DARK MATTER

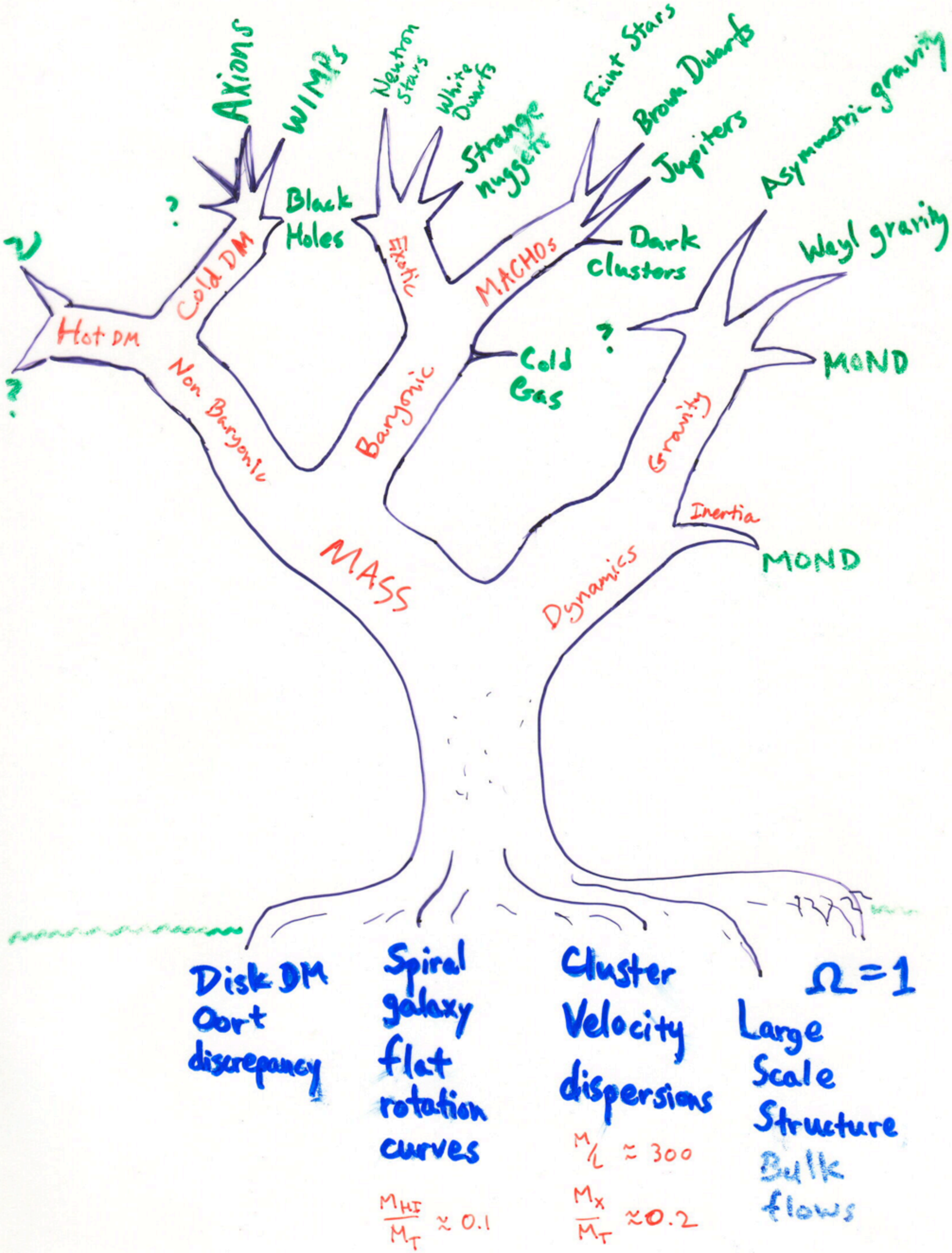
ASTR 333/433

TODAY

LAWS OF GALACTIC ROTATION

APPLICATION

ELLIPTICAL GALAXIES



Empirical Laws of Galactic Rotation

- Flat rotation curves (Rubin-Bosma Law)

  Rotation curves tend asymptotically towards a constant rotation velocity that persists to indefinitely large radii: $V(R \rightarrow \infty) \rightarrow V_f$

- Tully-Fisher relation (Luminous, Stellar Mass, and Baryonic TF relations)

  The baryonic mass of galaxies scales as the fourth power of the flat rotation velocity: $M_b = AV_f^4$

- Central density relation (lower surface brightness galaxies exhibit larger mass discrepancies)

  The central dynamical surface densities of galaxies is related to their central surface brightnesses: $\Sigma_{dyn}(R \rightarrow 0) = f[\Sigma_*(R \rightarrow 0)]$

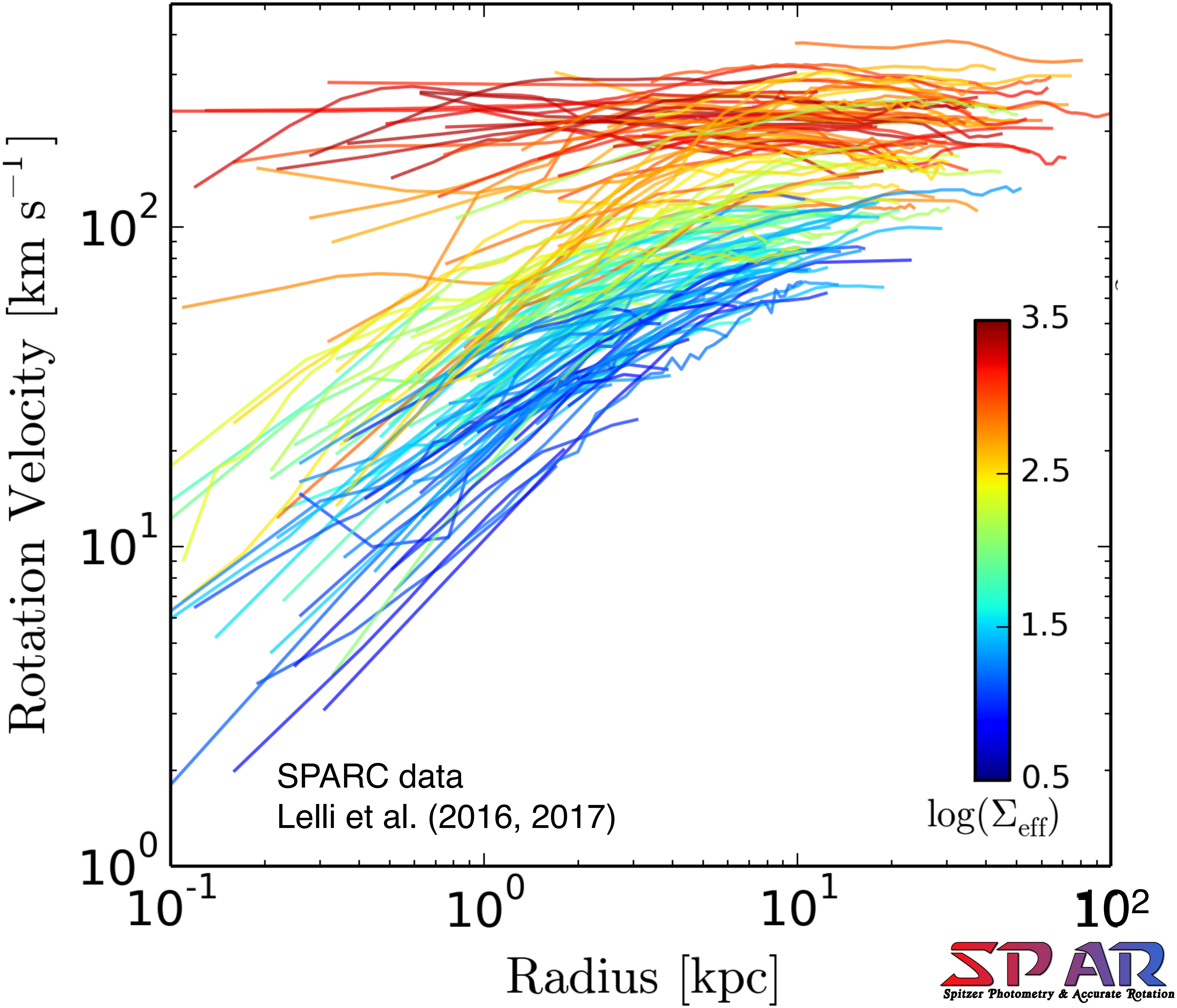
- Renzo's rule (Sancisi's Law)

  "For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa." (Sancisi 2004).

- Radial acceleration relation

  The observed centripetal acceleration is related to that predicted by the observed distribution of baryons: $\mathrm{g}_{\mathrm{obs}} = \mathcal{F}(\mathrm{g}_{\mathrm{bar}})$

Applications: both qualitative and quantitative



SPARC data
Lelli et al. (2016, 2017)

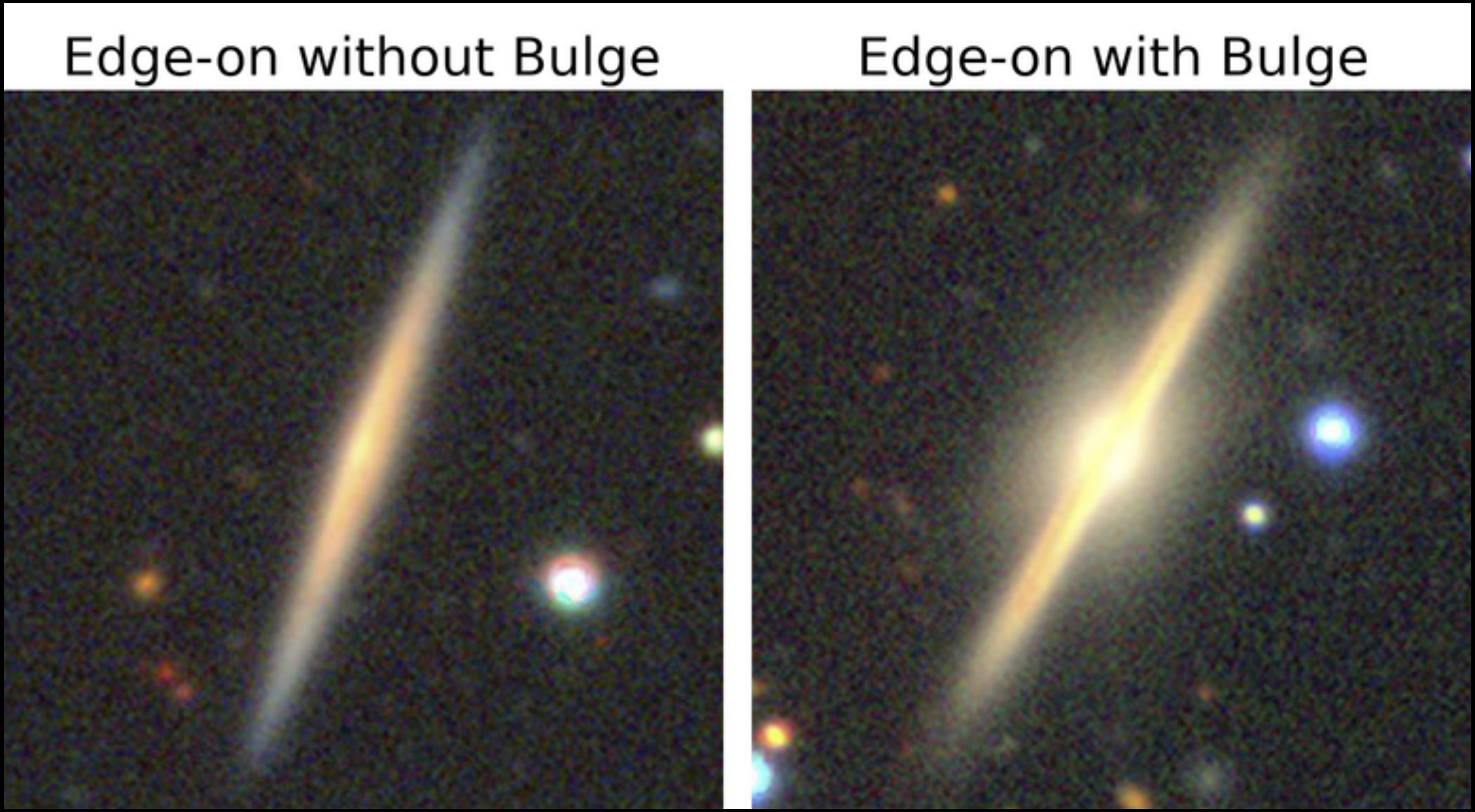
SPARC
Spitzer Photometry & Accurate Rotation Curves

