Cleveland Astronomical Society
7 December 2017

The Mysterious Missing Mass and the Acceleration Discrepancy

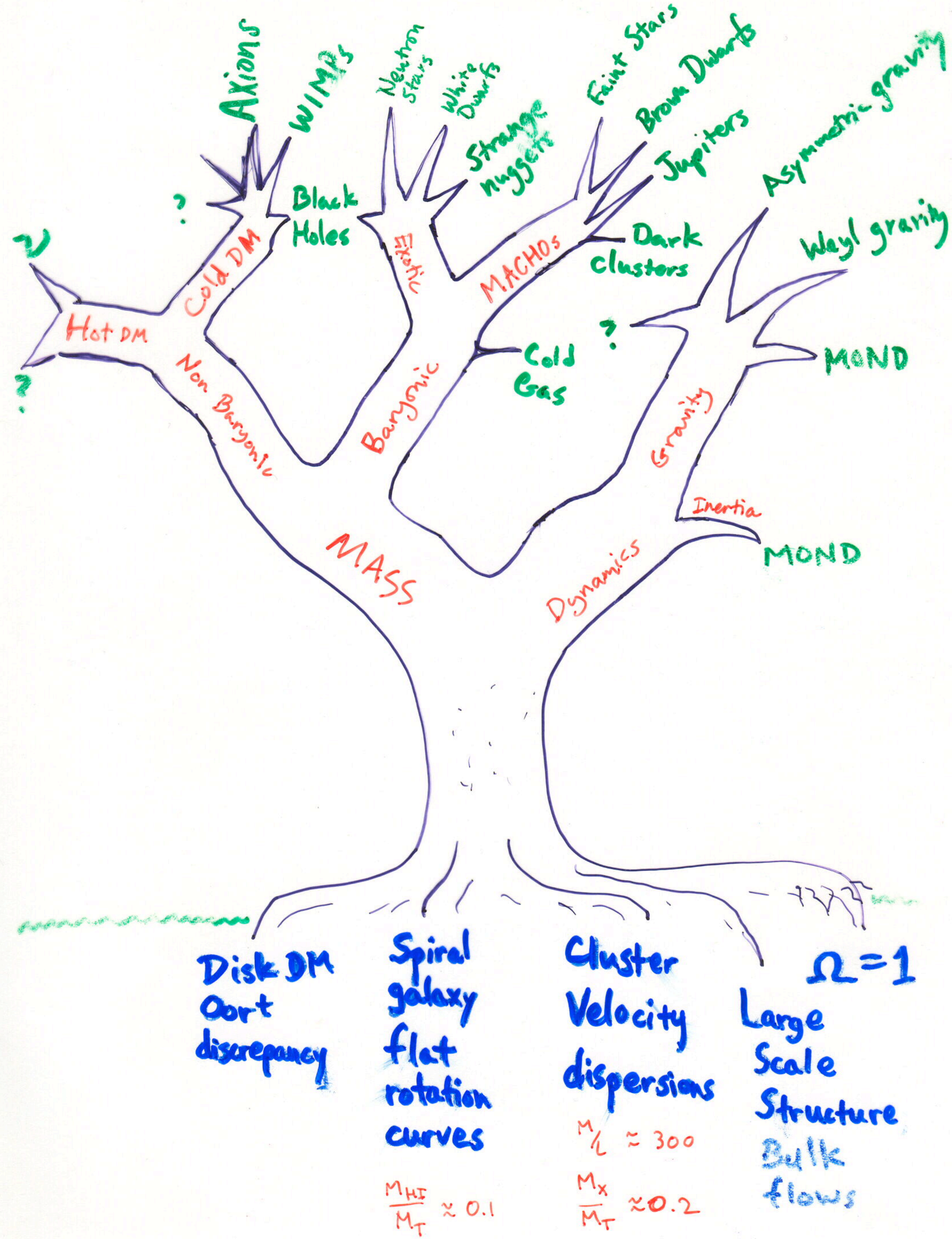
Stacy McGaugh

Case Western Reserve University Est. 1826

The Dark Matter tree

Hypothesized solutions

Roots of the problem



What gets us into trouble is not what we don't know.

It's what we know for sure that just ain't so.

Josh Billings

Orating

Writing

Philosophizing

- Josh Billings

(paraphrased)

c. 1874

A few things we know for sure...

$$\nabla^2 \Phi = 4\pi G\rho$$
$$F = ma$$

which basically means

$$V^2 = \frac{GM}{R}$$

ergo...

The universe is filled with non-baryonic cold dark matter.

Cold Dark Matter

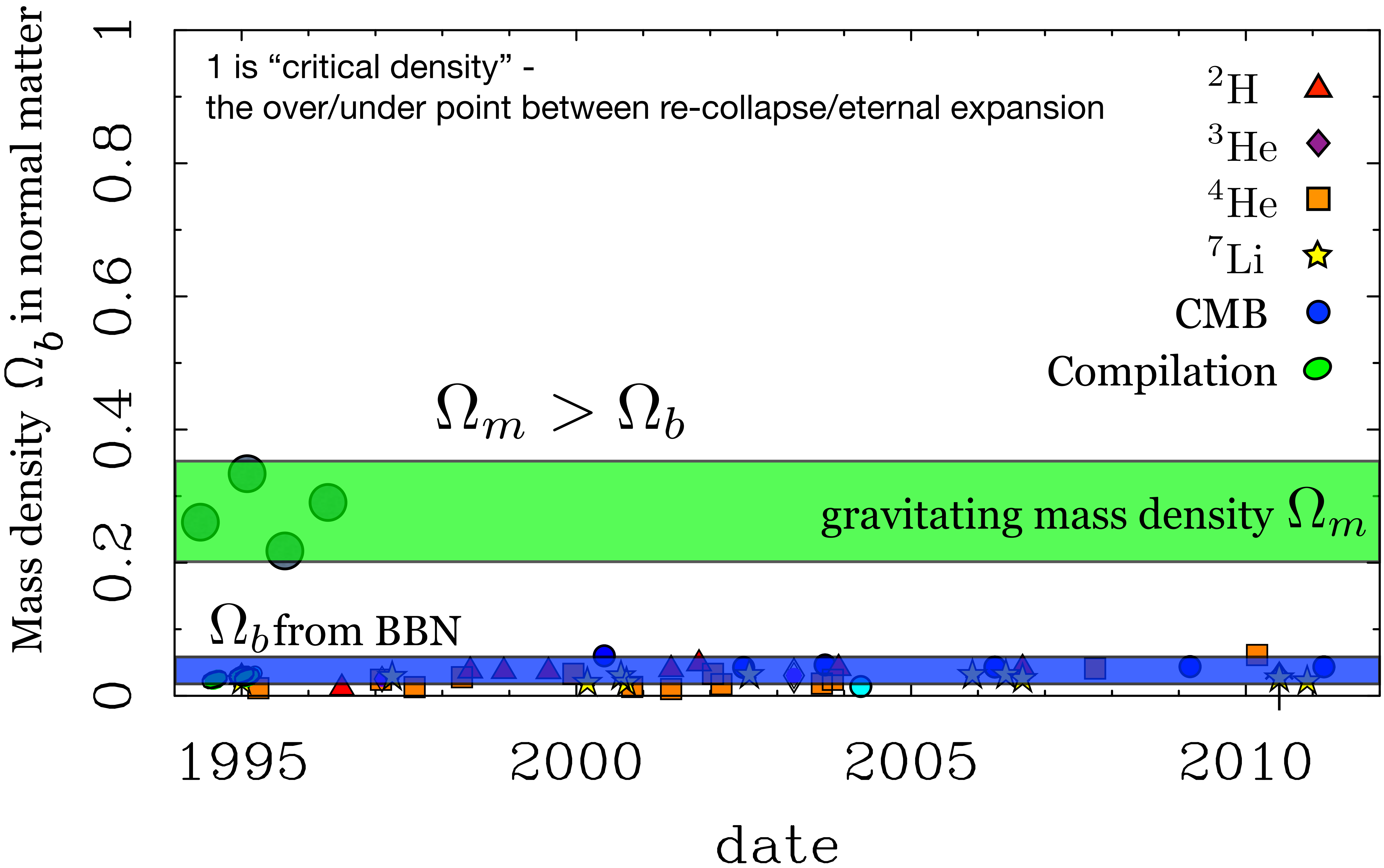
Some new particle, usually assumed to be a
WIMP (Weakly Interacting Massive Particle)
These don't interact electromagnetically, so very dark.

Two big motivations:

1) total mass outweighs normal mass from Big Bang Nucleosynthesis

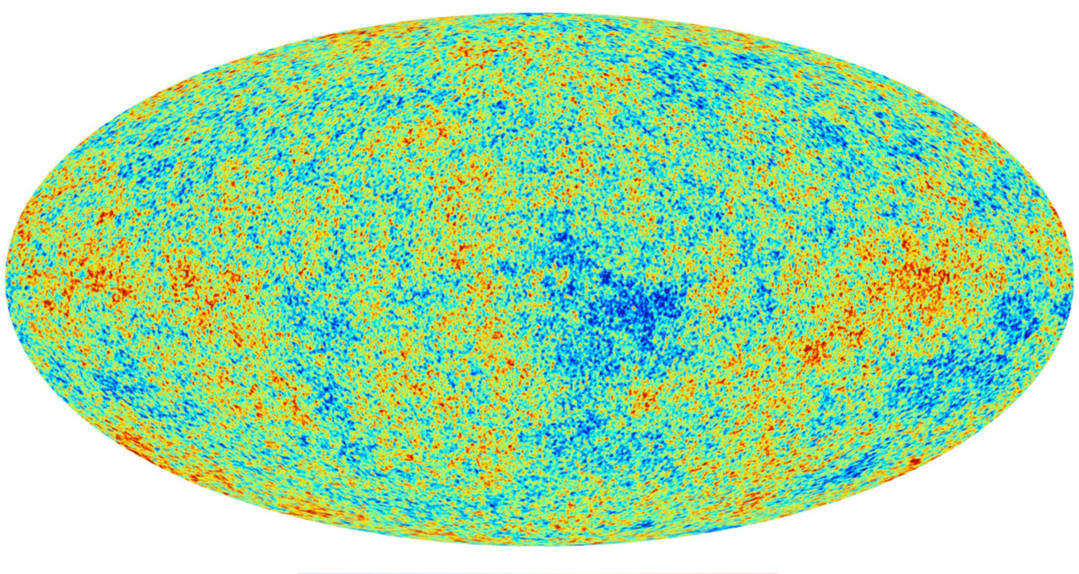
2) needed to grow cosmic structure

(1) There's more mass than BBN allows in baryons



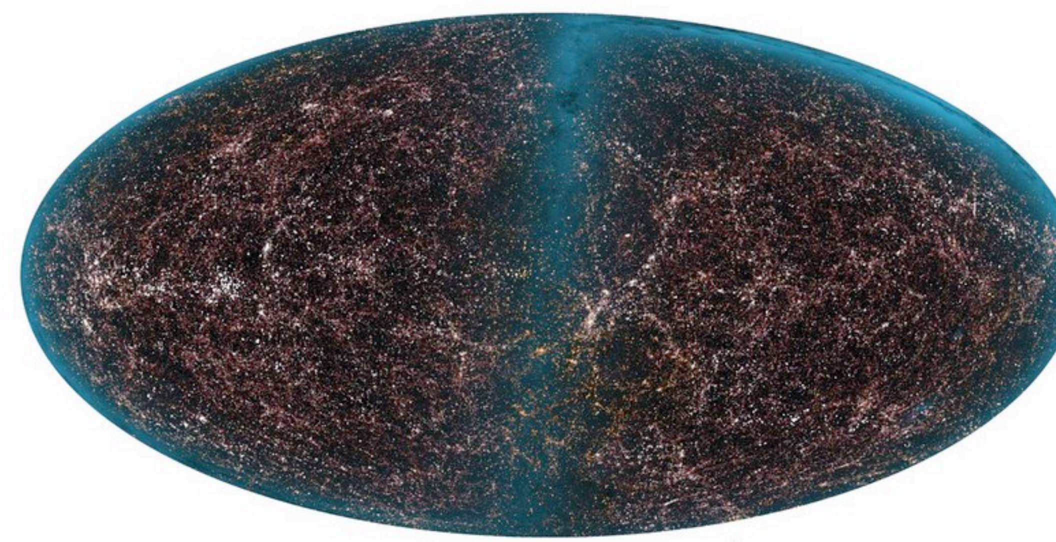
(2) There isn’t enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

