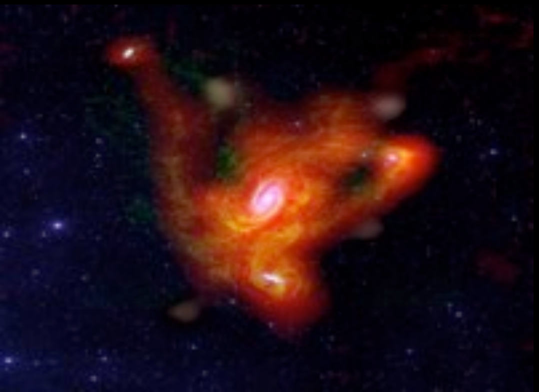
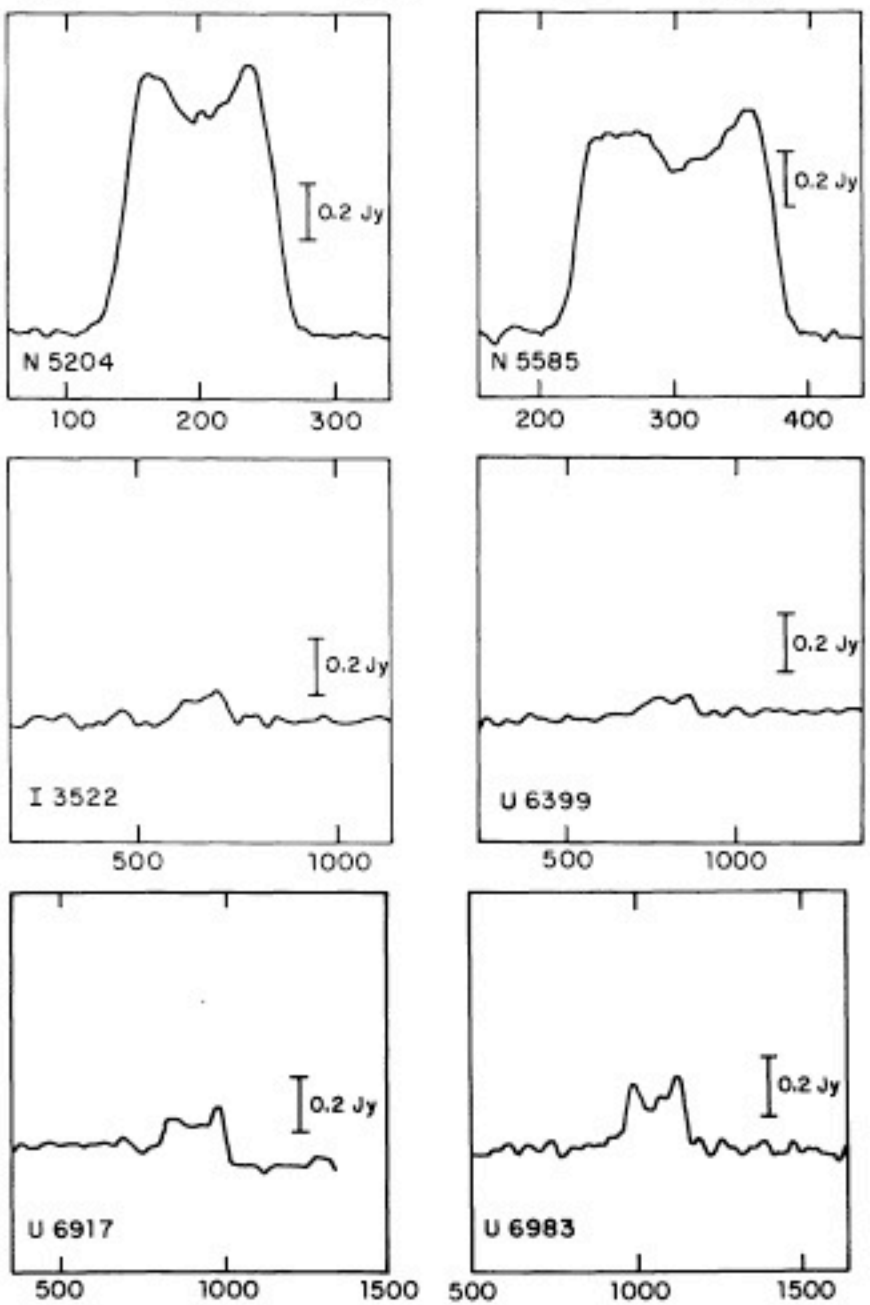
NRAO - TF35: Global Properties of HI in Galaxies Workshop - 1 April 2012

# The Baryonic Tully-Fisher Relation

Stacy McGaugh
University of Maryland



# Tully & Fisher (1977)





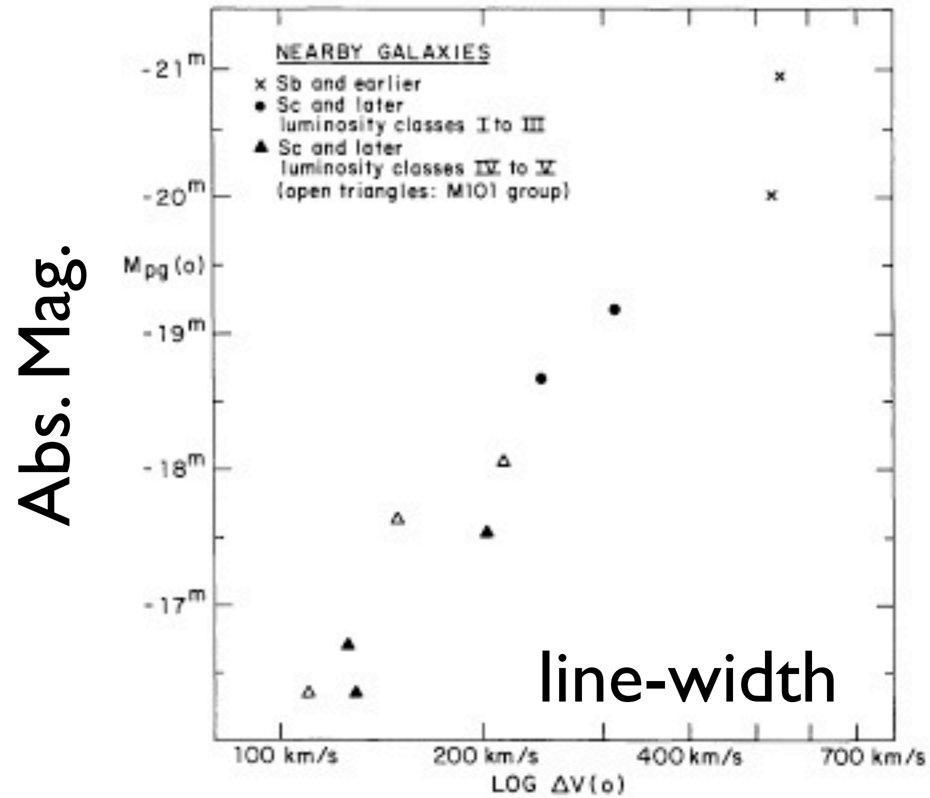




**Fig. 1.** Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

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)


9/30/10
74° F
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3/30/10

# Tully & Fisher (1977)

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

TF great for distances, which are an essential step towards physical understanding:

what does it mean?

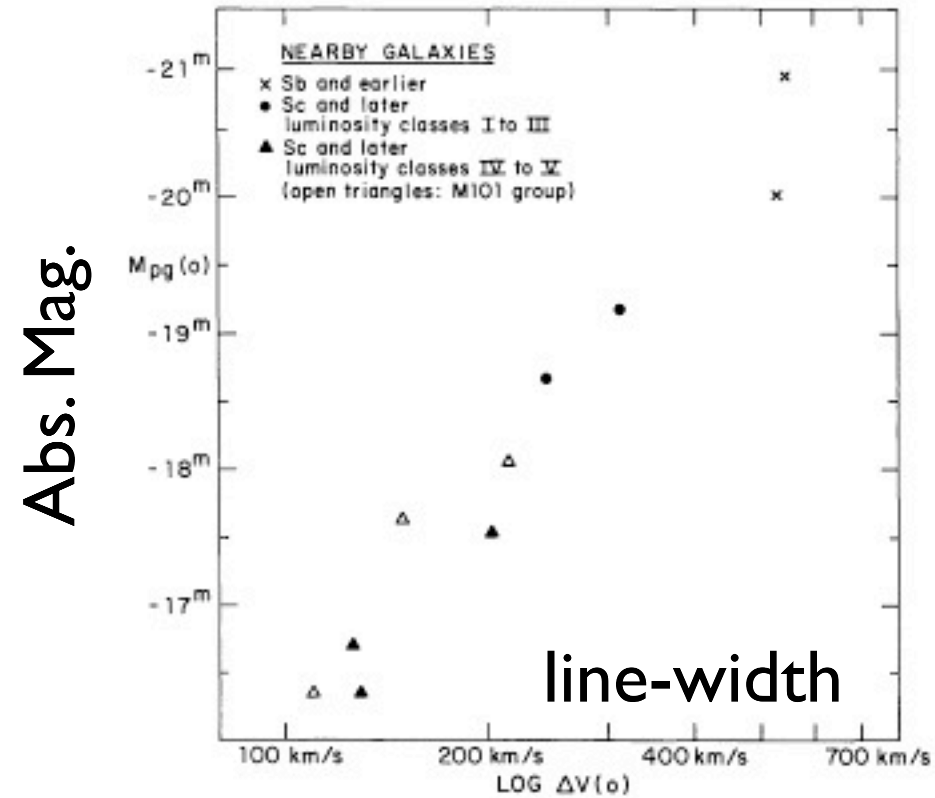



**Fig. 1.** Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

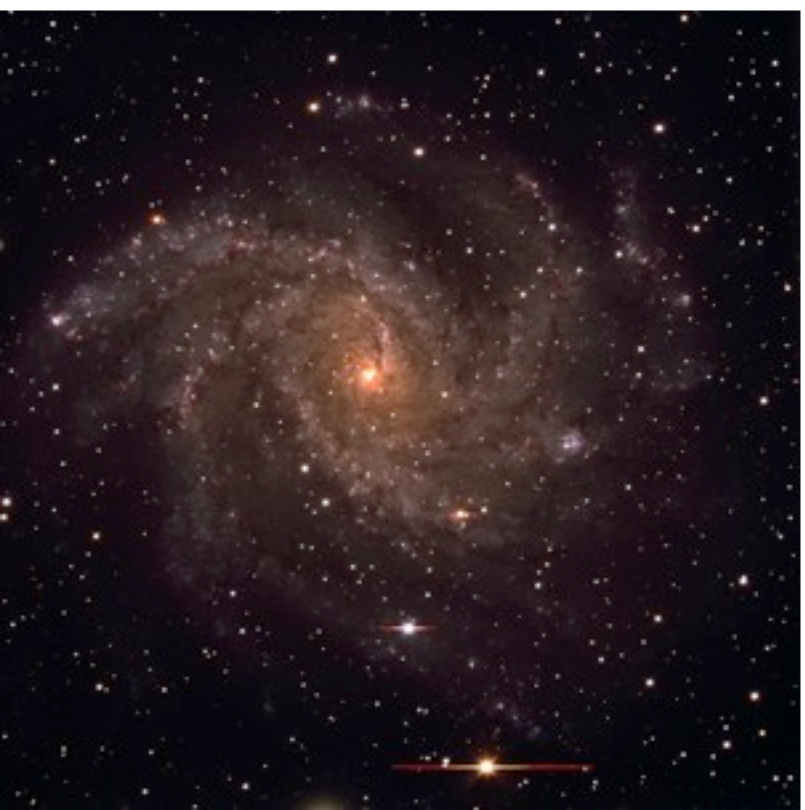
***“The Tully-Fisher Relation is God!”***

Sancisi (1995, private communication)

What we measure

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

NGC 6946



Rotation curve data from

Boomsma et al (2008) [HI]

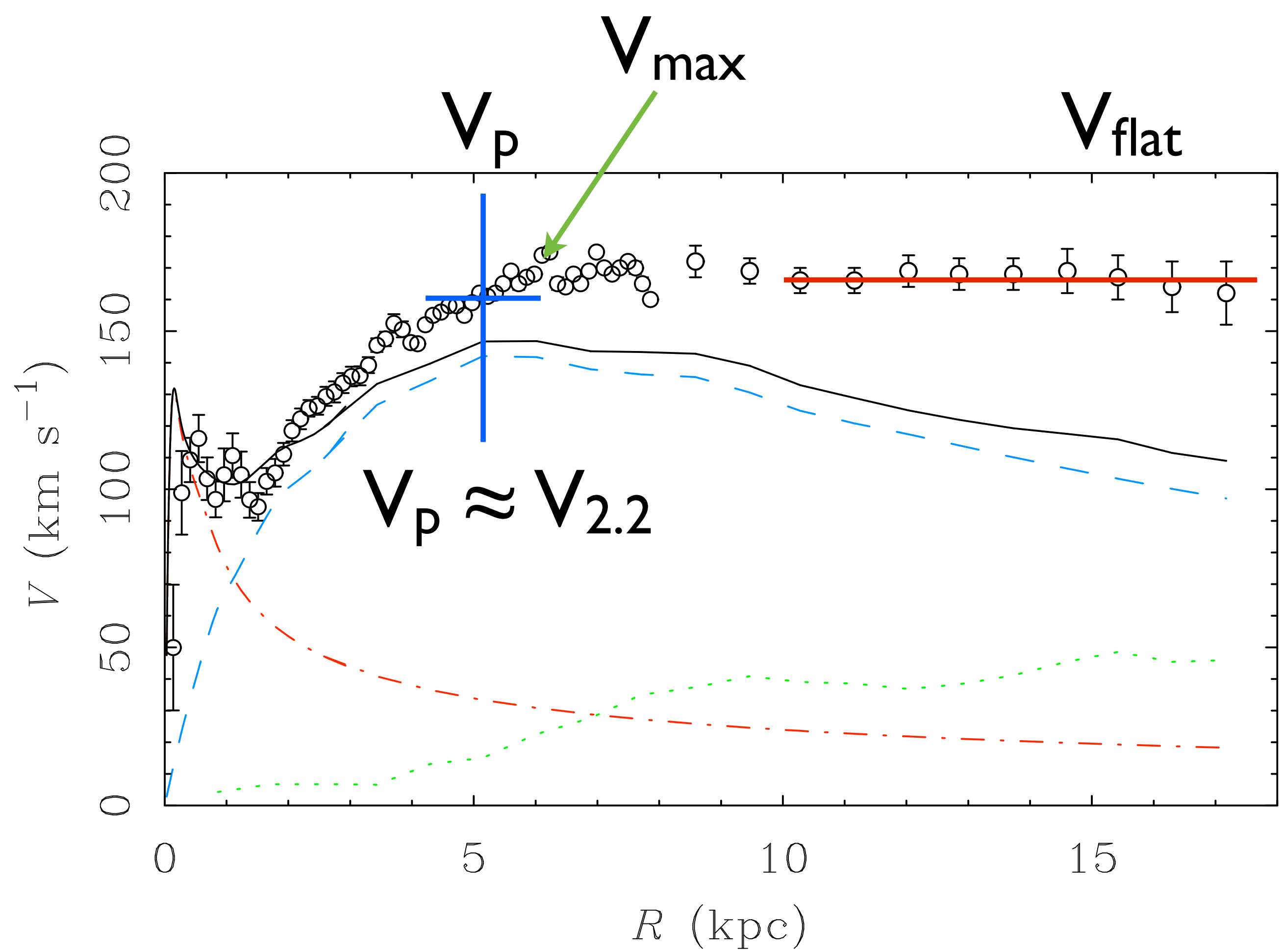
Daigle et al (2006) [Ha]

Blais-Ouellette et al (2004) [Ha]

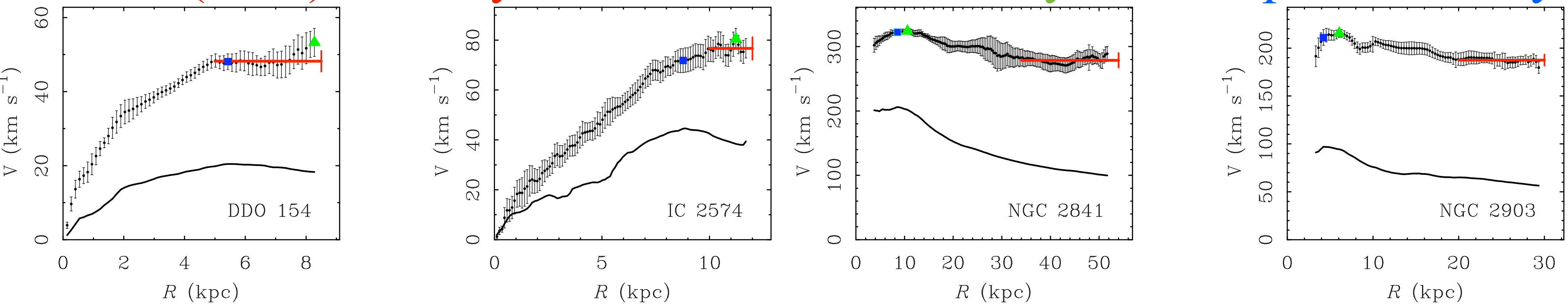
Mass model built from

2MASS K-band data (SSM)