Central Density Relation: lower surface brightness means slower rotation curve rise

High surface brightness

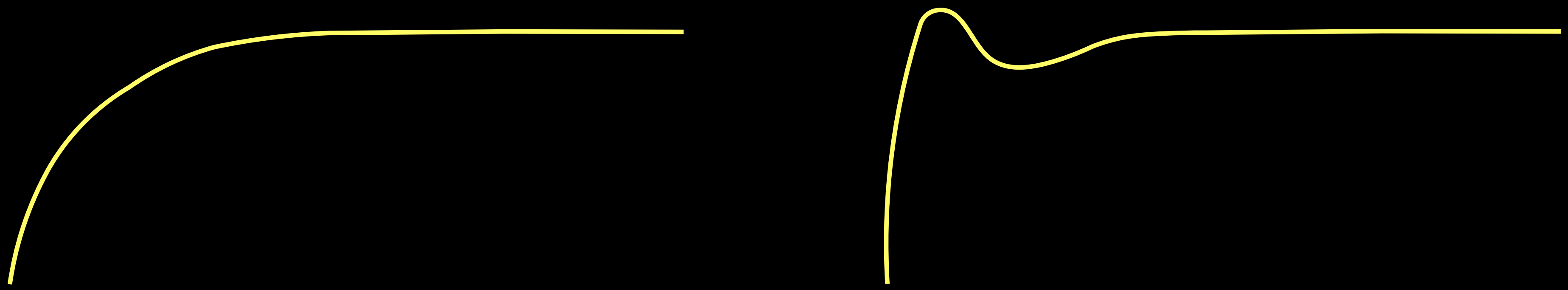
Low surface brightness

Renzo’s rule: features in the light map to features in the rotation curve

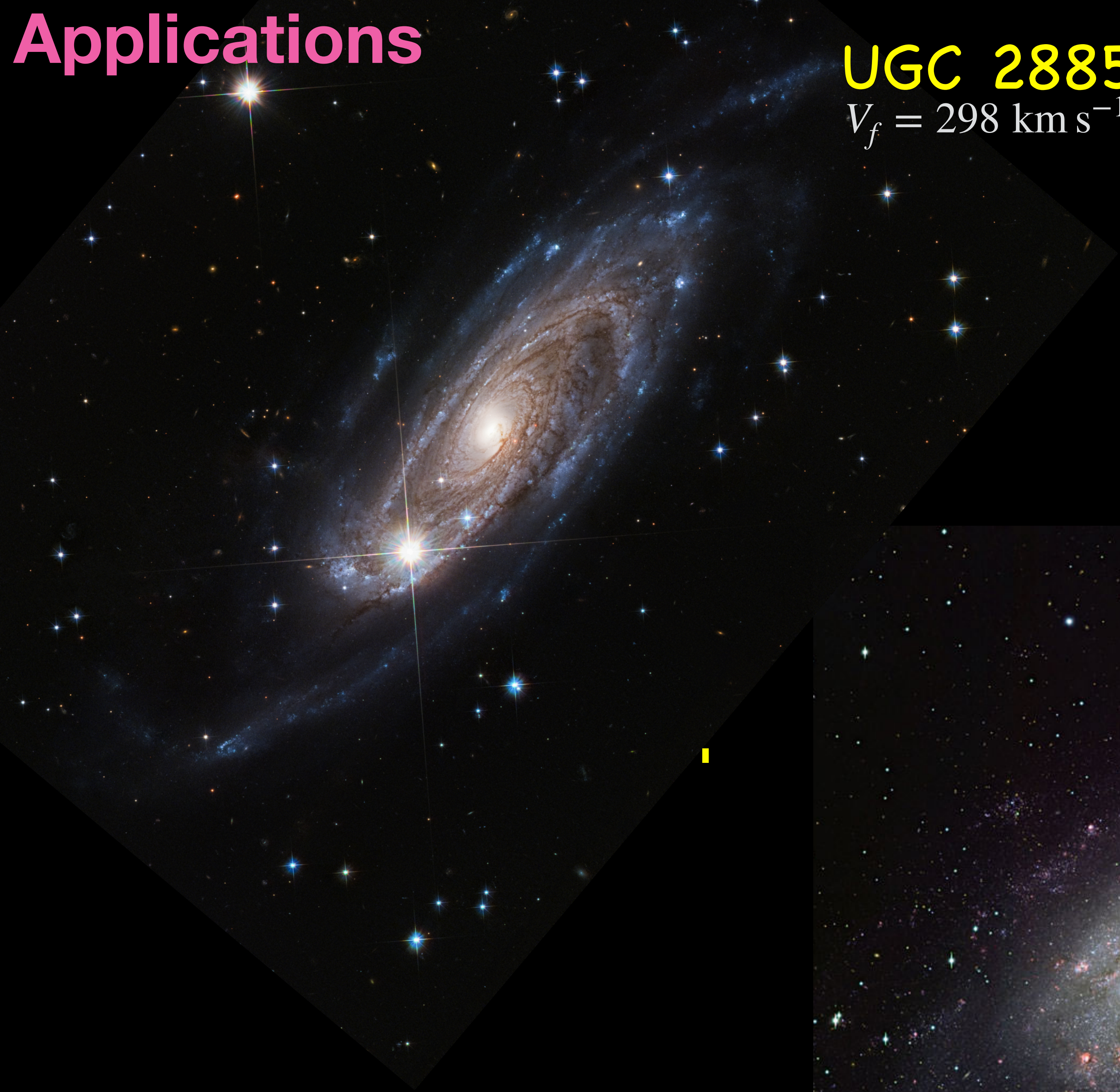


Edge-on without Bulge

Edge-on with Bulge



Applications



UGC 2885

$V_f = 298 \text{ km s}^{-1}$

What is the baryonic mass of each galaxy?

Which relation to use?

NGC 2403

$V_f = 131 \text{ km s}^{-1}$

DDO 154

$V_f = 53 \text{ km s}^{-1}$

All the systematic properties involve a critical acceleration scale.

- Baryonic Tully-Fisher Relation

$$\mathrm{g}_{\dagger}^{\mathrm{BTFR}} = 1.24 \pm 0.14 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

(McGaugh 2011)

- Central Density Relation

$$\mathrm{g}_{\dagger}^{\mathrm{CDR}} = G\Sigma_{\dagger} = 1.27 \pm 0.05 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

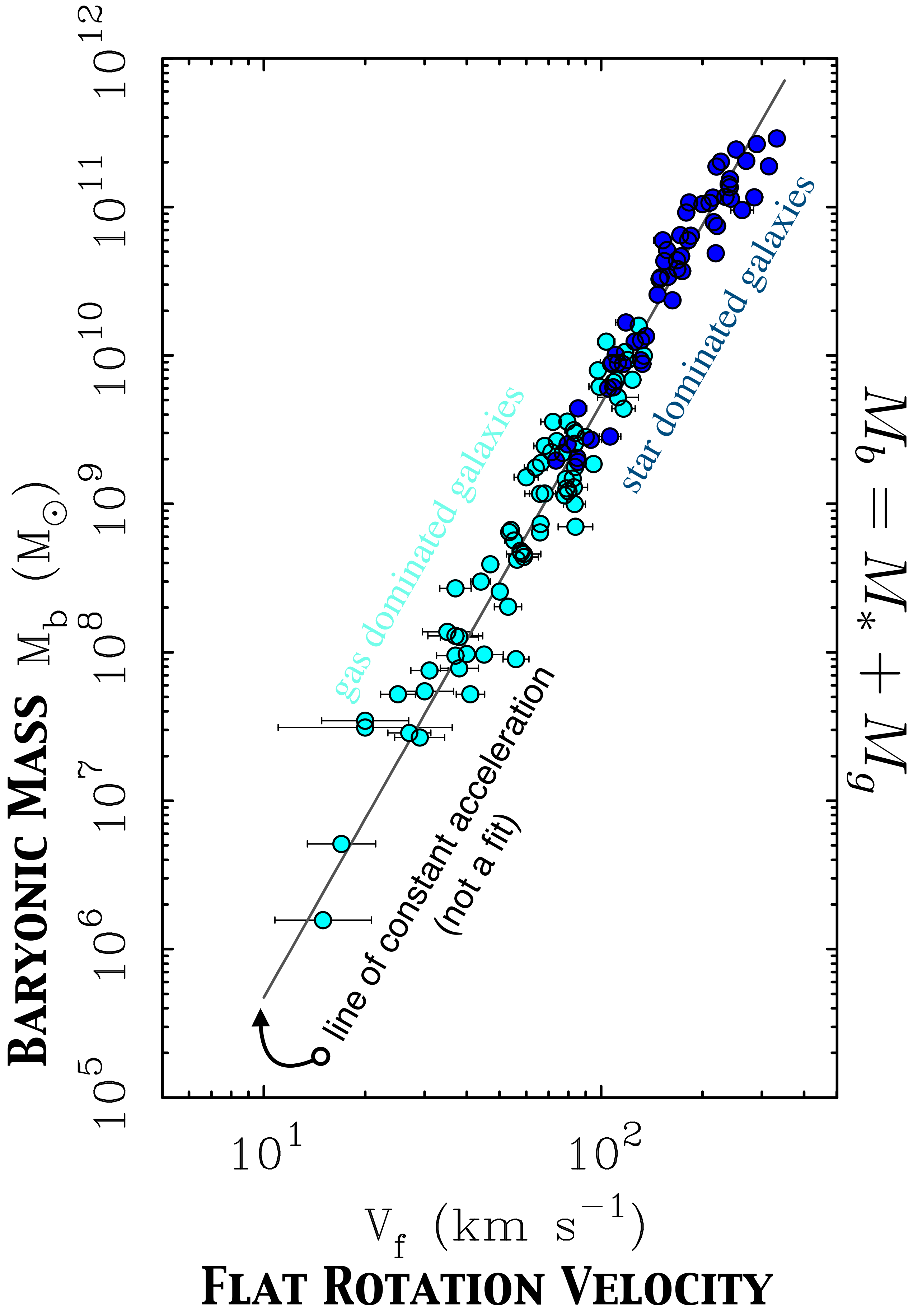
(Lelli et al. 2016)

- Radial Acceleration Relation

$$\mathrm{g}_{\dagger}^{\mathrm{RAR}} = 1.20 \pm 0.02 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

(McGaugh et al. 2016)

Baryonic Tully-Fisher Relation



Can construct a characteristic acceleration for each galaxy

$$g_\dagger = \frac{\zeta V_f^4}{G M_b}$$

Galaxies closely follow a single, universal acceleration.

