Elliptical Galaxies: Kinematics

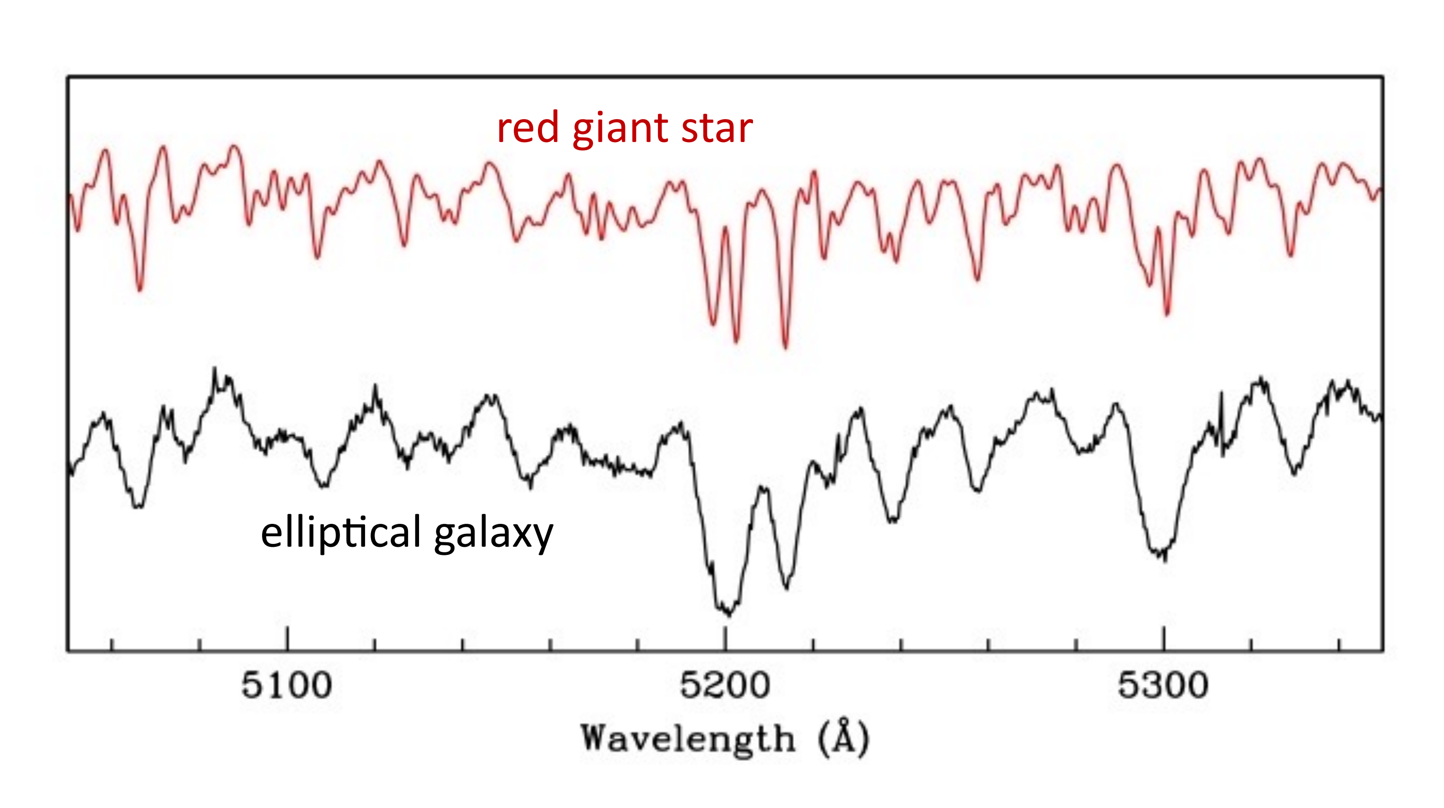
Without much cold gas or star formation, can't get kinematics from 21-cm or Hα emission lines. Must get kinematic information from stellar absorption lines, which is harder.

When we take a spectrum of an elliptical, we see projected stellar velocities, integrated along the line of sight. This broadens spectral lines.

Integrated light in ellipticals is dominated by old stellar populations: luminous red giants.

Take a red giant spectrum and broaden/shift it in wavelength to match observed galaxy spectrum.

Central wavelength and width of line gives us the mean line-of-sight velocity $\langle V \rangle$ and velocity dispersion (σ).



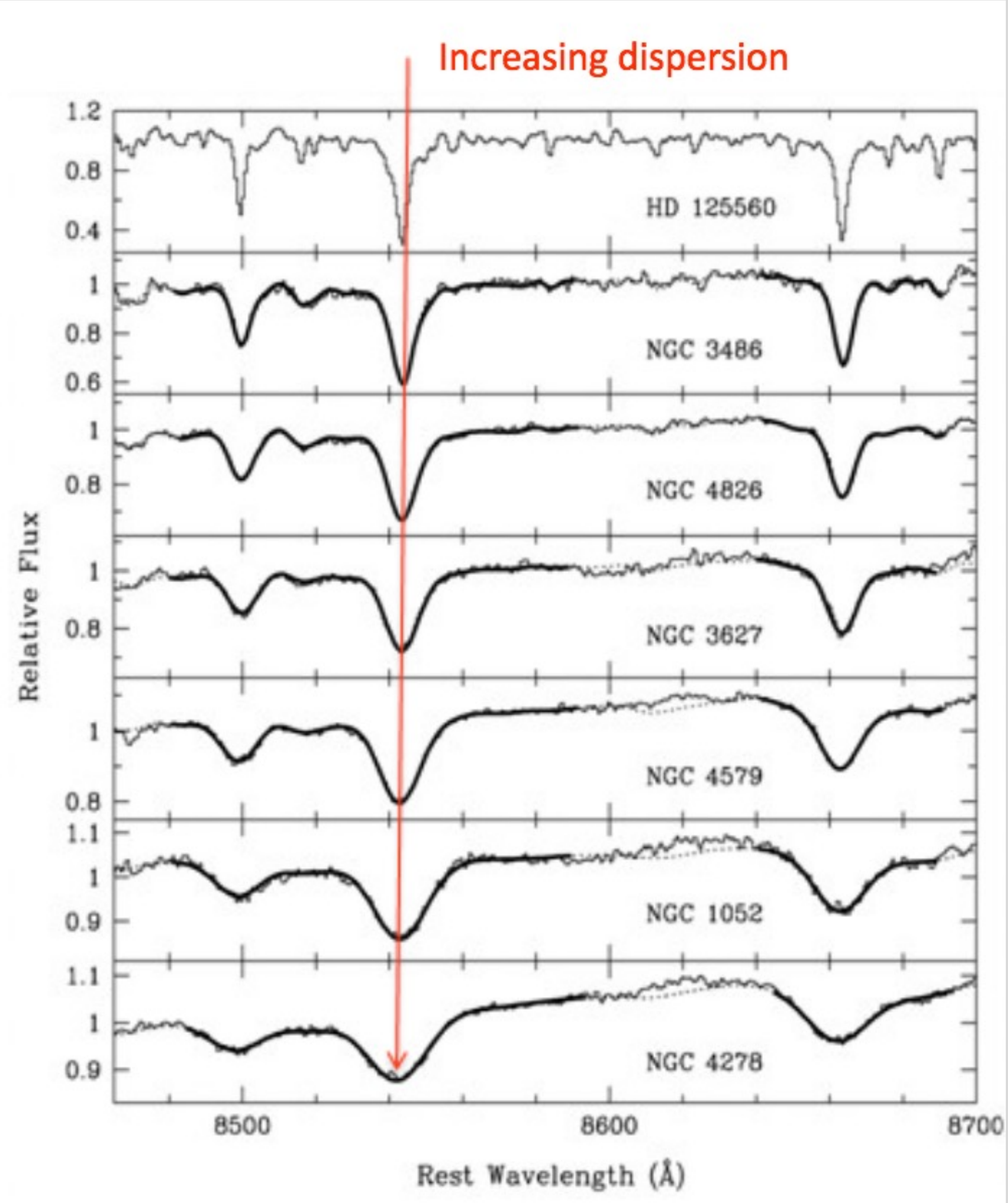
Broadening and velocity dispersion

Red giant star spectrum

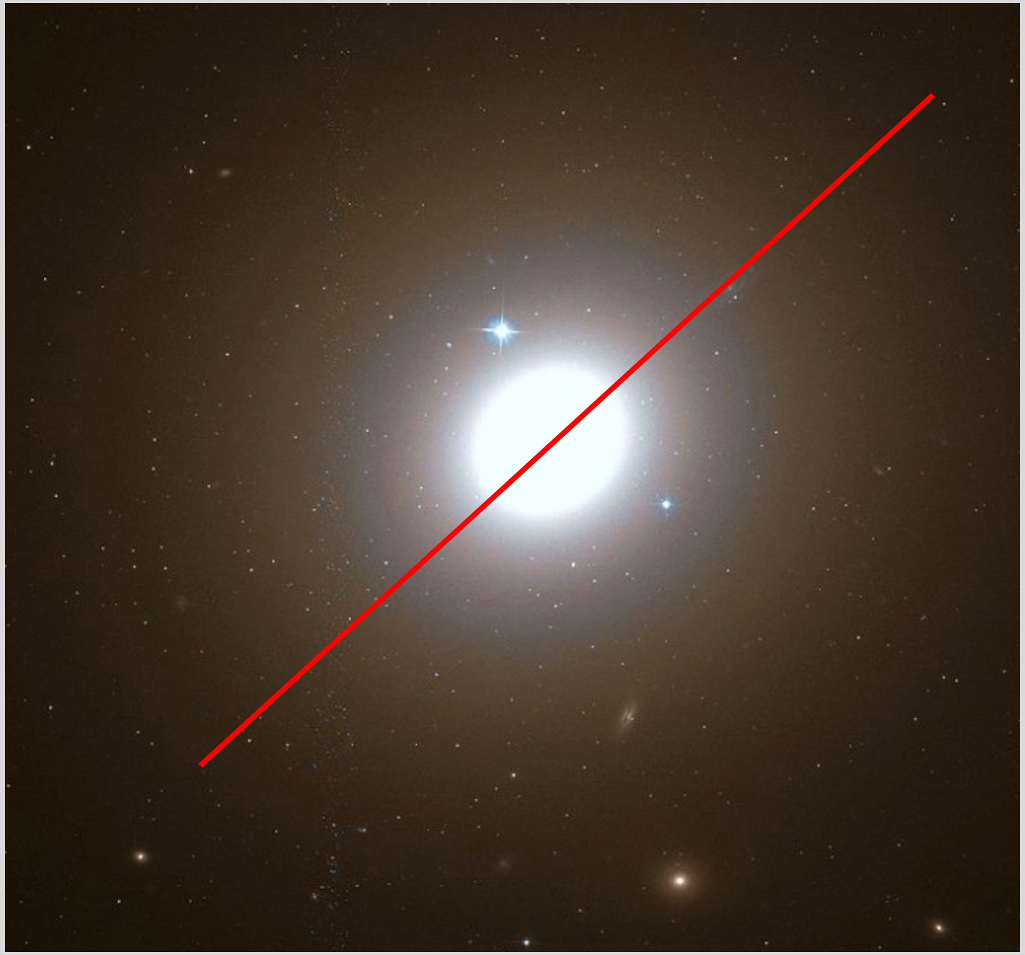
Absorption lines are broadened in wavelength, showing that ellipticals typically have low rotation (V_c) and large velocity dispersion (σ).

