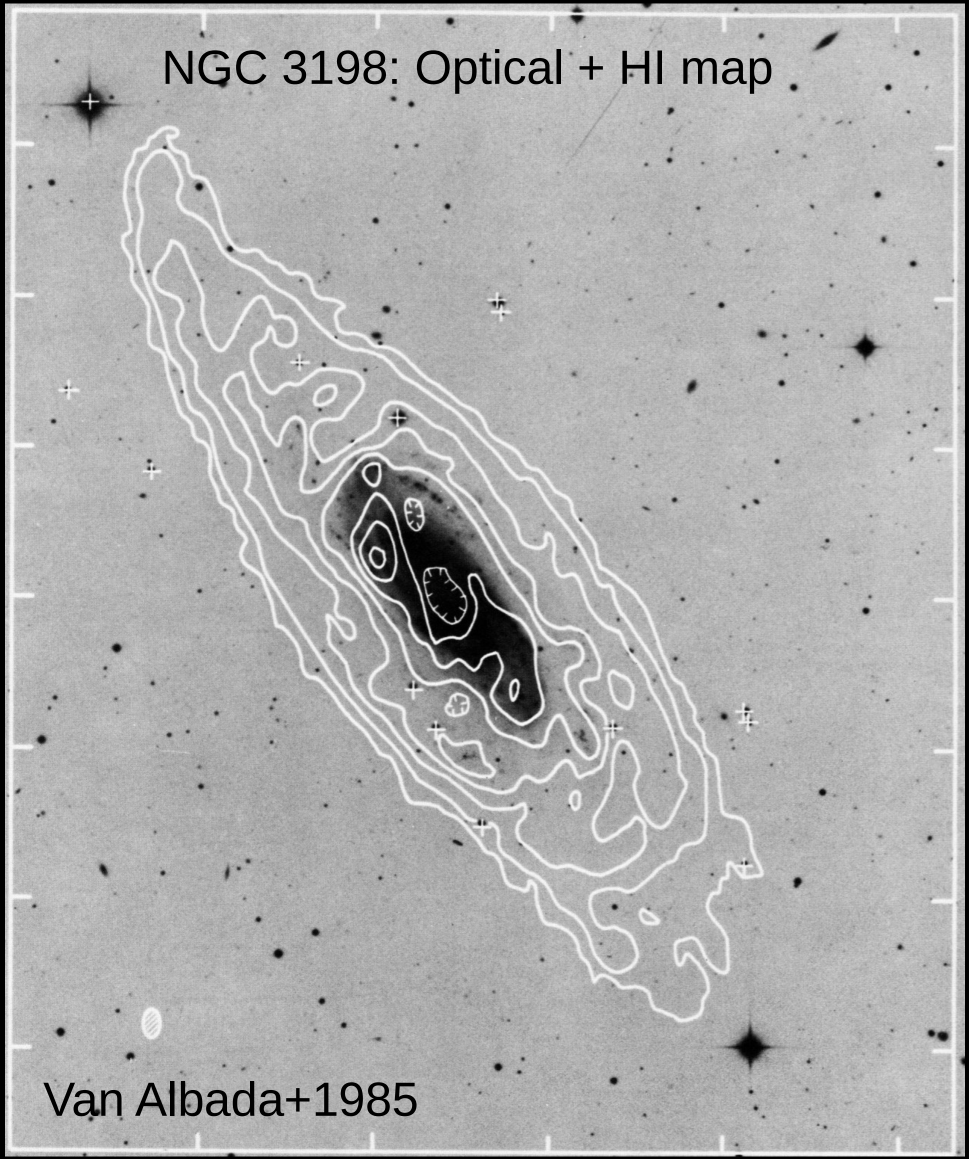
The tight coupling between baryons and DM in galaxies

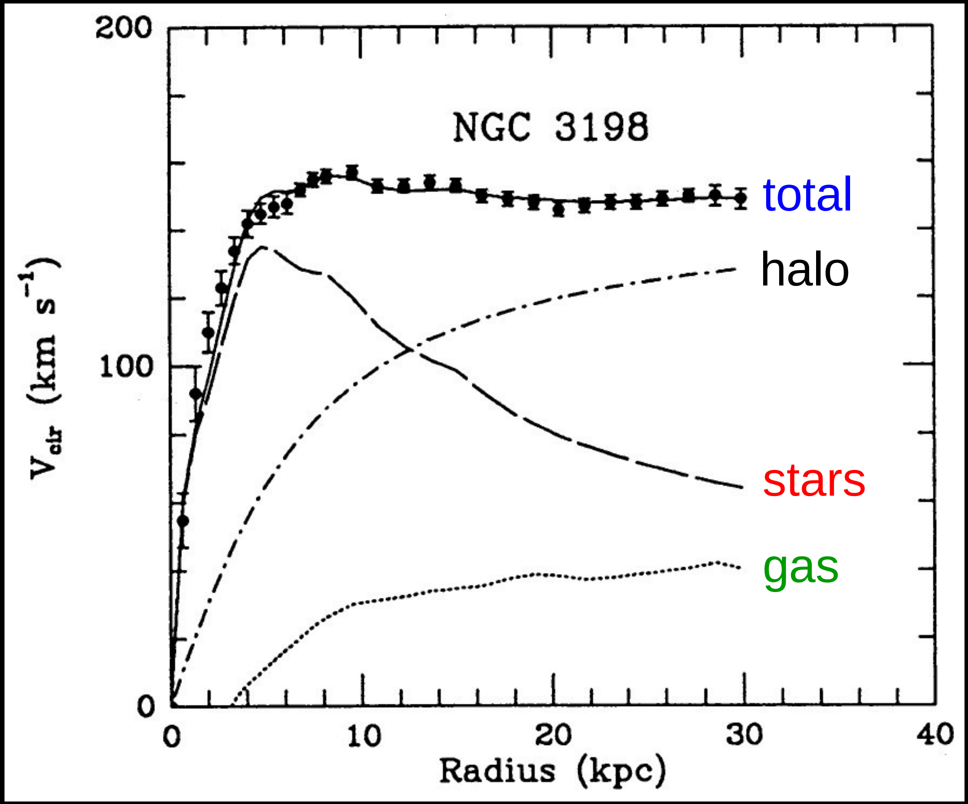
Federico Lelli

European Southern Observatory

In collaboration with
Stacy McGaugh (Case Western Reserve University)
Pengfei Li (Case Western Reserve University)
Marcel Pawlowski (University of California – Irvine)
James Schombert (University of Oregon)

Rotation curves: historical evidence for DM





Classic Approach:

- Assume spherical DM halo: $\rho = \rho(r)$
- Rotation curve fit with 3 parameters: ρ_0, r_s (DM halo) and M_*/L (stars)

$$V^2_{obs} = M_*/L \bullet V^2_{stars} + V^2_{gas} + V^2_{DM}(\rho_0, r_s)$$

Outline

I. The SPARC Galaxy Database

II. The Radial Acceleration Relation (RAR)

III. Models in LCDM and Open Problems

SPARC

Spitzer Photometry & Accurate Rotation Curves

Database for 175 Late-Type Galaxies at z~0

(spirals and dwarf irregulars):

astroweb.case.edu/SPARC

Lelli, McGaugh, Schombert 2016, AJ

SPARC

Spitzer Photometry & Accurate Rotation Curves

- HI+Hα Rotation Curves from Literature
  - 30 years of radio and optical 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

SPARC

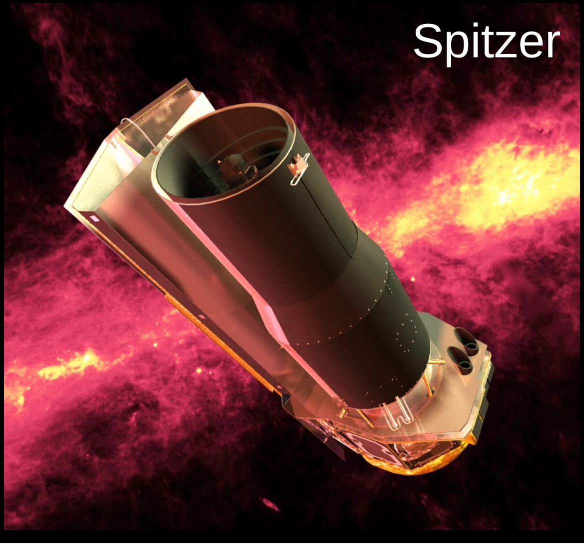
Spitzer Photometry & Accurate Rotation Curves

- HI+Hα Rotation Curves from Literature
  - 30 years of radio and optical observations
  - PhD theses from the University of Groningen

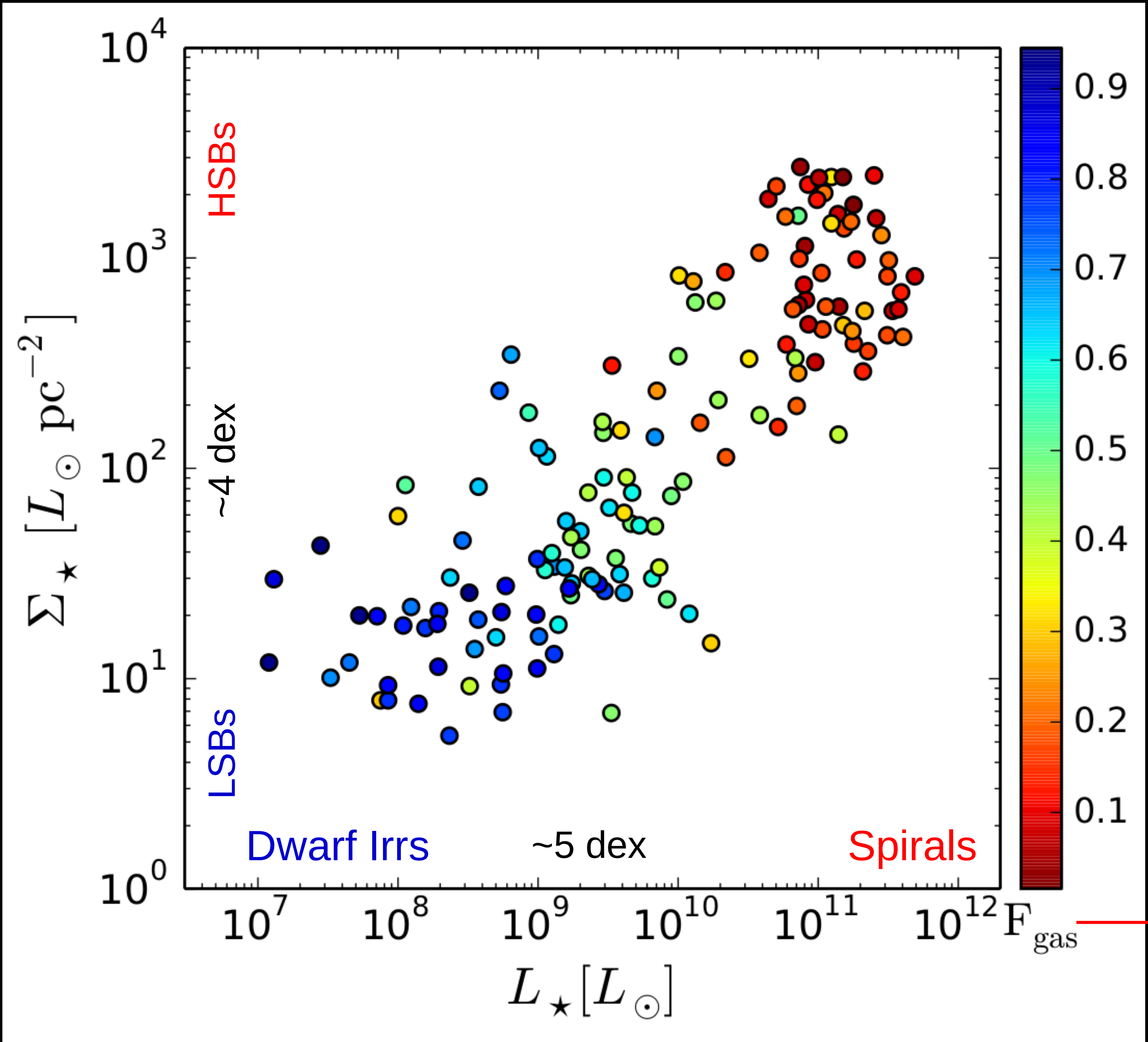
    Begeman 1987; Broeils 1992; Verheijen 1997; de Blok 1997; Swaters 1999; Noordermeer 2005; Lelli 2013 + other studies

- Homogeneous Photometry at 3.6 μm
  - Optimal tracer of the stellar mass: $M_* = \Upsilon_* L$
  - Smaller variations of Υ_* in the NIR than optical

    Verheijen 2001; Bell & de Jong 2001; Martinsson+2013; Meidt+2014; McGaugh & Schombert 2014; Schombert & McGaugh 2014; Querejeta+2015; Röck+2015; Herrmann+2016; Norris+2016.



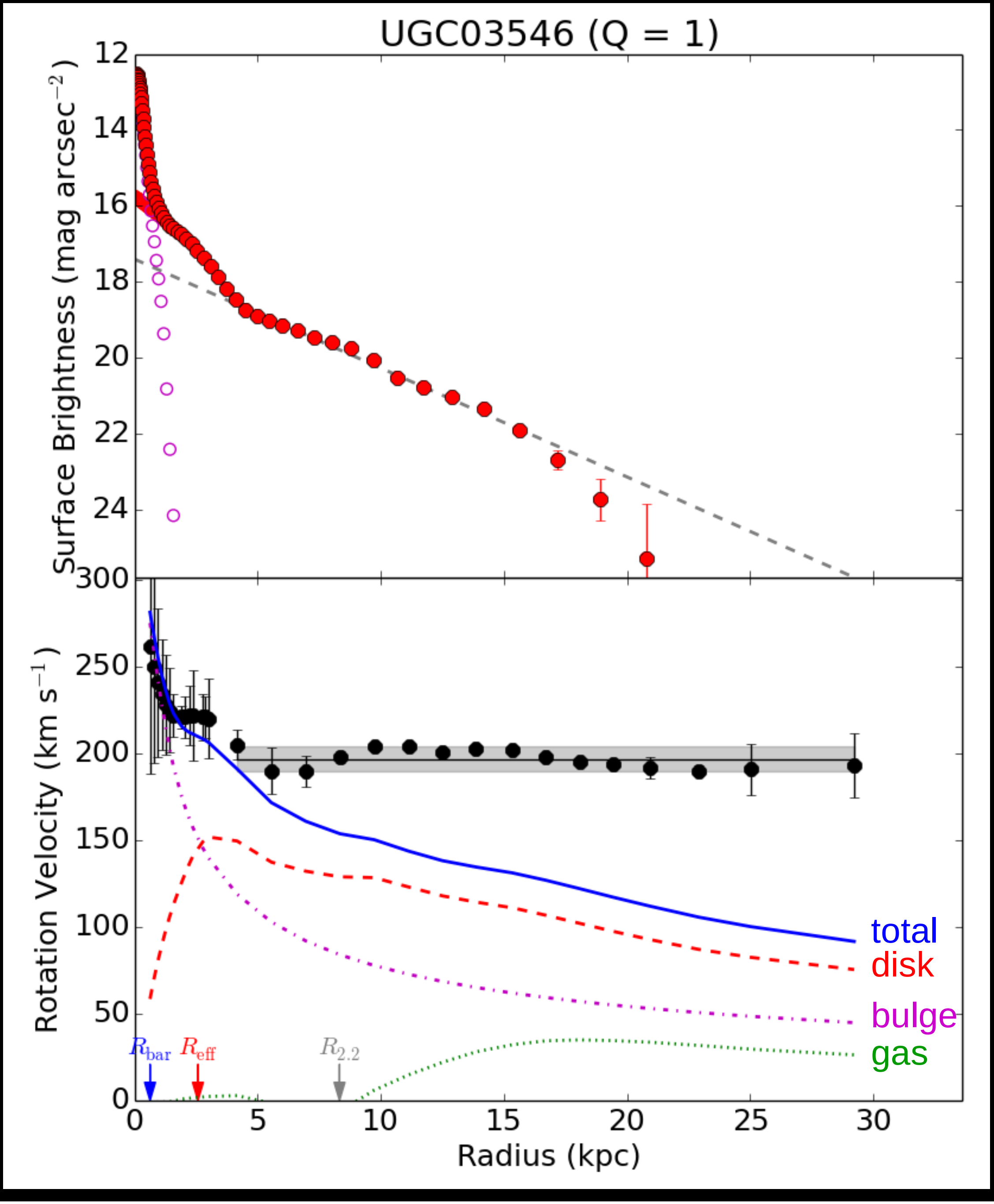
Widest possible range of disk properties

