HEART OF DARKNESS

by

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ABSTRACT

A few decades ago, black holes were a theoretical quirk. Highly probable on paper, they were doubted more than touted; many scientists didn't believe they even existed. Today, however, black holes appear to be everywhere, from behemoths in the cores of almost every galaxy to more modest, stellar-mass objects spattering the Milky Way's arms. Astronomers suspect that supermassive black holes like Sagittarius A* (the compact dark object at the center of our galaxy) may be a cosmic mafia manipulating the galaxies that house them, possibly even controlling galaxy growth. If this suspicion turns out to be true, black holes may have had more influence on cosmic structure than any other object.

This thesis explores how black holes became science from pseudoscience, focusing on three shifts in astronomy: detailed proper motion measurements of stars zooming around the galactic center, the discovery of the apparent relationship between galaxies and their central supermassive black holes, and the development of working numerical simulations of black hole mergers. These three steps have led up to the Event Horizon Telescope, a project which will combine radio telescopes around the world to peer into the innermost spacetime warps surrounding Sagittarius A*. If all goes well, astronomers may finally glimpse the "silhouette" of the Milky Way's central supermassive black hole within the next decade, directly testing whether Einstein's theory of general relativity is right.

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From below, the 37-meter radio telescope at the Haystack Observatory looks like a giant mushroom. The antenna's two hundred tons tower above my head in the warm gloom of the radome, the Epcot-like bubble of resin and fiberglass panels that protects the dish from the elements and echoes with "dome thunder" when the wind rises. Bars of metal framework cookie-cutter the dome's tan surface into triangles. Some of the bottom panels are water-damaged, splotched with ochre swipes that resemble failed stained glass. Only the damaged panels show glimpses outside, but the whole thing—minus the metal—is actually transparent to radio waves, explains my guide, Haystack astronomer Sheperd Doeleman. If we had radio goggles on, he says, we wouldn't even *see* the dome.

It's hard to imagine not seeing a 150-foot-wide opaque snow globe, but I take him at his word.

This antenna, arcing above the tree line about a forty-five minute drive northwest of Boston, won't be here much longer. The U.S. Air Force uses the scope to track satellites, and their desire for a smoother, more precise dish will soon bring one of the largest cranes in the country to lift off the radome, remove the antenna, and put another mushroom top in its place. The new dish will have a surface so level that its highest point will be 0.1 millimeters high, three times better than the present antenna; if Asia were equally flat, Mount Everest would rise a mere 67 feet into the air. Such smoothness will allow researchers to better see past Earth's atmosphere when tuning in to radio frequencies from space.

The dish may become part of the Event Horizon Telescope project, a network of radio telescopes Doeleman and an international collaboration of astronomers are assembling. EHT antennae observe in unison across the world; when fully united, they will act like a single dish so large it would stretch from the South Pole to southern Europe. The project's astronomers will combine their observations much as detectives combine witnesses' views of a crime scene in order to probe the enigmatic dark objects known as black holes.

Black holes are cosmic mysteries seen only by their effects. Astronomers know they are massive, compact objects—the biggest ones stuff the mass of billions of Suns into a space smaller than the Solar System, like shoving the entire Earth into the top of your pinky finger. They lurk among the stars and at the center of nearly every large galaxy in the universe, including our own. Scientists assume that these unseen monsters are the black holes predicted by Einstein's equations of general relativity. But in fact, the evidence for that assumption is as unseen as the black holes themselves. No one *really* knows what lies at the centers of galaxies.

Doeleman intends to change that. A calm, collected, yet intensely enthusiastic man, he exudes authority even when his disheveled dark hair curls up near one temple like a single horn. He wields a presence in a room, an intelligence that shines through his friendly, down-to-earth nature. Doeleman's collaborators call the project "Shep's Event Horizon Telescope," like a dream made solid in the vision of one man. The technique the EHT will use to peer into the hearts of galaxies isn't Doeleman's invention, nor is he the only observer to use it to study supermassive black holes. But of roughly thirty participants who gathered at Haystack for a workshop this past January, Doeleman stood as flag bearer and captain. Astronomers from across the world have allied with him in his quest, representing observatories nestled in the French Alps, perched atop a dormant Hawaiian volcano, bunkered down in the bitter cold of Antarctica. With him, these astronomers plan an attack on one of the greatest mysteries of the cosmos.

The focus of their assault lies at the event horizon. The event horizon is the point of no return around a black hole, the closest distance light can approach before the black hole's gravity captures it forever. Einstein's equations make specific predictions about what this environment should look like: if a disk of gas and dust surrounds the black hole, the event horizon will be a dark silhouette framed by streaks of light, superimposed on a softer glow. It is an environment no one has ever seen. Within the next decade, if everything goes smoothly, that will no longer be the case.

The EHT's first target is the supermassive black hole allegedly sulking at the center of our own Milky Way Galaxy, an object known in astronomers' argot as Sagittarius A* (pronounced "A-star"). While the case for Sgr A* being a black hole is strong, it remains a galactic Al Capone, eluding conviction, thumbing its nose at astronomers, dancing just out of reach of the handcuffs of scientific certainty. But Doeleman's team has already detected some kind of structure in the gas and dust near (what may be) Sgr A*'s event horizon; even now they are piercing closer within the object's influence. Doeleman hopes to actually image the event horizon's silhouette in five or six years, nailing its identity once and for all.

That's an incredible shift from a few decades ago, when black holes were a theoretical quirk. Highly probable on paper, they were doubted more than touted; many scientists didn't believe they even existed. Nowadays, though, black holes appear to be everywhere, from behemoths in the cores of almost every galaxy to more modest, stellar-mass objects spattering the Milky Way's arms. Astronomers suspect that supermassive black holes like Sgr A* may be a cosmic mafia manipulating the galaxies that house them, possibly even controlling the growth of these immense systems of stars, systems across which light can take hundreds of thousands of years to travel. If this suspicion turns out to be true, black holes may have had more influence on the structure of the cosmos than any other object. As Doeleman puts it, "Understanding the whole history of the universe is locked up in understanding black holes."

The Golden Age

Einstein never liked black holes. He thought they didn't smell right, physically. A man led by his intuition, Einstein was loathe to accept something so counter to his sense of reality as an object that, overwhelmed by the force of its own gravity, had collapsed to a singularity.

Singularities are odd ducks. German astrophysicist Karl Schwarzschild derived their existence in 1915 and 1916 when he explored how a star would affect the space and time around it. He did so by developing the first exact solution to Einstein's equations of general relativity, which describe gravity as *geometry*. In general relativity, gravity arises when massive objects stretch spacetime, the unified fabric of the four dimensions (three of space and one of time). This new vision of space and time as a single, palpable, *bendable* object was one of the revolutions Einstein's theory carried with it. What we perceive as gravity's downward pull is actually our constant falling along the curves in spacetime created by mass and energy. The more massive and compact an object, the more spacetime curves around it.