$t = 3.8 \times 10^5$ yr



very smooth: $\delta\rho/\rho \sim 10^{-5}$

$t = 1.4 \times 10^{10}$ yr

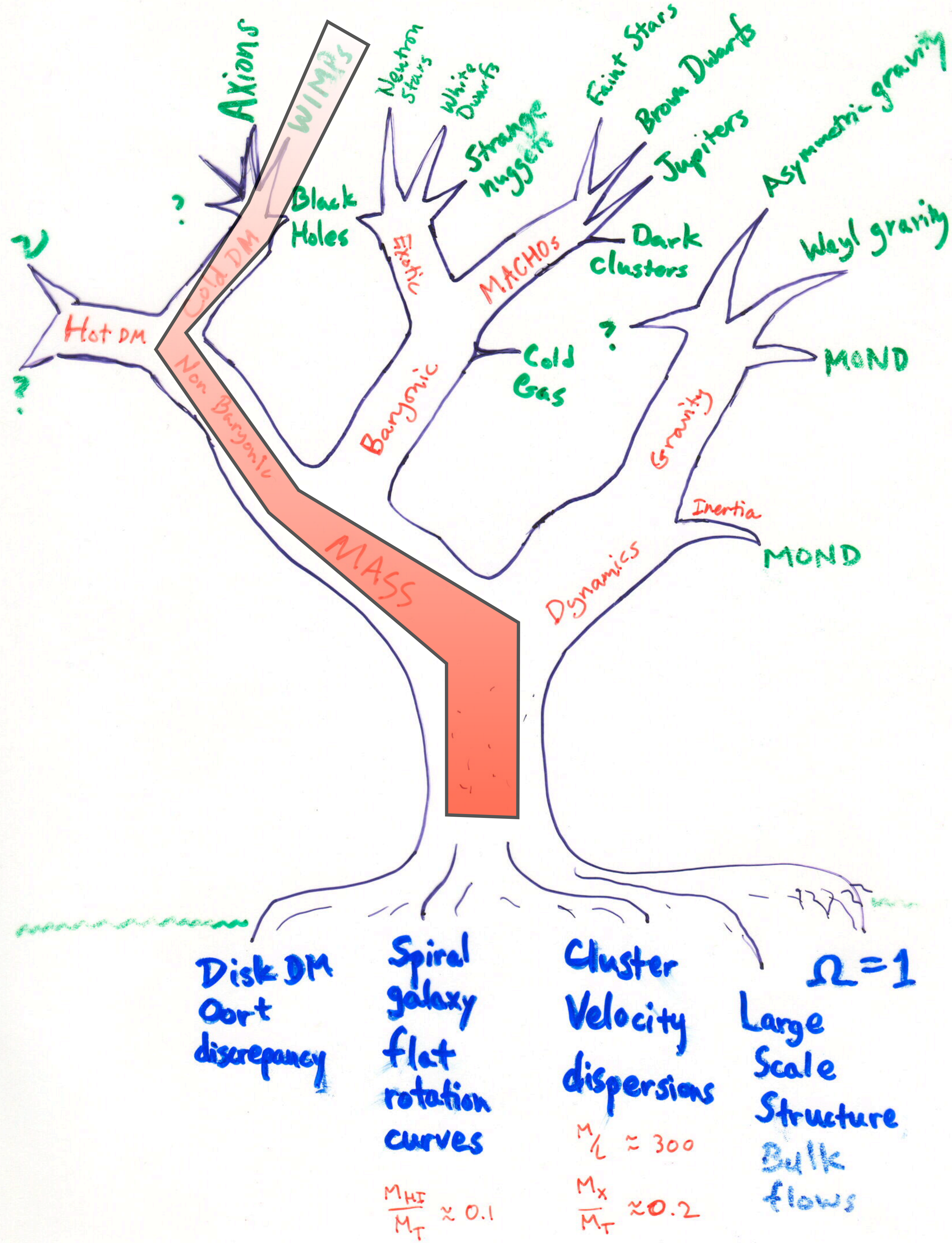


very lumpy: $\delta\rho/\rho \sim 1$

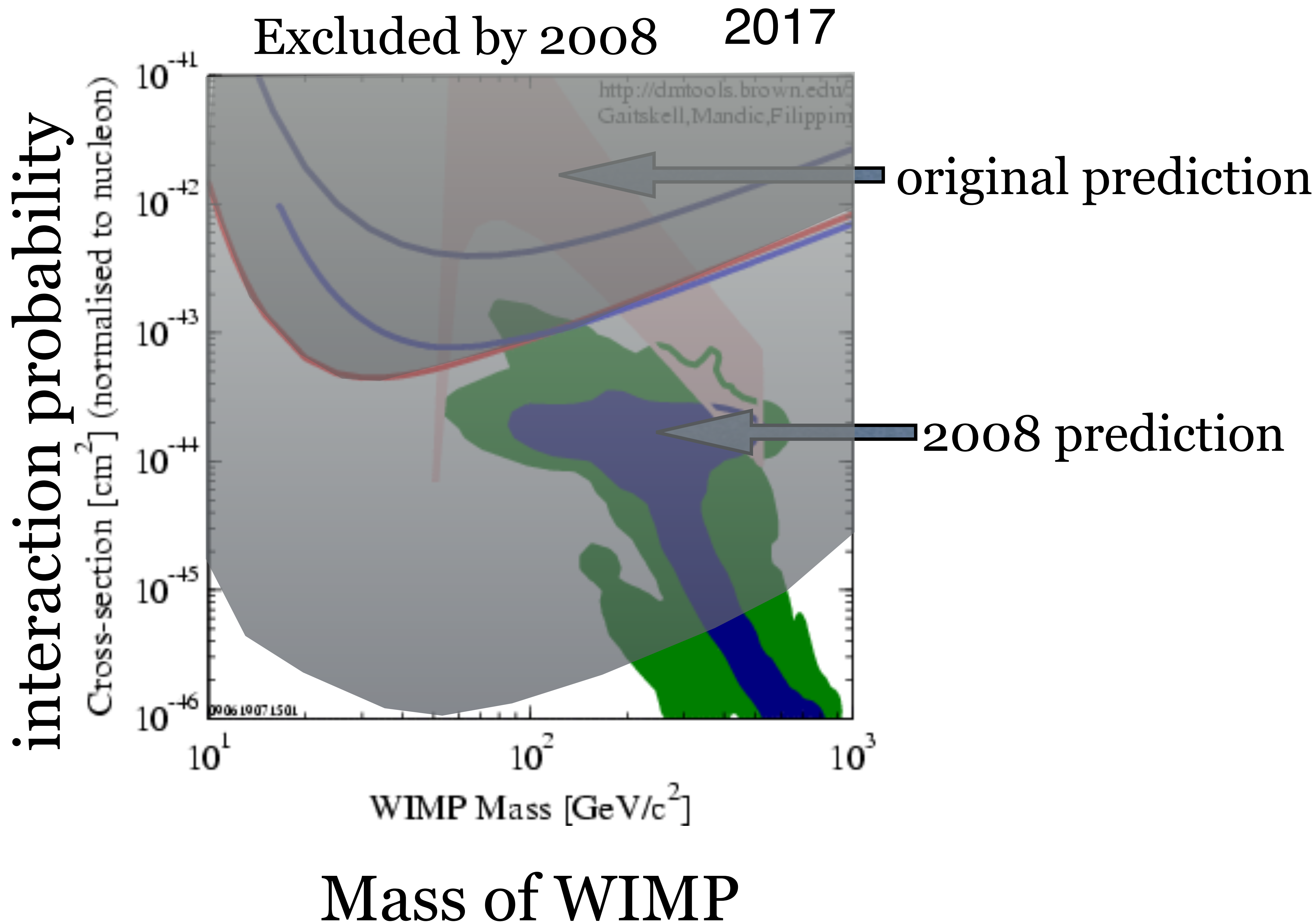
$$\delta\rho/\rho \propto t^{2/3}$$

Both (1) and (2) hold if and only if Einstein taught us everything we need to know.

Amongst all hypothesized solutions, WIMPS are the most popular.

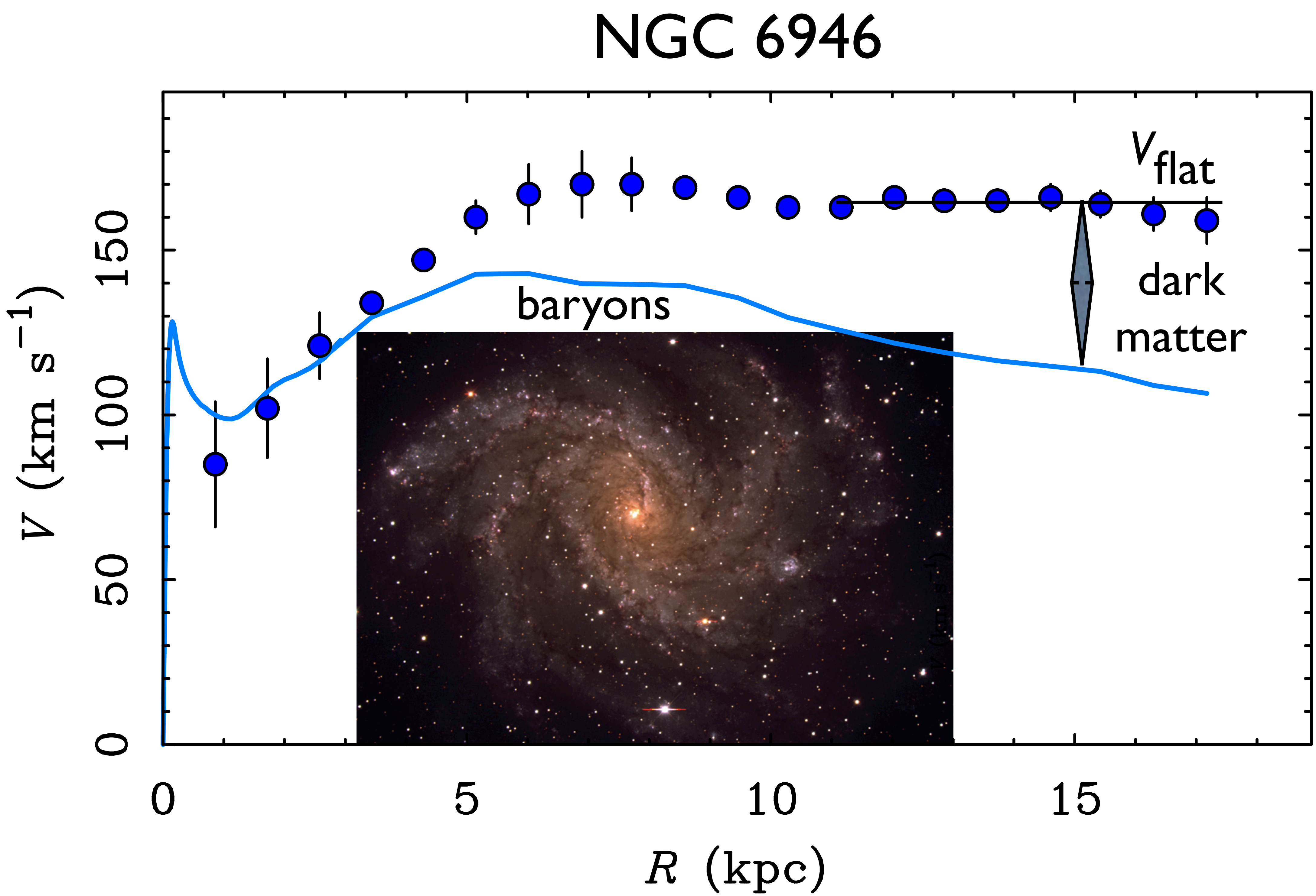


WIMPs are hiding



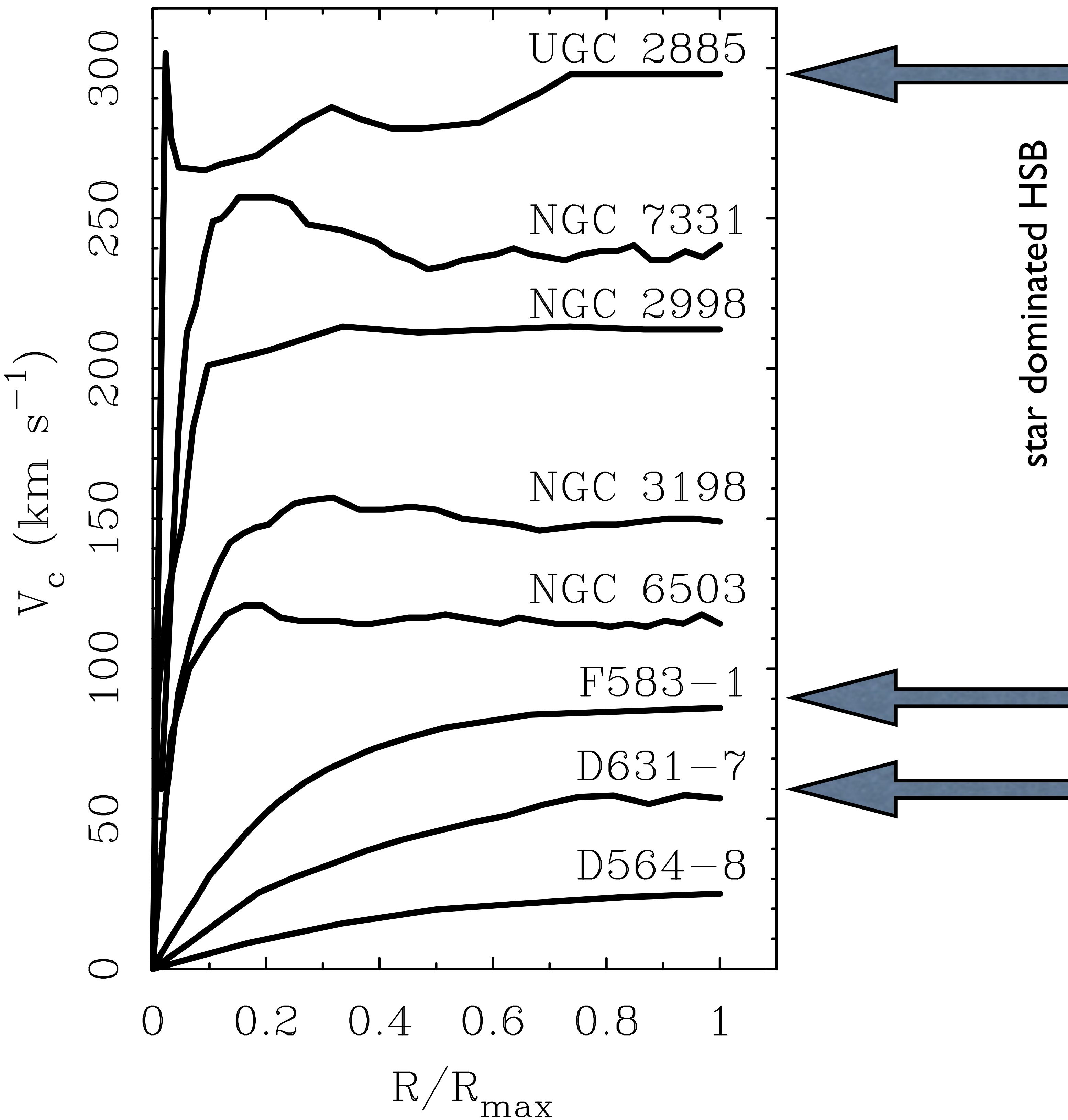
WIMP detection experiments

The mass discrepancy in galaxies appears at a universal acceleration scale



Solve Poisson equation numerically to obtain V(r) for observed baryon distribution

