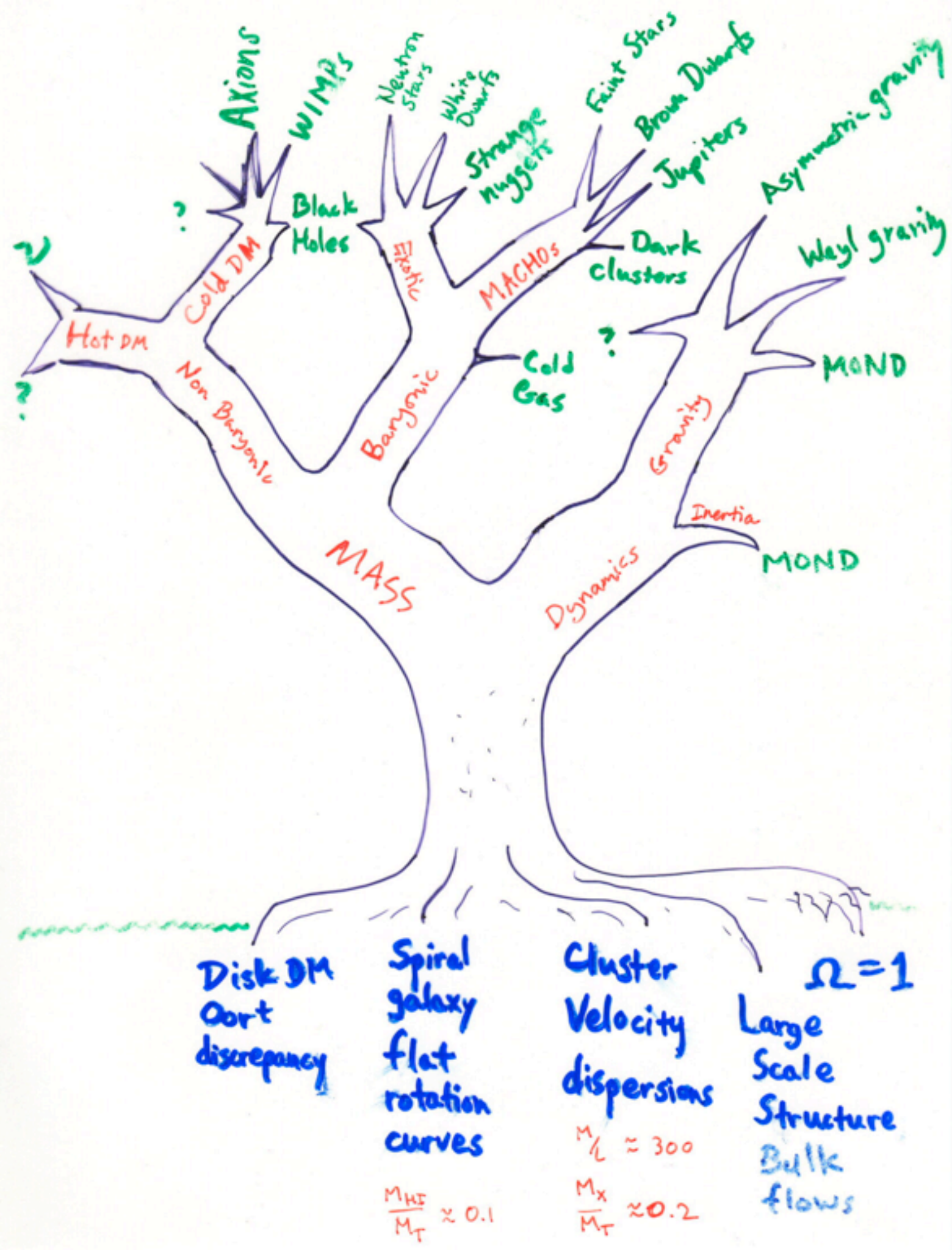# Dark Matter

ASTR 333/433
Fall 2013
M T 4:00–5:15pm
Sears 552

Prof. Stacy McGaugh
Sears 573
368-1808
stacy.mcgaugh@case.edu
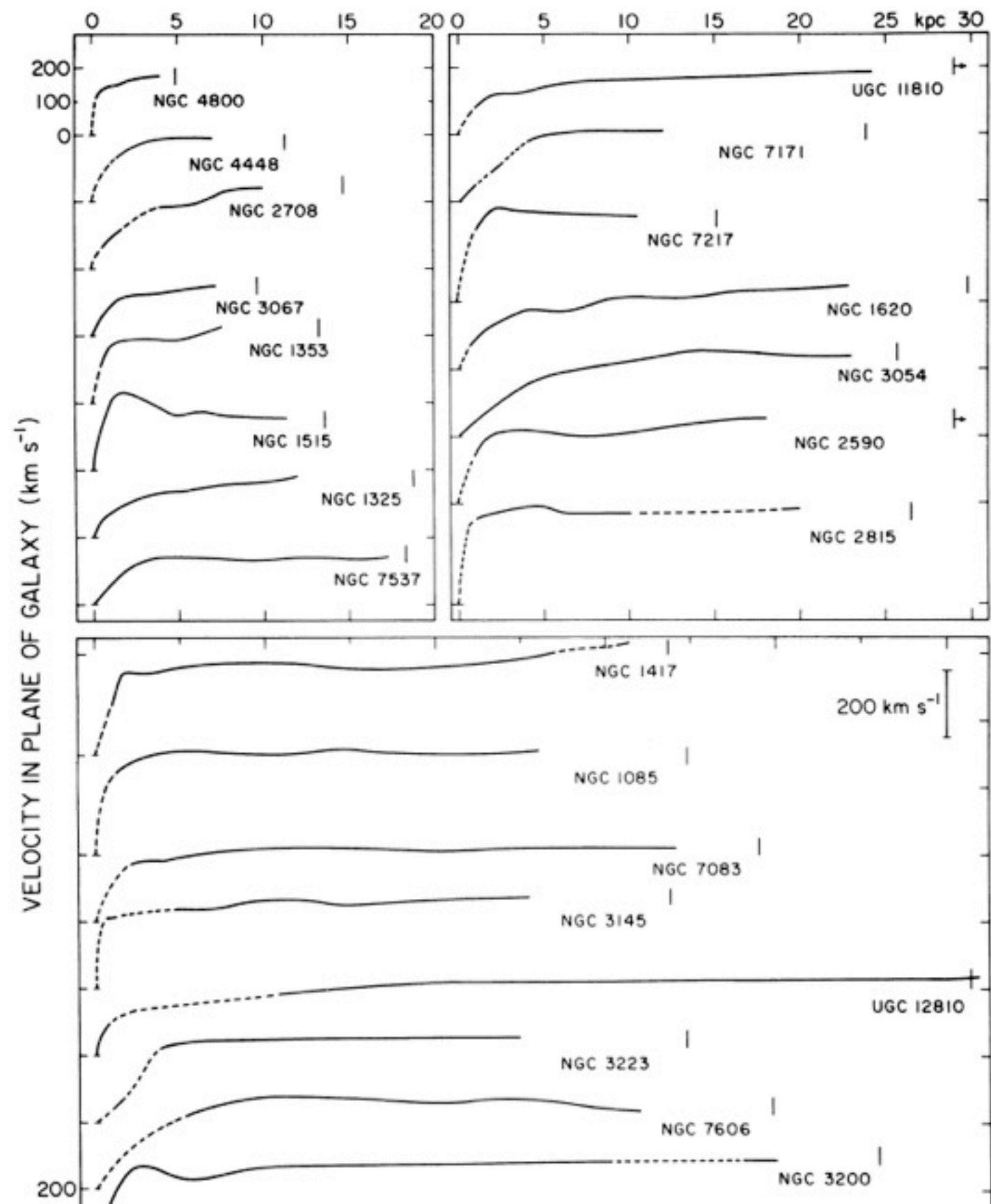
Case Western Reserve University EST. 1826

Empirical Laws of Galactic Rotation

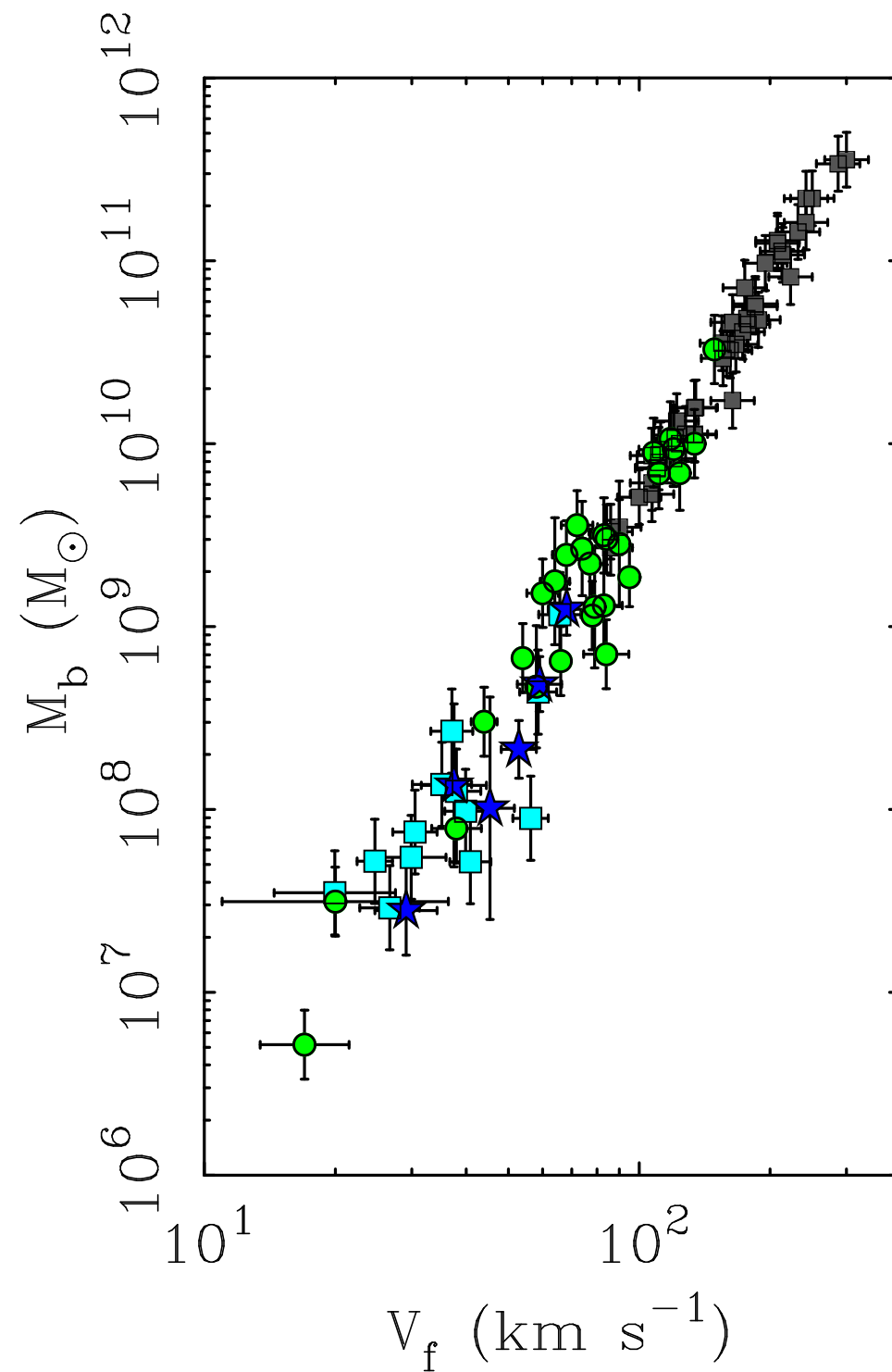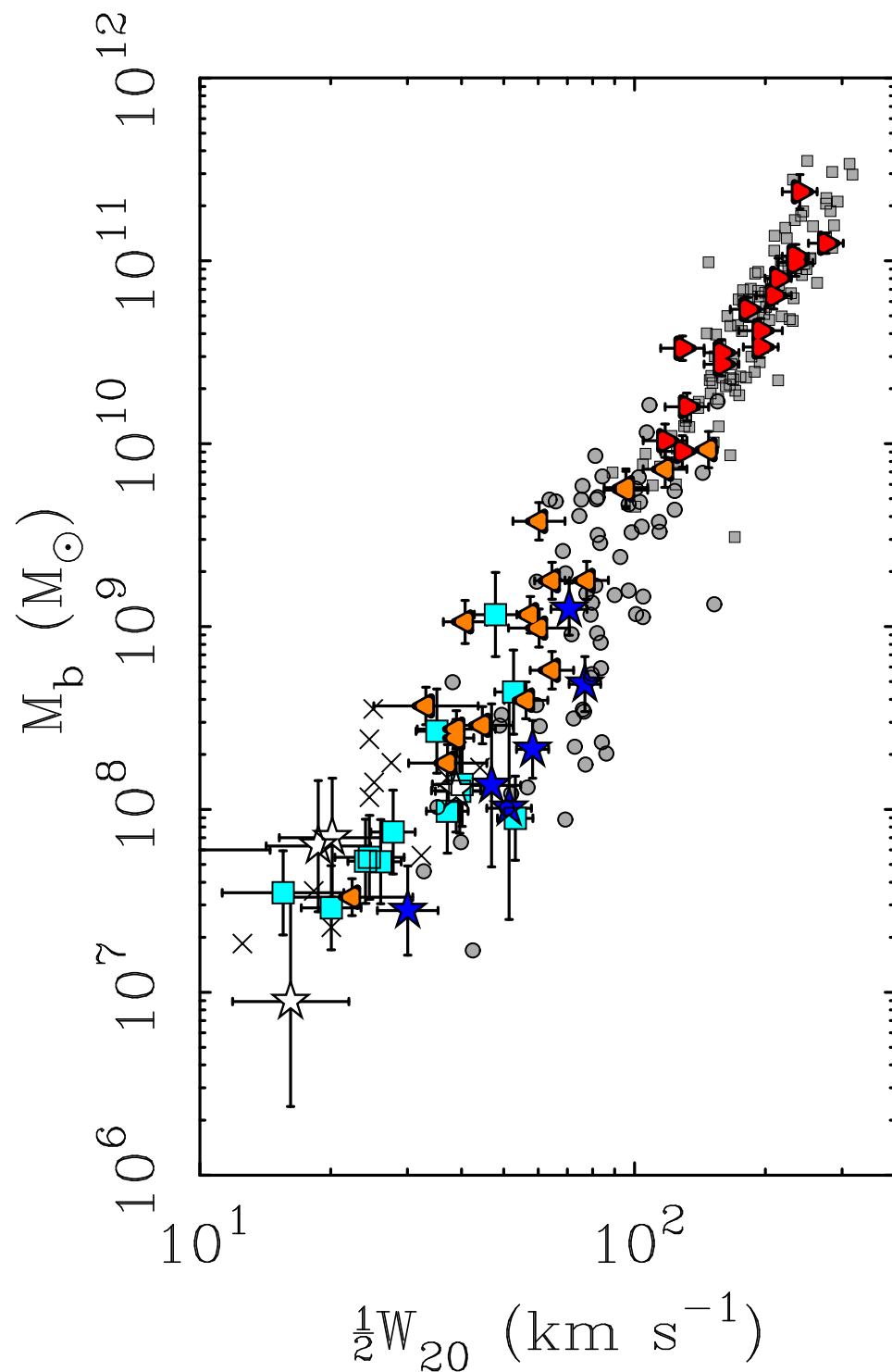Homework 2
due Oct 15
(tomorrow)