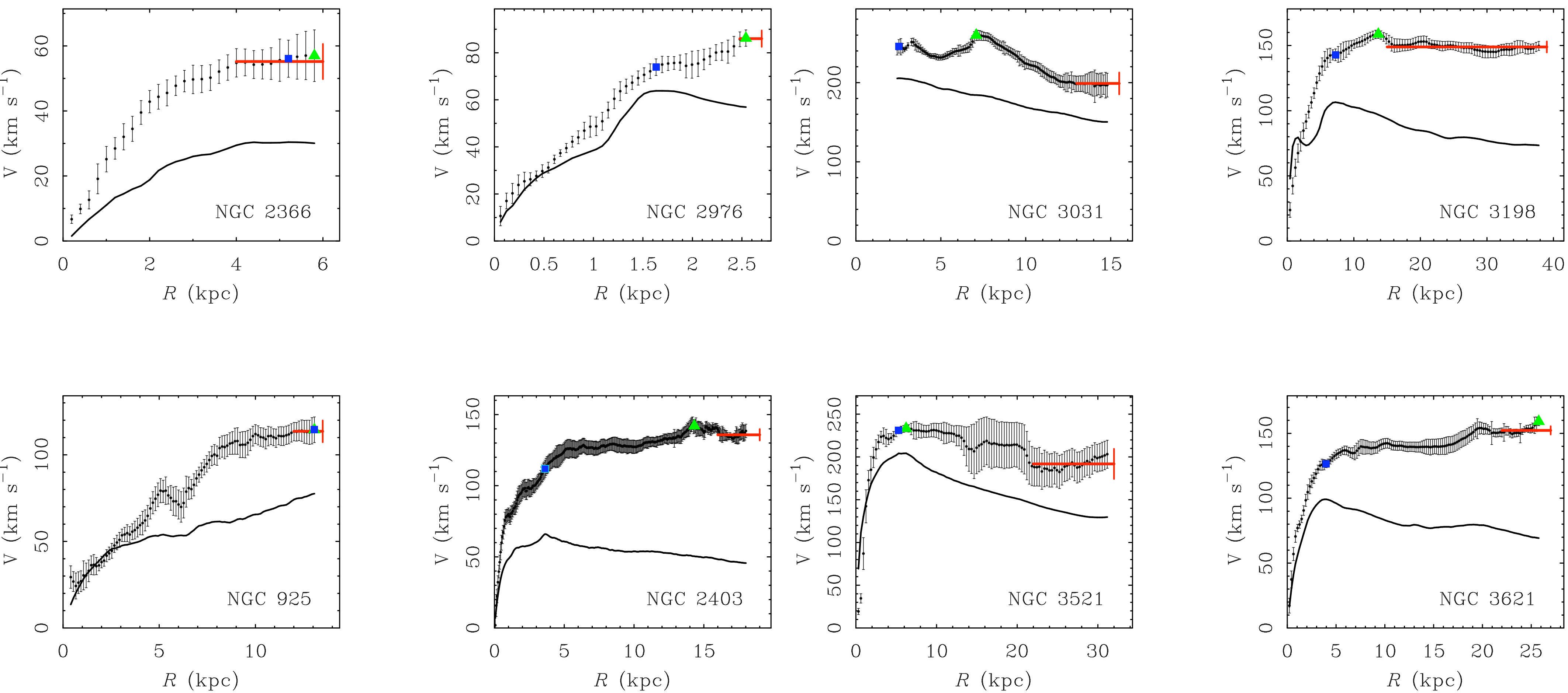
(note tiny bulge - Renzo's rule)



outer (~flat) velocity maximum velocity peak velocity

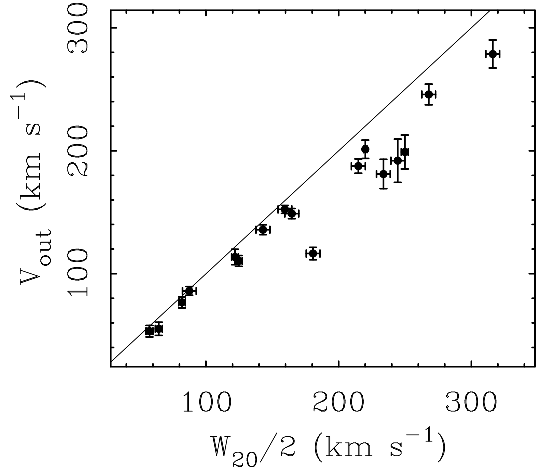


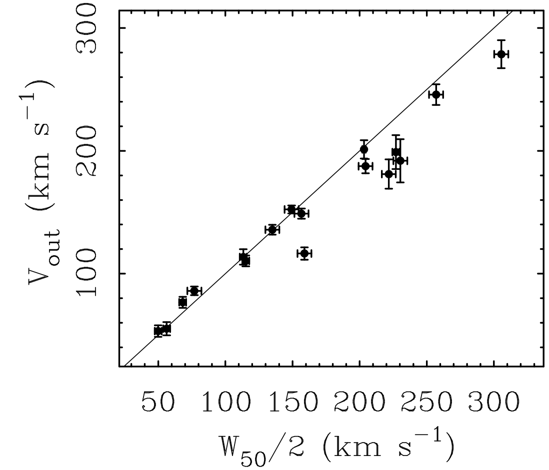

THINGS data (Walter et al 2008)



# Velocity estimators:

$V_{flat}$



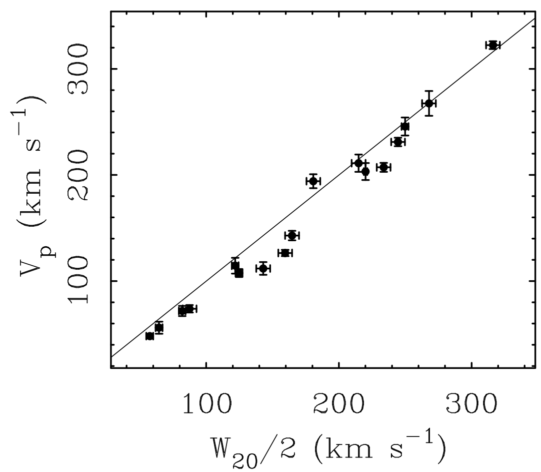



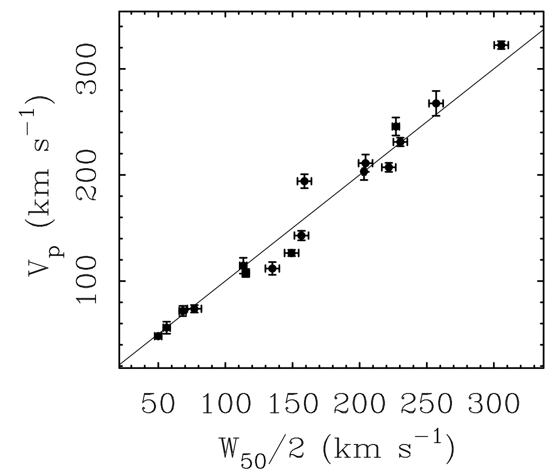

THINGS data
(Walter et al 2008)

$W_{20}$

$W_{50}$

$V_p$

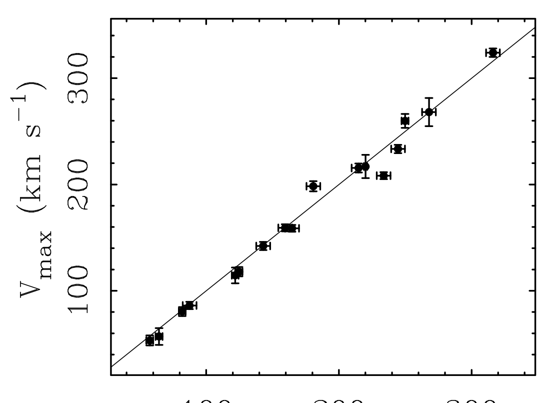


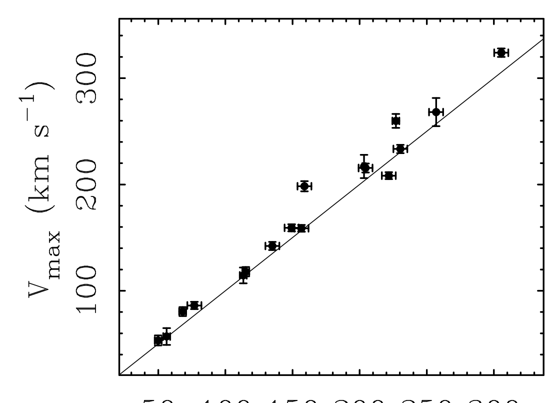




$W_{20}$

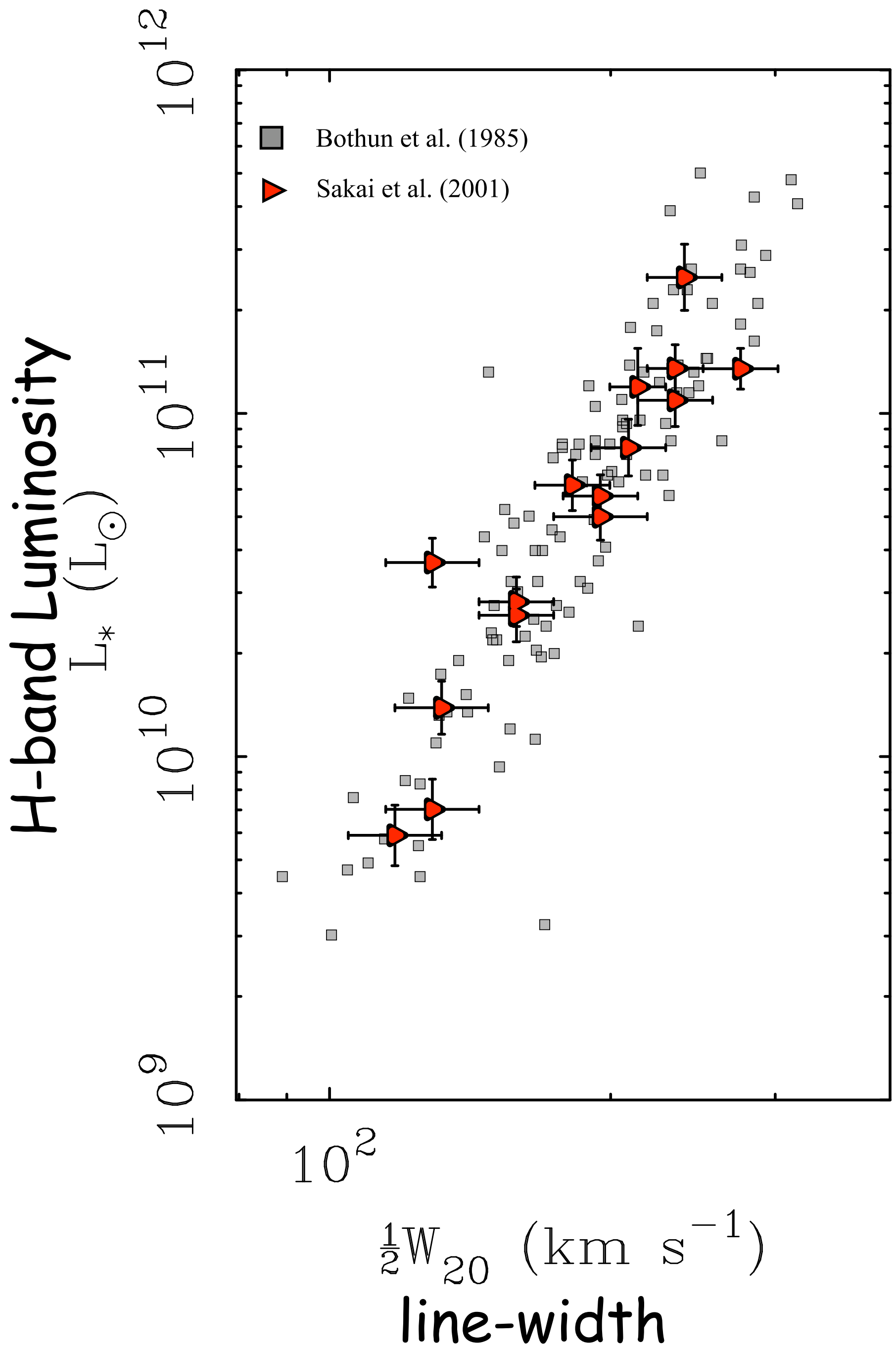
$W_{50}$

$V_{max}$



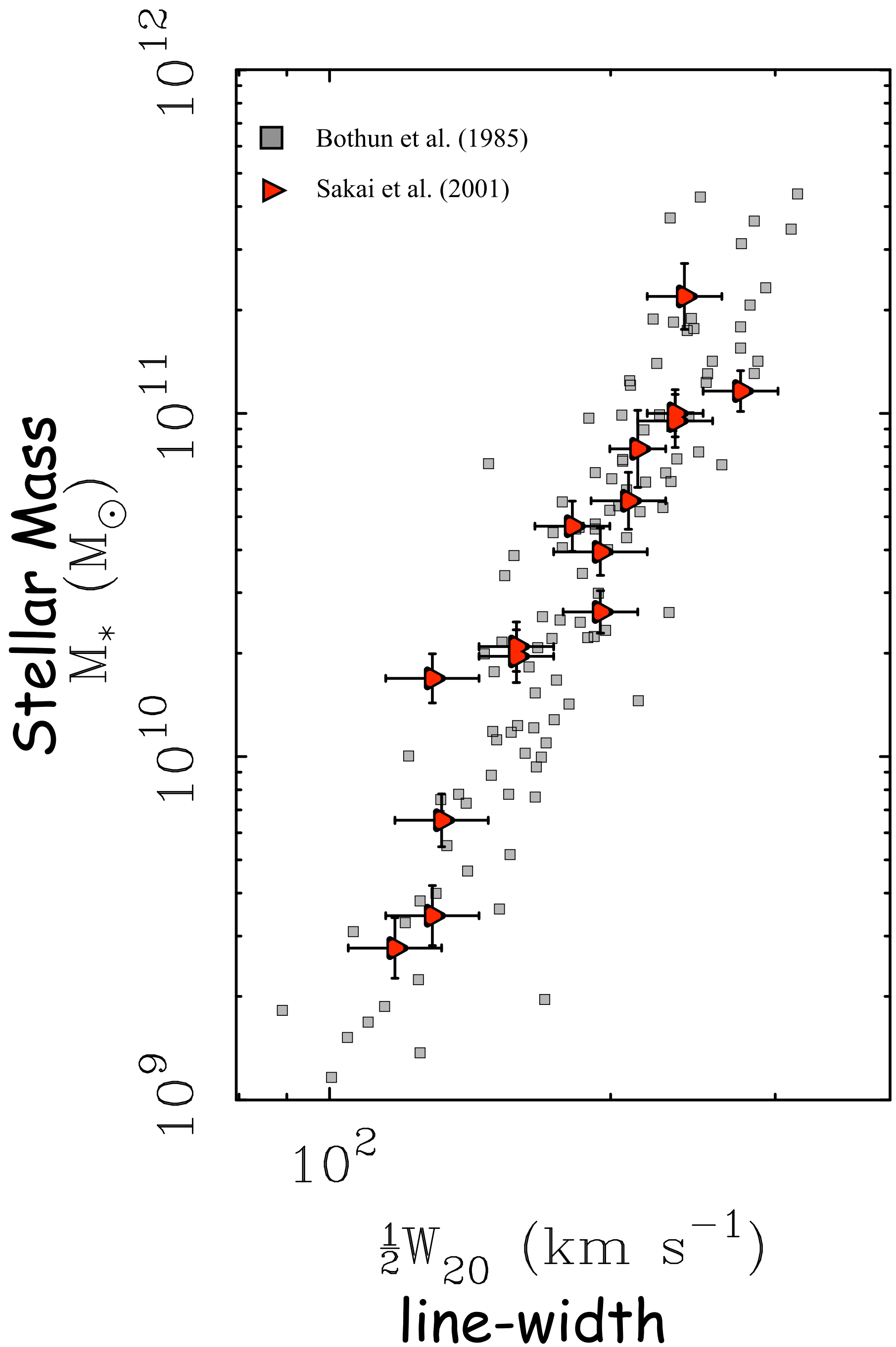



# Tully-Fisher relation




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

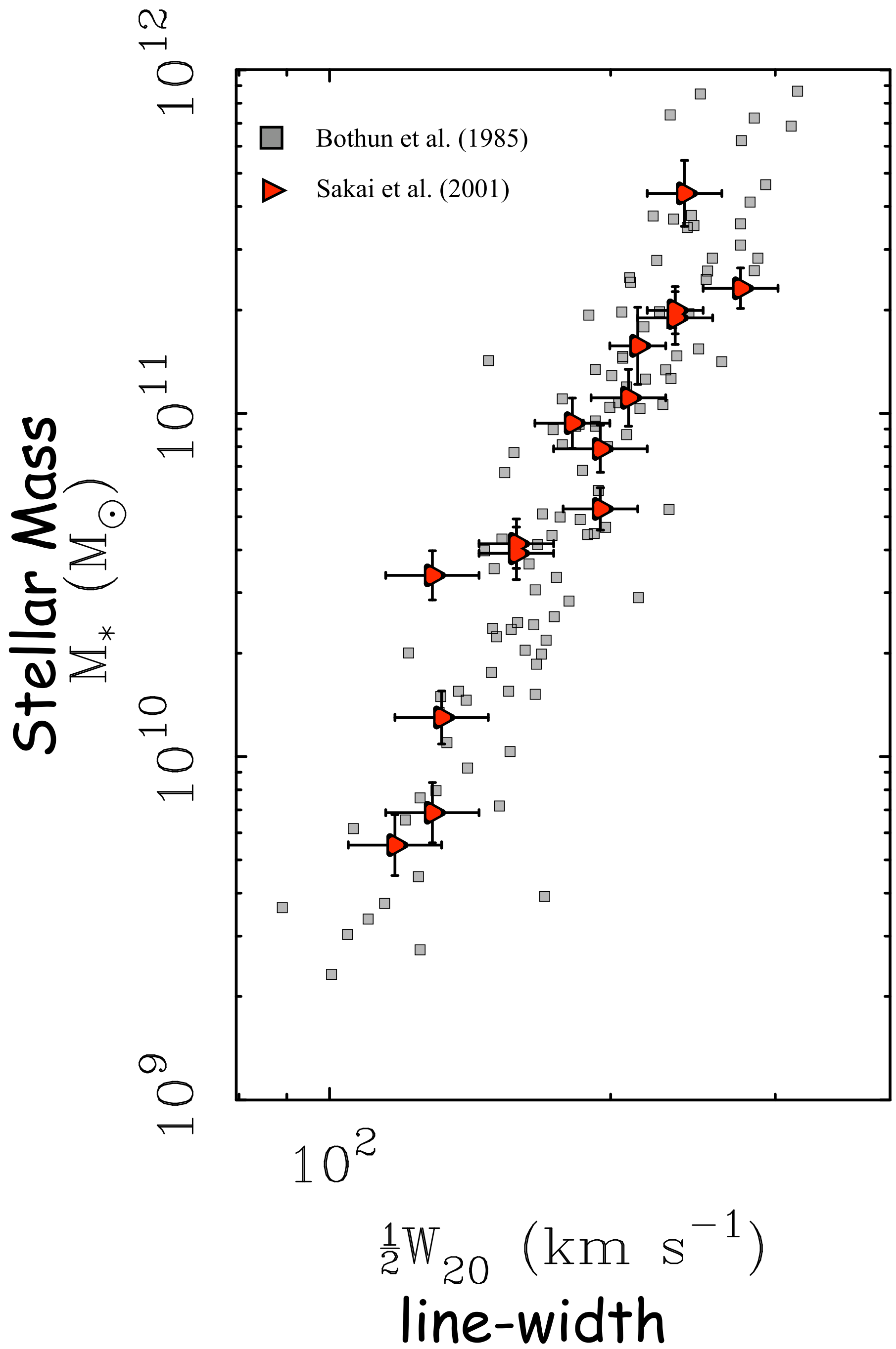
# Stellar Mass Tully-Fisher relation




nominal M*/L (Kroupa IMF)

