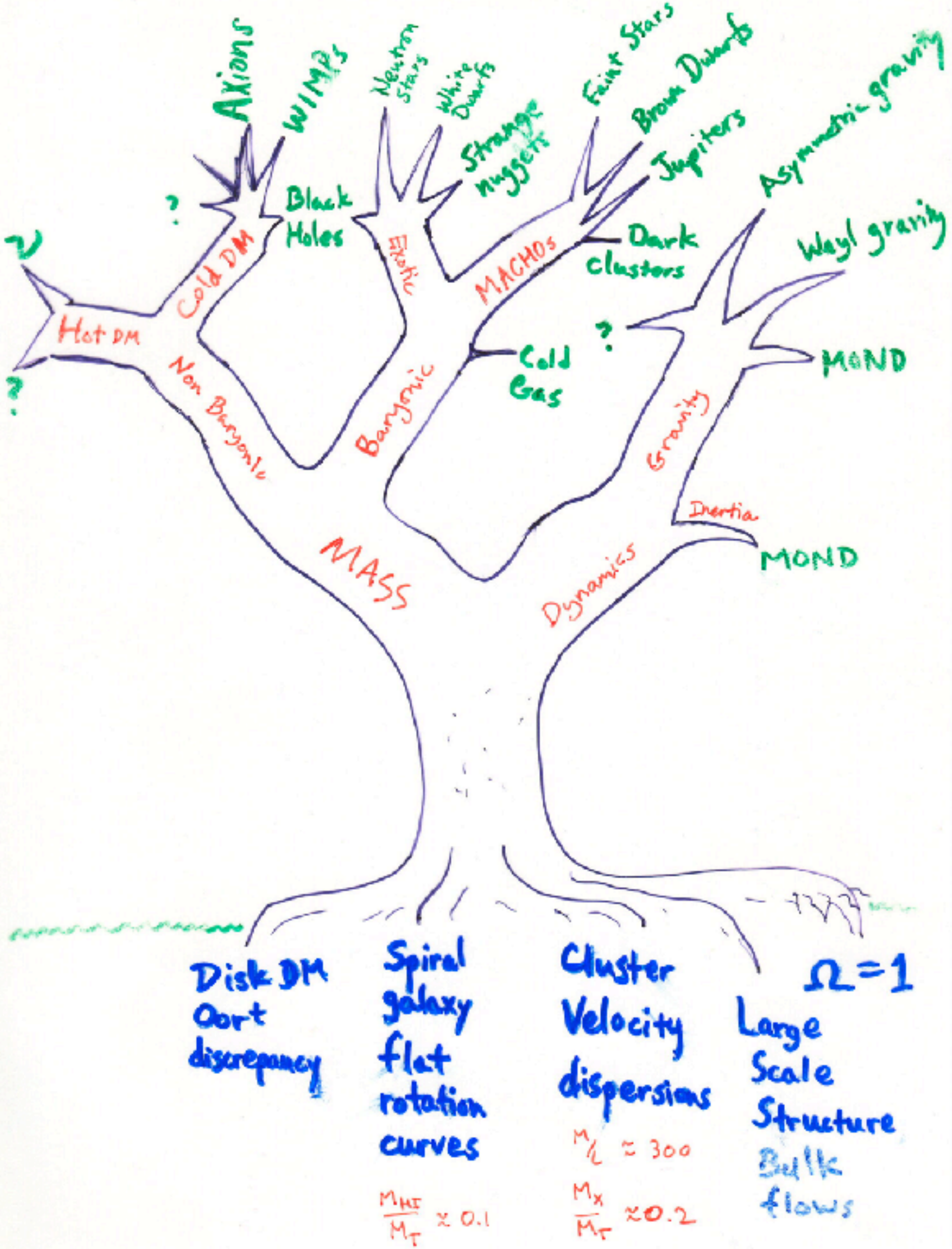
DARK MATTER

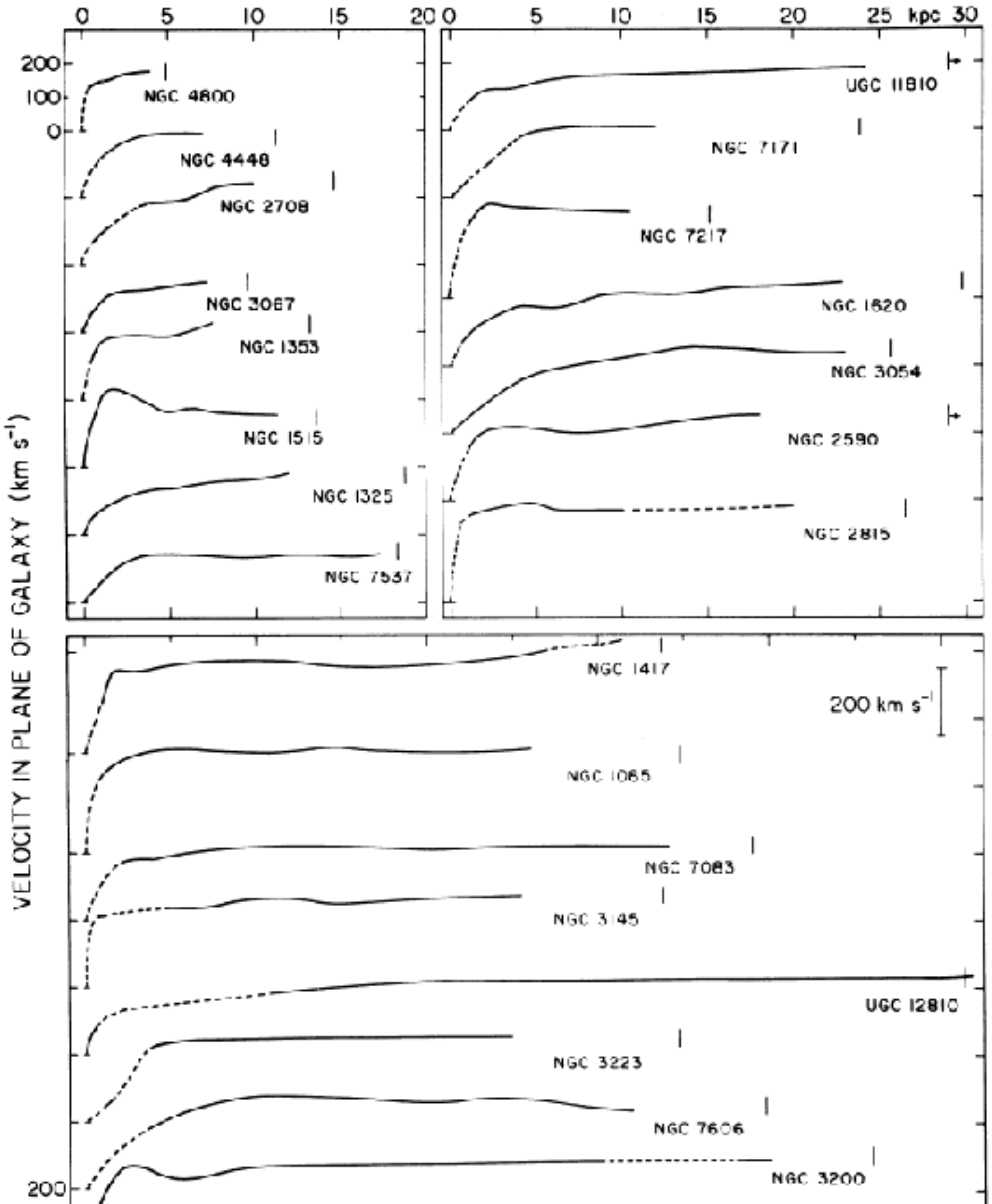
ASTR 333/433

TODAY
GALACTIC ROTATION
THE THIRD LAW
HALO MODELS

Homework 2 Due March 1
Midterm March 8



- The rotation speed of galaxies tends to become approximately constant at large radii, a condition which persists indefinitely

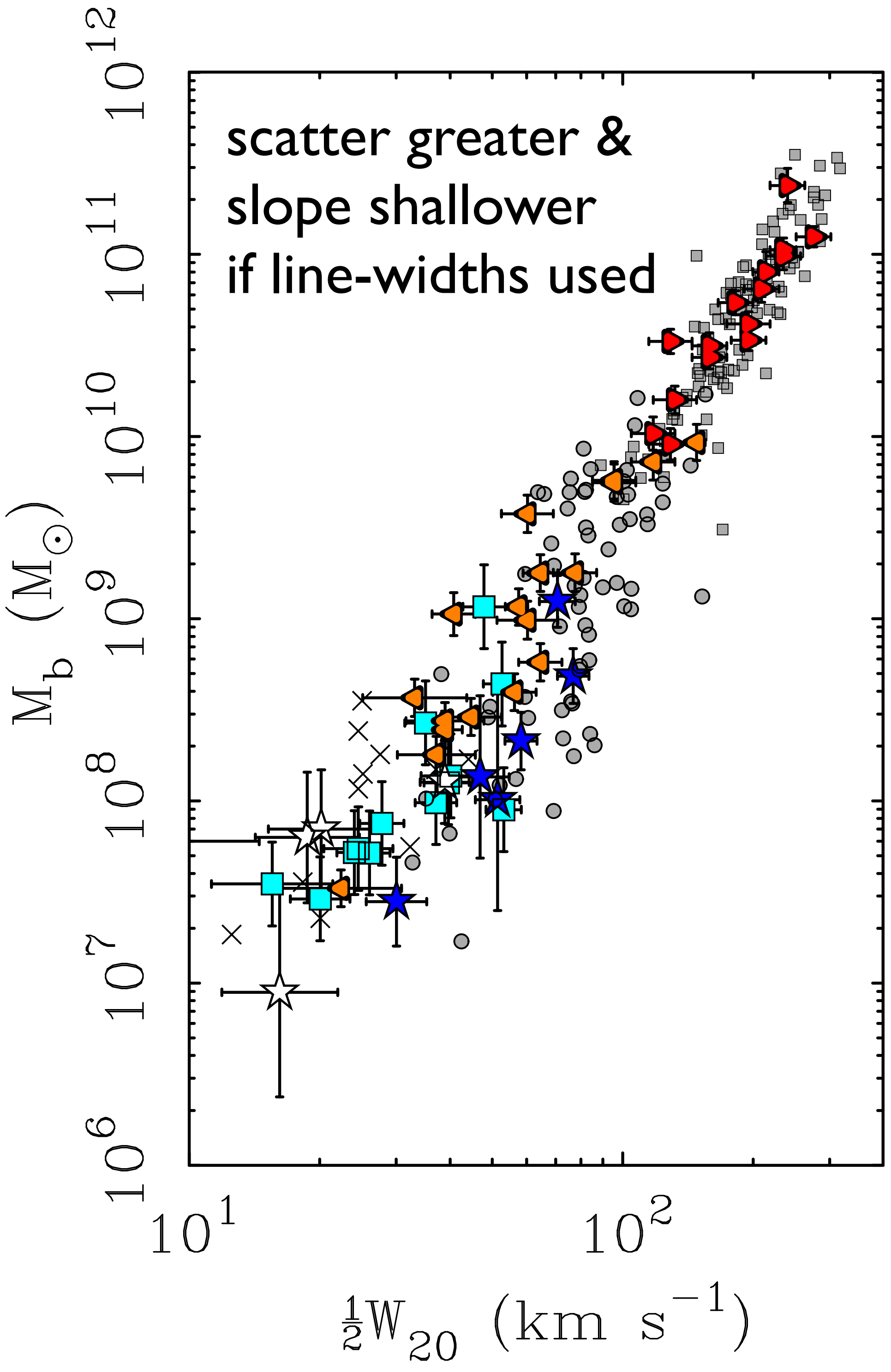


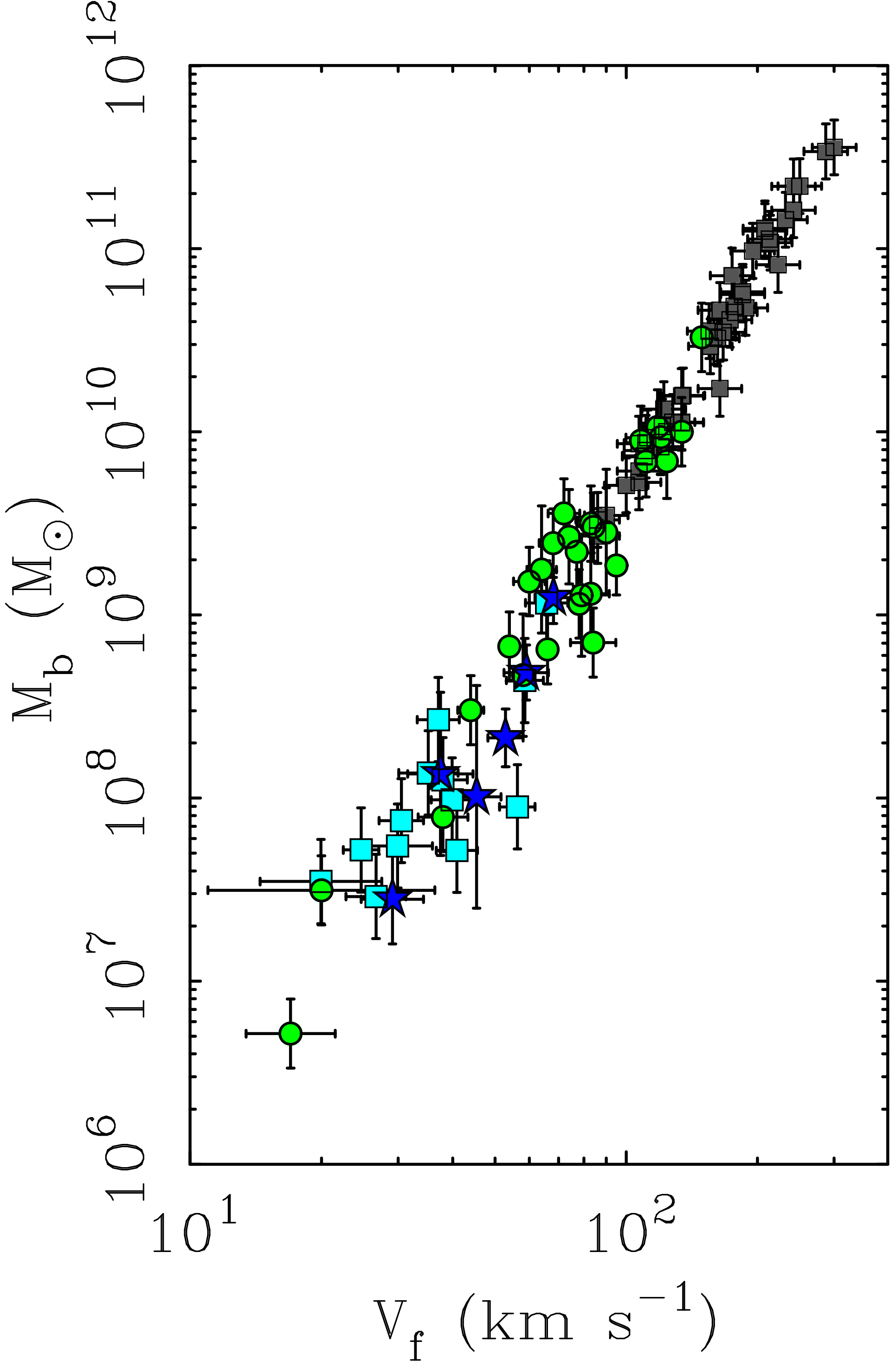
- The baryonic mass of a galaxy is proportional to the fourth power of the flat rotation speed.

