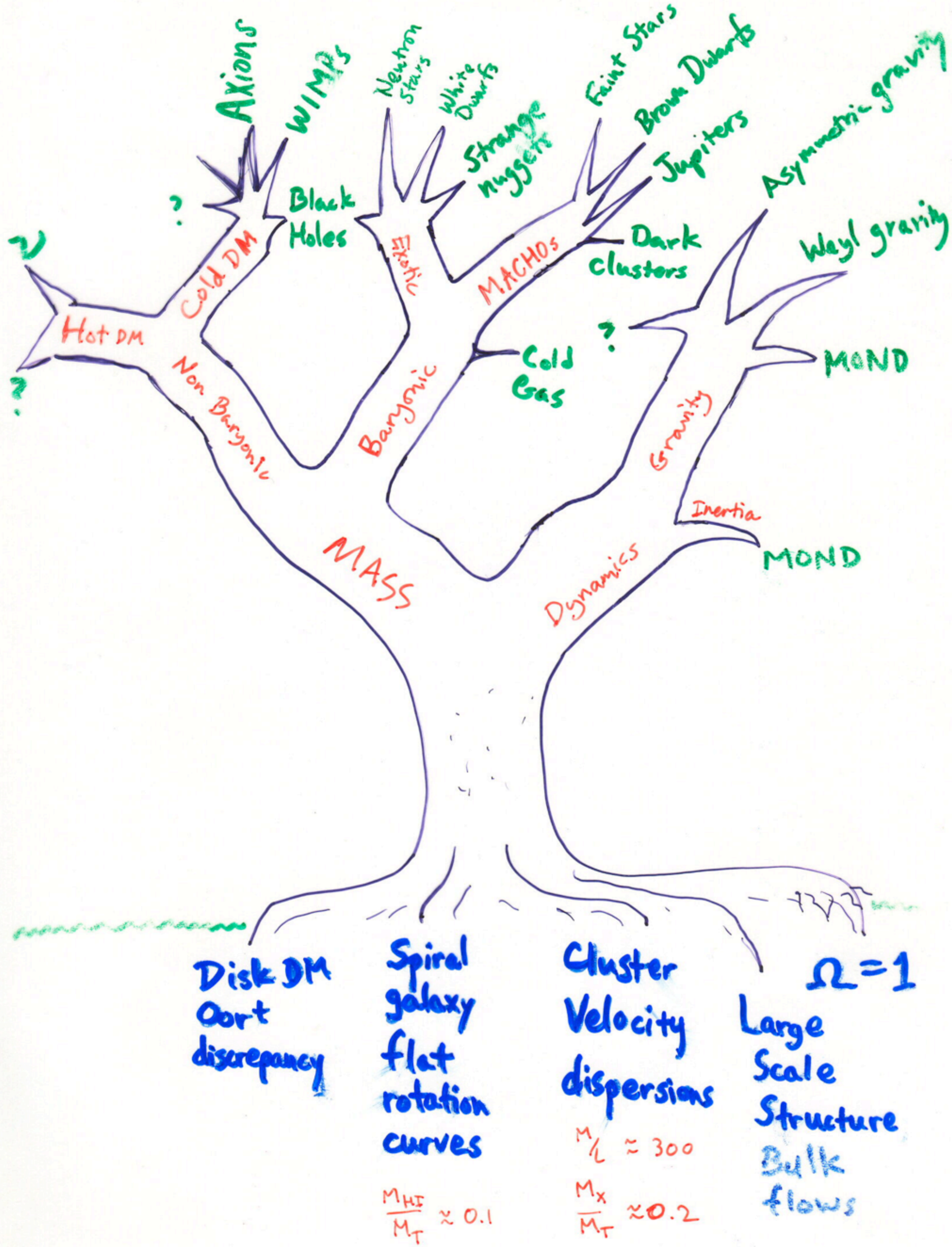
DARK MATTER

ASTR 333/433

TODAY

LAWS OF GALACTIC ROTATION

Homework 1
Due Now



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: $V(R \to \infty) \to V_f$

- 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: $\Sigma_{dyn}(R \to 0) = f[\Sigma_*(R \to 0)]$

- 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: $\mathrm{g_{obs}} = \mathcal{F}(\mathrm{g_{bar}})$

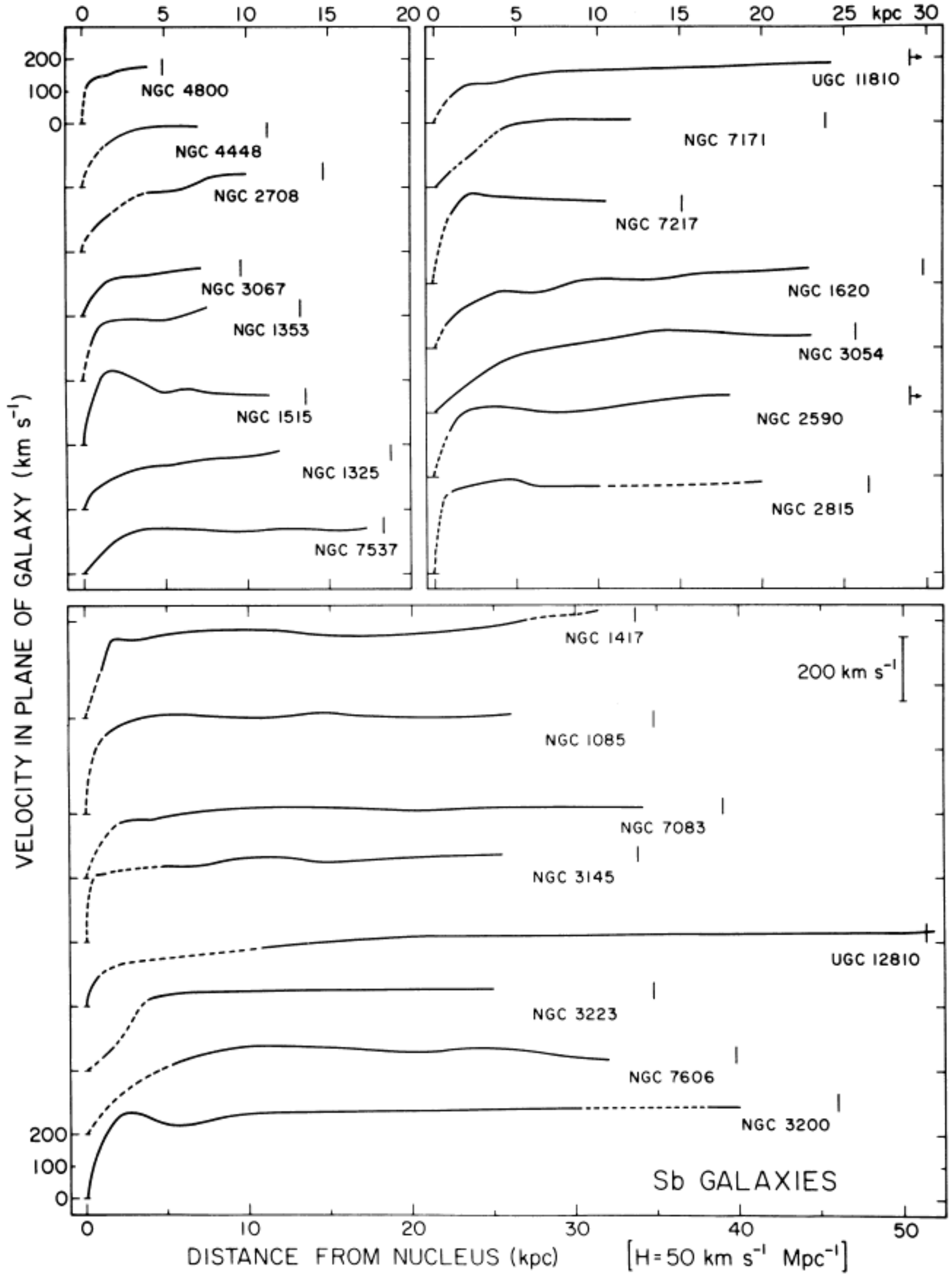


FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to increasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25}, the isophote of 25 mag arcsec^{-2}, corrected for effects of internal extinction and inclination. Regions with no measured velocities are indicated by dashed lines.

