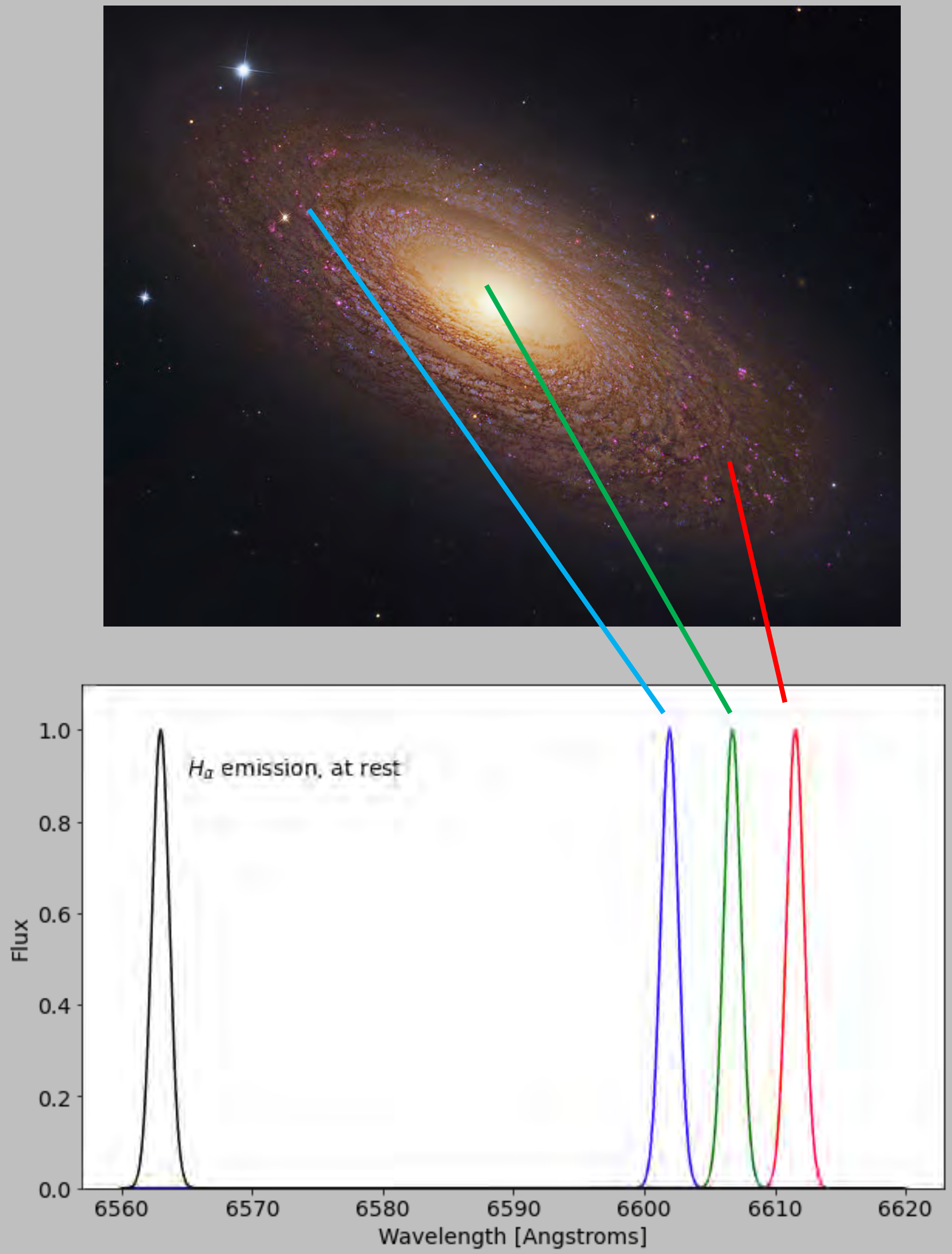
Kinematics: Spiral Galaxies vs Elliptical Galaxies

Spiral Galaxies: Lots of cold gas and star formation.

We can use emission lines from HII regions or 21-cm emission from neutral hydrogen gas to get Doppler shifts and velocities, and measure rotation curves.

Emission line wavelengths:

- Galaxy center: shifted due to the overall motion of the galaxy towards or away from us
- Edges: shifted relative to center, showing rotation



Compare circular motion (V_c) to velocity dispersion (σ). For the Milky Way typical values give

$$\frac{V_c}{\sigma} = \frac{220}{30} \approx 7$$

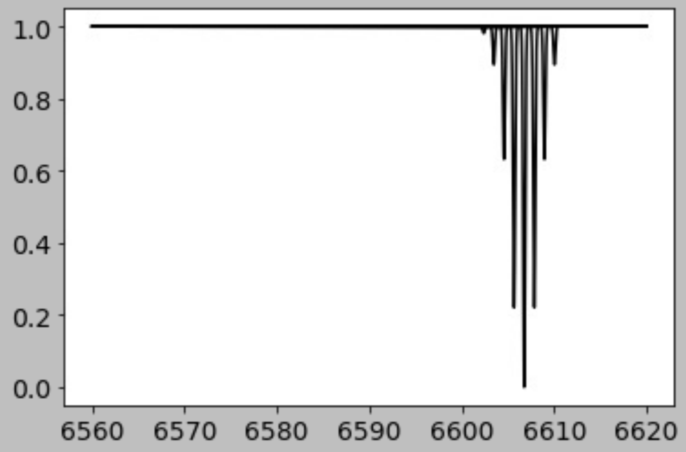
So most of the galaxy's motion is bulk motion (rotation) not random motion (dispersion). We call this a **dynamically cold** galaxy.

Kinematics: Spiral Galaxies vs Elliptical Galaxies

Elliptical Galaxies: Very little cold gas and star formation.

We use absorption lines in the integrated spectra to show us the distribution of stellar velocities. Along any line of sight through the galaxies, the spread in velocities broadens the absorption lines.

Individual stars



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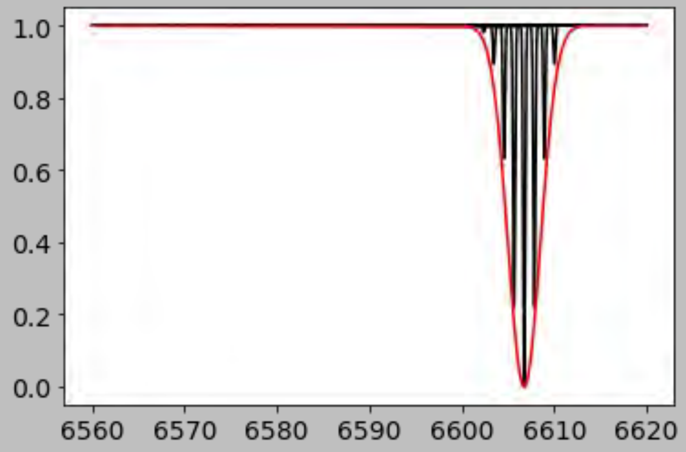
Individual stars…
blend together…



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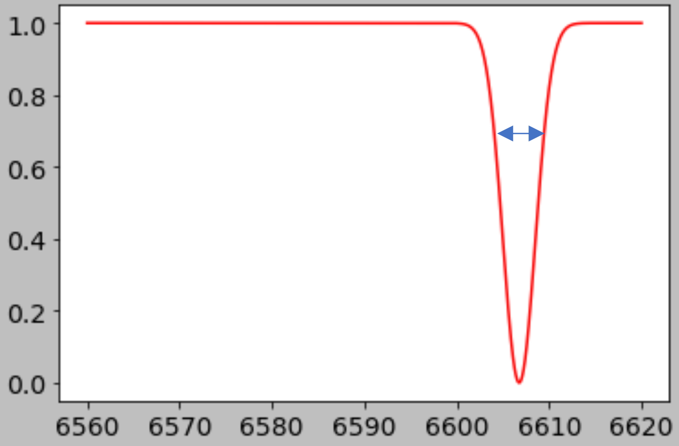
Individual stars…
blend together…
to make broader
absorption lines.

