Galaxy Dynamics from the SPARC project

Federico Lelli

Cardiff University

In collaboration with:

S.S. McGaugh (CWRU), J.M. Schombert (UOregon), P. Li (CWRU), N. Starkman (Toronto), M.S. Pawlowski (IAP), H. Katz (Oxford), H. Desmond (Oxford), A. Di Cintio (IAC), C. Brook (IAC).

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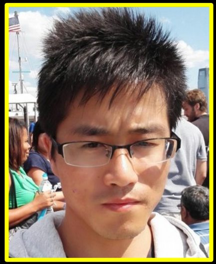

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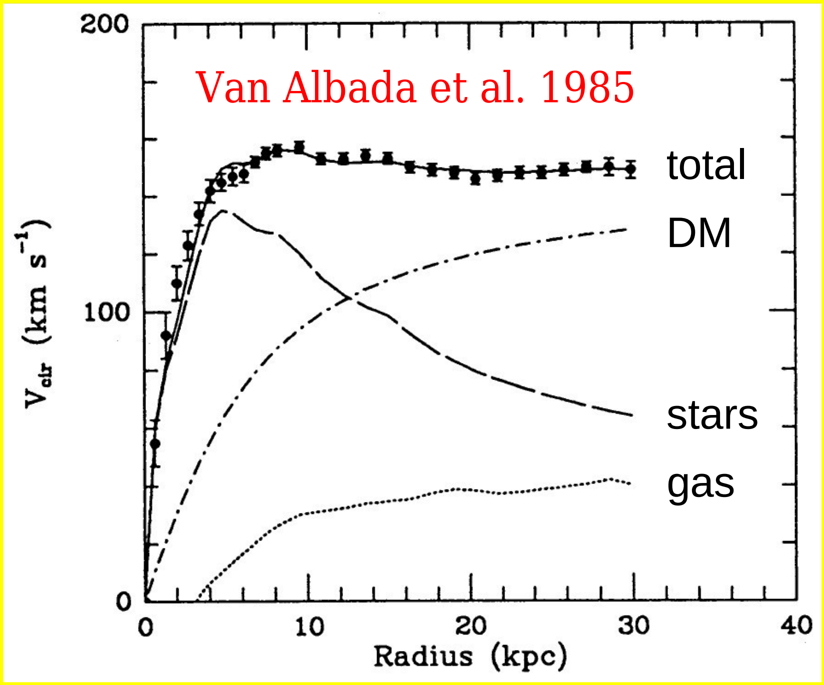
Outline:

1. Intro: Galaxy Dynamics & SPARC
2. Dark Matter Halos in a ΛCDM context
3. Dynamical Laws of Disk Galaxies

1. Introduction:

Galaxy Dynamics & SPARC

Why Studying Galaxy Dynamics?



Evidence of "missing mass"

- Dark Matter Halos ↔ Cosmology

- Alternatives to Particle Dark Matter
  (e.g. MOND, Modified Gravity, etc.)

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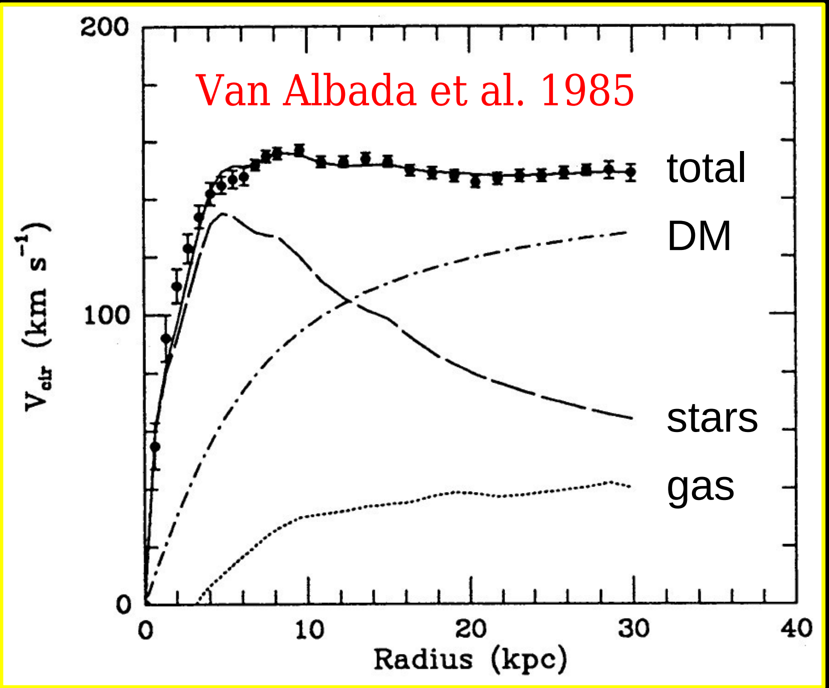

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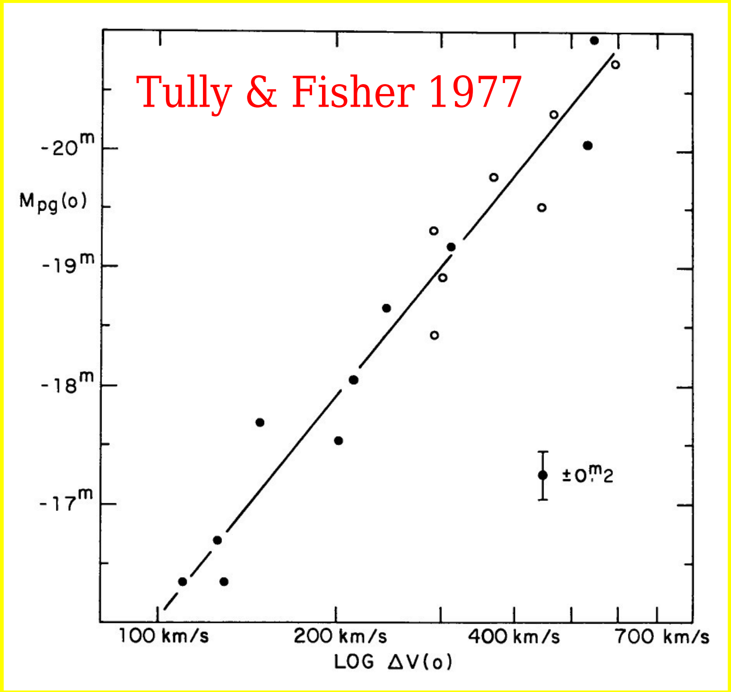


Galaxy Formation & Evolution

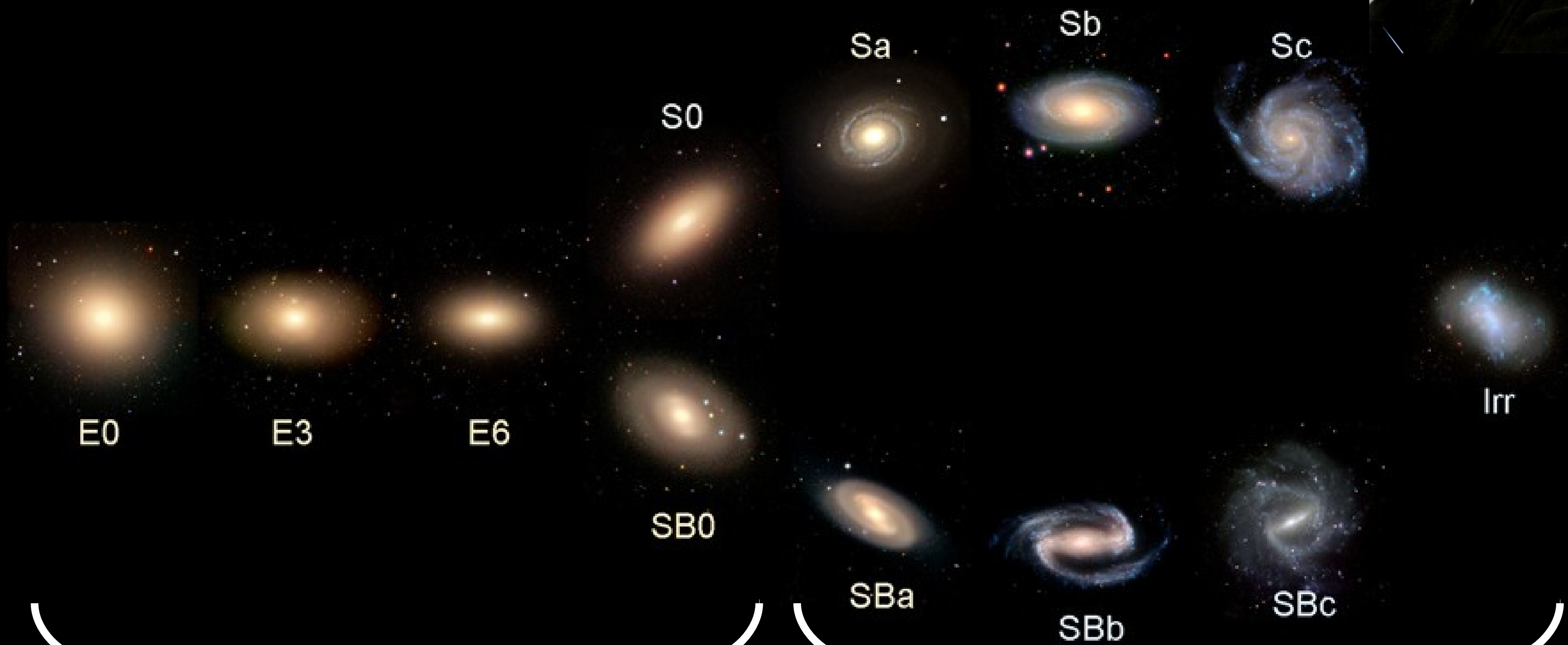
- Galaxy Scaling Laws (e.g. Tully-Fisher)

- Disk Stability ↔ Star Formation

- Gas Turbulence ↔ Stellar Feedback

Galaxies: "Island Universes"

Hubble's Galaxy Classification Scheme



Early-Type Galaxies (ETGs): E and S0

No/Little Star Formation

→ Mostly old stars → Red colors

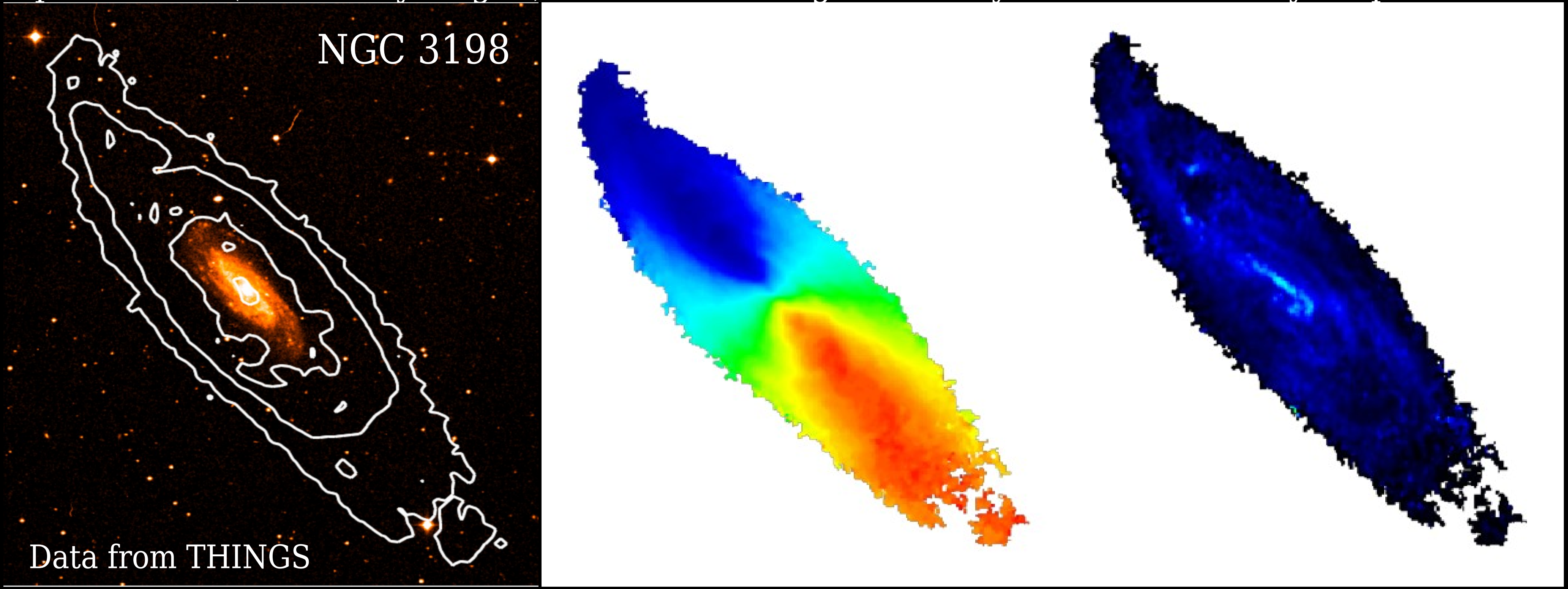
Late-Type Galaxies (LTGs): S and Irr

On-going Star Formation

→ Both young & old stars → Blue colors

Extended cold gas disks in LTGs

Optical + HI (Atomic Hydrogen) | HI Line-of-Sight Velocity | HI Velocity Dispersion



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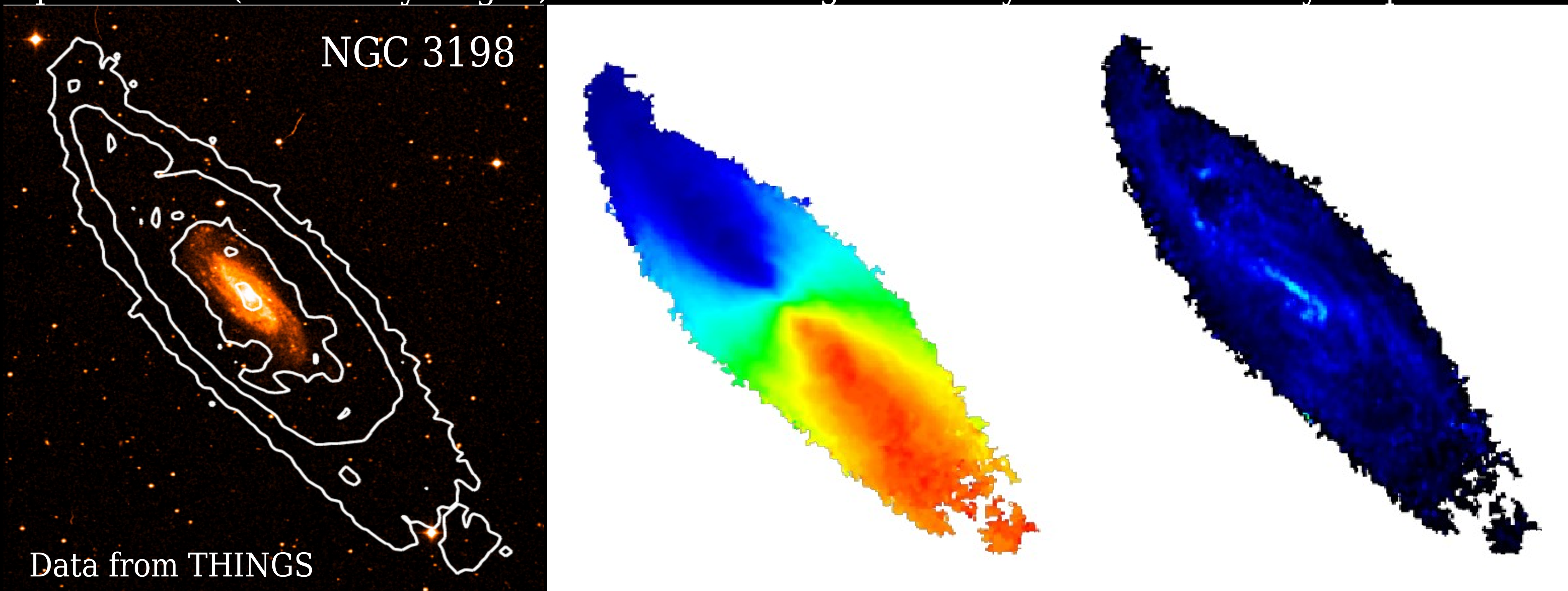

Circular velocity of a test particle in an *axisymmetric* potential:

$$V_c^2 \overset{\text{def}}{=} -R\frac{\partial \Phi}{\partial R} = V_{rot}^2 + \sigma_R^2 \left[-2\frac{\partial \ln \sigma_R}{\partial\, lnR} - \frac{\partial \ln \rho}{\partial\, lnR} - 1 + \frac{\sigma_\phi^2}{\sigma_R^2} - \frac{R}{\sigma_R^2}\frac{\partial \left(\overline{V_{rad} V_z}\right)}{\partial z} \right]$$

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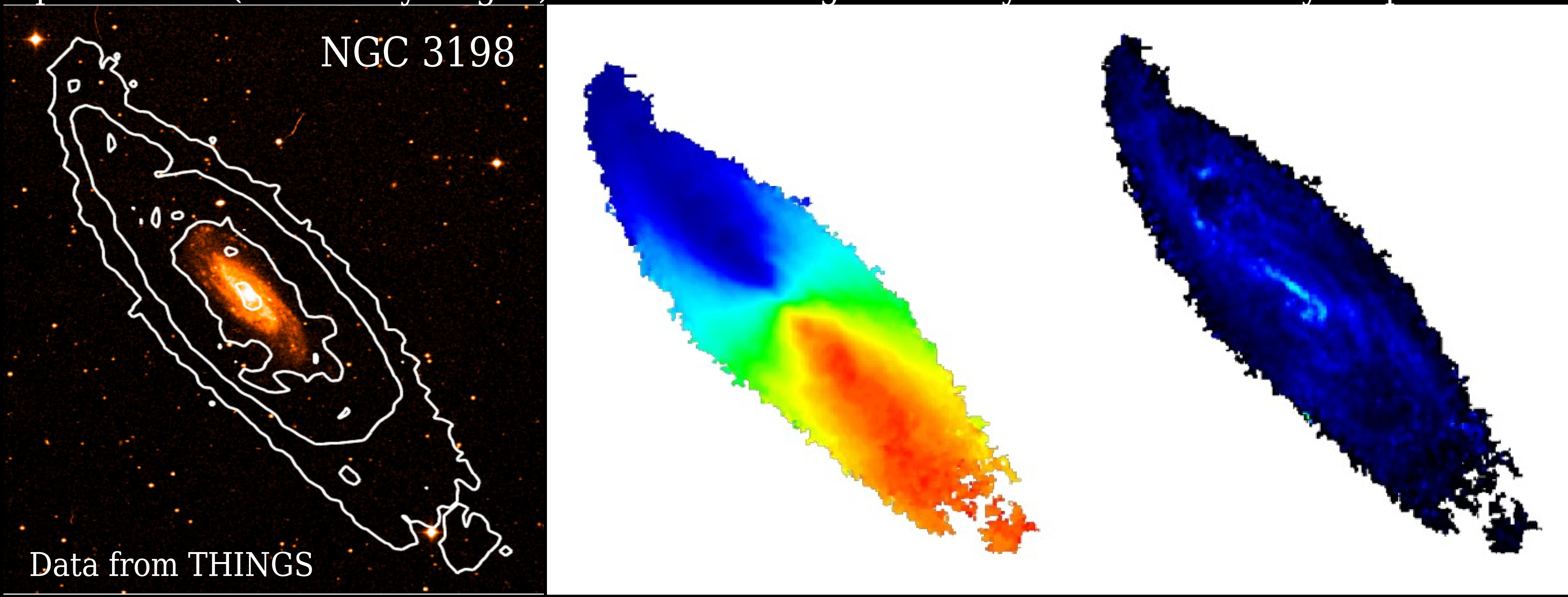

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For cold gas disks: $\sigma^2 \ll V^2_{rot} \rightarrow V_c = V_{rot}$

Extended cold gas disks in LTGs

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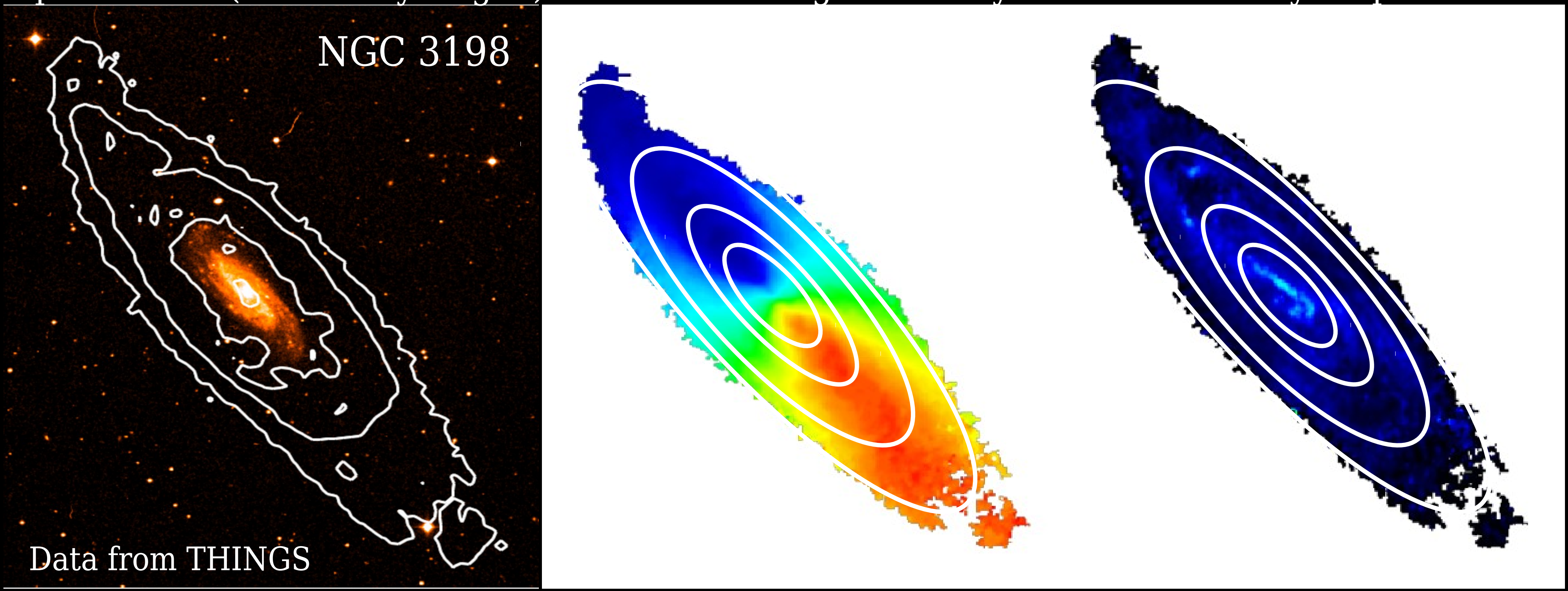


Deprojection from sky plane to galaxy plane:

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

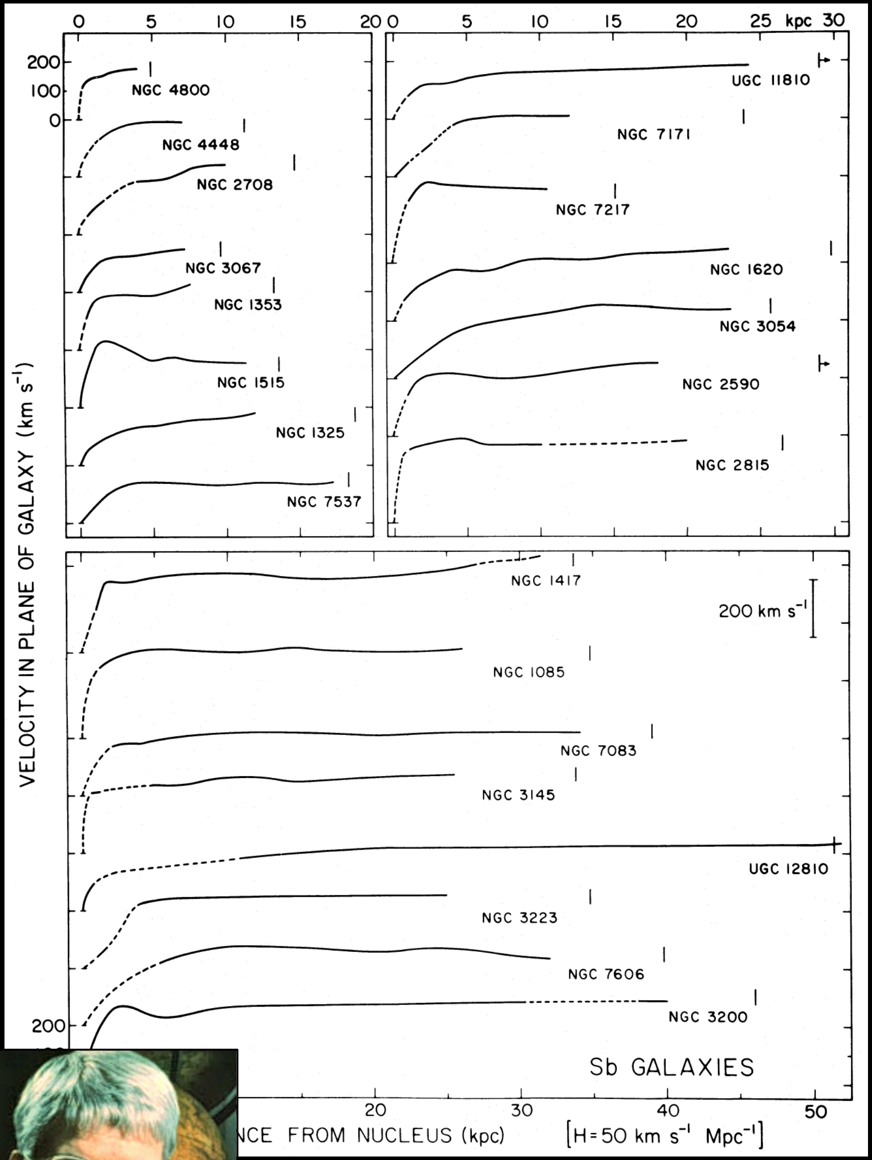
$\cos(\theta) = \mathrm{fnc}(\text{position angle, center})$

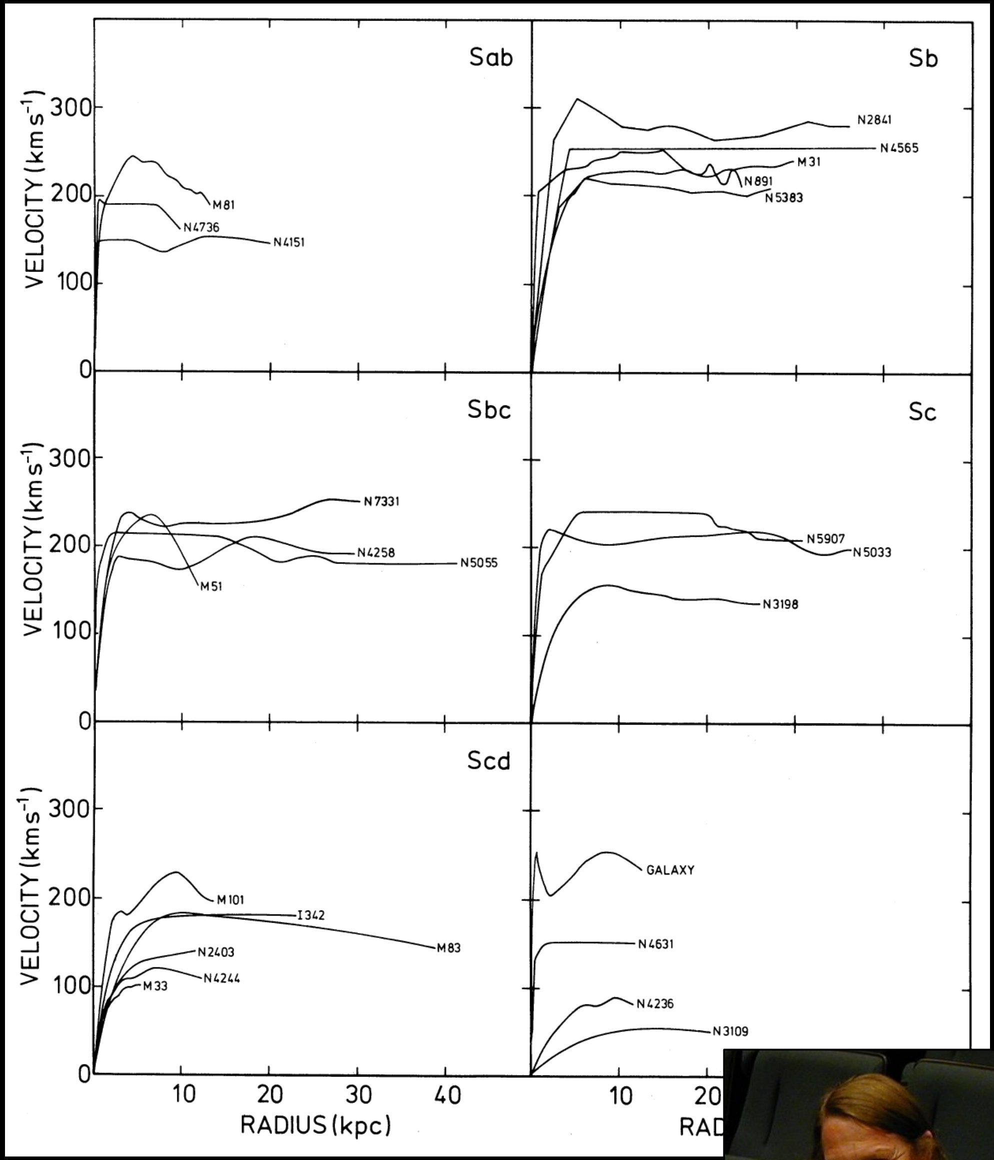
i = disk inclination angle

θ = azimuthal angle

V_{sys} = systemic velocity (Hubble exp + peculiar)

