Empirical Laws of Galactic Rotation

Homework 2
due Feb 25

midterm Mar 3

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]

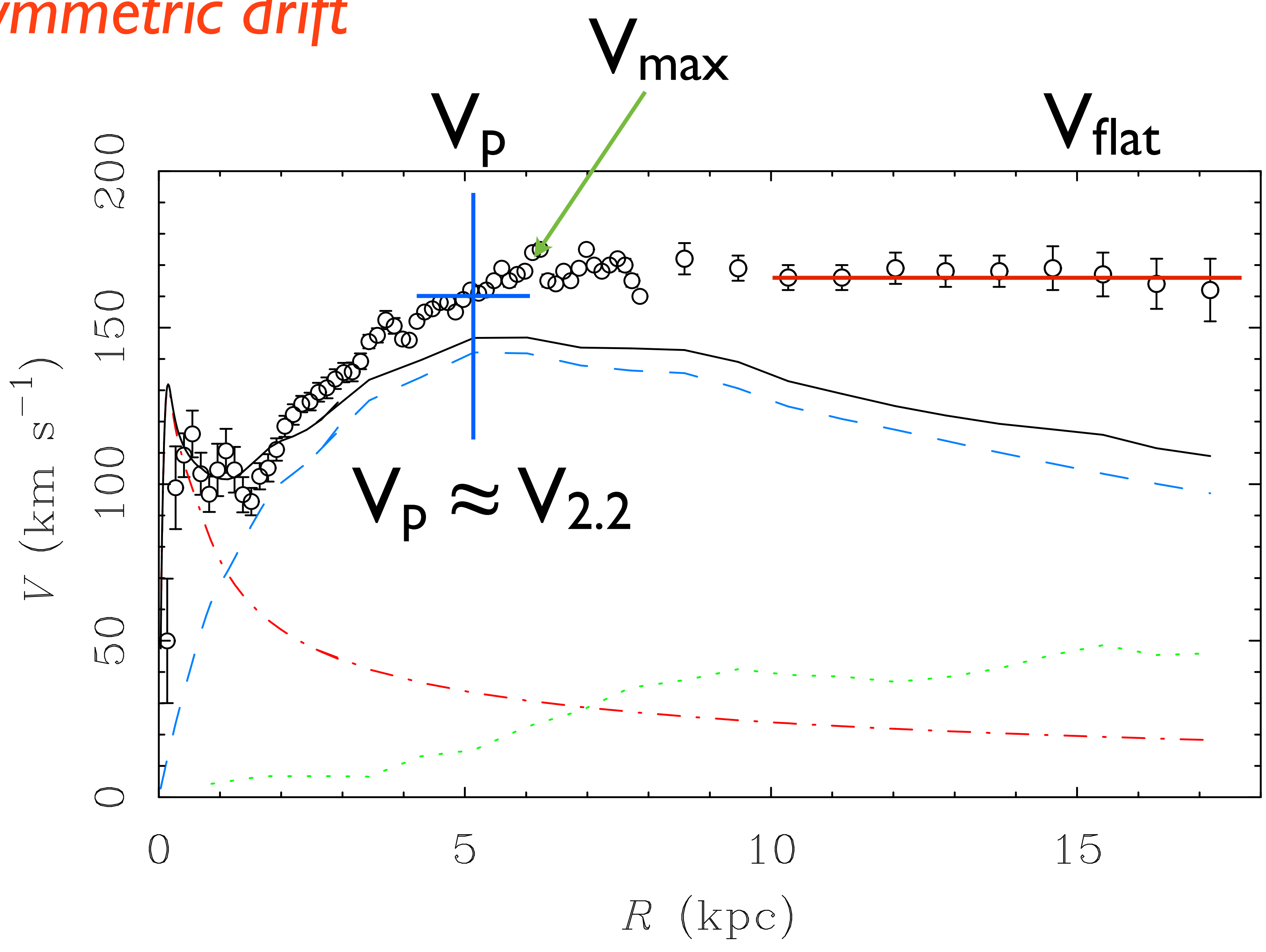
Daigle et al (2006) [Ha]

Blais-Ouellette et al (2004)

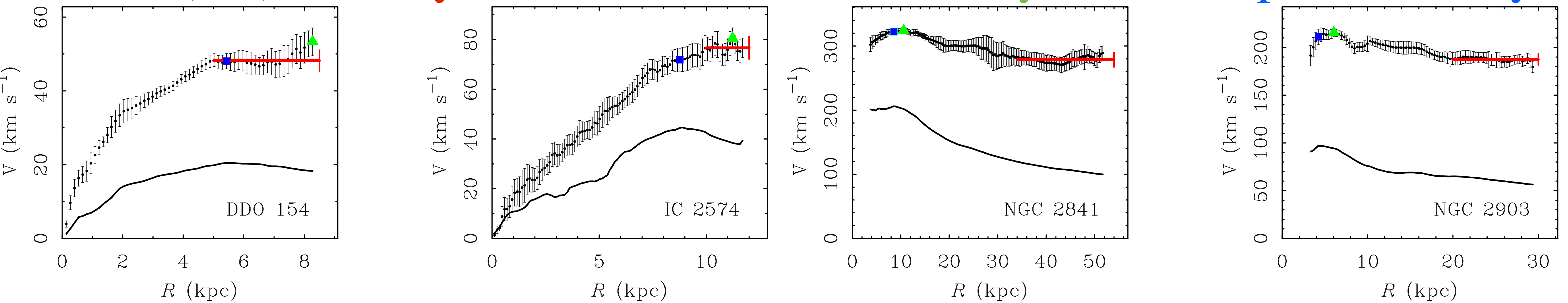
Mass model built from

2MASS K-band data (SSM)

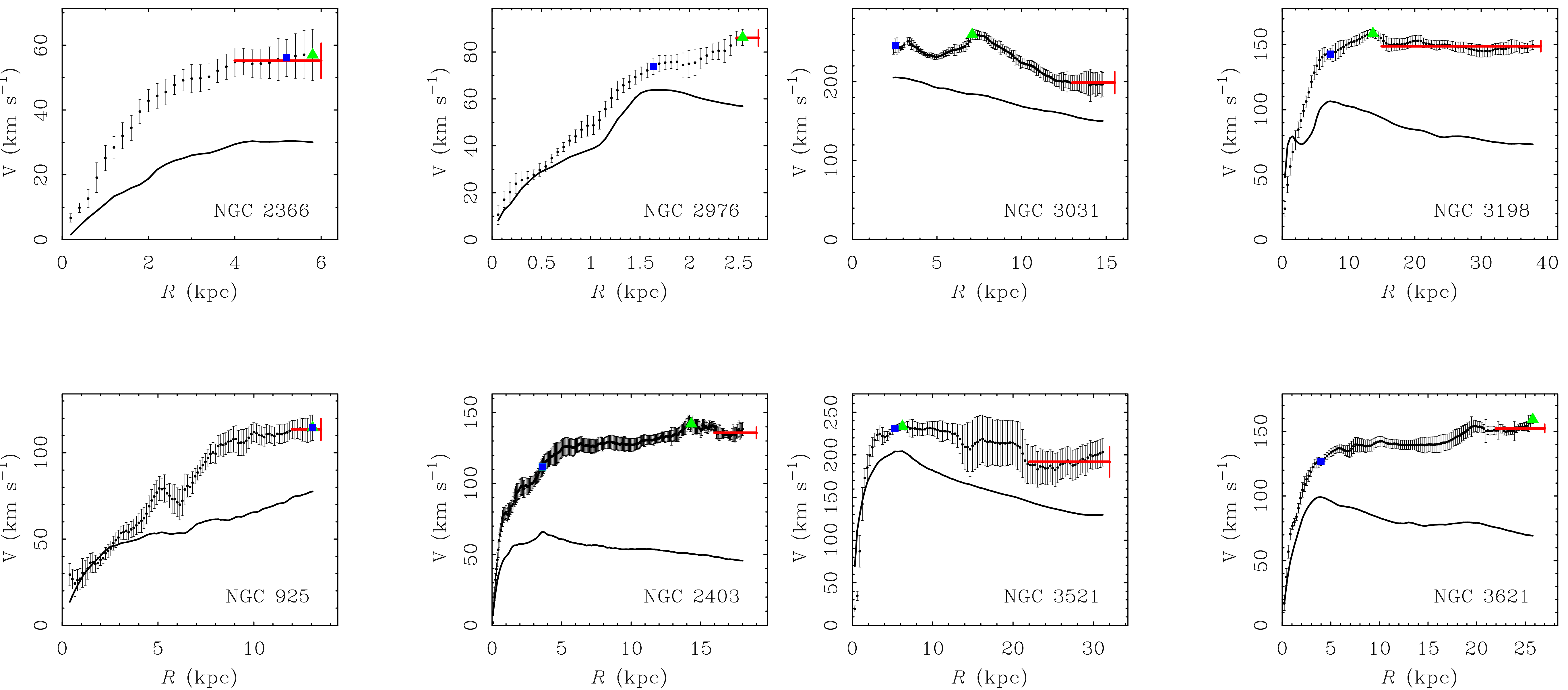
NGC 6946



outer (flat) velocity   maximum velocity   peak velocity

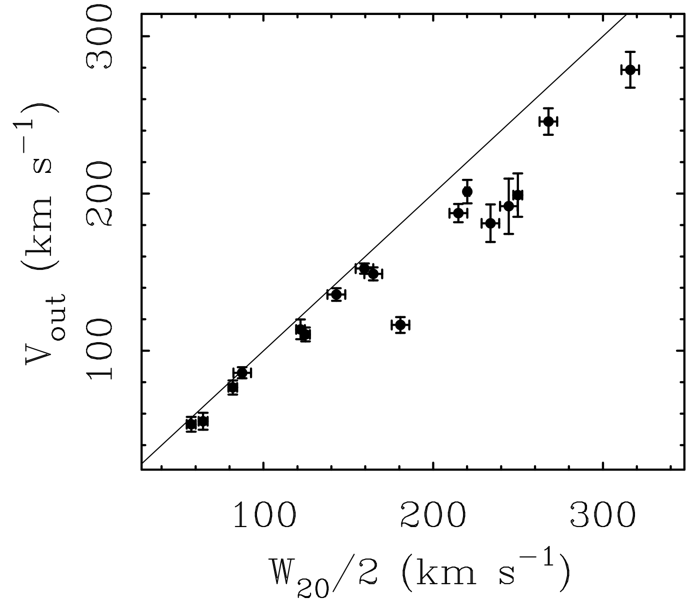


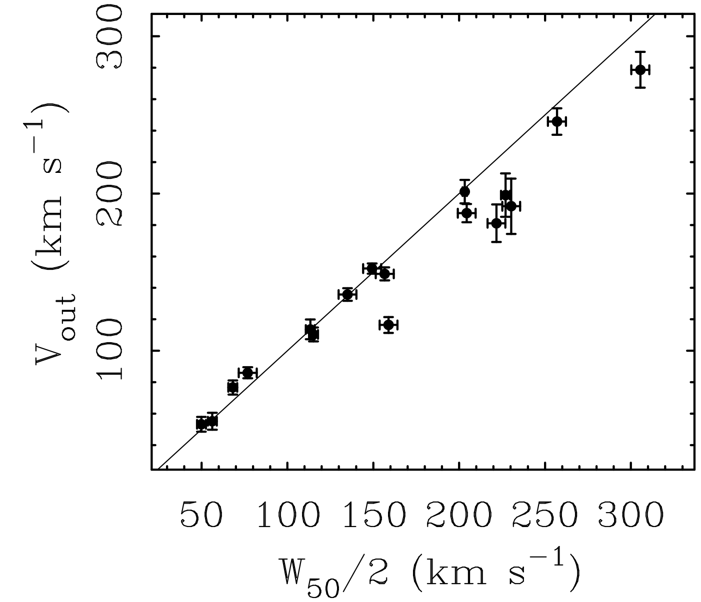
THINGS data (Walter et al 2008)



Velocity estimators:

V_{flat}

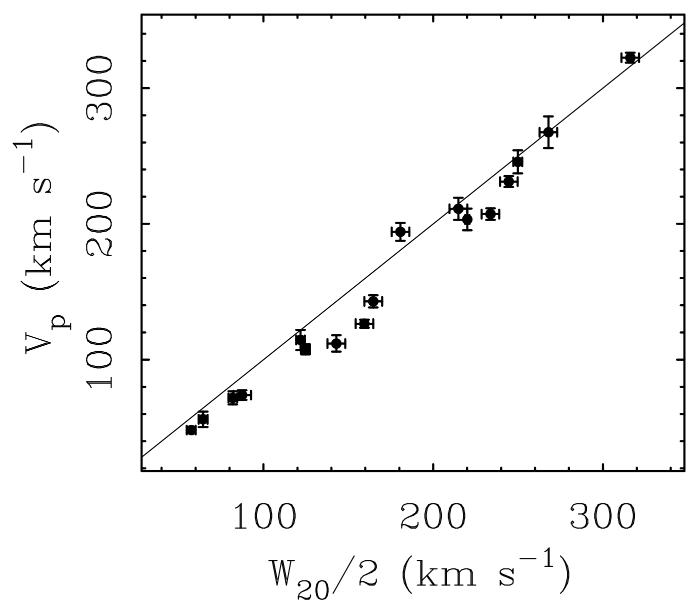


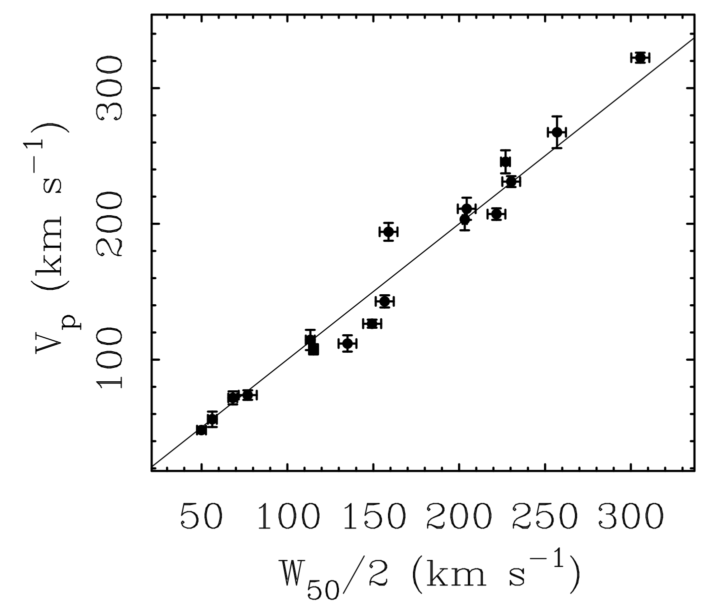


W_{20} W_{50}

THINGS data
(Walter et al 2008)