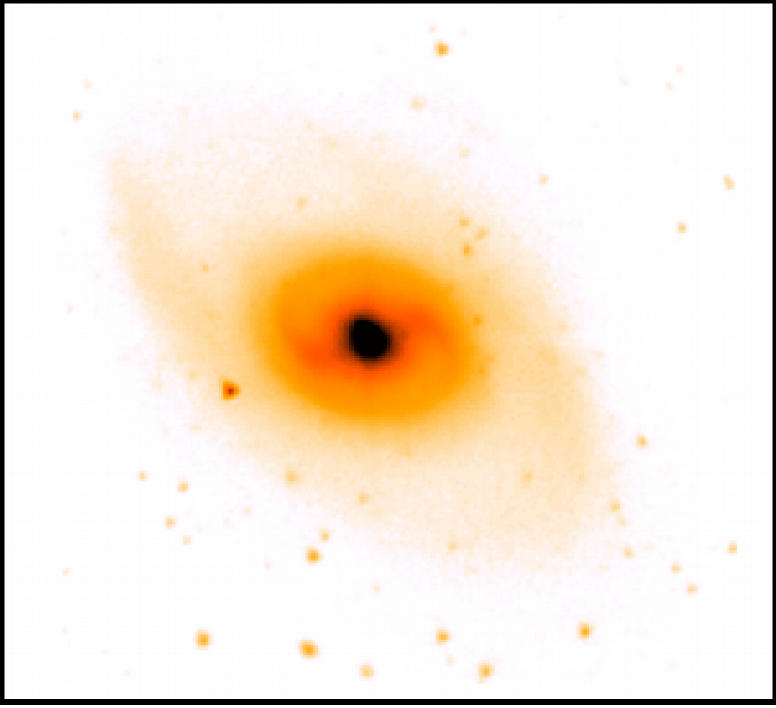


M_{gas}/M_{bar}

Basically any known galaxy type with a rotating HI disk.

Example: High-Mass, High-Density Spiral

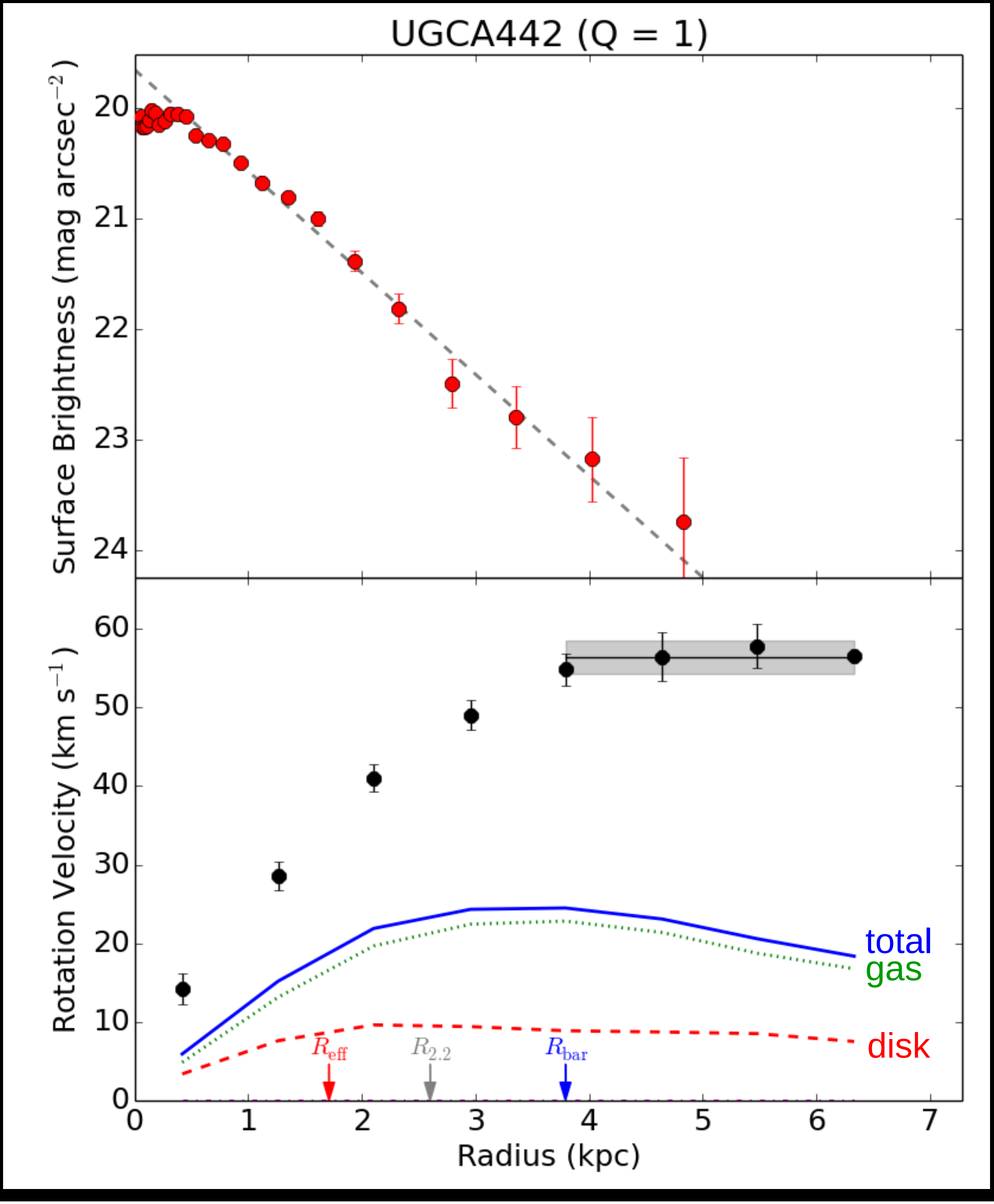


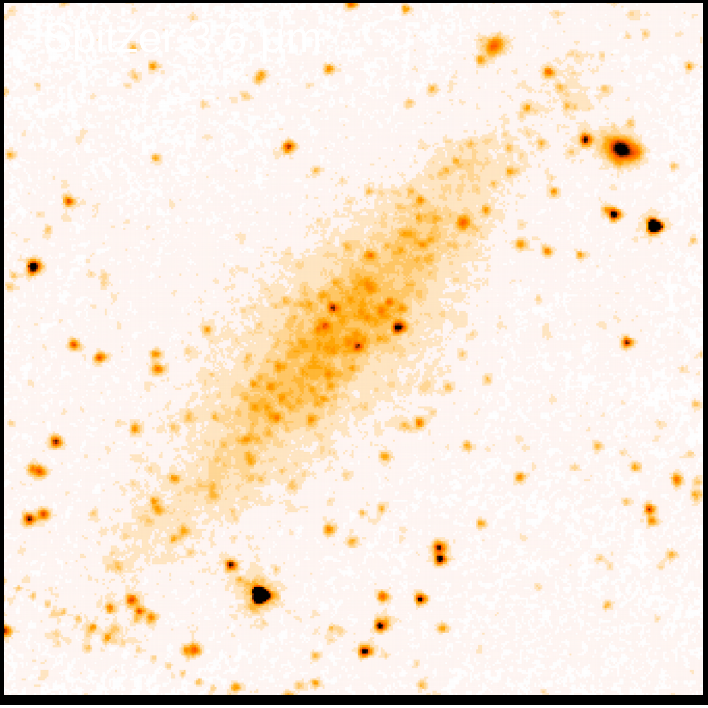


$$\nabla^2\Phi_{bar}(R,z) = 4\pi G\ \rho_{bar}(R,z)$$

- 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

Example: Low-Mass, Low-Density Dwarf





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

- 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

SPARC

Spitzer Photometry & Accurate Rotation Curves

1. Basic Data & Structural Relations: Lelli+2016a, AJ
2. Baryonic TF Relation: Lelli+2016b, ApJL
3. Central Density Relation: Lelli+2016c, ApJL
4. Radial Acceleration Relation (I): McGaugh+2016, PRL
5. Radial Acceleration Relation (II): Lelli+2017a, ApJ
6. Testing DM Halo Profiles: Katz+2017, MNRAS
7. Testing Emergent Gravity: Lelli+2017b, MNRAS
8. Radial Acceleration Relation (III): Li+2018, A&A

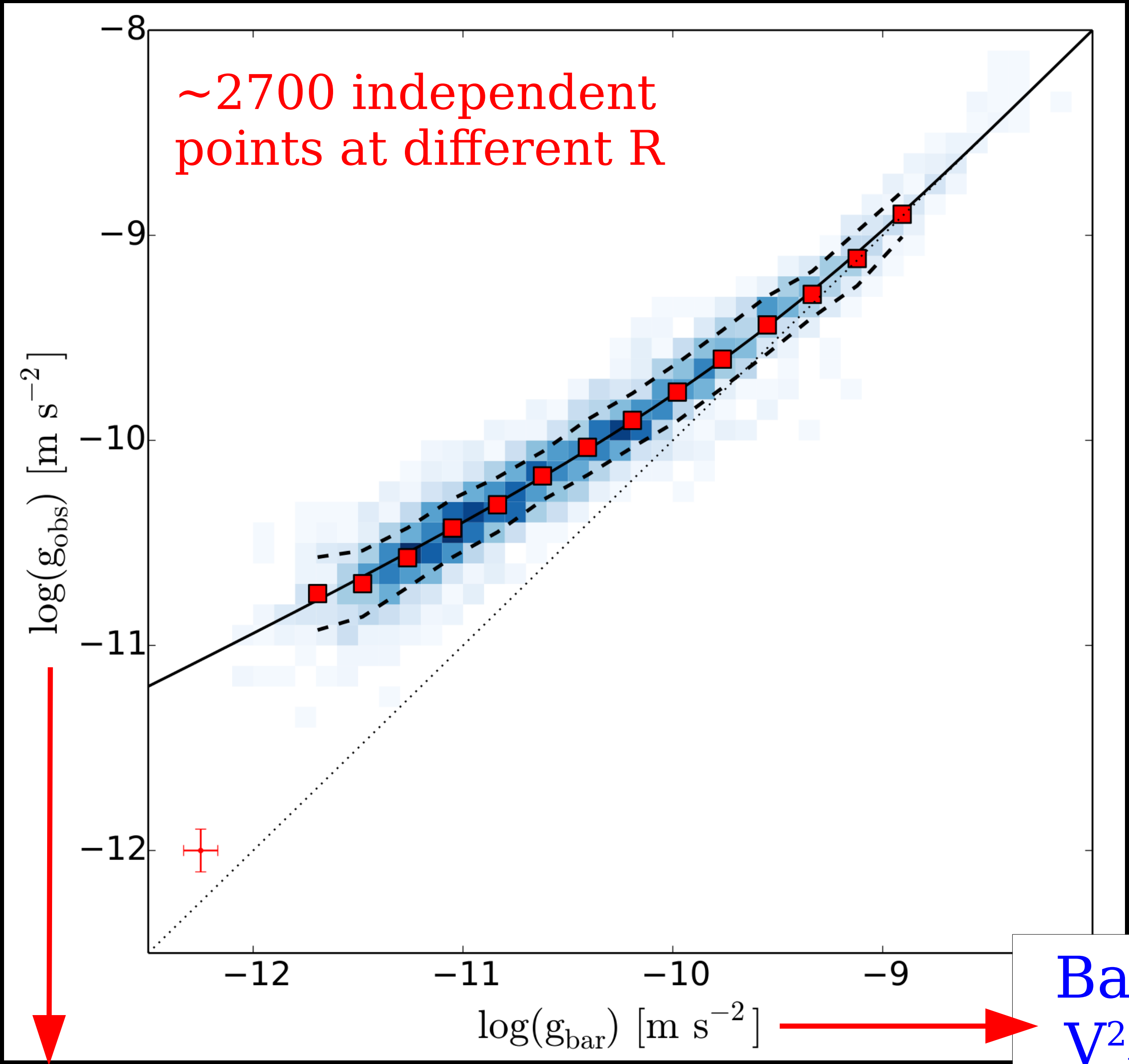
SPARC

Spitzer Photometry & Accurate Rotation Curves

1. Basic Data & Structural Relations: Lelli+2016a, AJ
2. Baryonic TF Relation: Lelli+2016b, ApJL
3. Central Density Relation: Lelli+2016c, ApJL
4. Radial Acceleration Relation (I): McGaugh+2016, PRL
5. Radial Acceleration Relation (II): Lelli+2017a, ApJ
6. Testing DM Halo Profiles: Katz+2017, MNRAS
7. Testing Emergent Gravity: Lelli+2017b, MNRAS
8. Radial Acceleration Relation (III): Li+2018, A&A

II. Radial Acceleration Relation

Radial Acceleration Relation (RAR)



For all galaxies:

$\Upsilon_{disk} = 0.5\ M_{\odot}/L_{\odot}$

$\Upsilon_{bulge} = 0.7\ M_{\odot}/L_{\odot}$

McGaugh+2016, PRL

Lelli+2017, ApJ

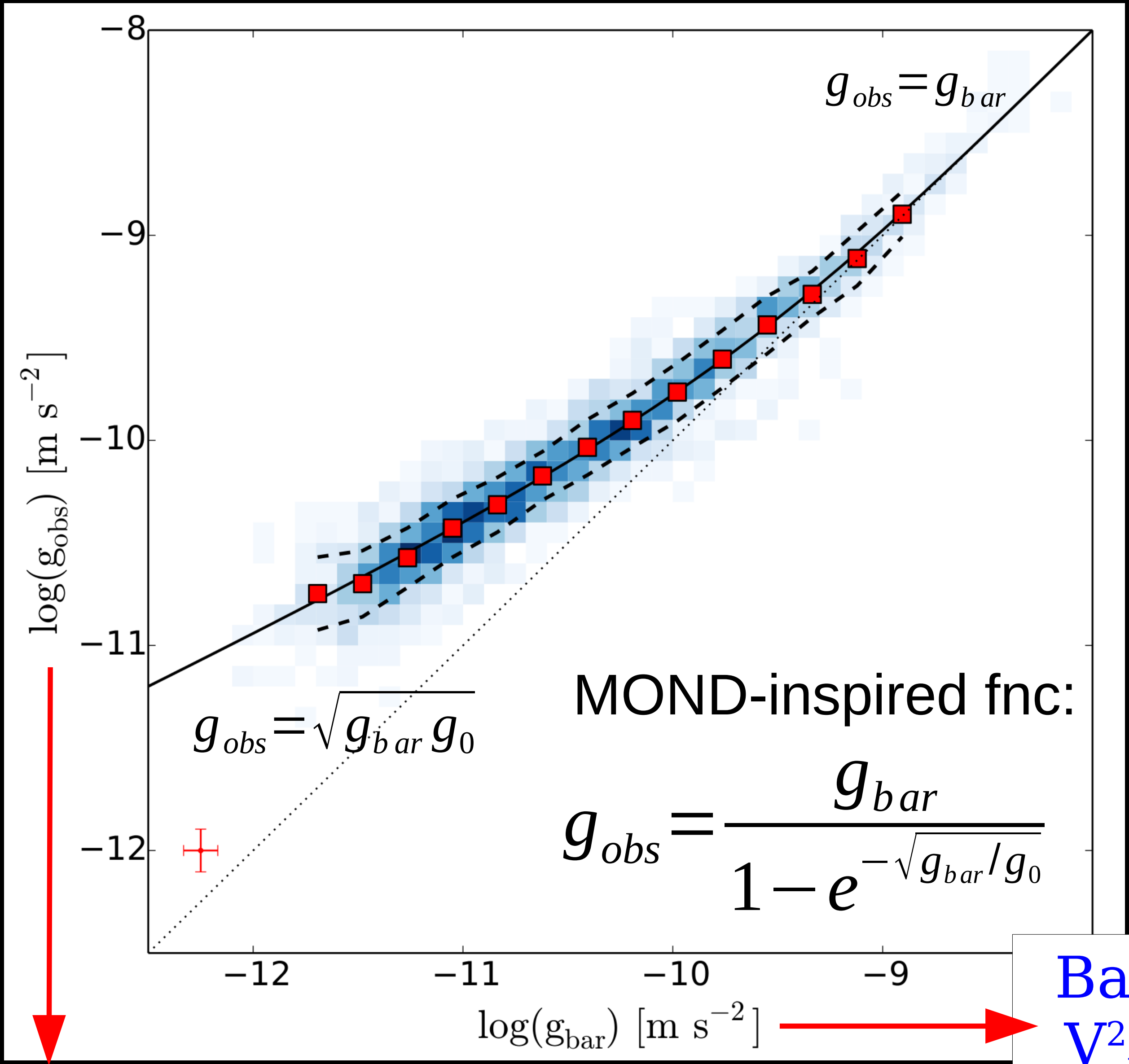
Total Acceleration: $V^2_{obs}/R = -\nabla\Phi_{tot}$

Baryonic Force:

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

$\nabla^2\Phi_{bar} = 4\pi G\ \rho_{bar}$

Radial Acceleration Relation (RAR)



For all galaxies:

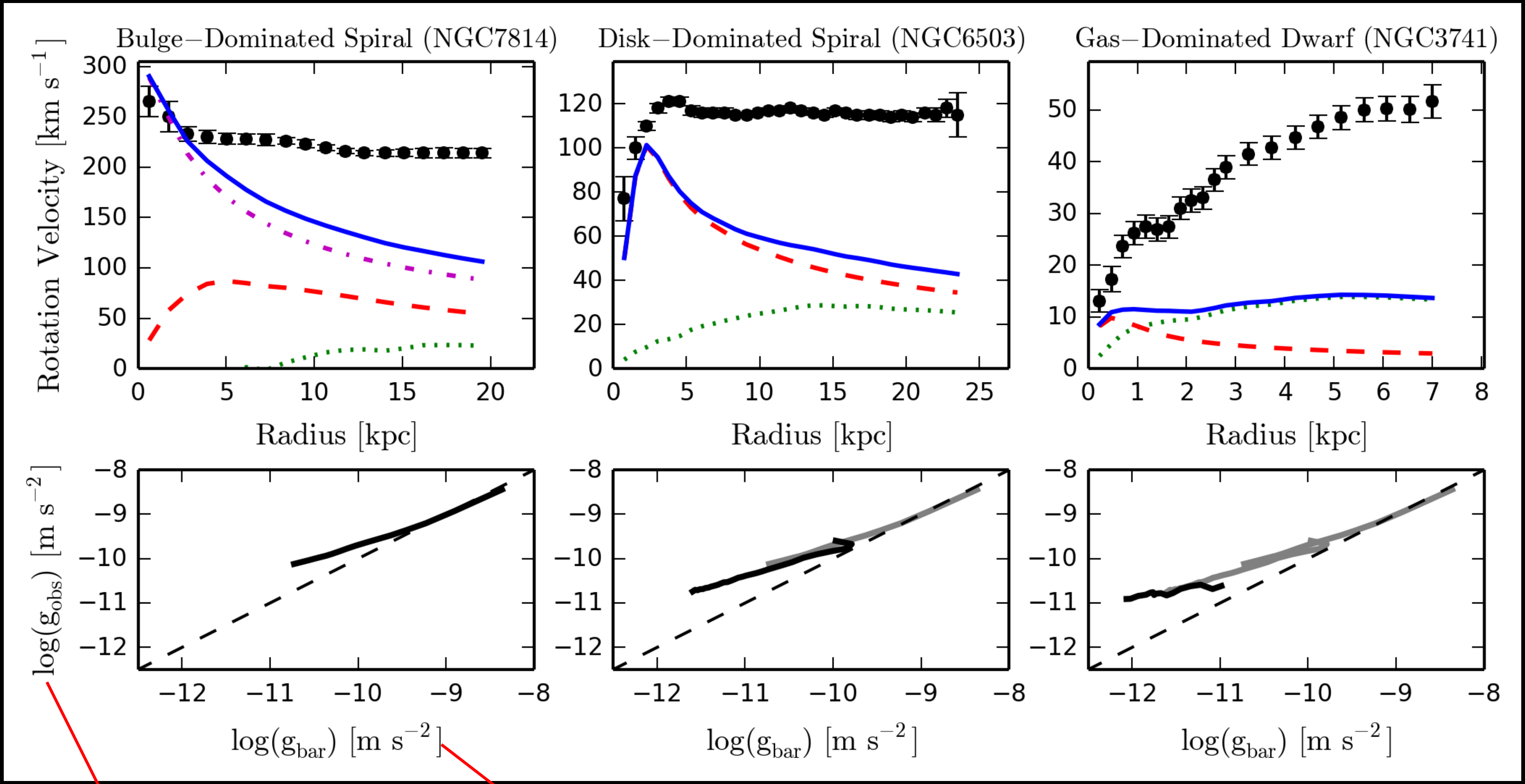
$\Upsilon_{disk} = 0.5\ M_\odot/L_\odot$
$\Upsilon_{bulge} = 0.7\ M_\odot/L_\odot$

McGaugh+2016, PRL
Lelli+2017, ApJ

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

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

Very different galaxies but ONE relation



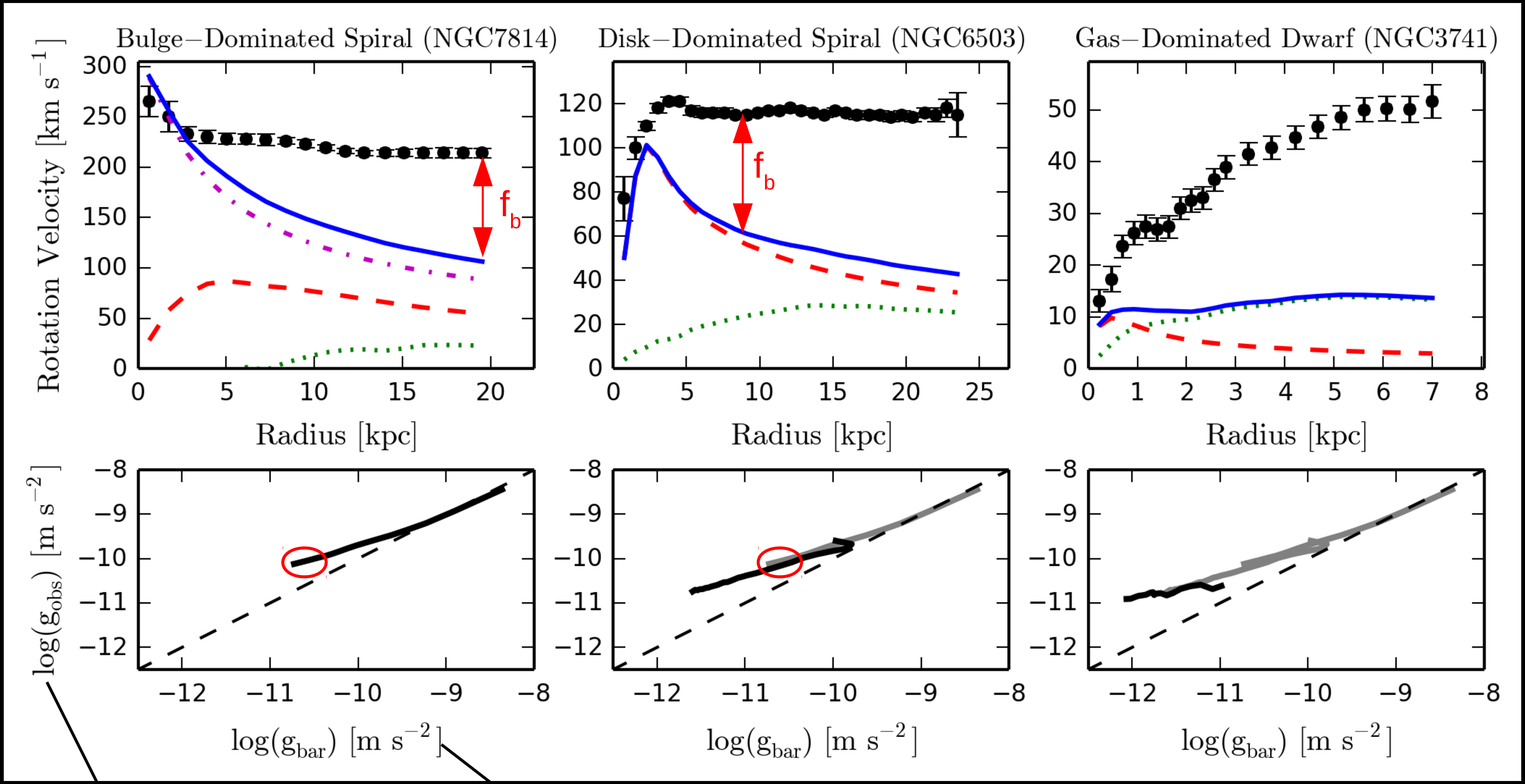
$V^2_{obs}/R = -\nabla\Phi_{tot}$

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

$\nabla^2\Phi_{bar} = 4\pi G\, \rho_{bar}$

McGaugh, LELLI, Schombert (2016)

Very different galaxies but ONE relation

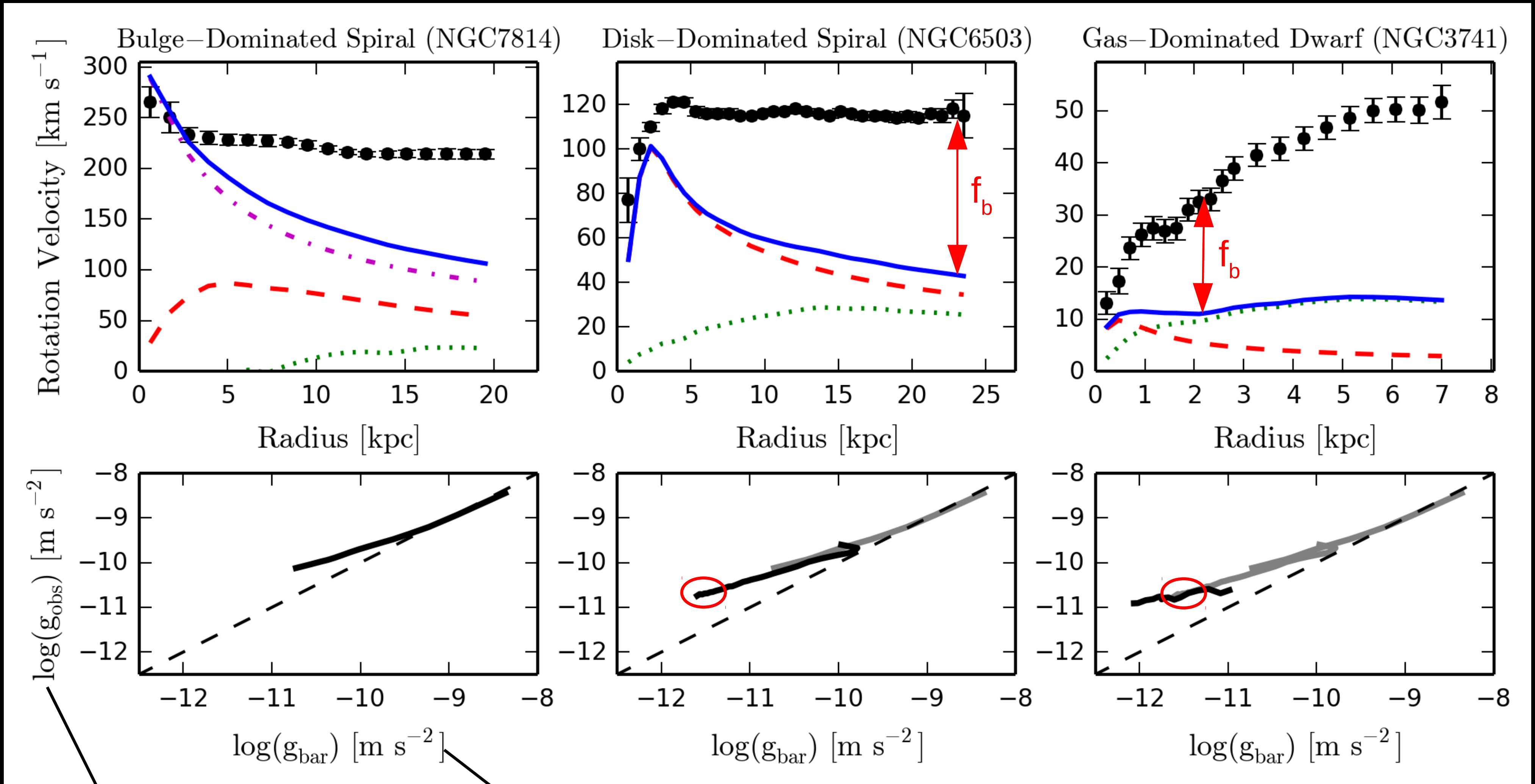


$$V^2_{obs}/R = -\nabla\Phi_{tot}$$

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

McGaugh, LELLI, Schombert (2016)

