The Tully-Fisher Relation

Federico Lelli

KES Lecture

Outline

1. Brief Historical Introduction

The HI 21-cm line and the Tully-Fisher relation

2. Physics Behind the TF relation

General implications for dark matter in galaxies

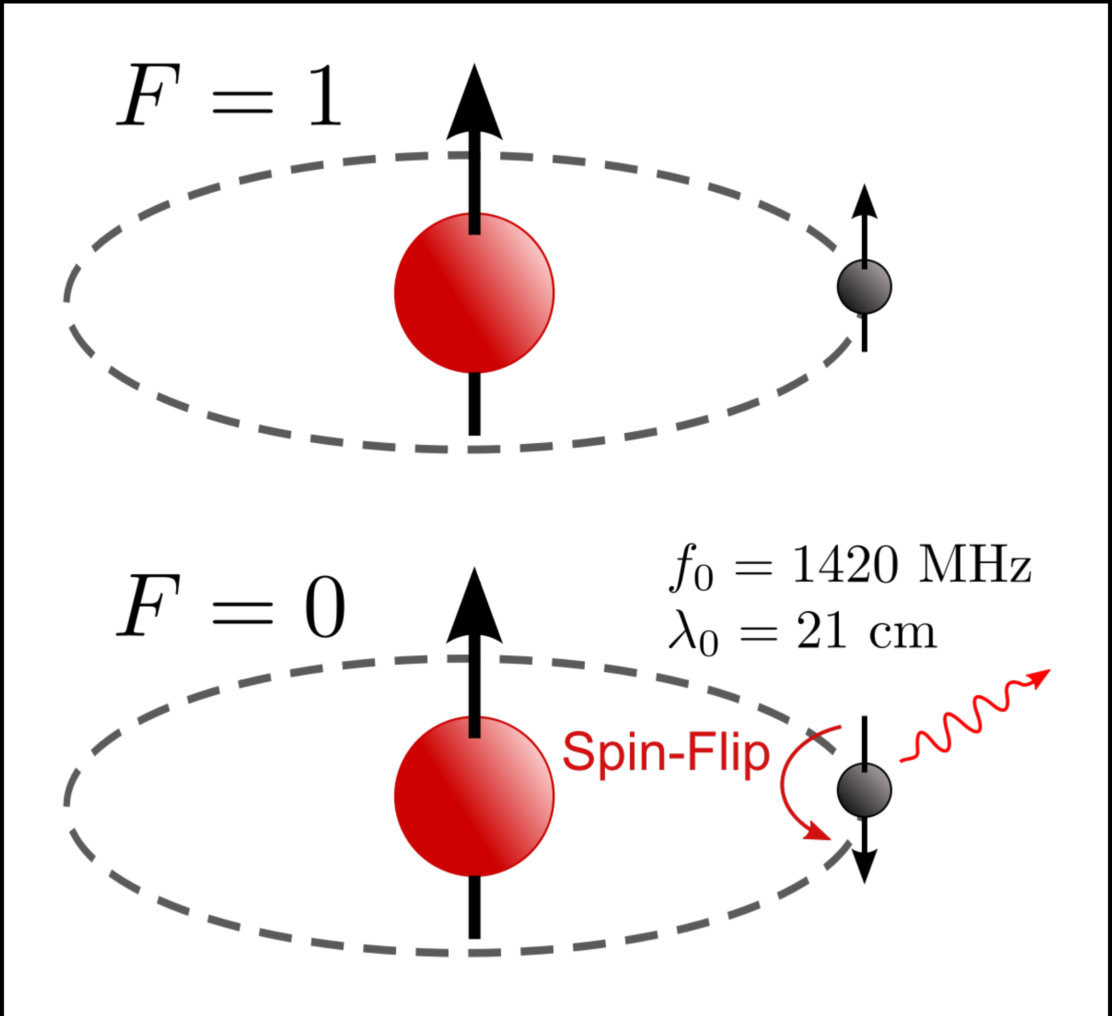
3. The TF relation in a LCDM context

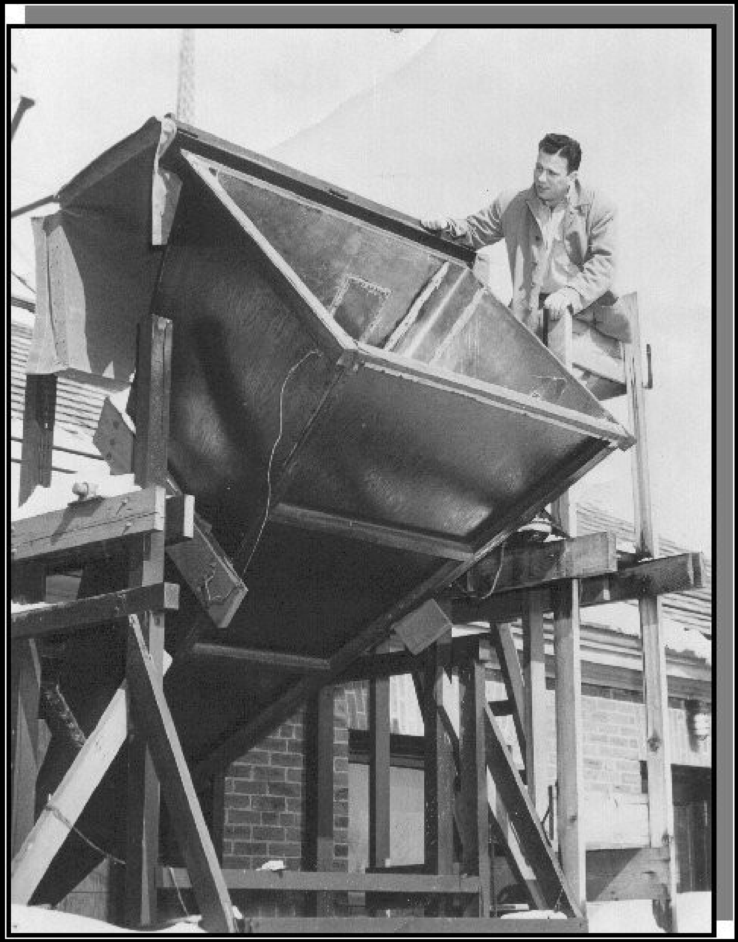
General implications on missing baryons & more

1. Introduction

The 21-cm line of Atomic Hydrogen

- Hyperfine structure of Atomic Hydrogen (HI)
- Predicted to be observable by Van de Hulst (1944)
- First detected by Ewen & Percell (1951)





Ewen installing his antenna out of a window at Lyman Lab in Harvard

HI obs with single-dish radio telescopes

Resolution = λ/D if λ=21cm, we need a big D!

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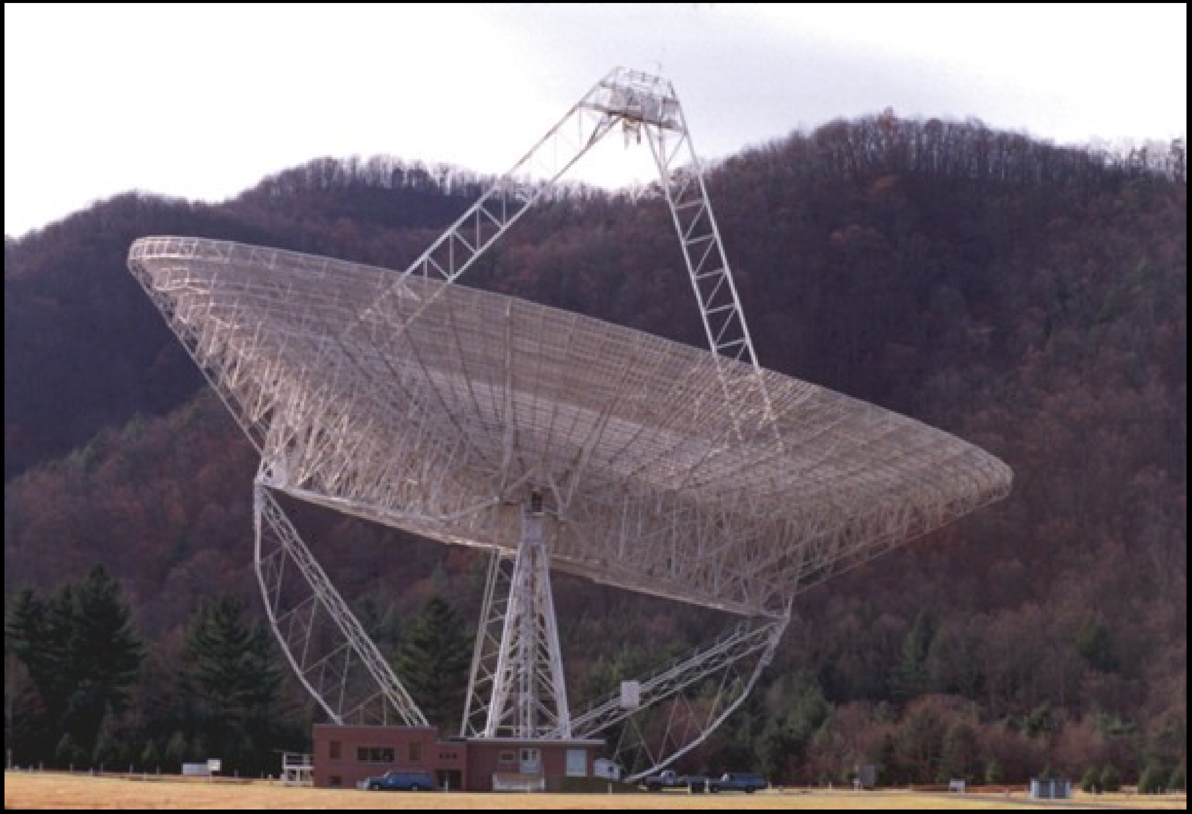
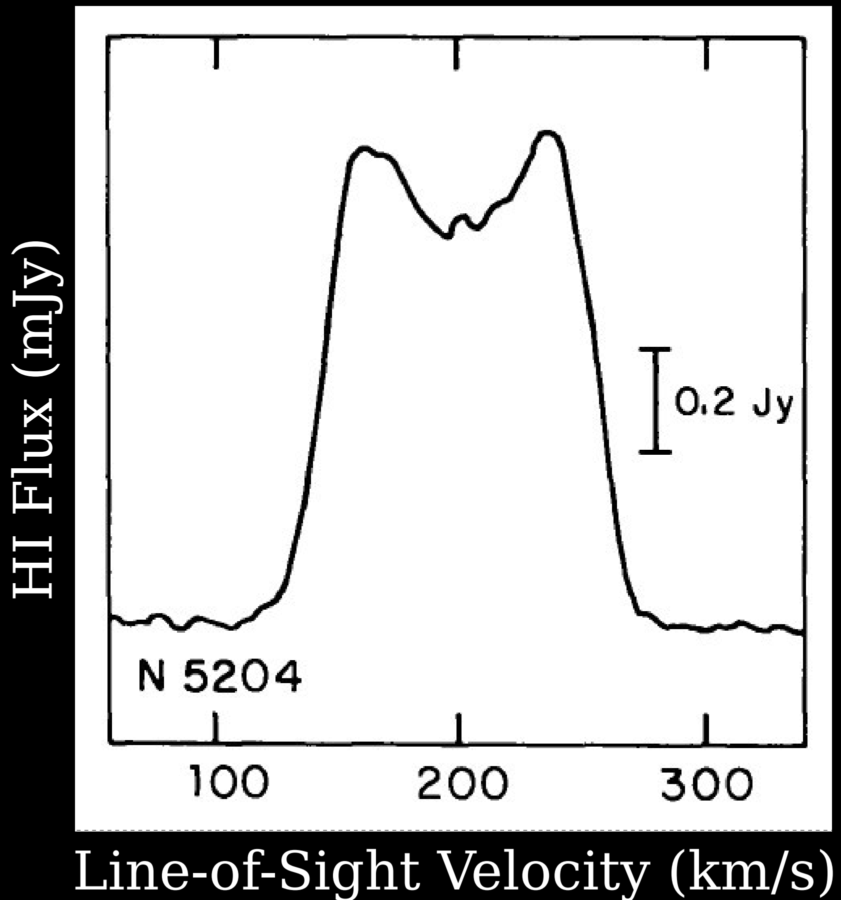
NRAO 91m and 43m telescopes, used by Fisher & Tully (1975)



D = 91 m → R~8'. Cannot resolve galaxies outside LG!

But the spectral resolution was good (down to ~5 km/s)

HI integrated spectra for galaxies



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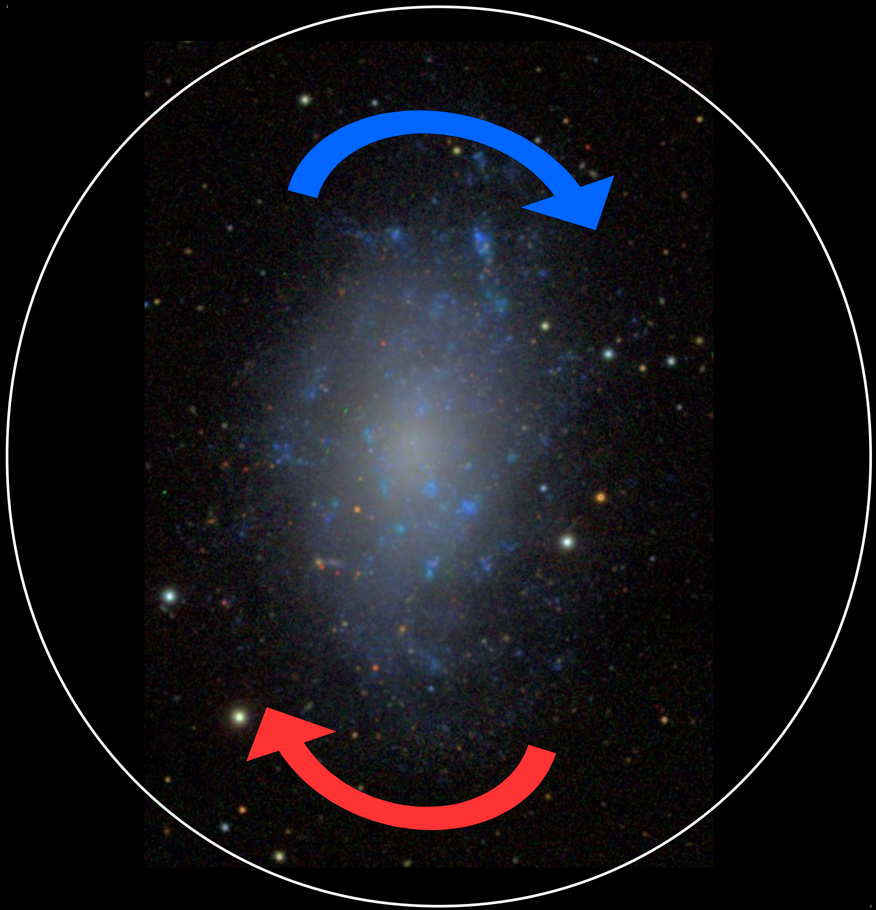
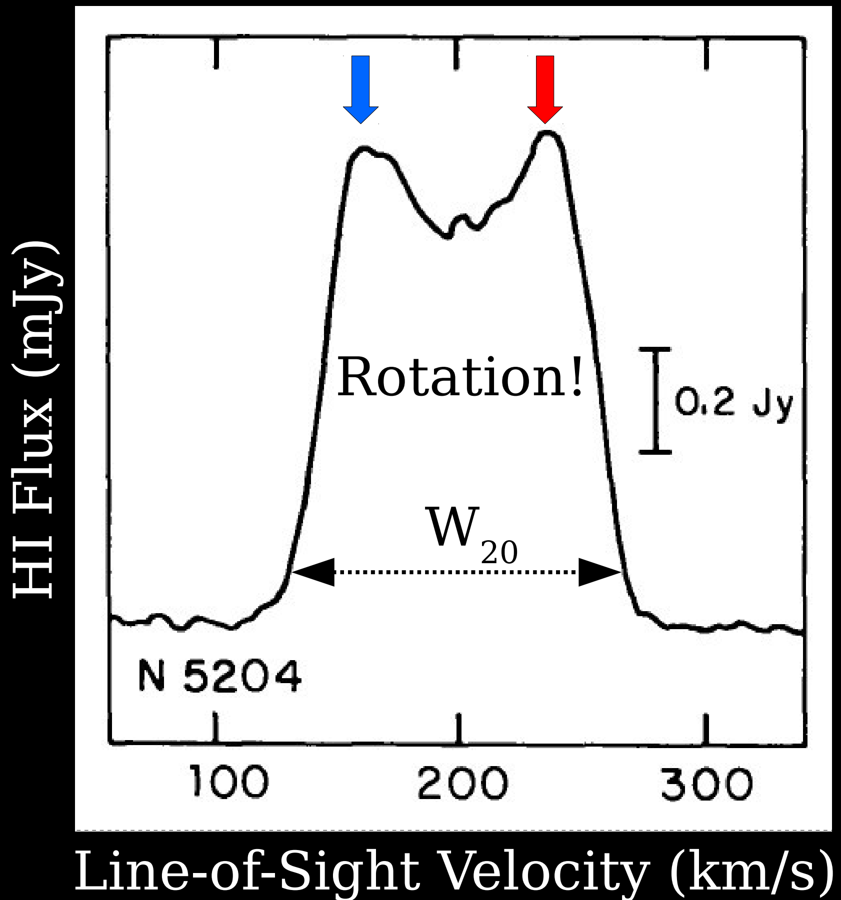
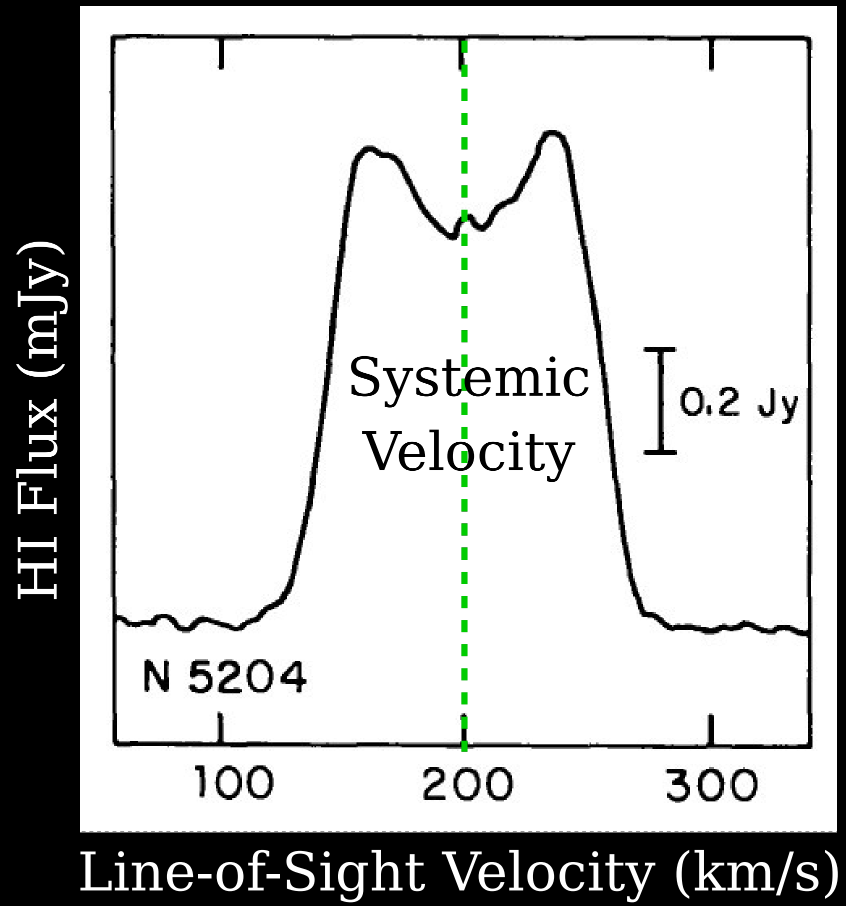




- HI Line-Width: W_{20} (20% of peak flux) ~2 rotation velocity

HI integrated spectra for galaxies



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- Systemic Velocity / Redshift: $z \sim V_{sys}/c$ for low V_{sys}

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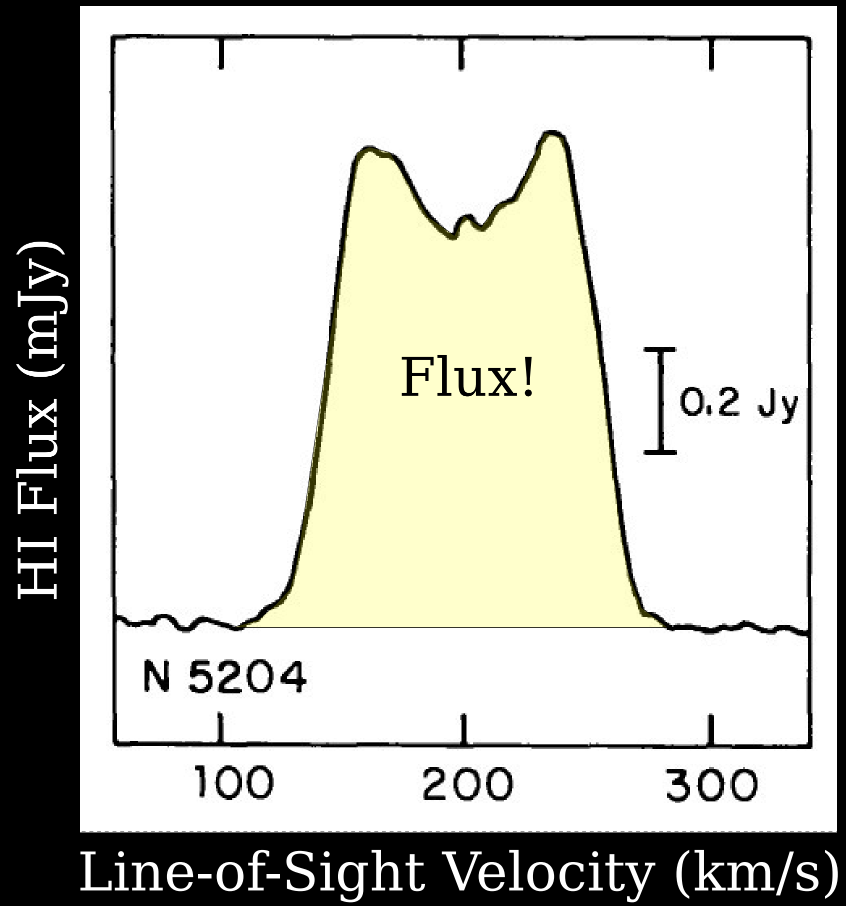

