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Black Holes and Einstein: A Commentary on the Types of Black Holes That Produce Gravitational Waves

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Black Holes and Einstein: A Commentary on the Types of Black Holes That Produce Gravitational Waves

Perhaps the most the notorious player in the astronomical field, objects known as black holes captivate the imaginations of scientists and average folk the world over, but as much as we adore hypothesizing about what black holes are like, there is so much that we're only just finding out about. From 1909 until 1918, famed physicist Albert Einstein predicted many characteristics of spacetime and the effect of massive objects on it, including the notion of an energy-carrying wave moving at the speed of light that causes ripples through the fabric of spacetime, otherwise known as gravitational waves. A relatively recent field of astrophysical study is the study of gravitational waves, a phenomenon first conceived of by the most famous physicist in history, Albert Einstein.

In this paper, I intend to discuss binary black hole mergers that produce such gravitational waves, the mergers that have been discovered already by gravitational wave observatories, and the future of gravitational wave observation. Throughout my life, like many others, I have always found the concept of black holes fascinating. The idea of something so dense that it actually pulls space and matter inward in particular was always intriguing to me. For this paper, I have found numerous sources ranging from books by famous astrophysicists to first-hand research published by the LIGO and Virgo gravitational wave observatories and theories first proposed by none other than Albert Einstein. In this essay, I will define black holes and explain how they are created, explain the mechanics of a black hole merger and the nature of gravitational waves in relation to black hole mergers, elucidate how those gravitational waves created by black hole mergers are detected by laser interferometry and provide information about the gravitational wave detectors, I will also discuss what detections have been made so far, as well as the future of black hole gravitational wave observations, including what further detections are predicted to occur in the near future, and future gravitational wave detectors that are planned for construction or currently being built.

Black holes have entered the public consciousness more or less through the lens of science fiction, where they either play the role of cosmic villain, gobbling up matter such as stars and planets indiscriminately like a vacuum cleaner with an insatiable appetite, or they play a more whimsical role, where they provide humanity with a means of either traveling insanely quickly through vast swathes of space or even traveling in time! However, while black holes are plenty interesting, as far as we know, they aren’t capable of allowing humanity to accomplish such great feats, nor do we need to fear a black hole suddenly appearing over the Earth and sucking us in. In order to understand the concepts that will be covered in the course of this essay, it is necessary to gain a better understanding of the true nature of black holes.

In order to understand black holes, one must first understand the nature of spacetime. The best way to think of spacetime is as if it were like a rubber sheet, with a black hole or other massive object, such as a star or planet, like a ball placed in the center of said rubber sheet. The massive object, much like a ball on a rubber sheet, distorts the fabric of spacetime, bending and warping it around the object. Famed American physicist John Archibald Wheeler in his 1998 autobiographical work *Geons, Black Holes, and Quantum Foam*, describes the nature of gravity and spacetime in the succinct way “Spacetime tells matter how to move; matter tells spacetime how to curve,” meaning that objects will fall into the curvature of spacetime around another object while they themselves curve the spacetime as well (Wheeler 234). Dr. James Overduin, a professor of theoretical physics at Towson University wrote an article called “Einstein’s Spacetime” for Stanford University in 2007, where he gives the same example of spacetime being a rubber sheet, however with a massive object being represented by a bowling ball and a smaller object represented by a marble. He states that, when the marble is pulled to the bowling ball, “it is not because the smaller mass is attracted by a force emanating from the larger one, but because it is travelling along a surface which has been deformed by the presence of the larger mass” almost as if the bowling ball had carved a groove within the fabric of spacetime that the marble travels within (Overduin).

Perhaps the most famous aspect of black holes that most people are familiar with is that of the event horizon, the point at which it is no longer possible to escape the extreme gravity of the black hole. Black holes, as massive objects like the bowling ball in Dr. Overduin’s example, warp this fabric of spacetime to such a degree that anything that enters it cannot leave again. This includes light and other radiation, despite the speed of light being faster than anything known in the Universe at this time. As Dr. Chad Orzel helpfully explains in his book *How to Teach Relativity to Your Dog* (237). Black holes are a relatively newly discovered phenomenon, only just conceived of nearly a hundred years ago, and having only been named in the 1960s, by John Archibald Wheeler (Orzel 237). Jean-Pierre Luminet, a French astrophysicist, defines a black hole in his book *Black Holes* as a “region of spacetime inside which the gravitational field is so intense that it prevents all matter and radiation from escaping,” meaning that anything that is pulled into the black hole, including light, is forever trapped in the “cosmic prison” (Luminet 124). Not long after Einstein published his *Theory of Relativity*, while serving in World War I, physicist Karl Schwarzschild utilized Einstein’s equations from his *Theory of Relativity* to mathematically express that if one were to “compress a sphere of matter so that its radius becomes smaller than a critical value;” written as $R = \frac{2GM}{c^2}$ with G standing for the gravitational constant, M for mass and c for the speed of light; the result would be an object that “curves spacetime so strongly that light from the object can never reach the outside world,” (Orzel 237).

This Schwarzschild radius is the “minimum radius that a sphere of some mass can have before it forms a black hole,” and when a black hole eventually does form, the mathematical value of the black hole’s Schwarzschild radius becomes what is known as the black hole’s event horizon or the “boundary between the interior of a black hole and the rest of the Universe,” meaning that any anything that goes past that Schwarzschild radius is never again observable to the outside Universe (Orzel 311, 304). If that’s a bit hard to imagine, James Stein explains in an article for NOVA and PBS, that if one were to compress the Earth into a sphere with a radius of “approximately one inch,” like, say if you were to “squeeze the mass of the Earth into a sphere the size of a ping-pong ball,” it would become a black hole. The Earth-mass, ping-pong ball sized black hole would probably have an incredibly small event horizon, meaning that it would be remarkably easy to be drawn in past the point of no return, so to speak, because of what lies on the other side of the region referred to as an event horizon. Beyond the event horizon is what most people conceive of as the black hole itself, the singularity. The singularity is the part of the black hole that “contains all its mass” in an “infinitesimal point at the center”, where the warping of spacetime is the most significant, all of the black hole’s mass squeezed into such a small space, pulling spacetime into itself (Orzel 240, 311).

