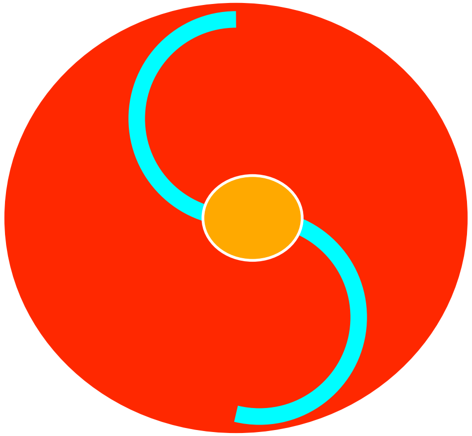
AS1001:Extra-Galactic Astronomy

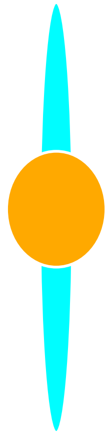
Lecture 6: Galaxy Orientation, Black Holes & Quasars

Galaxy Inclination



FACE-ON

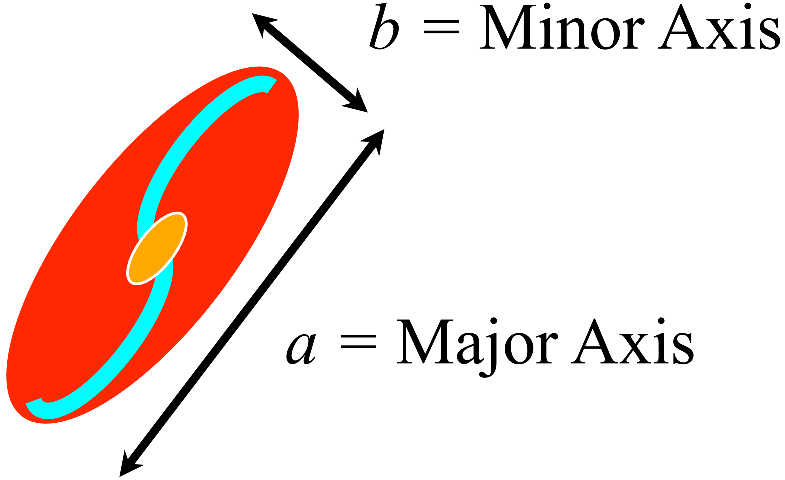
Inclination $i = 0^{o}$



EDGE-ON

Inclination $i = 90^{o}$

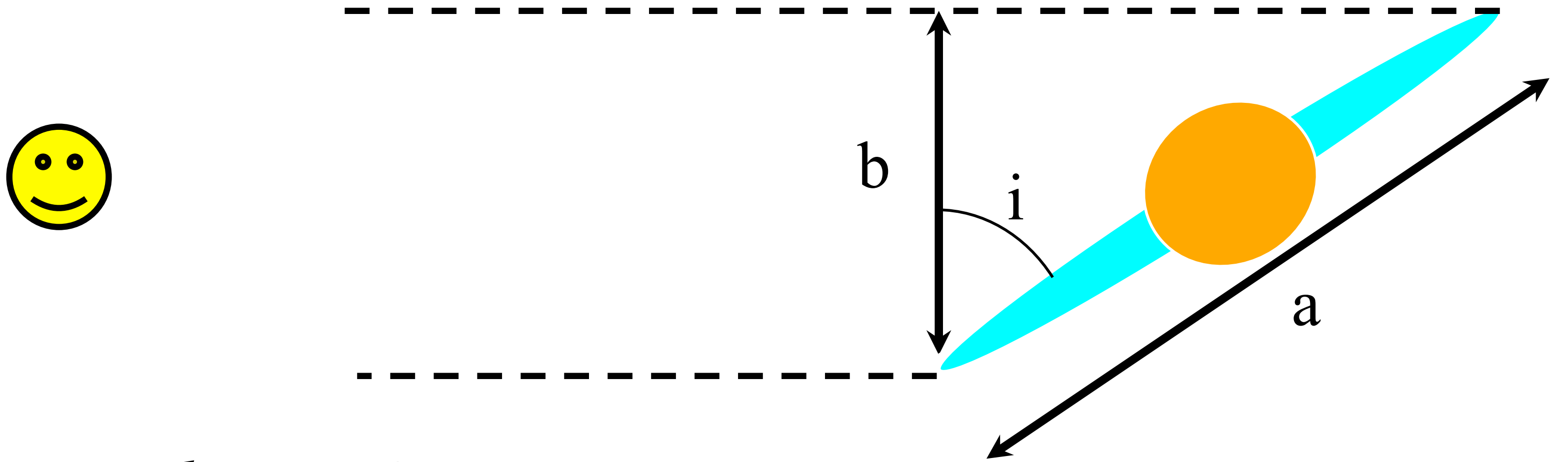
All galaxies are viewed with some inclination:



Calculating the Inclination

- Assuming a thin circular disc:
- Inclination, i, given by:

$$\boxed{\cos(i) = \frac{b}{a}}$$



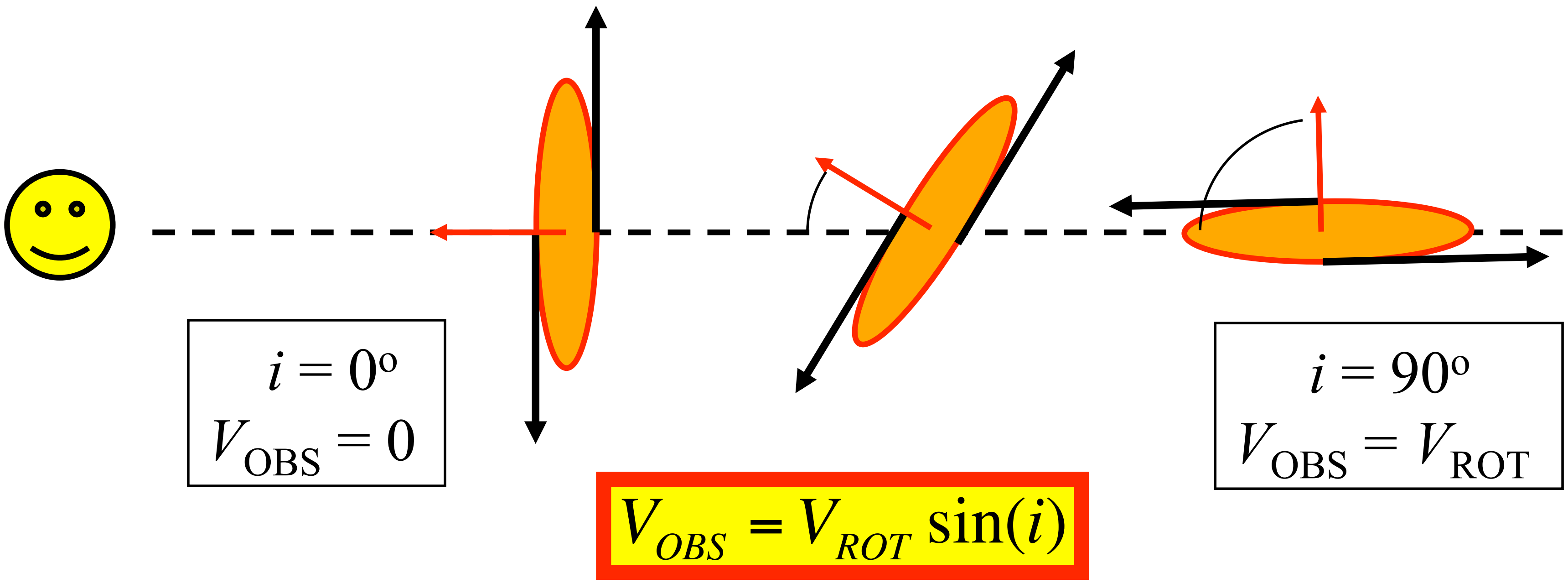
- $a = b$, $i = 0^{o}$
- $b = 0$, $i = 90^{o}$

NB: a is always measurable

Line-of-sight velocity

The **Doppler Shift** measures the component of velocity **along the line of sight.**

Need to correct for inclination.