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

Galaxies



Elliptical Galaxies: Major Axis Kinematics



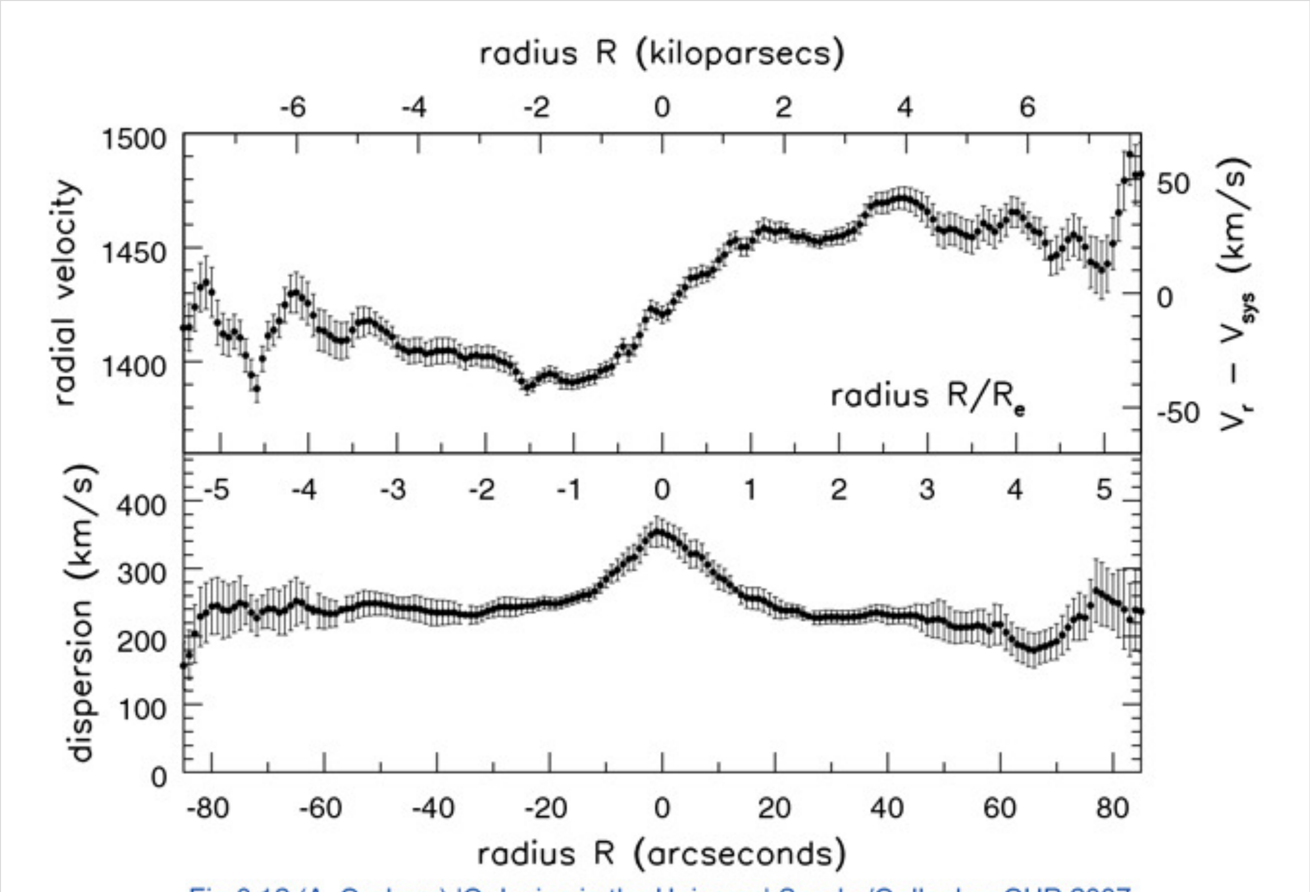


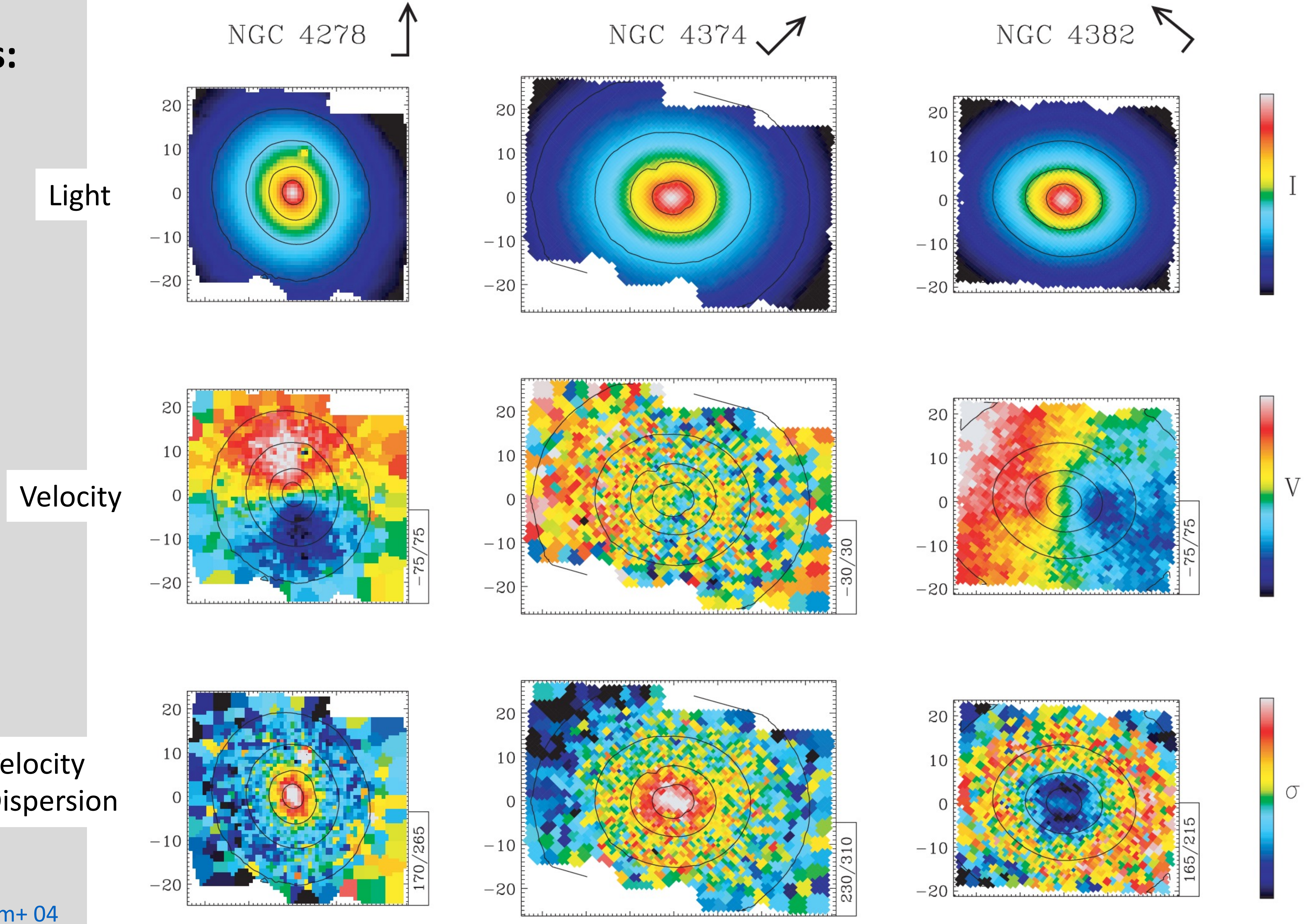
Fig 6.12 (A. Graham) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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: 2D Kinematics

We can see a modest amount of rotation in many ellipticals.



