

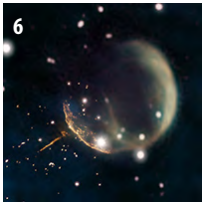
# Mercury

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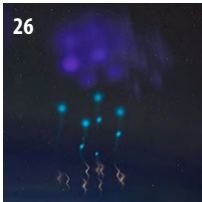
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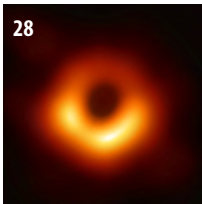
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## on the cover

On April 10, 2019, the Event Horizon Telescope (EHT) Collaboration released the historic first image of a black hole. The black hole is the supermassive monster located in the heart of the massive elliptical galaxy Messier 87 (M87), approximately 55 million light-years distant. [EHT Collaboration]

# Lifting the Curtain

After decades of wondering, the Event Horizon Telescope has revealed what a black hole *really* looks like.

By **Steve Murray**



This is the Event Horizon Telescope's first target—the supermassive black hole in the core of the galaxy M87 [EHT Collaboration]

Well, the wait is over.

On April 10, a series of international press conferences gave audiences their first-ever view of a black hole: an image of a fuzzy black circle surrounded by a blotchy smear of yellow and red that may transform astrophysics. But the road to this historic achievement was long and arduous.

Astronomers of the Event Horizon Telescope (EHT) project (see Mika McKinnon's article in *Mercury's* Winter 2018 issue) had been poring over their data since April 2017, when they trained a world-spanning telescope on two supermassive black holes. Their goal was to penetrate through light-years of dust and gas and capture images of these enigmatic bodies.

Although the scientific community—and the public at large—waited well over a year for results, the team wasn't about to be rushed. After two decades invested in designing and building their array, developing their simulation models, and refining their data processing methods, the EHT scientists were intentionally slow and deliberate. They wanted to get it right.

Stellar-mass black holes are a product of a star's collapse, when all of its matter shrinks to a singularity—an infinitesimal point with immense gravity. The origin of supermassive black holes, the gravitational monsters that are known to live in the centers of most galaxies, however, is more mysterious and one of the questions that the EHT hopes to answer.

Regardless of their mass, while Einstein's theories hypothesized black holes, and careers have been spent developing the mathematics to characterize them, all the evidence we have is indirect: stars orbiting an invisible point in space or ripples in space-time that announce hidden collisions. Astronomers still needed to see a real one, which meant capturing an image. And the supermassive black holes that dominate galactic cores turned out to be the best candi-



Simulations of the emissions generated near to the event horizon of a black hole—shown here—closely match what the EHT observed, agreeing with Einstein's general relativity. [EHT Collaboration]

dates for the EHT.

"One of the strengths of the EHT experiment is that we we'll produce the best evidence for the existence of black holes," said Geoffrey Bower, Institute of Astronomy and Astrophysics at Academia Sinica, and EHT Science Council Co-Chair.

At a critical distance, the gravity of a black hole becomes so strong that even photons moving at the speed of light don't have enough energy to escape. As light itself gets pulled in, its departure marks the dark sphere of the "event horizon," a boundary where new physics behaviors may be found. [Continues on page 31]

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# the anatomy of a black hole

Courtesy of ESO, ESA/Hubble, M. Kornmesser/N. Bartmann

## Singularity

At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity. All the matter and energy that fall into the black hole ends up here. The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

## Event horizon

This is the radius around a singularity where matter and energy cannot escape the black hole's gravity; the point of no return. This is the "black" part of the black hole.

## Photon sphere

Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow". The Event Horizon Telescope is hoping to see both the ring and the "shadow".

## Relativistic jets

When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space. The GMVA will study how these jets form.

## Innermost stable orbit

The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

## Accretion disc

A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.

