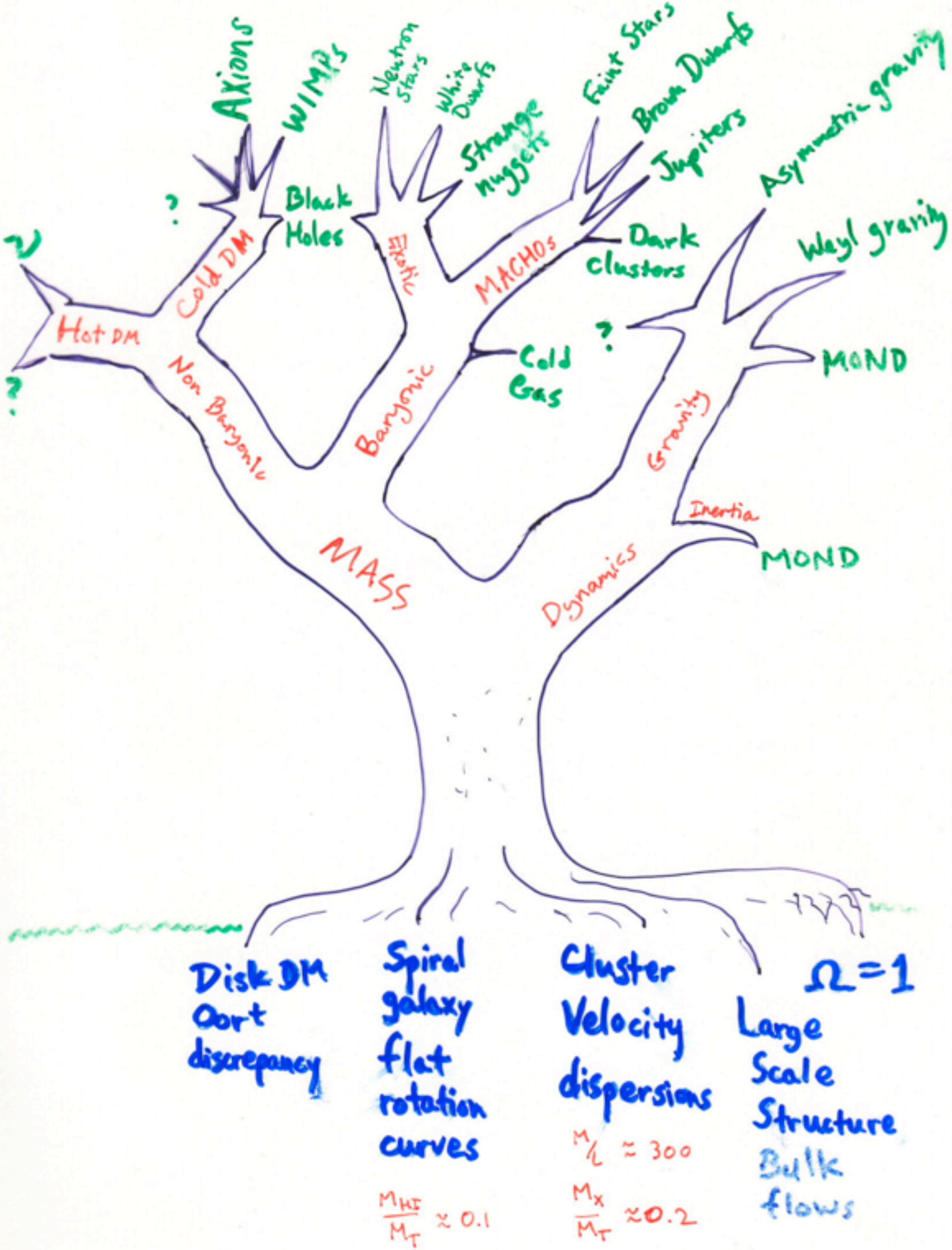
DARK MATTER

ASTR 333/433

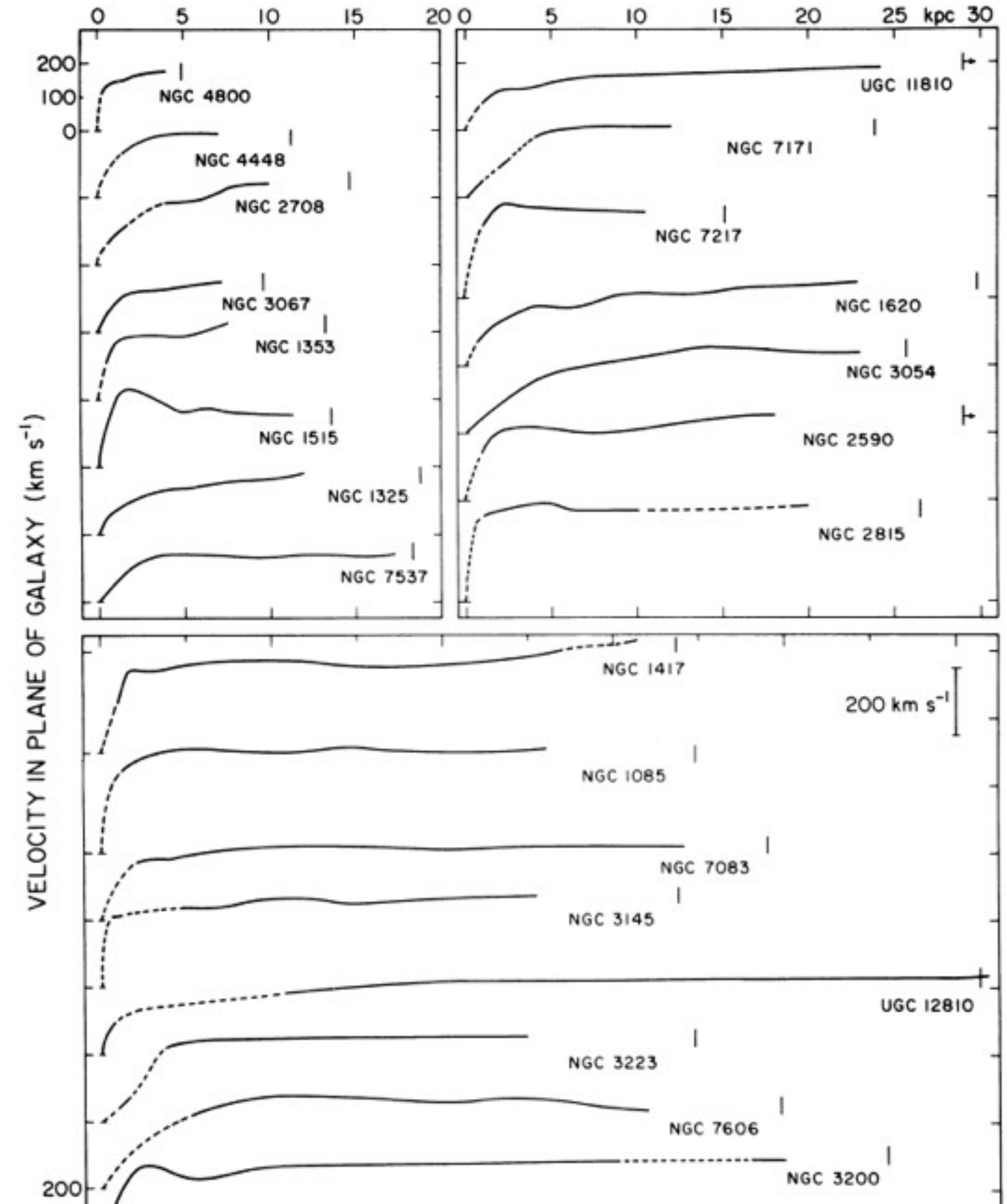
TODAY
GALACTIC ROTATION
THE THIRD LAW
HALO MODELS

Homework due Feb 25
Midterm March 1



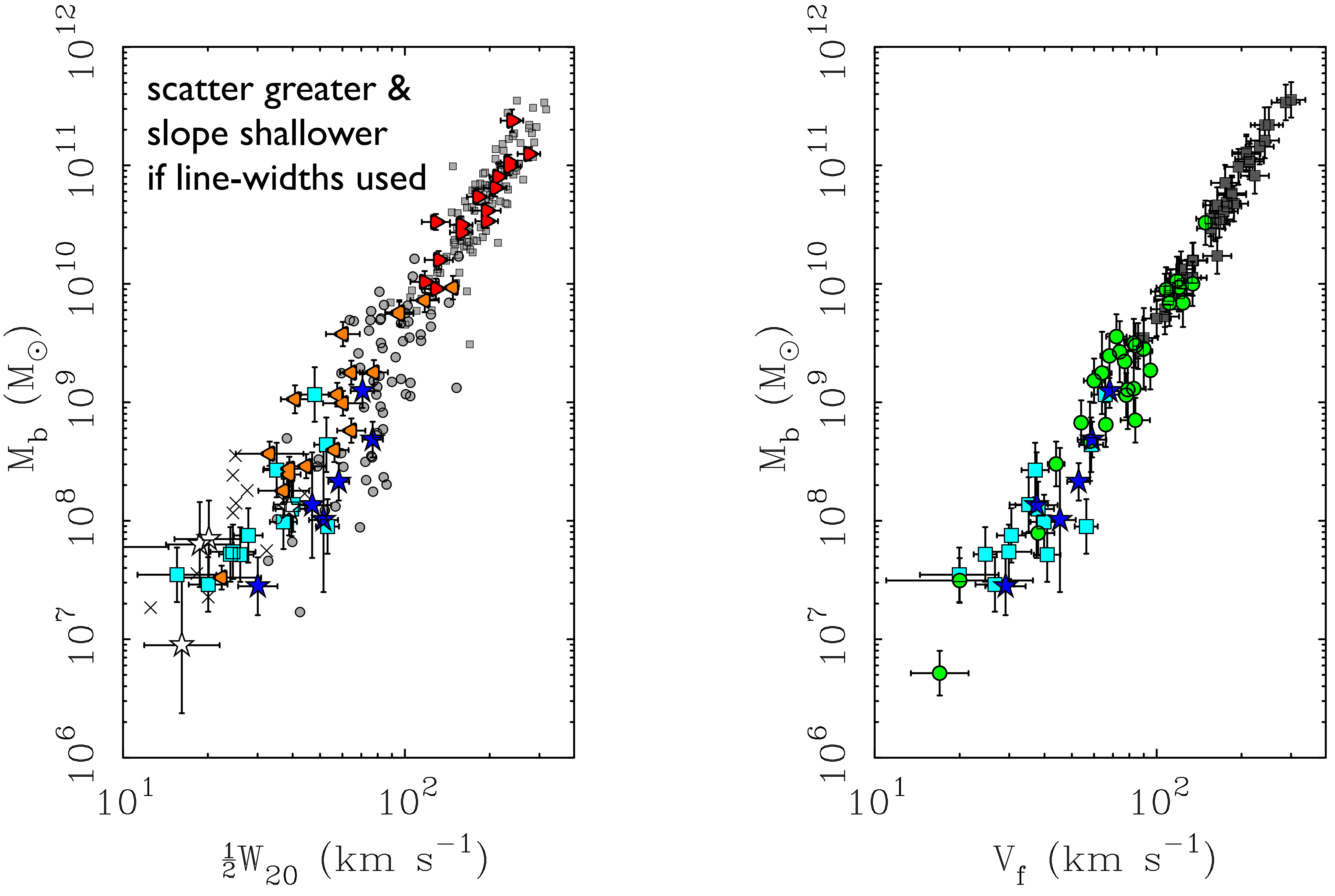
CASE WESTERN RESERVE
UNIVERSITY
EST. 1826

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



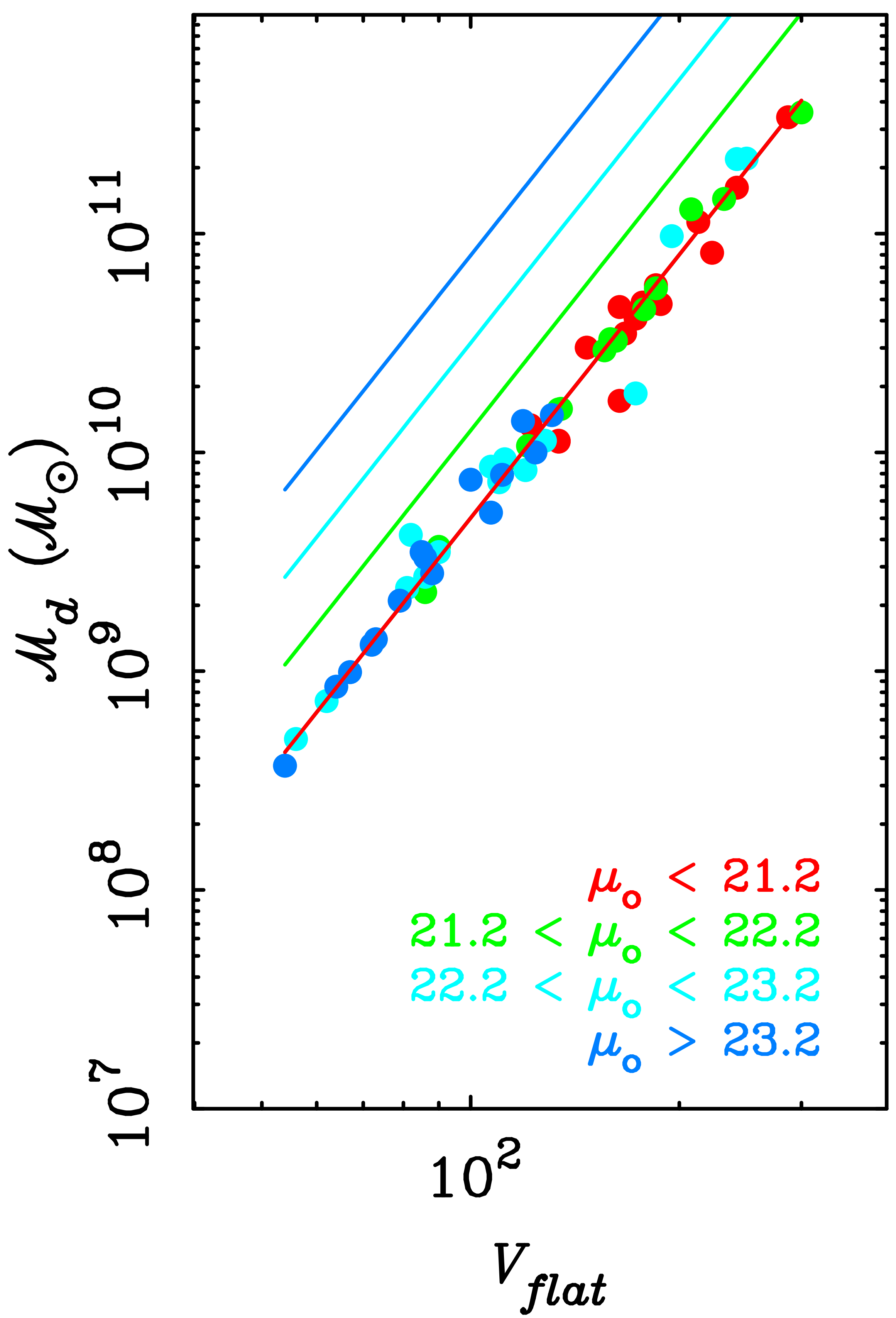
2. The mass of a galaxy is proportional to the fourth power of the constant rotation speed.

