Describe in single words only the good things that come into your mind about MOND.

Given the many compelling successes of the concordance cosmology, the various interlocking but distinct lines of evidence supporting it, and its basis in the highly successful theory of General Relativity, it seems quite unreasonable to doubt the existence of CDM.

Given the obvious organization of the data, the many predictive successes of MOND, and the inability of ΛCDM in many cases to make comparable predictions, it seems quite unreasonable to believe in the existence of invisible mass from beyond the Standard Model of particle physics that pervades the universe with nary a signal in the laboratory.

both quotes from McGaugh 2015, Canadian Journal of Physics, 93, 250

Predictions are suppose to keep us honest & objective

A priori predictions	Gold standard
Must be so	Silver
Can be fit	Bronze
Just making stuff up	too much freedom (e.g., epicycles)

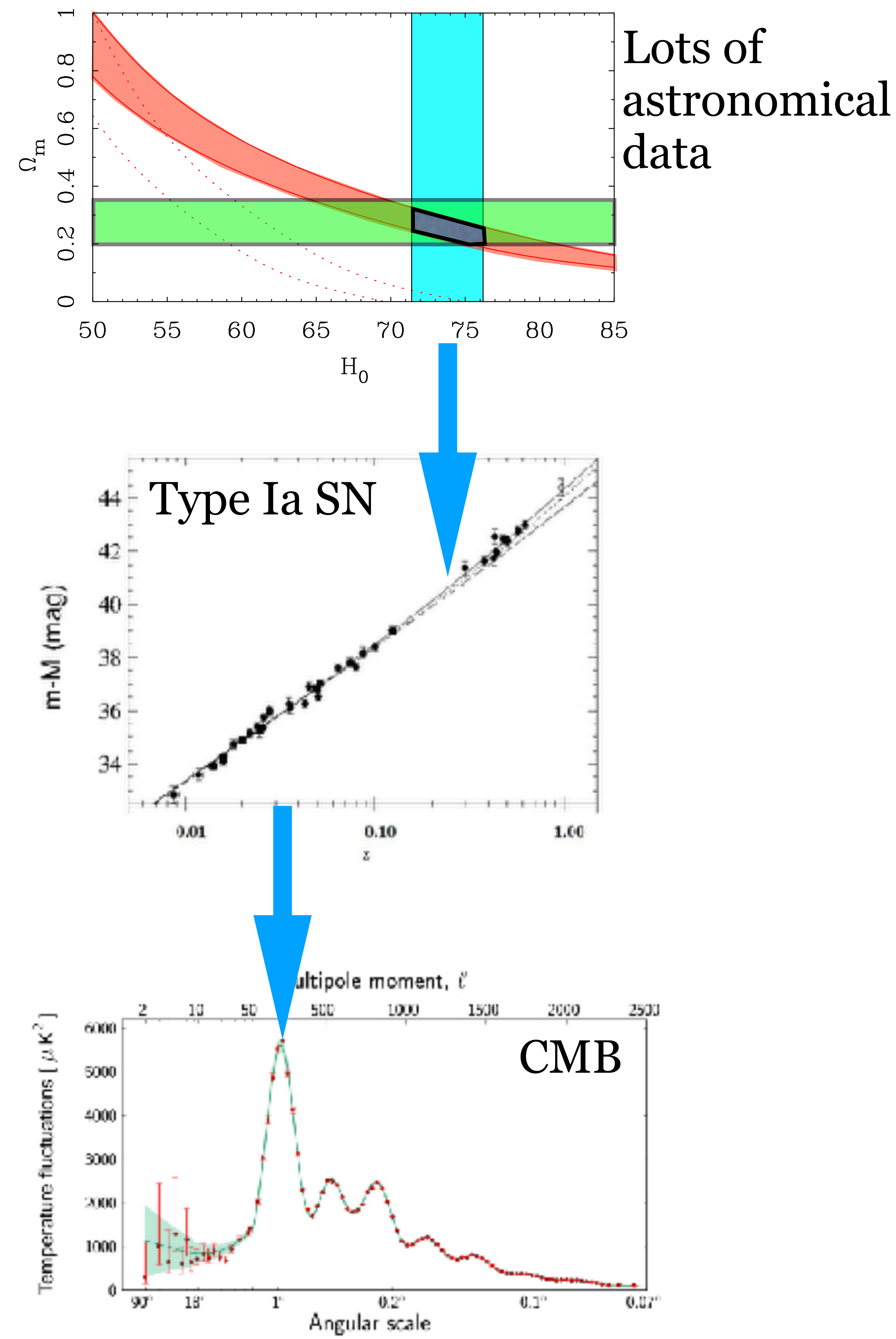
The recognition and acknowledgement of anomalies result in crises that are a necessary precondition for the emergence of novel theories and for paradigm change.

- Thomas Kuhn

What counts as an anomaly in CDM?

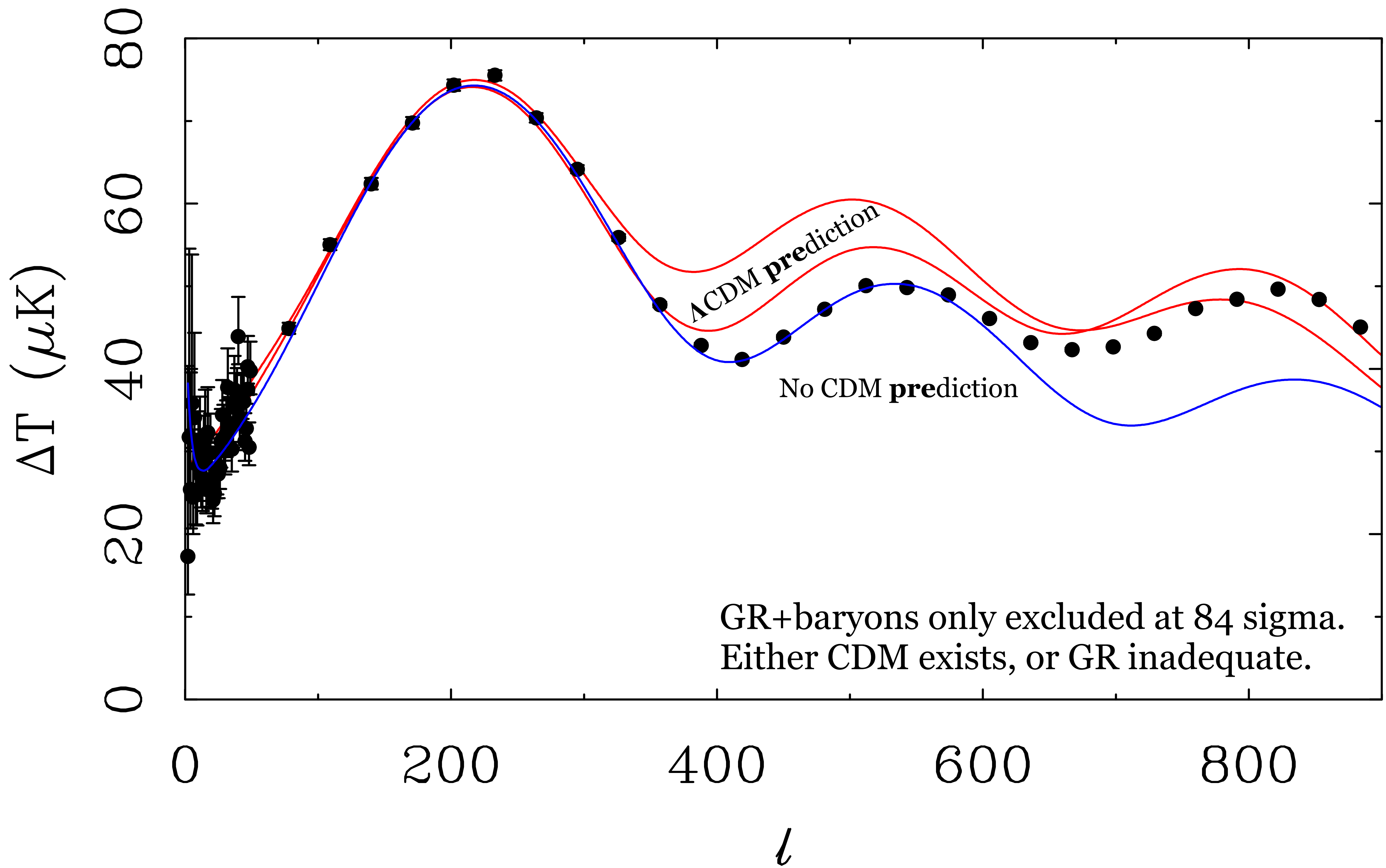
Successful LCDM predictions

- 1995: concordance model (e.g., Ostriker & Steinhardt 1995) $\Omega_m \approx 0.3$ $\Omega_\Lambda \approx 0.7$
  - Predicts acceleration (McGaugh 1996) $q_0 \leq -0.5$
- Observed in SNIa (Riess; Perlmutter et al 1998)
  - Predicts flat geometry
- Observed in First peak of CMB power spectrum (2000)
- Predicts BAO scale



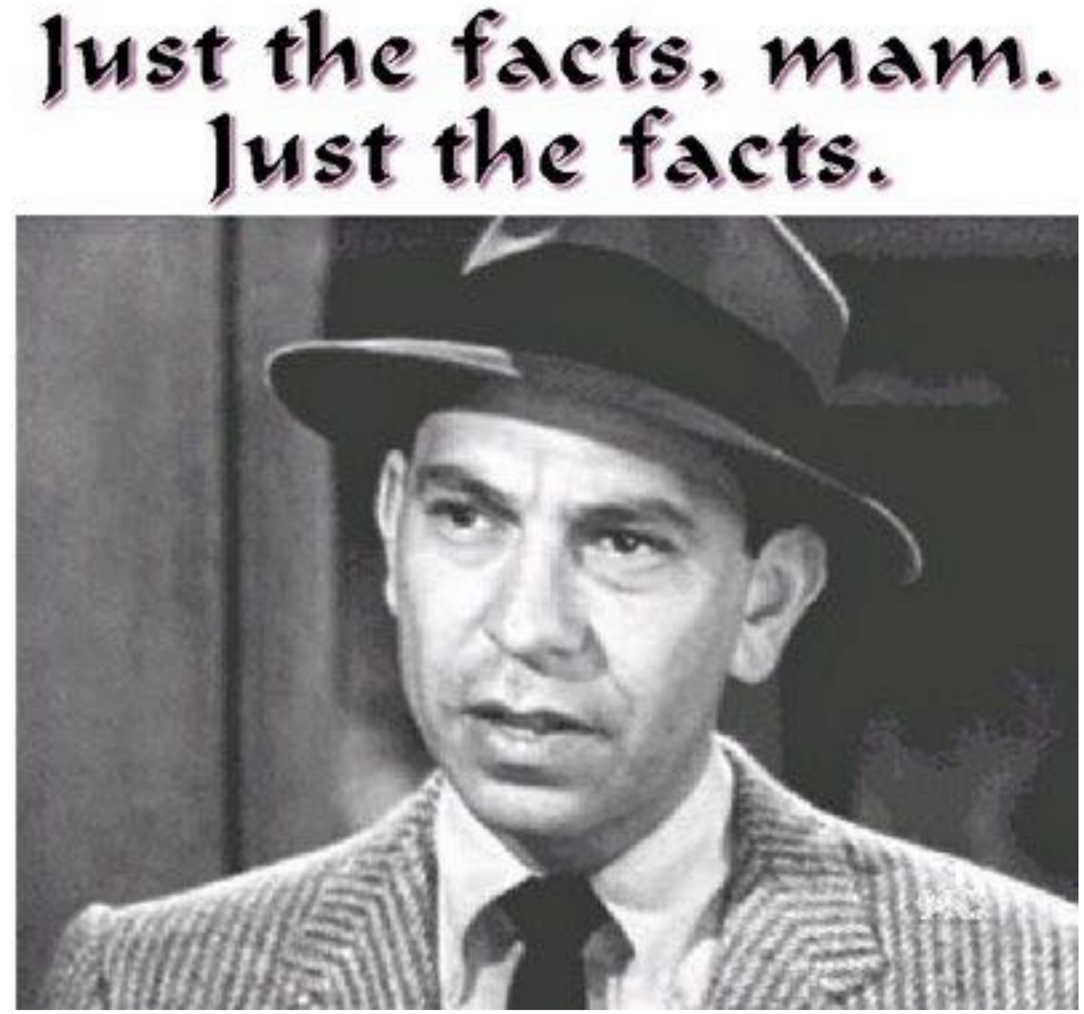
ΛCDM prediction misses 2nd peak but can be tuned

No CDM prediction nails 2nd peak but misses 3rd



Laws of Galactic Rotation

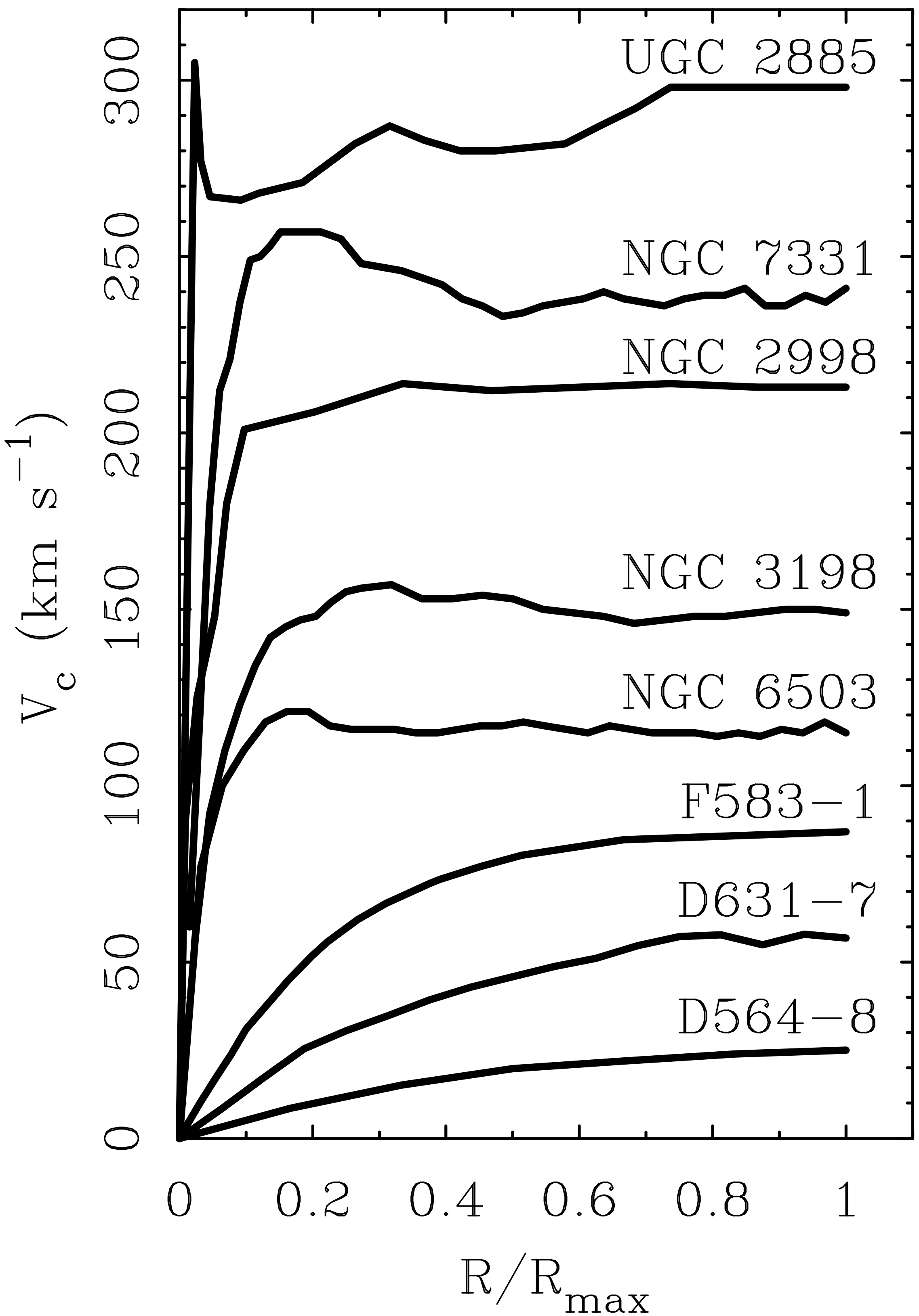
1. Flat Rotation Curves
2. Baryonic Tully-Fisher Relation
3. Sancisi's Law
4. Central Density Relation
5. Radial Acceleration Relation



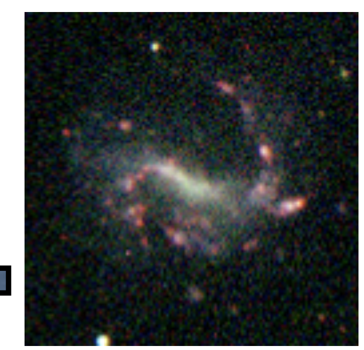
Empirically established regularities that need to be explained in any theory.

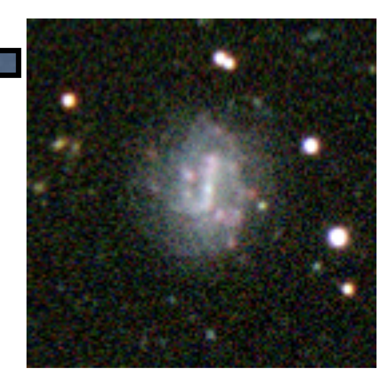
These have all been known in some form or another for a long time, but only the first informed the development of the dark matter paradigm.

