An introduction to the Tully-Fisher relation

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Why studying the Tully-Fisher relation?

1. Empirical tool to measure galaxy distances

→ Measure H_0 and peculiar velocities (galaxy flows)

Need: Large galaxy samples (low-resolution HI surveys)

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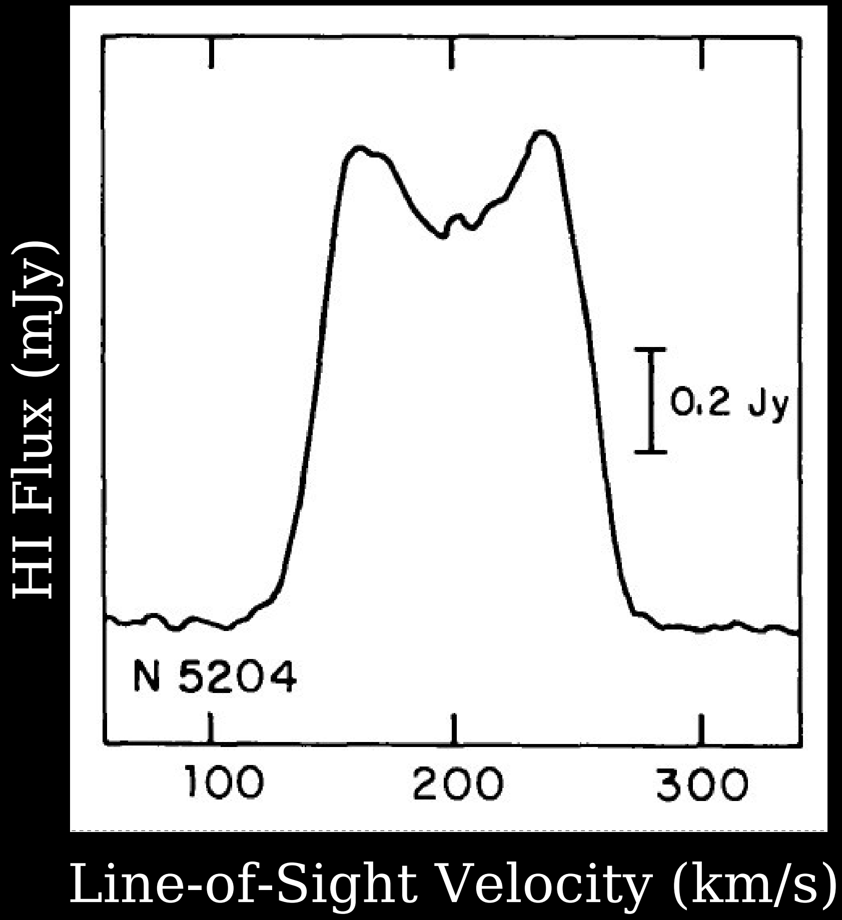
Spatially Integrated HI Observations



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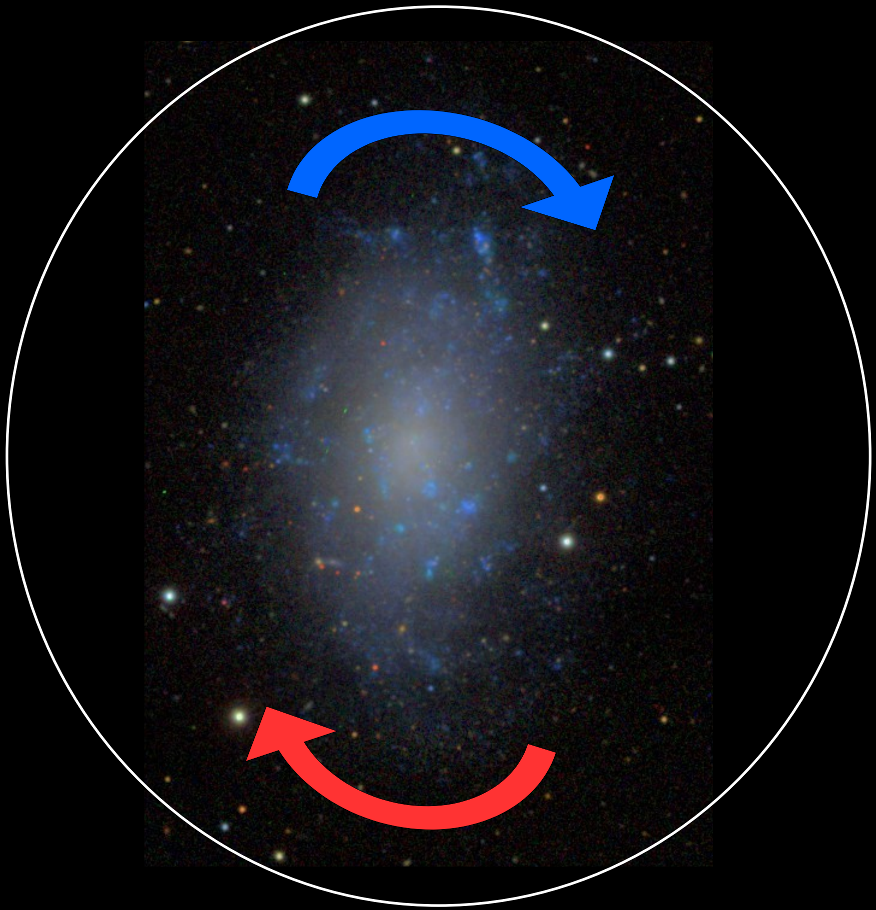

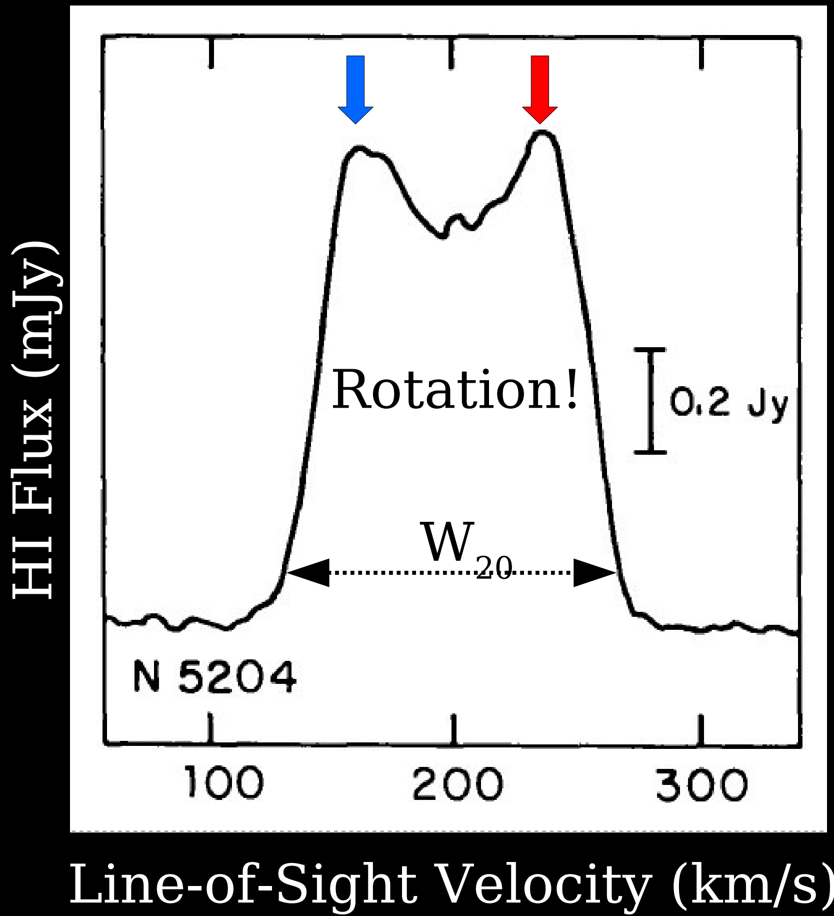

- HI Line-Width: W_{20} (20% of peak flux) $\simeq 2 \langle V_{rot} \rangle \sin(i)$

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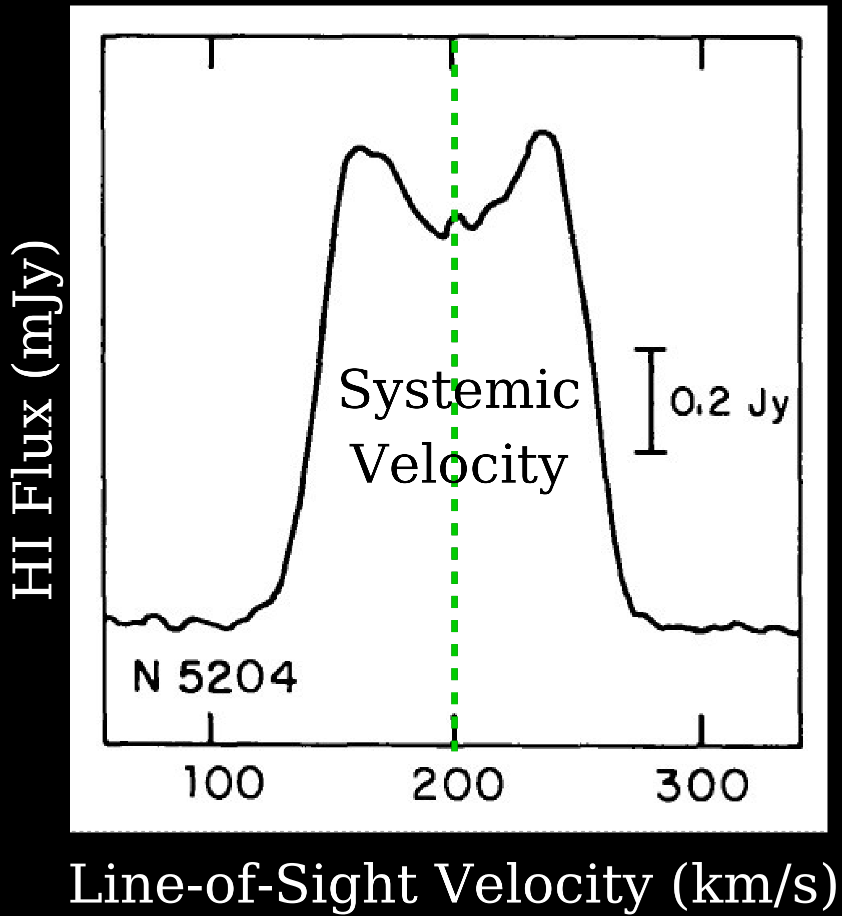

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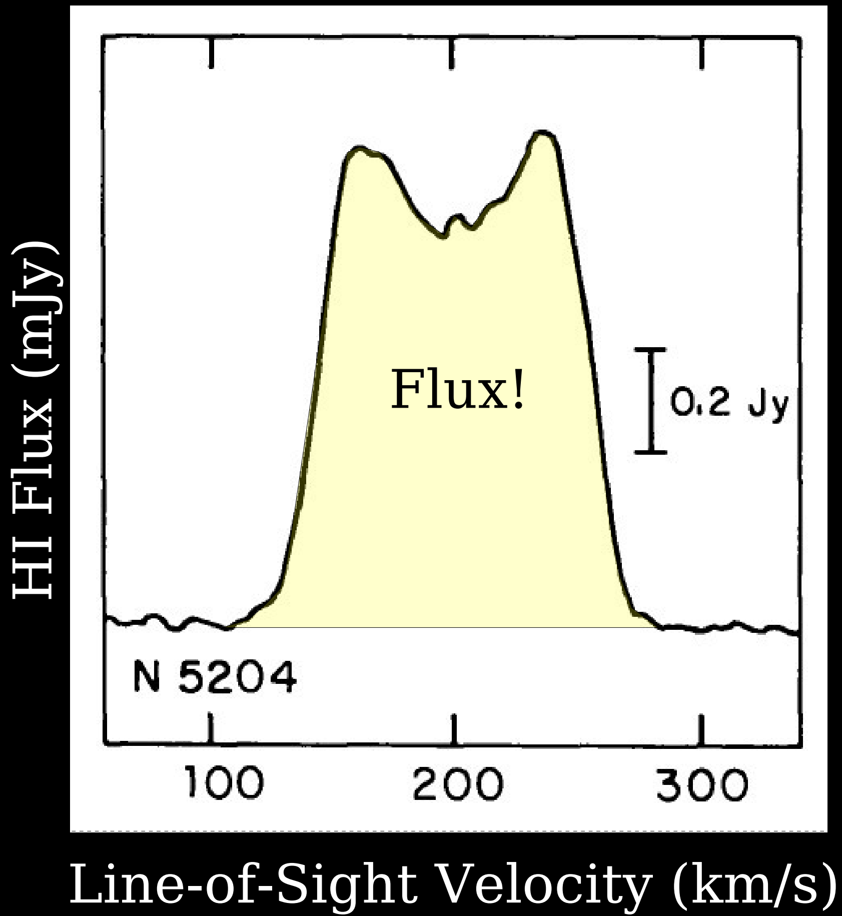