$$M_b = 47V_f^4$$



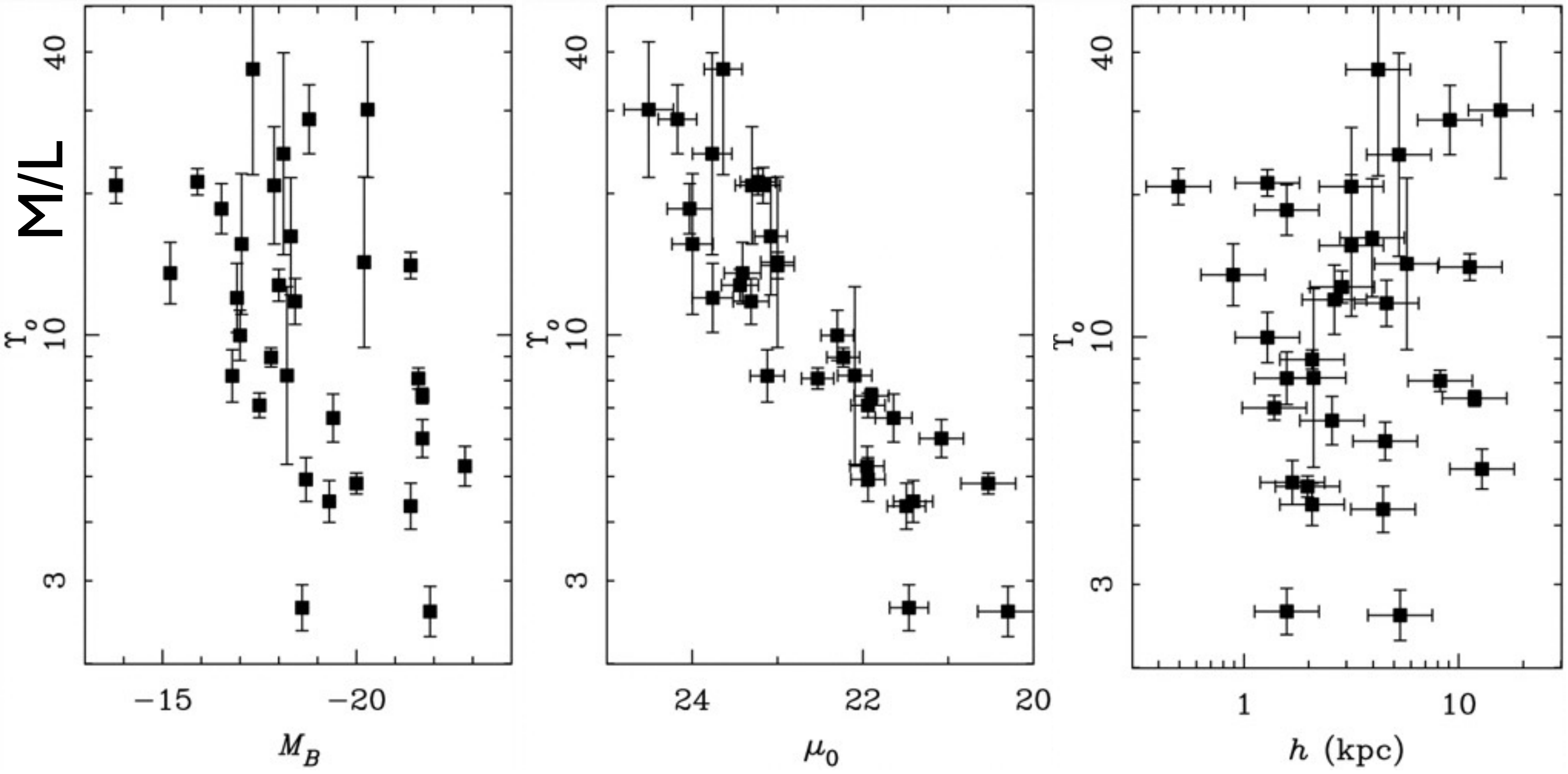
No residuals from TF with size or surface brightness

Eclosed M/L anti-correlates with surface brightness



dynamical M/L enclosed by 4 scale lengths

$M = V^2 R/G$ with $R = 4R_d$



Absolute magnitude

central surface brightness

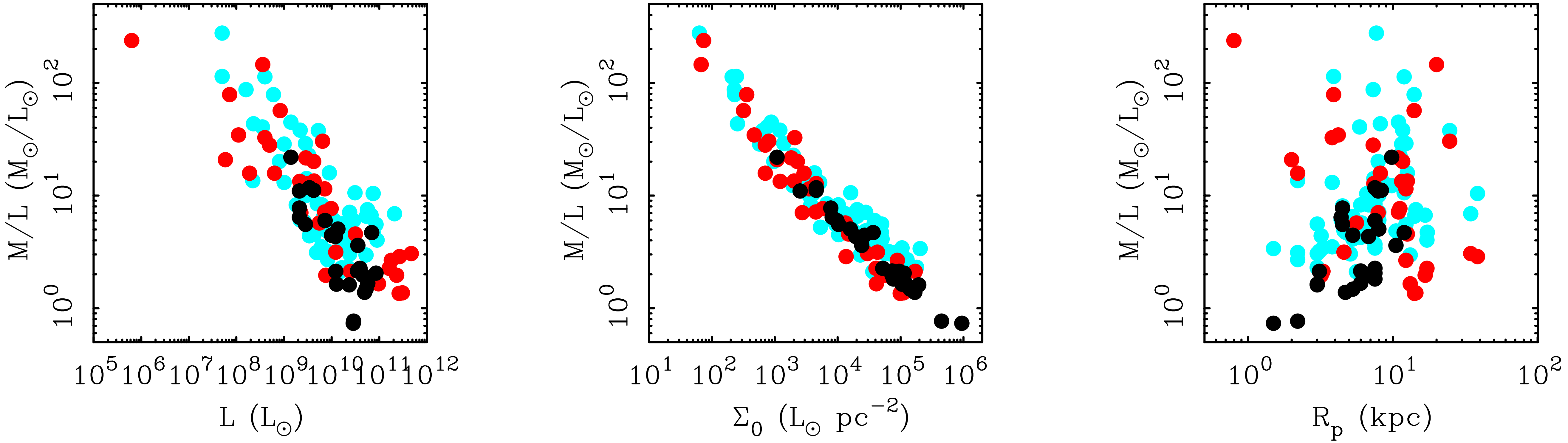
disk scale length

McGaugh & de Blok (1998)

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

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

LSBs dark matter dominated



HSBs not so much

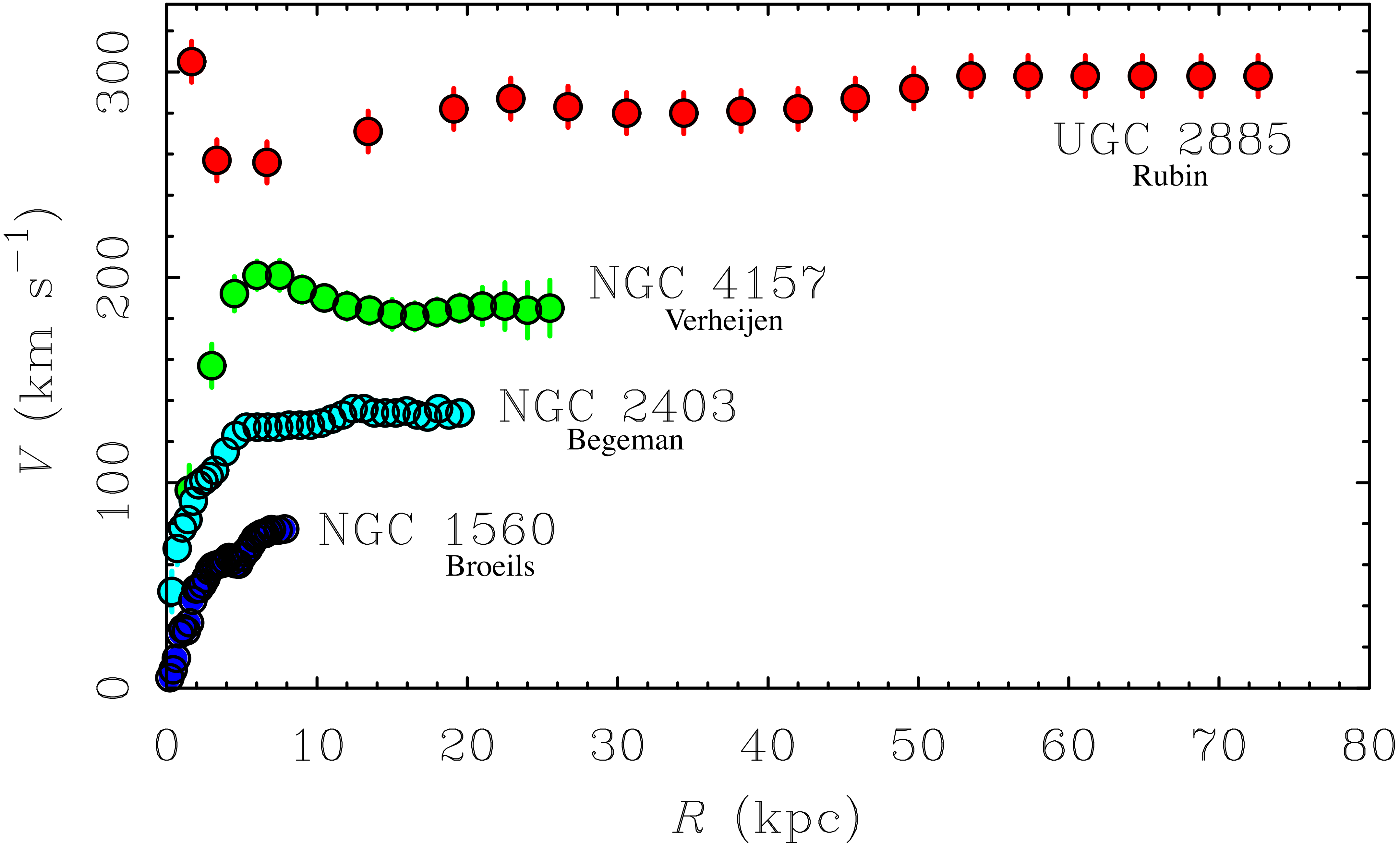
Same result for any optically defined length scale

You get what you assume.

McGaugh (2014) [review]

3. 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)
  - 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.

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

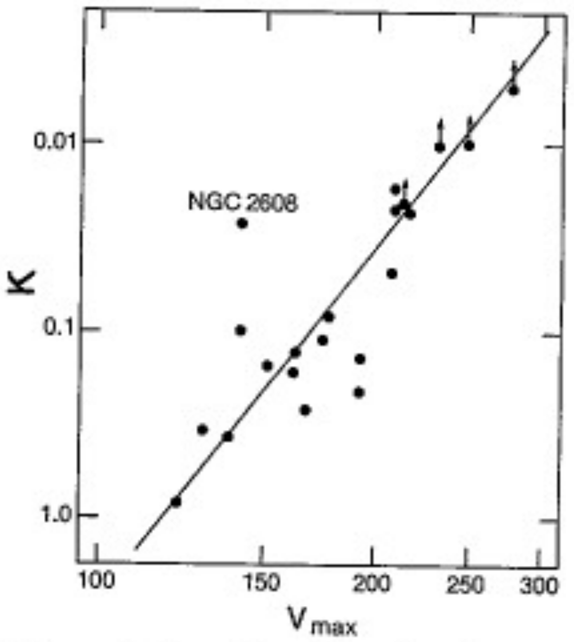


FIG. 3.—The correlation of log κ, the radius where the rotational velocity equals 100 km s^{-1} in units of the isophotal radius, vs. log $V_{\max}$. The line is the mean of the two regressions and has a slope equal to 6.3 ± 0.5. NGC 2608, the only strongly barred galaxy in the sample, was excluded from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

Rotation curve shapes correlate with galaxy properties

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

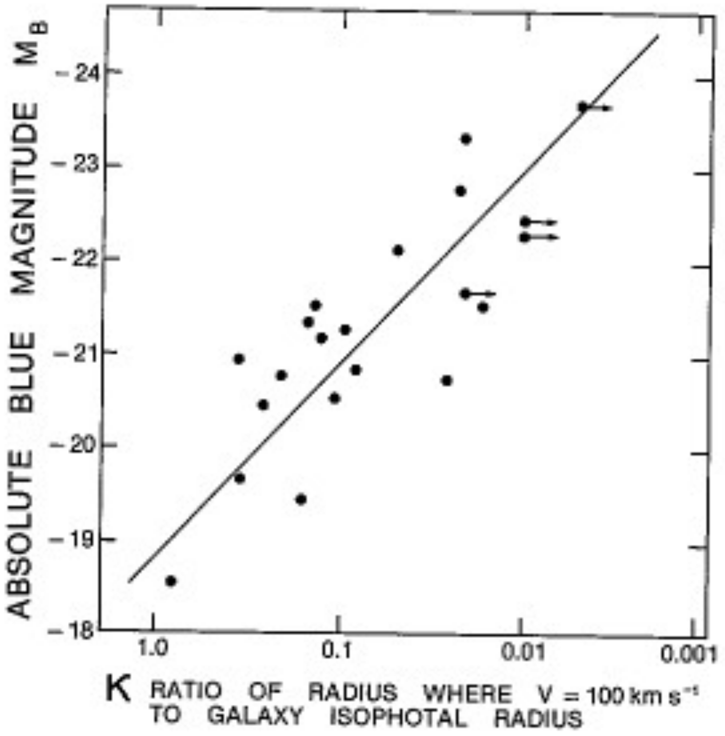


FIG. 2.—The correlation of M_B with log κ, the radial distance in the galaxy where the rotational velocity equals 100 km s^{-1}, in units of the isophotal radius. For lowest-luminosity Sc galaxies, the rotational velocity reaches 100 km s^{-1} only near the limits of the optical image ($\kappa \approx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