ζ is a factor of order unity that accounts for the geometry of disk galaxies, which are not spherical cows. We adopt $\zeta = 0.8$ (McGaugh 2005).

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Central Density Relation

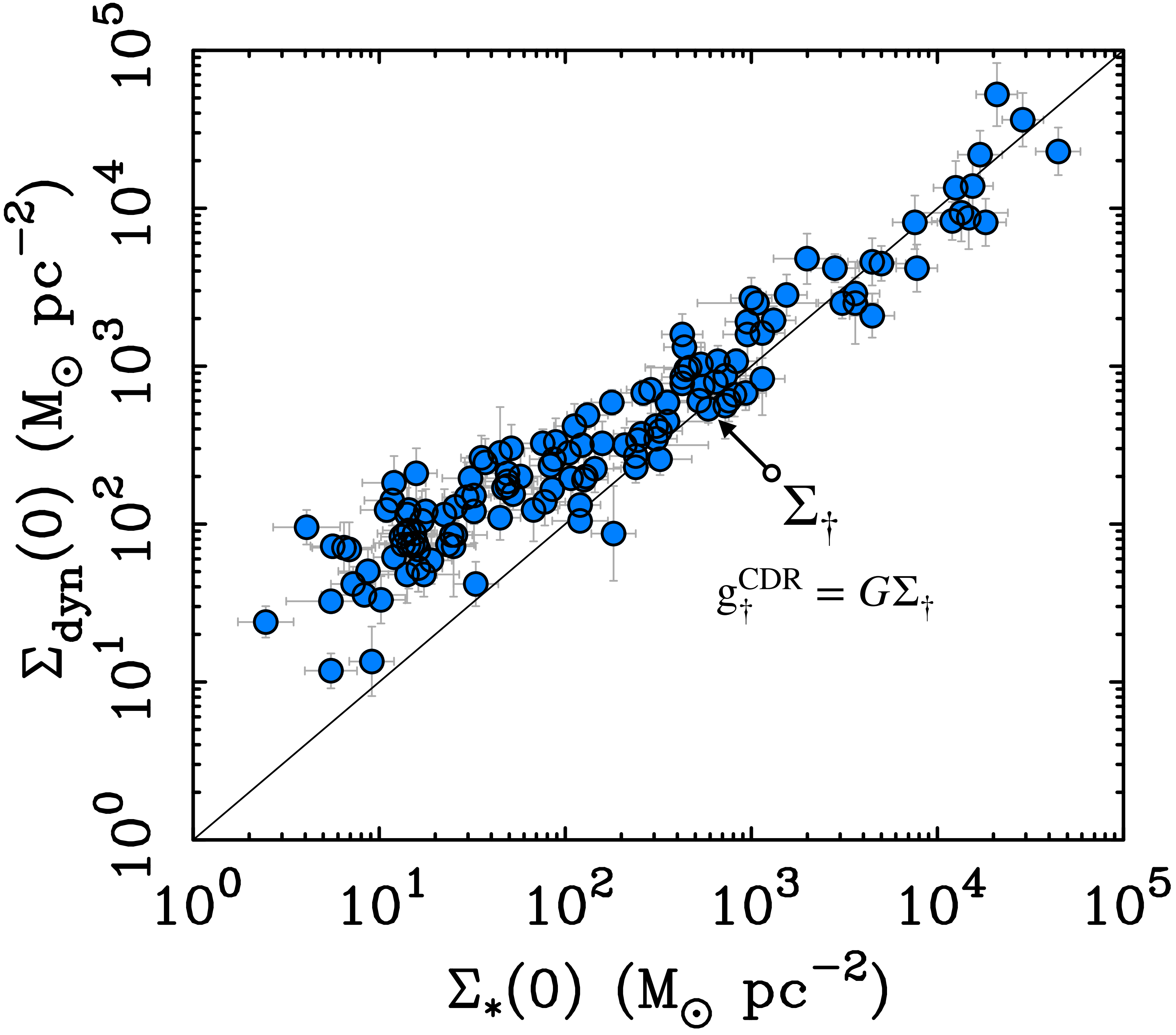
Lelli et al. (2016)

The *dynamical* central mass surface density correlates with the central surface brightness of stars in galaxies.

central dynamical surface density

Toomre (1963)

$$\Sigma_{dyn}(0) = \frac{1}{2\pi G}\int_0^\infty \frac{V^2(R)}{r^2}dR$$



$$g_\dagger^{\mathrm{CDR}} = G\Sigma_\dagger$$

central surface brightness

<u>All the systematic properties involve a critical acceleration scale.</u>

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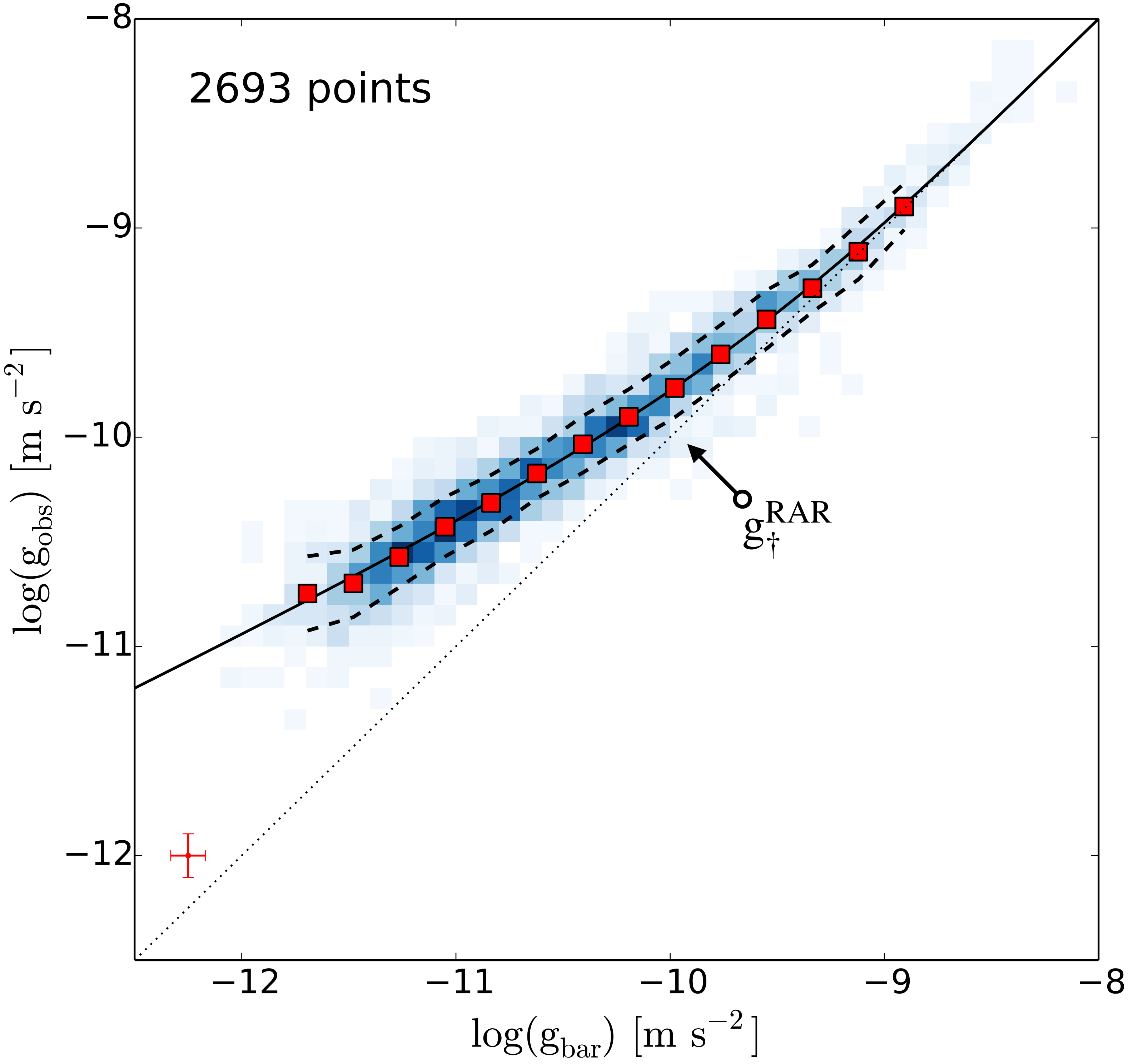
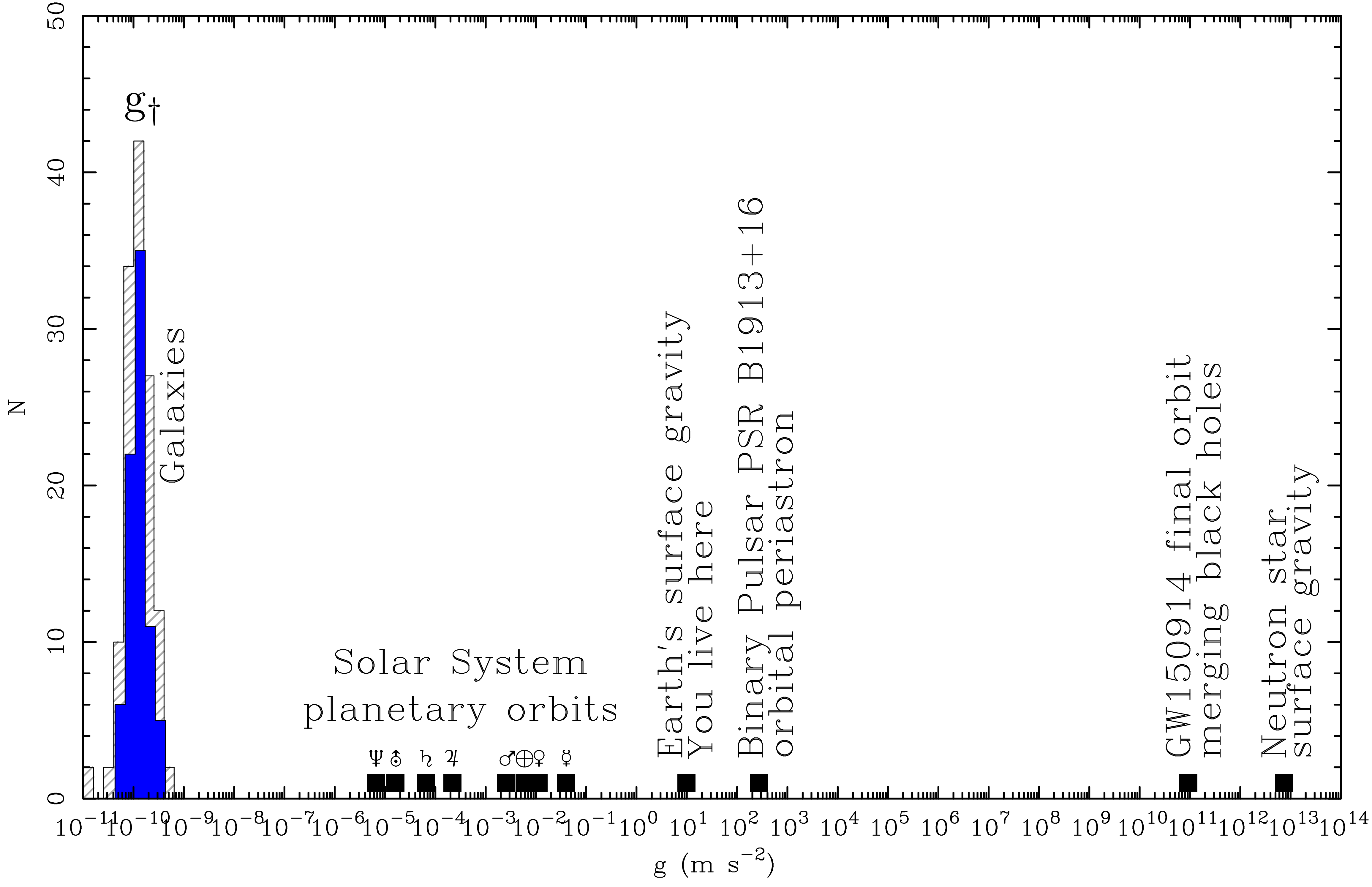
Radial Acceleration Relation (RAR)