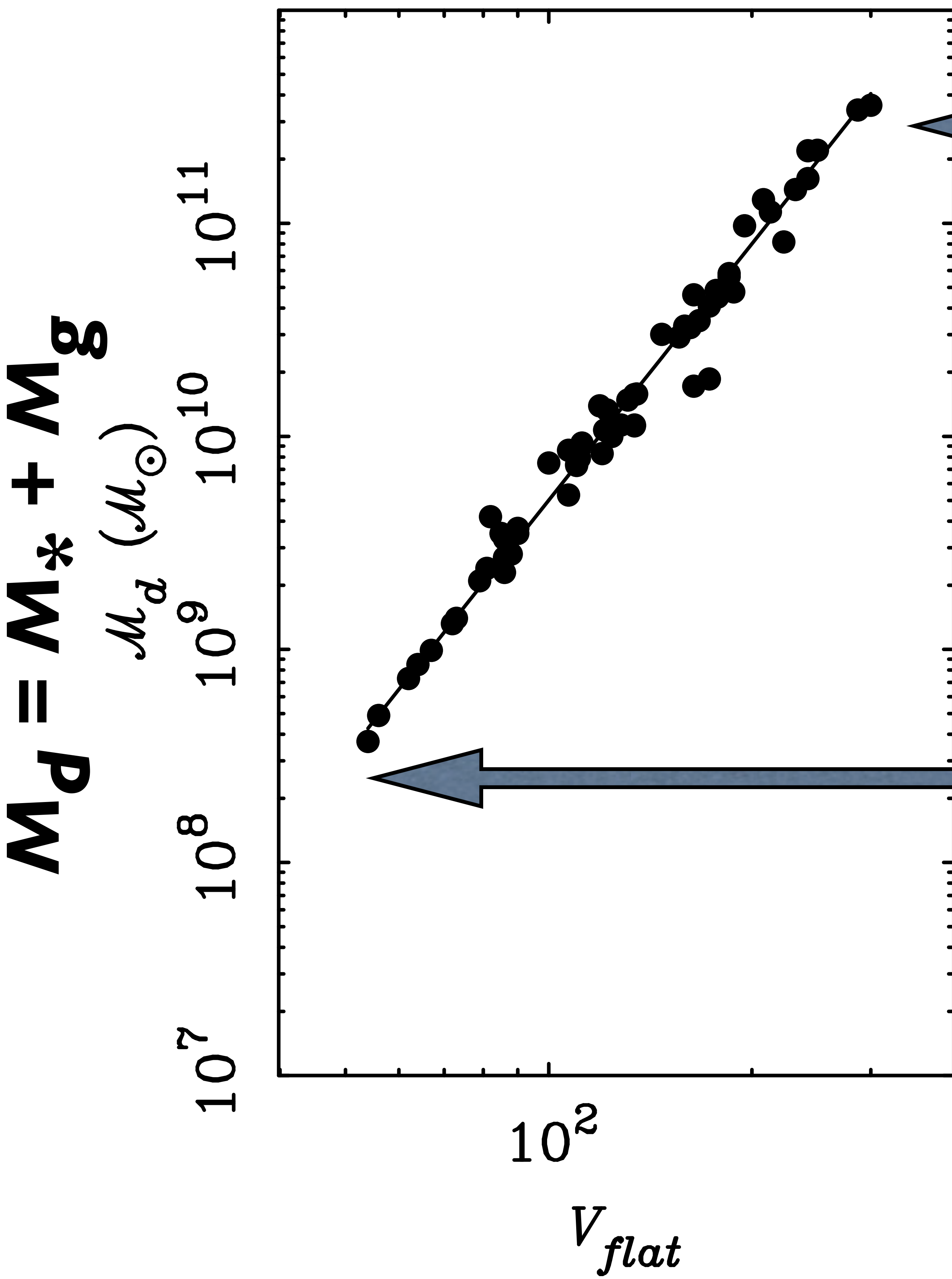
Flat rotation curves

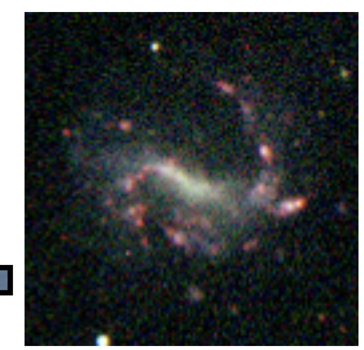


star dominated HSB

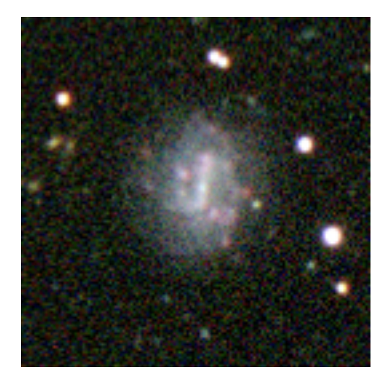
gas dominated LSBs

Tully-Fisher Relation

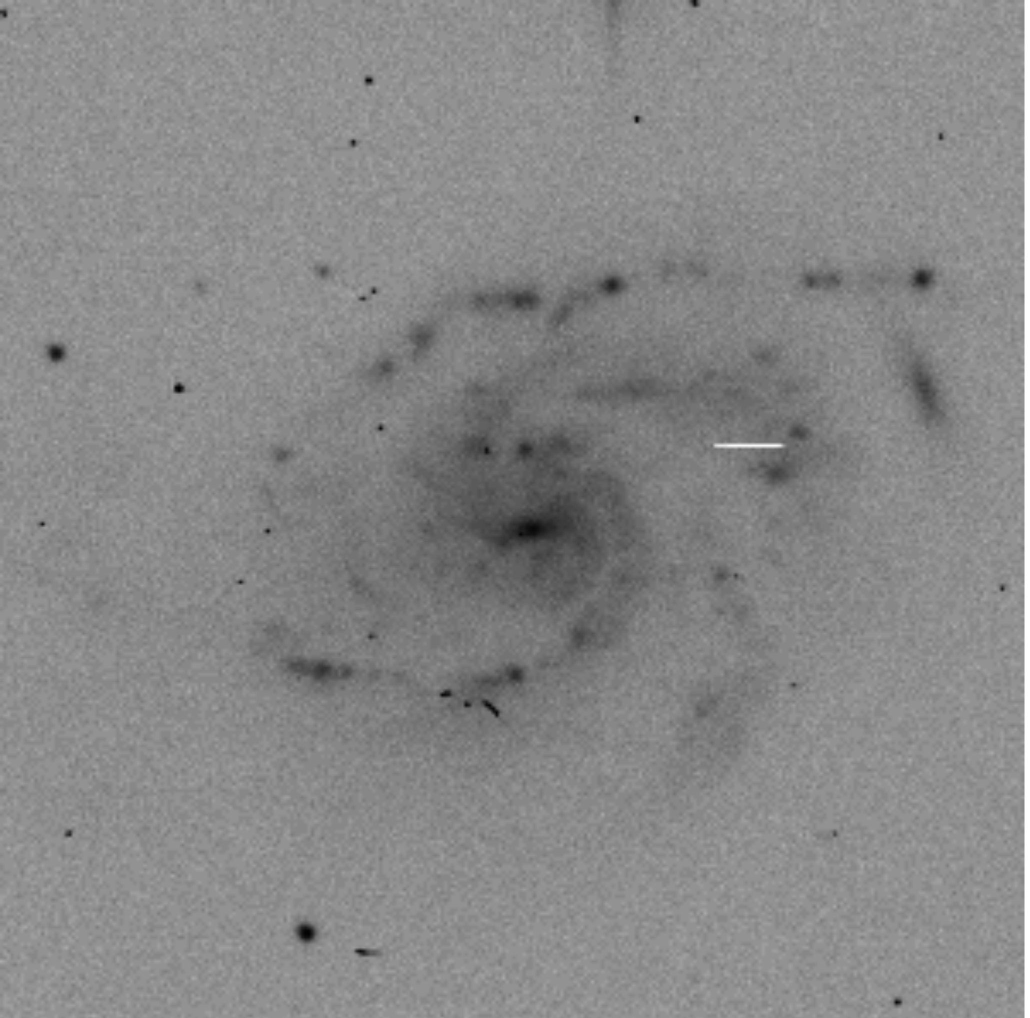




Big galaxies rotate fast

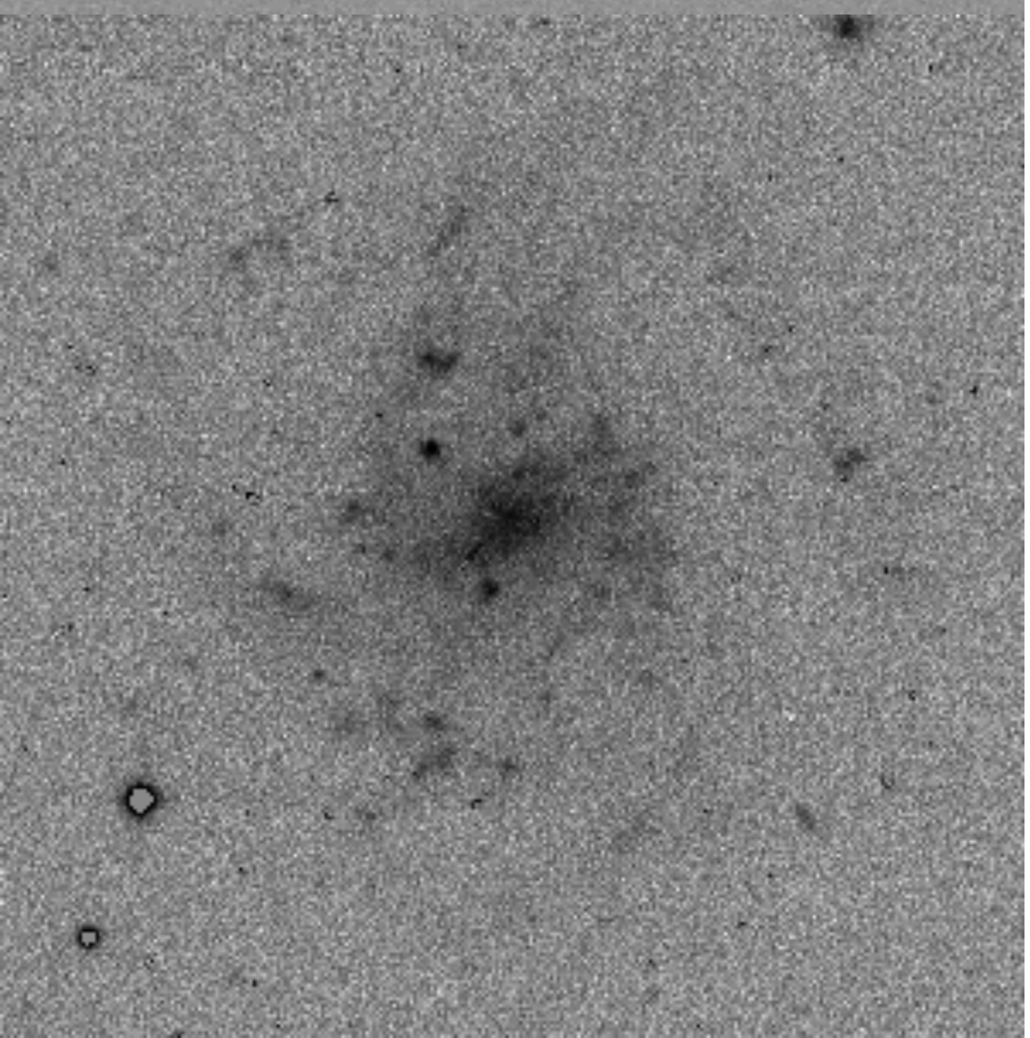


Small galaxies rotate slowly



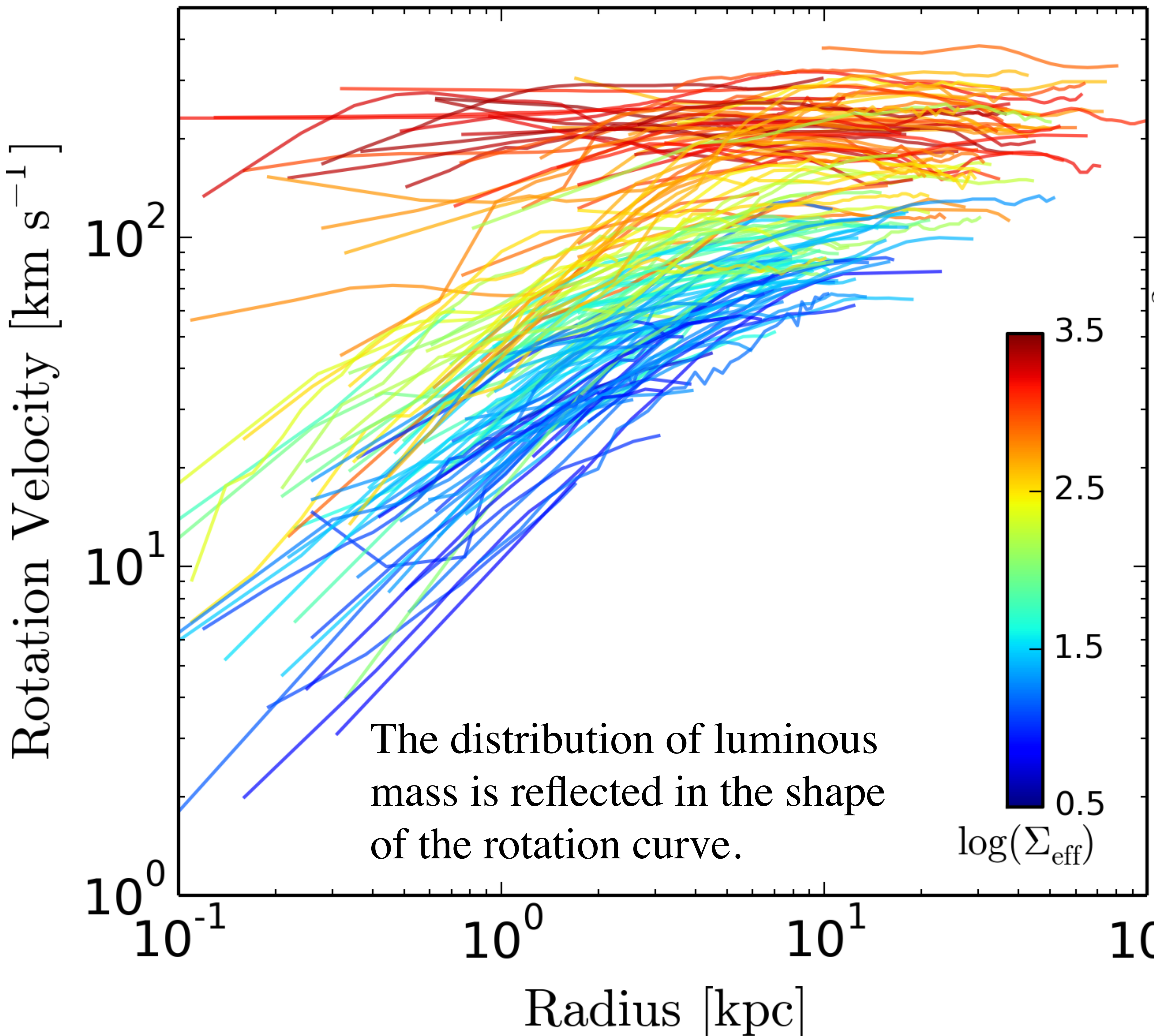
Some galaxies are

High Surface Brightness (HSB)

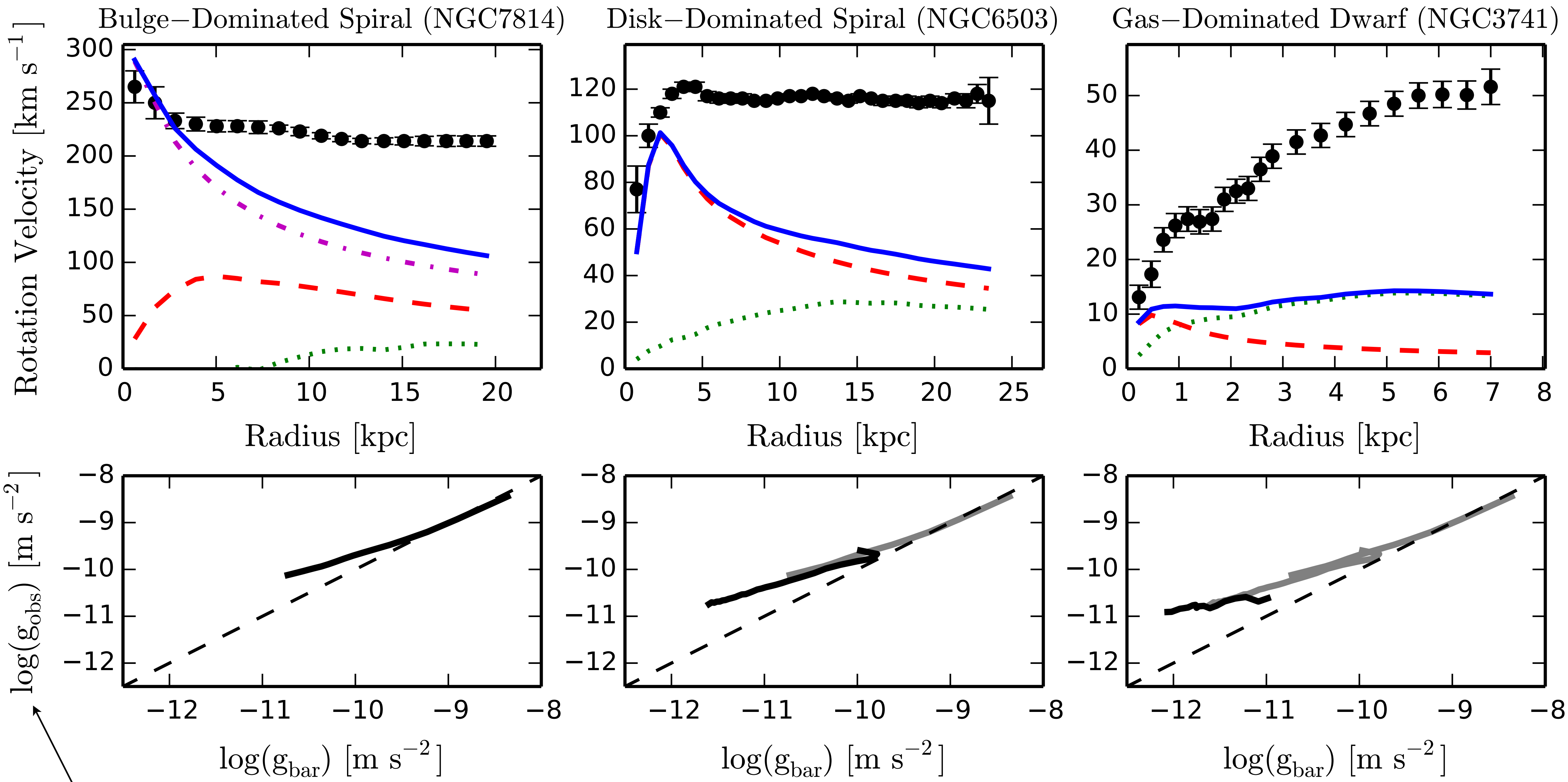


Others are

Low Surface Brightness (LSB)



Rotation Velocity [km s^{-1}]
10^2
10^1
10^0
10^{-1}
10^0
10^1
Radius [kpc]
3.5
2.5
1.5
0.5
log(Σ_{eff})
The distribution of luminous mass is reflected in the shape of the rotation curve.