Emsellem+ 04

Elliptical Galaxies: Projected vs True Velocity dispersion

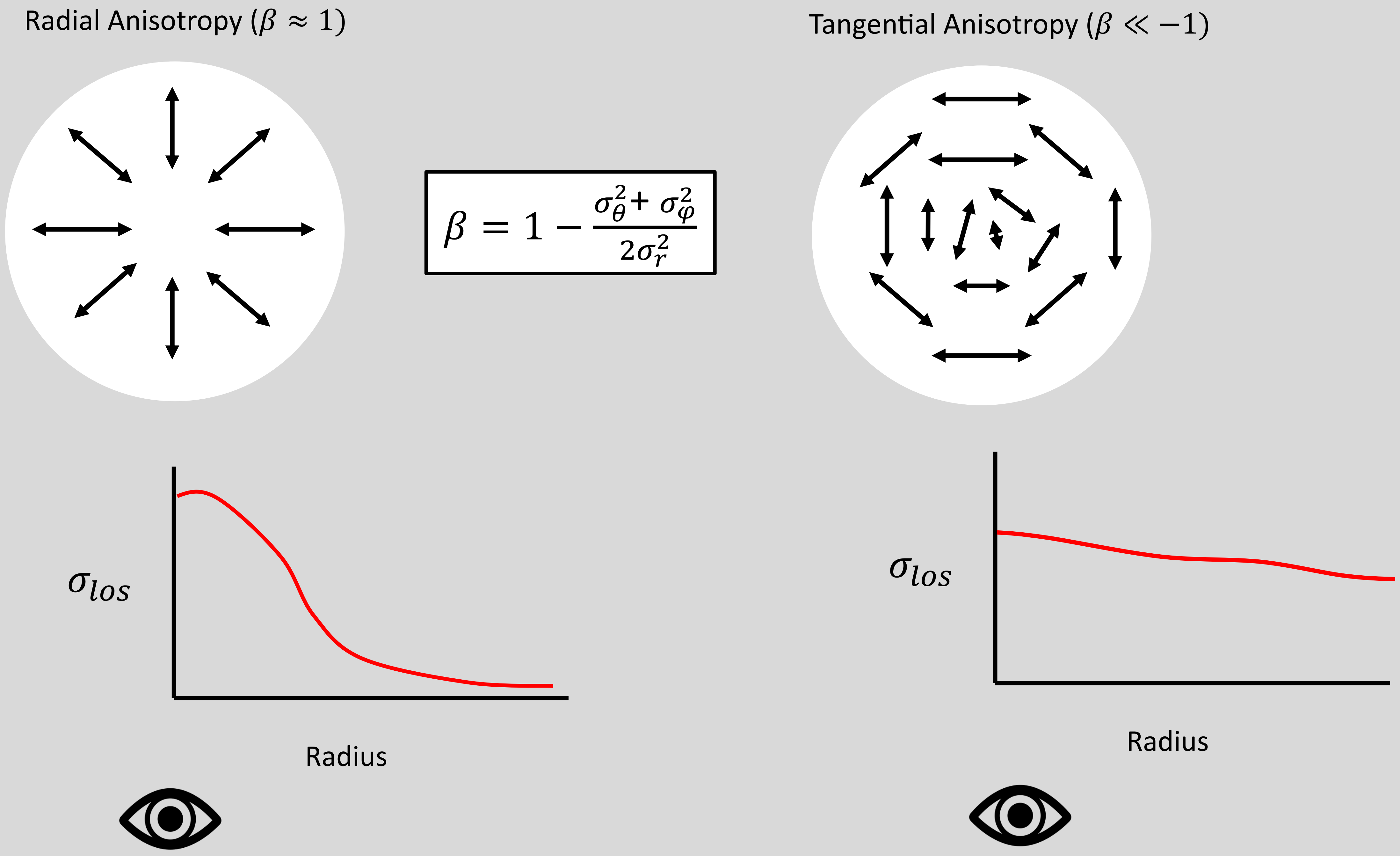
We observe / measure a projected ***line of sight*** velocity dispersion: σ_{los}
But physically, the stars have motion in 3 directions, with a total dispersion given by: $\sigma_v^2 = \sigma_r^2 + \sigma_\theta^2 + \sigma_\varphi^2$

How do we relate these things?

- Assume **isotropy**:
  - $\sigma_r = \sigma_\theta = \sigma_\varphi$, then $\sigma_v = \sqrt{3}\sigma_{los}$

- Assume **radial anisotropy**:
  - $\sigma_r \neq \sigma_\theta = \sigma_\varphi$.
  - Anisotropy parameter: $\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\varphi^2}{2\sigma_r^2}$.
    - $\beta = 1$: radial orbits
    - $\beta = 0$: isotropic orbits
    - $\beta = -\infty$: circular orbits *(but not necessarily net rotation!)*

Thought experiment: what would the projected velocity dispersion profile $\sigma_{los}(R)$ look like for a galaxy with:
- Large radial anisotropy: $\beta \sim 1$
- Large tangential anisotropy: $\beta < -1$


Radial Anisotropy ($\beta \approx 1$)
Tangential Anisotropy ($\beta \ll -1$)
$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\varphi^2}{2\sigma_r^2}$
σ_{los}
Radius
σ_{los}
Radius

Example: Dark Matter vs Anisotropy

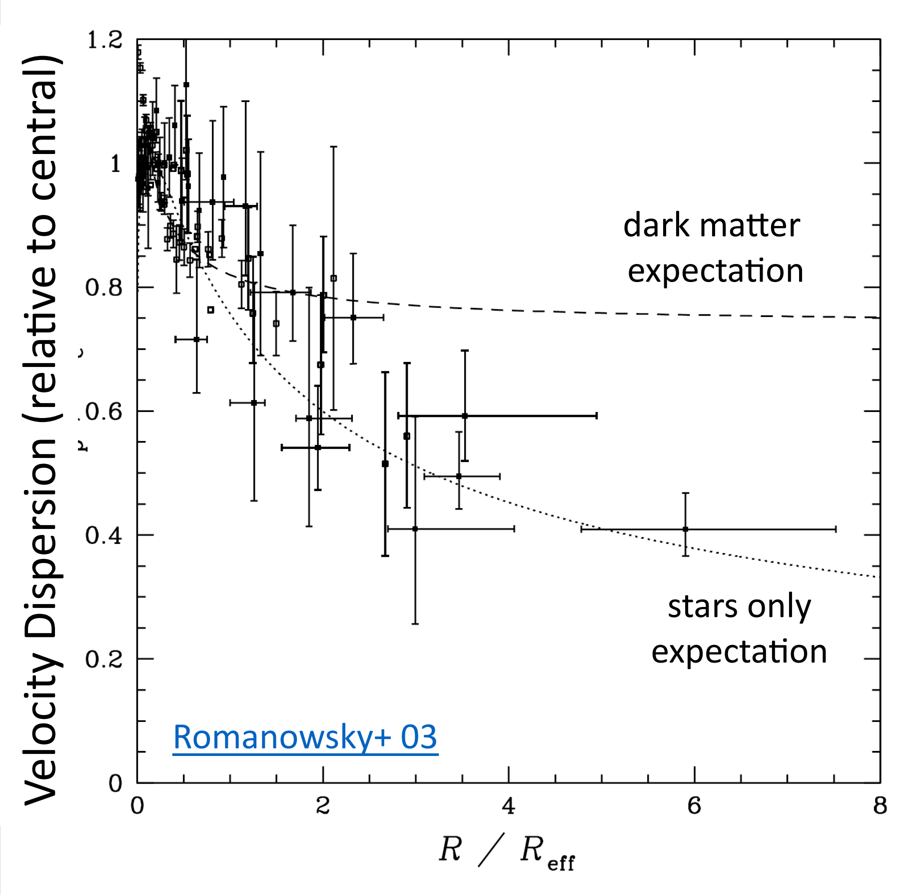
Projected velocity dispersion measures decline at large radius in some eliiptical.

For isotropic models, this would mean no dark matter:

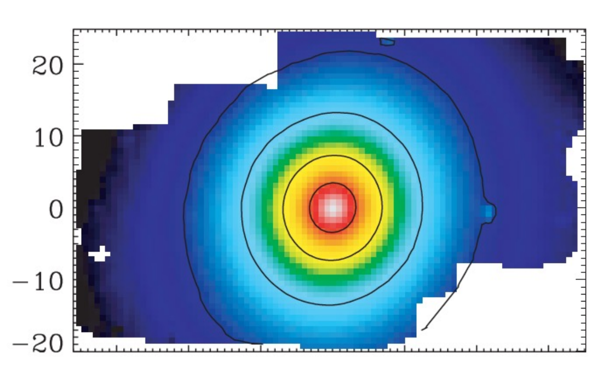
$$\sigma_v^2 = 3\sigma_{los}^2 \sim GM_{stars}(r)/r$$

But could also be due to large radial orbit anisotropy ($\beta > 0$) in outer regions, which would make the velocity dispersion drop faster with radius.

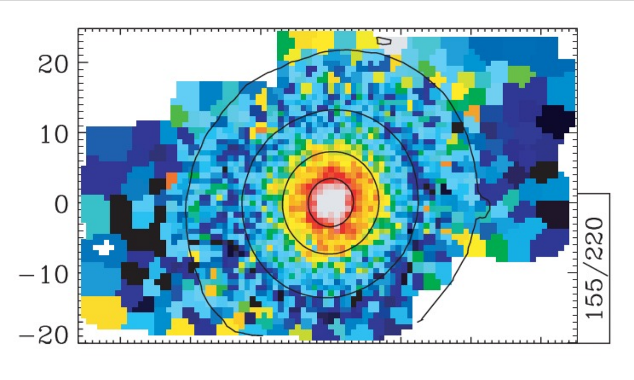
How can we tell? With exquisite data, radial orbits and tangential orbits give different line profile shapes and can be determined spectroscopically.