Flat Rotation Curves of LTGs





Optical - Ionized Gas (Hα)

V. Rubin et al. (1981)

Radio - Atomic Gas (HI)

A. Bosma (1981)

SPARC

Spitzer Photometry & Accurate Rotation Curves

Sample of LTGs at z=0 with the best available kinematic data:

All data are public: www.astroweb.cwru.edu/SPARC

Master paper: Lelli, McGaugh, Schombert 2016, AJ, 152, 157

SPARC

Spitzer Photometry & Accurate Rotation Curves

- HI Rotation Curves for 175 LTGs

  - 35 years of interferometric HI observations

  - PhD theses from the University of Groningen

    Begeman 1987; Broeils 1992; Verheijen 1997; de Blok 1997; Swaters 1999; Noordermeer 2005; Lelli 2013 + other studies

  - Hα rotation curves for ~30% of the sample

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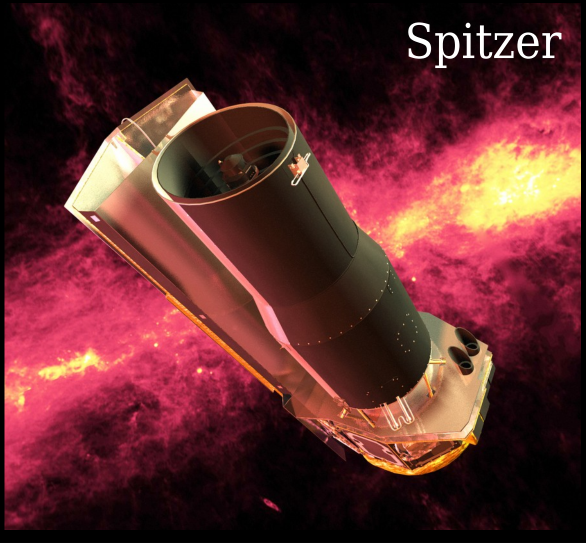
  - Hα rotation curves for ~30% of the sample

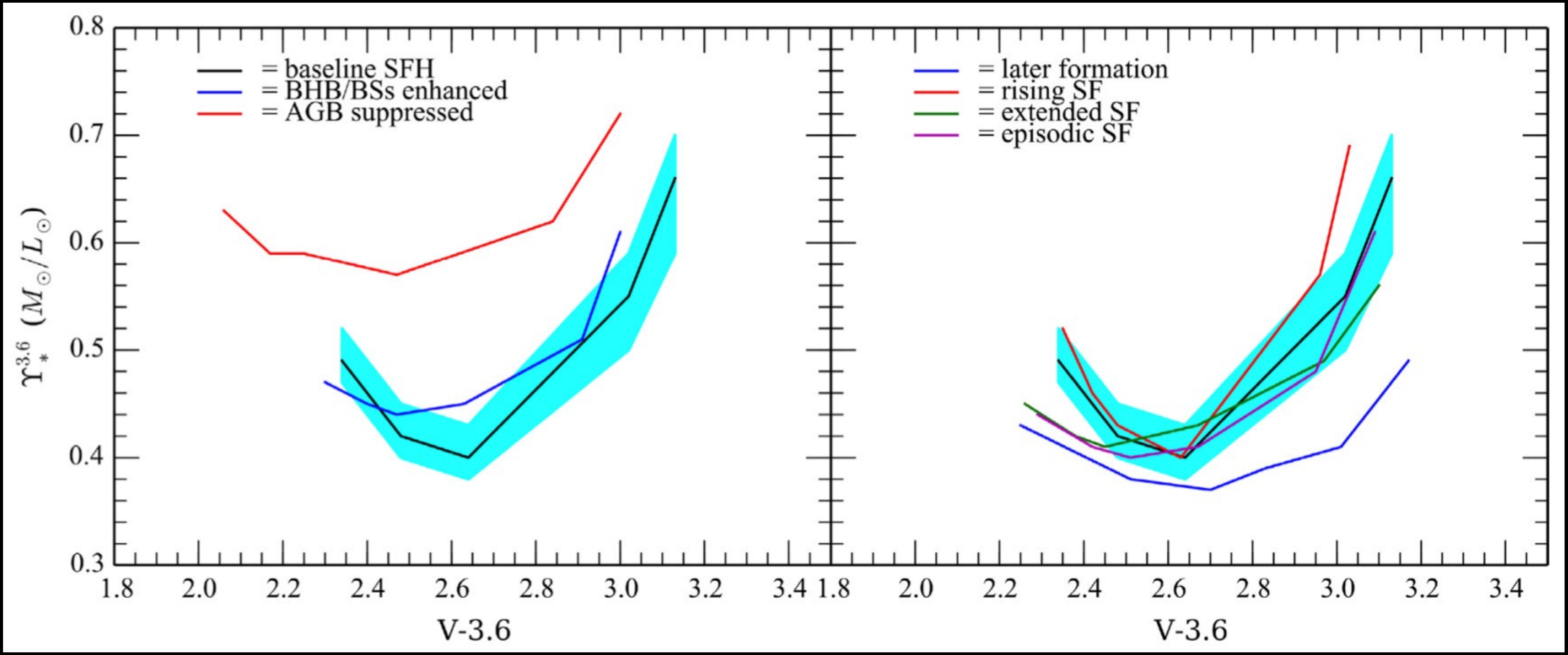
- Homogeneous Photometry at 3.6 μm
  - NIR light is the best tracer of the stellar mass
  - From stellar population models:

    $\Upsilon_*^{3.6} = M_*/L_{3.6} \sim 0.5\ M_\odot/L_\odot$ with ~25% scatter

    Bell & de Jong 2001; Meidt+2014; McGaugh & Schombert 2014; Röck+2015; Herrmann+2016; Norris+2016; Zhang+2017



M_*/L *vs* Color Relations for LTGs



Schombert, McGaugh, Lelli (2019)

Complex Stellar Pop. Models:

- Extended Star-Formation Histories (sum of single stellar pops)
- Chemical Enrichment Histories (both [Fe/H] and α/Fe)
- Less Understood Phases in Stellar Evolution (AGB, BHB, BS)

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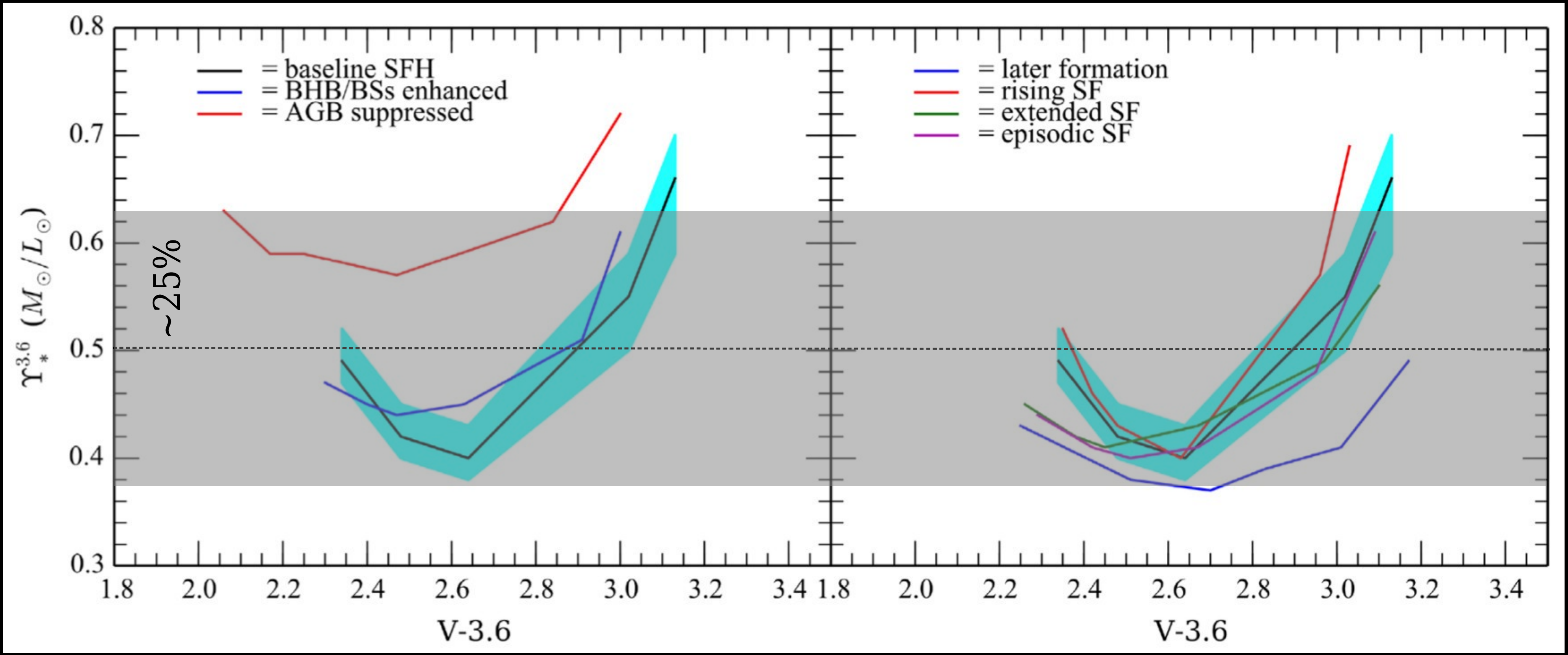

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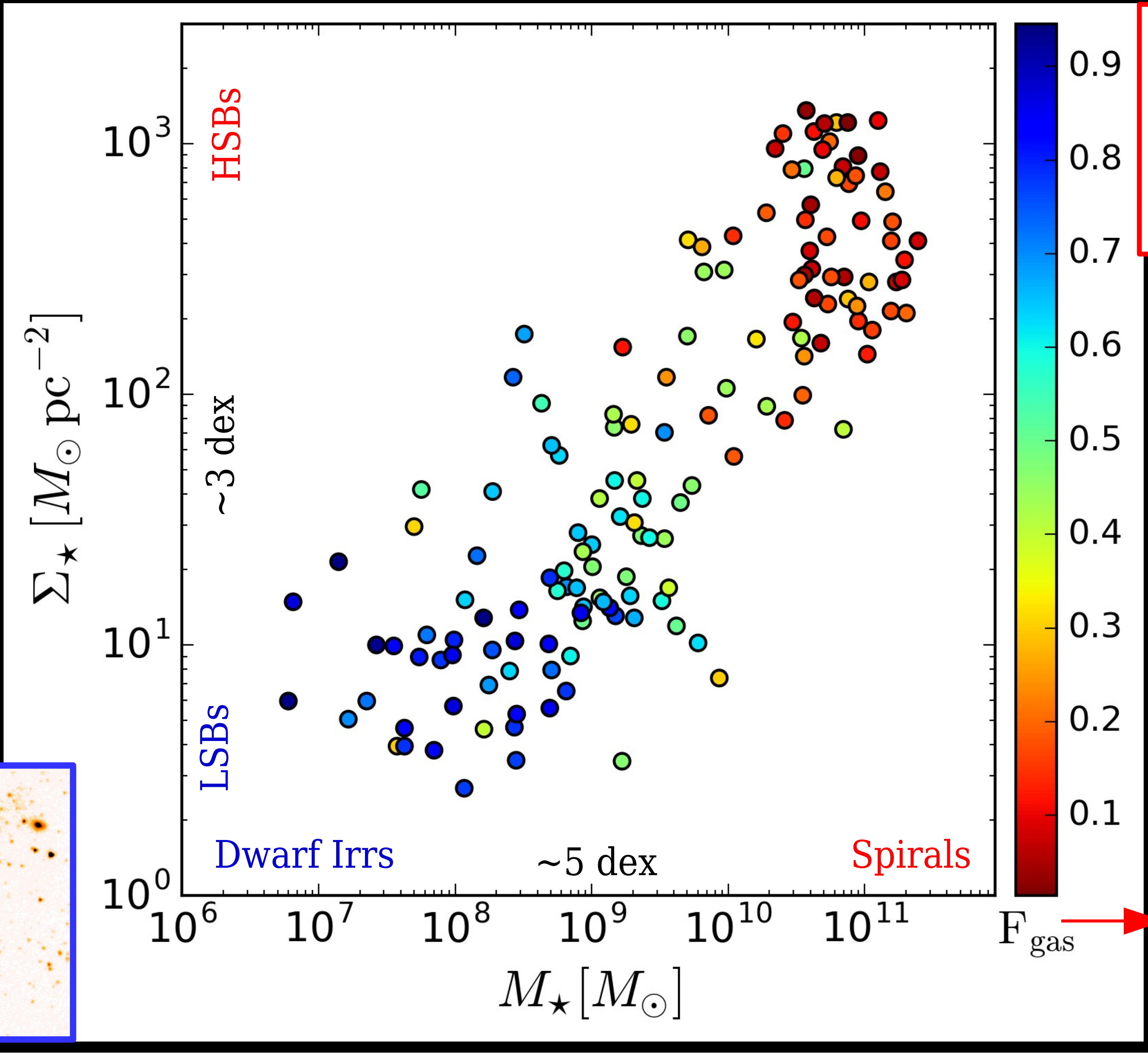
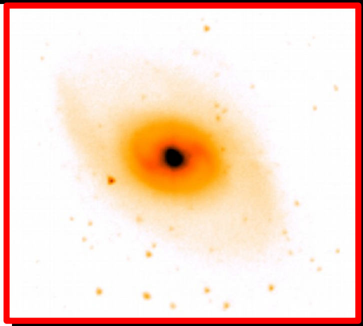
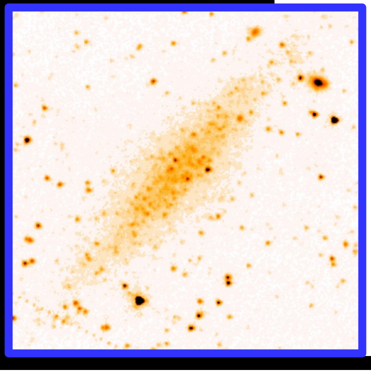
$\Upsilon_*^{3.6}$ spans a very narrow range (<2) contrary to optical bands (>10)

Very Wide Range of Galaxy Properties



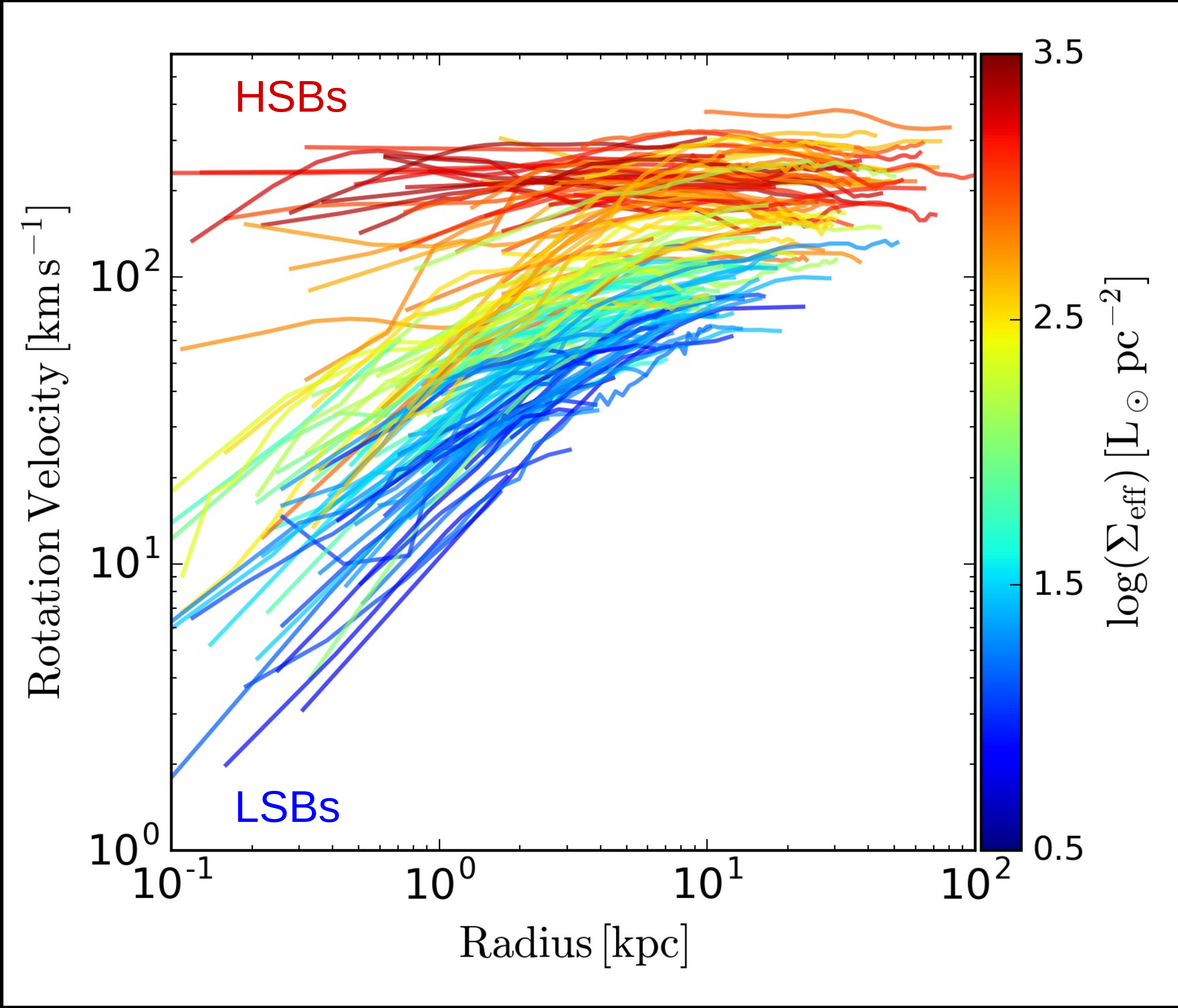




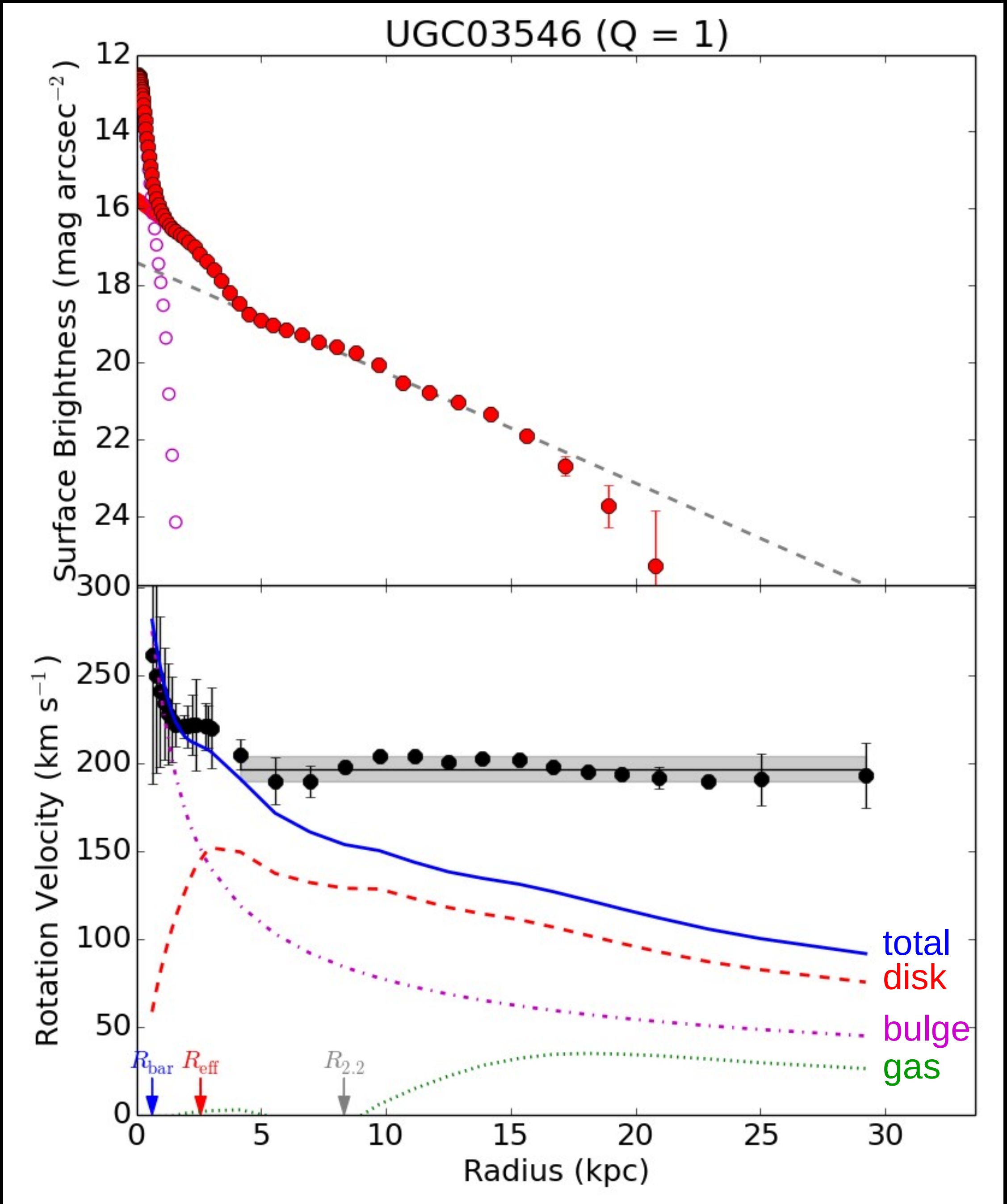
$\Upsilon_*^{3.6} = 0.5$

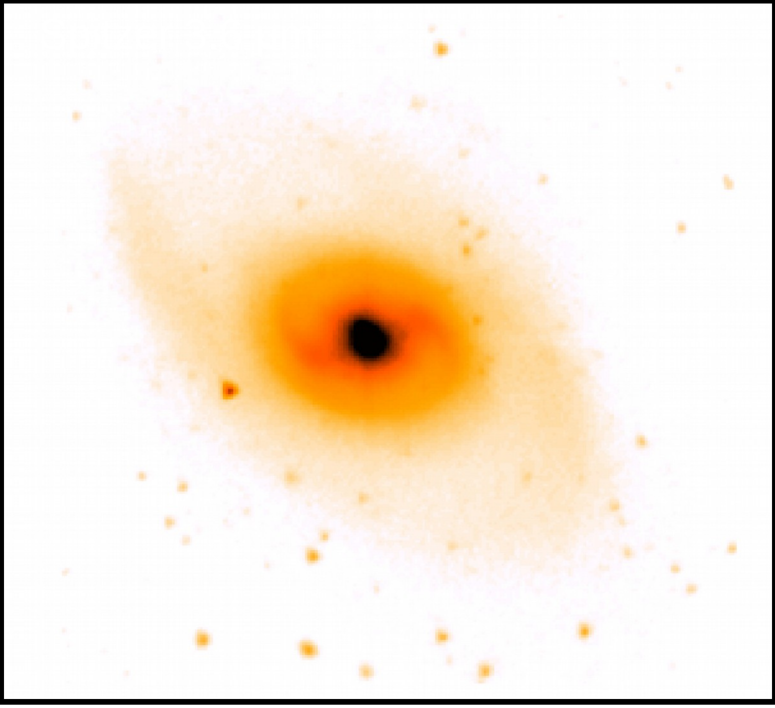
$F_{gas} \rightarrow M_{HI}/M_{bar}$

Hybrid HI+Hα Rotation Curves



Example: High-Mass, High-Density Spiral





$$\nabla^2\Phi_{bar}(R,z) = 4\pi G\, \rho_{bar}(R,z)$$

- Vertical Structure:
  - Disks: $\exp(-z/h_z)$ with $h_z \propto h_R$
  - Bulges: spherical symmetry
- Stellar mass-to-light ratio:
  - $\Upsilon_* = 0.5\ M_\odot/L_\odot$ for disks
  - $\Upsilon_* = 0.7\ M_\odot/L_\odot$ for bulges

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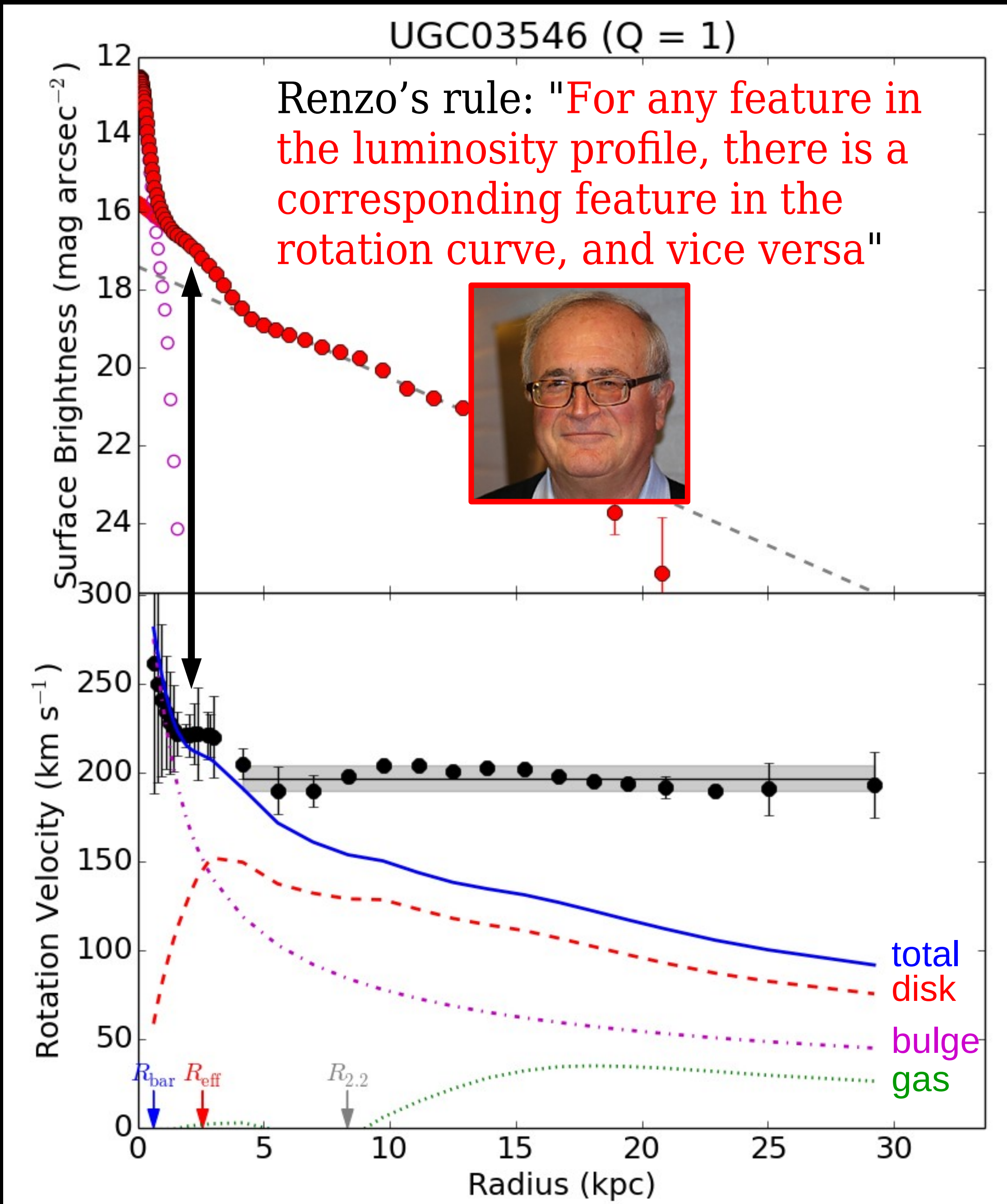

