

Black Holes Explained

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RELATIVITY

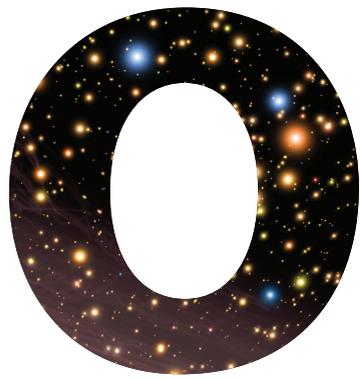
RIGHT OR WRONG?

Einstein's relativity replaced Newton's gravity. Now observations of black holes might test the limits of Albert's masterpiece.

by Jesse Emspak

The event horizon of the supermassive black hole at the center of the Milky Way appears dark against a bright maelstrom of swirling gas and infalling matter. Astronomers hope to probe general relativity's limits by imaging this black hole.

ADOLF SCHALLER FOR ASTRONOMY



ON FEBRUARY 11, 2016, two teams of scientists announced the first observation of gravitational waves, a phenomenon that Albert Einstein's general theory of relativity had predicted a century earlier. The Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo collaborations had caught ripples in space-time itself: the wake of two black holes that collided and merged more than a billion light-years away.

It was a triumph for general relativity. But to physicists, it wasn't an end; it was a beginning. Black holes — objects so dense that not even light can escape — proved Einstein right. Now, scientists want to use them to stretch relativity to its limits, and perhaps even break it.

"It's not that we think relativity's wrong," says Andrea Ghez, a professor of physics and astronomy at the University of California, Los Angeles, and director of UCLA's Galactic Center Group. "It's just incomplete."

Astronomers and physicists are working to probe black holes with radio telescopes and gravitational waves, as well as tracking the motions of stars and other matter around black holes to see if they follow the rules laid down by Einstein a century ago.

The general theory of relativity has passed every test physicists have devised so far. It underlies our understanding of space, time, and gravity; Global Positioning System satellites even take it into account. It superseded Isaac

Newton's conception of gravity as a force that acts instantaneously at a distance.

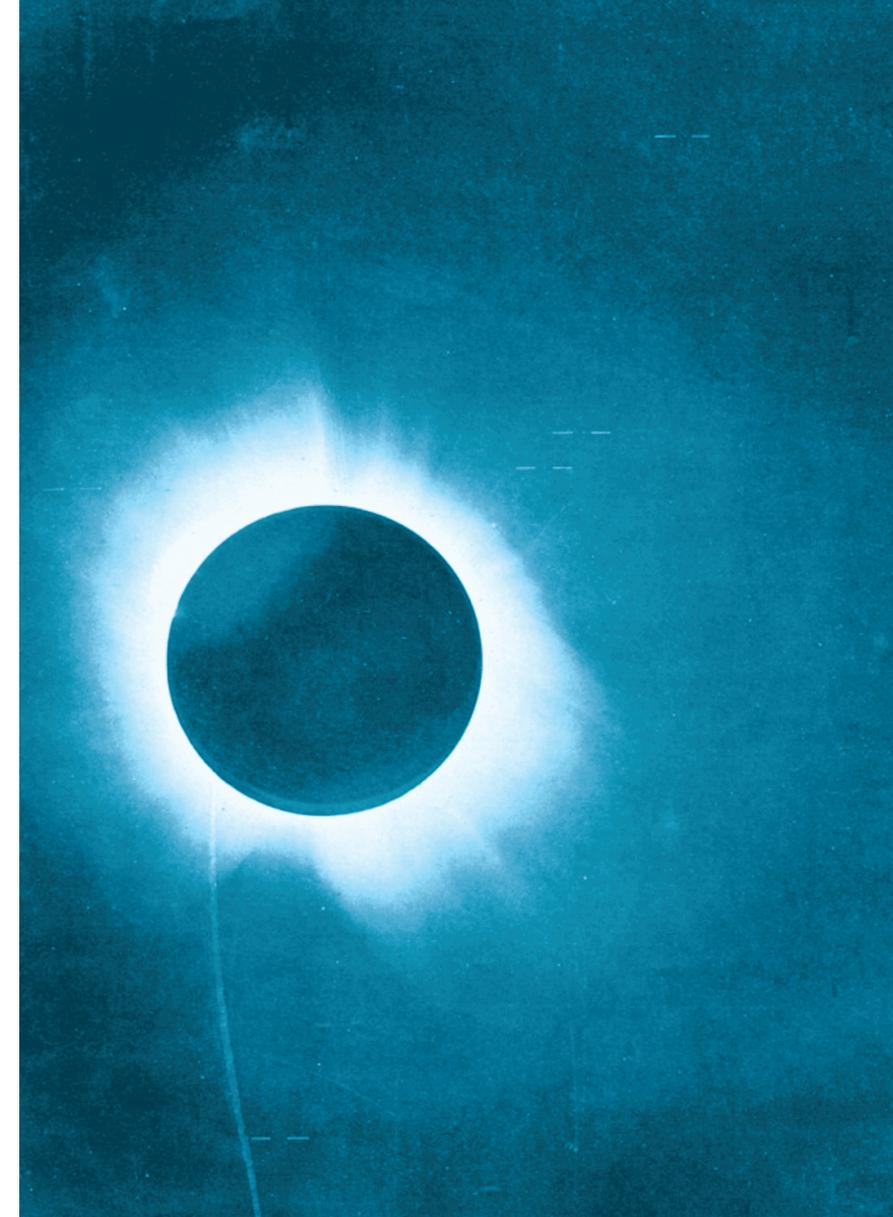
While the math in general relativity is more complex than in Newton's gravity, its basic principles can be stated simply. Relativity treats gravity as a curvature in space-time. (Space-time itself merely adds time as a coordinate to the three normal space coordinates: length, width, and height.) An object bends the fabric of space-time, making a gravitational "well" at the location where a planet, star, black hole — or anything with mass — resides.

Meanwhile, light follows a curved path, bending around the edges of the well. An object with enough mass can behave like a lens, making objects behind it visible. And light traveling out of a gravity well is stretched, becoming redder as it climbs out. Time also slows as gravity gets stronger, so clocks near a black hole, a star, or even Earth's surface will tick more slowly than those farther away.

