Dark Matter

ASTR 333/433
Spring 2024
TR 11:30am–12:45pm
Sears 552

http://astroweb.case.edu/ssm/ASTR333/

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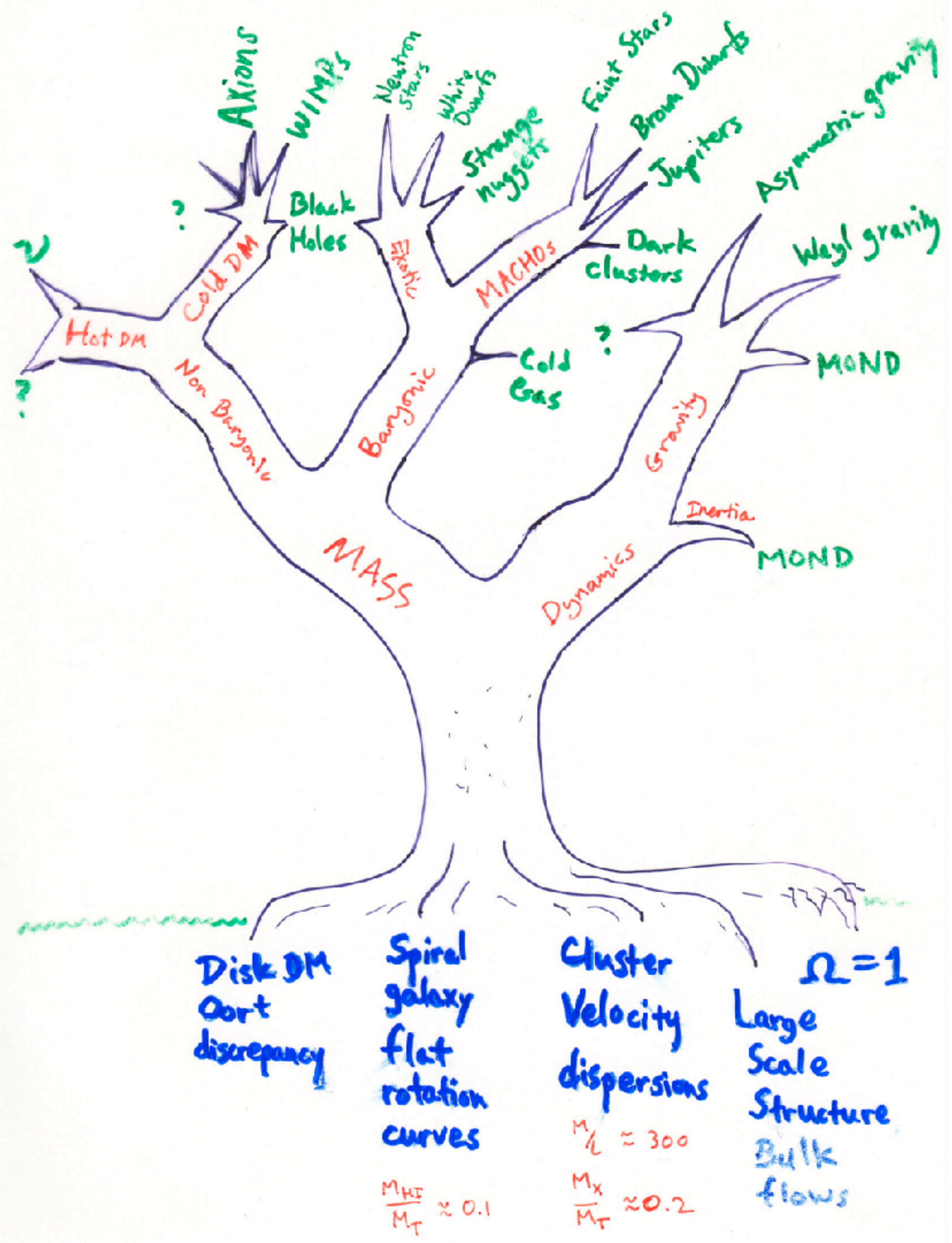
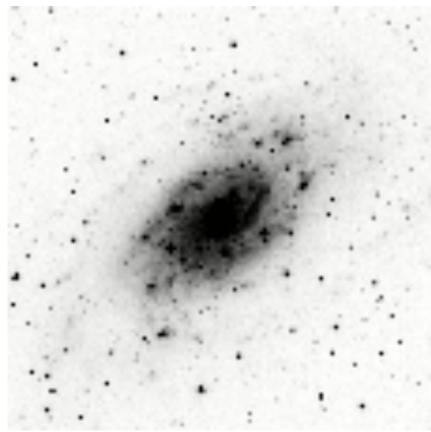
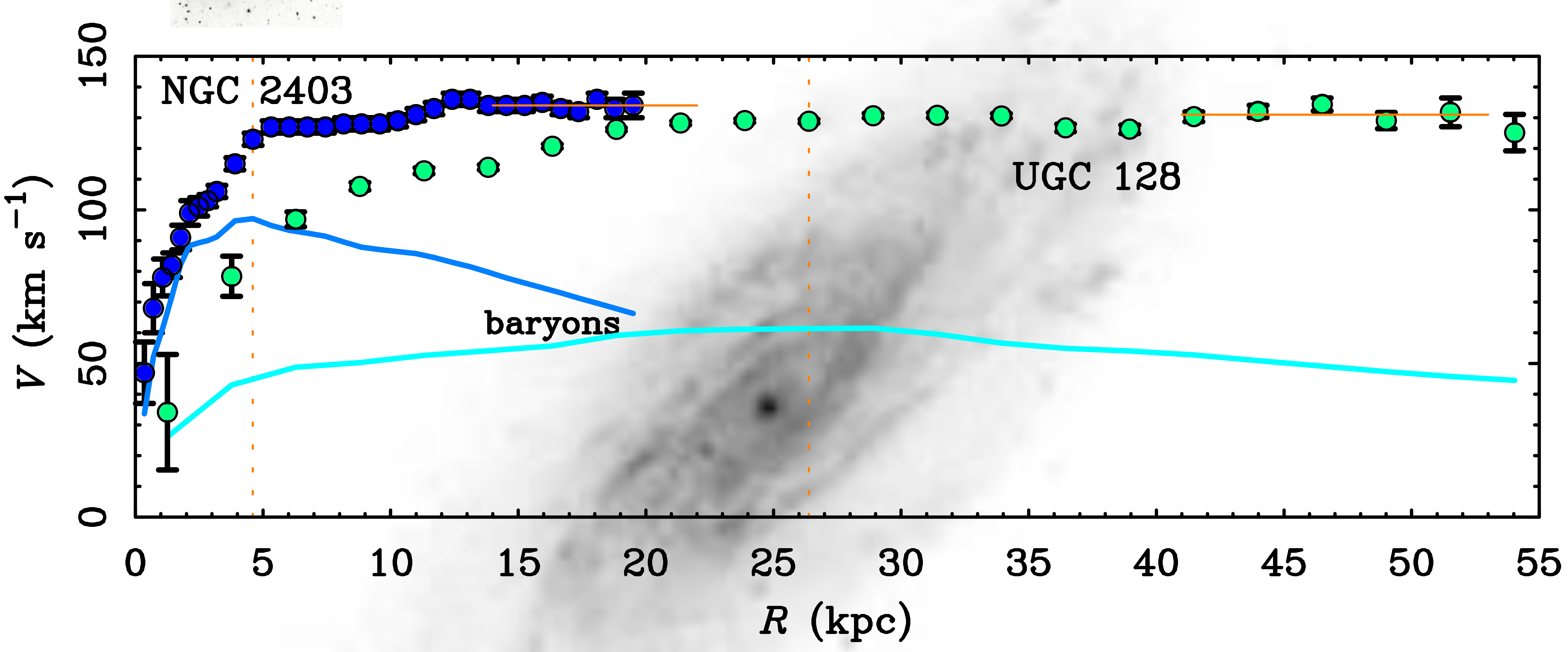


No residuals from TF with size or surface density





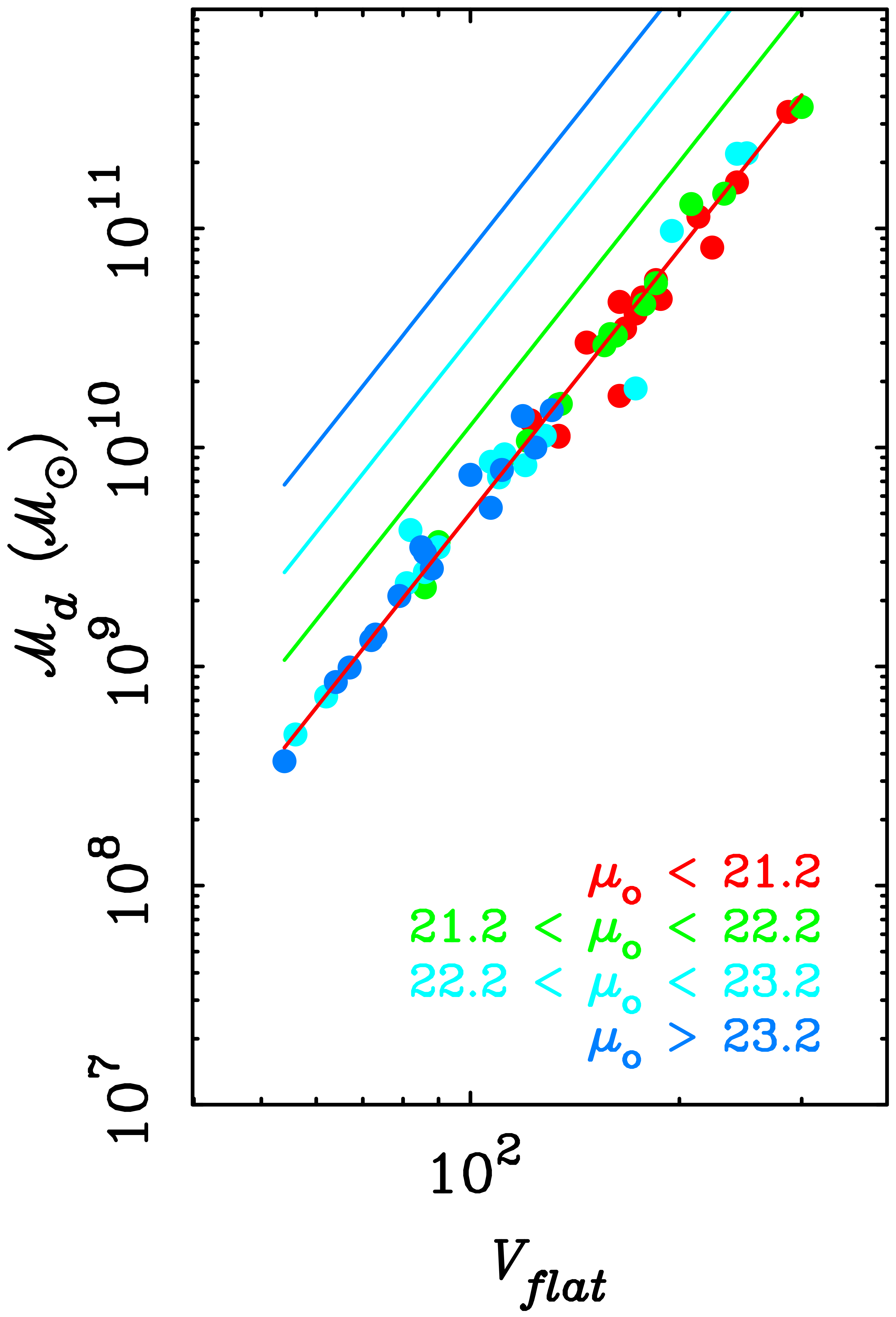
TF pair: two galaxies with the same mass and rotation speed, but very different size and surface density.

which is strange, since

$$V^2 = \frac{GM}{R}$$

No residuals from TF with size or surface brightness

(Zwaan et al 1995; Sprayberry et al 1995; McGaugh & de Blok 1998)



$$V^2 = \frac{GM}{r}$$

$$V^4 = \frac{G^2M^2}{r^2}$$

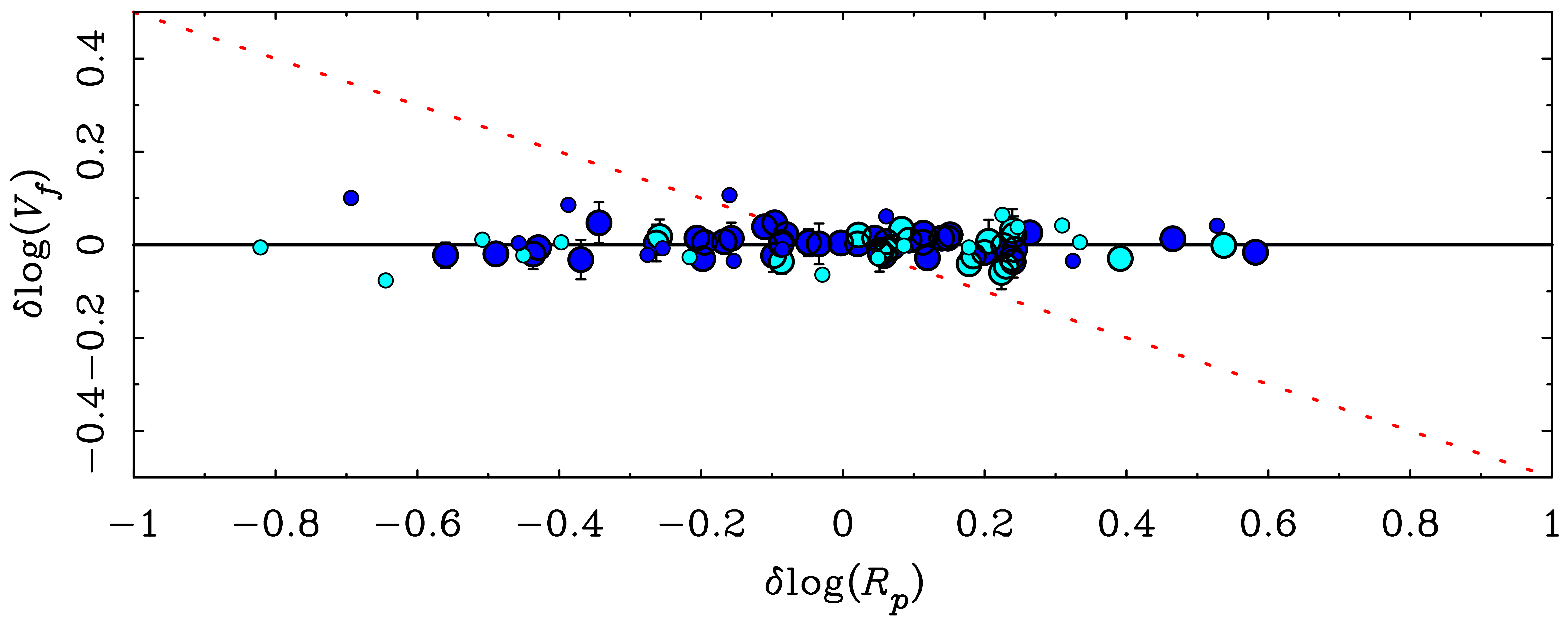
$$V^4 \propto \left(\frac{M}{r^2}\right) M = \Sigma M$$