Rotation curves tend to become flat at large radii

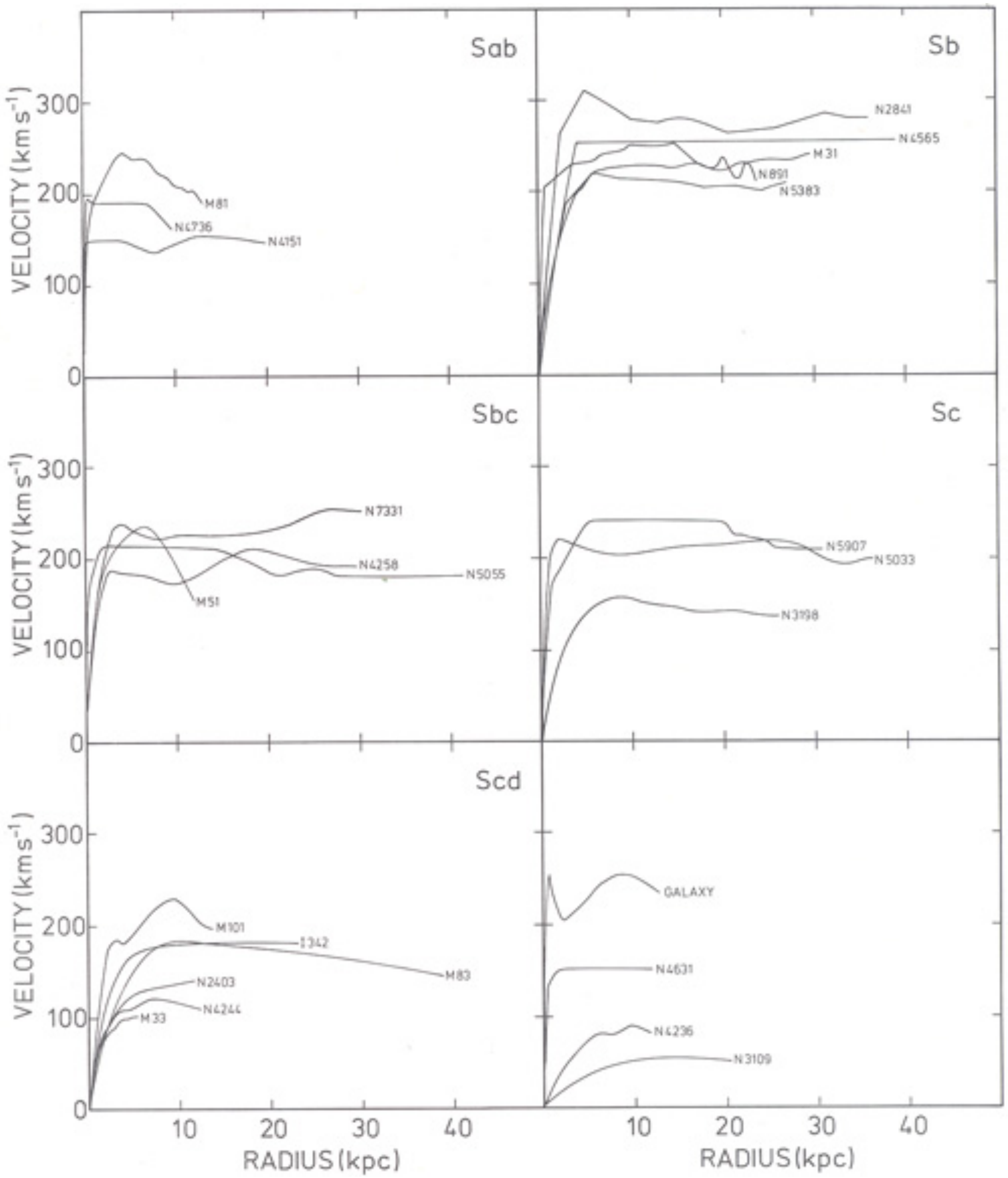
$$V \propto \text{const}$$

$$M \propto R$$

$$\rho \propto R^{-2}$$

Optical data from
Rubin, Thonnard, & Ford 1978, *ApJ*, **225**, L107

Radio data from
Bosma 1981, *AJ*, **86**, 1825



...and stay pretty flat to the largest radii probed

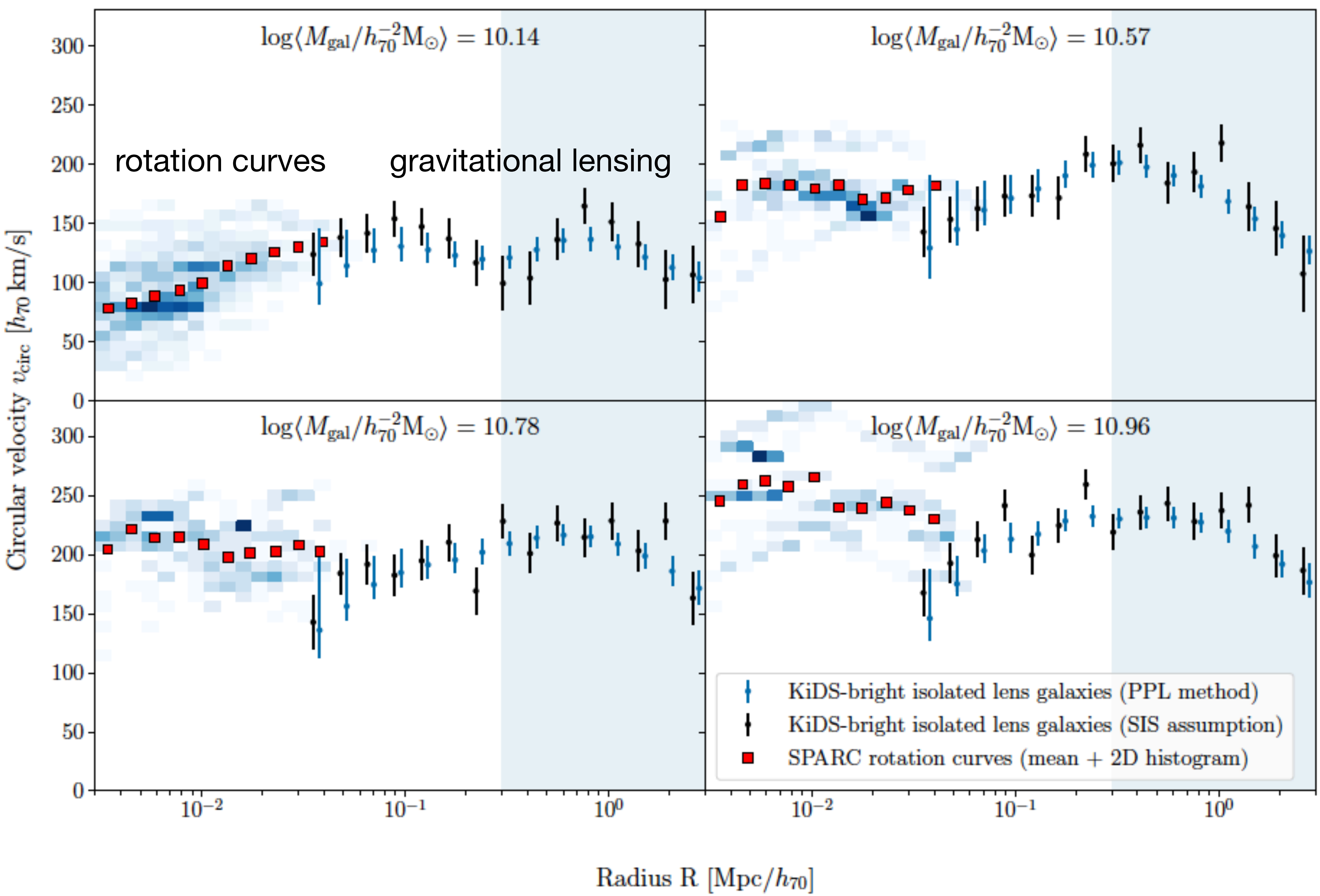
Historically, 21cm data were an important independent validation that flat rotation curves persisted to much larger radii than could be explained by the observed luminous mass.

See IAU Symposium 100 pp. 87-88
(Kalnajs on mass models)

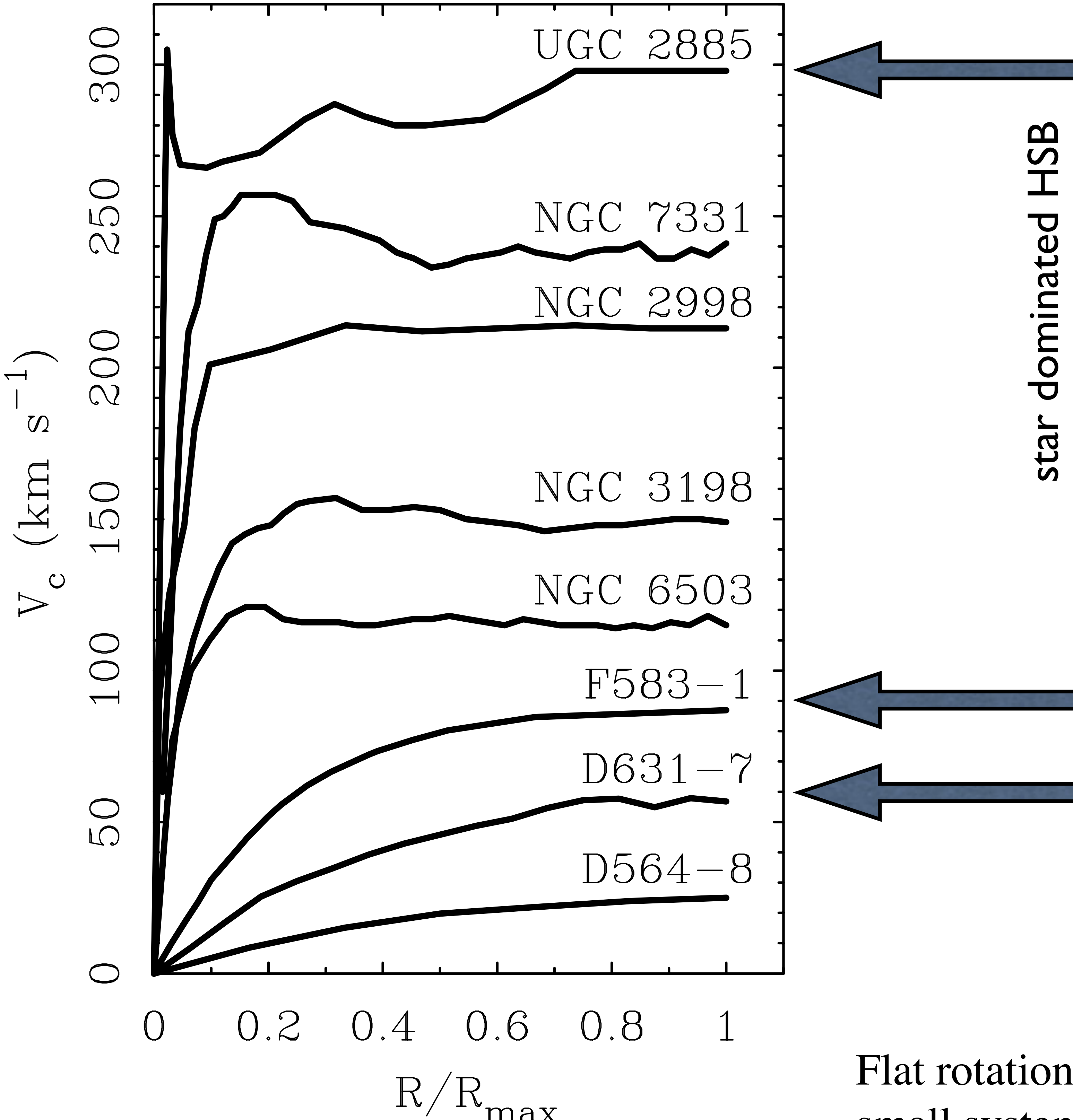
Gravitational Lensing data

…even to Mpc scales!?

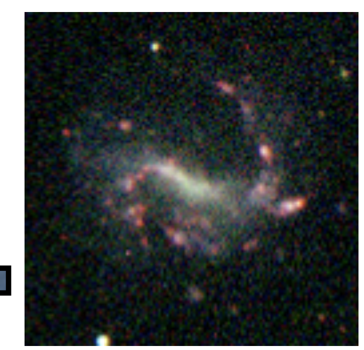
M. M. Brouwer et al.: The lensing RAR: testing MG and CDM with KiDS-1000



Tully-Fisher: Rotation curve amplitude correlates with observed mass:



star dominated HSB



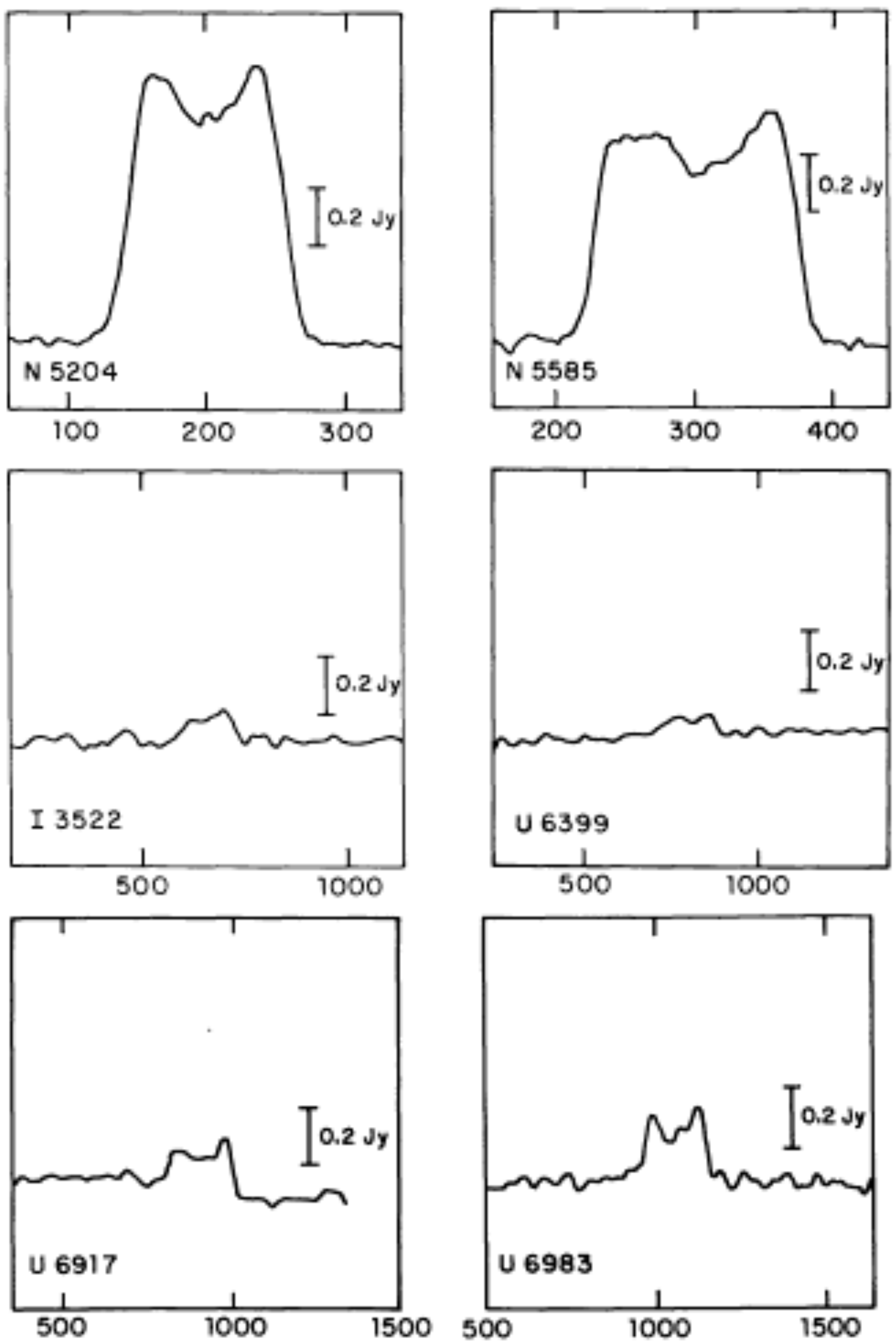
gas dominated LSBs

Flat rotation curves continue to occur in quite small systems (e.g., Leo P with V_f ~ 15 km/s)

Tully & Fisher (1977)

Great for distance scale work.