Very different galaxies but ONE relation



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

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

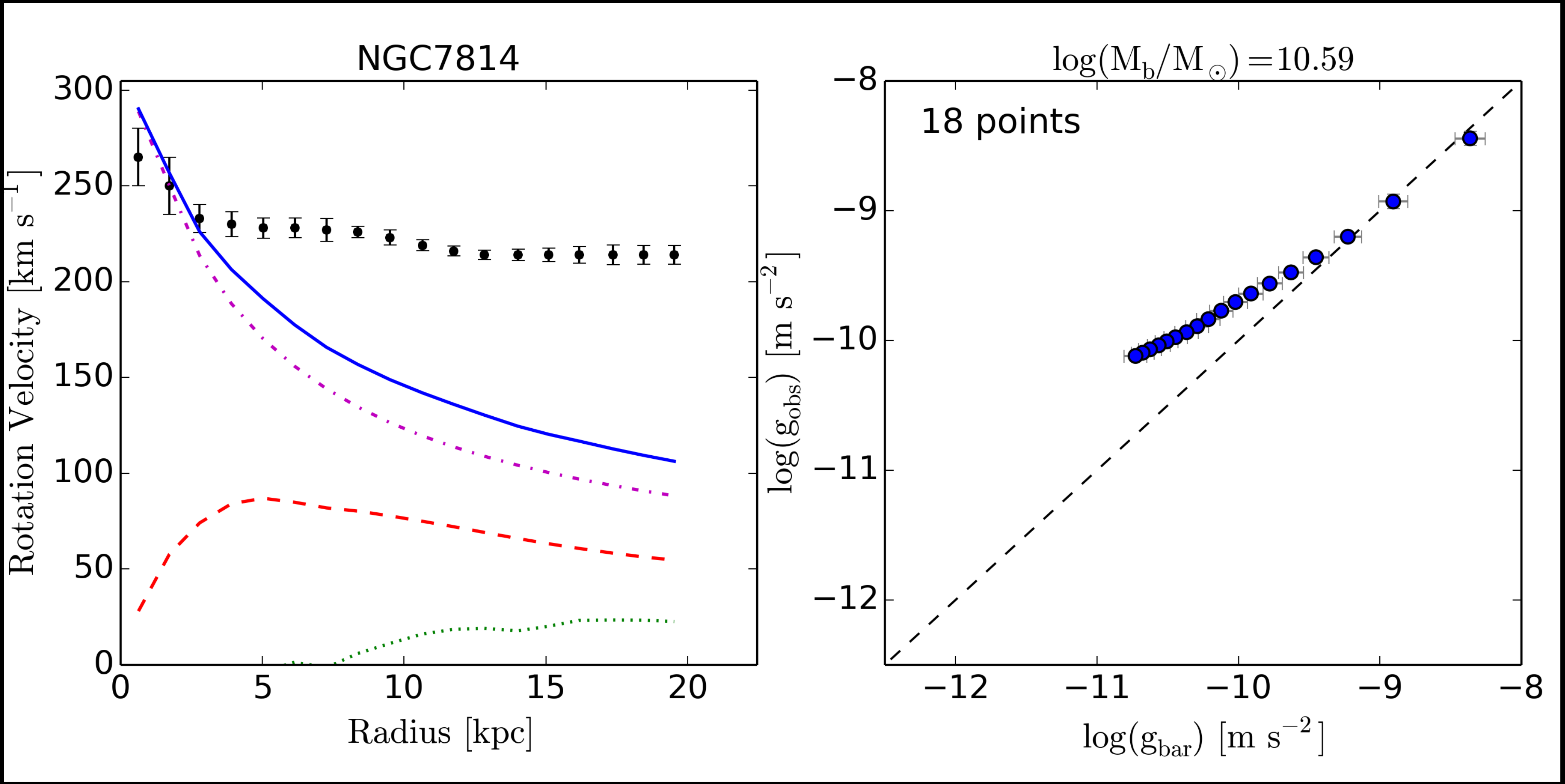
$\nabla^2\Phi_{bar} = 4\pi G\, \rho_{bar}$

McGaugh, LELLI, Schombert (2016)

Building up the Radial Acceleration Relation

Large Diversity in Rotation Curves

Regularity in Acceleration Plane

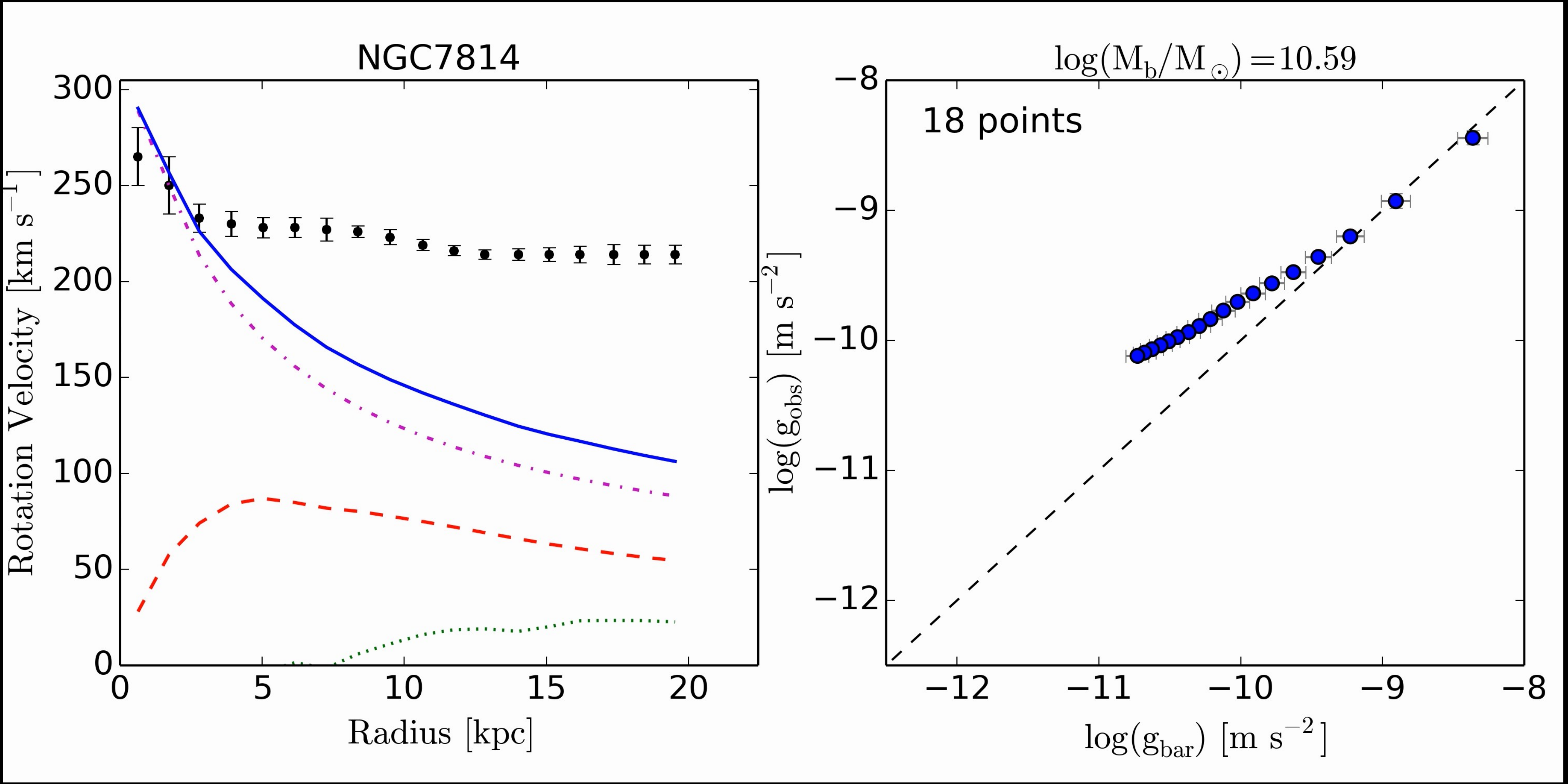


Lelli et al. (2017), ApJ

Building up the Radial Acceleration Relation

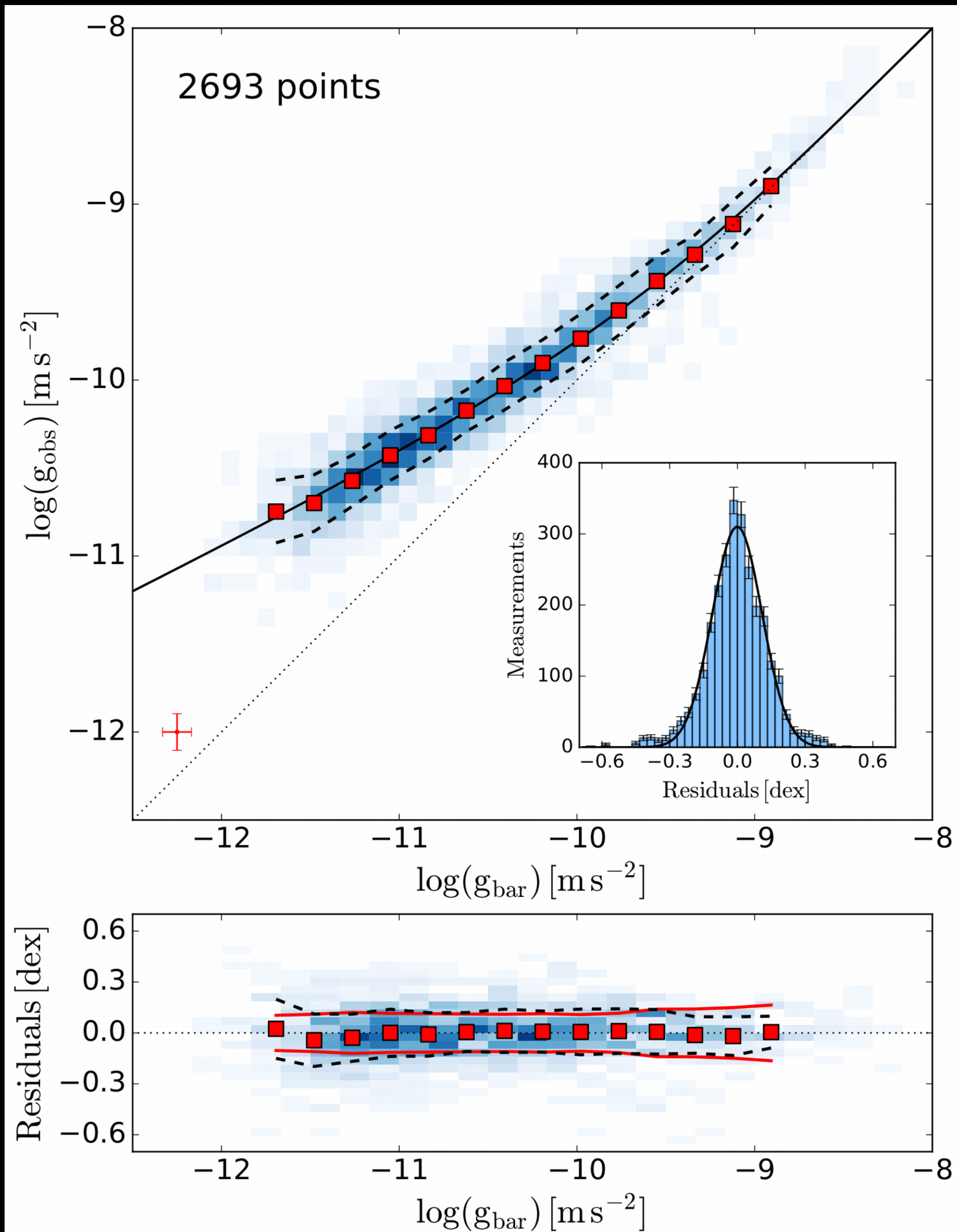
Large Diversity in Rotation Curves

Regularity in Acceleration Plane



Lelli et al. (2017), ApJ

Is There Any Intrinsic Scatter?



Uncertainties drive scatter!

err(g_{bar}) → Υ_*, 3D geometry

err(g_{obs}) → Dist, Inc, V_{rot}

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

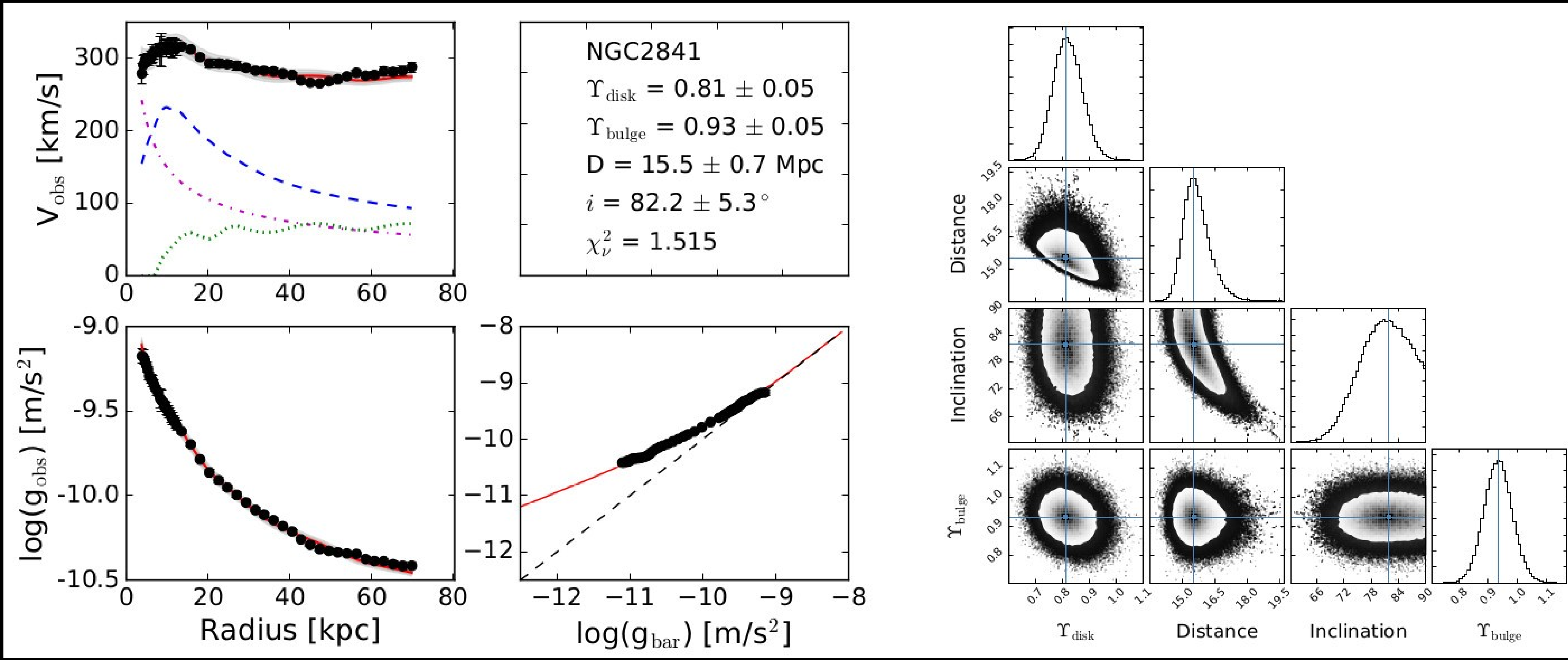
σ_{obs} → measured rms

σ_{err} → error propagation

σ_{int} → consistent with zero!