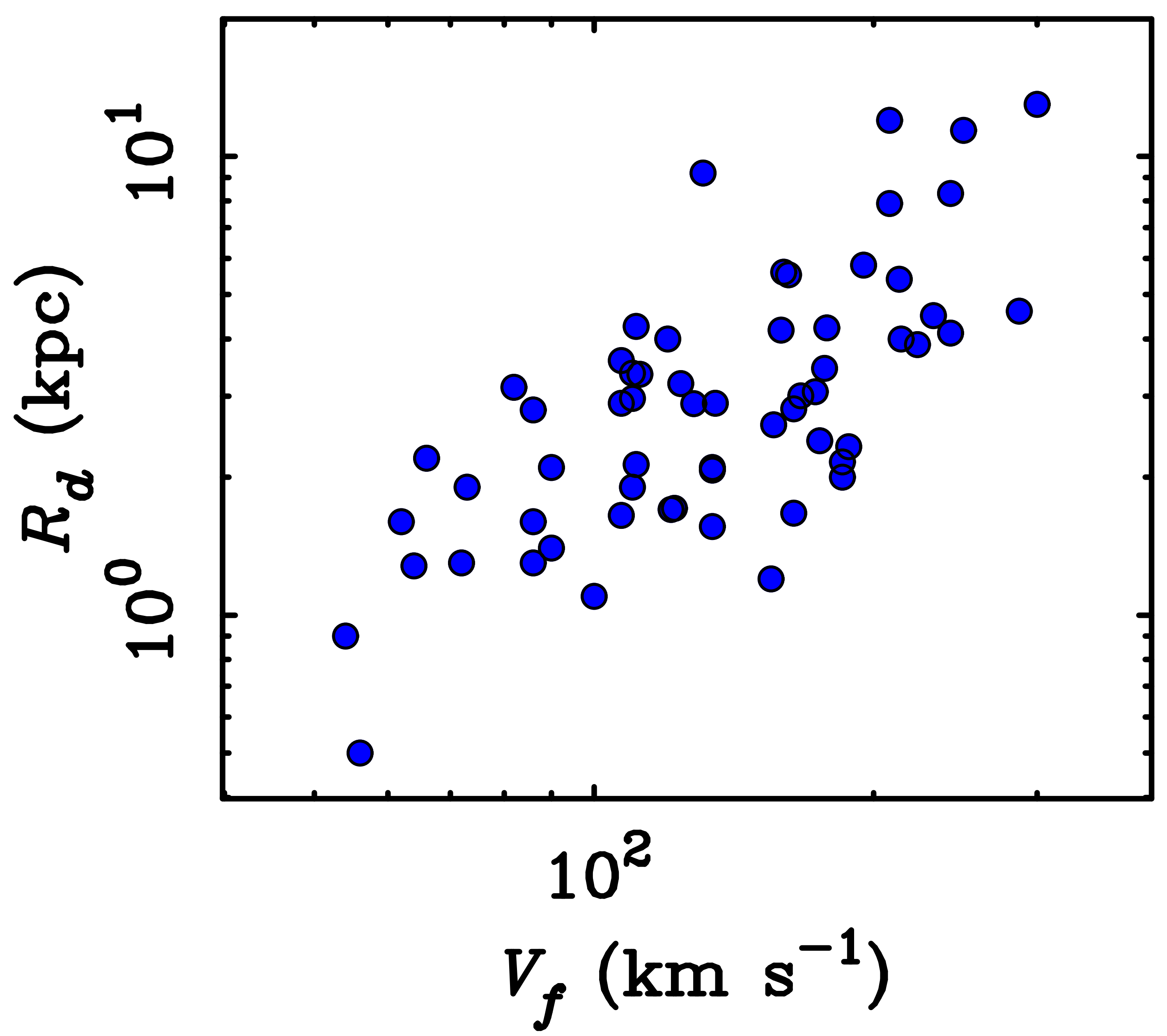
$$V^4 \propto M$$

TF recovered iff surface density Σ constant

No residuals from TF with size or surface density for disks

despite lots of scatter in size-mass relation





$$V^2 = \frac{GM}{R} \rightarrow \frac{\delta \log(V)}{\delta \log(R)} = -\frac{1}{2}$$ expected slope (dotted line)

Note: large range in size at a given mass or velocity

TF already the edge-on projection of disk fundamental plane

Baryonic TF Relation

- Fundamentally a relation between the baryonic mass of a galaxy and its rotation velocity
  - $M_b = M_* + M_g = A V_f^4$
  - doesn't matter if it is stars or gas
- Intrinsic scatter negligibly small
  - Can mostly be accounted for by the expected variation in stellar M*/L
- Physical basis of the relation remains unclear

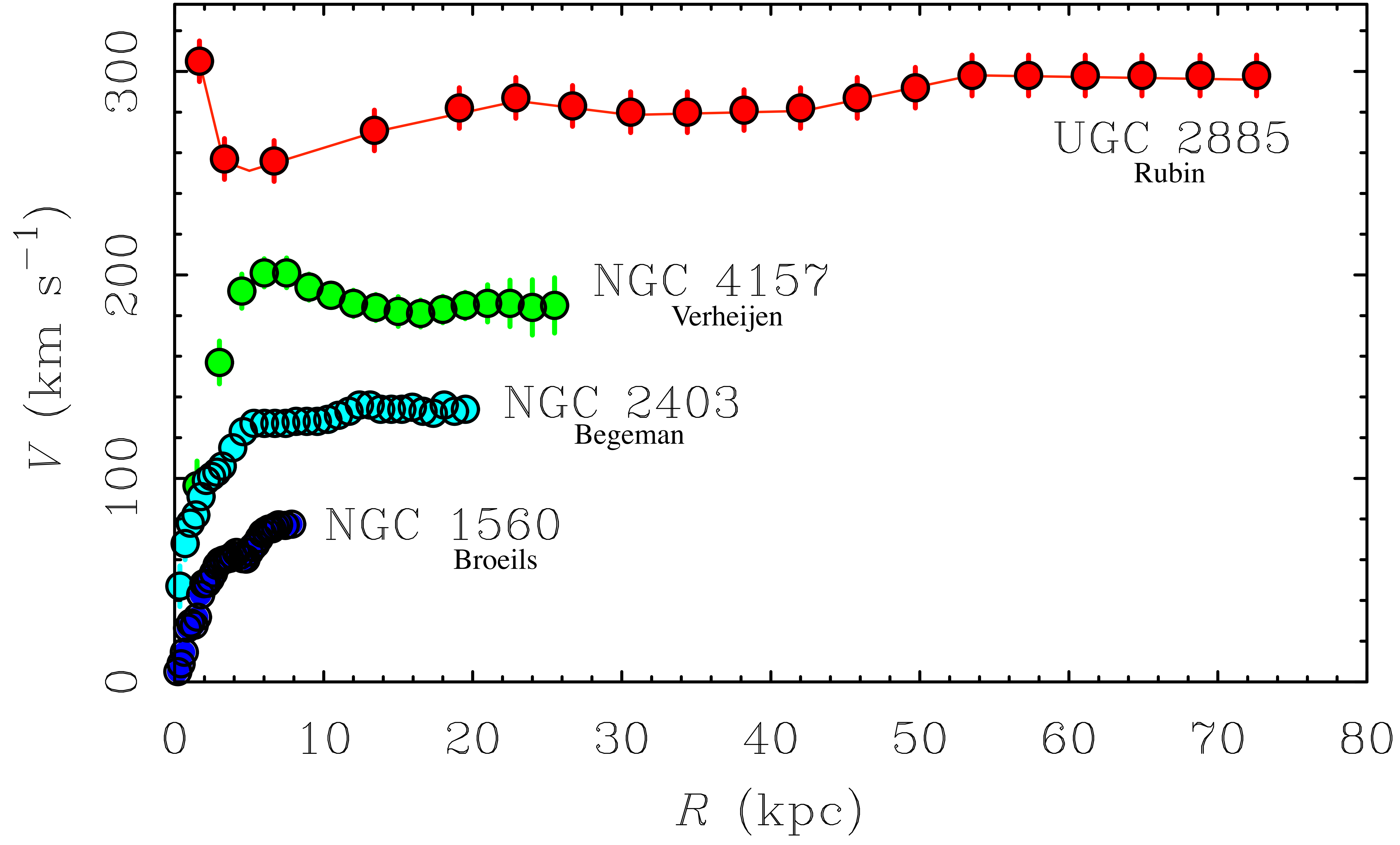
$$A = 47\ M_\odot\,km^{-4}\,s^4$$

Normalization consistently in the range $45 < A < 50$ over the past 20 years.

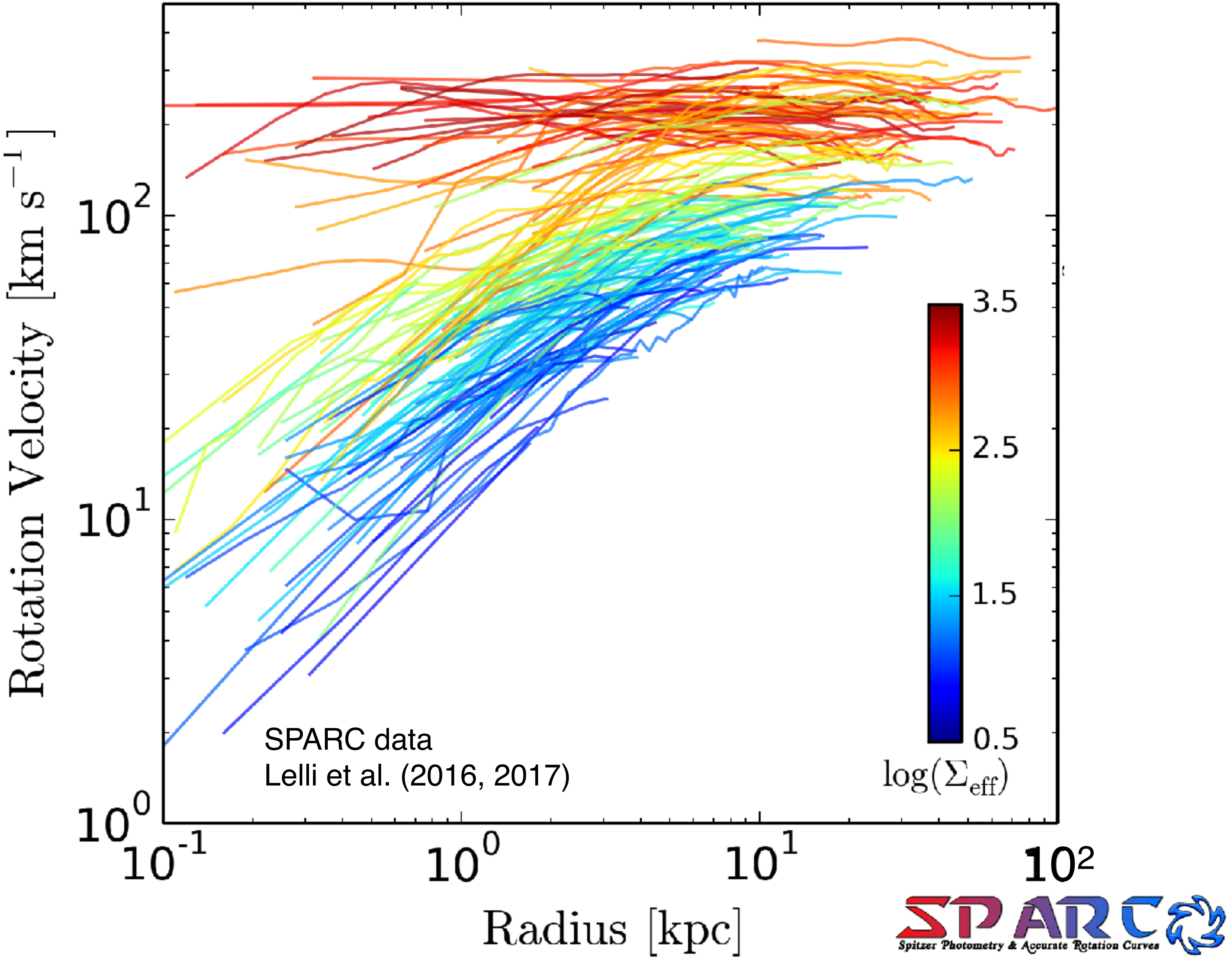
Relation has real physical units if slope has integer value -
Slope appears to be 4 *if* Vflat is used.