Example: Inclination Corrections

A long-slit spectrum aligned with a galaxy's major axis has an [OII] line at 3900A that shifts by 5A from one side to the other side of the galaxy. The major-to-minor axis ratio is 3. What is the rotational velocity of the outermost stars ?

$$\cos i = b/a = 1/3 \qquad i = \cos^{-1}(1/3) = 70.5^0$$

$$\sin i = \sqrt{1-\cos^2 i} = \sqrt{1-(1/9)} = \sqrt{8/9} = 0.94$$

Note: (5 A)/2

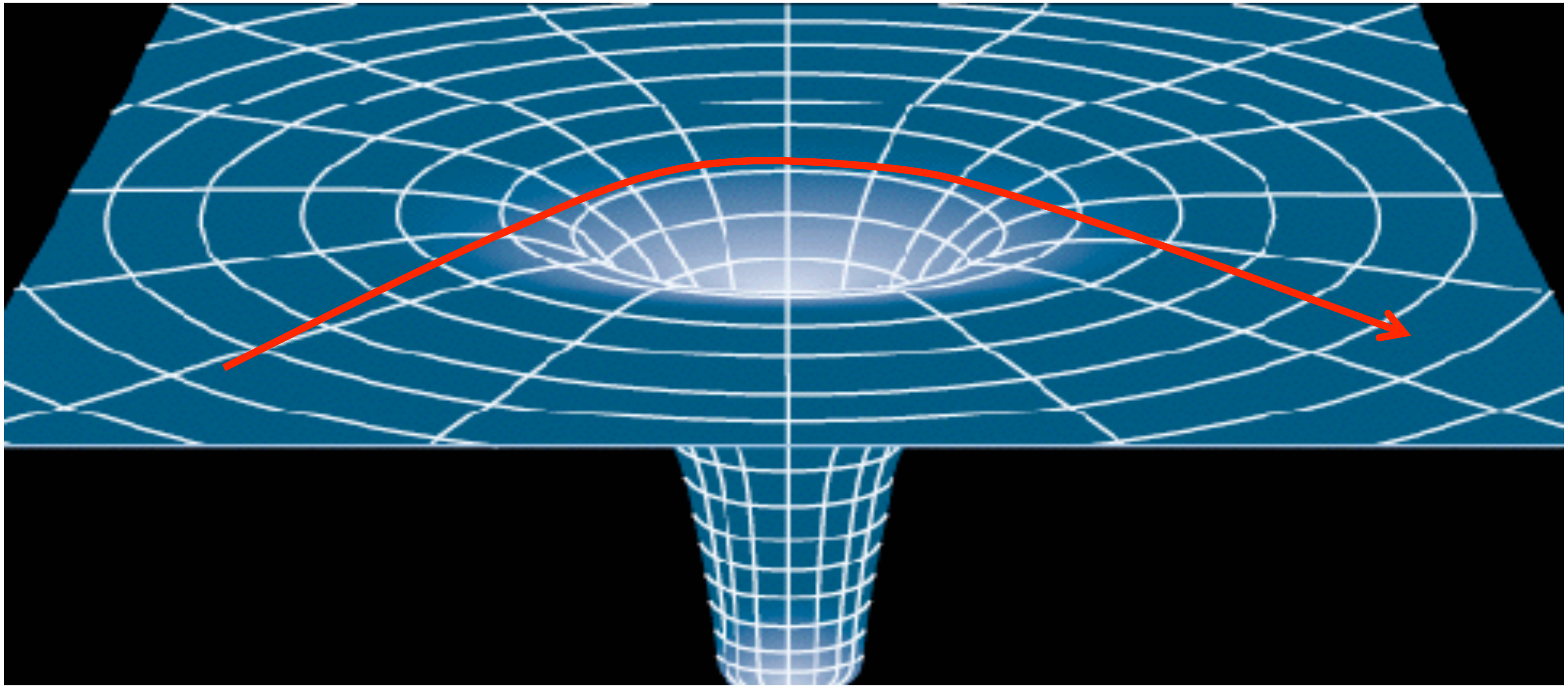
$$V_{OBS} = \frac{\Delta\lambda}{\lambda} c = \frac{2.5\,\mathrm{A}}{3900\,\mathrm{A}} \times \left(3\times10^5\ \mathrm{km/s}\right) = 192\ \mathrm{km/s}$$

$$V_{ROT} = \frac{V_{OBS}}{\sin(i)} = 204\ \mathrm{km/s}$$

Note: λ=3900 and not 3727

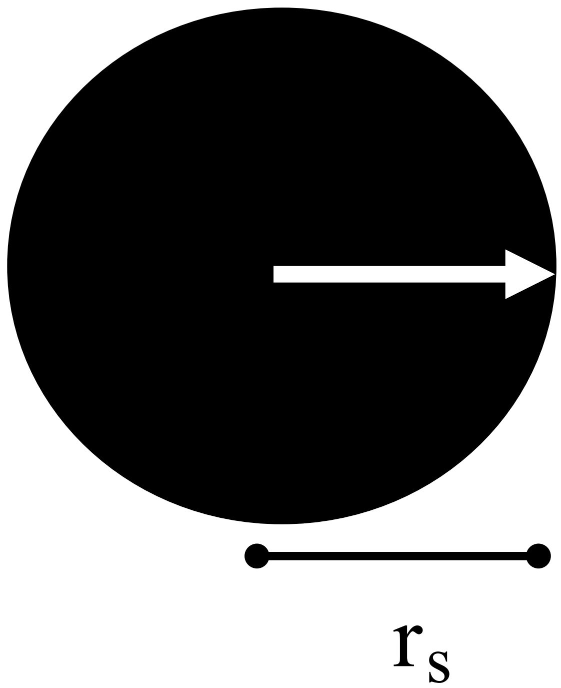
Black Holes

Gravity = curvature of space-time by matter/energy. Pack mass into a small enough volume, and the space-time can be so distorted that nothing, not even light, cannot escape.



The Schwarzschild Radius

- Where the escape velocity equals the speed of light.
- Nothing, not even light, can escape from inside the Event Horizon, at the Schwarzschild Radius r_s.
- Escape velocity: set Kinetic Energy = Gravitational Energy



$$\frac{1}{2} m \mathrm{v}^2 = \frac{G M m}{r}$$

$$\mathrm{v}_{\mathrm{esc}} = \left(\frac{2 G M}{r} \right)^{1/2}$$

$$r_S = \frac{2 G M}{c^2} = 3\,\mathrm{km} \left(\frac{M}{M_{sun}} \right)$$

Types of Black Hole

- Stellar-mass
  - Formed when a very massive star goes supernova

$$\boxed{\mathbf{M}_{\mathrm{BH}} \sim 10\,\mathbf{M}_{\otimes}}$$

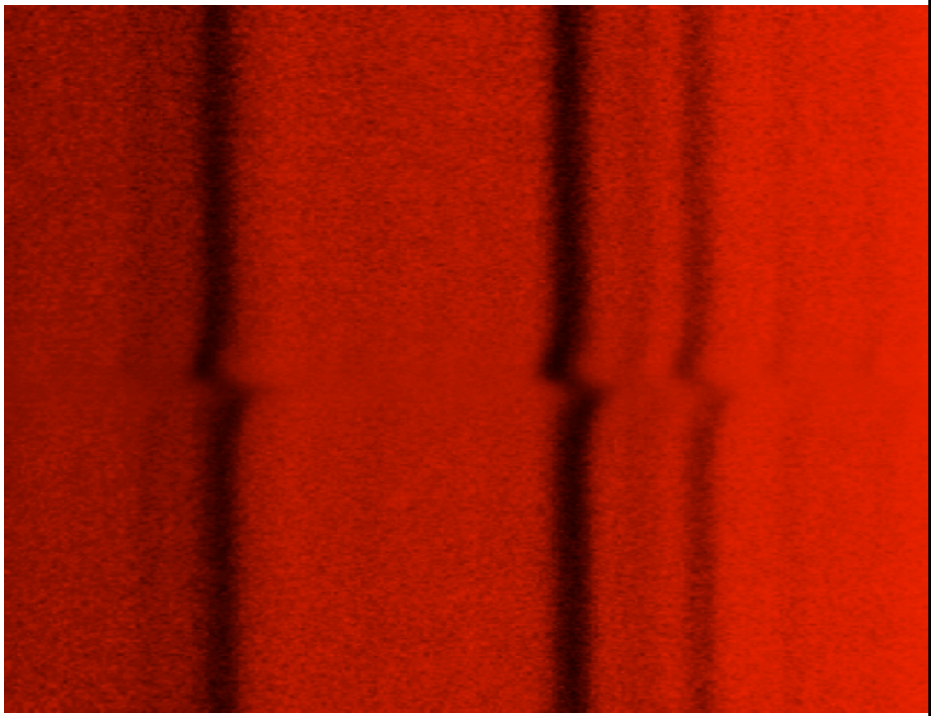
- Super-massive
  - Formed in galaxy cores

$$\boxed{\mathbf{M}_{\mathrm{BH}} \sim 10^{7-9}\,\mathbf{M}_{\otimes}}$$

- Most large galaxies have a super-massive black-hole (SMBH) in their core.

