The first direct detection of gravitational waves was made on 14th September 2015 by the LIGO collaboration. Discuss the nature and detection of gravitational waves and their importance to science.

Introduction

If you were on Earth on 14th September 2015, your body would have ever-so-slightly stretched and compressed without you even noticing. Why? Because on that day, a ripple in the fabric of spacetime, known as a gravitational wave, passed through our planet.

The waves were produced from the collision of two black holes of 36 and 29 solar masses, which merged to form a spinning, 62-solar-mass black hole, 1.3 billion light-years away (Commissariat, 2016, p.1).

Although this is one of the most energetic, cataclysmic and violent events possible in the Universe, by the time the waves reach Earth, they are *thousands of billions* of times weaker - the amount of space-time wobbling they generated was 10,000 times *smaller than the nucleus of an atom (LIGO, 2025)*! And that's the reason you didn't feel anything unusual on 14th September 2015.

What was remarkable about this event was that it was the first time the gravitational waves were detected by scientists on Earth. The detection was made by the newly upgraded LIGO (Laser Interferometer Gravitational-wave Observatory) detectors – one in Hanford, Washington, and the other in Livingston, Louisiana (US), which were engineered to perform such incredibly precise measurements.

The gravitational-wave signal lasted in both of LIGO's interferometers for 0.2 seconds and was named GW150914 ("GW" for *gravitational wave* and the date of observation 2015-09-14). (Commissariat, 2016, p3). This remarkable discovery validated a prediction made by Albert Einstein and brought in a new era of exploring the universe through gravitational-wave astronomy.

I have carried out some research into the nature and detection of gravitational waves, and their importance to science, which I discuss in this essay.

Nature of Gravitational Waves

Gravitational waves are 'ripples' in space-time caused by some of the most violent and energetic events in the Universe. Gravitational waves were predicted by Albert Einstein in 1916 as part of the general theory of relativity. In this theory, gravity is a phenomenon resulting from the curvature of spacetime (which in turn is caused by the presence of mass). If the masses move, the curvature of spacetime changes.

Einstein showed that if massive accelerating objects go into motion that is not spherically symmetric, it would disrupt space-time in such a way that 'waves' of space-time would spread in all directions away from the source, compressing and expanding space–time as they flow. Einstein predicted that these cosmic ripples would travel at the speed of light.

In principle, even small accelerating bodies generate gravitational waves – Earth and moon for example. But those systems are so small in astronomical terms that the waves generated are far too weak to detect with our instruments. That’s why scientists look out for more massive systems, that are very far outside of our own solar system. (Clegg, 2018, p. 36-37)

Since Einstein published his general theory of relativity, scientists have predicted that binary-star or black-hole systems, particularly just as they hit each other, will produce the greatest gravitational waves in our universe (refer to Figure 1). However, such waves had never been directly detected, until 14th September 2015.

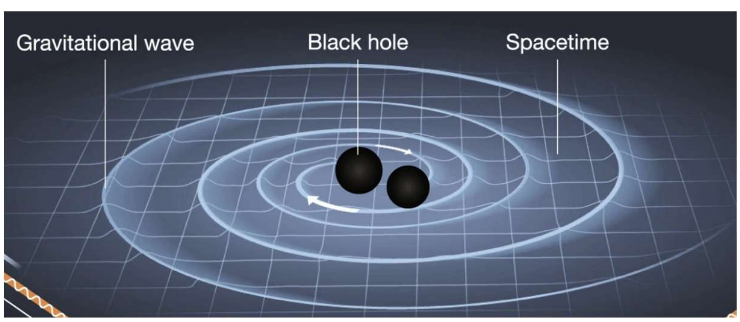


Figure 1. Impression of or black-hole system producing gravitational waves (Miller and Yunes, 2019). ***Note that gravitational waves themselves are invisible.***

Modern day astronomers have defined four categories of gravitational waves depending on what object or system generates the waves:

- Compact Binary Inspiral (produced by orbiting pairs of massive and dense ("compact") objects like black holes and neutron stars).
- Continuous (produced by a single spinning/rotating massive object like a neutron star or supernova).
- Stochastic (small gravitational waves are passing by from all over the Universe all the time, mixed together at random).
- Burst (from short-duration unknown sources).
  (LIGO, 2025)

Each type of event/category generates a characteristic set of gravitational-wave signals, in a particular frequency (refer to Figure 2):

