Active Galactic Nuclei

Active galaxies
Radio galaxies, QSOs, Blazars, Seyferts
Accretion disks and jets

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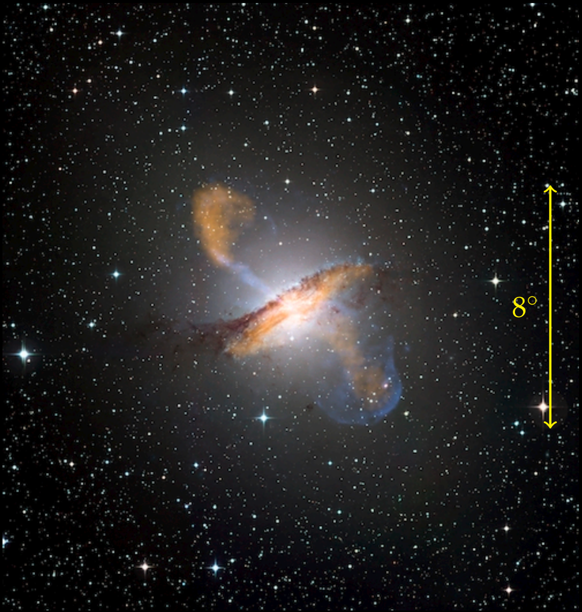
University of Rochester

Active Galactic Nuclei (AGN)

- The Eddington luminosity (or Eddington limits)
- The Galactic center ($r < 3$ pc): Keplerian motion around a black hole
- Radio galaxies, quasars, and blazars
- Relativistic and superluminal motion in quasar jets
- Seyferts: active spiral galaxies
- AGN accretion disks

Reading: Kutner Sec. 19.2–19.5; Ryden Sec. 21.1–21.3, & 21.Appendix



Composite image of Cen A in optical (ESO/WFI), radio (MPIfR/ESO/APEX), and X-ray (NASA/CXC).

Will any black hole do?

Not any black hole will be suitable. The large luminosity itself can stop the accretion due to the outward radiation pressure exerted on infalling material.

- Accretion will be able to take place steadily only if the force of gravity the black hole exerts on the infalling material exceeds the force from radiation pressure.
- Thus, the more massive the black hole, the larger the luminosity it can emit by accretion.
- The maximum luminosity possible via accretion is called the **Eddington luminosity**, and is defined by the point where gravity and radiation pressure are in balance.

Radiation & the motion of Solar-System bodies

Imagine a small spherical body of radius R a distance r from a star with luminosity L, such that $R \ll r$ and $R \gg \lambda$. The power it absorbs from starlight is

$$P_{\text{in}} = \frac{dE_{\text{in}}}{dt} = \frac{L}{4\pi r^2}\pi R^2$$

i.e., the input flux times the cross section. The rate at which it absorbs momentum is

$$\frac{dp_{\text{in}}}{dt} = \frac{1}{c}\frac{dE_{\text{in}}}{dt} = \frac{LR^2}{4cr^2}$$

Since it emits blackbody radiation equally in all directions, the total momentum from output radiation is zero and so there is a net force on the body from the input radiation:

$$\sum_i F_i = F_{\text{rad}} = \frac{dp_{\text{in}}}{dt} = \frac{LR^2}{4cr^2}$$

The Eddington luminosity

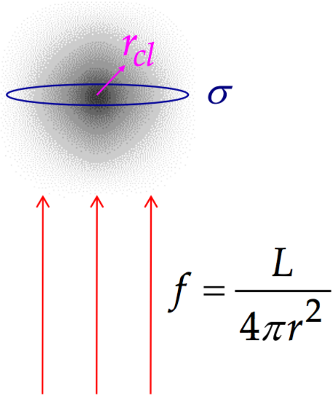
To get the Eddington luminosity, we need to consider the radiation pressure on a gas rather than solid particles or bodies. We will start by considering the areas of the electron and proton shadows, $\pi R^2 = \sigma_e$ or σ_p.