$$M_b = AV_f^4$$

$$45 \leq A \leq 50\ \mathrm{M_\odot\ km^{-4}\ s^4}$$

range of calibrations

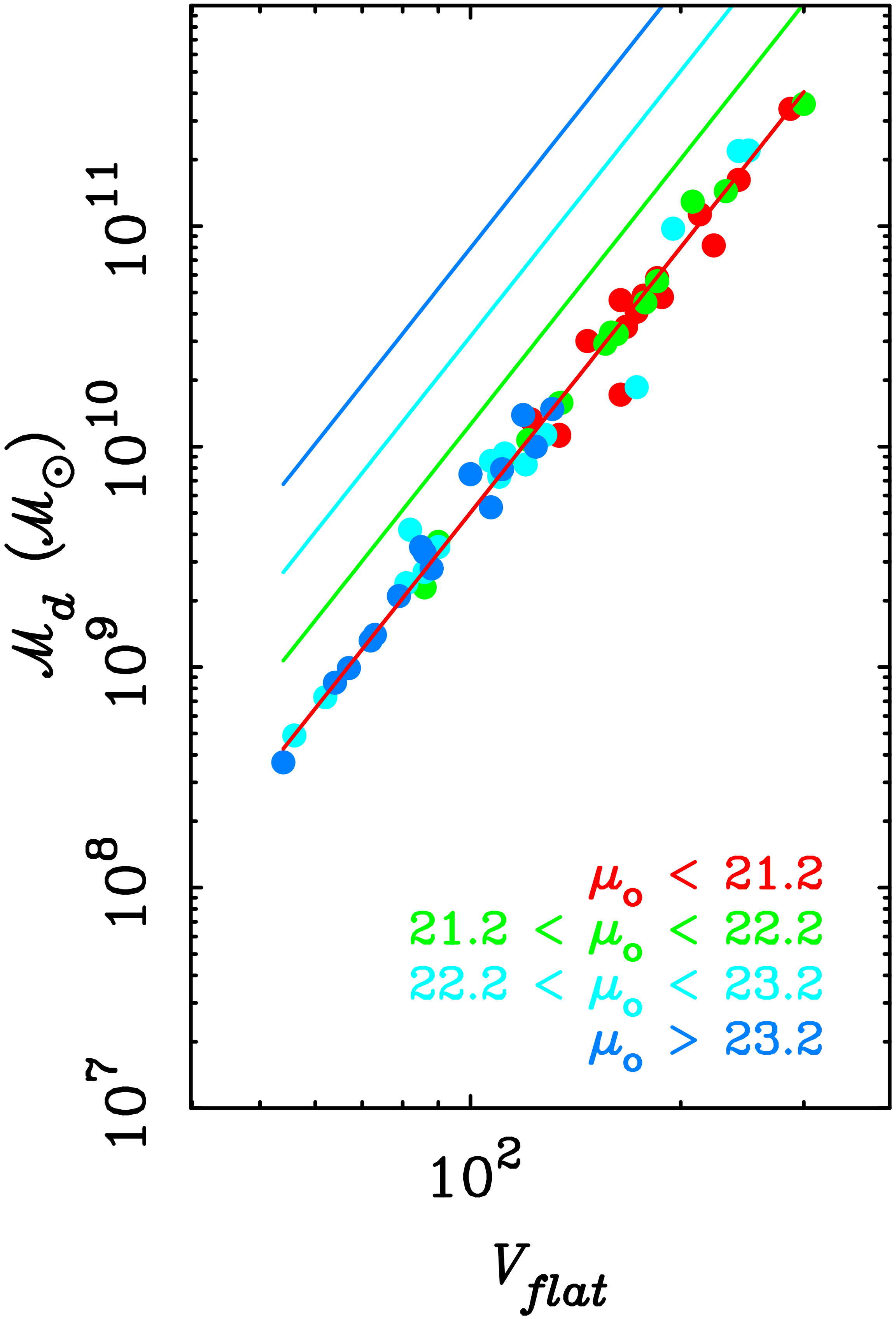

scatter greater & slope shallower if line-widths used



No residuals from TF with size or surface brightness

Enclosed dynamical M/L anti-correlates with surface brightness

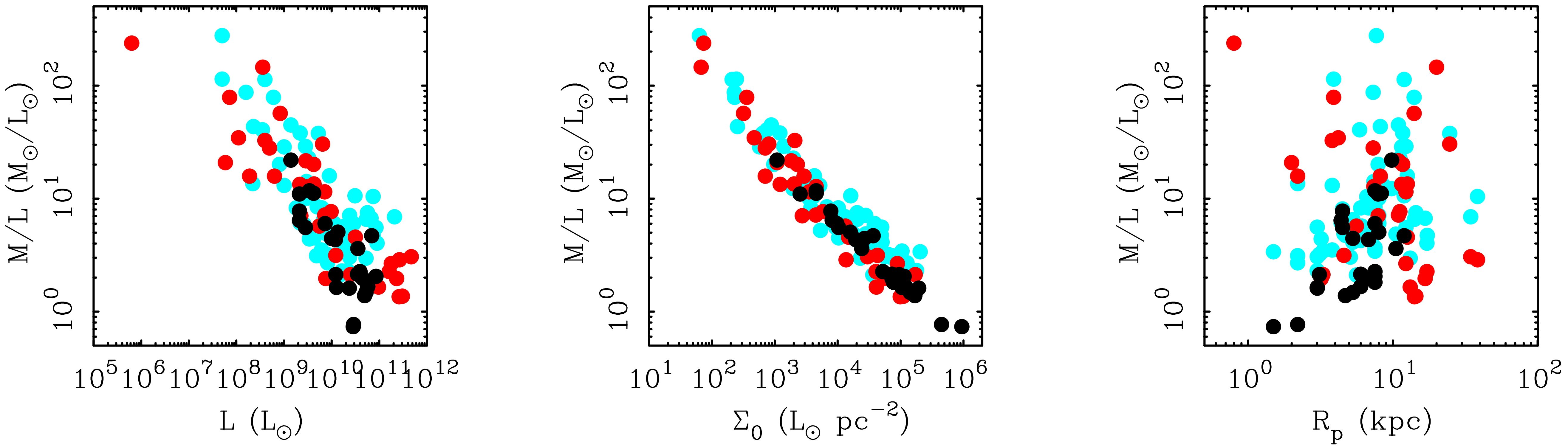
(Zwaan et al. 1995)



$$M = \frac{V^2 R}{G} \quad \text{with} \quad R = R_p$$

● B-band data
● K-band data
● [3.6] data

LSBs dark matter dominated



HSBs not so much

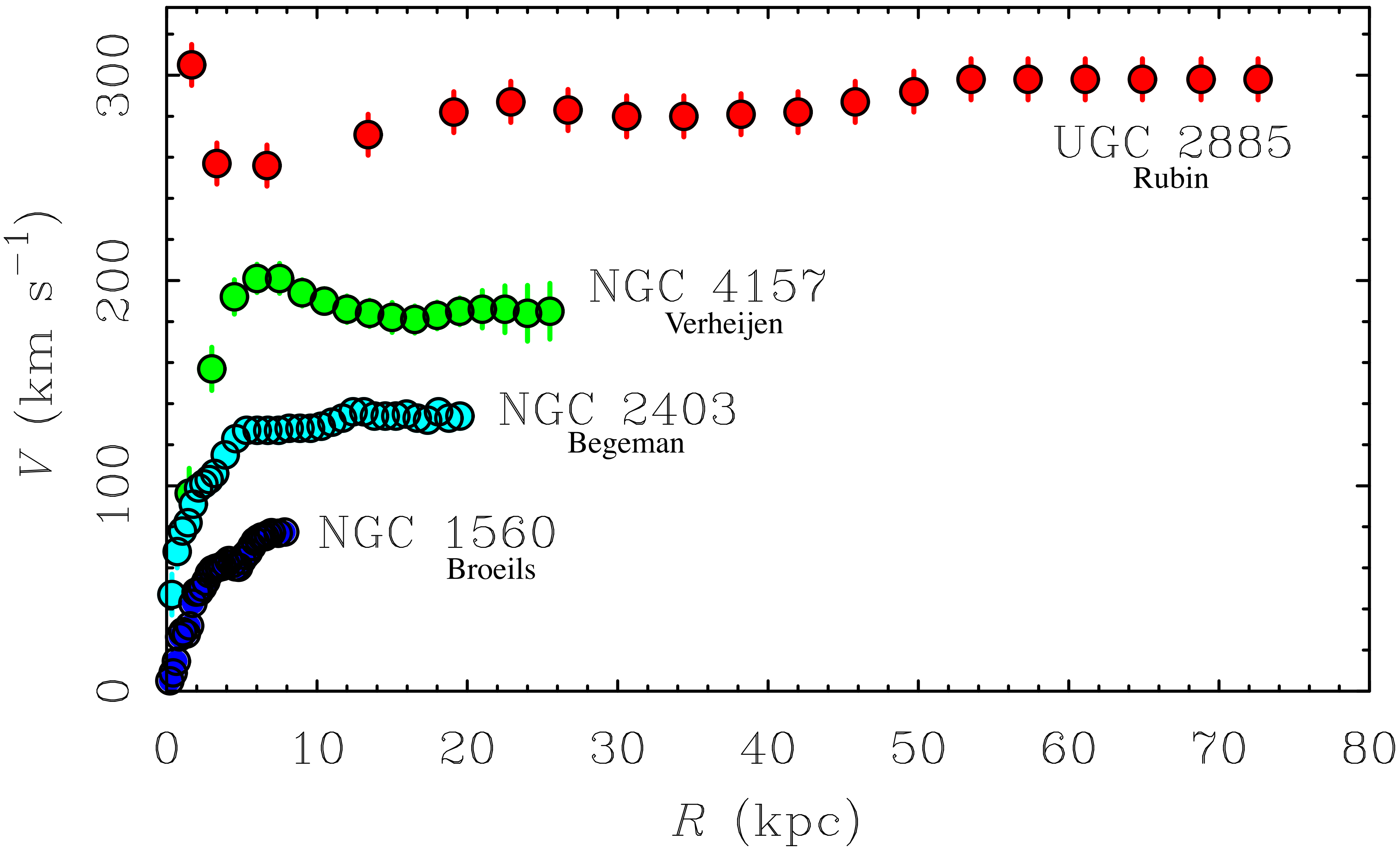
Same result for any optically defined length scale

You get what you assume.

McGaugh (2014) [review]

- Mass is coupled to light

Rotation curve shape depends on the baryon distribution



Light and Mass

- Many indications of a strong connection between the distribution of baryons and the dynamics:
  - Rotation curve shape correlates with luminosity (Rubin et al. 1980) [not just amplitude as in TF]
  - Universal Rotation Curve (Persic & Salucci 1996)
  - Central Density Relation (Lelli et al. 2017)
  - Renzo's Rule (Sancisi 2004)
  - Mass Discrepancy-Acceleration Relation (McGaugh 1998, 2004)
    - Related to the Radial Acceleration Relation (McGaugh et al. 2016)

Rotation curve shapes correlate with galaxy properties

Rubin, Burstein, & Thonnard 1980, *ApJ*, **242**, L149

only near the limits of the optical image ($\kappa \approx 1$); velocities of highest-luminosity Sc's reach 100 km s^{-1} in less than 1% of the optical radius ($\kappa < 0.01$). The plot of log κ versus log $V_{\max}$ (Fig. 3) emphasizes that κ is a reliable estimator of $V_{\max}$ and, hence, of absolute magnitude. Ignoring resolution effects for the most distant galaxies, this diagram is distance independent. Furthermore, a comparison of Figures 1 and 2 shows that the (log κ, M_B) relation is similar in form and scatter to the (log $V_{\max}$, M_B) relation, i.e., the conventional TF relation. The choice of 100 km s^{-1} as a fiducial mark in measuring κ is not particularly critical to the success of the (log κ, M_B) relation, although it should be located beyond local nuclear effects so as to relate to the overall rotation curve. It should not be affected by nonaxisymmetric barlike motions and local velocity perturbations often observed at small nuclear distances.

From our published rotation curves, it is clear that an adopted measure could be chosen from a fairly wide range of velocities up to and including, of course, the velocity peak. Any one of such measures would serve as a luminosity discriminant. Thus the relationships exhibited in Figures 1 and 2 are representative of a family of dynamical-luminosity relationships. The family of such measures will be explored in detail in a future paper.

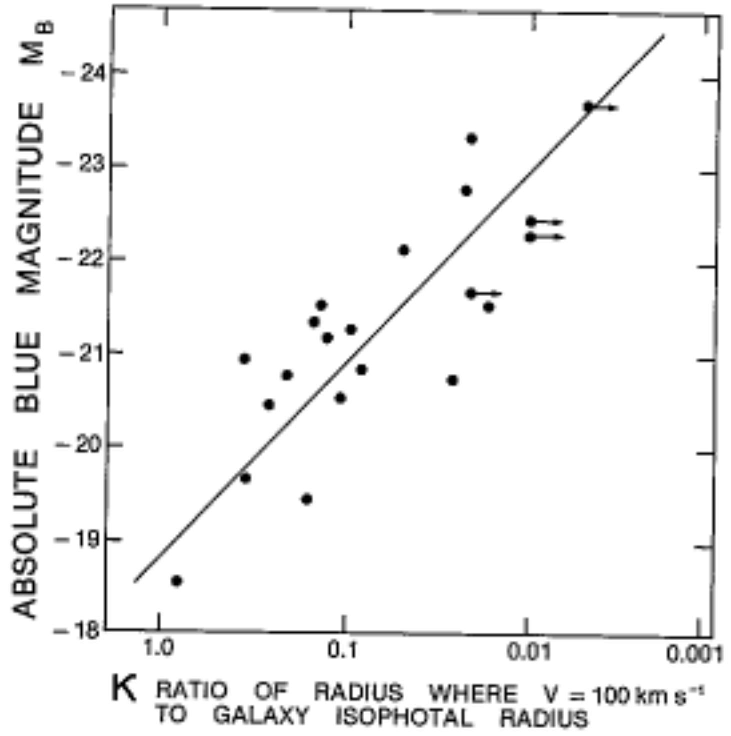


FIG. 2.—The correlation of M_B with log κ, the radial distance in the galaxy where the rotational velocity equals 100 km s^{-1}, in units of the isophotal radius. For lowest-luminosity Sc galaxies, the rotational velocity reaches 100 km s^{-1} only near the limits of the optical image ($\kappa \approx 1$), while for high-luminosity Sc's, the rotational velocity reaches 100 km s^{-1} in less than 1% of the optical radius ($\kappa < 0.01$).

nical scale and in Figure 4b scaled to the size of the galaxy. At every radial distance r in the constant-

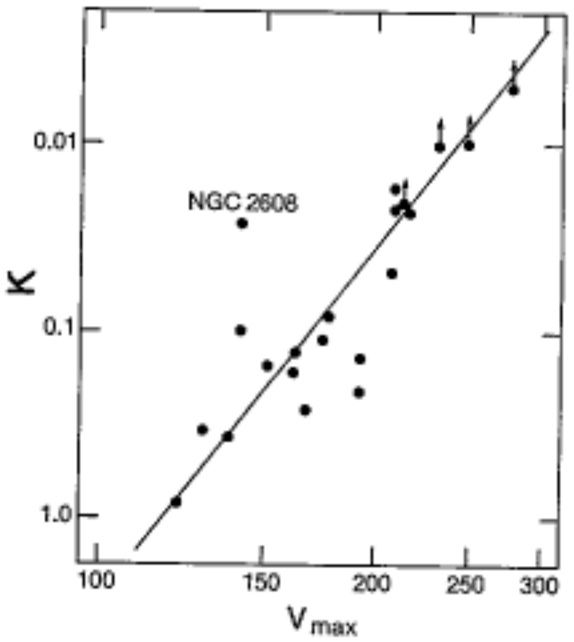


FIG. 3.—The correlation of log κ, the radius where the rotational velocity equals 100 km s^{-1} in units of the isophotal radius, vs. log $V_{\max}$. The line is the mean of the two regressions and has a slope equal to 6.3 ± 0.5. NGC 2608, the only strongly barred galaxy in the sample, was excluded from the solution.

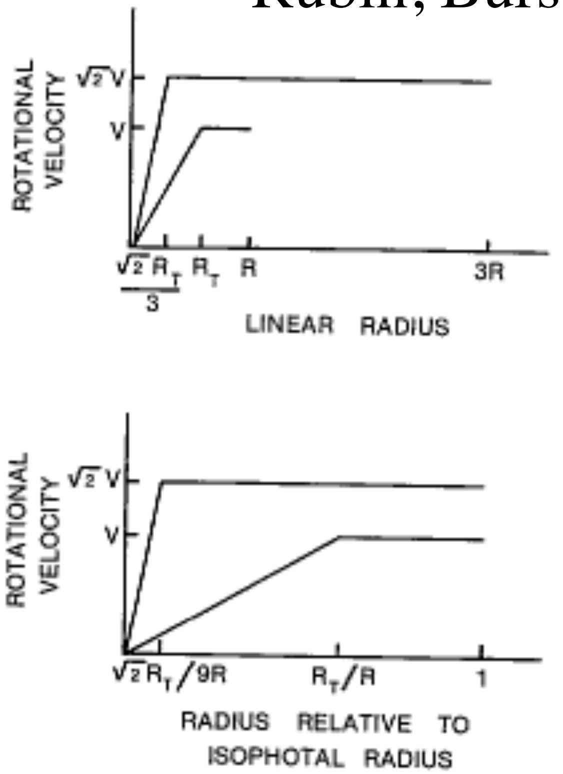
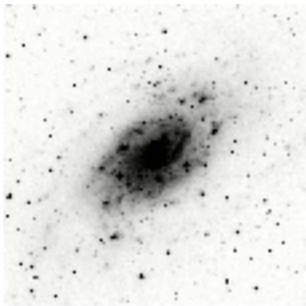
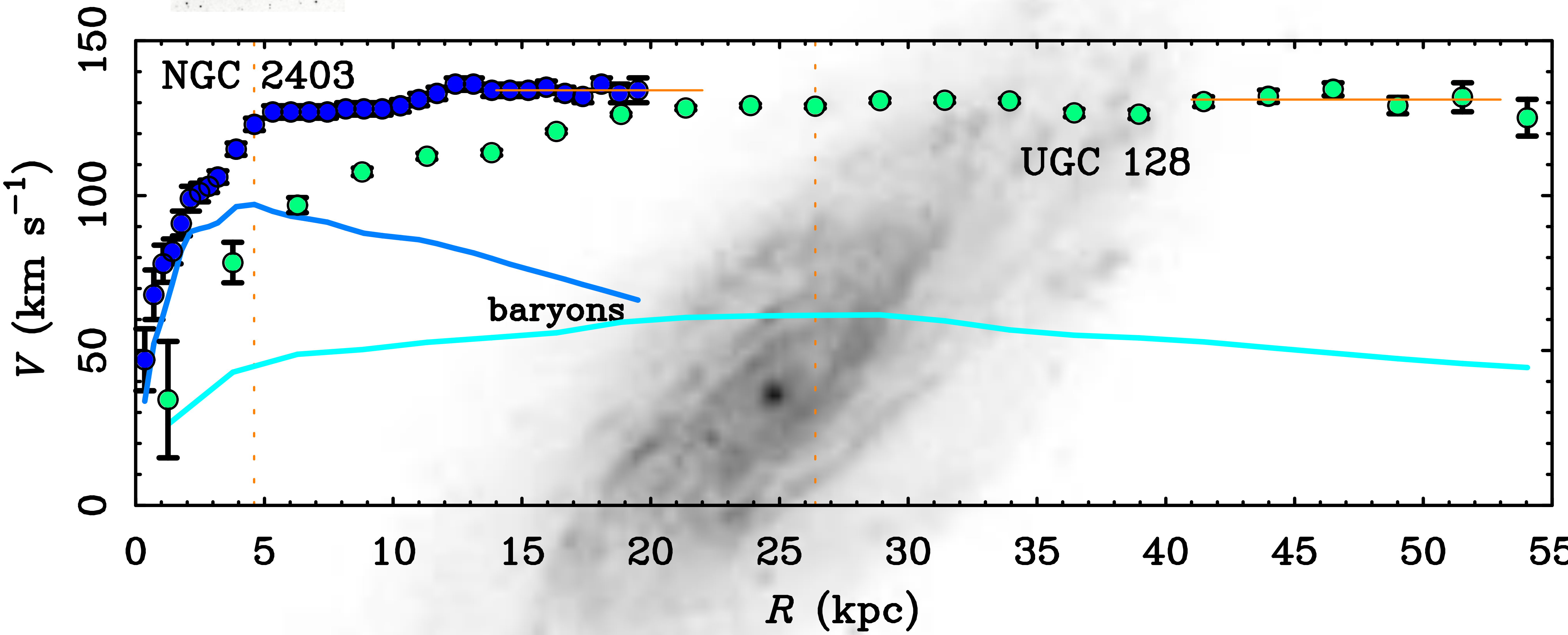