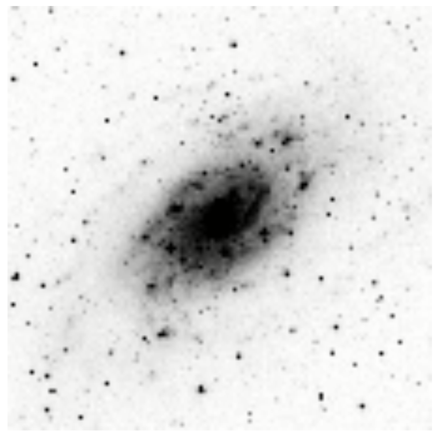
Rotation curve amplitude depends on the mass of stars and gas (BTFR)

Rotation curve shape depends on the distribution of stars and gas

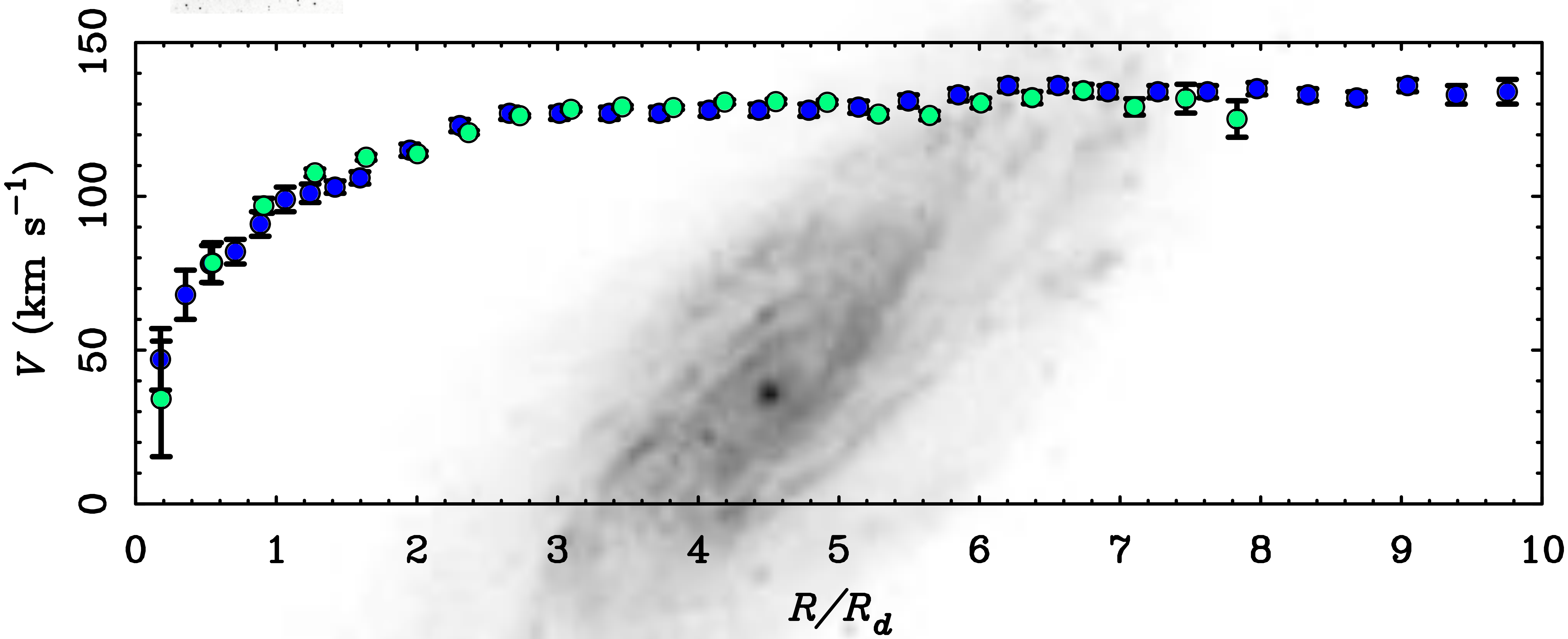


Rotation curve shape correlates with baryonic surface density





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)

Central Density Relation

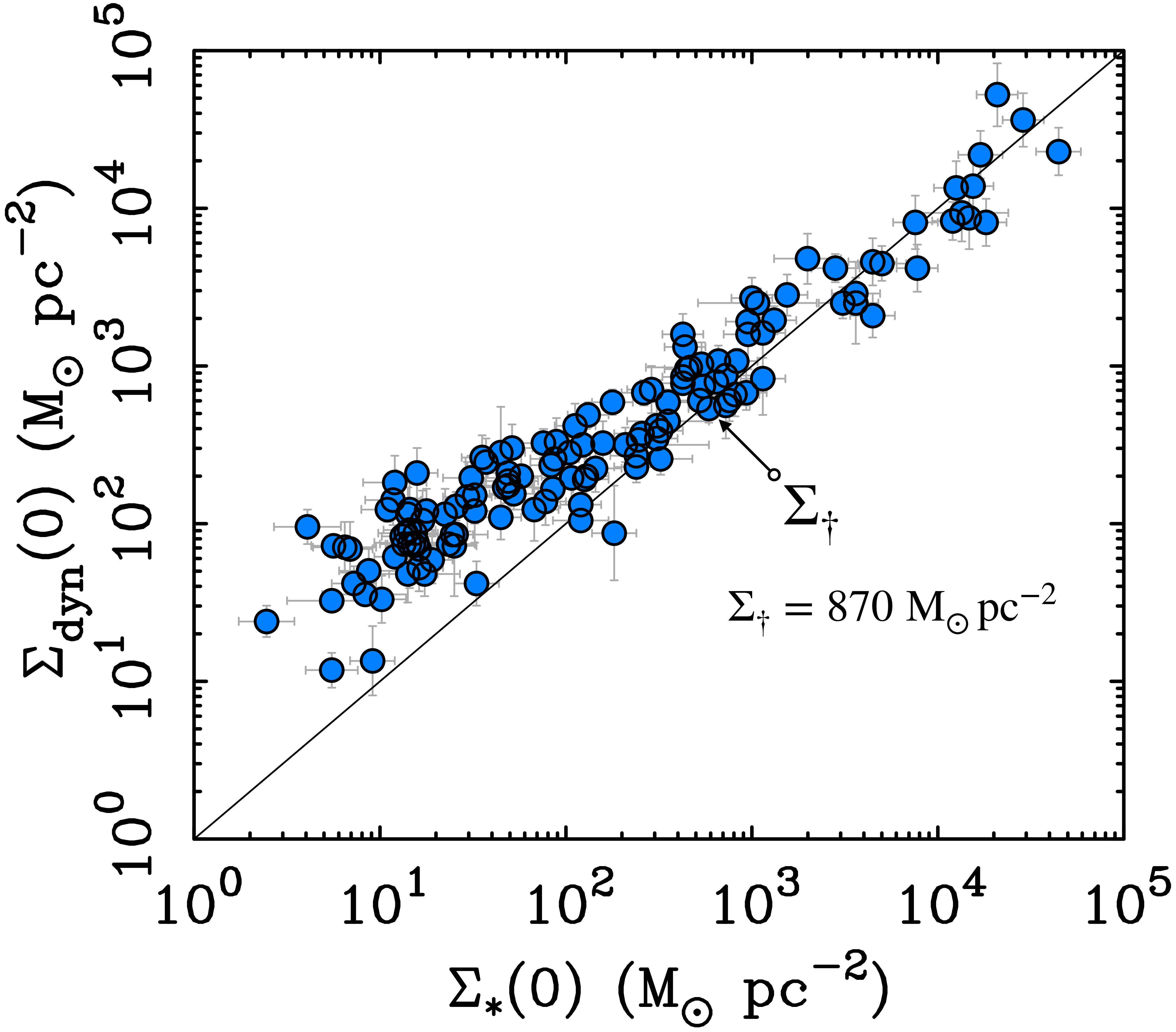
Lelli et al. (2016)

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

central dynamical surface density

Toomre (1963)

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



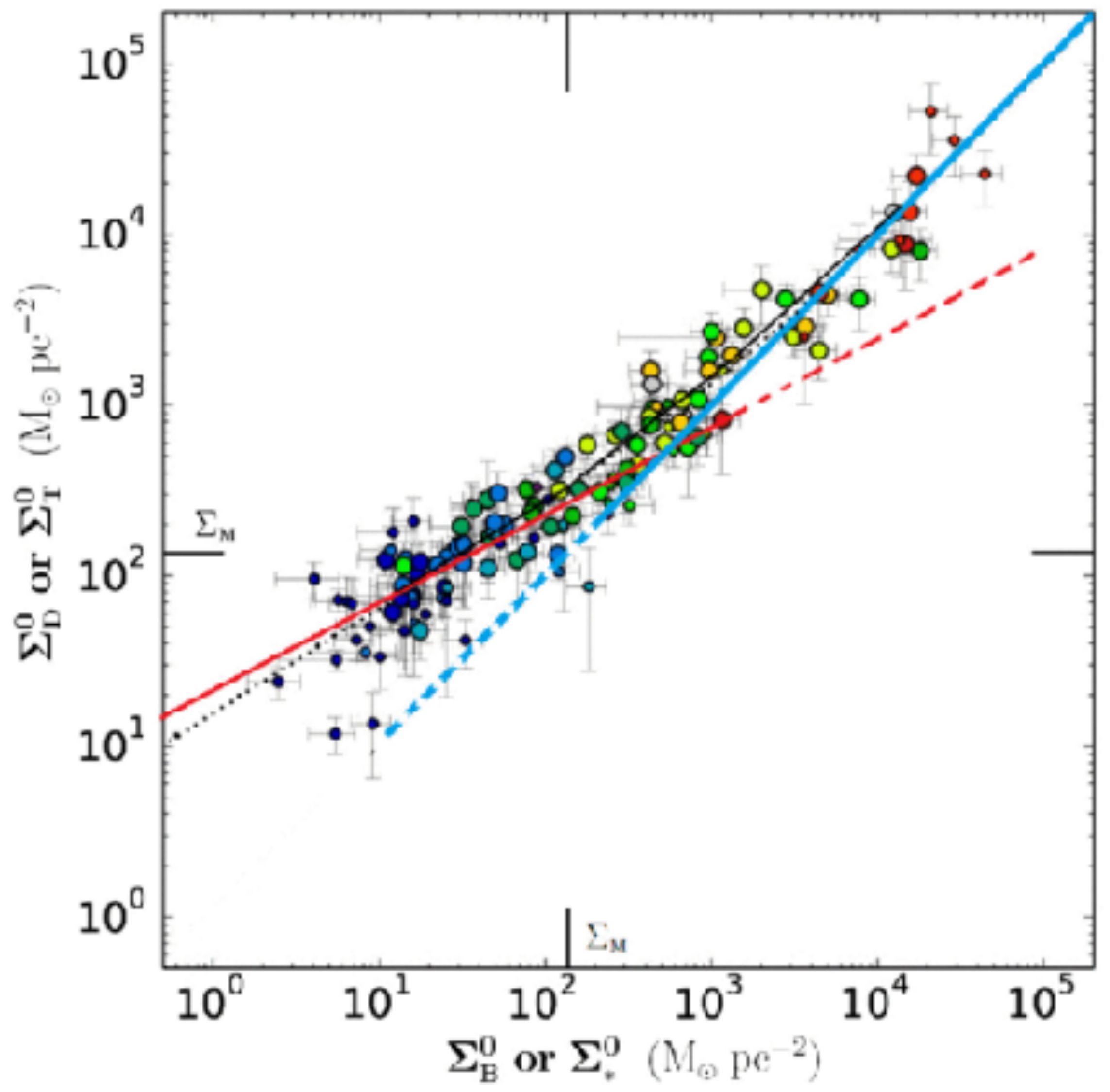
central surface brightness

Dynamical central mass surface density $\Sigma_{dyn}(R=0)$:

$$\Sigma_{dyn}(0) = \frac{1+q_0}{2\pi G}\int_0^\infty \frac{V^2}{R^2}dR$$

q_0 is the disk thickness: $q_0 \approx 0.15$

$$\Sigma_{dyn}(0) = \frac{1}{2\pi}\Sigma_\dagger f(y) \qquad y = \frac{\Sigma_*(0)}{2\pi\Sigma_\dagger}$$



$$f(y) = \frac{y}{2} + y^{1/2}\left(1+\frac{y}{4}\right)^{1/2} + 2\sinh\left(\frac{y^{1/2}}{2}\right)$$

Asymptotically,

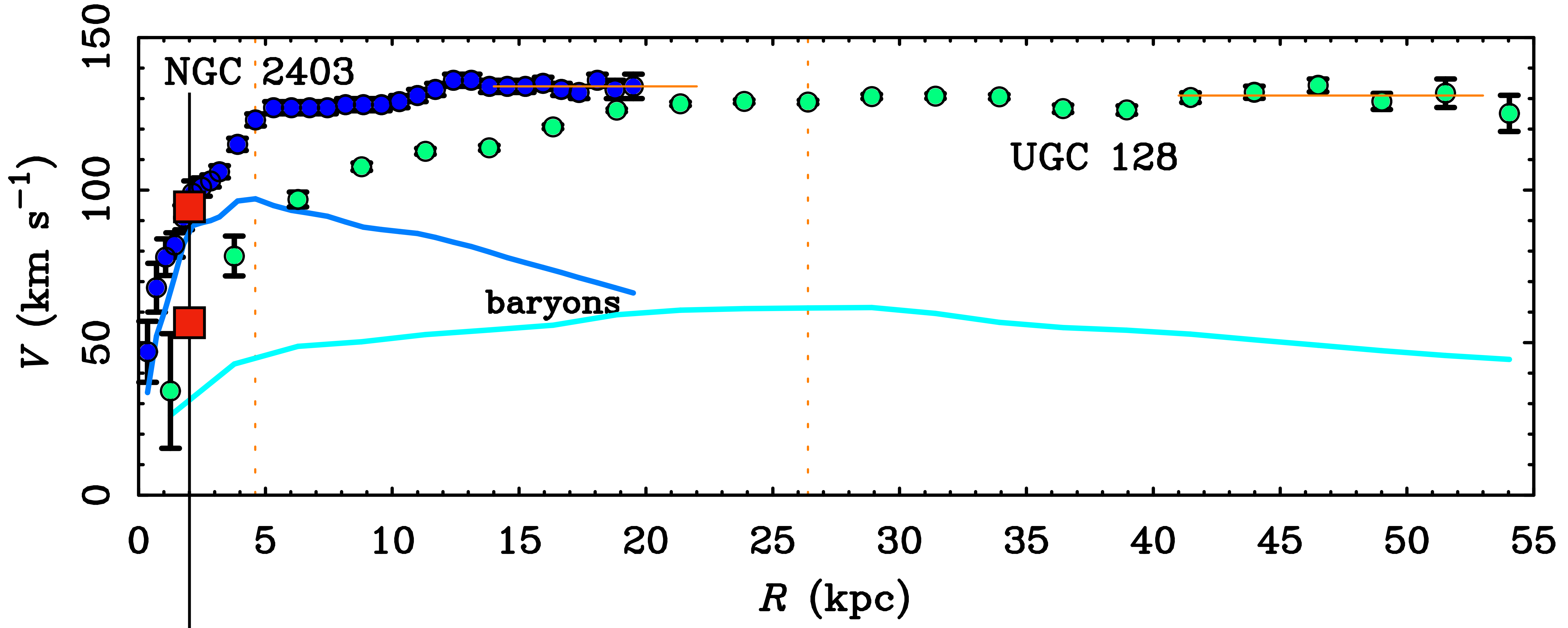
$$\Sigma_{dyn}(0) \to \Sigma_*(0) \text{ for } \Sigma_*(0) \gg \Sigma_\dagger$$

linear at high surface density

$$\Sigma_{dyn}(0) \to \left(\frac{1}{\pi}\Sigma_\dagger\Sigma_*(0)\right)^{1/2} \text{ for } \Sigma_*(0) \ll \Sigma_\dagger$$