1. Flat rotation curves



star dominated HSB



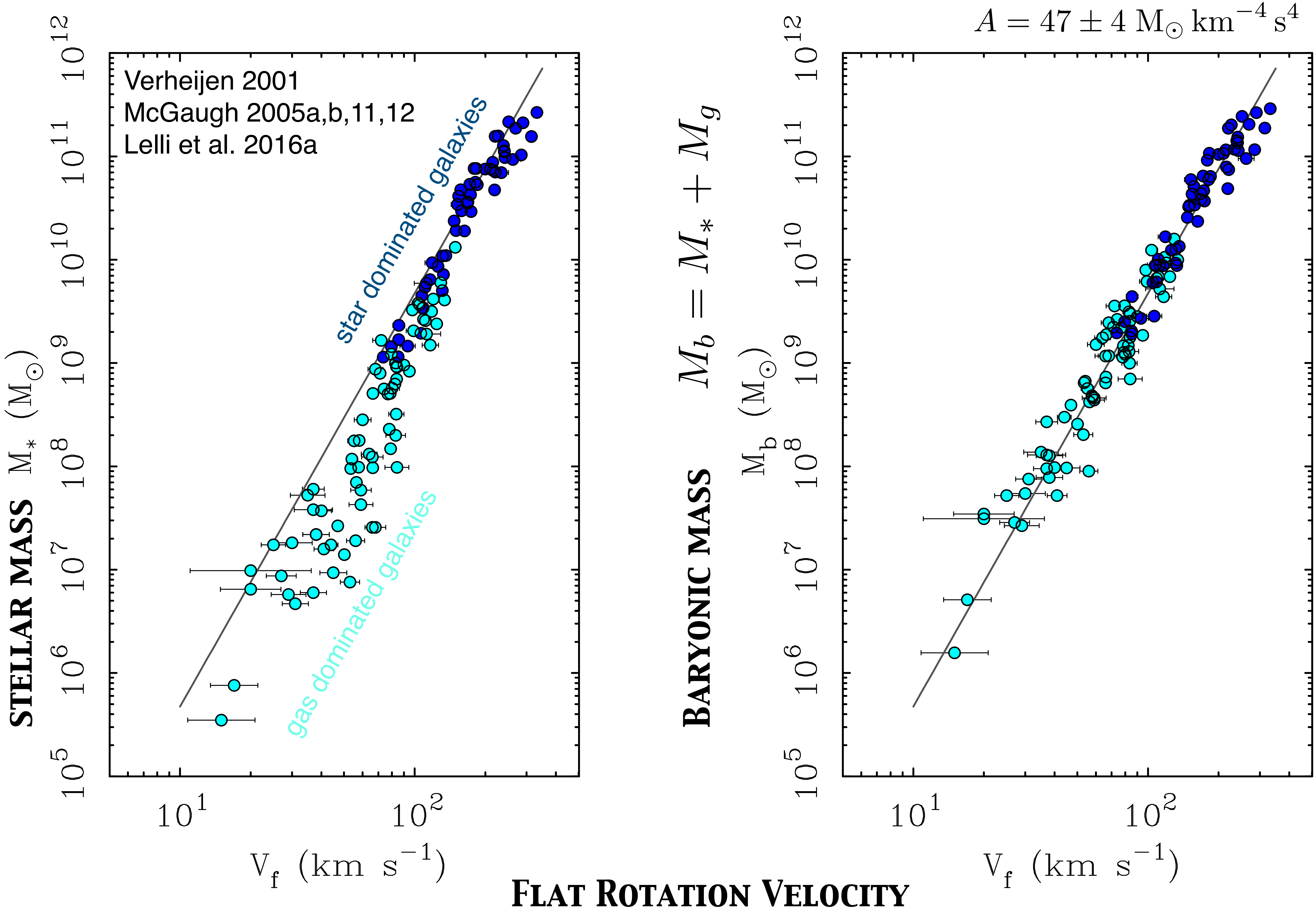


gas dominated LSBs

Rubin et al. (1978)
Bosma (1981)

2. Baryonic Tully-Fisher Relation $M_b = AV_f^4$

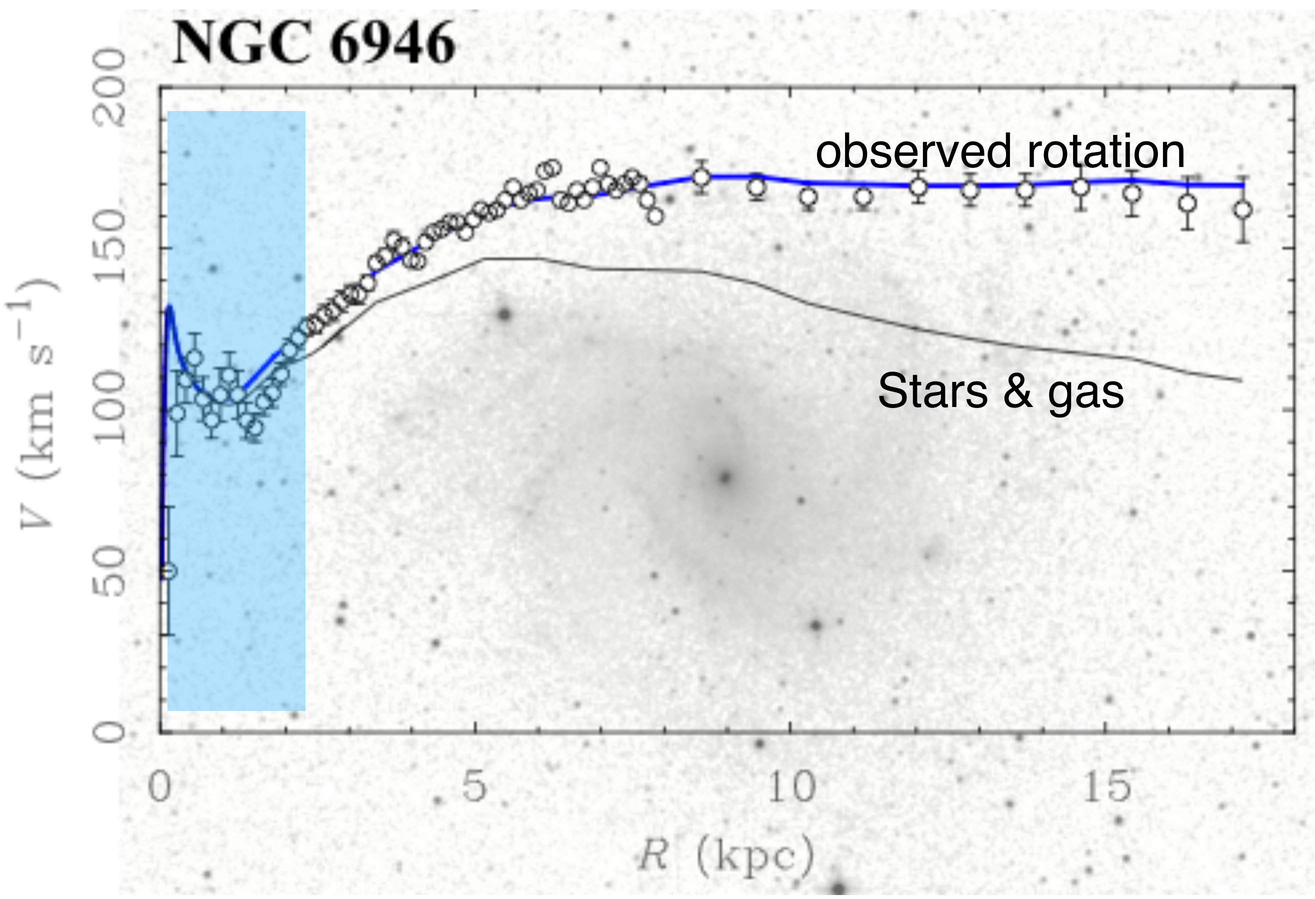
$A = 47 \pm 4 \ \mathrm{M_\odot \, km^{-4} \, s^4}$



3. Renzo's Rule/Sancisi's Law

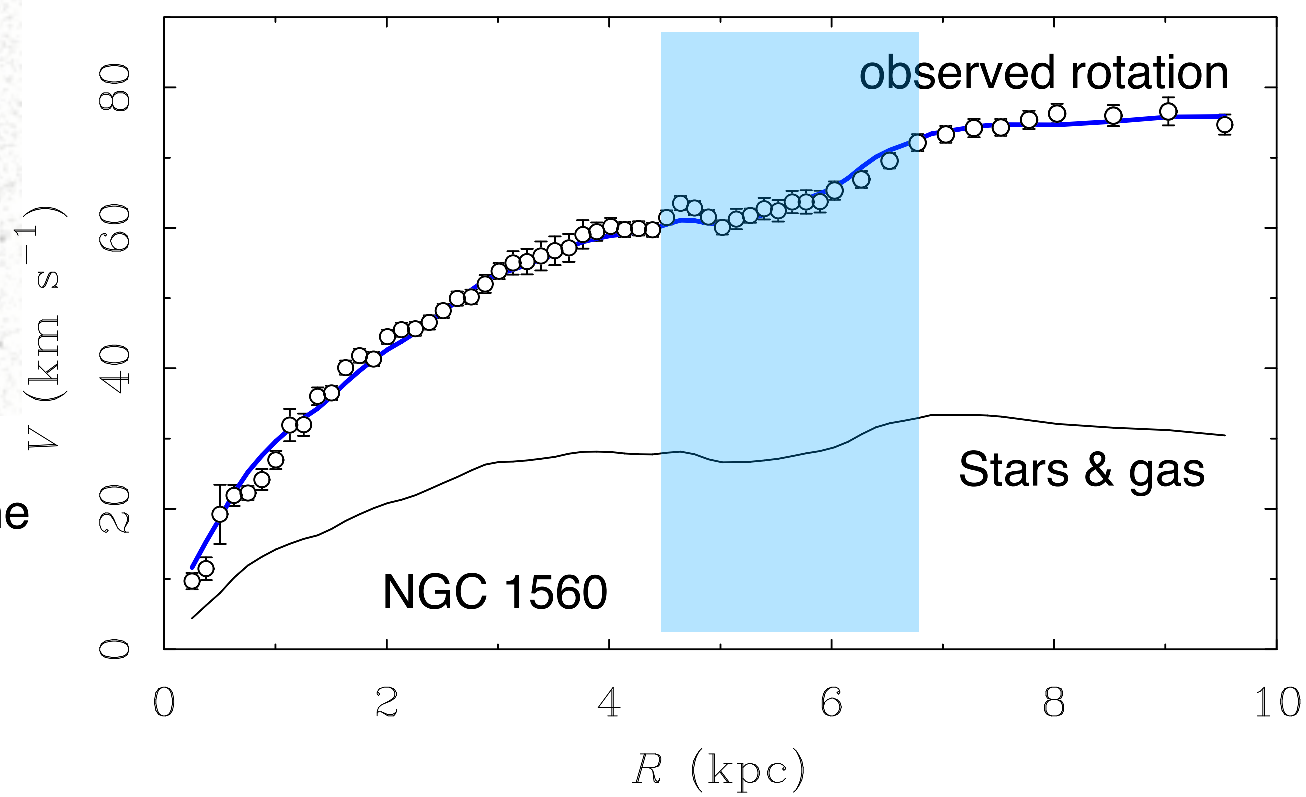
Sancisi 2004

"When you see a feature in the light, you see a corresponding feature in the rotation curve, and vice-versa."



The central bulge component of NGC 6946 is only 4% of the total light, but it has a perceptible effect on the kinematics.

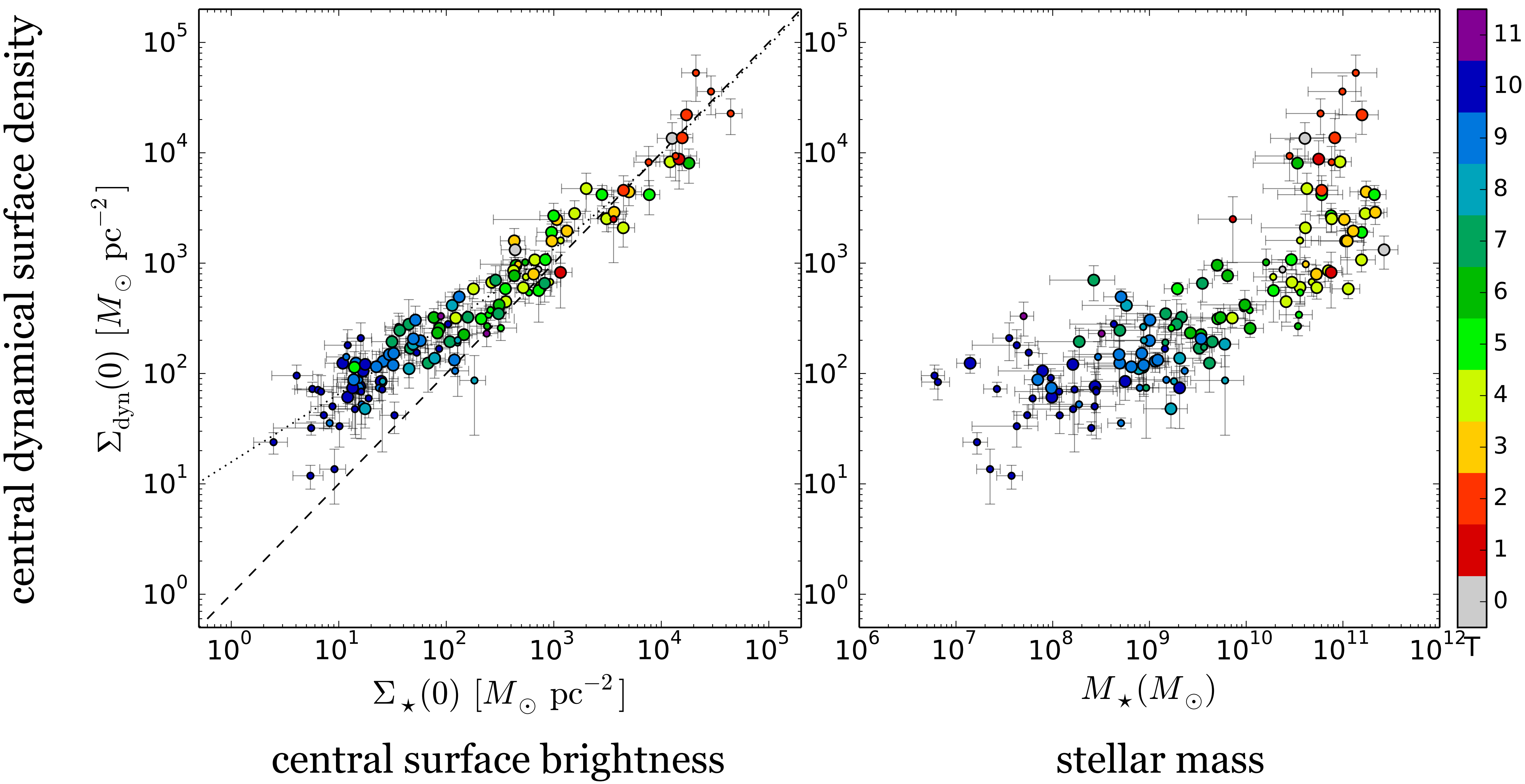
An asymmetric feature in the gas distribution of NGC 1560 has a corresponding feature in the kinematics despite the large amplitude of the mass discrepancy.



4. Central Density Relation

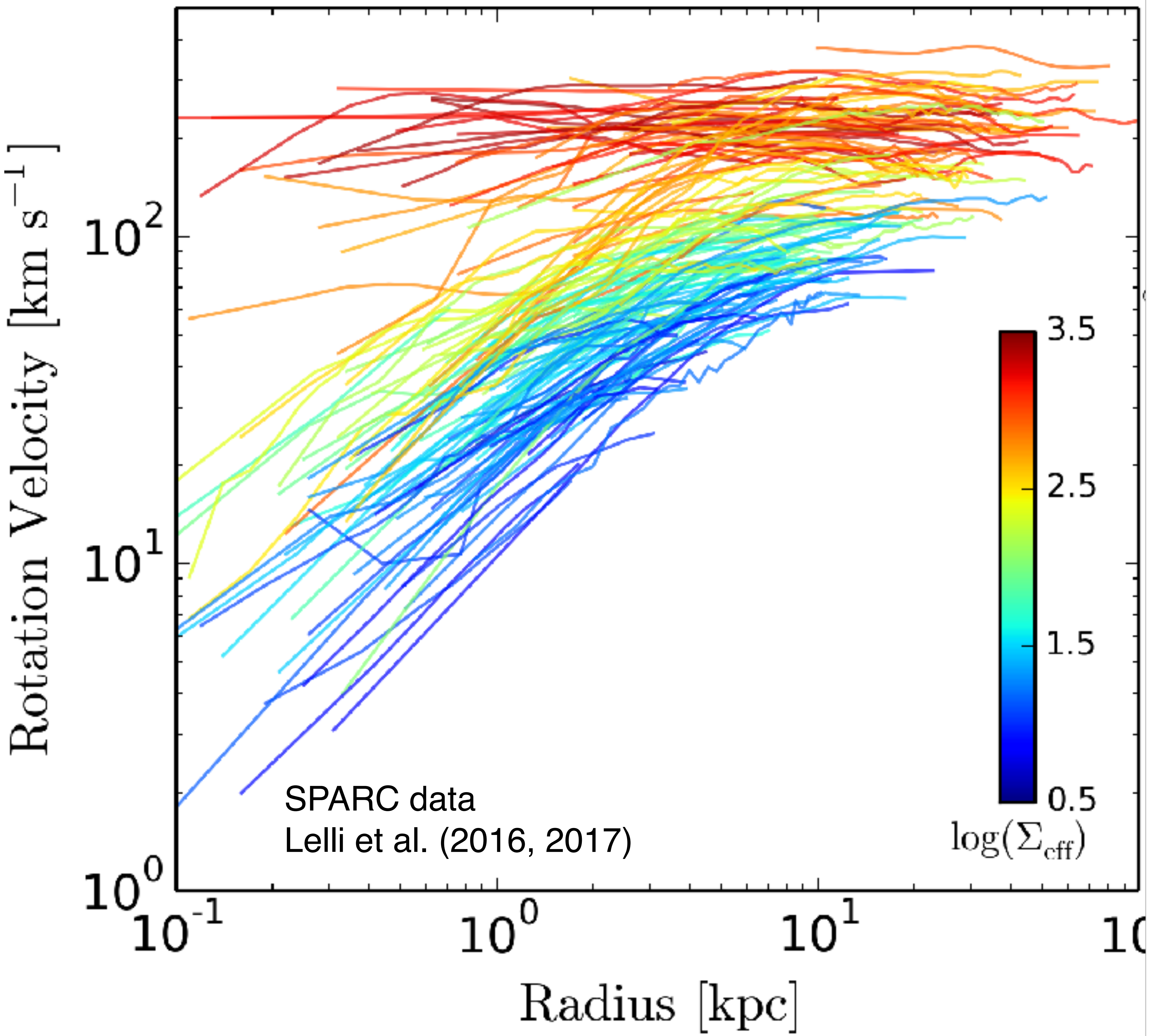
Lelli et al. 2016b

The central mass surface density measured dynamically correlates with the central surface brightness of stars (more so than with total mass).