"Classical radius:" assume rest energy comes from electrostatic potential energy:

$$mc^2 = \frac{e^2}{r_{\mathrm{cl}}}$$

$$R \approx r_{\mathrm{cl}} = \frac{e^2}{mc^2} = \begin{cases} 2.8 \times 10^{-13}\ \mathrm{cm} & (e^-) \\ 1.5 \times 10^{-16}\ \mathrm{cm} & (p^+) \end{cases}$$

$$\sigma \approx \pi r_{\mathrm{cl}}^2 = \frac{\pi e^4}{m^2 c^4}$$



The Eddington luminosity

Clearly most of the force is exerted on the electrons (bigger cross section). Done more carefully — accounting for quantum mechanics and for photon scattering rather than absorption — gives the **Thomson cross section**:

$$\begin{aligned}\sigma_e &= \frac{8}{3}\pi r_{\mathrm{cl},e}^2 = \frac{8\pi e^4}{3m_e^2c^4} \\ F_{\mathrm{rad},e} &= \frac{dp_{\mathrm{in}}}{dt} = \frac{L\sigma_e}{4\pi c r^2} \\ &= \frac{2e^4 L}{3m_e^2c^5r^2}\end{aligned}$$

Each electron will drag a proton with it, regardless of whether the gas is neutral or ionized, because on macroscopic scales the gas has equal numbers of electrons and protons and the electrostatic attraction between them is strong.

The Eddington luminosity

Similarly, each proton will drag an electron with it. The gravitational force exerted by the black hole on each proton is of course much larger than that on an electron.

Accretion takes place if $F_{\mathrm{grav},p} + F_{\mathrm{grav},e} > F_{\mathrm{rad},p} + F_{\mathrm{rad},e}$, or, to a good approximation, $F_{\mathrm{grav},p} > F_{\mathrm{rad},e}$.

Thus, in order to accrete while shining at luminosity L, the mass M of the black hole must be such that $\frac{GMm_p}{r^2} > \frac{2e^4 L}{3m_e^2 c^5 r^2}$:

$$L < \frac{3GMm_p m_e^2 c^5}{2e^4} \equiv L_E \qquad \text{given } M$$

$$M > \frac{2e^4 L}{3Gm_p m_e^2 c^5} \qquad \text{given } L$$

where L_E is the Eddington luminosity.

QSO BHs have to be supermassive

Now that we have an expression for the maximum luminosity that can be produced by accretion onto a body of mass M, we can estimate M given $L = 10^{12} L_\odot$:

$$M > \frac{2e^4 L}{3 G m_p m_e^2 c^5} = 3 \times 10^7 M_\odot$$

So a **supermassive black hole is required**, at least 10× larger than the central BH in the Milky Way.

There are QSOs with luminosities as large as $10^{14} L_\odot$, so we should expect to find central black holes in excess of $10^9 M_\odot$, equivalent to the total mass of a good-sized galaxy.

The event horizon radius of the minimum-mass black hole that would power 3C 273 is

$$R_{\mathrm{Sch}} = \frac{2GM}{c^2} = 0.6\ \mathrm{AU}$$

QSO BHs have to be supermassive

Clearly, such a black hole must be quite different in origin from the stellar-mass black holes we considered earlier in the semester. Since stars do not form larger than about $100M_\odot$, they could not have arisen via a stellar collapse.

In fact, the origin of supermassive black holes is not well understood.

- Leading models involve the interaction of galaxies and the transfer of interstellar matter between them during the interaction.

Supermassive BHs have observational consequences that we should see without much trouble.

- Ultra-high luminosities not possible via normal stellar processes.
- Material within a galaxy passing close to a BH like this should exhibit large (even relativistic) speeds, showing up in Doppler shifts and proper motions.

