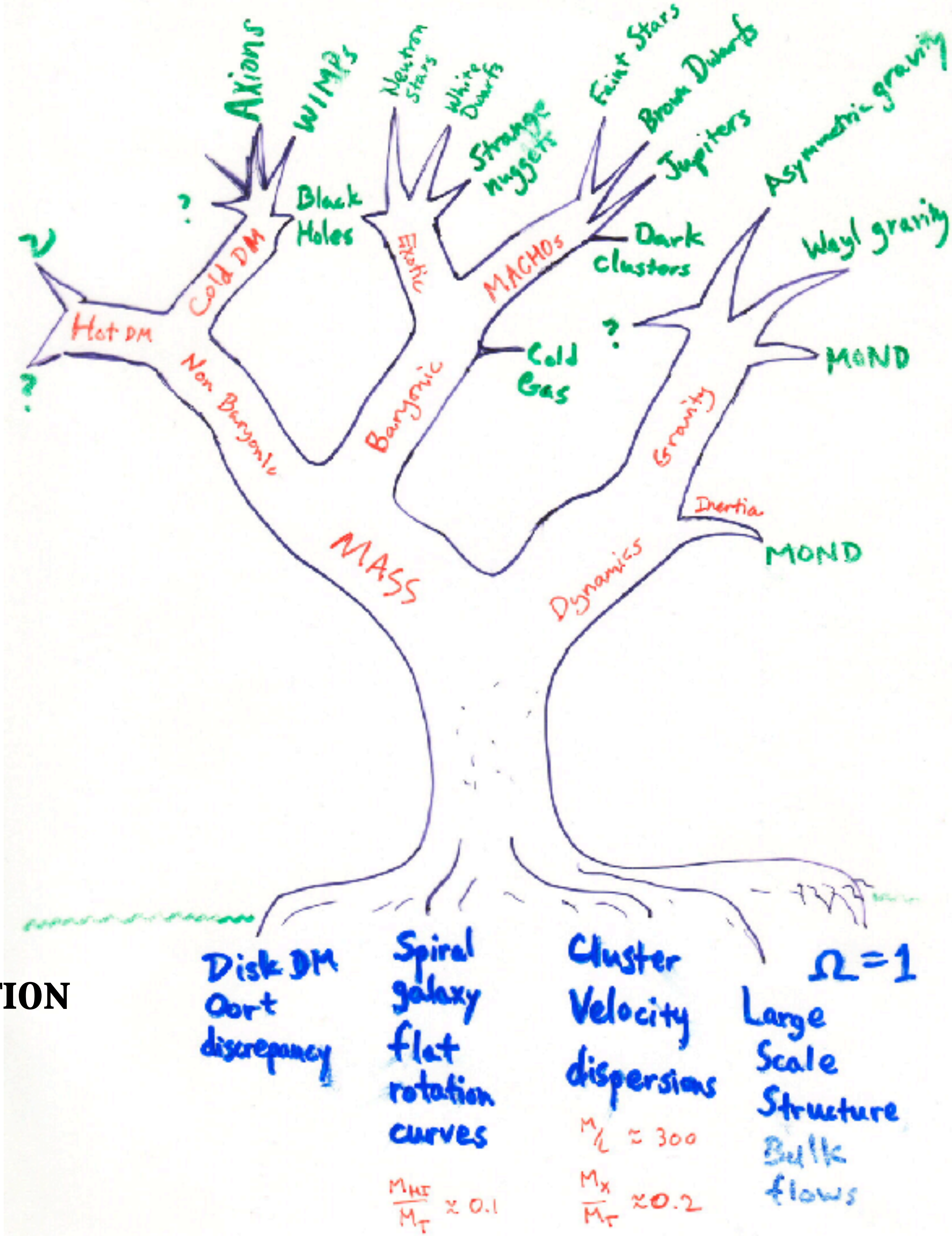
Dark Matter

ASTR 333/433
Spring 2018
T R 4:00-5:15pm
Sears 552

TODAY

- Laws of Galactic Rotation
  - Flat rotation curves
  - Tully-Fisher
  - Universal Rotation curve
  - central Density Relation
  - Renzo's Rule
  - Radial acceleration relation



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: $M_b = AV_f^4$

- Rotation curve shape varies with luminosity (Persic-Salucci "universal rotation curve")

  The shape of rotation curves varies systematically with luminosity, declining mildly at high L and rising slowly at low L: $V(R) = F(L, R_d)$

- 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 (Milgrom's Law)

  The observed centripetal acceleration is related to that predicted by the observed distribution of baryons:

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

$$\mathrm{g_{bar}} = \frac{V_{\mathrm{bar}}^2}{R} = -\frac{\partial \Phi_{\mathrm{bar}}}{\partial R}$$

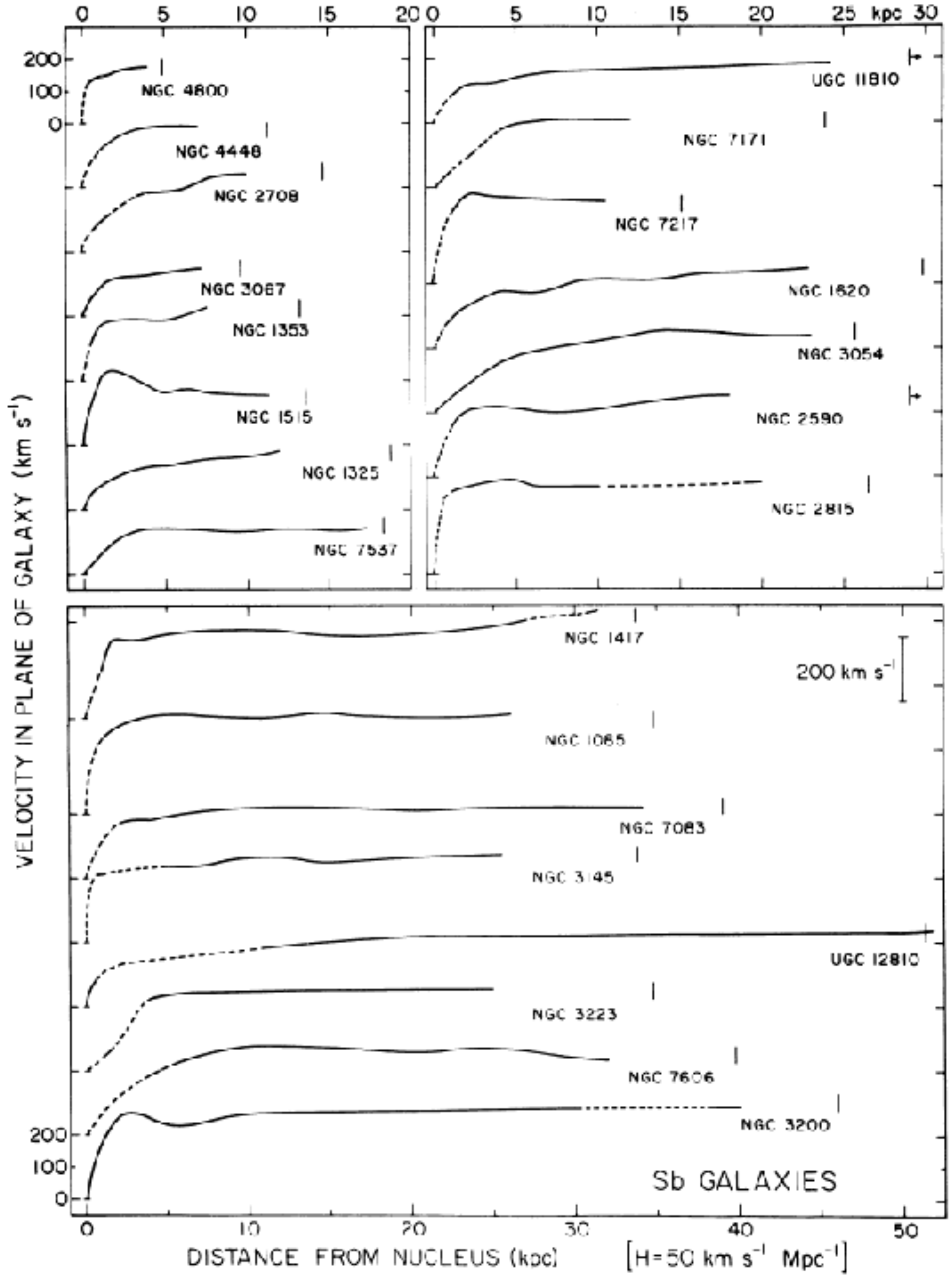


FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to increasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25},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

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

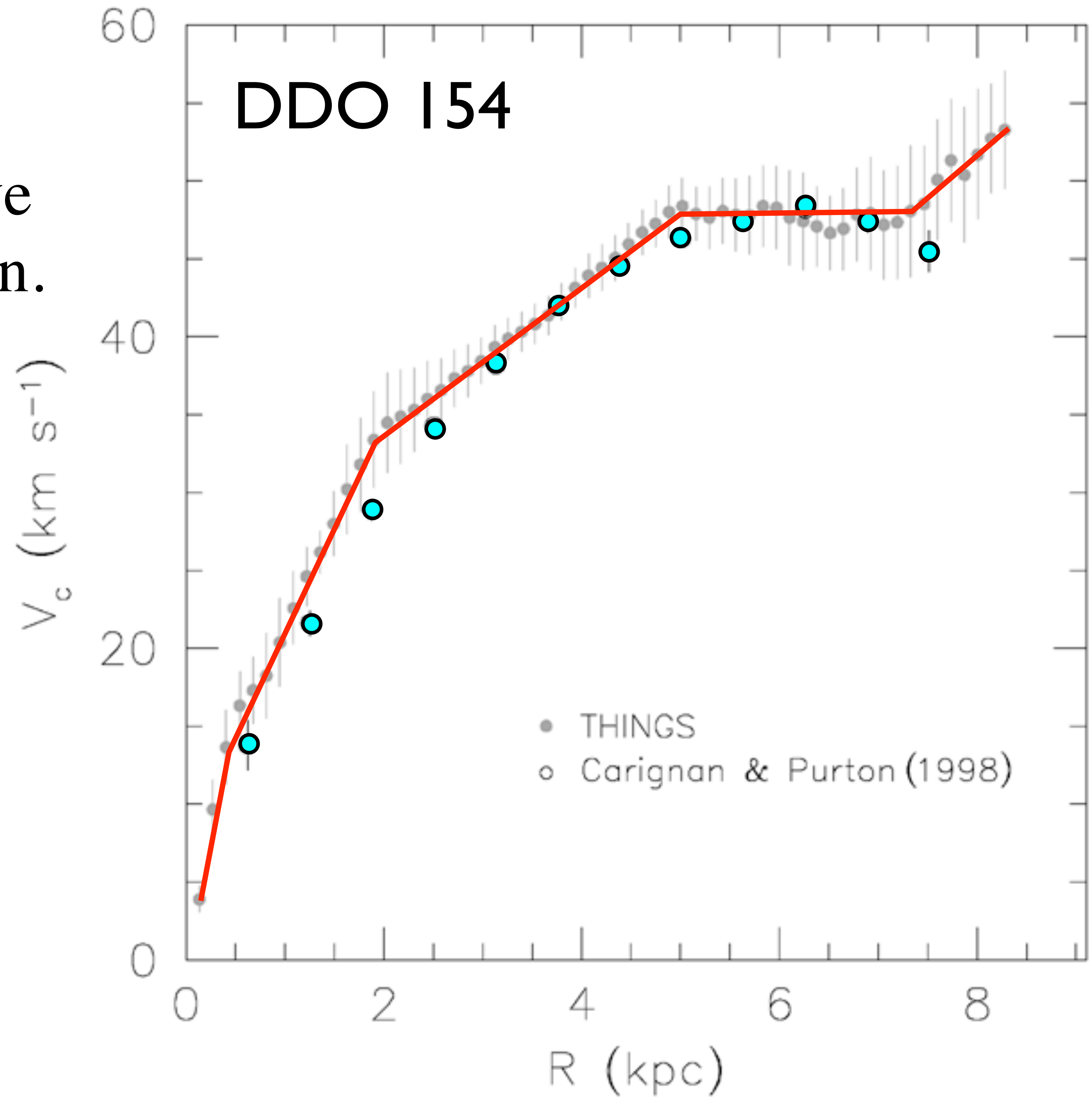
$$M \propto R$$

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

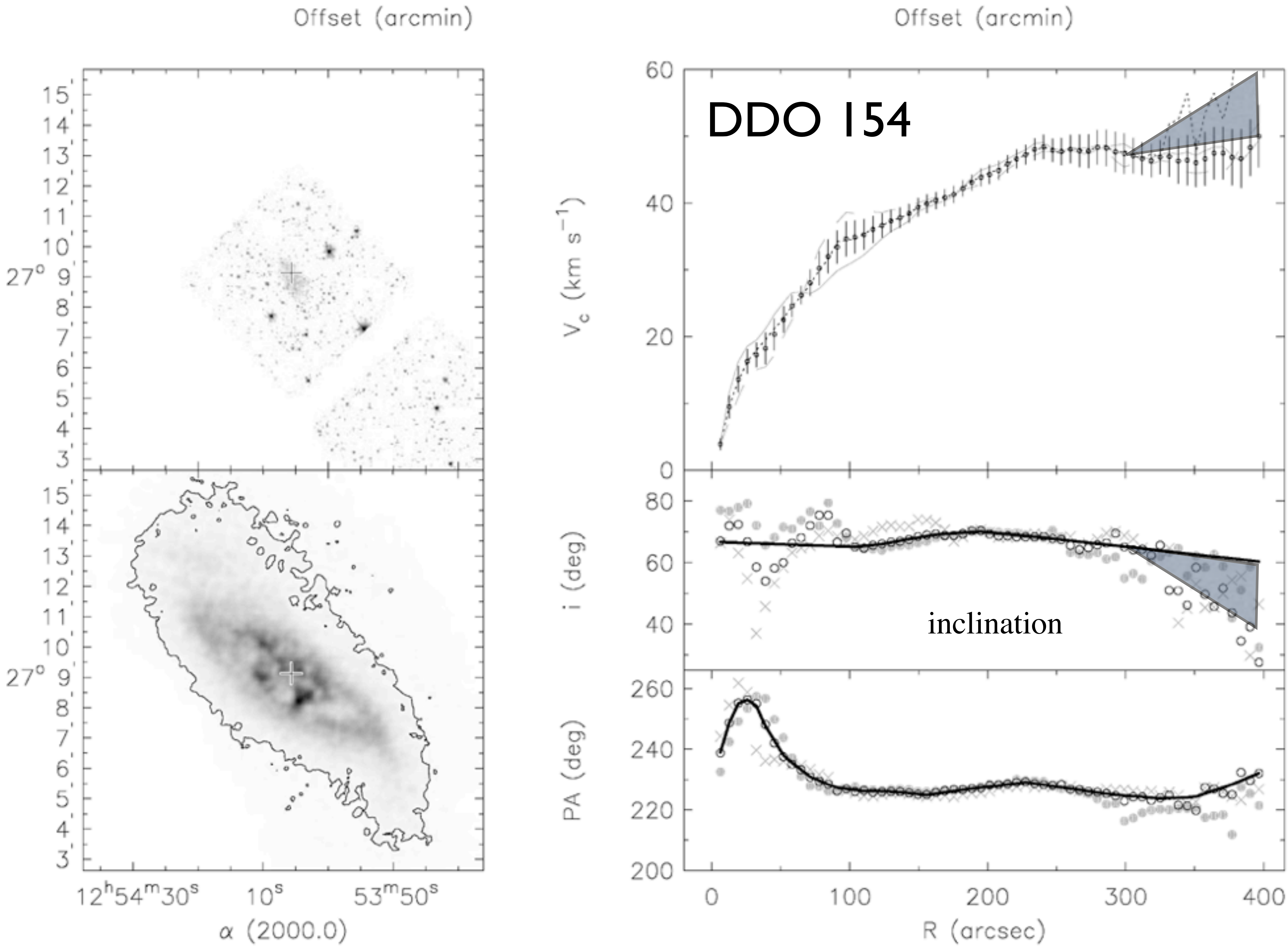
Optical data from Rubin, Thonnard, & Ford 1978, *ApJ*, **225**, L107

Presumably this behavior cannot persist indefinitely, but there are no clear counter-examples.

Cases where rotation curves were thought to perhaps be declining have so far turned out to flatten.



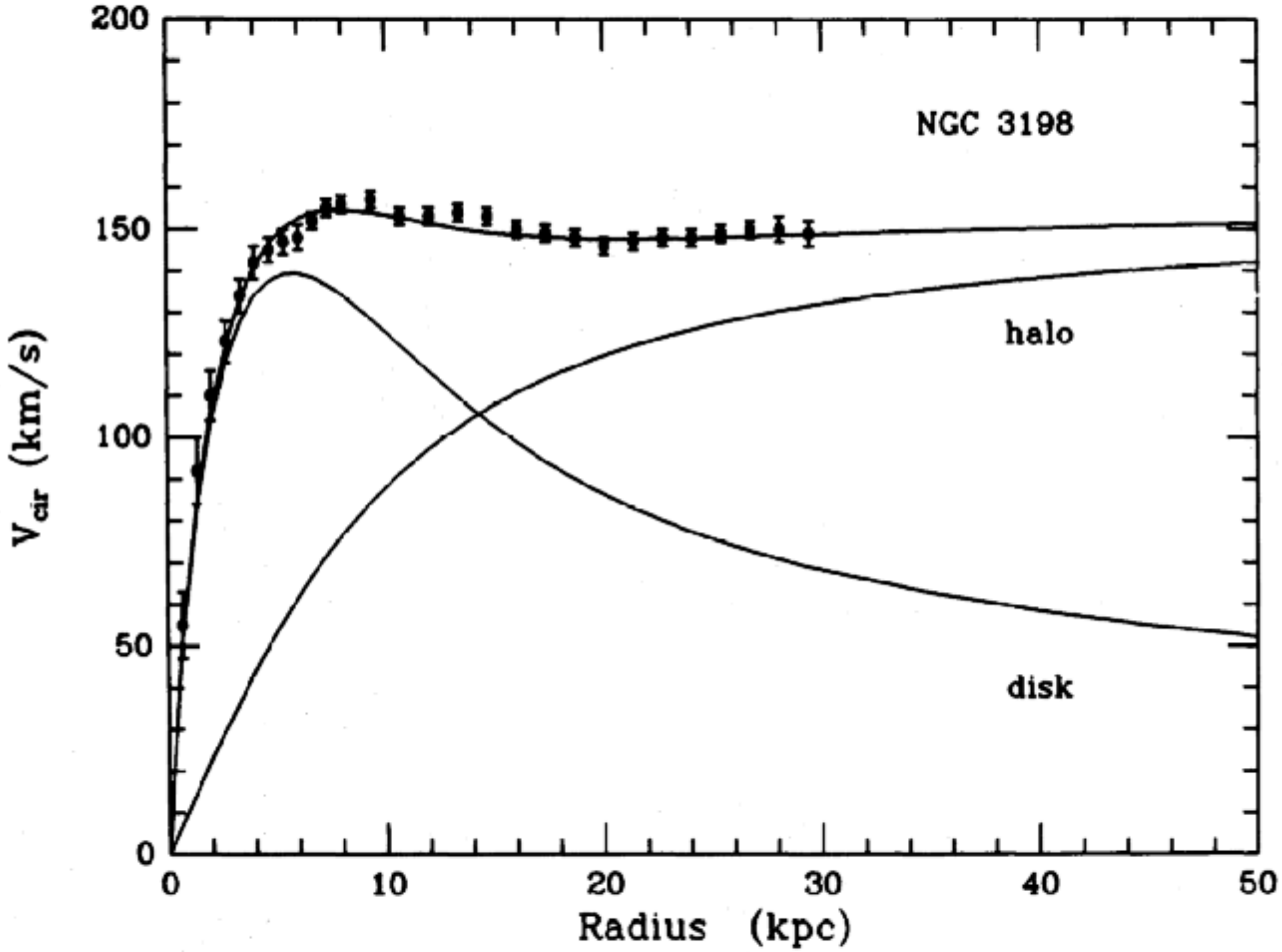
de Blok et al. (2008 [THINGS]):
"We do not find steep declines in velocity in the outer rotation curves of NGC 3521, NGC 7793, DDO 154, and NGC 2366. Where declines are observed, they are gentler, and (within the uncertainties in rotation velocity and inclination) consistent with flat rotation curves."


