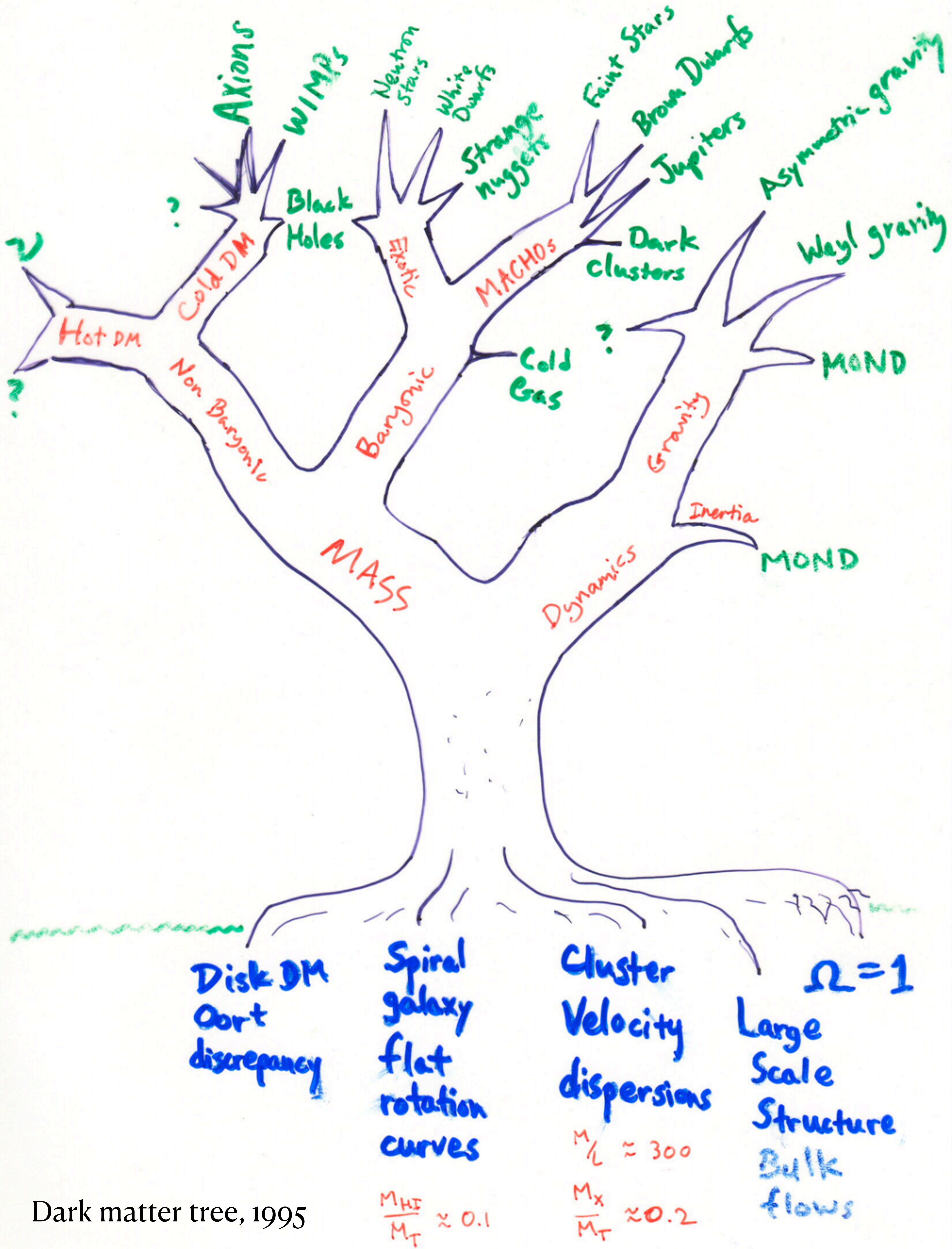
Predictions and outcomes: tests of ΛCDM and MOND

Stacy McGaugh
Case Western Reserve University



Dark matter tree, 1995

Two primary concerns

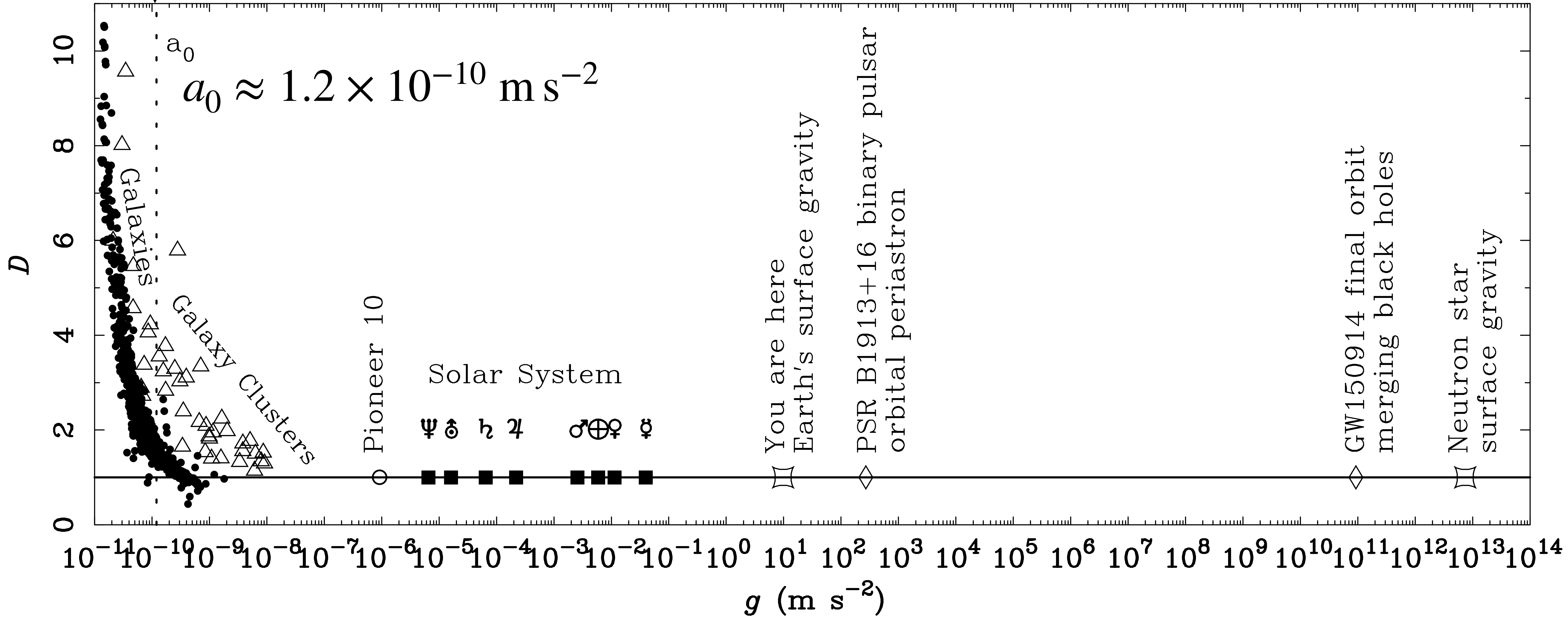
1. The Data and 2. the Scientific Method

- **The Data**
  - Galaxies obey empirical Laws of Nature
  - There is a ubiquitous acceleration scale in the data

We have to agree what the data say before
we can hope to agree to its interpretation

- Flat rotation curves
- Baryonic Tully-Fisher Relation
- Central Density Relation
- Sancisi's Law
- Radial Acceleration Relation

- **The Scientific Method**
  - Hypothesis testing
    - A priori predictive ability
    - Falsification



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

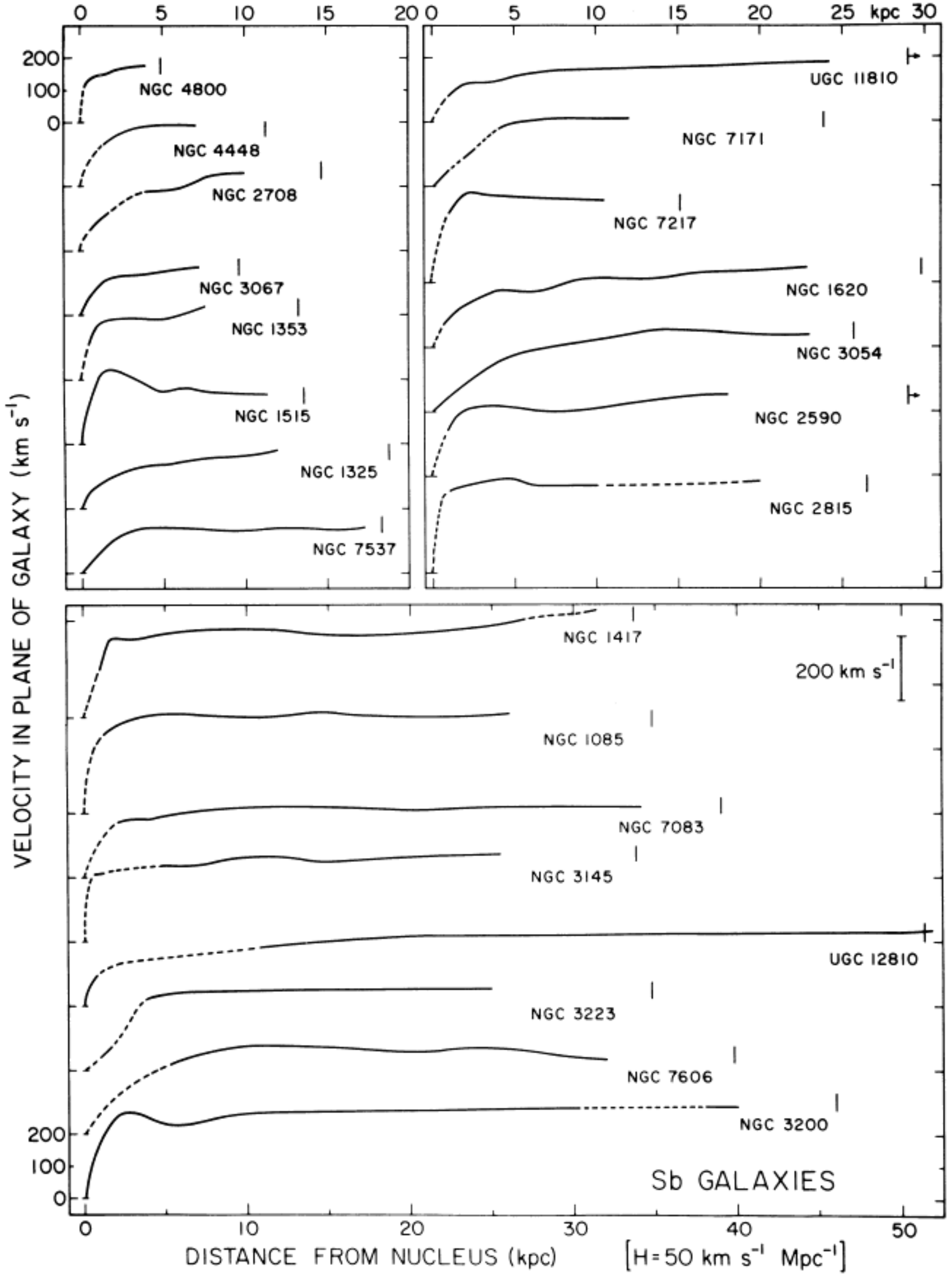


FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to increasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25}, 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.

Flat rotation curves

Rotation curves tend towards approximate flatness at large radii.

This is a *de facto*
Law of Nature

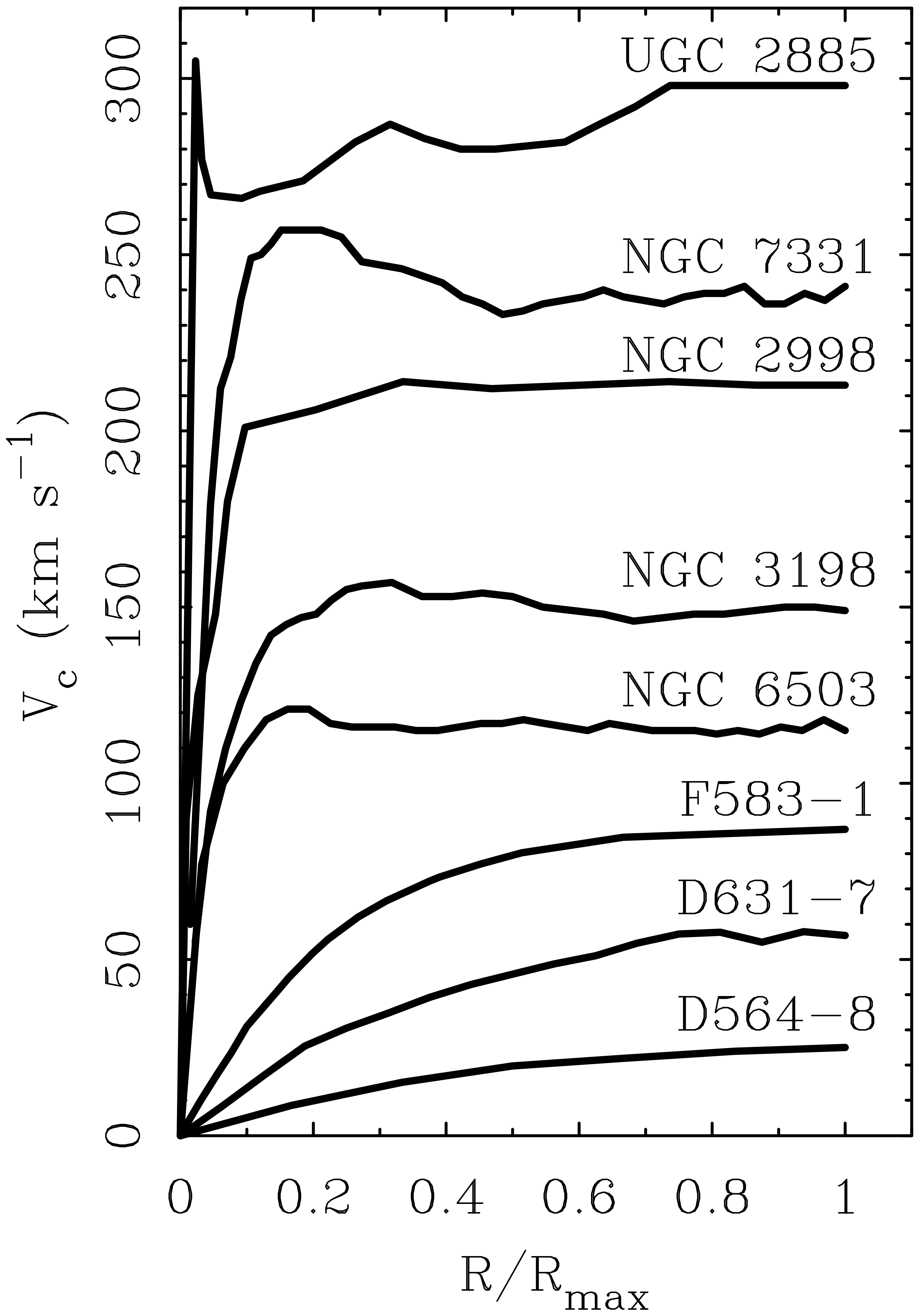
Here, flat means a constant rotation speed within 5%

Flat rotation curve amplitude correlates with baryonic mass

Galaxies are very orderly.

That rotation curves are flat is only the beginning of the story.

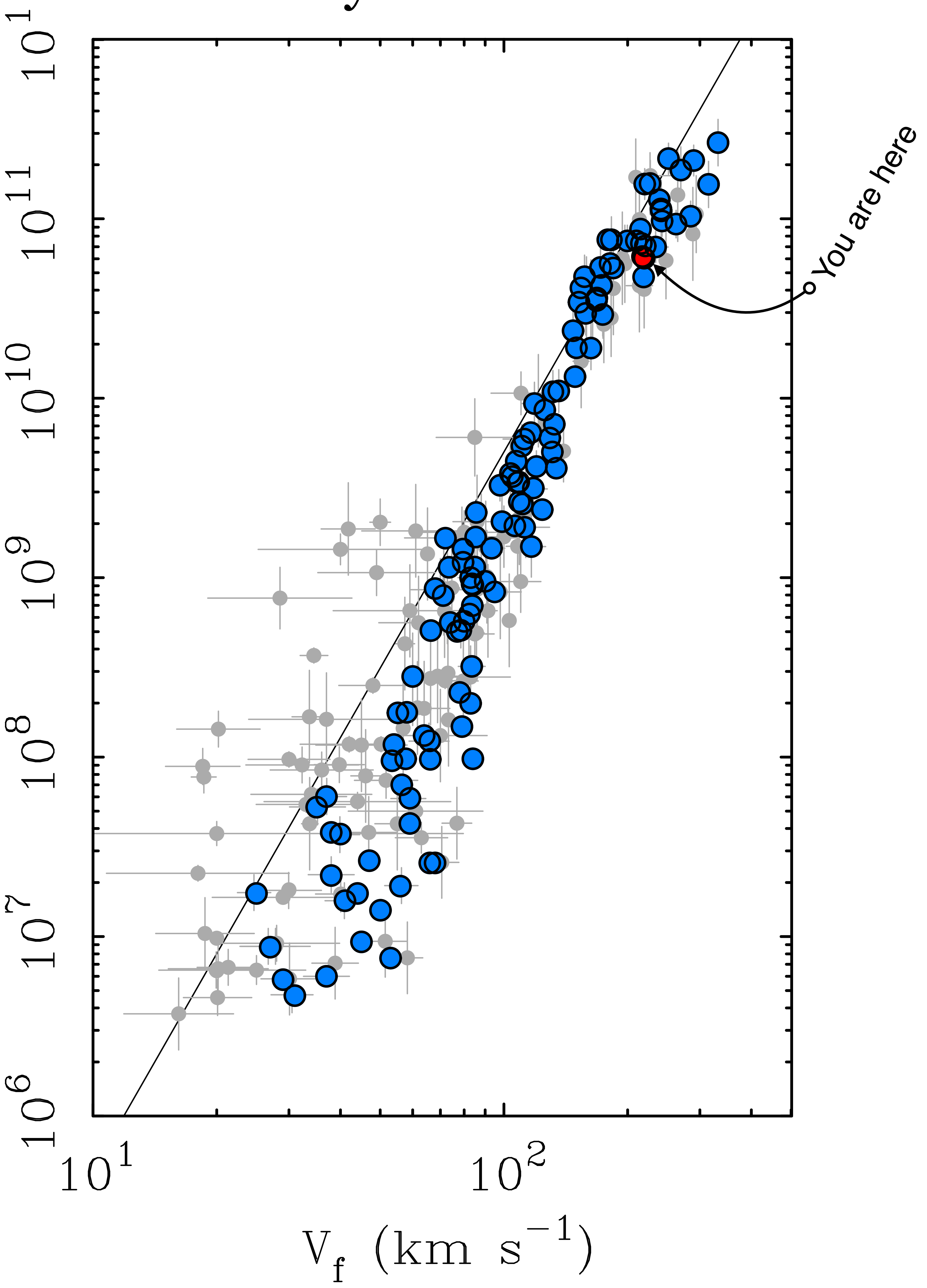
The speed at which galaxies spin correlates with their visible mass.