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

independent quantities

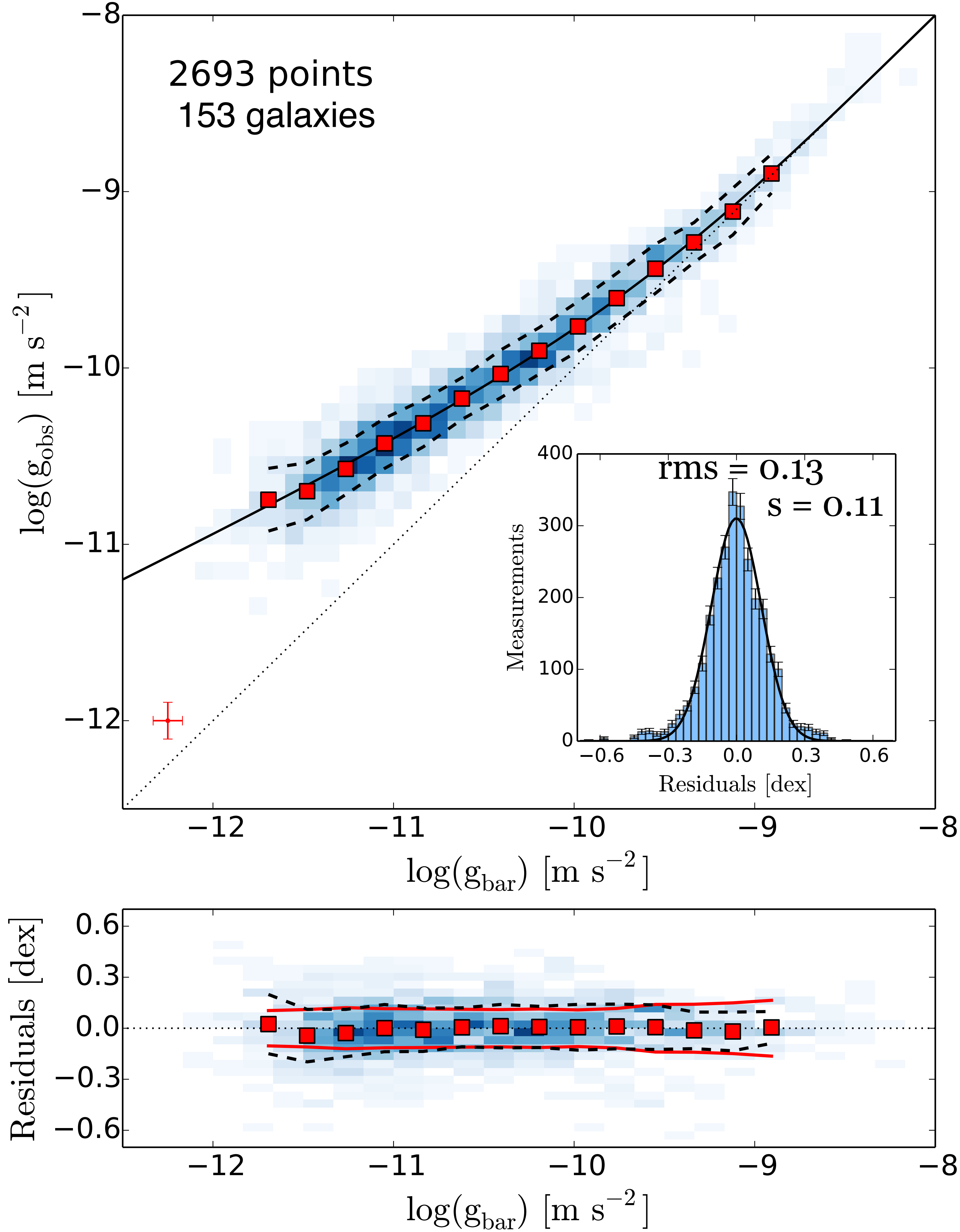
$$g_{\rm bar} = \left|\frac{\partial \Phi}{\partial R}\right|$$

acceleration from rotation curve

acceleration from baryon distribution

All galaxies obey the same

Radial Acceleration Relation



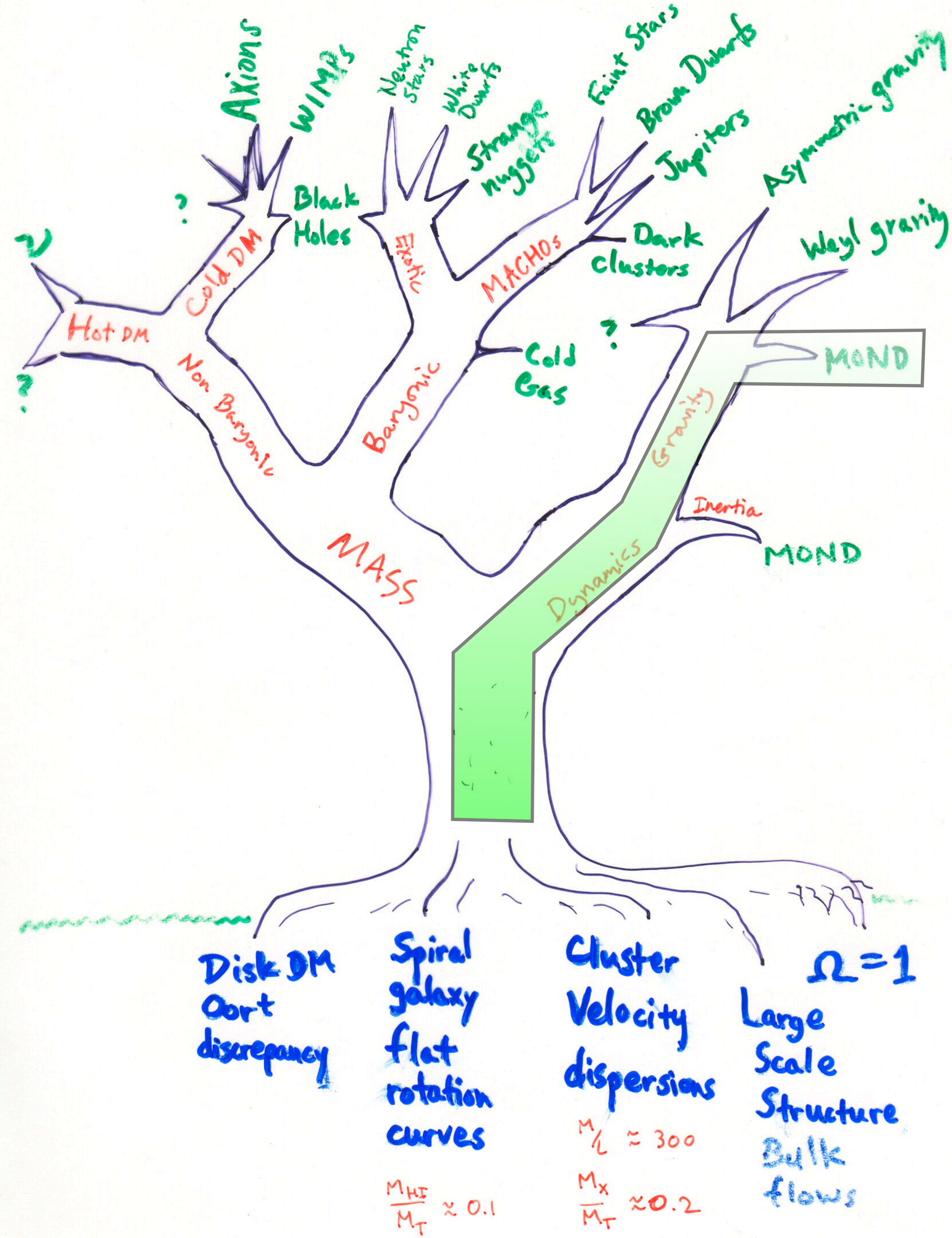
The tail of normal matter wags the dark matter dog

critical acceleration scale

10^{-10} m/s/s

This behavior was predicted by a theory called MOND invented by Moti Milgrom

This theory modifies gravity instead of invoking dark matter.



MOND

MOdified Newtonian Dynamics

introduced by Moti Milgrom in 1983

instead of dark matter, suppose the force law changes such that

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

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

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
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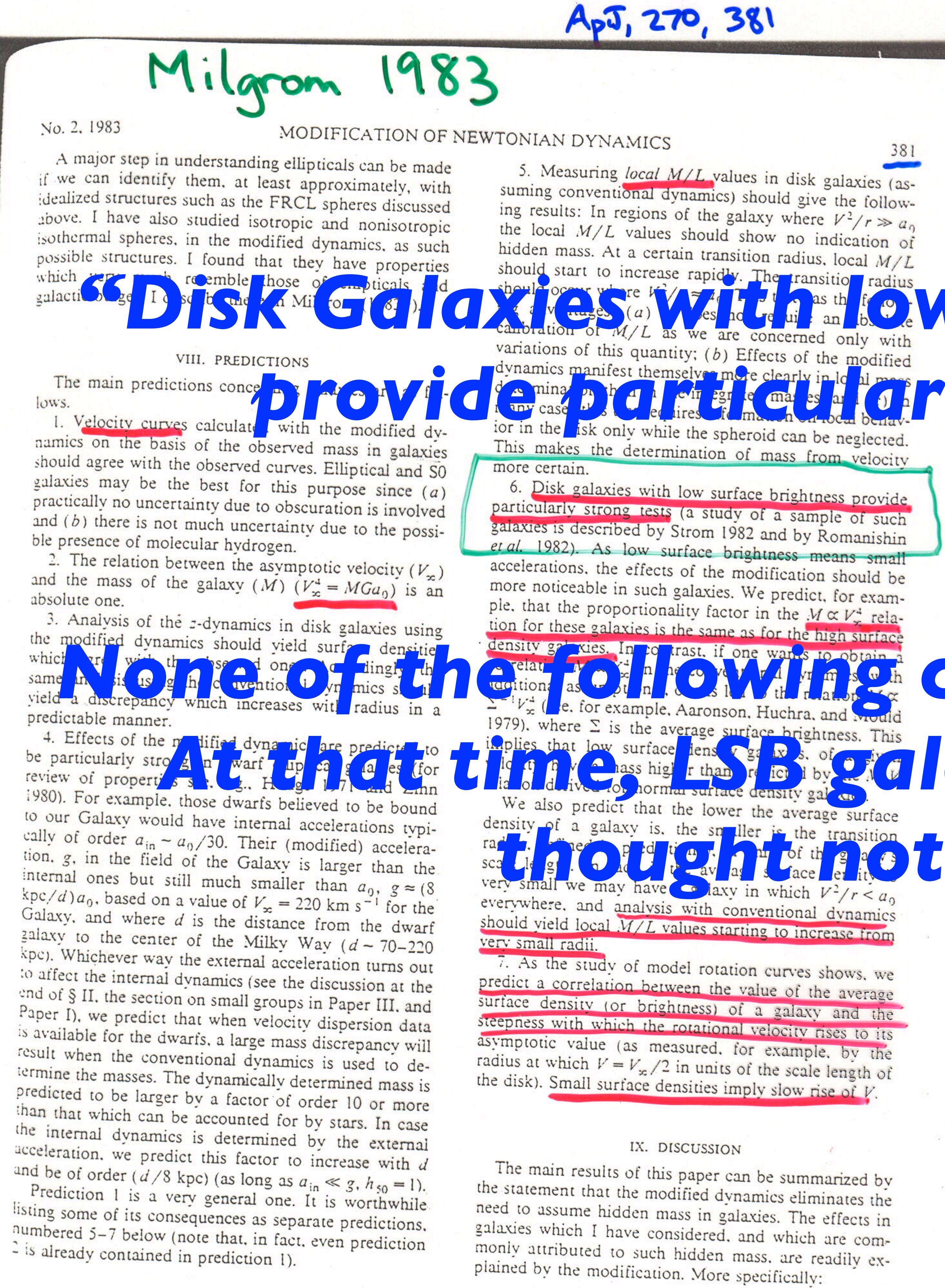
- Stellar Population Mass-to-Light Ratios

"Disk Galaxies with low surface brightness provide particularly strong tests"

None of the following data existed in 1983. At that time, LSB galaxies were widely thought not to exist.



No. 2, 1983 MODIFICATION OF NEWTONIAN DYNAMICS 381

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 [illegible] resemble those of ellipticals [illegible] galacti[c] [illegible] Mi[illegible]

VIII. PREDICTIONS

The main predictions conce[illegible] lows.

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 surf[ace] densitie[s] which [illegible] same [illegible] yield a discrepancy which increases with radius in a predictable manner.

4. Effects of the m[o]dified dyna[mics are] predic[ted] to be particularly stro[ng] [illegible] review of propert[ies] [illegible] 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, $g \approx (8\ \text{kpc}/d)a_0$, based on a value of $V_\infty = 220$ 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 is determined by the external acceleration, we predict this factor to increase with d and be of order (d/8 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 5–7 below (note that, in fact, even prediction 2 is already contained in prediction 1).

