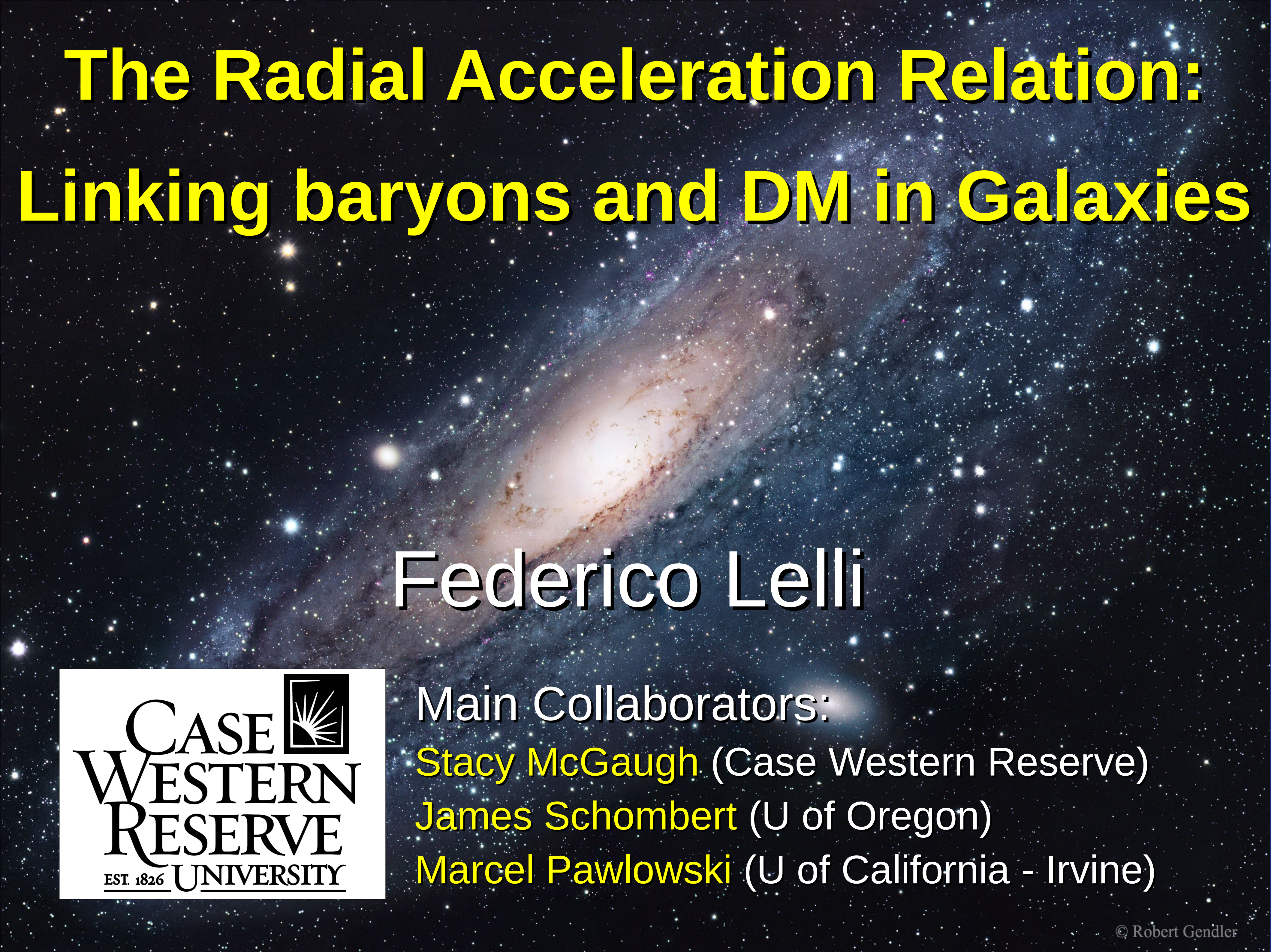


The Radial Acceleration Relation: Linking baryons and DM in Galaxies

Federico Lelli

Main Collaborators:
Stacy McGaugh (Case Western Reserve)
James Schombert (U of Oregon)
Marcel Pawlowski (U of California - Irvine)

CASE WESTERN RESERVE UNIVERSITY EST. 1826

Outline:

I. Introduction: Dynamics of Galaxies

Rotation curves, mass models, scaling relations.

II. The SPARC Galaxy Database

Largest compilation of galaxy mass models to date.

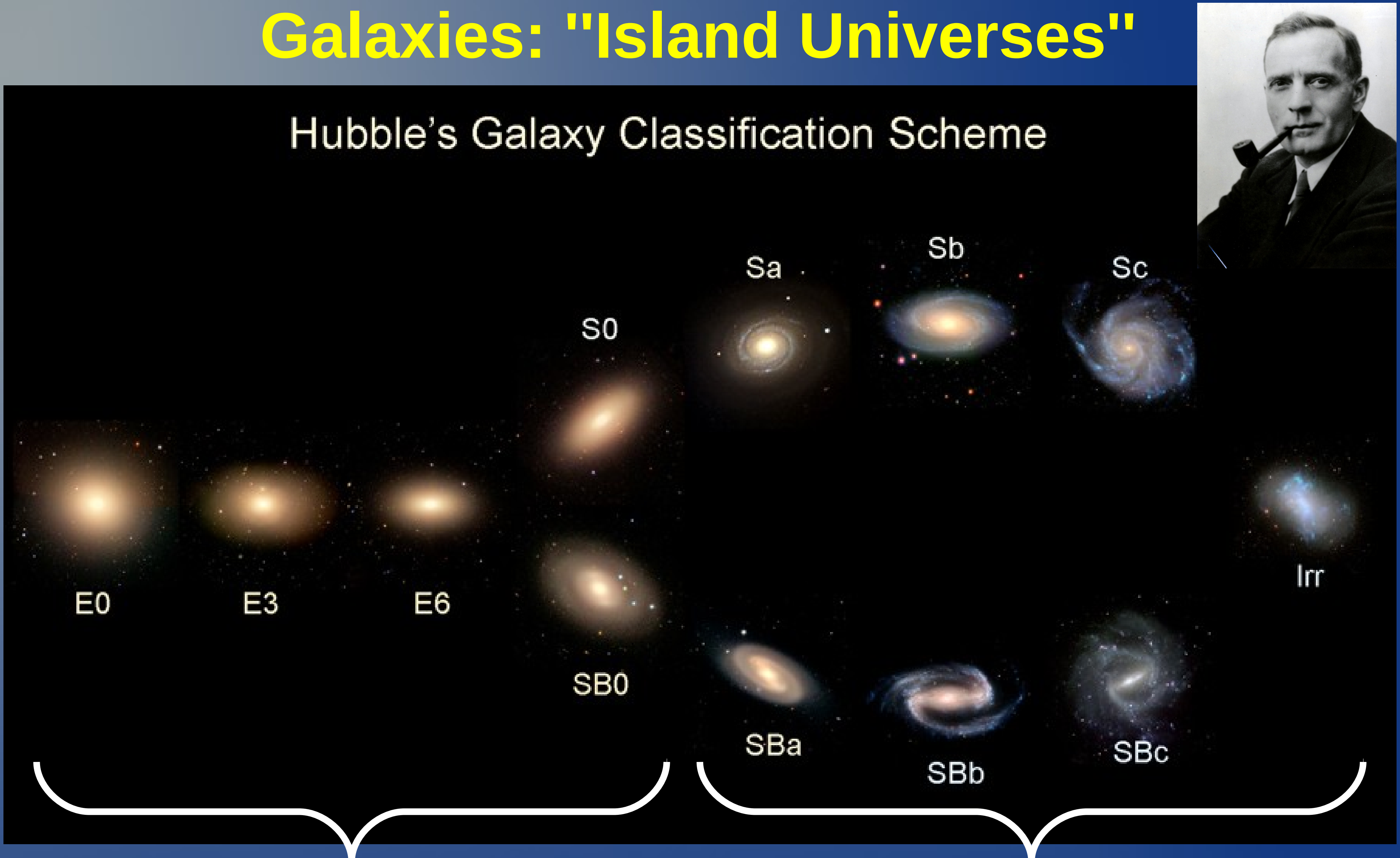
III. The Radial Acceleration Relation

<u>Local</u> link between baryons and dark matter in galaxies.

I. Introduction:

Dynamics of Galaxies

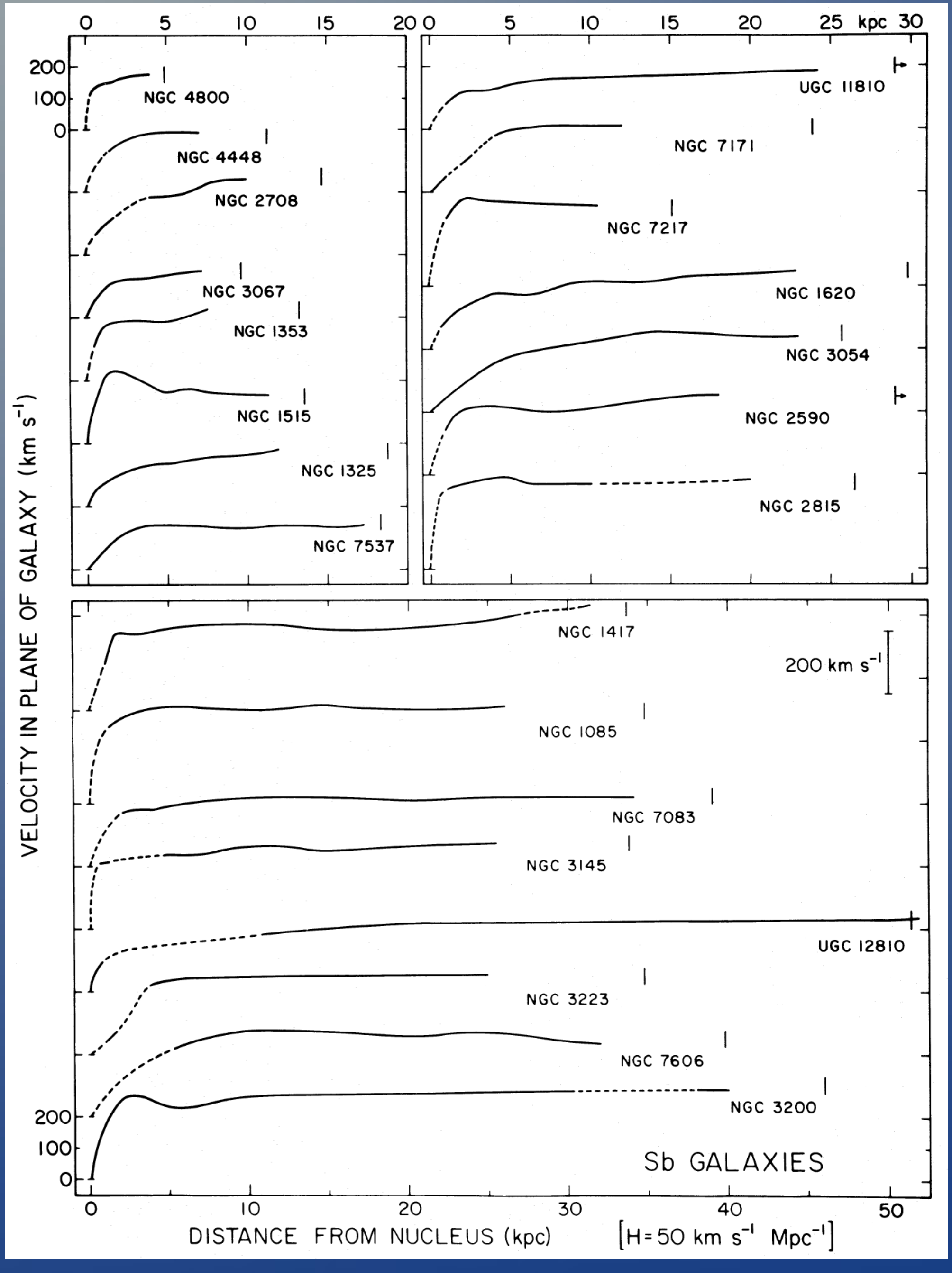
Galaxies: "Island Universes"



Early-Type Galaxies (ETGs): E and S0
Little Cold Gas → No Star Formation
→ Dominated by Old Stars

Late-Type Galaxies (LTGs): S and Irr
Disk of Cold Gas → Star Formation
→ Both Young & Old Stars

Galaxy Rotation Curves are Flat at Large Radii



Historical Evidence for Mass Discrepancies

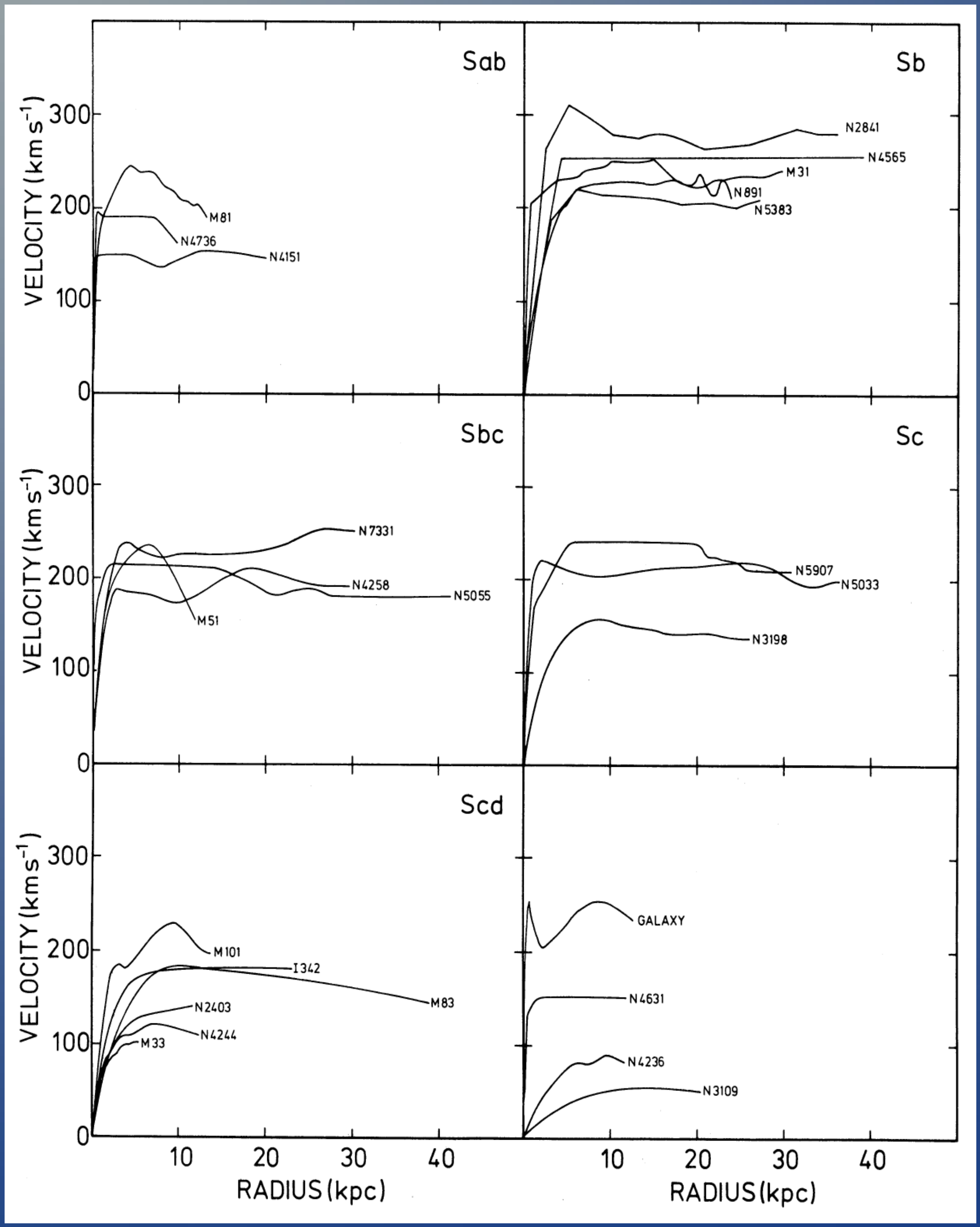
$$V = \mathrm{const}$$

$$M_{tot} \propto r$$

$$\rho_{tot} \propto r^{-2}$$

Optical Observations of Ionized Gas
V. Rubin et al. (1978, 1982)

Galaxy Rotation Curves are Flat at Large Radii



Historical Evidence for Mass Discrepancies

$$V = \text{const}$$

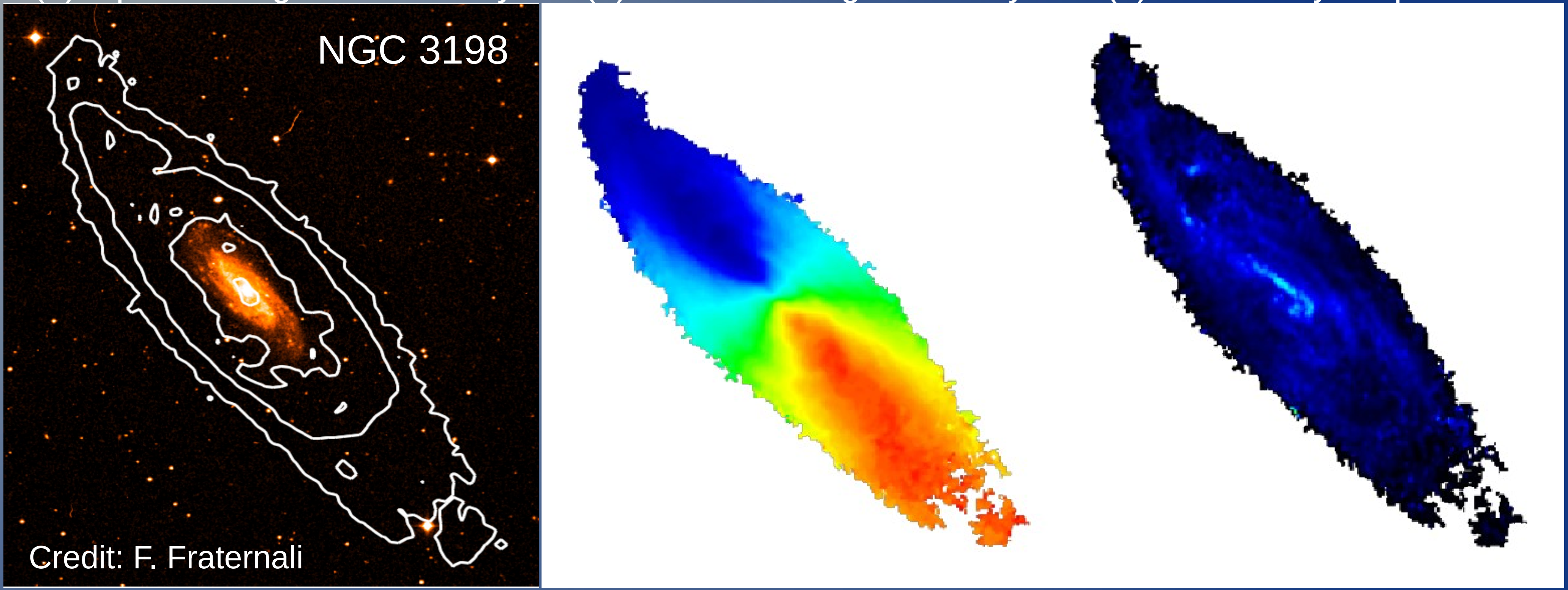
$$M_{tot} \propto r$$

$$\rho_{tot} \propto r^{-2}$$

Radio Observations of Neutral Gas
A. Bosma (1978, 1981)