Imagine a rubber sheet pulled taut. If you put an orange on it, the rubber might stretch a little, but not much. If you set a bowling ball on the sheet instead, though, it will stretch the rubber down into a well like a fist stretches pizza dough. The more massive an object, the greater the well it creates in the rubber.

The geometry that Schwarzschild derived from Einstein's equations predicted exactly this phenomenon: spacetime will curve extremely around a massive, compact star. The compact part is important. A piece of plywood and a bowling ball might have the same mass, but the bowling ball will cause the rubber sheet to stretch down into a much deeper well. Schwarzschild's calculations showed that the more compact a star, the deeper the spacetime well it would create, and that, at a certain size, a star of a given mass will actually cause such an extreme curvature in spacetime that light from the star will never escape from the well.

These "Schwarzschild singularities" bothered many scientists, including Einstein (although they arise naturally from his equations). Stars should not be able to contract *that* much.

All this was purely theoretical. Unpopular, and theoretical. But then in 1939 Robert Oppenheimer and his graduate students George Volkoff and Hartland Snyder showed that, when a star above a few solar masses exhausts its fuel, it will "contract indefinitely": its gravity will overwhelm its internal pressure, causing it to collapse down past its event horizon to . . . well, to something.

That changed the game. Physicist John Wheeler and his postdoc Masami Wakano followed up in the 1950s, hoping to prove Oppenheimer and Volkoff wrong. Instead, they calculated that massive stars would *indeed* implode, forming what Wheeler came to call a black hole. Suddenly, these objects were sticking their noses in exactly where no one thought they should: reality.

A black hole is a cosmic whirlpool, the spacetime inside twisted, curved, stretched, swirled, like nothing we've ever seen. It is an object made of warped spacetime held together by its own gravity. The gravity is generated by the energy of the warping (because mass and energy are equivalent, according to $E=mc^2$). So the warp produces the gravity and the gravity maintains the warp. It's a vicious cycle kind of thing.

From the outside, though, a black hole is simple. Black holes are like macroscopic elementary particles, the electrons of the visible universe. Like electrons, black holes can be completely described with three numbers: mass, spin, and charge. Because charges cancel each other out on astronomical scales, knowing the mass and spin of a black hole should give scientists everything they need to know about the object's history. It's like the black hole's background check.

Theoretical physics enjoyed a black hole "golden age" in the late 1960s and 1970s, when scientists began trying to describe things like rotating or merging black holes and building computer simulations that could handle complex calculations. But they were theorists, playing with theoretical objects. Black holes looked nice on paper, but were they real? To be more than a physicist's daydream, black holes had to prove themselves astronomically.

For stellar-mass black holes, that proof came with observations of objects like Cygnus X-1. This binary system was a puzzle when first discovered in 1964, shining far too brightly in X-ray wavelengths to be a normal pair of stars. But the X-ray light did match that which would come from gas superheated as it swirls around a black hole. Because you can calculate the masses of two objects orbiting each other based on their movements around their partner, astronomers were able to determine a mass between 15 and 20 solar masses for the X-ray-bright companion, a mass that—if a normal star—should have corresponded to a large and brilliantly glowing orb of gas. Because an orb was nowhere to be seen, astronomers argued that the object was a small black hole feeding off an accretion disk of material coming from its massive companion star. Over time the evidence was solid enough that, in 1990, Cambridge astrophysicist Stephen Hawking finally lost his bet with Caltech physicist Kip Thorne and conceded that observations were strong enough to say Cyg X-1 was indeed a black hole.

A black hole like Cyg X-1 would have an event horizon roughly 70 miles across, slightly less than the distance from Philadelphia to New York City. Yet there is a stranger species of black hole, one that, while detected earlier, took longer to convince the astronomical community. This leviathan is the supermassive black hole, an object that can be a billion times more massive than the Sun. Such a creature would have an event horizon about 3.5 billion miles wide, nearly four times the distance between the Earth and the Sun.

Evidence for these gigantic beasts first appeared in the 1950s and 1960s, when astronomers began detecting incredibly bright point-like objects that looked like stars but weren't. They lay far beyond the reaches of the Milky Way, blazing from the distant past, when the universe was only a few billion years old. But while these sources were far enough away to look like pinpricks on the sky, their light was very different from starlight: it came not from a single orb but from an entire region, a galactic core so bright that its light overwhelmed the glow of its entire galaxy. This core, in some cases barely the size of the Solar System, managed to put out more energy than 100 billion stars.

These "quasi-stellar objects" (soon shortened to *quasars*) at first appeared too bizarre to be real. Nothing astronomers knew of at the time could put out that much energy from a region so small. The Sun produces 40 million billion billion watts of energy (that's a four with twenty-six zeros after it) by fusing hydrogen into helium in its core, a process that astronomers had only really begun to understand in the 1940s. Quasars, however, can produce one *trillion* times this amount of energy.

On first glance, black holes might not seem like the answer to this conundrum: black holes swallow light, they don't emit it. But a supermassive black hole was exactly the solution offered in the 1960s by scientists in the United States and the Soviet Union. A single bit of matter spiraling in toward the event horizon of a black hole can convert up to ten percent of its mass into energy before falling in—which is, per $E=mc^2$, a whole lot of juice. In comparison, hydrogen atoms fusing into helium in the Sun's core convert less than one percent of their mass into energy, and yet they will provide enough fuel to keep the Sun shining for another five billion years.

Black holes might also explain the jets seen shooting from some active galaxies. These jets can span millions of light-years, sometimes spewing far beyond their galaxies' borders into intergalactic space. They appear to be streams of high-energy particles beamed out from a compact, central engine. While the details are hazy, astronomers suspect material falling in toward the black hole might interact with magnetic fields twisted through the disk of the gas and dust circling the beast. Or the material could be spun up by some kind of dynamo effect created by a spinning supermassive black hole, then shot out along the disk's poles.

To some, these explanations sounded more absurd than the quasars themselves. "I thought at the time that it was crazy to think that million or billion solar mass black holes were the objects that powered quasars," says Doug Richstone, an astronomer at the University of Michigan, Ann Arbor. "And I don't think I was particularly unusual in thinking it was crazy."

Richstone did not find the incredible jets, like the one shooting out of the core of the elliptical galaxy M87, convincing. Nor did he particularly buy the evidence for an accretion disk in the center of the spiral galaxy NGC 4258, which for decades some lauded as the best candidate for a supermassive black hole. What won him over was not the lively black holes, but the dead ones.

In 1969 British astrophysicist Donald Lynden-Bell suggested that quasar corpses might be hiding in the "normal" galaxies around us today. If galaxies in the past had supermassive black holes, there was no reason to think these dark objects had disappeared. Instead, it seemed more likely that their food supply had run out, leaving them to hibernate in the inhospitable conditions of galaxies unwilling to fork over gas and dust to feed them. Lynden-Bell and astrophysicist Martin Rees proposed two years later that one of these dead black holes could be lying at the center of the Milky Way.