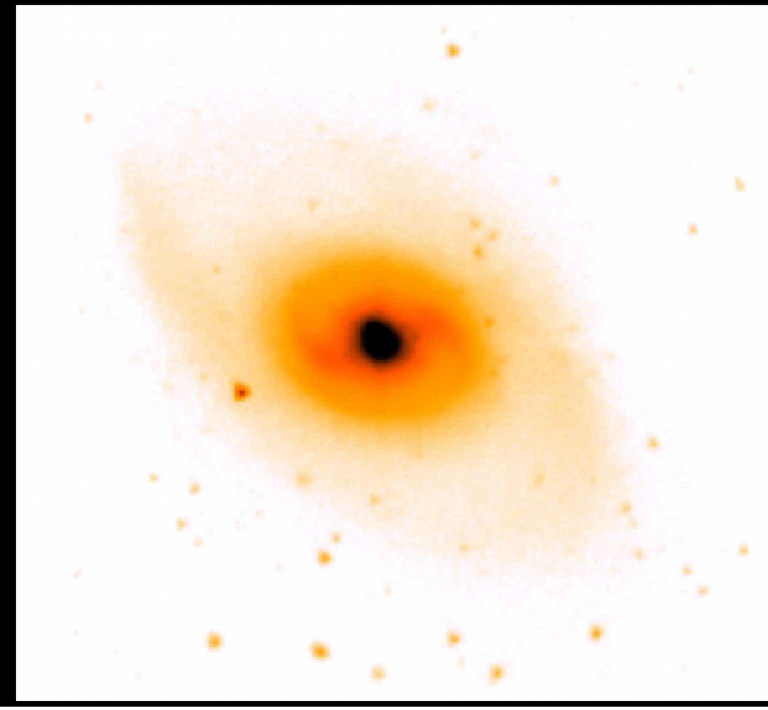

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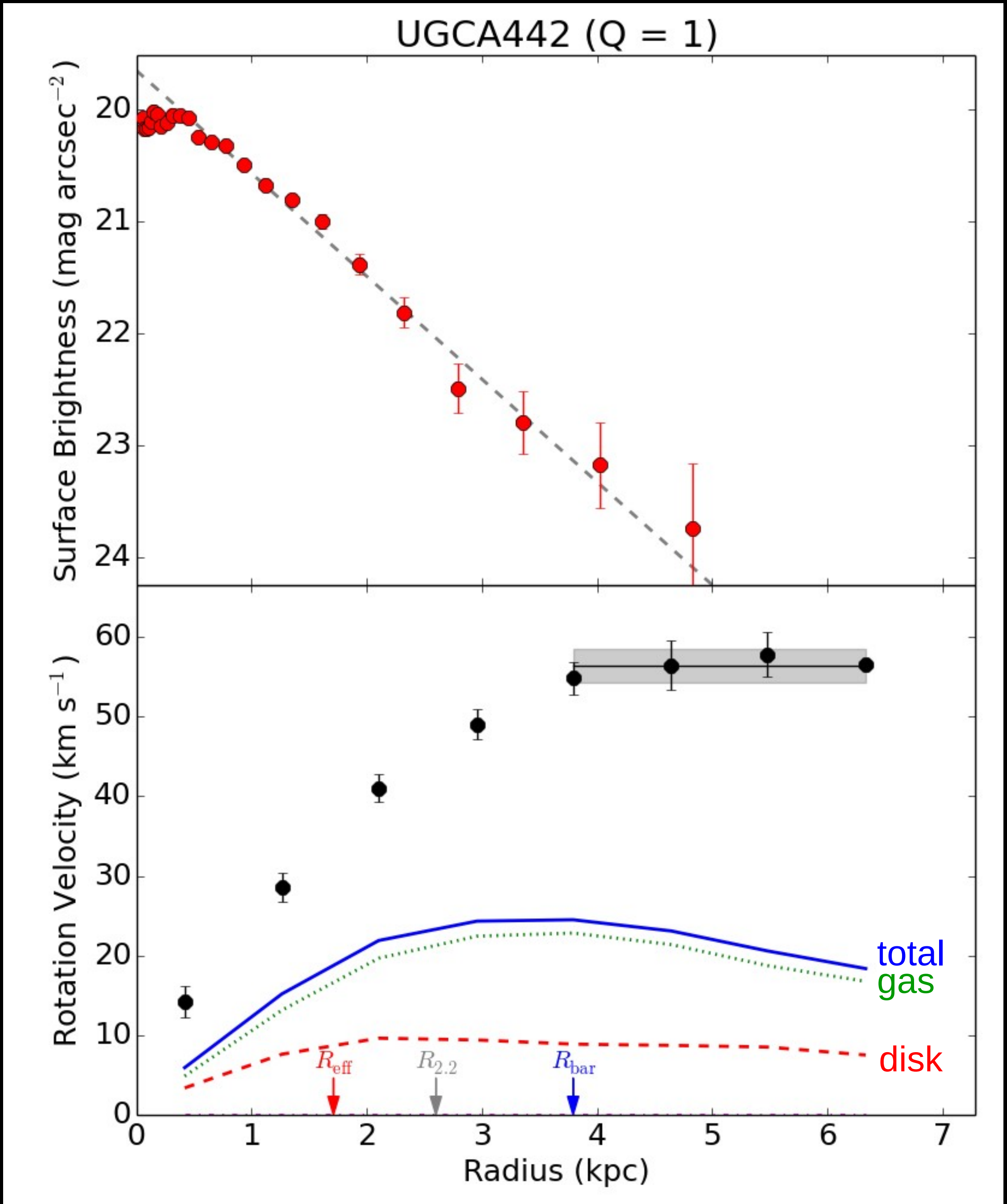
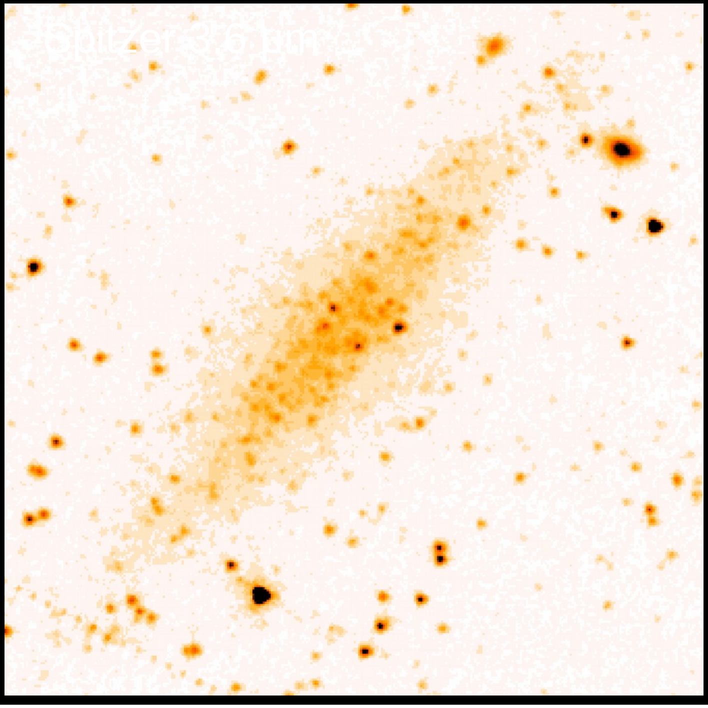
Example: Low-Mass, Low-Density Dwarf





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SPARC papers (a few more in prep…)

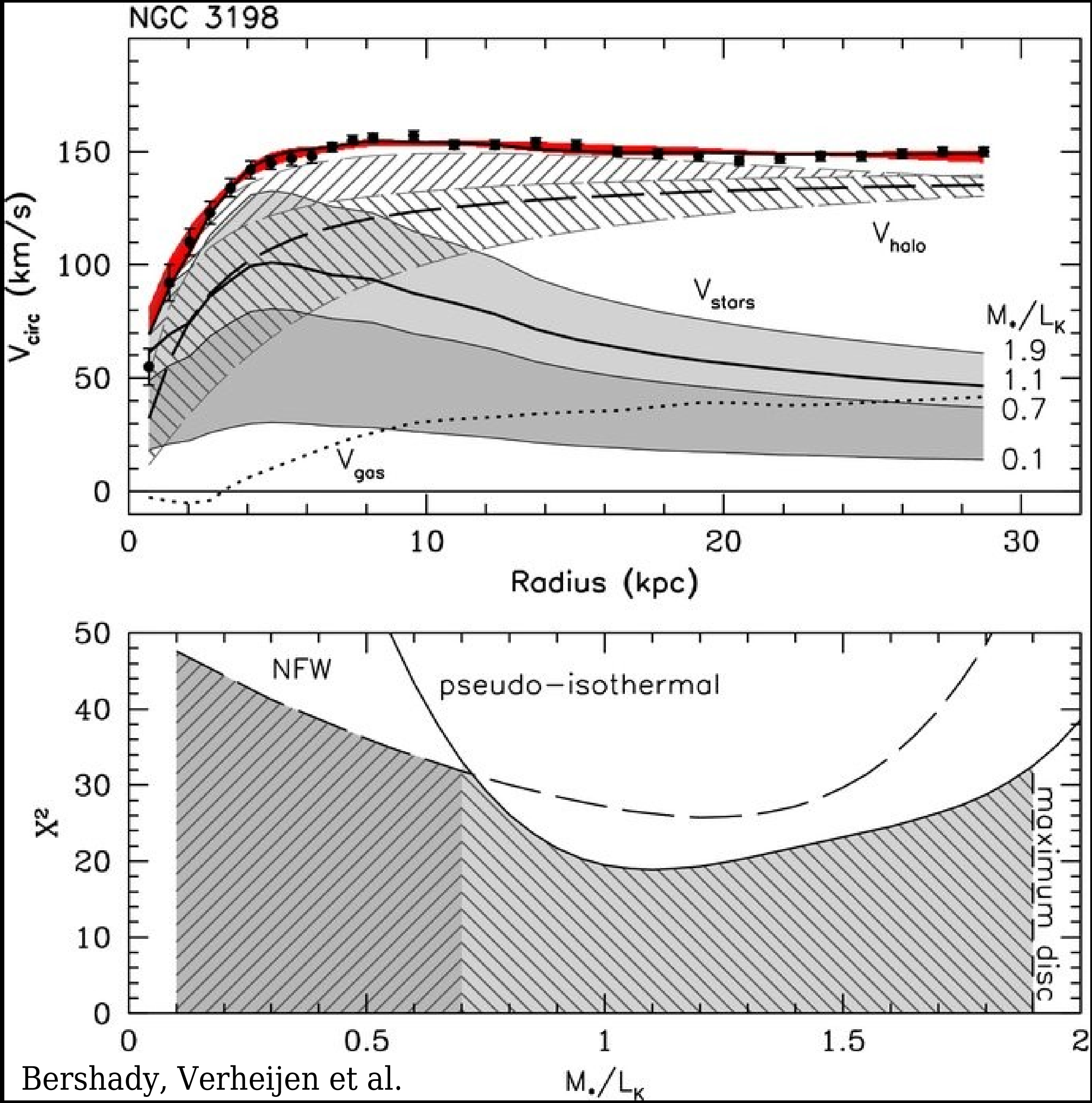
1. Basic Data & Structural Relations: Lelli, McGaugh, Schombert 2016a, AJ
2. Baryonic Tully-Fisher Relation (I): Lelli, McGaugh, Schombert 2016b, ApJL
3. Central Surface Density Relation: Lelli et al. 2016c, ApJL
4. Radial Acceleration Relation (I): McGaugh, Lelli, Schombert 2016, PRL
5. Radial Acceleration Relation (II): Lelli et al. 2017a, ApJ
6. The Cusp-*vs*-Core Problem: Katz, Lelli et al. 2017, MNRAS
7. Testing Emergent Gravity: Lelli, McGaugh, Schombert 2017b, MNRAS
8. Radial Acceleration Relation (III): Li, Lelli et al. 2018, A&A
9. Maximum-Disk Models: Starkman, Lelli et al. 2018, MNRAS
10. Missing Baryons and Energy Budget: Katz et al. 2018, MNRAS
11. Scaling Relations for DM Halos: Li, Lelli et al. 2019, MNRAS
12. Halo Mass – Velocity Relations: Katz et al. 2019, MNRAS
13. Stellar M/L – Color Relations: Schombert, McGaugh, Lelli 2019, MNRAS
14. Residuals in M-V and M-R Relations: Desmond et al. 2019, MNRAS
15. Baryonic Tully-Fisher Relation (II): Lelli et al. 2019, MNRAS
16. The Halo Mass Function from HI kinematics: Li, Lelli et al. 2019, ApJL
17. A Catalog of DM Halo Fits: Li, Lelli et al. 2020, ApJS, 247, 31

- ΛCDM-driven approach: fit RCs with DM halos
(Katz et al. 2017, 2018, 2019; Li et al. 2019a,b, 2020)

- Data-driven approach: empirical scaling laws
(Lelli et al. 2016a,b,c; 2017a,b; 2019; McGaugh 2016)

2. Dark Matter Halos
in a ΛCDM context

Rotation-Curve Fits with DM Halos



Bershady, Verheijen et al.

Assume DM density profile:

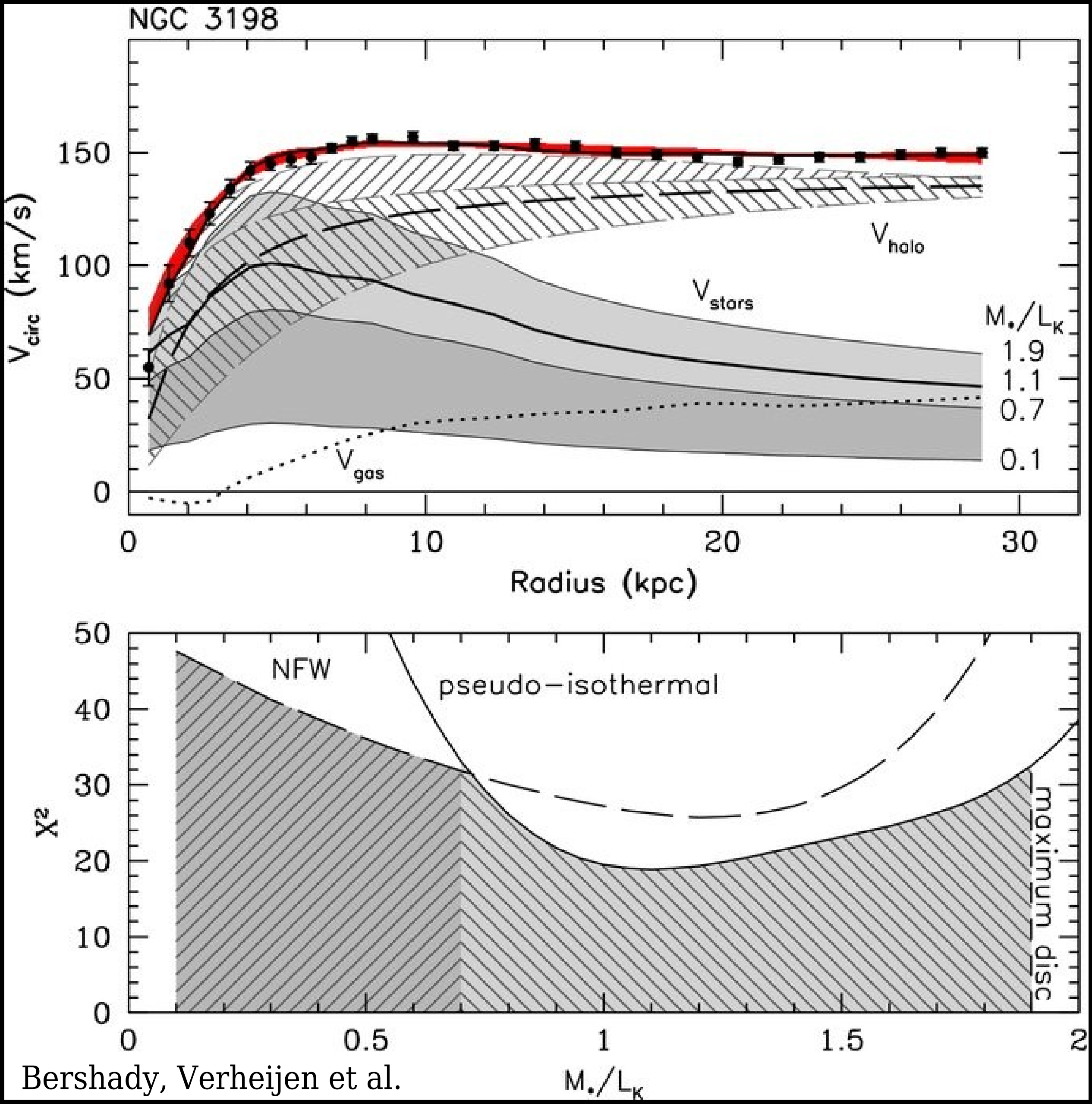
$\rho_{DM} = \rho(r; \rho_s, r_s)$

$(\rho_s, r_s) \rightarrow (M_{200}, C_{200})$

M_{200} = enclosed ρ_{DM} is 200 critical density of Universe

$C_{200} = R_{200}/r_s$

Rotation-Curve Fits with DM Halos



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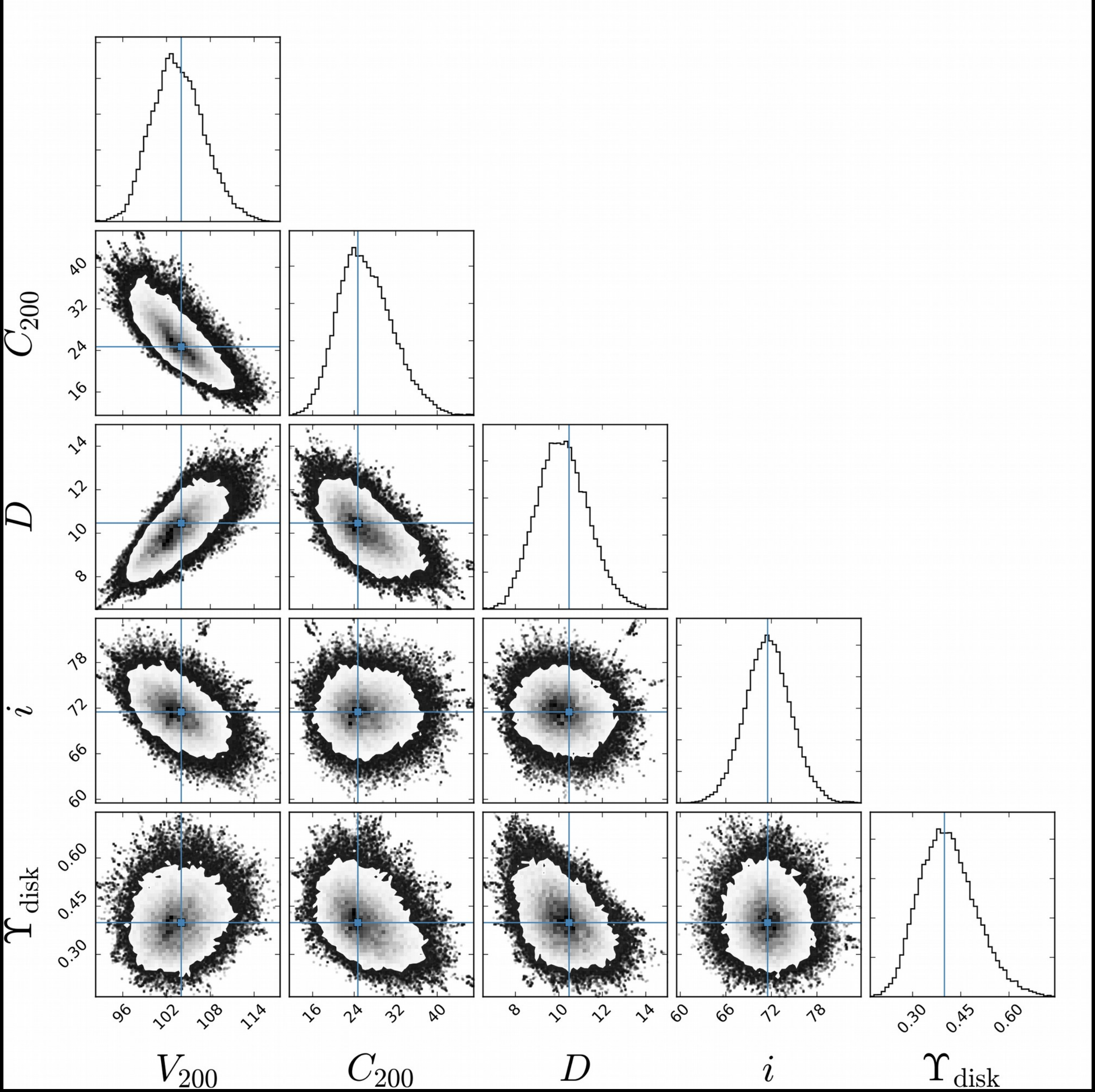
Parameter Degeneracies:

- Υ_* = mass-to-light ratio
- Galaxy Distance
  20% $\delta D \rightarrow$ 40% δM_{bar}
- Disk Inclination
  $M_{dyn} \propto V_c \propto 1/\sin(i)$

MCMC Fits in a Bayesian Framework



Galaxy Prior:

1) $\Upsilon_* = 0.50$ + 25% error

2) Distance + error

3) Inclination + error

Katz, Lelli+2017; Li+2019, 2020

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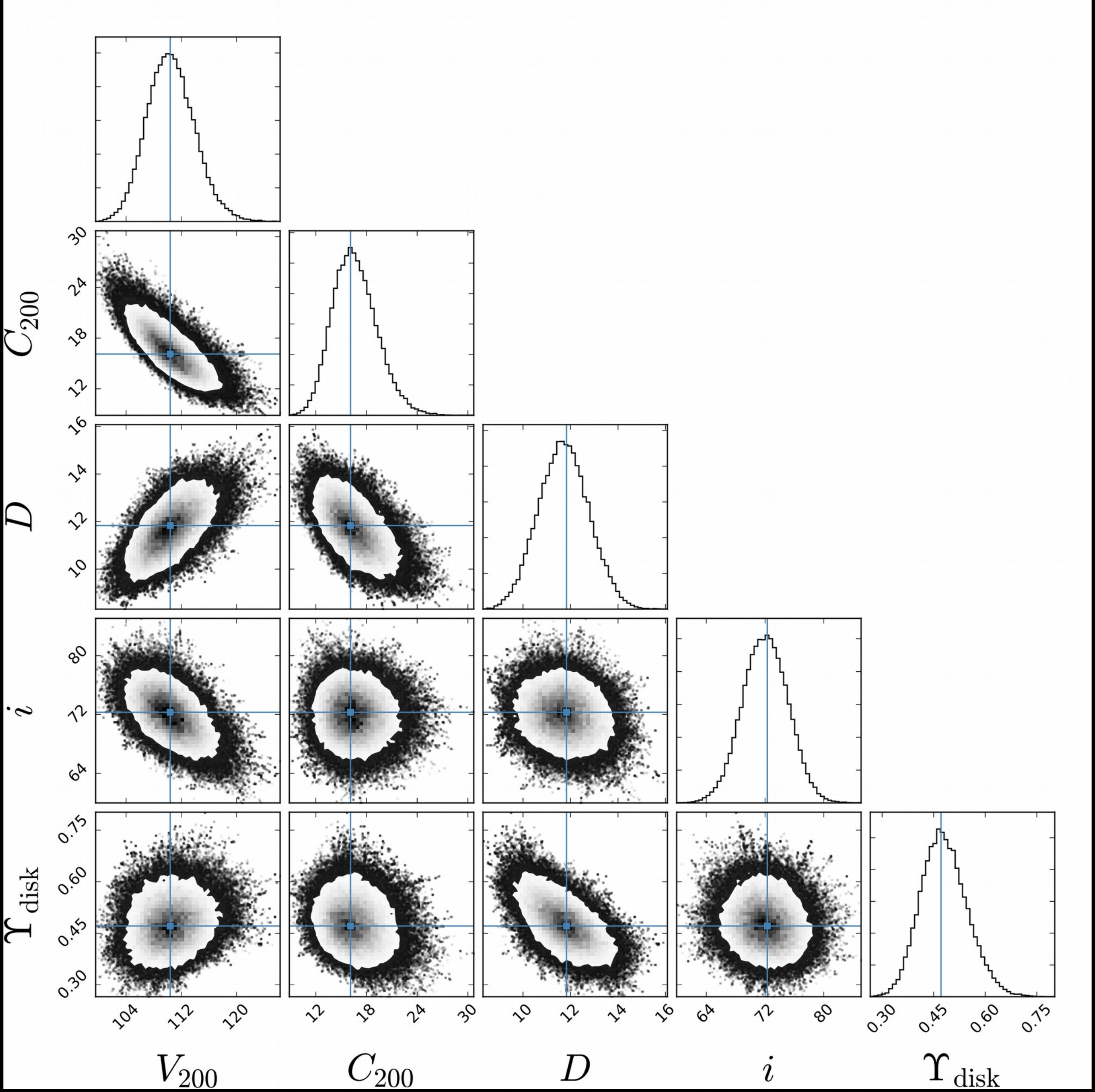

Galaxy Prior:

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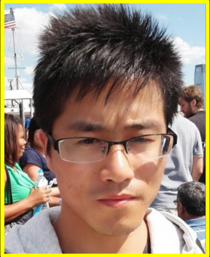
3) Inclination + error

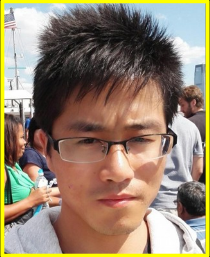
ΛCDM Prior:

1) M_* - M_{200} relation from abundance matching (e.g. Moster et al. 2013)
2) M_{200} - C_{200} relation from cosmo simulations (e.g. Macciò et al. 2008)

Katz, Lelli+2017; Li+2019, 2020



Fits with 7 halo profiles (Li+2020)



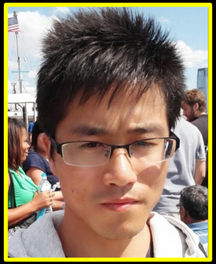
Fits with 7 halo profiles (Li+2020)

From empirical considerations → inner core (ρ ∝ cons)

1) Pseudo Isothermal (van Albada et al. 1985)

2) Burkert (Burkert 1995)

3) Lucky13 (Li, Lelli et al. 2020)



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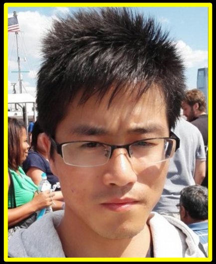
From DM-only simulations → inner cusp ($\rho \propto r^{-1}$)

4) NFW (Navarro, Frank & White 1996)
5) Einasto (with cuspy α values; see Navarro 2004)



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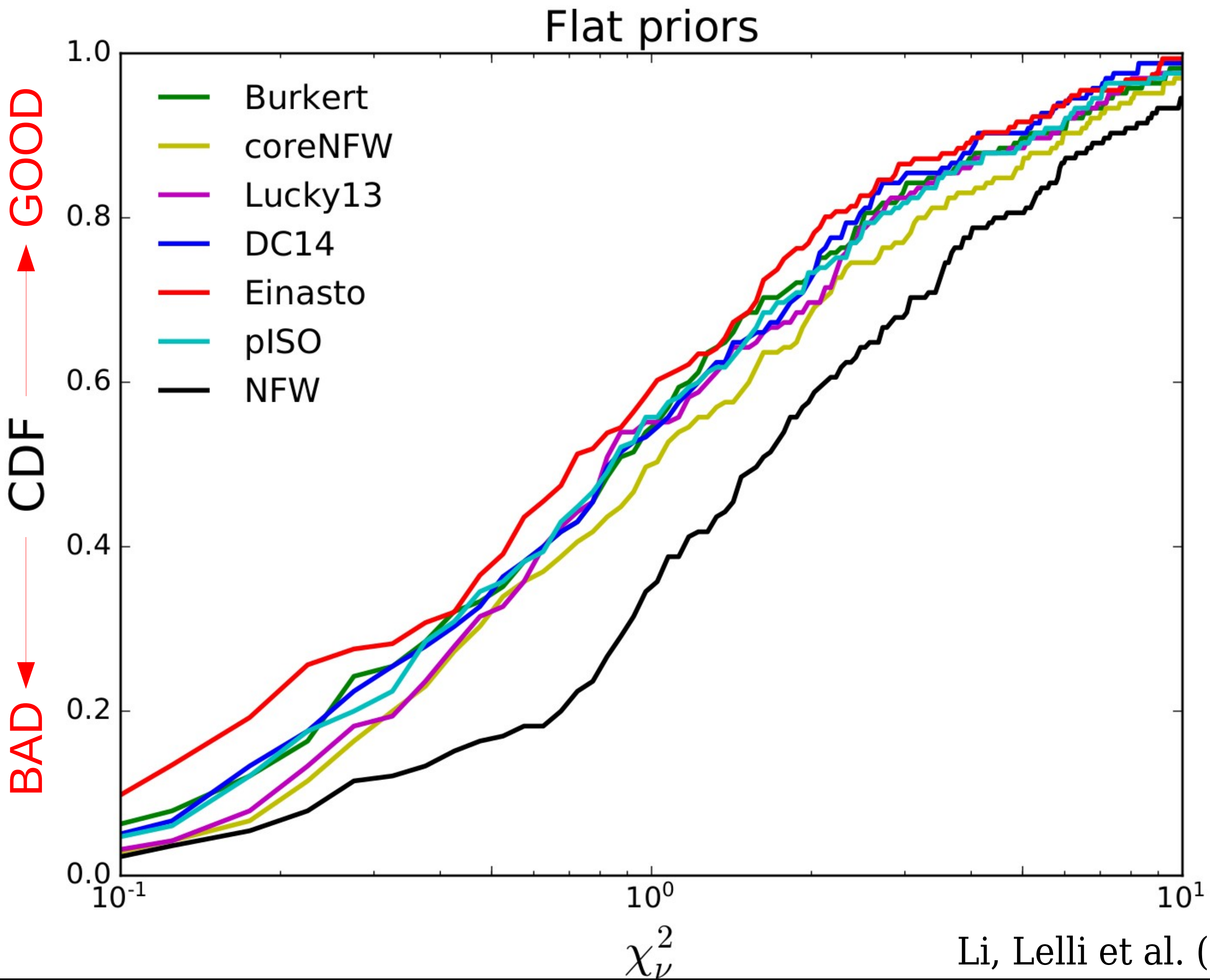
From hydro simulations → cusp-core transformation

6) DC14 (Di Cintio et al. 2014)

7) CoreNFW (Read et al. 2016)

Quality of DM Halo Fits:



Li, Lelli et al. (2020)