McGaugh+2016, PRL; Lelli+2017, ApJ

MCMC Fits to Individual Galaxies

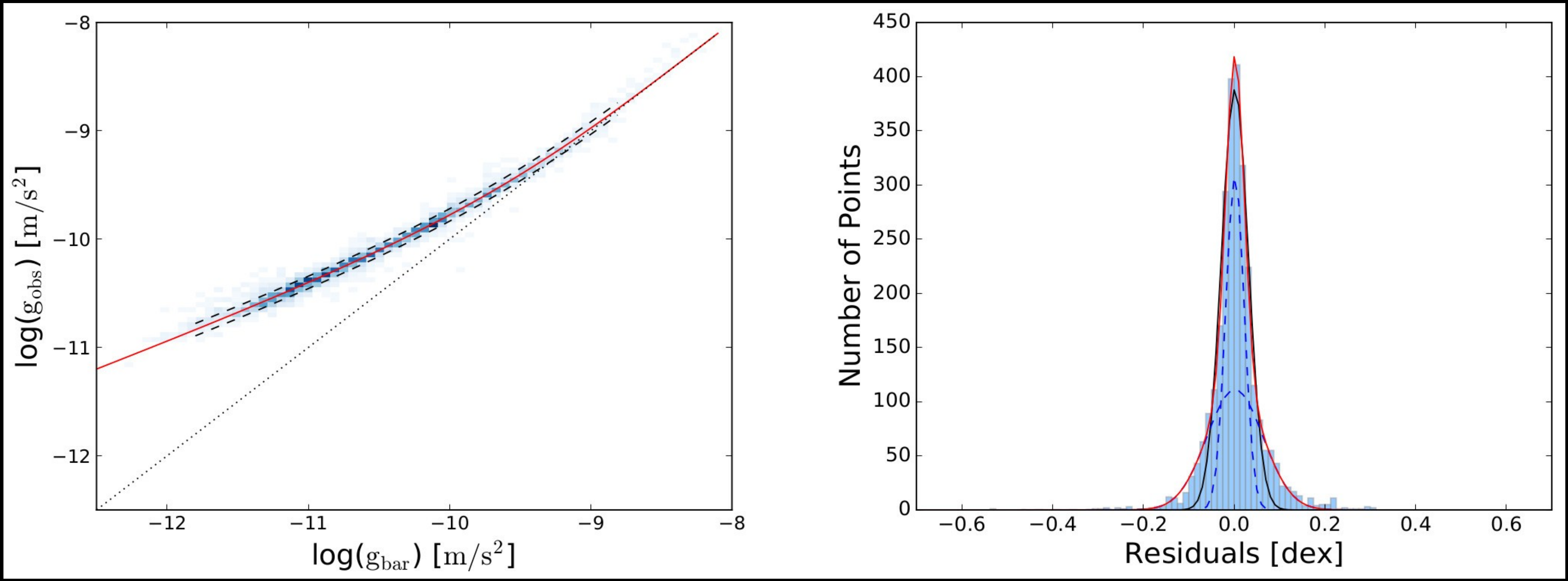


Fit the mean relation to individual galaxies marginalizing over D, i, $\Upsilon_{disc,}$ and $\Upsilon_{bul.}$

Gaussian priors on free parameters with $\sigma = \sigma_{err}$

Li, LELLI, McGaugh, Schombert 2018, A&A

MCMC Fits to Individual Galaxies

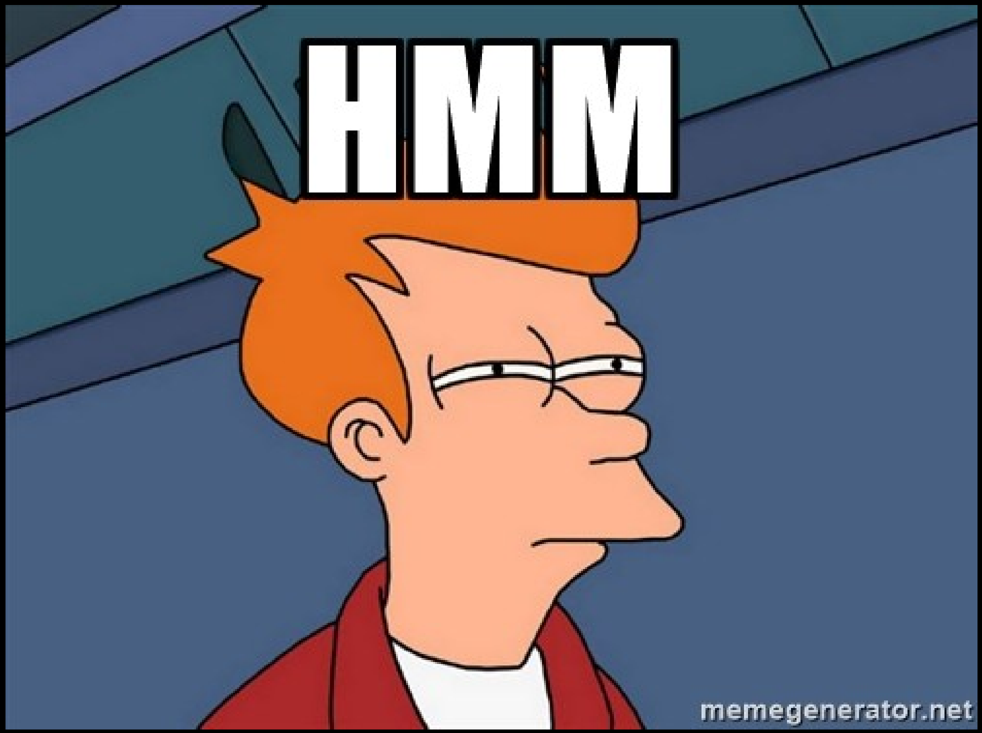


Extremely tight relation: σ_{obs} = 0.057 dex (~13%)

Not trivial because D, i, and Υ_* are global prop!

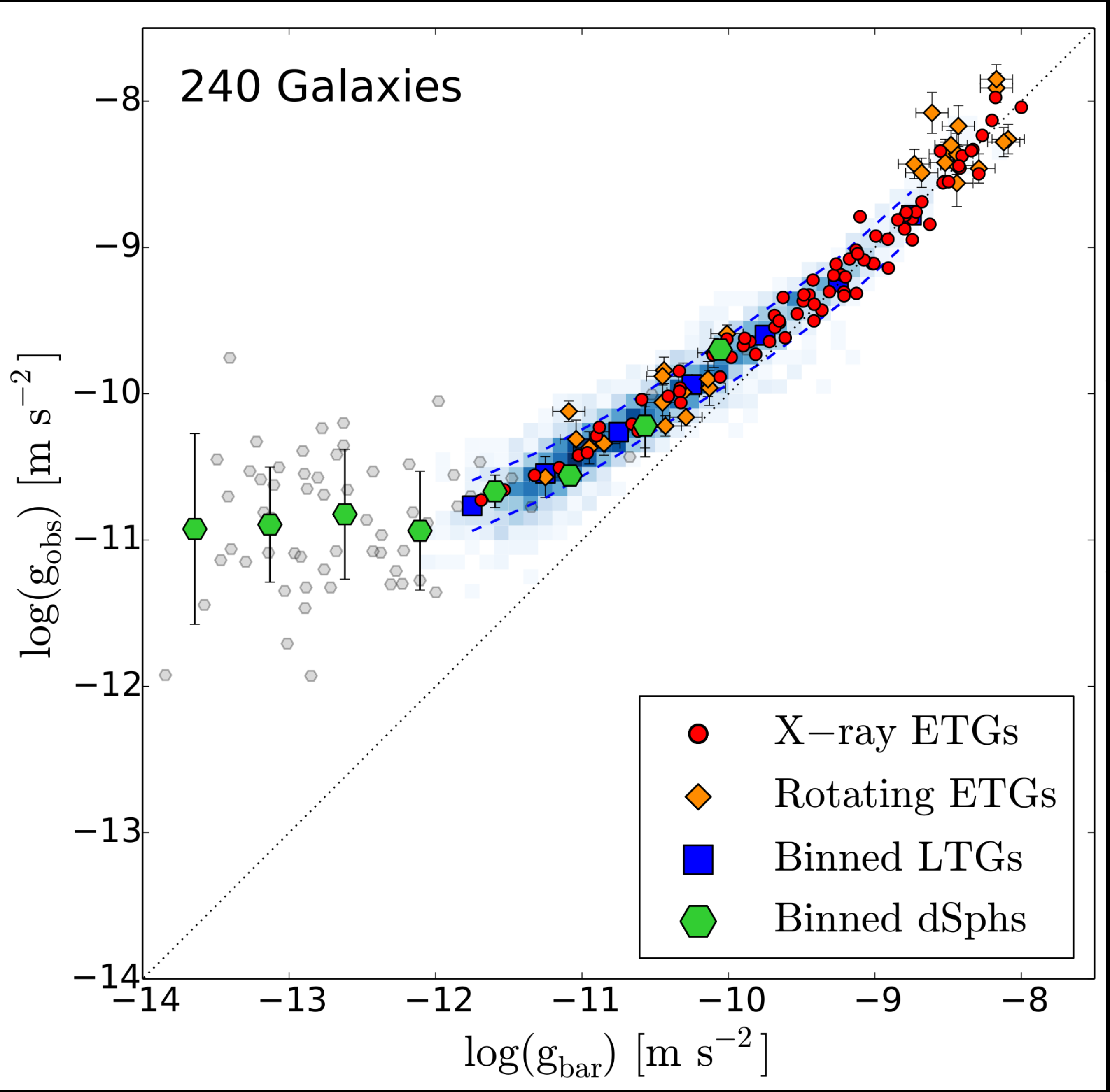
Residual best-fitted by two Gaussians:

it can be explained by two error sources in V_{rot}!



OK. This works for star-forming galaxies... What about passive ones (ETGs)?

Radial Acceleration Relation for ETGs



Massive Ellipticals:

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

Rotating ETGs:

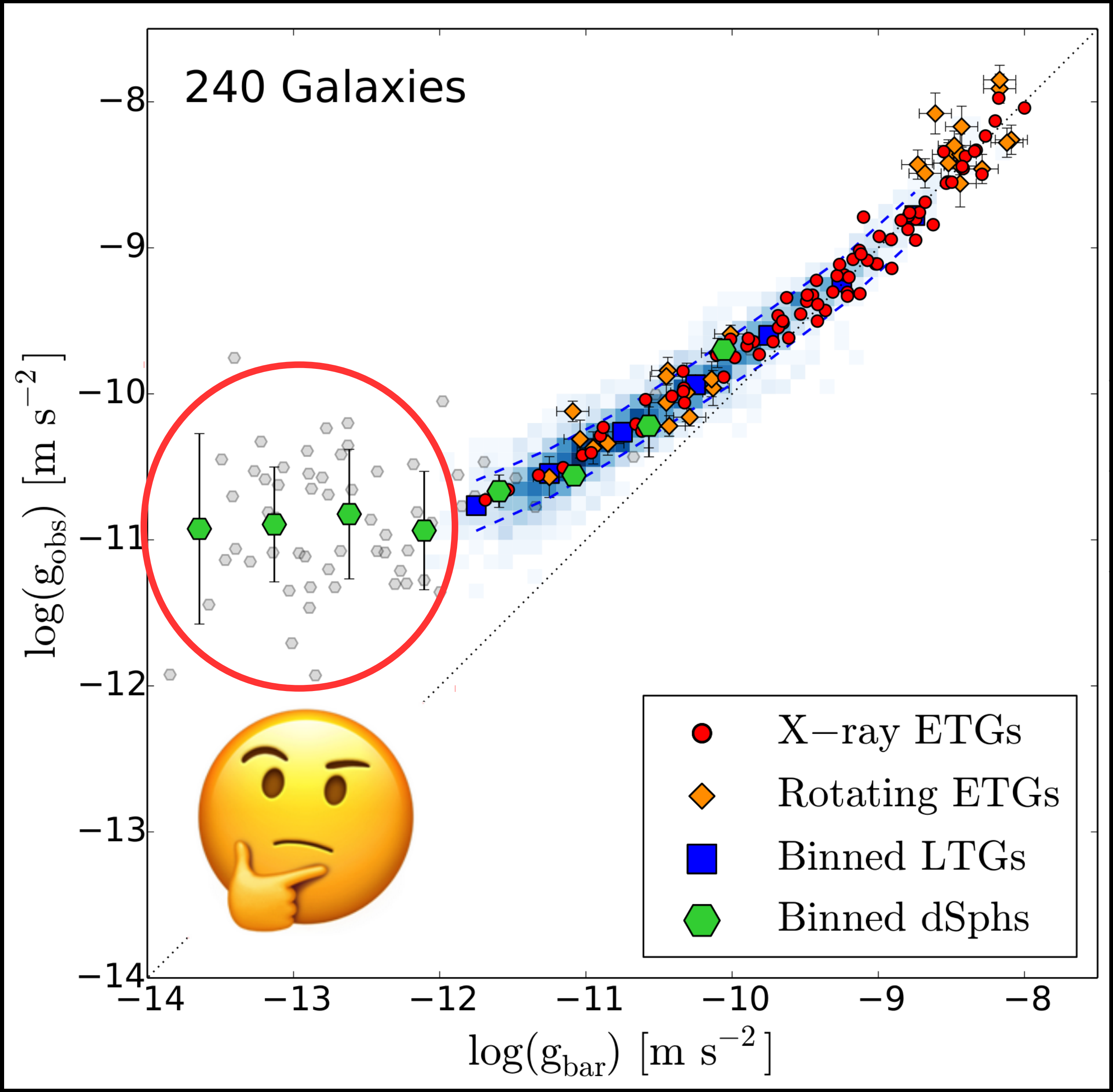
g_{obs} from stellar kinematics + Jeans Axisymmetric Models (Atlas^{3D} - Cappellari+2010)

Dwarf Spheroidals:

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

Lelli+2017, ApJ

Radial Acceleration Relation for ETGs



Massive Ellipticals:

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

Rotating ETGs:

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

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

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

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

For our fiducial fitting F: $$M_{DM}(R) = \frac{R^2}{G} \frac{g_{bar}}{\exp\left(\sqrt{g_{bar}/g_0}\right) - 1}$$

We can infer the DM profile empirically only from the baryons with a ~30% accuracy!

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

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

For our fiducial fitting F: $M_{DM}(R) = \frac{R^2}{G} \frac{g_{bar}}{\exp\left(\sqrt{g_{bar}/g_0}\right) - 1}$

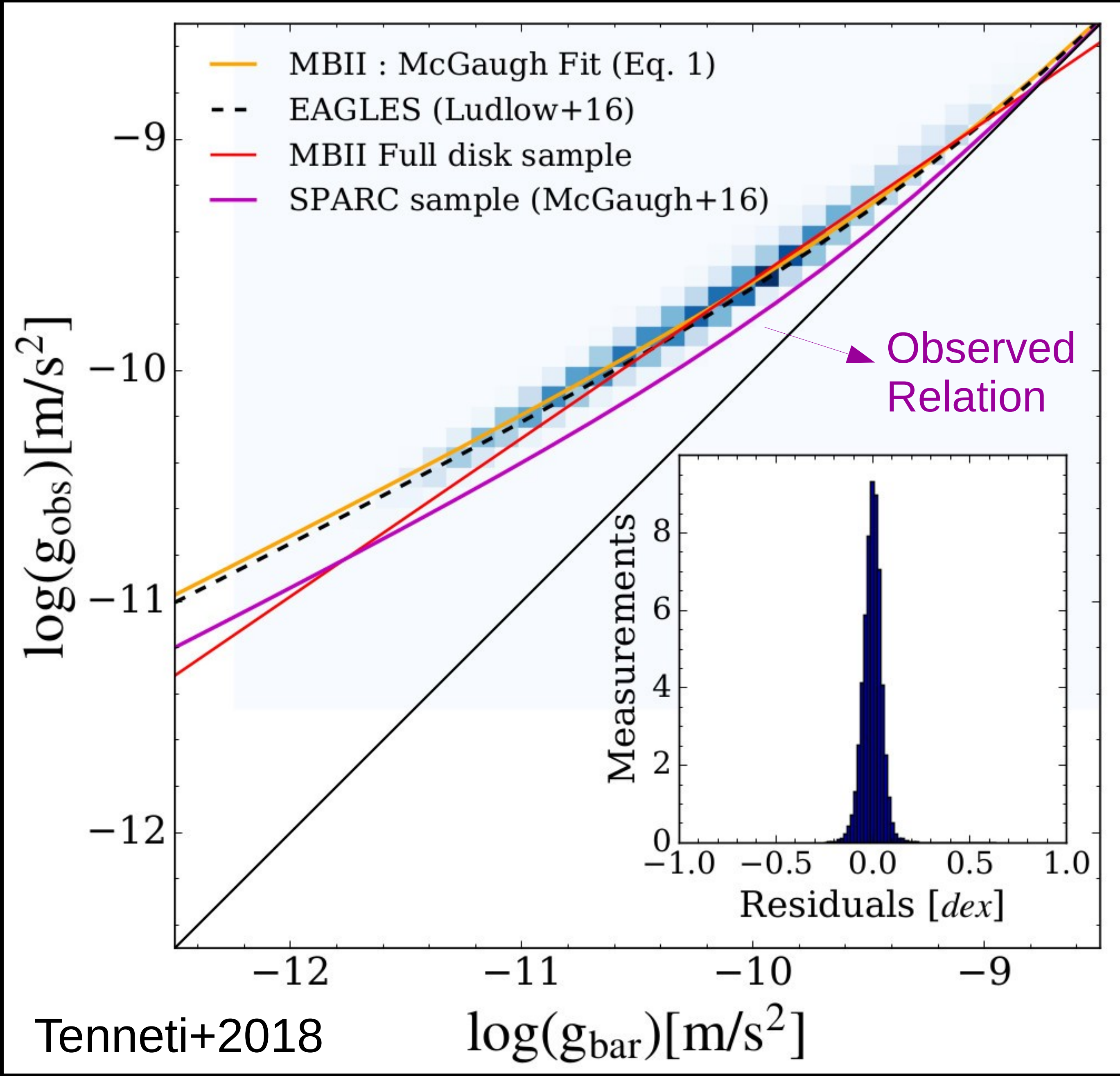
"Cusp-Core" is just a symptom of a more serious illness:

Baryon-DM coupling at each radius (not just the center).