Offset (arcmin)
Offset (arcmin)
DDO 154
inclination
V_c (km s^{-1})
i (deg)
PA (deg)
R (arcsec)
α (2000.0)
27°
12h54m30s
10s
53m50s

Mass models

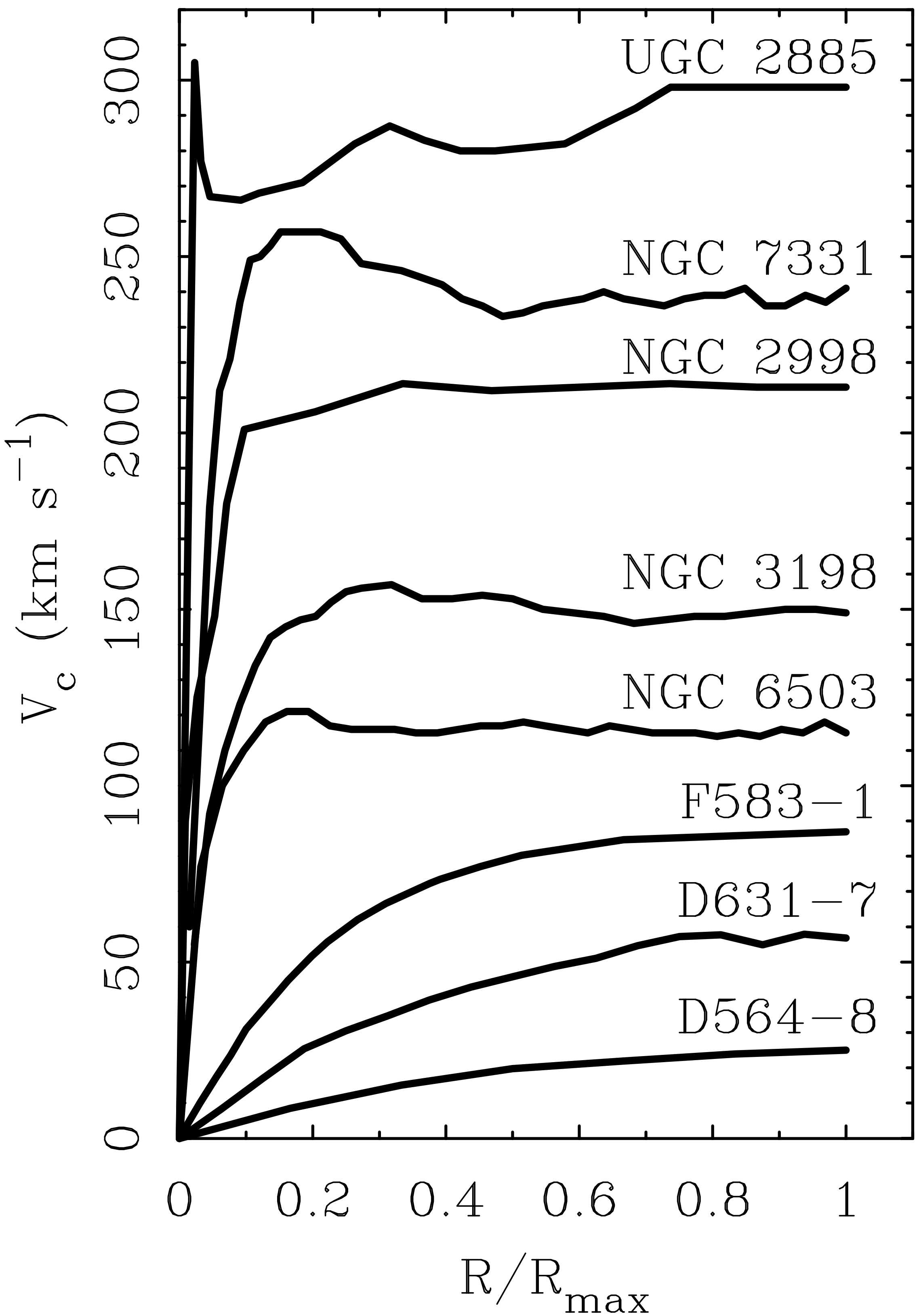
van Albada et al. (1985)

DISTRIBUTION OF DARK MATTER IN NGC 3198

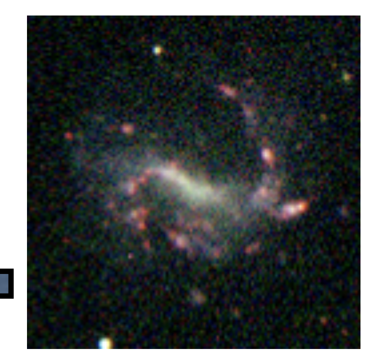


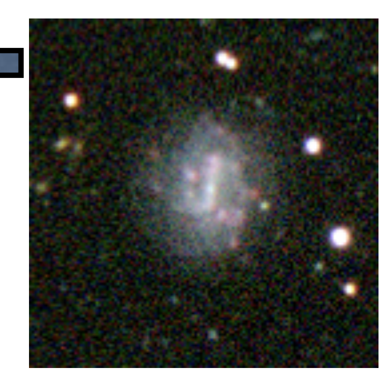
$$V_{tot}^2 = V_{disk}^2 + V_{halo}^2$$

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



star dominated HSB



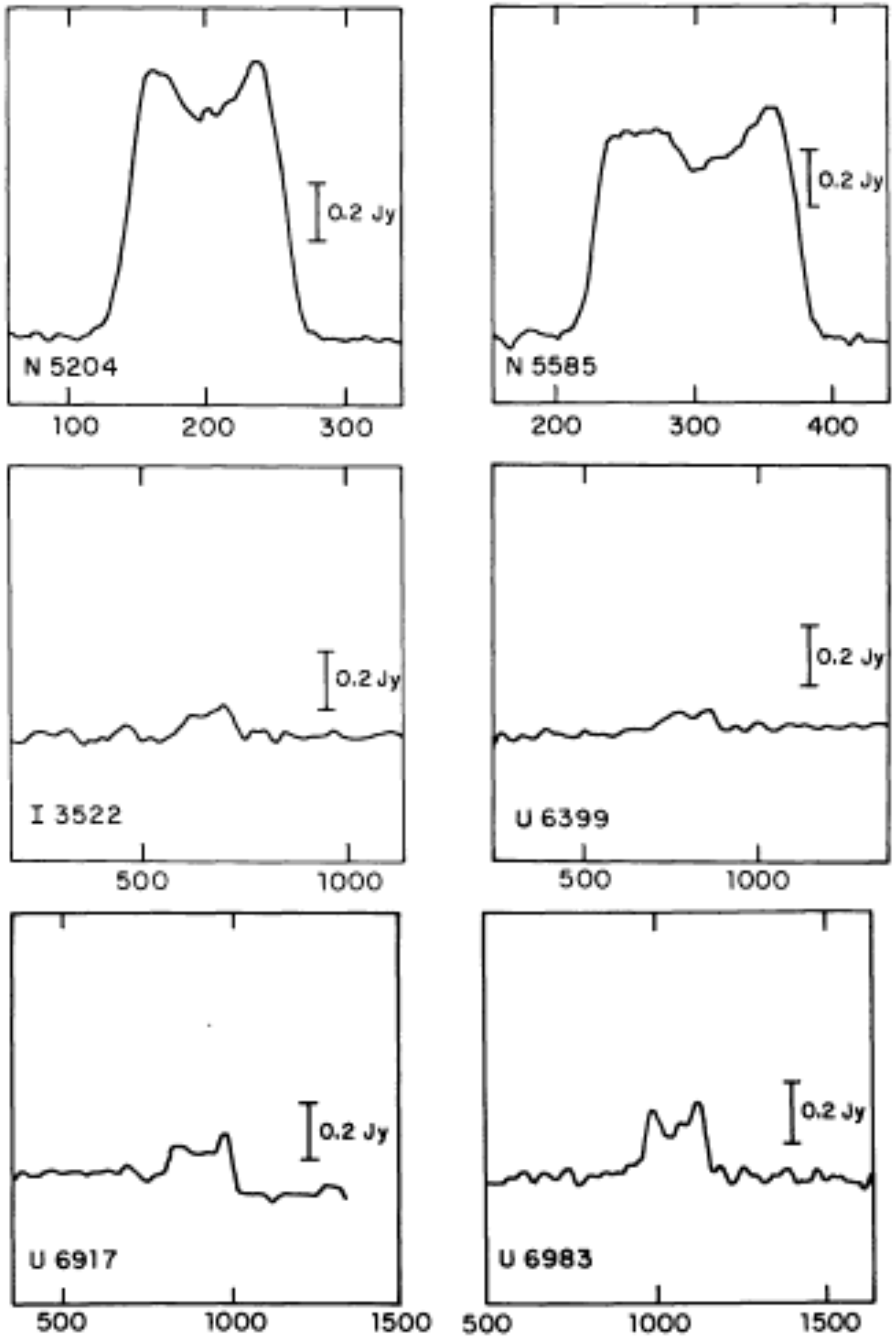


gas dominated LSBs

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?



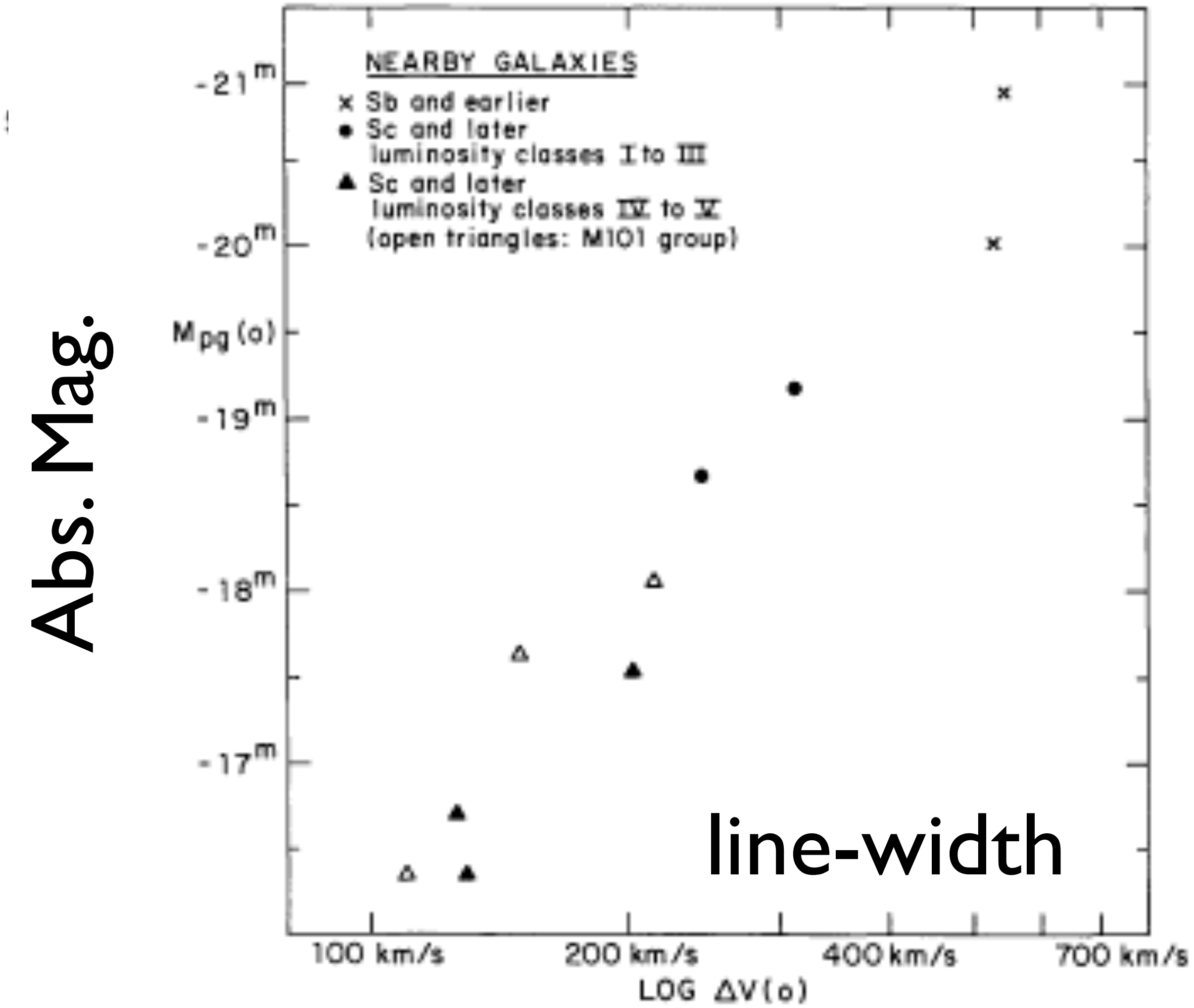


Fig. 1. Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

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*)
  - Worry about internal extinction, 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]

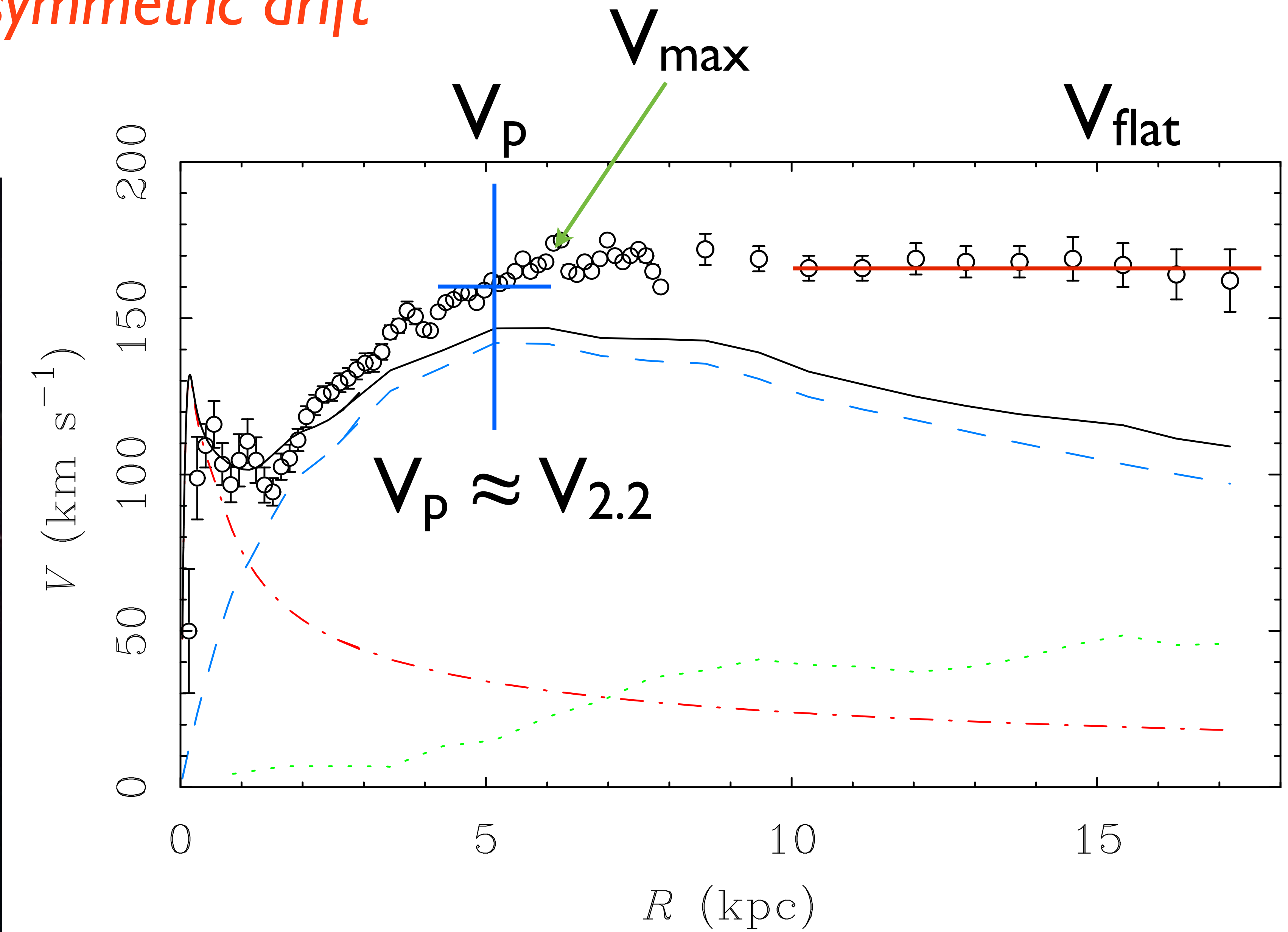
Daigle et al (2006) [Ha]

Blais-Ouellette et al (2004)

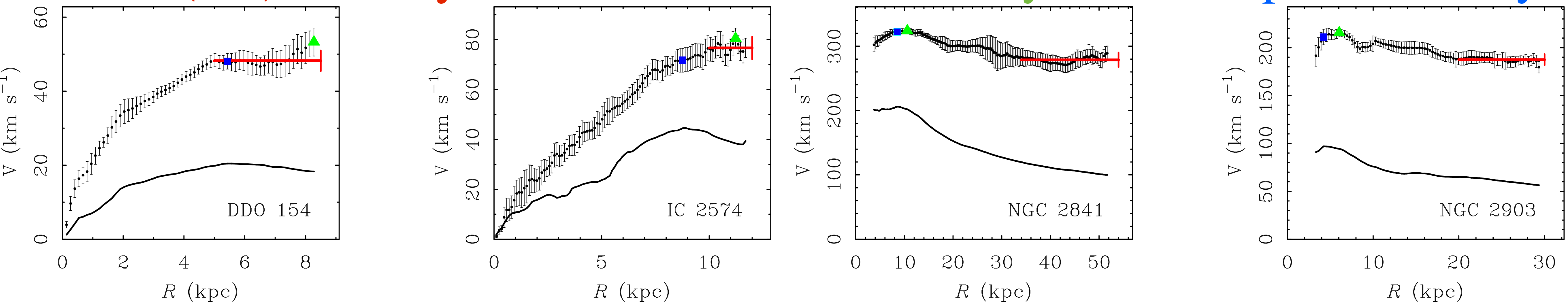
Mass model built from

2MASS K-band data (SSM)

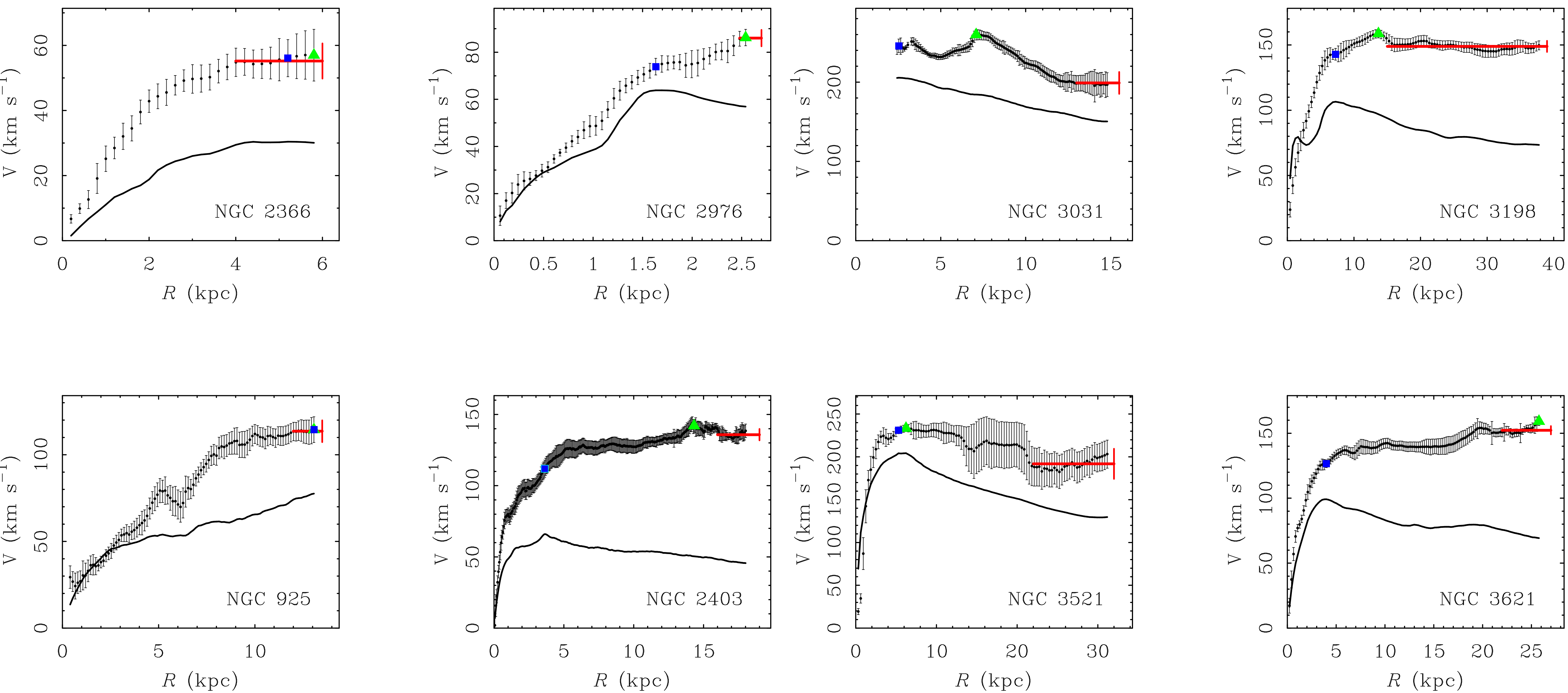
NGC 6946



outer (flat) velocity maximum velocity peak velocity

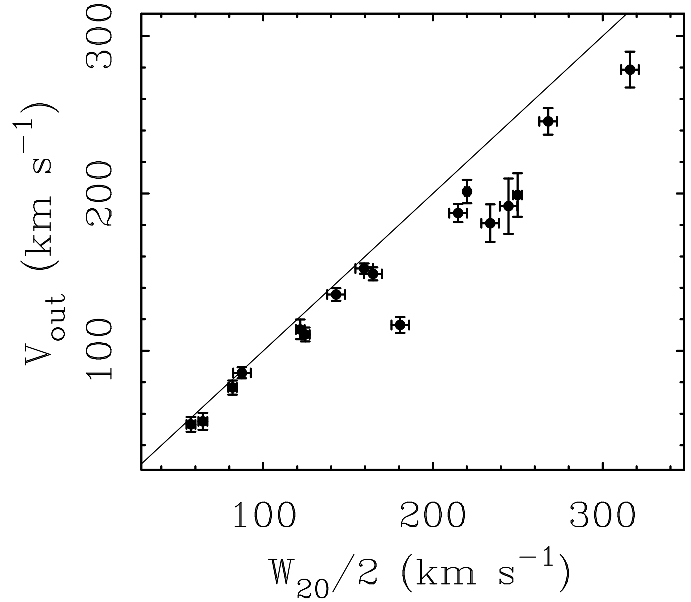


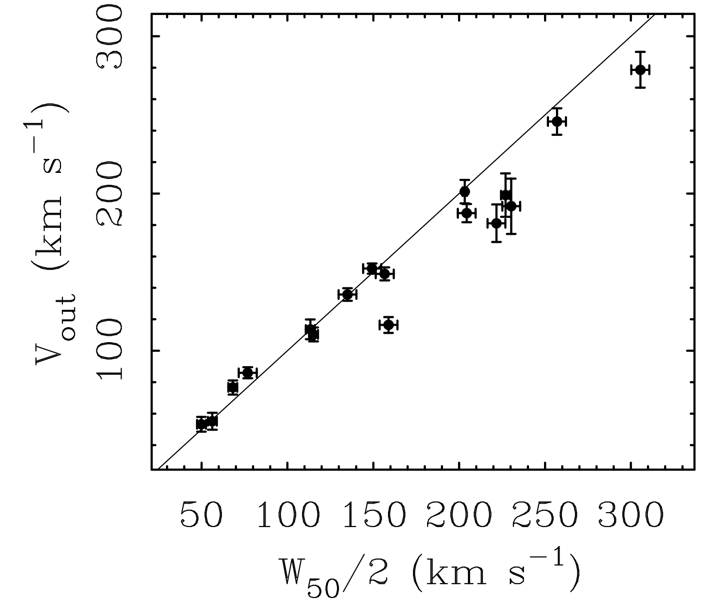
THINGS data (Walter et al 2008)



Velocity estimators:

V_{flat}

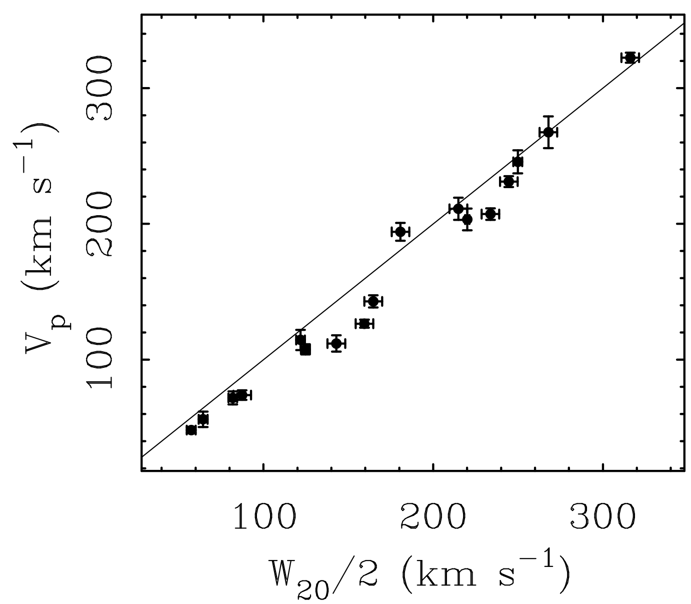


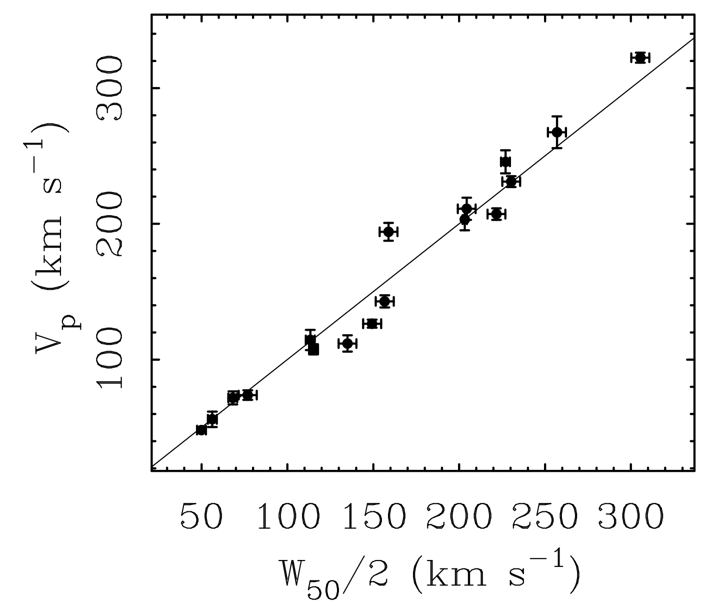


W_{20} W_{50}

THINGS data
(Walter et al 2008)