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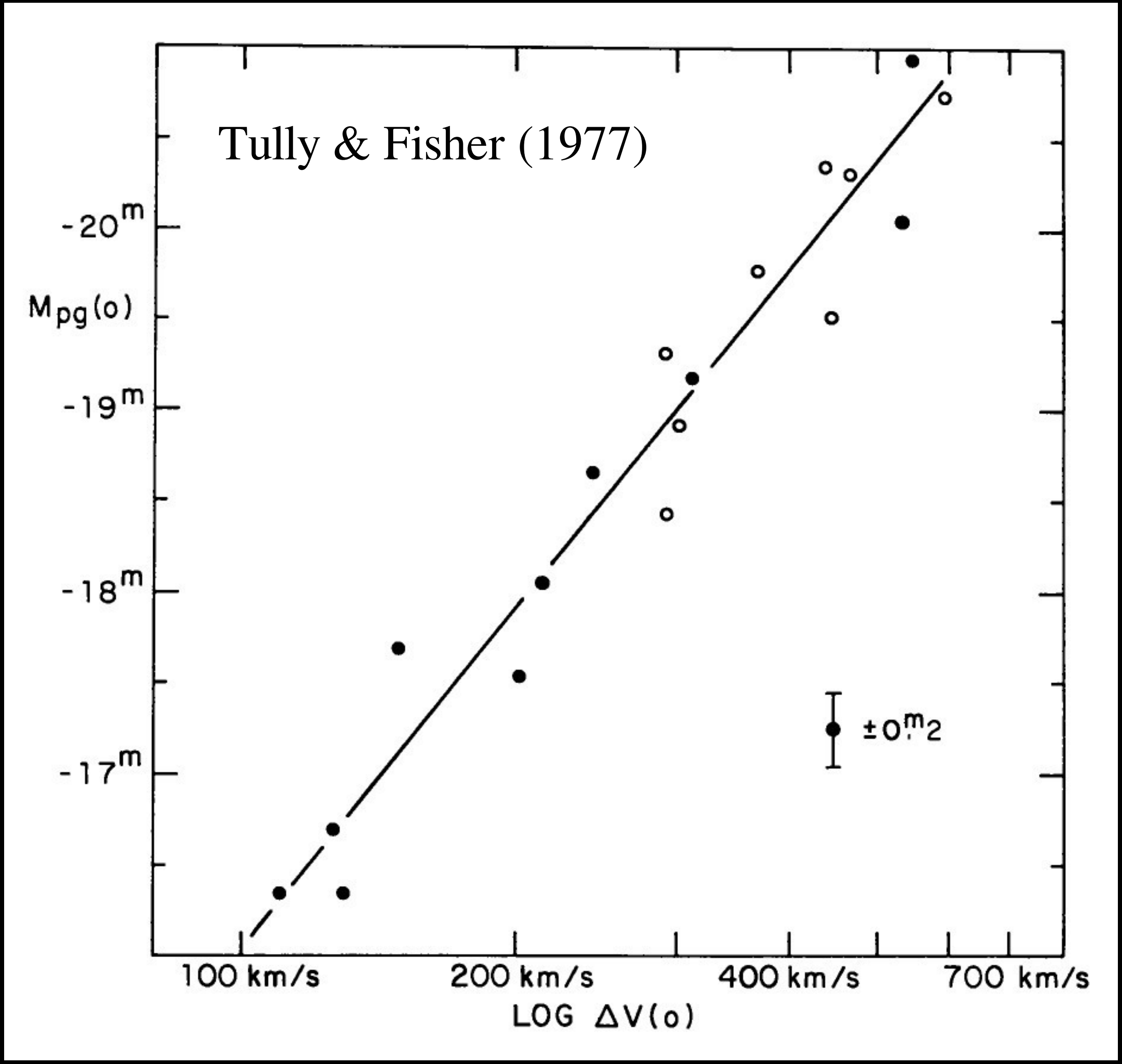
- Systemic Velocity / Redshift: $z \simeq V_{sys}/c$ for low z
- Total HI flux / HI mass: $M_{HI} = 236\, d_L^2\, [\mathrm{Mpc}]\, S_{HI}\, [\mathrm{mJy\ km/s}]$

The Classic Tully-Fisher (TF) Relation

Absolute Magnitude (∝ Distance^2)



HI Line-Width (Distance Independent)

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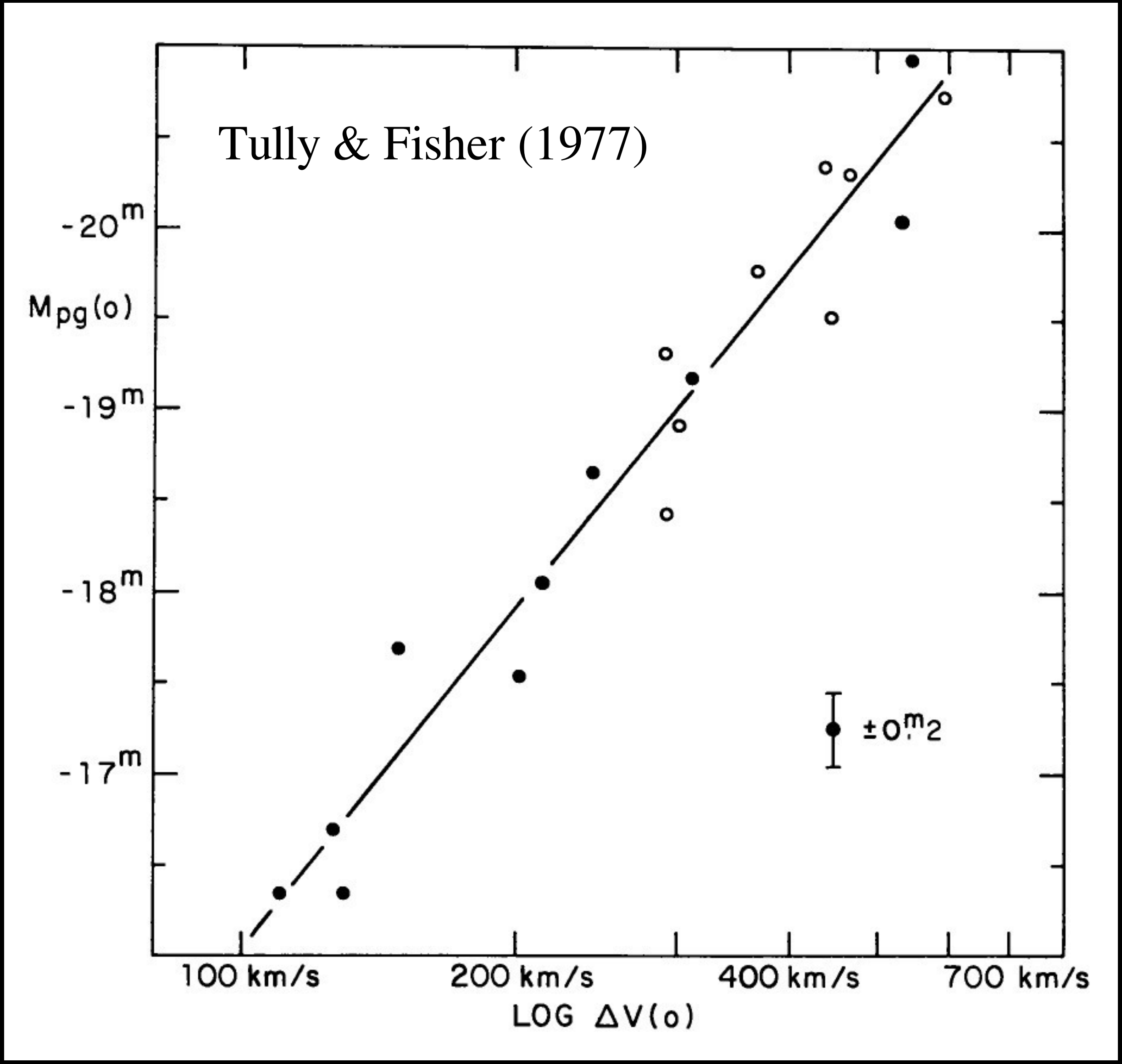

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STEP 1:
Calibrate TF relation using galaxies with known distance (from Cepheids, TRGB, etc.)

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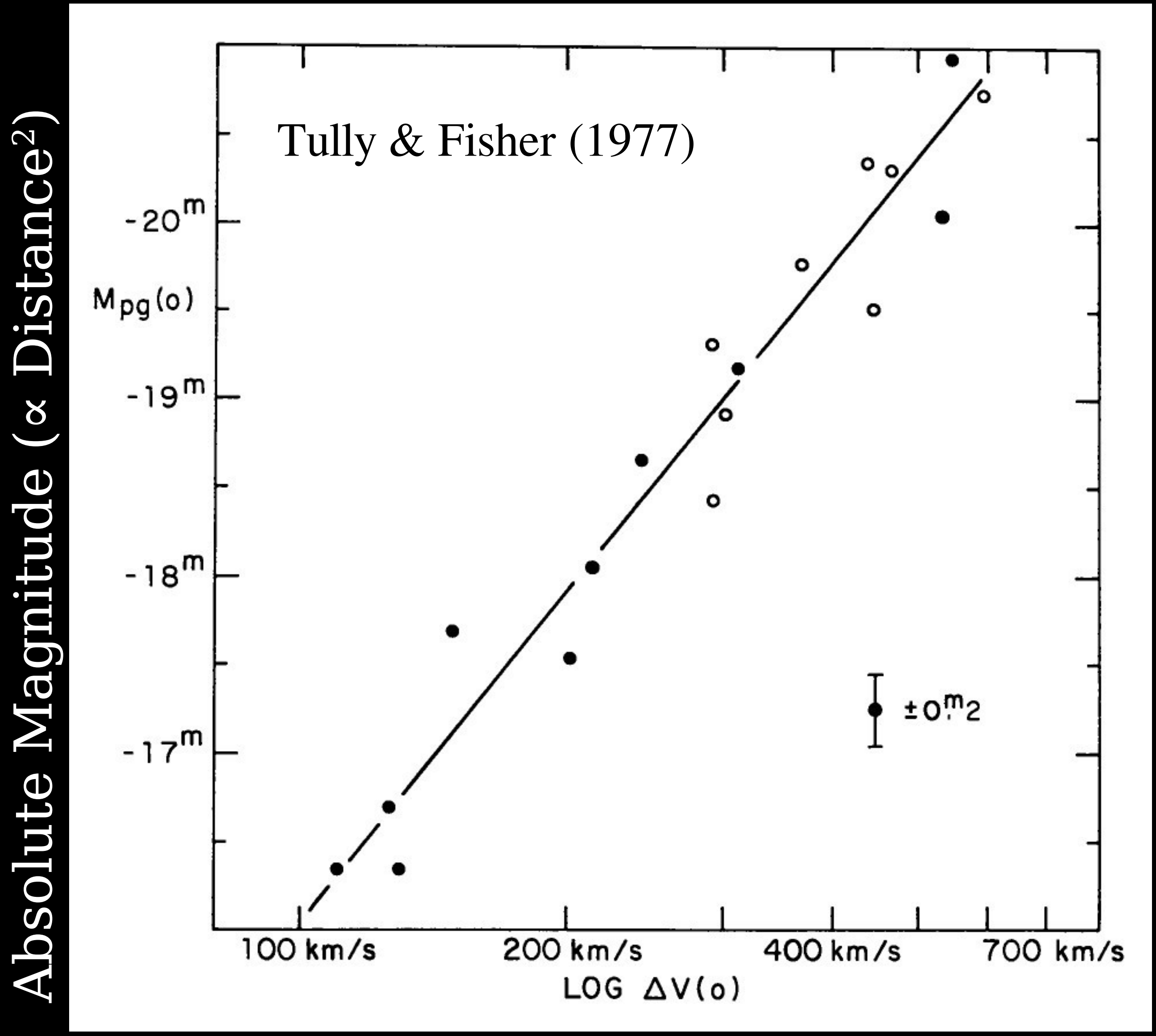

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Measure HI line-widths & apparent mags from radio & optical/IR surveys

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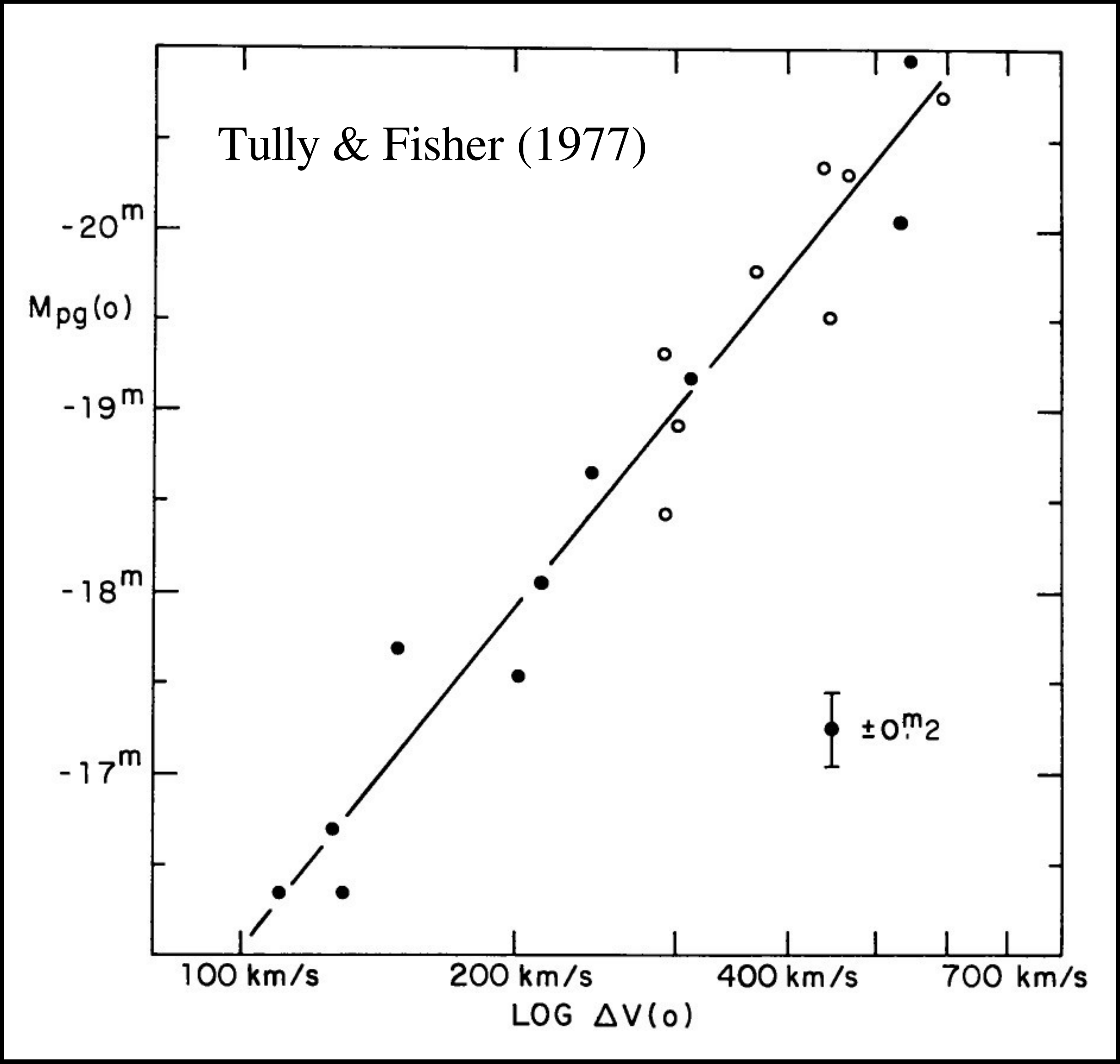

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STEP 1:
Calibrate TF relation using galaxies with known distance (from Cepheids, TRGB, etc.)