But why does it happen?



R. B. Tully and J. R. Fisher: Distances to Galaxies

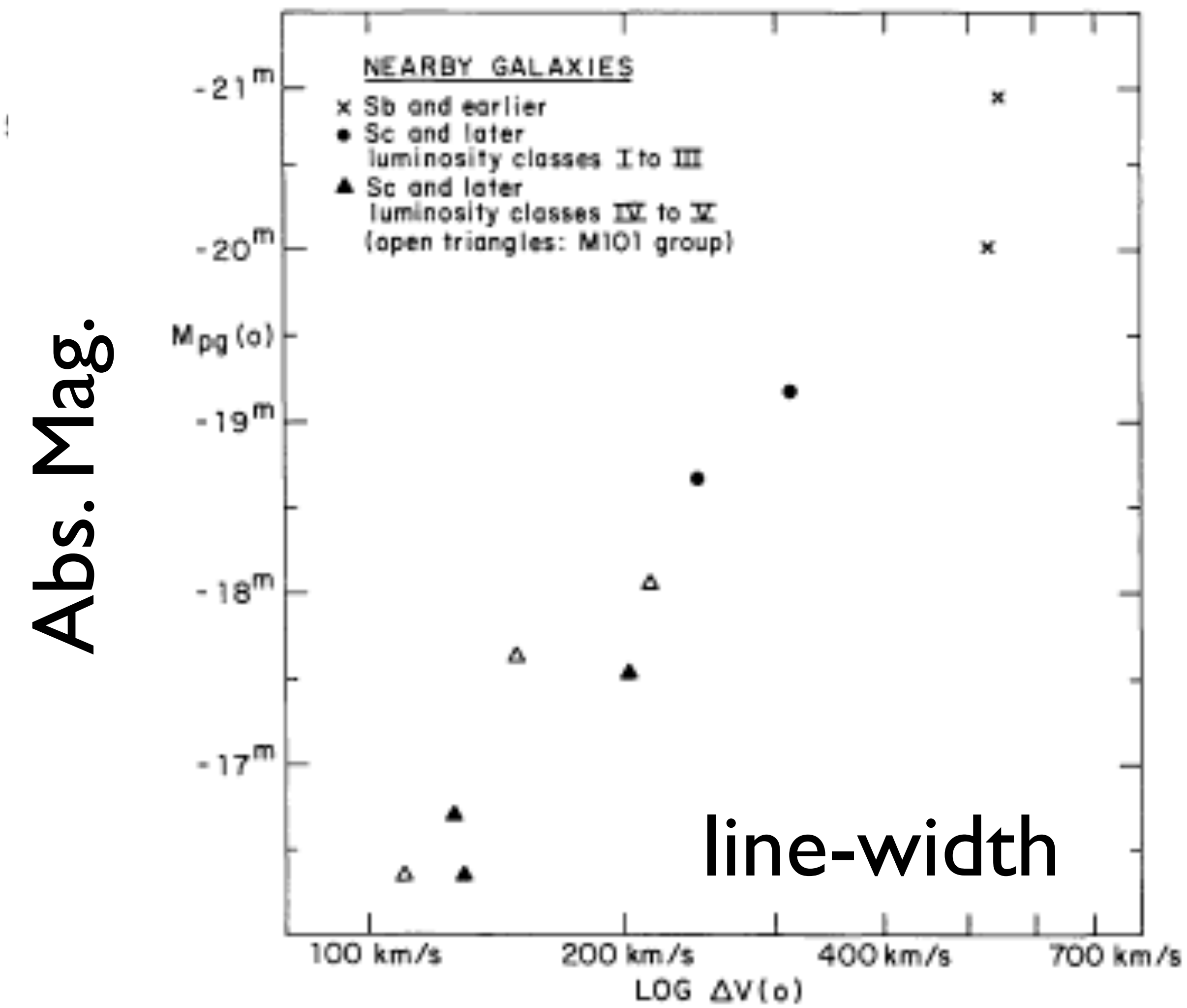


Fig. 1. Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

others from ST I and ST III]; (4) photographic magnitudes (Holmberg, 1958); (5) magnitude corrections due to galactic extinction according to the precepts in ST I [based on Sandage (1973), except that the source for M31 and M33 is McClure and Racine (1969), and for NGC 2403 is Tammann and Sandage (1968)]; (6) magnitude corrections due to galactic absorption as a function of inclination according to the precepts used by Sandage and Tammann (1974d, hereafter ST IV)

Observables

- Luminosity (must calibrate with known D)
  - Band pass (*BVRIJHK*) [slope varies with band]
  - Mass - stars, gas, stars+gas
- Rotation Velocity
  - line-widths; rotation curves
    - $W_{20}, W_{50}; V_{flat}, V_{2.2}, V_{max}$
  - inclination corrections $1/\sin(i)$
  - turbulence/non-circular motions

Luminosity measures

- Band pass
  - slope becomes steeper from bluer to redder bands (*B I H*)
  - internal extinction is a concern, especially for blue bands and highly inclined galaxies
- Mass
  - Can convert luminosity to stellar mass by estimating the stellar M/L via population modeling.
    - IMF biggest systematic uncertainty

What we measure

- Luminosity
  - Stellar Mass
  - Gas: HI, H_2
- Rotation speed
  - line-width
  - rotation curve

Uncertainties

- Distance
  - Stellar M*/L
  - HI flux, X-factor
  - velocity dispersion
  - *inclination*
  - *asymmetric drift*

Rotation curve data from

Boomsma et al (2008) [HI]

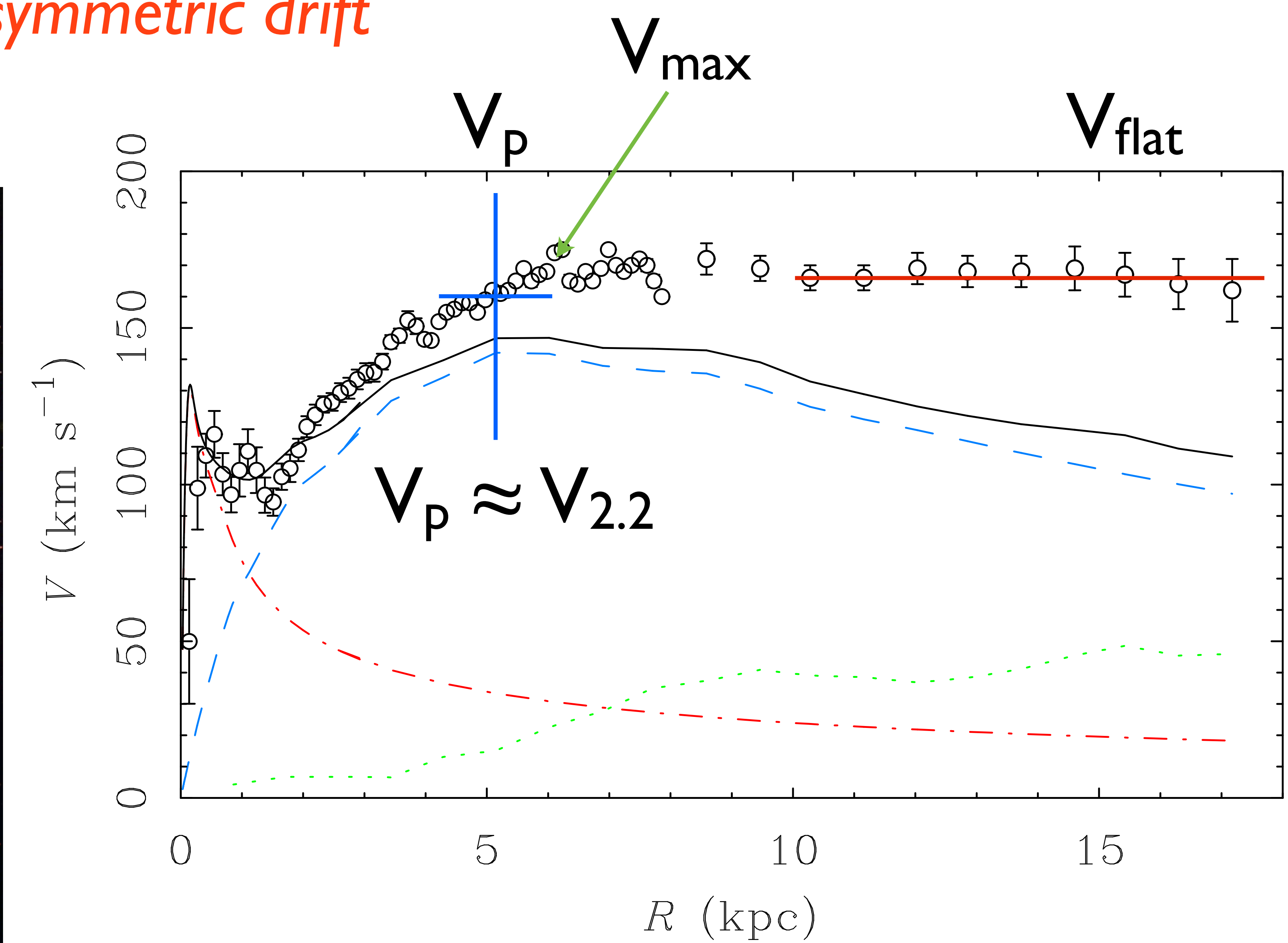
Daigle et al (2006) [Ha]