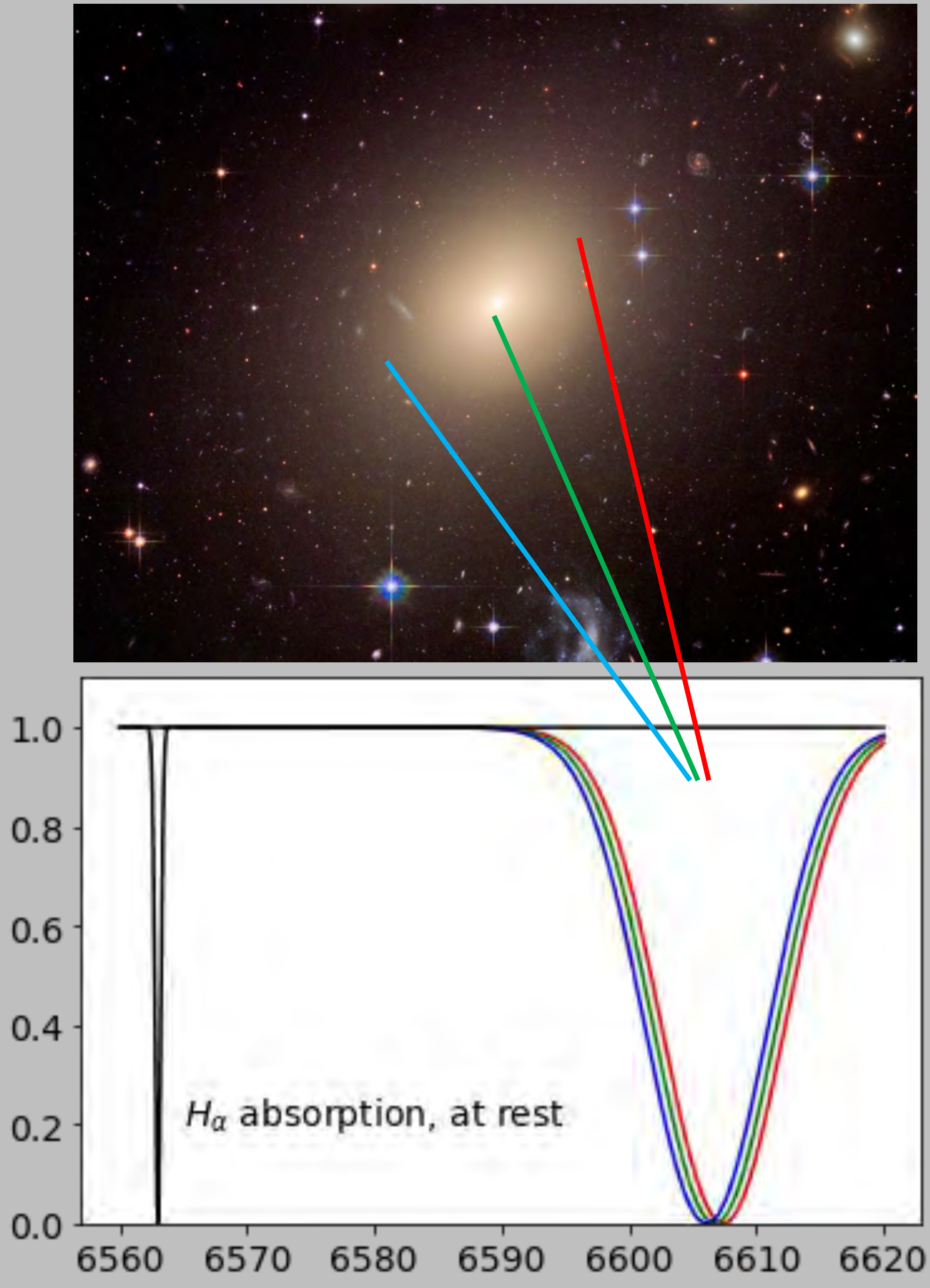
Width shows
velocity dispersion.



Ellipticals typically large velocity dispersion and low rotation:

$$\frac{V_c}{\sigma} = \frac{35}{350} \approx 0.1$$

So most of the galaxy's motion is random motion (dispersion) not bulk rotation. We call this a **dynamically hot** galaxy.