Is it complete?

Although relativity has passed every test with flying colors, gaps exist that have driven research for decades. A prime example is that Einstein's gravity does *not* seem to fit into quantum mechanics, even though the three other fundamental forces of nature do. Each of the other three forces is mediated by particles: Photons carry the electromagnetic force, gluons carry the strong nuclear force, and W and Z bosons carry the weak nuclear force. But no one has yet observed the corresponding particle that should carry the gravitational force — the graviton — though current theories say it should exist.

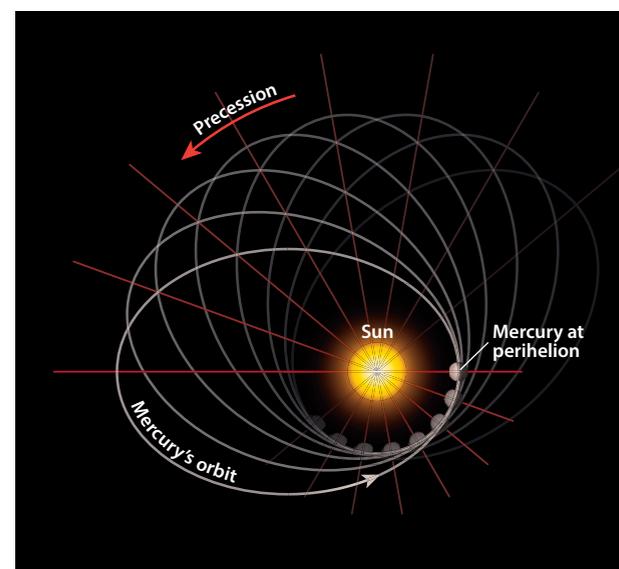
Ghez says that some phenomena don't quite fit into Einstein's paradigm. Universal expansion is one. While it's true that general relativity implies galaxies should be racing apart, the underlying reasons why cosmic expansion seems to



"It's not that we think relativity's wrong. It's just incomplete."

Andrea Ghez

This photo of the May 1919 solar eclipse shows that the positions of stars (inside the dashed lines) have changed in accordance with general relativity when their light passed near the Sun's limb. F.W. DYSON, A.S. EDDINGTON, AND C. DAVIDSON



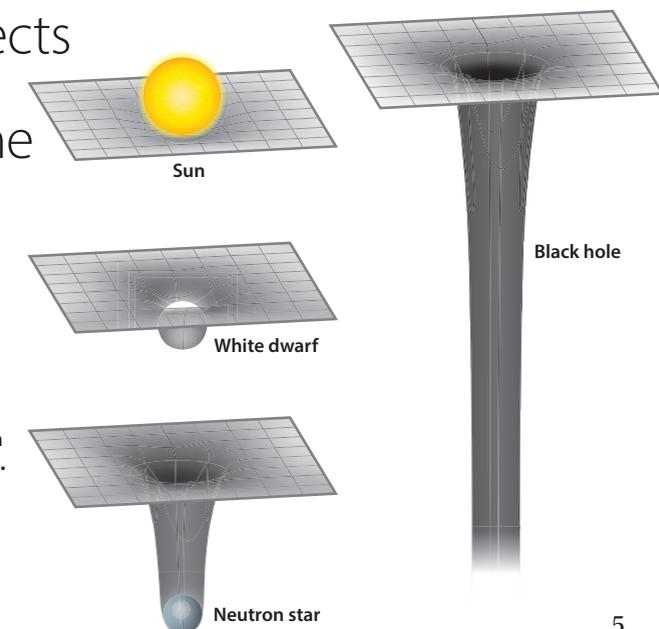
Mercury's shifting perihelion

The perihelion of Mercury, the point in the planet's orbit where it comes closest to the Sun, precesses nearly 2° per century. Newton's laws accounted for all but 43" of this change; general relativity resolved the rest. The advance illustrated here is exaggerated to show detail. ASTRONOMY: ROEN KELLY

How objects distort space-time

Any object with mass warps space-time. But objects with more mass and greater density create greater gravity wells. This illustration compares the relative deformations from different objects. Notice that a black hole essentially rips a hole in the fabric of space-time.

ASTRONOMY: KELLIE JAEGER



be accelerating are still controversial. "Is that because we don't have the right theory to describe gravity?" she asks. "Observationally, now we are just pushing the edges. We want a more complete version of gravity; there's evidence this version isn't good enough."

Tim Johannsen, a postdoctoral fellow at the University of Waterloo in Ontario, studies gravity in extreme environments. He agrees that black holes may offer a way to find relativity's breaking points. "There have been many experimental tests of general relativity, but hardly any of them have probed the strong-field regime in the immediate vicinity of a black hole so far," he says.

The first tests involved the far weaker field surrounding the Sun. For example, the point in Mercury's orbit where it



Above: The Einstein Cross vividly shows the effects of gravitational lensing. Light from a distant quasar passes through the outskirts of a diffuse galaxy, which acts as a lens to magnify and bend the quasar's light into four distinct images. ESA/HUBBLE AND NASA

Right: Gravitational lensing also occurs on grand scales. Here, the giant galaxy cluster MACS J0717.5+3745 magnifies and distorts light from more distant galaxies, warping their light into arcs and streaks. NASA/ESA/THE HST FRONTIER FIELDS TEAM (STScI)

comes closest to the Sun, called perihelion, advances about 2° per century. Relativity accounts for the tiny fraction, just $43''$ per century, that Newton's laws cannot. And observations of a total solar eclipse in 1919 found a small bending of light by the Sun's gravitational field. Later, the discoveries of gravitational lensing and gravitational waves helped confirm relativity's power to explain nature. It would seem that Einstein is in good shape, but the nagging question is whether his theory will hold up under more extreme conditions, or eventually show its incompleteness as Newton's theory did.

