Dark Matter

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

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

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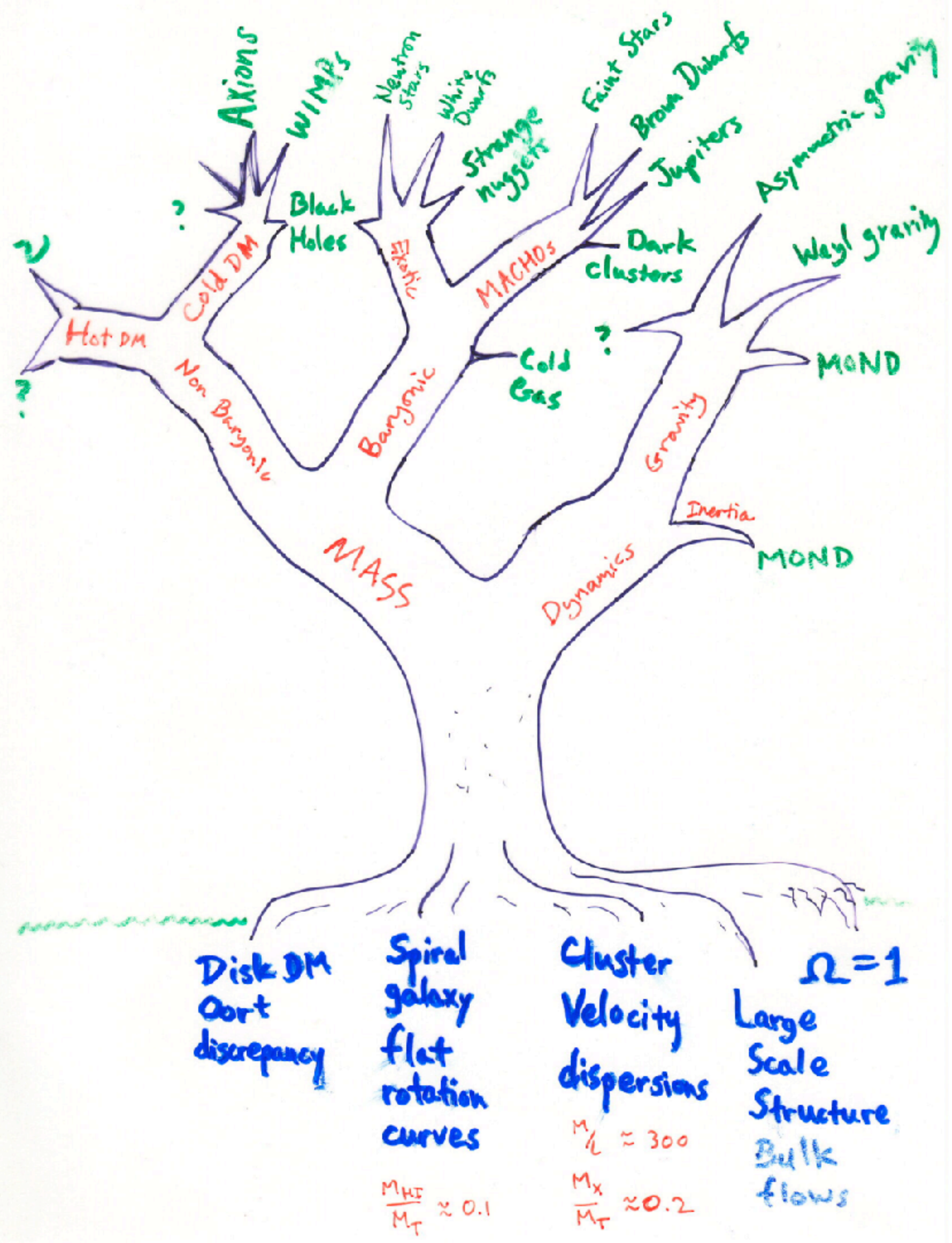
HOMEWORK DUE

Case Western Reserve University
Est. 1826



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

TF / BTFR

- 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: $M_b = A V_f^4$

diversity

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

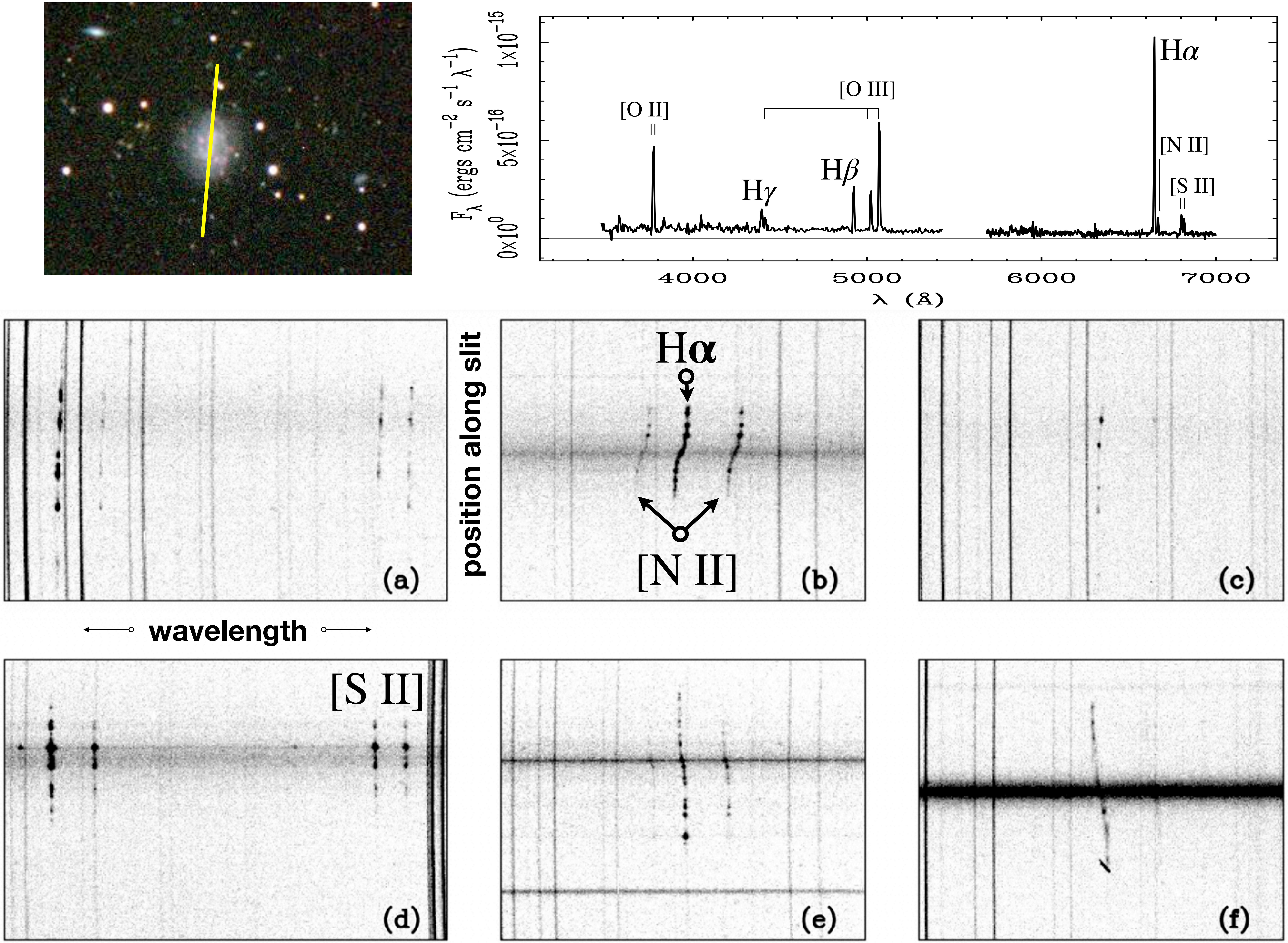
- Renzo's rule (Sancisi's Law)

  "For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa." (Sancisi 2004).

RAR

- Radial acceleration relation

  The observed centripetal acceleration is related to that predicted by the observed distribution of baryons: $\mathrm{g}_{\mathrm{obs}} = \mathcal{F}(\mathrm{g}_{\mathrm{bar}})$



[O II]
[O III]
Hγ
Hβ
Hα
[N II]
[S II]
F_λ (ergs cm^-2 s^-1 λ^-1)
0x10^0
5x10^-16
1x10^-15
4000
5000
6000
7000
λ (Å)
position along slit
Hα
[N II]
wavelength
[S II]
(a)
(b)
(c)
(d)
(e)
(f)

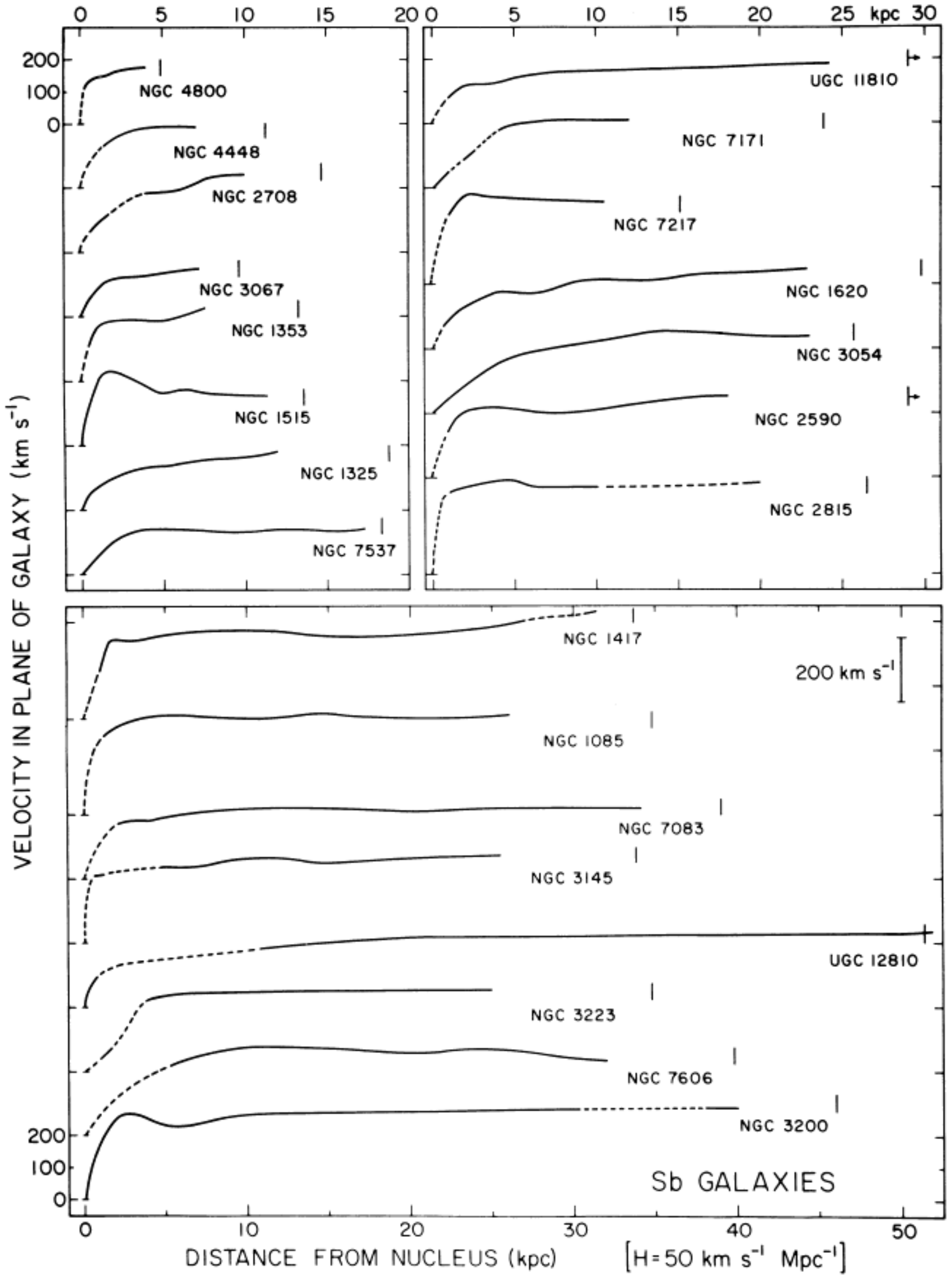


FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to increasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25}, 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

