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” 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).

How we know black holes exist

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

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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.

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

Liz Kruesi is an associate editor of Astronomy magazine. She has no interest in seeing a black hole up close.
Astronomers have identified 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 supernova explosion.

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 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.

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Now you see it, now you don't

Scientists have gained other clues from a handful of these objects, but they think every galaxy may harbor one at its center. "To prove that it's a black hole, you have to have evidence that there's an event horizon, and if one exists, it can't just disappear," says Ron Remillard of the Massachusetts Institute of Technology in Cambridge. "The material heats up and emits infrared radiation as it approaches the massive object, but the signal disappears as the black hole's gravity takes over."

Not just the Milky Way

In addition to the Milky Way, scientists have found three other candidate galaxies that almost certainly harbor supermassive black holes. One is the Mammouth, a part of the Virgo cluster. Although the galaxy is about 30 million light-years from Earth, astronomers have monitored 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 solar-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 5 billion times more mass than 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 only 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 scale of the solar system.)

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 are easily tracked. They determined the speed at which the objects were moving. It then calculated that some 30 million solar masses sit within that...
cent the speed of light. “The radio emission moving toward Earth at more than 90 percent of the speed of light was detected by a team of astronomers who use the Karl G. Jansky Very Large Array to image the jet in radio wavelengths, “explains Gebhardt. “They found that this material was responsible for the radio jet.”

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 sight of an event horizon would be solid evidence, but scientists haven’t found one yet. In the next few years, they just might.

Telescope arrays are in the works that will 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.

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 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, the Event Horizon Telescope, will try to directly observe the 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.

According to general relativity, a black hole’s immense gravity can warp space-time around so much that light could not escape its clutch. “One prediction is that you 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.

A black hole’s dinner

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).