Over 25 decades in acceleration,
galaxies only exist around 1 Å/s/s

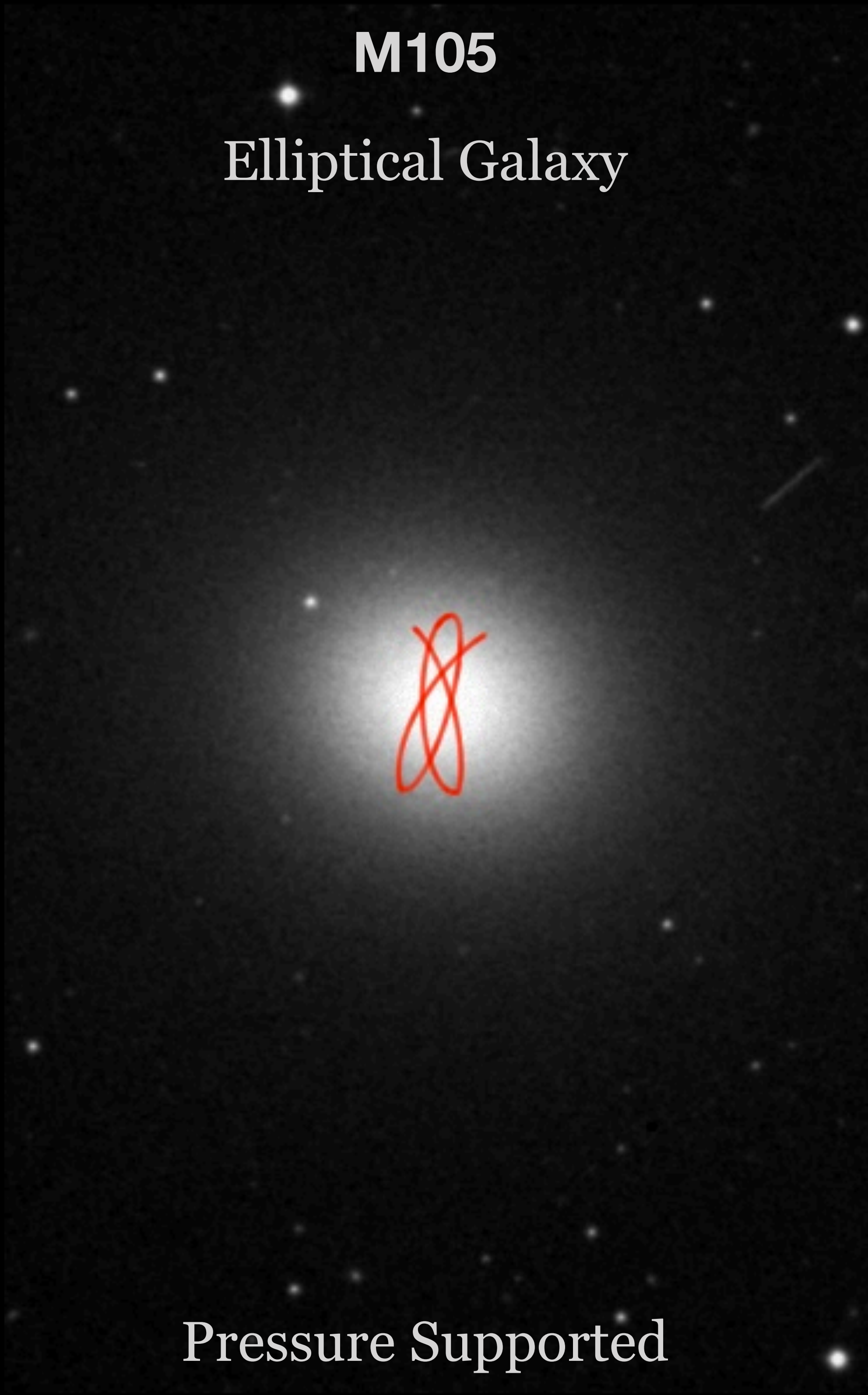
$g_\dagger$ is a special value



Elliptical Galaxies

Elliptical galaxies are presumed to reside in dark matter halos, but the evidence is less obvious than for spirals.