V_p

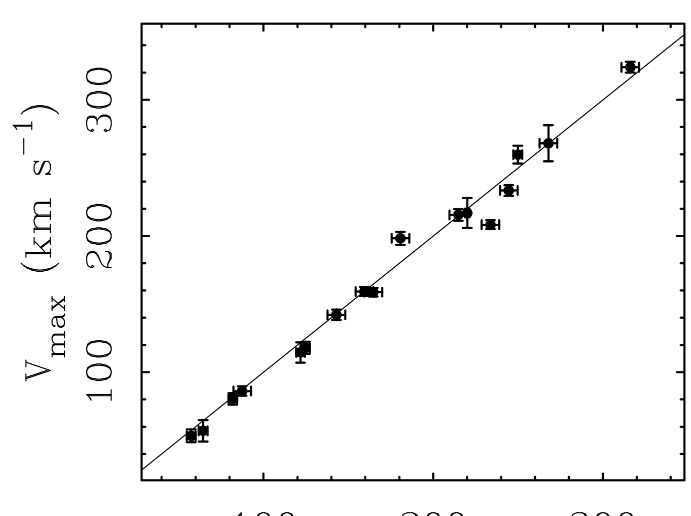


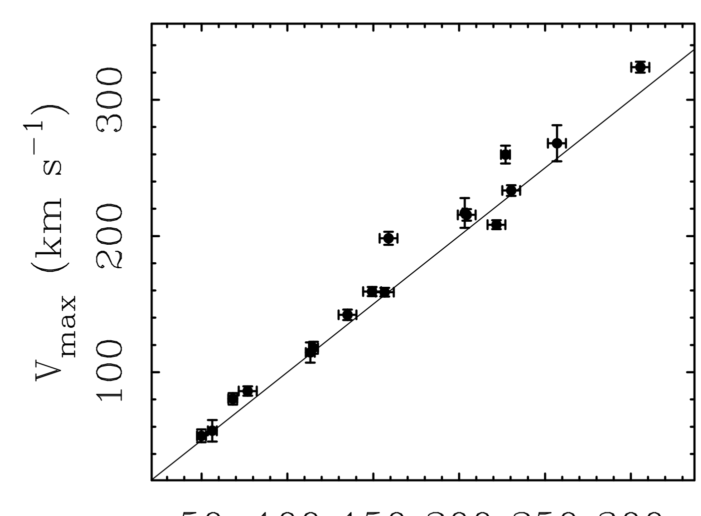


W_{20} W_{50}

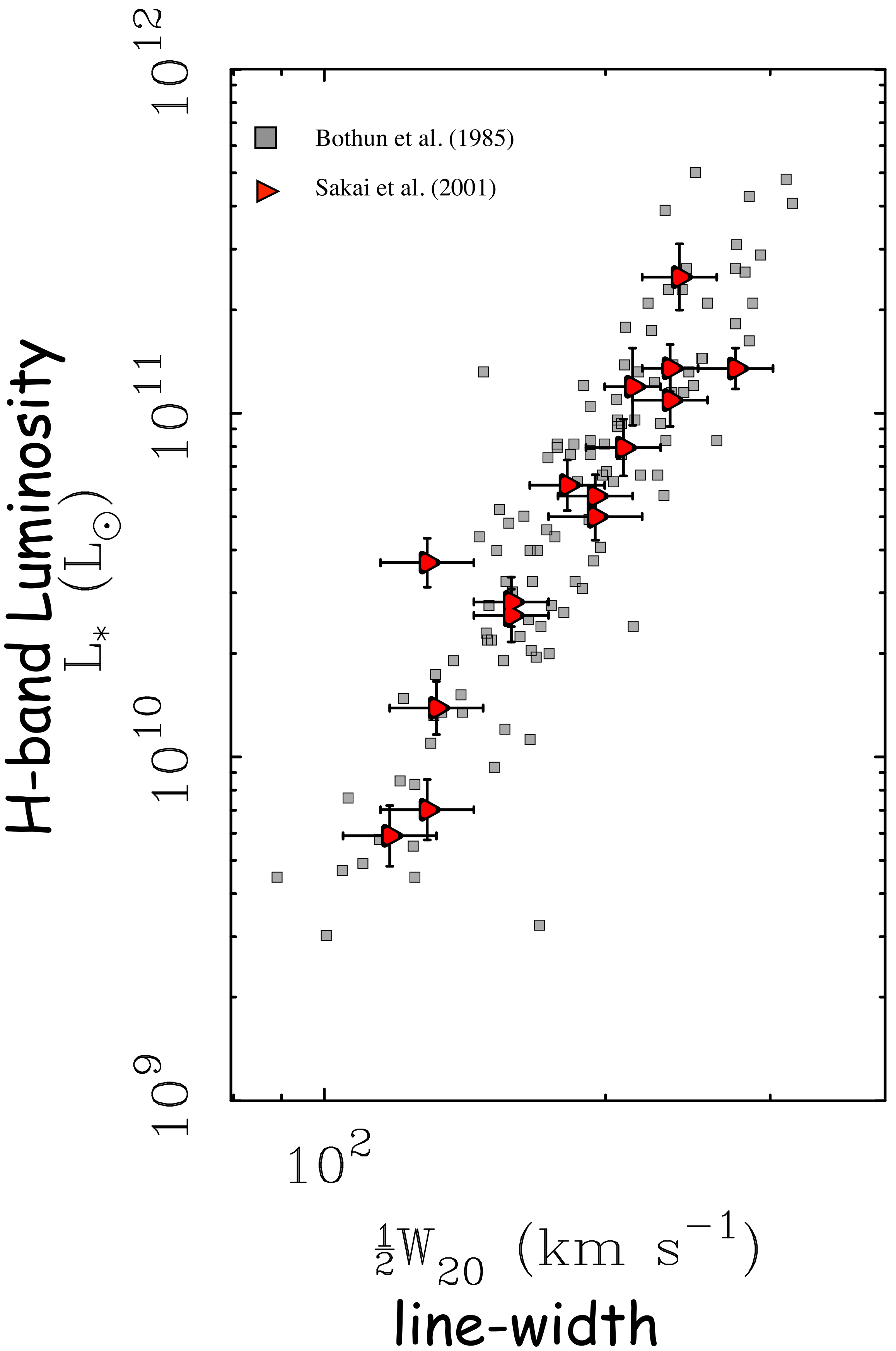
Different velocity measurements correlate but are not identical. TF relations fit using linewidths will differ from those fit using resolved rotation curves.

V_{max}



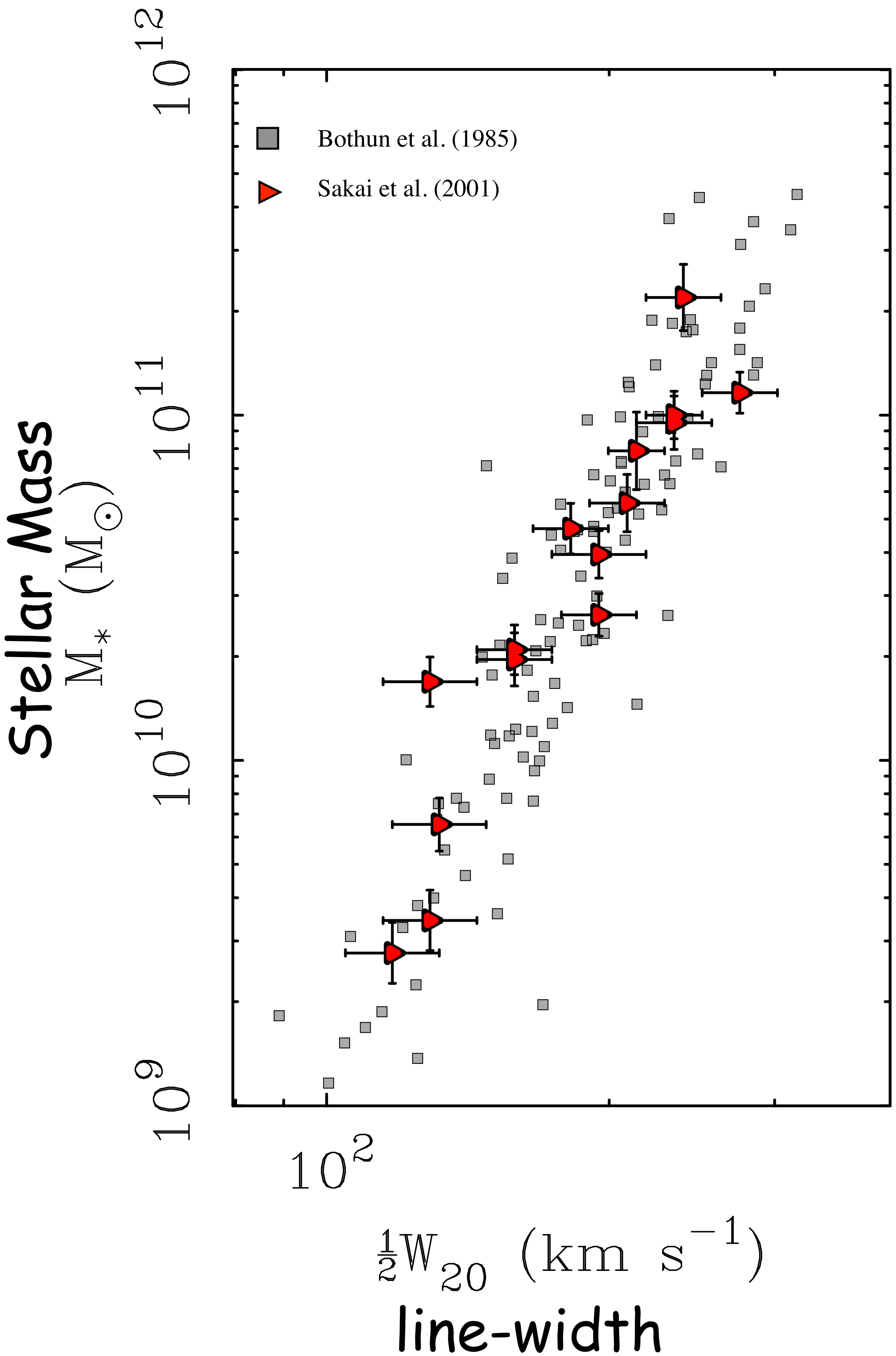


Tully-Fisher relation



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

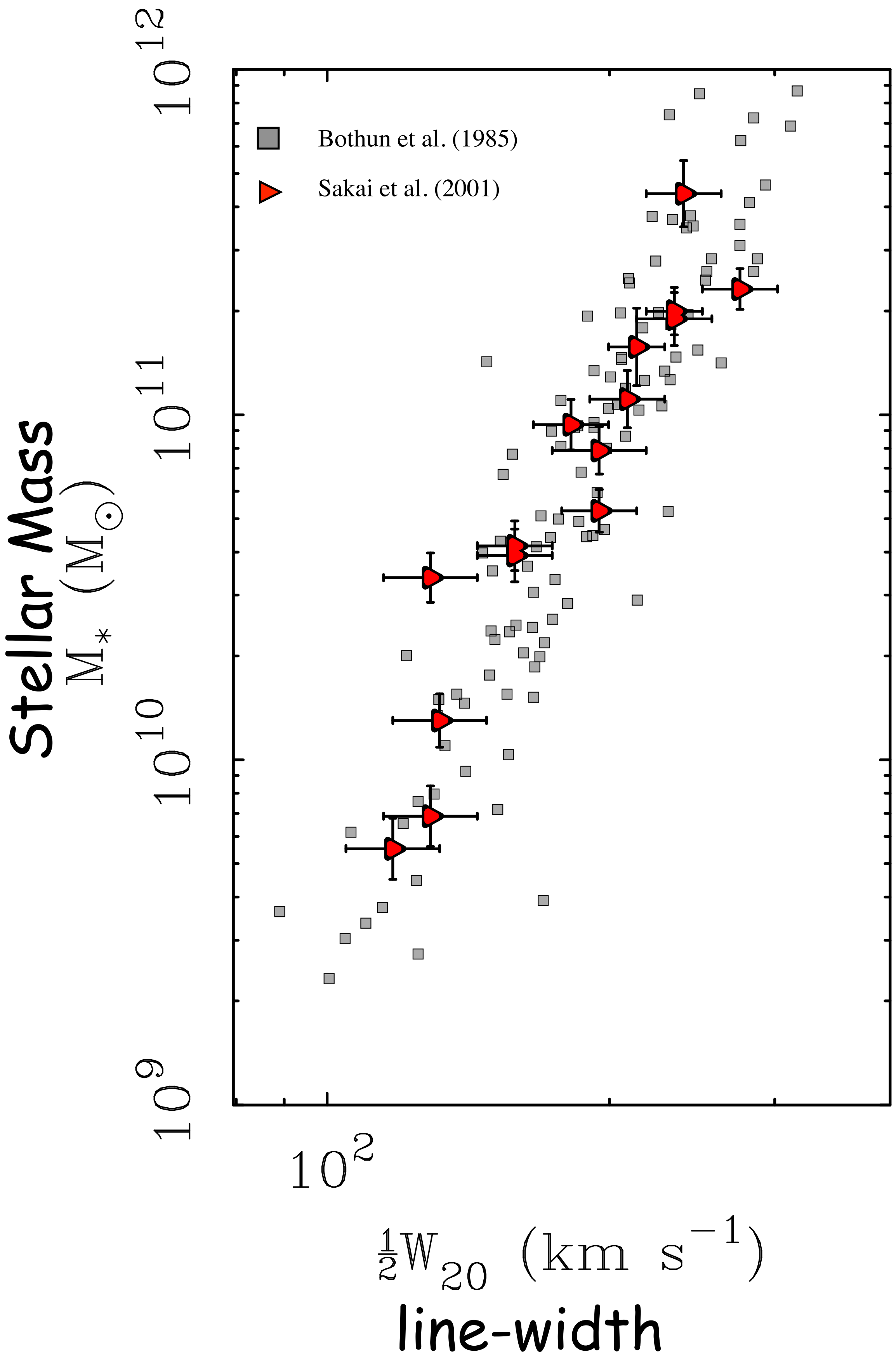
Stellar Mass Tully-Fisher relation



nominal M*/L (Kroupa IMF)

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

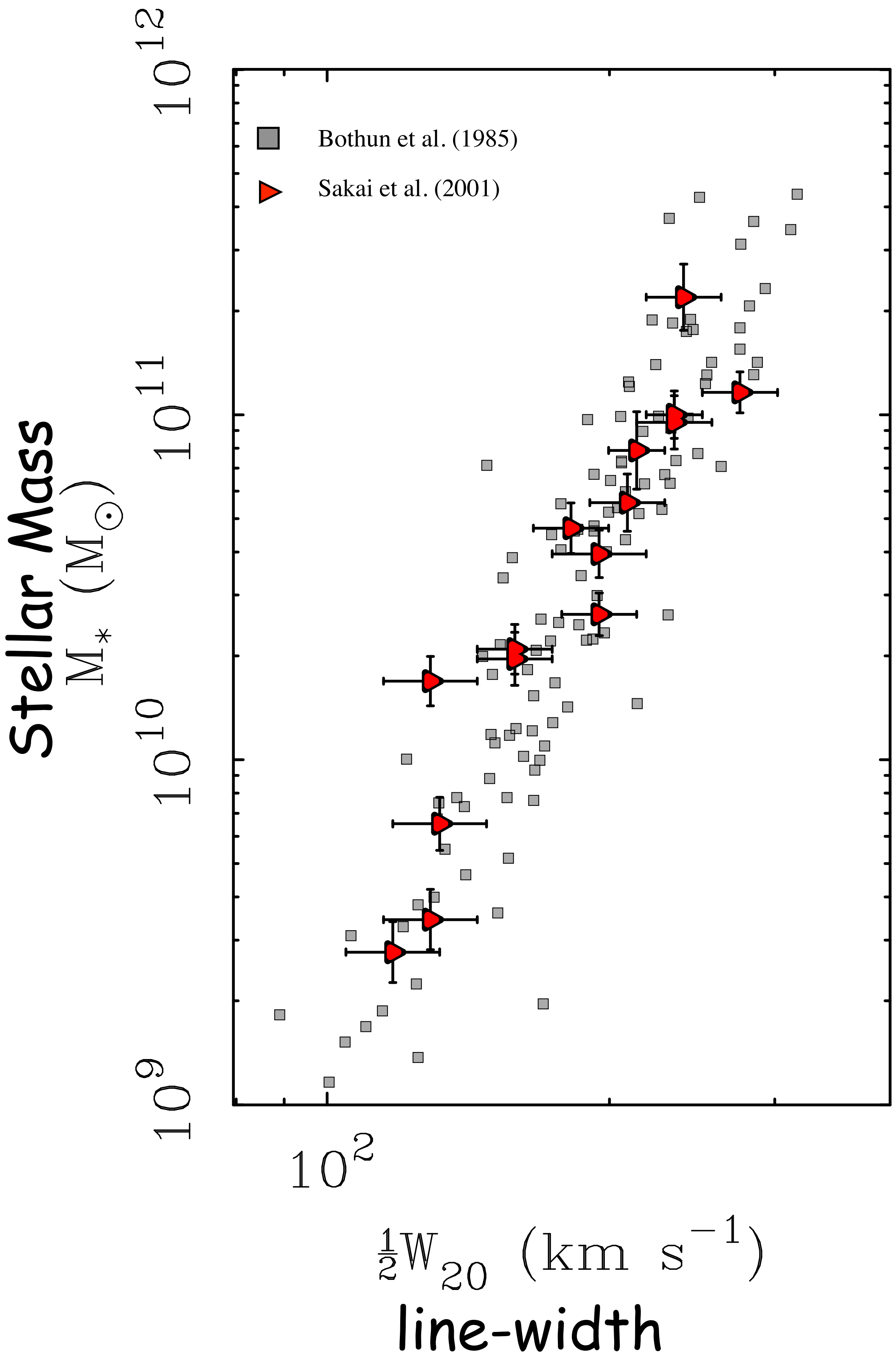
Stellar Mass Tully-Fisher relation



double M*/L

...but stellar mass is completely dependent on choice of mass-to-light ratio (and degenerate with distance)

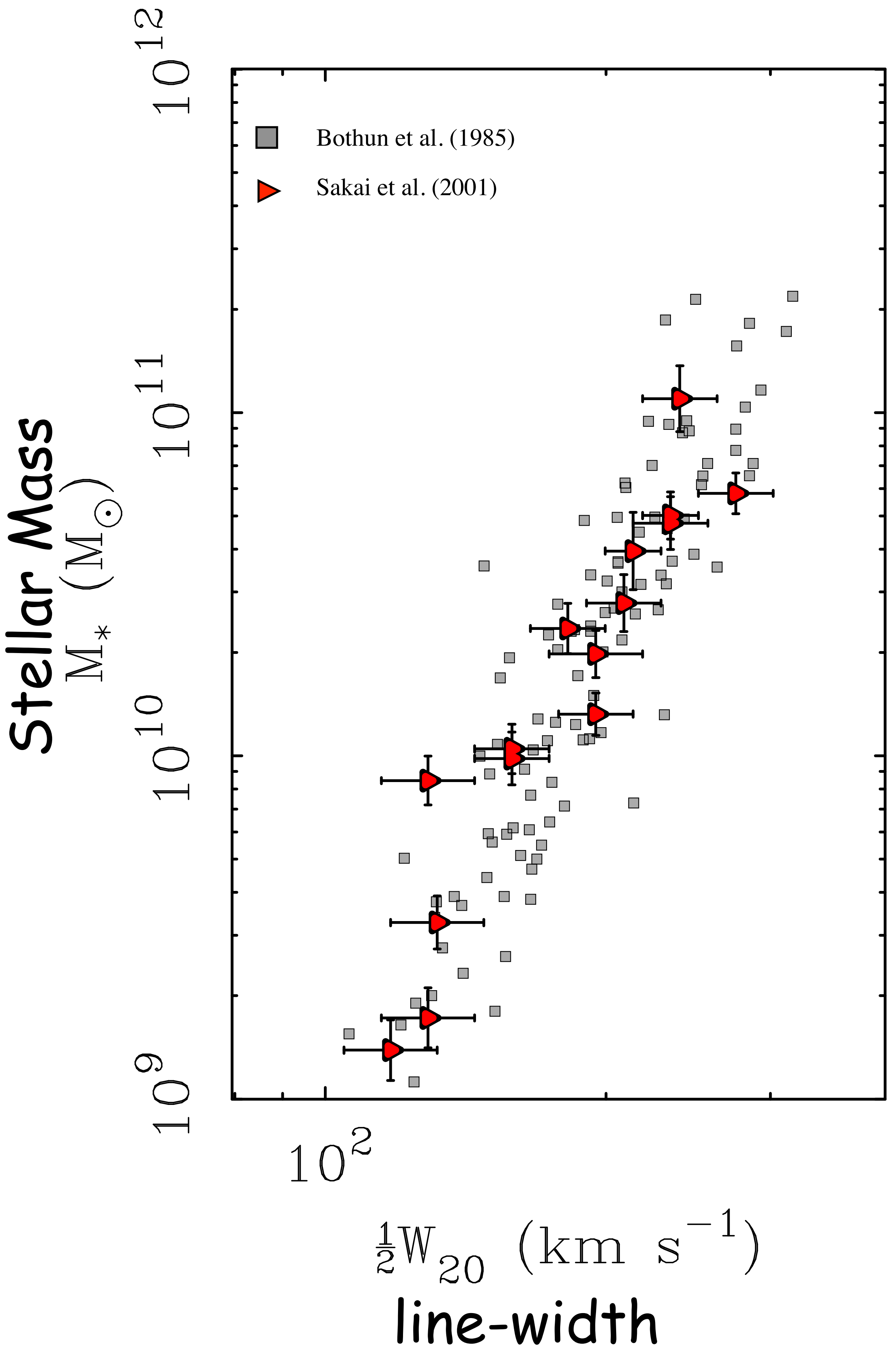
Stellar Mass Tully-Fisher relation



nominal M*/L

...but stellar mass is completely dependent on choice of mass-to-light ratio (and degenerate with distance)