STEP 2:
Measure HI line-widths & apparent mags from radio & optical/IR surveys

STEP 3:
Infer distances for large galaxy samples (< 300 Mpc)

→ H_0 = 80 km/s/Mpc

(Tully & Fisher 1977)

Classic Applications of the TF relation

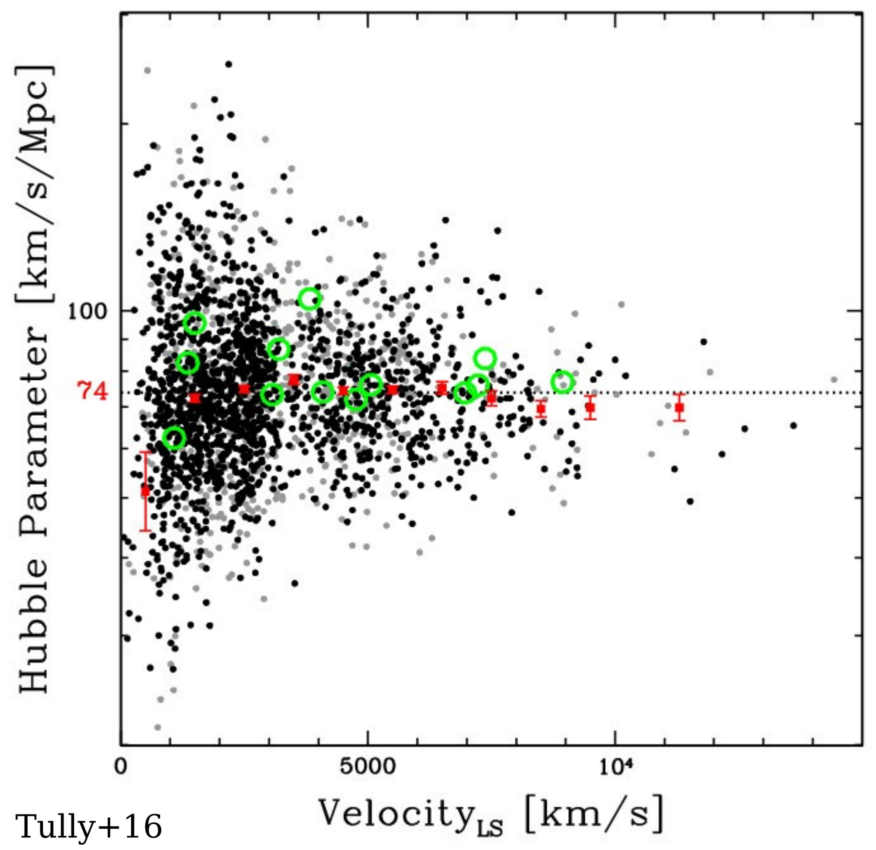
1 - Hubble constant

$V_{sys} \simeq H_0\, d_L + V_{pec}$ at low z

H_0 = 75.0 +/- 2.0 km/s/Mpc (Tully+16)

H_0 = 75.1 +/- 2.3 km/s/Mpc (Schombert+19)

H_0 = 75.5 +/- 2.5 km/s/Mpc (Kourkchi+22)



Tully+16

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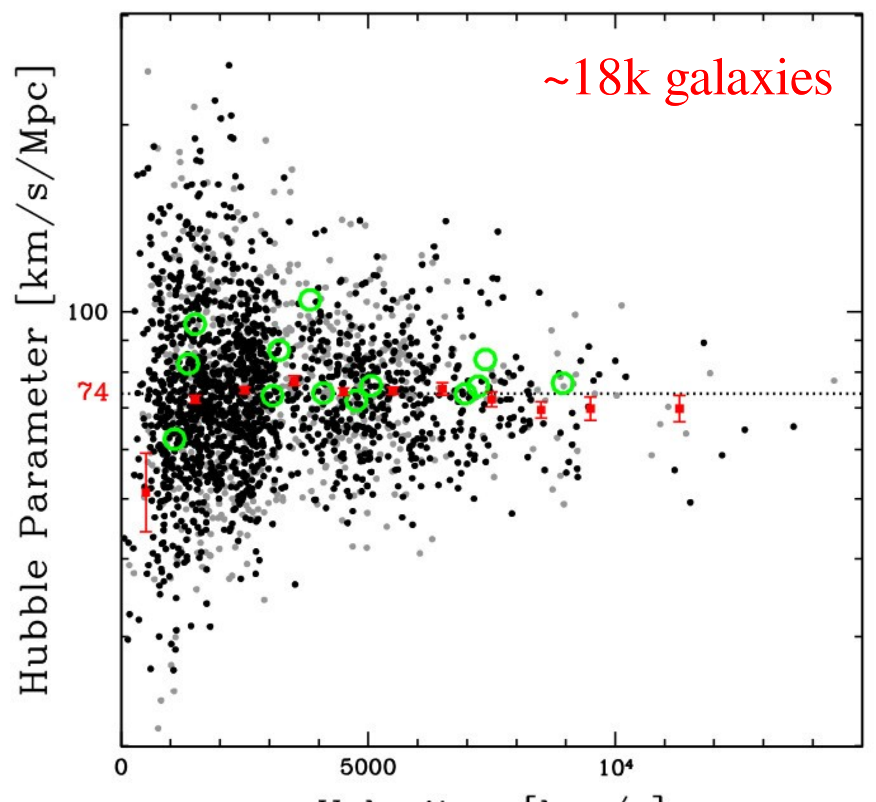


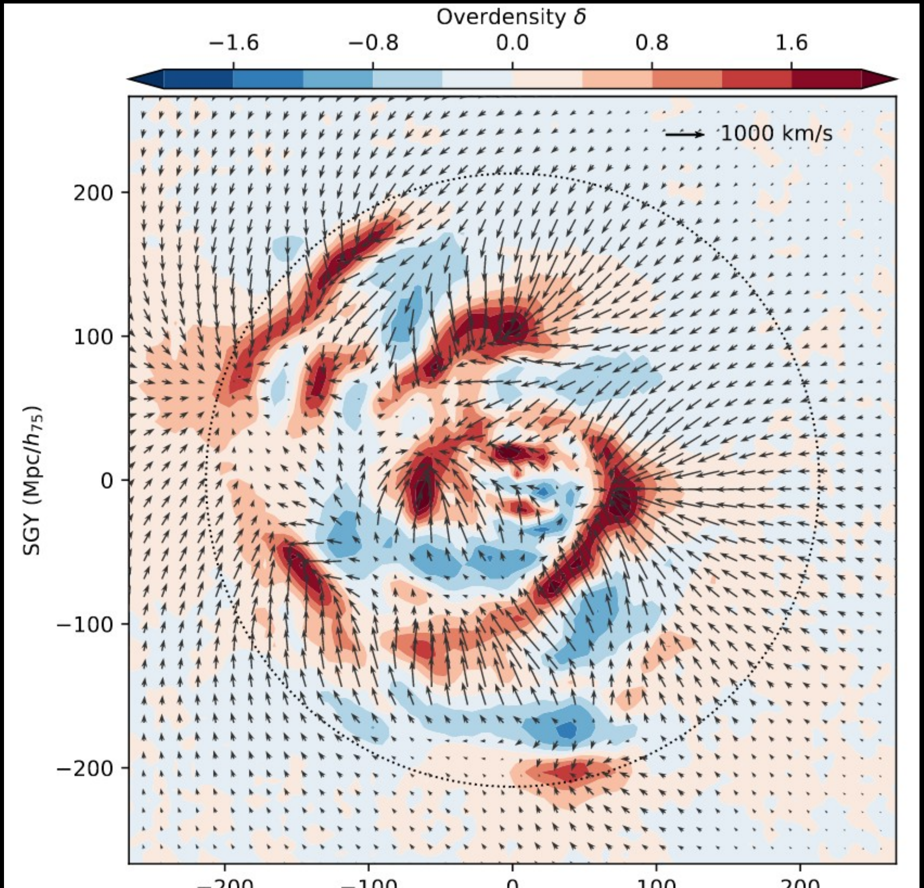
Tully+16

2 - Galaxy Flows

$V_{pec} = c\,[z_{obs} - z_{cos}(d_L)] \,/\, [1 + z_{cos}(d_L)]$

$z_{cos} = f\,(d_L;\, H_0,\, \Omega_m,\, \Omega_\Lambda)$

(Tully+16, Graziani+19, Kourkchi+20)



Graziani+19

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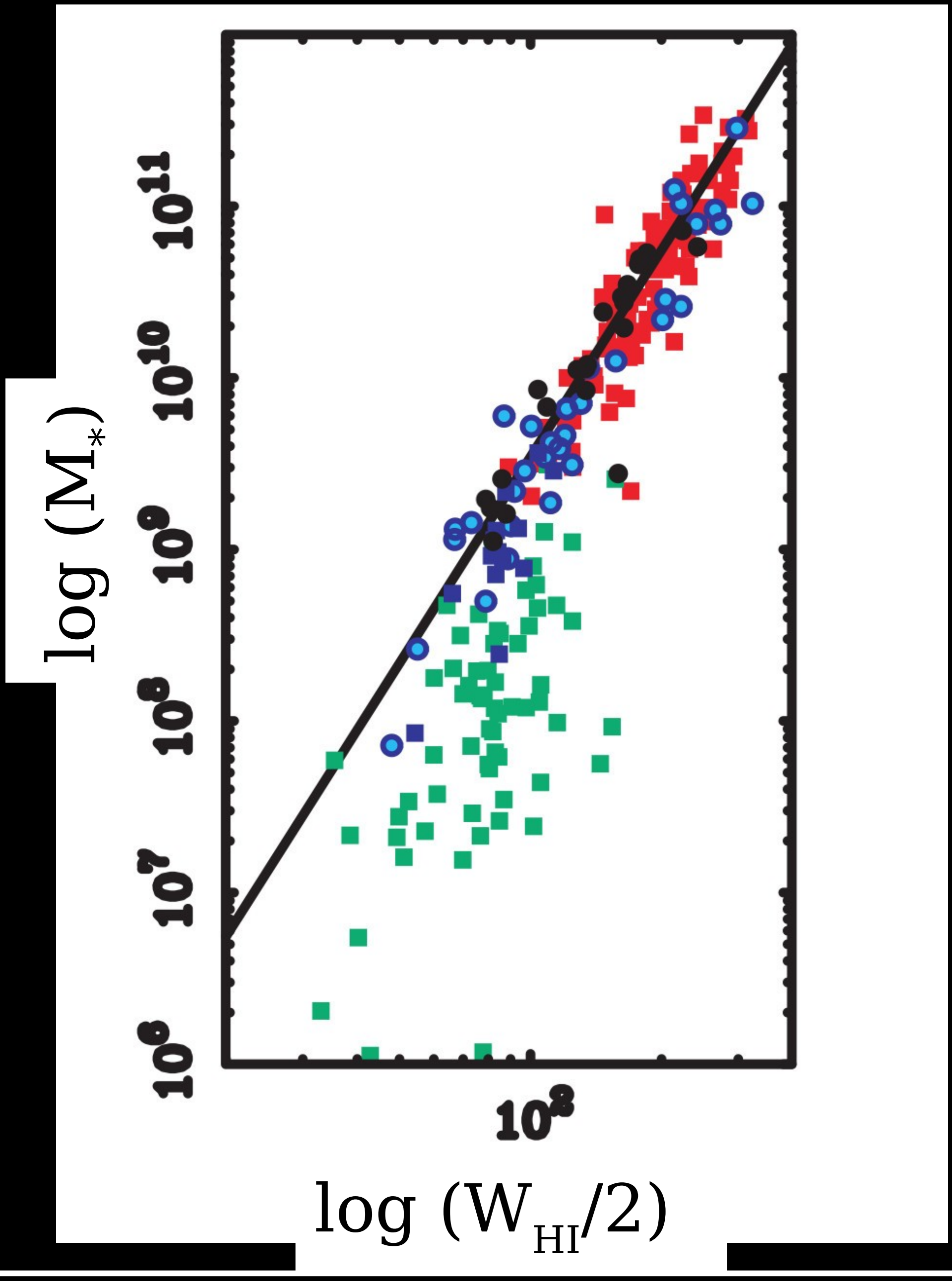
Luminosity and HI linewidth are proxies for more fundamental physical quantities!