The SMBH in M31

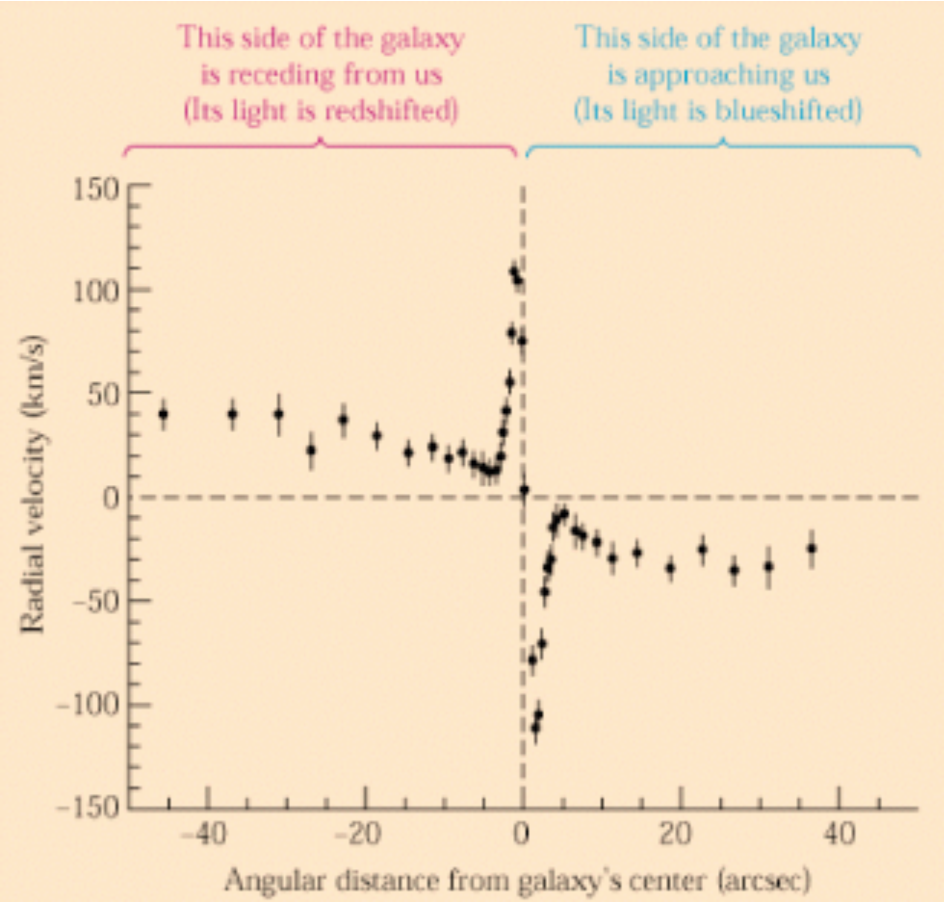
Stars orbiting near the core



Spectra showing velocities of stars on either side of the the core

The SMBH in M31

- Star velocities v > 110 km/s for r < 2.5 pc



Use Virial Theorem to calculate the Mass

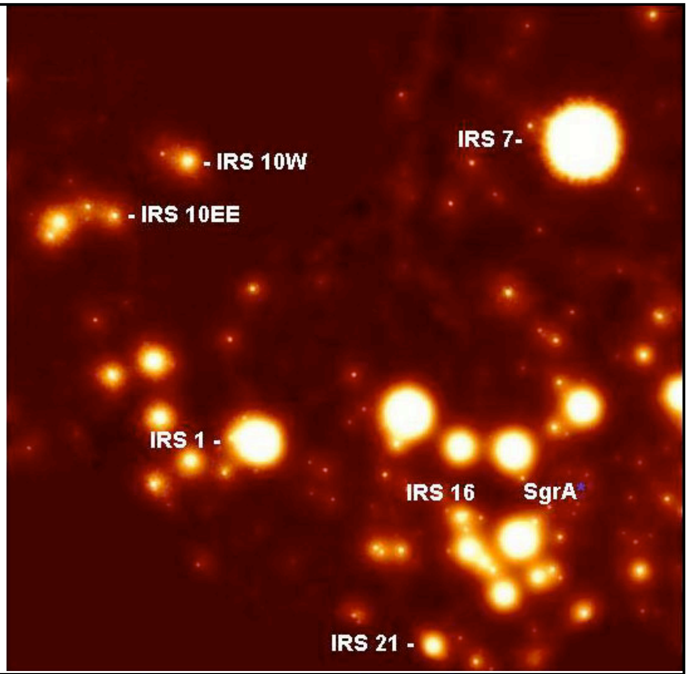
$$\mathbf{M}_{\mathrm{CORE}} = \frac{\mathrm{v}^2 r}{G}$$

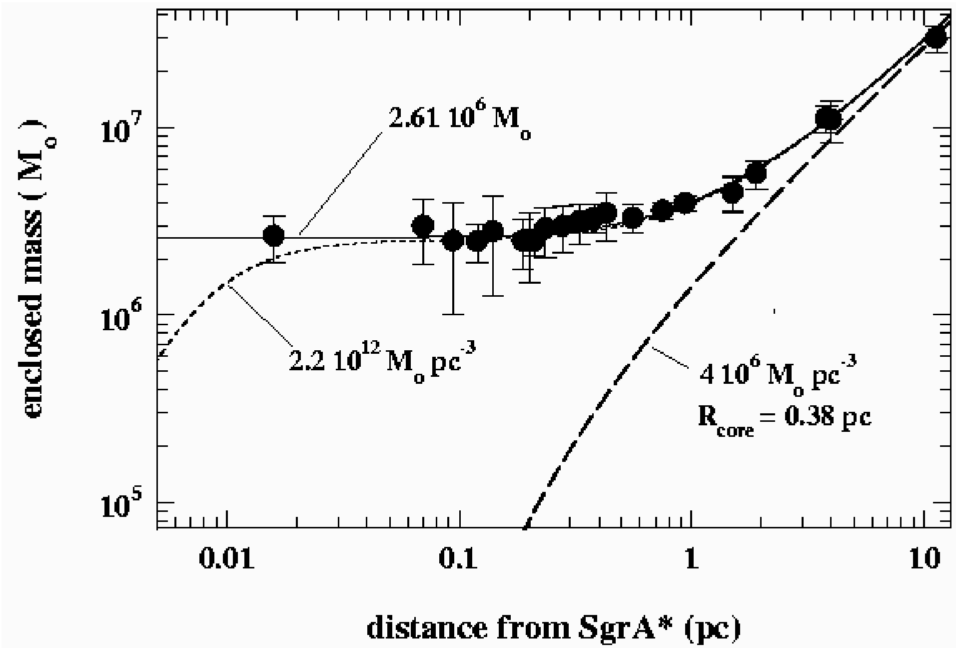
$$= \frac{(110 \times 10^3)^2 \times 2.5 \times \left(3 \times 10^{16}\right)}{6.67 \times 10^{-11}}$$

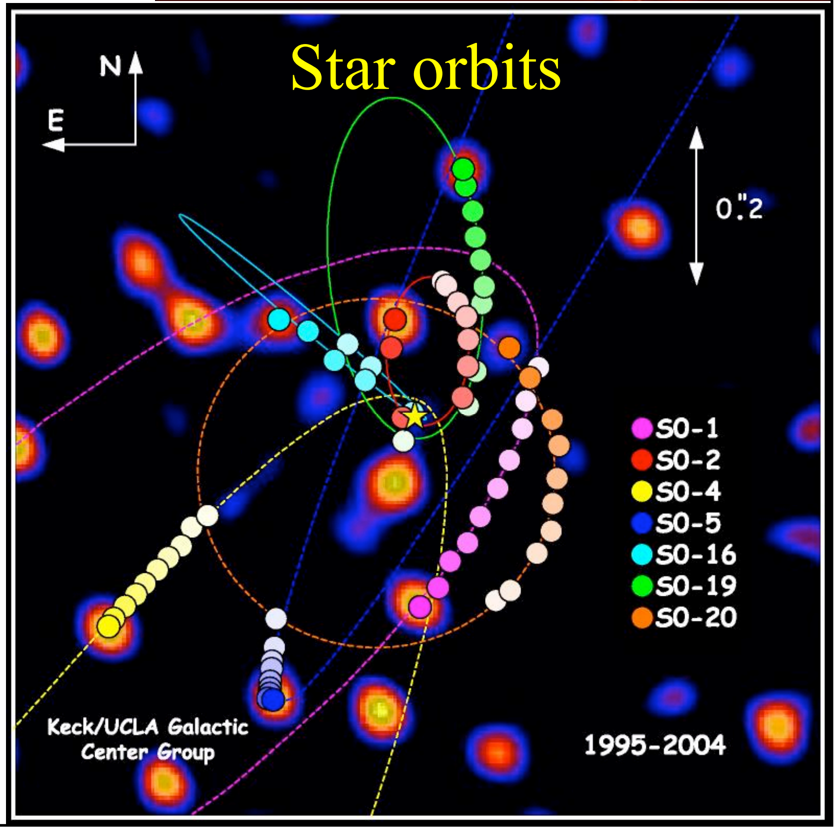
$$= 1.4 \times 10^{37}\,\mathrm{kg} = 6.8 \times 10^6 \mathbf{M}_{\otimes}$$