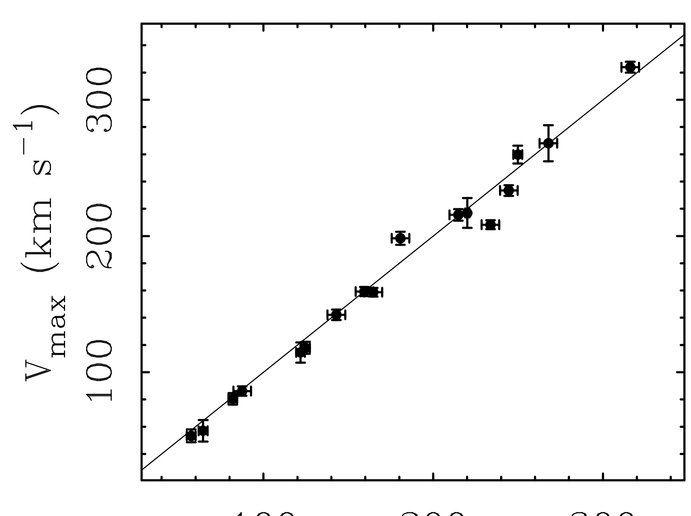
V_p

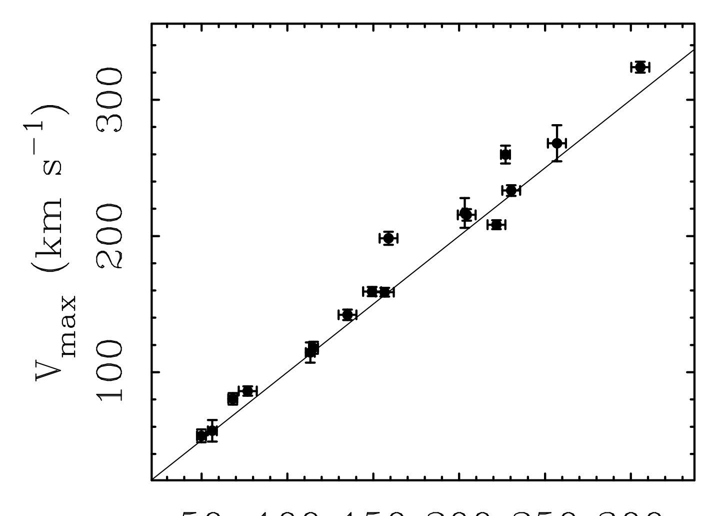




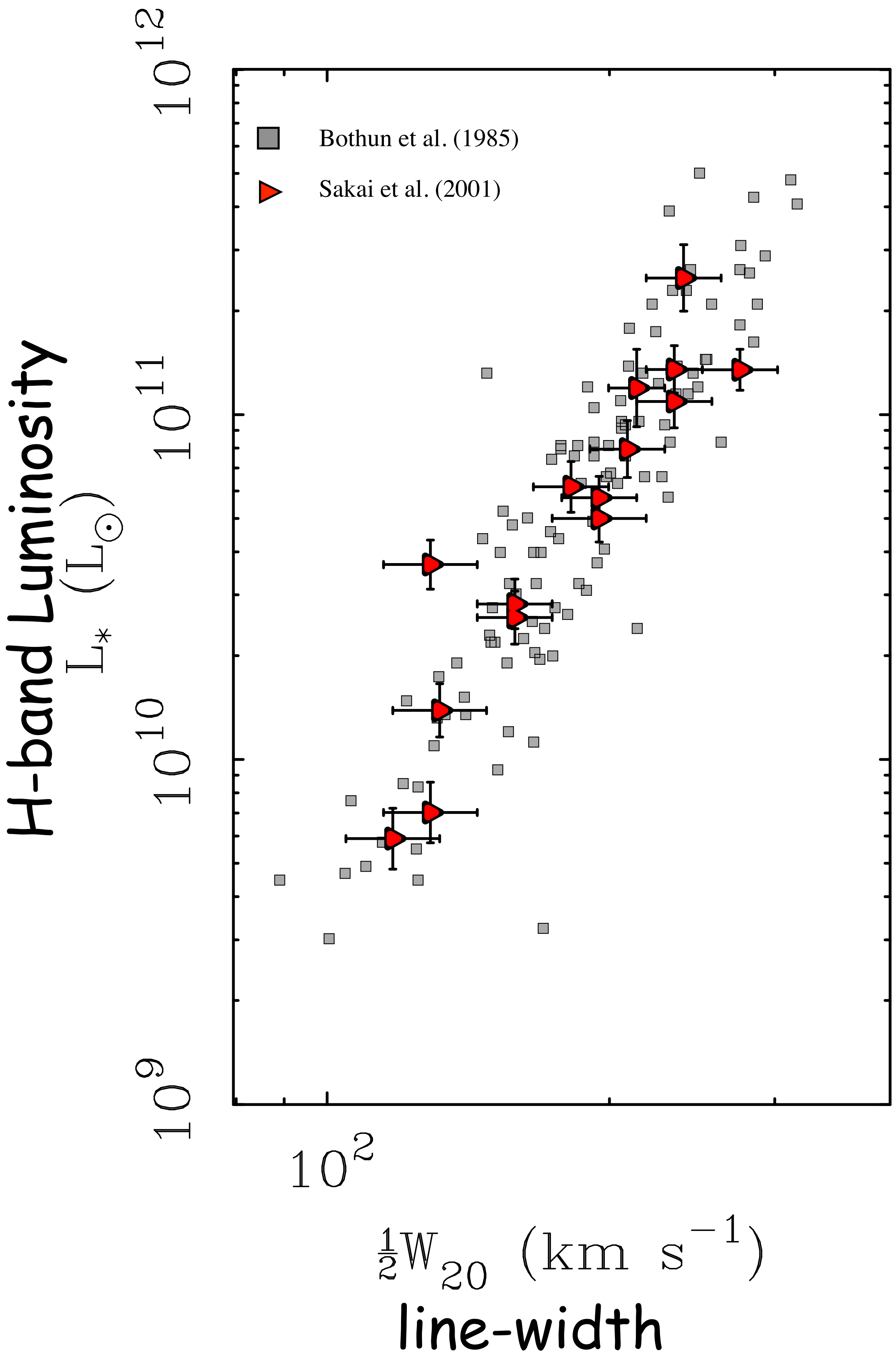
W_{20} W_{50}

V_{max}



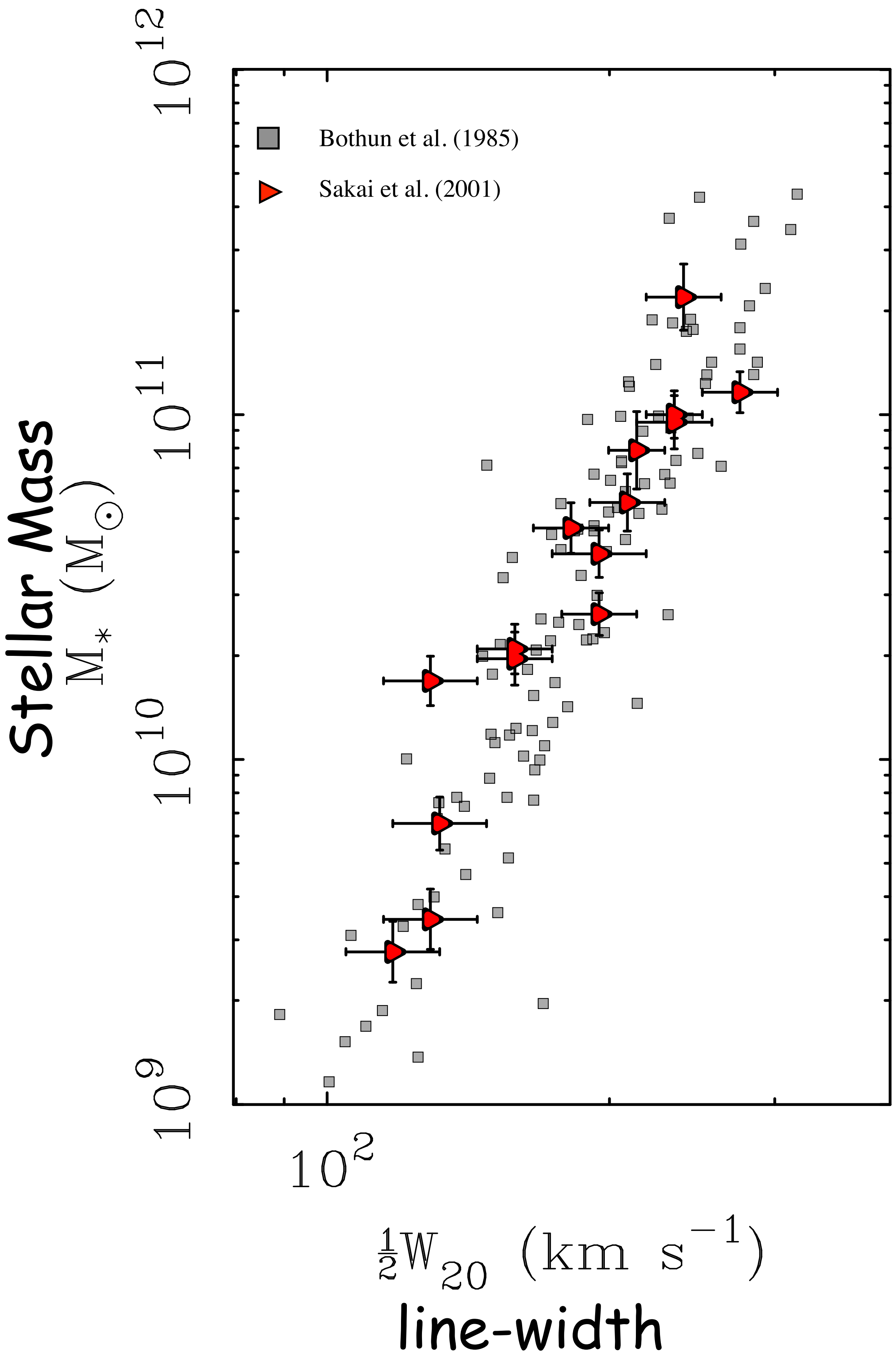


Tully-Fisher relation



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

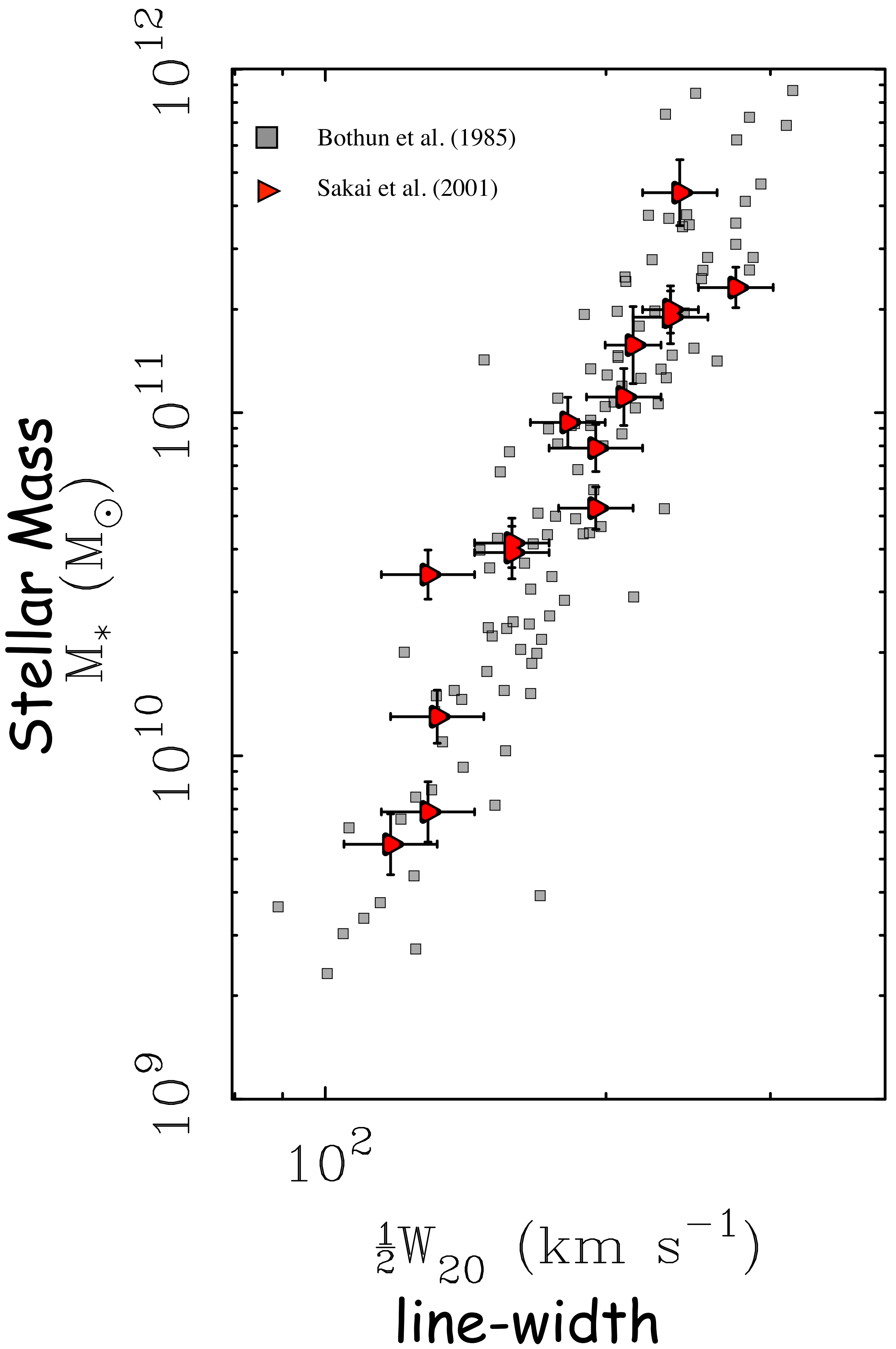
Stellar Mass Tully-Fisher relation



nominal M*/L (Kroupa IMF)

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

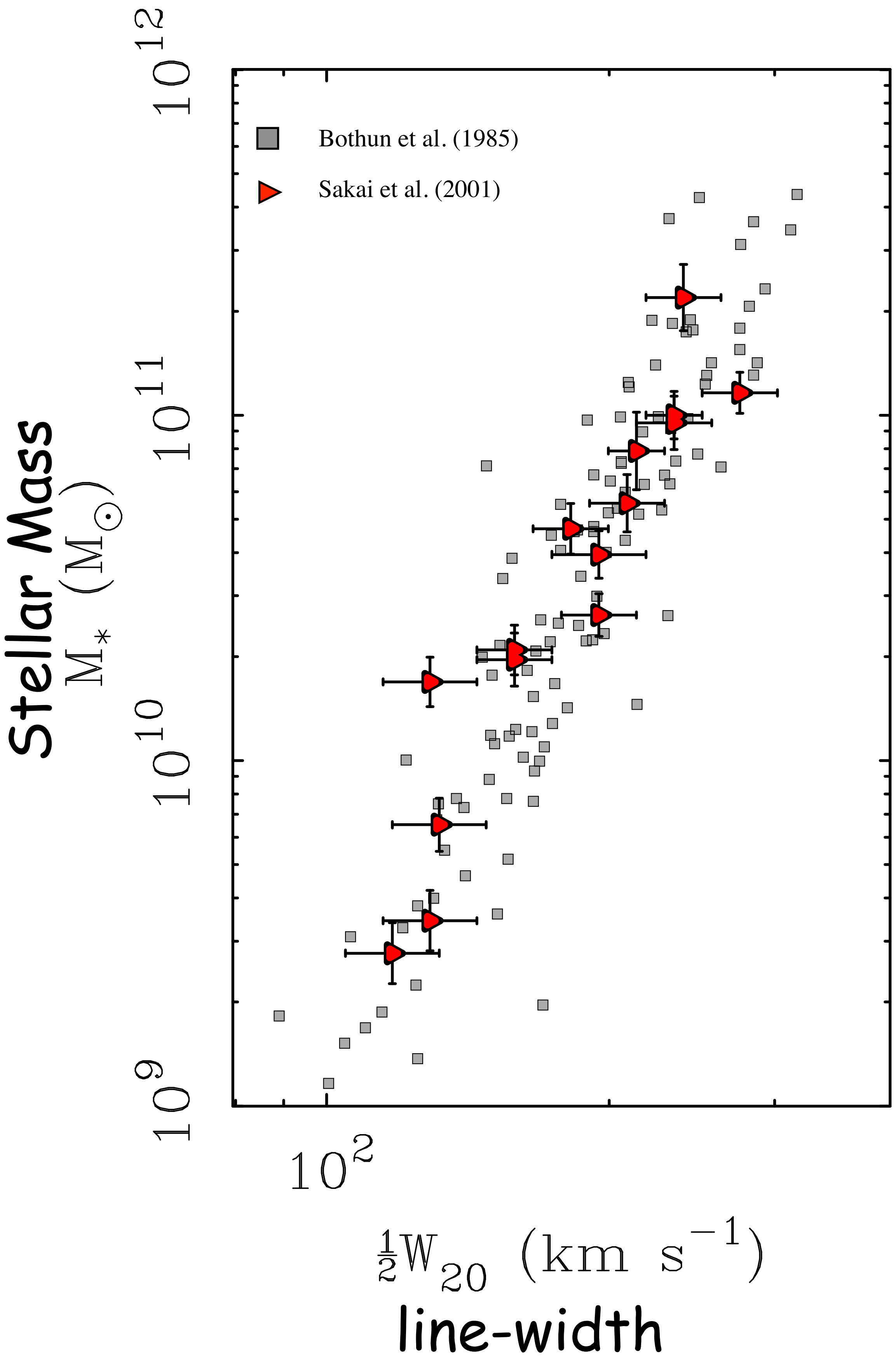
Stellar Mass Tully-Fisher relation



double M*/L

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

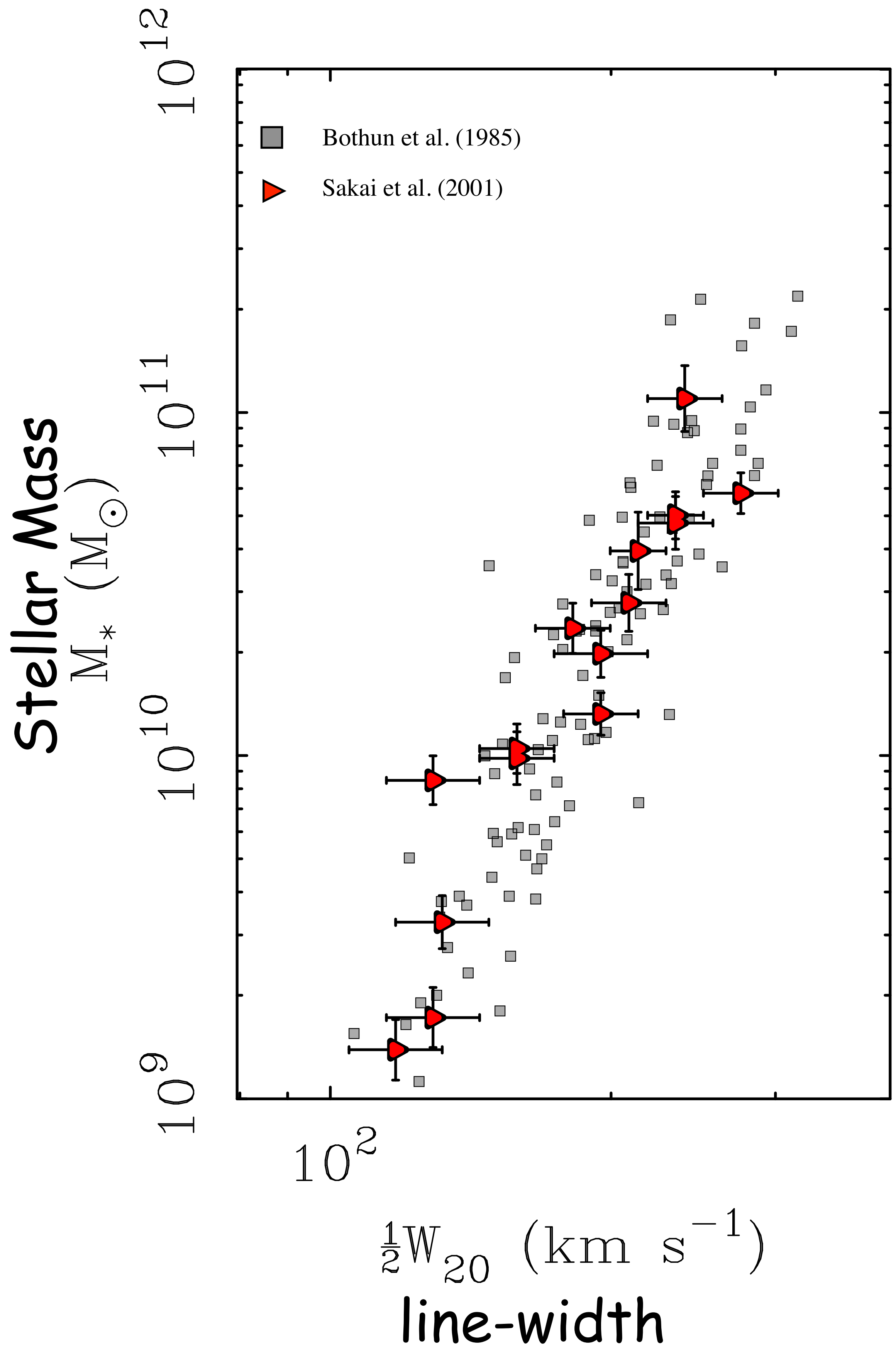
Stellar Mass Tully-Fisher relation



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)

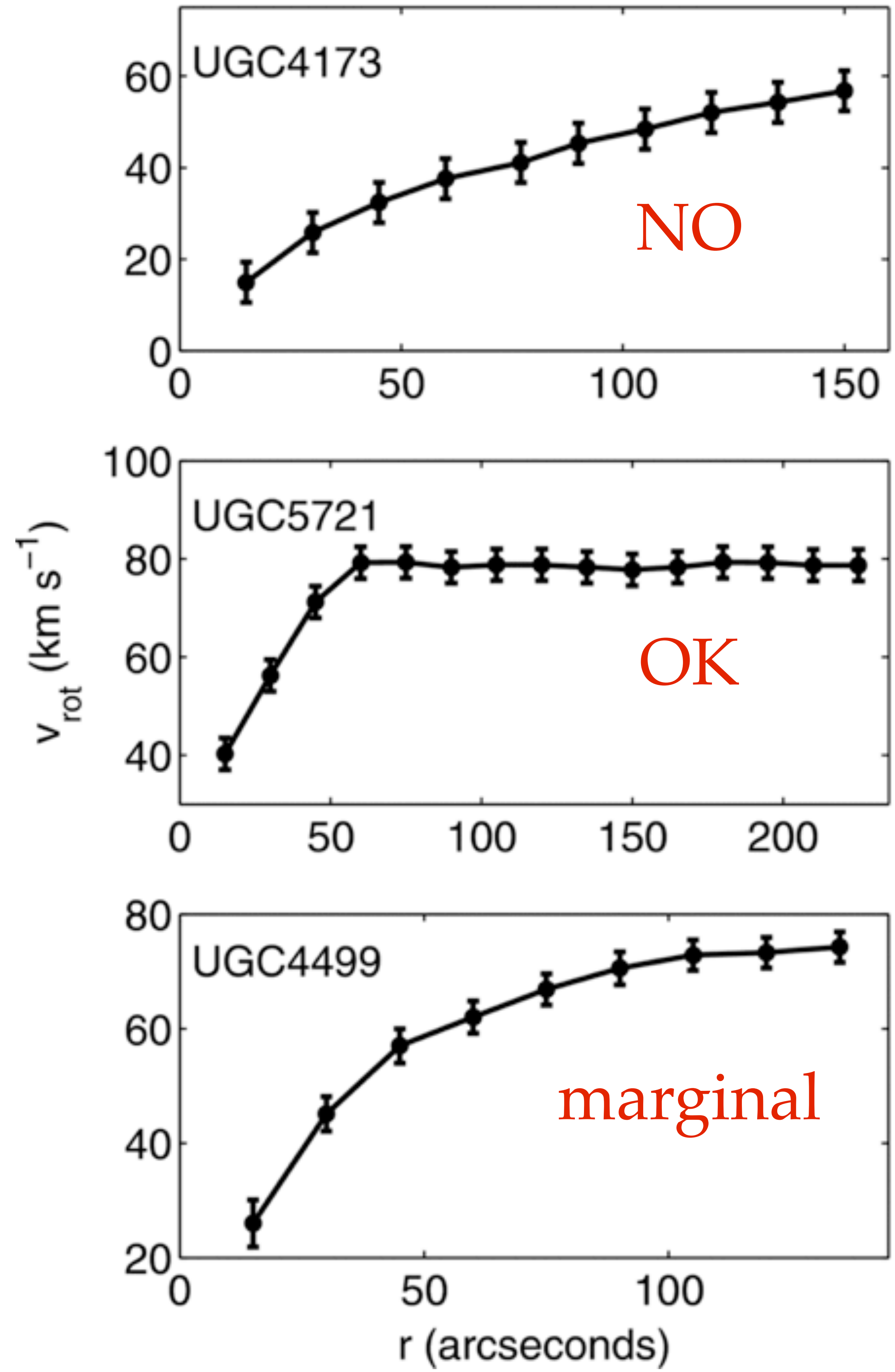
Stark, McGaugh, & Swaters et al. (2009)

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

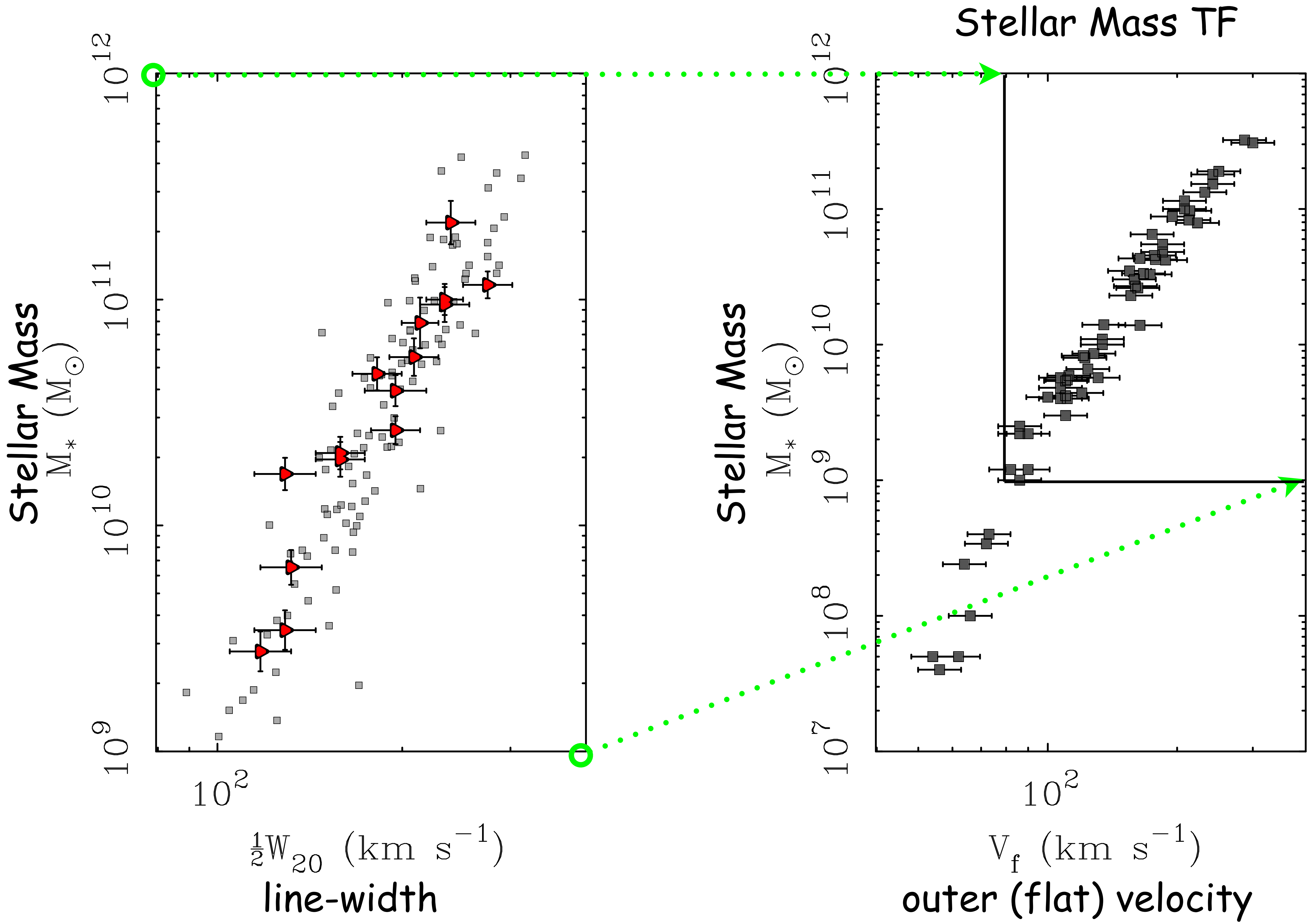
$$\frac{\partial \log V}{\partial \log R} < 0.1$$

works well as a criterion.