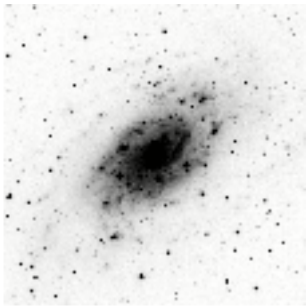
FIG. 4.—Schematic rotation curves for two Sc galaxies on a linear (*upper*) and relative (*lower*) radius scale. The higher-luminosity galaxy is chosen to have its velocity in the flat portion $\sqrt{(2)}$ times that of the lower-luminosity galaxy. Then the nuclear velocity gradient, turnover radius, and radial extent are fixed by the observations as shown (see text and Table 2).

Remember our TF pair?

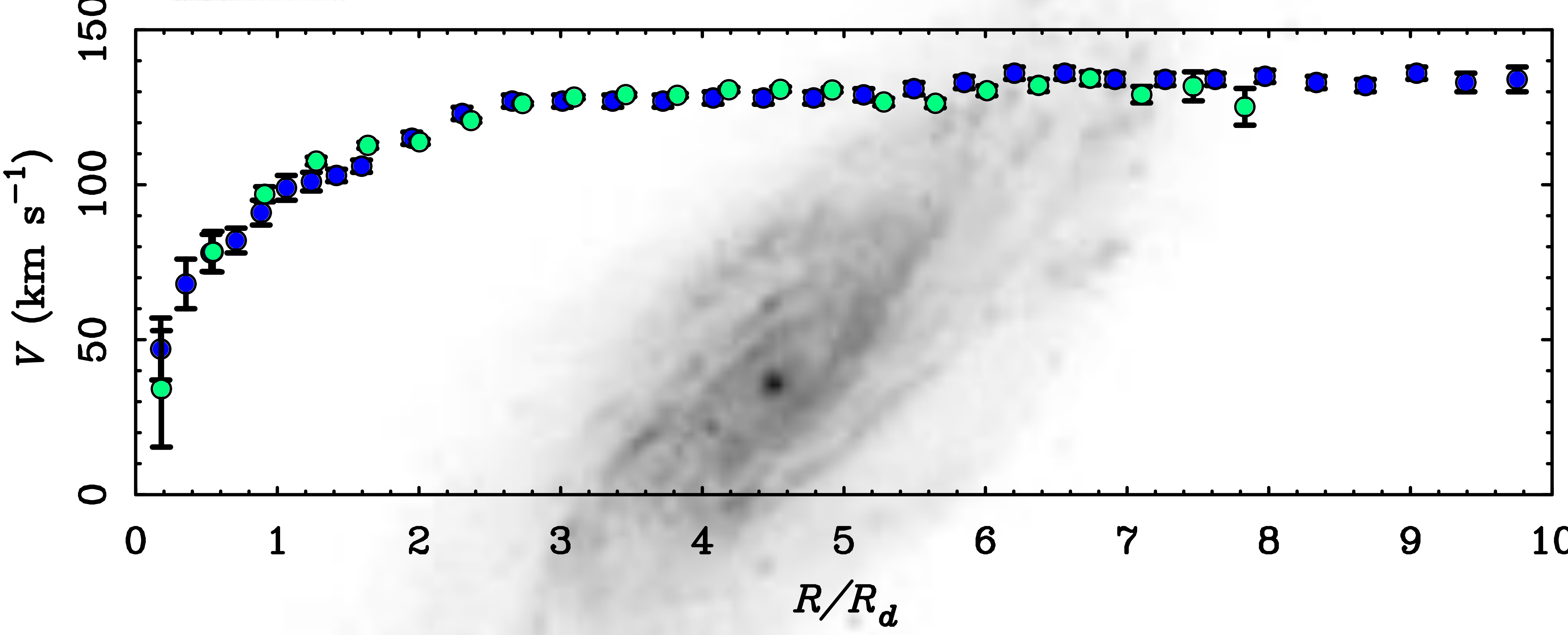




Radius in physical units (kpc)



The dynamics knows about the distribution of baryons, not just their total mass



Radius normalized by size of disk.

Persic & Salucci 1996
de Blok & McGaugh 1996
Tully & Verheijen (1998)
Nordermeer & Verheijen (2007) [URC nor quite right formulation]
Swaters et al. (2009)

Universal Rotation curve (Persic & Salucci 1991)

$V(R/R_{opt})$ correlates with Luminosity.

NOT just $V(R)$ - must be normalized by optical size R_{opt}

R_{opt} variously defined; usually proportional to the exponential disk scale length R_d.

Universal galaxy rotation and dark matter 33

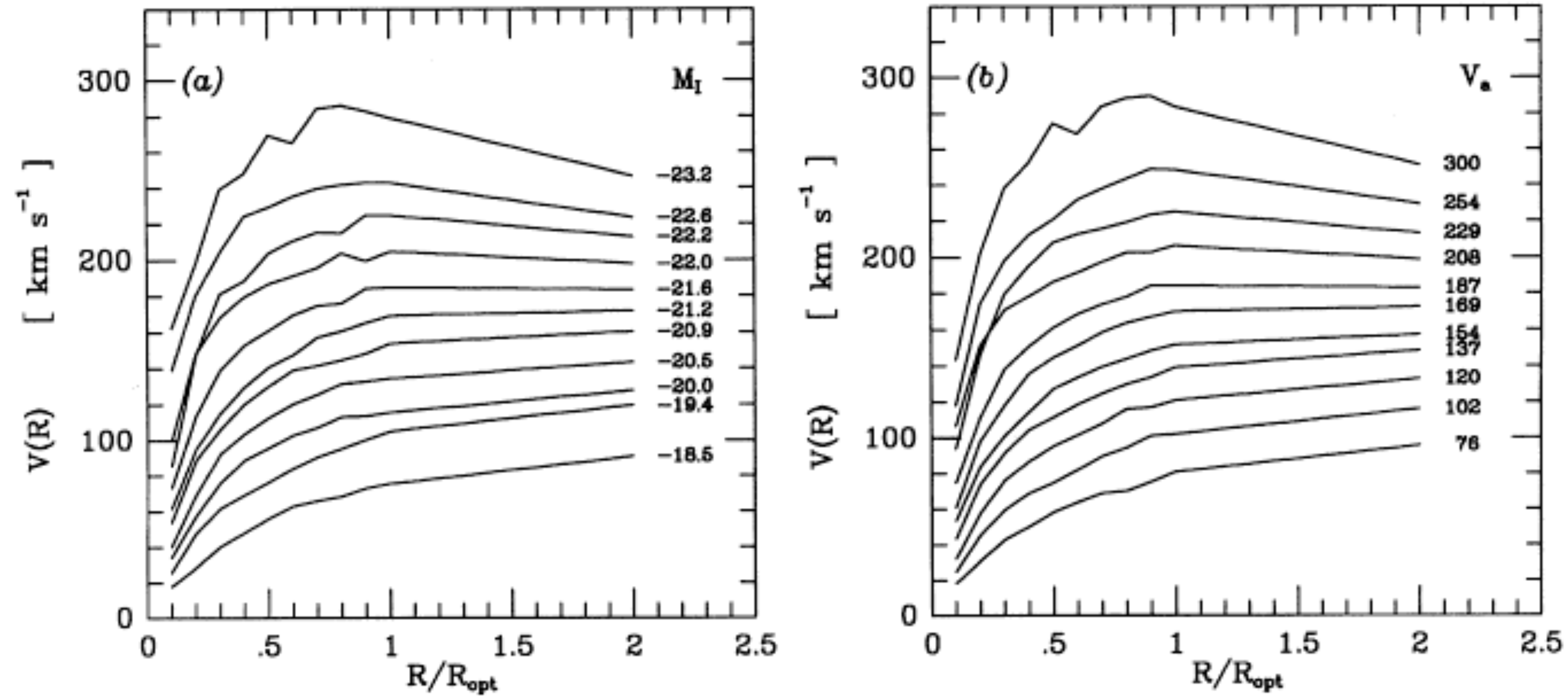


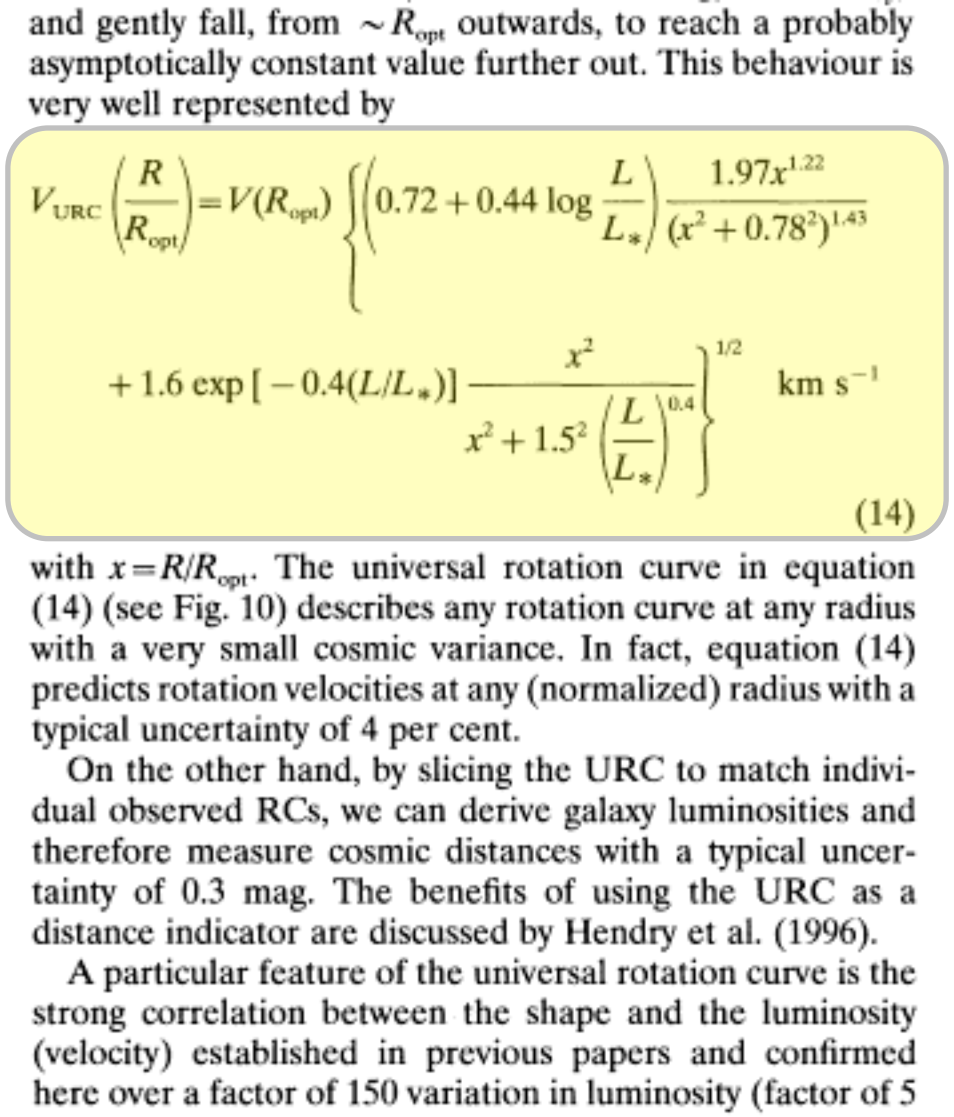
Figure 4. The universal rotation curve of spiral galaxies. Radii are in units of R_{opt}.

Universal Rotation curve
(Persic, Salucci & Stel 1996)

$V(R/R_{opt})$ correlates with Luminosity.

Bright galaxies have steeply rising rotation curves that slowly decline towards the flat velocity.

Faint galaxies have slowly rising rotation curves that gradually approach the flat velocity.



and gently fall, from $\sim R_{opt}$ outwards, to reach a probably asymptotically constant value further out. This behaviour is very well represented by

$$V_{URC}\left(\frac{R}{R_{opt}}\right)=V(R_{opt})\left\{\left(0.72+0.44\log\frac{L}{L_*}\right)\frac{1.97x^{1.22}}{(x^2+0.78^2)^{1.43}}\right. \\ \left.+1.6\exp[-0.4(L/L_*)]\frac{x^2}{x^2+1.5^2\left(\frac{L}{L_*}\right)^{0.4}}\right\}^{1/2}\ \mathrm{km\ s^{-1}} \tag{14}$$

with $x=R/R_{opt}$. The universal rotation curve in equation (14) (see Fig. 10) describes any rotation curve at any radius with a very small cosmic variance. In fact, equation (14) predicts rotation velocities at any (normalized) radius with a typical uncertainty of 4 per cent.

On the other hand, by slicing the URC to match individual observed RCs, we can derive galaxy luminosities and therefore measure cosmic distances with a typical uncertainty of 0.3 mag. The benefits of using the URC as a distance indicator are discussed by Hendry et al. (1996).

A particular feature of the universal rotation curve is the strong correlation between the shape and the luminosity (velocity) established in previous papers and confirmed here over a factor of 150 variation in luminosity (factor of 5

Universal galaxy rotation and dark matter 33

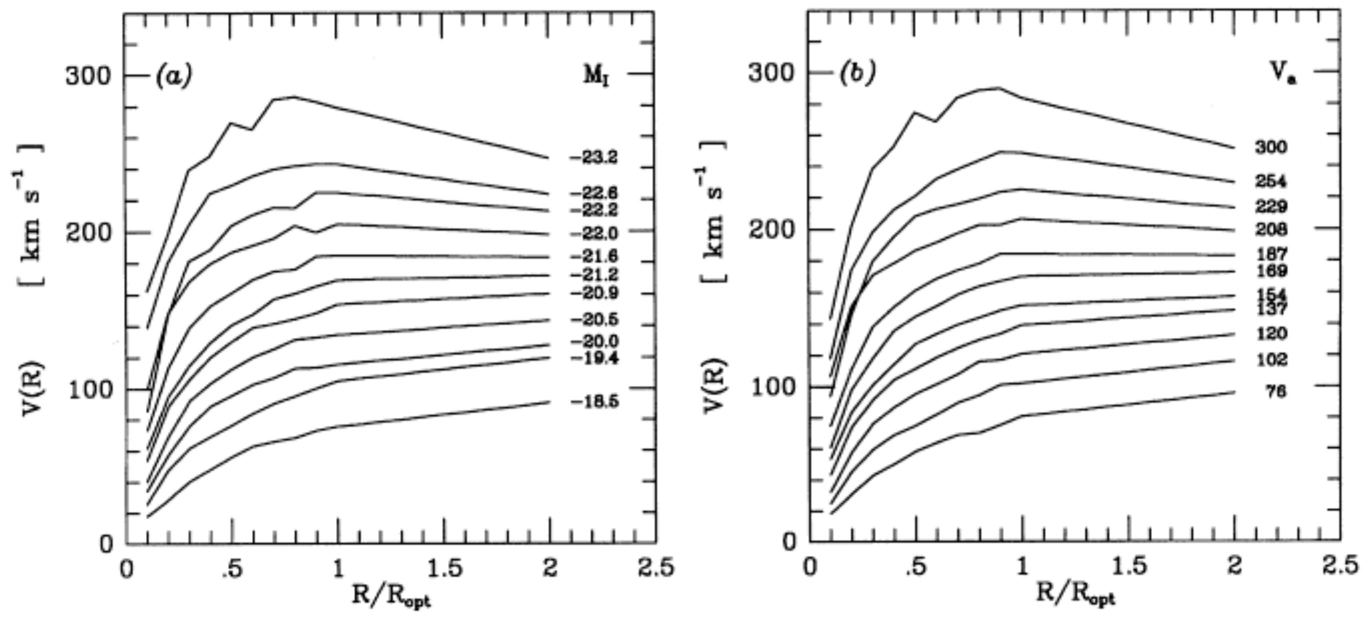


Figure 4. The universal rotation curve of spiral galaxies. Radii are in units of R_{opt}.

