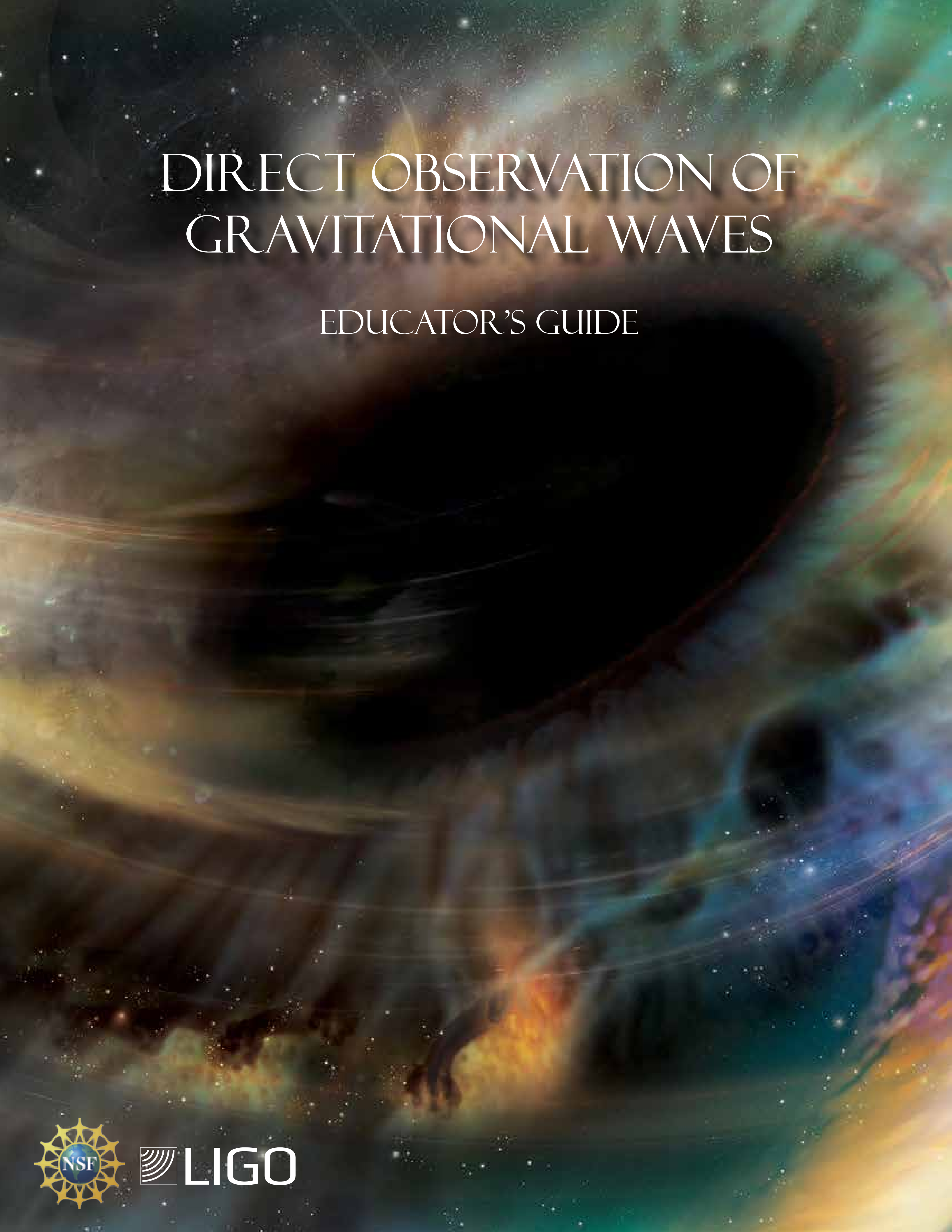

DIRECT OBSERVATION OF GRAVITATIONAL WAVES

EDUCATOR'S GUIDE

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http://www.ligo.org

Content

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Introduction

On September 14, 2015, the Laser Interferometer Gravitational-wave Observatory (LIGO) received the first confirmed gravitational wave signals. Now known as GW150914 (for the date on which the signals were received in 2015, 9th month, day 14), the event represents the coalescence of two black holes that were previously in mutual orbit. LIGO's exciting discovery provides direct evidence of what is arguably the last major unconfirmed prediction of Einstein's General Theory of Relativity. This Educator's Guide provides a brief introduction to LIGO and to gravitational waves, along with two simple demonstration activities that you can do in your classroom to engage your students in understanding LIGO's discovery. Additional resources are also provided to extend your explorations of Einstein's Universe.

Activity 1 – Coalescing Black Holes

Brief overview:

Students interact with a demonstration of orbiting spheres that have an increasing orbital frequency as they coalesce.

Science Concepts:

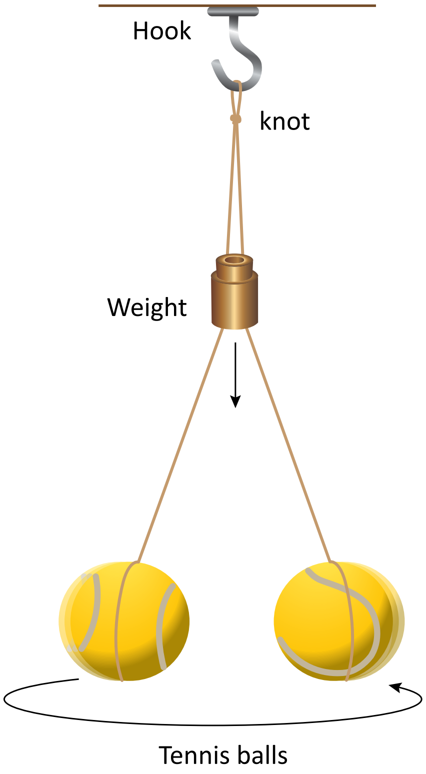
Gravitational waves are ripples in spacetime produced by some of the most violent events in the cosmos, such as the collisions and mergers of massive compact stars or black holes. These ripples travel at the speed of light through the Universe, carrying with them information about their origins.

Duration: 30 min

Essential Question:

What happens when two black holes spiral in towards each other?

Grades: 5 – 12



Activity 2 – Warping of Spacetime

Brief overview:

Students explore the behavior of two orbiting spheres in spacetime.

Science Concepts:

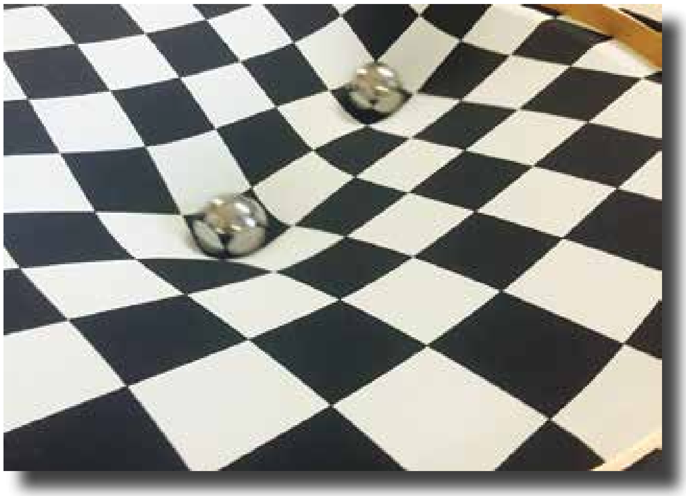
A pair of orbiting black holes will produce gravitational waves, which are ripples in the fabric of spacetime. Gravitational waves will carry energy away from the pair, causing their orbit distance to shrink and their orbital period to decrease. Eventually the black holes will coalesce. LIGO's detectors can measure the gravitational waves produced by the system during the coalescence.

Duration: 30 min

Essential Question:

How do binary black holes warp spacetime?

Grades: 5 – 12



Background

Gravitational Waves as Signals from the Universe

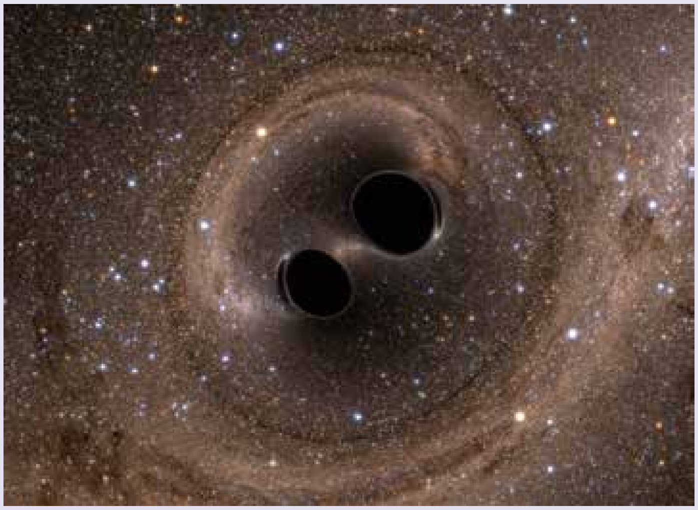


Figure 1: Numerical simulation of two merging black holes. Credit: SXS

Gravitational waves are 'ripples' in the fabric of spacetime caused by accelerating masses such as colliding black holes, exploding stars, and even the birth of the universe itself. Albert Einstein predicted the existence of gravitational waves in 1916, derived from his General Theory of Relativity. Einstein's mathematics showed that massive accelerating objects would disrupt spacetime in such a way that waves of distorted space would radiate from the source. These ripples travel at the speed of light through the universe, carrying information about their origins, as well as clues to the nature of gravity itself. Two black holes in mutual orbit will revolve around each other emitting gravitational waves and losing orbital energy as illustrated in Figure 1. Over time, the energy loss causes the stars to move closer together and orbit around each other faster and faster until they eventually merge together, or coalesce. This type of merger has never before been directly observed, and it is the type of event that emitted the gravitational waves detected by LIGO on September 14, 2015.

Historically, scientists have relied primarily on observations with electromagnetic radiation (visible light, x-rays, radio waves, microwaves, etc., see Figure 2) to learn about and understand phenomena in the universe. In addition, some types of subatomic particles, including neutrinos and cosmic rays, have been used to study cosmic objects. Scientists build different types of telescopes and observatories in order to detect these different types of signals. Some telescopes are located on the ground (e.g., visible light and radio), some are located on satellites orbiting Earth (such as x-ray and gamma-ray, as well as the Hubble Space Telescope which images visible light and ultraviolet), and still others are buried in ice (neutrino detectors) or are far underground (particle detectors). Each provides a different and complementary view of the universe, with each new window bringing exciting new discoveries.