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

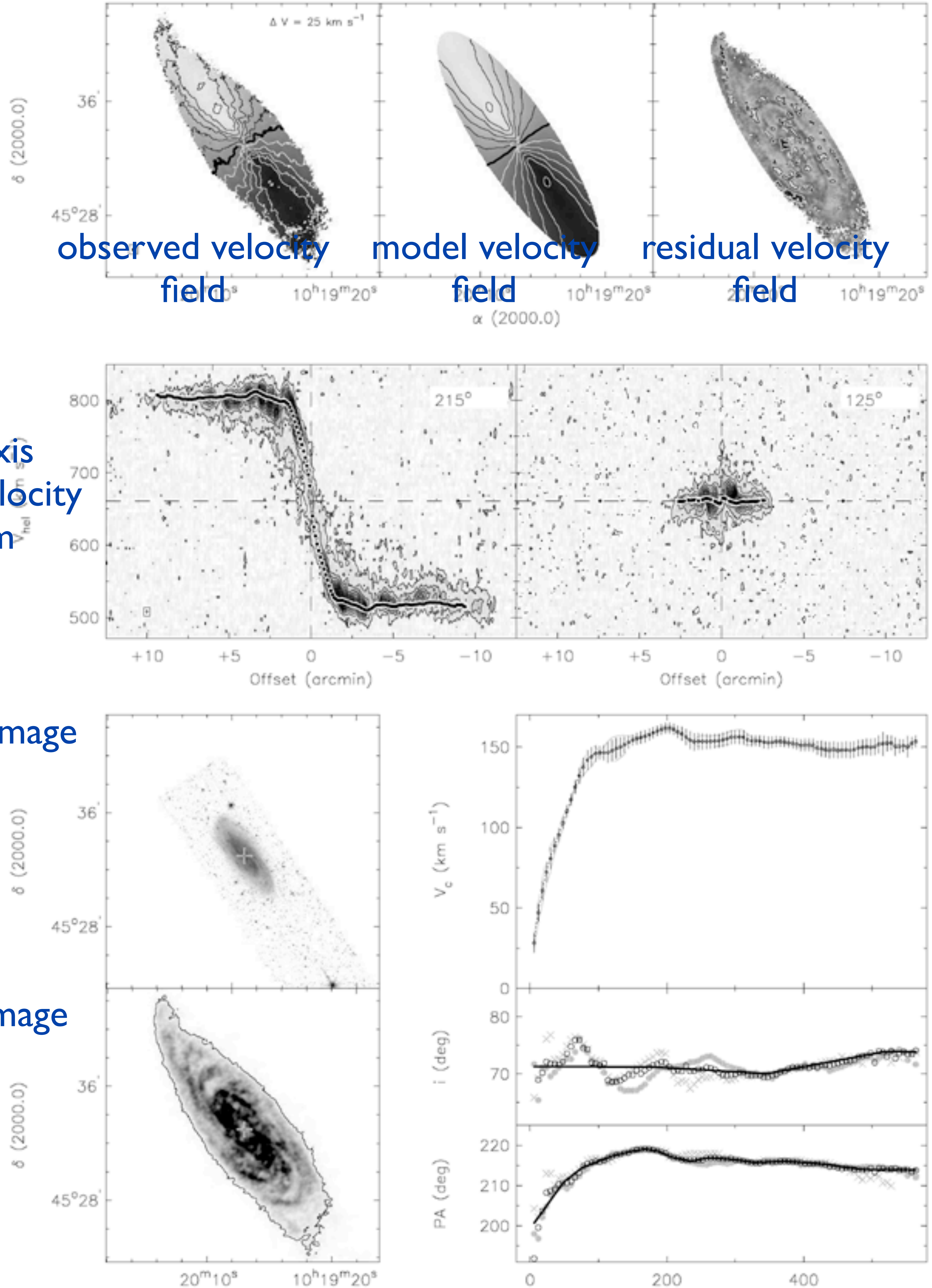
$$M \propto R$$

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

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

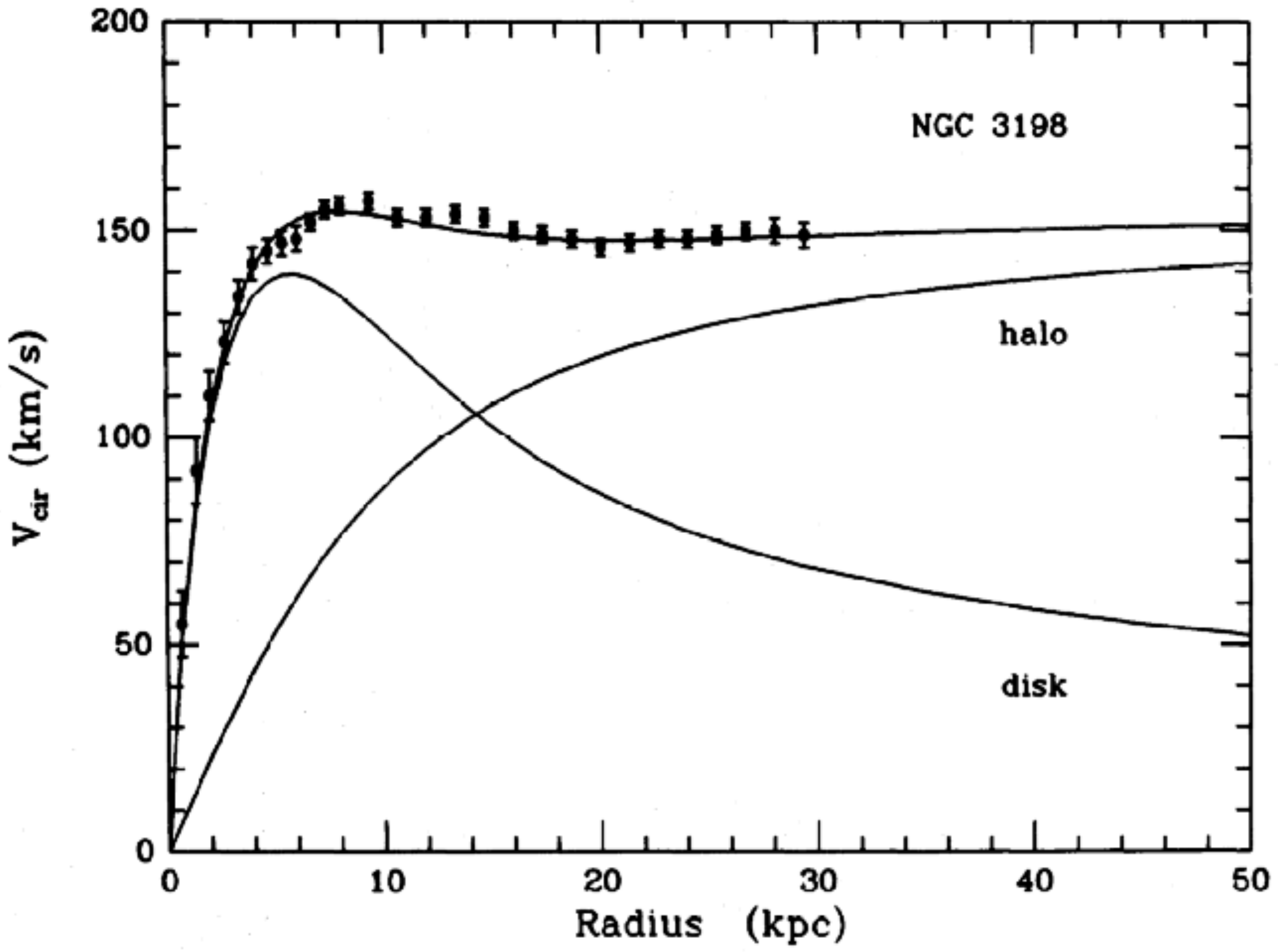
NGC 3198

Radio data



van Albada et al. (1985)

