

hand, for a Schwarzschild black hole, its shadow has an angular diameter d about $d \sim 10\theta_g$, where $\theta_g \equiv GM/(Dc^2)$ with D being the distance to the black hole. The fact that the angular size of a black hole shadow is proportional to the ratio of mass over distance singles out two supermassive black holes, M87* and Sgr A*, respectively at the centers of the giant elliptical galaxy M87 and our own spiral galaxy, the Milky Way, as two most promising sources for imaging [7, 8]. M87* and Sgr A* were chosen as the primary targets by the Event Horizon Telescope Collaboration [9], a collaboration that aims to directly contemplate matter and light dynamics in the neighbourhood of black hole event horizons.

In order to resolve a black hole shadow image with an angular diameter d , one needs to have $\delta\theta \lesssim d$ at the least. Therefore, astronomers need to decrease the observing wavelength λ and increase the telescope aperture \mathcal{D} . The Event Horizon Telescope observes at a nominal wavelength $\lambda = 1.3\text{mm}$, considering the emission spectrum of the accretion disks around supermassive black holes, as well as the propagation characteristics, including interstellar scattering and so on, of light towards the Earth. For a telescope bound to the Earth, the largest “aperture” one can make use of is the diameter of the Earth itself, $\mathcal{D}_\oplus \simeq 1.3 \times 10^4\text{ km}$. It is exactly the philosophy behind the initiative of the Event Horizon Telescope [9]. The Event Horizon Telescope coherently uses a large telescope array consisting of a global network of radio telescopes, with an effective aperture diameter roughly the size of the Earth. Because of the unprecedented angular resolution, combined with advanced analysis schemes that are tailored to the Event Horizon Telescope data, the black hole shadows of M87* and Sgr A* were resolved for the first time [7, 8]. Representative images of them are shown in Fig. 1, and the crescent shadow structures are evident for both black holes [7, 8].

The first image of a black hole shadow was revealed by the Event Horizon Telescope Collaboration in 2019 for M87*, with data taken by eight telescopes in the April 2017 campaign [7]. These telescopes span geographic locations including Arizona, Chile, Hawai’i, Mexico, the South Pole, and Spain. With various independent tests performed for data processing, calibration, and imaging, combined with extensive comparisons and fits to a library of general relativistic magnetohydrodynamic simulations and synthetic images from ray tracing, the angular crescent diameter of M87* shadow is finally measured to be [10]

$$d = 42 \pm 3 \mu\text{as}. \quad (2)$$

Supplementing it with the known distance of M87*, $D = 16.8^{+0.8}_{-0.7}\text{Mpc}$, the Event Horizon Telescope Collaboration obtained the mass of the supermassive black hole in M87,

$$M = (6.5 \pm 0.7) \times 10^9 M_\odot, \quad (3)$$

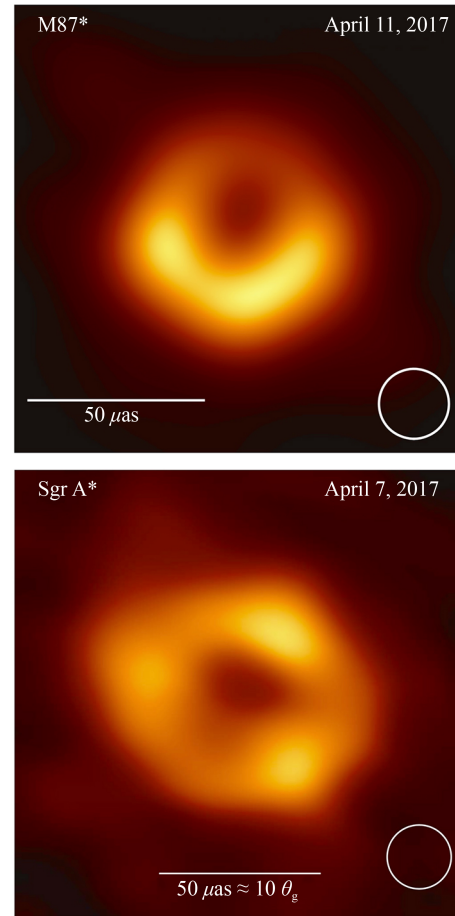


Fig. 1 Representative black hole shadow images shown in units of brightness temperature for M87* (upper) [7] and Sgr A* (lower) [8], produced from observations in the April 2017 campaign by the Event Horizon Telescope Collaboration. Reproduced by permission of the AAS.

which is consistent with independent measurements from stellar dynamics, and disproves the measurements with gas dynamics [10].