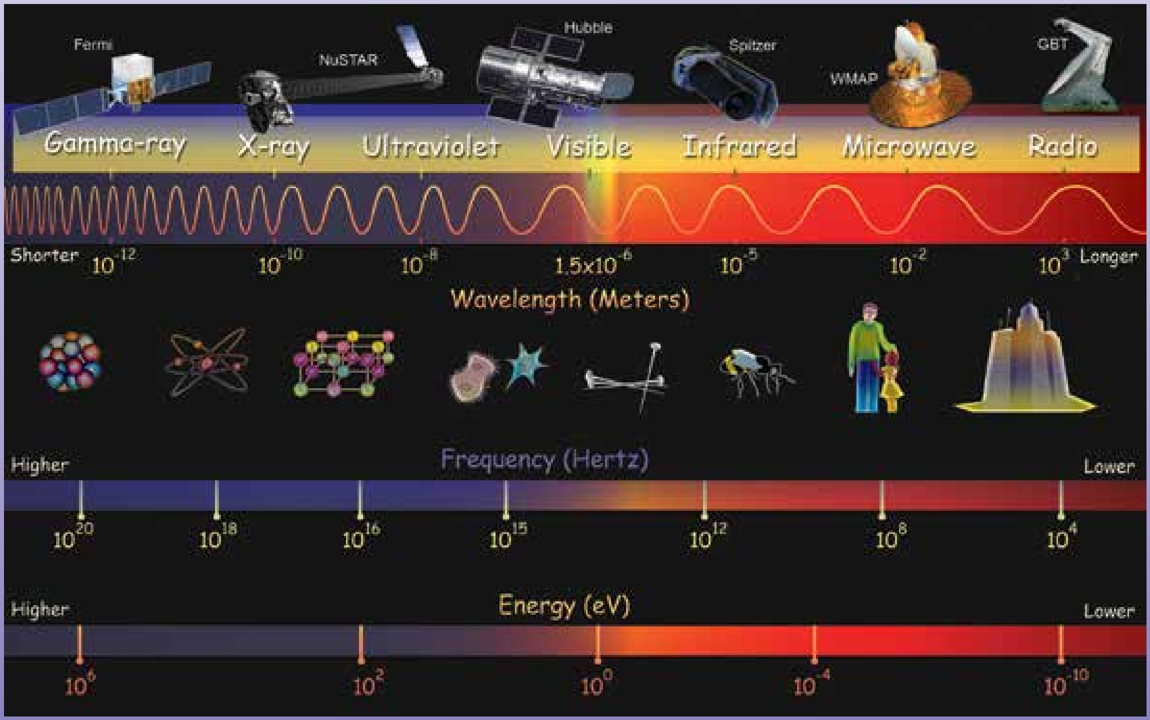


Fig. 2: Electromagnetic Spectrum. Credit: SSU E/PO/Aurore Simonnet

Just as different cosmic objects generate different wavelengths across the electromagnetic spectrum, different physical systems are expected to generate different wavelengths of gravitational waves. These in turn can be observed by different types of observatories. Figure 3 illustrates the expected strengths of the gravitational wave, usually called *h*, wavelength bands and types of sources expected in each band. LIGO (and other similar-size ground-based interferometers such as Virgo in Italy) are sensitive to gravitational waves with frequencies in the range 10 - 2000 Hz.

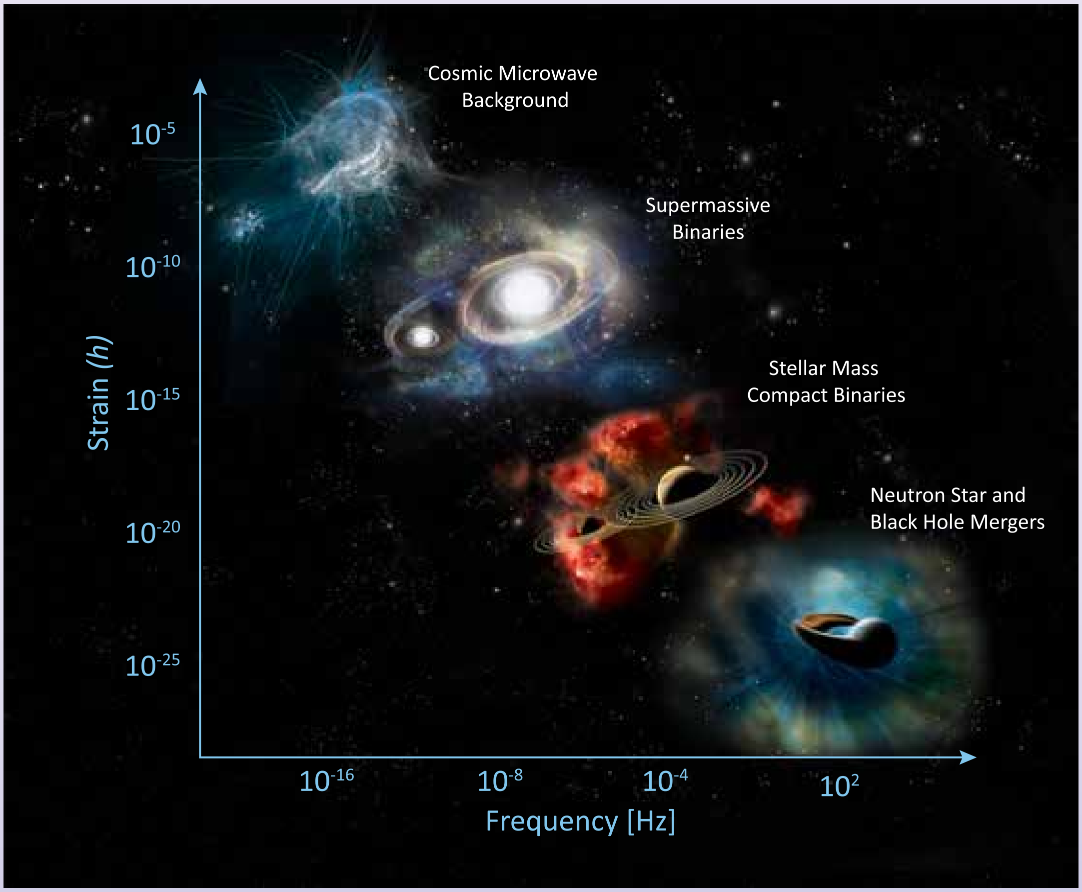


Figure 3: Gravitational Wave Spectrum. This figure plots the predicted strain (h, y-axis) vs. the frequency of expected gravitational waves in Hz (x-axis) for different types of cosmic objects. Credit: SSU E/PO/Aurore Simonnet

Gravity from Newton to Einstein

Legend has it that Isaac Newton had a flash of insight about gravity when he was hit on the head by an apple which fell from a tree under which he was sitting. Today, he is credited with the mathematical expression that explains how the force of gravitational attraction between two objects depends on their masses and their separation - it is called Newton's Law of Gravitation. In reality, our understanding of gravity grew slowly out of many astronomical observations that were made by ancient Babylonians, Egyptians and Greeks. They were trying to understand the motions of the planets and to be able to predict the occurrences of celestial events, such as eclipses of the Sun or Moon.

In Ancient Greece, the most widely held view was that the Earth was the center of the solar system, and that the Sun and the planets revolved around it. In fact, this was the dominant view of the cosmos for many centuries. In the early 1500s, this paradigm was radically challenged because of the efforts of the Polish astronomer, Nicolas Copernicus. His work, which placed the Sun at the center, with the Earth as only one of many planets in orbit around it, was published in 1543. Over the next 100 years, work by astronomers Tycho Brahe, Johannes Kepler and Galileo Galilee was also important in establishing the exact motions of the planets in our Solar System.

In 1687, physics began to separate from astronomy with the invention by Isaac Newton of a mathematical formalism known as calculus. Calculus allowed Newton to write down his famous universal law of gravity, and to understand that the same law that described the Moon's orbit governed an apple falling on one's head on the Earth. Newton realized, for the first time, that these two very different phenomena could be unified by one mathematical rule. In his honor, we now express the strength of any type of force in newtons, and we teach Newton's Law of Gravitation:

$$F = \frac{G\, m_1\, m_2}{r^2}$$

where m_1 and m_2 are the masses of two objects, r is the distance between them, and G is a proportionality constant called the Universal Gravitational Constant. Its value was first experimentally determined by British scientist Henry Cavendish in 1798.

Newton's Law of Gravitation correctly describes the movement of most of the bodies in the solar system, as well as the familiar motion of objects on Earth. However, in certain cases, scientists found discrepancies between the predictions of Newton's simple formulation of gravity and what they actually observed. One of these is the orbit of Mercury, which has a peculiar anomaly that we will discuss below.

Figure 4: Newton, apples and the Moon.
Credit: SSU E/PO Aurore Simonnet

In the 1890s, a teenage Albert Einstein started upon a path that would eventually eventually lead to a more comprehensive view of gravity than Newton's. The work of physicist James Clerk Maxwell in the 1870s united the concepts of electricity and magnetism in a powerful framework. Maxwell realized that fluctuations in the electromagnetic field, such as those produced by vibrating electric charges, would produce electromagnetic waves - light waves. As a teenager Einstein imagined moving alongside a light wave at the speed of light. He realized that in this frame of reference the light wave would appear to freeze. The electric and magnetic fields would oscillate in time as shown in Figure 5, but he wouldn't see the wave moving away from him. The problems associated with this "frozen wave" picture led Einstein to the key insight that the speed of light is the same for all observers, independent of their state of motion. He also assumed that the laws of physics must be the same for all observers.