midterm Oct 29

1. The rotation speed of galaxies tends to become approximately constant at large radii, a condition which persists indefinitely
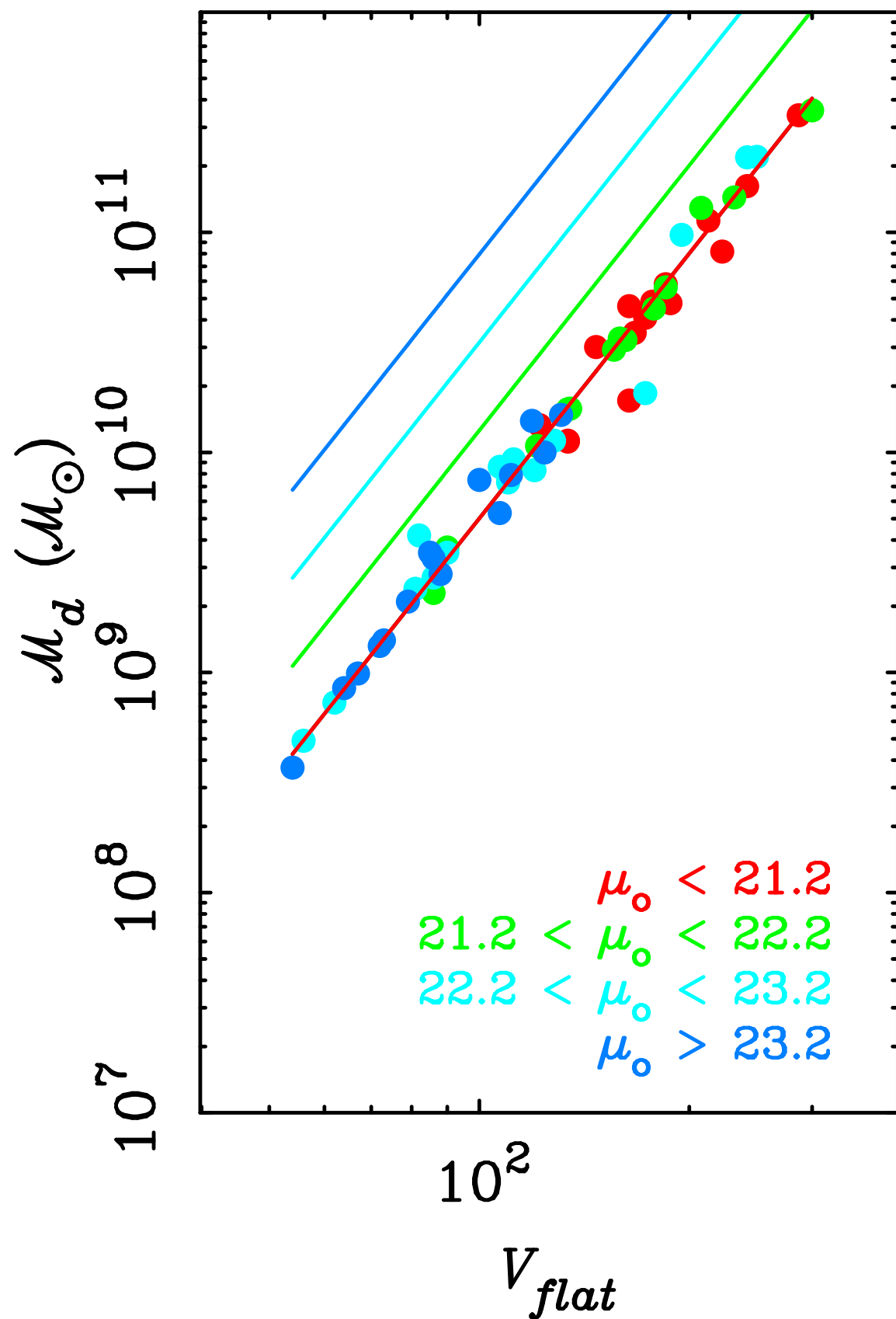
2. The mass of a galaxy is proportional to the fourth power of the constant rotation speed.
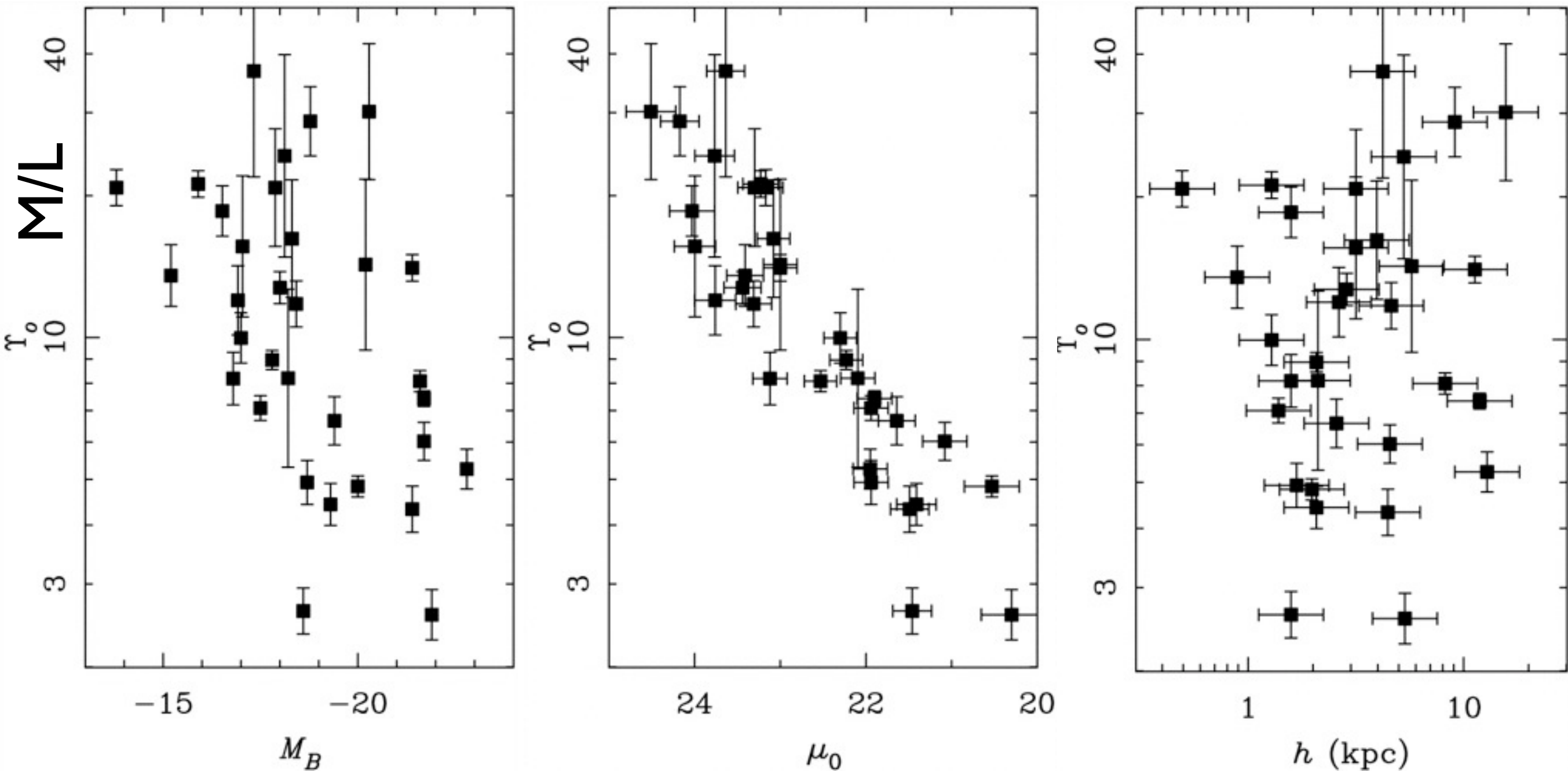
$$M_b = 47V_f^4$$

No residuals from TF with
size or surface brightness

means M/L anti-correlates
with surface brightness

$\mu_o < 21.2$
$21.2 < \mu_o < 22.2$
$22.2 < \mu_o < 23.2$
$\mu_o > 23.2$

dynamical M/L enclosed by 4 scale lengths

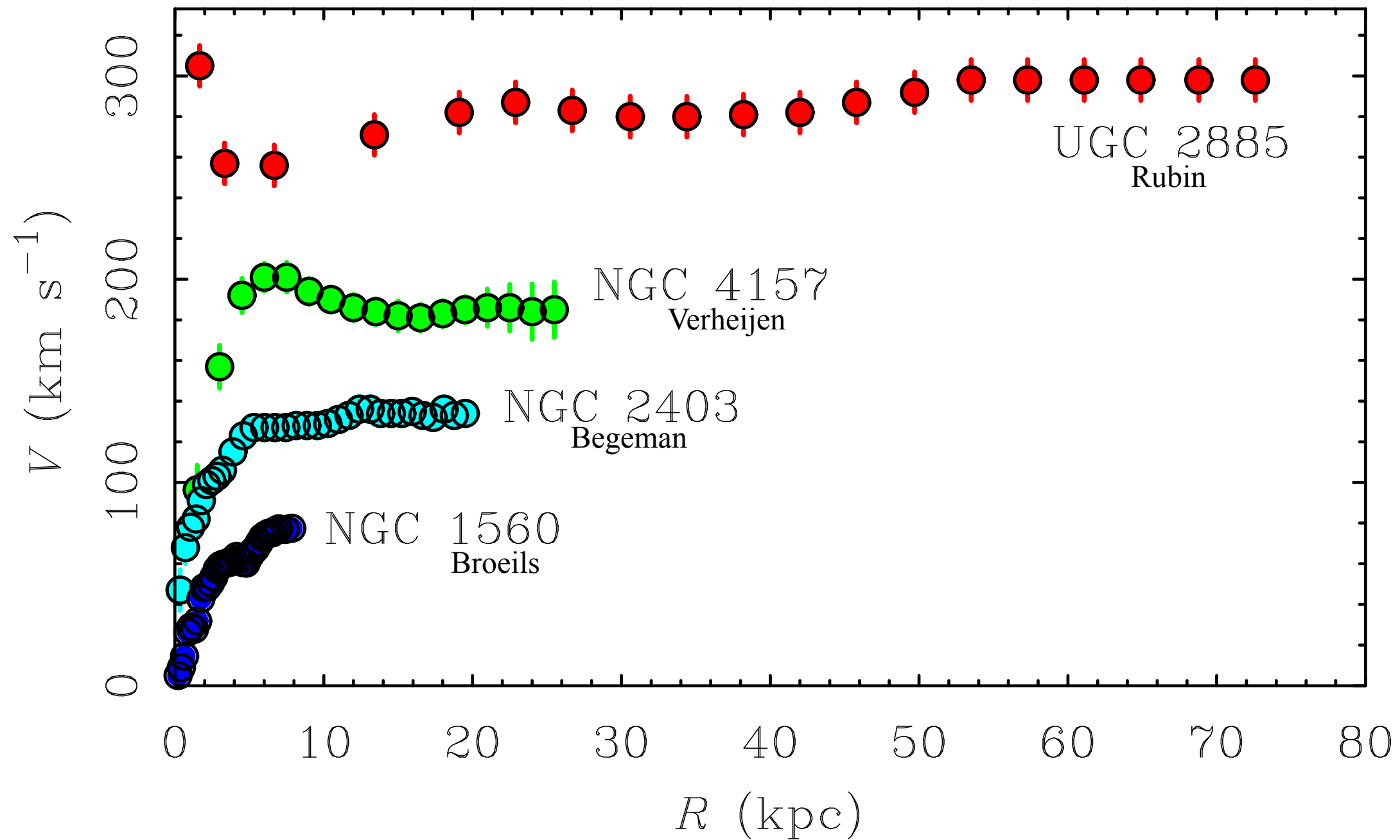$$M = V^2 R/G \quad \text{with} \quad R = 4R_d$$

Absolute magnitude   central surface brightness   disk scale length

3. 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)

    - Universal Rotation Curve (Persic & Salucci 1996)

    - Renzo's Rule (Sancisi 2004)

    - Mass Discrepancy-Acceleration Relation (McGaugh 2004)

