HOW TO HUNT FOR A BLACK HOLE

By creating a telescope the size of Earth, astronomers hope to grab the first images of an event horizon — the point of no return.

BY DAVIDE CASTELVECCHI

Here's how to catch a black hole. First, spend many years enlisting eight of the top radio observatories across four continents to join forces for an unprecedented hunt. Next, coordinate plans so that those observatories will simultaneously turn their attention to the same patches of sky for several days. Then, collect observations at a scale never before attempted in science — generating 2 petabytes of data each night.

This is the audacious plan for next month's trial of the Event Horizon Telescope (EHT), a team-up of radio telescopes stationed across the globe to create a virtual observatory nearly as big as Earth. And researchers hope that when they sift through the mountain of data, they will capture the first details ever recorded of the black hole at the centre of the Milky Way, as well as pictures of a much larger one in the more distant galaxy M87.

The reason this effort takes so much astronomical firepower is that these black holes are so far from Earth that they should appear about as big as a bagel on the surface of the Moon, requiring a resolution more than 1,000 times better than that of the Hubble Space Telescope. But even if researchers can nab just a few, blurry pixels, that could have a big impact on fundamental physics, astrophysics and cosmology. The EHT aims to close in on each black hole's event horizon, the surface beyond which gravity is so strong that nothing that crosses it can ever climb back out. By capturing images of what happens outside this zone, scientists will be able to put Einstein's general theory of relativity to one of its most stringent tests so far. The images could also help to explain how some supermassive black holes produce spectacularly energetic jets and rule over their respective galaxies and beyond.

But first, the weather will have to cooperate. The EHT will need crystal-clear skies at all eight locations simultaneously, from Hawaii to the Andes, and from the Pyrenees to the South Pole. These and other constraints mean that the team gets only one two-week window every year to make an attempt. "Everything has to be just right," says EHT director

ESA ADVANCED CONCEPTS TEAM; S. BRUNIER / ESO

NIK SPENCER/NATURE; AVERY BRODERICK/UNIVERSITY OF WATERLOO (IMAGES MIDDLE & BOTTOM)

Sheperd Doeleman, an astrophysicist at Harvard University in Cambridge, Massachusetts.

"Radio astronomers relish the challenge of doing the almost impossible," says Roger Blandford, an astrophysicist at Stanford University in California who is not part of the collaboration. And the EHT could present them with their toughest challenge yet.

MONSTERS OF THE UNIVERSE

Astronomers have known since the 1970s that an odd source of radiation lurks in the heart of the Milky Way. Radio telescopes had picked up an unusually compact object in the dusty central region of the Galaxy, within the constellation Sagittarius. They named the object Sagittarius A* — Sgr A* for short — and eventually gathered compelling evidence that it was a supermassive black hole, with a mass equal to that of about 4 million Suns. The black hole M87* in the centre of the galaxy M87 is even larger, at some 6 billion solar masses. In terms of angular size in the sky, these two have the largest known event horizons of any black holes.

Although scientists have a pretty good idea of how smaller black holes can form, no one knows for sure how these supermassive monsters develop. And for a long time, astronomers doubted that they could achieve the resolution required to image them in any detail.

The challenge comes down to basic optics. The resolution of a telescope depends mostly on its width, or aperture, and on the wavelength of the light at which it is observing. Doubling the width of the telescope allow scientists to resolve details half as wide, and so does halving the wavelength. At wavelengths of 1.3 or 0.87 millimetres — the only radiation bands that do not get absorbed by the atmosphere or scattered by interstellar dust and hot gas — calculations suggested that it would take a radio dish much larger than Earth to image Sgr A* or M87*.

But in the late 1990s, astrophysicist Heino Falcke, then at the Max Planck Institute for Radio Astronomy in Bonn, Germany, and his collaborators pointed out that the optical distortion caused by a black hole's gravity would act like a lens, magnifying Sgr A* by a factor of five or so[1]. That was good news, because it meant that Sgr A* might be within the reach of very-long-baseline interferometry (VLBI) on Earth. This is a technique that integrates multiple observatories into one virtual telescope — with an effective aperture as big as the distance between them.

