com/selection-and-detection-of-high-frequency-relic-gravitational-waves-fangyu-li-zhenya-chen-chongqing-university-chongqing-400044-china-robert-m-l>) Archived (<https://web.archive.org/web/20160216001919/http://www.docfoc.com/selection-and-detection-of-high-frequency-relic-gravitational-waves-fangyu-li-zhenya-chen-chongqing-university-chongqing-400044-china-robert-m-l>) 2016-02-16 at the [Wayback Machine](#). page 12
89. The idea of using laser interferometry for gravitational wave detection was first mentioned by Gerstenstein and Pustovoit 1963 Sov. Phys.–JETP 16 433. Weber mentioned it in an unpublished laboratory notebook. Rainer Weiss first described in detail a practical solution with an analysis of realistic limitations to the technique in R. Weiss (1972). "Electromagnetically Coupled Broadband Gravitational Antenna". Quarterly Progress Report, Research Laboratory of Electronics, MIT 105: 54.
90. LIGO Scientific Collaboration; Virgo Collaboration (2010). "Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors". *Classical and Quantum Gravity*. **27** (17): 17300. arXiv:1003.2480 (<https://arxiv.org/abs/1003.2480>). Bibcode:2010CQGra..27q3001A (<https://ui.adsabs.harvard.edu/abs/2010CQGra..27q3001A>). doi:10.1088/0264-9381/27/17/173001 (<https://doi.org/10.1088/0264-9381/27/17/173001>). S2CID 15200690 (<https://api.semanticscholar.org/CorpusID:15200690>).
91. "Einstein@Home" (<http://einstein.phys.uwm.edu/>).
92. Hellings, R.W.; Downs, G.S. (1983). "Upper limits on the isotropic gravitational radiation background from pulsar timing analysis". *Astrophysical Journal Letters*. **265**: L39–L42. Bibcode:1983ApJ...265L..39H (<https://ui.adsabs.harvard.edu/abs/1983ApJ...265L..39H>). doi:10.1086/183954 (<https://doi.org/10.1086/183954>).
93. Arzoumanian Z, et al. (NANOGrav Collaboration) (2018). "The NANOGrav 11-year Data Set: Pulsar-timing Constraints On The Stochastic Gravitational-wave Background". *The Astrophysical Journal*. **859** (1): 47. arXiv:1801.02617 (<https://arxiv.org/abs/1801.02617>). Bibcode:2018ApJ...859...47A (<https://ui.adsabs.harvard.edu/abs/2018ApJ...859...47A>). doi:10.3847/1538-4357/aabd3b (<https://doi.org/10.3847/1538-4357/aabd3b>). S2CID 89615050 (<https://api.semanticscholar.org/CorpusID:89615050>).
94. Hobbs, G.; et al. (2010). "The International Pulsar Timing Array project: using pulsars as a gravitational wave detector". *Classical and Quantum Gravity*. **27** (8): 084013. arXiv:0911.5206 (<https://arxiv.org/abs/0911.5206>). Bibcode:2010CQGra..27h4013H (<https://ui.adsabs.harvard.edu/abs/2010CQGra..27h4013H>). doi:10.1088/0264-9381/27/8/084013 (<https://doi.org/10.1088/0264-9381/27/8/084013>). S2CID 56073764 (<https://api.semanticscholar.org/CorpusID:56073764>).
95. Kramer, Sarah (11 February 2016). "This collision was 50 times more powerful than all the stars in the universe combined" (<https://www.businessinsider.com/black-hole-collision-energy-50-times-universe-2016-2>). *Business Insider*. Retrieved 2020-09-06.
96. "Observation of Gravitational Waves from a Binary Black Hole Merger" (https://www.ligo.caltech.edu/system/media_files/binaries/301/original/detection-science-summary.pdf) (PDF). LIGO, with the collaboration of Virgo interferometer. 2016. Retrieved 2015-09-14.
97. Heathcote, William (2018). *MYP Physics Years 4 & 5: A concept-based approach*. Great Clarendon Street, Oxford: Oxford University Press. p. 56. ISBN 9780198397960.
98. Abbott BP, et al. (LIGO Scientific Collaboration & Virgo Collaboration) (16 October 2017). "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral". *Physical Review Letters*. **119** (16): 161101. arXiv:1710.05832 (<https://arxiv.org/abs/1710.05832>). Bibcode:2017PhRvL.119p1101A (<https://ui.adsabs.harvard.edu/abs/2017PhRvL.119p1101A>). doi:10.1103/PhysRevLett.119.161101 (<https://doi.org/10.1103/PhysRevLett.119.161101>). PMID 29099225 (<https://pubmed.ncbi.nlm.nih.gov/29099225>).

99. "GW170817 Press Release" (<https://www.ligo.caltech.edu/page/press-release-gw170817>). *LIGO Lab | Caltech*. Retrieved 2017-10-17.
100. ME Gerstein; VI Pustovoit (1962). "On the Detection of Low-Frequency Gravitational Waves". *ZhETF* (in Russian). **16** (8): 605–607. Bibcode:1963JETP...16..433G (<https://ui.adsabs.harvard.edu/abs/1963JETP...16..433G>).