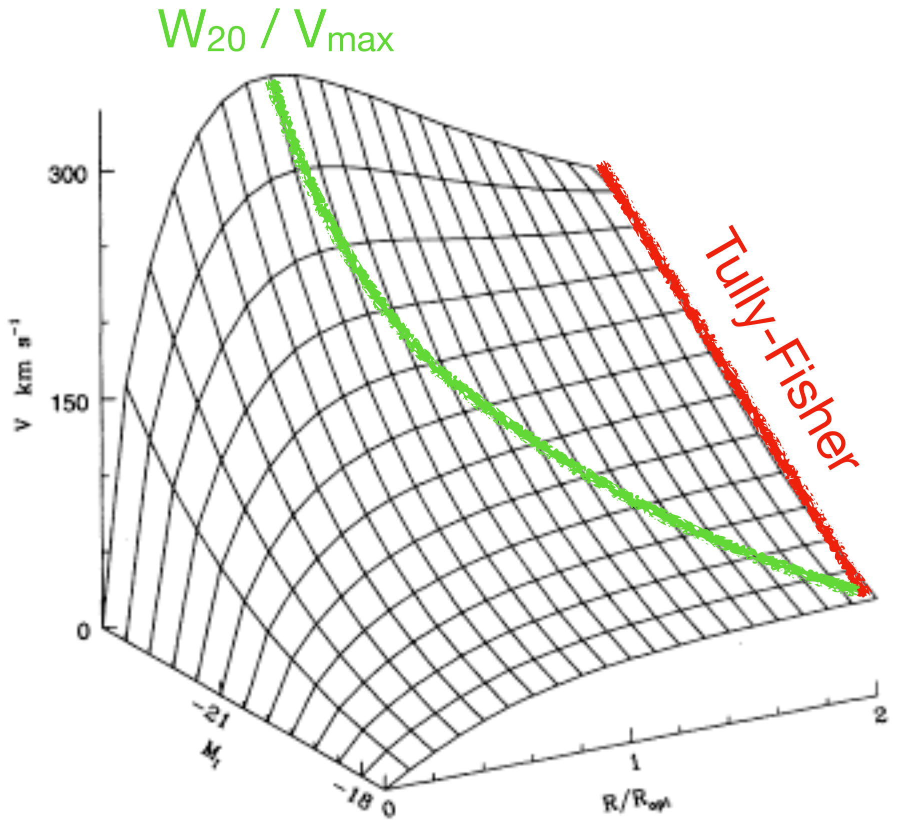
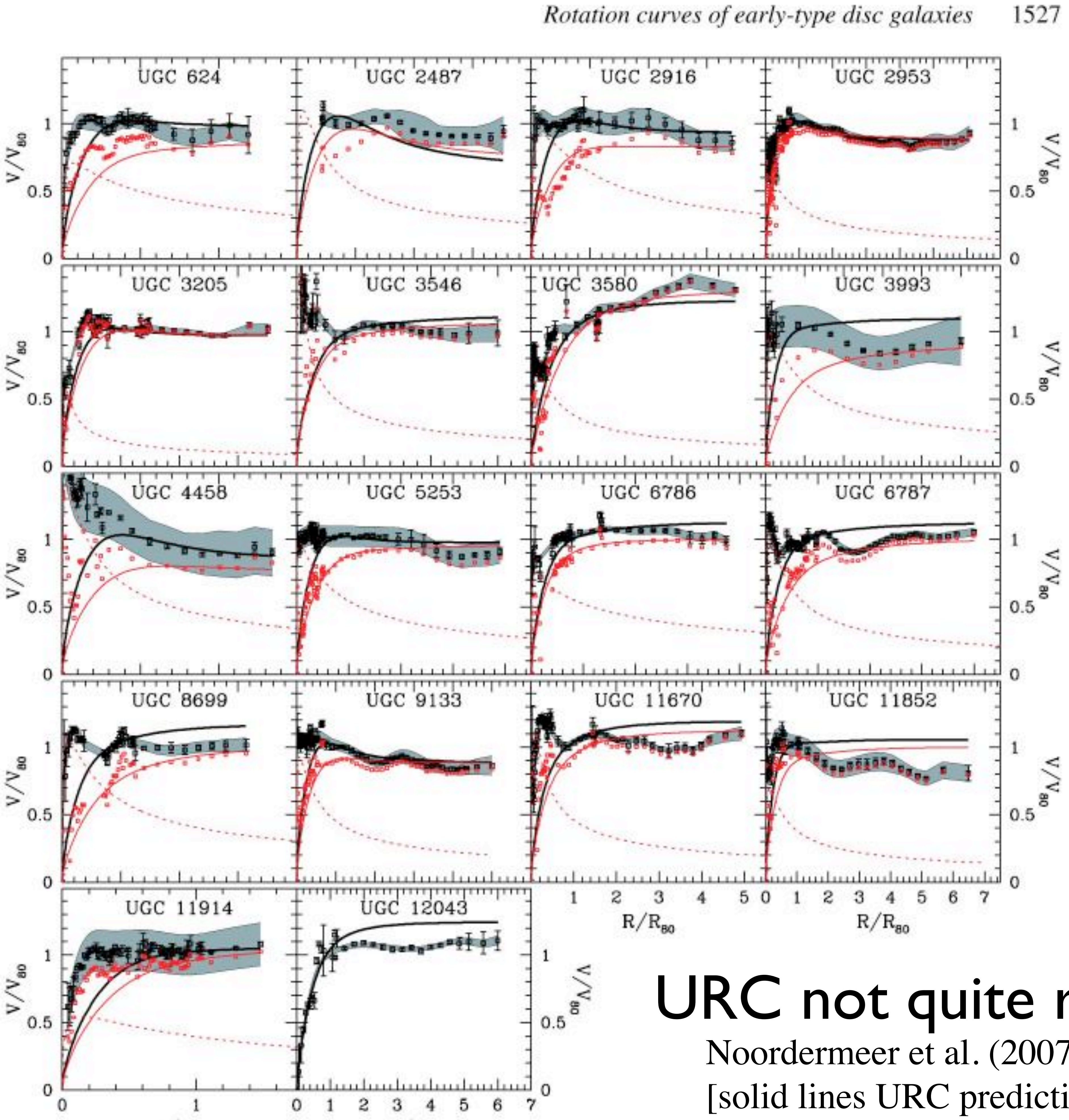
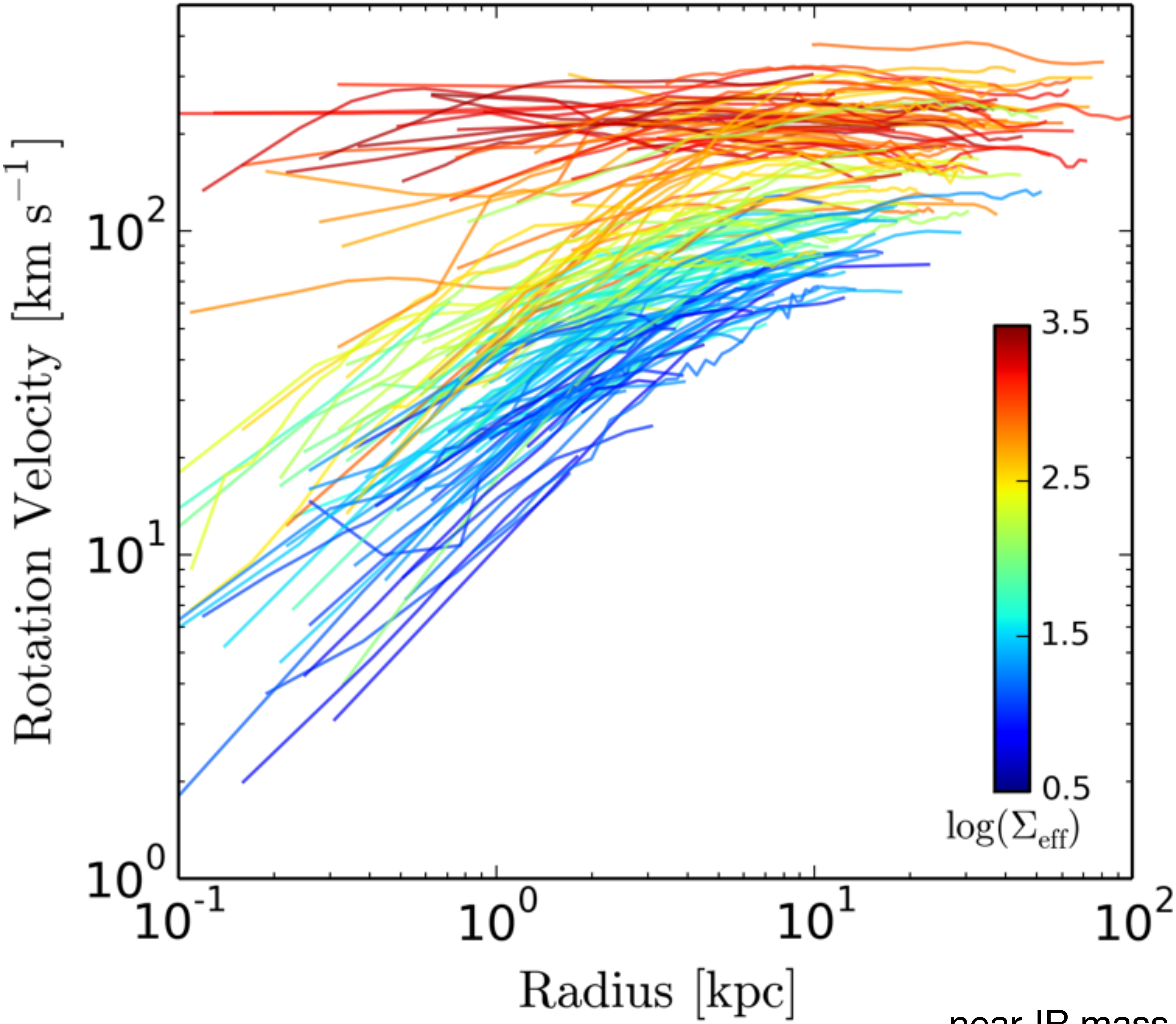


Figure 10. The URC surface.

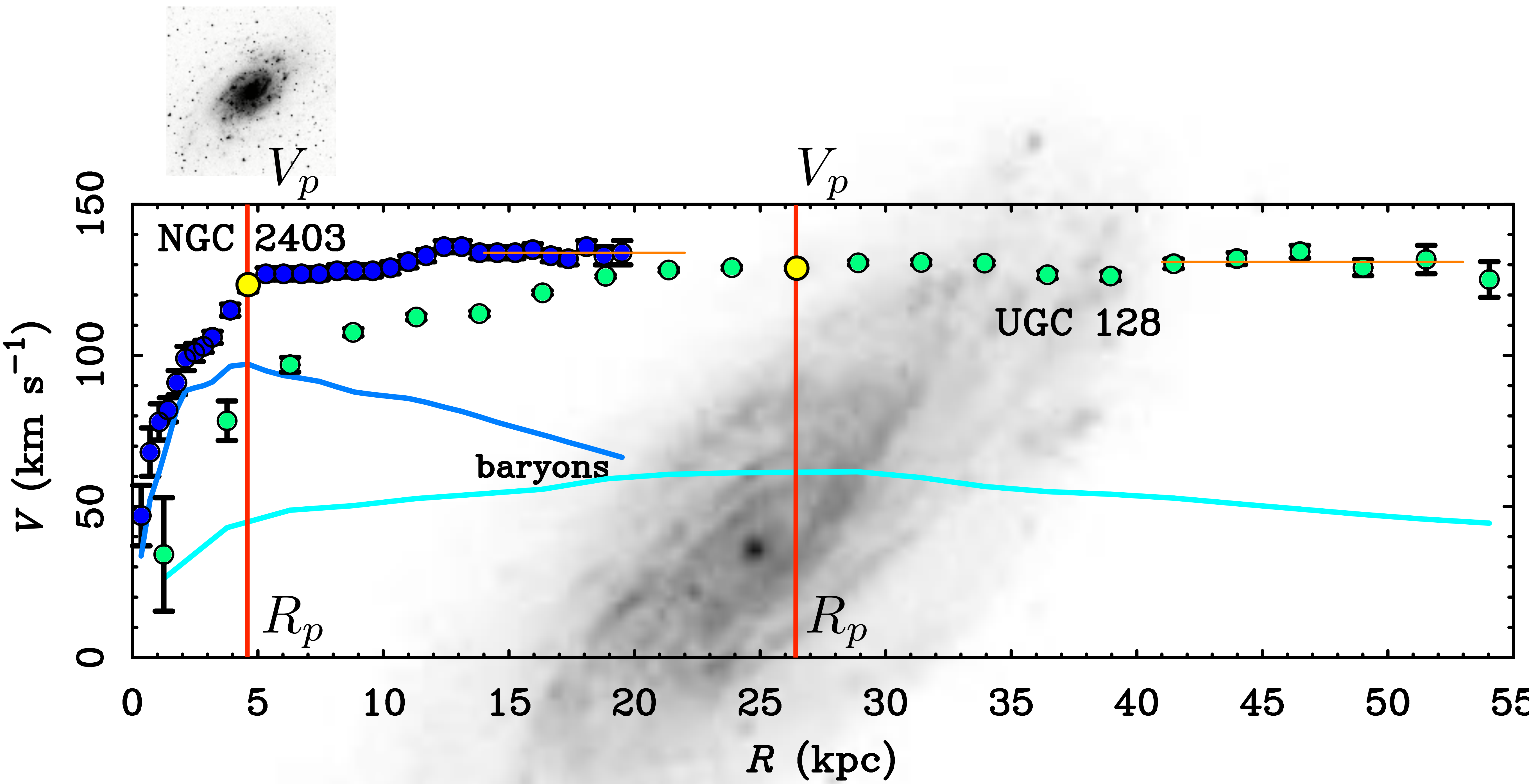


URC not quite right

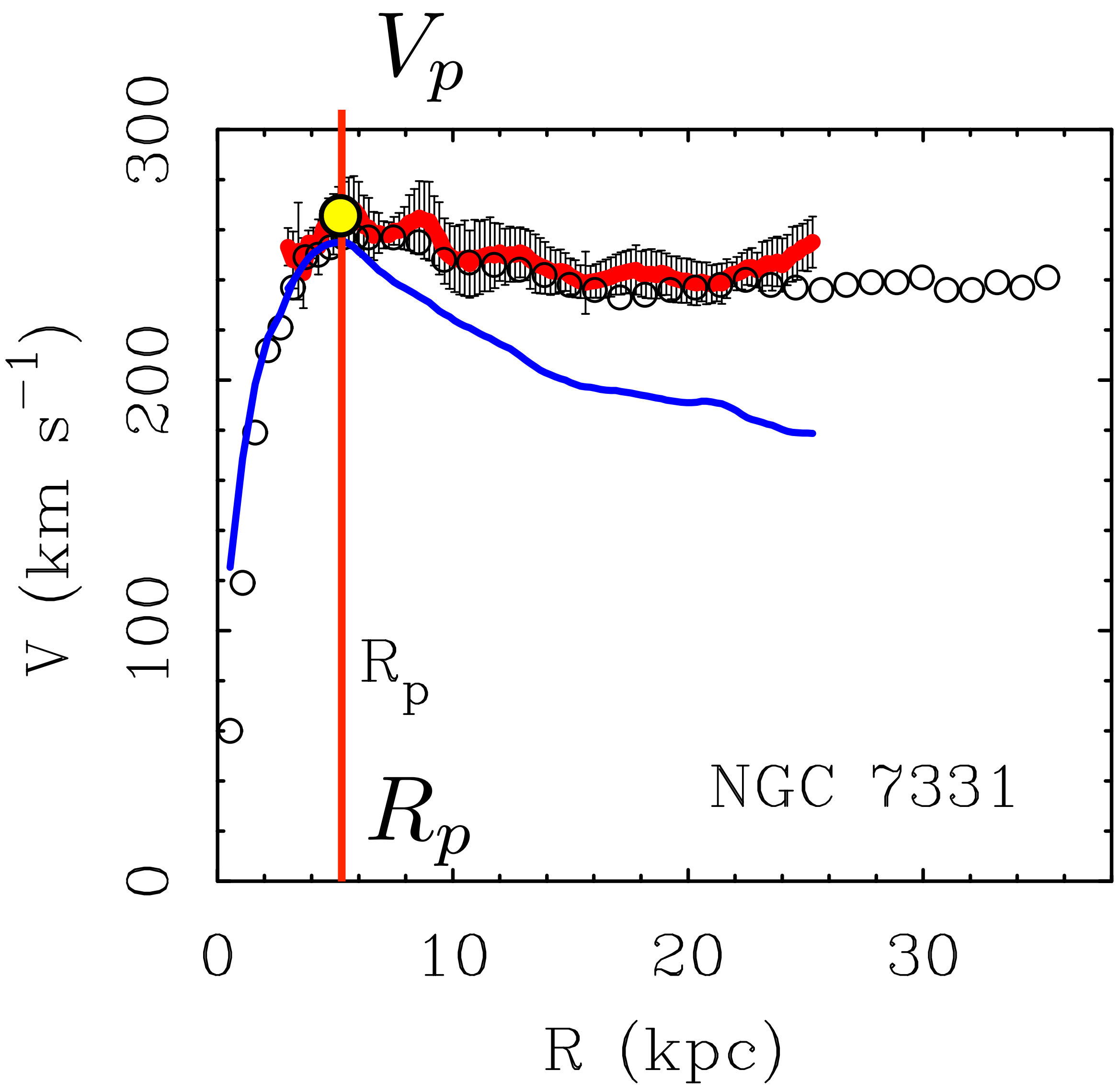
Noordermeer et al. (2007)
[solid lines URC prediction]