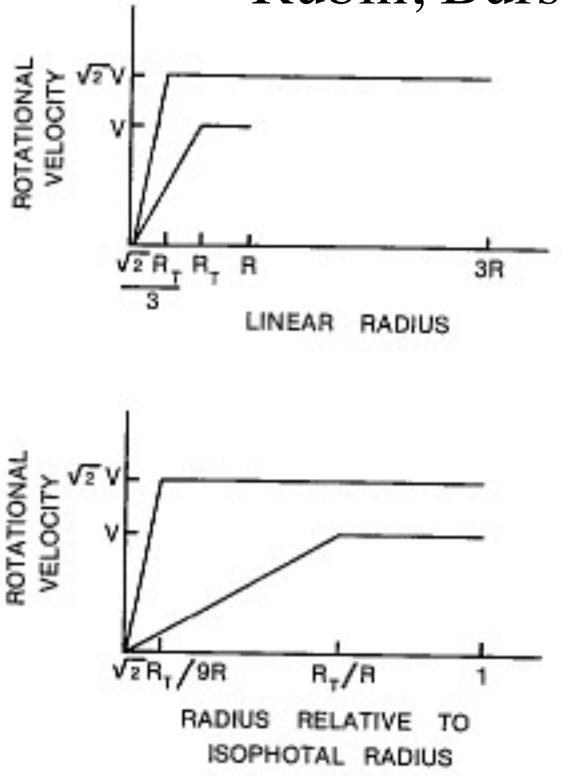
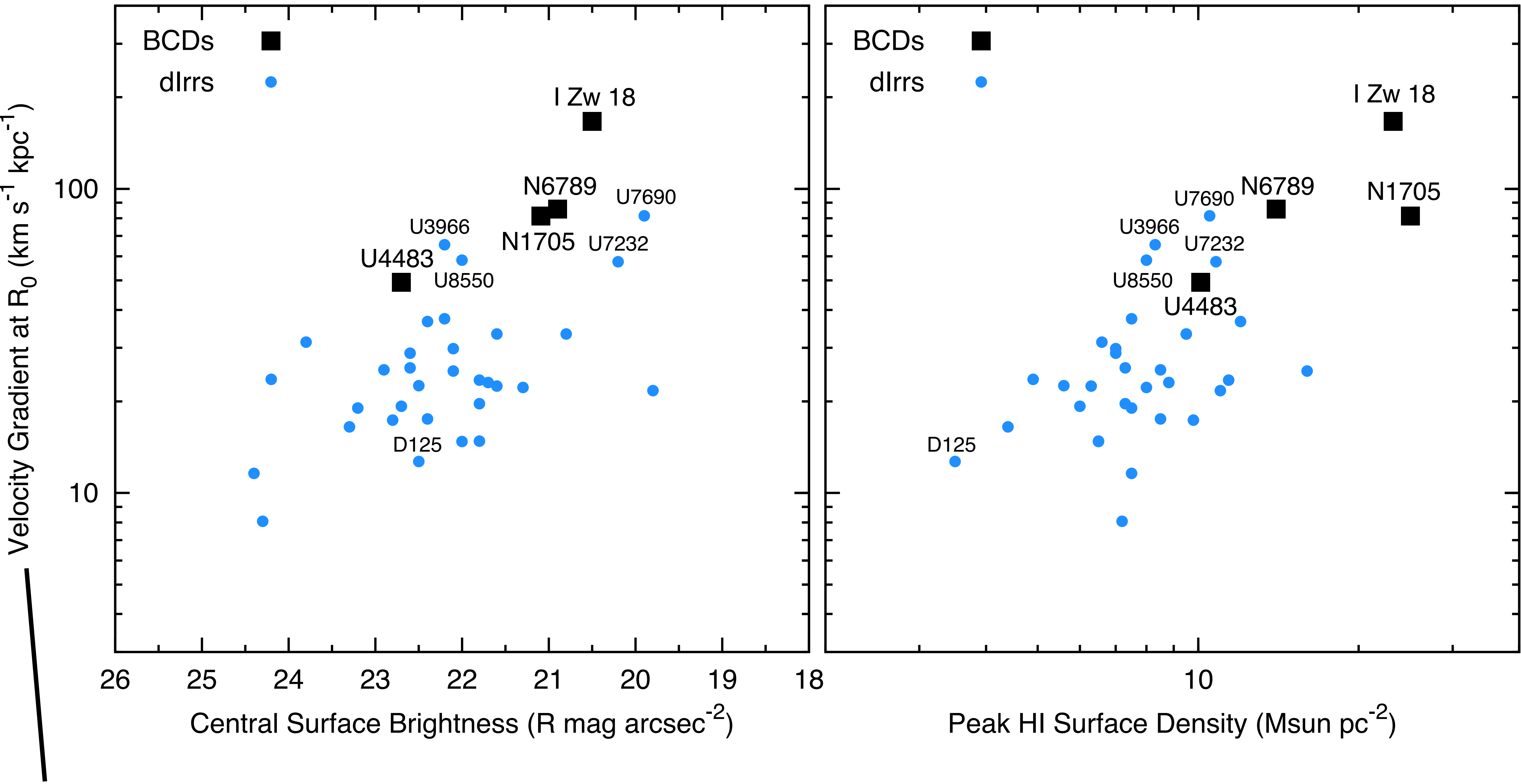


FIG. 4.—Schematic rotation curves for two Sc galaxies on a linear (*upper*) and relative (*lower*) radius scale. The higher-luminosity galaxy is chosen to have its velocity in the flat portion √(2) times that of the lower-luminosity galaxy. Then the nuclear velocity gradient, turnover radius, and radial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

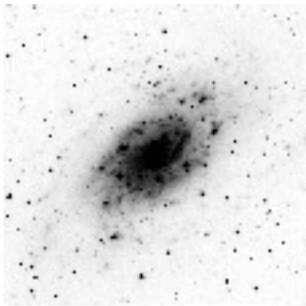
Lelli et al. (2012)

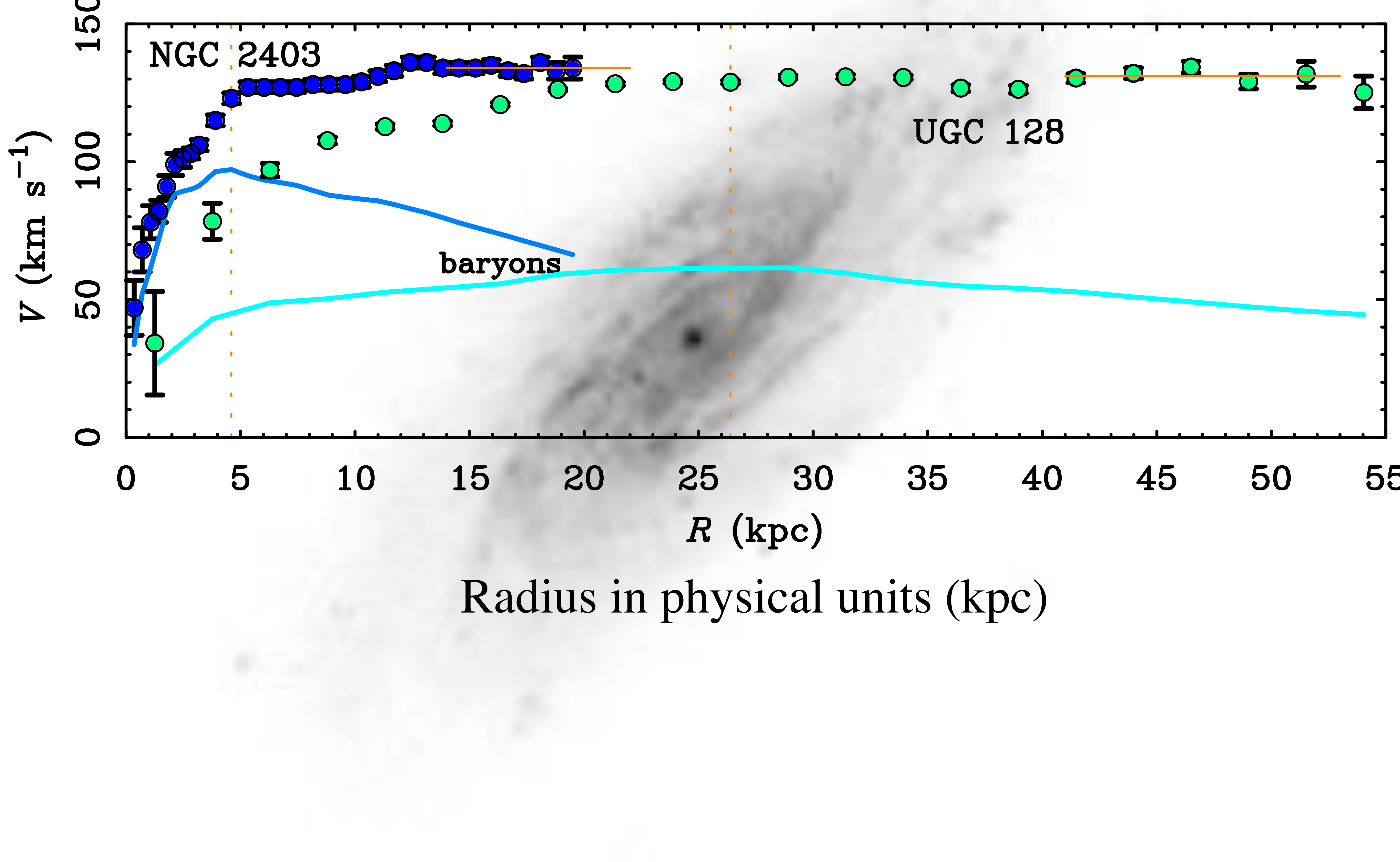


$$\frac{V(R_d)}{R_d}$$

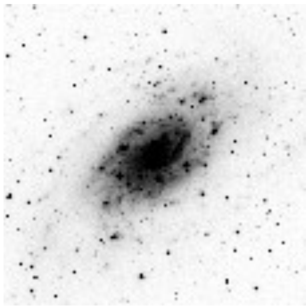
The higher the surface brightness,
the steeper the rotation curve gradient.

Remember our TF pair?

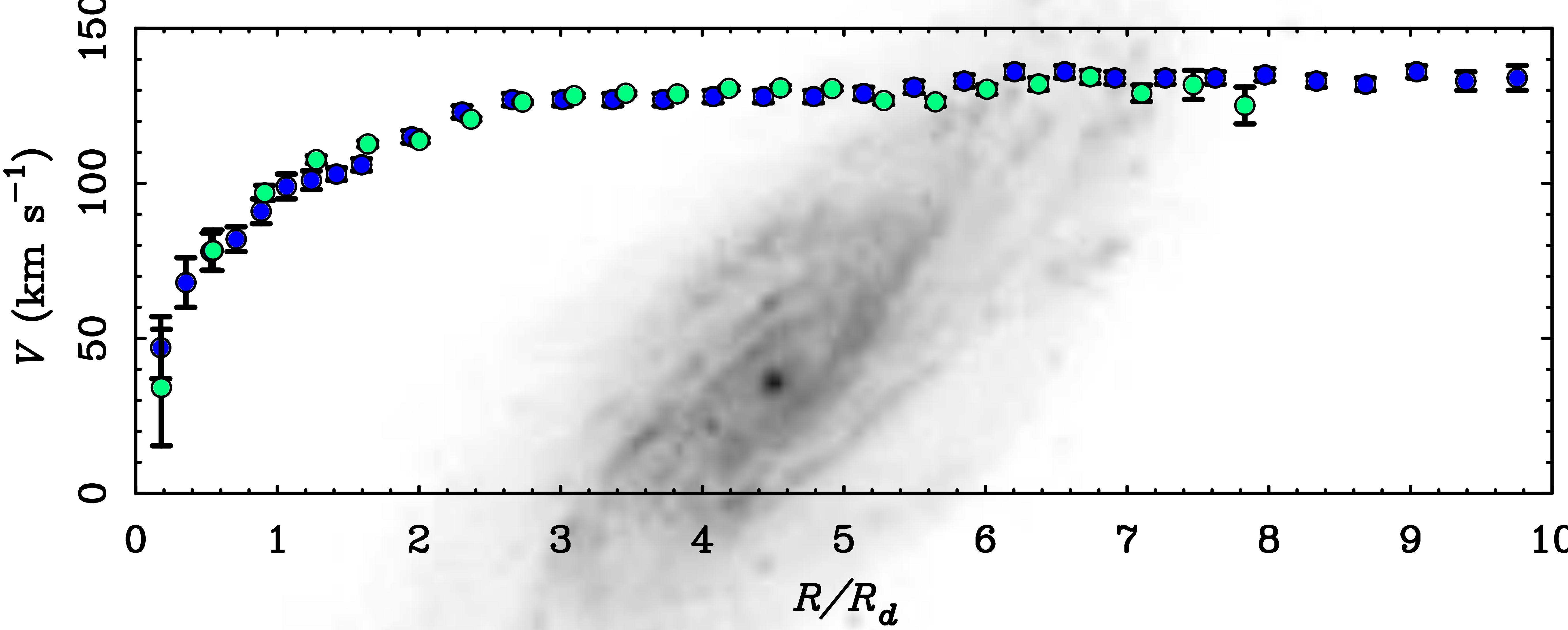




Radius in physical units (kpc)