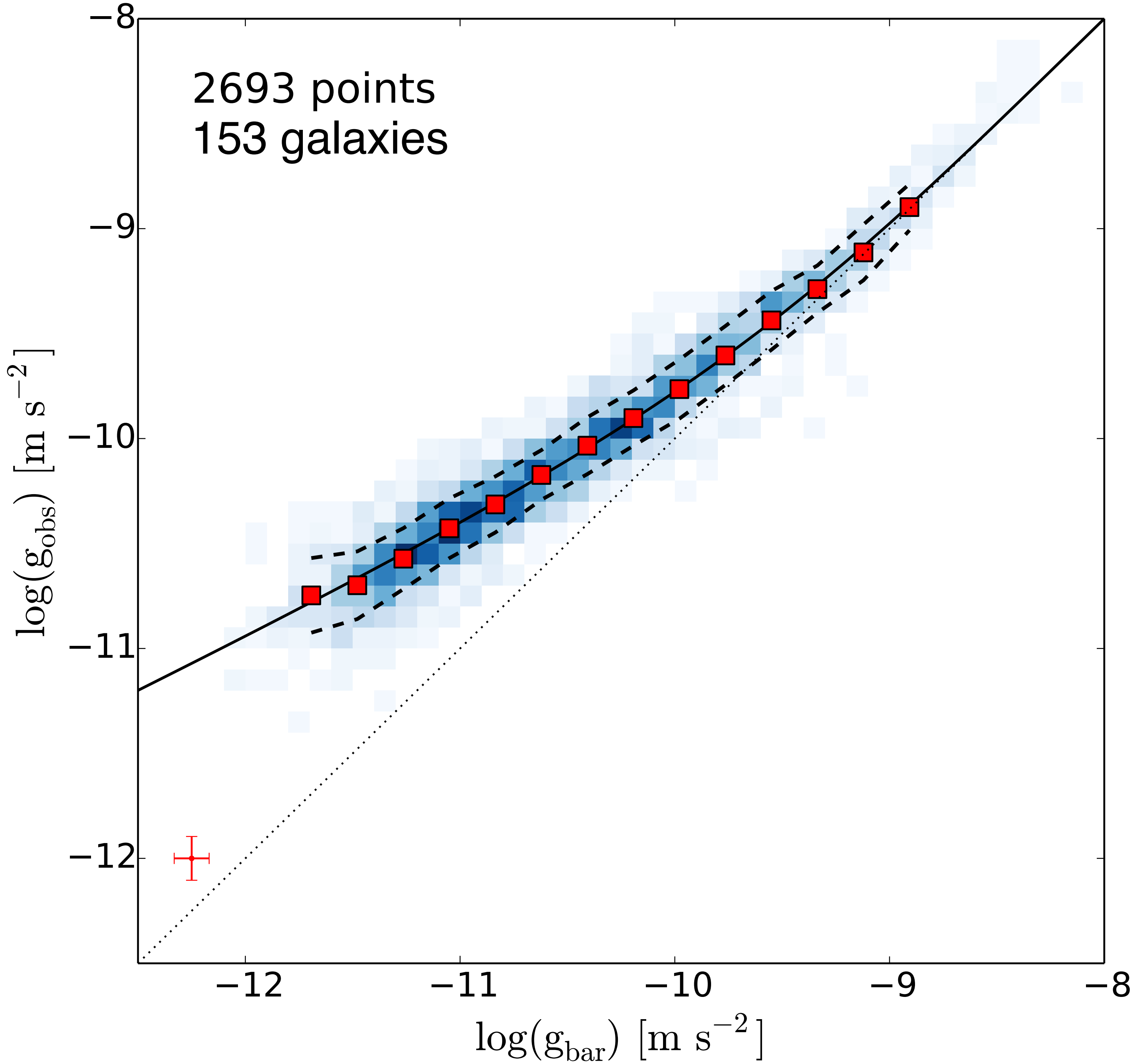
The need for dark matter only becomes apparent at low surface density, which is equivalent to low acceleration ($a \approx G\Sigma$)

Rotation curve shape correlates with baryonic surface density



5. Radial Acceleration Relation

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

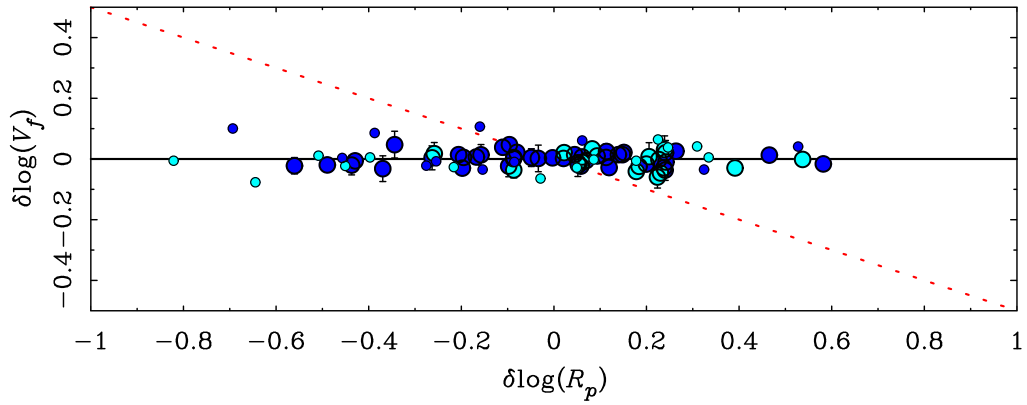


$$g_{\rm bar} = -\frac{\partial \Phi_{\rm bar}}{\partial R}$$

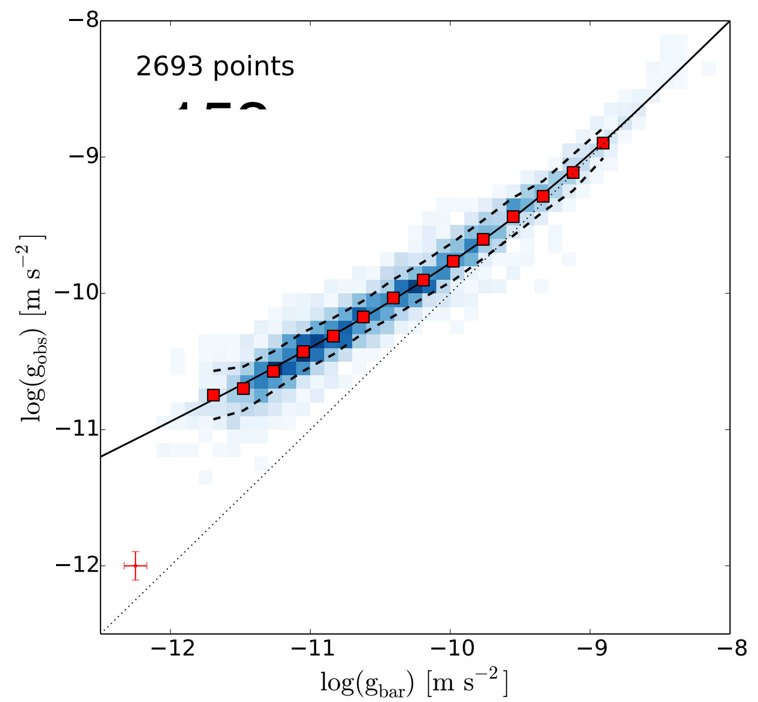
McGaugh et al. 2016
Lelli et al. 2017
Li et al. 2018

Anomalies

- Fine-tuning in TF
  - no size residuals
  - no intrinsic scatter

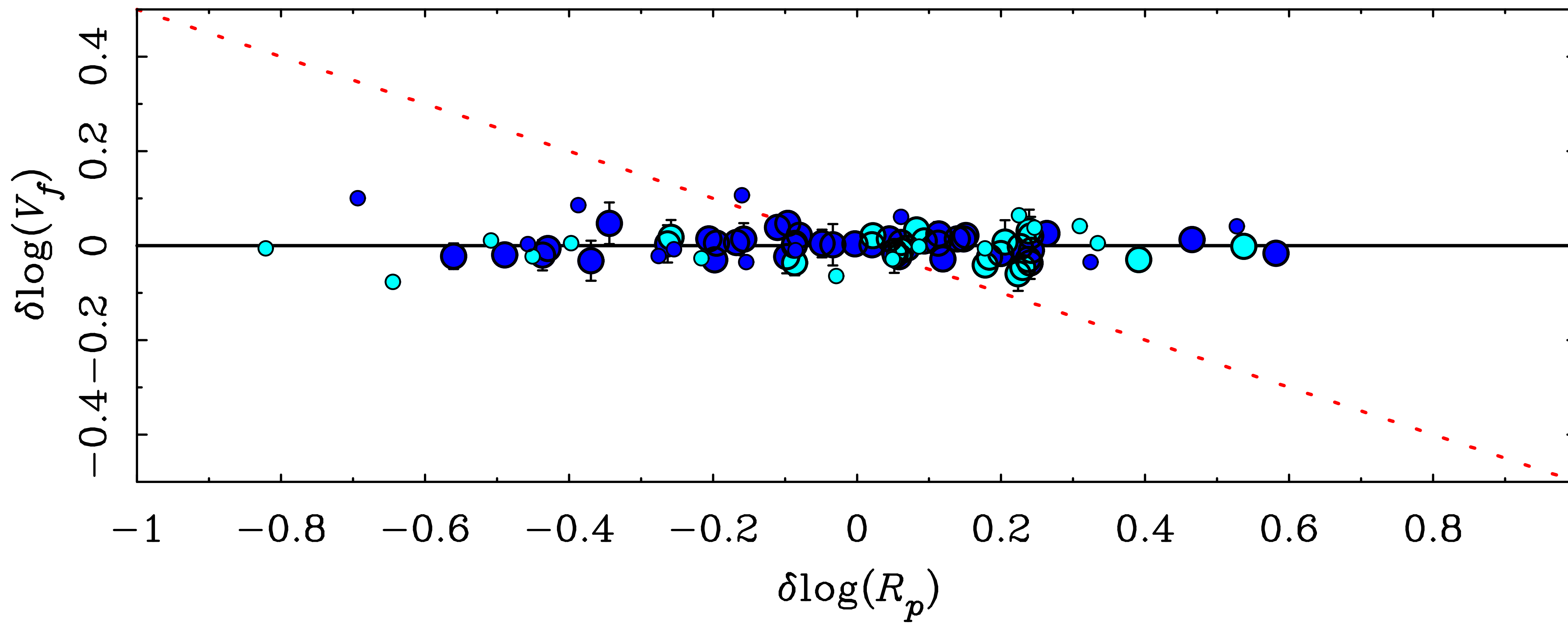


- Fine-tuning in the dark matter distribution
  - DM distribution set by baryon distribution
  - no intrinsic scatter



- That MOND has [m]any predictions come true

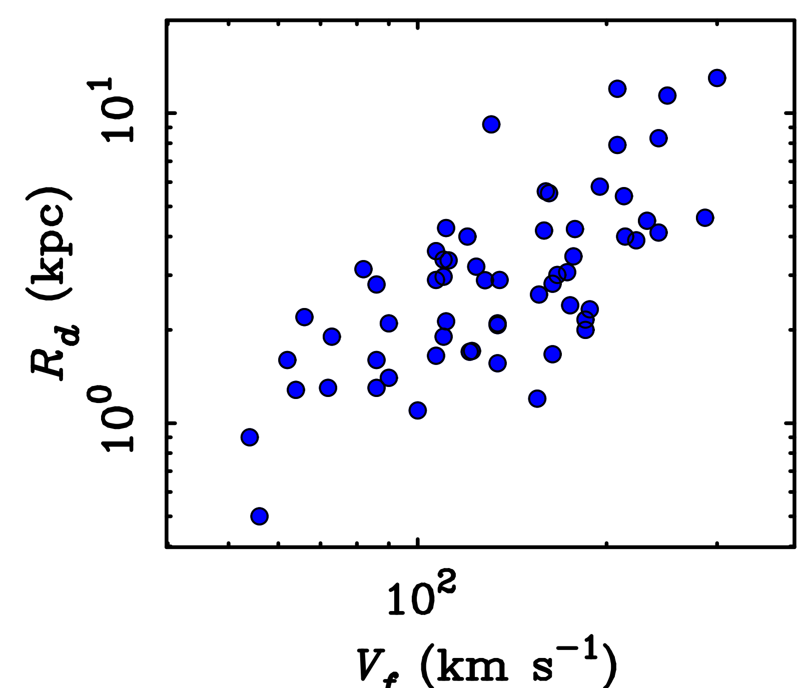
No residuals from BTFR with size or surface brightness



$$V^2 = G\left(\frac{M_b}{R_b} + \frac{M_{dm}}{R_{dm}}\right)$$

Fine-tuning anomaly: M/R for each component must balance to keep V constant. We'd expect the opposite effect from adiabatic compression.

Galaxies exist over a large range in M_b/R_b at fixed velocity



Dark Matter distribution anomaly

The Radial Acceleration Relation can be used to infer the dark matter distribution just by looking at a galaxy.

total $$g_{obs} = \mathcal{F}(g_{bar})$$

$$\mathcal{F} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_{\dagger}}}}$$

dark matter $$g_{DM} = g_{obs} - g_{bar}$$

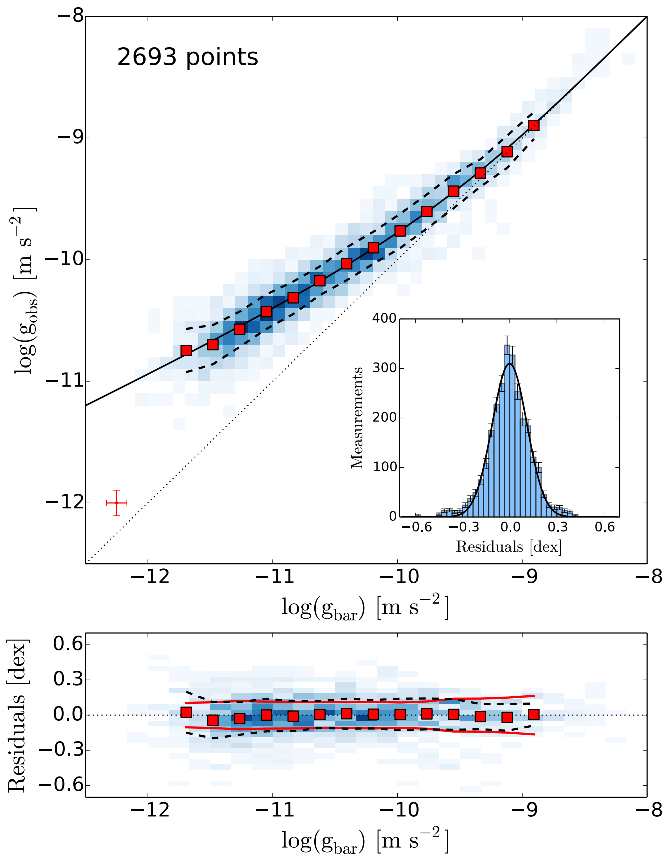
$$g_{\dagger} = 1.20 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

$$\pm 0.02\ (\mathrm{random}) \pm 0.24\ (\mathrm{systematic})$$

$$g_{DM} = \mathcal{F}(g_{bar}) - g_{bar}$$

The dark matter distribution is specified by the baryon distribution

That's weird - the baryonic tail wags the dark matter dog.



- MOND (Milgrom 1983)

Change force law at low acceleration $a_0 = 1.2 \times 10^{-10}\,\mathrm{m\,s^{-2}}$

Newtonian regime

$a = g_N$ for $a \gg a_0$

MOND regime

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

Regimes smoothly joined by an interpolation function

$$\mu\left(\frac{a}{a_0}\right) a = g_N$$

$\mu(x) \rightarrow x$ for $x \ll 1$

$\mu(x) \rightarrow 1$ for $x \gg 1$

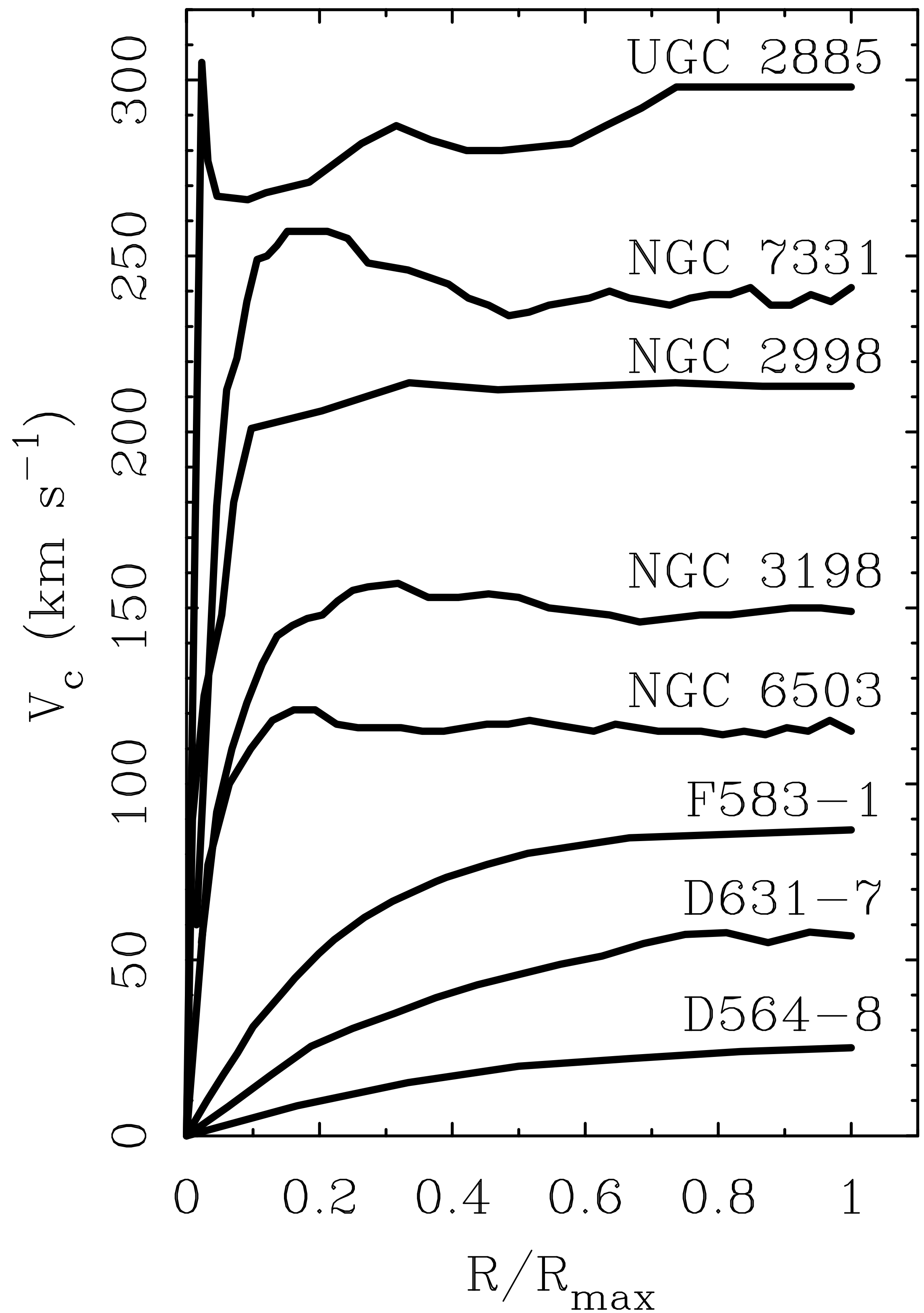
$x = \frac{a}{a_0}$

MOND

How does MOND fare?