Accretion disc

Event horizon

Relativistic Jet

Singularity

Photon sphere

Innermost stable orbit



The South Pole Telescope in the Antarctic is one of the more extreme components of the EHT Collaboration. [SPT Collaboration]

While general relativity theory has weathered some pretty strong tests since it was proposed, it has to fail somewhere because it's incompatible with quantum mechanics. Although scientists don't know where or how that breakdown might occur, it's a strong bet that right at the edge of the event horizon is the most likely place to look. Gravity here is stronger than anywhere else in the universe, so even small deviations from general relativity should show themselves. "This gives us a chance to study some of the most enigmatic objects in the universe," said Bower, "to test Einstein's theory of general relativity, and to work in a regime where our understanding of physics is incomplete."

Although an event horizon is a surface without light, the material around it can provide the contrast needed to see it. Gas and dust

particles generate heat and light as they collide and compress on their inward journey. The resulting swirl of high-energy matter is an accretion disk, orbiting the black hole at nearly the speed of light. As that light is bent by gravity, it frames the event horizon in an inky "silhouette," larger than the event horizon itself, but just as informative for science.

### Picking Your Targets

The EHT team selected two supermassive black holes for study: Sagittarius A\* (Sgr A\*) at the center of the Milky Way and the black hole at the center of Messier 87 (M87), an elliptical galaxy in the constellation Virgo. They are both smart choices.

Size mattered to the project. The EHT array has a resolving power of about 20 microarcseconds ( $\mu\text{as}$ ), so targets had to be big enough to "see" with this equipment. Sgr A\* is 26,000 light-years away and about 30 times as big as our Sun. The size of its event horizon is calculated to be 50  $\mu\text{as}$  (about the size of a DVD on the surface of the Moon if viewed from the Earth). M87 is 2,000 times more distant but 1,500 times as big, so its event horizon is about 20 to 40  $\mu\text{as}$ .

"I'm always amazed at the good fortune we've had with these two objects," said Dan Marrone, Associate Professor of Astronomy and Steward Observatory at the University of Arizona. "Not only are they both just barely resolvable with our earth-sized telescope, they're both what you would call low luminosity active galactic nuclei (AGN)." When black holes gather material at a high rate, the heat and light generated by the accretion disk overwhelms and blocks the event horizon from astronomical study. Fortunately, both Sgr A\* and M87 are accreting very slowly, so astronomers are confident they can see down to their event horizons. "If we picked some other source with a higher [accretion] rate," he adds, "it would be like trying to look through the Sun's photosphere down to its surface," an

impossible task as the glare of the bright material would completely obscure it.

These two black holes also have different features, so astronomers can glean new knowledge by comparing them. Some of the matter falling into a black hole can be expelled as a jet along the axis of rotation. Jets are found in about 10 percent of all supermassive black holes at the centers of active galaxies, and they're some of the most powerful phenomena in the universe. While Sgr A\* doesn't appear to have a jet, M87 is shooting material out across a distance of 5,000 light years.