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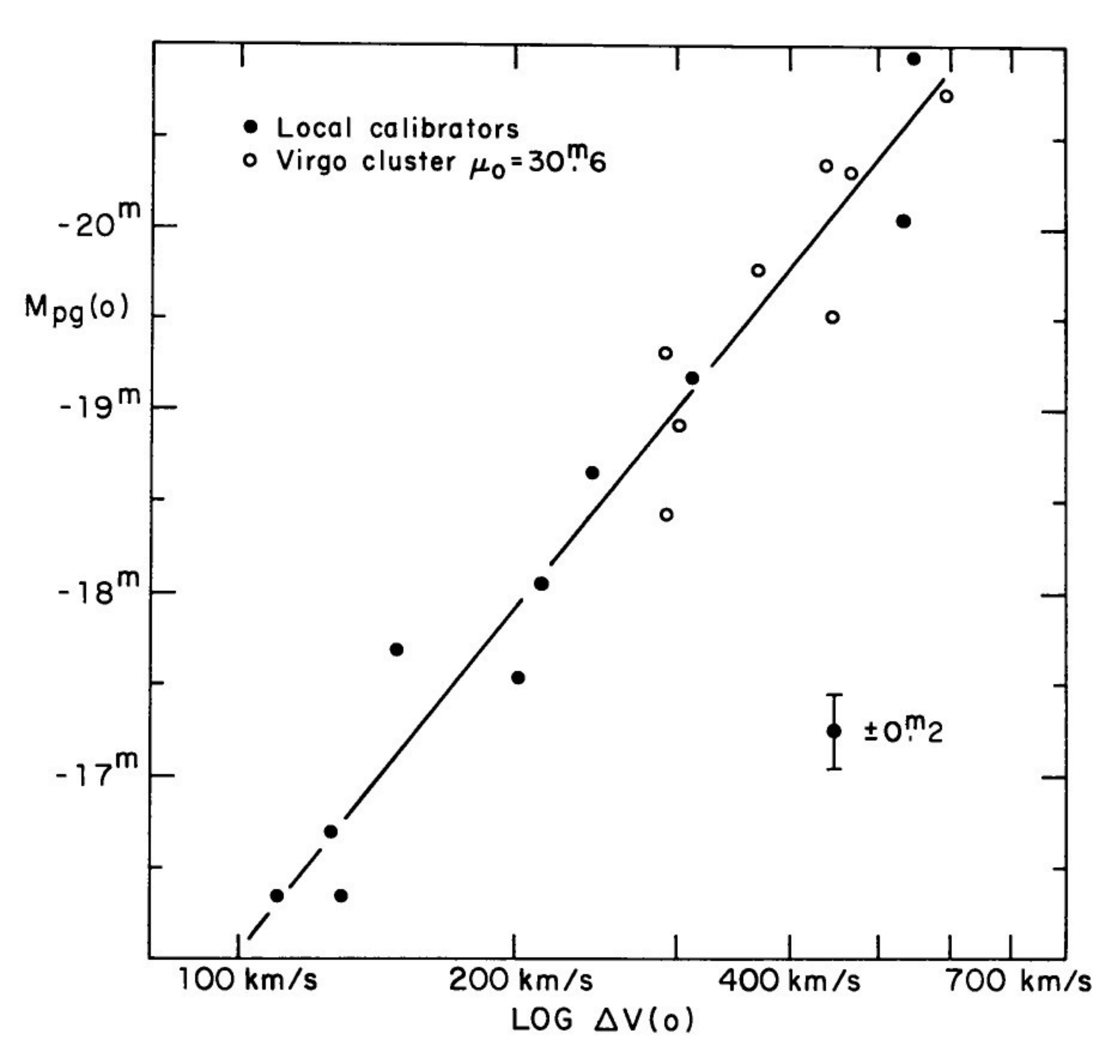
- Systemic Velocity / Redshift: $z \sim V_{sys}/c$ for low V_{sys}
- Total HI flux / HI mass: $M_{HI} = 236\ D^2\ [\mathrm{Mpc}]\ S_{HI}\ [\mathrm{mJy\ km/s}]$

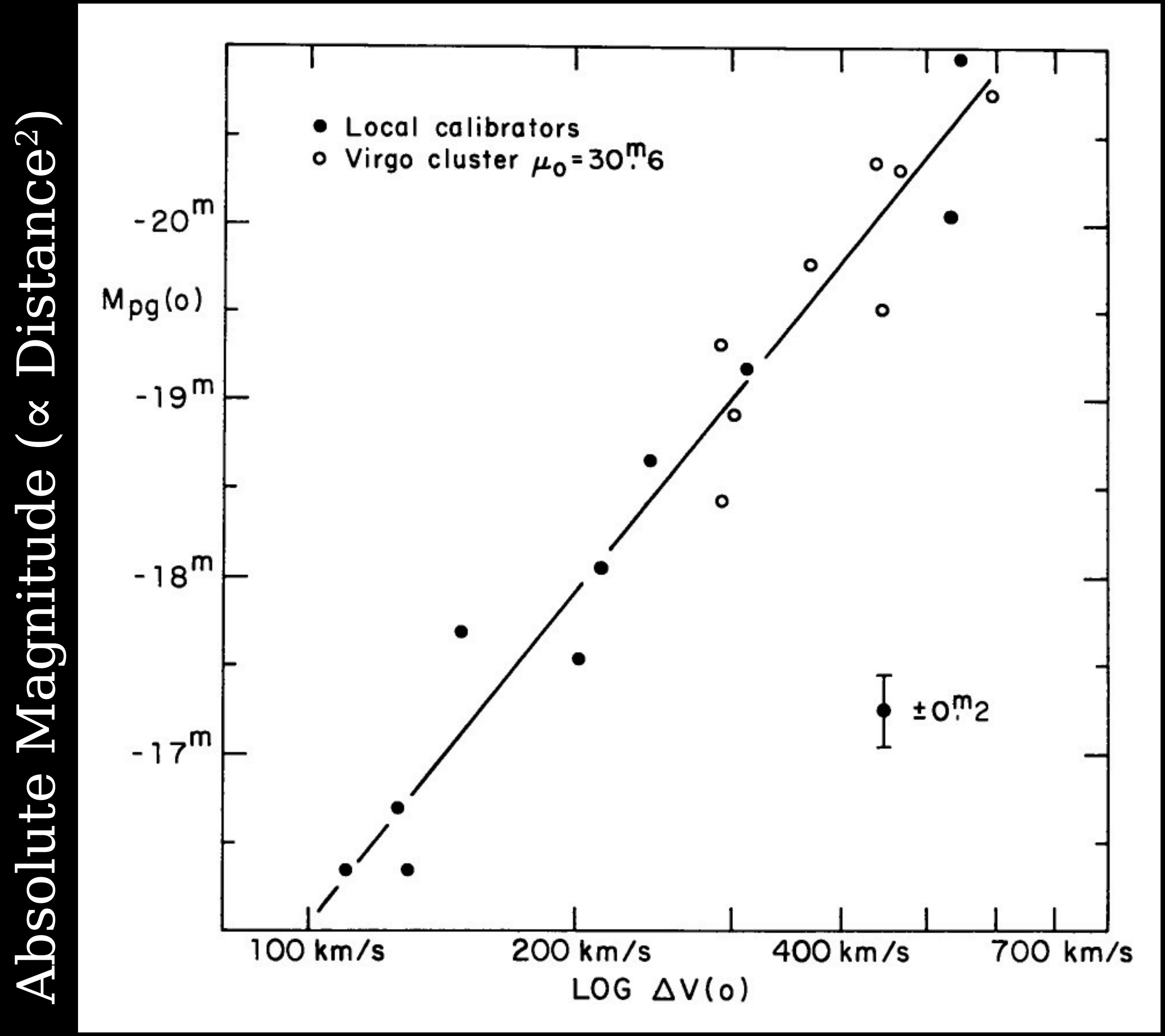
The Original Tully-Fisher Relation (1977)

Absolute Magnitude ($\propto$ Distance^2)



HI Line-Width (Distance Independent)

The Original Tully-Fisher Relation (1977)



HI Line-Width (Distance Independent)

STEP 1:
Calibrate TF relation using galaxies with known distance (from Cepheids, TRGB, etc.)

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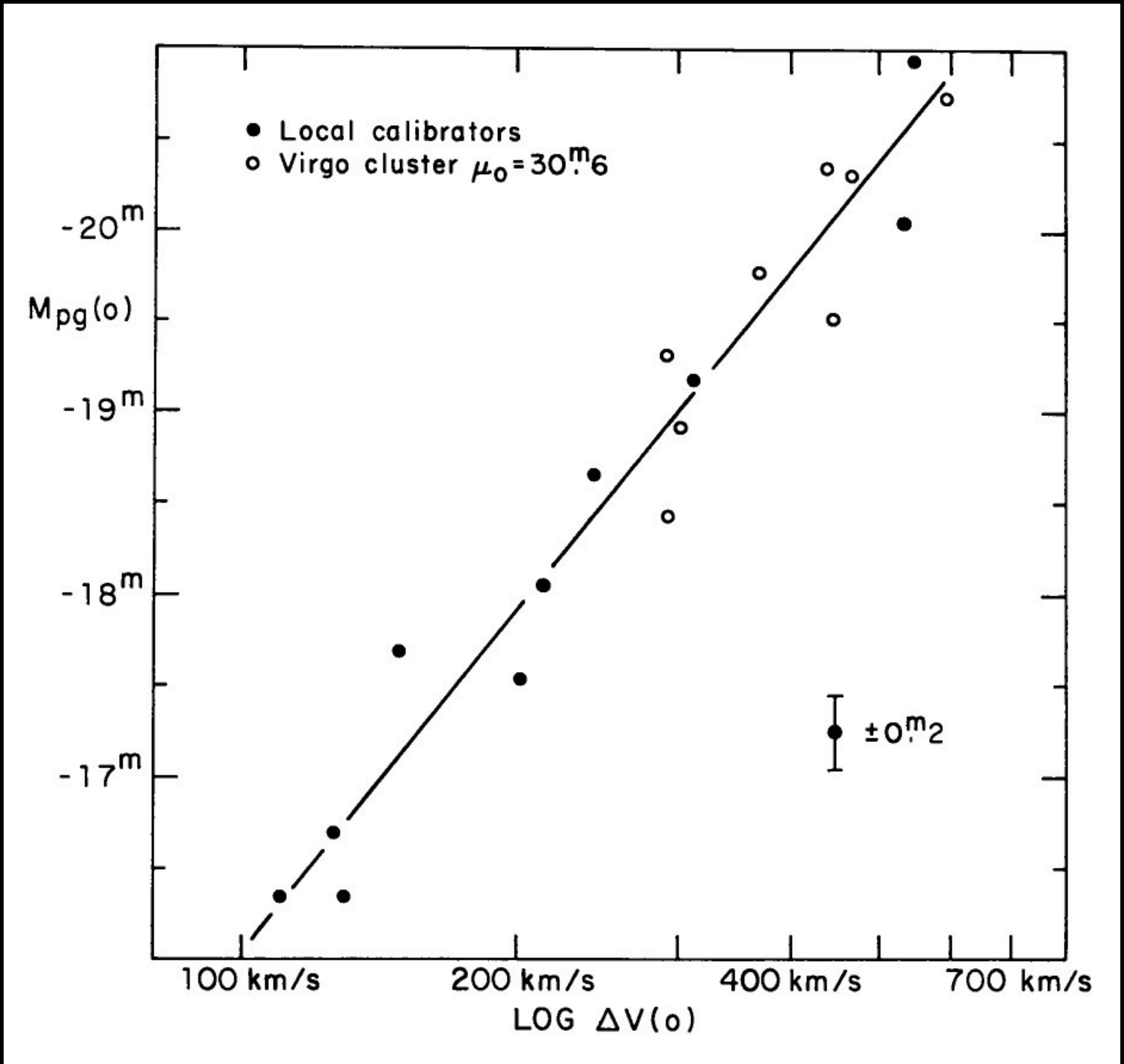

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Measure HI line-width (radio) & apparent mag (optical/IR) from large surveys

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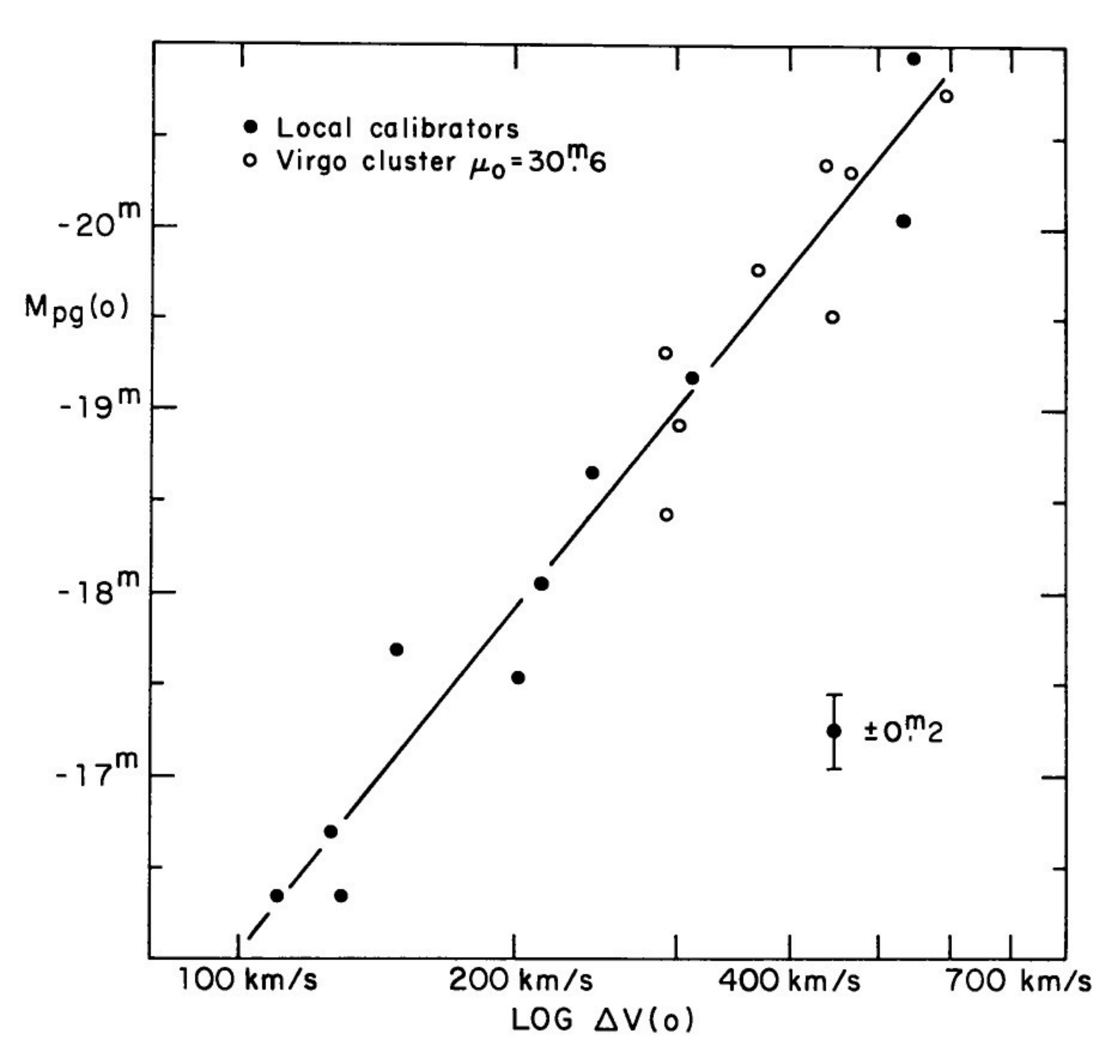

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STEP 1:
Calibrate TF relation using galaxies with known distance (from Cepheids, TRGB, etc.)

STEP 2:
Measure HI line-width (radio) & apparent mag (optical/IR) from large surveys

STEP 3:
Infer distances (< 300 Mpc) for large galaxy samples (~18000 objs in Tully+2016)

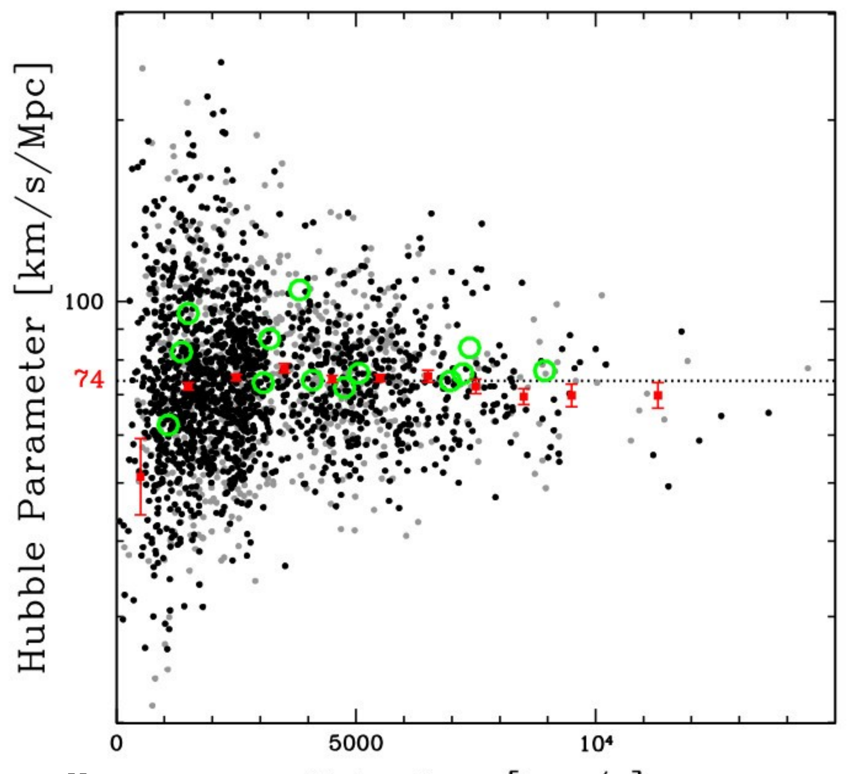
Classic Applications of the TF relation

1-Measure Hubble constant

$V_{sys} \sim H_0 D + V_{pec}$ at low z

H_0 = 80 km/s/Mpc (Tully & Fisher 1977)

H_0 = 75 +/- 2 km/s/Mpc (Tully+2016)



Tully+2016

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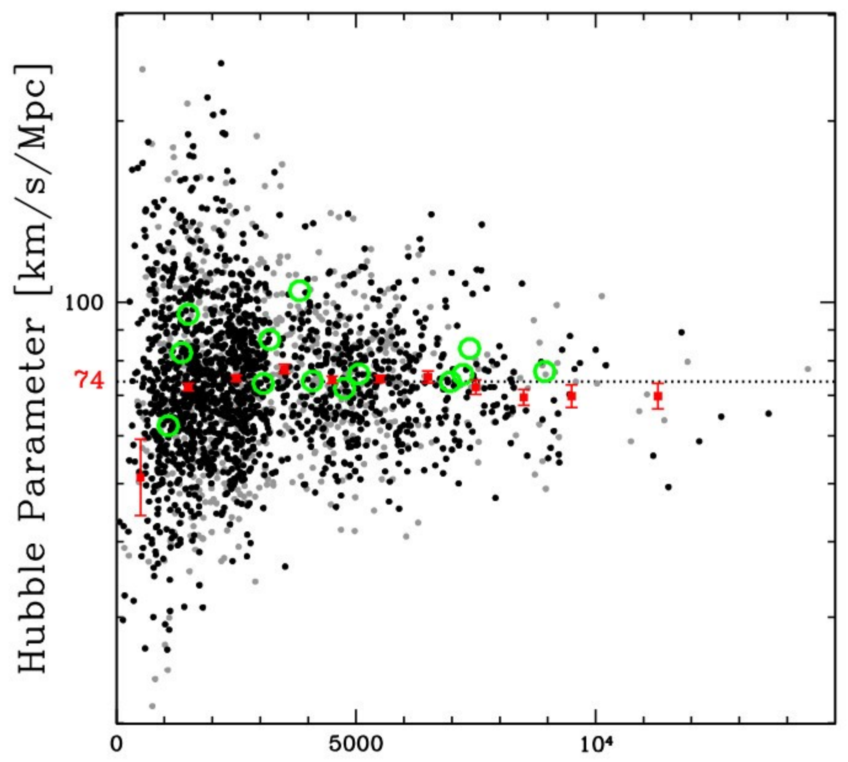
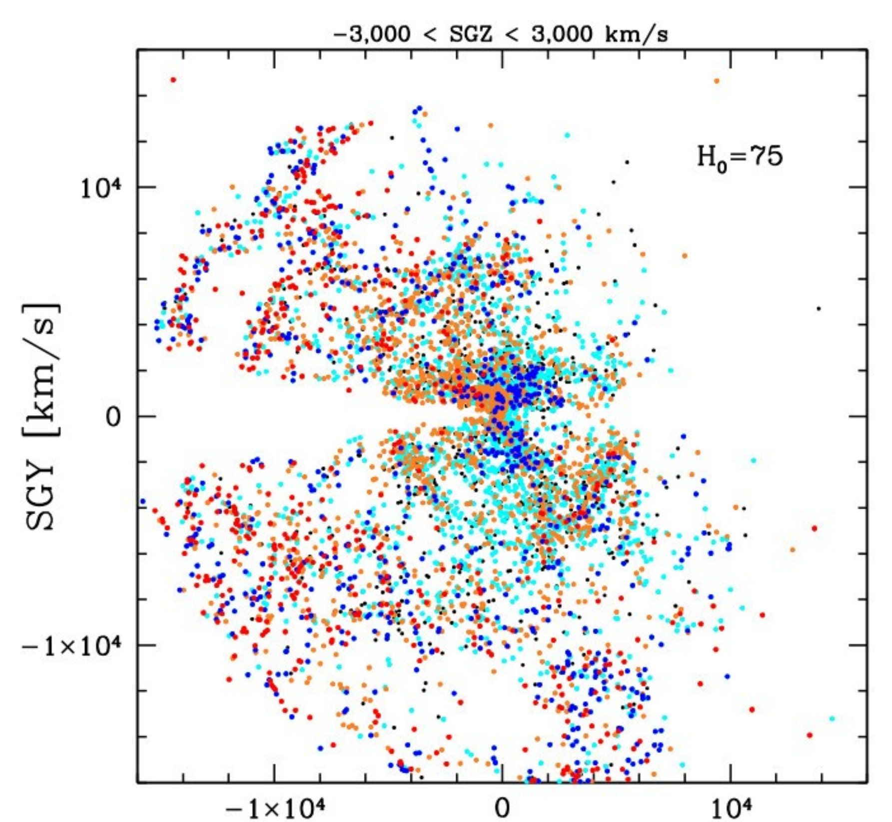


