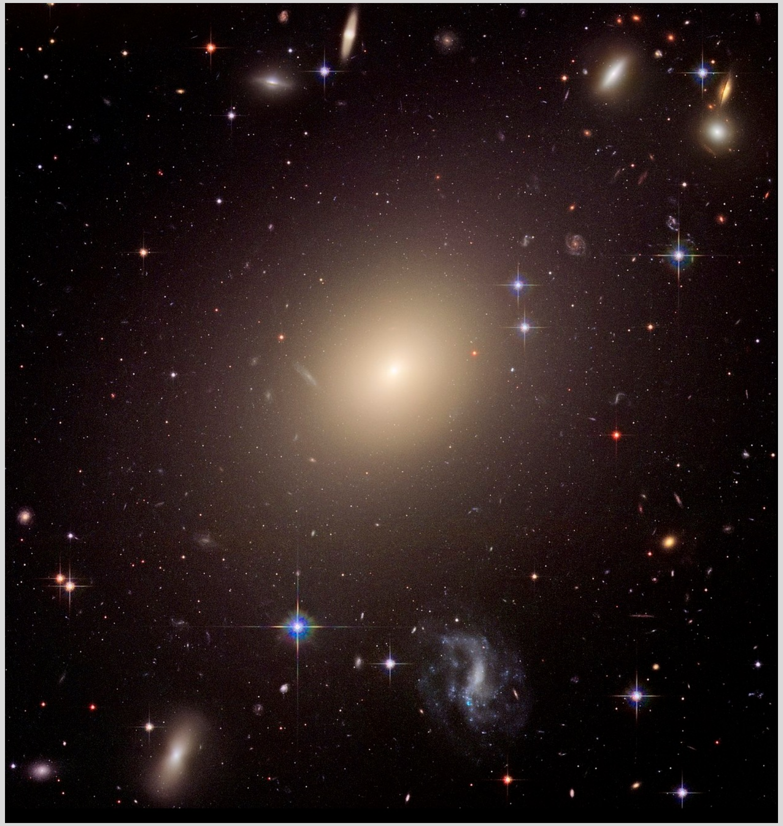
Elliptical galaxies: dynamics and evolution

Stars form from cold gas. Where we see cold gas in galaxies, it is in thin rotating disks. If stars form from that gas, they should also be in disks.

Ellipticals aren’t like that; why are their stars moving so randomly?



Relaxation, or: how are orbits randomized?

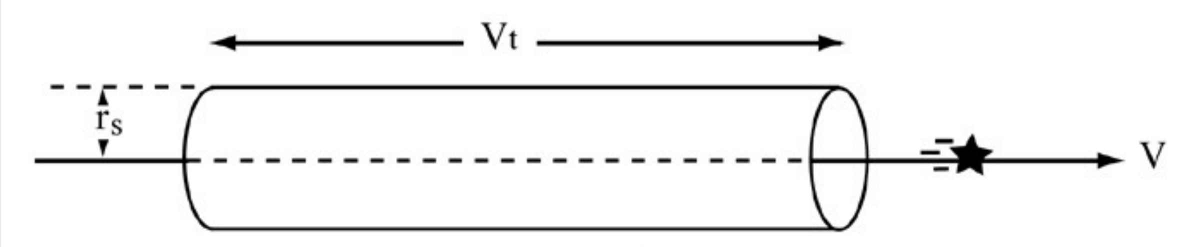
Relaxation: a process by which stars diffuse away from their initial orbits.

One relaxation process is **close encounters of stars**: close enough that the gravitational potential from the star is comparable to the kinetic energy of motion. For two stars of mass m, his gives a scattering radius (r_s) of

$$\frac{Gm^2}{r} \gtrsim \frac{1}{2}mV^2 \quad \Rightarrow \quad r_s \approx \frac{2Gm}{V^2} \approx 1\,AU$$

How often does this happen?

Over a time t, a star in motion will sweep out a cylinder of radius r_s that has a volume $\pi r_s^2 Vt$. If the density of stars per unit volume is given by n, then we would expect one encounter in a time where $n\pi r_s^2 Vt = 1$.



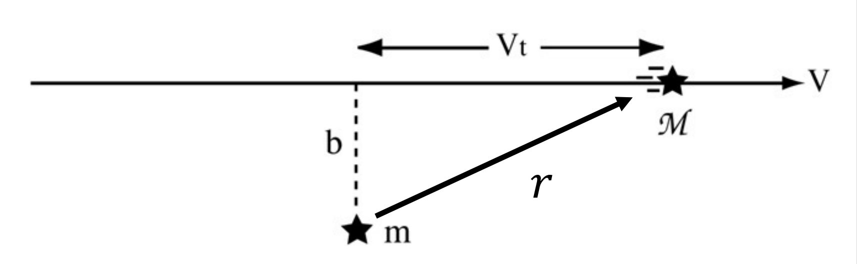
Thus the time between encounters is given by

$$t_s = \frac{1}{n\pi r_s^2 V} = \frac{V^3}{4\pi G^2 m^2 n} \approx 4{\times}10^{12}\,\mathrm{yr}\left(\frac{V}{10\,\mathrm{km/s}}\right)^3 \left(\frac{m}{M_\odot}\right)^{-2} \left(\frac{n}{1\,\mathrm{pc}^{-3}}\right)^{-1}$$

This is much greater ($\approx 300\times$) than the age of the universe, so close encounters do not matter much.

Weak encounters (S&G 3.2.2)

What about the effect of many distant encounters continually nudging the star off its initial orbit? Consider a distant flyby of two stars at a distance b. The perpendicular force is given by



$$\vec{F}_\perp = \frac{GmM}{r^2}\left(\frac{b}{r}\right) = \frac{GmMb}{(b^2+V^2t^2)^{3/2}} = M\frac{d\vec{V}_\perp}{dt}$$

Integrate this over time to get

$$\Delta V_\perp = \frac{1}{M}\int_{-\infty}^{\infty}\vec{F}_\perp(t)dt = \frac{2Gm}{bV}$$

So the star is deflected through a (small) angle $\alpha = \frac{\Delta V_\perp}{V} = \frac{2Gm}{bV^2}$

Over time, the star will experience many weak deflections, which gives rise to a squared velocity change of

$$\langle \Delta V_\perp{}^2 \rangle = \int_{b_{min}}^{b_{max}} \boxed{nVt}\,\boxed{\left(\frac{2Gm}{bV}\right)^2}\,\boxed{2\pi b\, db} = \frac{8\pi G^2 m^2 n t}{V}\boxed{\ln\left(\frac{b_{max}}{b_{min}}\right)}$$

number of encounters
scattering per encounter
probability of encounter
the "Coulomb logarithm"

$$\ln\left(\frac{b_{max}}{b_{min}}\right) \equiv \ln\Lambda$$

Relaxation time: where $\langle \Delta V_\perp{}^2 \rangle = V^2$. So

$$t_{relax} = \frac{V^3}{8\pi G^2 m^2 n \ln\Lambda} = \frac{2\times10^{12}\ \mathrm{yr}}{\ln\Lambda}\left(\frac{V}{10\ \mathrm{km/s}}\right)^3\left(\frac{m}{M_\odot}\right)^{-2}\left(\frac{n}{1\ \mathrm{pc}^{-3}}\right)^{-1}$$

Weak encounters (S&G 3.2.2)

$$t_{relax} = \frac{2\times10^{12}\ \mathrm{yr}}{\ln\Lambda}\left(\frac{V}{10\ \mathrm{km/s}}\right)^3\left(\frac{m}{M_\odot}\right)^{-2}\left(\frac{n}{1\ \mathrm{pc}^{-3}}\right)^{-1}$$

So what about this pesky Coulomb logarithm?

$$\ln\Lambda \equiv \ln\left(\frac{b_{max}}{b_{min}}\right)$$

b_{min}: close scattering radius, $r_s \approx 1AU$
b_{max}: size of the stellar system. ≈ 300 pc – 30 kpc, depending on what kind of galaxy (dwarf, giant?)

so $\ln\Lambda \approx 18 - 22$. Exact value doesn't matter. Diffusion of orbits will still be very slow, occurring over 100 billion year timescales. Again, this is $\approx 10\times$ the age of the universe.

