AstroTalk: Behind the news headlines of March 2018

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Standard sirens: listening to gravitational waves

Recent detections of Einstein's gravitational waves have caused great excitement among astronomers and the public alike. Beyond the hype and excitement, however, gravitational-wave sources have tremendous potential to once and for all tightly constrain the three-dimensional structure and geometry of the Universe on the largest scales. Within the next few decades, the current era of precision cosmology is therefore poised to smoothly transition to a new era of gravitational-wave astrophysics.

Einstein was right. Perhaps unsurprisingly, he was also far ahead of his time. His ground-breaking insights, meticulously pursued just after the turn of the twentieth century, implied that physical mergers of some of the most massive objects in the Universe could cause ripples in space and time. Think of the final gasps of coalescing massive black holes or dense neutron stars—the small cores resulting from the violent stellar death throes of stars which were originally at least eight to ten times as massive as our own Sun. Yet, observational confirmation of shocking Einstein's ideas took the better part of a century. Many years of preparation by a large international team of scientists, engineers, and students pushing the boundaries of their technological capabilities finally paid off in just the last few years. In February 2016, LIGO—the Laser Interferometry Gravitational-wave Observatory—declared Einstein's General Theory of Relativity an uncontested cornerstone of modern physics.

General relativity describes the familiar force of gravity as a geometric property of space and time, which combine into a four-dimensional stretchable fabric Einstein coined 'spacetime'. It includes—but goes well beyond—Isaac Newton's famous law of universal gravitation from 1687. Newton's breakthrough, popularized by the familiar story about a falling apple, was initially reported by his friend and biographer William Stukeley in 1752. Stukeley recalled a meeting in the shade of some apple trees in Newton's garden, when the scientist contemplated the effects of gravity on Earth:

> "*After dinner, the weather being warm, we went into the garden and drank thea, under the shade of some apple trees… he told me, he was just in the same situation, as when formerly, the notion of gravitation came into his mind. It was occasion'd by the fall of an apple, as he sat in contemplative mood. Why should that apple always descend perpendicularly to the ground, thought he to himself…*"

Monopoles, dipoles, and quadrupoles

Einstein's phenomenal brainpower built on Newton's ideas, producing a highly complex theory that allowed him to precisely predict the rate at which radiation resulting from mergers of massive objects is released. You might wonder how near-immutable quantities like stellar or black-hole masses can produce radiation. Einstein based his predictions on a concept scientists call the 'mass quadrupole moment'. This quantity can be computed by multiplying the total amount of matter locked into a double-star system composed of two black holes or two neutron stars that are bound together by gravity—and which, hence, orbit each other—with the square of the binary system's extent in space.

Monopoles, dipoles, and quadrupoles are mathematical tools that describe possible patterns in which, for example, electric charge or matter may be distributed in space: see Figure 1. The mass *quadrupole* quantifies how close our binary system represents a purely spherical geometry. A sphere has zero quadrupole, while a rod or a flat disk both have sizeable quadrupole values. After all, rods and disks are balls that have been stretched or squashed along a preferred direction, so they are no longer round.

A system's mass *monopole*—its combined mass (m) and energy (E), which Einstein showed to be equivalent through his famous equation $E = mc^2$, where c is the speed of light—does not change with time. Neither does its center of mass, its mass *dipole*. However, its *quadrupole* may actually be time variable. This can be understood easily by considering two balls attached by a spring. By stretching them apart and then allowing them to oscillate, their quadrupole will cycle through smaller and larger values. On astronomical scales, time-variable mass quadrupoles may result in radiation in the form of 'gravitational waves', the ripples in spacetime Einstein predicted in 1915.

We can understand this by thinking of electromagnetic radiation analogies—the type of radiation produced by the properties of electricity and magnetism with which we are familiar in everyday life. A single, non-moving electric charge (an electric monopole) cannot radiate. This would violate the fundamental law of nature that states that the total amount of charge in a system is always conserved; radiation would cause charge to leak from the system. However, an oscillating charge will produce radiation in the form of a 'dipole radiation field', shown in Figure 1. Dipole radiation is usually the strongest energy source, but to produce radiation requires acceleration—that is, a change in the velocity—of a system's center of charge relative to its center of mass. This can be achieved by attaching positive and negative charges to either end of a spinning rod. Because the circular paths traced by the charges deviate continuously from straight lines, this motion corresponds to acceleration toward the center of the circle.

Since we cannot generate systems composed of positive and negative masses (after all, negative masses don't exist), massive stellar binary systems don't generate any dipole radiation. This is so, because the center of such a system's 'gravitational charge' is the same as its center of mass. Accelerating gravitational *quadrupoles* do release radiation, however. Gravitational quadrupole radiation is produced if our masses are distributed such that both ends of the spinning rod are given the same 'gravitational charge'. However, binary black holes or neutron stars of the same mass and which trace circular orbits around one another will not generate gravitational waves. LIGO's first gravitational-wave detection (see Figure 2), known as event GW150914—indicating that it was observed on 2015 September 14—originated from the merger of two black holes with *unequal* masses that were 30 and 36 times more massive than our Sun.