Atomic Hydrogen (HI): Radio Data at 21 cm

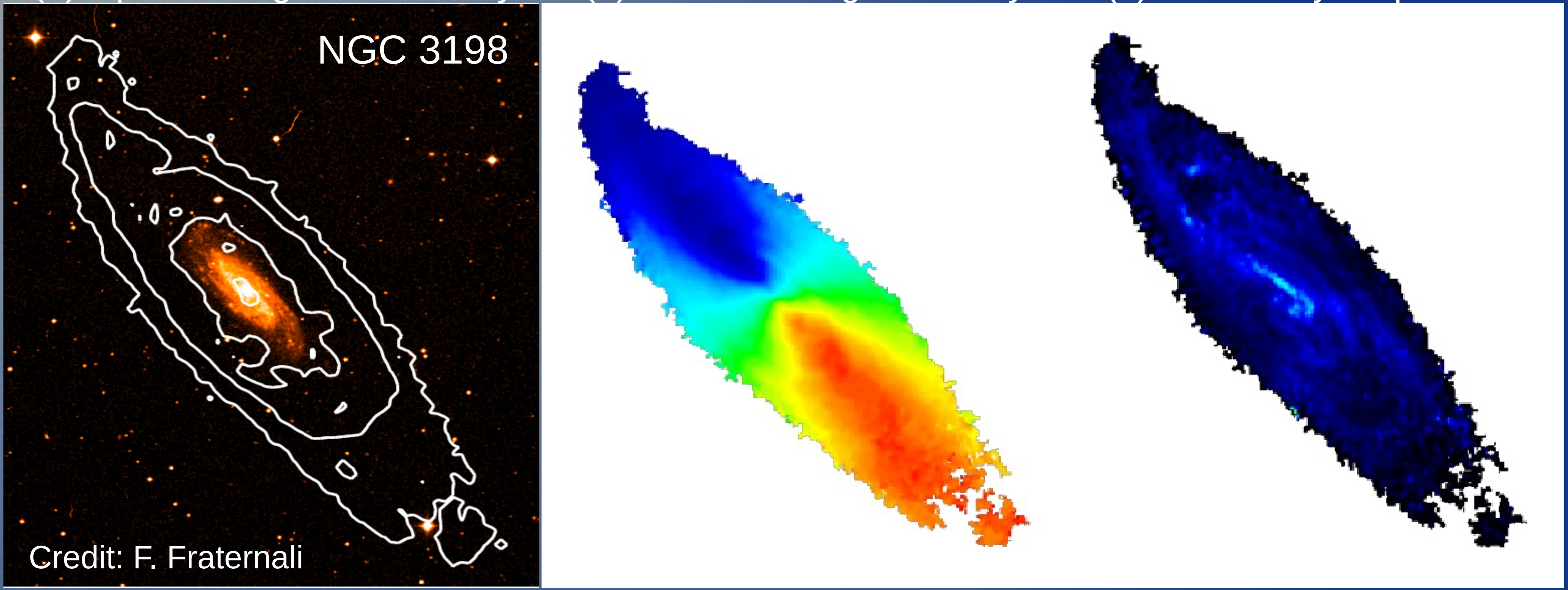
(1) Optical Image + HI density (2) HI Line-of-Sight Velocity (3) HI Velocity Dispersion



Good tracer of the total gravitational potential: $$\frac{V_{rot}^2}{R} = -\frac{\partial \Phi_{tot}}{\partial R}$$

Atomic Hydrogen (HI): Radio Data at 21 cm

(1) Optical Image + HI density (2) HI Line-of-Sight Velocity (3) HI Velocity Dispersion



Good tracer of the total gravitational potential: $\frac{V_{rot}^2}{R} = -\frac{\partial \Phi_{tot}}{\partial R}$

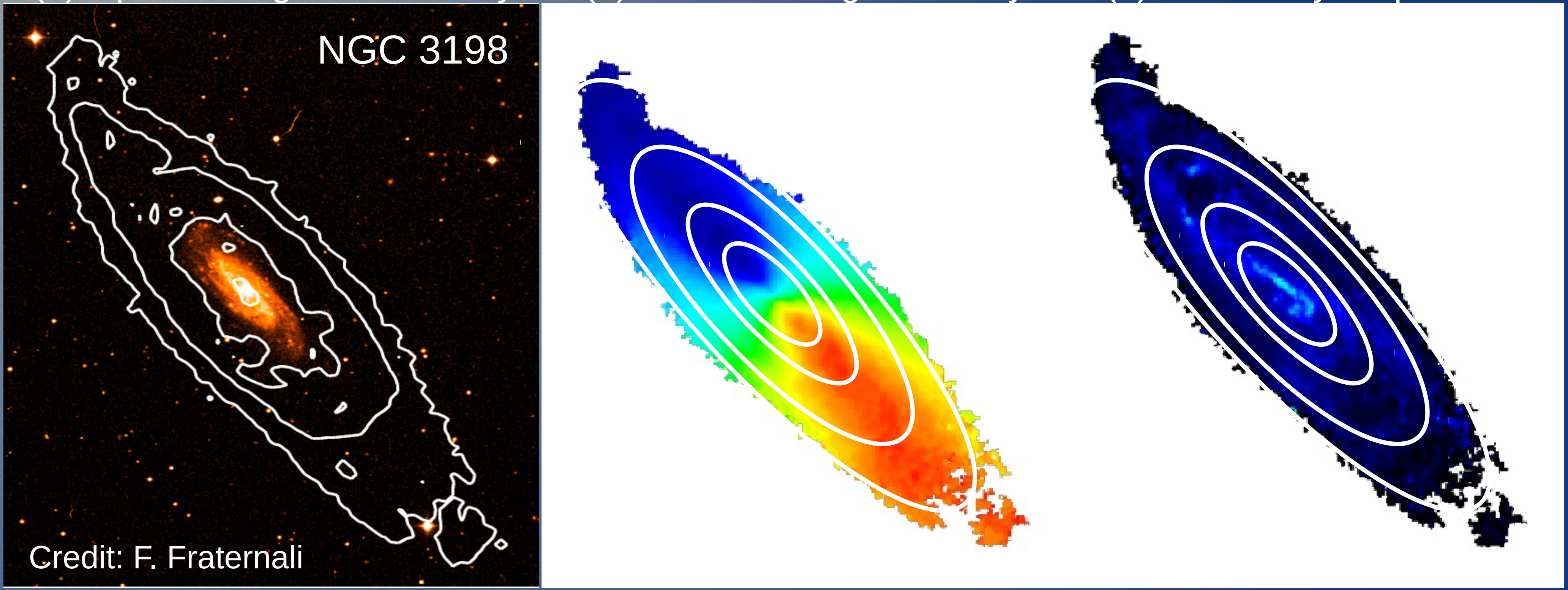
(1) HI is more extended than the stars → trace the kinematics out to large R

(2) HI is in a rotating disk → deviations from circular orbits are small (~10 km/s)

(3) HI velocity dispersion is small (~10 km/s) → pressure support is negligible

Atomic Hydrogen (HI): Radio Data at 21 cm

(1) Optical Image + HI density (2) HI Line-of-Sight Velocity (3) HI Velocity Dispersion



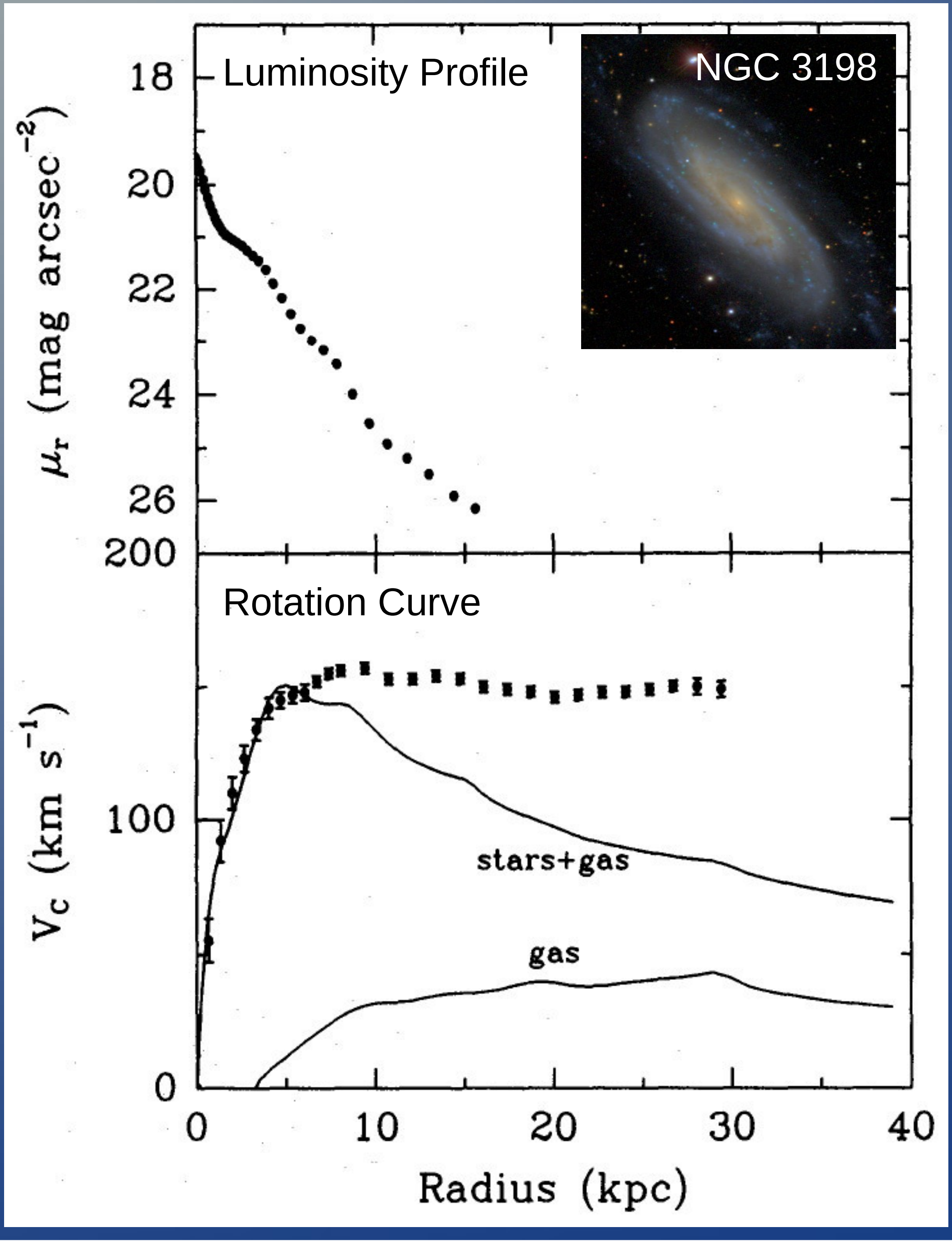
Deprojection from sky plane to galaxy plane:

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

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

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

Mass Models for Late-Type 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

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

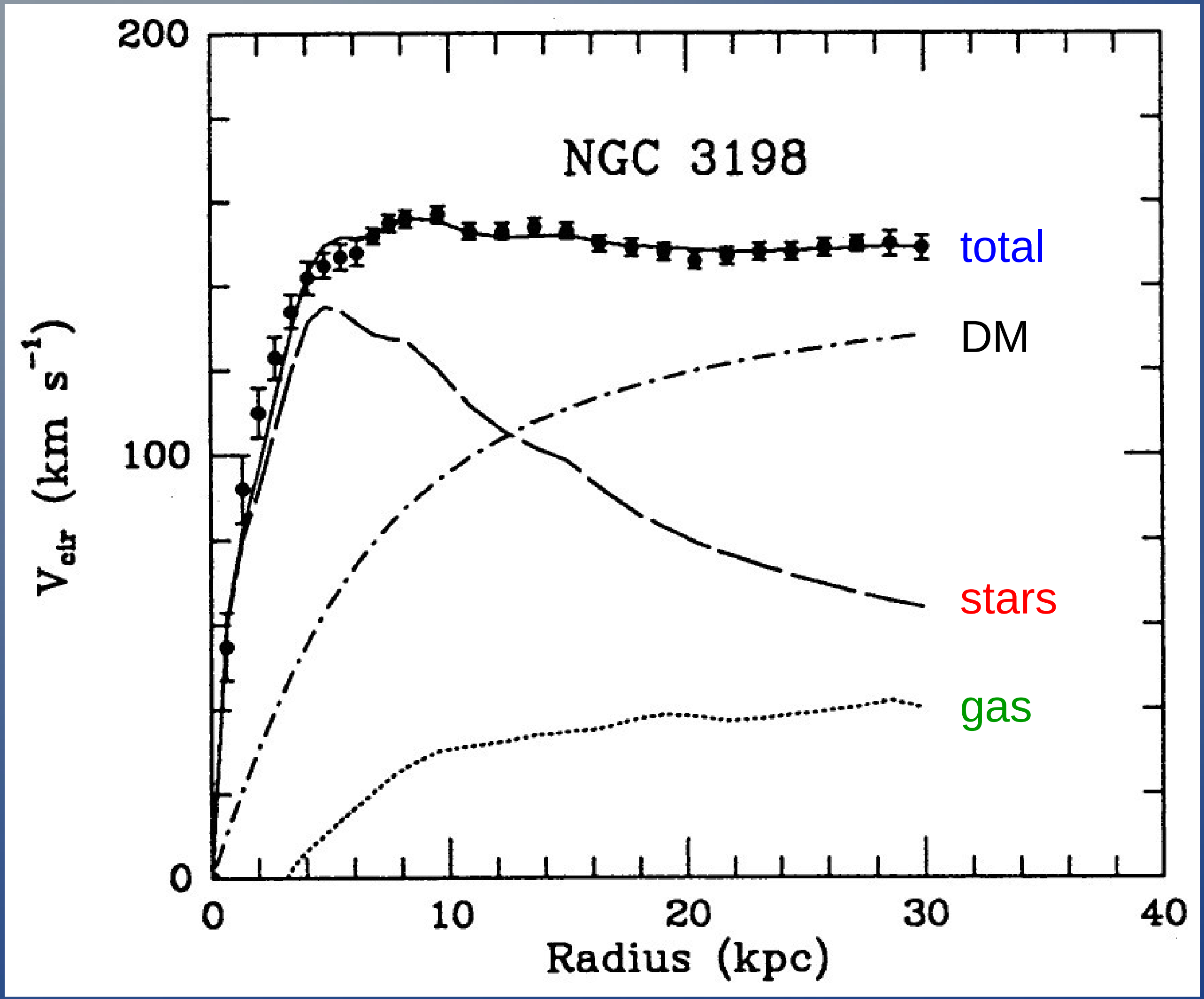
Sum over all baryonic contributions

$$V_b^2(R) = \sum_i V_i^2(R)$$

Casertano 1983; van Albada+1985; Begeman 1987

Mass Models with a Dark Matter Halo

$$V^2_{total} = \Upsilon_* \cdot V^2_{stars} + V^2_{gas} + V^2_{DM}(\rho_0, r_s)$$



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

Mass Model with 3 Free Parameters:

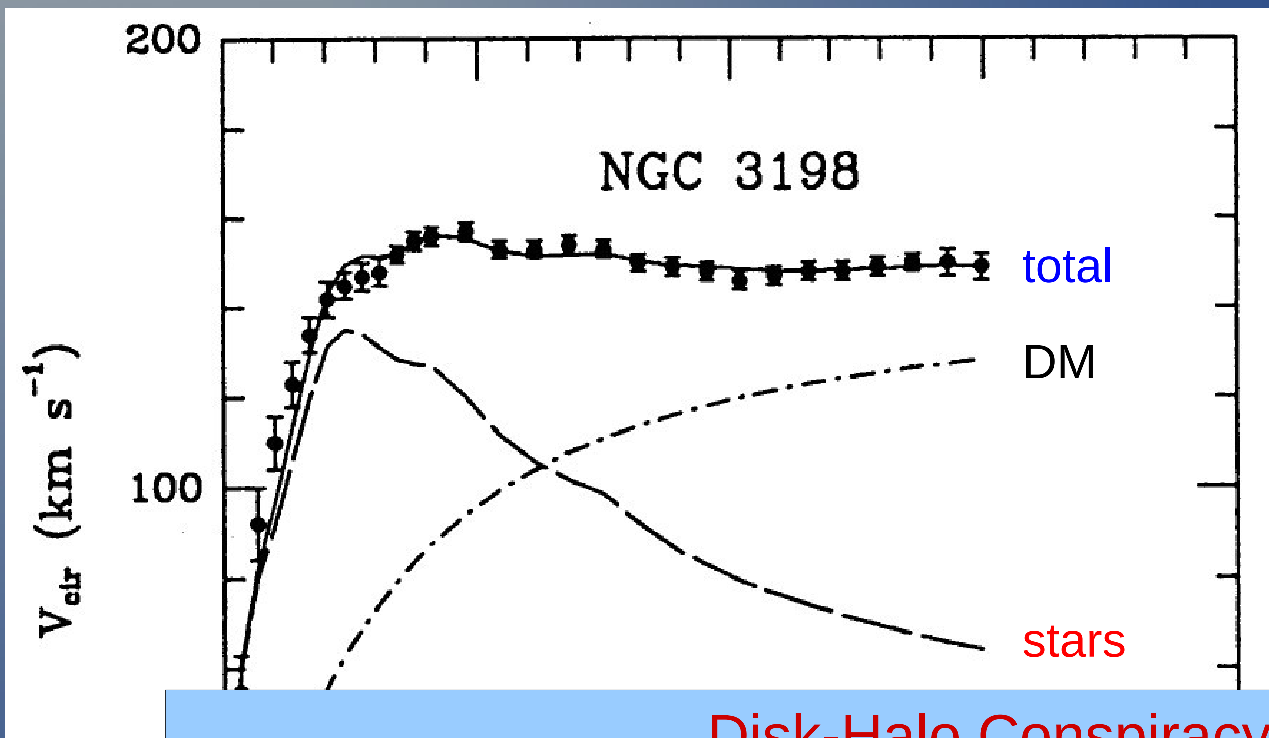
- ρ_0 and r_s for DM halo
- Υ_* = mass-to-light ratio for stars.

Υ_* depends on the stellar populations in the galaxy.

Not needed for the gas: Conversion from 21cm flux to gas mass is known from atomic physics of H + correction for He (BBN)

Mass Models with a Dark Matter Halo

$$V^2_{total} = \Upsilon_* \cdot V^2_{stars} + V^2_{gas} + V^2_{DM}(\rho_0, r_s)$$



Mass Model with 3 Free Parameters:

- ρ_0 and r_s for DM halo
- Υ_* = mass-to-light ratio for stars.

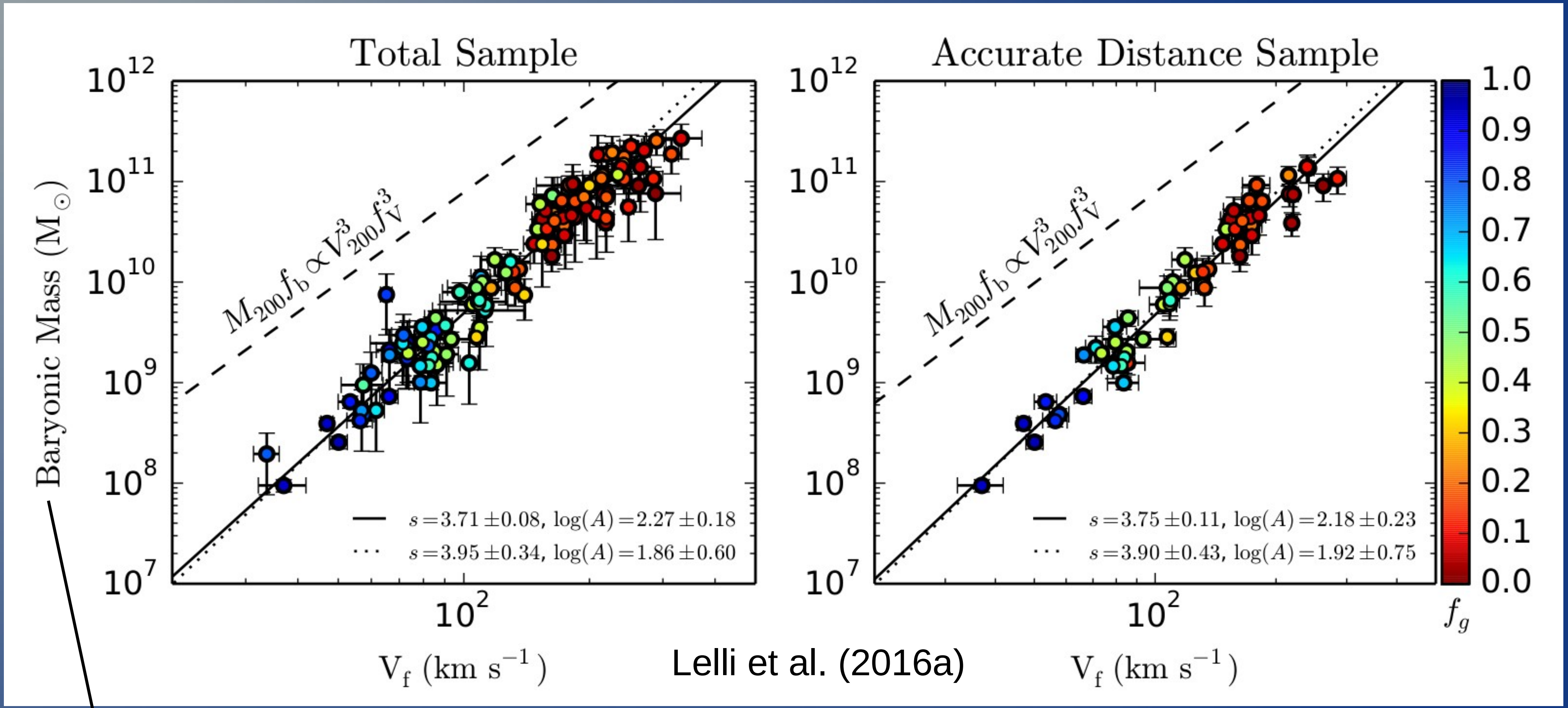
Υ_* depends on the stellar populations in the galaxy.

Disk-Halo Conspiracy:

"Luminous matter and dark matter seem to conspire to produce the flat observed rotation curves in the outer region."

