Observational Indications of the External Field Effect

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11 March 2021 **George Washington University**

- Galaxies: some relevant properties
  - kinematic laws
- MOND
- Equivalence Principles
  - Weak, Strong, Einstein
- External Field Effect
  - detections in Local Group dwarfs
  - detections in spiral galaxies

Galaxies exist over a huge dynamic range in

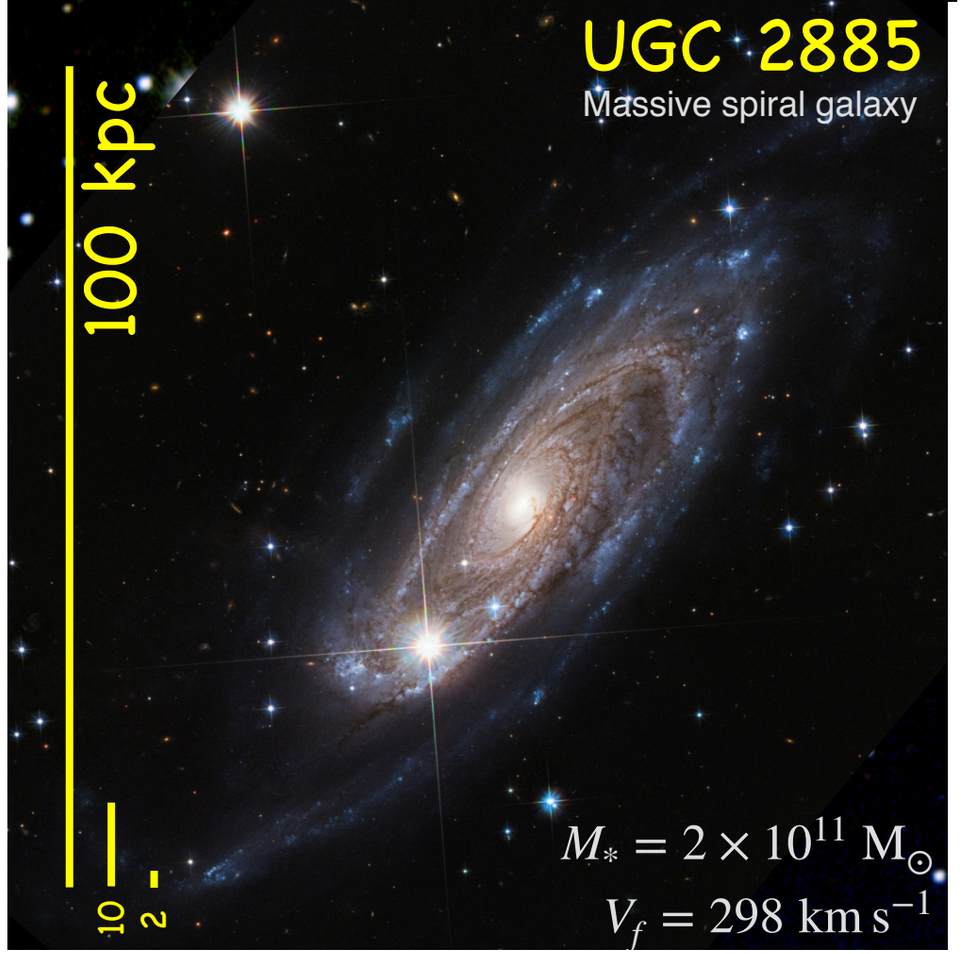
Rotation velocity
$20 < V_f < 300$ km/s

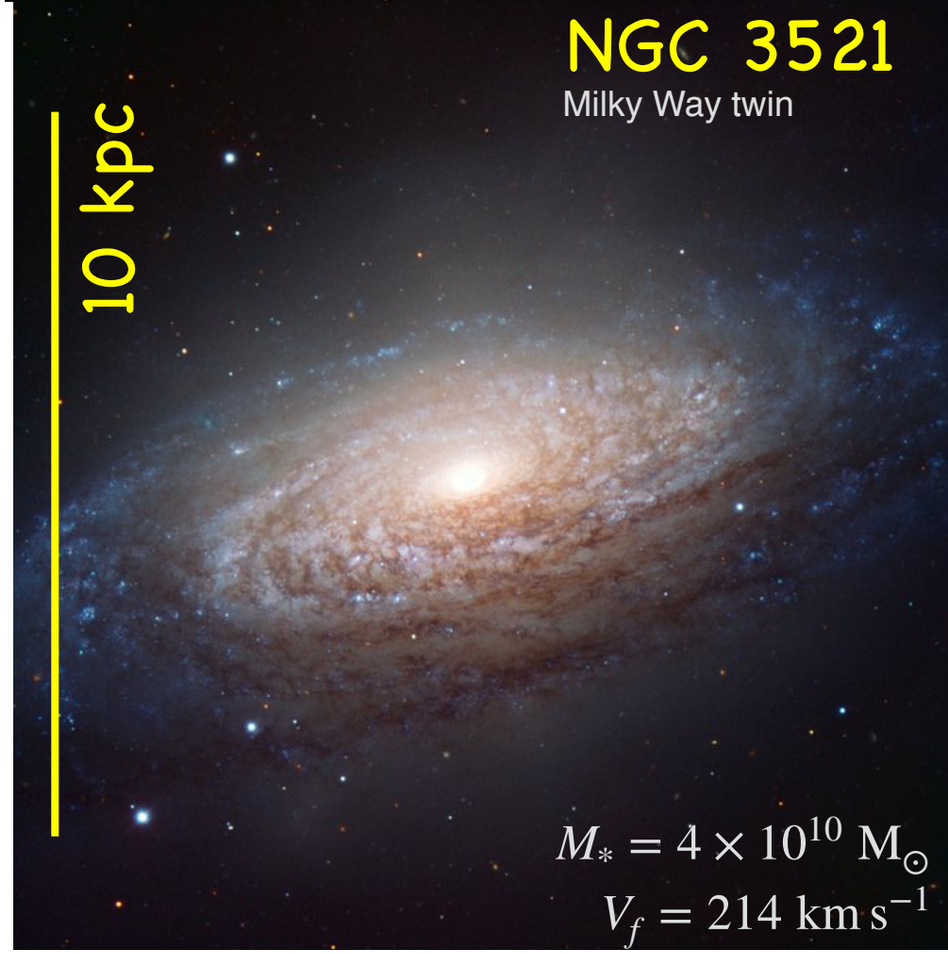
Luminosity
$1\text{x}10^7 < L_{[3.6]} < 5\text{x}10^{11}\ L_\odot$

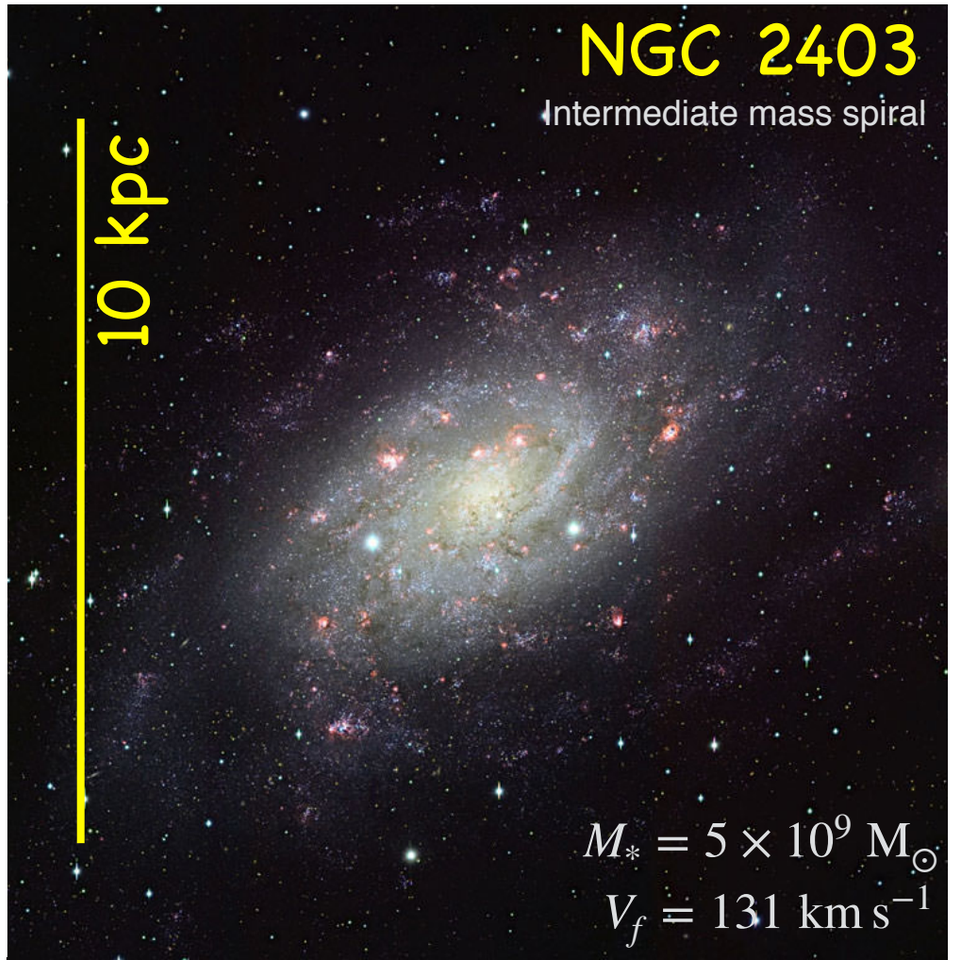
Gas mass
$1\text{x}10^7 < M^* < 5\text{x}10^{10}\ M_\odot$

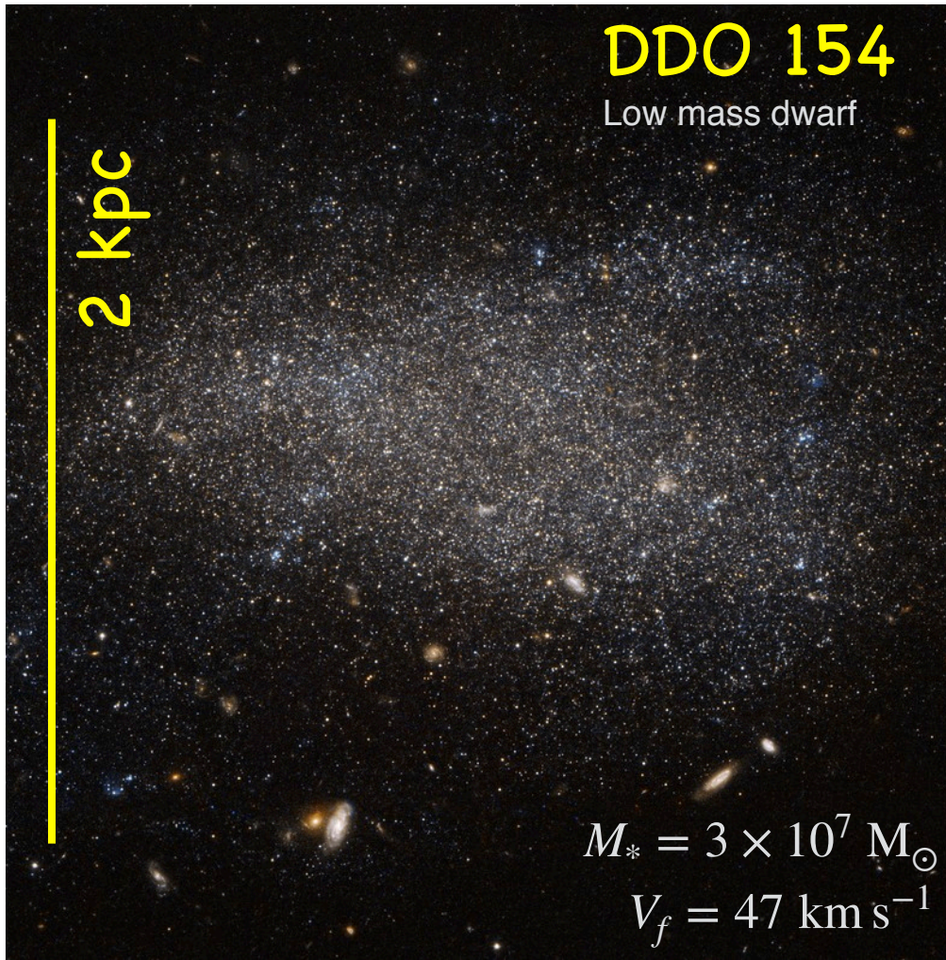
Surface brightness
$5 < \mu_e < 3\text{x}10^3\ L_\odot\ pc^{-2}$

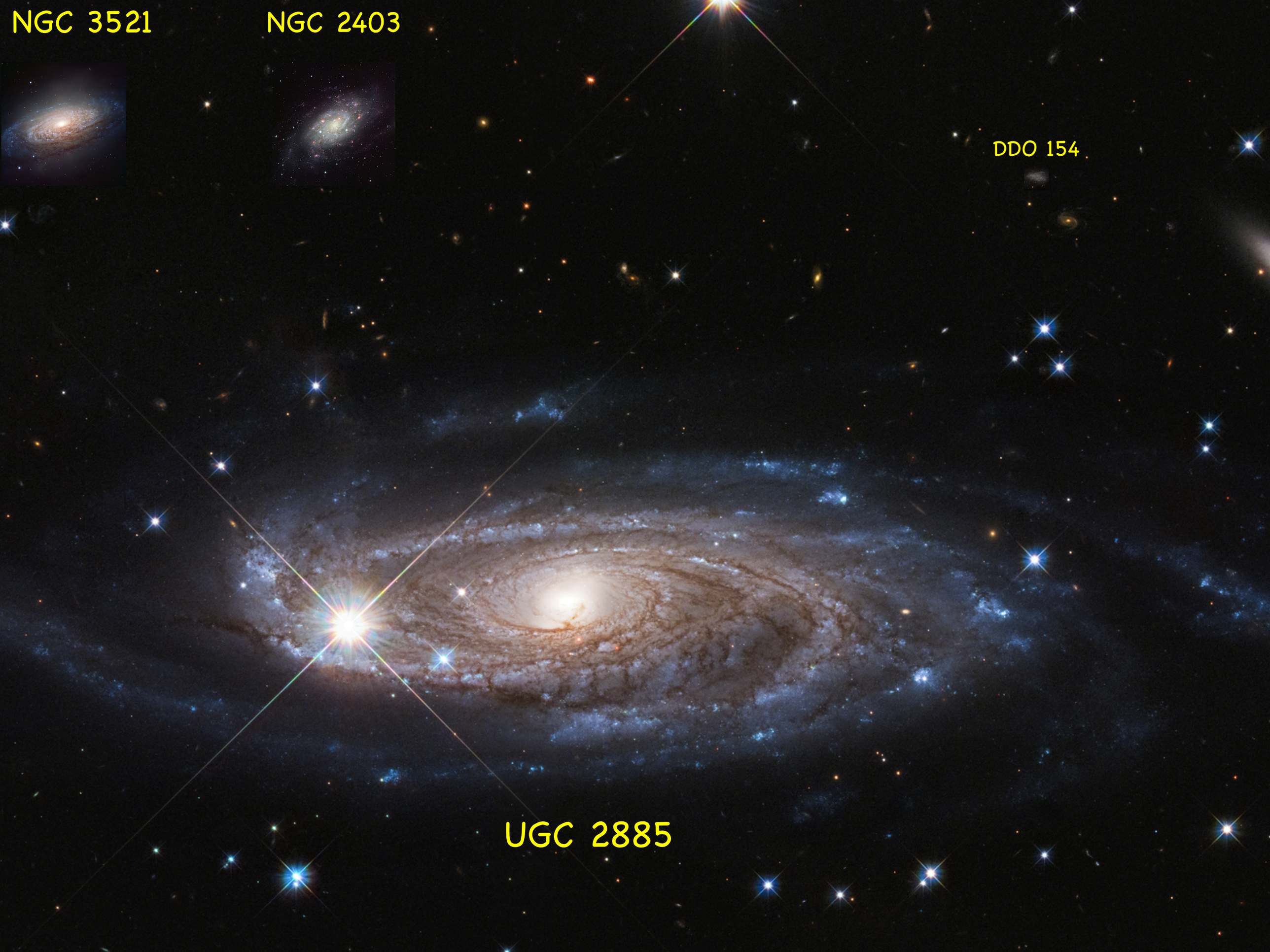
Gas fraction
$0.03 < f_g < 0.97$





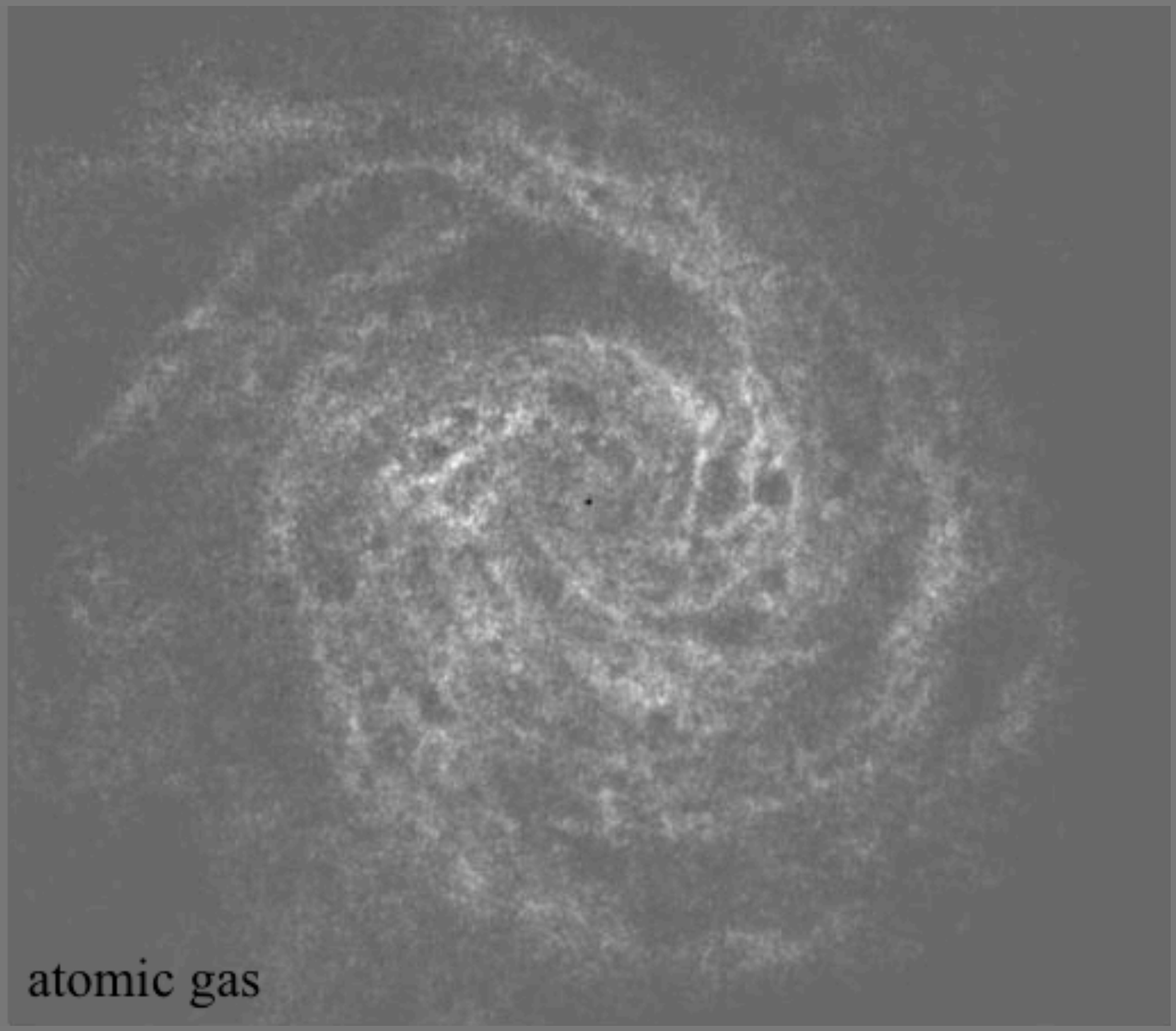





NGC 3521
NGC 2403
DDO 154
UGC 2885

Galaxies are made of gas as well as stars

near infrared

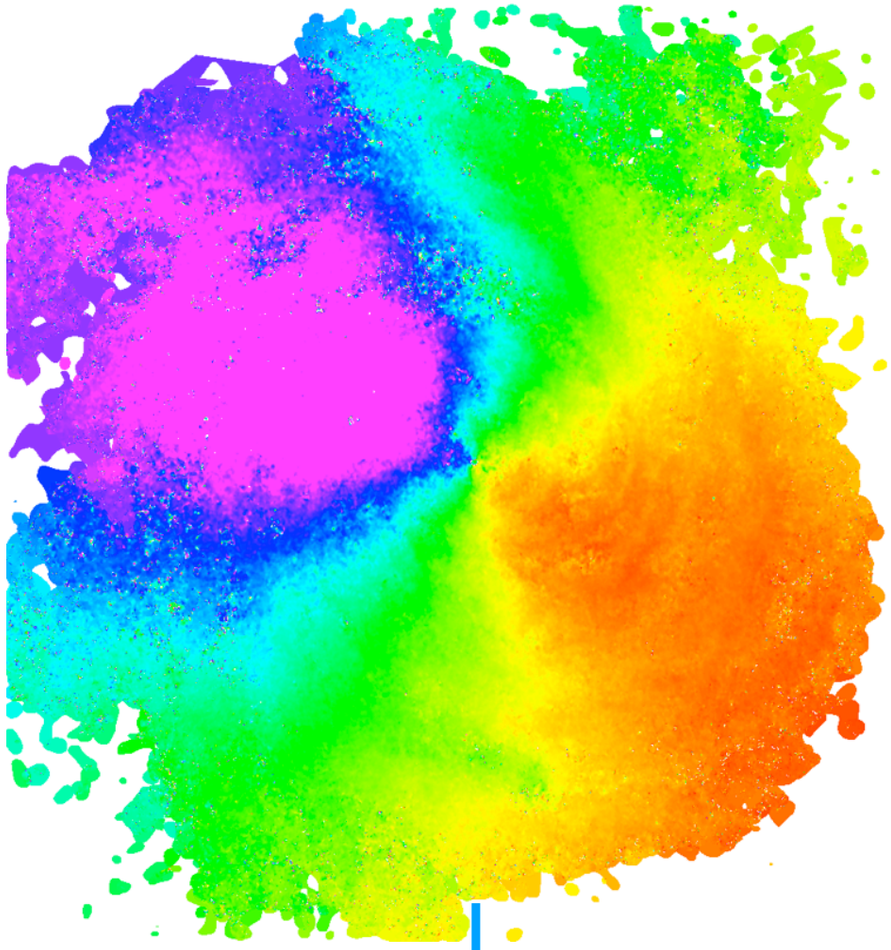


atomic gas

NGC 6946 stars & gas

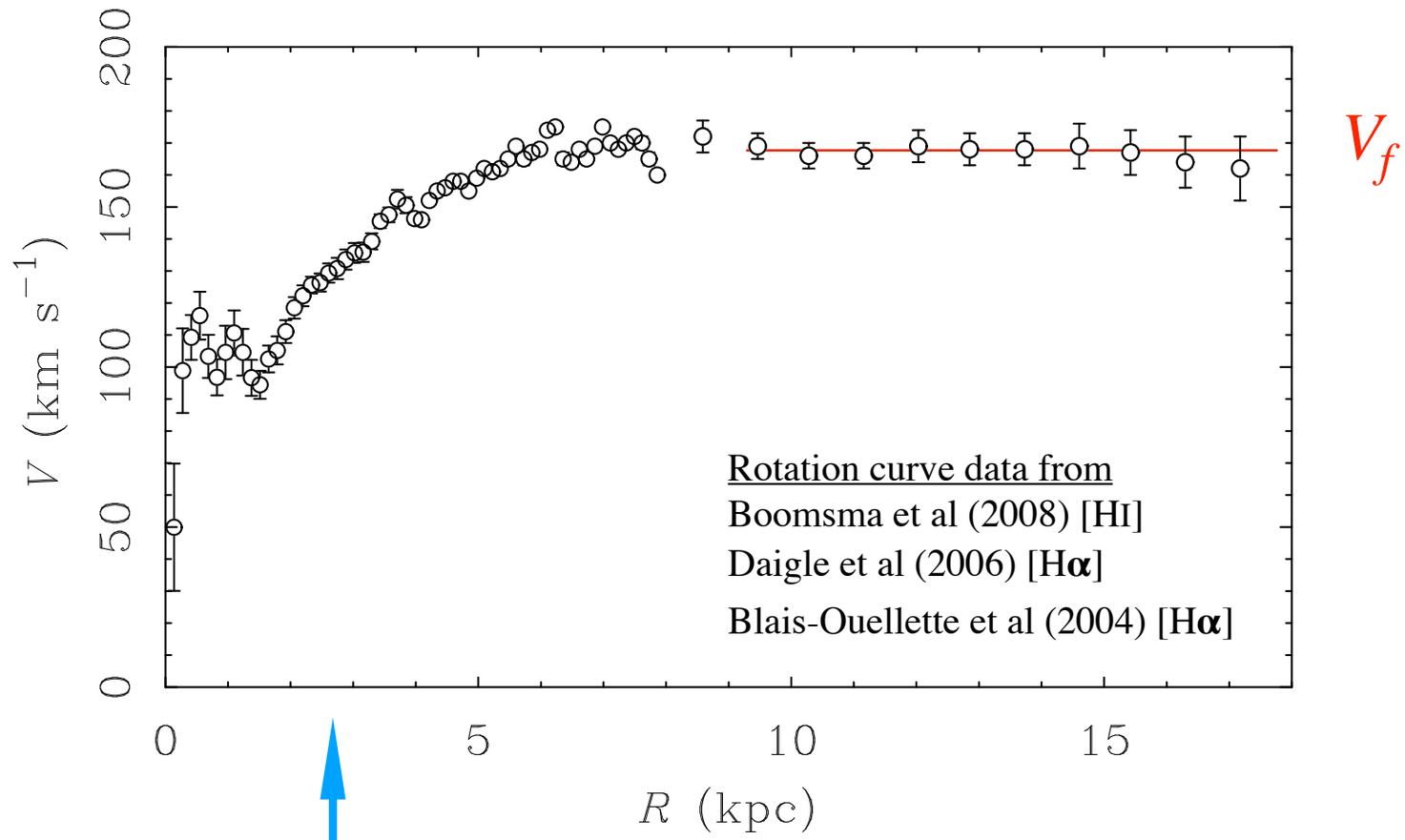
21cm interferometric observations give atomic gas distributions and velocity fields

NGC 6946

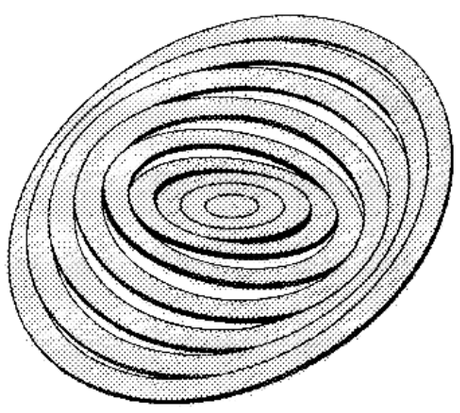


THINGS (Walter et al. 2008; de Blok et al. 2008)

Rotation curve



tilted ring model



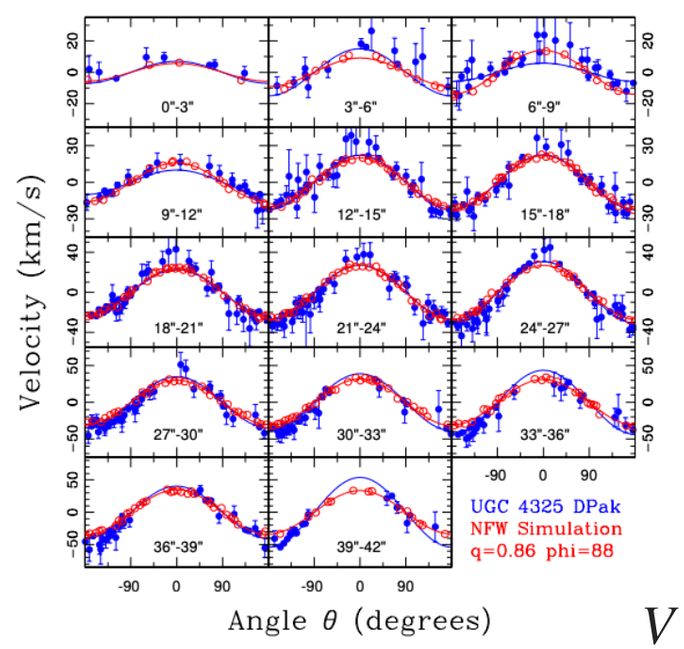


Figure 5.6: – The (0.86, 88°) simulation results (red) over-plotted with the observed UGC 4325 data (blue). The simulation and data match well between ∼ 12″ - 30″.