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

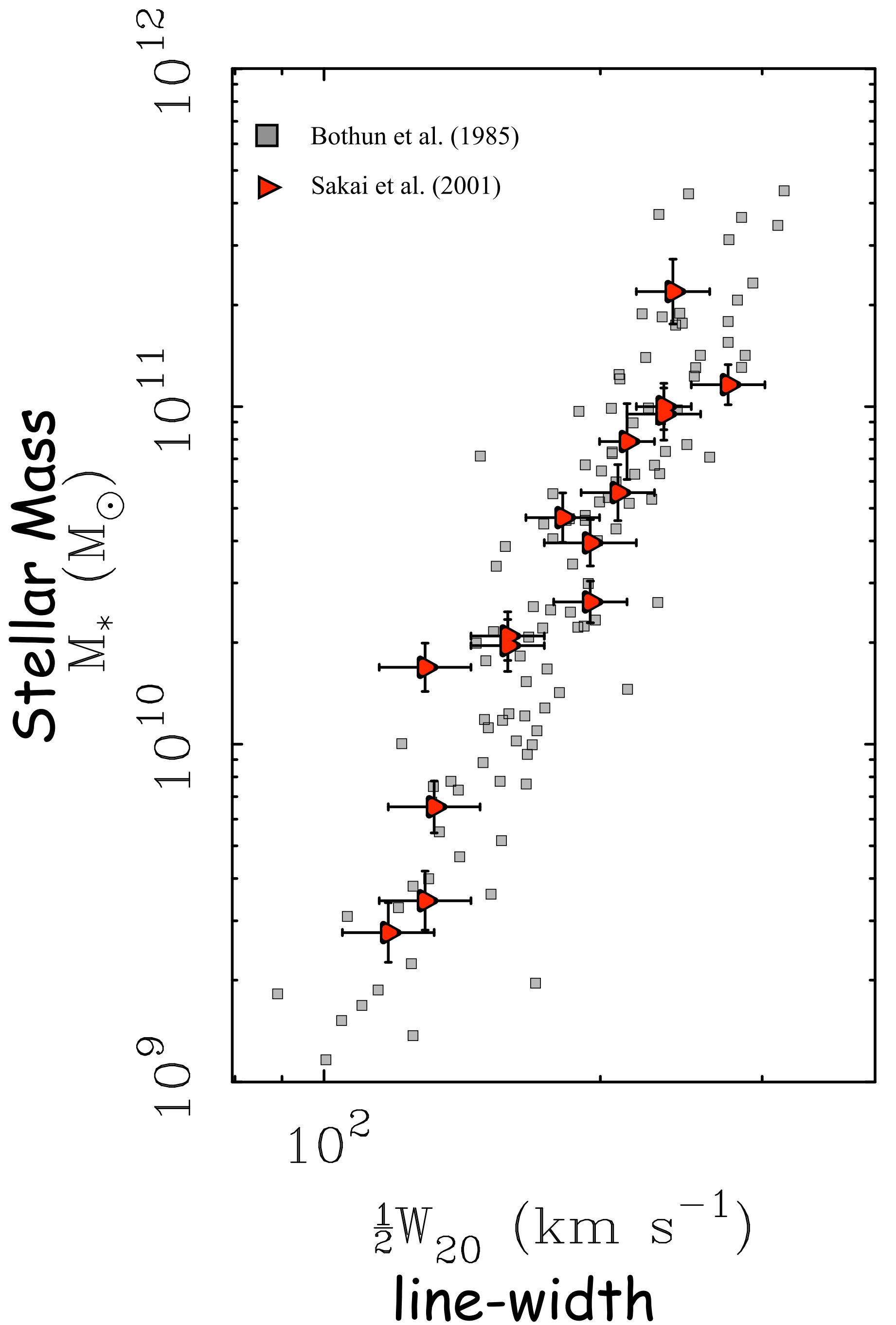
# Stellar Mass Tully-Fisher relation




double M*/L

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

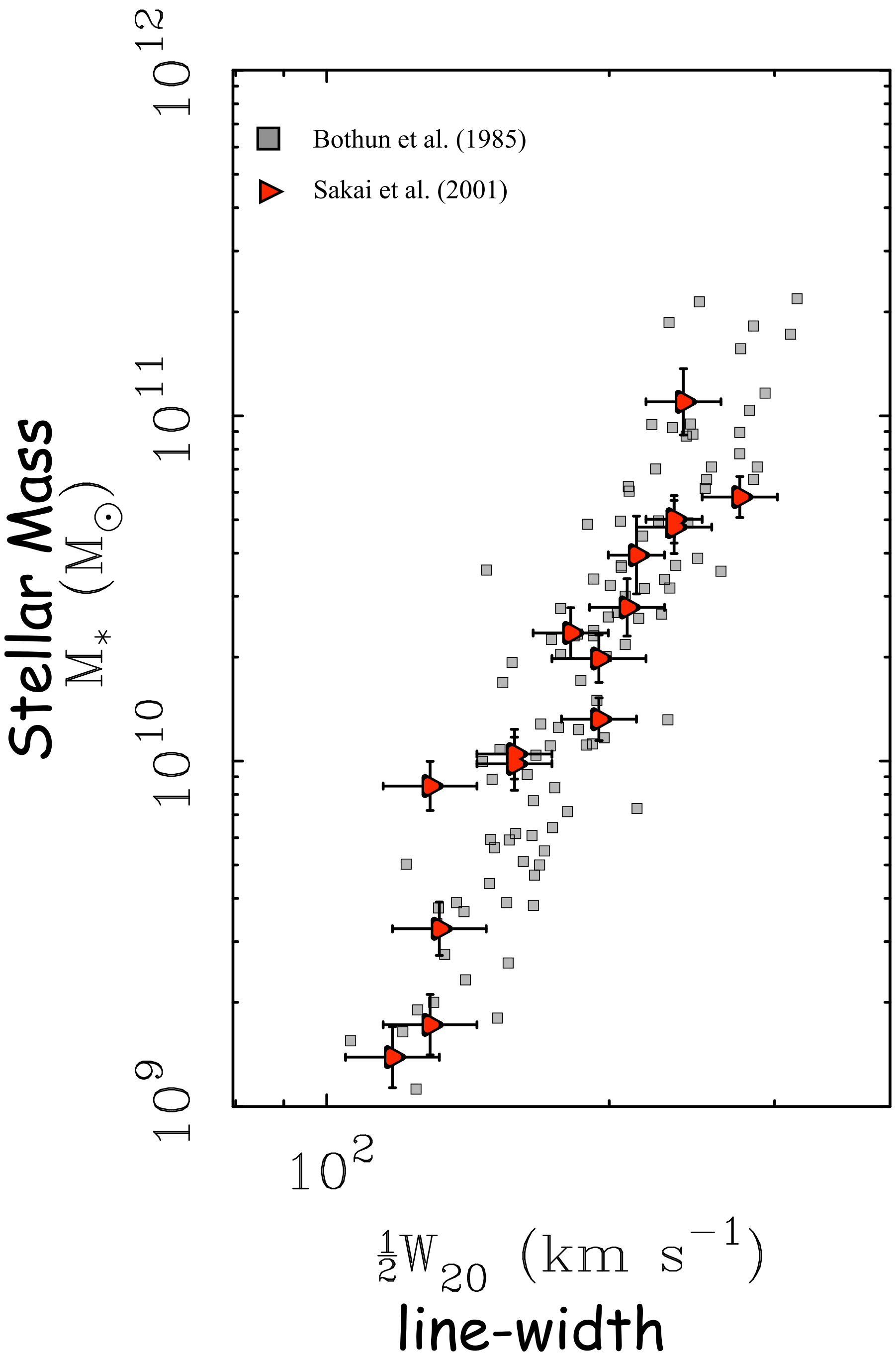
# Stellar Mass Tully-Fisher relation




nominal M*/L

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

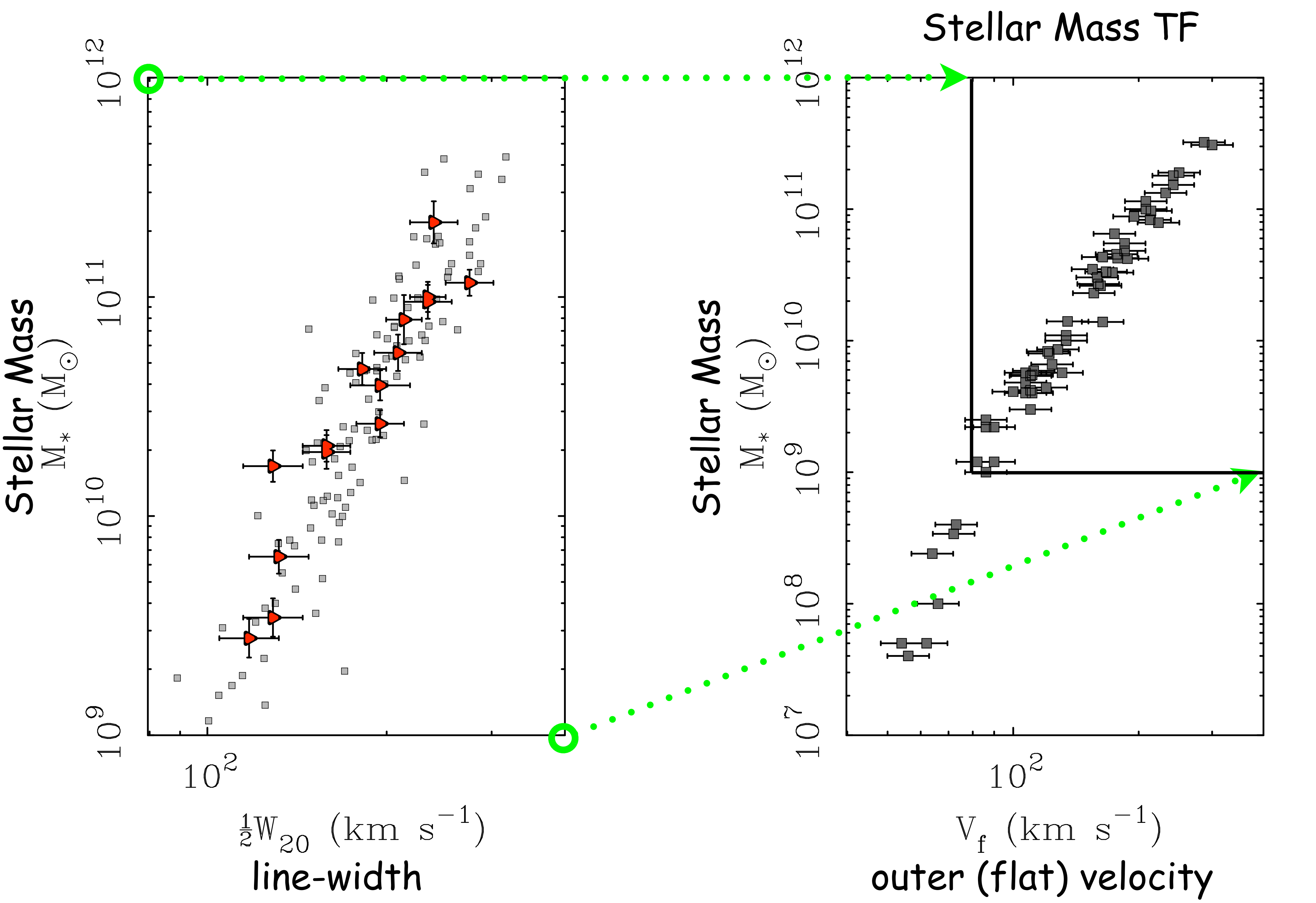
# Stellar Mass Tully-Fisher relation




half M*/L

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

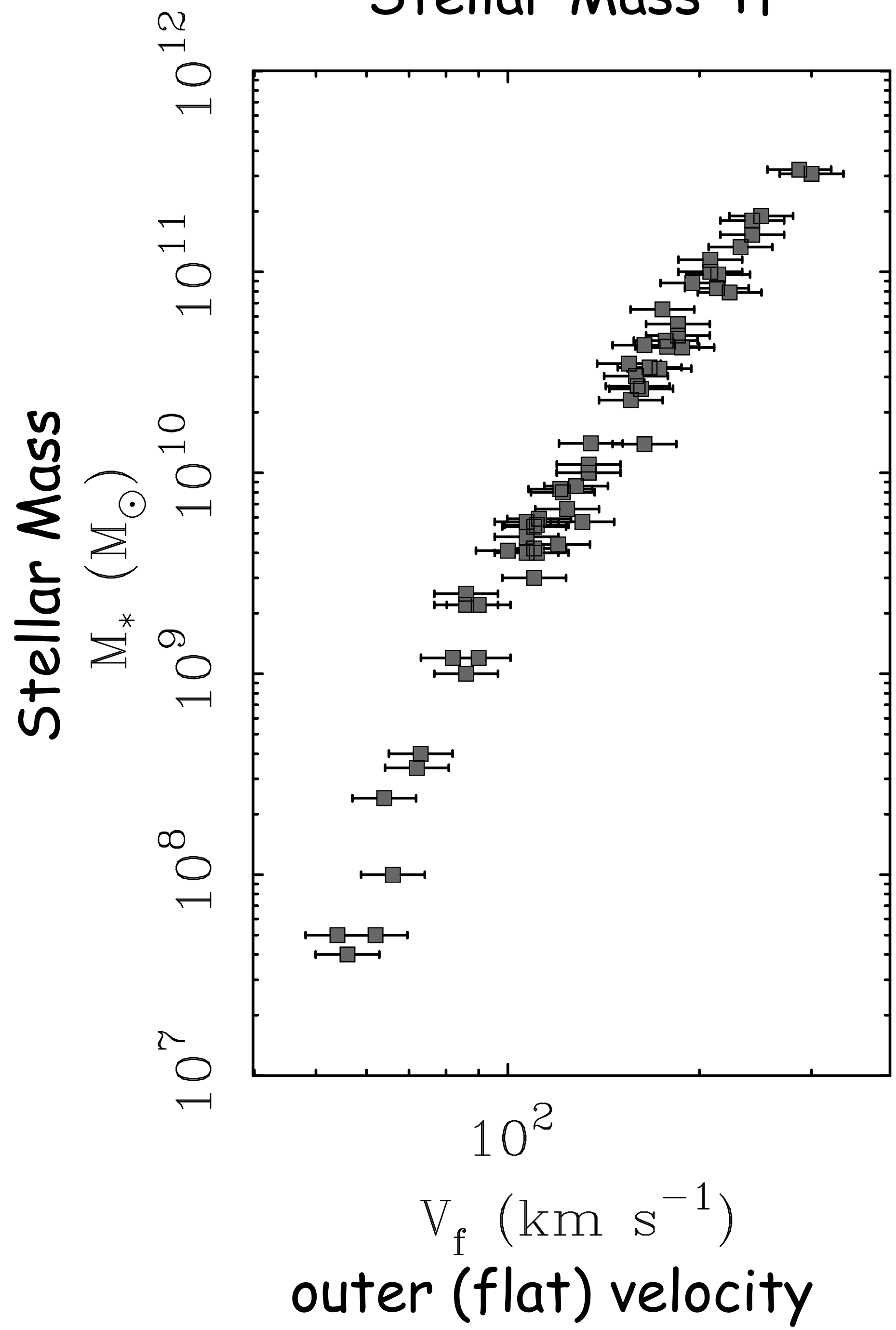
# Scatter in TF relation reduced with resolved rotation curves (Verheijen 2001)