Scatter in TF increases as threshold weakened.

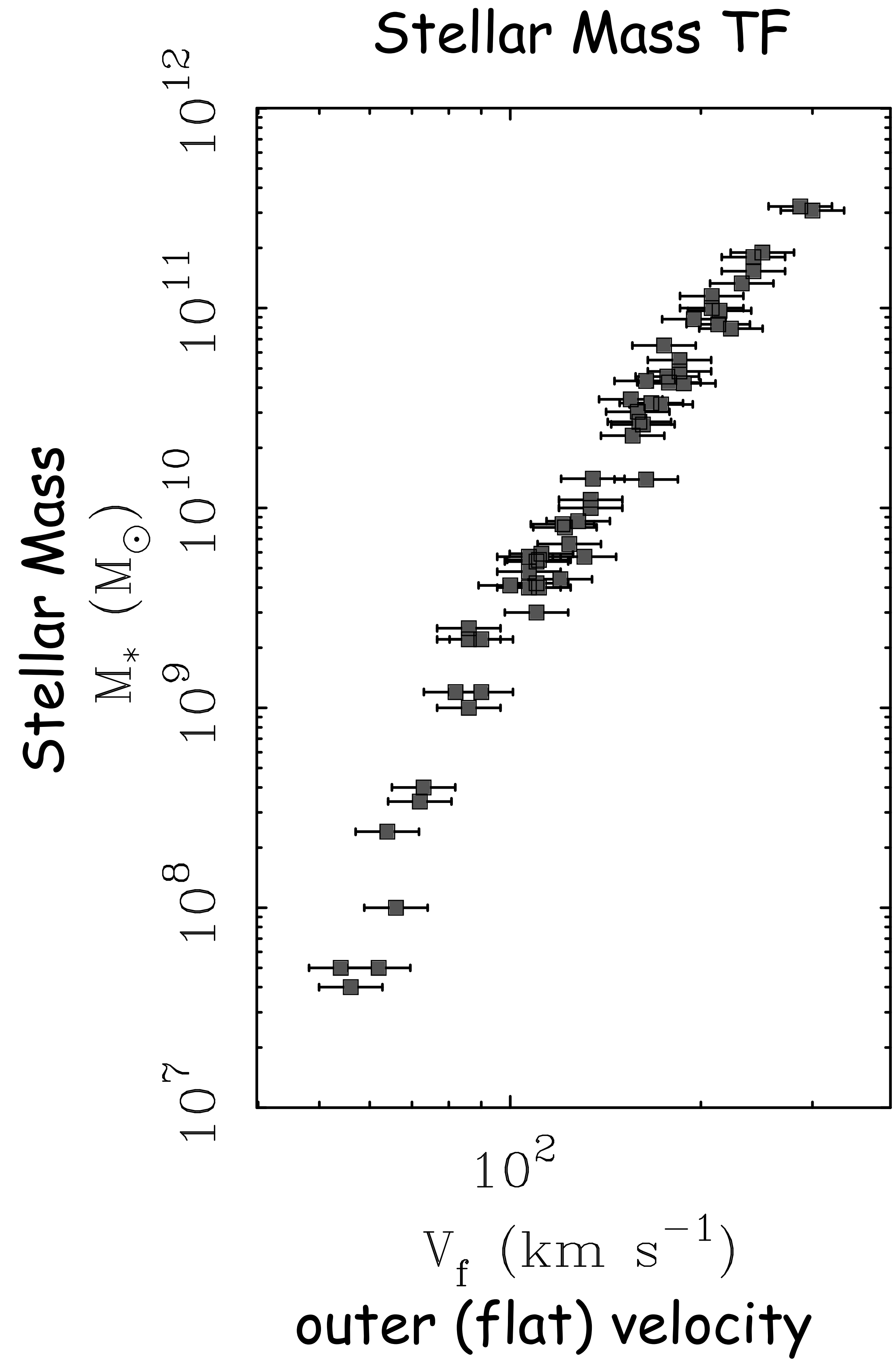


Scatter in TF relation reduced with resolved rotation curves (Verheijen 2001)



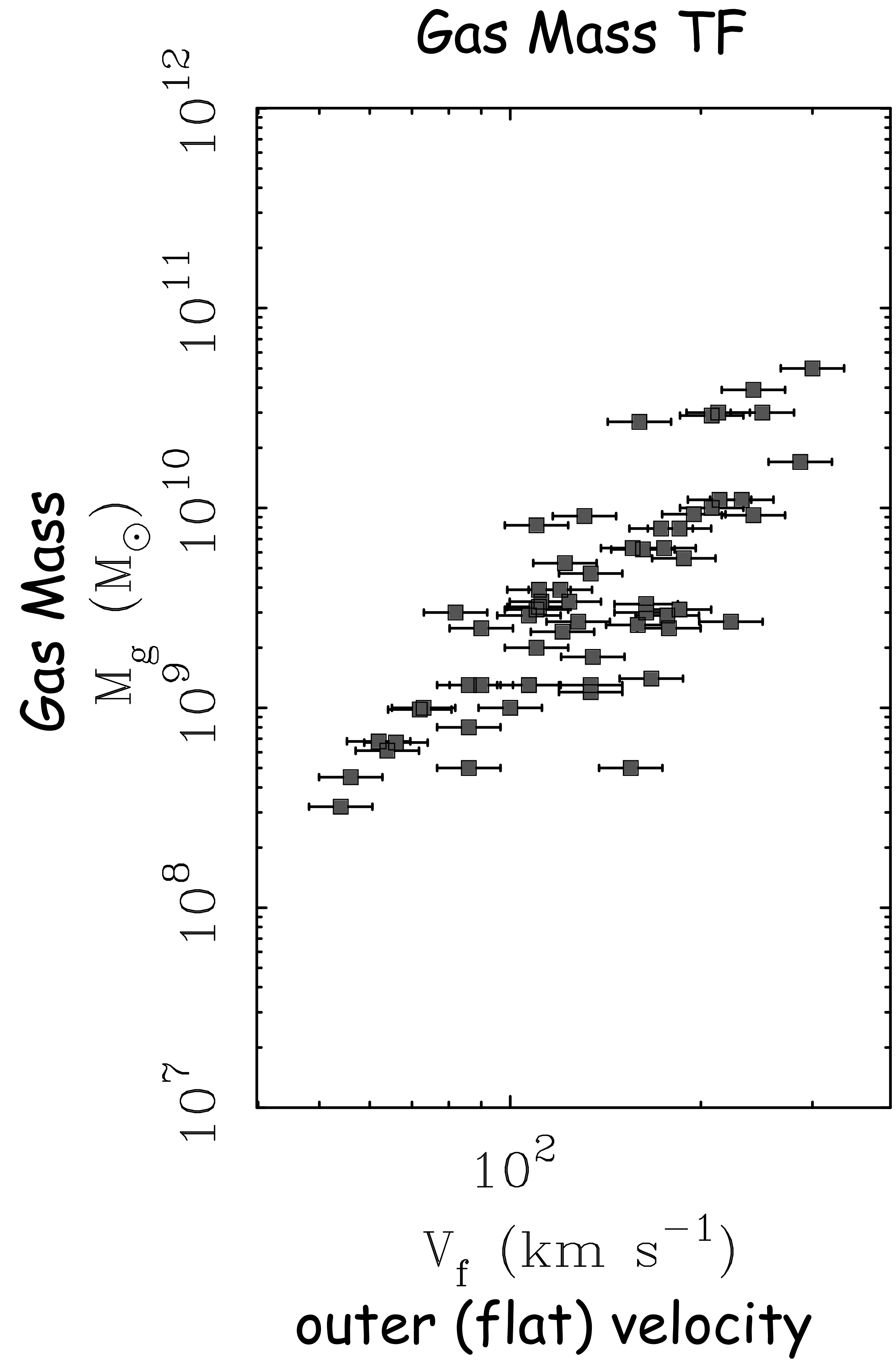
Low mass galaxies tend to fall below extrapolation of linear fit to fast rotators (Matthews, van Driel, & Gallagher 1998; Freeman 1999)

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



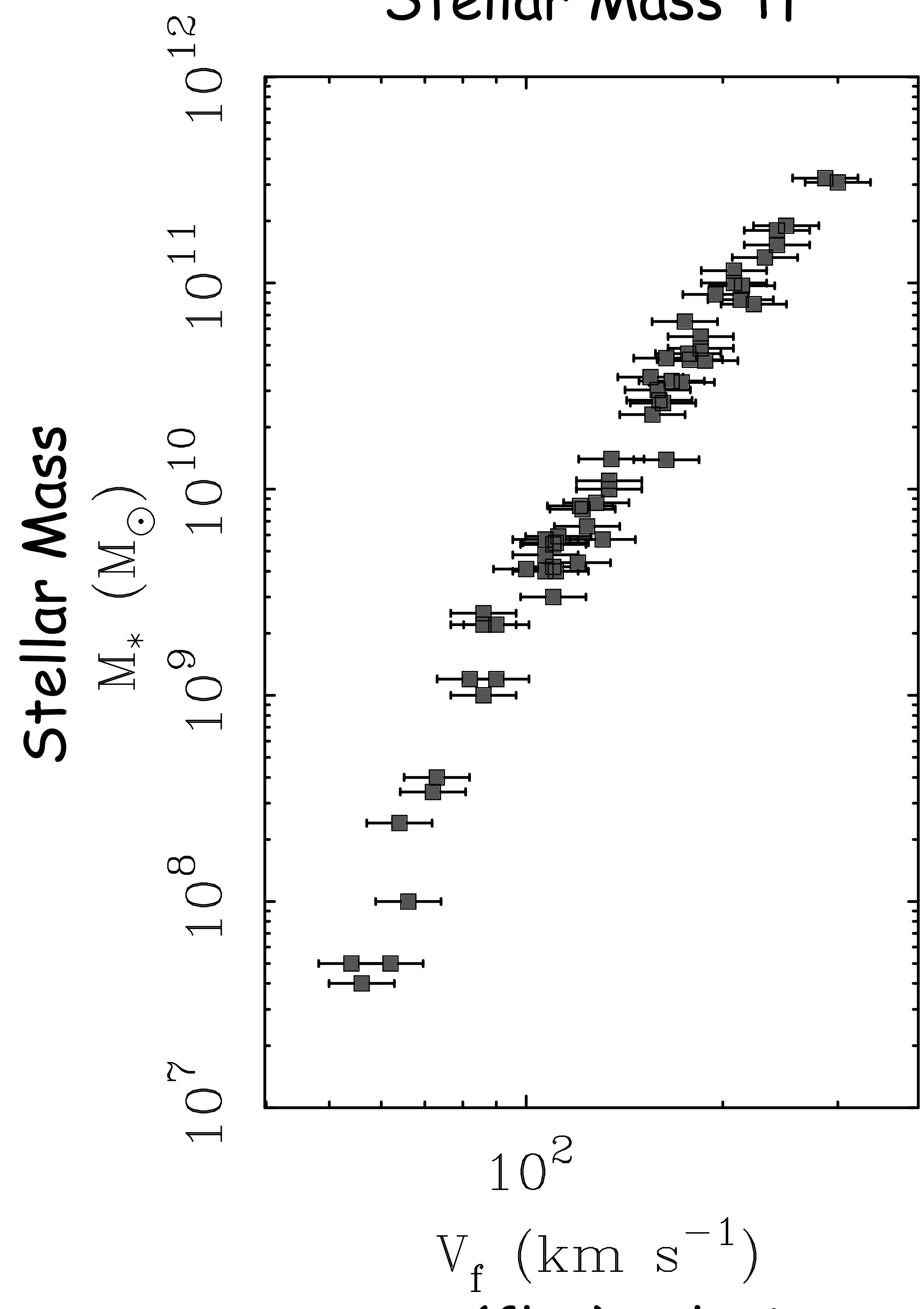
Gas mass by itself does NOT produce a good TF relation, at least for fast rotators.

$$M_g = 1.4 M_{HI}$$



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

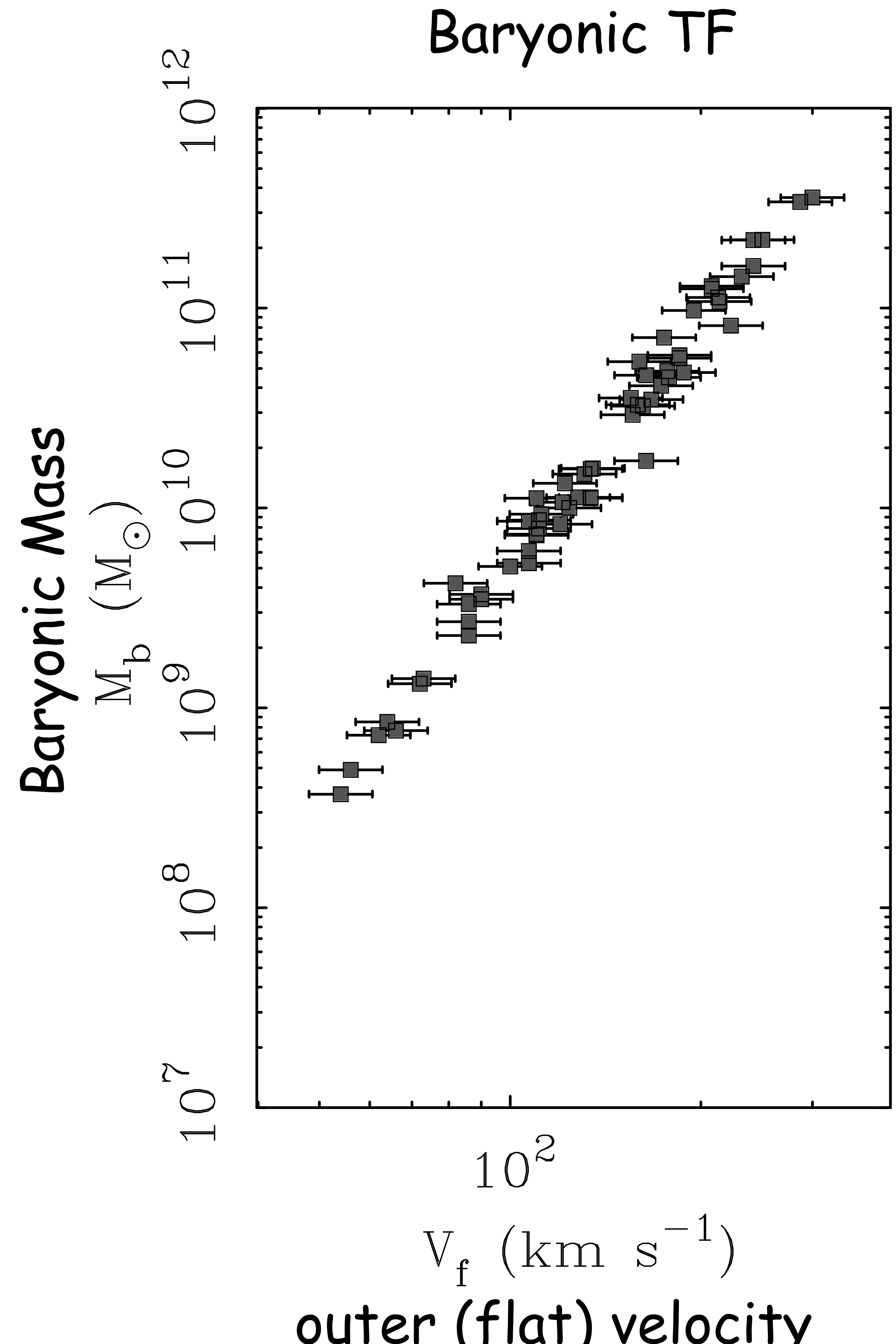
Stellar Mass TF



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

$$M_b = M_* + M_g$$

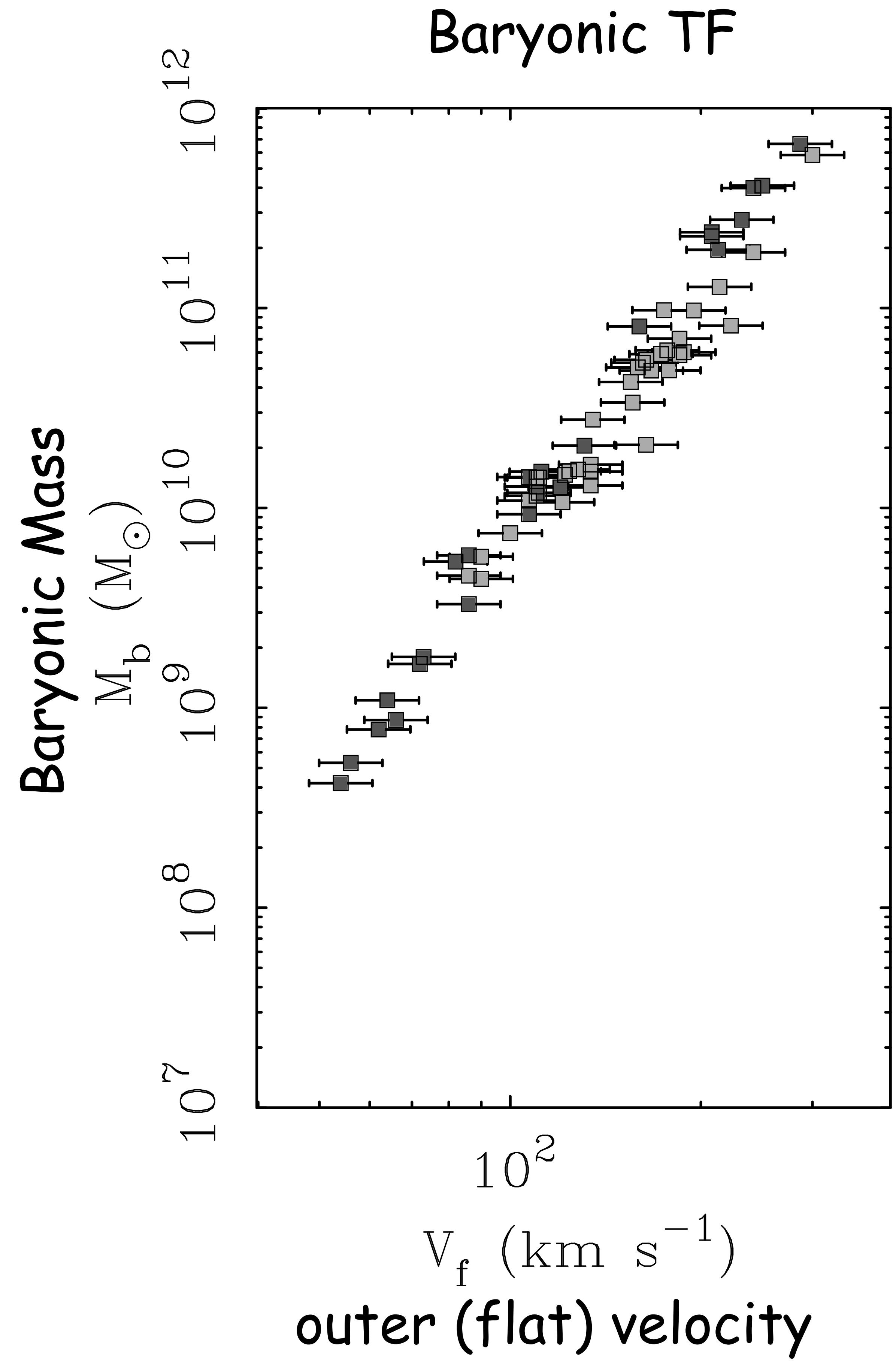
Baryonic mass is the important physical quantity. It doesn't matter whether the mass is in stars or in gas.