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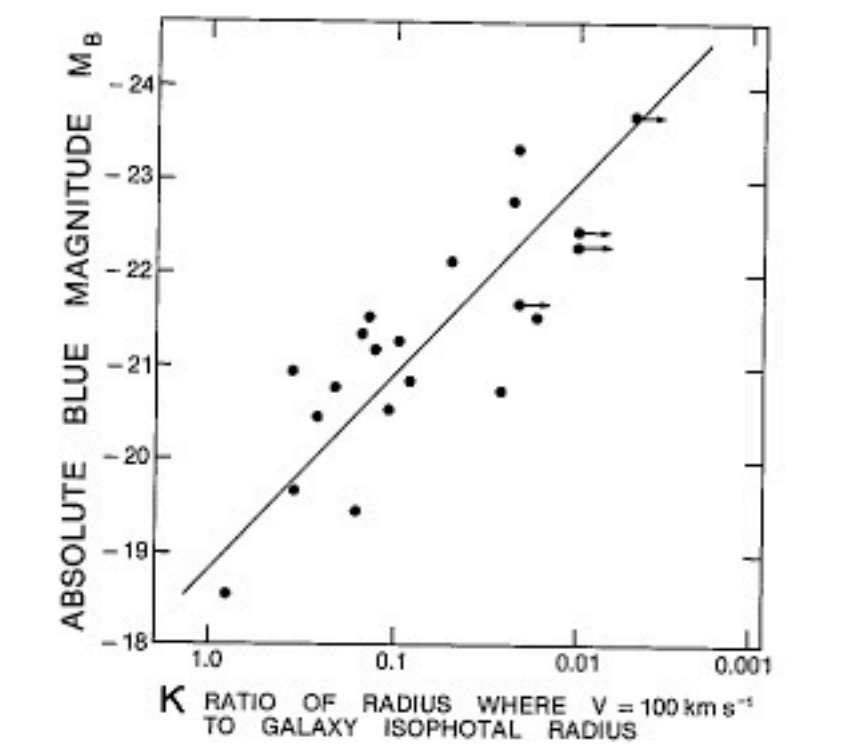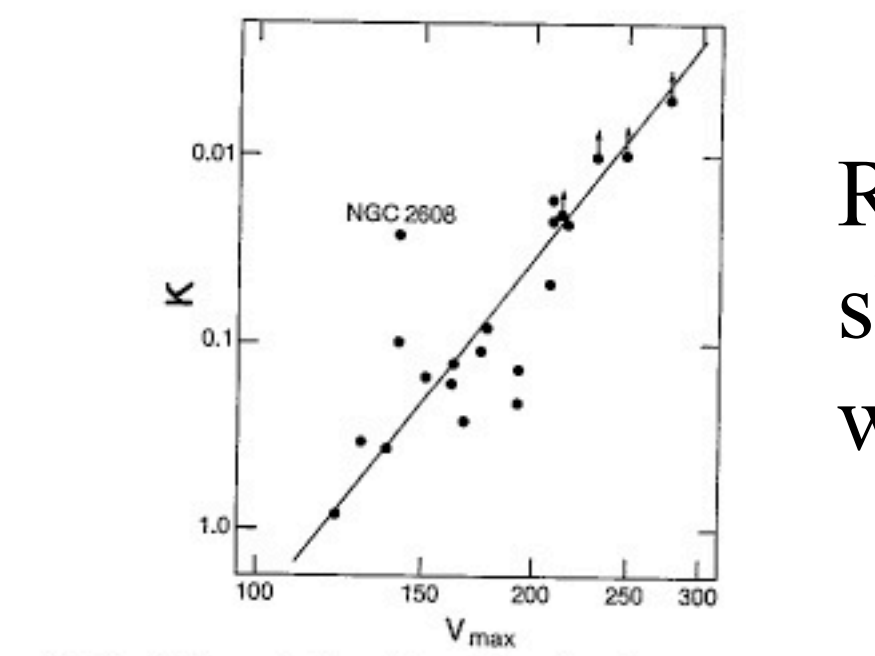
FIG. 3.—The correlation of log κ, the radius where the rotational velocity equals 100 km s^{-1} in units of the isophotal radius, vs. log V_{max}. The line is the mean of the two regressions and has a slope equal to 6.3 ± 0.5. NGC 2608, the only strongly barred galaxy in the sample, was excluded from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

Rotation curve shapes correlate with galaxy properties

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

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 ($\kappa < 0.01$).
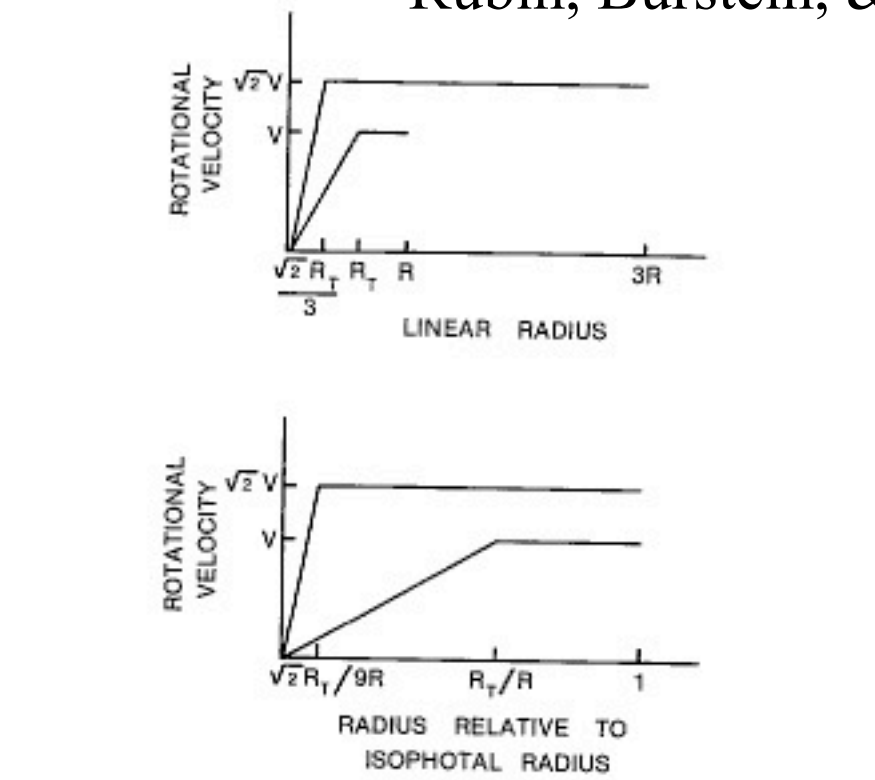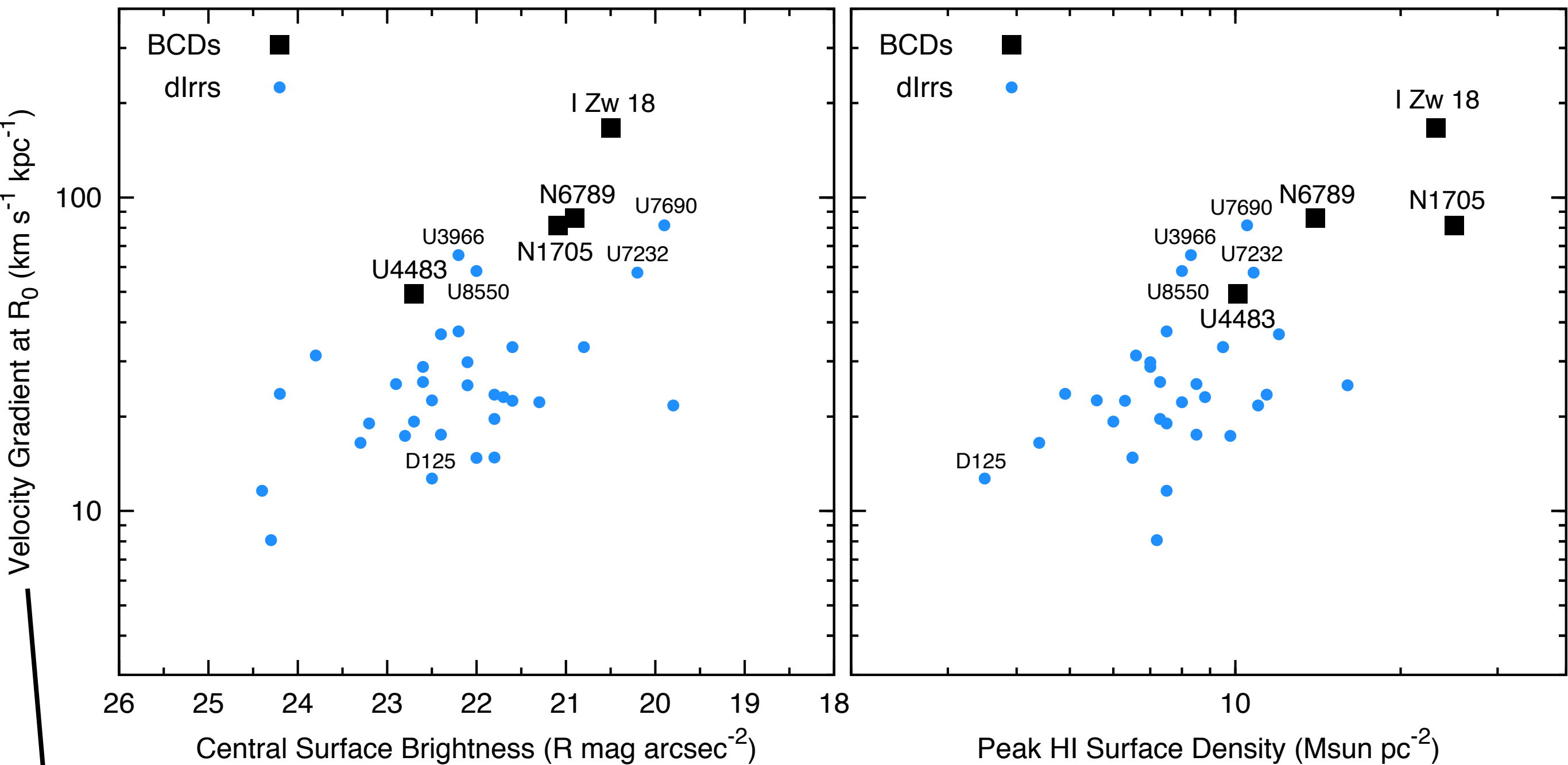
FIG. 4.—Schematic rotation curves for two Sc galaxies on a linear (*upper*) and relative (*lower*) radius scale. The higher-luminosity galaxy is chosen to have its velocity in the flat portion $\sqrt{(2)}$ times that of the lower-luminosity galaxy. Then the nuclear velocity gradient, turnover radius, and radial extent are fixed by the observations as shown (see text and Table 2).
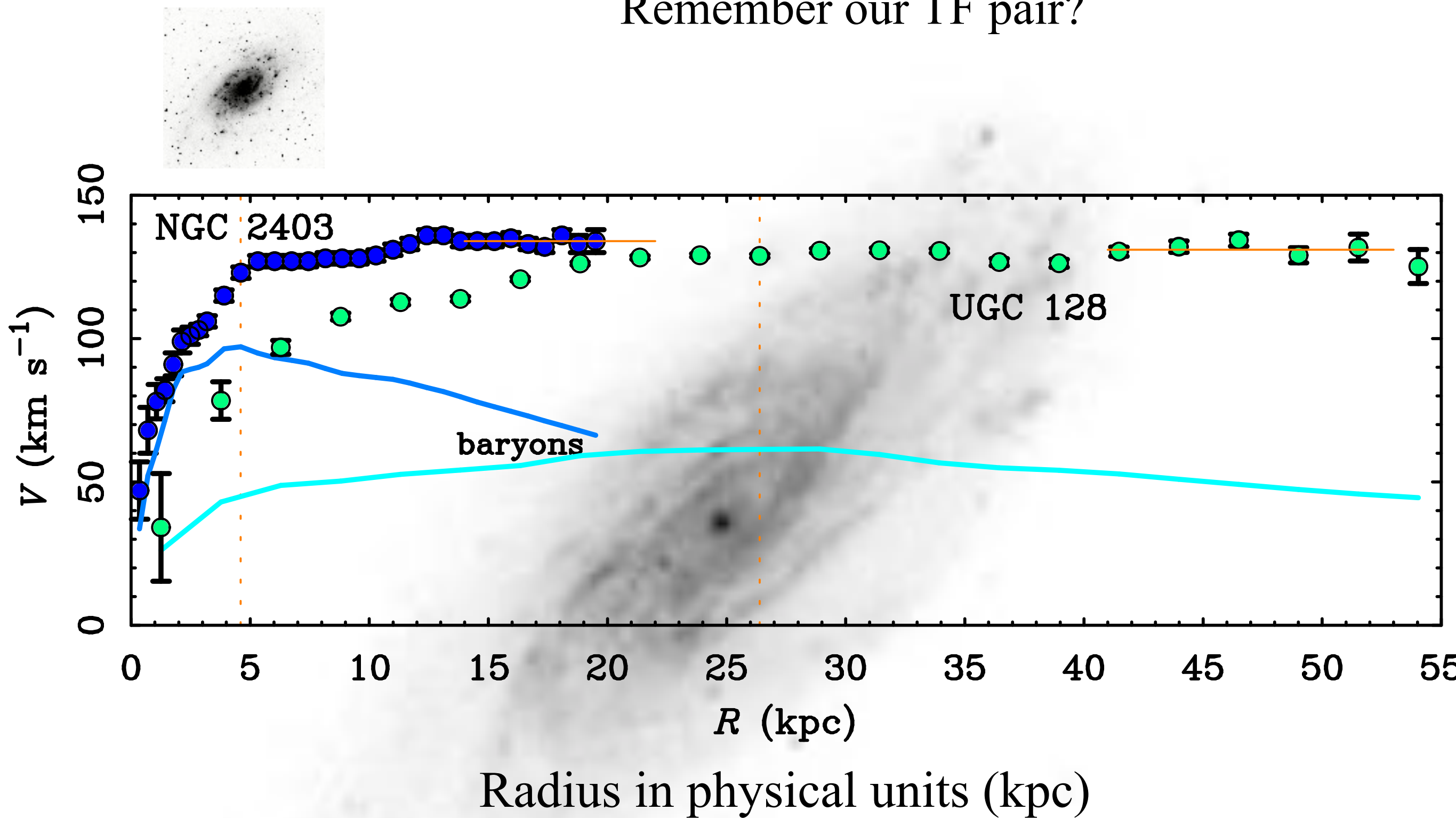
Lelli et al. (2012)
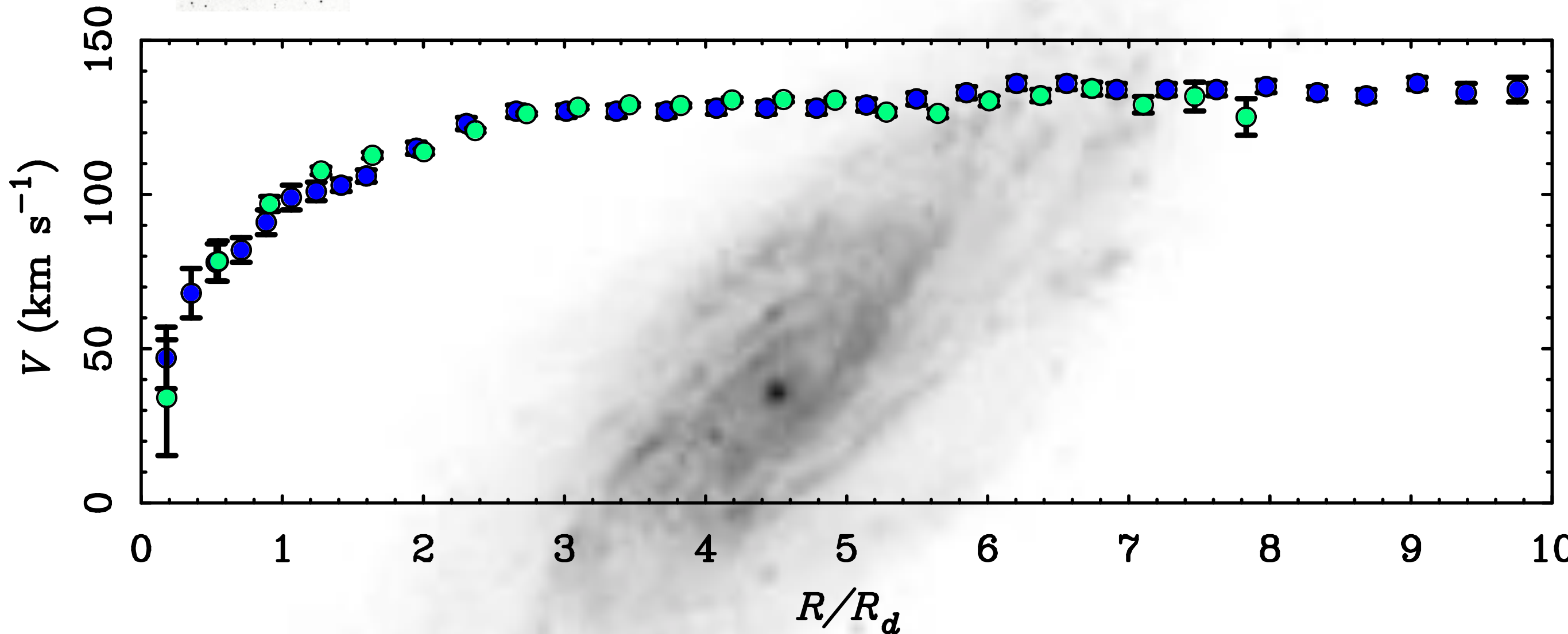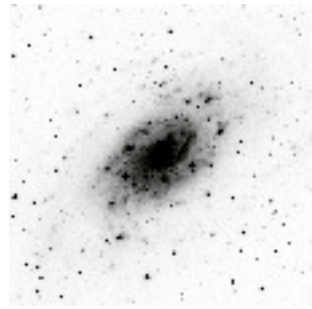
$$\frac{V(R_d)}{R_d}$$