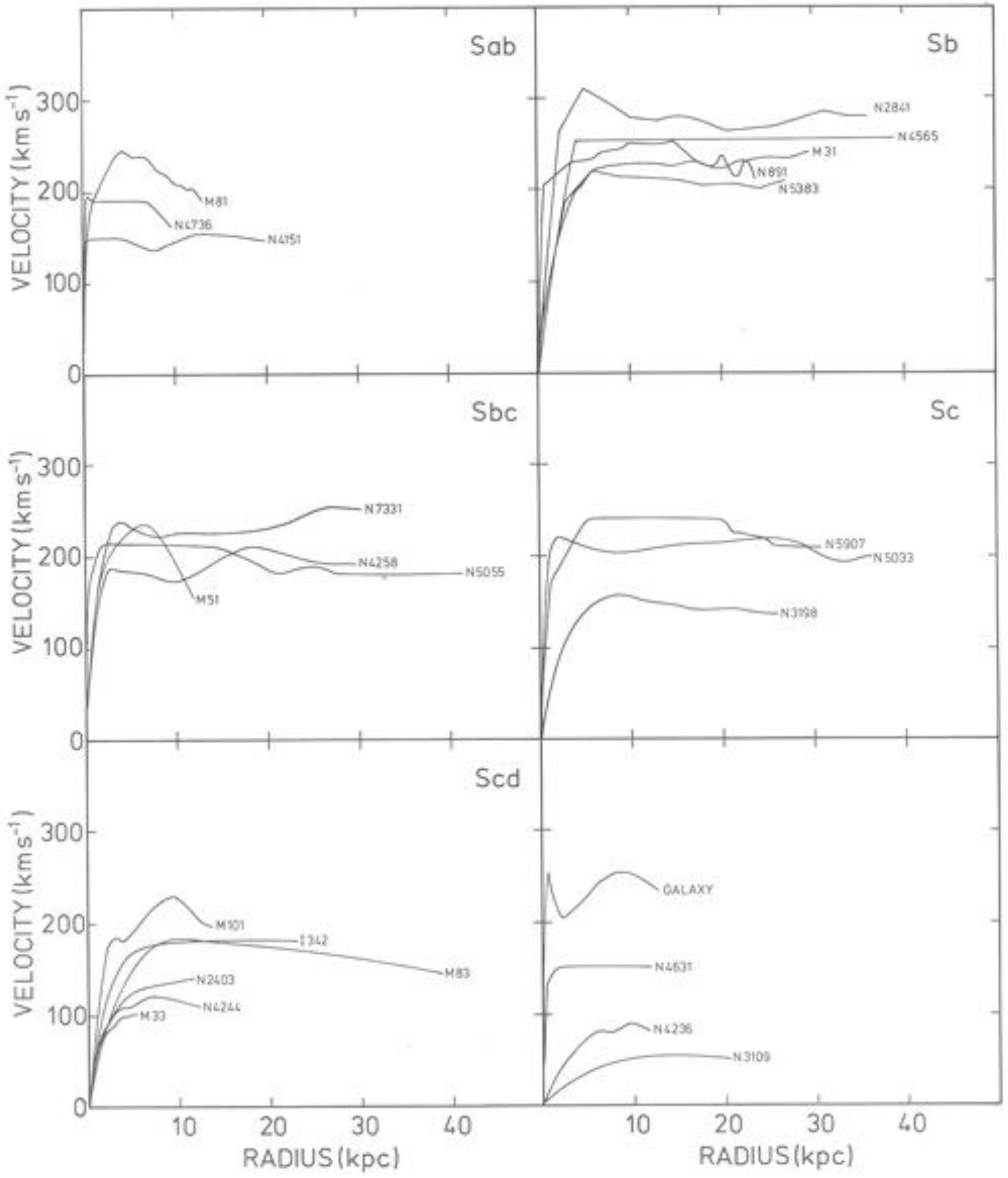
DISTRIBUTION OF DARK MATTER IN NGC 3198



$$V_{cir}^2 = V_{disk}^2 + V_{halo}^2$$

Maximum disk can explain data at small radii, but not at large radii: need something new!

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



Rotation curves stay flat to the largest radii probed

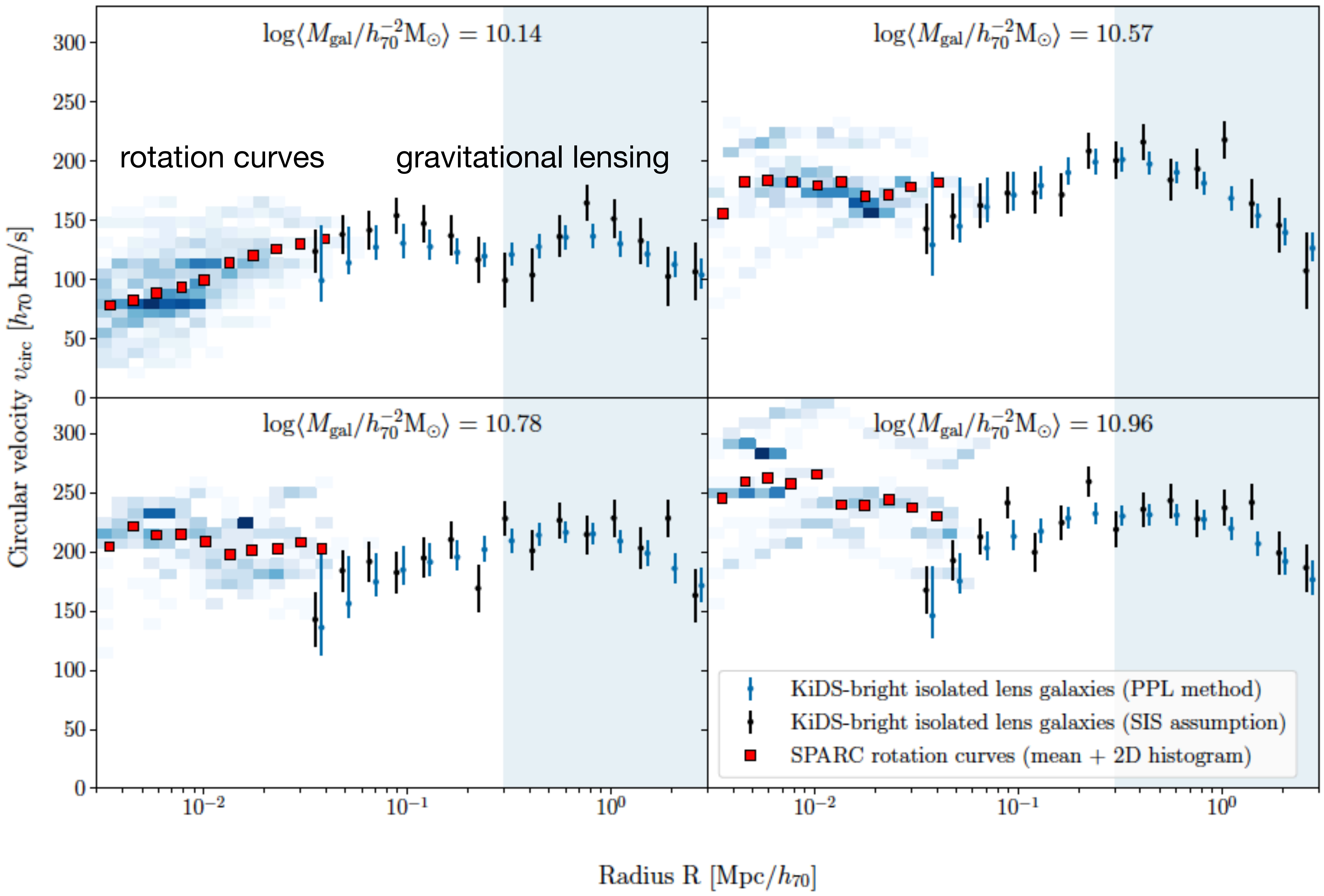
Historically, 21cm data were an important independent validation that flat rotation curves persisted to much larger radii than could be explained by the observed luminous mass.