Astronomical distances

The merging binary system was located some 1.3 billion light years from Earth. You probably just glossed over that distance, without really appreciating the vast dimensions of the Universe. The human mind is rather poor at estimating 'a billion' compared to 'a million', so let's briefly digress from the gravitational-wave story. If you compiled a million sheets of paper, your stack would reach as high as a 30-floor building. However, if you stacked a billion sheets of paper, it would stand ten times taller than Mt Everest. Let us now consider the 1.3 billion light-year distance to GW150914 in a setting we can relate to more easily. If we shrunk the Sun to the size of a ping-pong ball, the Earth would be a speck of dust some 2.5 meters away, Jupiter a pea 12 meters away, and the nearest star—α Centauri—would be more than 700 kilometers (435 miles) away. The diameter of our Milky Way galaxy, some 100 000 light years, would span 15 million kilometers (9.3 million miles), a stretch that in reality covers more than 30 times the distance between the Earth and the Moon.

And so far we haven't even left our own galaxy yet. Let us therefore compress the scales further and represent the 150 million kilometers (93 million miles) from the Earth to the Sun, a distance of 8 light minutes, by the thickness of a typical sheet of paper. On this scale, α Centauri is almost 22 meters away, and the diameter of the Milky Way would be equivalent to a stack of papers reaching a height of 500 kilometers (310 miles). The 2 million light years to Andromeda, the nearest large galaxy, would require a stack of papers of almost 10 000 kilometers (more than 6000 miles) high. That first gravitational-wave event, GW150914, would be found on top of a hypothetical stack of papers of 6.4 million kilometers (4 million miles) tall. Some of the most distant objects in the Universe, more than 10 billion light years away, would require an imaginary paper tower of 50 million kilometers (31 million miles) high. In real life, that corresponds to one third of the distance from the Earth to the Sun.

Sound waves

GW150914 was caused by a merger of the most massive black holes observed through gravitational radiation to date; the four confirmed and one possible binary black-hole events observed since then were all produced by much less massive black-hole mergers. But it is not just the unequal masses that give rise to gravitational waves. The slow spiraling together and the eventual cataclysmic coalescence of the binary black holes causes the acceleration—and changes the extent of the matter distribution in space—that ultimately produces the gravitational radiation. This extracts energy from the system, so that the black holes continue to spiral together at an ever increasing pace, eventually leading to their merger and the triggering of a high-intensity pulse of gravitational waves.

But don't get the wrong impression: gravitational waves are extremely difficult to detect—that's why it took so long since Einstein's initial brain wave to detect them with the most sensitive detectors on Earth. On their journey across the Universe, gravitational waves stretch and compress the fabric of spacetime by tiny amounts. In practice, for every kilometer length of an arm such as that of the LIGO detector, we must be able to detect displacements of the detector's mirrors to an accuracy of better than 10^{-18} meters—that is, 0.000 000 000 000 000 001 m. That minute displacement is equivalent to one thousandth of the diameter of the nucleus of a hydrogen atom (a proton), which is much smaller in relative size even than the sizes of waves on the ocean's surface compared with the curvature of the Earth. Just think about that for a moment and consider how you would detect such ripples from across the Universe! Figure 3 shows how the LIGO team managed to achieve their detections; the first detections are shown in Figure 4.

The compression and stretching of gravitational waves makes them similar to sound waves: the human ear is sensitive to pressure differences caused by compression and subsequent expansion of the density of air molecules, a concept known as 'longitudinal waves'. The analogy of using gravitational waves to 'listen to the Universe' is further established by the realization that gravitational-wave detectors are 'all-sky' detectors with rather limited potential to localize a source. Human hearing is similarly poor at locating the origin of sound waves, yet we usually have high-resolution vision. For these reasons, gravitational-wave events are also known as standard 'sirens'. The amplitudes of the gravitational waves, in essence the heights of their peaks and troughs, can be used as distance probes.

Precision mapping of the Universe

In principle, detections of gravitational-wave signals can be used to determine the distances to massive black-hole or neutron-star binary systems to an accuracy of better than 10%. Distance estimates can be improved significantly, in theory to better than 1% in some cases, if an 'electromagnetic counterpart' can be identified, such as an astronomical object or an event 'afterglow' observed through electromagnetic radiation, such as visual light, heat radiation, or radio waves. And this is where the use of gravitational-wave sources becomes really interesting for cosmologists. Cosmologists study the evolution of the Universe as a whole, from the Big Bang almost 14 billion years ago to the present day; they aim to constrain its future evolution and eventual fate using careful measurements of the three-dimensional structure of matter on the largest scales.

Cosmology received a big boost in 2011, when the Nobel Prize in Physics was awarded to the scientists leading two competing international teams that had both concluded that the well-known large-scale expansion of the Universe was actually accelerating. This led to the introduction of a new component to the composition of the Universe, an outward-pushing pressure commonly known as 'dark energy'. The nature of this pressure force is as yet unknown, but both teams concluded that its action was required to match the observed intensities of a specific type of exploding star, 'Type Ia' supernovas. These supernovas—which are thought to result from the implosion of a white dwarf star or perhaps from the merger of binary white dwarfs—were fainter than expected if they were indeed located at their independently inferred distances. Given that their maximum intensities are reasonably well-understood, the implication was that they were more distant than expected—hence the accelerated expansion of the Universe and the need for dark energy.

This was a major revelation. It meant that the Universe would be 'open'—implying that the total amount of matter in the Universe is not enough to convert the expansion into a contraction solely through the pull of gravity—and it will therefore continue to expand forever. Cosmology has seen major breakthroughs in recent years, to the extent that we have now reached the era of ‘precision cosmology’: the agreement between the most detailed observations of the structure and geometry of the Universe on the largest scales and the predictions of the current-best cosmological model are now so good that the discipline’s long-term foundation seems secure.