The Milky Way's central black hole

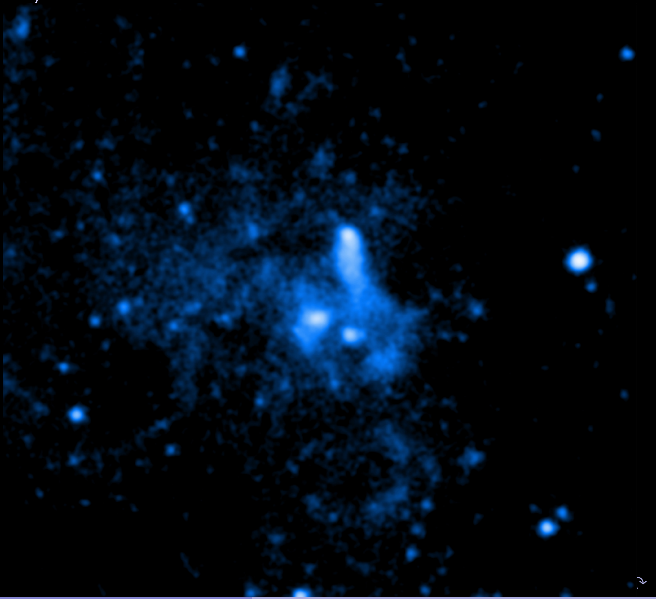
The dynamical center of the Galaxy is heavily extinguished. It cannot be seen at visible through longer X-ray wavelengths.

- It is bright in IR and radio and **hard** (short-wavelength) X-rays, which are transmitted through the dust.
- It was the first extraterrestrial object seen in radio by Karl Jansky in 1933.

Within the central 3 pc we find a dense cluster of stars, a bright compact radio source, and a swirl of gas clouds.

- Small bright radio source is called Sagittarius A*, or **Sgr A***.
- Sgr A* lies **precisely** at the center of the Galaxy (center of rotation): $(\alpha, \delta)_{\mathrm{J2000}} =$ 17:45:40.0409, -29:00:28.118.

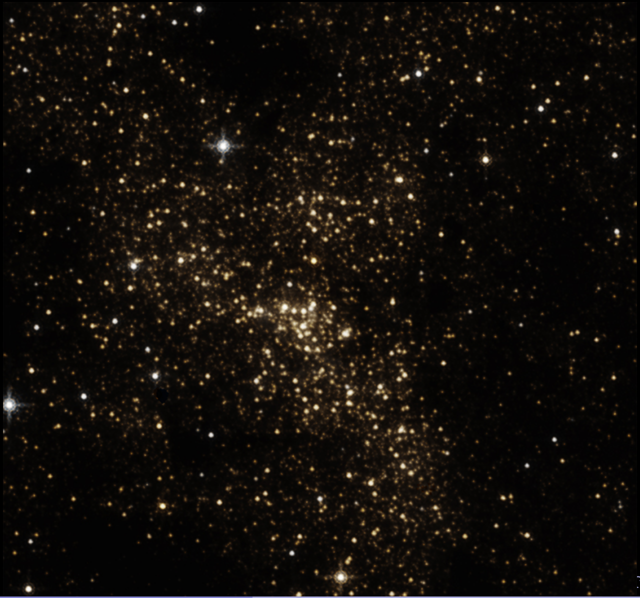
Central 6pc of Sgr A West in X-rays



Sgr A* is the brightest starlike object in the center of this image taken with the Chandra X-ray observatory (CXC) (Wang et al. 2013).

Central 6pc of Sgr A West in Near Infrared

Sgr A* does not appear in this picture due to the fact that it is drowned out by light from all of the neighboring stars (NASA/STScI).



Orbital motion & the center of the Milky Way

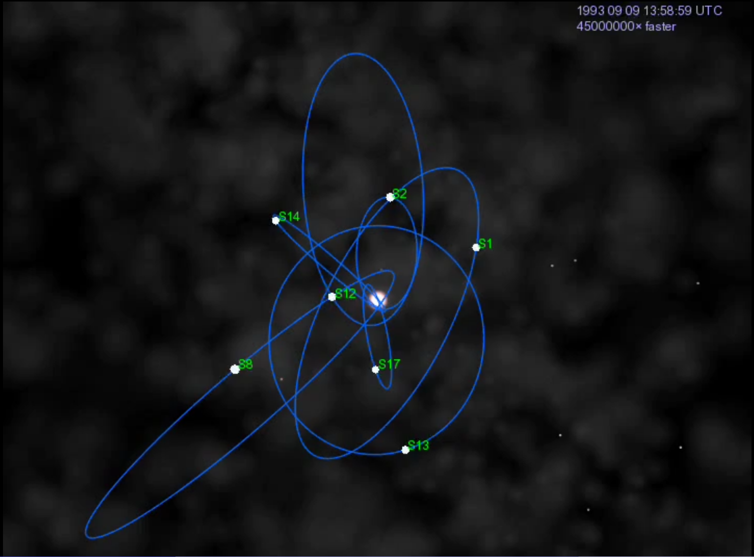
Over the course of the past 40 years, astronomers have measured velocities related to orbital motion about the center for many objects that lie within 1 pc of the Galactic center:

- radial velocities of gas clouds
- radial velocities of stars
- proper motions of stars

The orbits do not lie in the plane of the rest of the Galaxy, but that does not matter; these are "test particles" we can use to determine the gravitational potential in the Galactic center.

Stellar motions near Sgr A*

Orbital solutions for stars next to Sgr A*, from the MPE Galactic Center group.

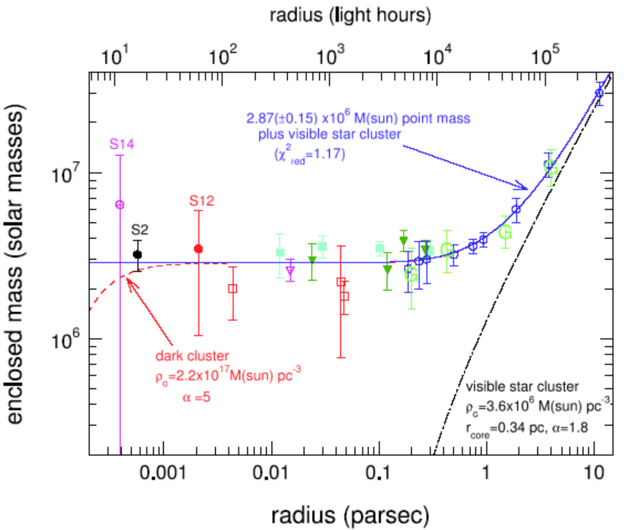


The black hole at the center of the Galaxy

- If the central stellar cluster were the only mass present (i.e. no central massive black hole) then the orbital velocities would decrease toward zero with r since $M(r)$ would decrease to 0.
- If there is a massive black hole, the mass enclosed by the stellar orbits

$$M(r) = \frac{rv^2}{G}$$

should approach the mass of the black hole as $r \to 0$.



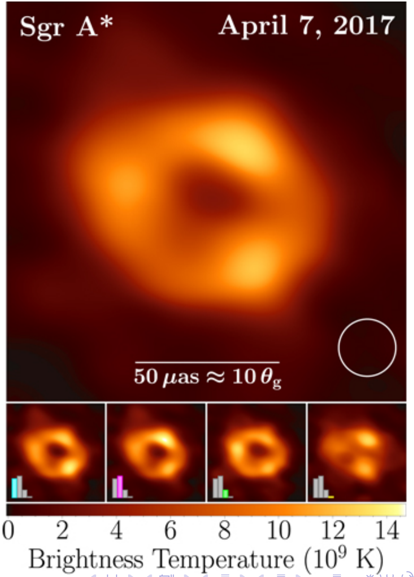
Results from stellar and gas-cloud Doppler shifts and proper motions (Schöedel et al. 2003).

The black hole at the center of the Galaxy

Thus there is a black hole at the center of the Milky Way, and its mass is $(4.3 \pm 0.1) \times 10^6 M_\odot$ (GC 2022). It spins at 25% of its maximum rate.

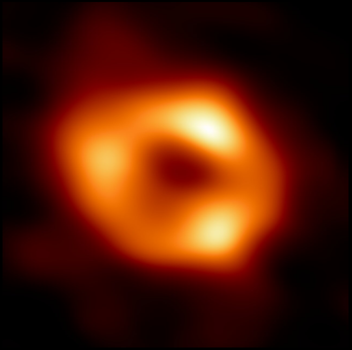
- Presumably the radio and X-ray components of emission from Sgr A* are the outermost and innermost parts of the accretion disk around the black hole.
- It turns out that supermassive black holes are *very common in galactic nuclei*, but the prominent examples — those in active galactic nuclei — are considerably more massive ($10^9 M_\odot$).