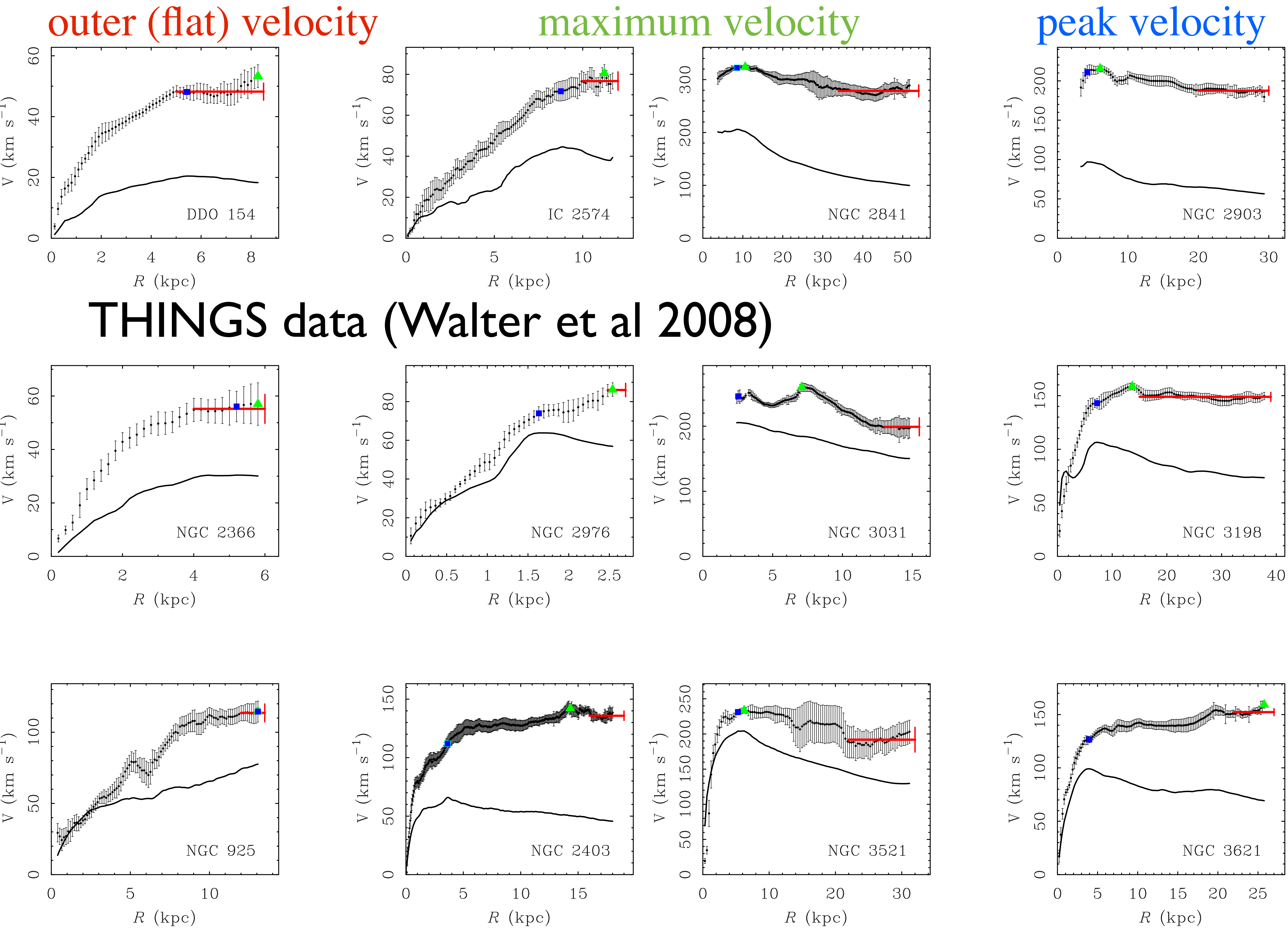
Blais-Ouellette et al (2004)

Mass model built from

2MASS K-band data (SSM)

NGC 6946

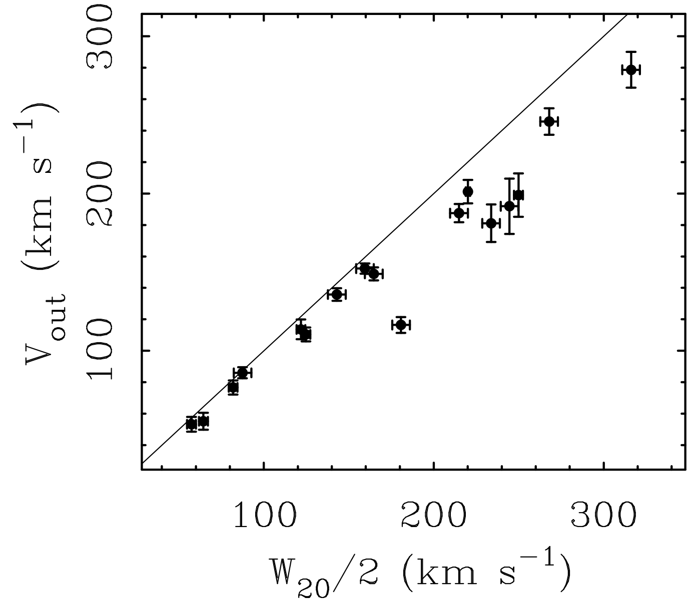


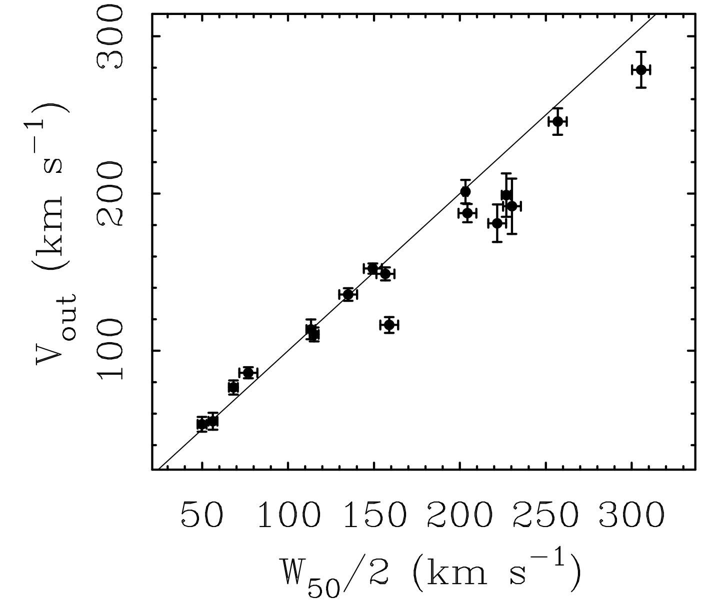


outer (flat) velocity
maximum velocity
peak velocity
THINGS data (Walter et al 2008)
DDO 154
IC 2574
NGC 2841
NGC 2903
NGC 2366
NGC 2976
NGC 3031
NGC 3198
NGC 925
NGC 2403
NGC 3521
NGC 3621
V (km s^-1)
R (kpc)

Velocity estimators:

V_{flat}

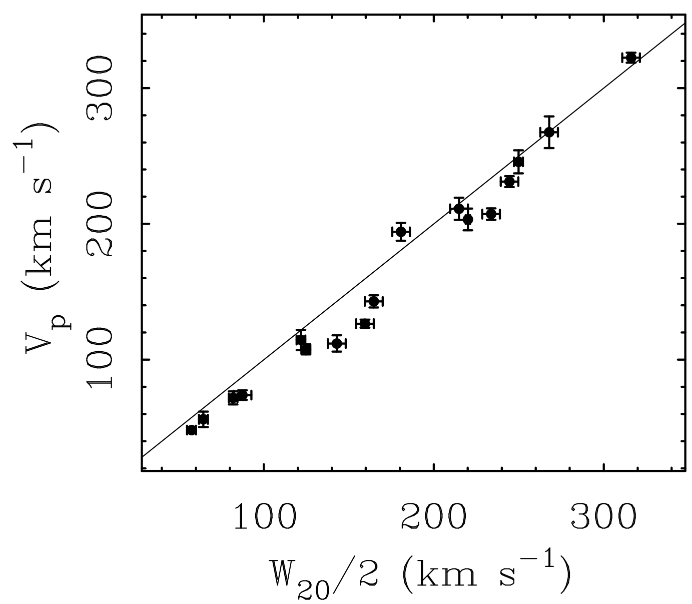


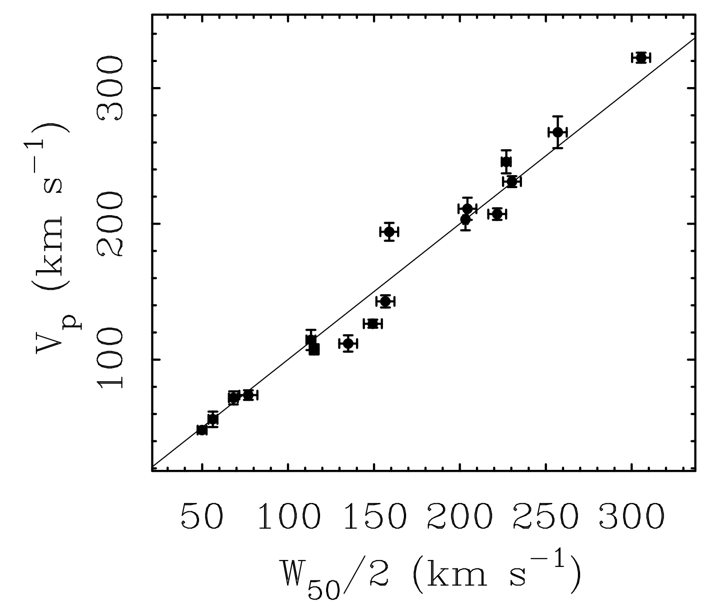


THINGS data
(Walter et al 2008)