The sinusoidal variation of velocity in each ring measures the position angle, inclination, and rotation curve $V_c(R)$.

$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

to which we make tilted ring fits

F568-1

assuming nominal mass-to-light ratio

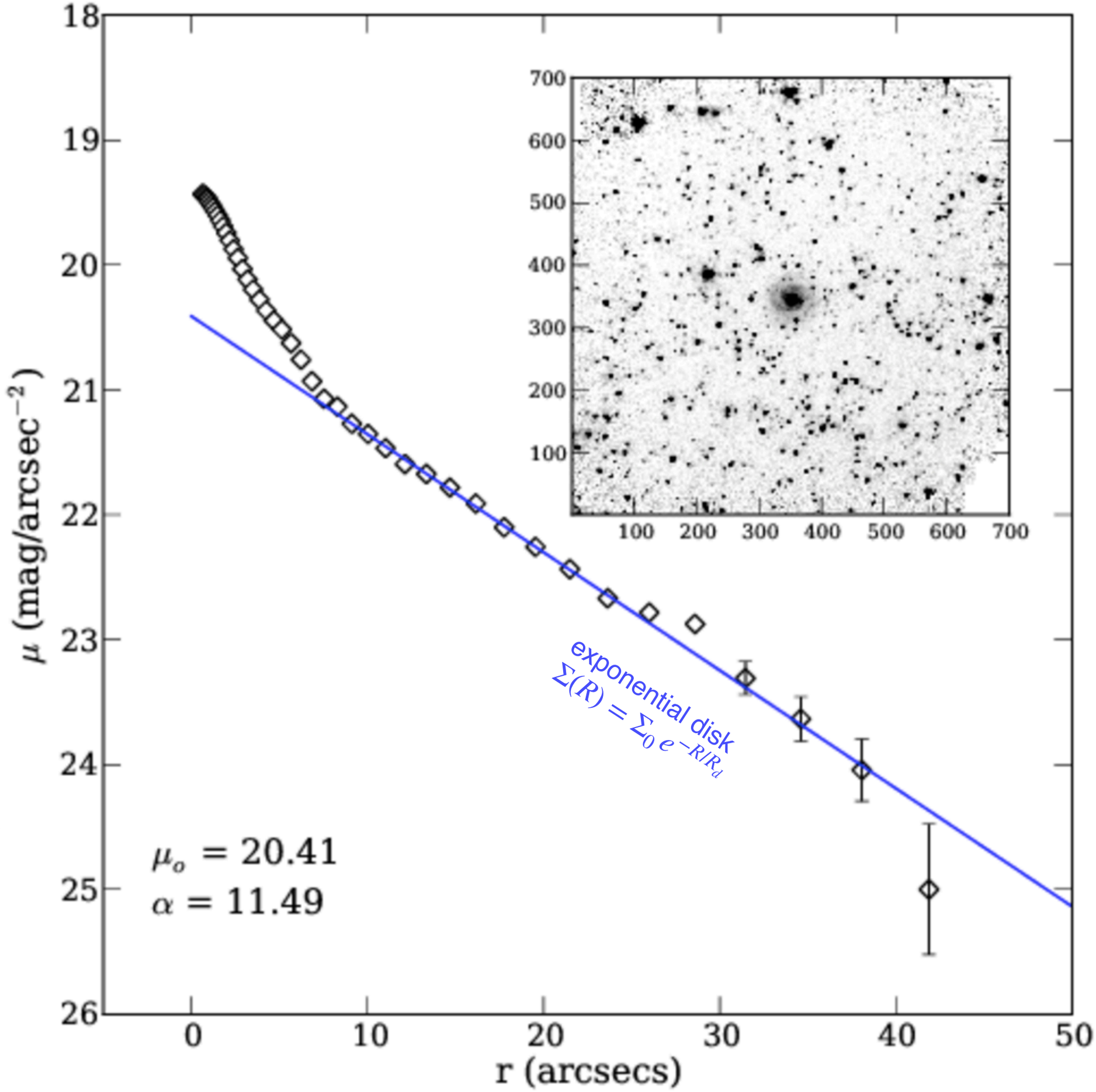
$\mu \rightarrow \Sigma_*$

assuming nominal disk thickness

$\Sigma_* \rightarrow \rho_*$

$$\nabla^2 \Phi_* = 4\pi G \rho_*$$

Surface photometry quantifies the variation of surface brightness with radius. These data are used to numerically solve the Poisson equation to obtain the gravitational potential of the stars.



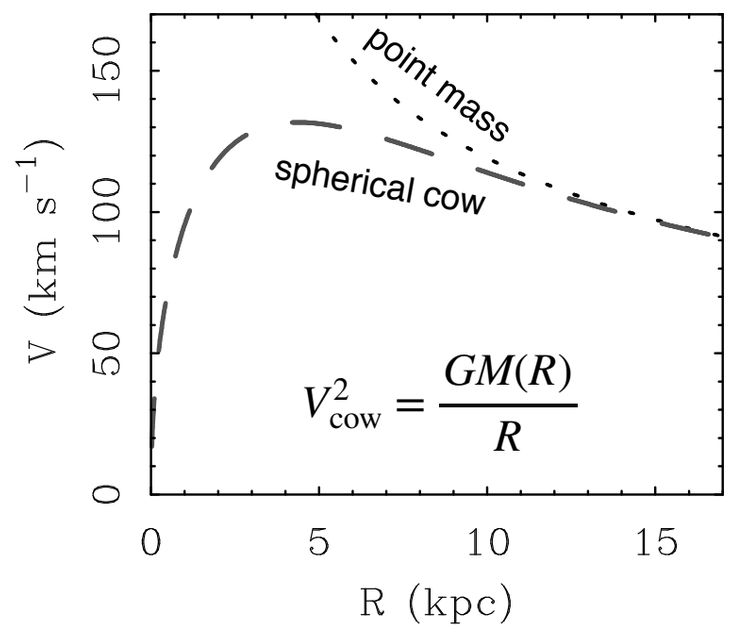
Examples for the size and mass of NGC 6946

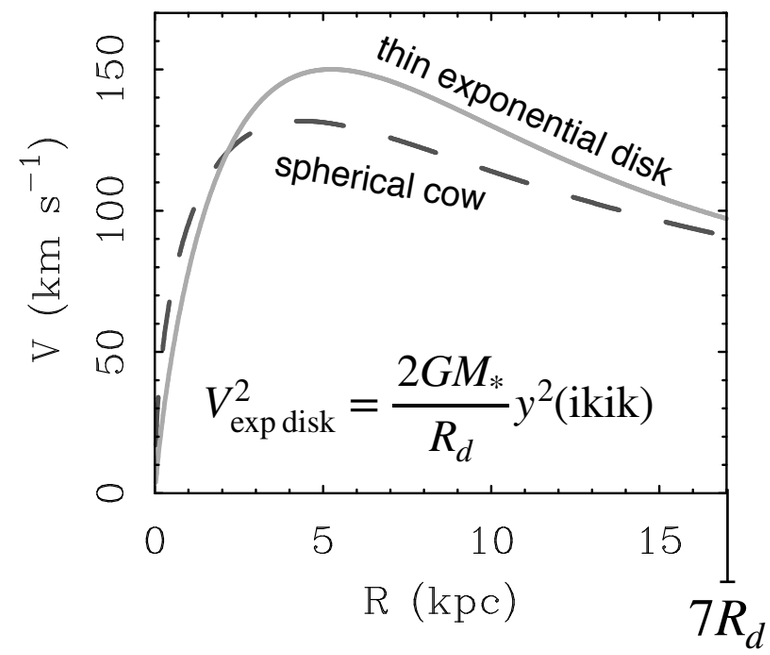
$$M_* = 3.3 \times 10^{10}\ \mathrm{M}_\odot$$
$$R_d = 2.44\ \mathrm{kpc}$$

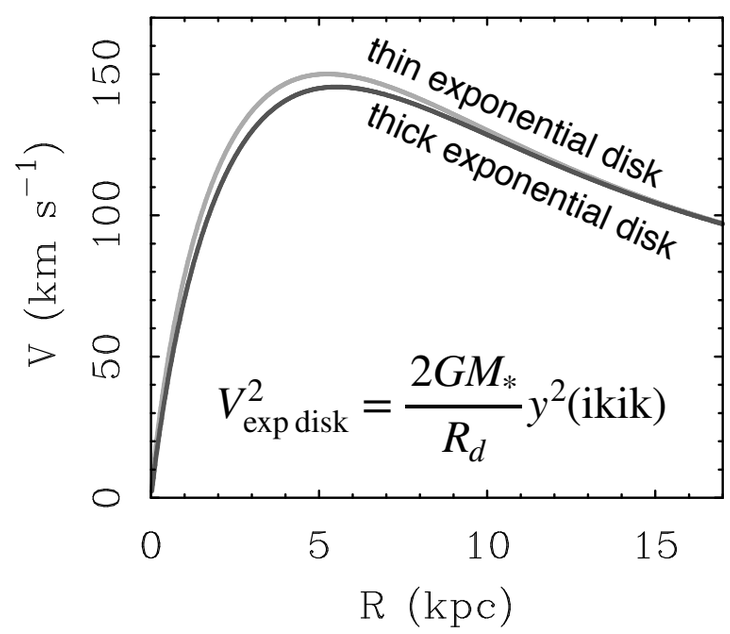
Progressive approximations
in mass modeling

- Point Mass
- Spherical Cow
- thin exponential disk
- thick exponential disk
- surface density $\Sigma(R)$
- 2D $\Sigma(R, \phi)$ [e.g., bars]
- 3D $\rho(R, \phi, z)$
- 3D + non-equilibrium

We numerically solve the Poisson equation to obtain the gravitational potential Φ_* from the observed surface density $\Sigma_*(R)$

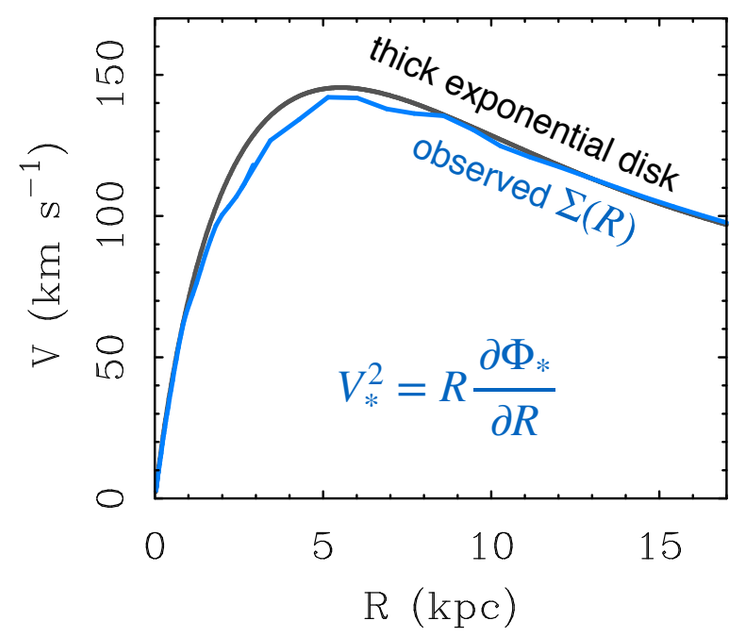






$$\mathrm{ikik} = [I_0(y)K_0(y) - I_1(y)K_1(y)]$$

$$y = \frac{R}{2R_d}$$



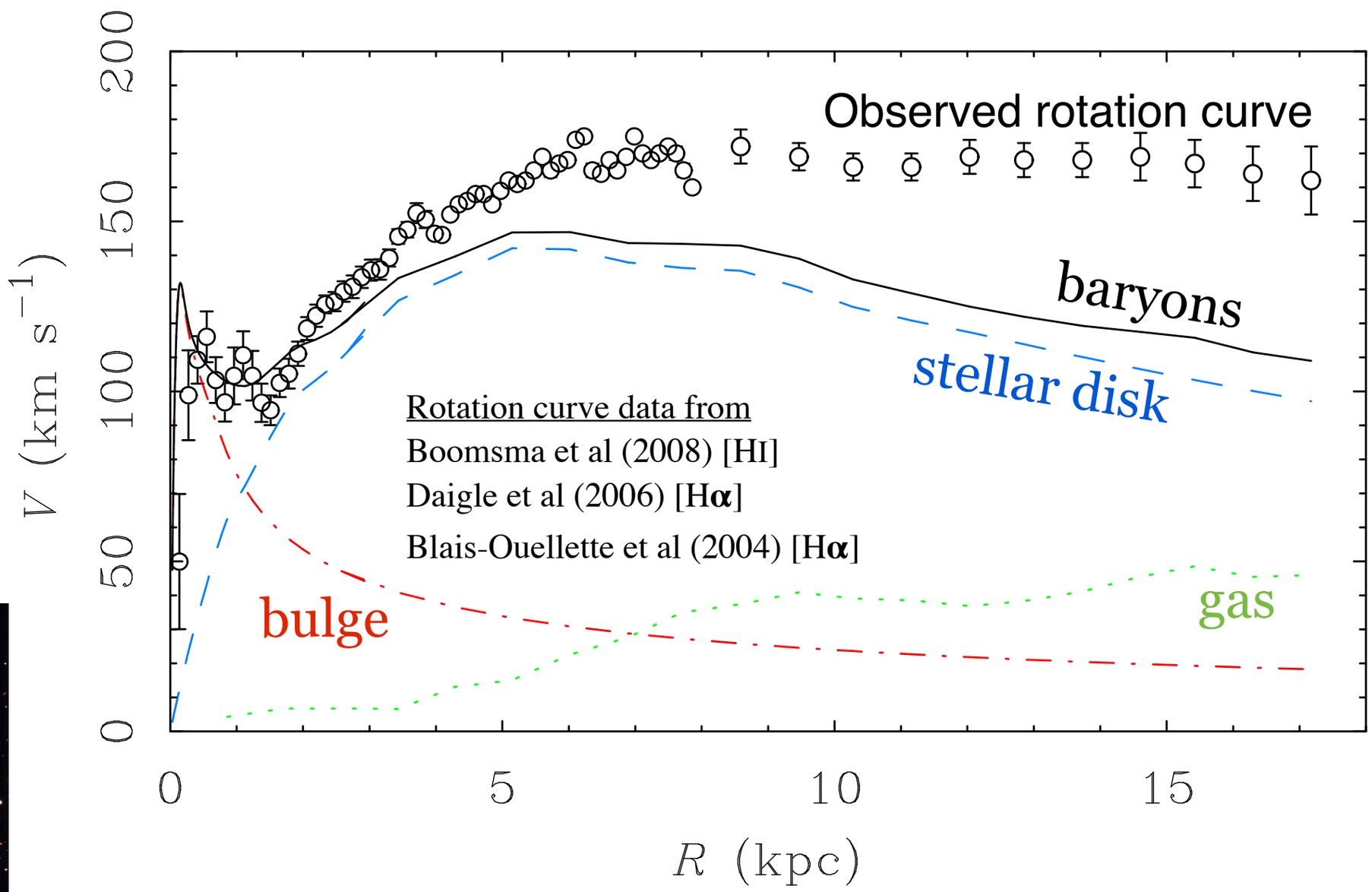
Now have

Surface density for
- stars
- gas

and corresponding rotation curves for each component

Observed rotation curve

NGC 6946



$$V_{\rm bar}^2 = V_{\rm disk}^2 + V_{\rm bulge}^2 + V_{\rm gas}^2$$

Photometric Scaling Relations are weak, have lots of intrinsic scatter.

Kinematic Scaling Relations

1. Flat Rotation Curves
2. Renzo's Rule
3. Baryonic Tully-Fisher Relation
4. Central Density Relation
5. Radial Acceleration Relation

Kinematic Scaling Relations are strong, have little intrinsic scatter.

McGaugh et al. 2019, IAU 353 (arXiv:**1909.02011**)

1. Rotation curves become flat at large radii

Rubin, Thonnard, & Ford 1978, *ApJ*, **225**, L107

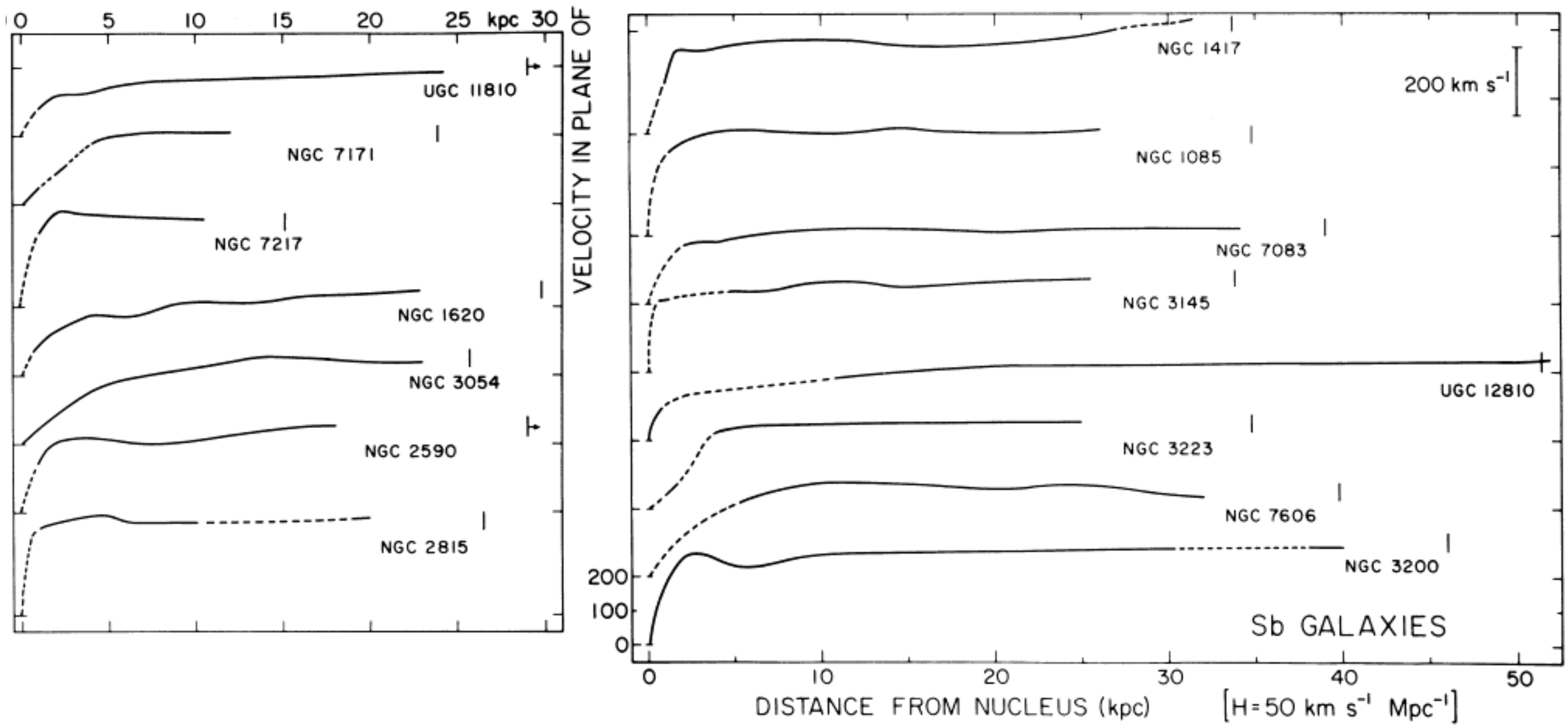
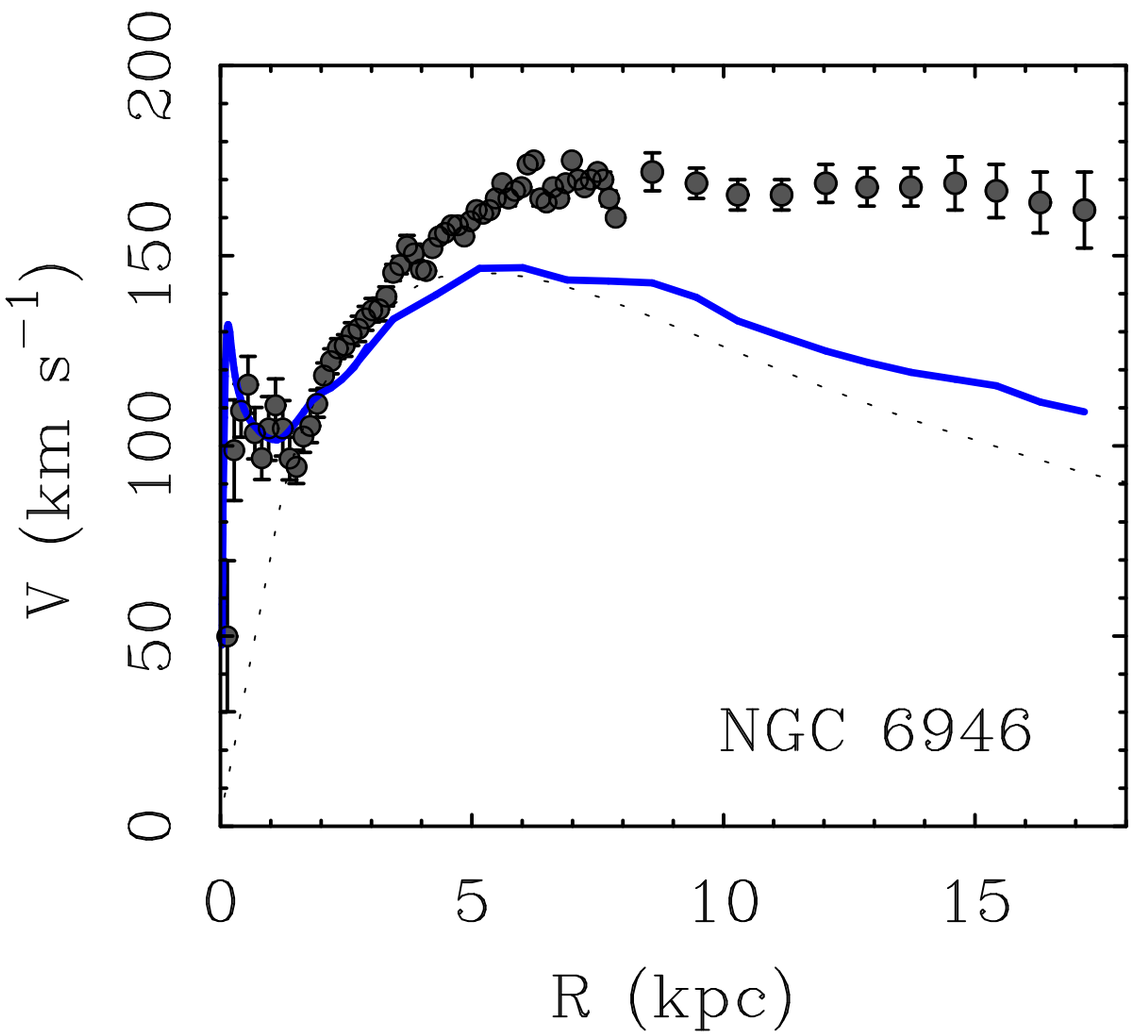


FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to ncreasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks he location of R_{25}, the isophote of 25 mag arcsec^{-2}, corrected for effects of internal extinction and inclination. Regions with no measured velocities are indicated by dashed lines.