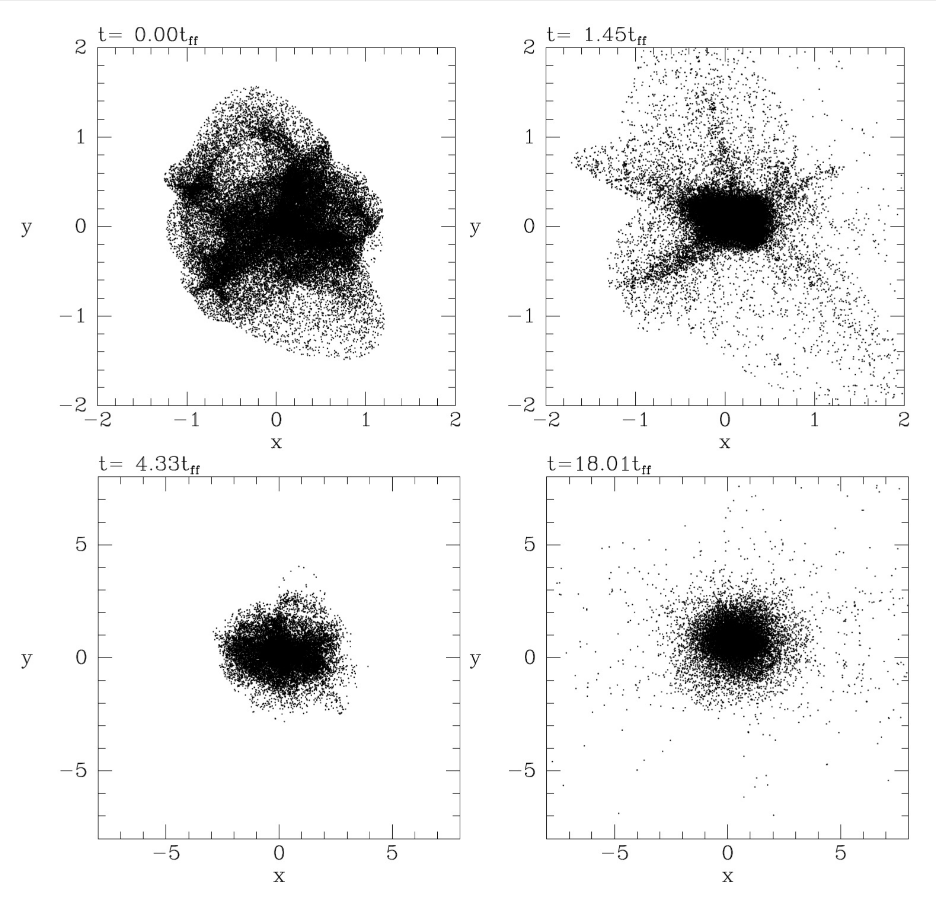
Upshot: In galaxies, scattering of stars by other stars are (statistically) unimportant. **Galaxies are "collisionless".**

So why are elliptical galaxies so disordered?

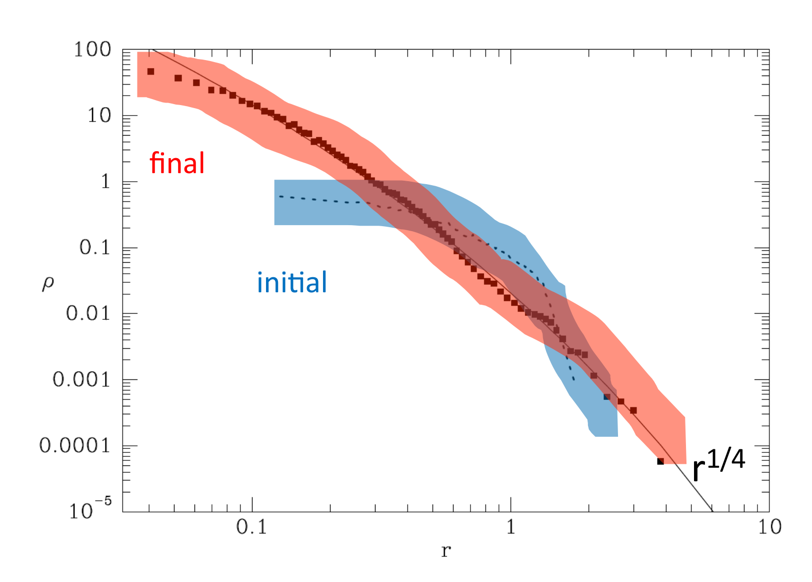
Violent relaxation

All these calculations rely on conservation of energy along the orbit. But if the potential well changes with time, energy cannot be conserved, because $E = \frac{1}{2}v^2 + \phi(\vec{x}, t)$. Changing potential ⇒ changing energy ⇒ randomization of orbits

Look at simulations of gravitational collapse. Start with a spherical roughly constant density distribution of stars, perturb them slightly, and then let gravity do its thing.



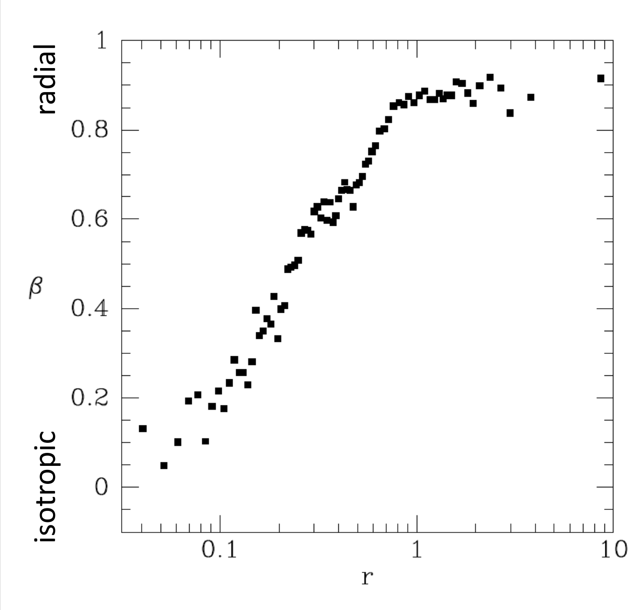
Density profile



↑ $r^{1/4}$-like density profile...