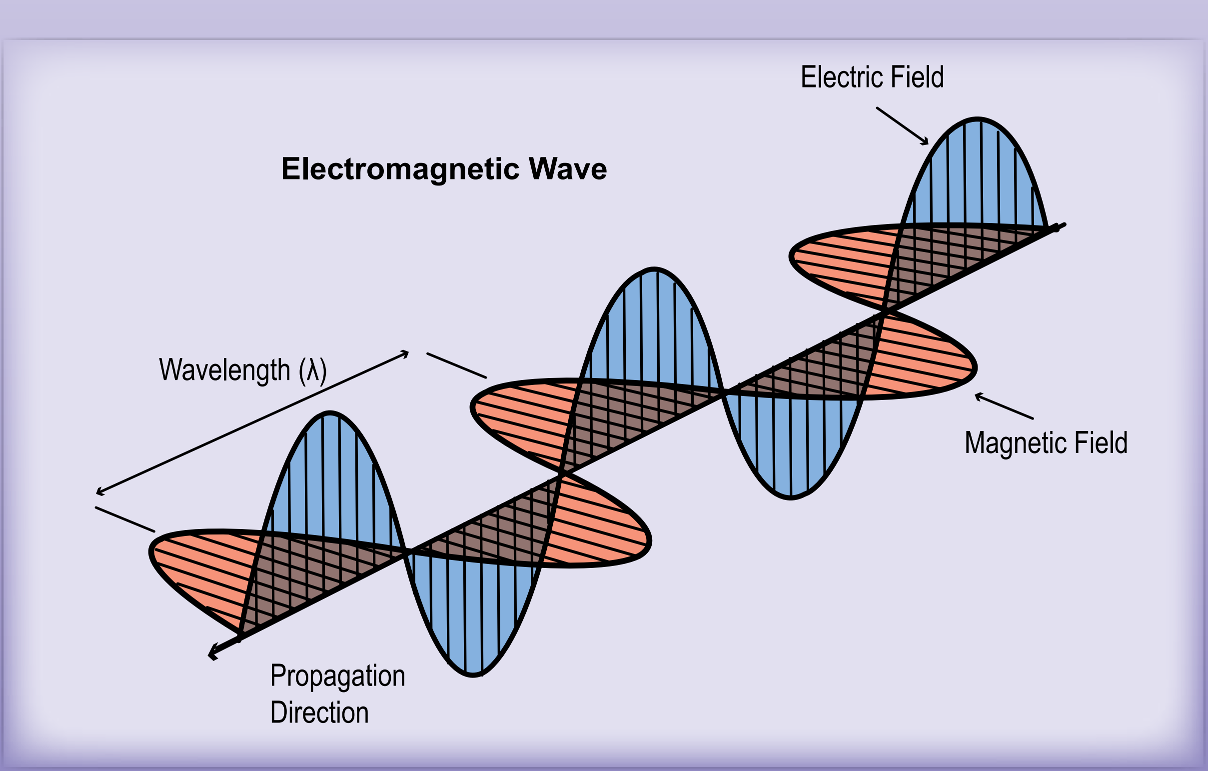


Figure 5: Electromagnetic wave. Credit: SSU E/PO Aurore Simonnet

Einstein elevated these two assumptions to physical principles, called the *principles of special relativity*. They apply to situations in which observers or objects are moving at a constant speed and direction. His resulting theory, the *Special Theory of Relativity,* though inconsistent with our common-sense notions of the world, has been shown to be entirely consistent to extremely high accuracy, with all experimental tests.

When Albert Einstein published his first paper on special relativity in 1905, he did not yet fully grasp its geometrical nature. He came to appreciate these aspects of the theory over the next several years while working with mathematician Hermann Minkowski (1864–1909). Minkowski developed the idea of spacetime, in which events occur in a four-dimensional "space" that includes both (the three dimensions of) space and (one more dimension of) time—hence, the name. In 1915, Einstein published a new work on a General Theory of Relativity, a new mathematical formalism to extend his Special Theory to situations in which objects were able to accelerate. It was the culmination of a decade of concentrated effort.

Since any object that is moving in a circular orbit is accelerating (since its direction is constantly changing, even if its speed remains constant), the General Theory has wide applicability to massive objects in the Universe. In particular, it can be applied to objects that appeared to violate the predictions made using Newton's simpler formalism, such as the orbital movement of the planet Mercury.

Unlike the other planets, Mercury has a slight variation in its orbit from the predictions of Newtonian gravitational theory. The orbit is not a closed ellipse as the theory predicts. It has a small amount of overshoot. This means that the entire orbit is slowly turning as the planet orbits the Sun. What we mean by this is that the point of closest approach to the Sun, called the perihelion, slowly rotates around the Sun, as does the point of greatest distance from the Sun, the aphelion (see Figure 6).

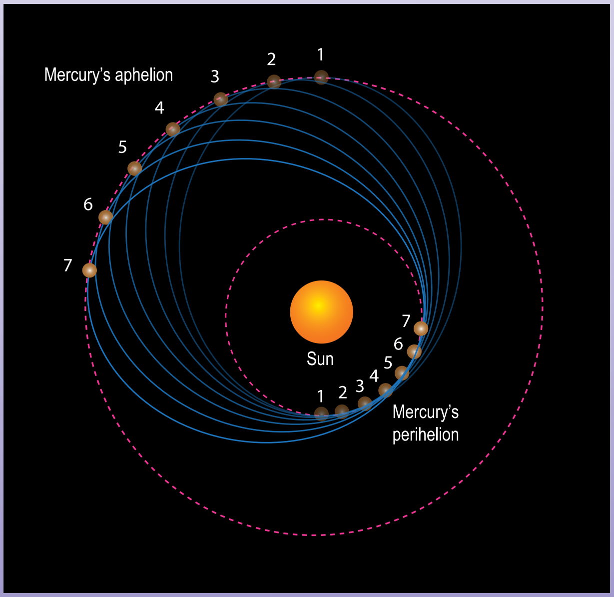


Figure 6: As Mercury orbits the Sun, its orbit slowly precesses around the Sun. This means that the position of the perihelion and aphelion slowly circle the Sun. Newtonian gravity cannot account for all of this motion, but general relativity does. The eccentricity of the orbit has been greatly exaggerated in this figure. Credit: SSU E/PO Aurore Simonnet

The amount of this orbital shift is very small, and most of it is caused by gravitational tugs exerted by the other planets, primarily Jupiter, on Mercury as it goes around the Sun. However, even when the gravitational effects of the other planets are accounted for using Newton's Law of Gravitation, Mercury still travels an extra 2.9×10^{-5} degrees of rotation (beyond 360 degrees) for each orbit. Such a small amount is too small to be seen in a single orbit, but it accumulates over time. After a century, Mercury has rotated an extra 0.012 degrees beyond the predictions of Newtonian gravity. This is still a small angle, but it is measurable.

Albert Einstein was aware of Mercury's anomalous orbit. When his new theory seemed complete enough to be applied to the orbit he did the calculation. There were no free parameters in Einstein's General Theory that could be used to adjust it to the correct value. The only relevant inputs were the mass of the Sun and the size and eccentricity of Mercury's orbit. When Einstein made the calculation, his theory predicted that Mercury should precess around the Sun at precisely the amount of the observed anomaly.

Essential to Einstein's theory is the concept that masses distort spacetime – the four dimensional mathematical coordinate system mentioned earlier. This distortion is often called *curvature,* but that is not a very descriptive term. Stretching is probably better. You can probably best understand this idea intuitively if you imagine trying to paste a flat piece of graph paper onto the surface of a globe. You will not be able to do so without tearing or crinkling the paper, causing the lines to misalign in various ways. If you instead had a sheet of rubber with lines on it like graph paper, instead of tearing you could stretch the rubber in some areas, and compress it in others. If you were careful enough you could completely cover the globe in this way without any tears. This stretching and compressing would distort the lines on the sheet, just as gravity distorts the coordinates in spacetime. In fact, gravity *is* this coordinate distortion. What it means is that, in some places a "centimeter" is shorter than a centimeter in other places where the gravitational field strength is different. It also means that a "second" in some places is a longer time interval than it is in other places – that's the time-stretching part of spacetime.

It is difficult to visualize something in four dimensions, so scientists usually use a representation called an "embedding diagram" to indicate how much an object of a certain mass would stretch two-dimensions of space, portrayed as a type of rubber sheet. In this type of visualization shown in

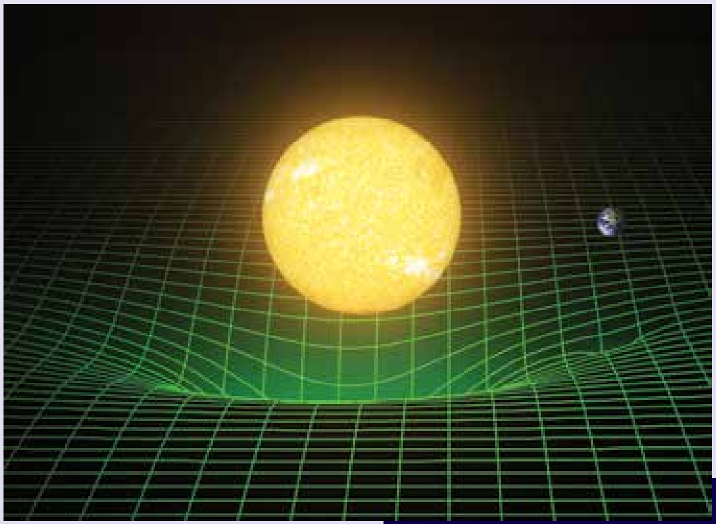


Figure 7a (above): *The Sun creates a deeper dent in spacetime fabric when compared to the Earth, a much less massive body. Credit: LIGO/T. Pyle*

Figure 7a, more massive objects create deeper indentations in the rubber sheet of spacetime. Any object moving through spacetime will encounter areas of stretching, and will follow curved paths as it travels as a result. This is true even for light rays.

It is important not to take embedding diagrams too literally. They are only aids to visualization – and misleading ones, at that. In real spacetime, our three-dimensional space need not be embedded in a higher four-dimensional one, nor does our four-dimensional spacetime have to be embedded in a fifth. The stretching and compression of spacetime does not require the existence of any higher dimension, so just as you could draw a stretched and compressed set of coordinates on a flat, two-dimensional table (think of an Aitoff world map), the stretching and compressing of spacetime occurs in a four-dimensional space, with no need for any extra dimensions. In particular, black holes are not "funnel shaped," any more than stars are. These aids are just a way to help visualize how mass affects spacetime. Figure 7b shows a better representation of spacetime curvature near a massive object, although it too is limited by the two-dimensional surface of this guide.