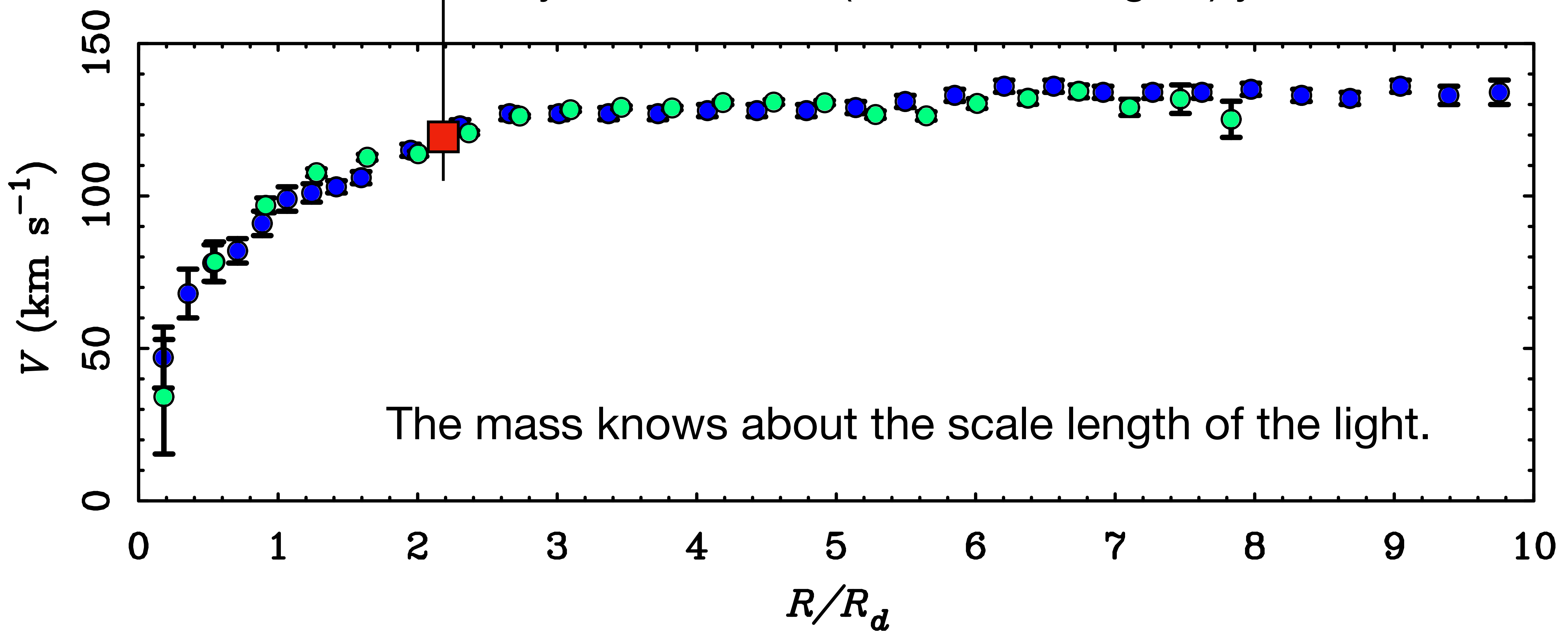
square root at low surface density

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

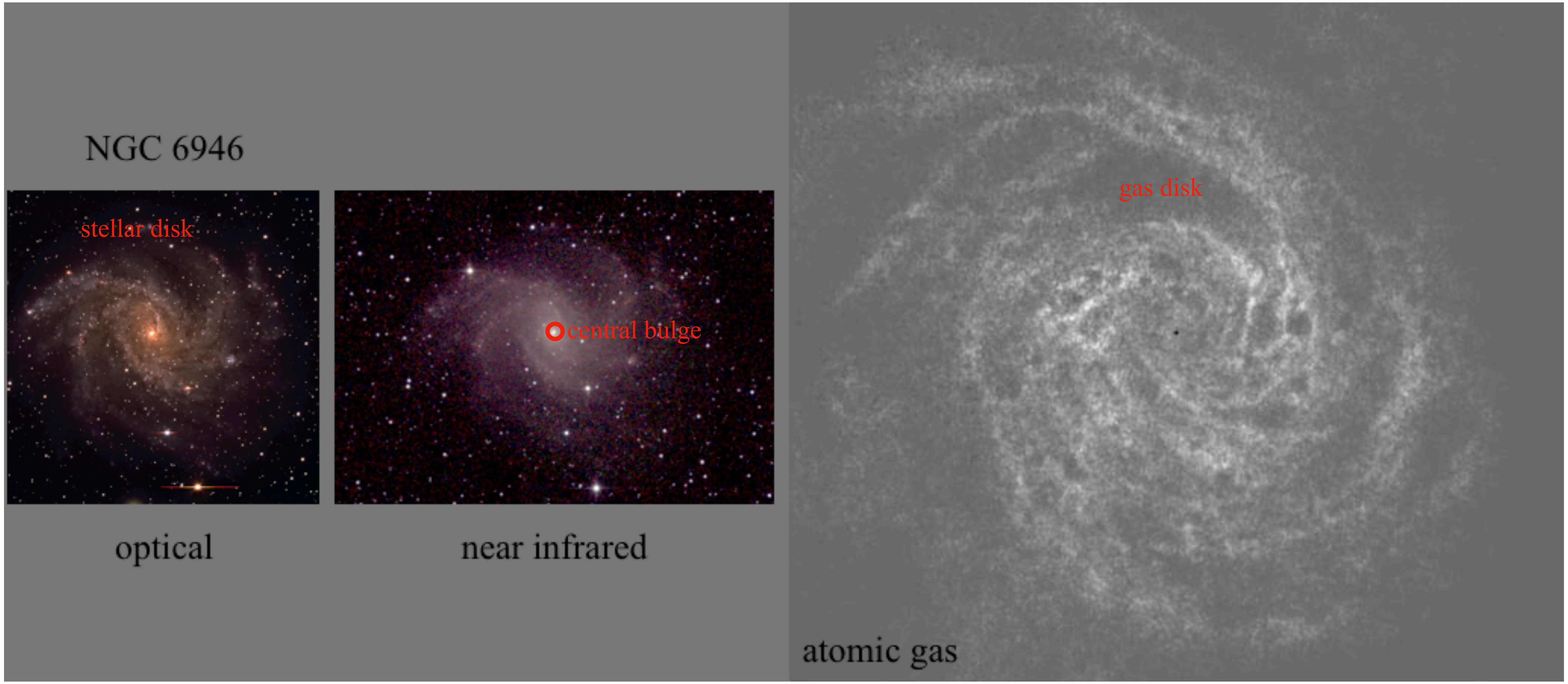


If you measure V(R in kpc) you infer **diversity**.

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

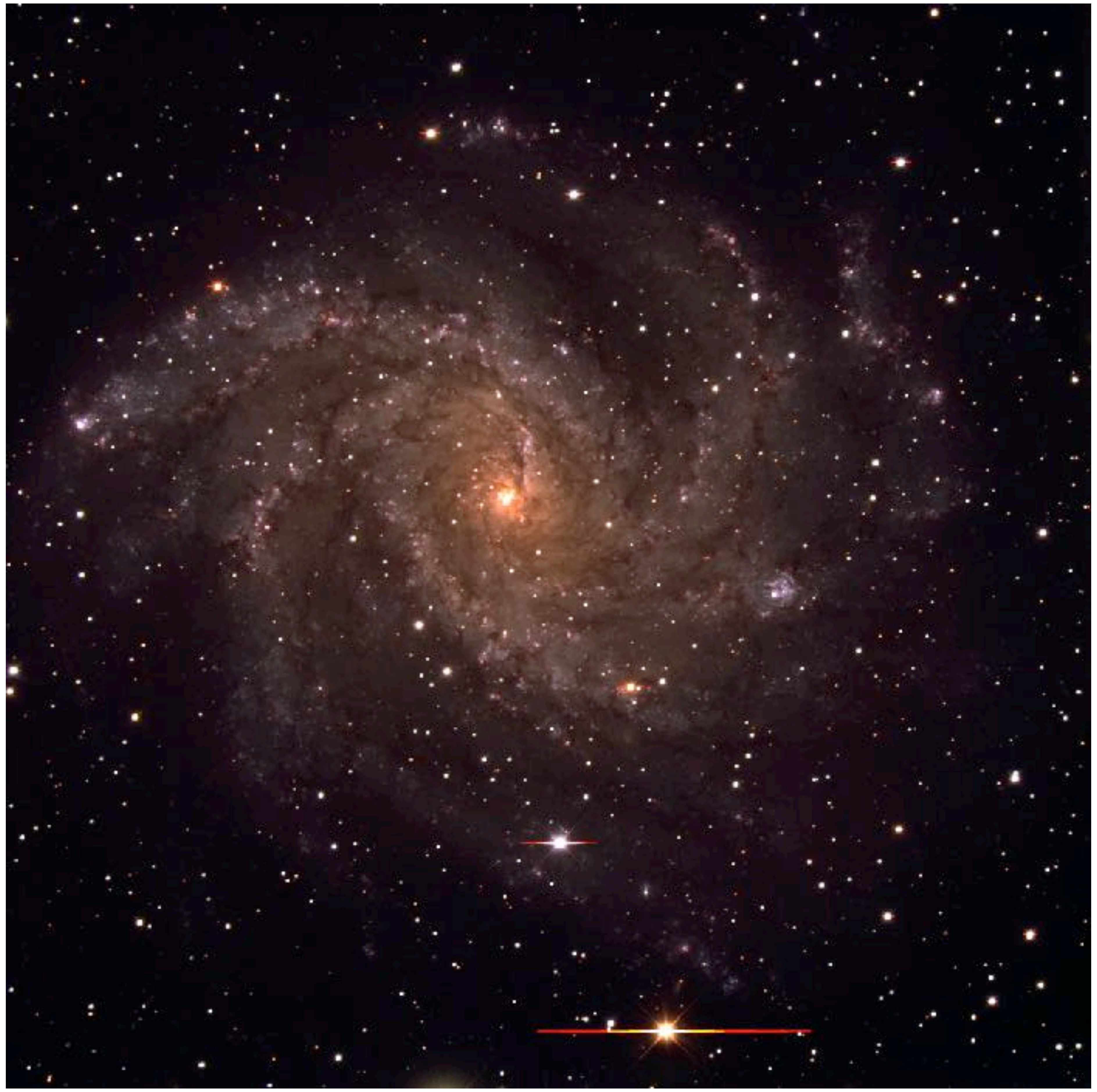


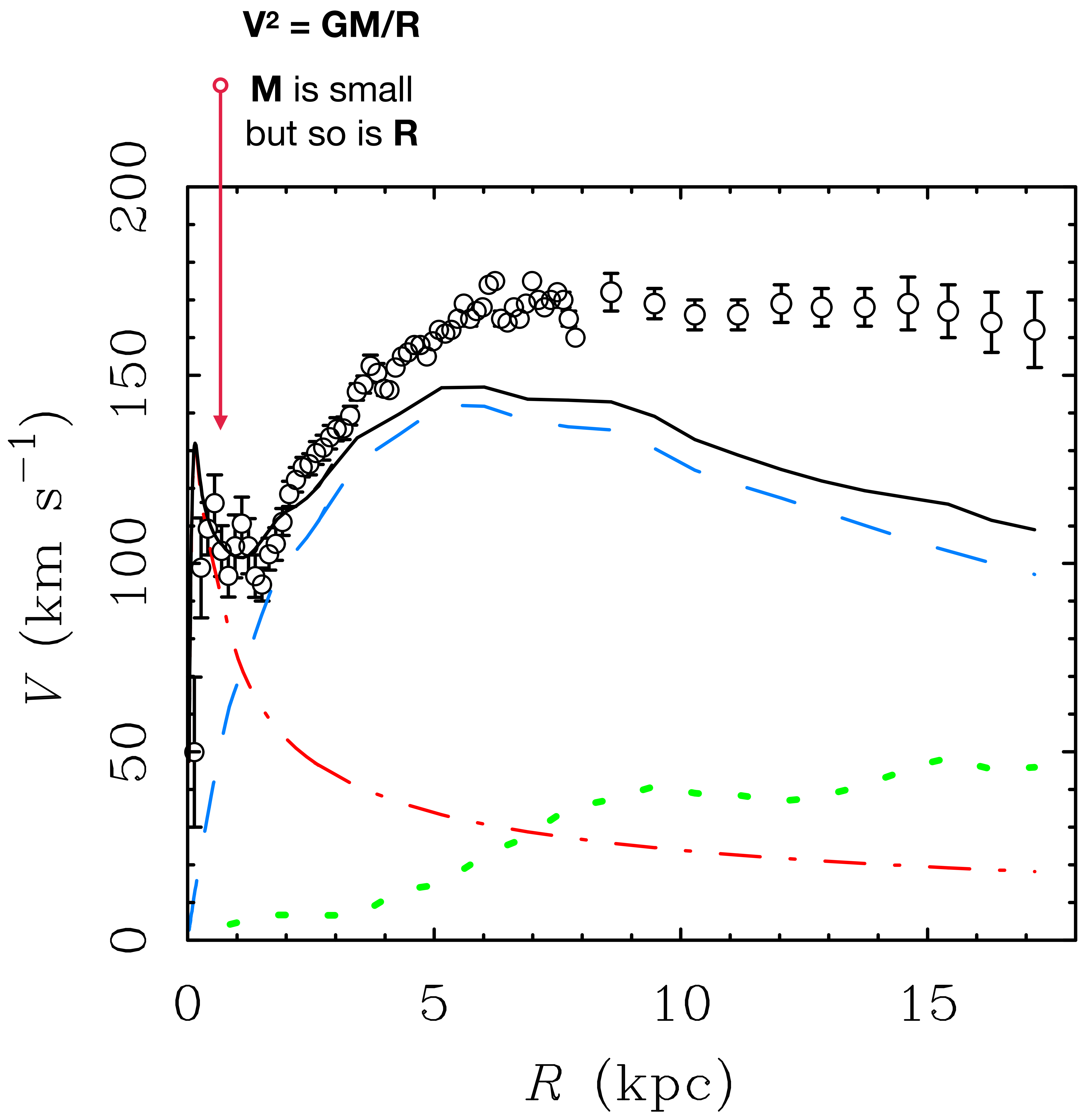
- Renzo's Rule: (2004 IAU; 1995 private communication)
"When you see a feature in the light, you see a corresponding feature in the rotation curve."



The central bulge component of NGC 6946 is only 6% of the total light, but it has a perceptible effect on the kinematics.

Note the up-down-up morphology - this requires a maximal bulge; can't explain that with a dark matter halo.