While all black holes are defined using the same terms, both mathematically and in regard to vocabulary, there are different types of black holes. They are mainly grouped together by their mass, measured in terms relative to our Sun called solar masses. The Sun is one solar mass. Black holes may also be defined by the way in which they were created. First, there are what is known as stellar-mass black holes, whose masses range between three solar masses and one hundred solar masses. In her book *Black Holes,* Marcia Bartusiak states that stellar-mass black holes are a "possible endpoint . . . in the lifetime of a star" and that "it is estimated that one star in a thousand ends its life hidden behind an event horizon, with one hundred million of them residing in the Milky Way alone" which may sound like a great deal many stars that die and leave a stellar-mass black hole as their corpse (Bartusiak 181). However, one must take into account that, according to author Jaime Trosper in her article "How Many Stars, Planets, and Black Holes Are in Our Galaxy?," the Milky Way galaxy "most likely has 400 billion stars (though it could have as few as 200 billion) [sic]" which makes the number of stars that could form stellar-mass black holes only about 0.025-0.05% of the stars in our galaxy (Trosper). Now, while one might wonder how it is that stars make that leap from shining brilliantly in space to becoming a black hole, it isn't a wholly enigmatic process, from what we currently understand about it.

Colin Robson spells out the three ways in which a stellar-mass black hole can be formed in his article "The Formation of Stellar-mass Black Holes: The Making of Energetic Destroyers." He begins by explaining that a neutron star in a binary system, a system that contains two stars "where one star can suck material from another," can create a stellar-mass black hole in two ways (Robson). The first, by allowing the neutron star in the system to "slowly accrete (accumulate) material" until it reaches a point where "it becomes too massive . . . to keep it from collapsing into a black hole;" as the activity within the neutron star is no longer able to hold back the gravity that has increased as it has gotten larger (Robson).The second: the neutron star merges with the other star in its binary system, which is "either a white dwarf or another neutron star" (Robson). The third and final way that a stellar-mass black hole can be formed is "through a core collapse supernova" and only stars with "20+ solar masses end in a supernova and create a black hole" (Robson). This process, according to COSMOS: THE SAO Encyclopedia of Astronomy in their article titled "Stellar Black Hole," occurs "once the core of the star has completely burned to iron" which means that nuclear fusion, the process that gives stars their energy, has stopped (COSMOS). The heavy iron core collapses due to those energy-creating nuclear forces no longer being able to hold back the star's intense gravity (Robson; COSMOS). In essence, the supernova occurs because once a star begins to create the element iron, that nuclear process actually must "absorb energy in order to fuse into heavier elements" which then means that the star no longer is producing energy, but is losing it, causing its core to begin to draw in on itself, the friction of which causes the supernova explosion and then leaves behind a black hole in its place (COSMOS, "Core-Collapse").

Another type of black hole that is rumored to exist is what is referred to as a primordial black hole. Luminet explains that the early universe, known as the primordial universe, was a time when the universe didn't have a "well-defined structure" (Luminet 219). It had the possibility of being "agitated by slight fluctuations" that were able to "grow and dissociate themselves from the universal expansion" (Luminet 219). This was occurring at the time due to the inflation of the universe, and may have created early galaxies and early black holes by lumping together in such a way that the universal expansion didn't pull the matter apart from itself (Luminet 219). Therefore the "excess mass" that had lumped together began to increase in density due to the conditions of the universe at that early period of time (Luminet 219). Basically, when the Universe was still in its early stages, its nature was much different. Matter wasn't uniformly distributed but tended to clump together in dense clumps, which led to the formation of early galaxies, and possibly primordial black holes. These primordial, early, black holes had no size constraint on them, like those that develop from the collapse of a star to form a black hole with the mass of approximately three suns (Luminet 220). That means that primordial black holes could be exceptionally small, if found to exist, even being as small as “the size of an elementary particle” like the Higgs-Boson or an electron or neutrino, which cannot be observed with the naked eye (Luminet 220). It is unlikely that we will ever observe such small black holes, even with extremely delicate instrumentation used to detect tiny particles like those mentioned. The only hope that we have for detecting primordial black holes would be in detecting what is known as Hawking radiation or the slow evaporation of “mass as blackbody radiation,” that affects tiny primordial black holes more so than larger black holes. Black holes “evaporate more rapidly the smaller they are” (Luminet 222). In order for a primordial black hole to still be around after tens of billions of years, its minimum mass would need to be a billion tons or “roughly the mass of a mountain,” while the radius of a such a black hole would only be “10^{-13} centimetres, the same as a proton” and those black holes smaller than 1,000,000,000 tonnes have already evaporated, while those with a mass greater than 5.03×10^{-8} solar masses are “in the process of increasing in size” because “the rate at which they increase in size exceeds the rate at which they evaporate” (Luminet 222). In order to find primordial black holes that are in the process of evaporation but have not yet evaporated, one would have to be able to find a black hole with a mass between 1 billion tonnes and 5.03×10^{-8} solar masses during its last “tenth of a second of its existence” when the “evaporation becomes explosive” and destroys the black hole, converting its mass into energy in the process (Luminet 222).

