HOW WE KNOW BLACKHOLESEXIST

Despite their invisibility, black holes noticeably modify their environments by producing high-speed jets and abnormally quick stellar movements. by Liz Kruesi

In the late 18th century, two scientists (John Michell and Pierre-Simon Laplace) separately theorized that a star could be so massive that not even light could escape its surface. But nothing more was made of these "dark stars" until the 20th century, when Albert Einstein published his general theory of relativity. His idea turned the notion of gravity on its head: It isn't really a push/pull force, but instead describes how mass affects the fabric of space-time. And general relativity made possible the reality of those dark stars.

In 1916, just one year after Einstein published his theory, physicist Karl Schwarzschild calculated general relativity's gravitational equations in an extreme case (when an object has a mass near infinity) and found that the fabric of space-time would fold in on itself, creating a "singularity" — a region with zero volume and infinite density. Such a point would not allow matter or even light to escape. Today's term for this object — a black hole — came 50 years later, around the same time researchers began discovering hints of them.

Now, after 40 years of research, scientists are positive these extremely dense bodies exist, and that there are two different types. Astronomers categorize black holes as either stellar mass (which range from three to tens of times our Sun's mass and mark the end state of a massive star) or supermassive (which are millions to billions of times our star's mass and sit at the centers of galaxies).

The smaller variety

Over the years, different methods have convinced scientists that both types of black holes exist. One of the most successful techniques astronomers have used to find both stellar and supermassive black holes is monitoring the movements of stars near suspected black holes. They use the visible companion in a binary system as a tracer.

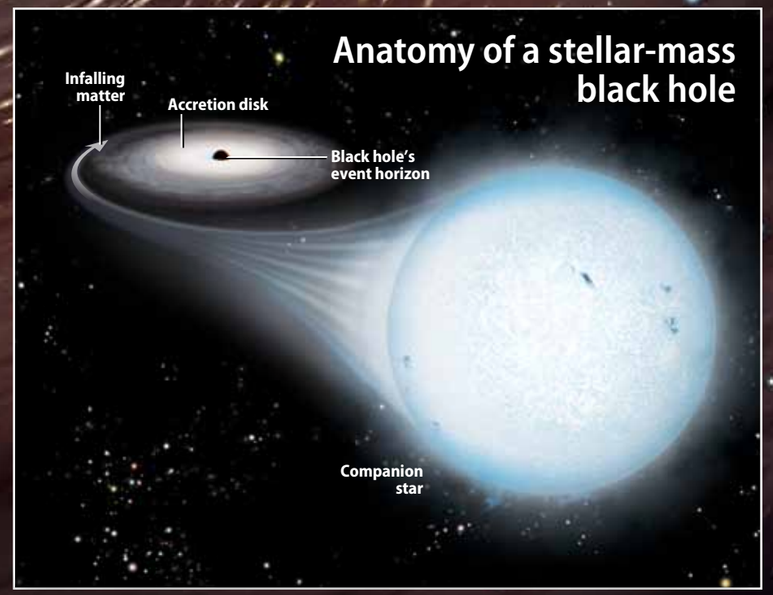
This method arose in the late 1960s when X-ray detectors aboard satellites spotted sources of X-rays in our galaxy. Many of these changed brightness over fractions of a second, so astronomers called them "X-ray transients." Scientists soon realized that some of these objects were binary systems.

In X-ray binaries, if the two bodies are close enough, the compact object pulls hot gas from the star. The stellar material heats up to millions of degrees due to friction and emits X-rays. The unseen compact companion could be a neutron star or a black hole; both are small enough to appear "invisible" until gas falls onto them, which then heats up and produces a bright X-ray source. To distinguish between the two possibilities, scientists need the invisible object's mass, which they can determine using basic physics laws.

Astronomers collect data through the visible star's spectral emission, which tells them about the star's composition and movement. As the star moves away from Earth in its orbit around its invisible companion, its emission shifts slightly toward the red end of the electromagnetic spectrum; as it speeds toward our planet, its emission shifts to the blue end. From the amount the spectrum shifts, astronomers can determine how fast the visible star is moving and how long it takes to complete one orbit. Then, using the same law of physics that dictates how the planets orbit the Sun, they can calculate the mass of the unseen companion.