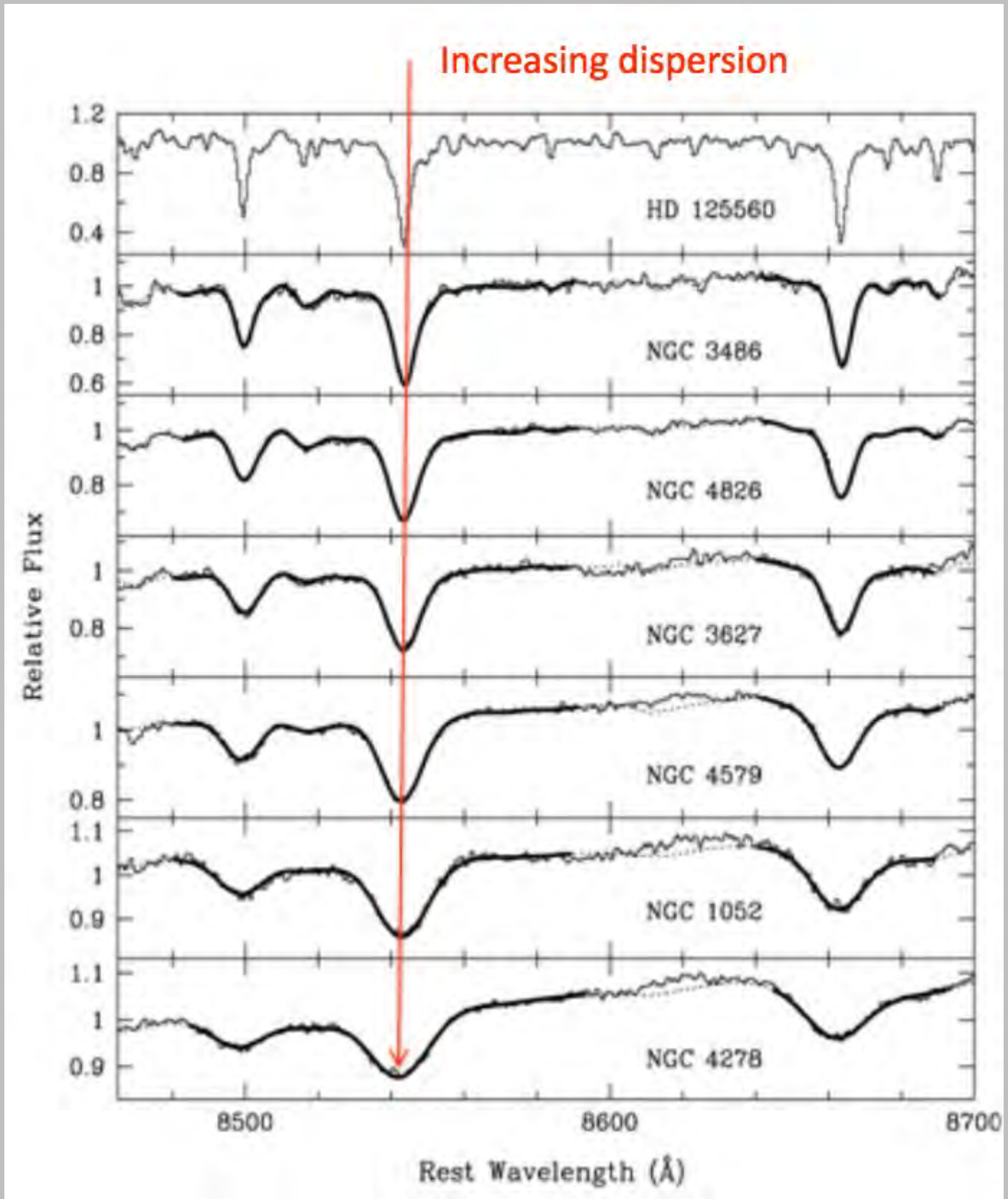
Broadening and velocity dispersion

Individual Red Giant Star

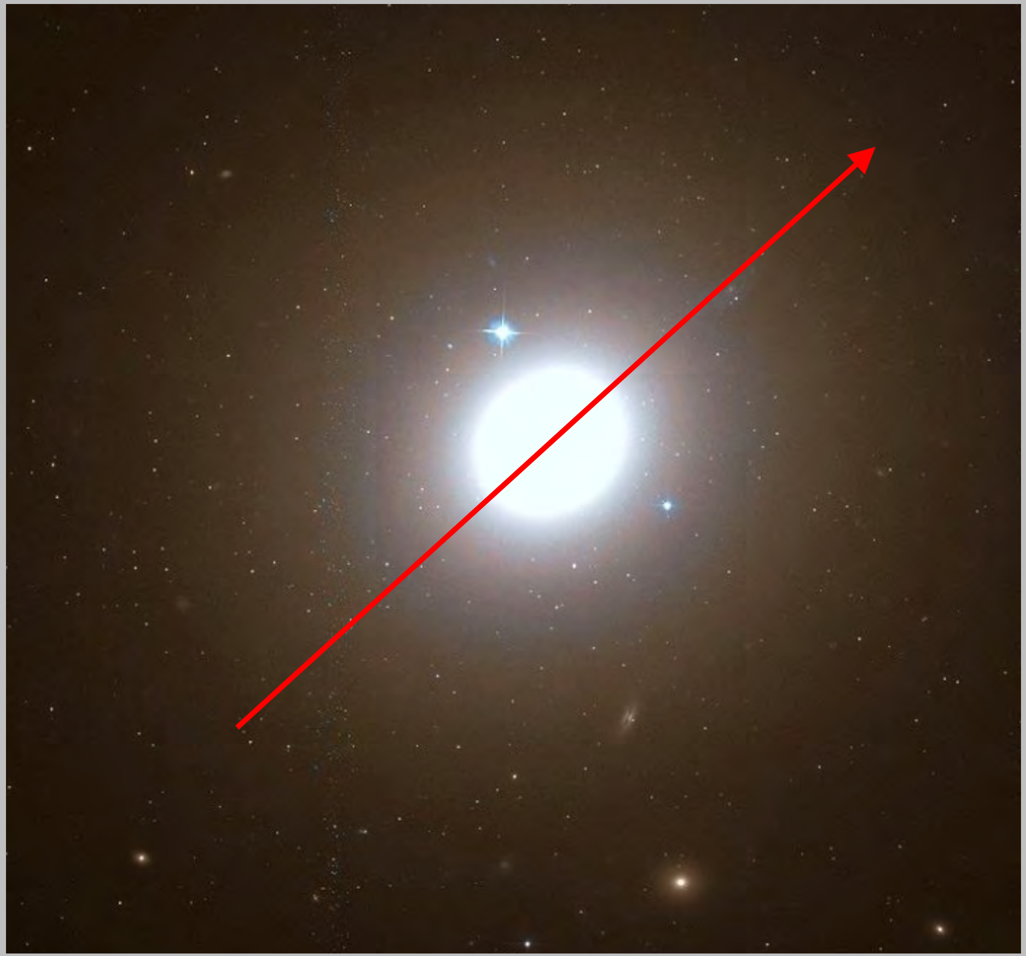
Absorption lines are broadened in wavelength, showing that ellipticals typically have low rotation (V_c) and large velocity dispersion (σ).

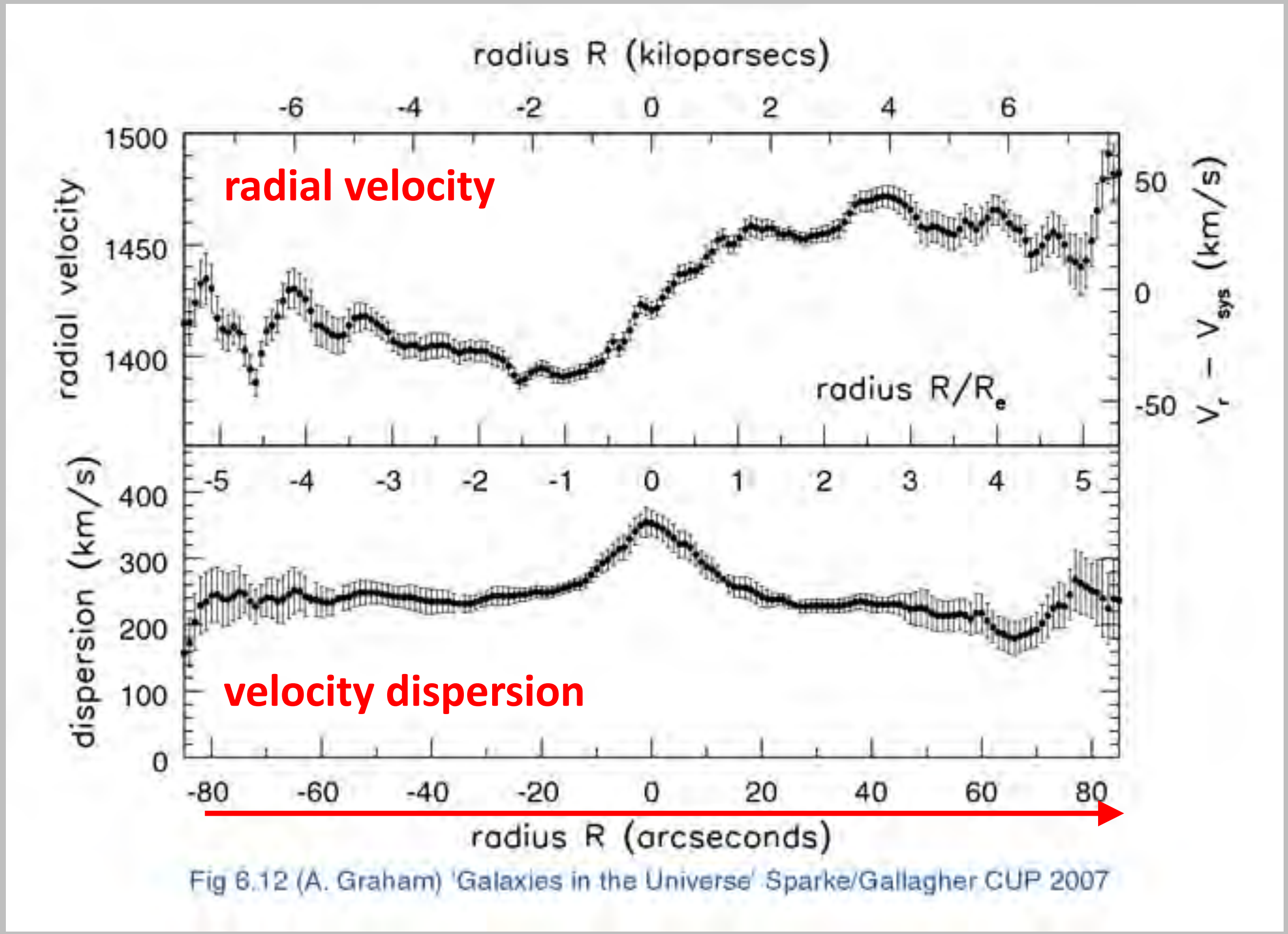
Elliptical galaxies are "dynamically hot" galaxies, with $V_c/\sigma < 1$.

Galaxies



Elliptical Galaxies: Major Axis Kinematics





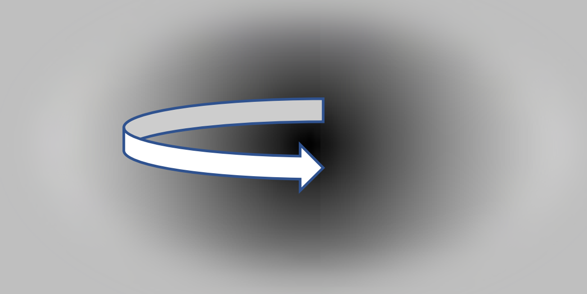
NGC 1399: $\sigma \approx 350$ km/s, $V_c \approx 35$ km/s, $V_c/\sigma \approx 0.1$

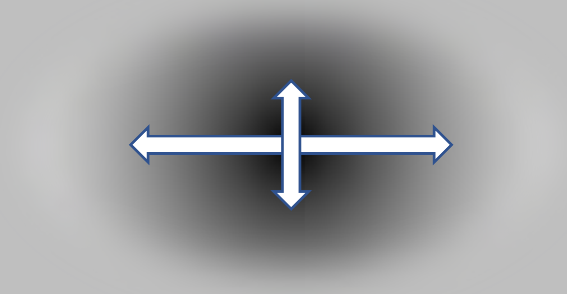
(Compare to Milky Way disk: $\sigma \approx 30$ km/s, $V_c \approx 220$ km/s, $V_c/\sigma \approx 7.3$)