Renzo's Rule:

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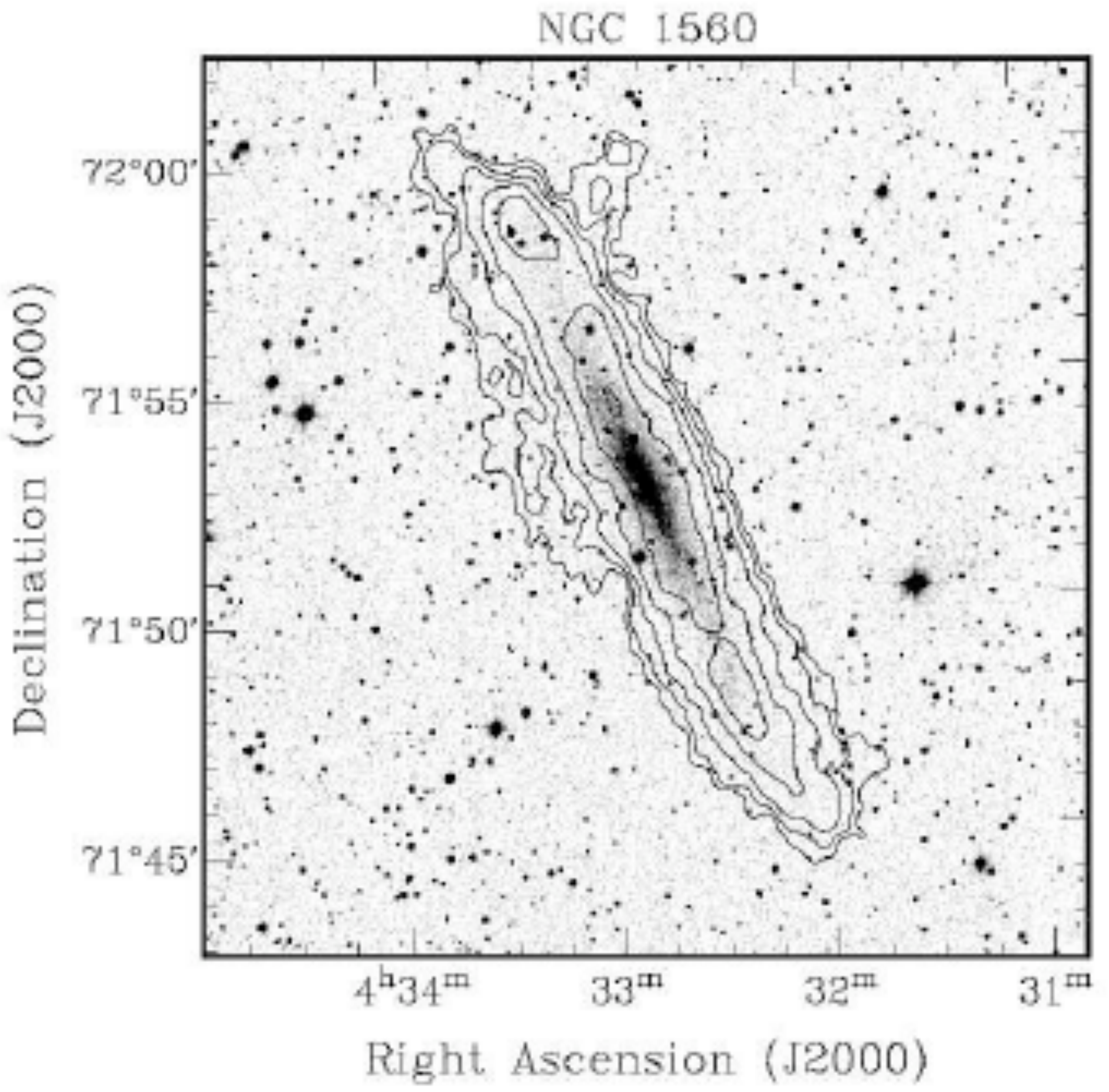
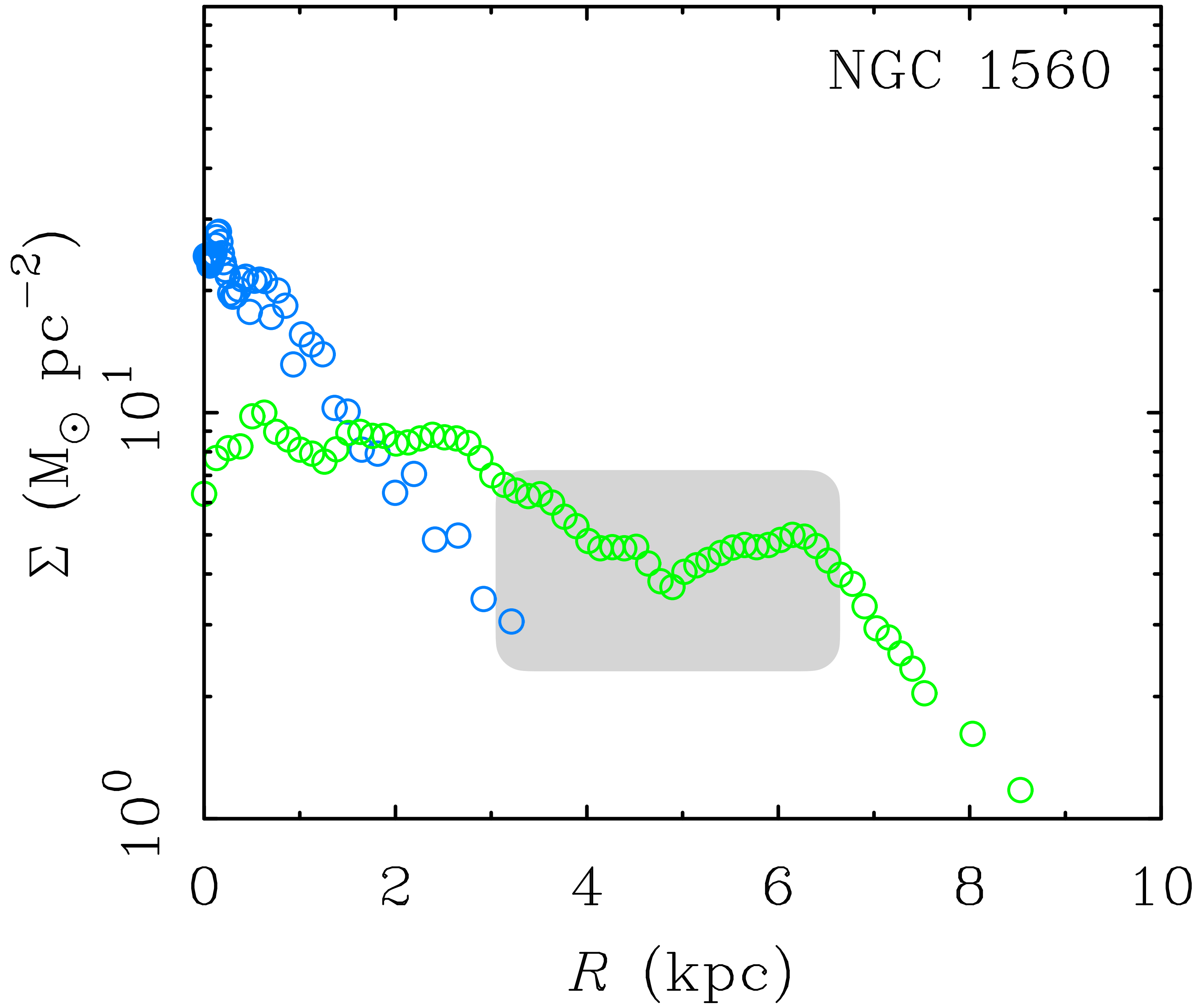
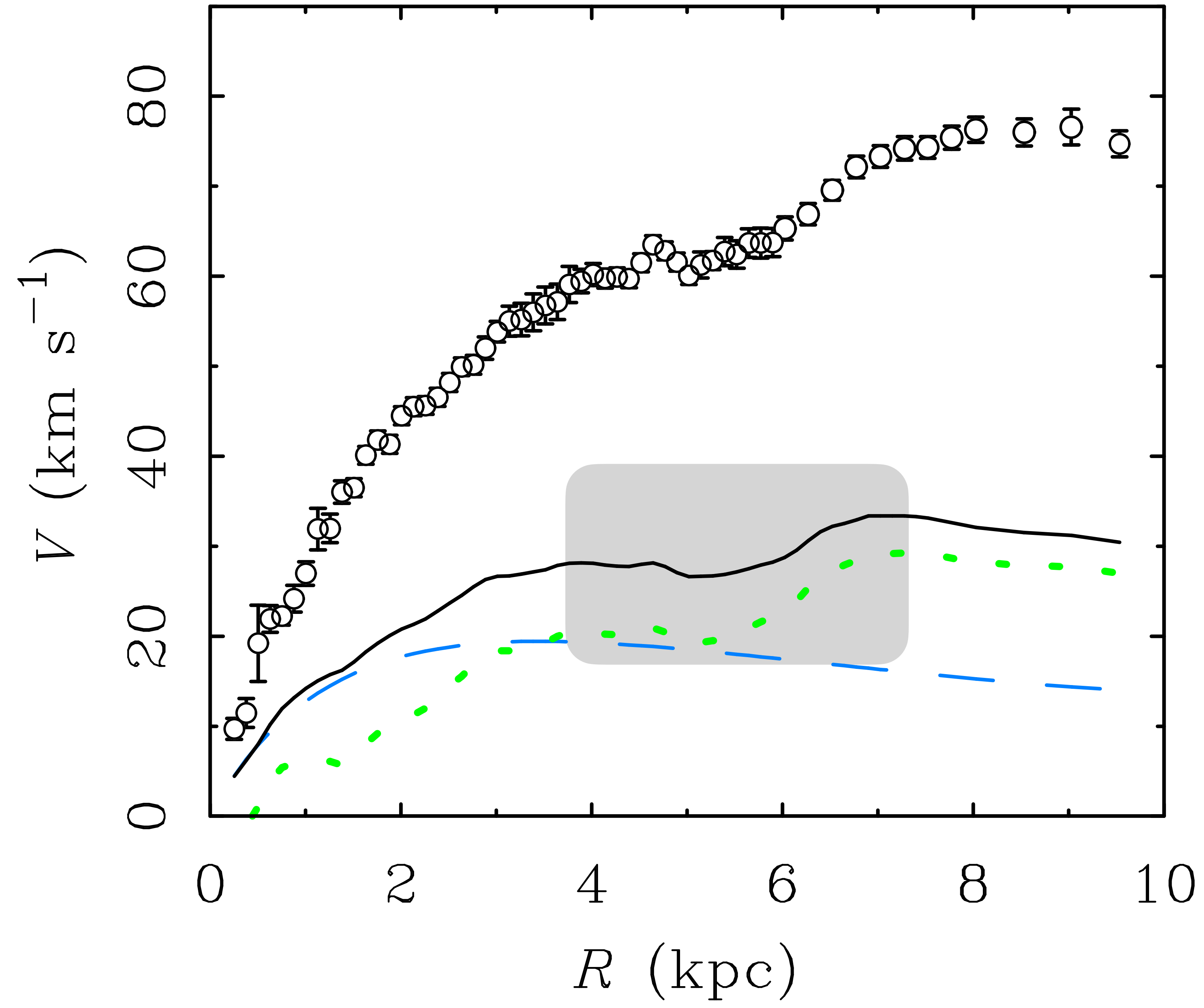


Gentile et al. (2010)





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

Mass models for baryonic components

$$V_b^2(r) = V_{bulge}^2(r) + \underbrace{V_{disk}^2(r)}_{\text{depends on } M_*/L} + V_{gas}^2(r)$$

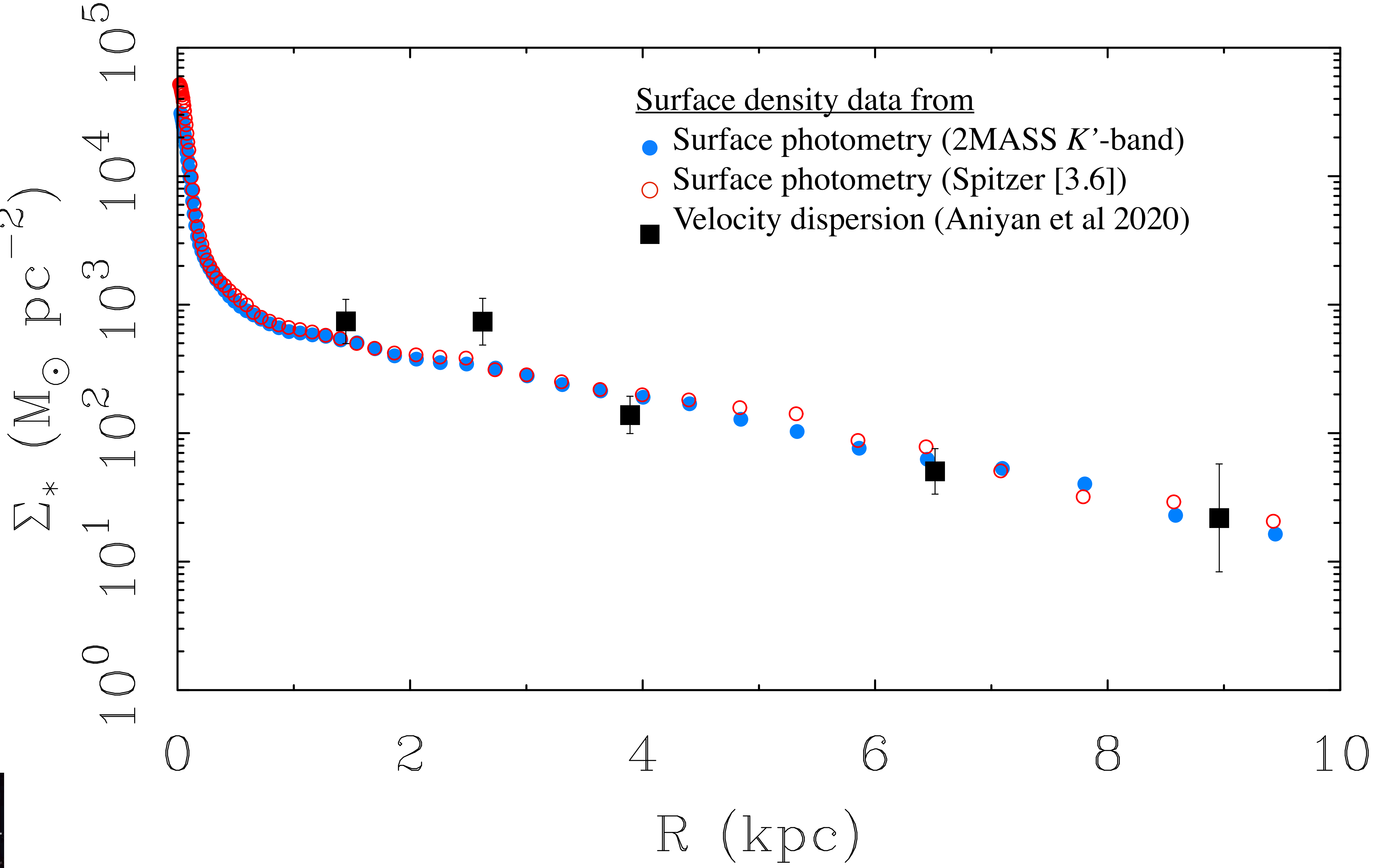
- Bulge
  - not always spherical; sometimes more bar-like
- Stellar Disk
  - exponential a crude approximation
  - in practice, solve numerically for the observed surface brightness profile with DISKFIT or ROTMOD (in GIPSY)
- Gas disk
  - usually just HI; CO tracks stars

