

Black Holes

The Most Luminous Objects in the Universe, But No Light!

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When a massive star exhausts the nuclear fuel whose burning keeps it hot, the star's internal pressure plunges. Gravity overwhelms the pressure and pulls the star inward upon itself. The star implodes, shrinking smaller and smaller, and the gravity on its shrinking surface becomes stronger and stronger (because of Newton's inverse square law). Ultimately, when the star has shrunk to a few tens of kilometers size, its gravity grows so enormous that nothing, not even light, can escape its grip. The star creates a *black hole* around itself. The star itself, inside the black hole, continues to shrink and is destroyed by a *singularity* of infinite, chaotic gravity that resides at the hole's center. This story is an unequivocal prediction of Albert Einstein's general relativity theory.

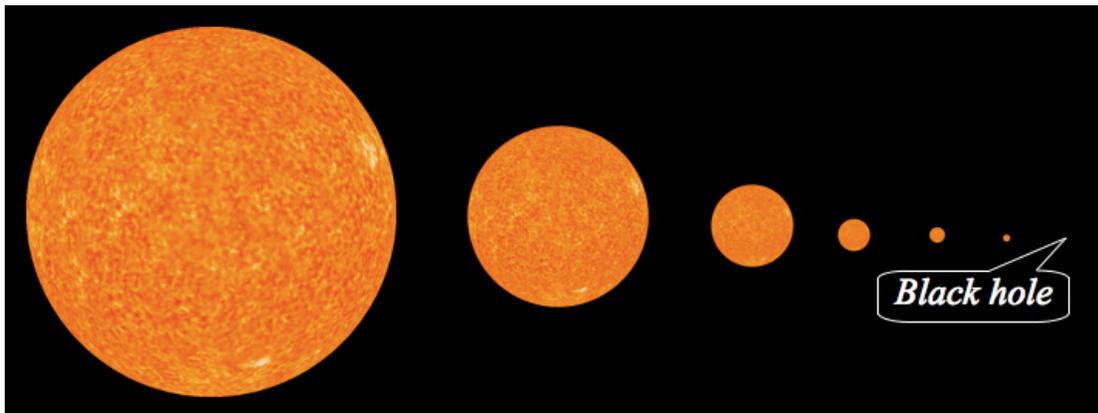


Figure 1. The Implosion of a Star to form a black hole

How a Black Hole Affects its Environment

There are millions of black holes in our Milky Way galaxy, and trillions in the Universe; and they can wreak havoc on their environments:

If the imploding star had a companion star orbiting it, the black hole will inherit the companion. The hole's gravity can then pull gas off the companion, and the gas will spiral inward toward the hole, producing a gaseous disk so hot that it emits X-rays rather than light. Astronomers see many such disks, encircling heavy, dark objects that must be black holes.

In the centers of galaxies, such as our Milky Way, supermassive black holes have somehow formed – perhaps from the implosion of supermassive stars, perhaps from the collision and merger of many smaller black holes. These giant holes, a million to 10 billion times heavier than the Sun, and with sizes as large as our solar system, can tear stars apart and spread the stellar debris around themselves as hot, gaseous disks.

Magnetic fields, embedded in such a disk interact with a vortex of twisting space that sticks out of the black hole (and that I shall discuss later), to produce gigantic jets of outflowing energy. These jets sweep out into intergalactic space, sometimes carrying as much luminosity as all the stars in the galaxy put together! Astronomers have seen and studied hundreds of these jets and their surrounding disks, but have never seen the central black holes because they are black. They emit no light.



Figure 2. A black hole encircled by a hot, gaseous accretion disk, and two jets emerging from the hole's vicinity. [From K.S. Thorne, *Black Holes and Time Warps* (Norton, 1995).]

Warped Spacetime Around a Black Hole

What is a black hole made from? Not from matter like you and me, but from warped space and time.

As an analogy to explain this, imagine a child's trampoline, a large sheet of rubber attached to tall stilts. A heavy rock bends the rubber downward as shown in Figure 3. Now, imagine you are an ant; a blind ant. The rubber sheet is your entire universe, and you explore it by measuring its shape. You measure the circumference of a circle surrounding the central rock by walking around it, and you then measure the circle's diameter. You walk and walk and walk along the diameter. It is a great distance, you discover; the diameter, in fact, is far larger than the circumference. Being an intelligent ant, you conclude that the space of your universe is warped. It does not have the flat geometry described by Euclid; rather, it has the geometry of a warped rubber sheet.