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

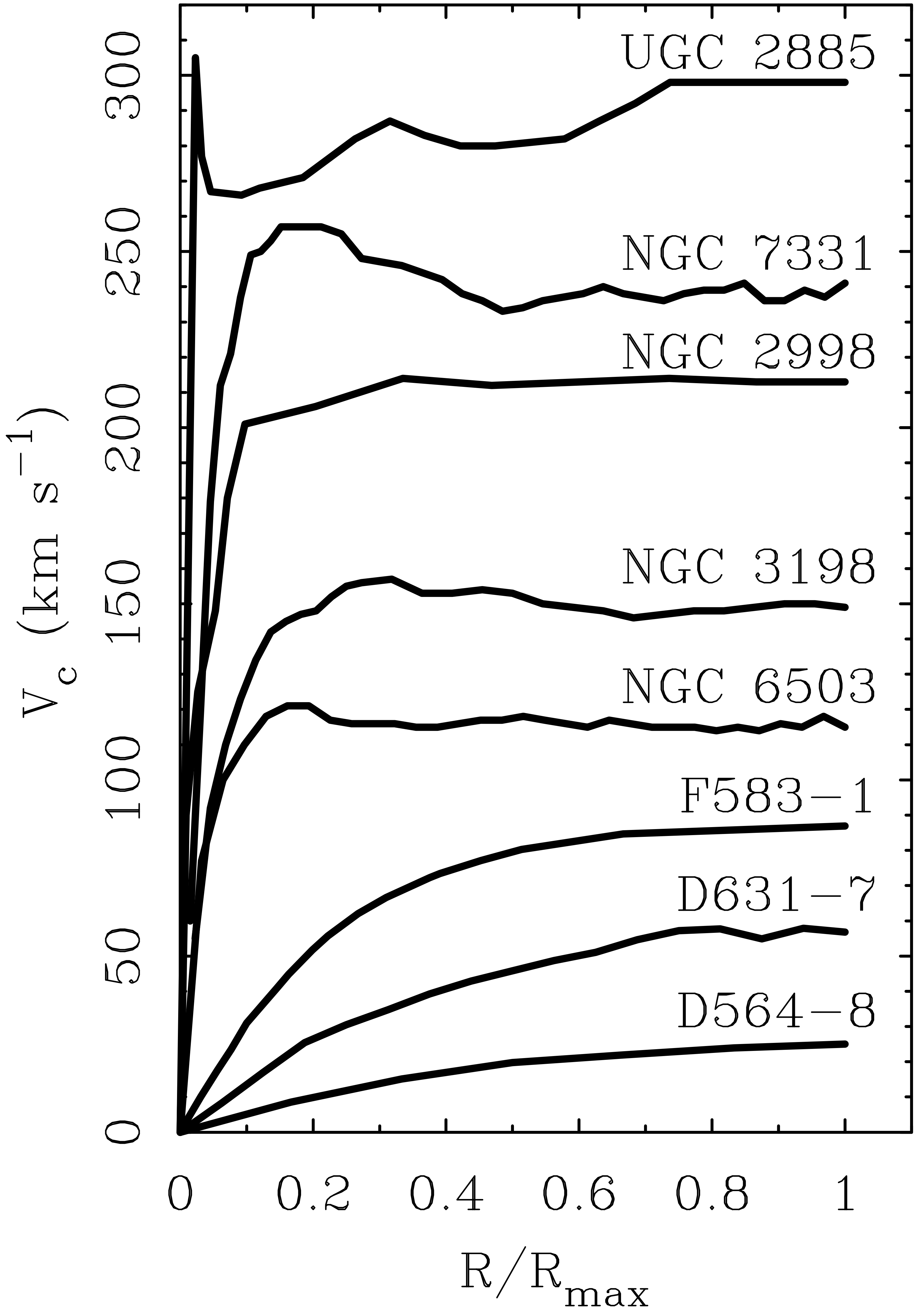
Gravitational Lensing data

…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

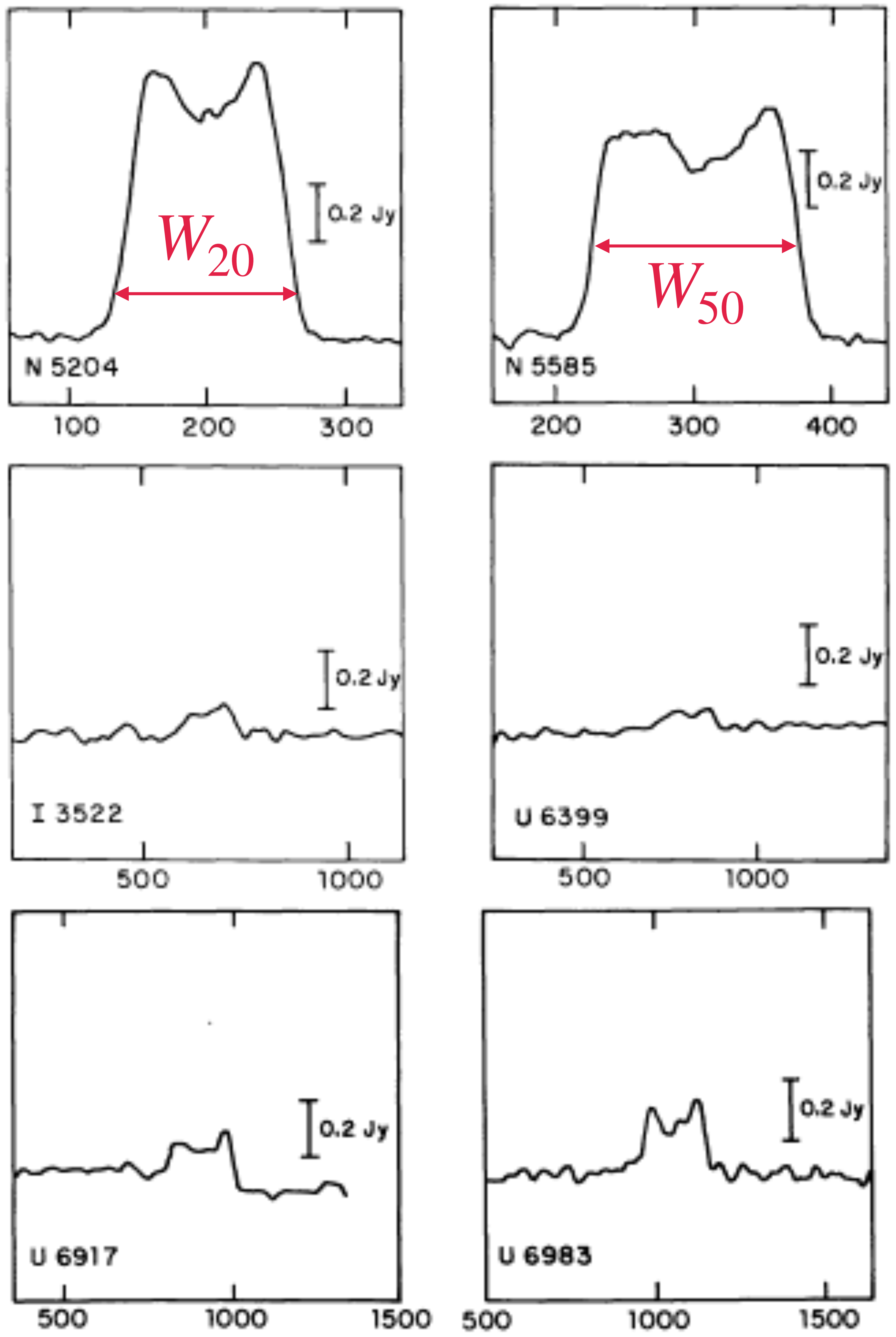
gas dominated LSBs

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

Tully & Fisher (1977)

Great for distance scale work.
But why does it happen?

line-width



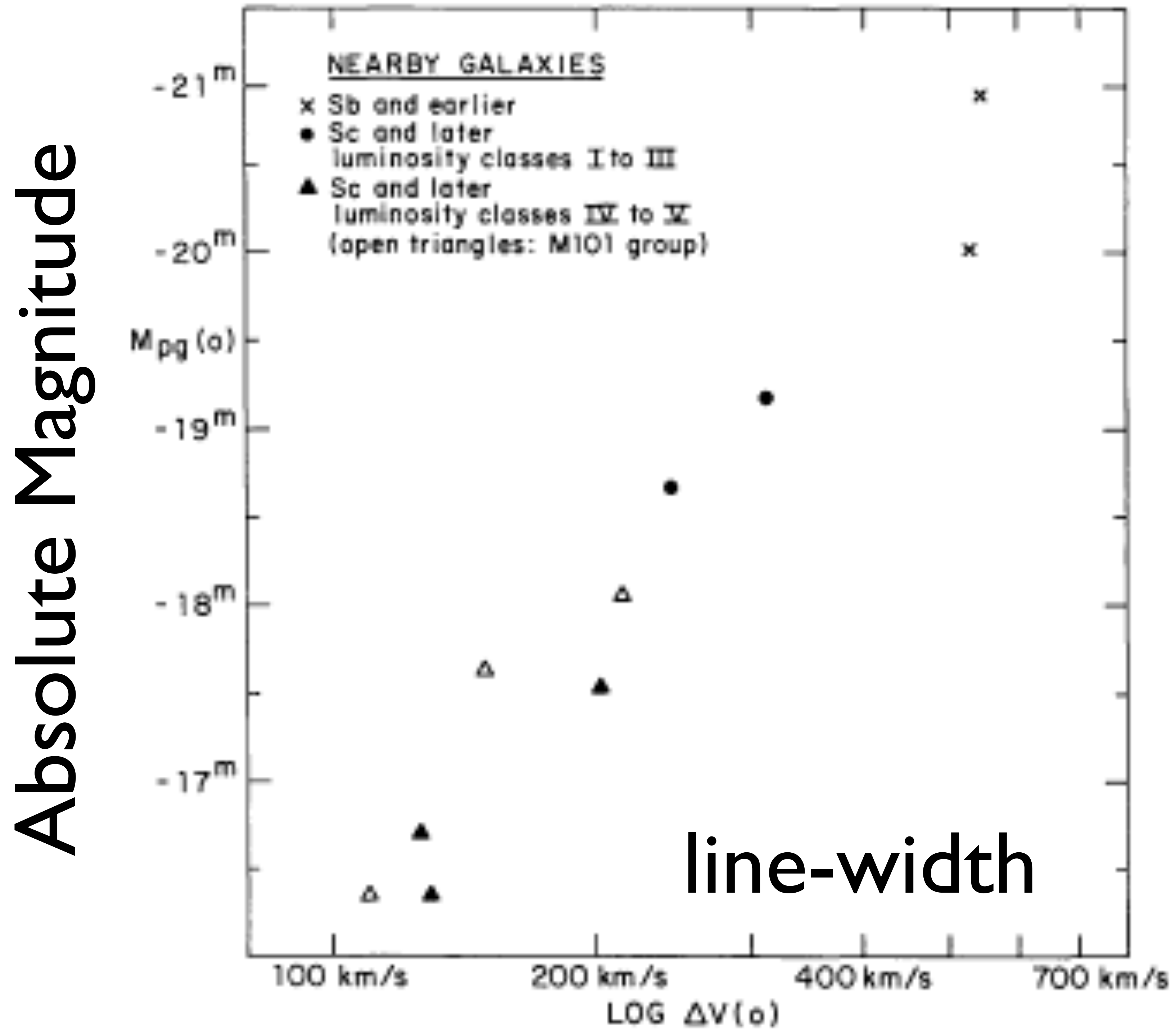


Fig. 1. Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

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)

we take these uncert
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We have precisely
tions presented in ST
not in total agreement
the complete lack of co
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of the results we are g
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clearly comparable as
that the two Sb system
correction (following
modestly affect (steep
not the measurement
because both the nea
Sb systems, at simila
with similar inclinatio
In explicitly follow
given in ST IV we d
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scale, but for the pro
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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]

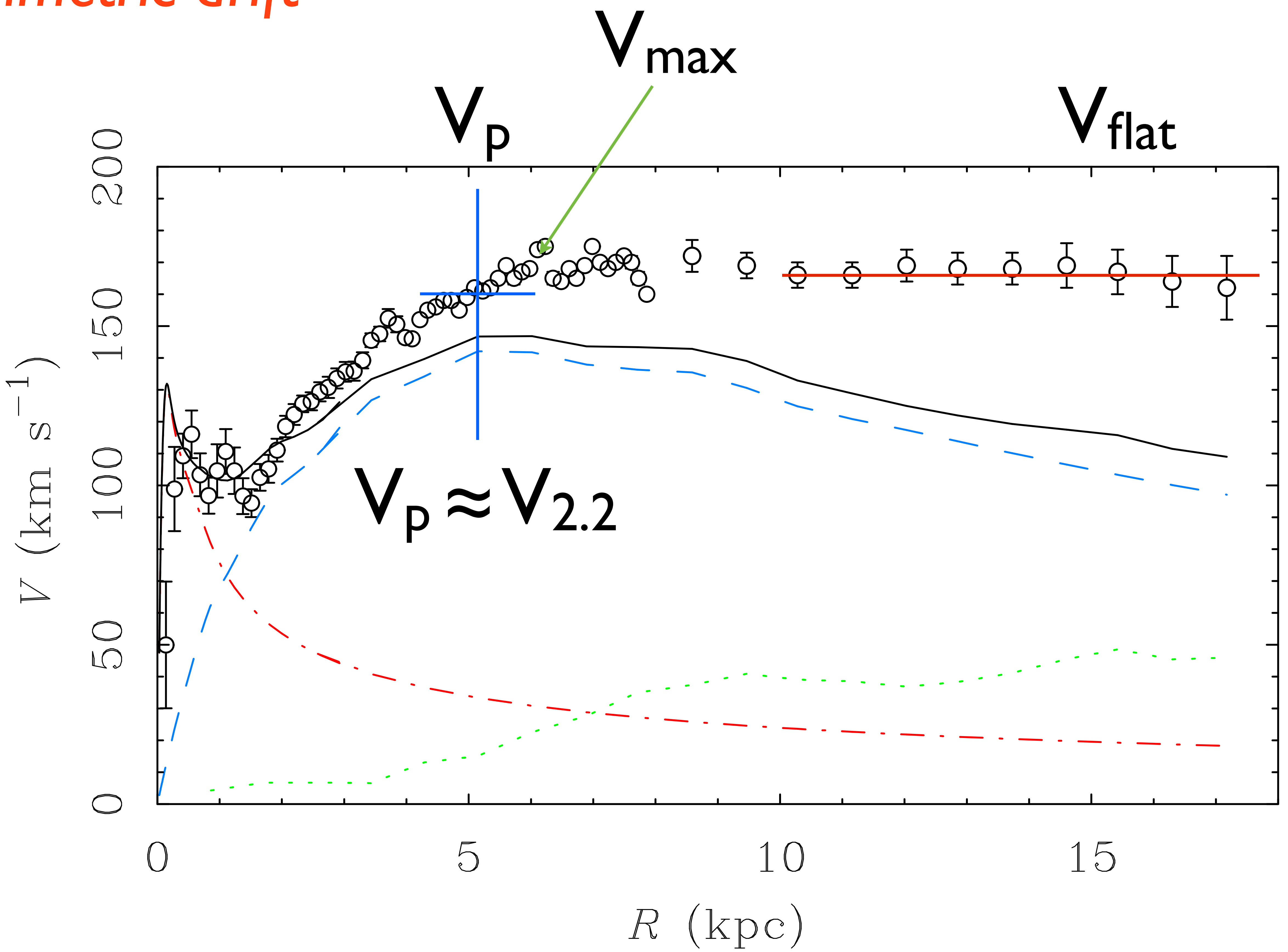
Daigle et al (2006) [Ha]

Blais-Ouellette et al (2004) [Ha]