Yet even with the knowledge that general relativity might not be the last word, any new theory still has to fit all the results that have come before. "The bar is getting higher," says Nicholas Yunes, a physicist at Montana State University. "Whatever theory of gravity you decide to devise, at the very least it has to predict the same gravitational waves that [LIGO] observed."

Forging a black hole

To make a black hole, you need to compress a lot of mass into a very small



space. Einstein's theory says it doesn't matter what that mass is, but astronomers think nature makes stellar-mass black holes when massive stars die. All stars spend most of their lives fusing hydrogen into helium in their cores. The energy this produces creates an outward pressure that balances the inward pull of gravity. After a star exhausts its core hydrogen, it eventually starts to fuse helium into carbon.

More massive stars can tap into additional fuels. Ultimately, silicon fuses into iron and nickel. But the process stops there because fusing heavier elements consumes, rather than releases, energy. The star can no longer support its own weight with radiation pressure from fusion, so it collapses. The implosion triggers a shock wave that tears the star apart in a violent supernova explosion. For stars that begin life with more than 20 solar masses, the core left behind collapses to infinite density and becomes a singularity. An event horizon forms around the singularity, and you have a black hole.

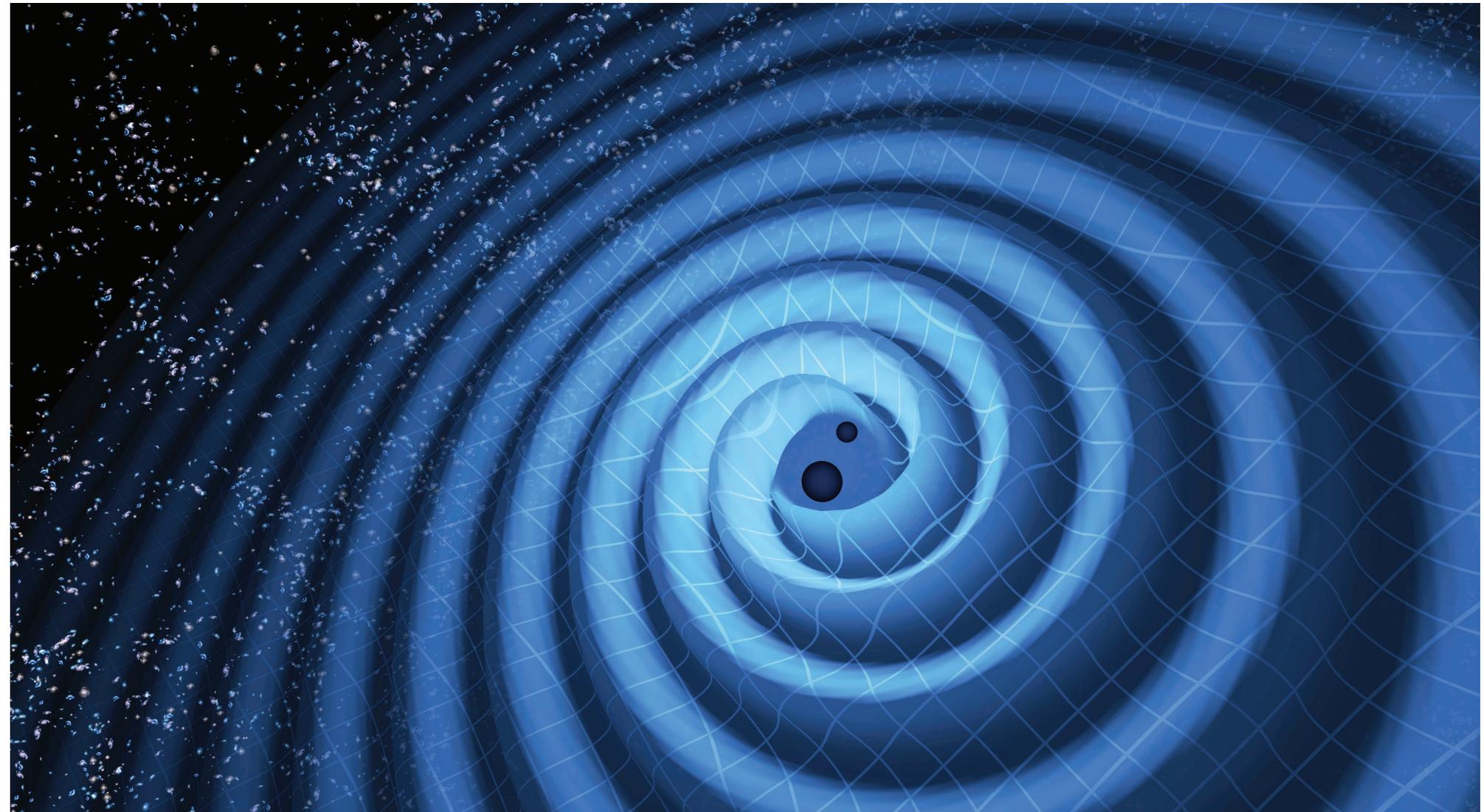
The event horizon — the point of no return — is surprisingly small. The black hole at the center of the Milky Way Galaxy, known as Sagittarius A* (pronounced A-star), holds about 4 million times the Sun's mass, but its event horizon is only 15 million miles (24 million kilometers) across. It would fit inside Mercury's orbit with plenty of room to spare. A black hole with 10 times the Sun's mass would have an event horizon that spans 37 miles (60 km) and would fit inside Rhode Island. And if Earth were compressed into a black hole, it would be the size of a marble. The event horizon radius increases in direct proportion to the black hole's mass, but unlike Hollywood treatments, black holes don't vacuum matter up. If an Earth-mass black hole replaced our planet, the Moon's orbit wouldn't change.

The small size matters because the gravitational field changes drastically as one approaches the event horizon. That's why black holes are such good arenas for testing relativity. The gravity wells are steep — a person 3 feet (1 meter) from an Earth-mass black hole would feel a force more than 40 trillion times the gravity at Earth's surface. In the vicinity of a black hole, the bending of light is

“How do you convince yourself you know what Newton is predicting?”