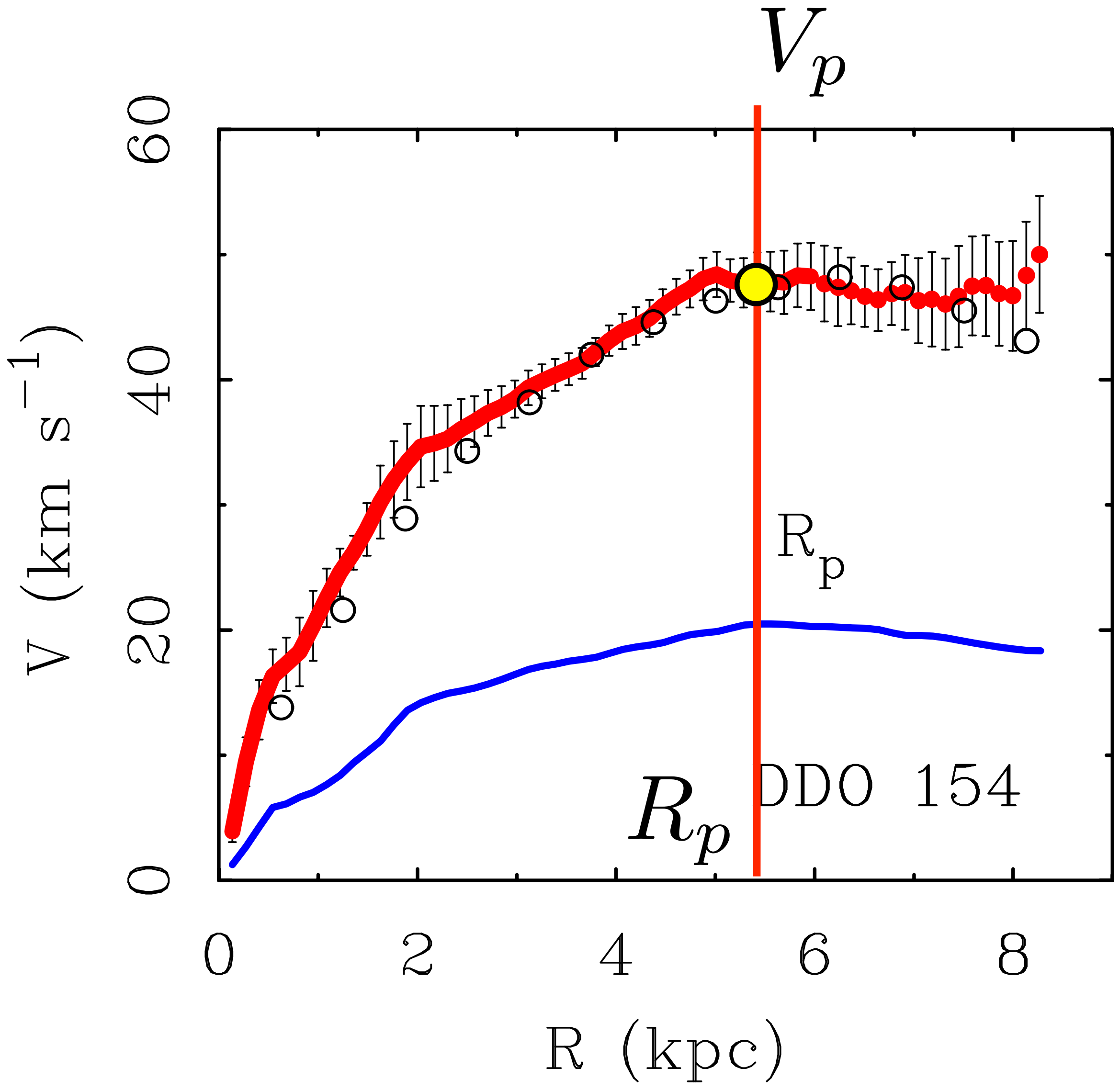
near-IR mass models



Radius in physical units (kpc)



High mass galaxy



Low mass galaxy

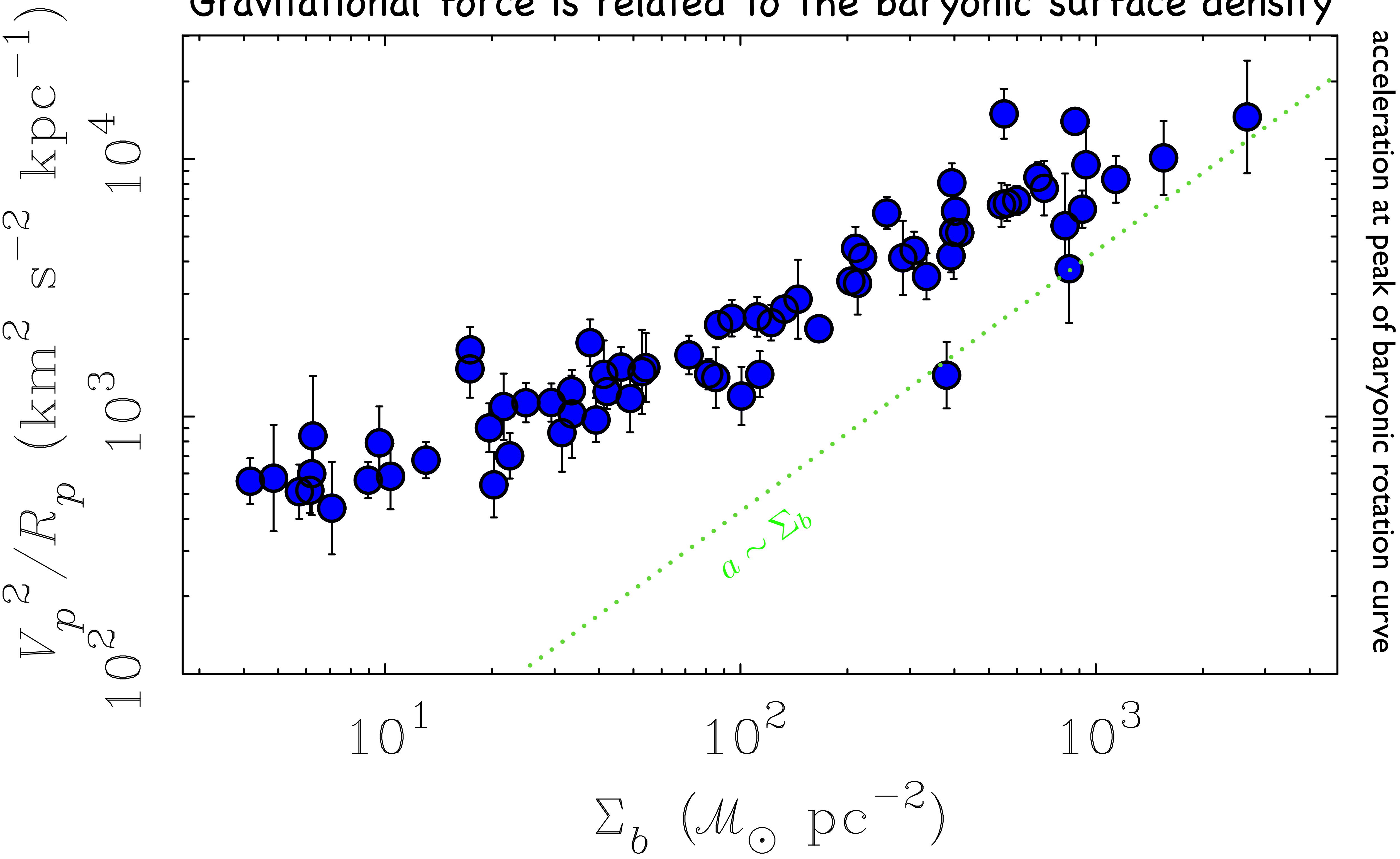
Just looking at the peak radius

$$a \sim \Sigma_b^{1/2}$$

$$\Sigma_b = \frac{3M_b}{4R_p^2}$$

Pseudo-exponential disk including bulge & gas as well as disk stars

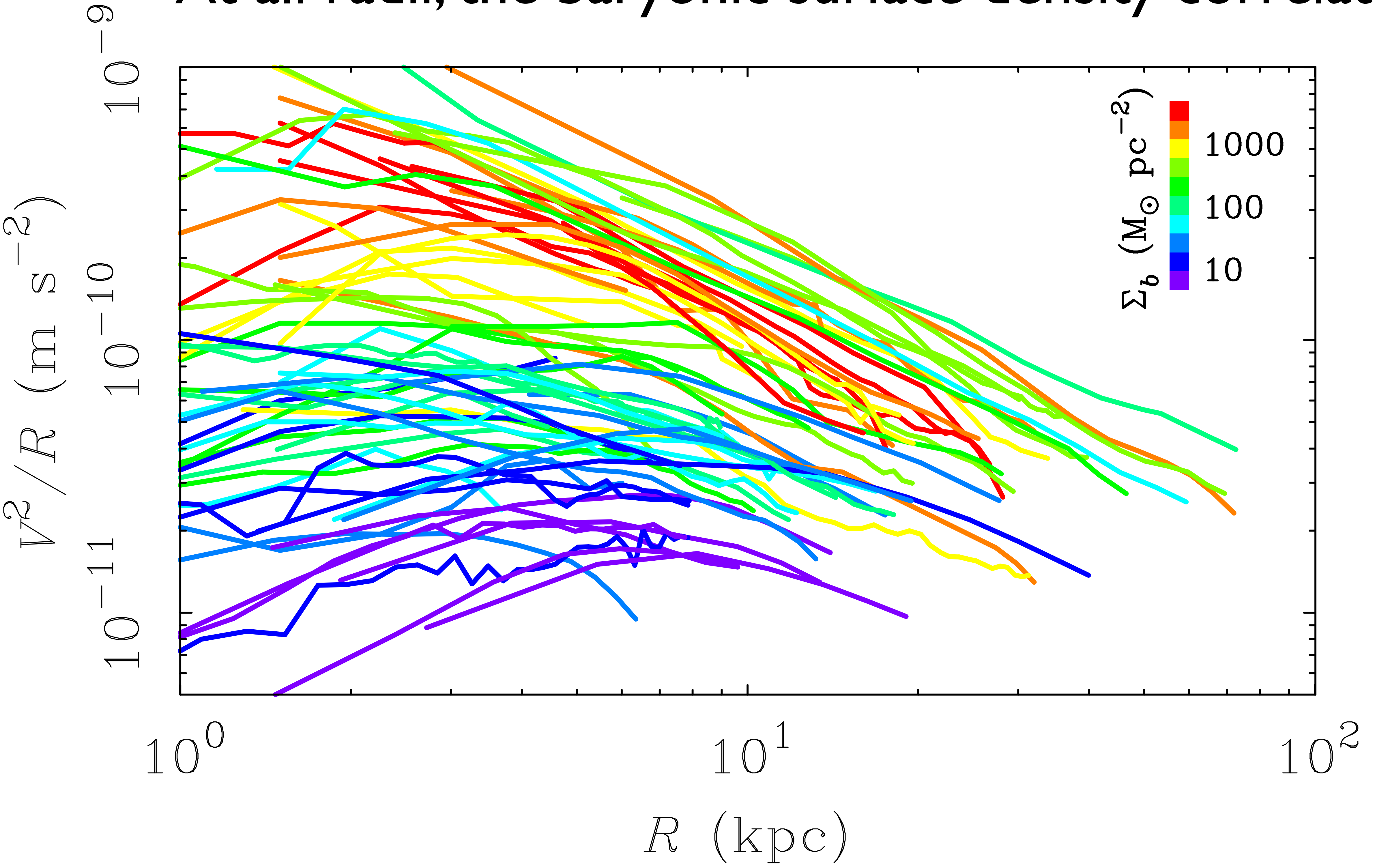
Gravitational force is related to the baryonic surface density



acceleration at peak of baryonic rotation curve

central baryonic surface density

At all radii, the baryonic surface density correlates



with the acceleration (gravitational force per unit mass)