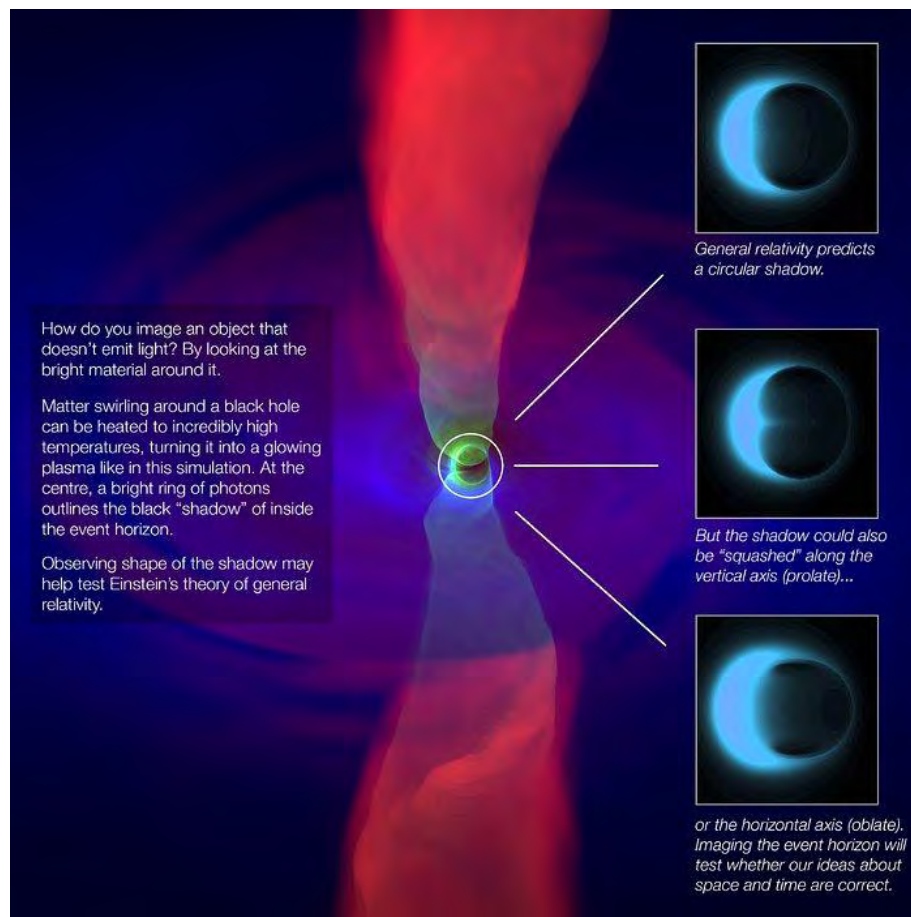
### The Long Road to Results

The EHT uses telescopes distributed across the Earth, operating as a single instrument through very long baseline interferometry (VLBI). Galactic dust obscures our view of black holes in the optical spectrum. The radio wavelengths have proven a better place to study structural detail, so EHT astronomers have focused on the shortest part of the radio spectrum—millimeter wavelengths—as their best viewing window.

Early observations began with telescopes in Arizona, California, and Hawaii. Results improved as the network grew, but building it took time. The interferometry used by the EHT team required more precise timing of observations than most telescopes were capable of providing. Researchers therefore had to add new hardware and digital processing software to several instruments to integrate them into the array. In 2012, the team measured the innermost orbit of the accretion disk around M87 and in 2015 they recorded the magnetic field around Sgr A\*.

The 66-dish network of the Atacama Large Millimeter/submillimeter Array (ALMA) was added in 2017. Now equipped with eight linked telescopes, the EHT astronomers collected their best data

in April of that year, accumulating enormous volumes of data. Ultimately, at an acquisition rate of eight Gigabits per second from each site, they filled half-a-ton of hard drives with five Petabytes of data by the time they were done—that amounts to more than half a ton of hard drives, or the rough equivalent to 5,000 years of MP3 files, EHT scientists said during the April 10 announcement.



This diagram shows a simulation of the outflow (bright red) from a black hole and the accretion disk around it, with three possible shapes of the event horizon's shadow. The EHT's first image of M87's supermassive black hole appears to have a circular shadow, or silhouette, agreeing with general relativity's predictions. [ESO/N. Bartmann/A. Broderick/C.K. Chan/D. Psaltis/F. Ozel]