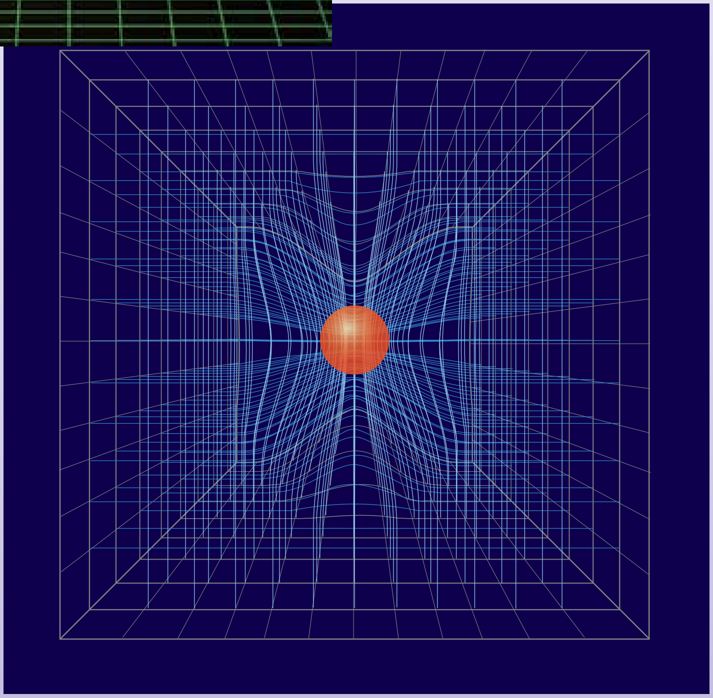


Figure 7b (right): Better representation of spacetime curvature near a massive object than the traditional funnel-shaped embedding diagram. Credit: SSU E/PO Aurore Simonnet

Gravitational Waves

To understand Einstein's prediction of gravitational waves, let's revisit Newton's Law of Gravitation, described above. There is nothing in this law that describes how the effects of gravity are transmitted from one place to another. In fact, according to this law, if we move one of the masses to a different point in space, then the other mass "knows" this instantly, and it reacts accordingly. This ability of gravity to act instantly across any distance puzzled many contemporaries of Newton. It also violates Einstein's Special Theory of Relativity, as it is not possible for any signal or information to cross space faster than light can travel.

In general relativity, gravity is not a force as envisioned by Newton. Instead, gravity is the result of spacetime being distorted, and the distortions of spacetime are caused by the distribution of mass and energy. Changing the mass-energy distribution will generally change the spacetime curvature, and thus also the gravitational effects of objects in that spacetime. However, when a mass distribution is changed, the effects of that change are not carried instantaneously to all points in space. The information is carried at the speed of light by ripples in the spacetime fabric – small stretches and compressions in the coordinates describing the spacetime. These ripples are called *gravitational waves*.

An analogy might help to understand how this works. We can imagine an observer living in a houseboat at the edge of the sea. If there is a storm far out to sea, the observer might not be aware of that fact, for instance if the storm is over the horizon. However, storms generally have strong winds that create large waves. These waves travel outward from the storm in all directions, generally at speeds of a few meters per second. Eventually the waves will reach the shore where our observer lives, and the large swells will cause the houseboat to rock back and forth. In this way the observer might become aware of the storm's existence even if the storm never approaches the shore at all— surfers are aware of this and use satellites to track storms so that they can predict when the waves at a certain beach might be good for surfing. Replace the storm in our analogy with a binary star system, and the surface of the sea with spacetime. You can see how we might be able to detect the stars, at least in principle, by measuring the rippling waves of spacetime caused by the stars' motion.

These gravitational waves carry energy, of course, and since the waves are being produced by the movement of stars in space, the star system must be losing some of its energy to the waves, thereby affecting the binary orbit. So if binary stars create gravitational waves, then they must slowly spiral in toward each other as the waves carry the system's energy away.

Einstein's theory predicts an exact relation between the size of the orbit and the rate at which it should shrink as the waves are emitted. However, in order for these effects to be observed, scientists needed to discover a binary system in which two massive objects are orbiting very close to one another, and figure out a way to measure the orbital changes precisely.

Such a system was discovered in the early 1970s by two scientists working at the Arecibo radio telescope in Puerto Rico, then the most sensitive radio telescope in the world. One of the researchers, a graduate student named Russell Hulse, was at Arecibo to find pulsars. These are rapidly rotating, highly magnetic neutron stars with masses about 1.4 times that of our Sun. They show pulses of emission as they spin that are analogous to those from a light house as its beam rotates. Pulsars generally have very stable pulse separations and at the time, they constituted the most accurate "clocks" known. However, one of the pulsars discovered by Hulse, called PSR 1913+16, showed a periodic variation in its pulse separation. Pulses would arrive slightly early on successive pulses, then switch and arrive slightly late, repeating the variation pattern roughly every eight hours.

Upon discussing this pulsar with his advisor, Joseph Taylor, it became clear that what they were observing was a pulsar in orbit around another star. However, given the orbital period of only eight hours, the companion had to be extremely small— and dim, since no companion was visible. Further careful observations suggested that the companion itself was also a neutron star, though not one that emitted pulses; it was not a pulsar.

By timing the pulses from the so-called Hulse-Taylor pulsar system over many years, the scientists were able to show that the system's orbital period is slowly decreasing, and the two neutron stars are gradually spiraling into one another. The rate of energy loss implied by the inspiraling can be compared to that predicted from general relativistic gravitational radiation. The two match very closely, within the uncertainties associated with the various measured properties for the system, as seen in Figure 8.

While not a direct detection of gravitational waves, the orbital decay of PSR 1913+16 is convincing evidence that such waves exist in the form that general relativity predicts for them. Hulse and Taylor received the 1993 Nobel Prize in physics for their discovery of this binary pulsar system. Since their original discovery, other systems have been found that exhibit similar orbital decay, all indirectly suggesting the existence of gravitational waves.

In practice it is extremely difficult to directly detect the presence of gravitational waves because the stretching and compressing of spacetime is minuscule. It tends to be swamped by local non-gravitational effects which have nothing to do with distant orbiting stars.

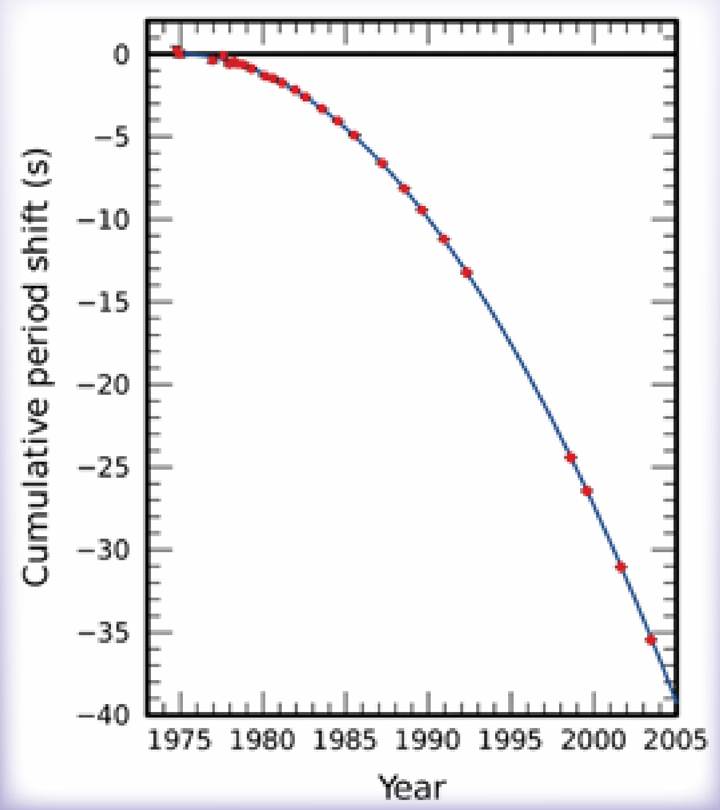


Figure 8: This figure shows almost 30 years of data illustrating the changing size of the orbit of the Hulse-Taylor binary pulsar. The shrinking orbit leads to a change in the orbital period that is measured each year. The measured points (red squares) are plotted along with the theoretical prediction (blue line). Credit: J. M. Weisberg and J. H. Taylor, ASP Proceedings, 2005.

The Direct Observation of Gravitational Waves by LIGO

Like electromagnetic waves, gravitational waves are transverse waves that travel at the speed of light. Einstein's General Theory of Relativity allows us to predict the strength and frequency of these waves, just as Maxwell's equations can be used to predict the strength and frequency of electromagnetic waves emitted from various types of objects and processes. However, electromagnetism is a much stronger force than gravity and it is easy to detect a wide spectrum of electromagnetic waves from common sources. Earthbound gravitational wave detectors such as LIGO consist of suspended and widely-separated "test masses" (mirrors). The spacings between these test masses will change when gravitational waves pass by a detector. But the change will be tiny! Scientists expect that extraordinarily violent astrophysical events will produce gravitational waves which, when they pass through a detector, will alter the spacings between the test masses by no more than 10^{-19} meter.

LIGO (Laser Interferometer Gravitational-wave Observatory) is the world's largest gravitational wave observatory. LIGO consists of two laser interferometers located thousands of kilometers apart, one in Livingston, Louisiana and the other in Hanford, Washington. LIGO uses the physical properties of light and of space itself to detect gravitational waves. It was funded by the US National Science Foundation, and it is managed by Caltech and MIT. Hundreds of scientists in the LIGO Scientific Collaboration, in many countries, contribute to the astrophysical and instrument science of LIGO. There are also other gravitational wave observatories in the world, including Virgo in Italy and GEO 600 in Germany.

Figure 9 LIGO Hanford and LIGO Livingston.
Credit: Caltech/MIT/LIGO

LIGO consists of two perpendicular, 4-km "arms" as depicted in Figure 10. A laser beam is fired into a beam splitter that sends half the light down one of these arms, and half down the other. The mirrors then reflect the light back the way it came, and the beam splitter combines the two beams back into one, sending the combined beam to a detector. LIGO carefully tunes the lengths of the detector arms so that the light from the arms almost completely cancels out, or undergoes destructive interference, when the reflected beams recombine back at the beam splitter. However, if the arm lengths change slightly due to a passing gravitational wave, then the differences in length will introduce a small difference in phase between the beam from different arms. The waves that would have cancelled each other at the beam splitter will now travel different path lengths and end up producing some light at the detector.