But there are still some aspects of our understanding of the large-scale structure of the Universe that remain worrisome. The expansion of spacetime causes stretching of the electromagnetic spectrum, that is, of the distribution of an object’s intensity across the wavelength regime. Spectra have features—absorption and emission lines that indicate which chemical elements a source is composed of or which it may be hidden behind—that encode the amount of wavelength expansion, just like a barcode. As the Universe expands, this ‘barcode spectrum’ gets stretched. One can think of spacetime as a rubber band, so when it gets stretched, any waveform on the rubber band gets stretched too. As a consequence, the wavelength becomes longer and, therefore, redder. This ‘redshift’ is an indication of the amount by which spacetime has been stretched; it depends on an object’s distance from Earth and—importantly—on the cosmological model adopted.

The Nobel Prize-winning teams used observations of supernovas at redshifts, z, of around 0.5. Light emitted at $z = 0.5$ has taken just over 5 billion years to reach us, although the exact time depends on the actual geometry of the Universe. Cosmological models must make a number of assumptions about the geometry of the Universe as a whole, particularly as to whether it is ‘open’, ‘closed’, or ‘flat’: see Figure 5. Mathematically, a flat Universe is easiest to deal with; it describes the geometry of space as we know it from everyday experience: the three angles of a triangle combine to a total of 180 degrees. Open and closed geometries, on the other hand, imply total angles of more or less than 180 degrees, which makes the models rather more complicated. Based on the current-best cosmological model, sources at a redshift of $z = 1$ emitted their radiation when the Universe was half its present age of about 13.7 billion years.

Again, here we encounter the tendency of astronomers to reduce the vast sizes and timescales they deal with routinely to numbers one can relate to more easily. Let us therefore consider these timescales in a more familiar setting. A million seconds make up 12 days, but to get to a billion would take you 31 years if you keep counting. Continuing to 5 billion years, by the same token this would take us back to 1862, when Abraham Lincoln was US President and the Civil War raged; counting on to 13.7 billion years would send us back in time to 1592, one hundred years after Columbus’ now-famous first voyage across the Atlantic Ocean, the year when Galileo invented the thermometer, and an outbreak of the plague in London killed some 17 000 people over the next 12 months.

Distance ladders

The maximum intensities of Type Ia supernovas can be standardized to an accuracy of around 15%. These objects, therefore, provide very useful approximations to ‘standard candles’ for distance determination—objects of the same brightness no matter where they are located in the Universe. They can be observed to redshifts of z = 0.5 to 1 because of their high intensities. Unfortunately, however, we have not yet achieved a full theoretical understanding of the physics driving these explosive events.

Gravitational-wave sources could potentially be used as independent distance tracers covering a similar distance range, although they extend to the 'cosmic horizon', well beyond z = 10, where we can probe light that was emitted less than 500 million years after the Big Bang. That would allow us to explore the properties of distant galaxies that existed when the Universe was only 3.5% of its current age. Importantly, the use of gravitational-wave sources at these distances doesn't require us to make assumptions about the best cosmological model. So far, however, the distances estimated for the first five or six confirmed and suspected binary black hole-related gravitational-wave events range from just one to about three billion light years only.

Independent distance determinations to objects that are located a significant fraction of the way to the edge of the observable Universe are sorely needed to better understand its geometry on the largest scales. However, they are also difficult to obtain and depend on assumptions related to the processes responsible for the generation of the emission we observe on Earth. Direct distance determinations, that is, distance measurements that are only based on geometrical considerations, are mostly limited to the nearest stars, for which we can determine annual parallax angles—in essence, we can measure the elliptical paths traced on the sky over the course of a year by these nearby stars with respect to the background stars, which is ultimately a projection on the sky of the Earth's orbit around the Sun.

At greater distances, we may be lucky and have access to small numbers of unique objects that can help us determine reliable geometric distances in random, favorable directions. Such sources may include eclipsing binary systems, to which we can apply Johannes Kepler's Third Law to determine geometric distances. Kepler's Third Law relates the physical distance between the two components in a binary system to their orbital period. The angular separation on the sky can be measured using state-of-the-art observational facilities, while measurements of the period allow us to derive a linear size. Since the angular and linear sizes apply to the same system, a distance follows directly. In addition, for expanding sources such as planetary nebulae—stars at the ends of their lives that have expelled their outer atmospheres into often colorful configurations—we can measure their expansion on the sky and also along our sightline. Assuming the same expansion rates in all three dimensions, this gives us rather well-defined distances. Supernova light echoes in the nearest galaxies, where reflecting dust clouds surrounding the supernova will light up once the supernova's expanding sphere of light has reached them, can be used in a similar fashion; given that this happens at progressively larger angles on the sky and at the speed of light, the distance to the supernova itself can be tightly constrained. But application of such geometrical considerations becomes practically impossible beyond the galaxies in what is endearingly known as the 'Local Group', which extends approximately 3 million light years from the Milky Way.

By some lucky coincidence, we could still obtain direct distance measurements to a small number of fortuitously observed spiral galaxies through observations of their rotation rates, but even that method loses power beyond the nearest large clusters of galaxies; the most distant galaxy with a direct, rotation-based distance estimate is located some 400 million light years away, but that distance only corresponds to a redshift of $z \approx 0.03$—not even close to the distance range of interest for cosmology, beyond $z \approx 0.5$.