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

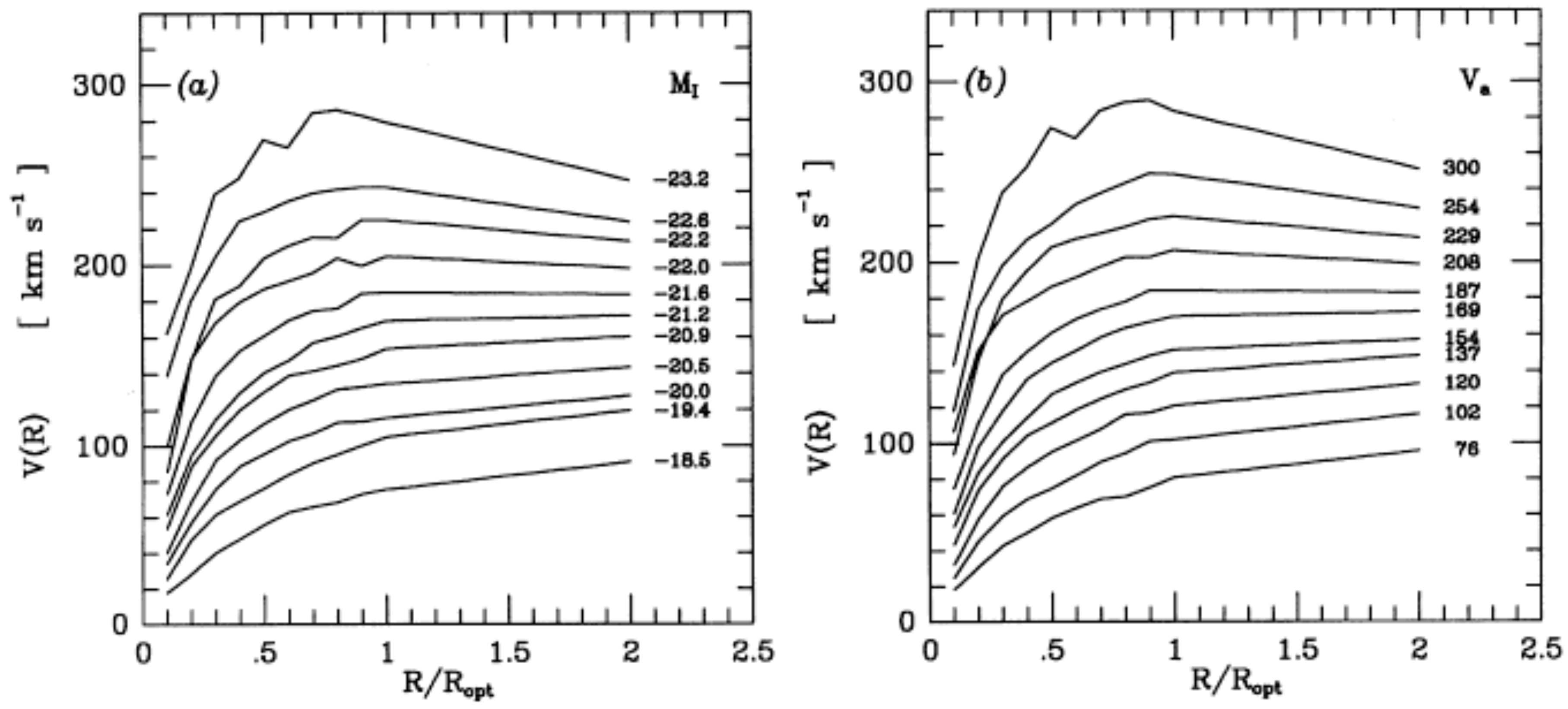
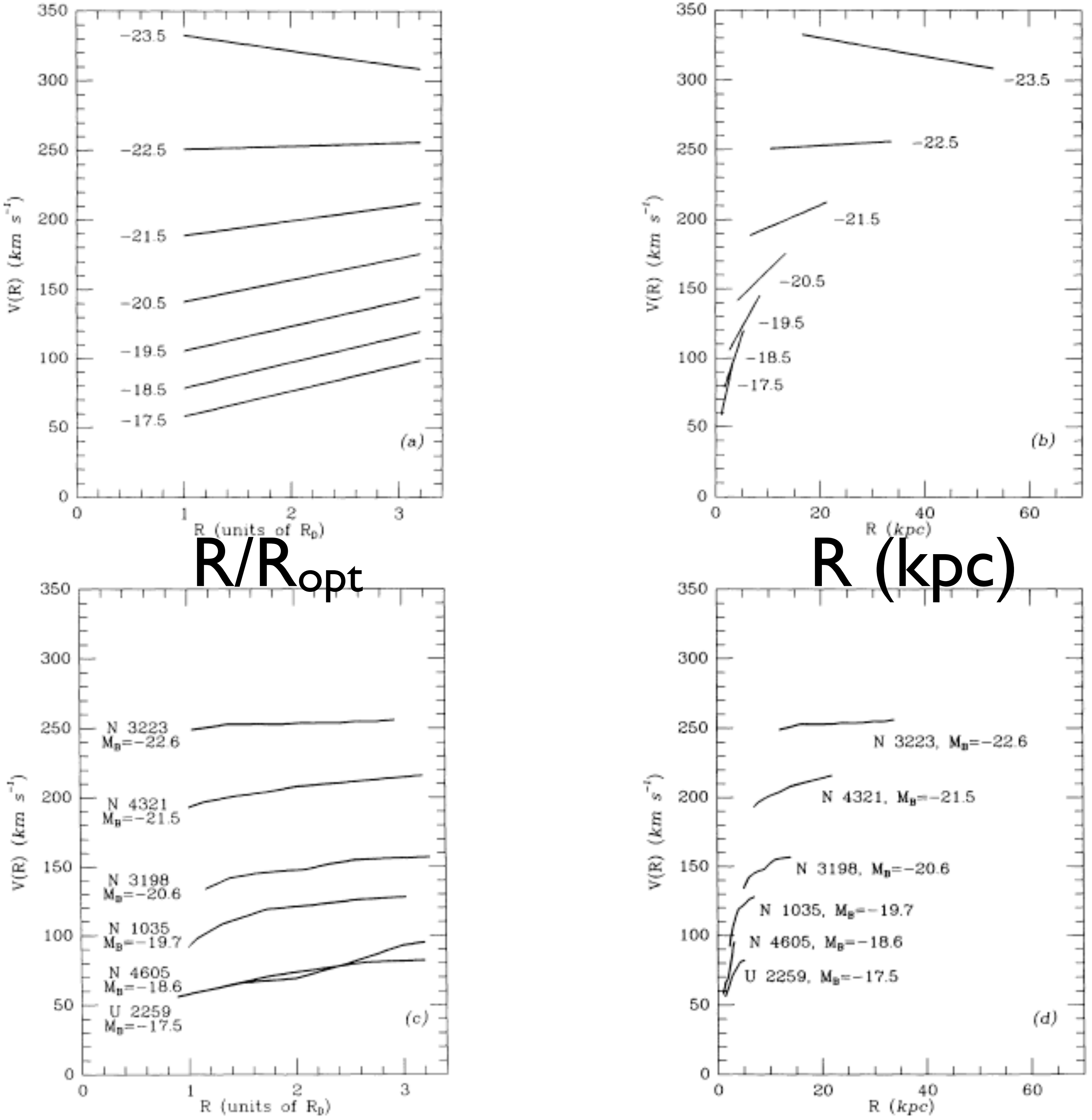


Figure 4. The universal rotation curve of spiral galaxies. Radii are in units of R_{opt}.

64 PERSIC AND SALUCCI Vol. 368

computed V(R)



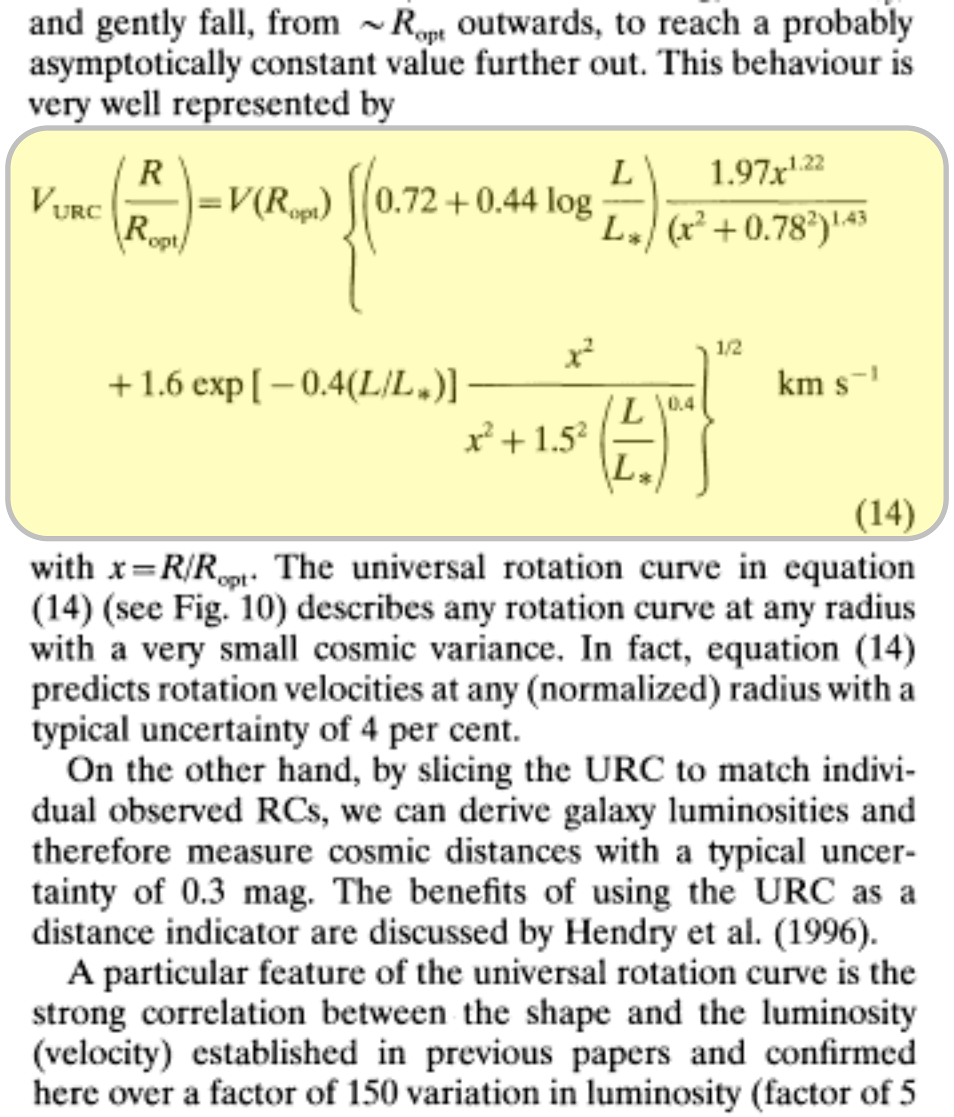
R/R_{opt}

R (kpc)

observed V(R)

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

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

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

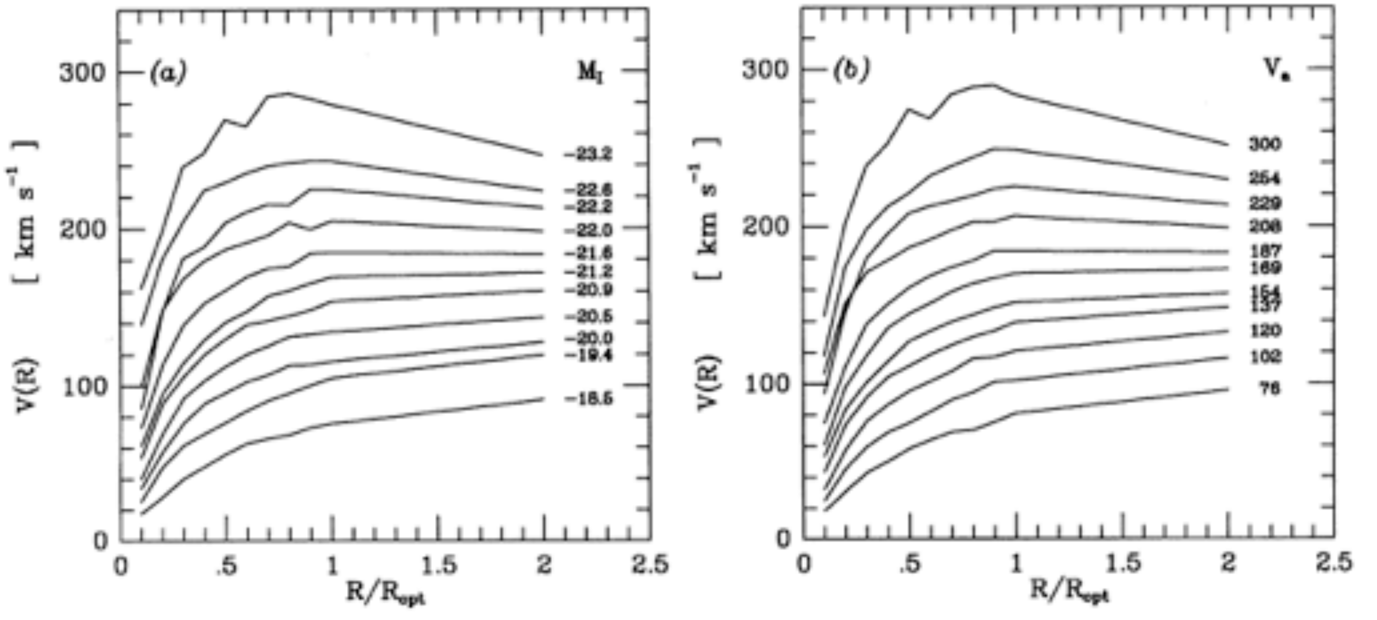


Figure 4. The universal rotation curve of spiral galaxies. Radii are in units of R_{opt}.

