

12. Imaging Black Holes

What should a black hole accretion disk look like?

Suppose we are viewing a thin accretion disk around a black hole, nearly edge-on but slightly tilted. The hot gas in the disk will be “glowing” in different forms of electromagnetic radiation.

What should we “see” if we are close enough to resolve the image?

- Near side of the accretion disk, in front of the BH.
- Far side of the accretion disk, above and below the BH, with photons that have been gravitationally bent around the BH.
- A darker region inside the innermost stable circular orbit (ISCO), where disk emission is faint.
- A bright ring set by the radius where photons can orbit the black hole many times before coming to us.
- A dark “shadow” inside this ring, where photons from the far side of the disk are blocked by the BH event horizon.

The image should be asymmetric. Emission from gas moving towards us at speeds close to c is boosted in brightness, and emission from gas moving away from us is suppressed in brightness.

This phenomenon (brighter emission from approaching material) is called “Doppler boosting.”

Overall scale of image is set by the black hole mass, which determines R_{Sch} and thus the size of the shadow, photon ring, ISCO.

Asymmetry and detailed appearance depend on the spin of the black hole and the spatial distribution of the gas (e.g., is it really a thin disk or a thick donut?), which is also affected by magnetic fields in the gas.

There may also be a jet perpendicular to the accretion disk, and more radiation is emitted from the jet.

Angular size of a black hole image

The black hole at the Milky Way center is $4 \times 10^6 M_{\odot}$ at a distance of 25,000 light years = 2.4×10^{17} km.

Using

$$R_{\text{Sch}} = 3 \text{ km} \left(\frac{M}{M_{\odot}} \right),$$

the angular diameter of its event horizon is

$$\theta = \frac{2 \times 3 \times 4 \times 10^6 \text{ km}}{2.4 \times 10^{17} \text{ km}} = 10^{-10} \text{ radians.}$$

This is about the same angular size as a half-dollar coin at the distance of the moon.

The galaxy Messier 87 is about 2000 times further from us than the center of the Milky Way, but its central BH is about 1000 times more massive, so the angular size is comparable.

More precisely, $M = 6 \times 10^9 M_{\odot}$ at a distance of 5×10^{20} km, so the angular diameter of the event horizon is

$$\theta = \frac{2 \times 3 \times 6 \times 10^9 \text{ km}}{5 \times 10^{20} \text{ km}} = 0.7 \times 10^{-10} \text{ radians.}$$

To the best of our knowledge, these two black holes have the largest angular size as seen from the solar system.

There should be stellar mass black holes that are closer, but they are *much* less massive so their event horizons are *much* smaller.

Angular resolution limit

The angular resolution limit of a telescope with a mirror diameter D observing radiation of wavelength λ is

$$\theta_{\min} = \lambda/D \quad \text{radians.}$$

Only structure larger than θ_{\min} can be resolved.

Roughly speaking: the direction of waves of wavelength λ coming from directions less than θ_{\min} apart are not distinguishable.

This is a fundamental physical limit. Atmospheric blurring or imperfections in the mirrors (or radio antennas) may make images blurrier than this limit.

For visible light (roughly $\lambda = 1$ micron $= 10^{-6}$ m) and a 10-meter diameter mirror (the largest on an optical telescope)

$$\theta_{\min} = \frac{10^{-6} \text{ m}}{10 \text{ m}} = 10^{-7} \text{ radians.}$$

This is nowhere close to what's needed to resolve a BH image.

Radio interferometry

There is a trick that can help.

By carefully combining signals from telescopes separated by *distance* d , one can get some of the same resolution that one would have from a single mirror or antenna of diameter D .

This challenging technique is called interferometry (because you have to get the waves to interfere with each other), and it is easier when the wavelength λ is longer.

It has been done for decades at radio wavelengths (where λ is $\sim 0.01 - 1$ meters) and is just becoming feasible at optical wavelengths (where $\lambda \sim 10^{-6}$ meters).

The Very Large Array of radio telescopes (in New Mexico) can get separations as large as $d = 50 \text{ km} = 5 \times 10^4$ meters and observe at wavelengths as short as $0.5 \text{ cm} = 0.005$ meters.

This gives angular resolution

$$\theta_{\min} = \frac{\lambda}{d} = \frac{5 \times 10^{-3} \text{ m}}{5 \times 10^4 \text{ m}} = 10^{-7} \text{ radians,}$$

similar to the best optical telescopes.

Still not enough.

The Event Horizon Telescope

Over the past decade, the world has built a lot of radio telescopes that are sensitive at $1 \text{ mm} = 10^{-3} \text{ m}$ (a.k.a. microwaves).

The Event Horizon Telescope is an effort to perform radio interferometry with many of these telescopes (which are usually used separately) spread over the globe.

The distance d is thus similar to the diameter of the earth, $12,800 \text{ km} \approx 10^7 \text{ m}$ with an angular resolution

$$\theta_{\min} = \frac{10^{-3} \text{ m}}{10^7 \text{ m}} = 10^{-10} \text{ radians.}$$

This is what's needed to resolve the scale of the Milky Way black hole or the Messier 87 black hole! Challenging experiment, in part because the telescopes cover only a tiny fraction of the earth's surface (obviously), so one has to recover the radio "image" from very incomplete information. First results for M87 published in 2019. The Milky Way is proving harder because of variable interference from material near the galactic center.

Image of the M87 black hole

The image shows a ring of emission, brighter on one side (i.e., asymmetric), with an angular diameter of about 2×10^{-10} radians.

This ring is roughly three times the expected diameter of the event horizon itself.

The center of the ring is at least 10 times darker than the ring itself.

Interpretation

The Event Horizon Telescope (EHT) collaboration has interpreted their results by comparing them to the predictions of supercomputer simulations of gas accretion and gravitational light bending.

Because we don't know the geometry of the gas accretion and the jet, and because the image is imperfect, there are uncertainties in the interpretation.

What seems most secure:

- The emission ring is the "photon ring" caused by (radio) photons that can orbit many times around the black hole.
- The asymmetry is caused by Doppler boosting, implying that gas on the lower side of the orbit is moving towards us.
- The central dark region is the shadow cast by the event horizon.
- The more distant accretion disk (beyond the ISCO) is too faint to see with the EHT's current sensitivity.

GR calculations predict that the diameter of the photon ring is $5.2R_{\text{Sch}}$. The measured diameter implies a black hole mass of $6.5 \times 10^9 M_{\odot}$.

This value is consistent with, though a bit higher than, the value inferred from the motions of stars near the center of M87.

Prospects

By observing on different days (now over several years), we are learning about variability of the emission and thus variability of the gas accretion.

This variability, and improving sensitivity, are giving us better information about the accretion flow, which in turn gives better information about the black hole mass and spin.

These measurements will steadily improve with time and technological advances, and we should also get results for the Milky Way black hole.

What we've learned so far

The M87 EHT image is consistent with what's expected for gas accretion onto a spinning super-massive black hole with the event horizon and strong light bending predicted by GR.

What we hope to learn

A lot about gas accretion onto the M87 and Milky Way black holes.

How the jet in M87 is formed.

The spins of the two black holes. How close are they to the maximum spin allowed by GR? This in turn tells us about the way that the black holes grew.

More stringent tests of GR predictions. Will we find evidence that GR becomes inaccurate in the regime of strong gravity close to black hole event horizons?

(This evidence would have to be pretty strong for us to believe it.)