Tully+2016

2-Study Galaxy Flows

$V_{pec} = (V_{mod} - H_0 D) / (1 + H_0 D/c)$

$V_{mod} = f(z, D, \Omega_m, \Omega_\Lambda)$

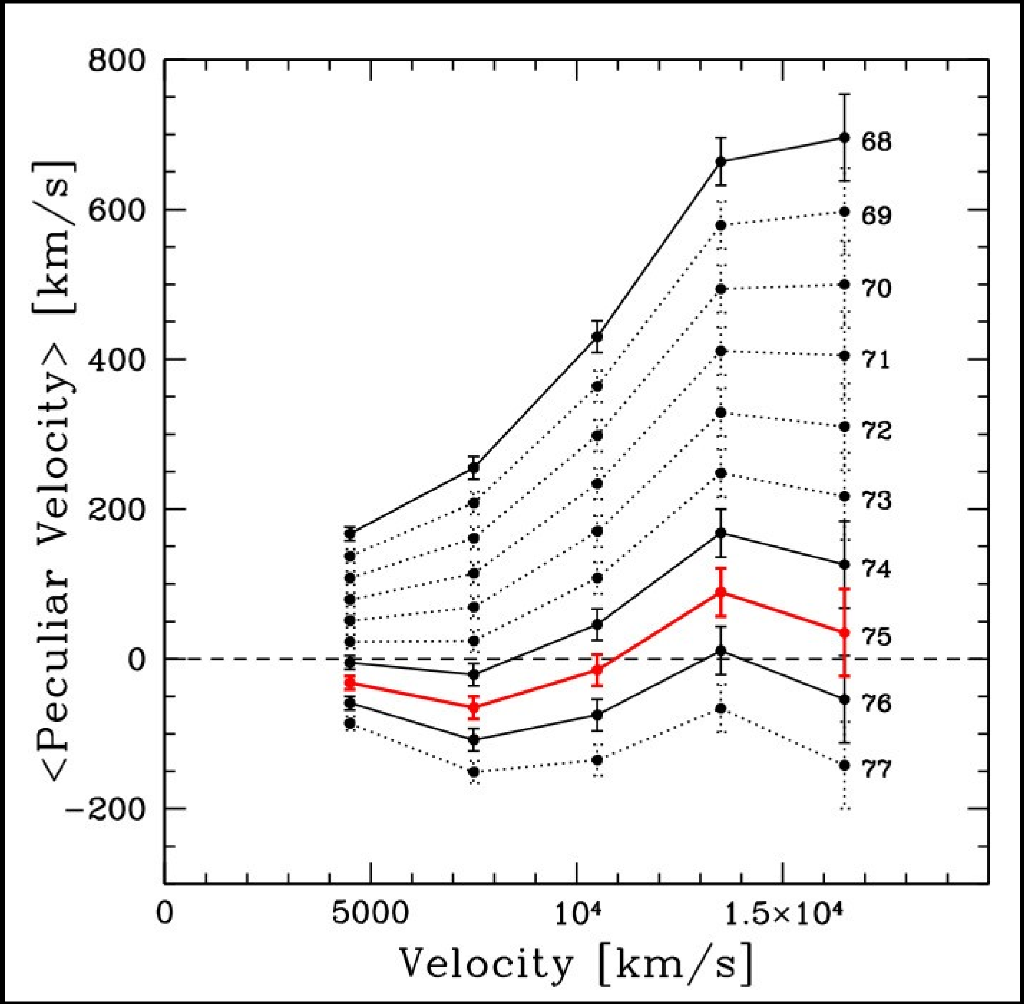


Tully+2016

Peculiar Velocities & The Hubble Constant

$V_{pec} = (V_{mod} - H_0 D) / (1 + H_0 D/c)$ $V_{mod} = f(z, D, \Omega_m, \Omega_\Lambda)$

Fix Ω_m and Ω_Λ (or equivalently q_0), vary H_0 and get different V_{pec}



Tully+2016

H_0 = 75 +/- 2

2. Physics Behind
the Tully-Fisher relation

L_λ and W_{HI} are proxies for more fundamental quantities!

Goal: find the quantities that give the tighter relation

Luminosity ~ Stellar Mass

The TF relation is tigher in the NIR than in the optical
(e.g. Aaronson+1979, Verheijen 2001, Ponomareva+2017)

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$\Upsilon_* = M_*/L$ shows small galaxy-to-galaxy variations in the NIR
(less sensitive to star-formation history, dust extinction, etc.)

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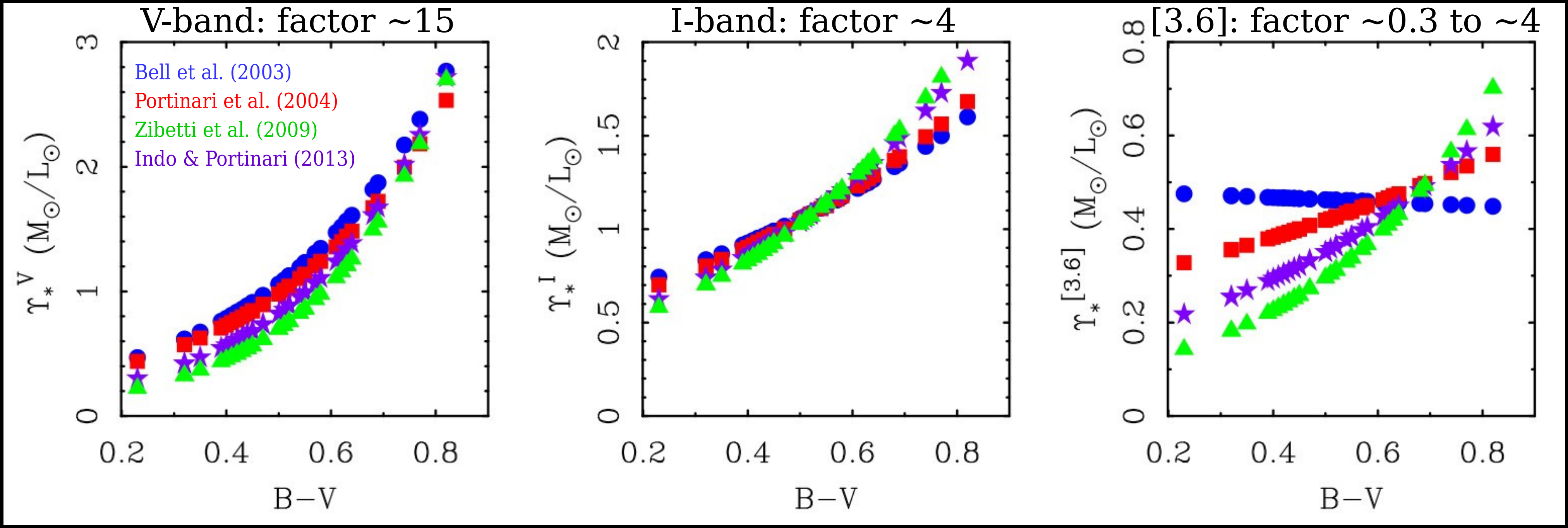
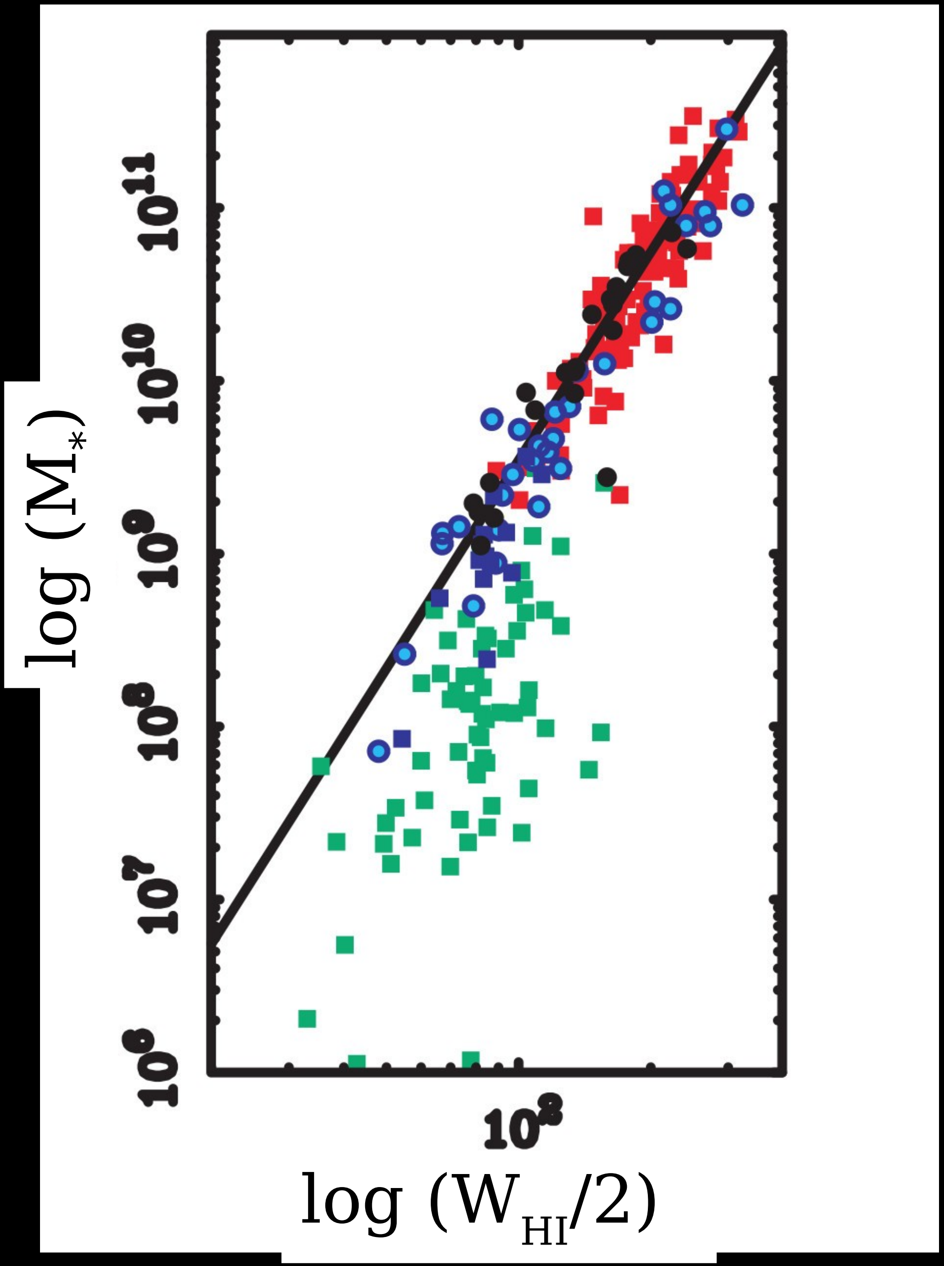


Predicted Υ_* -Color Relations from stellar population synthesis models

$\Upsilon_*^{[3.6]} \sim 0.5\ M_\odot/L_\odot$ with ~30% scatter (e.g., Meidt+2014; Norris+2016; Schombert+2019)

Stellar Mass is not enough!

Stellar-Mass TF Relation



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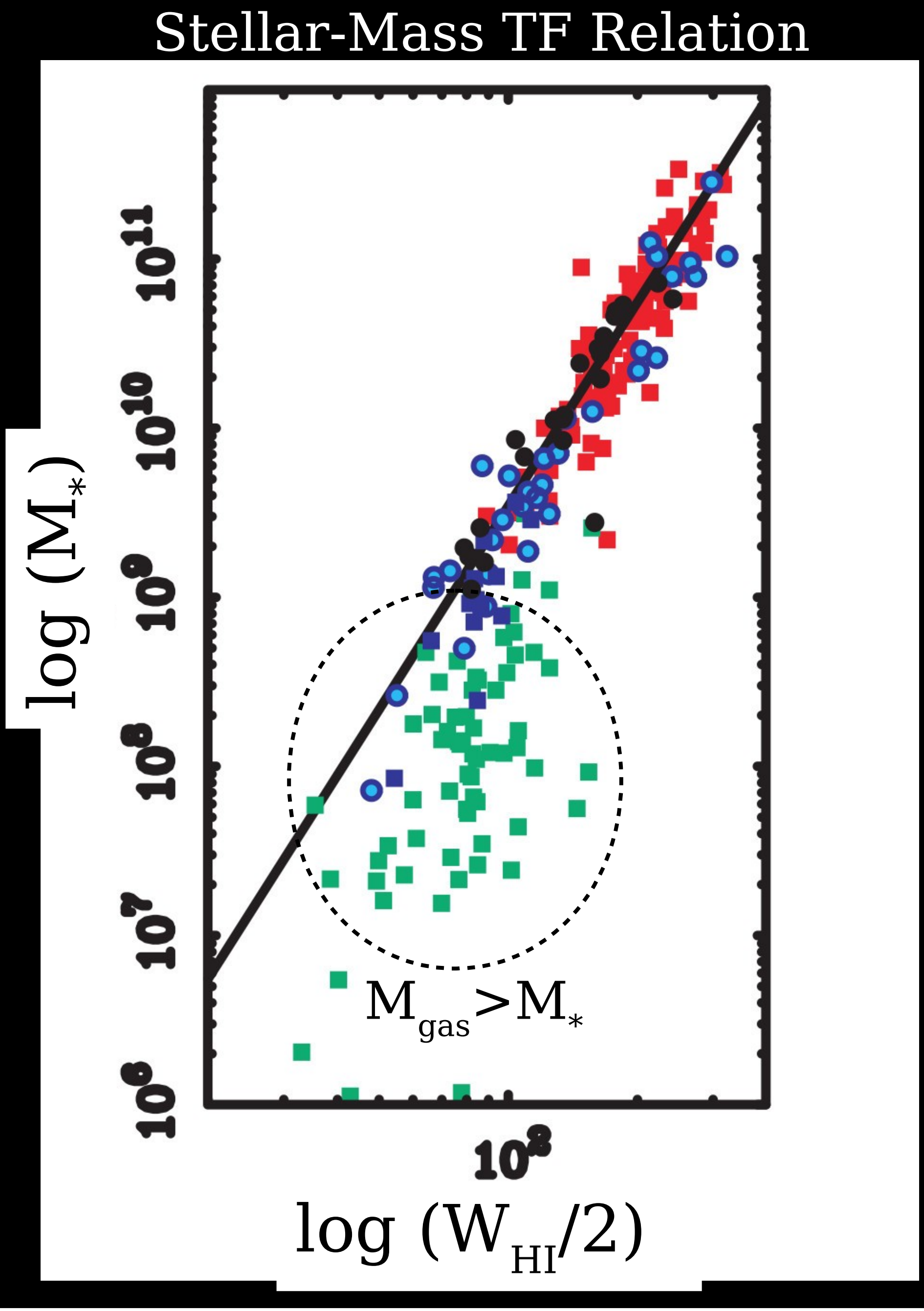
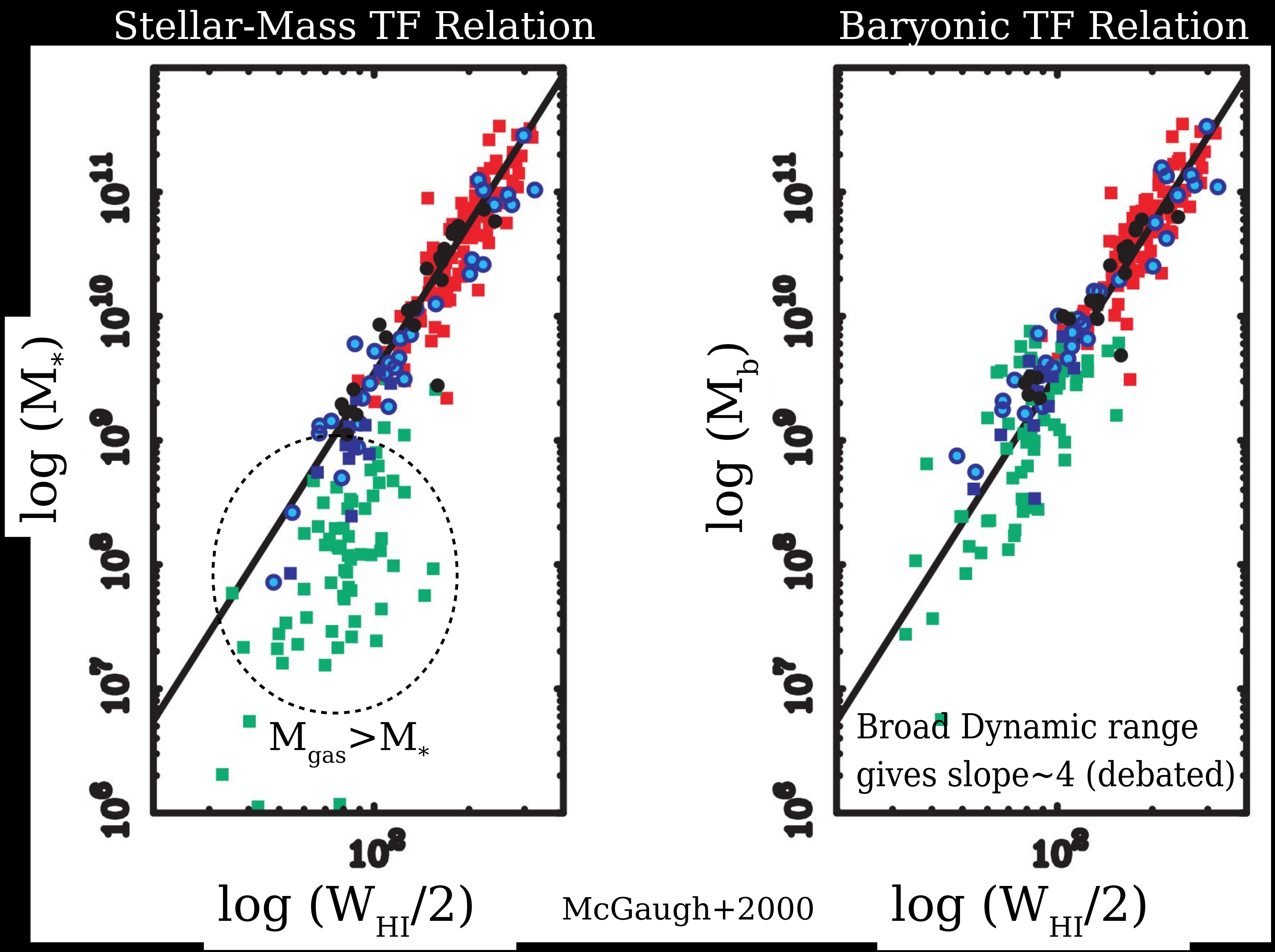
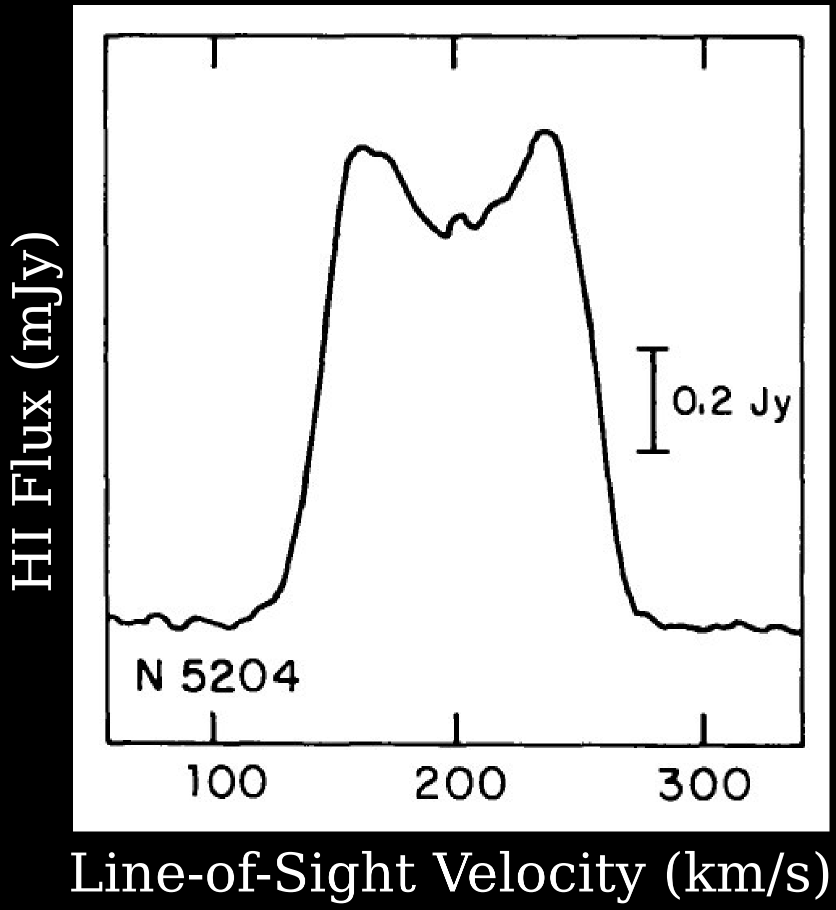


Baryonic Mass (stars+gas) is the key!



What's the HI line-width really measuring?



The HI line profile depends on $\Sigma_{HI}(R)$, $V_{rot}(R)$, inclination!

Need to spatially resolve HI distribution and kinematics!