Elliptical Galaxies: Rotation vs Dispersion

Why are ellipticals flattened? Two possibilities:

- **Rotational support**: ellipticals are flattened due to relatively large spin (higher V_c/σ)
- **Pressure support**: ellipticals have higher velocity dispersion along one (or more) axes: $\sigma_x > \sigma_y$

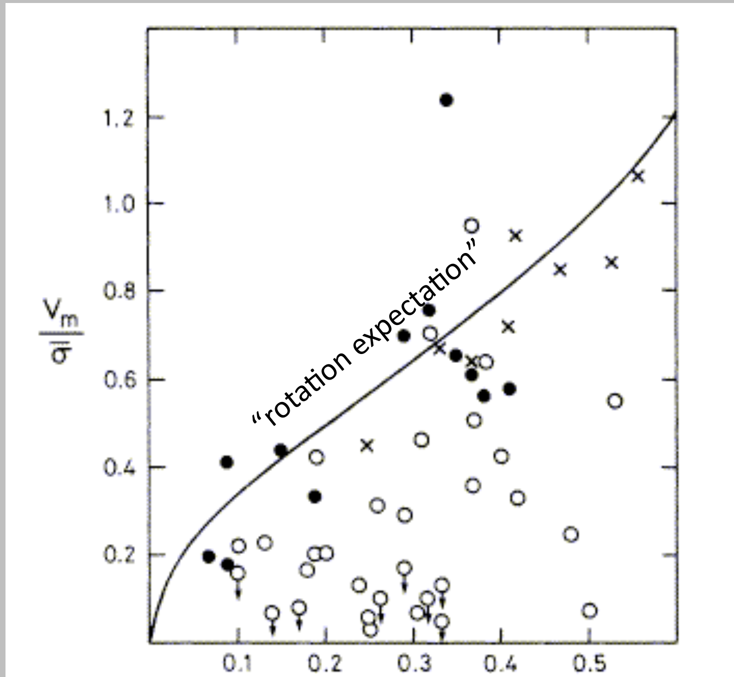




You can calculate the amount of rotation you'd need to flatten an elliptical to a certain flatness. If flattening is due to rotation, flatter ellipticals should have higher value of V_c/σ.

This works for low luminosity ellipticals (black dots), but not for luminous ellipticals (open circles). ⇒

So we say low luminosity ellipticals are more likely to be "rotationally supported", while luminous ellipticals are "pressure supported".



Davies+ 83

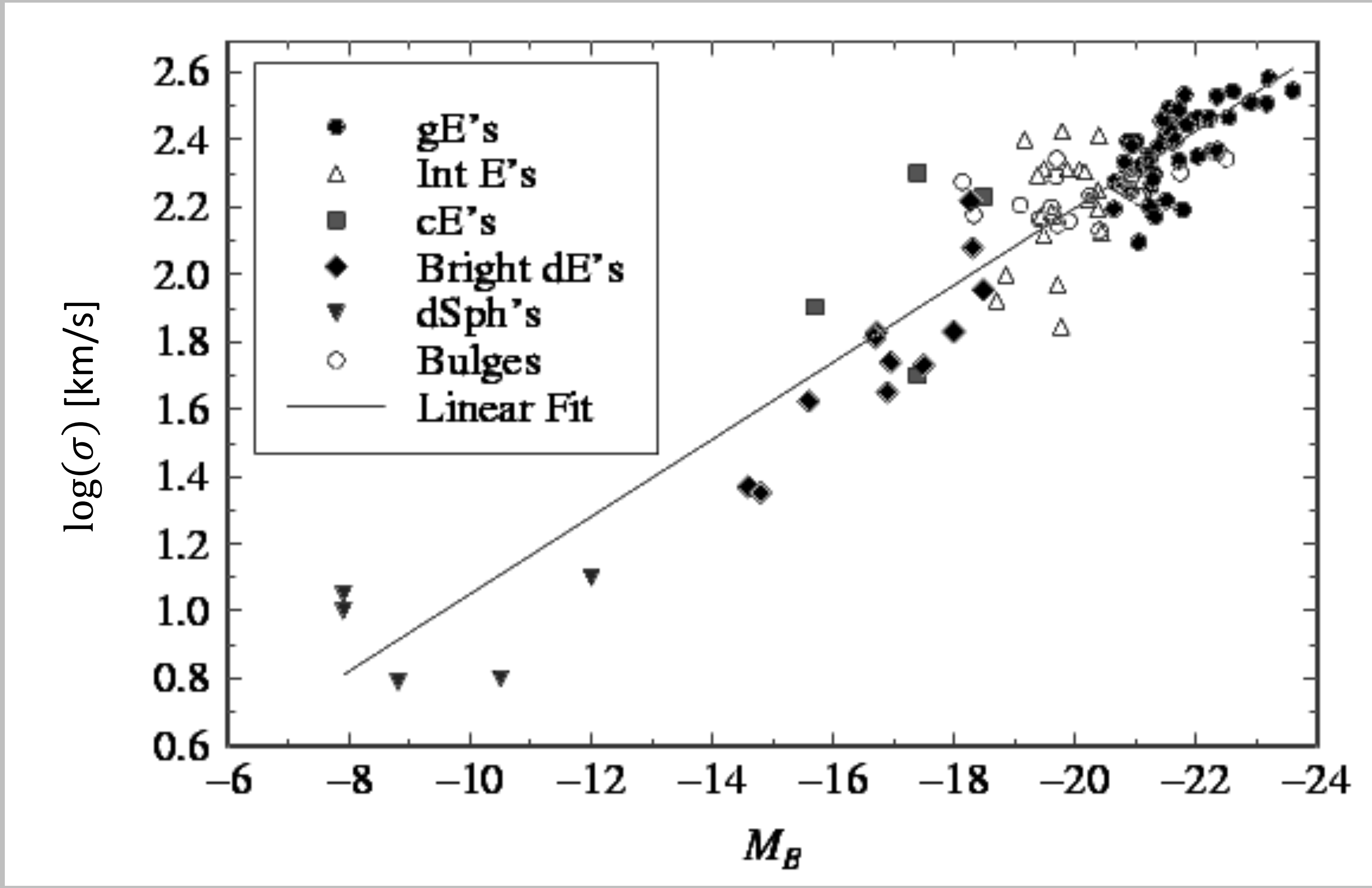
Elliptical Galaxies: Kinematic Scaling Relationships

Remember the Tully-Fisher relation for spiral galaxies: $L \sim V_c^{\alpha}$ where $\alpha \approx 3-4$.

Is there a similar relationship for elliptical galaxies using the velocity dispersion (σ)?

Yes, for ellipticals, the **Faber-Jackson relation** correlates velocity dispersion with absolute magnitude ⇒

But the scatter around the F-J relation (about 1 magnitude) is much larger than in T-F (a few tenths of a mag). *Why?*