Stellar Mass Tully-Fisher relation



half M*/L

...but stellar mass is completely dependent on choice of mass-to-light ratio (and degenerate with distance)

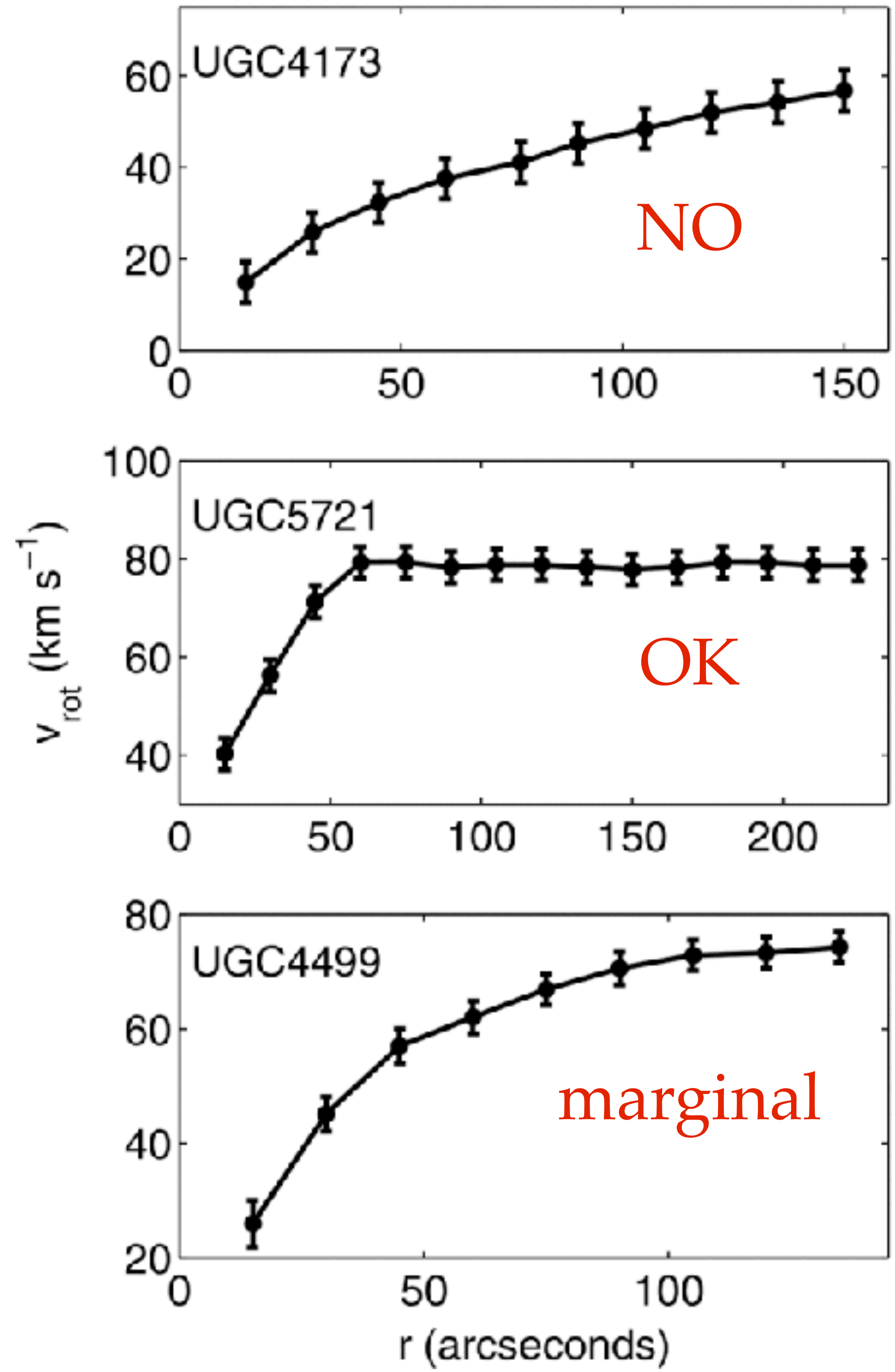
Stark, McGaugh, & Swaters et al. (2009)

If you want to use Vflat, you have to observe far enough out to measure it.

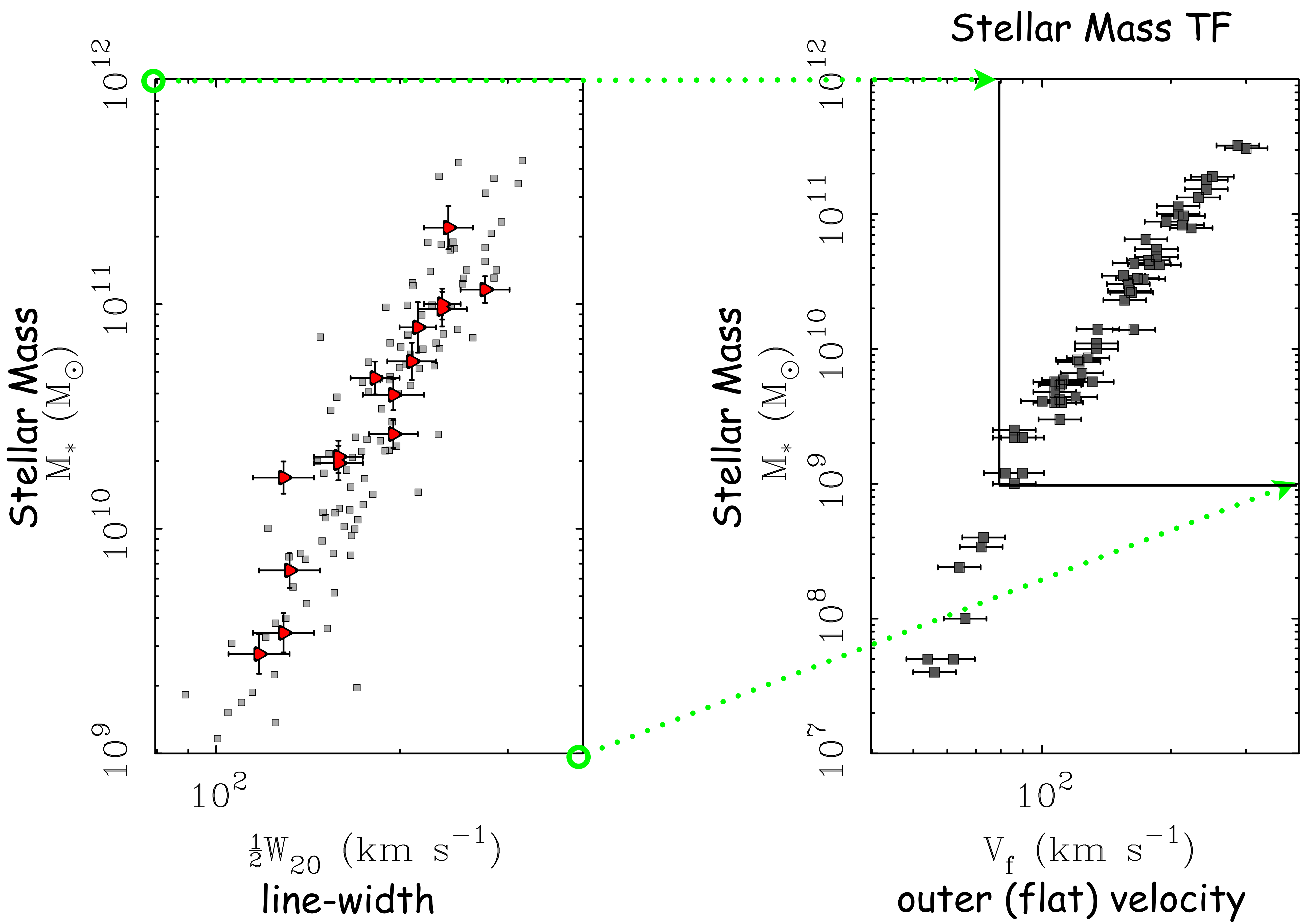
$$\frac{\partial \log V}{\partial \log R} < 0.1$$

works well as a criterion.

Scatter in TF increases as threshold weakened.

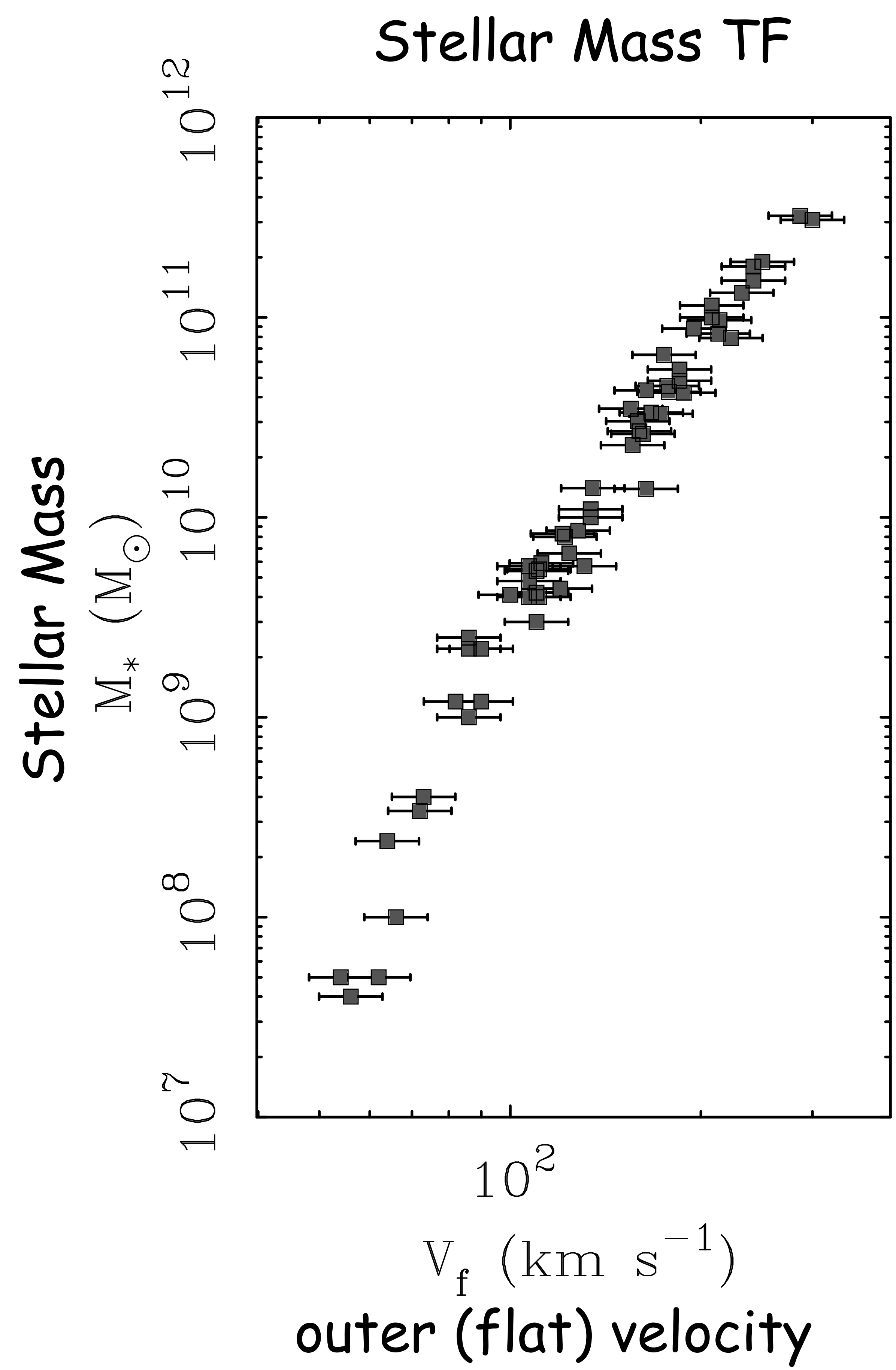


Scatter in TF relation reduced with resolved rotation curves (Verheijen 2001)



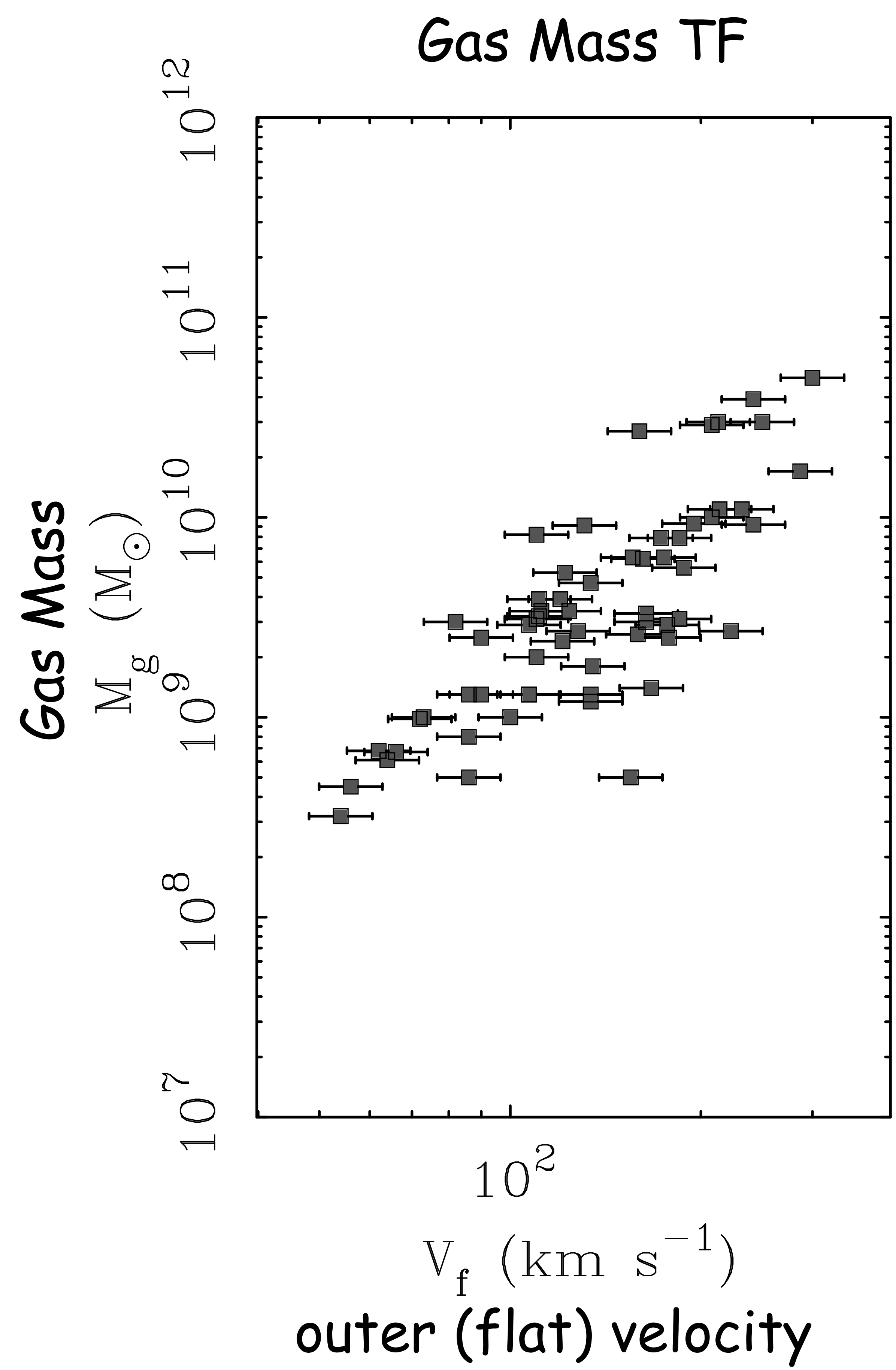
Low mass galaxies tend to fall below extrapolation of linear fit to fast rotators (Matthews, van Driel, & Gallagher 1998; Freeman 1999)

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

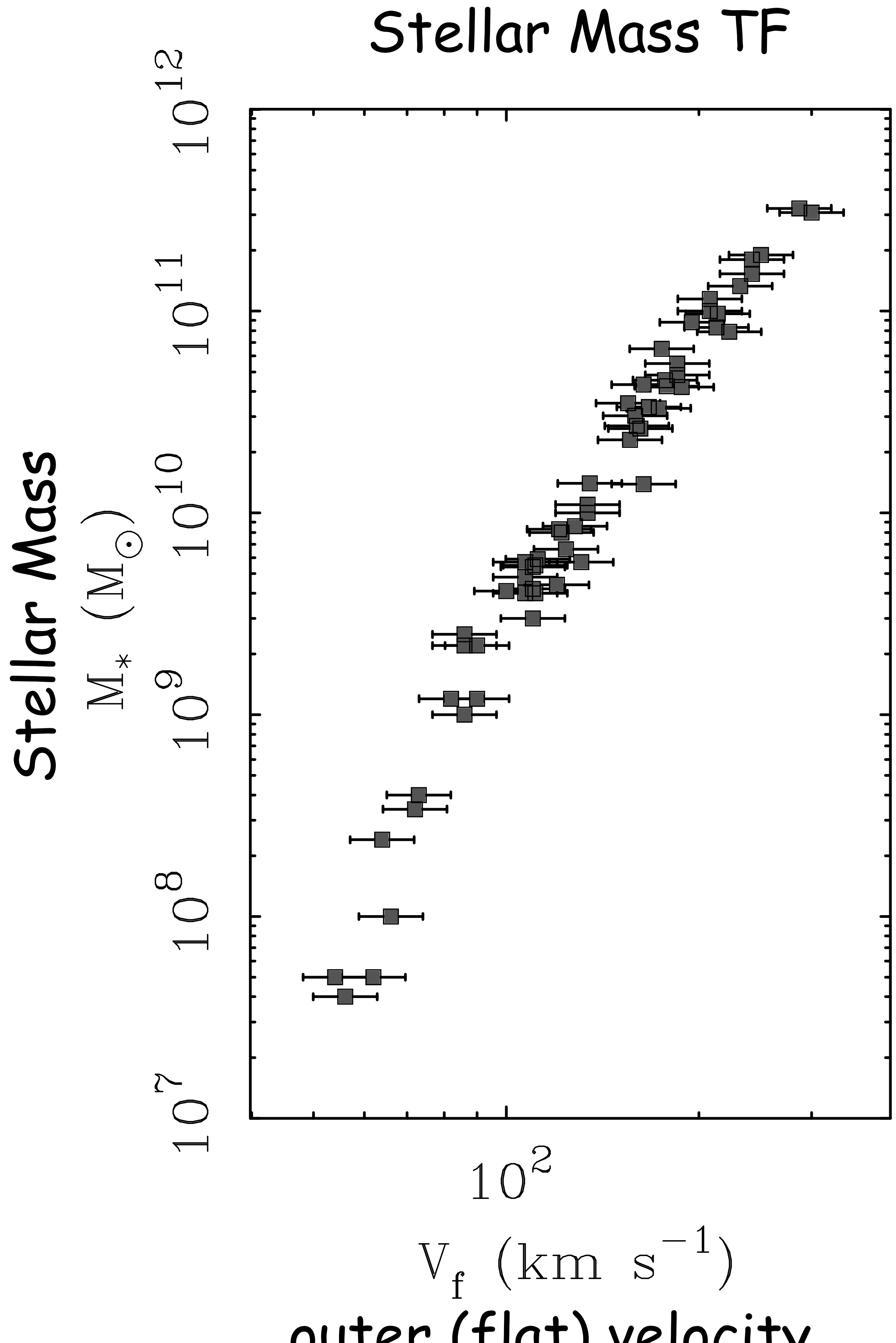


Gas mass by itself does NOT produce a good TF relation, at least for fast rotators.

$$M_g = 1.4 M_{HI}$$



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

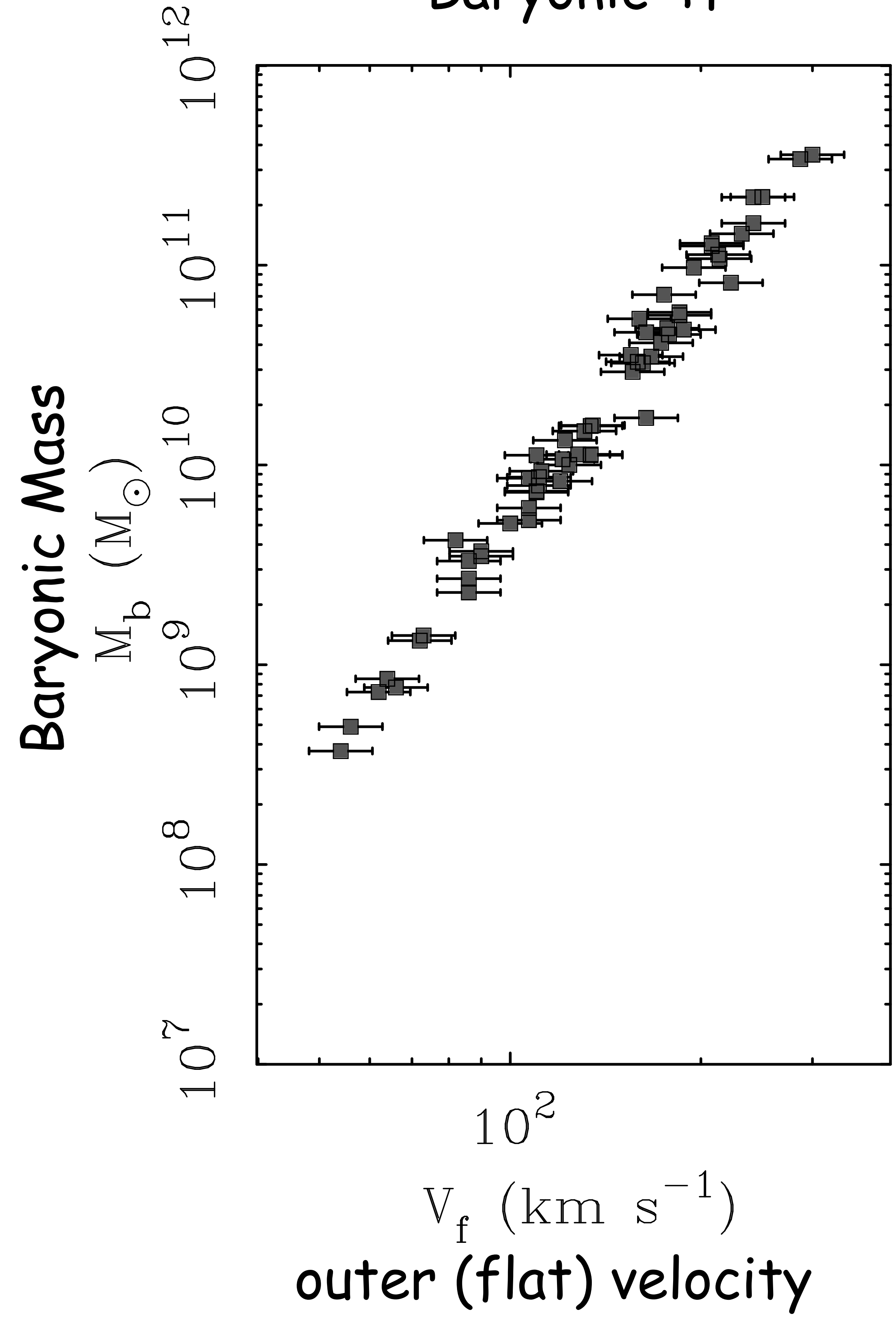


Adding gas to stellar mass restores a single continuous relation for all rotators.