Stellar orbits in galaxies

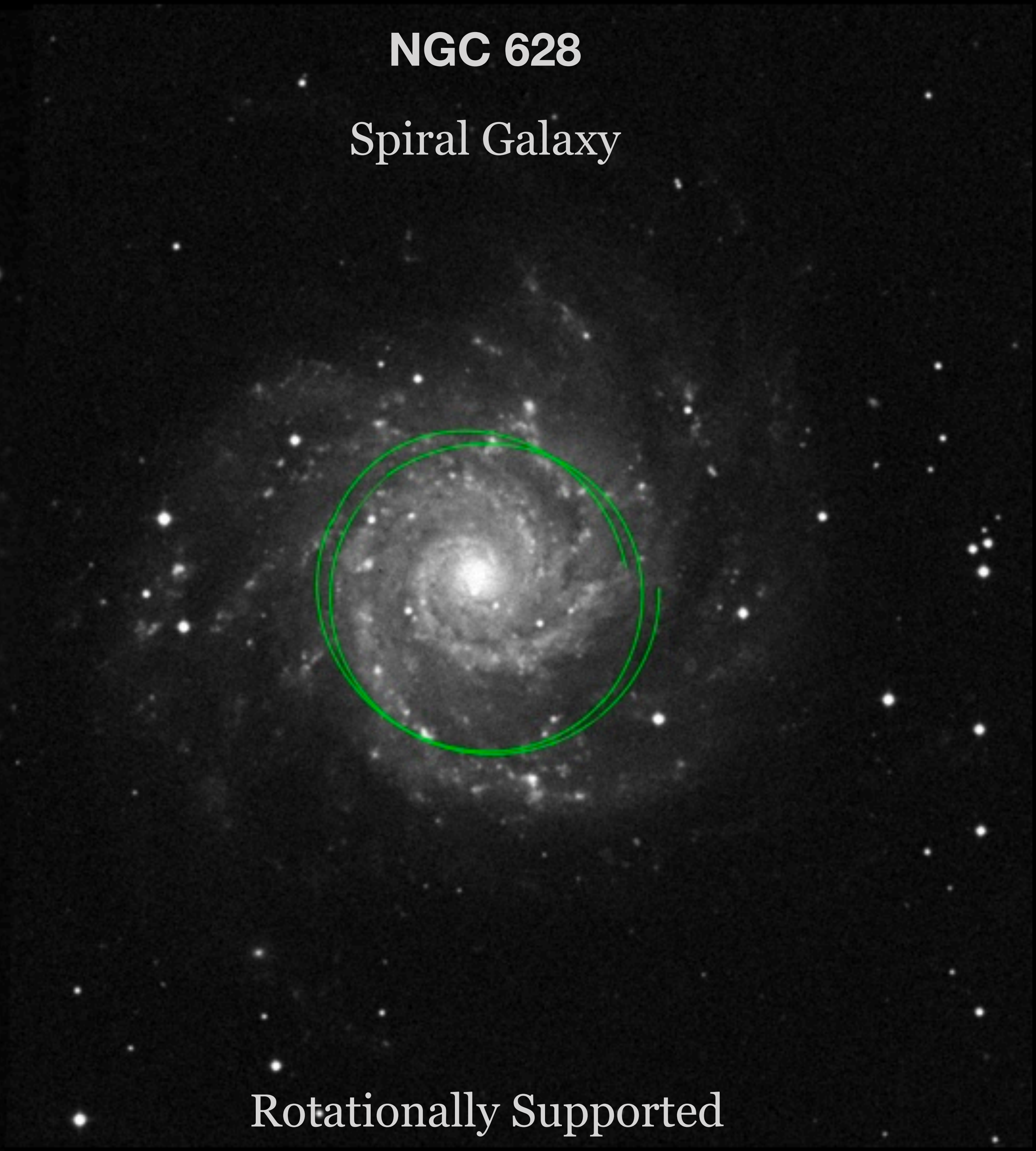


M105

Elliptical Galaxy

Pressure Supported

Eccentric radial orbits
Random orientations



NGC 628

Spiral Galaxy

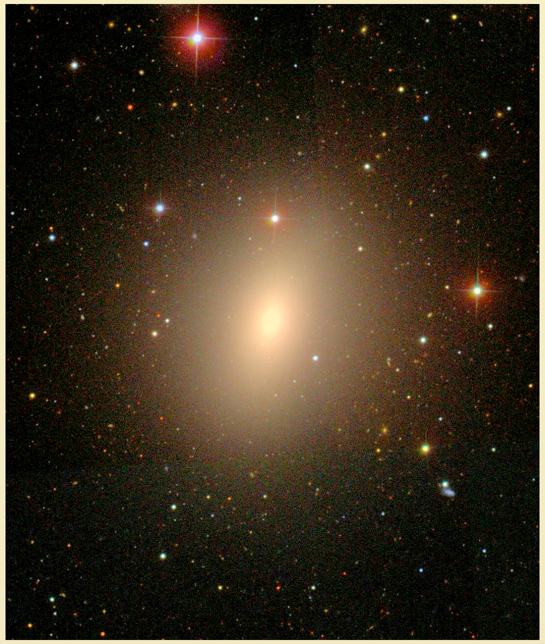
Rotationally Supported

Nearly circular orbits
Same direction, same plane

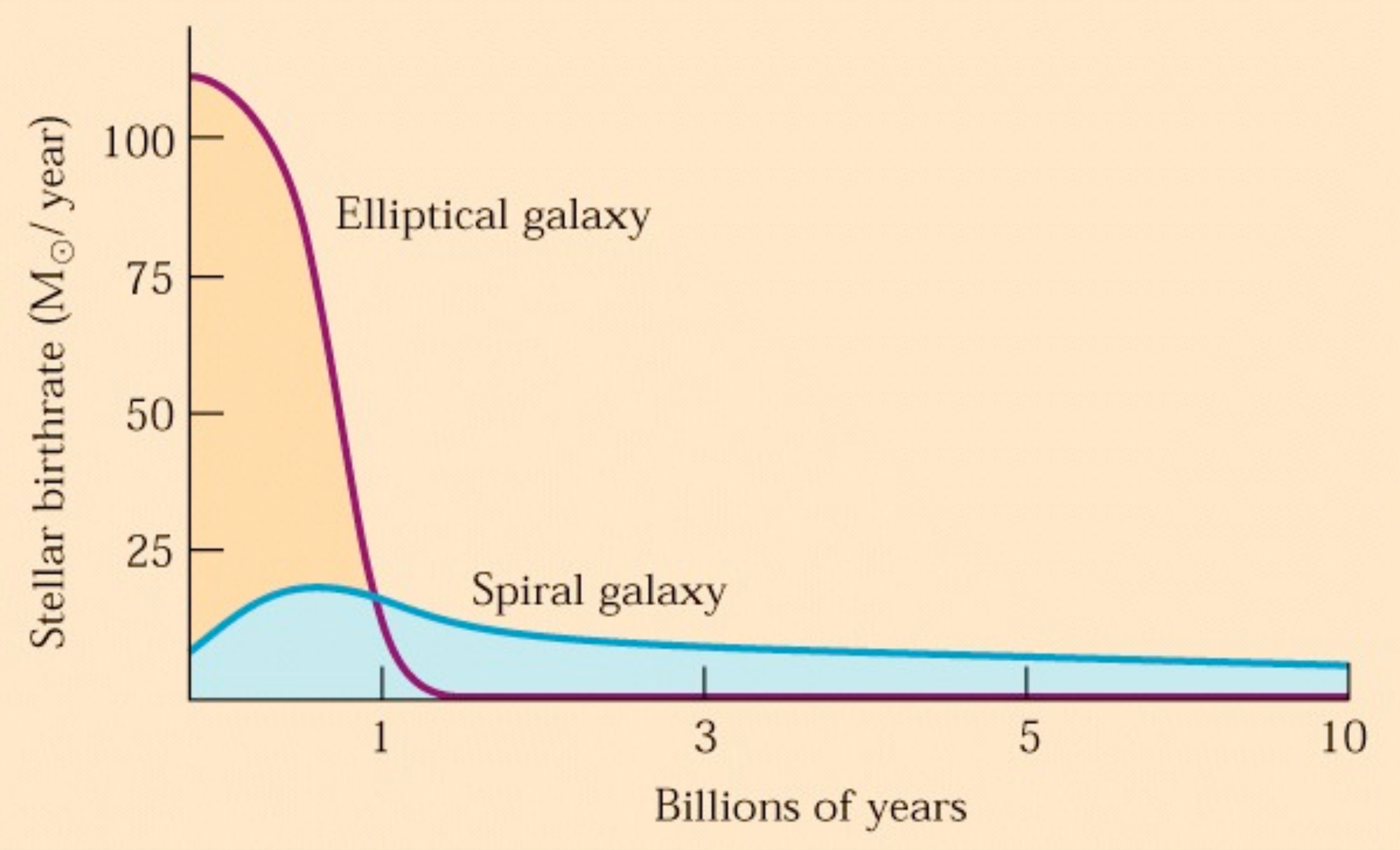
Elliptical Galaxies

Generic Star Formation History

Elliptical



old stars

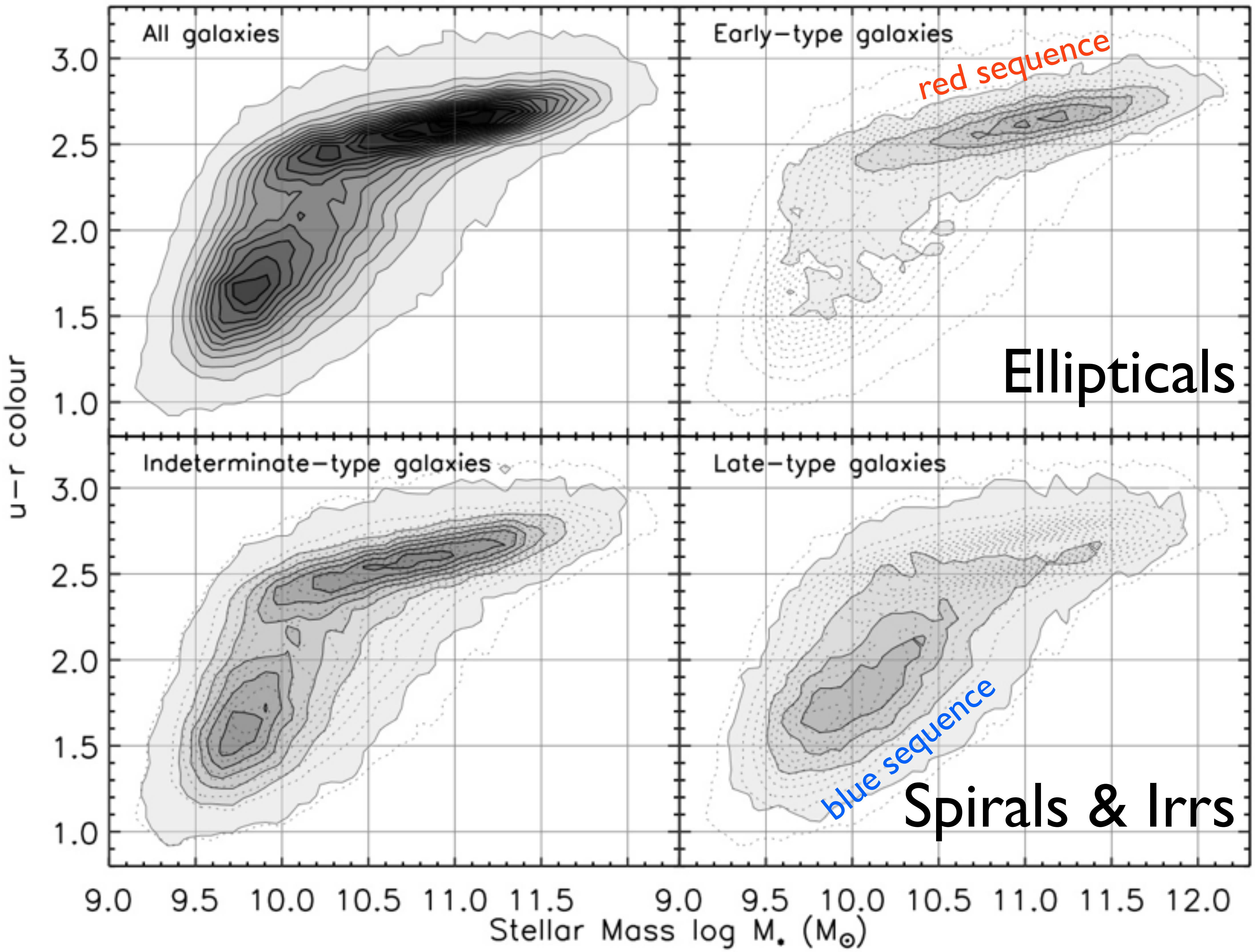


Expect the older stars in elliptical galaxies to have higher mass-to-light ratios than in spirals.

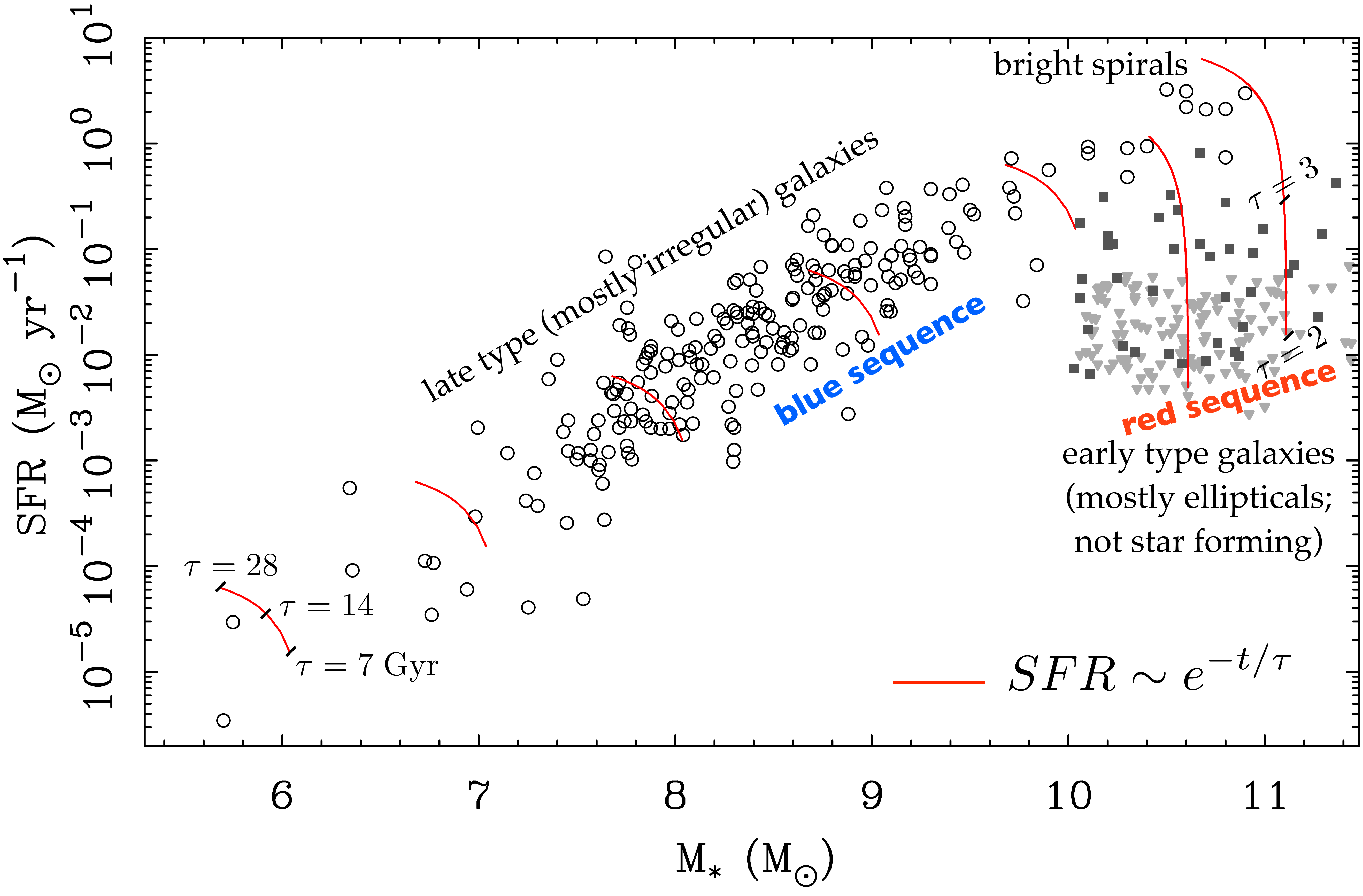
Spiral

old stars
young stars
cold gas

color-magnitude relation for galaxies



"Main Sequence of Star Forming Galaxies"