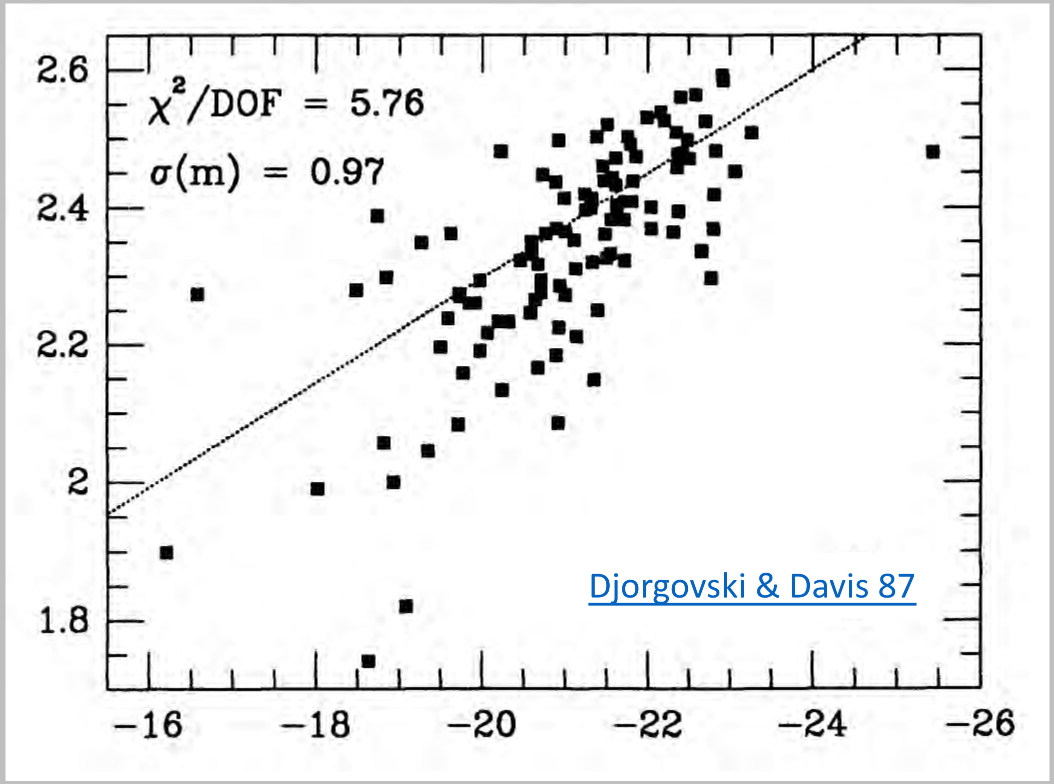
Elliptical Galaxies: Kinematic Scaling Relationships

Think about the observables you can measure for ellipticals:

- Luminosity (or absolute magnitude, M)
- Size (half-light radius, r_e)
- Average surface brightness or luminosity density inside r_e: $\langle\mu\rangle_e$ or $\langle I\rangle_e$
- Velocity dispersion (σ)

Since $\langle I\rangle_e = L/\pi r_e^2$, if you measure two of L, $\langle I\rangle_e$, and r_e, you can calculate the third. So we say that **only two of those properties are independent of each other**. If we add velocity dispersion to the list, we have three independent observables.

Do any of these independent properties correlate with each other?



$\log\sigma$ [km/s] (y-axis) vs M_B (x-axis)
(This is Faber-Jackson)

Correlation yes, but a lot of scatter! 😒

Elliptical Galaxies: Kinematic Scaling Relationships

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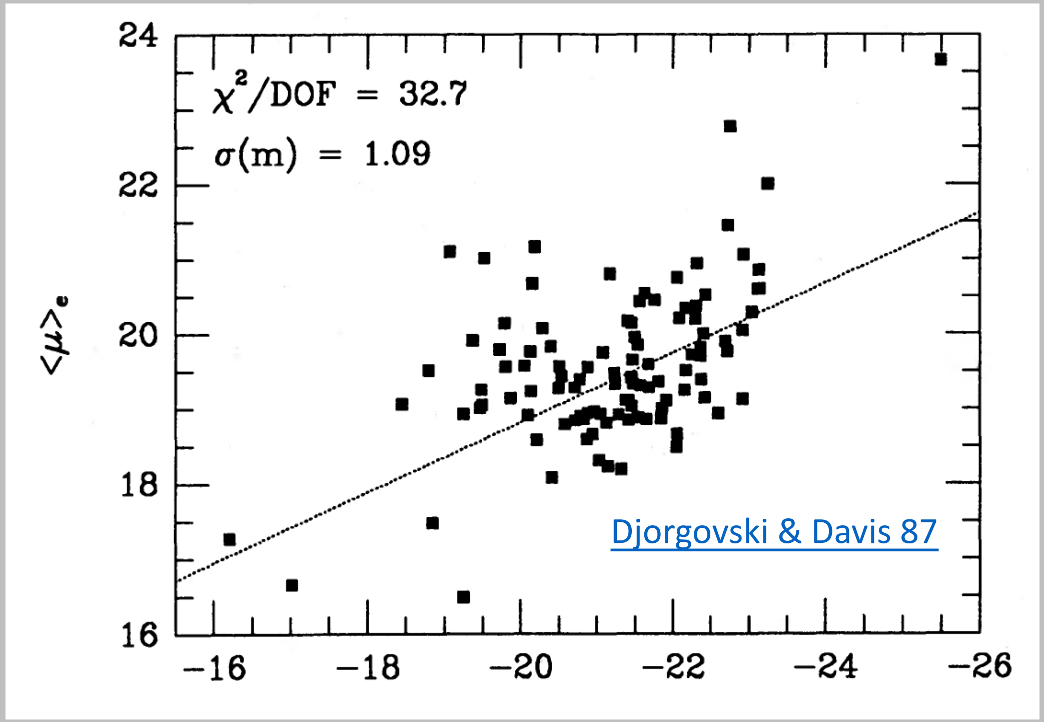

$\langle\mu\rangle_e[B$-mags/arcsec$^2]$ (y-axis) vs M_B (x-axis)

Blurgh, no correlation 🤮

Elliptical Galaxies: Kinematic Scaling Relationships

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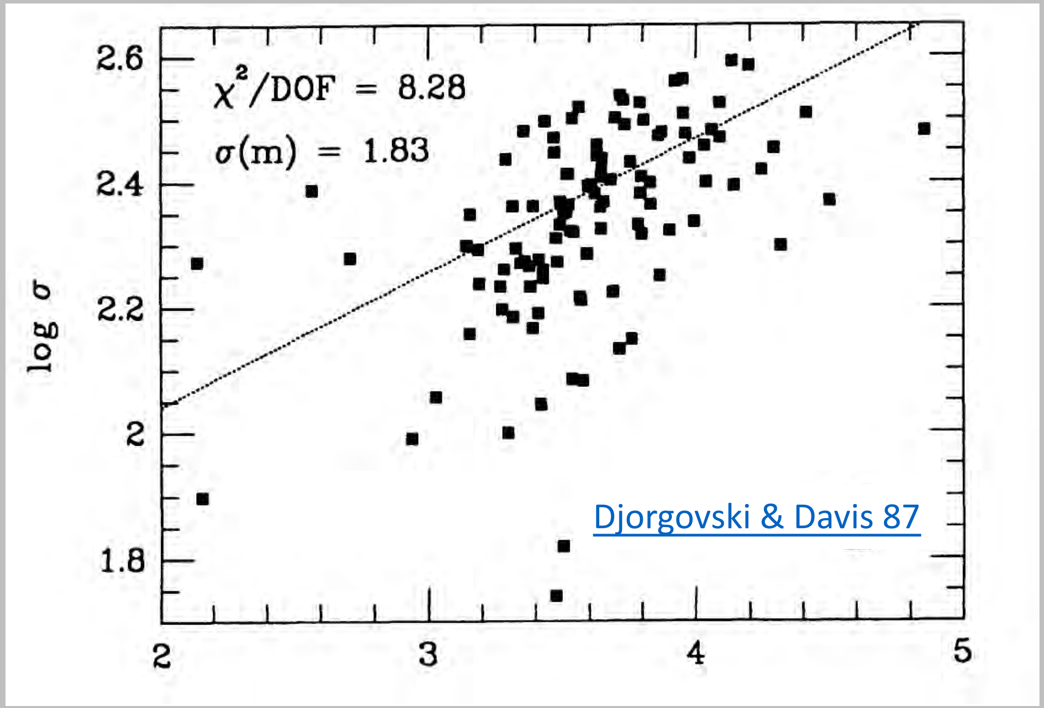
Do any of these independent properties correlate with each other?

What now? How about a combination of all three?