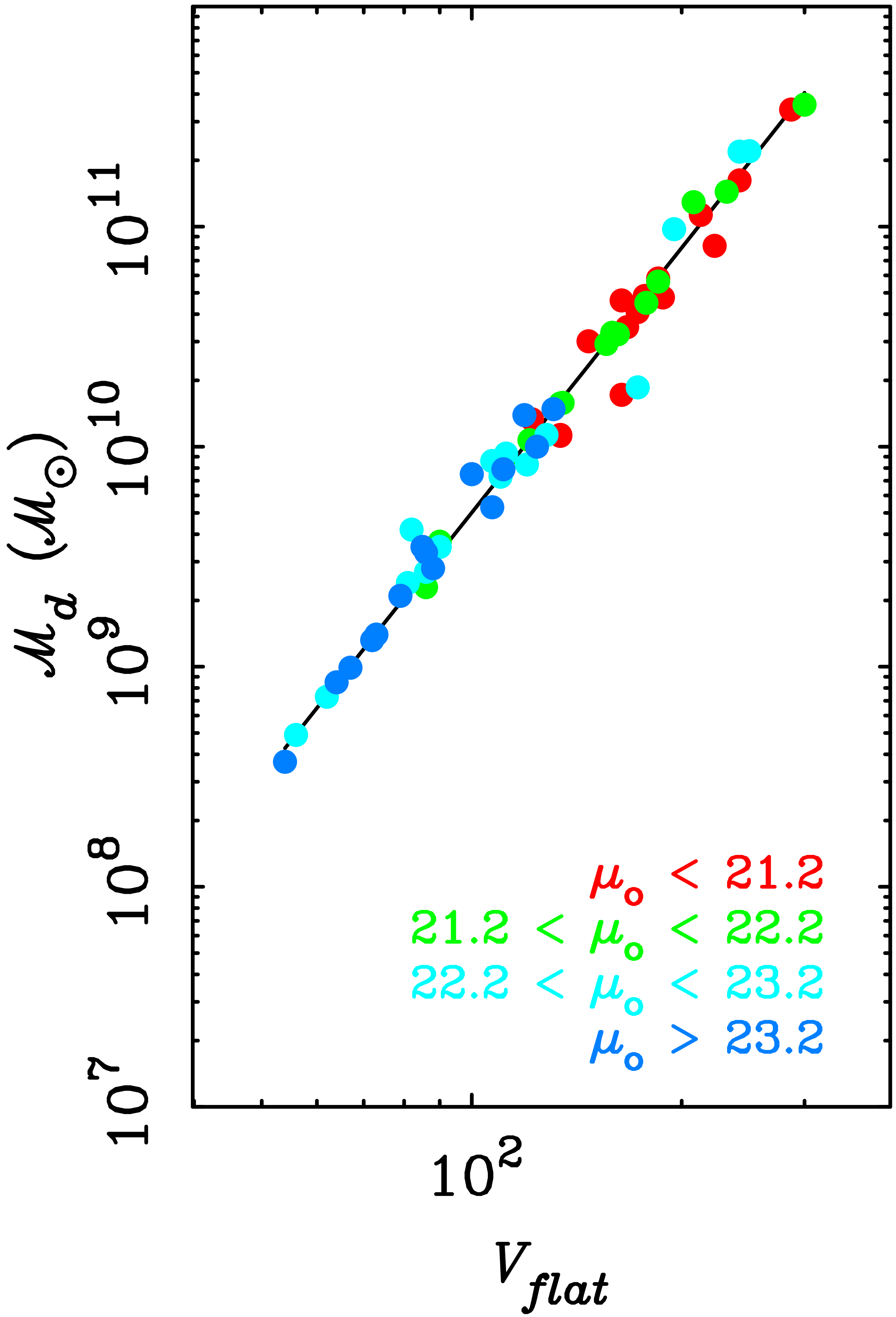
5. Measuring *local M/L* values in disk galaxies (assuming conventional dynamics) should give the following results: In regions of the galaxy where $V^2/r \gg a_0$ the local M/L values should show no indication of hidden mass. At a certain transition radius, local M/L should start to increase rapidly. The transition radius should occur where $V^2/$[illegible] (*a*) [illegible] 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 de[termination] [illegible] many case[s] [illegible] ior 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 relat[ion] [illegible] additional [illegible] $\Sigma^{-1}V_\infty^4$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that low surface dens[ity] [illegible] mass hig[her] [illegible] normal surface density gal[axies]. We also predict that the lower the average surface density of a galaxy is, the smaller is the transition [illegible] very small we may have [a gal]axy 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.

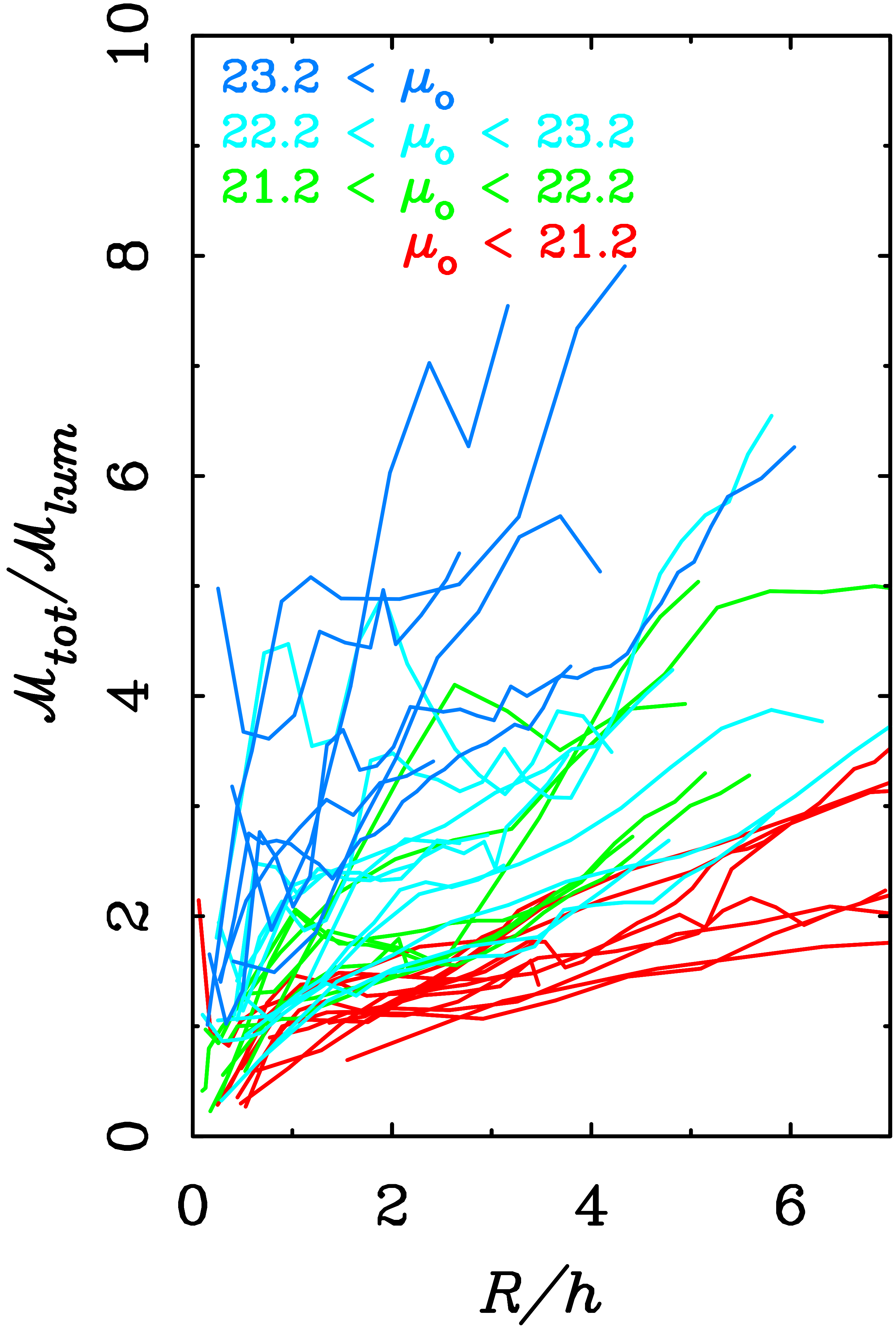
IX. DISCUSSION

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:



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



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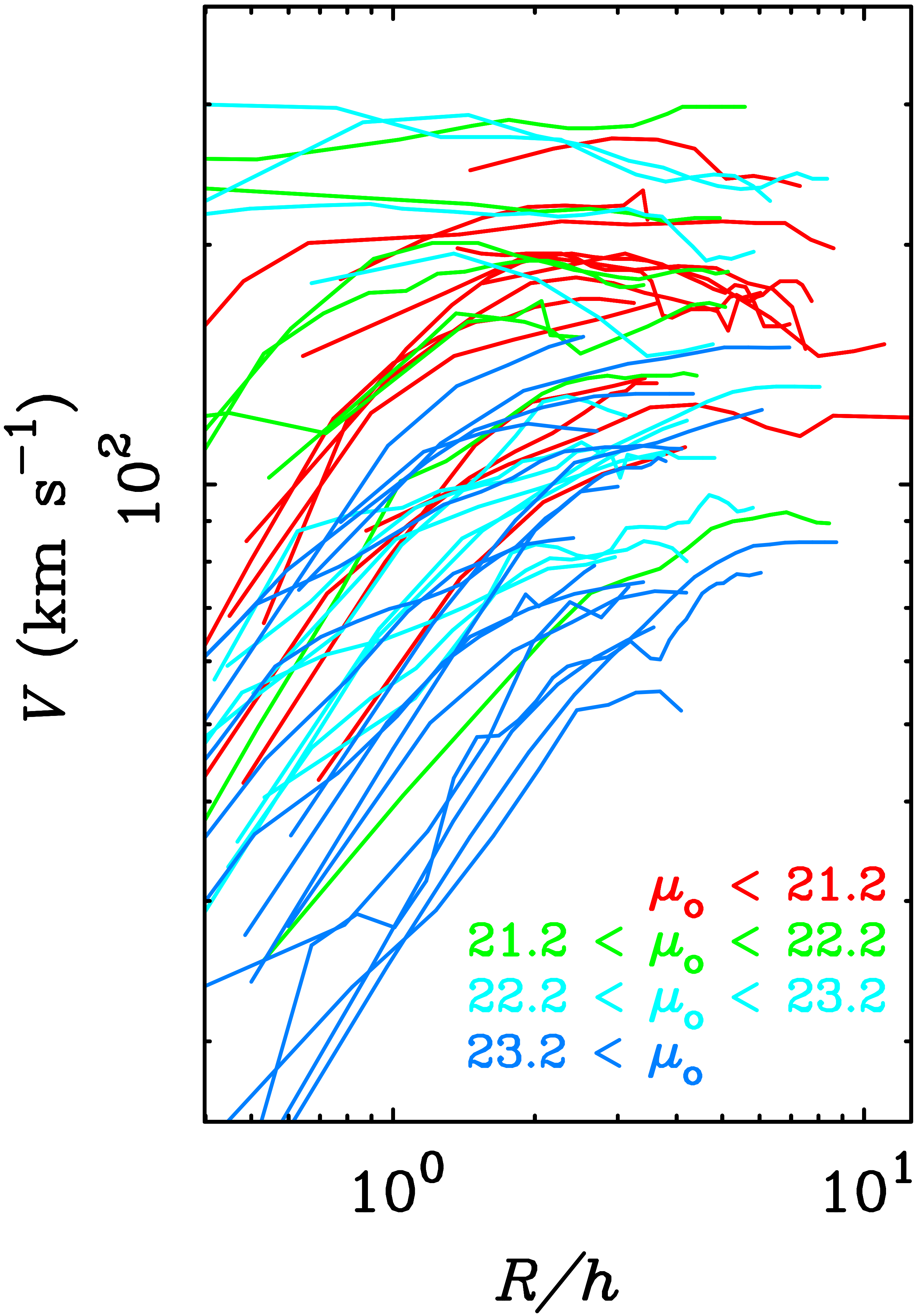

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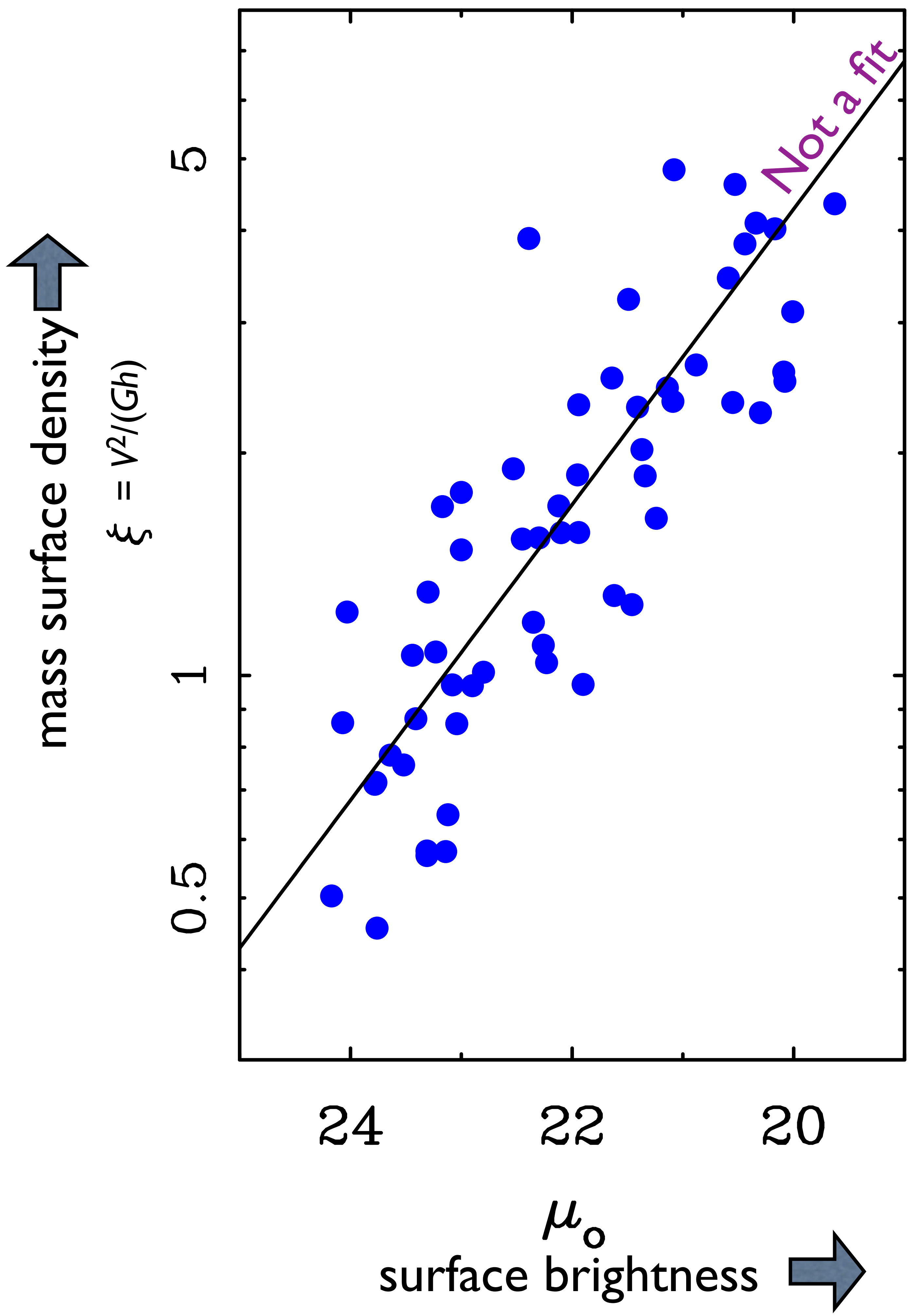

