## 13. 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 $R_{\rm Sch}$ 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

Recall (from §11) that the angle subtended by a length $l$ at distance $D$ is

$$\theta = \frac{l}{D} \text{ radians.}$$

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

Using

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

the angular *diameter* of its event horizon (twice the angular radius) is

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

This is about the same angular size as a golf ball at the distance of the moon (4 cm / 400,000 km).

The galaxy Messier 87, which is the biggest nearby elliptical and has a central radio/optical/X-ray jet, is about 2000 times further from us than the center of the Milky Way.

Stellar velocities imply that its central BH is about 1000 times more massive, so the angular size is comparable.

More precisely, the mass estimated from stellar velocities is $M = 6 \times 10^9 M_\odot$ at a distance of $5 \times 10^{20}$ 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.

**The Event Horizon Telescope**

Recall (from §11) that radio interferometry, the careful combination of signals from telescopes separated by a distance $D$, can resolve structures larger than

$$\theta_{\text{min}} = \frac{\lambda}{D} \, ,$$

where $\lambda$ is the wavelength of the EM radiation being observed.

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

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

which is similar to the resolution of the best (single mirror) optical telescopes but not close to resolving a BH event horizon.

Over the past decade, the world has built a lot of radio telescopes that are sensitive at 1 mm $= 10^{-3}$ 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

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

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.

**Image of the M87 black hole**

First results for M87 published in 2019.

The image shows a ring of emission, brighter on one side (i.e., asymmetric), with an angular diameter of about $2 \times 10^{-10}$ 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 $5.2 R_{\rm Sch}$. 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.

**Image of the Milky Way's central black hole**

The MW's central BH is referred to as Sgr A$^*$, the brightest point in radio source A in the constellation Sagittarius.

First results from the EHT for this BH were published in 2022, based on observations made in 2017.

Like the M87 images, the Sgr A$^*$ images show a central shadow and a surrounding ring of emission.

We are learning about the accretion flow around Sgr A$^*$ and its variability, but these images are somewhat harder to interpret than those of M87 even though the angular size of the event horizon is slightly larger.

**Prospects**

*What we've learned so far*

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

The same is true for Sgr A$^*$, though the tests are less stringent because interpreting the images is more challenging.

Recent studies in polarized radio waves have begun to tell us about the magnetic fields in these accretion flows.

*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.)