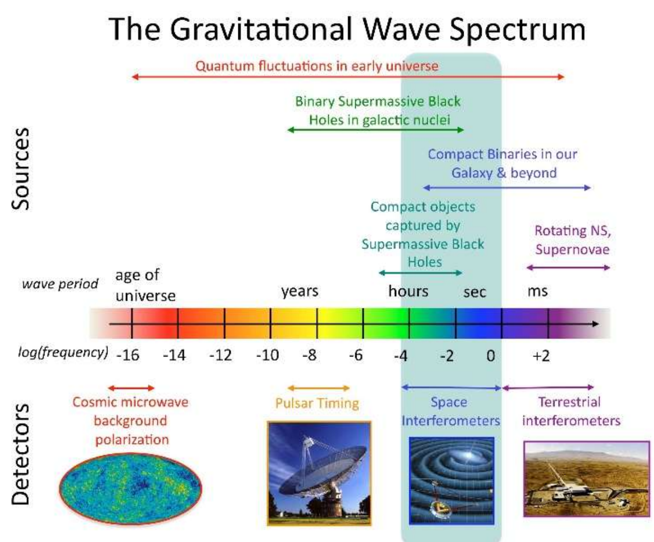


Figure 2. Gravitational Wave spectrum Image (NASA, 2025)

So far, all of the objects LIGO has detected fall into the compact binary inspiral category. LIGO can detect frequencies in the 30 to 6000 Hertz range. These happen to be similar frequencies to audible sound waves, which is why gravitational waves are sometimes given incorrect, if poetic, description of interstellar sound" (Clegg 2018, p37)

Detection of Gravitational waves

Indirect Measurement/Detection:

Scientists, using Einstein's general relativity equations, predicted that a binary system (two masses orbiting each other) will loose energy through gravitational waves. This will manifest as aloss of kinetic energy and cause the orbiting objects to spiral inwards, and their orbit's period to reduce (until a collision). This occurs despite being in a vacuum and if we simply applied Newtonian mechanics it would predict objects remaining in steady orbit forever.

In 1974 the Hulse-Taylor Pulsar (rotating neutron star that emits regular pulses of radio waves) was observed by scientists. Taylor and his student Hulse measured the pulsar intensity period and noticed it varied in a regular way, indicating that it was in orbit with another star. Over many years the pulsar was observed with high accuracy and it was shown that the orbital period was decreasing with time. The discovery of the Hulse-Taylor pulsar and subsequent work to show indirect evidence of gravitational waves was awarded the 1993 Nobel Prize for physics.

"It was not definitive proof of the existence of gravitational waves – the waves had not actually been detected , and it was always possible the decay of orbits could have another cause – but the observation was very strong supporting evidence for the existence of such waves" (Clegg, 2019, p.63).

Direct Measurement/Detection:

The ultimate proof that gravitational waves are real could only come from their direct detection/observation – picking up the waves generated by the source itself.

Direct detection of gravitation waves relies on the fact that as a gravitational wave passes an observer, that observer will find spacetime distorted (Refer to Figure 3). 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 is inversely proportional to the distance from the source.

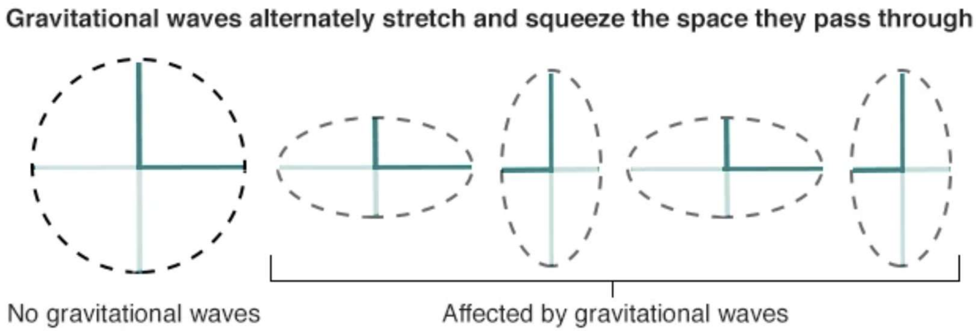


Figure 3 (Ghosh, 2016)

Gravitational waves are constantly passing Earth; however, even the strongest have a minuscule effect since their sources are generally at a great distance. For example, the waves from GW150914 when they reached the Earth, only changed the length of a 4 km LIGO arm by a thousandth of the width of a proton. This tiny change can be detected only with the most sophisticated detectors.

LIGO's groundbreaking detection of gravitational waves was made possible by a remarkable detector design. The two observatories in the US have two long tunnels called arms, which are 4 kilometres long and are perpendicular to each other (refer to Figure 4). At the ends of each arm are “test masses” – which are 40-kilogram mirrors made of ultra pure silicon, suspended like pendulums to isolate them from vibrations. The fused silica suspensions are designed to minimize thermal noise and seismic noise using sensors and feedback technique The suspensions were the UK deliverable within the LIGO project. (Hammond, G. 2025, Private Interview). To ensure absolute precision, the entire setup is housed in an ultrahigh vacuum (pressure inside is a trillionth of the atmospheric level) (Clegg, 2018), isolating it from any outside interference.