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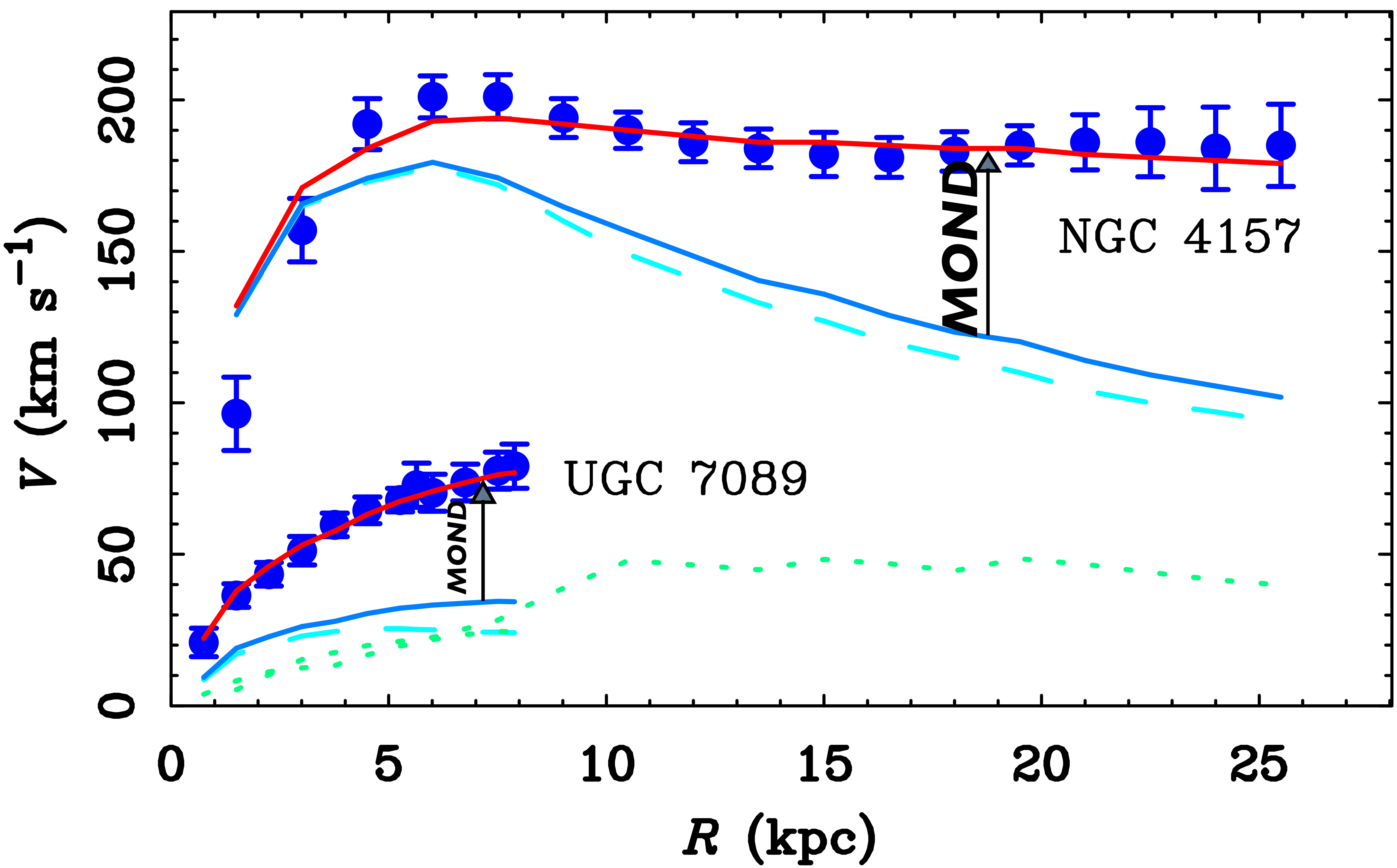
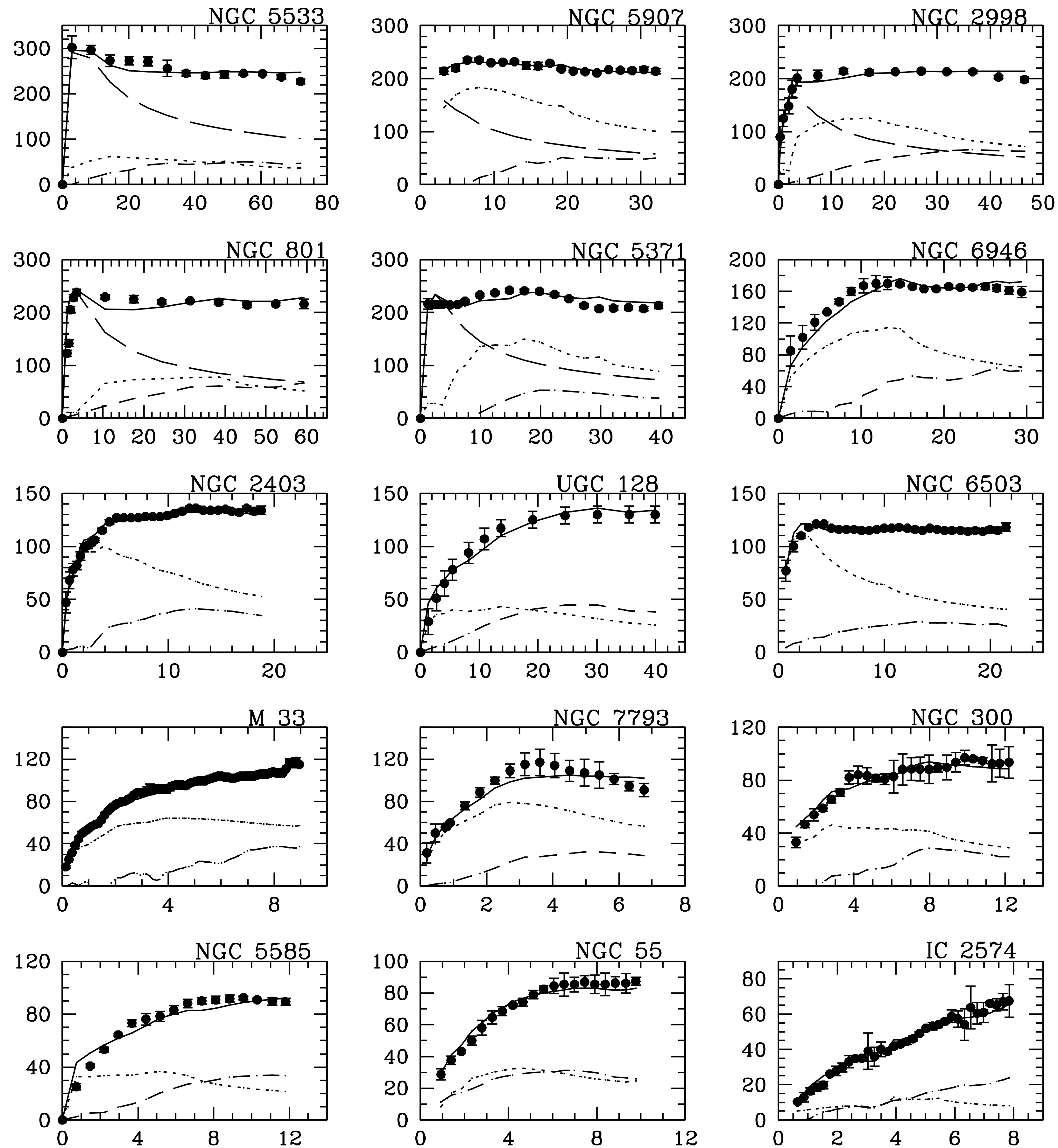
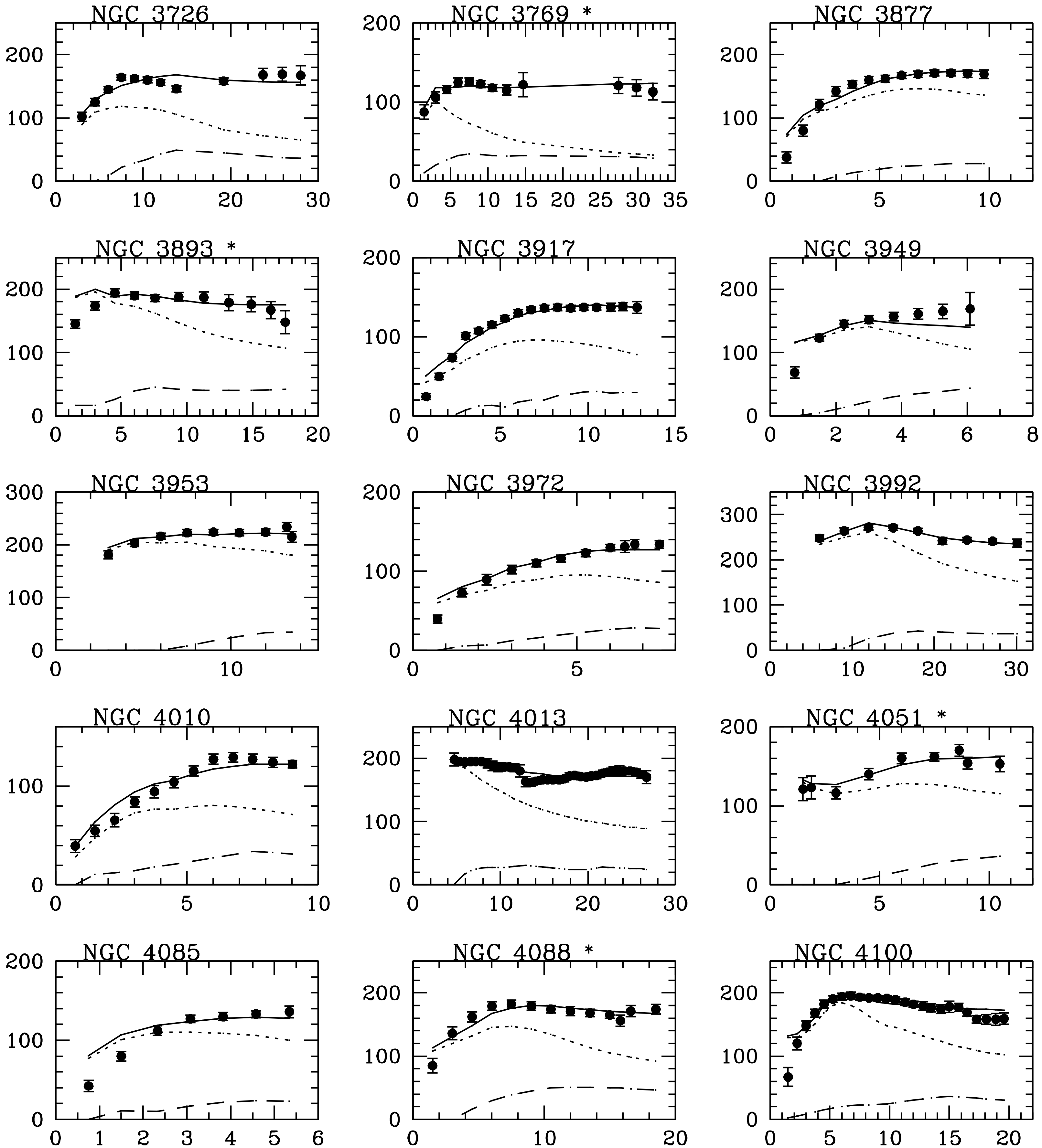

V (km s^{-1})
R (kpc)
NGC 4157
UGC 7089
MOND
MOND
0
50
100
150
200
0
5
10
15
20
25