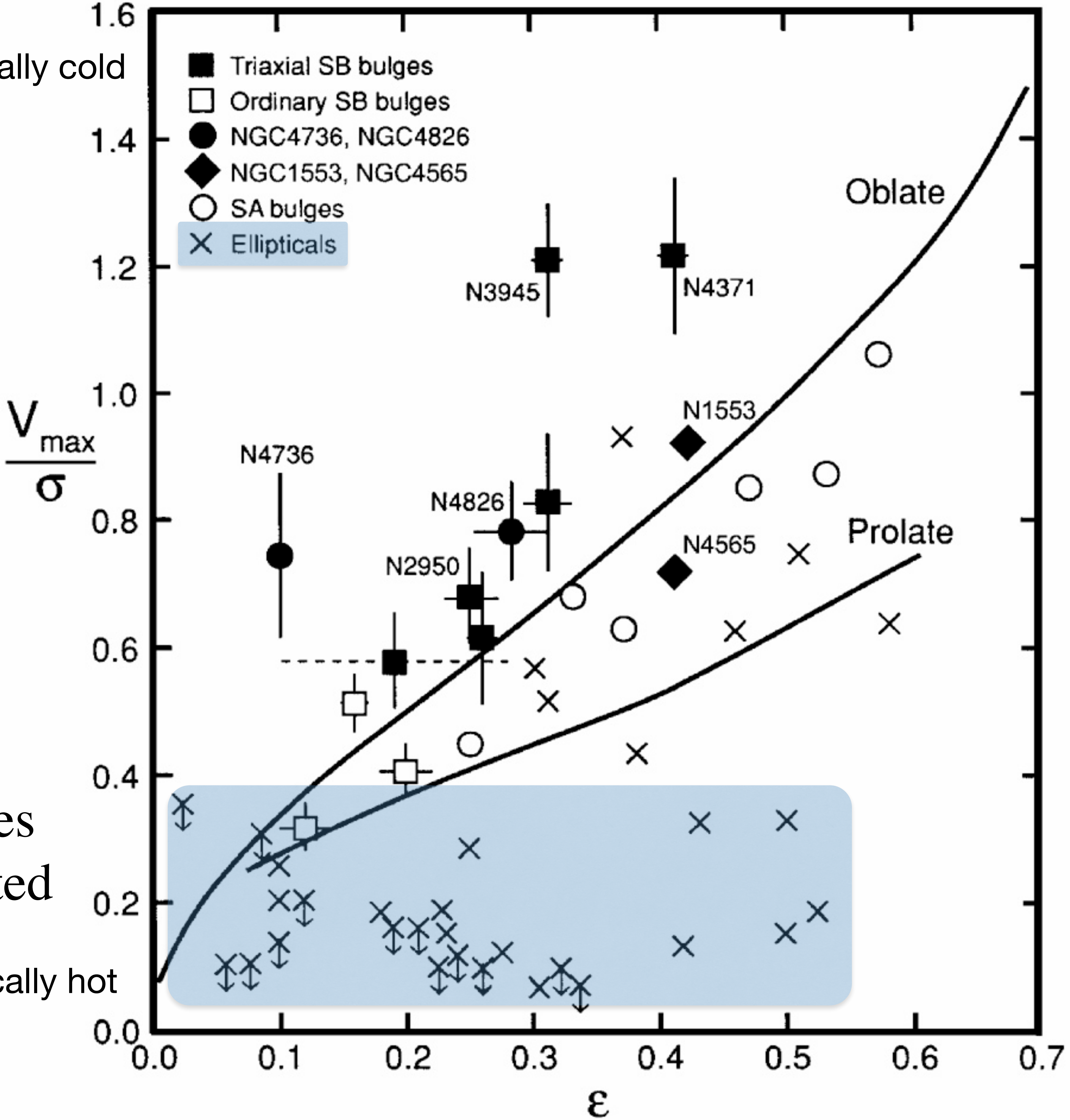
dynamically cold

Spiral galaxies
way off scale

$$\frac{\text{rotation}}{\text{dispersion}}$$

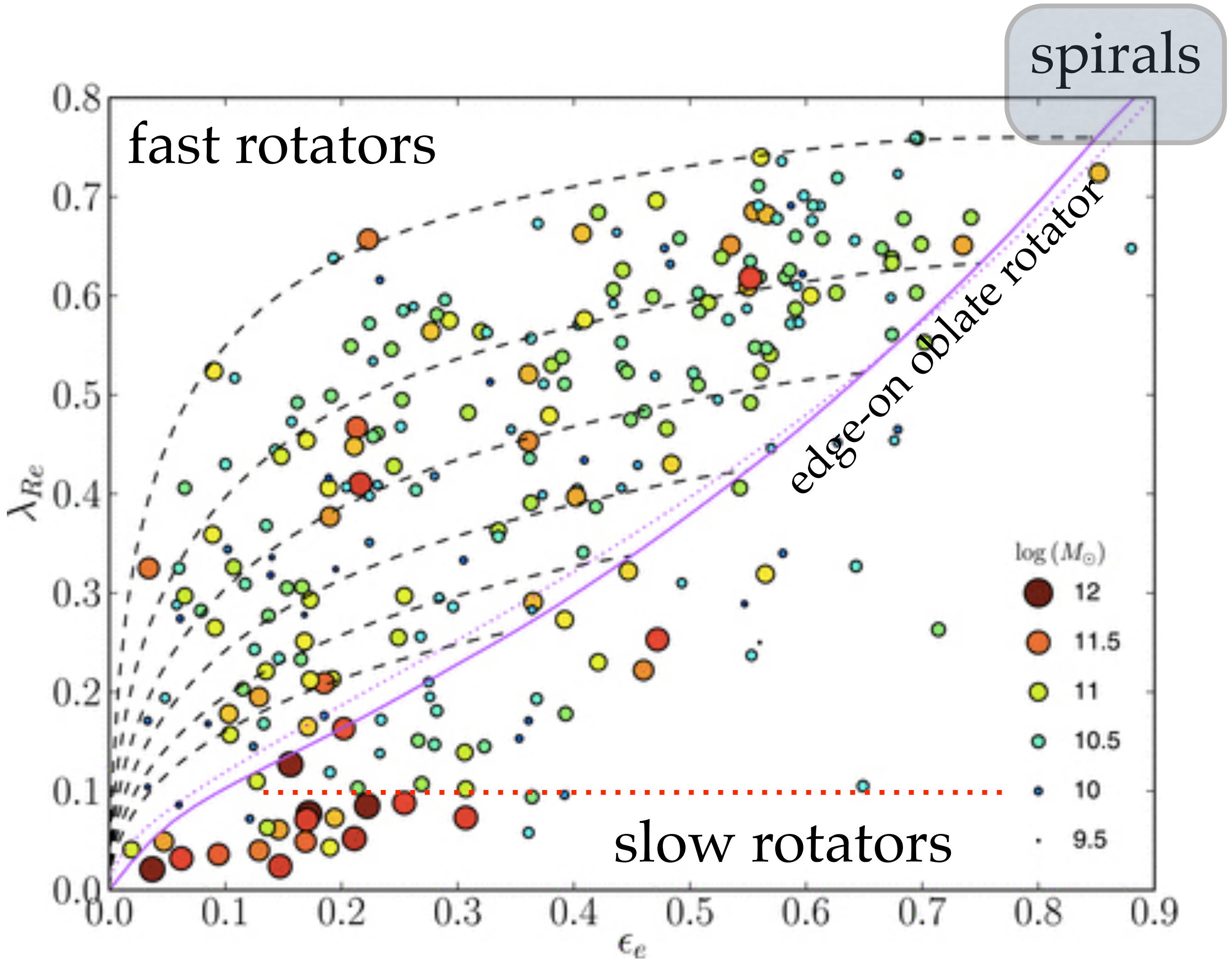
Elliptical galaxies
pressure supported

dynamically hot



$$\lambda_R = \frac{\langle R|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle}$$

specific angular momentum



spirals

fast rotators

edge-on oblate rotator

slow rotators

ellipticity

Massive ellipticals mostly pressure supported (slow rotators) while many (not all) lower mass ellipticals are fast rotators. These are often S0 galaxies.

Dashed lines represent different inclinations for different intrinsic ellipticities