Further reading

- Bartusiak, Marcia. *Einstein's Unfinished Symphony*. Washington, DC: Joseph Henry Press, 2000.
- Chakrabarty, Indrajit (1999). "Gravitational Waves: An Introduction". *arXiv:physics/9908041* (<https://arxiv.org/abs/physics/9908041>).
- Landau, L. D. and Lifshitz, E. M., *The Classical Theory of Fields* (Pergamon Press), 1987.
- Will, Clifford M. (2014). "The Confrontation between General Relativity and Experiment" (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5255900>). *Living Reviews in Relativity*. **17** (1): 4. *arXiv:1403.7377* (<https://arxiv.org/abs/1403.7377>). Bibcode:2014LRR....17....4W (<https://ui.adsabs.harvard.edu/abs/2014LRR....17....4W>). doi:10.12942/lrr-2014-4 (<https://doi.org/10.12942%2Flrr-2014-4>). PMC 5255900 (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5255900>). PMID 28179848 (<https://pubmed.ncbi.nlm.nih.gov/28179848>).
- Saulson, Peter R. (1994). *Fundamentals of Interferometric Gravitational Wave Detectors*. World Scientific. Bibcode:1994figw.book.....S (<https://ui.adsabs.harvard.edu/abs/1994figw.book.....S>). doi:10.1142/2410 (<https://doi.org/10.1142%2F2410>). ISBN 978-981-02-1820-1.
- Barish, Barry C.; Weiss, Rainer (1999). "LIGO and the Detection of Gravitational Waves". *Physics Today*. **54** (10): 44. Bibcode:1999PhT....52j..44B (<https://ui.adsabs.harvard.edu/abs/1999PhT....52j..44B>). doi:10.1063/1.882861 (<https://doi.org/10.1063%2F1.882861>).

Bibliography

- Berry, Michael, *Principles of Cosmology and Gravitation* (Adam Hilger, Philadelphia, 1989). ISBN 0-85274-037-9
- Collins, Harry, *Gravity's Shadow: The Search for Gravitational Waves*, University of Chicago Press, 2004. ISBN 0-226-11378-7
- Collins, Harry, *Gravity's Kiss: The Detection of Gravitational Waves* (The MIT Press, Cambridge Massachusetts, 2017). ISBN 978-0-262-03618-4.
- Davies, P.C.W., *The Search for Gravity Waves* (Cambridge University Press, 1980). ISBN 0521231973.
- Grote, Hartmut, *Gravitational Waves: A history of discovery* (CRC Press, Taylor & Francis Group, Boca Raton/London/New York, 2020). ISBN 978-0-367-13681-9.
- P. J. E. Peebles, *Principles of Physical Cosmology* (Princeton University Press, Princeton, 1993). ISBN 0-691-01933-9.
- Wheeler, John Archibald and Ciufolini, Ignazio, *Gravitation and Inertia* (Princeton University Press, Princeton, 1995). ISBN 0-691-03323-4.
- Wolf, Harry, ed., *Some Strangeness in the Proportion* (Addison–Wesley, Reading, Massachusetts, 1980). ISBN 0-201-09924-1.

External links

- [Laser Interferometer Gravitational Wave Observatory \(http://www.ligo.caltech.edu/\)](http://www.ligo.caltech.edu/). LIGO Laboratory, operated by the [California Institute of Technology](#) and the [Massachusetts Institute of Technology](#)
 - [Gravitational Waves \(http://www.nature.com/news/gravitational-waves-1.19321\)](http://www.nature.com/news/gravitational-waves-1.19321) – Collected articles at [Nature Journal](#)
 - [Gravitational Waves \(http://www.scientificamerican.com/report/the-discovery-of-gravitational-waves/?WT.mc_id=SA_FB_PHYS_SR\)](http://www.scientificamerican.com/report/the-discovery-of-gravitational-waves/?WT.mc_id=SA_FB_PHYS_SR) – Collected articles [Scientific American](#)
 - [Video \(94:34\) – Scientific Talk on Discovery \(https://cds.cern.ch/record/2131411\)](https://cds.cern.ch/record/2131411), Barry Barish, CERN (11 February 2016)
 - Christina Sormani, C. Denson Hill, Paweł Nurowski, [Lydia Bieri](#), David Garfinkle, and Nicolás Yunes (August 2017). "A two-part feature: The Mathematics of Gravitational waves" (<https://doi.org/10.1090%2Fnoti1551>). *Notices of the American Mathematical Society*. **64** (7): 684–707. doi:10.1090/noti1551 (<https://doi.org/10.1090%2Fnoti1551>). ISSN 1088-9477 (<https://www.worldcat.org/issn/1088-9477>).
-

Retrieved from "https://en.wikipedia.org/w/index.php?title=Gravitational_wave&oldid=1070388556"

This page was last edited on 7 February 2022, at 06:39 (UTC).

Text is available under the Creative Commons Attribution-ShareAlike License; additional terms may apply. By using this site, you agree to the Terms of Use and Privacy Policy. Wikipedia® is a registered trademark of the Wikimedia Foundation, Inc., a non-profit organization.