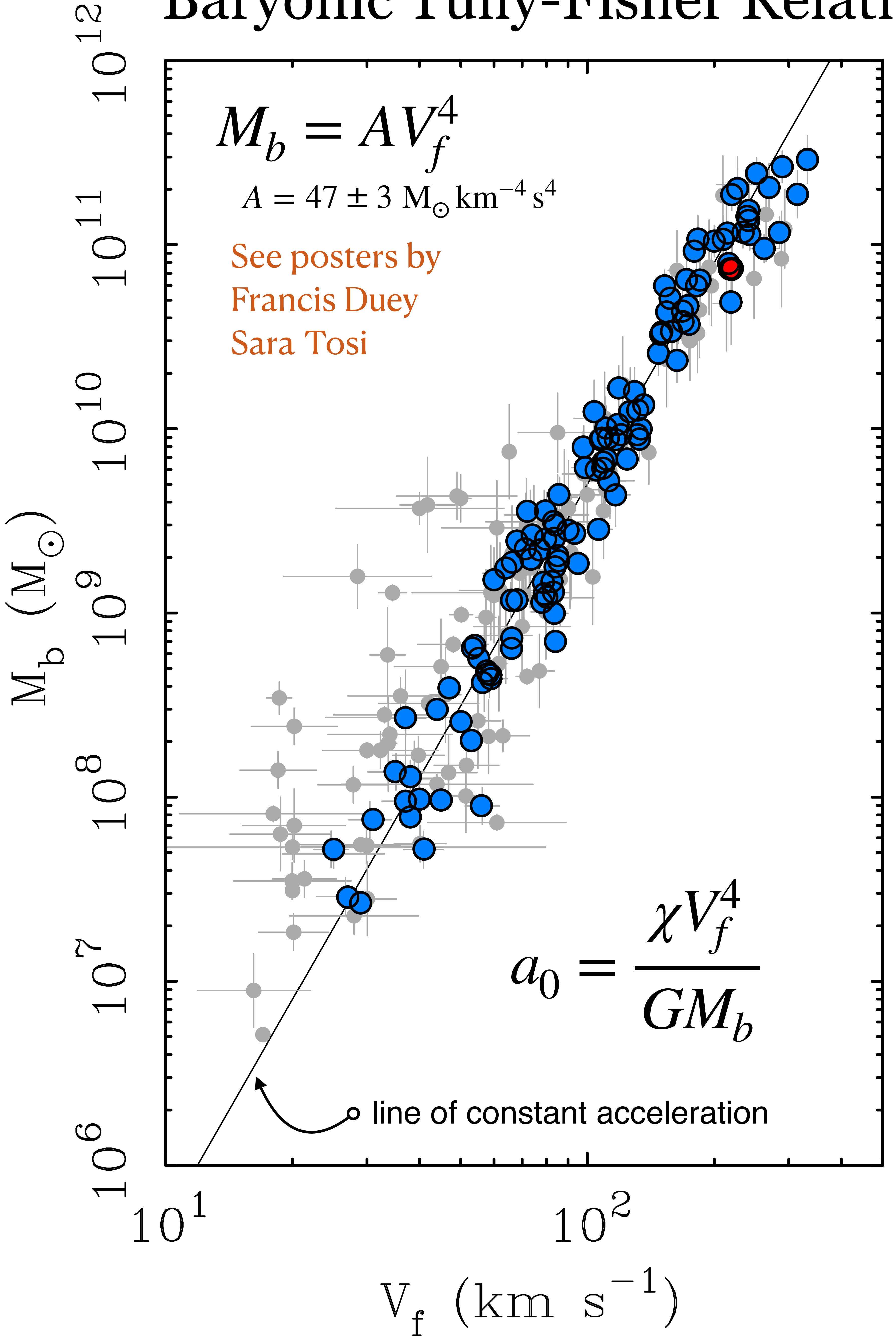
star dominated HSB

gas dominated LSBs

Stellar Mass Tully-Fisher Relation



Baryonic Tully-Fisher Relation



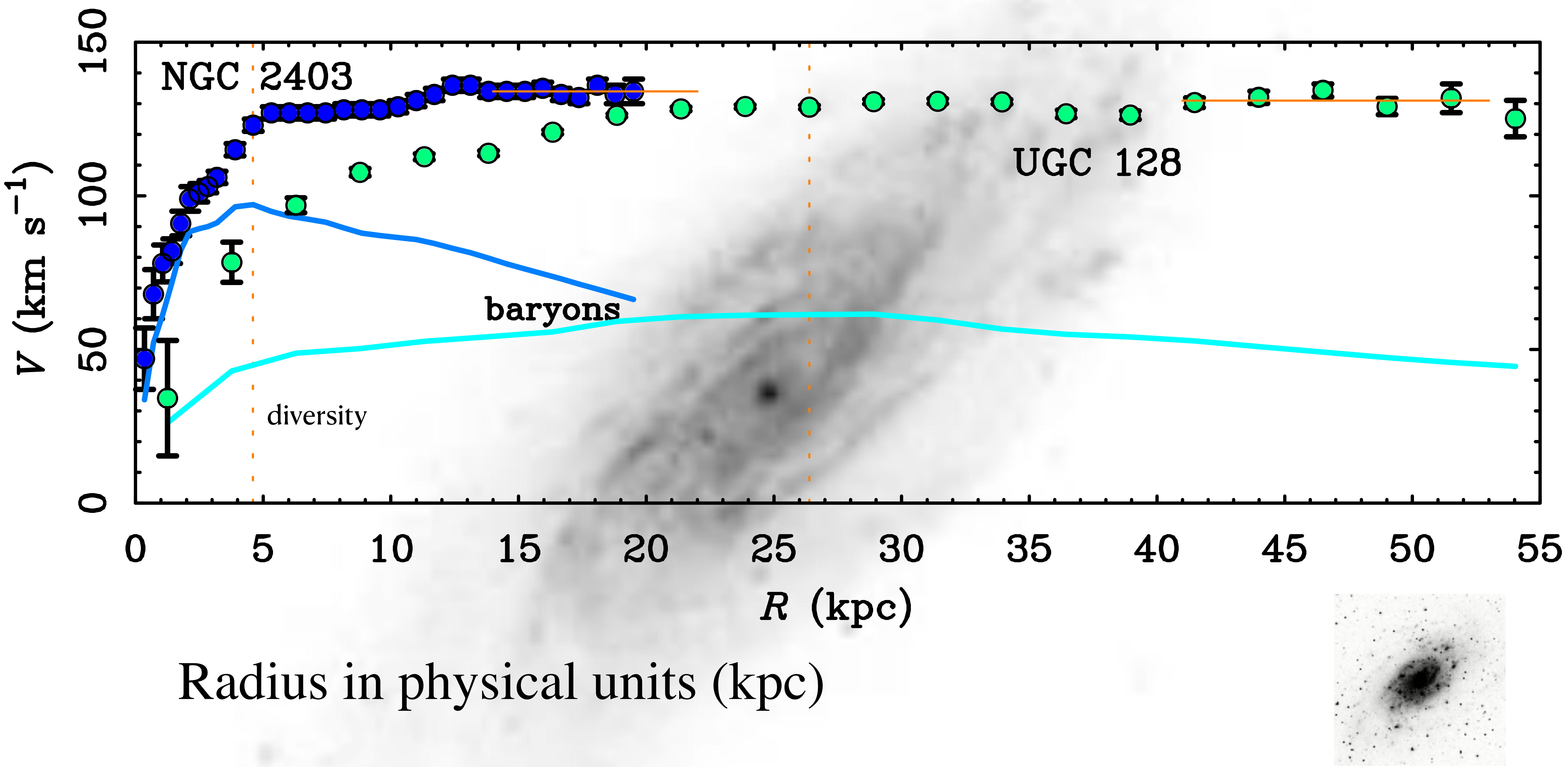
$$M_b = AV_f^4$$

$A = 47 \pm 3\ M_\odot\ km^{-4}\ s^4$

See posters by
Francis Duey
Sara Tosi

$$a_0 = \frac{\chi V_f^4}{GM_b}$$

Dynamics knows about the distribution of light as well as the total mass.



Radius in physical units (kpc)

NGC 2403 and UGC 128 have the same mass and flat rotation speed but very different mass distributions

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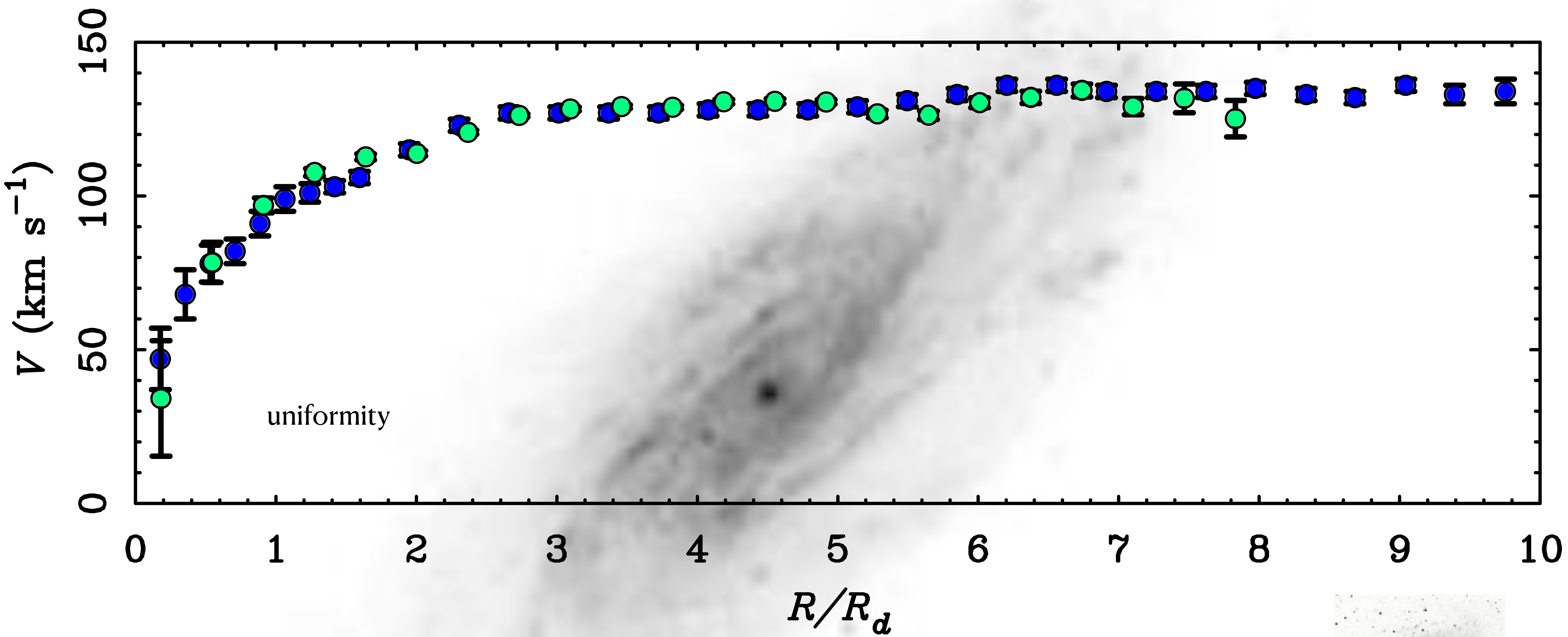
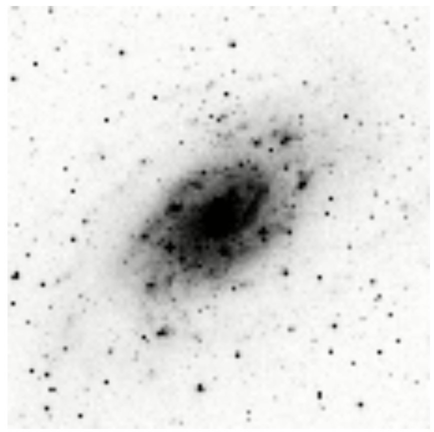


Radius normalized by size of disk.



NGC 2403 and UGC 128 have the same mass and flat rotation speed but very different mass distributions

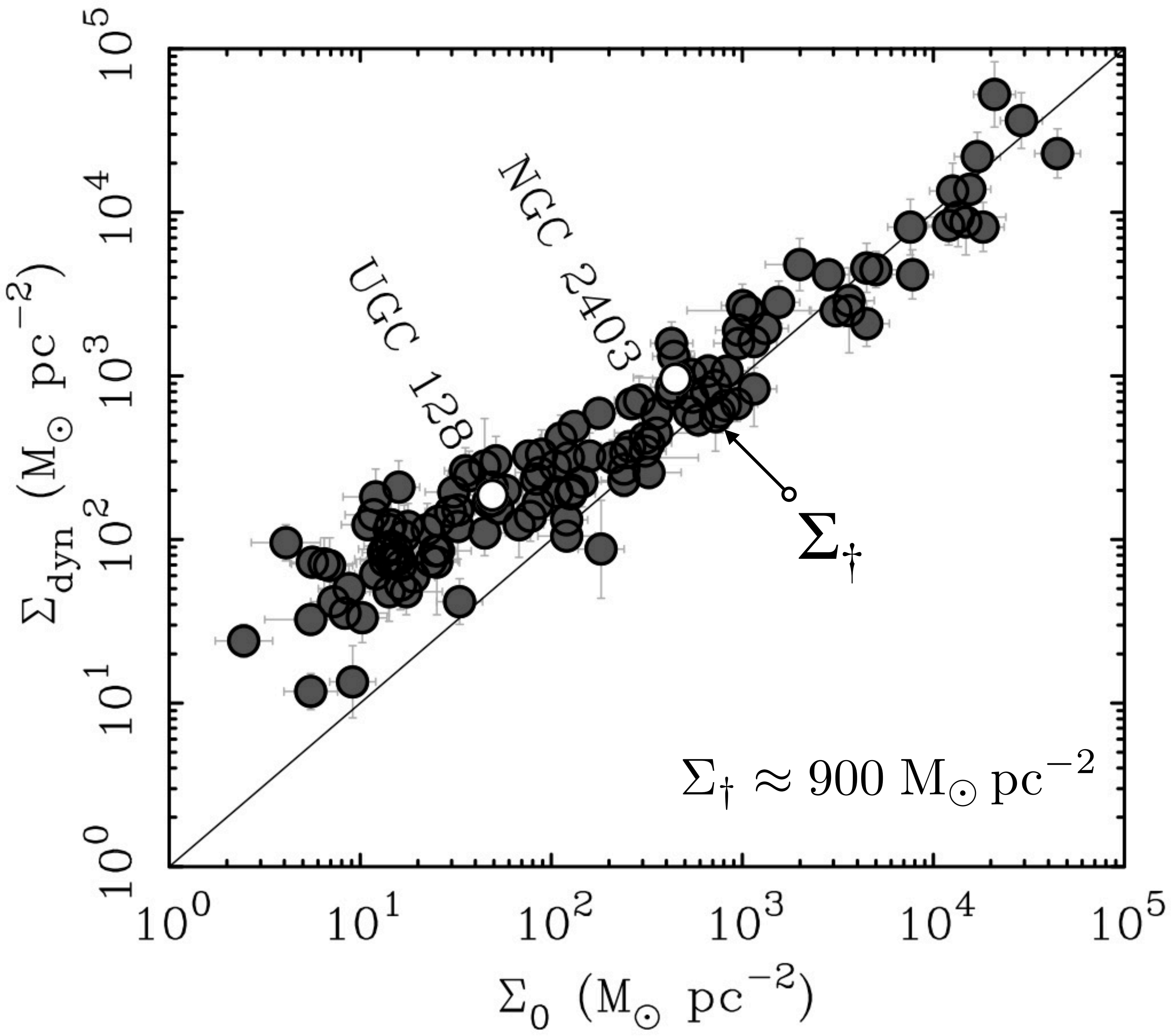
Central Density Relation

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 dynamical surface density



central surface brightness

Again a characteristic acceleration appears

$$a_0 = G\Sigma_\dagger$$

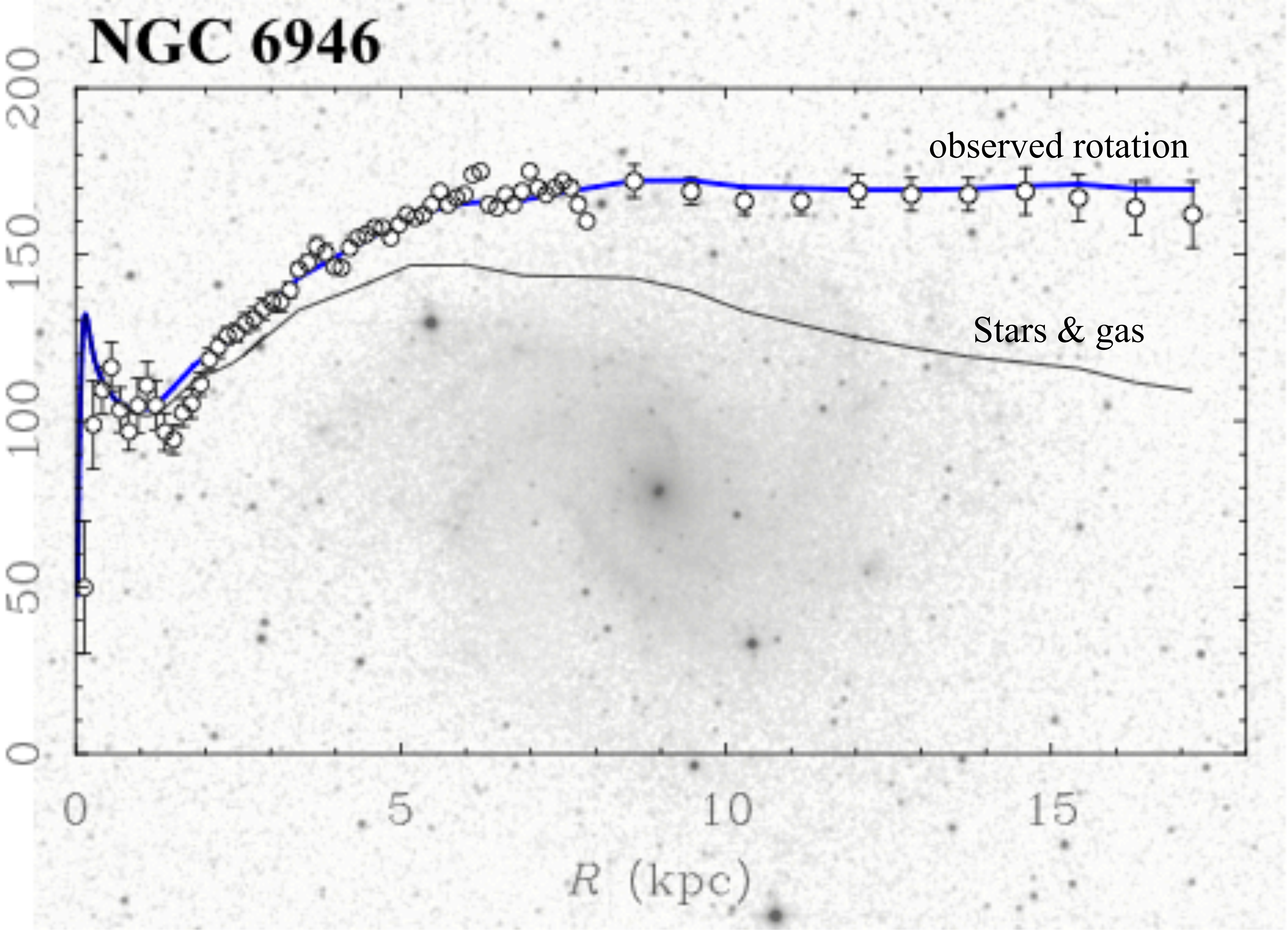
See talk by
Federico Lelli
Wednesday

This subsumes the diversity of rotation curves but is more general.