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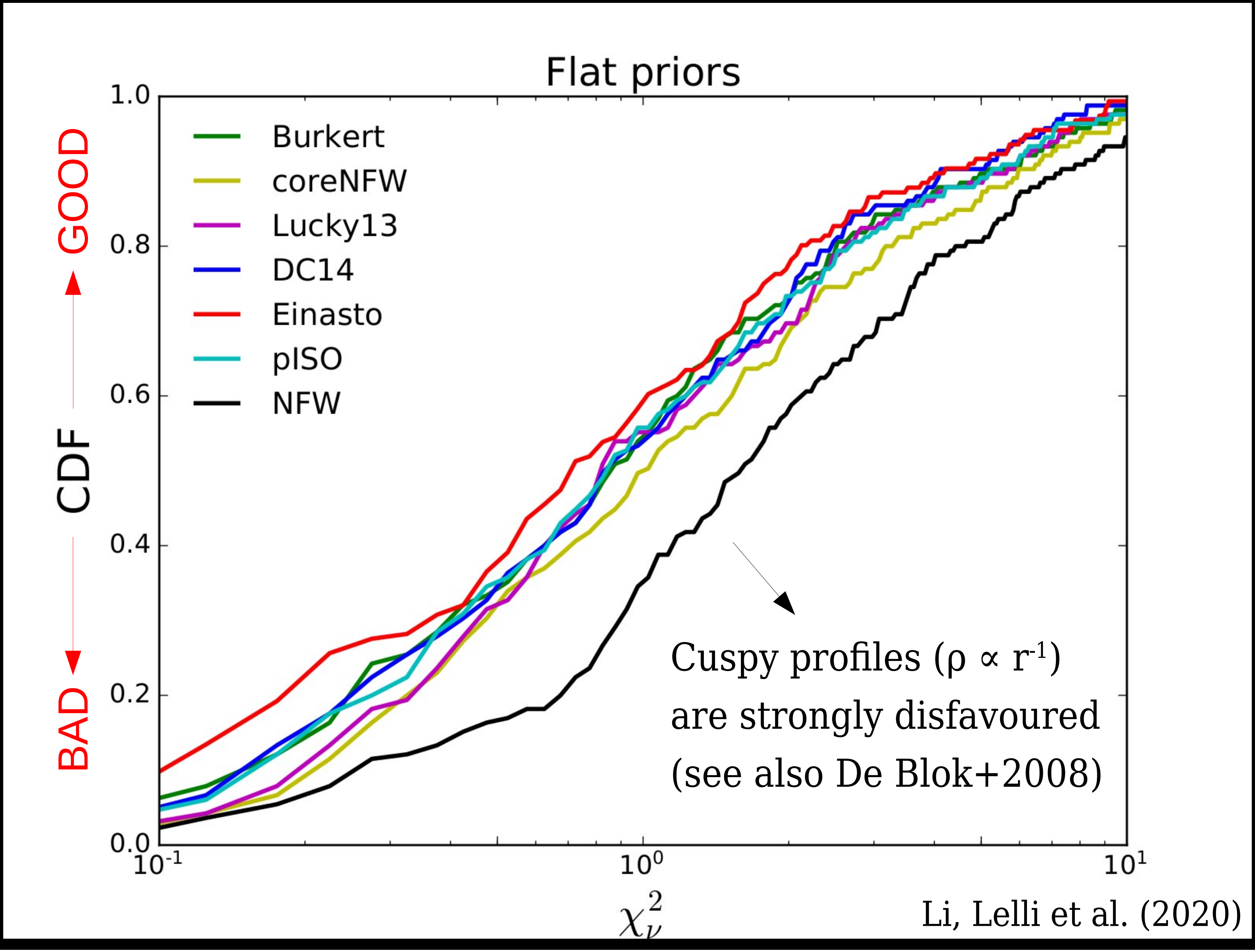
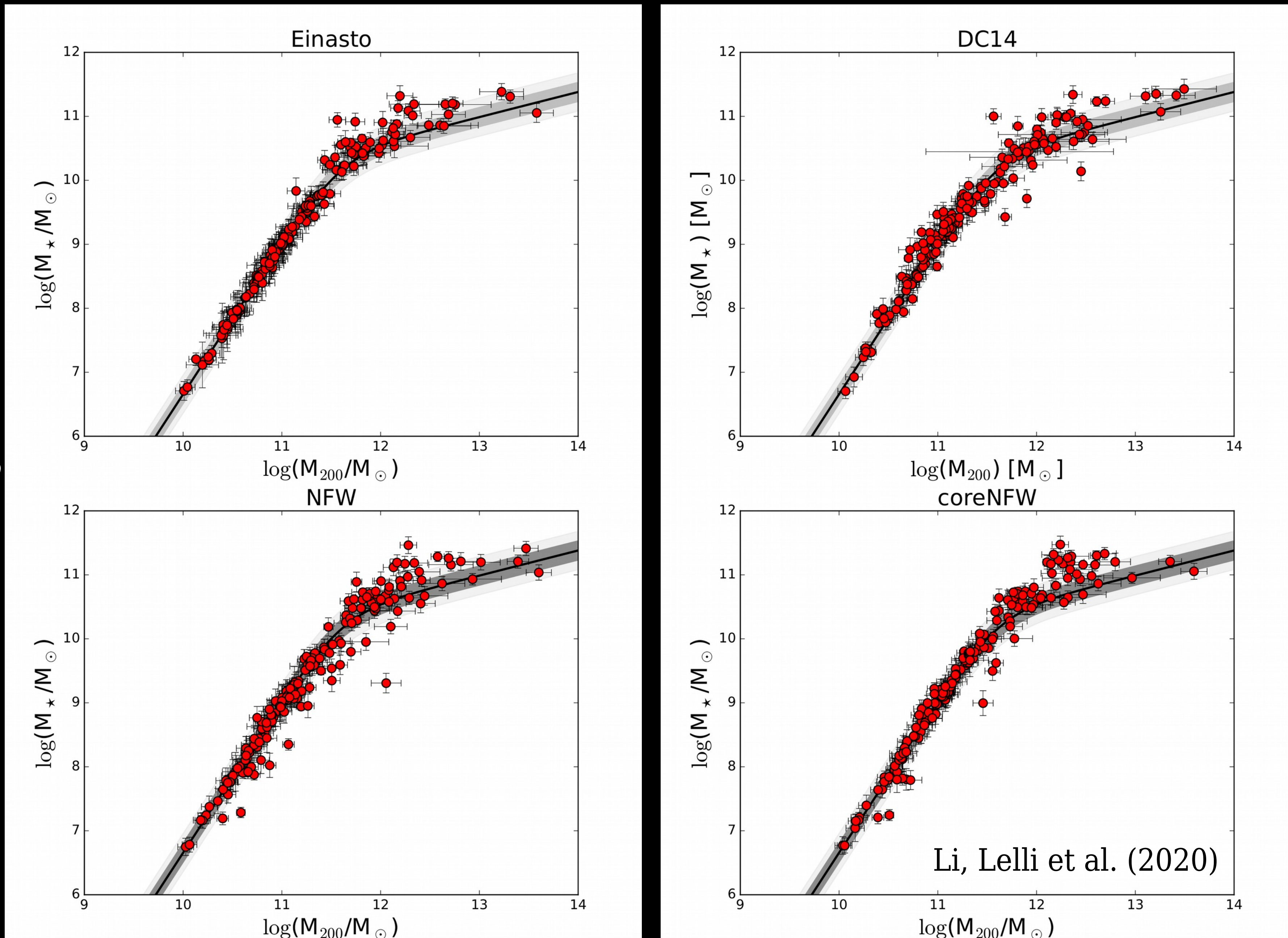


M_*-M_{200} relation: Overall recovered

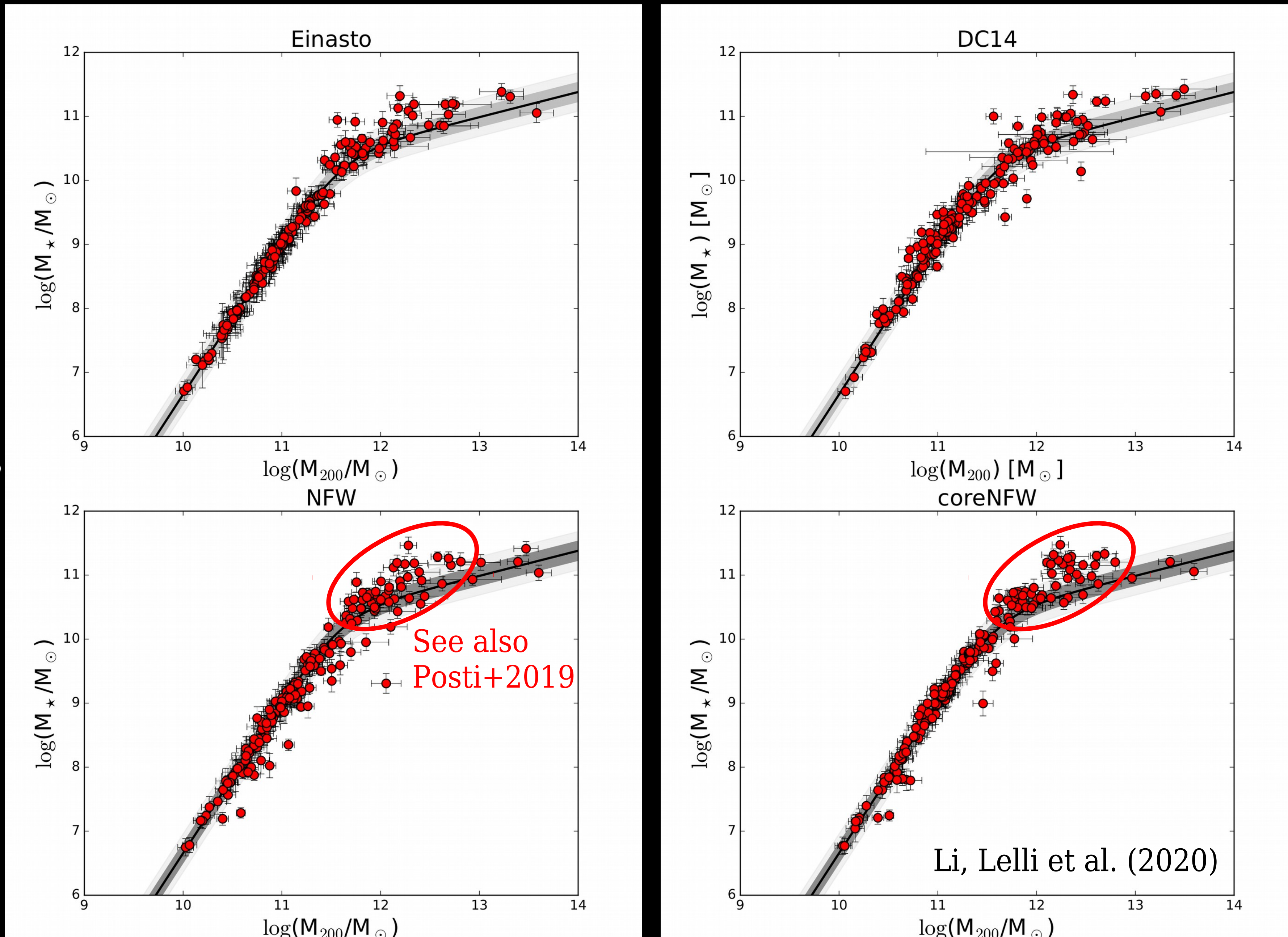
From DM-only simulations



From hydrodynamic simulations

M_*-M_{200} relation: Overall recovered

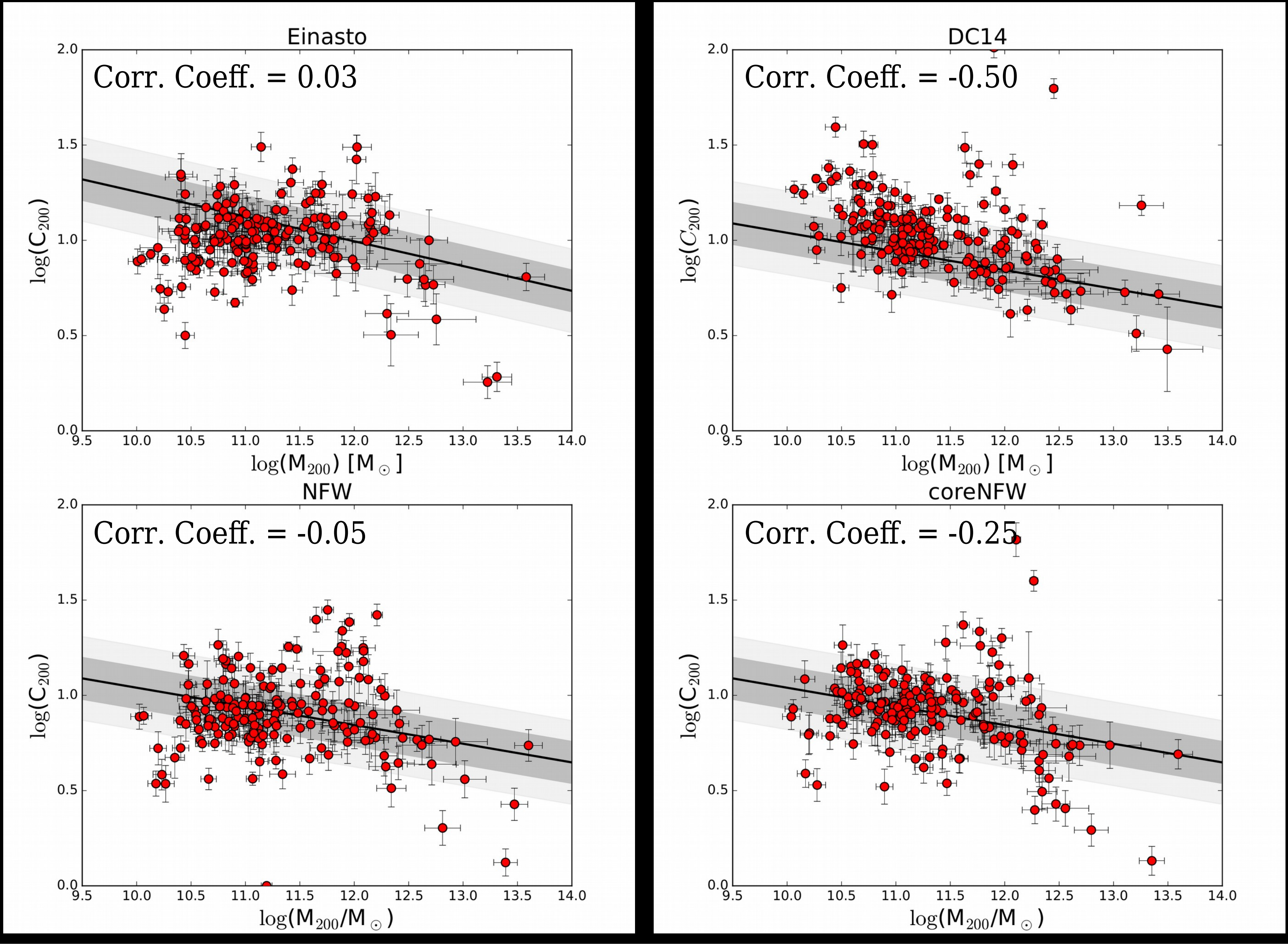
From DM-only simulations



From hydrodynamic simulations

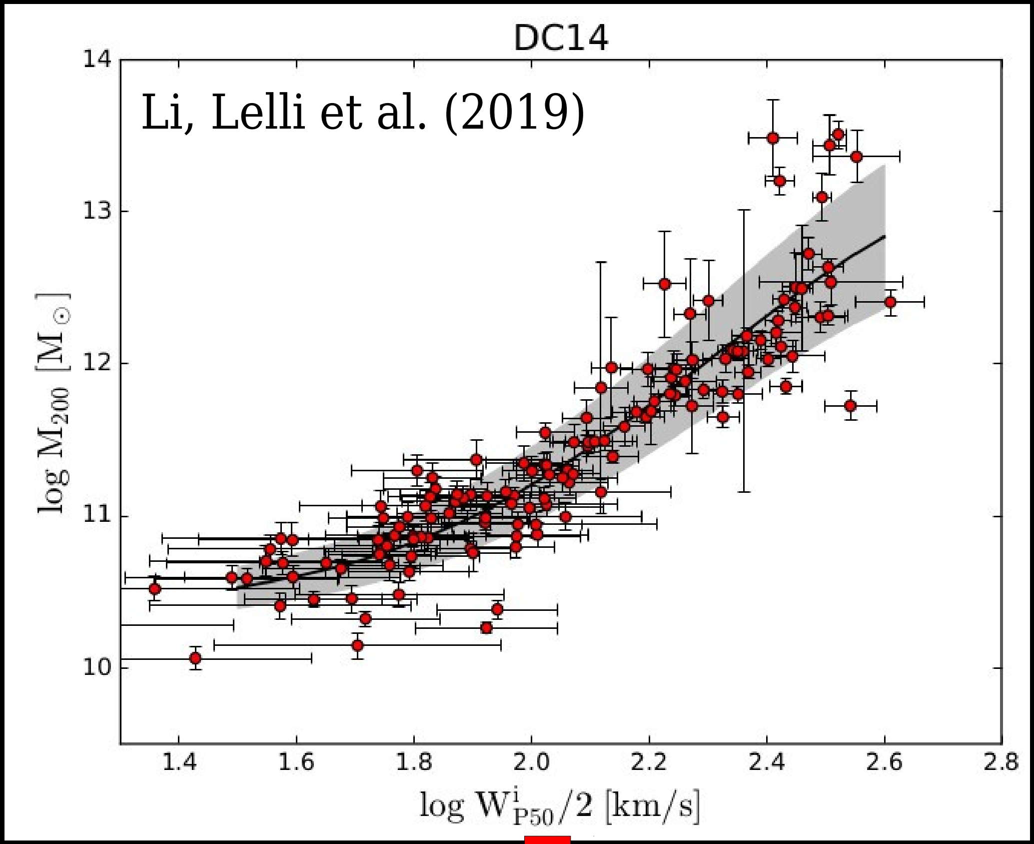
M_{200}-C_{200} relation: more problematic

From DM-only simulations



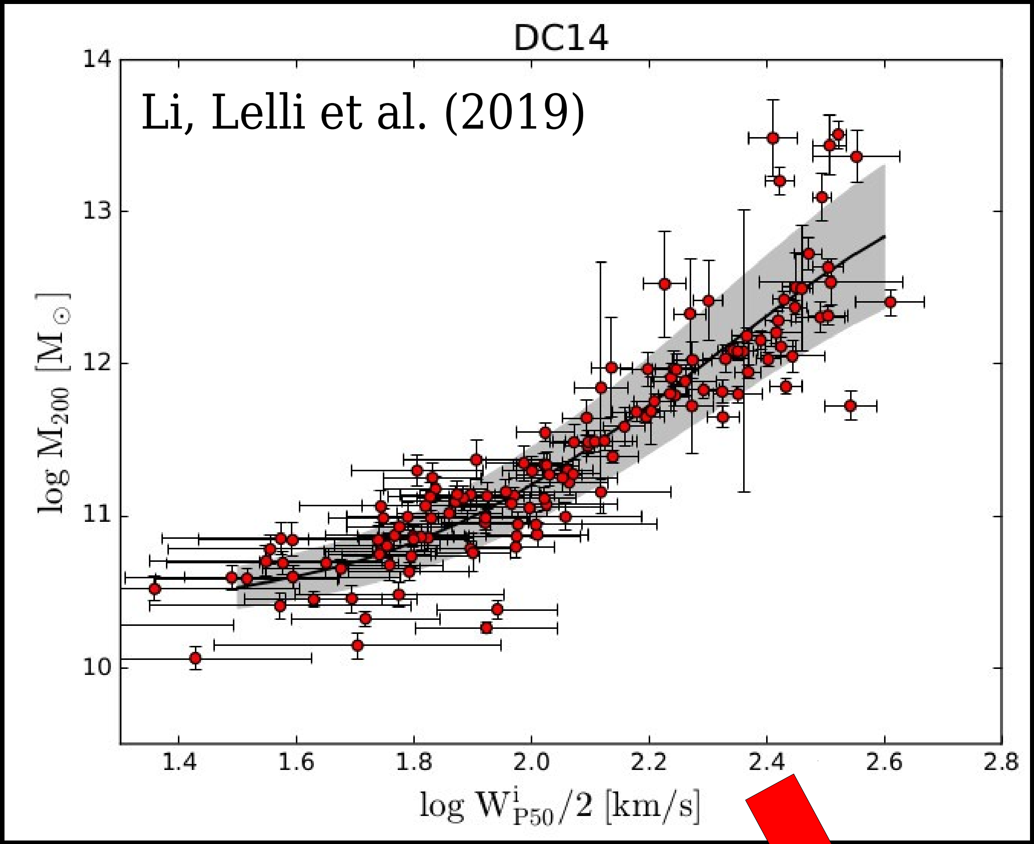
From hydrodynamic simulations

The Halo Mass Function of LTGs



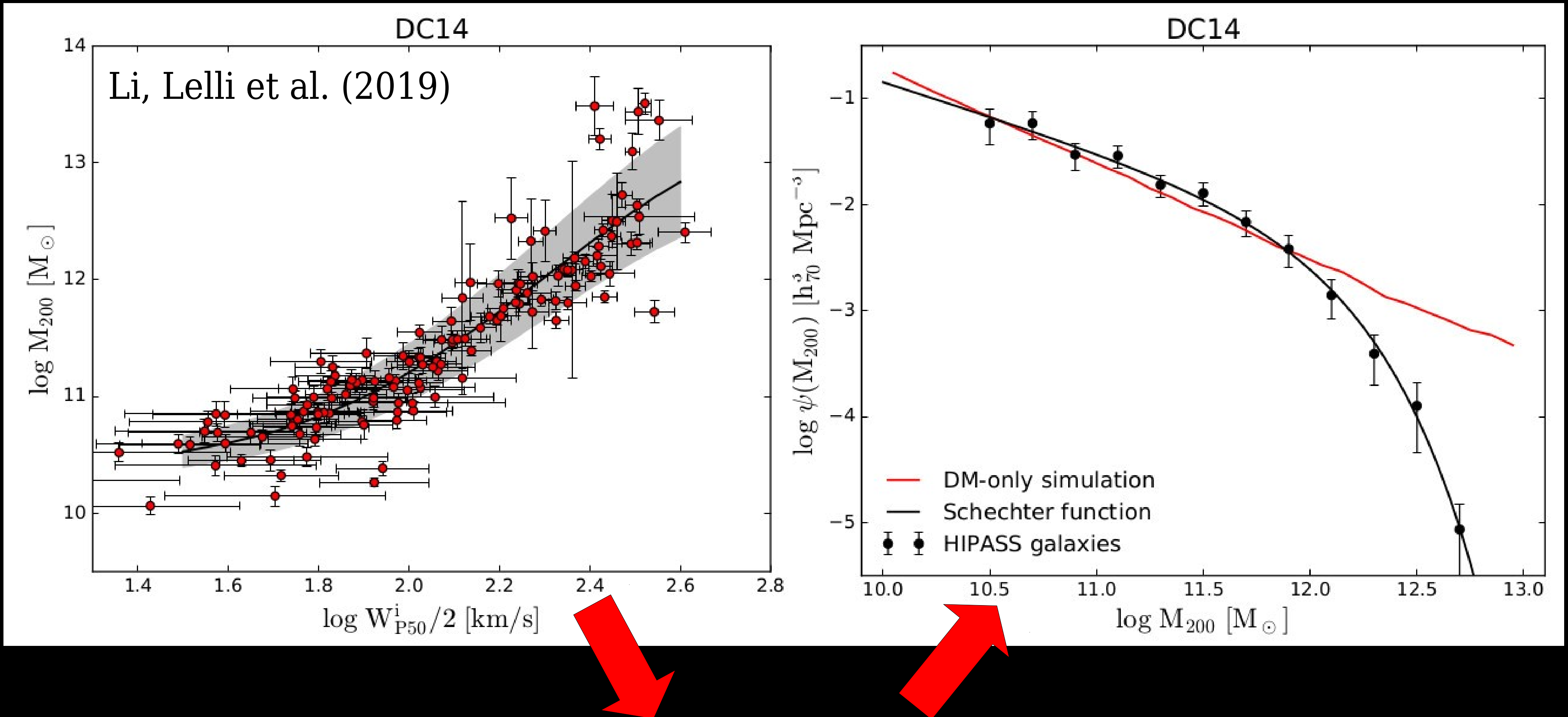
HI line-width from unresolved observations = cheap quantity!

The Halo Mass Function of LTGs



~1400 galaxies with HI line-widths from HIPASS (Zwann+2010)

The Halo Mass Function of LTGs



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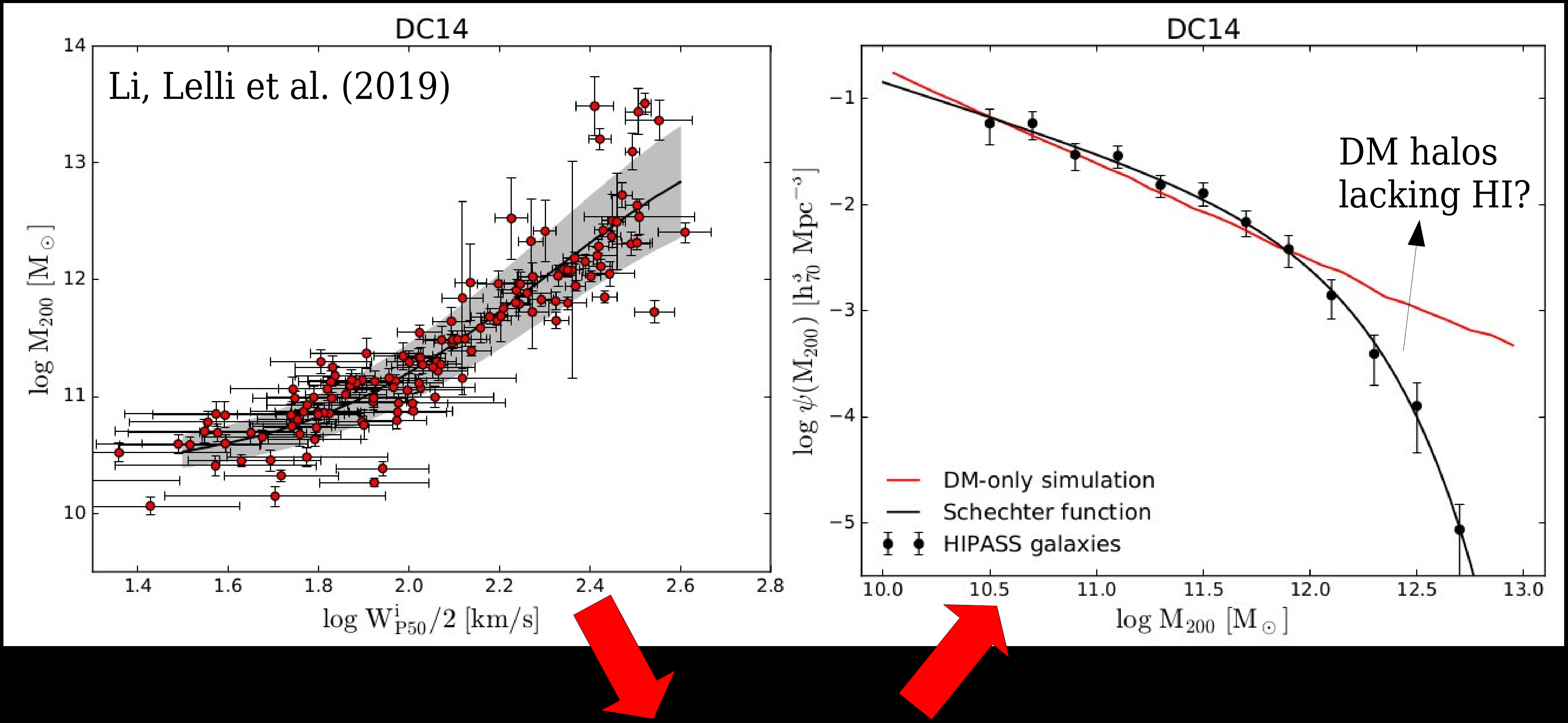

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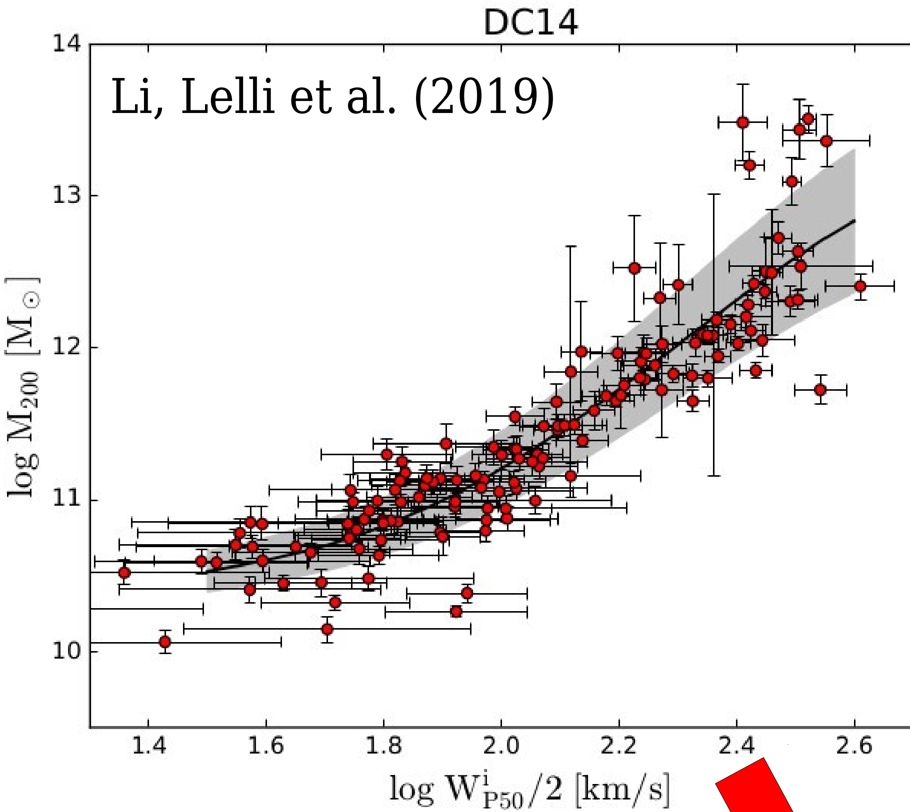
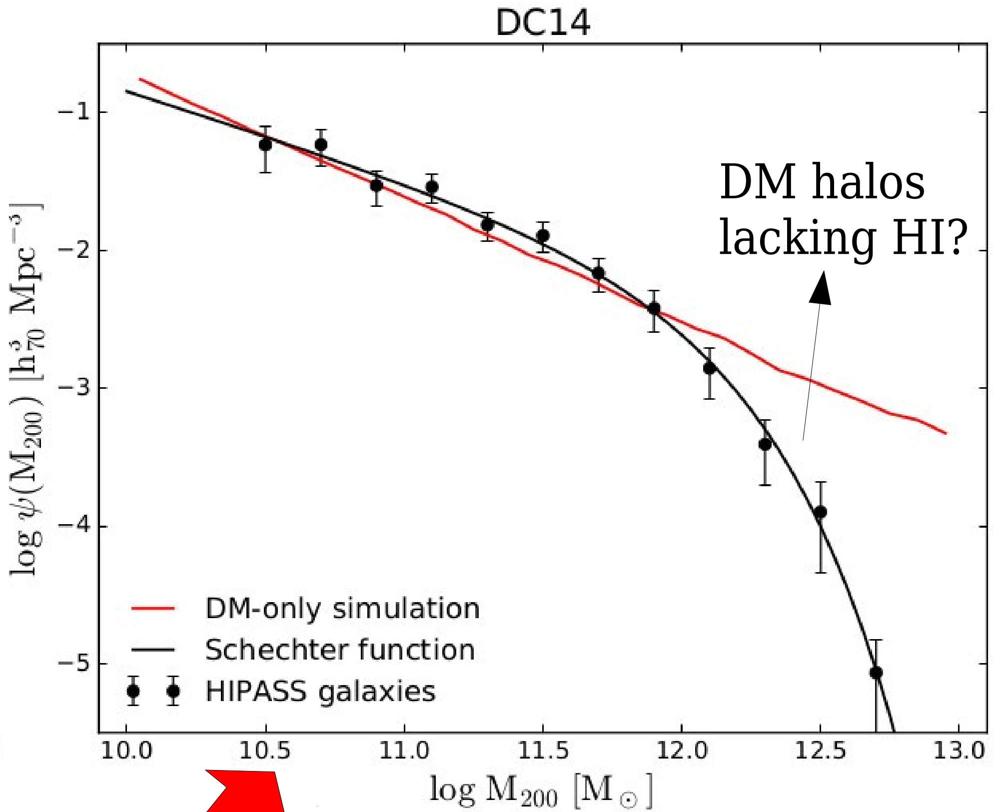
The Halo Mass Function of LTGs