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

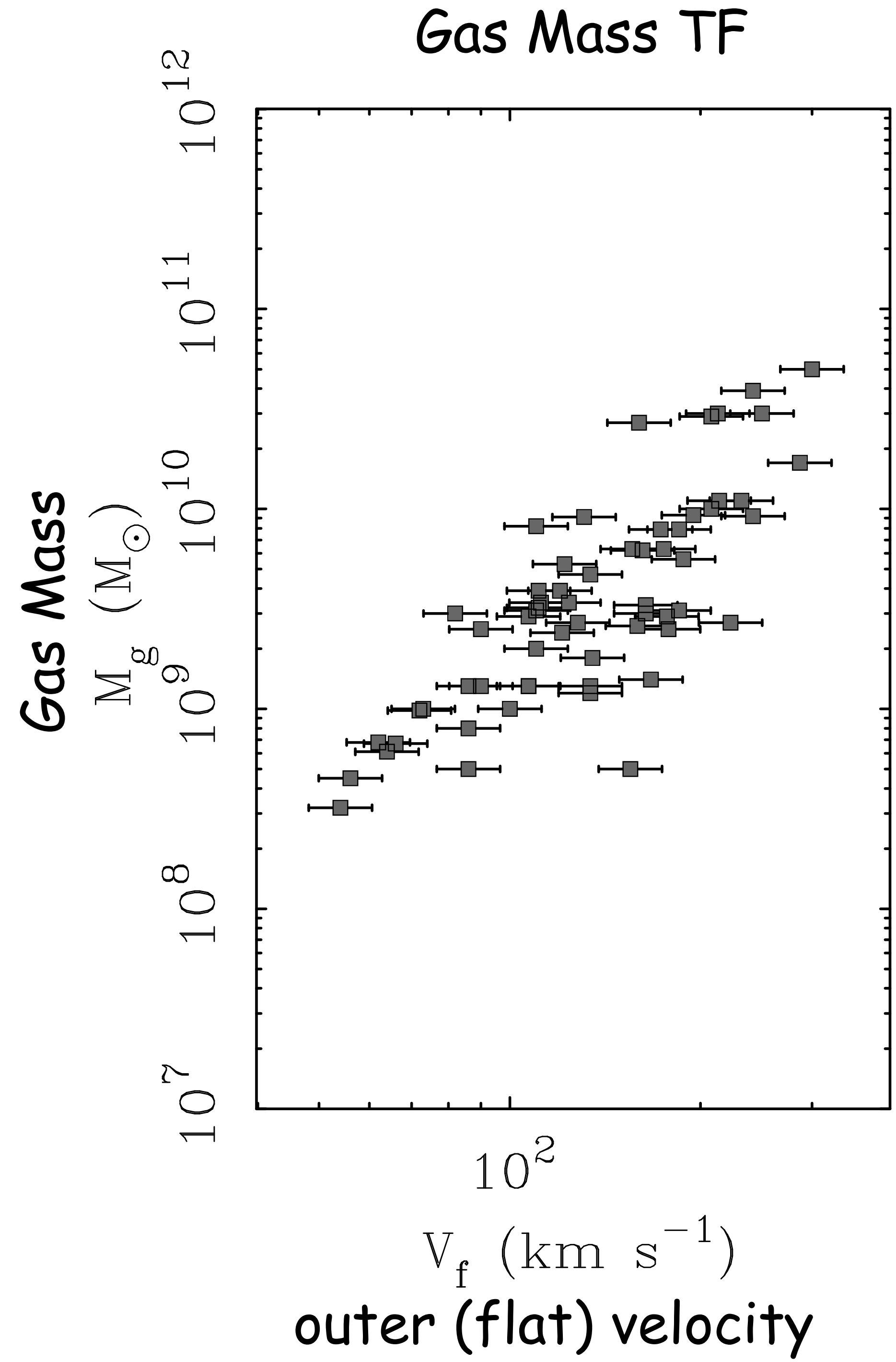
$$M_* = \left(\frac{M_*}{L}\right) L$$

## Stellar Mass TF



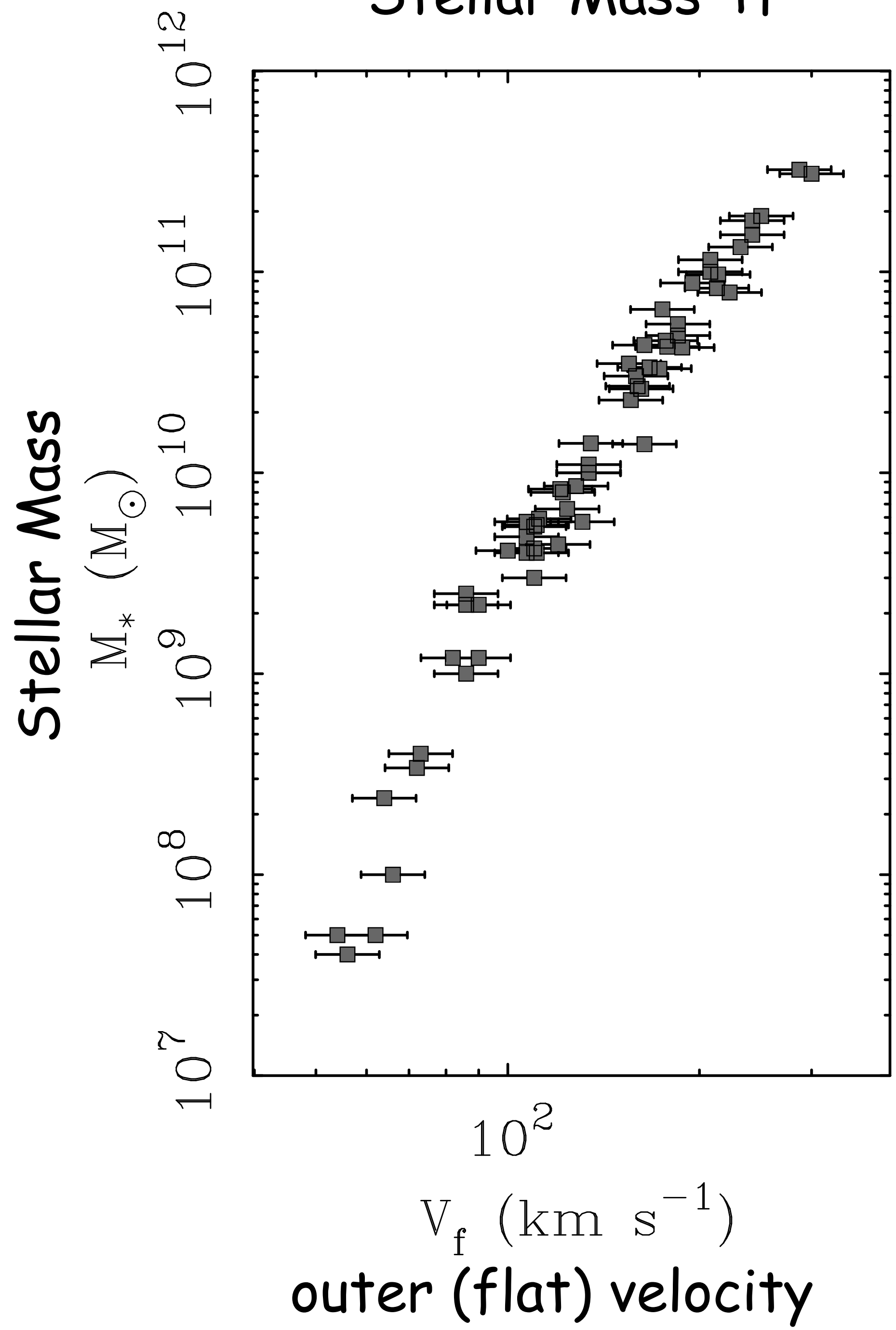
Gas mass by itself does NOT produce a good TF relation, at least for fast rotators.

$$M_g = 1.4 M_{HI}$$



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

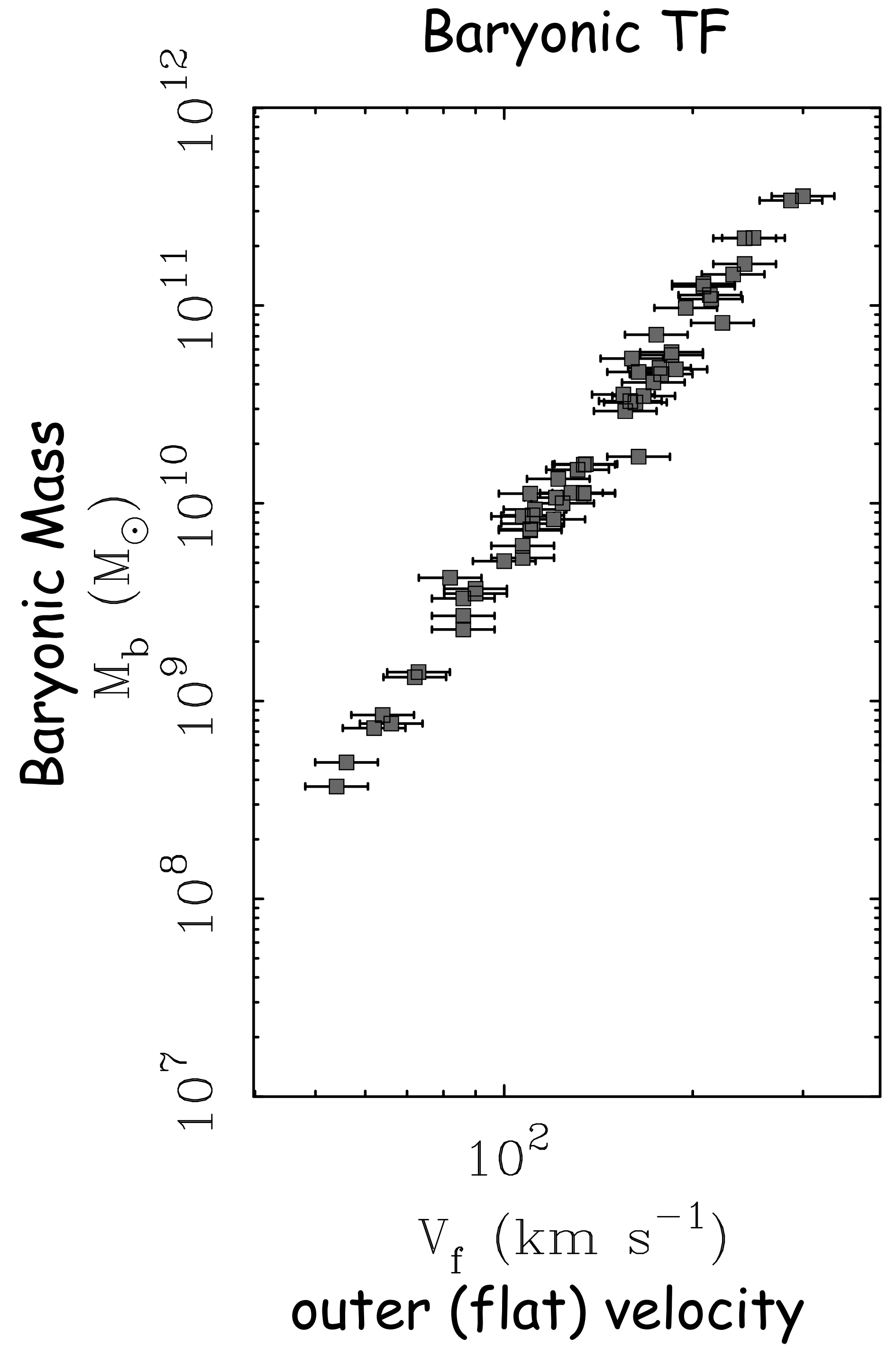
Stellar Mass TF



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

$$M_b = M_* + M_g$$

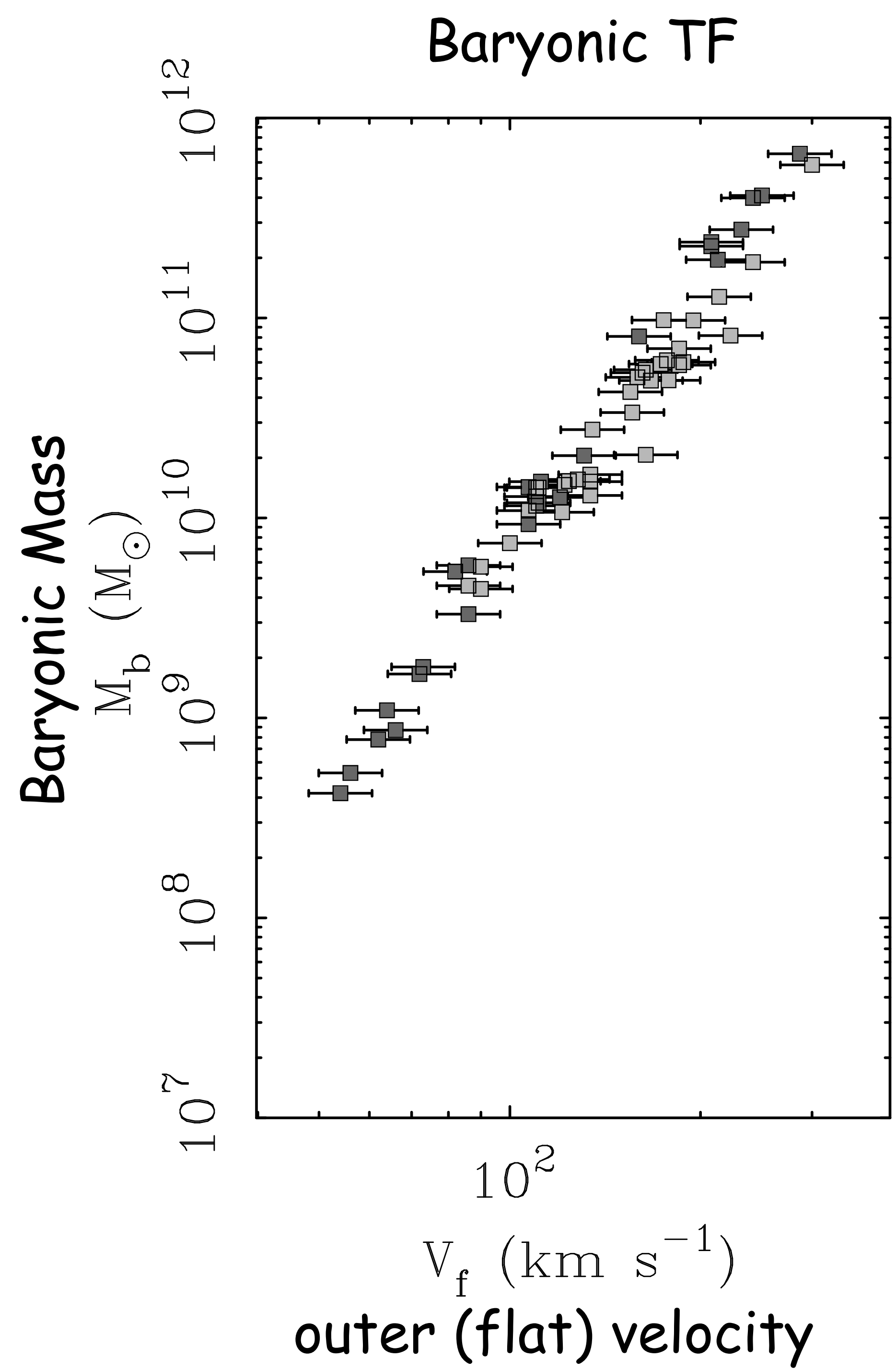
Baryonic mass is the important physical quantity. It doesn't matter whether the mass is in stars or in gas.



Twice Nominal M*/L

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

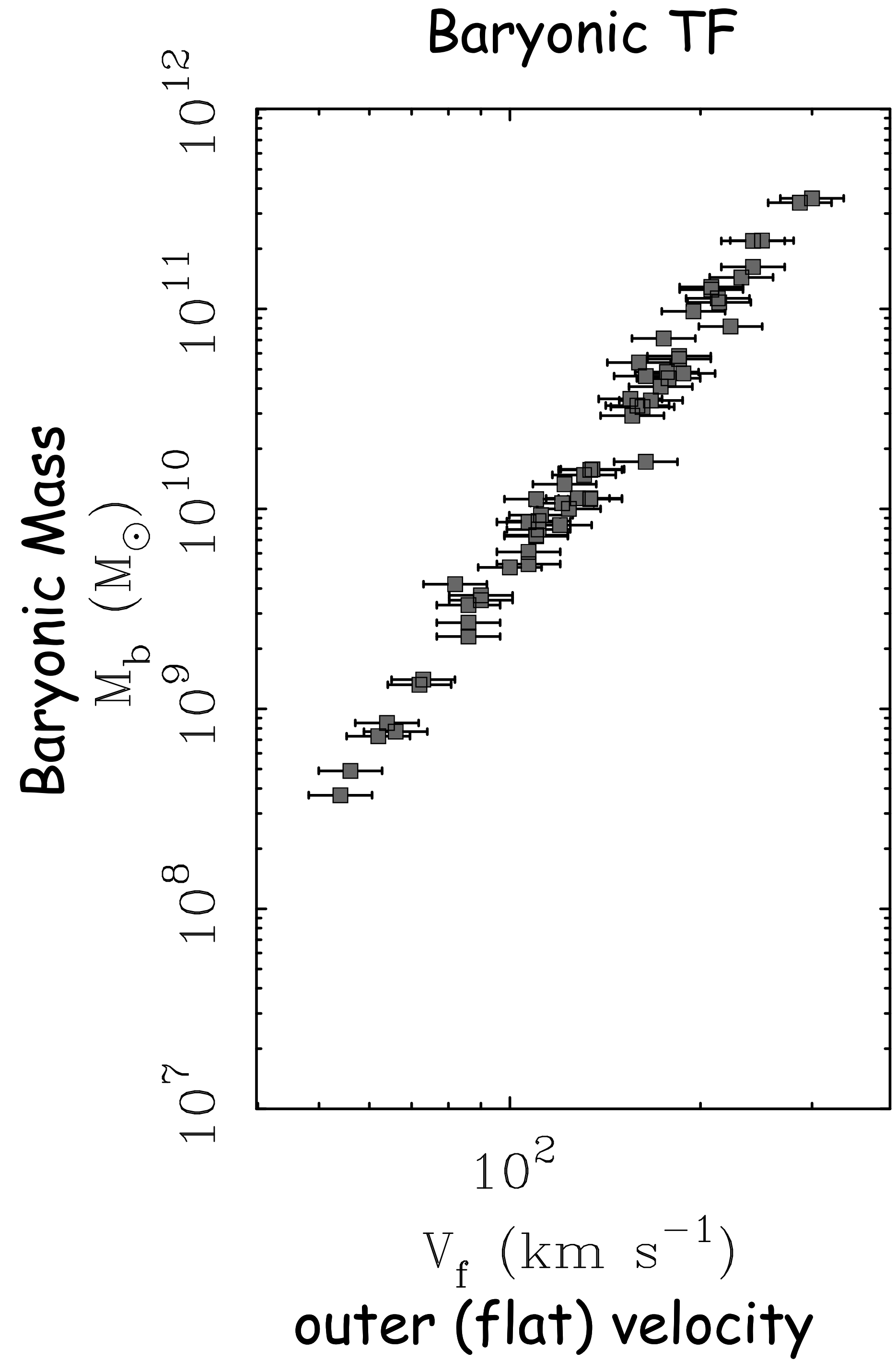
Scatter increases as we diverge from the nominal M*/L.