The reason that there is any hope of imaging Sgr A*, and the larger M87*, is that they are surrounded by superheated plasma, possibly the residue of stars that did not get swallowed up outright but got torn apart under the intense gravitational stress. The gas forms a rapidly rotating 'accretion disk', with its inner parts slowly spiralling in. Falcke and his colleagues reckoned that a VLBI network spread along the entire globe, and working at around 1 mm wavelength, should be just about sensitive enough to resolve the shadow cast by Sgr A* against the halo of gas of the accretion disk.

The team also made the first simulations of what such a network might see. Contrary to most artistic depictions of black holes, the accretion disk does not disappear behind the object the way Saturn's rings can partly hide behind the planet. Around a black hole, there's no hiding: gravity warps spacetime, and here the effect is so extreme that light rays go around the black hole, showing multiple distorted images of what lies behind it. This should make the accretion disk appear to wrap around the black hole's shadow like a halo. (The 2014 hit *Interstellar* was the first movie to accurately depict this kind of warping of light around a black hole.)

But it won't be a standard halo, of the type seen in many Renaissance paintings. The inner regions of the accretion disk orbit at nearly the speed of light, so one side of the disk — the side rotating towards the observer — should look much brighter than the other. The result should be something similar to a crescent Moon (see 'Power of the dark').

In 2004, Falcke, who is now at Radboud University in Nijmegen, the Netherlands, was part of a team that made one of the first VLBI observations of Sgr A*. The US-based network they used, set up by the National Radio Astronomy Observatory, spanned 2,000 kilometres, and took data at 7-mm wavelength[2]. This allowed them to get no more than a blob of light: it was like seeing the black hole through frosted glass.

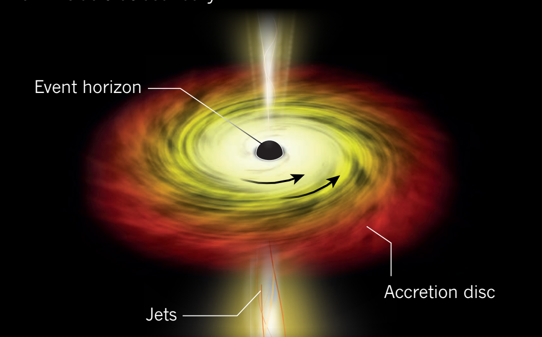
Meanwhile, starting in 2007, a team led by Doeleman made its own VLBI observations of Sgr A* (ref. 3) and M87* (ref. 4). Using VLBI networks of three observatories, the team made measurements at 1.3 mm, enabling them to close in towards the event horizon. Although the researchers didn't capture an image of the event horizon, they were able to put upper bounds on its size.

Eventually, the two groups joined forces and merged with others to form the current EHT collaboration. And as the team grew, so did the number of telescopes enlisted for the imaging effort.

In April, the EHT will have a total of four, or possibly five, nights' observing time — a limit set mostly by their use of the state-of-the-art, US$1.4-billion Atacama Large Millimeter Array (ALMA) in Chile, one of the world's most oversubscribed observatories. They plan to spend two nights on Sgr A* and

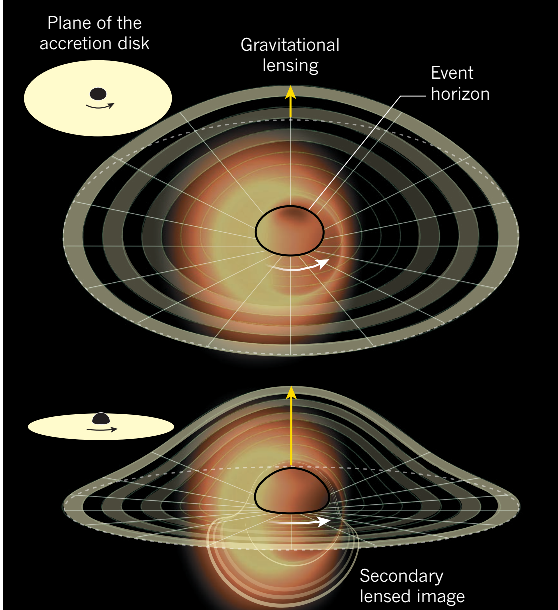
POWER OF THE DARK

The Event Horizon Telescope aims to reveal the edge of a black hole. These objects are surrounded by accretion disks: swirling masses of matter that spiral inwards. Anything that falls past the event horizon disappears from view because light cannot escape from inside that boundary.