Twice Nominal M*/L

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

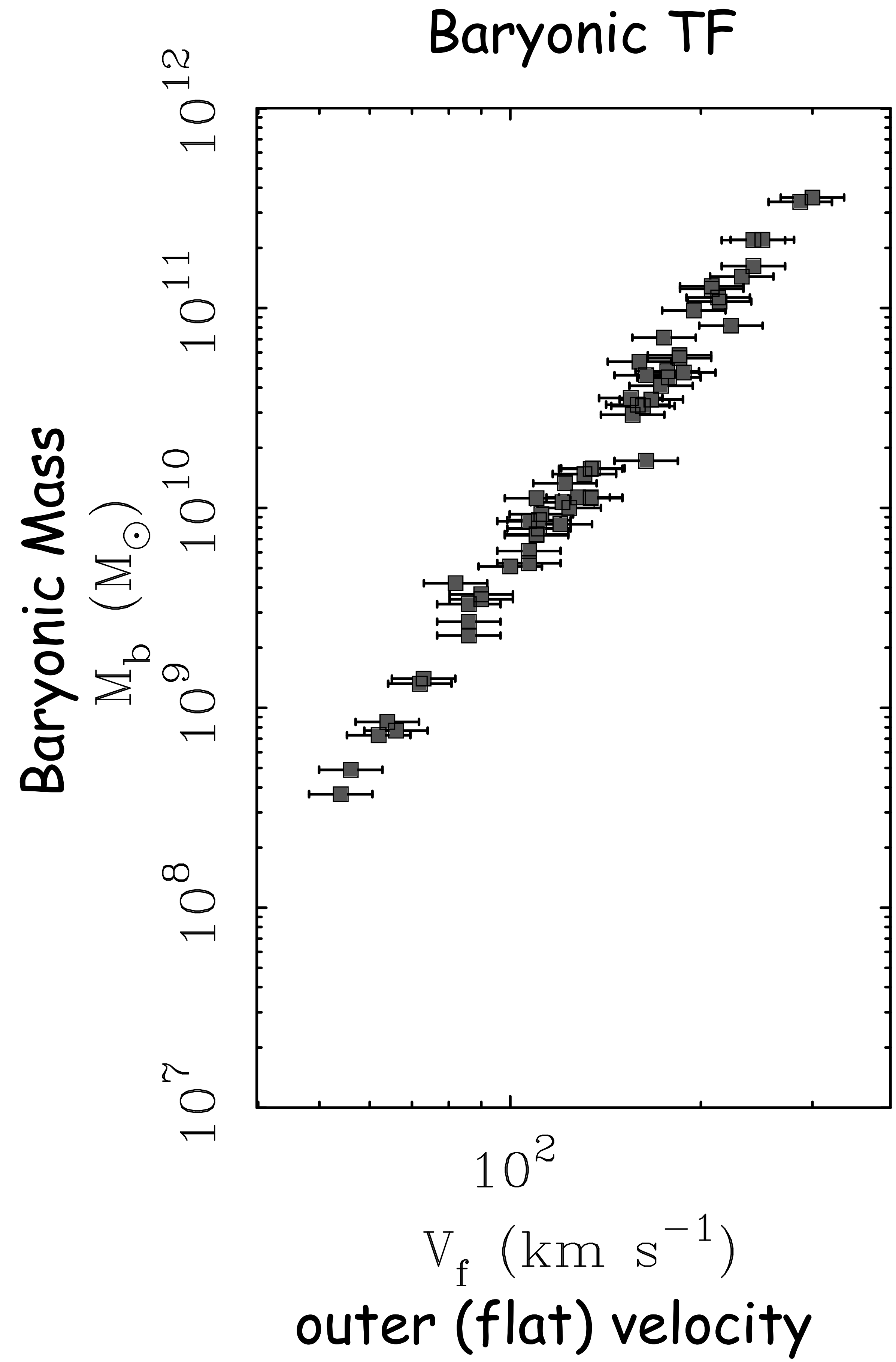
Scatter increases as we diverge from the nominal M*/L.



Nominal M*/L

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

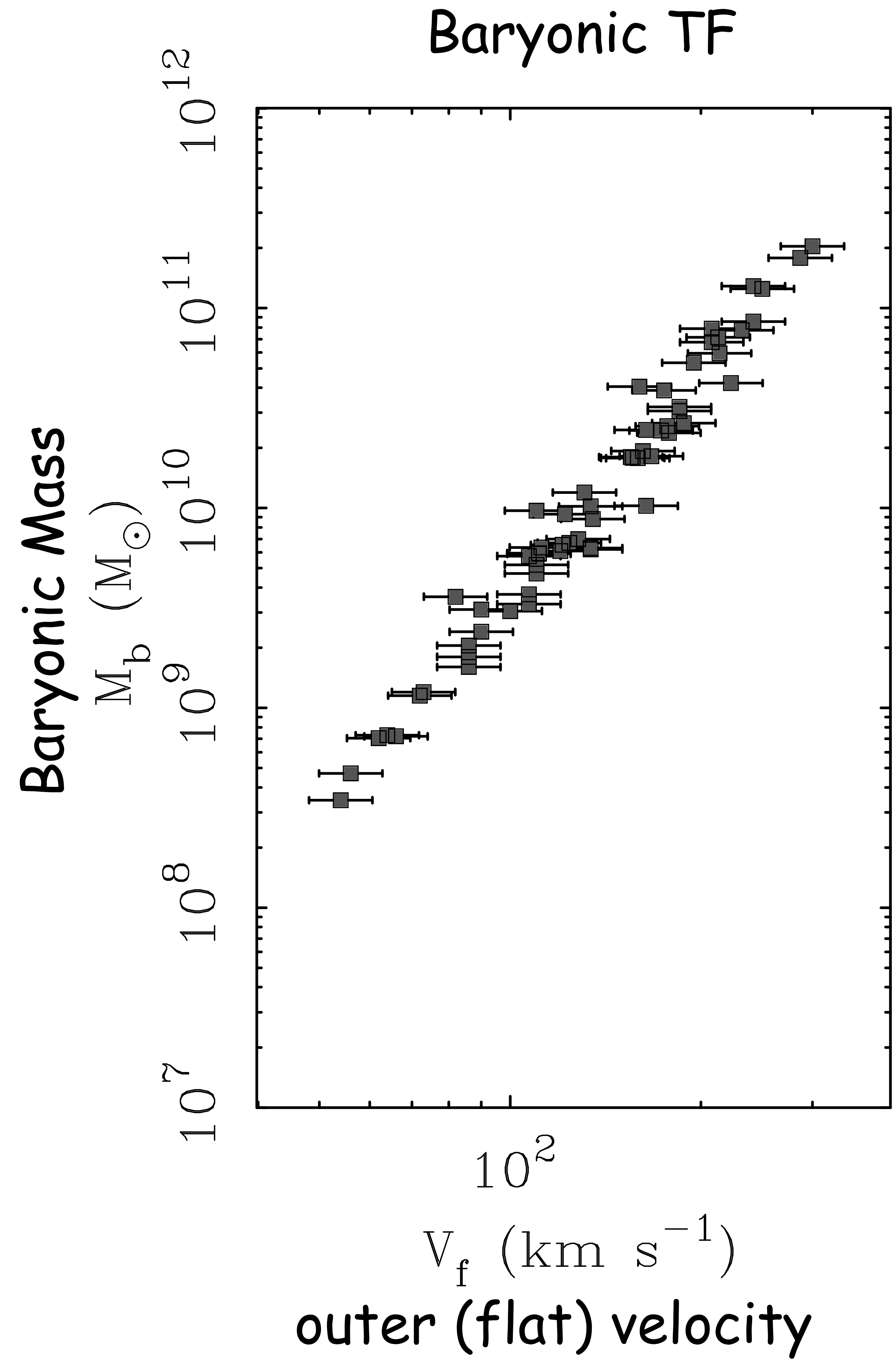
Scatter increases as we diverge from the nominal M*/L.



Half Nominal M*/L

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

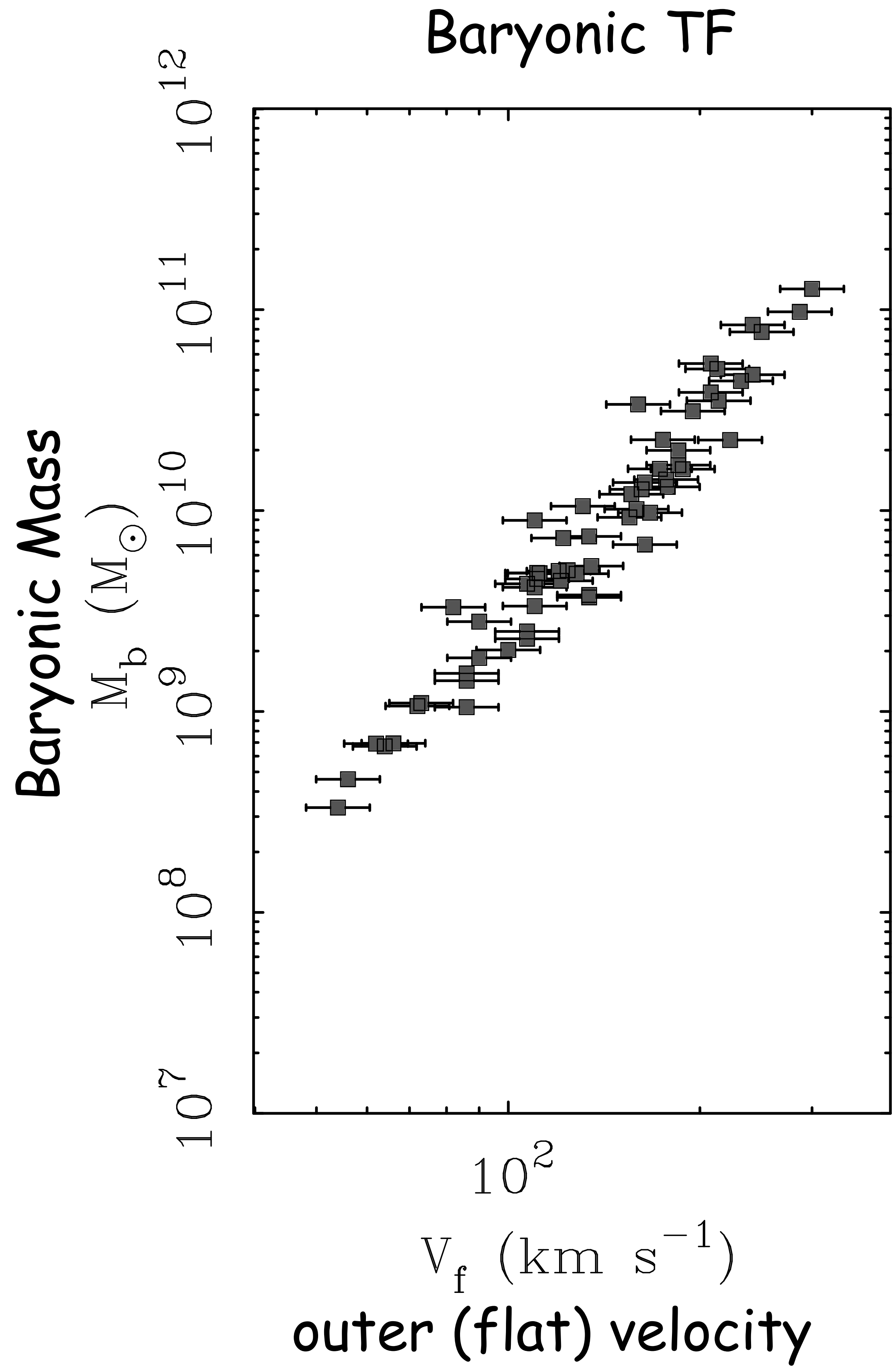
Scatter increases as we diverge from the nominal M*/L.



Quarter Nominal M*/L

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

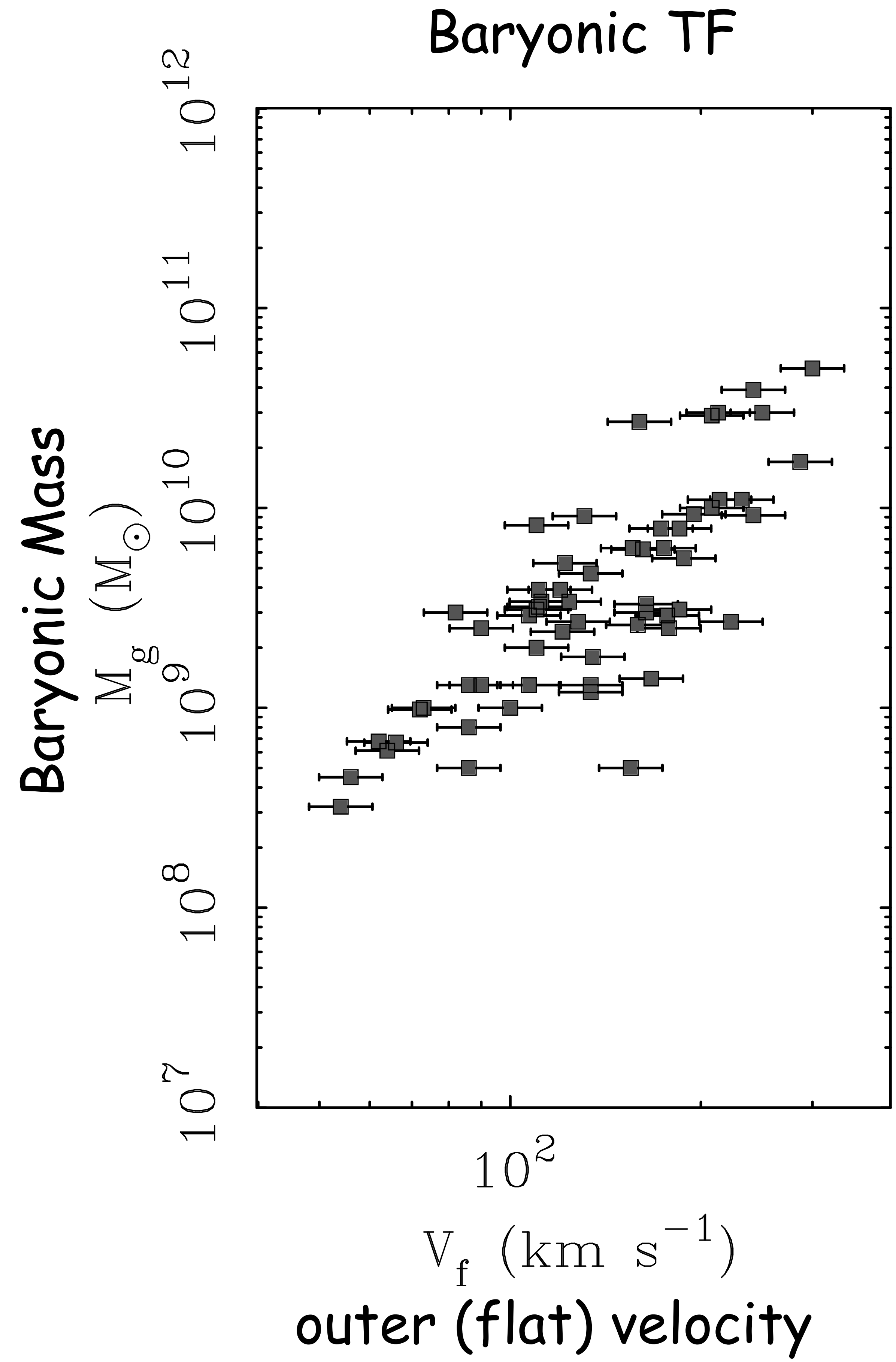
Scatter increases as we diverge from the nominal M*/L.



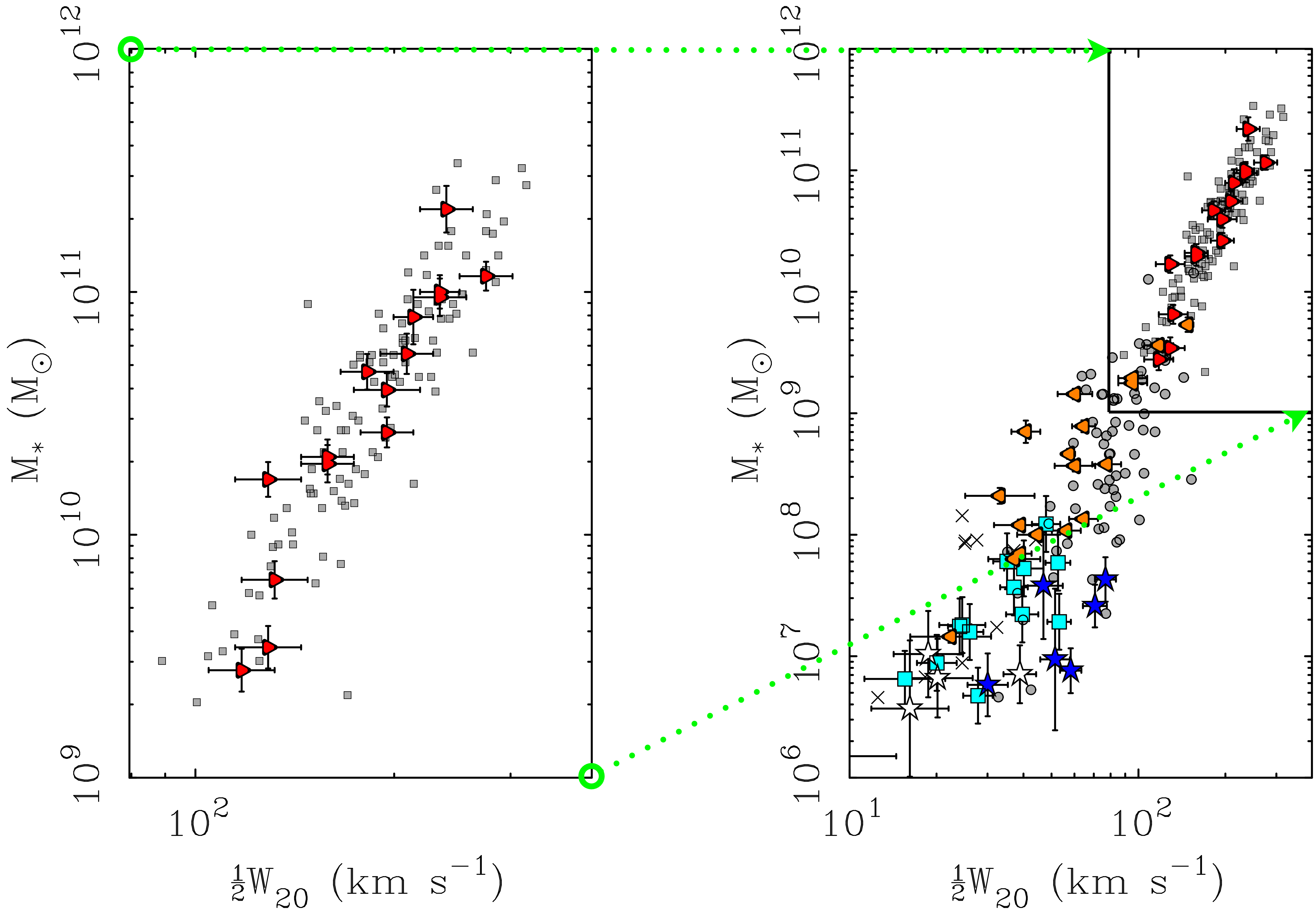
Zero M*/L

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

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



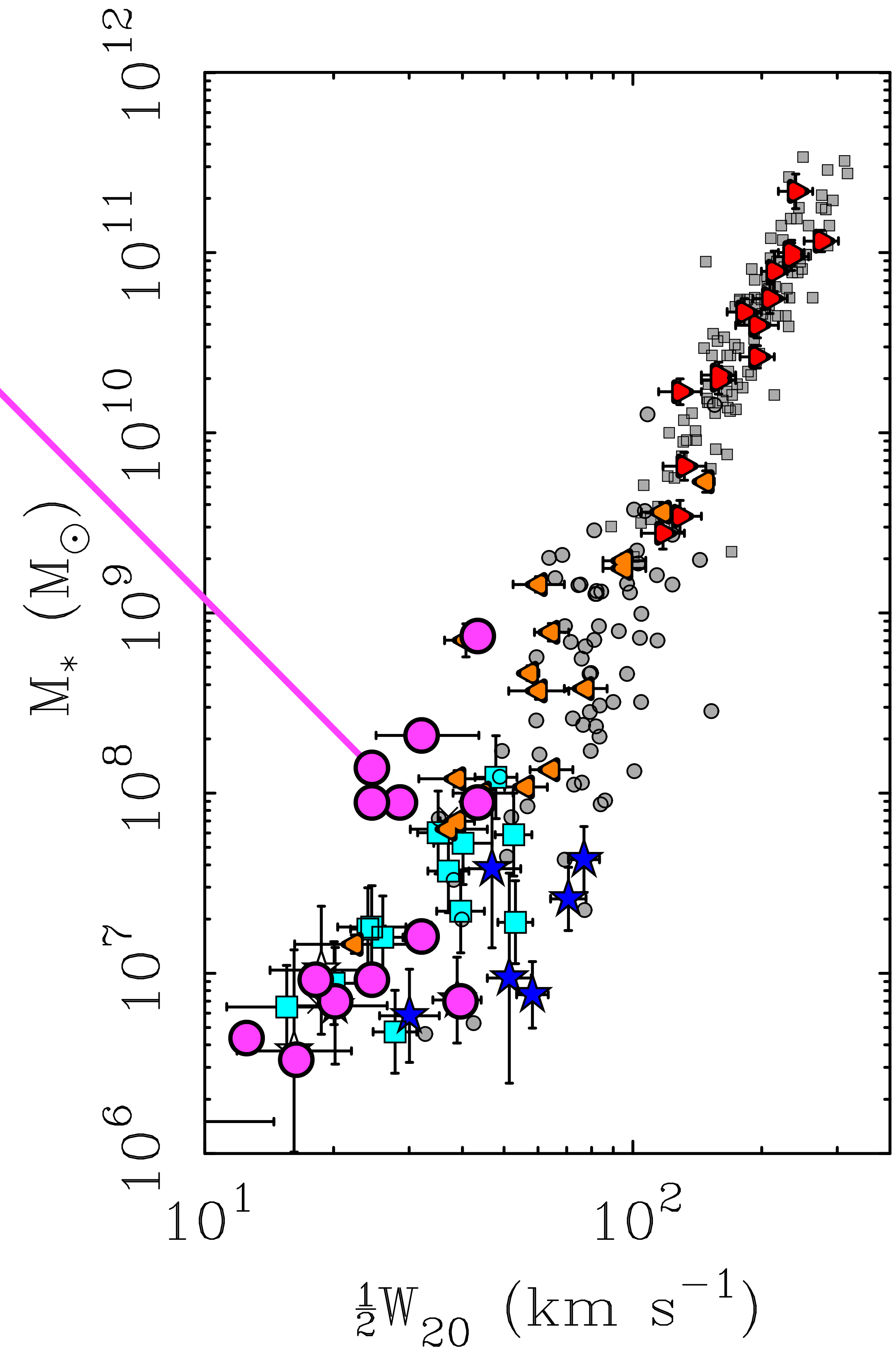
Low mass galaxies considerably expand range of the TF relation.
Gas dominated galaxies can provide absolute calibration of mass scale.



