QUICK STUDY

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Imaging black holes

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The Event Horizon Telescope will combine data from a worldwide network of radio telescopes to image the shadow that a black hole casts on the surrounding plasma.

Within months of the publication of Albert Einstein's general relativistic field equations in 1915, Karl Schwarzschild had derived the equations' first nontrivial solution—the black hole spacetime. Ever since then, the physics and astronomy communities have had a love–hate relationship with black holes. It took almost half a century before they were considered anything more than a mathematical curiosity. Today the existence of black holes is widely accepted, but they remain perplexing nevertheless. In most attempts to unify quantum field theory and general relativity, black holes present paradoxes that are hard to resolve.

Formally speaking, a black hole is a vacuum spacetime with all the mass concentrated in an infinitesimally small region at the center. At large distances from the concentration, the gravitational field behaves like that of any other object. However, a black hole is surrounded by a virtual surface, called the event horizon, from which nothing can escape, not even light. For a nonspinning black hole, the radius of the event horizon, called the Schwarzschild radius R_S, is equal to $2GM/c^2$, where G is the gravitational constant, M is the mass of the black hole, and c is the speed of light. An ongoing project called the Event Horizon Telescope (EHT) is now attempting to image black holes with horizon-scale resolution.

Seeing in the dark

In the observation of gravitational waves recognized by the 2017 Nobel Prize in Physics, detectors at the Laser Interferometer Gravitational-Wave Observatory listened to spacetime ringing as two black holes coalesced. Imaging black holes will give EHT scientists a different way to investigate physics just outside the horizons of these enigmatic objects. Specifically, an image can provide spatially resolved information about strong-field gravitational effects in stationary spacetimes and about the interaction of the horizon with the surrounding matter. However, by their very definition, horizons do not emit light. It is therefore difficult to see how they lend themselves to imaging.

To see black holes, the EHT looks for the silhouettes they cast on background emission. Photons that are directed radially outward from a black hole can escape its gravitational field only if they are outside the event horizon. Photons that are not radially directed can be trapped at even greater distances. In fact, any photon with an inward radial momentum component is destined to cross the horizon once it passes the so-called photon orbit radius. As long as there is a source of photons outside the black hole, such as hot material falling into the black hole, there will be radiation on which the black hole will cast a shadow, a silhouette that can be imaged. Figure 1 shows a simulation of what the EHT might see.

The size of the shadow is fully determined by general relativity. Its outline is the photon orbit radius, magnified because of gravitational lensing. For a nonspinning black hole, the photon orbit is at 1.5 R_S and the silhouette size turns out to be $R_{shadow} = \sqrt{27}/2\ R_S$. For a spinning black hole, the photon orbit lies deeper in the gravitational field of the black hole. However, photons experience a higher degree of lensing than for black holes that don't spin. As a result, the size of the black hole shadow is independent of the spin and orientation of the black hole to within 4%.

And array we go

The angular size of the silhouette as observed on the sky depends on the mass of the black hole and its distance from us—and it is exceptionally small. Of all known black holes, the ones with shadows that subtend the largest angle in the sky are the supermassive black hole, Sagittarius A* (Sgr A*), in the center of our galaxy and the black hole in the center of the M87 galaxy in the Virgo cluster. The black hole in M87 is about 1000 times farther away than Sgr A* but also 1000 times more massive. Even for those black holes, the angular size of the shadow is about 50 microarcseconds, equivalent to the angle subtended by a donut placed on the surface of the Moon.

The optimal wavelengths to image the shadows of the cen-

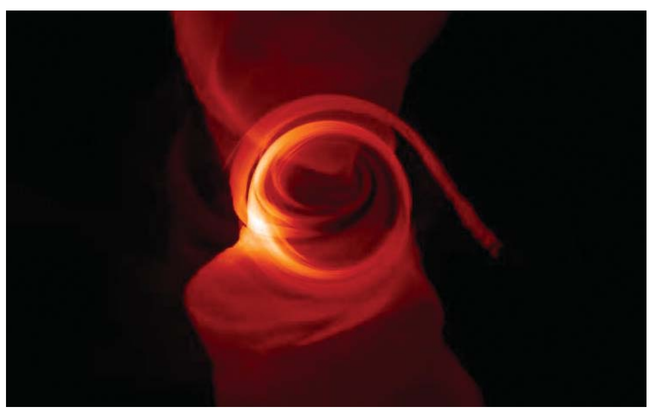

FIGURE 1. THE BLACK HOLE at the center of the Milky Way radiates as it accretes hot plasma. This three-dimensional simulation of 1.3 mm radiation shows the circular shadow cast by the black hole. The shadow is not fully dark because some radiation is emitted between the black hole and the viewer. (Courtesy of Chi-kwan Chan/University of Arizona.)