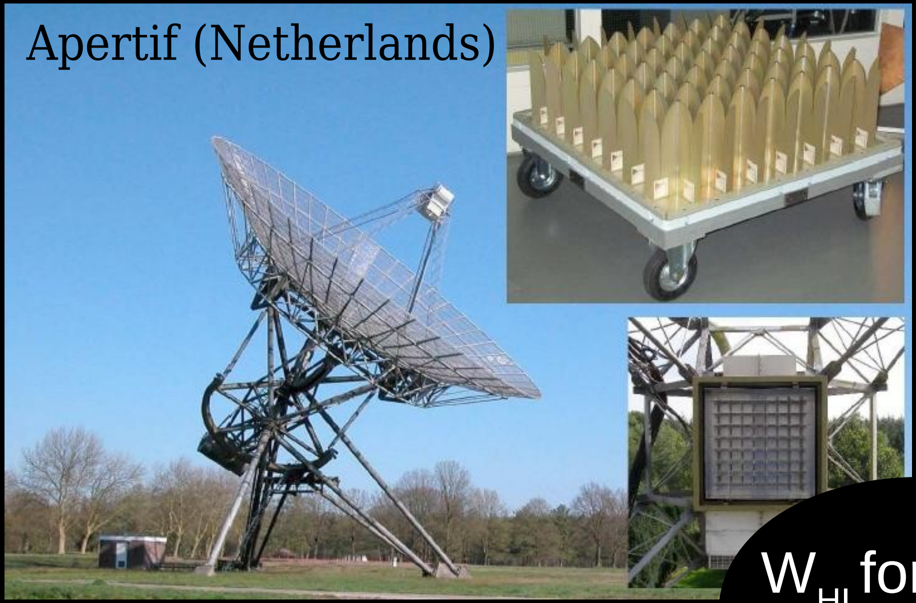




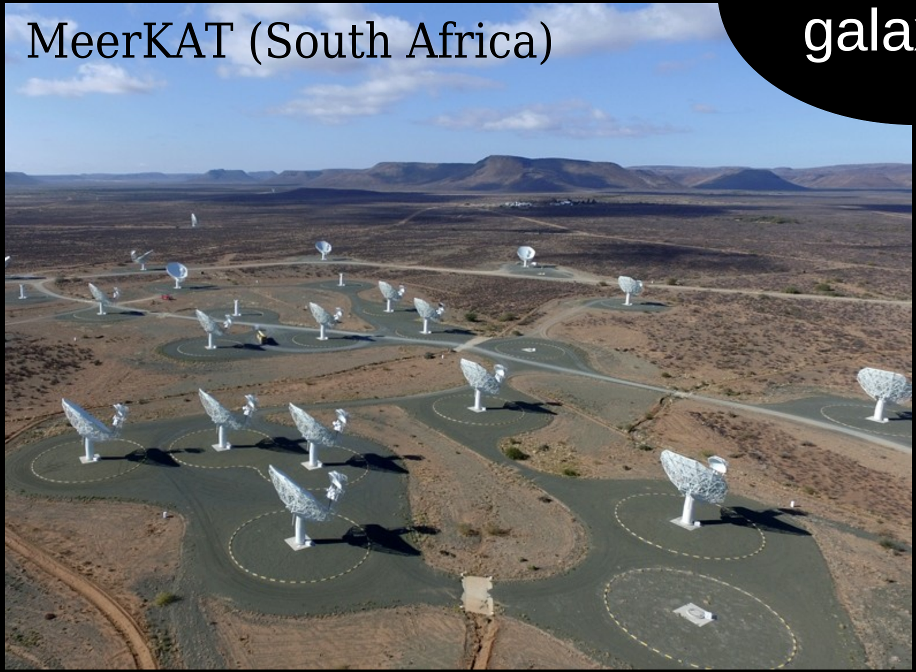
~1400 galaxies with HI line-widths from HIPASS (Zwann+2010)

No analog of the "missing satellite problem" in the field population down to M_{200}~$10^{10.5}$ → need to push to lower halo masses!

Powerful method for up-coming HI surveys



W_{HI} for ~10^5 galaxies!



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  DM cores are *really* needed (stellar feedback?)

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  DM cores are *really* needed (stellar feedback?)

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  No ΛCDM halo model is fully self-consistent

- First measurement of the Halo Mass Function:

  ΛCDM prediction is confirmed $10^{10.5} < M_{200} < 10^{12}$

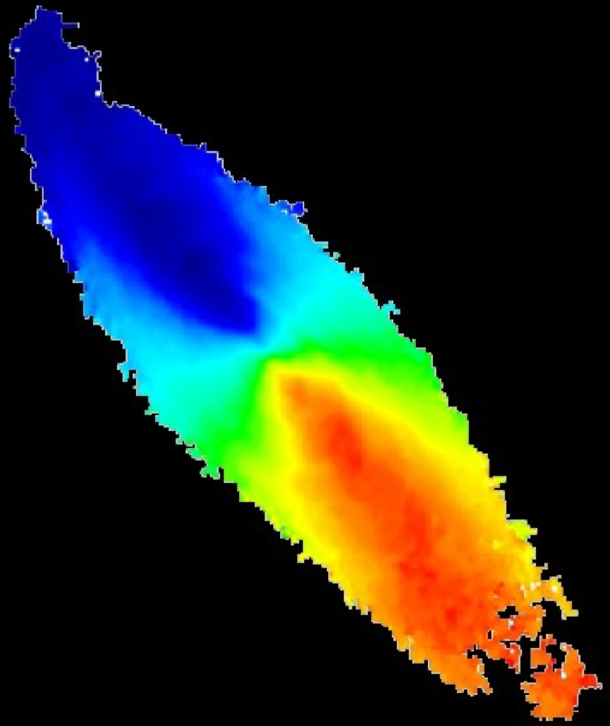
  New HI surveys will boost statistics & dynamic range!

3. Dynamical Laws of Disk Galaxies

Dynamical Laws of Disk Galaxies

Baryonic quantity
(gas and stars)

Dynamical quantity
(from gas kinematics)



Dynamical Laws of Disk Galaxies

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$V_{flat} \propto M_{bar}$ for $R \rightarrow \infty$

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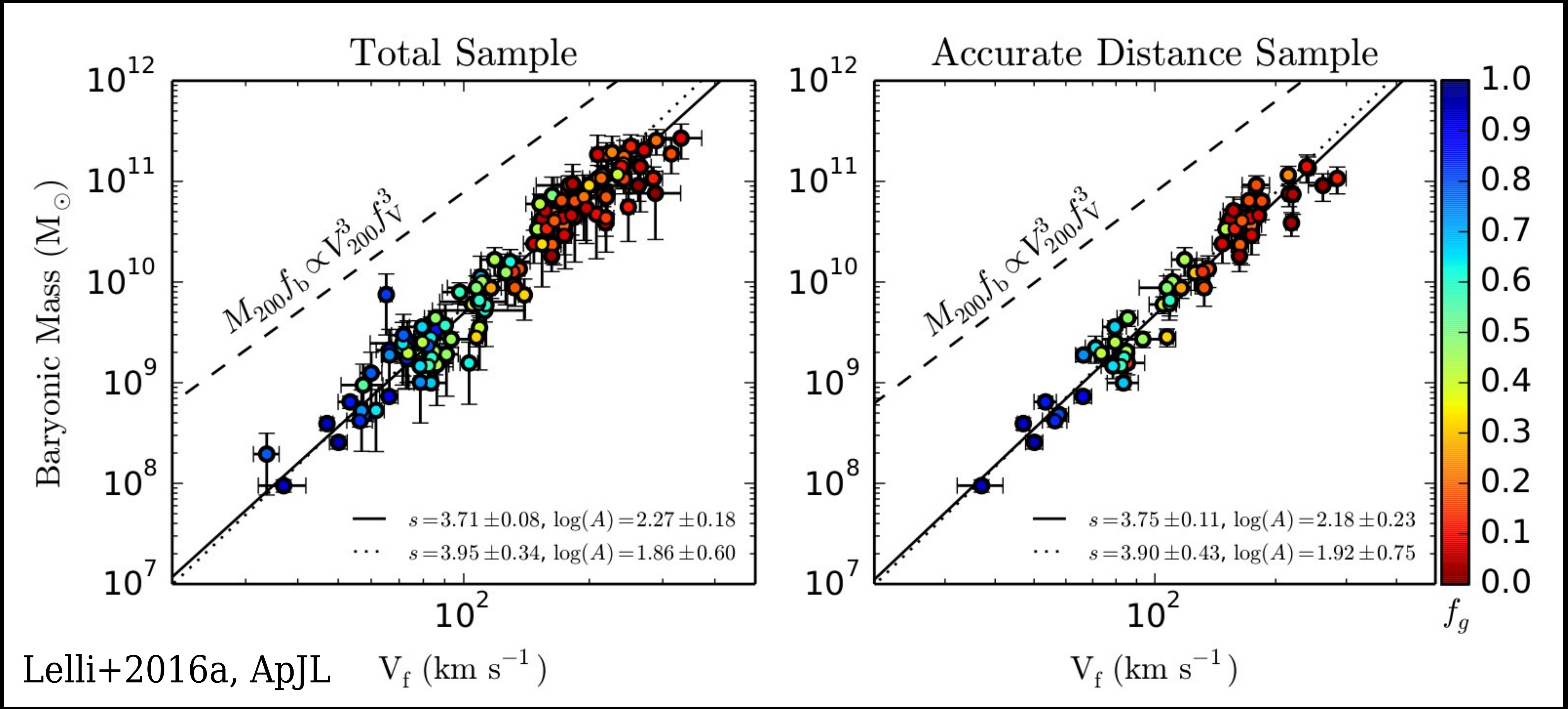
$\Sigma_{dyn} \propto \Sigma_{bar}$ for $R \rightarrow 0$

3rd. Radial Acceleration Relation (RAR)

$g_{obs} \propto g_{bar}$ for any R

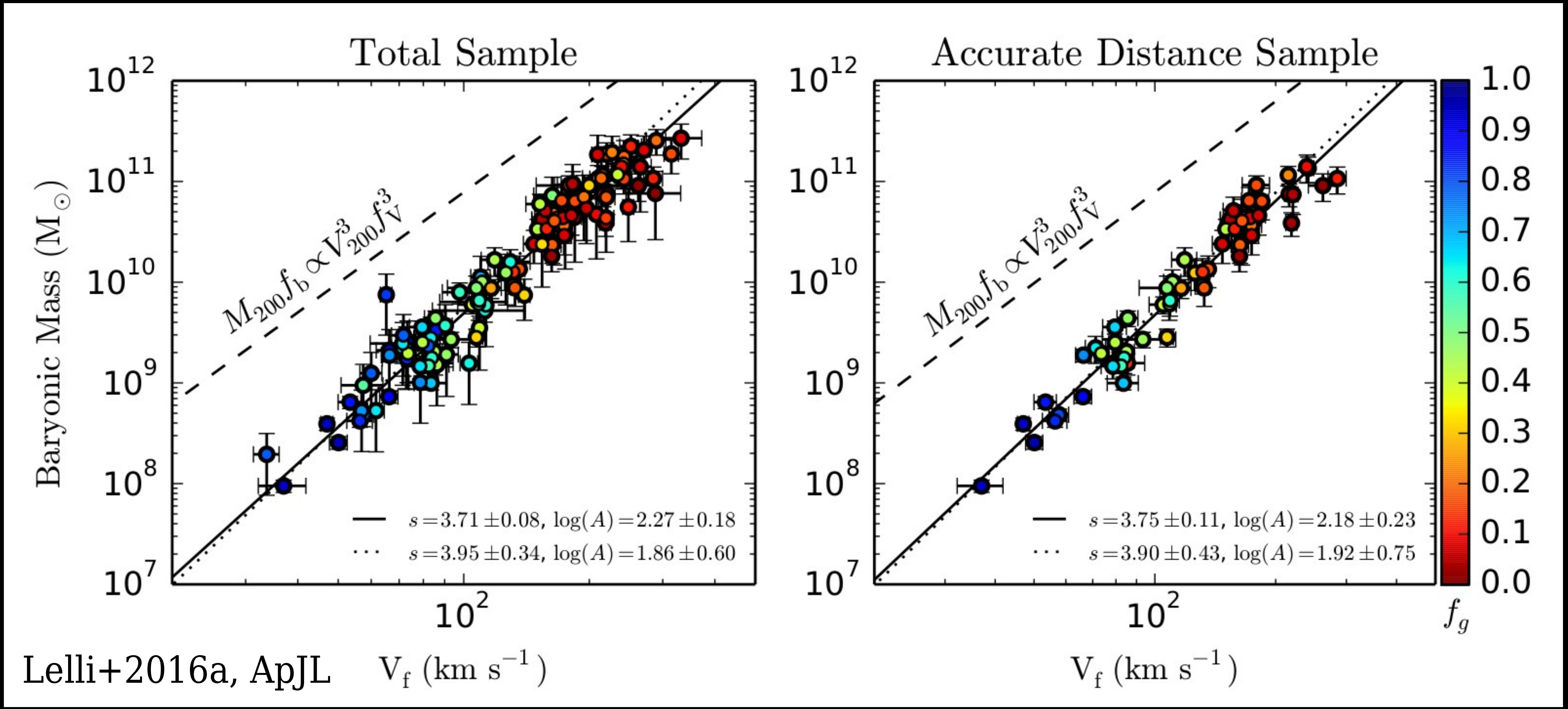
1st Law – Baryonic Tully-Fisher Relation



Some BTFR studies: McGaugh+2000, 2005, 2012; Verhejen 2001; Bell & de Jong 2001; Geha+2006; Noordermeer & Verheihen+2007; Begum+2008; Avila-Reese+2008; Stark+2009; Trachternach+2010; Gurovich+2010; Catinella+2012; Zaritsky+2014; Papastergis+2016; Bradford+2016; Ponomareva+2018

Golden Rule: As the data quality increases, the scatter decreases!

1st Law – Baryonic Tully-Fisher Relation

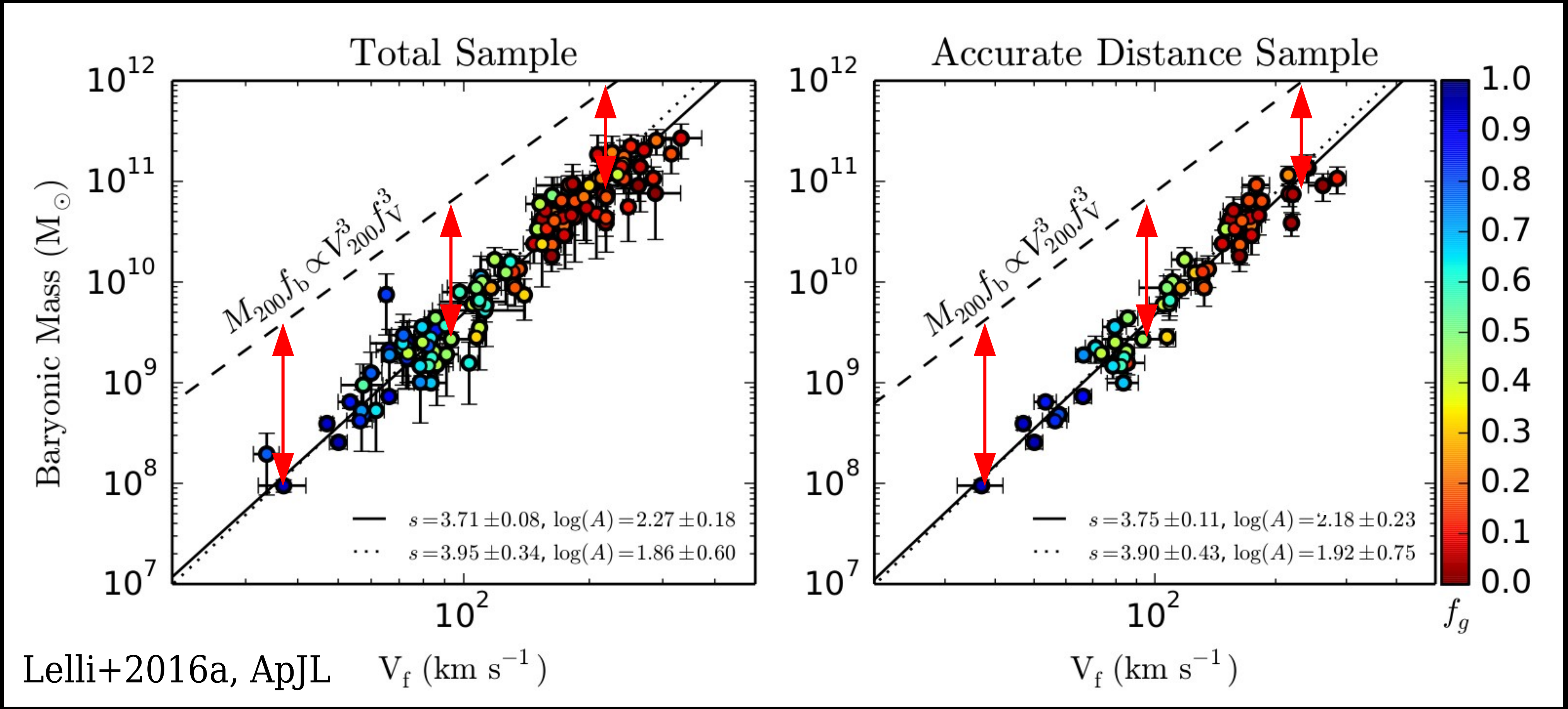


Assuming baryon fraction in galaxies = cosmic value (CMB)

→ wrong normalization and slope! Missing baryons problem!

Possible solution: stellar/AGN feedback keeps baryons hot

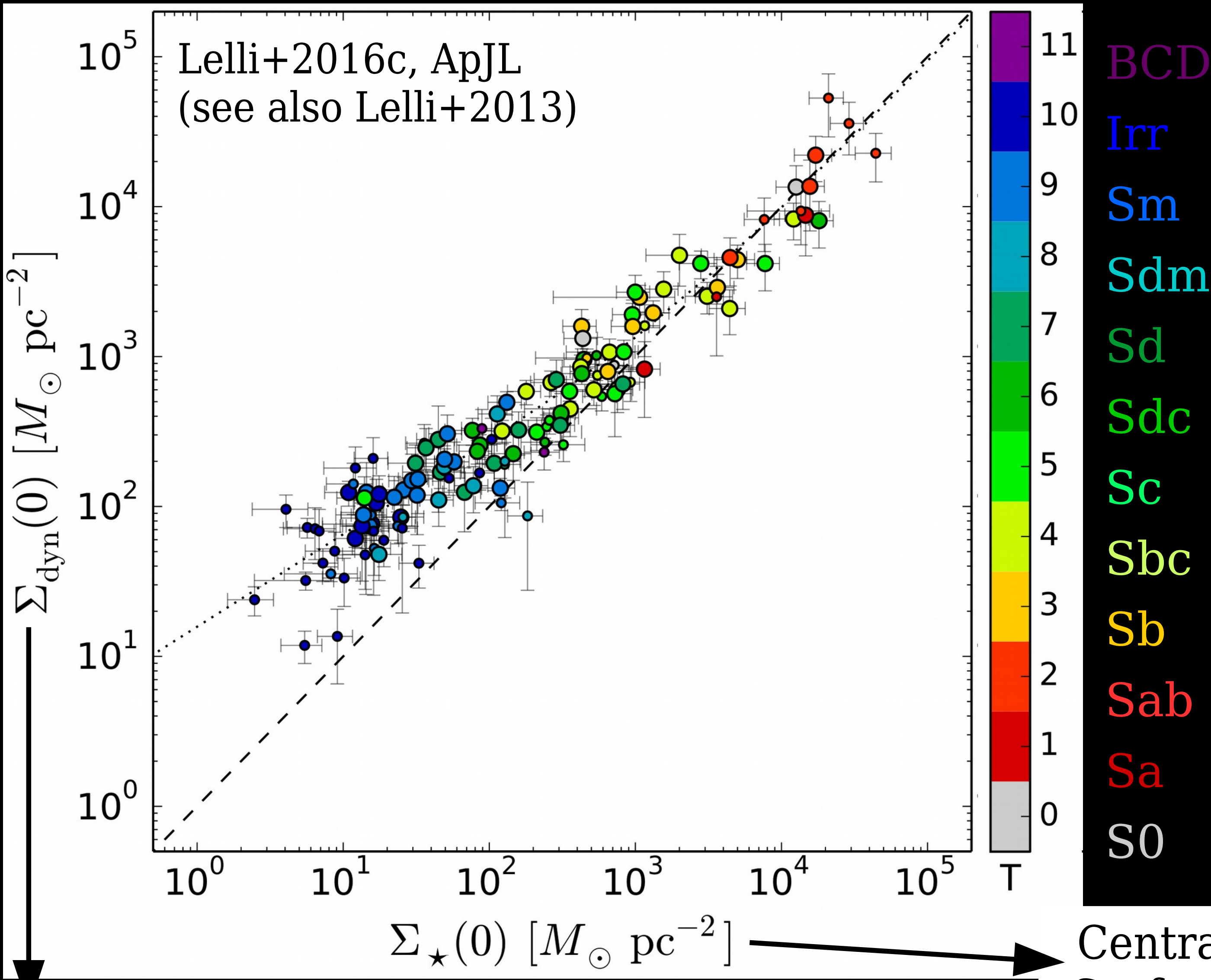
1st Law – Baryonic Tully-Fisher Relation



Each halo must know precisely how many baryons to hide:

Galaxy formation must be highly fine-tuned in ΛCDM!

2^{nd} Law – Central Density Relation

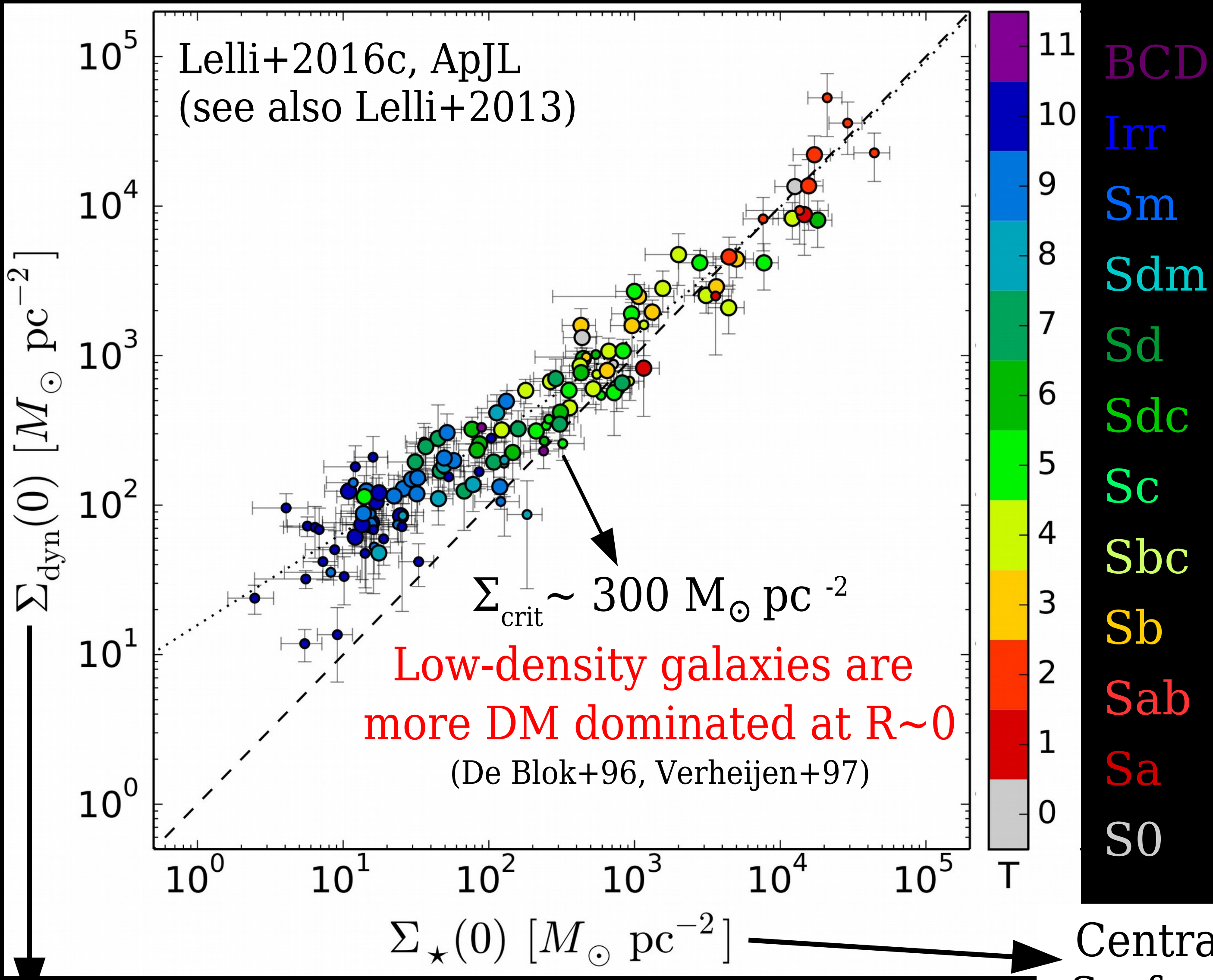


Central Stellar Surface Density

$$\Sigma_{dyn}(0) = \frac{1}{2\pi G}\int_0^\infty \frac{V^2(R)}{R^2}dR,$$

Toomre (1963): Central Dynamical Density for Self-Gravitating Disks.