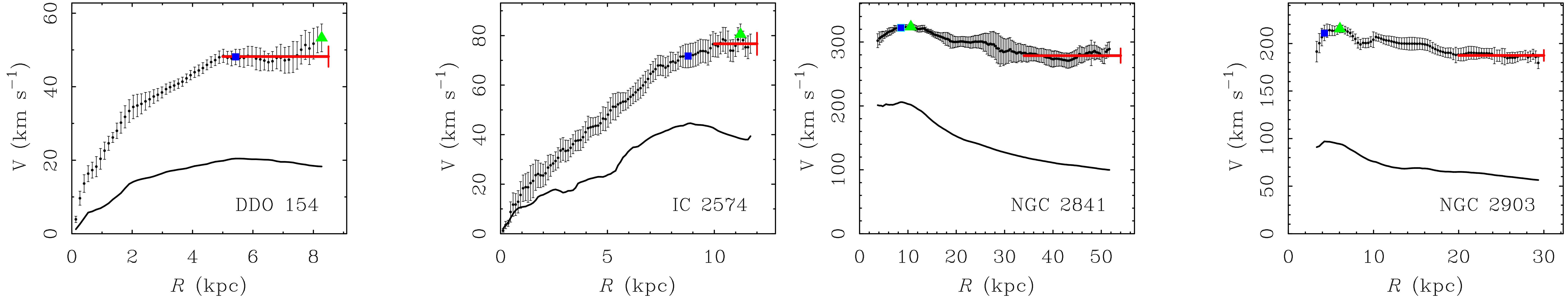
Mass model built from

2MASS K-band data (SSM)

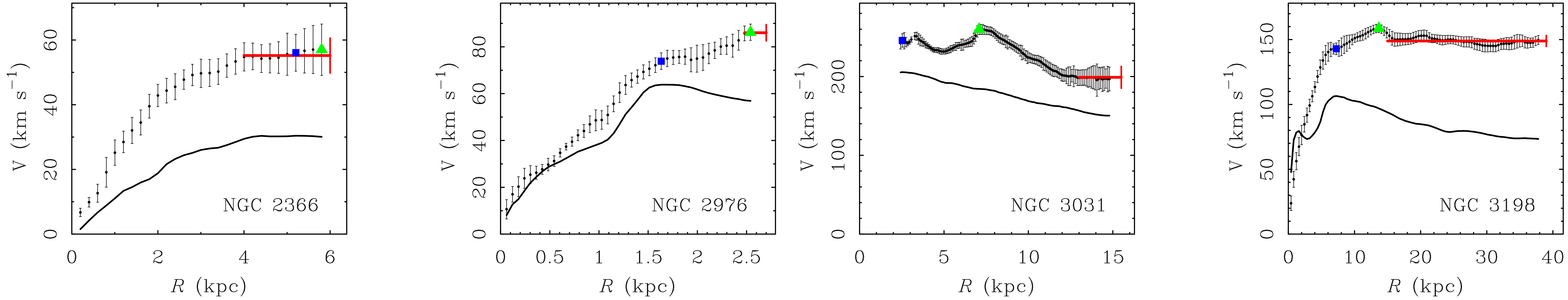
NGC 6946

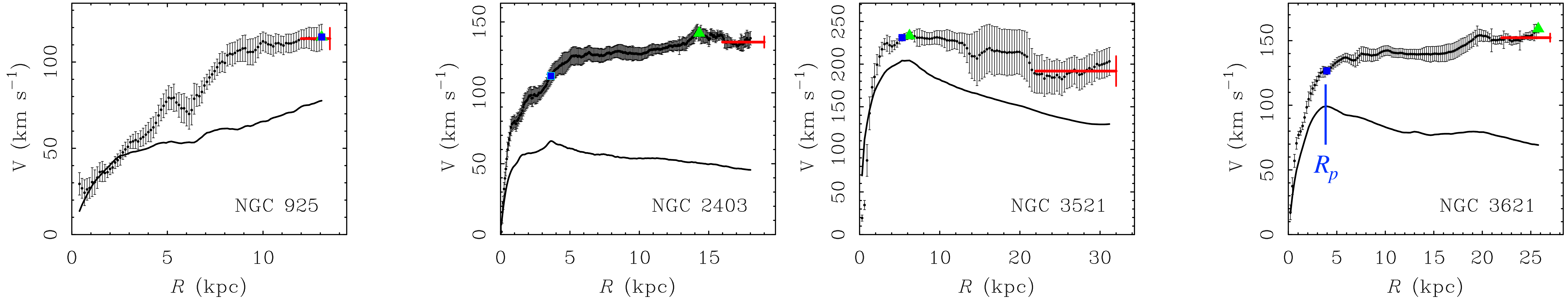


outer (flat) velocity | maximum velocity | peak velocity



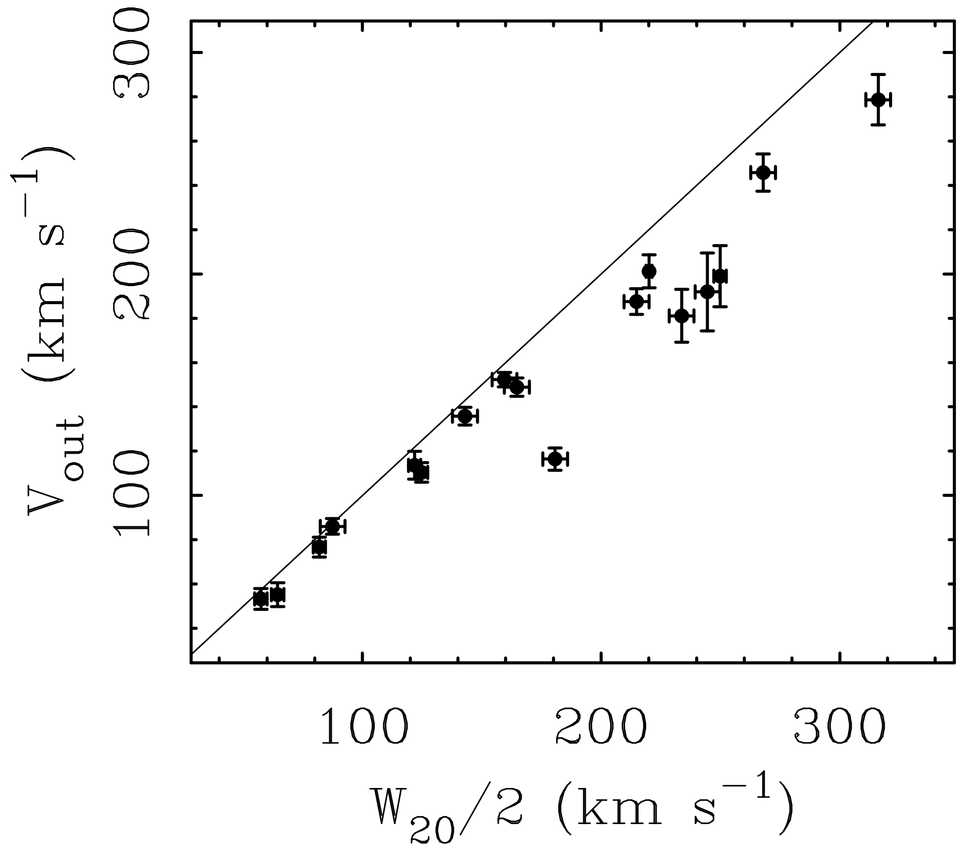
THINGS data (Walter et al 2008)

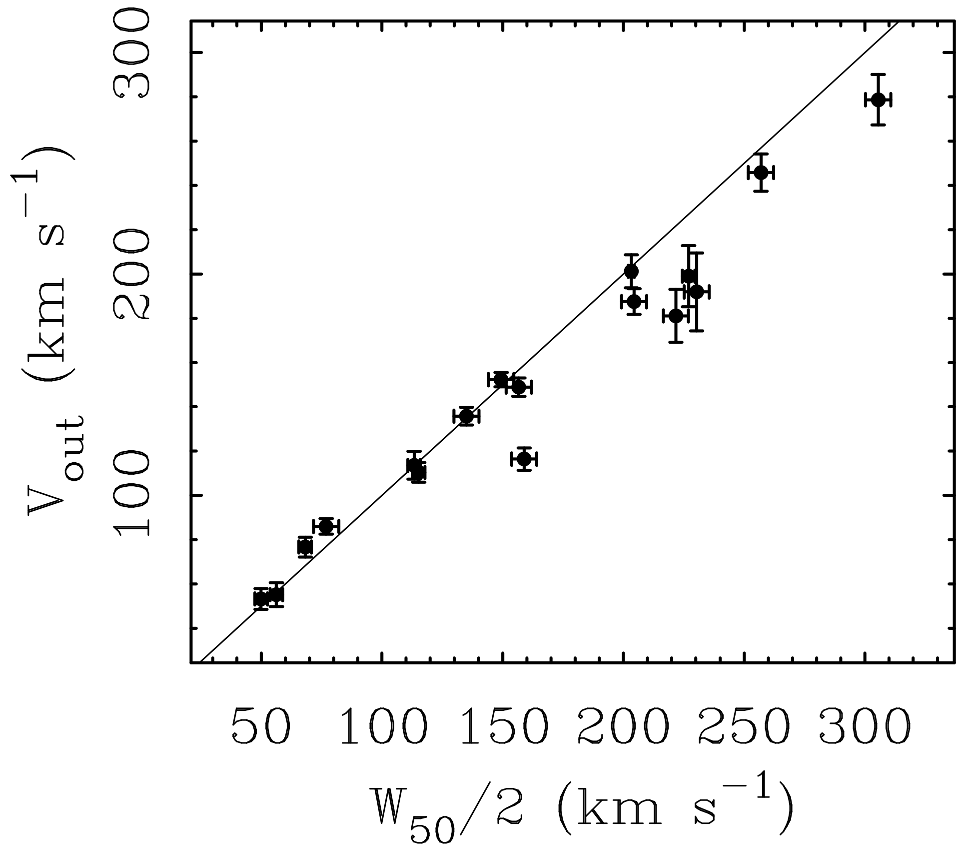




Velocity estimators:

V_{flat}

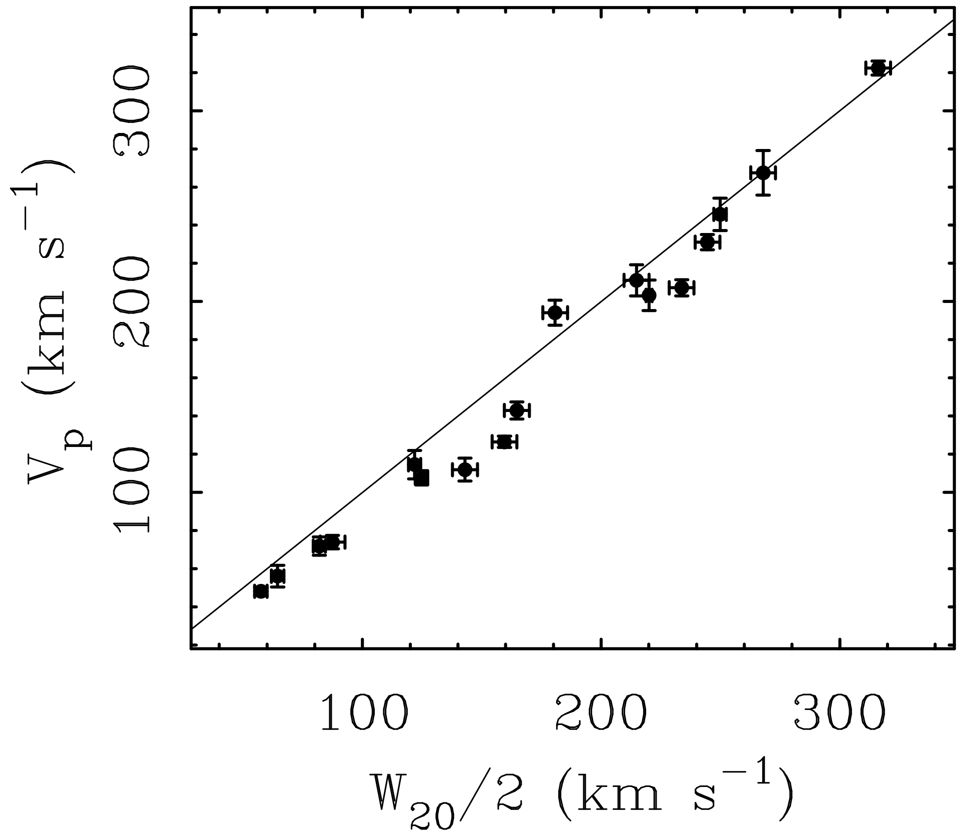


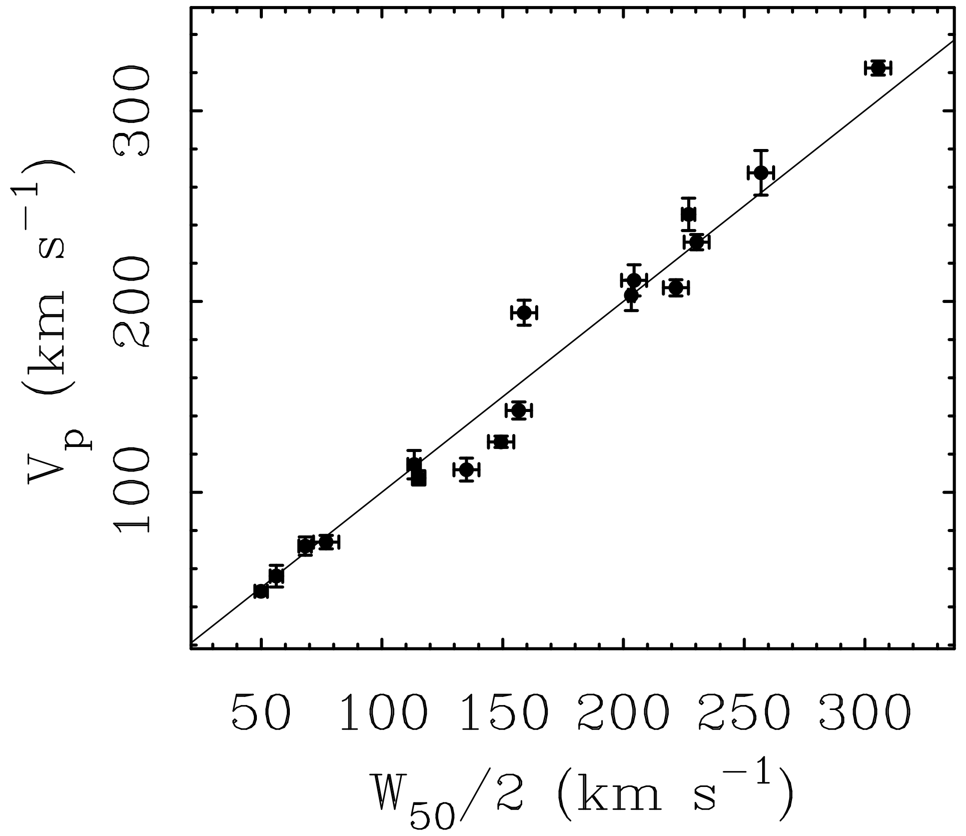


THINGS data
(Walter et al 2008)

W_{20} W_{50}

V_P

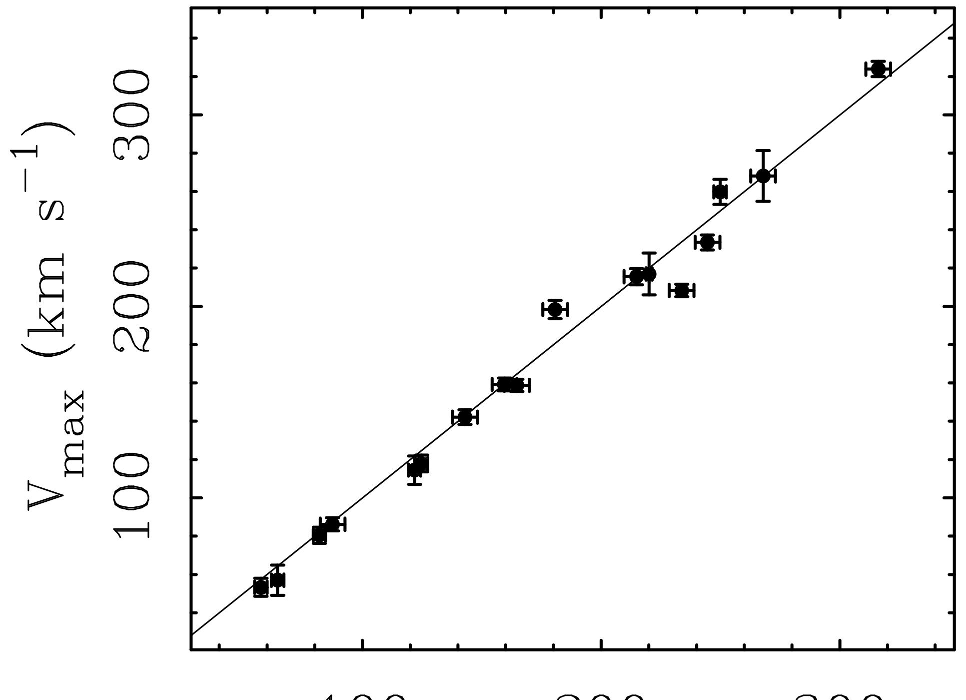


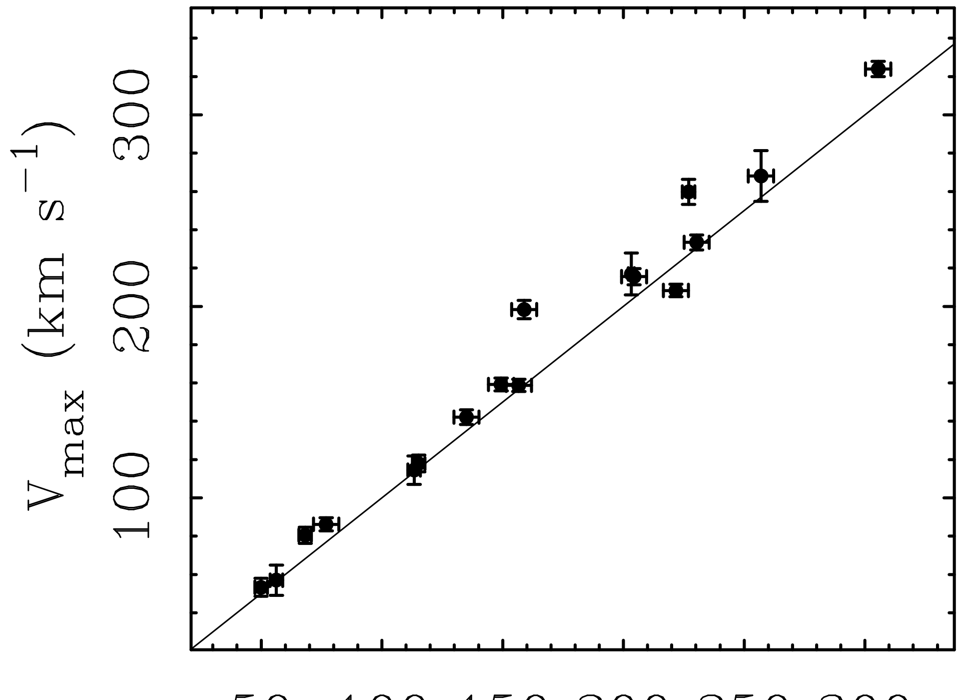


Different velocity measurements correlate but are not identical. TF relations fit using linewidths will differ from those fit using resolved rotation curves.

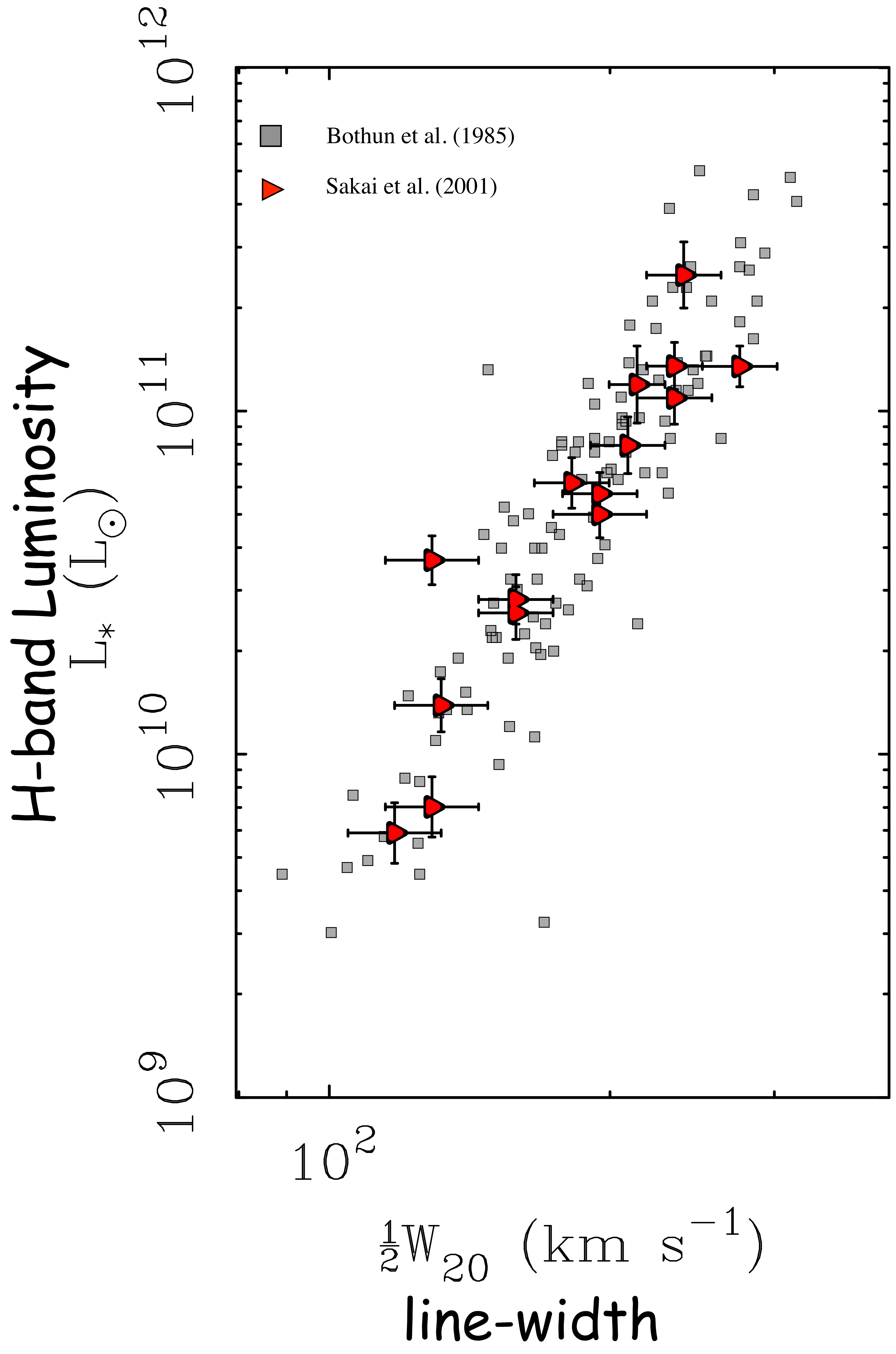
W_{20} W_{50}

V_{max}





Tully-Fisher relation



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

$$L = \frac{M_*}{(M_*/L)}$$

mass-to-light ratio of stellar population

(bandpass dependent)