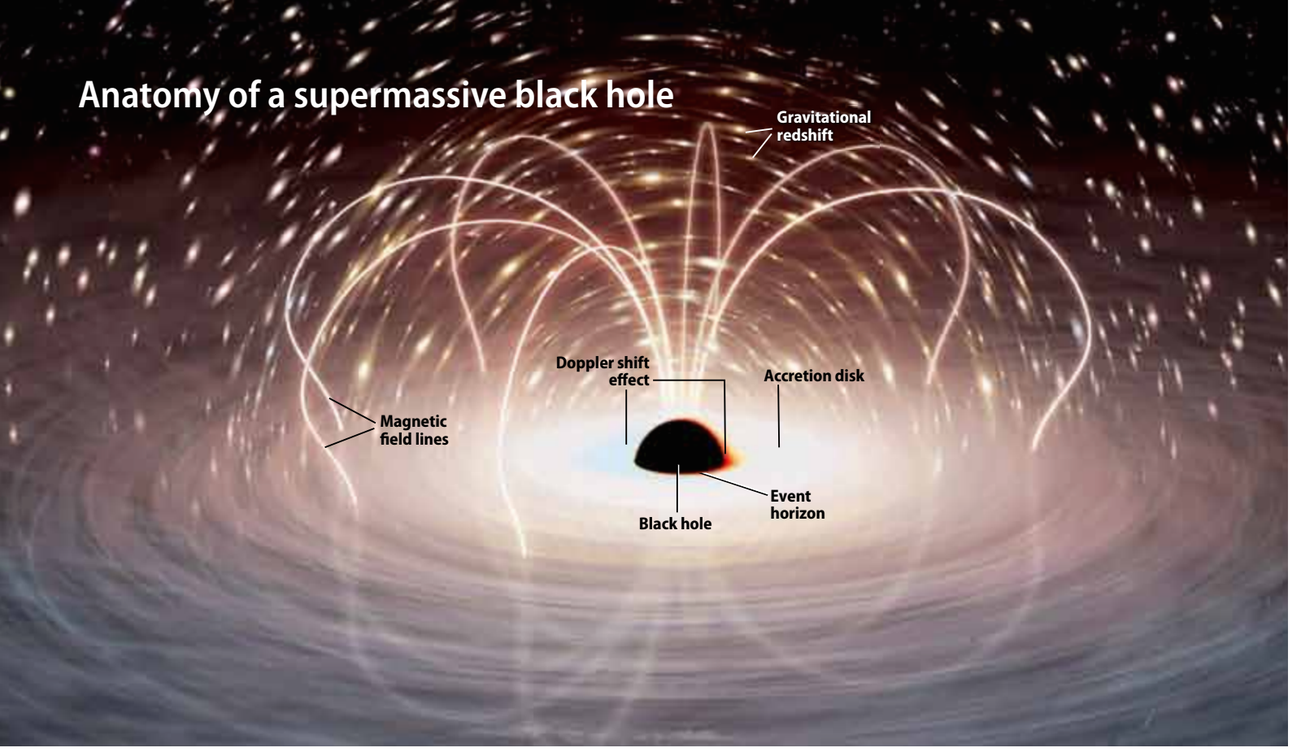
Liz Kruesi *is an associate editor of* Astronomy *magazine. She has no interest in seeing a black hole up close.*

A black hole warps space-time to the extreme, creating a point where the cosmic fabric folds in on itself. Any mass or light that comes within a certain distance — called the event horizon — will fall in and never escape. *Astronomy*: Roen Kelly



A stellar-mass black hole is the last stage of evolution of a star that once was at least 30 times our Sun's mass. This black hole holds between about three and tens of solar masses crammed into an area about the size of a large city. *Astronomy*: Roen Kelly

Astronomy magazine © 2013 Kalmbach Publishing Co. This material may not be reproduced in any form without permission from the publisher. www.Astronomy.com



A supermassive black hole contains millions to billions of solar masses in an area comparable to the solar system. Astronomers are nearly certain of a handful of these objects, but they think every galaxy may harbor one at its center. *Astronomy*: Roen Kelly

If it's less than about three times the Sun's mass (called a solar mass), it's a neutron star. If the companion holds more than three solar masses, it's likely a black hole. From such measurements, astronomers have identified about 20 stellar-mass black hole candidates.

Cygnus X-1 was one of the first X-ray binaries studied. In 1971, astronomers noticed that a hot blue giant star, HDE 226868, sat at the same location in the sky as an X-ray source. This star moved at about 43 miles per second (70 kilometers per second) around an unseen companion, completing an orbit in 5.6 days.