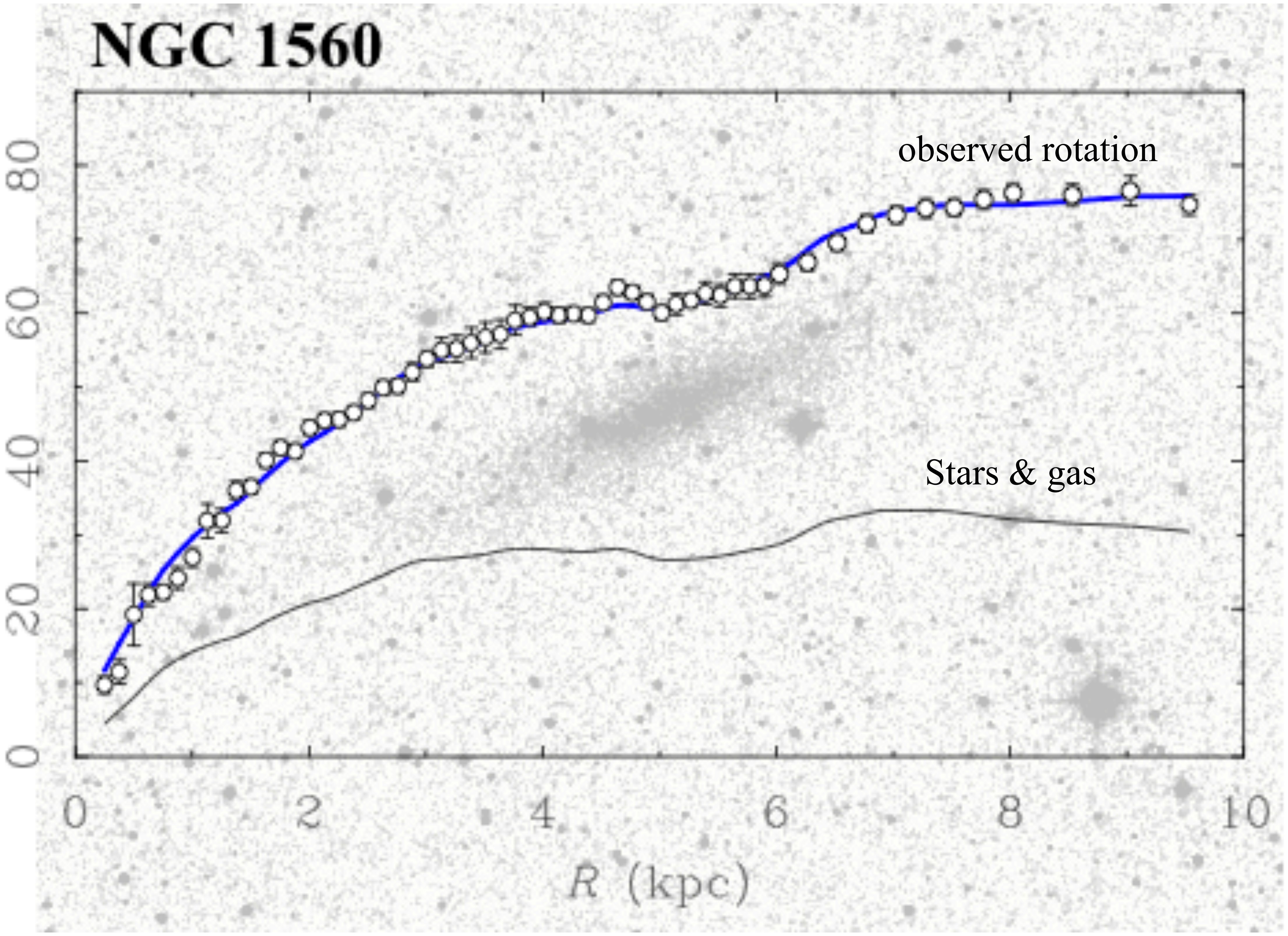
Sancisi's Law (aka Renzo's Rule)

Sancisi (2004)

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



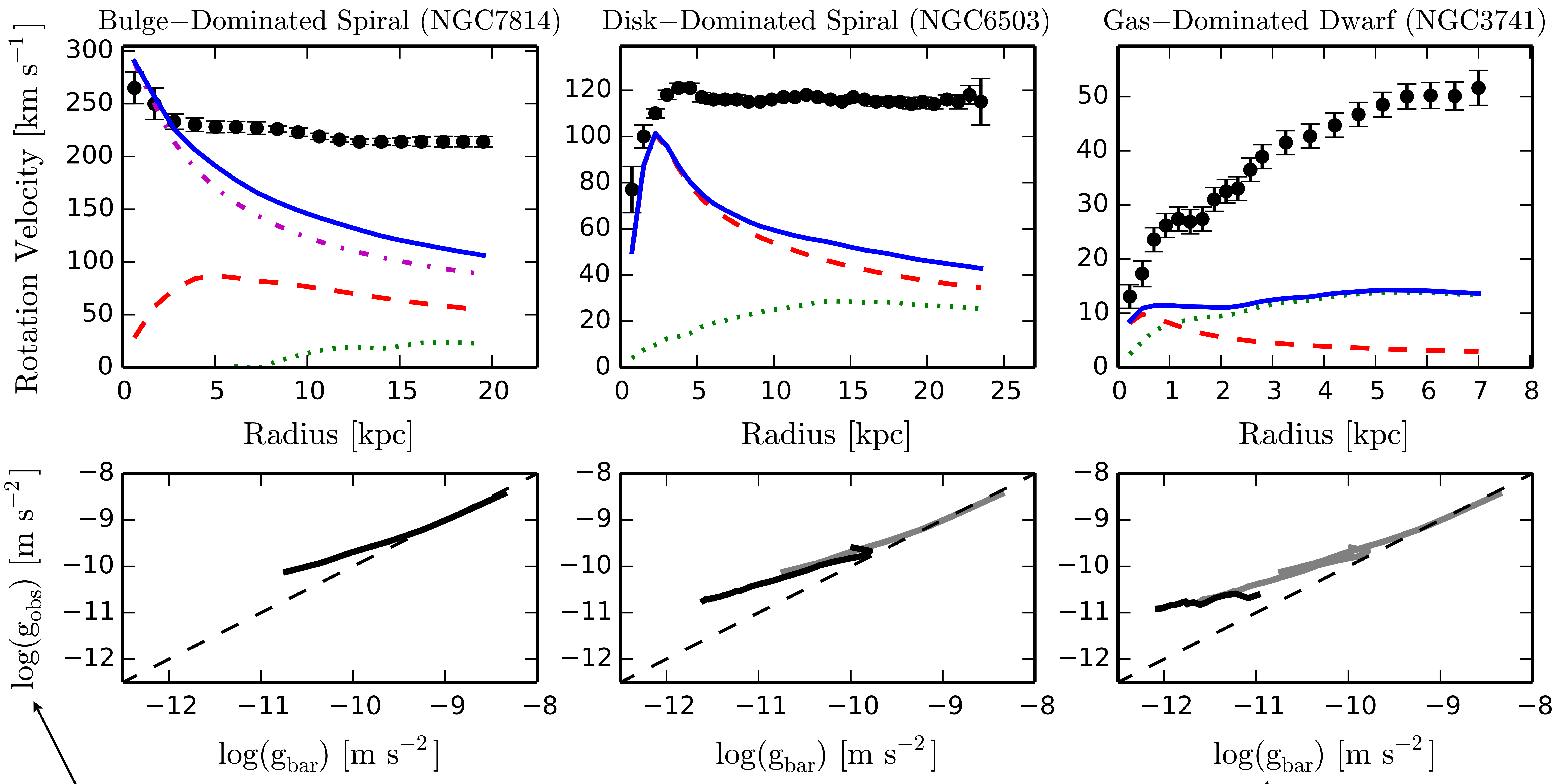
The central bulge component of NGC 6946 is only 4% of the total light, but it has a perceptible effect on the kinematics.



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.

$V(R)$

$g_{\mathrm{obs}}(g_{\mathrm{bar}})$



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

determined from rotation curve

independent quantities

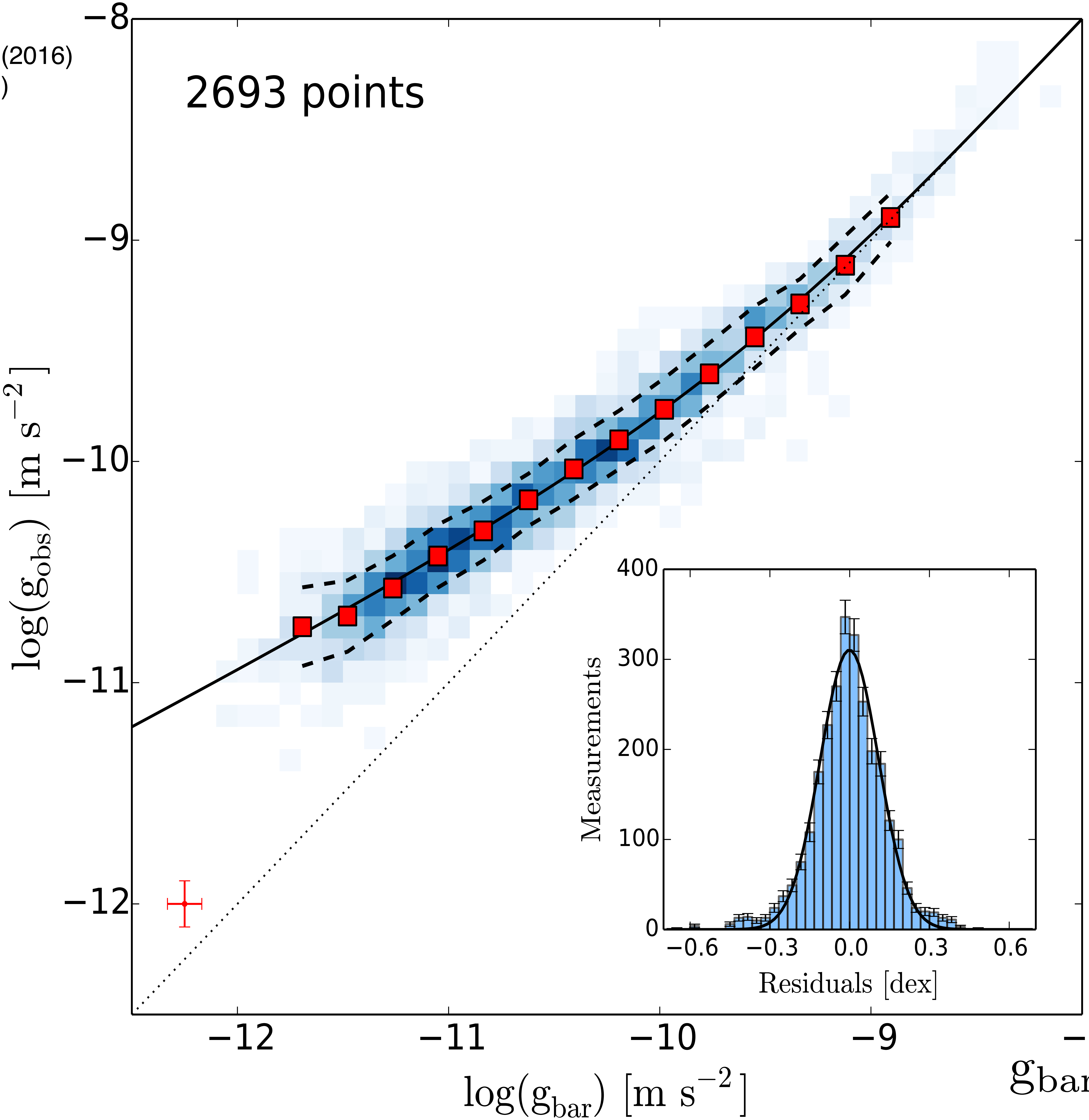
$$g_{\mathrm{bar}} = -\frac{\partial \Phi_{\mathrm{bar}}}{\partial R}$$

determined from baryon distribution

Radial Acceleration Relation

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

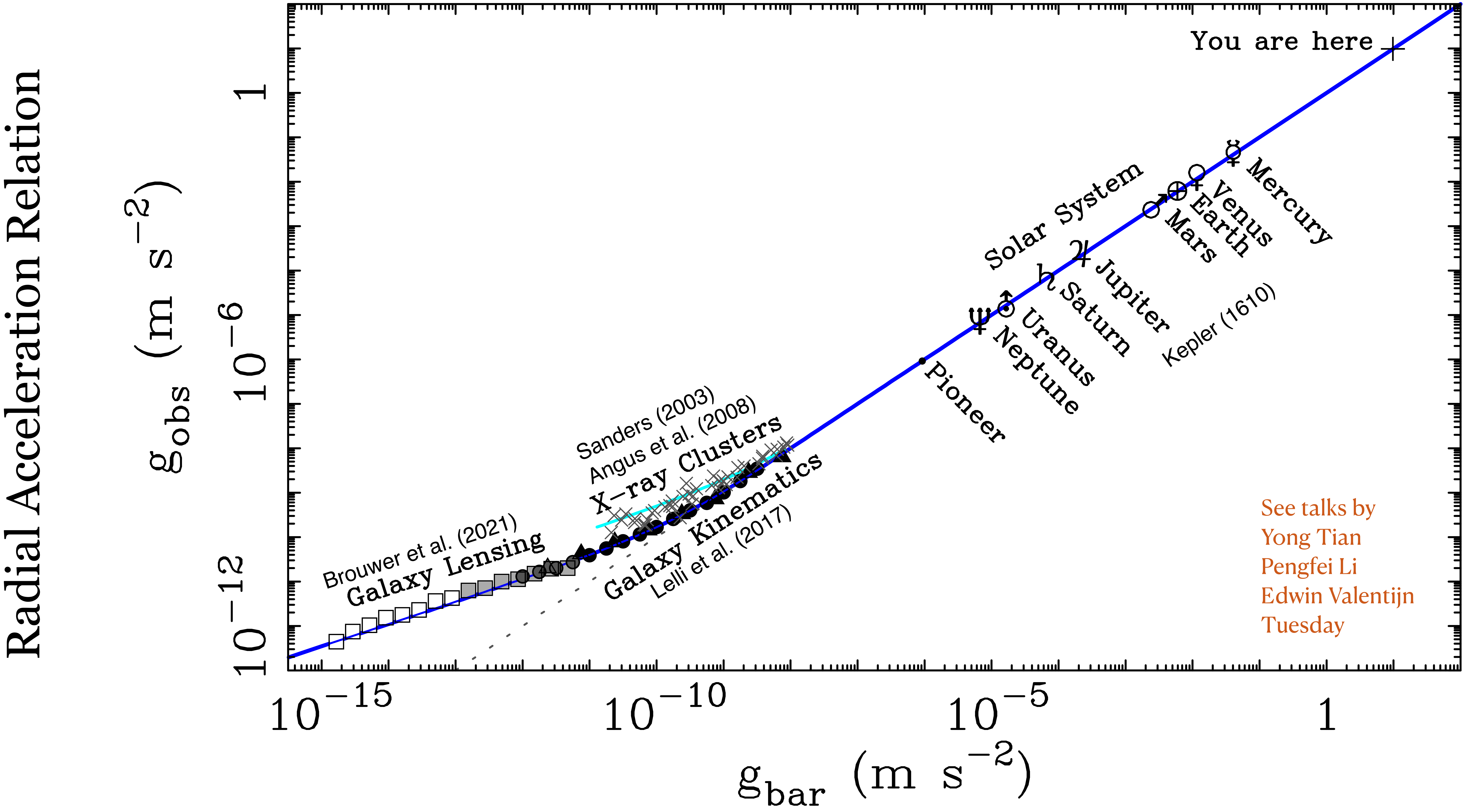
McGaugh et al. (2016)
Lelli et al. (2017)



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

See talks by
Harry Desmond
Kyu-Hyun Chae
later today

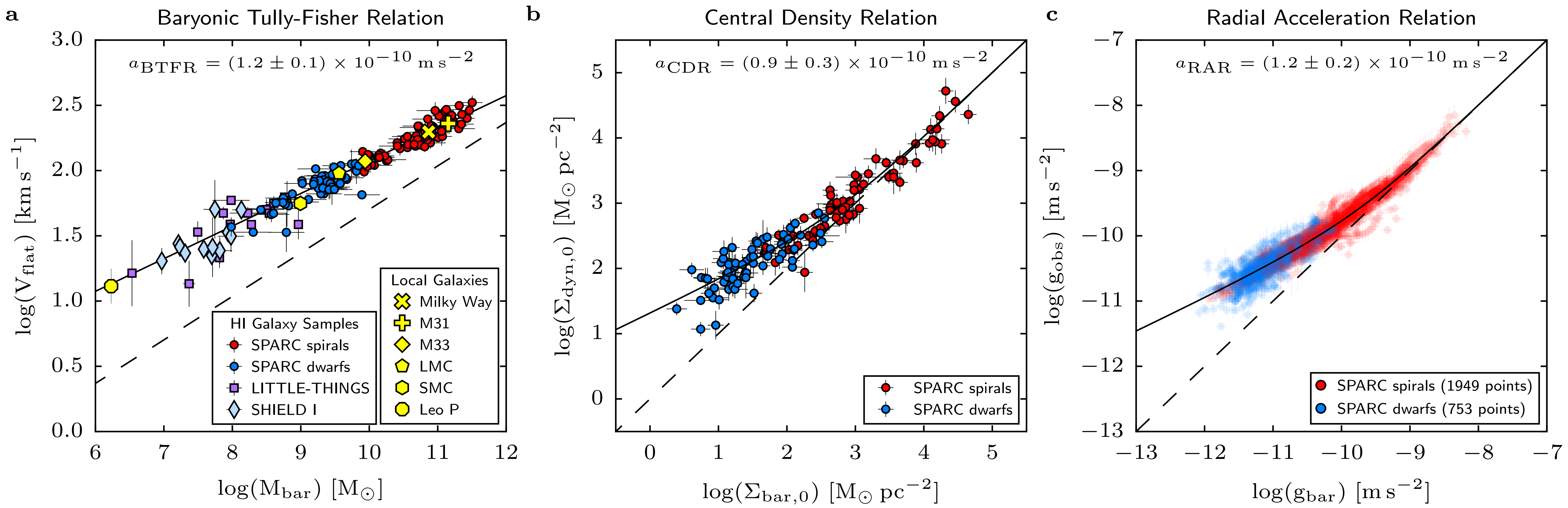
Lensing data extend to much lower accelerations
Solar System data extend to much higher accelerations



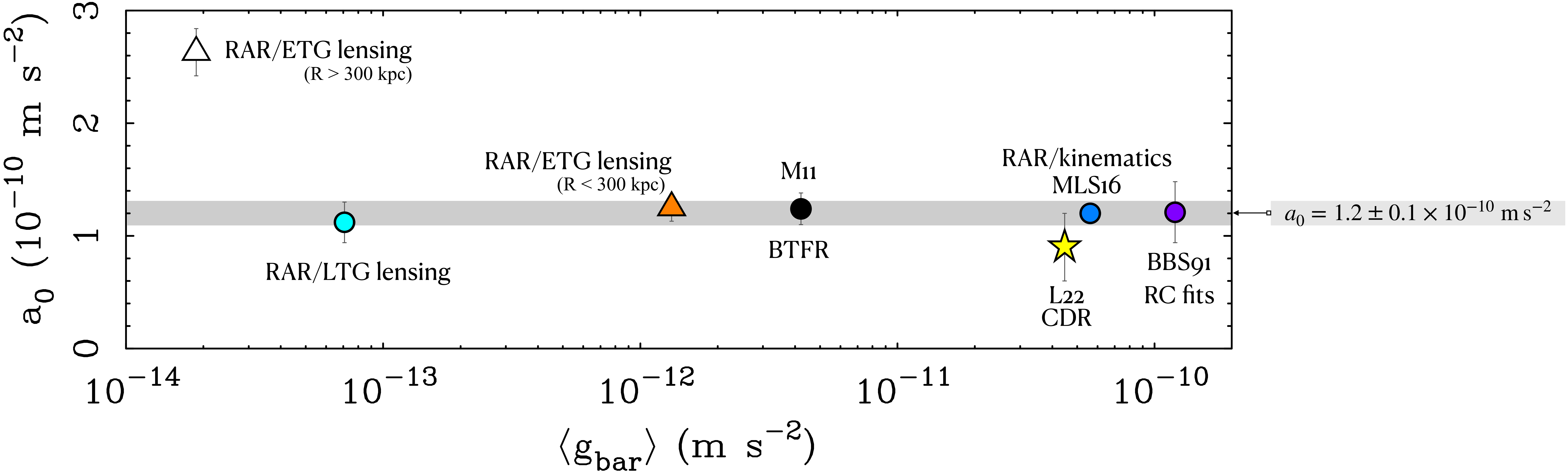
See talks by
Yong Tian
Pengfei Li
Edwin Valentijn
Tuesday

The acceleration scale is ubiquitous in the data

- Baryonic Tully-Fisher Relation
- Central Density Relation
- Radial Acceleration Relation


Lelli (2022)

Different methods indicate the same acceleration scale over a wide range of $g_{\rm bar} \lesssim a_0$



Two primary concerns

1. The Data and 2. the Scientific Method

1. - **The Data**
    - Galaxies obey empirical Laws of Nature
    - There is a ubiquitous acceleration scale in the data

2. - **The Scientific Method**
    - Hypothesis testing
        - A priori predictive ability
        - Falsification

In order to compare two theories, we need a null hypothesis from both. This is not always on offer: what does dark matter predict?