$$g_{\rm bar} = \frac{V_b^2}{R}$$

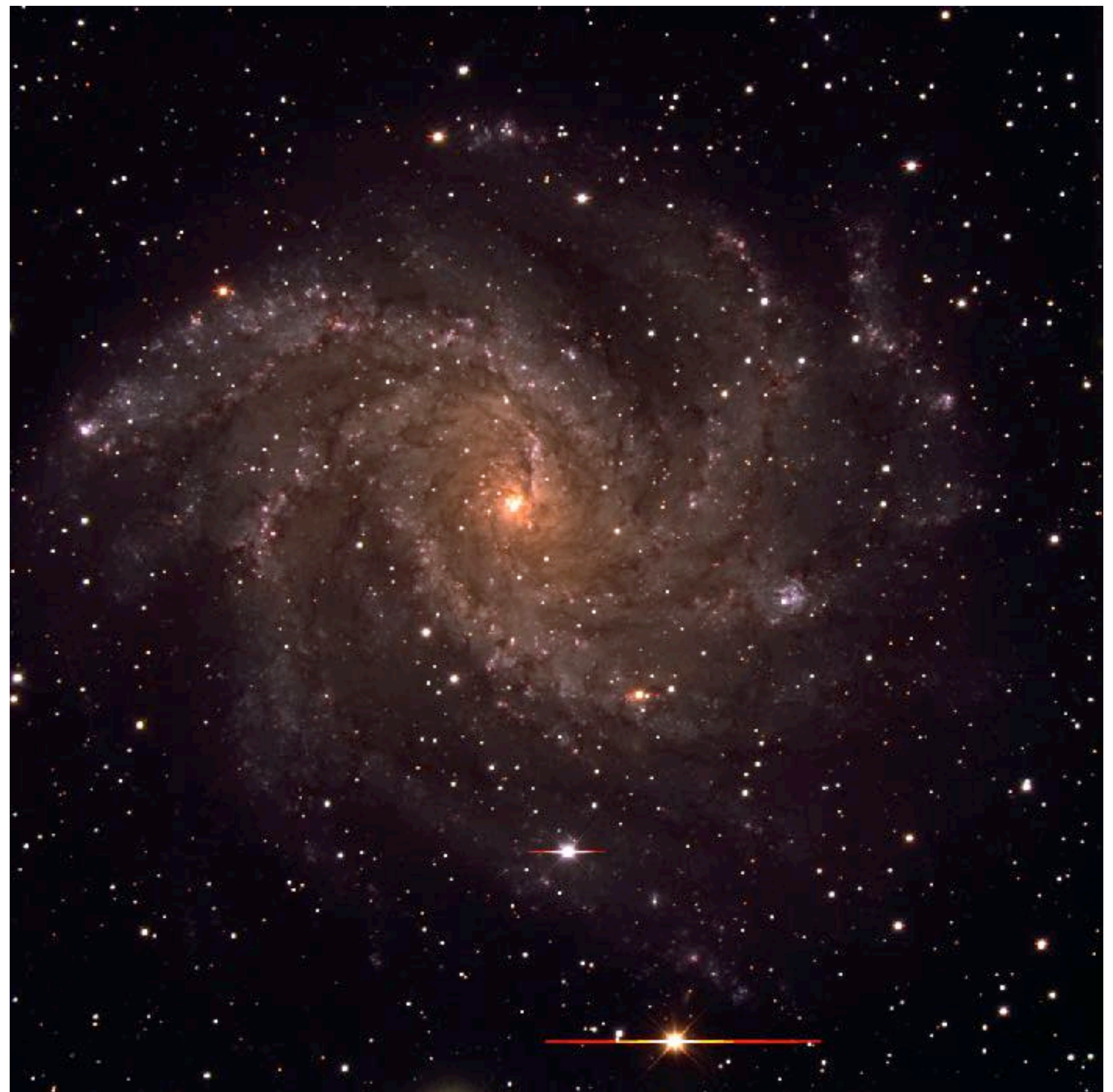
Now have

Surface density for
  stars
  gas
and corresponding rotation curves for each component

Observed rotation curve

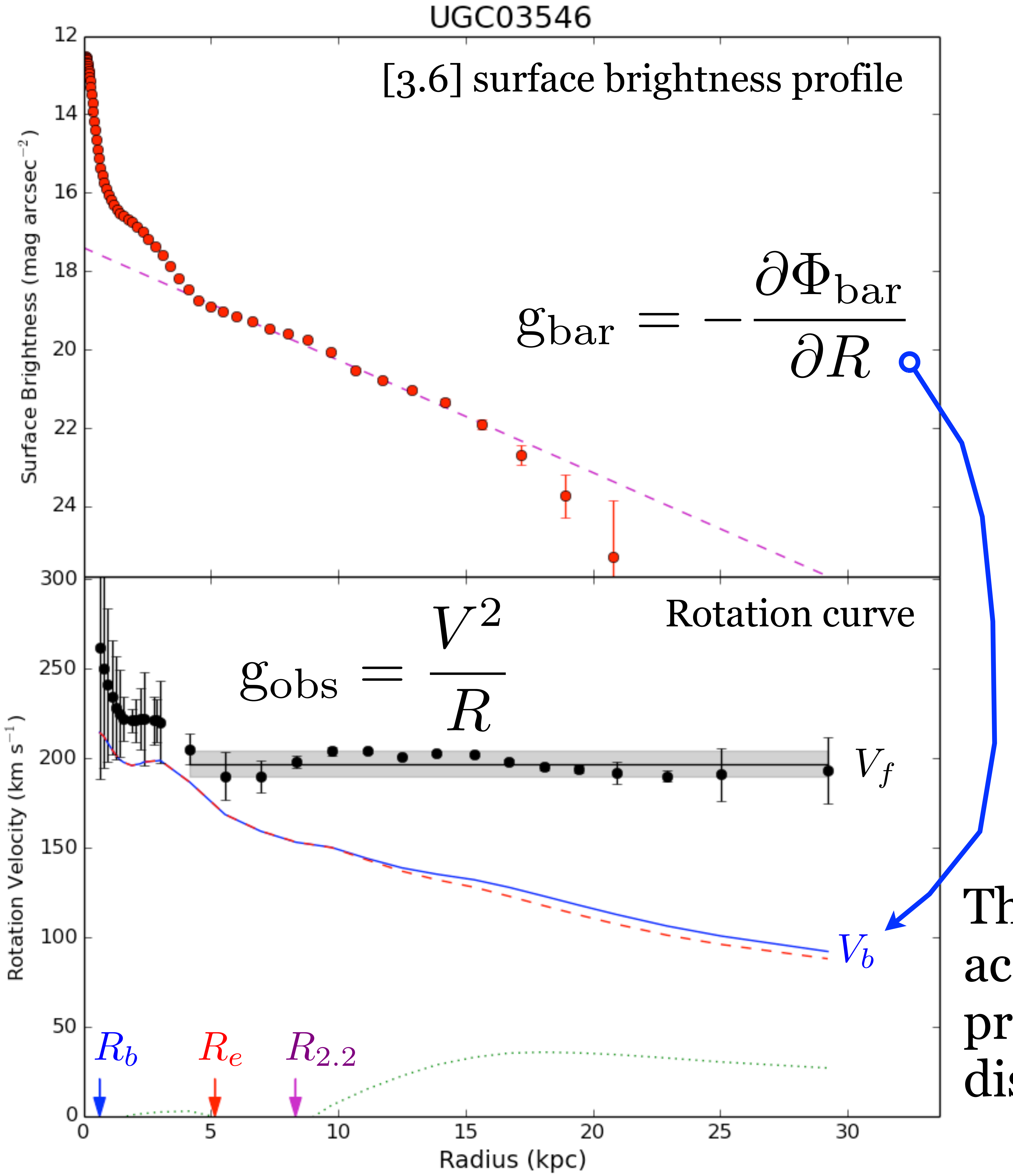


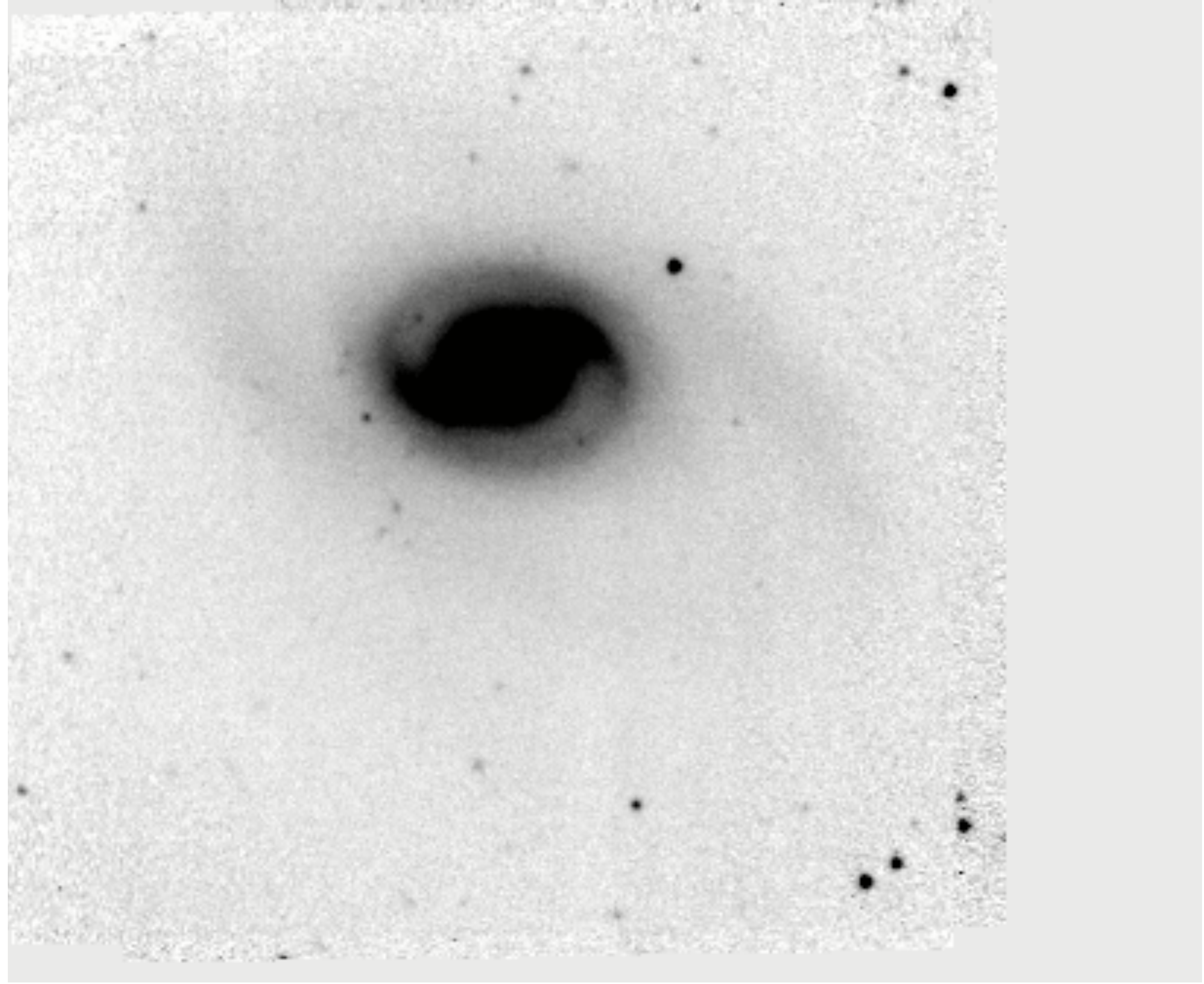
NGC 6946



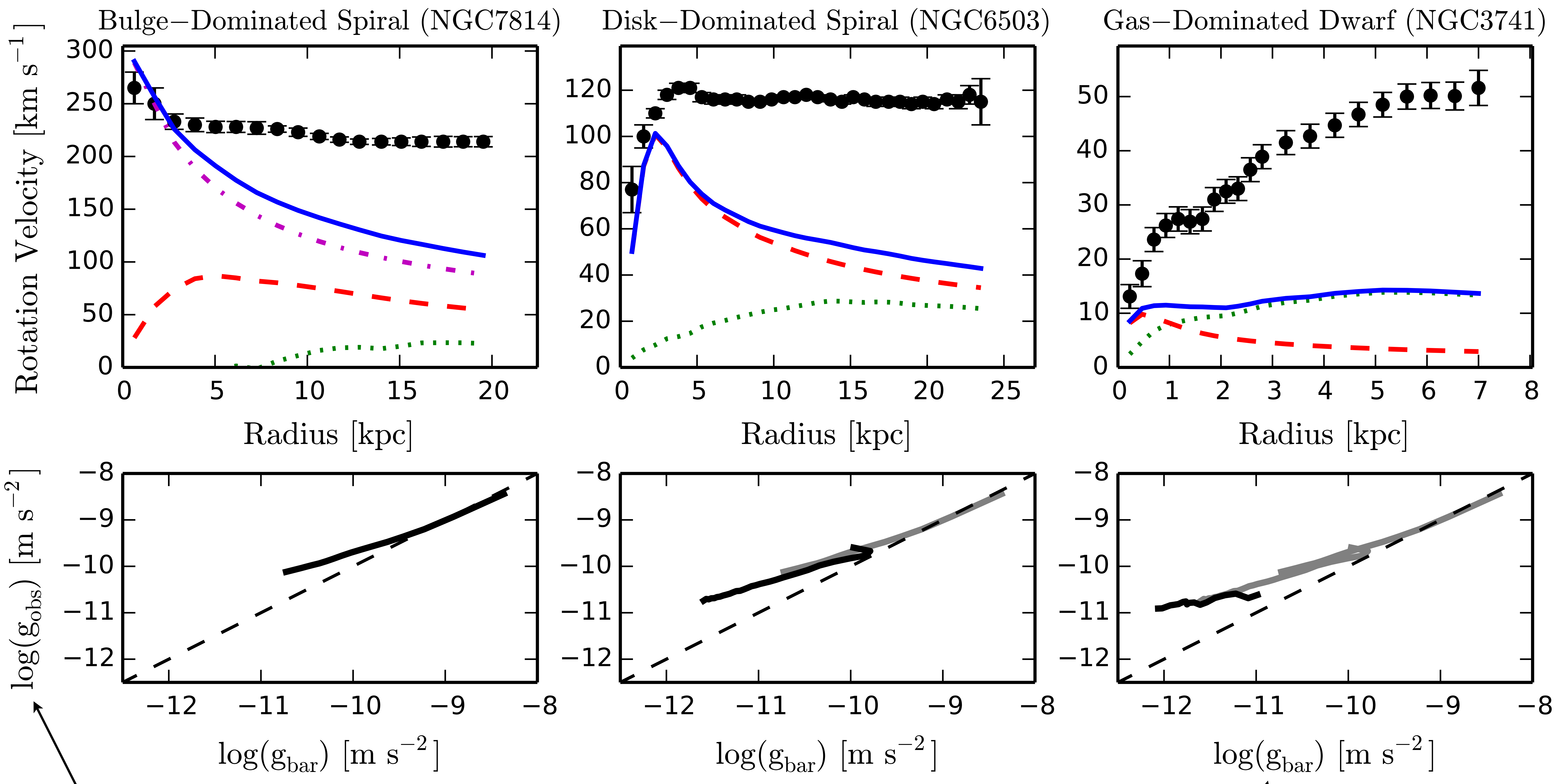
$$\sigma_z^2 \approx 2\pi G \Sigma h_z$$

What about everything in between?