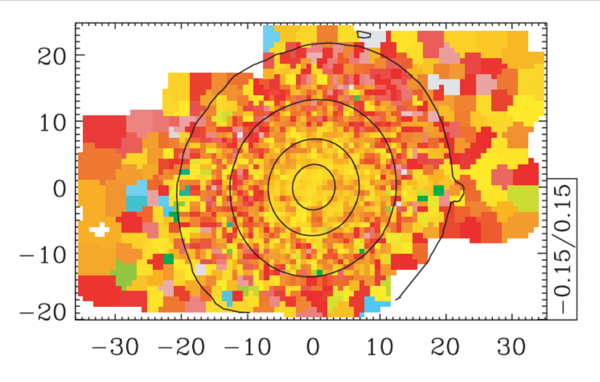
NGC 3379 Emsellem+ 04



Light profile



Velocity dispersion



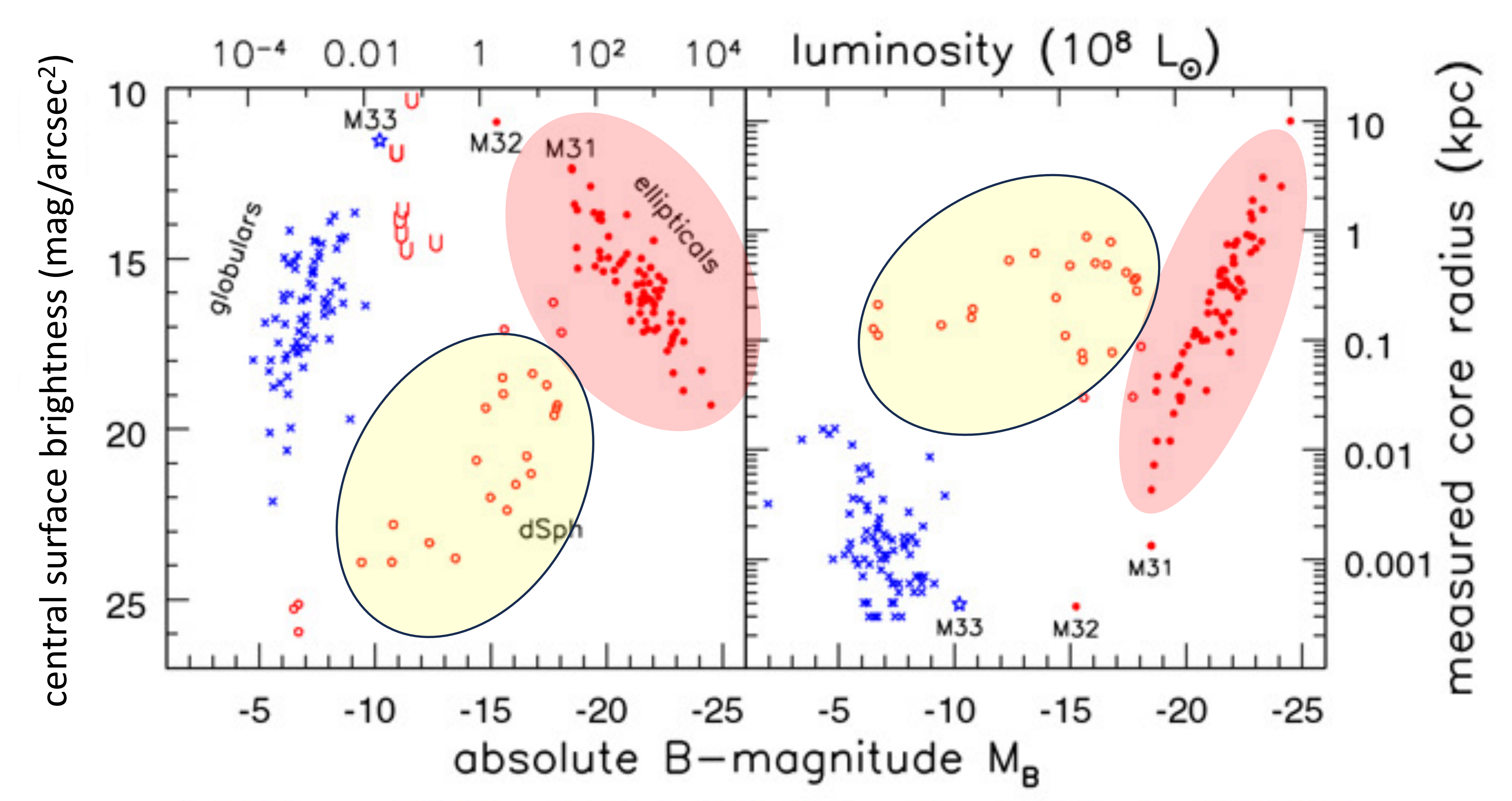
Radial anisotropy

yellow: isotropic
red: radially biased

Structural relations

For ellipticals, luminous galaxies are larger and lower in surface brightness (more diffuse).

Note that dwarf spheroidals behave differently – they are not just “scaled down” ellipticals.
So as we talk about ellipticals, we are talking about mid-to-large ellipticals, not dwarfs.



S&G Fig 6.6

Scaling relationships: kinematic

Simple correlations between structural and kinematic properties are weaker than in spirals.

Recall tight correlation between V_{rot} and L for spirals, the Tully-Fisher relationship.

For ellipticals, the analogous relationship is the Faber-Jackson relationship connecting luminosity (abs-mag) and velocity dispersion:

$$M = a \log \sigma + b.$$

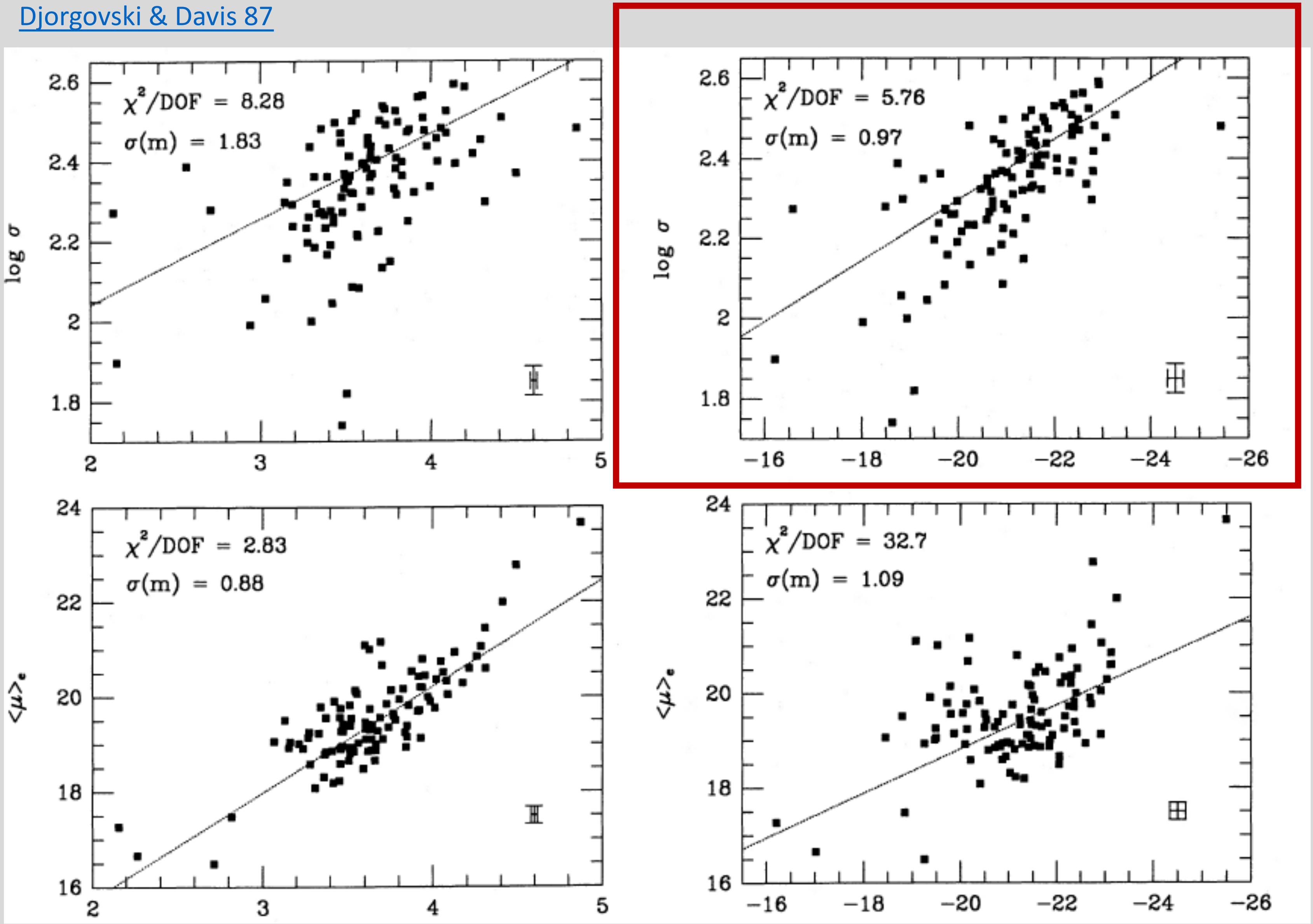
But F-J shows much more scatter than T-F!

σ: velocity dispersion
$\langle \mu \rangle_e$: average surface brightness
r_e: effective radius
M: total absolute magnitude

$h = H_0/100$

Faber-Jackson relation

[Djorgovski & Davis 87]



log r_e (h^{-1} pc) Absolute Mag (for h=1)

Scaling relationships: The Fundamental Plane

σ: velocity dispersion
$\langle I \rangle_e$: average surface brightness (in flux units, not mag/arcsec^2)
r_e: effective radius

But tight correlation between a combination of parameters: size (r_e), velocity dispersion (σ), and surface brightness (μ_e or I_e).

The Fundamental Plane:

$$r_e \sim \sigma^x I_e^y$$

or

$$\log r_e = x \log \sigma + y \log I_e$$

$$x \approx 1.24, y \approx -0.82$$

(in Gunn r filter)