No freedom to fit arbitrary DM halos!

III. Models in LCDM

The RAR from Hydrodynamic Simulations



MUGS2 simulations:
Keller & Wadsley 2017

EAGLE+APOSTOLE:
Ludlow et al. 2018

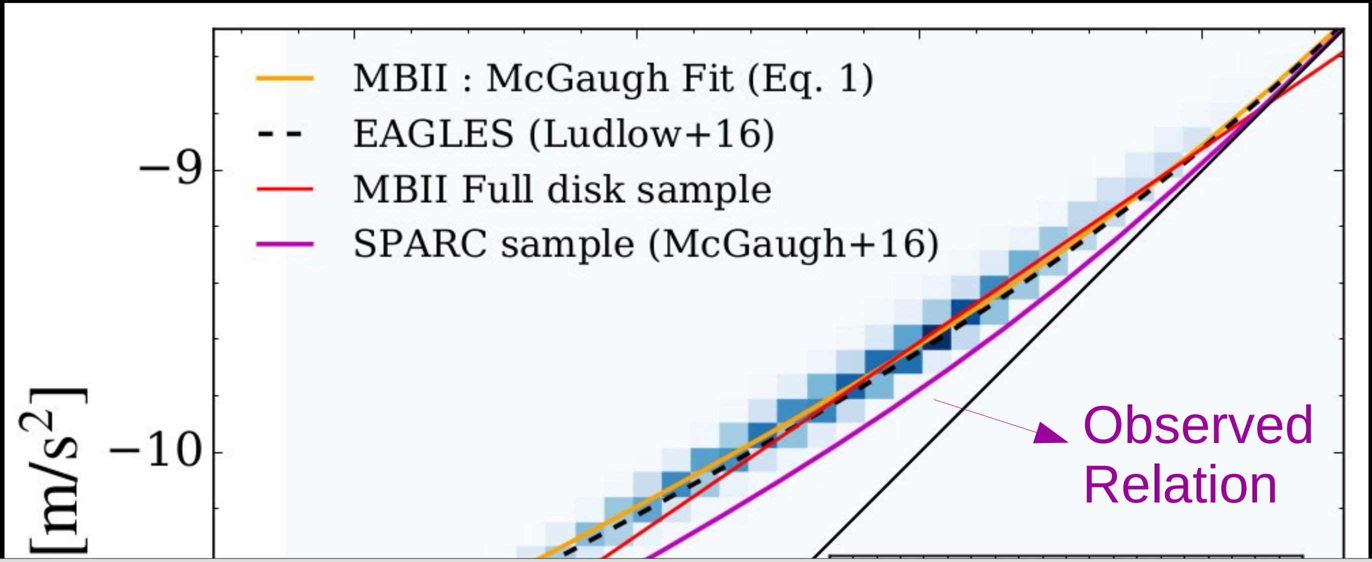
MassiveBlack II:
Tenneti et al. 2017

ZOMG simulations:
Garaldi et al. 2018

In Summary:

- RAR is reproduced but shape is a problem
- Sims have too much DM inside galaxies at every radius (~50%)

The RAR from Hydrodynamic Simulations



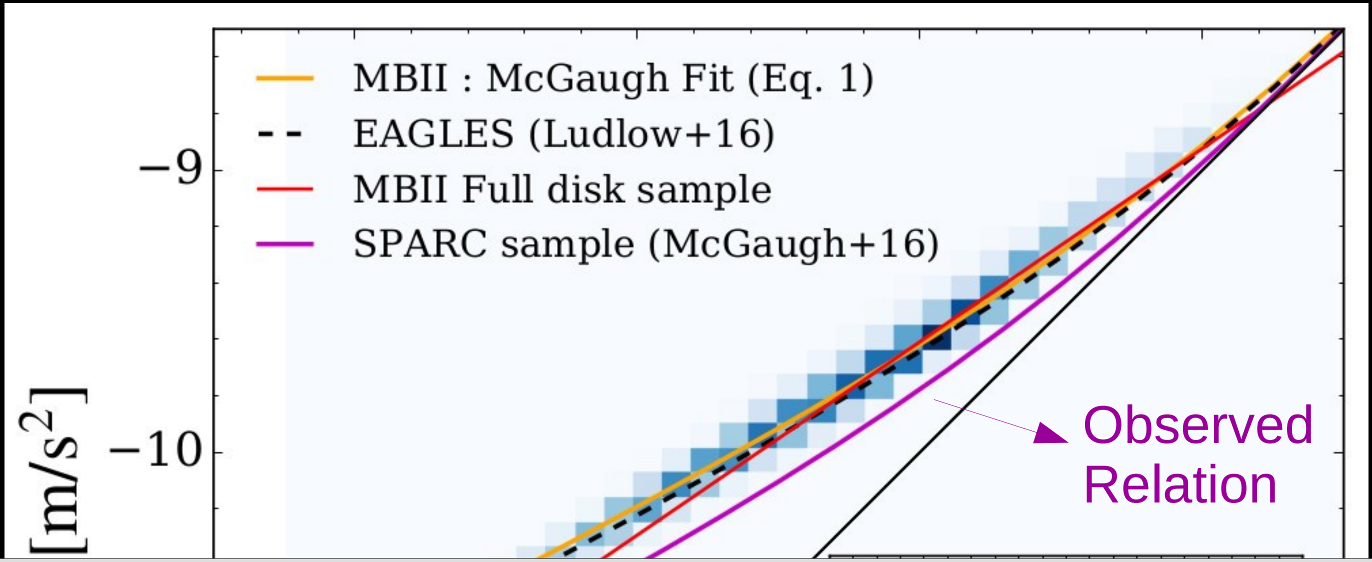
MUGS2 simulations:
Keller & Wadsley 2017

EAGLE+APOSTOLE:
Ludlow et al. 2017

MassiveBlack II:
Tenneti et al. 2018

OBSERVATIONS: g_0 = 1.20 ± 0.24 (sys) x 10^{-10} m s^{-2}

The RAR from Hydrodynamic Simulations



MUGS2 simulations:
Keller & Wadsley 2017

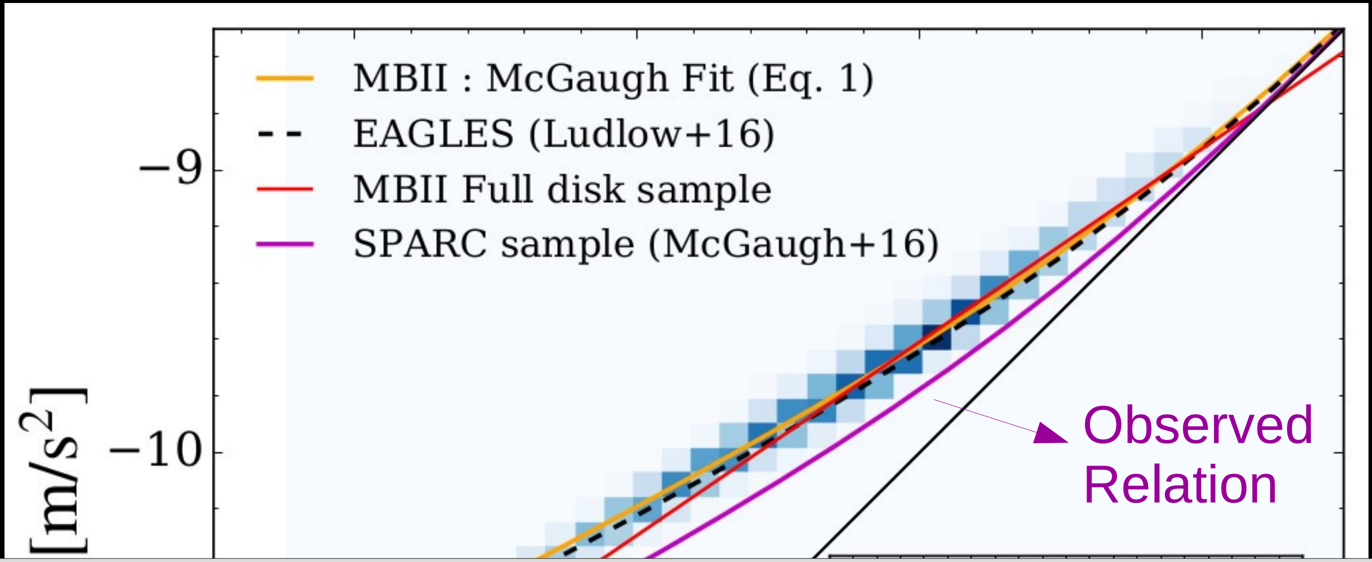
EAGLE+APOSTOLE:
Ludlow et al. 2017

MassiveBlack II:
Tenneti et al. 2018

OBSERVATIONS: $g_0 = 1.20 \pm 0.24$ (sys) x 10^{-10} m s^{-2}

EAGLE: $g_0 = 2.6$ x 10^{-10} m s^{-2} → 5.8σ discrepancy

The RAR from Hydrodynamic Simulations



MUGS2 simulations:
Keller & Wadsley 2017

EAGLE+APOSTOLE:
Ludlow et al. 2017

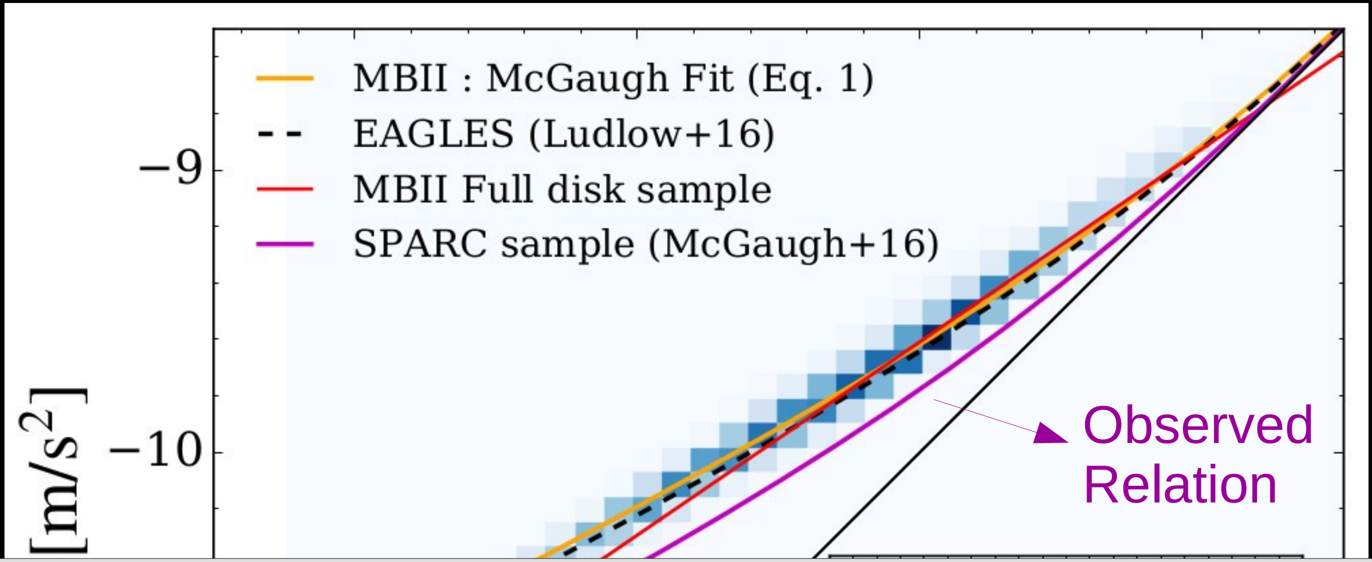
MassiveBlack II:
Tenneti et al. 2018

OBSERVATIONS: $g_0 = 1.20 \pm 0.24$ (sys) x 10^{-10} m s^{-2}

EAGLE: $g_0 = 2.6 \times 10^{-10}$ m s^{-2} → 5.8σ discrepancy

MassiveBlack II: $g_0 = 2.0 \times 10^{-10}$ m s^{-2} → 3.3σ tension

The RAR from Hydrodynamic Simulations



MUGS2 simulations:
Keller & Wadsley 2017

EAGLE+APOSTOLE:
Ludlow et al. 2017

MassiveBlack II:
Tenneti et al. 2018

OBSERVATIONS: $g_0 = 1.20 \pm 0.24$ (sys) x 10^{-10} m s^{-2}

EAGLE: $g_0 = 2.6 \times 10^{-10}$ m s^{-2} → 5.8σ discrepancy

MassiveBlack II: $g_0 = 2.0 \times 10^{-10}$ m s^{-2} → 3.3σ tension

ZOMG: $g_0 = 1.4 \times 10^{-10}$ m s^{-2} → ~1σ agreement

RAR from Semi-Empirical Analytic Models

Di Cintio & Lelli (2016): RAR-like relation emerges in ΛCDM once we impose 4 basic scaling relations:

1) M_h – c from N-body simulations

2) M_* – M_h from abundance matching

3) M_* – R_* from observations

4) M_* – M_{gas} from observations

RAR from Semi-Empirical Analytic Models

Di Cintio & Lelli (2016): RAR-like relation emerges in ΛCDM once we impose 4 basic scaling relations:

1) M_h – c from N-body simulations

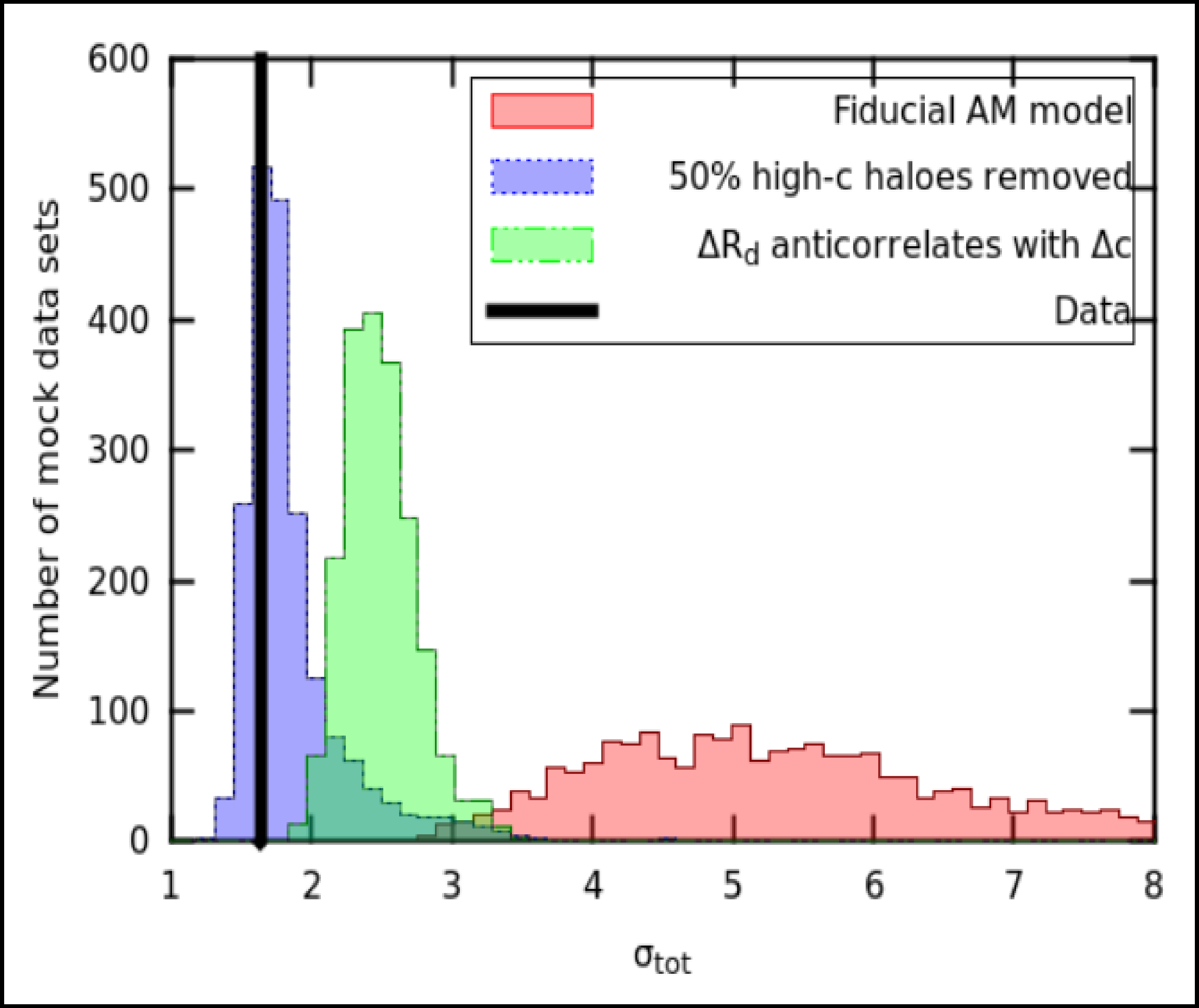
2) M_* – M_h from abundance matching

3) M_* – R_* from observations

4) M_* – M_{gas} from observations

Existence of the RAR is not a problem per se.
Real problem is the RAR tightness: all these relations have significant intrinsic scatter! Where does it go?

RAR from Abundance-Matching Models



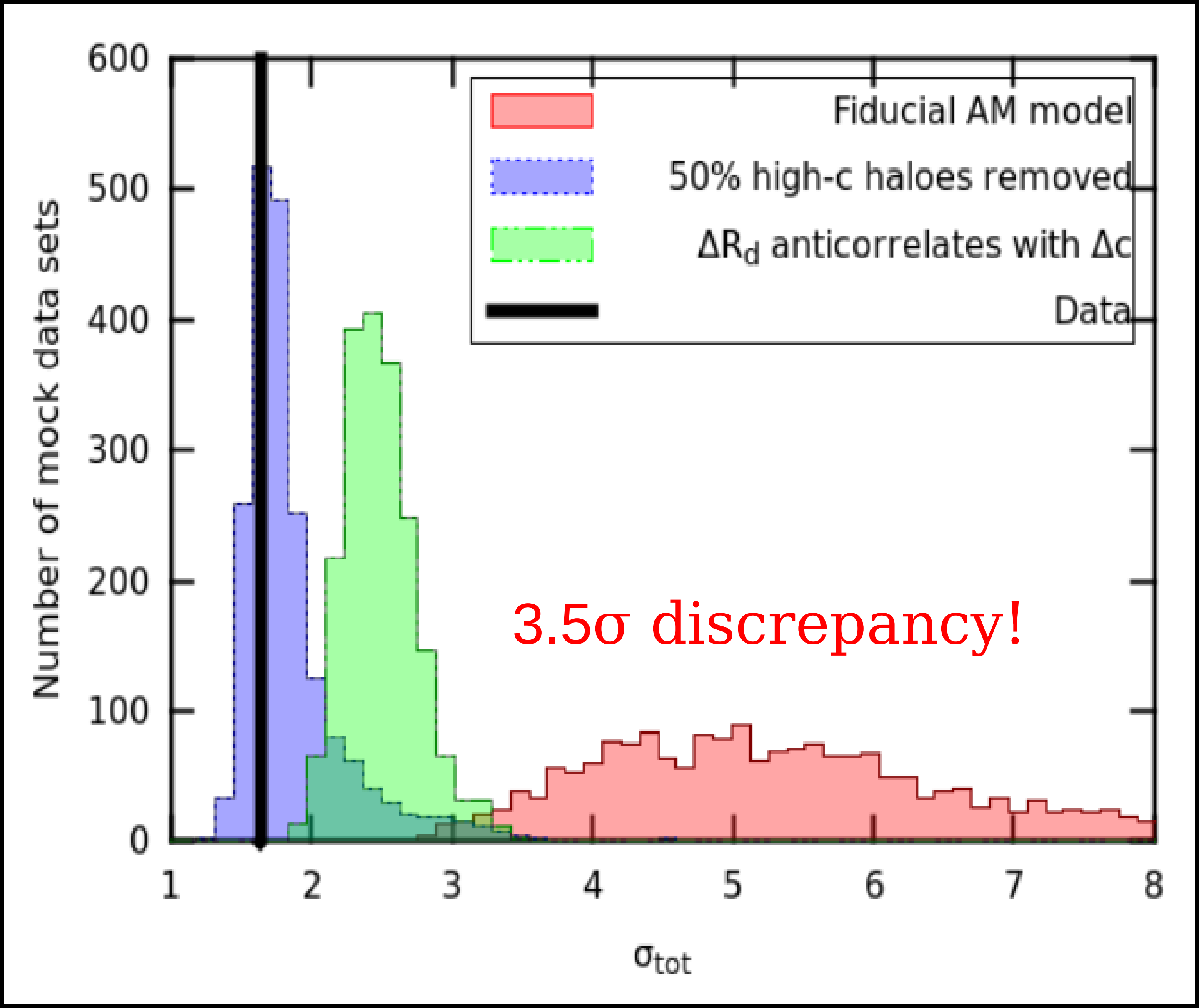
Desmond (2017):

1- Take N-body sims and assign each SPARC galaxy into a DM halo using AM

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

RAR from Abundance-Matching Models



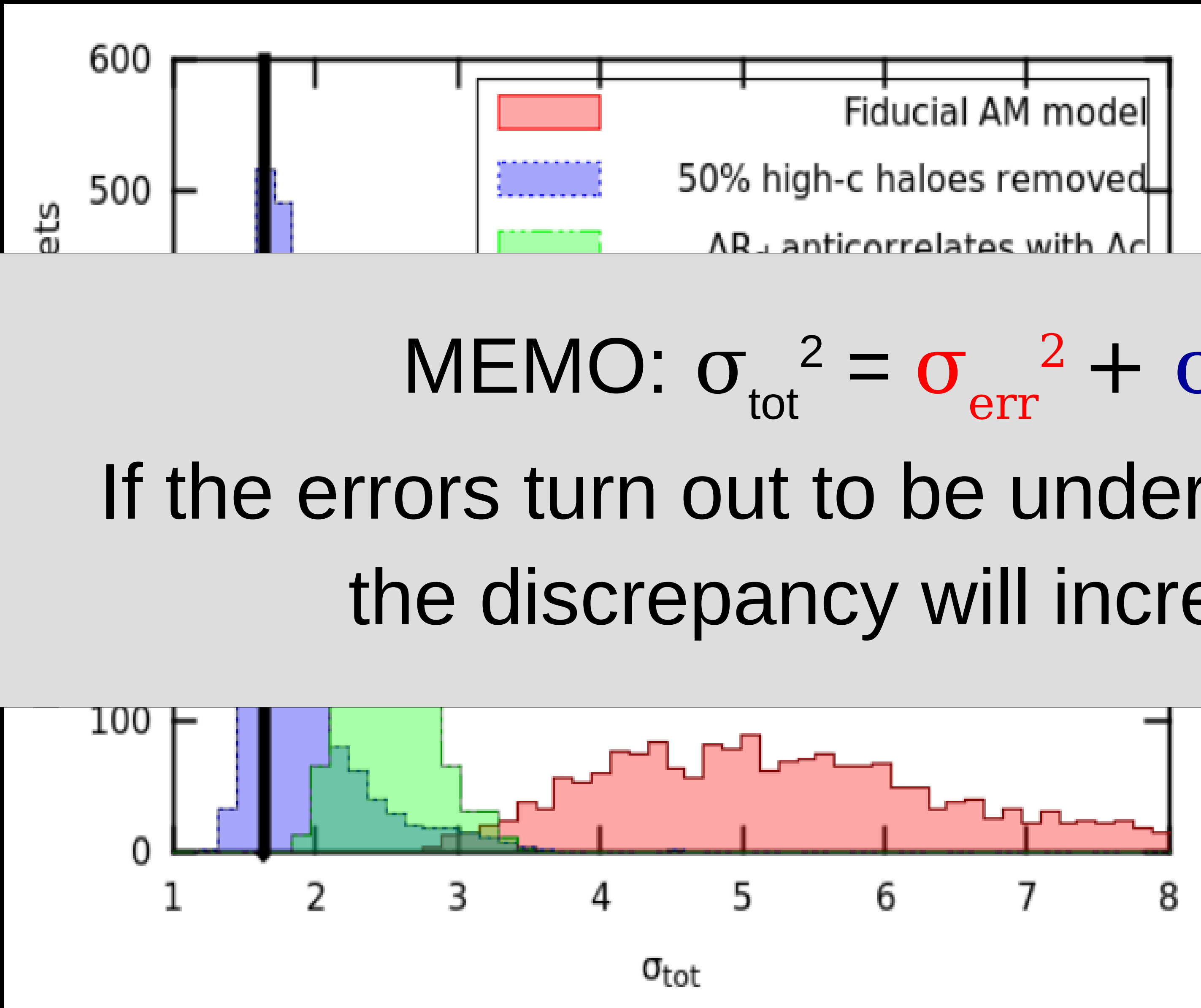
Desmond (2017):

1- Take N-body sims and assign each SPARC galaxy into a DM halo using AM

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

RAR from Abundance-Matching Models



Desmond (2017):

1- Take N-body sims and assign each

MEMO: $\sigma_{tot}^2 = \sigma_{err}^2 + \sigma_{int}^2$

If the errors turn out to be under-estimated, the discrepancy will increase!

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

Conclusions:

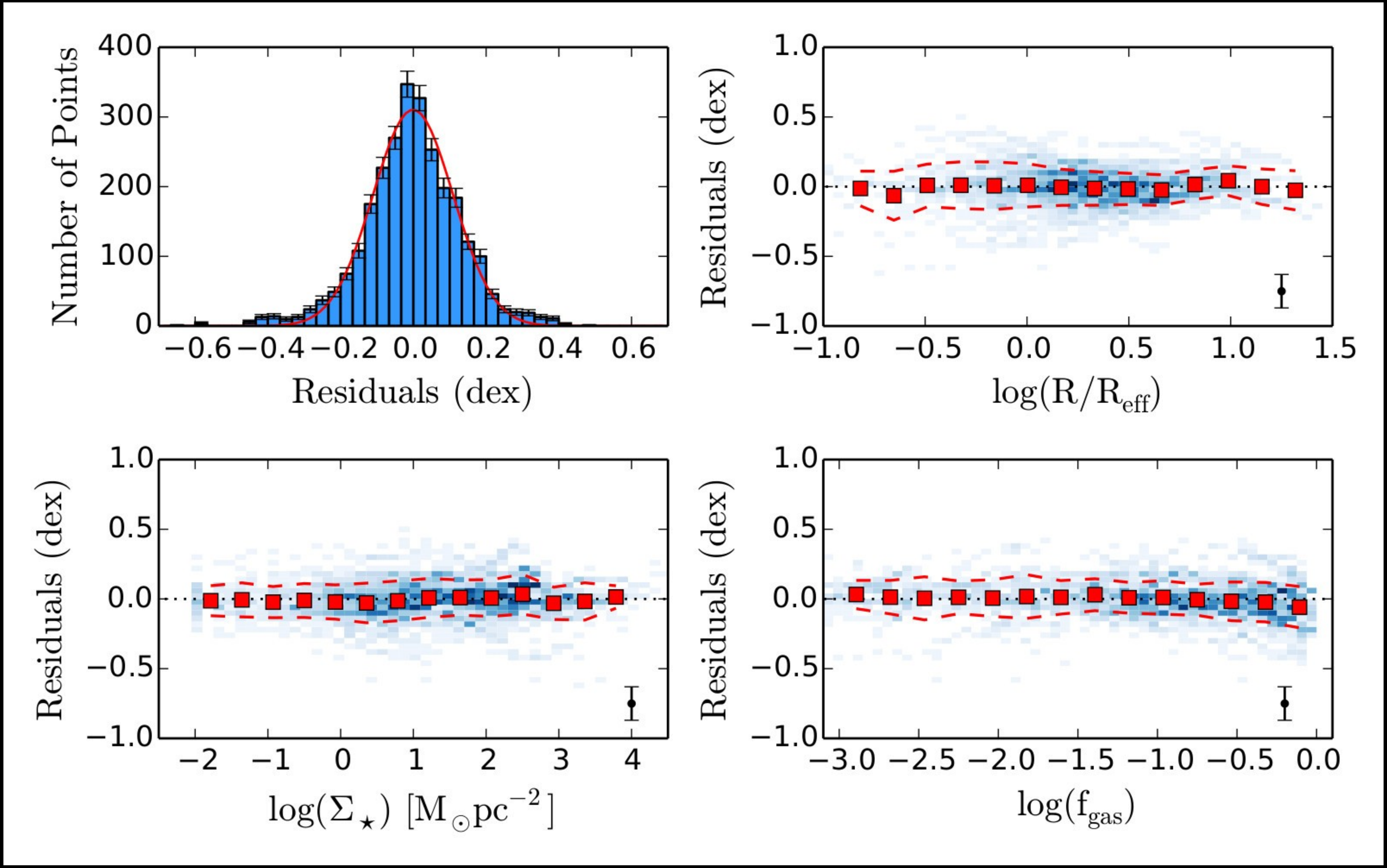
- Local, tight coupling between baryons and DM in galaxies over ~5 dex in mass.

- There is an acceleration scale in galaxies.