Milky Way's SMBH

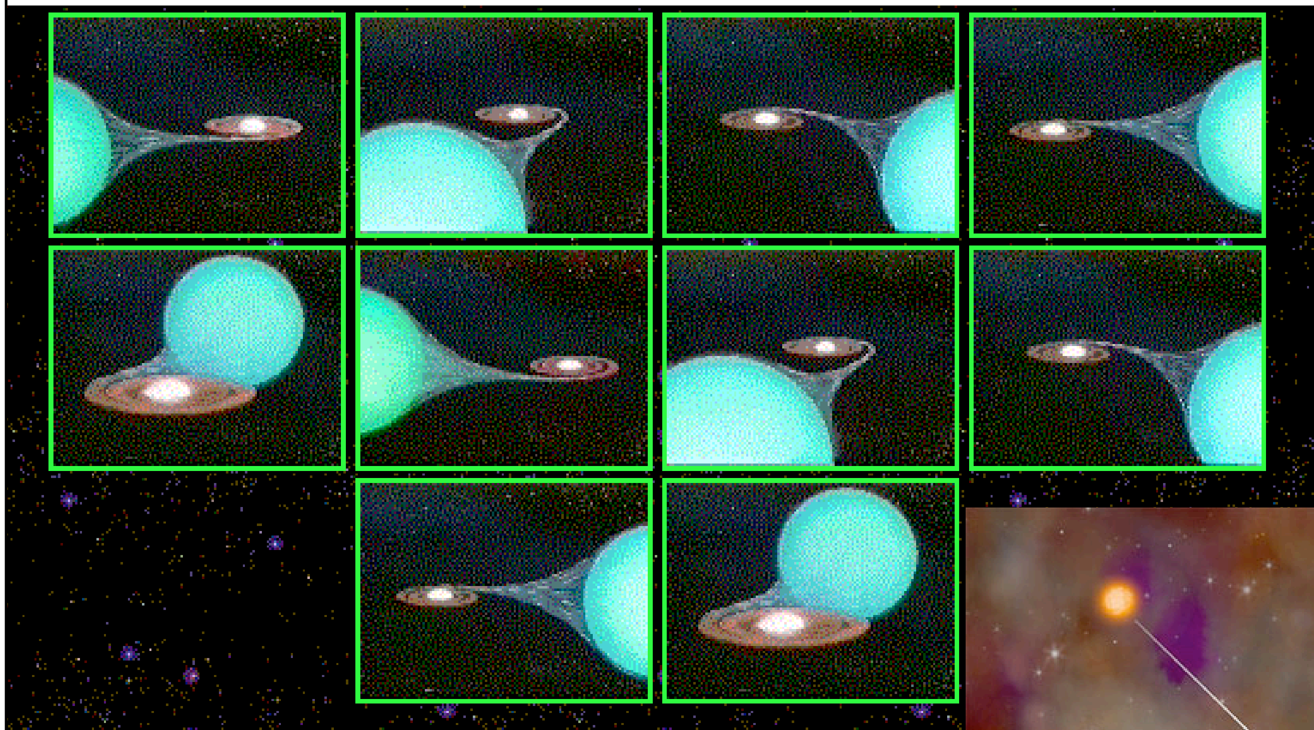
- Infrared images (to see thru dust) show a compact star cluster.
- Star velocities v > 1000 km/s inside r = 0.01 pc!
- => 3 x 10^6 M_{sun} Black Hole in the Milky Way's core







Stars orbiting a Black Hole



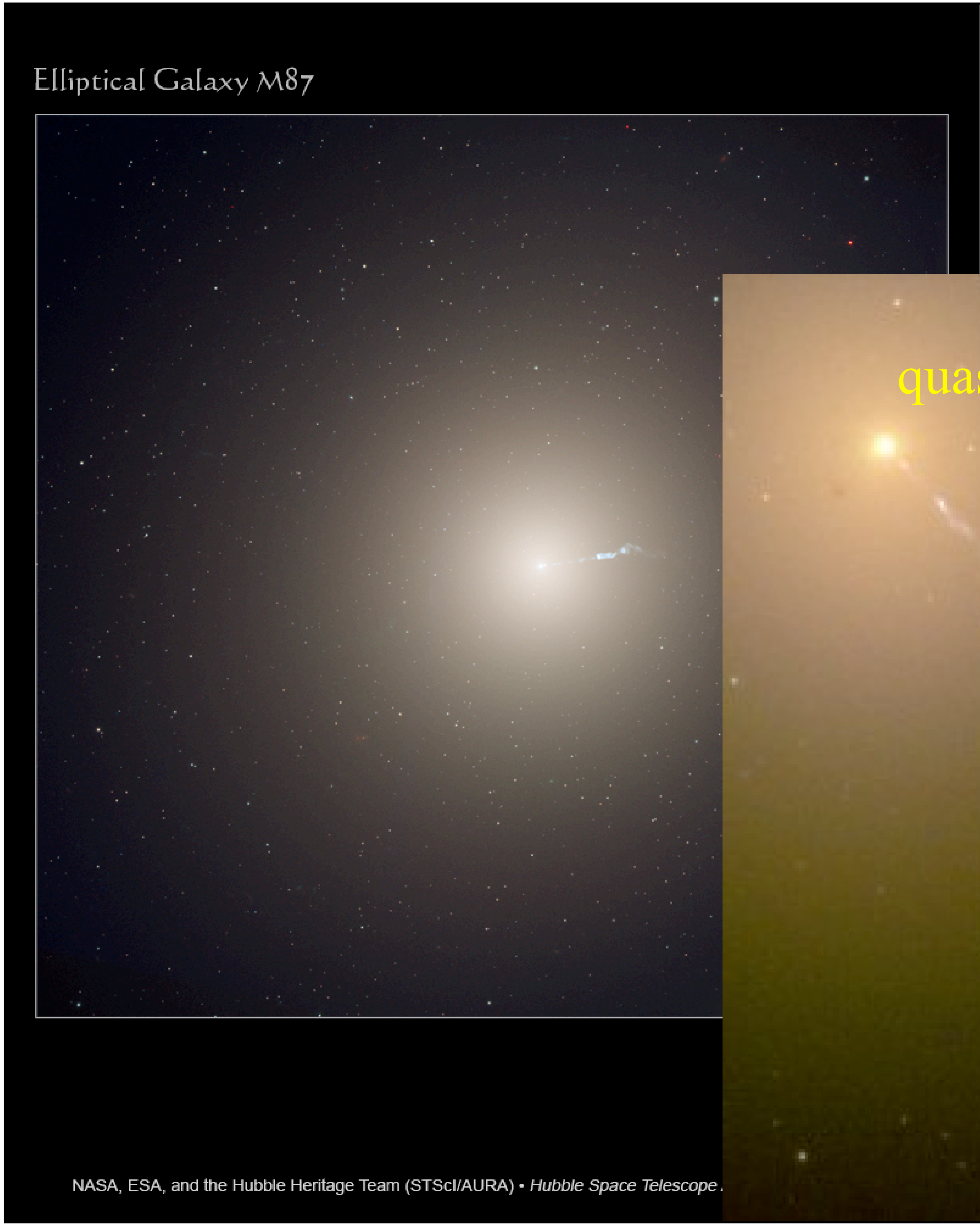
Circular orbit:
Stars can orbit safely. If star close enough to fill its "Roche lobe", mass transfer forms an Accretion Disk.