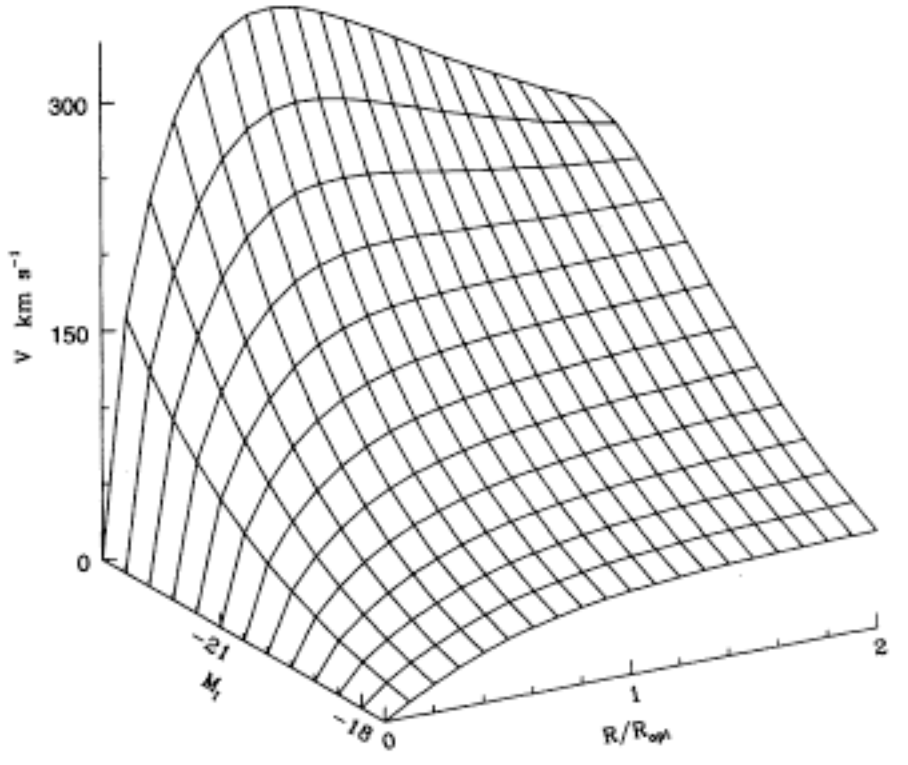
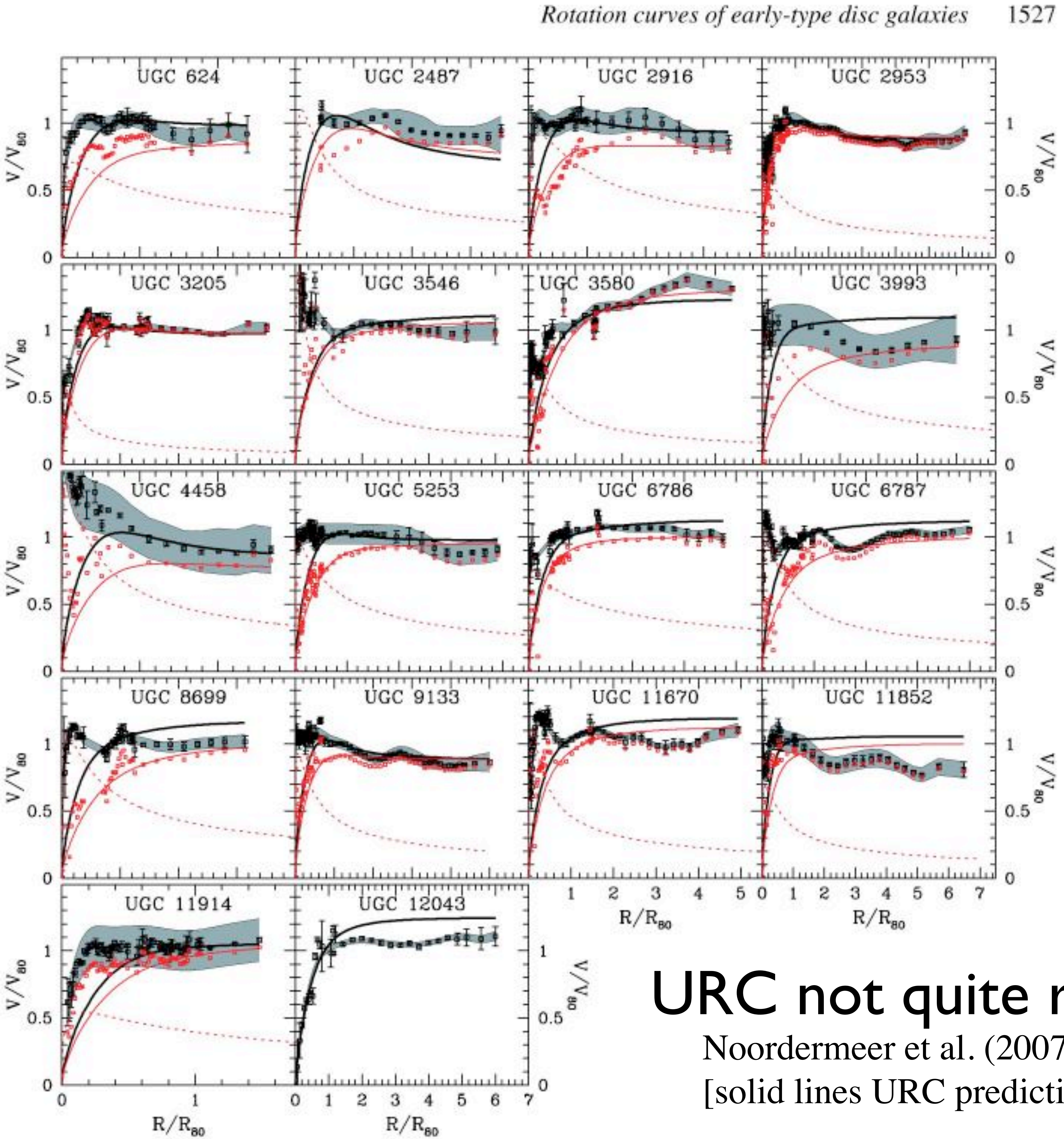


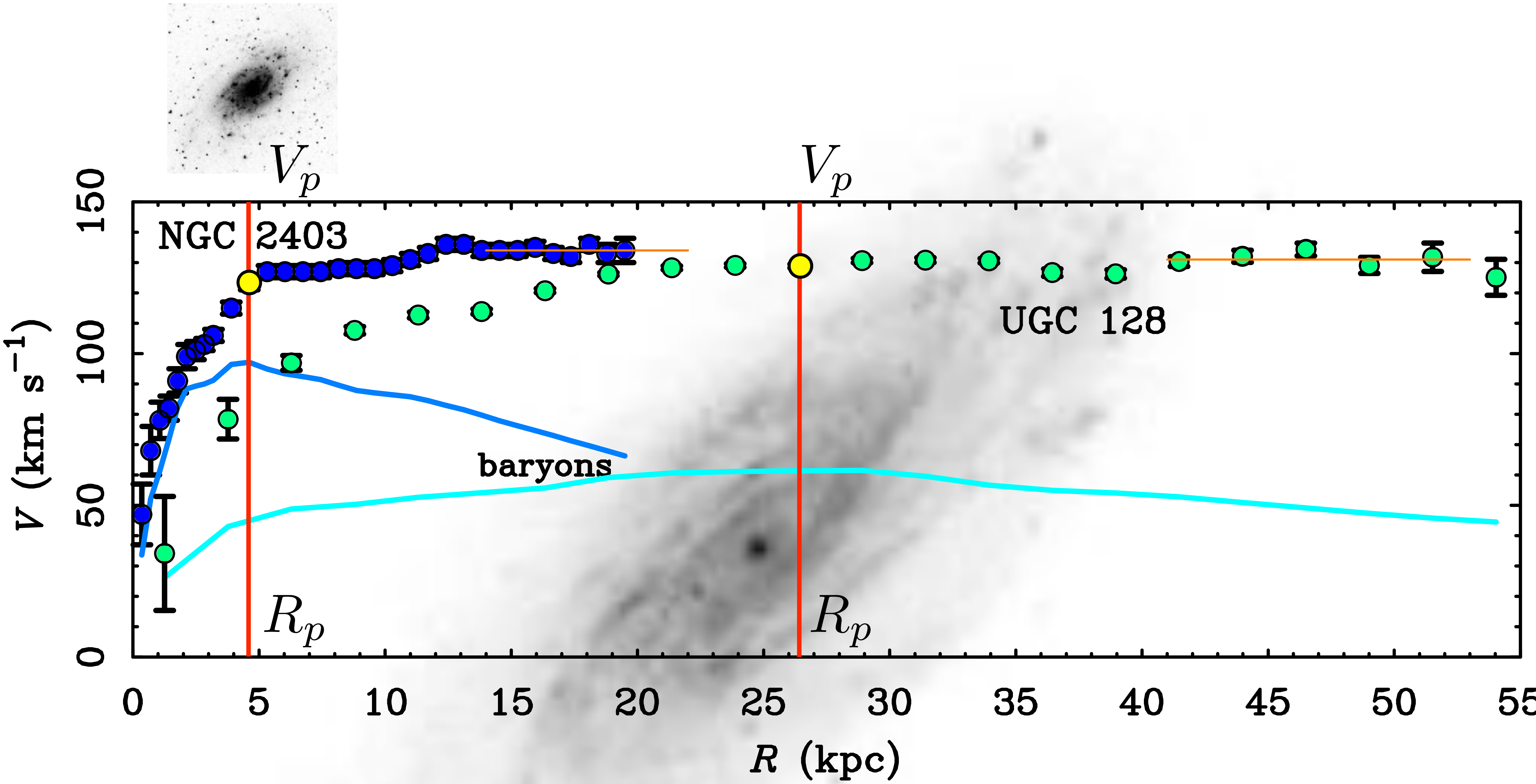
Figure 10. The URC surface.



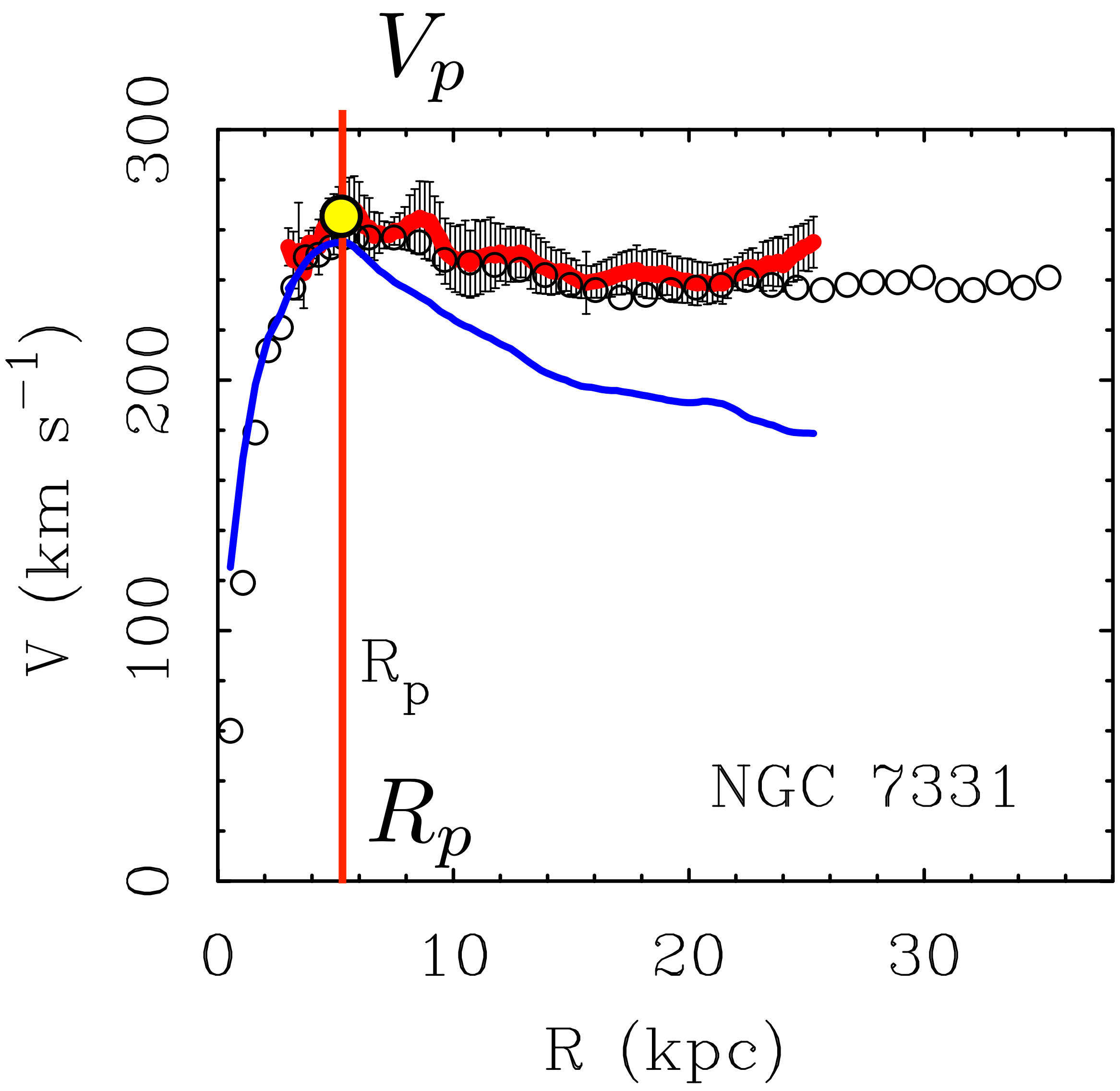
URC not quite right

Noordermeer et al. (2007)