Compared to the average size of garden variety stellar-mass black holes, or to the tiny black holes of theoretical primordial black holes, supermassive black holes really seem to earn their name. Amina Kahn wrote in the article “Astronomers Discover the Smallest Known Supermassive Black Hole” for the LA Times that the smallest supermassive black hole ever detected weighed in at “a mere 50,000 solar masses,” about “100,000 times smaller than some of its oversized peers” (Kahn). Granted, this is hard to conceptualize as small (Kahn). However, in comparison, Sagittarius A*, the supermassive black hole at the center of our galaxy, the Milky Way, is “between 4 million and 5 million solar masses” and isn’t even the largest supermassive black hole ever detected (Kahn). While supermassive black holes are not as common as stellar-mass black holes, they are expected to be found in a plethora of places throughout the known universe, perhaps because of their advanced age when compared with stellar-mass black holes. According to Fulvio Melia in his book *The Edge of Infinity: Supermassive Black Holes in the Universe*, “many astronomers suspect that almost every large normal galaxy harbors a supermassive black hole at its center” (Melia 79). However, he stresses that at the time of writing, “direct measurements of supermassive black holes have been made in over 38 galaxies,” and that those direct measurements only work when “we can see the individual stars in motion about the center source of gravity” because the orbits of stars are altered in such a way around an invisible source that astronomers are able to conclude that a supermassive black hole resides in that invisible spot (Melia 79). This indirect observation of supermassive black holes through the observation of nearby stars’ orbits was actually what initially confirmed the presence of a supermassive black hole at the center of our own galaxy. Melia goes on to note that no supermassive black holes have been found in “galaxies that lack a central bulge,” in other words, a galaxy that is just a “flat, spinning disk[]” (Melia 79). However, “astronomers have found a supermassive black hole in every galaxy observed that contains a bulge component” like our own Milky Way galaxy and the Andromeda galaxy (Melia 79). Both of these galaxies have a bulge and a disk with supermassive black holes at their centers and became the spiral galaxies that they are today through countless mergers with other galaxies (Melia 79). This means that a collision between two galaxies may be responsible for two black holes merging together to form a single supermassive black hole (Melia 79). This is supported by the idea that the age of a galaxy's supermassive black hole is comparable with the age of the galaxy it resides in. Melia explains that the age of supermassive black holes "scales with the age of the galaxy itself," which means that if a supermassive black hole is 2 billion years old, for example, its galaxy is also 2 billion years old (Melia 18-19). Astronomers have found that "the masses of black holes in young galaxies" are less than the masses of black holes found in older galaxies they get "progressively heavier with age" by pulling in "stars and gas from the surrounding medium" with no sign of stopping (Melia 18-19).

With a general background on the nature of black holes, it's possible to proceed to the phenomena that can actually be directly detected to provide proof of black holes: the merging of two black holes in a binary system. It's necessary to begin with how these binary systems of black holes come into being, of which there are more than one possible origin. COMPAS, a website run by the Astrophysics & Space Research Group at the University of Birmingham, explains on their website in an article titled "How Do Binary Black Holes Form?" that one way that binary black hole systems can be formed is by the evolution of a pair of stars that "started out at quite wide separations" from one another (COSMOS). They grow closer as they expand into larger stars and begin to exchange matter with one another, only to create a chain-reaction within their cores that causes them eject material, shrinking the distance between them further (COMPAS). Once the stars reach the end of their lifetimes and become black holes, their orbits around one another will continue to shrink until, eventually, the black holes are pulled toward one another in a type of dance that ends with a merged black hole in their place, though a significant amount of mass is lost in the process due to the energy that is involved. The result of such a merger creates a special effect on the fabric of spacetime, known as a gravitational wave. This type of binary black hole fusion is referred to as “isolated binary evolution” which essentially means that the system in which the binary system evolved was not heavily populated by other stars (COMPAS). It takes a “few million years to form two black holes, with a subsequent delay of billions of years before the black holes merge” as it takes time for stars to go through their entire life cycle and even longer for the resulting black holes’ orbits to decay to the point that they begin the process known as coalescence, another term for merger (COMPAS). Fulvio Melia specifies that another way that black hole binary systems can be formed is possibly within a dense environment such as a globular cluster, a cluster of very old stars usually on the fringes of a galaxy, where black holes can grow “through the merger of smaller collapsed objects”, essentially stellar black holes (Melia 83). Black holes with a mass closer to that of our Sun, can grow larger given that their environment has plenty of mass and matter to consume, eventually growing closer to one another as they grow and their gravitational forces increase, pulling each closer until their orbit around one another decreases and they inevitably collide (Melia 83).

As for the mechanics of the binary black hole merger itself, as Assistant Professor of Physics at Montclair State University Marc Favata explains in the article “The Basics of Binary Coalescence”, when two black holes are in the process of merging together or are starting to “coalesce”, they experience the stages “inspiral”, “merger”, and “ringdown” (Favata). Favata begins his explanation of the stages of binary coalescence by showing this diagram, which helps to depict both the stages of coalescence as well as the behavior of the gravitational waves throughout each stage:

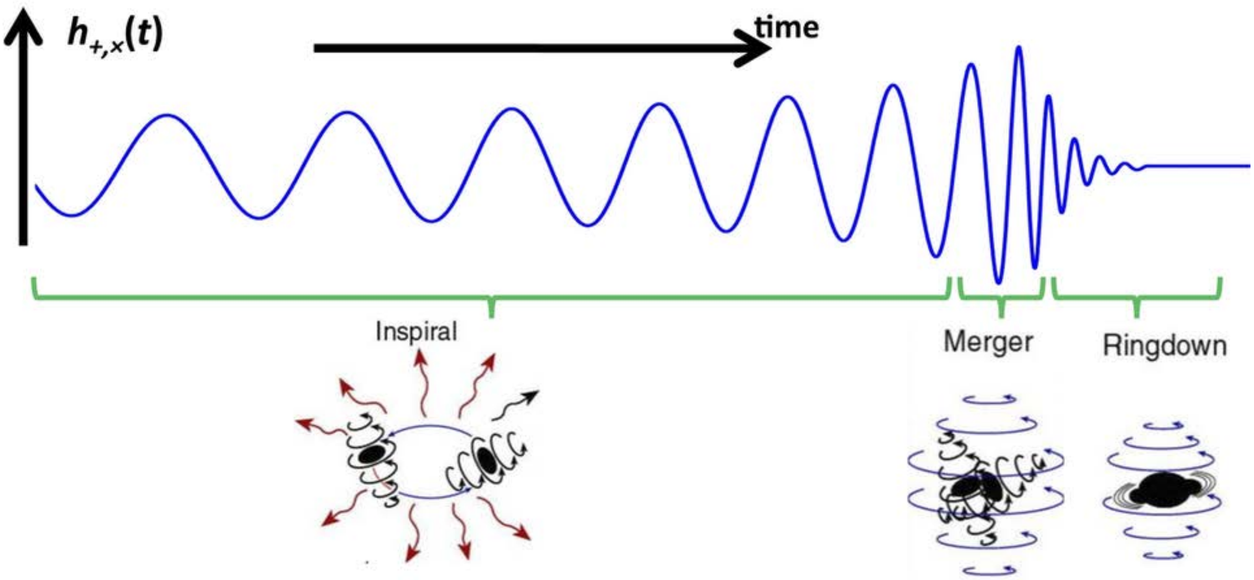

Fig. 1. “The Basics of Binary Coalescence”

(Favata et al.)

As can be witnessed by the diagram, Figure 1, the first step of binary coalescence is inspiral. Despite the fact that the two black holes may start out far apart, they still “emit weak gravitational waves” which “carry away energy from the [binary] system,” eventually causing the binary black holes to “orbit with a smaller radius” which makes the black holes “orbit [each other] faster and faster,” while “the waves they emit release more and more energy,” causing the “system to shrink even faster” (Favata). This process is what is known as the inspiral stage of coalescence, during which the amplitude, or height of the gravitational wave, is “increasing with time” (Favata). The next step, the merger, occurs once the binary black holes have sufficiently inspiraled, to the point where “the two black holes get close enough to collide together to form a single black hole” (Favata). According to Favata, the “strongest [gravitational waves] are emitted during this process [of merging]”. The final step in a binary black hole merger is what is referred to as the “ringdown”, the final merged product of which is described by research professor Harry Collins in his book *Gravity’s Kiss* as being quite similar to “a huge spherical blob of very stiff jelly that quivers in one direction then another before it settles" and then stops producing gravitational waves that we are capable of observing (Favata, Collins 92). Favata further explains that the "ringdown" phase creates a black hole with "large distortions in its shape" and that it behaves "like a struck bell", while those "distortions are quickly radiated away as more [gravitational waves]", as can be evidenced by the final portion of Figure 1, where the gravitational waves slowly taper off (Favata).

Between 1916 and 1918, Einstein first proposed the idea of gravitational radiation, also known as gravity waves, by inferring that gravitational radiation is produced by massive objects and capable of radiating outward through space, as electromagnetic radiation radiates from a source that creates it. In the article "What are Gravitational Waves?," LIGO explains that gravitational waves propagate through spacetime like ripples in a pond, spreading out through the fabric of spacetime, even at great distances (LIGO). Dr. Chad Orzel states that spacetime is "flexible" and has the ability to "support disturbances that propagate like waves," which allows for gravitational waves to "ripple outward from the source, stretching and compressing spacetime as they go" (Orzel 251-252). Considering that gravitational waves are required by Einstein's theory of relativity to travel at the speed of light, it is no wonder that they are capable of reaching Earth from extreme distances (Orzel 251-252). Now, obviously as massive objects such as planets and stars and black holes exist within the fabric of spacetime, it is possible for an observer to witness the effects of gravitational waves upon all celestial bodies, provided that one had the ability to measure it. What gravitational waves do to spacetime is "compress and stretch the fabric of spacetime" as they ripple outward (Bartusiak 176-178). In other words, the wave "compresses space in one direction" while simultaneously "expanding space in the perpendicular direction," (Bartusiak 176-178). As distance between the source of the gravitational waves and the observation point increases, this effect is weakened dramatically, to the point where any change created by expansion or compression is smaller than the “width of a proton particle,” (Bartusiak 177).

Now, with the change of compression and expansion within spacetime decreasing by such a wide margin by the time gravitational waves reach the Earth, one might correctly assume that it takes very sensitive equipment to measure such infinitesimal differences in spacetime. Currently, there are two scientific laser interferometry observatories operating and detecting gravitational waves. The method with which laser interferometers measure gravitational waves is through examining the type wave interference that occurs.

The website SXS, or Simulating Extreme Spacetime, explains the method for measuring the compression and expansion of spacetime that gravitational waves create. According to SXS, an interferometer is a scientific device which makes use of the interference of the laser’s light waves. This device is capable of measuring changes in length with extraordinary precision, making it possible to detect the minute changes in distance that would occur if a gravitational wave were to pass through the interferometer (SXS). As a wave is a “disturbance which brings some medium higher or lower than that medium would be without any waves,” interference can mean that when “two different waves are traveling along [this] medium and meet,” it creates the phenomena of destructive interference or constructive interference in the process (SXS).