"It was a controversial idea," Rees, now British Astronomer Royal, says nearly forty years later. "At that time it was controversial whether quasars were just one big object or whether they were really just a dense cluster of stars."

A star cluster was reasonably normal. Sure, the stars would have to have been stuffed into the core pretty tightly, but stars were something astronomers were familiar with, something they had studied for thousands of years. Black holes were a wildcard. They just didn't seem like a rational choice.

Yet evidence for (what looked like) dead black holes was exactly what started popping up in the 1970s and 1980s as astronomers surveyed the centers of nearby galaxies. They watched the motions of gas and stars in galactic cores, calculating from them how much mass lay in the galaxies' hearts. The speed at which an object moves in its orbit depends on how much mass it's circling and how far away it is from that mass. If it's close in to a lot of mass, the object orbits faster than it would if it were farther out, just as Earth orbits faster than Neptune does around the Sun. The motions of gas and dust astronomers observed in galactic cores suggested that material was orbiting *very* massive centers, centers on the order of millions of solar masses or more. And because the gas and dust circled so close in to the center, the unseen mass also had to fit into a very small space—a couple of light-years wide at most. Even if a cluster of stars could pack itself that tightly, the stars would be so close together that they would soon crash into each other and create a black hole. Stellar clusters looked less and less likely, and by 1988 Richstone was convinced.

"It's kind of like finding the bones of the dinosaurs after you already know there are dinosaurs," he says of quasar relics. Looking back into the early universe, astronomers confronted these objects in galaxies without knowing what they could be. "It was kind of a riddle," he continues. "So then you go poking around in your backyard and you find these dinosaur bones, these big black holes that are now dead. They're not accreting anything, and it completely fits together with the objects you observe, and it completely—as far as I was concerned—settled the case."

A Caravan of Stars

The case file for the existence of the Milky Way's central black hole officially opened in 1978. John Lacy, then a graduate student at the University of California, Berkeley, trekked up the terracotta-colored hills of northern Chile to sit beneath the arc of our galaxy's dusty disk and the faint, beguiling glow of its central bulge. In the company of his advisor and two other astronomers, Lacy put to work the group's spectrometer. The spectrometer, an instrument that splits light into lines just like a prism exposes the colors in sunbeams, allowed the scientists to break open the mid-infrared wavelengths where light is just beyond the reddest gleam a human eye can see. In this range, lines from neon atoms missing an electron stand out starkly. This infrared light penetrates the dust that obscures our view of the galaxy's center and allows us to see into the core.

Lacy and his cohorts spent most of the Aprils of 1977 and 1978 tracking the ionized neon gas as it swirled around the Milky Way's center. The gas's motions suggested a massive object lurked inside the clouds' orbits: just as you can use the paths of the planets to measure the mass of the Sun, the astronomers used the velocities of the gas to detect a mass 8 million times that of our star hidden deep within the galaxy. This dark mass wasn't the focus of the paper Lacy lead-authored in 1978—in fact, it only receives a single sentence in the paper's conclusion. Nevertheless, it started people thinking.

By 1978, Lynden-Bell and Rees' suggestion that the Milky Way housed a dead quasar had had some time to sink in. That same year, Rees wrote an article for *New Scientist* magazine claiming black holes were the "best buy" model for quasars; he even pointed to ionized neon measurements as evidence that the compact radio source called Sgr A* coincided with a slow-eating supermassive black hole. That's not to say the idea was universally accepted. Rees spent a good portion of the article defending the black-hole model, especially against those who argued that quasar activity demanded "new physics" instead of these queer spacetime beasts.

It was a strange era in astronomy: George Rieke, an astronomer at the University of Arizona, claims that Lacy's work started "a scientific bandwagon." Black holes were terribly popular, so popular, in fact, that Rieke and his wife Marcia say they were "ostracized" when they downplayed the possibility of a central black hole in the Milky Way in the 1980s. But officially, the proof wasn't strong enough. Astronomers like the Riekes—and there were enough of them to keep the publications from that time toeing the line, filled with vague, noncommittal hints that *some* kind of compact object *might* be present in galactic cores—remained unconvinced that Lacy and his companions had demonstrated a black hole sat at the Milky Way's center. In point of fact, Lacy and his team weren't sure, either.

Part of the problem was the gas they had observed. Gas, unlike stars, responds to forces other than gravity, including friction between clouds and between the clouds and the thinner interstellar medium they pass through. These forces could also influence how the gas moved. An outflow wind blowing across the gas, for example, would cause an extra push unrelated to gravitational forces. So would interactions with magnetic fields. That meant the gas might not be whirling around due to gravity alone; at least, that's what the skeptics claimed. Even if it was, the humongous mass the clouds orbited was not necessarily a single object. The gas was only a few light-years out from the center, but that was still too far away to exclude the possibility that the central mass was a dense star cluster, not a black hole.

But gas isn't the only matter near the galactic center: individual stars also live there. Stars talk straight where gases mince words. Stars whiz through space totally unaffected by friction. Their motions depend solely on gravity, whether it be in the pull of another star they orbit or the slingshot fling of an encounter that sends them shooting off into the expanse. If stars were whirling around the Milky Way's center like the gas appeared to be, their velocities would offer sounder evidence for a central mass.

Astronomers pursued such stars throughout the 1980s using spectrographs to measure stars' radial velocities. Radial velocity is the motion of a star toward or away from us directly along our line of sight. This motion shifts the light coming from the star by a minute amount, stretching or squishing the wavelengths depending on which direction the star is moving. When the star moves away from us, the wavelengths are stretched out, becoming longer and, therefore, slightly redder; when the star moves toward us, the wavelengths are compressed, becoming shorter and bluer. It's the same effect that makes an ambulance siren sound higher pitched when the ambulance is coming toward you and lower pitched when it has passed and is racing away. Knowing stars' radial velocities allows astronomers to visualize how the stars are circulating around the core, with some approaching us as they come around the curve just as others move away.

The high speeds measured in the 1980s and 1990s pointed unanimously to an invisible collection of matter in the galactic center totaling at least one million solar masses. These measurements convinced many astronomers, but others continued to hold out. Some sounded cautionary horns against jumping to conclusions. In a 1995 review article, astronomers John Kormendy and Doug Richstone wrote, "This subject is dangerous. We enter it with expectations. We need to protect ourselves, lest we convince ourselves prematurely that we have proved what we expect to find."

Through the lenses of time, colored by our present-day confidence in the existence of black holes, Kormendy and Richstone's caution might appear overbearing, perhaps even paranoid:

> [T]he Galactic center [black hole] case is fundamentally more uncertain than those of the best candidates. . . . The case for a massive dark object is strong enough to be taken seriously. But further work is needed. . . . Have we discovered [black hole]s in galaxy nuclei? Rigorously, we have not.

These astronomers were trying to set the field's feet firmly on bedrock. At that stage, the observations were not sound enough to rule out all alternative theories, even if those theories became more and more fantastical as data built up. The community dug in its heels.