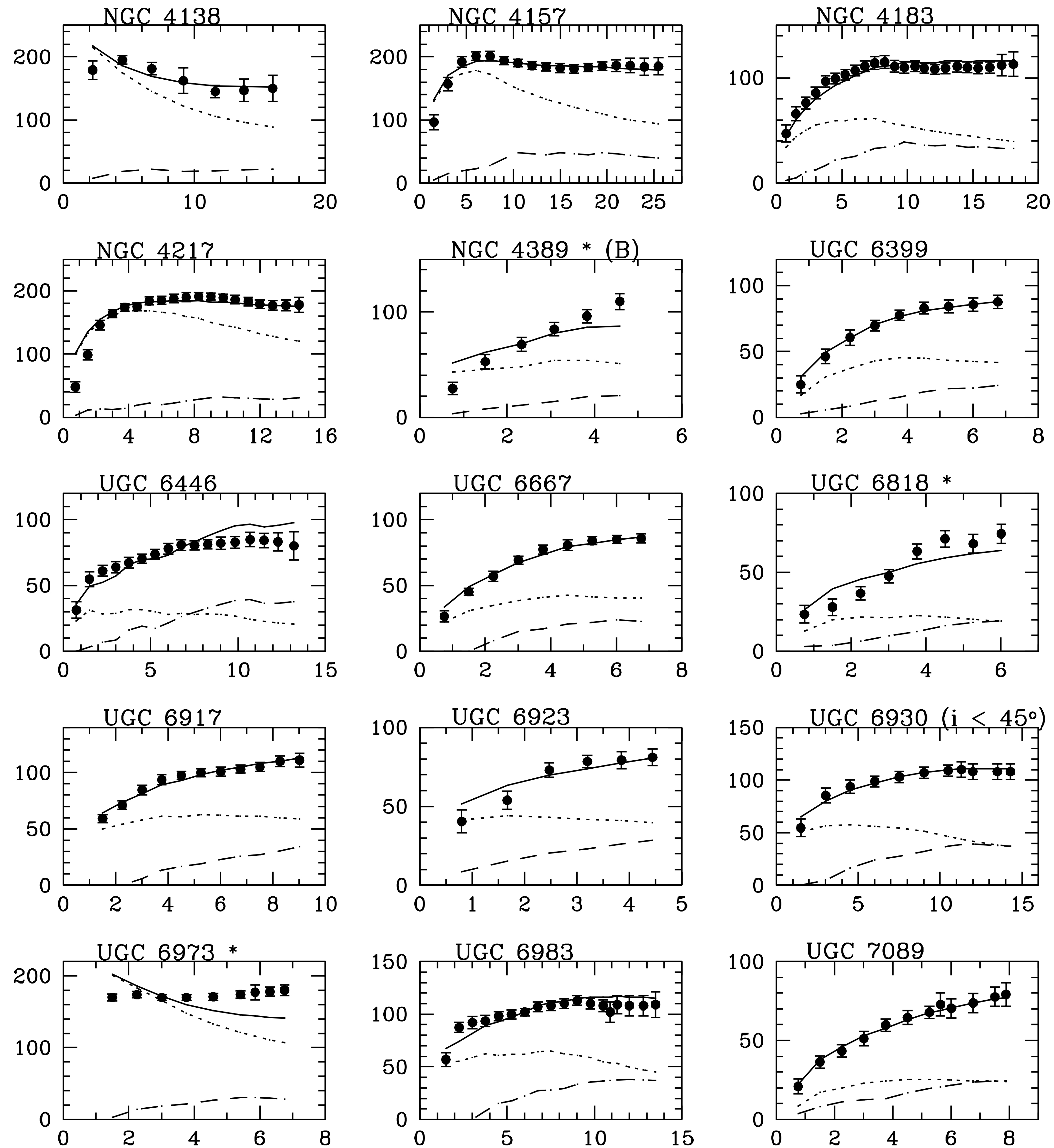


Sanders & McGaugh 2002, *ARA&A*, **40**, 263

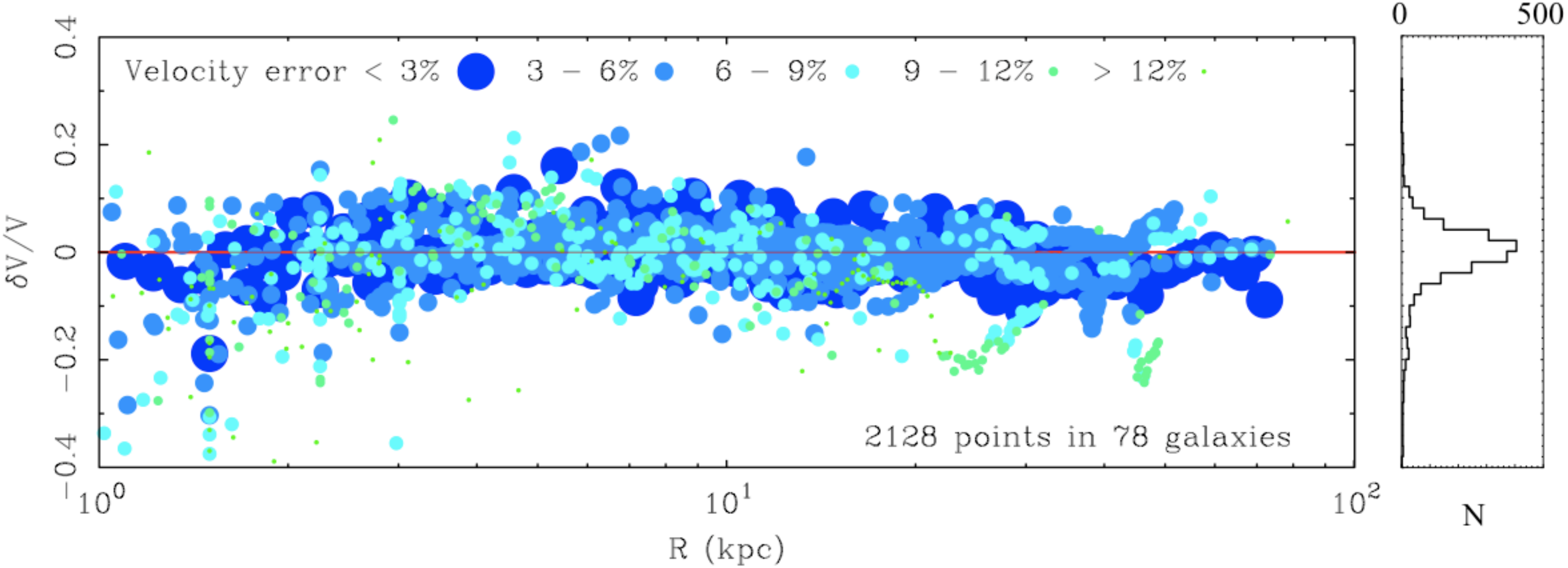
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



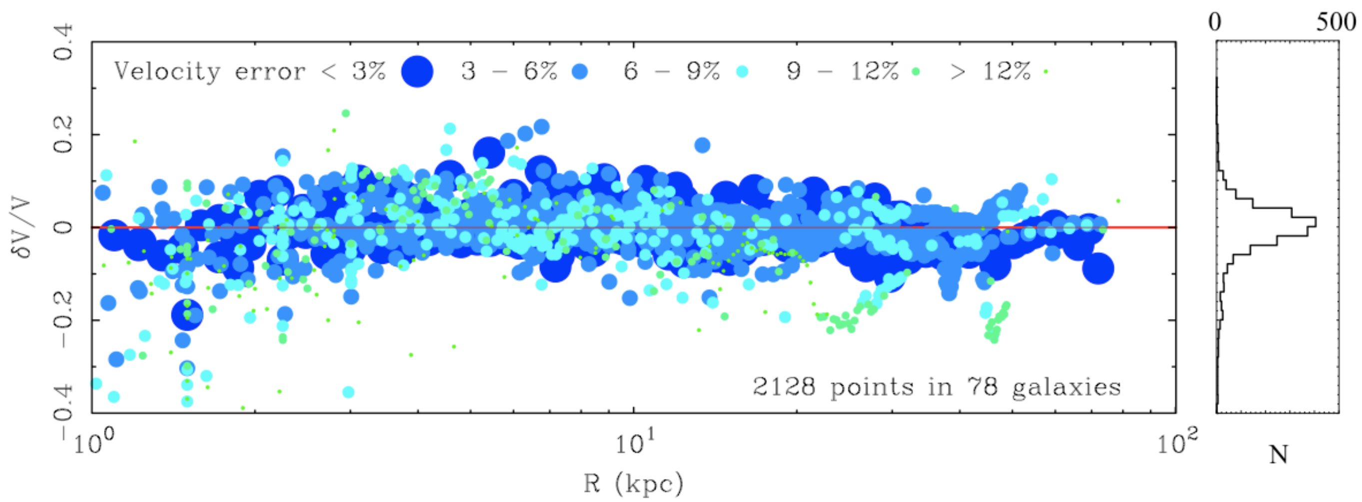
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



Residuals of MOND fits



MOND predictions



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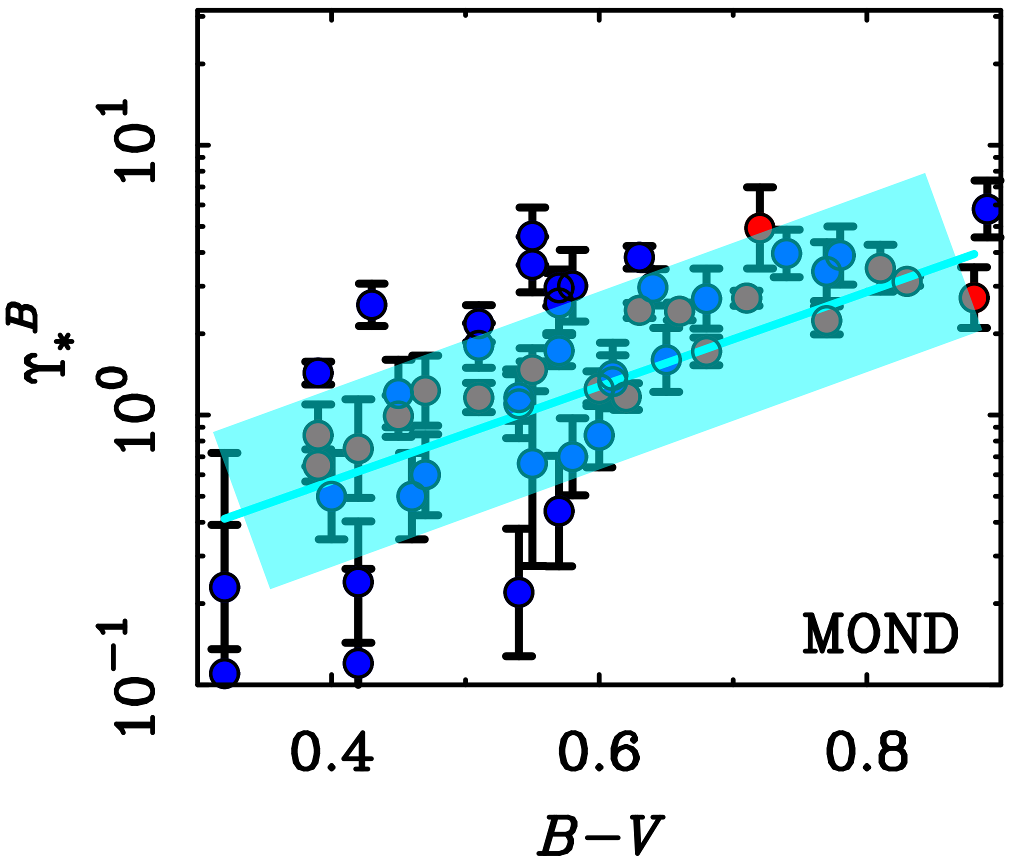
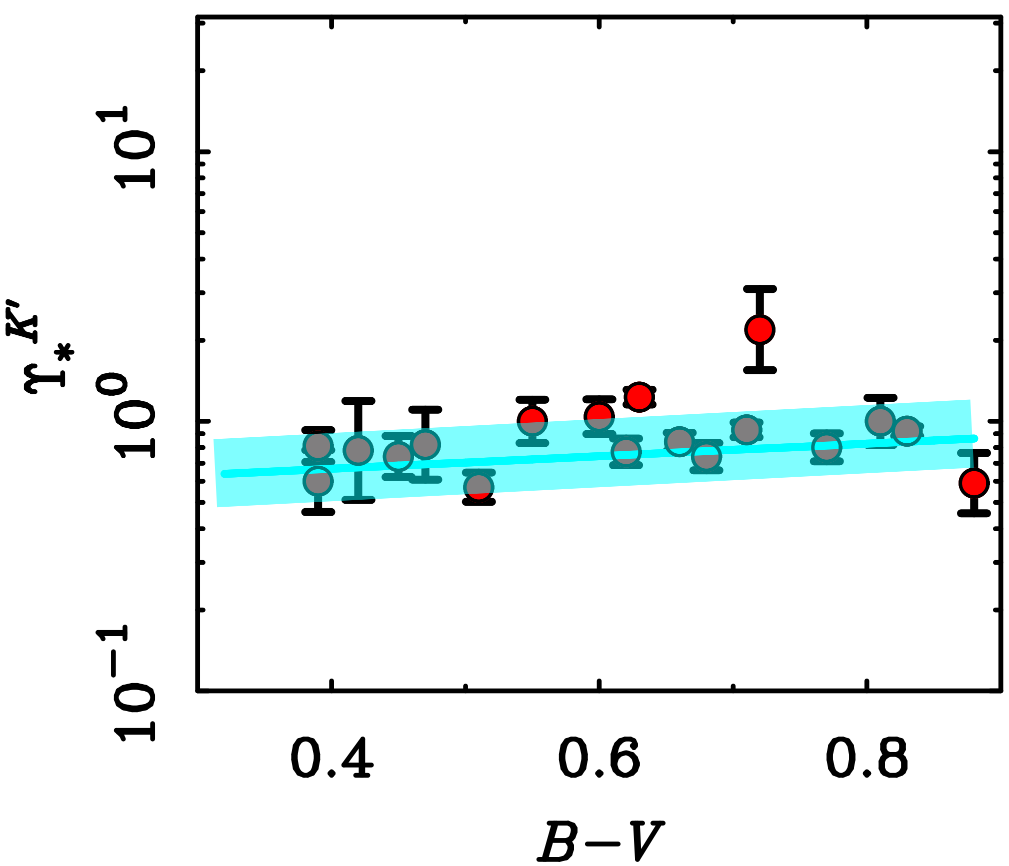
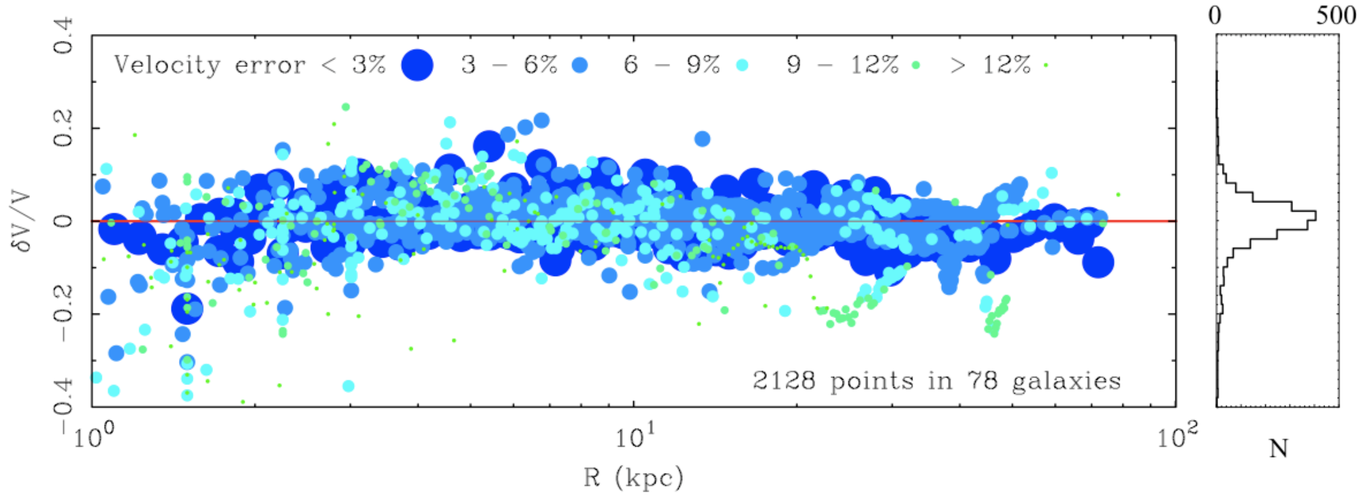
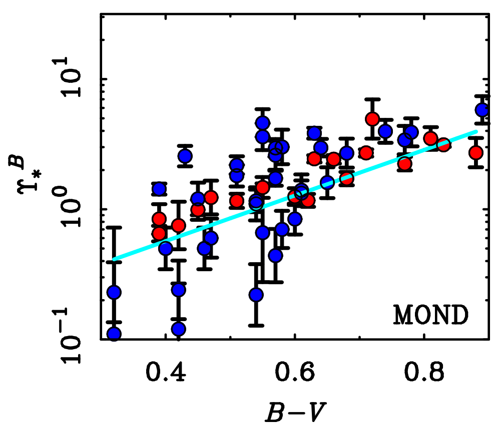


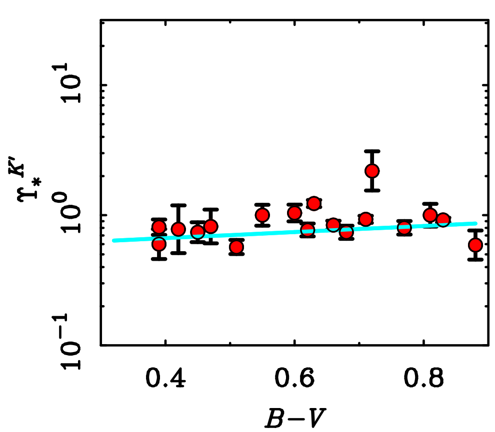
Line: stellar population model
(mean expectation)