$\log\sigma$ [km/s] (y-axis) vs $\log r_e$ [pc] (x-axis)

Ugh, also not great 😢

Elliptical Galaxies: The Fundamental Plane

Fundamental Plane: a tight correlation between physical size (r_e in pc or kpc) and a combination of velocity dispersion and luminosity density (σ in km/s, $\langle I \rangle_e$ in $L_\odot/\mathrm{pc}^2$):

$$\log r_e = 1.24 \log \sigma - 0.82 \log\langle I \rangle_e + \mathrm{C}$$

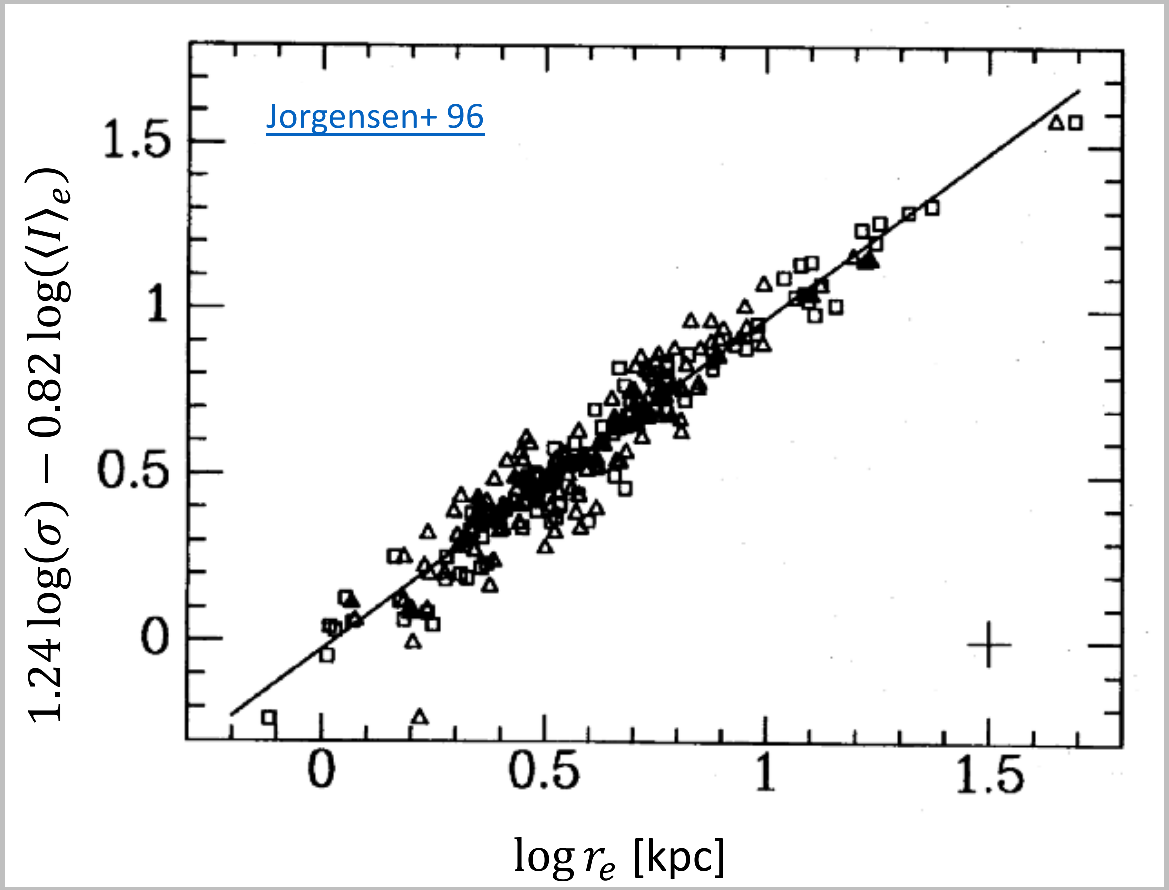
or

$$r_e \sim \sigma^{1.24} \langle I \rangle_e^{-0.82}$$

Why is it called the Fundamental *Plane*?

A correlation between two variables (x and y) is a **line**.
A correlation between three variables (x, y, and z) is a **plane**.

Plotting one parameter against a combination of the other two means that we are projecting the 3D plane onto a 2D plot.



The Importance of Scaling relationships
(or: Why is Mihos going on and on about this stuff?)

⇒ They give us ways to derive distances to galaxies

Note that one axis is always physical (TF: absolute magnitude; FP: physical size) and the other is pure observable (TF: circular velocity, FP: combination of velocity dispersion and surface brightness).

Tully-Fisher: measure circular speed (V_c), get absolute magnitude (M). measure apparent magnitude (m), then get galaxy distance from

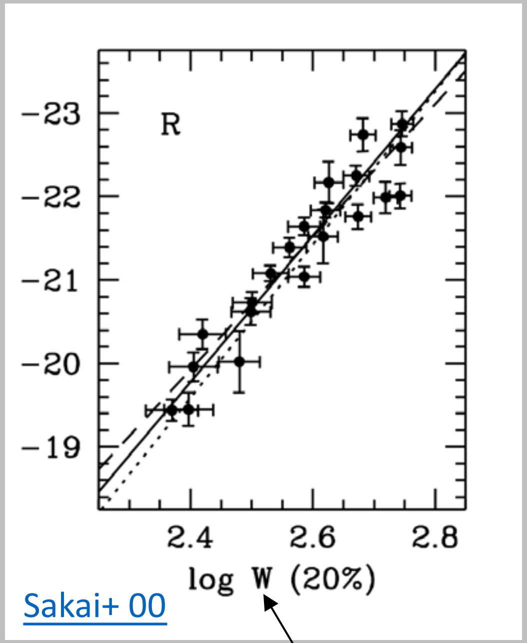
$$m - M = 5\log D - 5.$$

Fundamental Plane: measure velocity dispersion (σ) and surface brightness ($\langle\mu\rangle_e$ or $\langle I\rangle_e$), get physical size ($r_{e,phys}$). Measure angular size ($r_{e,obs}$ in arcsec) and get distance from

$$r_{e,phys} = \frac{r_{e,obs}D}{206265}$$

Spirals:
Tully-Fisher

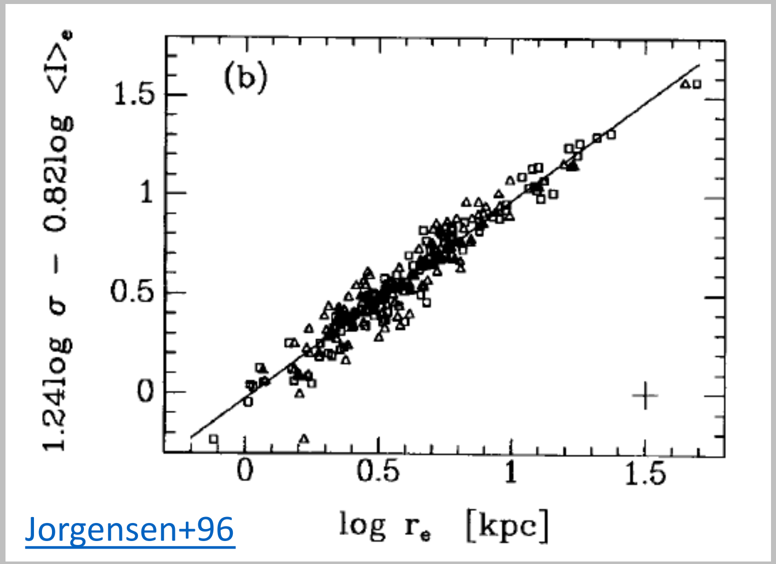
M_R



Sakai+ 00

$W \approx 2V_c$

Ellipticals:
Fundamental Plane



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The Importance of Scaling relationships
(or: Why is Mihos going on and on about this stuff?)

⇒ **They give us ways to derive distances to galaxies**

⇒ **They tell us about dark matter and stellar populations in galaxies**

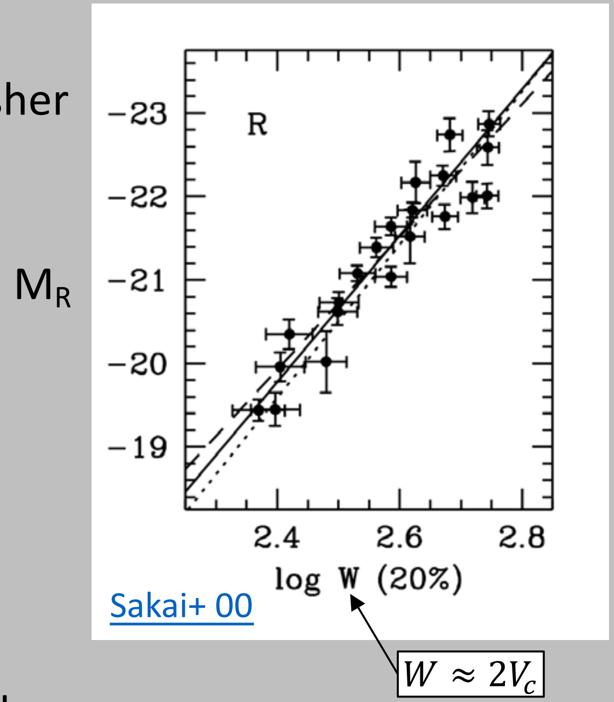
One term involves dynamical motion (V_c or σ), which depends on total mass (incuding dark matter), while the othes depend only on the stars.