Andrea Ghez

The LIGO and Virgo collaborations have detected gravitational waves from the mergers of several black hole pairs. This illustration depicts the merger seen December 25, 2015, when black holes of 8 and 14 solar masses merged into a single 21-solar-mass object. LIGO/T. PYLE



easy to spot, and effects like time dilation and deviations from Newtonian mechanics are large enough to observe readily. If relativity stops working, then near a black hole is where we are likely to see it happen.

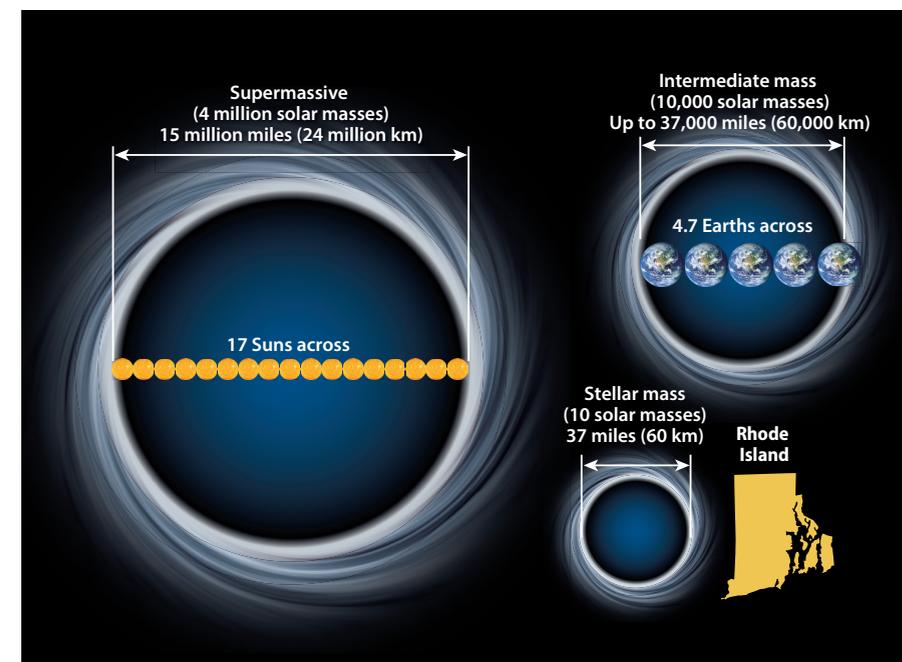
The hurried paths of stars

To track down some of these relativistic effects, Ghez's research team is using a method similar to the one scientists used to analyze Mercury's orbit. Sagittarius A* is the closest supermassive black hole, and astronomers can resolve individual stars orbiting it. One in particular, called S2, takes 16 years to complete its highly elliptical orbit. The black hole's mass is why the star goes so fast. By the time it makes its closest approach to Sagittarius A* in mid-2018, at a distance about three times as far from the black hole as Pluto is from

the Sun, it will be moving at between 1 and 2 percent the speed of light.

After years of observations, data from 2018 will give the researchers enough information to measure deviations from Newton's laws due to general relativity accurately, Ghez says. Paradoxically, the relativistic effects are so large they actually make it more difficult to do a Newton's-law calculation. “How do you convince yourself you know what Newton is predicting?” she says. Thus far, Einstein's theory should show a difference from a Newtonian calculation of about 120 miles per second (200 km/s). Further deviations from that might show that Einstein's theory is starting to fray.

The team's observations also touch on another mystery, says Ghez. Stars near the galactic center should be relatively old. The clouds of gas and dust that



The sizes of black holes

The diameter of a black hole's event horizon increases in direct proportion to its mass. A black hole with 10 times the Sun's mass would span 37 miles (60 km), while the one in the Milky Way's center measures 17 Suns across.

ASTRONOMY: ROEN KELLY



One of LIGO's twin detectors (above) is in Livingston, Louisiana, some 25 miles (40 km) east of Baton Rouge. The other detector is in Hanford, Washington.

CALTECH/MIT/LIGO LAB

would give birth to stars shouldn't be stable so close to a supermassive black hole; calculations based on relativity show that tidal forces should disrupt them. Yet stars near the center skew young. Unless someone can invoke a mechanism for quickly getting these youngsters in from an outer region, they demonstrate that scientists must be missing something.

In the shadows

Johannsen is among the astronomers taking a different tack, using the Event Horizon Telescope (EHT) to see if relativity breaks down in the "shadow" of a black hole.

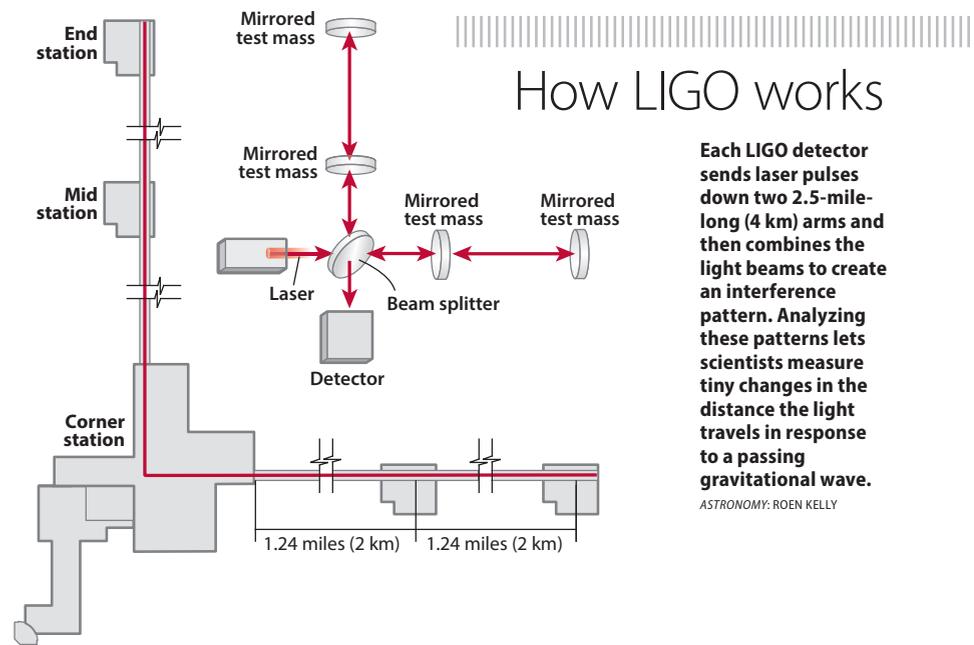
The EHT is a collection of radio telescopes spread around the world. Using a technique called very long baseline interferometry, the telescopes work together to achieve a resolution comparable to a single instrument with a diameter nearly as wide as our planet. The array delivers enough resolution for radio astronomers to observe the edges of Sagittarius A*, as well as the much larger supermassive black hole that lurks at the center of the giant elliptical galaxy M87 in the Virgo