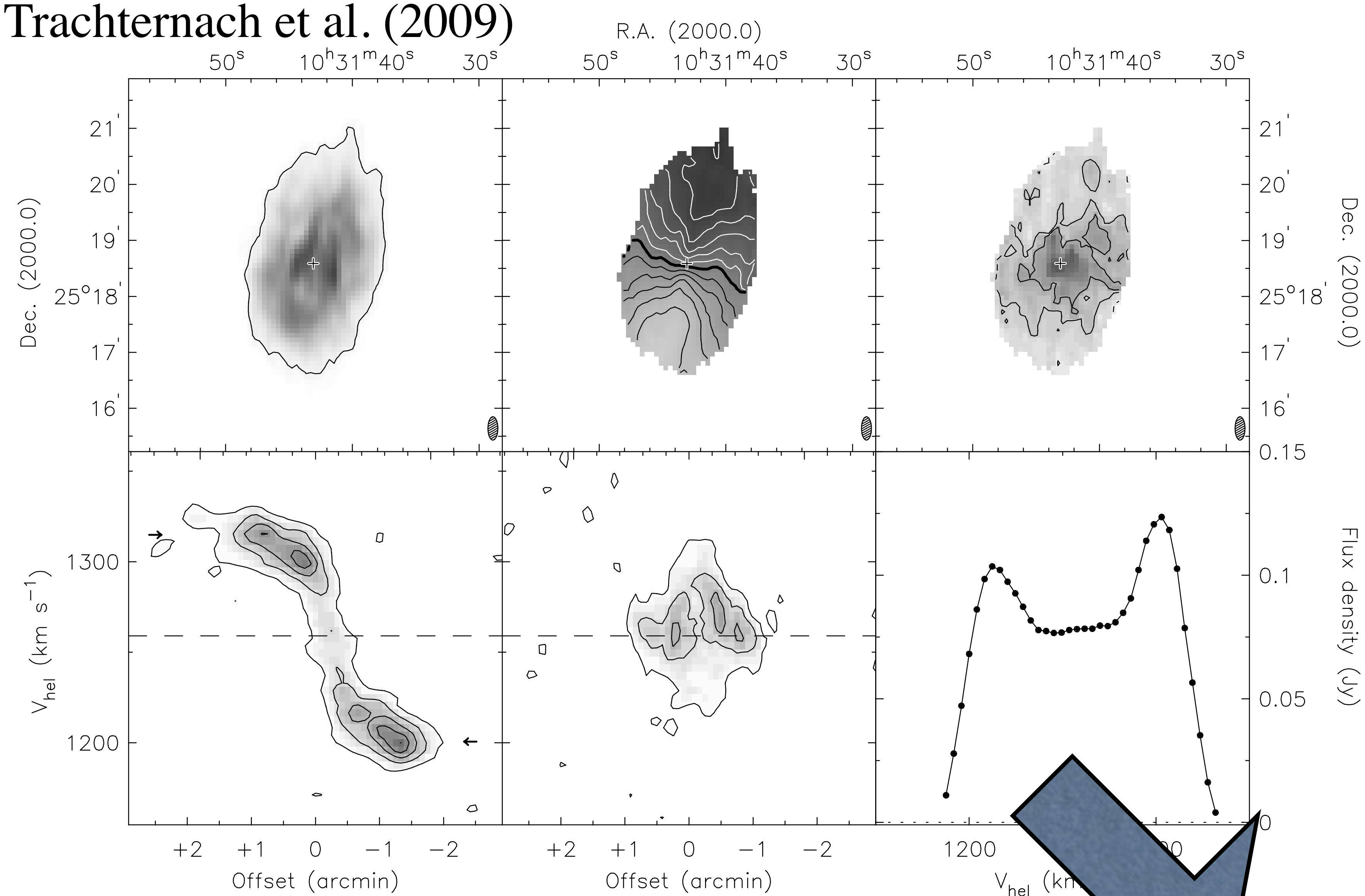
Gotta believe the data.

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).

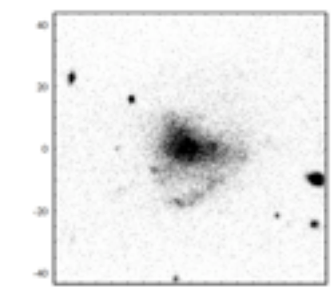


Trachternach et al. (2009)

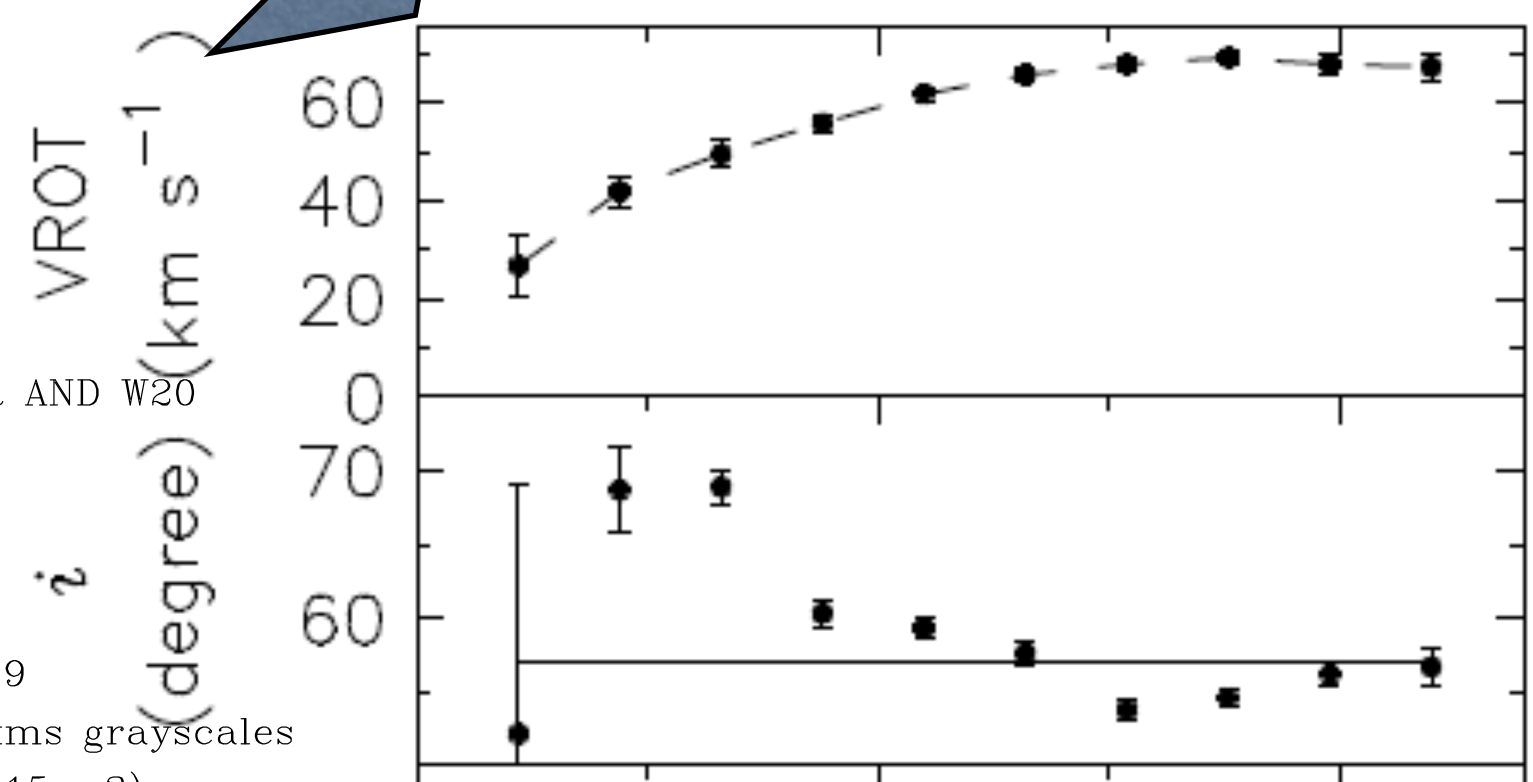


HI

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

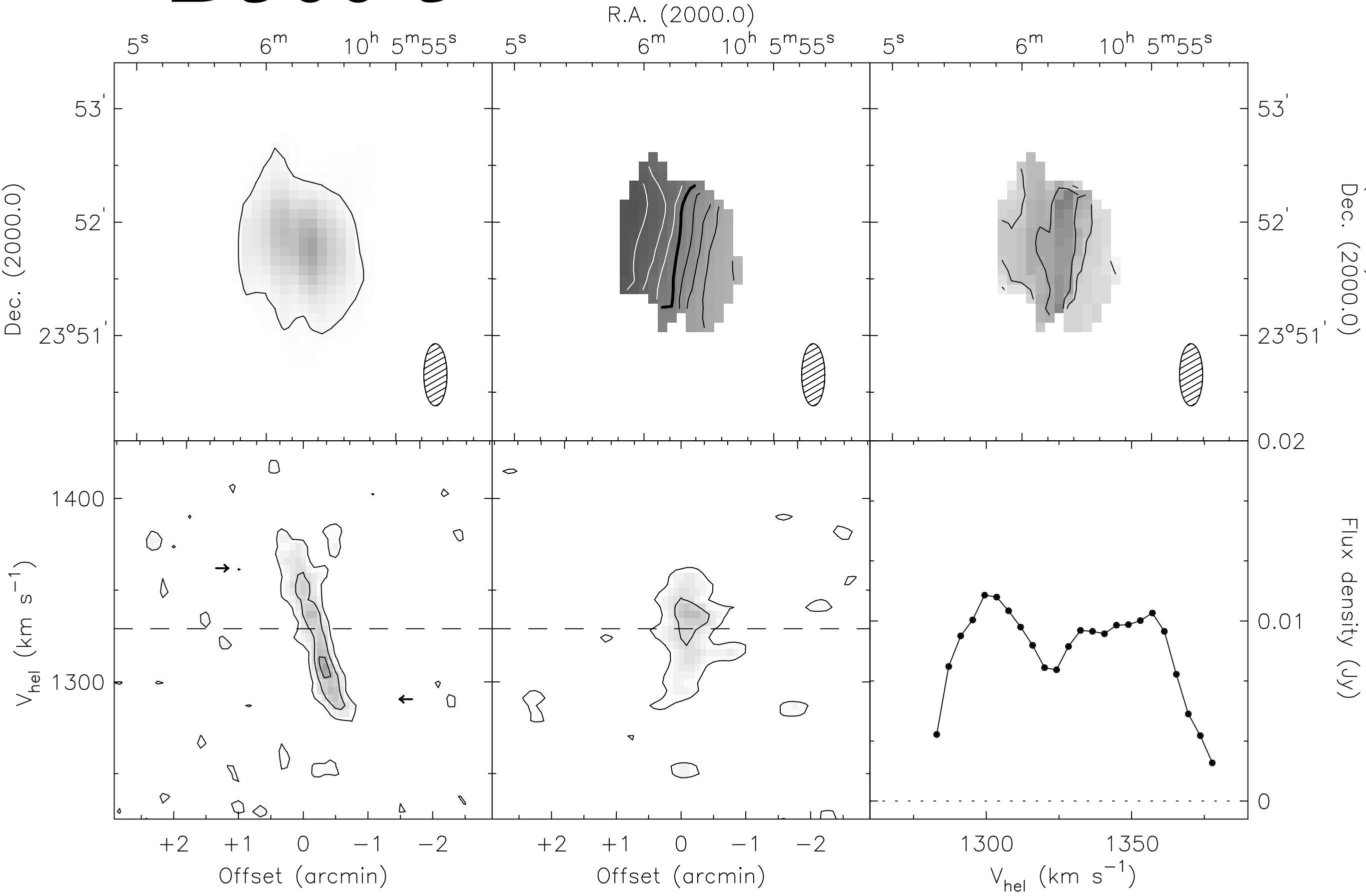
Vsys= 1259, deltaV=10km/s

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

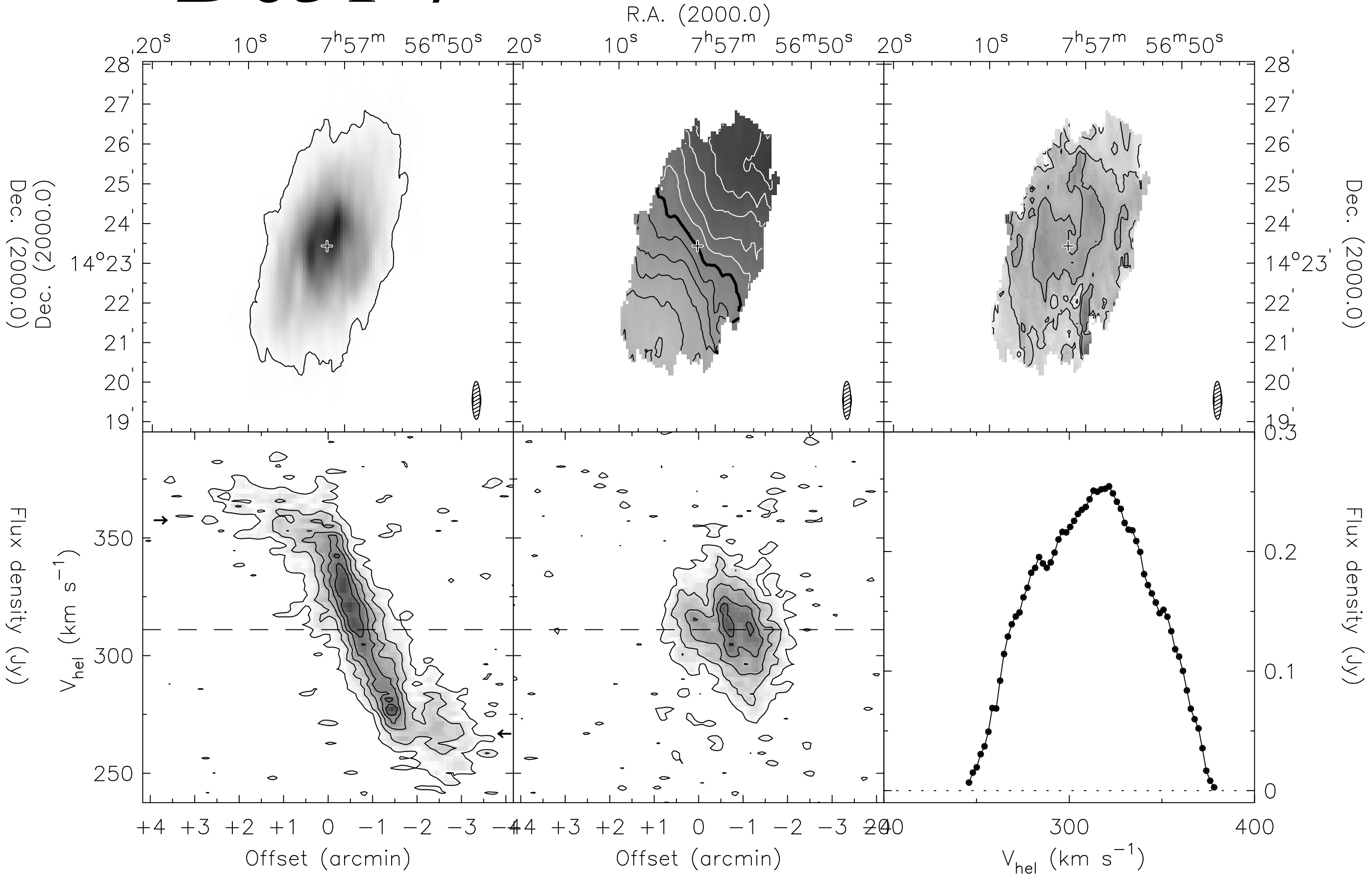
MOM2: 5,10,15 km/s contours, 2−40kms grayscales

Trachternach et al. (2009)