Objective: find the quantities that give the tighter relation

Optical/Near-IR Luminosity → Stellar Mass

Stellar-Mass TF Relation



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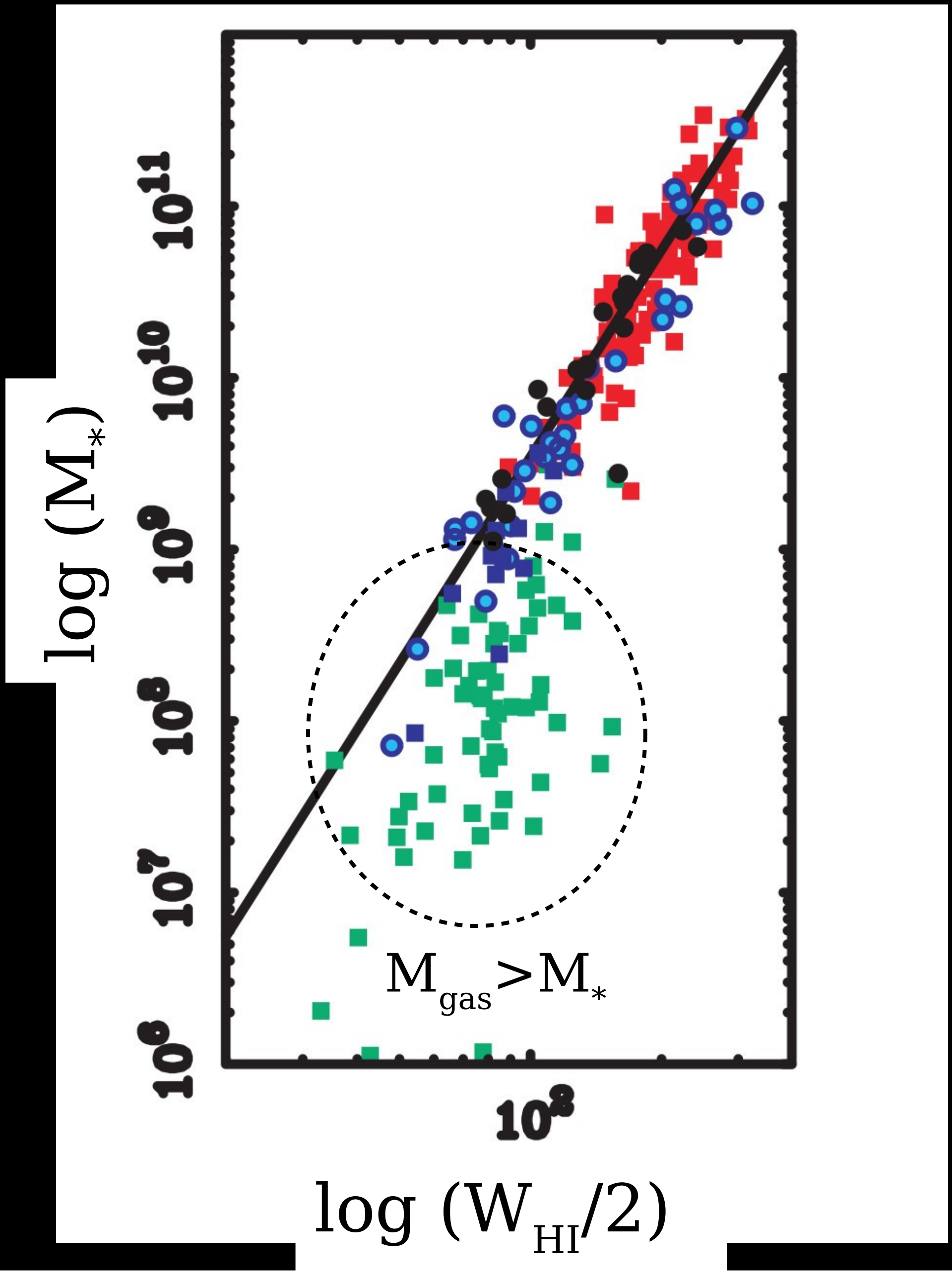
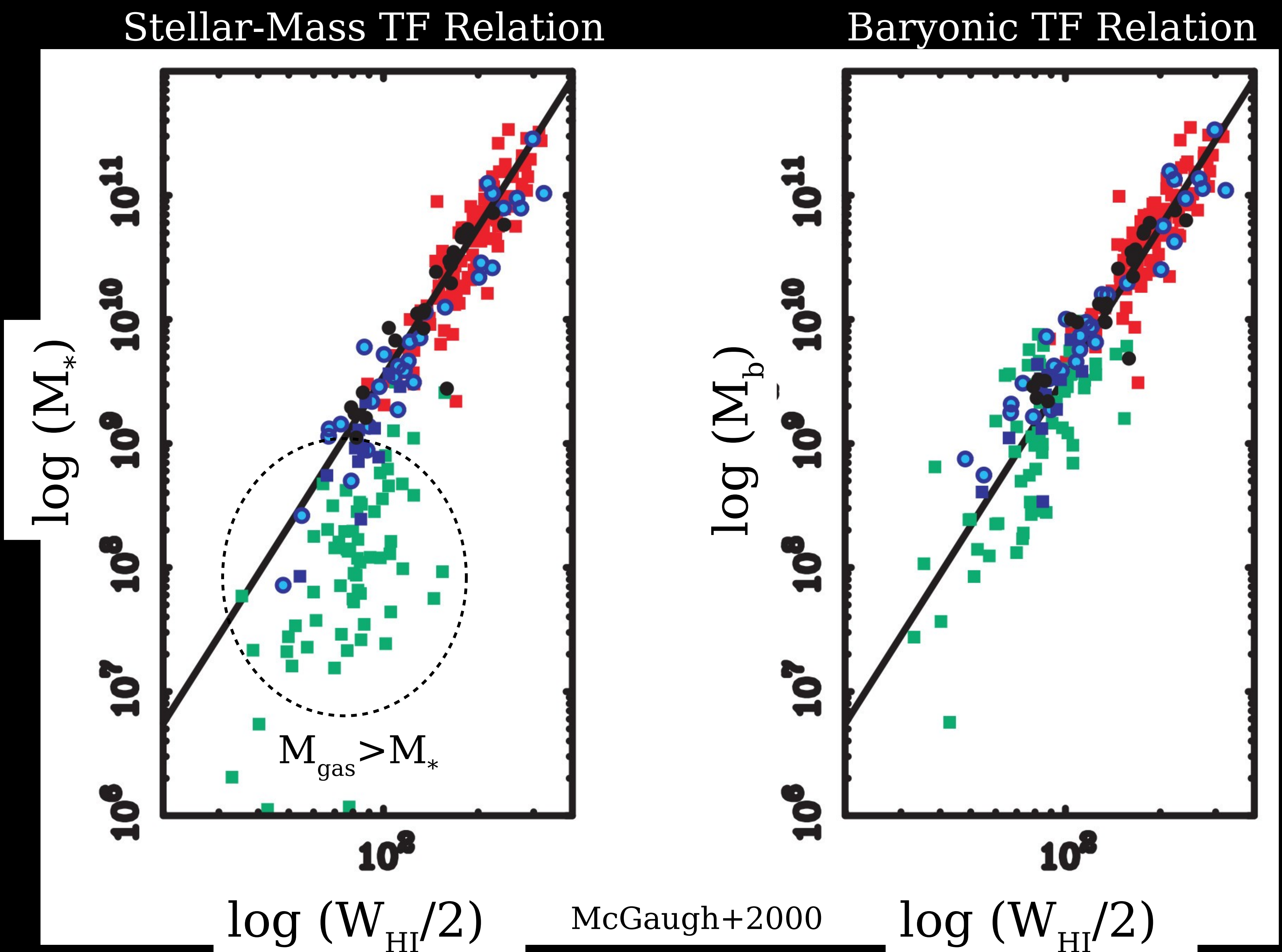
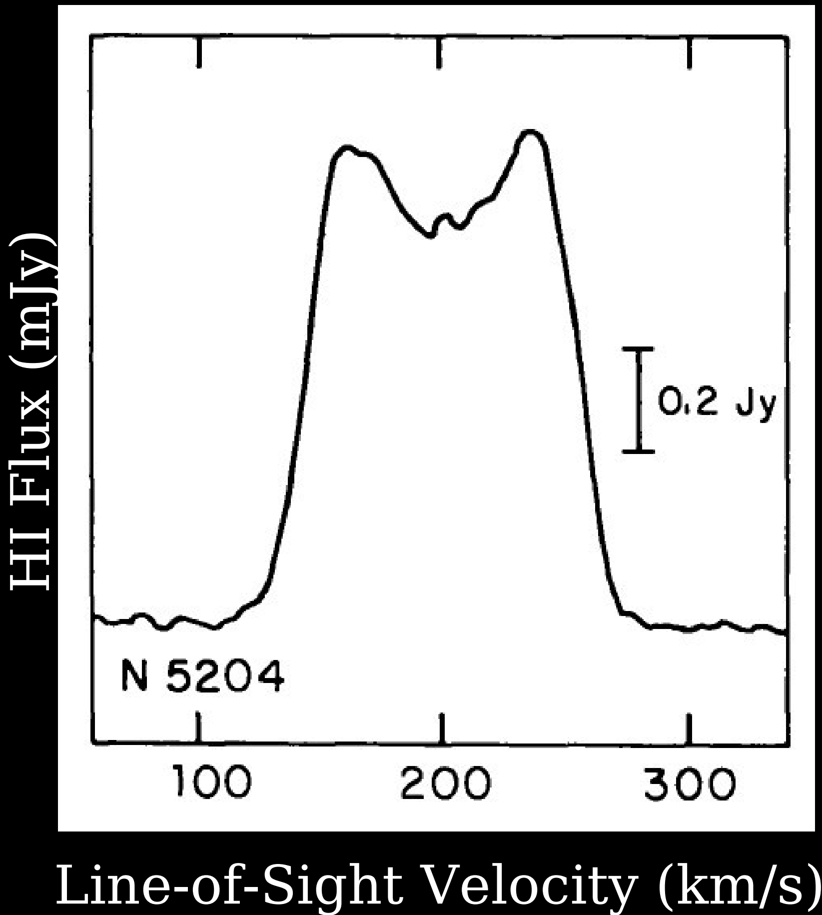


Baryonic Mass (stars+gas) is the key!



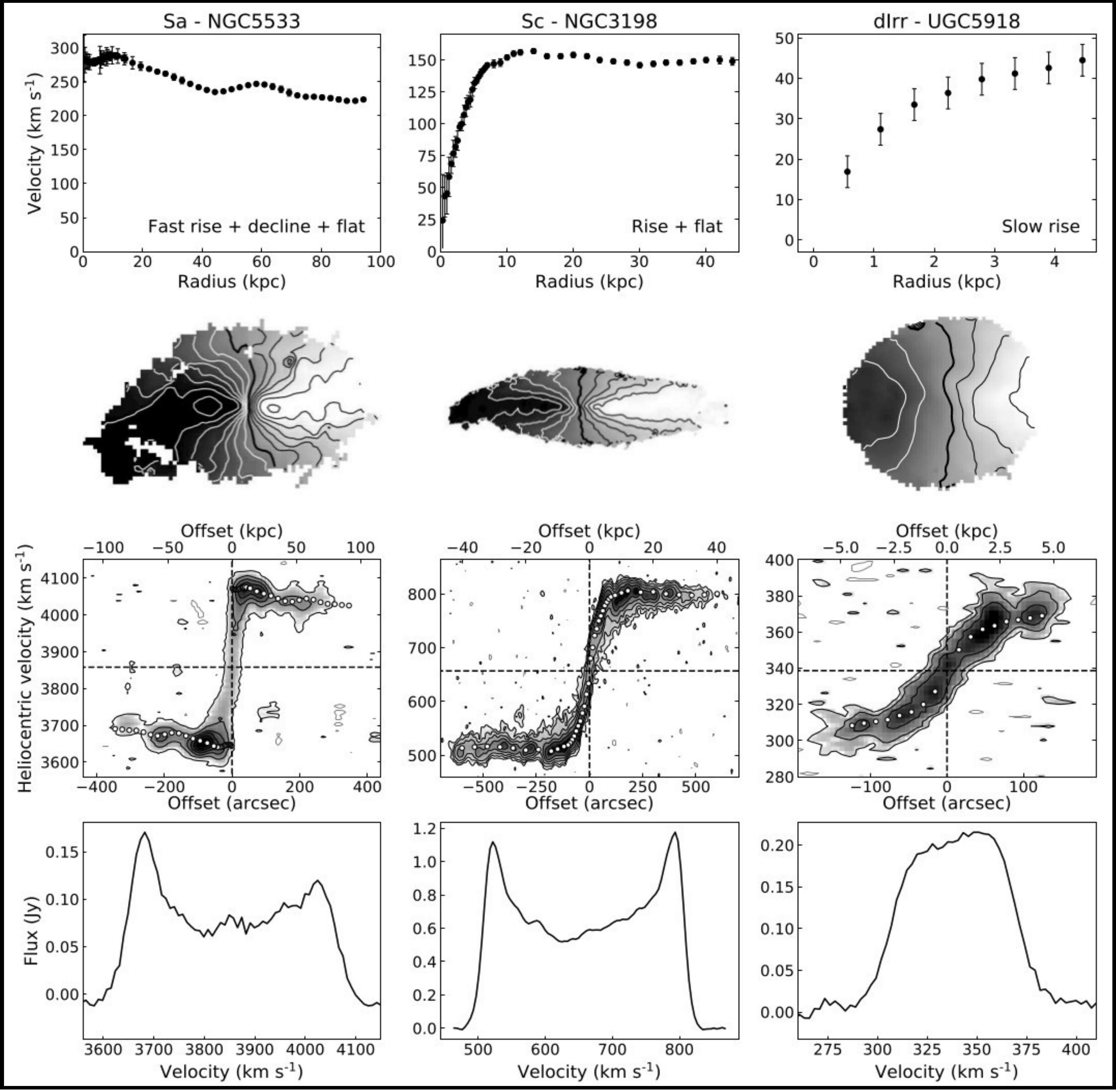
What's the HI line-width really measuring?



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

Need to spatially resolve HI distribution and kinematics!