(van Albada & Sancisi 1986)

Baryonic Tully-Fisher Relation (BTFR)

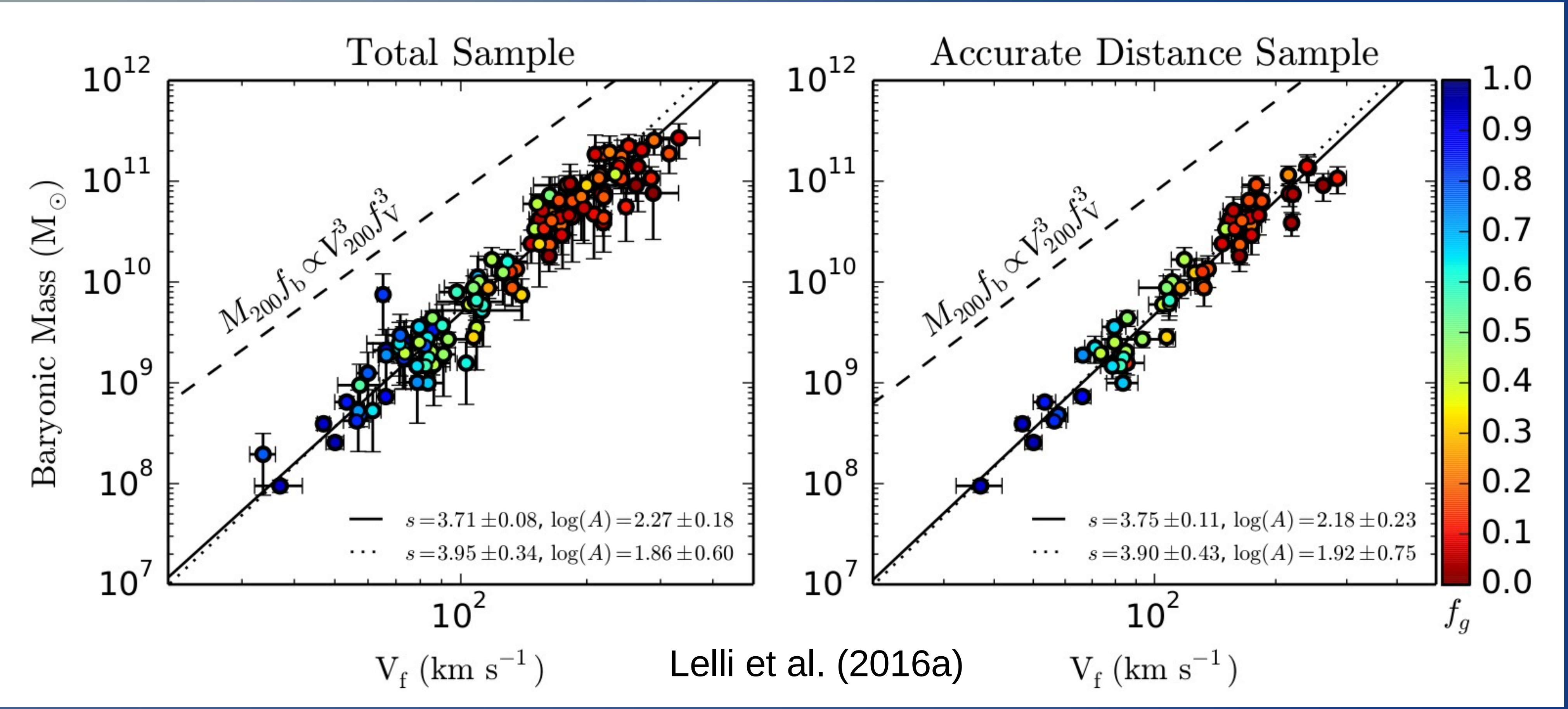


$M_* + M_{gas} \propto D^2$

As the data quality increases, the scatter decreases!

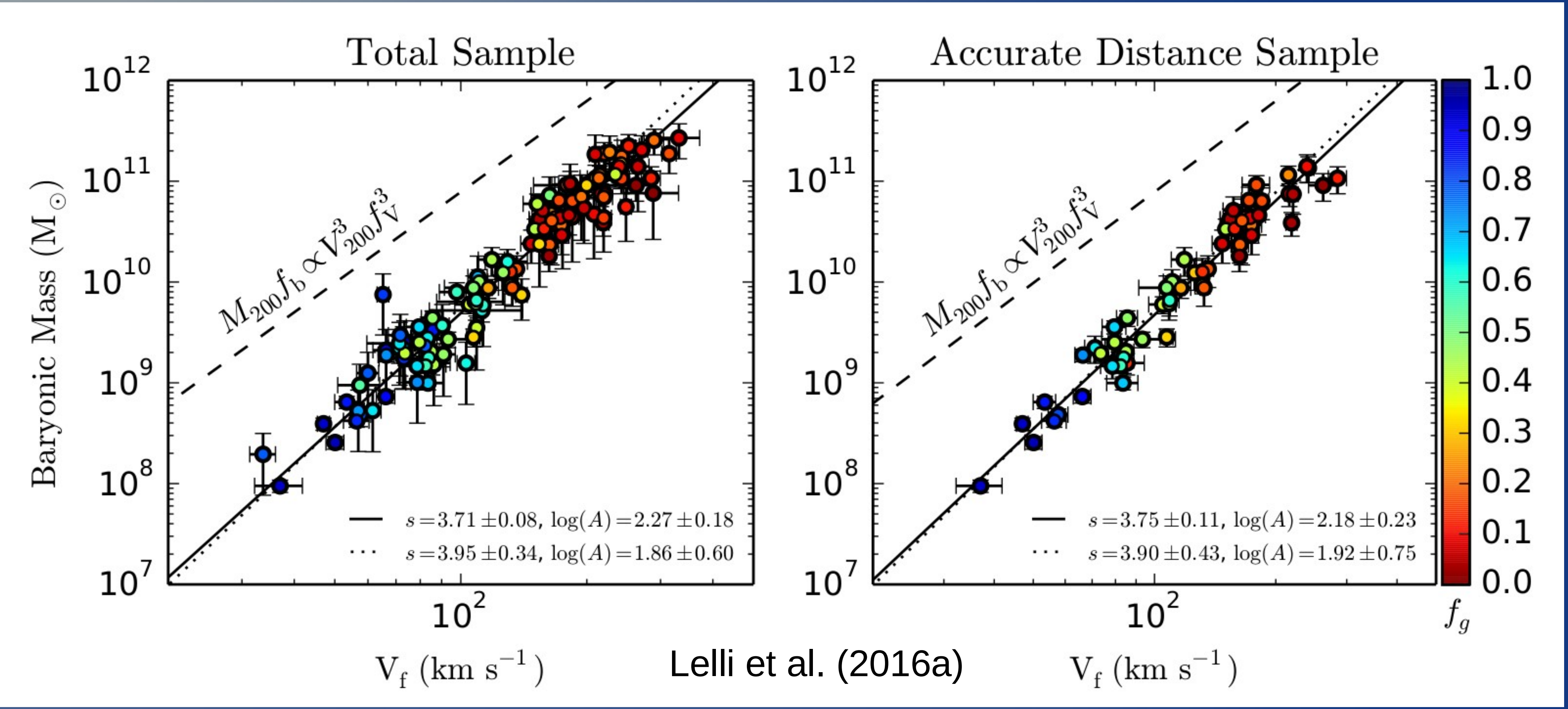
Some BTFR studies: Freeman 1999; Walker 1999; McGaugh+2000, 2005, 2012; Verhejen 2001; Bell & de Jong 2001; Geha+2006; Noordermeer & Verheihen+2007; Begum+2008; Avila-Reese+2008; Stark+2009; Trachternach+2010; Gurovich+2010; Catinella+2012; Zaritsky+2014; Papastergis+2016

Baryonic Tully-Fisher Relation (BTFR)



In ΛCDM: $M_{200} = (10GH_0)^{-1} V_{200}^3$

Baryonic Tully-Fisher Relation (BTFR)

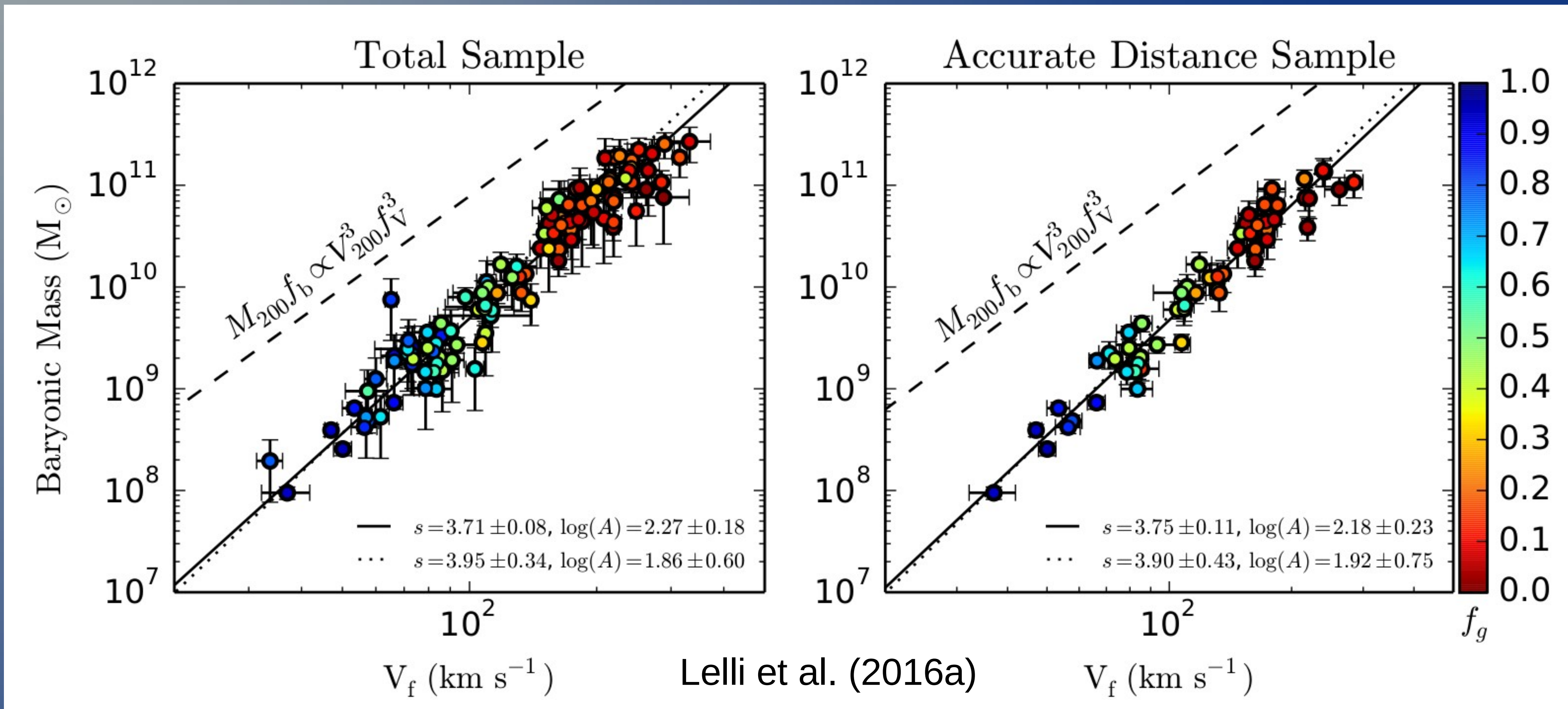


Lelli et al. (2016a)

In ΛCDM: $M_{200} = (10GH_0)^{-1} V_{200}^3$

$f_b = M_b/M_{200}$ $f_V = V_f/V_{200}$ $\rightarrow$ $M_b = (10GH_0)^{-1} (f_b/f_V^3) V_f^3$

Baryonic Tully-Fisher Relation (BTFR)



Lelli et al. (2016a)

In ΛCDM: $M_{200} = (10GH_0)^{-1} V_{200}^3$

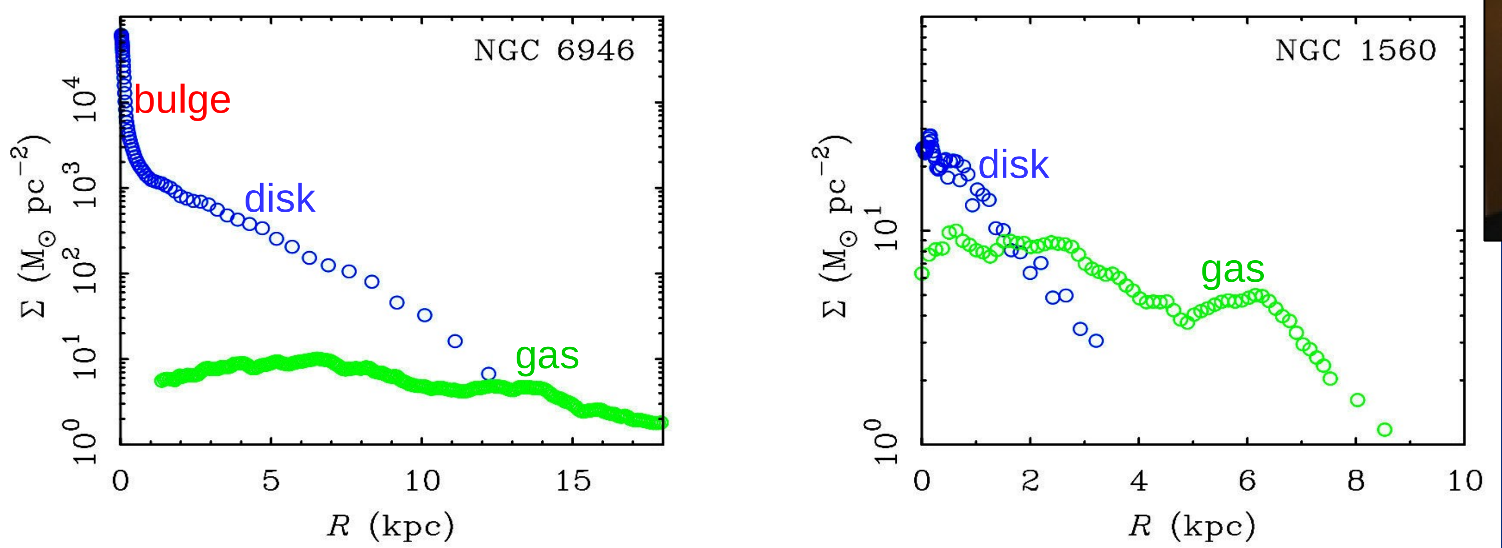
$f_b = M_b/M_{200}$ $f_V = V_f/V_{200}$ → $M_b = (10GH_0)^{-1} (f_b/f_V^3) V_f^3$

Assuming $f_V = 1$ and $f_b = f_{CMB}$ → normalization and slope wrong!

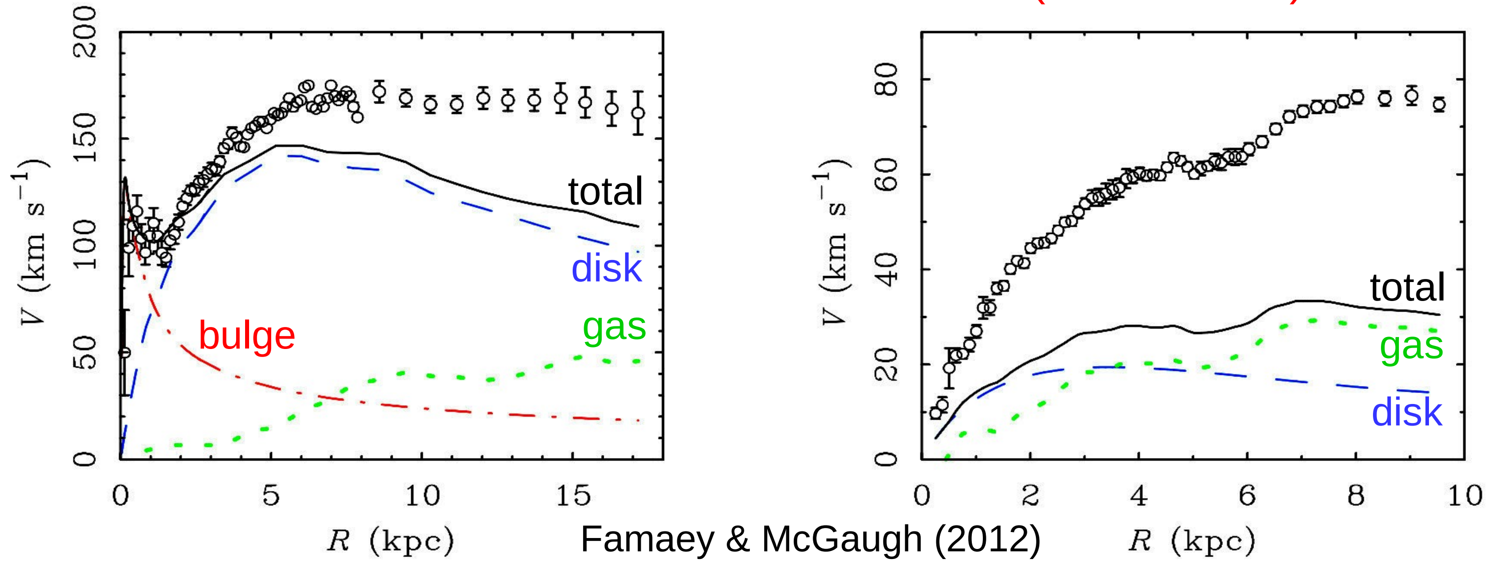
BTFR is only the tip of the Iceberg!

There is much more information in the shape of the rotation curve!

Renzo's Rule



"For any feature in the luminosity profile of a galaxy there is a corresponding feature in the rotation curve and vice versa" (Sancisi 2004)



Famaey & McGaugh (2012)

Confirmed over the years: Kent 1987; Corradi & Capaccioli 1991; Casertano & van Gorkom 1991; Broeils 1992; McGaugh & de Blok 1998; McGaugh 2004, 2005; Noordermeer+2007; Swaters+2009, 2012; Lelli+2010, 2012a,b

Can we quantify this Baryon-Dark Matter coupling with some empirical scaling law?

SPARC

Spitzer Photometry & Accurate Rotation Curves

Database for 175 LTGs (spirals and irregulars):

www.astroweb.cwru.edu/SPARC

Lelli, McGaugh, Schombert 2016b, AJ, 152, 157

SPARC

Spitzer Photometry & Accurate Rotation Curves

- HI Rotation Curves for 175 galaxies

  - 30 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

  - Hybrid Hα/HI rotation curves for ~30% sample

SPARC

Spitzer Photometry & Accurate Rotation Curves

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  - PhD theses from the University of Groningen

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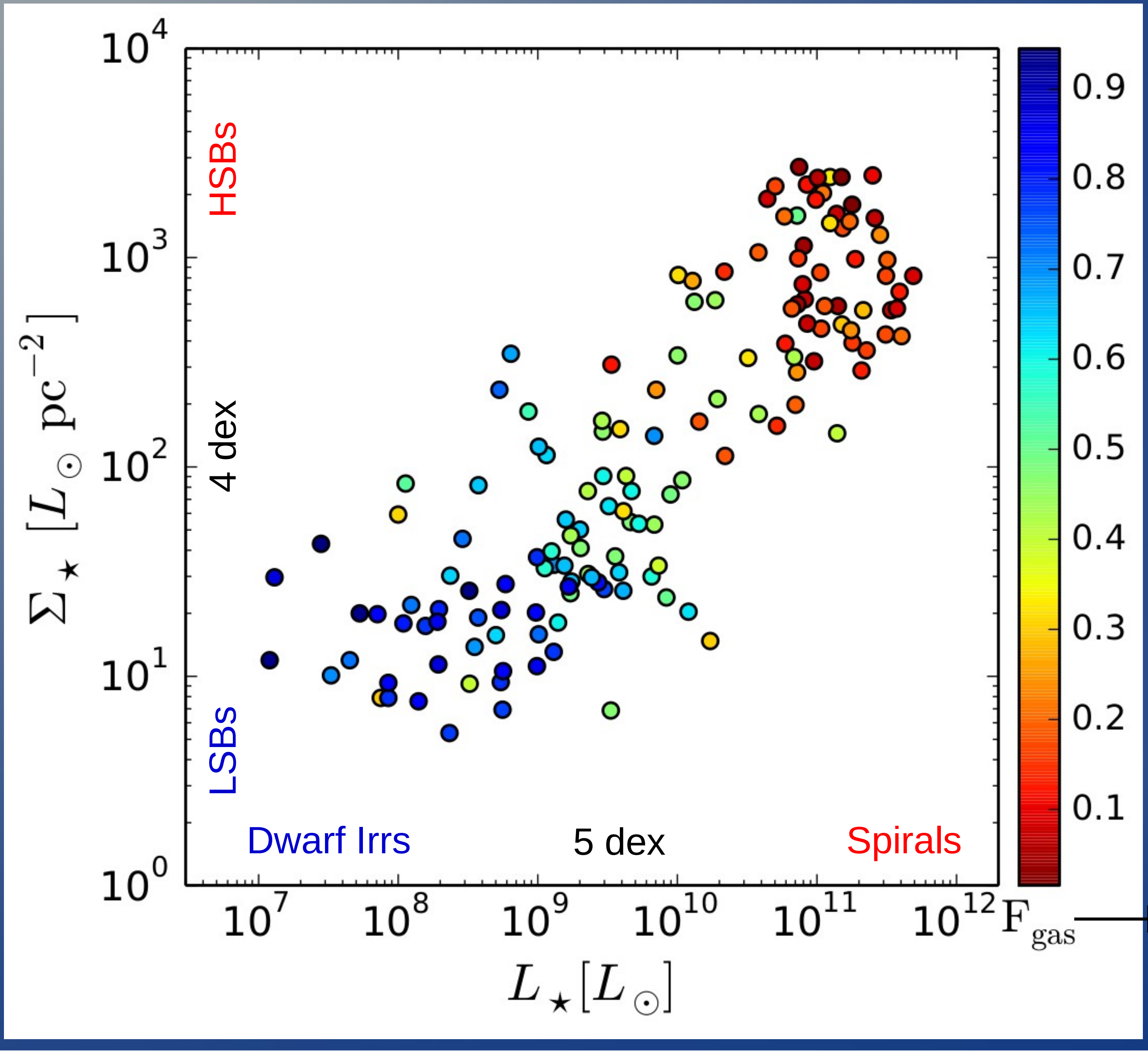
  - Hybrid Hα/HI rotation curves for ~30% sample