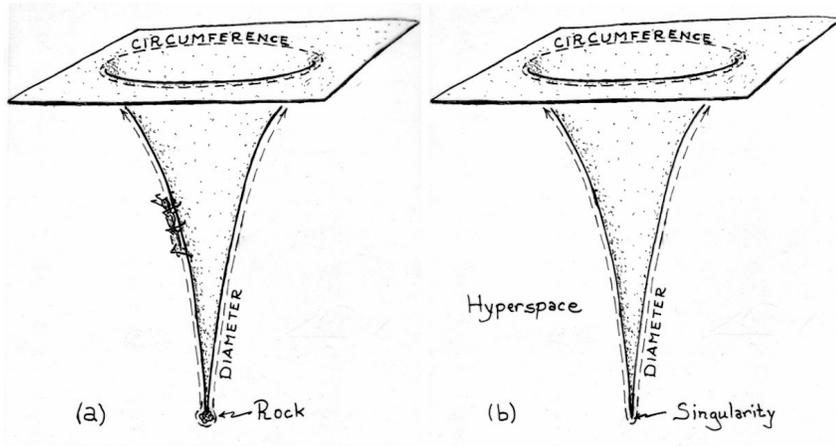


Figure 3. (a) A trampoline with a rock at its center and an ant exploring its shape. (b) Space around a black hole, as viewed from a higher dimensional hyperspace that is not part of our Universe.

If we, in our Universe, could take a 2-dimensional slice through the equator of a black hole and measure its shape, we would find a shape identical to that of the ant's rubber sheet: a diameter far larger than circumference (Figure 2b). The hole's space is bent downward in some higher-dimensional "hyperspace" that is not part of our universe. And at the center, in place of a heavy rock, there is a *singularity* where space is infinitely sharply warped – a vicious singularity that destroys any matter that strays into its vicinity.

Suppose I fall into a black hole, transmitting microwave signals to you on the outside as I fall; see Figure 4a. When I reach the black hole's edge, which we call its *horizon*, gravity becomes so strong that my signals can no longer escape. Inside the horizon, the signals get pulled downward into the singularity along with me. I pay the ultimate price that I can't publish the results of my explorations. I also die, and my results die with me.

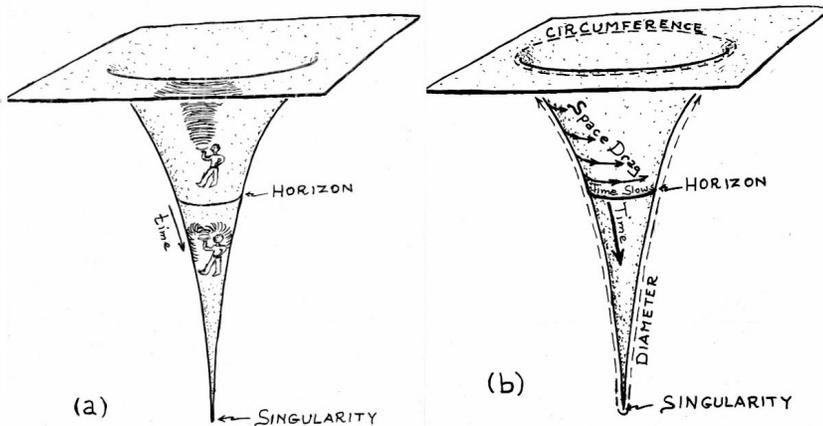


Figure 4. (a) I fall into a black hole, transmitting microwave signals to you as I fall. (b) The warping of time and dragging of space into motion around a black hole.

The horizon and its overwhelming gravity are actually produced by an extreme time warp: Near the horizon, time's rate of flow slows to a crawl (Figure 4b). If you were to fly down near a black hole's horizon and hover there for a few days and then return home to Earth, you would discover that millions of years have elapsed on Earth. You have aged only a few days, but your friends are long since dead.