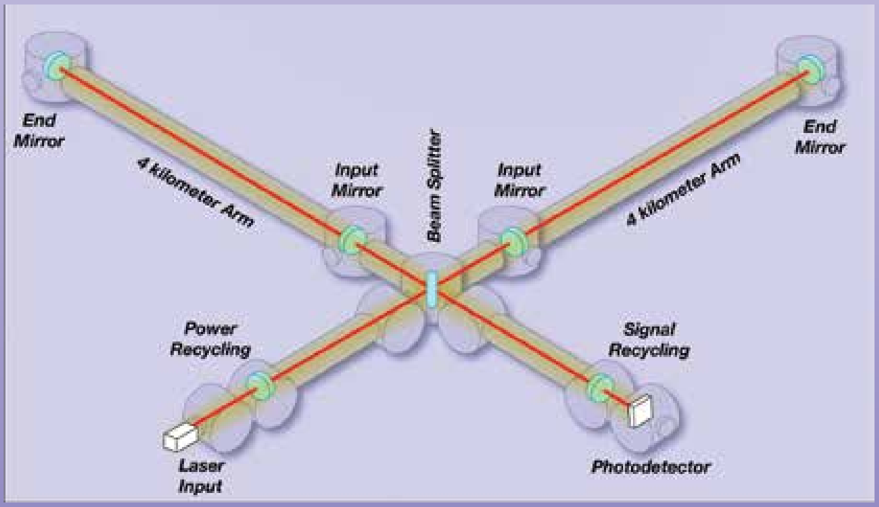
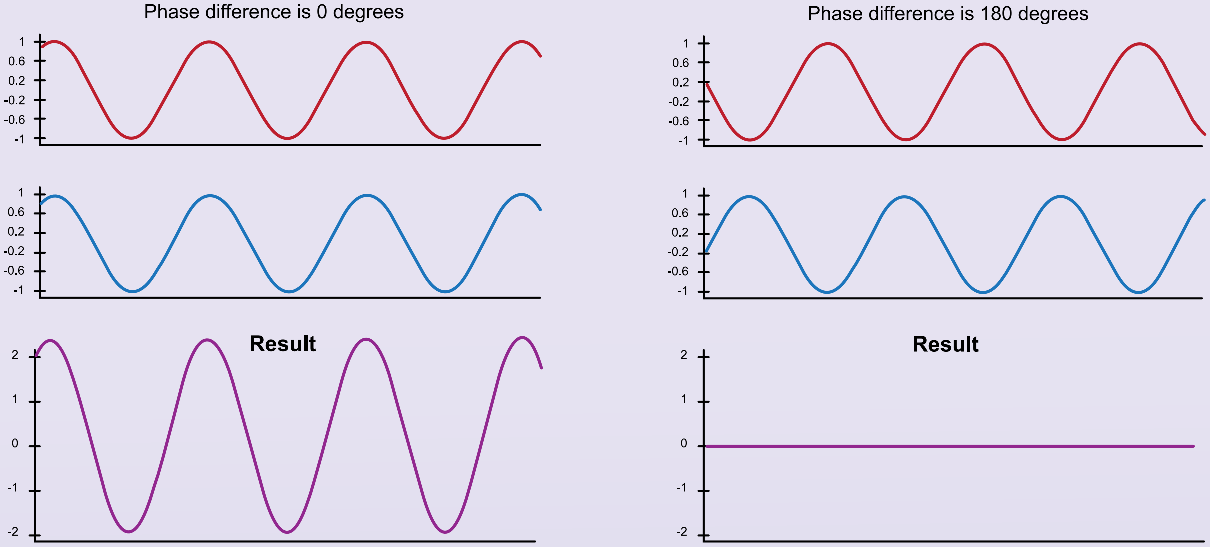


Figure 10: Basic design of the LIGO interferometers. Credit: LIGO/Shane Larson

It is this interference property of light that is exploited by LIGO to detect gravitational waves. When a gravitational wave passes by, the stretching and compressing of space causes the arms of the interferometer alternately to lengthen and shorten, one getting longer while the other gets shorter, and then vice-versa. As the interferometers' arms change lengths, the laser beams traveling through the arms travel different distances resulting in a change in the "interference" between the waves. The change in length of an arm divided by the length of that arm is the parameter called the "strain" (or *h*, see Figure 3).



Figures 11a and 11b: Illustration of the interference pattern produced by two waves that are a) in phase and b) 180 degrees out of phase. Credit: SSU E/PO Aurore Simonnet

LIGO scientists search the data to find the pattern of arm length changes predicted by general relativity to come from different types of gravitational wave sources. As a binary system coalesces (or "inspirals"), the frequency of the emitted gravitational waves will increase until the two objects merge – after this cataclysmic event, the system will "ring down" for a while. Scientists calculate the exact waveforms predicted for systems with different mass objects and then compare these predicted curves to the data to determine the masses of the objects (and the type of objects) that have merged. Figure 12 shows the data received by the two LIGO interferometers at Livingston and Hanford on September 14, 2015, together with the best fit gravitational waveforms – a binary system with two black holes, each approximately 30 – 35 times that of our Sun, located at a distance that is at least 1 billion light years!

The top two plots in Figure 12 show data received at Livingston and Hanford, along with the best-fit shapes for the waveforms for each (smoother curves). These best-fit waveforms represent models of the gravitational wave signals from a black hole coalescence, based on the equations from Albert Einstein's theory of general relativity. Time is plotted on the X-axis and strain (*h*) on the Y-axis. Strain represents the miniscule fractional amount by which distances are distorted.

As the plots reveal, the LIGO data very closely match Einstein's predictions. Furthermore, the best-fit models to the data were separately determined for each observatory, and returned the same results!

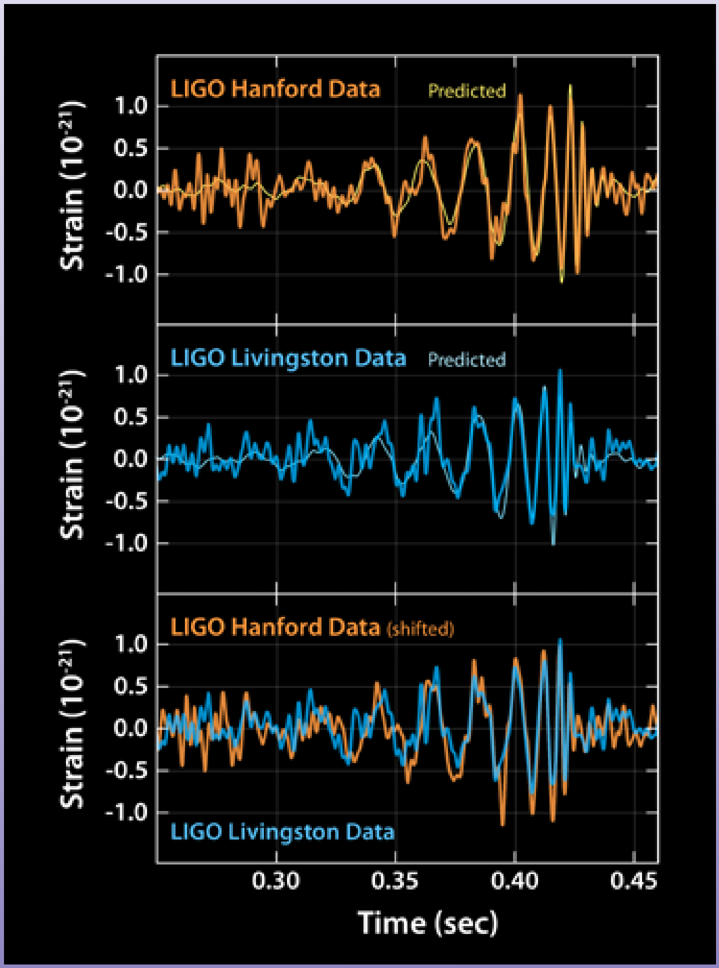


Figure 12: Data and Best-fit Models for LIGO's Direct Detection of Gravitational Waves. Credit: LIGO

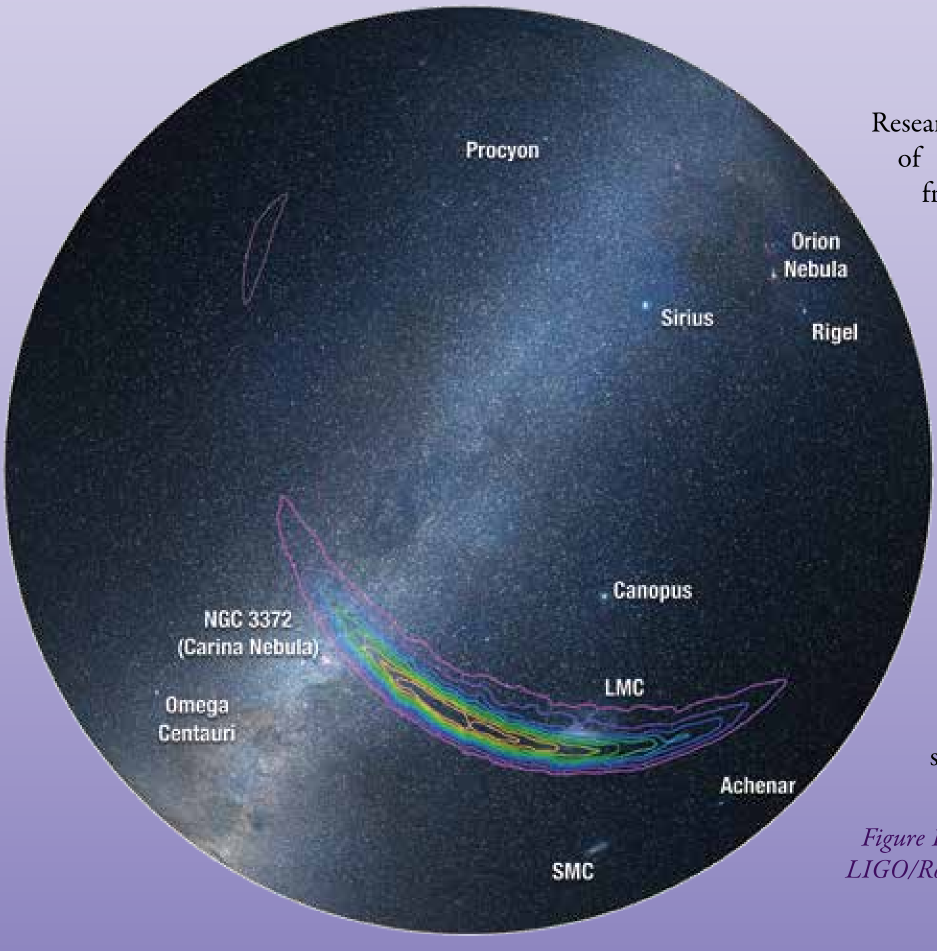
The final bottom plot in Figure 12 compares the data from both detectors. The Hanford data have been inverted for comparison, due to the differences in orientation of the detectors at the two sites. The data were also shifted in time to correct for the travel time of the gravitational wave signals between Livingston and Hanford. (The Livingston waveform was observed 7 milliseconds before Hanford's.) This demonstrates that both detectors witnessed the same event, confirming the detection.

Table 1 gives some of the important parameters measured by LIGO for this discovery event, dubbed GW150914 after the date on which it was observed.