After gathering more data, the scientists calculated that the companion was at least four solar masses. Today, astronomers know HDE 226868 tips the scales at about 19 solar masses and its unseen companion contains some 15 solar masses. They are also convinced that the invisible object is a black hole that's the stellar remnant of a once extremely massive star.

Now you see it, now you don't

Scientists have gained other clues from X-ray binaries. In 2006, astronomers announced a study monitoring radiation linked to about three dozen X-ray binary systems. Out of those, 13 contained expected neutron stars, 18 comprised suspected black holes, and a handful were unclassified sources. The team, led by Ronald Remillard of the Massachusetts Institute of Technology (MIT) in Cambridge, analyzed nine years of data from the Rossi X-ray Timing Explorer (RXTE) and found 135 X-ray flashes that corresponded to the neutron star candidates, whereas the signal died out when observing the black hole candidates. This is exactly what scientists would expect if accreted material moved toward and past a black hole's boundary of no return — its "event horizon." The team watched as energy disappeared.

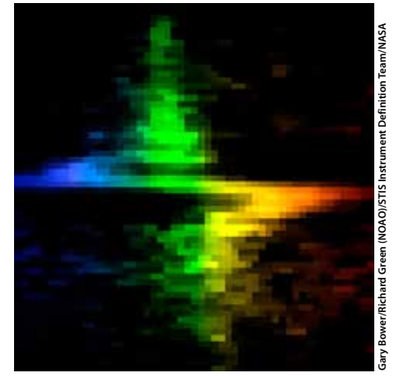
"X-ray flashes [indicate the] fusion of material that builds up on the surface of a neutron star," says Eliot Quataert of the University of California, Berkeley. "Black holes don't have such a surface," and therefore no flashes.

The lack of X-ray flashes is indirect proof that an event horizon exists, and if one exists, so does a black hole. "To prove that it's an event horizon, you have to have missing energy," says Karl Gebhardt of the University of Texas at Austin. "It has to be there and then not [be] there." Astronomers also have seen similar cases of "missing" energy associated with supermassive black hole candidates.

THE STRONGEST EVIDENCE THAT BLACK HOLES EXIST LIES AT THE CENTER OF OUR GALAXY.

The larger variety

The strongest evidence that black holes exist lies at the center of our galaxy. Two groups of astronomers — one led by Reinhard Genzel of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, and the other led by Andrea Ghez of the University of California, Los Angeles — have monitored the movements of dozens of stars at the Milky Way's center for 15 years. "The orbits of the stars are consistent with ellipses," says Quataert. "What that tells you is that the gravity that makes the stars move the way they move is consistent with a single object at the center, just like [how] in our solar system the Sun is at the center."



Gary Bower/Richard Green (NOAO)/STIS Instrument Definition Team/NASA

Scientists can figure out how quickly gas, or even a star, is moving around a black hole by looking at its spectrum. As the gas, in the case shown here, speeds toward Earth in its orbit, it appears bluer; as it moves away from Earth, it shifts to red. Scientists used this observation to determine that the gas within 26 light-years of M84's core whips around at 220 miles per second (360 kilometers per second). For the gas to move so quickly, some 300 million solar masses would need to lie within that distance.

The Milky Way Galaxy's core holds the most-convincing black hole candidate. Astronomers have studied the object, called Sagittarius A*, using radio, infrared, and X-ray telescopes and have ruled out other possible entities. NASA/CXC/MIT/F. K. Baganoff, et al.

From measurements of those stars' orbits, astronomers determined the mass of the unseen object inside their orbits; the center of the Milky Way Galaxy contains some 4 million solar masses within a region about the size of our solar system. The size and the mass then give the object's density. "And once you have the density, that's what really tells you if it's a black hole or other strange models," says Gebhardt.

Astronomers used to propose that the galaxy's center harbors clumps of neutron stars or white dwarfs, but both Genzel's and Ghez's teams have "been able to probe close enough to the black hole that, effectively, all other models that can try to explain that amount of mass have been ruled out," says Gebhardt.