Rotation Curves for Different Galaxies



Rotation Curve:

V_{rot} *vs* Radius

Velocity Field:

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

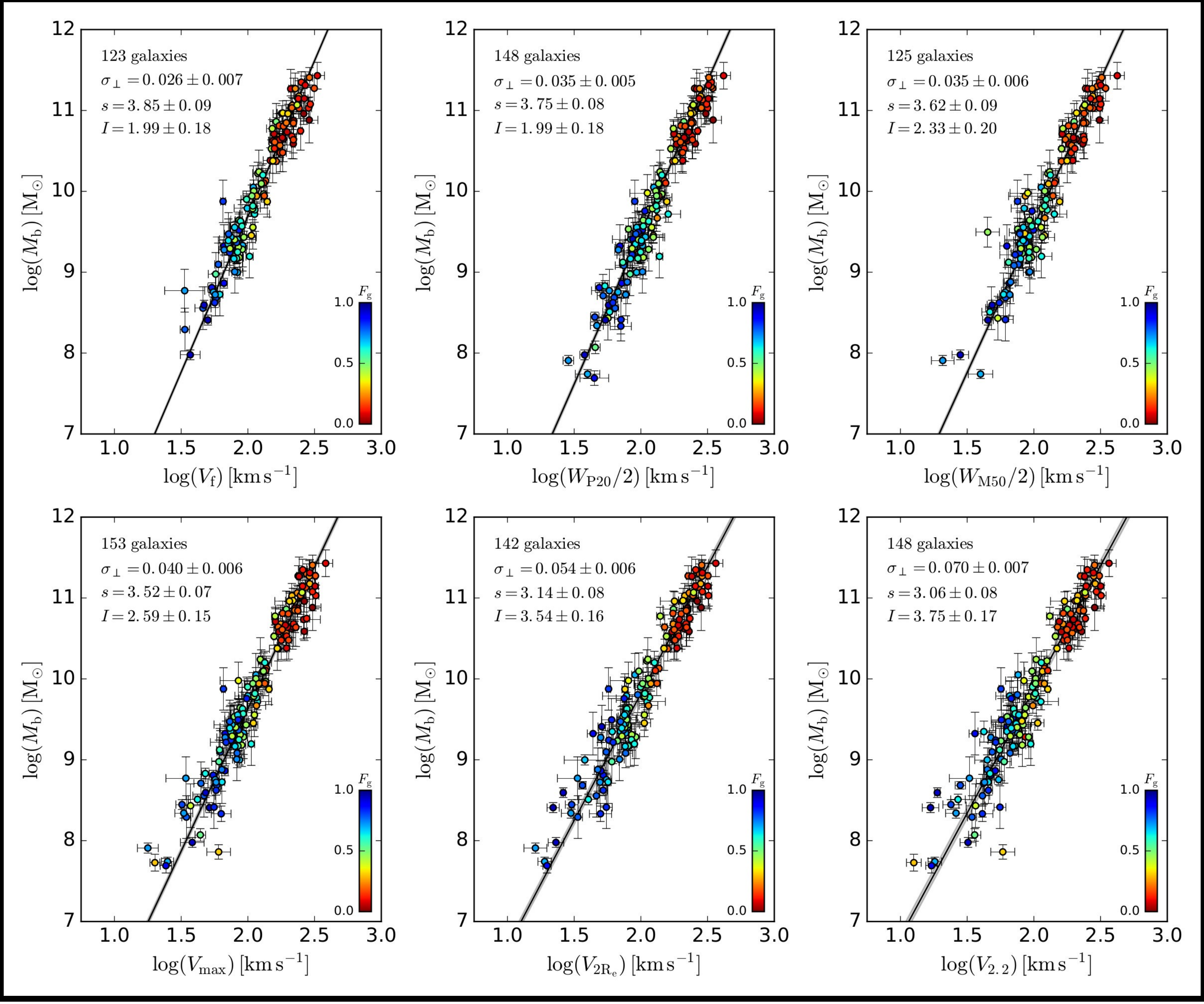
Major-Axis PVD:

$V_{rot} \sin(i)$ *vs* Radius

Global HI profile:

Cimatti, Fraternali, Nipoti (2019)

BTFR for different velocity definitions



Lelli+2019

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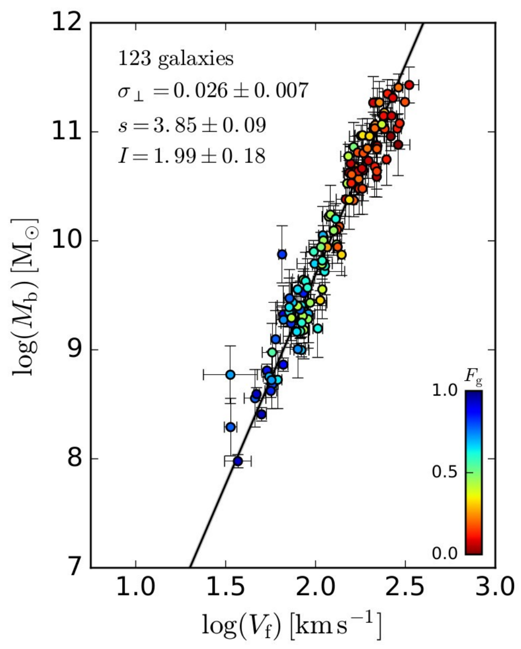
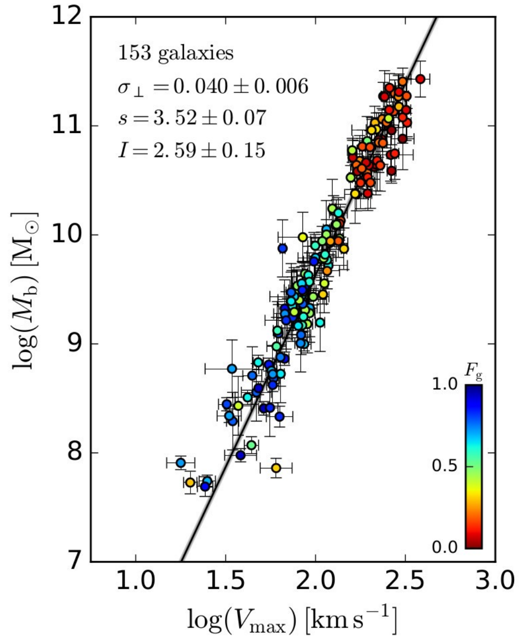
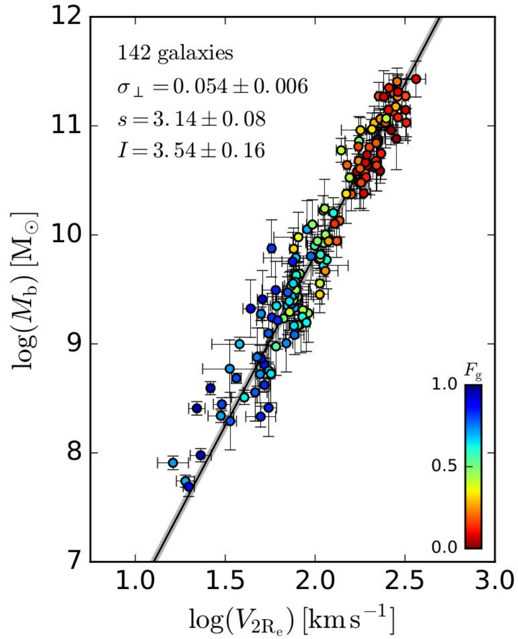


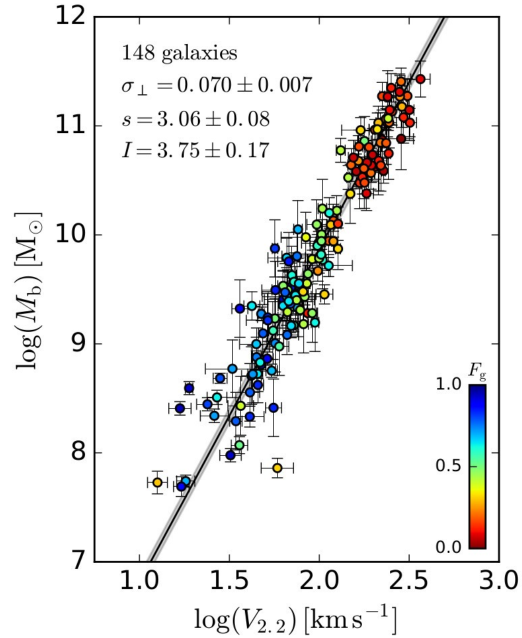
The mean rotation velocity along flat part (V_f) gives the tightest and steepest BTFR!

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

Counter intuitive: Baryons important near the center but M_b best correlate with V_f (mostly set by the dark matter halo)!

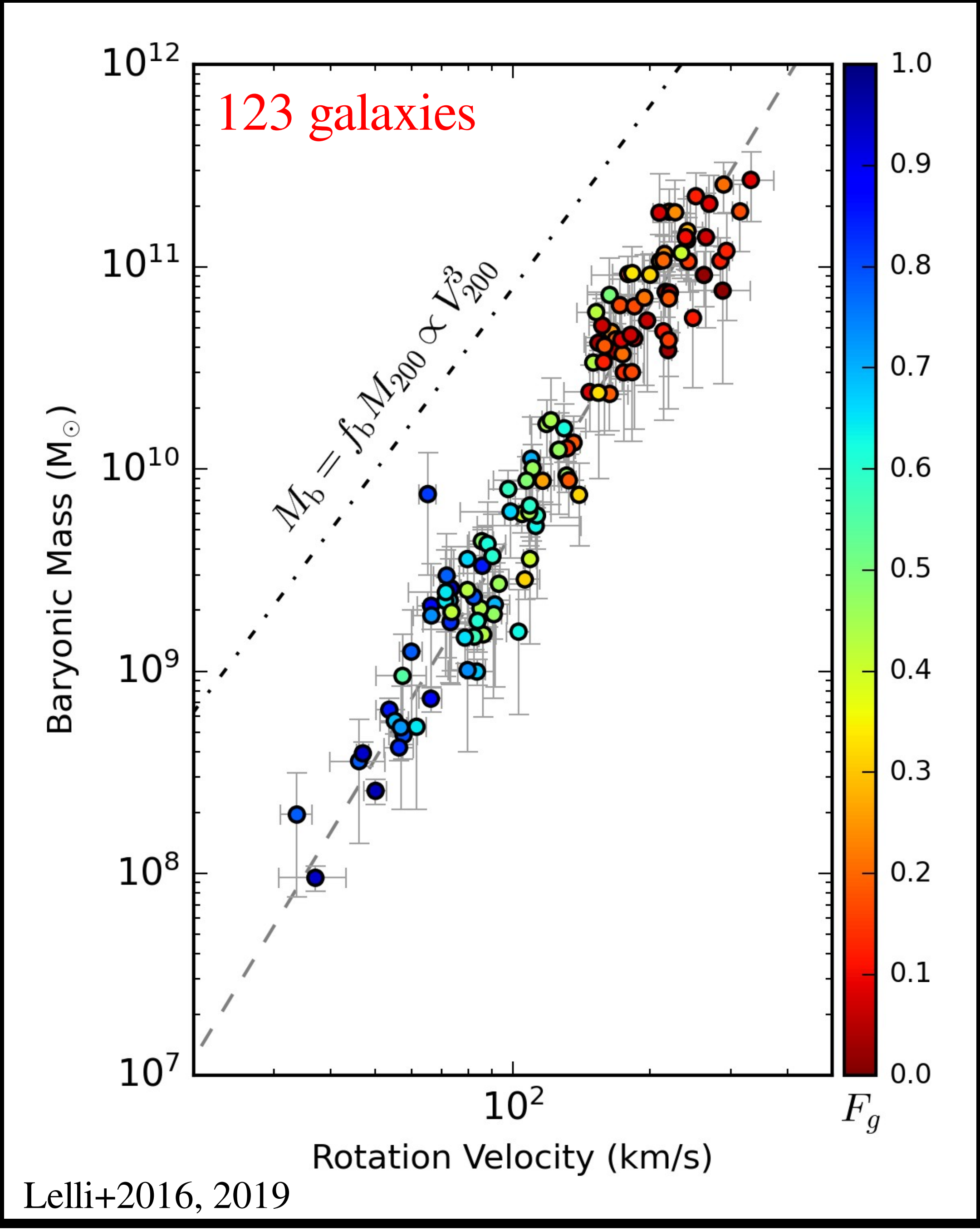






Lelli+2019

Baryonic TF relation in a ΛCDM context



From basic arguments (McGaugh 2012):

$$M_b = \sqrt{\frac{2}{\Delta}} \frac{1}{GH_0} f_b f_V^{-3} V_f^3$$

$$f_b = \frac{M_b}{M_\Delta} \qquad f_V = \frac{V_f}{V_\Delta}$$

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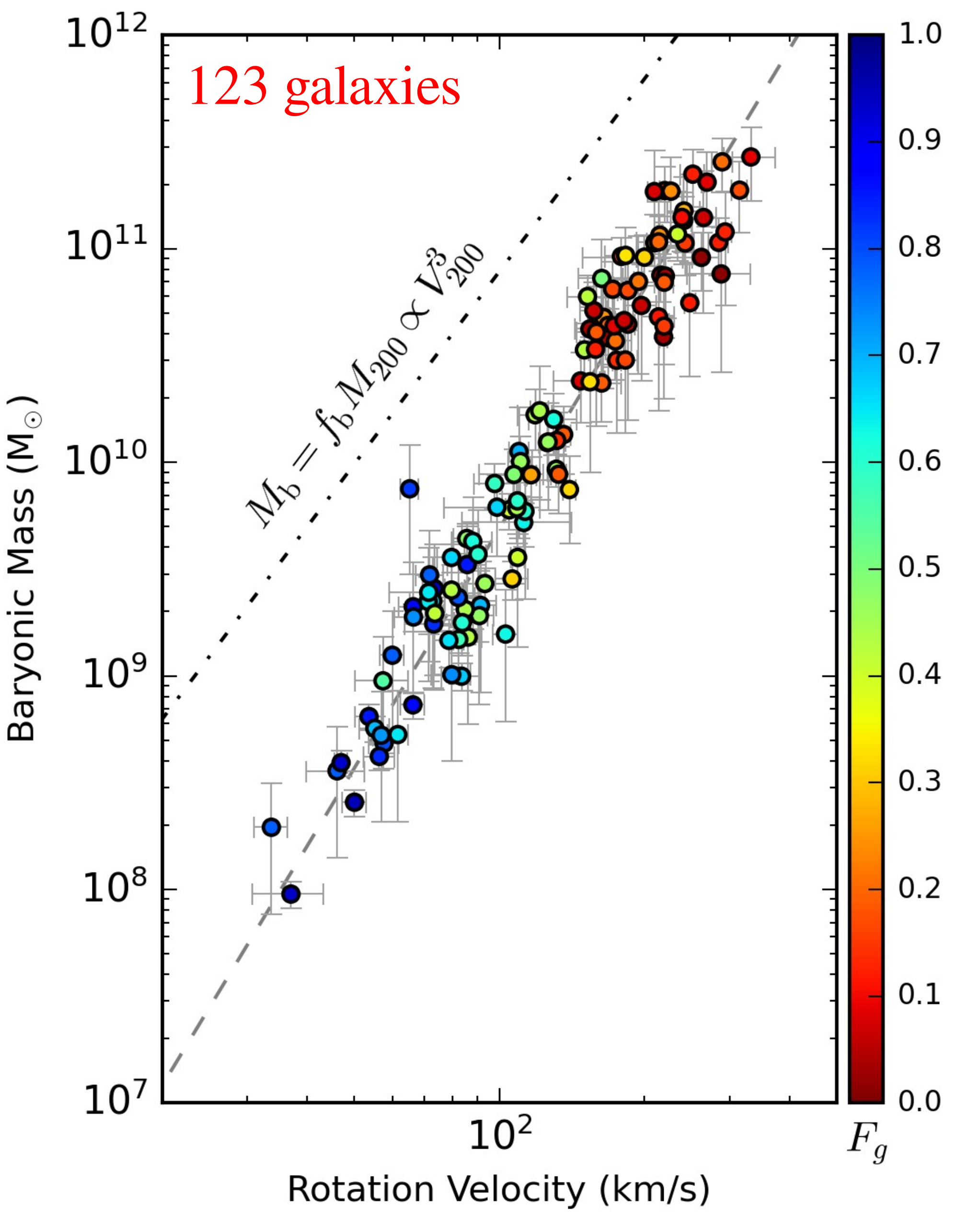