Recently in 2022, the Event Horizon Telescope Collaboration published the second black hole shadow image, now for Sgr A*, the supermassive black hole residing at our own Milky Way [8]. The image shares the same April 2017 observing campaign as M87* with the same set of eight telescopes, but its analysis was extended for another three years. The main difficulty in Sgr A* shadow image construction is ultimately related to its black hole mass, being $M \sim 4 \times 10^6 M_\odot$, about 1500 times lighter than M87*. In general relativity, the dynamic timescale is more or less proportional to the black hole mass. Correspondingly, the image pattern for M87* is supposed to vary on a timescale about 5 days (maximal spin) to 1 month (zero spin), while for Sgr A* it is to vary from 4 minutes (maximal spin) to half an hour (zero spin) [8]. The black hole shadow image for M87* is therefore basically static during the observation campaign, while the intra-hour variability of the Sgr A*



image severely calls for novel imaging methods. Nevertheless, proper algorithms were developed within the Event Horizon Telescope Collaboration, and a vast number of quality tests verified the data analysis procedure. The angular diameter of the Sgr A* shadow is measured to be [8, 11]

$$d = 51.8 \pm 2.3 \mu\text{as}. \quad (4)$$

When this number is supplemented with an independent distance measurement from maser parallaxes $D = 8.15 \pm 0.15$ kpc, the mass of Sgr A* can be determined to be $4.0_{-1.0}^{+1.1} \times 10^6 M_{\odot}$ [12]. Such a mass measurement is in a close agreement with decade-long optical/infrared monitoring of the stellar orbits of S-stars around Sgr A*, which move at much larger separations to the black hole [13, 14].

For the case of Sgr A*, as we already have mass-to-distance ratio measurements from stellar orbital dynamics [13, 14], it is useful to turn the reasoning around and use the black hole shadow image to test the nature of Sgr A* [15]. The measured shadow size is within $\sim 10\%$ of what a Kerr black hole predicts. This fact can be folded to put constraints on the parameterized deviations from a Kerr spacetime, as well as ruling out parameter space for black hole mimickers, such as naked singularities [15, 16]. These kinds of novel approaches exploited some untouched parameter space in testing alternative gravity theories. The combination of M87* and Sgr A* data even reinforced the power in using black hole shadows to test strong-field gravity [15].

Black holes are fundamental and elegant predictions from Einstein's general relativity. The concept goes way beyond what Newtonian gravity can perceive. Now the direct measurements of black hole shadows from two supermassive black holes with mass different by a factor of a thousand not only provided us with clues for black holes' role in the evolution of galaxies [17], but also probed central concepts of curved spacetimes in the highly curved strong-field regime. These studies are strengthened when the polarimetric information is augmented [18]. In the future, extending the global very long baseline interferometry array to the next-generation Event Horizon Telescope and even possibly including telescopes in space [19] will boost the angular resolution further and provide much sharper black hole shadow images. Making black hole shadow "movies" with many more successive high-quality observations is another interesting research direction to engage dynamic processes and investigate time-varying features. Together with gravitational waves [20, 21], as well as orbits of S-stars [13, 14] and radio pulsars [22–24], imaging of black hole shadows is becoming an essential and powerful tool to study black hole physics and the nature of spacetime.