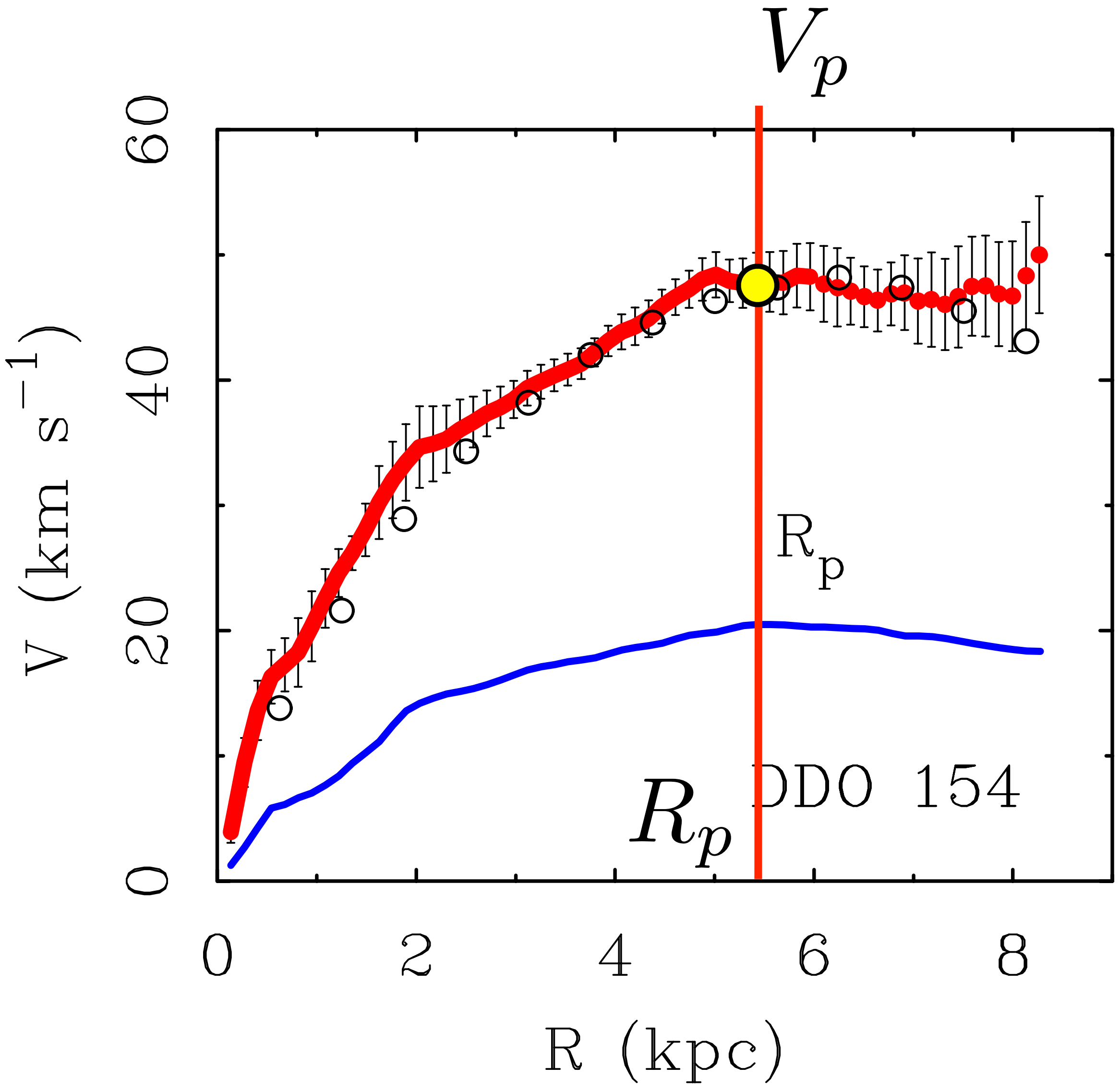
[solid lines URC prediction]



Radius in physical units (kpc)



High mass galaxy



Low mass galaxy

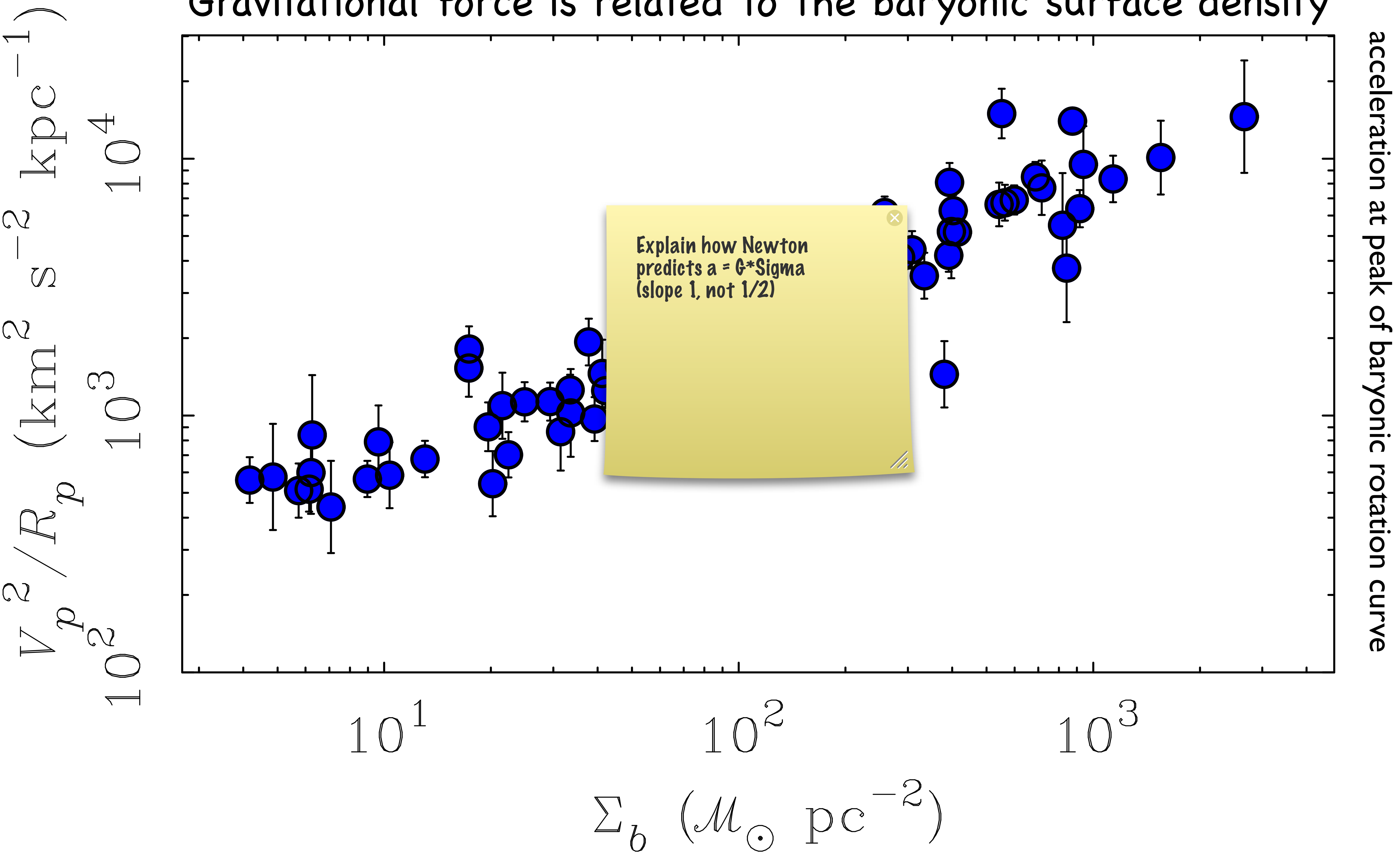
Just looking at the peak radius

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

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

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

Gravitational force is related to the baryonic surface density

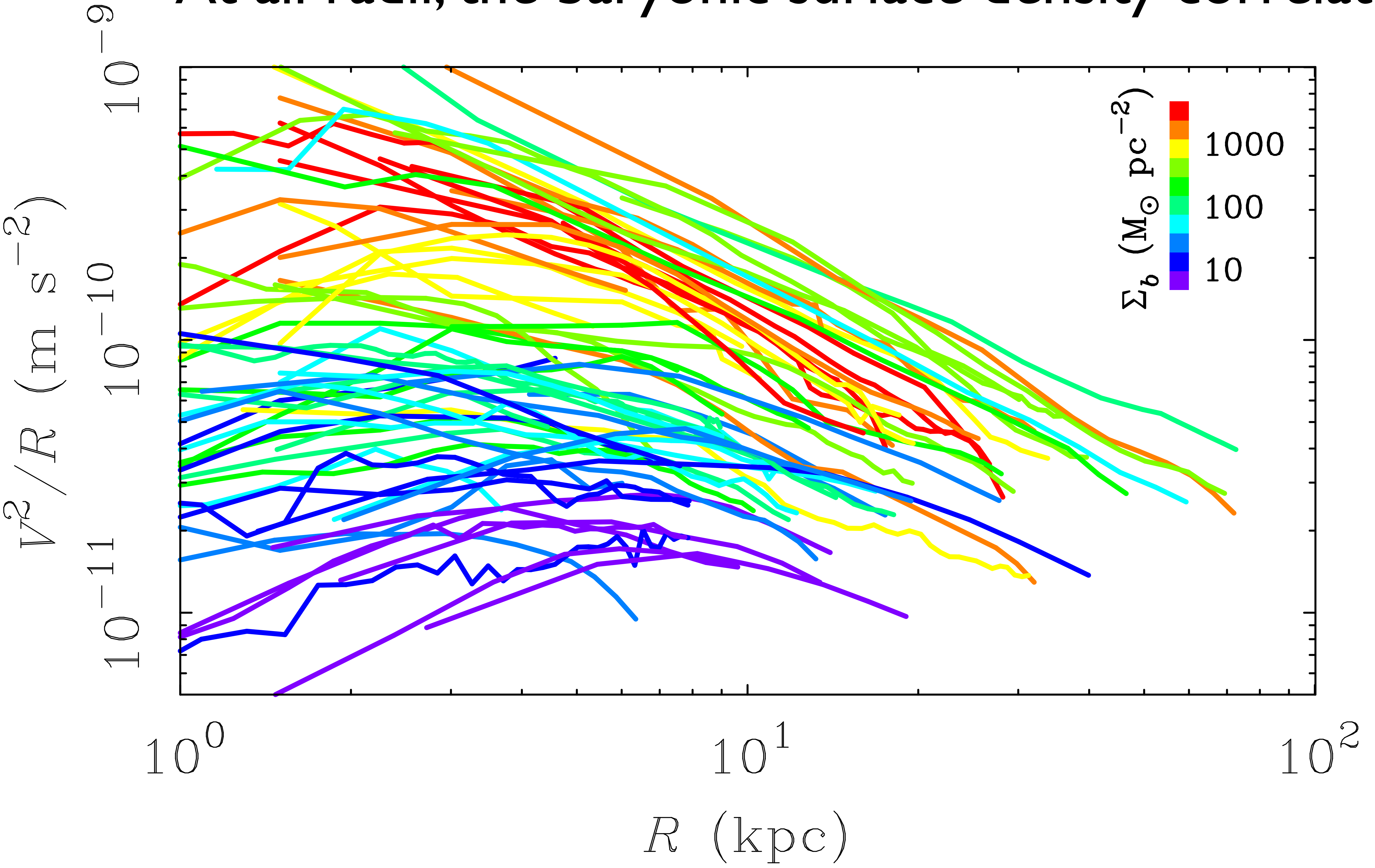


Explain how Newton predicts a = G*Sigma (slope 1, not 1/2)

acceleration at peak of baryonic rotation curve

central baryonic surface density

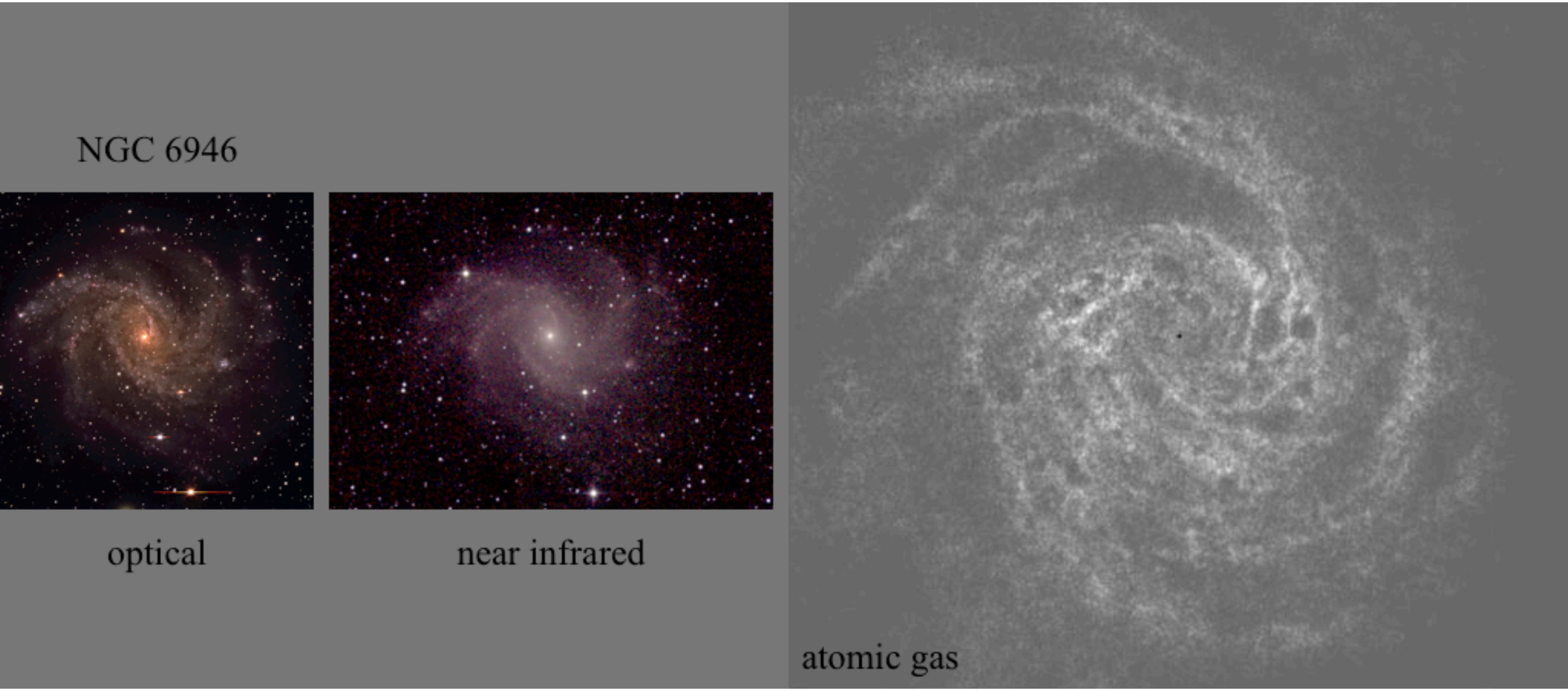
At all radii, the baryonic surface density correlates