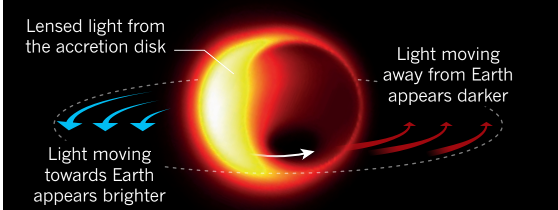
WARPED LIGHT

Because of the intense gravity near black holes, light emitted by the accretion disk gets warped around the event horizon. Even the part of the disk behind the black hole is visible from the front.



UNEVEN HALO

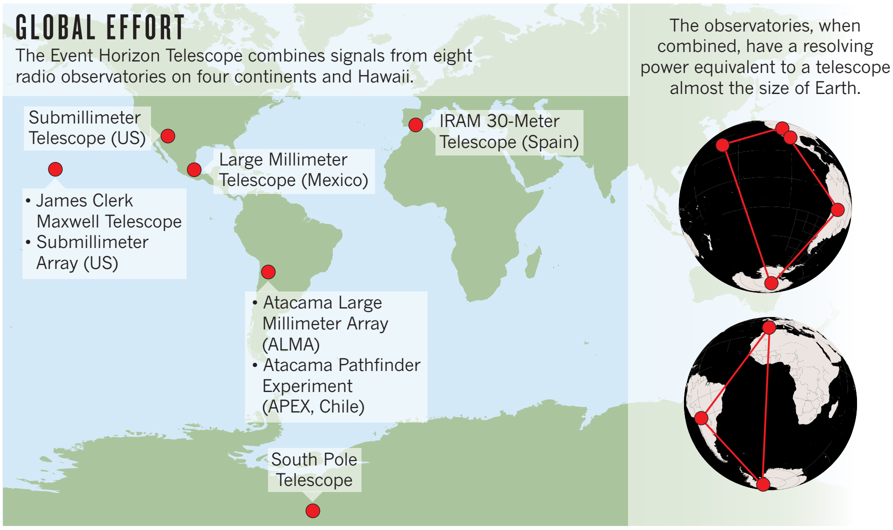
Radiation collected by the Event Horizon Telescope could resemble this simulation of light bending around a black hole. One side appears brighter because more of the radiation is shifted towards the observing wavelengths.



two on M87*. At each observing station, atomic clocks will tag the arrival time of every crest and trough of every electromagnetic wave to the nearest one-tenth of a nanosecond, explains Feryal Özel, a theoretical astrophysicist at the University of Arizona in Tucson.

In typical interferometry, the arrival times at different locations are compared in real time, and triangulated to their point of origin to reconstruct an image. But with so many observatories scattered around the globe (see 'Global effort'), including in places with slow Internet links, the researchers will have to record the streams separately and compare them later. "We're not going to have a picture appear before us on the screen," Daniel Marrone, an astrophysicist at the University of Arizona, says. This means that the EHT will need to record data at a faster rate than any previous experiment of any kind, says Avery Broderick, an astrophysicist at the University of Waterloo in Canada. A typical night will yield about as much data as a year's worth of experiments at the Large Hadron Collider outside Geneva, Switzerland.

The racks of hard disks containing the data will be flown to two central locations, where computer clusters will combine them into one picture, a task that could take up to six months. Only once that phase is completed will the data analysis — the actual scientific study — begin. The team will probably not have results to publish until well into 2018.



JET SEEKERS

Astrophysicists have high hopes for the results from the EHT. They are particularly interested in data that could help to explain one of the most spectacular phenomena in the cosmos: the giant jets of particles that certain supermassive black holes spew out into intergalactic space at close to the speed of light. Some such black holes, including M87*, sport jets even longer than their host galaxies. But not all do: if Sgr A* has any, they are too small or too feeble to have been spotted yet.