Now, Einstein's Law of Time Warps says that "*Things like to live where they age the most slowly, and gravity pulls them there*". On Earth, time flows more slowly than in outer space by 4 parts in 10 billion, and that (according to Einstein) is enough to account for the gravity that holds us on the Earth's surface. Since the slowing of time becomes enormous as one nears a black hole's horizon, the pull of gravity becomes enormous there; and precisely at the horizon, time slows to a complete halt, so the pull of gravity is infinite. Inside the horizon, time still flows – but, strangely, it flows in a direction that you would have thought is spatial: toward the singularity at the hole's center. This is why nothing can get out of a black hole; to get out, things would have to travel upward, which means backward in time, and nothing can do that. This explanation of a black hole's blackness is equivalent to the "infinite gravitational pull" explanation. The two explanations are related by Einstein's Law of Time Warps.

If the star that imploded to create the black hole was spinning (and all stars spin, at least a little bit), then the black hole will spin. The hole's spin drags space into a whirling motion near itself – a fast whirl near the horizon and slower farther away, like the whirling air in a tornado. See Figure 4b. Anything that falls into the hole gets grabbed by the whirling space, like a straw grabbed by a tornado's whirling wind, and gets whipped around and around the hole, faster and faster as it nears the hole's horizon.

Figure 5 is a precise map of the warped spacetime around a fast-spinning black hole, as predicted by Einstein's relativity. The shape of the 2-dimensional surface is precisely that of the hole's space, in its equatorial "plane", as seen from hyperspace. The colors

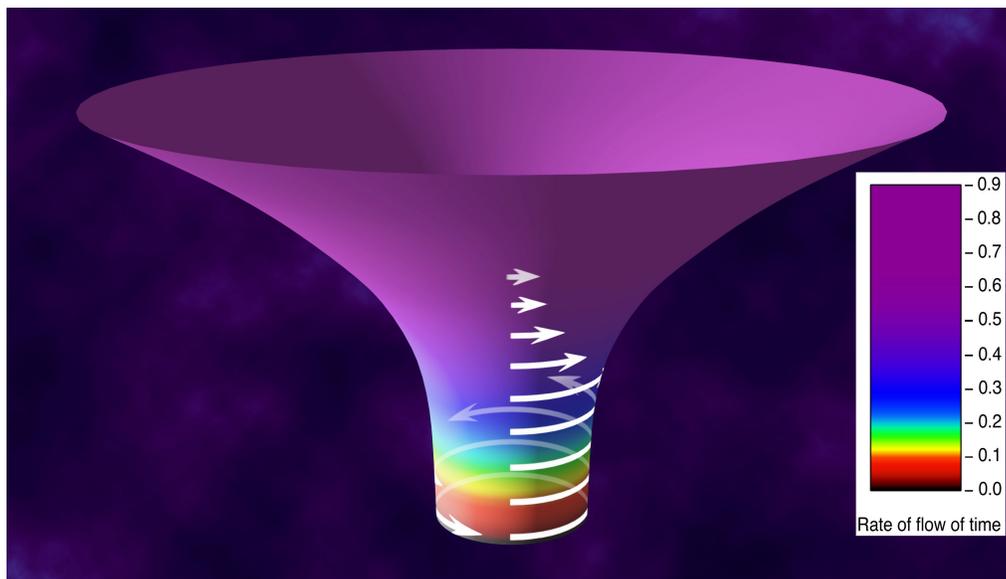


Figure 5. A map of the warped spacetime around a fast-spinning black hole.

Indicate the slowing of time near the horizon. The horizon is the black circle at the bottom (it becomes a sphere if we examine the hole's full 3-dimensional space rather than just its two-dimensional equatorial "plane". The white arrows indicate the speed of whirl of space caused by the hole's rotation.

Gravitational Waves, Colliding Black Holes, and Vortexes of Twisting Space

If two massive stars orbit around each other in a binary system, and both stars implode to form black holes, the result is two black holes orbiting each other: a *black-hole binary*. As these holes travel around each other, they produce ripples in the fabric of space that travel outward, like water waves from your finger if you stir it in a quiet pond. Those ripples are called *gravitational waves*. They travel into the universe at the speed of light, carrying a detailed, but encoded, picture of their source, the orbiting black holes. The waves also carry energy.