Lelli+2016, 2019

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Simplest working hypotheses:

$f_b = f_{cosmic} = \Omega_b / \Omega_m$ From CMB

$f_V = O(1)$ OK for most halo profiles

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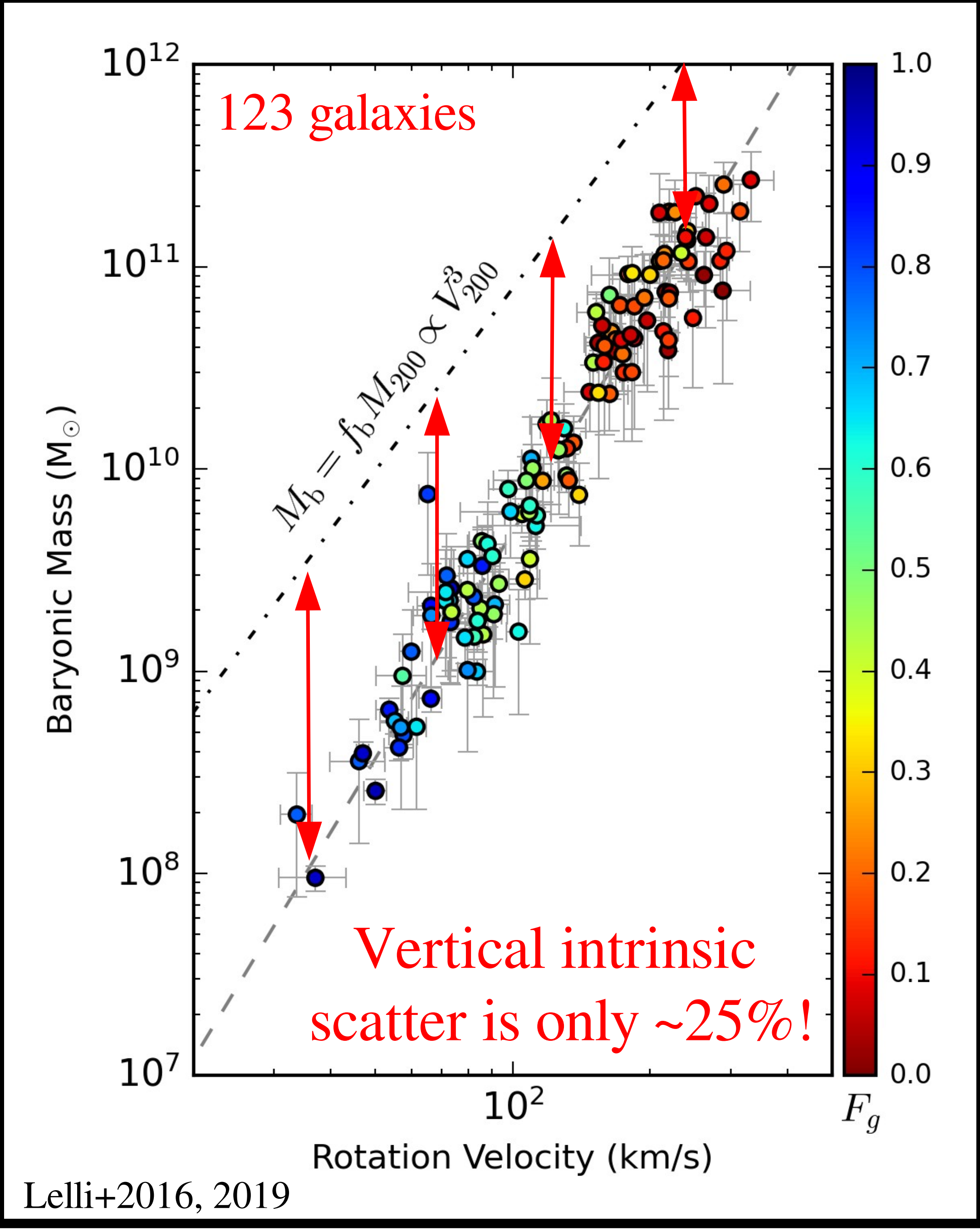

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To get lower normalization:

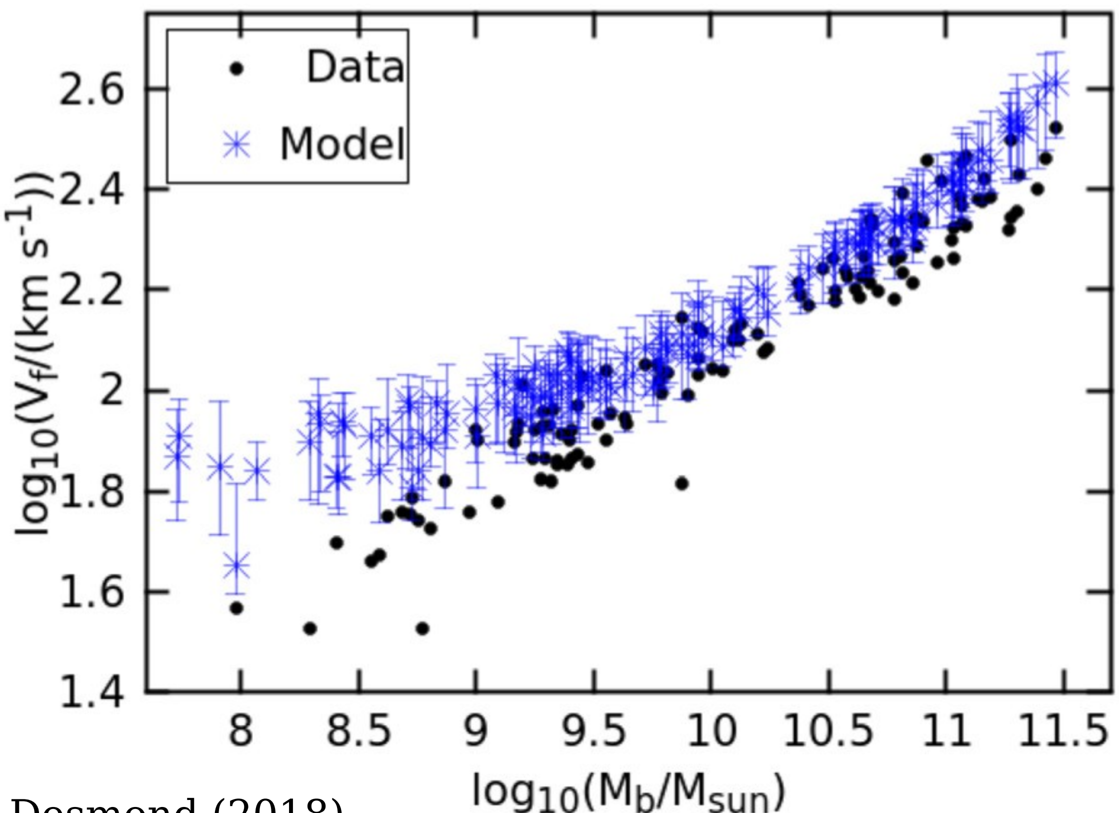
$f_b < f_{CMB}$ → missing baryons problem

To get slope of about 4:

f_b must systematically vary with V_f

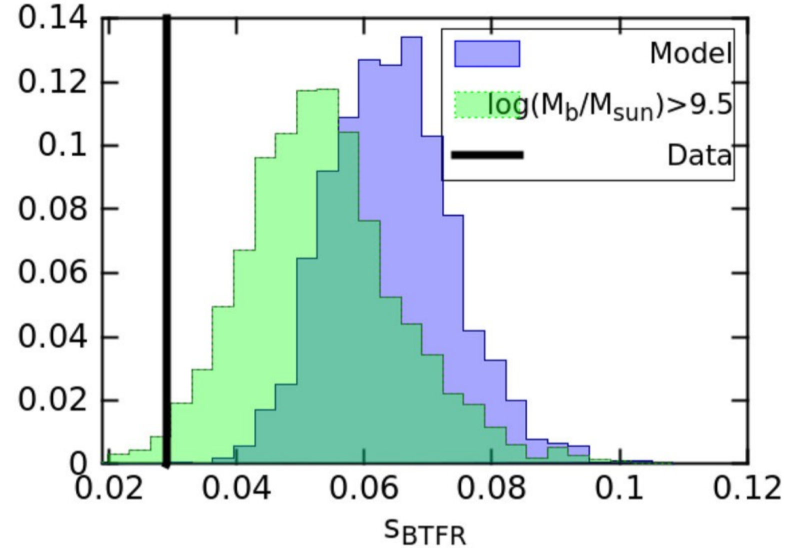
→ fine-tuning problem for ΛCDM!

BTFR from semi-empirical ΛCDM models

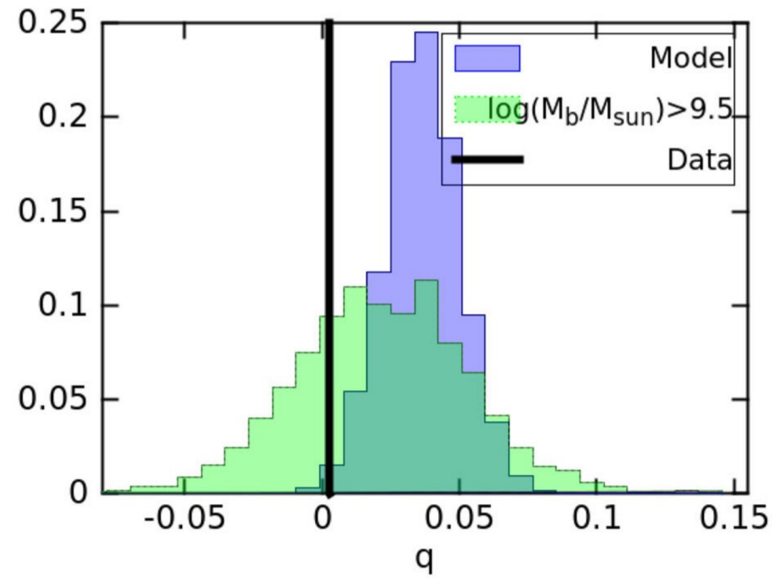


Desmond (2018)

Scatter is 3.6σ too high!



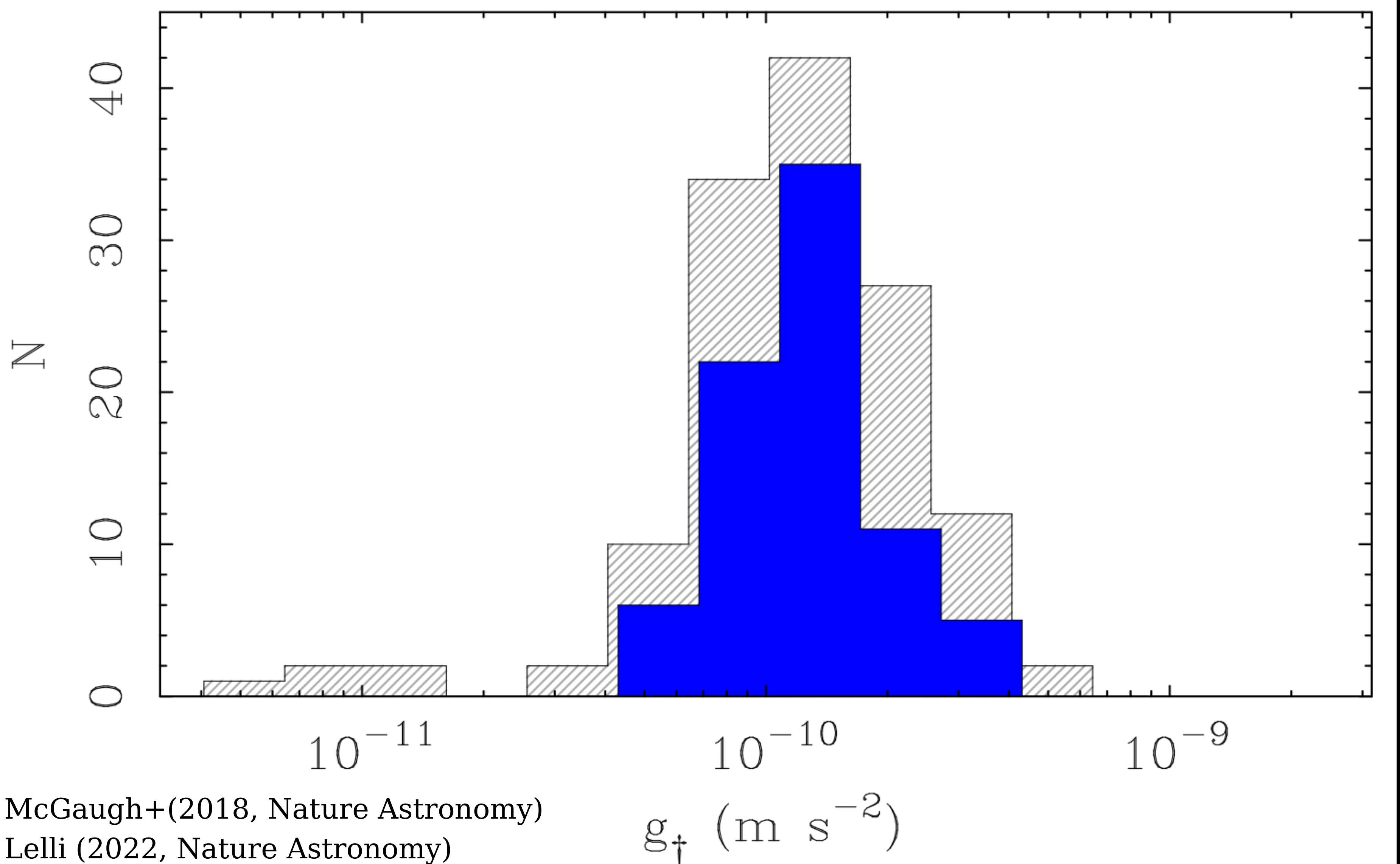
Curvature is 3σ too strong!