1. Flat Rotation Curves
2. Baryonic Tully-Fisher Relation
3. Sancisi’s Law
4. Central Density Relation
5. Radial Acceleration Relation

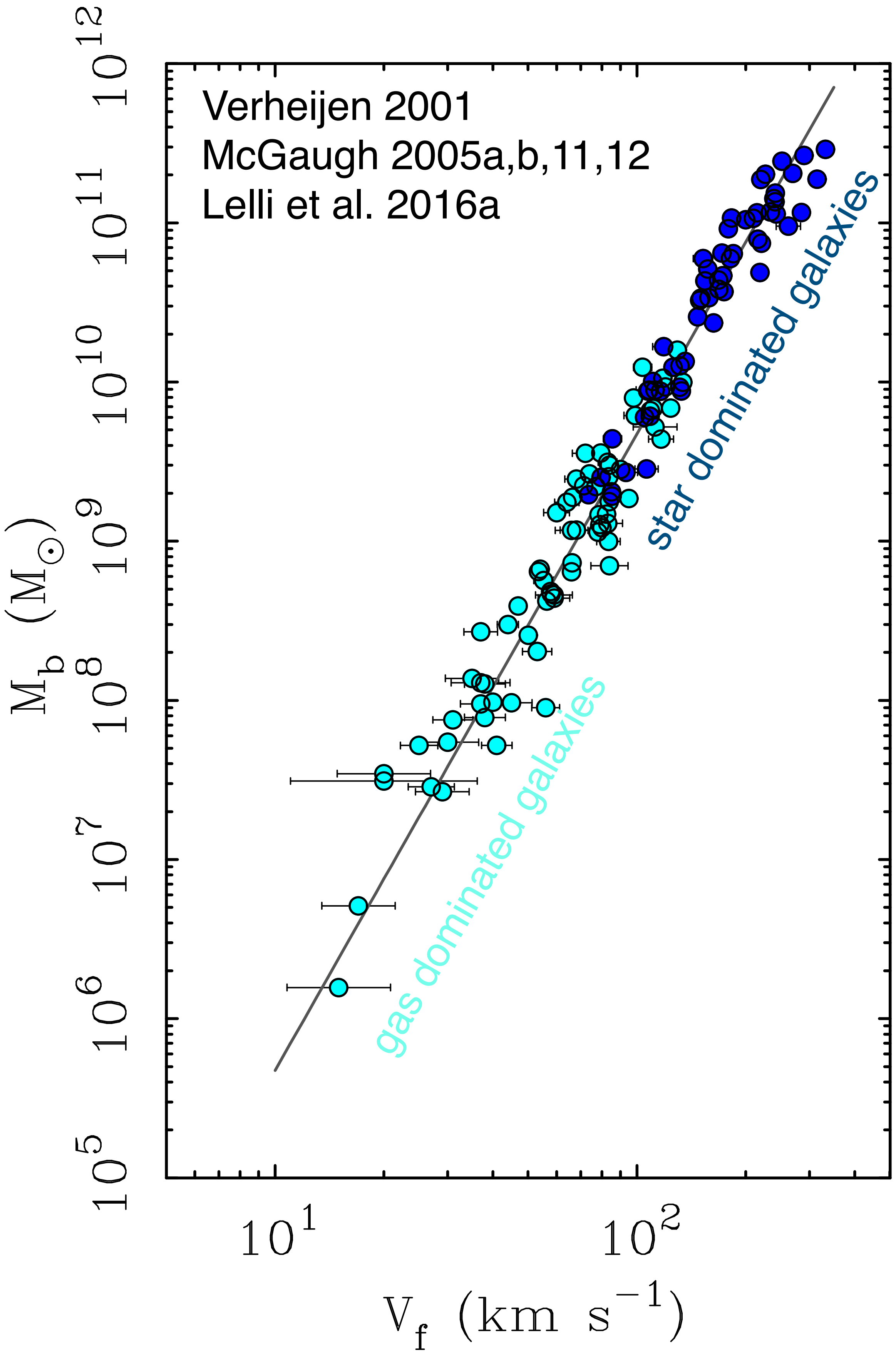
1. Flat rotation curves



MOND

Flat rotation curves were the major motivation for MOND

2. Tully-Fisher Relation



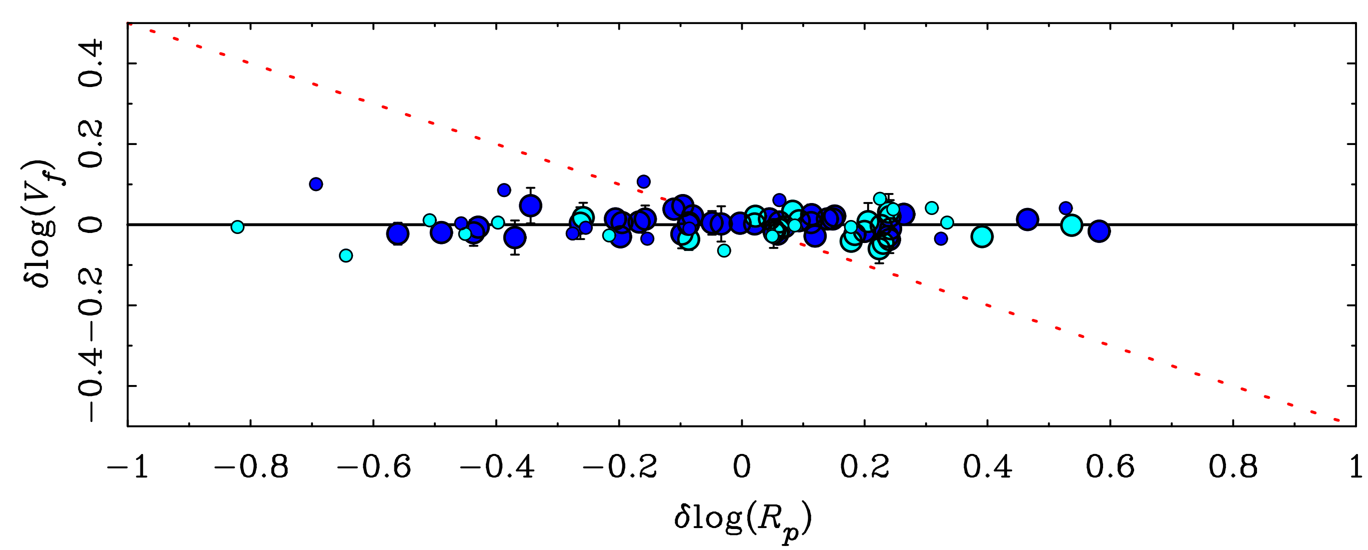
MOND

1983: the Tully-Fisher relation is absolute

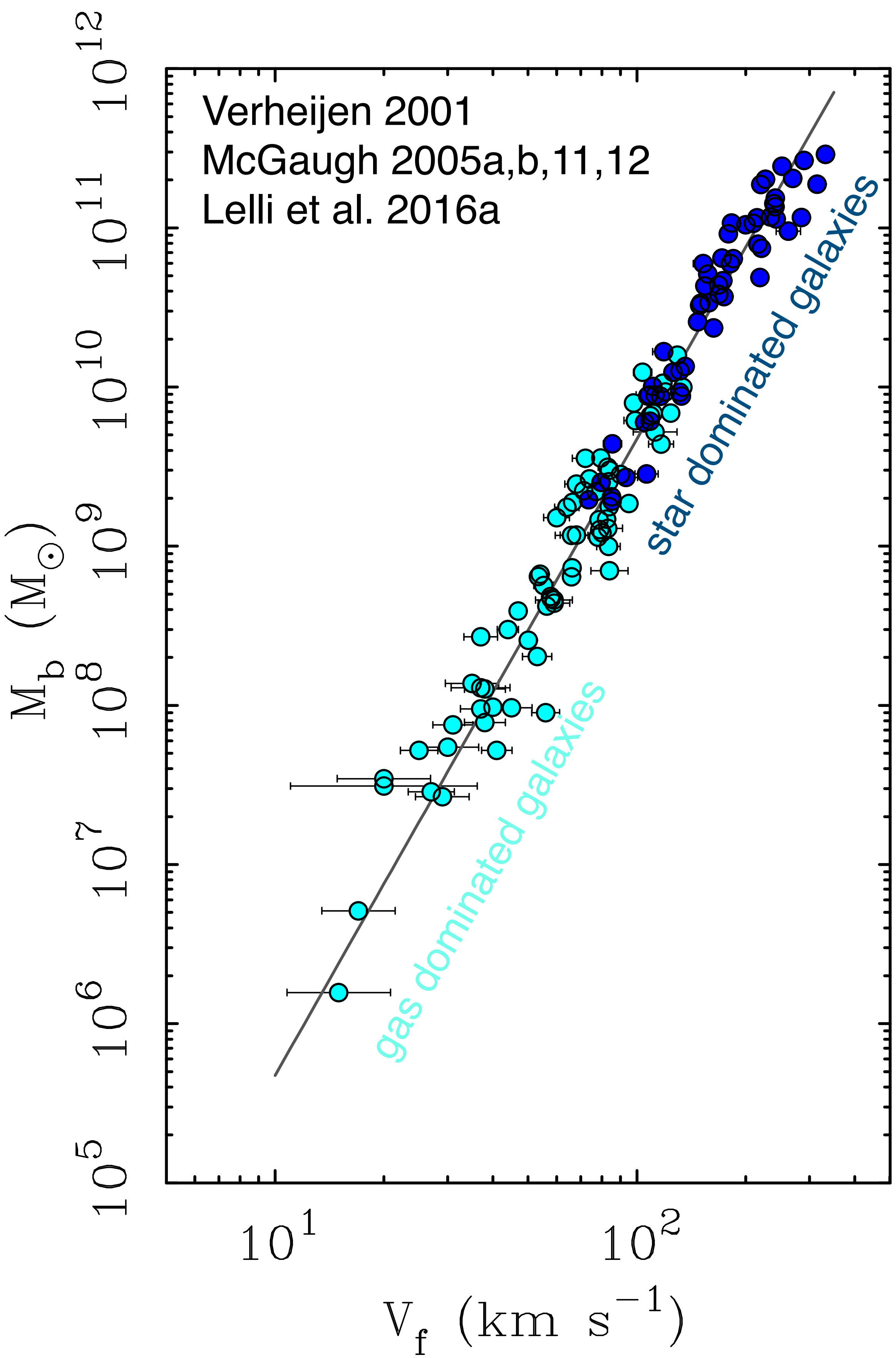
$$M_b = AV_f^4$$

- Slope = 4
- Normalization A = X/(a_0G)
- Fundamentally a relation between baryonic mass and V_{flat} (what you see and what you get)
  - nothing to do with unseen mass
- No Dependence on Surface Brightness
  - no residuals with radius, gas fraction, etc.
  - no intrinsic scatter

2018: these predictions have been repeatedly corroborated.



2. Tully-Fisher Relation

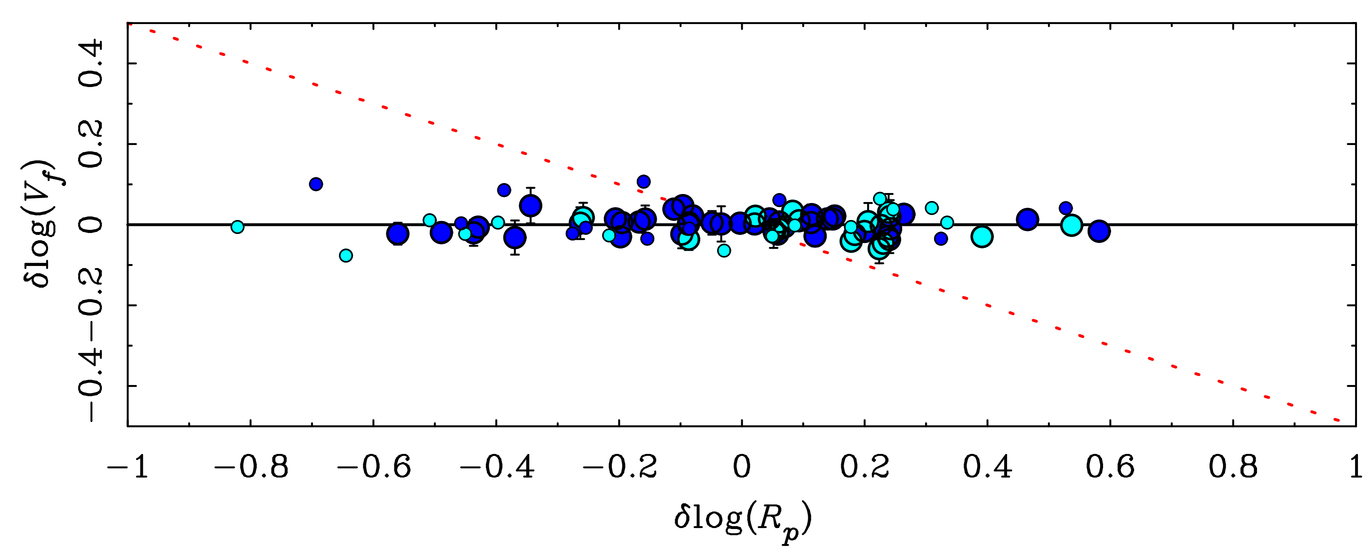


LCDM

1983: ?
1995: residuals should correlate with size/SB.
1998: slope should be 3 (e.g., MMW98)
1999: disks need to be sub-maximal to avoid residual correlations (Courteau & Rix)
2000: TF is baryonic?
2001: slope can be ~3.5; residual correlations balanced by those in halo properties

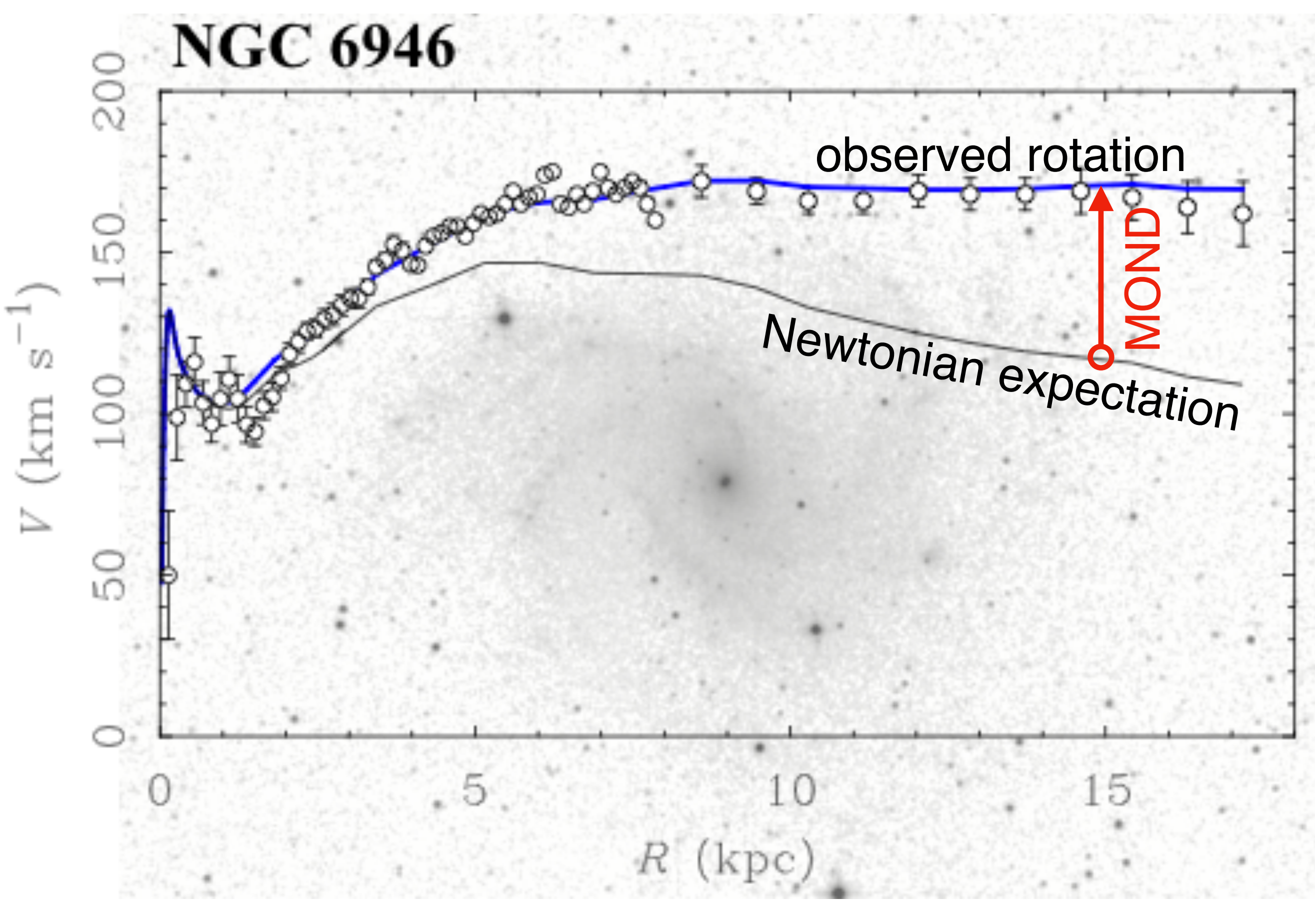
2001-present: depends on who you ask
Many models have sharp bends or predict offsets for "satellites" that are not observed.

High surface brightness disks like the Milky Way definitely near maximal (as shown by microlensing towards the bulge), so fine-tuning unavoidable.



3. Renzo's Rule/Sancisi's Law

"When you see a feature in the light, you see a corresponding feature in the rotation curve, and vice-versa."

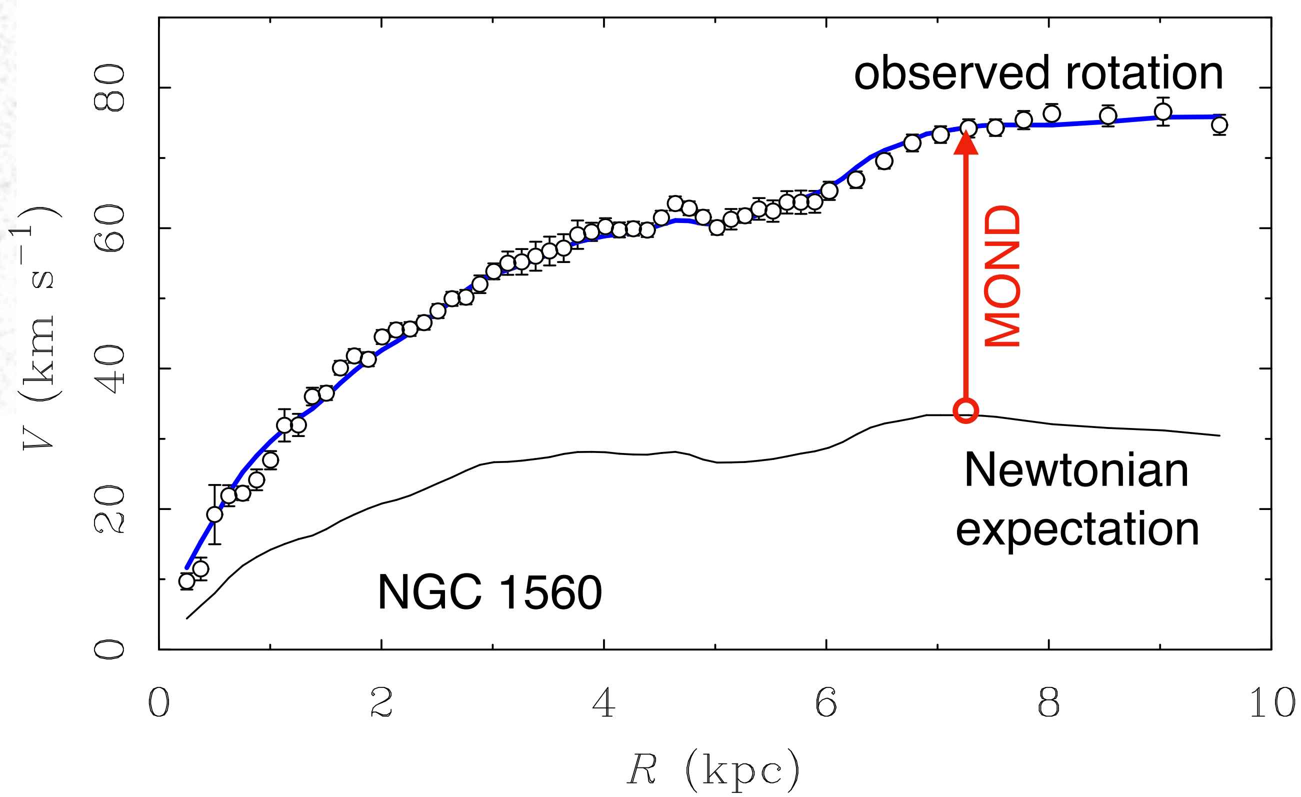


MOND ☆

Renzo's Rule follows naturally.