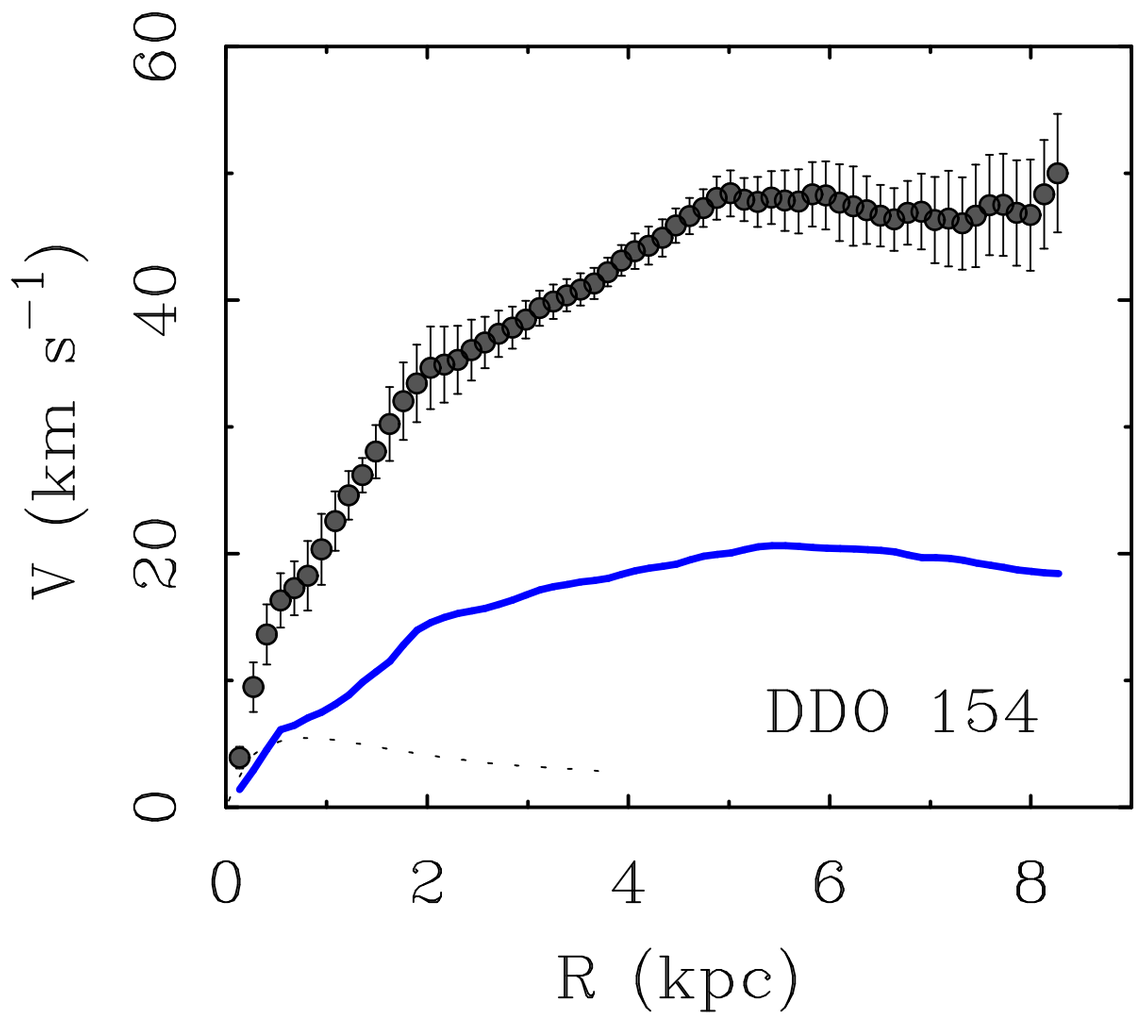
2. Renzo's Rule

For every feature in the luminosity profile, there is a corresponding feature in the rotation curve, and vice-versa.

Sancisi (2004)



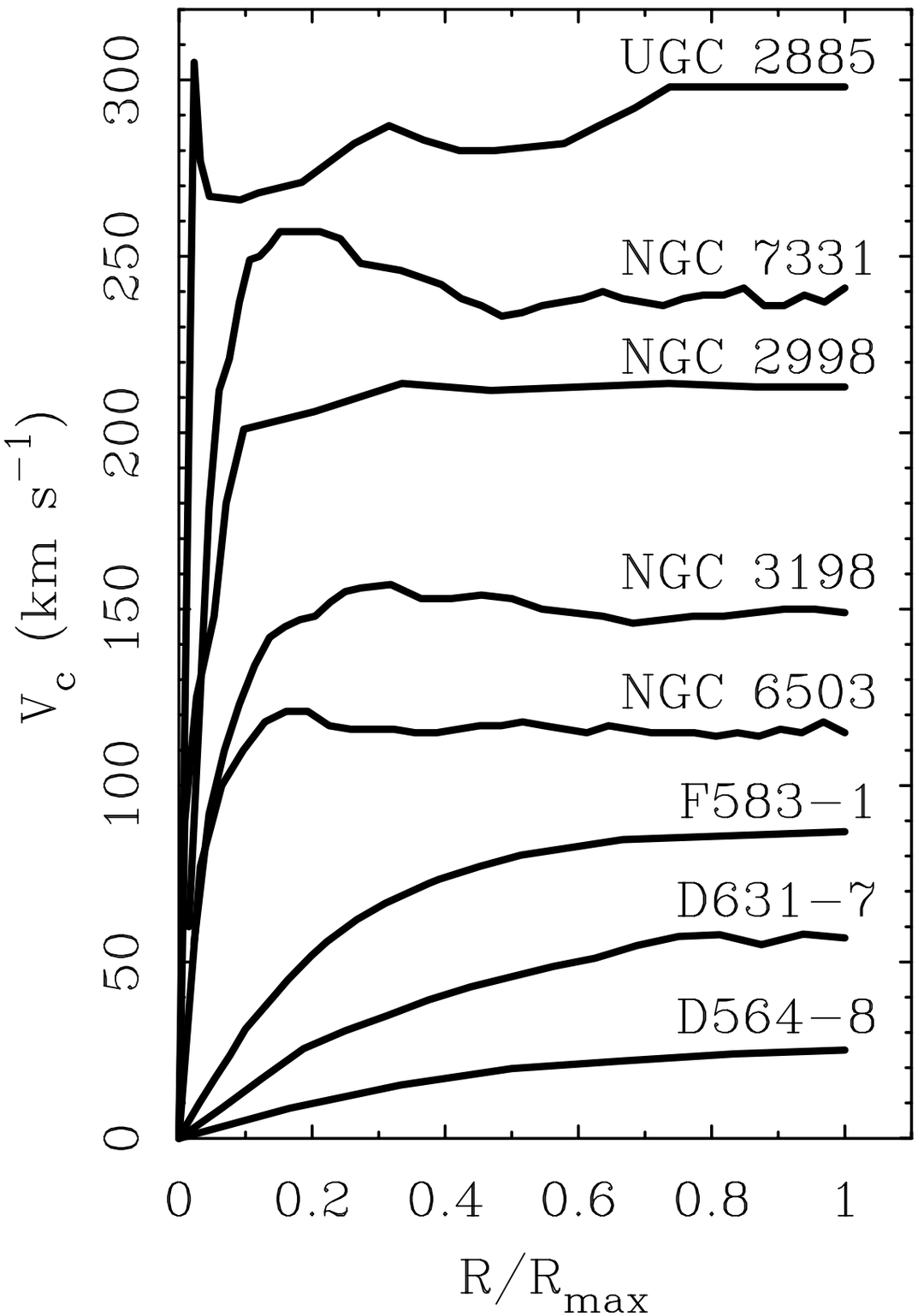
High surface brightness galaxies near maximal (the stars suffice to explain the velocity at small radii).



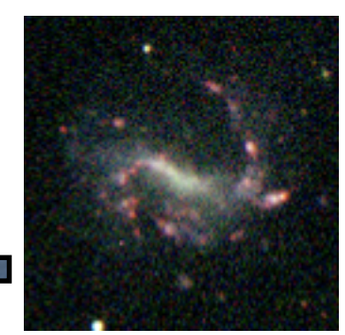
Low surface brightness galaxies are far from maximal (nevertheless, Renzo's rule holds).

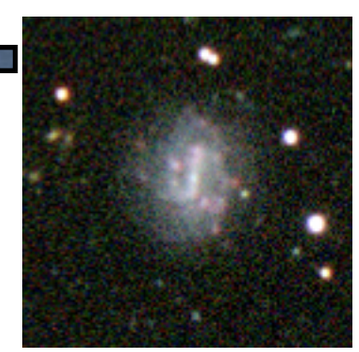
3. Tully-Fisher relation (Tully & Fisher 1977)

amplitude of rotation speed correlates with mass



star dominated HSB



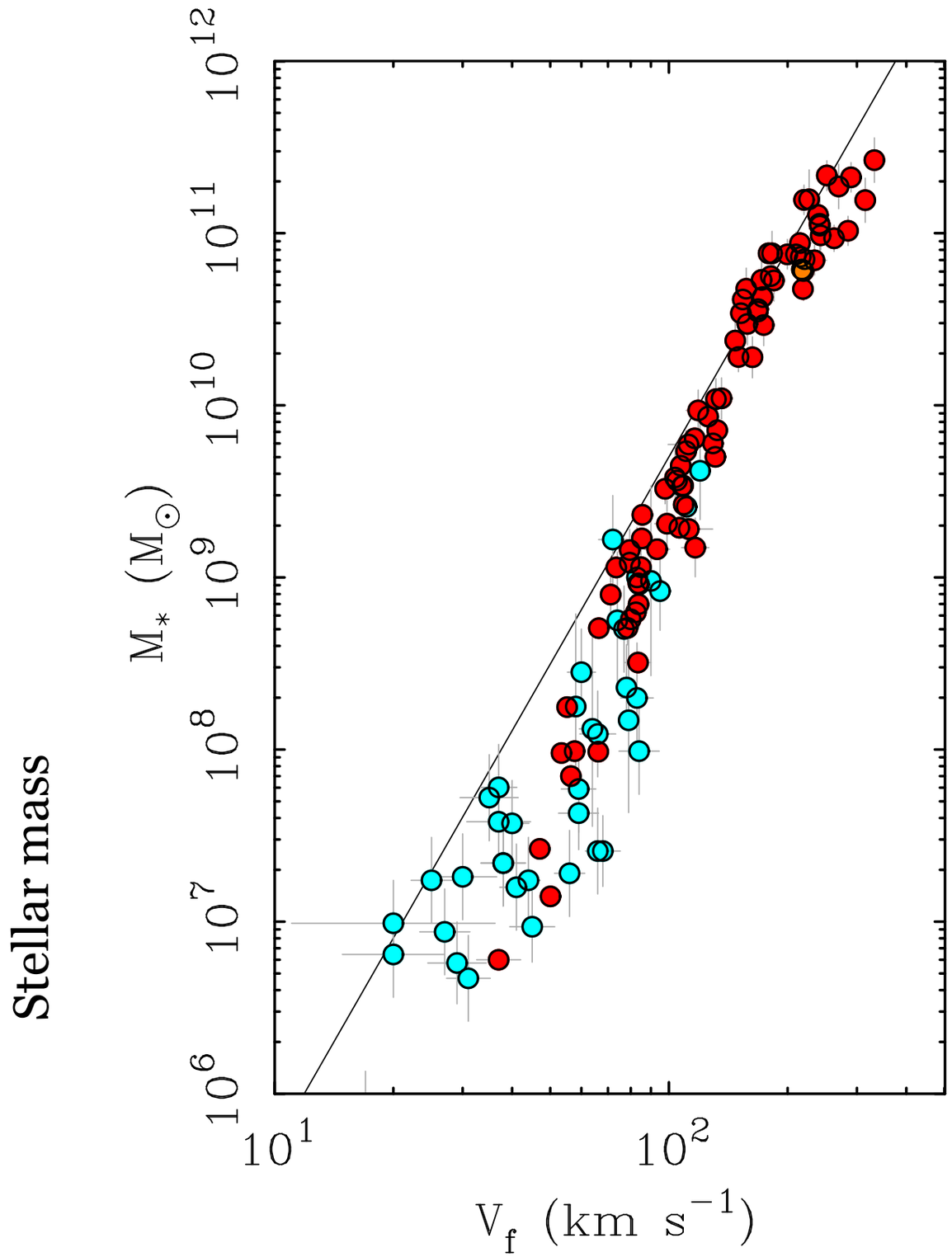


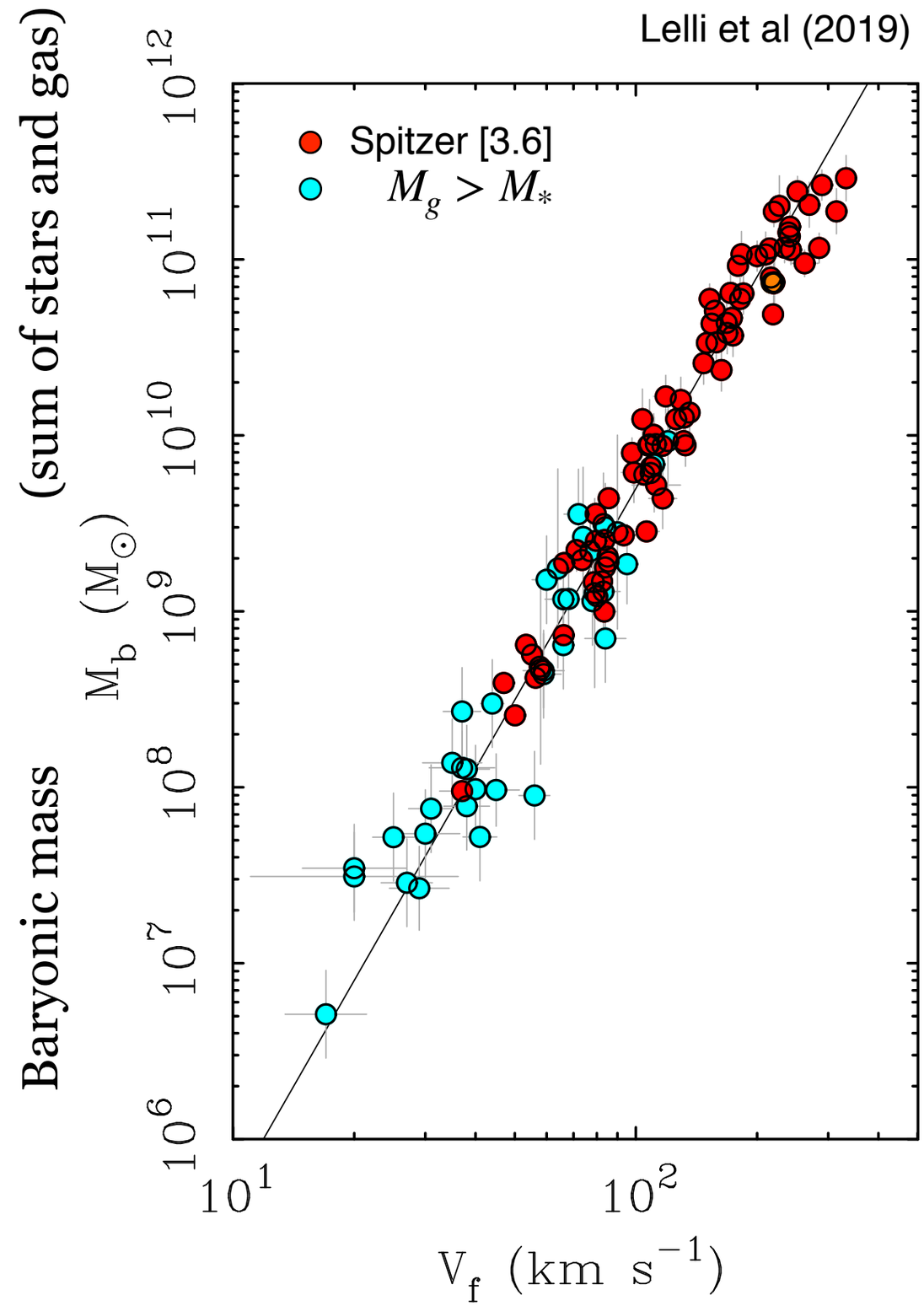
gas dominated LSBs

flat rotation speed minimizes scatter

3. Tully-Fisher relations

amplitude of flat rotation correlates with mass





flat rotation speed

3. Tully-Fisher relations

amplitude of flat rotation correlates with mass

2019

The fundamental relation
is between
baryonic mass
and the amplitude of the
flat rotation speed

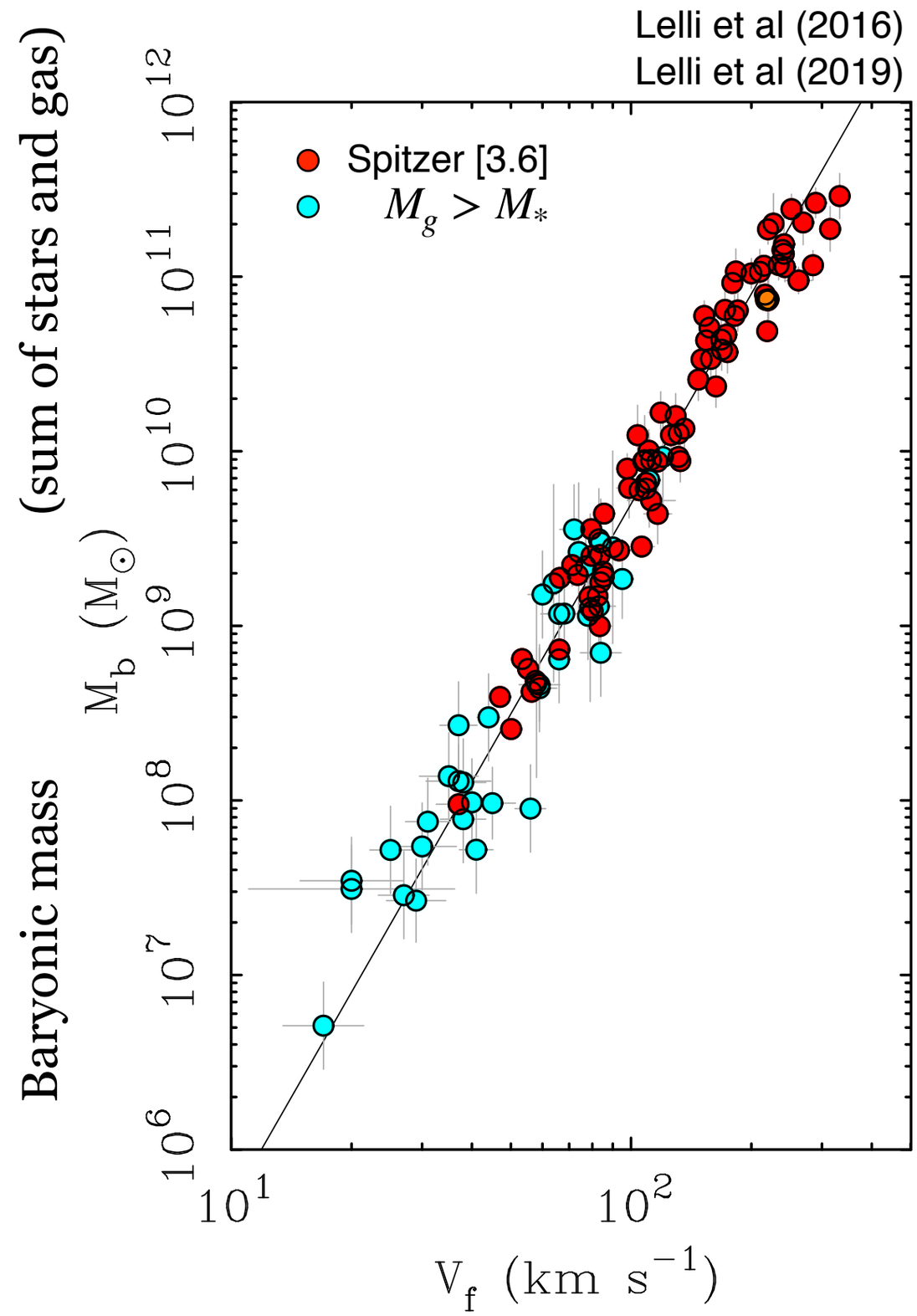
$$M_b = M_* + M_g = AV_f^4$$

$$A = 48.5 \pm 3.3\ \mathrm{M}_\odot\,(\mathrm{km\,s^{-1}})^{-4}$$

there is remarkably little
intrinsic scatter

$$\sigma_M < 0.11\ \mathrm{dex}$$

which is about what is
expected for scatter in
stellar population M*/L



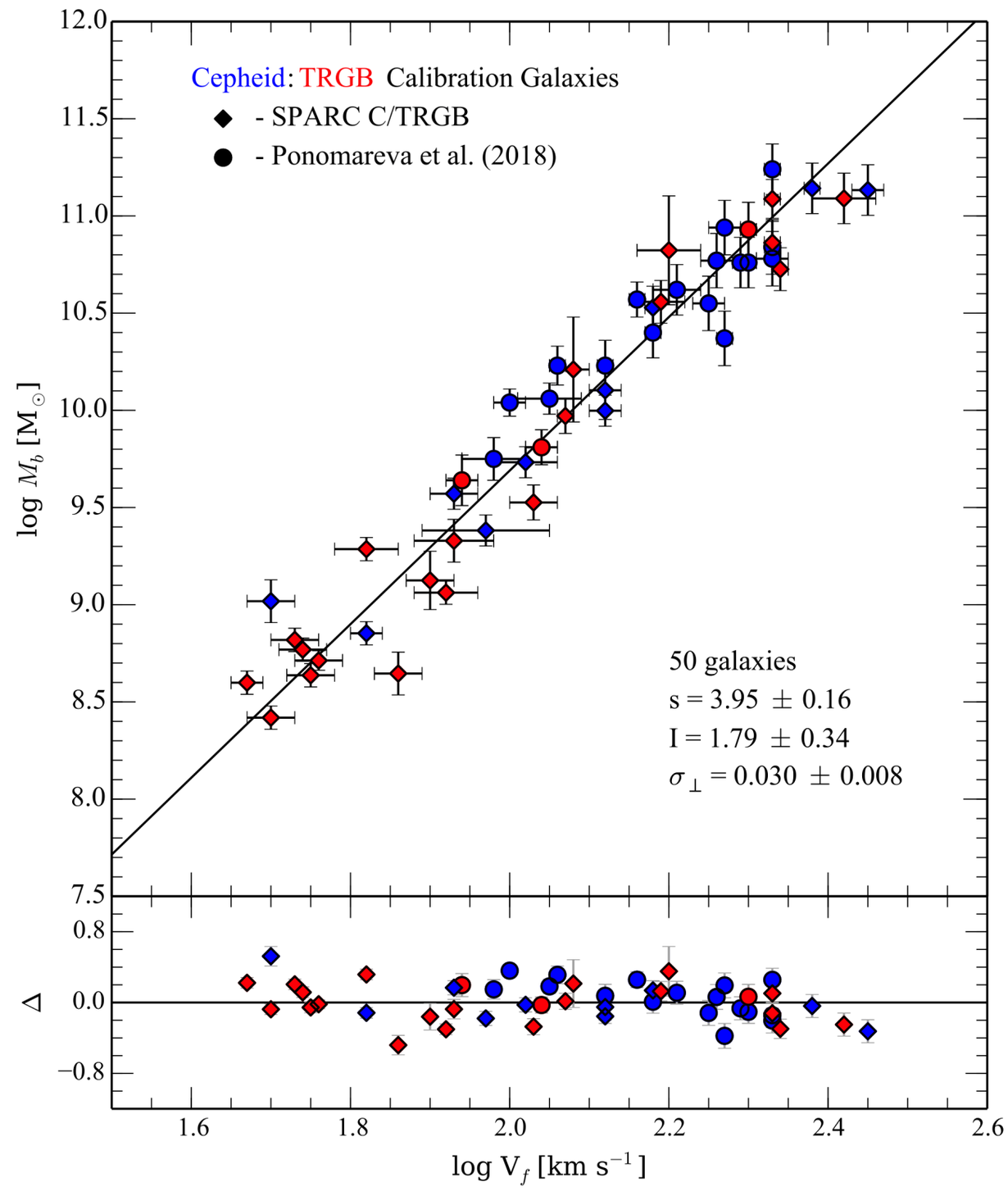
flat rotation speed

Example application:
Calibrate BTFR with 50 galaxies having distances that are known via either Cepheids of Tip of the Red Giant Branch measurements.