Scatter on BTFR should emerge from

- Scatter in $f_b = M_b/M_{200}$
  (galaxy formation is stochastic!)
- Scatter in $f_v = V_f/V_{200}$
  (halo properties, e.g., M_{200}-C_{200} relation)

Slope~4 ➡ Acceleration Scale



McGaugh+(2018, Nature Astronomy)
Lelli (2022, Nature Astronomy)

On dimensional grounds: $g_\dagger = V_f^4 / (G_N M_b)$

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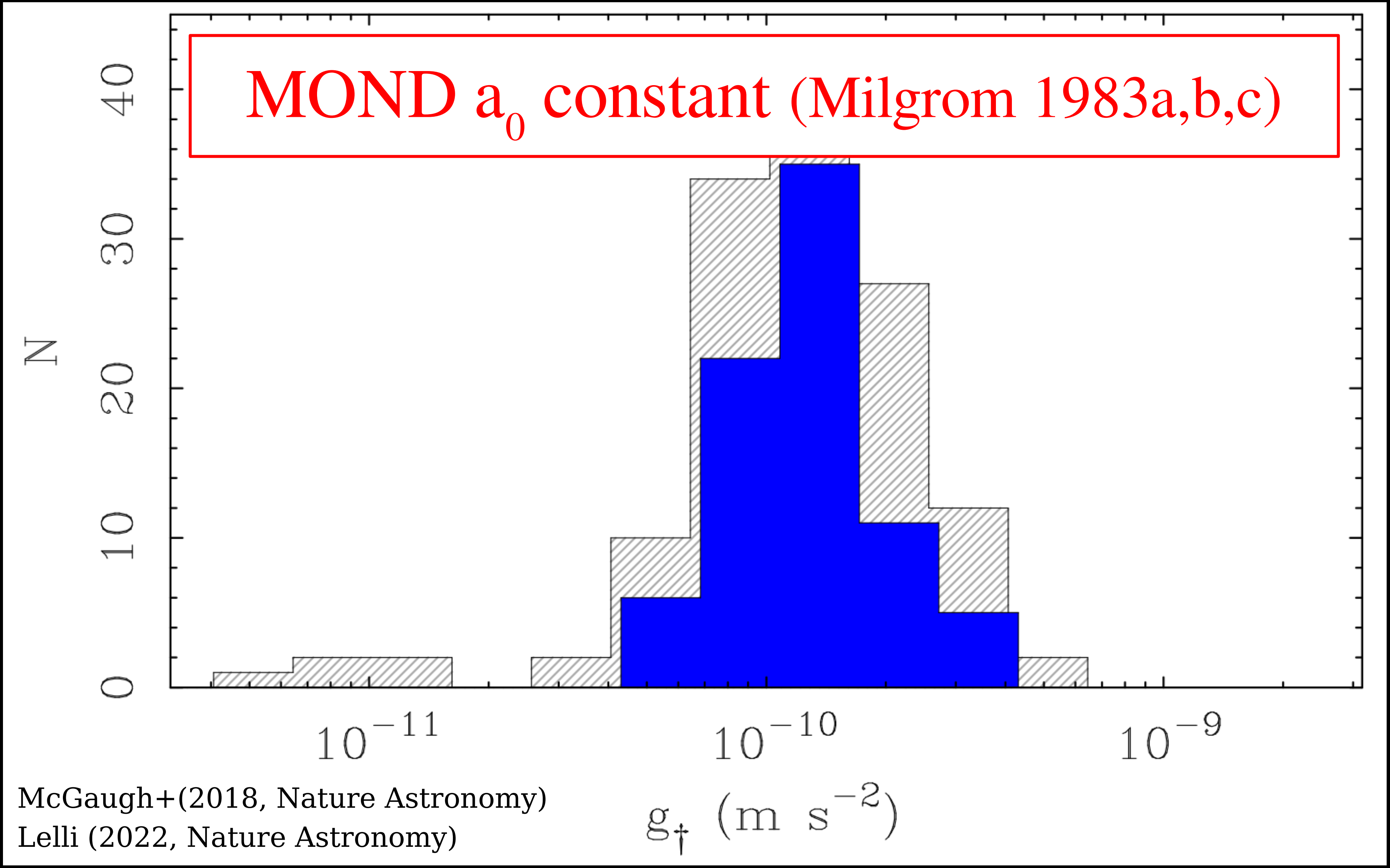

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Take-home points on the TF relation

1. Empirical tool to measure galaxy distances

→ $H_0 \simeq 75 \pm 2$ km/s/Mpc (Tully+16, Schombert+19, Kourkchi+22)

→ Galaxy flows: mass distribution within 200 Mpc (Graziani+19, Kourkchi+20)

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2. Baryonic TF relation (M_b vs V_f) is most fundamental

→ Link between baryons and DM in galaxies (McGaugh+2000, Verheijen+2001)

→ Small intrinsic scatter (25%): fine-tuning problem in ΛCDM (Lelli+2016)

→ Slope ≃ 4: Acceleration scale of ~10^{-10} m/s^2 (McGaugh+2018, Lelli 2022)

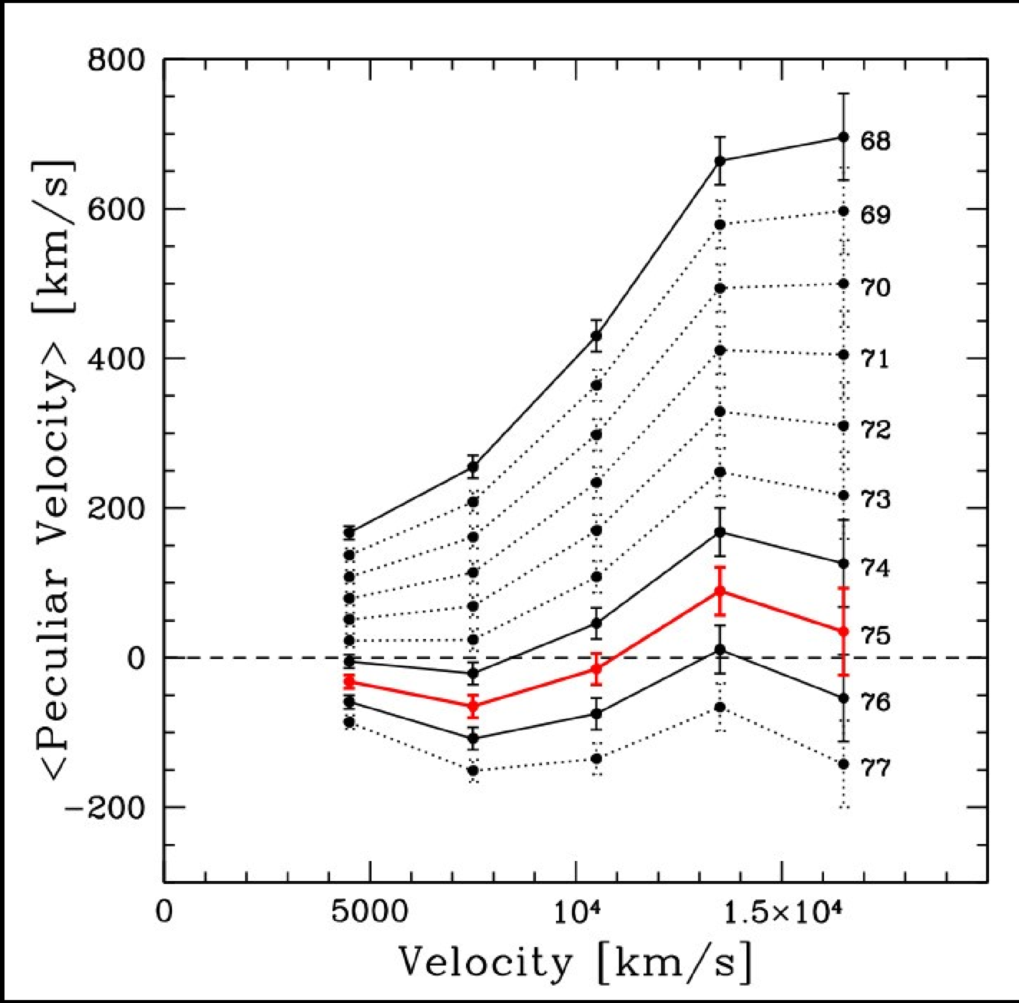
→ Consistent with a-priori predictions of MOND (Milgrom 1983a,b,c)

More Slides

Peculiar Velocities & Hubble Constant

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

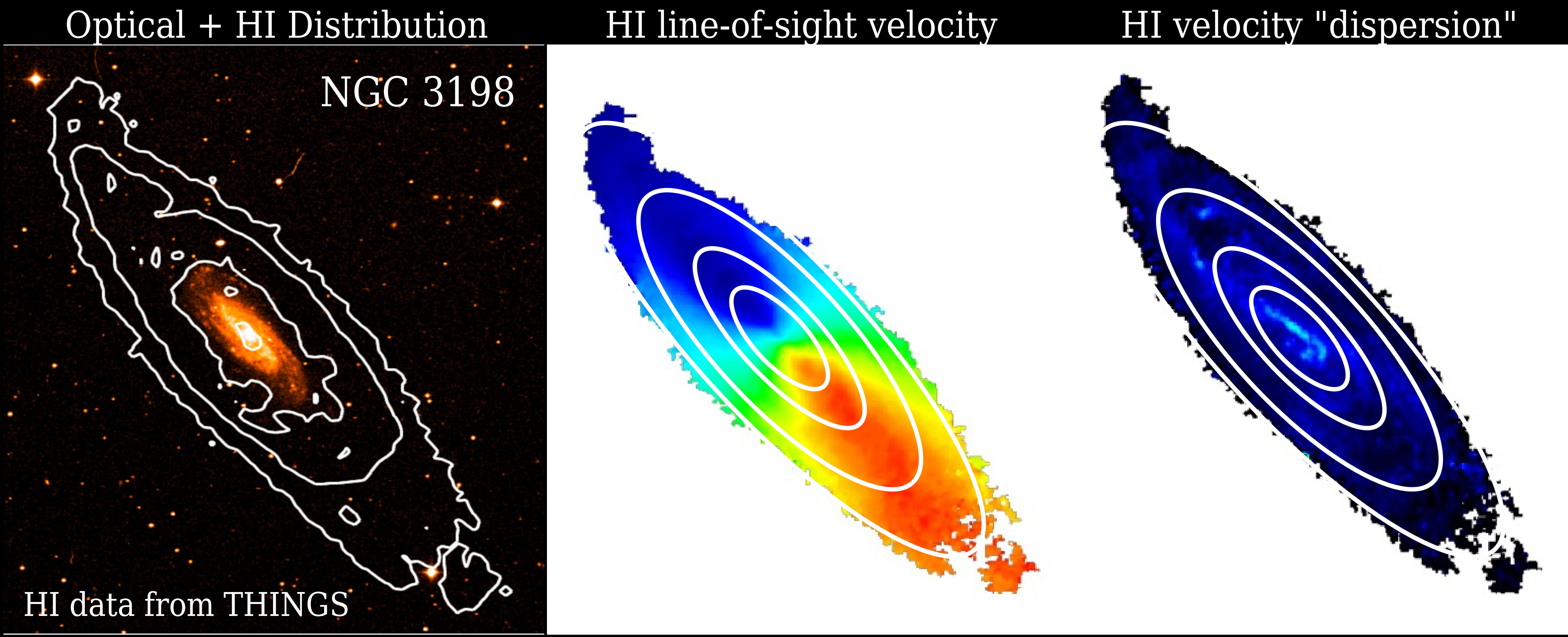
Fix Ω_m and Ω_Λ (or equivalently q_0), vary H_0 and get different V_{pec}



Cosmicflows:
10k galaxies

Tully+2016:
H_0 = 75 +/- 2

HI distribution and kinematics



How to derive a rotation curve:

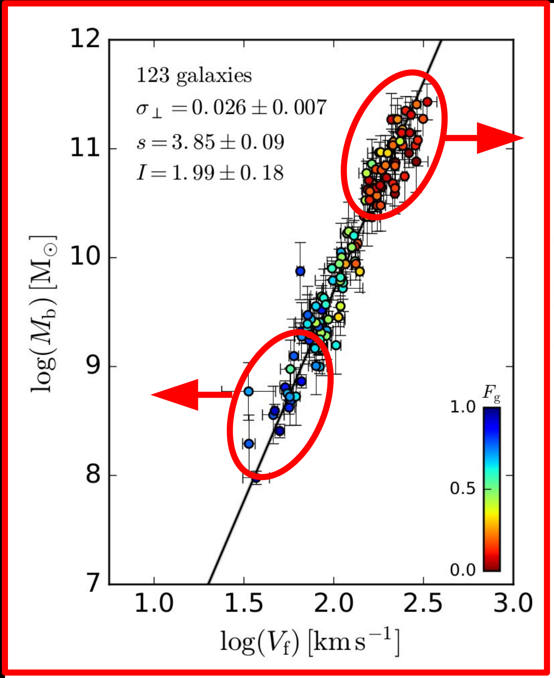
- Divide galaxy into a set of concentric rings
- Deprojection from sky plane to galaxy plane