Nominal M*/L

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

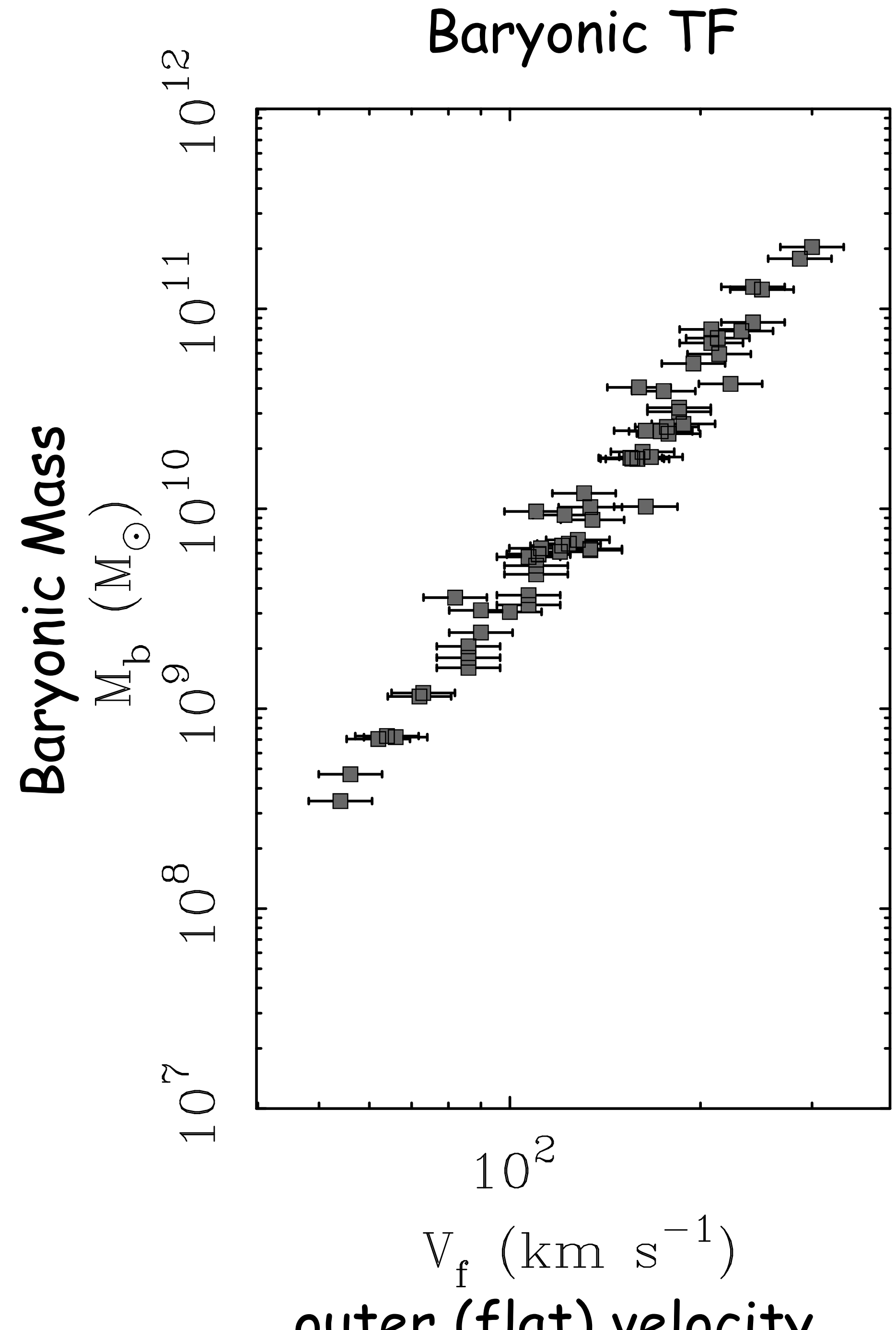
Scatter increases as we diverge from the nominal M*/L.



Half Nominal M*/L

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

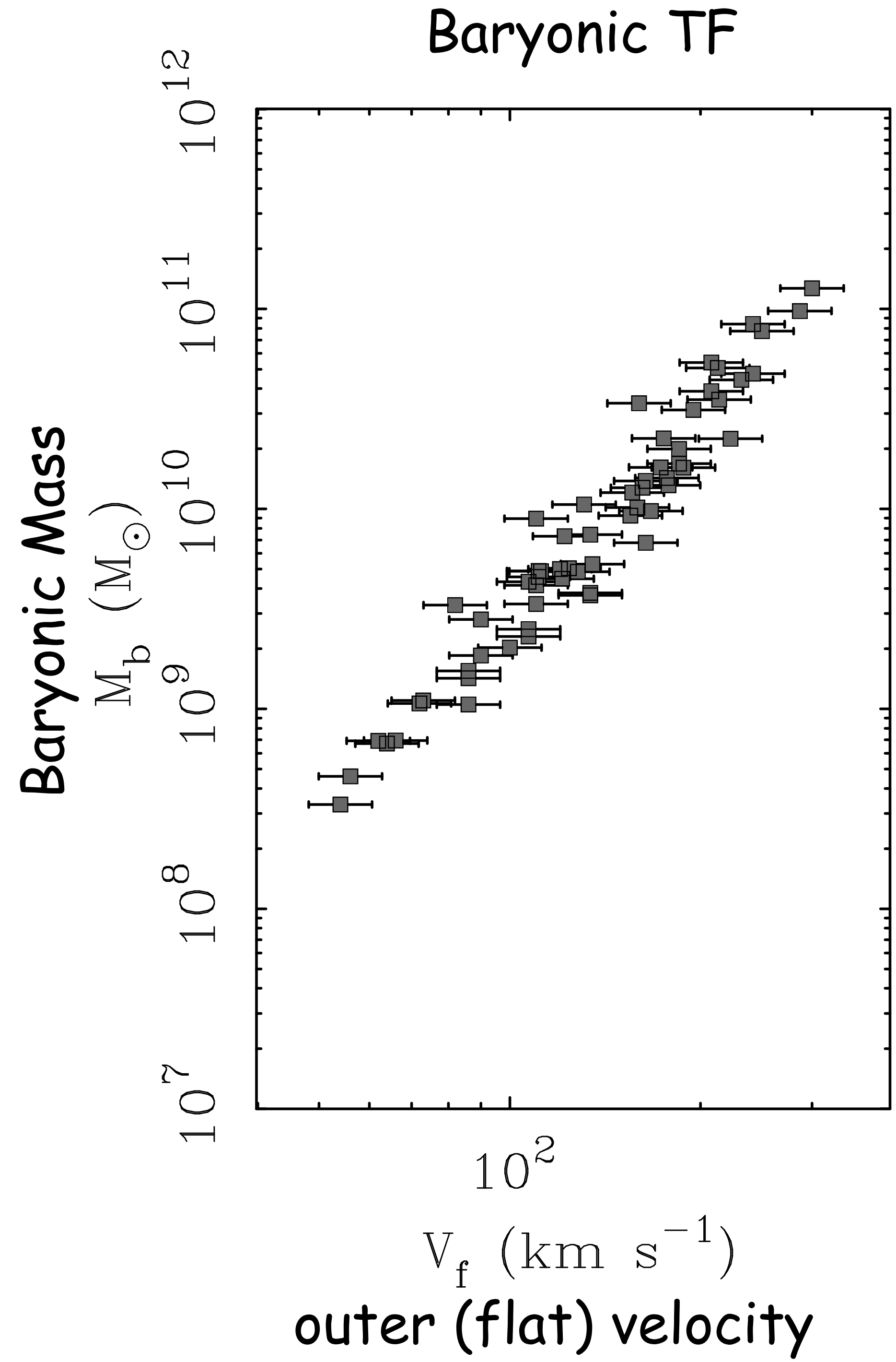
Scatter increases as we diverge from the nominal M*/L.



Quarter Nominal M*/L

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

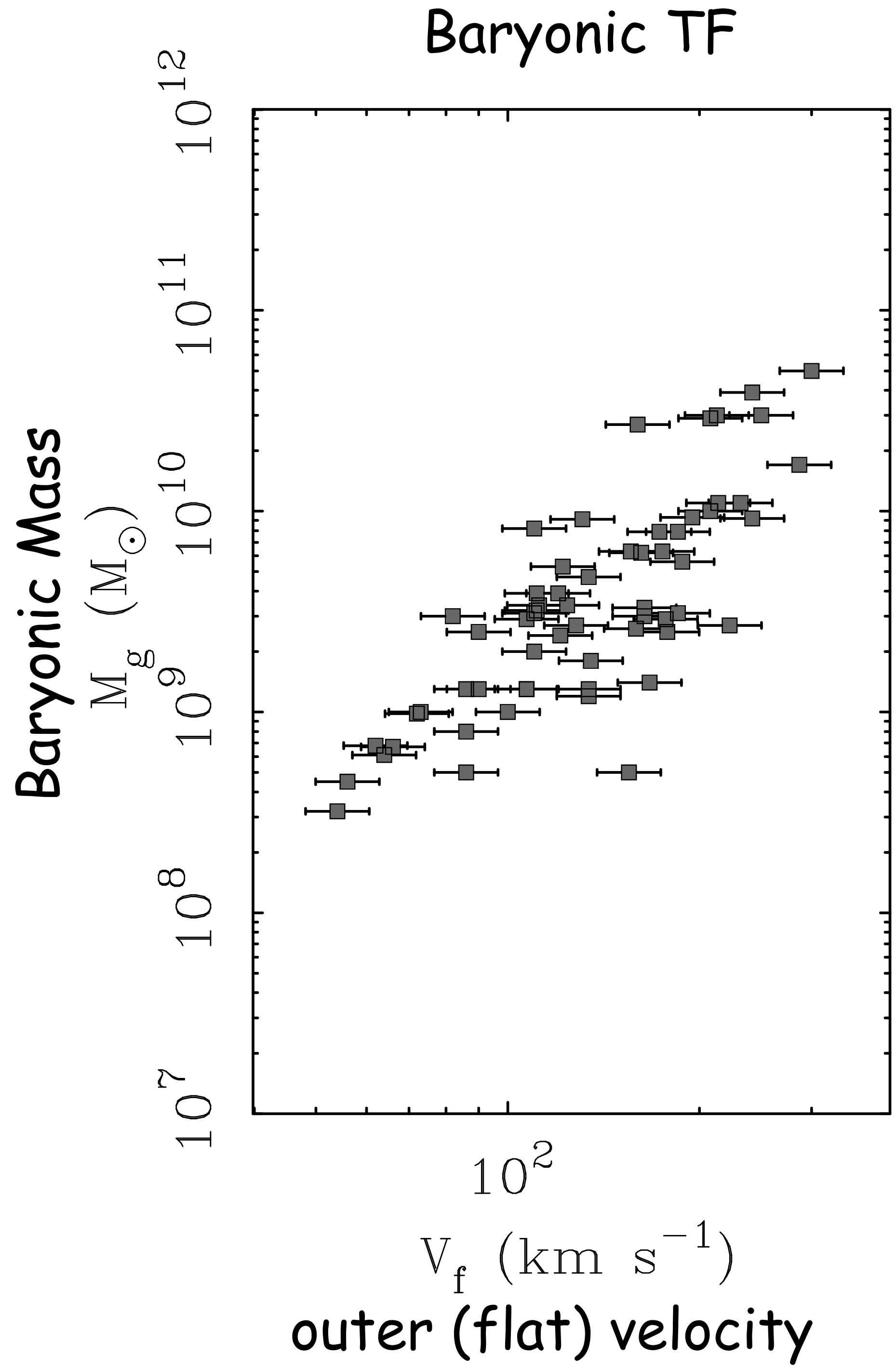
Scatter increases as we diverge from the nominal M*/L.



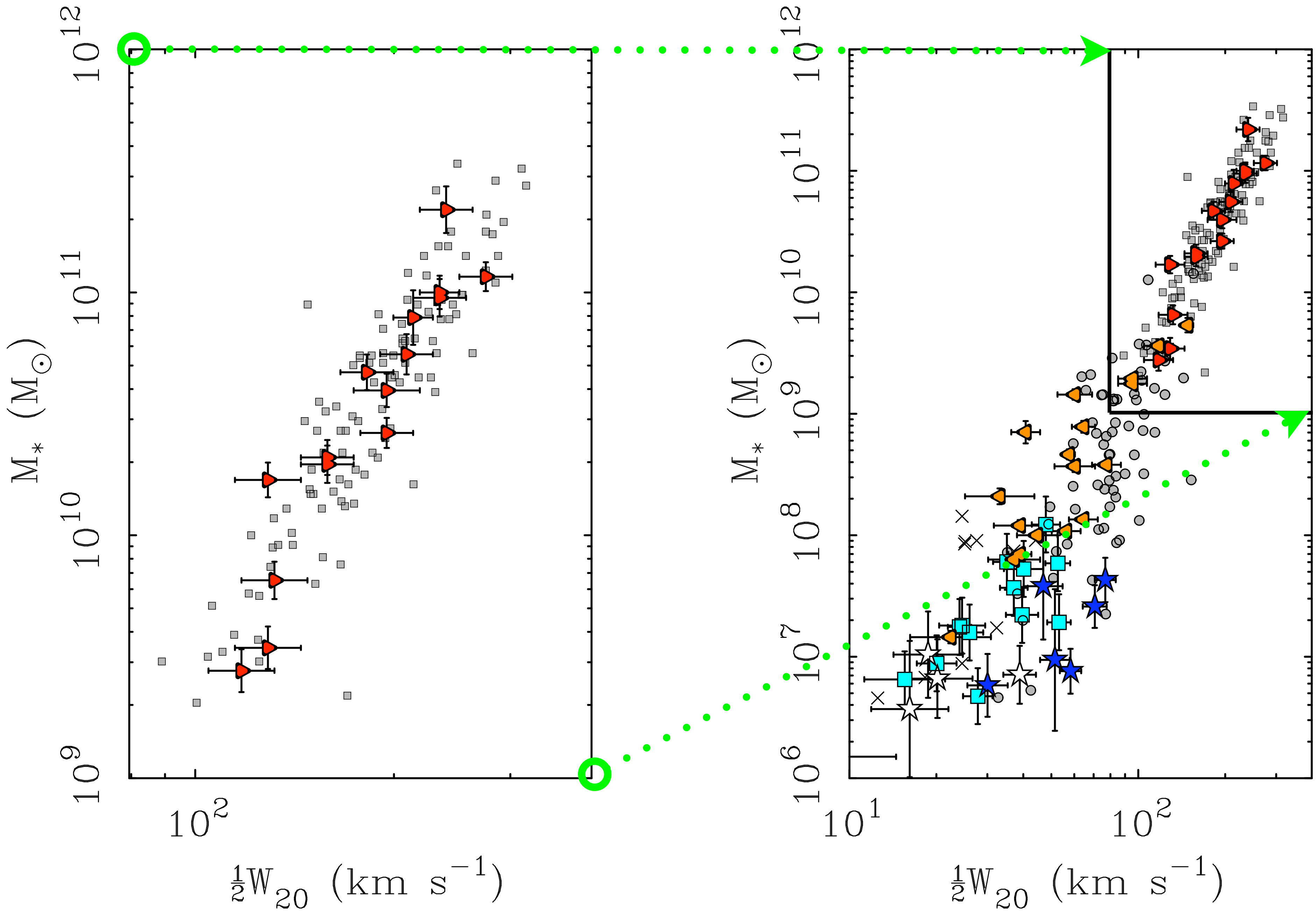
Zero M*/L

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.