W_{20} W_{50}

V_p

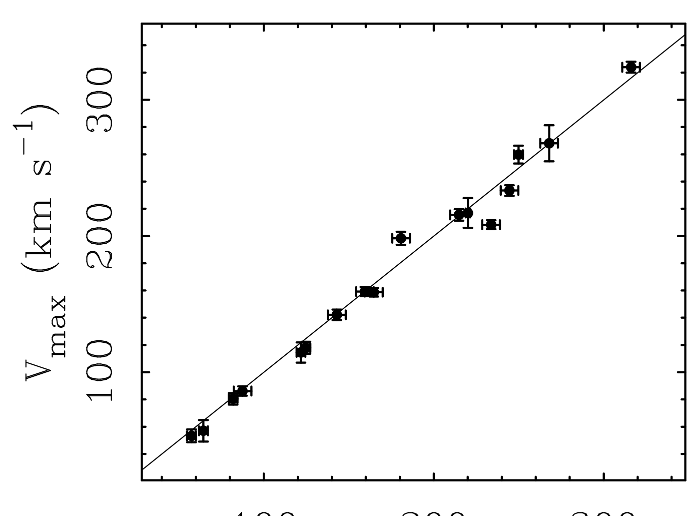


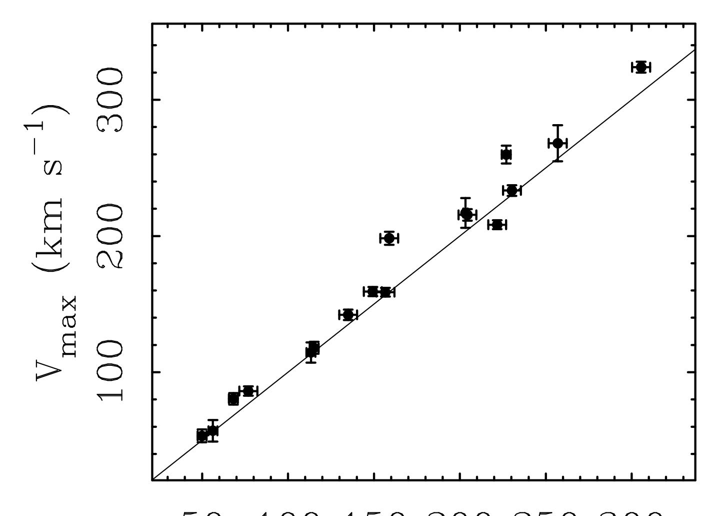


W_{20} W_{50}

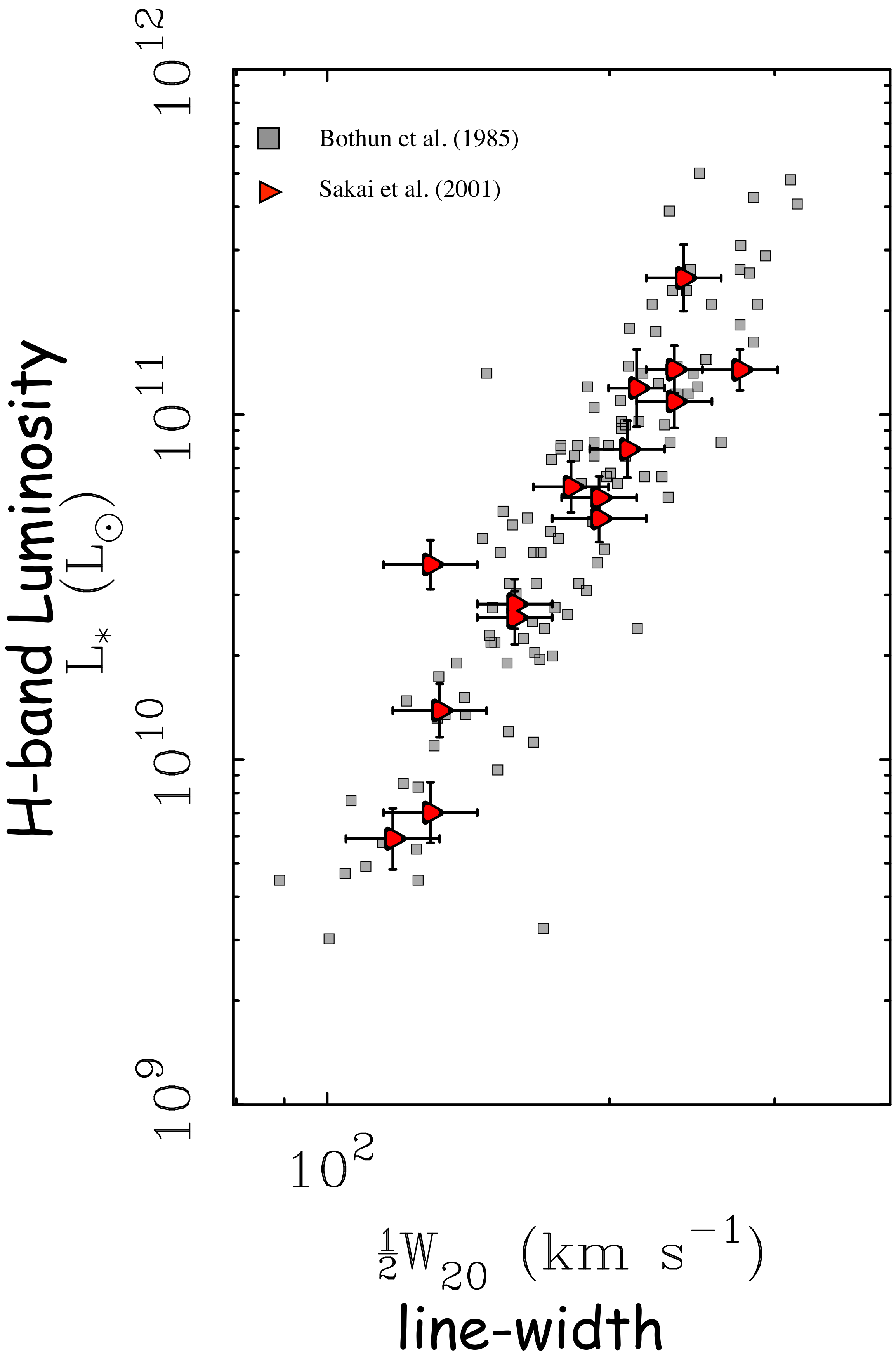
Different velocity measurements correlate but are not identical. TF relations fit using linewidths will differ from those fit using resolved rotation curves.

V_{max}





Tully-Fisher relation

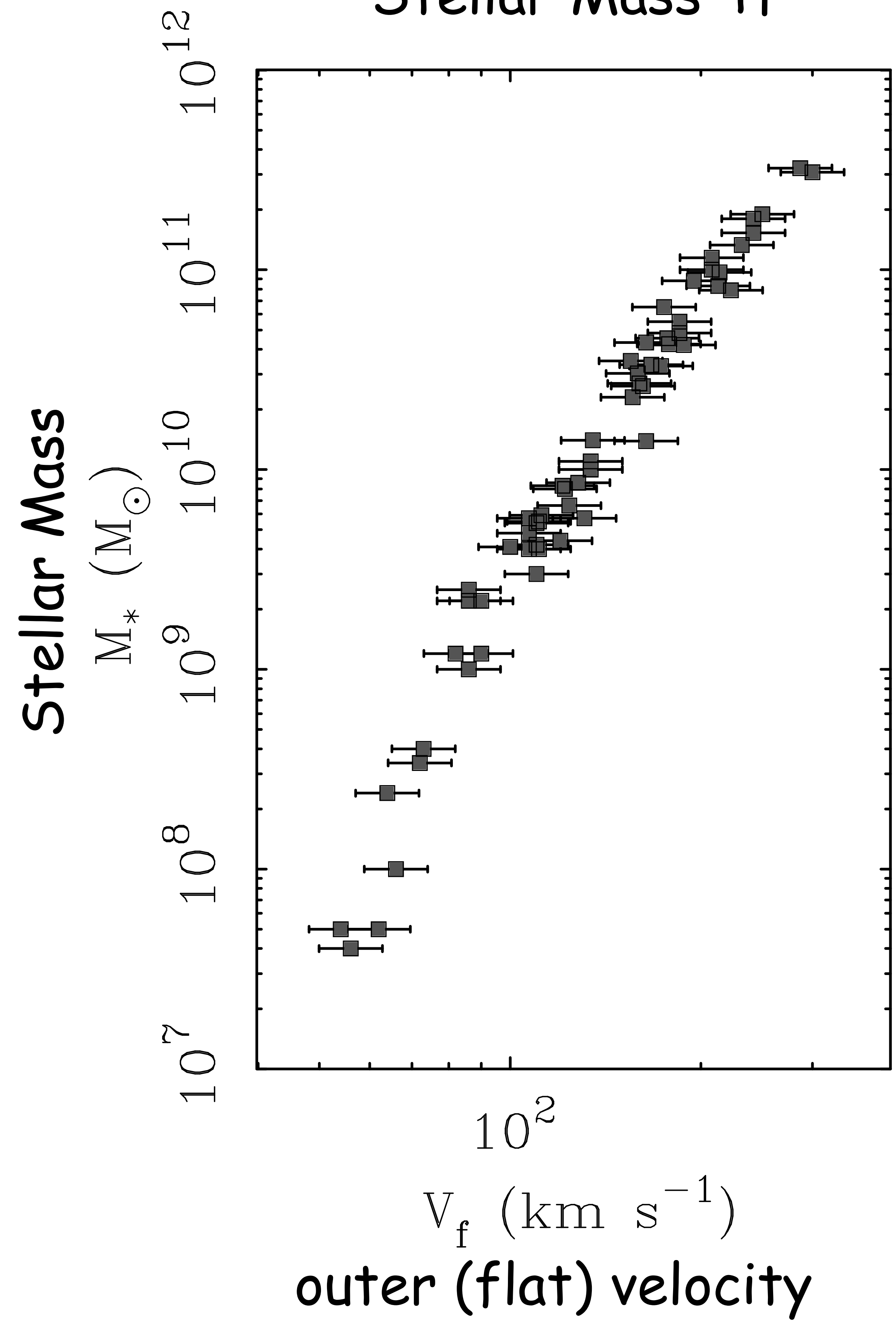


Luminosity and line-width are presumably proxies for stellar mass and rotation velocity.

Low mass galaxies tend to fall below extrapolation of linear fit to fast rotators (Matthews, van Driel, & Gallagher 1998; Freeman 1999)

$$M_* = \left(\frac{M_*}{L}\right) L$$

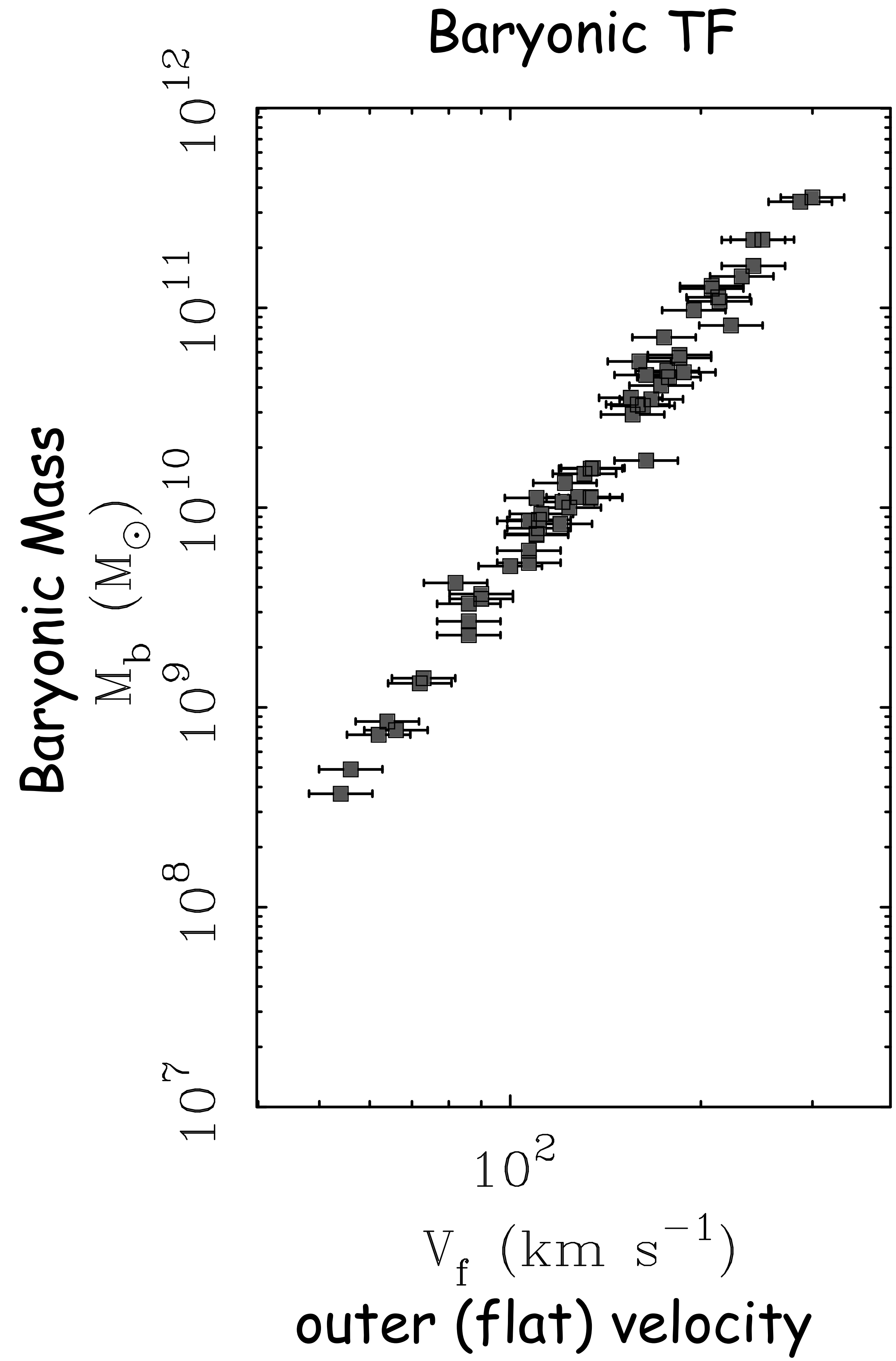
Stellar Mass TF



Adding gas to stellar mass restores a single continuous relation for all rotators.

$$M_b = M_* + M_g$$

Baryonic mass is the important physical quantity. It doesn't matter whether the mass is in stars or in gas.