HI obs with radio interferometers

R~λ/B with B=max distance between two antennas

HI obs with radio interferometers

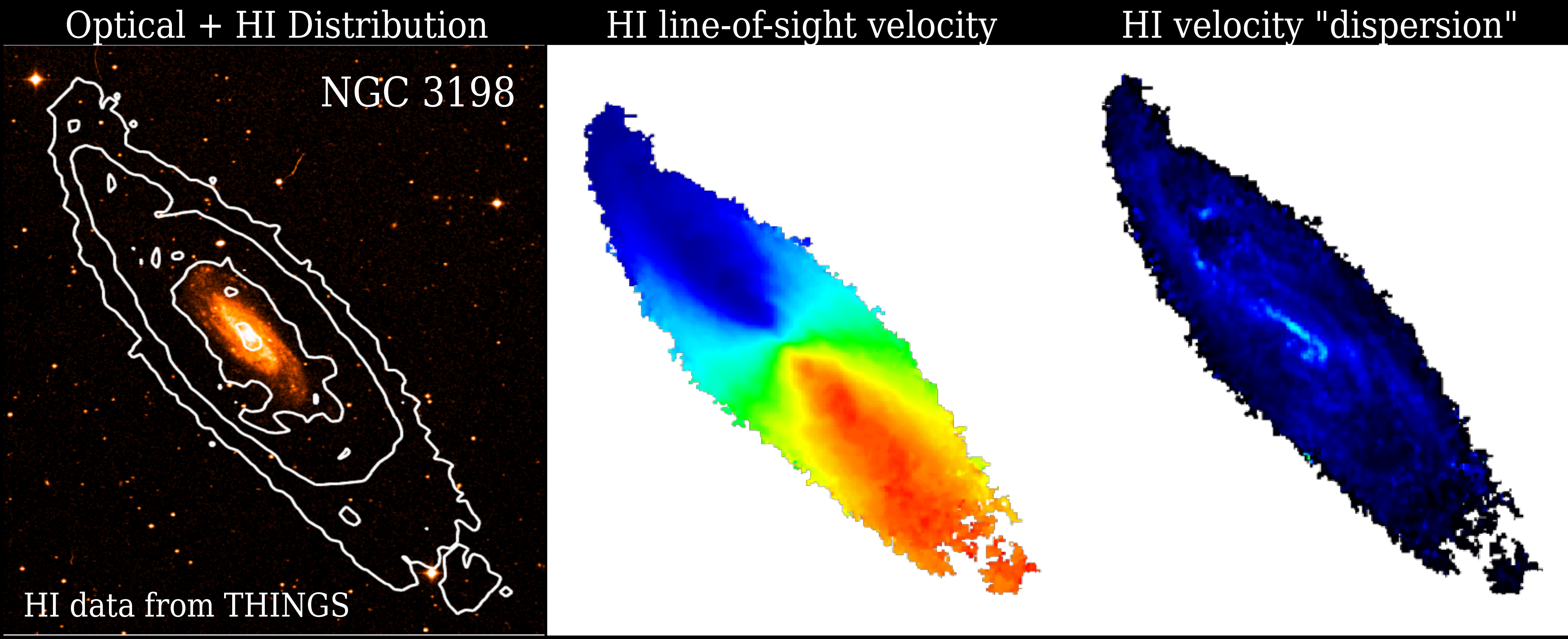
R~λ/B with B=max distance between two antennas

WSRT (Netherlands)
HI resolution up to ~15”
Typical surveys done at ~30”

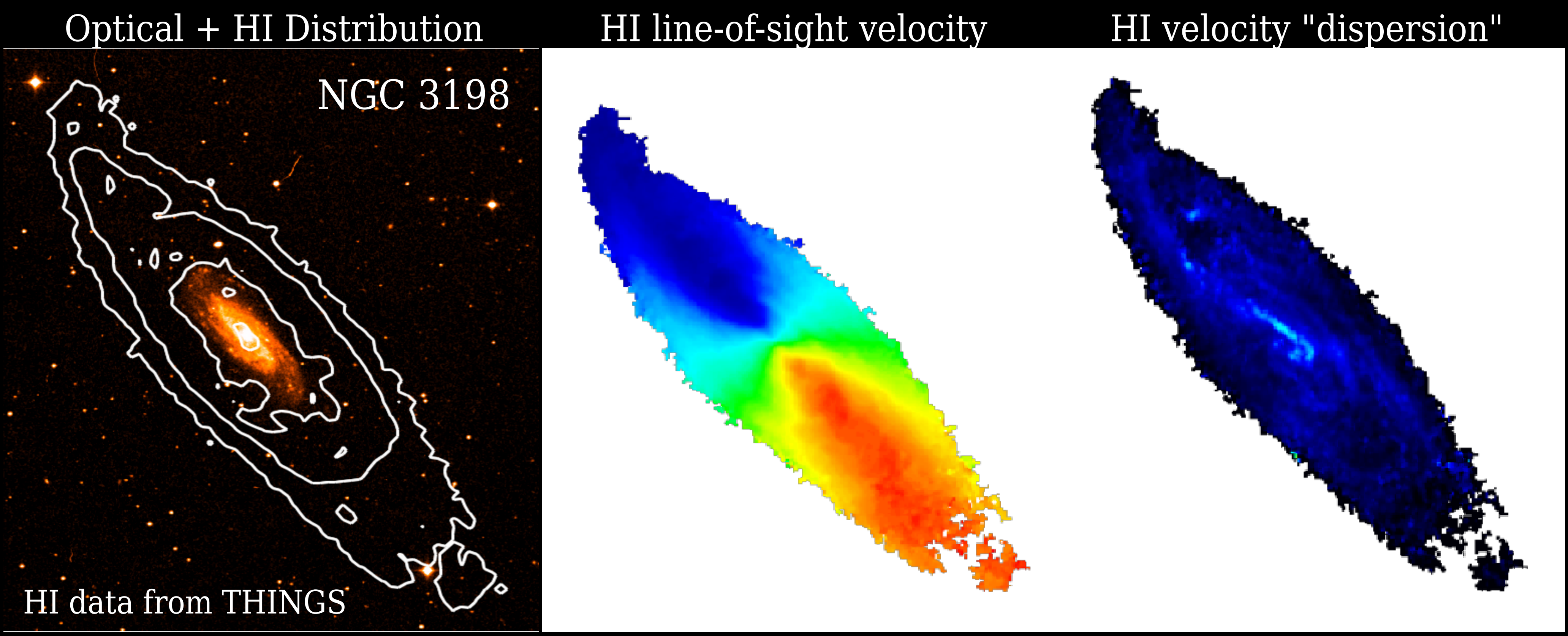
VLA (New Mexico)
HI resolution up to ~2”
Typical surveys done at 5”-10”

But HI interferometry is time costly! HI samples drop from ~18000 objects with single-dish observations (Tully+2016) to ~200 with interferometry (Lelli+2016).

HI distribution and kinematics



HI distribution and kinematics

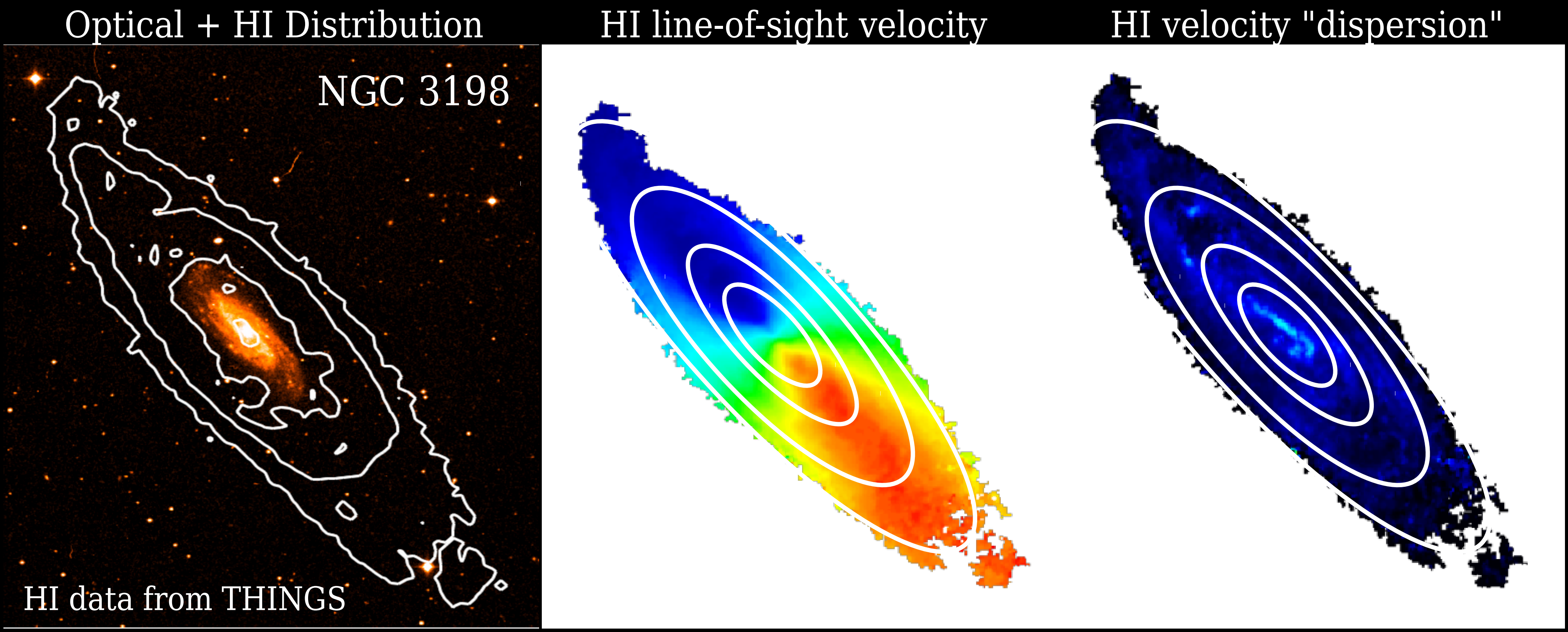


Key Points:

- HI distribution is more extended than stellar one (typically by a factor of 2)
- HI kinematics is generally consistent with rotation (non-circular motions small)
- HI velocity dispersion is ~8-10 km/s → negligible pressure support (unlike stars)

$$V_{rot} \sim V_{circ} = \mathrm{sqrt}(R\, d\phi/dR)$$

HI distribution and kinematics



How to derive a rotation curve:

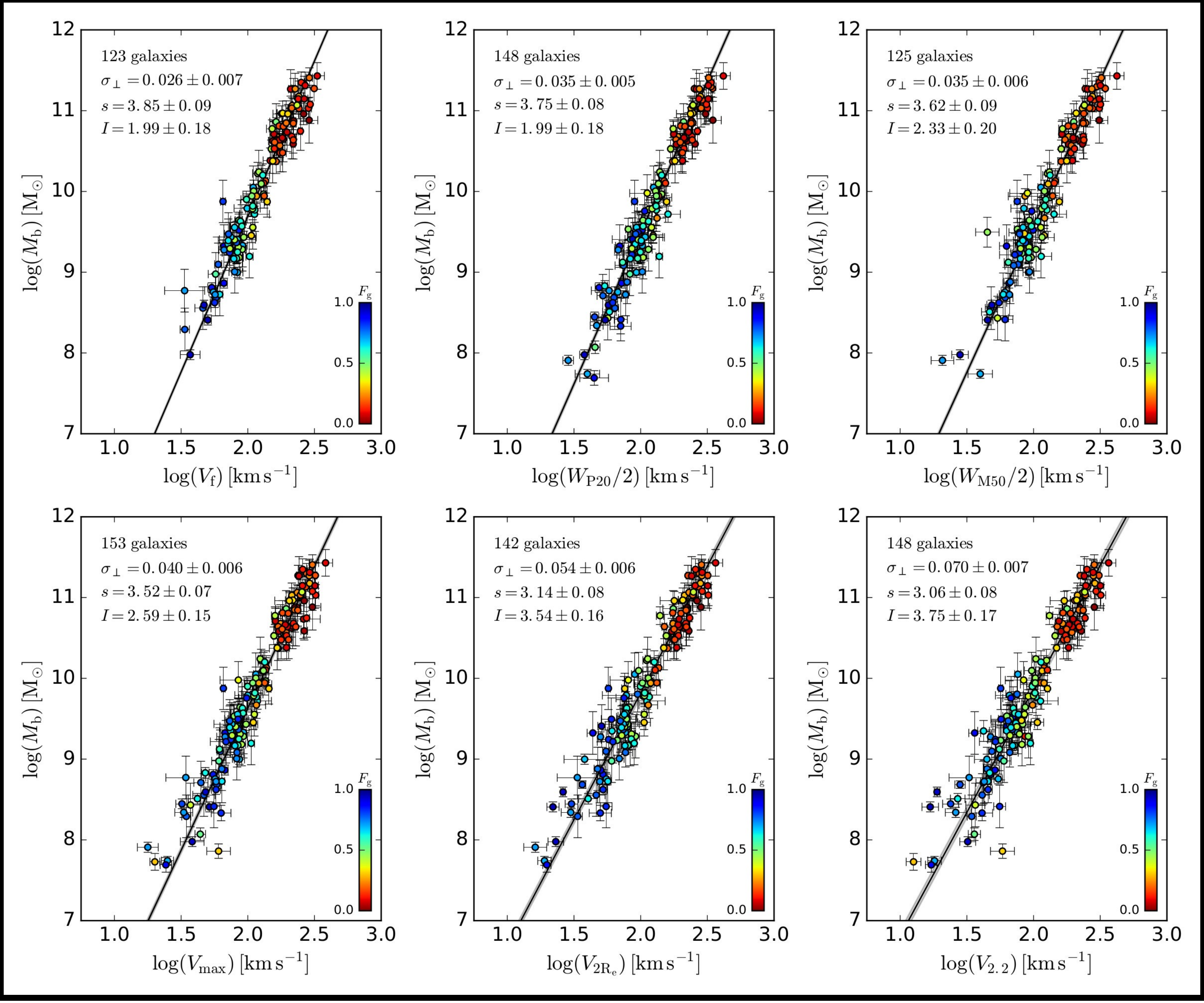
- Divide galaxy into a set of concentric rings
- Deprojection from sky plane to galaxy plane

$V_{l.o.s.} = V_{sys} + V_{rot} \sin(i) \cos(\theta)$

$\cos(\theta) = \text{fnc}(\text{center, position angle})$

i = disk inclination angle
θ = azimuthal angle
V_{sys} = systemic velocity

BTFR for different velocity definitions



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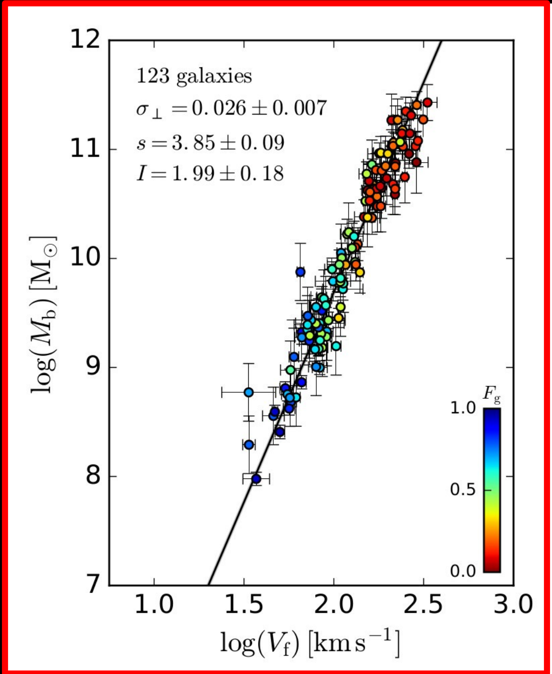
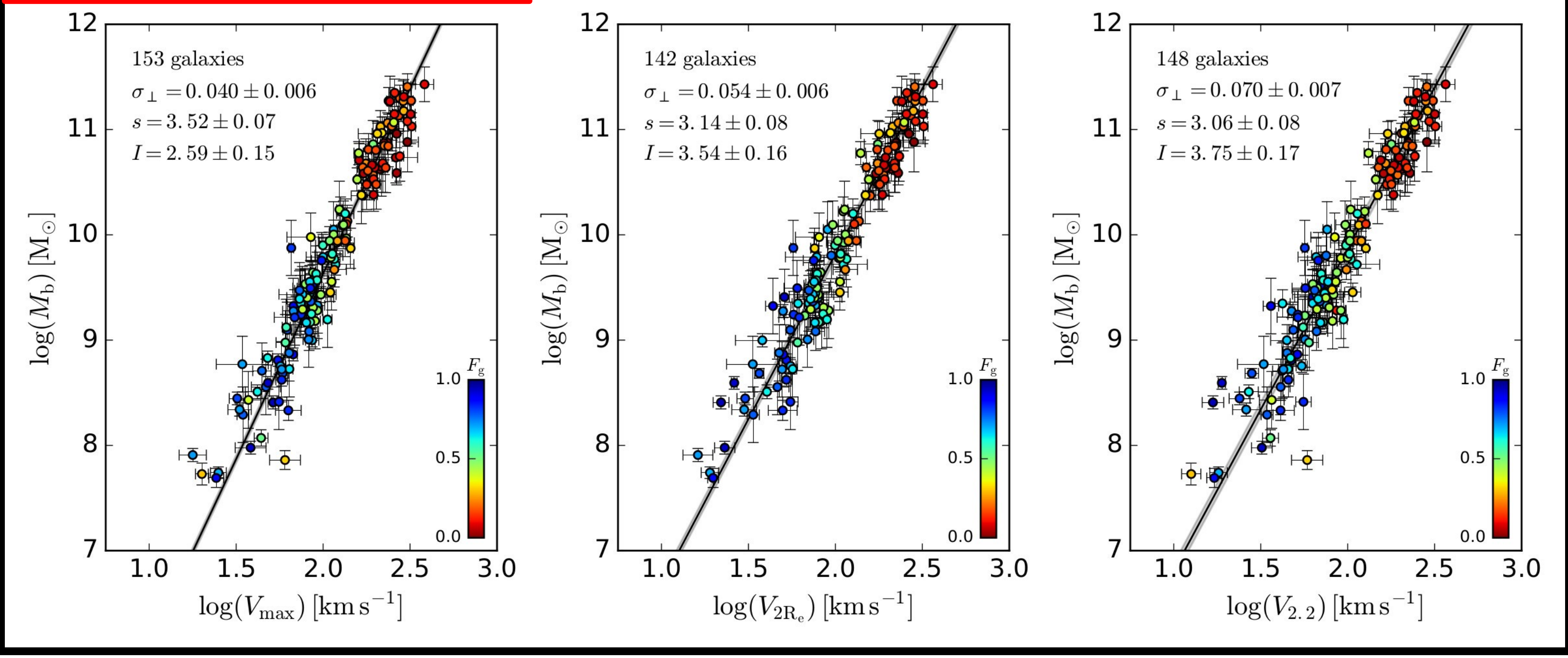


The flat rotation velocity (V_{flat}) gives the tightest and steepest BTFR!

(Verheijen 2001; Noordermeer & Verheijen 2007; McGaugh 2005; Ponomareva+2017; Lelli+2019)



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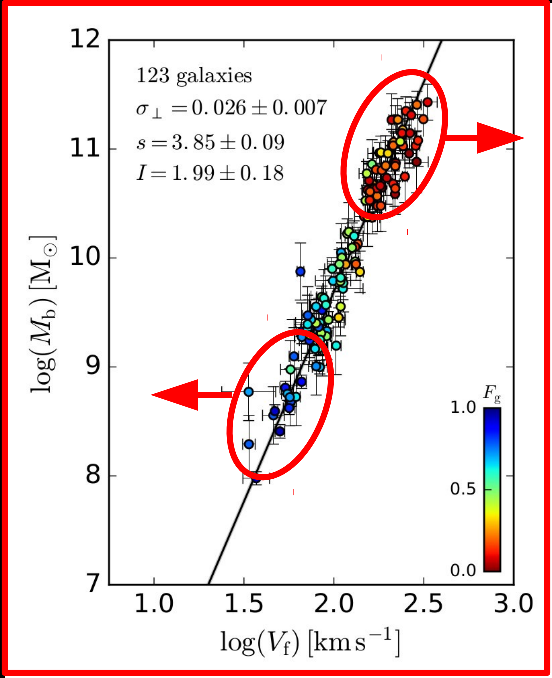


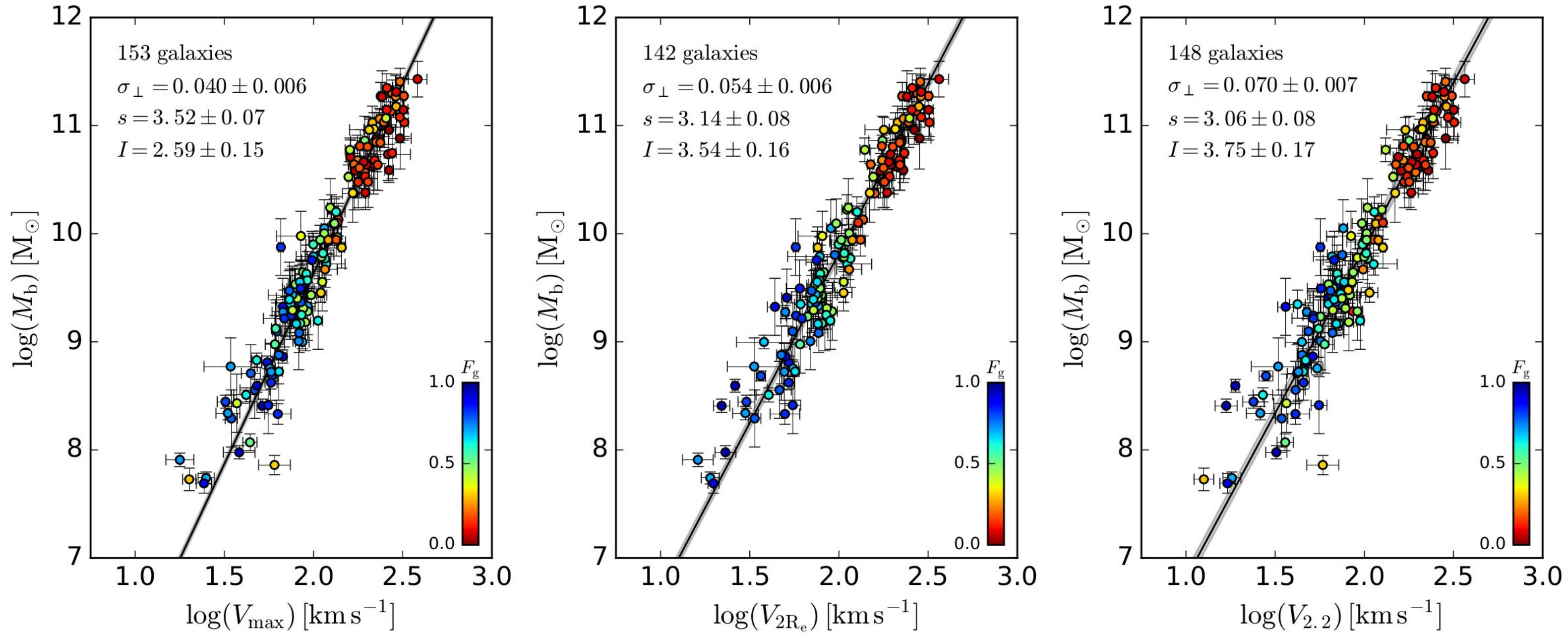
Why M_b-V_{flat} relation is steeper?