- **Homogeneous Photometry at 3.6 μm**
  - Optimal tracer of the stellar mass: $M_* = \Upsilon_* L$
  - Υ_* is roughly constant in the NIR (~0.1 dex)

    Bell & de Jong 2001; Bell+2003; Portinari+2004; Meidt+2014; Schombert & McGaugh 2014; McGaugh & Schombert 2014

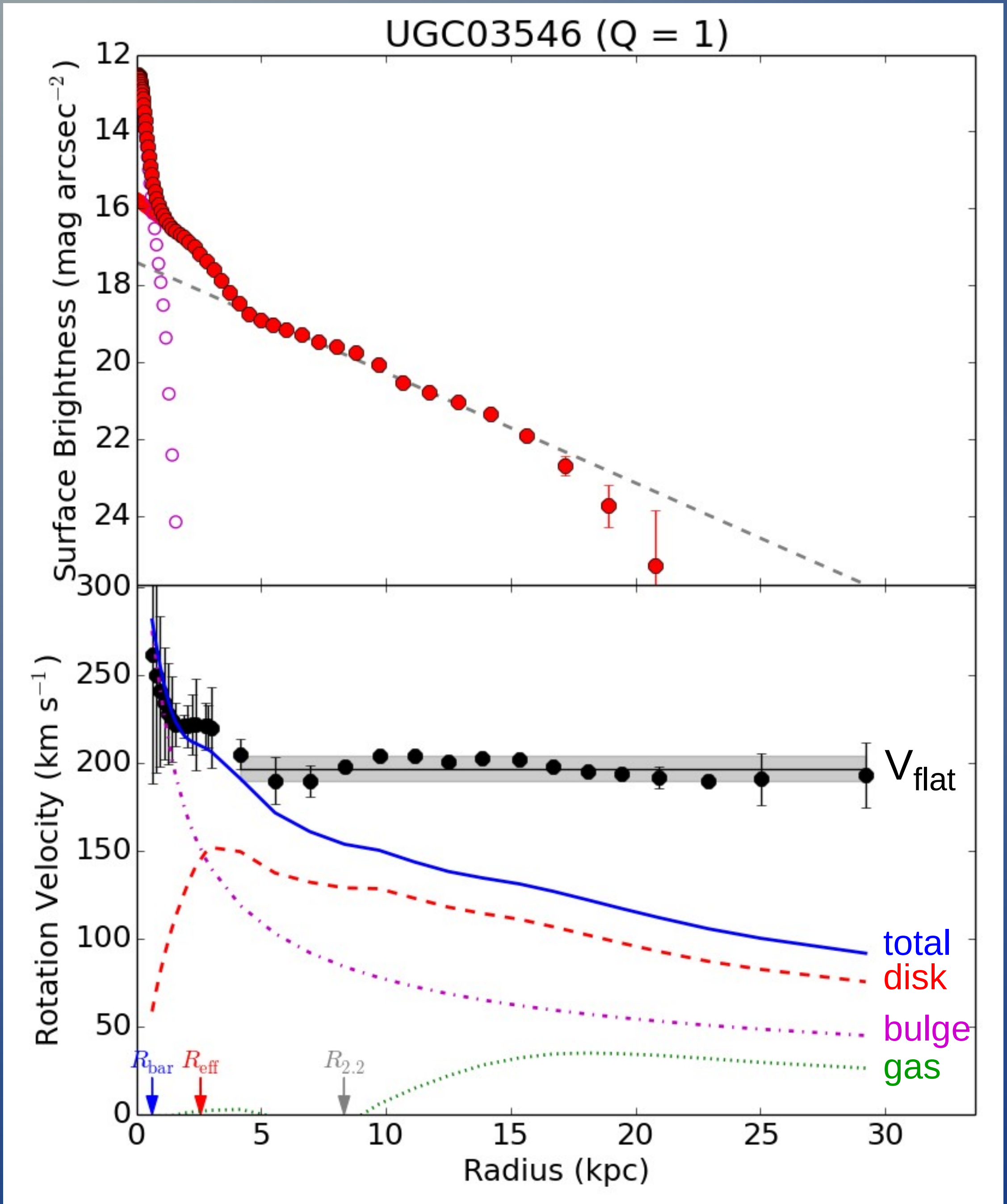
Widest possible range of disk properties

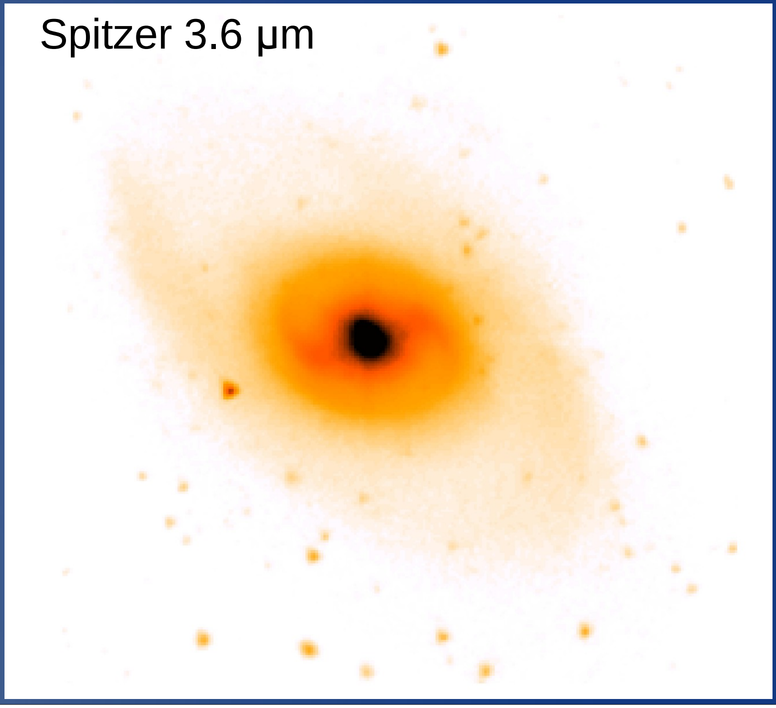


M_{gas}/M_{bar}

Basically any known galaxy type with a rotating HI disk.

Example: High-Mass HSB Spiral

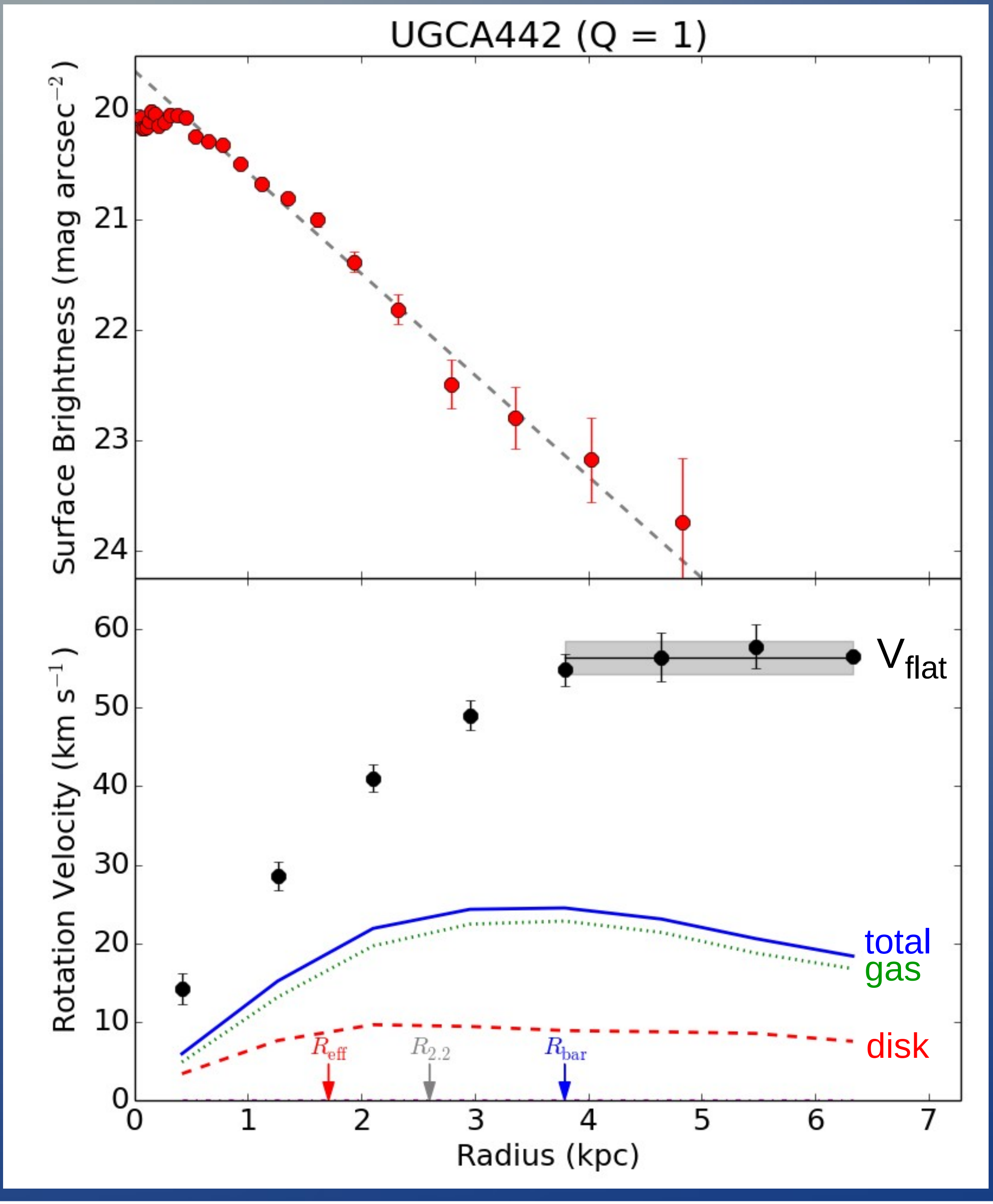


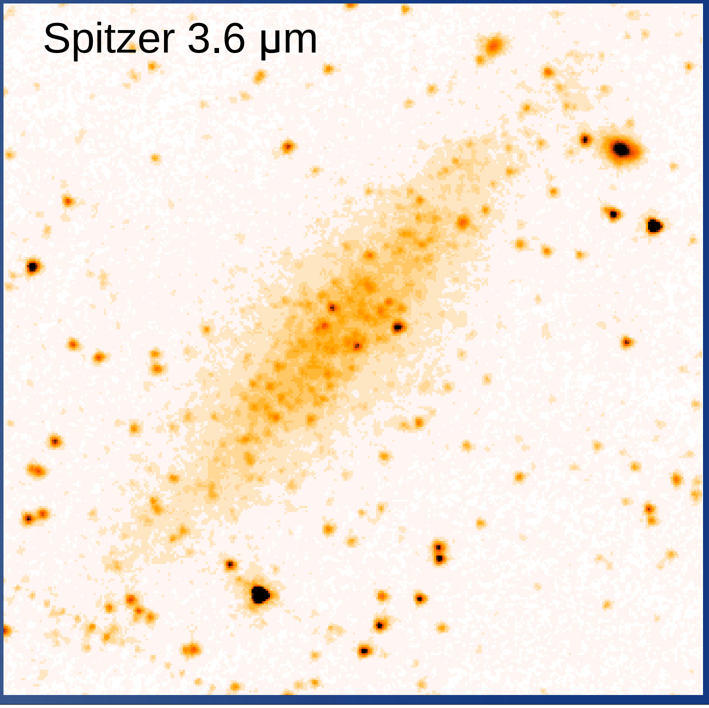


$$\nabla^2 \Phi_{bar}(R,z) = 4\pi G\, \rho_{bar}(R,z)$$

- 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 LSB Dwarf





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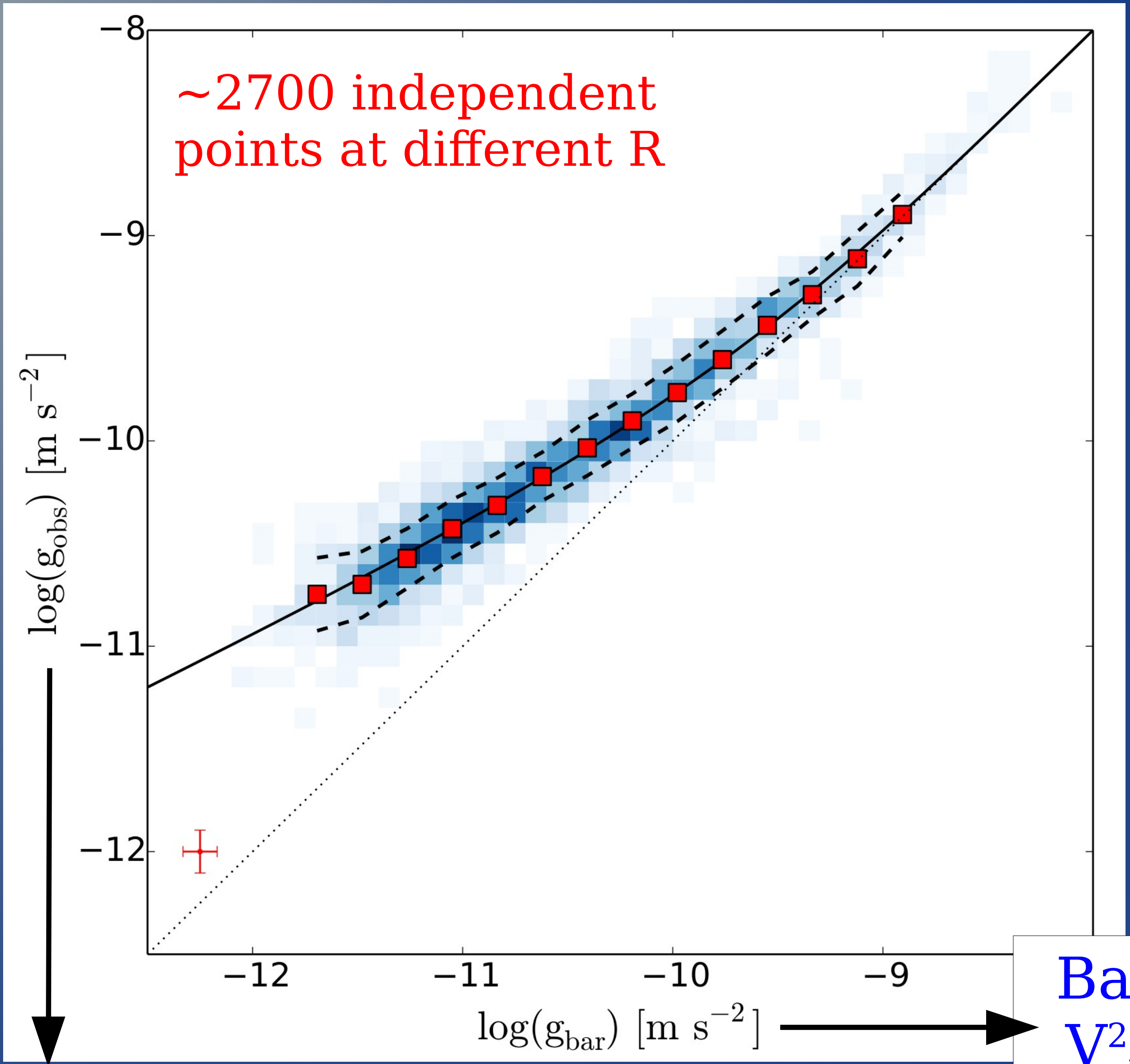
III. Radial Acceleration Relation

McGaugh, Lelli, Schombert 2016, PRL, 117, 201101

Lelli, McGaugh, Schombert, Pawlowski 2016d, submitted to ApJ

<u>Local</u> link between baryons and DM



For all galaxies:

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

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

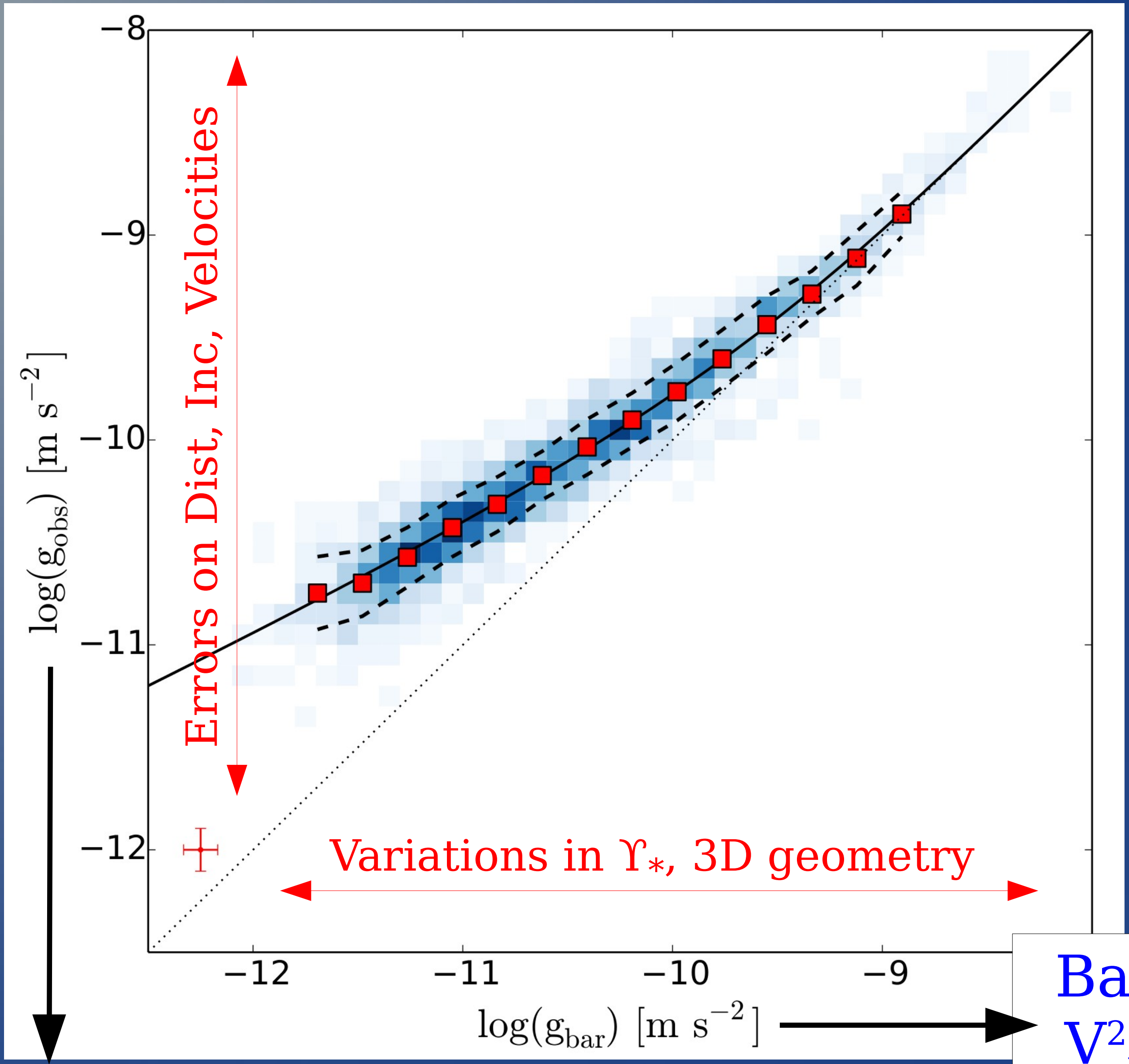
Baryonic Force:

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

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

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

Local link between baryons and DM



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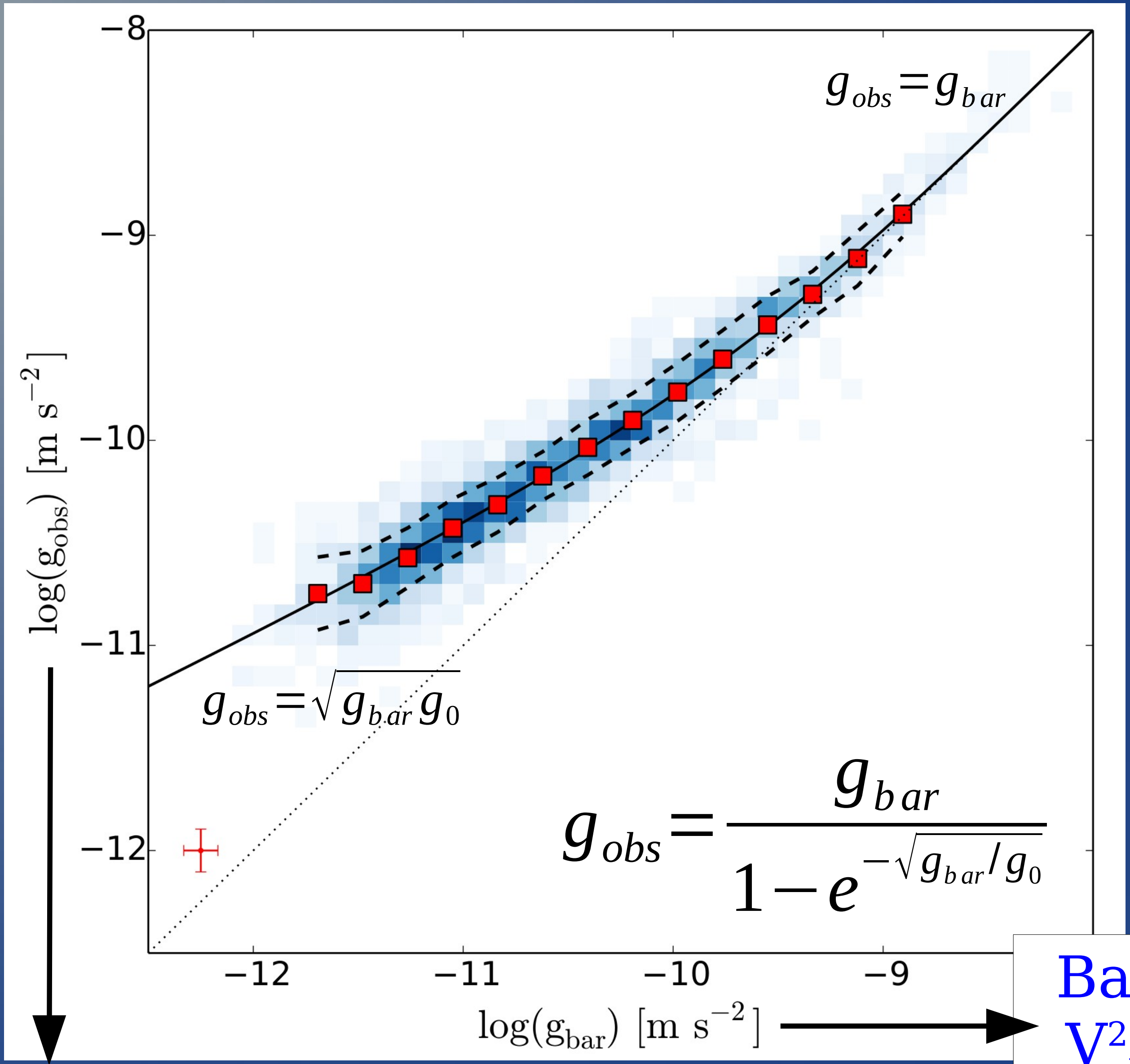
Local link between baryons and DM



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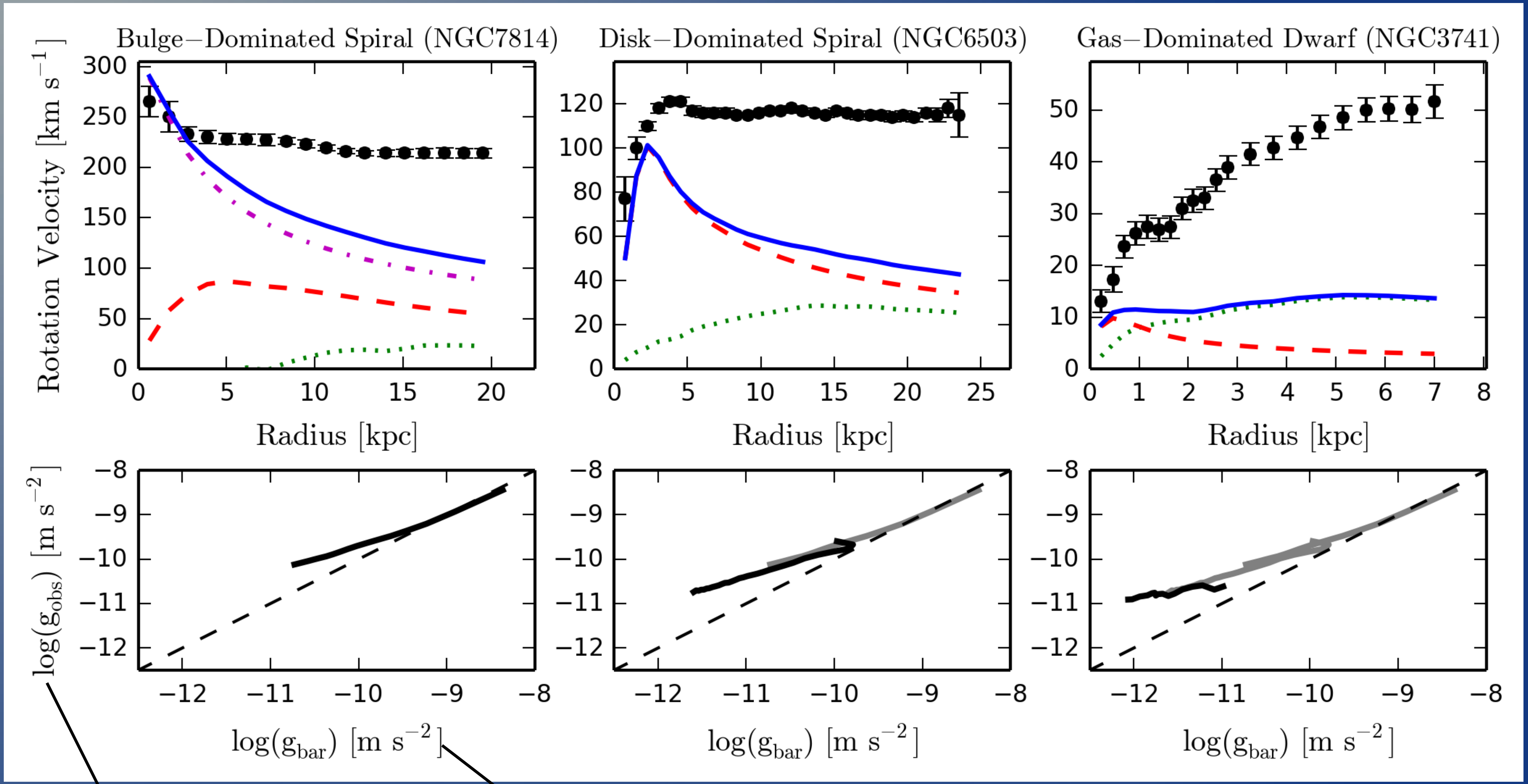
Total Acceleration: $V^2_{obs}/R = -\nabla\Phi_{tot}$

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

Very different galaxies but ONE relation



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

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

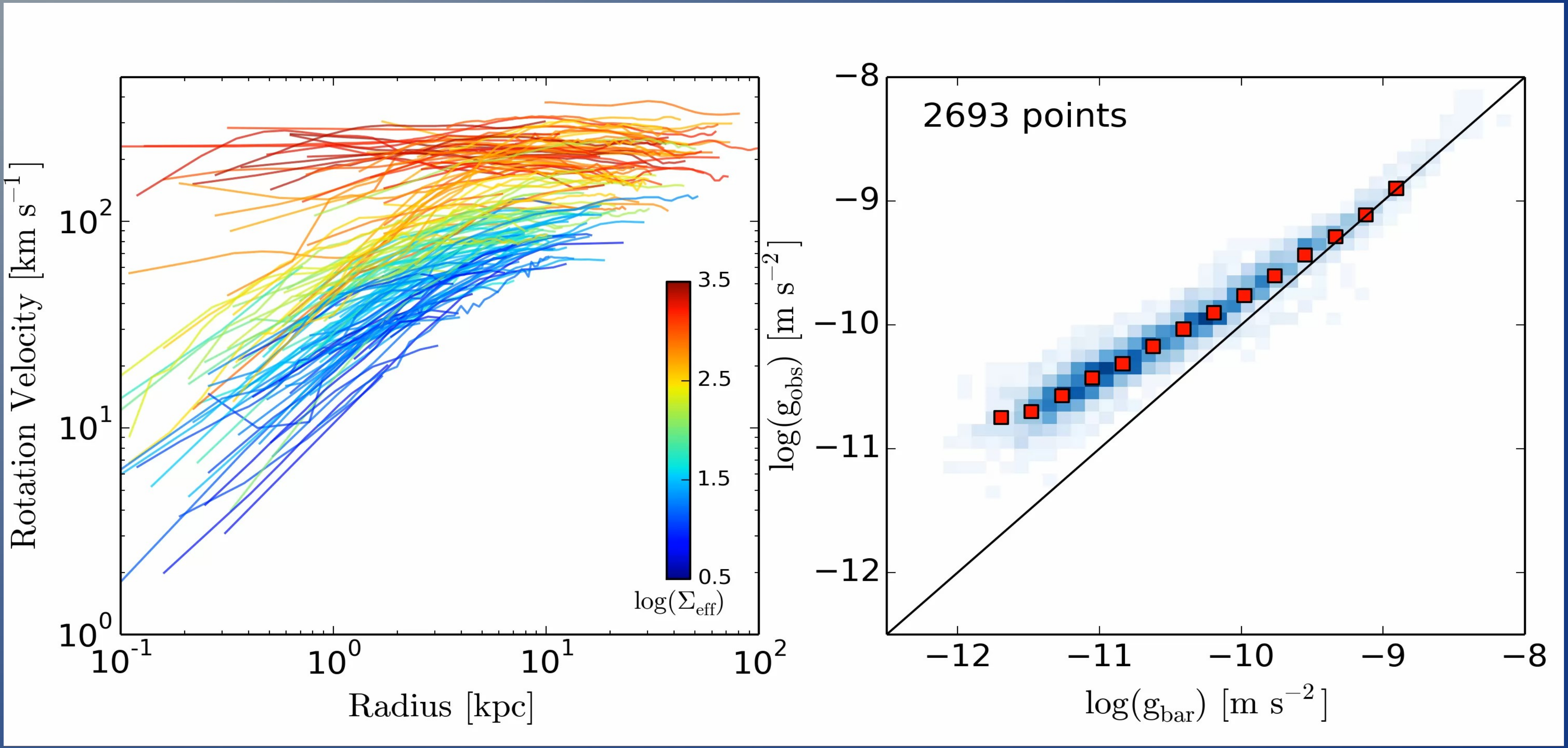
$\nabla^2\Phi_{bar} = 4\pi G\, \rho_{bar}$

McGaugh, Lelli, Schombert (2016)

Building up the Radial Acceleration Relation

Large Diversity in Rotation Curves

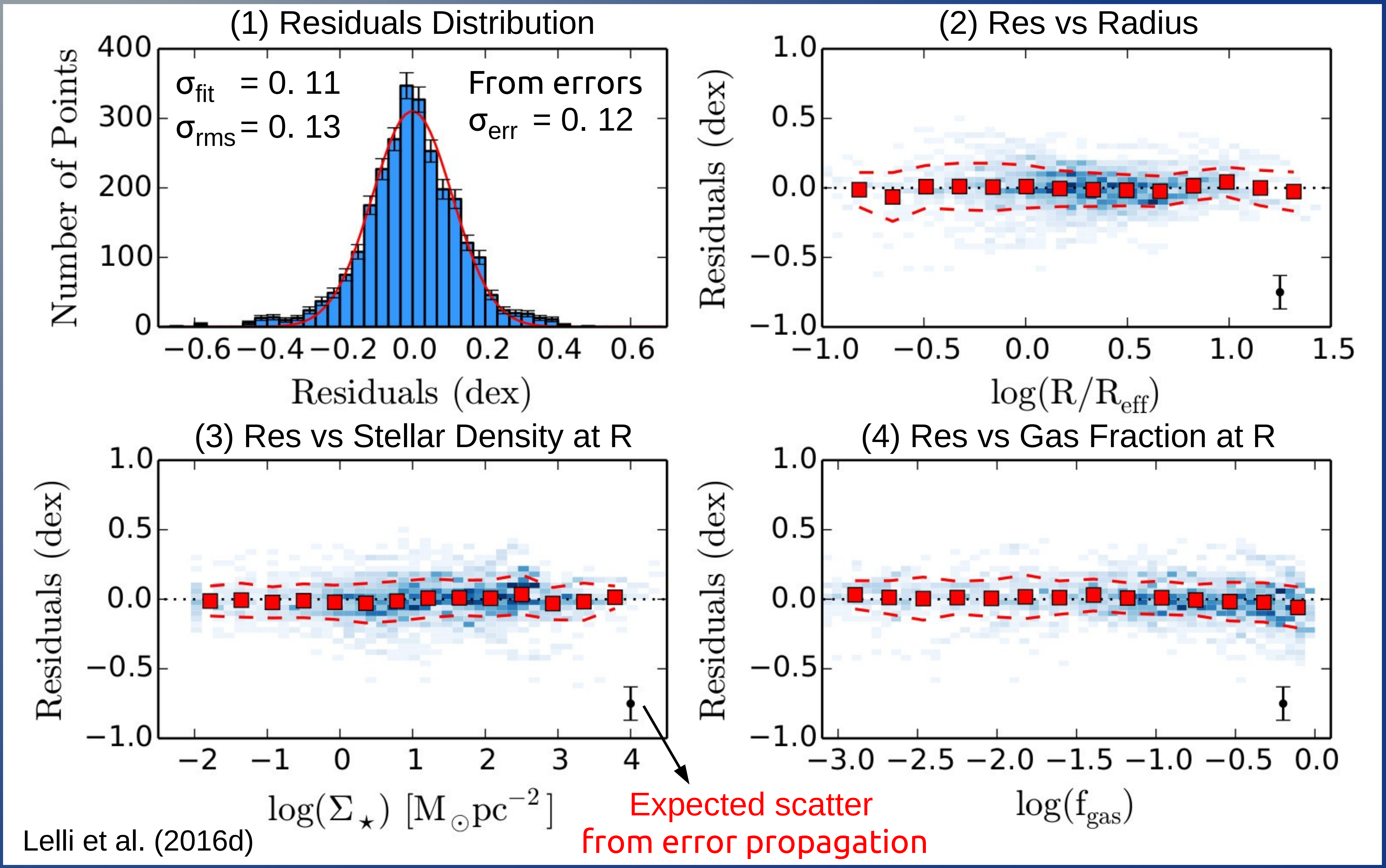
Regularity in Acceleration Plane



Lelli et al. 2016d, submitted to AJ

Video available at astroweb.cwru.edu/SPARC/

Scatter and Residuals around the RAR

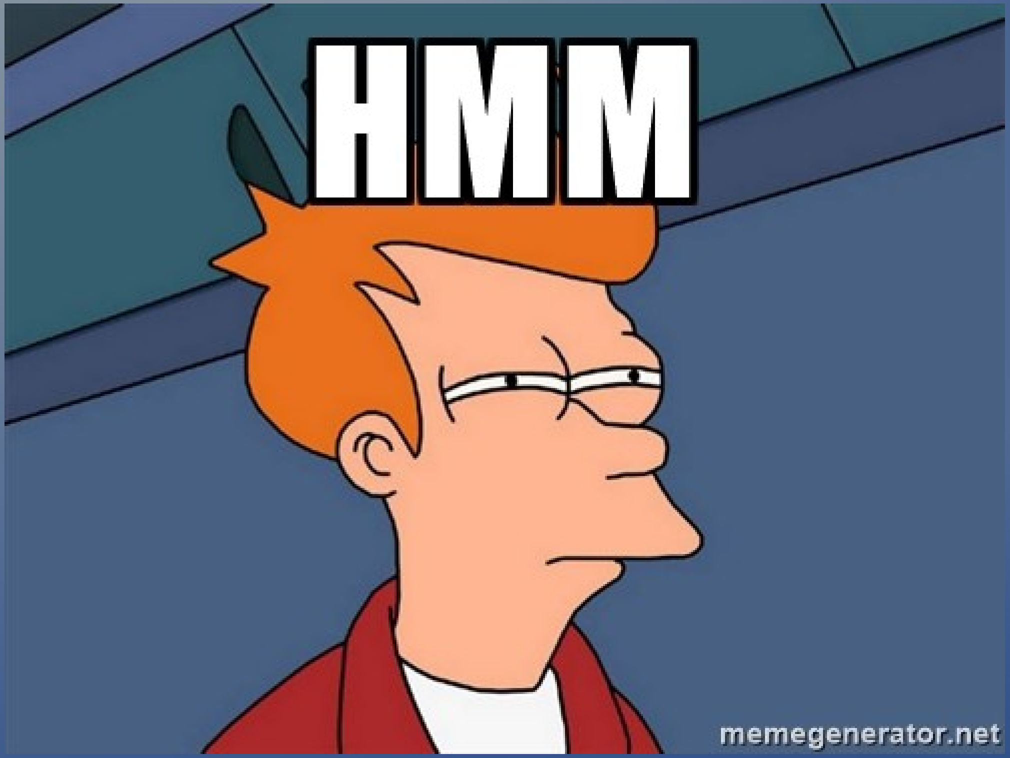


We can infer the DM distribution from g_{bar}!

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

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

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

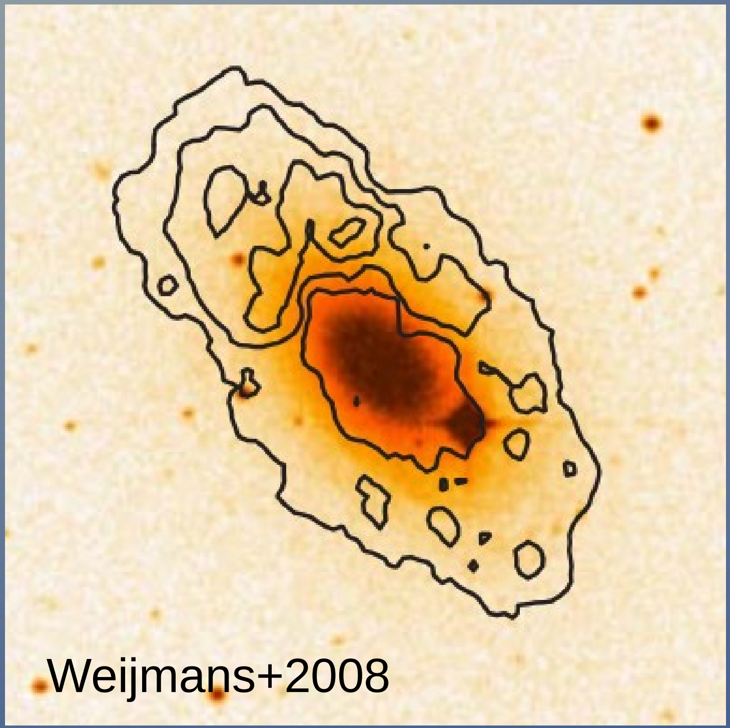


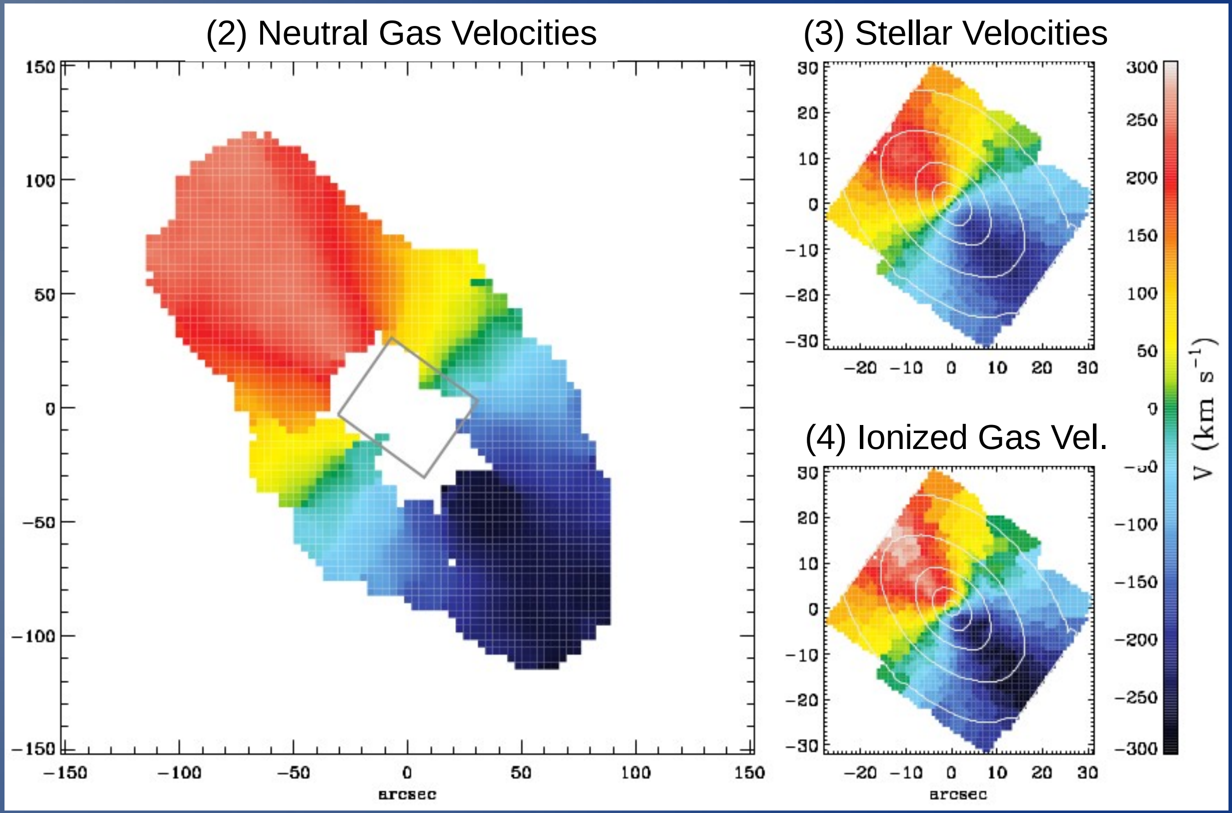
OK. This works for LTGs, but...

what about ETGs?