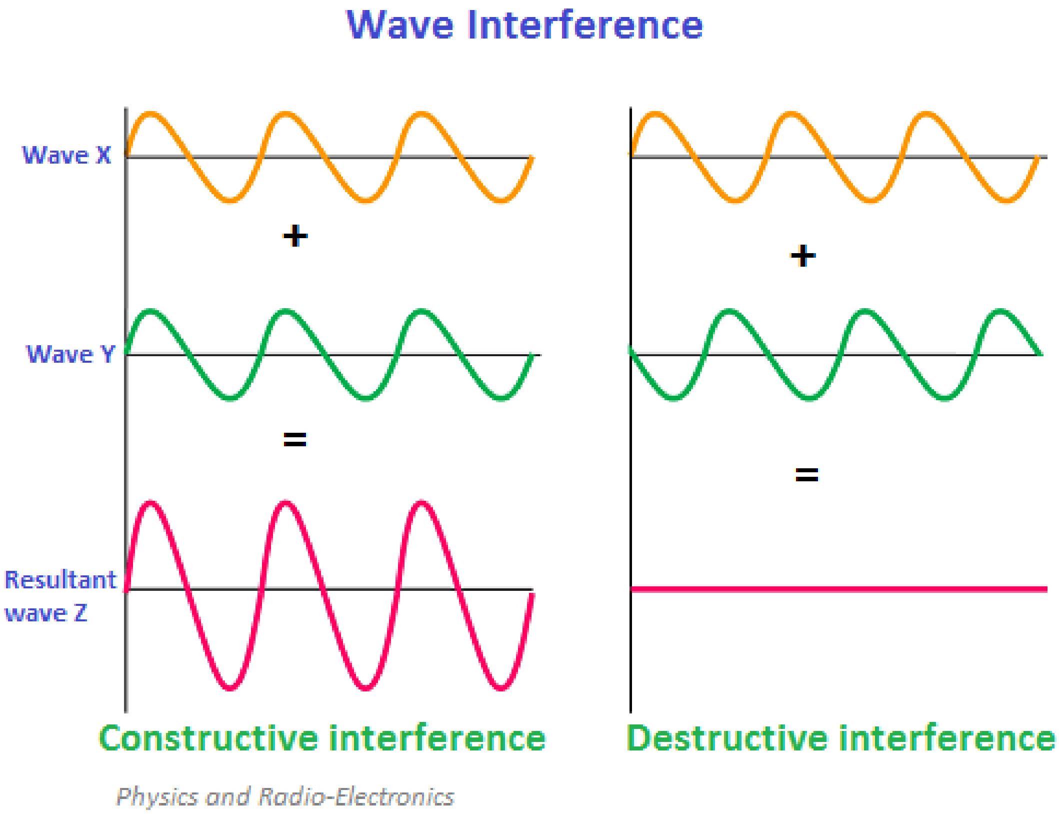

Fig. 2. “Wave Interference”

(Physics and Radio-Electronics)

As seen on the left side of the illustration, Figure 2, destructive interference is what happens when one of those two waves “tries to bring the medium higher,” while the other wave “tries to bring the medium lower” in essence “they cancel each other out” because there is then “no change in the medium” itself (SXS). Constructive interference, however, is what happens when both waves “try to change the medium in the same way,” building on each other and “disturb[ing] the medium more than either wave could manage alone,” because “their peaks match up at the same time” (SXS). With destructive interference, those peaks and valleys do not match up (SXS).

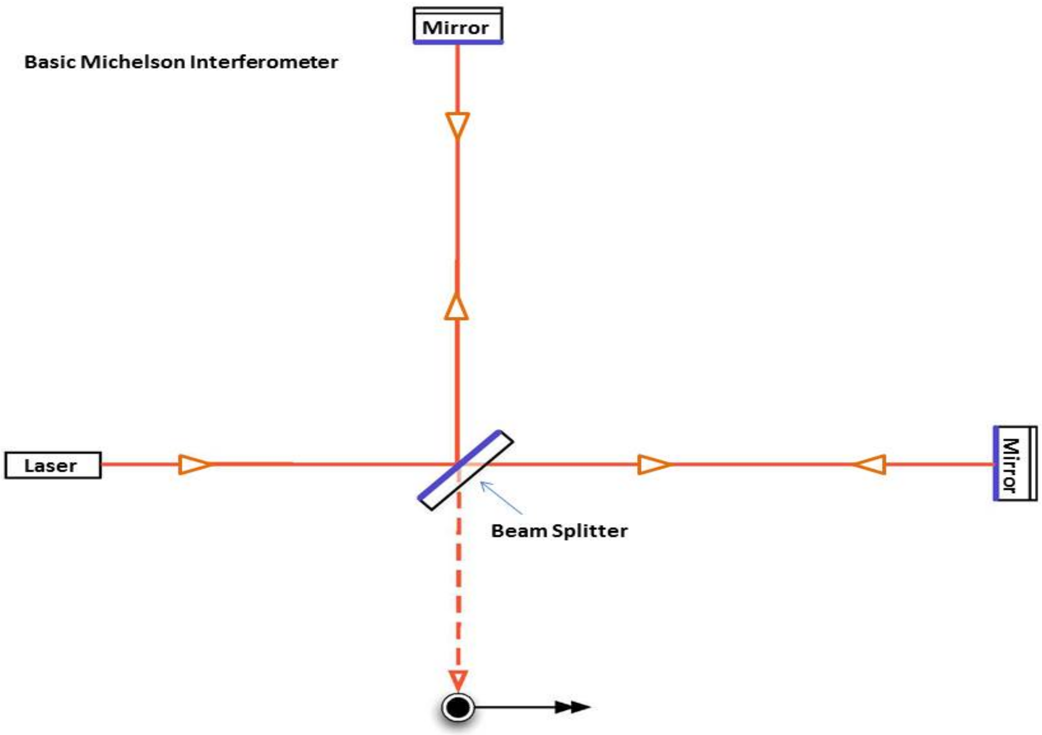

Fig. 3 “Basic Michelson Interferometer”

(Caltech/MIT/LIGO Laboratory)

Now, basic laser interferometry utilizes the ability of a laser “split into two parts” by a “semi-reflective” mirror known as a “beam splitter” and reflected back by two other mirrors into a detector, to make the laser’s two light waves “switch between interfering constructively and destructively” (SXS). This ensures that “they will switch between producing very large waves and producing no waves at all” by “keeping one wave in place and shifting the other by just a little bit—half a wavelength” or approximately “1/100,000 of an inch,” a small distance that is easily detectable by such a sensitive instrument (SXS). As seen in Figure 3, a laser is pointed at that beam splitter and reflected both upwards to a mirror and to the left to another mirror, before both of the beams are reflected back to the beam splitter mirror, becoming a single beam once more before it heads to where the detector would be. This is represented by the dashed line beneath the beam splitter in the diagram. Because of the way a laser interferometer works, if a gravitational wave were to pass through an interferometer, one of the beams' wavelengths would suddenly become shorter or longer than the other, changing how their peaks and valleys line up, leading to either destructive or constructive interference which could be easily detected once compared with the other beam, because its overall length would be shorter or longer by a tiny fraction.