Suggestions of novel approaches to determining distances directly are proposed occasionally, although they do not always measure up to their promises upon closer inspection or application in practice. A promising method to determine geometric distances to quasars—the most distant and brightest galaxies in the Universe—using the size of their broad-emission-line regions (see Figure 6) as a 'standard ruler' may buck this trend, however. In everyday life, one can envision that the distance between the headlights of a car would be a good standard ruler. After all, if you know the actual separation of the headlights, you can estimate how far away the car is. This analogy is entirely correct, but of course while we can directly measure the separation of the headlights, we cannot do the same for the sizes of the broad emission-line regions surrounding the massive black holes in the centers of high-redshift quasars.

Nevertheless, this proposed standard ruler approach essentially corresponds to a 'quasar parallax': the linear sizes of these broad-emission-line regions, which are caused by irradiation of the gas clouds in their central regions by a high-intensity source, is known from light-travel-time measurements—a technique known as 'reverberation mapping'—while their apparent size on the sky may be measured using some of the most sophisticated radio telescopes we have access to today. Already around the turn of the current century, a few visionary astronomers confidently predicted that it would soon become plausible to measure the sizes of these quasar emission-line regions out to redshifts of $z \approx 2$ with high enough accuracy.

For all practical purposes, however, even if this approach were supported by new developments, it would still only allow us to obtain direct distant measures to a very small number of suitable objects at such high redshifts. For large-scale distance mapping of statistically large numbers of sources, we have to resort to a stepwise approach, known as the astronomical 'distance ladder'. Here, the accuracy of the distances to every rung of the ladder relies on careful measurements of the distances to objects on the previous rungs. Without access to direct, geometric measurements, the most commonly used methods of distance determination rely on our understanding of the physics driving the emission processes in nearby objects, assuming that the same physics is at work at any other distance.

For some types of distance tracers, we can actually determine their intrinsic intensities, or those of large collections of such objects, based on independently determined geometric distances in the nearby Universe. Assuming that these brightnesses remain the same no matter where the objects are located (that is, adopting the standard candle assumption), observations of similar but fainter sources at much greater distances can then be converted into distance differences. As we saw already, the maximum intensities of Type Ia supernovas have long been used as potential standard candles, although it actually requires some work—and also adoption of a number of assumptions—to convert the observed intensities to the standard candle scale.

Known unknowns

And this is where some of the key remaining systematic uncertainties currently prevent further progress. Scientific measurements are affected by two types of uncertainties, including statistical measurement errors and systematic uncertainties. Statistical or random measurement errors can be adequately reduced by obtaining more observations or by keeping the shutter of one's camera open for longer to improve the detection efficiency. Systematic uncertainties, however, remain the same, no matter how many observations one collects and irrespective of the total observing time. These uncertainties are most troublesome, because they are directly related to the nature and accuracy of the physical assumptions made or the method applied. They can only be reduced once better assumptions are made or by application of improved methods.

So far, Type Ia supernovas represent the only class of object that has been used to conclusively determine that the expansion of the Universe seems to be accelerating—that was the key conclusion for which the 2011 Nobel Prize in Physics was awarded, after all. However, given the lingering systematic uncertainties affecting supernova-based distances, it is highly desirable to develop independent techniques of distance determination that are applicable at the same distances—and this is where gravitational-wave sources could play a decisive role as standard sirens. They could serve as independent confirmation of the supernova distances but also to probe the structure of the Universe on the largest scales in their own right. The gravitational-wave era is now truly upon us, and new horizons in astrophysics are beckoning.

Identification!

Conclusive determination of the nature of the objects that emit gravitational waves is crucial in taking the next step in our quest to further constrain the properties of the Universe and its structure on cosmological scales. We're not quite there yet. In October 2017, gravitational-wave astronomy announced its second major result after the initial discovery announcement in early 2016, which already led to the award of the 2017 Nobel Prize in Physics. In fact, the team also won the million-dollar Kavli Prize in Astrophysics in 2016. I vividly remember being present, in early June 2016, at the opening of the World Science Festival at Stonybrook University in New York, when the Kavli Prize laureates were announced by video link from the Norwegian Academy of Sciences. Both Rainer Weiss and Kip Thorne, two of the three later Nobel laureates, were also in attendance, so there was keen anticipation of what was about to happen. When the Kavli Prize winners were announced, thunderous applause erupted, which lasted for quite some time and which clearly showed the high regard both men are held in. I was particularly struck by the humility of both scientists—a lack of pretense that gave the occasion a truly awe-inspiring aura.

The neutron-star binary merger GW170817 (observed on 2017 August 17) may well be the single event that will eventually be credited to truly having opened up a new field; it was the first optical detection of a gravitational-wave source. You might wonder, why all the fuss? Detection and identification of the actual astronomical counterparts of gravitational-wave sources is essential for a full understanding of the physics driving the merger event. This achievement cannot be overstated: it allows us to determine a precise location, in a distinct galaxy, for which one could potentially determine a reliable distance. The detection of a first optical counterpart was momentous, yet it didn't even come close to solving the cosmological puzzles of our time. The merger event was moderate by any reasonable measure: it provided evidence of the last breaths of two neutron stars with masses just a little greater than that of our Sun in a nearby galaxy, known by its catalog identification NGC 4993, at a distance of some 130 million light years (see Figure 7). That makes this stellar merger the closest gravitational-wave source detected so far. Events at significant cosmological distances will, however, soon be within reach of our detection capabilities: gravitational-wave astrophysics is truly a technology driver. This is now leading to a real buzz of excitement in the astronomical community.