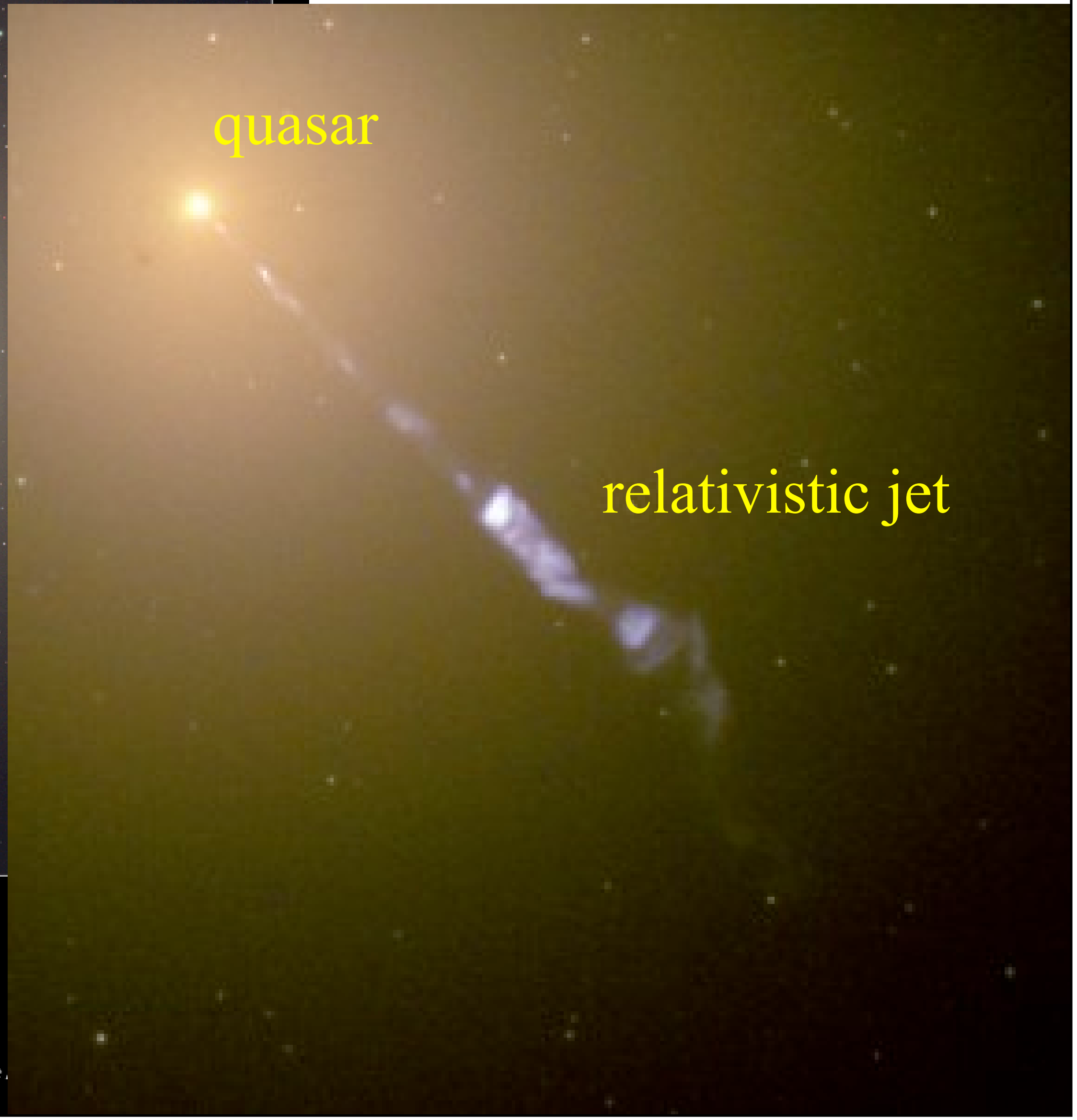
Highly elliptical orbit: Black hole tides can shred a star that comes too close. Debris forms an Accretion Disk, eventually swallowed by hole.

Discovery of Quasars

- Quasars are Super-Massive Black Holes "feeding".
- Originally known as Quasi-Stellar Objects (QSOs).
- For many years "stars" with unknown spectral features were found but their nature unknown !
- 1963: Martin Schmidt recognised that QSOs have known emission lines with large redshifts
  (hence QSO luminosities >> galaxies)
- Hence QSOs are extra-galactic objects but:
  – Appear star-like (i.e., not extended but point-like)
  – Outshine galaxies (by up to 10^5 times)
  – Very broad emission lines ($\Delta v \sim 10^4$ km/s)
  – X-ray and radio emission (from relativistic jets)

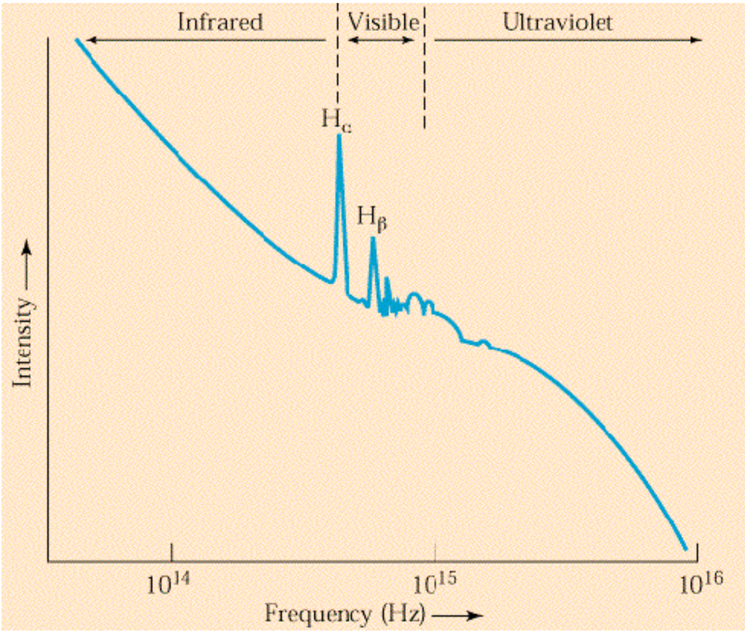
M87

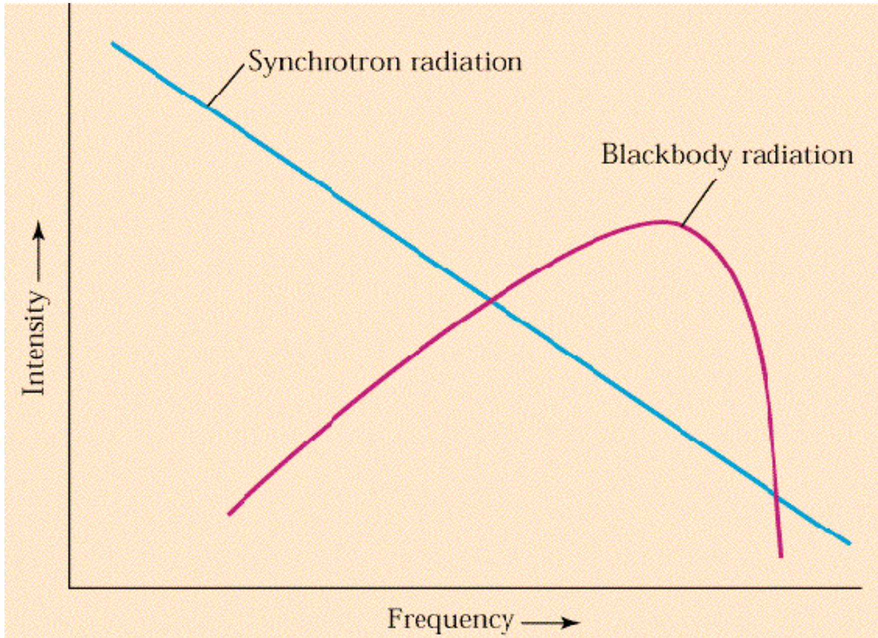

Elliptical Galaxy M87
NASA, ESA, and the Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope


quasar
relativistic jet

Quasar Spectra

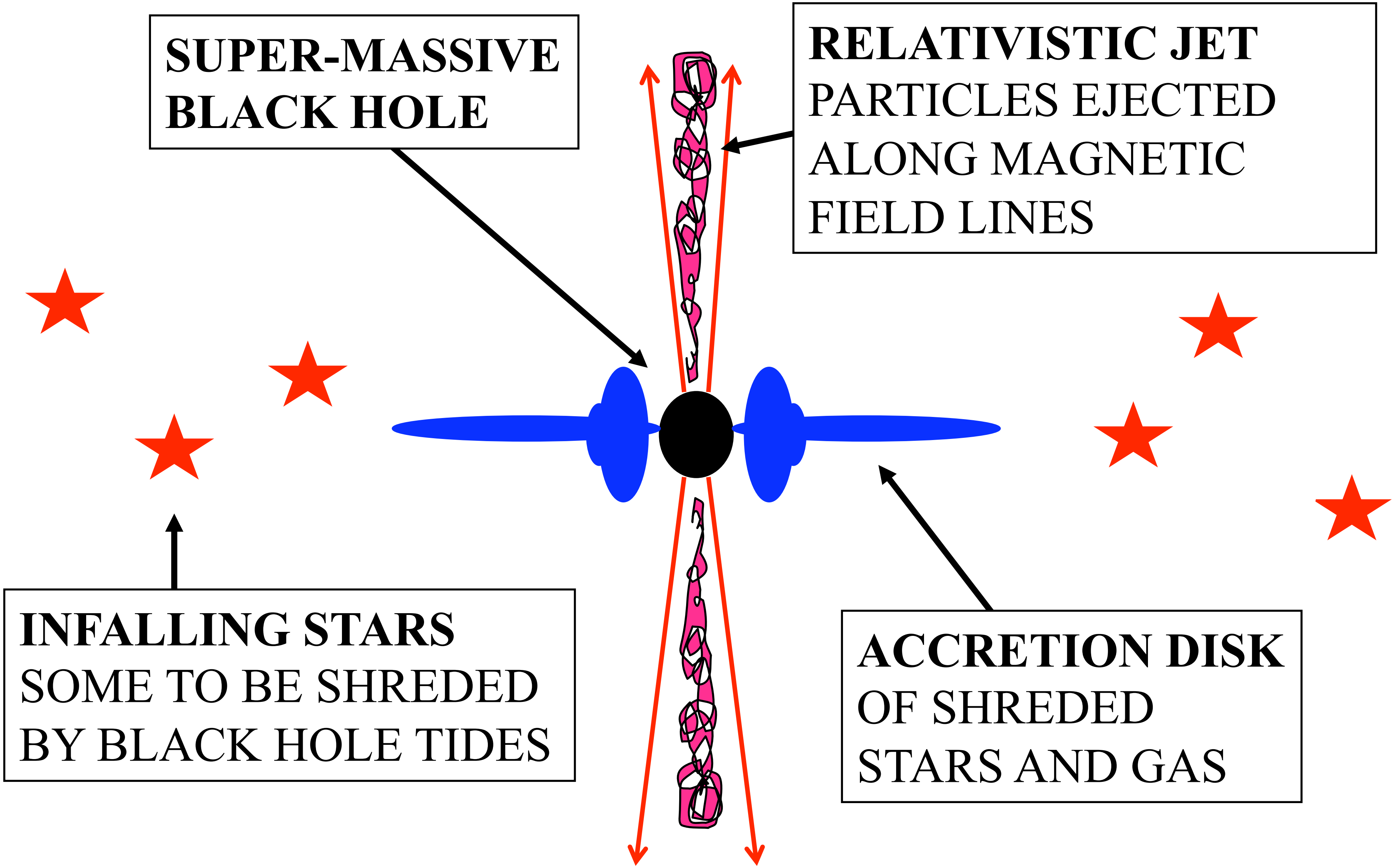
- QSO spectra show both thermal (Blackbody) and non-thermal (Synchrotron) emission.