The higher the surface brightness,
the steeper the rotation curve gradient.

Remember our TF pair?

NGC 2403

UGC 128

baryons

V (km s^{-1})

R (kpc)

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}

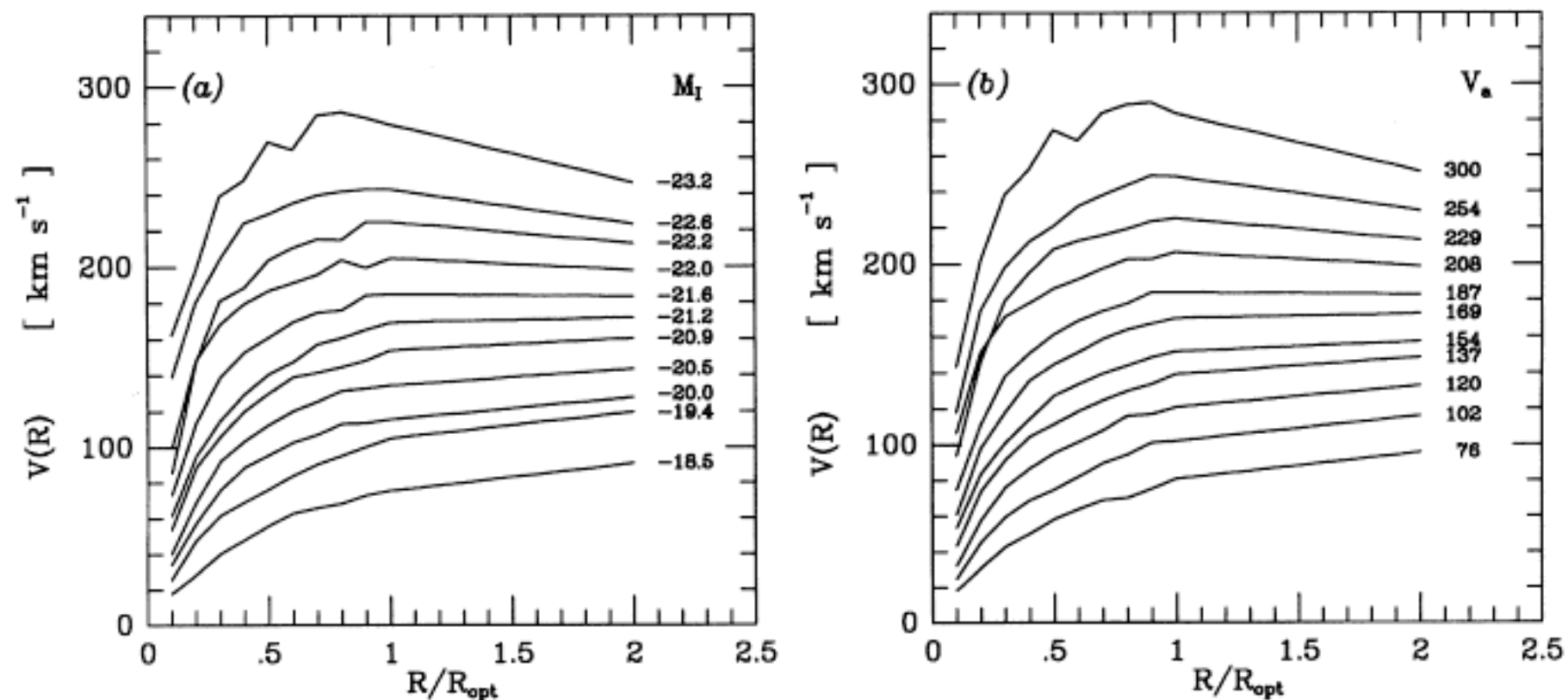**Figure 4.** The universal rotation curve of spiral galaxies. Radii are in units of R_{opt}.

$$\Delta = \frac{\partial \log V}{\partial \log R}\Big|_{R_{max}}$$

$$\Delta = 0.12 - 0.24 \log(L_B/L_B^*)$$

PERSIC AND SALUCCI
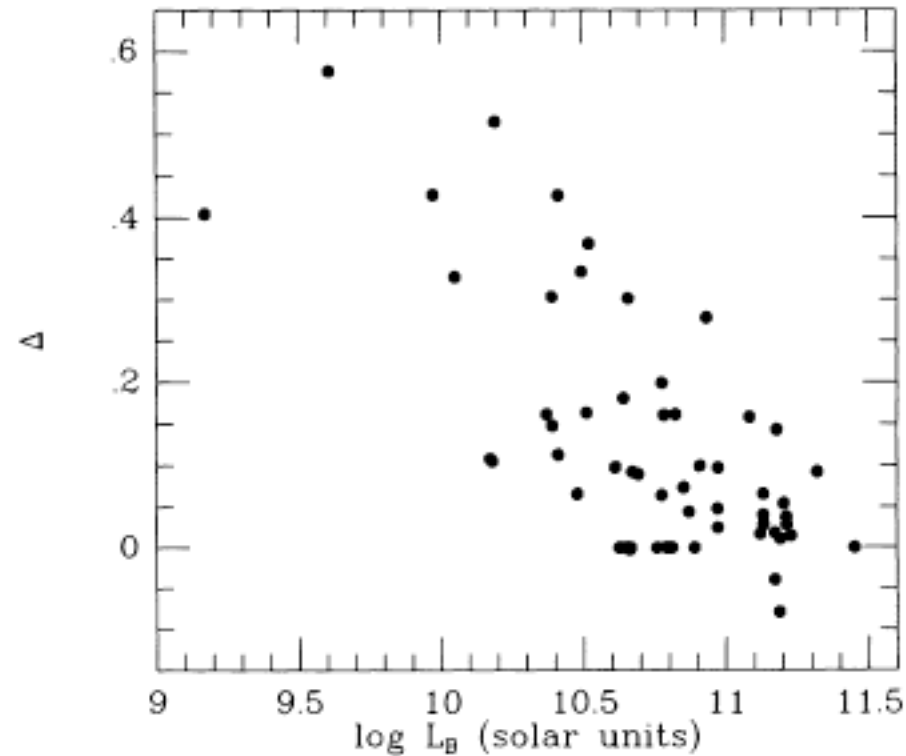

$$M_B^* = -21.5$$

FIG. 1

FIG. 1.—The fractional increase of velocity between the radius of maximum disk contribution and the optical radius (defined as 2.2 and 3.2 exponential-disk length scales, respectively) as a function of absolute blue luminosity in our sample of 58 rotation curves. A strong correlation is clearly visible. Rotation curves get flatter with increasing luminosities, and even decline for some very luminous galaxies.

computed V(R)
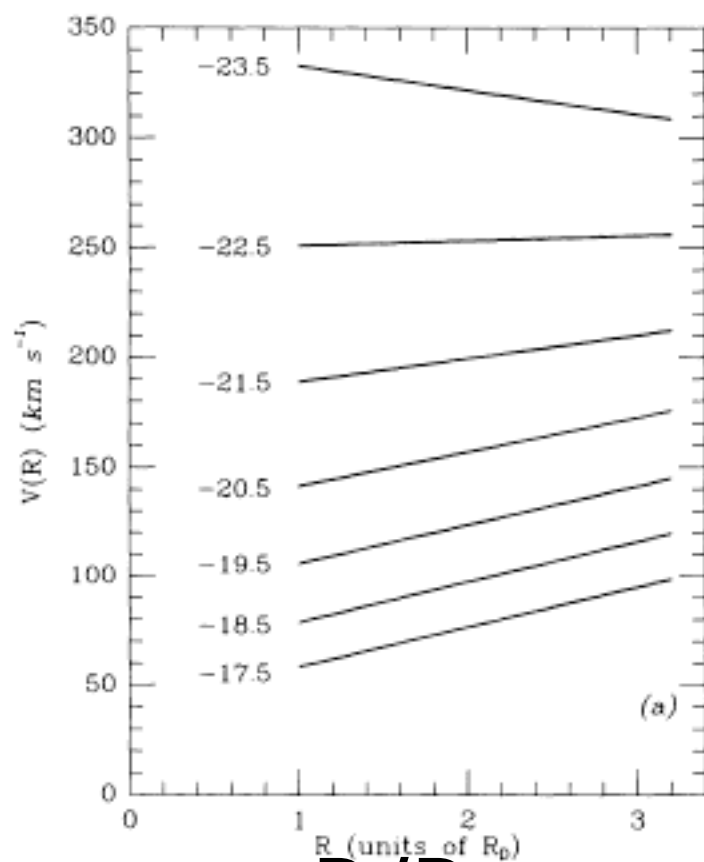
observed V(R)
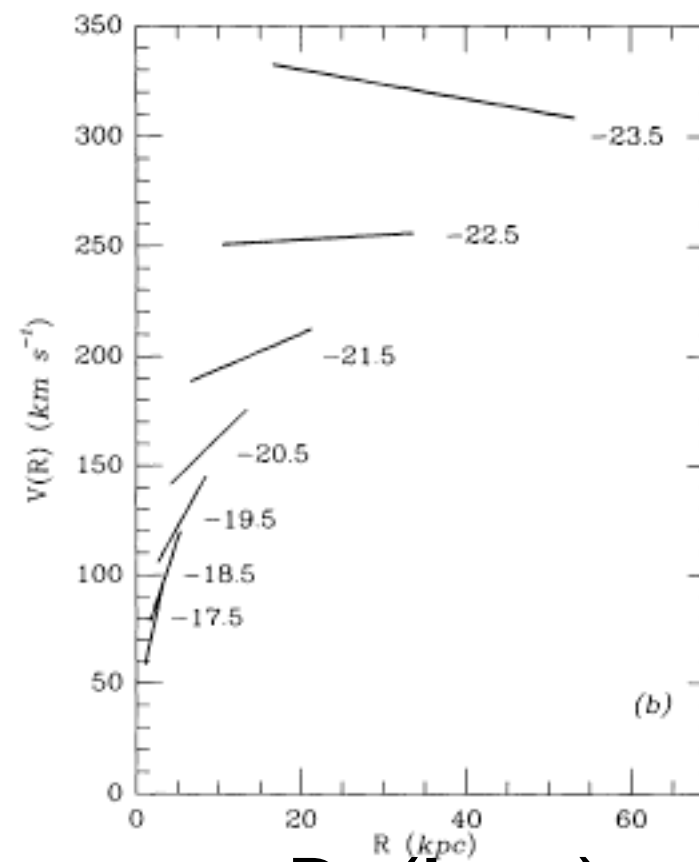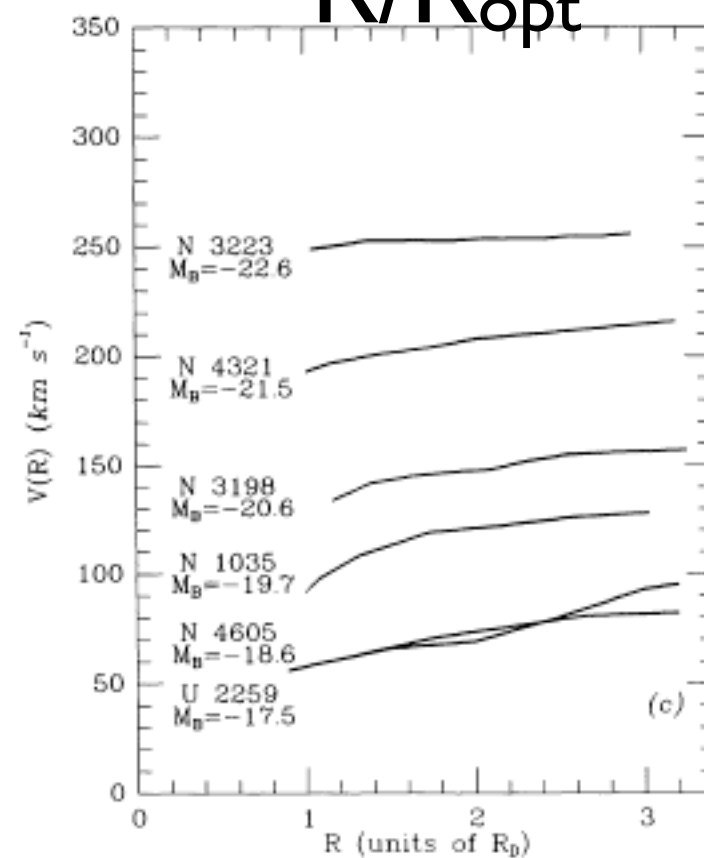
R/R$_{opt}$