$$M_b = M_* + M_g$$

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

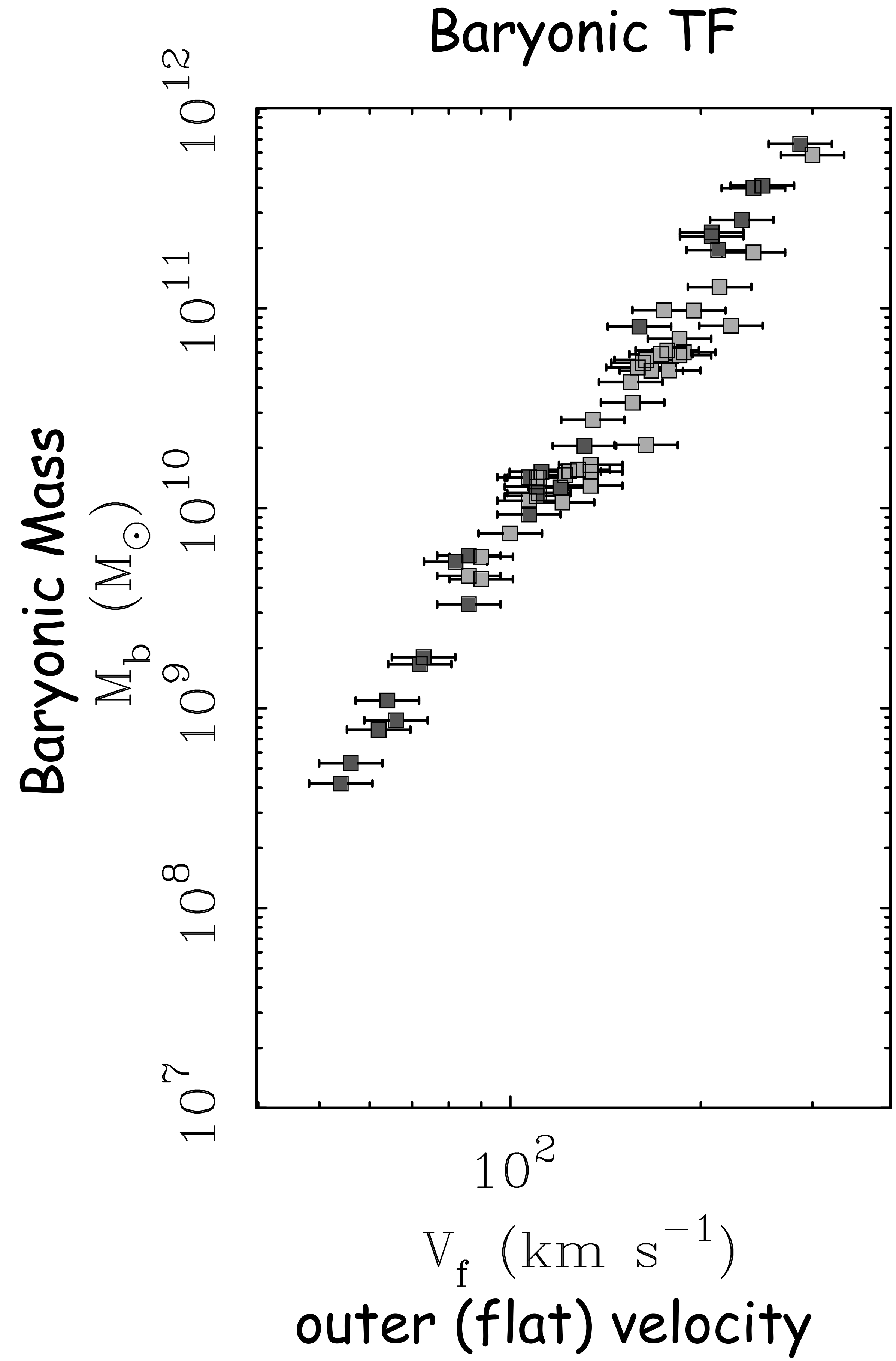
Baryonic TF



Twice Nominal M*/L

Now instead of a translation, the slope pivots as we vary M*/L.

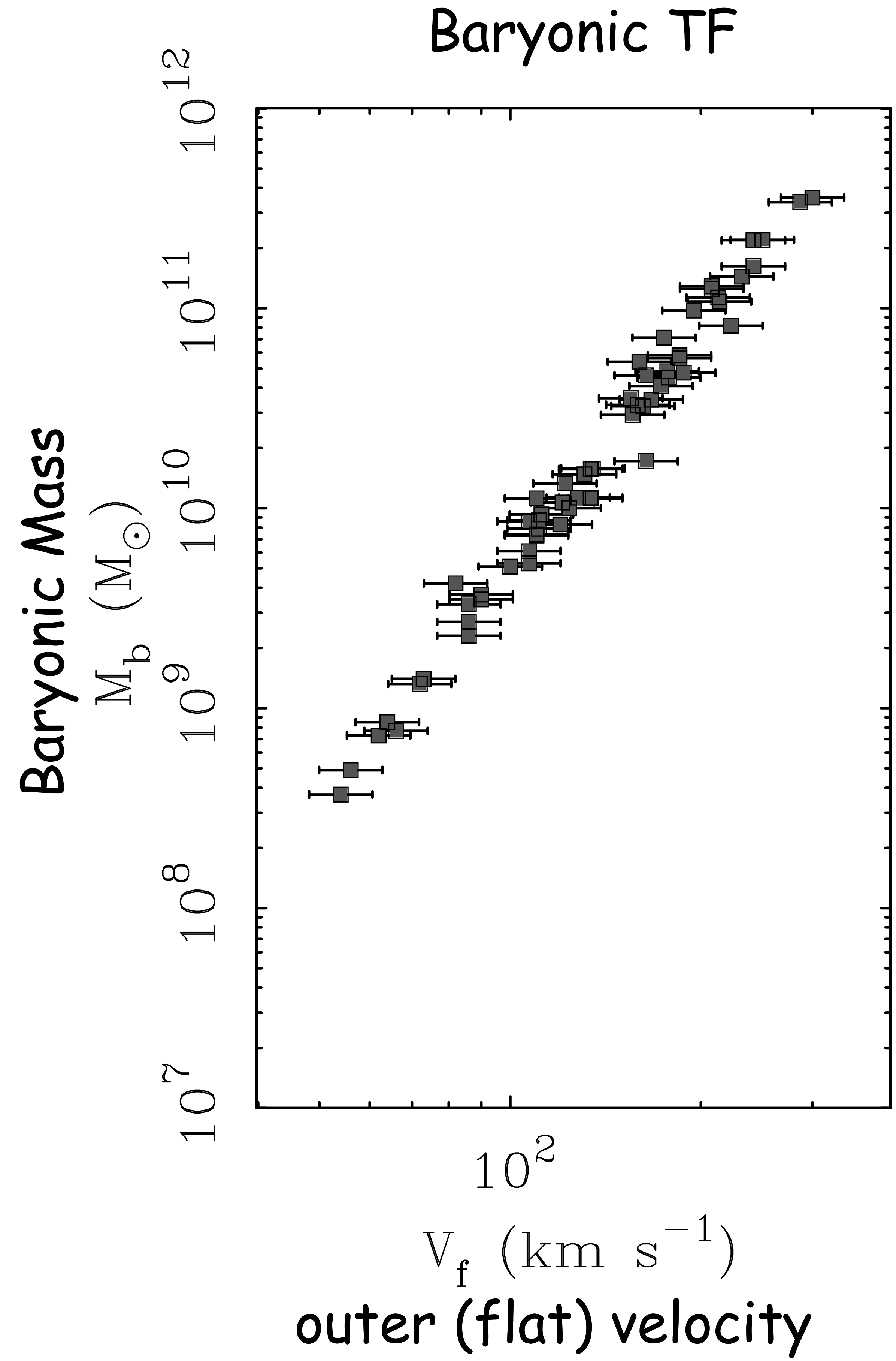
Scatter increases as we diverge from the nominal M*/L.



Nominal M*/L

Now instead of a translation, the slope pivots as we vary M*/L.

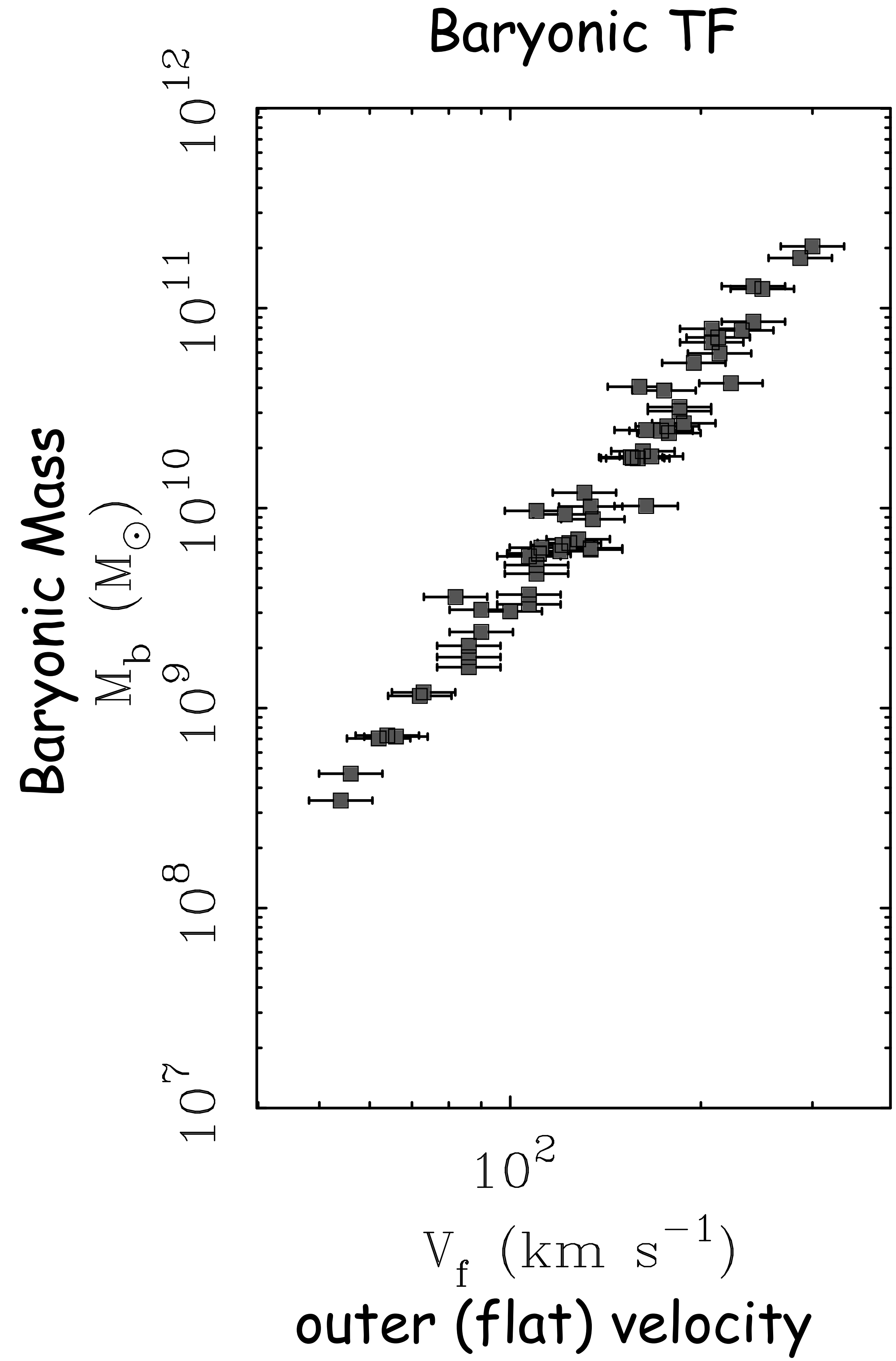
Scatter increases as we diverge from the nominal M*/L.



Half Nominal M*/L

Now instead of a translation, the slope pivots as we vary M*/L.

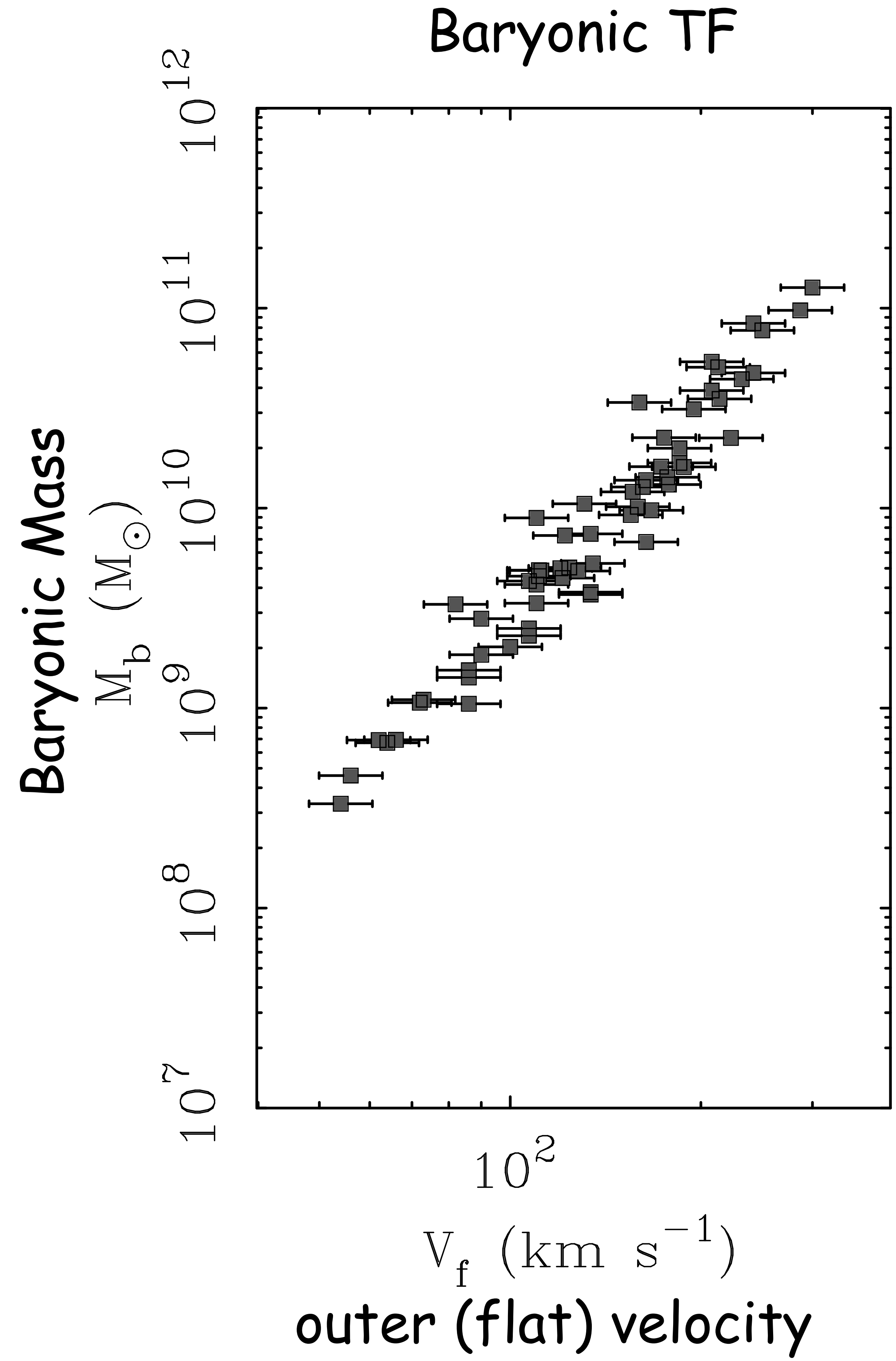
Scatter increases as we diverge from the nominal M*/L.



Quarter Nominal M*/L

Now instead of a translation, the slope pivots as we vary M*/L.

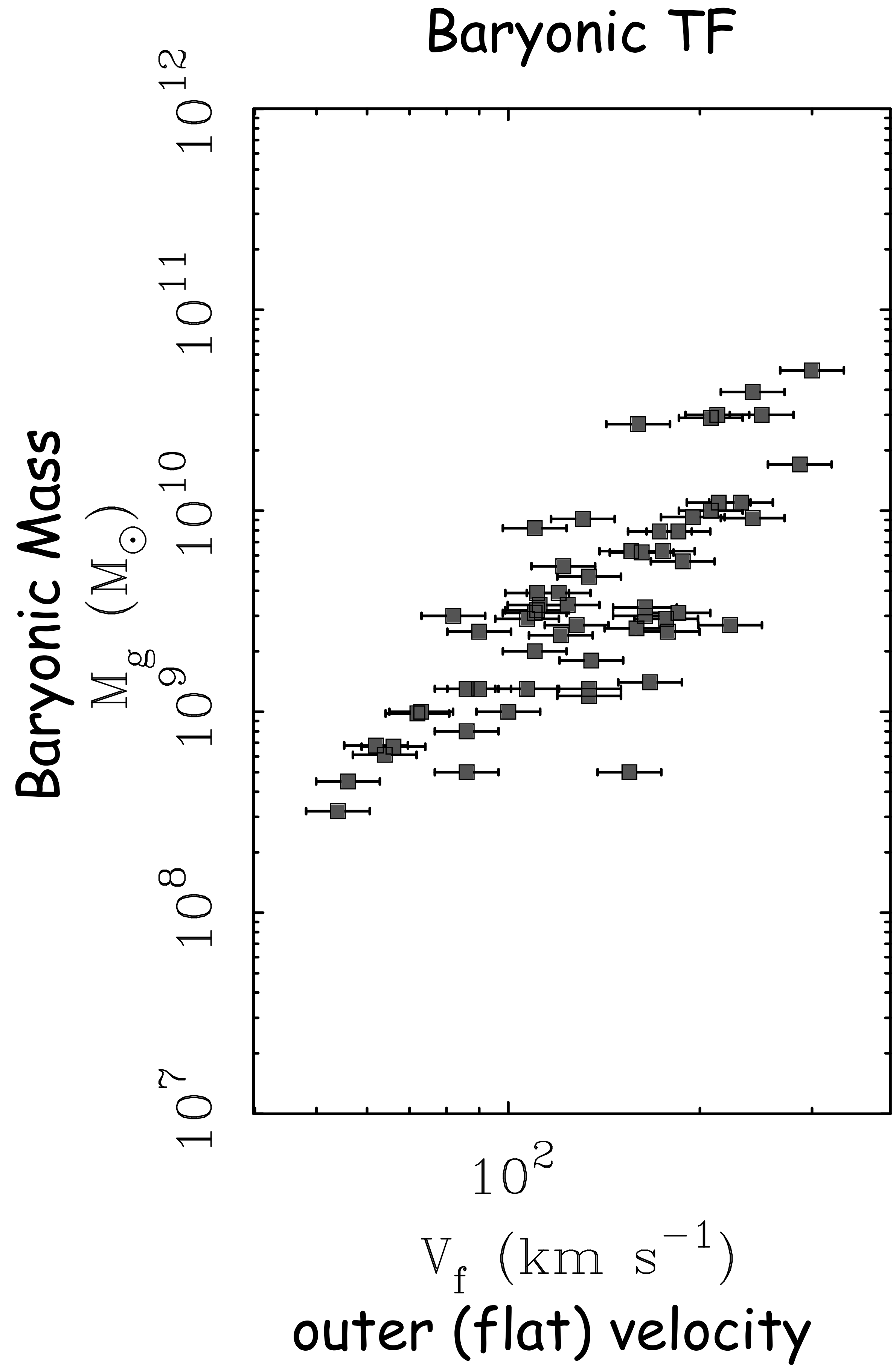
Scatter increases as we diverge from the nominal M*/L.



Zero M*/L

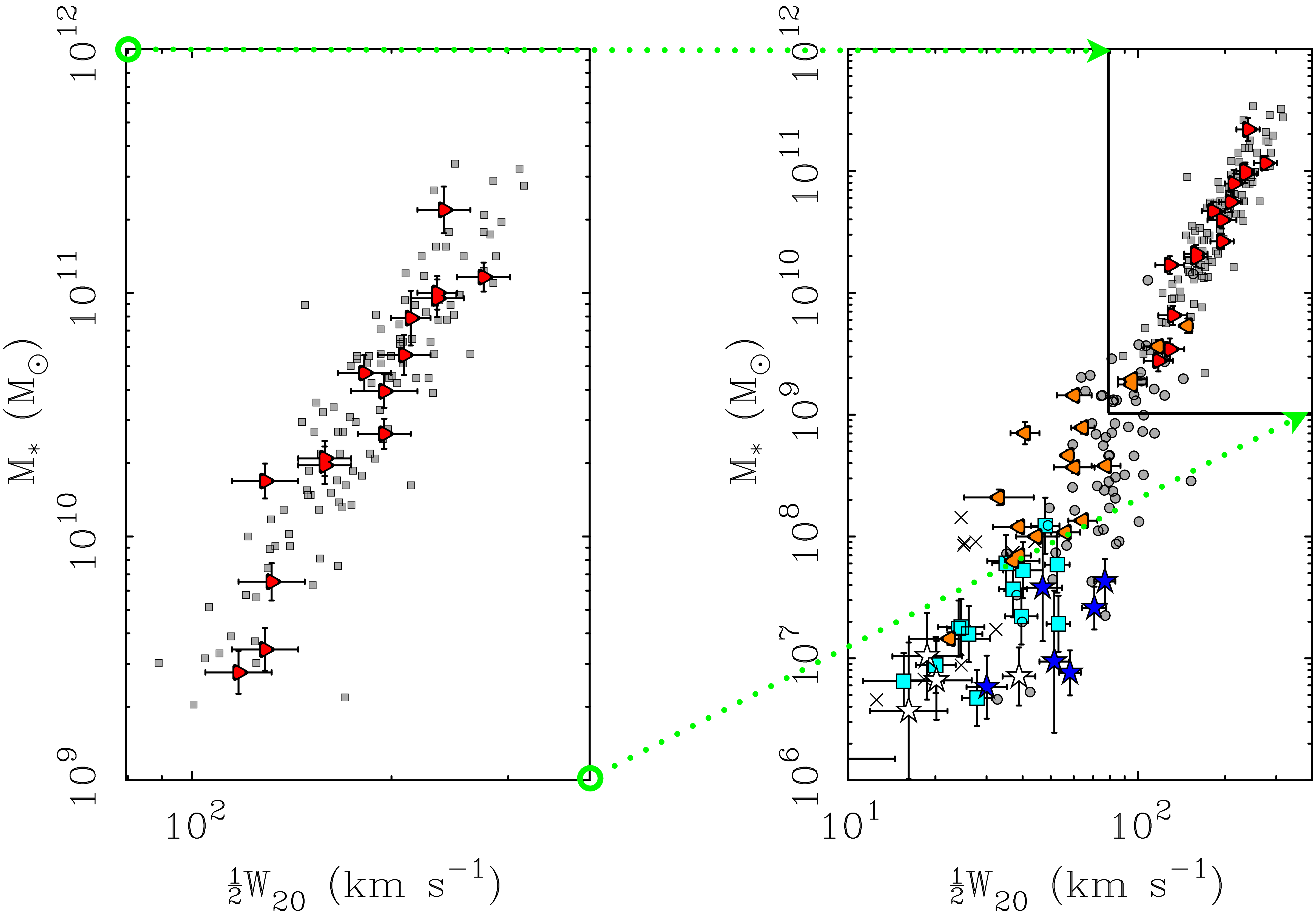
Now instead of a translation, the slope pivots as we vary M*/L.