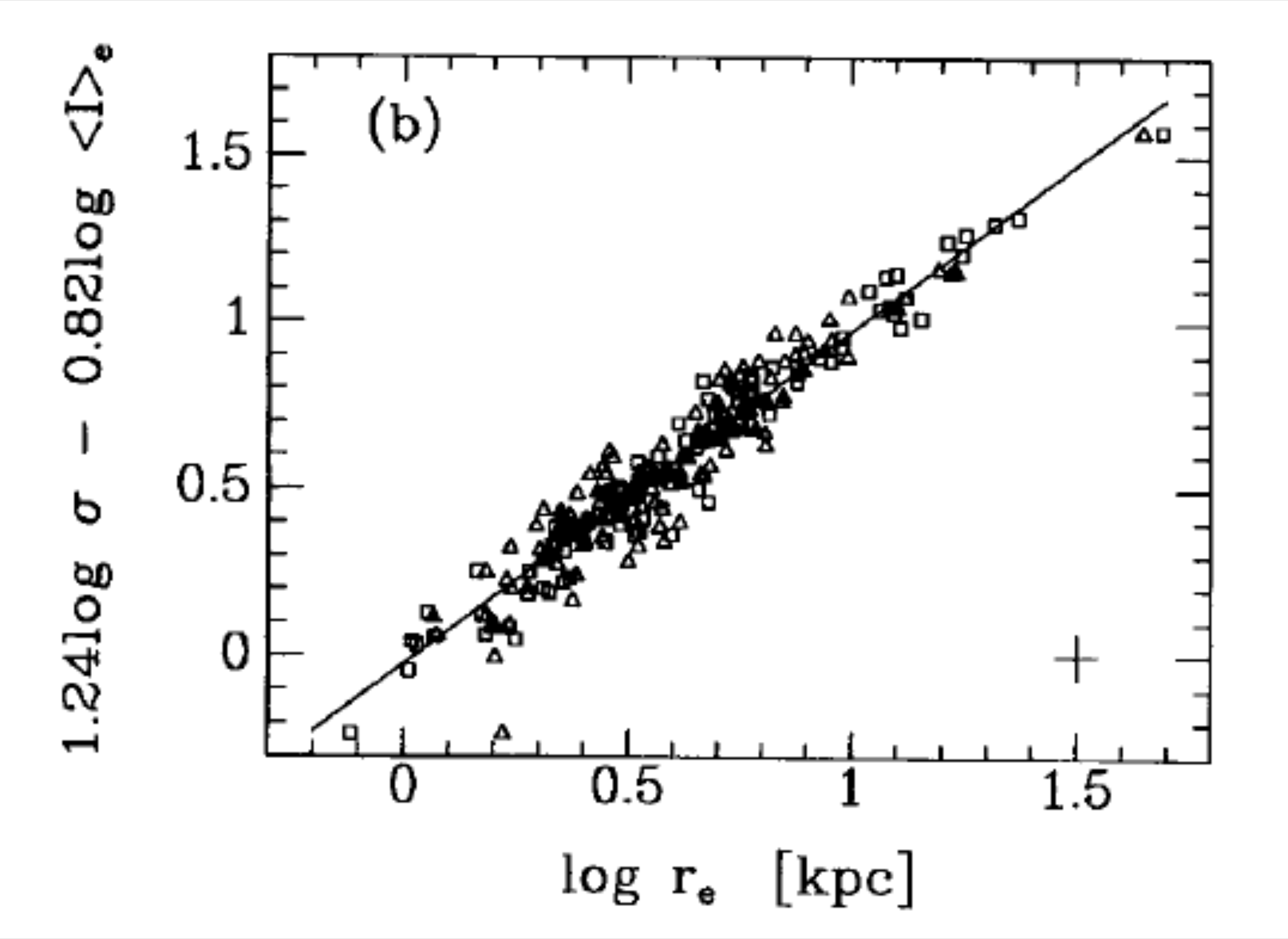
Simple gravitational scaling arguments would predict (recall the discussion of Tully-Fisher):

$$r_e \sim \sigma^2 I_e^{-1} \left(\frac{M}{L}\right)^{-1}$$

Why the difference with the observed parameters?

- changes in (M/L)?
- velocity anisotropy?

Jorgensen+96



The Importance of Scaling relationships

A means to **derive distances** to galaxies:

> Note that one axis always is distance-dependent (M_R or physical r_e), the other is distance-independent observable (W or σ and I). If you apply the scaling relationship, the observables give you the distance.

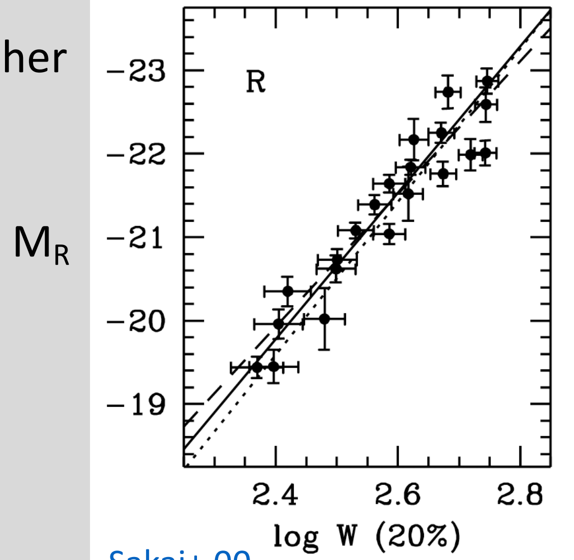
A means to **study galaxy evolution** and stellar populations:

> One axis always involves light (M_R or I). If you know distance, you can compare observed light with expectation from the scaling relationship. Discrepancies tell you about intrinsic variations between galaxies.

A means to **study dark matter** in galaxies:

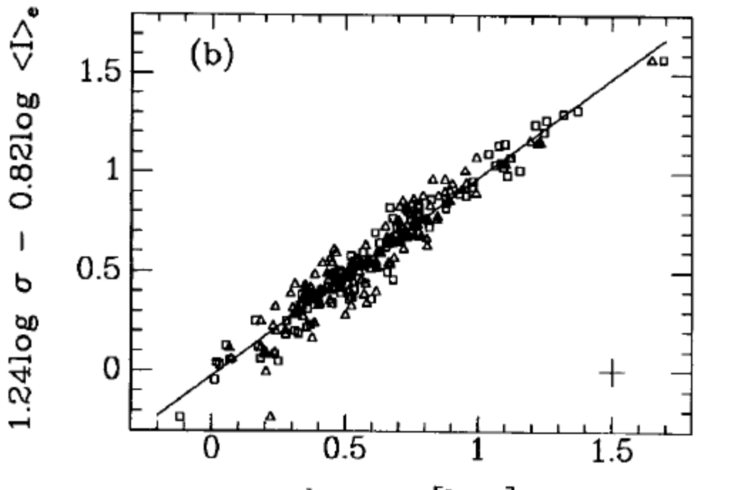
> One axis always involves dynamical motion, which is determined by total mass (baryons + dark matter). If you know distance and understand stellar populations, you can constrain dark matter content.

Spirals:
Tully-Fisher



Sakai+ 00

Ellipticals:
Fundamental Plane

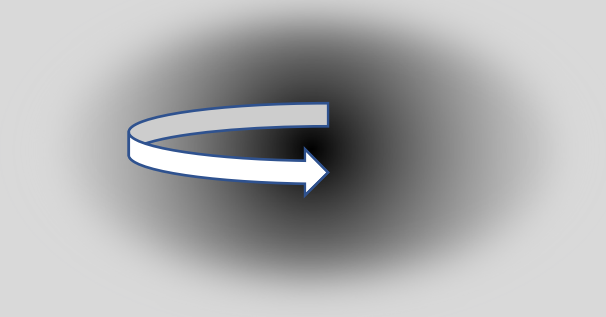


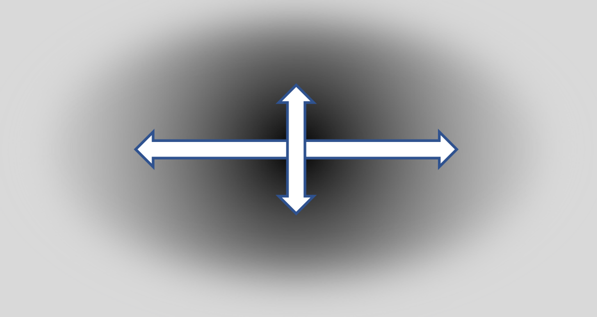
Jorgensen+96

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: $\sigma_x > \sigma_y$





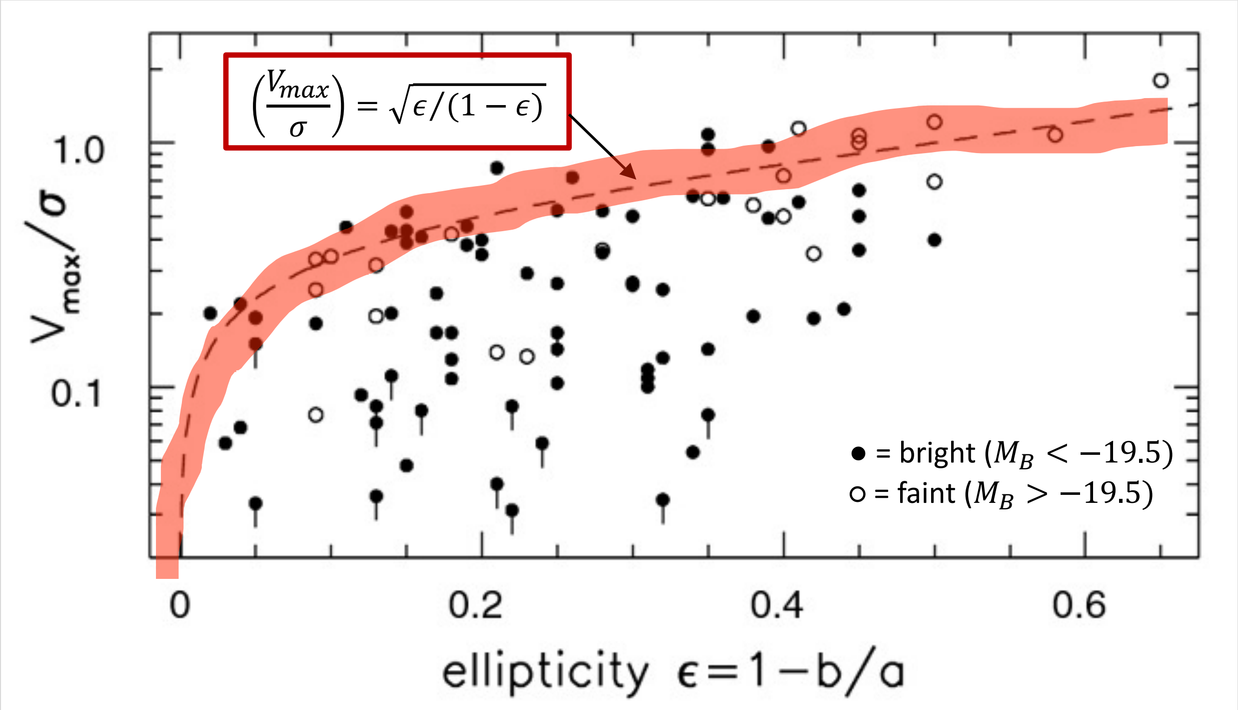
How could we tell?