The observed centripetal acceleration is linked to that predicted by the observed distribution of baryons.



$$g_{\rm obs} = \frac{V^2}{R}$$

independent quantities

$$g_{\rm bar} = -\frac{\partial \Phi_{\rm bar}}{\partial R}$$

determined from rotation curve

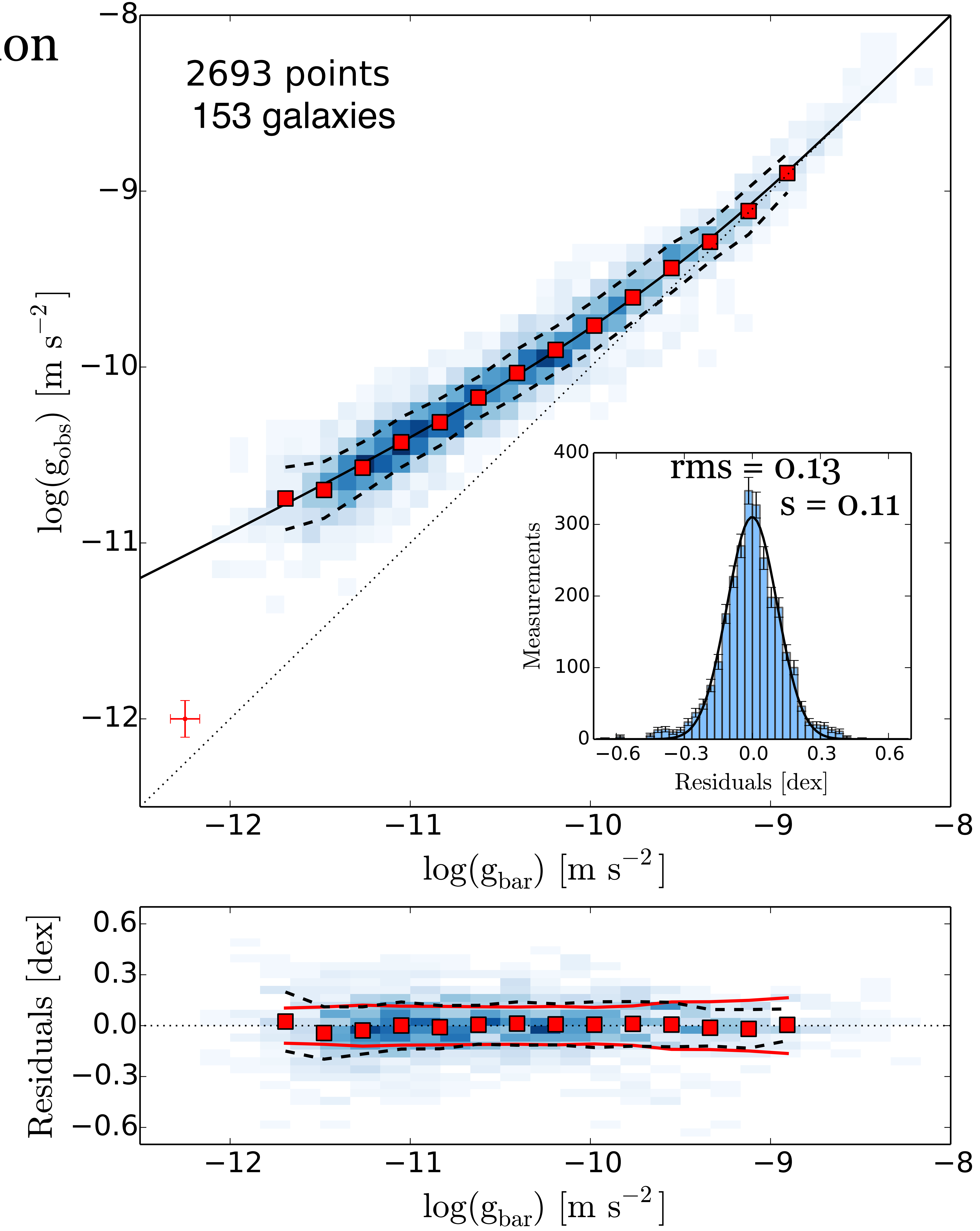
determined from baryon distribution

Radial Acceleration Relation

(RAR)

Constructed from 153 galaxies with 21cm rotation curves and near-IR surface photometry from the *Spitzer* space telescope.

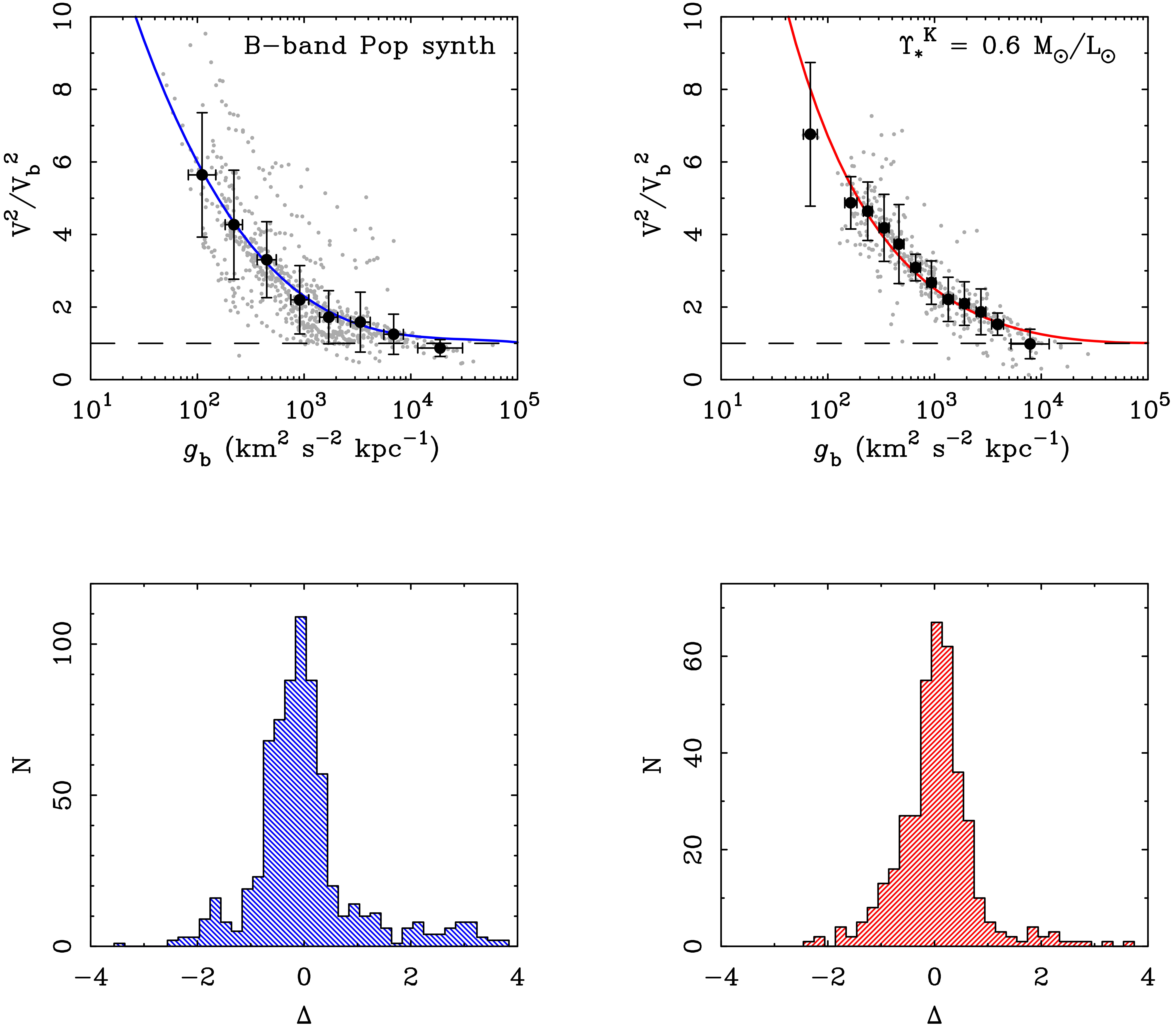
Apparently the mass-to-light ratio in the near-IR is close to constant: individual galaxies do not stand out in this relation.



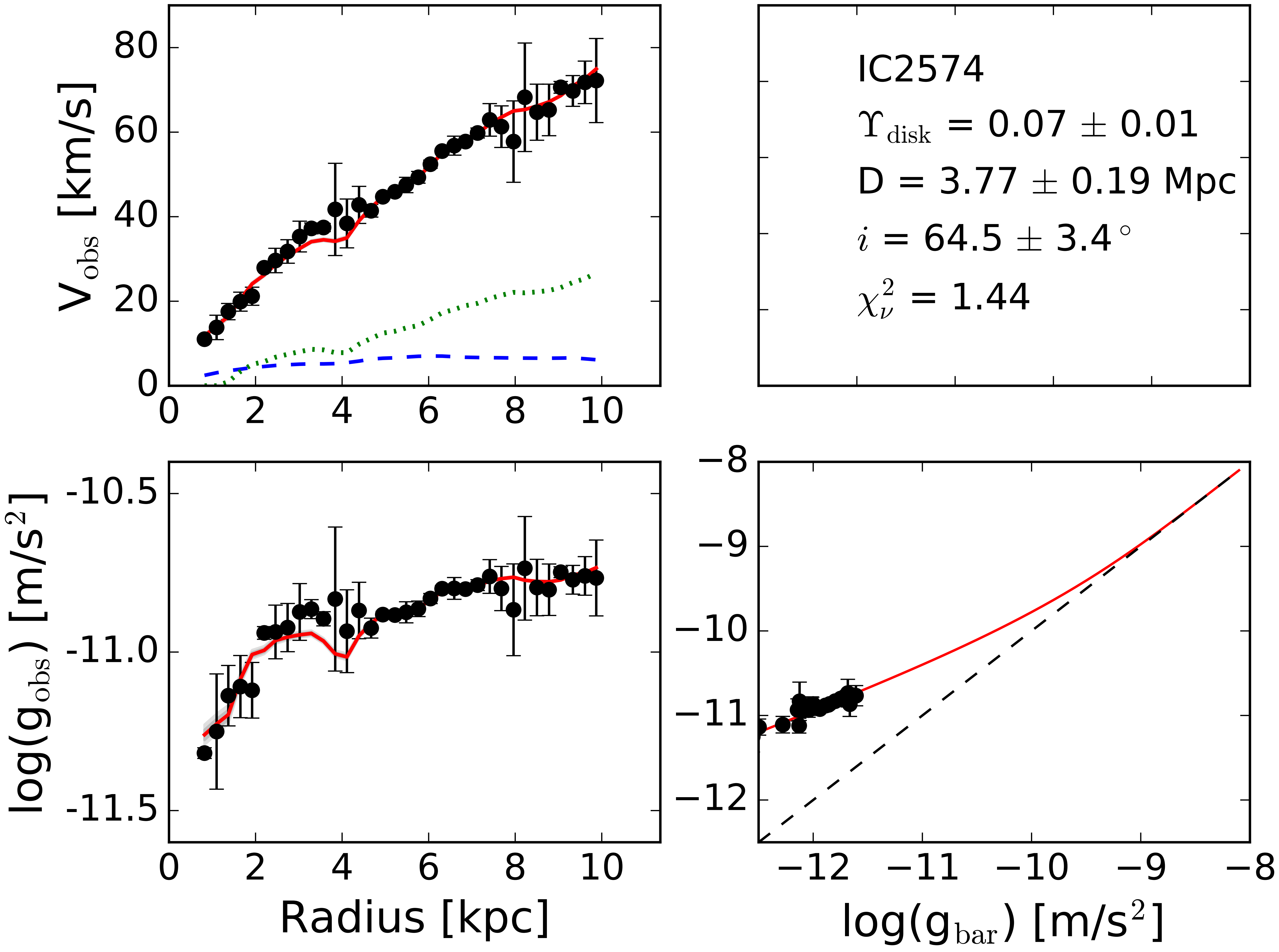
MDAR

$$\mathcal{D} = \frac{\mathrm{g_{obs}}}{\mathrm{g_{bar}}} = \frac{V^2}{V_b^2}$$

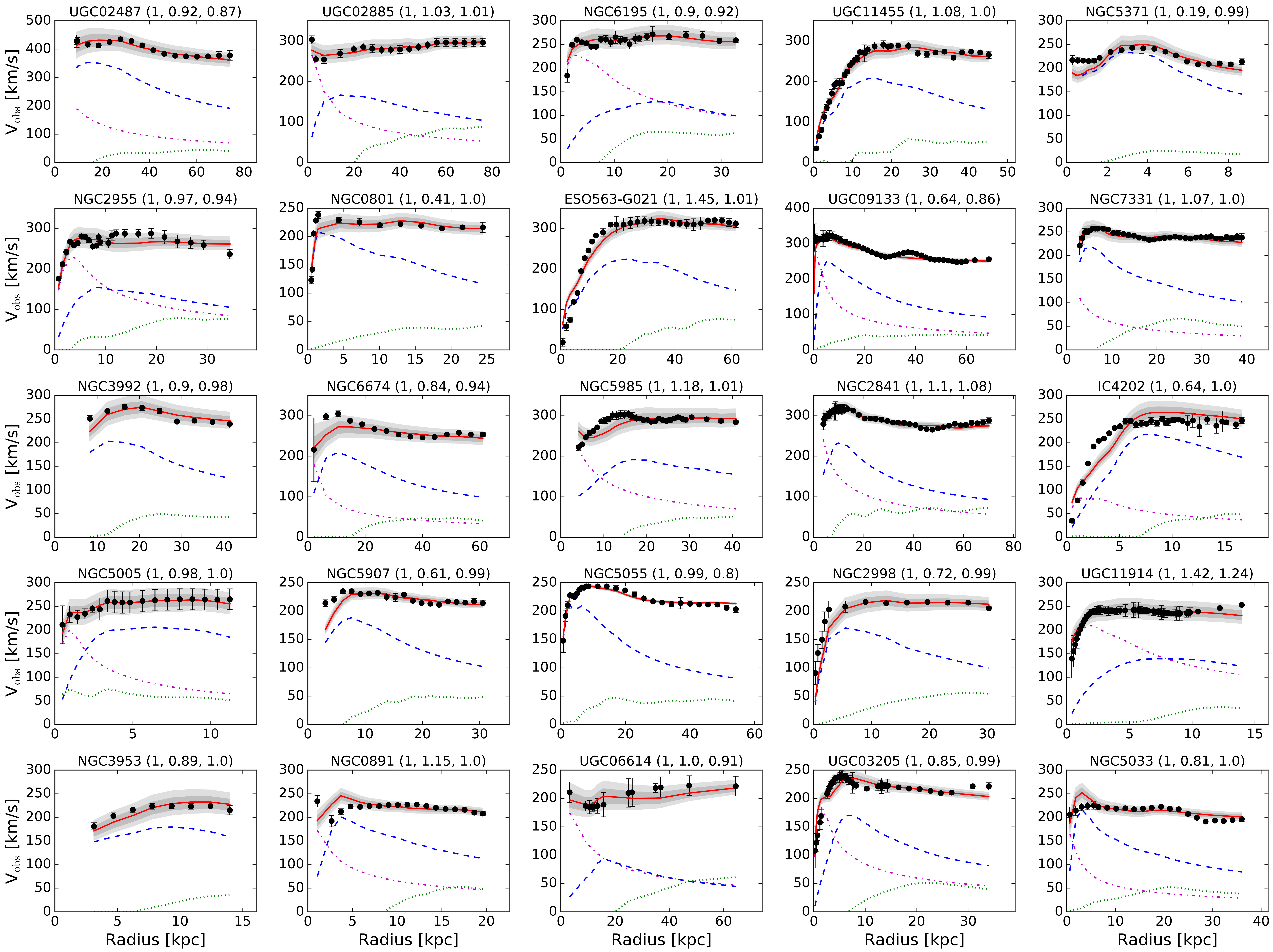
The Radial Acceleration Relation is equivalent to the Mass Discrepancy-acceleration relation, just with independent x & y axes.