"RADIO ASTRONOMERS RELISH THE CHALLENGE OF DOING THE ALMOST IMPOSSIBLE"

Scientists are not even sure what these jets are made of, but they seem to play an outsized role in cosmic evolution. In particular, by heating interstellar matter, jets can prevent that material from cooling down to form stars, thus shutting down galaxy growth, Broderick says. "Jets rule the fate of galaxies."

The most likely explanation for the jets, astrophysicists say, is that they are produced by rapidly twisting magnetic fields just outside the black hole, but it is unclear where their energy comes from. In the 1970s, Blandford and his colleagues proposed two alternative models: in one, the energy comes from the accretion disk; in the other it is drawn from the spin of the black hole itself (which is not necessarily aligned with the rotation of the accretion disk). In 2015, Doeleman's group reported[5] the first hints of structure in the magnetic field around Sgr A*, using VLBI at 1.3 mm. Their results suggest that black-hole spins are a more likely candidate than accretion disks for fuelling the jets, says Blandford, but the full power of the coming experiments could make that conclusion much more solid, as well as revealing whether Sgr A* has any jets at all.

At a more fundamental level, looking at the size and shape of the event horizon will test Einstein's theory of gravity for the first time in the extreme regime around a supermassive black hole. This will follow on from the historic discoveries announced last year by LIGO, the Laser Interferometer Gravitational-wave Observatory, which captured the signal of gravitational waves produced by the merger of black holes about as massive as large stars. Its findings were hailed as the most dramatic evidence yet for the existence of black holes, but they have not yet provided incontrovertible evidence. Moreover, supermassive black holes are millions or billions of times larger, Broderick points out. "What we're looking at is a place where we don't necessarily know how the physics works."

There is even the chance that the EHT will find something different from a black hole in the target areas. Theorists have produced a number of alternative ideas to explain what happens when matter collapses under its own weight. In some of these theories, black holes never form, because gravitational collapse stops before the stellar remnants cross the point of no return. That could result in a super-compact star with a hard surface that might emit radiation detectable by the EHT.

But astrophysicist Carlos Barceló, of the Institute of Astrophysics of Andalusia in Granada, Spain, says that finding anything like that is a long shot. "I am a bit sceptical that this observation is going be able to distinguish between classical black holes and more exotic kinds of objects." He and others say that LIGO might have a better chance of testing those models, for example by detecting echoes in the merger of two black holes.

As VLBI observations keep improving, however, they might reach the point at which scientists will be able to tell if the event horizon is as symmetrical as general relativity implies, says Alexander Wittig, a mission analyst at the European Space Research and Technology Centre in Noordwijk, the Netherlands. "A future version of the Event Horizon Telescope could reach resolutions that allow us to distinguish more intricate features in the shape of the shadow," Wittig says. For that goal, Falcke is already dreaming up arrays of space telescopes that could make the EHT even bigger than Earth itself.

For now, though, astronomers will gladly settle for a few pixels that will give them their first peek at these elusive behemoths. They have had so many imaginary pictures swirling in their heads, often inspired by science-fiction books and movies like *Interstellar*. "To demonstrate that radio astronomers can catch up with Hollywood and show us pictures of black holes that actually exist," says Blandford, "that is a magical idea." ■

Davide Castelvecchi *is a reporter for* Nature *in London.*

1. Falcke, H., Melia, F. & Agol, E. *Astrophys. J.* **528,** L13–L16 (2000).
2. Bower, G. C. *et al. Science* **304,** 704–708 (2004).
3. Doeleman, S. S. *et al. Nature* **455,** 78–80 (2008).
4. Doeleman, S. S. *et al. Science* **338,** 355–358 (2012).
5. Johnson, M. D. *et al. Science* **350,** 1242–1245 (2015).

CORRECTION

The News Feature 'How to hunt for a black hole ' (*Nature* **543,** 478–480; 2017) erred in saying that Heino Falcke led a team that made one of the first VLBI observations. He was one of the team's investigators.