At sizeable fractions of the distance to the edge of the observable Universe, few other methods are available to trace the true structure of it all. To do so, we would ideally want to use distance tracers that cover large areas on the sky—on those scales the Universe is highly homogeneous. However, at the present time we only have access to very distant objects in fortuitous directions where something special may be happening, such as a distant source that is magnified by a massive foreground cluster of galaxies through 'gravitational lensing' (so that we can study the background sources more easily) or galaxy clusters seen as silhouettes in X-rays against the cosmic microwave background radiation, the left-over 'echo' of the Big Bang. We can use the small increments in energy of the cosmic microwave background photons by the gas pervading these galaxy clusters—known as the 'Sunyaev–Zel'dovich effect'—to obtain approximate distances. Yet none of these alternative methods have the same potential as the new field of gravitational-wave astrophysics.

The era of precision cosmology is now truly upon us. Einstein's predictions can now finally be tested to their fullest extent. I am sure that he would have relished this opportunity if it had happened during his lifetime. But such is the nature of science: progress comes in leaps and bounds. It may seem slow at times, but confirmation of ground-breaking ideas takes effort and careful scrutiny. Einstein wouldn't have had it any other way.

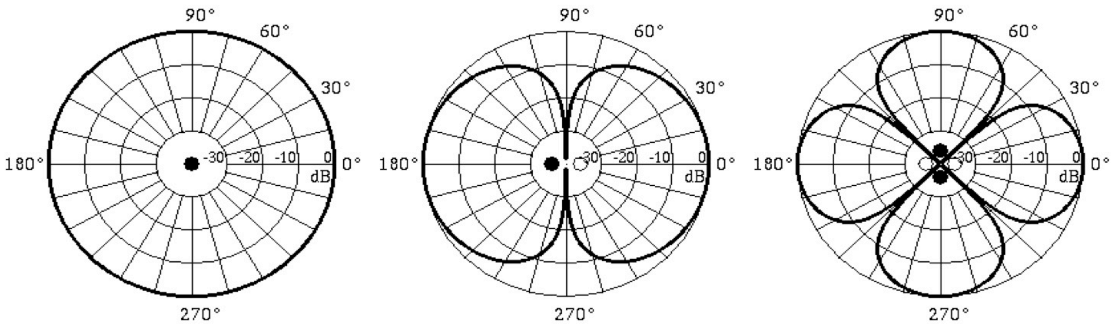

Figure 1: (*left*) Monopole, (*middle*) dipole, and (*right*) quadrupole radiation fields (thick black lines) in two dimensions. (*Credit: Daniel A. Russell, The Pennsylvania State University; Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License*)