As the orbiting black holes lose energy to the waves, they gradually spiral together, then collide and merge to form a single, larger black hole, as depicted in Figure 6. When they collide, the holes emit gigantically strong gravitational waves. The waves' luminosity (the power emitted per unit time) is 10,000 times greater than the luminosity of all the stars in the universe, put together. *Ten thousand universe luminosities, and no light!* only gravitational waves. If the holes have small masses, say 10 times as great as the Sun, then the collision and humongous waves are brief: a few milliseconds. If the holes are supermassive – the denizens of the cores of two galaxies that themselves have collided and merged – the collision and waves last longer: a few days or even a year. The waves carry a detailed, encoded picture of the collision, a picture we would like to extract and study. To this I shall return.

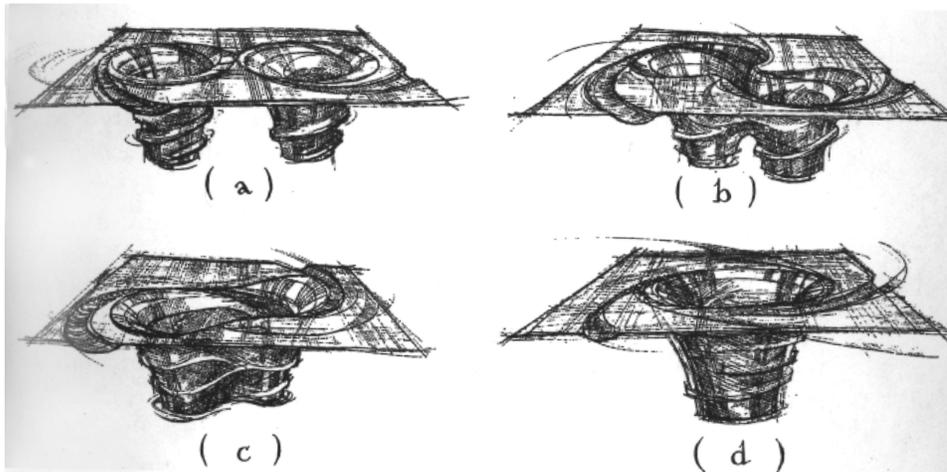
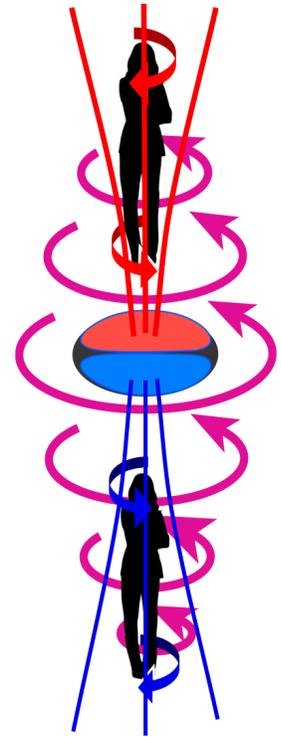


Figure 6. An artist's conception of two black holes in a binary, spiraling inward, colliding, and merging to form a single black hole

The tornados of whirling space, attached to each black hole in a binary, behave wondrously when the holes collide. To explain this, I must first describe the tornados more carefully.

Imagine two people hanging above a black hole's poles, as in Figure 7. The top person's feet are closer to the hole than her head, so they get dragged by the hole's whirling space (purple arrows) faster than her head. As a result, her head sees her feet dragged counter clockwise (lower red arrow), and – remarkably – her feet see her head dragged counterclockwise (upper red arrow). It's like wringing water out of a wet towel; your left hand sees your right turn counterclockwise, and your right hand, looking at your left, sees it turn counterclockwise. In this sense, the whirling space at the hole's north pole has a counterclockwise twist.



This twist was recently discovered in Einstein's equations, by a team of young physicists working with. And we discovered that the twist is guided by, i.e. carried by and controlled by, things we call *vortex lines*, a name we have borrowed from the theory of fluids. There are counterclockwise vortex lines, collected into a single *vortex*, sticking out of the north pole of the black hole (colored red in Figure 7) and a vortex of clockwise vortex lines sticking out of the south pole (colored blue). These are similar to magnetic field lines that stick out of the earth, but instead of guiding compass needles like a magnetic field lines do, they control the twist of space, and they twist everything they encounter. We have painted the hole's horizon the color of the vortex lines that stick out of it. Figure 7

My team has simulated the inspiral and collision of two spinning black holes using a large cluster of computers. Our simulations revealed that, when the holes collide and merge, their four vortexes of twisting space get deposited on the merged hole's horizon. As the merged hole, itself, spins, it splays the four vortexes outward and backward, like four streams of water splaying out from a whirling sprinkler head (Figure 8a). As these vortexes spiral outward into the universe, they become gravitational waves.