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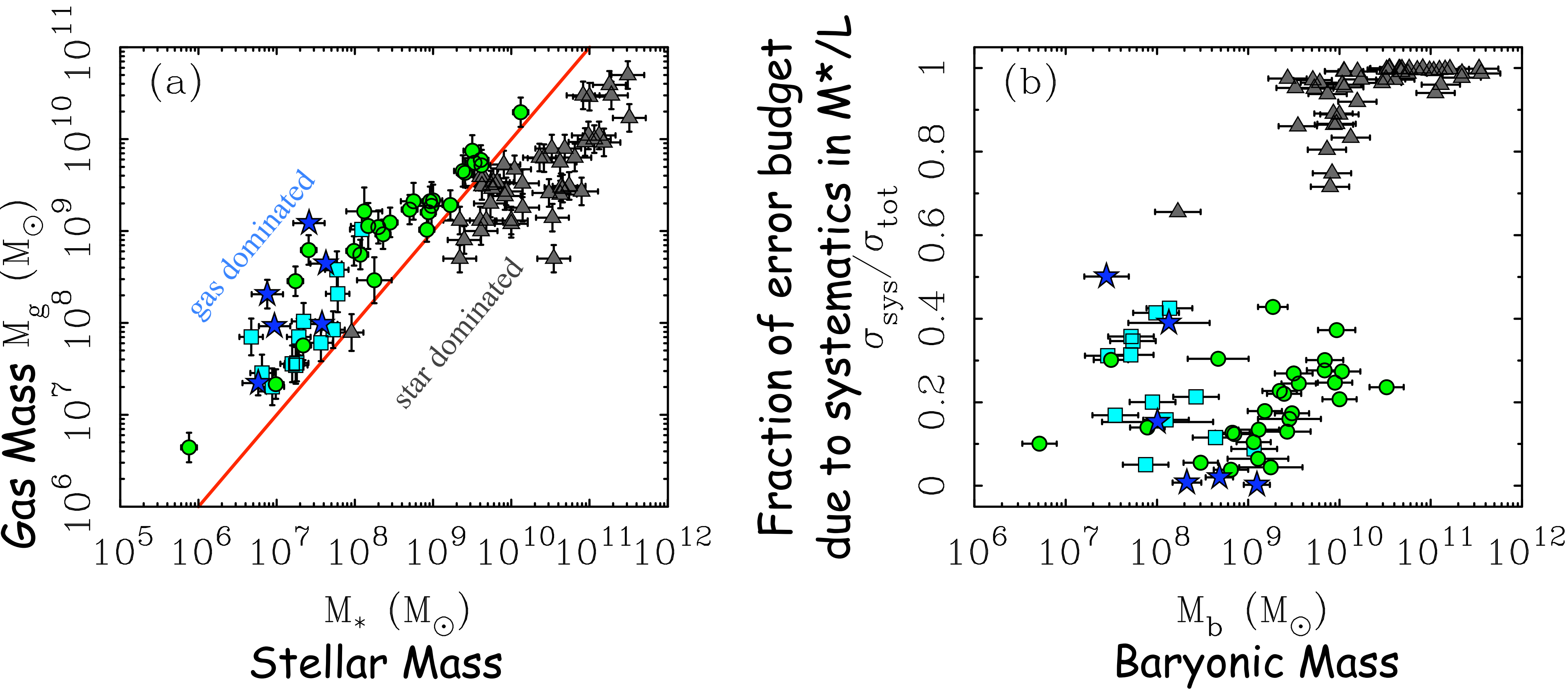
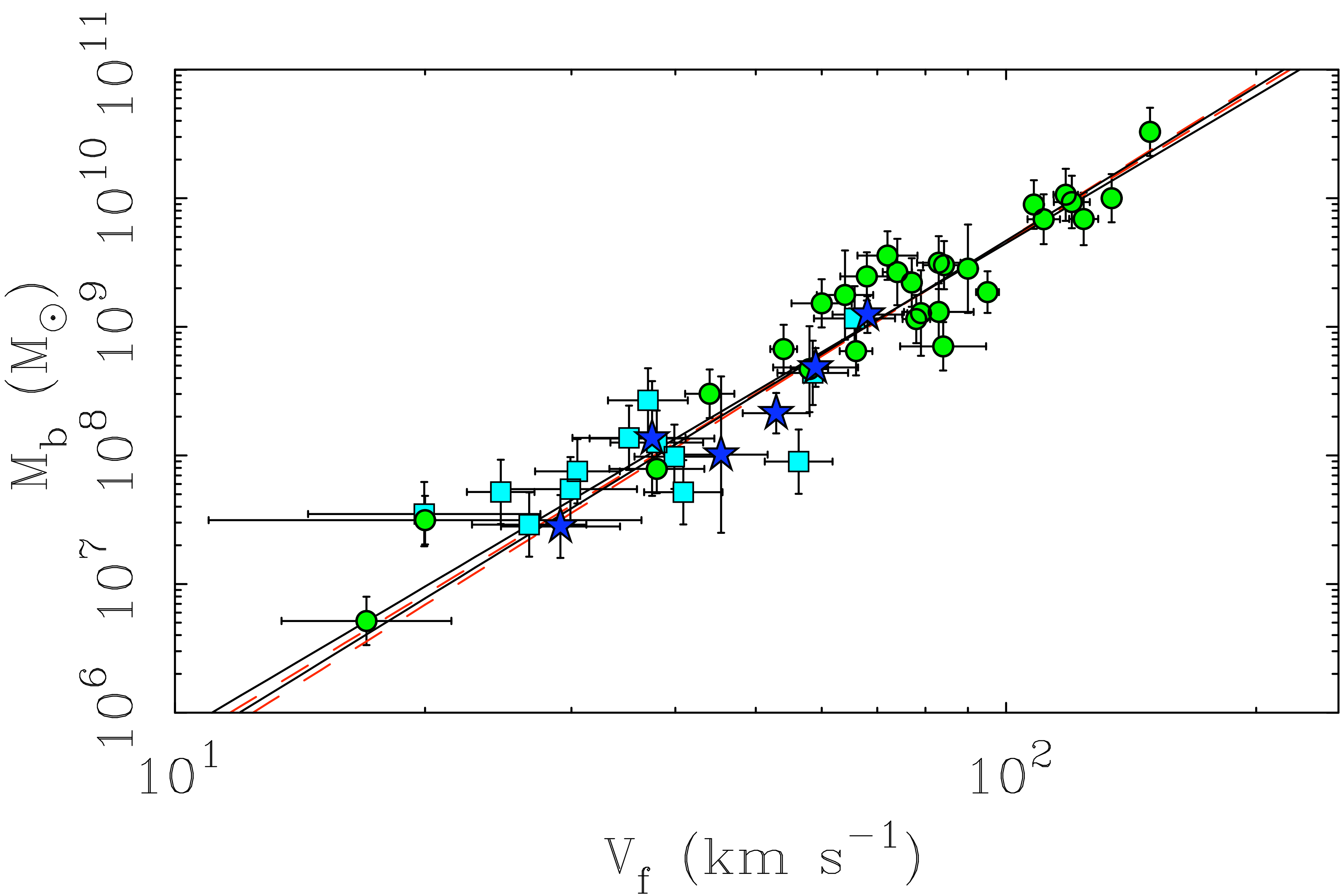



Systematic errors in M*/L no longer dominate the error budget for galaxies with Mg > M*.

# Gas Rich Galaxy Baryonic Tully-Fisher relation
(Stark et al 2009; Trachternach et al 2009; McGaugh 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 $A = 47 \pm 6\ \mathrm{M}_\odot\, \mathrm{km}^{-4}\, \mathrm{s}^4$

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

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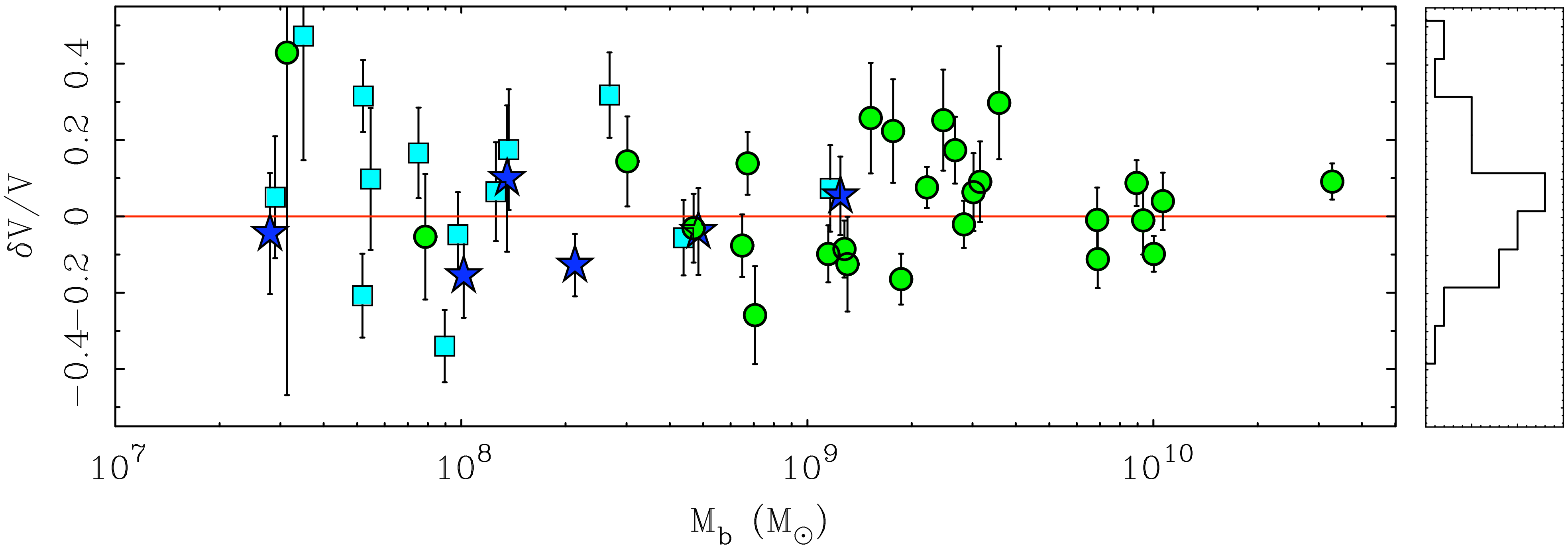
Stark, McGaugh, & Swaters (2009, AJ, 138, 392)

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

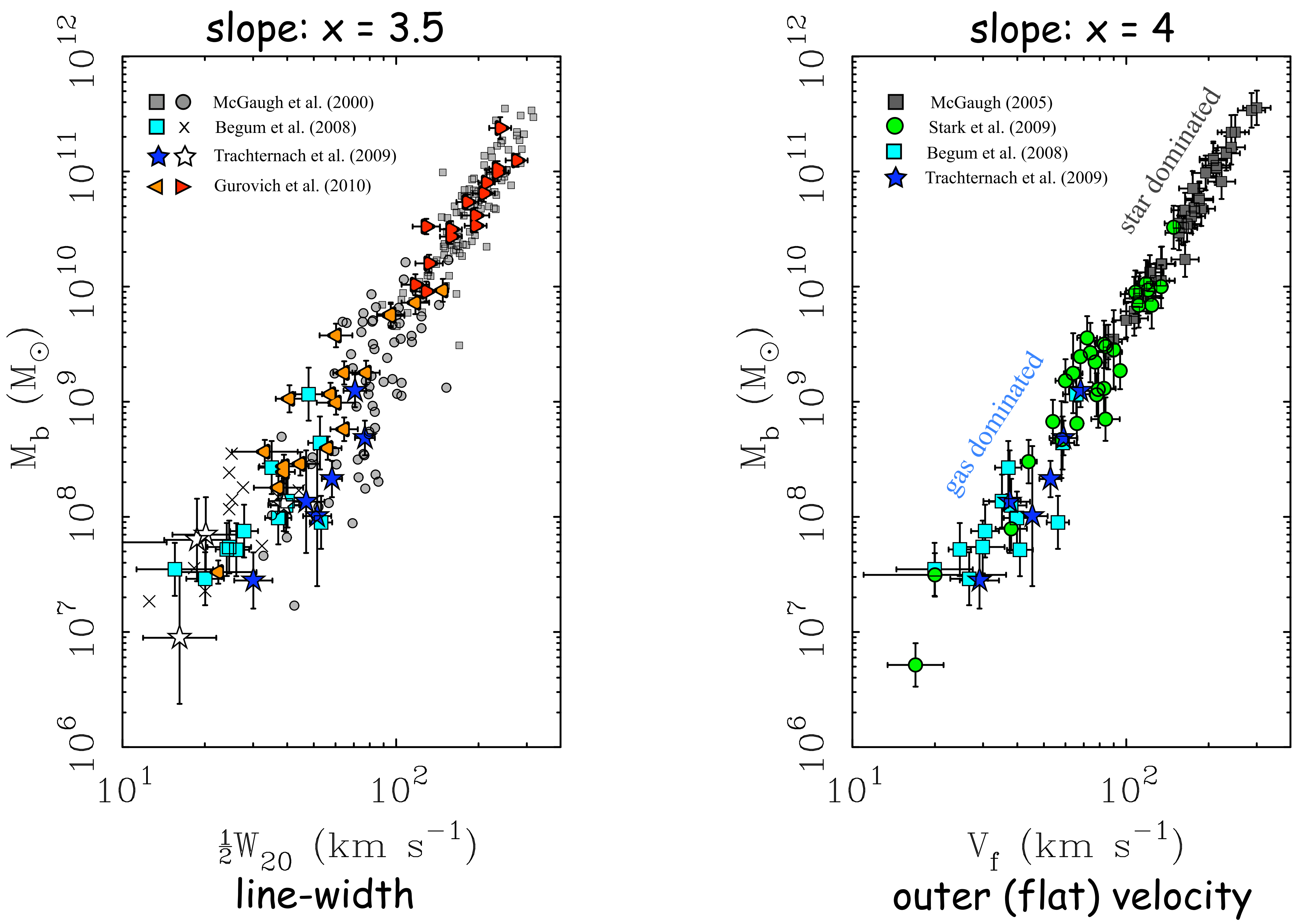
Intrinsic scatter small - consistent with zero