The Event Horizon Telescope (a global long-baseline interferometric radio network) recently imaged the light orbiting around Sgr A*'s event horizon (EHT 2022).

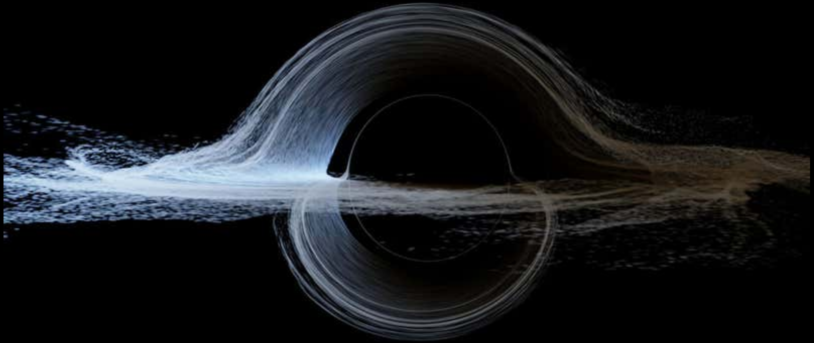


What are we seeing?

Image of our black hole,
Sgr A*

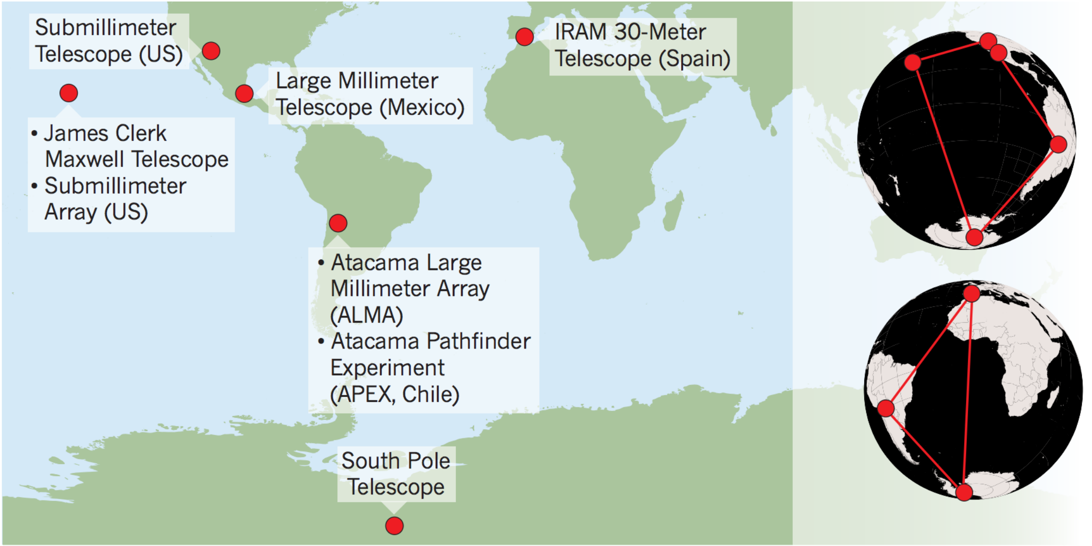


Simulation of a black hole



The Event Horizon Telescope

The global mm-wavelength network comprising the Event Horizon Telescope (Castelvecchi 2017).



Active galaxies & AGN

Several types of galaxies are known to have active nuclei.

The following types were discovered by radio astronomers, and thousands are now known:

Quasars (a.k.a. QSOs) come in two varieties: radio-loud and radio-quiet.

Radio galaxies also come in two varieties: broad-line and narrow-line

These were discovered by visible-light astronomers, and hundreds are now known:

Seyfert galaxies are all radio-quiet, in both broad-line and narrow-line types.