LIGO was the first laser interferometer that was used for gravitational wave observation. LIGO stands for "Laser Interferometer Gravitational-wave Observatory" and is based within the United States. However, the LIGO that is currently operating is Advanced LIGO, which is not the original laser interferometer that was operated by that observatory. Initially, as reported by LIGO on their website, the original LIGO was constructed in 1999, and its "search for gravitational waves began in 2002 and concluded in 2010, during which time no gravitational waves were detected" (LIGO). The experience proved to be worthwhile, though, as it allowed LIGO to "prepare for the next phase of LIGO's search" and ultimately "led to a complete redesign of LIGO's instruments" which was completed "between 2010 and 2014," creating a "10-fold increase in sensitivity" which led to an ability to "listen for gravitational waves 10 times further away than initial LIGO," (LIGO). This increase in sensitivity proved to be successful "within days", where its predecessor was not "in 8 years of operation" (LIGO). Now,
while LIGO is typically referred to as a singular entity, it is actually comprised of more than one laser interferometer. The LIGO website lists under its facilities tab, that the interferometers are "located in fairly isolated areas of Washington (LIGO Hanford) and Louisiana (LIGO Livingston), and separated by 3,002 km (1,865 miles)" while its research is performed at the California Institute of Technology in Pasadena, California and the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts who are also sponsors of LIGO (LIGO).

Interestingly enough, LIGO isn't alone in its search for gravitational waves. Calla Cofield, a senior writer for space.com, points out in an article titled "Gravitational-Wave Detector Catches Lightest Black Hole Smashup Yet" that the two LIGO locations aren't the only ground-based laser interferometry observatories in existence (Cofield). LIGO has "a companion in [their] search" for objects producing gravitational waves (Cofield). The Virgo Gravitational Wave Observatory "came online in Italy" in August of 2017, making two "joint signal detections that [same] month –a black hole merger on August 14, and the first-ever detection of a binary neutron star merger on August 17," setting up a partnership to help confirm gravitational wave detections (Cofield).

On Virgo's website, in articles titled "Virgo In a Nutshell" and "Advanced Virgo," Virgo shares details about their most recently created laser interferometry observatory (Virgo). It was "designed and built by a collaboration between the French Centre National de la Recherche Scientifique (CNRS) and the Italian Istituto Nazionale di Fisica Nucleare (INFN)" and that it is operating in Cascina, Italy, "a small town near Pisa on the site of the European Gravitational Observatory (EGO)" (Virgo). Like LIGO, Advanced Virgo also underwent significant upgrades after their original versions failed to detect to gravitational waves, which increased both of their sensitivities by a factor of ten (Virgo). The partnership between the LIGO sites and Virgo are especially important, because interaction between the three during the detection of a gravitational wave observatory allows for a process known as triangulation (Virgo, "A Worldwide Network"). Virgo explains that in order to find the location that the gravitational waves are originating from "a triangulation process is necessary" (Virgo). Triangulation requires "at least three antennas placed at different position [sic] on Earth," in a process "very similar to that used by seismologists to determine where earthquakes originate," allowing astronomers to have a more definite idea of where the source of the gravitational waves is located than they would when the LIGO locations were the only operational system of gravitational wave observation (Virgo). Additionally, for these companion observatories, LIGO and Virgo, working together allows them to "disentangle real gravitational signals from spurious ones" or false signals coming from sources like the movement of Earth's tectonic plates or other such interference (Virgo). They have been collaborating with one another since 2007 (Virgo).

Despite the fact that their advanced detectors have only been working since 2015, Calla Cofield states that, so far, five binary black hole mergers have been detected by LIGO, all of which "have involved . . . stellar-mass black holes" since their very first definite detection of gravitational waves on September 14, 2015. However, the most recent detection of gravitational waves produced by a binary black hole merger, known as event GW170608, "involv[ed] some of the lightest black holes that the observatory has yet detected, at seven and 12 times the mass of the [S]un" (Cofield). This produced a "black hole 18 times the mass of the [S]un," which was suggested by Eve Chase, a doctoral student at Northwestern University and LIGO collaborator to possibly be "the lightest combined-mass black hole detected by LIGO" and may link "two separate populations of black holes," the ones detected by laser interferometry observations such as LIGO and ones previously detected "through X-ray observations" (Cofield). The LIGO Scientific Collaboration released an issue brief and research report about the most recent detection GW170608, titled "Observation of a 19-Solar-Mass Binary Black Hole Coalescence" (LIGO). This event discussed in Cofield's article, was published on November 15, 2017, although the initial observation was "observed by the twin LIGO detectors June 8, 2017" (LIGO Scientific Collaboration). According to another LIGO Scientific Collaboration issue brief and related research report titled “GW150914 – The First Direct Detection of Gravitational Waves,” the first ever direction observation of a binary black hole merger, as stated earlier, was “observed by the LIGO’s twin observatories on September 14, 2015” and “confirm[ed] a key prediction of Einstein’s theory of general relativity and provide[d] the first direction evidence that black holes merge” (LIGO Scientific Collaboration). This rewarded a hundred years of physics work and helped cement the study of gravitational waves as a new subset of astronomy and astrophysics (LIGO Scientific Collaboration). In between the events GW150914 and GW170608, the very first observation of gravitational waves and the most recent respectively, there were the events GW151226, GW170104, and GW170814. Information on GW170104 and GW151226 were both published month of June 2017 by the LIGO Scientific Collaboration in issue briefs and related research reports titled “GW170104” and “GW151226,” respectively. GW170104 was observed after GW151226, on January 4, 2017, although information on GW170104 was released first (LIGO Scientific Collaboration). An article by Massimiliano Razzano for Virgo titled “GW151226, The Second Event”, states that on “December 26, 2015 at 03:38:53 UTC, the LIGO and Virgo scientists . . . observed gravitational waves for the second time” (Razzano). However, it makes no mention of Virgo’s interferometer (Virgo). This is because, as reported in an article by Michelle Starr titled “IT’S OFFICIAL: Gravitational Waves Were Just Detected With the Greatest Precision Ever”, the first use of the Advanced Virgo Laser Interferometer Observatory occurred when “Advanced Virgo joined LIGO for an observation run on 1 August [2017]” (Starr). Less than two weeks later, a “detection of a collision between two black holes using not two detectors, but three” was made utilizing both LIGO detectors and the new Advanced Virgo detector, which “vastly improv[ed] the accuracy, by a factor of about 10, with which astronomers [were able to] pinpoint the source of the waves” (Starr). This increase in accuracy has a great deal to do with the positions of each observatory; the LIGO detectors, as previously stated, are in Washington and Louisiana, while Virgo is located in Italy.