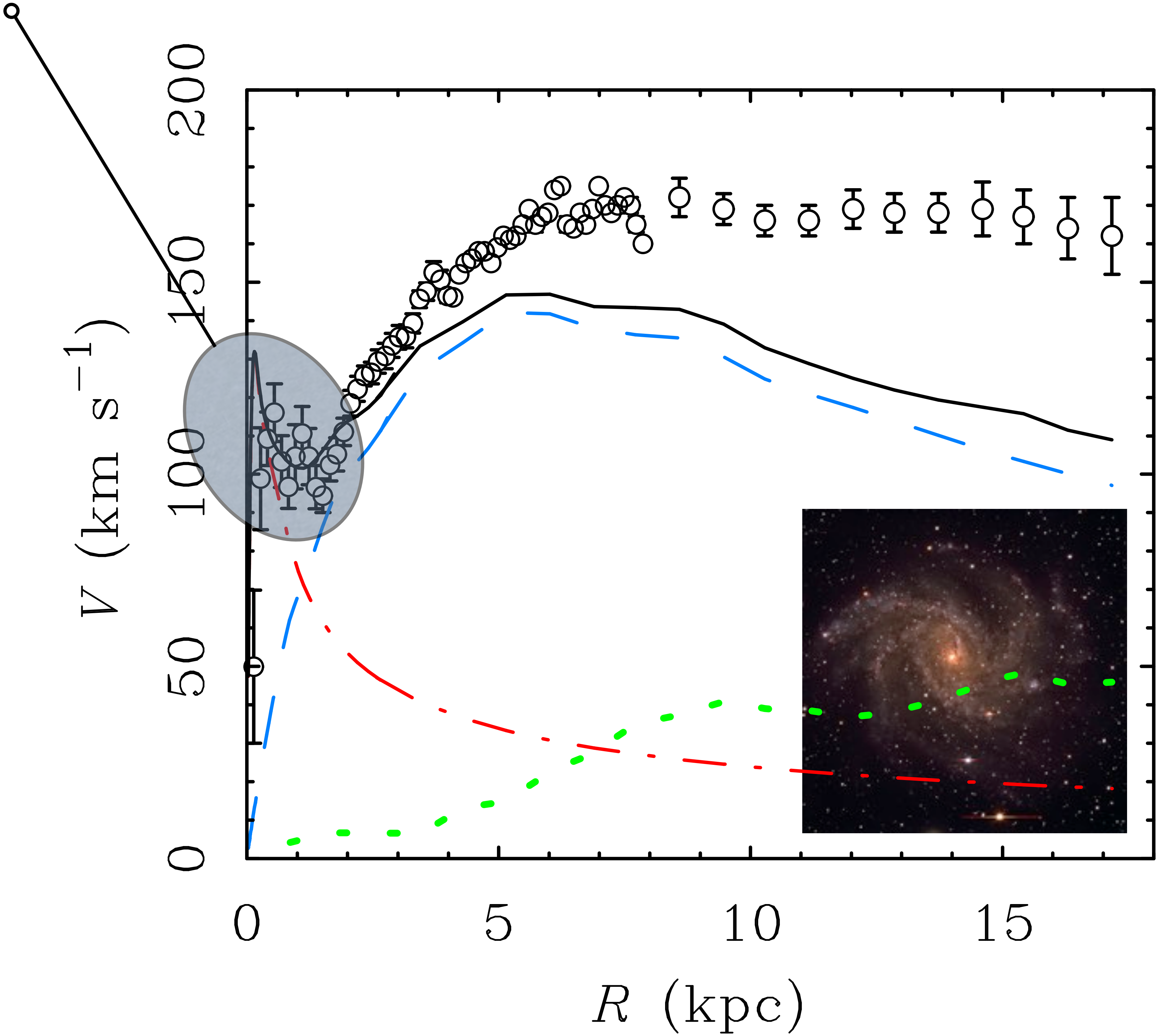
with the acceleration (gravitational force per unit mass)

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.”

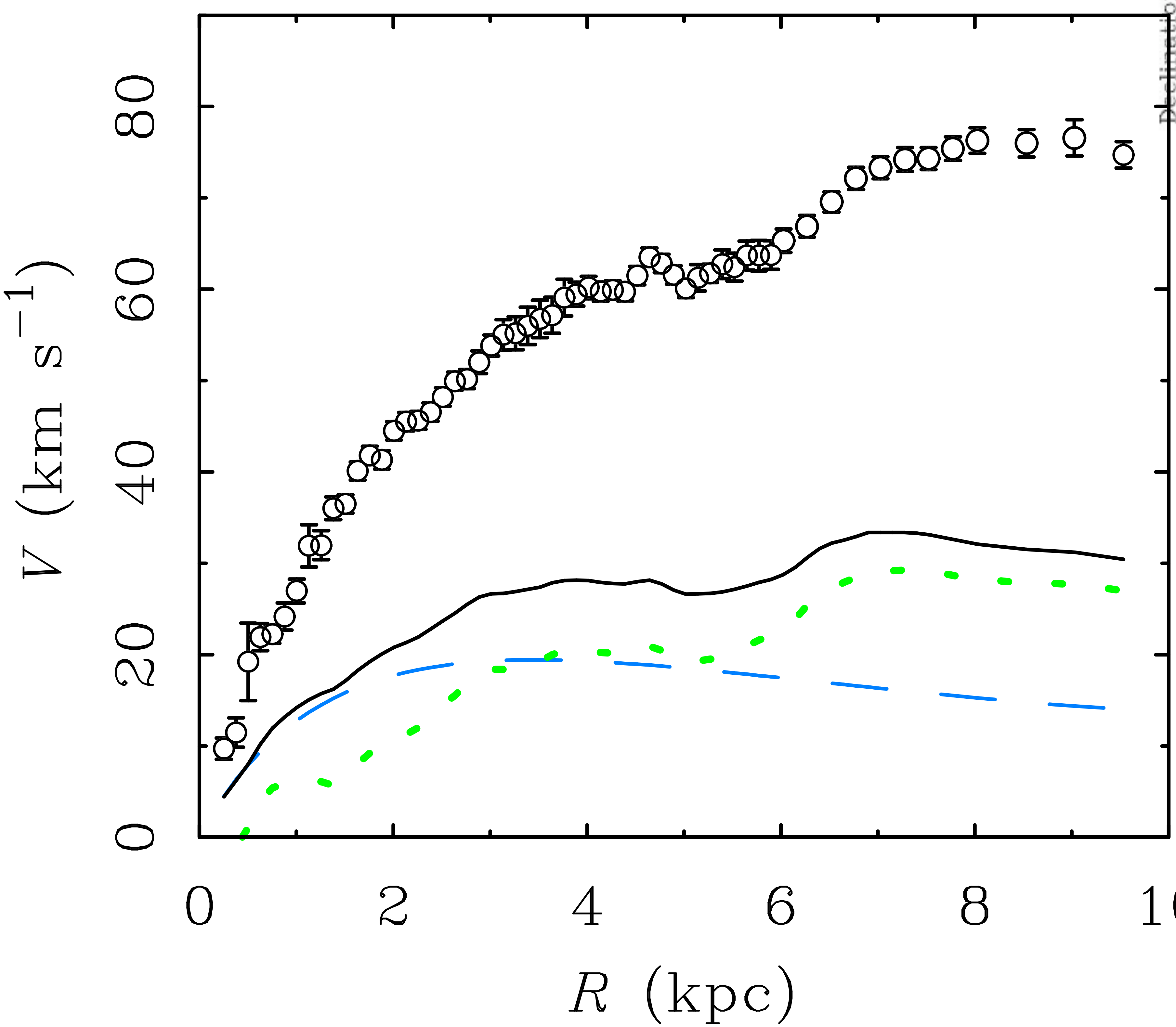


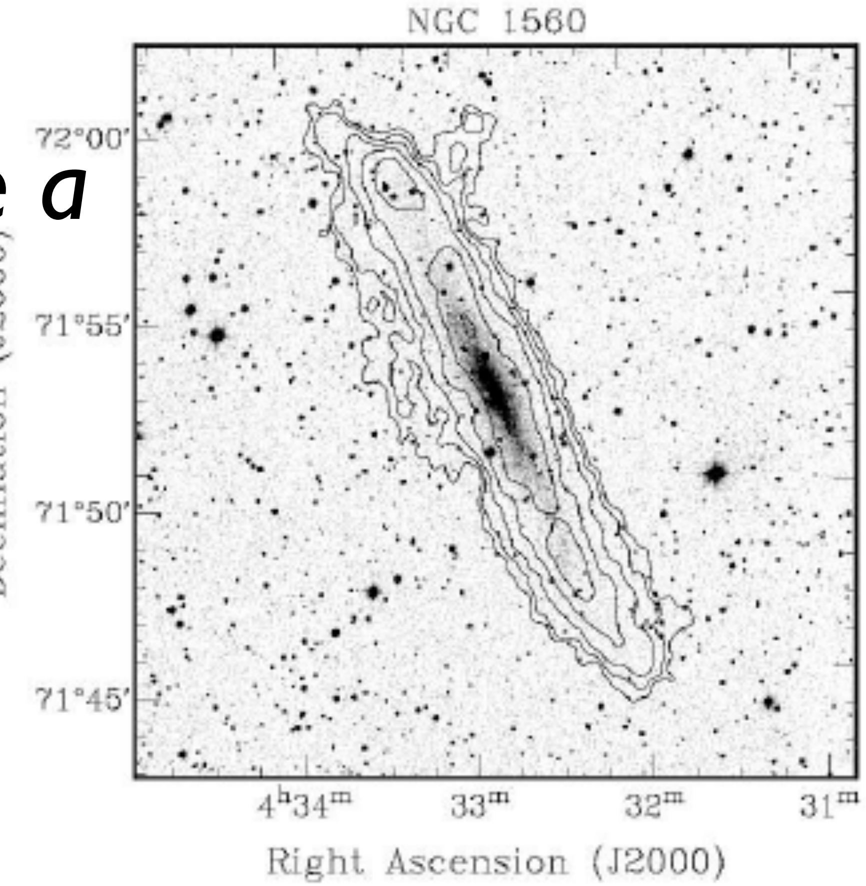
In NGC 6946, a tiny bulge (just 4% of the total light) leaves a distinctive mark.



Renzo's Rule:

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





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."

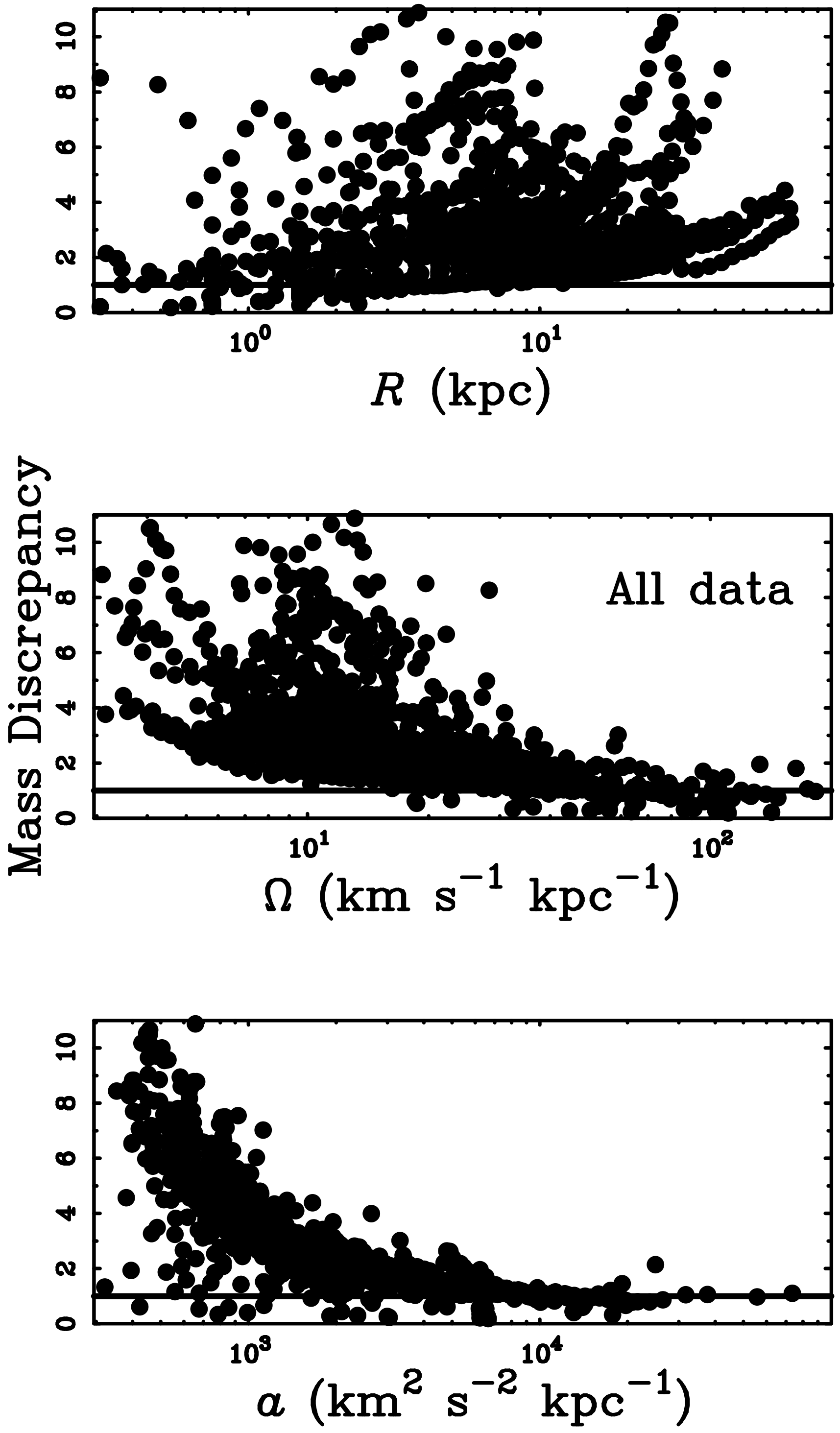
The distribution of mass is coupled to the distribution of light.