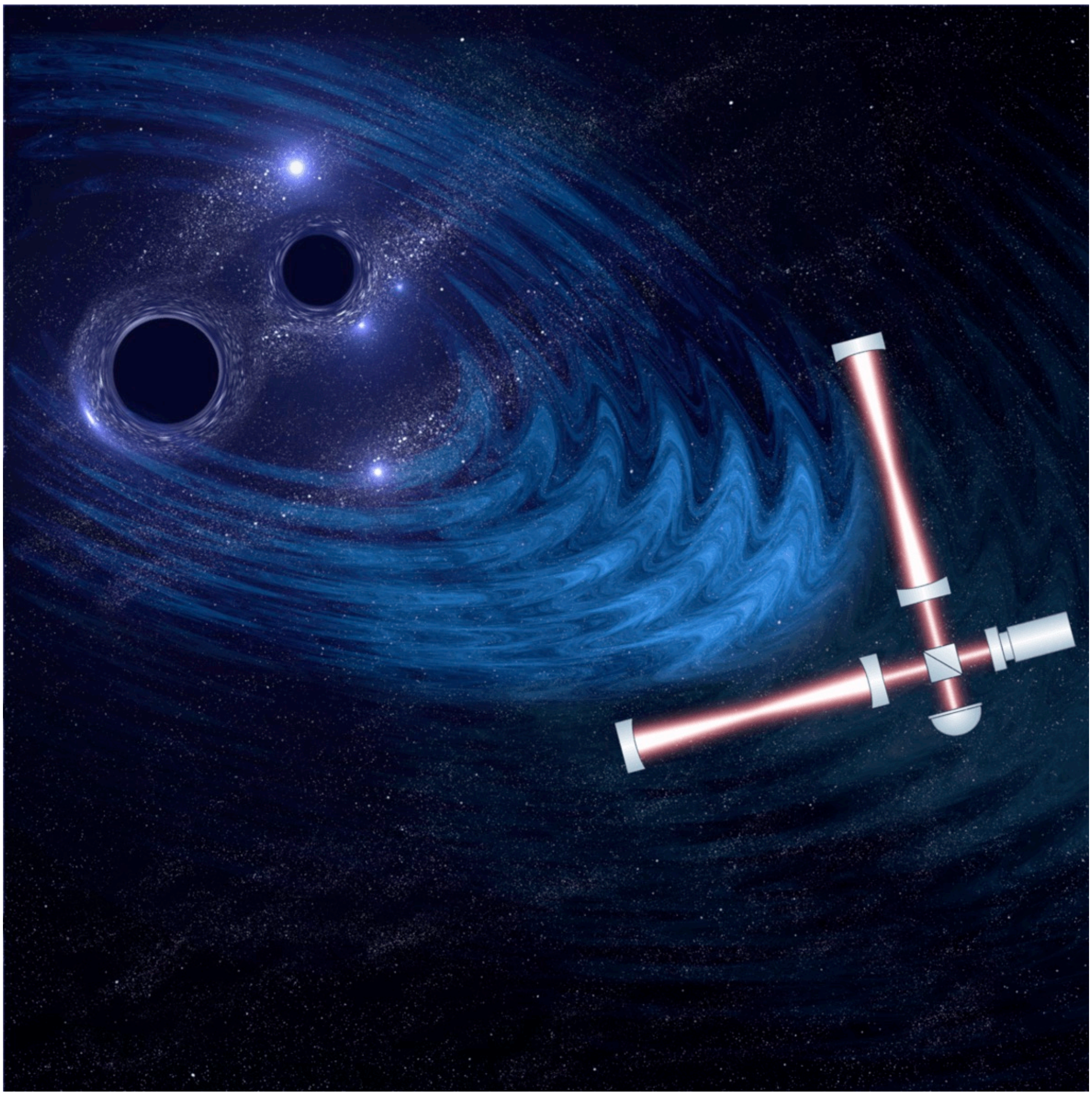

Figure 2. Artist's impression of the binary black hole merger GW150914, which released the gravitational waves first observed by LIGO. (*Credit: Christopher Berry, University of Birmingham Gravitational Waves Group, CC BY-ND*; https://phys.org/news/2016-02-gravitational-discoveredtop-scientistsrespond.html)

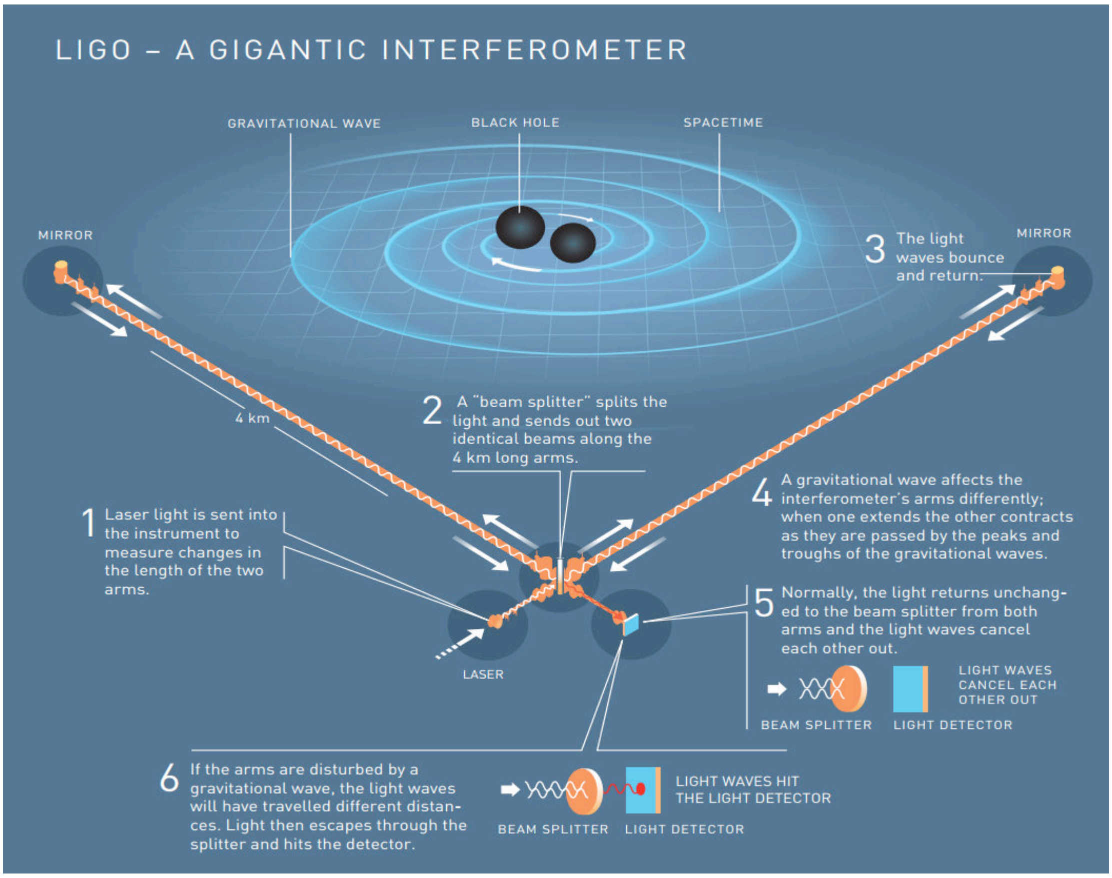

Figure 3. Principles of gravitational-wave detection (*Credit: LIGO; CC BY-ND*)