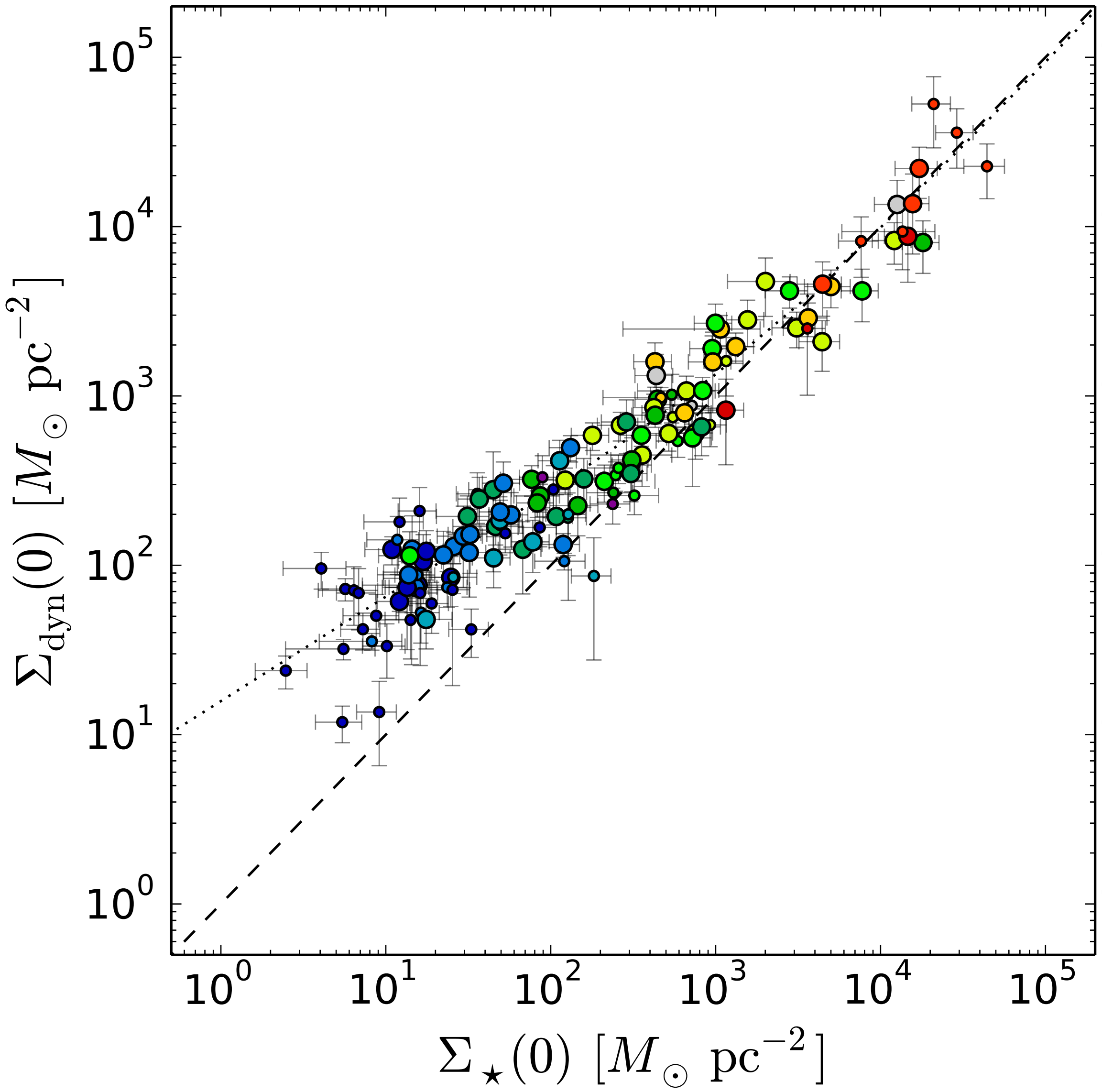
optical mass models

- The Central density relation

The Central mass surface density correlates with surface brightness

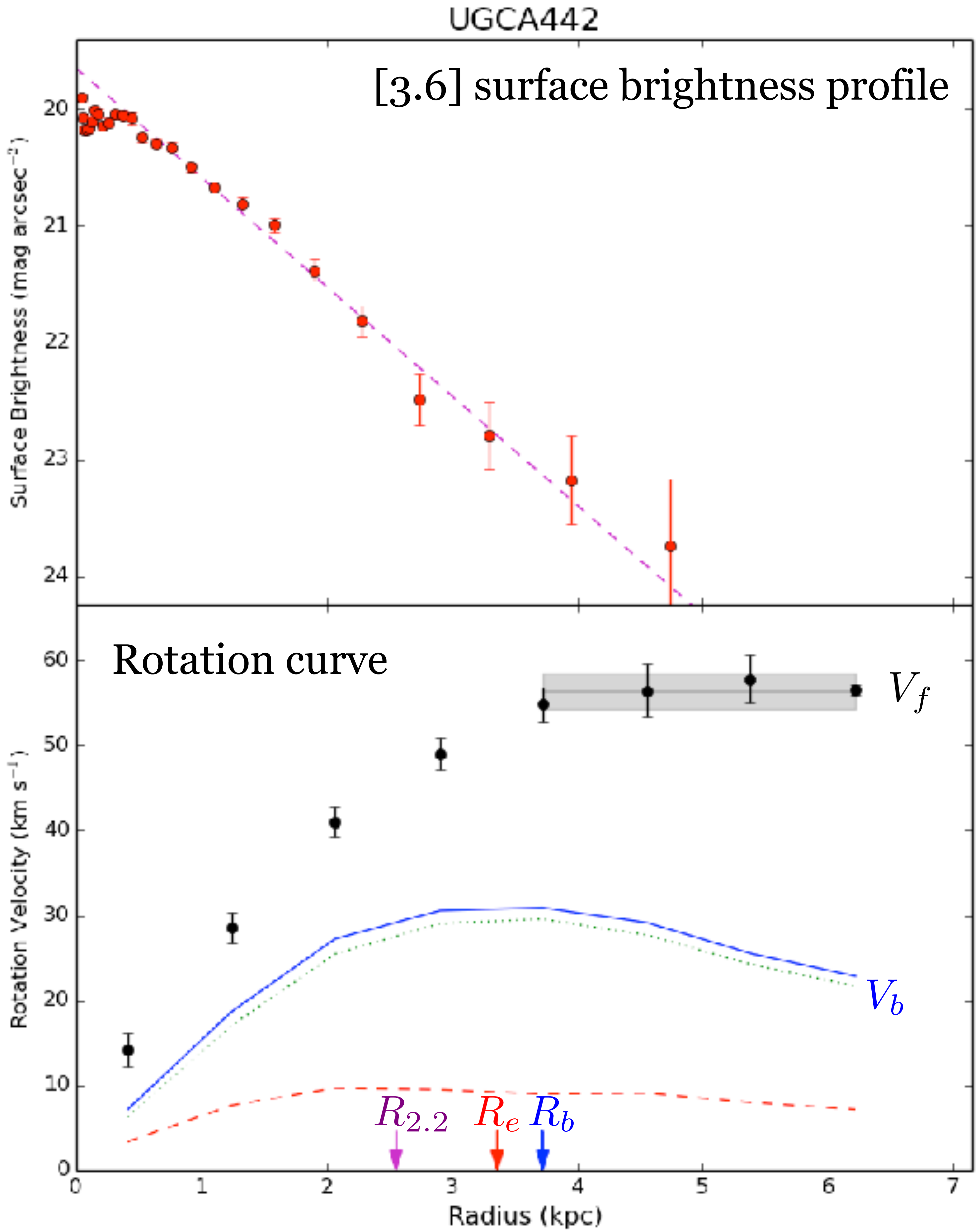
Dynamical mass surface density

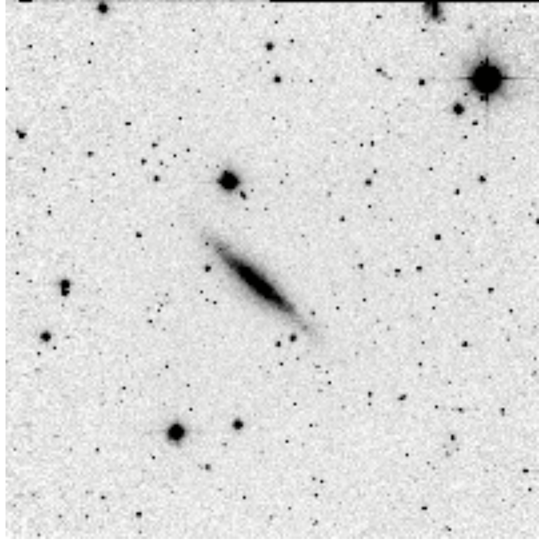
$$\Sigma_{dyn}(0) = \frac{1}{2\pi G}\int_0^\infty \frac{V^2(R)}{r^2}dR$$



Central surface brightness
(e.g., of exponential disk)