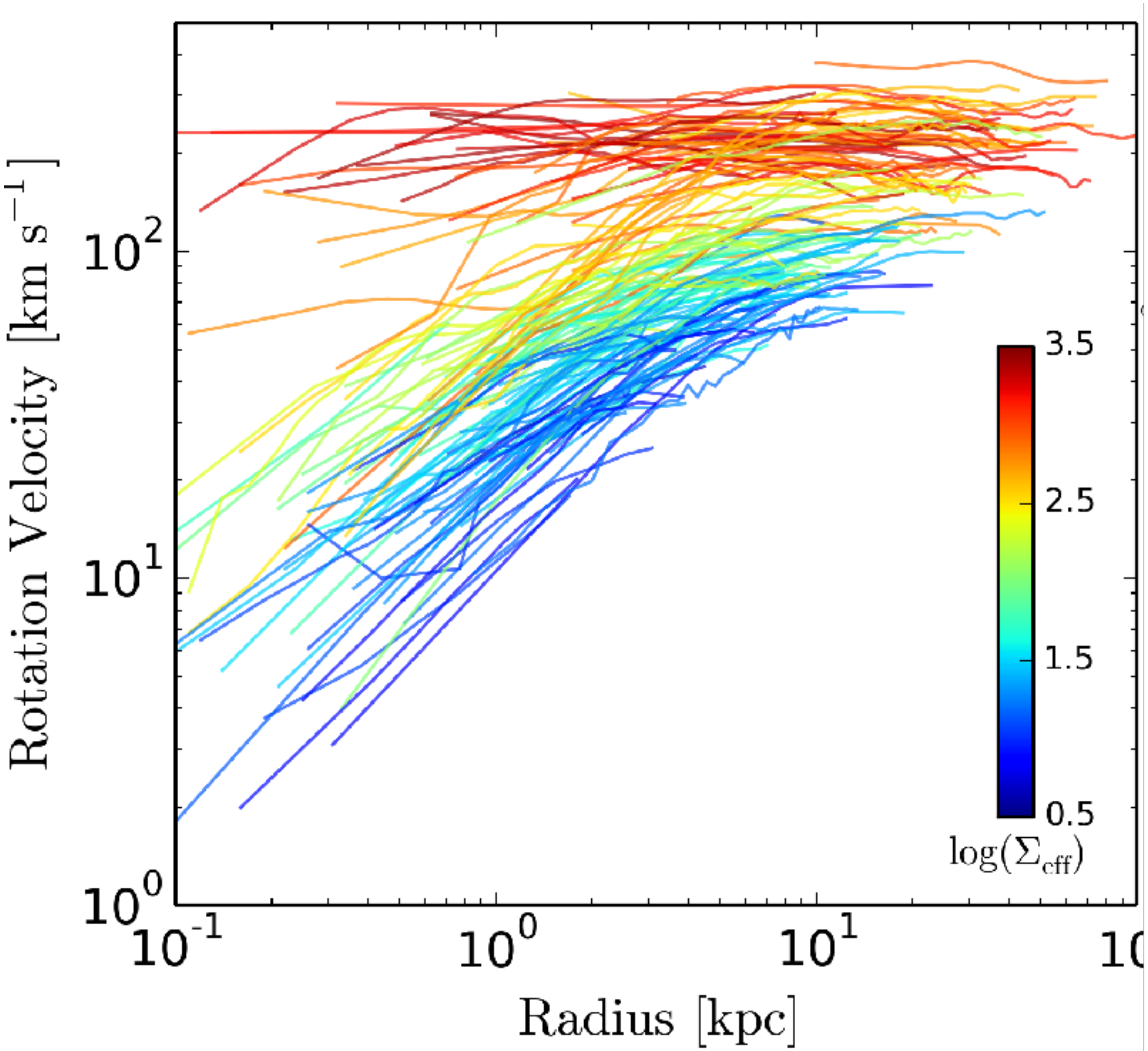
MOND encapsulates a mathematical rule for mapping the baryon-predicted rotation curve predicted by Newton to the observed rotation curve.

We need to understand why. It is not scientific to just assume it will work out.



4. Central Density Relation

<u>MOND</u> ☆



The central density relation follows naturally in MOND… indeed, this relation can be derived from MOND.

The systematic variation in rotation curve shape with baryonic surface density was explicitly predicted by Milgrom (1983). ☆

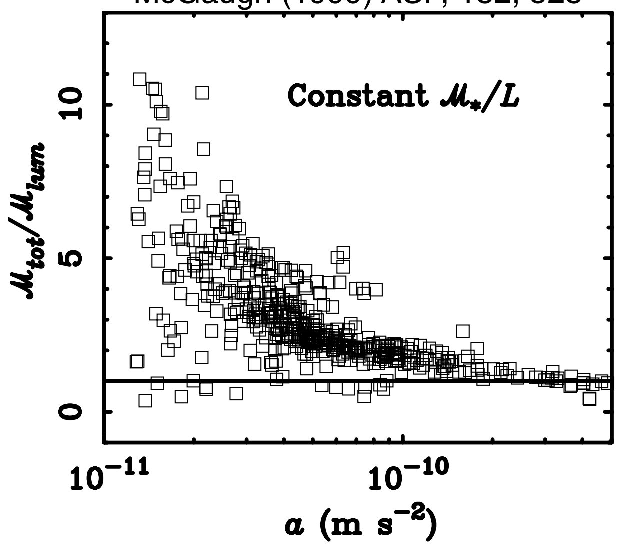
I.e., not just the central surface density, but that at all radii.

5. Radial Acceleration Relation

<u>MOND</u>

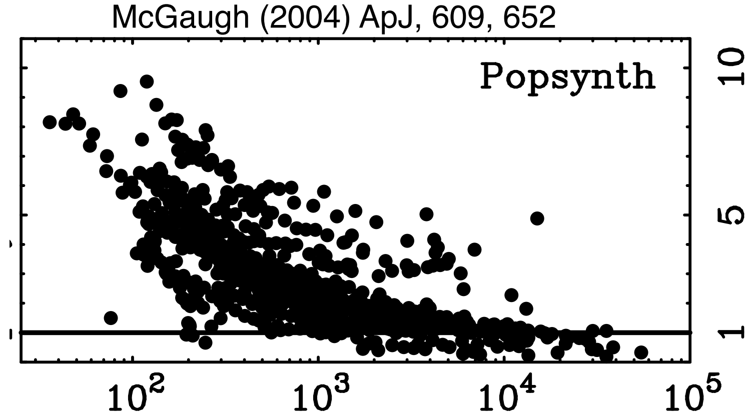
1998 data - 24 galaxies

McGaugh (1999) ASP, 182, 528



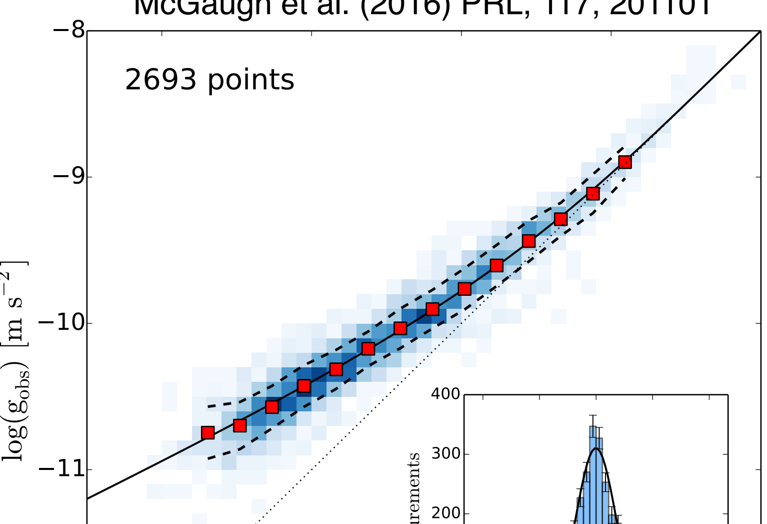
2004 data - 60 galaxies

McGaugh (2004) ApJ, 609, 652



2016 data - 153 galaxies

McGaugh et al. (2016) PRL, 117, 201101



1983: The observed acceleration follows from that predicted by the distribution of baryons.

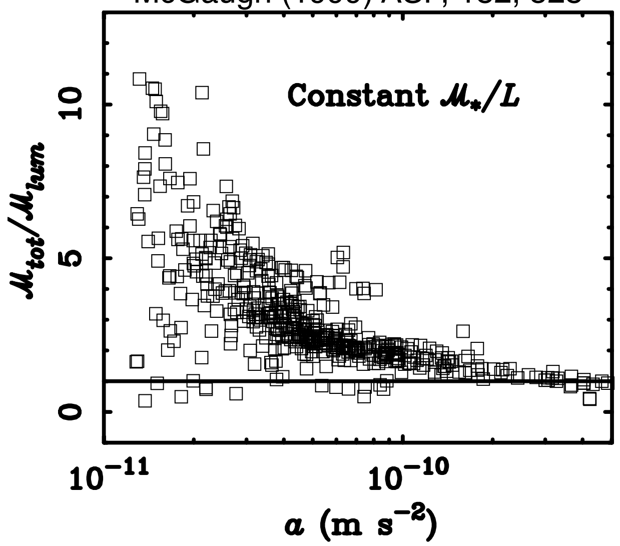
The empirical RAR is exactly what is expected in MOND.

The shape of the RAR is the interpolation function of MOND.

5. Radial Acceleration Relation

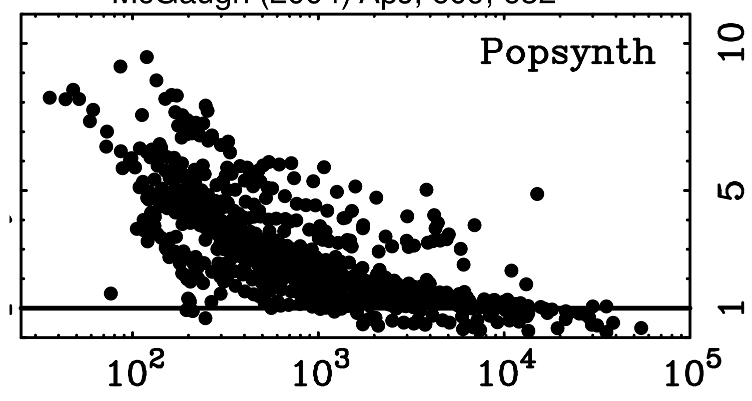
1998 data - 24 galaxies

McGaugh (1999) ASP, 182, 528



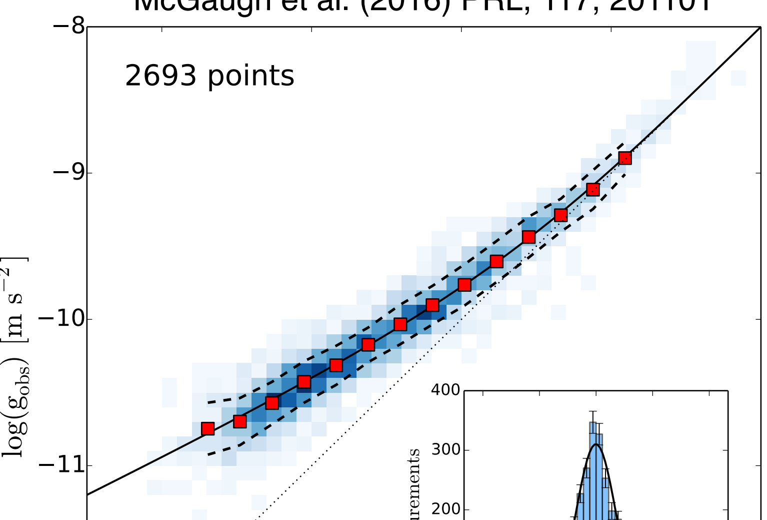
2004 data - 60 galaxies

McGaugh (2004) ApJ, 609, 652



2016 data - 153 galaxies

McGaugh et al. (2016) PRL, 117, 201101



LCDM

1983: ?

1997: NFW halos + baryons

1998: Beam smearing might have affected a few galaxies, so lets ignore inconvenient rotation curves.

2000: But we can explain it anyway.

2005: “We don’t have to explain MOND!”
- Anatoly Klypin

2006: Slit misplacement might have affected a few galaxies, so lets ignore inconvenient rotation curves.
- summary talk at KITP conference, Oct. 2006

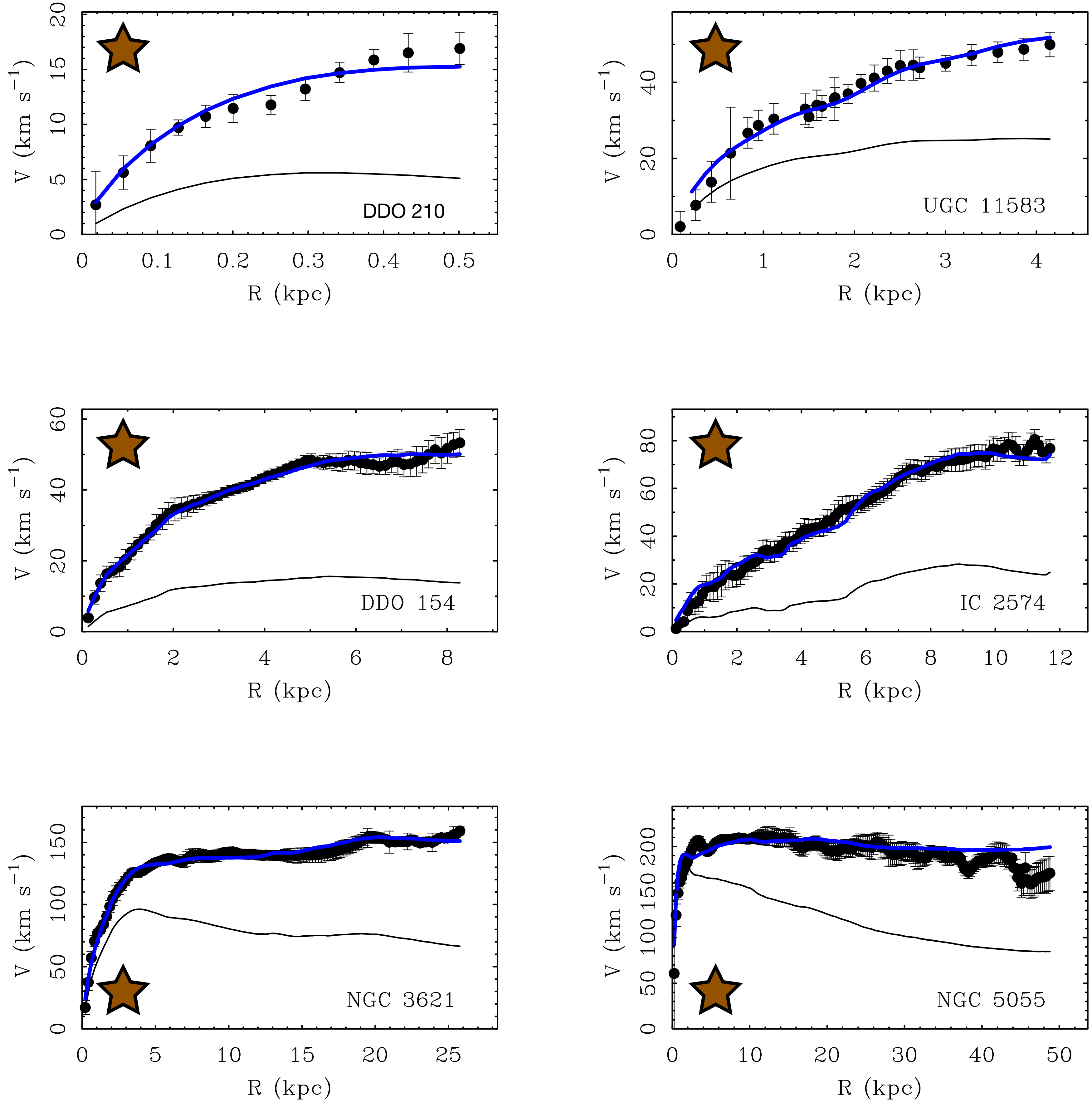
< *A decade of deafening silence.* >

2016: We can do that!

Well, sort of.
The model ***g_+*** *found by Ludlow et al differs from the data by* ***70 sigma****.*

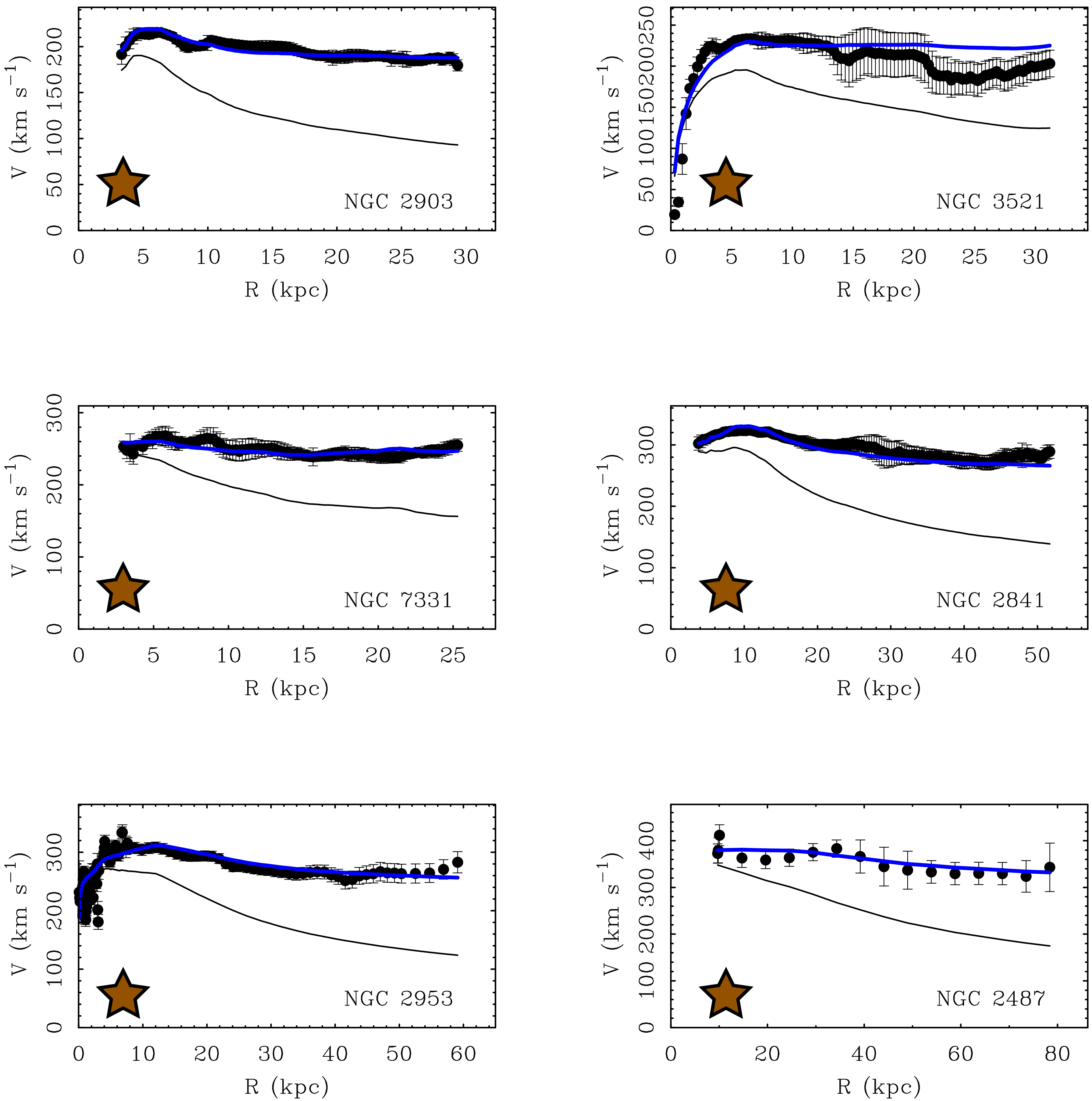
Can make MOND fits for every galaxy for which there is available data

Famaey & McGaugh 2011



Every galaxy is an independent test.