Cluster. Accretion disks of gas and dust surround both black holes. Such disks tend to form around black holes because their strong tidal forces rip apart any object that gets too close. Friction within the disk heats the material to millions of degrees before it falls into the hole, and the gas glows brightly in wavelengths ranging from X-rays to radio.

Since black holes act like lenses, Johannsen's team expects to see a perfect ring of light as the photons from behind the black hole are bent around it. (Although most researchers describe the

dark void at the center of the ring as a "shadow," it is really a silhouette of the black hole against the bright background light.) If that ring isn't a perfect circle and shows some oscillations, then a quantum effect may be happening. It would be the first time anyone has seen anything like it around a black hole.

"The shape of a given shadow is almost entirely determined by gravity alone and not by the particulars of the gas and dust that are swirling around the black hole," says Johannsen. "Therefore, the detection of the shadow can potentially be a clean



Each LIGO detector sends laser pulses down two 2.5-mile-long (4 km) arms and then combines the light beams to create an interference pattern. Analyzing these patterns lets scientists measure tiny changes in the distance the light travels in response to a passing gravitational wave.

ASTRONOMY: ROEN KELLY



The 1.9-mile-long (3 km) arms of the Virgo interferometer are nestled in the countryside near Pisa, Italy. This instrument works in tandem with the twin LIGO interferometers in the United States.

THE VIRGO COLLABORATION

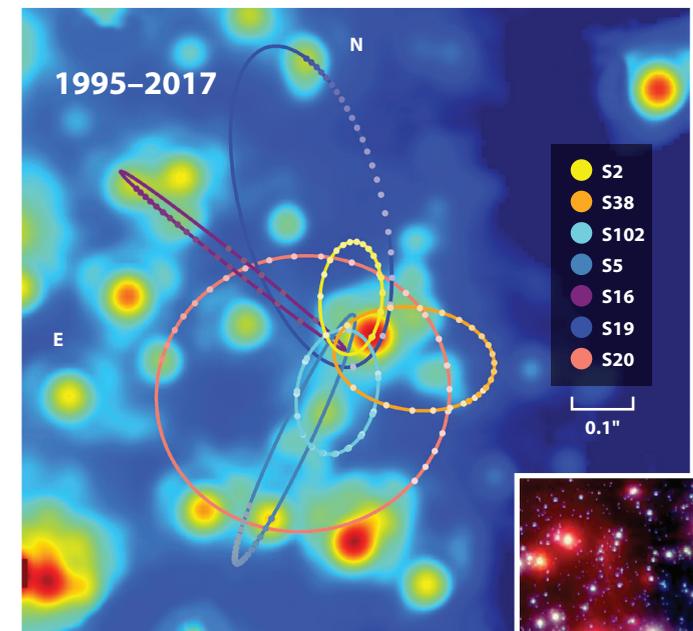
measurement of the underlying theory of gravity without many of the complications that come with those messy surroundings."

General relativity says the shape of the shadow should be nearly circular with a fixed size. Other theories of gravity posit other shapes. "If we find any of those deviations, there are two possibilities: Either [general relativity] is not correct in the strong-field regime, or [general relativity] still holds but the object is not a black hole but some exotica. Either one would be quite a sensation."

Riding the waves

Perhaps one of general relativity's most famous predictions was gravitational waves. (While Einstein's theory gave gravitational waves a sound mathematical basis, the concept was not unique to him: Henri Poincaré and Oliver Heaviside also floated the concept.) Einstein predicted that accelerating massive objects would cause space-time to ripple. The resulting waves would propagate at the speed of light and not at an infinite speed as Newton's formulation of gravity predicted. As of March 2018, astronomers with the LIGO and Virgo collaborations have picked up unequivocal evidence for gravitational waves six times.

LIGO and Virgo are interferometers. A laser is fired at a beam splitter that



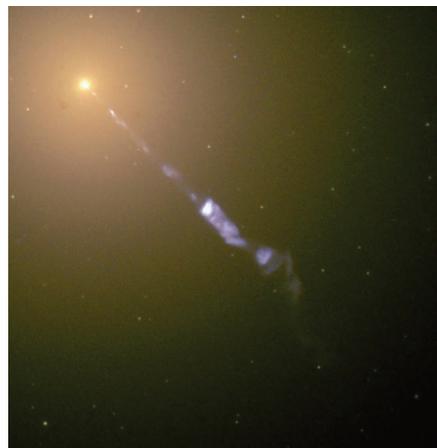
Researchers using the 10-meter Keck Telescope have tracked the motions of a handful of stars in orbit around Sagittarius A*. They expect these observations will soon allow them to detect deviations from Newton's laws.

KECK/UCLA GALACTIC CENTER GROUP

sends the light down two perpendicular arms. Each of LIGO's arms is 2.5 miles (4 km) long, while each Virgo arm extends 1.9 miles (3 km). The two beams bounce off mirrors at the end of the arms and return to the beam splitter, where they combine into a single beam before heading into a photodetector. If the two beams travel precisely the same distance before merging, they will either cancel each other out or reinforce each other, and the photodetector will either pick up nothing, or it will see light as bright as the original beam.



Thousands of stars crowd the core of our galaxy, which harbors a 4 million-solar-mass black hole called Sagittarius A*. This near-infrared image reveals many of those stars, some interstellar dust, and the faint glow surrounding the black hole. ESO



“The puzzle is getting completed one piece at a time.”