Early-Type Galaxies with outer HI rings/disks

(1) Stars + Neutral Gas Map





Key results from Atlas^{3D} Survey (Cappellari+2010; Serra+2011)

- 85% of ETGs have rotating stellar components (but $V_*/\sigma_* < 1$)

- 20% of ETGs have rotating, low-density HI disks or rings

Our Sample: 16 ETGs with <u>both</u> stellar rotation and outer HI disks

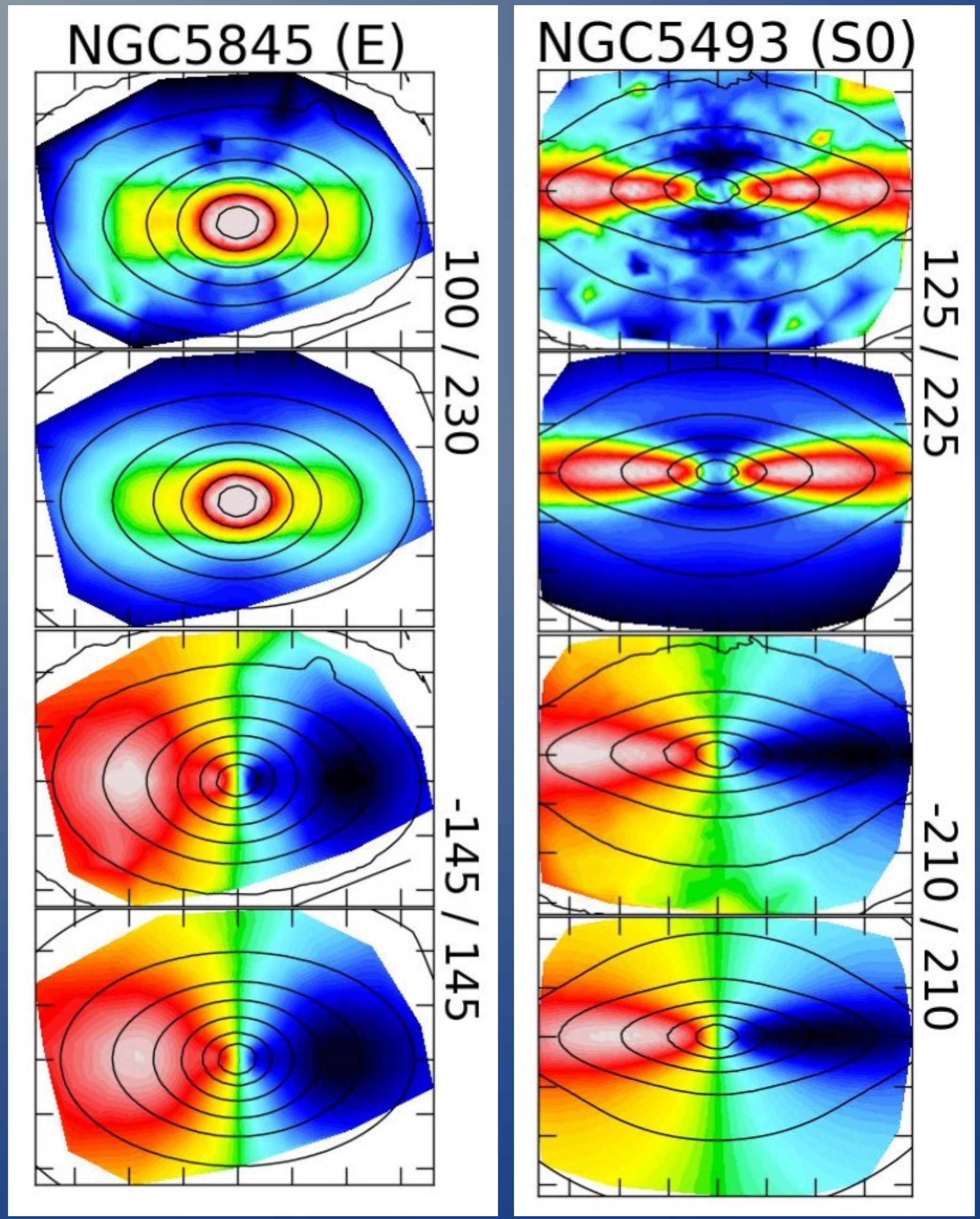
Jeans Axisymmetric Models (JAM)

Observed $\sqrt{(V^2 + \sigma^2)}$

Model $\sqrt{(V^2 + \sigma^2)}$

Observed Velocities

Model Velocities



Assumptions:

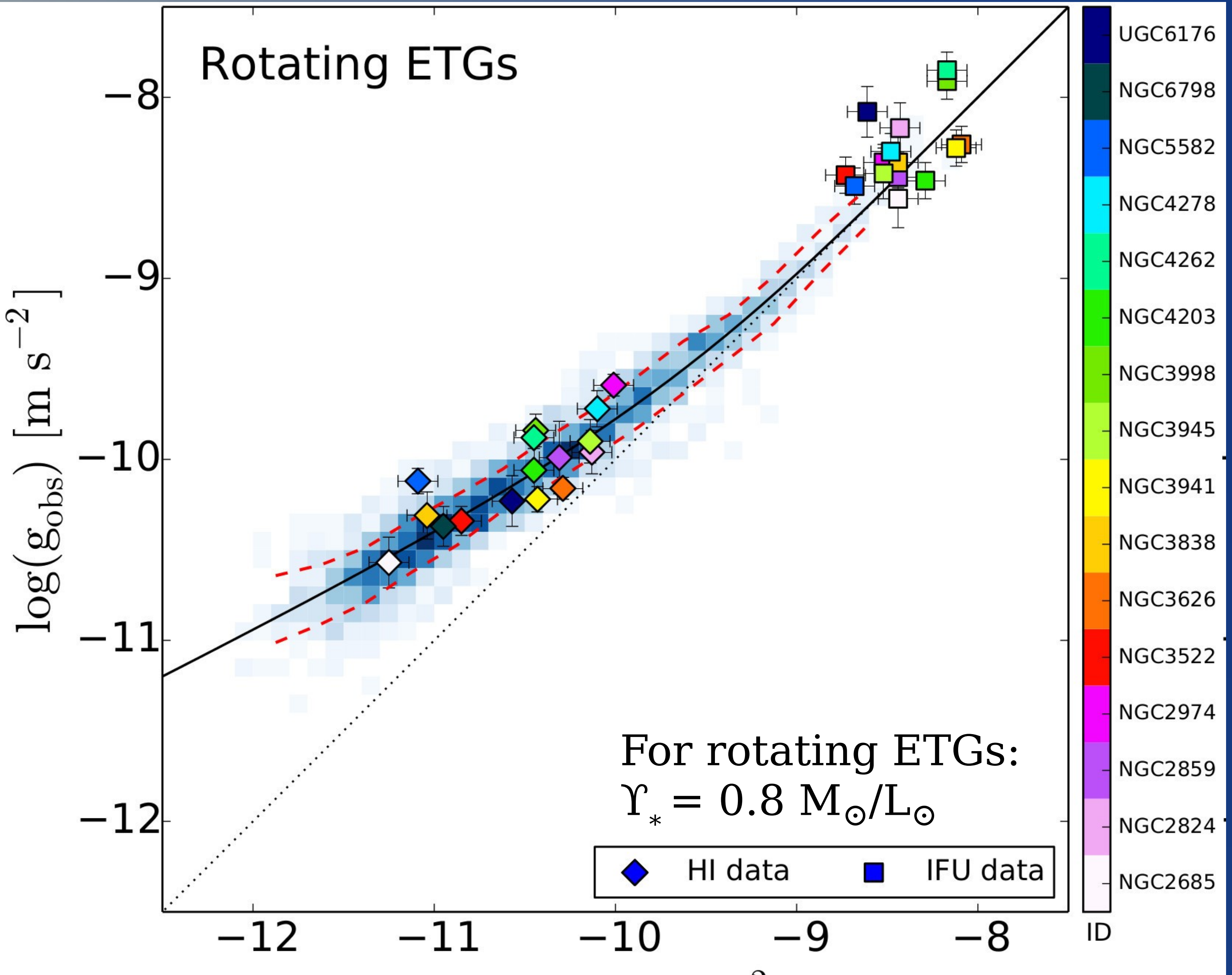
- Axial Symmetry
- $\sigma_\theta = \sigma_R > \sigma_z$
- Mass follows light
- M/L constant with R

V_{max} = max circular V

$g_{obs} = V_{max}^2 / R_{max}$

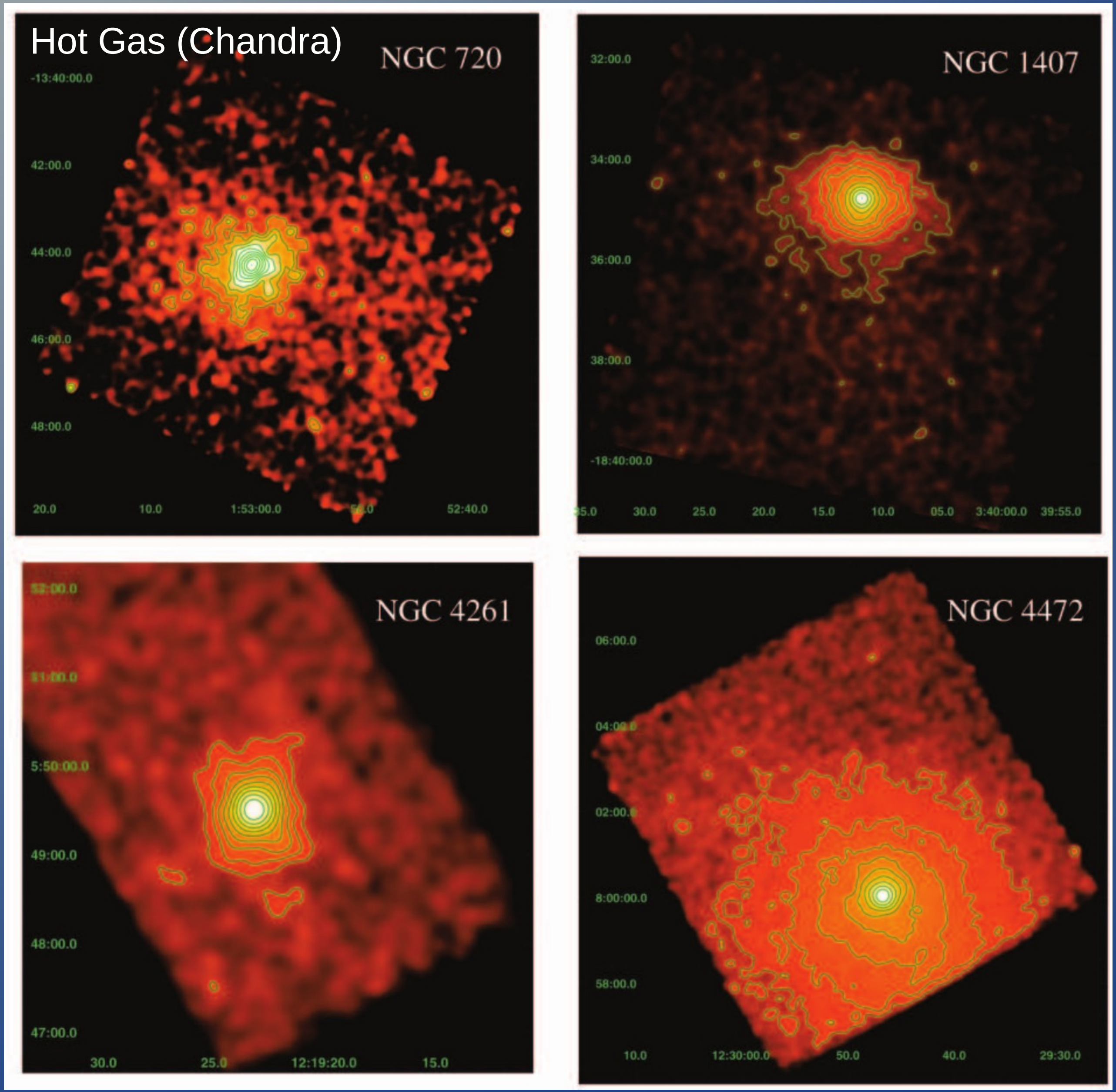
Cappellari+(2013, 2016)

Rotating ETGs follow the same RAR as LTGs



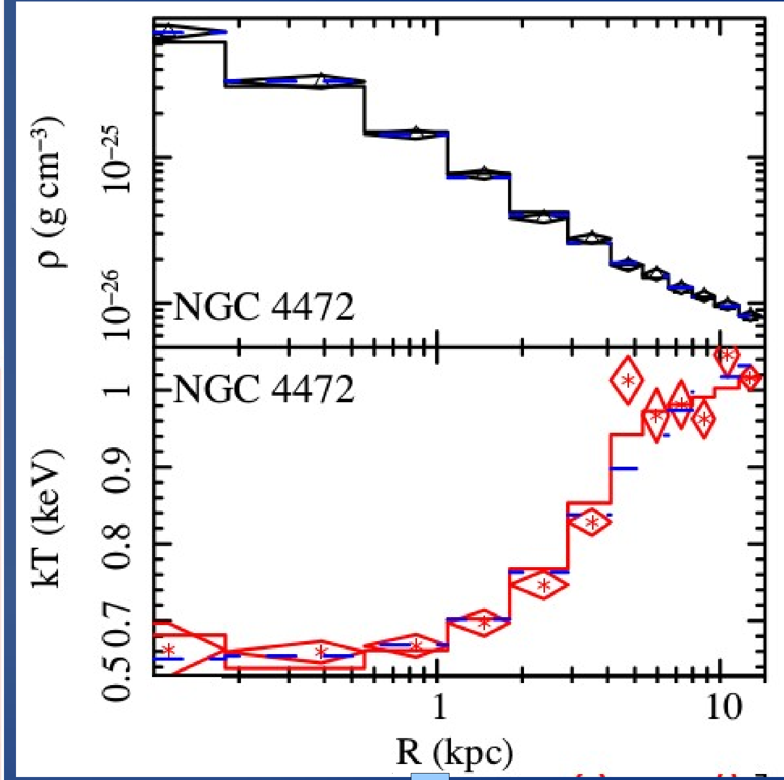
Lelli et al. (2016d)

Non-rotating Massive Ellipticals: X-ray haloes



Hydrostatic equilibrium:

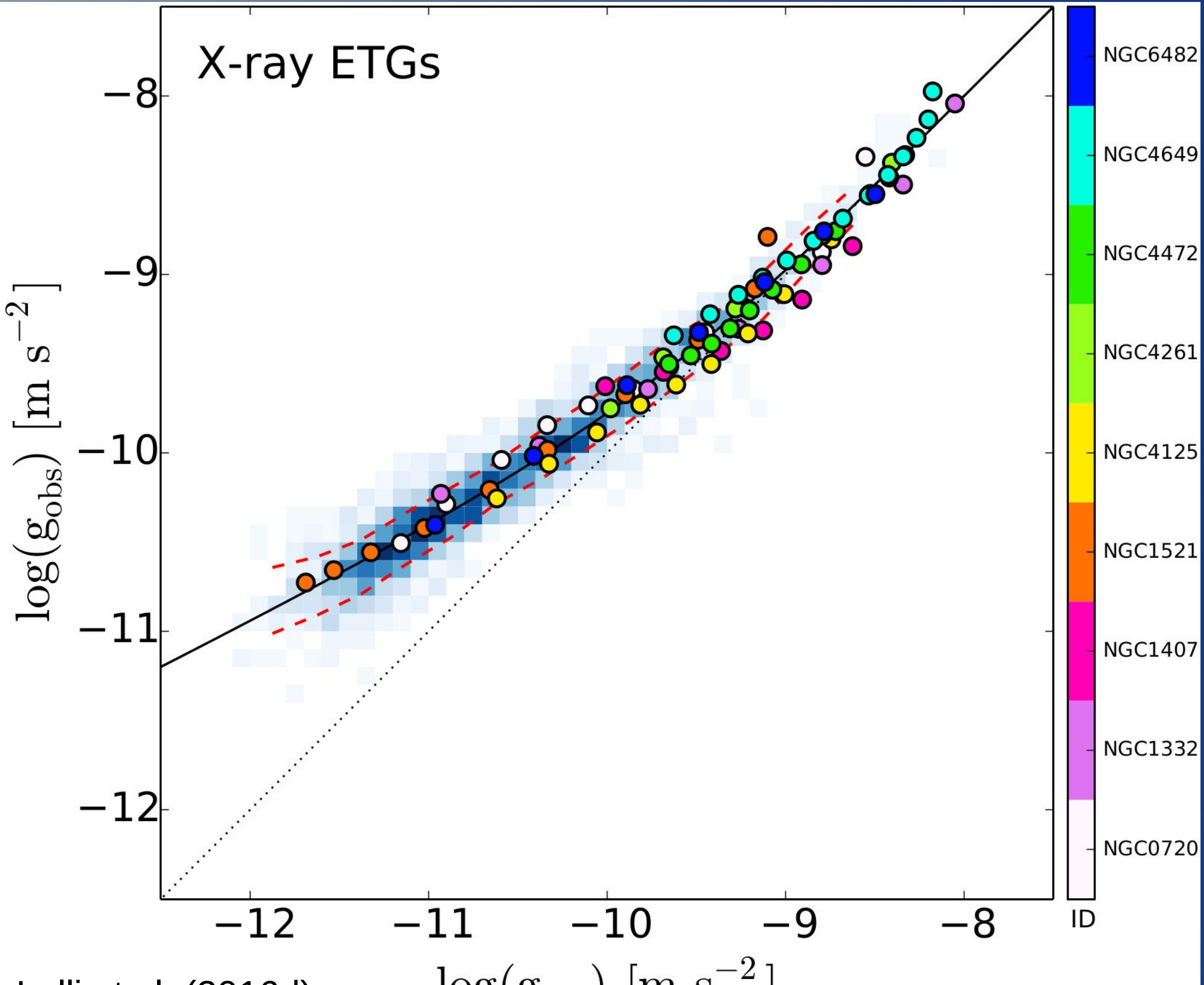
$$M(<r) = -\left[\frac{r k_B T}{\mu m_a G}\right]\left[\frac{d\ln\rho_{\rm gas}}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$



$$g_{\rm obs}(r) = -\nabla\Phi_{\rm tot}(r) = \frac{G M_{\rm tot}(<r)}{r^2}$$

Our sample: 9 X-ray ETGs from Humphrey+(2006, 2009, 2011, 2012)