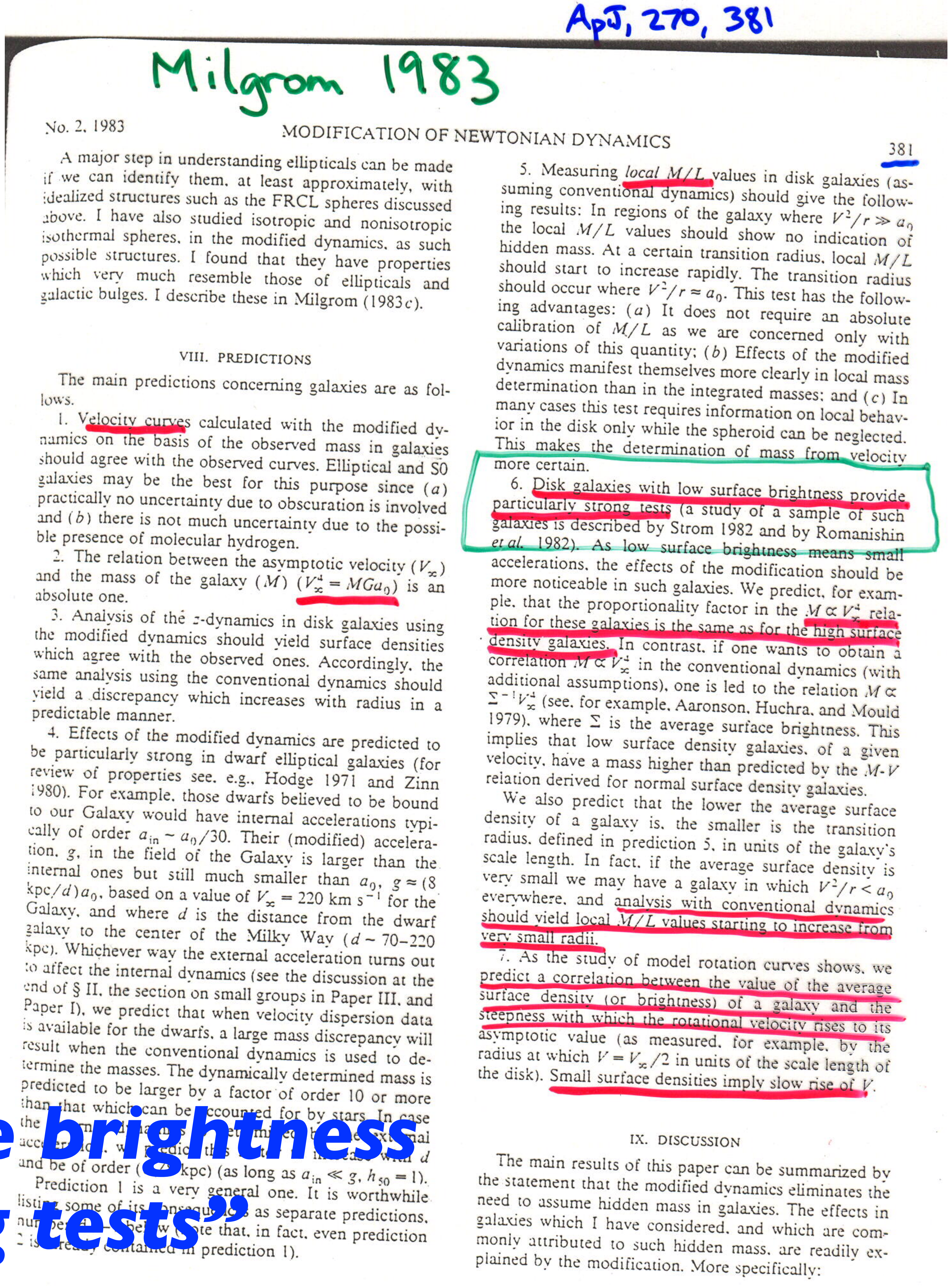
Predictive power in the Scientific Method

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)
Don’t know	?	
Just wrong	X	

MOND predictions

- The Tully-Fisher Relation
  - Slope = 4
  - Normalization = $1/(a_0 G)$
  - 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



ApJ, 270, 381

Milgrom 1983

A major step in understanding ellipticals can be made if we can identify them, at least approximately, with idealized structures such as the FRCL spheres discussed above. I have also studied isotropic and nonisotropic isothermal spheres, in the modified dynamics, as such possible structures. I found that they have properties which very much resemble those of ellipticals and galactic bulges. I describe these in Milgrom (1983*c*).

VIII. PREDICTIONS

The main predictions concerning galaxies are as follows.

1. Velocity curves calculated with the modified dynamics on the basis of the observed mass in galaxies should agree with the observed curves. Elliptical and S0 galaxies may be the best for this purpose since (*a*) practically no uncertainty due to obscuration is involved and (*b*) there is not much uncertainty due to the possible presence of molecular hydrogen.

2. The relation between the asymptotic velocity (V_∞) and the mass of the galaxy (M) ($V_\infty^4 = MGa_0$) is an absolute one.

3. Analysis of the z-dynamics in disk galaxies using the modified dynamics should yield surface densities which agree with the observed ones. Accordingly, the same analysis using the conventional dynamics should yield a discrepancy which increases with radius in a predictable manner.

4. Effects of the modified dynamics are predicted to be particularly strong in dwarf elliptical galaxies (for review of properties see, e.g., Hodge 1971 and Zinn 1980). For example, those dwarfs believed to be bound to our Galaxy would have internal accelerations typically of order $a_{in} \sim a_0/30$. Their (modified) acceleration, g, in the field of the Galaxy is larger than the internal ones but still much smaller than a_0, $g \approx (8\ \mathrm{kpc}/d)a_0$, based on a value of $V_\infty = 220\ \mathrm{km\ s^{-1}}$ for the Galaxy, and where d is the distance from the dwarf galaxy to the center of the Milky Way ($d \sim 70$–220 kpc). Whichever way the external acceleration turns out to affect the internal dynamics (see the discussion at the end of § II, the section on small groups in Paper III, and Paper I), we predict that when velocity dispersion data is available for the dwarfs, a large mass discrepancy will result when the conventional dynamics is used to determine the masses. The dynamically determined mass is predicted to be larger by a factor of order 10 or more than that which can be accounted for by stars. In case the internal dynamics [illegible] the external acceleration, we predict th[illegible] to increase with d and be of order ([illegible] kpc) (as long as $a_{in} \ll g$, $h_{50} = 1$).

Prediction 1 is a very general one. It is worthwhile listing some of its consequences as separate predictions, numbered [illegible] below (note that, in fact, even prediction 2 is already contained in prediction 1).

5. Measuring *local M/L* values in disk galaxies (assuming conventional dynamics) should give the following results: In regions of the galaxy where $V^2/r \gg a_0$ the local M/L values should show no indication of hidden mass. At a certain transition radius, local M/L should start to increase rapidly. The transition radius should occur where $V^2/r \approx a_0$. This test has the following advantages: (*a*) It does not require an absolute calibration of M/L as we are concerned only with variations of this quantity; (*b*) Effects of the modified dynamics manifest themselves more clearly in local mass determination than in the integrated masses; and (*c*) In many cases this test requires information on local behavior in the disk only while the spheroid can be neglected. This makes the determination of mass from velocity more certain.

6. Disk galaxies with low surface brightness provide particularly strong tests (a study of a sample of such galaxies is described by Strom 1982 and by Romanishin *et al.* 1982). As low surface brightness means small accelerations, the effects of the modification should be more noticeable in such galaxies. We predict, for example, that the proportionality factor in the $M \propto V_\infty^4$ relation for these galaxies is the same as for the high surface density galaxies. In contrast, if one wants to obtain a correlation $M \propto V_\infty^4$ in the conventional dynamics (with additional assumptions), one is led to the relation $M \propto \Sigma^{-1} V_\infty^4$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that low surface density galaxies, of a given velocity, have a mass higher than predicted by the M-V relation derived for normal surface density galaxies.

We also predict that the lower the average surface density of a galaxy is, the smaller is the transition radius, defined in prediction 5, in units of the galaxy's scale length. In fact, if the average surface density is very small we may have a galaxy in which $V^2/r < a_0$ everywhere, and analysis with conventional dynamics should yield local M/L values starting to increase from very small radii.

7. As the study of model rotation curves shows, we predict a correlation between the value of the average surface density (or brightness) of a galaxy and the steepness with which the rotational velocity rises to its asymptotic value (as measured, for example, by the radius at which $V = V_\infty/2$ in units of the scale length of the disk). Small surface densities imply slow rise of V.

IX. DISCUSSION

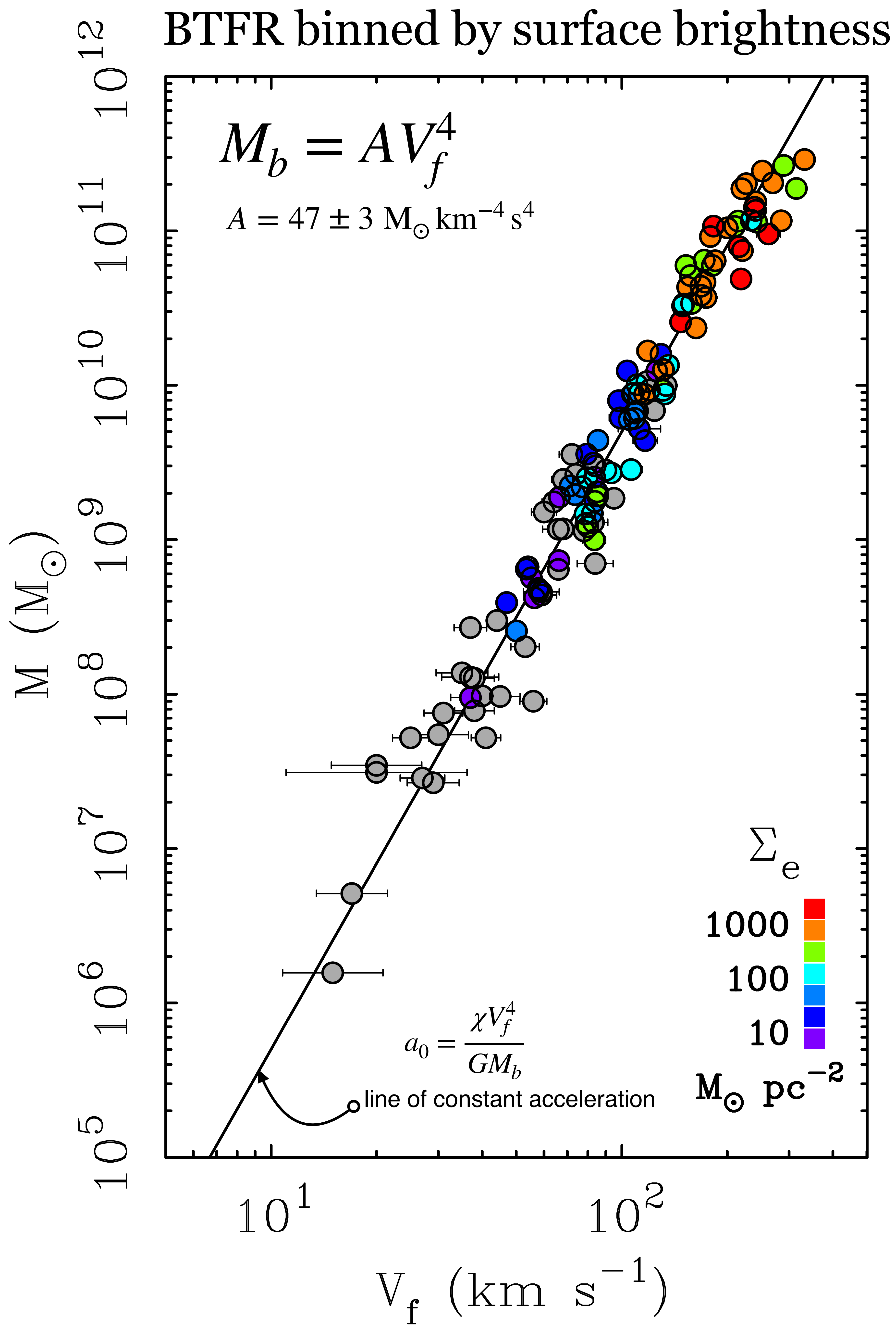
The main results of this paper can be summarized by the statement that the modified dynamics eliminates the need to assume hidden mass in galaxies. The effects in galaxies which I have considered, and which are commonly attributed to such hidden mass, are readily explained by the modification. More specifically:

“Disk Galaxies with low surface brightness provide particularly strong tests”

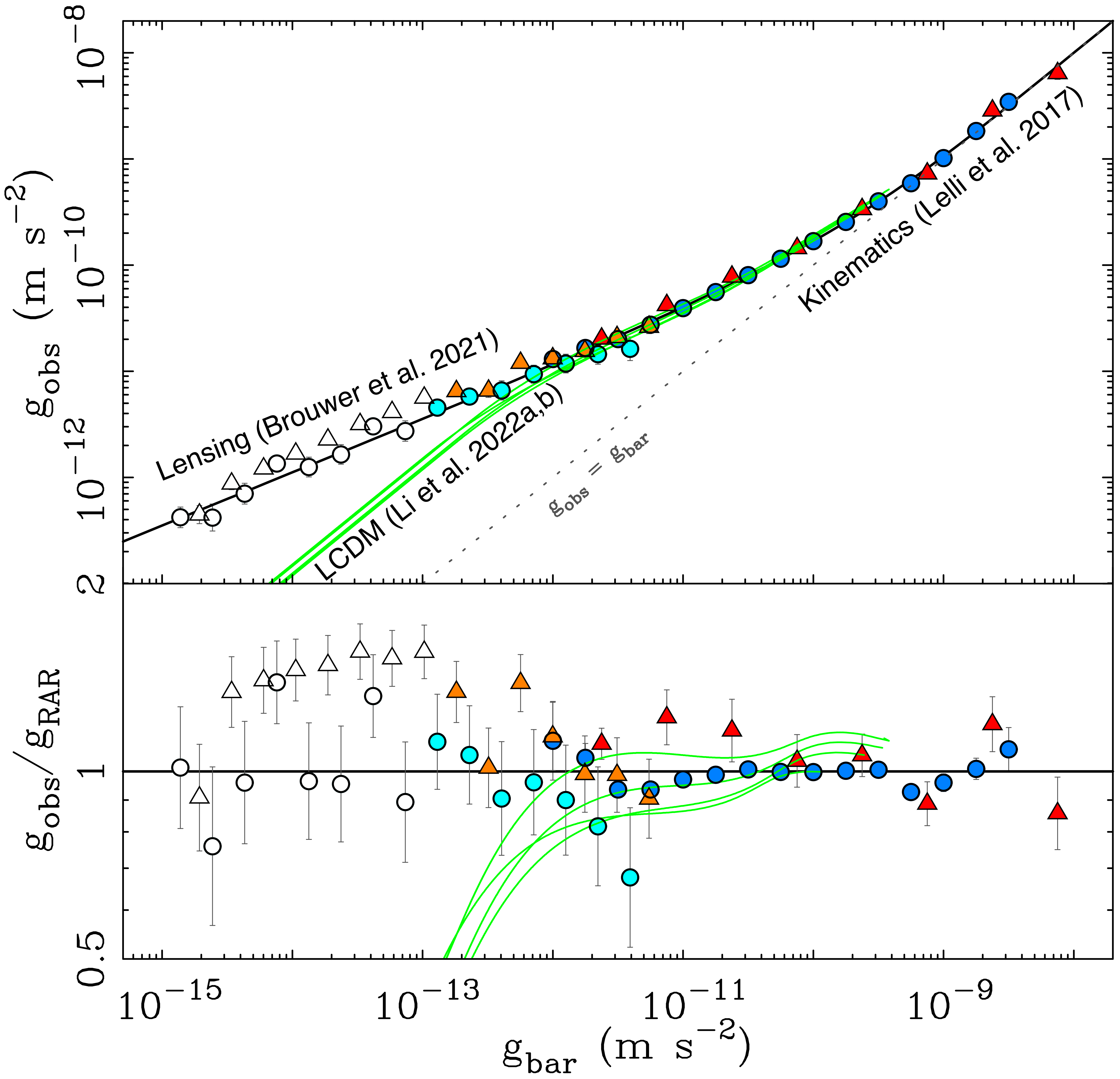
Predictions of Milgrom (1983b) that have been corroborated

- 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

Using a DM model I had developed, I predicted that there would be a surface brightness-dependent shift in TF (a second parameter effect). Many DM-based models predict this, as it follows directly from $V^2 = GM/r$, which differs from $V_f^4 = a_0GM$.
Only MOND predicted this correctly in advance.
Only MOND provides a satisfactory explanation to this day.



Lensing data the RAR extend to much lower accelerations



Lensing data extend the test to very low accelerations. These data persist in following the extrapolation of the RAR (black line) that was predicted by MOND. They do not follow the prediction of LCDM (green lines). Exactly how LCDM fails is model-specific, but the turndown away from the data at low acceleration is generic: the outer regions of NFW halos have density profiles that decline as r^{-3} while the data indicate $\rho \sim r^{-2}$, i.e., rotation curves that remain flat.