Applied to ~100 galaxies with high quality rotation curves, this provides a local measurement of the Hubble constant:

$$H_0 = 75.1 \pm 2.3 \text{ (stat)} \ \pm 1.5 \text{ (sys) km s}^{-1}\text{ Mpc}^{-1}$$

Schombert, McGaugh, & Lelli 2020, AJ, 160, 71



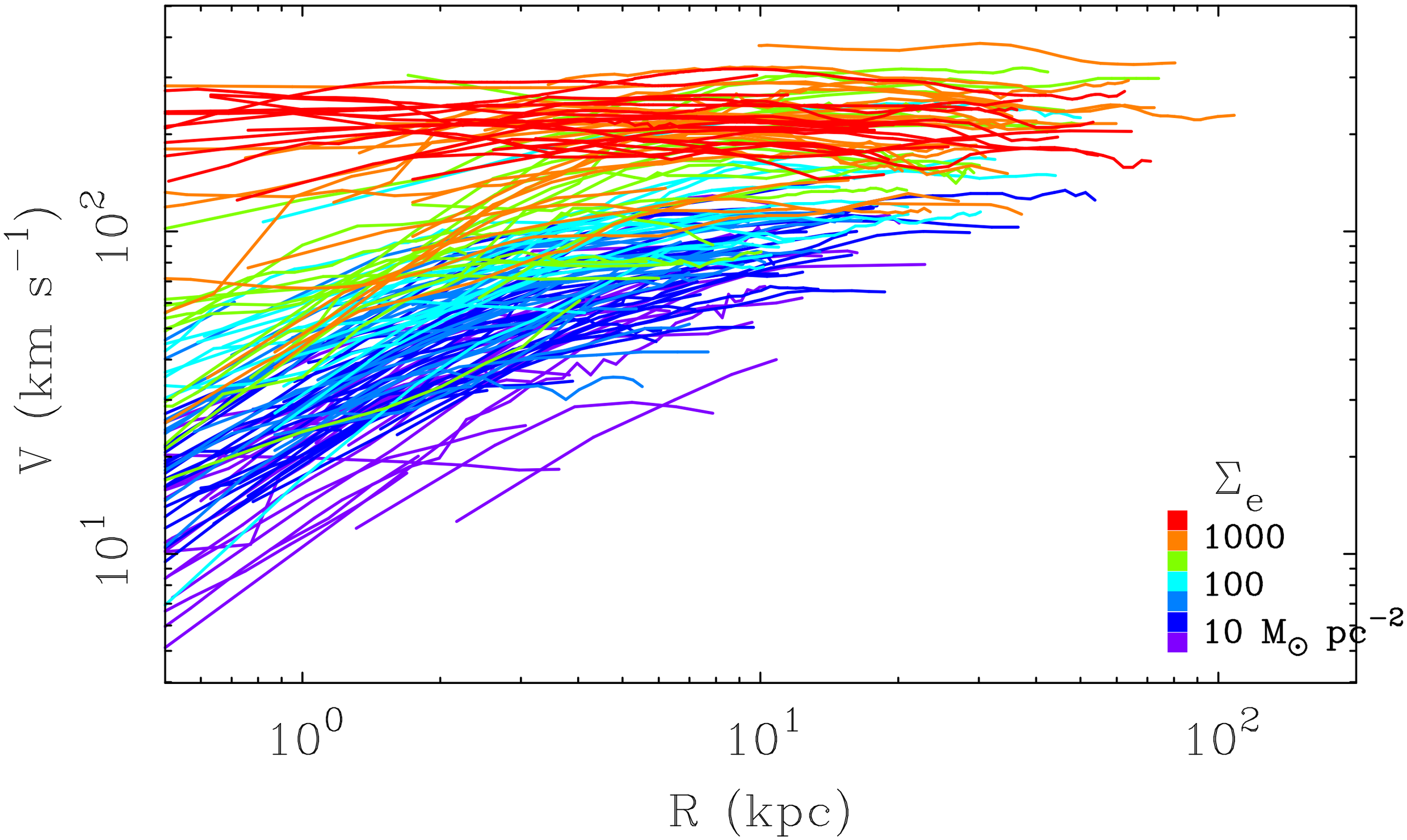
This is consistent with the application of the traditional luminosity-linewidth Tully-Fisher relation to a much larger sample of ~10,000 galaxies.

$$H_0 = 75.1 \pm 0.2 \text{ (stat)} \ \pm 3 \text{ (sys) km s}^{-1}\text{ Mpc}^{-1}$$

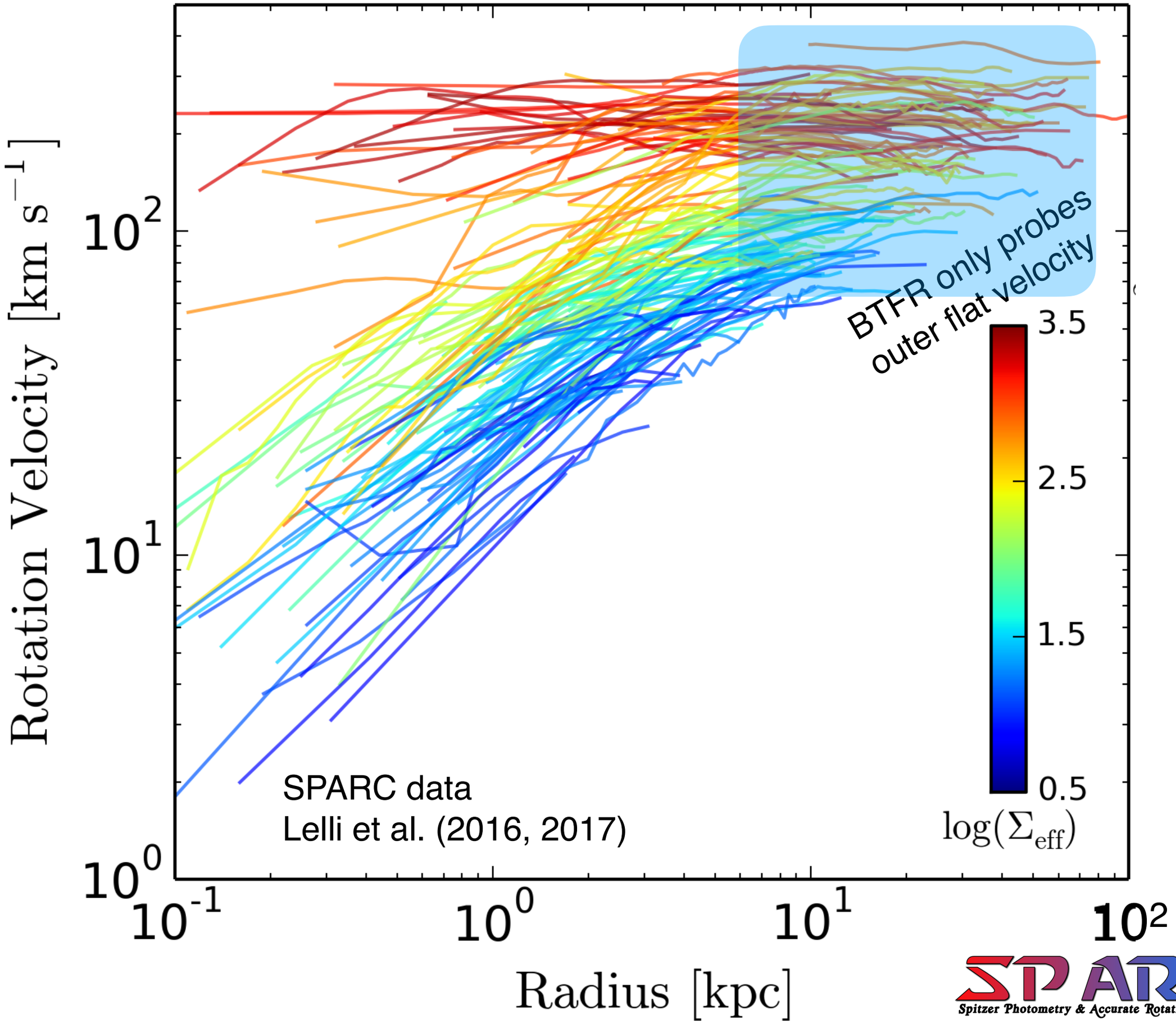
Kourkchi, Tully, *et al*. 2020, arXiv:2009.00733

The shape of the rotation curve correlates with the stellar surface density.

Lelli et al (2016)
Spitzer [3.6] data

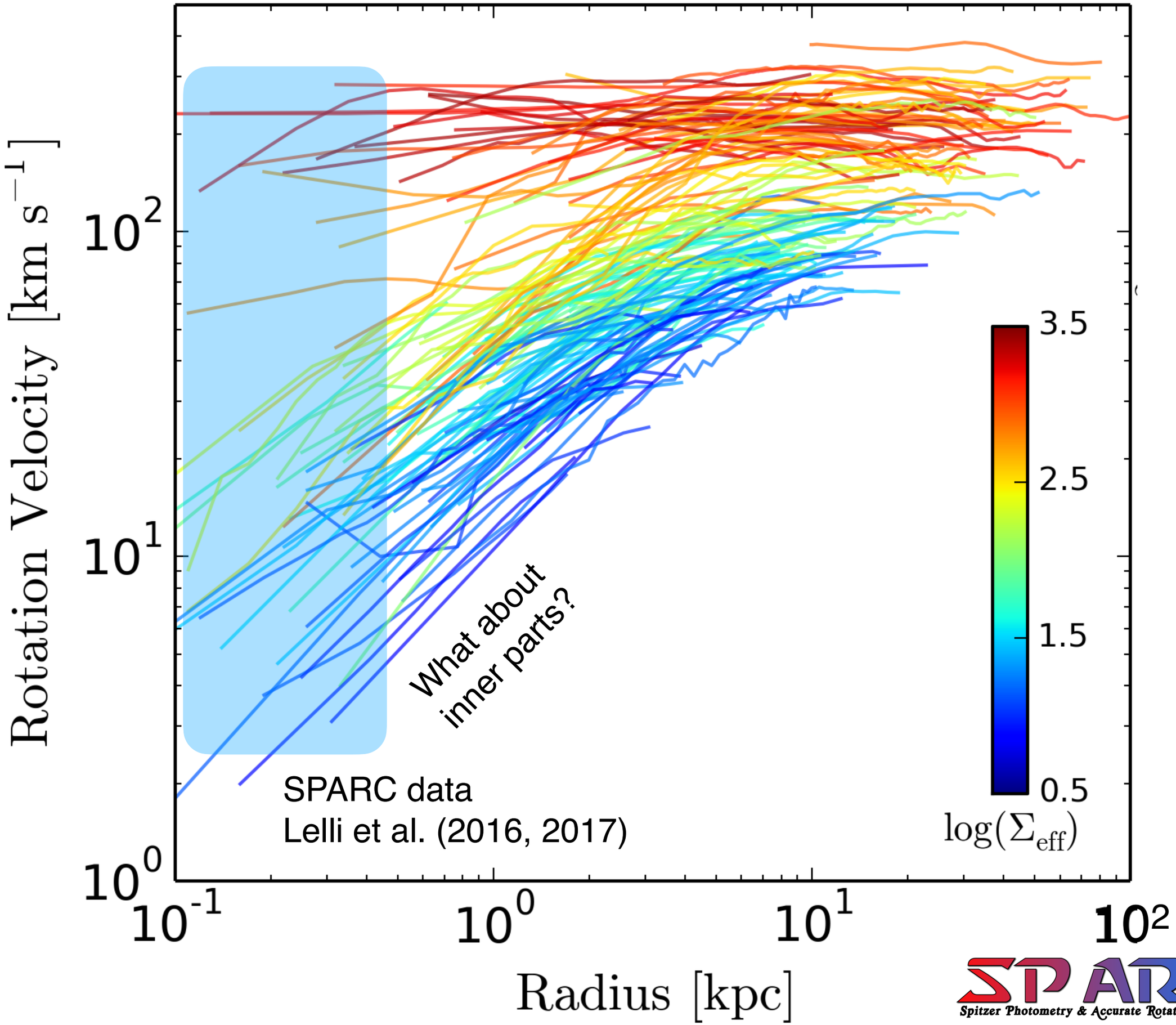


Rotation curve shape correlates with baryonic surface density



SPARC
Spitzer Photometry & Accurate Rotation Curves

Rotation curve shape correlates with baryonic surface density



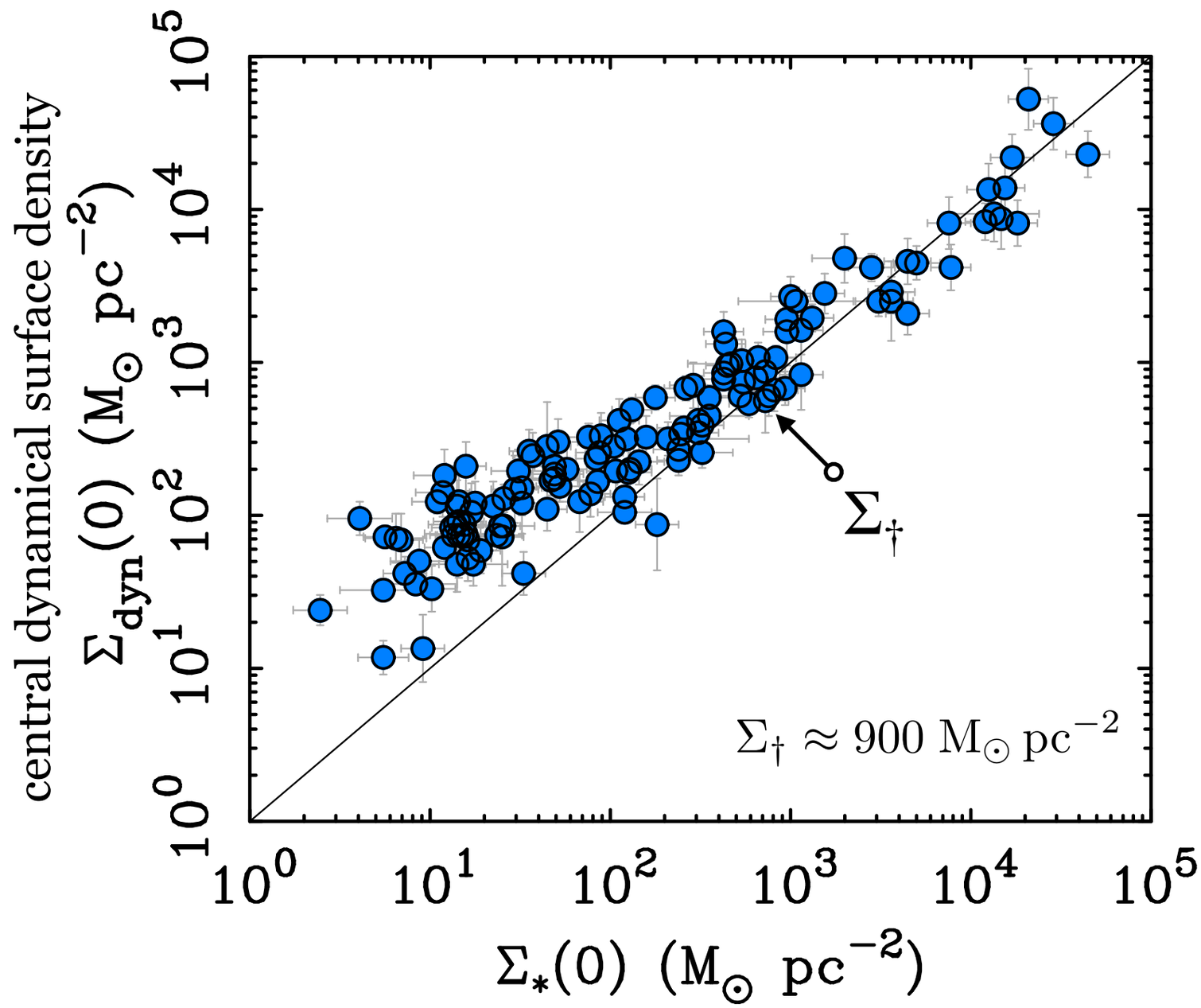
SPARC
Spitzer Photometry & Accurate Rotation Curves

4. Central Density Relation

Lelli et al. (2016)

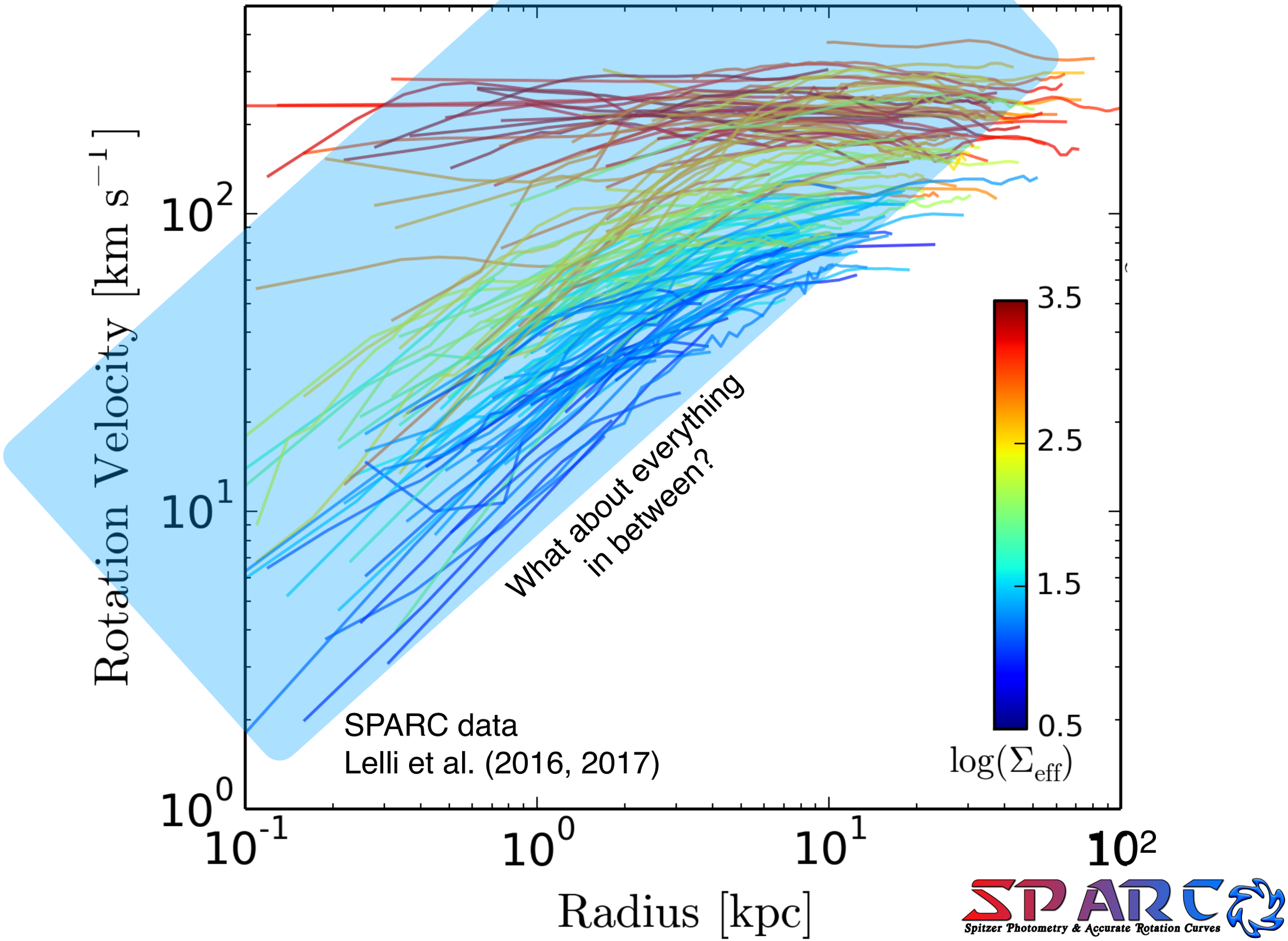
The *dynamical* central mass surface density correlates with the central surface brightness of stars in galaxies.

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

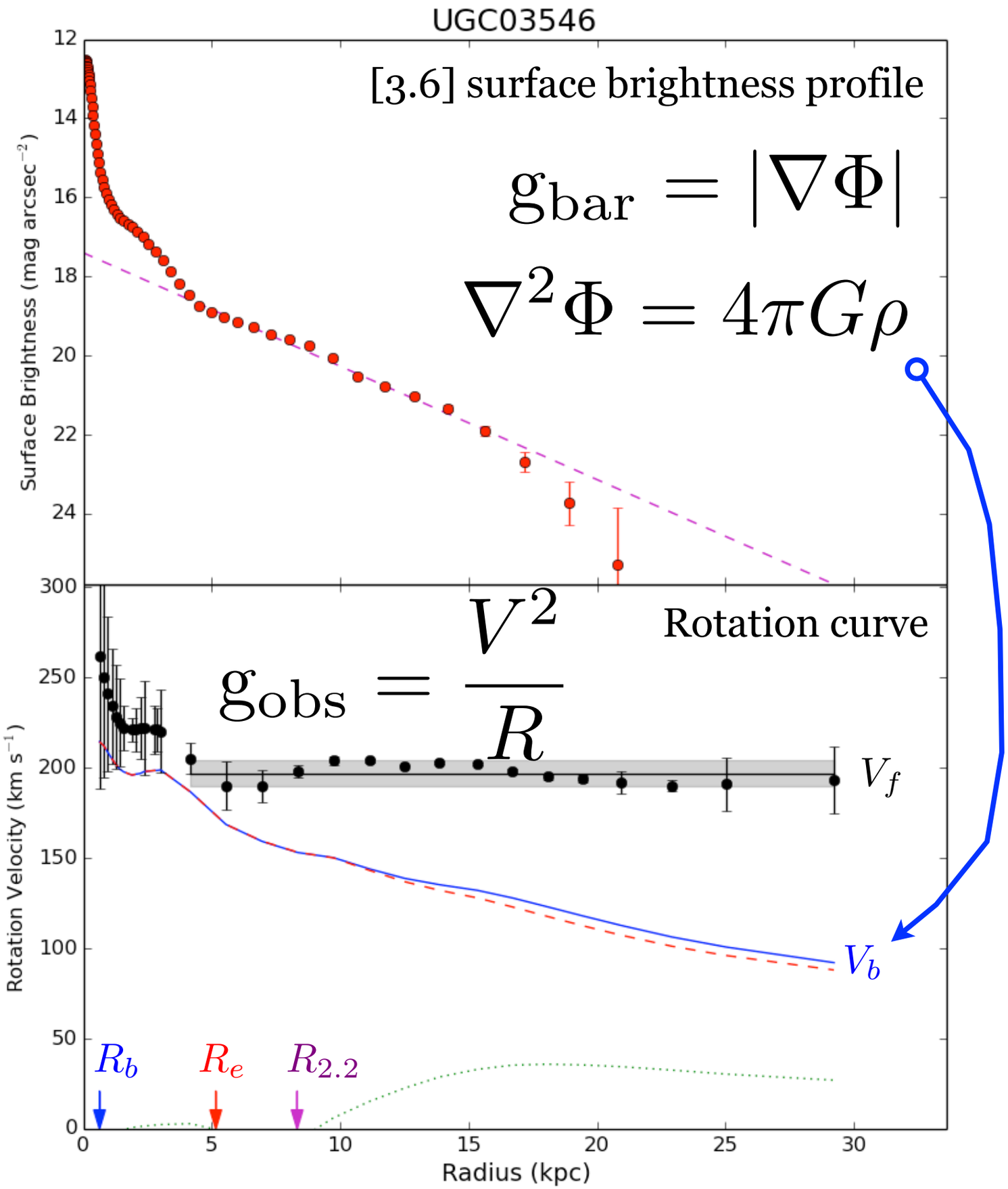


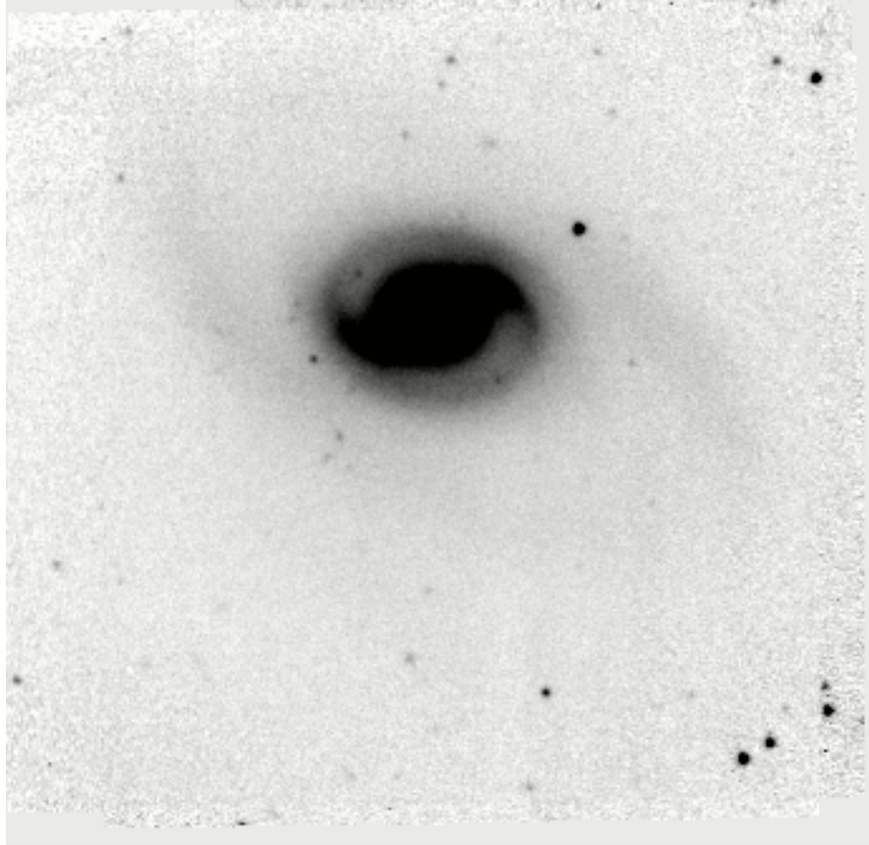
central surface brightness

Rotation curve shape correlates with baryonic surface density

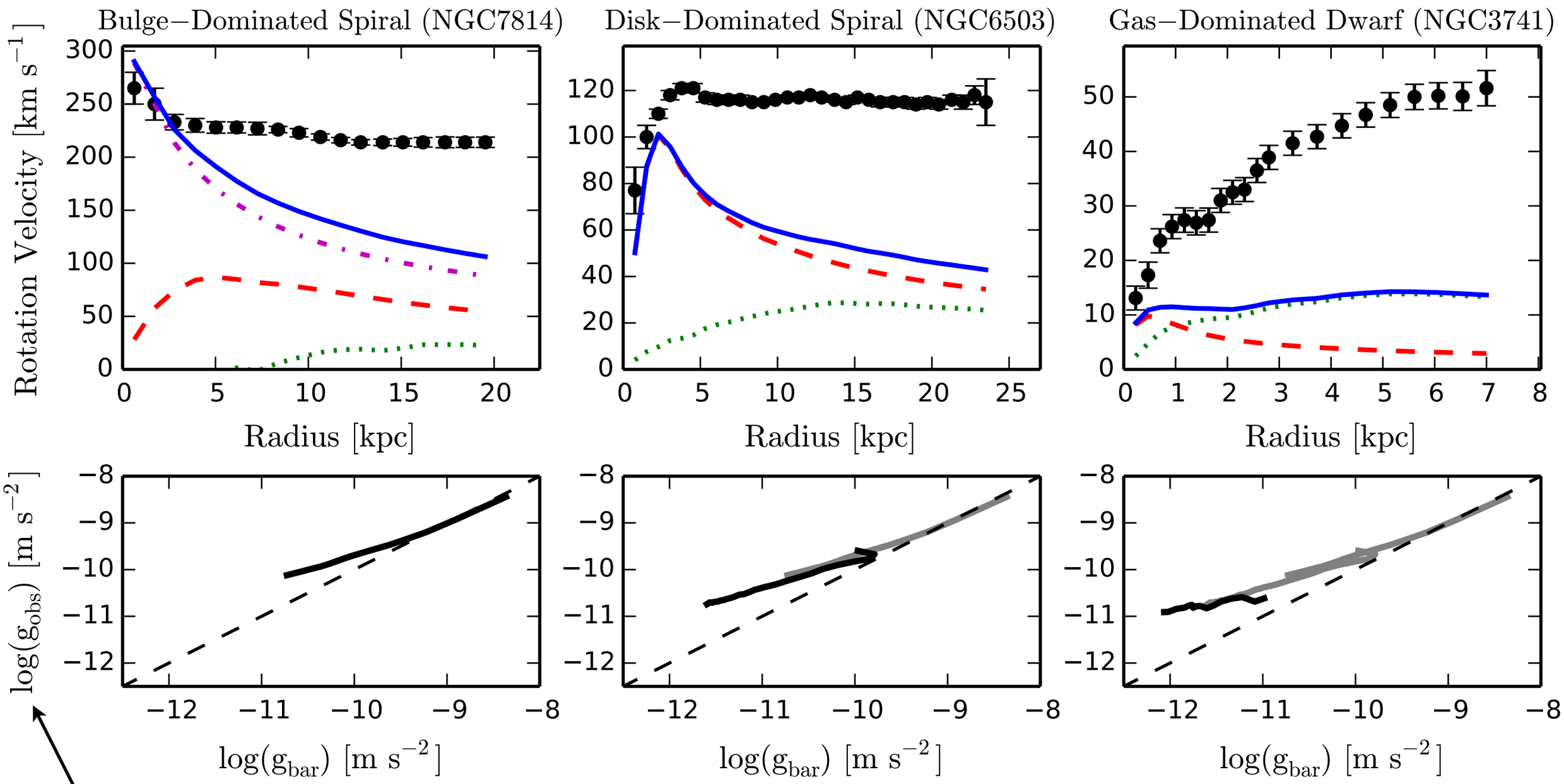


What about everything in between?