There seem to be more discoveries regarding gravitational waves made every few months, but there is still plenty to learn about what events can produce gravitational waves that are detectable here on Earth and more gravitational wave observatories that are planned for construction in the near future. The LISA, or the Laser Interferometer Space Antenna is planned to be exactly as it sounds and much more, a gravitational wave observatory in space led by the European Space Agency with a little help from NASA, or the National Aeronautics and Space Administration (NASA). However, it’s not going to consist of one spacecraft making observations in space (NASA). It will be three spacecraft reflecting lasers back and forth to one another, separated by millions of miles (NASA). There’s are certain advantages to this, as it will allow scientists to detect gravitational waves that ground-based interferometers cannot, because gravitational waves that occur at lower frequencies require an antenna so large that it must be in space (NASA). According to the LISA homepage at the NASA website, the three spacecraft involved will use their lasers to “create an equilateral triangle in space," as illustrated in Figure 4 (NASA). The paths between each pair of spacecraft, referred to as LISA’s arms, will extend millions of miles,” (NASA). They will then measure “distance changes in these arms caused by passing gravitational waves,” which will be able to detect even more slight disturbances than any Earth based detectors ever could (NASA).

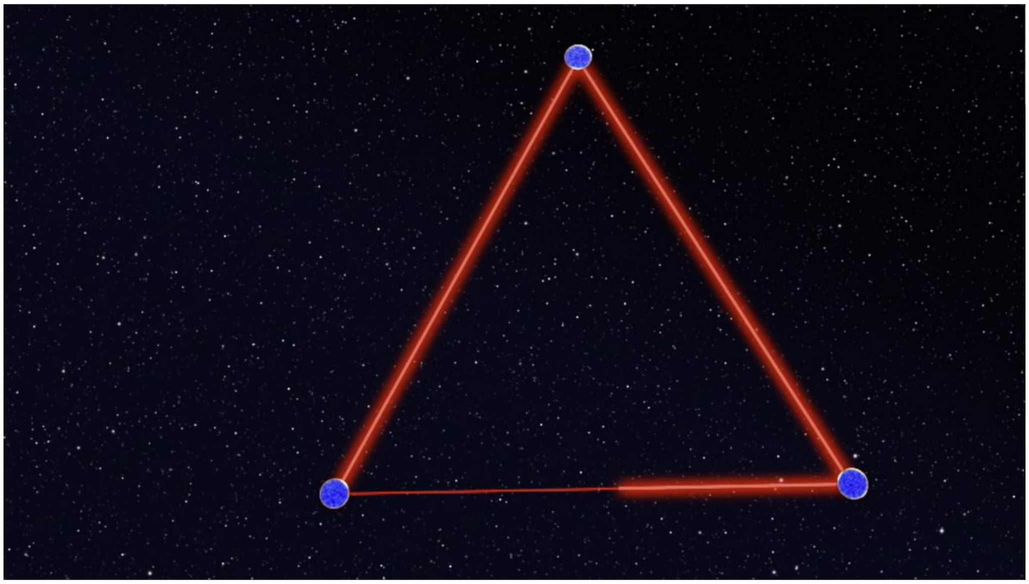

Fig. 4 “LISA in 3 Arm Configuration”

(AEI /MM/exozet, eLISA Science Team)

Fascinatingly, the LISA is not the only space-based laser interferometer planned for the near the future. Japan is also planning their own space-based laser interferometer gravitational wave observatory, to be called DECIGO. DECIGO, which stands for DECi-hertz Interferometer Gravitational wave Observatory has been in the works for nearly a decade or more. According to the Japan Aerospace Exploration Agency (JAXA) and a report published by Japanese scientists titled “The Japanese Space Gravitational Wave Antenna”, DECIGO will operate on a frequency band between the planned LISA gravitational wave observatory and ground-based observatories (Seiji Kawamura, et al.). DECIGO could observe “inspiral sources [whose frequencies] . . . have moved above the LISA band” or “inspiral sources [whose frequencies] have not yet moved into the terrestrial detector band;” this means that DECIGO could potentially detect things that the other observatories, LIGO and Virgo, cannot. This is because the gravitational waves sources are incredibly distant, so the frequencies of the waves become lower, or redshifted, due to the expansion of the Universe. With the “extremely high sensitivity” that DECIGO is expected to have, the scientists involved expect that data gathered by DECIGO will provide further information on the “characterization of dark energy”, the “formation mechanism of supermassive black holes in the center of galaxies”, and may even help to substantiate and further clarify the theory of inflation which refers to the period after the Big Bang where the universe expanded rapidly (Seiji Kawamura, et al).