R (kpc)
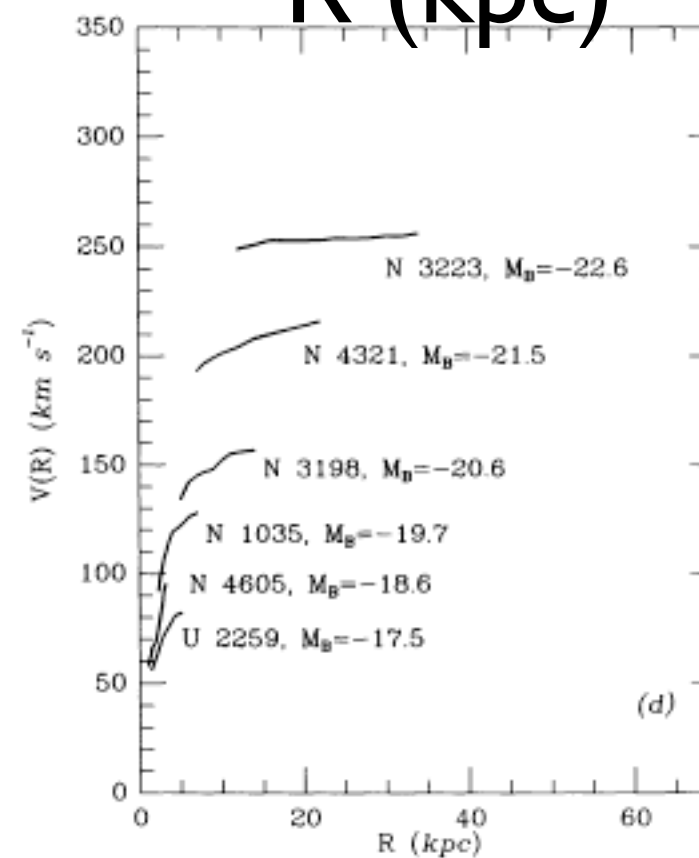
Universal Rotation curve
(Persic, Salucci & Stel 1996)

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

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

$$V_{URC}\left(\frac{R}{R_{opt}}\right) = V(R_{opt}) \left\{ \left(0.72 + 0.44 \log \frac{L}{L_*}\right) \frac{1.97 x^{1.22}}{(x^2 + 0.78^2)^{1.43}} \right.$$

$$\left. + 1.6 \exp\left[-0.4(L/L_*)\right] \frac{x^2}{x^2 + 1.5^2 \left(\frac{L}{L_*}\right)^{0.4}} \right\}^{1/2} \quad \text{km s}^{-1}$$

(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
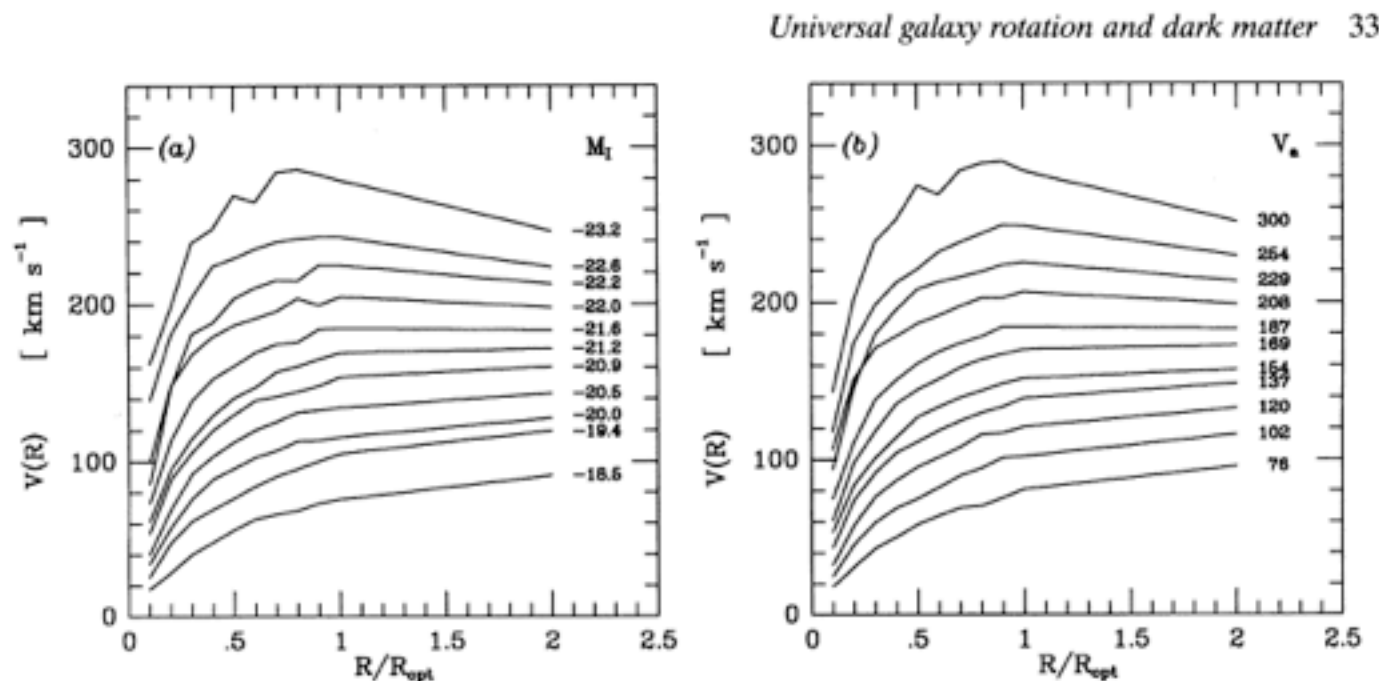

Universal galaxy rotation and dark matter 33

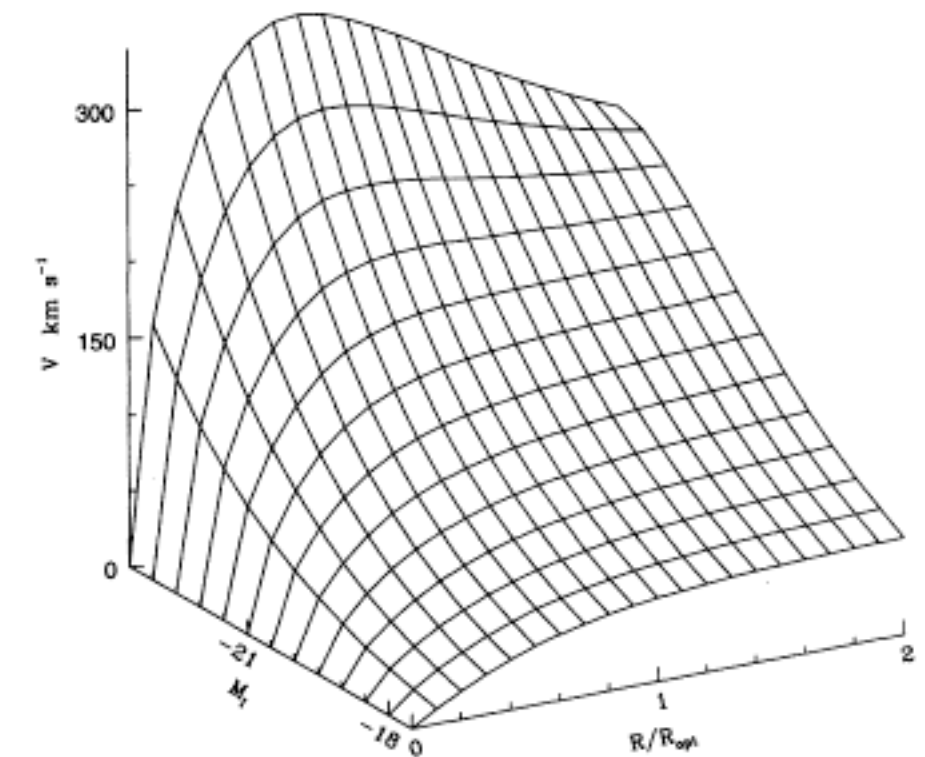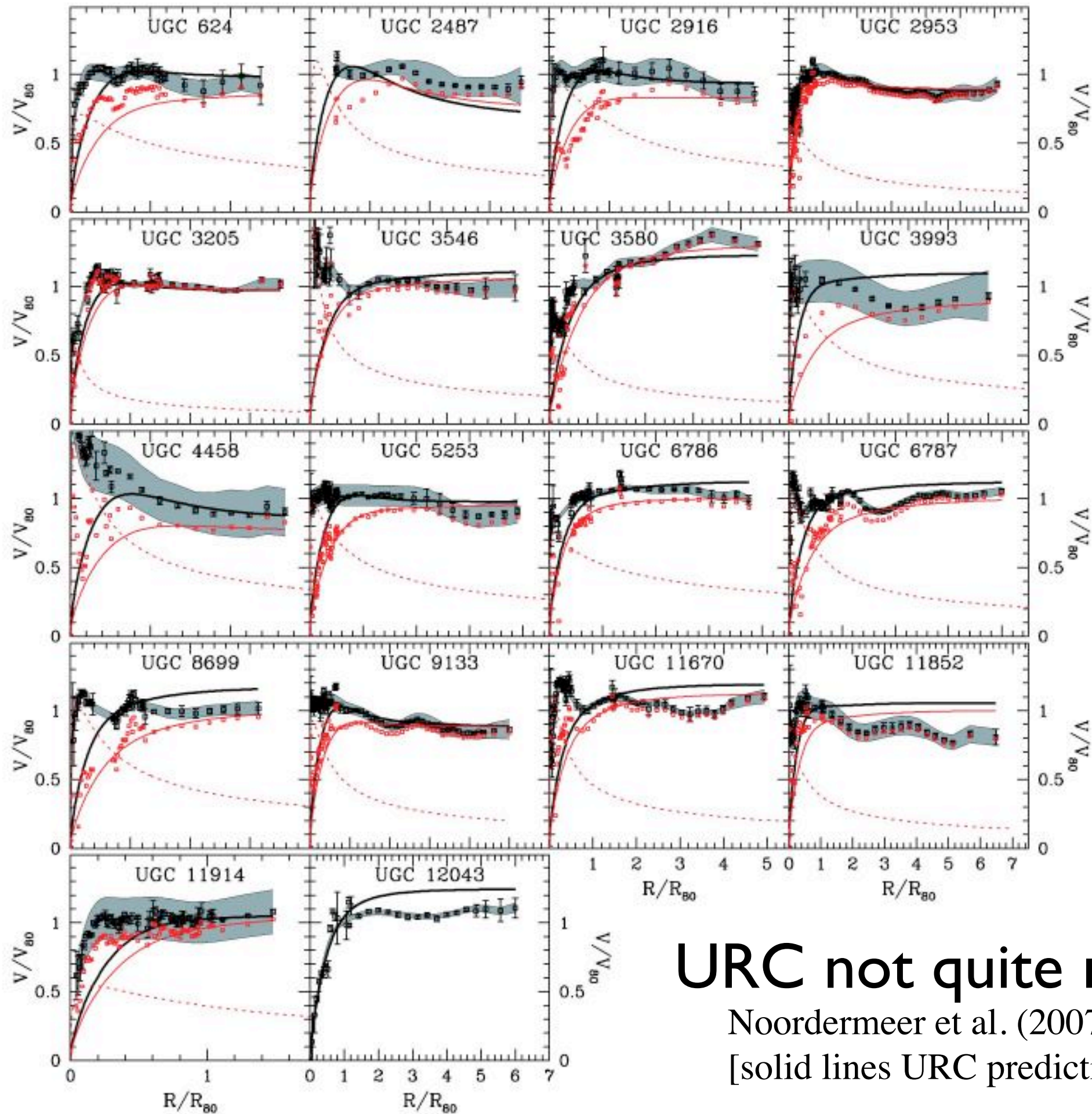Figure 4. The universal rotation curve of spiral galaxies. Radii are in units of R_{opt}.
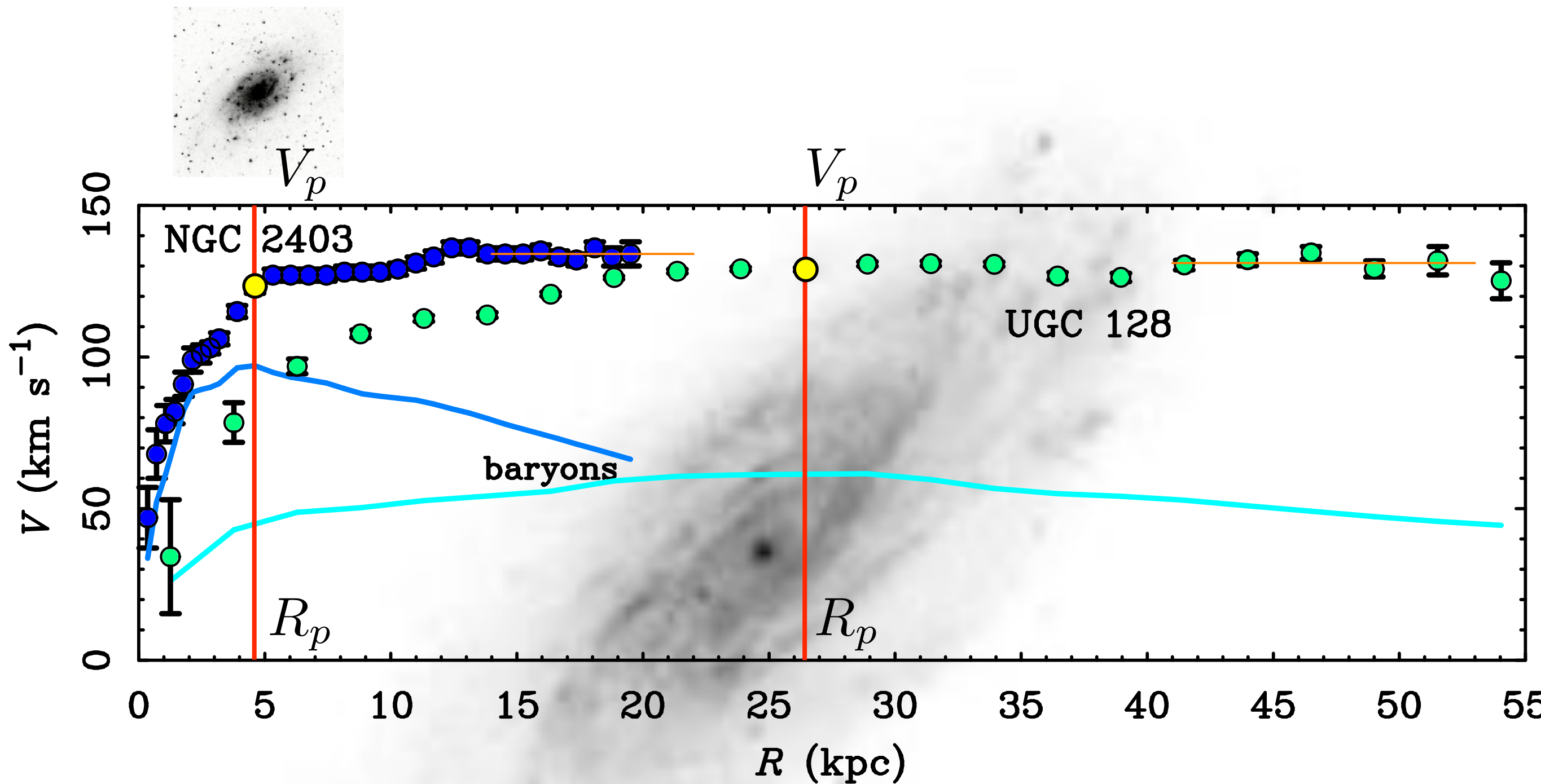