Nicholas Yunes

LIGO’s two detectors and Virgo’s one are designed so the photodetectors record nothing if the arms stay the same length. But if the beams travel a different distance — as one would expect if passing gravitational waves distorted space-time — then the photodetectors will record an interference pattern, and the merged beam will appear brighter or dimmer than the original one. The interferometers can detect changes in the lengths of their arms as small as $\frac{1}{10,000}$ the width of a proton.

The detection of gravitational waves doesn’t mean Einstein’s theory can rest, however. In many ways, their detection raises as many questions as it answers. A few theorists have started to poke at the observations to see if they reveal hints at a quantum theory of gravity, or at least some connections that don’t violate quantum mechanics.

In late 2016, for example, researcher Jahed Abedi of the Sharif University of Technology in Tehran, along with Hannah Dykaar and Niayesh Afshordi of the University of Waterloo, proposed that “echoes” in the gravitational wave signal might indicate there were some tiny structures near the event horizons of the merging objects, pointing to physics beyond general relativity. The idea wasn’t met with a lot of enthusiasm from fellow scientists. In a set of back-and-forth papers, skeptics stated that they had reservations about the theoretical basis. The next question is whether these echoes will show up in future observations.

Left: The supermassive black hole at the center of M87 emits a high-powered jet of subatomic particles. Although this elliptical galaxy lies more than 50 million light-years from Earth, astronomers hope to image its black hole with the Event Horizon Telescope because it is more than 1,000 times the mass, and thus diameter, of the Milky Way’s central black hole.

NASA/ESA/THE HUBBLE HERITAGE TEAM (STSCI/AURA)

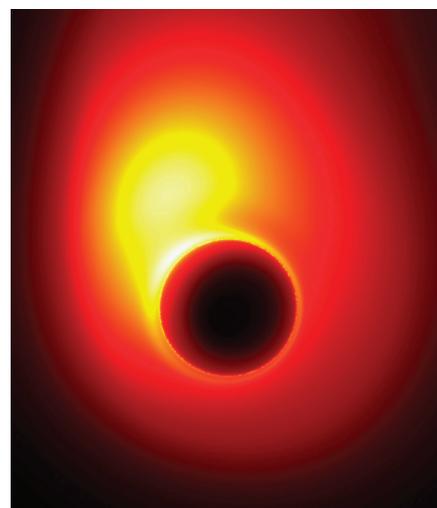
Right: The Milky Way and aurora australis shine down on the South Pole Telescope, one of about a dozen instruments that form the Event Horizon Telescope. This virtual Earth-sized observatory seeks to image a black hole’s event horizon.

DANIEL MICHALIK/SOUTH POLE TELESCOPE

A weighty particle

Gravitational waves also may reveal physics beyond relativity in other ways, notes Kent Yagi, a theoretical astrophysicist at the University of Virginia. One way is simply by constraining parameters like the mass of the graviton. If this particle has no mass, then gravitational waves should move at the speed of light, he says. A graviton with mass means that gravitational waves can’t, by definition, go that fast.

If the graviton has mass, it has to be quite small. “We can constrain it to no more than 10^{-20} eV [electron volt] with the first detection, but beyond that, we don’t know. Maybe it’s 10^{-23} eV,” says Yunes. (An electron volt is a common measure of energy in particle physics; scientists often use it as a unit of mass by dividing a particle’s energy by the speed of light squared, per Einstein’s famous



This computer-generated model shows the “shadow” of the 4 million-solar-mass black hole at the Milky Way’s center. Astronomers hope to compare such models with images of the black hole made with the Event Horizon Telescope, to look for any deviations from general relativity.

EVERY BRODERICK (UNIVERSITY OF WATERLOO/PERIMETER INSTITUTE)

equation, $E=mc^2$.) But at a certain point, if there’s no mass detected, one has to wonder if it’s massless — or even exists.

Meanwhile, other scientists have taken a crack at looking for quantum effects at large scales using combinations of black holes and neutron stars. Neutron stars are the corpses of stars born with more than about eight times the Sun’s mass, but less than the 20 solar masses needed to make black holes. They have powerful magnetic fields, and some send focused beams of radio waves in our direction at regular intervals like a lighthouse beacon — pulsars.

John Estes of Long Island University and his colleagues have proposed using the precisely timed signals from a pulsar orbiting a black hole to probe the region near the event horizon. Since black holes bend light, the pulsar’s signal would be delayed by a discrete amount when the

pulsar passes behind the black hole. If quantum effects are important, then that delay would change in ways general relativity cannot predict, and might even reveal something about how quantum mechanics works with relativity.

But there’s another reason to do these kinds of tests. It is far from clear that gravity — and thus general relativity — applies the same way at different scales. Leo Stein of Caltech notes that the physics one encounters near a supermassive black hole, like the one at the center of the Milky Way, might be different from the physics near a stellar-mass black hole.

LIGO, for example, showed us that gravitational waves are generated in the expected way near a stellar-mass black hole. The steepness of the curvature of space just outside the event horizon is smaller for larger black holes, however.

“It’s potentially very different physics,” Stein says. “When curvatures are large, you need to use LIGO. When interested in physics on the millions-of-kilometers scale, there are things you might be able to test with the EHT. In the middle is stuff we have got nailed down, at the solar system scale.”

“Cosmologists are interested in changing the theory of gravity at very large distance scales,” he says. “String theorists and high-energy physicists are changing the theory of gravity at the quantum level.”

As with many mysteries, however, we may have to wait for observations to tell us one way or the other which theory is correct. “The puzzle is getting completed one piece at a time,” says Yunes. ♪

Jesse Emspak is a science writer who lives and works in New York City.



Decades of simulations suggest this is what gas and dust look like spiraling around a black hole. We could soon see the real thing.

BIG IDEA

Black Hole Close-Up

An Earth-sized telescope will capture the unseeable.