The observed centripetal acceleration is linked to that predicted by the observed distribution of baryons.



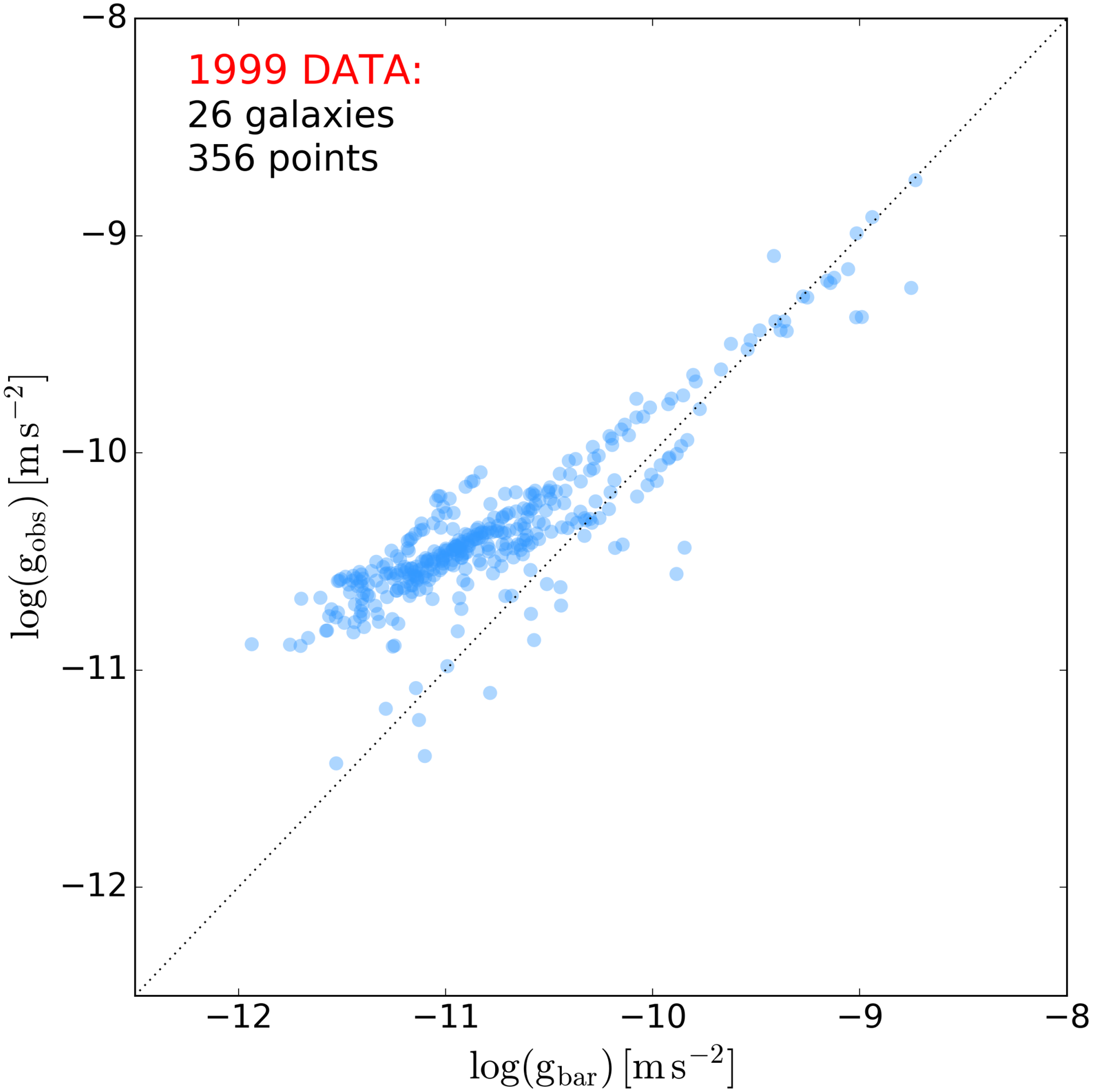
$$g_{obs} = \frac{V^2}{R}$$

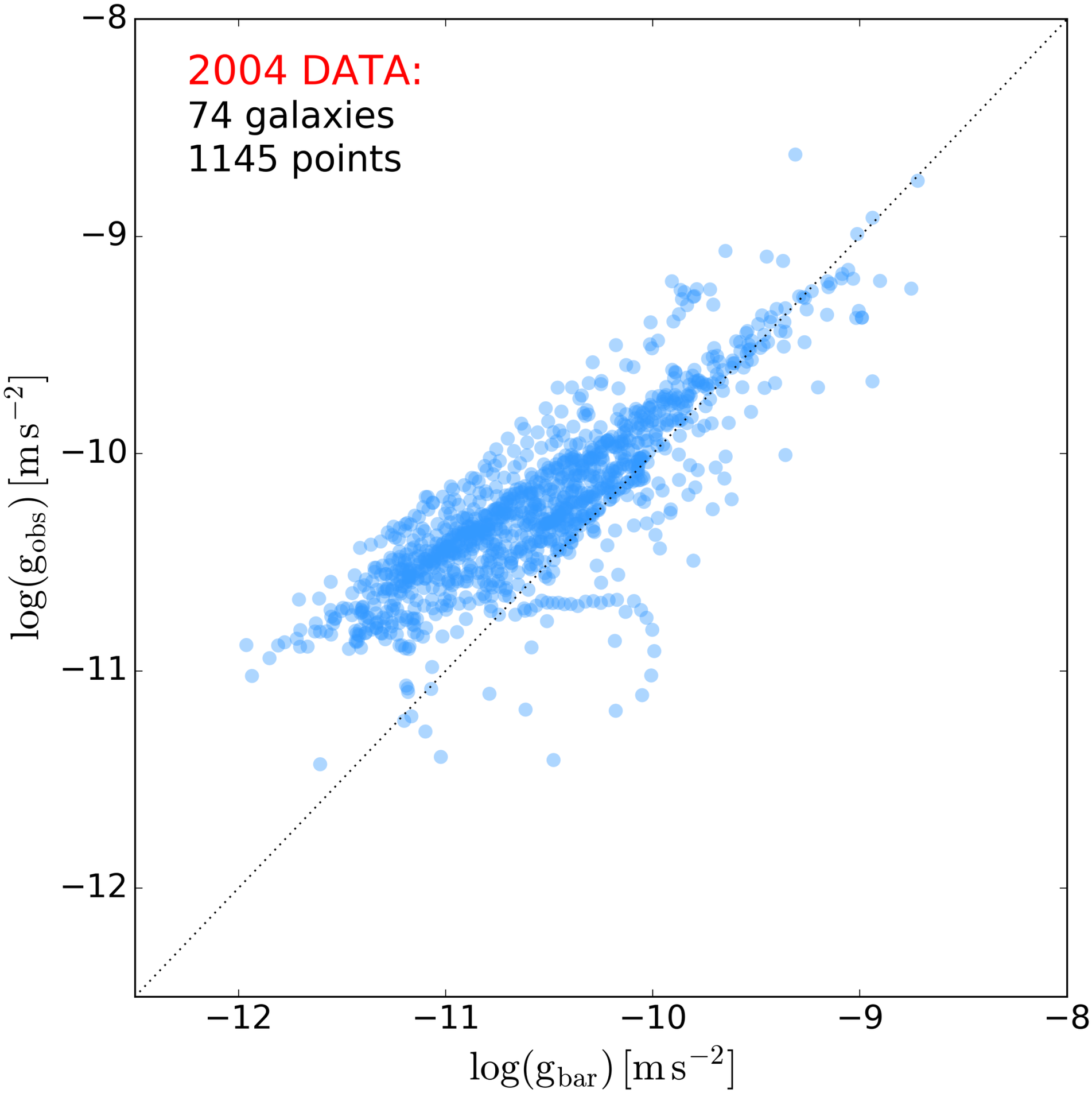
independent quantities

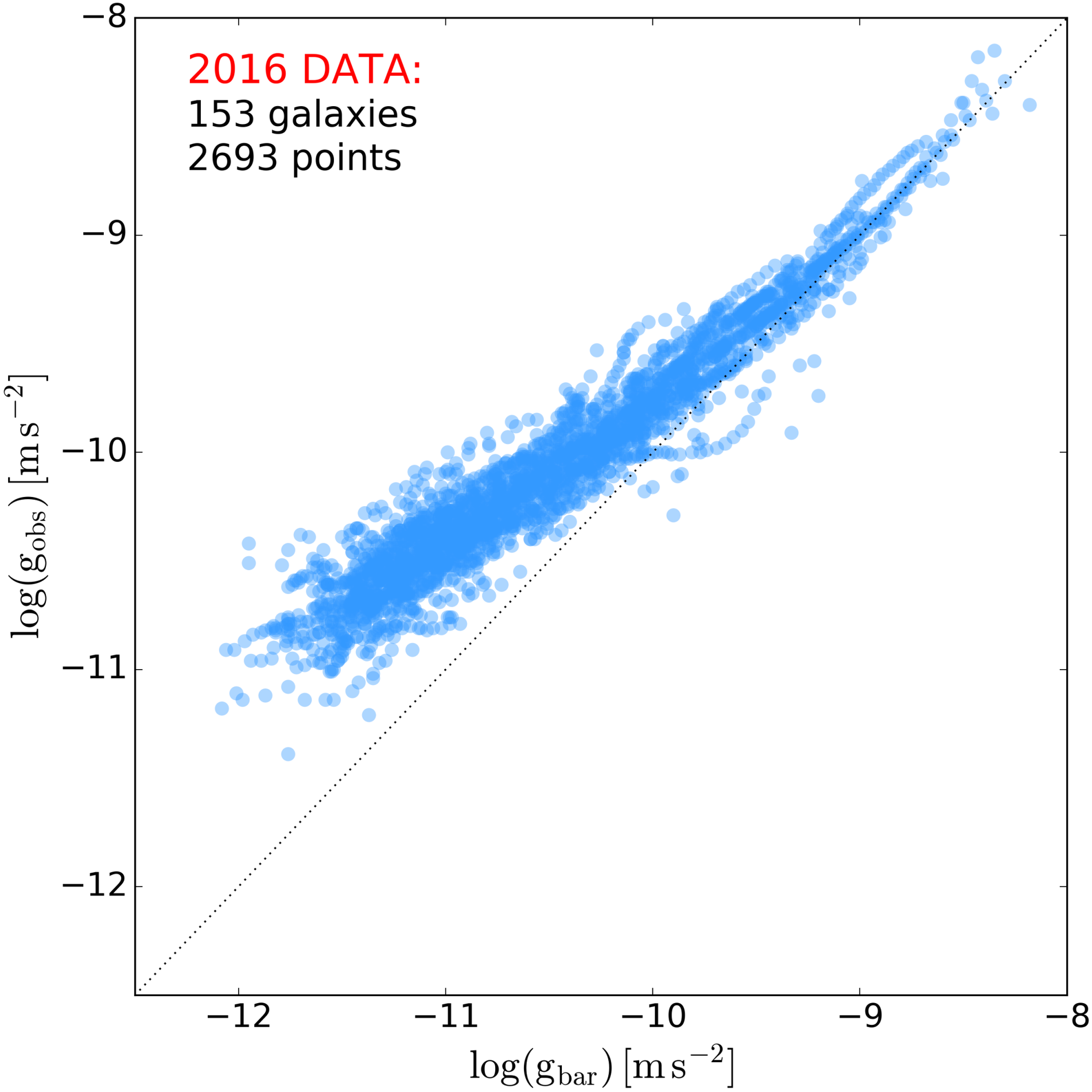
$$g_{bar} = \left|\frac{\partial \Phi}{\partial R}\right|$$

determined from rotation curve

determined from baryon distribution


1999 DATA:
26 galaxies
356 points
−8
−9
−10
−11
−12
−12
−11
−10
−9
−8
$\log(g_{obs})\,[m\,s^{-2}]$
$\log(g_{bar})\,[m\,s^{-2}]$


2004 DATA:
74 galaxies
1145 points
−8
−9
−10
−11
−12
−12
−11
−10
−9
−8
$\log(g_{obs})\,[m\,s^{-2}]$
$\log(g_{bar})\,[m\,s^{-2}]$


2016 DATA:
153 galaxies
2693 points
−8
−9
−10
−11
−12
−12
−11
−10
−9
−8
$\log(g_{obs})\,[m\,s^{-2}]$
$\log(g_{bar})\,[m\,s^{-2}]$

5. Radial Acceleration Relation

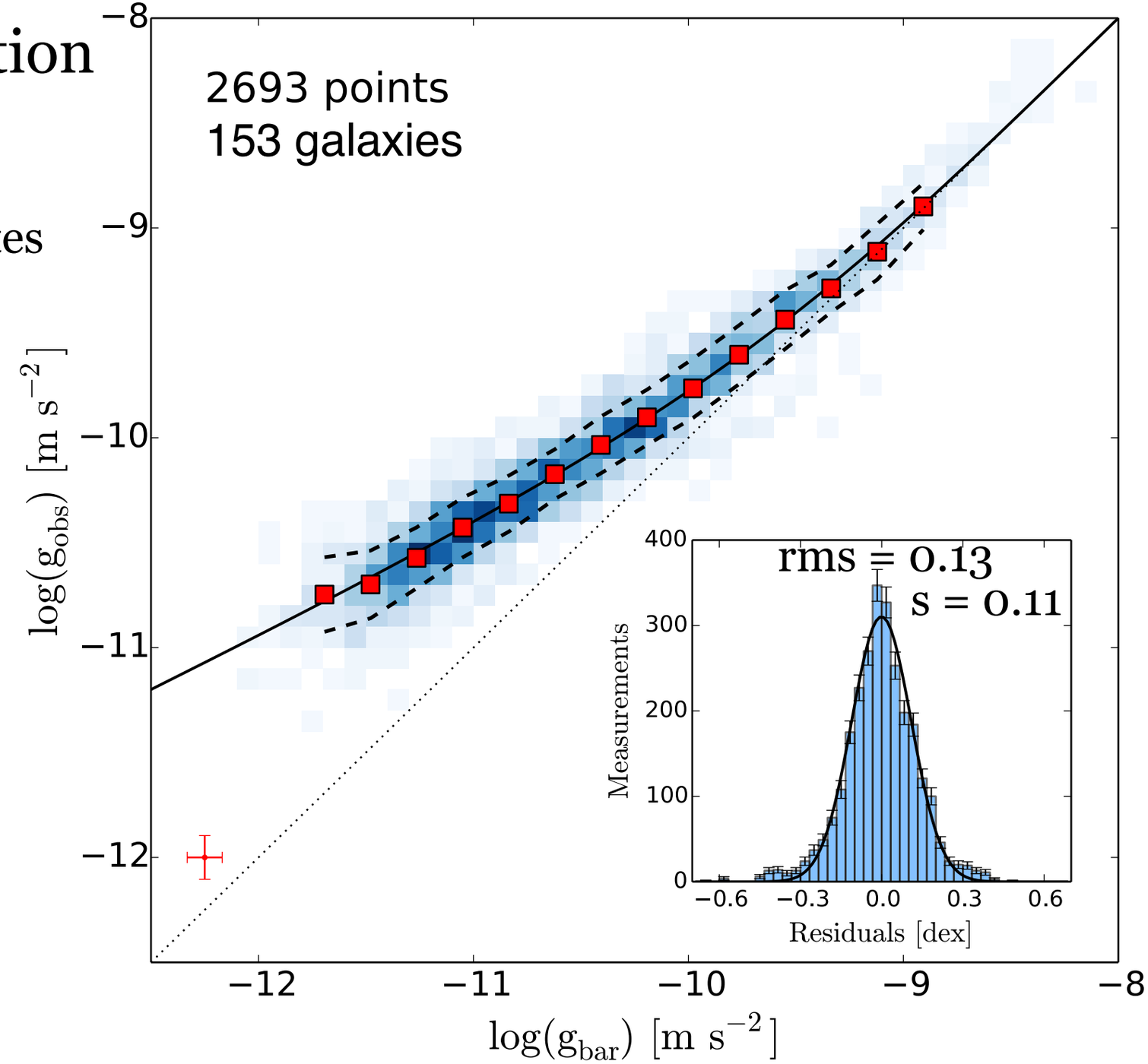
The observed acceleration correlates with that predicted by the baryons

The data are well fit by

$$g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_\dagger}}}$$

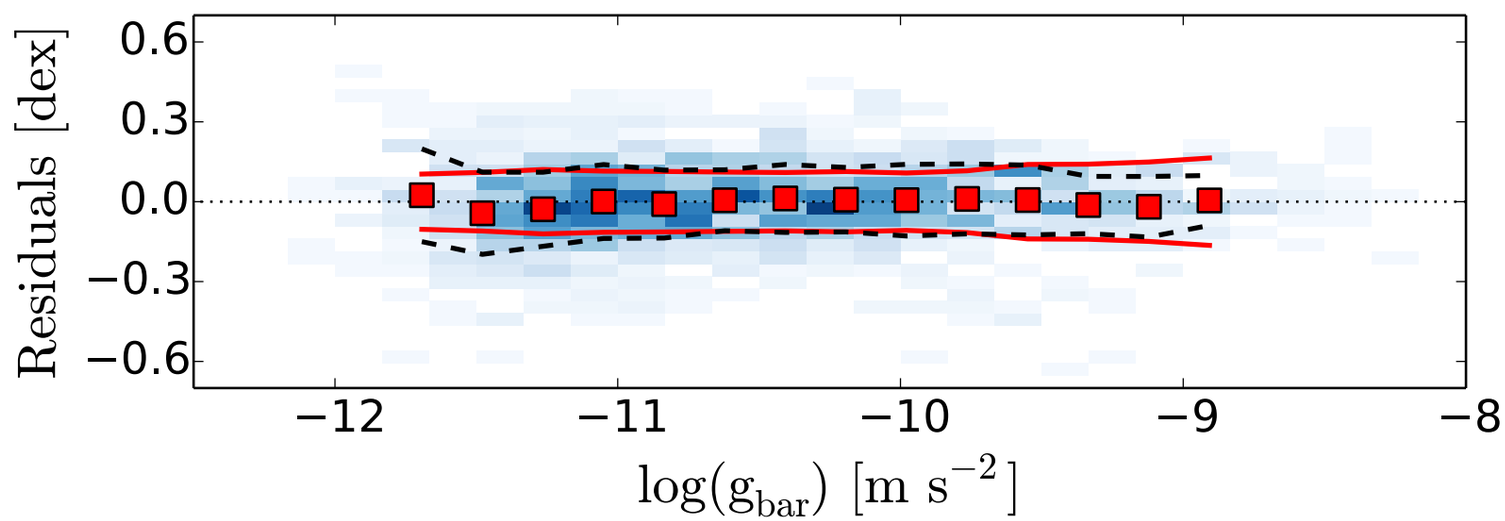
$$g_\dagger = 1.20 \times 10^{-10}\ {\rm m\,s^{-2}}$$

± 0.02 (random) $\pm\, 0.24$ (systematic)



observed rms scatter

scatter expected from observational errors



The data are consistent with zero intrinsic scatter

These are like Kepler's laws, but for galaxies

Kinematic Scaling Relations

1. Flat Rotation Curves
2. Renzo's Rule
3. Baryonic Tully-Fisher Relation
4. Central Density Relation
5. Radial Acceleration Relation

Kinematic Scaling Relations are strong, have little intrinsic scatter.

McGaugh et al. 2019, IAU 353 (arXiv:**1909.02011**)

The quantitative relations involve a critical acceleration scale.

This acceleration scale is ubiquitous in galaxy data.