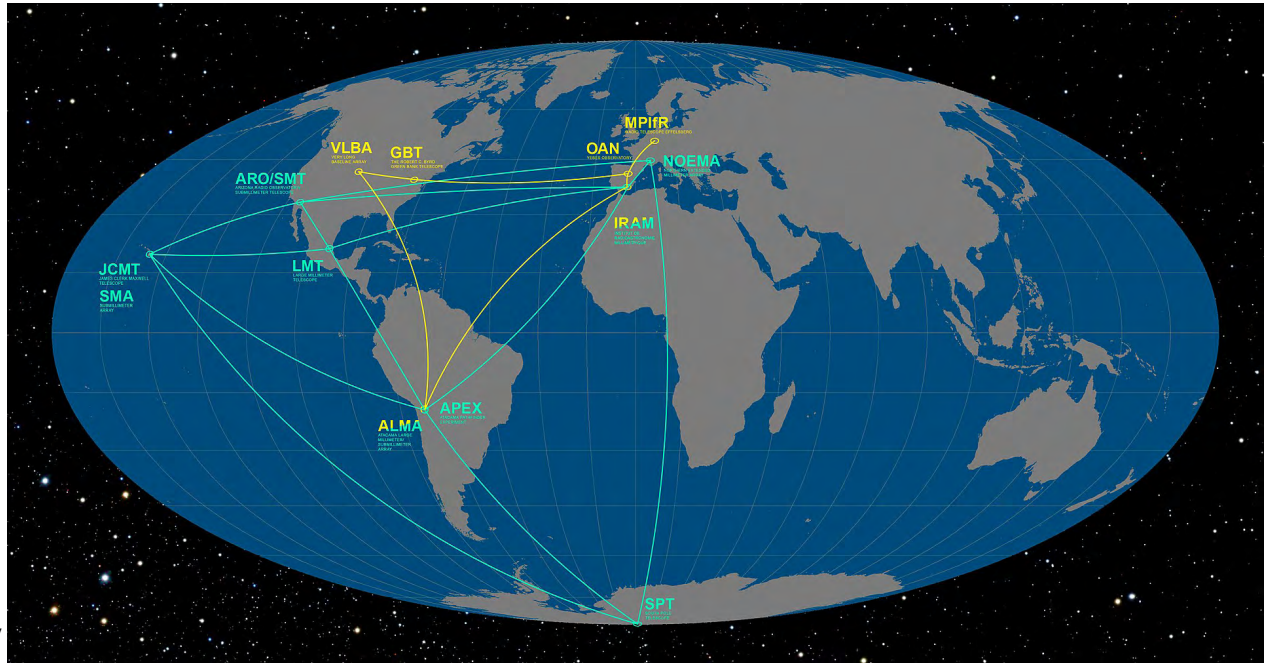
The Haystack Observatory in Westford, Massachusetts and the Max Planck Institute for Radio Astronomy in Bonn, Germany performed independent processing of the data beginning with detailed quality checks of the raw records, to filter out the effects of atmospheric turbulence and noise. The researchers used bright quasars in the data set as reference signals to calibrate observations across all of the participating telescopes. Then their real search began.

“We want to make sure that whatever we present is producible in many different ways,” said Feryal Özel, Professor of Astronomy and Astrophysics at the Department of Astronomy at University of Arizona. And as of early 2019, there were hints that their multiple analysis efforts were heading toward convergence. “The tools are orthogonal. The results are not.”

### Expectations and Room for Surprise

The nature of the silhouette (the dark shadow of an event horizon, framed by the light being lensed around it) has drawn initial interest. One of the biggest questions was whether or not the shadow was there, and whether the EHT could measure that shadow to see if it was consistent with what we’d expect from an event horizon.

As more images are recorded, features of the accretion disk will get a lot of attention, too. “My thesis work started with studying one of our targets, Sgr A\*, and trying to understand how black holes accrete,” said Marrone. “My hope has always been that we can answer this question. Can we see material falling onto it?”