2nd Law – Central Density Relation



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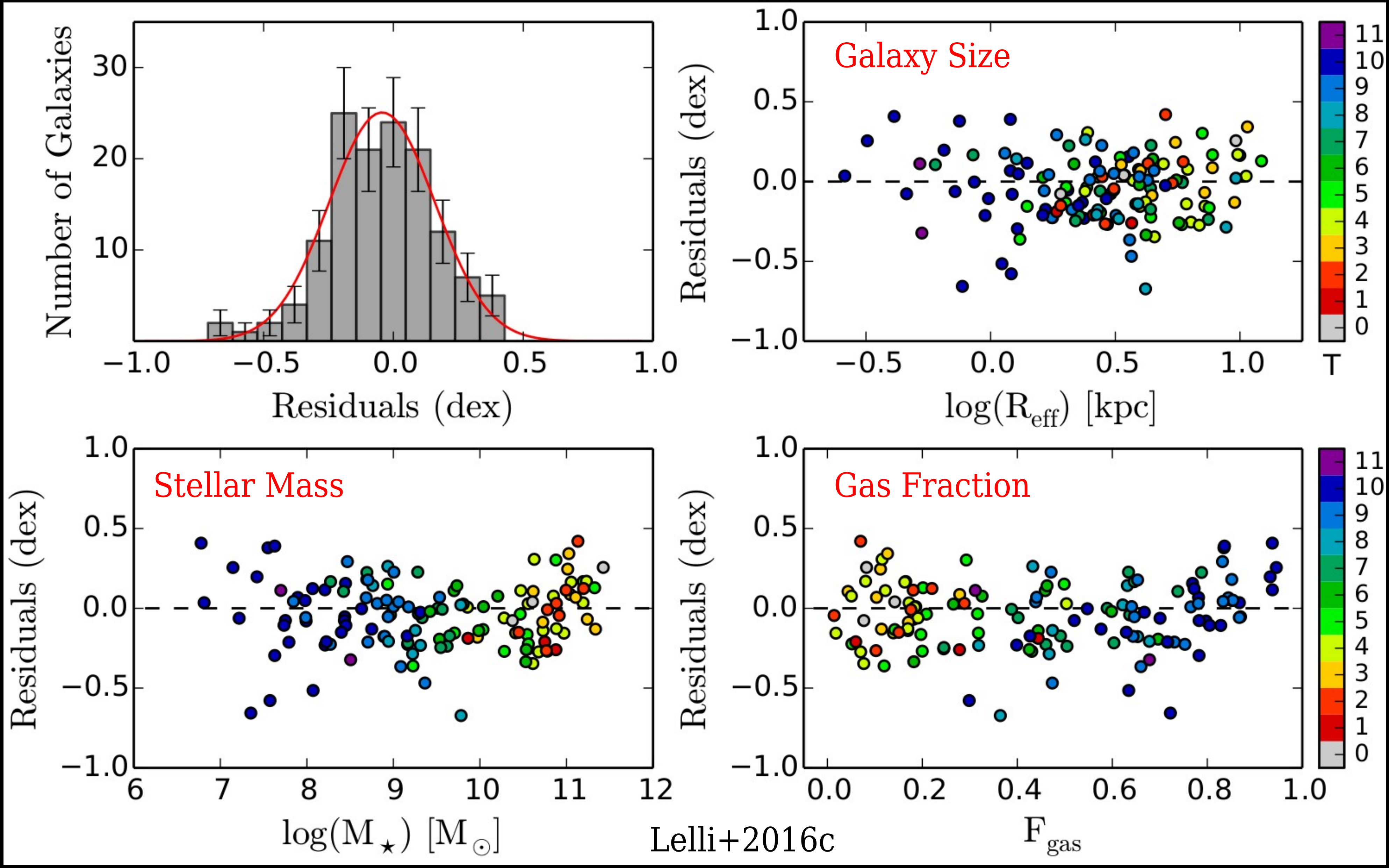
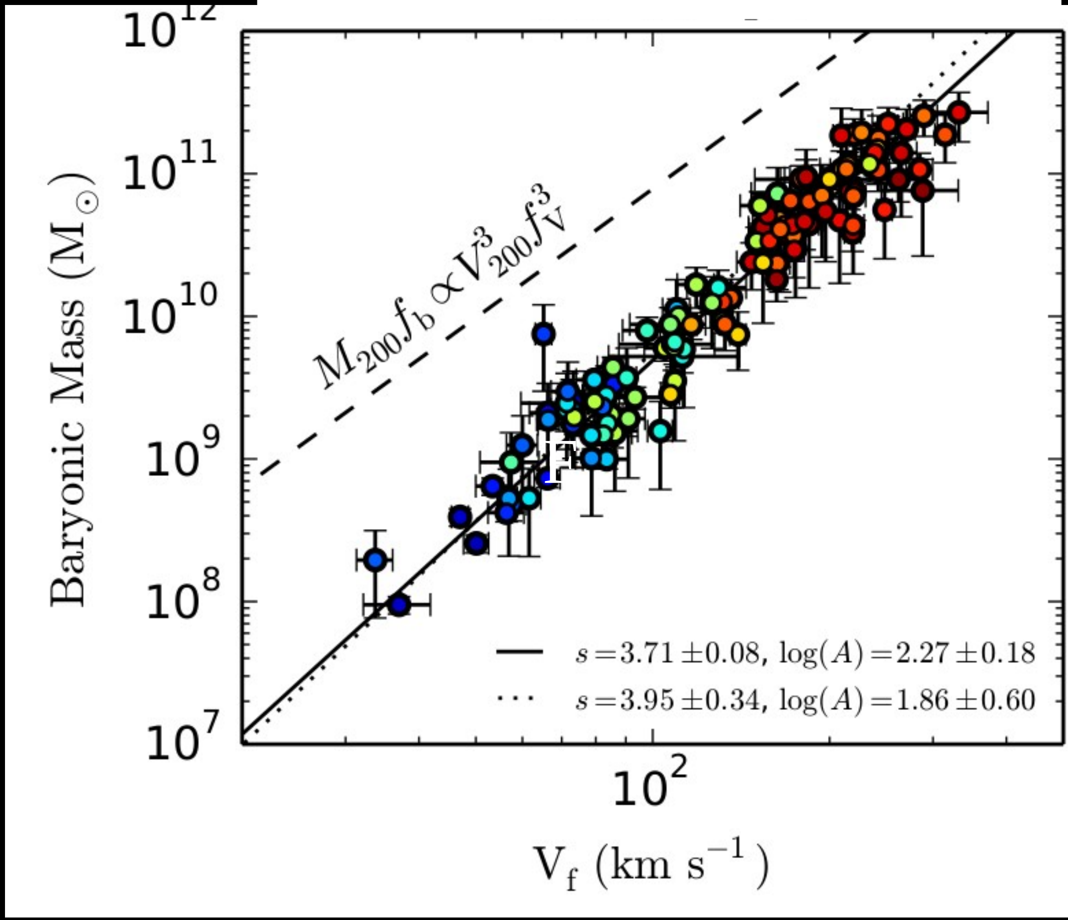
No Residual Correlations across the CDR



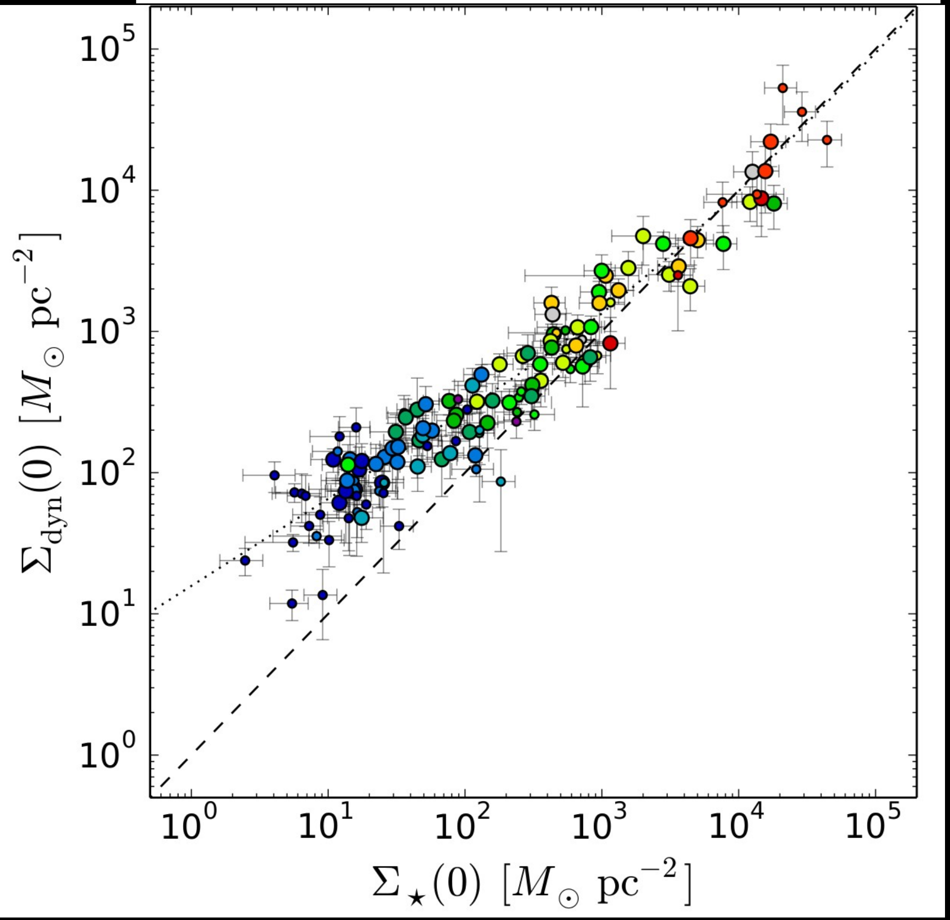
Newton's Shell Theorem does NOT apply. We expect correlations with disk mass or size!

These are "asymptotic" relationships

Baryonic Tully-Fisher (R→∞)



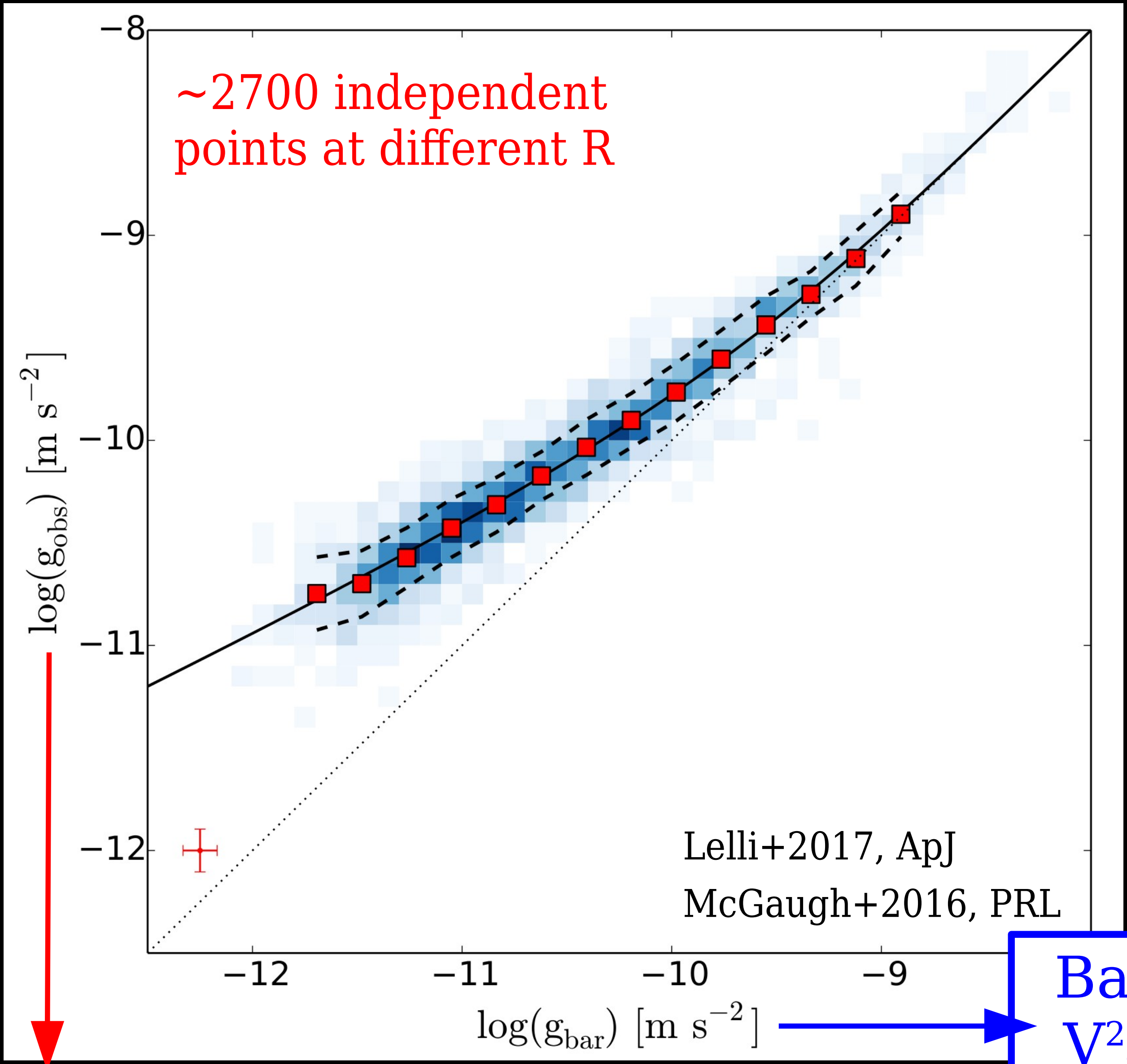
Central Density Relation (R→0)



Each point represents a single galaxy...

but we can use each individual point in the rotation curve!

3rd Law - Radial Acceleration Relation



Baryon Gravity:
$V^2_{bar}/R = -\nabla\Phi_{bar}$
$\nabla^2\Phi_{bar} = 4\pi G\,\rho_{bar}$

Total Acceleration: $V^2_{obs}/R = -\nabla\Phi_{tot}$

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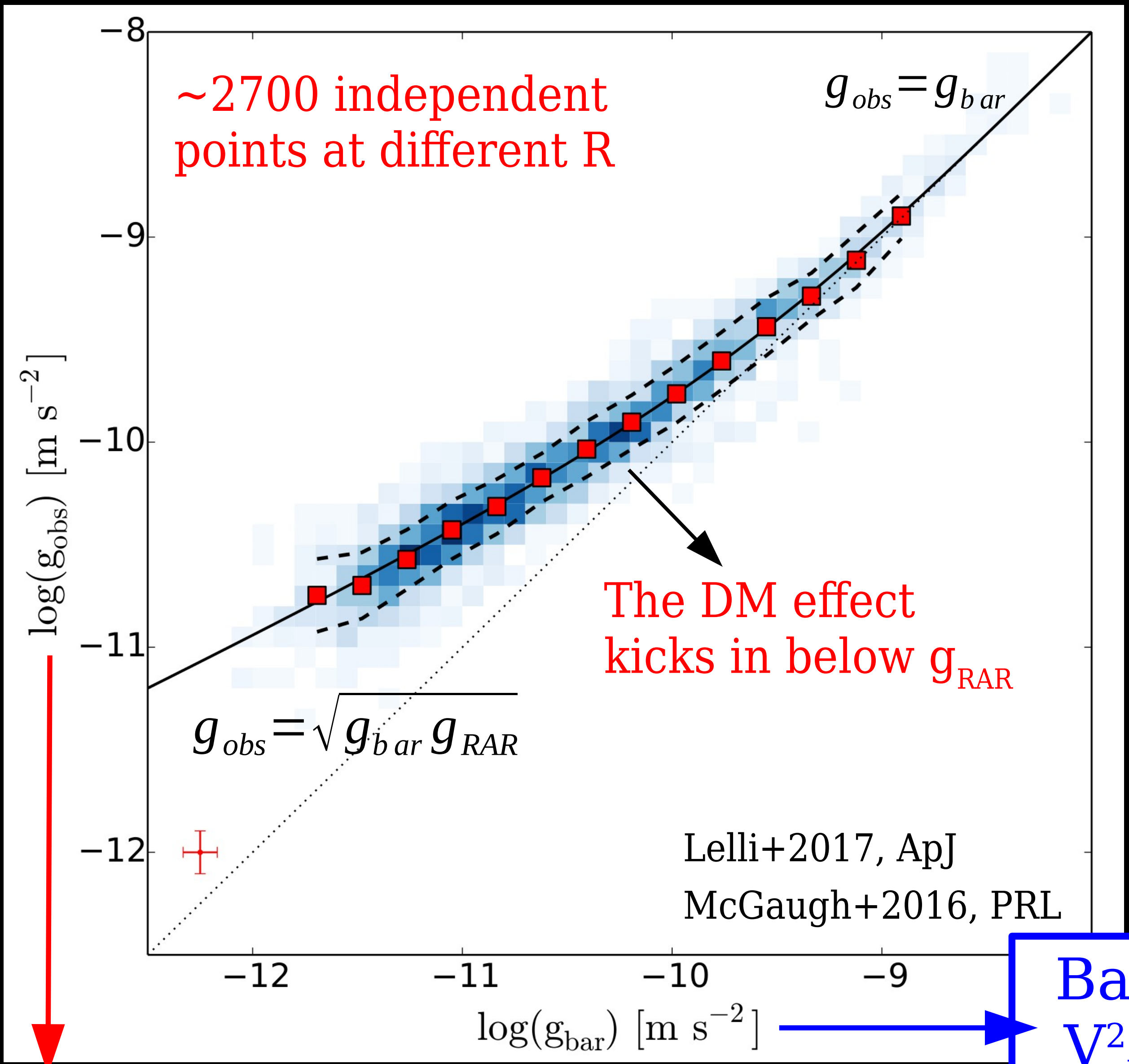

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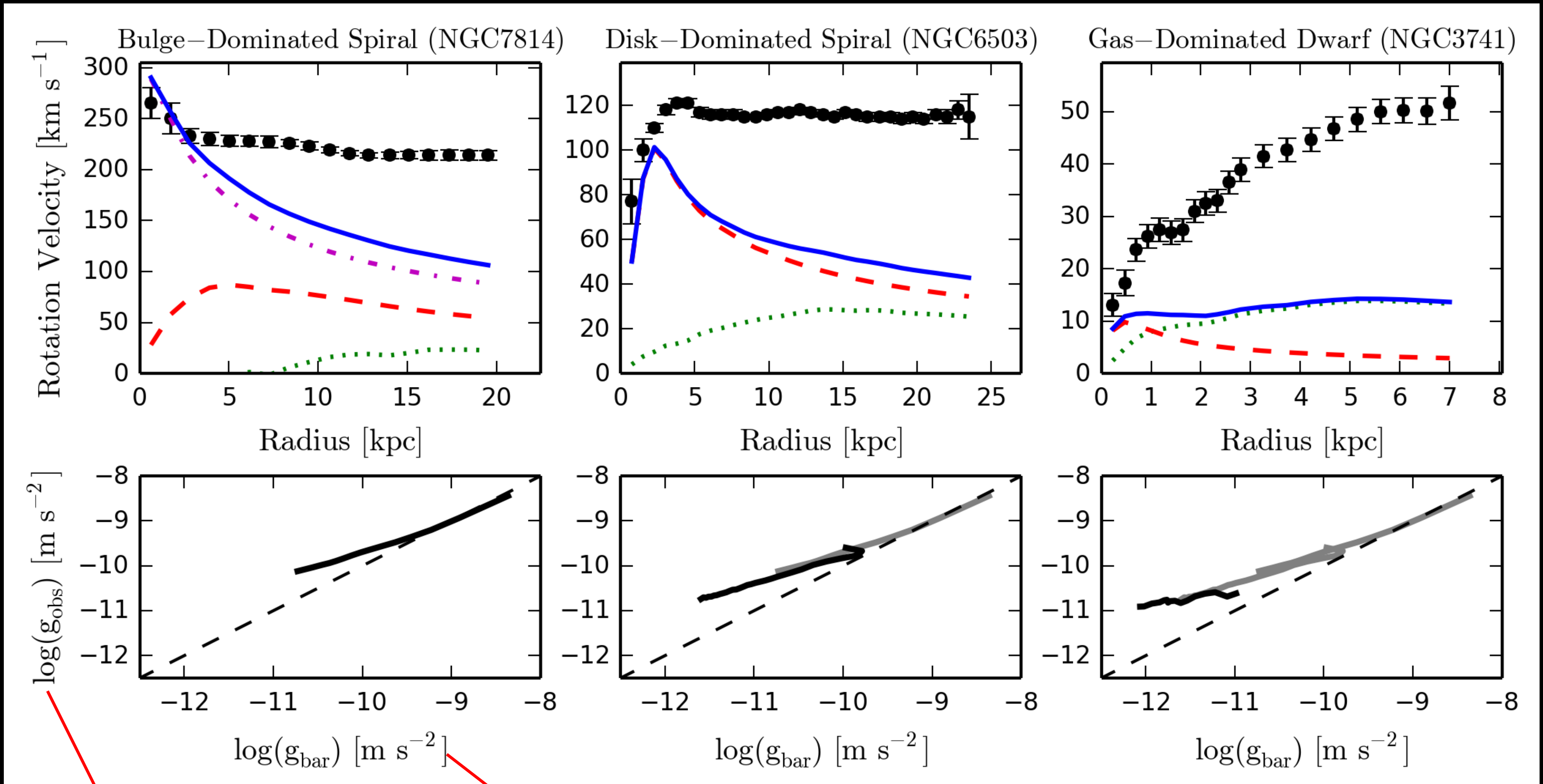
Very different galaxies but same relation

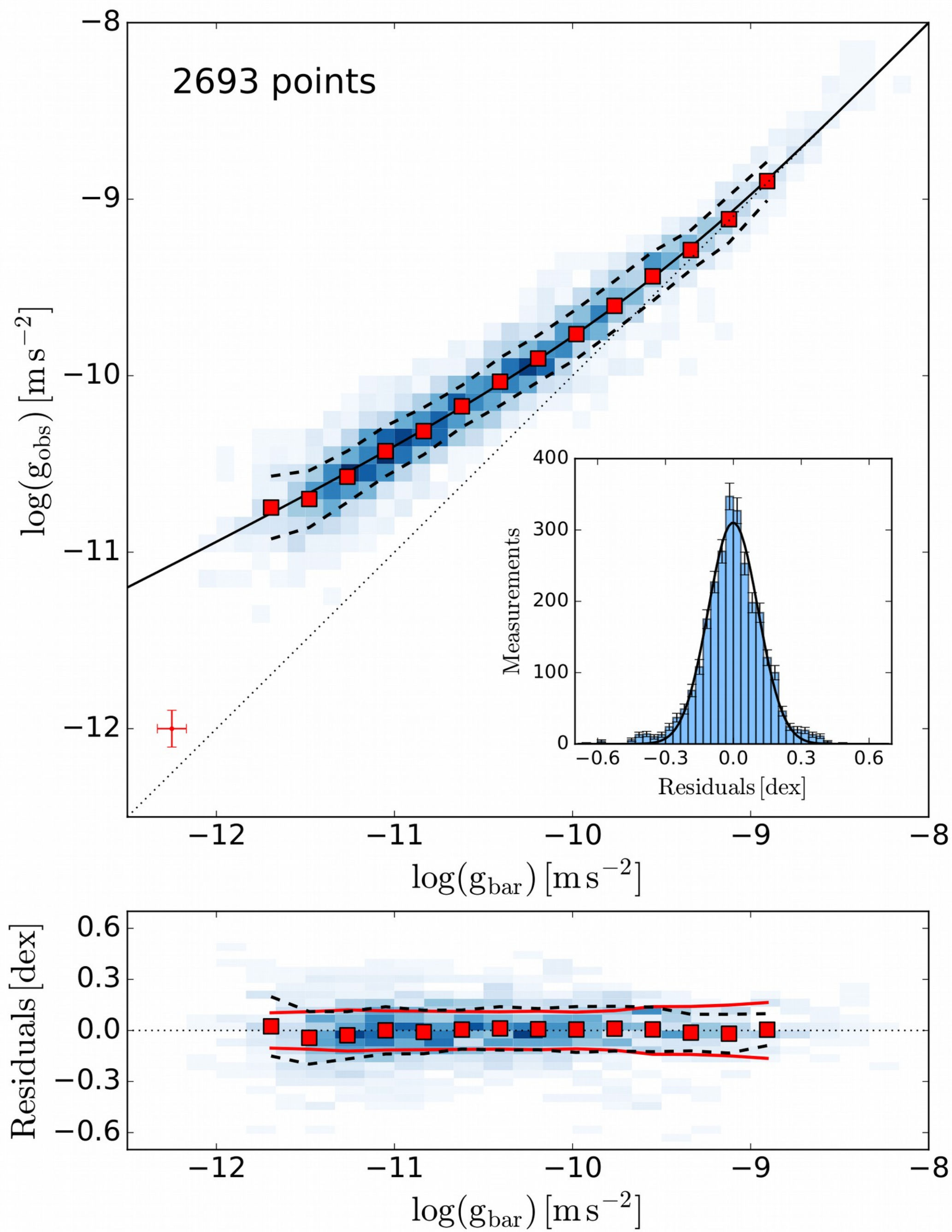


$$V^2_{obs}/R = -\nabla\Phi_{tot}$$

$$V^2_{bar}/R = -\nabla\Phi_{bar}$$
$$\nabla^2\Phi_{bar} = 4\pi G\, \rho_{bar}$$

McGaugh, Lelli, Schombert (2016)

Is There Any Intrinsic Scatter?



<u>Uncertainties drive scatter!</u>

err(g_{bar}) → Υ_*, 3D geometry

err(g_{obs}) → Dist, Inc, V_{rot}

$$\sigma_{obs}^2 = \sigma_{err}^2 + \sigma_{int}^2$$

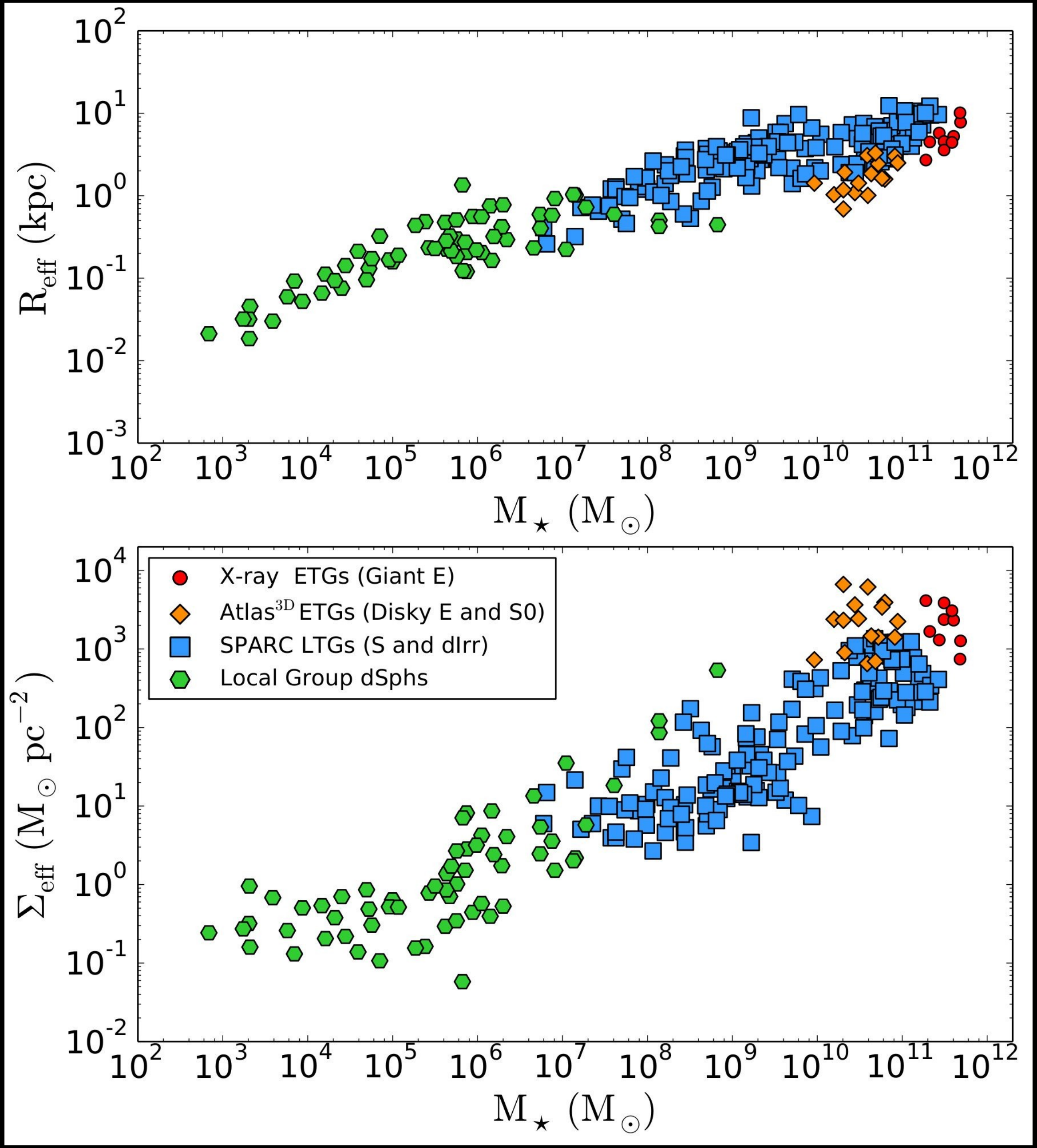
σ_{obs} → measured rms~30%

σ_{err} → error propagation

σ_{int} → consistent with zero

McGaugh+2016; Lelli+2017; Li+2018

What about Early-Type Galaxies?



Giant Ellipticals:

g_{obs} from hot X-rays haloes in hydrostatic equilibrium (Humprey+2006, 2009, 2012)

Disky Es and S0s:

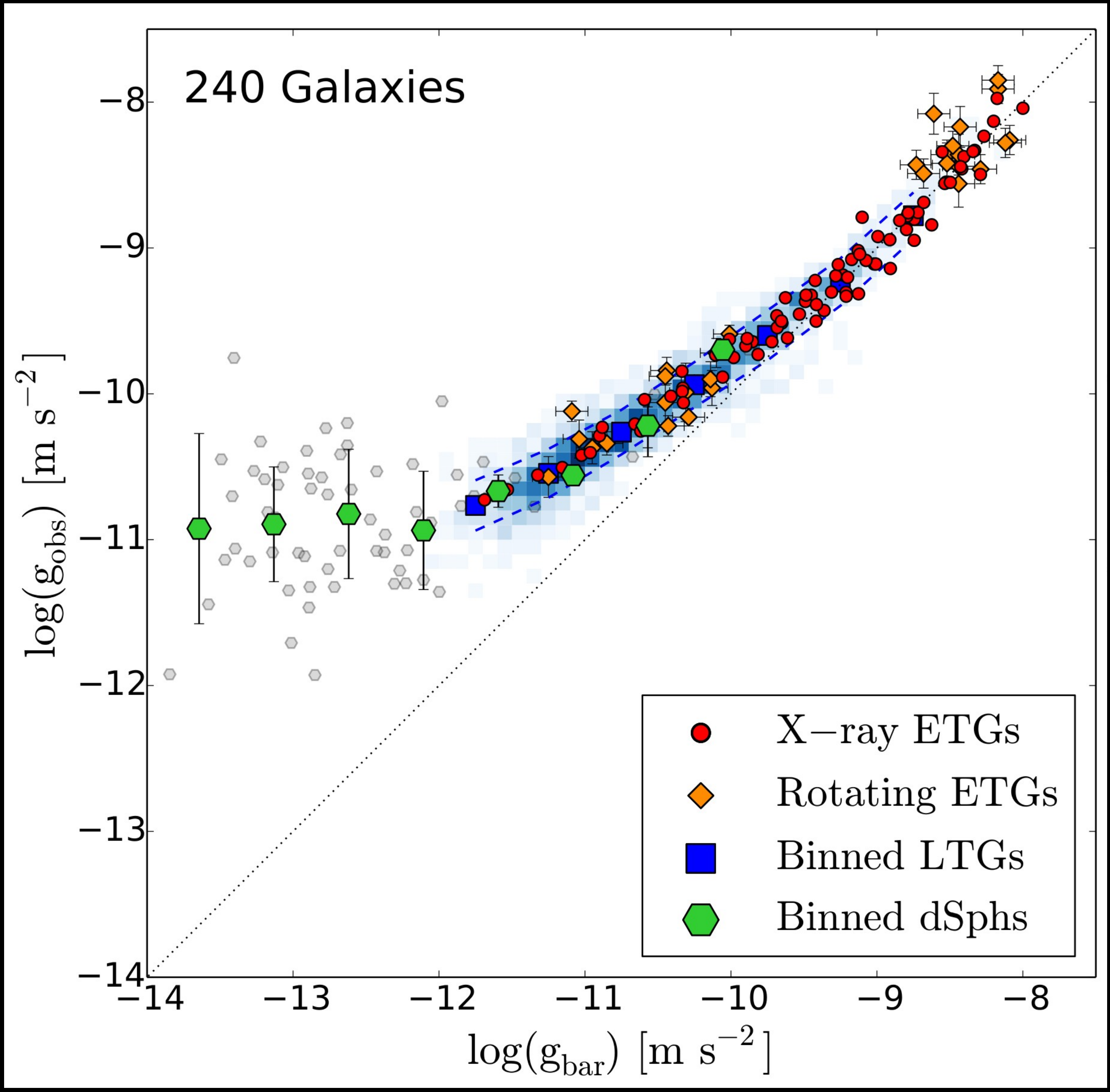
g_{obs} from stellar kinematics+ Jeans Axisymmetric Models (Atlas^{3D} - Cappellari+2010)

Dwarf Spheroidals:

g_{obs} from stellar kinematics+ Jeans Spherical Models (many many references...)