* * *

Andrea Ghez loves black holes. She talks about them with rapid-fire words, sentences battling with each other to come out of her mouth. During her grad student years, Ghez was lured into working with high resolution imaging, techniques that could compensate for blurring effects from Earth's atmosphere, by the claim that they could be used to find black holes. It soon became evident, however, that the technology wasn't sensitive enough for such observations. Later on, Ghez decided to use these techniques to study stars at the center of the Milky Way, attacking the black hole question from the side instead of straight on.

The Milky Way's center does not ascend quite as high in the sky over the Keck telescope domes as it does above the mountains of Chile, but Hawaii was where Ghez, now a professor at UCLA, and her team set their sights. Braving the fickle weather and fighting the mental clouds brought on by the altitude—you are forbidden to observe alone on Mauna Kea, lest altitude sickness strike you down—the astronomers spent a few precious nights in June of 1995 and 1996 and May of 1997 taking thousands of infrared photos of the innermost regions of our galaxy. They then laboriously combined each exposure, barely more than one tenth of a second long, to reduce distortions from Earth's atmosphere.

"We worked for a year to develop the algorithm to make the first image," Ghez says of their data from 1995. Nevertheless, the learning curve was steep: by 1998 they only needed one day.

What they—and their competitors, led by Reinhard Genzel at the Max Planck Institute in Germany—were looking for was clear evidence of stellar movement that would implicate the presence of a supermassive black hole. The radial velocity shifts in stars' spectra had convinced many, but these observers wanted to do better: they wanted to actually catch the stars on camera moving across the sky. Unlike previous work, Ghez and Genzel were looking at stars' *proper motions*, the path stars appear to take—left-right, up-down—on the celestial canvas. Proper motion studies can be done without a spectrograph, unlike radial velocity measurements; the astronomers track the stars by snapping high-tech photos from year to year. If speeds measured by proper motions supported those calculated from radial velocities, it might be enough to prove the Milky Way did hide one of the quiet beasts Lynden-Bell and Rees had predicted.

The second year the astronomers climbed Mauna Kea to gaze into our galaxy's core, they knew they were on the right track.

"In '96, the minute you took the second picture, you could tell that something interesting was going on," Ghez says. The scene had changed. Several of the stars they had seen the year before were nowhere near their old locations. Observations became a game of hide-and-seek as the observers worked to match up the old stars in the new field. Using the two sets of observations (1995 and 1996), the astronomers plotted start and finish points. They knew how far the stars had traveled, and they knew how long it had taken them to do it. With time and distance they could calculate the velocity (remember that old chant from high school? "Rate times time equals distance").

The answer? Nearly 900 miles per *second*—more than one thousand times faster than a bullet.

These stars, giant fireballs several times bigger than the Sun, were rocketing around a region less than three-tenths of a light-year wide at speeds no star should reach—unless, that is, they were orbiting a *lot* of mass, packed into a *very* small space.

The scientists went back to Hawaii in 1997 to check their results. There was no doubt: the stars were speed demons. The motions were amazing, but they were real, and with no other forces to explain the results except gravity the astronomers presented them to the world as solid evidence for a supermassive black hole.

However, for many Doubting Thomases, it wasn't quite enough.

"You know, it's fascinating how science gets done, and how you convince a community," Ghez says of those years—and it was *years* before the observers managed to silence all the questions. Whether the stars were zipping through space was not the issue: the calculations were believable. What wasn't clear was whether the stars were actually orbiting the galactic center in the first place. What if they were shooting through the core on their way to somewhere else, like a semi ramming through a traffic roundabout? Dissenters asked for evidence that the stars weren't traveling in a straight line right out of the center. If they weren't, it meant they were responding to the gravity of something nearby—or, ideally, orbiting that something.

When Ghez's team complied in 2000, more objections arose: plot the orbits, detractors said. Track the stars' progress as they follow their elliptical paths. The observers went back to the telescope. Over the next three years, they watched the galactic center for nearly thirty nights cumulatively, making many treks up and down the Hawaiian volcano. They poured over images, identifying stars and pegging positions. They created models. Then they played connect-the-dots. And lo the curves they drew through their data points—more than 250 measurements by the end—traced out beautiful, credible ellipses that all looped around the same small region, that invisible gravitational center marked on images with nothing more than a tiny plus sign.

Meanwhile, the German team, working independently with data from the European Southern Observatory in Chile, had also produced spectacular images of stars in their orbits around the Milky Way's center. With new technology improving blurring correction by a factor of ten, both teams were able to compile their images into *videos*. Not simulated progressions of computer-generated dots. Actual, honest-to-goodness photos, taken with real cameras attached to real telescopes on real mountaintops, of stars careening around the galactic center at whiplash speeds.

Nearly a decade after the German team released their 2002 video, physicist Scott Hughes still remembers the feeling the images gave him. "When I first saw those [videos] it was kind of a 'Wow this is a paradigm-changing observation,'" he says. To actually be able to watch stars move, not in the sedate progress of the constellations overhead but in an all-out sprint, is one of a handful of developments that Hughes looks back on as pivotal changes in the field of black holes since he entered it in the 1990s.

The videos were not impressive just for their gee-golly punch. Nor was their science revolutionary: astronomers had measured stellar motions for years. But they were the climax of decades of effort that made alternative theories to black holes—like central, dense star clusters—more or less obsolete. In order to explain the stellar velocities Ghez's team had published in 1998, a star cluster would have had to be dense enough to fit the mass of one trillion Suns within the innermost few light-years of the Milky Way. So tightly stuffed, the cluster wouldn't have survived for long: the stars would have quickly collided and created a black hole instead. Either way astronomers looked at it, a black hole was the best explanation for what lay at the heart of our galaxy.

"Supermassive black holes were a nice idea, it was a nice explanation for active galactic nuclei," Ghez explains, "but there was no definitive evidence that supermassive black holes really did exist." Star orbits made the case. Nothing else could explain the observations. These enormous objects, too weird to be real for so many decades to so many scientists, actually filled the cosmos, actually sat at the center of our own galaxy. If the Milky

Way was home to a black hole four million times the mass of the Sun, it wasn't too absurd to suspect such monsters sit in the cores of almost every one of the billions upon billions of galaxies we can see.

But, if there, what were they doing?

Cosmic Slavery

The first galaxies, it is thought, formed from clumps of gas and a few primordial stars. Over time these gaseous clumps, each as massive as a million Suns, merged and collapsed, compressing the gas to form more stars even as they coalesced into coherent systems, much like the galaxies we see today.

From then on out, it was a mad game of cannibalism. Galaxies caught by each other's gravitational fields tore each other into strips of superheated gas and spit stars back out like crumbs. They merged to form new systems in a never-ending process of galactic evolution, creating the disks of spirals like the Milky Way, the bulbous spheres of ellipticals. Often they left behind streams of orphaned matter or distorted dwarf galaxies, which circled the larger galaxy until they, too, were eaten in the endless cosmic feast. The scarfing continues today.