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

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

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

BTFR for different velocity definitions



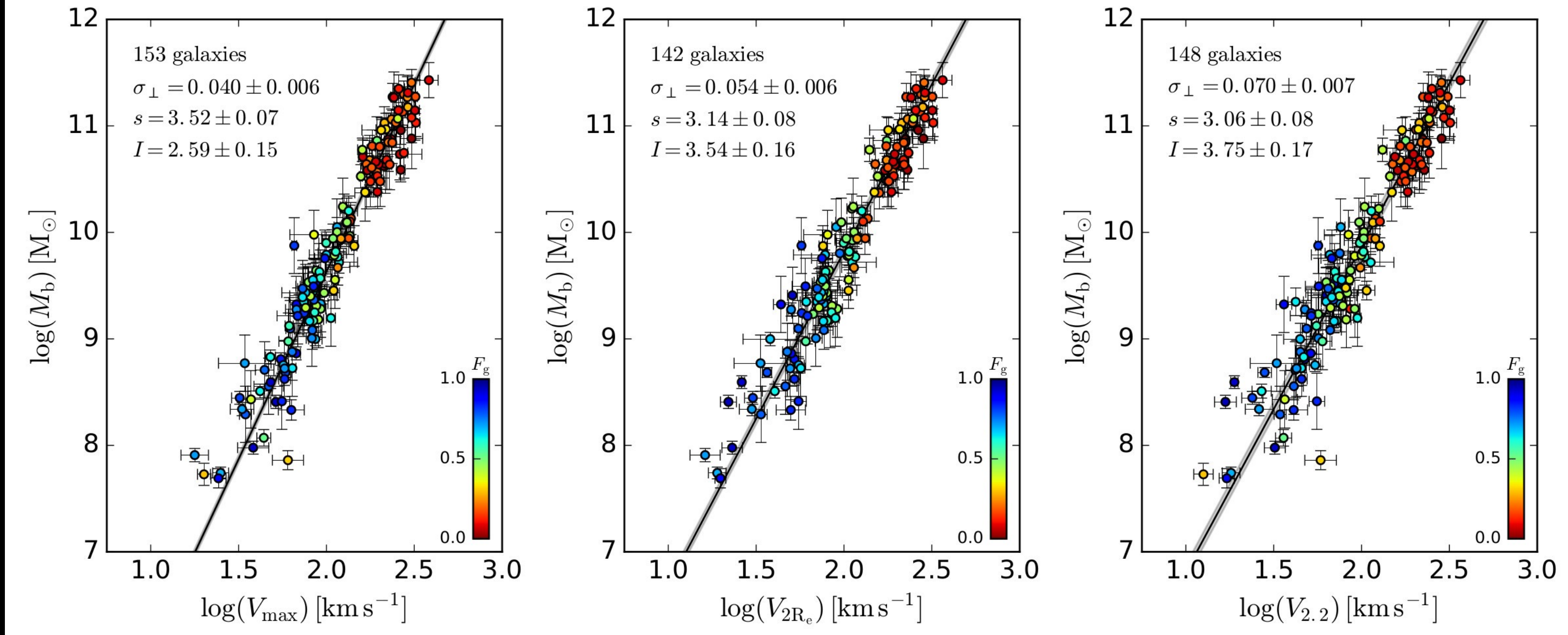
Why M_b-V_{flat} relation is steeper?

Rotation curve shapes!

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

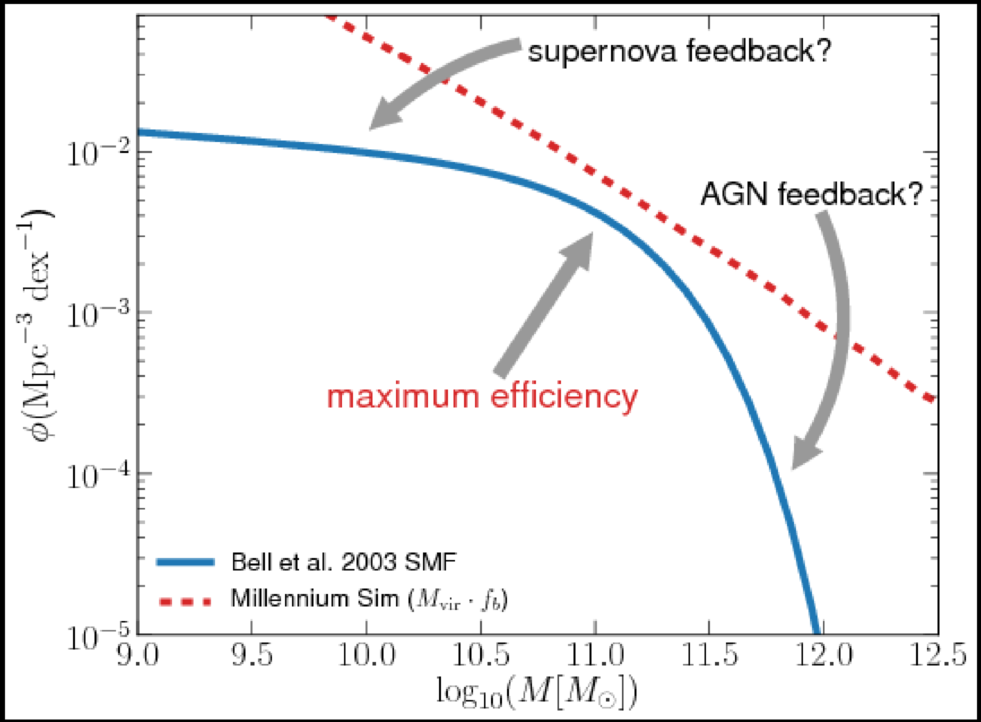
At low M_b: rising RCs → $V_{in} < V_{flat}$

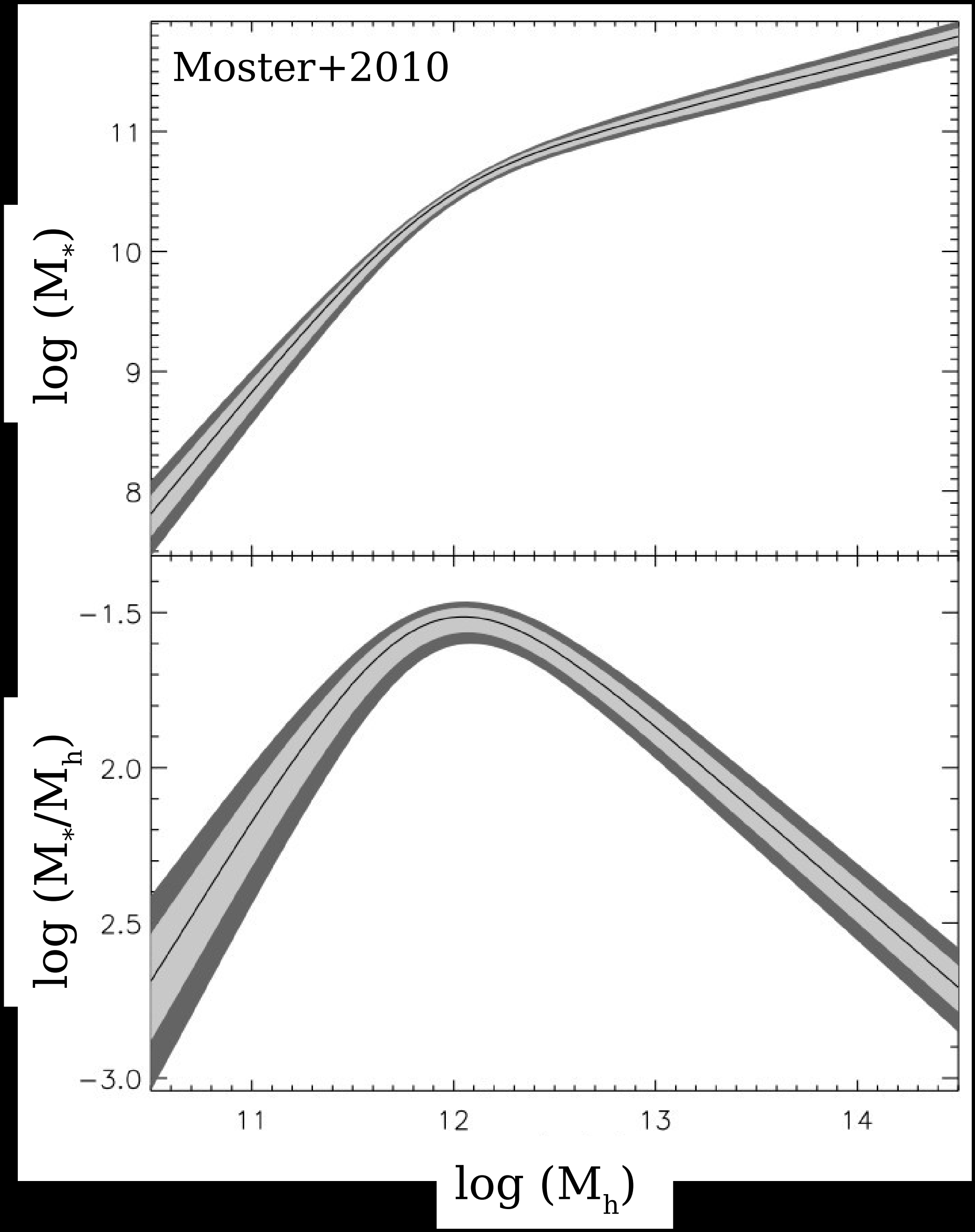
Inner velocities give shallower BTFR



Lelli+2019

The Stellar Mass Function Problem





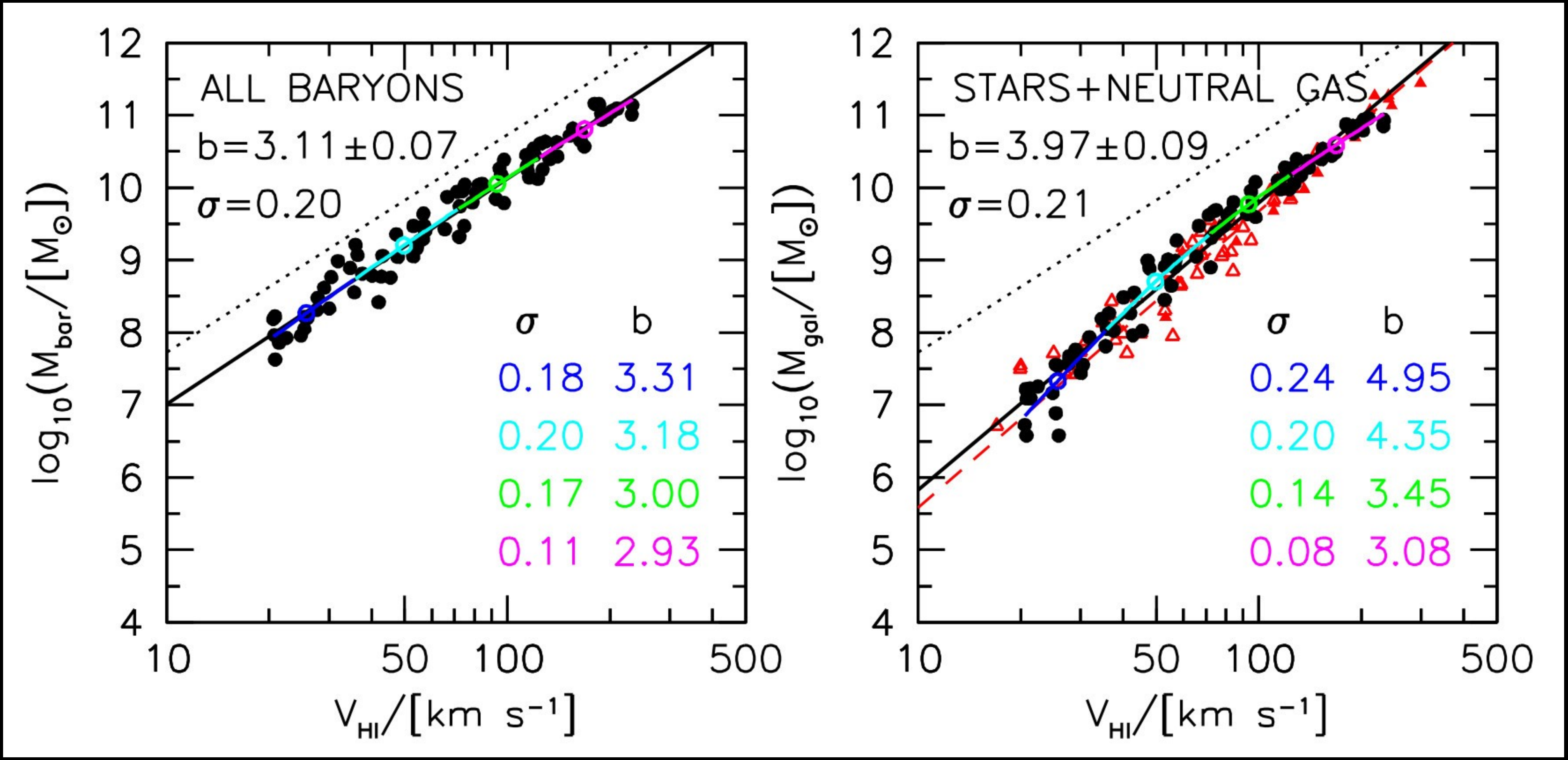
A constant M_*/M_h cannot reproduce the observed stellar mass function!

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 relationship

BTFR from hydrodynamical simulations

If we could measure hot gas... What we can actually measure!



NIHAO zoom-in cosmological simulations of galaxy formation (Dutton+2017)
BTFR curvature has almost disappeared and the scatter is small.