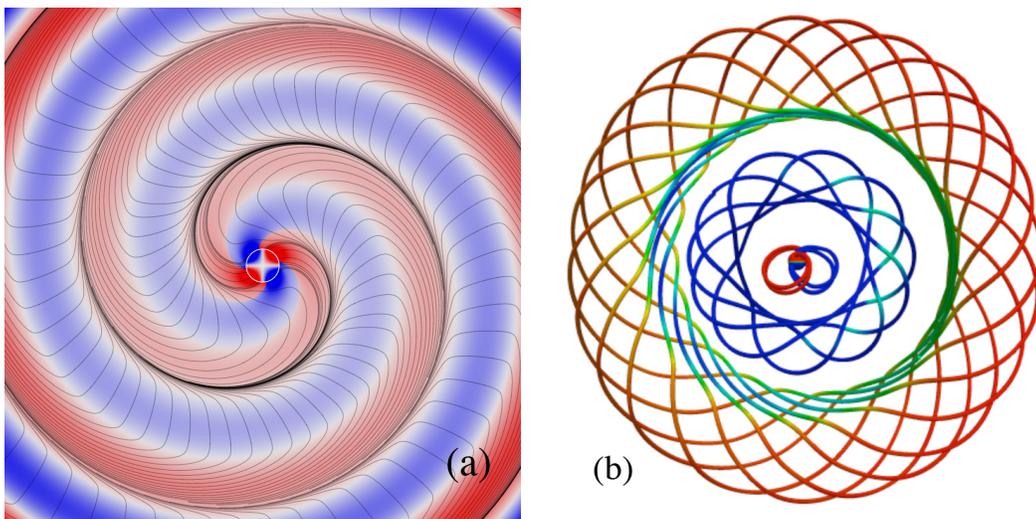


Figure 8: (a) Four vortexes of twisting space, sticking out of a merged, spinning black hole. (b) Vortex rings ejected by a merged, nonspinning black hole.

If, instead of spiraling together from a binary orbit, the two black holes collide head on, then the four vortexes attached to the merged black hole do not acquire an outward spiral. Instead, each vortex sloshes back and forth between clockwise twist and counter-clockwise, and with each slosh, the hole throws off a toroidal vortex ring that resembles a smoke ring (Figure 8b). As these rings travel outward, they become gravitational waves.

Black Hole Tears Neutron Star Apart; Multimessenger Astronomy

The power of a black hole's vortexes is illustrated in Figure 9, which shows snapshots from a computer simulation of a spinning black hole ripping apart a companion neutron star. The star is 1.5 times as massive as the Sun and has a diameter of 25 kilometers. The black hole is 4.5 times as massive as the Sun and spins around the axis marked by a red line. The star and black hole initially orbit each other in a horizontal plane (Fig. 8a). As they orbit, they lose energy to gravitational waves and, consequently, spiral inward. As they near each other, the hole's gravity begins to tear the star apart (Fig. 8b), and the hole's vortexes then throw the disrupting star upward, into the hole's equatorial plane (perpendicular to the red line; Figs. 8c and then 8d). Imagine the power required to throw 1.5 solar masses of nuclear material upward from the horizontal plane and into the hole's equatorial plane! The hole's vortexes are impressive.

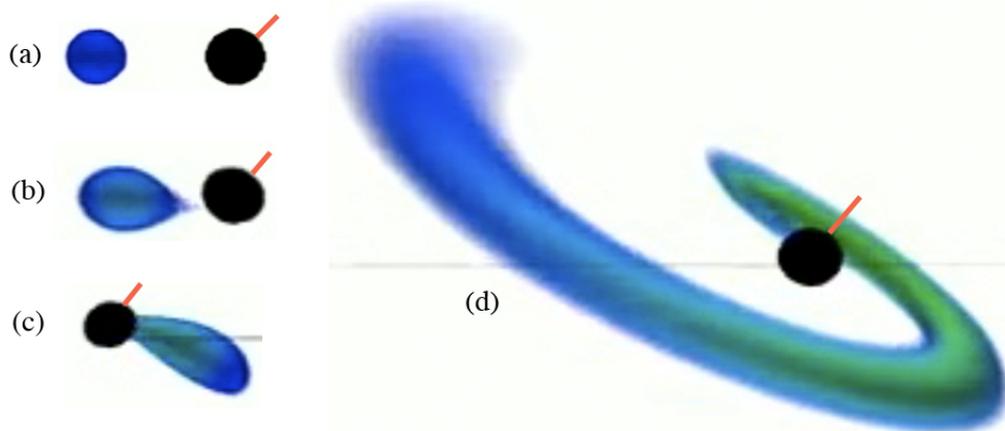


Figure 8. A spinning black hole tears apart a neutron star, one made from nuclear matter.