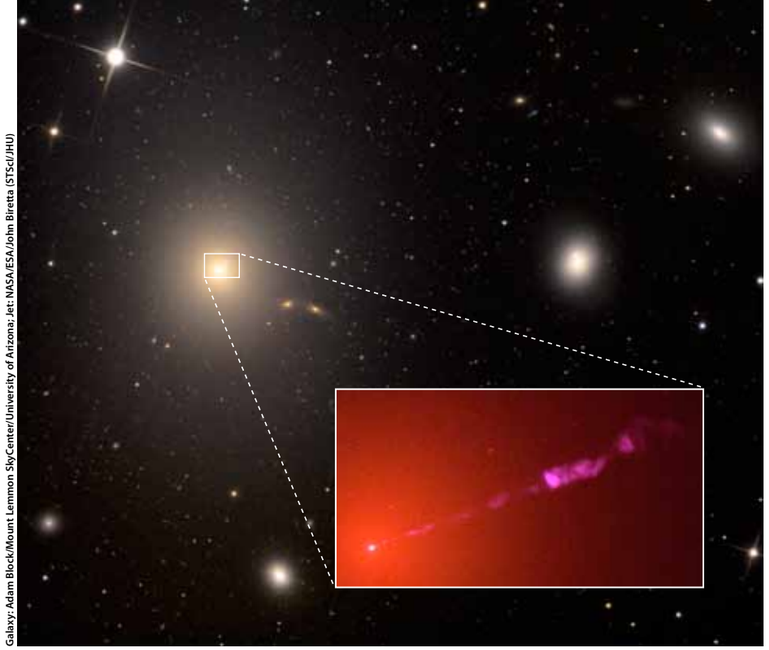
Identifying the object at our galaxy's center, which astronomers call Sagittarius A*, didn't just involve the motions of those few dozen stars — although they do provide the strongest evidence. In 2003, Genzel's team observed a brief infrared signal from the same location as the theorized supermassive black hole. The emission brightened, faded, and disappeared 30 minutes later. The team pinpointed the radiation's location to just a few thousandths of an arcsecond (corresponding to a distance of a few light-hours) from the black hole, and they think it results from material falling past the event horizon. The material heats up and emits infrared radiation as it approaches the massive object, but the signal disappears as the black hole's grip overtakes the gas, pulling it beyond the point of no return.

Not just the Milky Way

In addition to the Milky Way, scientists know of three other candidate galaxies that almost certainly harbor supermassive black holes. One is the mammoth M87, part of the Virgo cluster. Although the galaxy is about 50 million light-years from Earth, astronomers can monitor the movements of individual stars. They also track the motion of gas near the galaxy's center by observing particular spectral lines.

Gas and stars in the disk that surrounds a black hole revolve quickly. Just like in the stellar-mass candidates, astronomers can observe the redshift and blueshift of the material's spectral lines. The amount of shift corresponds to how fast the stuff is moving. Using this velocity and the amount of time stars take to complete a full orbit around the center of M87, Gebhardt and colleagues determined that the object at the center of the accretion disk holds some 6.6 billion times our Sun's mass — that's more than 1,000 times that of the Milky Way's central black hole. M87's central supermassive black hole holds that huge mass within a region about three times the solar system's width. (The same team also measured the masses at the centers of NGC 4889 and NGC 3842: Each holds some 10 billion solar masses in a space a few times the solar system's size.)

Astronomers used a different method in the late 1990s and early 2000s to calculate the mass of the suspected black hole at the center of the galaxy M106 (NGC 4258). They found a handful of water masers — objects that amplify light of a specific frequency, and thus are easy to track — within the inner 3 light-years of the galaxy. By observing the motions of those masers with the Very Long Baseline Array of radio telescopes scattered across the globe, the team determined the speed at which the objects were moving. It then calculated that some 30 million solar masses sit within that



Galaxy: Adam Block/Mount Lemmon SkyCenter/University of Arizona; Jet: NASA/ESA/John Biretta (STScI/JHU)

Elliptical galaxy M87 in Virgo almost certainly holds a central supermassive black hole containing 6.6 billion solar masses. The object also shoots out high-speed jets of matter and radiation (inset).

region, which is smaller than the distance between the Sun and the next nearest star.

M106, along with the Milky Way, M31, and M87, contains a central object with such a high density that astronomers have ruled out any other explanation. These four galaxies almost certainly harbor supermassive black holes at their cores.

Marking the spot

Ever since the 1960s, when astronomers began discovering extremely luminous distant galaxies called quasars, they've wondered what creates them. The leading theory is that as a supermassive black hole's gravity distorts space-time nearby, it also twists its magnetic field. So when material spirals into the black hole, magnetic field lines funnel radiation and matter into regions perpendicular to the disk. This creates high-speed jets.