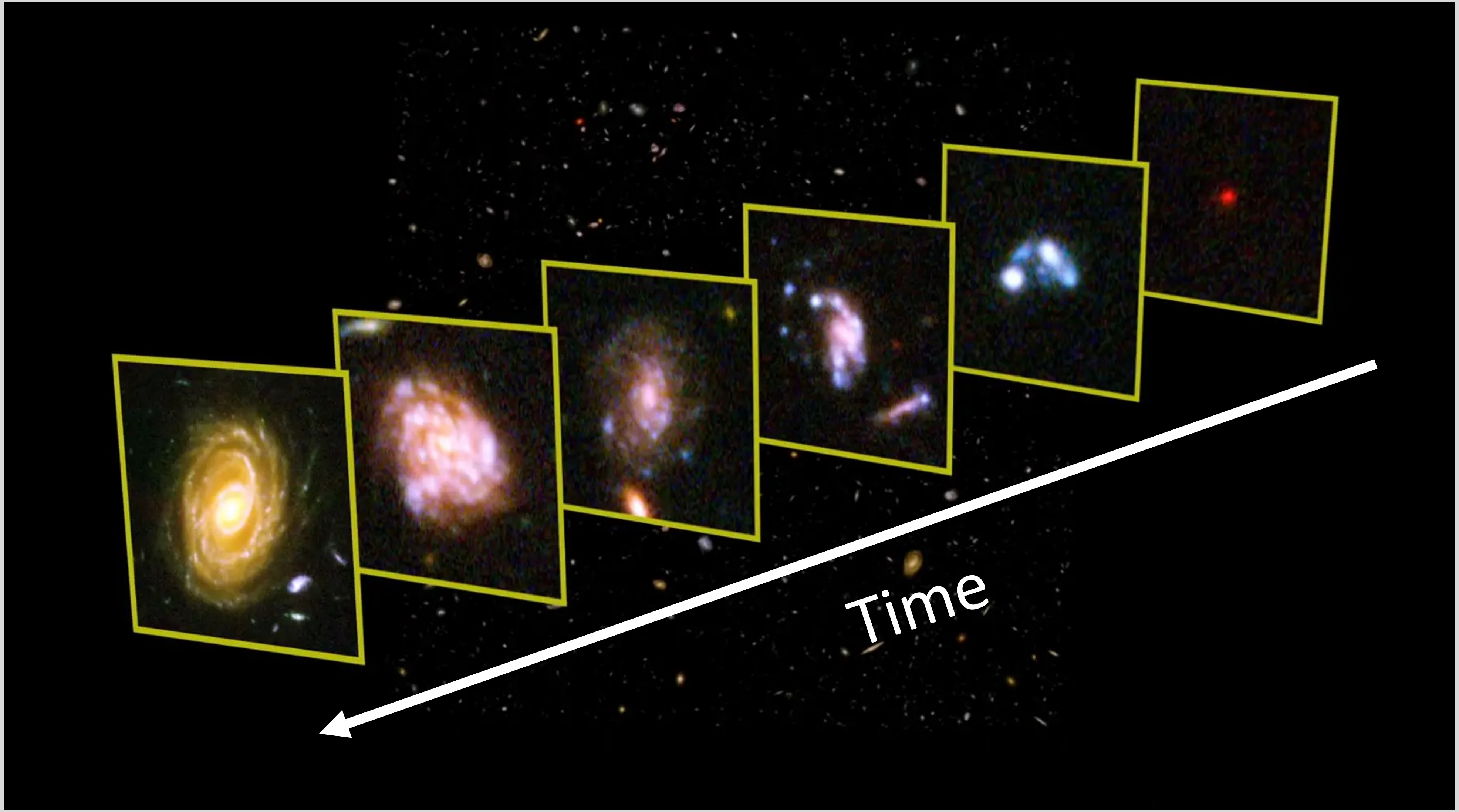
...with radially-biased anisotropy →

Velocity anisotropy



Violent relaxation

Hierarchical growth of galaxies (small things mergering to make big things) is one example of the violent relaxation process.



Violent relaxation

Galaxy mergers are another example of the violent relaxation process.

Black Holes

Centers of galaxies often have supermassive black holes ($M_{BH} \sim 10^6 - \text{few} \times 10^9 M_\odot$). How can we detect these objects?

"Sphere of Influence": where the circular velocity around a black holes is comparable to the velocity dispersion of the surrounding stars:

$$V_{c,BH}^2 = \frac{GM_{BH}}{r} \approx \sigma^2$$

or

$$r_{BH} \approx \frac{GM_{BH}}{\sigma^2} \approx 45 \left(\frac{M_{BH}}{10^8 M_\odot}\right) \left(\frac{\sigma}{100\ \text{km/s}}\right)^{-2} \text{pc}$$

Inside this radius, the gravitational influence of the black hole should begin to dominate stellar velocities, and we should see a signature in the kinematics.

Example: NGC 1399 (Fornax)

- $\sigma = 350$ km/s, $M_{BH} = 10^9 M_\odot, r_{BH} \approx 36$ pc.
- At d=20 Mpc, this is an angular size of 0.4 arcsec.
- Need Hubble or ground-based adaptive optics!