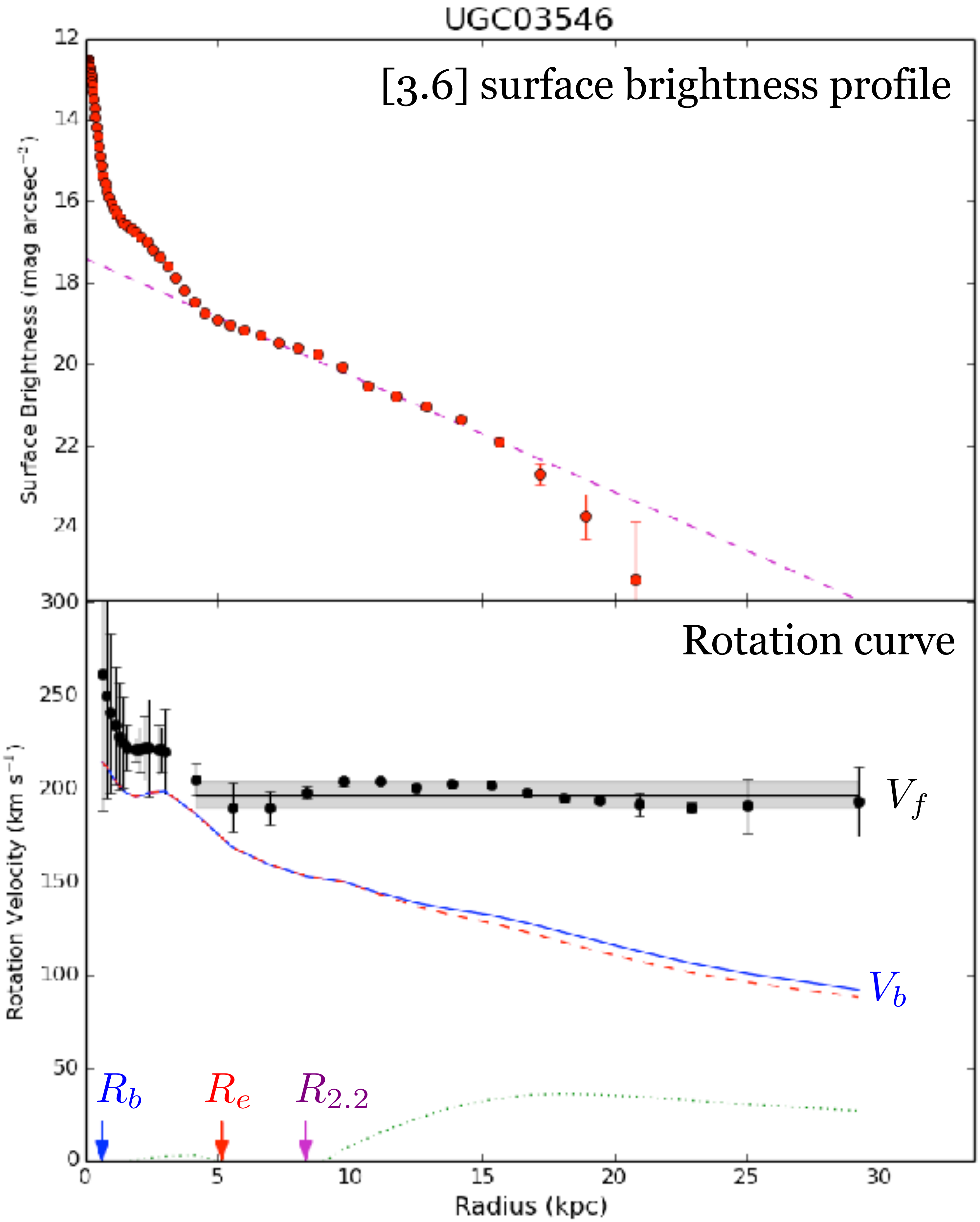
LSB galaxy

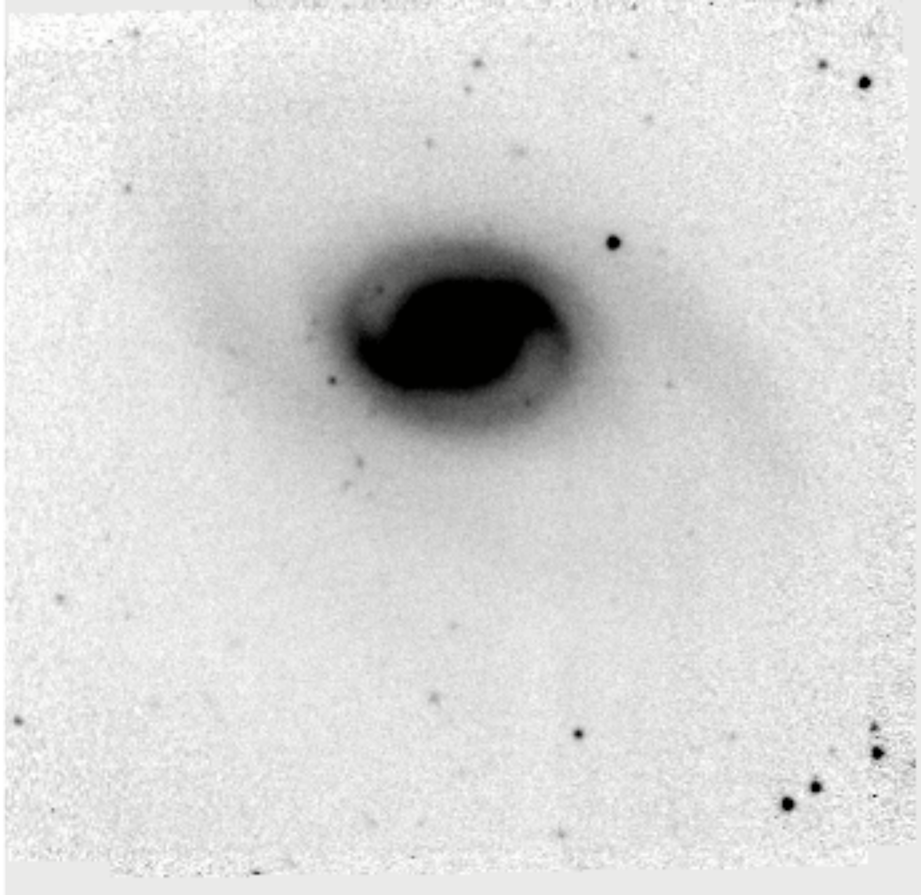




Low surface brightness galaxies have slowly rising rotation curves

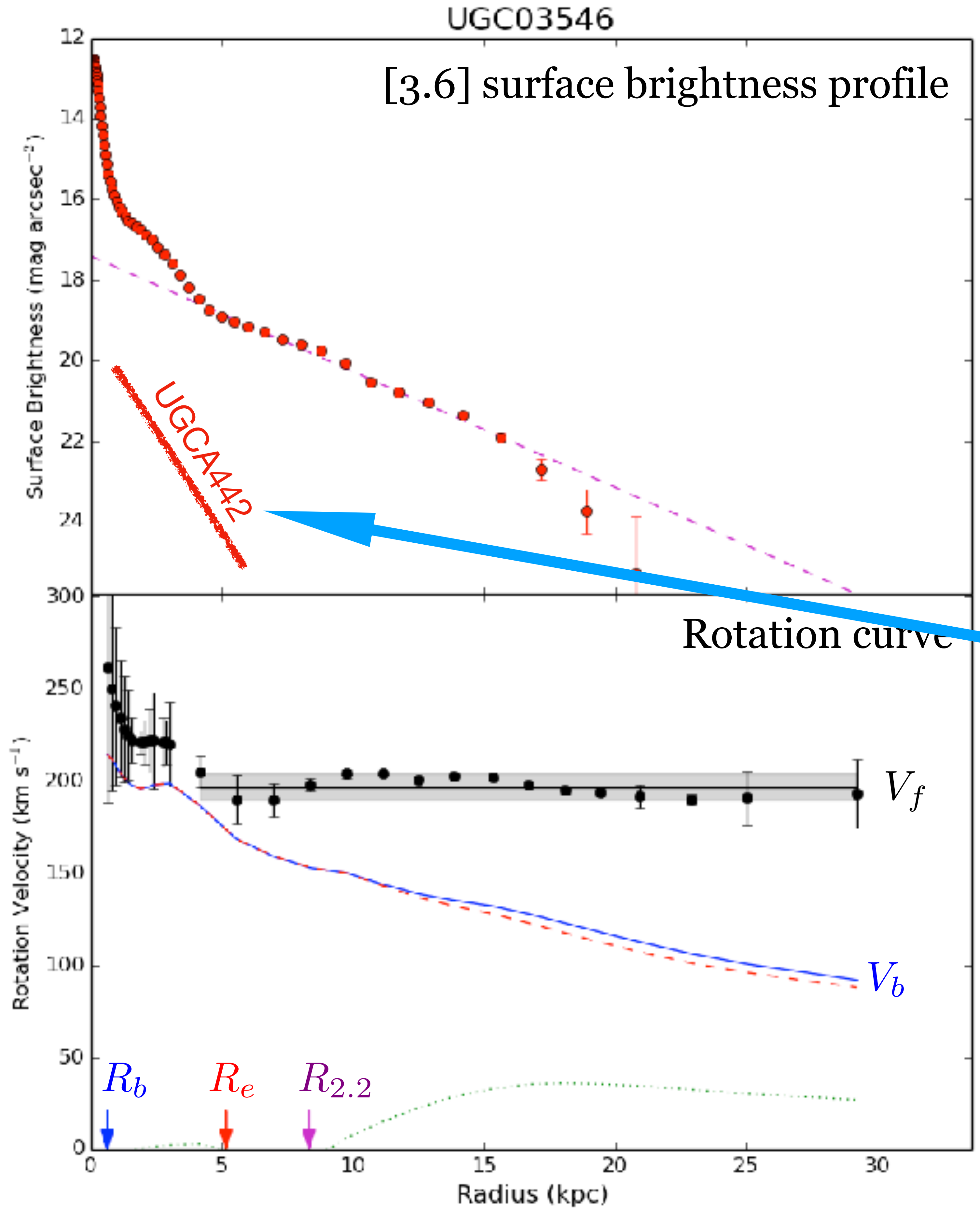
HSB galaxy

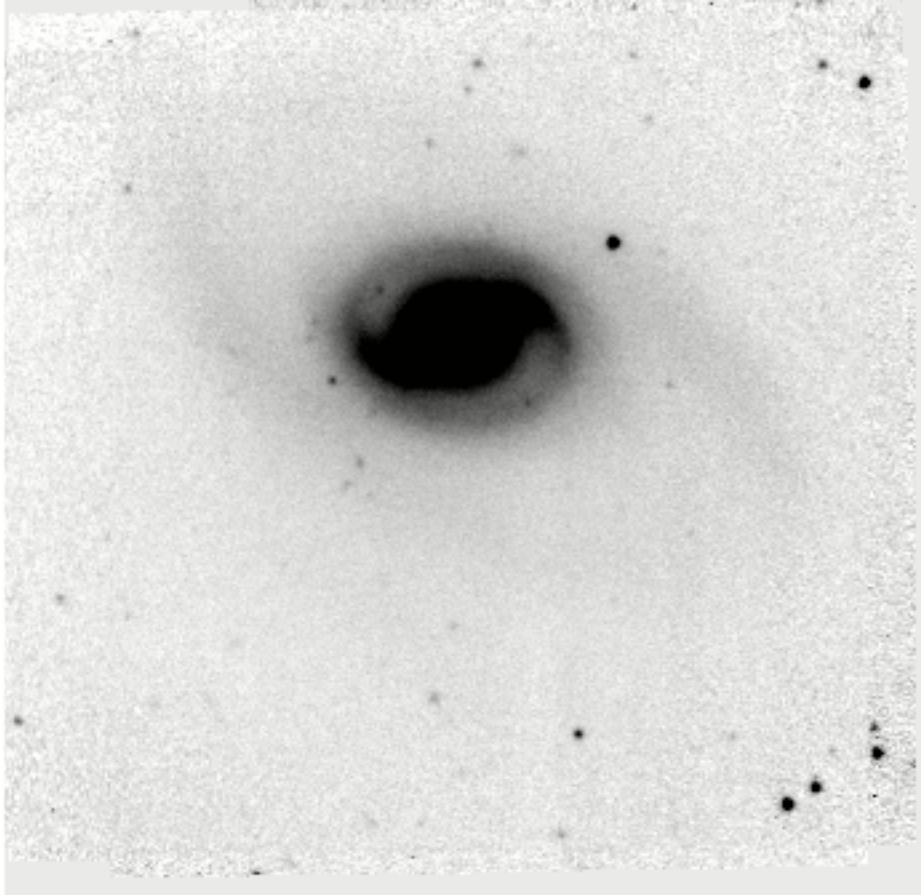


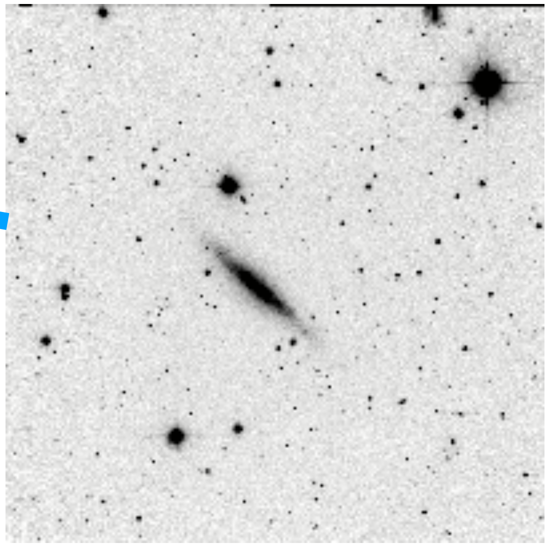


High surface brightness galaxies have rapidly rising rotation curves

HSB galaxy





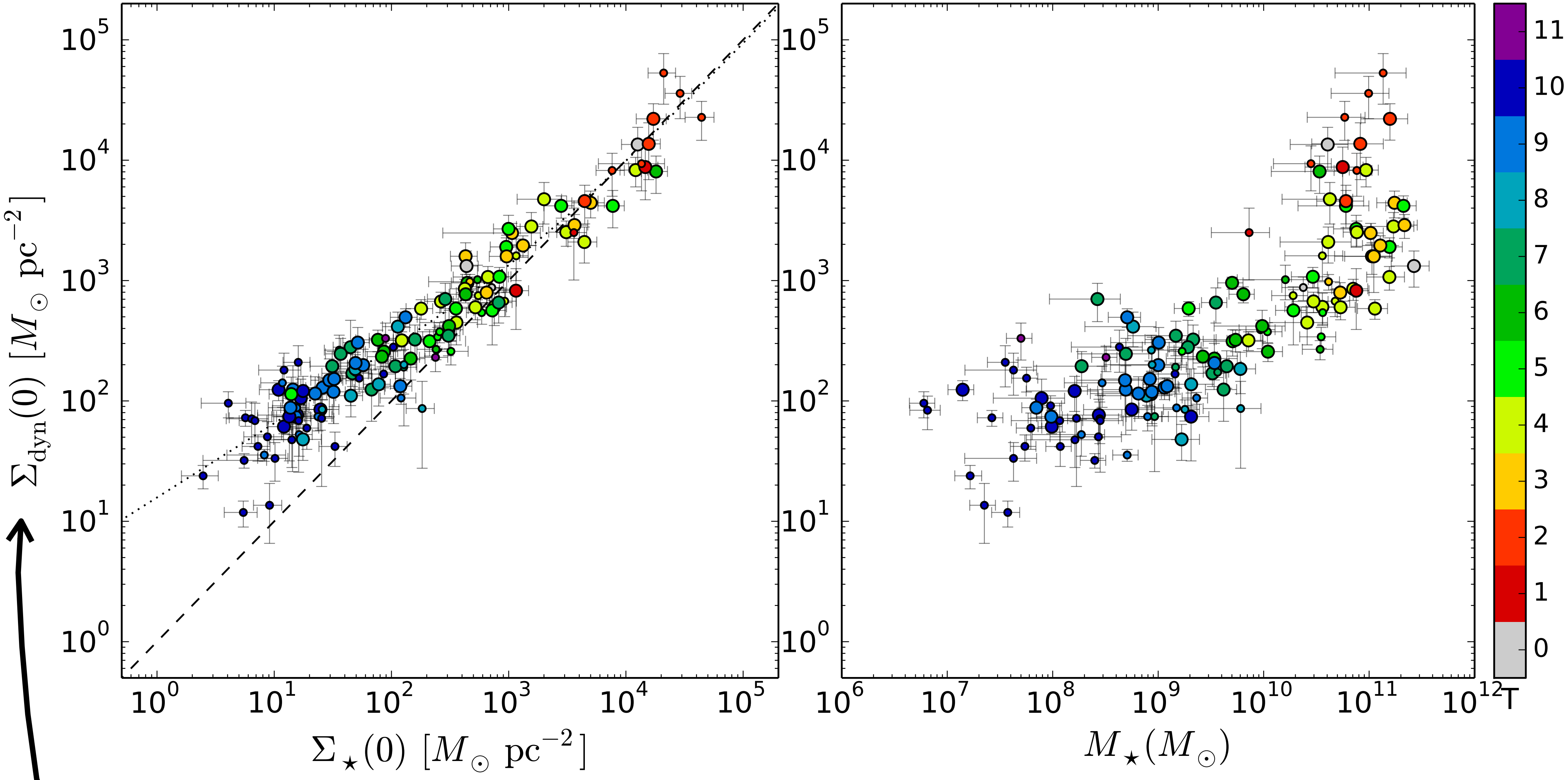


High surface brightness galaxies have rapidly rising rotation curves

The central dynamical surface density measured by the inner rotation curve gradient correlates with the central surface brightness (more so than mass).

Light predicts mass. X & Y axes are independent.

central dynamical surface density



central surface brightness

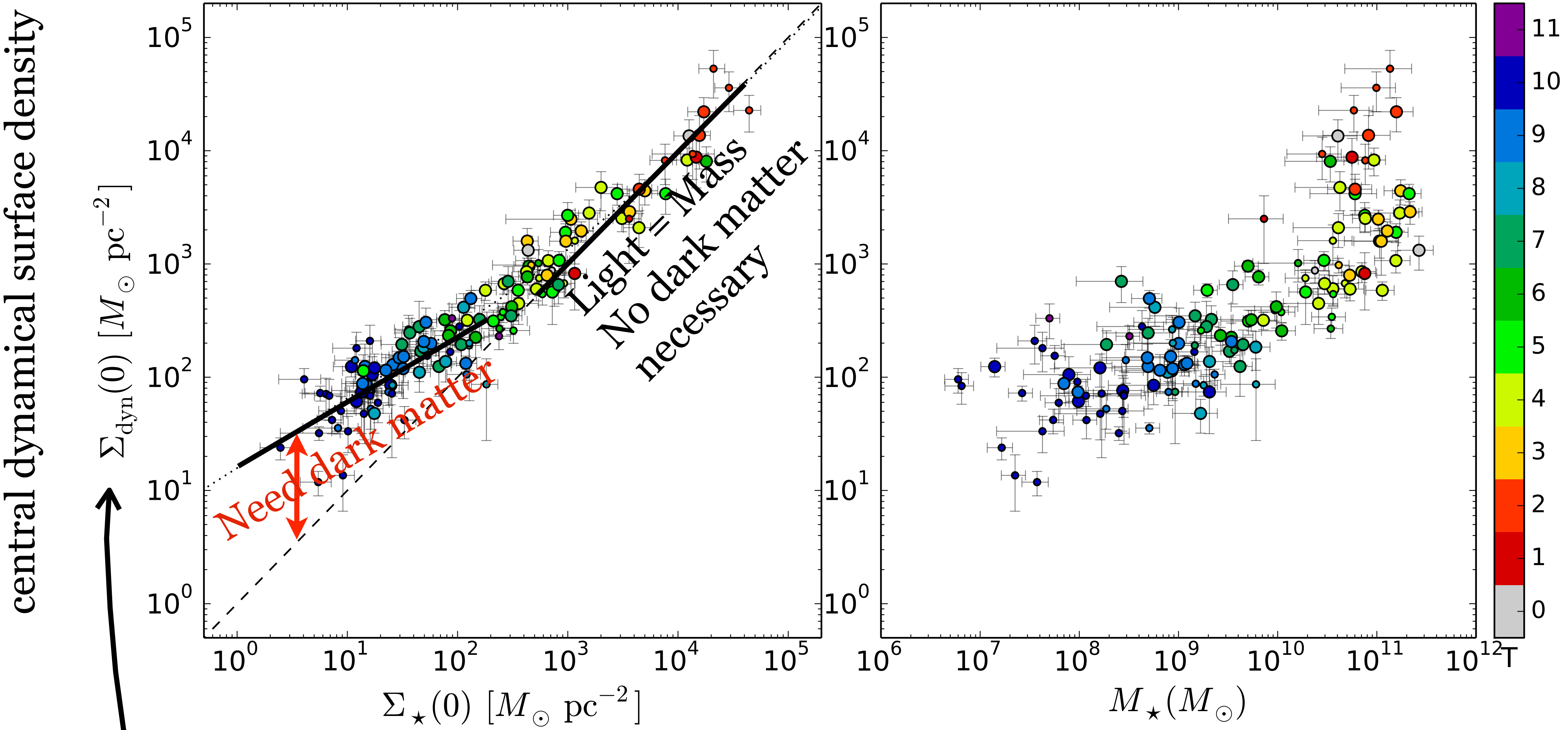
stellar mass

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

Toomre (1963)

The central dynamical surface density measured by the inner rotation curve gradient correlates with the central surface brightness (more so than mass).

Low surface brightness galaxies are dark matter dominated.



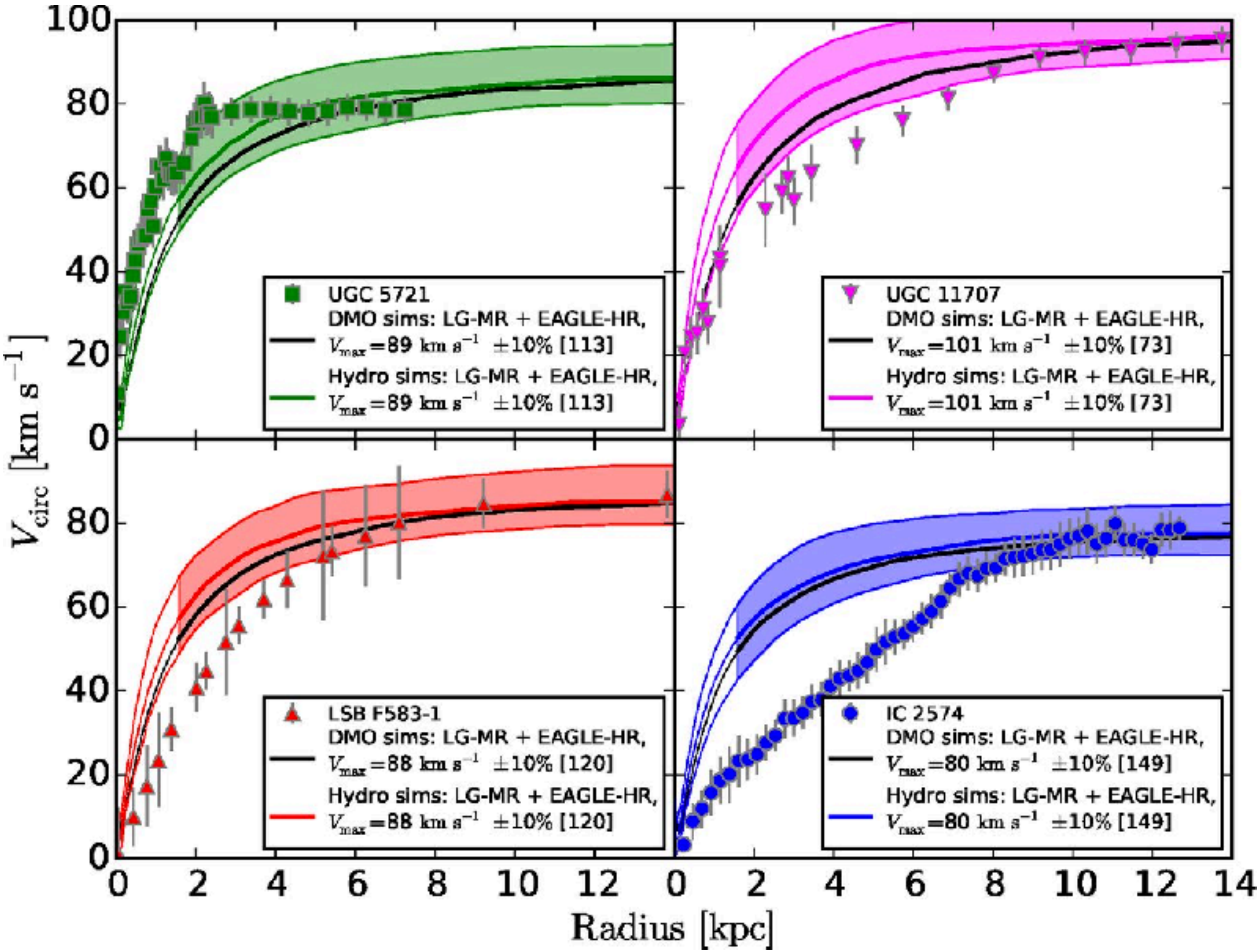
central surface brightness

stellar mass

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

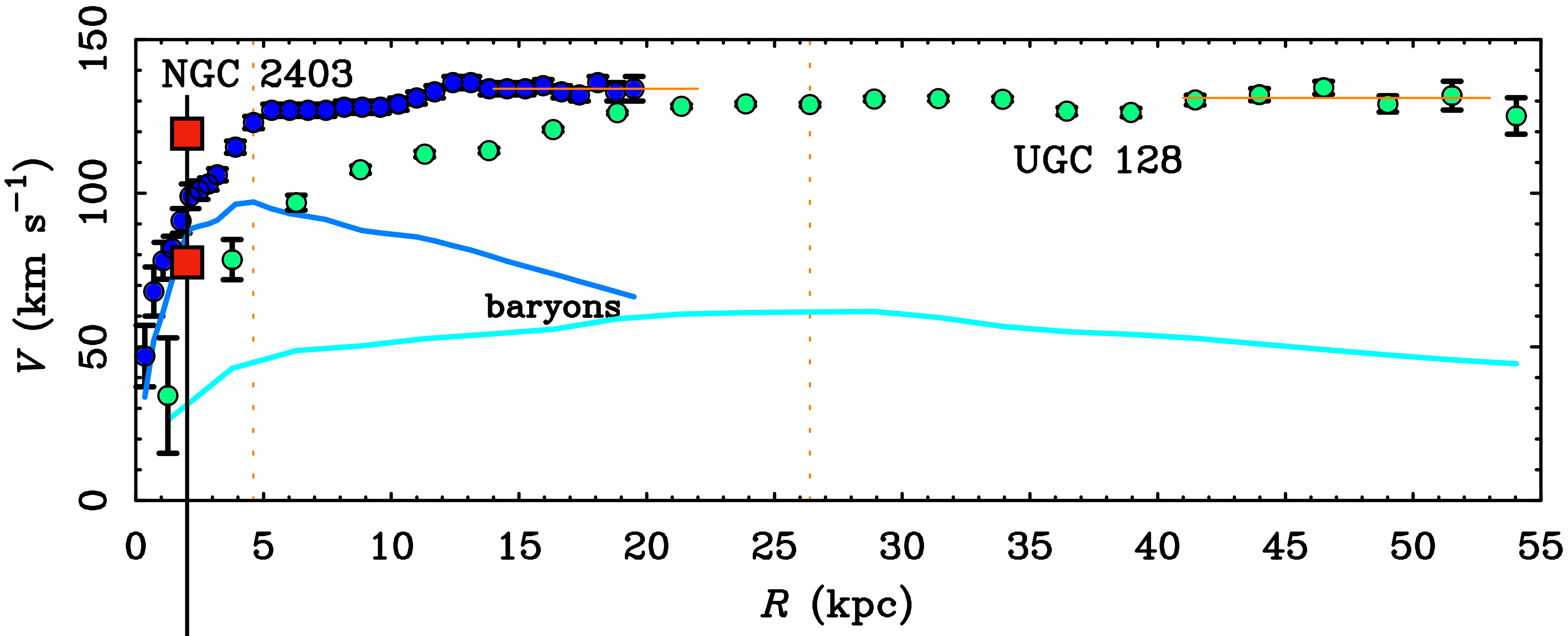
Toomre (1963)

Oman et al. (2015, MNRAS, 452, 3650) - rotation curve “diversity”