Lelli+2017, ApJ

Radial Acceleration Relation for ETGs



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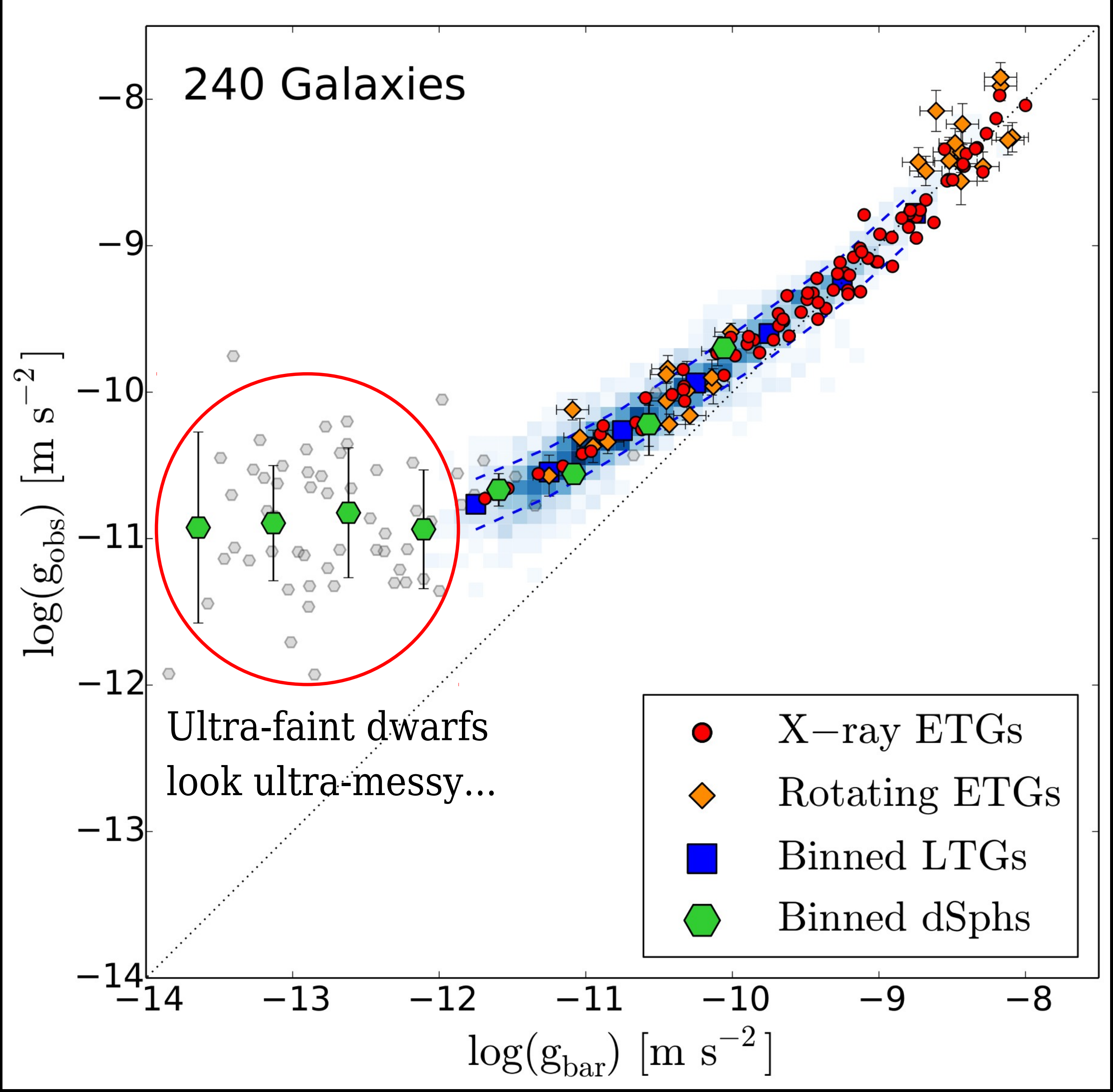

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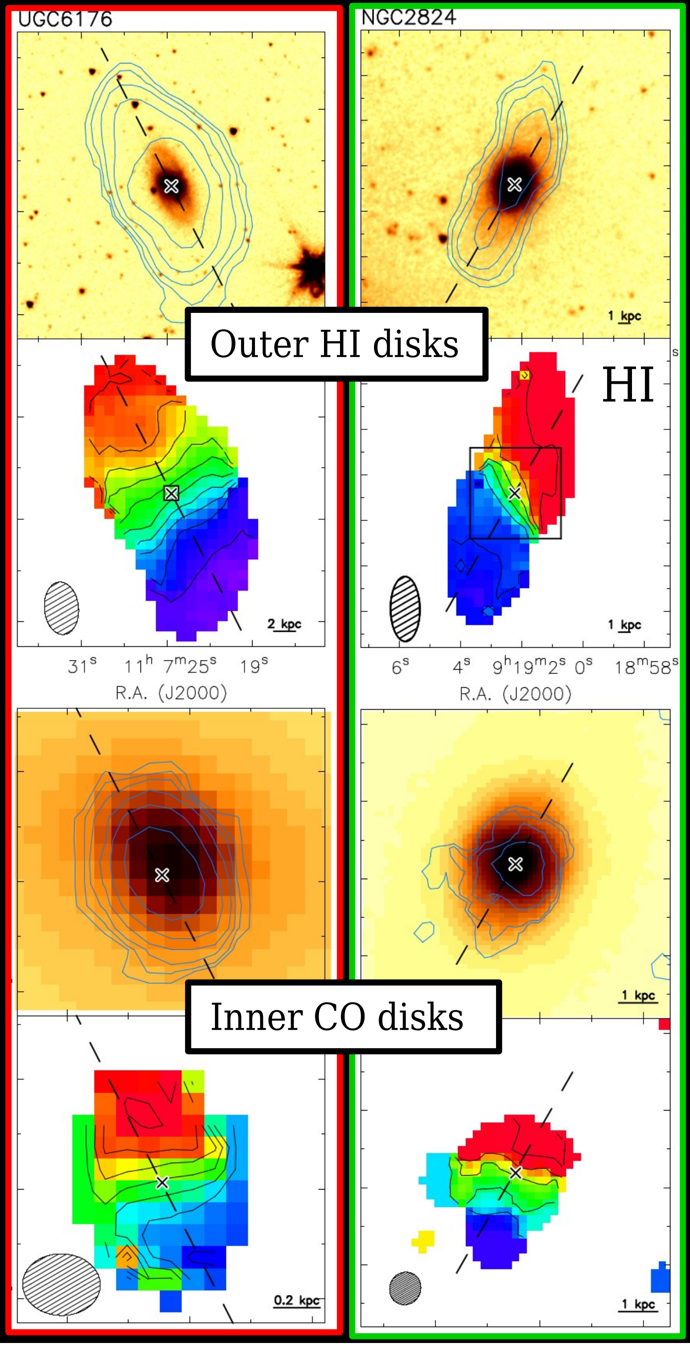
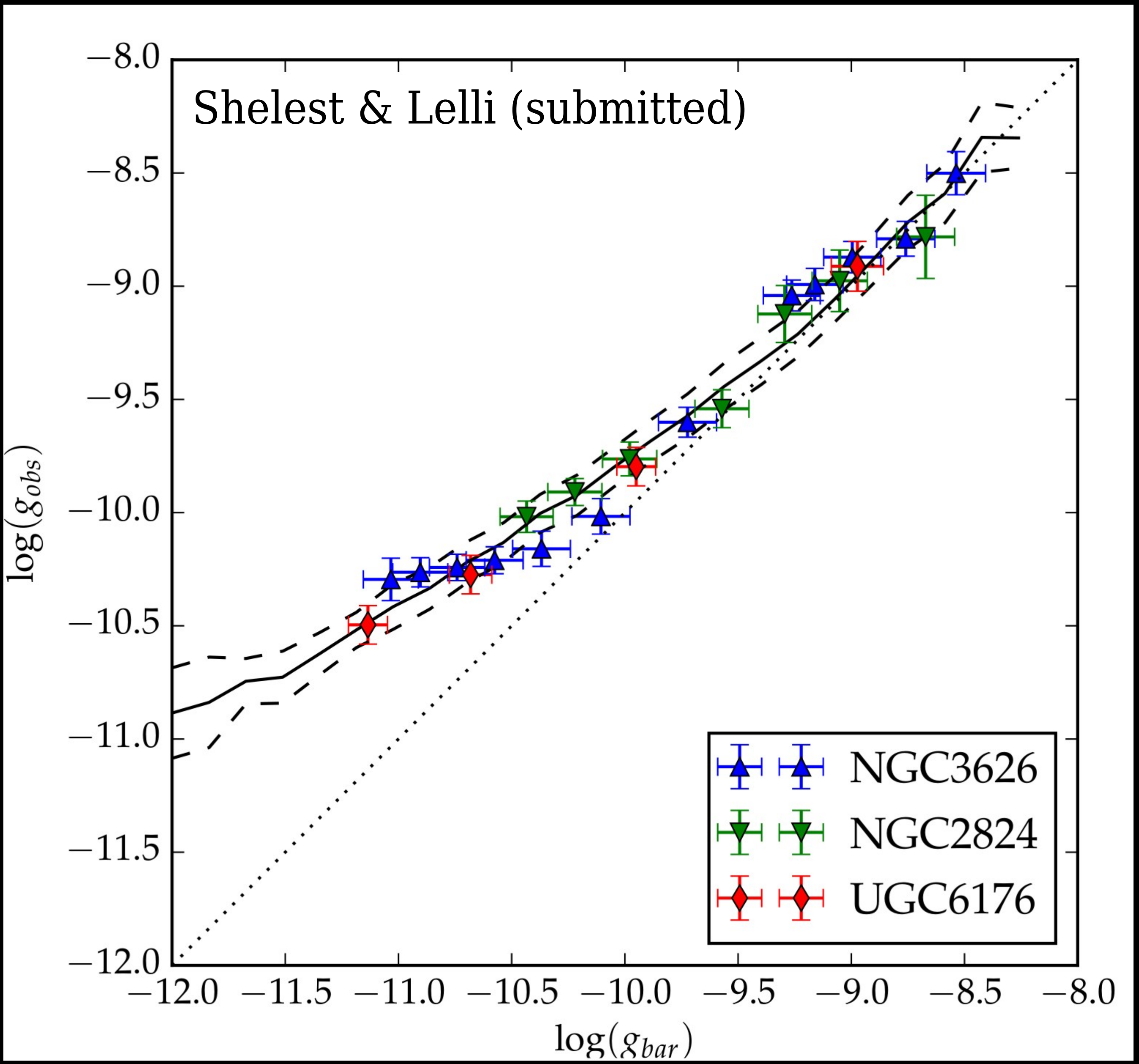
Lelli+2017, ApJ

RAR confirmed in three "special" S0s





We can infer the DM profile <u>empirically</u> from the baryons with a ~30% accuracy!

From the observations: $g_{DM} = g_{obs} - g_{bar} = F(g_{bar})$

For a spherical DM halo: $M_{DM}(R) = \frac{R^2}{G} F(g_{bar})$

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"Cusp-vs-Core" is a symptom of a more serious illness:

Baryon-DM coupling occurs at any radii!

Acceleration Scales:

1st . Baryonic Tully-Fisher: $V_f^4 \propto M_{bar}$ for $R \to \infty$

Normalization ~ $1/(G_N \cdot g_{BTF}) \rightarrow$ global M_{tot}/M_{bar}

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g_{RAR} dictates when $M_{tot}/M_{bar} > 1$ in a single galaxy

$g_{BTF} \sim g_{CDR} \sim g_{RAR}$ despite they play very different roles!

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study

Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of *r* at large radii, thus resulting in asymptotically flat velocity curves.

2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass.

3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears.

4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.

5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2 \times 10^{-8}(H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})^2 \text{ cm s}^{-2}$, which is of the order of $CH_0 = 5 \times 10^{-8}(H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1}) \text{ cm s}^{-2}$.

The main predictions are:

1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.

2. The $V_\infty^4 = a_0 GM$ relation should hold exactly.

3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing *r* in a predictable way.

Milgrom 1983, ApJ, 270, 371

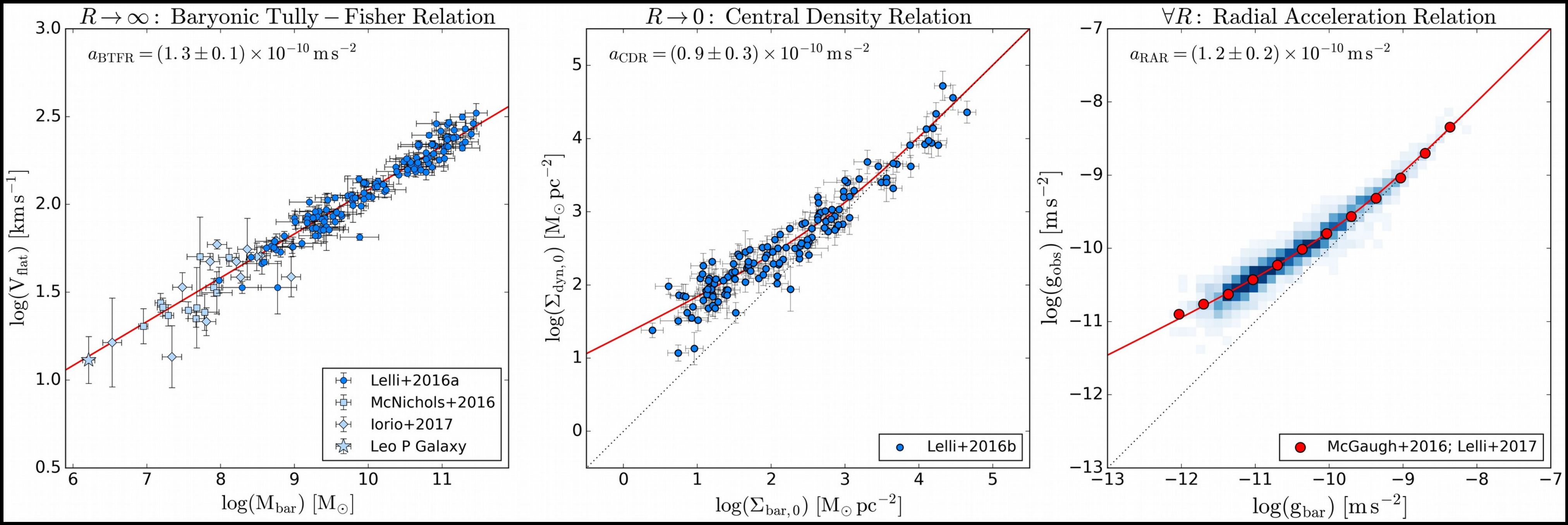
1st - BTFR

2nd - CDR

3rd - RAR

Summary of Part II:

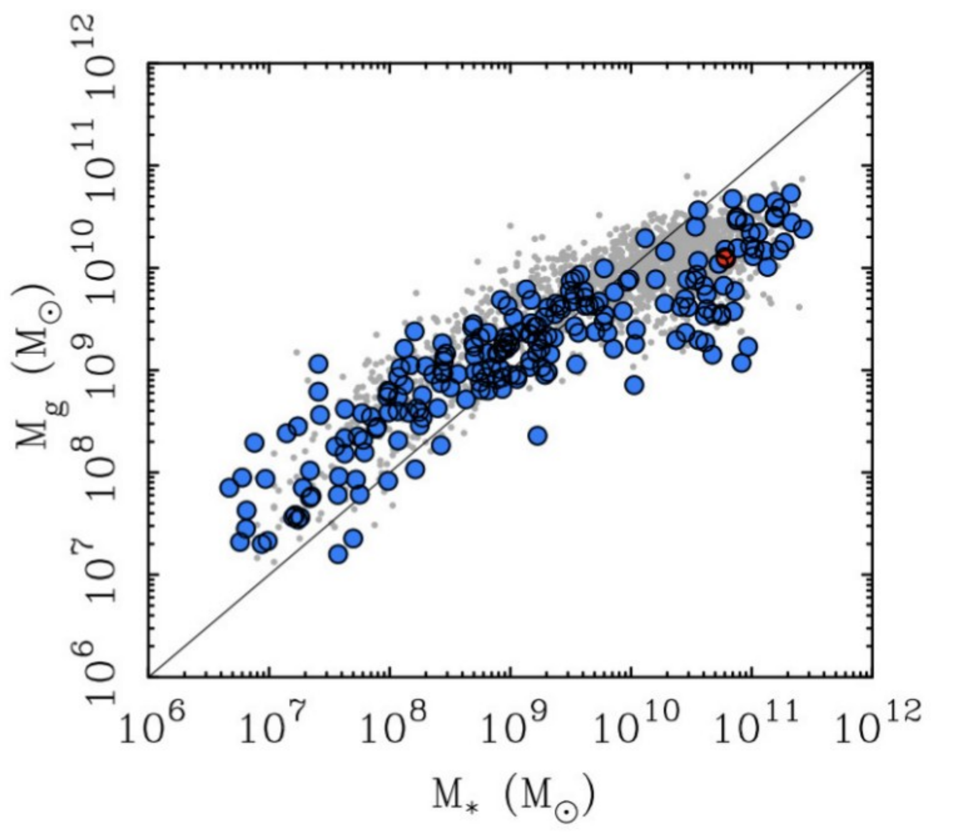
There is a tight baryon-DM coupling in galaxies, which is summarized by three empirical laws:

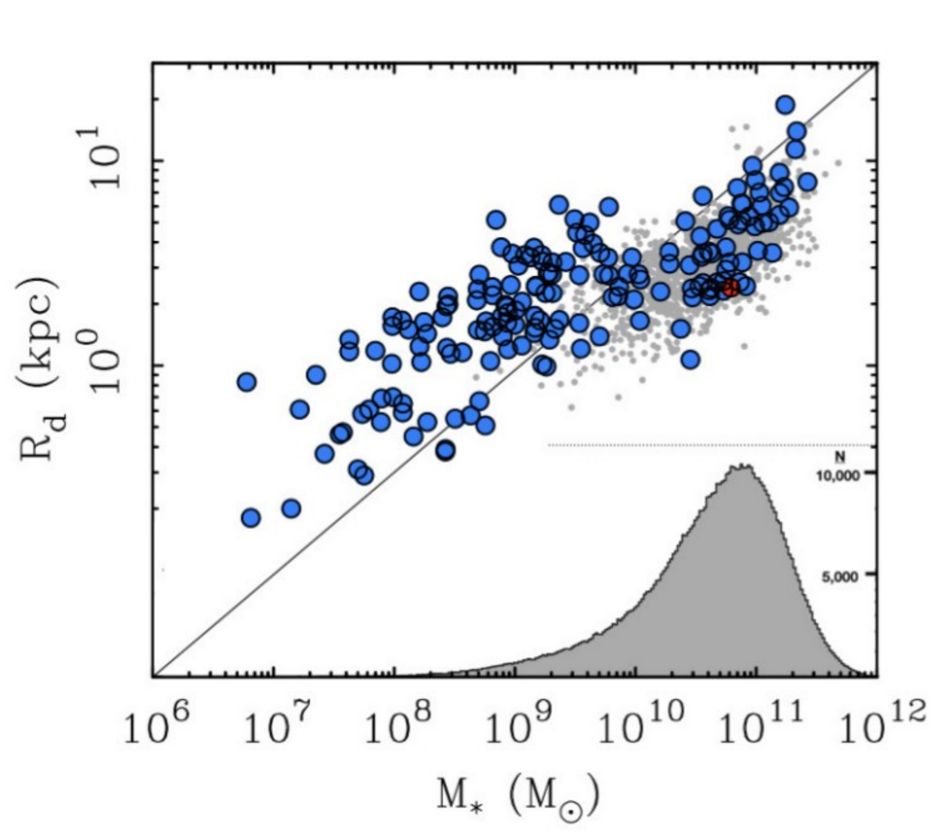


- No freedom in fitting arbitrary DM halo profiles
- Predicted a-priori by MOND (Milgrom 1983)
- Fine-tuning problem for galaxy formation in ΛCDM

Thank you!

SPARC vs larger "complete" samples

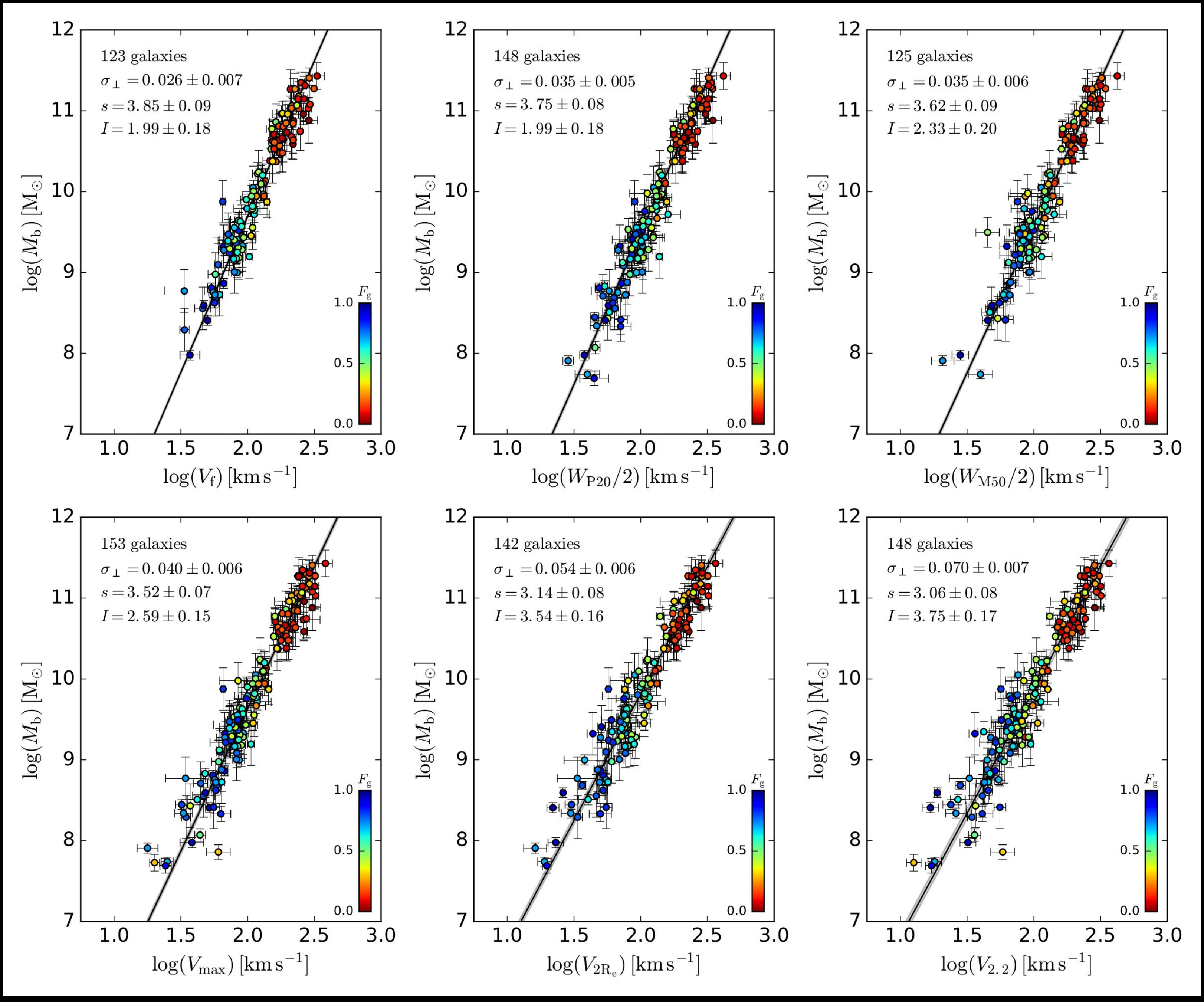




Grey dots: HI-selected data from Bradford+2015 (single-dish survey)

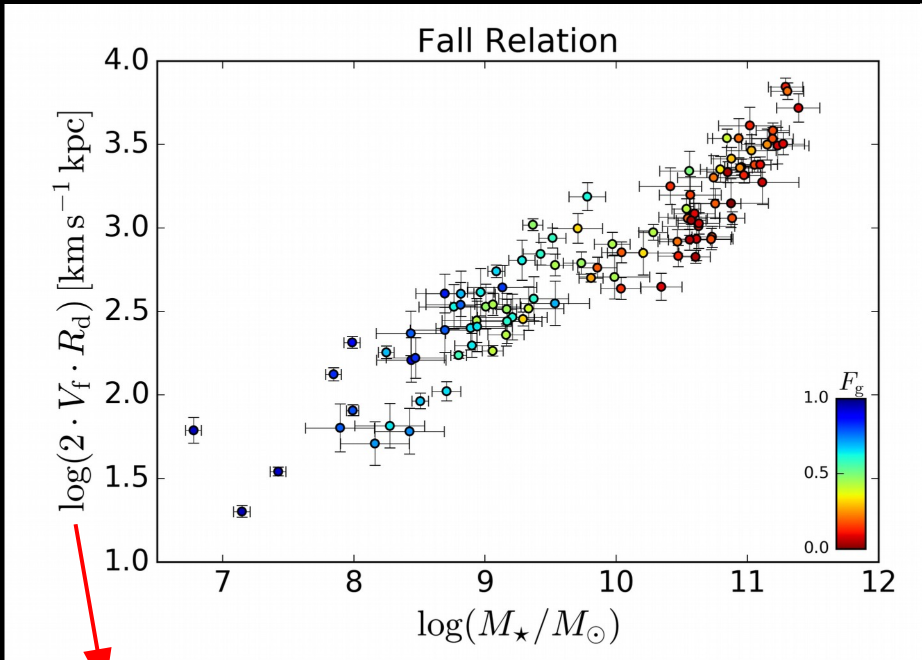
Grey dots: Hα-selected galaxies from Courteau+2007 (long-slit surveys)
Histogram: all galaxies in the SDSS DR7.

Which velocity best correlates with M_b?