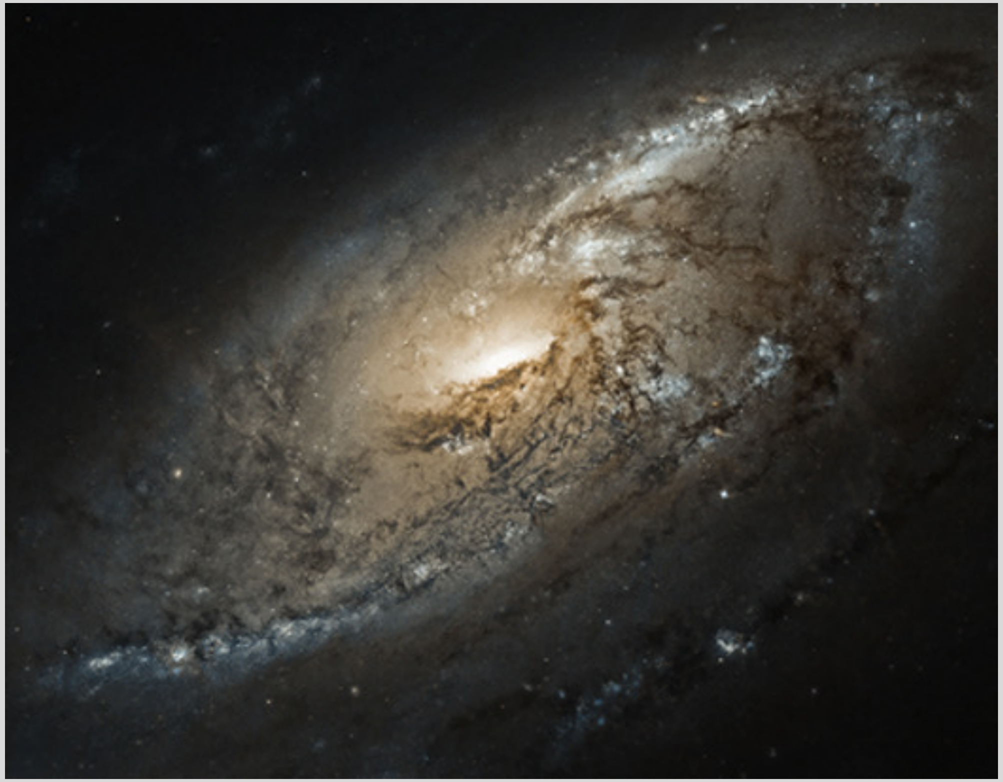
Measure via stellar kinematics

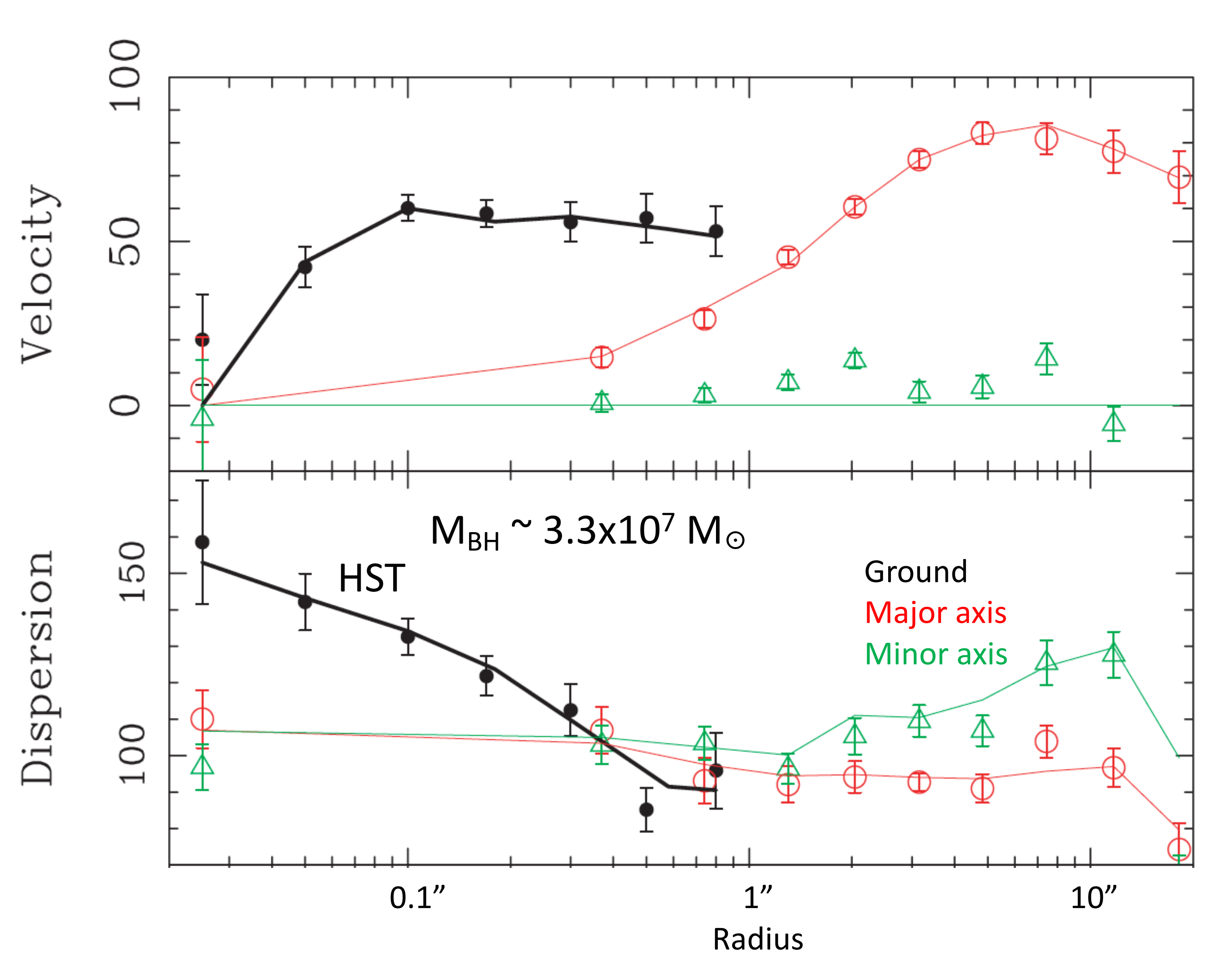
NGC 4258 Siopis+09

Rising velocity dispersion near center.

Must be careful to distinguish between gravitational effects of a black hole and the signature of radial anisotropy.

NGC 4258



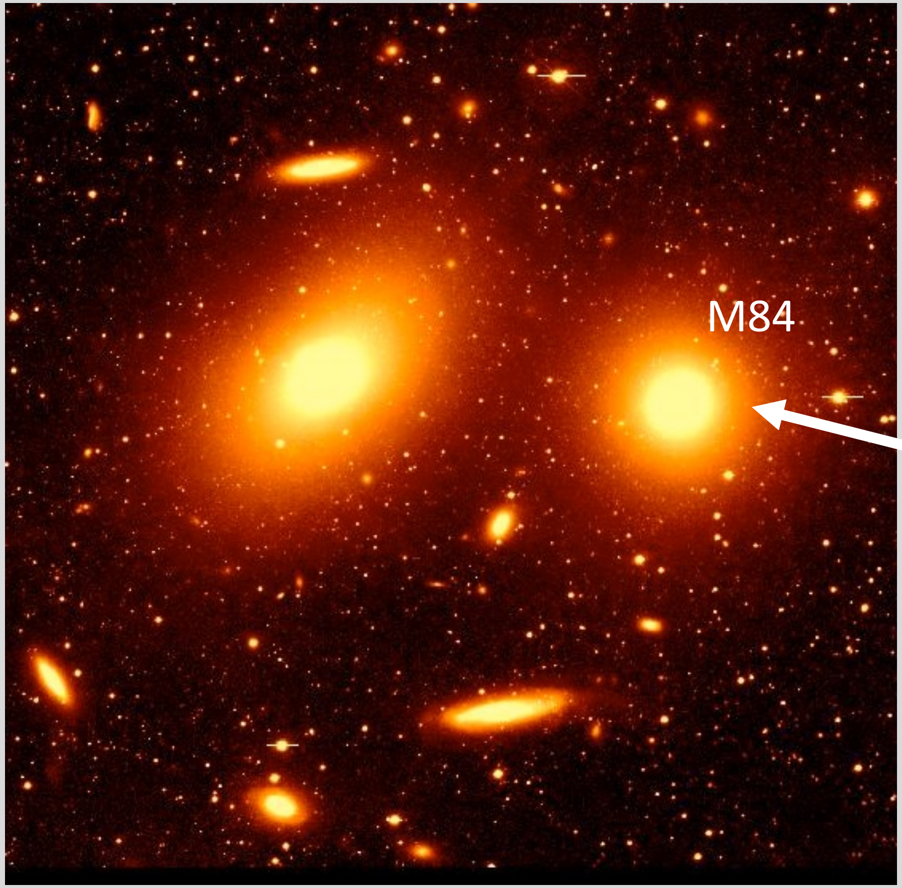


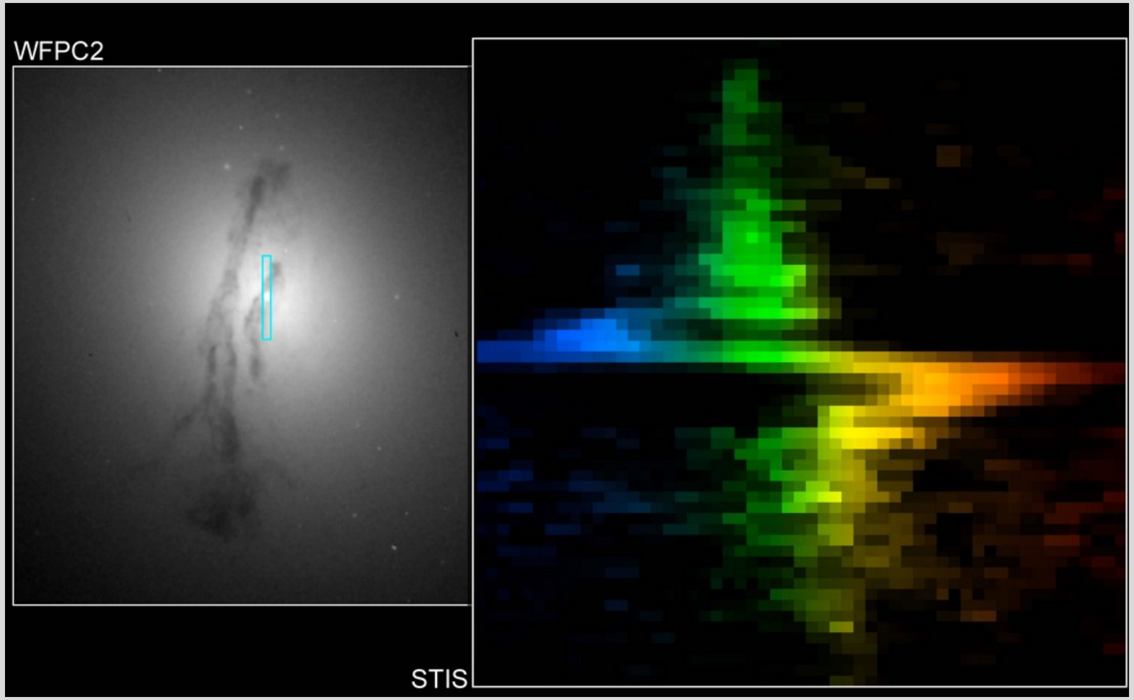
Note logarithmic scale on radius!