The approximate location of the source of gravitational waves detected on Sept. 14, 2015 by the twin LIGO observatories is shown in Figure 13, overlaid on a visible-light sky map of the southern hemisphere. The colored lines represent different probabilities for where the signal originated: the purple line defines the region from within which the signal was emitted, at 90% confidence. The inner yellow line defines the 10% confidence region.

Table 1 – Important Parameters for GW150914

Time detected	September 14, 2015 09:50:45 UTC	
Mass (in units of Solar Mass)	Black Hole 1	36^{+5}_{-4}
	Black Hole 2	29 ± 4
	Final Mass	62 ± 4
GW Energy	3.0 ± 0.5 $M_{\odot}c^2$	
Distance	410^{+160}_{-180} Mpc ~1.34 × 10^9 light years	
Redshift	$0.09^{+0.03}_{-0.04}$	
Observing band	35-350 Hz	
Peak strain *h*	1.0 × 10^{-21}	



Researchers were able to narrow in on the location of the gravitational wave source using data from the LIGO observatories in Livingston, Louisiana, and Hanford, Washington. The gravitational waves arrived at Livingston 7 milliseconds before arriving at Hanford. This time delay revealed a particular slice of sky, or ring, where the signal must have come from. Further analysis of the varying signal strength at both detectors ruled out portions of the ring, leaving the remaining patch shown on this map.

In the future, when the Advanced Virgo gravitational wave detector in Italy is up and running, and later the KAGRA detector in Japan, scientists will be able to even better pinpoint the locations and sources of signals.

Figure 13: Approximate location of LIGO signals. Credit: LIGO/Roy Williams, Shane Larson and Thomas Boch

Black Holes

Most people think of a black hole as a voracious whirlpool in space, sucking down everything around it. But that's not really true. A black hole is a place in space where gravity is so strong that matter or energy could only escape from it by traveling faster than the speed of light, which isn't possible according to the laws of physics. If you take an object and squeeze it down in size, or take an object and pile mass onto it, its gravity (and escape velocity) will go up. At some point, if you keep doing that, you'll have an object with so much gravity that the escape velocity can exceed the speed of light. Since that's the ultimate speed limit of the Universe, anything venturing too close would get trapped forever. The distance from the black hole at which no light can escape is called its event horizon. A black hole with the mass of our Sun has an event horizon that has a radius of only 3 km. In other words, you would have to compress all the mass in our Sun down to fit within a sphere that has a 3 km radius in order to turn it into a black hole! Compressing an object to such an extent causes it to collapse since no known force can support it against its own weight at that point. Its matter is squeezed out of existence, converted to pure energy of the gravitational field. Scientists think that all that remains of such an object is a highly warped region of spacetime from which nothing can escape – a black hole.

Figure 14: Voracious black hole at the center of a galaxy, having a gourmet meal. Credit: SSU E/PO Aurore Simonnet

One way for a black hole to form is in a supernova, an exploding star. When a star with more than about 25 times the mass of the Sun ends its life, it explodes. The outer part of the star is flung outward at high speed, but the inner part of the star, its core, collapses. If there is enough mass, the gravity of the collapsing core will compress it so much that it can become a black hole. In the case of GW150914, there must have originally been two very massive stars relatively close together. They aged at approximately the same rate, and their resulting supernova explosions did not disrupt the binary system. This would happen if most of the mass of the system was captured into the collapsing cores rather than expelled from the system by the explosion. The cores that collapsed into black holes each had masses approximately 30 - 35 times that of our Sun. Until LIGO's discovery of GW150914, scientists had never before observed two black holes merging.

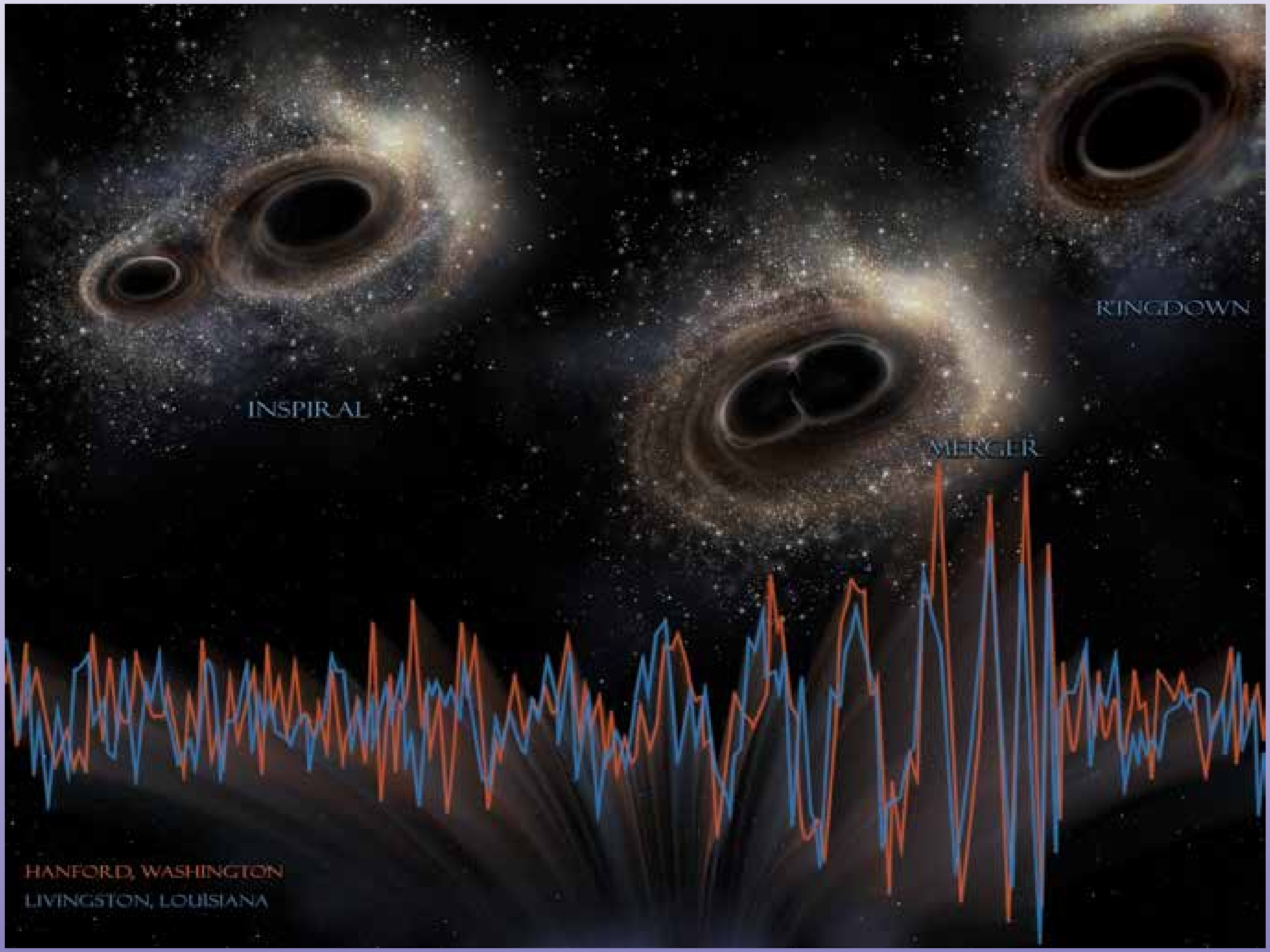


Figure 15: Artist's depiction of the merger process of two black holes, accompanied by the actual waveforms detected by LIGO Hanford and Livingston detectors. Credit: SSU E/PO Aurore Simonnet

Activities

Activity 1 – Coalescing Black Holes

Duration:
30 mins

Essential Question:

What happens when two black holes spiral in towards each other?

Objectives

Students will observe that the orbital frequency increases as the orbital separation between the two objects decreases.

Science Concepts:

Gravitational waves are ripples in spacetime produced by some of the most violent events in the cosmos, such as the collisions and mergers of massive compact stars or black holes. These ripples travel at the speed of light through the Universe, carrying with them information about their origins.

When two compact objects orbit each other, they radiate gravitational waves. This carries away energy thereby decreasing the orbital distance and increasing the orbital speed. The resulting waveform is known as a chirp because the frequency of the wave and the amplitude of the wave are both increasing. By scaling this wave to frequencies in the audio range, you can hear this chirp.

The demonstration presented here models the late stages of binary inspiral with the same properties as a chirping gravitational wave source such as GW150914.

Figure 1. presents key results of the analysis of GW150914. The middle part of the figure shows the reconstruction of the gravitational-wave strain pattern, as seen by the Hanford detector.

Note, in particular, the impressive agreement between this pattern (shown in grey) and (shown in red) the best-matching computed waveform, for two coalescing black holes, as predicted by general relativity.

A cartoon representing all three stages of the event is showing at the top of the figure: the inspiral, as the two black holes approach each other; the merger as the black holes join together and the subsequent ringdown, as the single black hole that has newly formed briefly oscillates before settling down.

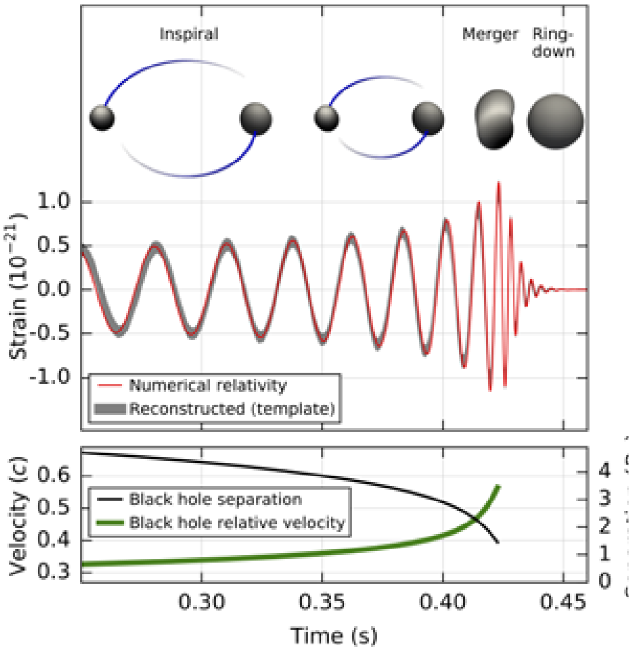


Figure 1: GW150914 models. Credit: LIGO

Materials

For each classroom, to use as a demonstration

- String – medium weight monofilament fishing line works best, but any smooth string should suffice.
- Weight – A brass bushing, stack of washers, or stack of nuts
- 2 Balls – Two tennis balls may be the easiest to see in a large classroom. Wiffle balls, golf balls, or mounds of clay will also work

Optional

- Black modeling clay or paint
- 2 Piezoelectric buzzers – 12 mm works best
- 2 Button cell batteries – LR44 1.5V batteries fit between the leads of the 12 mm buzzers
- Push button recordable sound module or sound box
- Computer with speakers

Getting Started

This demo is best done with an open area in which to hang the string. You can hang this from the top of a doorway, from a hook in the ceiling, or from a simple stand.