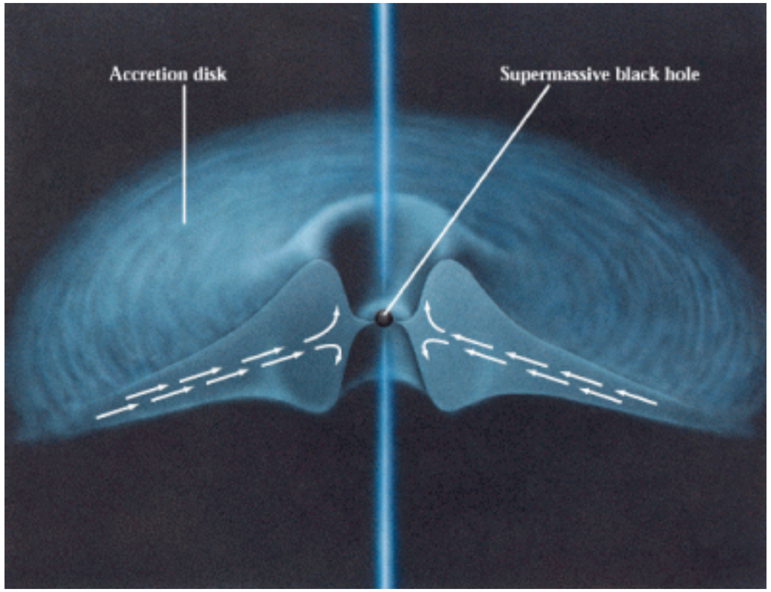
- Blackbody from multi-temperature Accretion Disk.
- Synchrotron from Relativistic Jets: relativistic charged particles electrons spiraling around magnetic field lines.

Simplified Quasar Model

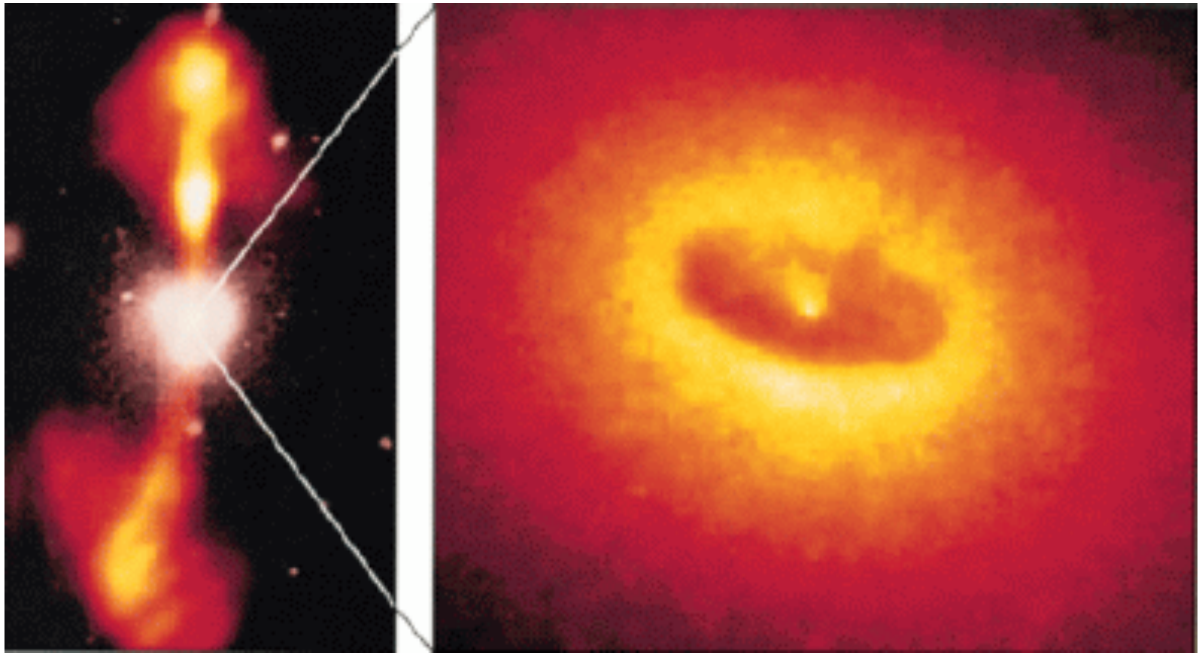


SMBH Model/Observations

MODEL



OBSERVATIONS
(NGC 4261)



Quasars: Powered by Accretion

- Gravitational energy is released as mass accretes.
- Friction in the accretion disk moves angular momentum outward as the gas spirals in. Friction also heats the gas.
- Accretion Disk Temperature Profile:

$$T(r) \sim \left(\frac{3 G M \dot{M}}{8 \pi \sigma r^3} \right)^{1/4} = 10^6 K \left(\frac{\dot{M}}{\mathrm{M_{SUN}} / \mathrm{yr}} \right)^{1/4} \left(\frac{M}{10^8 \mathrm{M_{SUN}}} \right)^{-1/2} \left(\frac{r}{r_S} \right)^{-3/4}$$

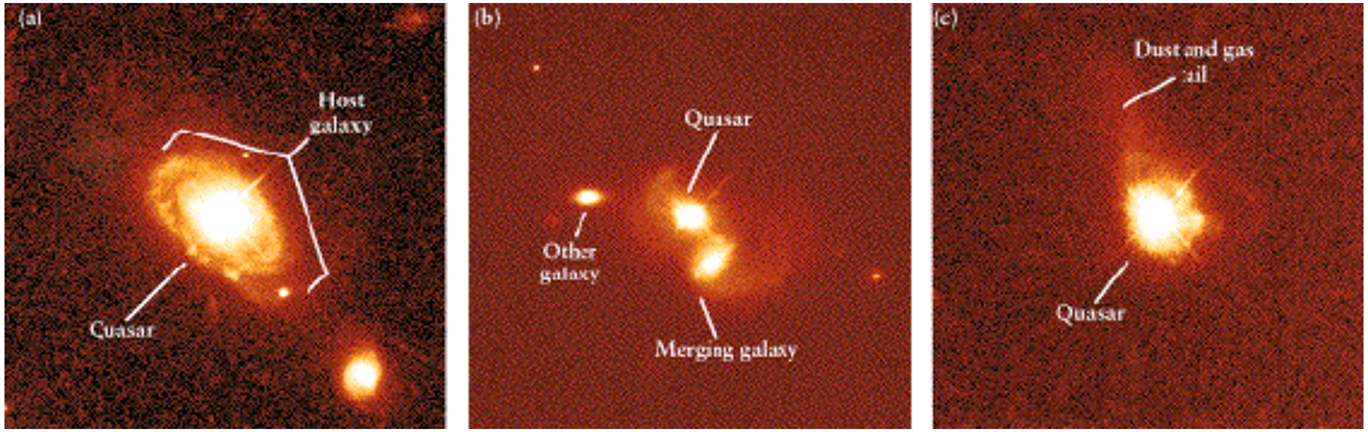
- Accretion Luminosity:

$$L \sim \frac{G M \dot{M}}{r_S} = \eta \dot{M} c^2 \sim 10^{11} \mathrm{L_{SUN}} \left(\frac{\dot{M}}{\mathrm{M_{SUN}} / \mathrm{yr}} \right)$$

- η = Efficiency of converting rest mass energy into light:
  - Up to 15% for accretion onto a black hole
  - Much smaller for nuclear fusion

Types of Active Galactic Nuclei

- 1993: HST reveals “Quasar fuzz” = host galaxy.