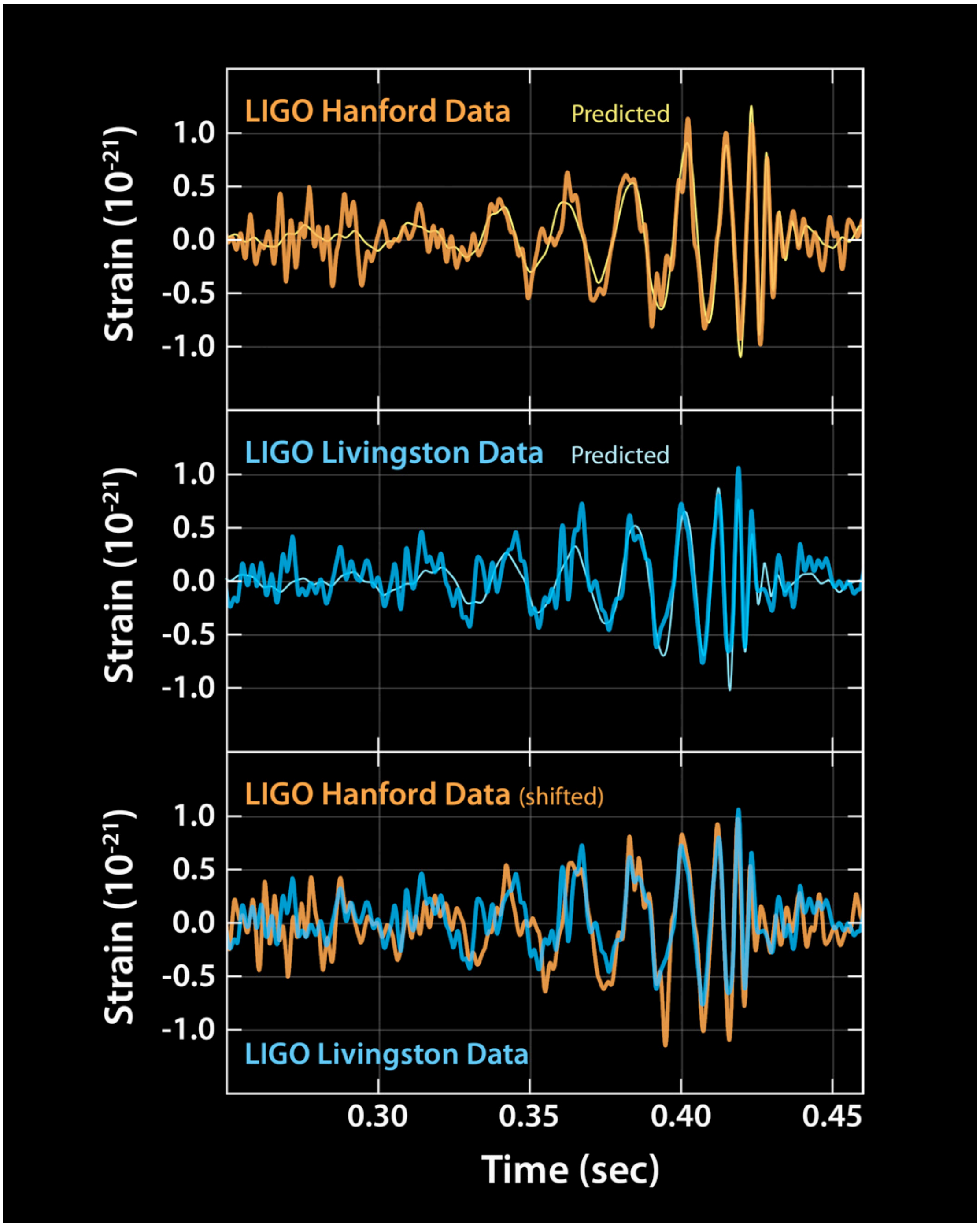

Figure 4. The signals of gravitational waves detected simultaneously by the twin LIGO observatories at Livingston (Louisiana) and Hanford (Washington). Note the extremely small 'strain' values, which represent the distortions of spacetime observed by the detectors. (*Credit: LIGO, CC BY-ND*)