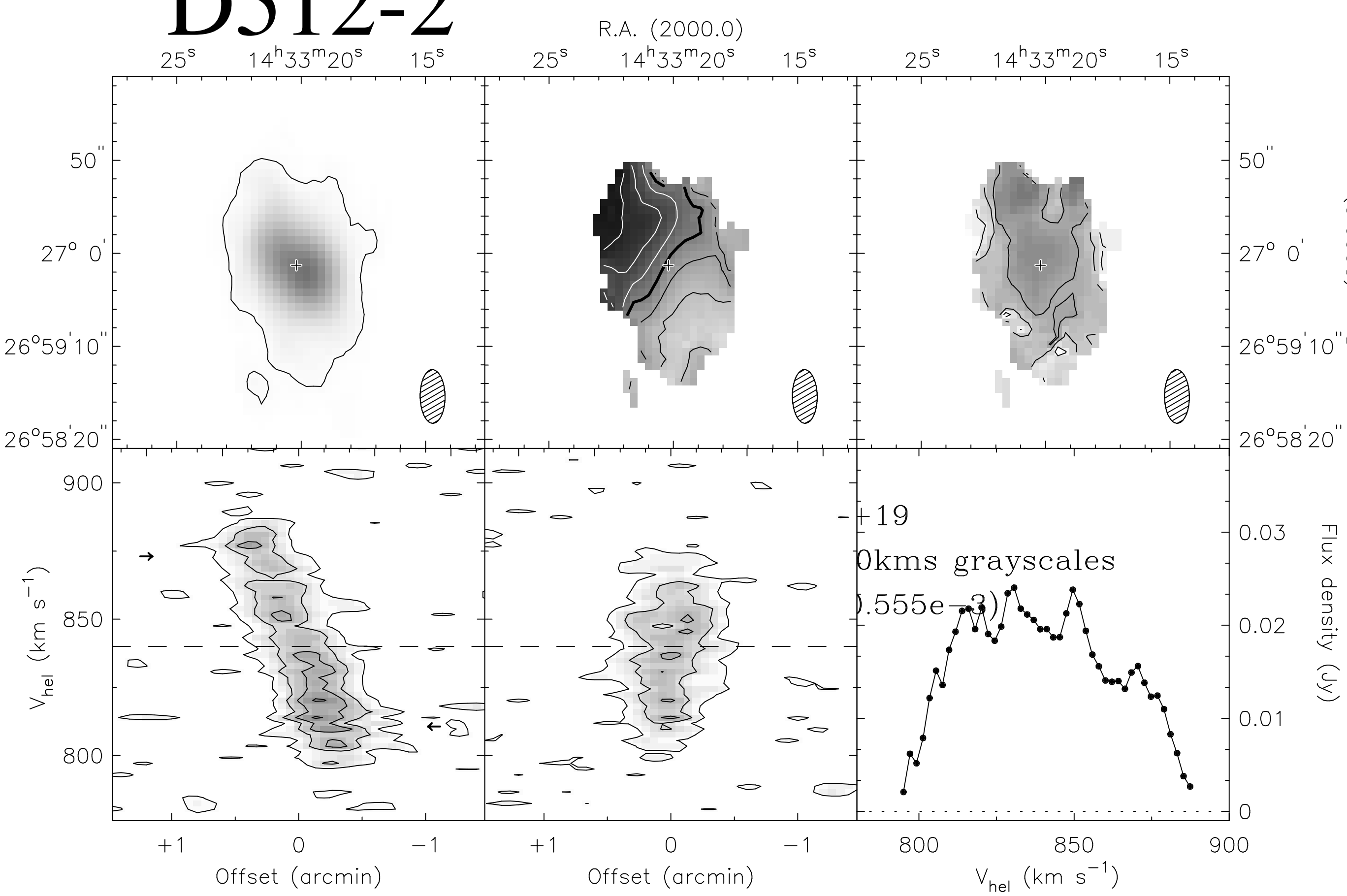
D500-3



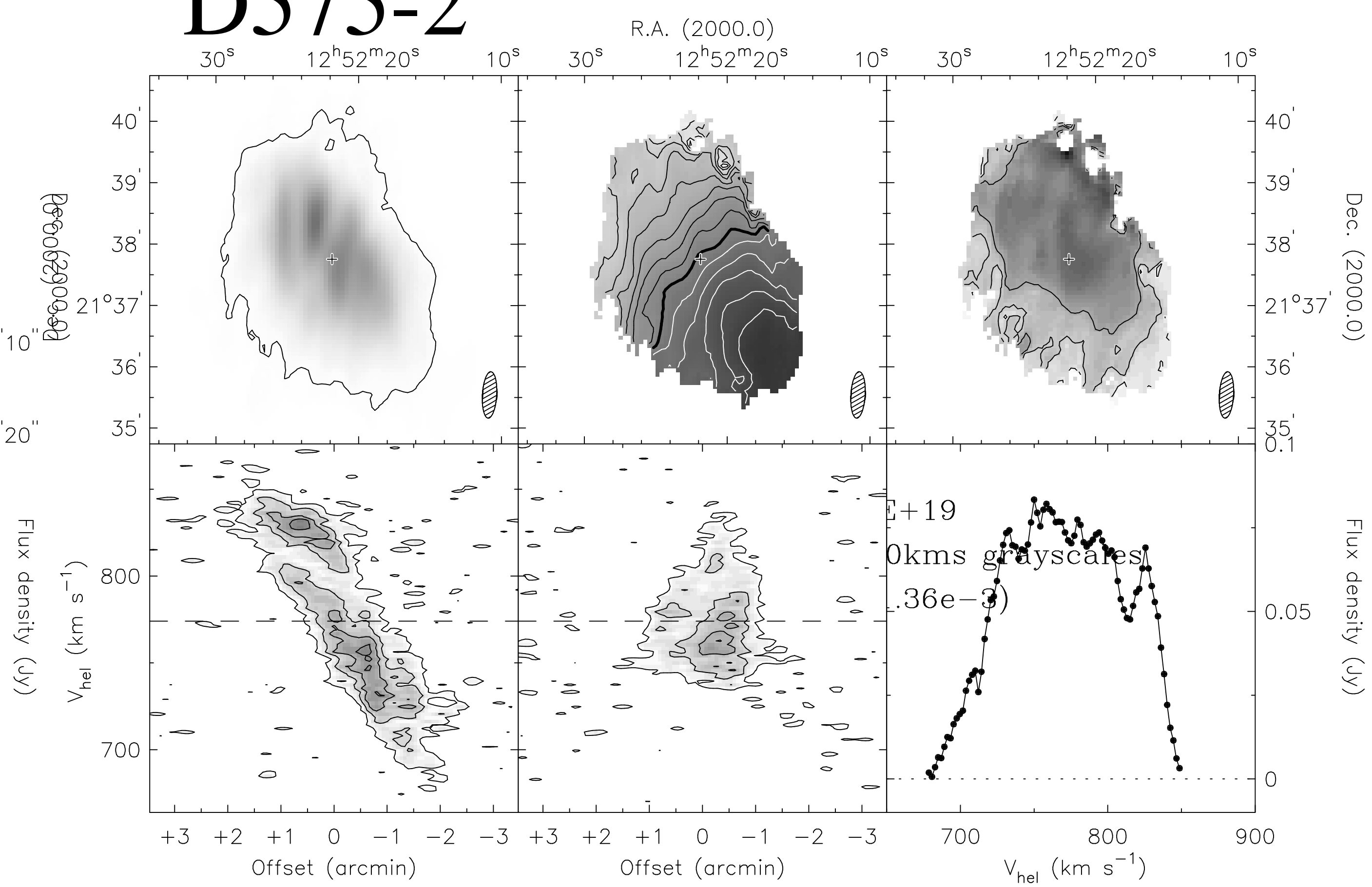
D631-7

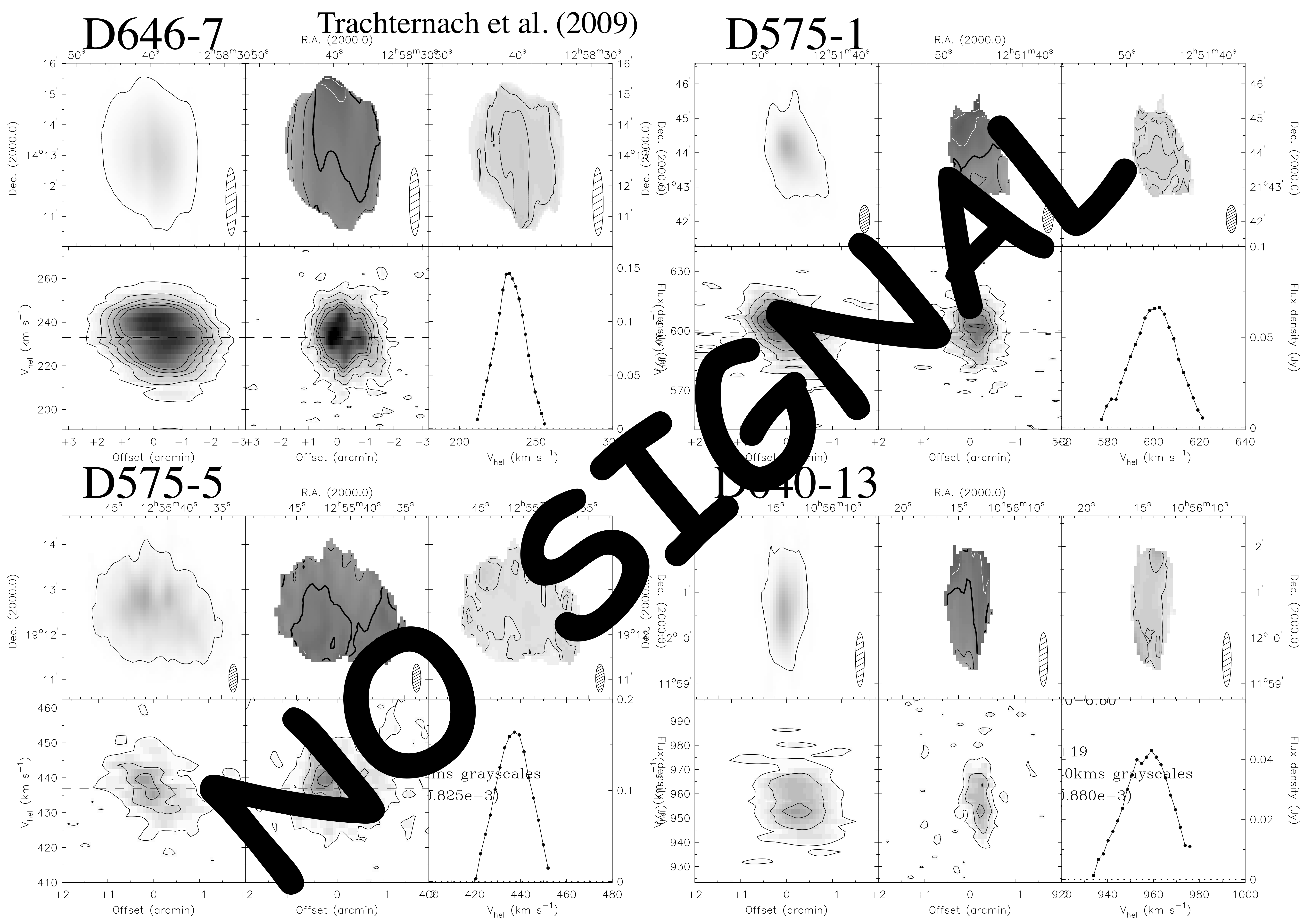


D512-2

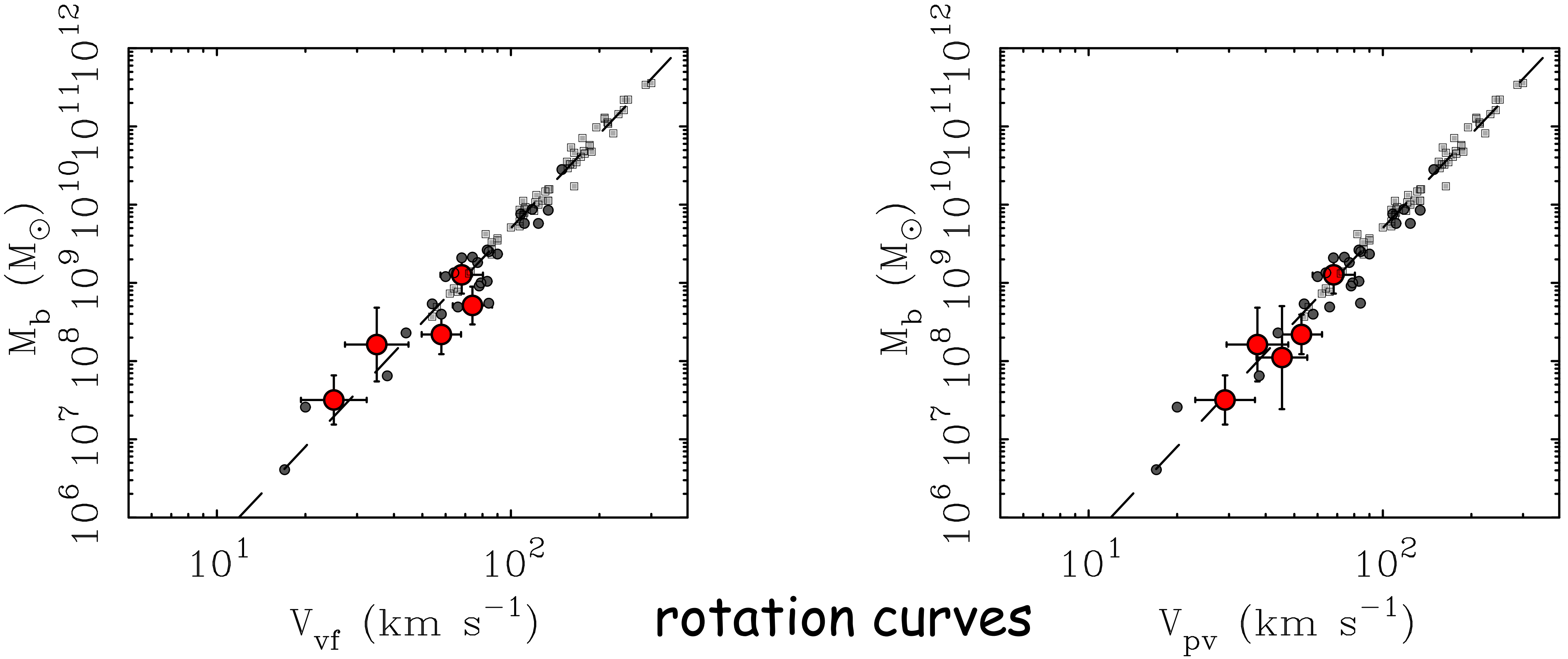


D575-2



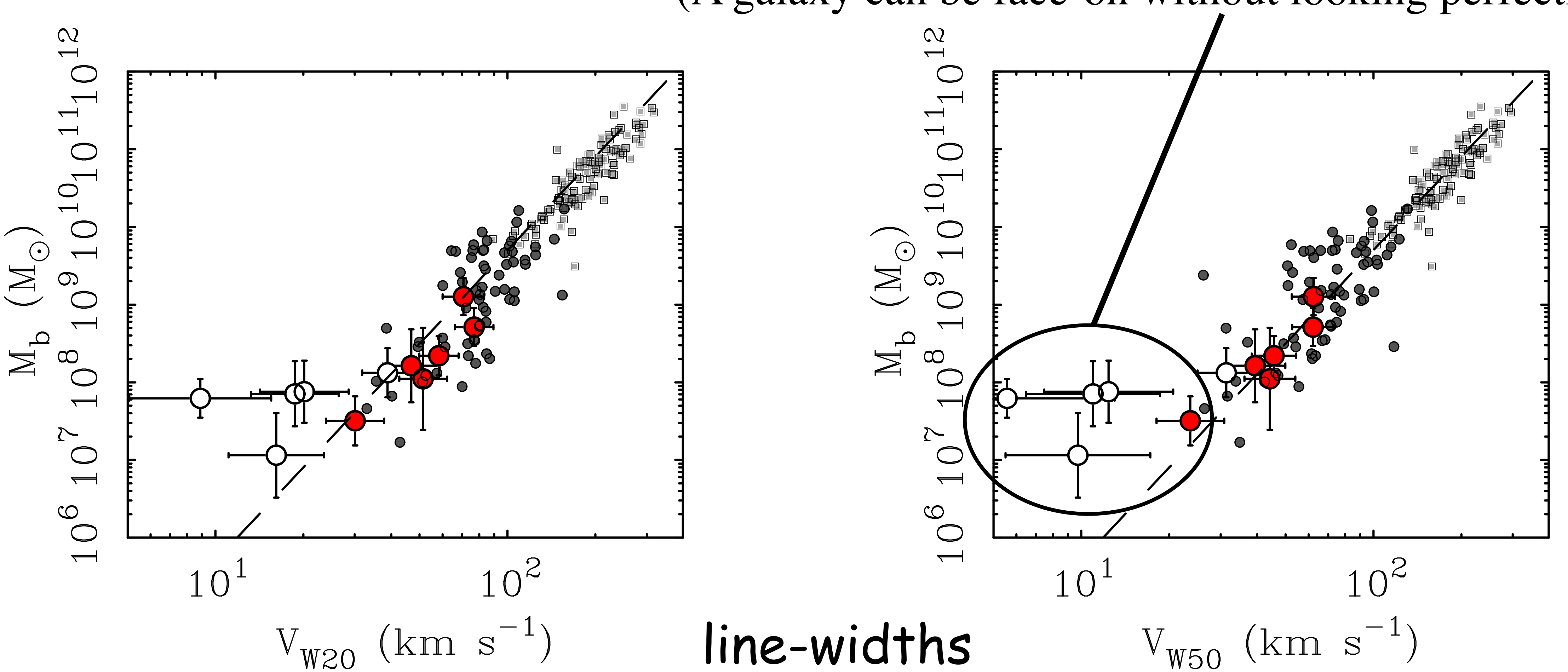


Note that you can measure a line-width even if there is no evidence of rotation.

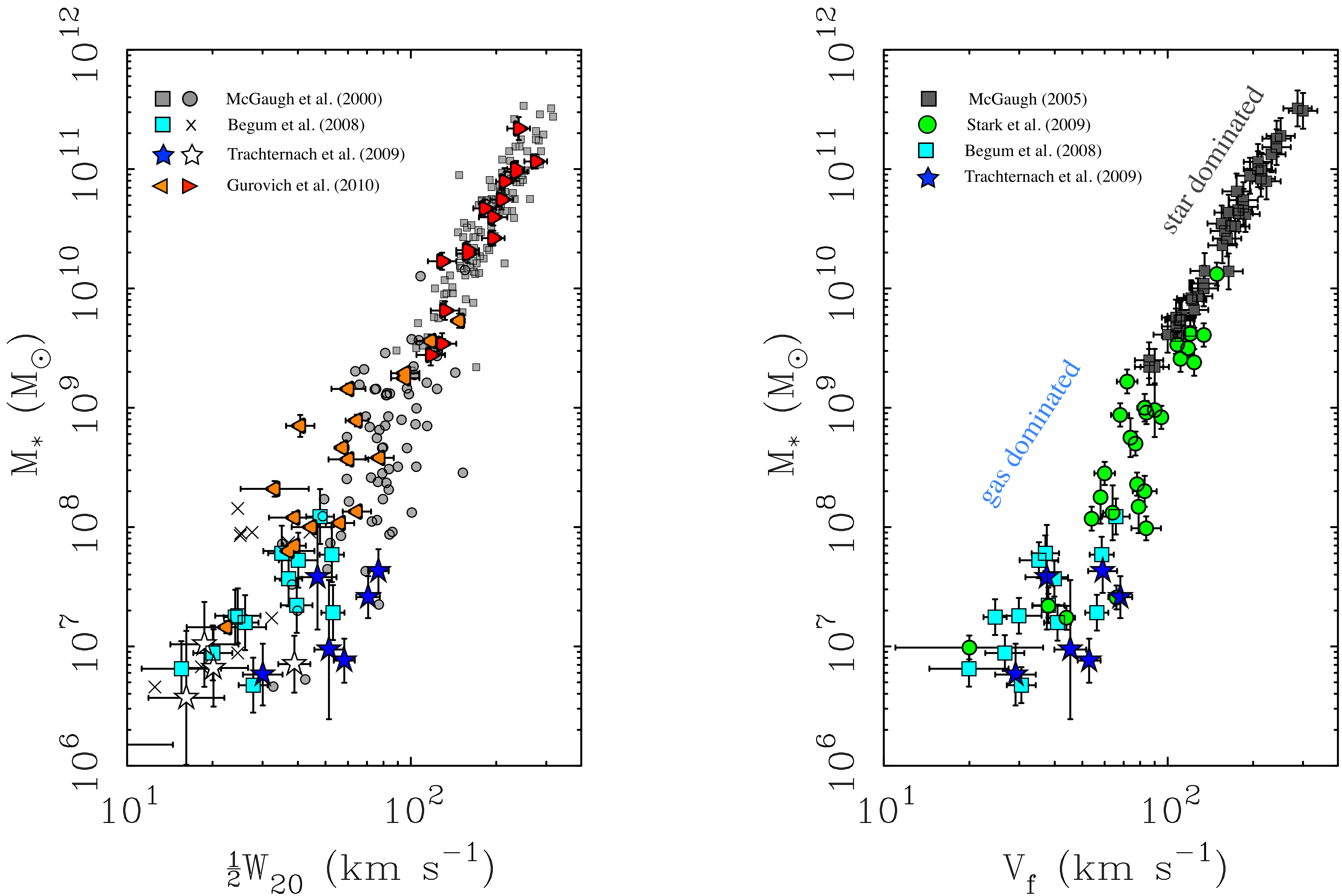


Trachternach et al. (2009)

Systematic inclination errors bias data to left of the BTFR.
(A galaxy can be face-on without looking perfectly circular.)