1. Cut a 1-2 meter piece of string
2. Attach two balls to each end of the string. If using tennis balls, use a razor or knife to cut a 2-4 cm notch in the ball. Squeeze the ball to open the notch and push in the knotted end of the string.
3. Grab the string in the center and thread it through the weight
4. Tie a small loop in the string at its center point. Hang the loop on the hook. The tennis balls now should now hang side-by-side at the same height. The weight will rest at the bottom of the string just above the tennis balls.
5. Hang the demo in an open space

Optional

6. Cover the balls with black modeling clay or paint to simulate black holes
7. Stick two piezoelectric buzzers inside hollow balls to simulate the inspiral and ringdown sounds (note: you are actually hearing the Doppler effect for each ball, but the beats will speed up as the balls spiral inward)
8. Use a push button recordable sound module or sound box to record the GW150914 sound at *http://losc.ligo.org//events/GW150914/*
   The event is very fast. You can use audio software to slow it down.
9. Use a computer with speakers to play the videos at the following website: *http://mediaassets.caltech.edu/gwave*

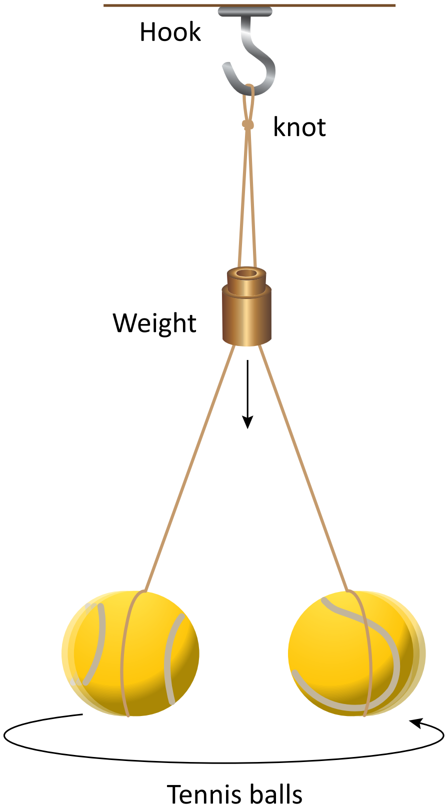


Figure 2: Demo set up.
Credit: SSU E/PO Aurore Simonnet

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Procedure:

1. Pull the two balls apart forcing the weight up to the top of the string.
2. Carefully, throw the two balls so that they orbit in the same direction (both clockwise or both counterclockwise) with the same speed. This may take some practice to get right.

As the mass slowly falls and the string winds up, the orbit will contract and the two balls will speed up. The balls will eventually "merge" or come together. This mimics the chirp of the gravitational wave signal.

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Questions

1. What do the two balls represent?
2. The mass sliding down the string removes energy from the system. What is this analogous to in the binary black hole system?

Answers

1. Each ball represents one of the black holes
2. The mass is absorbing the energy from this simple orbital system. With the merging black holes responsible for GW150914, gravitational waves are carrying away this energy.

Activity 2 – The Warping of Spacetime

Duration: 30 mins

Essential Question:

How do binary black holes warp spacetime?

Objectives

Students will observe ripples in fabric representing spacetime as massive objects orbit and merge.

Science Concepts:

This demonstration allows for a visual depiction of the effect of orbiting masses on a two-dimensional representation of the fabric of spacetime. Newton saw objects with increasing mass as having an increasing escape velocity while Einstein saw them as making deeper "dents" in the fabric of spacetime. A black hole makes such a deep "dent" that it forms a bottomless well. The sides of the well are so steep that even light cannot escape once it has fallen past the event horizon. Stars and even other black holes can orbit safely well outside of this event horizon. When two black holes are orbiting near enough to each other, The gravitational waves carry energy away from the system, eventually causing the black holes to merge into a single, more massive black hole. While we won't see these waves in our simple two-dimensional model, we will see the large dents created by the two massive weights.

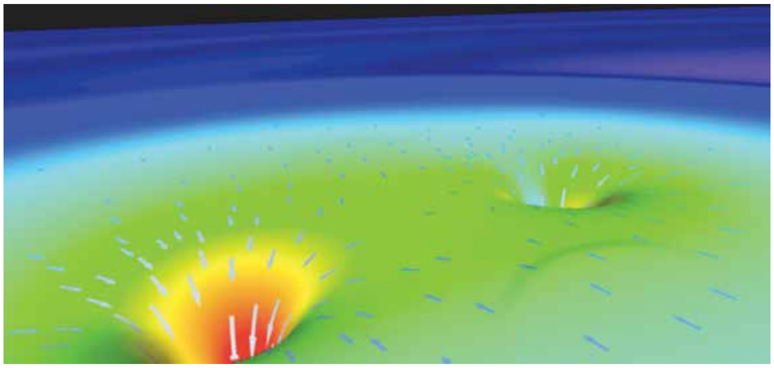


Figure 1: Computer simulation of the warping of space and time around two colliding black holes observed by LIGO on September 14, 2015. Near the black holes, the colors depict the rate at which time flows. In the green regions outside the holes, time flows at its normal rate. In the yellow regions, it is slowed by 20 or 30 percent. In the red regions, time is hugely slowed. Far from the holes, the blue and purple bands depict outgoing gravitational waves, produced by the black holes' orbital movement and collision. Credit: SXS.

Materials

For each group of 4 or 5 students or to use as a classroom demonstration:

- 1 embroidery hoop ~23 ½ inch (60 cm) diameter
- Spandex fabric ~1 yard (91 cm x 91 cm)
- 2 chrome ball bearings 2 inch (5 cm) diameter
- 2 bouncy balls

Procedure:

This demonstration starts out with a description of gravity as a geometric property of spacetime. It will end with a demonstration of two "black hole" objects orbiting each other and inspiraling.

AVOID MISCONCEPTIONS: This demonstration is only a 2-dimensional representation of the real thing. To avoid misconceptions make sure you ask your students questions like: What is on the "other side" of the black hole in 3-dimensions? Space acts the same in all 3 dimensions. There is no front and back to a black hole. It is a spherical "dent" in spacetime.

Getting Started:

Stretch the fabric through the embroidery hoop and pull taut and flat. This may take 2 or 3 people. You want the printed side of the fabric to face upward while the rim is pointed up like a bowl.

Figure 2: Spacetime fabric setup

Part 1: Single black hole or other massive object

1. Start by explaining that the intense gravity around large massive objects dramatically bends the fabric of spacetime. This is why things “fall” into black holes and gravitate towards the large objects, just like the Earth and the planets “stick” around the Sun in their orbits.
2. Use at least three students to hold onto the spacetime hoop, such that it is horizontal and the rim of the hoop is facing up like a bowl (so the balls don’t fall out when they are placed on the fabric). Ask the students to imagine that they are holding a chunk of spacetime. Note that it is very flat and smooth without the presence of any massive objects.

Figure 3: Single Black Hole

3. Carefully set one chrome sphere into the center of the hoop. Ask the students what this represents. (They should say a black hole or at least a star.)
4. Now hold up two bouncy balls and ask them what they think those should represent. (They should say stars.) If their first answer isn’t “stars,” ask them if they can think of anything in space that would orbit around a black hole. Keep asking them questions that lead them to the answer of stars. (Note: if they say planets, that is not entirely incorrect, but all the planets that have been observed orbit around stars, and none have yet been observed to reside in galaxies near black holes.)
5. Now let one or two other students attempt to get the stars to orbit the black hole. Have the group record what they see happening to the spacetime fabric and the stars. Make sure to have them include what the black hole and stars are doing.
6. Once they have recorded their observations, start discussing how this bending of space-time happens with all massive objects, even us! Have them look at how the little bouncy balls actually make a small indentation in the fabric. This is just how less-massive objects bend spacetime.
7. Now tell them that instead of a black hole imagine now that the weight is the Sun. Now ask them what the bouncy balls represent. (They should say planets). Just like a black hole or any massive object, the Sun keeps the planets gravitationally bound to it.
8. Once you have explained the above content let the students play a few minutes more with the hoops. One fun challenge is to see which student can get his or her star to orbit around the black hole for the greatest number of revolutions before it falls in.

Part 2: Merging Black Holes

1. Remove the bouncy balls and bring out the second chrome weight. Begin by asking what would happen if you place each sphere on the edge of the fabric. Since they have no initial velocity and they are both creating large dents, they will quickly roll towards each other.
2. Ask the students what it would take to get the two weights to orbit around each other. Allow for a few moments of testing with both weights. The students should eventually find that the two balls need an initial kick or push to get them in orbit. In fact any orbit requires an object to have an initial perpendicular velocity.
3. You can confirm this by placing the “black hole” in the center of the fabric and trying to roll one of the bouncy balls on a line perpendicular to the direction to the central object. The path will curve naturally, leading to an orbit.
4. Now focus on the sound it makes when the balls inspiral and finally merge. Ask the students what they think is causing the sound. It is actually the two balls ringing against each other. First you will have a loud clang followed by a slowly decaying ring. This is a sound wave that crudely resembles the gravitational waves emitted during the merger and ring down phases of GW150914.

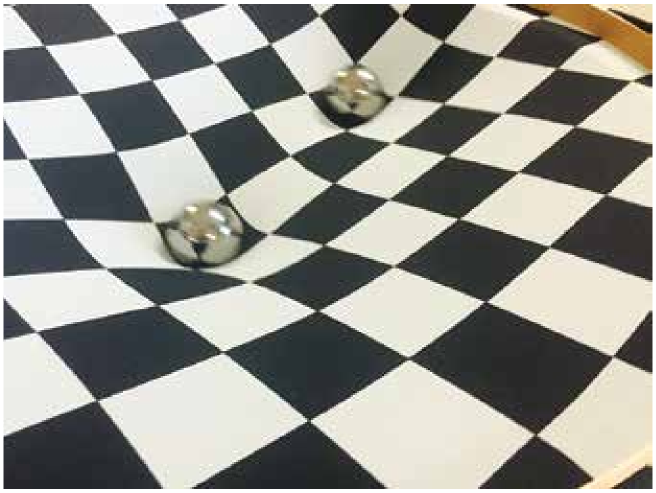


Figure 4: Merging Black Holes

What other phenomena can you model?