ASTROPHYSICIST JEAN-PIERRE LUMINET didn't have a supercomputer when he showed the world what a black hole looks like. He just had an IBM 7040 and a bunch of punch cards. He knew from theory that black holes do not emit light. But the material that swirls around them — dust and gas stripped from stars — shines all the way to its inanimate death. Light from that material, Luminet thought, would trace the black hole's shape, including warps in space-time from its extreme gravity.

When the fridge-sized IBM spit out results in the late '70s, Luminet used ink and pen to plot out an image by hand. He saw the black hole's event horizon, the point beyond which nothing can escape; and an accretion disk, the gathering of matter siphoned from nearby stars. Although the black hole had just one disk, gravity had morphed its appearance, like a fun house mirror, into two perpendicular disks. They appeared brighter closer to the black hole, and more luminous on one side than the other.

Some four decades later, the basics of Luminet's black-hole predictions still stand. But his image and all others are paintings, not photographs. That's about to change. Scientists working with the Event Horizon Telescope (EHT) will soon release an actual portrait of Sagittarius A* (pronounced "A-star"), the supermassive black hole at the center of our galaxy. As a backup, they have data on another one in a nearby galaxy called M87. The image could help demystify one of the universe's most mysterious objects, and even help explain how galaxies like the Milky Way form and evolve.

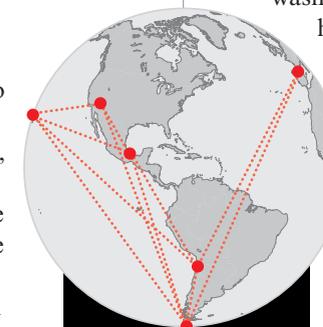
The EHT isn't just one telescope: It's

a network of eight radio telescopes in Hawaii, Arizona, Spain, Mexico, Chile and Antarctica. Astronomers align these instruments to study the same object at the same time. The scientists then combine data from these eight antennas into one image that looks like it came from a telescope as big as the biggest distance between the telescopes. In other words, they create a virtual telescope the size of Earth.

It's called very long baseline interferometry, or VLBI. But there's a trick to it. According to Shep Doeleman, director of the EHT, "the secret sauce to VLBI, the thing that makes it work, is that at each of the telescopes that participates in our observations, we have placed an atomic clock."

As each telescope stares at Sagittarius A*, the data gets stamped with the atomic time, like it's clocking out of a shift. Then, scientists line up each bit taken at, say, 5:13 p.m. GMT, with all the other 5:13 p.m. GMT bits.

To do that alignment, though, the clocked-out bits must meet in person, at a central facility. Researchers usually share their data online, but this job, with its many petabytes, is too big for the internet. "The only way to get [the data] anywhere is by flying hard disks around," says Doeleman. Researchers call this the "sneakernet," and it's the ultimate analog-digital mash-up.



The EHT isn't just one telescope: It's a network of eight radio telescopes in Hawaii, Arizona, Spain, Mexico, Chile and Antarctica.

The team did its first real observing run in April 2017 with the Atacama Large Millimeter-submillimeter Array (ALMA) in Chile. It's a weapon powerful enough to let EHT peer right into a puncture in space-time. Wielding that secret weapon wasn't simple. The astronomers

had to combine data from ALMA's 66 dishes into a single recording before they combined it with the other telescopes' observations.

Still, even with ALMA, and nearly a year of analysis time, they haven't made a picture yet. And it's the fault of a whole continent: Antarctica and its South Pole Telescope. Astronomers had to wait for southern spring before they could fly the pallet of data out. It arrived for processing at MIT's Haystack Observatory in December.

Why is a black hole snapshot worth all this effort? To Doeleman, it's about the strangeness of the science. "These are really the most

mysterious objects in the universe," he says. "There's nothing that comes close, except maybe life itself."

And life itself, at least life as we know it, doesn't know what black holes look like, what happens within them, what that means for how galaxies form and evolve, or how that birth and growth led, at least on Earth, to life that can look out and learn how its galaxy works.

"There are very few topics where we say we just really have no idea what happens at that point in the universe," says Doeleman. "One of those may be consciousness. And another one is the black hole."

—SARAH SCOLES

OPPOSITE: ROEN KELLY/DISCOVER THIS PAGE: ALISON MACKREY/DISCOVER

FOUND: Einstein's Ripples in Space-Time

LONG AGO in a galaxy 1.3 billion light-years away, two black holes collided. Each was dozens of times heavier than the sun, and they orbited each other 100 times a second. As the behemoths merged, they also shed a tremendous amount of energy, the equivalent of three times our sun's mass. That energy radiated away as a gravitational ripple in space and time, which swept across the cosmos until it reached Earth.

BILLIONS OF YEARS AGO
Two black holes spiral toward each other.

They merge, releasing energy as a ripple in space-time.

The wave first hit the Laser Interferometer Gravitational-wave Observatory (LIGO) in Hanford, Wash., in September 2015. Then, traveling at the speed of light, it hit the twin LIGO facility in Livingston, La., less than 10 milliseconds later.

At both observatories, extremely sensitive laser measurements inside miles-long tunnels caught the waves' tiny stretches and squeezes of space-time. The disturbance was so small, it would warp the 25 trillion miles to the nearest star system by just the width of a human hair — but LIGO saw it. Soon, elated scientists were receiving alerts across the planet. "We have detected gravitational waves. We did it," LIGO executive director David Reitze said in early February, when the research was published in *Physical Review Letters*.

No playwright could have composed a more perfect script. The historic finding arrived almost exactly a century after Albert Einstein used his general theory of relativity — which

states that a mass creates gravity by warping space-time — to predict gravitational waves. For generations of physicists and engineers, the confirmation also completed a decades-long hunt for proof, as well as months of excited rumors.

Because gravity is relatively weak, only the most extreme cosmic events — supernovas, spinning neutron stars, colliding black holes — generate waves LIGO can detect. So scientists were surprised to catch one immediately after starting to hunt in September following an equipment upgrade; they captured a second signal Christmas night. For the first time, astronomers had heard the cosmos.

SHEDDING LIGHT ON BLACK HOLES

Black holes are aptly named. They emit and reflect no light. Before LIGO, astronomers could only infer a black hole's existence by watching the behavior of objects caught in its gravitational grip. But LIGO isn't bound by sight.