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

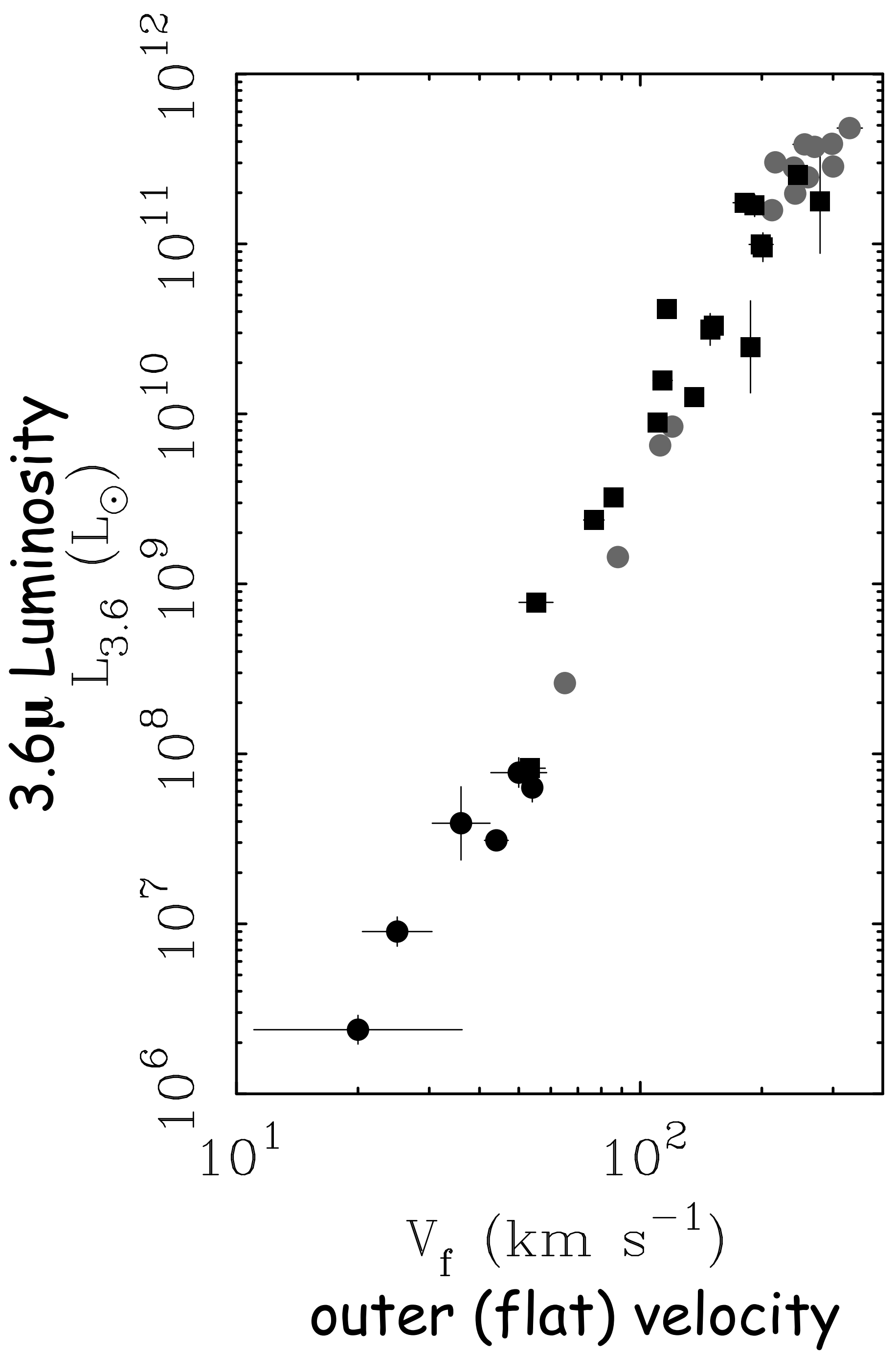


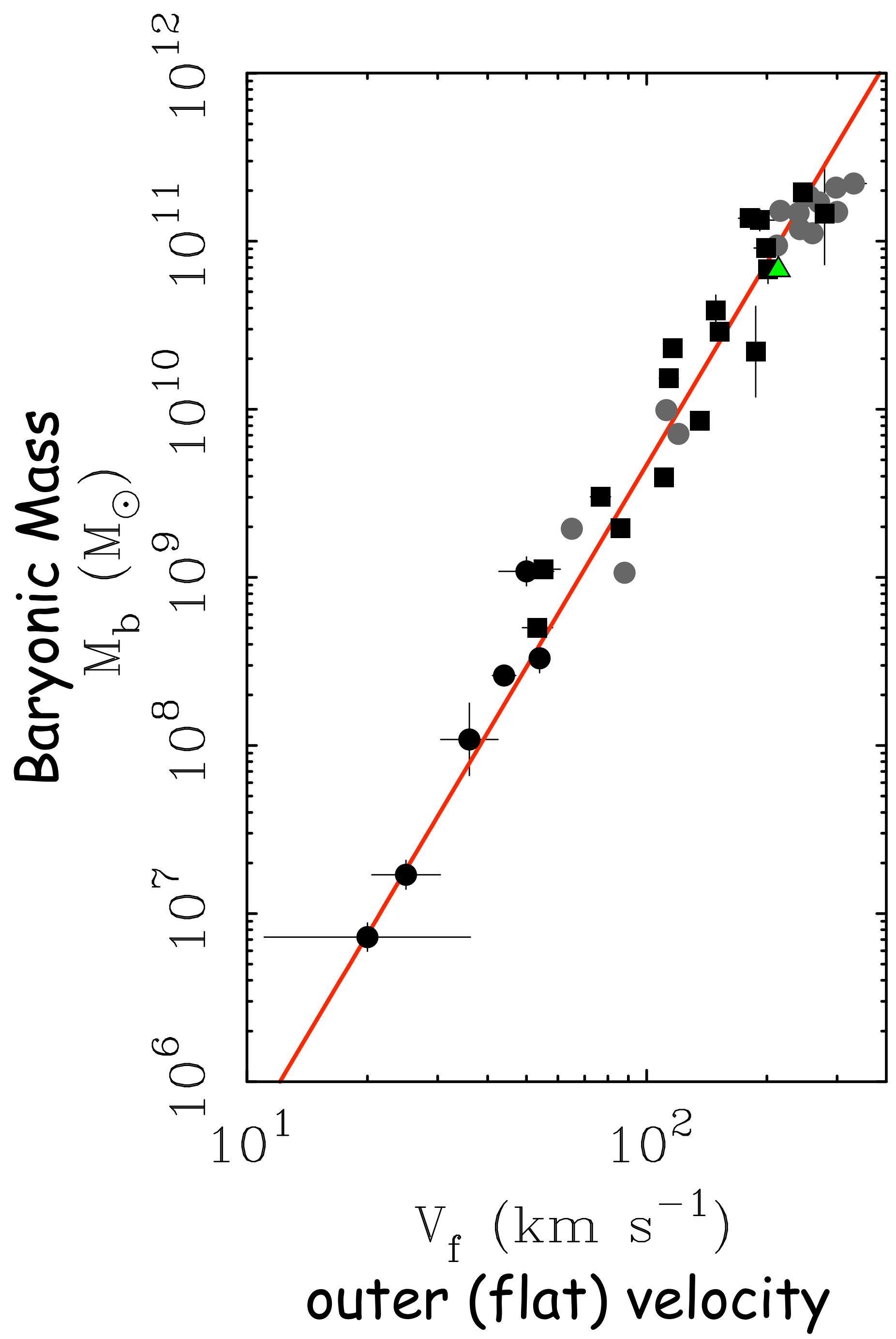

(consistent with UMa result of Verheijen 2001)

# Baryonic Tully-Fisher relation: slope depends on Velocity estimator

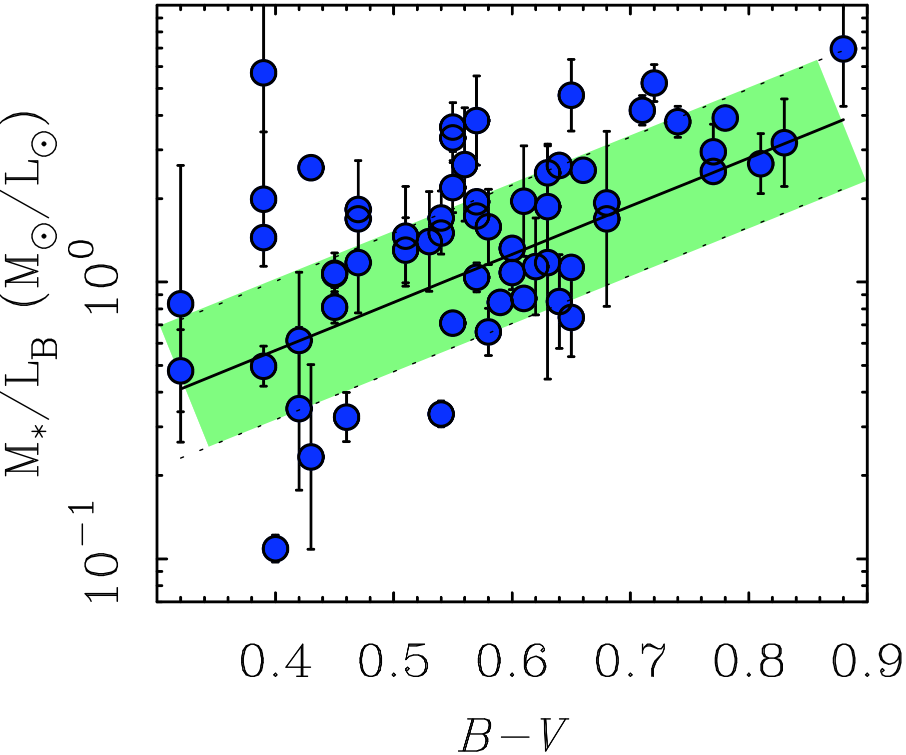


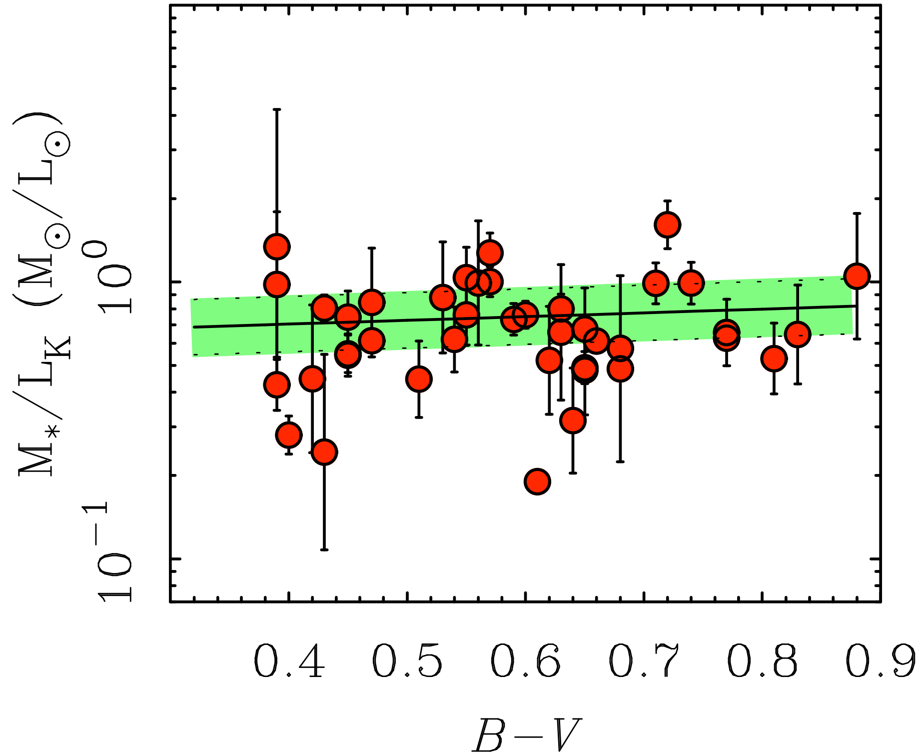
Data from Spitzer



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




Recovers expected

- slope
- normalization
- scatter

constrains IMF: ~ Kroupa

excludes models with excess TP-AGB contributions

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

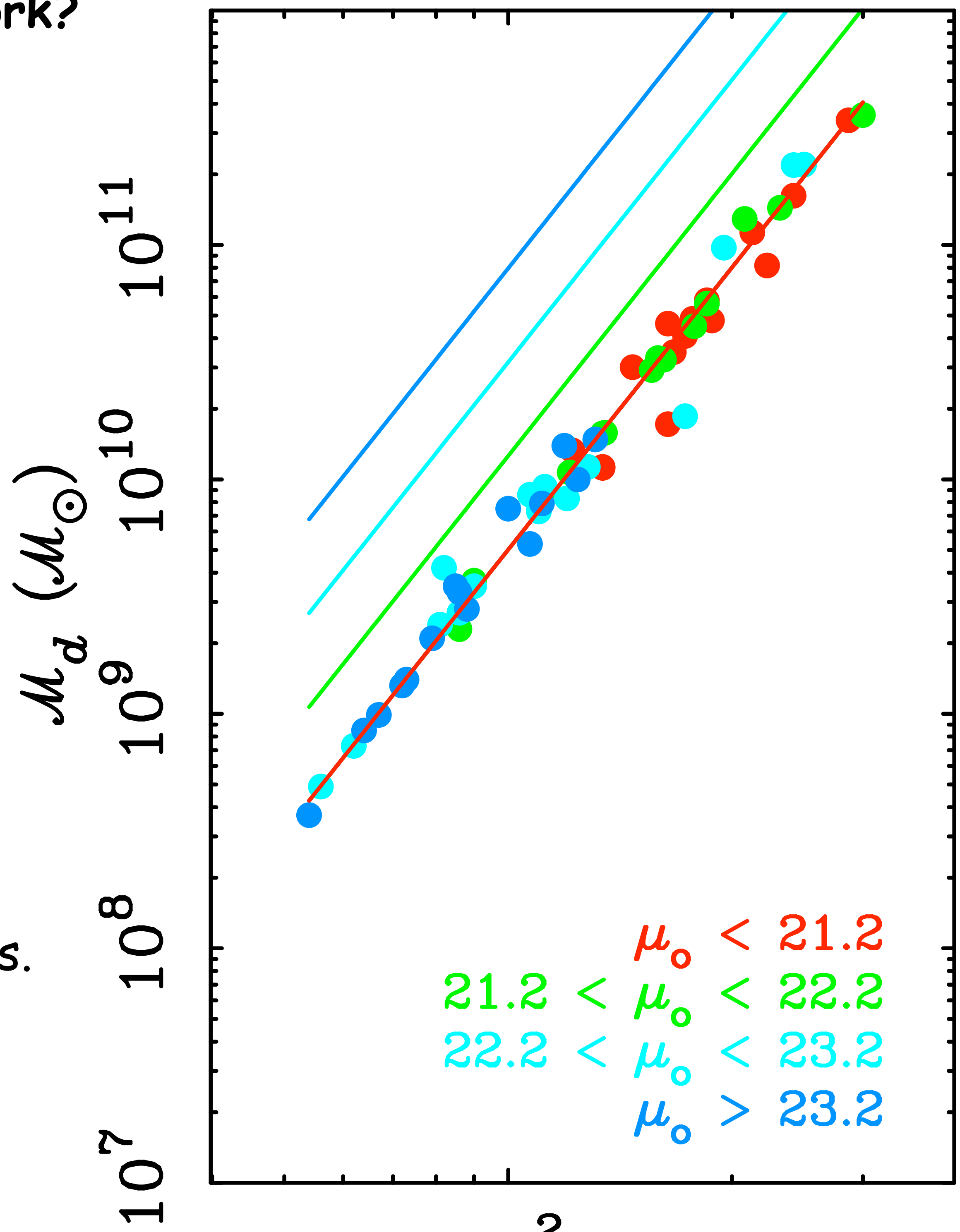
## But why does it work?

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

$$V^4 \sim M\Sigma$$

Aaronson et al (1979)

Galaxies of different surface brightness should fall on different, parallel TF relations.



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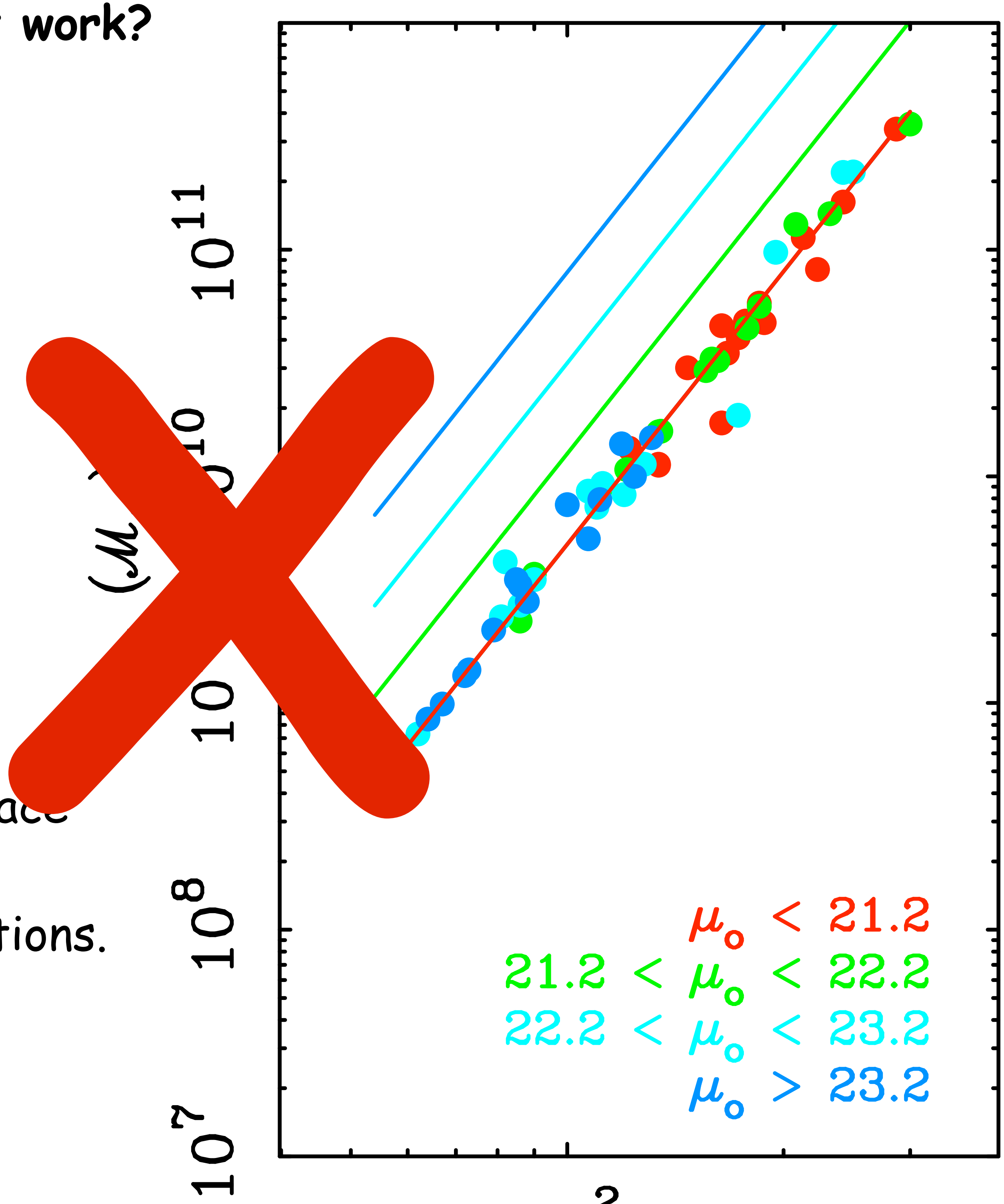
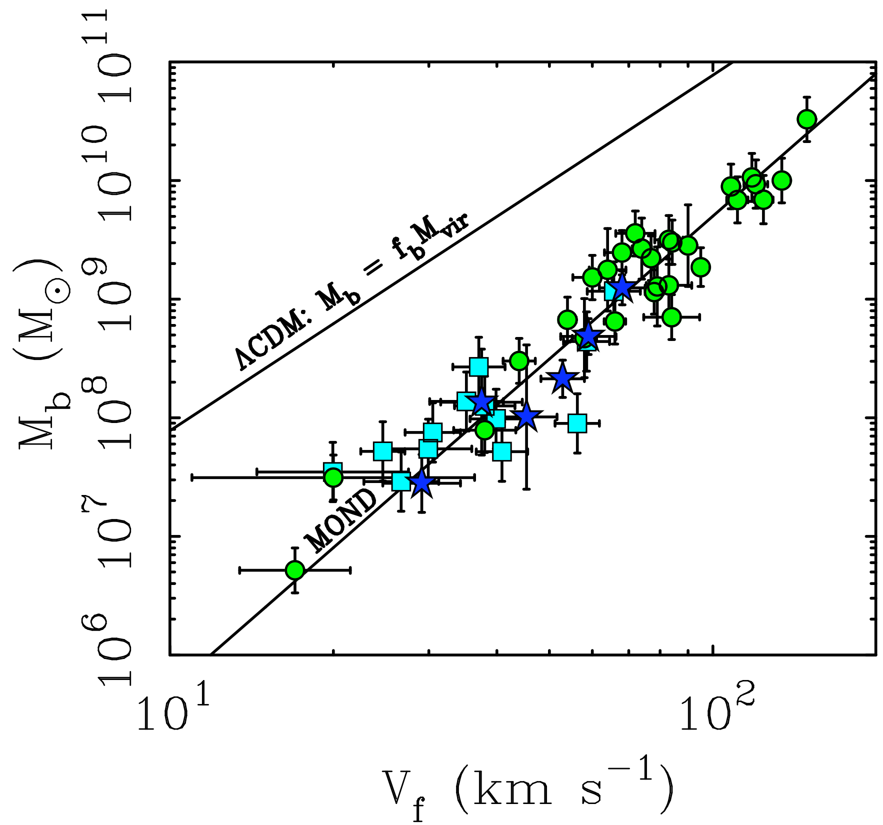


# But why does it work?

CDM halo mass-velocity relation

$$M_b \sim f_b M_{tot} \sim V^3$$

Wrong slope, wrong normalization.