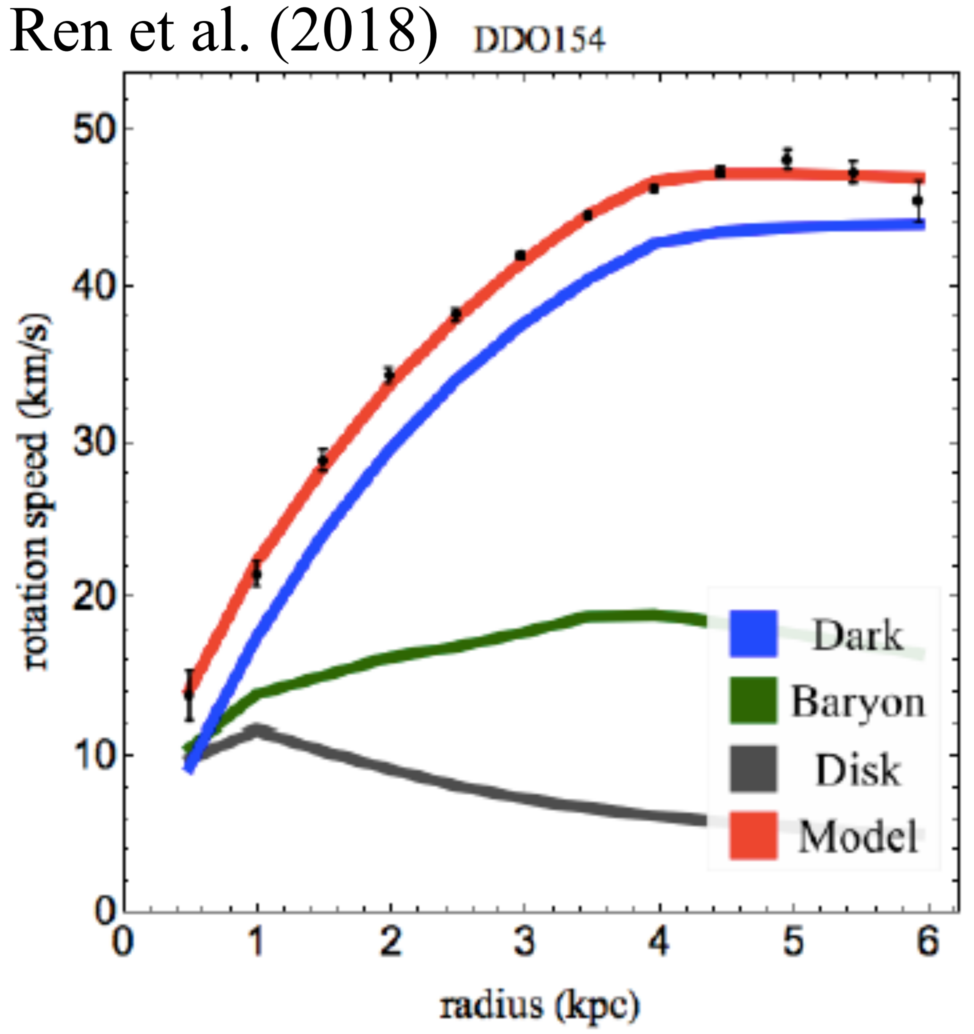
Other failings of LCDM models:

- they tend to show a segregation by mass that is not observed.
- they do not extend into the Newtonian regime, often predicting dark matter where none is needed, hooking back to lower $g_{\rm bar}$ as $g_{\rm obs}$ increases (this is the cusp-core problem).

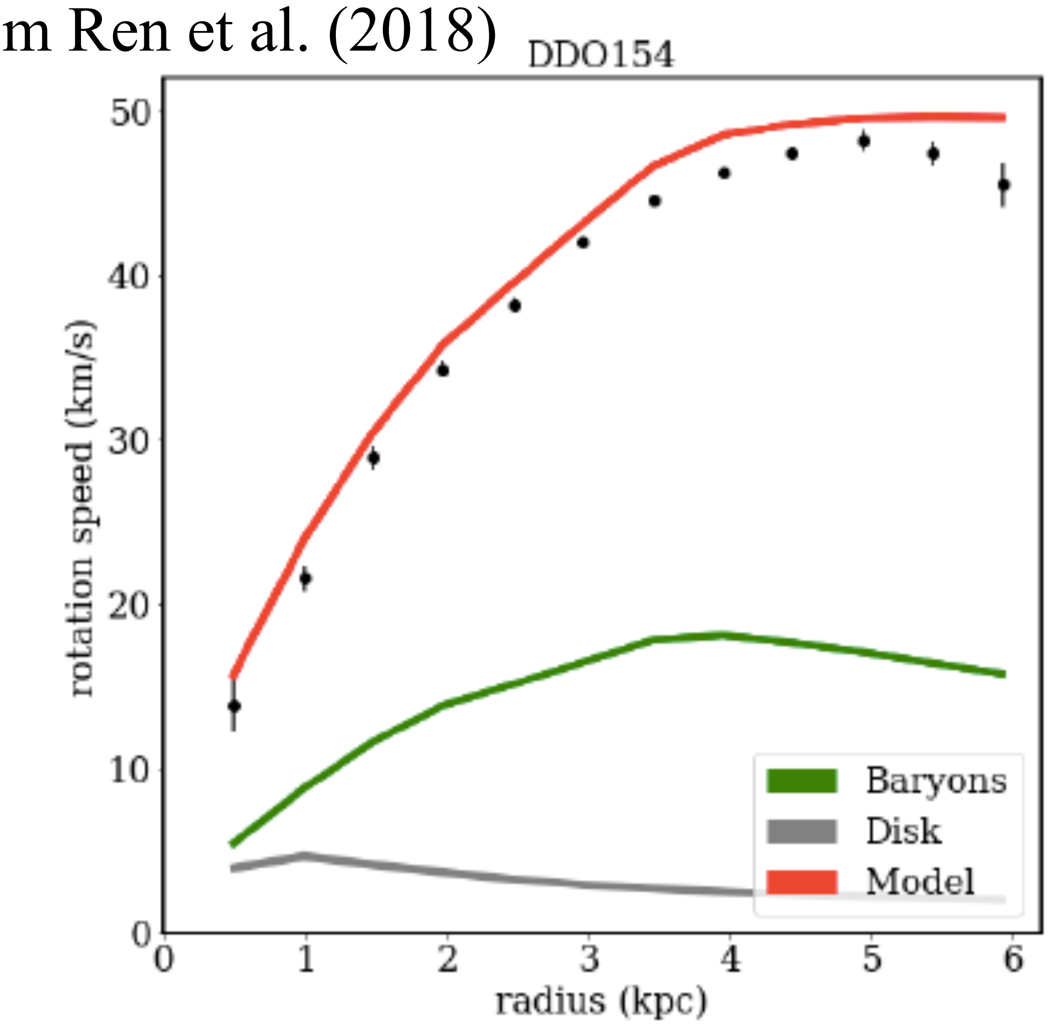
Variations on models fail at different points, but these failures are fairly generic.

Dark matter is easily fooled; MOND is not

SIDM fit from Ren et al. (2018)



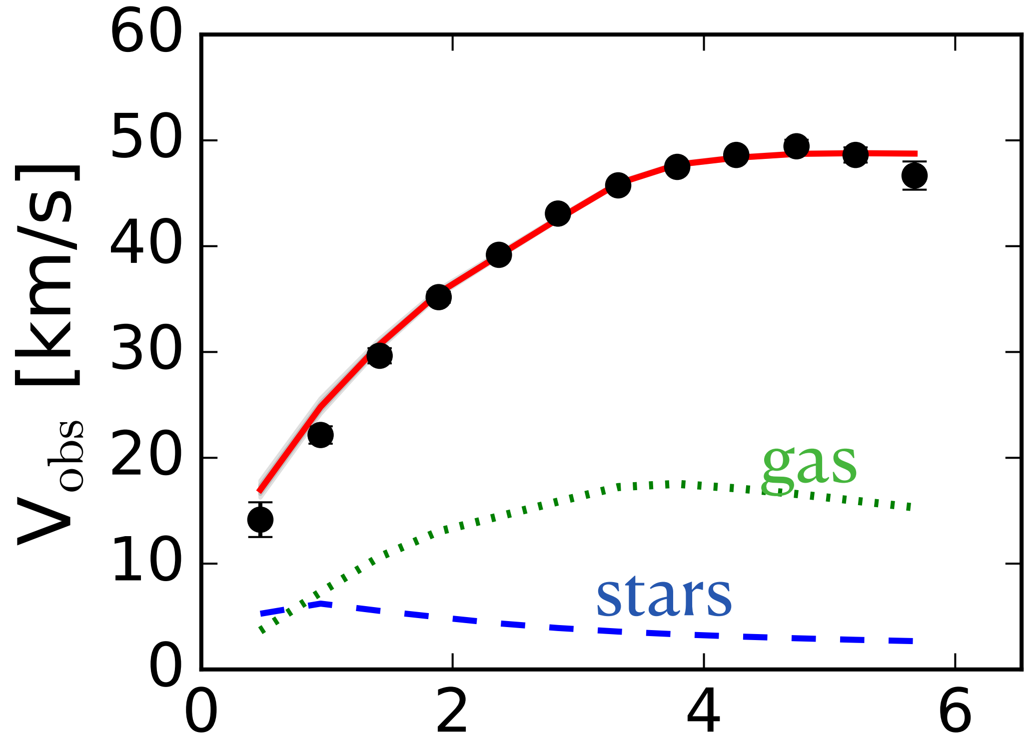
MOND fit from Ren et al. (2018)



MOND misses!

This assumes the distance and inclination are perfectly known

MOND fit from Li et al. (2018)



MOND does not miss. It tells you the distance.

DDO154

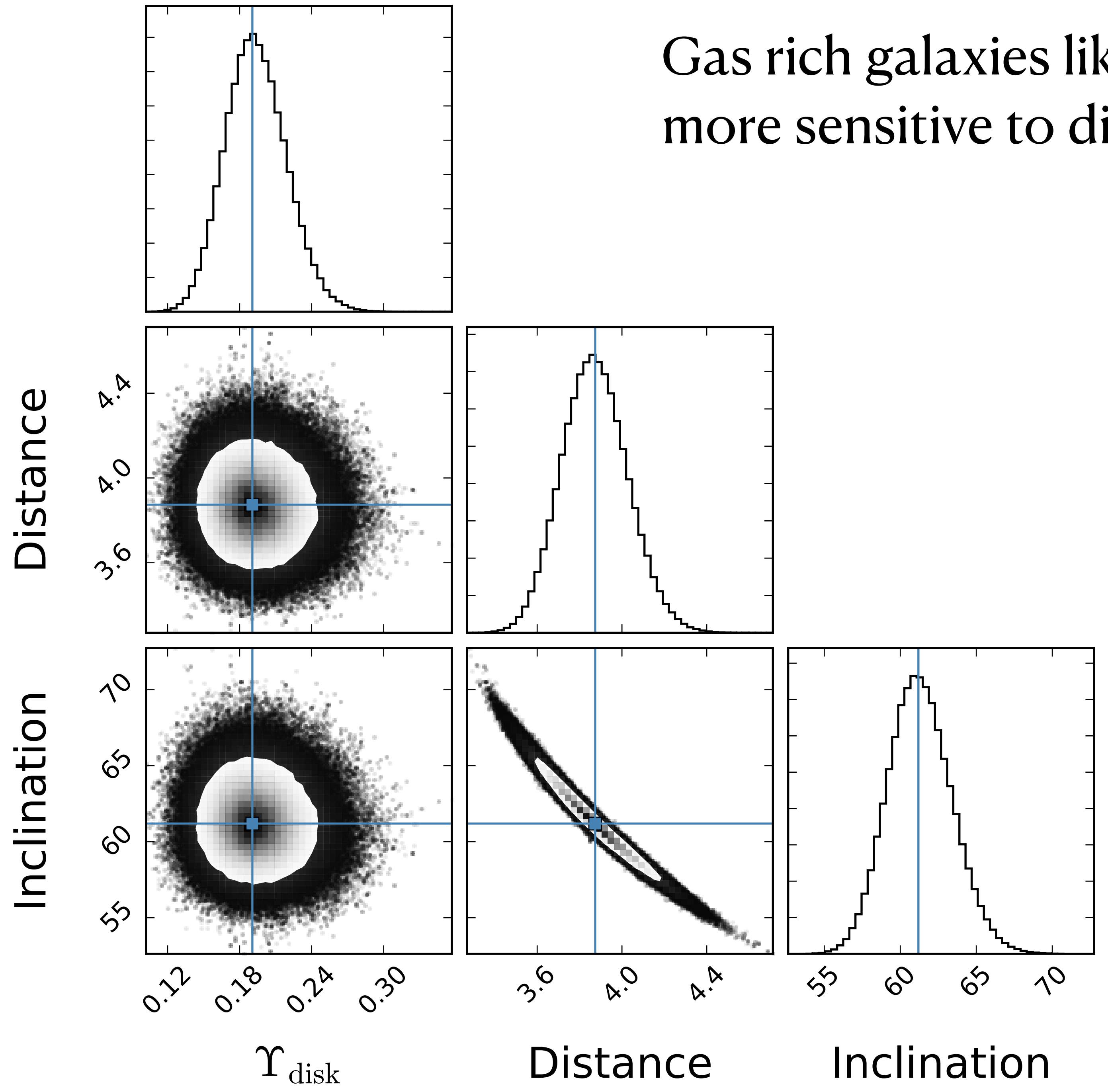
$\Upsilon_{\rm disk}$ = 0.19 ± 0.03

D = 3.87 ± 0.16 Mpc

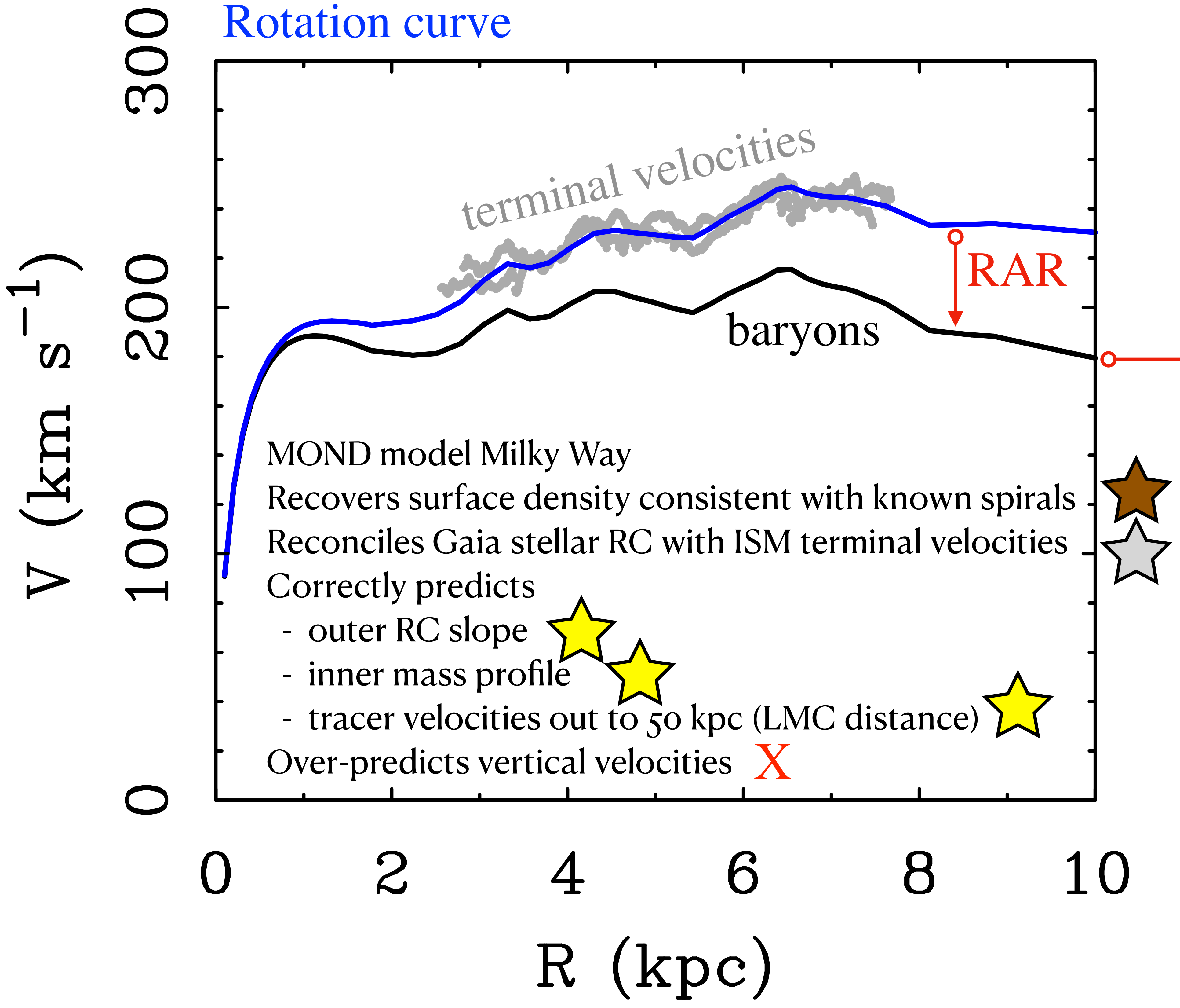
i = 61.2 ± 2.1 $^\circ$

χ^2_ν = 3.47

$D_{\rm TRGB}$ = 4.04 ± 0.08 Mpc



Gas rich galaxies like DDO 154 can be more sensitive to distance than M_*/L



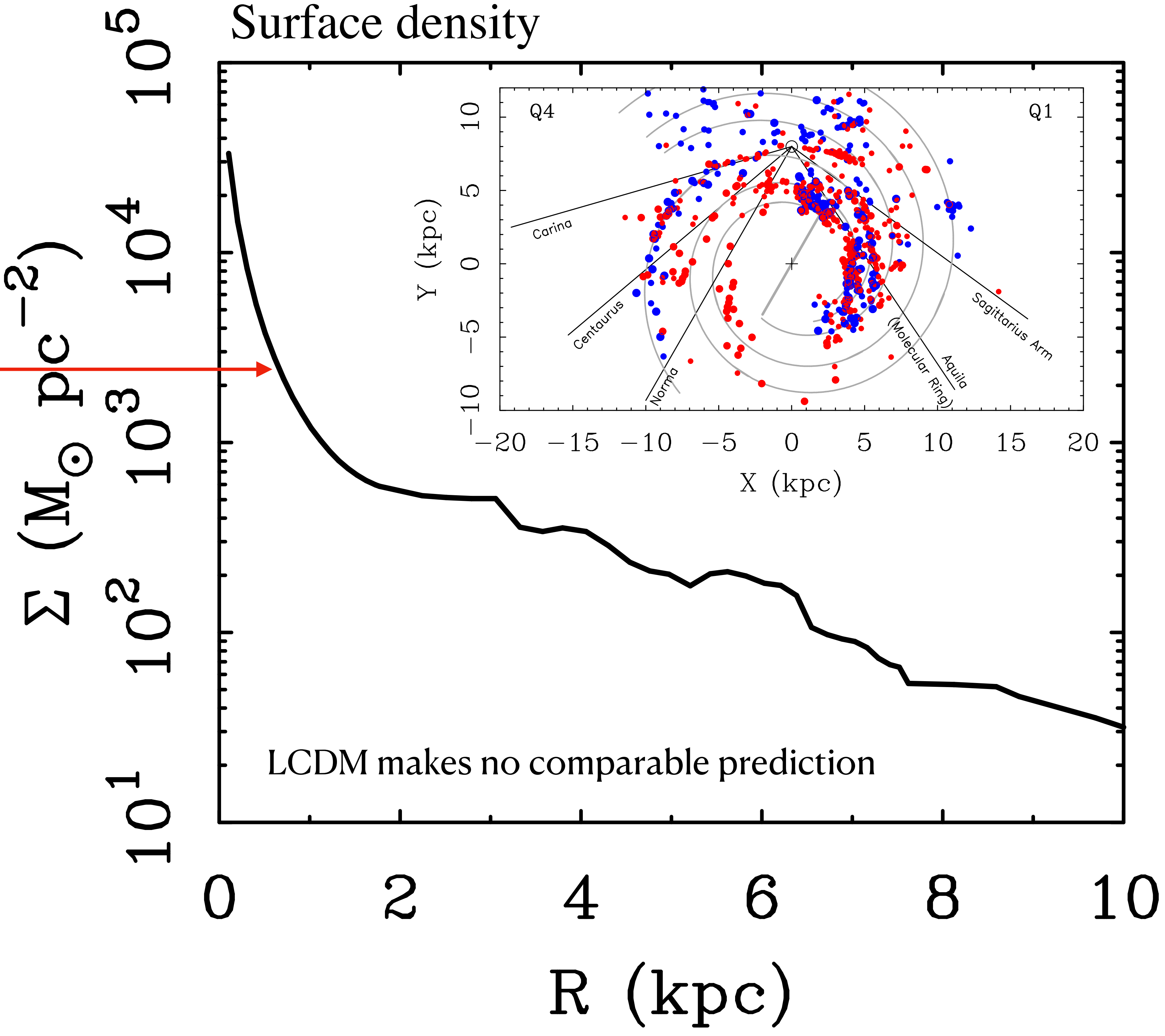
MOND model Milky Way

Recovers surface density consistent with known spirals

Reconciles Gaia stellar RC with ISM terminal velocities

Correctly predicts
- outer RC slope
- inner mass profile
- tracer velocities out to 50 kpc (LMC distance)