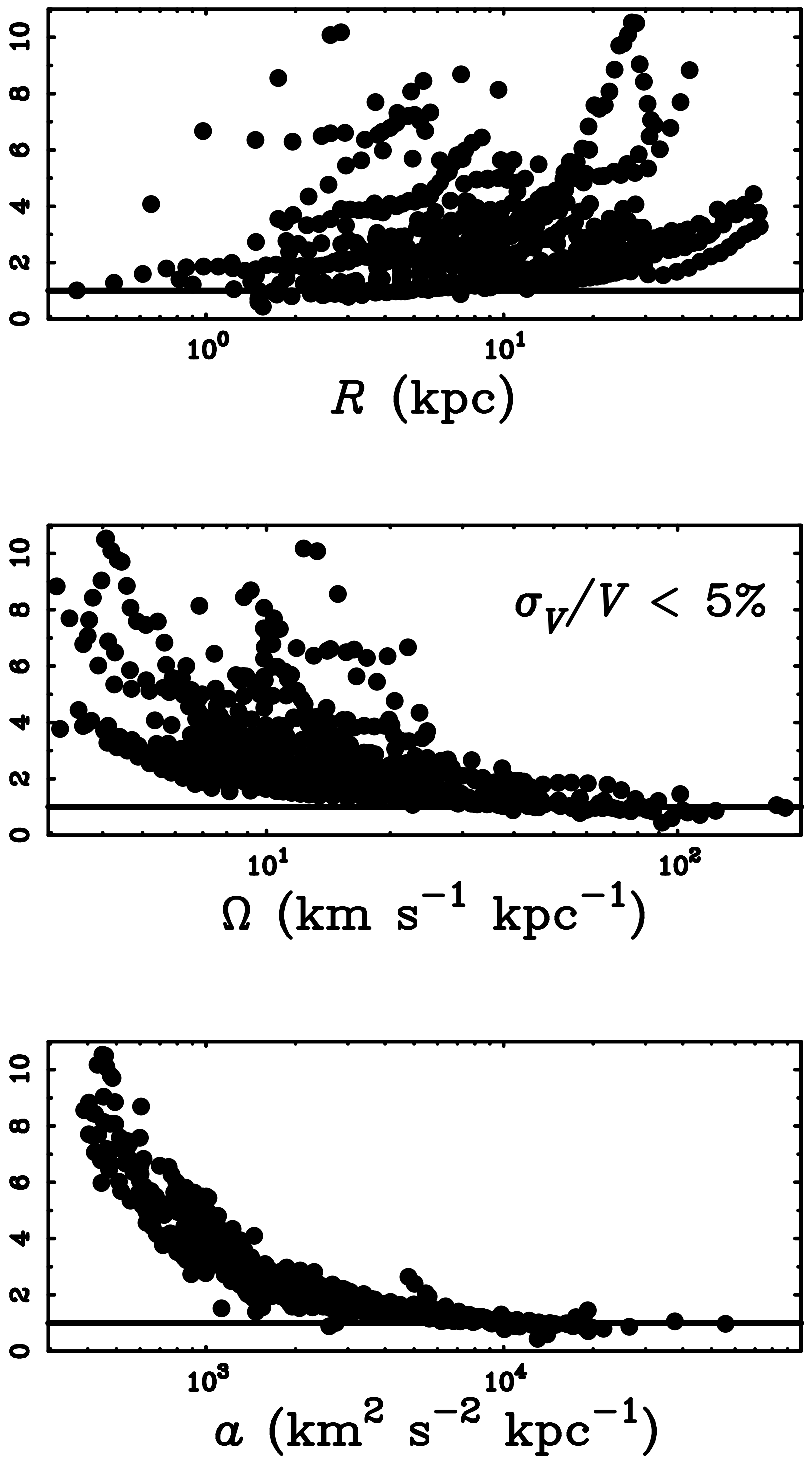
Quantify by defining the Mass Discrepancy:

$$\mathcal{D} = \frac{V^2}{V_b^2} = \frac{V^2}{\Upsilon_\star v_\star^2 + V_g^2} \approx \frac{M(< R)}{M_b(< R)}$$

The Mass Discrepancy correlates with acceleration and baryonic surface density

McGaugh (2004)





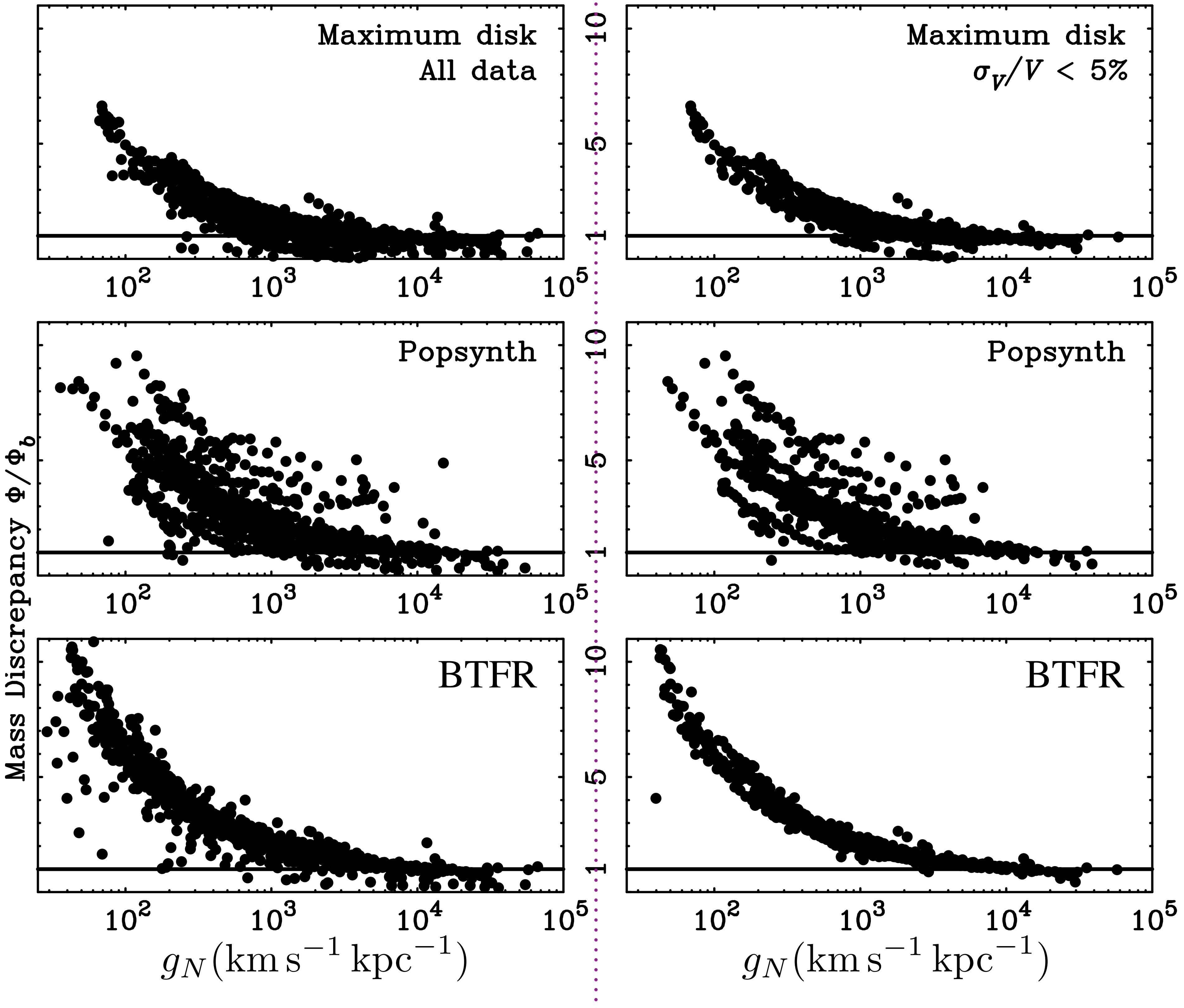
radius

orbital
frequency

acceleration

74 galaxies
> 1000 points
(all data)

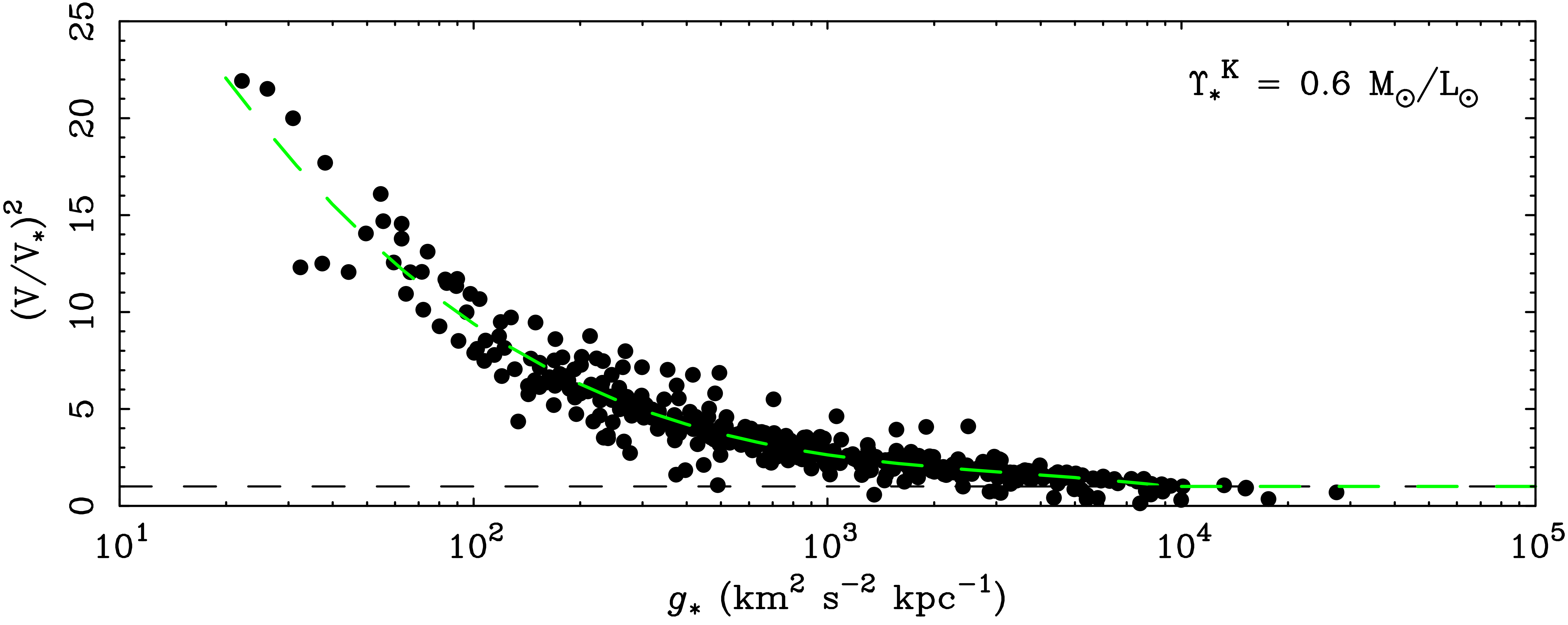
60 galaxies
> 600 points
(errors < 5%)

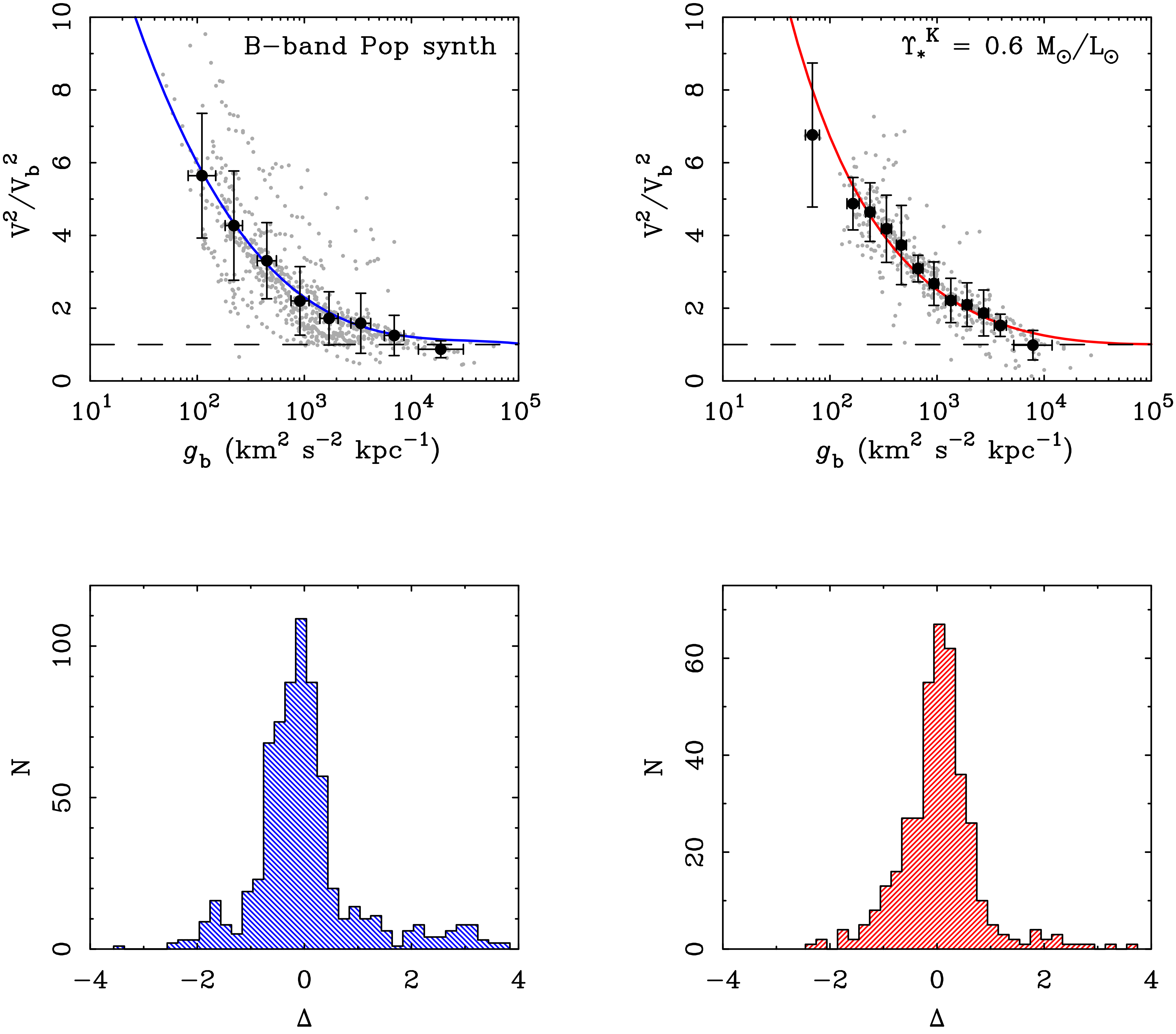


The relation between the mass discrepancy and acceleration persists for any plausible choice of M*/L

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

***K*'-band data**
(Verheijen 1997)
30 galaxies
220 independent points




B−band Pop synth
$\Upsilon_*^K = 0.6\ M_\odot/L_\odot$
V^2/V_b^2
g_b (km^2 s^{-2} kpc^{-1})
0
2
4
6
8
10
10^1
10^2
10^3
10^4
10^5
N
0
50
100
0
20
40
60
Δ
−4
−2
0
2
4

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