This picture is relatively recent. In the mid-1960s the vogue theory said that there had been a unique era of galaxy formation many billions of years ago, in which much more massive clouds of gas collapsed individually, each forming a single large galaxy. Rising evidence for galactic cannibalism, however—stars of distinct chemical heritages commingled in the same galaxy, images of distant systems wrapping their shredded arms around each other like circus contortionists—eventually changed scientists' minds.

Neither of these scenarios says much about supermassive black holes. Black holes appeared to be an afterthought in galaxy formation, a refuse pile, perhaps created by too much matter sinking into the core and triggering the infinite contraction described by Oppenheimer and Volkoff.

But inklings of a different story began appearing in the 1990s. Astronomers started noticing unexpected correlations between the mass of the central black hole and the properties of its host galaxy. Doug Richstone, on his way to becoming a quasar relic convert, paired up with astronomer Alan Dressler in 1987 to study the cores of two galaxies and the masses of their (hypothetical) central monsters. They found that more massive black holes sat in brighter galactic bulges, the spherical concentration of stars at a galaxy's center.

Other astronomers had found the same correlation. Over the next decade, they also discovered that, the more massive the black hole, the more massive the bulge and the larger the range of speeds for stars in that bulge. An increase in one parameter—the star speed ranges, for instance—predicted a particular increase in black hole mass, so particular that data points suggested a straight line: they tracked each other that closely. What's weird about the connection to star speeds in the bulge is that, unlike the stars Ghez and Genzel observed, these stars were too far out to be responding to the black hole's presence. At least, that should have been the case. Theoretically, if the central creature disappeared the bulge stars wouldn't know the difference, because their speeds depend on how the galaxy formed, not what's buried down in the middle somewhere. The fact that they did care about the black hole meant the galaxy was somehow intimately connected with its beast. But what *caused* that connection?

"We do not know," Richstone admits.

But the link between black hole and galaxy was clear, measurable in at least three different ways. It was intriguing. It was, perhaps, slightly disturbing. And it inspired astrophysicists Joseph Silk and Martin Rees to suggest in 1998 that black holes may play a key role in the formation and evolution of galaxies.

Such an idea, Rees allows, was "a bit surprising." *Surprising* strikes the ear as a good old-fashioned British understatement. The fact that supermassive black holes exist at all had thrown almost everyone for a loop. After that had come the revelation that not only did they exist, they were *common*. Nearly every large galaxy looked to have a quasar relic at its heart. Now, black holes appeared to have a major influence on the development of the building blocks of the cosmos, the billions upon billions of galaxies that form the universe's large-scale structure. All that power, given to a little whirlpool of spacetime perhaps one million trillionth the size of the galaxy. That's like a single atomic nucleus controlling a 30-story building.

How exactly such an influence would work—or whether it even exists—remains a hot topic. At the moment, astronomers' picture of supermassive black hole evolution is rather like a half-developed Polaroid. It's not clear when these objects first formed, or even how they formed. Observers have recently spotted quasars less than one billion years after the Big Bang, which means that these enormous creatures would have had to assemble *fast*, astronomically speaking. But as to what this early appearance means for the relationship between black hole and galaxy, scientists do not have a final answer.

Currently, explains astrophysicist Marta Volonteri, the most popular scenario for the evolution of black hole and galaxy is one of symbiosis. In a symbiotic relationship, the galaxy and black hole would share control, back-and-forth—a little bit of growth here leads to a little bit of damping there. Because the black hole grows when the galaxy feeds it, galactic growth through mergers or other changes would (presumably) siphon material off to the central beast, making the creature grow with the galaxy—hence, the bigger the galaxy, the bigger the black hole. In turn, the black hole's belches might create galactic-scale winds spewing material back out, heating the surrounding gas so much it cannot collapse to form stars. It might even push gas right out of the galaxy, halting galactic growth and, therefore, its own.

This model is entirely speculative. While many astronomers point to a feedback mechanism like this one to explain how a co-evolving black hole and galaxy would control each other's growth, the process is not understood. It might involve a competition for gas, in which the beast gobbles as much as it can before its blowback turns off the hose or stars gather up gas as they form and keep it from falling into the center, starving the creature. Why feedback would produce such a close correlation between black holes and galactic bulges isn't evident, and the feedback "solution" has many skeptics, including Volonteri. While she thinks some kind of feedback may be key, Volonteri worries that people are too quick to point to it to explain certain galactic characteristics, such as how a galaxy's brightness evolves over time. "It seems like a *Deus ex machina* thing," she says. "It works, but we don't actually know how it works." And whether the questions of *why* it works and *how* it works are being asked as rigorously as they should be is, well, an open question.

There are other options to explain the black hole-galaxy correlation, but they have their problems, too. There's the possibility that the beast depends fully on the galaxy, a slave to the galaxy's whim to feed it or not. Because the black hole's mass appears to be a set percentage of the bulge mass (around one- to two-tenths of a percent), some astronomers suggest that galaxies funnel a standard fraction of their gas to their cores. Why that would be, however, isn't known. It's also possible that the black hole reigns supreme over the galaxy, a situation which, Volonteri speculates, *might* occur when the black hole first forms. Astronomers simply do not have enough information to solve the conundrum: do black holes and galaxies coalesce at the same time? do they grow at different rates?—these questions and more have the field caught in eddies of enigma.

The one thing that is clear in all this cloudiness is that supermassive black holes are a lot more important than astronomers used to think. They may well be the most fundamental objects in the universe—no other single bit of matter may have had as great an influence on cosmic design. This idea has percolated through the astronomical community; these days, you'll hear it from many sides, not just from those in the trenches working on galactic evolution. Astronomers have latched onto the idea, possibly because it was so shocking. And so far, it shows no sign of abating.

Swallowed

"When I was six years old," says Hughes, thrown back in a leather lounge chair in his office like a patient talking with his psychologist, "my mom had read something about black holes, which she tried to describe to me. It didn't make any sense. So it's sort of my whole life I wanted to understand what my mom was talking about."

A few years older now, Hughes spends his days doing the finessed version of dropping pennies down the coin vortex at science museums: he uses computer simulations to model what happens when a small black hole and a big black hole spiral toward each other and merge. The simulations use something called numerical relativity, the development of computer codes to come up with an answer to a set of interrelated equations—like Einstein's—for which you know a solution exists but which isn't "one that has a simple closed form like we learn from all the books on my shelf," says Hughes.

It's perhaps surprising that, after all the decades Einstein's equations have been around, solving them can involve so much work. Generations of physicists since 1915 have grappled with the equations' deceptive elegance, the simple way in which they can be written with a few letters and an equal sign. There's a reason this succinct profundity causes so much trouble: "The field equations in general relativity that describe gravity are horrible," Hughes says bluntly. They involve ten interwoven equations, all of which must be solved *simultaneously*—and you have to make the right assumptions and approximations to do it, simplifications which are not written into the equations.