Scatter increases as we diverge from the nominal M*/L.



Low mass galaxies considerably expand range of the TF relation.

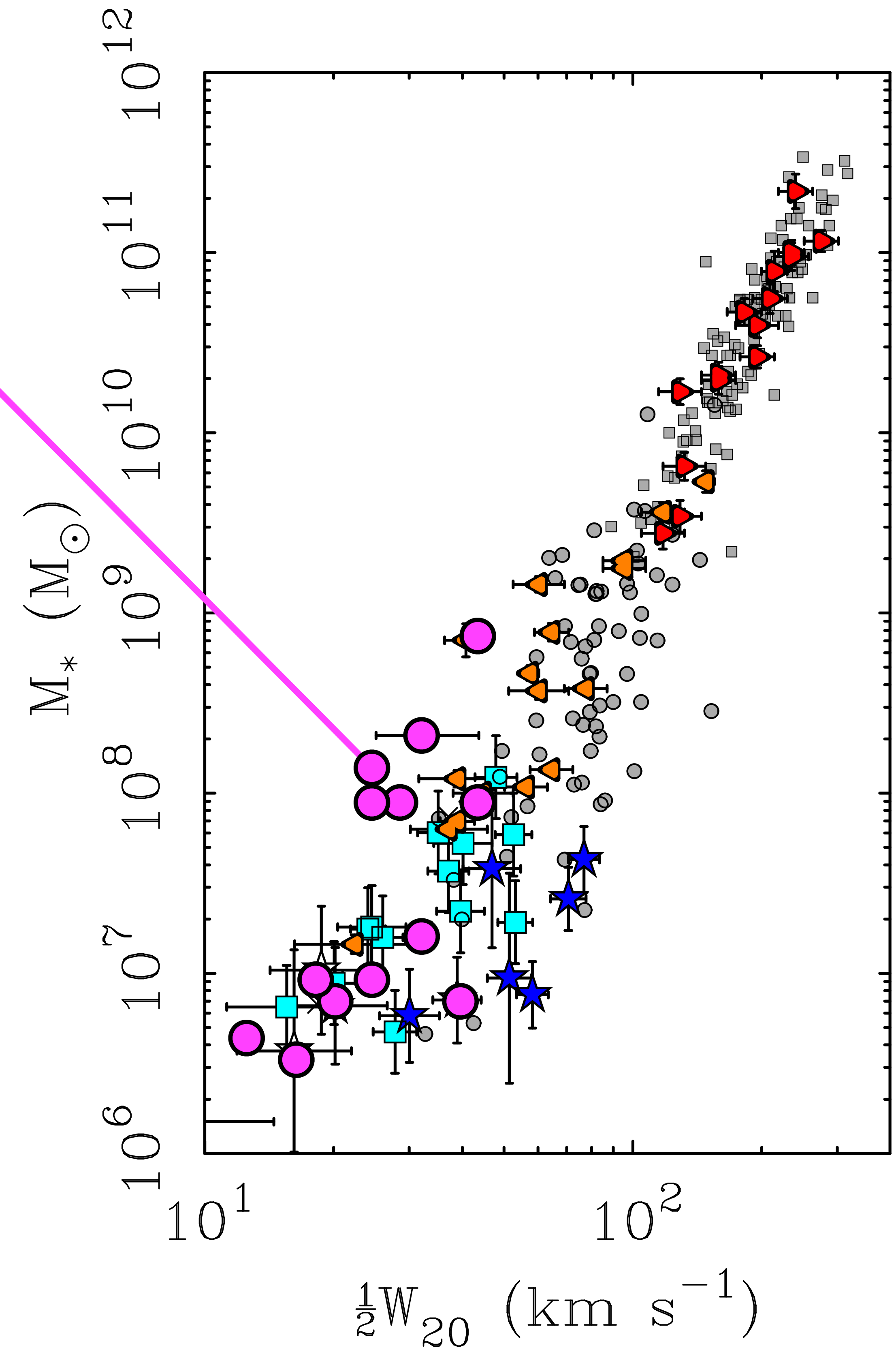
Gas dominated galaxies can provide absolute calibration of mass scale.



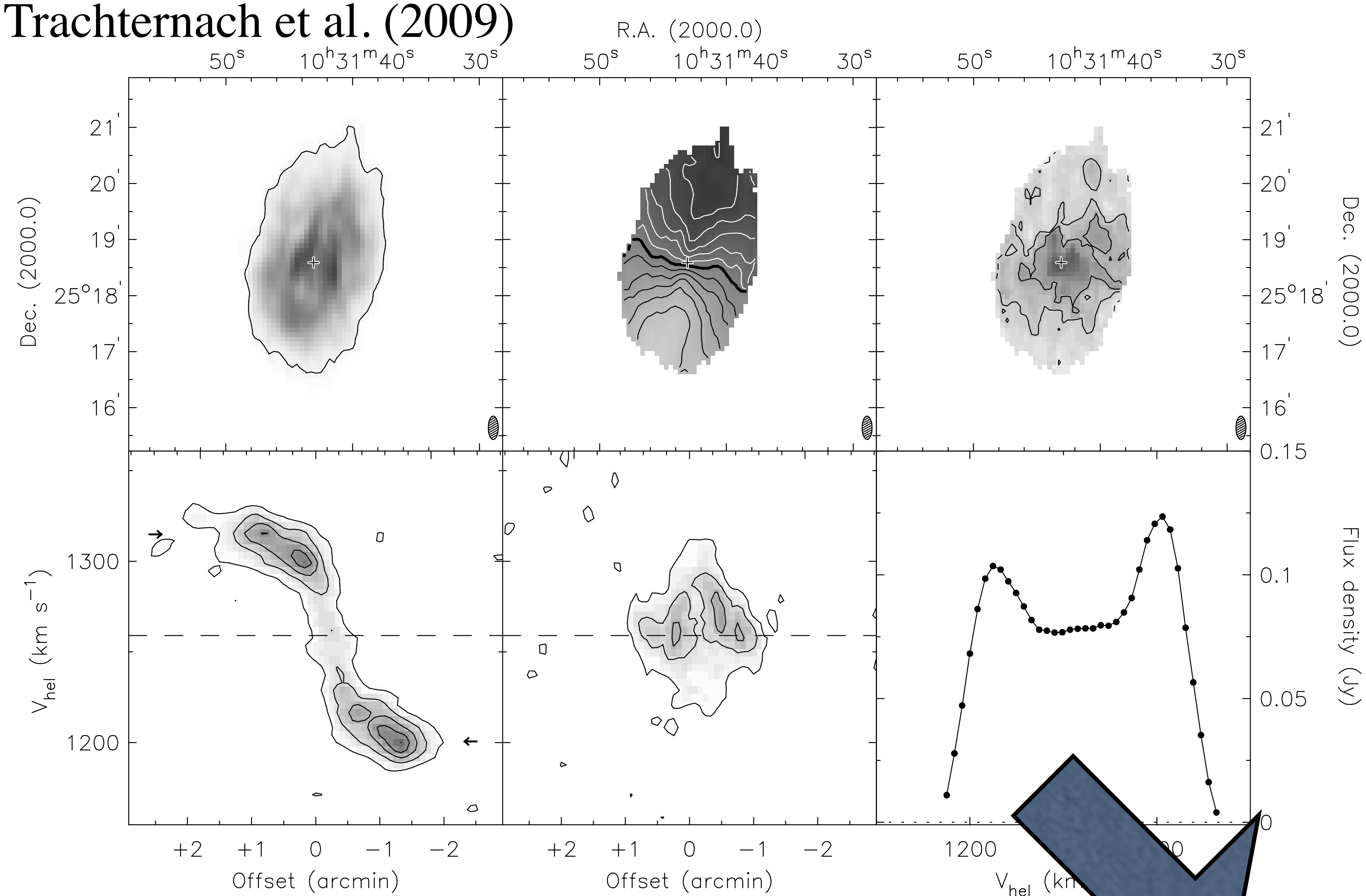
Gotta believe the data.

Biggest challenge for low mass systems is the inclination

e.g., Begum et al. (2008) estimate inclinations from both optical and HI morphology. Only half agree to within 12% in sin(i).

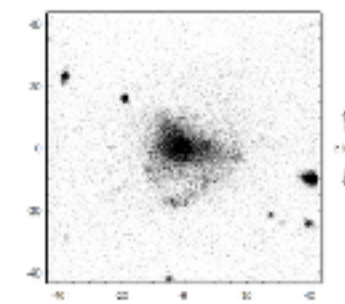


Trachternach et al. (2009)

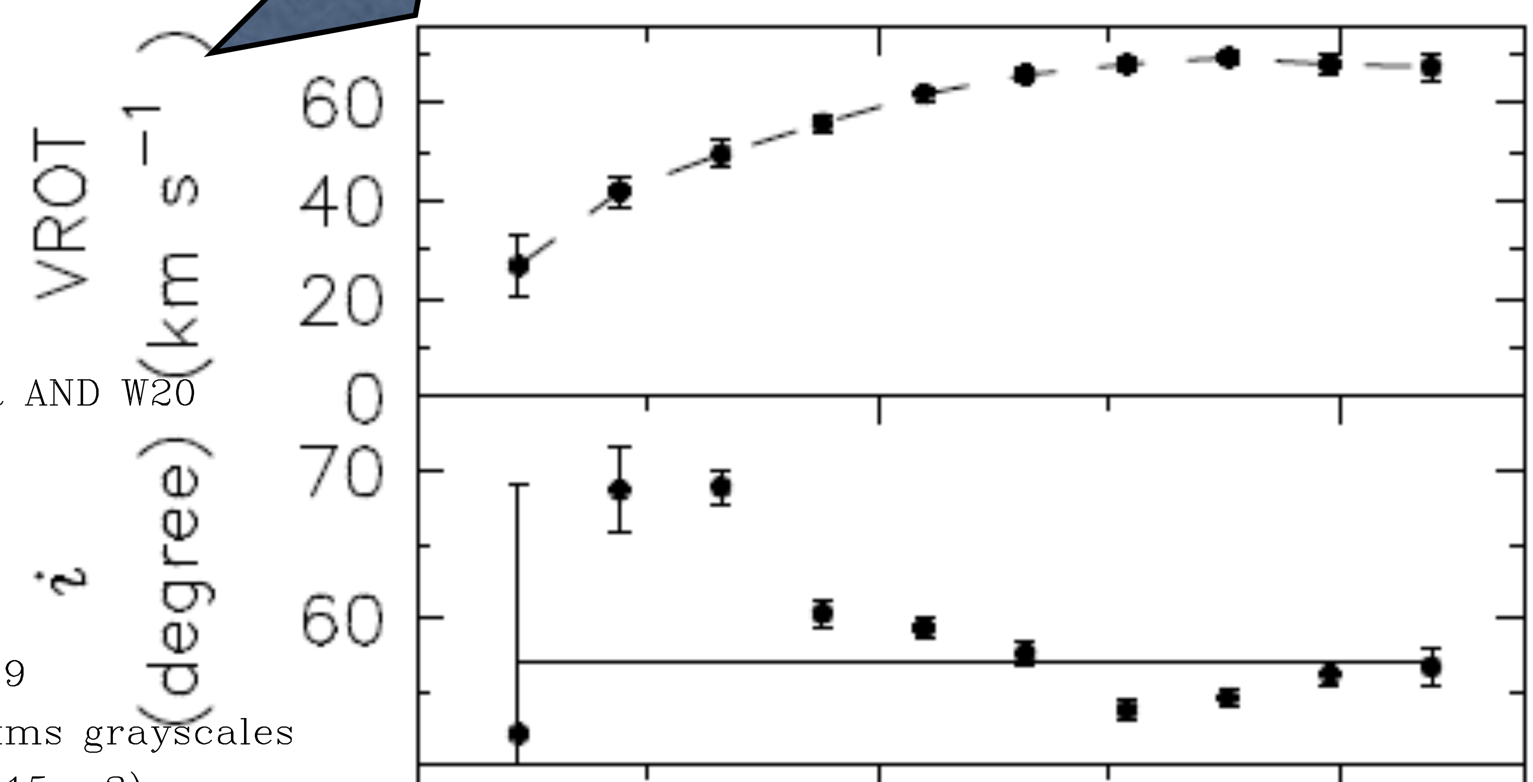


HI

Example low line-width, gas dominated galaxies with $M_\star < M_g$



optical



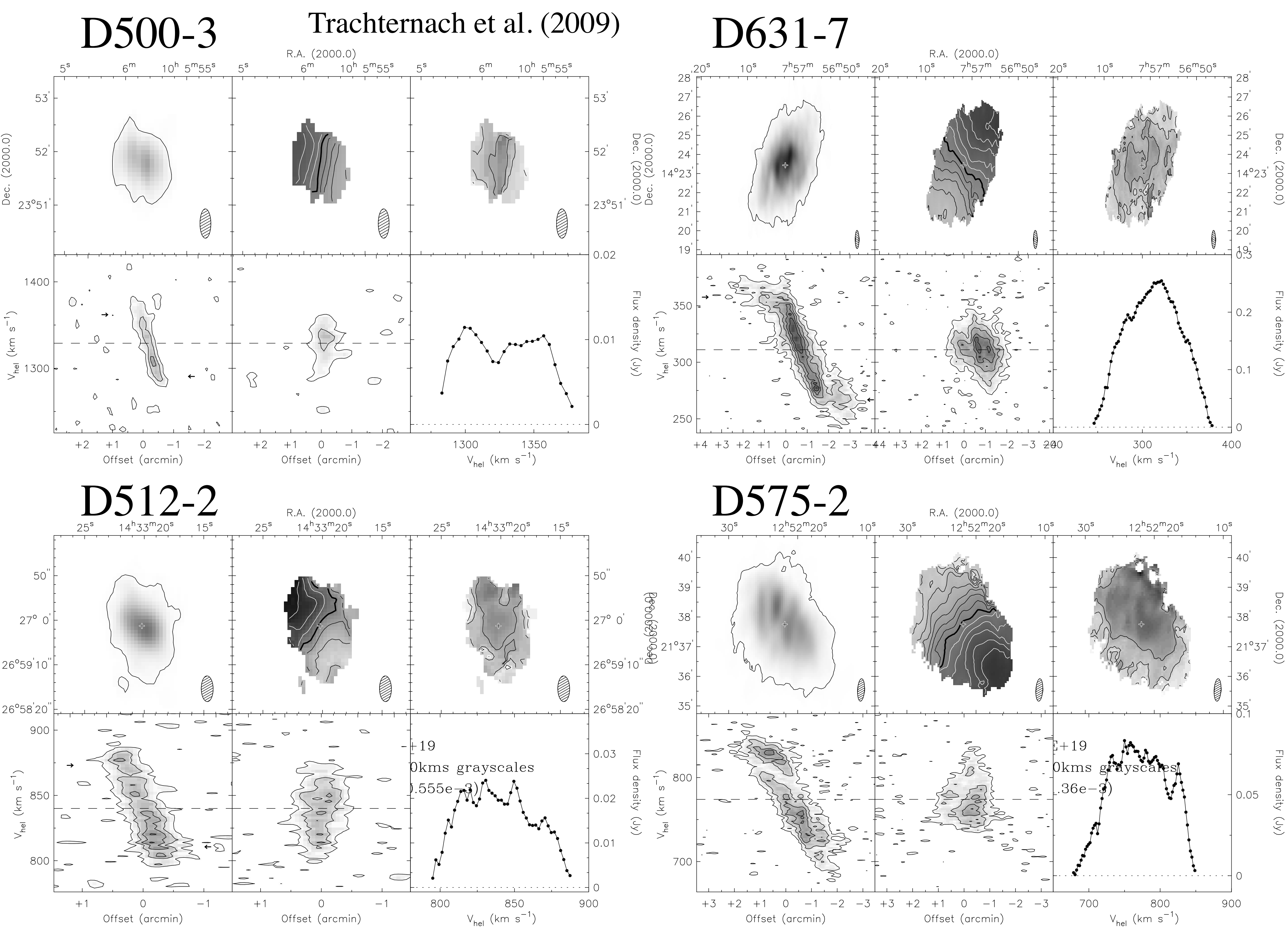
D500−2

"best−quality sample" Vrot AND Vflat AND W20
Vrot=67.7, vflat=68
I_{opt}=... I_{ell}=53 I_{kin}=57
box=−40 −40 40 40

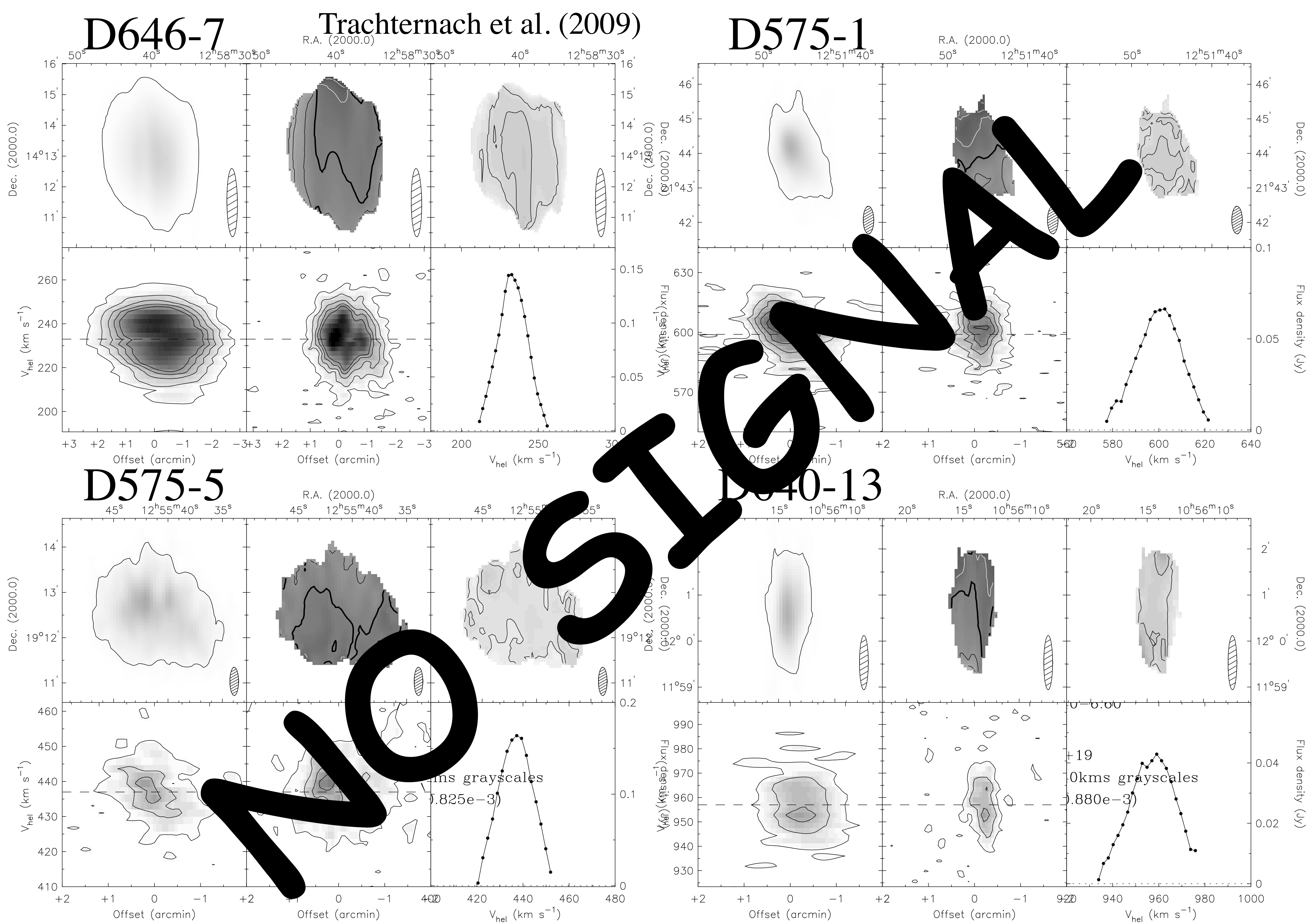
Vsys= 1259, deltaV=10km/s

3sigma=5,09mJy == nhi von 8.8 E+19

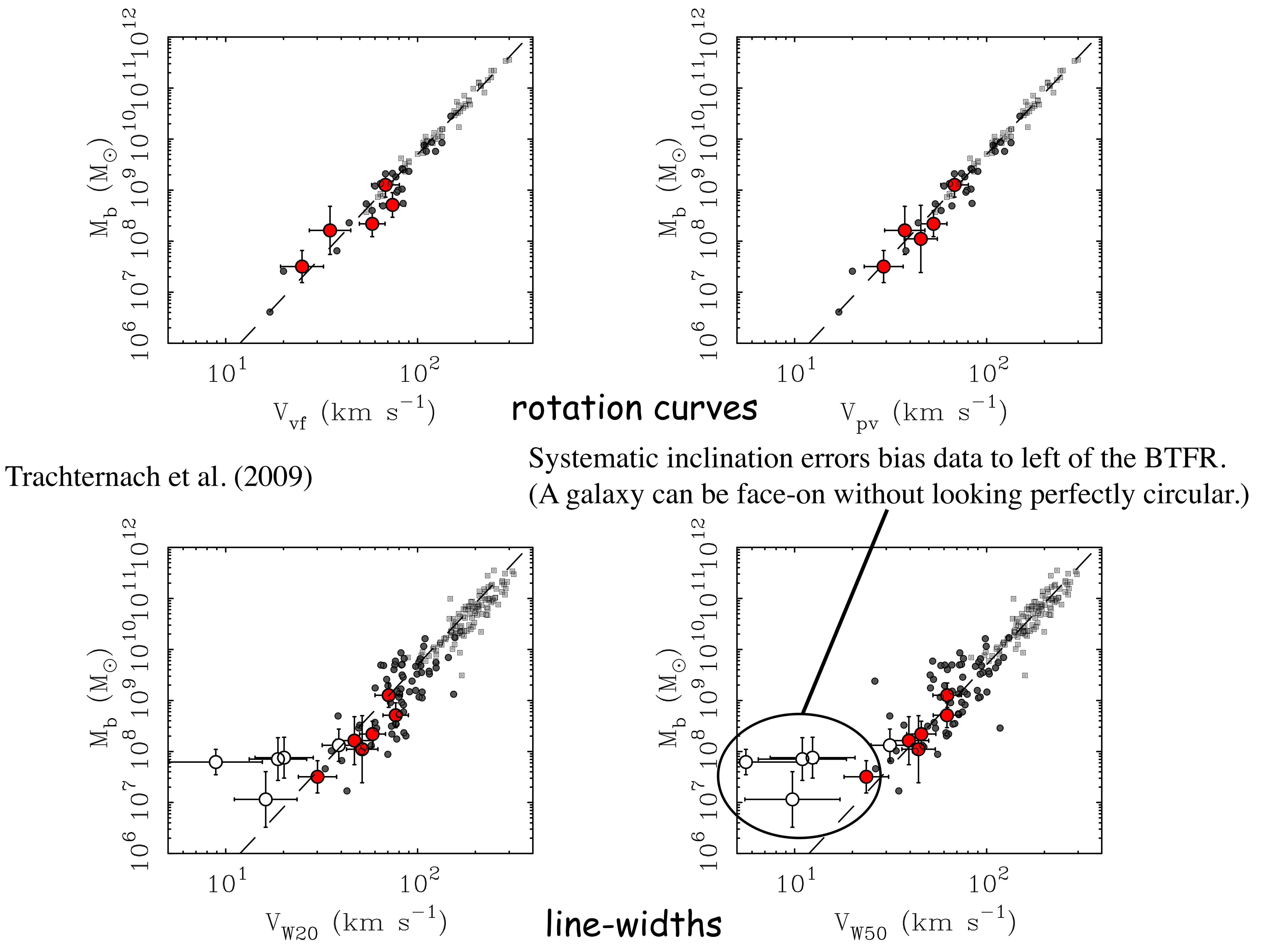
MOM2: 5,10,15 km/s contours, 2−40kms grayscales