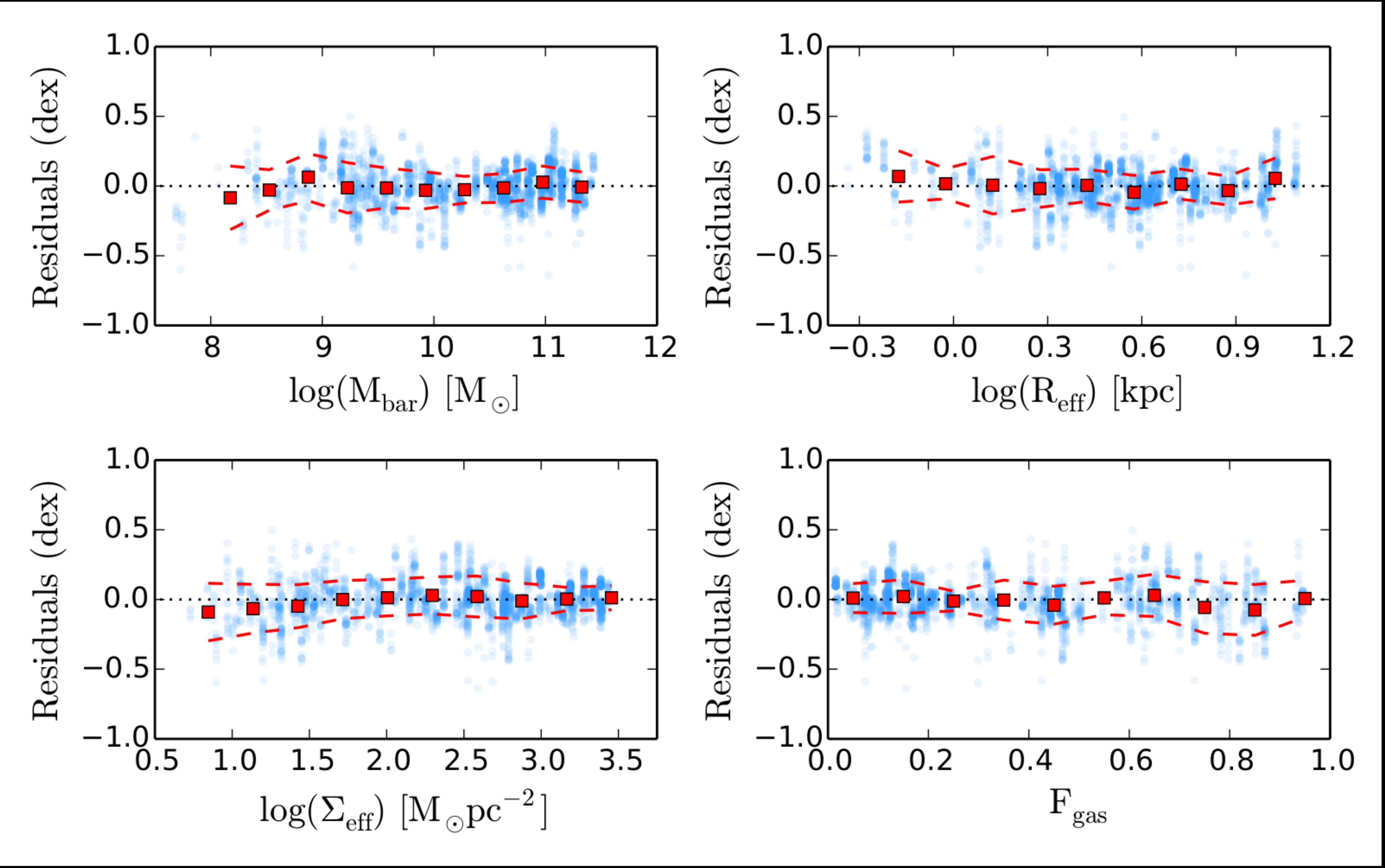
  If you like numerology: $g_0 \sim cH_0 \sim 10^{-10}$ m s^{-2}.

Questions?

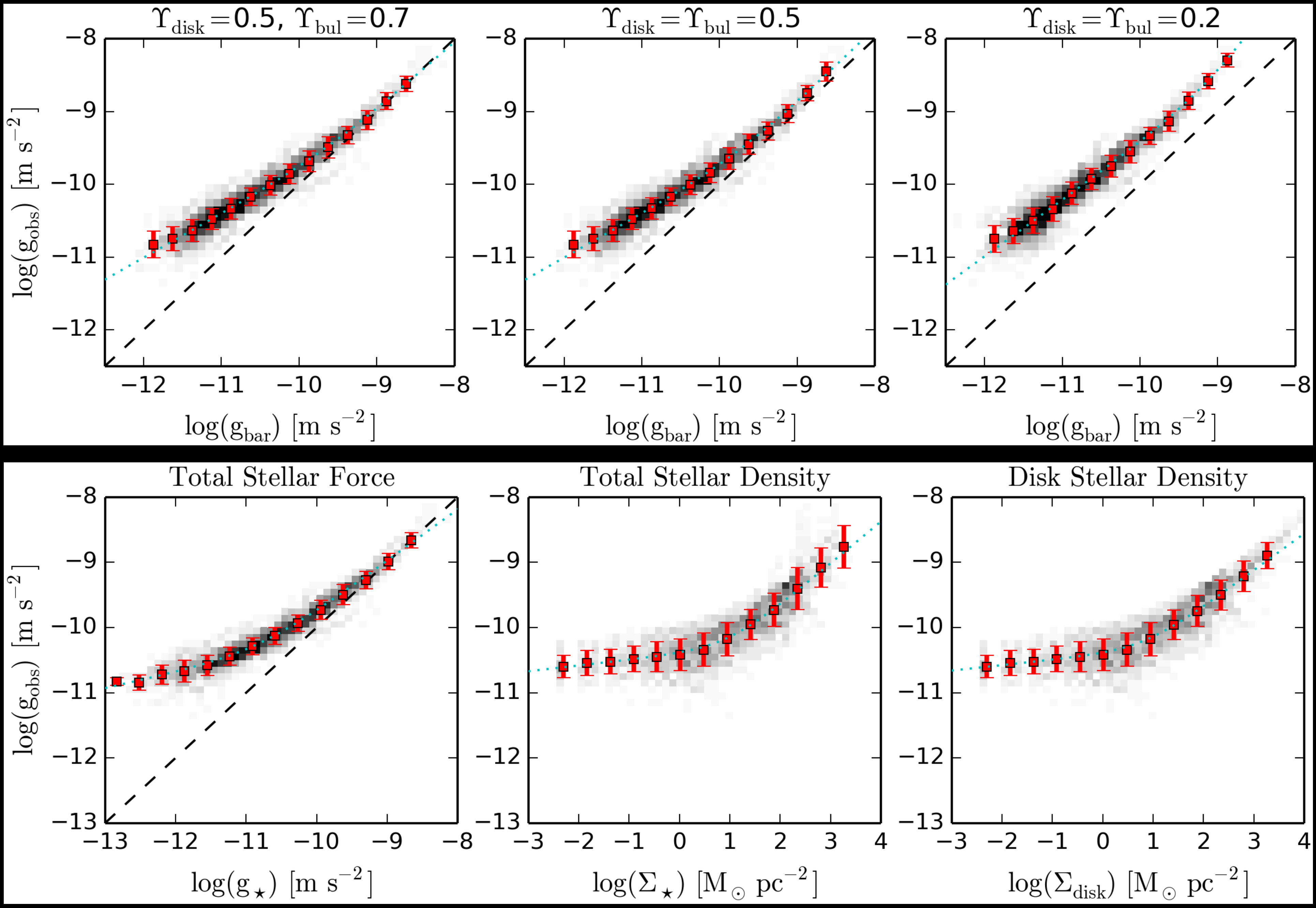
Residuals *vs* Local Galaxy Properties



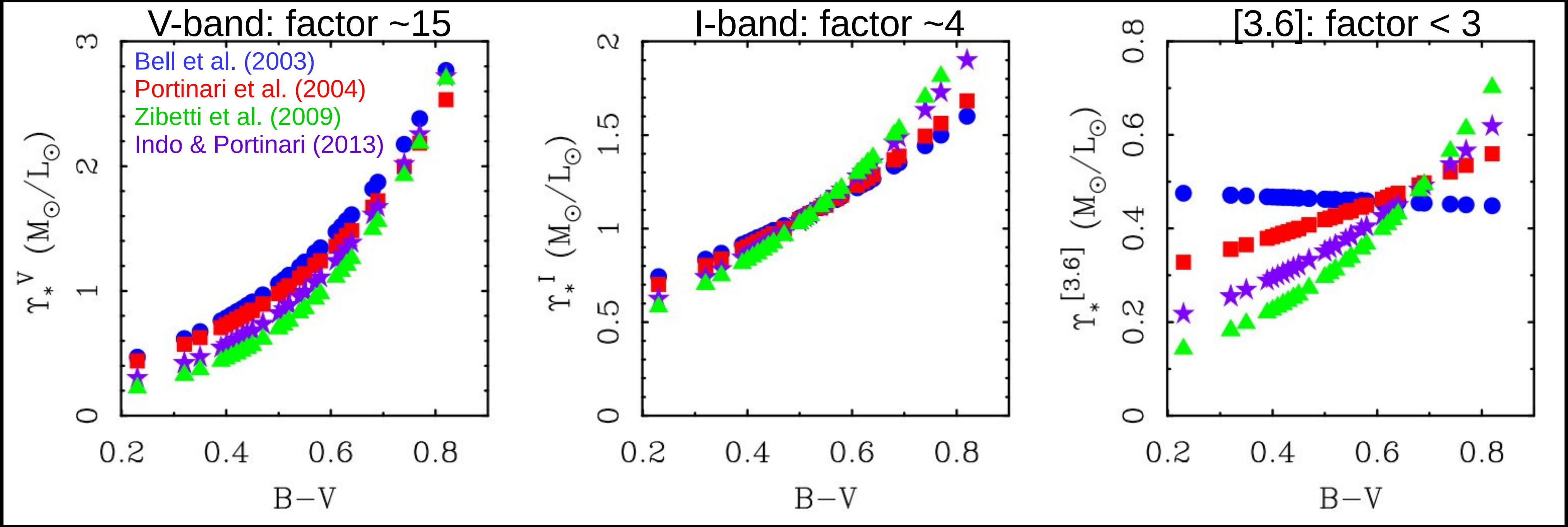
Residuals *vs* Global Galaxy Properties



Alternative versions of the RAR



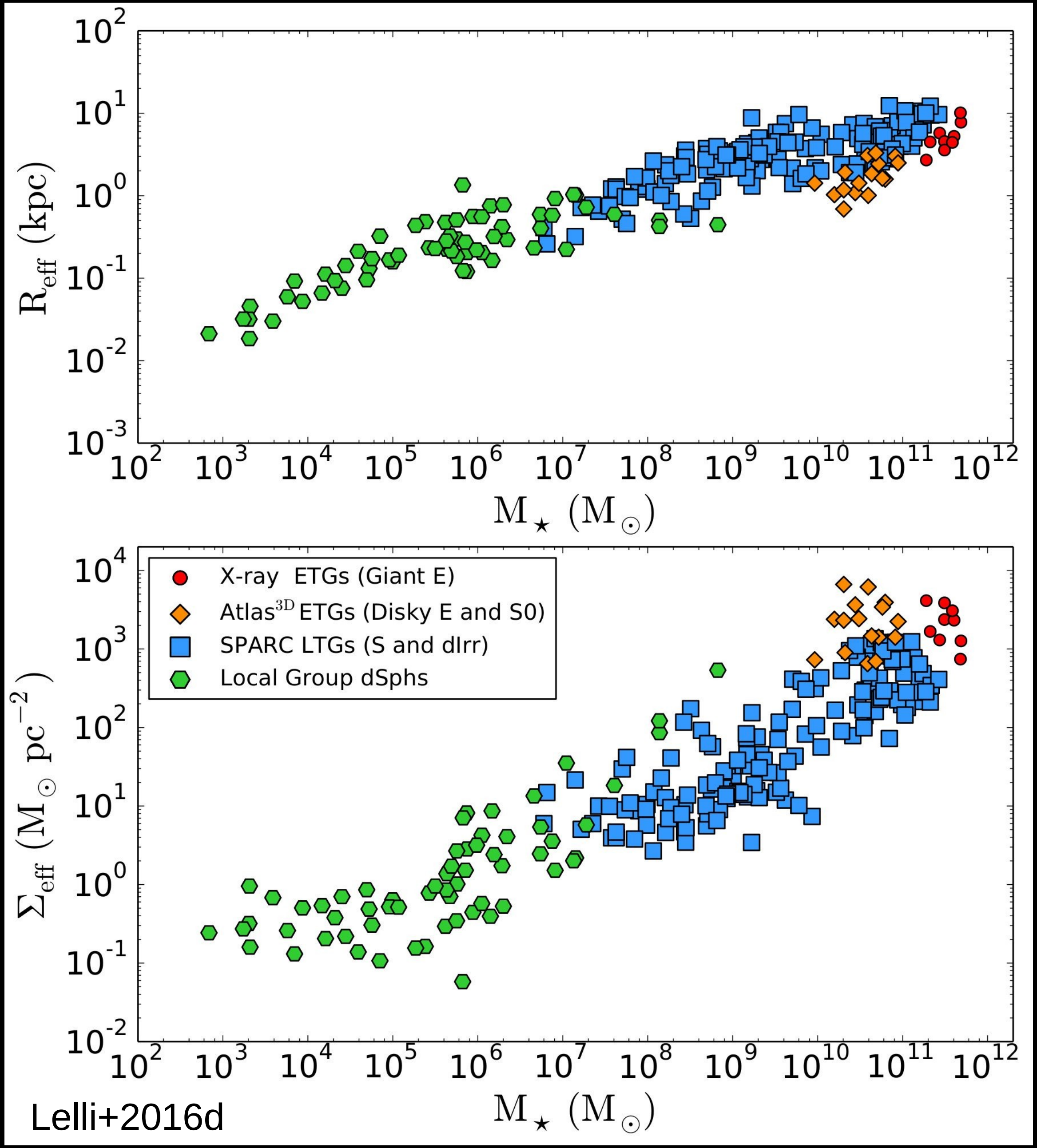
Spitzer [3.6] Photometry: Stellar Mass



Υ_*-color relations from SPS models (McGaugh & Schombert 2014)

- Υ_* shows smaller variations at [3.6] than optical bands
- Details depend on SPS model and assumed IMF
- Most recent models: $\Upsilon_{[3.6]}$ is nearly constant for LTGs (Meidt+2014; Schombert & McGaugh 2014; Norris+2016)

Dwarf Spheroidals (dSphs) in the Local Group



Satellites of MW and M31:

extremely low masses, sizes, densities, and accelerations!

"Classical" dSphs discovered between the '40 and the '80.

→ well-studied properties

"Ultrafaint" dSphs discovered during the past ~10 years with SDSS, DES and other surveys

→ properties remain uncertain

Open Problems for ΛCDM models:

1. Why is the RAR scatter so small?

   Is this consistent with stochastic hierarchical merging?

2. Why is the RAR low-acceleration slope ~0.5?

   $g_{obs} = \sqrt{(g_0 g_{bar})} \rightarrow V_{flat}^4 = M_{bar} / (g_0 G) \rightarrow$ Observed BTFR

   Whatever sets the RAR should also set the BTFR.

3. Why an acceleration scale? What sets its value?

   Different roles of g_0: baryon-to-DM transition (RAR)

   & global baryon-to-DM content (BTFR)!