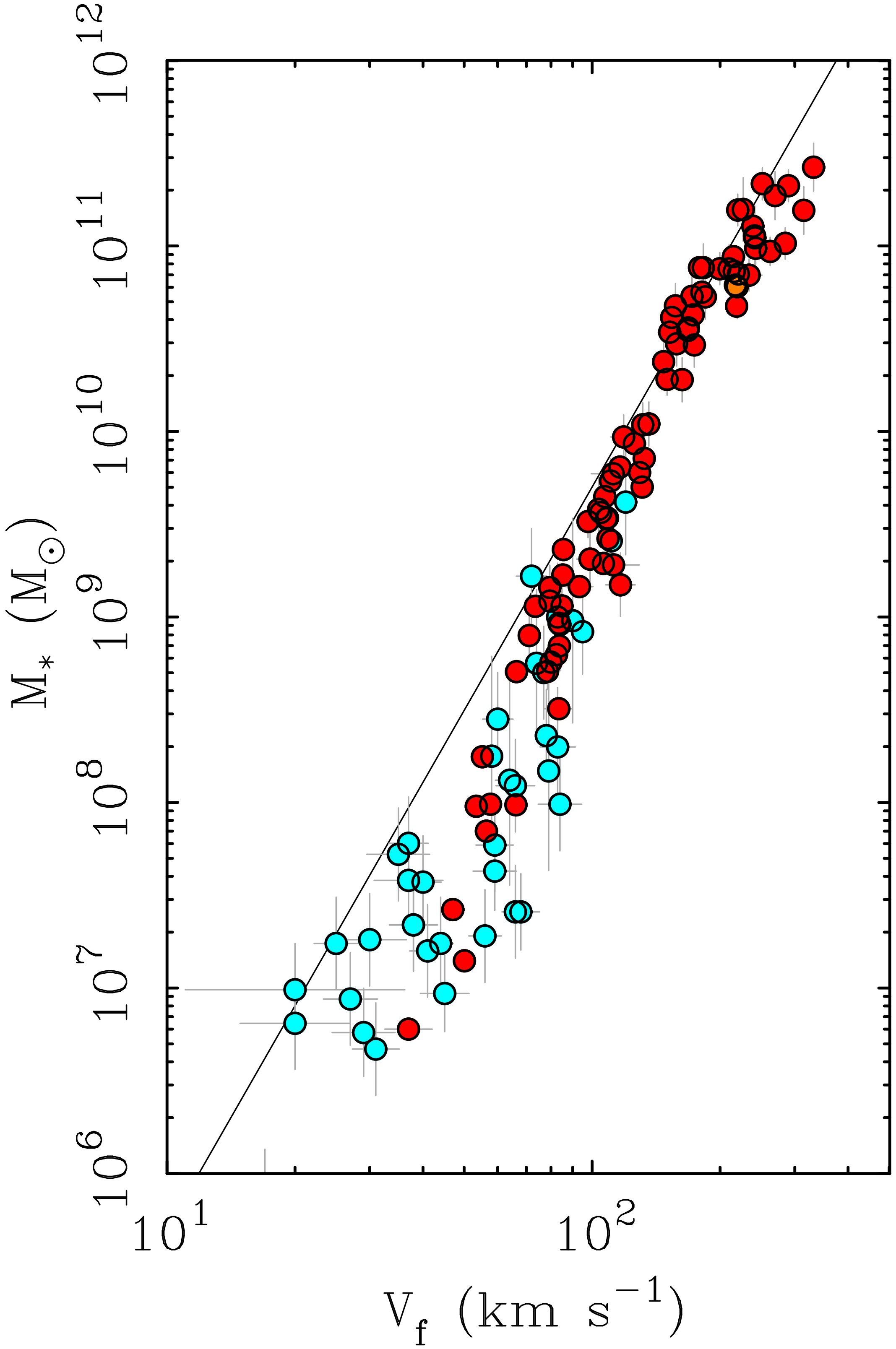


Tully-Fisher relations

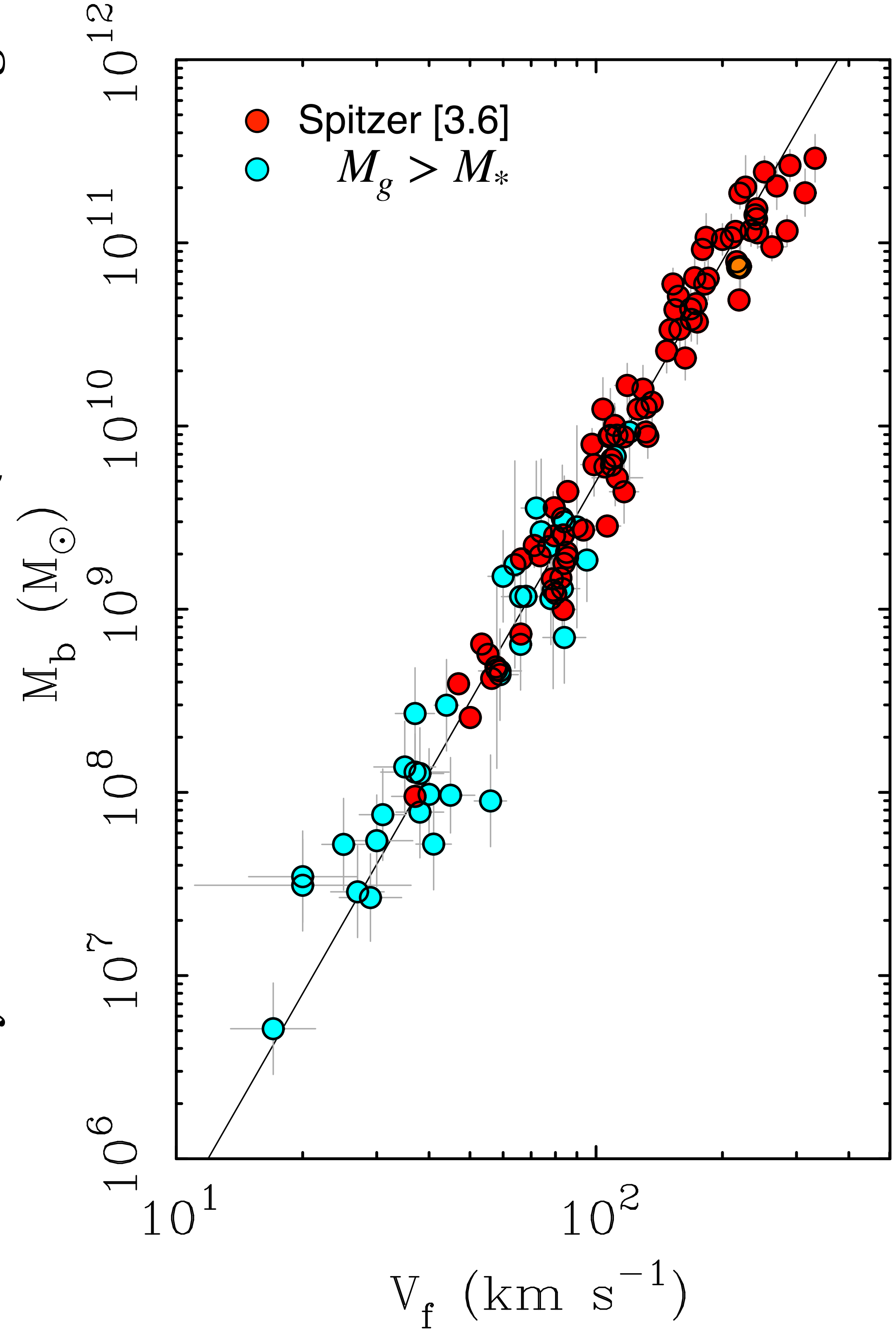
2019

amplitude of flat rotation correlates with mass

Stellar mass



Baryonic mass (sum of stars and gas)



flat rotation speed

Tully-Fisher relations

amplitude of flat rotation correlates with mass

The fundamental relation
is between
baryonic mass
and the amplitude of the
flat rotation speed

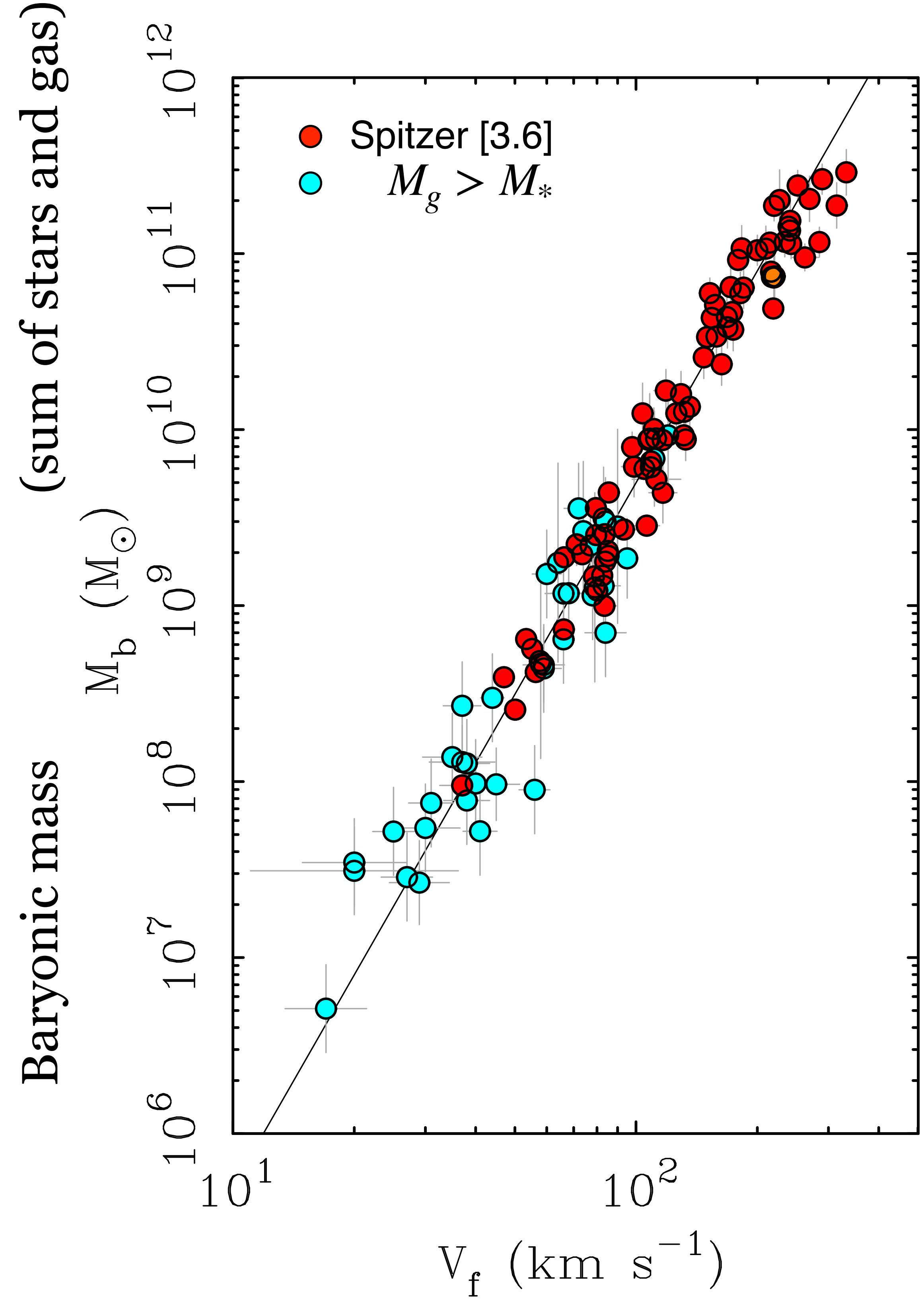
$$M_b = M_* + M_g = A V_f^4$$

$A = 48.5 \pm 3.3 \ \mathrm{M_\odot} \, (\mathrm{km\,s^{-1}})^{-4}$

there is remarkably little
intrinsic scatter

$\sigma_M < 0.11$ dex

which is about what is
expected for scatter in
stellar population M*/L



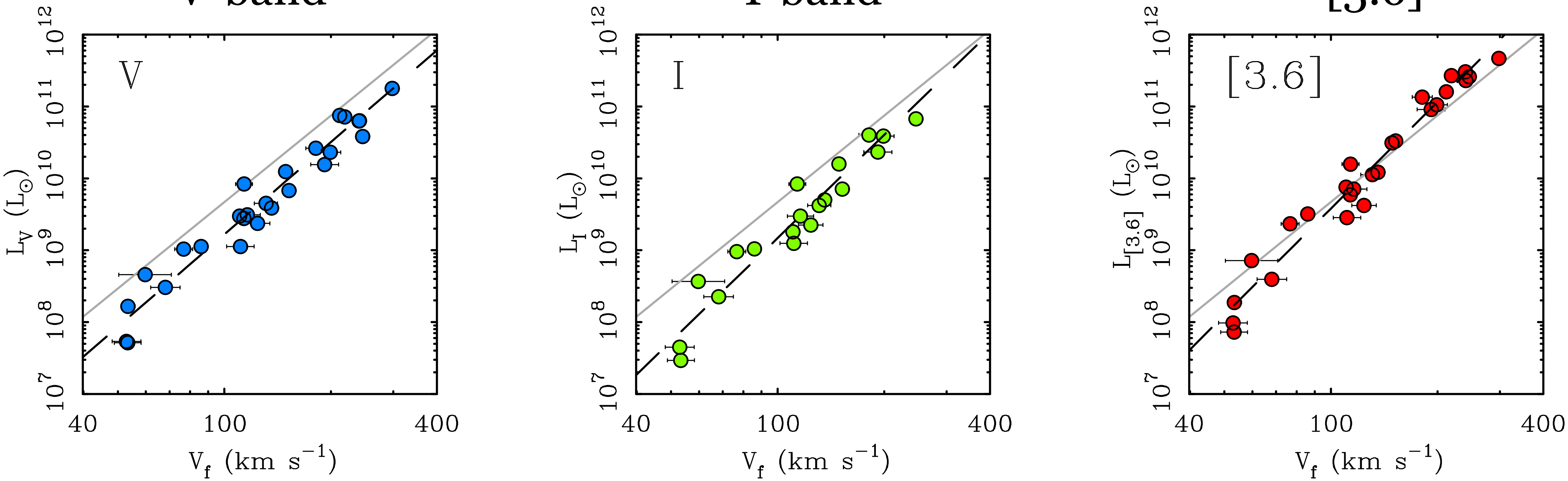
flat rotation speed

Population synthesis stellar mass-to-light ratios should provide same answer irrespective of band