X-ray ETGs follow the same RAR as LTGs

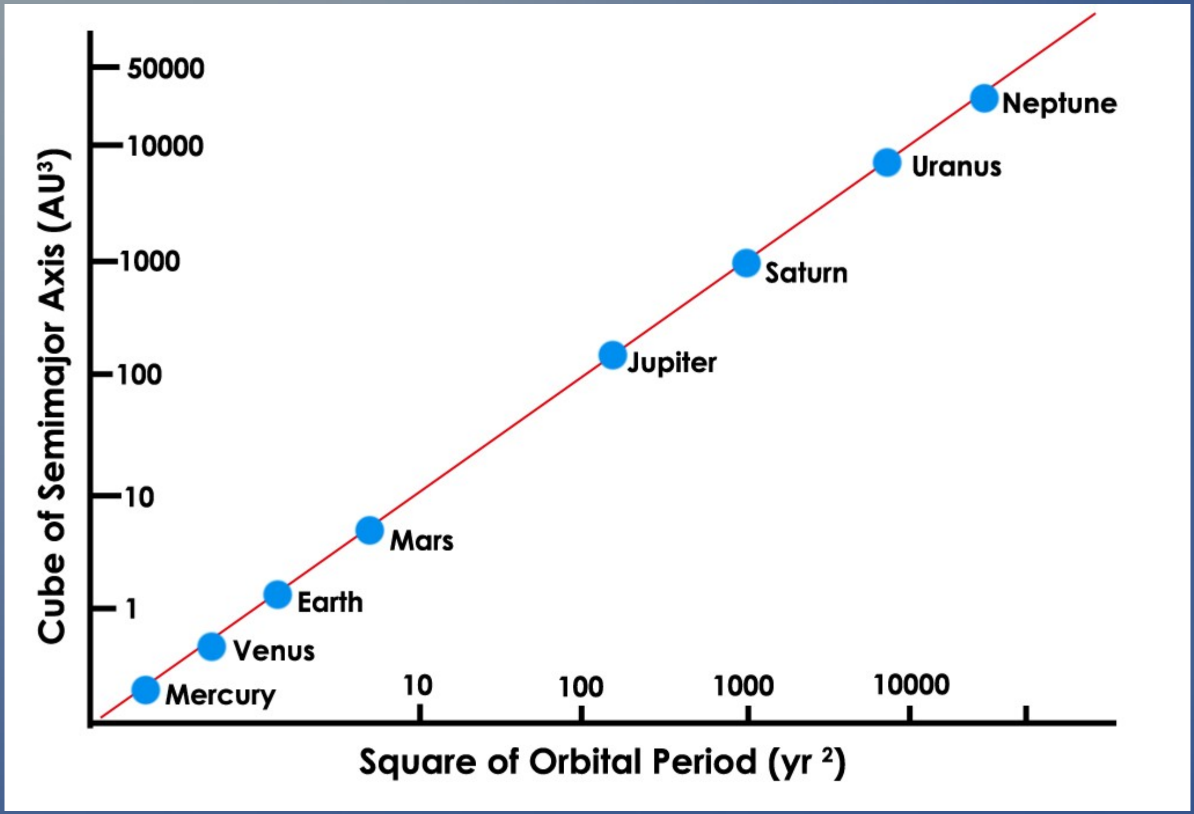


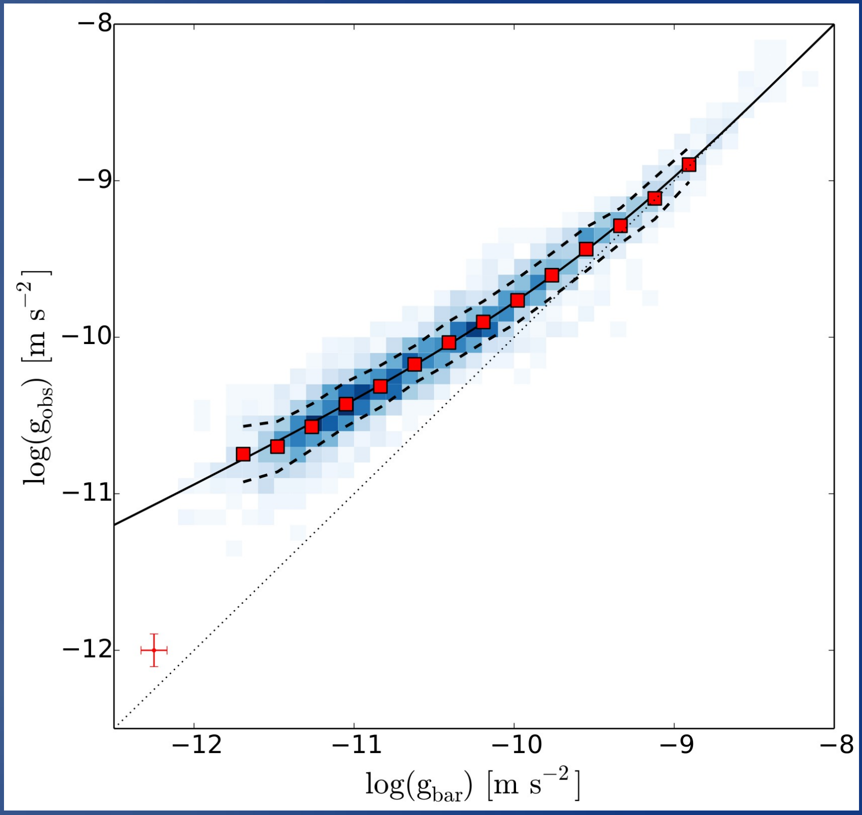
Lelli et al. (2016d)

A "Kepler" Law for Galaxies?

3rd Law of Kepler: a ↔ P

RAR: g_{bar} ↔ g_{obs}





The RAR follows with a minimum set of assumptions:

Poisson's Equation + stellar mass-to-light ratio

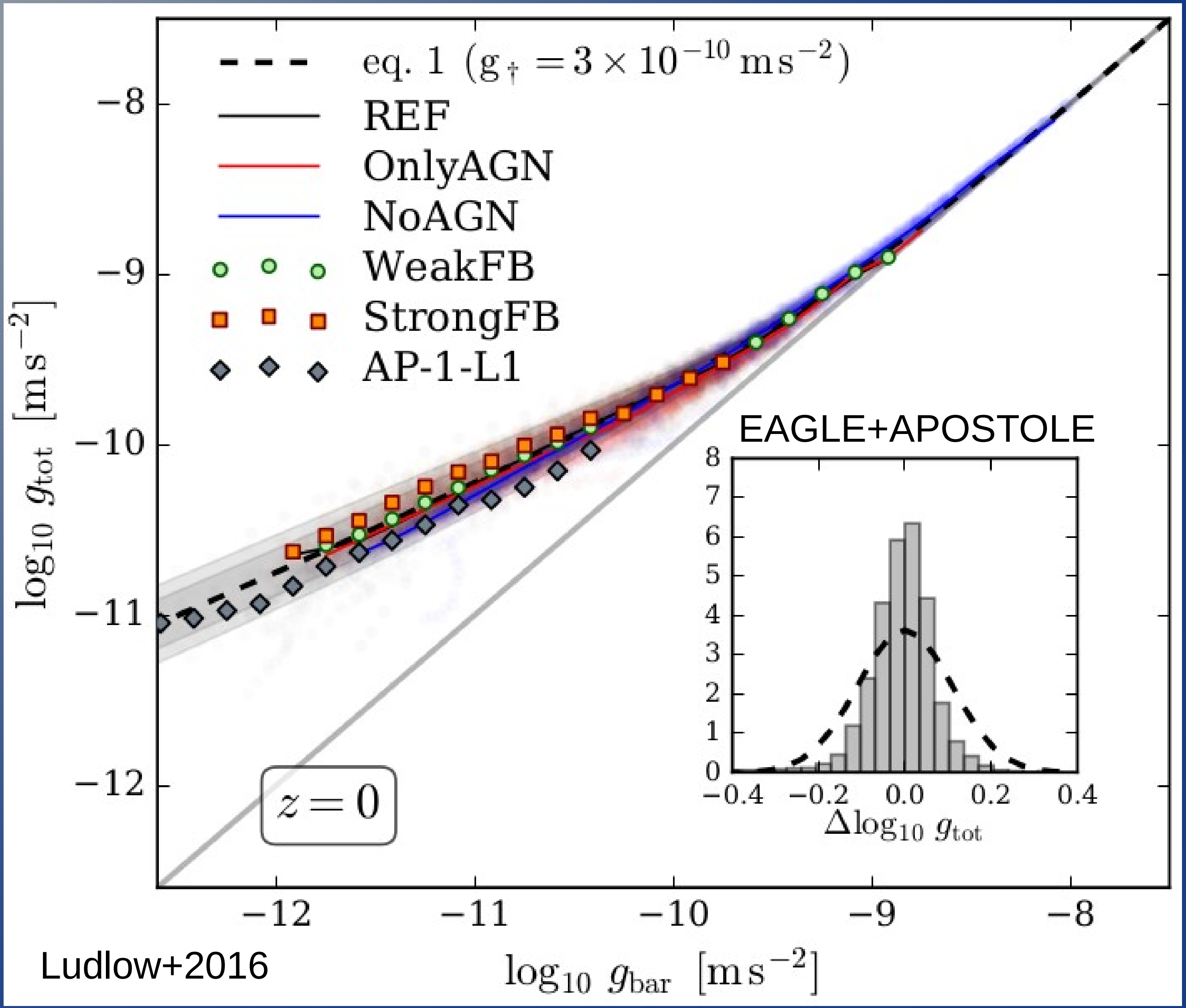
Possible Interpretations:

1. End product of galaxy formation in ΛCDM

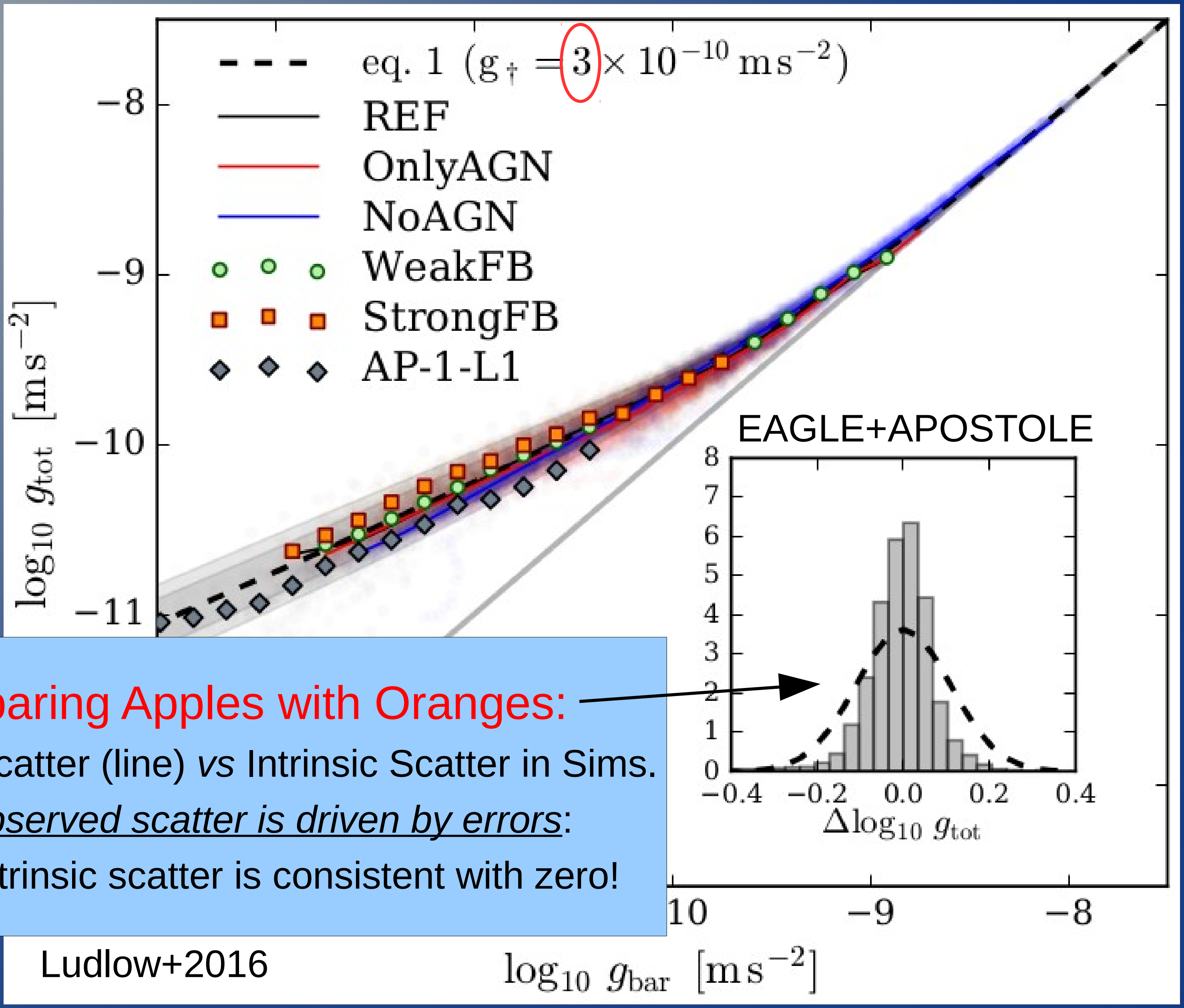
2. New Dynamical Laws instead of DM

3. New Physics in the Dark Sector / Dark Forces

RAR from Cosmological Simulations?



RAR from Cosmological Simulations?



Comparing Apples with Oranges:

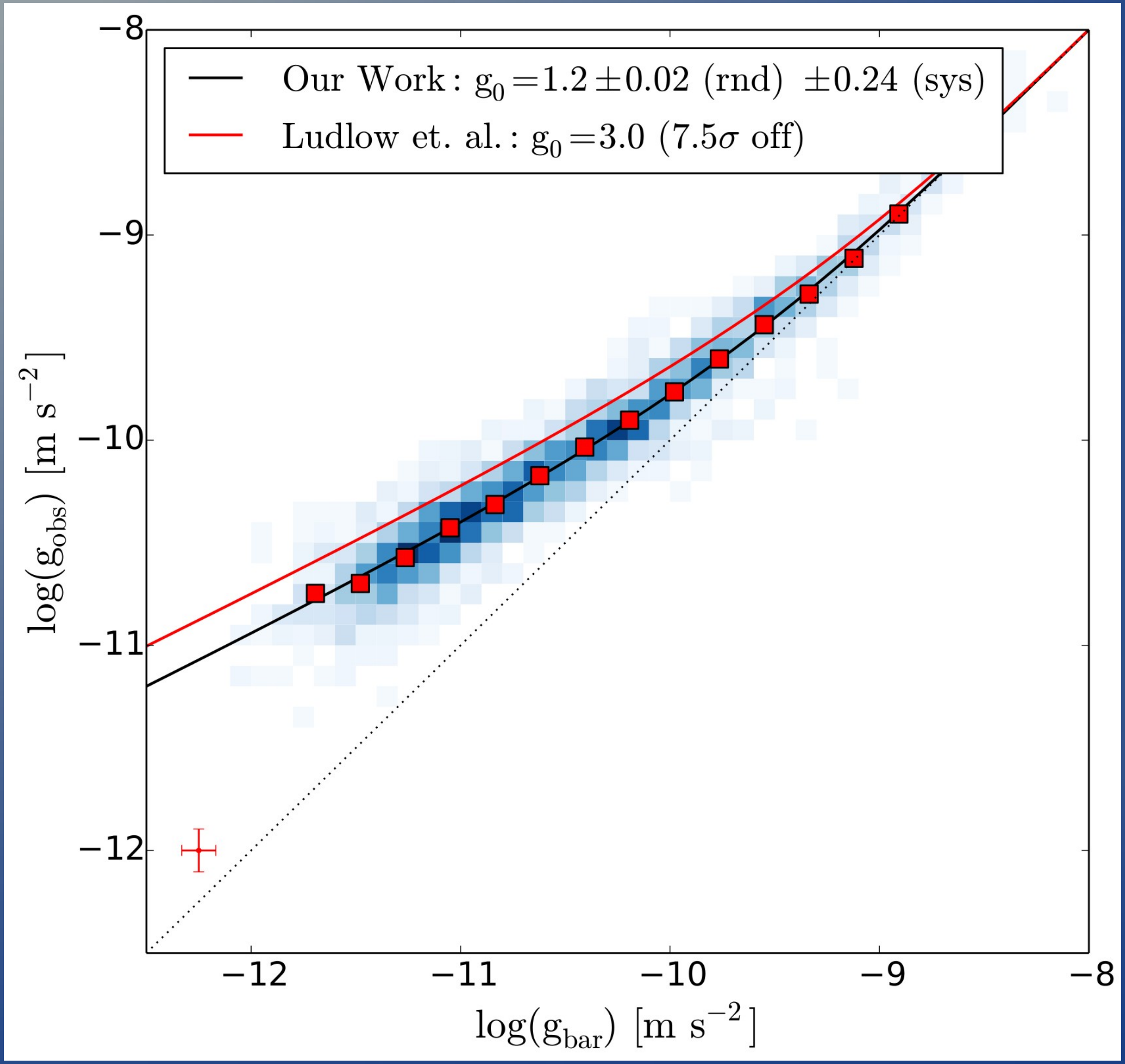
Observed Scatter (line) *vs* Intrinsic Scatter in Sims.

BUT *observed scatter is driven by errors*:

the real intrinsic scatter is consistent with zero!

Ludlow+2016

Actual Comparison with the data



Persistent issue for sims:

Too much DM in galaxies!

e.g. Cusp-Core Problem,

Too-Big-Too-Fail Problem

Other conceptual issues:

Why an acceleration scale?

Why the outer slope is 0.5?

Correlations with residuals?

Possible Interpretations:

1. End product of galaxy formation in ΛCDM

NB: "cusp-core", "too-big-to-fail" are symptoms of a more serious illness.

Issues: Stochastic and complex process. Why is scatter so small (if any)?

2. New Dynamical Laws instead of DM

3. New Physics in the Dark Sector / Dark Forces

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NB: MOND <u>predicted</u> the RAR before the data existed (Milgrom 1983)

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Dipolar DM (Blanchet & Le Tiec 2008, 2009)

Dark Superfluid (Khoury 2015)

} Hybrids (ΛCDM + MOND)

Issues: Adding new free parameters to ΛCDM is somewhat uncomfortable.

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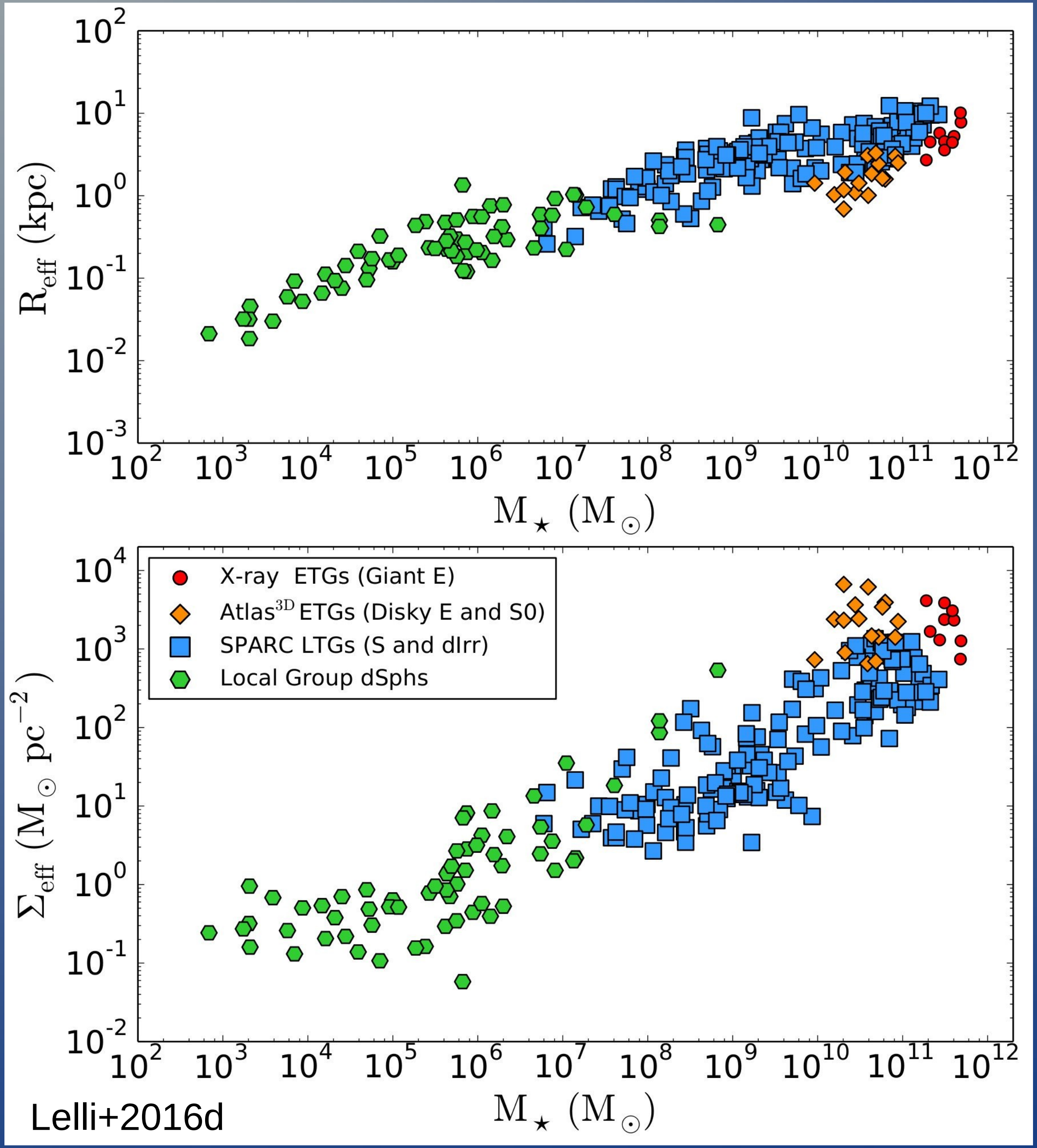
Additional Slides

Dwarf Spheroidals (dSphs) in the Local Group



Satellites of MW and M31:

extremely low masses, sizes, densities, and accelerations!