Use the virial theorem* (connecting kinetic energy to potential energy) to derive a relationship between ellipticity (ϵ) and ratio of rotation to dispersion (V_{max}/σ):

$$\left(\frac{V_{max}}{\sigma}\right) \approx \sqrt{\epsilon/(1-\epsilon)}$$

If E's were flattened by rotation, they should follow this relationship.

(see Sparke & Gallagher text, Section 6.2.3)*

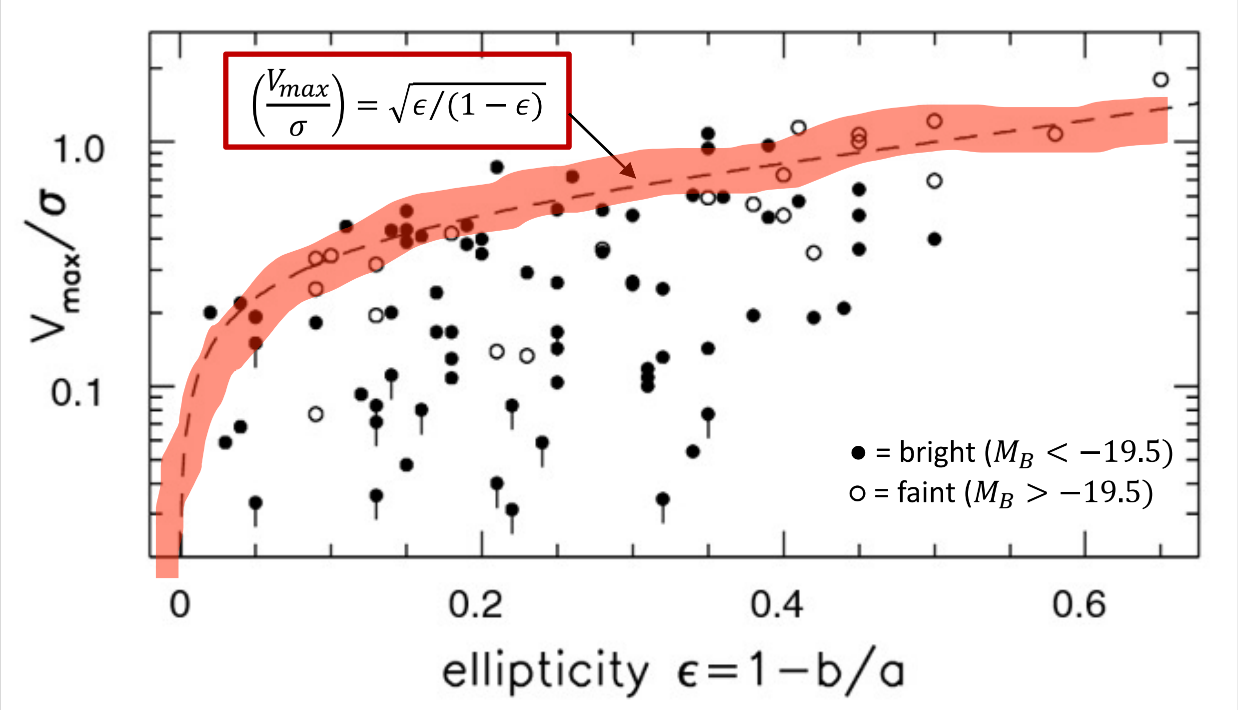


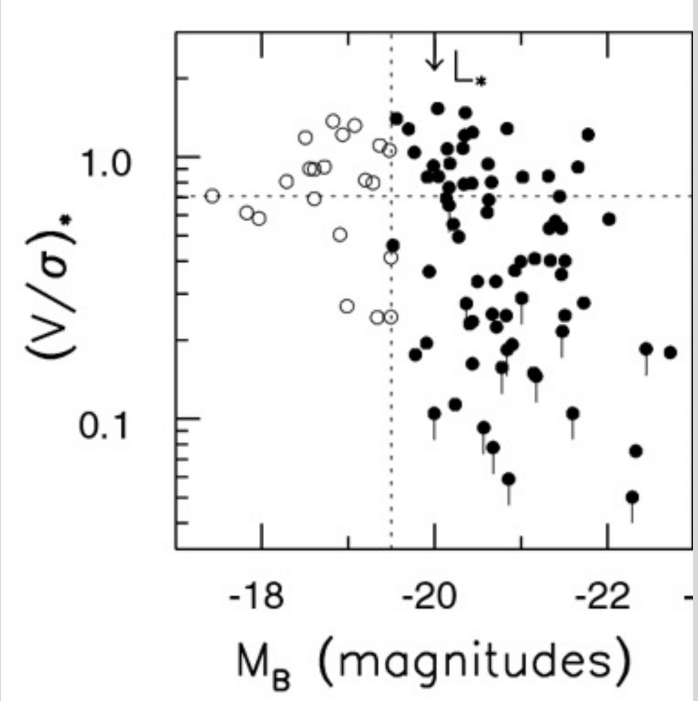
Rotation vs Dispersion

If we measure rotation, dispersion, and ellipticity, if ellipticals were flattened by rotation, they should follow the red/dashed line ⇒

Massive/luminous ellipticals generally rotate too slowly to be flattened by rotation. They are **pressure supported.**

Lower luminosity ellipticals are more likely to be (but not always) **rotationally supported**.





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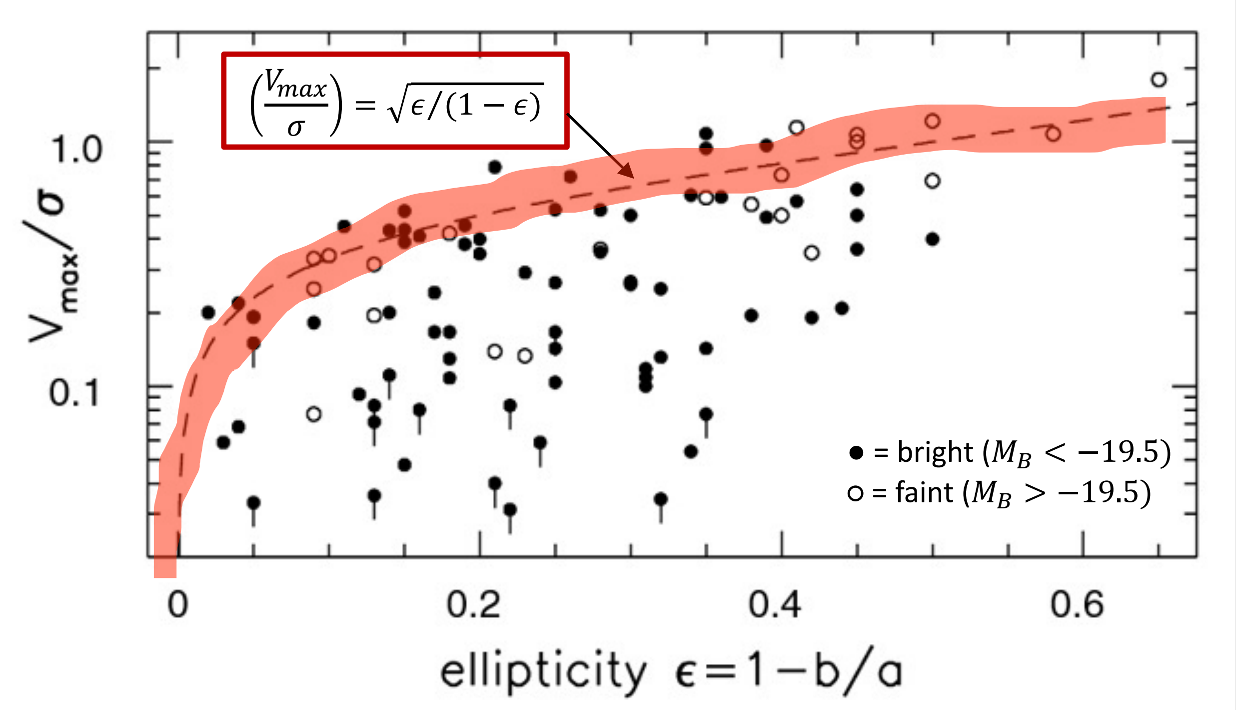
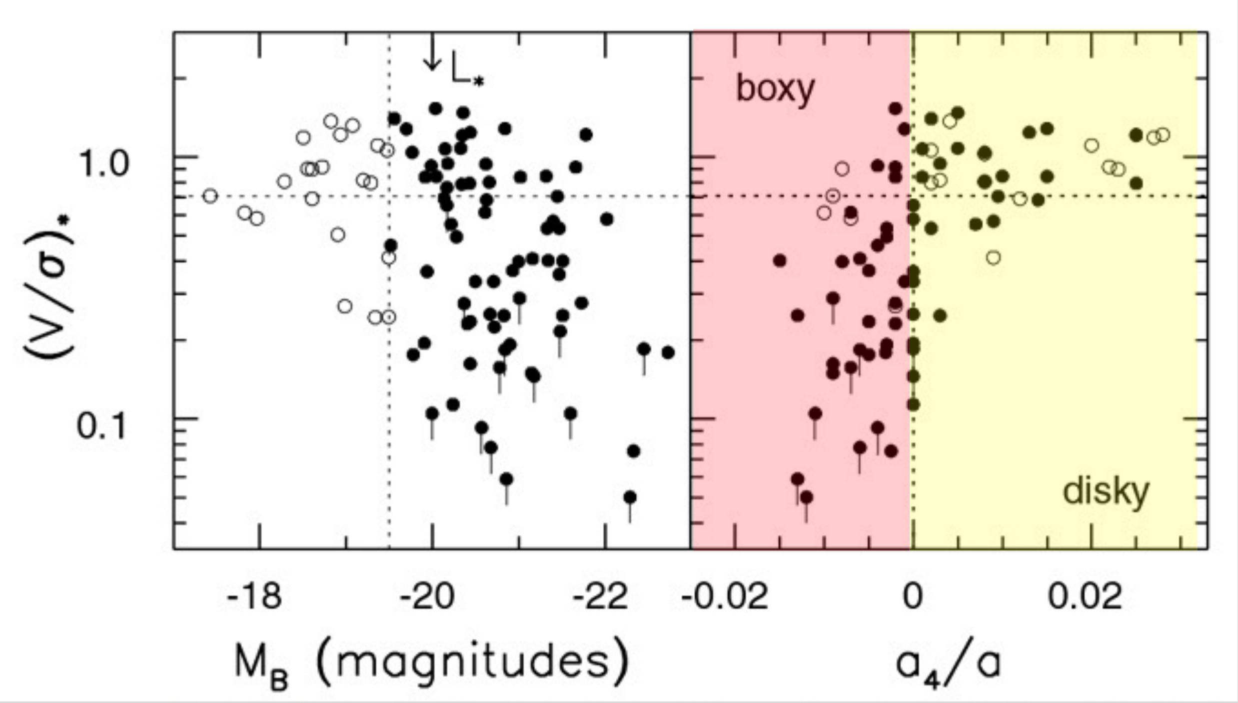
Boxy vs Disky

Slow rotators / high luminosity ellipticals tend to be boxy galaxies.