If you know distance by some means other than TF/FP, you can look at how these relationships differ between galaxies of different types, for example:

- Does the TF relation behave differently for Sa vs Sc galaxies?
- Is the FP relation different for ellipticals in galaxy clusters?
- Do these relationships change over time (by comparing nearby galaxies to very distant galaxies)?

Differences in these relationships tell you how stars and dark matter are distributed differently (or change) in galaxies.

Spirals:
Tully-Fisher



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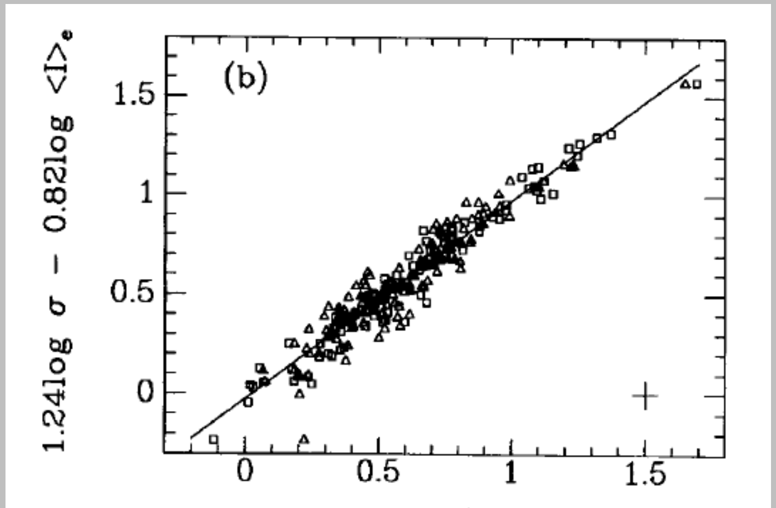
Ellipticals:
Fundamental Plane



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The Importance of Scaling relationships
(or: Why is Mihos going on and on about this stuff?)

⇒ They give us ways to derive distances to galaxies

⇒ They tell us about dark matter and stellar populations in galaxies

⇒ They tell us something fundamental about how galaxies form

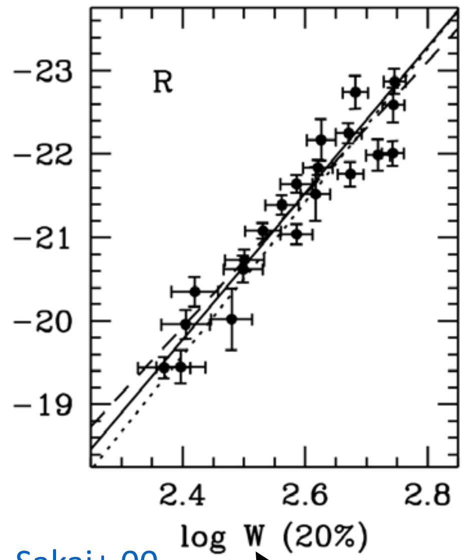
Why do galaxies follow these relationships? Many different physical process are involved in forming galaxies (dark matter, regular baryonic matter, gravity, star formation, gas physics, etc, etc), so how do all these processes work together to form such tight relationships?

We don't know!

With all these questions, the scatter around the relationship is very important. How much of that is real, how much is observational uncertainty? Lots of work going into these questions.....

Spirals:
Tully-Fisher

M_R



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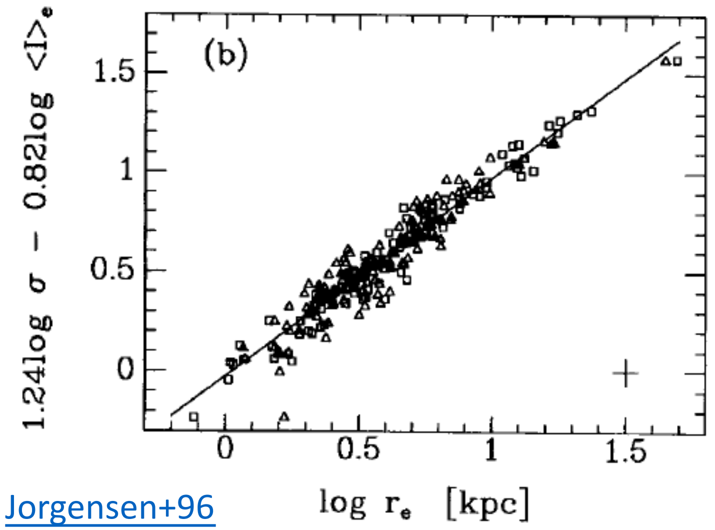
$W \approx 2V_c$