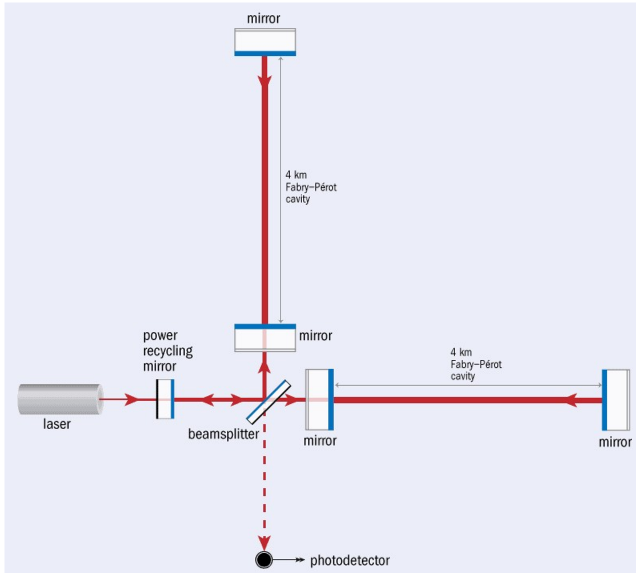
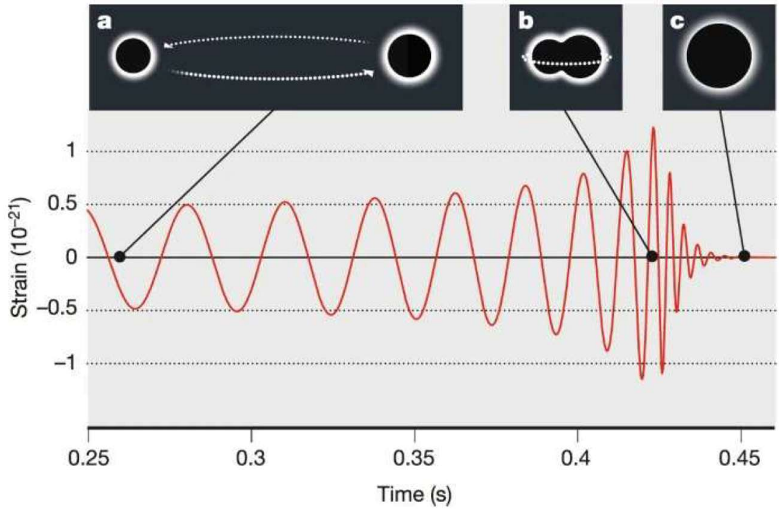


Figure 4. Schematic arrangement of LIGO (Commissariat, 2016, p3)

The teams at LIGO had to go to overcome many problems to ensure that these giant 4km arms were indeed in a vacuum, for example events like wildlife moving in during construction and defecating in the arms, which was acidic and reacted with the arm walls, producing gases.

During an experiment, a high-powered laser (200 watts) emitting light with a wavelength of 1064 nanometres is directed toward a special mirror called a beamsplitter (Commissariat, 2016). This mirror divides the laser beam in two, sending half of it down one arm and reflecting the other half into the second arm. Each arm acts like a kind of optical echo chamber, known as a Fabry–Pérot cavity, where the light bounces back and forth about 400 times in around 10 milliseconds. This makes it seem as if the arms are nearly 1,600 kilometres long, dramatically increasing LIGO's ability to detect even the tiniest disturbances in spacetime and reducing the uncertainty in its measurements.

Once the laser light finishes its journey through the arms, it returns to the beamsplitter. There, the two beams come back together and interfere with each other. Some of this recombined light travels through the beamsplitter and reaches a photodetector, which carefully measures any changes. If a gravitational wave has passed through Earth, it will have stretched and squeezed space just enough to slightly change the path lengths of the arms which will produce an interference pattern and therefore a signal that LIGO can detect.



a, **b**, Two black holes several orbits before their merger (**a**), and at the point of merger (**b**). **c**, The aftermath of the merger; the remnant has settled down into its final state as a single

Figure 5. Schematic signal recorded on 14 September 2015 by LIGO (Miller and Yunes, 2019).

On 14 September 2015, almost as soon as detectors were turned on, they gave a signal to be strong enough to be an unmistakable source, refer to Figure 5. LIGO team spend many months validating the analysis because events like earthquakes and even trucks driving by will also cause these patterns. So the scientists spent a long time filtering out these signals and in detection events, and cross referencing between the detector stations.

Hundreds of black hole mergers have been observed by LIGO since the first detection in 2015. The most surprising thing so far, from the few years of observing gravitational waves, is that the scientists are seeing a lot more black hole mergers than they were expecting in the early days (Hammond, G. 2025, Private Interview) .