Fast rotators / lower luminosity ellipticals tend to be disky galaxies.

⇒ Different formation histories for low and high L ellipticals!

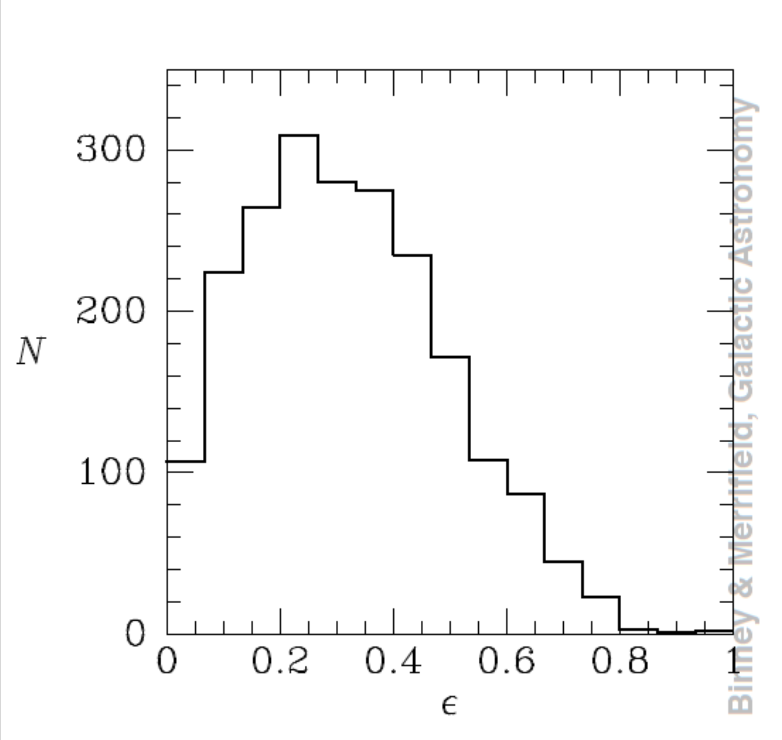




Intrinsic shapes of ellipticals

Cannot determine true axis ratios for any single galaxy, due to only seeing projected axis.

Need to do this statistically: adopt a model for true 3D axial ratios, model randomly projected shapes, adjust intrinsic shape model until real observations matched.



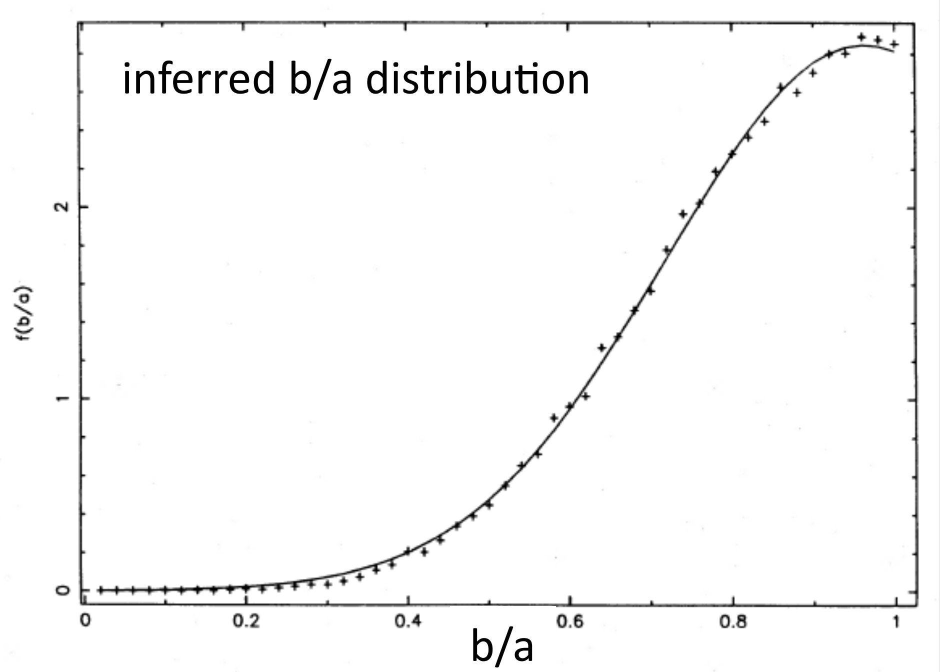
Observed shapes (1-b/a) of elliptical galaxies

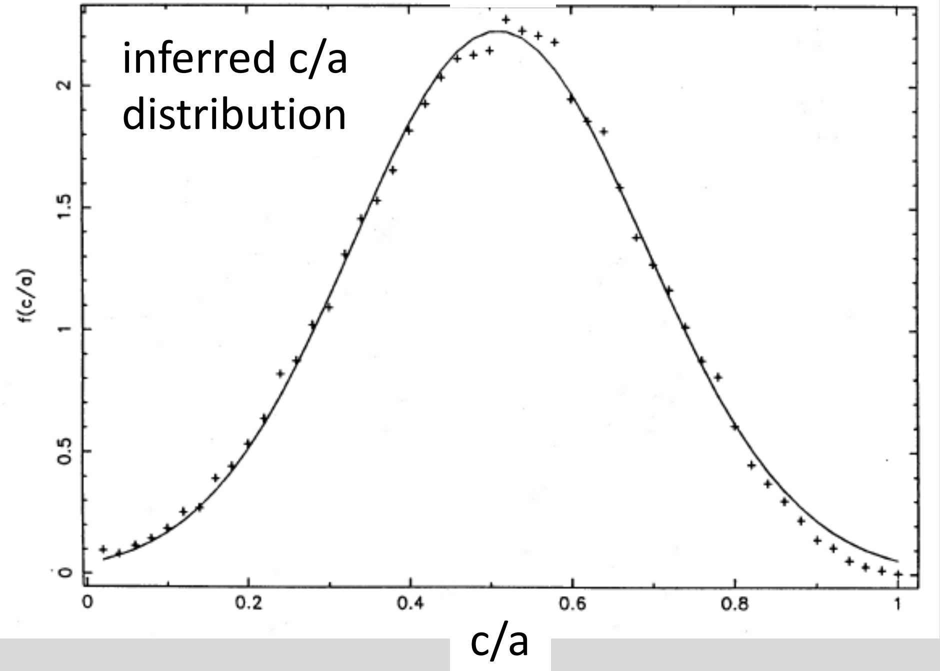
Best fit by a mix of shapes, not purely oblate or prolate.

E’s tend to be more oblate (🍔) than prolate (🏈).

But have a moderate amount of triaxiality.

Inferred **true** axis ratio distribution b/a, c/a: Lambas+92





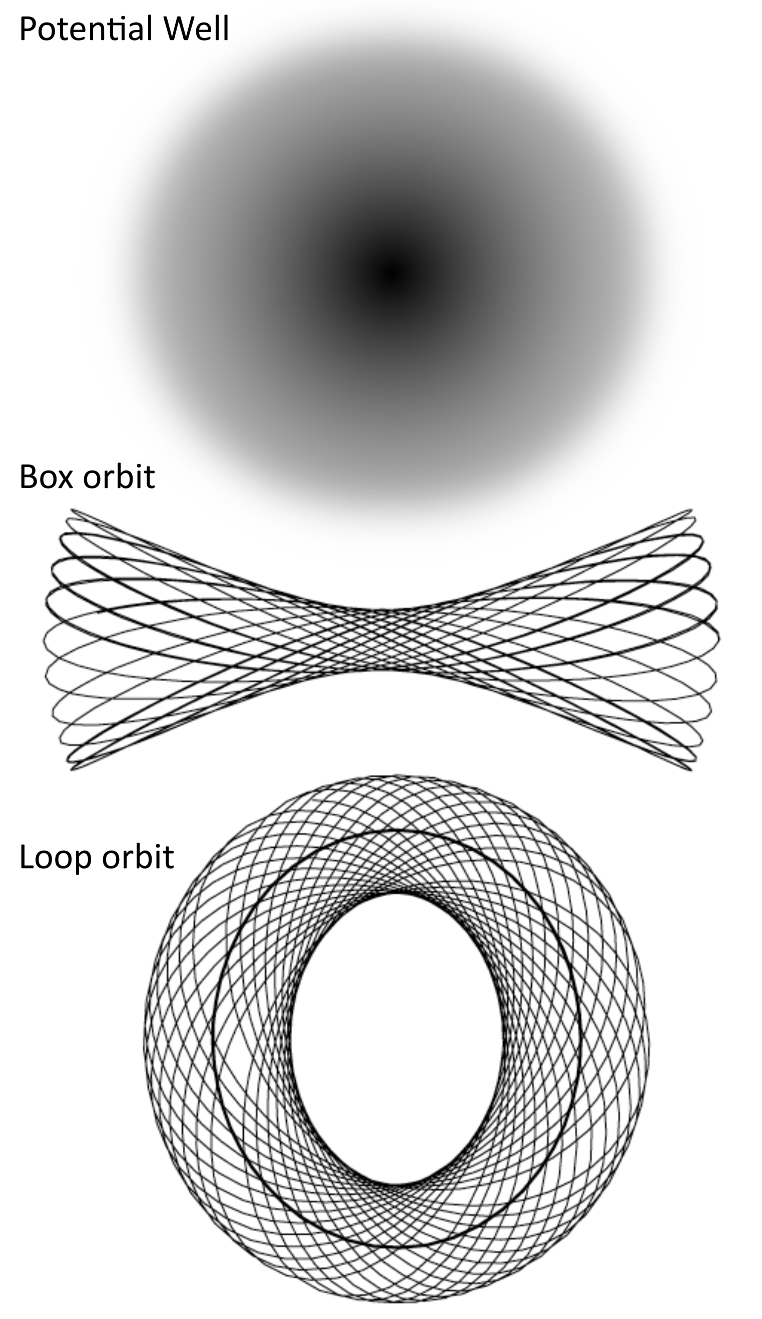
Orbits in elliptical galaxies

Recall disk galaxies: stars are on roughly circular orbits ($V_c/\sigma \gg 1$), and trace out rosette patterns on the disk plane.