Famaey & McGaugh 2011



Li et al. 2018

Can do this 175 times… ★★★…

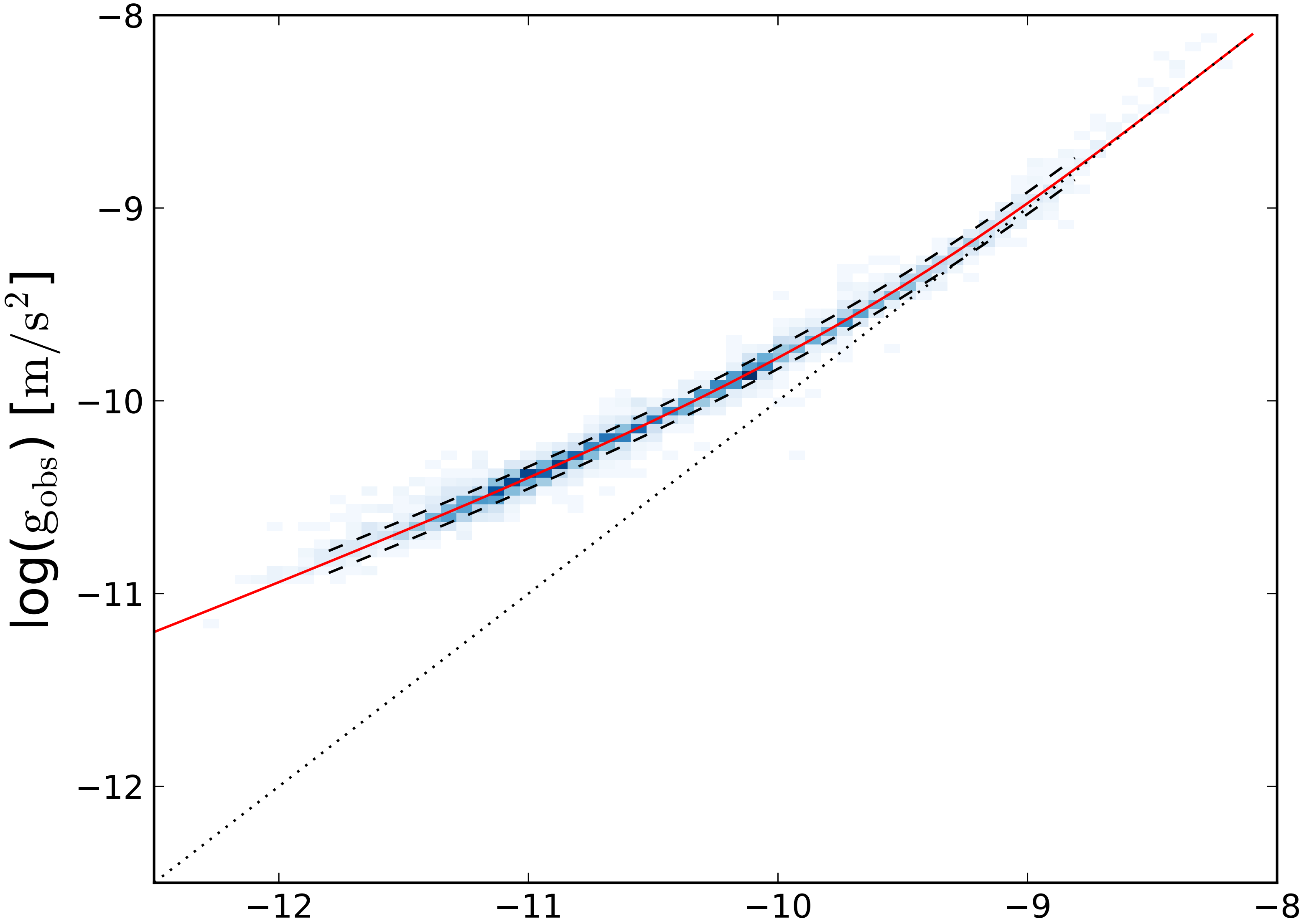
Radial Acceleration Relation

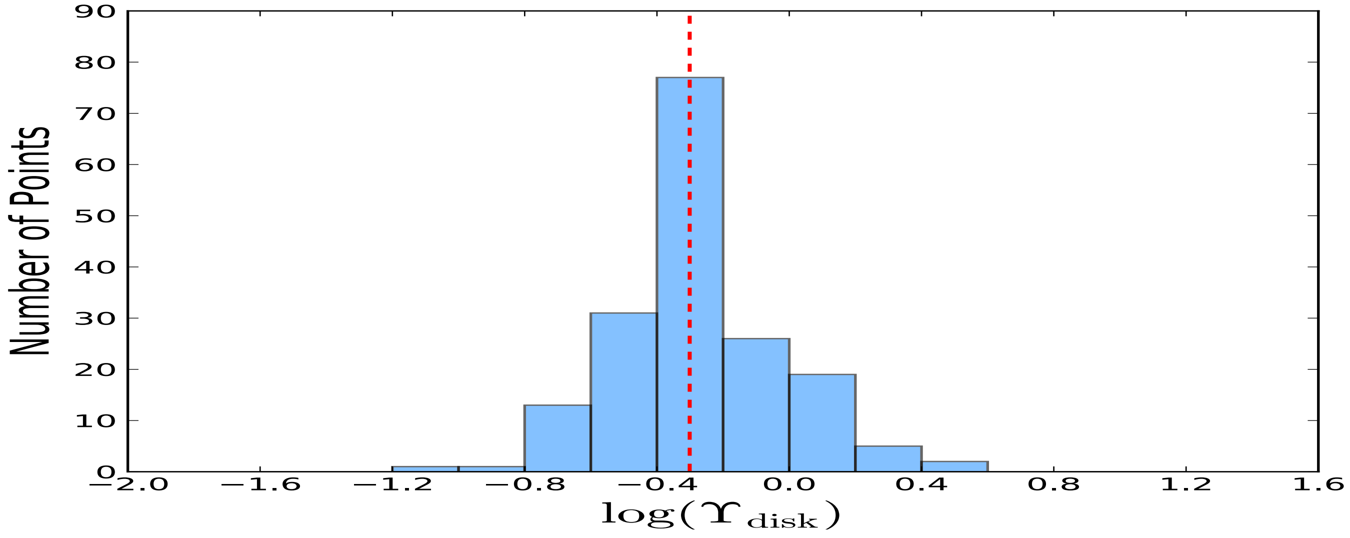
Scatter virtually disappears after marginalizing over the mass-to-light ratio and nuisance parameters (D, i)

The data are consistent with zero intrinsic scatter.

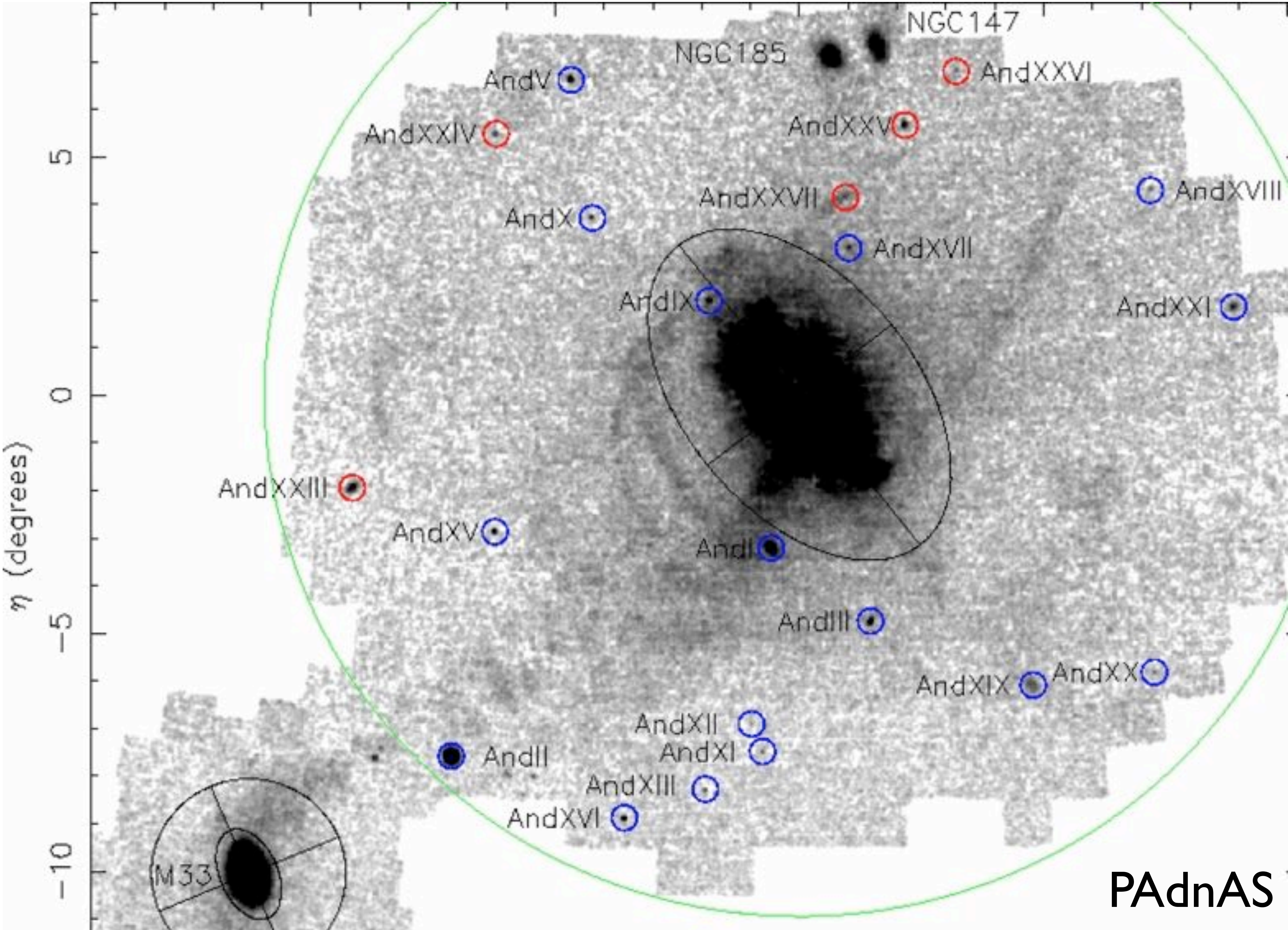
The scatter in M*/L is consistent with that expected from stellar population models.

The empirical RAR is indistinguishable from MOND.





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



PAdnAS

Newtonian regime

$g_{in} > a_0$

$$M = \frac{RV^2}{G}$$

e.g., surface of the Earth

ISO MOND regime

$g_{in} < a_0$

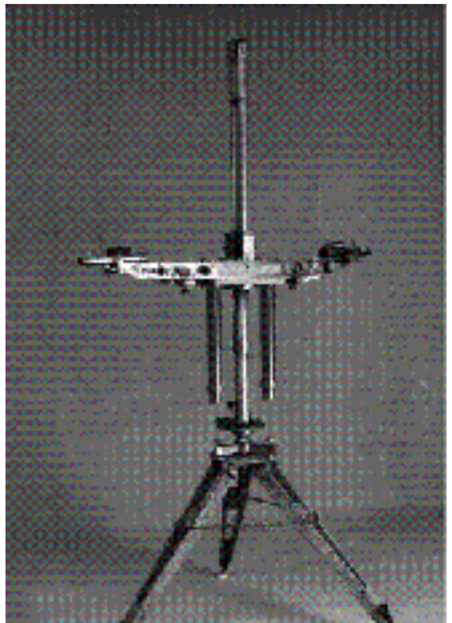
$$M = \frac{V^4}{a_0 G}$$

e.g., remote dwarf Leo I

External Field dominant Newtonian regime

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

$$M = \frac{RV^2}{G}$$



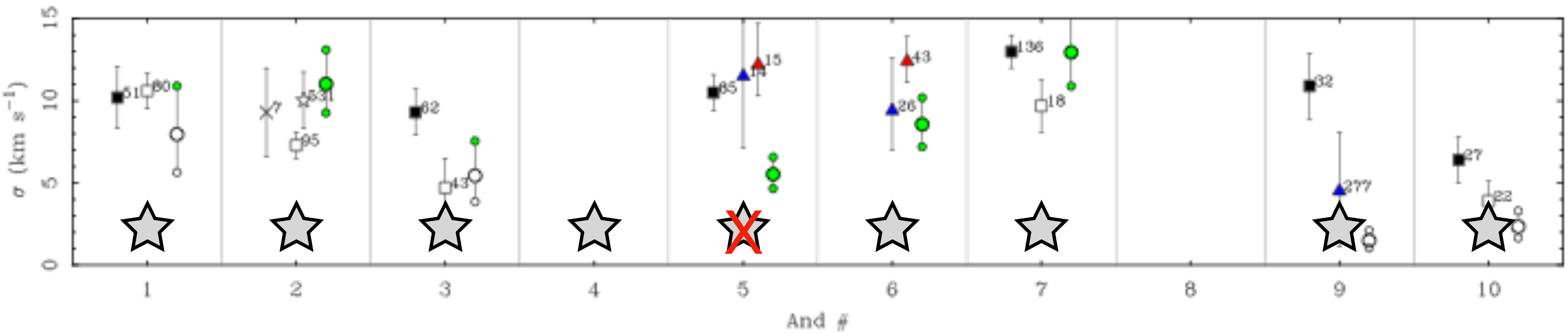
e.g., Eotvos-type experiment on the surface of the Earth

EFE External Field dominant quasi-Newtonian regime

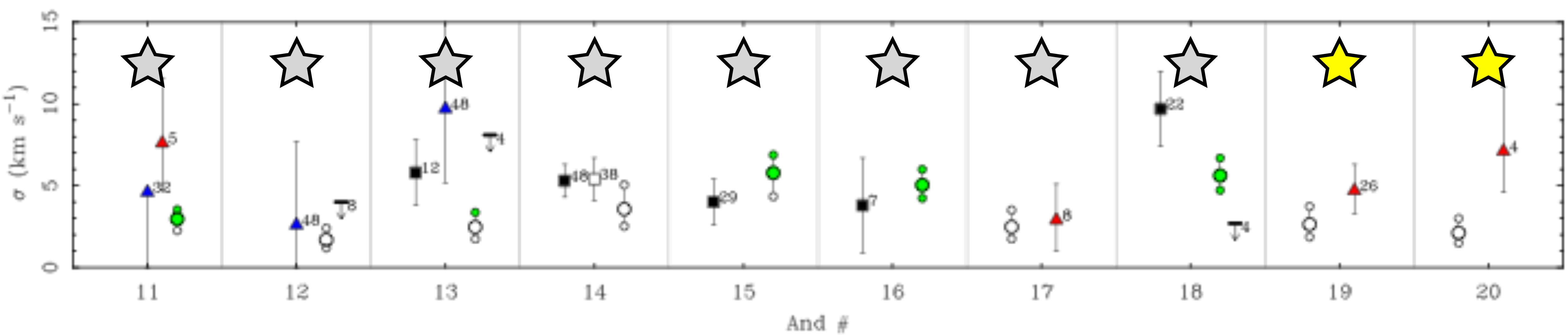
$g_{in} < g_{ex} < a_0$

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

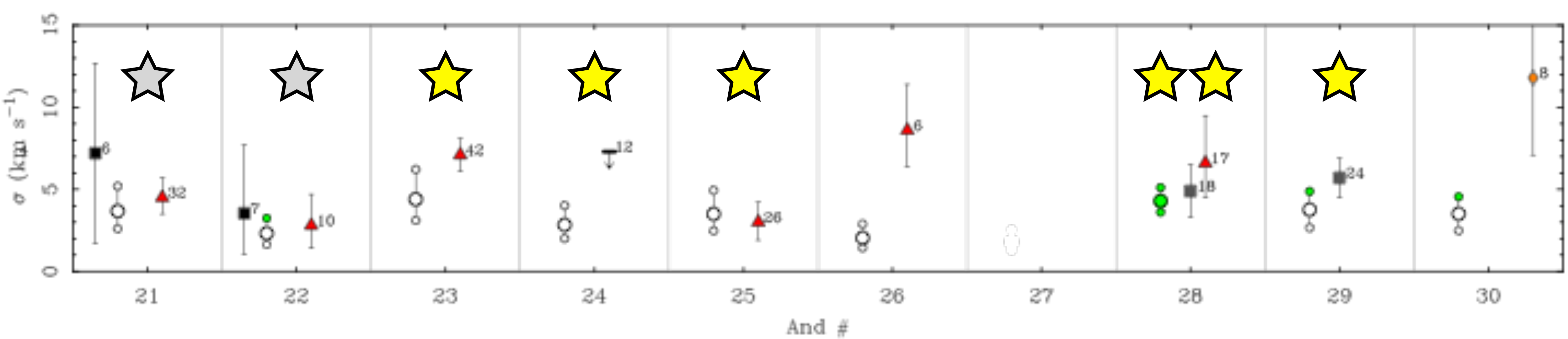
e.g., nearby dwarf Segue 1



MOND correctly predicts the velocity dispersion of the M31 dwarfs.

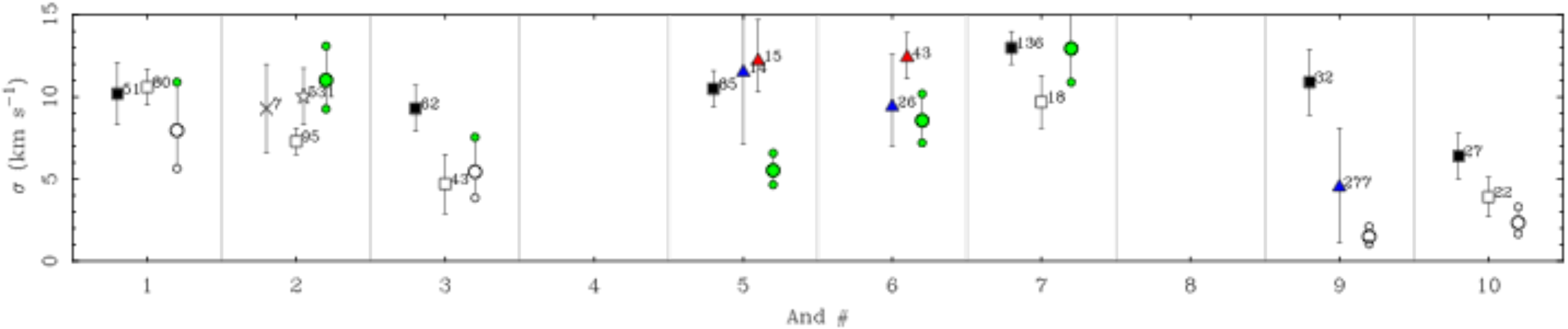


The prediction is completely a priori in And IXX, XX, XXIII, XIV...