$$M_* = f_d\,(f_b\,M_{200})$$

cosmic baryon fraction

detected baryon fraction

$$W_{20} \propto V_{max} \sim V_f$$

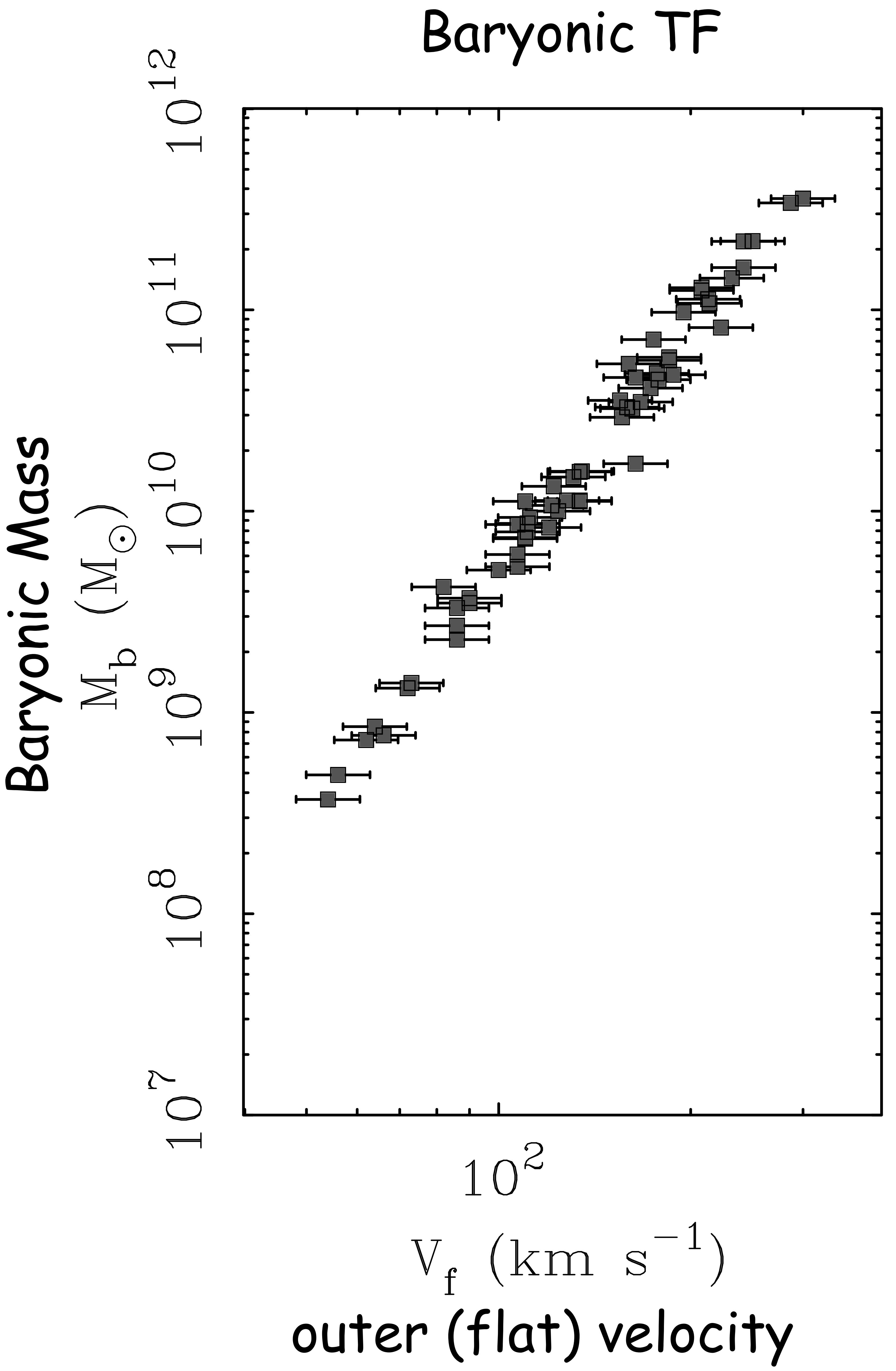
$$V_f = f_V V_{200}$$

$$V_{max} \stackrel{?}{=} f_{V_m} V_{max,halo}$$

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

$$M_b = M_* + M_g$$

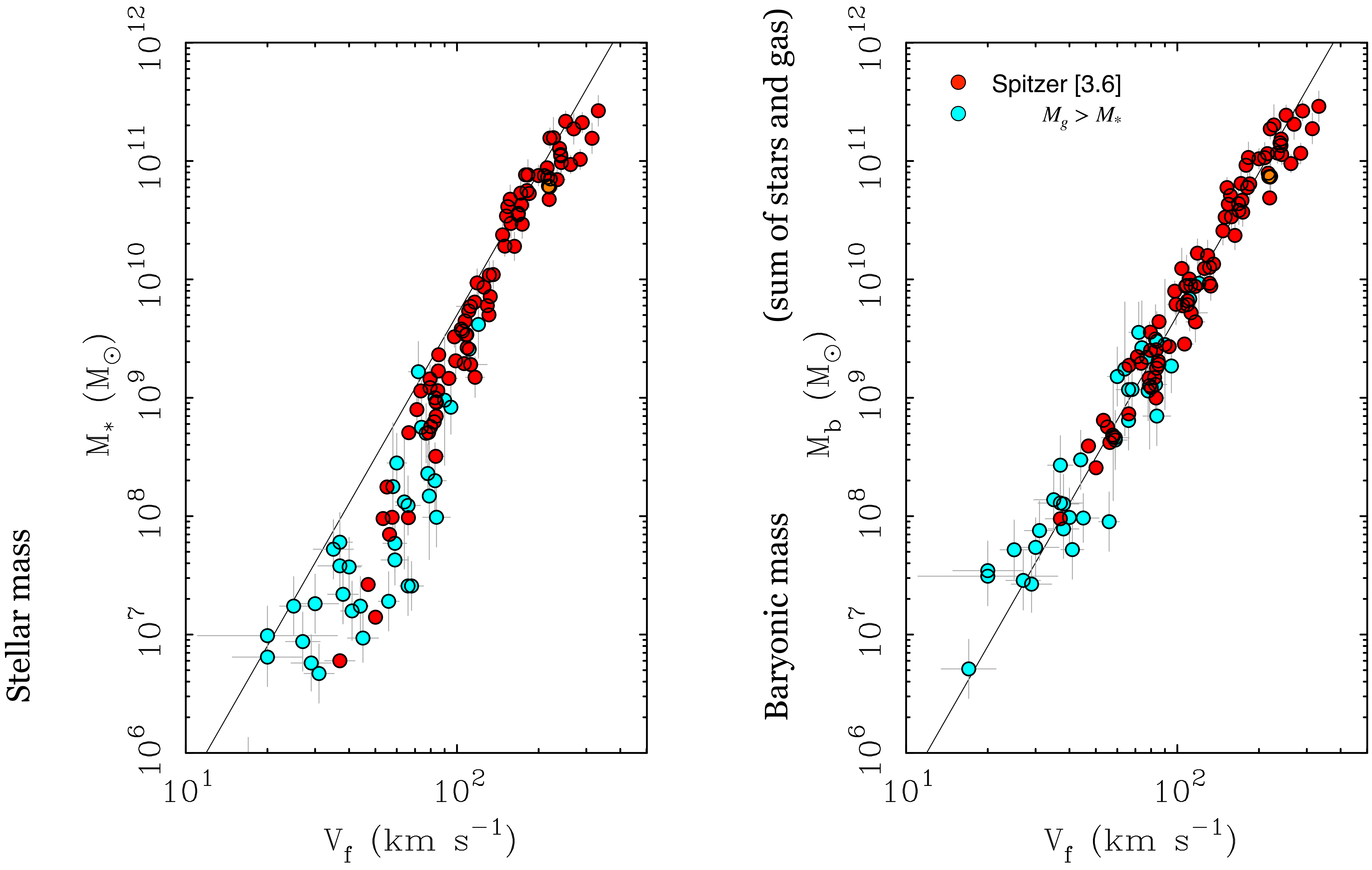
Baryonic mass is the important physical quantity. It doesn't matter whether the mass is in stars or in gas.