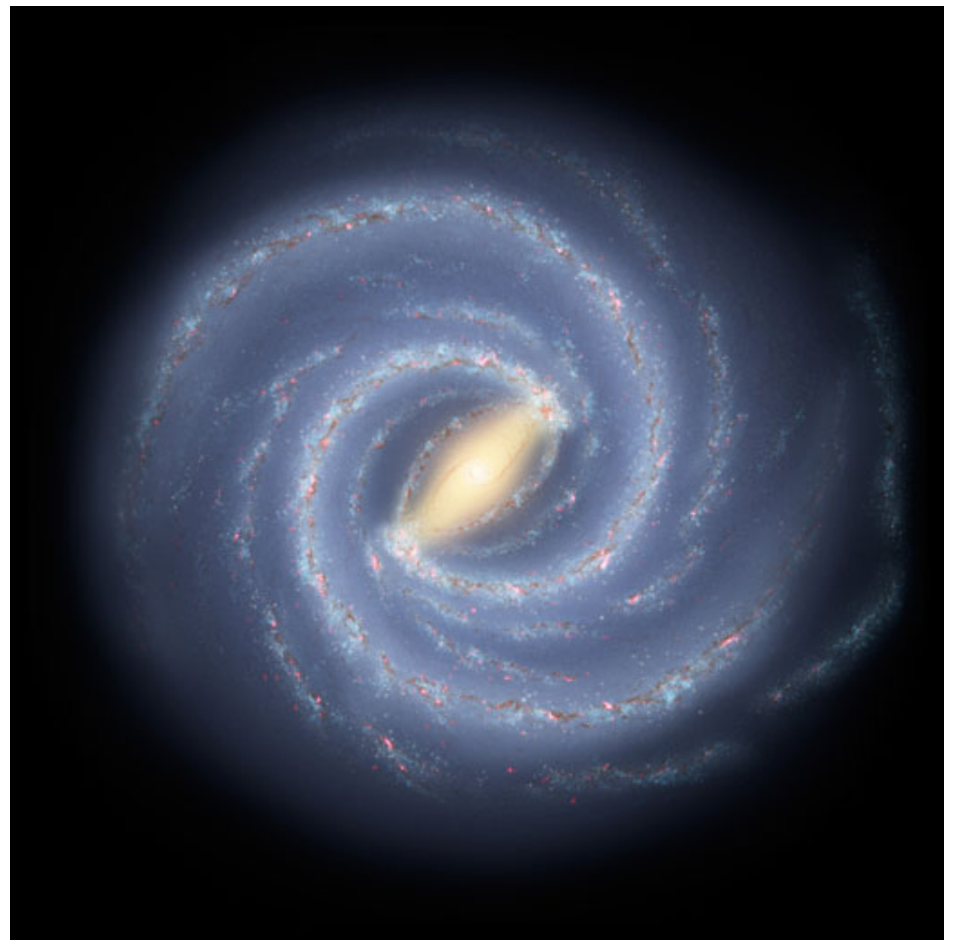
Over-predicts vertical velocities X

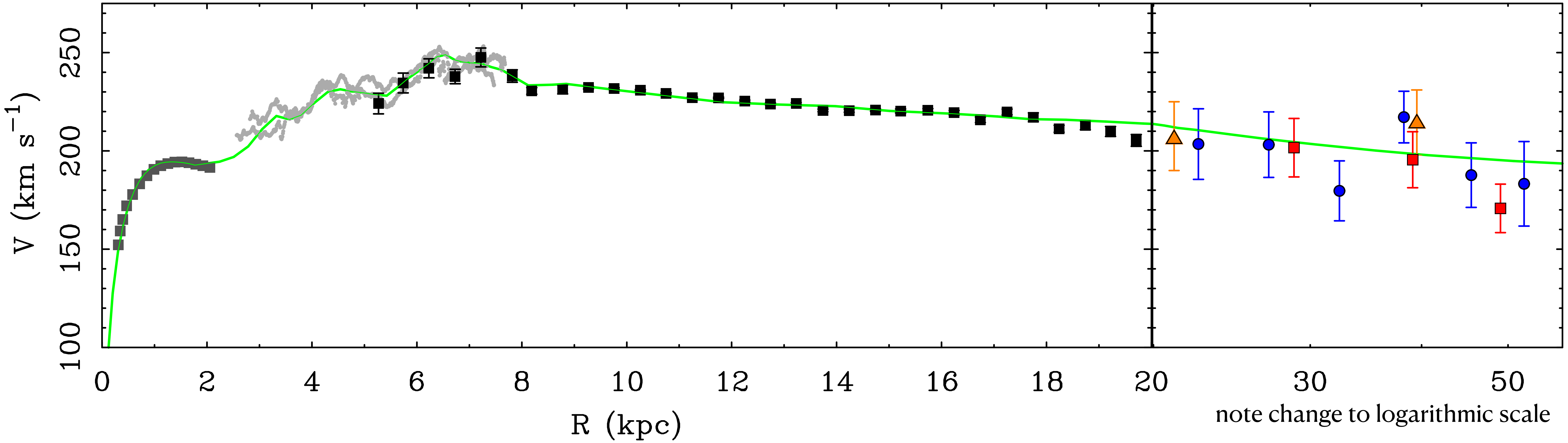


LCDM makes no comparable prediction

See talks by
Haxia Ma
Sofia Splawska
Tuesday

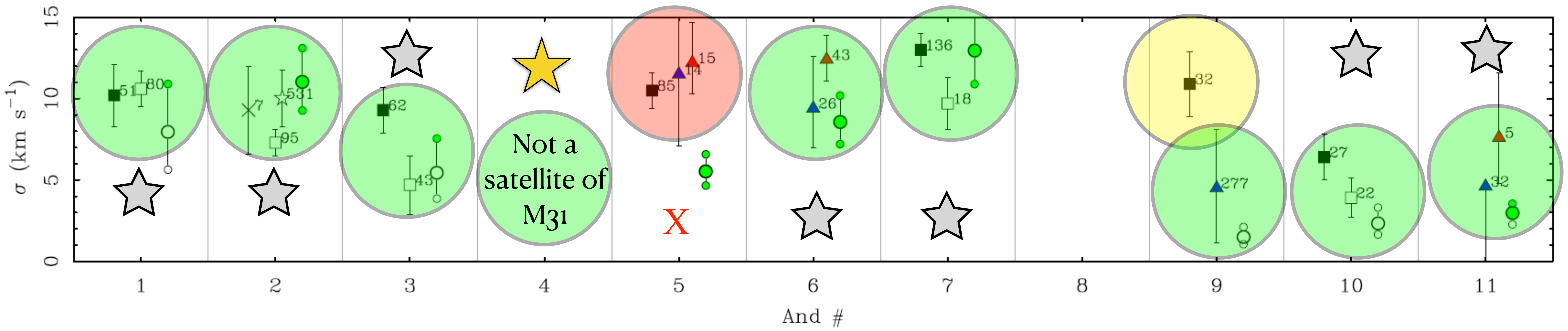
Milky Way



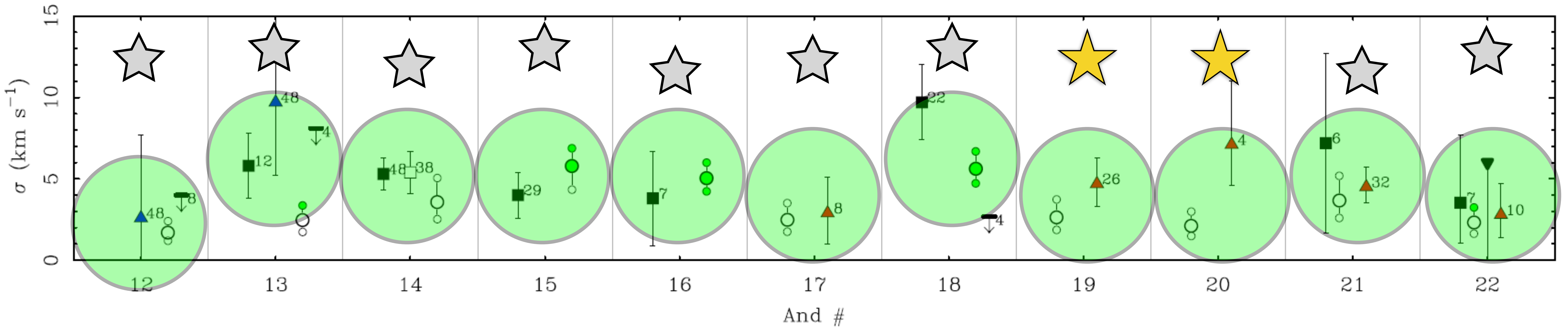


note change to logarithmic scale

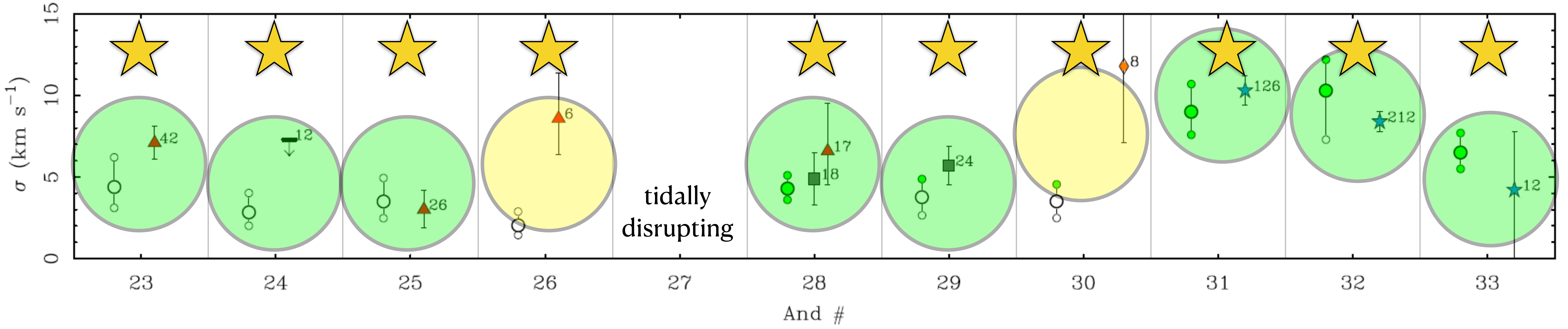
Satellites of Andromeda
MOND



It is not possible to make the same prediction successfully with dark matter. (Not for want of trying.)



The prediction is completely a priori in And IXX, XX, XXIII, XIV, XV, XVI, XVIII, XIX, XXX, XXXI, XXXII, & XXXIII.



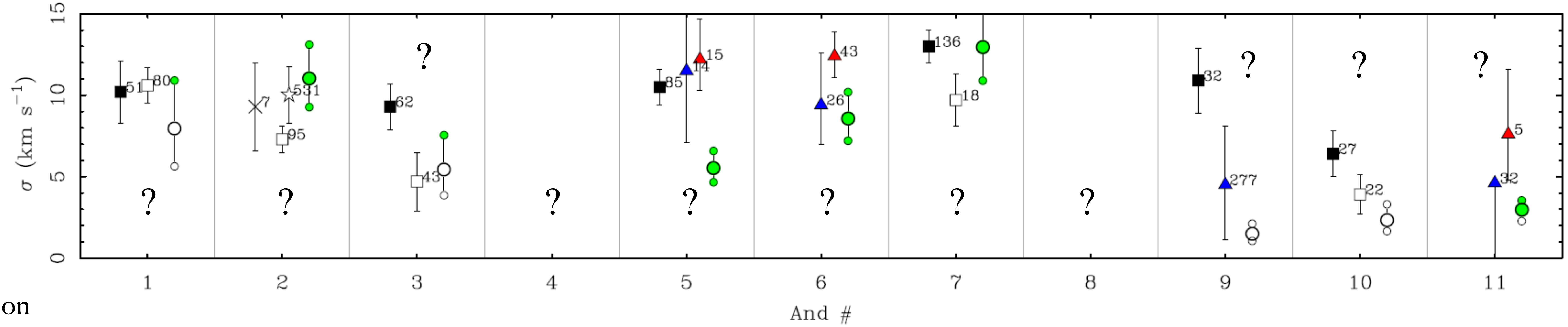
Velocity dispersions of M31 dwarfs correctly predicted (a priori in many cases) by MOND.

(McGaugh & Milgrom 2013a,b)

Satellites of Andromeda
LCDM

?

LCDM makes no comparable prediction



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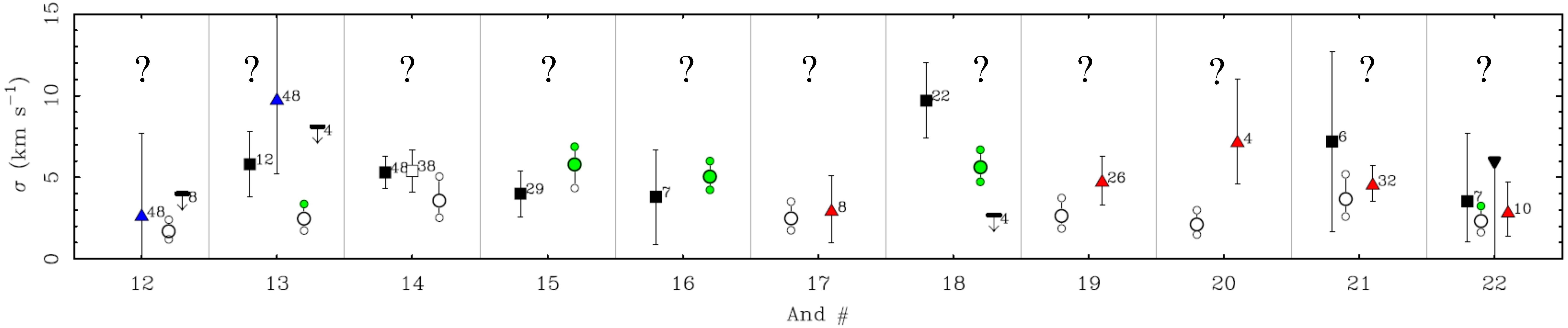
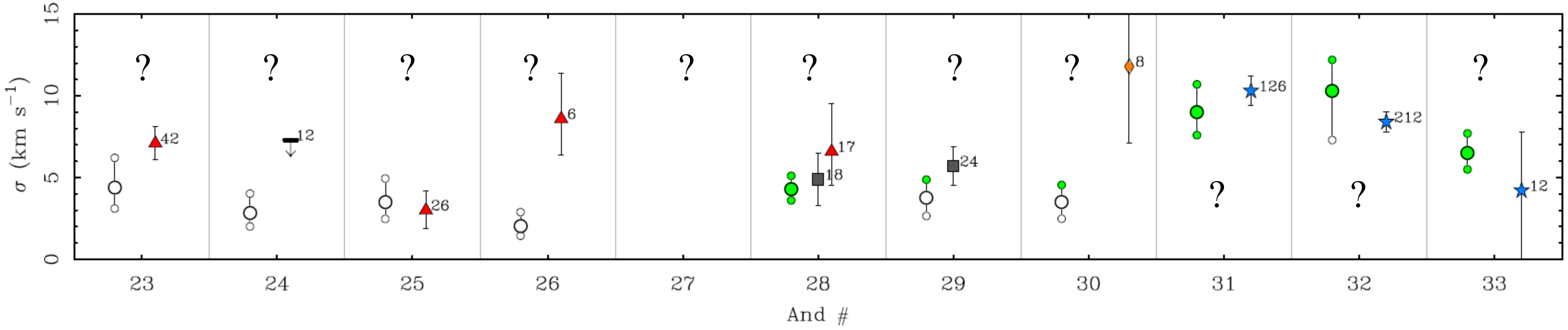




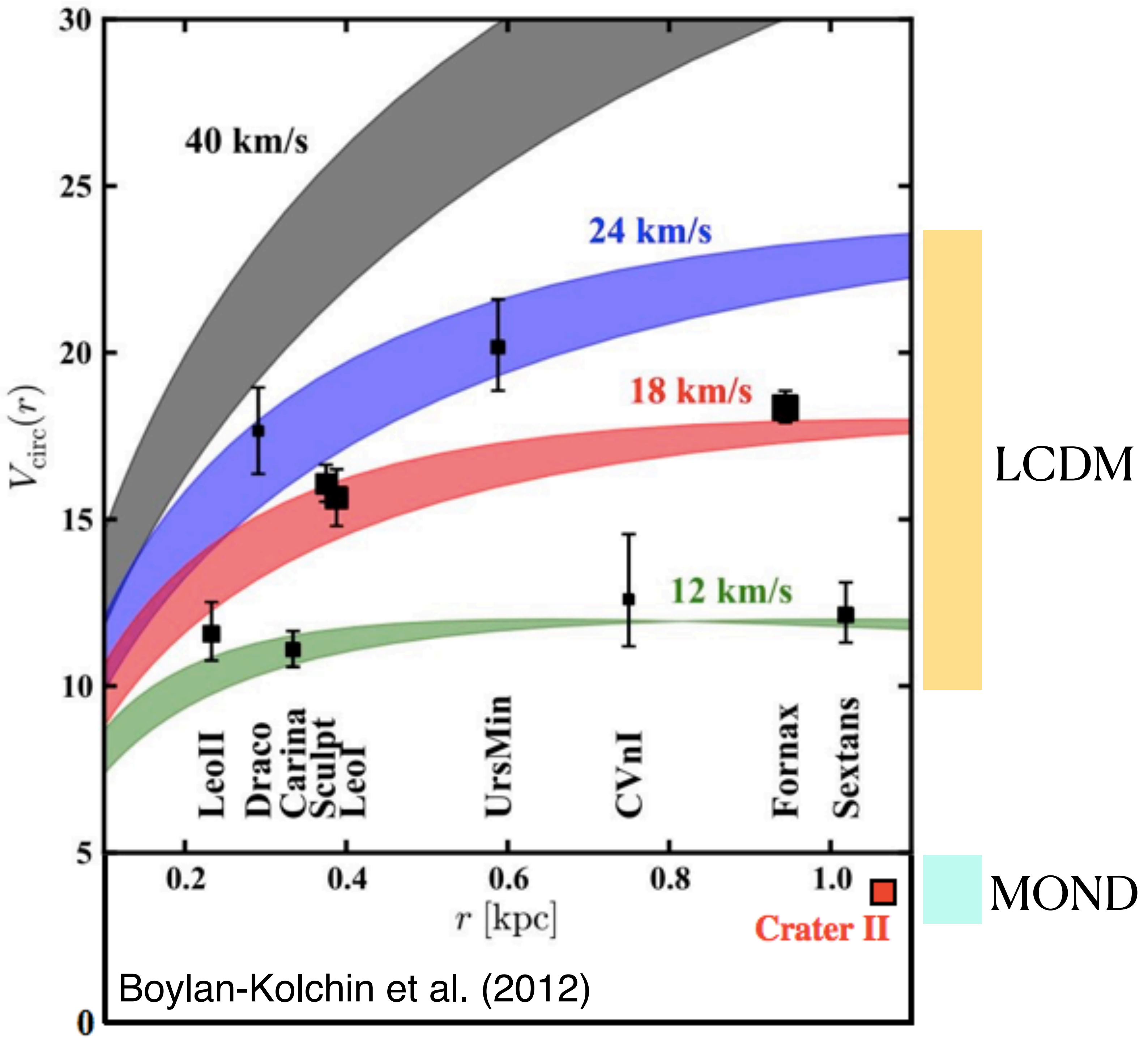
Crater 2

The unusually large Crater 2 provides another test.