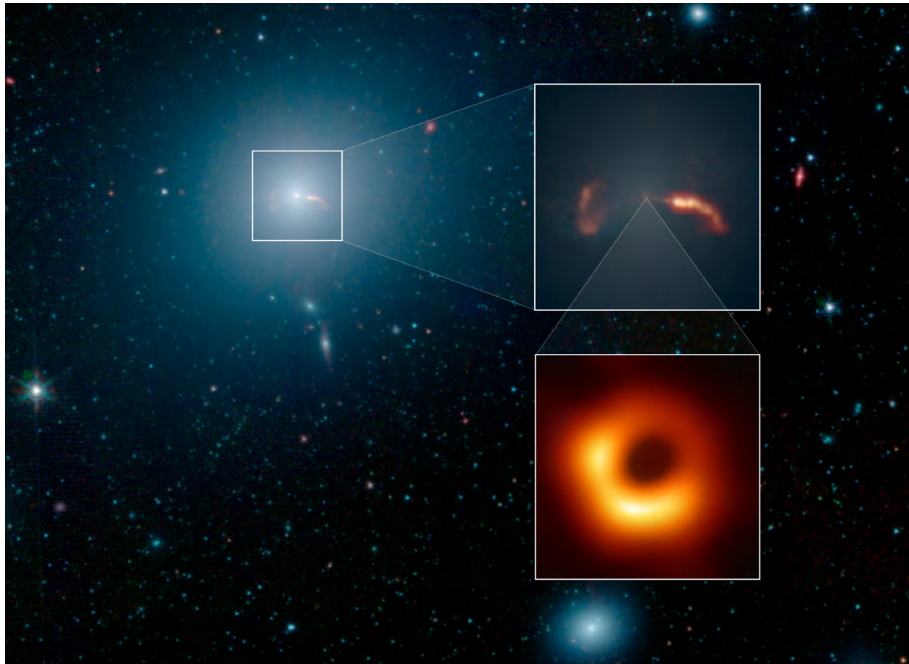
The locations of the participating telescopes of the Event Horizon Telescope (EHT, green) and the Global mm-VLBI Array (GMVA). [ESO]

Astronomers expect that accretion disks will demonstrate a huge Doppler Effect, as disk material shines brighter on one side of its orbit than the other.

Then there are the jets. “There’s all the very interesting astrophysical questions to ask about how jets form,” said Bower. “Why is there a powerful jet forming in the case of M87, but no jet or a very weak jet in Sgr A\*?” The jet shooting from M87 can reveal something about its dynamics. Theory states that jets are propelled by extremely strong magnetic fields from a black hole’s smallest orbit. The size of the jet can be used to determine this smallest orbit and, in turn, the spin of the black hole.

The enormous data set gathered by the EHT team will have scientific uses beyond black holes, of course. “There are lots of physics questions,” said Özel. “The gravitational fields are the strongest





The giant elliptical galaxy M87 as imaged by NASA's Spitzer Space Telescope in infrared wavelengths. Inset (top): Spitzer's view of M87's supermassive black hole generating powerful jets and (bottom) the EHT's view. [NASA, JPL-Caltech, EHT Collaboration]

anywhere in the universe and the gas is very hot, so a lot of different things happen to it."

Jim Cordes, George Feldstein Professor of Astronomy at Cornell University, intends to comb through the data to study pulsars. "You can do all these wild and wonderful things with pulsars because you can time them very accurately" said Cordes. "Finding a pulsar orbiting close in to a black hole would give us a different handle on the space-time, plasma, and magnetic field around it."

Although the first image has mesmerized the scientific community, it's still the pioneering achievement of a much longer science program. Work continues, even as the 2017 results are being processed and released. "There's more to do," said Marrone. "We're certainly not done yet."

Another observing cycle took place in April 2018 with an expanded array that included a telescope in Greenland. The new data set is twice the size of the one collected in 2017. Plans are in place for even longer programs of observing with additional instruments, as France joins the network next year with the NOEMA.

Additional data can be used to explore the temporal phenomena around these black holes by making "movies" from the imagery. Different timescales, up to decades long, could distinguish structural versus transient characteristics. "In the case of M87, the characteristic timescale for the source to change is 100 days," said Bower. "So coming back one year after the other, we may see different versions of what the system looks like. It would be a way to untangle what's fundamental from what's 'weather' in the system."

## Getting Ready

Before April 10, team members kept a rigorous discipline around their processes through early 2019, and chose their words prudently. "All I can say about the current status is, we're being exceedingly careful in our analyses," said Bower. "We're using multiple methods to confirm everything that we get."

Nevertheless, it was hard to hold back a building excitement within the team. "I can say that 2019 is going to be a good year," said Özel. "I don't think we're going to disappoint you."

Well, they didn't disappoint. M87 is here, to be followed by a train of scientific papers. Welcome to a new chapter in astrophysics. It was worth the wait. 🚩



**STEVE MURRAY** is a freelance science [writer](#) and NASA Solar System Ambassador. A former research engineer, he follows developments in astronomy, space science, and aviation.

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