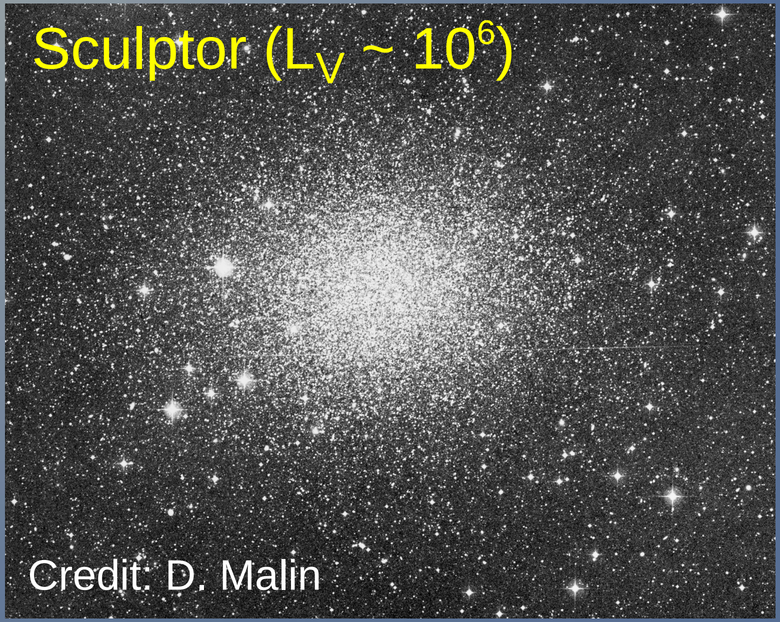
"Classical" dSphs discovered between the '40 and the '80.

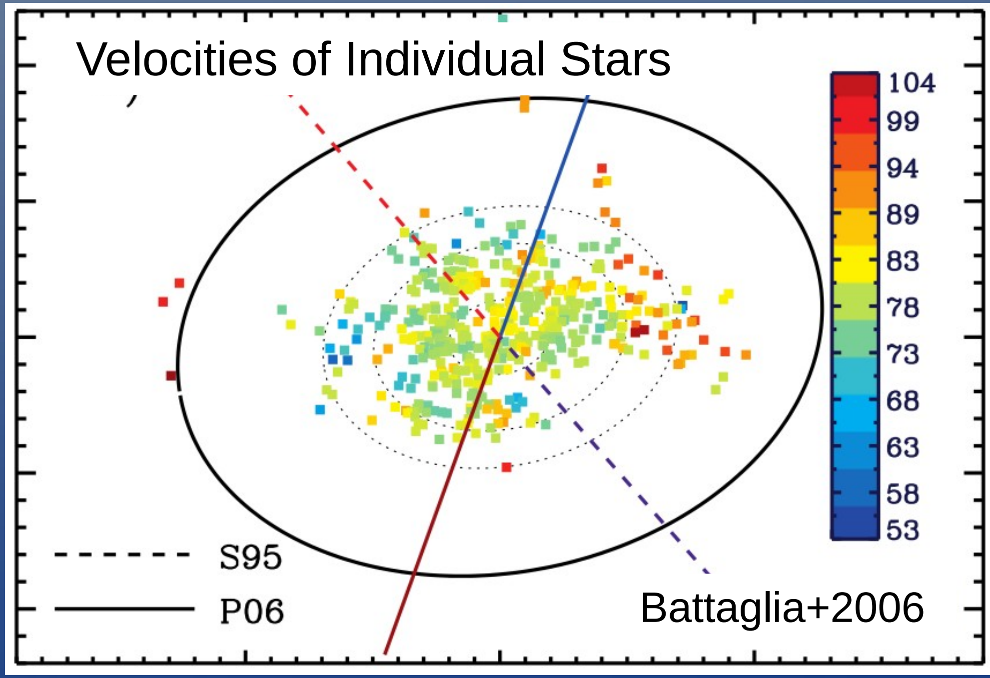
→ well-studied properties

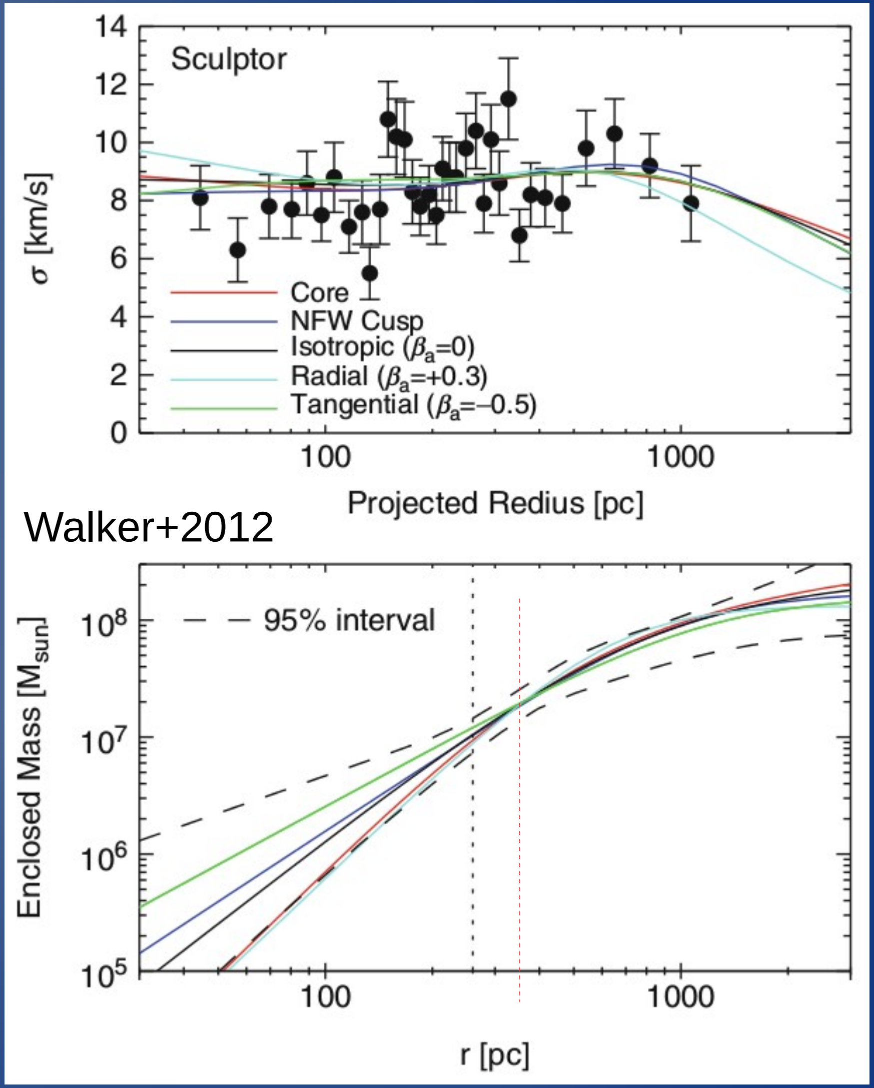
"Ultrafaint" dSphs discovered during the past ~10 years with SDSS, DES and other surveys

→ properties remain uncertain

Stellar kinematics in "classical" dSphs



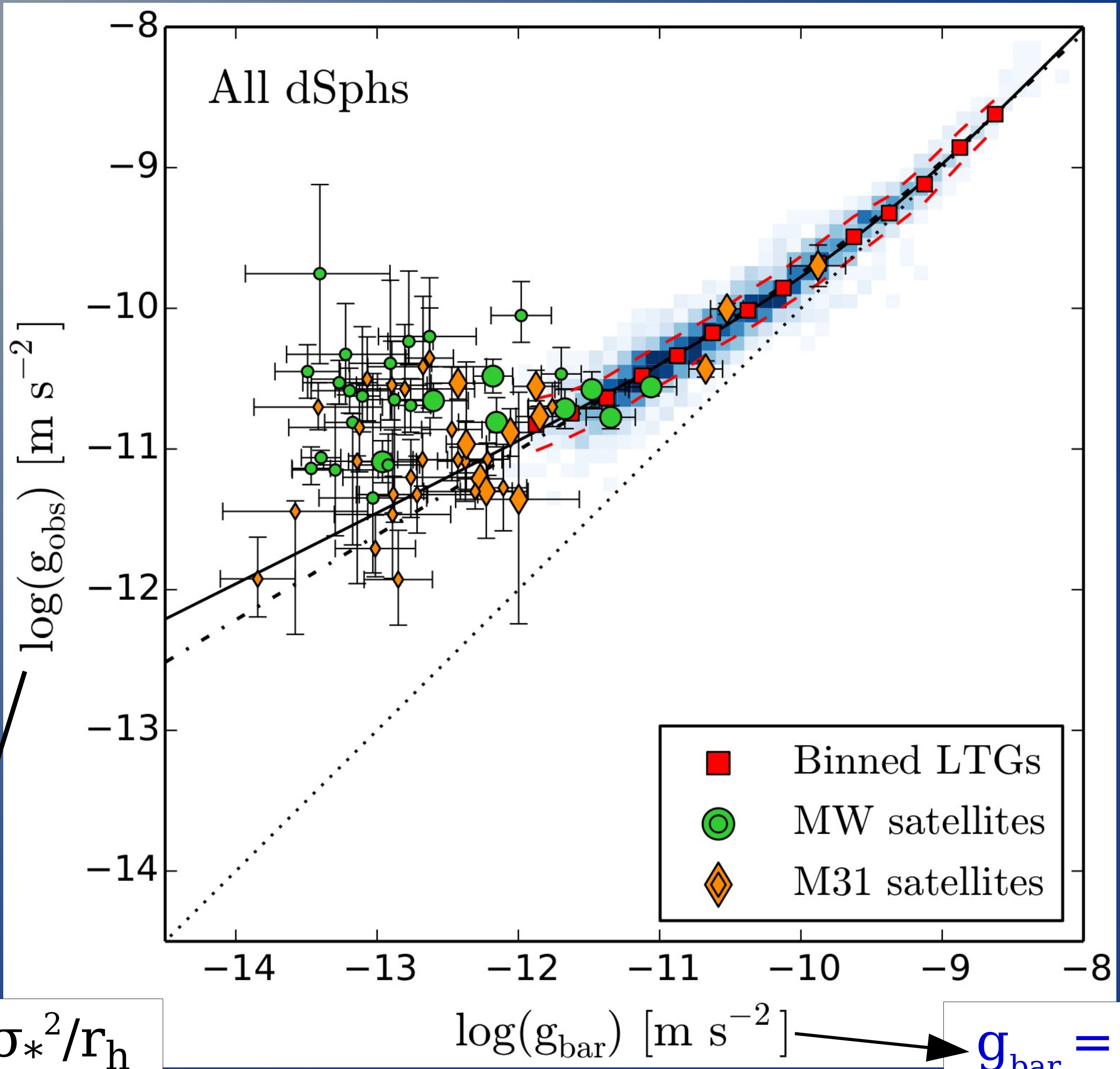




Mass-Anisotropy Degeneracy:

M_{tot} can be robustly estimated only at r_h = 4/3R_h (Walker+2009, Wolf+2010)

Radial Acceleration Relation for dSphs



$g_{obs} = 3\sigma_*^2/r_h$

$g_{bar} = GM_{bar}/r_h^2$

dSphs:
1 point per galaxy at the half-light radius r_h.

Large symbols:
Classical dSphs

Small symbols:
Ultrafaint dSphs

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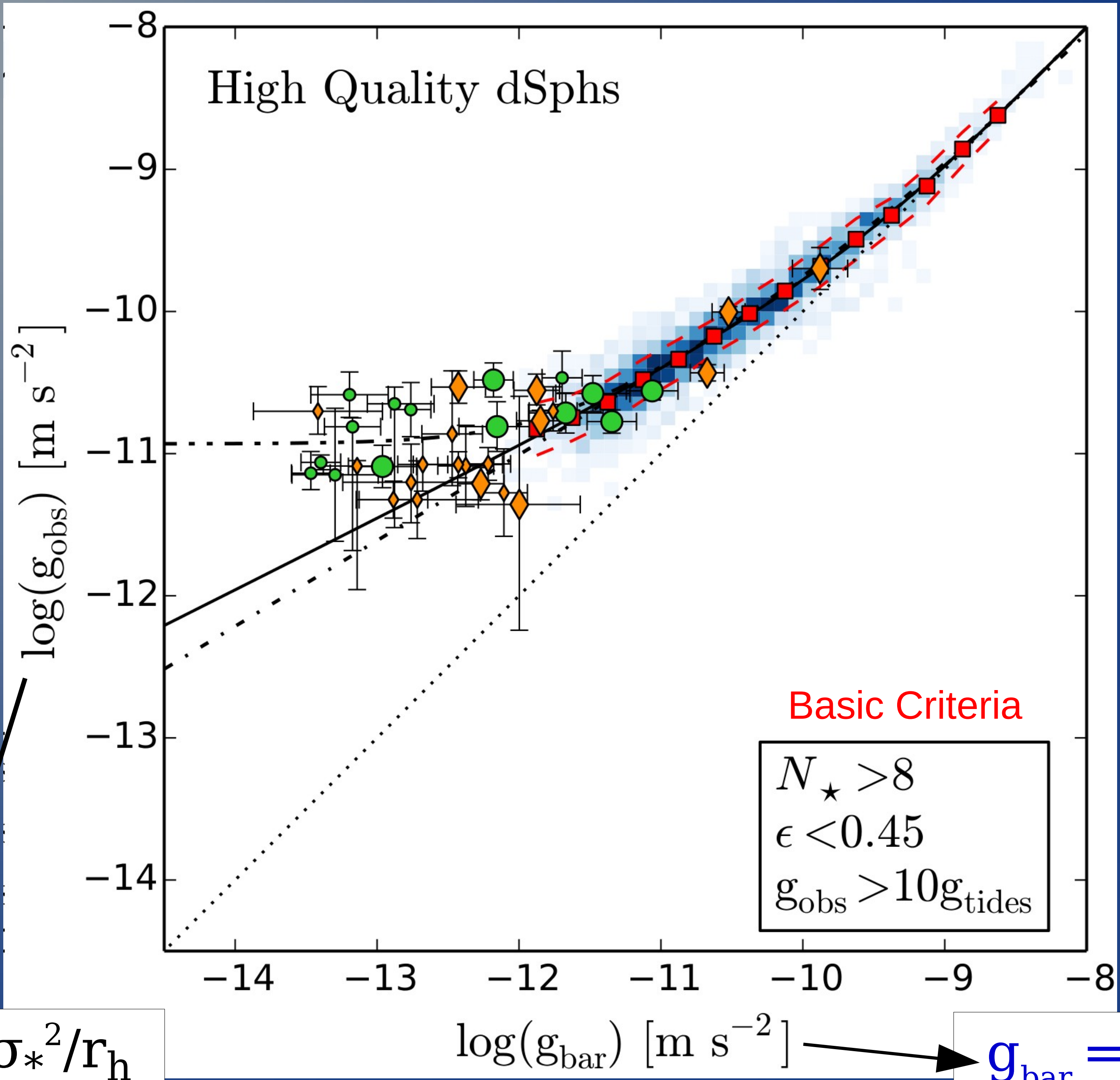

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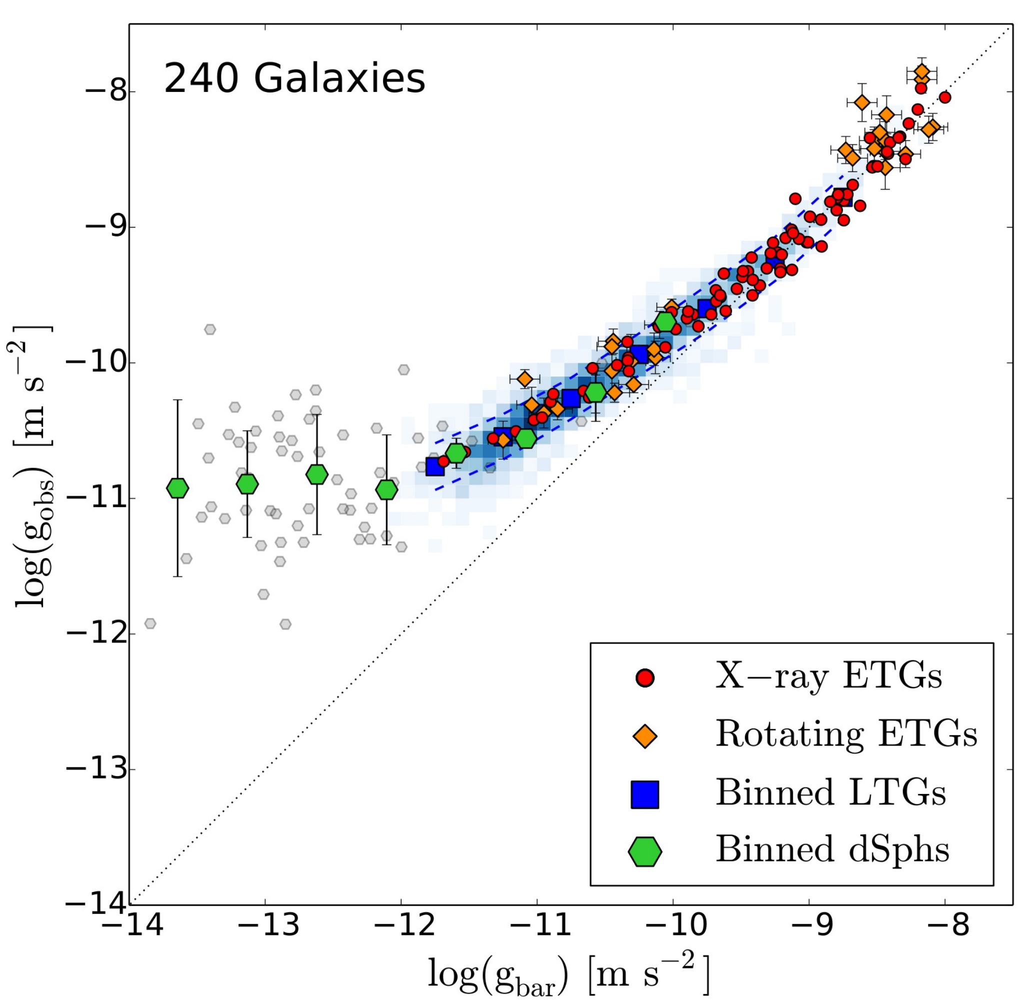
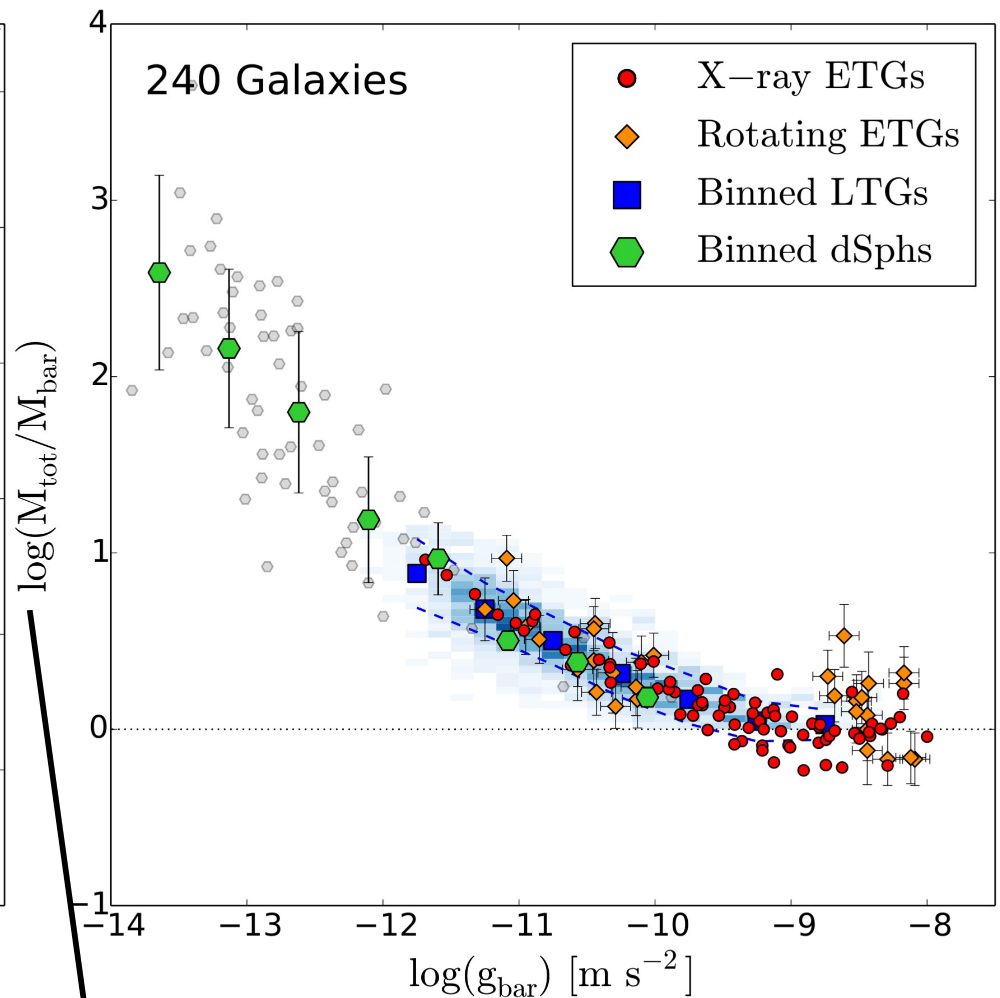
A "Kepler" Law for Galaxies?

Radial Acceleration Relation



Mass-Discrepancy Acceleration Relation



Lelli et al. (2016d)

$$M_{tot}/M_{bar} = g_{obs}/g_{bar}$$

MDAR (Sanders 1990; McGaugh 1999, 2004)

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4. dSphs may indicate a flattening at $\sim 10^{-12}$ m s^{-2}.