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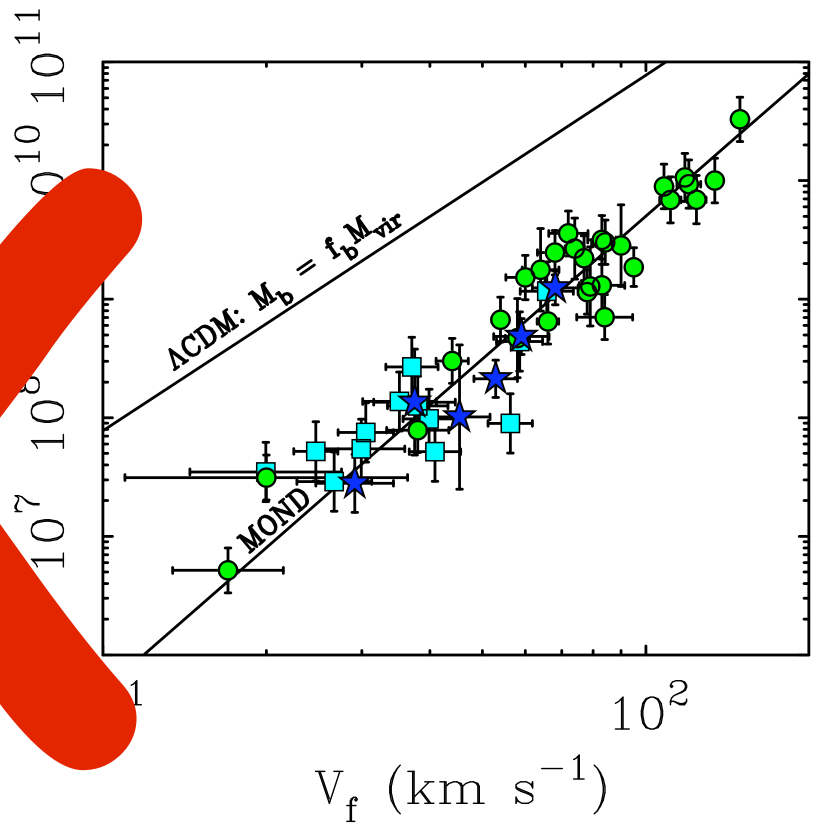


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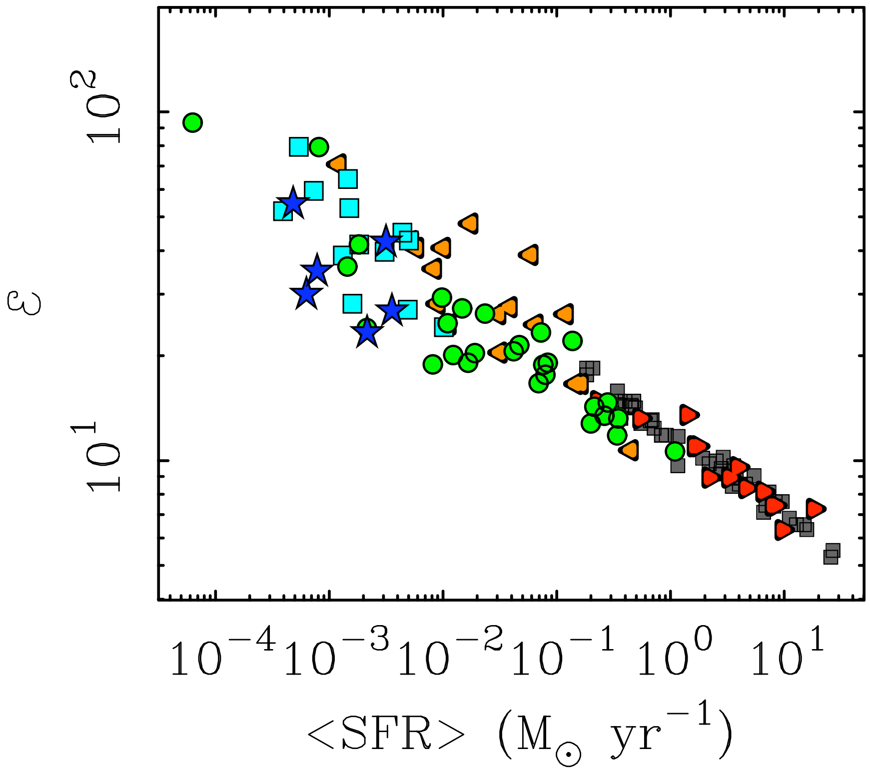
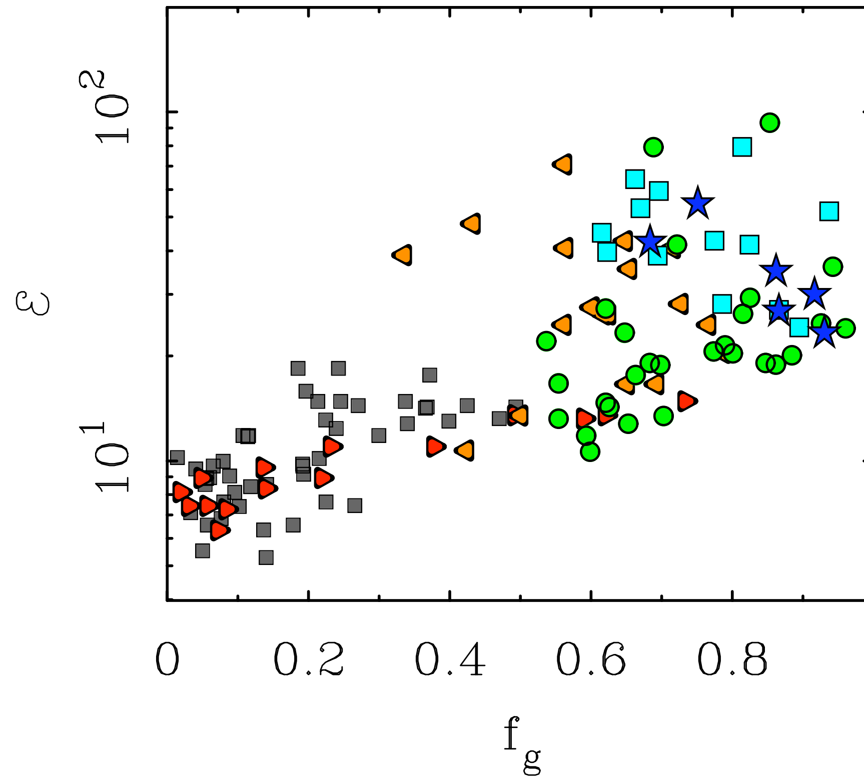
## But why does it work?

CDM+Feedback

$$M_b \sim f_d f_b M_{tot} \sim (f_v V)^3$$



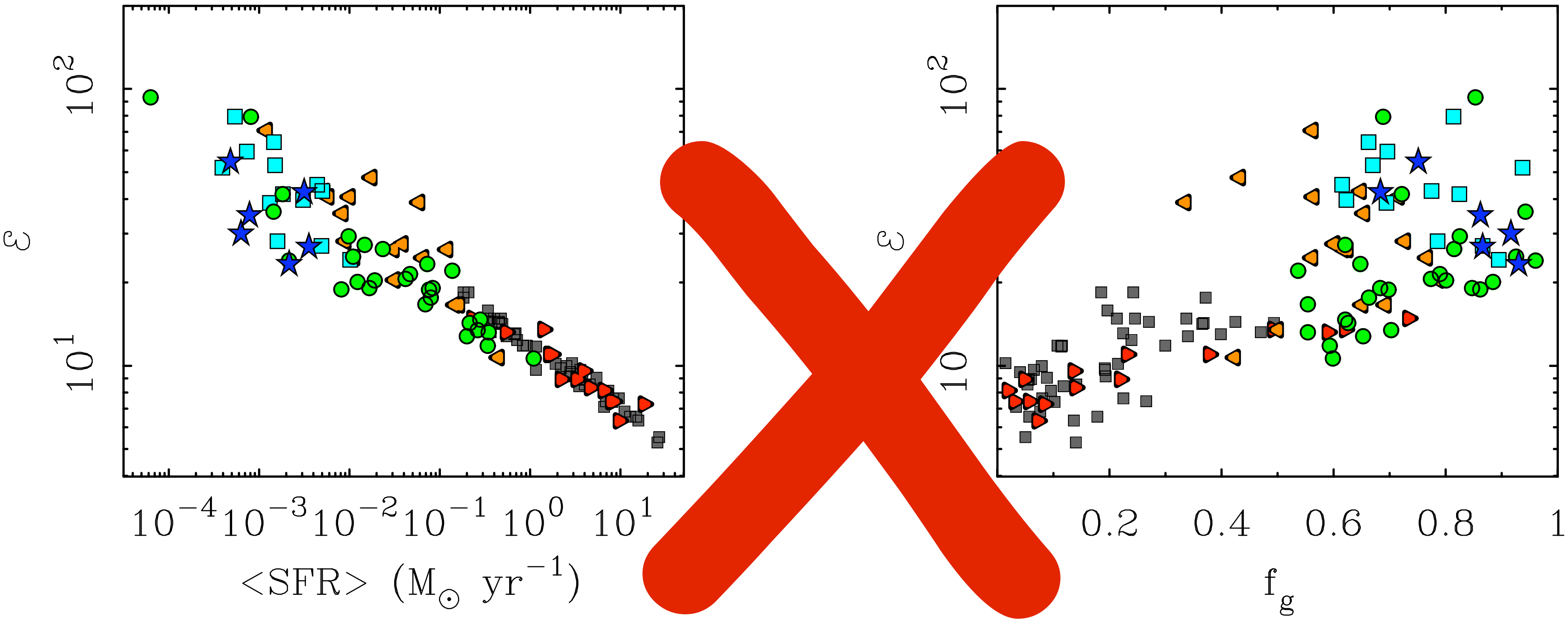

Can now fit anything. As long as the feedback from star formation is most effective in galaxies that have formed practically no stars.

$$\log \mathcal{E} = 1.2 - \log\left(\frac{V_f}{100\ \mathrm{km\,s^{-1}}}\right) - \frac{1}{2}\log\left(\frac{\Box}{100}\right)$$

## But why does it work?

CDM+Feedback

$$M_b \sim f_d f_b M_{tot} \sim (f_v V)^3$$

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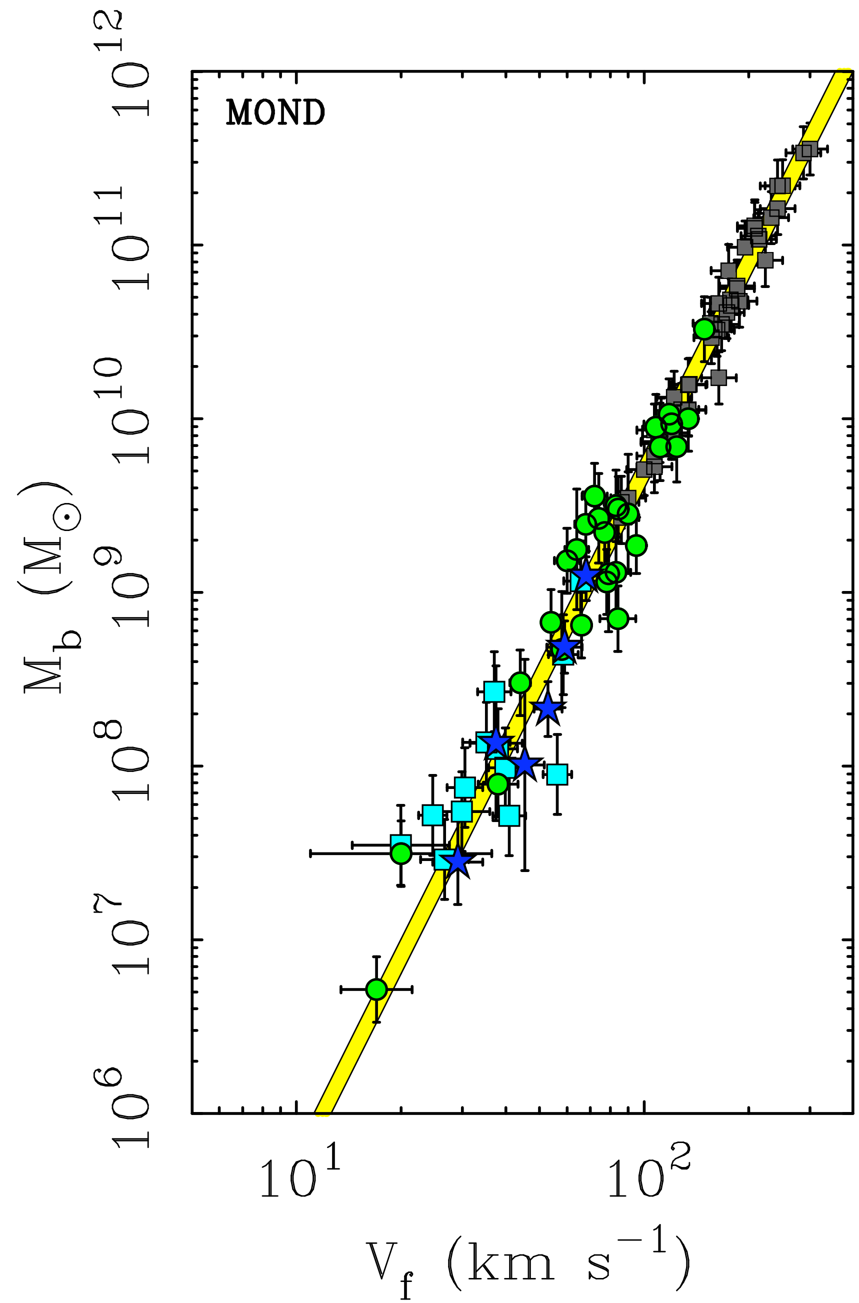
## But why does it work?

MOND

$$M_b = \frac{V^4}{a_0 G}$$

Imposed by force law.

Successfully predicted location of gas rich galaxies, but
We hate MOND.



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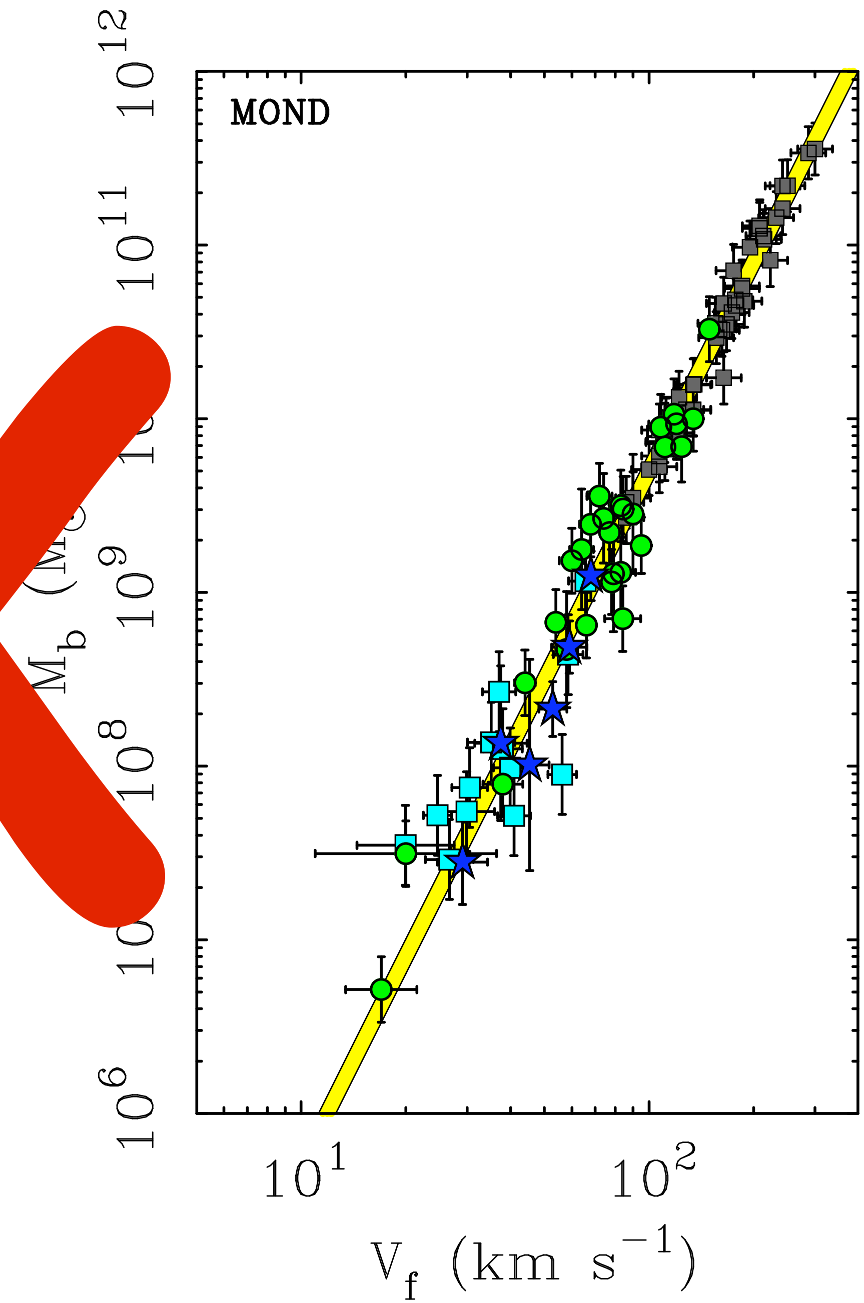


Imposed by force law.

Successfully predicted location of gas rich galaxies, but
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# Baryonic TF Relation

- Fundamentally a relation between the baryonic mass of a galaxy and its rotation velocity
- Intrinsic scatter negligibly small
- Physical basis of the relation remains unclear
- **Tantamount to Natural Law?**

TF is God!

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

# Application of Renzo's Rule to the Milky Way

- See poster