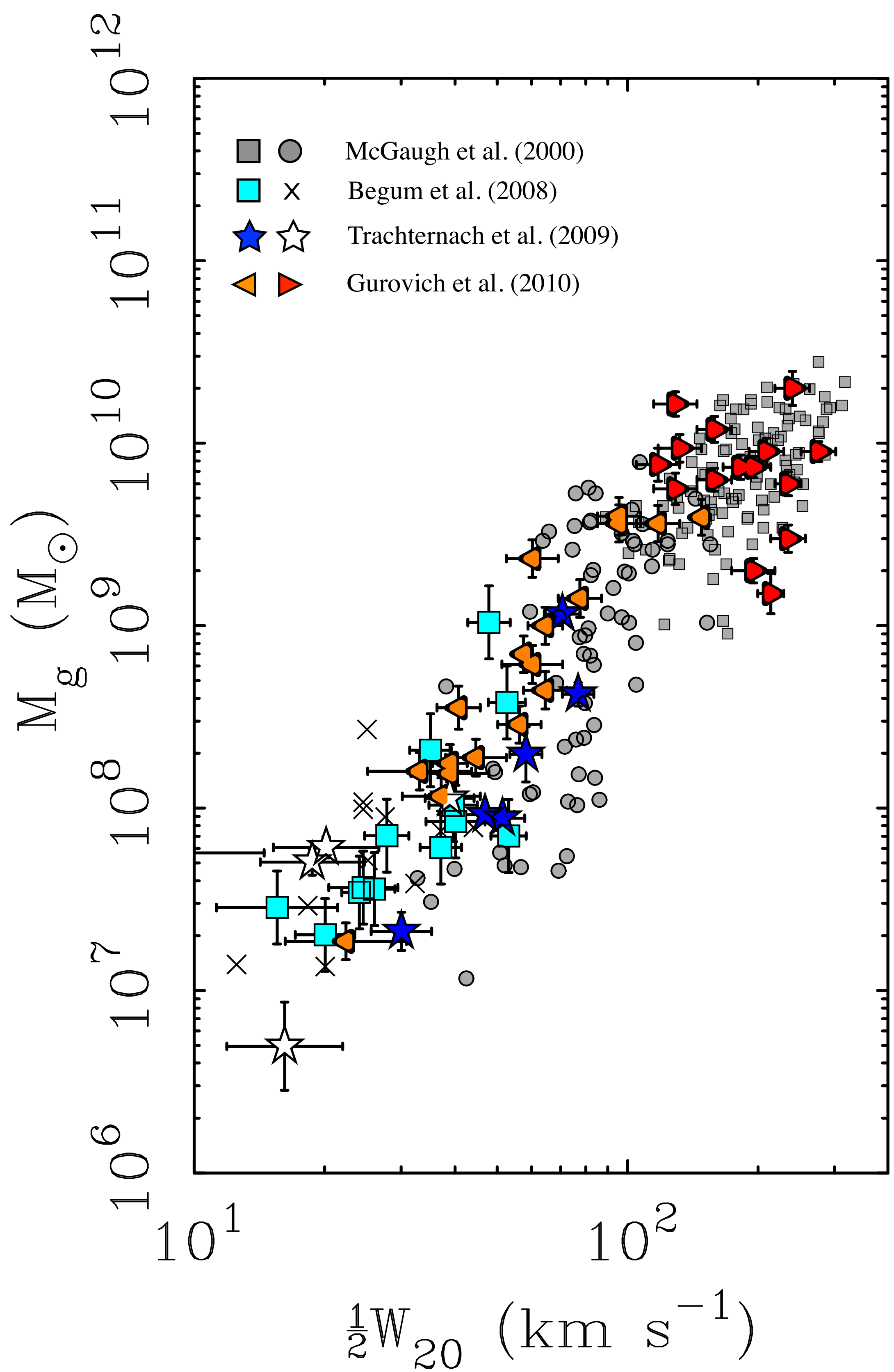
Stellar Mass Tully-Fisher relation



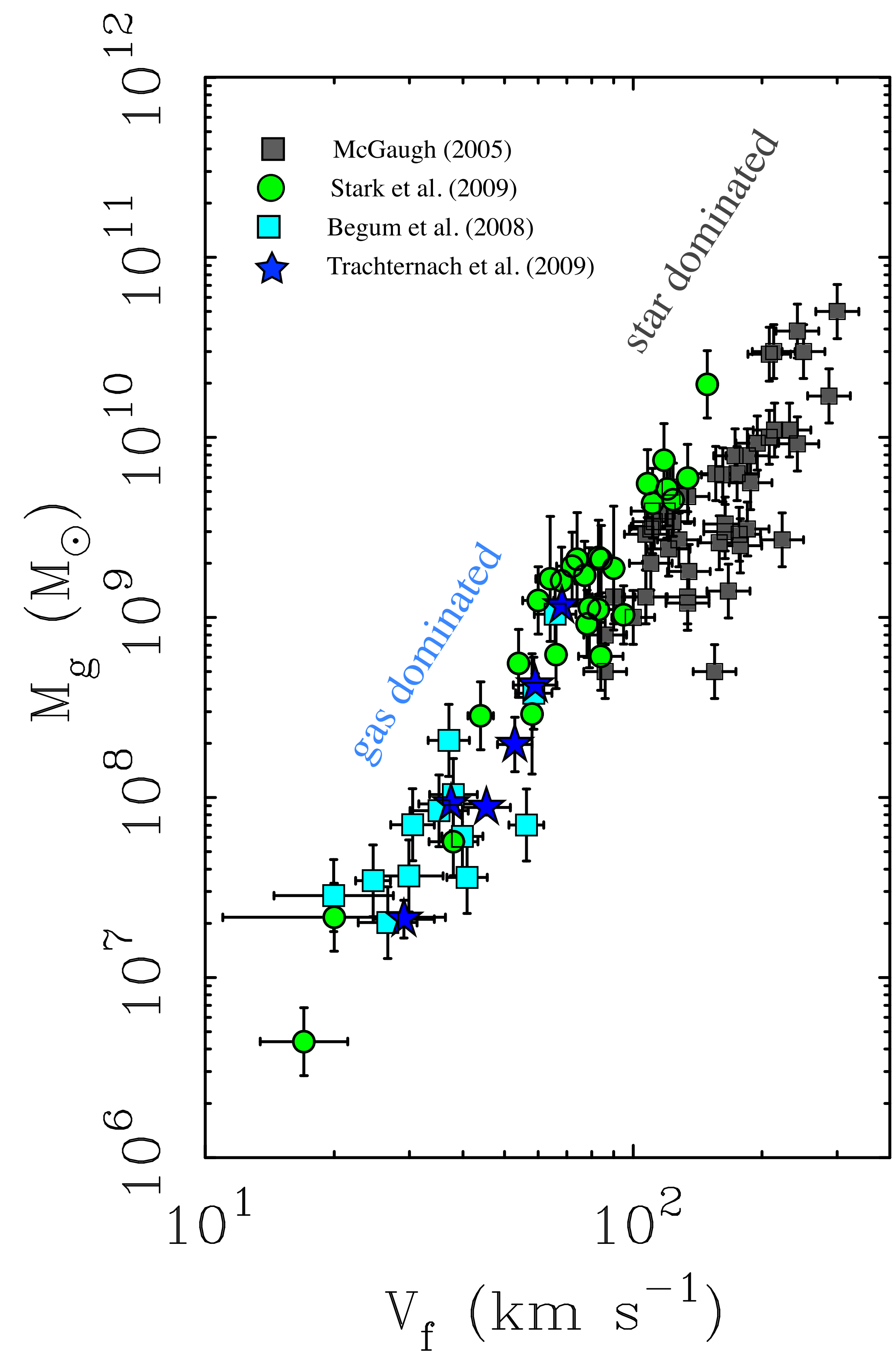
line-width

outer (flat) velocity

HI Tully-Fisher relation

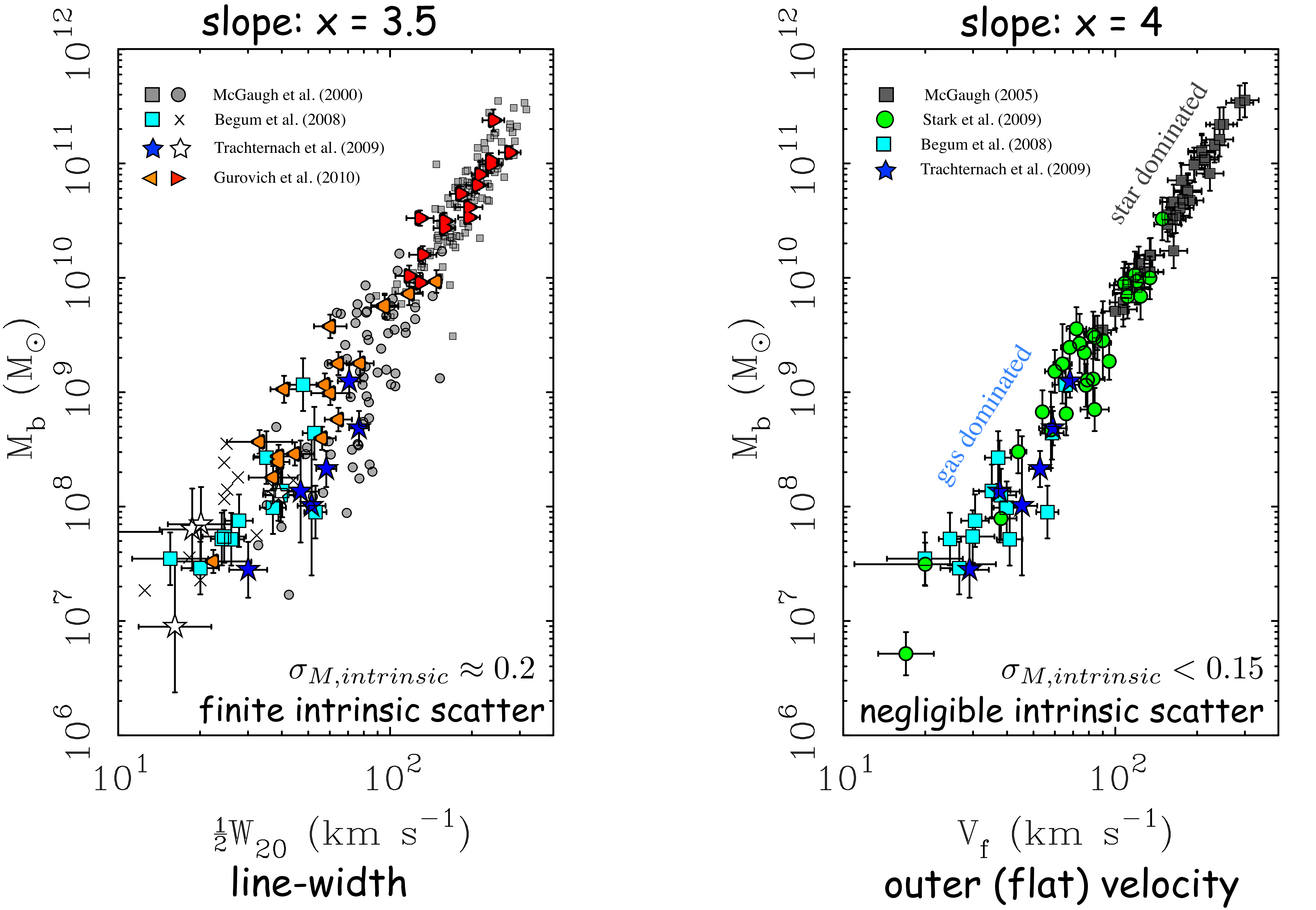


line-width

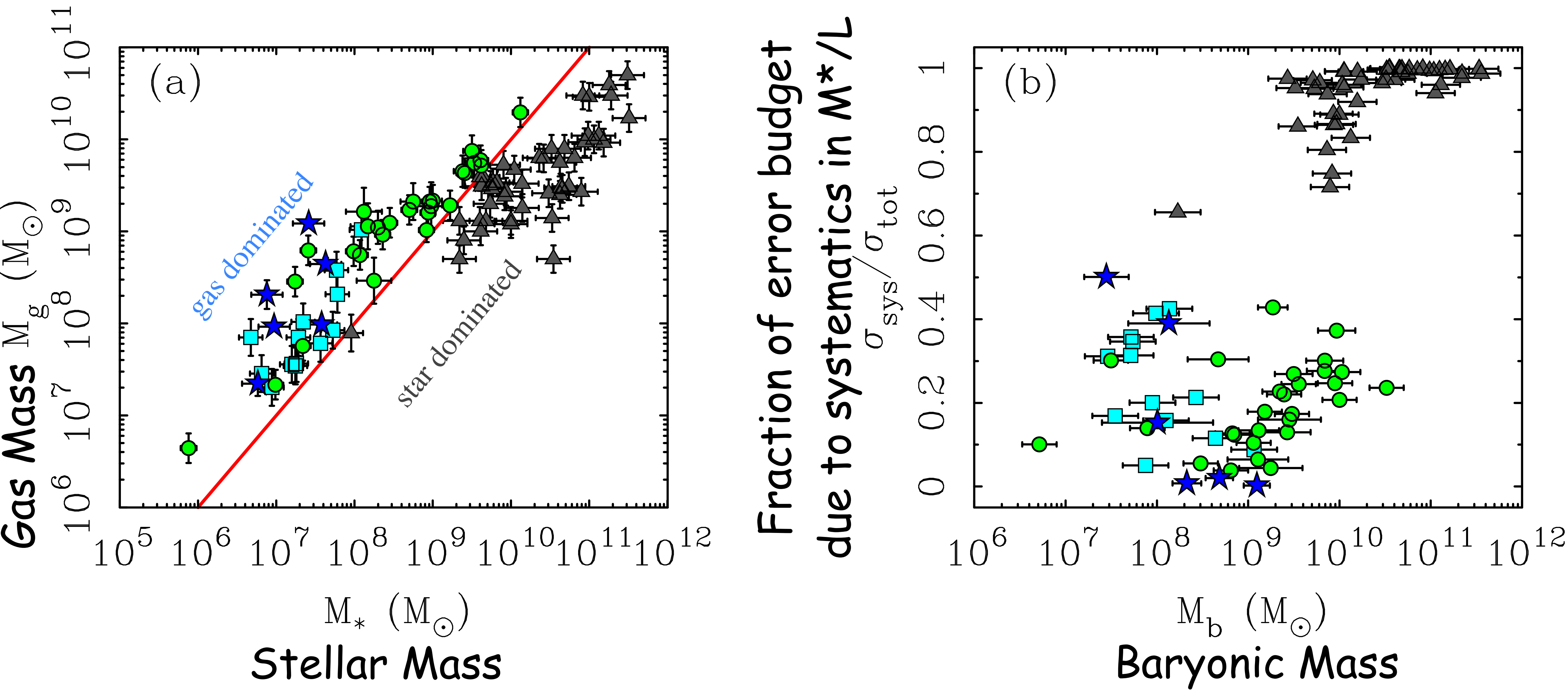


outer (flat) velocity

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

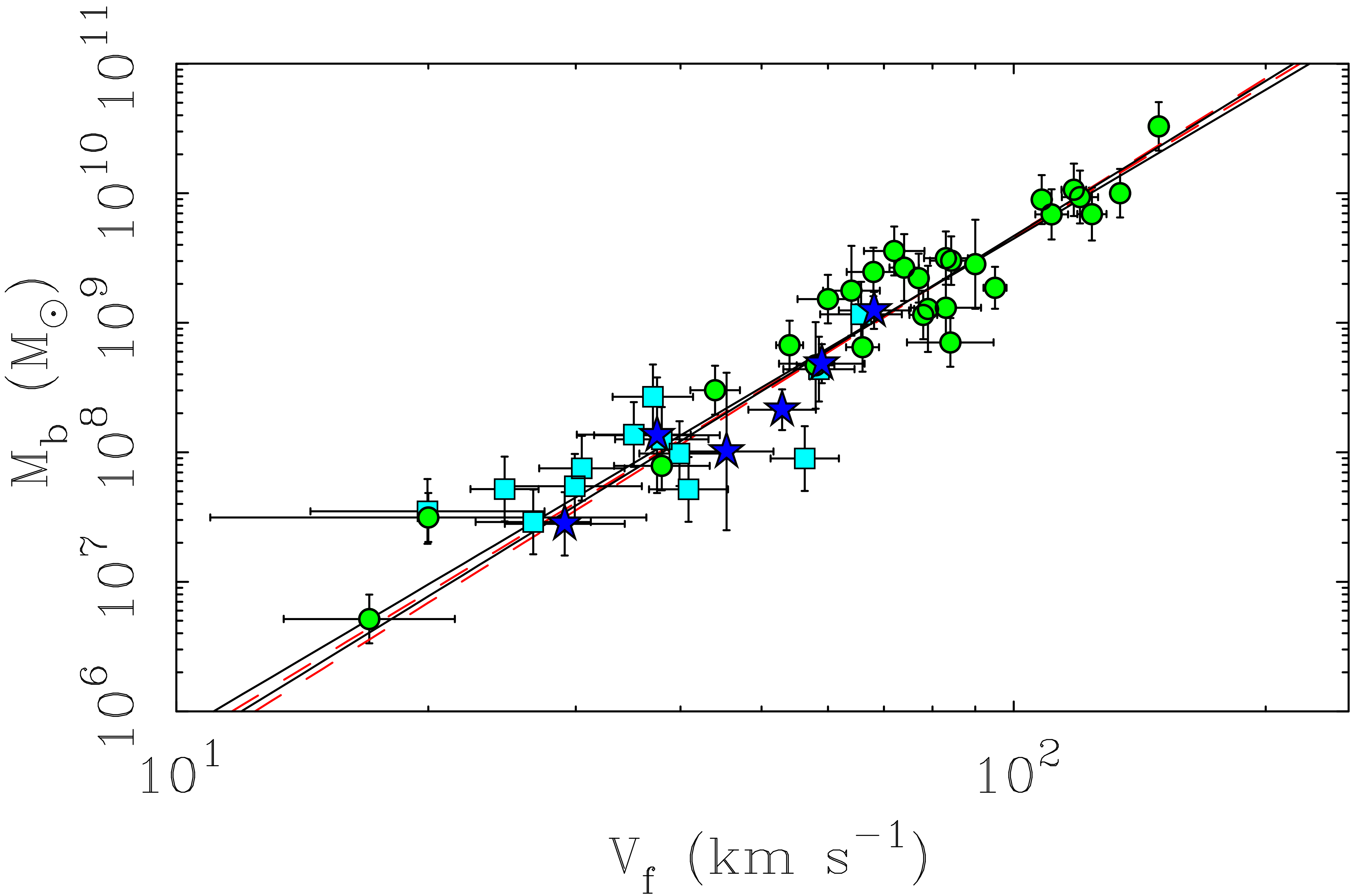


Gas dominated galaxies can provide absolute calibration of mass scale.



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

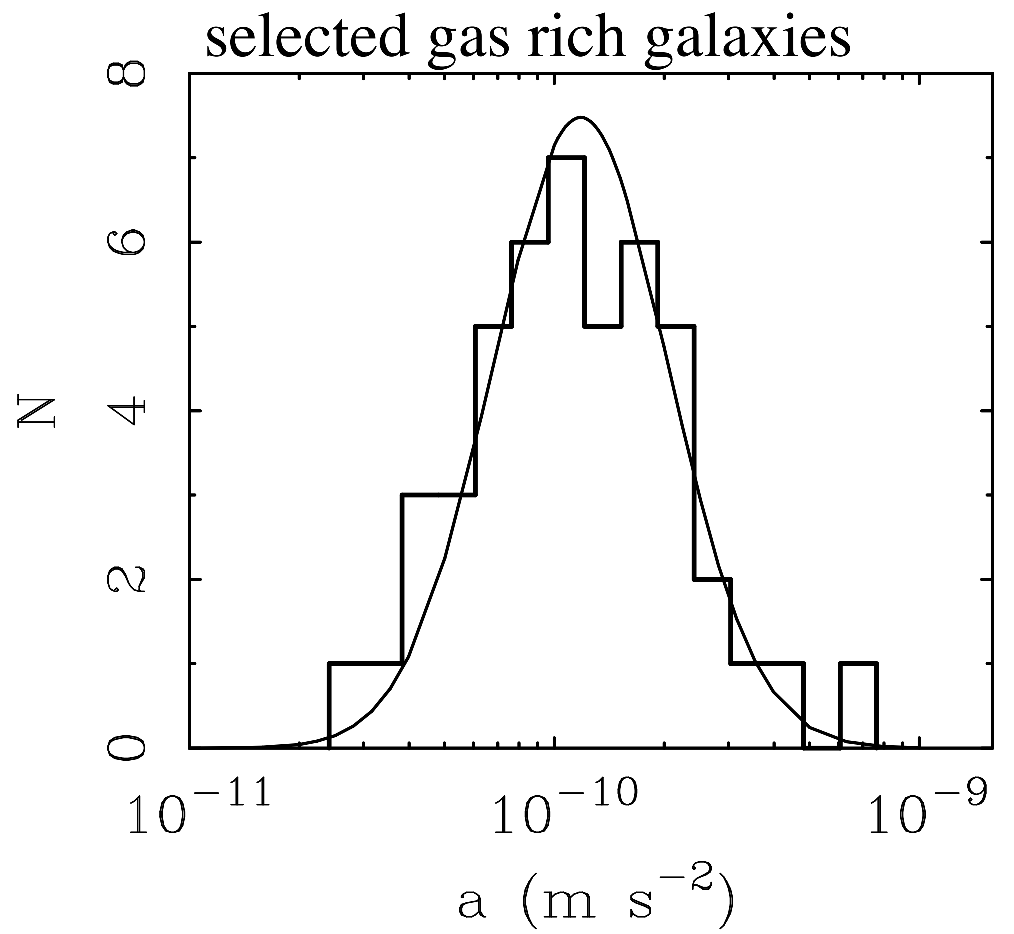
$M_b = A\, V_f^x$

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 $A = 47 \pm 6\ \mathrm{M_\odot\, km^{-4}\, s^4}$