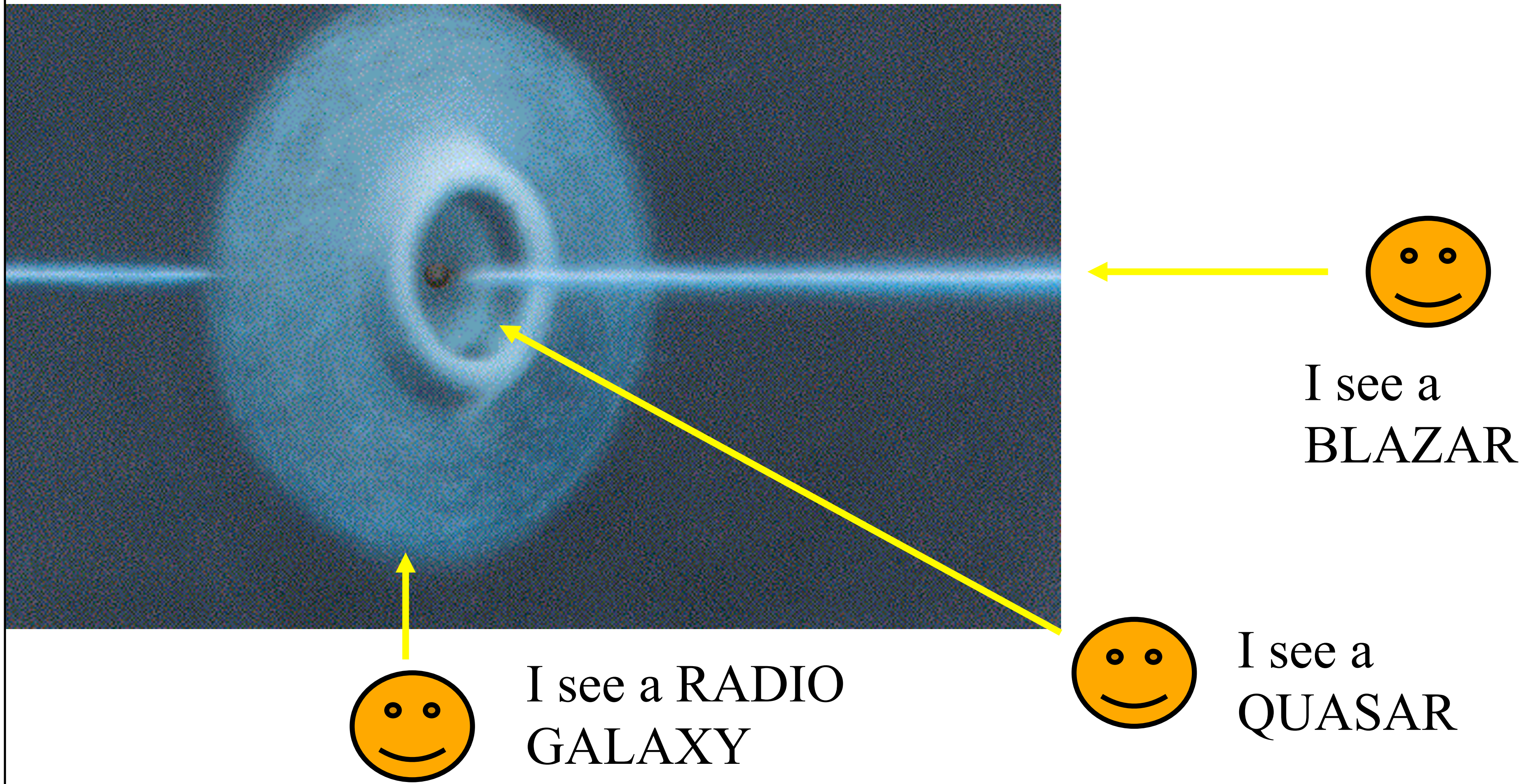


- Active Galactic Nuclei (AGN) in the cores of galaxies.
  - Quasar = Bright AGN outshining the host galaxy
  - Seyfert = Fainter AGN luminosity equals host galaxy
  - Radio Galaxy = AGN with radio lobes
  - Blazar = AGN with no lines and rapid variability

WHY SO MANY DIFFERENT TYPES ?

AGN Unification

Different AGN types are now understood to be due to different viewing angles:



The Quasar Era

- Redshift surveys find highest density of quasars per unit volume around redshift *$z \sim 2$-3*
- Large redshifts => large distances => large "lookback times" i.e., we see quasars as they were in the past, when the Universe was young.
- Nearest quasar: 3c273 at 250 Mpc

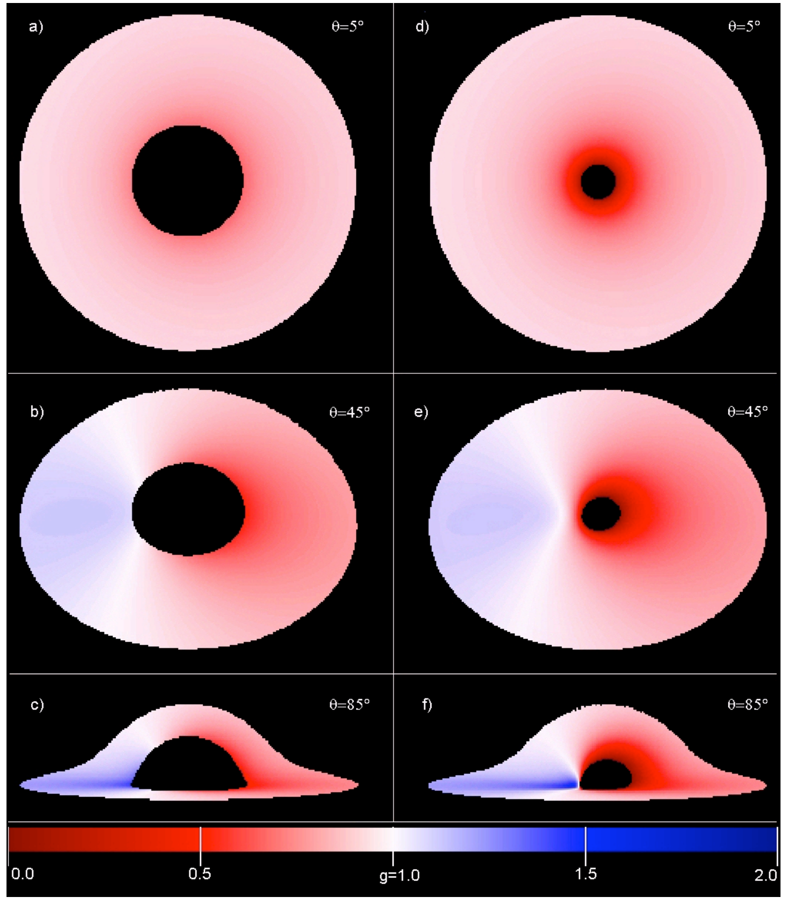
  vs 5 Mpc typical galaxy-galaxy distance.
- Thus, very low density of quasars today.
- Quasars were once common, but then died out.