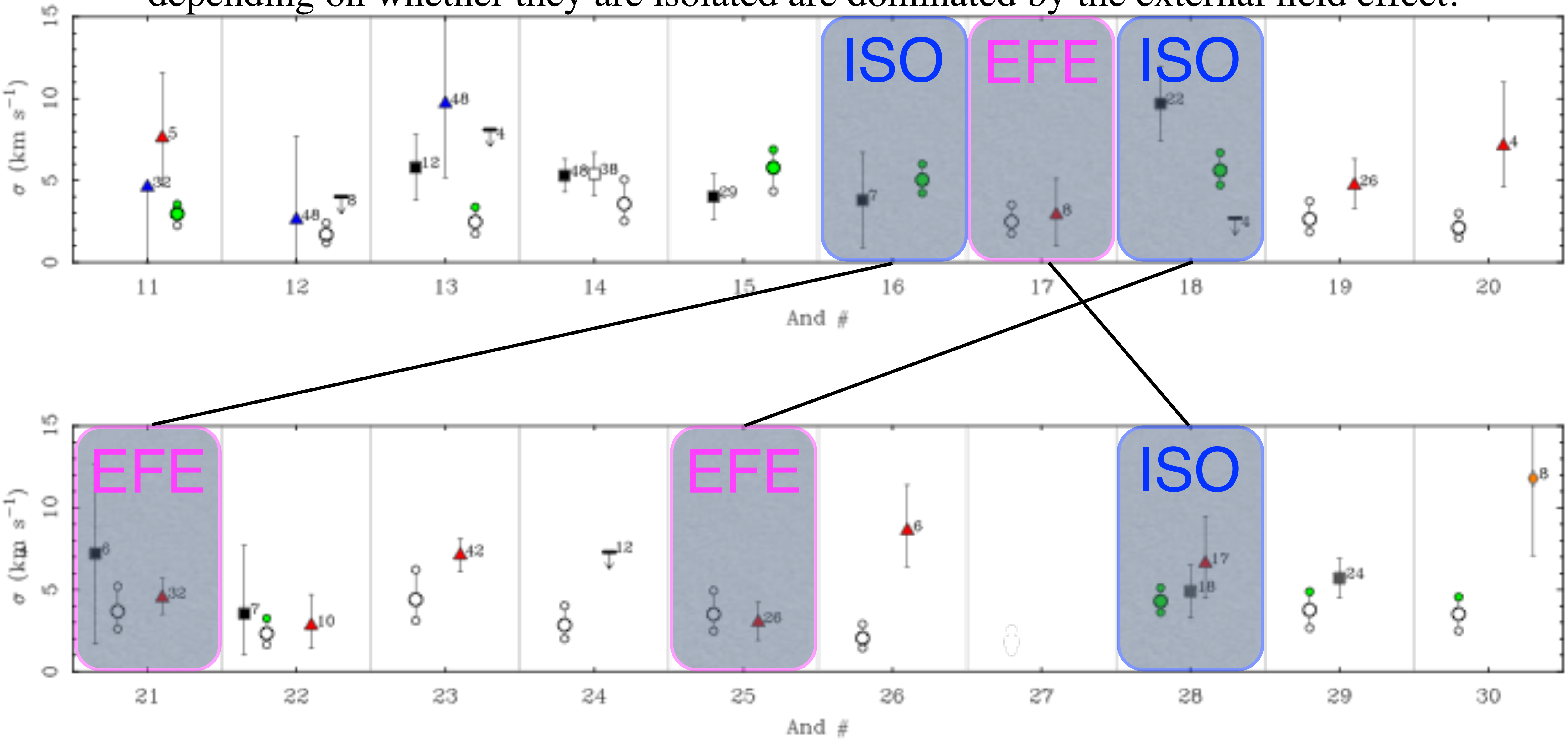


... XV, XVI, XVIII, XIX, XXX, XXXI, XXXII, & XXXIII.

(McGaugh & Milgrom 2013a,b)



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.

(McGaugh & Milgrom 2013a,b)

And XXVIII was noted by MM13 as a good case for its relative isolation; its prediction came out bang on.

And XIX, And XXI, and And XXV are notable for their large sizes. MOND predicted low velocity dispersions a priori, as observed.

In LCDM we have to invoke tidal disruption, post hoc. This requires radial orbits. We've already been through this for the Milky Way satellites, where the orbits of the classical dwarf satellites are relatively low eccentricity, as anticipated by McGaugh & Wolf (2010).

Crater 2

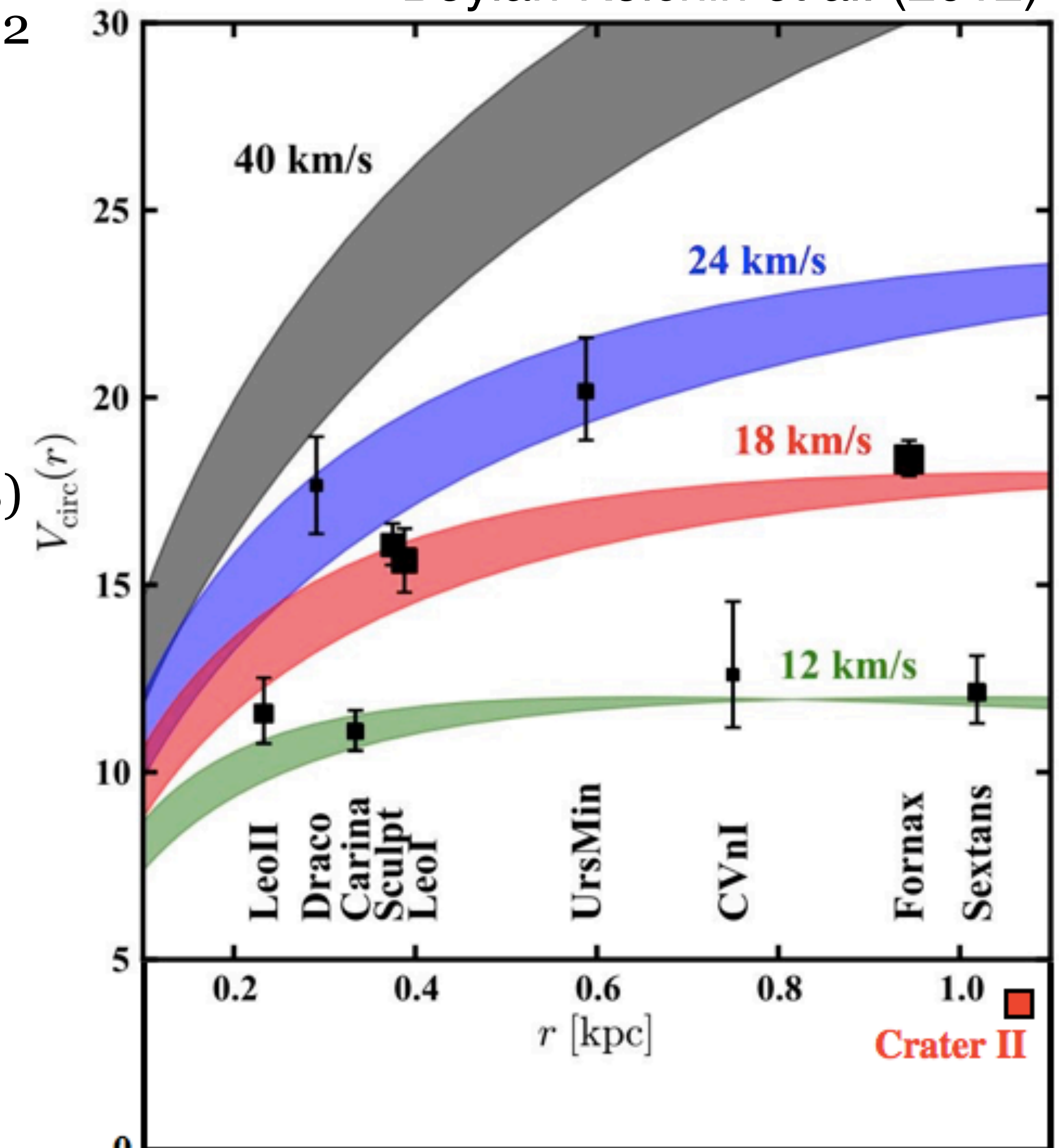
The recently discovered, ultra-diffuse Crater 2 provides another test. $L_V = 1.6 \times 10^5 \ \mathrm{L}_\odot$
$r_h = 1066 \ \mathrm{pc}$

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

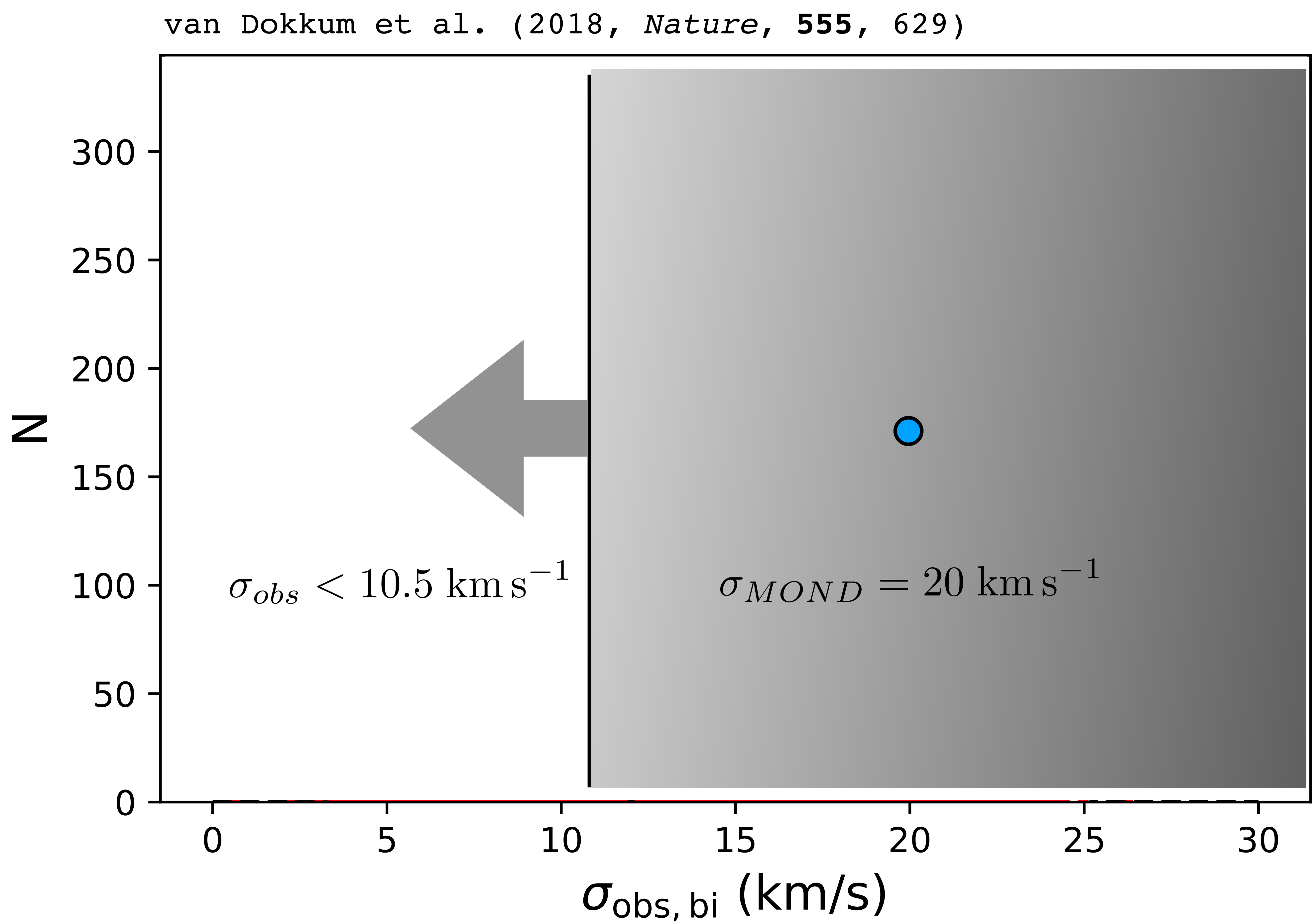
MOND predicts **2.1 +0.9/-0.6 km/s**
(in **EFE** regime McGaugh 2016, ApJ, 832 L8)

Subsequently observed: **2.7 ± 0.3 km/s**
(Caldwell et al. 2017, ApJ, 839, 20)

Boylan-Kolchin et al. (2012)



NGC 1052-DF2



van Dokkum et al. (2018, *Nature*, **555**, 629)
N
300
250
200
150
100
50
0
$\sigma_{obs} < 10.5\ \mathrm{km\,s^{-1}}$
$\sigma_{MOND} = 20\ \mathrm{km\,s^{-1}}$
0
5
10
15
20
25
30
$\sigma_{\mathrm{obs,\,bi}}$ (km/s)

NGC 1052-DF2

$\sigma_{MOND} = 13.4^{+4.8}_{-3.7}\,\mathrm{km\,s^{-1}}$ arXiv:1804.04167

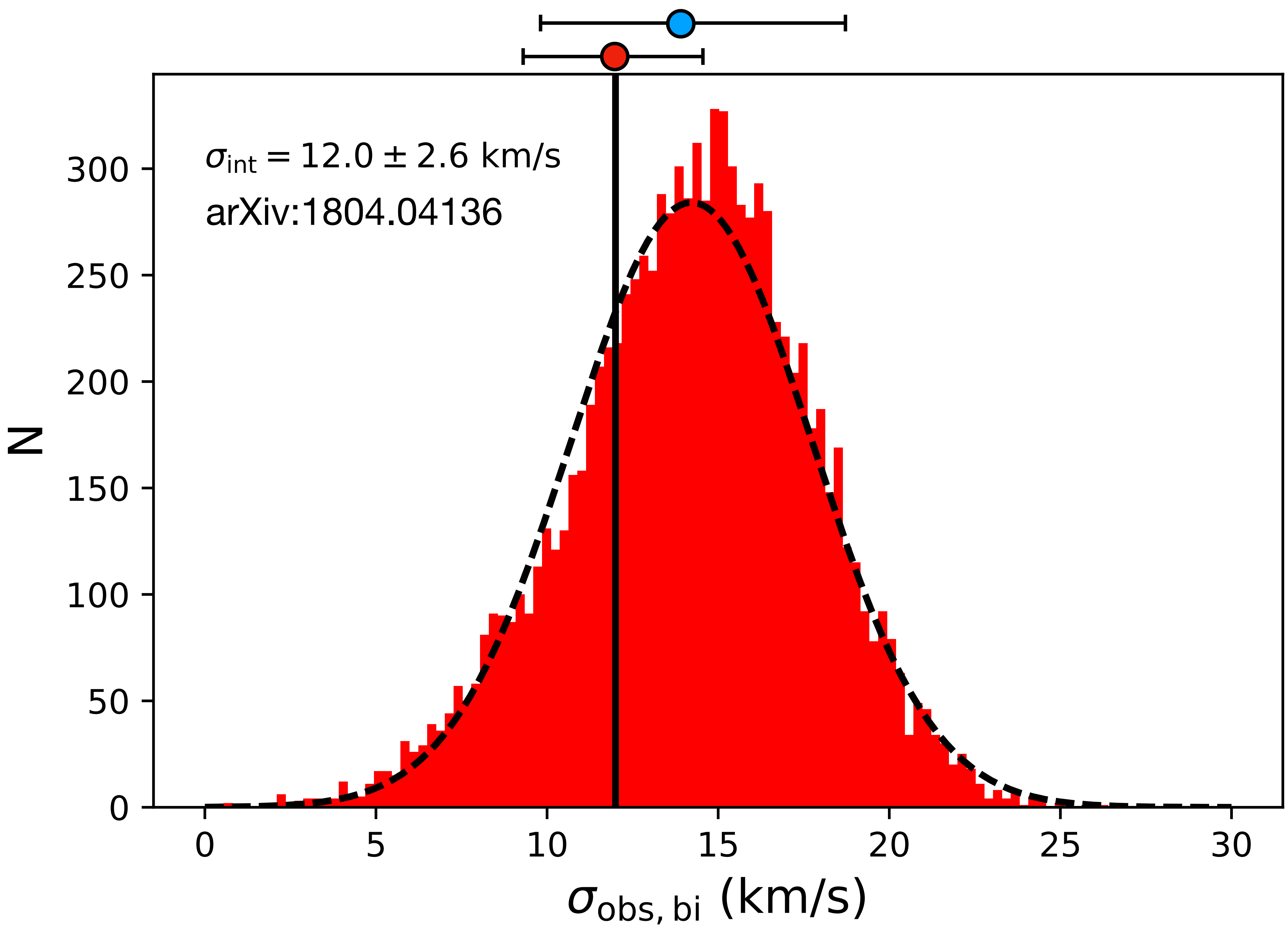
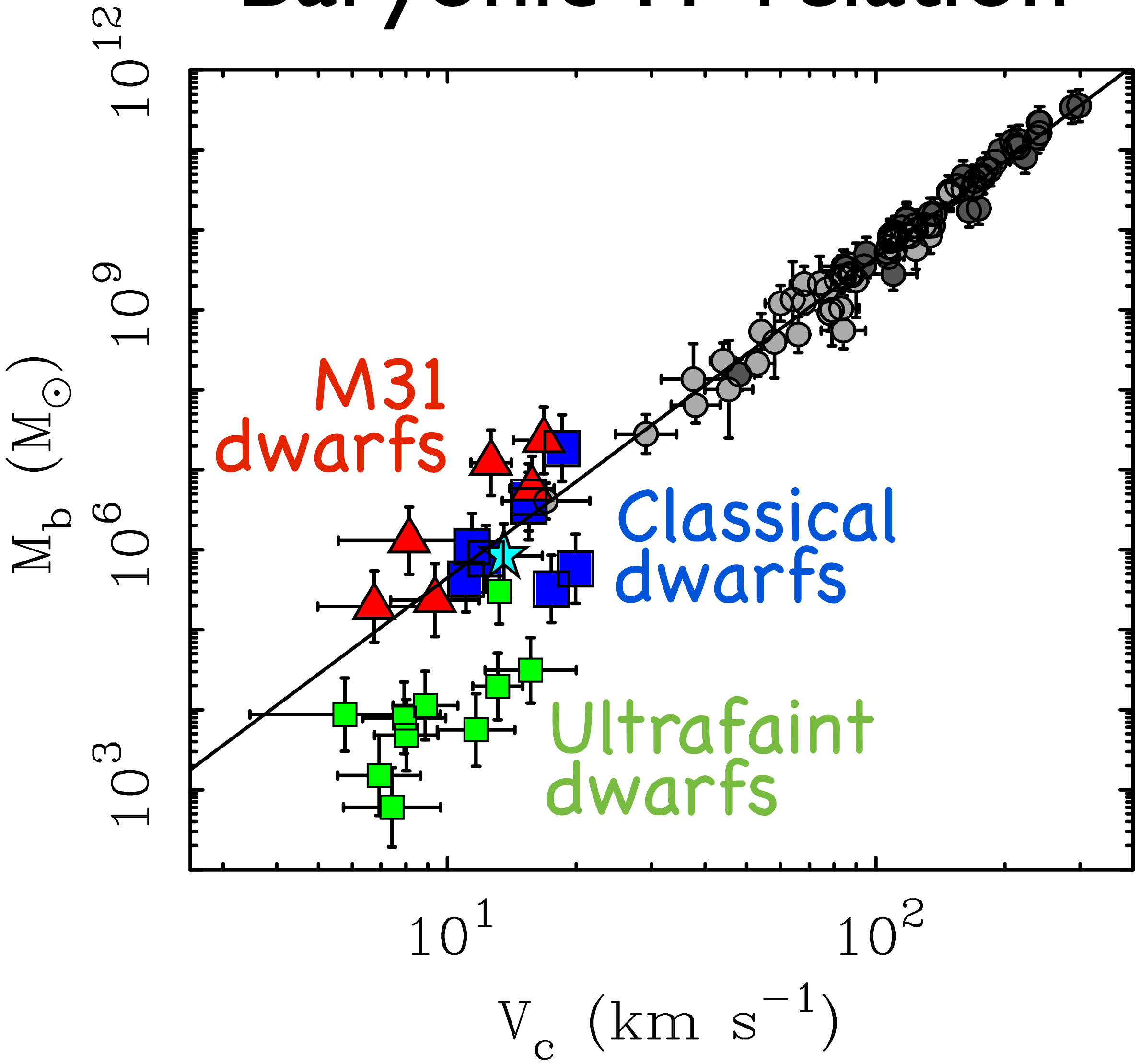


Figure 4. Results for measuring the observed biweight-midvairance dispersion from 10,000 resamples of the vD18b dataset. Here, the original velocities are perturbed within their 1 uncertainties as described in the text. The mean observed biweight for the sample comes out as $\sigma_{obs,bi} = 14.3 \pm 3.5$ km s^{-1}, giving $\sigma_{int,bi} = 12.0 \pm 2.5$ km s^{-1}, higher than the 90% upper limit from vD18b, and consistent with our MCMC analysis.