LCDM predicted ~ **17** km/s ± a lot

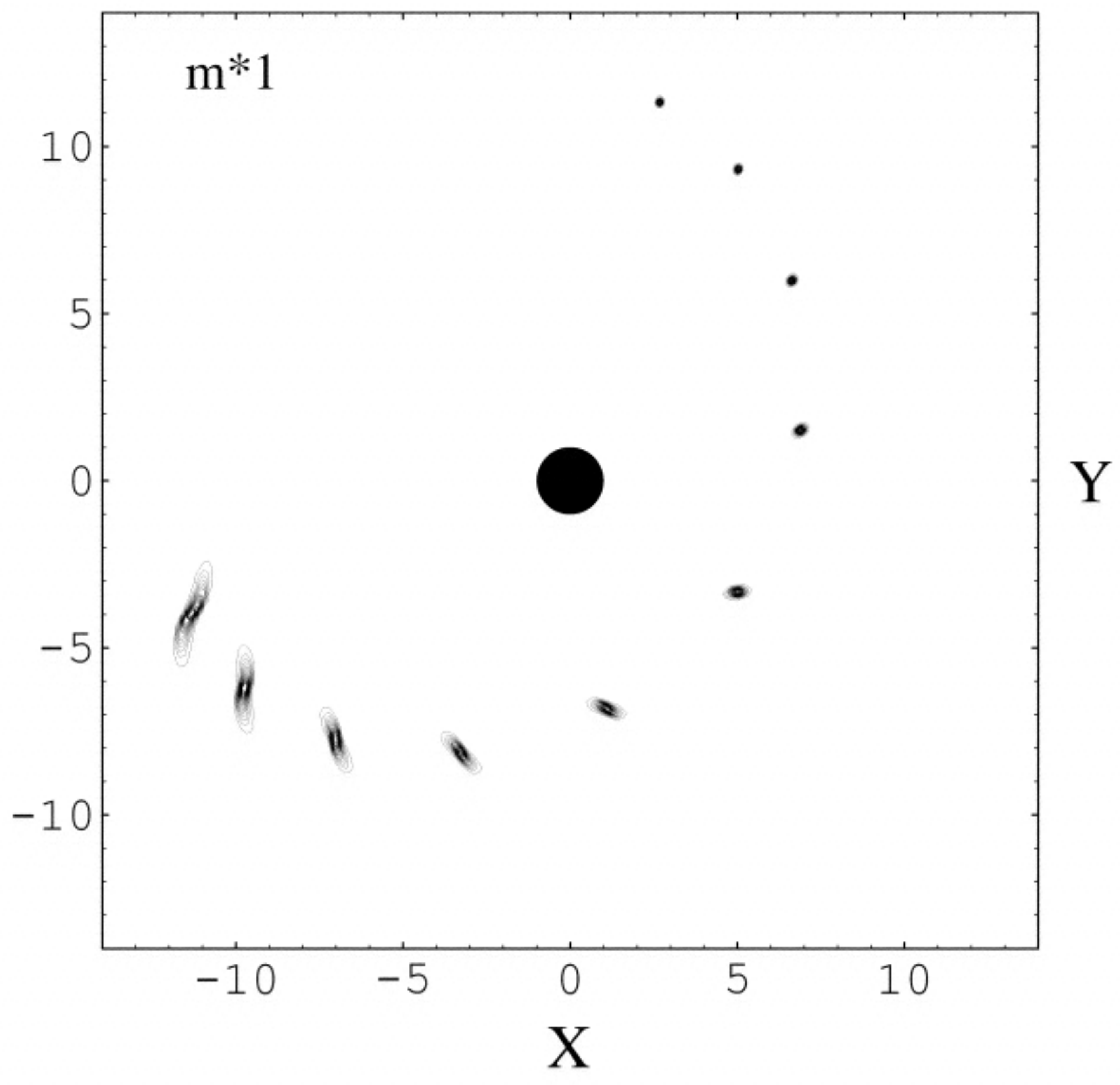
MOND predicted **2.1** +0.9/-0.6 km/s
(arXiv:1610.06189)

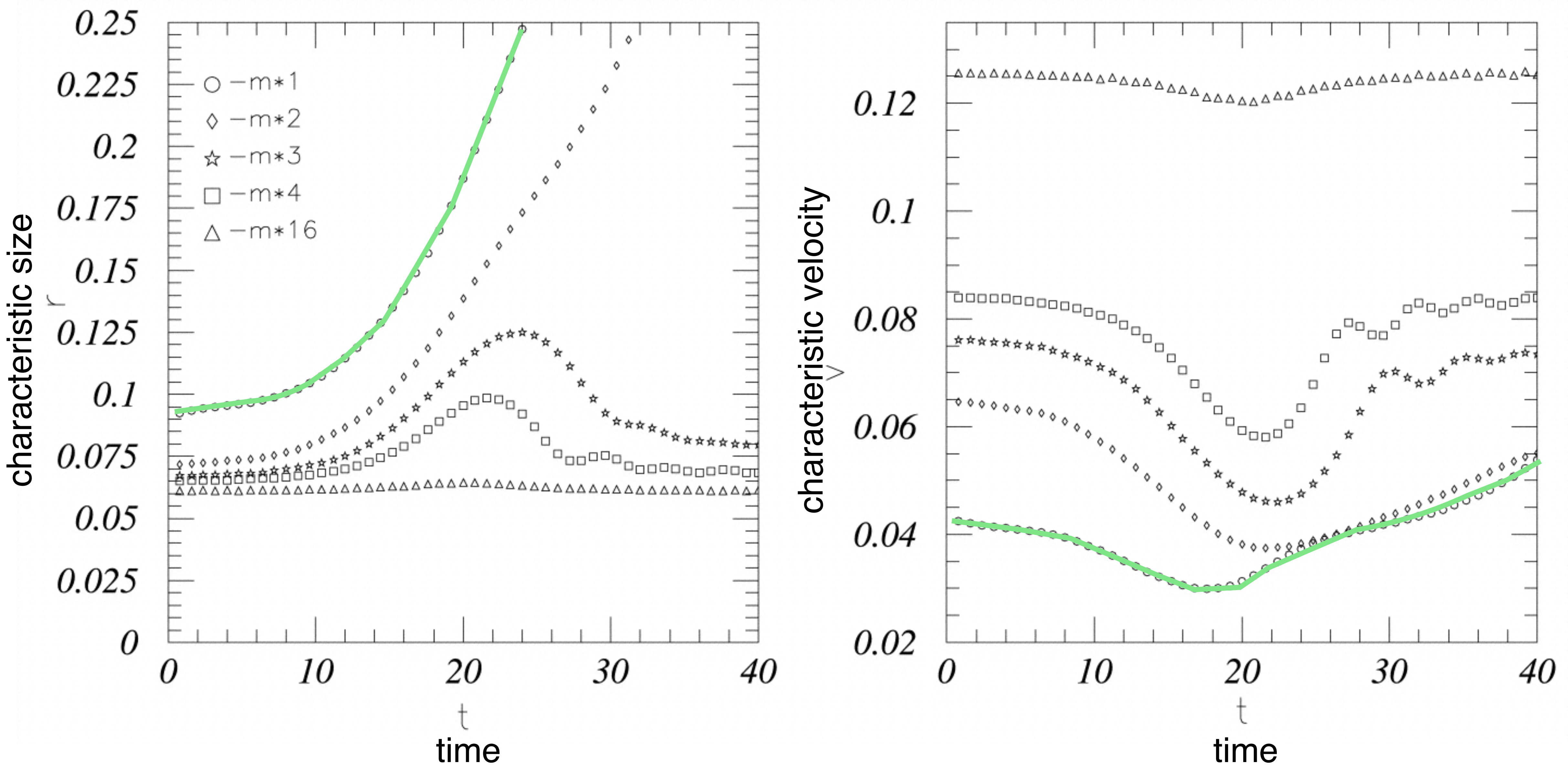
Subsequently observed: **2.7** ± 0.3 km/s
(arXiv:1612.06398)



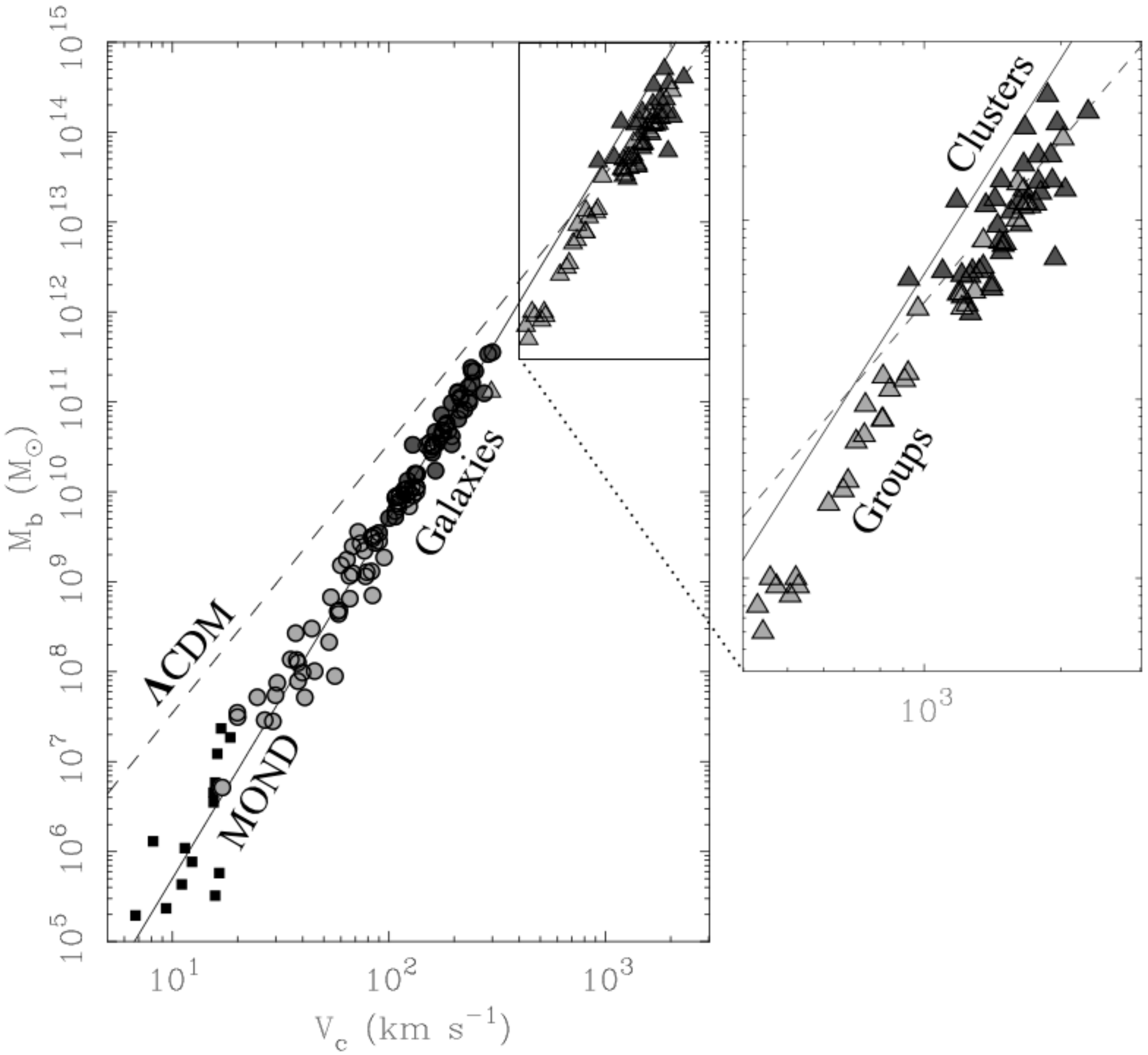
Boylan-Kolchin et al. (2012)

Brada & Milgrom (2000) anticipated the large size of a dwarf like Crater 2 being the consequence of a close pericenter passage.





Clusters



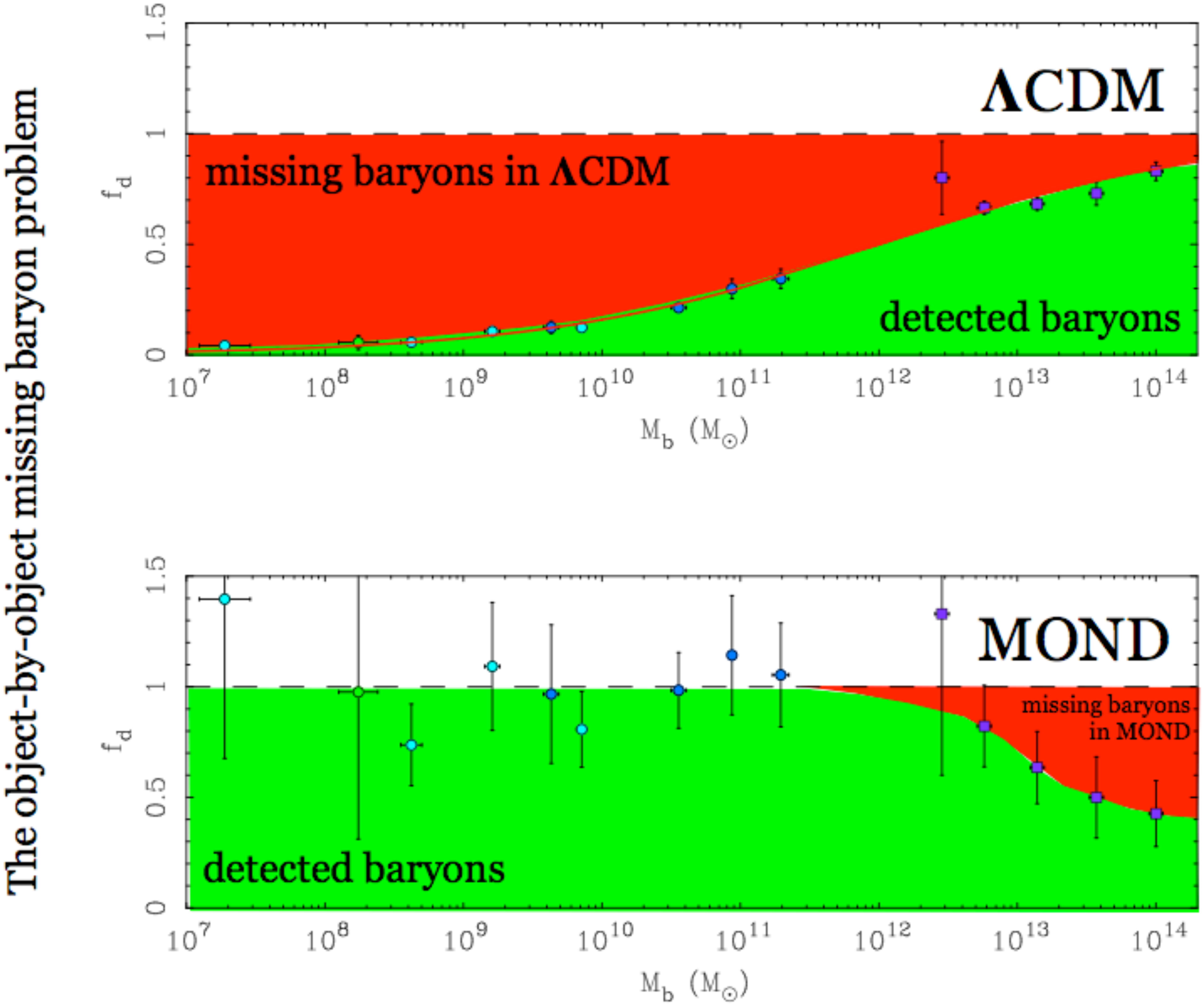
Clusters offset from BTFR defined by galaxies.
Implies a missing baryon problem.

	MOND	**LCDM**
mass budget	X	☆ $M \sim 10^{15}\ \mathrm{M}_\odot$ mass dependent X $M \sim 10^{14}\ \mathrm{M}_\odot$
M-T slope	★ $M_b \sim T^2$	X $M \sim T^{3/2}$
bulk velocities collision speeds	★ bulk $v \sim 1{,}000\ \mathrm{km\,s^{-1}}$	X bulk $v \sim 200\ \mathrm{km\,s^{-1}}$