- Baryonic Tully-Fisher Relation

$$g_\dagger^{\mathrm{BTFR}} = \frac{\chi V_f^4}{G M_b} = 1.24 \times 10^{-10} \pm 0.14 \ \mathrm{m\,s^{-2}}$$

(McGaugh 2011)

- Central Density Relation

$$g_\dagger^{\mathrm{CDR}} = G\Sigma_\dagger = 1.27 \pm 0.05 \times 10^{-10} \ \mathrm{m\,s^{-2}}$$

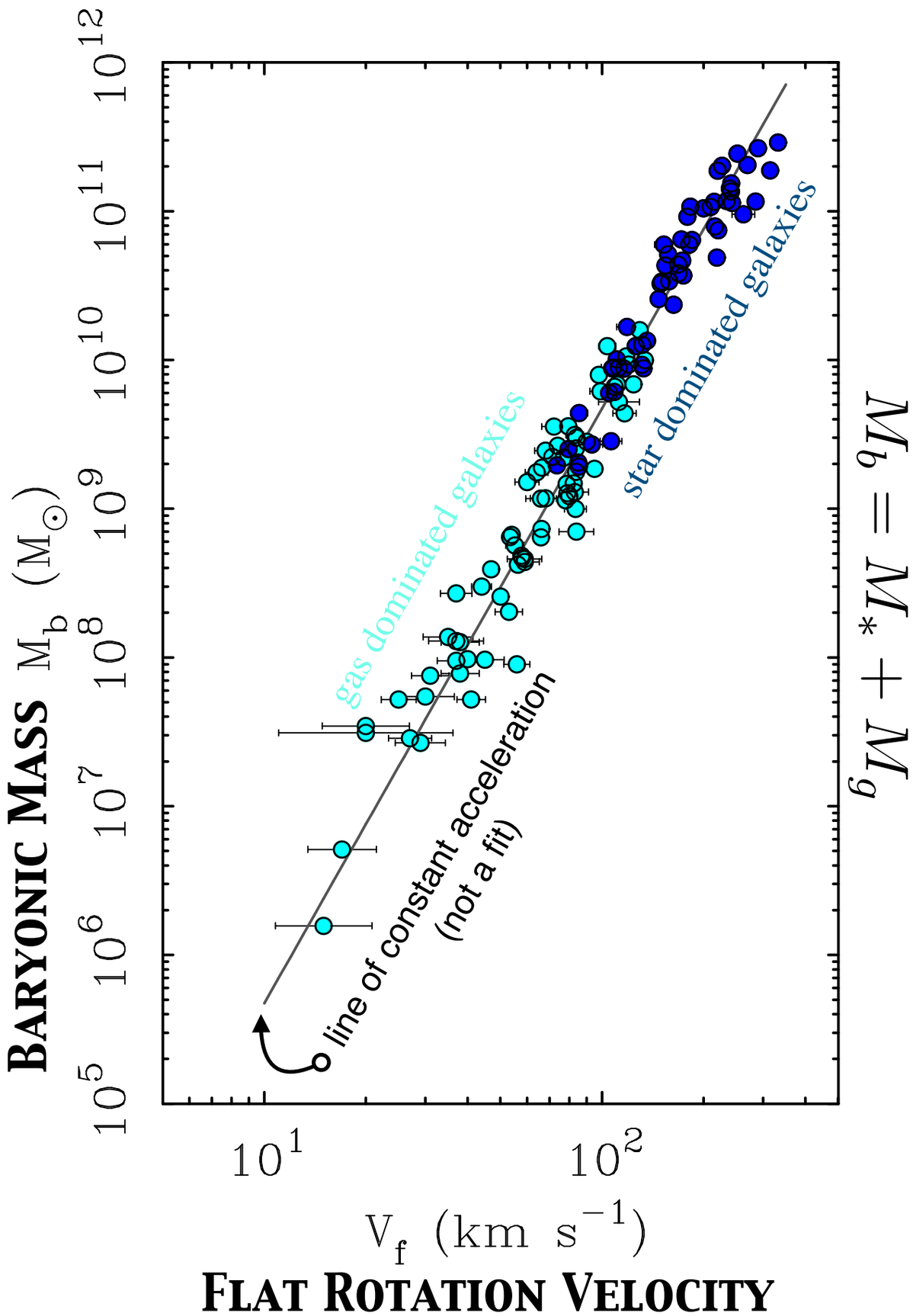
(Lelli et al. 2016)

- Radial Acceleration Relation

$$g_\dagger^{\mathrm{RAR}} = 1.20 \pm 0.02 \times 10^{-10} \ \mathrm{m\,s^{-2}}$$

(McGaugh et al. 2016)

Baryonic Tully-Fisher Relation



Can construct a characteristic acceleration for each galaxy

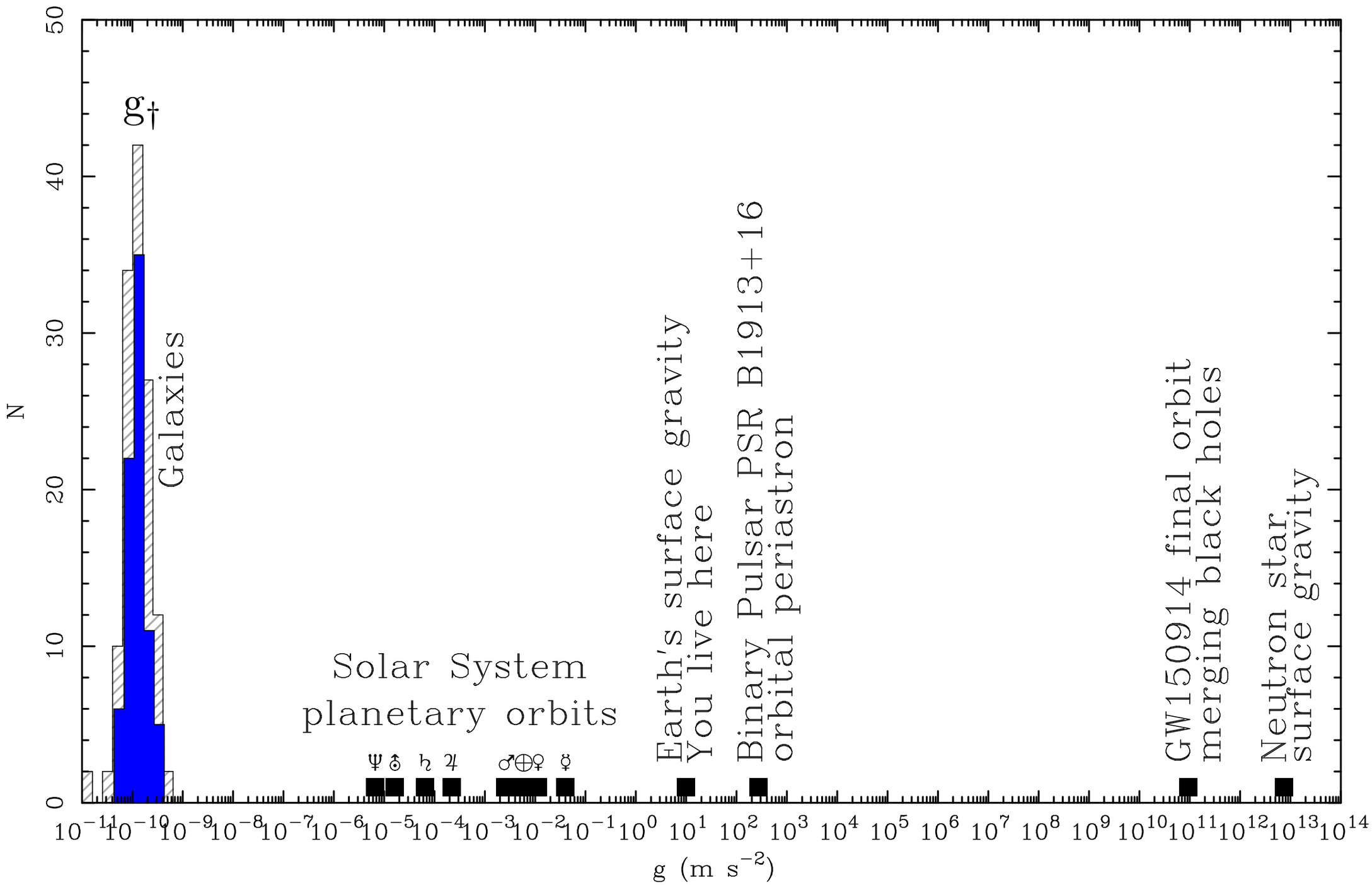
$$g_\dagger = \frac{\chi V_f^4}{G M_b}$$

Galaxies closely follow a single, universal acceleration.

χ is a factor of order unity that accounts for the geometry of disk galaxies, which are not spherical cows. We adopt $\chi = 0.8$ (McGaugh & de Blok 1998; McGaugh 2005).

Over 25 decades in acceleration,
galaxies only exist around 1 Å/s/s

$g_\dagger$ is a special value



Laws of Galactic Rotation

1. Flat Rotation Curves
2. Renzo's Rule
3. Baryonic Tully-Fisher Relation
4. Central Density Relation
5. Radial Acceleration Relation

There is a ubiquitous acceleration scale in the data: $g_\dagger = 1.2 \times 10^{-10}\ \mathrm{m\,s^{-2}}$

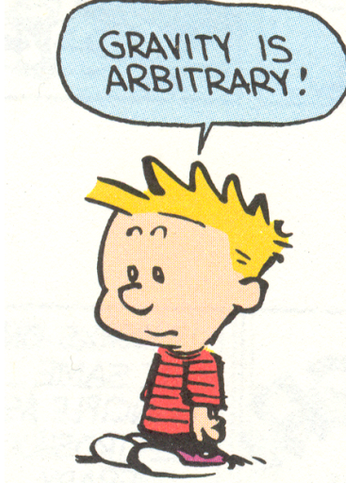
Modified gravity rather than dark matter?
MOND - predicted exactly what we see

MOND

Modified Newtonian Dynamics

introduced by Moti Milgrom in 1983

http://www.scholarpedia.org/article/The_MOND_paradigm_of_modified_dynamics



Modify the force law at an acceleration scale (*not* a length scale)

Above a critical acceleration a_0 everything is normal. Below that scale, gravity in, effect becomes stronger.

$$g_N = \mu(a/a_0)a$$

Newtonian and MOND regimes joined by smooth interpolation function $\mu(a/a_0)$ with asymptotic limits

$$a \to g_N \quad \text{for} \quad a \gg a_0$$

$$a \to \sqrt{g_N a_0} \quad \text{for} \quad a \ll a_0$$

$$a_0 = 1.2 \times 10^{-10}\ \mathrm{m\ s^{-2}}$$

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MOND can be interpreted as either a modification of gravity or inertia

modify inertia

$$F = m_i a$$

$$m_i \neq m_g$$

modify gravity

$$F = \frac{G m_1 m_2}{r^2}$$

$$g_N = \mu(a/a_0)a$$

Newtonian and MOND regimes joined by smooth interpolation function $\mu(a/a_0)$ with asymptotic limits

$$a \to g_N \quad \text{for} \quad a \gg a_0$$

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First theory derived from a Lagrangian by Bekenstein & Milgrom (1984)

$\nabla^2\Phi = 4\pi G\rho$ modified Poisson equation to $\nabla \cdot \left[\mu\left(\frac{|\nabla\Phi|}{a_0}\right)\nabla\Phi\right] = 4\pi G\rho$

Generalizes Newton but not Einstein

$g_N = \mu(a/a_0)a$ Newtonian and MOND regimes joined by smooth interpolation function $\mu(a/a_0)$ with asymptotic limits

$a \to g_N$ for $a \gg a_0$

$a \to \sqrt{g_N a_0}$ for $a \ll a_0$

$a_0 = 1.2 \times 10^{-10}\ \mathrm{m\ s^{-2}}$

Table 1. MOND Predictions and Tests.

Prediction	Test Positive?	*A Priori*?	
MASR (Tully–Fisher) (Baryonic Tully-Fisher Relation)			
Property 1. Normalization	Yes	No	
Property 2. Slope	Yes	☆ No	
Property 3. Mass & Asymptotic Speed	Yes	★ Yes	Not expected with DM
Property 4. Surface Brightness Independence	Yes	★ Yes	Contradicts DM?
Rotation Curves			
Property 5. Flat Rotation Curves (First Law)	Yes	No	
Property 6. Acceleration Discrepancy (RAR)	Yes	★ Yes	Not expected with DM
Property 7. Rotation Curve Shapes	Yes	★ Yes	
Property 8. Surface Brightness & Density (Central Density rel'n)	Yes	★ Yes	
Property 9. Detailed Fits	Yes	★ No	Not expected with DM
Property 10. Stellar Population Υ_*	Yes	★ —	
Property 11. Feature Correspondence (Renzo's rule)	Yes	★ —	Contradicts DM?
Disk Stability			
Property 12. Freeman Limit	Yes	☆ No	Not expected with DM
Property 13. Vertical Velocity Dispersions	?	No	
Property 14. LSB Galaxy Morphology	Yes	★ Yes	Contradicts DM?

Galaxies **8** (2020) 35 (arXiv:2004.14402)

Newtonian regime

$$g_{in} > a_0 \qquad M = \frac{RV^2}{G}$$

e.g., surface of the Earth

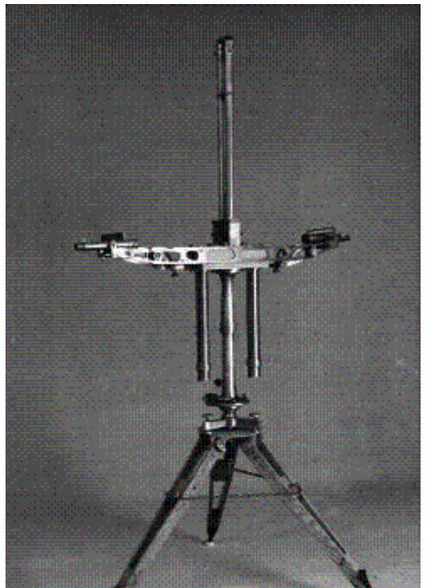
ISO MOND regime

$$g_{in} < a_0 \qquad M = \frac{V^4}{a_0 G}$$

e.g., remote dwarf Leo I

External Field dominant Newtonian regime

$$g_{in} < a_0 < g_{ex} \qquad M = \frac{RV^2}{G}$$



e.g., Eotvos-type experiment on the surface of the Earth

EFE External Field dominant quasi-Newtonian regime

$$g_{in} < g_{ex} < a_0 \qquad M = \frac{g_{ex}}{a_0}\frac{RV^2}{G}$$

e.g., nearby dwarf Segue 1

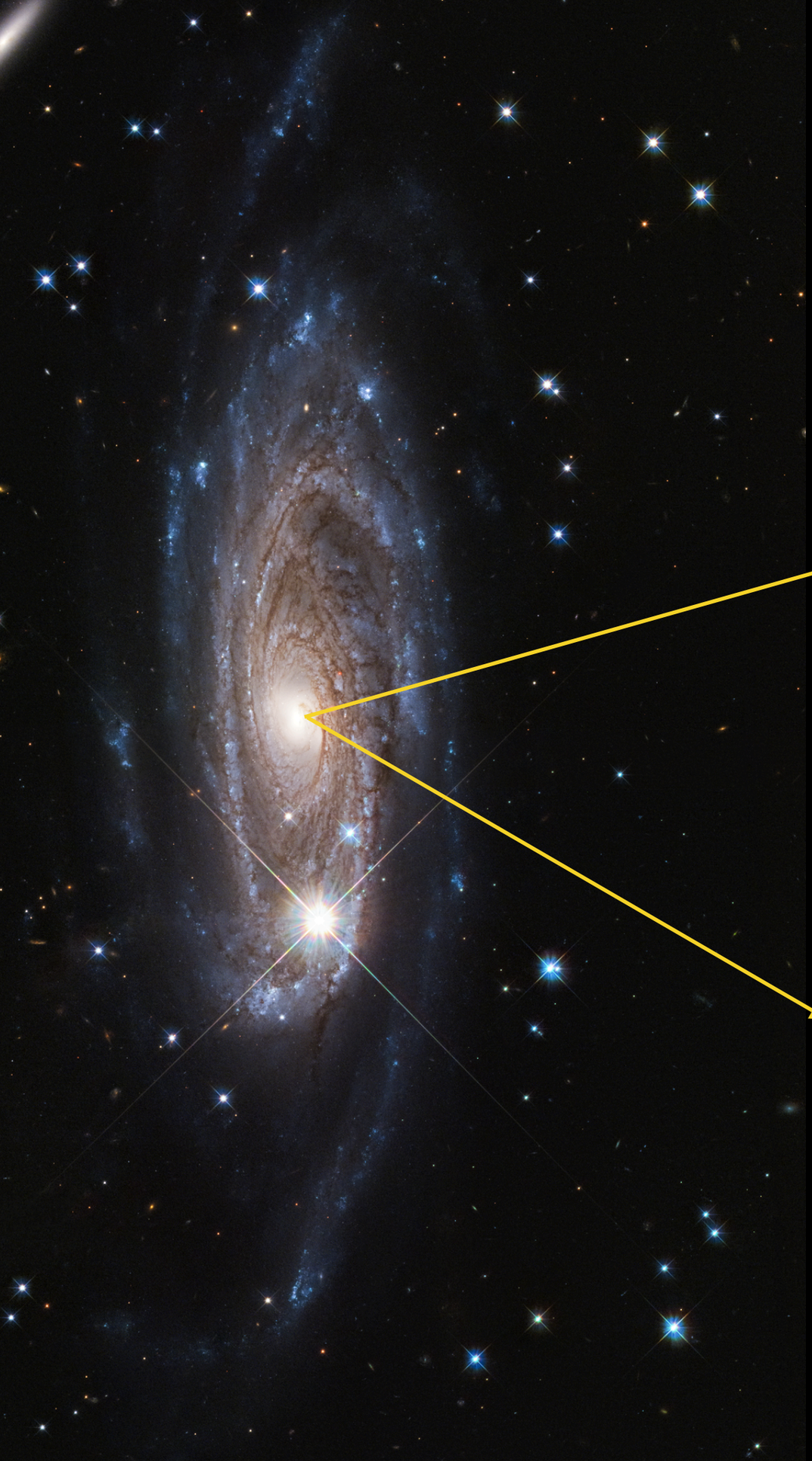
Equivalence Principles

Will (2014) *Living Reviews in Relativity* **17**, 4 (arXiv:1403.7377)

- Weak Equivalence Principle
  - universality of free fall

the motion of a particle is independent of its internal structure or composition

- Strong Equivalence Principle $m_i \equiv m_g$
  - WEP + Lorenz Invariance + Local Position Invariance
- Einstein Equivalence Principle
  - SEP but *excluding* gravity from Local Position Invariance
  - Doesn't matter where you do an E&M experiment, but it might matter where you do a gravitational experiment.



Deep MOND Regime

practically isolated; internal field dominates

$g_{ex} < g_{in} < a_0$

$$\sigma_{iso} = \left(\frac{4}{81} a_0 G M_*\right)^{1/4}$$

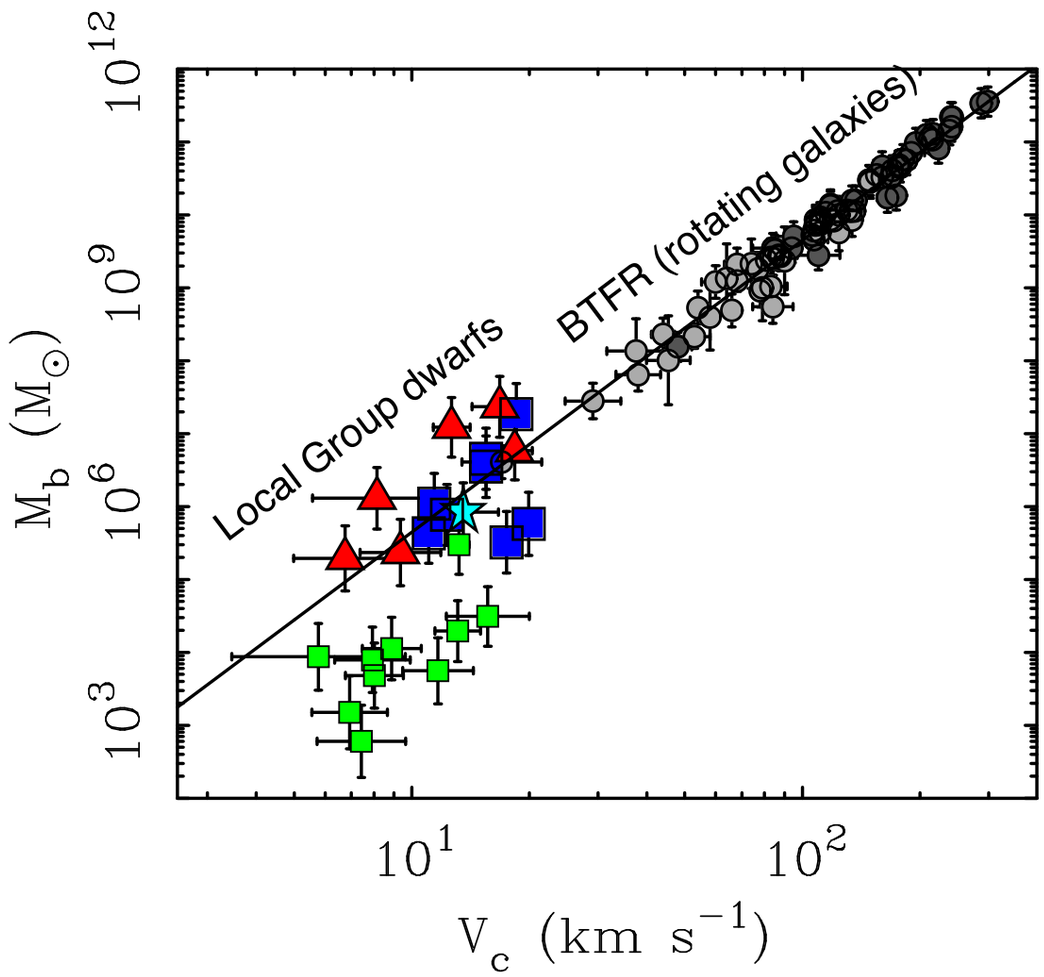
External Field Effect

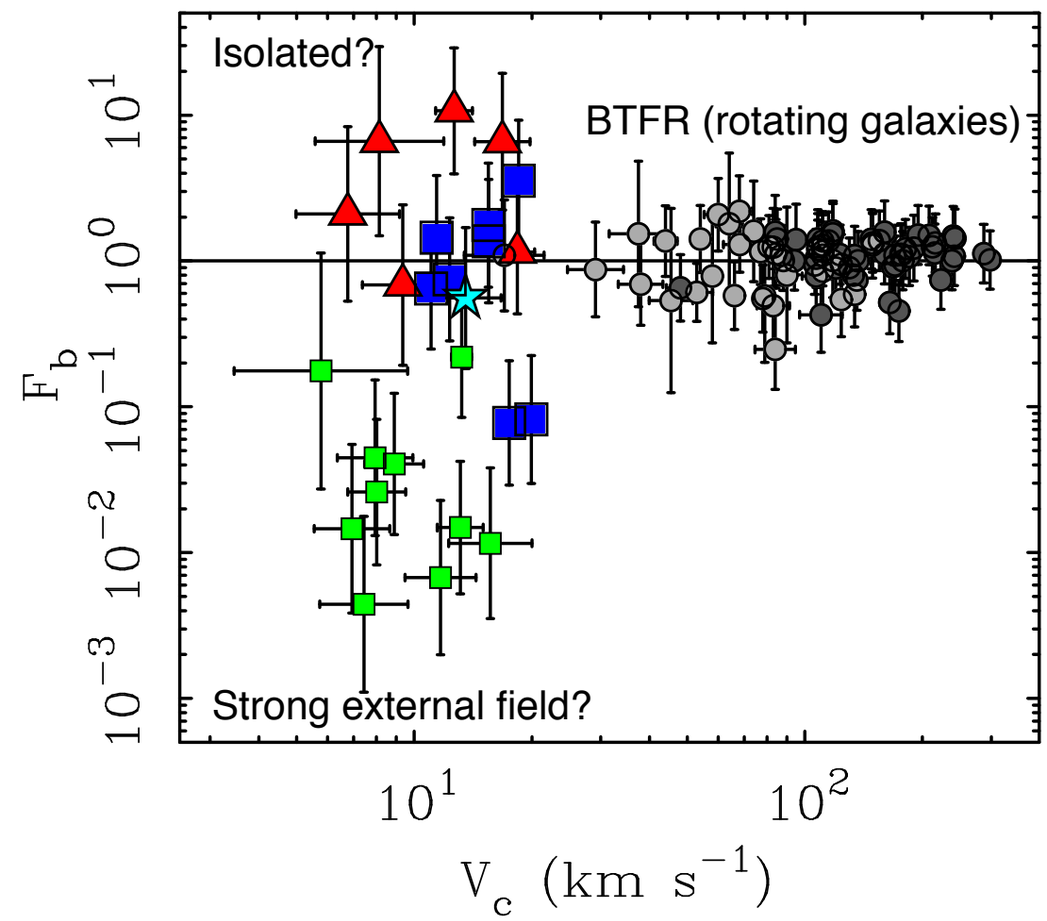
External field stronger than internal field

$g_{in} < g_{ex} < a_0$

$$\sigma_{efe} = \left(\frac{a_0 G M_*}{3 g_{ex} r_{1/2}}\right)^{1/2}$$

Some dwarf galaxies in the Local Group obey the Tully-Fisher relation; others don't.
Is this a sign of the EFE?





We can use MOND to predict the velocity dispersions of dwarf satellite galaxies in advance of their observation.