Tully-Fisher relations

amplitude of flat rotation correlates with mass

2019



flat rotation speed

Tully-Fisher relations

amplitude of flat rotation correlates with mass

2019

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

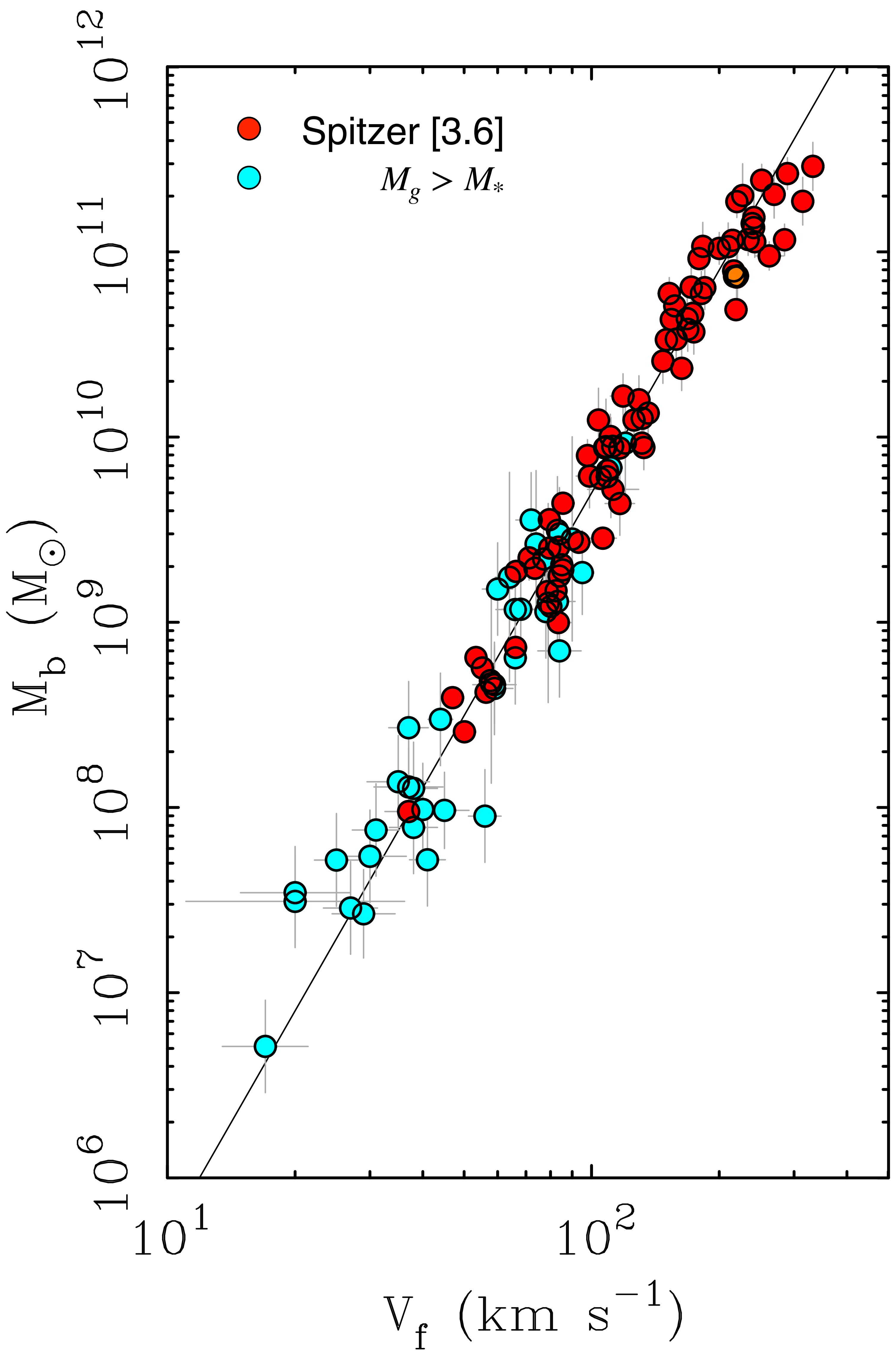
$$M_b = M_* + M_g = AV_f^4$$

$$A = 47 \pm 3\ \mathrm{M}_\odot\,(\mathrm{km\,s^{-1}})^{-4}$$

there is remarkably little
intrinsic scatter

$$\sigma_M < 0.11\ \mathrm{dex}$$

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

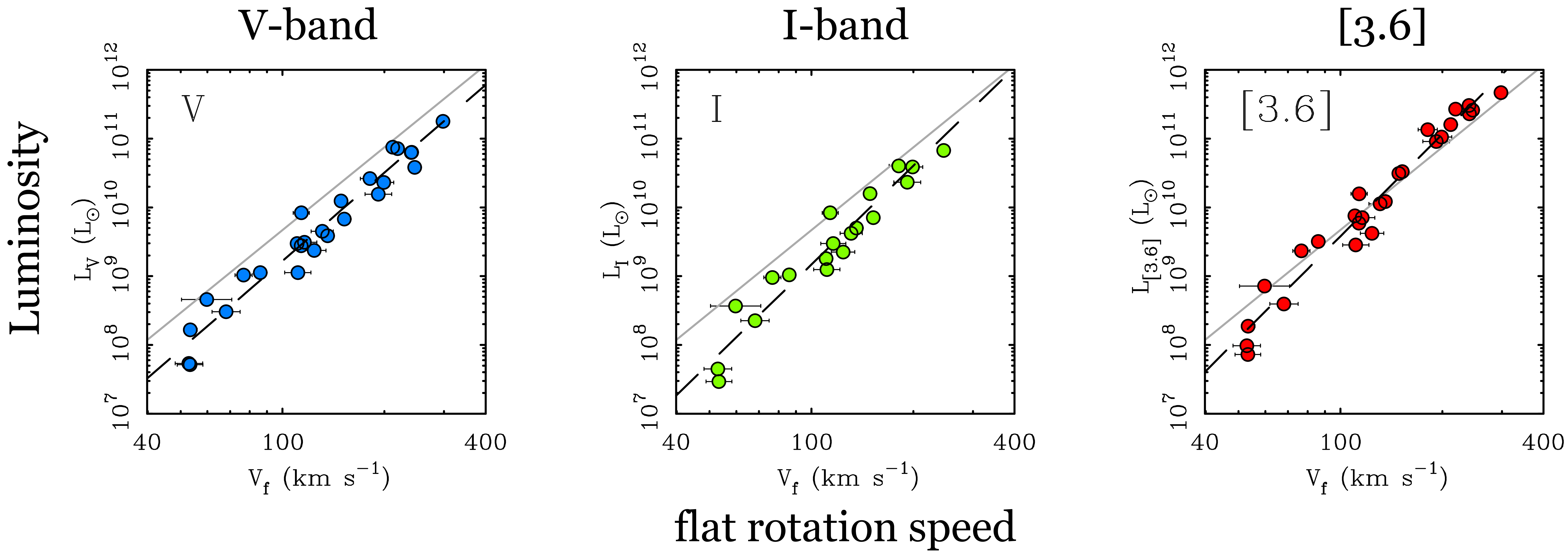


Baryonic mass (sum of stars and gas)

flat rotation speed

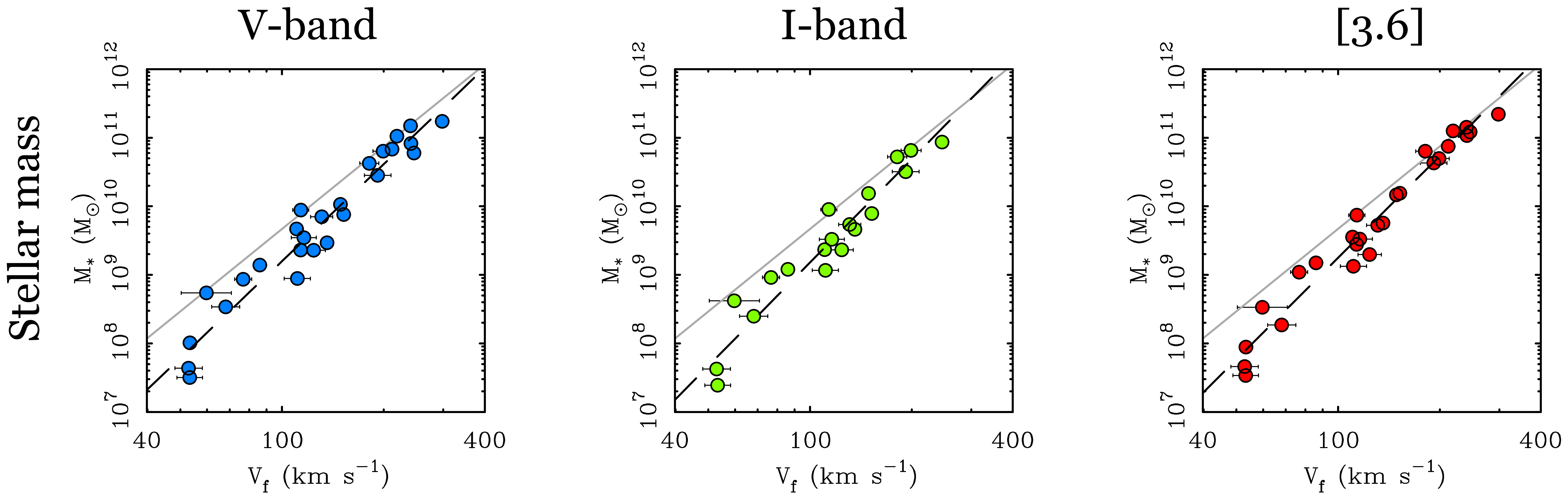
Population synthesis stellar mass-to-light ratios
should provide same answer irrespective of band

Raw luminosities



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

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



flat rotation speed

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

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

$$\Upsilon_*^{[3.6]} = 0.5\ \mathrm{M}_\odot/\mathrm{L}_\odot$$

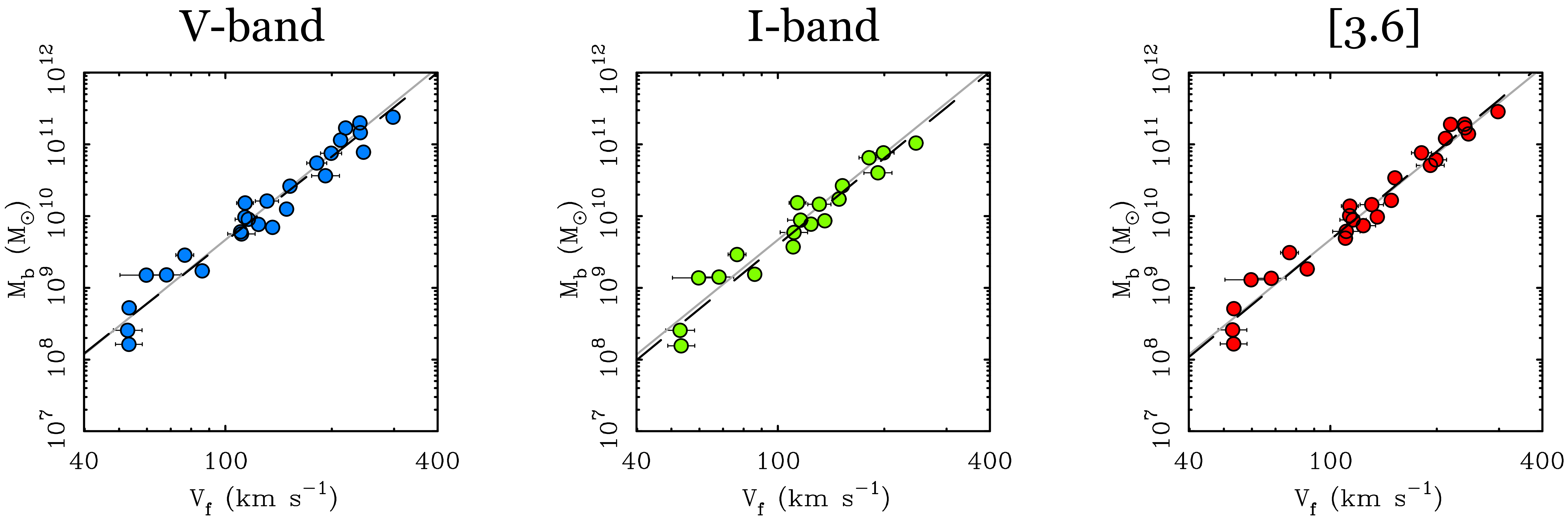
No perceptible color term

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

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

Baryonic mass $M_b = M_* + M_g$

Baryonic mass



flat rotation speed

McGaugh & Schombert (2015)