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References

1. A. Einstein, The Field Equations of Gravitation, *Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.)* 1915, 844 (1915)
2. K. Schwarzschild, On the gravitational field of a mass point according to Einstein's theory, *Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.)* 1916, 189 (1916), arXiv: physics/9905030
3. R. P. Kerr, Gravitational field of a spinning mass as an example of algebraically special metrics, *Phys. Rev. Lett.* 11, 237 (1963)
4. S. Chandrasekhar, The Mathematical Theory of Black Holes, Oxford University Press, 1983
5. J. P. Luminet, Image of a spherical black hole with thin accretion disk, *Astron. Astrophys.* 75, 228 (1979)
6. H. Falcke, F. Melia, and E. Agol, Viewing the shadow of the black hole at the Galactic center, *Astrophys. J. Lett.* 528, L13 (2000), arXiv: astro-ph/9912263
7. K. Akiyama, et al. (Event Horizon Telescope), First M87 Event Horizon Telescope results (I): The shadow of the supermassive black hole, *Astrophys. J. Lett.* 875, L1 (2019), arXiv: 1906.11238 [astro-ph.GA]
8. K. Akiyama, et al. (Event Horizon Telescope), First Sagittarius A* Event Horizon Telescope results (I): The shadow of the supermassive black hole in the center of the Milky Way, *Astrophys. J. Lett.* 930, L12 (2022)
9. S. Doeleman, E. Agol, D. Backer, F. Baganoff, G. C. Bower, A. Broderick, A. Fabian, V. Fish, C. Gammie, P. Ho, M. Honman, T. Krichbaum, A. Loeb, D. Marrone, M. Reid, A. Rogers, I. Shapiro, P. Strittmatter, R. Tilanus, J. Weintroub, A. Whitney, M. Wright, and L. Ziurys, Imaging an event horizon: Submm-VLBI of a super massive black hole, in: *Astro2010: The Astronomy and Astrophysics Decadal Survey*, Vol. 2010, p. 68, arXiv: 0906.3899 [astro-ph.CO] (2009)
10. K. Akiyama, et al. (Event Horizon Telescope), First M87 Event Horizon Telescope results (VI): The shadow and mass of the central black hole, *Astrophys. J. Lett.* 875, L6 (2019), arXiv: 1906.11243 [astro-ph.GA]
11. K. Akiyama, et al. (Event Horizon Telescope), First Sagittarius A* Event Horizon Telescope results (III): Imaging of the Galactic center supermassive black hole, *Astrophys. J. Lett.* 930, L14 (2022)
12. K. Akiyama, et al. (Event Horizon Telescope), First Sagittarius A* Event Horizon Telescope results (IV): variability, morphology, and black hole mass, *Astrophys. J. Lett.* 930, L15 (2022)
13. T. Do, et al., Relativistic redshift of the star S0-2 orbiting the Galactic center supermassive black hole, *Science* 365, 664 (2019), arXiv: 1907.10731 [astro-ph.GA]
14. R. Abuter, et al. (GRAVITY), Detection of the Schwarzschild precession in the orbit of the star S2 near the Galactic centre massive black hole, *Astron.*

- Astrophys.* 636, L5 (2020), arXiv: 2004.07187 [astro-ph.GA]
15. K. Akiyama, et al. (Event Horizon Telescope), First Sagittarius A* Event Horizon Telescope results (VI): Testing the black hole metric, *Astrophys. J. Lett.* 930, L17 (2022)
 16. P. Kocherlakota, et al. (Event Horizon Telescope), Constraints on black-hole charges with the 2017 EHT observations of M87*, *Phys. Rev. D* 103, 104047 (2021), arXiv: 2105.09343 [gr-qc]
 17. J. Kormendy and L. C. Ho, Coevolution (Or not) of supermassive black holes and host galaxies, *Ann. Rev. Astron. Astrophys.* 51, 511 (2013), arXiv: 1304.7762 [astro-ph.CO]
 18. K. Akiyama et al. (Event Horizon Telescope), First M87 Event Horizon Telescope results (VIII): Magnetic field structure near the Event Horizon, *Astrophys. J. Lett.* 910, L13 (2021), arXiv: 2105.01173 [astro-ph.HE]
 19. C. M. Fromm, Y. Mizuno, Z. Younsi, H. Olivares, O. Porth, M. De Laurentis, H. Falcke, M. Kramer, and L. Rezzolla, Using space-VLBI to probe gravity around Sgr A*, *Astron. Astrophys.* 649, A116 (2021), arXiv: 2101.08618 [astro-ph.HE]
 20. R. Abbott, et al. (LIGO Scientific, VIRGO, KAGRA), GWTC-3: Compact binary coalescences observed by LIGO and Virgo during the second part of the third observing run, arXiv: 2111.03606 [gr-qc] (2021)
 21. R. Abbott, et al. (LIGO Scientific, VIRGO, KAGRA), Tests of general relativity with GWTC-3, arXiv: 2112.06861 [gr-qc] (2021)
 22. D. Psaltis, N. Wex, and M. Kramer, A quantitative test of the No-hair theorem with Sgr A* using stars, pulsars, and the Event Horizon Telescope, *Astrophys. J.* 818, 121 (2016), arXiv: 1510.00394 [astro-ph.HE]
 23. G. C. Bower, S. Chatterjee, J. Cordes, P. Demorest, J. S. Deneva, J. Dexter, M. Kramer, J. Lazio, S. Ransom, L. Shao, N. Wex, and R. Wharton, Galactic center pulsars with the ngVLA, *ASP Conf. Ser.* 517, 793 (2018), arXiv: 1810.06623 [astro-ph.HE]
 24. G. Bower, S. Chatterjee, J. Cordes, P. Demorest, J. S. Deneva, J. Dexter, R. Eatough, M. Kramer, J. Lazio, K. Liu, S. Ransom, L. Shao, N. Wex, and R. Wharton, Fundamental physics with Galactic center pulsars, *Bull. Am. Astron. Soc.* 51, 438 (2019)