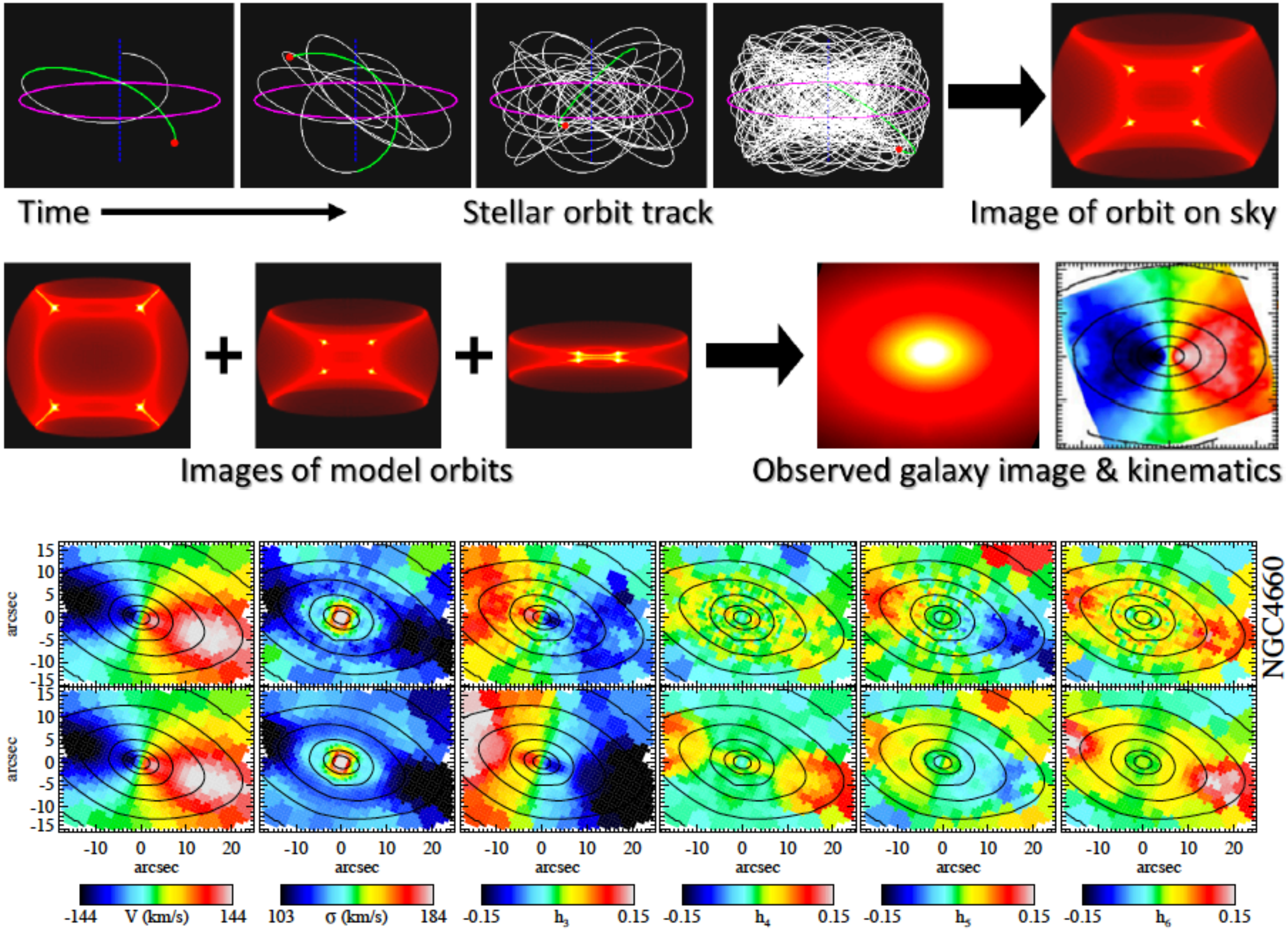
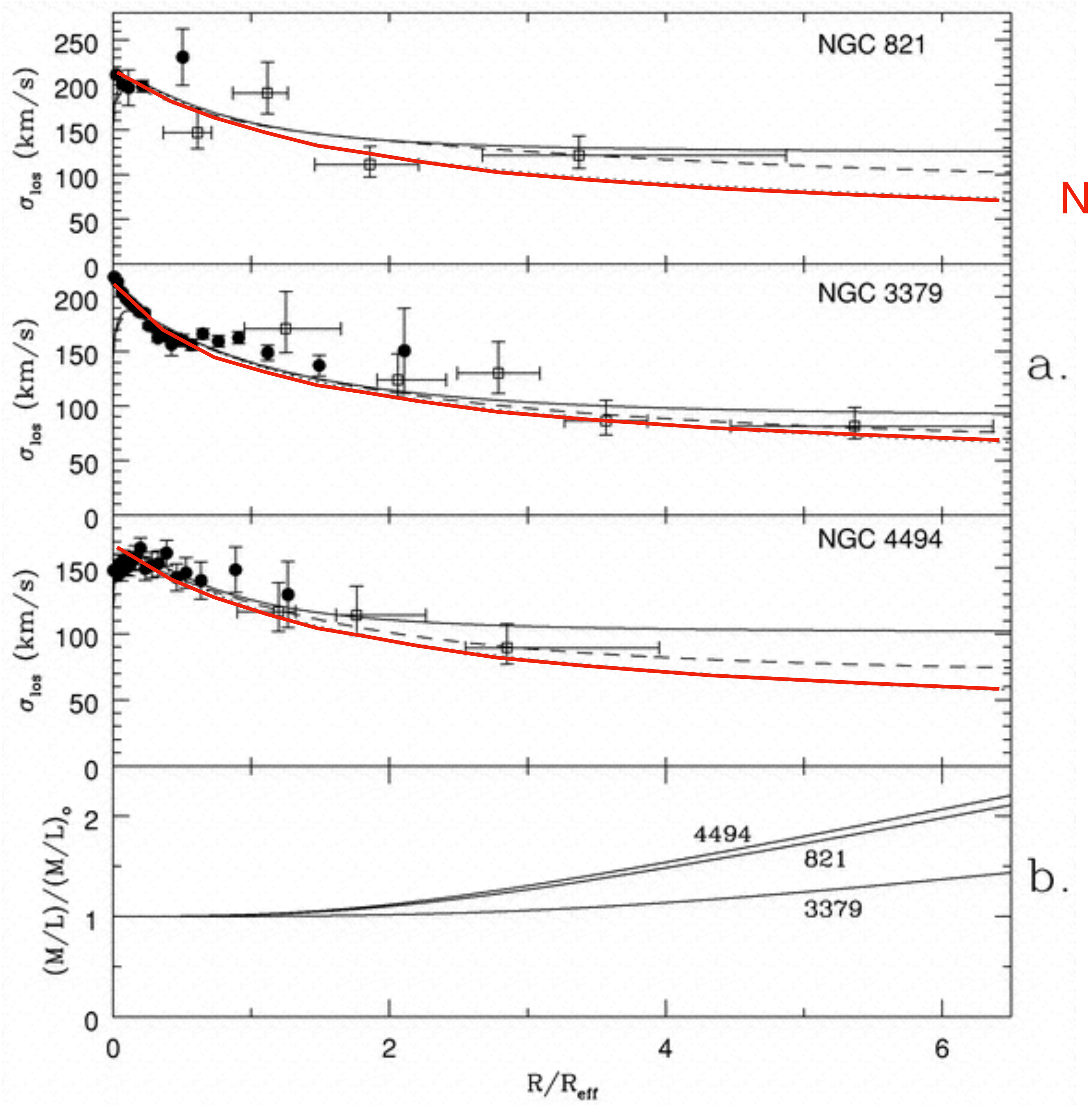


Figure 3. Schwarzschild's orbit-superposition method. *Top Row:* numerical integration of a single orbit in the adopted gravitational potential. After a sufficiently long time the density (of regular orbits) converges to a fixed distribution. *Middle Row:* the method finds the linear combination of thousands of orbits (three representative are shown here) which best fits the galaxy image and stellar kinematics. *Bottom two rows:* data (top) versus model (bottom) comparison. The model can fit the full stellar line-of-sight velocity distribution, here parametrized by the first six Gauss-Hermite moments (from Cappellari et al. 2007).

anisotropy

Velocity dispersion profiles for 3 ETGs

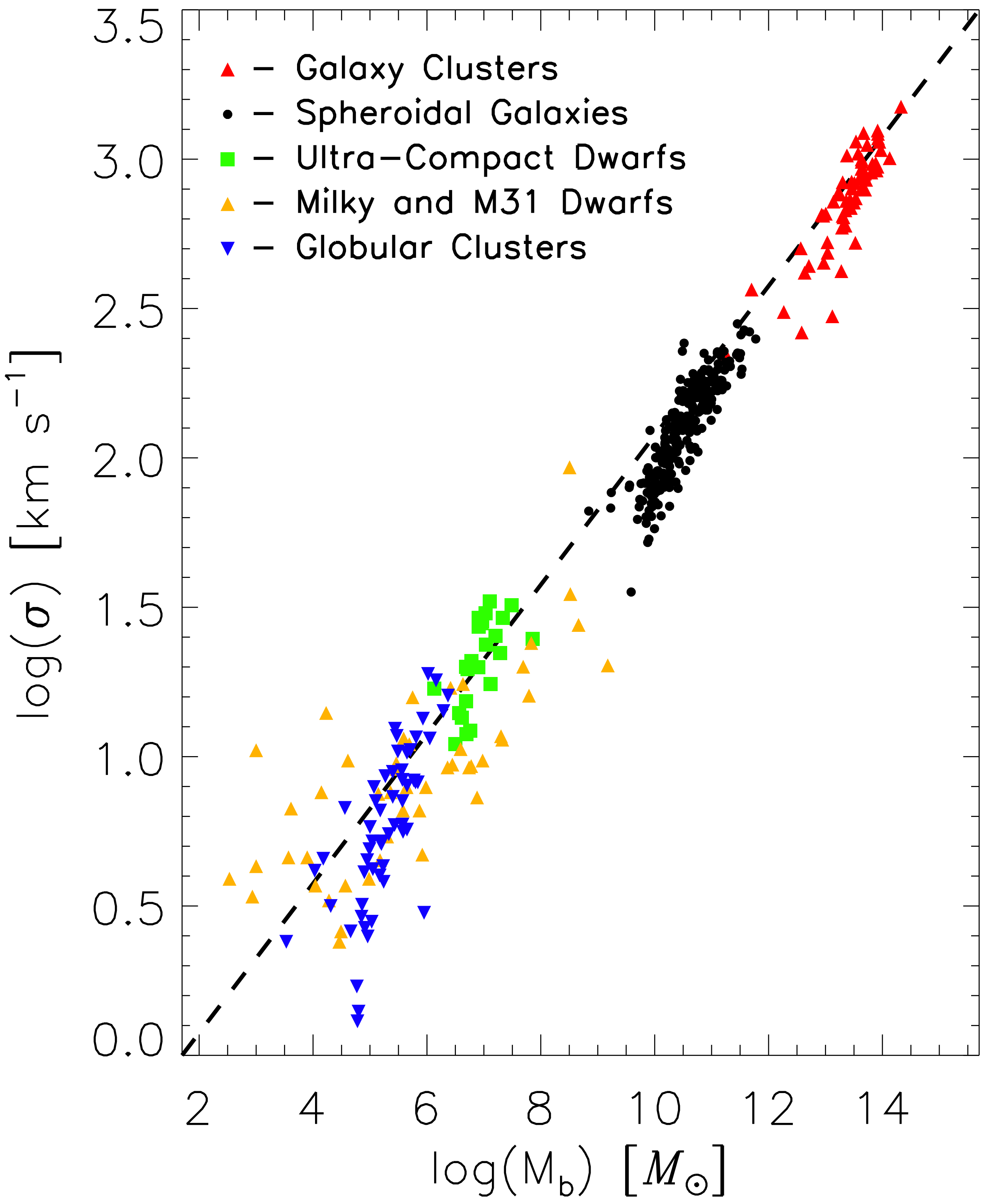
measured from stars at small R, PN at large R



No dark matter

Faber-Jackson (pressure supported)

Tully-Fisher for Ellipticals

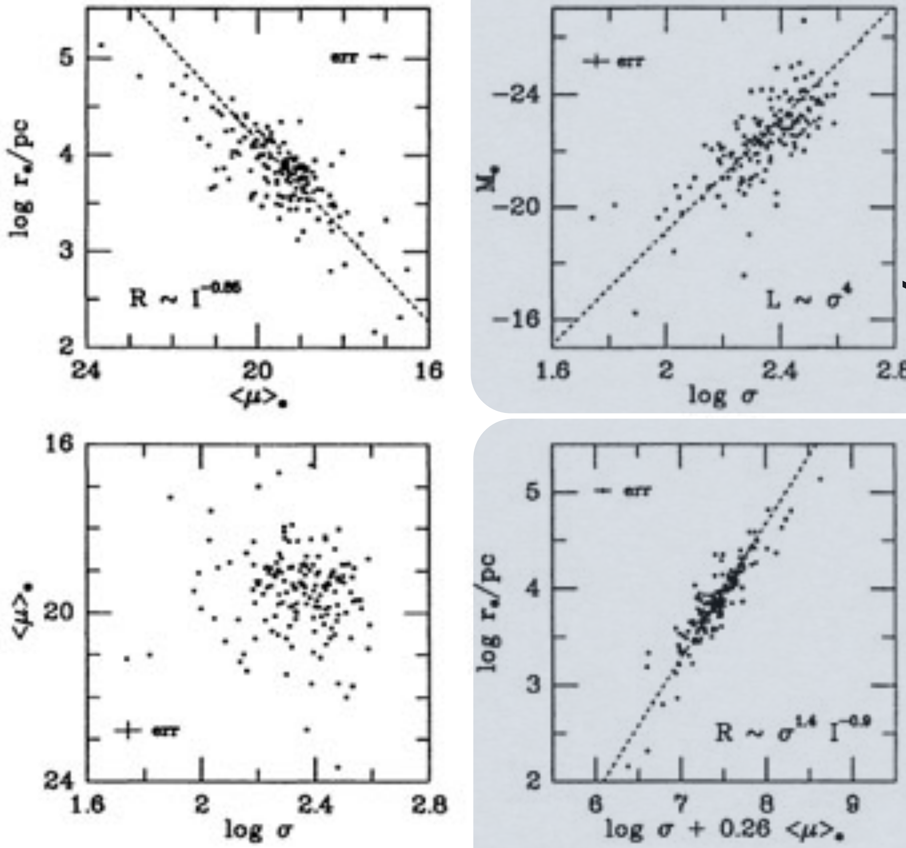


Fundamental Plane (pressure supported)

surface brightness

velocity dispersion

Faber-Jackson



size

luminosity

surface brightness

size

velocity dispersion

v-disp & surf bright.