Next Generation Science Standards

Science and Engineering Practices	**Disciplinary Core Ideas**	**Crosscutting Concepts**
Developing and Using Models Modeling in 9–12 builds on K–8 experiences and progresses to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed world(s). • Develop a model based on evidence to illustrate the relationships between systems or between components of a system. (HS-ESS21),(HS-ESS2-3),(HS-ESS2-6) • Use a model to provide mechanistic accounts of phenomena. (HS-ESS2-4)	**ESS1.A - The Universe and Its Stars**	**Cause and Effect** Mechanism and explanation. Events have causes, sometimes simple, sometimes multifaceted. A major activity of science is investigating and explaining causal relationships and the mechanisms by which they are mediated. Such mechanisms can then be tested across given contexts and used to predict and explain events in new contexts.
	PS2.B - Types of Interactions	**Systems and System Modeling** Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering.
	PS3.A - Definitions of Energy	**Energy and matter** Flows, cycles, and conservation. Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations.
	PS3.B - Conservation of Energy and Energy Transfer	
	PS3.C - Relationship Between Energy and Forces	
	PS4.A - Wave Properties	

Appendix A - Glossary

B

Binary system: A system in which two nearby objects orbit around their common center of mass

Black Hole: A region of spacetime having a gravitational field so intense that no matter or radiation can escape from within the event horizon

E

Electromagnetic radiation: A type of energy radiation which includes visible light, infrared light, ultra-violet light, radio waves, gamma rays, and x-rays. Electromagnetic waves are produced whenever charged particles are accelerated

Electromagnetic spectrum: the range of wavelengths or frequencies over which electromagnetic (i.e., light) radiation

G

General Theory of Relativity: A description of gravity as a geometric property of space and time (spacetime) where the curvature of spacetime is directly related to the mass or energy of matter

Gravitational constant: G, the proportionality constant in Newton's law of Gravitation. $G= 6.67 \times 10^{-11}\ \mathrm{N\ m^2\ kg^{-2}}$

Gravitational waves: Ripples in the curvature of spacetime, which propagate as waves travelling outward from accelerating masses

Gravity: An attractive force between any two objects that depends on their mass and separation (in Newtonian formalism)

I

Inspirals: Objects in a binary system that are losing energy due to the emission of gravitational waves. As the gravitational waves carry energy away from the binary system, the orbit decays, and the objects eventually merge.

Interferometer: A device that works by splitting a light beam into two separate beams that travel different light paths along two arms. Mirrors at the end of the arms reflect the beams back to the beam splitter, where they interfere upon being recombined. The interference pattern, typically a set of alternating bright and dark stripes, called fringes, displays subtle differences between the length of the two arms

L

Law of Gravitation (Newtonian): Any two bodies in the universe attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. $F = Gm_1m_2/r^2$

LIGO: An acronym for the Laser Interferometer Gravitational-wave Observatory

N

Neutron Star: A type of compact star that is the densest and smallest star known to exist. Rather than being made of atoms with nuclei and electrons, these stars are composed almost entirely of neutrons or other more exotic subatomic particles.

P

Pulsars: A spinning neutron star that emits a beam of radiation. As the beam repeatedly sweeps pass a detector on Earth, we view it as pulses of radiation.

S

Spacetime: A 4-dimensional coordinate system with three dimensions of space and one dimension of time that are used to locate objects and/or events.

Special Relativity: A description of spacetime in the special case of reference frames moving at constant speeds relative to one another and based on two postulates: 1) the laws of physics are identical in all inertial reference frames; and 2) the speed of light in a vacuum is the same for all observers.

Strain (*h*): A measure of how much a gravitational wave distorts spacetime and equal to the change in distance between two objects divided by the original distance $h = \Delta L/L$. Gravitational wave strains are extremely small when emitted from cosmic objects and detected at Earth. At the present time, LIGO can detect a deviation of 1 part in $5\text{x}10^{22}$. The peak gravitational wave strain detected from GW150914 is 1×10^{-21} which corresponds to changing the radius of Earth's orbit around the Sun by the diameter of a single atom.

Appendix B - Resources

LIGO Scientific Collaboration
http://ligo.org/
News, science goals, multimedia, and more

LIGO Laboratory at Caltech
https://ligo.caltech.edu/

LIGO Laboratory at MIT
http://space.mit.edu/LIGO/

Visit LIGO
http://www.ligo.org/students_teachers_public/visit.php
The LIGO Observatories in Hanford, WA and Livingston, LA invite you to visit our facilities. Each site has programs for students, teachers, and the public.

Virtual LIGO Tour – Livingston, LA
http://www.net3.hu/ligo/

Simulating Extreme Spacetimes (SXS) project (animated videos and more)
http://www.black-holes.org

LIGO Open Science Center GW150914 Event page (sound files)
https://losc.ligo.org/s/events/GW150914/audio/

Caltech Media Assets page for GW150914 press release and briefing
http://mediaassets.caltech.edu/gwave

Games and apps to explore black holes and gravitational waves
https://www.laserlabs.org/
http://www.blackholehunter.org

***Direct Observation of Gravitational Waves from a Binary Black Hole Merger* - Physical Review Letters publication**
http://link.aps.org/doi/10.1103/PhysRevLett.116.061102

Resources for Teachers
http://www.ligo.org/teachers.php

Additional Gravitational Wave Classroom Activities
www.einsteinsmessengers.org/activities.htm

Resources for Students
http://www.ligo.org/students.php

Submit your own LIGO question
https://ligo.caltech.edu/page/ask-ligo

Recommended reading and multimedia
https://ligo.caltech.edu/page/recommended-reading

Next Generation Science Standards
http://www.nextgenscience.org

Follow us on
Twitter: @LIGO
and
Facebook:
https://www.facebook.com/LigoScientificCollaboration/

Appendix C - Purchasing Information

Activity 1 Coalescing Black Holes

Monofilament fishing line
http://amzn.com/B000FT09CU

Bushing
http://amzn.com/B005ZCR5EC

Tennis balls
http://amzn.com/B0000BYRT0

Optional items:

Black Crayola Model Magic
http://amzn.com/B000F8QVVO

12 mm buzzers
http://amzn.com/B00B0Q4KKO

LR 44 button batteries
http://amzn.com/B00IHICPV4

Push button recordable sound module
http://amzn.com/B006NFHLLW

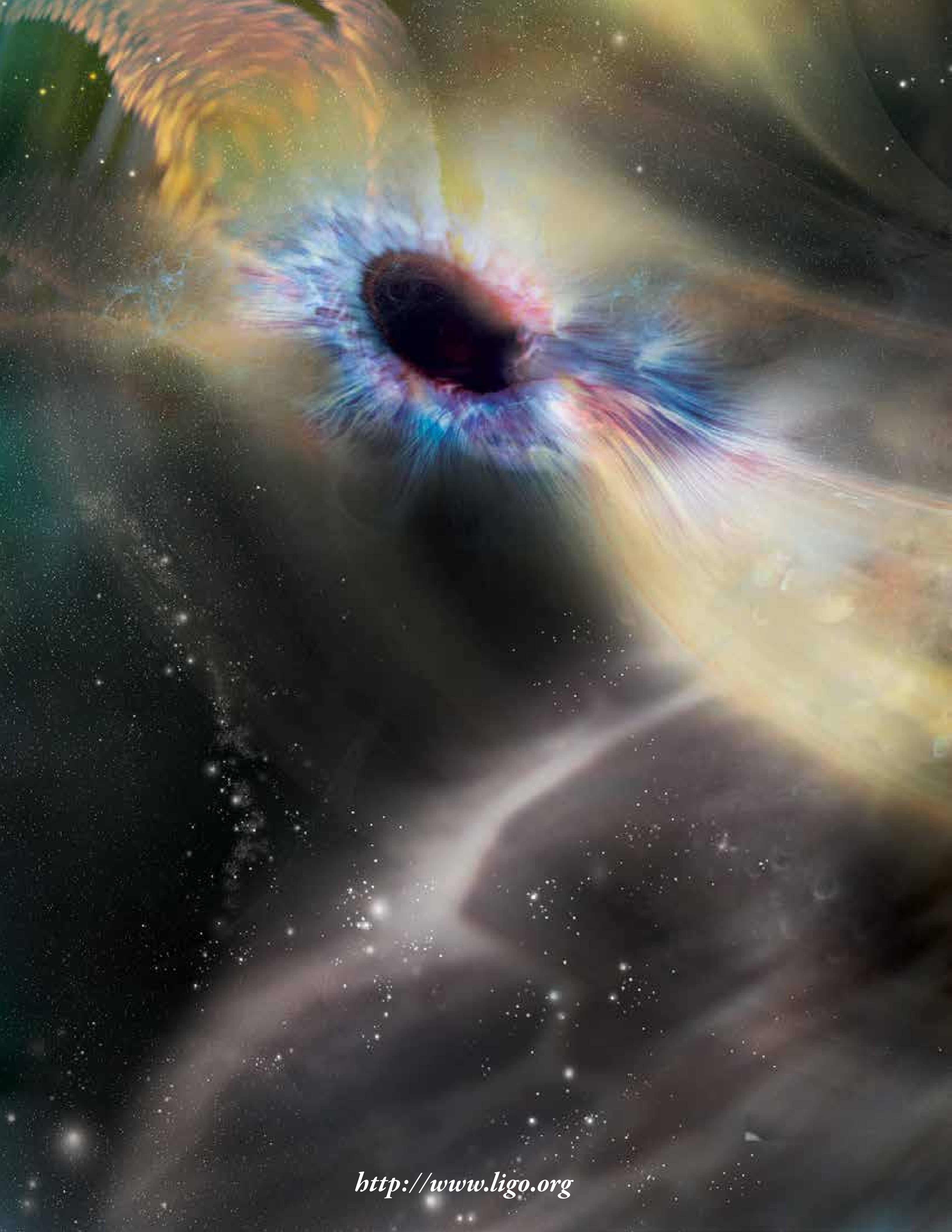
Activity 2 The Warping of Spacetime

Darice Quilting Hoops, 23 inch
http://amzn.com/B000B836GG

Two 2” chrome steel bearing balls
http://amzn.com/B007B2A3VQ

Checkerboard print spandex fabric
http://amzn.com/B00O72ZEQ2 or http://spandexworld.com/c3/catalog/product/9806

100 bouncy balls
http://amzn.com/B010LD0QTA



http://www.ligo.org