Its twin detectors and companion supercomputers can pick apart the strength and frequency of gravitational waves to learn a black hole's mass, spin and location.

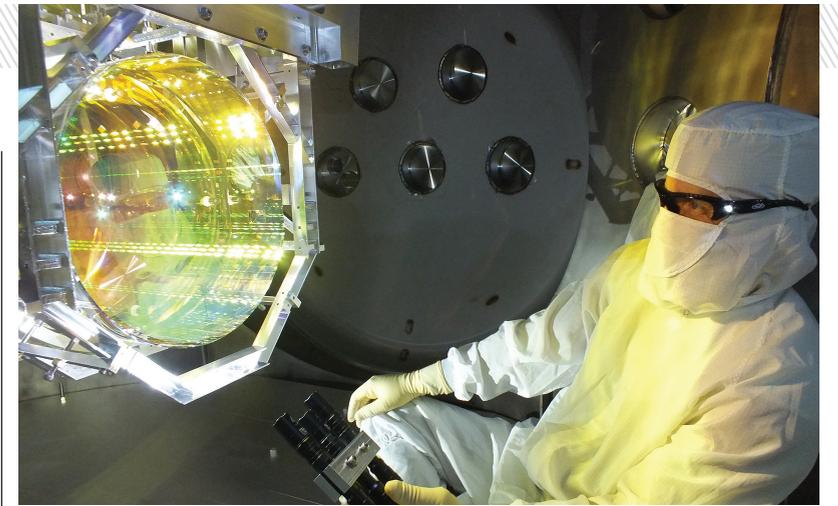
That makes LIGO akin to a new kind of telescope, one capable of listening to a previously invisible universe. The first colliding binary black holes that LIGO detected were 36 and 29 solar masses — far bigger than expected. The second pair were more in line with current theories.

And as LIGO continues to detect more collisions, the data about black holes will keep piling up. "We should have tens of detections over the next few years, and over a hundred through the end of the decade," says LIGO scientist Chad Hanna of Pennsylvania State University. "That's enough to do some pretty significant astronomy. That's a big population."

HOW DO STARS LIVE AND DIE?

By studying black holes, the ultimate fate of many stars, LIGO also could help rewrite the textbook version of stellar evolution.

Scientists have a pretty good idea of how single stars live and



A LIGO technician tests one of the observatory's mirror systems by shining light on its surface at an angle. The work, which took place before sealing the chamber, is extremely sensitive, requiring a white "bunny suit" and zero contamination.

die. Stars like our sun will grow into behemoths called red giants before they shed their outer layers and become an ethereal planetary nebula. Larger stars — those with more than about eight solar masses — will explode as supernovas. And, theoretically, any star at least 25 times bigger than the sun will end its life as a black hole.

But most stars in the Milky Way are actually binaries or multiples, part of a set. What happens to these stars when they die? Understanding stellar pairs, and how one's individual development affects the other, is fundamental to understanding stellar evolution

as a whole. We've only barely started to do that.

"Binary evolution is more complicated than single star evolution," says LIGO scientist Jolien Creighton of the University of Wisconsin-Milwaukee. "There's a lot more processes that can happen." By cataloging their stellar corpses using LIGO, astronomers can learn more about how these stars lived out their lives.

After its initial findings, LIGO took a break for upgrades before firing back up again in fall. As more gravitational wave detections stream in, from LIGO and its upcoming ground- and space-based brethren, astronomers will get a better picture of this invisible cosmos that Einstein saw so clearly. —ERIC BETZ

1.3 BILLION LIGHT-YEARS

The ripple sweeps across the cosmos.



These gravitational waves effectively shrink then stretch everything they pass through — though it's to a much smaller extent than shown here.

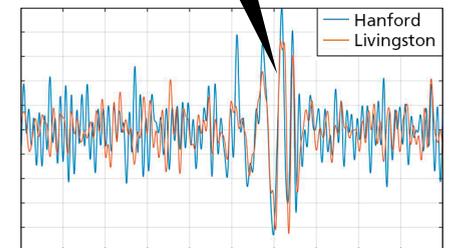
SEPTEMBER 2015
Eventually it reaches the LIGO facility in Hanford, Wash. ...

... and its twin in Livingston, La., less than 10 milliseconds later.

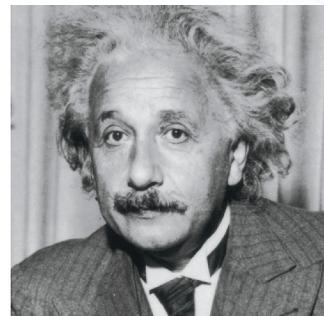
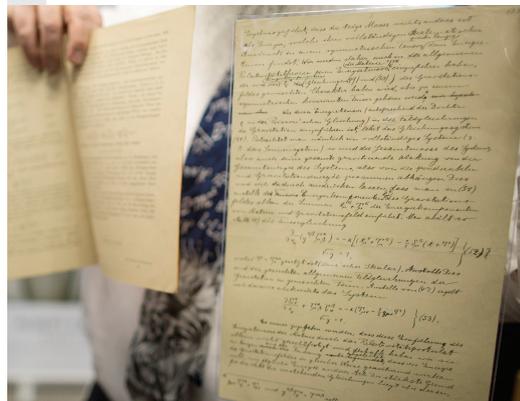


The Louisiana LIGO facility relied on precise observations of lengthy laser beams to detect gravitational waves.

The two facilities compare data to verify the discovery.



See an exclusive LIGO gallery and more at DiscoverMagazine.com/LIGO



Albert Einstein first suggested massive objects distort space-time, the fabric of the cosmos, almost exactly a century ago (left).

BLACK HOLES MERGING BY LIGOT; PYLE; BOTTOM ROW FROM LEFT: LIOR IMZRAHI/GETTY IMAGES; LAMBERT/KEystone/GETTY IMAGES; NASA

CLOCKWISE FROM TOP: MATT HEINZ/TECHNICAL/LIGO LAB; LIGO LAB (2); ALISON MACKEY/DISCOVER