By solving Einstein's equations you solve for spacetime itself. Because the geometry of spacetime, the way it stretches and curves, depends on the mass and energy in it, there are, technically, countless possible solutions to the general relativity equations. It's more like calculating a tip at dinner than answering a question on Jeopardy: the amount of the tip depends on the initial conditions of your meal—the cost of your dinner, how nice the waiter was. The same goes for calculating spacetime geometry in general relativity.

Nearly one hundred years after Einstein's work of genius, only two "pen and paper" black hole solutions for his equations exist: Schwarzschild's, for a black hole that doesn't spin, and one derived by New Zealand mathematician Roy Kerr in 1963, for one that does spin. The numerical simulations that Hughes and other physicists do today are just as exact as these two solutions, but they require a lot of computer-based number crunching. Unlike Schwarzschild and Kerr's solutions, numerical solutions allow physicists to watch how the spacetime curvature changes with time—say, for example, around two circling black holes as they approach each other and merge. Because the curvature of spacetime depends on what's in it (one black hole, two black holes) and because that stuff moves around over time, the shape of spacetime will also change from moment to moment. The ability to watch this change is crucial to simulations.

Numerical relativity has been around for several decades. Working simulations of merging black holes, though, that's another story. Before 2005, merger simulations crashed. Period. Theorists could do basic tasks like smash two black holes together, but when they tried to send the black holes into orbit around each other to scrutinize the inspiraling "penny path," numerical errors "would evolve away into junk," says Patrick Motl, a numerical relativist at Indiana University, Kokomo. The simulation shattered into smithereens.

Successful merger simulations shone like the Holy Grail to relativists—a glimmering, ever-desired but unattainable goal. They wanted to know how the mass and spin of the newly created black hole depends on the two progenitors from which it was made. Because its mass and spin completely describe a black hole, learning how these two quantities are connected to the object's history could answer a lot of questions about how it forms.

At the same time, there was an equally enticing carrot, at least from the physicists' perspective: how did the fabric of spacetime behave during events like mergers? In particular, what would the resulting gravitational waves look like?

Gravitational waves are ripples in spacetime, created by accelerating masses. They're vaguely like the wake left by a passing speedboat, except in this case the wake pushes back like the recoil of a fired gun. It is this recoil, masses' interaction with their own outgoing waves and the associated energy, that causes members of a binary black hole system to spiral in toward each other over time, sending out stronger gravitational waves as they go. These waves propagate out through space like the swell from a boulder falling into the sea, carrying with them the message of the merged black hole's parentage and place and time of birth.

This birth certificate is what relativists want to detect in order to prove such mergers happen in the universe, as they see little hope in being able to observe the events directly. It's been a long-cherished goal, with varying degrees of muscle behind it. In 1999, scientists finished constructing the Laser Interferometer Gravitational-Wave Observatory, or LIGO, two stations in the United States separated by roughly 2,000 miles (Washington state to Louisiana). Each station has a pair of L-shaped arms three miles long, with mirrors and lasers positioned to probe for gravitational waves. When a wave passes through an object, it should cause a minute change in the object's length. This size change, only one hundred millionth the diameter of a hydrogen atom, should reveal itself when laser beams pointed at small mirrors at the ends of the observatories' arms detect a change in the distance they span. Gravitational wave signals should be observable anywhere in the world. Because the detectors are highly sensitive to local vibrations, like construction drills or earthquakes, LIGO built two stations to confirm observations. So far, they have no definite results.

Einstein's equations predict gravitational waves, but theory—even one as lovely as general relativity—isn't the only reason scientists go to all the hassle of building things like LIGO. In 1974 astronomers Russell Hulse and Joseph Taylor discovered two objects whizzing around each other in space. Both were neutron stars, the stellar core left behind when a star dies by supernova but isn't massive enough to produce a black hole; one was blinking like a super-spinning lighthouse, a special kind of neutron star known as a pulsar. Over the next several years Taylor watched the pair and found that the objects took less time to orbit each other as the years went on—just as they would if the stars were releasing energy as gravitational waves and causing themselves to spiral together. In fact, the relativistic prediction nailed exactly the change in orbital period the astronomers observed, says Hughes. "If you take a look at the data and you lay on top of that data what the prediction is, you don't even have to do a fit, I mean they just lay right on top of one another." This observational evidence, albeit indirect, for gravitational waves won Taylor and Hulse the 1993 Nobel Prize in physics.

But these observations were not direct measurements of gravitational waves. Hence LIGO. And in order to understand any signals they might detect—or even to know what to look for in the first place—physicists wanted working simulations against which they could compare reality. What they had, however, were disasters. The more they banged their heads against the problem, the more excruciating their headaches were.

In 2005 Frans Pretorius invented relativistic ibuprofen. Pretorius, then at Caltech and the University of Alberta, Edmonton, had decided to pursue a line of attack unique from his peers. He chose to recast Einstein's equations in something called harmonic coordinates. The coordinates allowed him to reduce "all the 'nasty' non-linearities in the field equations," meaning that the functions were much smoother to handle.

This approach was completely different from other attempts at merger simulations, although, Pretorius notes, it did come from mixing together various ideas he had encountered elsewhere. Other physicists had tried co-rotating coordinates, hyperbolic formulations, auxiliary variables, puncture methods . . . all of which Pretorius found "ugly," because they made the equations even more complicated. While he did have to develop entirely new (and quite complex) computer codes, he didn't have to introduce all the extra constraints the other methods did.

Pretorius took his work to a conference of numerical relativists in Alberta that April. Standing up in front of several dozen of his peers, he presented a simulation that followed two black holes through an orbit, merger, and ringdown. The result, says Hughes, "scared the hell out of everyone."

"It blew my mind," he continues. As a postdoc, Hughes had tried drowning himself in relativistic computer code and quickly decided it wasn't for him. ". . . [O]ne of the reasons I left that community was that people have been struggling to do those kinds of calculations for years, and I frankly didn't think they were going to succeed. It was fantastic to be proven wrong."

"To be brutally honest," Pretorius admits, "I think the audience's reaction was a mixture of excitement and despair." For those not directly involved in merger simulations, the success was something to celebrate. On the other hand, for those who had worked for years to solve the conundrum, only to have someone succeed using a method completely different than anything they had tried, the achievement was a bit upsetting. "One person, in jest, afterward joked (paraphrasing) 'So what do the rest of us do now, commit suicide?'"

Pretorius's method, relativists worried, could be the *only* one that worked. Reproducing his results might take more than just tweaking their own codes: it could mean starting from scratch, throwing away years of effort. It could mean, basically, that their life's work was worthless.

Fortunately, two teams, one led by Joan Centrella at the NASA Goddard Space Flight Center, the other by Manuela Campanelli and Carlos Lousto (then both at the University of Texas at Brownsville) duplicated Pretorius's success a few months later by using the older techniques. They both reported their results that November at a workshop at NASA Goddard.