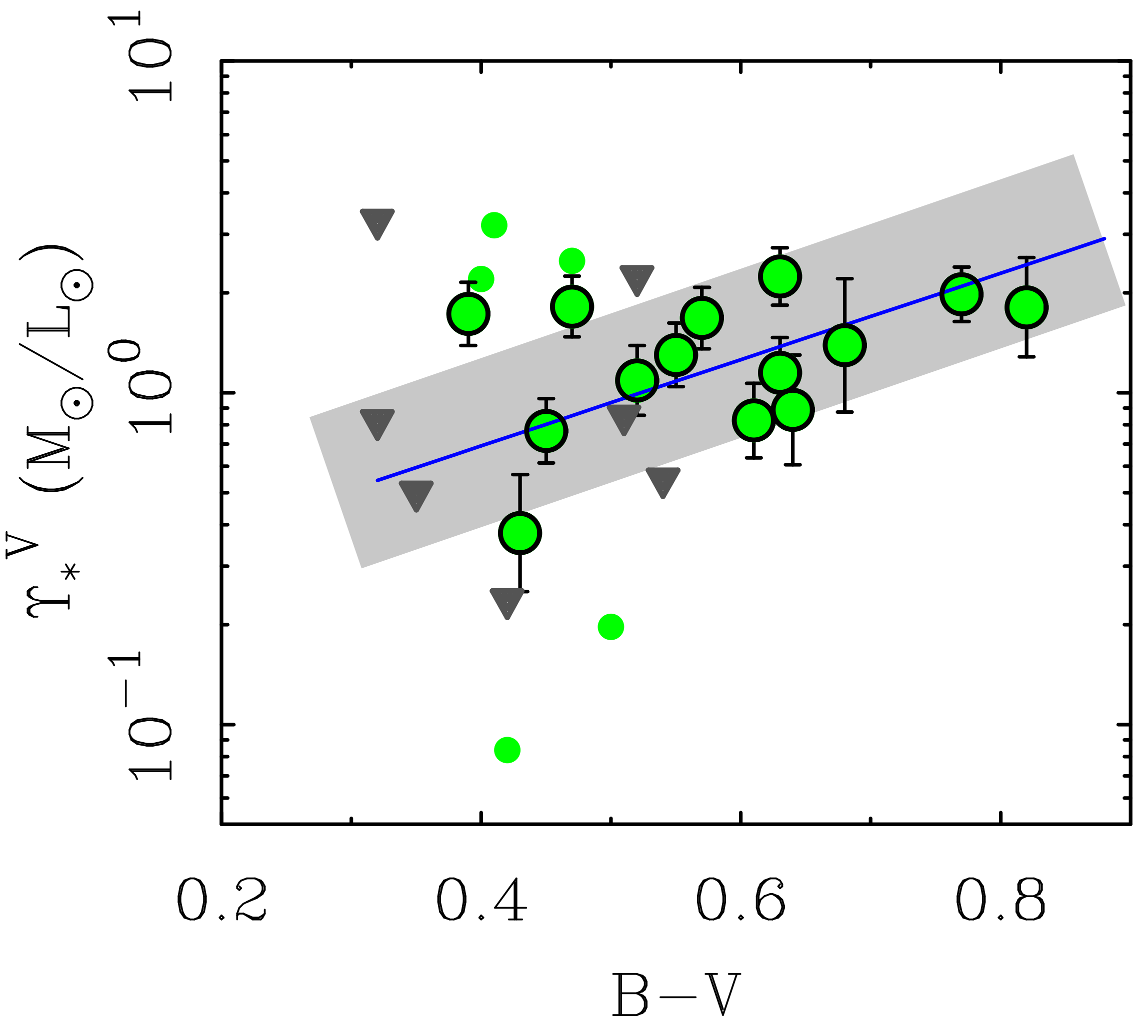


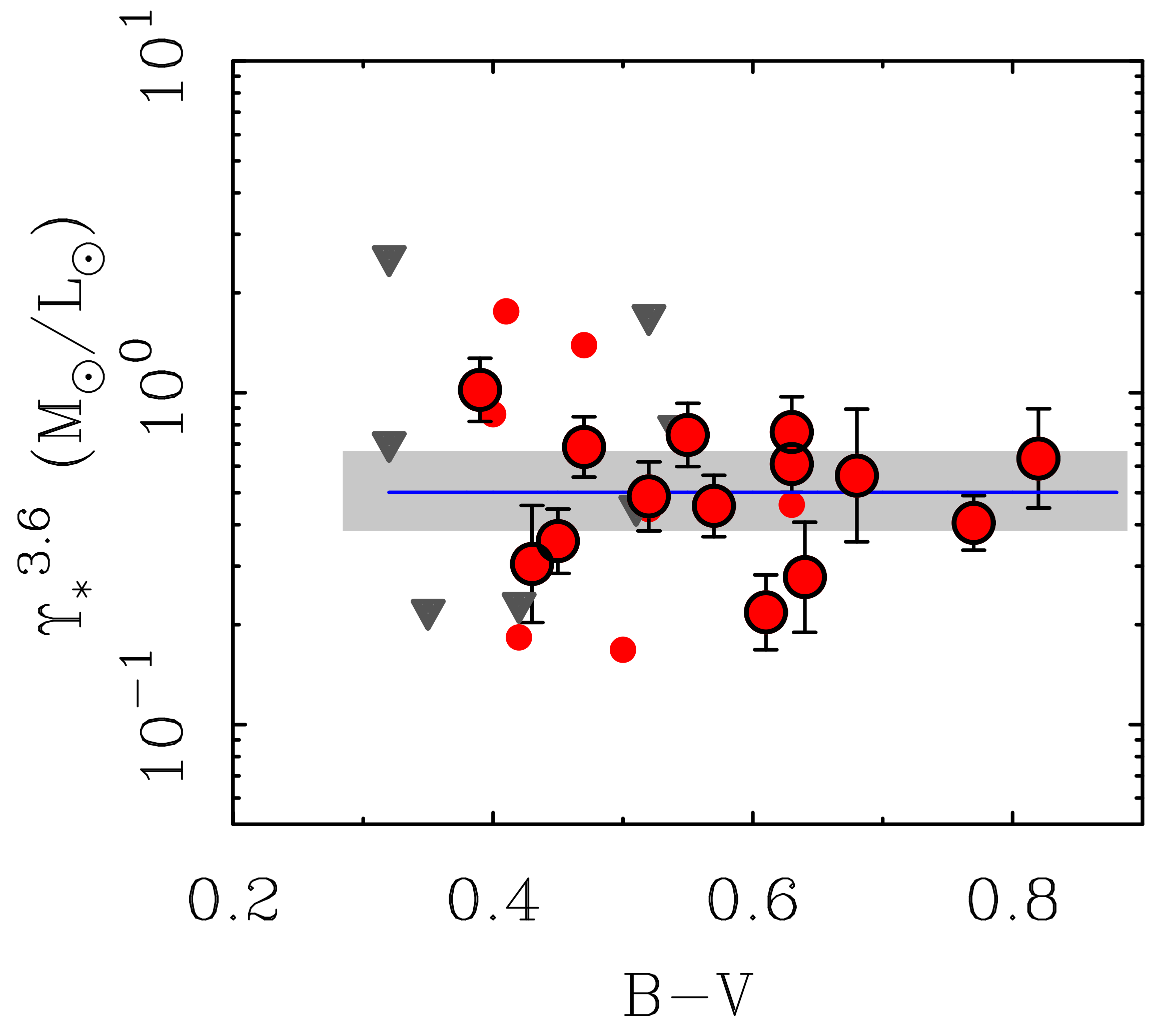
histogram: data

line: distribution expected from observational uncertainties.

The data are consistent with zero intrinsic scatter.

Stellar mass-to-light ratios in good accord with population synthesis models





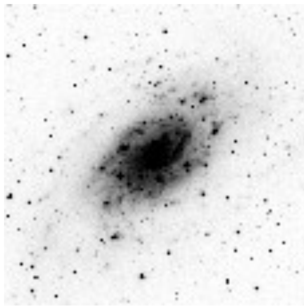
Recovers expected

- slope
- normalization
- scatter (little room left for other sources of scatter)

constrains IMF: ~ Kroupa

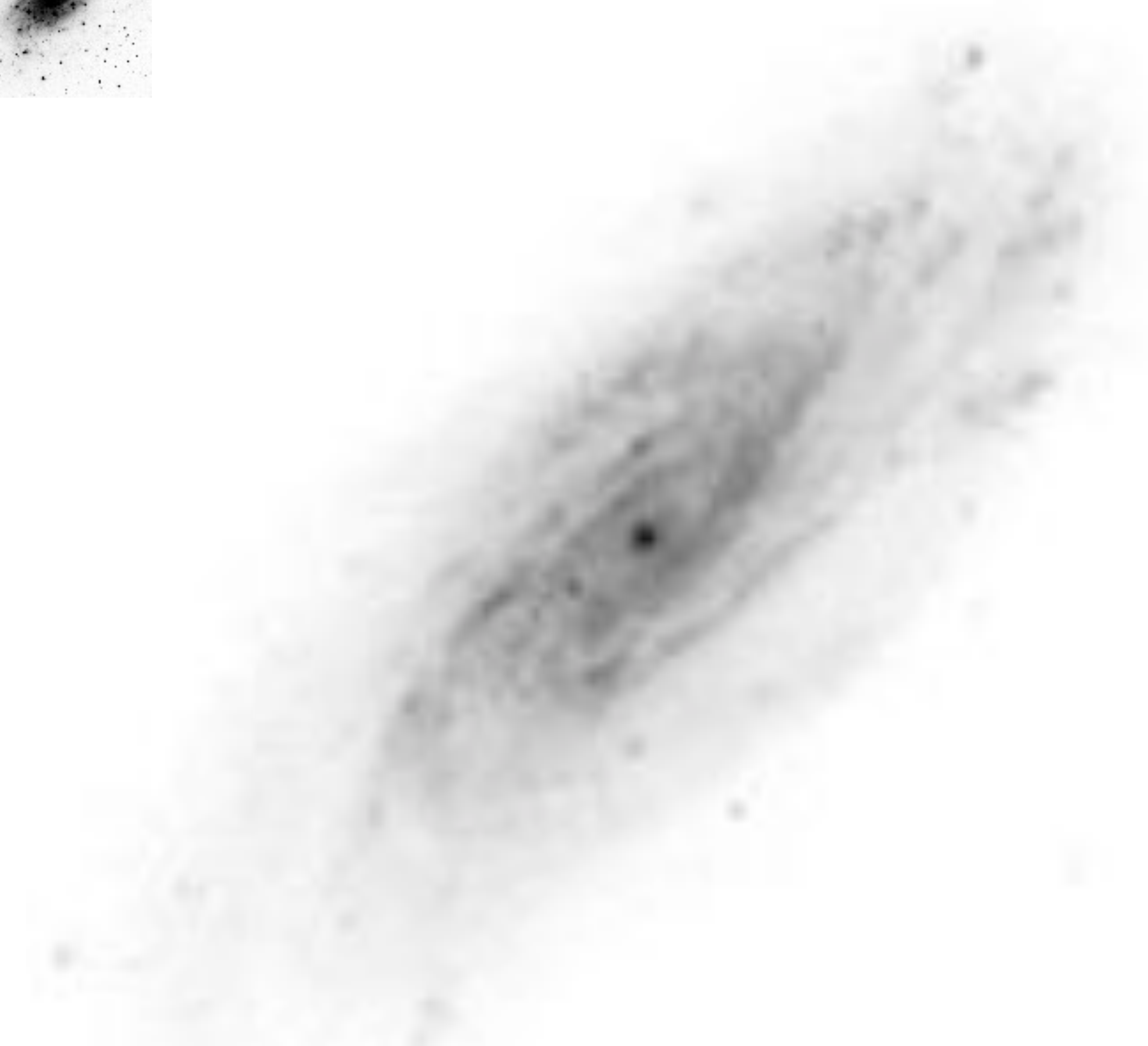
$$\frac{M_*}{L} = \frac{AV_f^4 - M_g}{L}$$

$$\langle \frac{M_*}{L_{3.6}} \rangle = 0.5 \frac{M_\odot}{L_\odot}$$

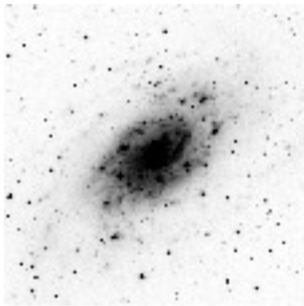


NGC 2403

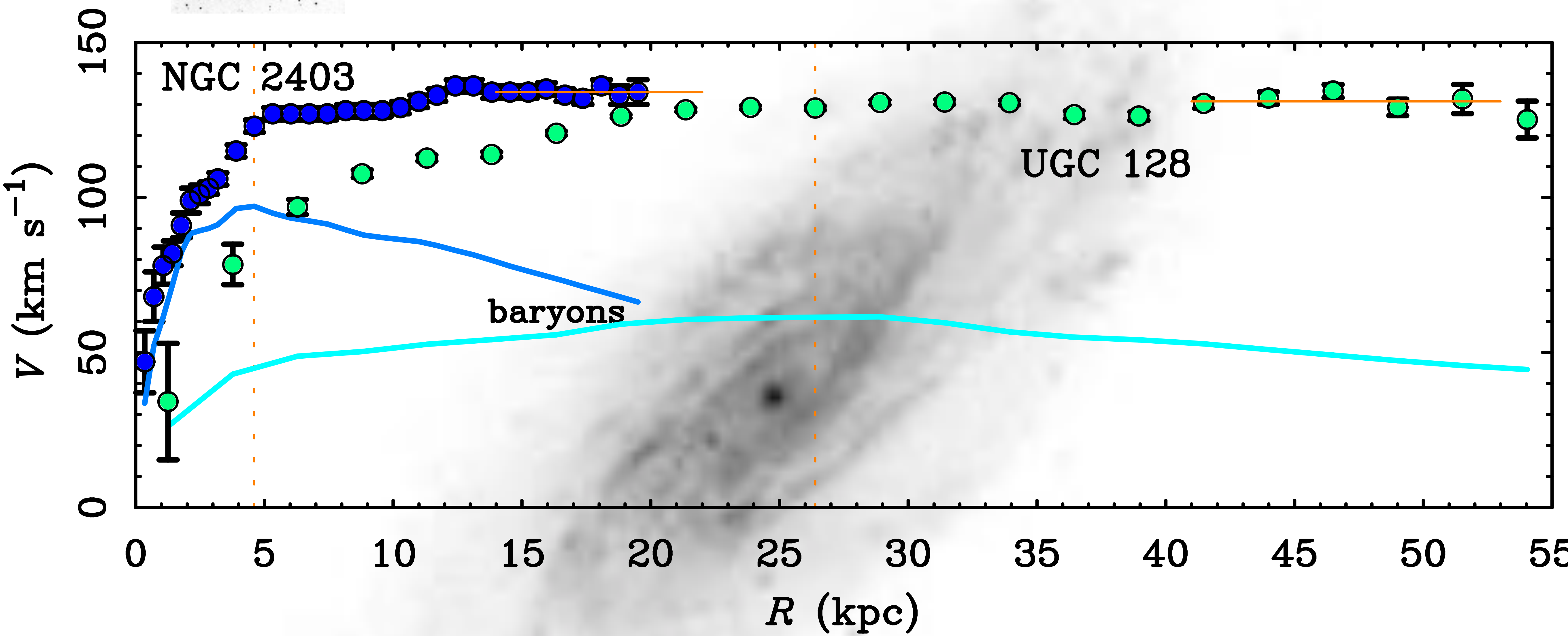
UGC 128



Size/surface brightness variations from TF



No residuals from TF with size or surface density

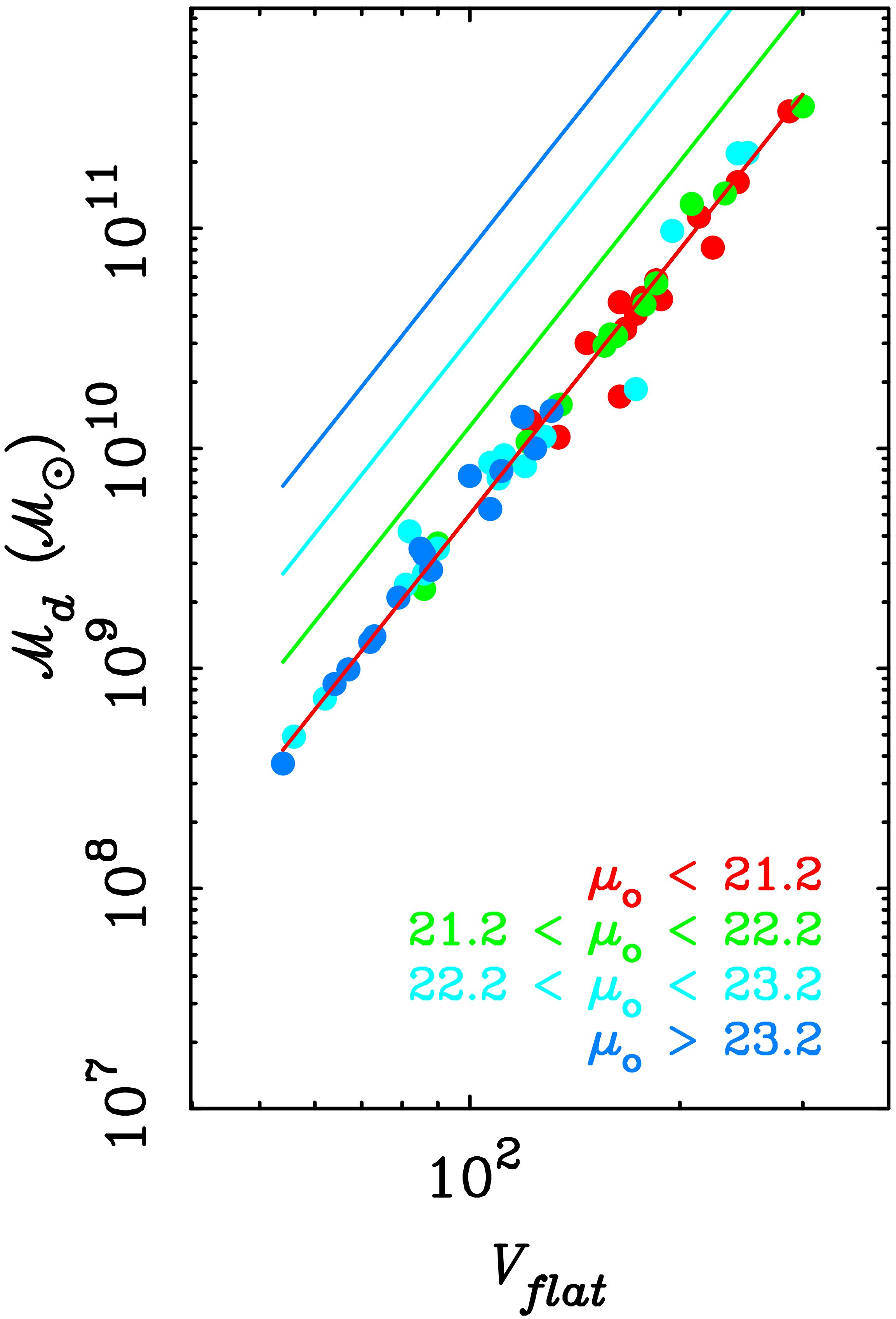


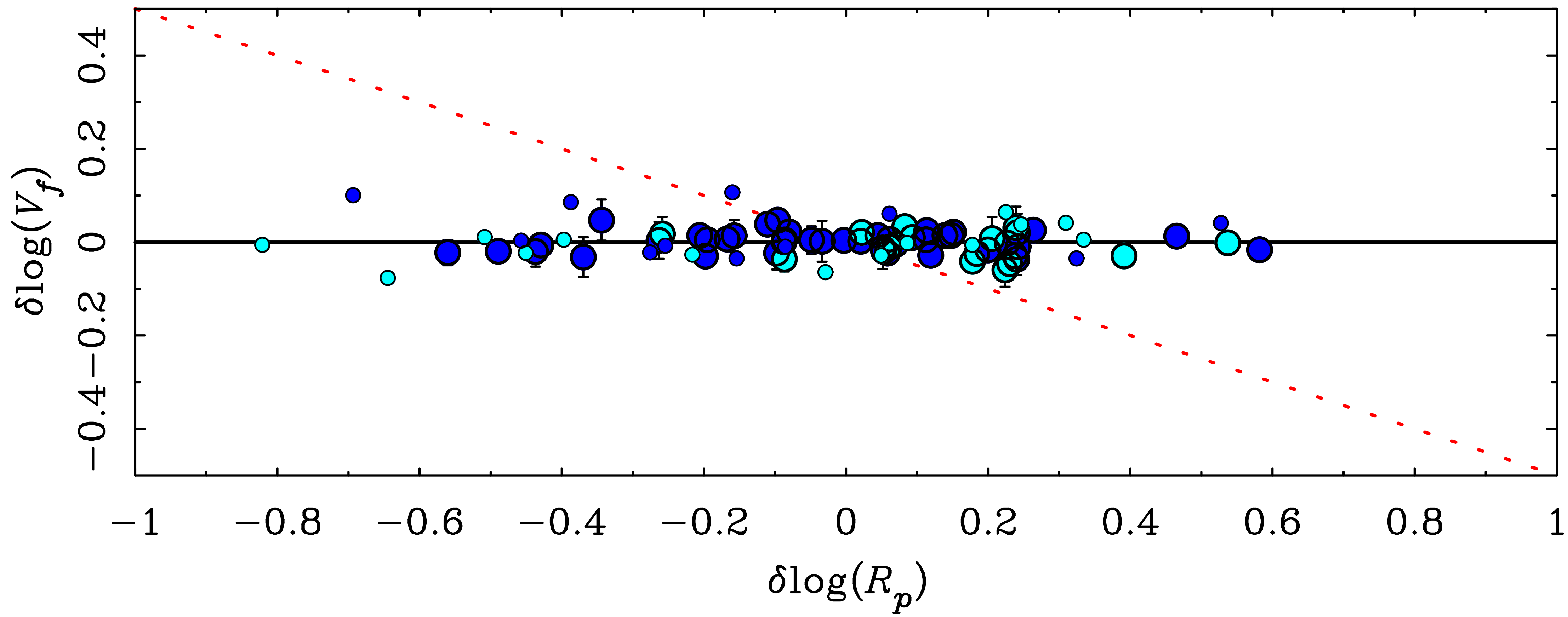
Same (M,V) but very different size and surface density

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)

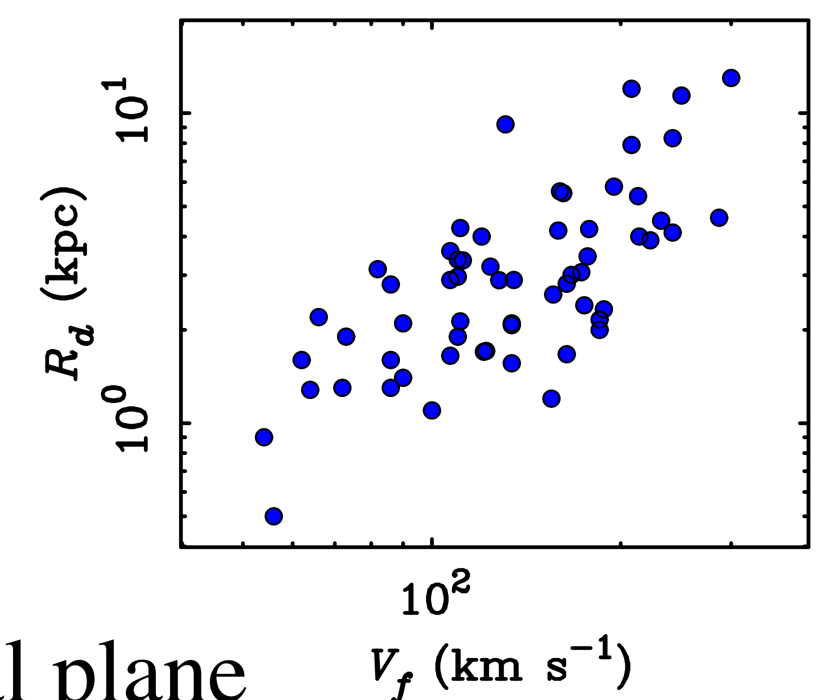




No residuals from TF with size or surface density for disks

$$V^2 = \frac{GM}{R} \;\rightarrow\; \frac{\delta\log(V)}{\delta\log(R)} = -\frac{1}{2}$$ 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.