About 70 per cent of the disrupted star's matter is quickly swallowed by the hole, according to this simulation by Matt Duez and colleagues at Cornell University. The remaining 30 percent gets strung out into a disk of very hot gas, which emits a short burst of neutrinos and gamma rays and then shines brightly with light.

Coordinated observations of the gravitational waves, neutrinos, gamma rays and light will reveal much about the black hole and its vortexes, the neutron star and its nuclear matter, and their behaviors in this cataclysmic event. Comparison with computer simulations will be crucial for understanding the observations. This is called *Multimessenger Astronomy* and will be an exciting enterprise when it begins, around 2017.

Gravitational Wave Observatories

How can we detect and monitor the gravitational waves? Each wave contains space-twisting vortices; but after traveling across the great stretches of intergalactic space, the vortices have become exceedingly weak. Their twist is far too small for detection with modern technology.

Fortunately, the waves also stretch space and squeeze it. This stretch and squeeze are also weak, but they are ideally suited for detection and monitoring by a technique called *laser interferometry*. Accordingly, in 1983 my colleagues Rai Weiss at MIT and Ron Drever at Caltech and I conceived the Laser Interferometer Gravitational Wave Observatory – *LIGO* for short.

The concept for LIGO's gravitational wave detectors is depicted in Figure 9. Four mirrors (each weighing 40 kilograms) hang from overhead supports. Two mirrors are oriented along one direction (say, east-west); the other two, along the perpendicular direction (say, north-south); and the mirrors on each "arm" are separated by 4 kilometers distance (denoted L in the figure). When a gravitational wave arrives, it pushes the east-west mirrors apart and the north-south mirrors together, by a tiny amount: $\Delta L = 10^{-17}$ centimeters (approximately). As the wave moves on from crest to trough, the directions of the stretch and squeeze reverse, and then reverse again; and the time pattern of those reversals (called the wave's *waveform*) carries, encoded, the picture of the wave's source. In LIGO, these motions are monitored using a laser beam – ultrahigh precision laser metrology, and pictures of the source are extracted from the observed waveform by comparing with computer simulations.

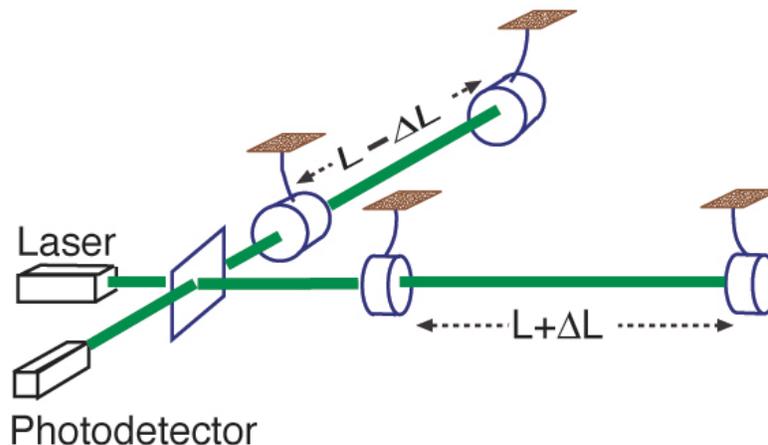


Figure 9. A laser interferometer gravitational-wave detector.

Weiss, who invented this idea, is brilliant. For several years, I was extremely skeptical at it could ever succeed, but I was wrong. To understand my skepticism, consider just how small are the mirror's motions: The thickness of a human hair is about 10^{-2} centimeters. Divide that by 100 and you get the wavelength of the light used in LIGO, one micron. Divide by 10,000 and you get the diameter of an atom, the smallest thing ever imaged by any kind of microscope. Divide by 100,000 and you get the diameter of the nucleus of an

atom. Divide by another factor 1,000 and you get the motions that LIGO must monitor: 10^{-17} centimeters!