Rotation curve shapes!

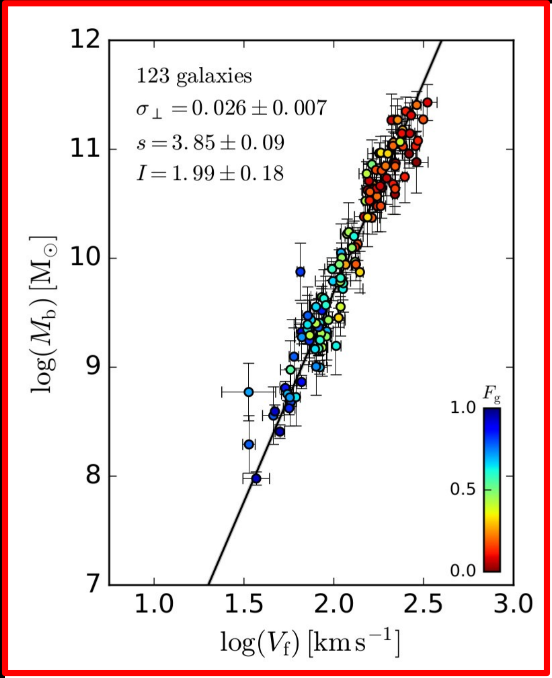
At high M_b: declining RCs → $V_{in} > V_{flat}$

At low M_b: rising RCs → $V_{in} < V_{flat}$

Inner velocities give shallower BTFR



BTFR for different velocity definitions



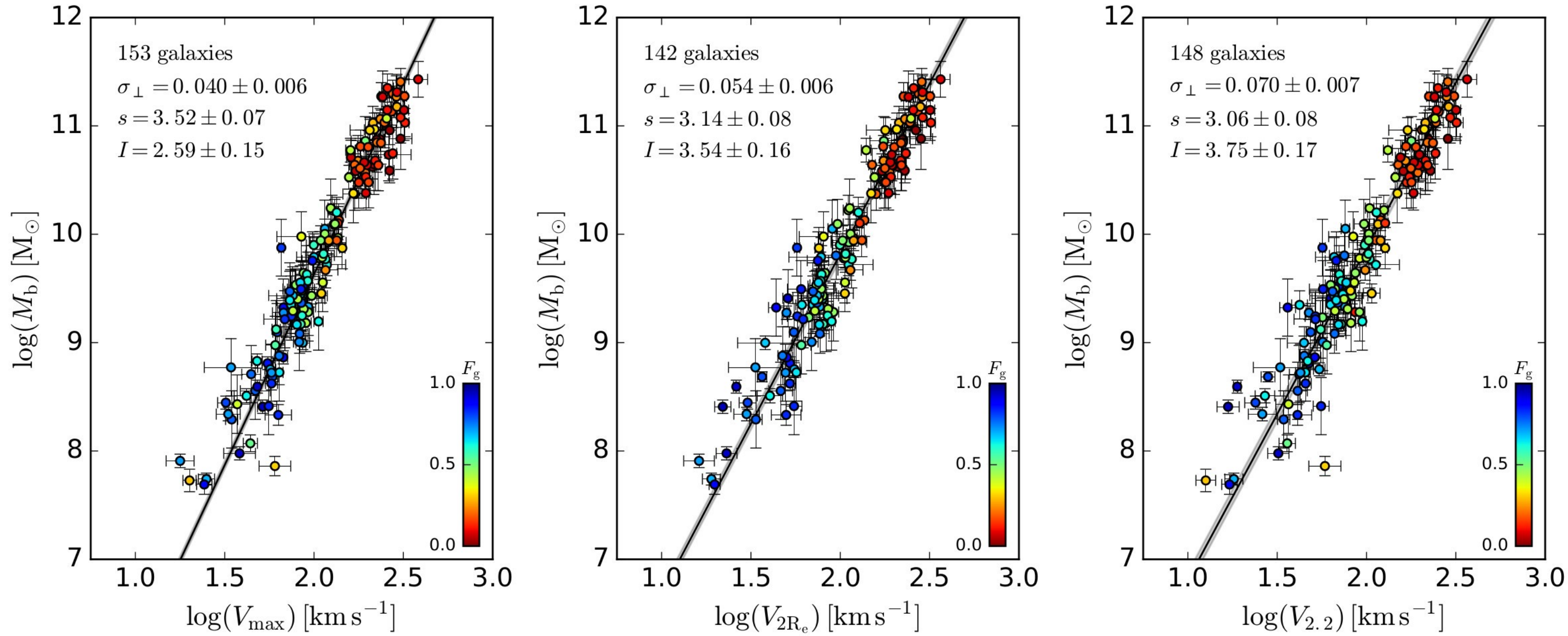
Why M_b-V_{flat} relation is tighter?

Counter-intuitive result!

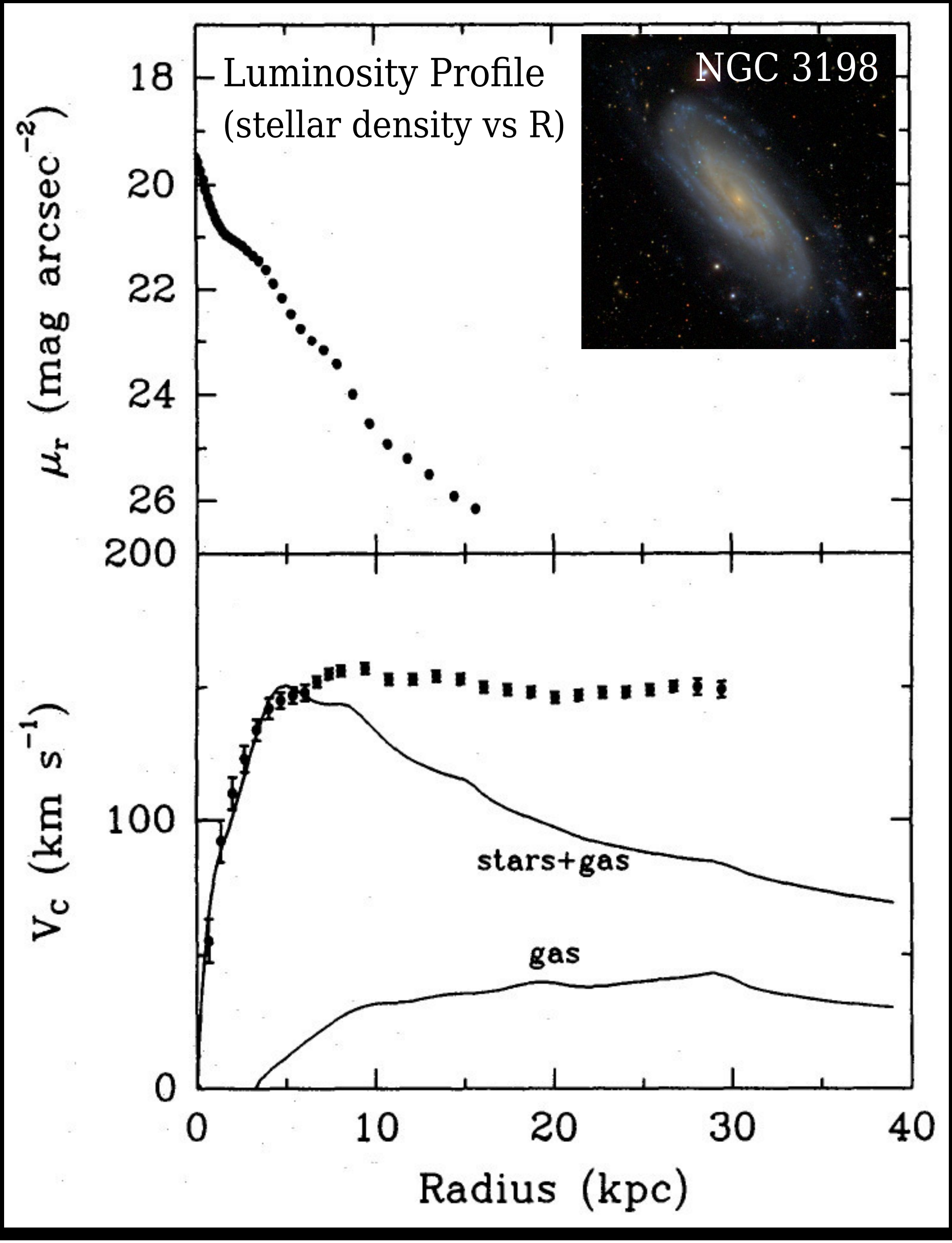
Baryons important near the center...

but M_b best correlate with V_{flat}

(set by the dark matter halo)!



Mass Models for Disk Galaxies



Solve Poisson's Equation for each baryonic component (i = stars, gas)

$$\nabla^2 \Phi_i(R,z) = 4\pi G \rho_i(R,z)$$

Assume nominal disk thickness

$$\rho_i(R,z) = \mu_i(R)\nu_i(z)$$

Find expected circular velocity

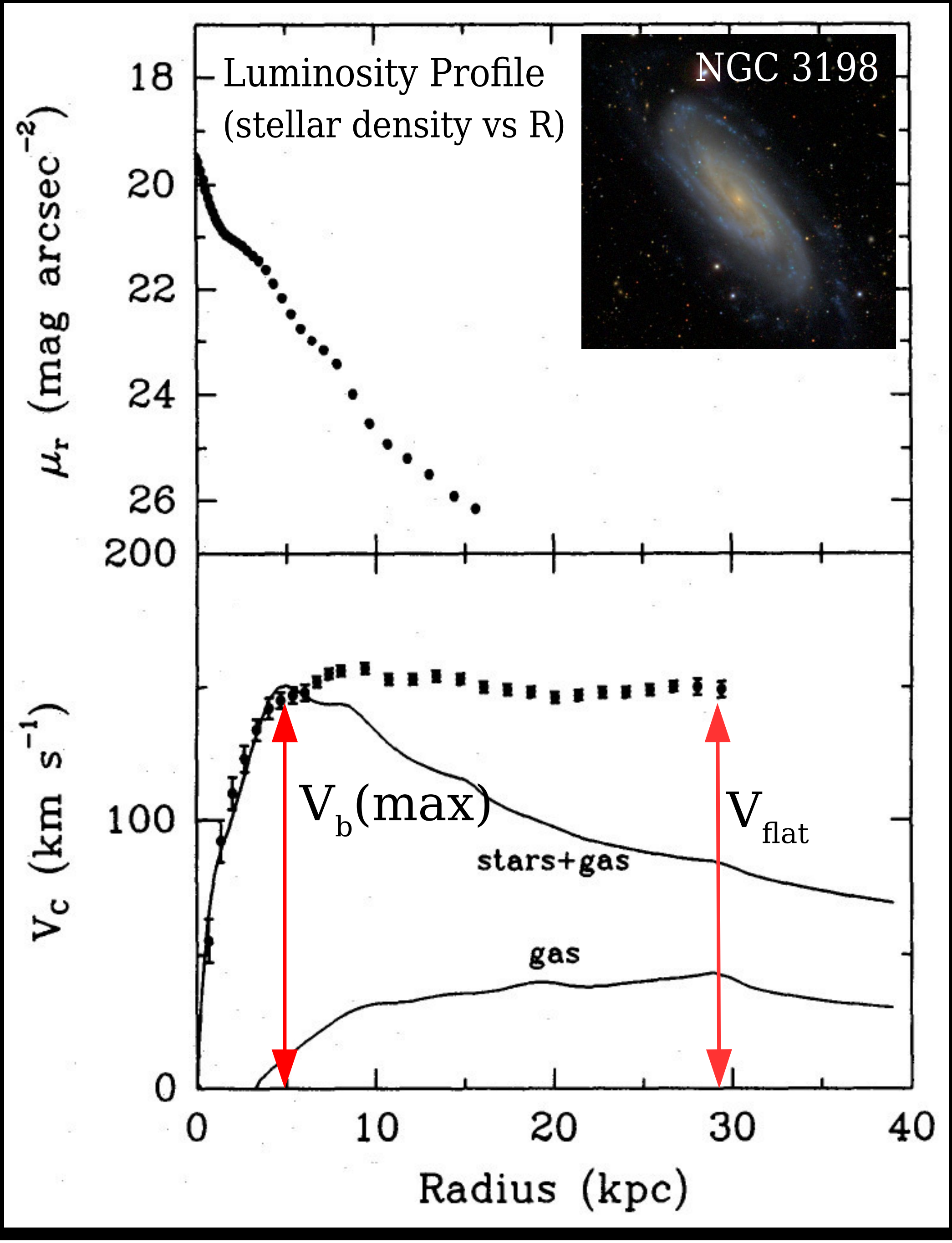
$$\frac{V_i^2(R,z=0)}{R} = -\frac{\partial \Phi_i(R,z=0)}{\partial R}$$

Sum over all baryonic contributions

$$V_b^2(R) = (M/L)V_{star}^2 + V_{gas}^2$$

van Albada et al. (1985); Begeman (1987)

Mass Models for Disk Galaxies

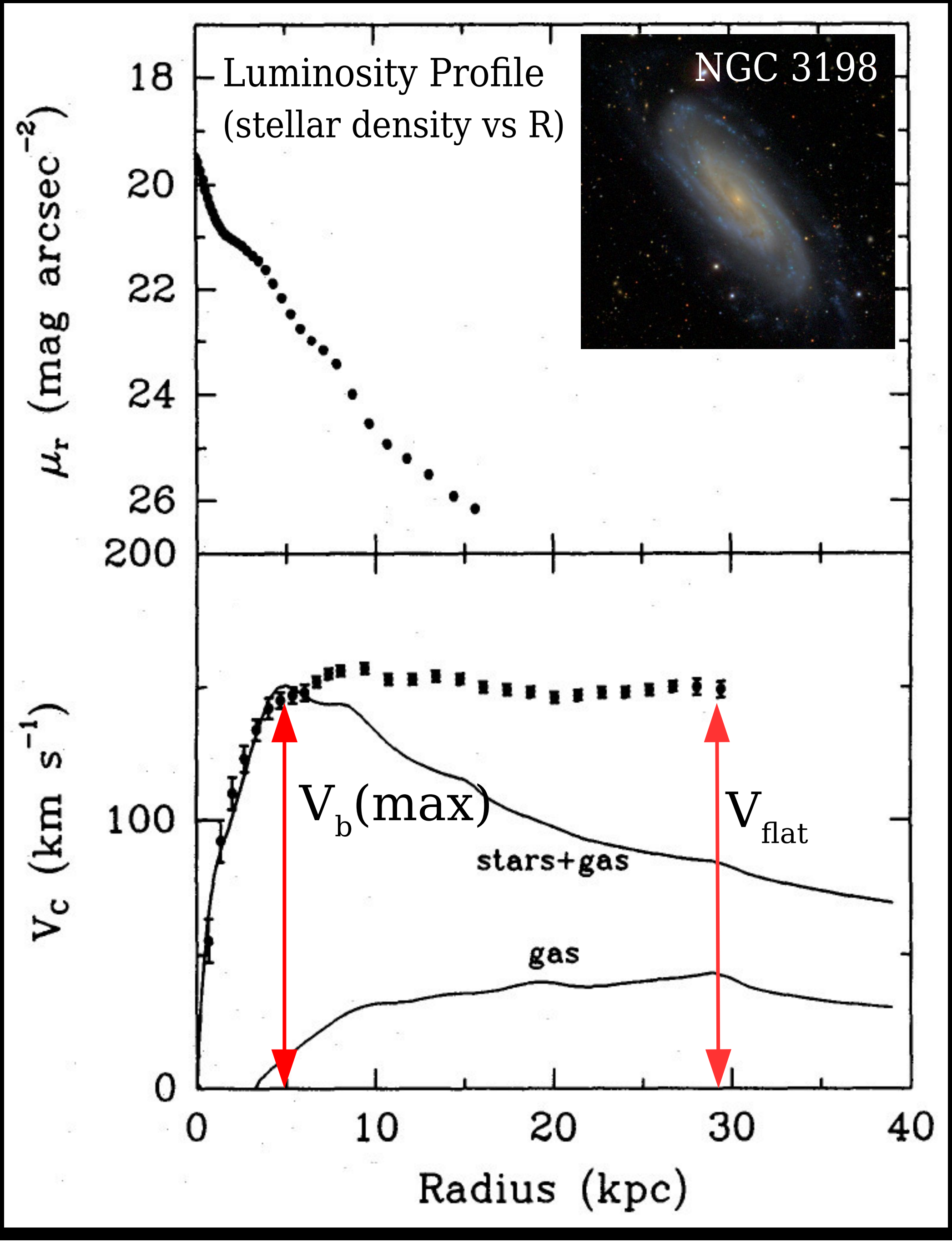


If we assume that all galaxy disks are maximal, then BTFR is trivial!

$$V_{flat} = V_b(max) = \sqrt{\alpha G M_b / R}$$

$\alpha = O(1)$ due to disk geometry

Mass Models for Disk Galaxies



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If you square this twice:

$$V_{flat}^4 = V_b(max)^4 = (\alpha G)^2 \Sigma_b M_b$$

Normalization set by Σ!

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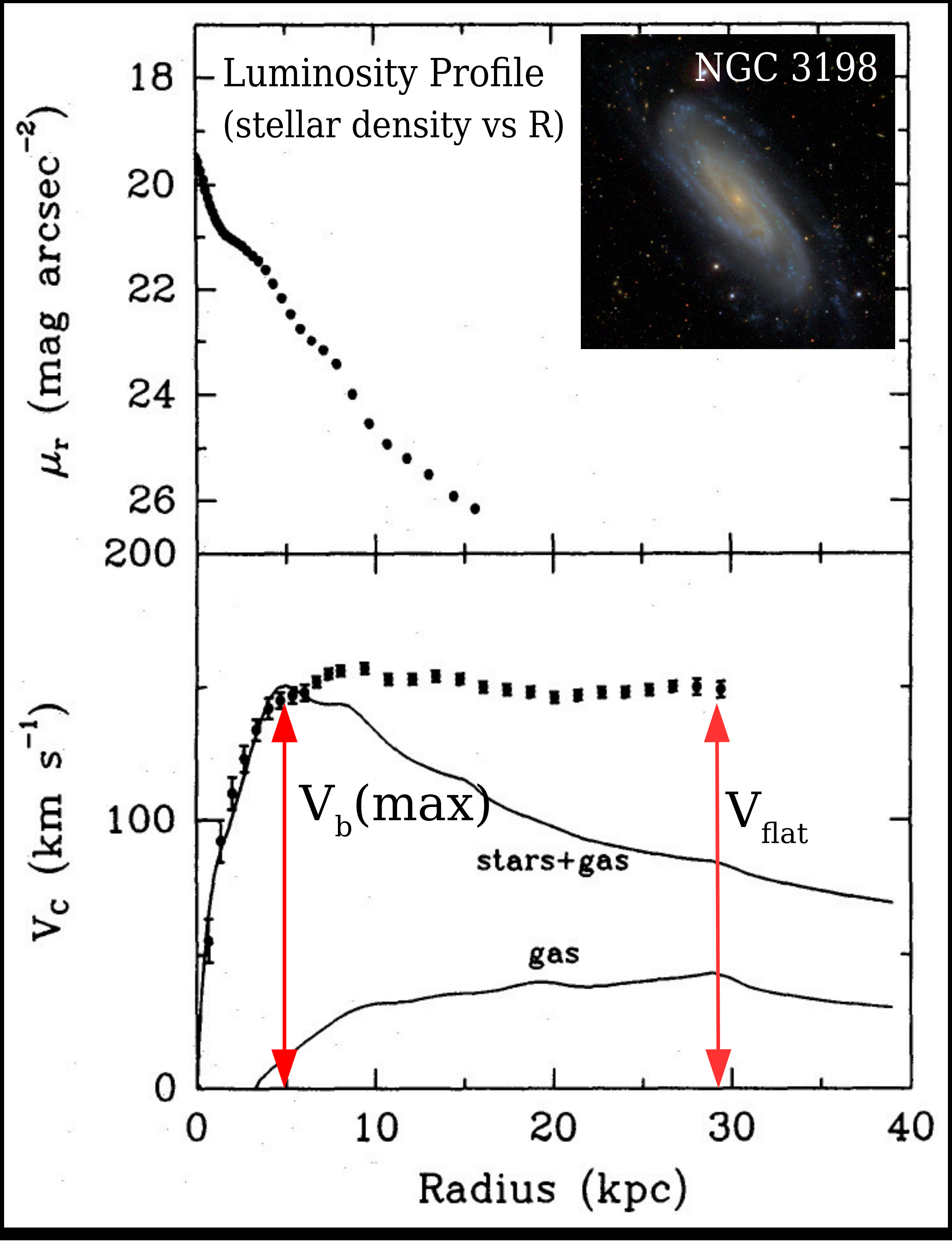

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Normalization set by Σ!