Figure 10. The URC surface.

URC not quite right

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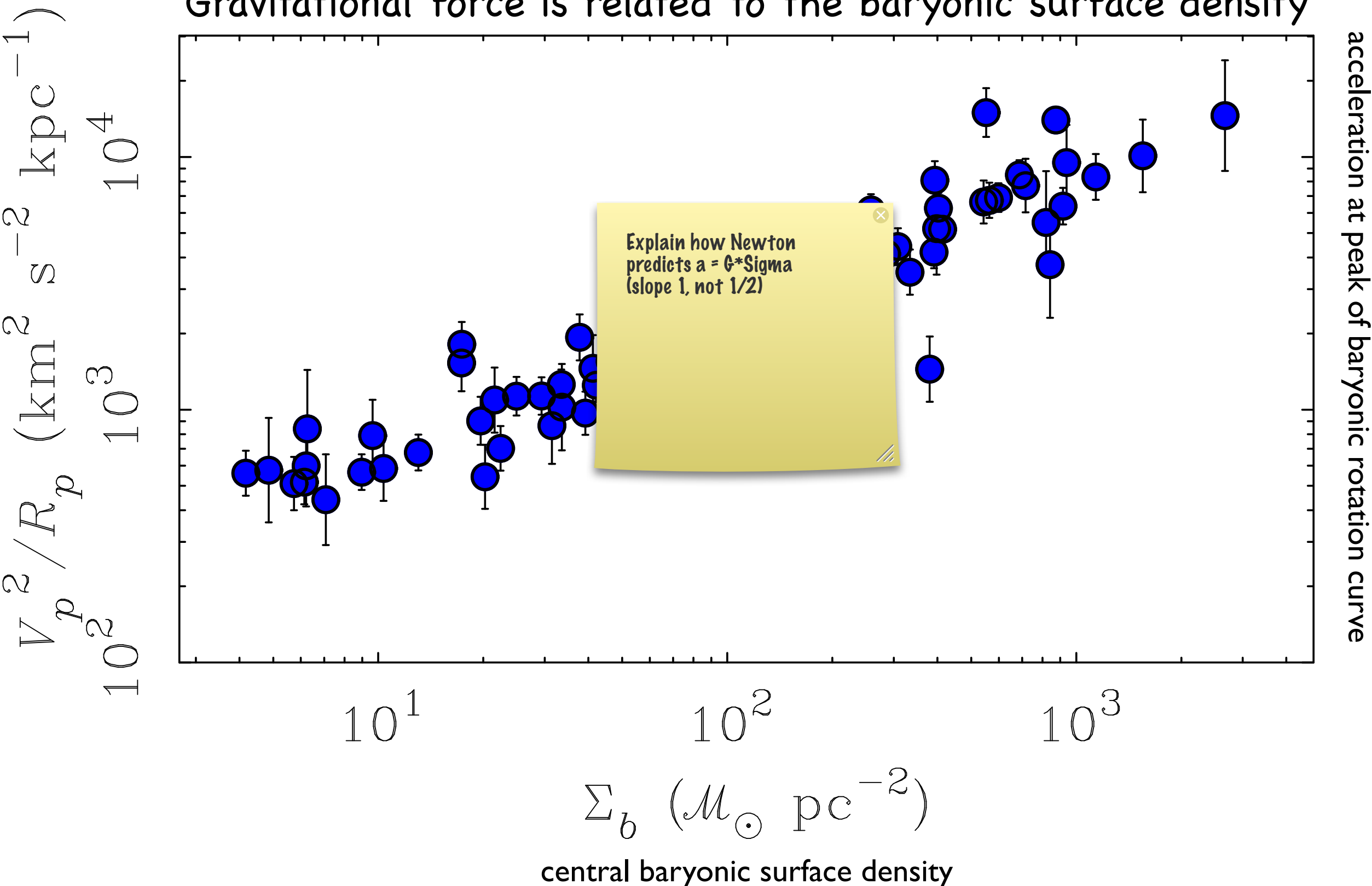[solid lines URC prediction]

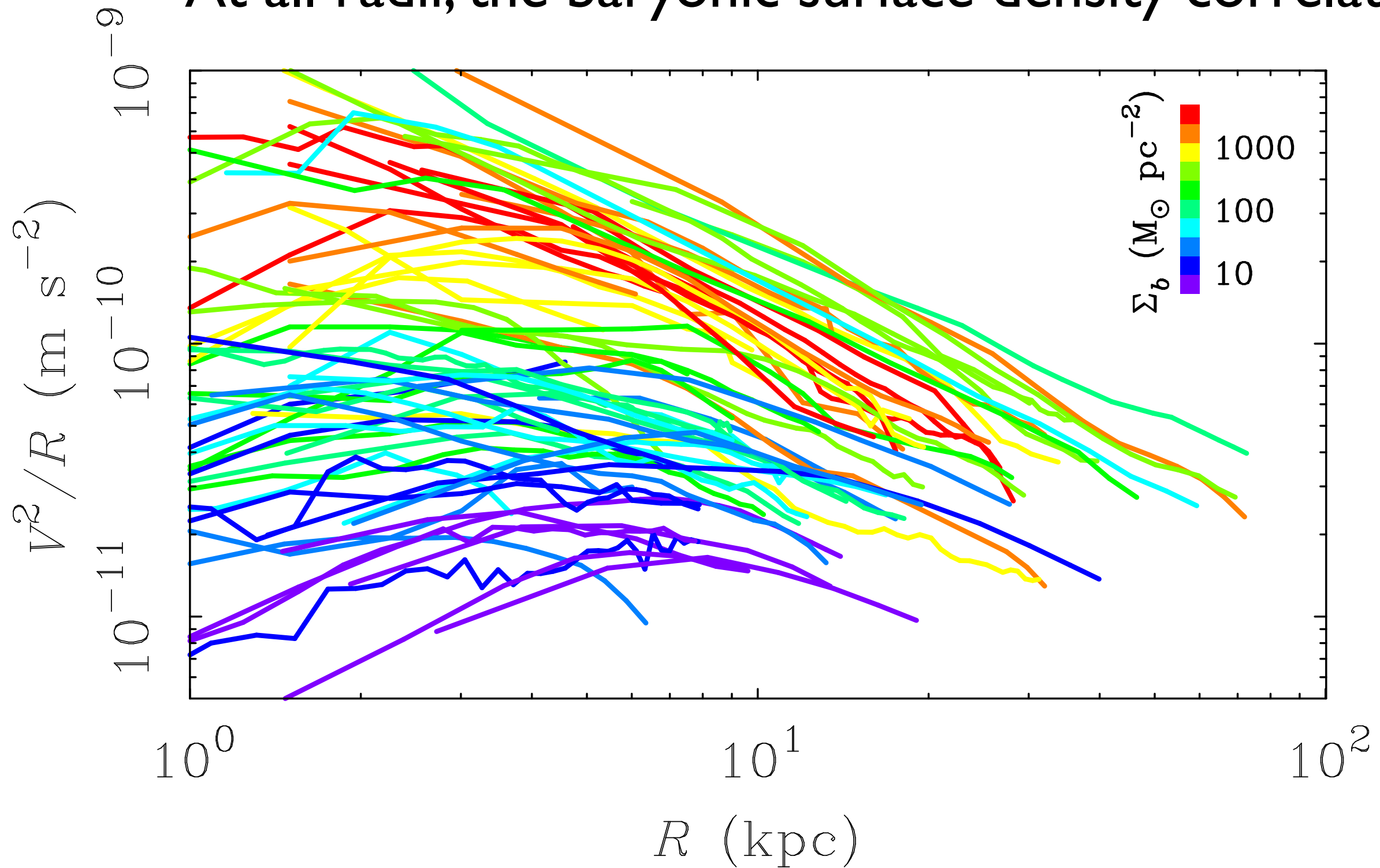Radius in physical units (kpc)

Just looking at the peak radius

$$a \sim \Sigma_b^{1/2} \qquad \Sigma_b = \frac{3M_b}{4R_p^2}$$

Gravitational force is related to the baryonic surface density

Explain how Newton predicts a = G*Sigma (slope 1, not 1/2)

V_p^2/R_p $\left(\mathrm{km^2 \ s^{-2} \ kpc^{-1}} \right)$

acceleration at peak of baryonic rotation curve

Σ_b $\left(\mathcal{M}_\odot \ \mathrm{pc^{-2}} \right)$

central baryonic surface density

At all radii, the baryonic surface density correlates

with the acceleration (gravitational force per unit mass)