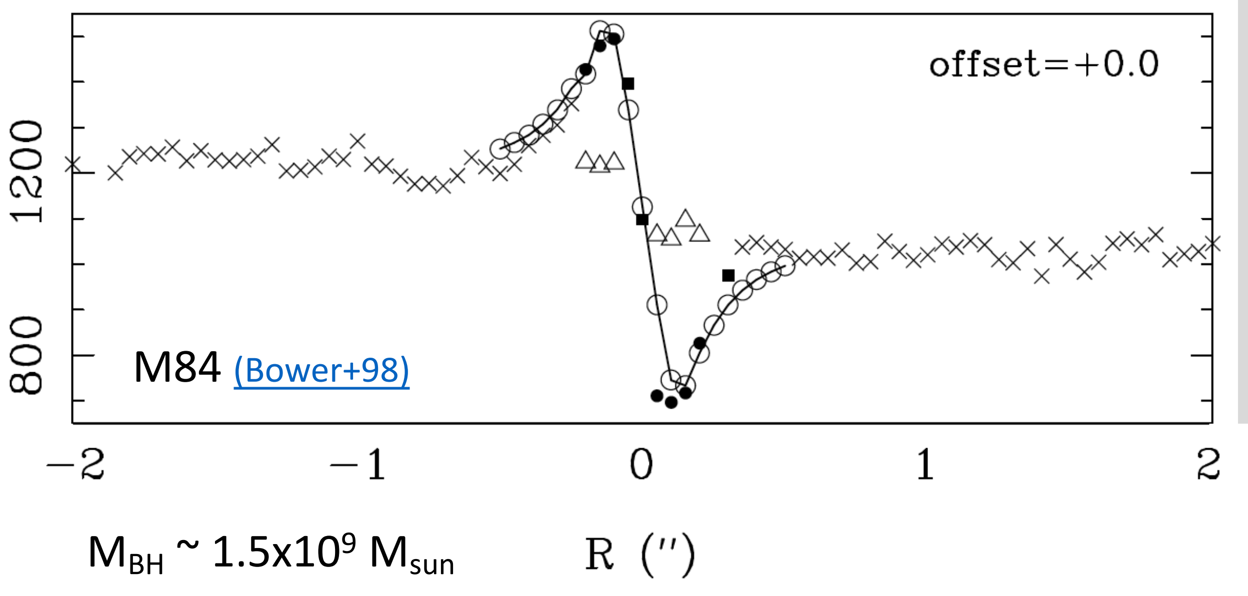
Measure via gas kinematics

Gas orbiting around the black hole shows rising circular velocity near center. *(Note: this is on scales much larger than the BH accretion disk!)*

Have to factor in the inclination of the disk.







Black Holes

Correlation with luminosity:

$$M_{BH} \sim L_{K,bulge}^{1.2}$$

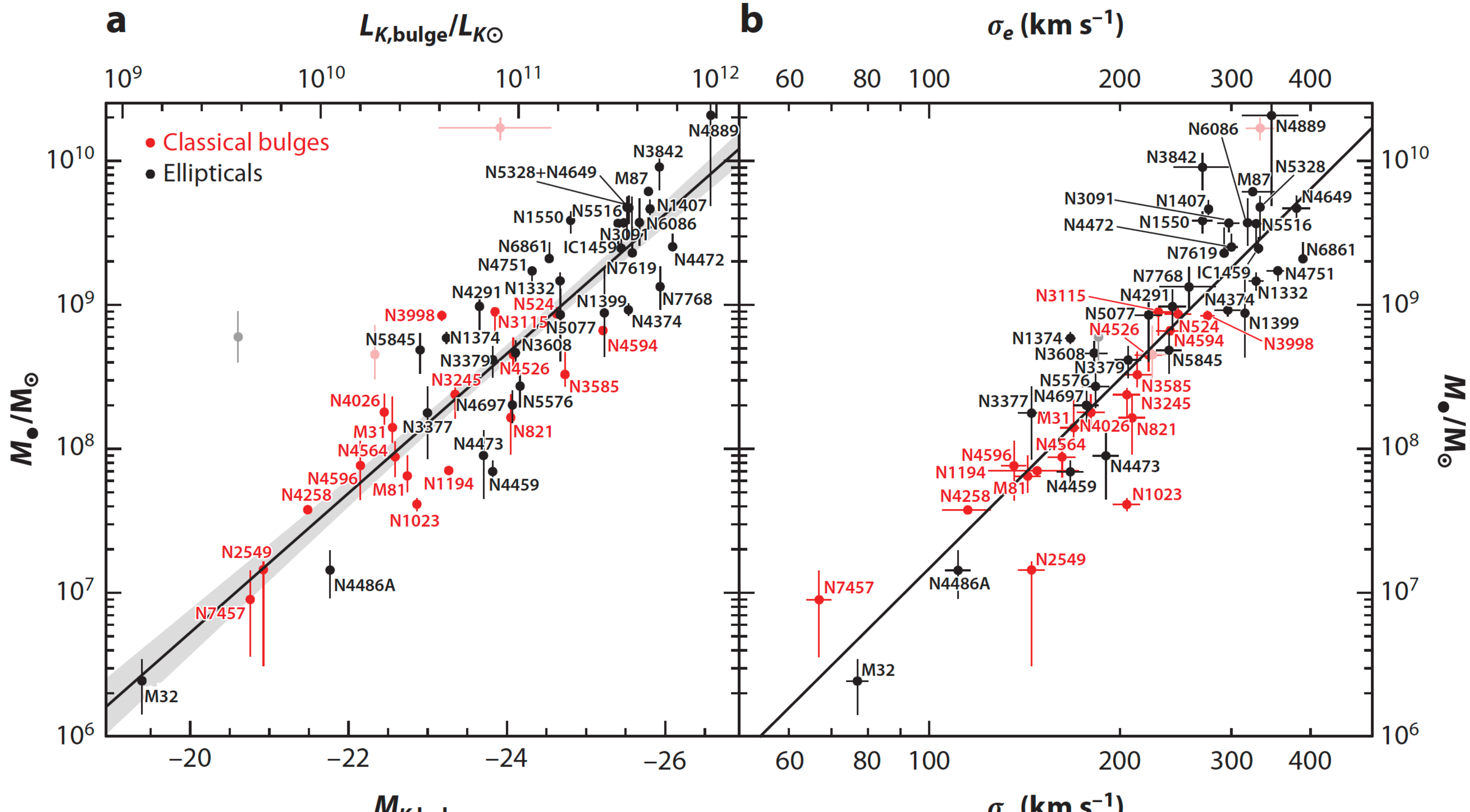
Correlation with velocity dispersion:

$$M_{BH} \sim \sigma_e^{4.4}$$

Black hole mass strongly tied to bulge mass, where "bulge" means

- spiral bulge, or
- elliptical galaxy

Both relations show a scatter in $\log(M_{BH})$ of ~ 0.3, or a factor of two in mass.