Ellipticals:
Fundamental Plane



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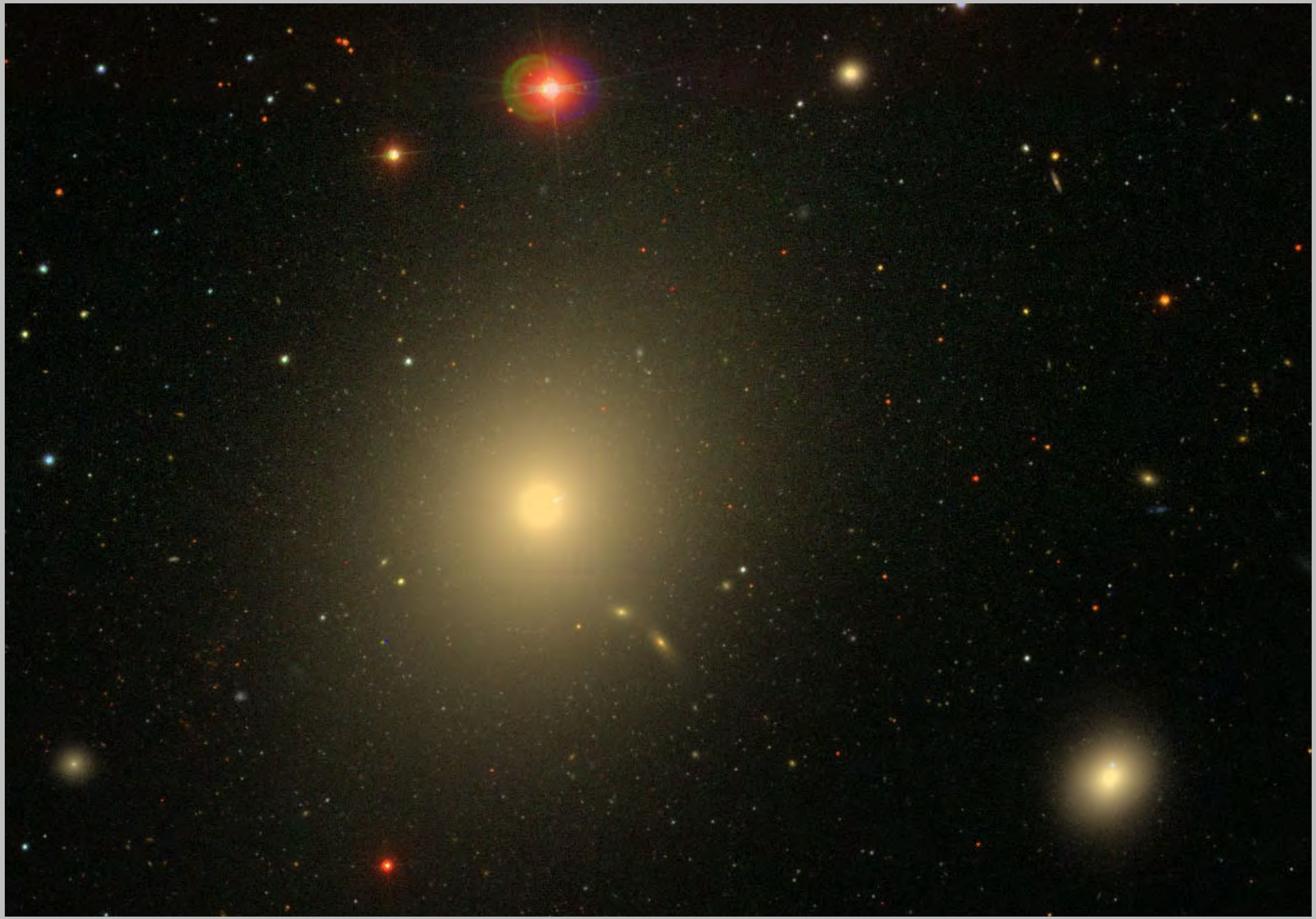
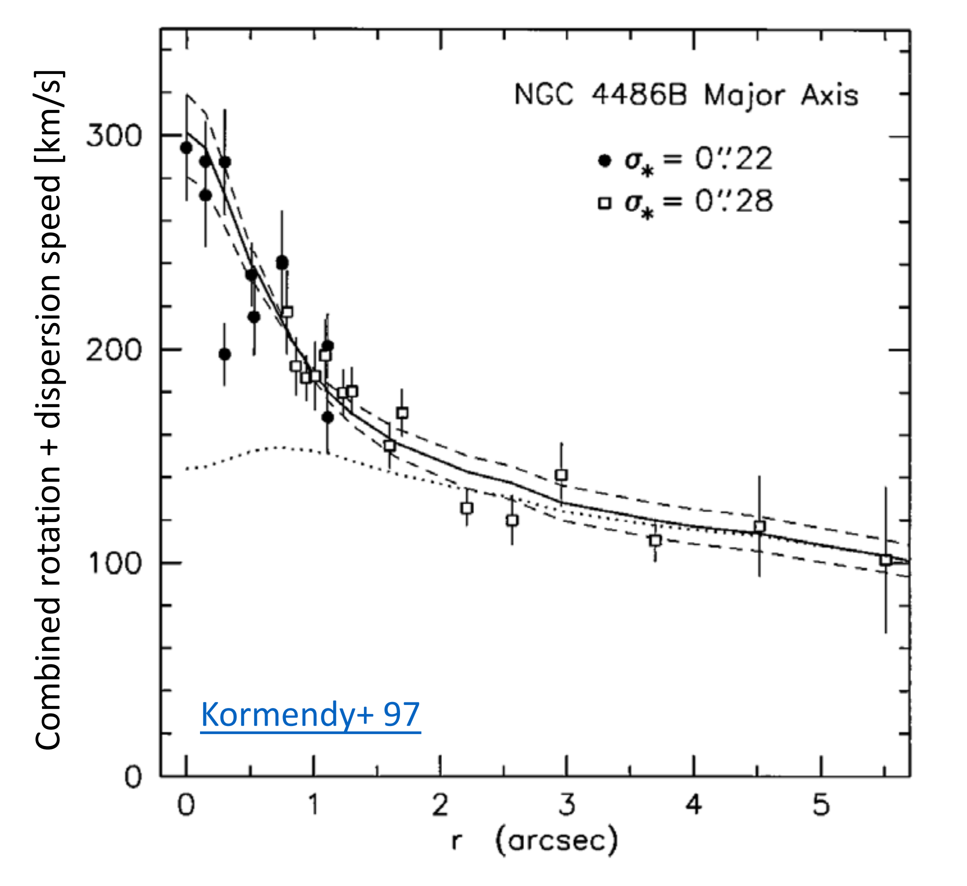
Supermassive Black Holes

Many ellipticals have been found to host supermassive black holes in the nuclei.

Look at the motions of stars near the center of NGC 4496B.





Dotted line: No black hole expectation.

Solid/dashed lines: Model based on stars + supermassive black hole with mass:

$$M_{BH} = 9\times10^{8}\ M_{\odot}$$

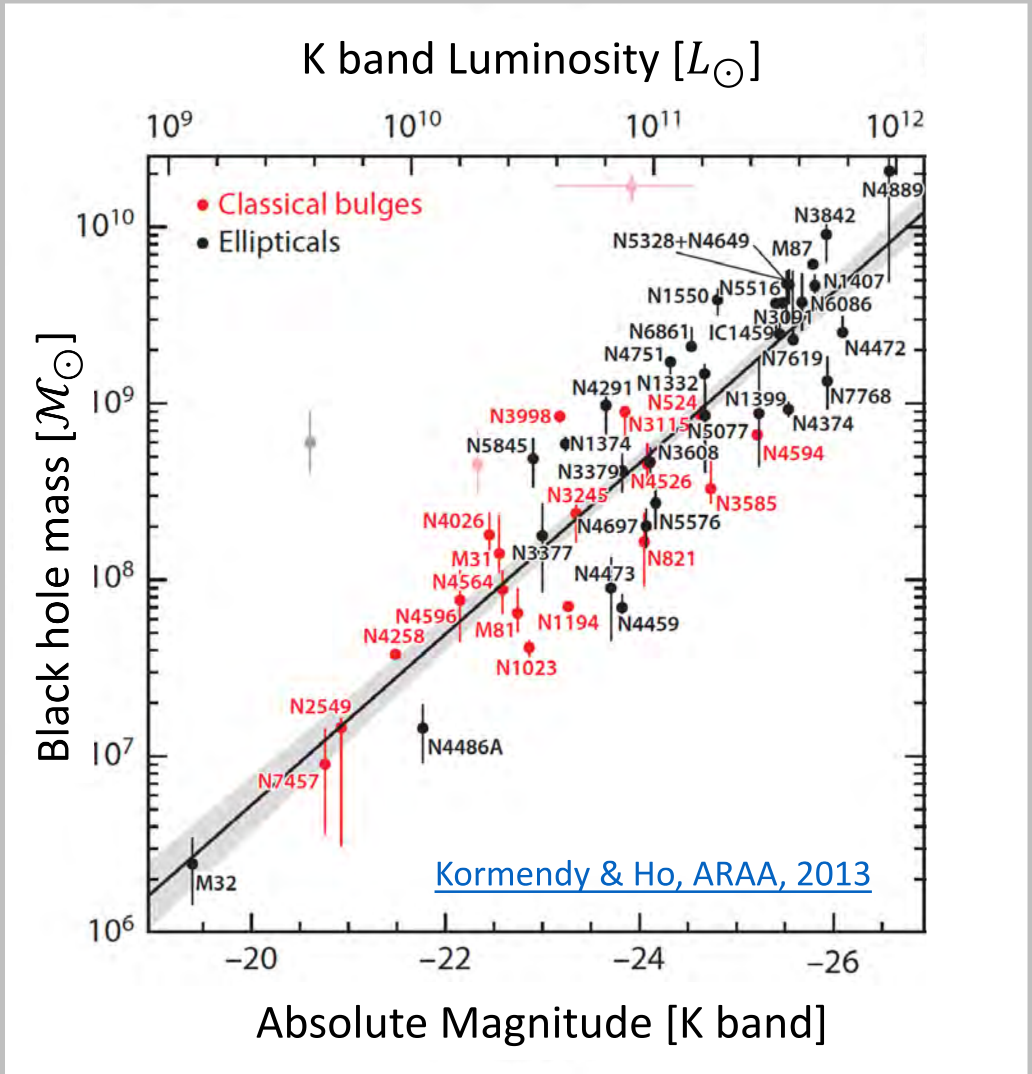
Supermassive Black Holes

Do this for many galaxies, plotting black hole mass versus galaxy absolute magnitude (or luminosity).

Black points: Elliptical galaxies
Red points: Bulges of spiral galaxies (ignoring their disk)

Strong correlation between black hole mass and *spheroid* luminosity (i.e., elliptical galaxy stars or spiral galaxy bulge stars).

And in spirals, no correlation at all between black hole mass and stellar mass of the *disk*.



Black holes have masses that are ≈ 0.1 % – 1% of the stellar mass of the entire spheroid.

Not enough to affect the dynamics of the galaxy as a whole, but does affect dynamics of the inner ≈ 50 – 100 pc.....