The National Astronomical Observatory of Japan reports on their website that DECIGO will “consist of three drag-free spacecraft, 1000 km apart from each other” (Gravitational Wave Project Office). The spacecraft are only going to move due to the influence of gravity as opposed to “solar radiation pressure” or other influences (Gravitational Wave Project Office). Each of the three spacecraft will consist of two floating mirrors, two photodetectors, and a laser (Gravitational Wave Project Office). With the three spacecraft arranged in a triangular shape, the lasers from each spacecraft will bounce off of the others’ mirrors, creating a “Fabry-Perot cavity” through which gravitational waves will be detected (Gravitational Wave Project Office). LIGO helpfully defines the term Fabry-Perot cavity on their website in an article titled, “LIGO’s Interferometer,” as an added feature used to make their 4-kilometer-long arms long enough to detect gravitational waves (LIGO). According to LIGO, Fabry-Perot cavities are an addition to the “basic Michelson design”, which is illustrated in Figure 3, and are “created by adding mirrors near the [laser] beam splitter that continually reflect parts of each laser beam back and forth within the…arms about 280 times before they are merged” together towards the interferometer’s detector (LIGO). The modified Michelson interferometer with Fabry-Perot cavities is illustrated in Figure 5 in this paper.

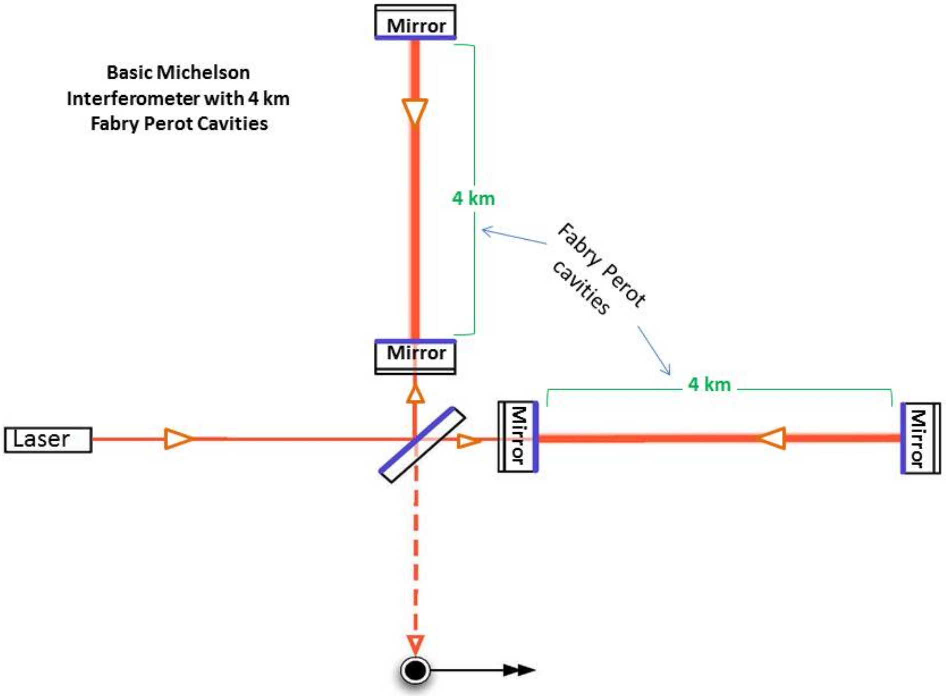

Fig. 5 “Basic Michelson Interferometer with Fabry-Perot Cavities”

(Caltech/MIT/LIGO Laboratory)

In addition to planning additional laser interferometry gravitational wave observatories, astronomers and astrophysicists are also predicting what sorts of gravitational wave events may be seen in the near future. As Meghan Bartels wrote in article titled “Two Supermassive Black Holes Are Set For A Catastrophic Collision That Will Send Shockwaves Throughout the Universe,” astrophysicists “think we’ll be able to detect collisions of supermassive black holes . . . within just the next ten years” (Bartels). However, ground-based laser interferometers won’t be able to detect these collisions because “those gravitational waves will be at much too deep a pitch for the LIGO detectors and . . . Virgo to pick up” (Bartels). Instead, the interferometers will be able to detect when, as Bartels states, the gravitational waves will “interfere with a very special type of star-like object called a pulsar,” which is an object that “twinkle[s] at a set rate that scientists can measure," due to the fact that pulsars emit "two jets of radio waves in opposite directions" while the pulsar "spin[s] along a different plane" which causes those jets to "spin like a spotlight" (Bartels). When gravitational waves produced by the merger of two supermassive black holes distort the spacetime where the pulsar is located, it will cause the pulsar to "wobble a little" which scientists can observe through a number of instruments dedicated to researching pulsars (Bartels). While this manner of observing gravitational waves is more indirect than using ground-based laser interferometers to observe such phenomena, it is possible that if the LISA and DECIGO are constructed, and launched into space, they may be able to detect the gravitational waves produced by a potential supermassive black hole merger.

The possibilities of further pursuing gravitational wave astronomy, especially in relation to binary black hole mergers, may mean that we gain a better understanding of the nature of black holes and of spacetime itself. Given how recent the field is, just barely over a hundred years old in concept and less than five years into definite existence, it's a testament to human innovation and understanding that we are providing evidence to Einstein's theories to such a substantial degree. From understanding black holes, how they form, the nature of binary black hole systems and how we can observe their effect on the universe through gravitational wave observation, it seems reasonable to expect that this new field of astronomy will continue to grow exponentially in the coming years. We may finally have some concrete answers to some of the mysteries of the universe that humanity does not yet have the knowledge to understand. The future of gravitational wave astronomy and observation is almost assuredly as bright as a supernova produced by a 20+ solar mass star.

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