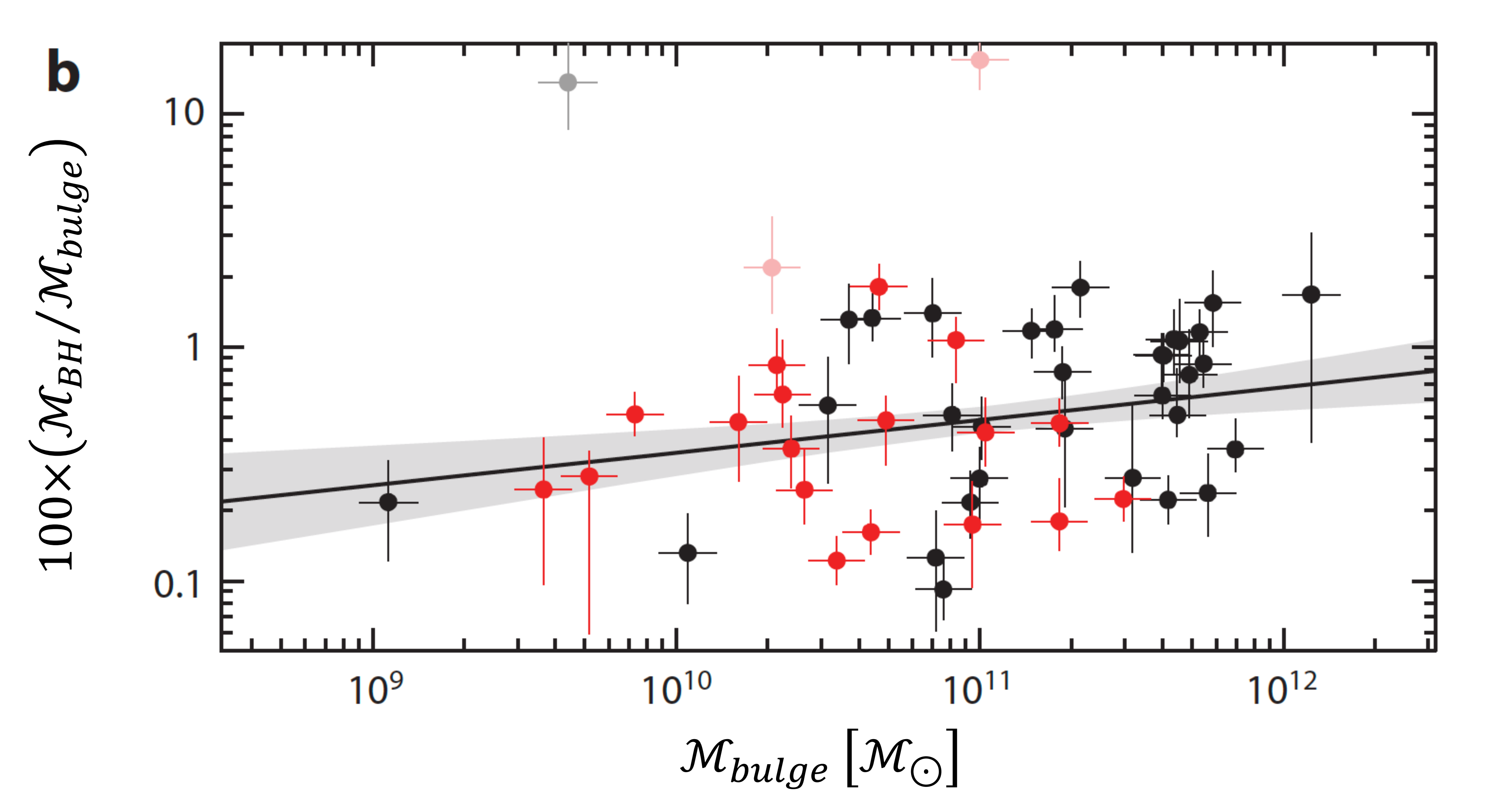


Kormendy & Ho, ARAA, 2013

Black Holes

Kormendy & Ho, ARAA, 2013

Black hole masses are generally **0.1–1%** of the “bulge” mass.



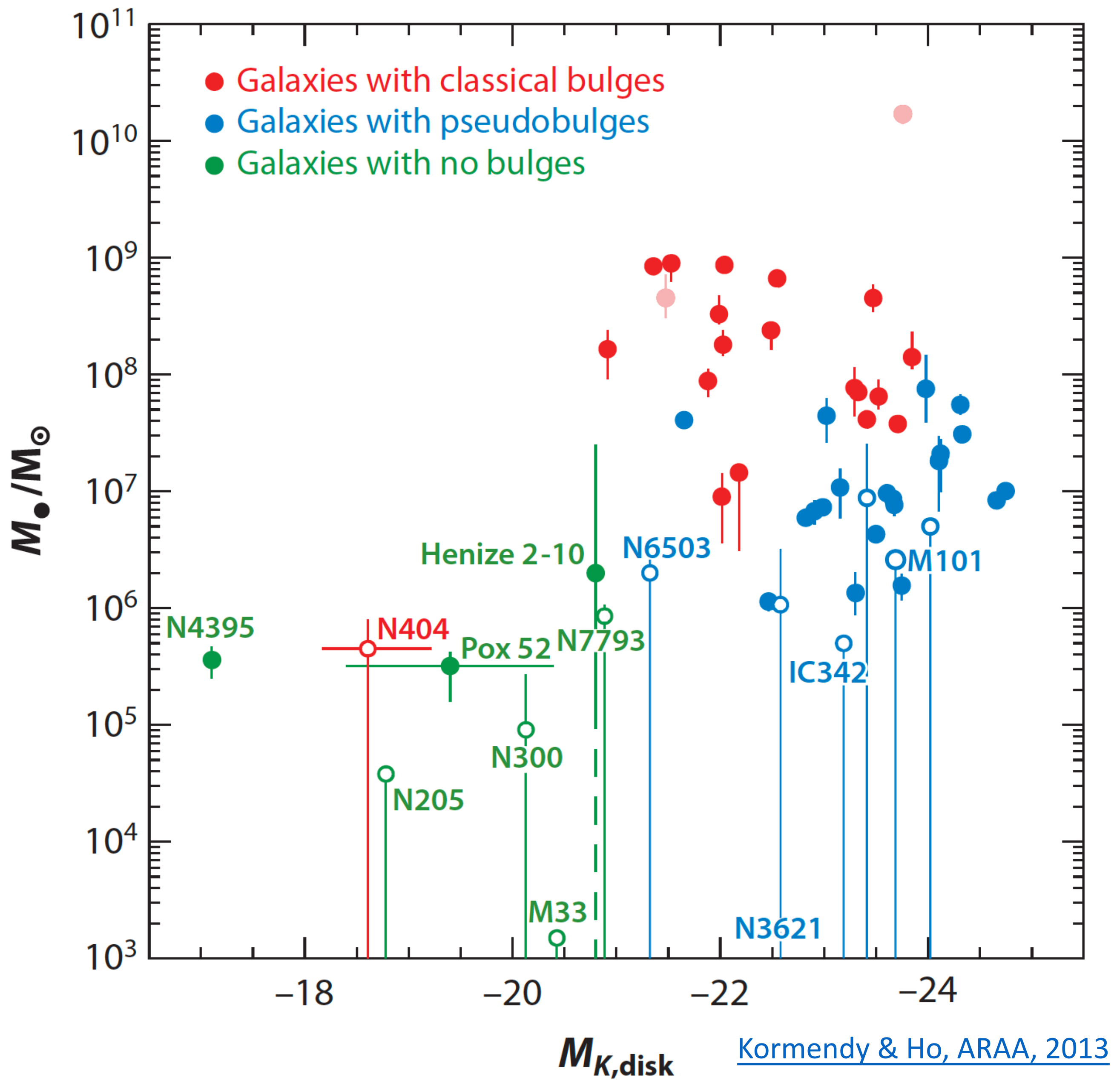
Black Holes

Black hole mass ***not*** coupled to disk mass.

So the coupling is not with the properties of the galaxy, but the properties of the bulge.

“**coevolutionary**”: whatever forms/grows the bulge also forms/grows the black hole.

Disks are a passive player in this evolution.