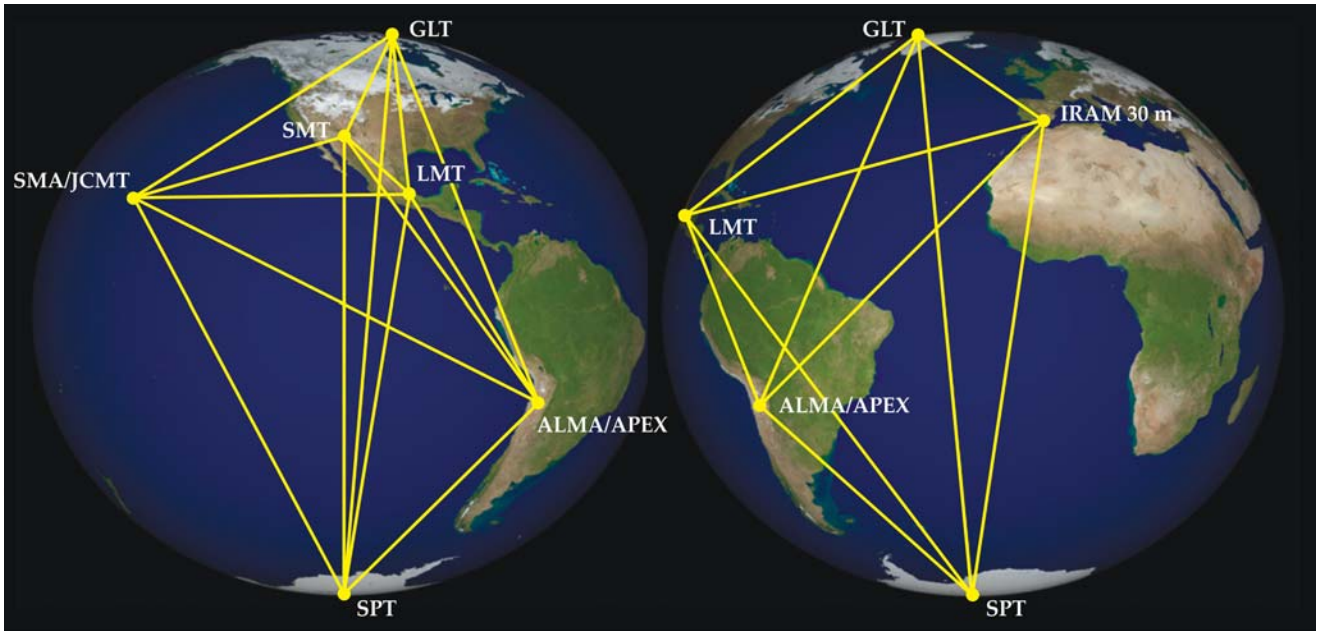

FIGURE 2. THE EVENT HORIZON TELESCOPE is a global array of millimeter telescopes (see http://eventhorizontelescope.org/array) that aims to take the first pictures of black holes. (Courtesy of Dan Marrone/University of Arizona.)

tral black holes in the Milky Way and M87 are in the millimeter range. At those wavelengths, the accreting plasma that surrounds the black holes shines brightly. Luckily, Earth's atmosphere and the interstellar medium are transparent at millimeter wavelengths, so observations of the black holes can be made from ground-based facilities. However, even for those large black holes, a millimeter-wave telescope able to resolve the black hole shadows would need to have a size approximately equal to the diameter of Earth.

A technique called aperture synthesis interferometry allows EHT scientists to combine signals from an array of telescopes around the globe and to produce images with the same angular resolution as a single telescope having the size of the entire array. The signals from all telescope pairs in the array are correlated in supercomputers to yield the components of the Fourier transform of the image in the sky. Powerful inversion techniques then allow the black hole image to be reconstructed from the measured Fourier components.

Starting in 2008, observations with telescopes in Hawaii, Arizona, and California demonstrated the technological feasibility of the EHT experiment. Even though data from the three stations are not sufficient for image construction, the inferred sizes of the black holes were comparable with expectations for their shadows. The first observations with the full EHT array (see figure 2) were carried out in April 2017. Each station collected a vast amount of data; in total, the stations obtained more than a petabyte. The data were too large to transfer electronically, so disks were shipped to two EHT correlation centers. The last set of disks arrived from the South Pole Telescope in December 2017, once flights from the South Pole resumed after the Antarctic winter. The EHT collaboration, with more than 200 members from institutions worldwide, is now in the midst of correlating, calibrating, and analyzing the data.

What powers it all?

Computer simulations and the early data indicate that the EHT will provide key insight into the working of the black hole accretion engine and will illuminate the interplay between the matter that crosses the horizon and the matter that may get collimated and ejected in powerful jets. Of the two primary EHT targets, Sgr A* shows no signature of a jet in any other observation, whereas M87 shows a prominent jet at many wavelengths that extends to many times the size of the galaxy. With its high-resolution images and ability to map magnetic field structures at horizon scales by means of light-polarization measurements, the EHT will help to identify the key properties of the black hole or the accretion flow that account for the presence or absence of prominent jets.

Accretion flows are expected to be turbulent, but one key feature of the EHT images—a signature of the black hole spacetime—is constant and independent of the properties of the surrounding plasma: the black hole shadow. Indeed, not only the size but also the shape of the shadow of a general relativistic black hole is nearly independent of the black hole spin and the observer's orientation. Moreover, current knowledge of the mass and distance to Sgr A* from monitoring stellar orbits in its vicinity yields a prediction, precise to within a few percent, of the size its shadow subtends in the sky. That prediction with no free parameters allows EHT to test the spacetime geometry of black holes at horizon scales.

Additional resources

▶ J. Bardeen, in *Black Holes*, C. DeWitt, B. S. DeWitt, eds., Gordon and Breach (1973), p. 241.

▶ S. Doeleman et al., "Event-horizon-scale structure in the supermassive black hole candidate at the galactic centre," *Nature* **455**, 78 (2008).

▶ M. Mościbrodzka et al., "Radiative models of Sgr A* from GRMHD simulations," *Astrophys. J.* **706**, 497 (2009).

▶ D. Psaltis et al., "A general relativistic null hypothesis test with Event Horizon Telescope observations of the black hole shadow in Sgr A*," *Astrophys. J.* **814**, 115 (2015).

▶ M. Johnson et al., "Resolved magnetic-field structure and variability near the event horizon of Sagittarius A*," *Science* **350**, 1242 (2015). PT