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."
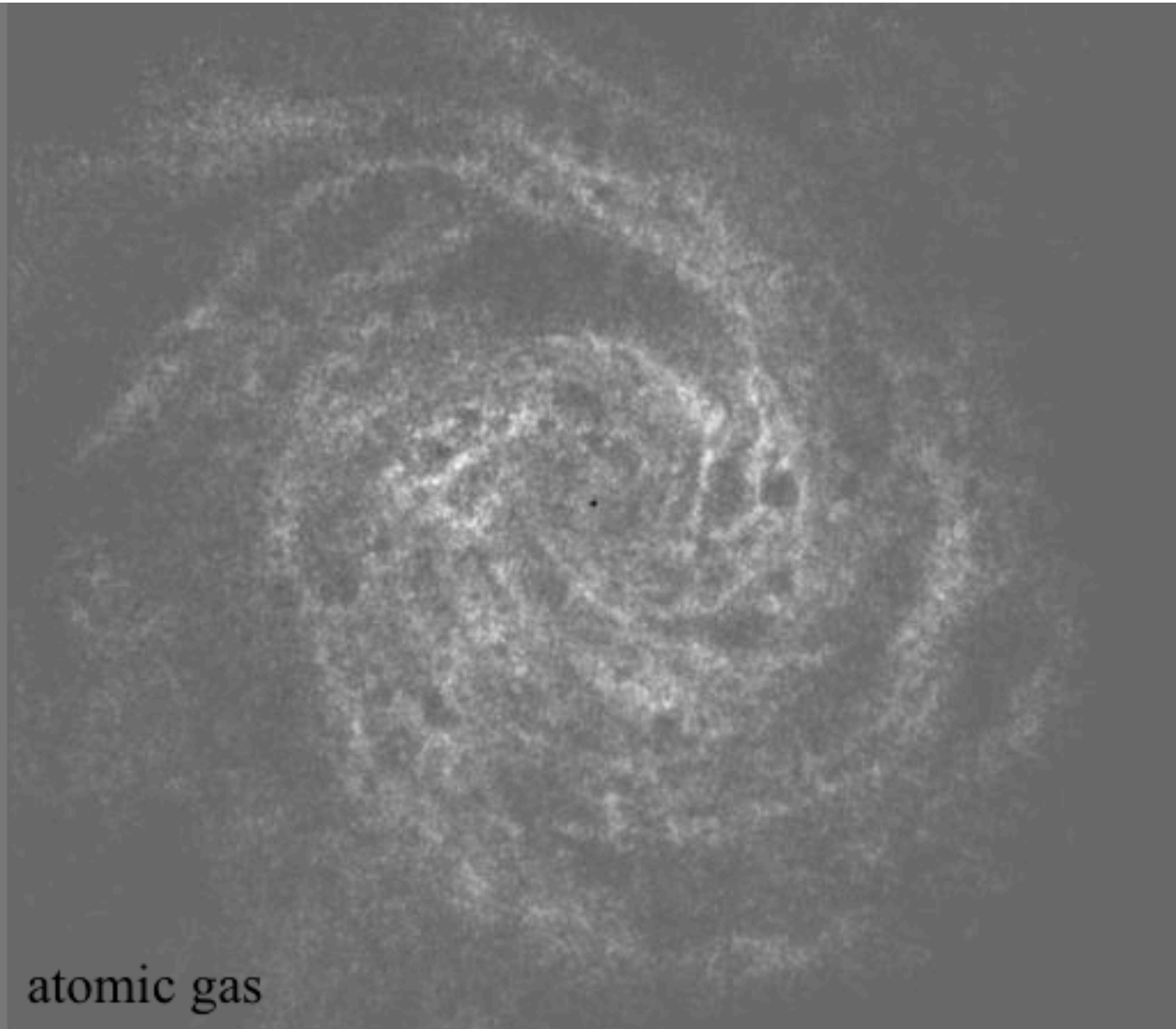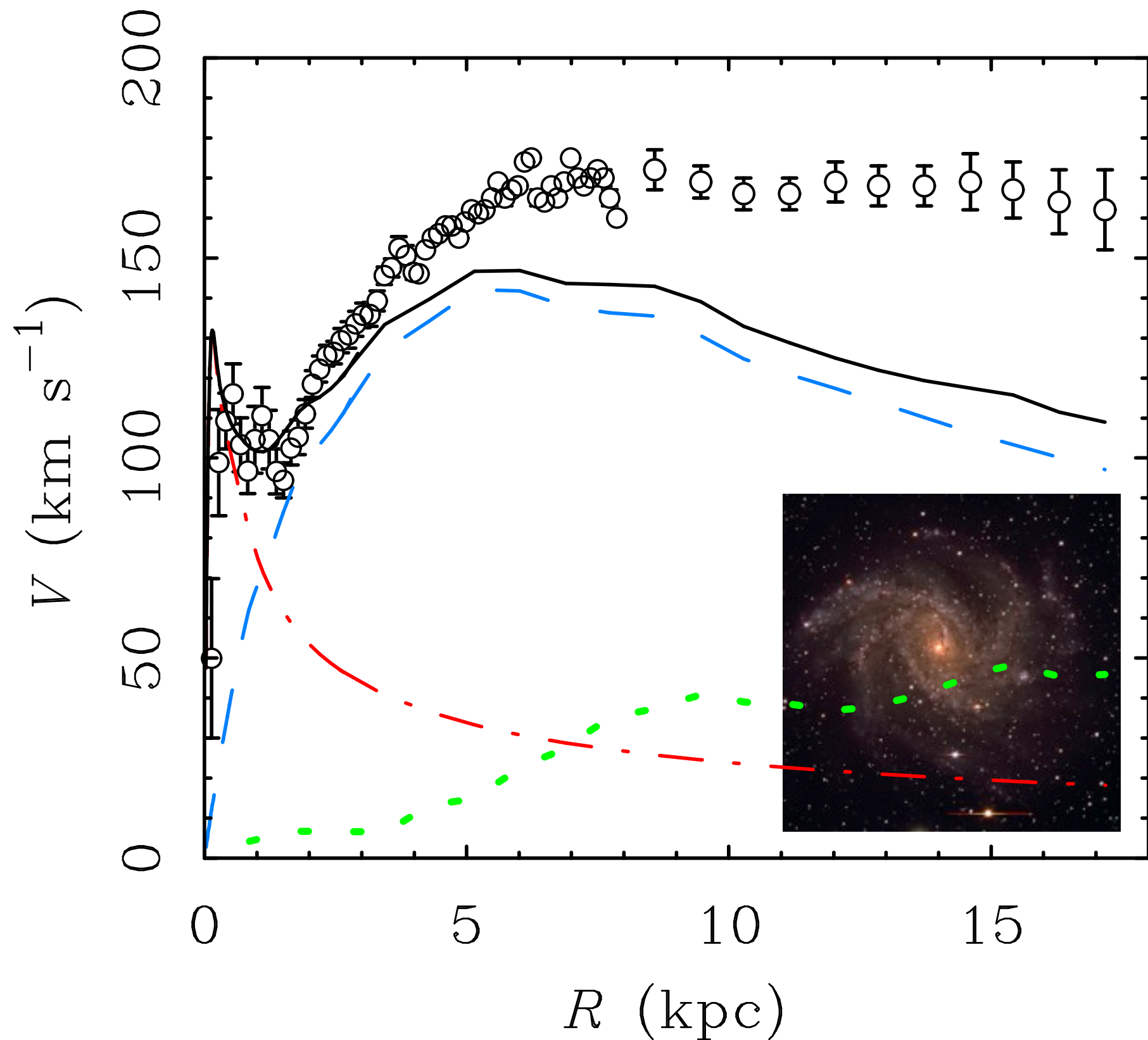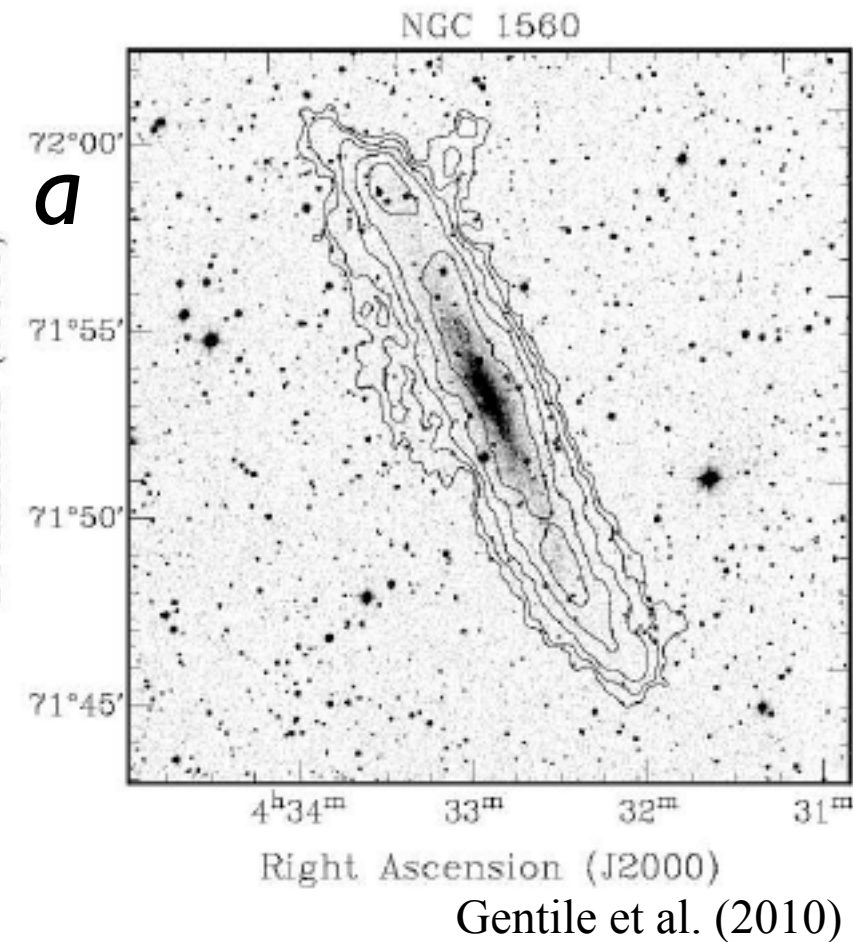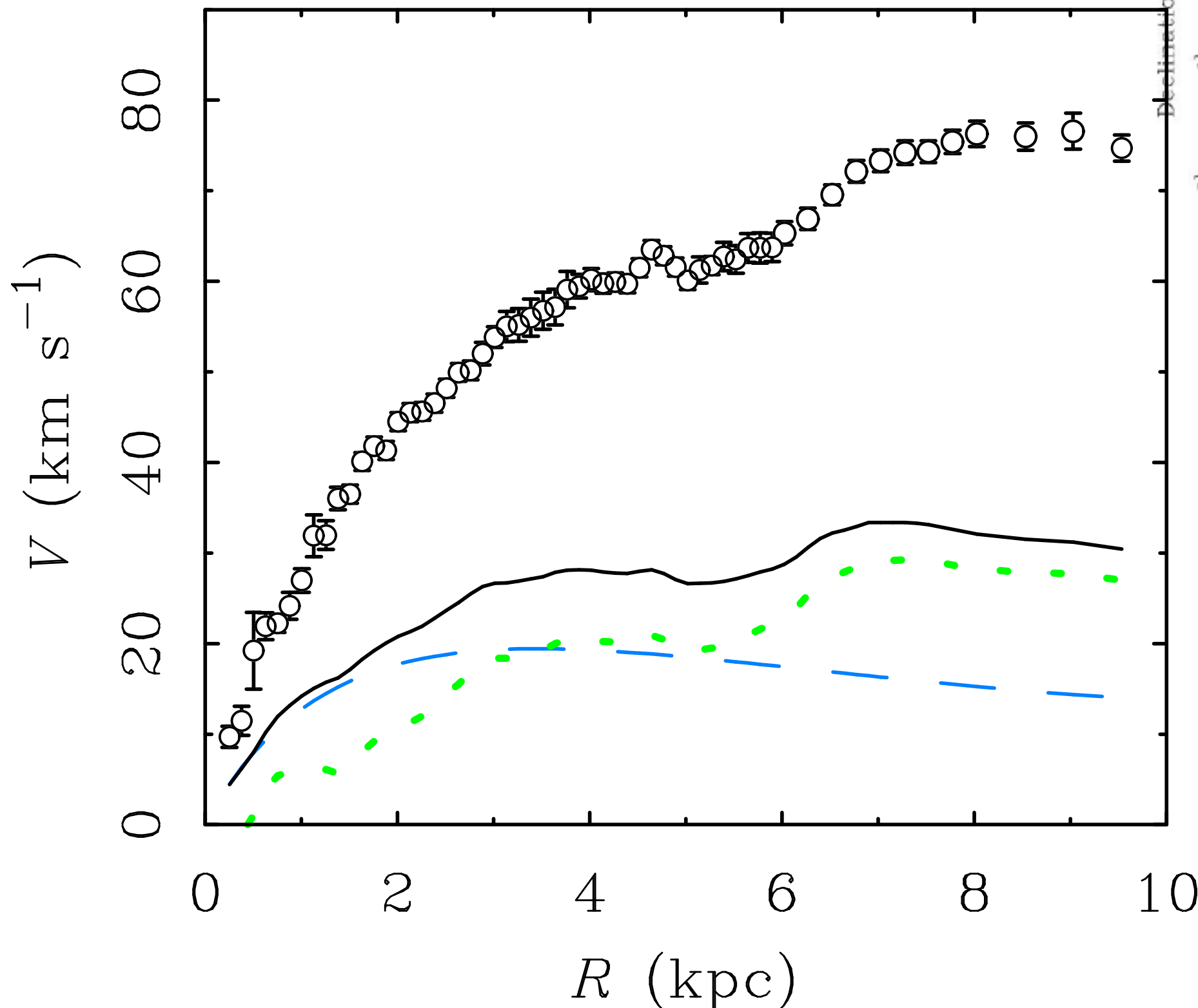

NGC 6946

optical

near infrared

atomic gas

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

Renzo's Rule:
"When you see a feature in the light, you see a corresponding feature in the rotation curve."

NGC 1560

Gentile et al. (2010)

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

Renzo's Rule:

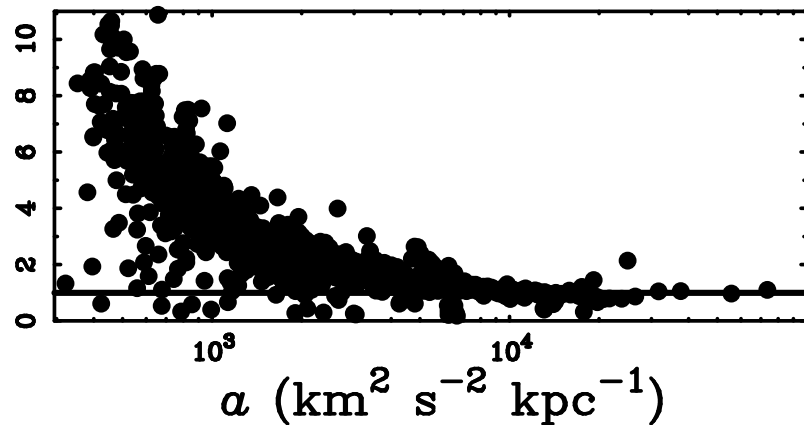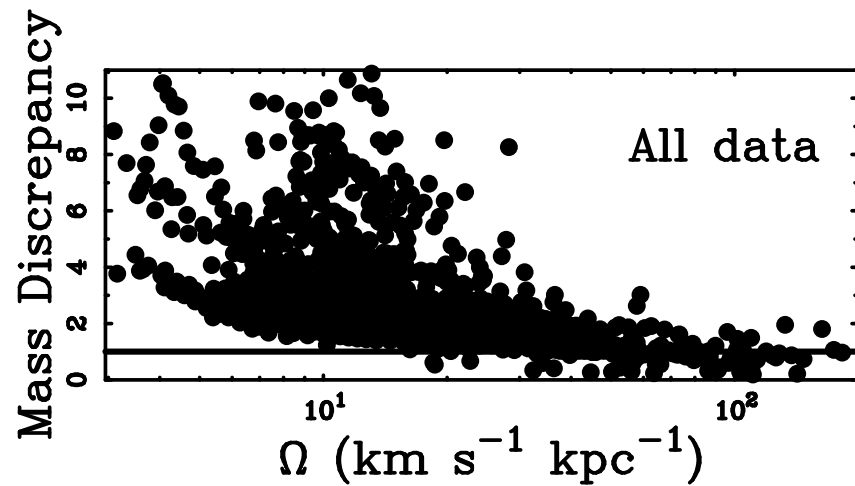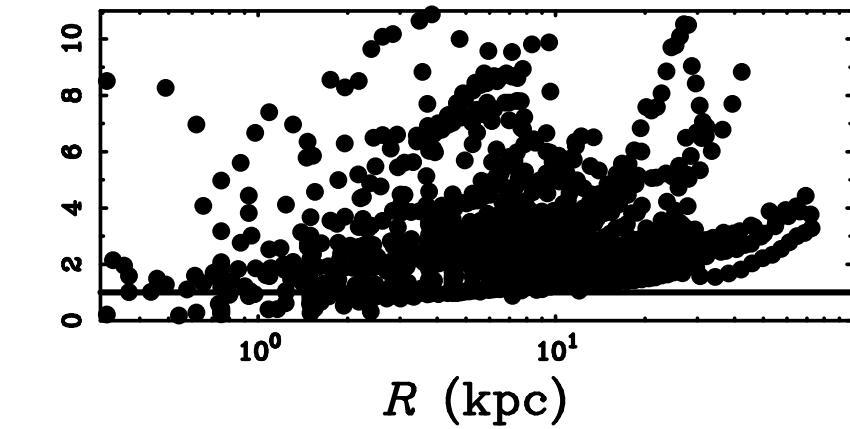*"When you see a feature in the light, you see a corresponding feature in the rotation curve."*