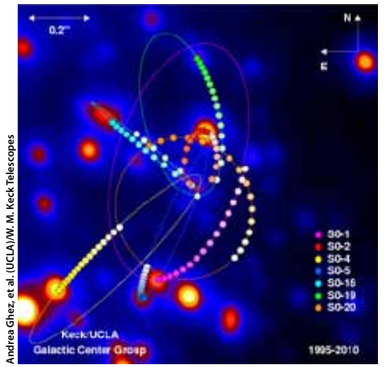
For decades, scientists have found radio sources at the same sky positions as possible black holes with matter moving at nearly the speed of light. But recent findings helped connect such radiation to black holes.

In one study using the Swift satellite, which looks for high-energy emissions, astronomers spotted X-ray flares in addition to gamma and radio emission at the same position. They found that this material was moving toward Earth at more than 90 percent the speed of light. "The radio emission occurs when the outgoing jet slams into the interstellar environment," explains Ashley Zauderer of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, leader of the radio study. "By contrast, the X-rays arise much closer to the black hole, likely near the base of the jet."

The researchers are convinced that they saw a star come too close to a black hole's event horizon. Gravity stretched it, funneling the gas into an accretion disk; the friction in the disk caused the star to emit X-rays. Then the material moved past the event horizon and the signal died out. In a couple years, scientists expect to be able to image the jet in radio wavelengths, which would add another level of confidence to the theory.

Using the RXTE, another team watched a similar situation. It spotted a faint oscillating signal from the binary system H1743-322 (which contains an unseen companion) that seemed to speed up; they think this was a blob of material orbiting close to the black hole. The signal then disappeared, and two days later the group saw a "bullet" of gas shoot out from the disk. The following day, they saw another on the opposite side.

Scientists also have detected high-speed jets shooting from the center of M87, in addition to M81, NGC 2273, and a handful of other galaxies, suggesting they all harbor supermassive black holes.



Andrea Ghez, et al. (UCLA)/W. M. Keck Telescopes

Astronomers tracked the motions of stars within 16 billion miles of the Milky Way's core and found that they're orbiting as though there's a single massive object at the center of our galaxy. Using basic physics laws, they determined a supermassive black hole about 4 million solar masses lies within a solar-system-sized region.

Looking for the absolute

Although scientists have found convincing evidence that black holes exist, "the defining property of a black hole is the existence of the event horizon — this point of no return," says Gebhardt. "The proof of that is very elusive." The sighting of an event horizon would be solid evidence, but scientists haven't found one yet. In the next few years, they just might.

THE EVENT HORIZON TELESCOPE WILL TRY TO DIRECTLY OBSERVE A BLACK HOLE'S BOUNDARY OF NO RETURN.

Telescope arrays are in the works that will have the resolution to image a region where no light emanates. "If the estimated event horizon of a black hole is large enough, you could see its optical absorption effects and you could actually see a hole if there was background material," says Gebhardt. The two best candidates for such an observation are the supermassive black holes at the centers of M87 and our Milky Way. These two objects would span a large enough area to take an image and see structure.

According to general relativity, a black hole's immense gravity can warp space-time around it so much that light could not escape its clutches. "One prediction is that you'd literally see the absence of emission from some region very close to the event horizon," explains Quataert. This extreme gravitational lensing creates what's called a black hole's "shadow," and it's a bit farther out than the event horizon.