Blazars a.k.a. BL Lacertae objects

Note that active galaxies are vastly outnumbered by normal galaxies.

Active galaxies & AGN

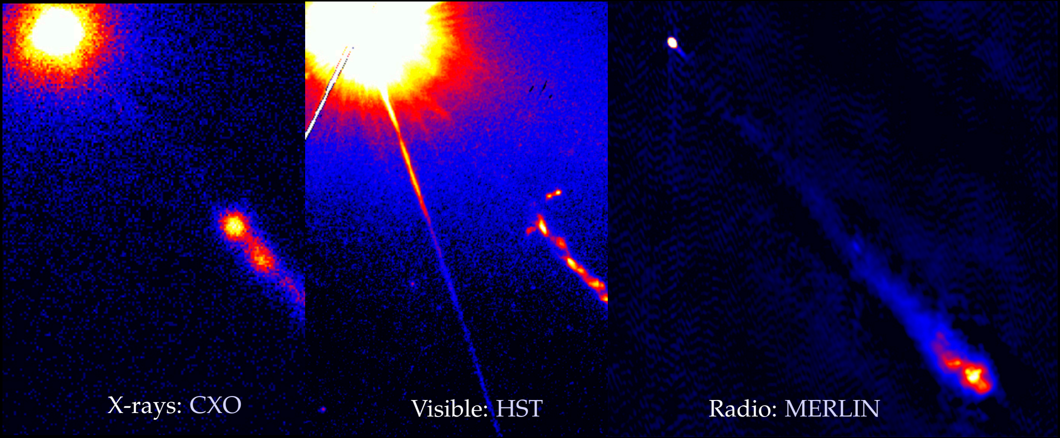
Different classes of active galaxies have a lot in common, despite their different appearances. The two most obvious common features:

- All have some sort of compact, “star-like,” object at their very centers that dominate the galaxies’ luminosities.
- They are more luminous by factors of 10 to 10^3 than normal galaxies of the same Hubble type, and therefore all are thought to contain accreting, supermassive black holes.

We began discussing **quasars** last time. Their distinguishing characteristics are:

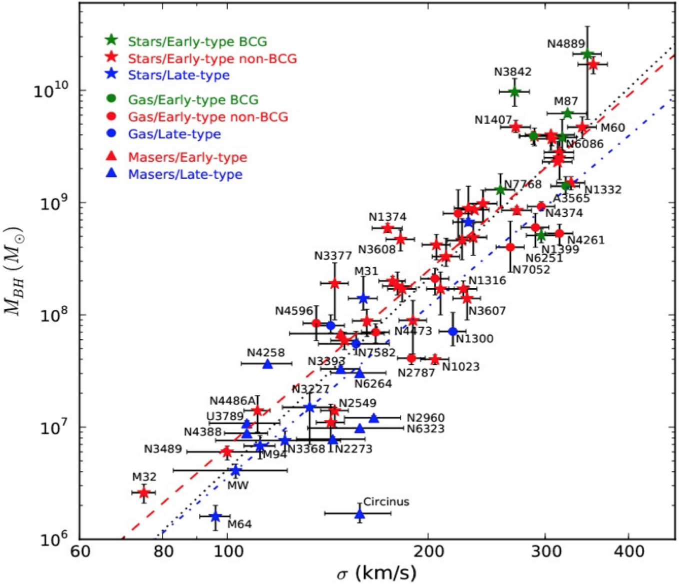
- Compact galaxy nucleus with extremely large luminosity
- One-sided jet

The archetypical quasar 3C 273



The luminosity of 3C 273, the first QSO discovered, is dominated by its starlike central core, visible in all three images above. It also has a jet but no “counterjet” visible on the other side of the quasar. The quasar is located inside an elliptical galaxy.

Measurement of black hole masses in AGN



Note that we did not say this could only be done for active galaxies. Many of the galaxies this plot of supermassive central black holes are not active.

An AGN requires a supermassive black hole *and* an ample supply of mass to be accreted. Not all SMBHs have a mass supply at the moment.