That just assumed constant M*/L. We can fit to the mean RAR, marginalizing over distance and inclination as nuisance parameters (Li et al. 2018)

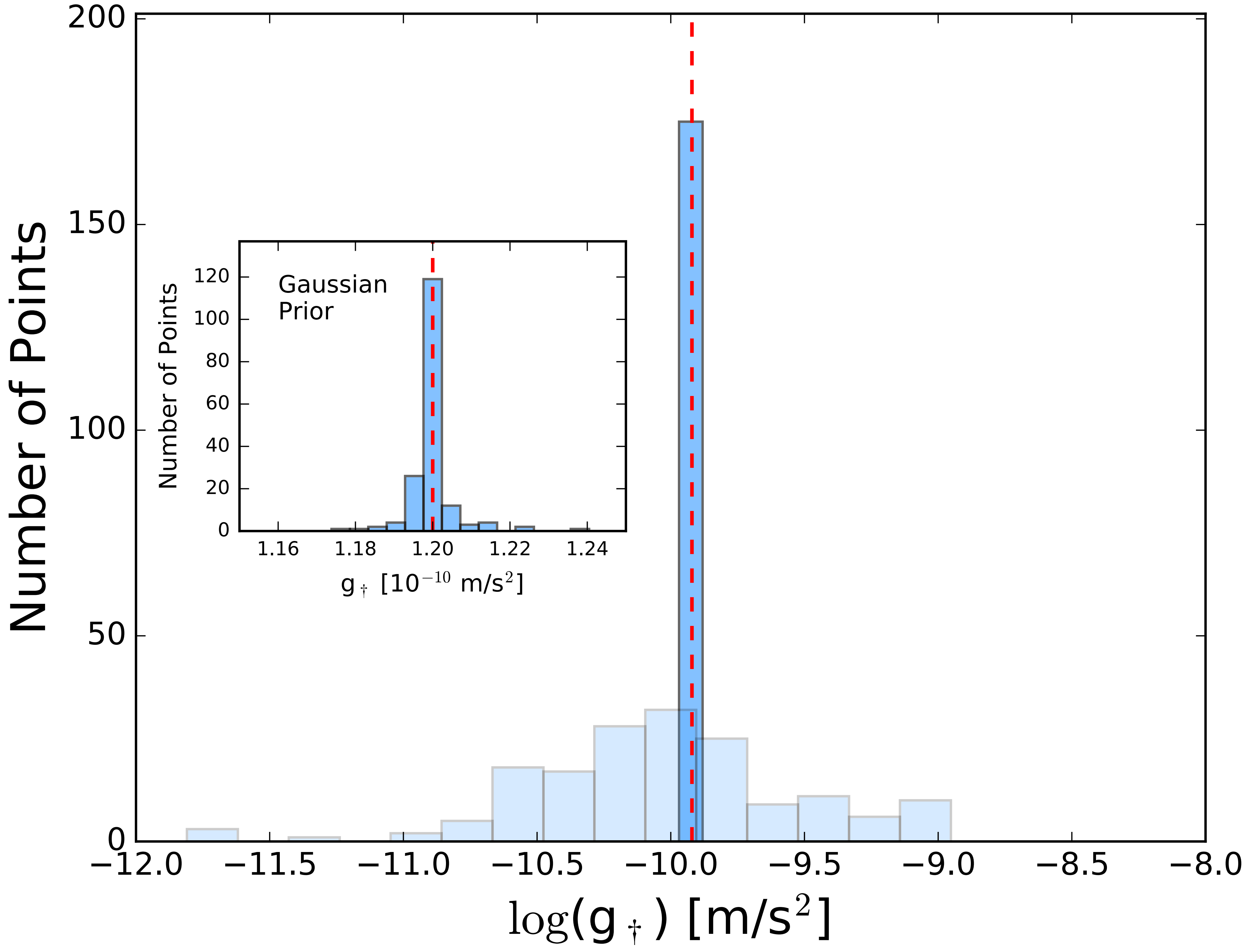


Li et al. 2018, A&A, 615, A3 (arXiv:1803.00022)

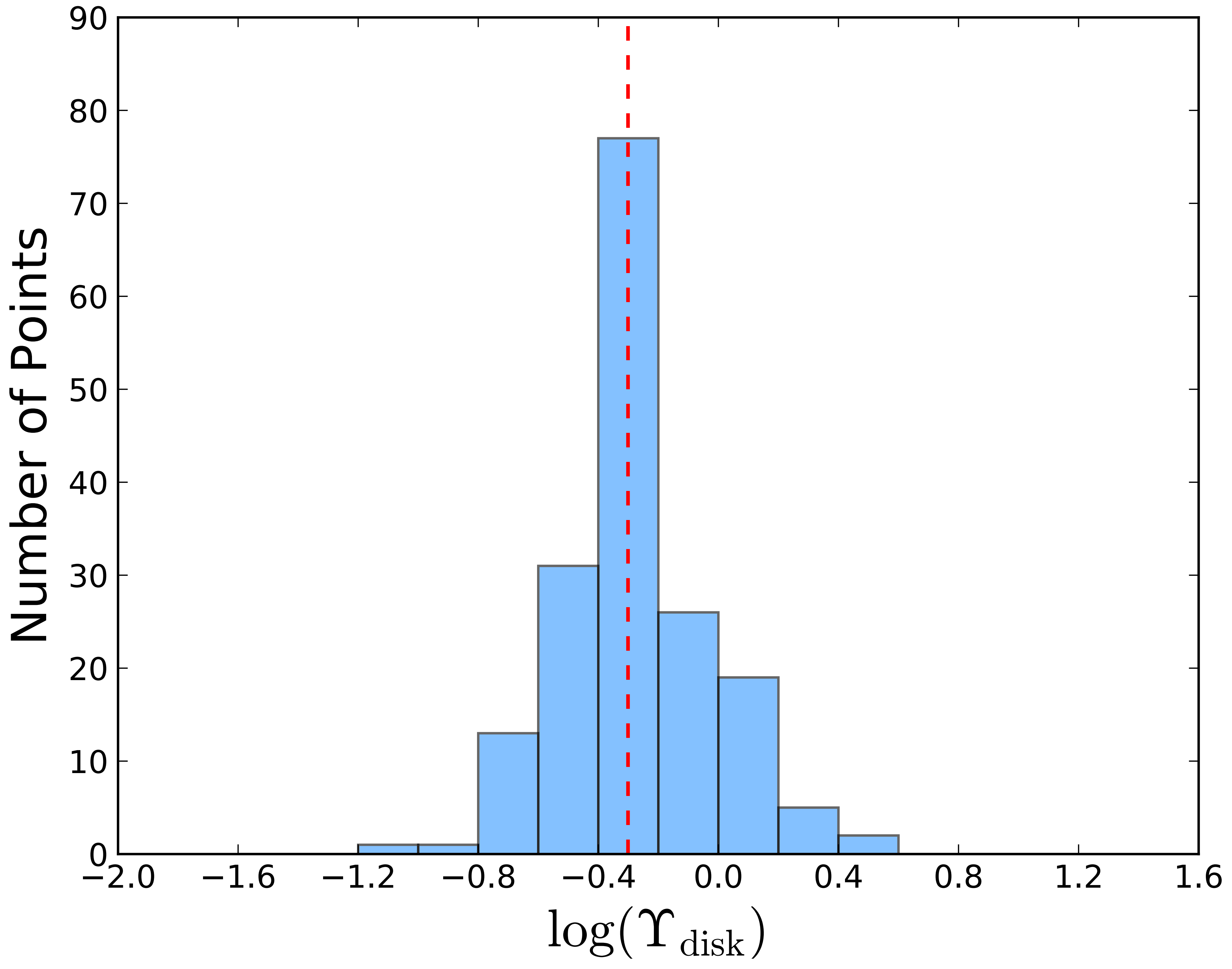

UGC02487 (1, 0.92, 0.87)
UGC02885 (1, 1.03, 1.01)
NGC6195 (1, 0.9, 0.92)
UGC11455 (1, 1.08, 1.0)
NGC5371 (1, 0.19, 0.99)
NGC2955 (1, 0.97, 0.94)
NGC0801 (1, 0.41, 1.0)
ESO563-G021 (1, 1.45, 1.01)
UGC09133 (1, 0.64, 0.86)
NGC7331 (1, 1.07, 1.0)
NGC3992 (1, 0.9, 0.98)
NGC6674 (1, 0.84, 0.94)
NGC5985 (1, 1.18, 1.01)
NGC2841 (1, 1.1, 1.08)
IC4202 (1, 0.64, 1.0)
NGC5005 (1, 0.98, 1.0)
NGC5907 (1, 0.61, 0.99)
NGC5055 (1, 0.99, 0.8)
NGC2998 (1, 0.72, 0.99)
UGC11914 (1, 1.42, 1.24)
NGC3953 (1, 0.89, 1.0)
NGC0891 (1, 1.15, 1.0)
UGC06614 (1, 1.0, 0.91)
UGC03205 (1, 0.85, 0.99)
NGC5033 (1, 0.81, 1.0)
V_{obs} [km/s]
Radius [kpc]

SPARC

No need to vary g+, which covaries with M*/L
The data constrain one or the other; not both
(Li et al. 2018)



The distribution of fitted M*/
L is reasonable



All the systematic properties involve a critical acceleration scale.

- Baryonic Tully-Fisher Relation

$$g_\dagger^{\rm BTFR} = 1.24 \pm 0.14 \times 10^{-10}\ {\rm m\,s^{-2}}$$

(McGaugh 2011)

- Central Density Relation

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

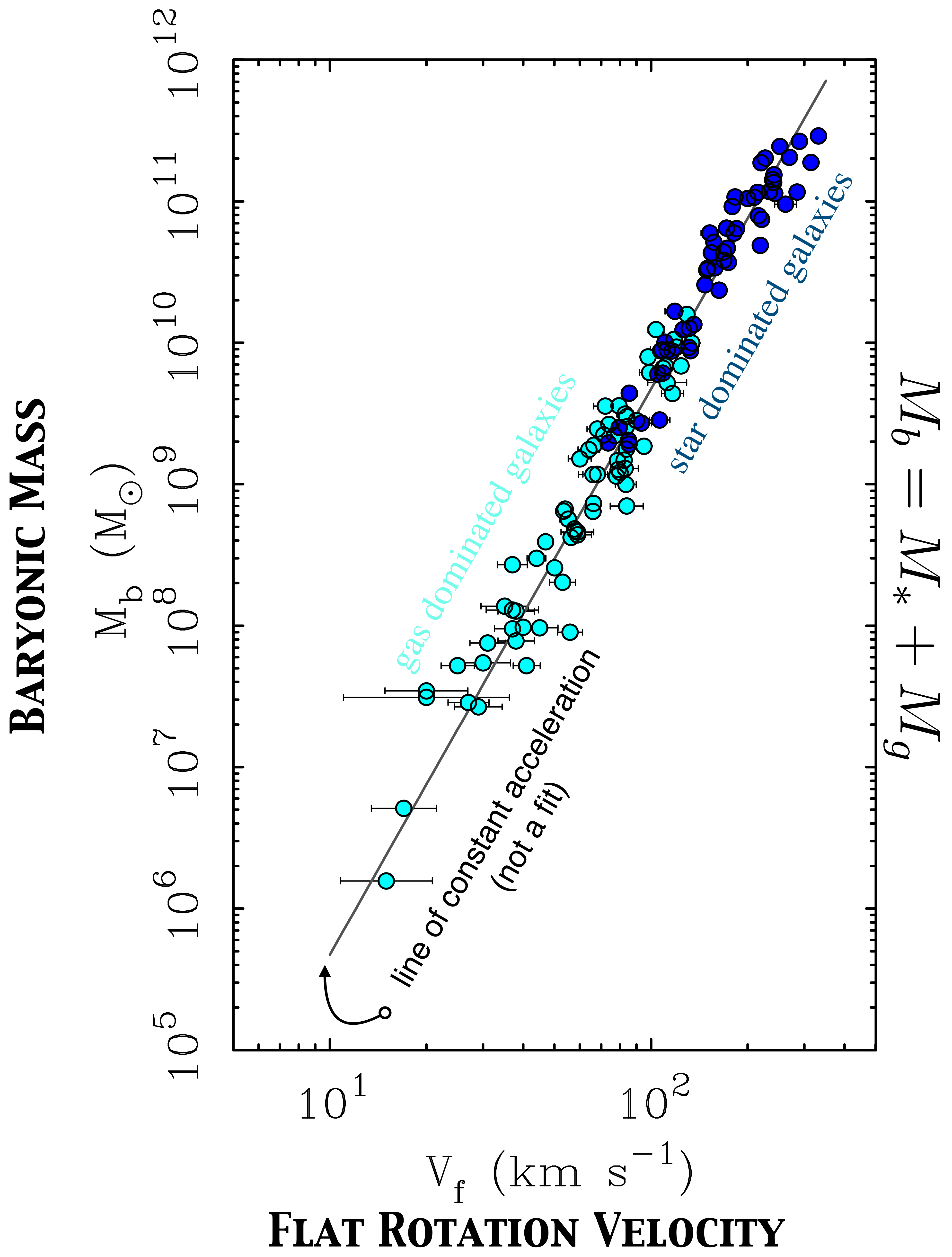
(Lelli et al. 2016)

- Radial Acceleration Relation

$$g_\dagger^{\rm RAR} = 1.20 \pm 0.02 \times 10^{-10}\ {\rm m\,s^{-2}}$$

(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).

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

$g_\dagger$ is a special value