Elliptical galaxies have low rotation, large random motions ($V_c/\sigma < 1$), and are mostly "pressure supported". What do the orbits look like?

Loop orbits: high angular momentum, avoid the center. Have a sense of rotation. Over time, the rosette boundaries will fill.

Box orbits: low angular momentum, pass arbitrarily close to the center. No net sense of angular momentum. Over time, the whole "pinched" rectangular-ish block will fill.



Orbits in 3D: Triaxiality

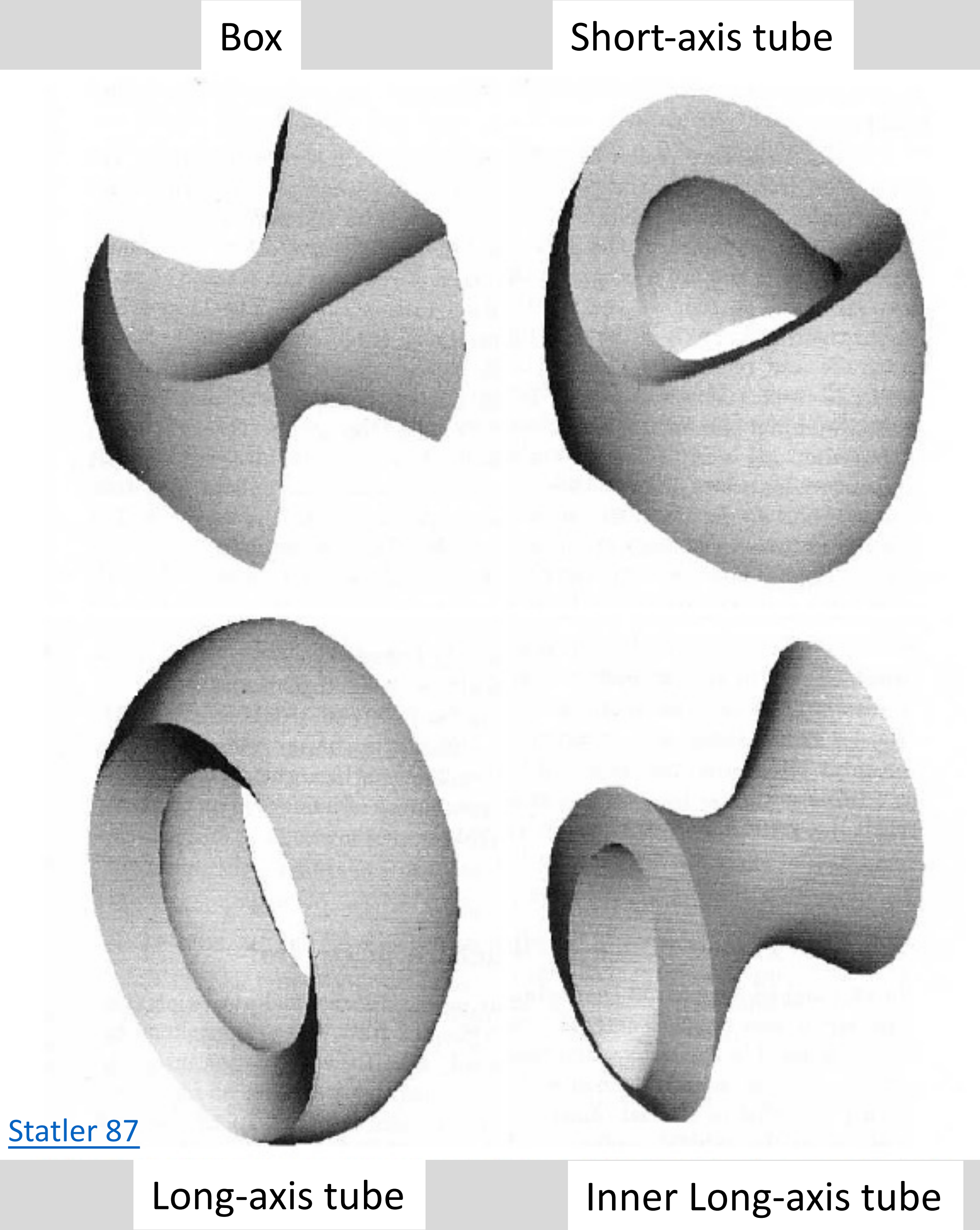
If the density of stars goes as $\rho(r) = \rho_0(r_0/r)^\alpha$, then the radial force acting on a star goes as

$$F_r(r) = -\frac{GM(<r)}{r^2} \sim \frac{Gr^3\rho}{r^2} \sim r^{1-\alpha}$$

so if the density near the center increases more slowly than $\rho \sim r^{-1}$, then $F_r \to 0$ near the center and the potential acts like a harmonic oscillator independent in three directions. All box orbits.

Tube orbits are 3D loops. Long- and short-axis tubes are stable, intermediate-axis tubes are not.

Since tube orbits have axisymmetry, box orbits are the ones that sustain triaxiality.



Orbits and shapes

Remember:

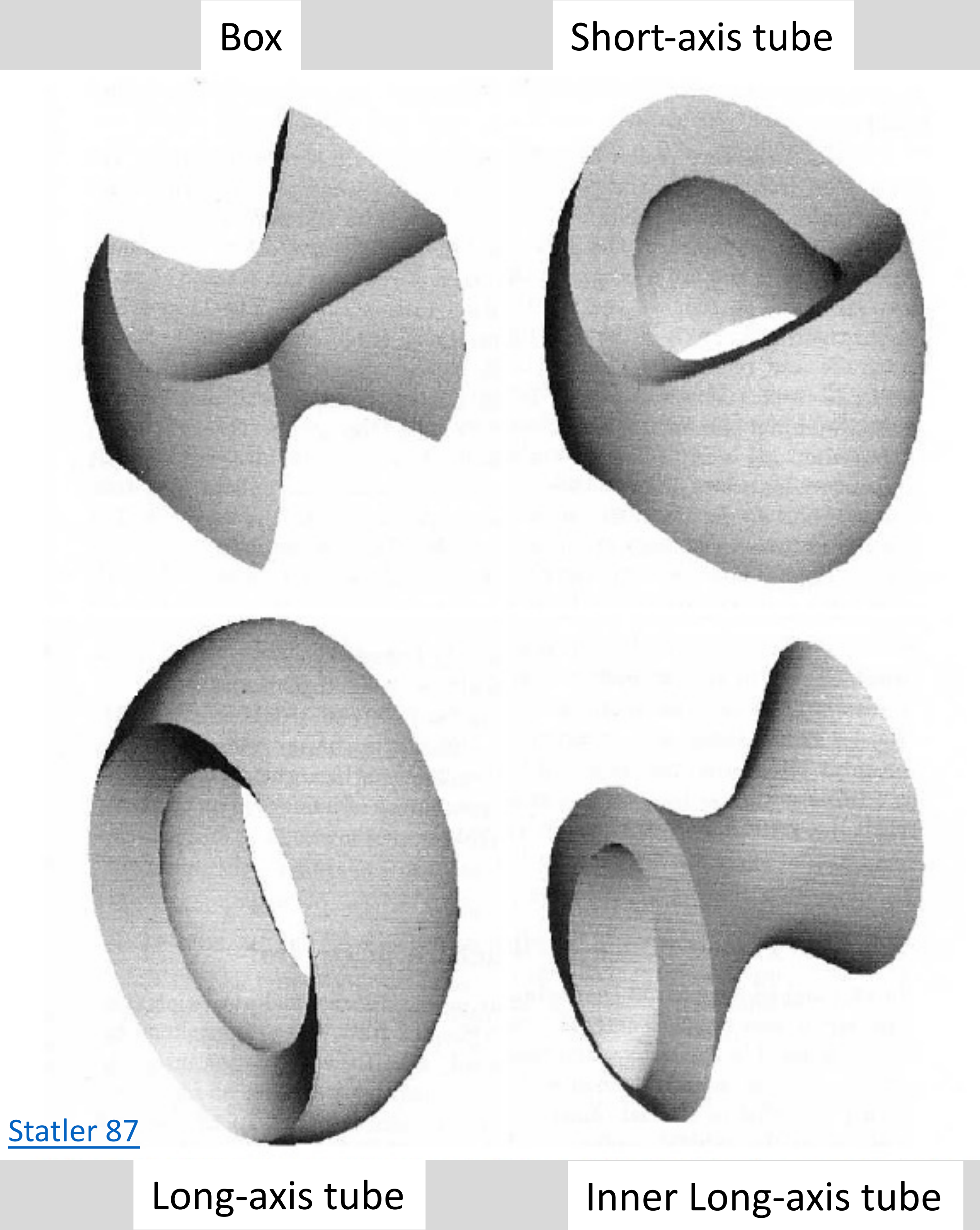
- A galaxy is made of stars.
- Where stars are is what sets the shape of the galaxy.
- The orbits set where the stars are.
- The stars set the potential (at least in the bright inner parts!)
- The potential (shape and radial profile) defines the orbit families.

So everything is interconnected. Change the potential, change the orbits, change the shape. Change the orbits, change the potential, change the shape....

If the density is much steeper than $\rho \sim r^{-1}$, orbits can be scattered off box orbits onto chaotic orbits.

- What could cause a very steep rise in density at the center?

- What would happen to the shape if you scattered orbits?



Statler 87