MOND

Modify gravity at an acceleration scale

Hypothesized by Milgrom (1983)

$a \gg a_0 \qquad a \to g_N$

$a \ll a_0 \qquad a \to \sqrt{g_N a_o}$

$$a_0 = 1.2 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

Unique & unsettling feature of MOND: the external field matters (violates Strong Equivalence)

Isolated MOND regime ISO

$$g_{ex} < g_{in} < a_0$$

Internal gravity of dwarf dominates

$$\sigma_{iso} = \left(\frac{4}{81} a_0 G M_*\right)^{1/4}$$

Prediction depends only on ***stellar mass***

EFE External Field Effect

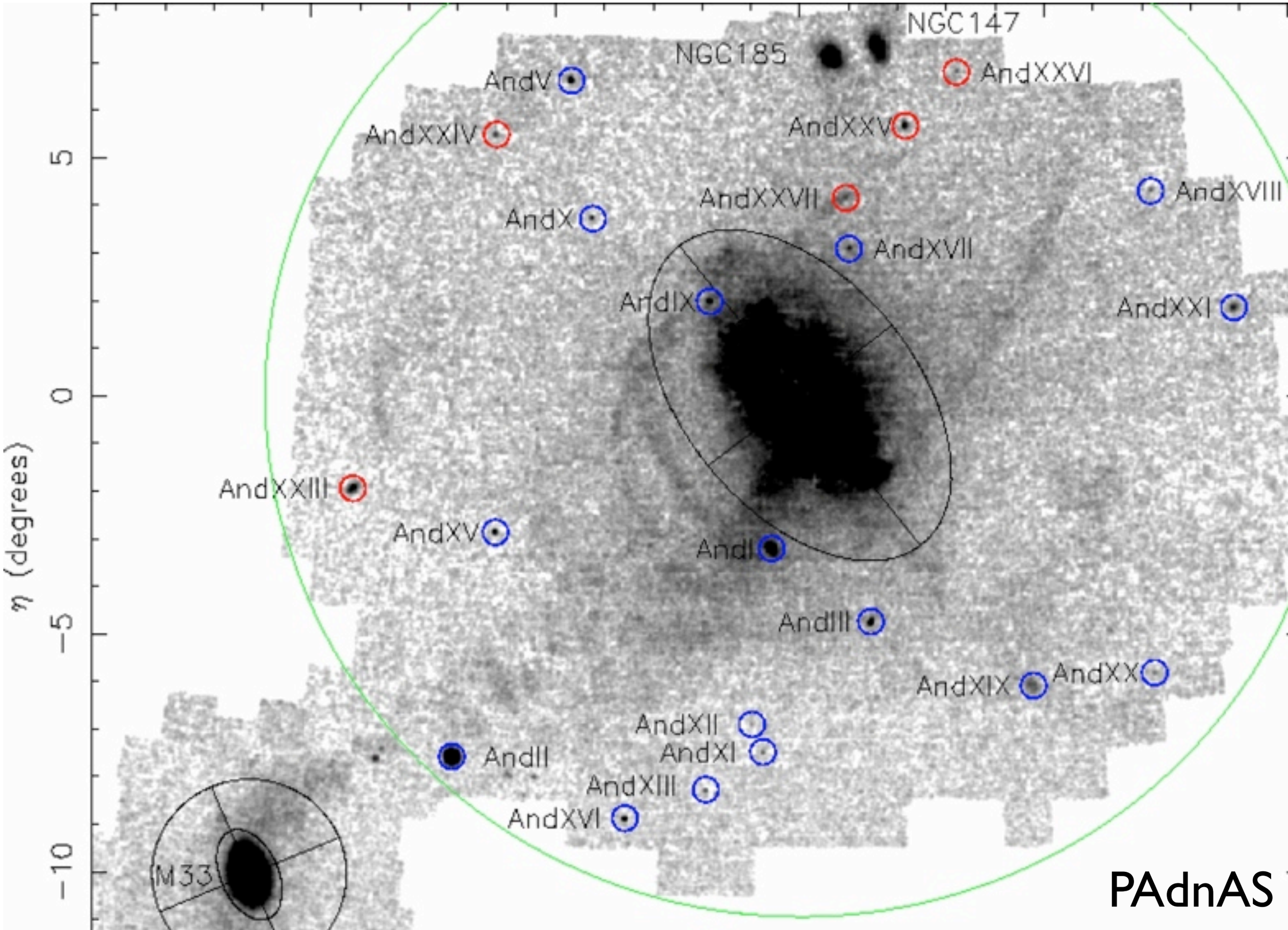
$$g_{in} < g_{ex} < a_0$$

External gravity of host dominates

$$\sigma_{efe} = \left(\frac{a_0 G M_*}{3 g_{ex} r_{1/2}}\right)^{1/2}$$

Prediction also depends on the ***size*** of dwarf and ***mass*** of and ***distance*** from host galaxy

The dwarf satellites of Andromeda (McGaugh & Milgrom 2013a,b)



Quantities used to predict the velocity dispersion

ISO $\sigma_{iso} = \left(\frac{4}{81} a_0 G M_*\right)^{1/4}$

Range of plausible stellar mass-to-light ratio

Luminosity $M_* = \Upsilon_* L_V$ $\Upsilon_*^V = 2^{+2}_{-1}\ M_\odot/L_\odot$

EFE

(V-band)

Luminosity $M_* = \Upsilon_* L_V$ $\Upsilon_*^V = 2^{+2}_{-1}\ M_\odot/L_\odot$

Half-light radius $r_{1/2}$

$$\sigma_{efe} = \left(\frac{a_0 G M_*}{3 g_{ex} r_{1/2}}\right)^{1/2}$$

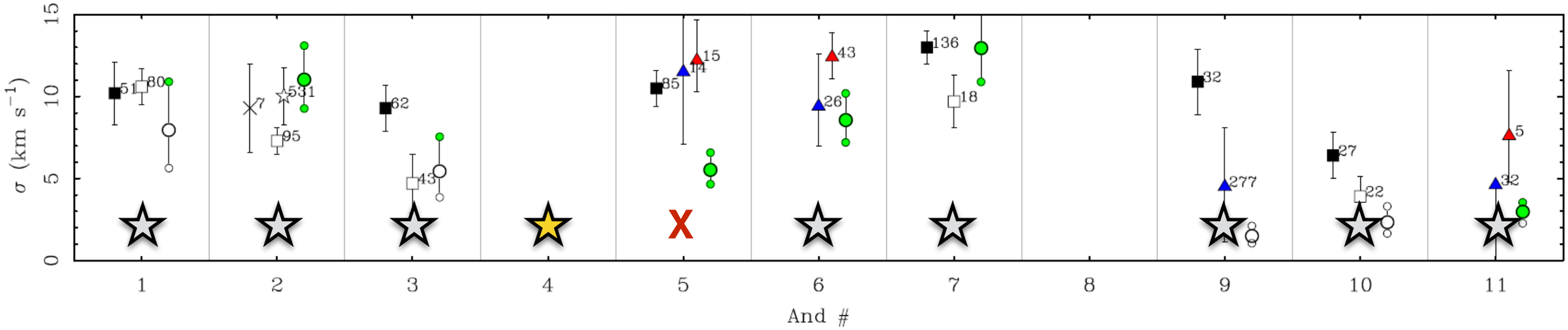
External field $g_{ex} = \frac{V_f^2}{D}$

adopt

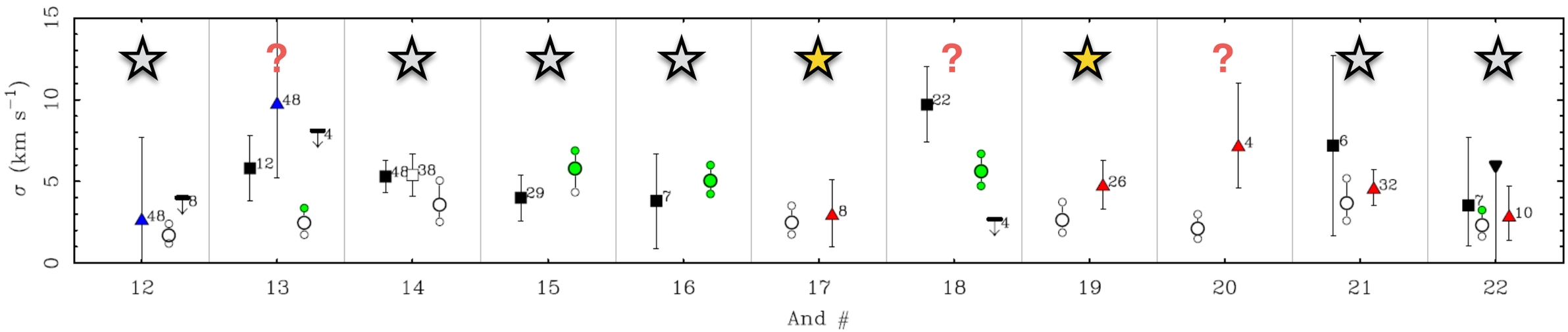
$$V_f = 230\ \mathrm{km\,s^{-1}}$$

for M31 (Chemin et al. 2009)

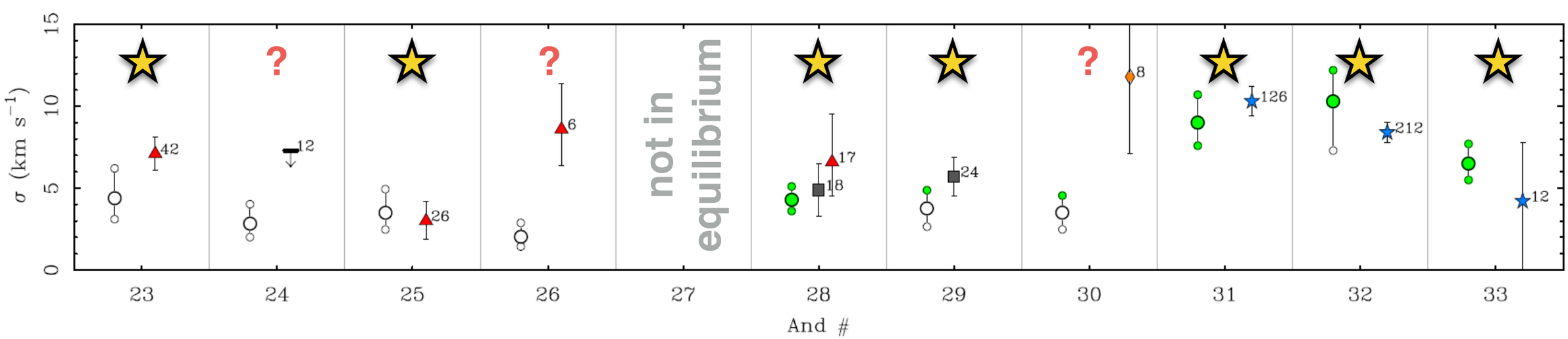
McGaugh & Milgrom (2013, ApJ, 766, 22)
McGaugh & Milgrom (2013, ApJ, 775, 139)
Pawlowski & McGaugh (2014, MNRAS, 440, 908)



MOND correctly predicts the velocity dispersion for most of the M31 dwarfs (silver stars).

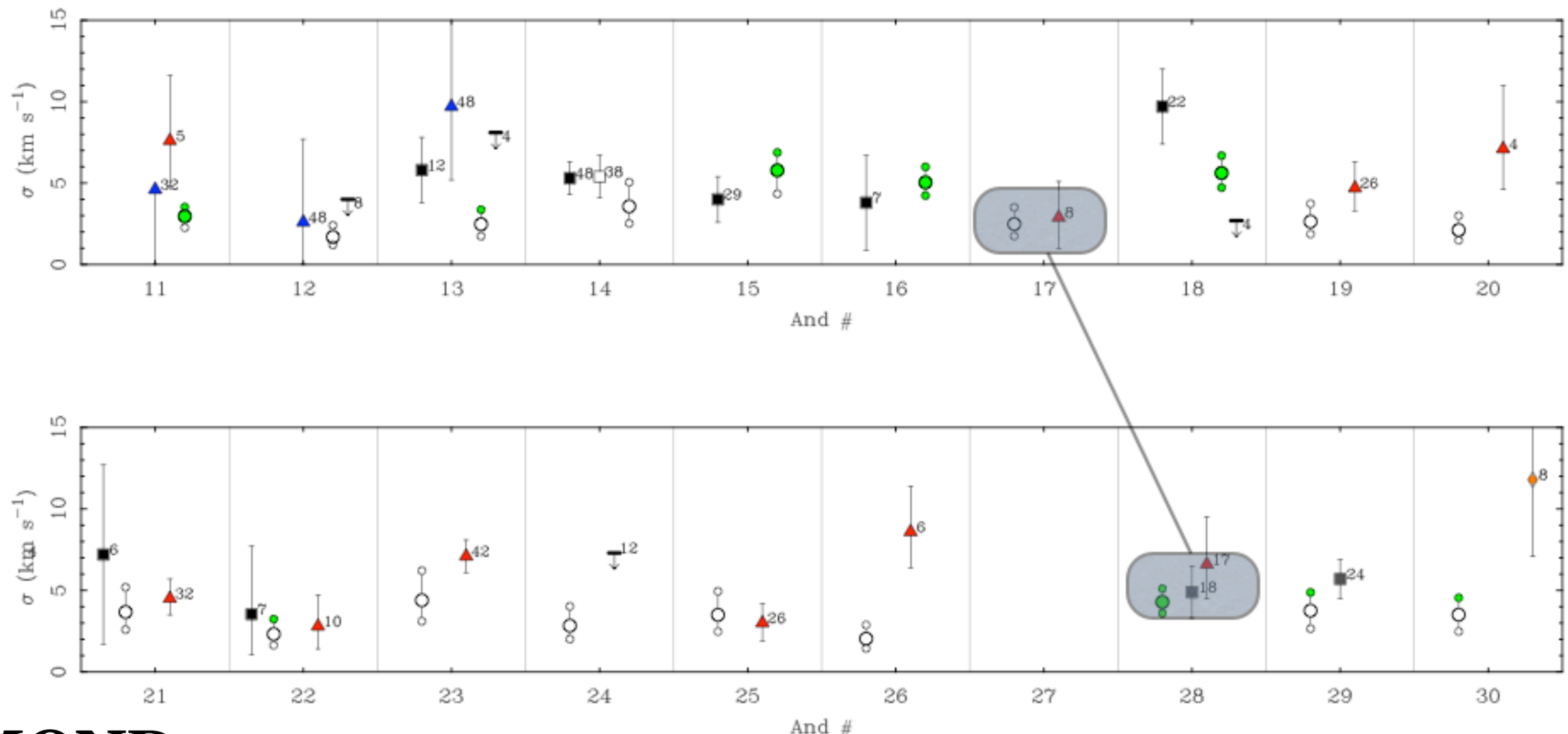


The prediction is completely a priori in many cases (gold stars).

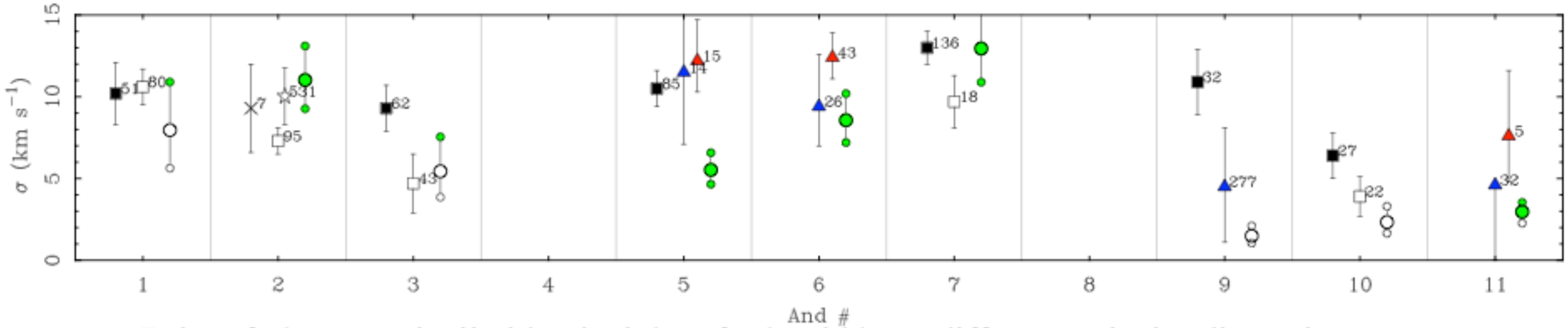


MOND Predictions of isolated case are GREEN circles; open circles are the predictions for when the EFE dominates

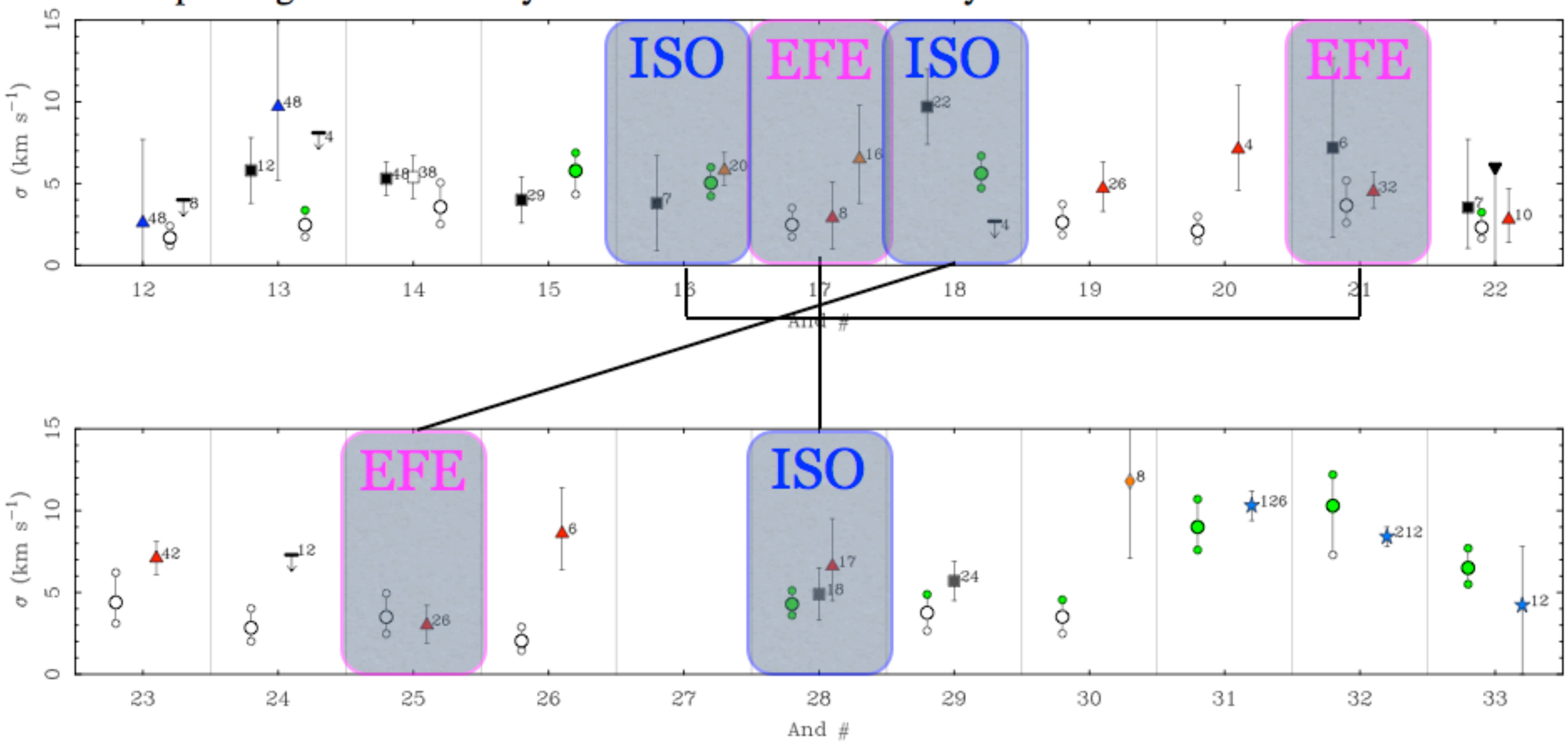
Name	Luminosity	R_e	σ_{obs}	σ_{pred}	
And XVII	2.60E+05	381	2.9	2.5	EFE
And XXVIII	2.10E+05	284	4.9	4.3	isolated



MOND Matched pairs of dwarfs - indistinguishable except for whether they're affected by the EFE or not.



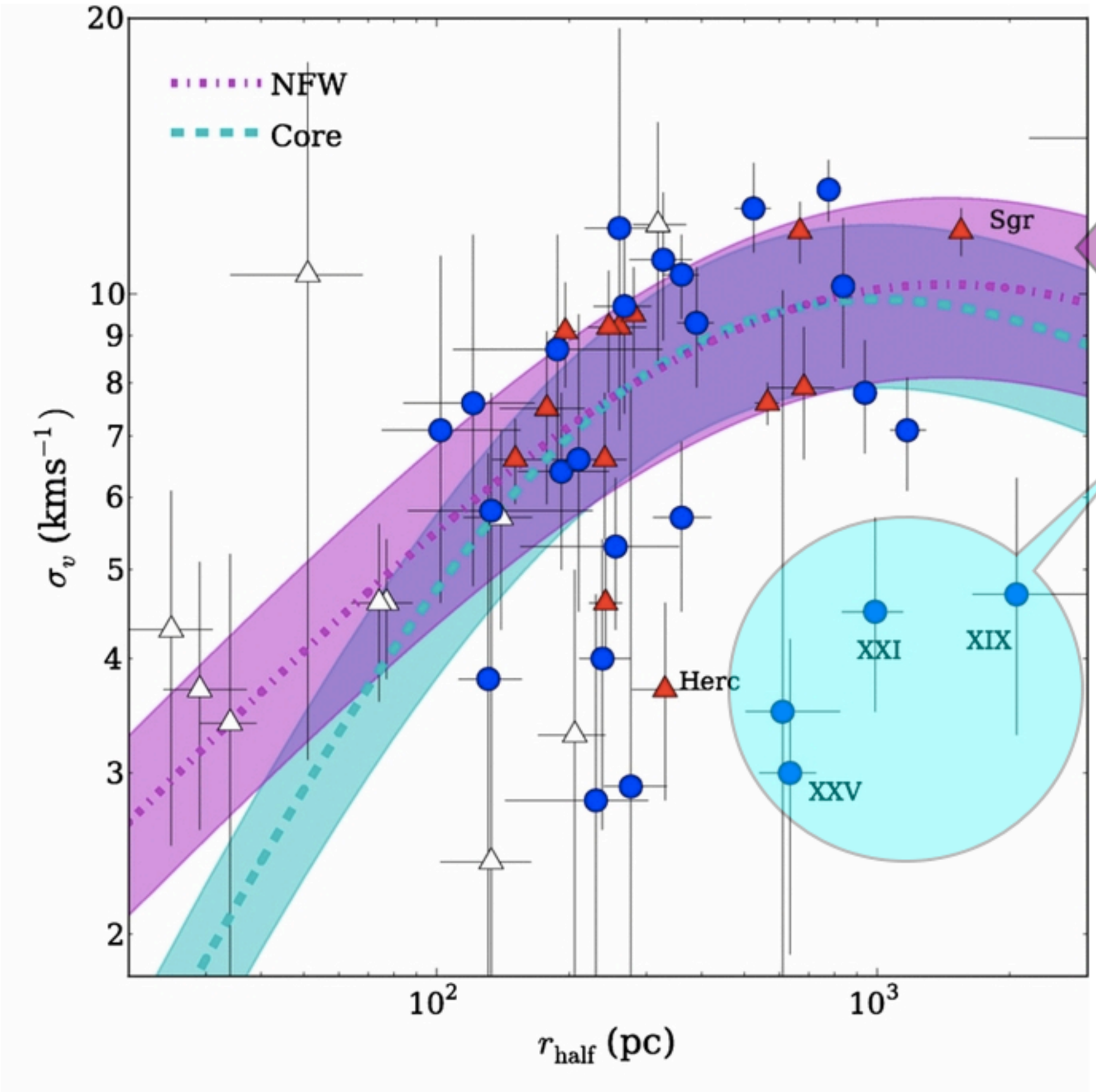
Pairs of photometrically identical dwarfs should have different velocity dispersion depending on whether they are isolated are dominated by the external field effect.



There is no EFE in dark matter - this is a unique signature of MOND.

MOND

Collins et al. (2014) (Fig. 5)



Halo models

Cases noted by Collins et al. (2014) as having anomalously low velocity dispersions for their large sizes were naturally predicted by the EFE.

It has become conventional to attribute anomalous cases to tidal disruption in CDM. MOND is very good at predicting which objects we'll need to invoke this for.

MOND

Crater 2

The recently discovered, ultra-diffuse Crater 2 provides another test.

$$L_V = 1.6 \times 10^5 \ \mathrm{L}_\odot$$
$$r_h = 1066 \ \mathrm{pc}$$

LCDM anticipates 10 - 17 km/s
(abundance matching; size-v. disp. rel'n)

MOND predicts 2.1 +0.9/-0.6 km/s
(in EFE regime arXiv:1610.06189)

Subsequently observed: **2.7** ± 0.3 km/s
(Caldwell et al. arXiv:1612.06398)

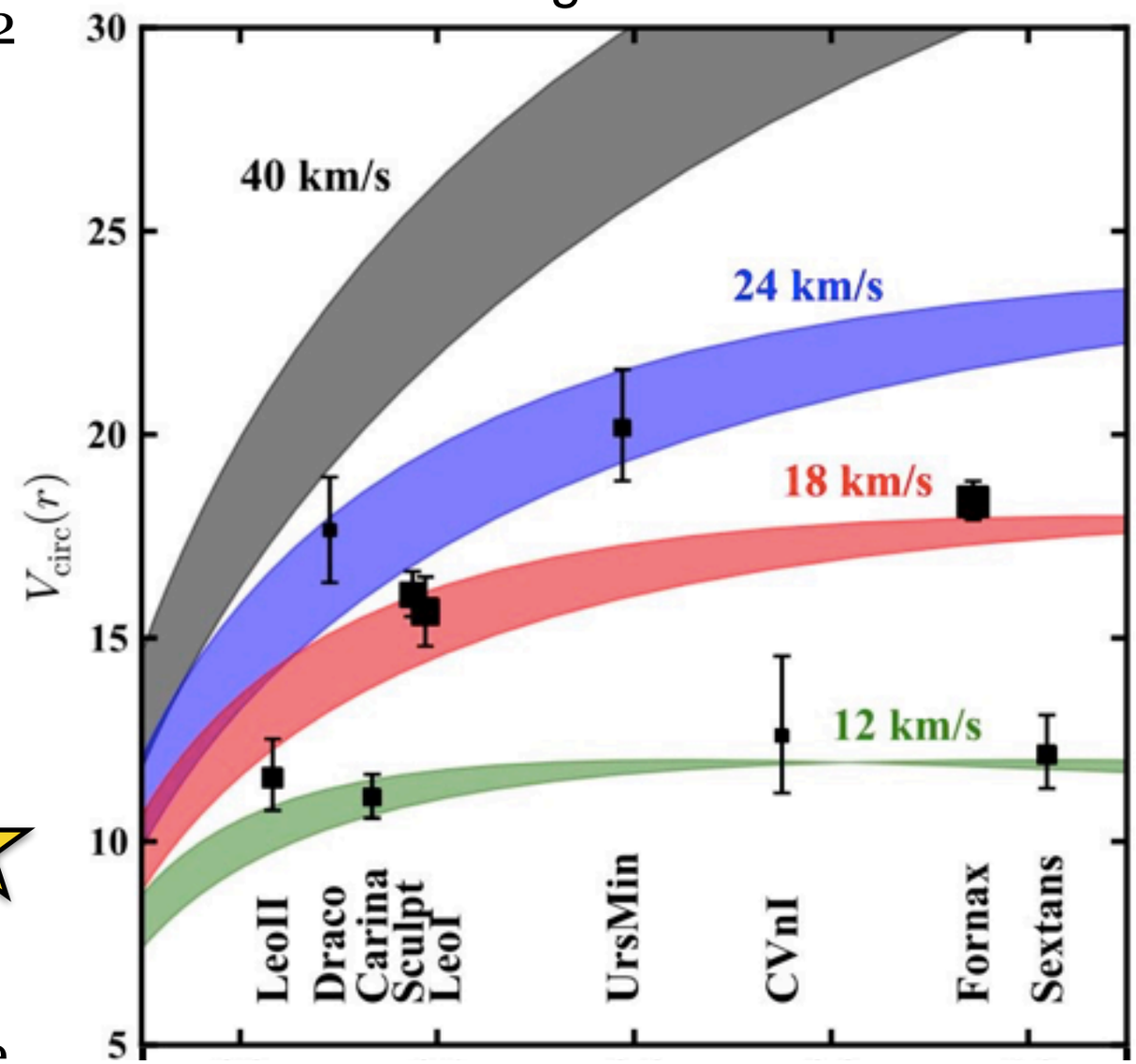
Consistent with a priori MOND prediction ★

Very hard to understand in the context of ΛCDM - incredibly low velocity at a very large radius.