Lelli+2019

The Tully-Fisher relation is VERY tight



Specific Angular Momentum (Fall 1983)

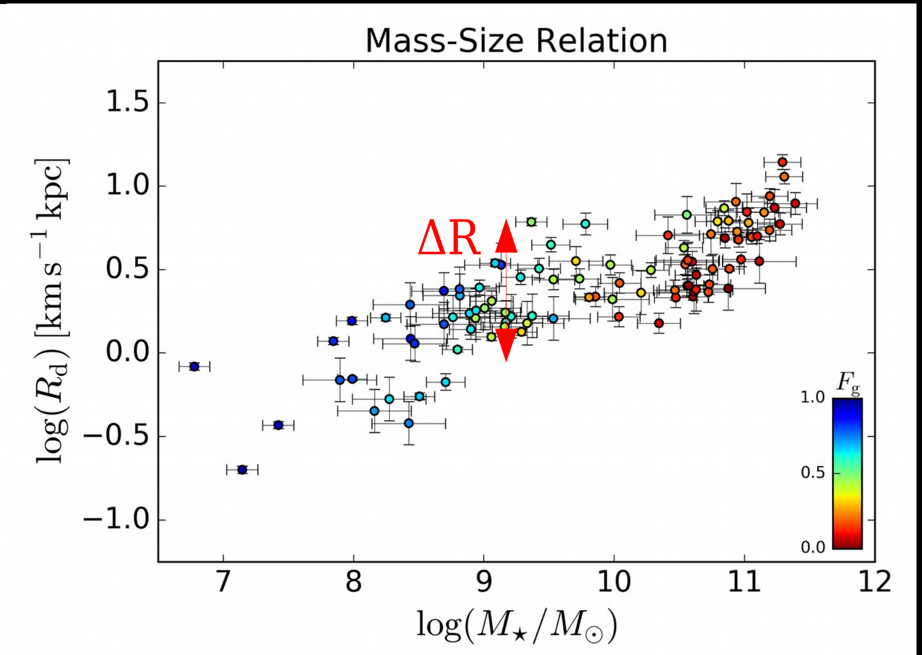
V_f - R_d residuals at fixed M_*:

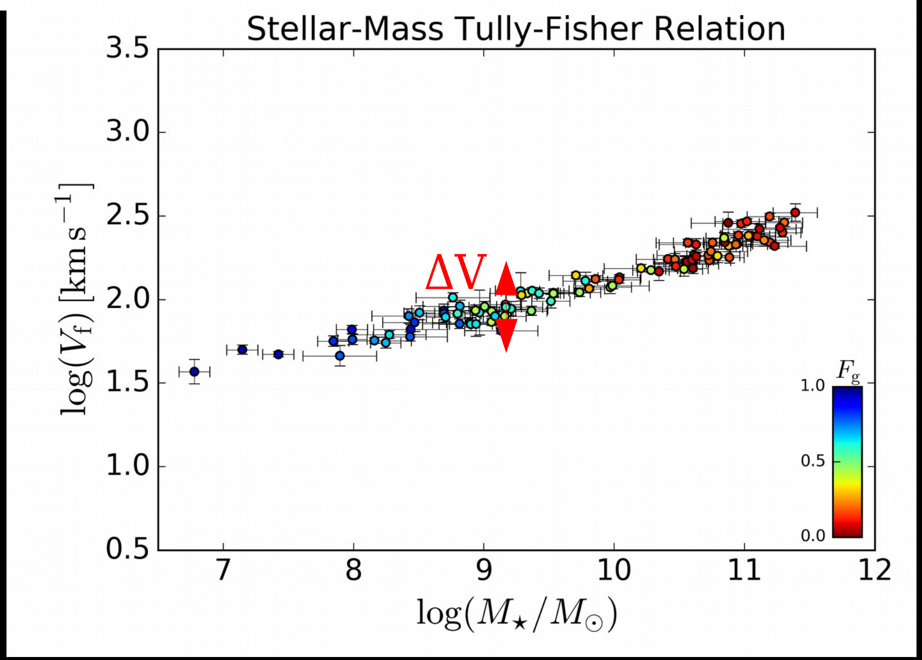
ΔV *vs* ΔR → No correlation

→ No value in adding R_d

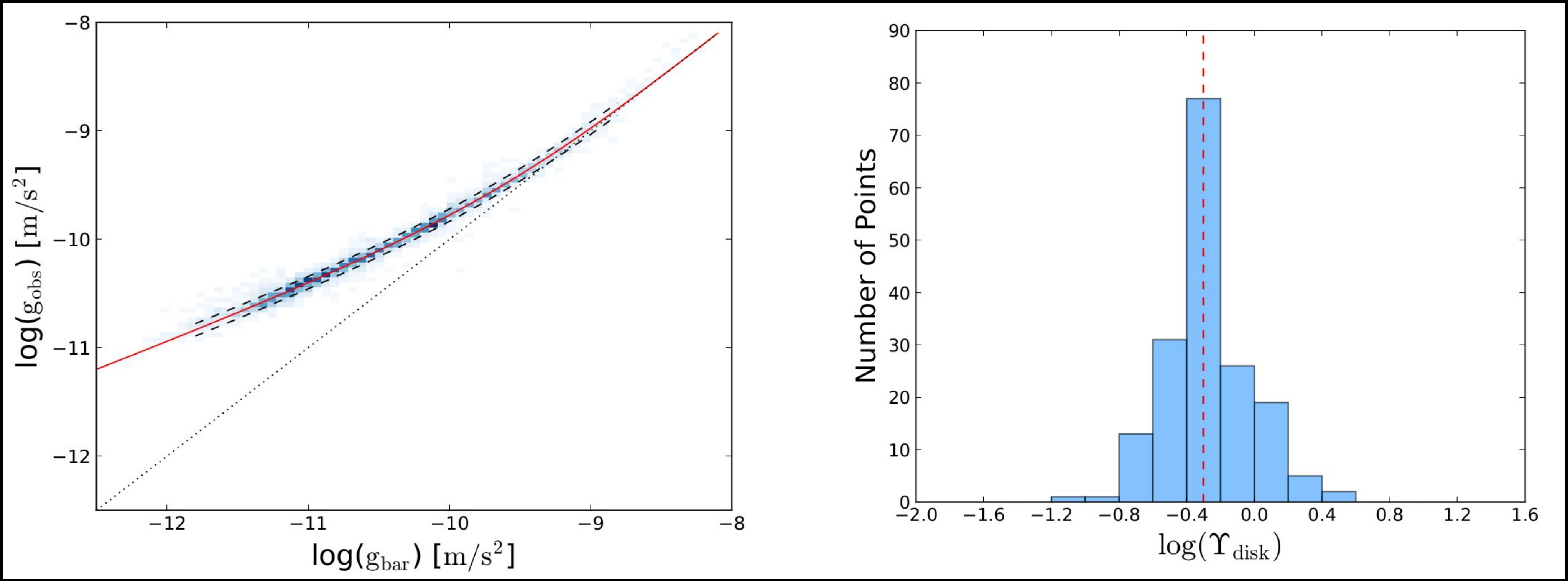
→ j_{gal} not proportional to j_{halo}

(see Desmond+2019)





Fitting the RAR to Individual Galaxies

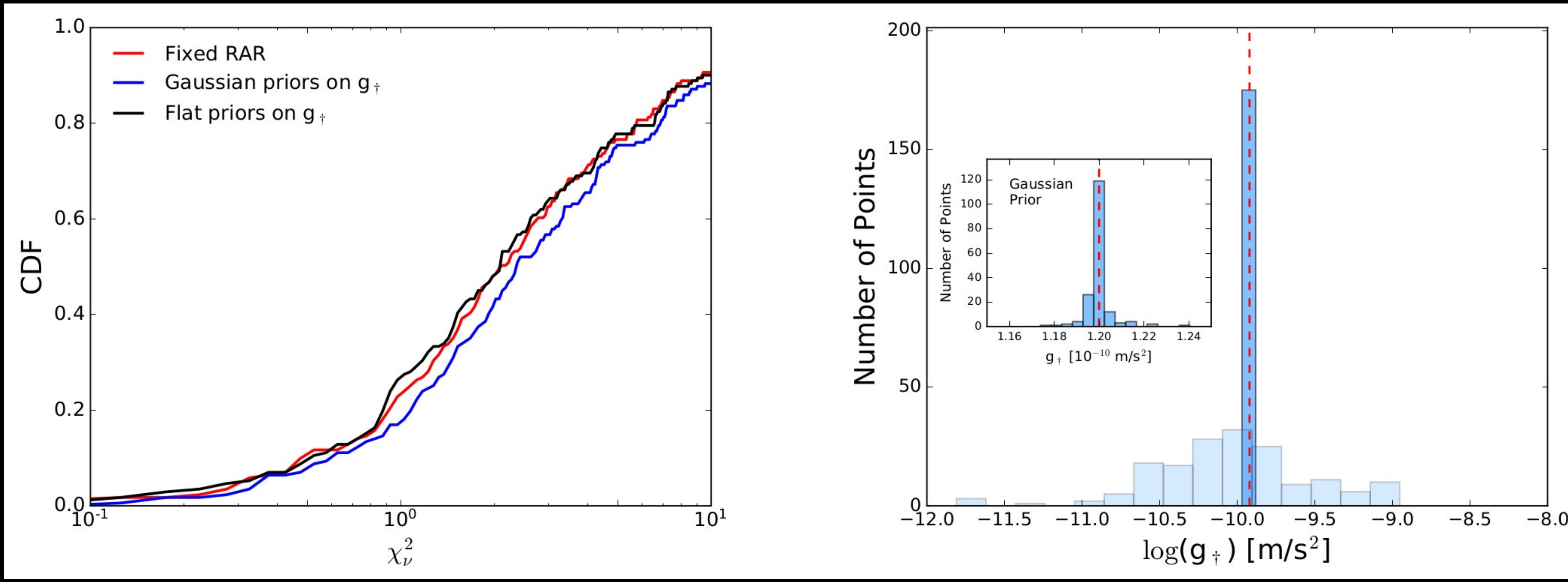


MCMC fits with 3 free parameters: M_*/L, Dist, inc

- extremely tight relation (~13%)
- sensible distribution of stellar M_*/L
- sensible values of distance and inclination

Li, Lelli, McGaugh, Schombert 2018, A&A

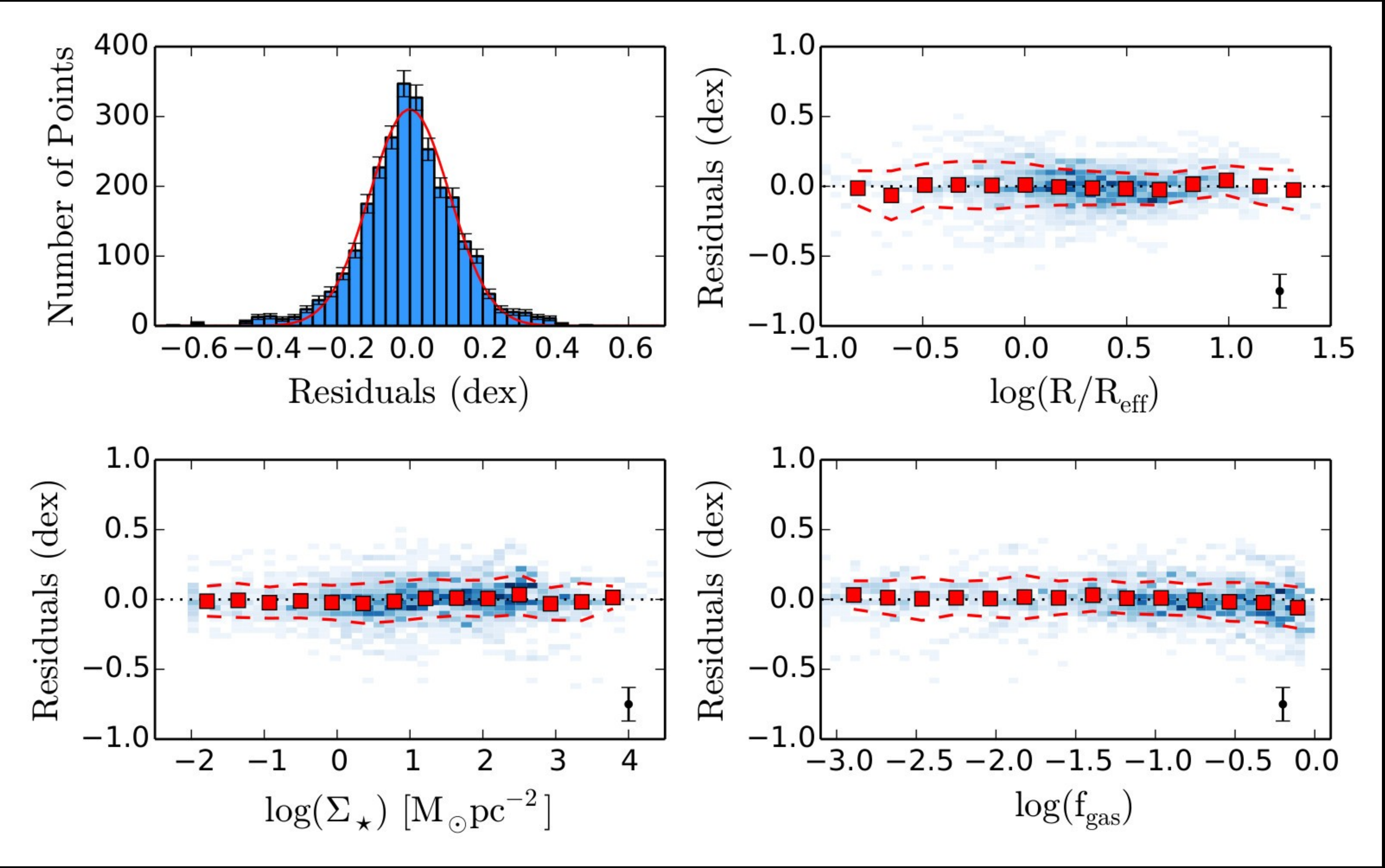
A variable acceleration scale? Well, no!



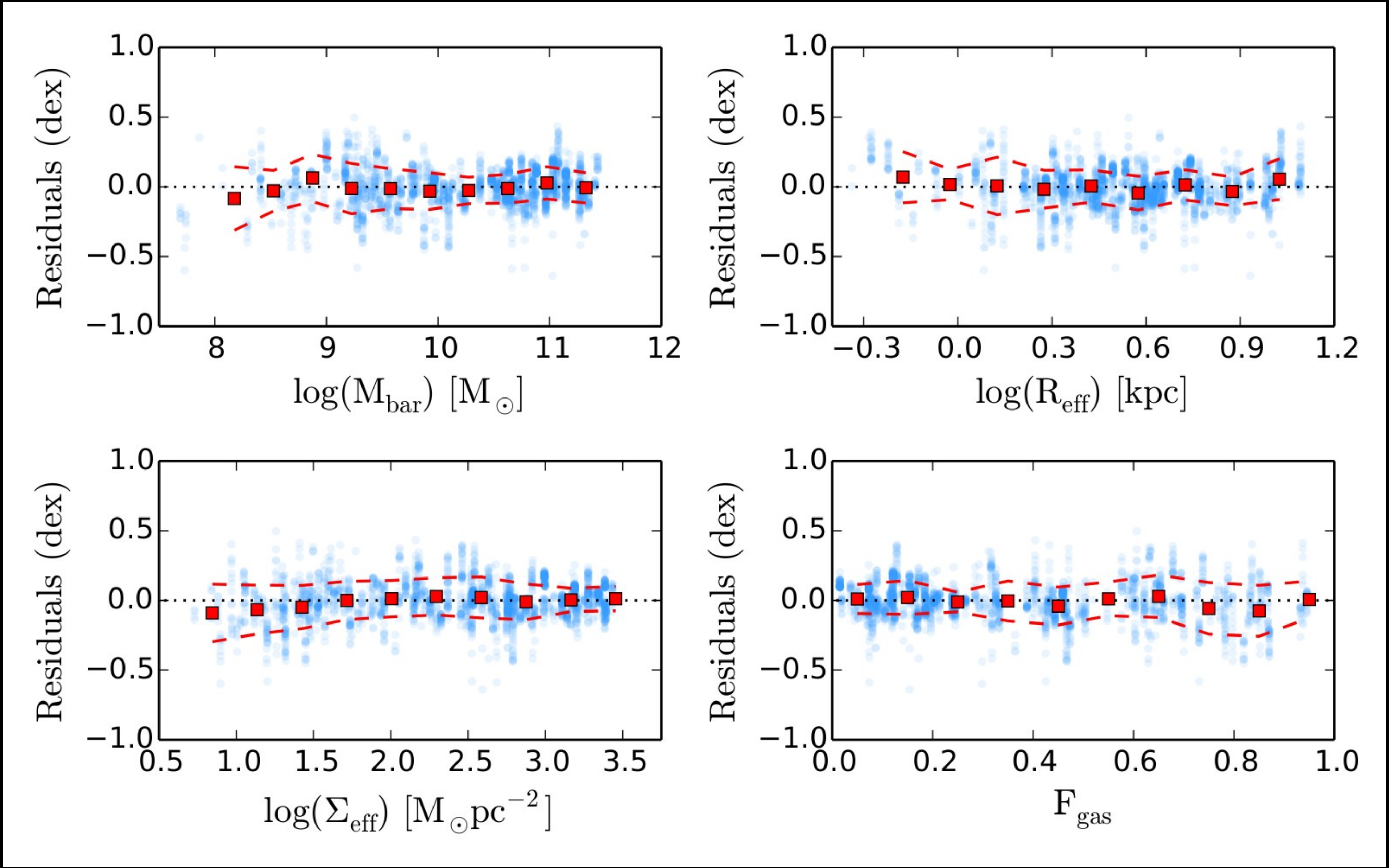
Results of RAR fits with a variable g_{+}:

- reduce-χ^2 does not improve despite more freedom
- g_{+} varies because it's degenerated with D, i, and Υ_*
- Gaussian prior returns a nearly constant g_{+}

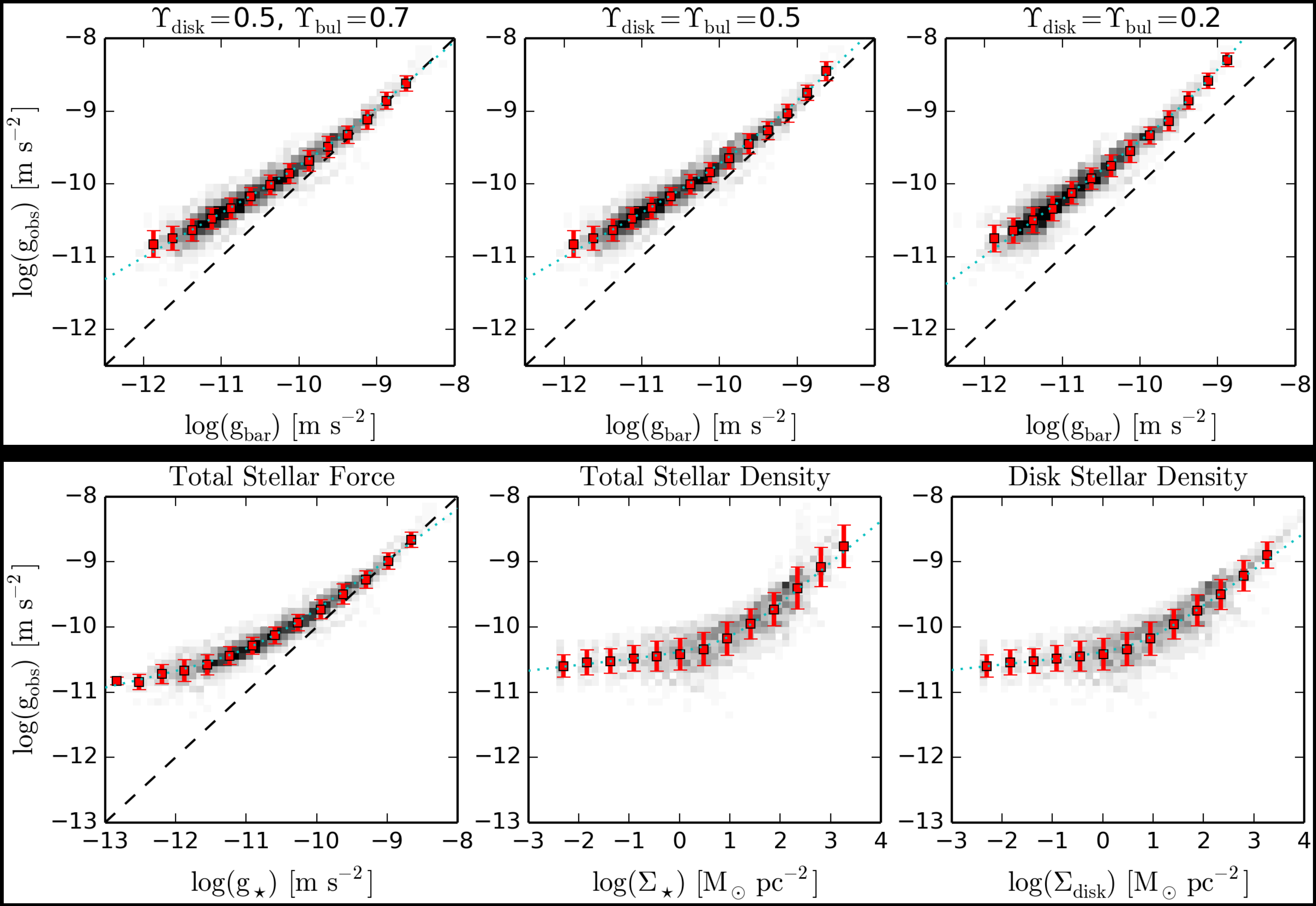
RAR Residuals *vs* Local Galaxy Properties



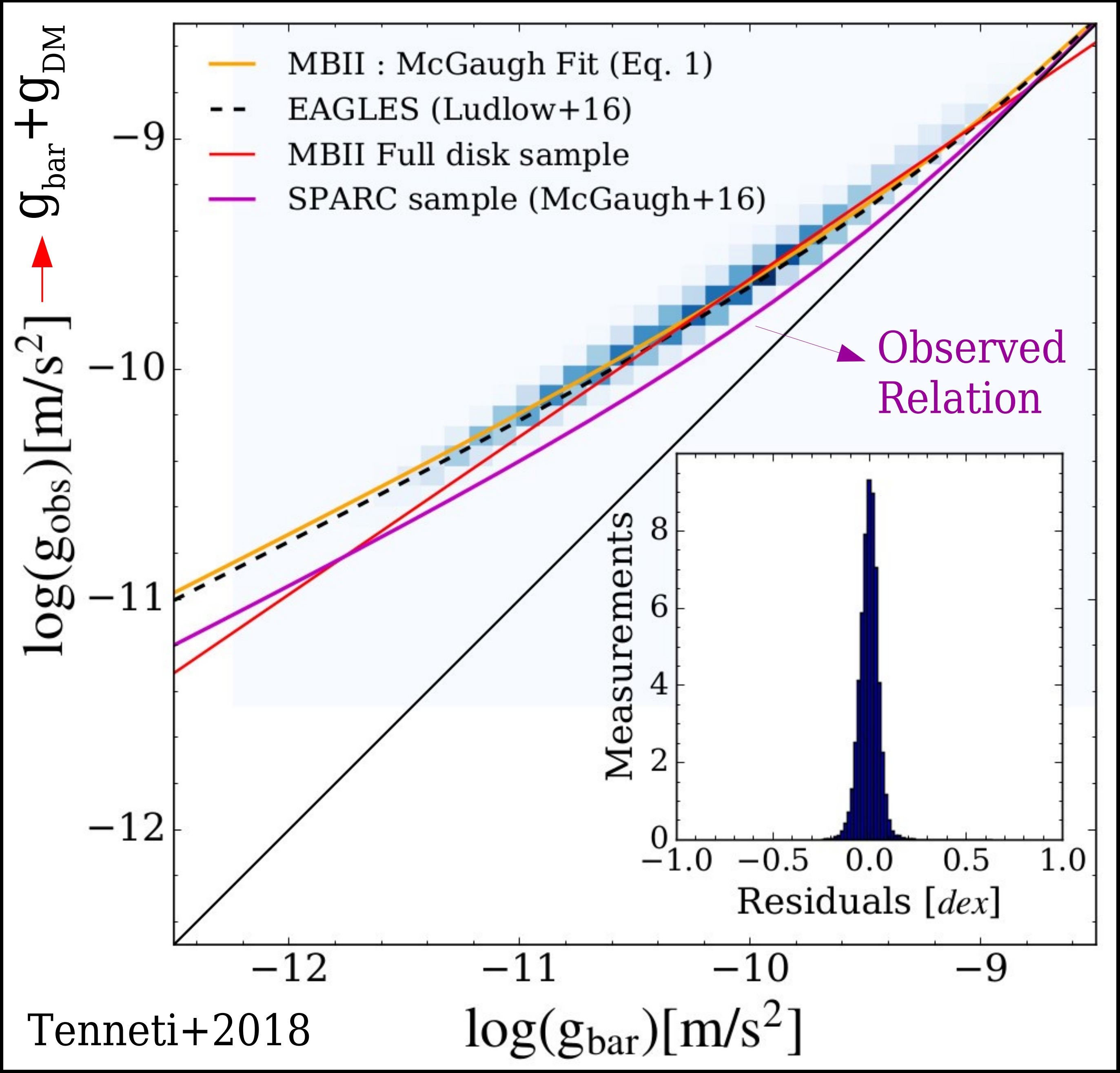
RAR Residuals *vs* Global Galaxy Properties



Alternative Versions of the RAR



RAR from ΛCDM galaxy-formation models



Open Issues:

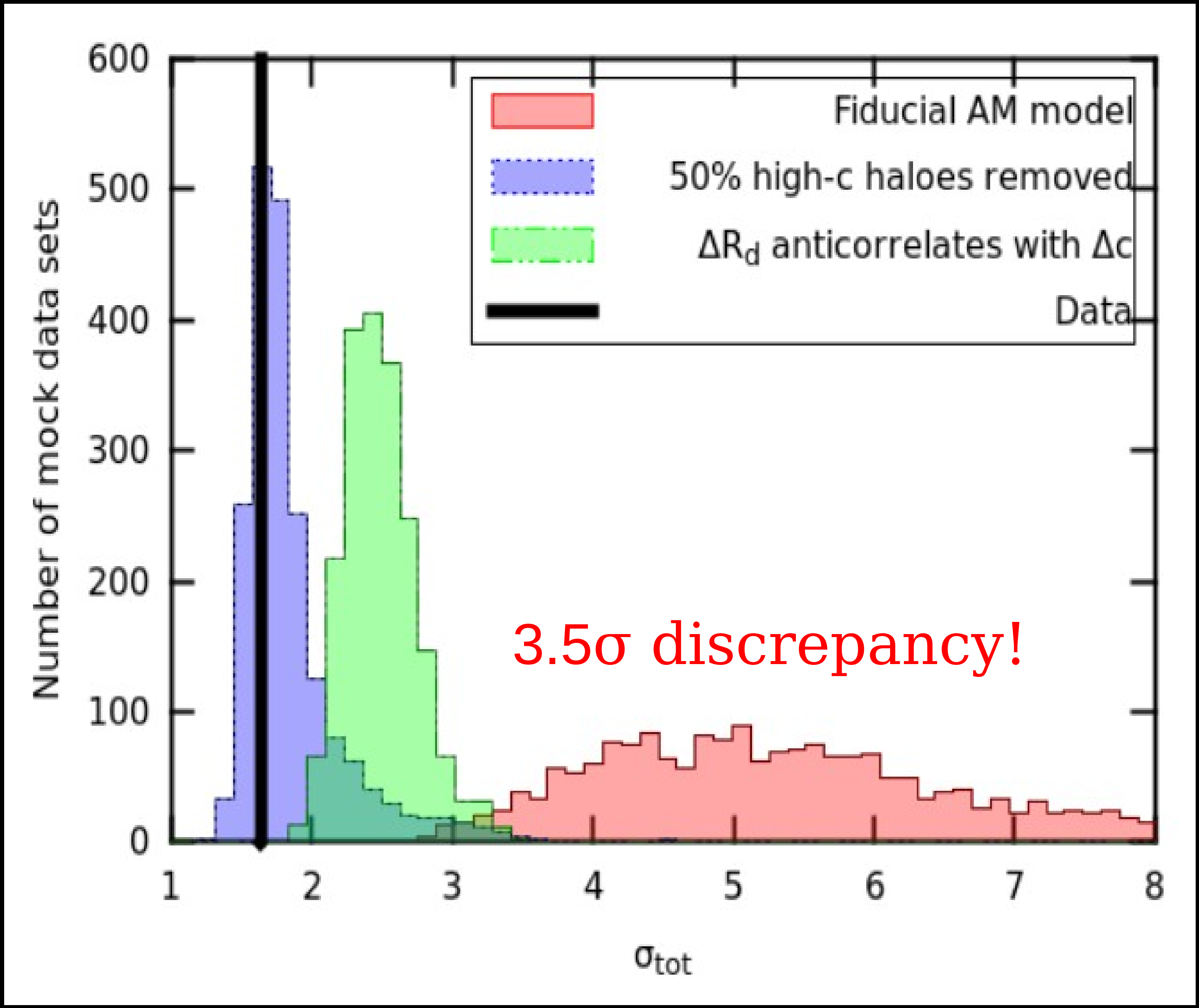
1) RAR shape:

DM contribtion is too high everywhere (Ludlow et al. 2017; Tenneti et al. 2018)

2) RAR scatter:

Too high when obs. errors are properly taken into account (Desmond 2017, 2018)

RAR from Abundance-Matching Models



Desmond (2017):

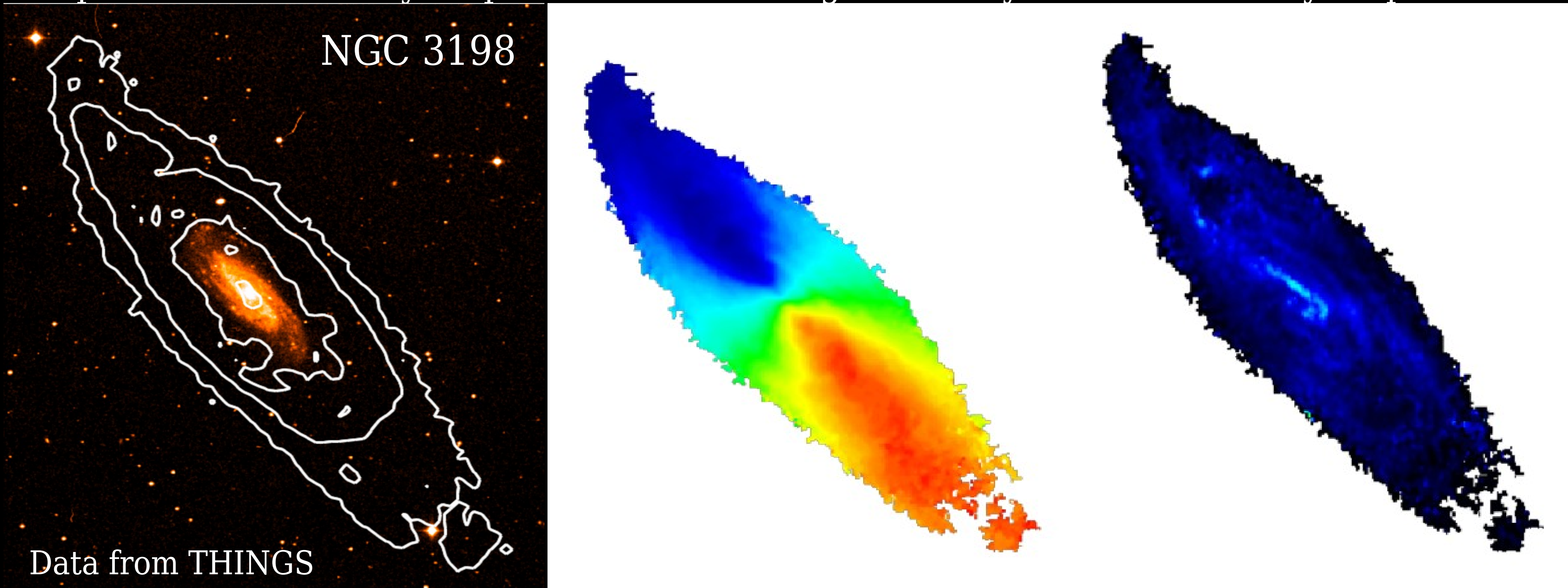
1- Take N-body sims and assign SPARC galaxy into DM halos with AM models

2- For each galaxy, $g_{tot} = g_{bar} + g_{DM}$ taking observed spatial sampling and errors into account

3- Repeat N-times perturbing M_* to account for variance

Interferometric HI Observations at 21 cm

Optical + HI Intensity Map | HI Line-of-Sight Velocity | HI Velocity Dispersion



- HI is more extended than the stars → trace kinematics out to large radii
- HI lies in a thin rotating disk → non-circular motions are small (<10%)
- HI velocity dispersion is small (~10 km/s) → pressure support is negligible

HI behaves as a test particle on a circular orbit! $$\frac{V_{rot}^2}{R} = -\frac{\partial \Phi_{tot}}{\partial R}$$