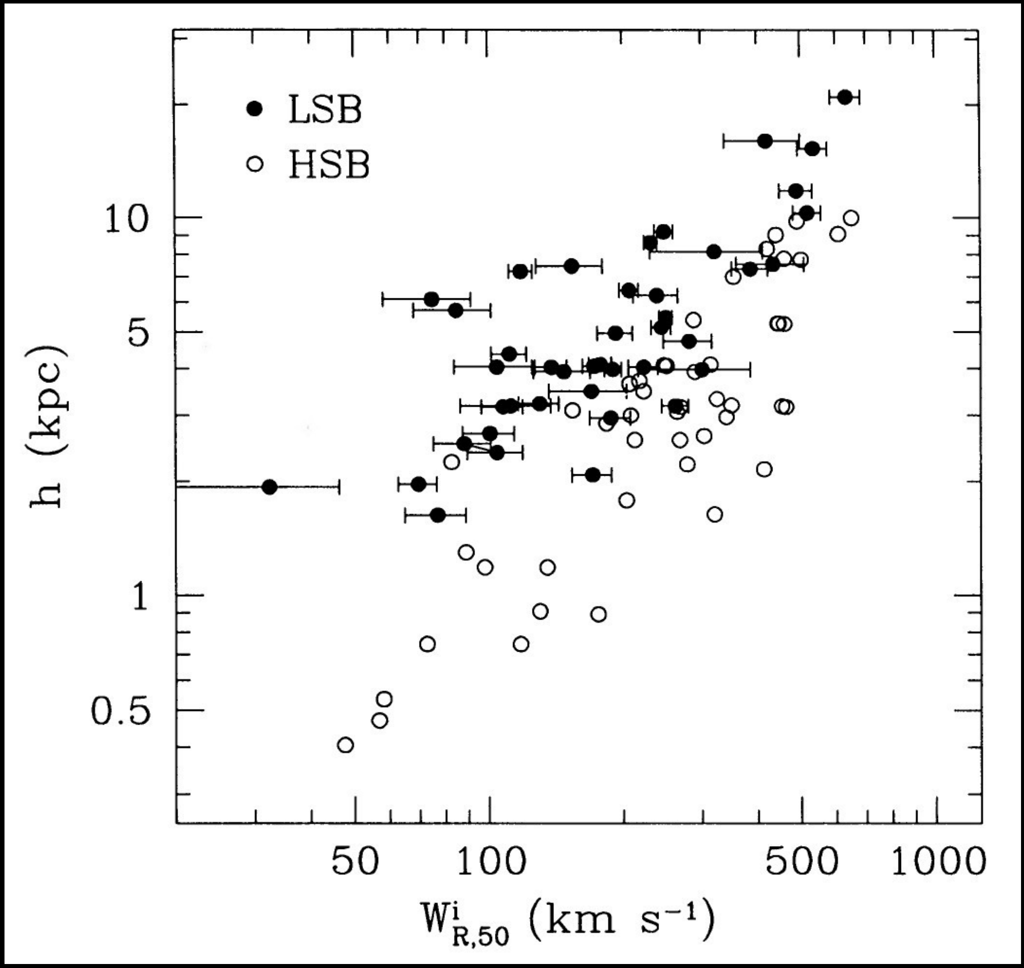
- Pre-90s: Σ thought to be constant for galaxy disks (Freeman's Law)
- Post-90s: LSB disks emerged (Schombert 1992; McGaugh 1994)
- Prediction: LSB galaxies should follow a different TF relation!

The Tully–Fisher relation for low surface brightness galaxies: implications for galaxy evolution

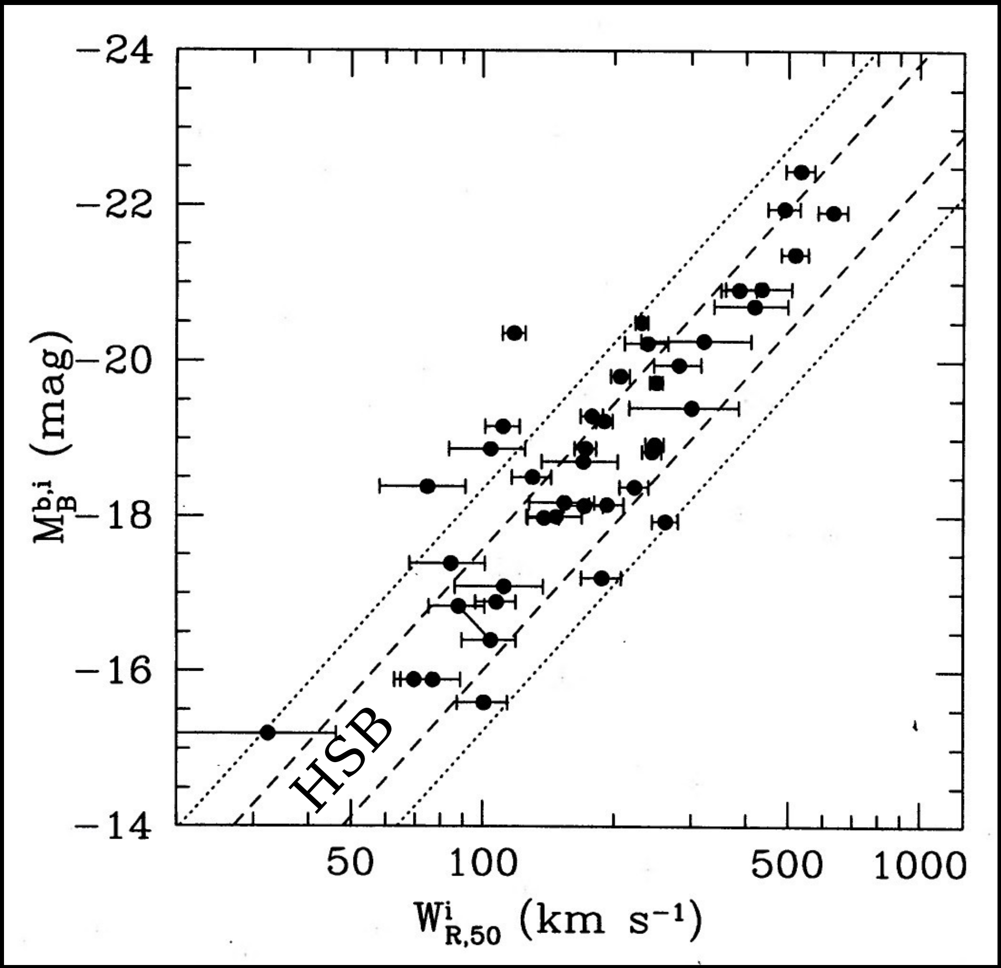
M. A. Zwaan,[1] J. M. van der Hulst,[1] W. J. G. de Blok[1] and S. S. McGaugh[2]
[1] Kapteyn Astronomical Institute, PO Box 800, 9700 AV Groningen, The Netherlands
[2] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

1995

LSB vs HSB: different sizes!



But LSB are on the same TFR as HSB!

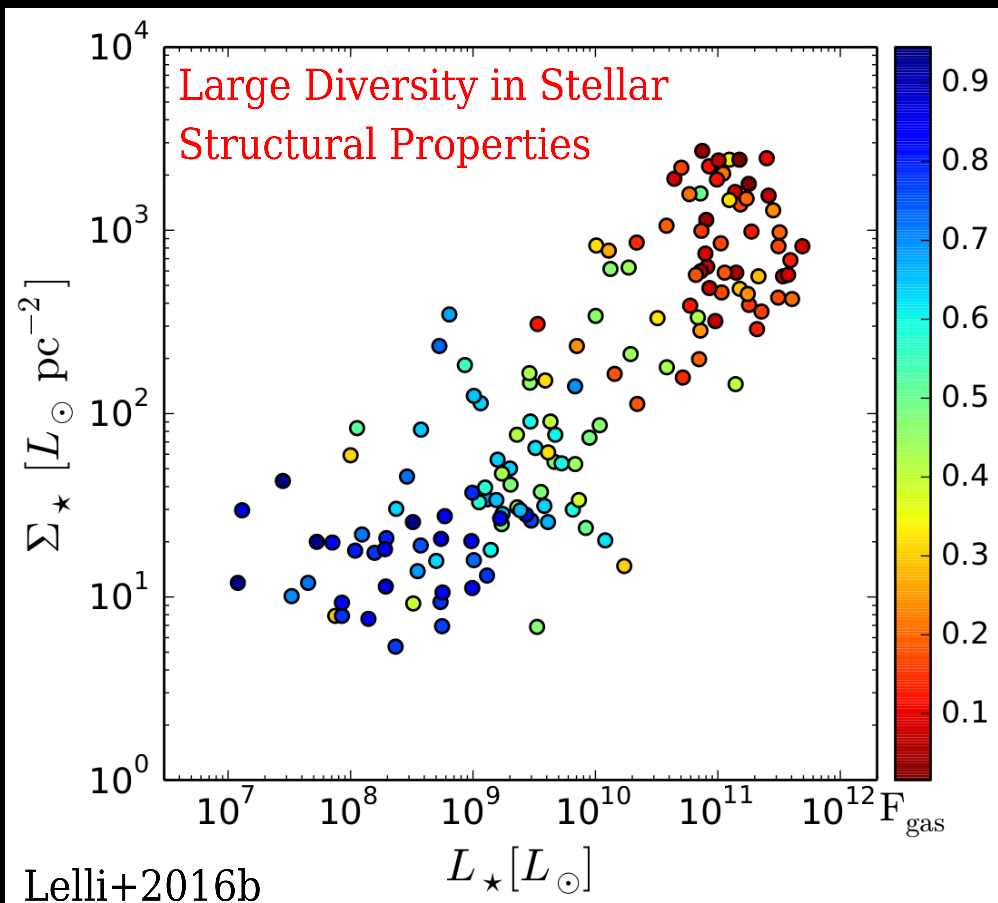


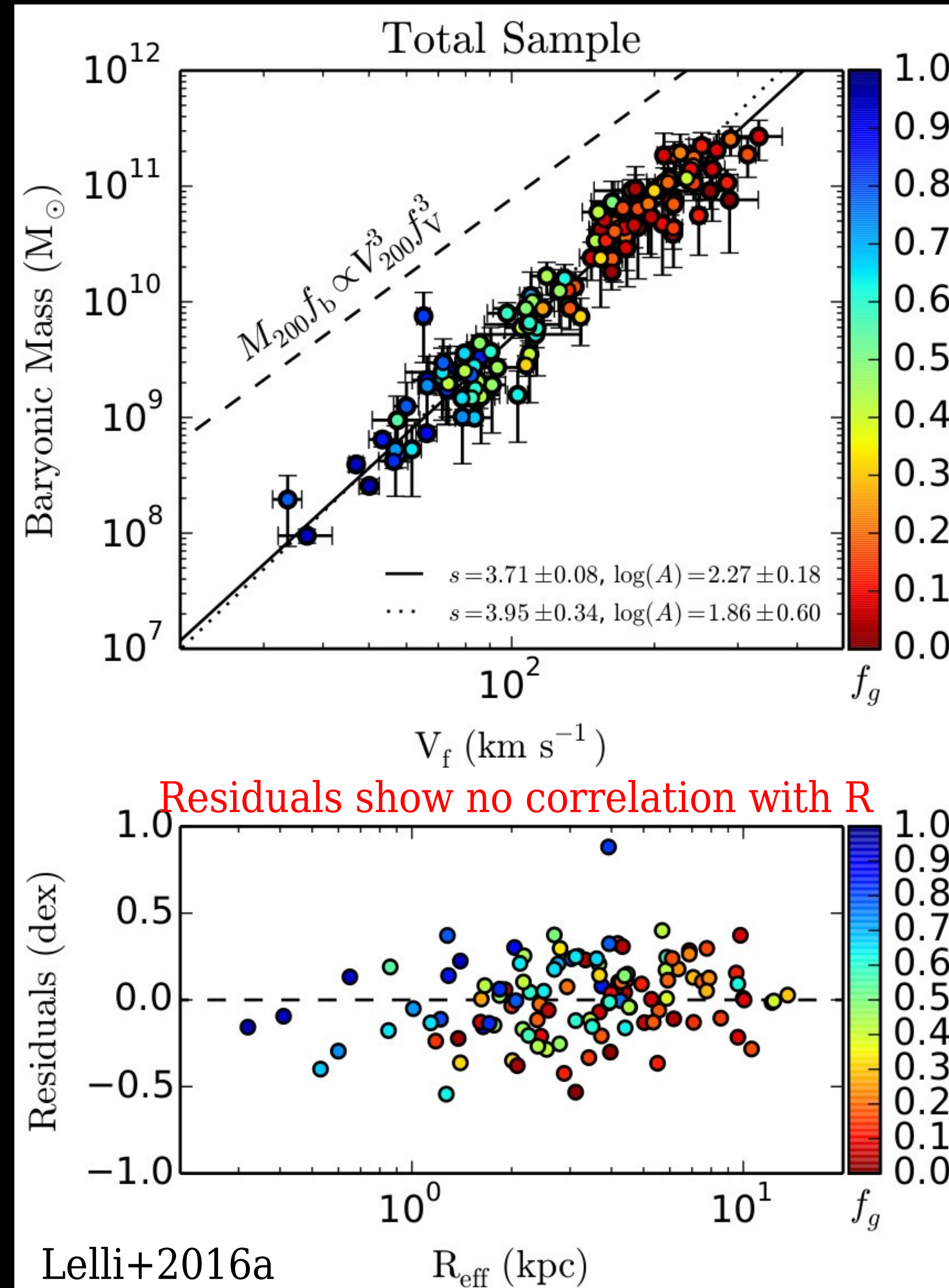
HSBs and LSBs lie on the same BTFR

SPARC

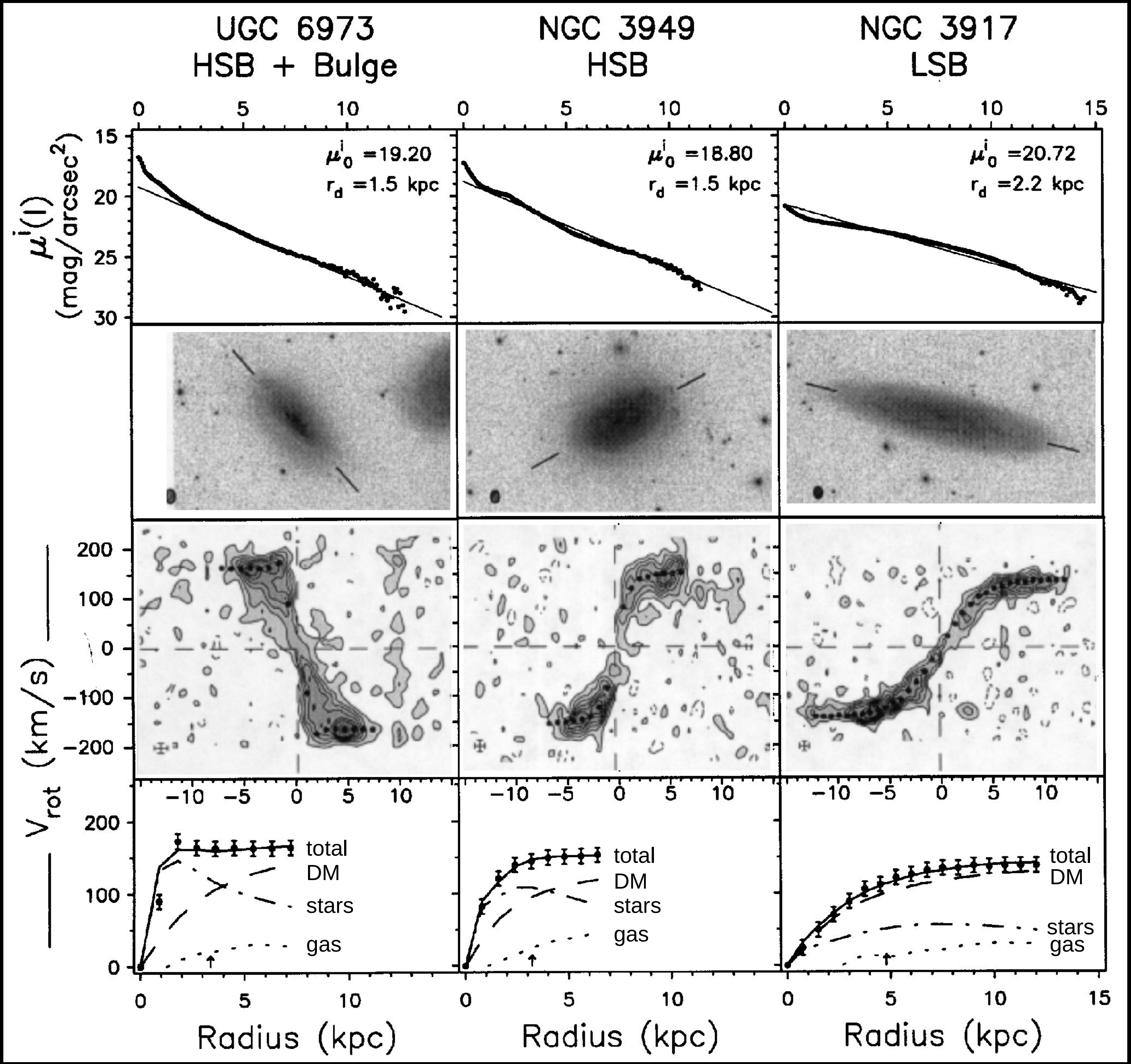
Spitzer Photometry & Accurate Rotation Curves

Database of 175 disk galaxies with HI interferometry and [3.6] photometry





A galaxy triplet on the BTFR

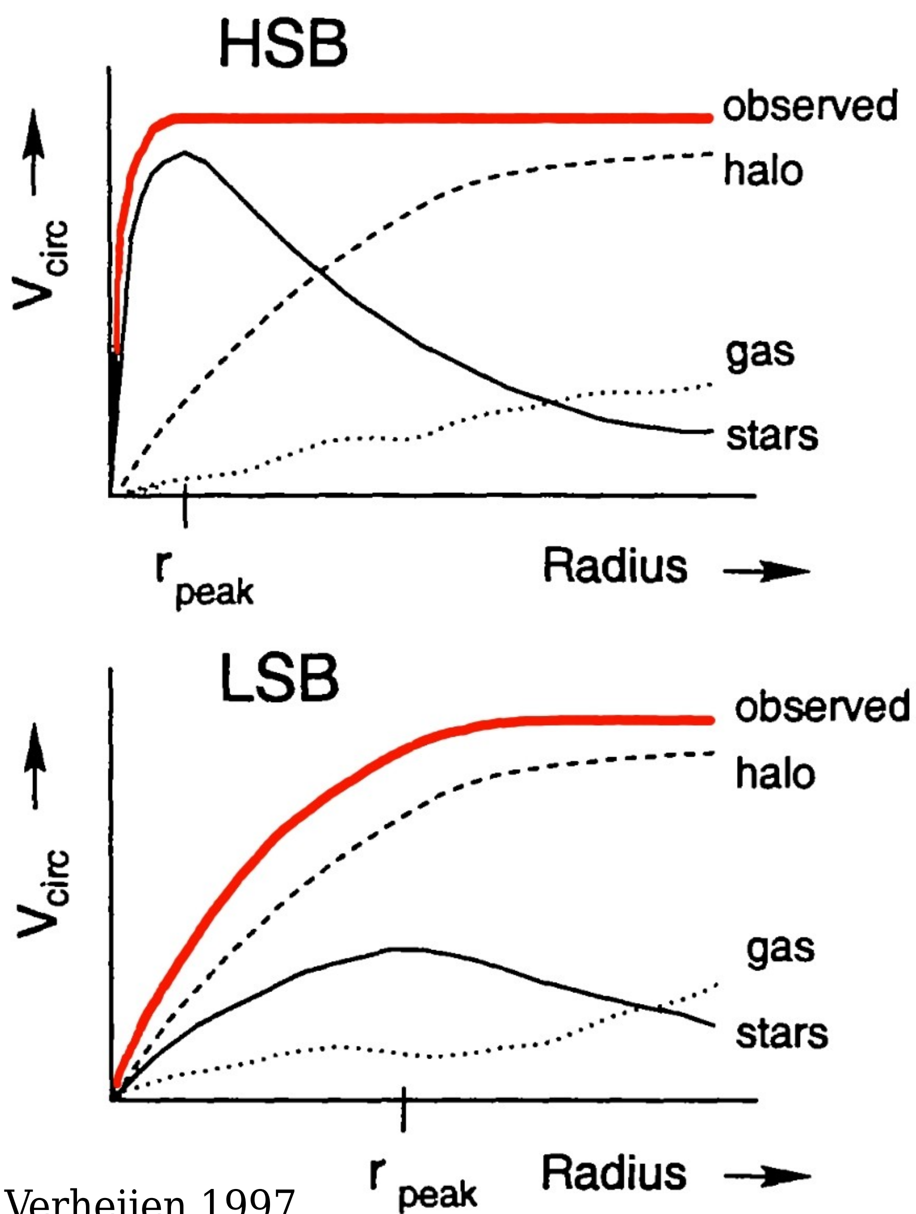


Same M_{bar} & V_{flat} but different SB

Different Rotation Curves & Mass Models

Tully & Verheijen (1997)

The HSB – LSB dichotomy



Verheijen 1997

HSB galaxies:

- Steeply rising rotation curves
- Maximum disk hypothesis

→ Realistic M_*/L.
Baryons dominate inner galaxy regions

LSB galaxies:

- Slowly rising rotation curves
- DM dominates at small R

Deriving the Tully-Fisher relation 2.0:

$$\frac{V_{rot}^{2}}{R} = \frac{\alpha\, G\, M_{tot}}{R^{2}}$$

Deriving the Tully-Fisher relation 2.0:

$$\frac{V_{rot}^2}{R} = \frac{\alpha G M_{tot}}{R^2} \longrightarrow V_{rot}^4 = (\alpha G)^2 \frac{\Sigma_b}{f_b^2} M_b \qquad f_b = \frac{M_b}{M_{tot}}$$

Deriving the Tully-Fisher relation 2.0:

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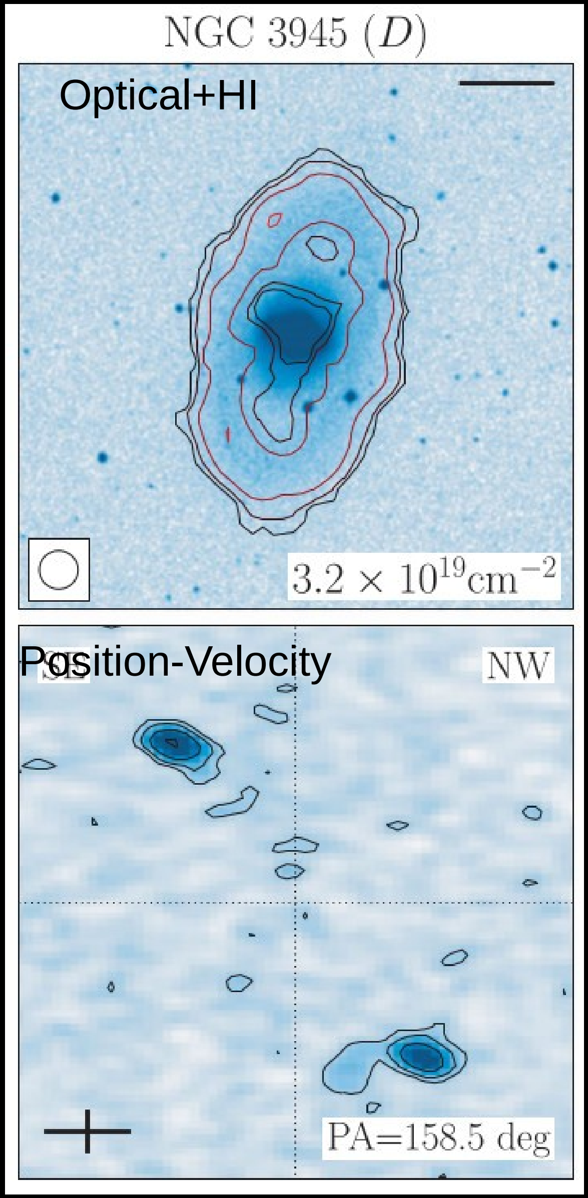
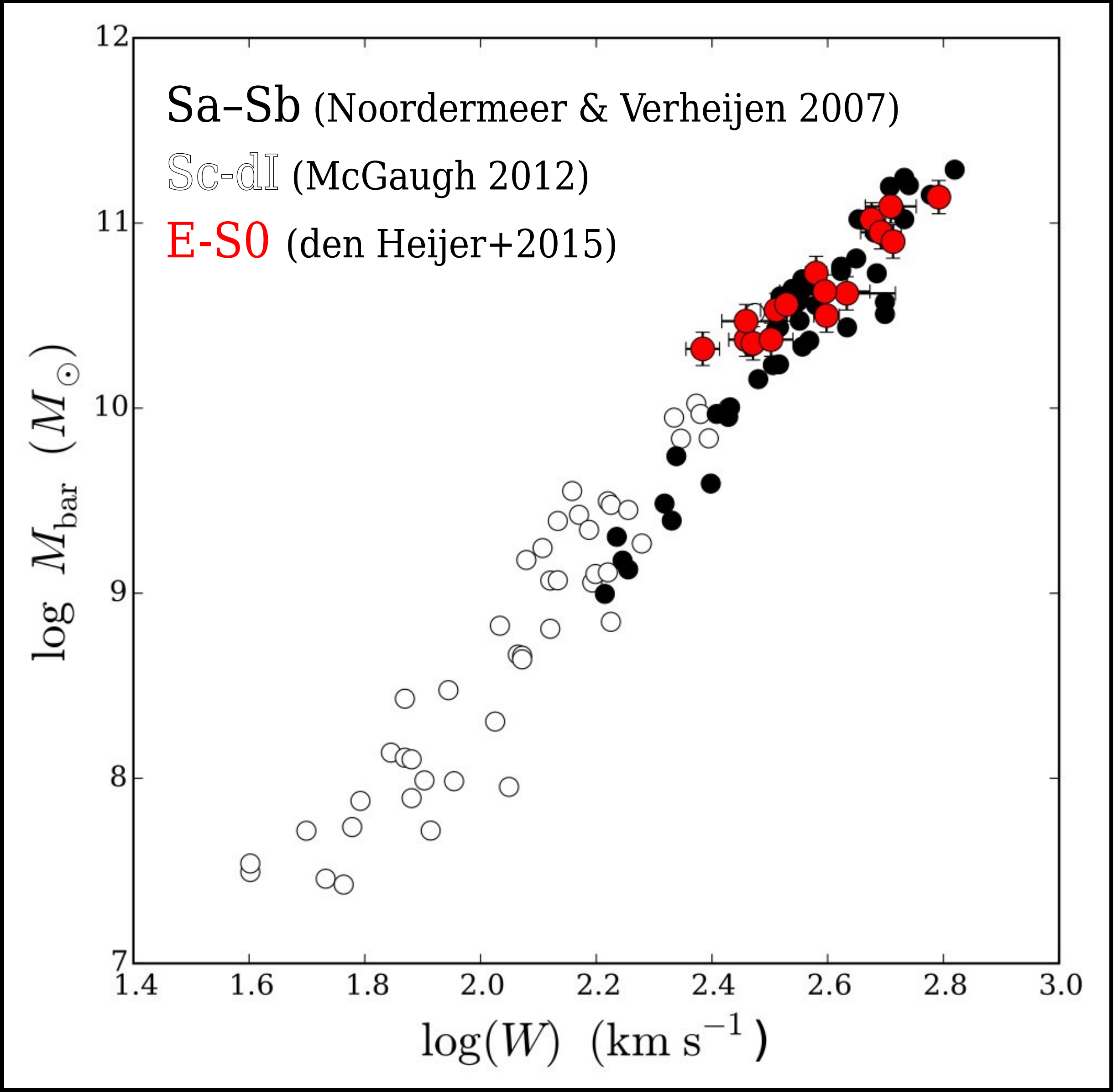
The tightness of the BTFR implies that $\frac{\Sigma_b}{f_b^2} \simeq const$

Fine-tuning problem at fixed baryonic mass:

As the average baryonic surface density decreases, the DM content must increase by a precise amount.

Early-type galaxies (E and S0) follow BTFR!





ETGs with outer, extended HI discs (Serra+2012, den Heijer 2015)

3. The Tully-Fisher relation in a LCDM context

Deriving the Tully-Fisher relation 3.0:

(1) $$M_{\Delta} = \frac{4\pi}{3} R_{\Delta}^{3} \cdot \Delta \cdot \rho_{crit}$$ $$\rho_{crit} = \frac{3 H_0^2}{8 \pi G}$$

Cosmological definition of dark matter halo mass (typically Δ=200)

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Cosmological definition of dark matter halo mass (typically Δ=200)

(2) $$\frac{V_\Delta^2}{R_\Delta} = \frac{G M_\Delta}{R_\Delta^2} \xrightarrow{(1)+(2)} M_\Delta = \sqrt{\frac{2}{\Delta}} \frac{1}{G H_0} V_\Delta^3$$

TF-like relation for DM halos

Deriving the Tully-Fisher relation 3.0:

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Cosmological definition of dark matter halo mass (typically Δ=200)

(2) $$\frac{V_\Delta^2}{R_\Delta} = \frac{G M_\Delta}{R_\Delta^2} \xrightarrow{(1)+(2)} M_\Delta = \sqrt{\frac{2}{\Delta}} \frac{1}{GH_0} V_\Delta^3$$

TF-like relation for DM halos

To measurable quantities: $$F_b = \frac{M_b}{M_\Delta} \qquad F_V = \frac{V_{flat}}{V_\Delta}$$

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Deriving the Tully-Fisher relation 3.0:

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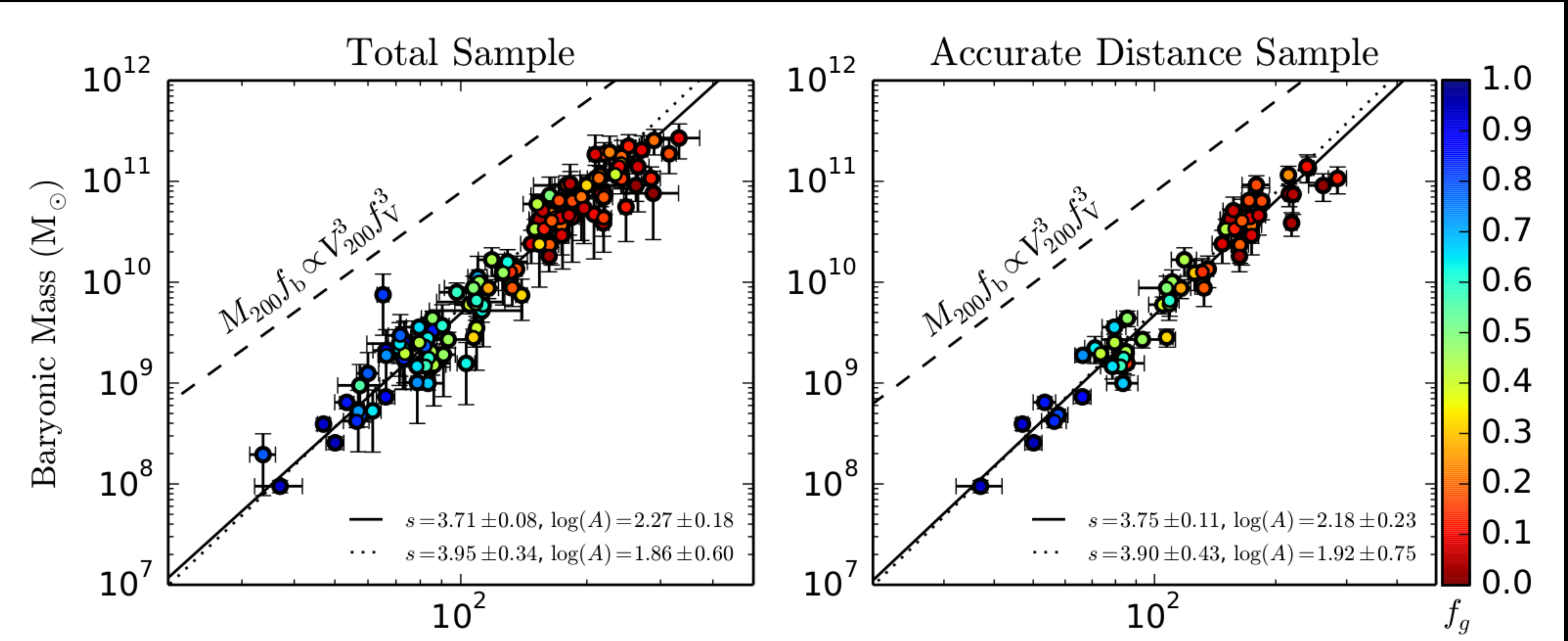
Working Hypothesis: $F_b = F_{cosmic}$ [CMB & galaxy clusters]

$F_V = 1$ [surely wrong but O(1) is ok]

Baryonic Tully-Fisher Relation vs LCDM



Lelli+2016a

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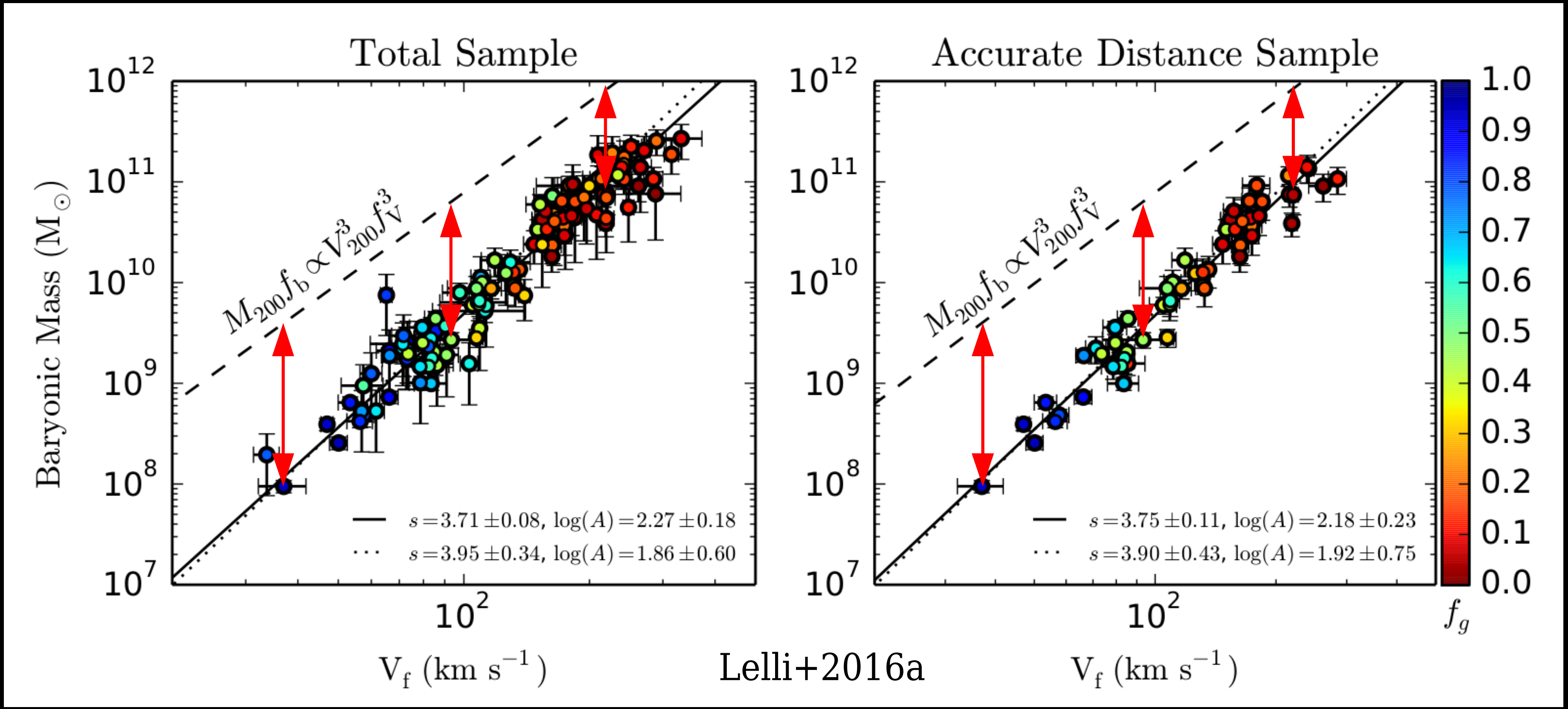
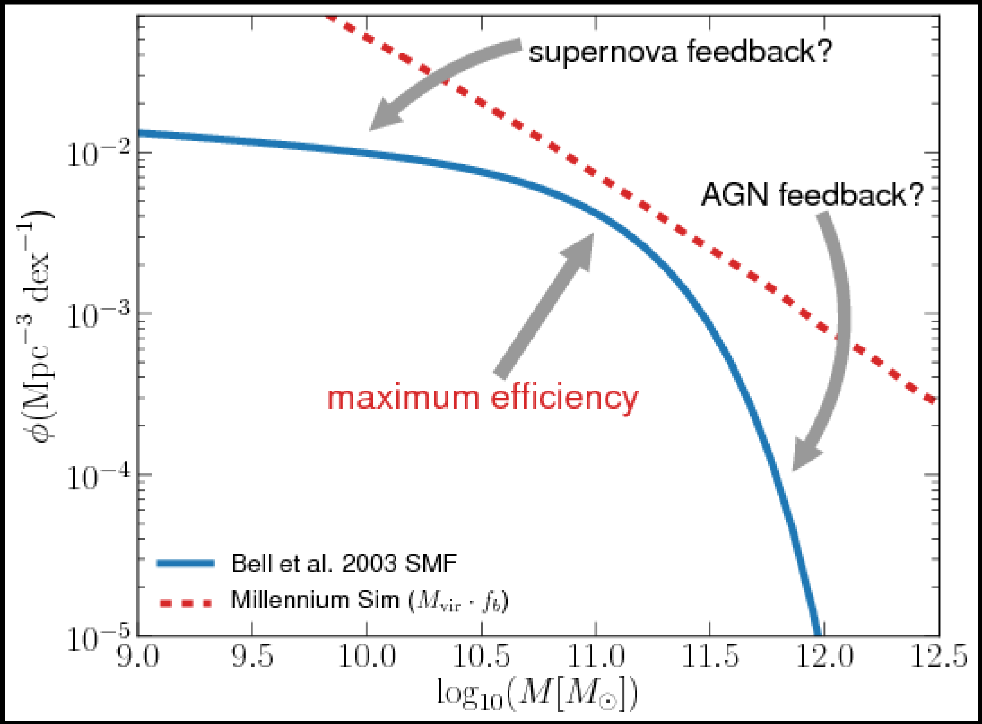


To fix normalization: $F_b < F_{CMB}$ → missing baryons (hot gas?)

To fix slope: F_b must systematically vary with V_{flat} (or M_{200})

Small scatter (<25%): additional fine-tuning problem!

The Stellar Mass Function Problem



A constant M_*/M_h can't reproduce the observed stellar mass function!

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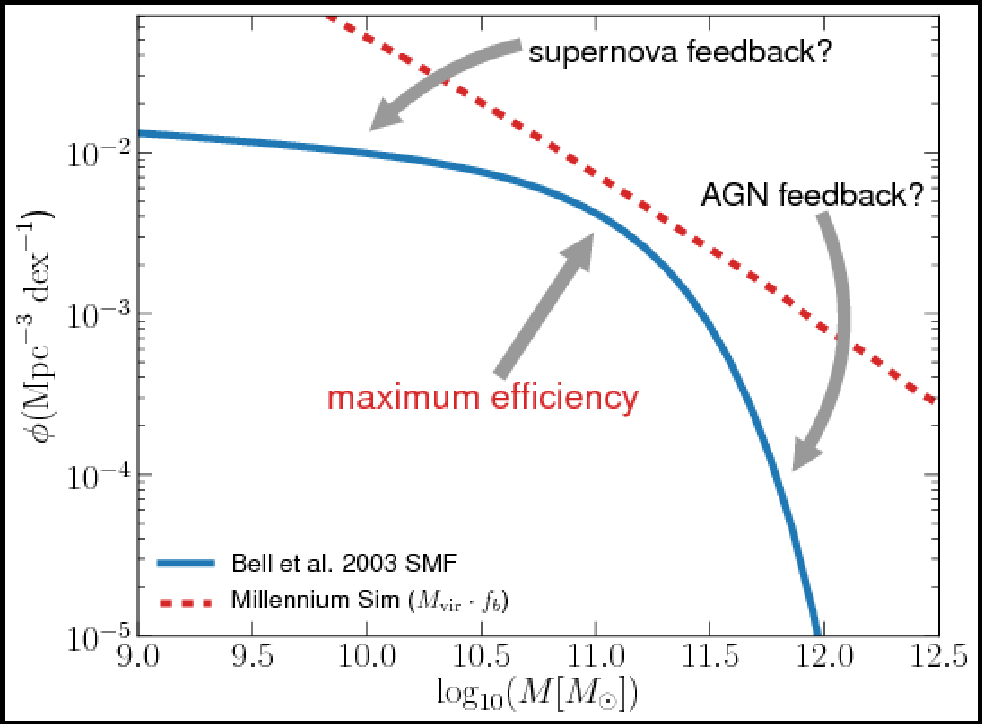

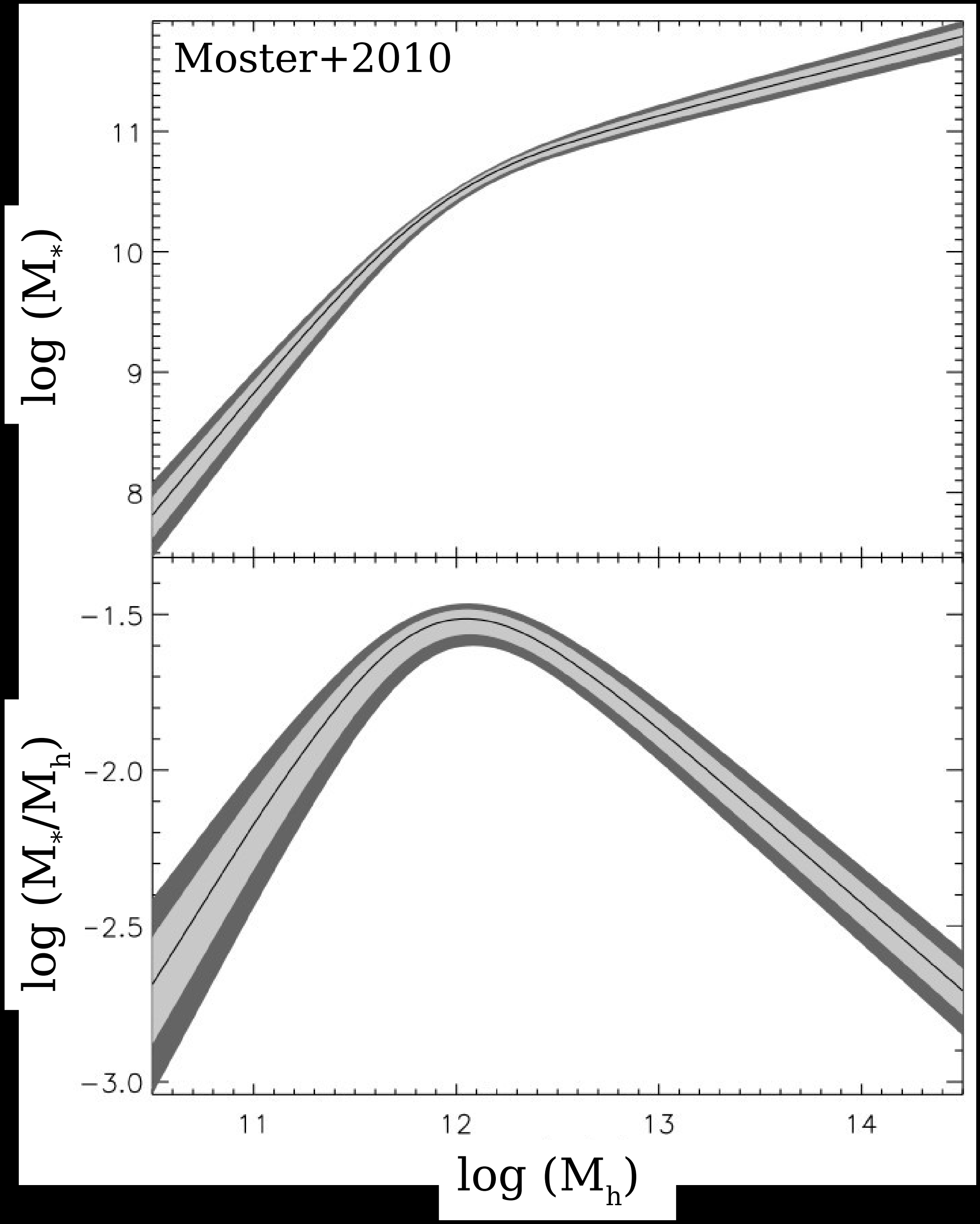

A constant M_*/M_h can't reproduce the observed stellar mass function!