Recently, the biggest one yet was caused by two black holes with masses of 100 and 140 times that of the Sun merging to form a final black hole weighing 225 solar masses (O'Callaghan, 2025). " Models of the black holes also suggest that they were spinning exceedingly fast – about 40 times per second, which is near the limit of what Einstein's general theory pf relativity predicts black holes can reach while remaining stable."

The new cutting-edge tools are currently being developed in the industry for analysis of LIGO results. They use AI to search through the very high dimensional parameter data to identify potential gravitational wave signals buried in noise, and to fit the data to experimental models. Machine learning algorithms help classify and characterise these signals, improving detection sensitivity and reducing false positives. (Hammond, G. 2025, Private Interview).

A third LIGO observatory, to be located in India, is under construction to enhance the global detection network. (Hammond, G. 2025, Private Interview).

Importance to Science

Confirmation of Einstein's Theory: Gravitational waves were predicted by Albert Einstein in 1916 as part of his general theory of relativity. Detecting them directly, was a powerful confirmation that Einstein's theory still holds true, even under the most extreme conditions in the universe.

Proof of Black Hole Mergers: The detection of the GW150914 waves provided the first solid evidence that black holes can form binary systems and collide.

New Way to Observe the Universe: Until 2015, astronomy relied mostly on electromagnetic radiation (light, radio waves, X-rays, etc.) to observe space. Gravitational waves opened an entirely new "sense" for observing the cosmos. This allows scientists to study events that are invisible to traditional telescopes, such as black hole mergers.

Previously, scientists had to rely on other matter to be present nearby in order to learn about black holes, because black holes do not emit electromagnetic radiation. Since the first detection of gravitational waves, scientists can now observe colliding black holes directly through the ripples they create in spacetime, allowing them to study these objects, without the need for surrounding matter or light.

In addition, "gravitational waves interact very weakly with matter (unlike EM radiation, which can be absorbed, reflected, refracted, or bent by gravity itself), they travel through the Universe virtually unimpeded, carrying information about their origins that is free of distortion." (LIGO, 2025)

New discoveries: The 2015 discovery marked the beginning of a new field of gravitational wave astronomy. Hundreds of black hole mergers have been detected since, which has already led to numerous discoveries in physics and astrophysics.

For example (Miller and Yunes, 2019):

- gravitational waves travel at the speed of light and this is irrespective of their frequency, just as predicted in the general theory of relativity.
- determined stringent constraints on the mass of the particle (as yet undetected) responsible for mediating the gravitational interaction: the gravitron.
- doubled the mass range of known black holes.
- the double neutron star event GW170817 led to discoveries about interior properties of neutron stars.

Technological Innovation: The tools used to detect gravitational waves (e.g. LIGO) are among the most sensitive instruments ever built. Their design has pushed the boundaries of engineering, optics, and data analysis, with potential future applications in other fields.

The Future: can we use the gravitational waves in a more direct way?

When the two black holes for the event GW150914 collided, about 3 times the mass of the sun was converted into gravitational waves in a fraction of a second—with a peak power output about 50 times that of the whole visible universe. (LIGO, 2025). However, harnessing this energy remains far beyond our reach. The fundamental challenge lies in the weakness of gravity itself, the strain amplitudes detected on Earth stretch spacetime only by a thousandth of the width of proton across 4km long detectors. This makes any meaningful energy transfer effectively negligible for us here on Earth. Even hypothetically, building resonant structures large and sensitive enough to absorb significant energy from gravitational waves would require planetary or stellar scale engineering. For this reason, even an advanced civilization capable of harnessing the energy of an entire galaxy would likely prefer more efficient alternatives such as Dyson spheres or large fusion reactors.

Perhaps in the distant future, gravitational waves will be used not as an energy source, but as a revolutionary medium for communication, navigation, and cosmological discovery. Since they interact extremely weakly with matter, gravitational waves can travel vast distances through space without scattering or absorption, making them ideal candidates for interstellar messaging systems. An advanced civilisation might develop gravitational wave transmitters and encode information via modulations in amplitude, frequency, or waveform shape. Such signals would be nearly impossible to intercept or interfere with, offering a secure, galactic-scale communication channel. Furthermore, gravitational wave sources such as neutron star mergers could function as stable beacons for a relativistic navigation network similar to GPS, but on an interstellar scale.

Conclusion

While the discovery of gravitational waves was primarily a scientific breakthrough, it has already led to several practical applications, particularly through the technologies developed to make the detection possible (for example Advanced Laser and Optics Technologies, Vibration Isolation). While these applications are indirect for now, the long-term benefits of gravitational wave research may be similar to how radio waves, once a purely theoretical concept, led to modern telecommunications. As we develop better detectors and understand the universe through gravitational waves, more unexpected technologies may emerge, just as past space research has led to GPS, MRI, and weather satellites.

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