If the universe is made of cold dark matter, why does MOND get *any* prediction right?

Boylan-Kolchin et al. (2012) MNRAS, 422, 1203

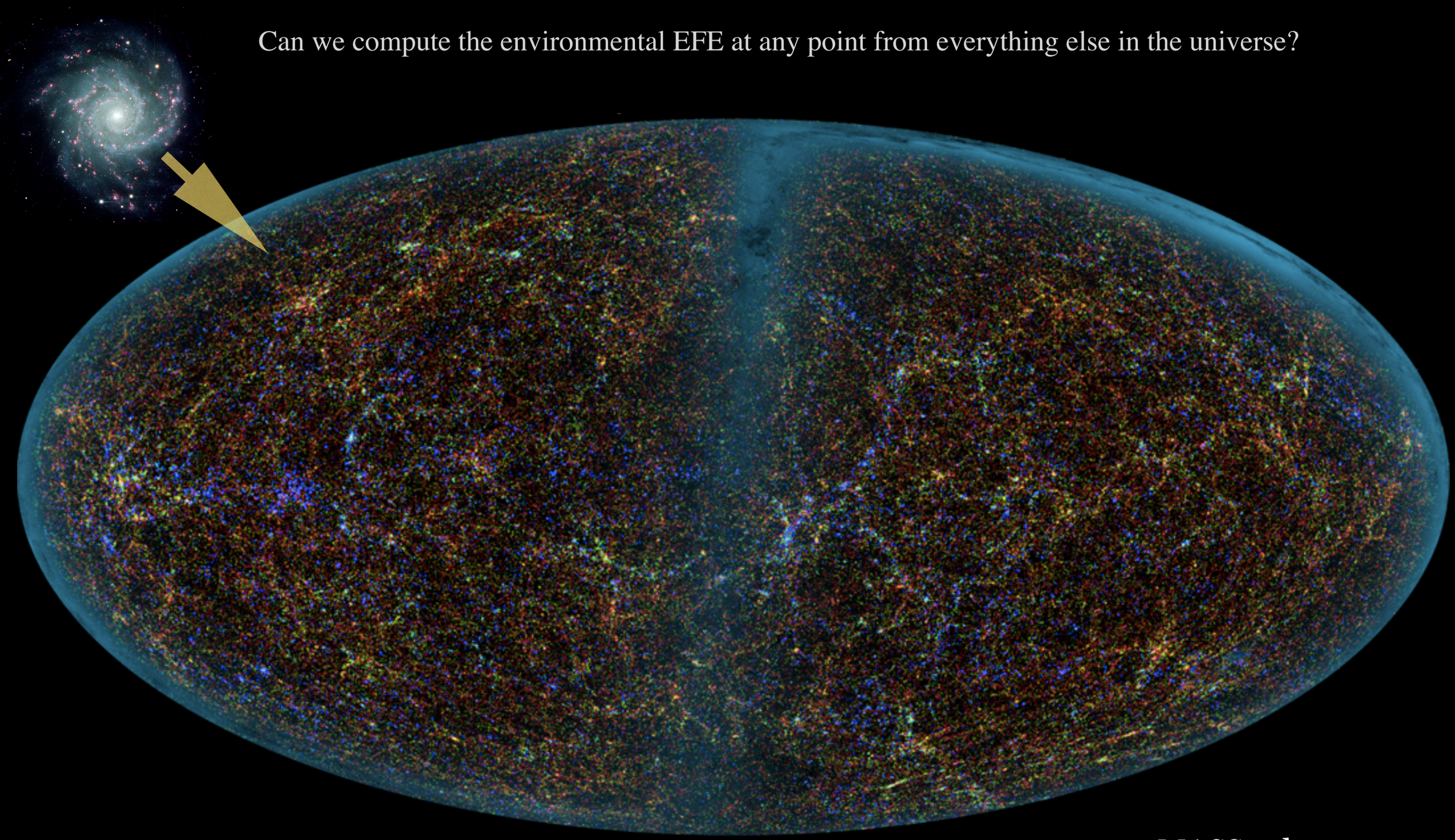
"Too Big To Fail"



Galaxies are never completely isolated

Every dot pictured here is a galaxy, color coded by redshift

Can we compute the environmental EFE at any point from everything else in the universe?

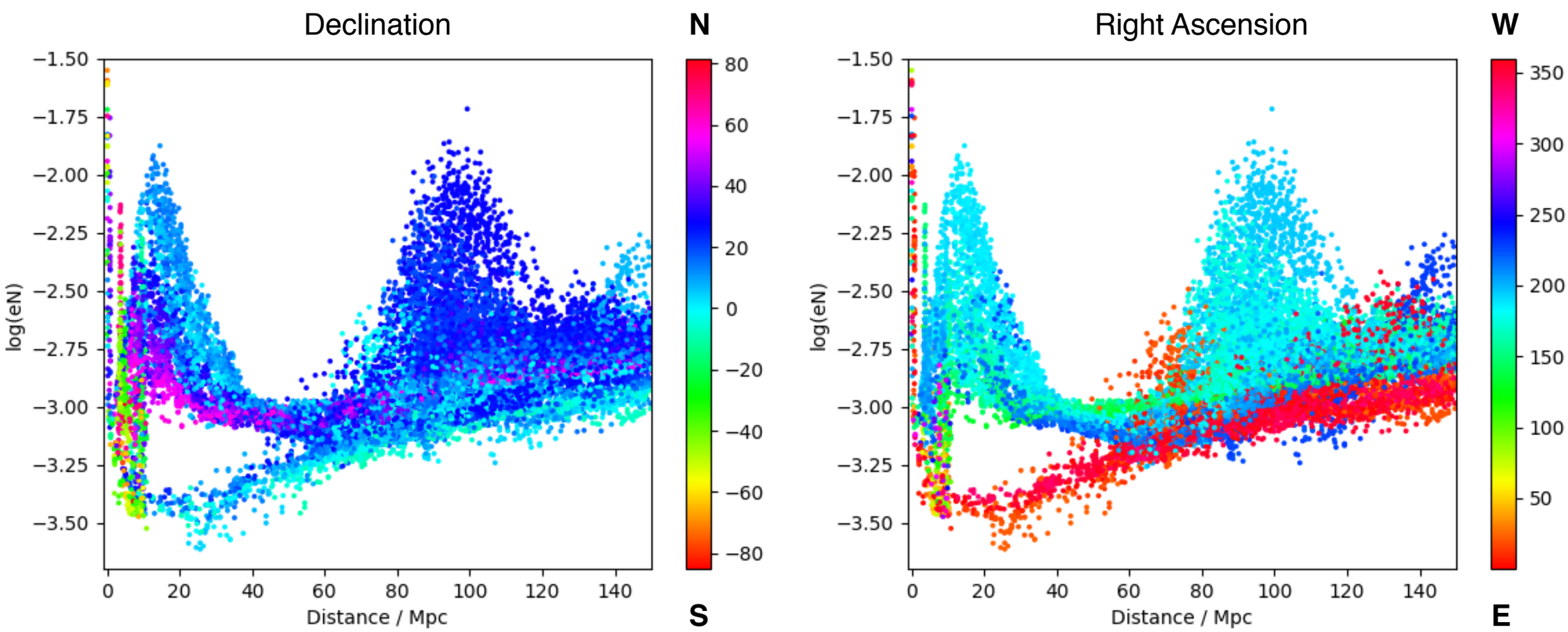


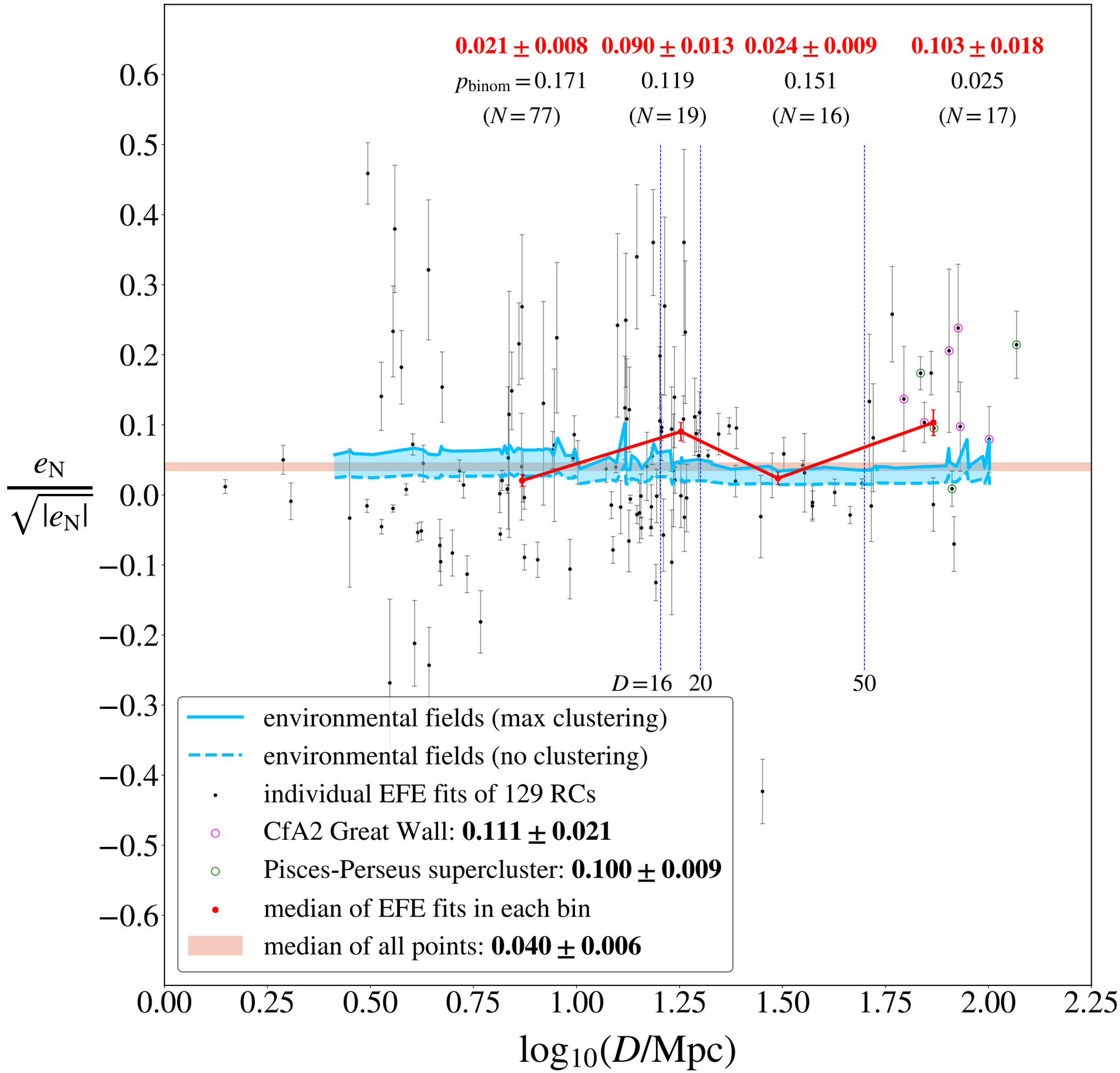
2MASS galaxy survey

An early estimate: “Taking these numbers at face value leads to $\langle a \rangle \sim 0.026$ Å s^{-2} “ (McGaugh & de Blok 1998)

That’s a mean environmental acceleration of about 2% of a_0.

The External Field estimated from the observed galaxy distribution (Desmond, private communication)




0.021 ± 0.008
0.090 ± 0.013
0.024 ± 0.009
0.103 ± 0.018
$p_{\rm binom} = 0.171$
0.119
0.151
0.025
($N = 77$)
($N = 19$)
($N = 16$)
($N = 17$)
$D = 16$
20
50
environmental fields (max clustering)
environmental fields (no clustering)
individual EFE fits of 129 RCs
CfA2 Great Wall: 0.111 ± 0.021
Pisces-Perseus supercluster: 0.100 ± 0.009
median of EFE fits in each bin
median of all points: 0.040 ± 0.006
$\frac{e_{\rm N}}{\sqrt{|e_{\rm N}|}}$
$\log_{10}(D/{\rm Mpc})$
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25

Chae et al. 2020, ApJ, 904, 51

The EFE in the Local Group is relatively strong for satellites of Andromeda and the Milky Way.

There should be a weak EFE everywhere that affects the outskirts of all galaxies. Can we detect this?

$$g_{ex} < g_{in} < a_0$$

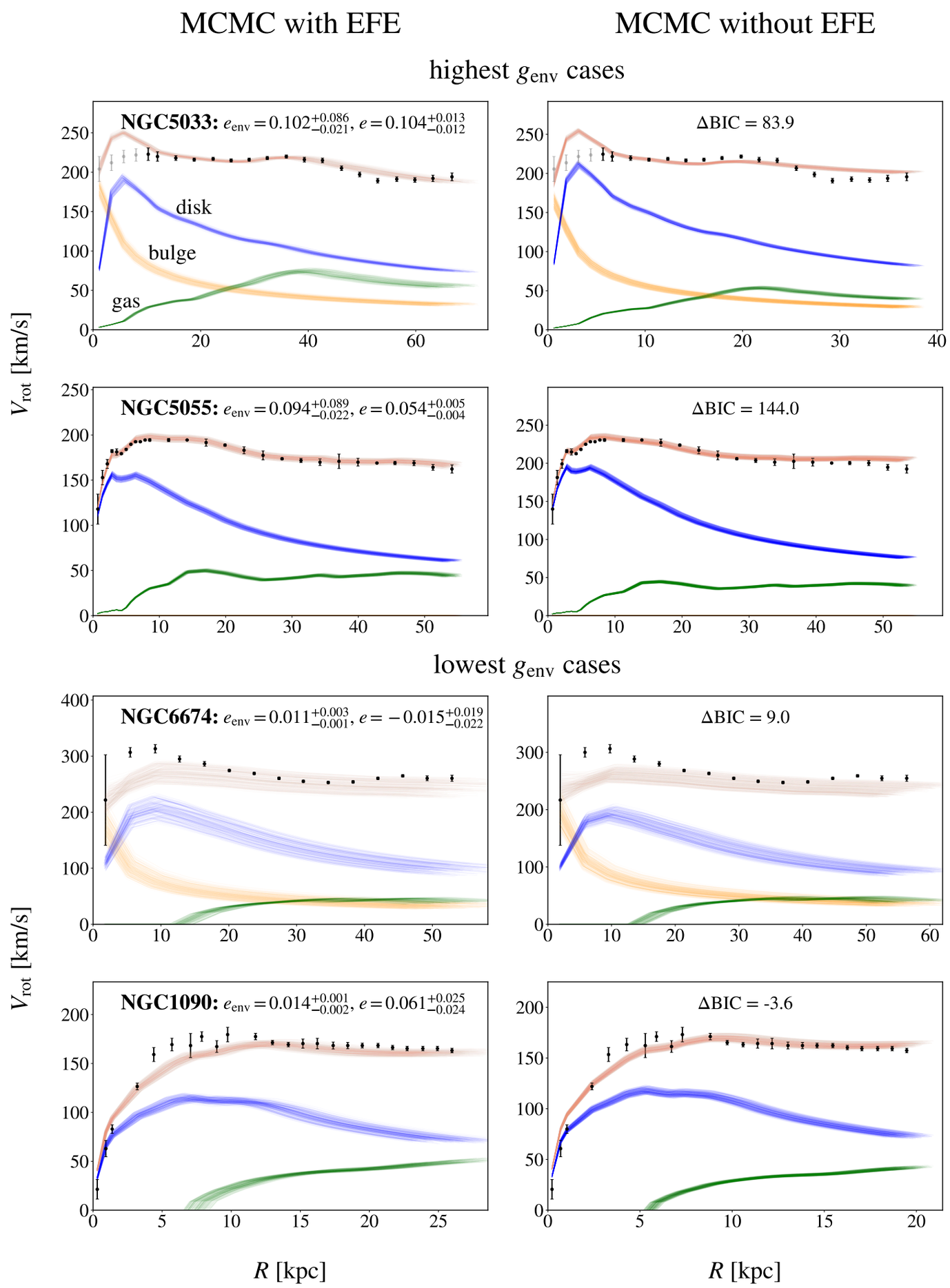
but

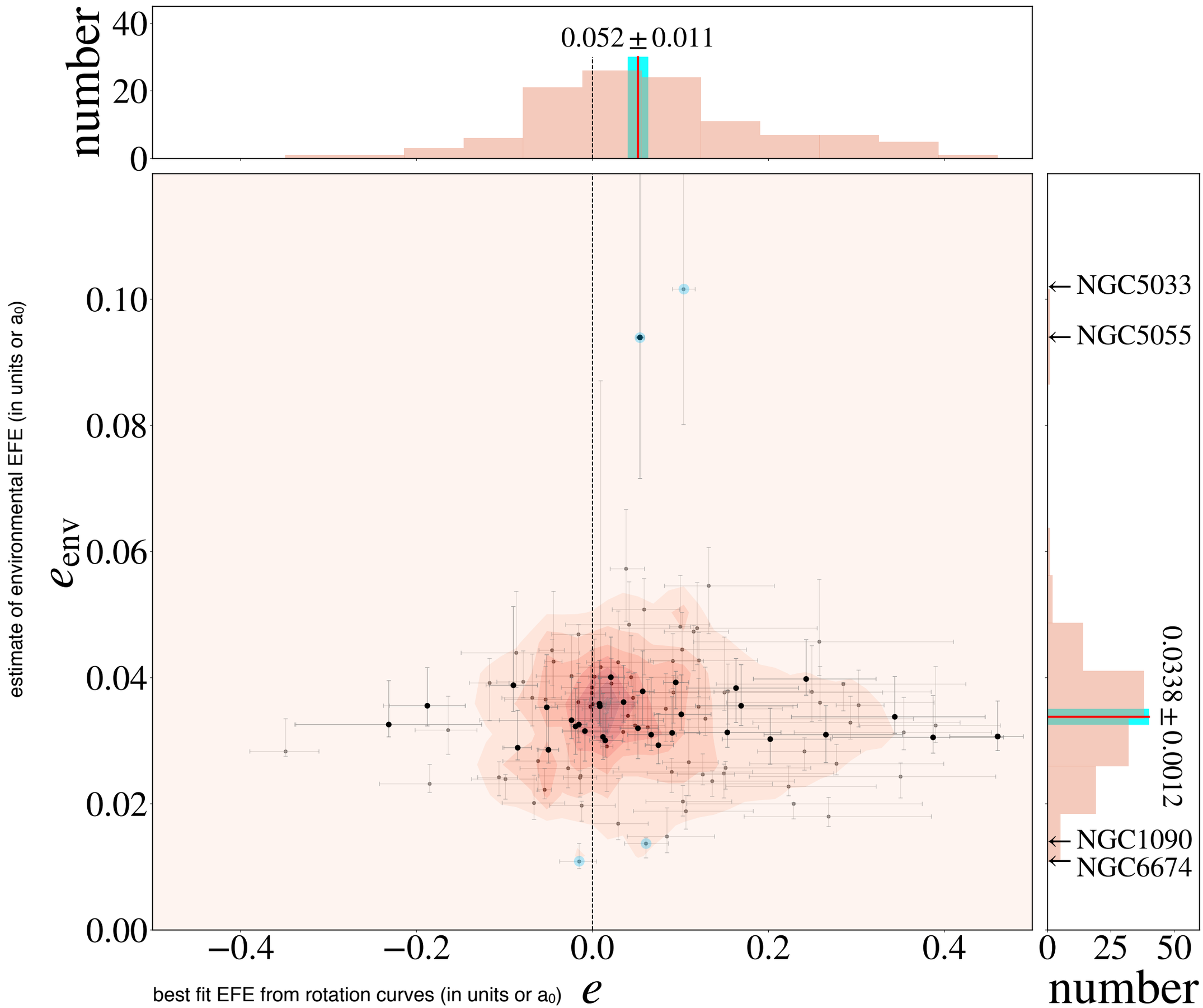
$$|\mathbf{g}_{in} + \mathbf{g}_{ex}| > |\mathbf{g}_{in}|$$

so

$$\mu(|\mathbf{g}_{in}|/a_0) \rightarrow \mu(|\mathbf{g}_{in} + \mathbf{g}_{ex}|/a_0)$$

$$|\mathbf{g}_{in} + \mathbf{g}_{ex}| \approx |\mathbf{g}_{in}| + |\mathbf{g}_{ex}|$$



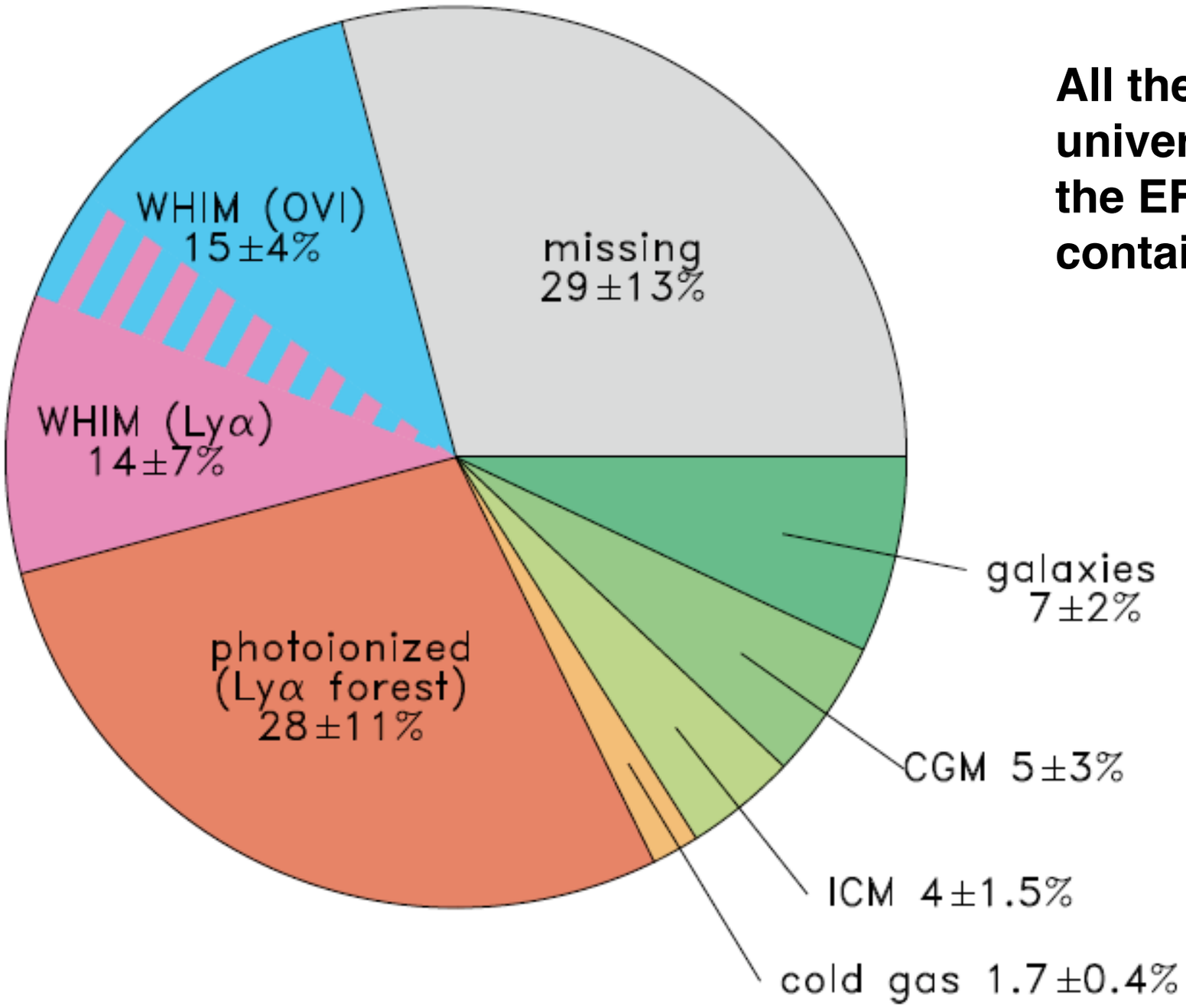

number
40
20
0
0.052 ± 0.011
0.10
0.08
0.06
0.04
0.02
0.00
$e_{\rm env}$
estimate of environmental EFE (in units or a0)
−0.4
−0.2
0.0
0.2
0.4
e
best fit EFE from rotation curves (in units or a0)
← NGC5033
← NGC5055
0.0338 ± 0.0012
← NGC1090
← NGC6674
0
25
50
number

The missing baryon problem

Cosmic baryon budget

(Shull et al arXiv:1112.2706)

$@\ z = 0$



All the baryons in the universe contribute to the EFE, but galaxies contain < 10% of them!

Conclusions

- Galaxies obey strict kinematic scaling laws
- The observed laws were predicted by MOND
- A further prediction of MOND is the External Field Effect (EFE)
  - violates the SEP, but not the WEP or EEP
- The EFE appears in two distinct sets of observations
  - Local Group dwarfs
  - Outskirts of spirals
- Outstanding EFE uncertainty: where are all the baryons?