Basics of Abundance Matching (AM):

- Order galaxies and halos by mass
- Assign the most massive galaxy to the most massive halo, and so on.
- Derive M_*-M_h relation

Interesting test for LCDM models:

(1) Assume M_*-M_h relation from Abundance Matching

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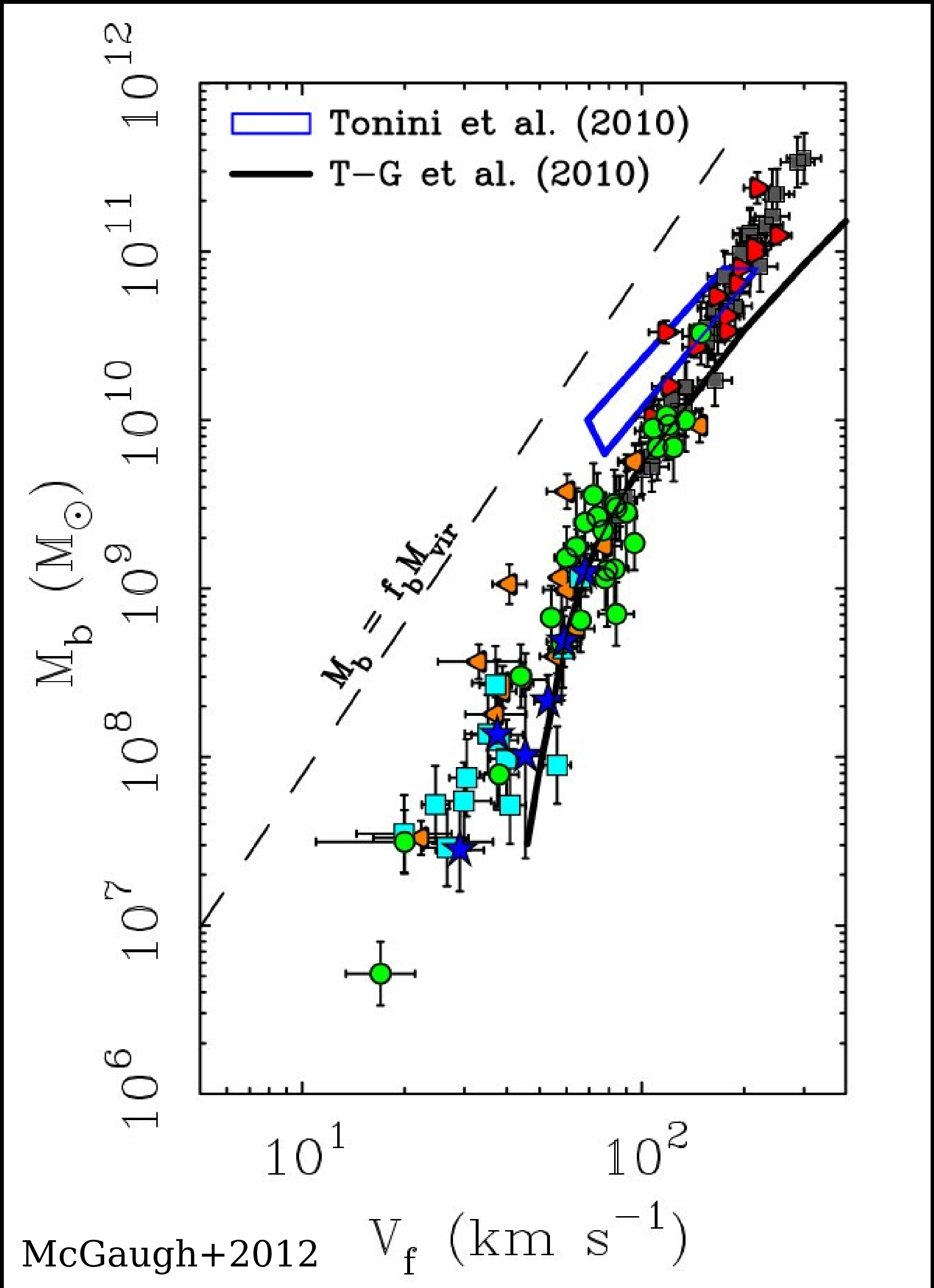
(3) Assume M_h-c relation of DM halos (from sims)

(4) Model the baryonic distribution with some recipe (e.g., angular momentum partition) or even better take it directly from the data (e.g. Desmond+2018)!

→ Calculate model rotation curves and BTFR!

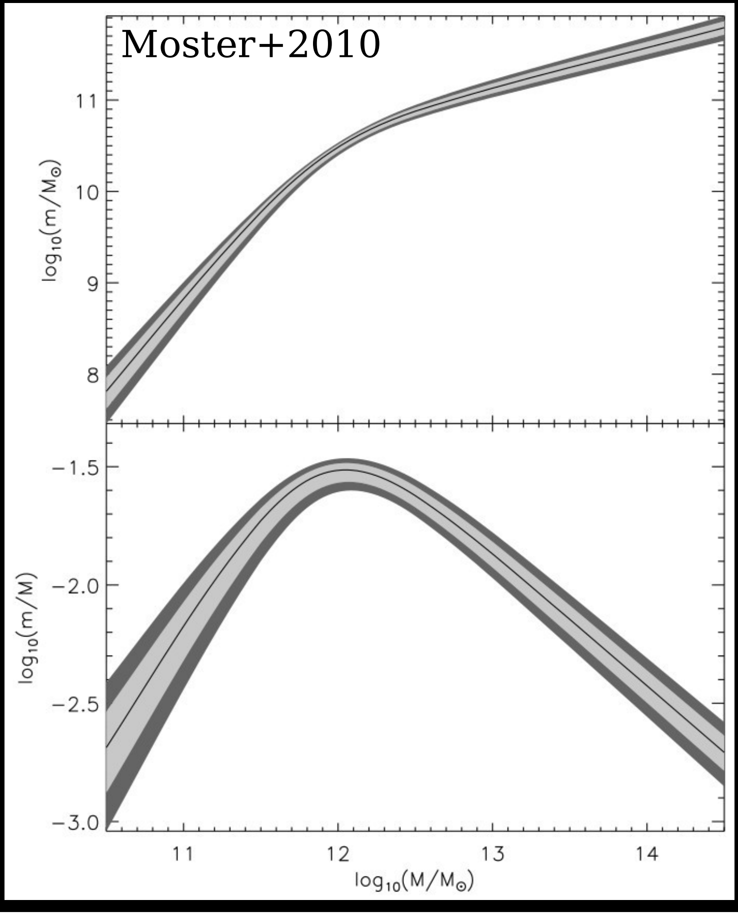
Basic AM models versus Observations



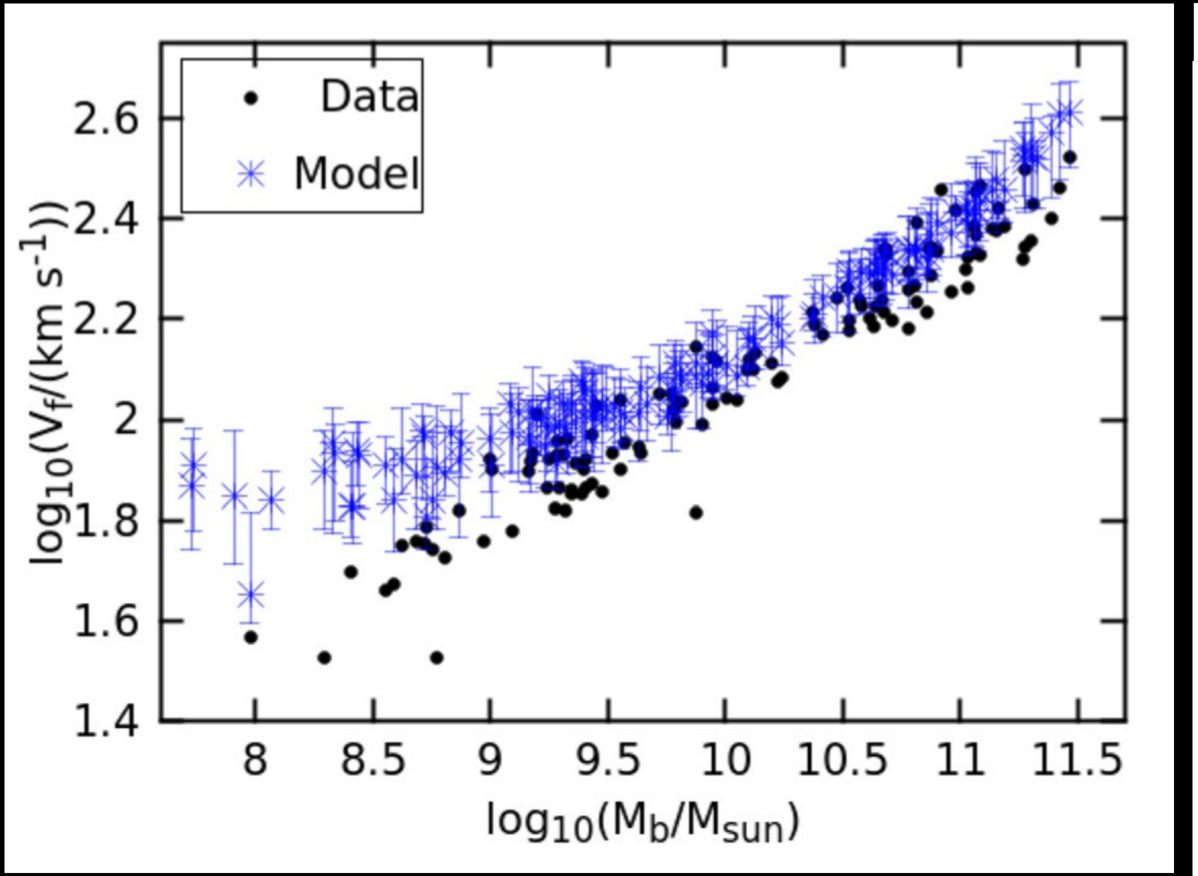
MIXED RESULTS:

- Normalization is OK: Good!
- Strong curvature: Bad!

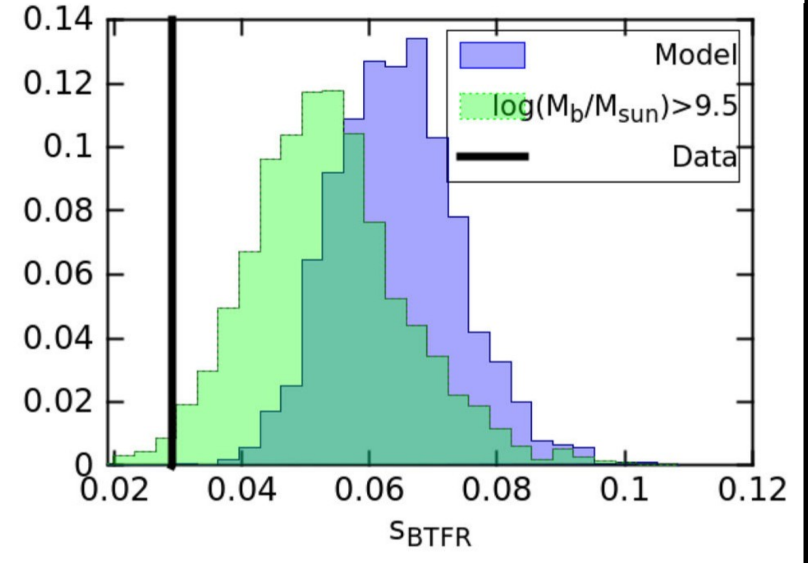
Unavoidable: M_*-M_h relation is non-linear in AM models!



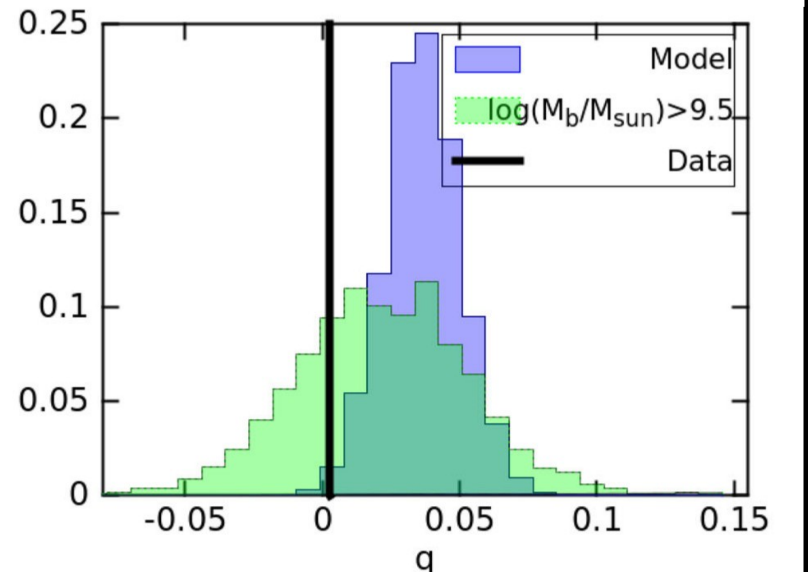
BTFR scatter is also a key test!



Scatter is 3.6σ too high!



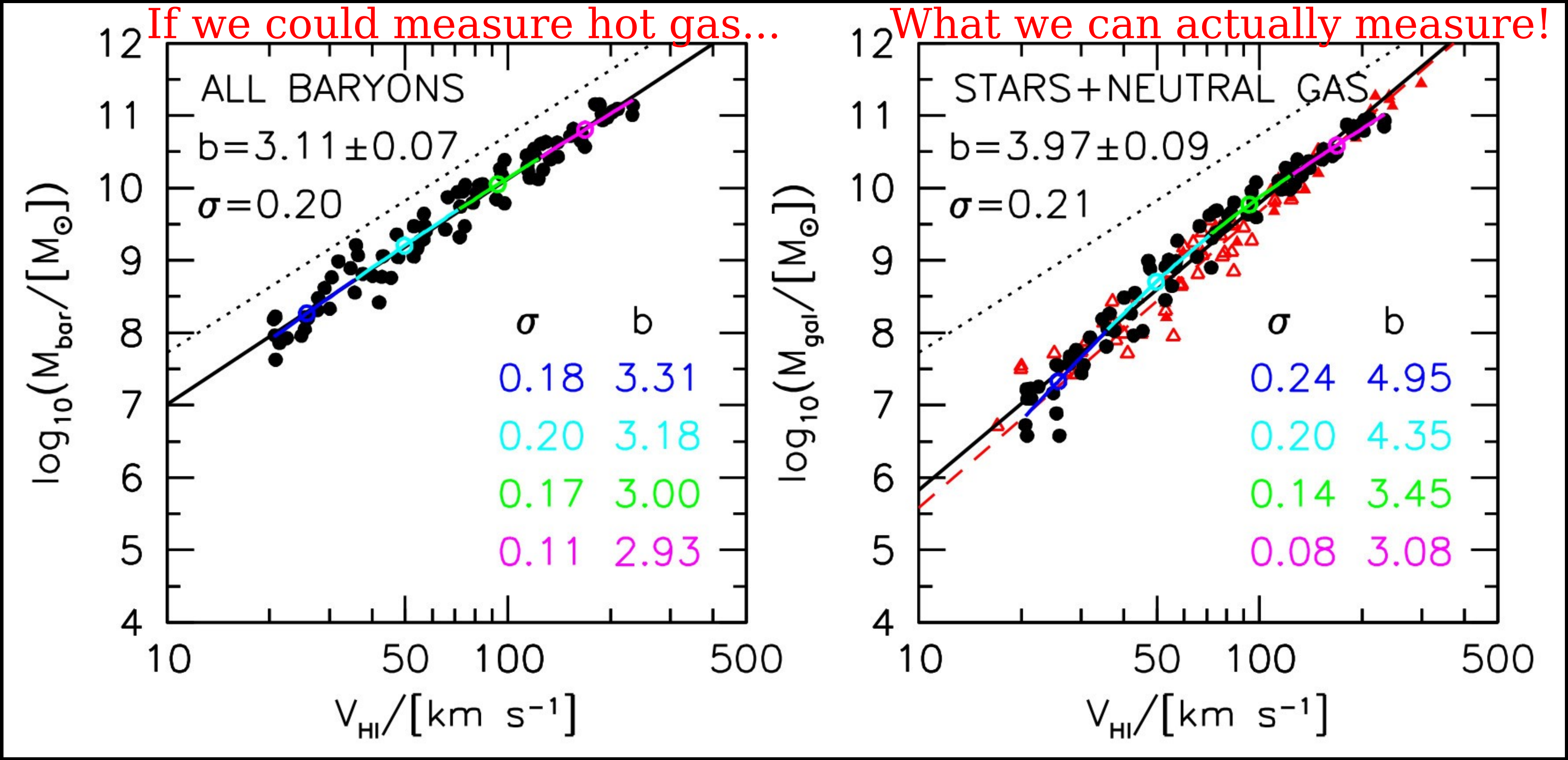
Curvature is 3σ too strong!



Desmond (2018):

- Abundance matching on SPARC galaxies
- Baryon distribution taken from obs.
- Differences must be due to DM halo!
- Repeat N-times to account for variance

BTFR from hydrodynamical simulations



NIHAO zoom-in cosmological simulations of galaxy formation (Dutton+2017)

BTFR curvature has almost disappeared and the scatter small.

This is remarkable... but how is this possible?

Where did the M_*/M_h scatter and the characteristic M_* go?

Messages to take home:

1. TF relation is not just a distance indicator!

It provides key information on baryons & DM in galaxies

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At fixed M_b, central DM fraction increases as Σ decreases

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As M_b decreases, missing baryons progressively increase

3. A blessing and a curse for LCDM models

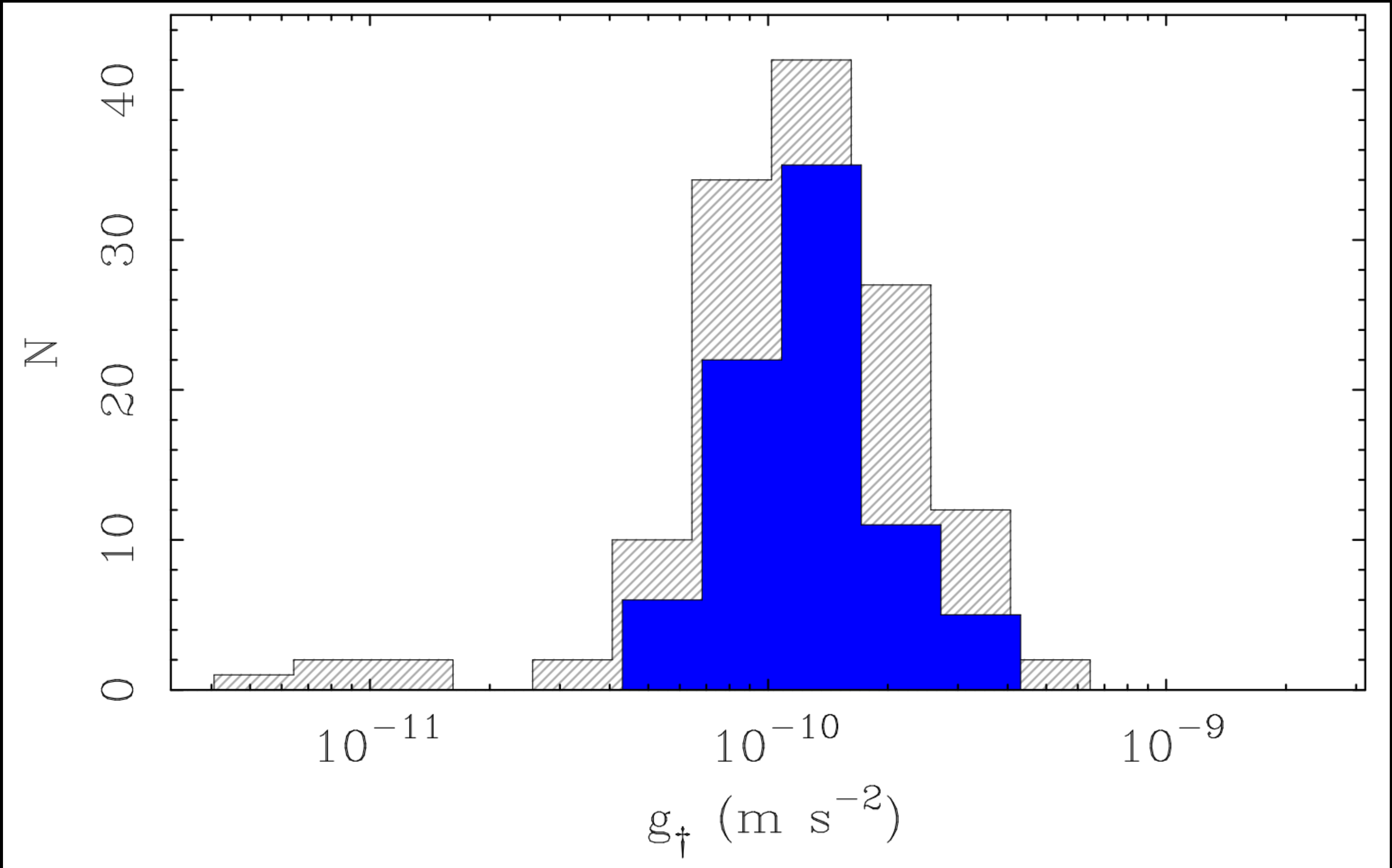
Normalization and slope are almost OK. Success of AM.

Curvature is not observed. Discrepancy with AM.

Scatter is too small. But galaxy formation is stochastic!

More Slides

Slope~4 ➡ Acceleration Scale



On dimensional grounds: $g_\dagger \sim V_f^4 / (GM_b)$