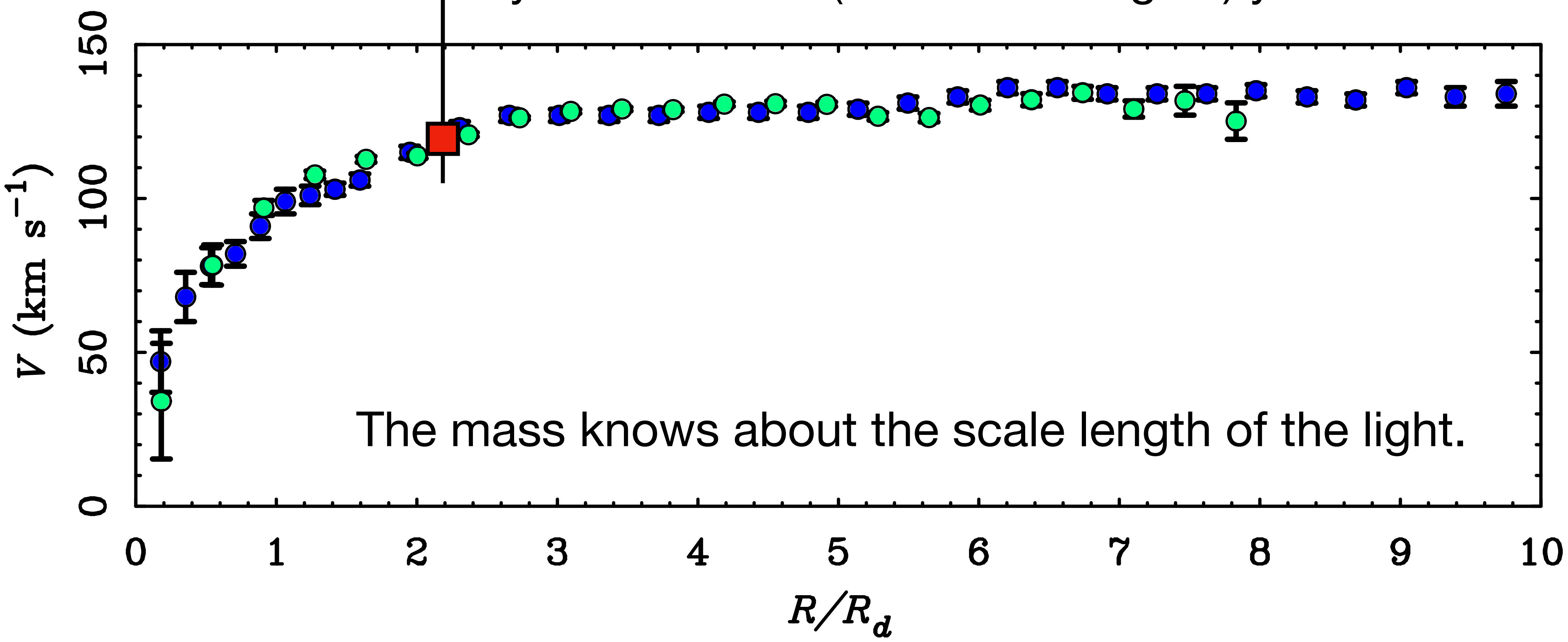
Galaxies of the same mass should have the same V(R). Instead, they have more like the same V(R/R_d).

What you get depends on how you look at it: what you assume & what you choose to measure:



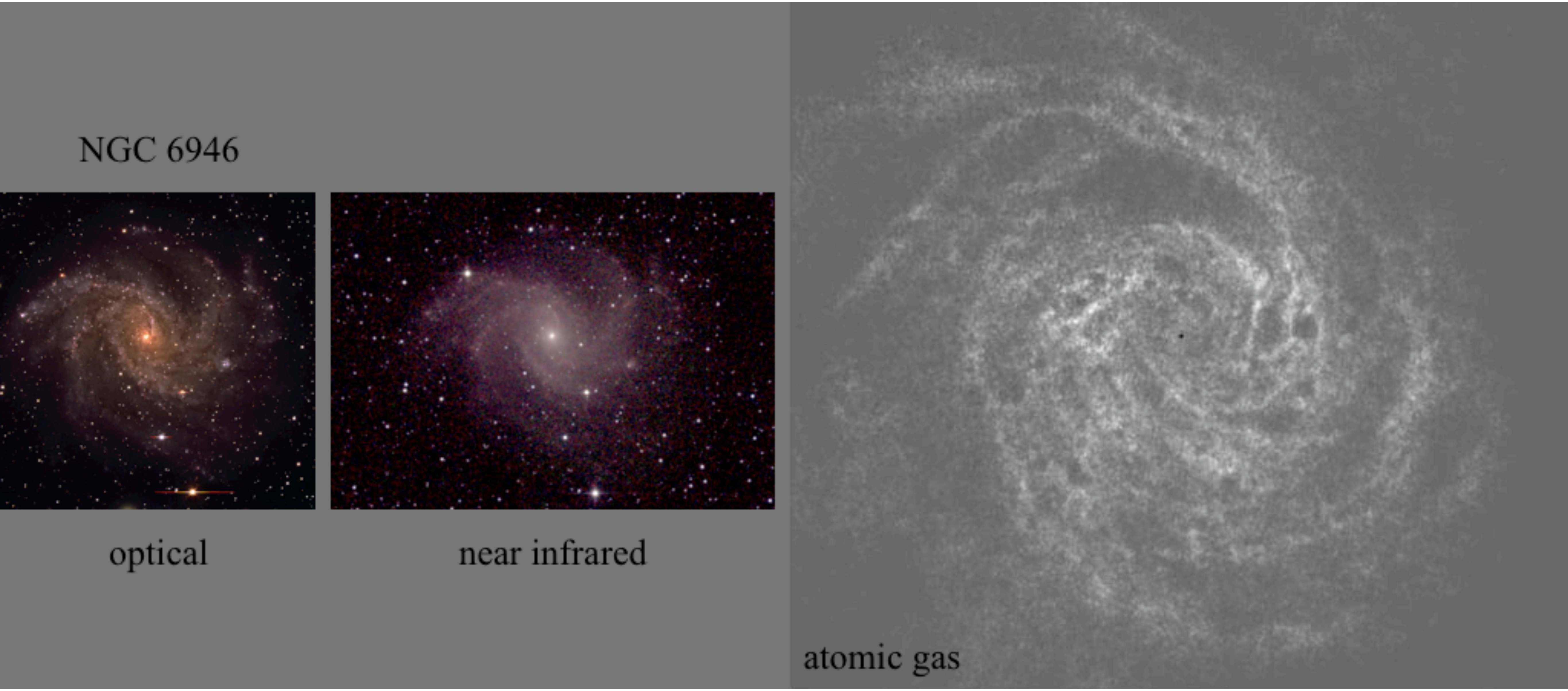
If you measure V(R in kpc) you infer **diversity**.

If you measure V(R in scale lengths) you infer **uniformity**.

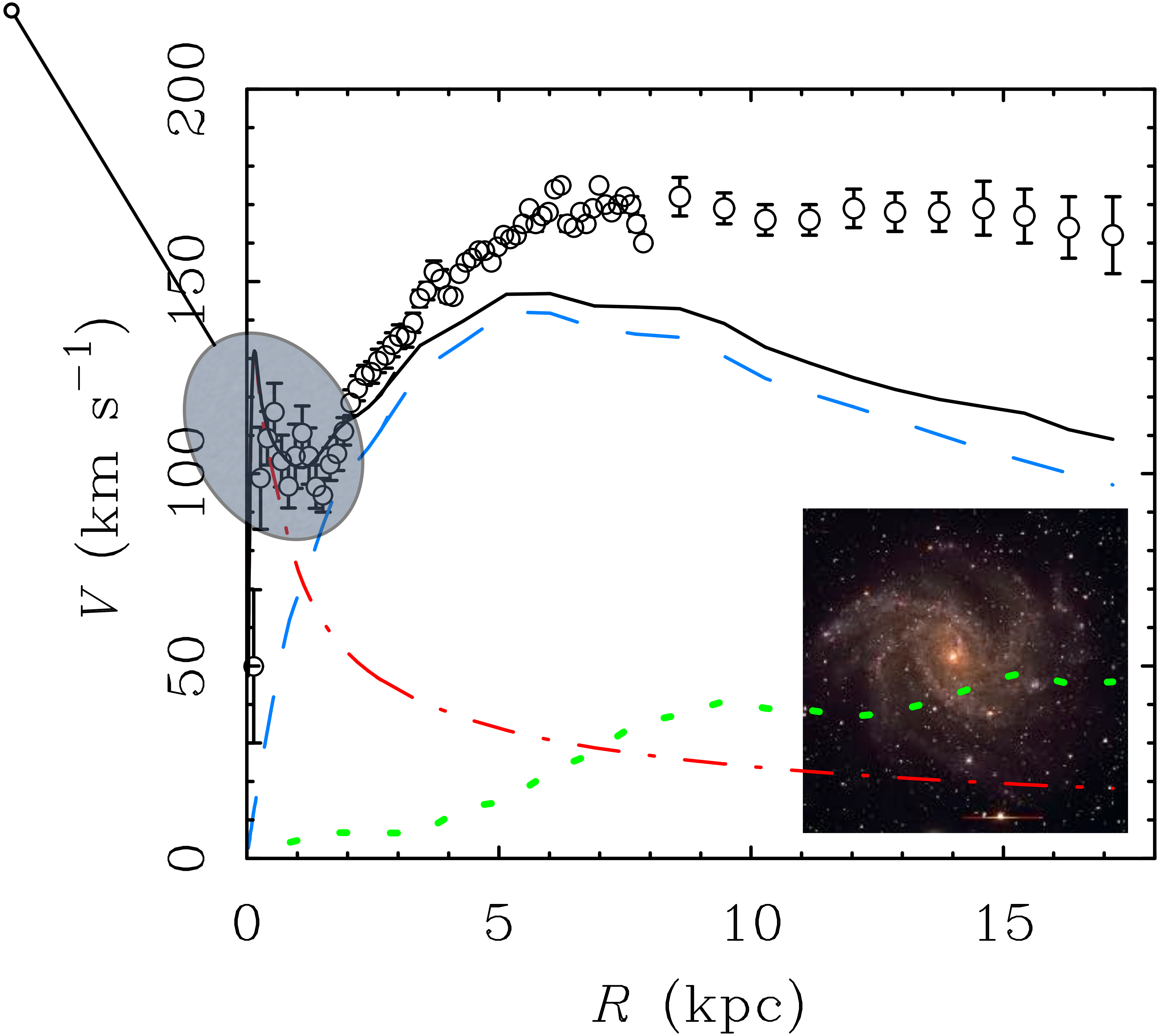


The mass knows about the scale length of the light.

- Renzo’s Rule: (2004 IAU; 1995 private communication)
  “When you see a feature in the light, you see a corresponding feature in the rotation curve.”



In NGC 6946, a tiny bulge (just 4% of the total light) leaves a distinctive mark.

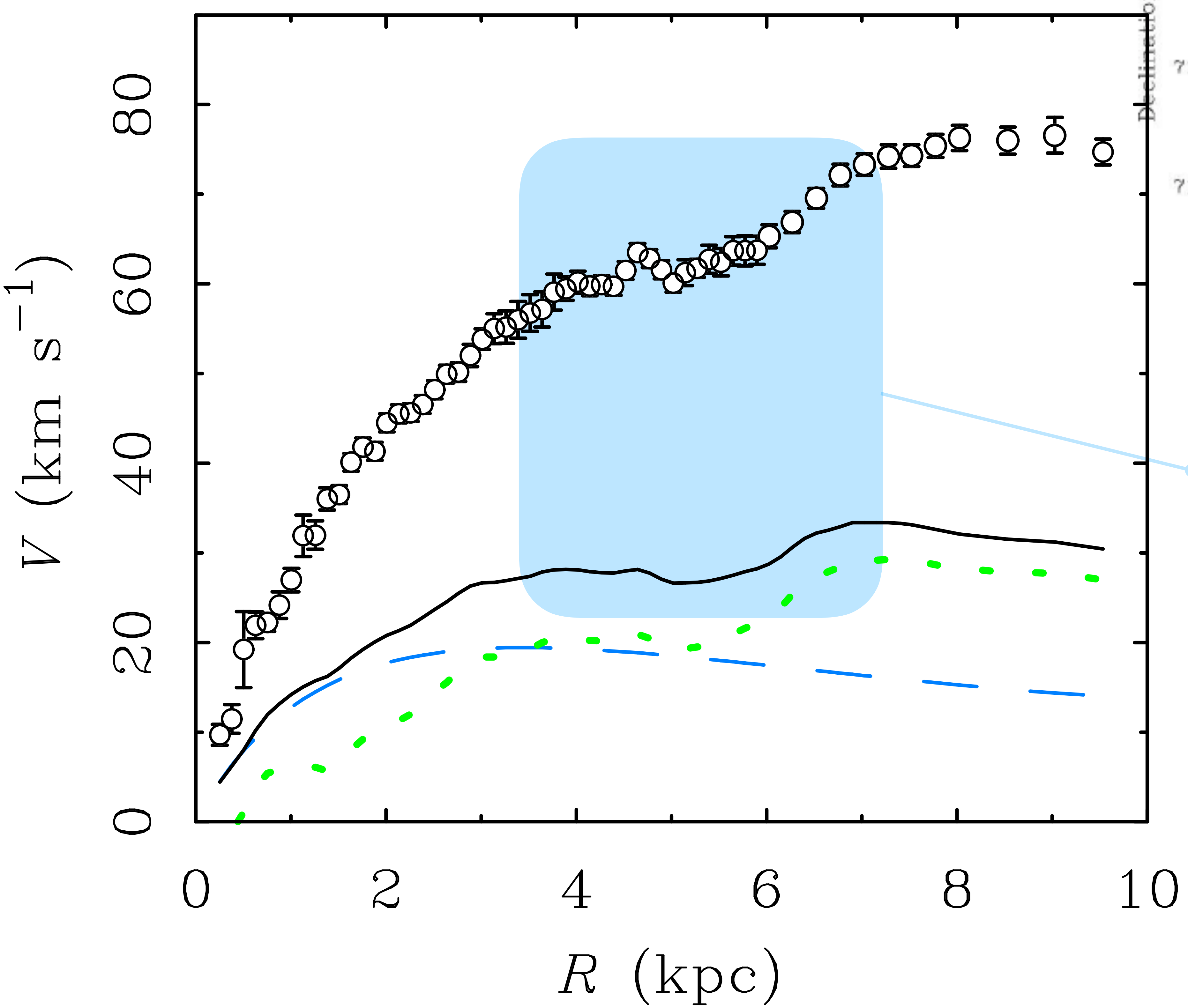


V^2 = GM/R

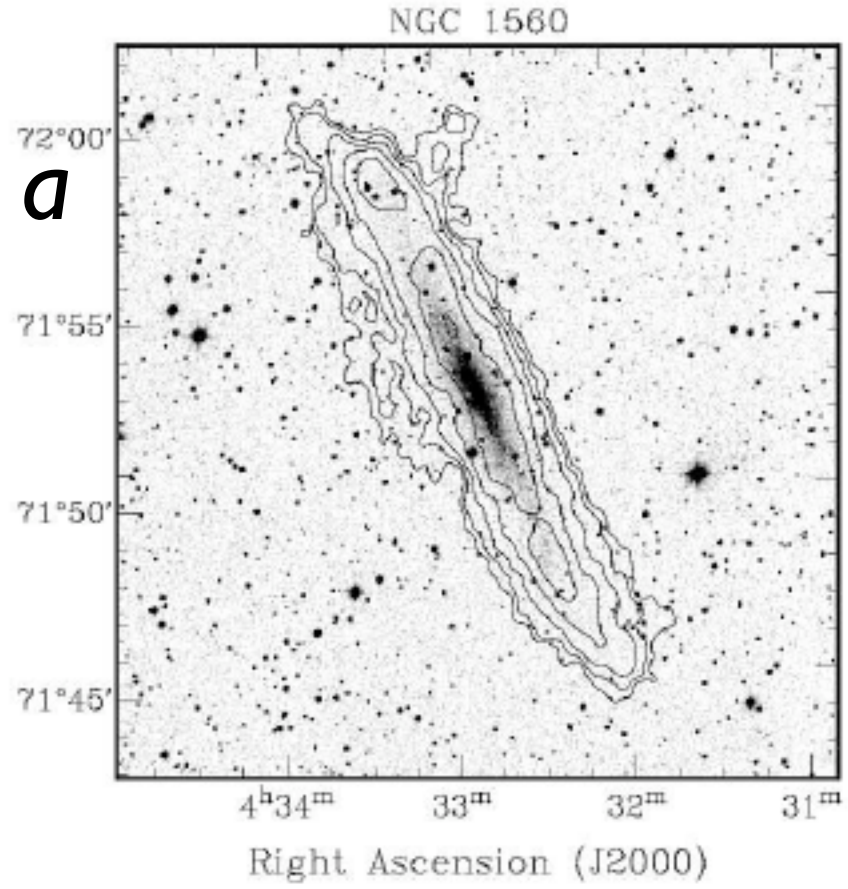
M is small
but so is **R**

Renzo’s Rule:

“When you see a feature in the light, you see a corresponding feature in the rotation curve.”



In NGC 1560, a marked feature in the gas is reflected in the kinematics, even though it accounts for little of the dynamical mass.



Gentile et al. (2010)