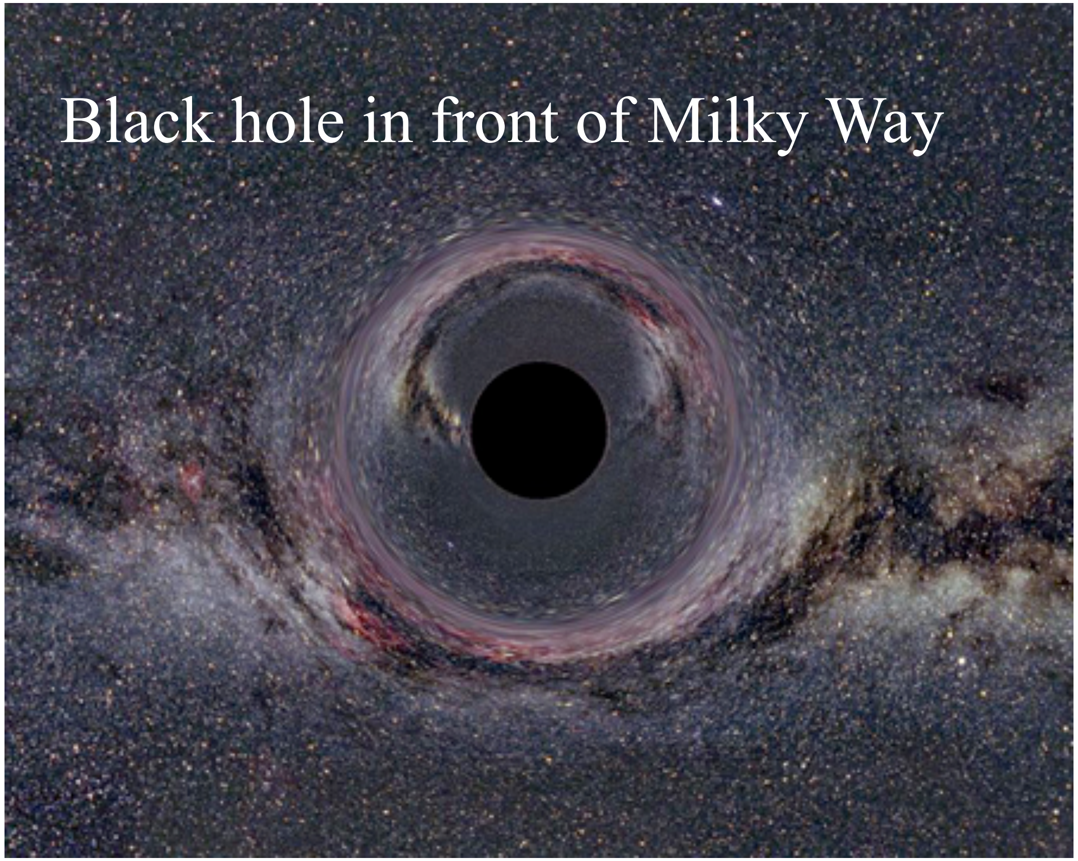
Quasars and Galaxy Formation

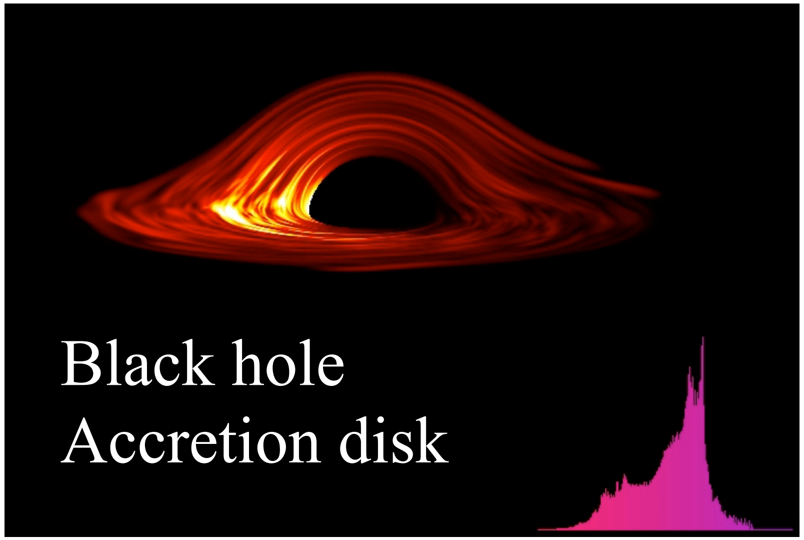
- All large nearby galaxies harbour a SMBH.
  When swallowing stars/gas, this becomes an AGN.
- During a mad feeding frenzy (e.g. triggered by merger with another galaxy) the SMBH may eat 1000 Msun/year. The galaxy temporarily becomes a Quasar, with an AGN 1000 times brighter than the starlight from the galaxy.
- SMBH, AGN activity, and Quasars are important for galaxy formation (e.g. SMBH mass is always a few % of the stellar bulge mass) but full story still being worked out.

Black Hole Lensing Effects

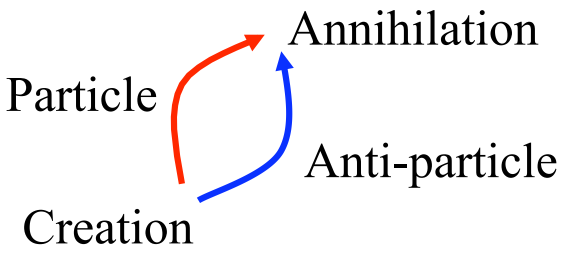
*Light rays bend toward the mass.
*Emerging photons are redshifted.
*Light is beamed and boosted in the direction of relativistic motion.







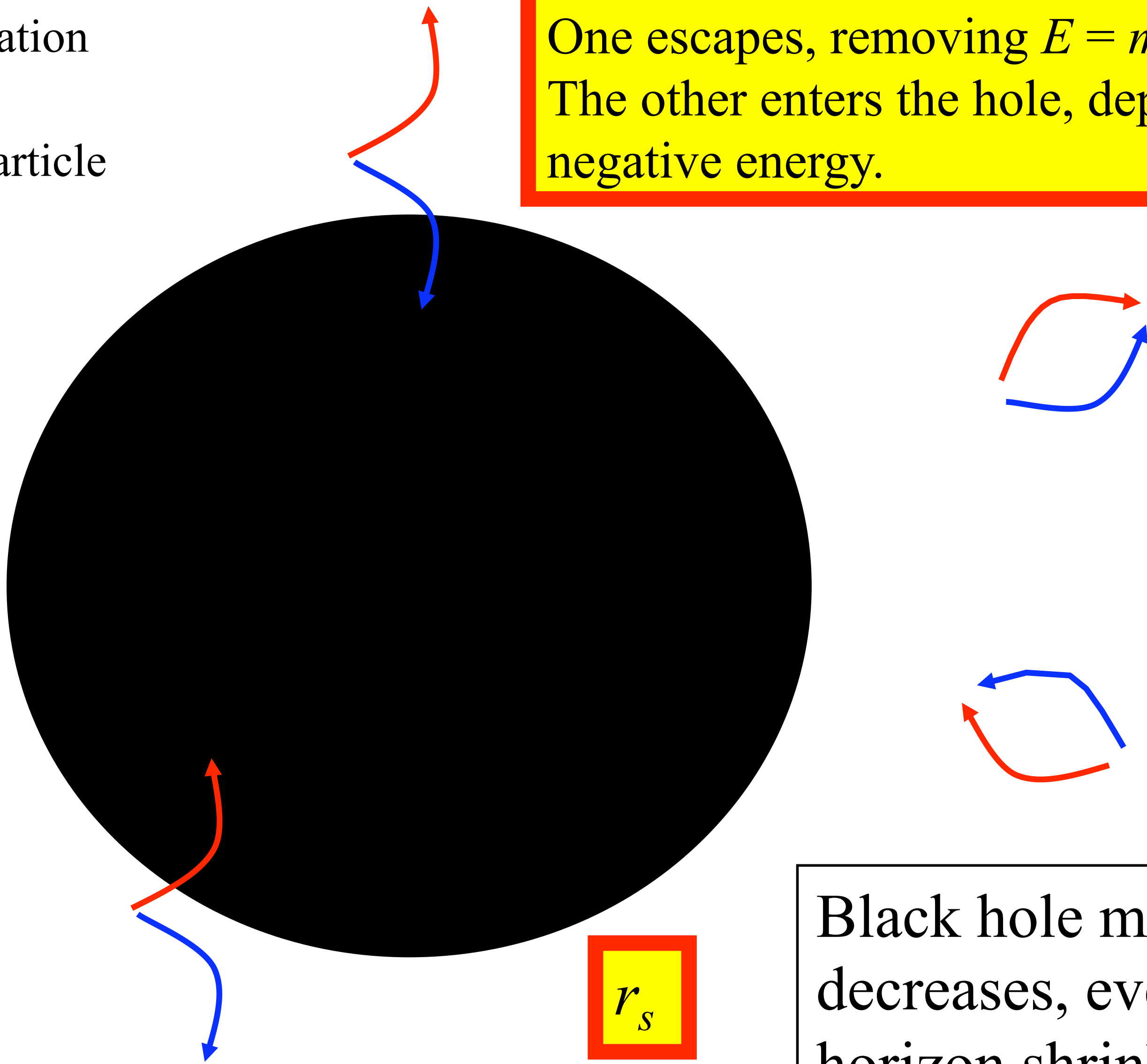
(small) Black Holes Evaporate

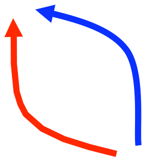


Virtual Pair

Borrow energy briefly from the quantum vacuum:
$\Delta E \; \Delta t \sim h \,/\, 2\,\pi$

One escapes, removing $E = m\,c^2$
The other enters the hole, depositing negative energy.





Black hole mass decreases, event horizon shrinks.

Black Holes Evaporate

- ***Hawking Radiation***: involves gravity (G), relativity (c), thermodynamics (k) and quantum mechanics (h).
- Black holes emit Blackbody radiation with a temperature

$$\boxed{k\,T = \frac{h\,G\,M_{bh}}{4\pi^2 c\, r_s^2} = \frac{h\,c^3}{16\pi^2 G\,M_{bh}}}$$

- Luminosity: $\boxed{L_{bh} = 4\pi\, r_s^2\, \sigma\, T^4}$
- Energy available: $\boxed{E_{bh} = M_{bh} c^2}$
- Evaporation time: $t_{bh} = E_{bh} / L_{bh}$
- $M_{bh} = 10^{15}$ kg (Everest) : $t_{bh} = 15$ billion years
- $M_{bh} = 5\ \mathrm{M_{sun}}$: $t_{bh} = 10^{62}$ years