D500-3
Trachternach et al. (2009)
D631-7
D512-2
D575-2
R.A. (2000.0)
Dec. (2000.0)
Offset (arcmin)
V_hel (km s^-1)
Flux density (Jy)

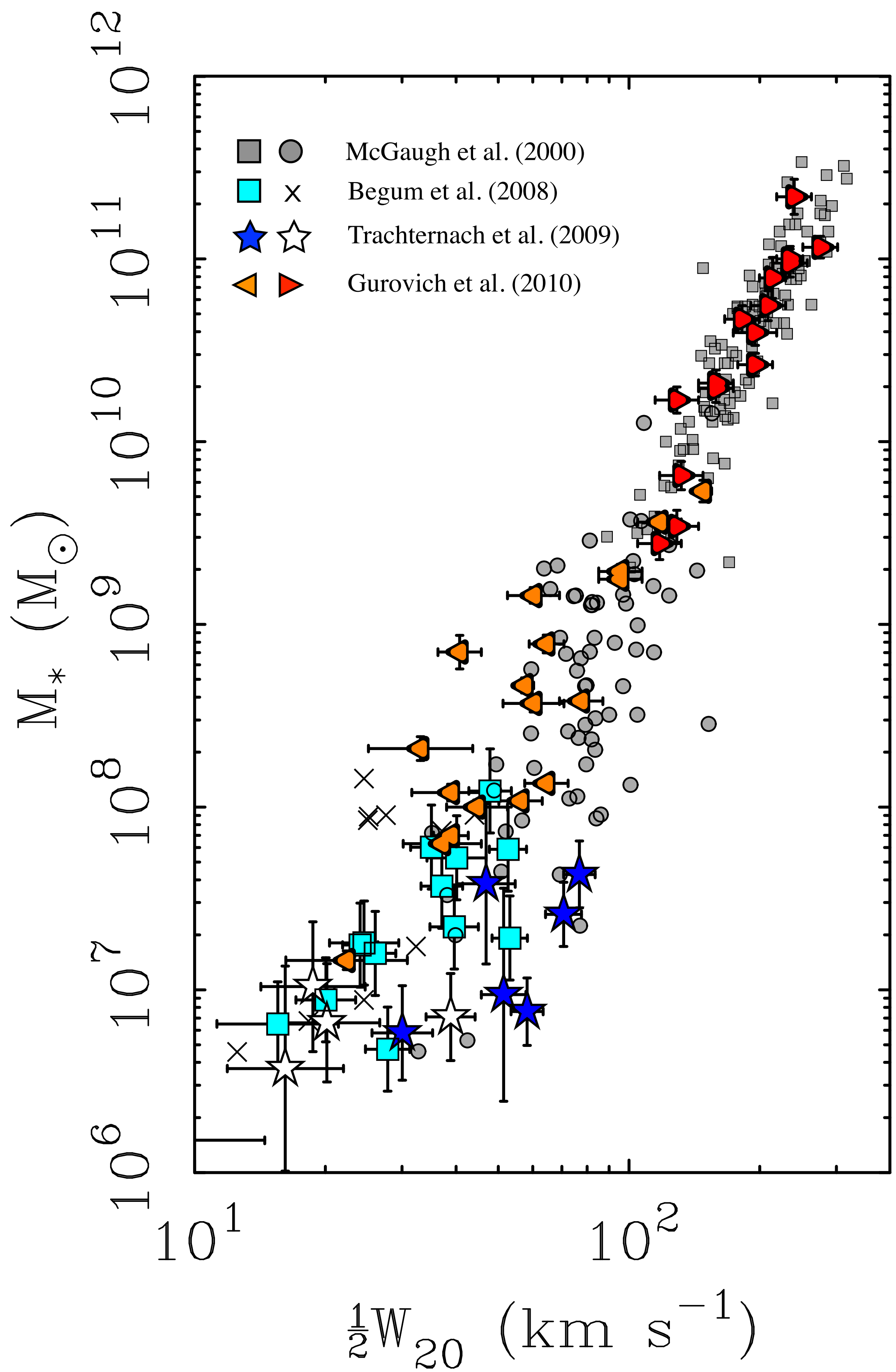


Note that you can measure a line-width even if there is no evidence of rotation.

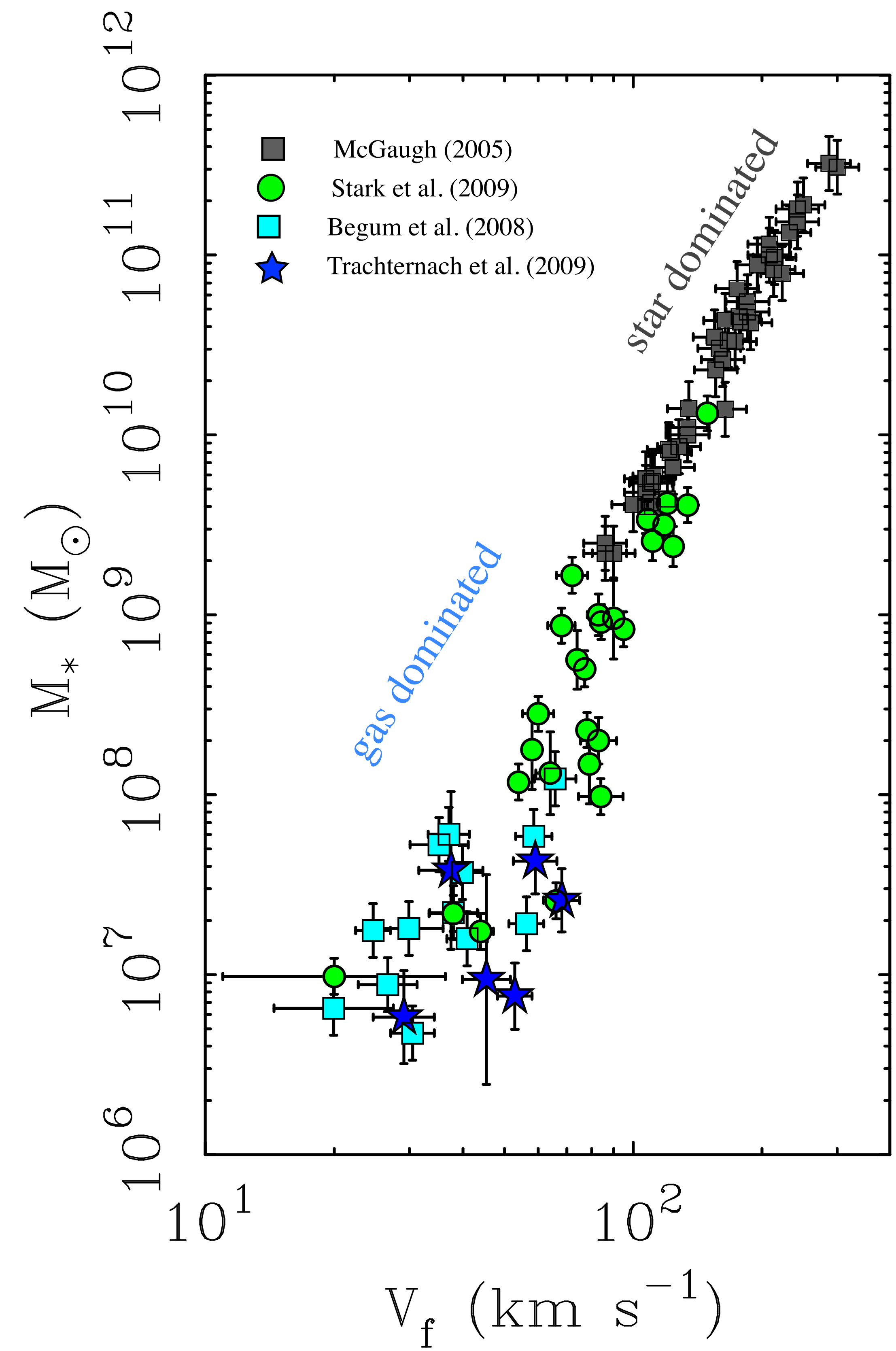


M_b ($M_\odot$)
10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12}
10^1 10^2
V_{vf} (km s^{-1})
V_{pv} (km s^{-1})
rotation curves
Trachternach et al. (2009)
Systematic inclination errors bias data to left of the BTFR.
(A galaxy can be face-on without looking perfectly circular.)
V_{W20} (km s^{-1})
V_{W50} (km s^{-1})
line-widths

Stellar Mass Tully-Fisher relation

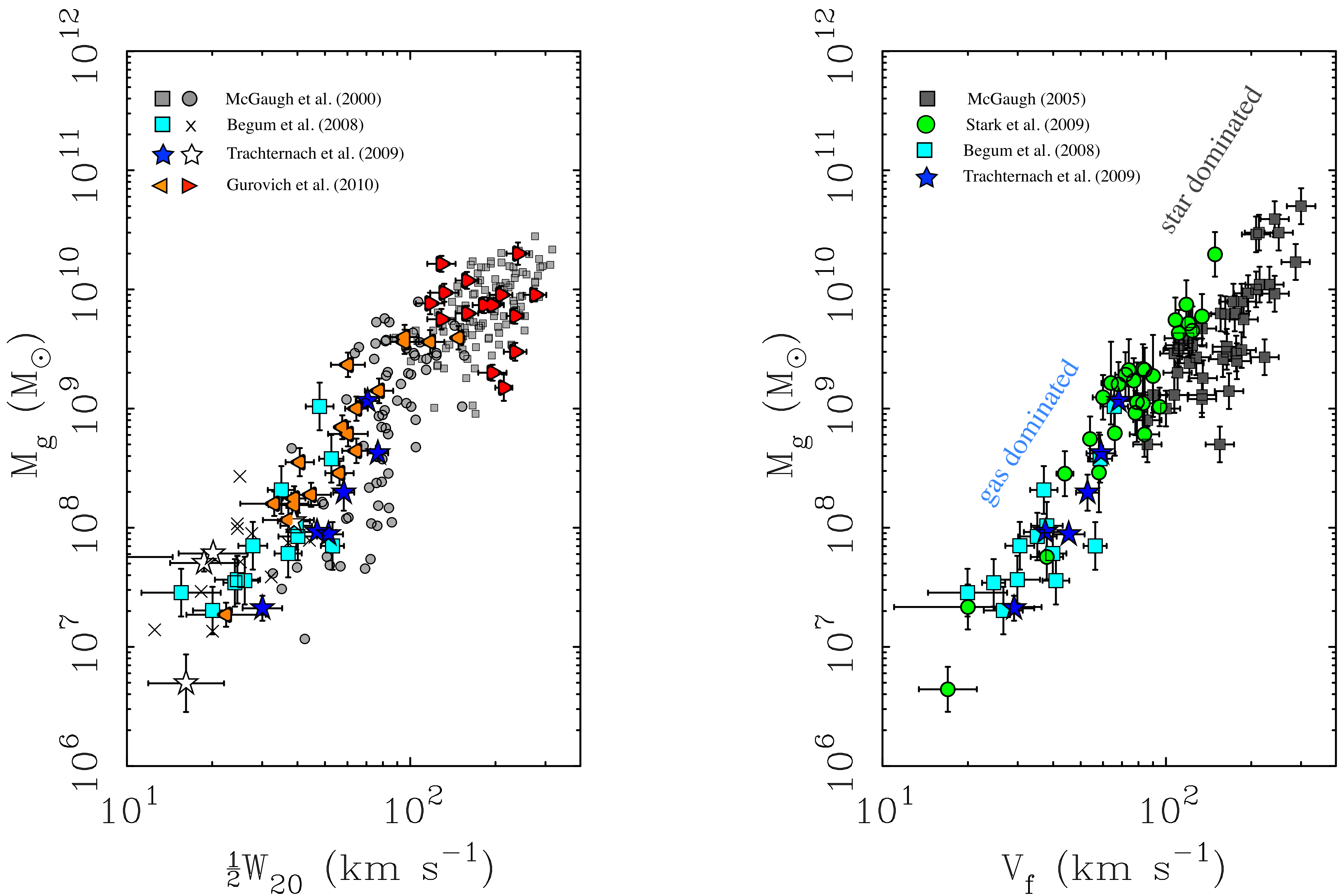


line-width



outer (flat) velocity

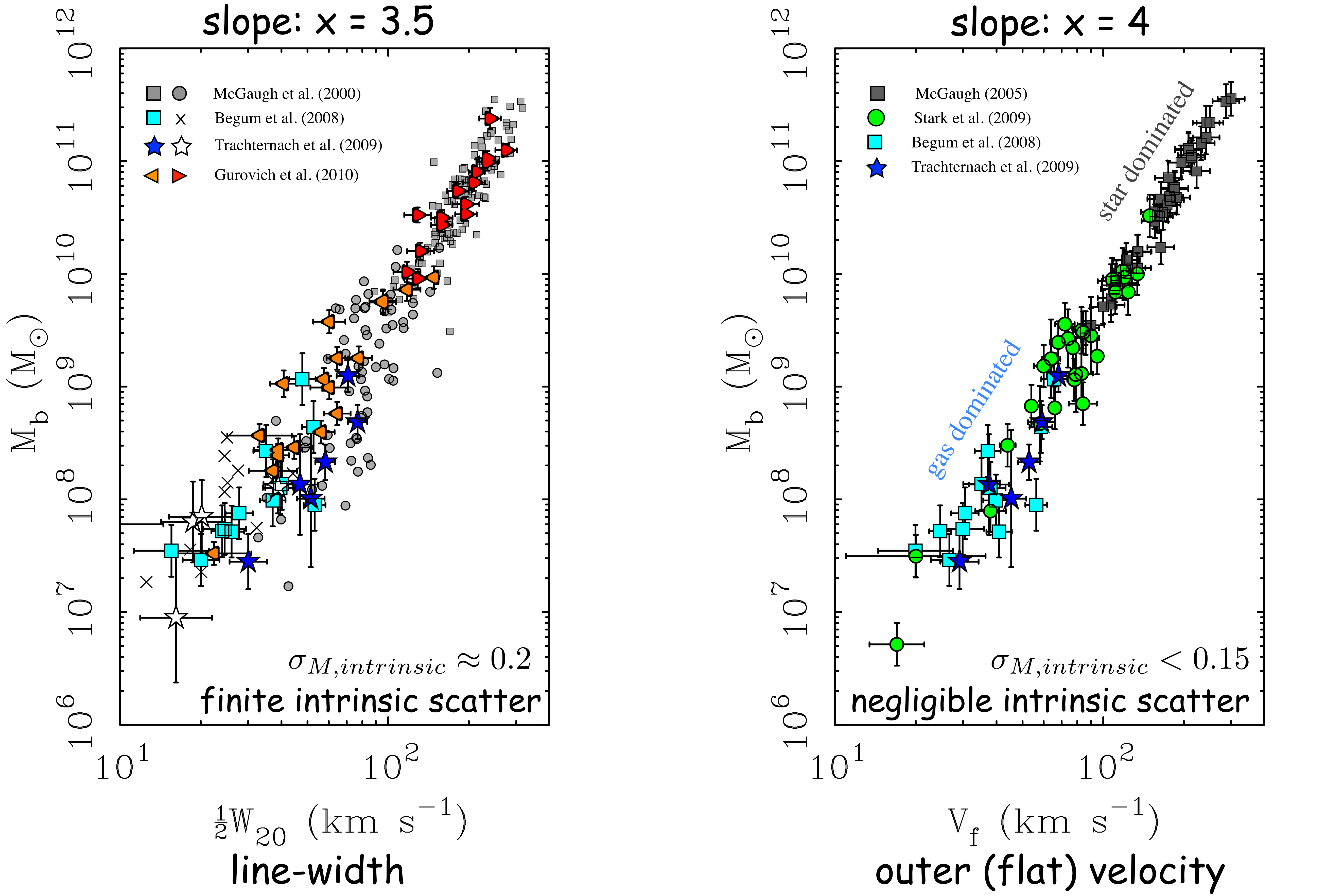
HI Tully-Fisher relation



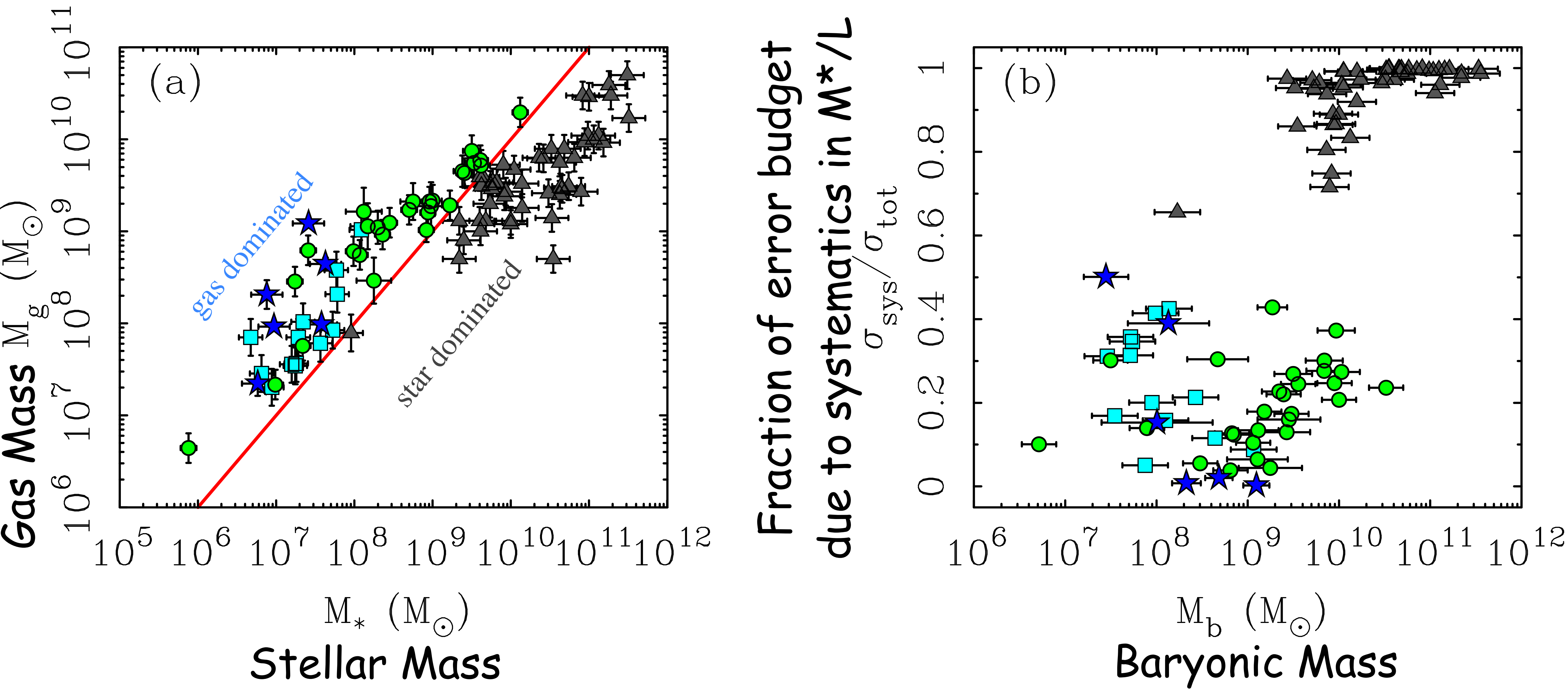
line-width

outer (flat) velocity

Baryonic Tully-Fisher relation: slope & scatter depend on Velocity estimator

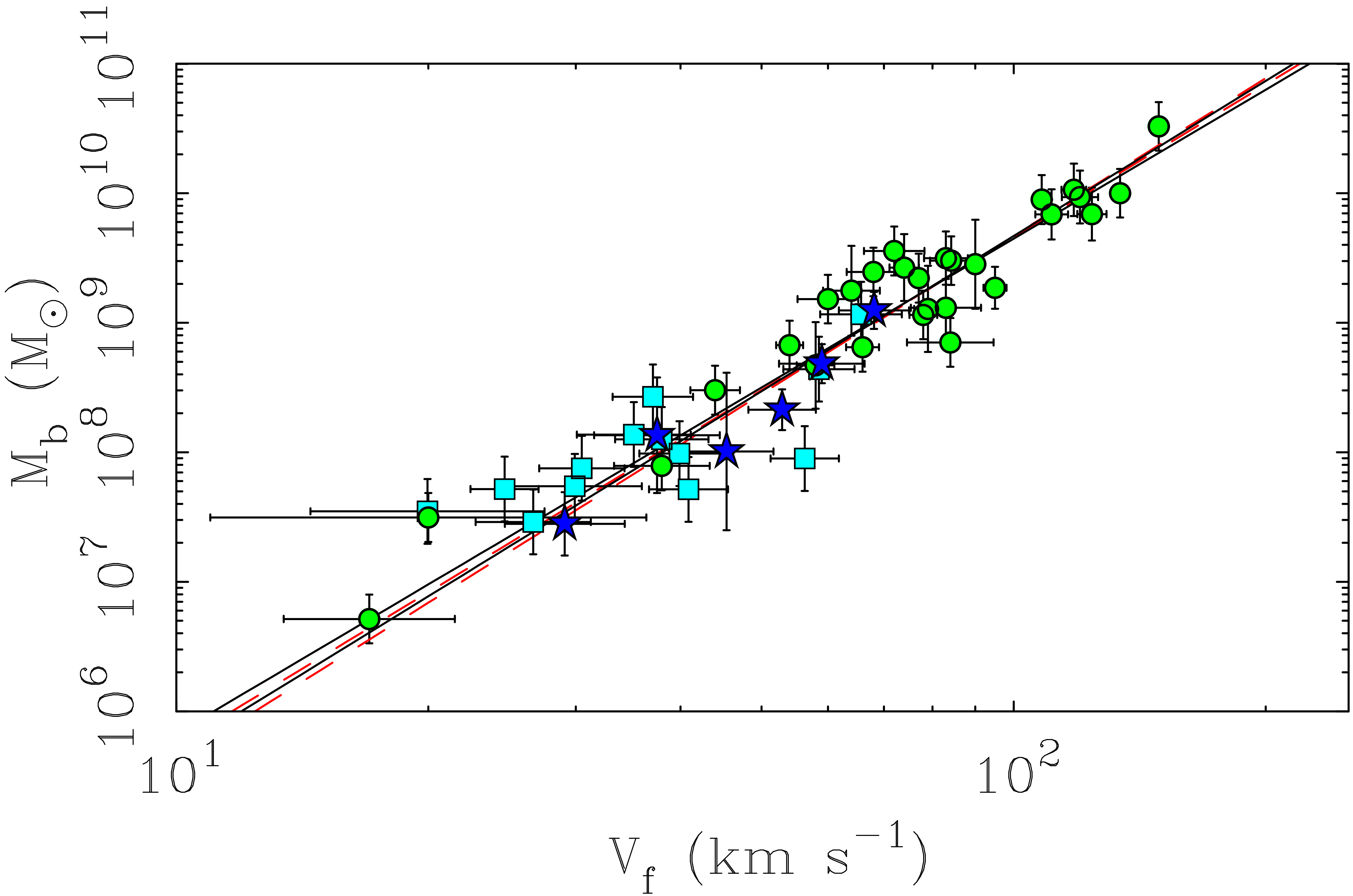


Gas dominated galaxies can provide absolute calibration of mass scale.