This distance is so small, that at this level of precision, LIGO's moving mirrors are governed not by the laws of classical physics, but rather by the laws of quantum physics. For example, the *Heisenberg uncertainty principle* dictates that the very act of measuring the location of a 40 kilogram mirror with this precision will inevitably perturb the mirror's velocity by an amount that is discernable in LIGO. Humans have never before seen a human-sized object behave quantum mechanically. In LIGO we will do so within the next several years, and to deal with this we have had to incorporate principles from a new, twenty-first century technology, called *quantum information theory*. My students and I spent much of our time in the early 1980s exploring the needed technology theoretically, and again in the early 2000s developing concrete designs for it.

LIGO is now nearing maturity. In the 1990s, my experimental colleagues (under the leadership of Caltech's Barry Barish) built facilities to house our gravitational wave detectors, and in 2000-2005, they installed a first generation of detectors and debugged them meticulously until they reached their design sensitivity. In 2005-2010, we carried out an initial set of searches for cosmic gravitational waves, not just from colliding black holes but from many other sources. We saw nothing; but that was expected:

When my colleagues and I proposed LIGO, we warned that this first generation of detectors might *not* be good enough to see waves. However, the experimenters had to build them and get experience with them as a precursor to building a second generation of detectors, called Advanced LIGO, which are far more complex technically and will be far more sensitive: sensitive enough to see a rich variety of waves. Our experimental team began installing Advanced LIGO into the LIGO facilities in October 2010, and the installation is going well. By 2017, and perhaps sooner, these detectors should be seeing many waves, and together with similar detectors in Europe (the French-Italian-Dutch *Virgo* Project and the German-British *Geo* Project), and other types of astronomical instruments, they should be ushering in the era of Multi-Messenger Astronomy.



Figure 10. LIGO's two gravitational-wave observatories. Left: Hanford, Washington. Right: Livingston, Louisiana

LIGO and its partners can only observe black holes less massive than about 1000 suns. Heavier black holes – the supermassive ones in the cores of galaxies like our Milky Way – produce waves with far longer wavelength (of order the distance between the Earth and the Moon, or the Earth and the Sun) and far lower frequency (one cycle per minute or hours or longer). These waves will be detected and monitored by a LIGO-like detector that flies in space: three spacecraft that track each other with laser beams. The European Space Agency is planning a space mission of this sort, called *LISA*, the Laser Interferometer Space Antenna, and will fly a precursor space mission to test its technology in 2014. (The US space agency NASA used to be a partner in LISA, but was forced to pull out of this and other astrophysics missions by huge cost overruns on the James Webb Space Telescope.)

For even heavier black holes, those weighing billions rather than millions of suns, a third type of detector is needed. These holes waves have wavelengths far larger than the solar system and wave periods of months to years. They are being sought using LIGO-like detectors in which one of the “mirrors” (really just a moving mass) is the Earth, and the other is a pulsar far out in interstellar space. Radio telescopes on Earth monitor the radio pulses from a network of dozens of these pulsars, looking for tiny oscillations in the pulses’ arrival times, caused by gravitational waves. This *International Pulsar Timing Array*, as it is called, is likely to detect its first gravitational waves in the coming ten years; maybe five.

Conclusions

Black holes are made from warped space and time – and that warping exhibits a remarkable richness. I have only exposed you to one piece of that richness: the *vortexes* of twisting space that black holes transfer to each other when they collide, and that generate outflying rings or spirals of gravitational waves. There are also objects called *tendexes*, that also stick out of black holes. They stretch and squeeze space in interesting ways and participate in the gravitational waves that black holes generate.

Numerical simulations are a powerful tool for probing these vortexes and tendexes theoretically. Gravitational wave observations will reveal them in Nature and show us their richness and influence in the real Universe. These tools – numerical simulations and gravitational wave detectors – are ushering in a golden era of research on black holes.

For Further Information:

I recommend following the development of this subject on the following websites:

1. <http://www.black-holes.org/> Numerical simulations of black holes by my research team.
2. <http://www.ligo.caltech.edu/> and <http://www.ligo.org/> The LIGO project for detecting gravitational waves and using them to explore the universe.