Raw luminosities

V-band I-band [3.6]

Luminosity



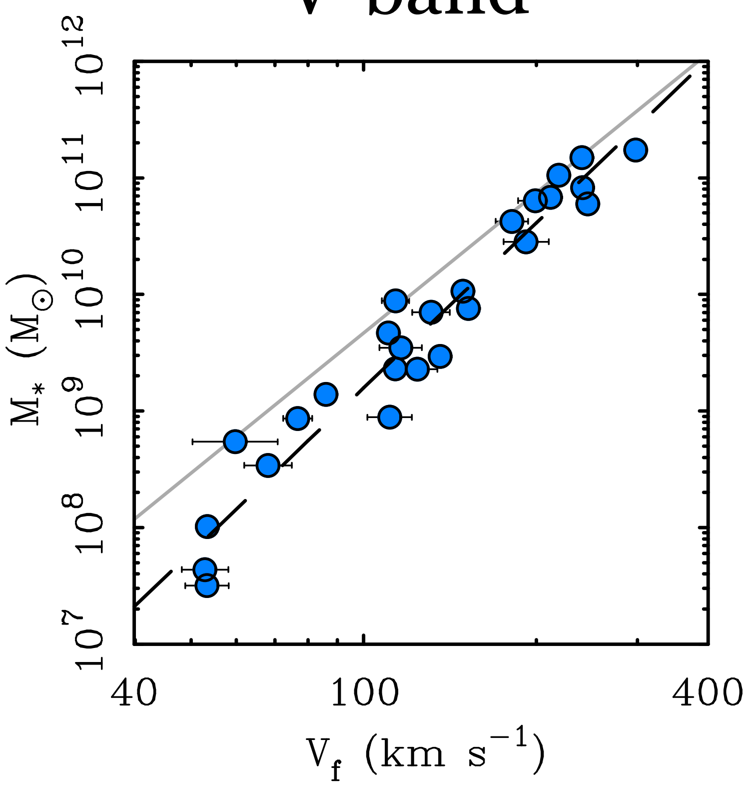
flat rotation speed

Population synthesis stellar mass-to-light ratios & do provide same stellar mass Tully-Fisher relation

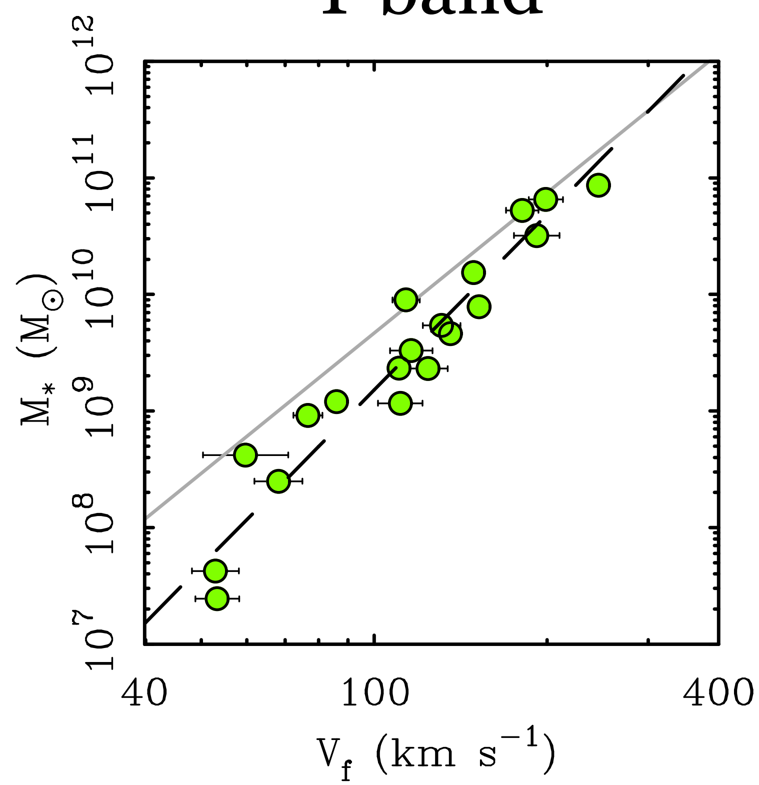
Stellar mass $M_* = \Upsilon_*^i L_i$

Stellar mass

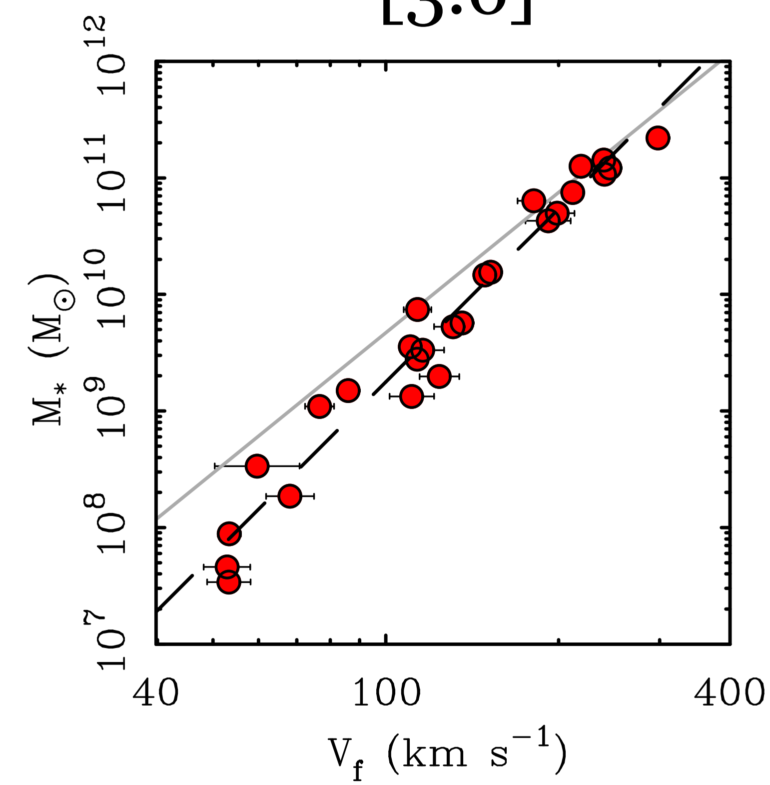
V-band



I-band



[3.6]



flat rotation speed

$$\log \Upsilon_*^V = -0.63 + 1.3(B-V)$$

$$\log \Upsilon_*^I = -0.28 + 0.6(B-V)$$

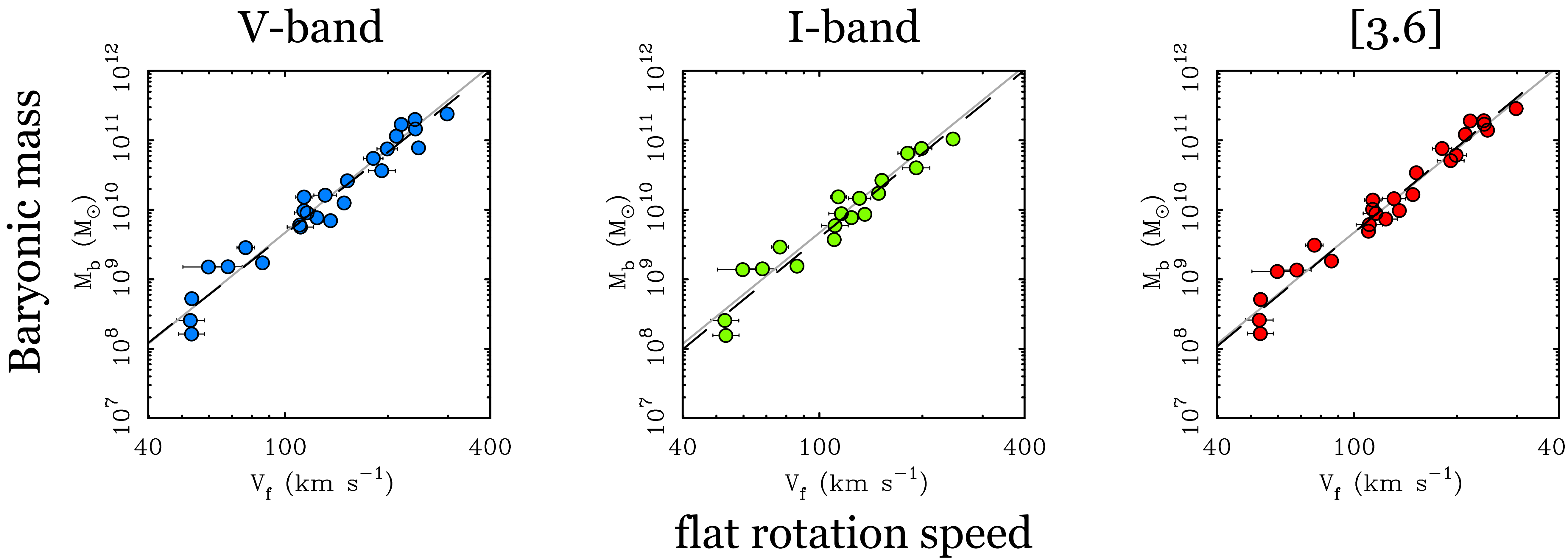
$$\Upsilon_*^{[3.6]} = 0.5\ \mathrm{M_\odot/L_\odot}$$

No perceptible color term

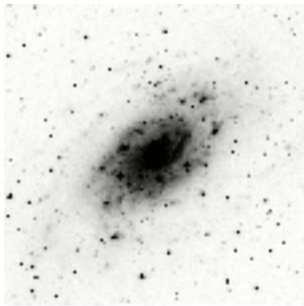
Schombert & McGaugh (2014)
McGaugh & Schombert (2014)

Population synthesis stellar mass-to-light ratios & baryonic Tully-Fisher relation