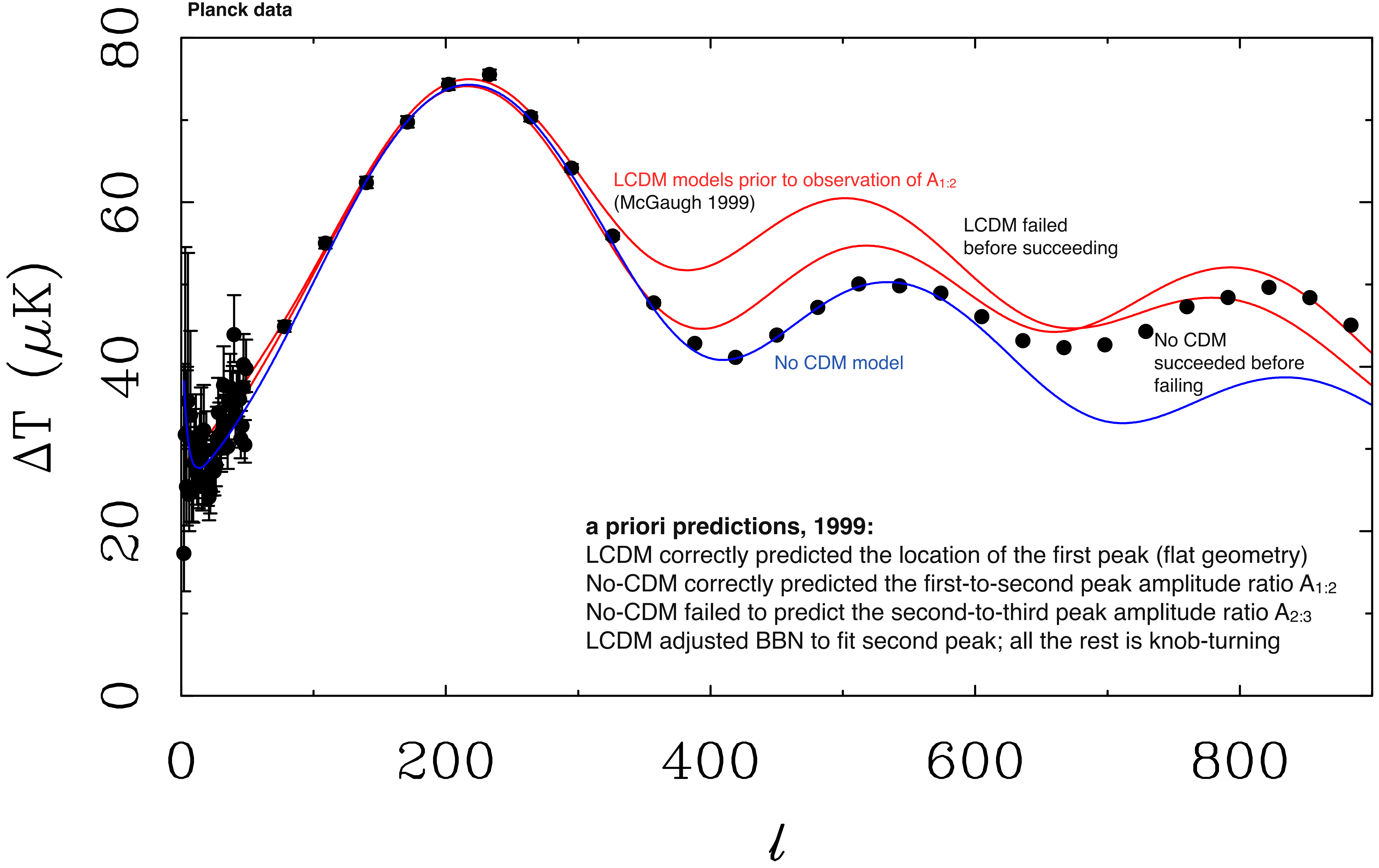
Clusters

mass budget

Missing baryons in clusters in MOND; everywhere else in LCDM



CMB

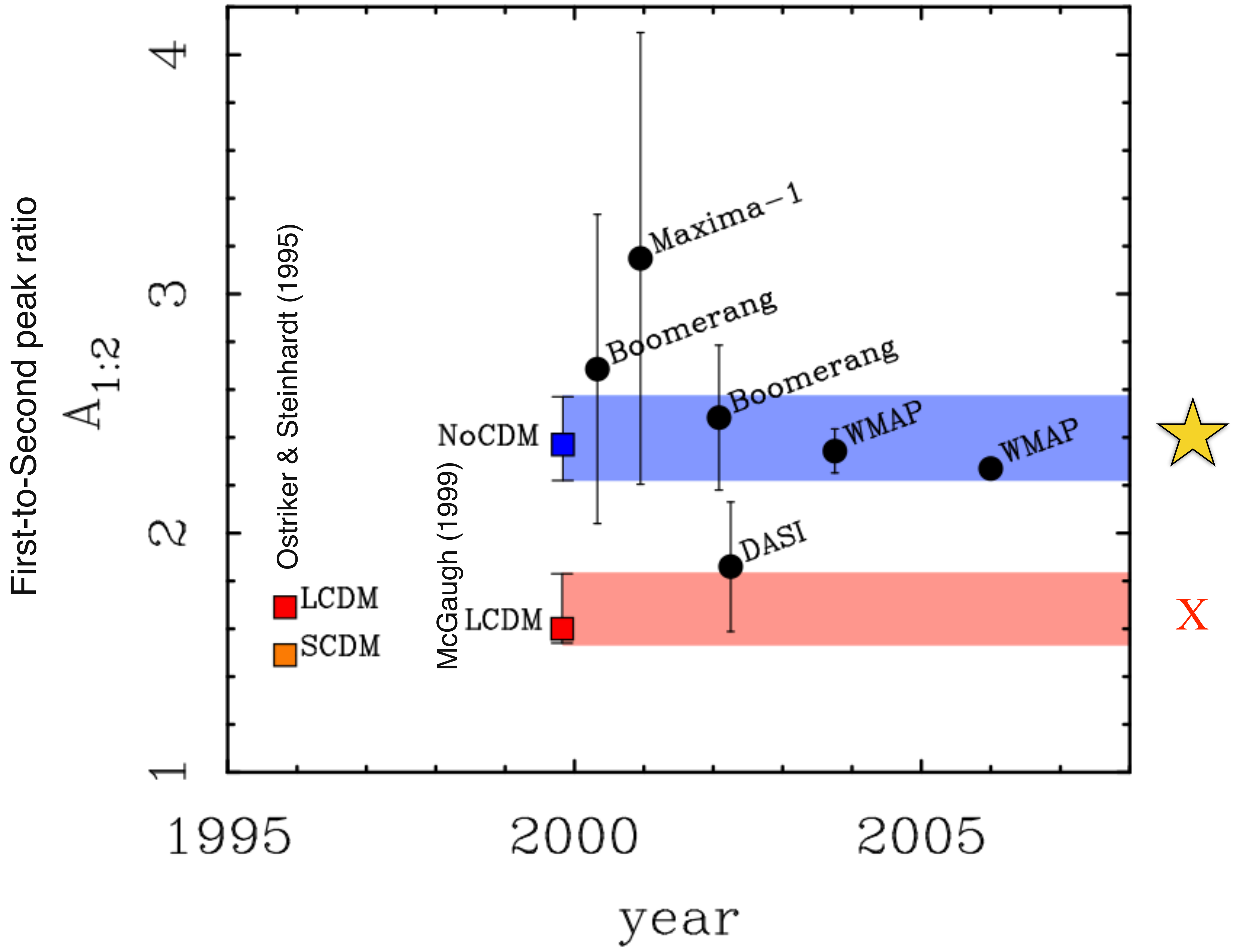


a priori predictions, 1999:
LCDM correctly predicted the location of the first peak (flat geometry)
No-CDM correctly predicted the first-to-second peak amplitude ratio $A_{1:2}$
No-CDM failed to predict the second-to-third peak amplitude ratio $A_{2:3}$
LCDM adjusted BBN to fit second peak; all the rest is knob-turning

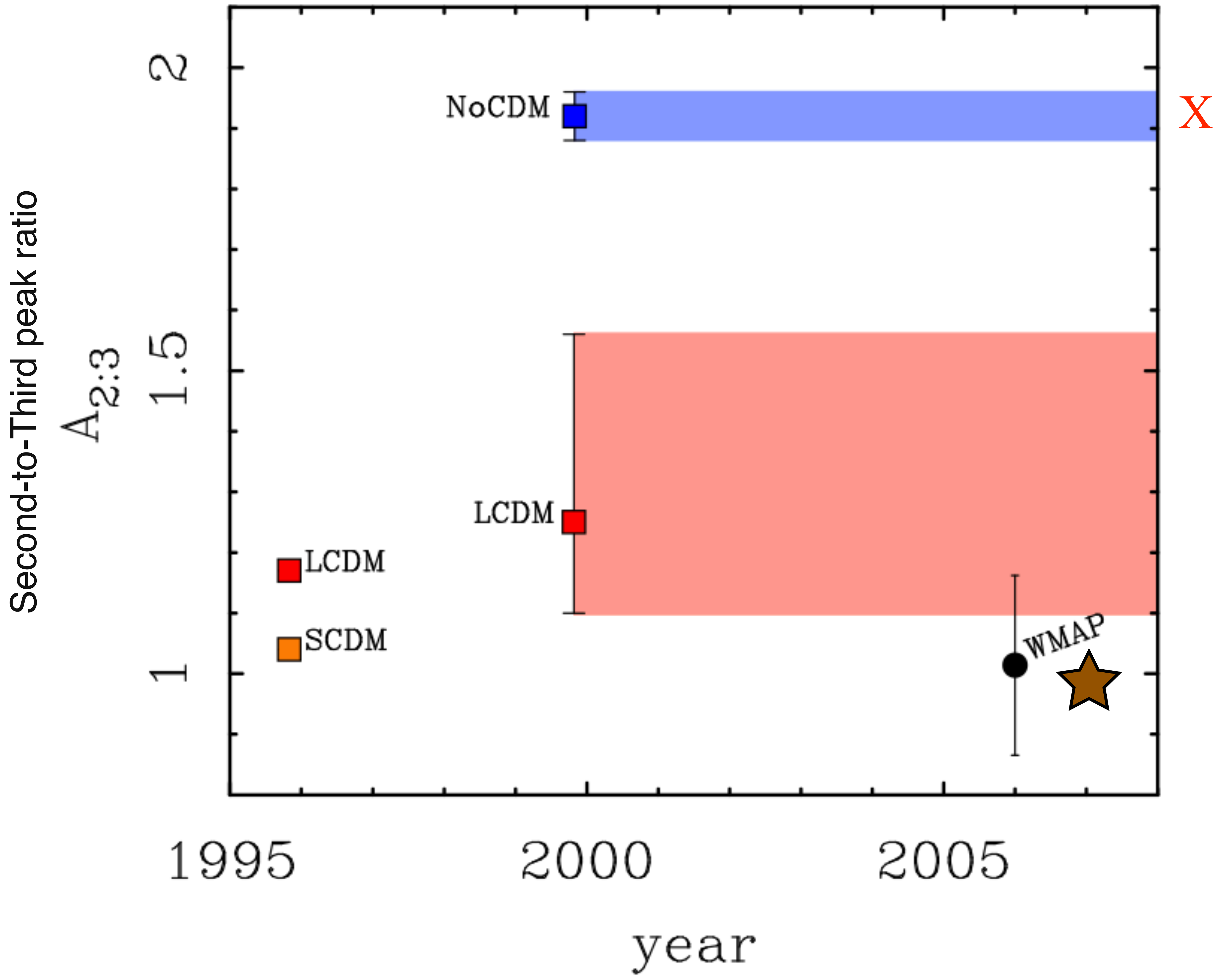
See talk by
Constantinos Skordis
Tuesday

CMB

No-CDM correctly predicted the first-to-second peak amplitude ratio $A_{1:2}$



No-CDM failed to predict the second-to-third peak amplitude ratio $A_{2:3}$



LCDM “wins ugly”: it was necessary to adjust BBN outside its established bounds to fit second peak; all the rest is knob-turning

Early galaxy formation

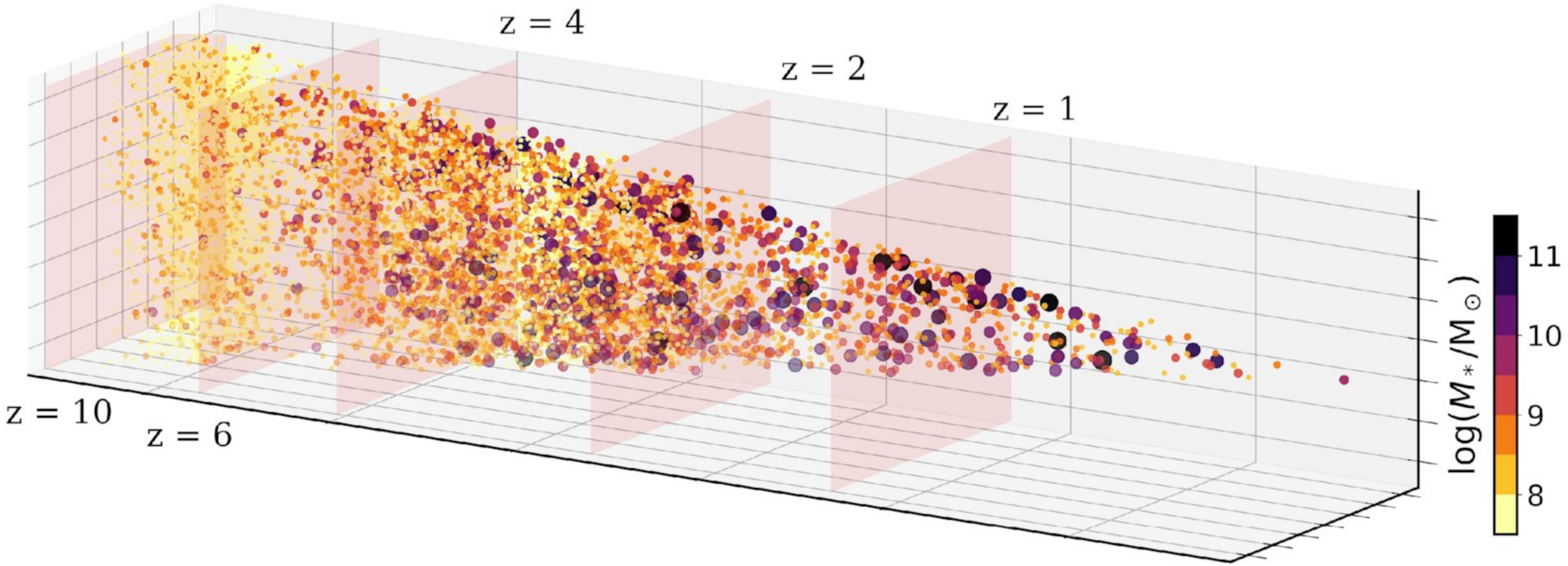
Galaxies grew too big too fast for LCDM

De Lucia+ (2006, 2007)

Early galaxy formation

Galaxies grew too big too fast for LCDM

Theoretical expectation



Three-dimensional visualization of a simulated light-cone of the COSMOS field. The cone-shaped feature is a manifestation of the predicted physical positions and distances for a fraction of the objects expected within the survey area along our line of sight.

Yung, Somerville, et al (2022, MNRAS, 515, 5416)

Early galaxy formation

That galaxies would grow big fast was predicted by MOND

LCDM

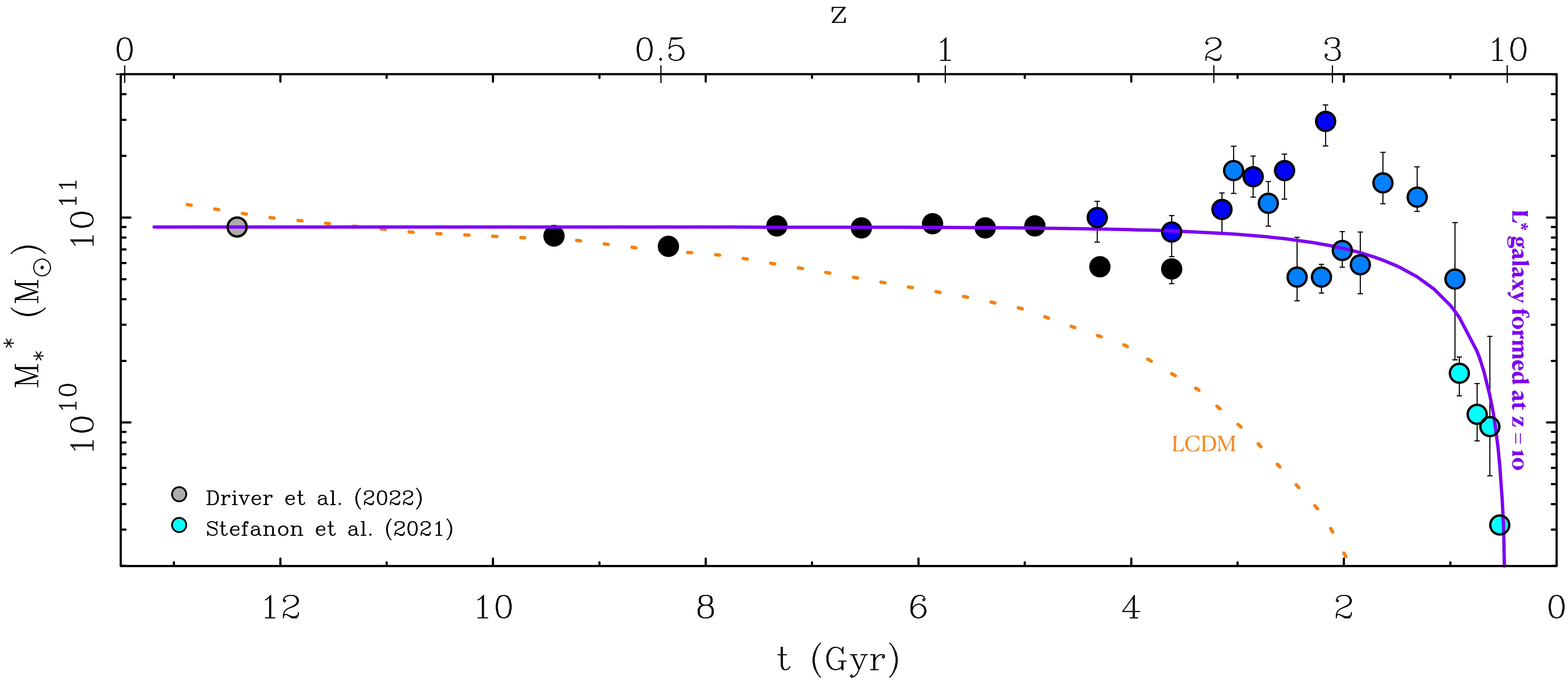
“present-day discs were assembled recently (at z<=1)”

Mo et al (1998) X

MOND

“Objects of galaxy mass are the first virialized objects to form (by z=10)” ★

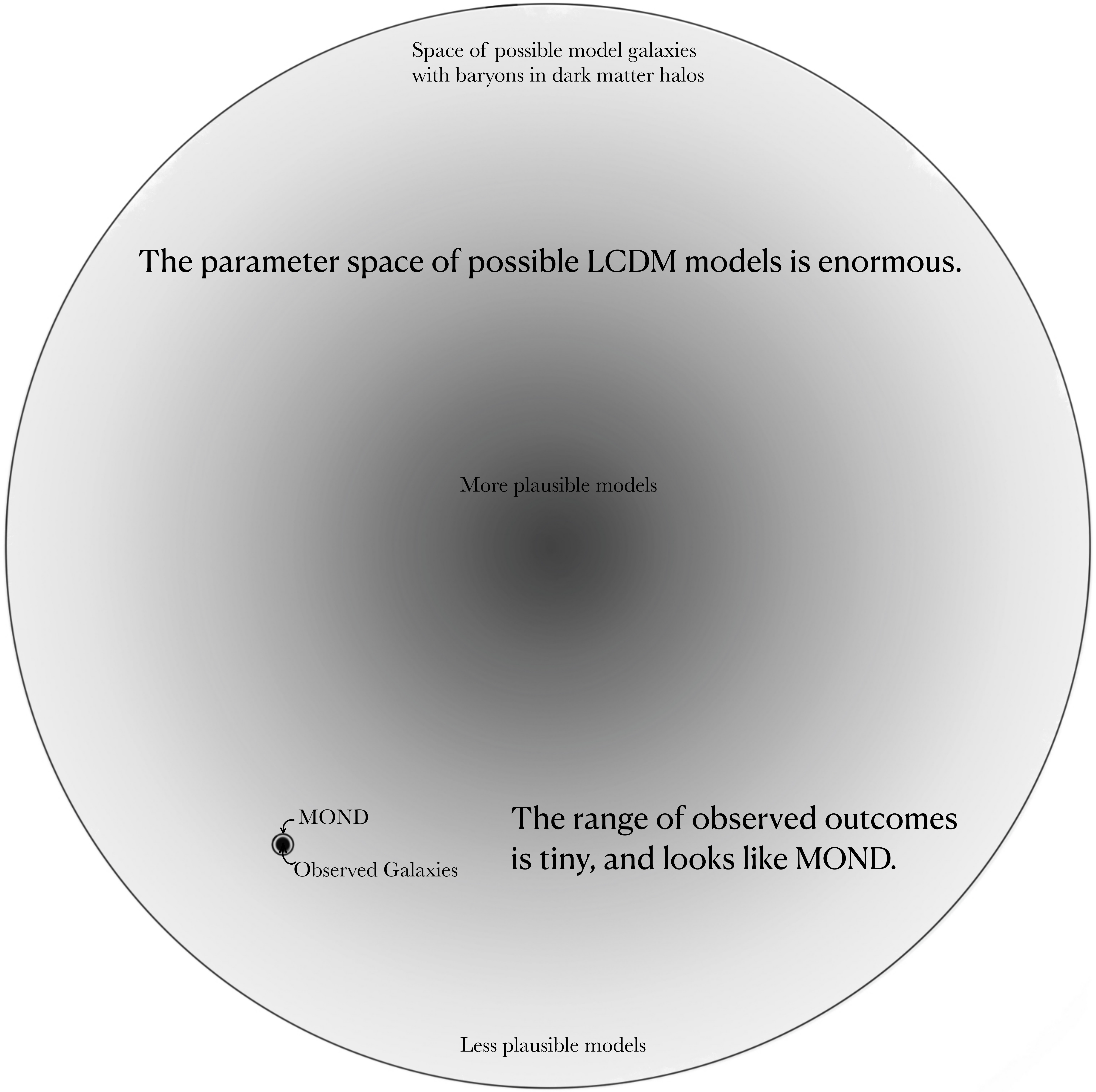
Sanders (1998)



Why does MOND get *any* prediction right?
This should not happen in LCDM.

Nature keeps plucking the same MOND-like needle from the haystack of possible dark matter outcomes. In a Bayesian sense, the prior probability for this to occur is negligibly small. It should not happen.

LCDM **does not** predict what MOND predicts and often **cannot** provide a satisfactory explanation.



The parameter space of possible LCDM models is enormous.

The range of observed outcomes is tiny, and looks like MOND.