The distribution of mass is coupled to the distribution of light.
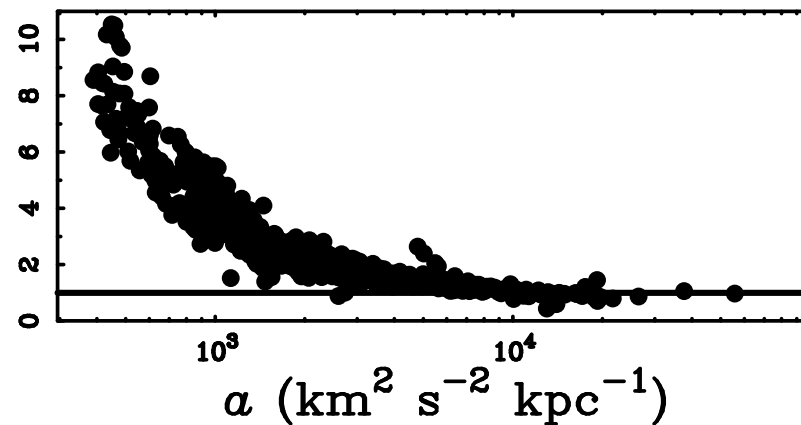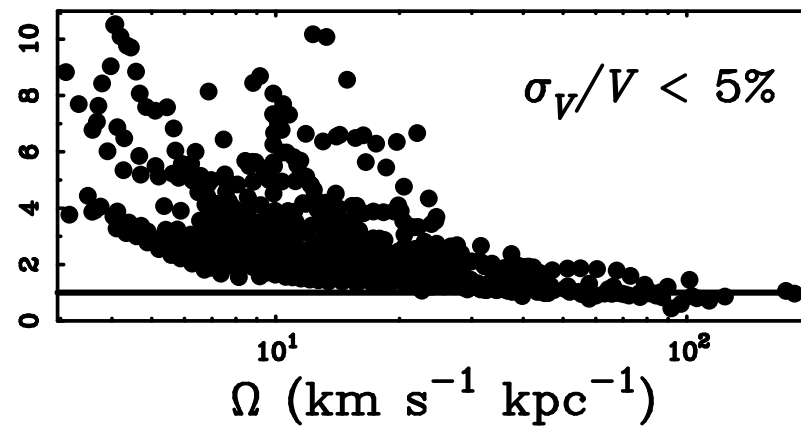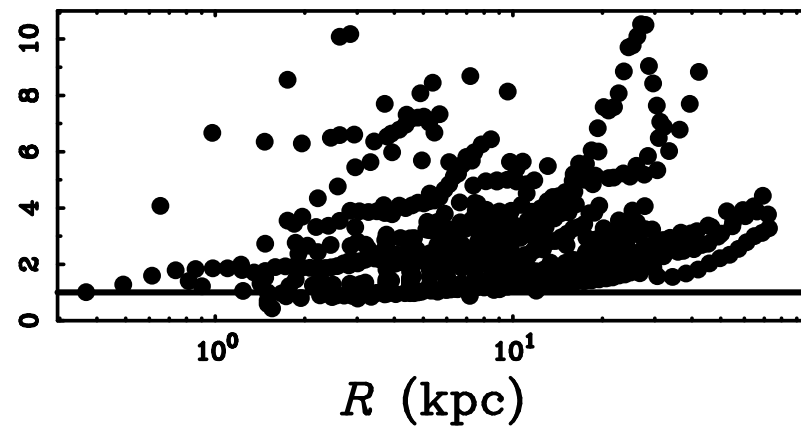
Quantify by defining the Mass Discrepancy:

$$\mathcal{D} = \frac{V^2}{V_b^2} = \frac{V^2}{\Upsilon_\star v_\star^2 + V_g^2}$$

The Mass Discrepancy correlates with acceleration and baryonic surface density

McGaugh (2004)

radius

orbital frequency

acceleration

All data

$\sigma_V/V < 5\%$

Mass Discrepancy

R (kpc)

R (kpc)

Ω (km s^{-1} kpc^{-1})

Ω (km s^{-1} kpc^{-1})

a (km^2 s^{-2} kpc^{-1})
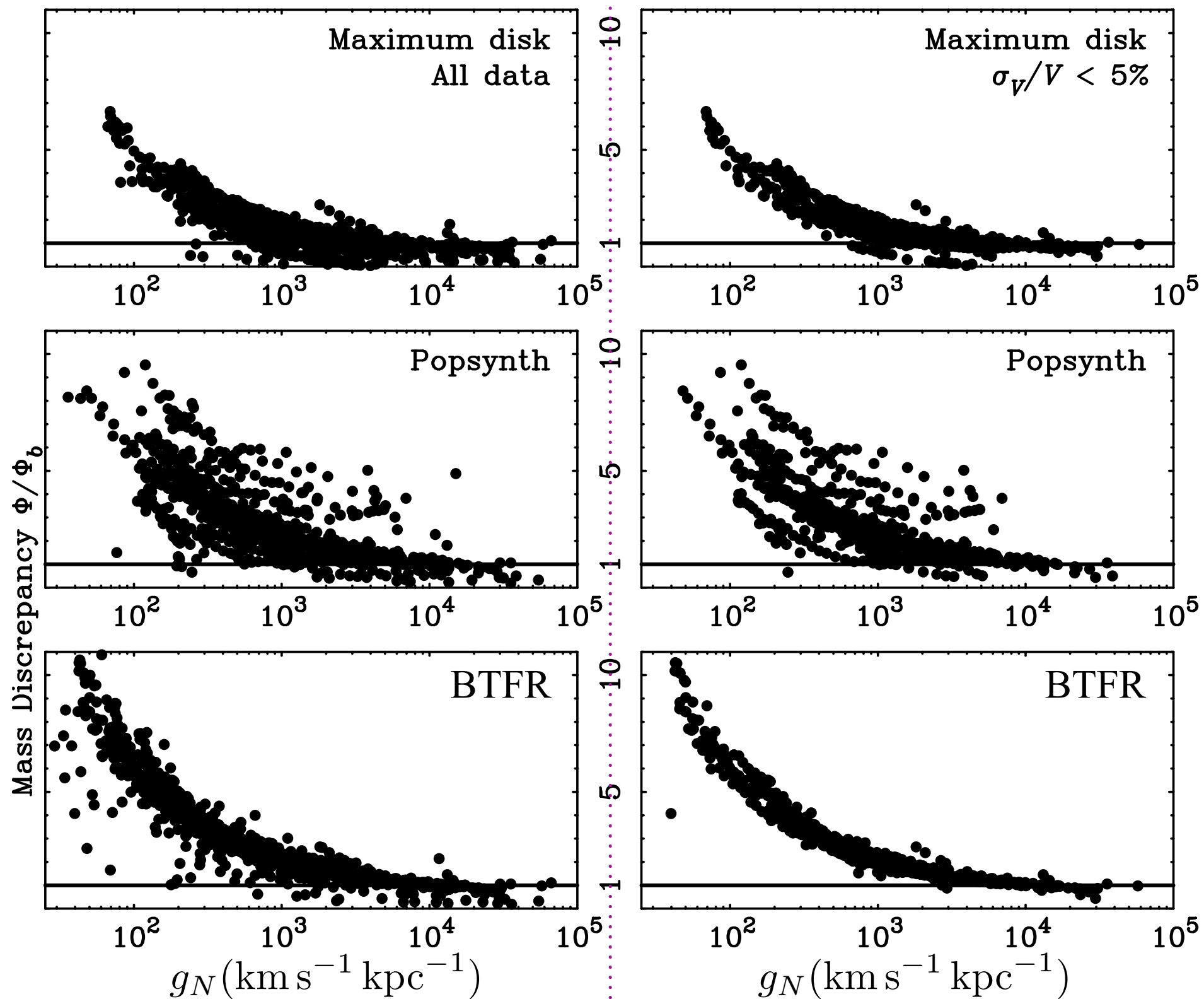
a (km^2 s^{-2} kpc^{-1})
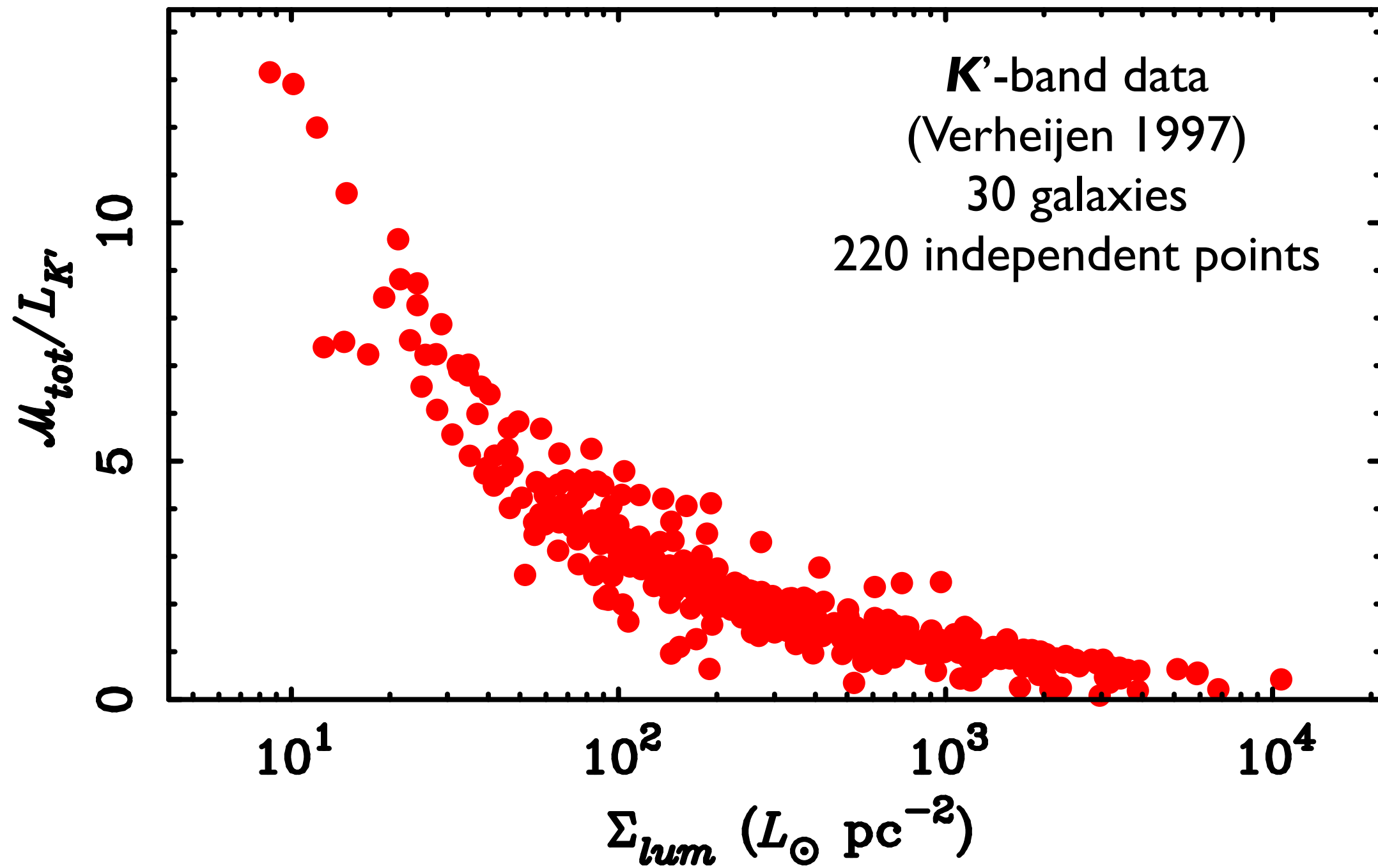
74 galaxies
> 1000 points
(all data)

60 galaxies
> 600 points
(errors < 5%)

The relation between the mass discrepancy and acceleration persists for any plausible choice of M*/L

Can see the effect directly in the data with no assumption on M*/L

$\textit{K}$'-band data
(Verheijen 1997)
30 galaxies
220 independent points

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)

  - Universal Rotation Curve (Persic & Salucci 1996)

  - Renzo's Rule (Sancisi 2004)

  - Mass Discrepancy-Acceleration Relation (McGaugh 2004)

3 Laws of Galactic Rotation

1. Rotation curves tend towards asymptotic flatness

2. Baryonic mass scales as the fourth power of rotation velocity (Baryonic Tully-Fisher)

3. Gravitational force correlates with baryonic surface density - the dynamics knows about the baryons

Just the facts, mam. Just the facts.