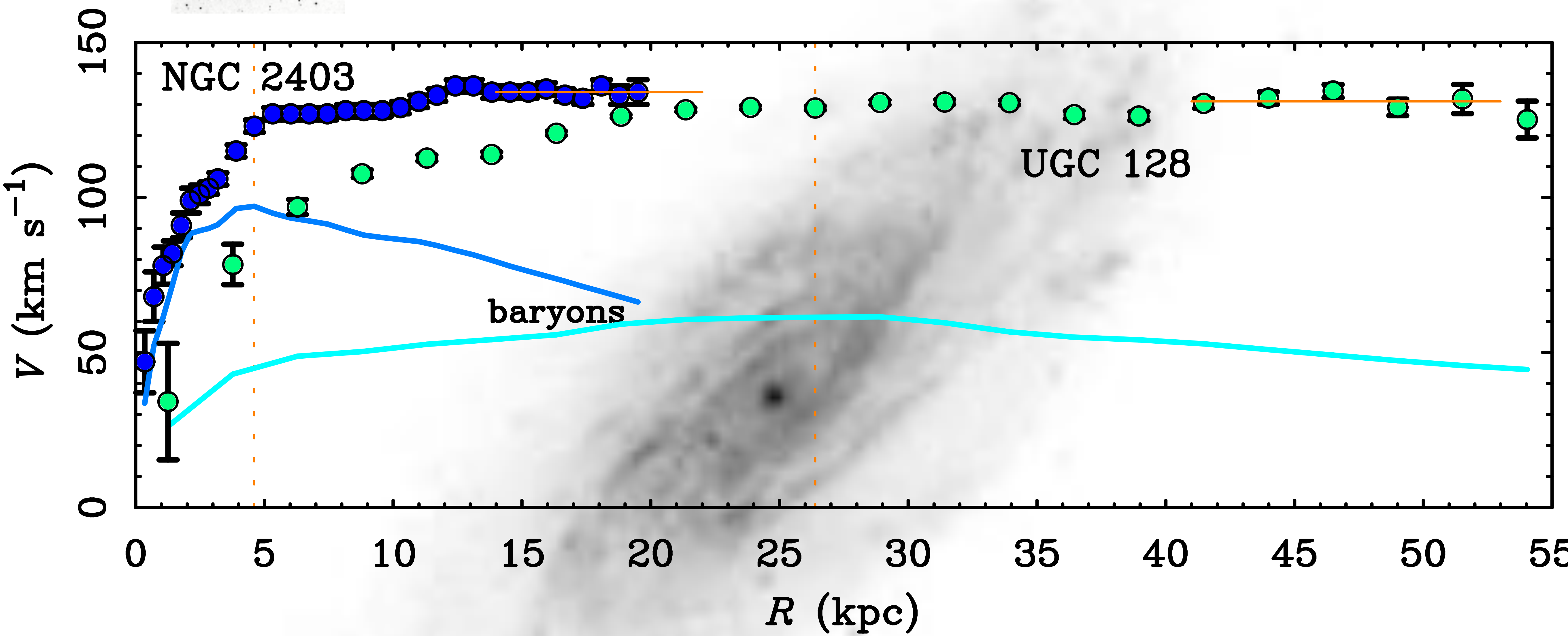
Baryonic mass $M_b = M_* + M_g$



McGaugh & Schombert (2015)



No residuals from TF with size or surface density

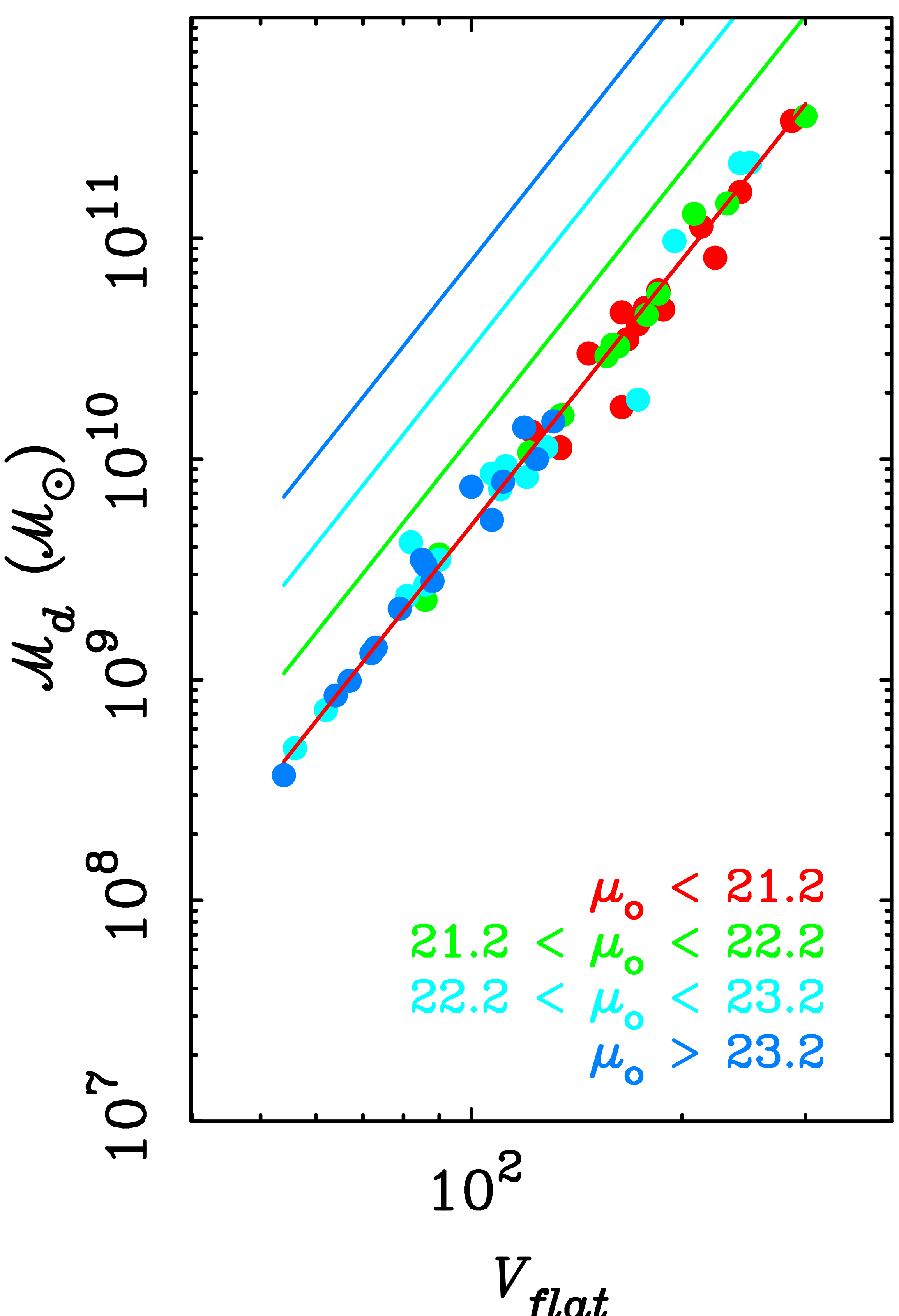


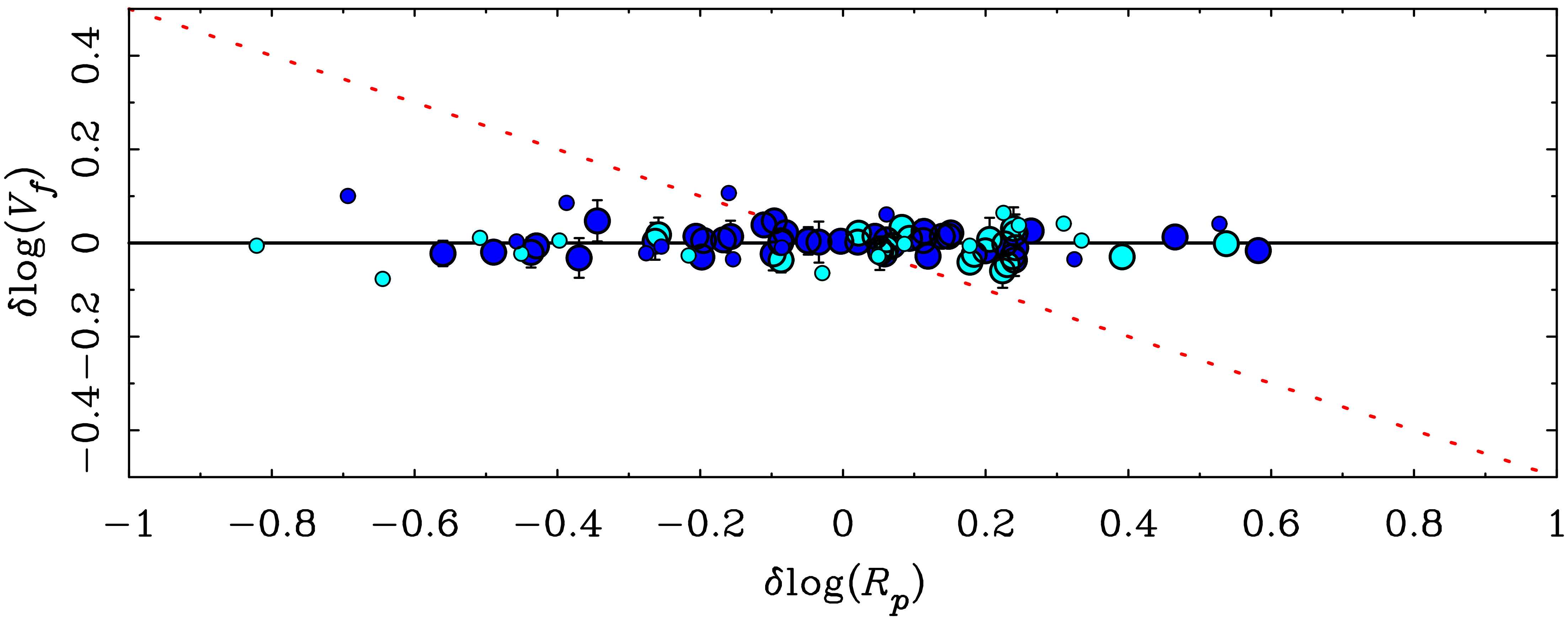
Same (M,V) but very different size and surface density

which is strange, since $V^2 = \frac{GM}{R}$

No residuals from TF with size or surface brightness

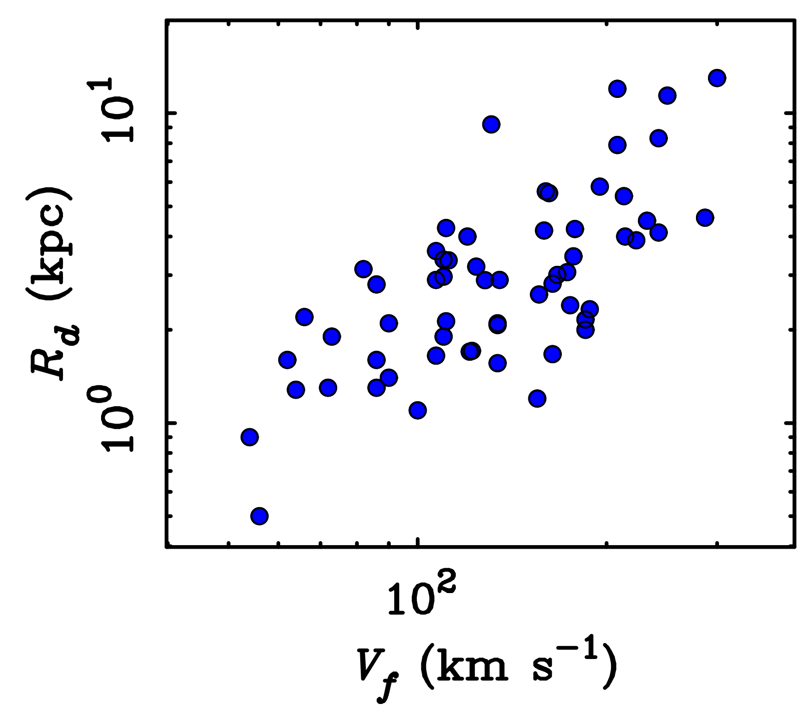
(Zwaan et al 1995; Sprayberry et al 1995; McGaugh & de Blok 1998)





No residuals from TF with size or surface density for disks

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



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

Baryonic TF Relation

- Fundamentally a relation between the baryonic mass of a galaxy and its rotation velocity
  - $M_b = M_* + M_g = 48.5 V_f^4$ (McGaugh 2012)
  - 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

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