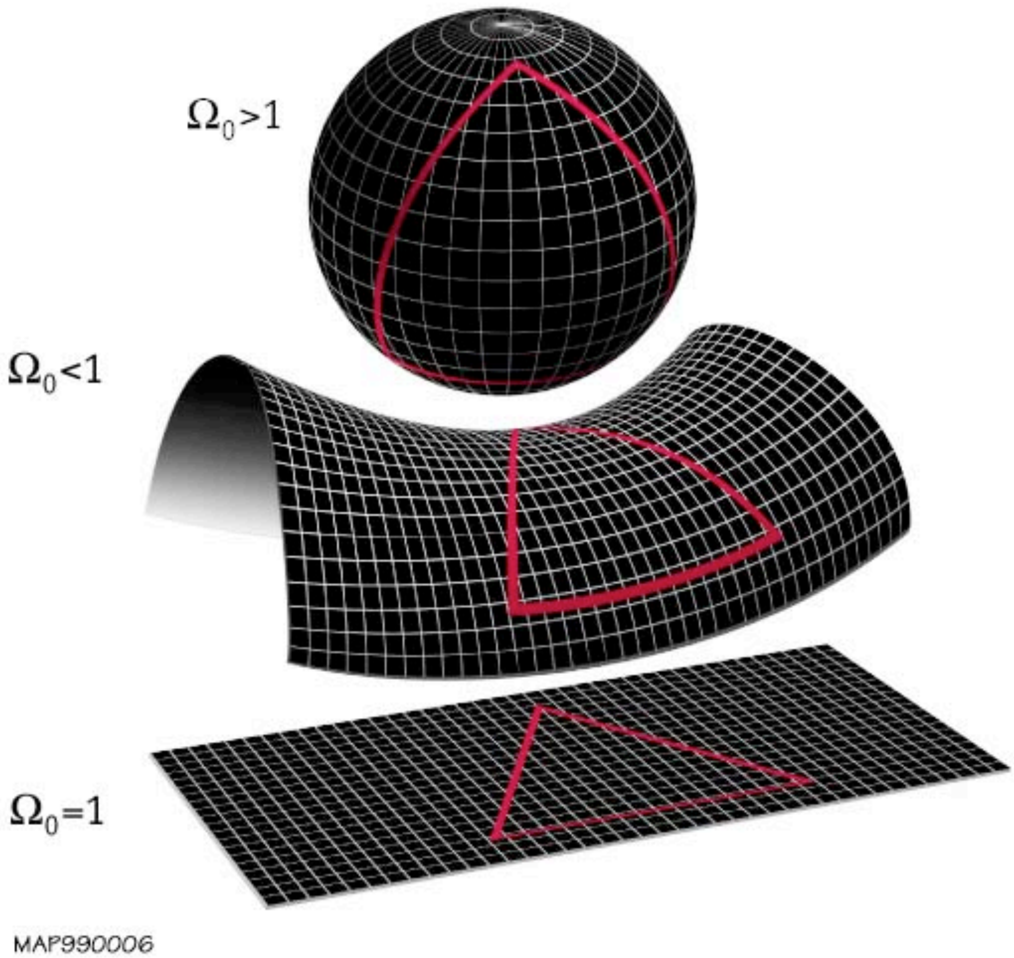

Figure 5: Visualization of (*top*) closed, (*middle*) open, and (*bottom*) flat universes. The geometry is described in terms of the Universe's density parameter Ω_0, the ratio of the actual density to the critical density for a flat Universe. (*Credit: NASA*)

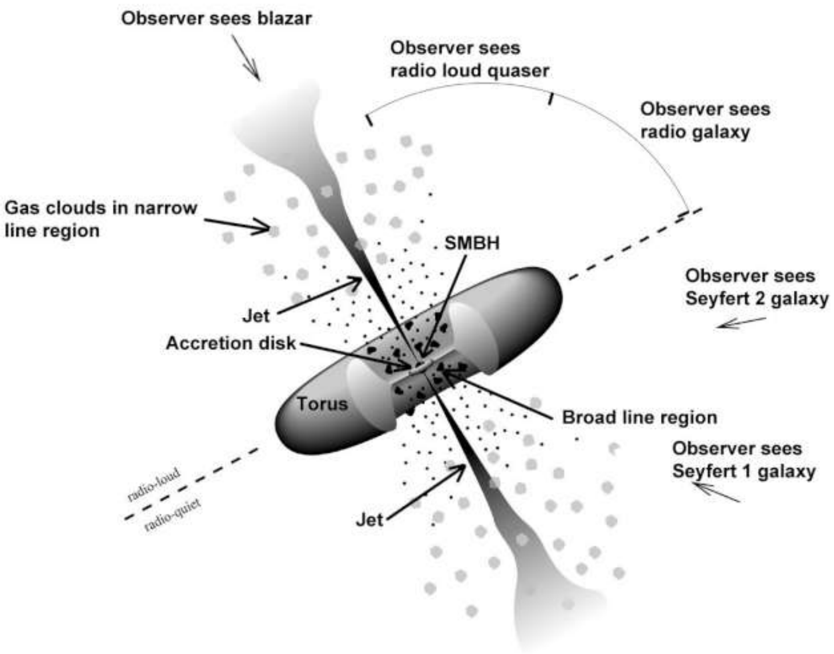

Figure 6. Unified model of so-called 'active galactic nuclei', also collectively known as quasars or quasi-stellar objects. The broad-line region in this model is located close to the central supermassive black hole (SMBH). (*Credit: NASA/Fermi Space Science Center*)

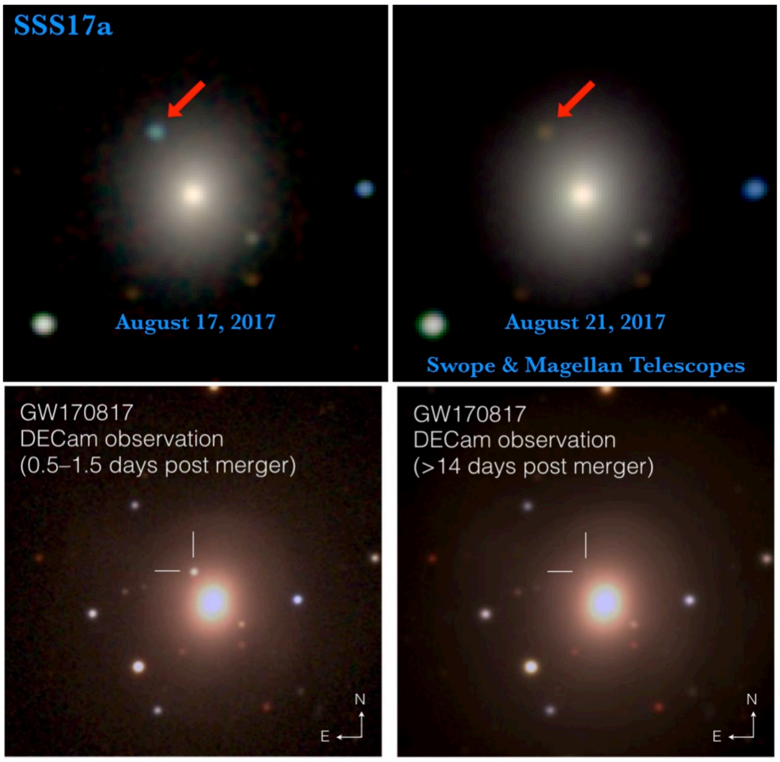

Figure 7: Detection of the optical counterpart of GW170817. (*Top*) Optical and near-infrared images of the first optical counterpart to a gravitational-wave source, SSS17a, in its galaxy, NGC 4993. The left-hand image was taken 11 hours after LIGO's gravitational-wave detection; confirmation was provided by the European Virgo detector. The right-hand image was obtained four days later. (*Credit: 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley*) (*Bottom*) Color composite images of NGC 4993. (*Credit: Soares-Santos et al. and DES Collaboration*)