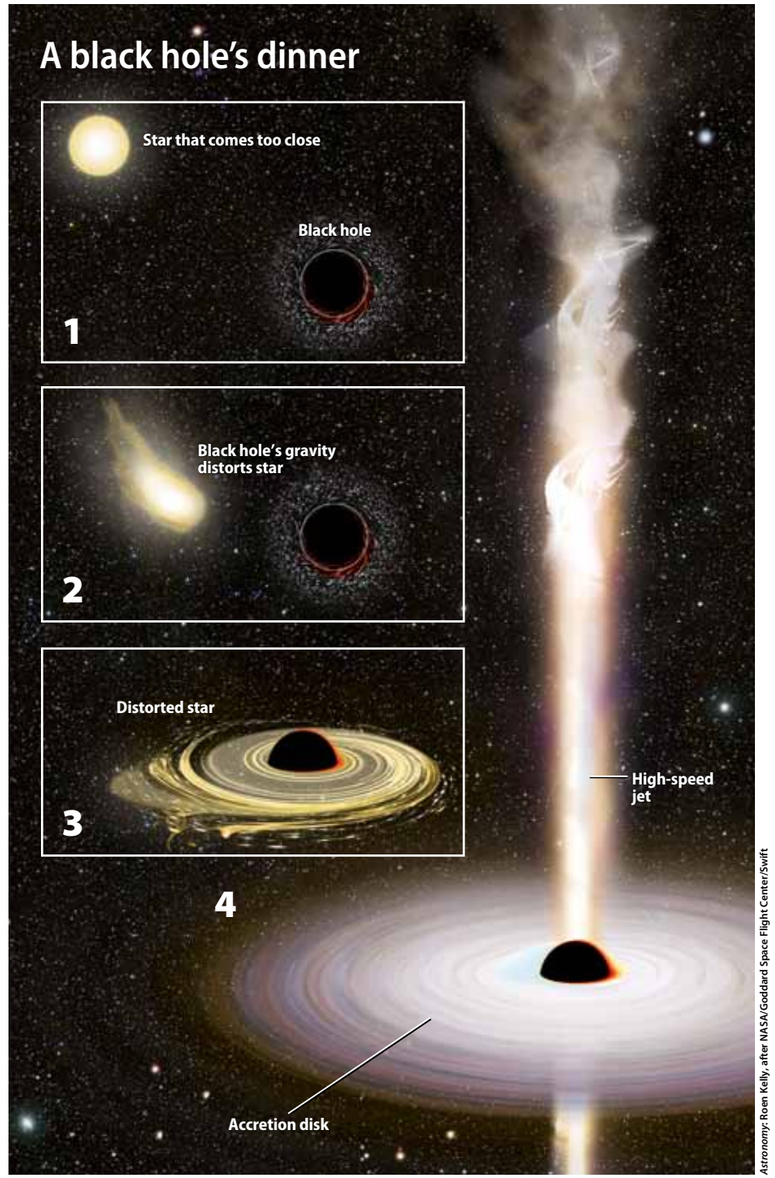
Any object with mass warps space-time, and therefore light passing near it would bend slightly. When you're far away, light deflects only a tiny amount. "But as you move closer to the black hole, that effect gets bigger," says Quataert. "And at some point, it's so dramatic that light rays can wrap all the way around the black hole and start looping around. And that happens somewhere outside the event horizon, at a well-defined place" predicted by general relativity. A direct observation of this shadow, such as a "dark spot" in background material, would prove the existence of black holes.

What the future holds

The key to seeing a shadow, event horizon, or material spiraling into a black hole is using a detector with high resolution. One group, led by Frank Eisenhauer of the Max Planck Institute, plans to use the Very Large Telescope array in Chile with an instrument it's creating to precisely measure the position of stars near a suspected black hole. This apparatus, called GRAVITY, should be able to measure the position of a light source with a resolution of 10 microarcseconds starting in 2014. "In the case of a flare — when the black hole lights up — the brightness is likely dominated by a single 'bright blob' orbiting the black hole at a radius of about three times the event horizon," explains Eisenhauer. "Since the orbiting blob is dominating the brightness in the black hole region, GRAVITY will measure the motion of this 'blob' on its in-spiral onto the black hole."

The next generation of X-ray telescopes might also probe material closer to the event horizon and even gas falling past that boundary. But these projects may have to wait until the 2020s.

A nearer-term instrument, called the Event Horizon Telescope, will try to directly observe a black hole's boundary of no return. Headquartered at MIT, the project will combine radio telescopes across the globe to form an Earth-wide instrument.



Astronomy: Roen Kelly, after NASA/Goddard Space Flight Center/Swift

If a star comes too close to a black hole's gravity, some of its gas will be pulled into a disk surrounding the black hole. This material heats up due to friction and radiates X-rays. As the gas loses energy, it falls past the black hole's event horizon. Some material might escape through funnels perpendicular to the disk. Astronomers have observed both the X-ray and radio emissions related to such an event.

Astronomers think it will be possible to image M87's supermassive black hole's event horizon within the next decade.

So, perhaps a century after Schwarzschild first calculated how the fabric of space-time would warp due to an object with nearly infinite density, astronomers might directly observe the telltale sign of the gravitational effects of the most realistic case known. But for now, the evidence they've compiled over the past five decades makes it certain that black holes exist. As Quataert says, "At this point, it's beyond a reasonable doubt."

View how stars orbit Sagittarius A* at www.Astronomy.com/toc.