Fundamental Plane

“Viral” fundamental plane

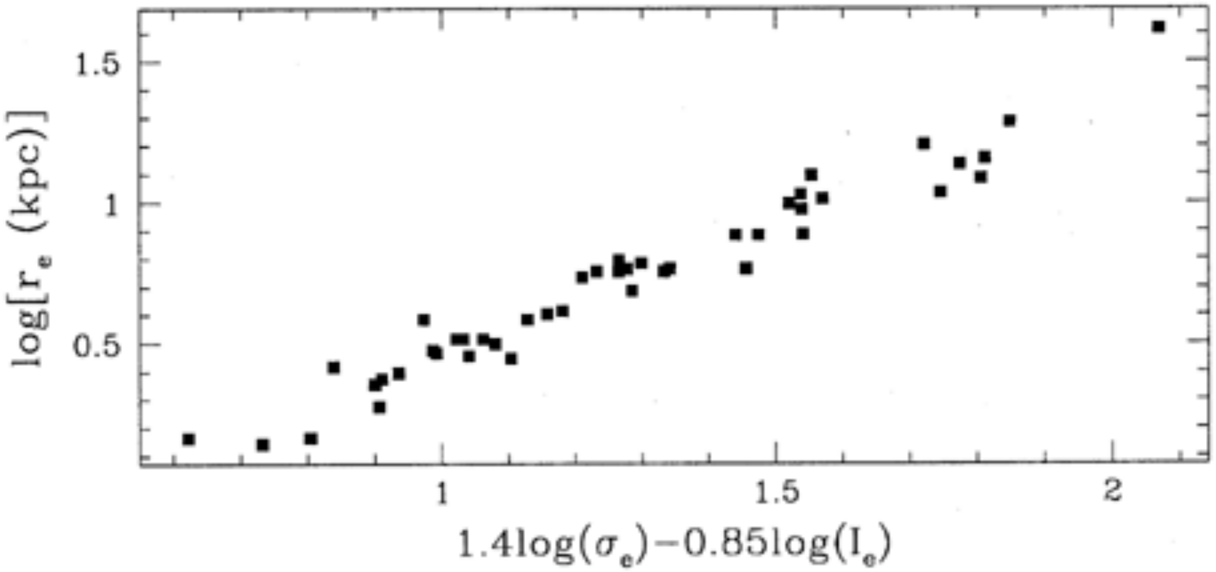
$$R_e \propto \sigma^2 I_e^{-1}$$

observed fundamental plane “tilted” wrt virial expectation:

$$R_e \propto \sigma^{1.4} I_e^{-0.85}$$

velocity dispersion & surface brightness

size

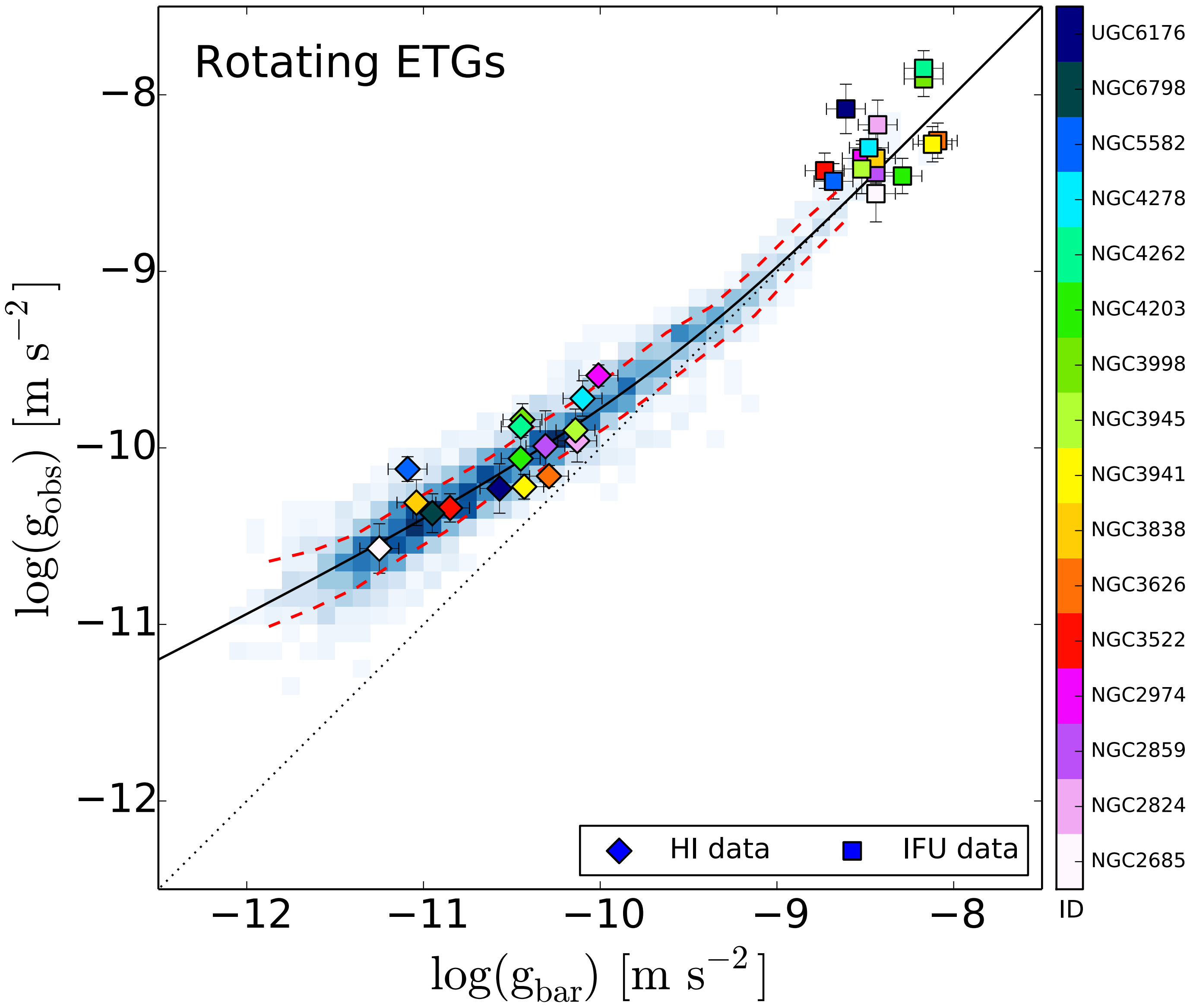


$$M \propto \sigma^2 R_e$$ virial theorom

$$L \propto I_e R_e^2$$ luminosity, surface brightness size

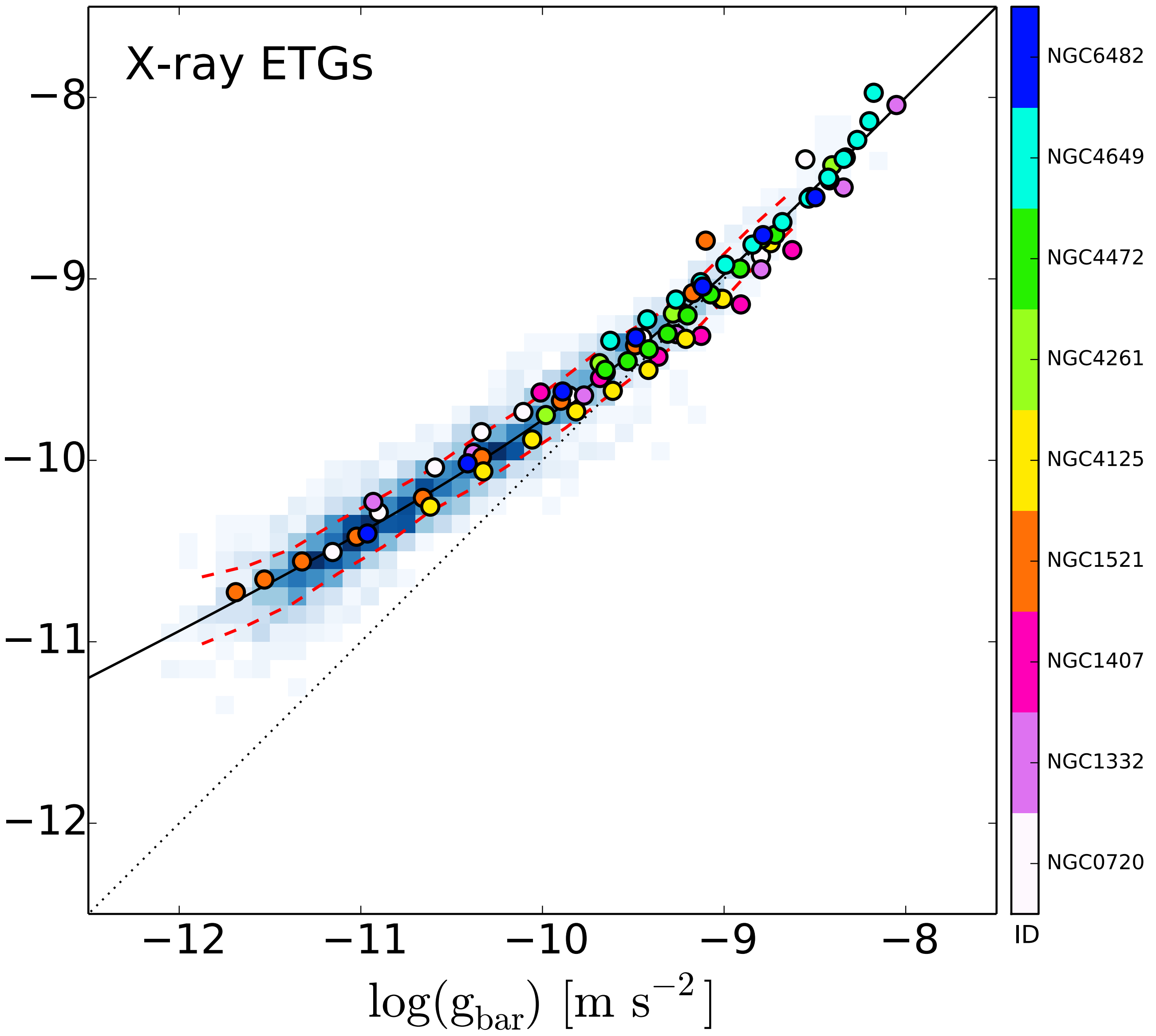
Radial Acceleration Relation in Elliptical galaxies

ATLAS^{3D} data (fast rotators)



Inner, high acceleration
data from optical IFU
Outer, low acceleration
points from HI 21 cm

X-ray Ellipticals (slow rotators)



Mass profiles from hydrostatic
equilibrium of X-ray gas.