"It was pretty stunning," Hughes says of Centrella's presentation, which he saw at a later meeting. "Thirty people (out of all thirty present) burst out in applause." While Pretorius's success had been the first, it was these two subsequent triumphs that "brought binary black hole computations to the masses," Hughes says, because they proved that the old methods were still valuable.

All these efforts have now paid off. Numerical simulations have catalyzed rapid changes in the theory of black holes, says Kip Thorne, who, as Feynman Professor of Theoretical Physics at Caltech, has been one of the leaders of black hole physics since the 1960s. Until recently, he says, physicists have only understood black holes that just sit still in space, happy as clams. "When they're highly dynamical—when two black holes collide or a black hole is just being born—we don't understand their dynamics much at all, or haven't until very recently," he says. ". . . [W]e never had the tools until now."

One of the answers that have come out of numerical simulations, he adds, is specific information about kicks. Kicks are just what they sound like, backlashes that can send a black hole careening through space. When black holes merge, they emit a burst of gravitational waves that can produce this recoil, which, if strong enough, sends the newly created black hole rocketing away from the place of its birth like a baseball in the World Series. The kick can reach speeds up to a few hundred miles per *second*, says Martin Rees, or more than ten thousand times the speed limit on a California freeway.

This kick is crucial to understanding how galaxies' supermassive black holes grow, Rees continues. When two galaxies merge, over time settling down into each other's embrace to form a new galaxy, the two central black holes of the original galaxies should slide to the middle. There, they may merge to make a new black hole, just like in numerical simulations. Here's where the kick comes in. Without a kick, the creatures should coalesce without more than a hiccup. If the recoil is large enough, though, the newborn black hole's speed may exceed that required to escape the gravity of the entire galaxy, and "the black hole may be kicked out of the galaxy and lost in the game, as it were," Rees says. Because smaller galaxies have lower escape velocities, such a process might explain why small galaxies rarely show signs of central black holes: they were jettisoned.

Simulations have also improved scientists' understanding of how black holes' spins may change. Over the last couple of years, simulations have shown that, if two spinning black holes merge, the black hole they form will tend to spin more slowly than either of the progenitor objects, Hughes says. This slowdown happens because it's more likely for the two spins to combine in a random way, partially canceling out, than to add together. If astronomers measure a slow spin for a supermassive black hole, mergers probably played a big role in its growth. On the other hand, if a black hole is spinning rapidly, it likely gained its mass by gobbling up gas.

Spin may play a key role in the jets spewing from quasars, too. Recent work by MIT astrophysicists suggests that these beams may form when the central supermassive black hole spins in the opposite direction from the rotation of the disk of gas and dust feeding it. The results are still tentative, but understanding black hole spin could help astronomers crack the case on quasars, much as quasars once pointed the finger at black holes.

Knowing the mass and spin precisely will also tell you the shape of the event horizon, whether it's perfectly spherical—as it would be if the black hole weren't spinning—or squished down from a perfect sphere into a more oblate shape, like a ball of dough flattened onto a cookie sheet. If Einstein is right, these two shapes (spherical or oblate) should be the only options, with faster spinning black holes having flatter event horizons, just as the Earth has a paunch at the equator from spinning around its axis. But if Einstein's description of gravity is wrong, the event horizon could have some other weird structure. Determining that shape would be a direct test of general relativity. If it matches predictions, astronomers will have given the theory a hefty boost of validity. If it doesn't, physicists will know they have some work to do.

Where No One Has Gone Before

But how do you check the shape of the event horizon if you cannot even see it? The nearest black hole candidate, the behemoth at the center of the Milky Way, is as good as invisible, covering the same amount of sky a dime would as seen from 62,000 miles away, or about one-fourth the distance to the Moon.

To many, the question was a moot point. We'll never be able to see a black hole, they said, so we have to come up with other ways to figure these things out. "When I first began doing this sort of work, on schemes by which one could test . . . whether [an object is] a black hole or not, I was originally thinking of it in the context of potential gravitational wave measurements, fifteen years from now," Hughes says. "And [then] I saw Shep give this talk." What Shep Doeleman said was that observing the silhouette of the event horizon might be possible. It sounded crazy, more science fiction than science. And yet there was rationale to the idea, firm scientific ground.

Doeleman's solution was the Event Horizon Telescope, a project designed to unveil the mystery of supermassive black holes. Until now, the evidence for black holes has been circumstantial. It may seem that the circumstantial evidence is good enough: indirect observations have managed to convince even the most recalcitrant that these leviathans are the powerhouses behind quasars, that they sleep in nearly every galactic core, that they may play a fundamental role in the buildup of cosmic structure. The case is strong.

Yet as good as it is, this evidence does *not* test Einstein's gravity and definitively prove a black hole is there. Despite the incredible stellar velocities measured by Ghez, Genzel, and others in the Milky Way's core, these motions are basically a seventeenth-century test of a twentieth-century theory. The stars still follow the elliptical paths derived by Johannes Kepler in 1609. They may zip around the central region like a car on a roller coaster curve, but they follow that curve with no sign of the anomalies general relativity predicts. Newton could describe their orbits just fine.

The orbits are nothing novel because the stars are still much too far away from the black hole to pass through the extreme spacetime curvature it creates. As small as a couple of light-years are compared to the entire galaxy, the stars' closest approaches to Sagittarius A* are still 500 to 600 times further out than the radius of the event horizon. At such a distance—larger than the farthest Pluto travels from the Sun—the stars don't enter the region where general relativity dominates.

There is an orbit around a black hole, however, that only general relativity can describe. This orbit is the closest path an object can follow around the black hole without falling in. It is called, therefore, the innermost stable circular orbit, or ISCO. The ISCO is not the event horizon, although it lies just outside that point of no return. But even though material inside the ISCO may still be outside the event horizon, that material will *always* plunge into the black hole eventually, no matter how fast it's going.

"And that's an orbit that Newton would look at and say 'That's crazy,'" Doeleman says. In Newtonian gravity, as long as material stays outside the object it's circling, it will continue to orbit, without spiraling in. The key to confirming black holes, then, the key to testing Einstein, lies within this region embracing the black hole.

It's by no means secure that general relativity is right. So far it has passed every test, from explaining delays in satellite signals traveling to Earth to predicting blips in the orbits of dense neutron stars as they whirl around each other like brilliant tops. But Newton's mechanics passed a lot of tests, too, in the two centuries between its publication and Einstein. And physicists know that general relativity doesn't describe the tiniest scales of the universe, the sizes at which they have to turn to the even more obscure science of quantum mechanics, in which particles are also waves and "exact" loses its meaning. The question is, how far can general relativity be pushed? Will black holes require a revamping of Einstein, some kind of splicing of general relativity and quantum theory? To answer this question, astronomers must probe the spacetime within the ISCO, home to some of the most extreme physics in the universe.