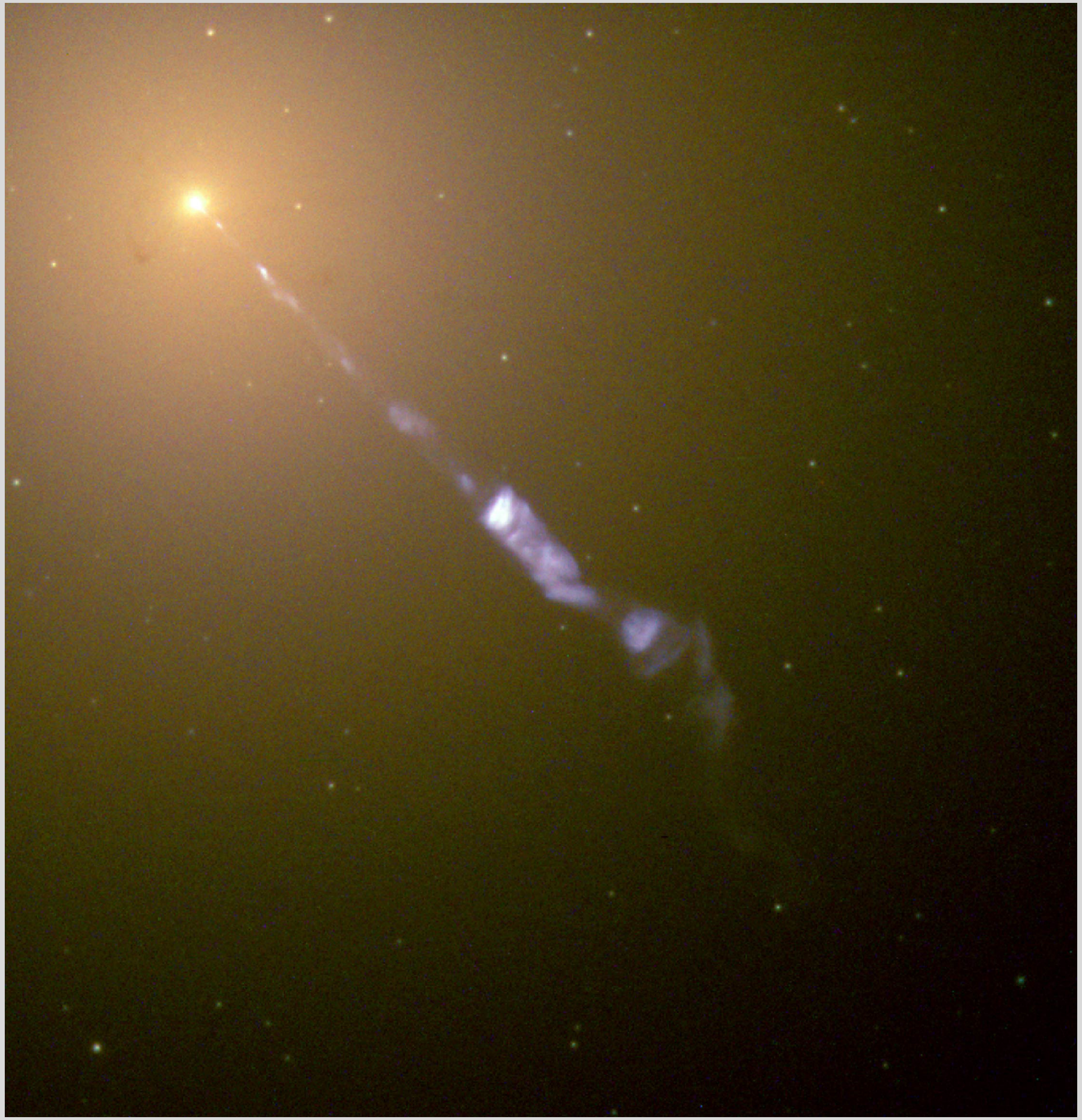


Kormendy & Ho, ARAA, 2013

remember for spirals:

- “classical bulge” = $r^{1/4}$-ish spheroidal bulge
- “pseudobulge” = disky/exponential bulge

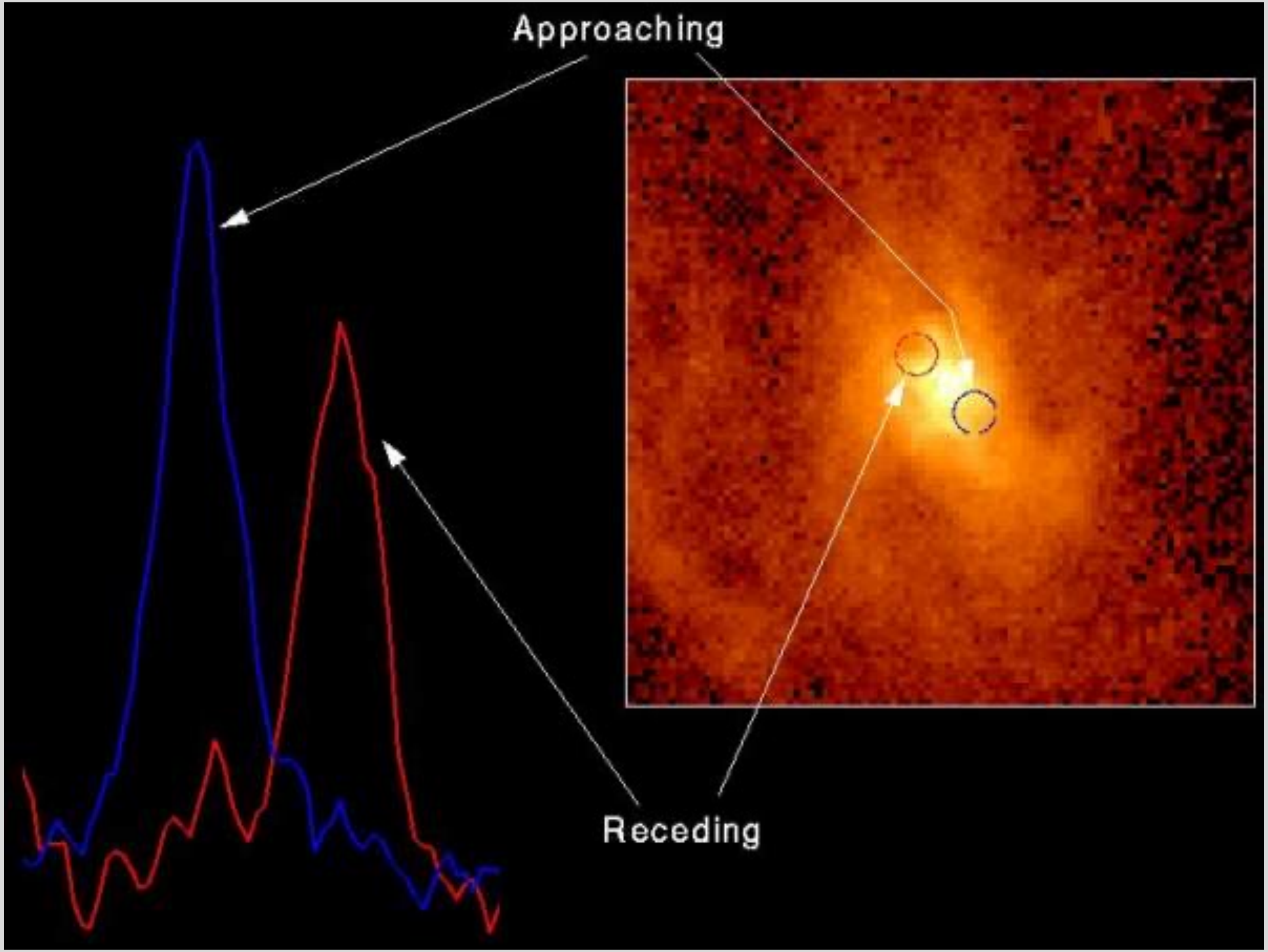
M87
Virgo elliptical
D=16.5 Mpc



M87

Gas kinematics near the center:

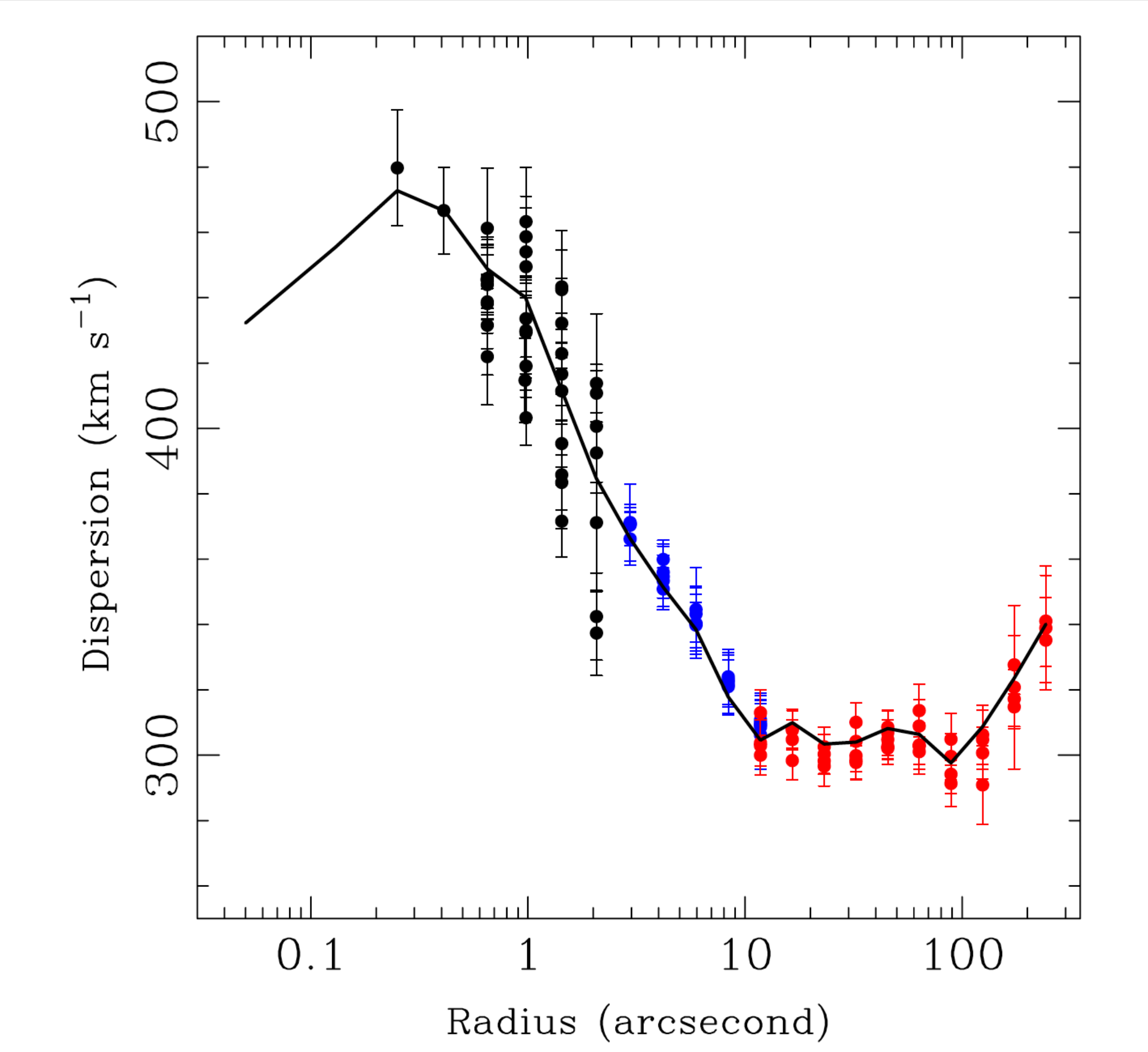
$M_{BH} \approx 3.5\text{x}10^9\ M_{\odot}$ (Walsh+13)