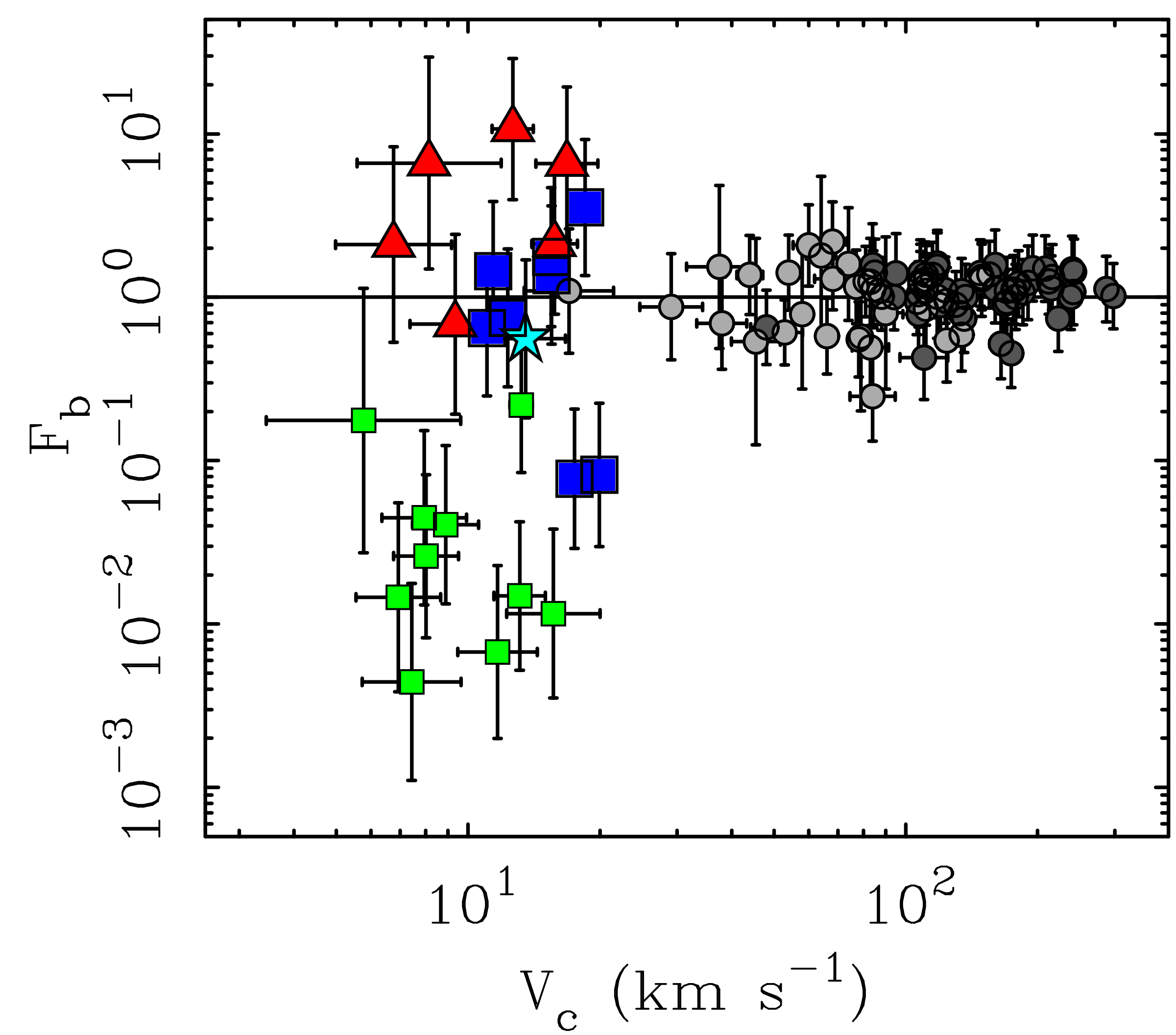
Tidal effects in ultrafaint dwarfs (McGaugh & Wolf 2010)

Also KITP Tuesday (Feb 2012)

Baryonic TF relation

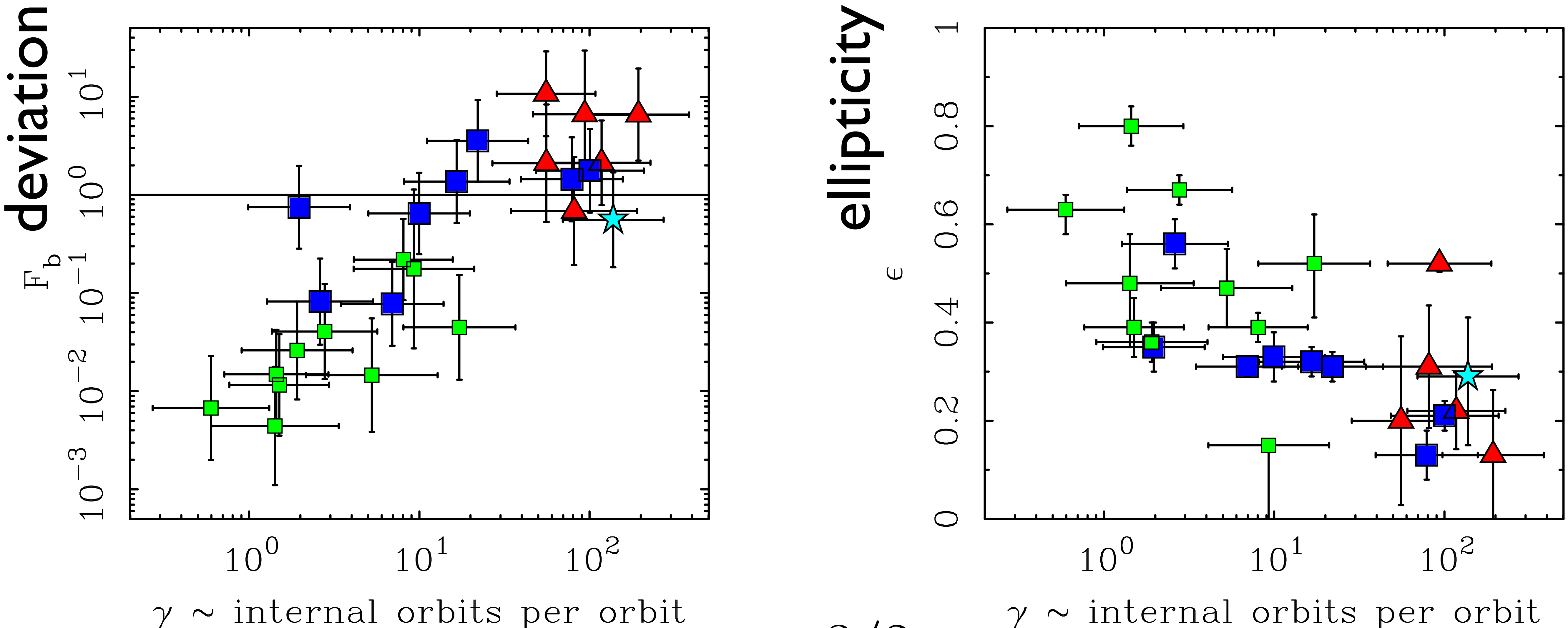


deviations



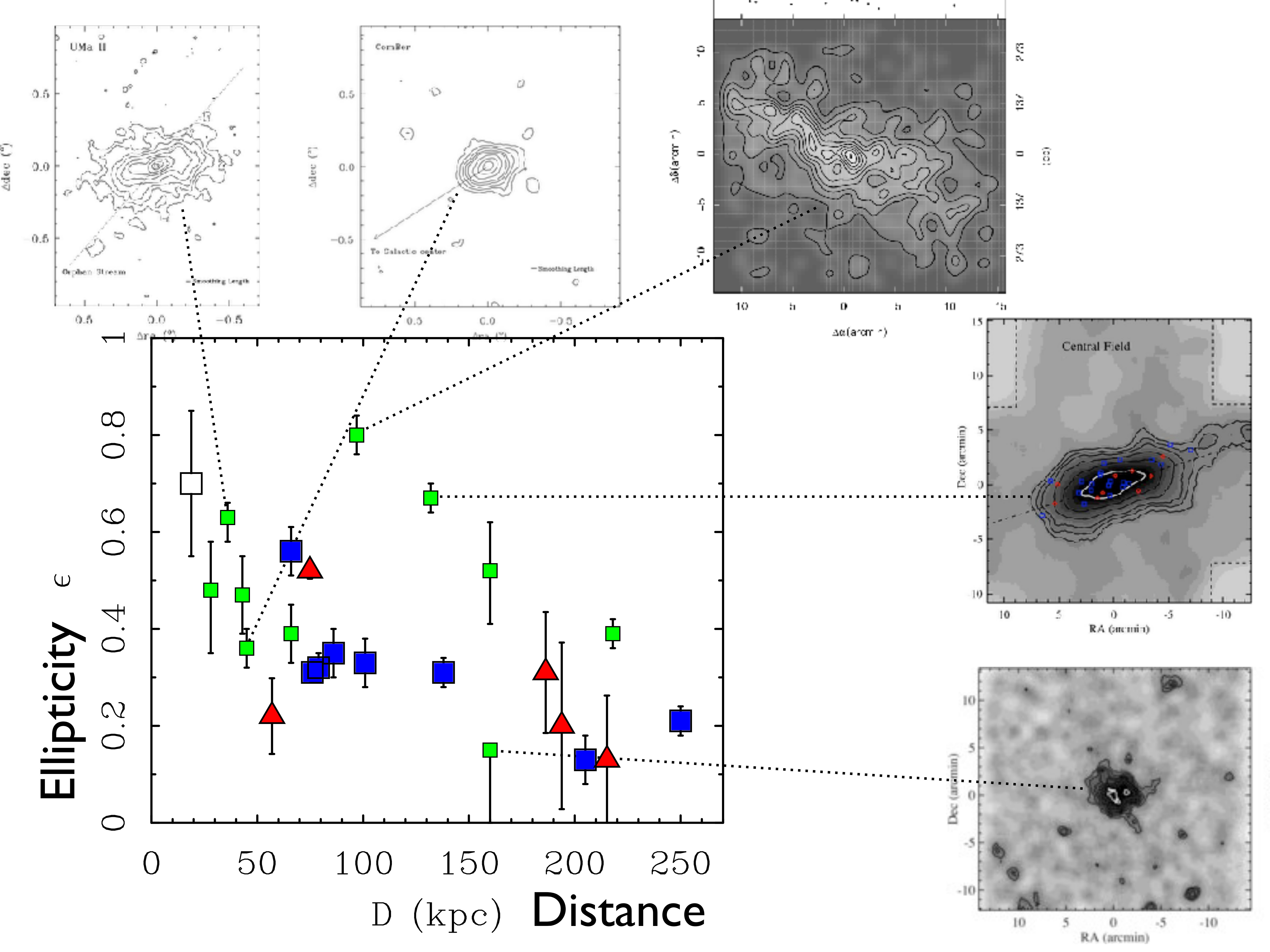
Velocity dispersions of ultrafaint dwarfs higher than predicted by MOND.

MOND provides a criterion for when tidal effects should be important.
Basically all ultrafaints known today should be out of equilibrium.



$$\gamma = \left(\frac{D}{r}\right)^{3/2} \left(\frac{m}{M}\right)^{1/2}$$

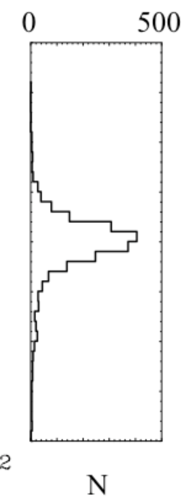
# of internal orbits a star at the half light radius makes for every orbit the satellite completes



UMa II
Orphan Stream
Smoothing Length
ComBer
To Galactic center
Smoothing Length
Central Field
Dec (arcmin)
RA (arcmin)
Dec (arcmin)
RA (arcmin)
Ellipticity
ϵ
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
D (kpc)
Distance

It's not just for rotation curves

MOND predictions



- The Tully-Fisher Relation
  - ✔ Slope = 4
  - ✔ Normalization = $1/(a_0G)$
  - ✔ Fundamentally a relation between Disk Mass and V_{flat}
  - ✔ No Dependence on Surface Brightness
- ✔ Dependence of conventional M/L on radius and surface brightness
- ✔ Rotation Curve Shapes
- ✔ Surface Density ~ Surface Brightness
- ✔ Detailed Rotation Curve Fits
- ✔ Stellar Population Mass-to-Light Ratios

✔ ***Radial Acceleration Relation***

- Disk Stability
  - ✔ Freeman limit in surface brightness distribution
  - ✔ thin disks
  - ✔ velocity dispersions
  - ✔ LSB disks not over-stabilized
- ✔ Dwarf Spheroidals

New Andromeda dwarfs and Crater 2 velocity dispersions predicted correctly in advance

- ✔ Giant Ellipticals
- X Clusters of Galaxies
- ? Structure Formation —

Sanders (1998)
First galaxies z > 10
cosmic web at z > 3
big clusters z > 2
voids swept clear by z = 0

- Microwave background
  - ✔ 1st:2nd peak amplitude; BBN
  - ✔ early reionization
  - enhanced ISW/gravitational lensing
  - X 3rd peak

Why does MOND get so many predictions right?

This simply should not happen.

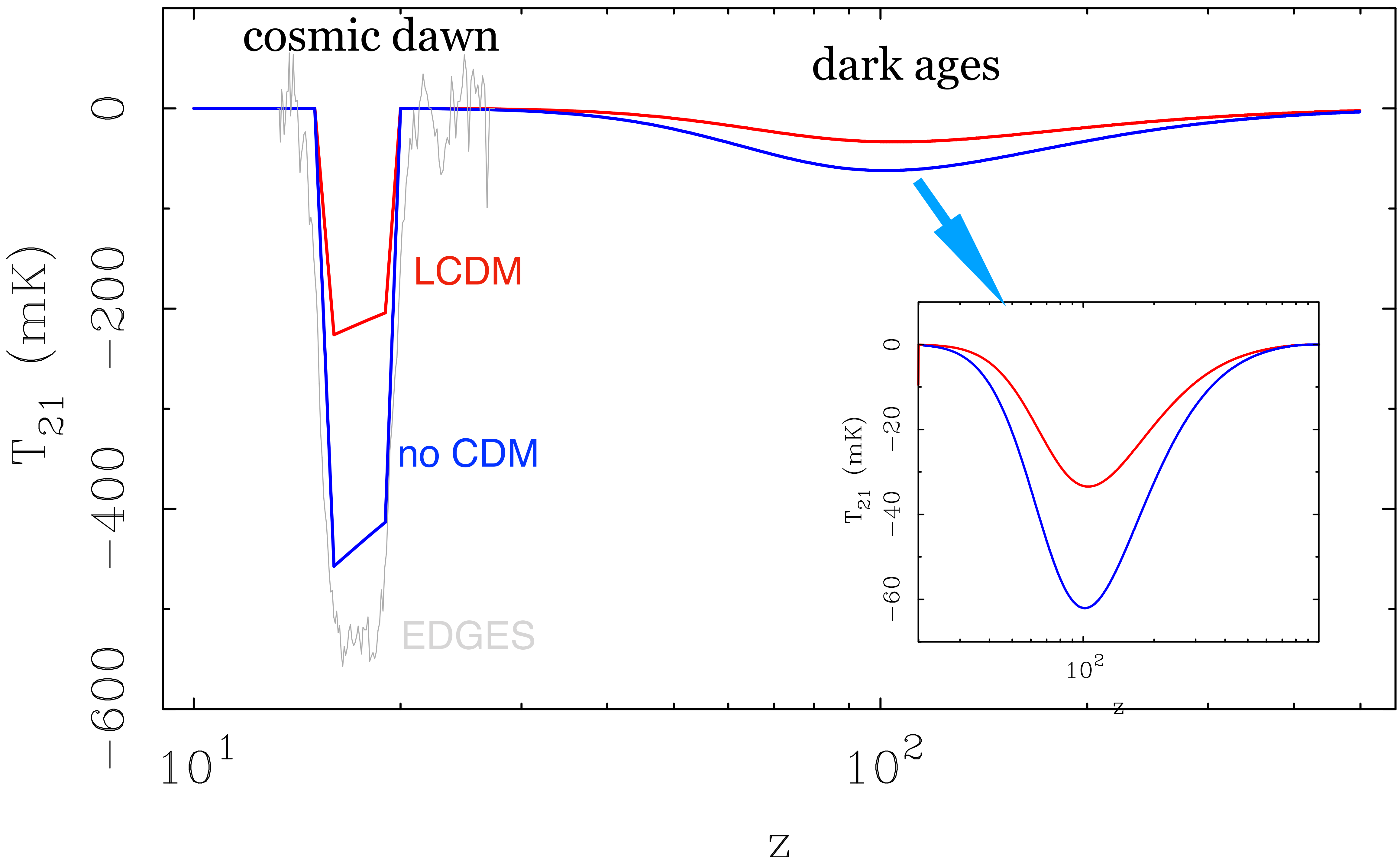
Imre Lakatos:
A research program is said to be progressing as long as its theoretical growth anticipates its empirical growth, that is as long as it keeps predicting novel facts with some success;

*it is **stagnating if** its theoretical growth lags behind its empirical growth, that is as long as **it gives only post-hoc explanations** either of chance discoveries or **of facts anticipated by**, and discovered in, **a rival program** (Lakatos, 1971, pp. 104–105).*

MOND qualifies as a “progressing program” by this standard.

LCDM can only give post-hoc explanations of facts anticipated by this “rival program.” By this standard, it has stagnated.

Prediction for 21 cm absorption at high redshift



Logical possibilities

- ΛCDM is fine; puzzling observations will be explained by complicated feedback processes ("gastrophysics").

  "Faced with the choice between changing one's mind and proving that there is no need to do so, almost everybody gets busy on the proof."
  \- J.K. Galbraith

- MOND gets many predictions right because there is something to it.

- Some hybrid (e.g., Blanchet's dipolar DM; Khoury's superfluid DM).

I have an even better idea. I'm going to place model galaxies in easily escapable dark matter halos by invoking overly elaborate and exotic feedback schemes.

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