Systematic errors in M*/L no longer dominate the error budget for galaxies with Mg > M*.

Gas Rich Galaxy Baryonic Tully-Fisher relation
(Stark et al 2009; Trachternach et al 2009; McGaugh 2011, 2012)



select $M_g > M_\star$

try fits with many different combinations of IMF and populations synthesis models

Table 4. BTF Fit to Gas Dominated Galaxies

$M_b = A\, V_f^x$

Subsample	N	$x_{v\|M}$	$A_{v\|M}$	$\chi^2_{\nu,v\|M}$	$x_{M\|v}$	$A_{M\|v}$	$\chi^2_{\nu,M\|v}$	x_{bis}	A_{bis}
Portinari-Kroupa	23	3.77	2.08	1.28	4.11	1.43	1.18	3.93	1.78
Portinari-Salpeter	14	3.59	2.44	1.42	4.37	1.02	1.46	3.94	1.79
Portinari-Kennicutt	26	3.74	2.14	2.01	4.33	0.99	1.85	4.01	1.62
Bell-Scaled Salpeter	23	3.77	2.09	1.41	4.09	1.47	1.31	3.93	1.80
Bell-Kroupa	26	3.72	2.17	2.30	4.36	0.94	2.10	4.01	1.61
Bell-Bottema	36	3.55	2.45	2.02	3.96	1.63	2.06	3.74	2.06

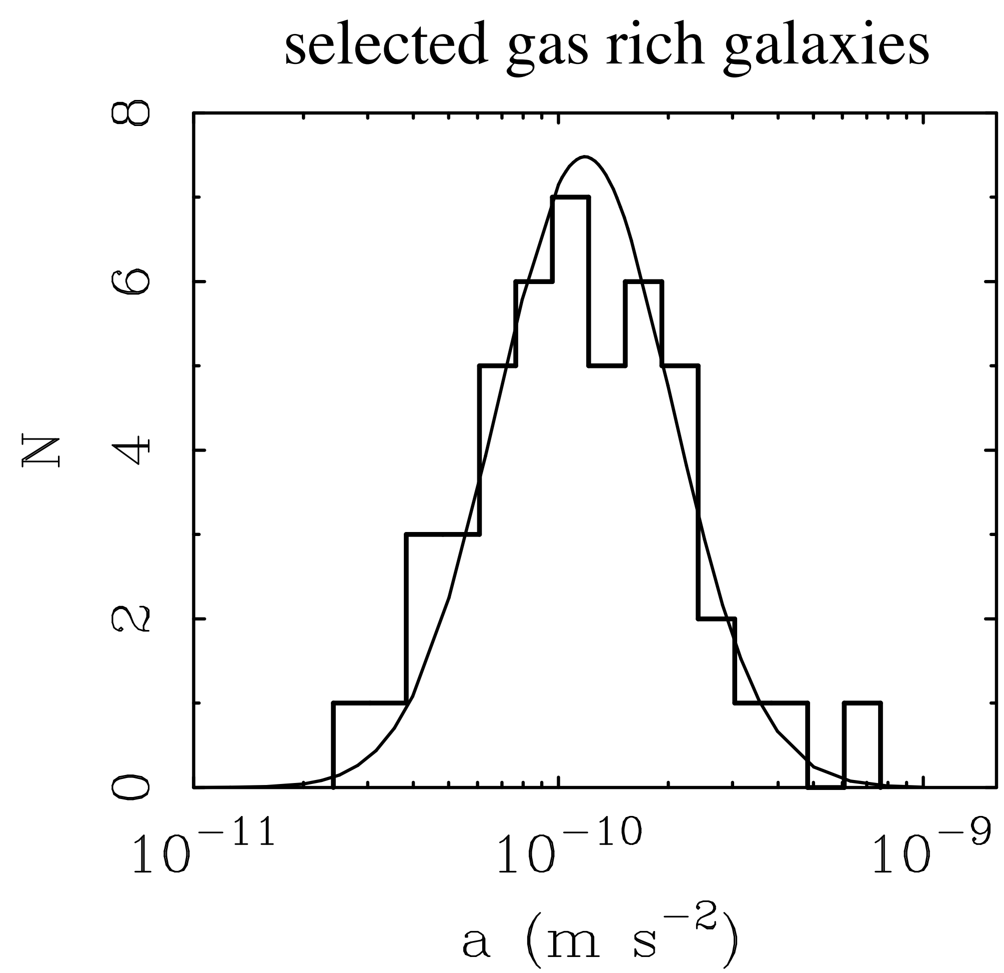
$$\text{slope } x = 3.94 \pm 0.07 \text{ (random)} \pm 0.08 \text{ (systematic)}$$

Stark, McGaugh, & Swaters (2009, AJ, 138, 392)

Fixing the slope to 4 gives $A = 47 \pm 6 \ \mathrm{M_\odot\, km^{-4}\, s^4}$

Slope 4 corresponds to an acceleration: $a = 0.8\frac{V_f^4}{GM_b}$ $\langle a\rangle = 1.24 \pm 0.14 \times 10^{-10}\ \mathrm{m\,s^{-2}}$

McGaugh (2011, 2012)

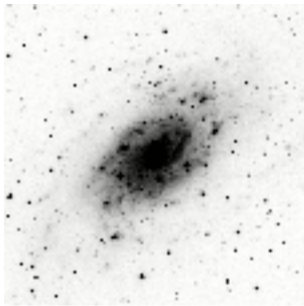


histogram: data

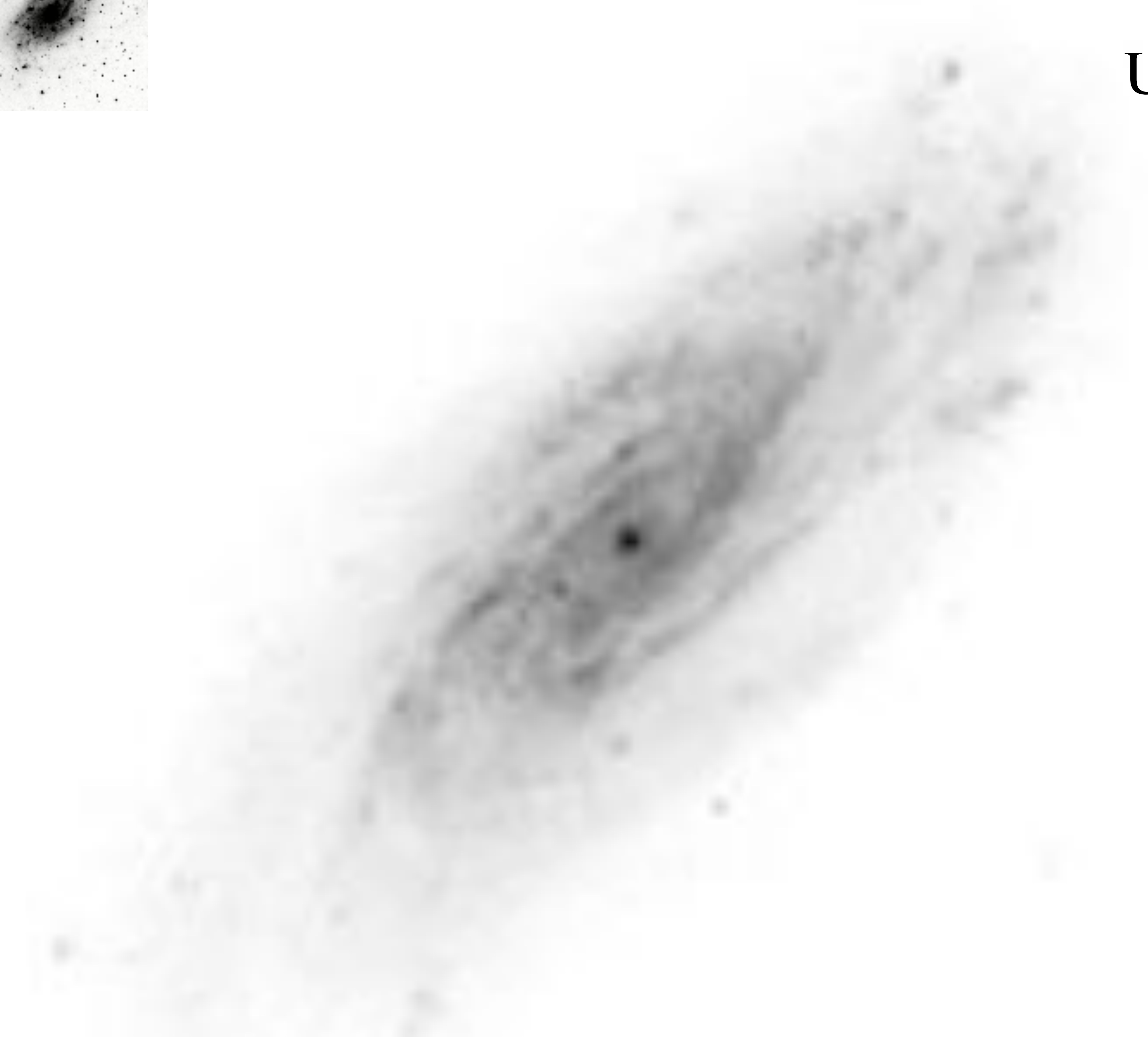
line: distribution expected from observational uncertainties.

The data are consistent with zero intrinsic scatter.

$$\sigma_M < 0.15\ \mathrm{dex}$$



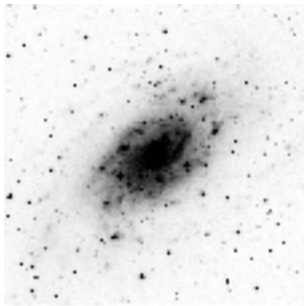
NGC 2403

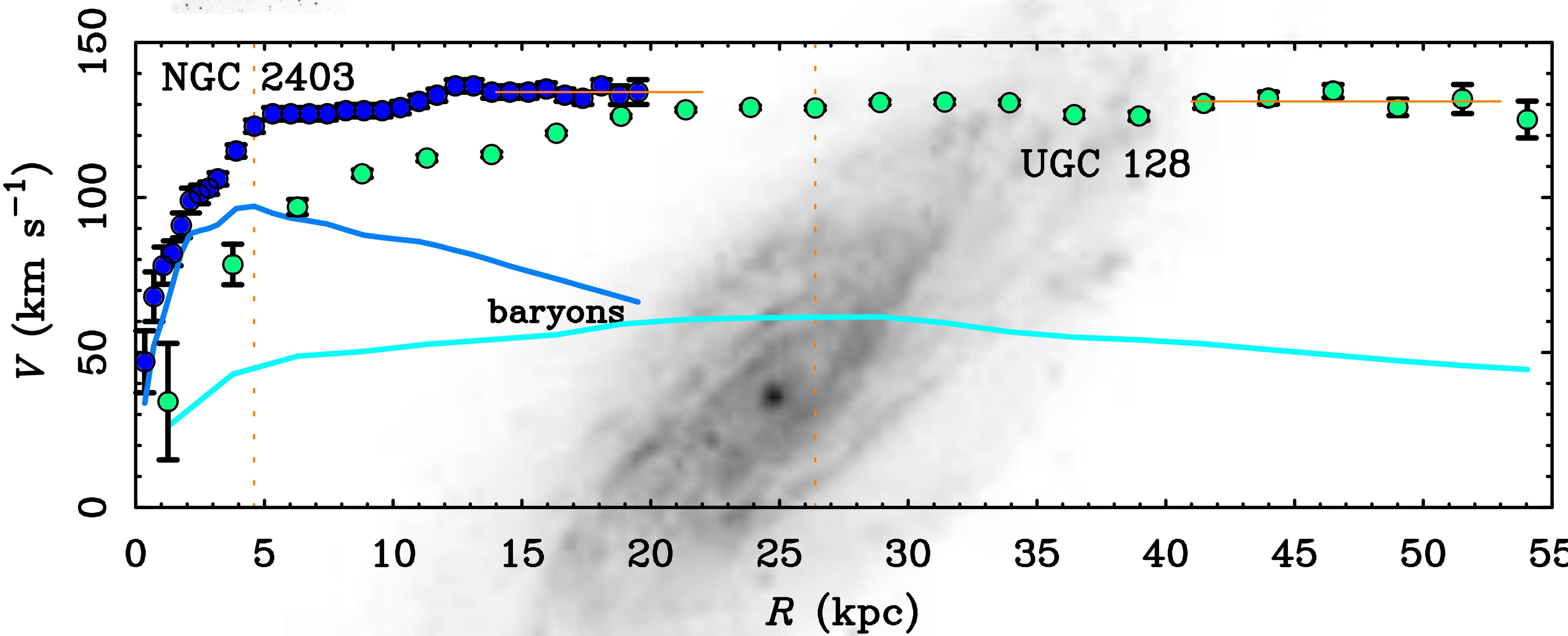


UGC 128

Size/surface brightness variations from TF

No residuals from TF with size or surface density



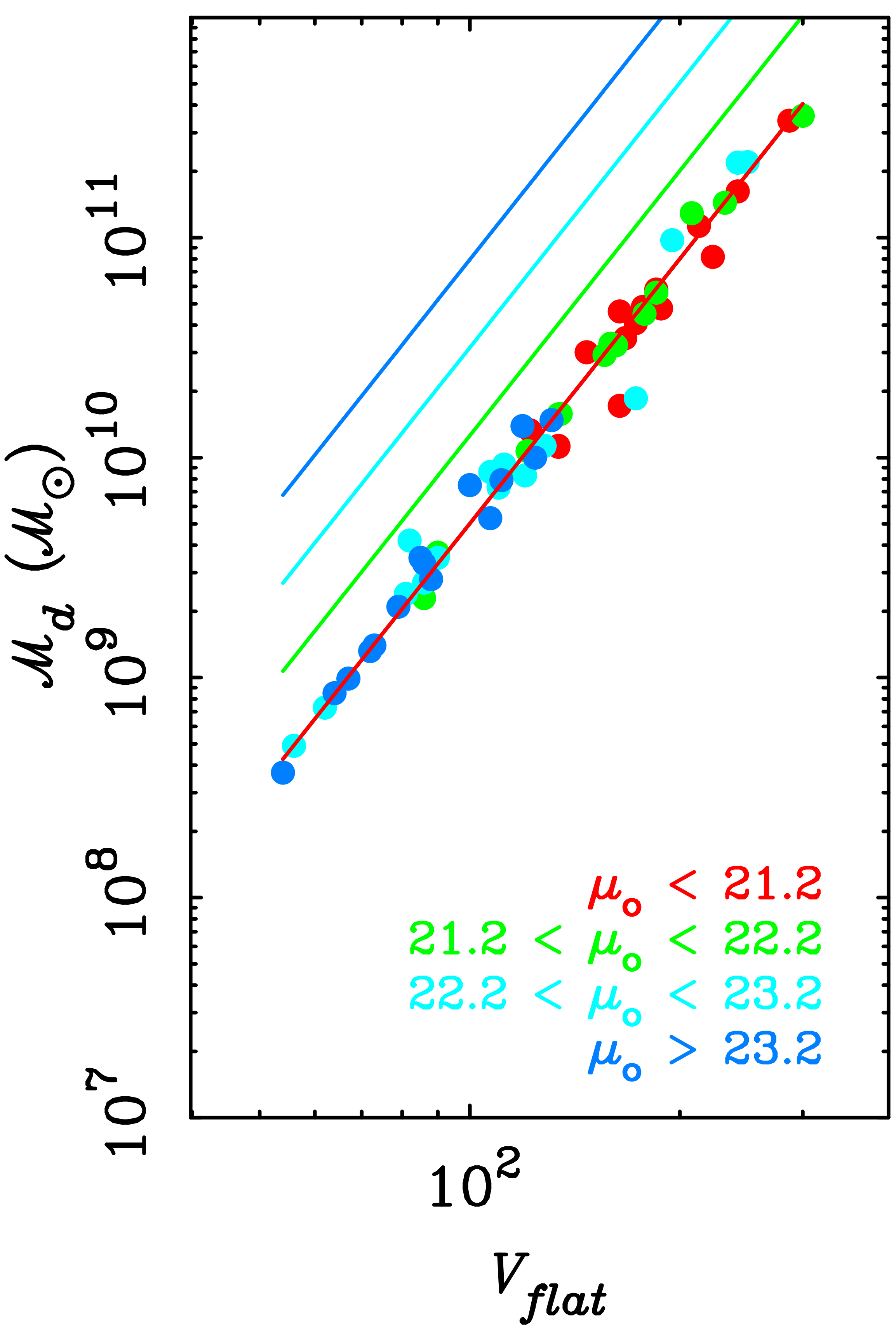


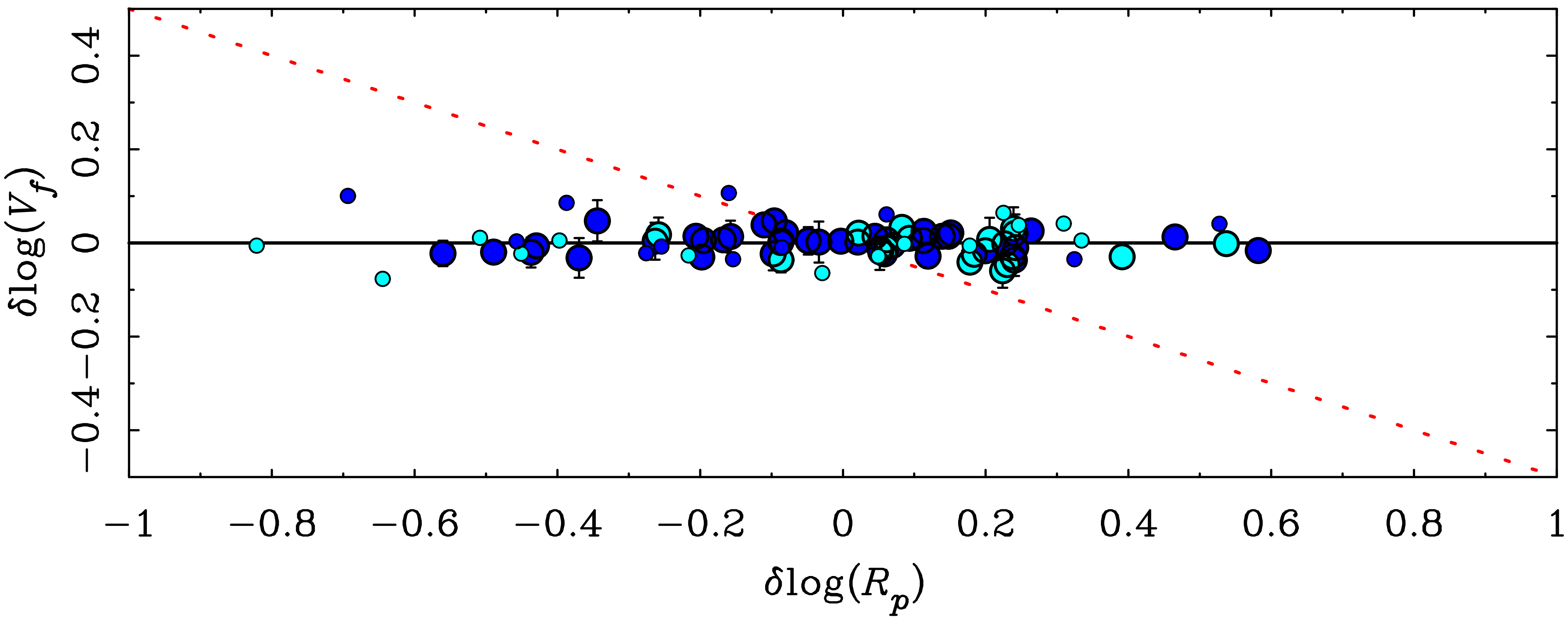
Same (M,V) but very different size and surface density

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

No residuals from TF with size or surface brightness

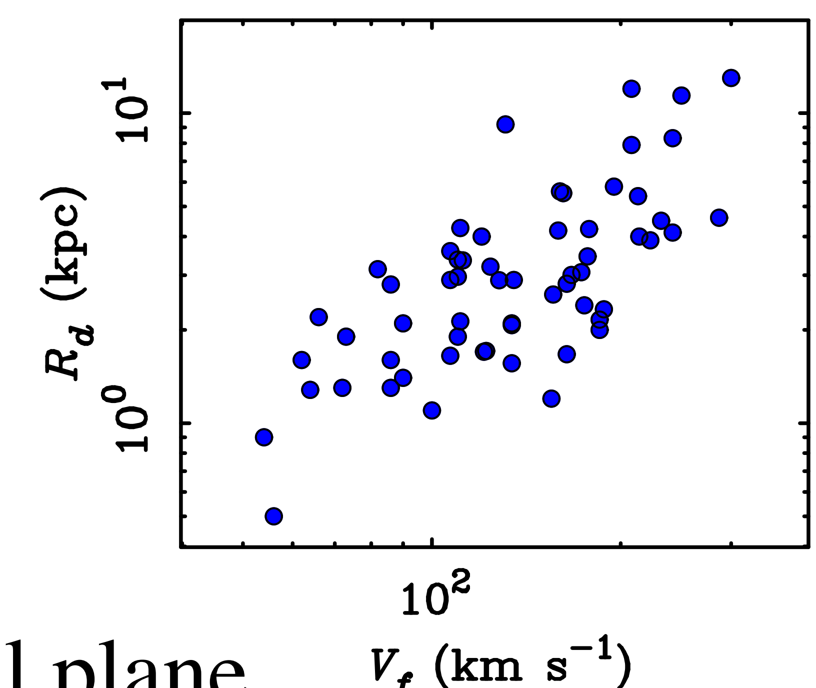
(Zwaan et al 1995; Sprayberry et al 1995; McGaugh & de Blok 1998)





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

TF already edge-on projection of disk fundamental plane

Baryonic TF Relation

- Fundamentally a relation between the baryonic mass of a galaxy and its rotation velocity
  - $M_b = M_* + M_g = 47 V_f^4$ (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.