It is this region on which the EHT has set its sights.

The EHT isn't just one telescope. The endeavor uses a technique called Very Long Baseline Interferometry, or VLBI, which combines multiple telescopes around the world to make one giant virtual telescope. To explain how VLBI works, Doeleman offers an analogy. Imagine you and a friend are standing at opposite ends of a pond of water. Your friend leans down and dips one finger into the glassy blue surface, creating perfectly circular ripples in the crystalline mirror that move out across the surface of the pond. Standing at the far end of this (rather large) pond, you are too far away to directly see what your friend is doing. You do, however, see the ripples as they gently lap the pebbles at your feet. Curious by nature, you gather together a group of friends, give them stopwatches and notepads, and send them out to stand along the shoreline, with instructions to record when they see the crests of the ripples hit their points on the shore.

Although the waves emanating from your friend's finger are beautifully circular, they'll hit the shore at different times at different places, Doeleman continues. But if your friends, using their synchronized watches, write down the time and the place of the waves they observe, you can bring them together later and reconstruct the wave front they saw. You will be able to say the fellow at the other end was dipping only one finger into the water, without ever seeing him.

VLBI works the same way as the gaggle of friends you gather together and send out. The waves measured are the waves of light emitted by blazing hot material as it falls toward the maw of the event horizon, and the light patterns created tell observers what kind of structure that material is part of—that is, whether it is part of an accretion disk feeding a central object—and whether the light shows signs of warping by extreme gravity. Even though astronomers cannot directly see the source, they can say what kind of source would create the wave fronts they see.

In the pond example you'll notice that the friends are spread out around the water's edge. The crucial point in VLBI is the distance between observers. For a single telescope, the resolution, the smallest size the telescope can distinguish, depends on how wide the mirror or antenna is. The larger the dish, the smaller the resolution, and the smaller the structure you can see.

But you can only build a telescope mirror so large before its weight overcomes the integrity of its shape. Once the smooth parabolic curve distorts, the telescope can no longer focus an image, and it becomes more or less useless.

Astronomers found a way around this obstacle with interferometry. Interferometry links various telescopes together and combines the properties of the light each observer sees into a single observation, just as the friends around the pond can compare notes. What is unique about radio telescopes is that they can be thousands of miles distant from each other when observing. While astronomers must observe simultaneously, they can bring their data together later and combine the information on their massive storage disks to create a single, cohesive picture. With interferometry, the distance between observers determines the resolution, not the size of the individual scopes. Make that distance large enough—say, from the Alps to Antarctica—and astronomers should be able to observe just as if they had a planet-sized telescope, all the way down to the scale of Sgr A*'s event horizon.

Suddenly, seeing the shape of a black hole doesn't sound so farfetched.

Doeleman and his colleagues have two goals. The first is to see the silhouette of the event horizon itself, proving the black hole is *really* there. If the beast is gobbling up matter, it will be sitting in the midst of glowing material made hot by friction and gravitational acceleration. Toward the middle of that material, where the black hole lies, the light will be struggling to escape the well the object makes in spacetime. This struggling takes a lot of energy. Light fighting to climb the sides of the well will therefore be fainter. On the other hand, light emitted by material on the far side of the event horizon, blocked from our direct view by the black hole, is bent by the object's extreme gravity like light directed with a lens, curving around the central object and into view. This lensed light should form long streaks around the "shadow" created by the dimmed light, looking rather like the diamond ring of sunlight peeking around the moon during a solar eclipse.

The size of the silhouette, given the mass of the black hole, is precisely described by general relativity, Doeleman says. "If we can measure [the exact size and shape of that] shadow, then we'll have some traction on deciding whether Einstein is right or not."

The second thing the astronomers hope to observe is how the structure of stuff changes as it goes round the black hole. The image of a bright patch, caused by a flaring bit of material as it orbits, should stretch out into a streak of light because of the strong gravity, bending and lensing in ways Newton's model does not predict. Astrophysicists are already working on how to use such "hot spots" to test general relativity. The emission around the event horizon will also depend on how the black hole feeds, how it accretes matter, and how that matter piles up as it's waiting to fall in, all things astronomers want to know, and all things—they hope—observing at this scale will tell them.

Doeleman and his colleagues have already managed to detect structure on the scale of about four times the event horizon's radius. What is that structure? "I'll be very honest with you, we don't really know," he says. The only thing they do know is that something *is* there. "We only used three telescopes, and you can't reconstruct the image from only three telescopes. So I know there's something compact there, I know there's something about the size of the event horizon, but I can't tell you exactly what it looks like."

The astronomers are working hard to dig even deeper into the Milky Way's core. Whether they succeed depends partly on infrastructure—whether they can organize observatories around the world and equip them to participate. It depends just as much, however, on funding. Currently the EHT astronomers, like much of the astronomical community, are waiting, breaths held close, for the results of the Astro2010 Decadal Survey. The National Research Council's Astronomy and Astrophysics Decadal Survey, a vast endeavor undertaken every ten years through the National Academy of Sciences, outlines research priorities for the field after intense proposal scrutiny by committees. It's a gargantuan effort, with panel meetings committed to strict secrecy. The first report was completed in 1964, and since then the decadal survey has become the field manual of astronomy. Projects contributing to the goals outlined by the survey receive more focus, more funding, and more telescope time.

The Council will release Astro2010 in September. If the EHT gains favor, Doeleman and his collaborators may be able to unveil our galaxy's greatest mystery by the end of the decade.

The Great Unknown

When faced with the uncertainty of funding, the bureaucracy of observatories, and the sheer magnitude of the effort before them, the EHT astronomers couldn't be blamed if they lost heart. But Ghez didn't faint at the analysis necessary to see stars move, or the Herculean effort required to convince her peers that the observations proved a black hole's presence. Numerical relativists didn't give up when their simulations crashed. And these astronomers, gathered together at Haystack to bolster their alliance and brainstorm their battle plan, their faces bright with winter and tenacious hope as they lined up in four rows on the observatory's steps and waited for the flash of a camera, can hardly fail to carry the baton.

"They use to be exotic," Doeleman says of these elusive dark objects. "Now they're very part and parcel to our tool box. But it's kind of like having a screw driver [and] not knowing where it comes from."

When asked why they study black holes, astronomers have different answers. Many point to the extreme physics of the surrounding spacetime, the chance to observe the most intense gravity environments in the cosmos. They raise questions about how these objects may influence the universe, whether they are really as fundamental as they now appear. Others have a more emotive reaction, like Ghez, who when asked this question practically shouted into the phone, "Because they're *cool*!" There's an undeniable attraction to black holes, a pull that opens itself to puns. They capture the imagination while shirking the eye, and it's hard to put a finger on the reason. Oddly, the best explanation came not from an astrophysicist, but from my own mother, as we were driving home along a small road in a small town, the unseen mysteries of the universe hidden above us in the sunlit sky: "It's like the Great Unknown—*right there*."

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