M87

Stellar kinematics near the center:

$M_{BH} \approx 6.6 \times 10^9 \, M_\odot$ (Gebhardt+11)



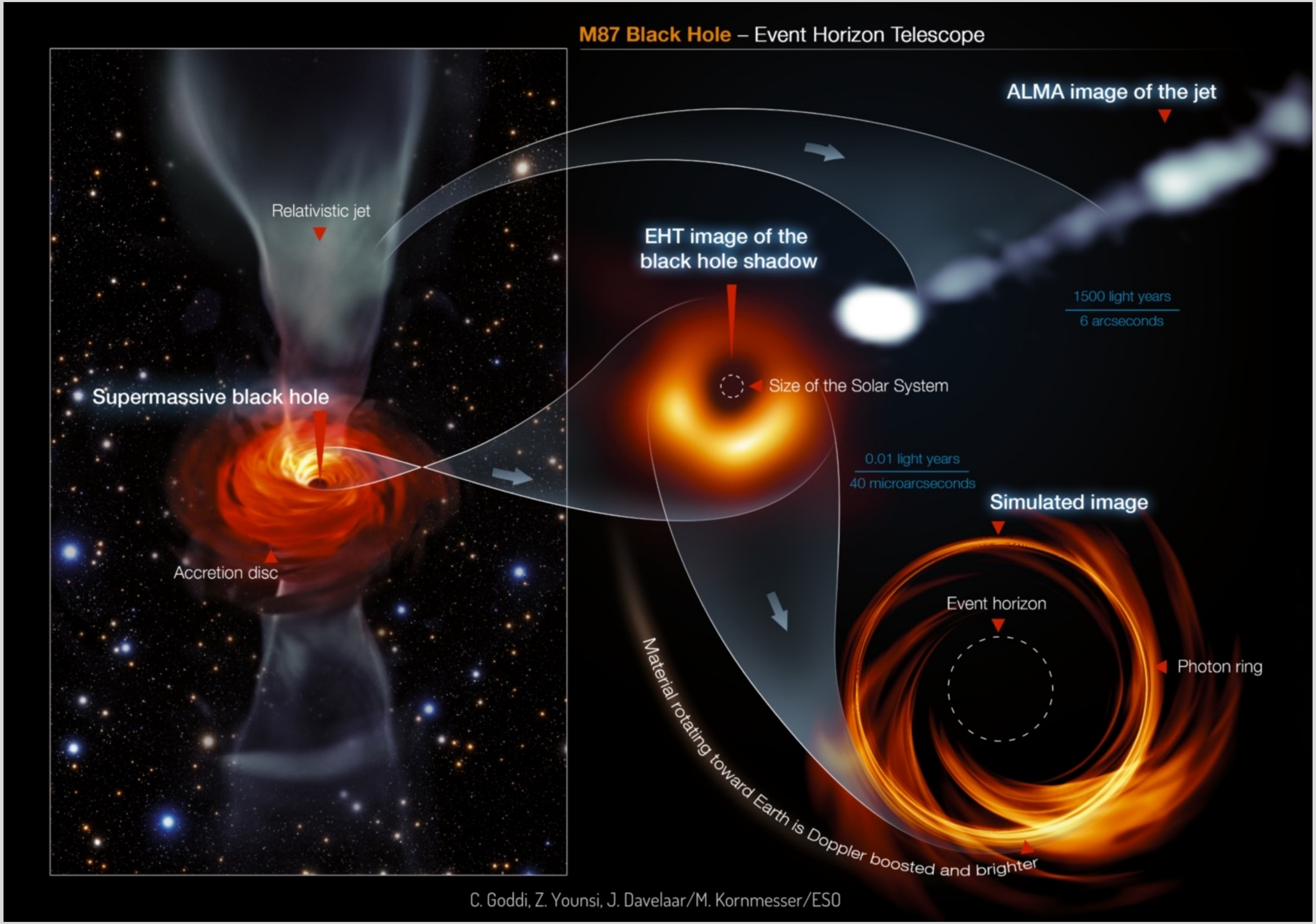
M87

The event horizon of the black hole is extremely small at the distance of M87:

$$R_s \equiv \frac{2GM_{BH}}{c^2}$$
$$\approx 3-6\times10^{-4}\text{ pc}$$
$$\theta = 4-8\times10^{-6}\text{ arcsec}$$

Event Horizon Telescope: world-wide array of radio telescopes doing radio interferometry of the hot gas around the black hole.

[EHTC 2019]



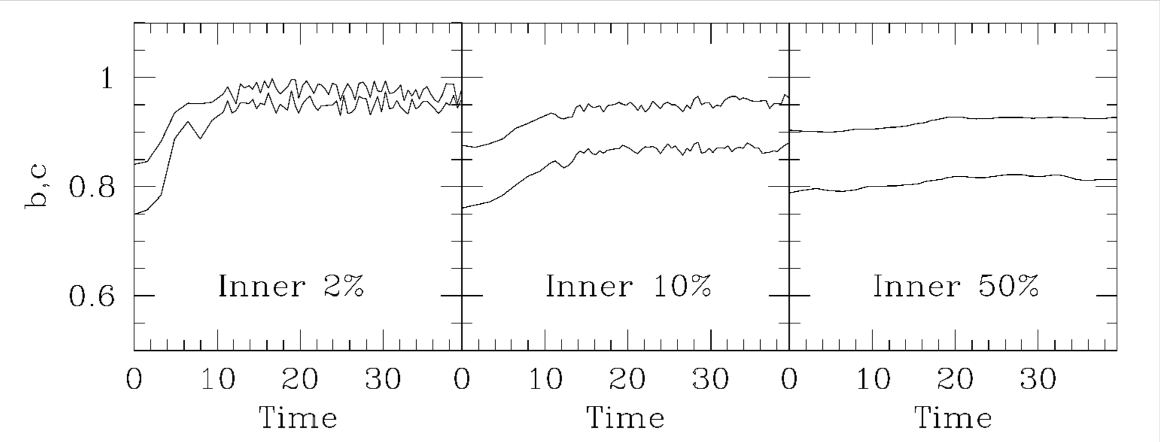
The effect of black holes

Black holes accrete matter and drive active galactic nuclei (AGN). They also inject energy into the interstellar medium via photoionization and shocks. But what do they do to the distribution of stars?

Black holes scatter stars off box orbits: erode triaxiality.

Simulation 👉: Grow 1% mass black hole in nucleus of triaxial galaxy model (a=1, b=0.85, c=0.75). Box orbits become chaotic and isotropic. Inner regions get rounder. Important for nucleus, less so for bulk of galaxy.

Holley-Bockelmann +02



Binary black holes: "scour nucleus", reduce central density.

Stars interact with binary black hole, gain energy, get ejected from nucleus. Black hole binary loses energy, binary gets closer ("hardens") eventually merges.

Question: Why would there be a binary black hole?

Simulation 👉: Multiple BH binary events.

Merritt 06