MOND predictions







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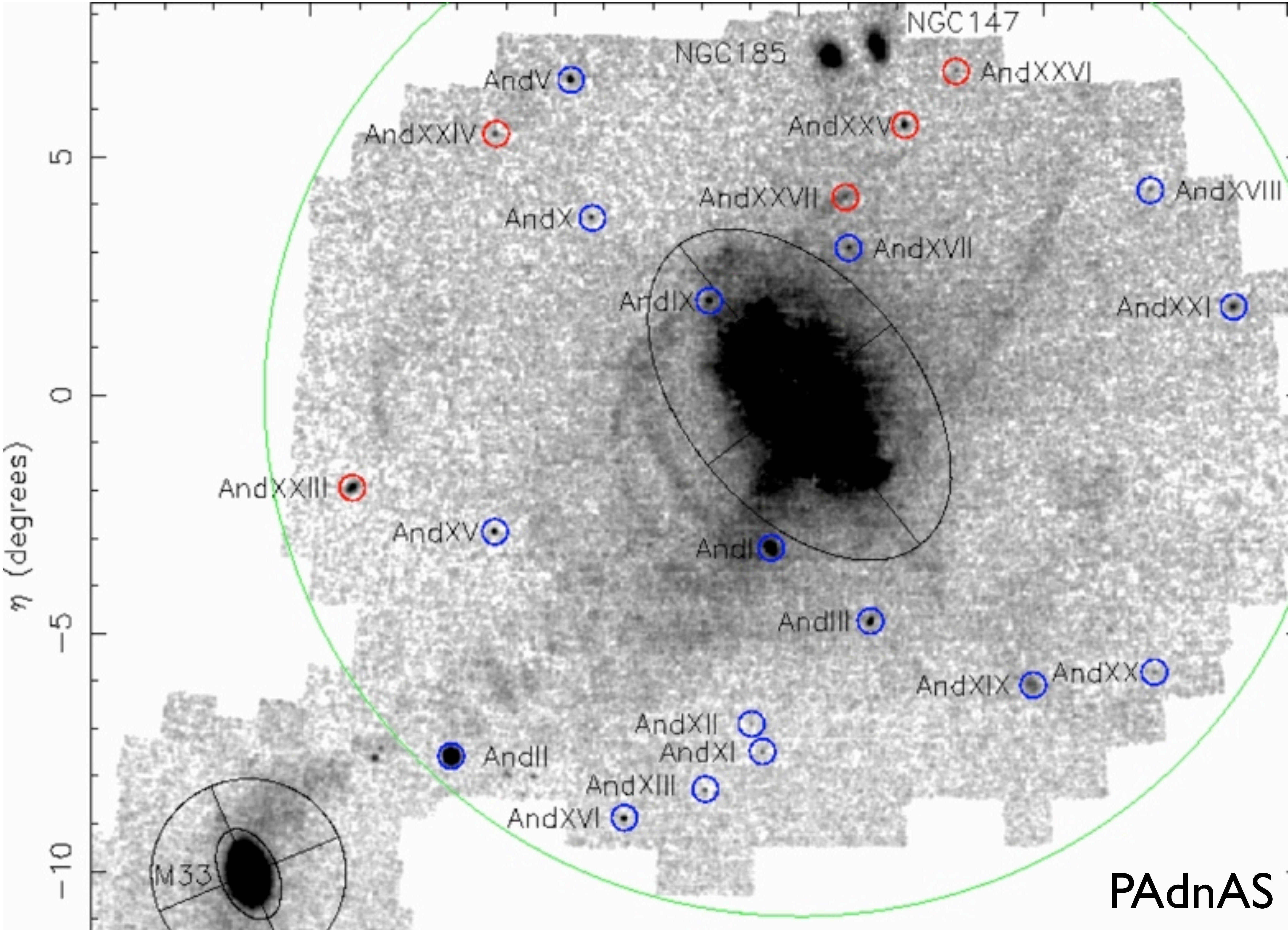
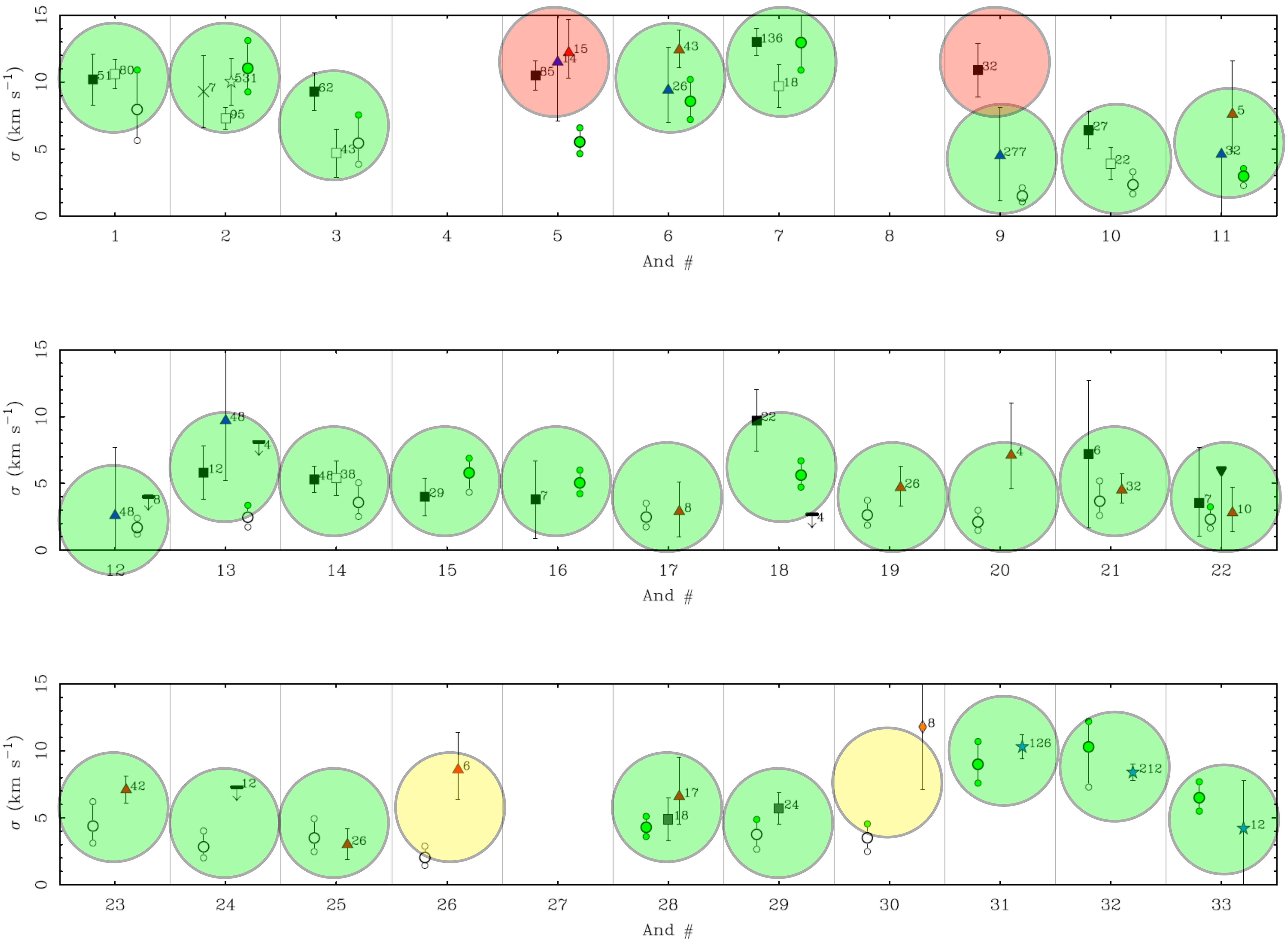
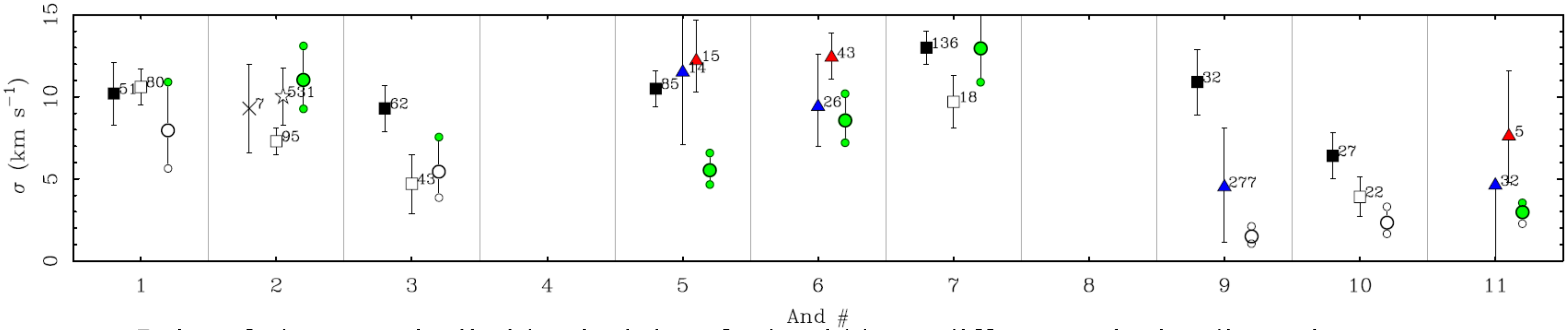
A new test: the dwarf satellites of Andromeda

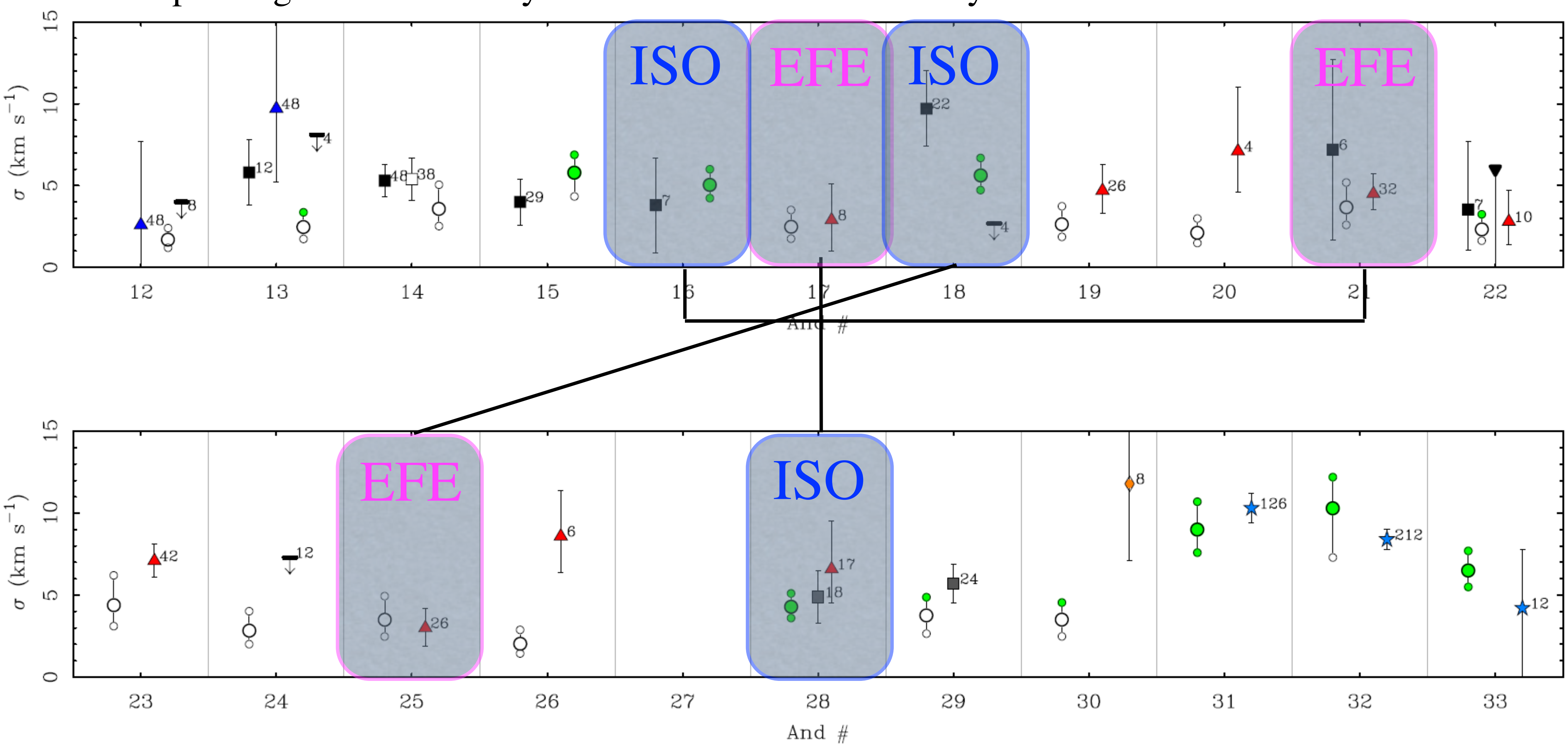




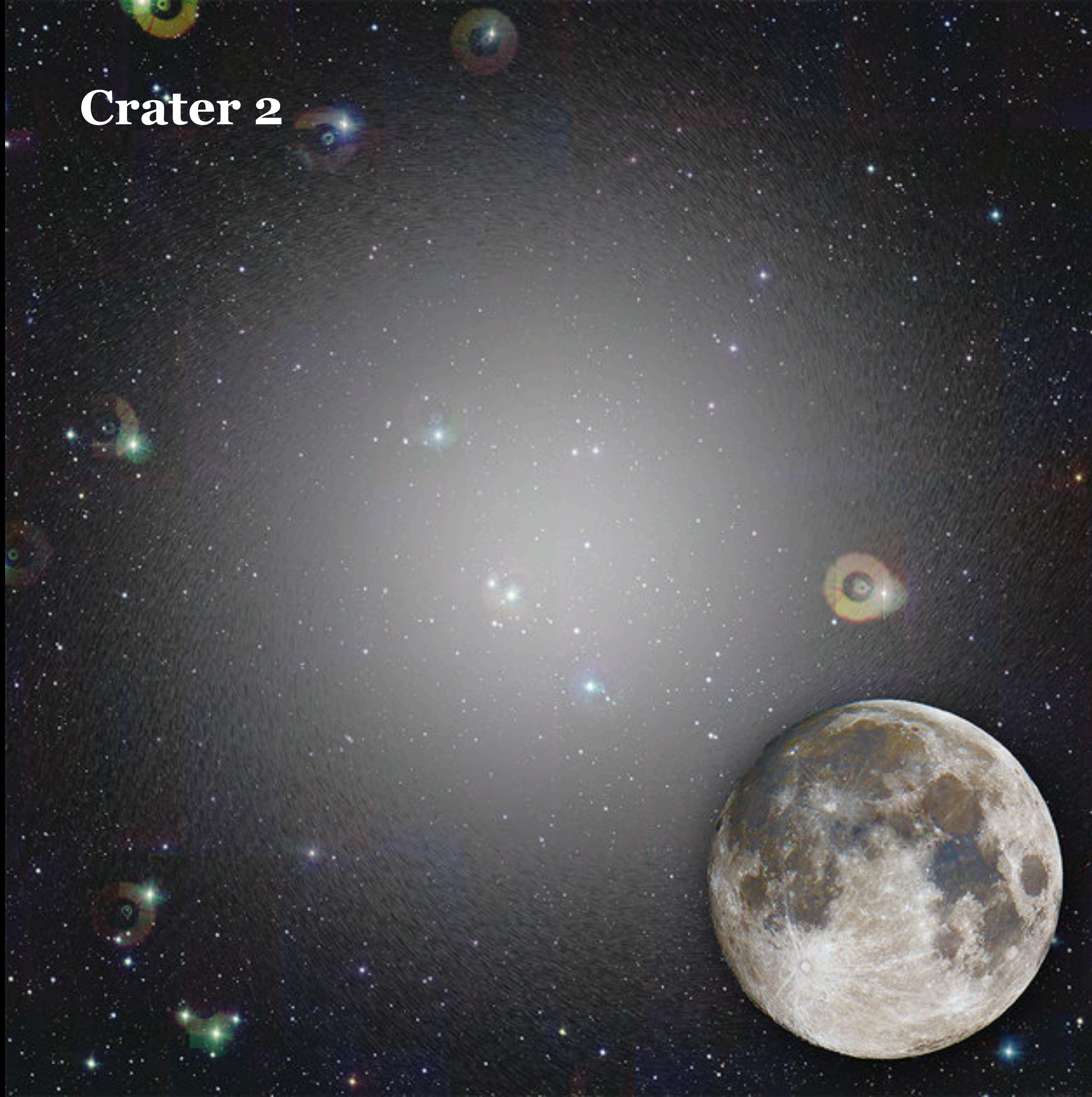
Velocity dispersions of M31 dwarfs correctly predicted (a priori in many cases) by MOND.



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.


Crater 2

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)
but makes no concrete prediction

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

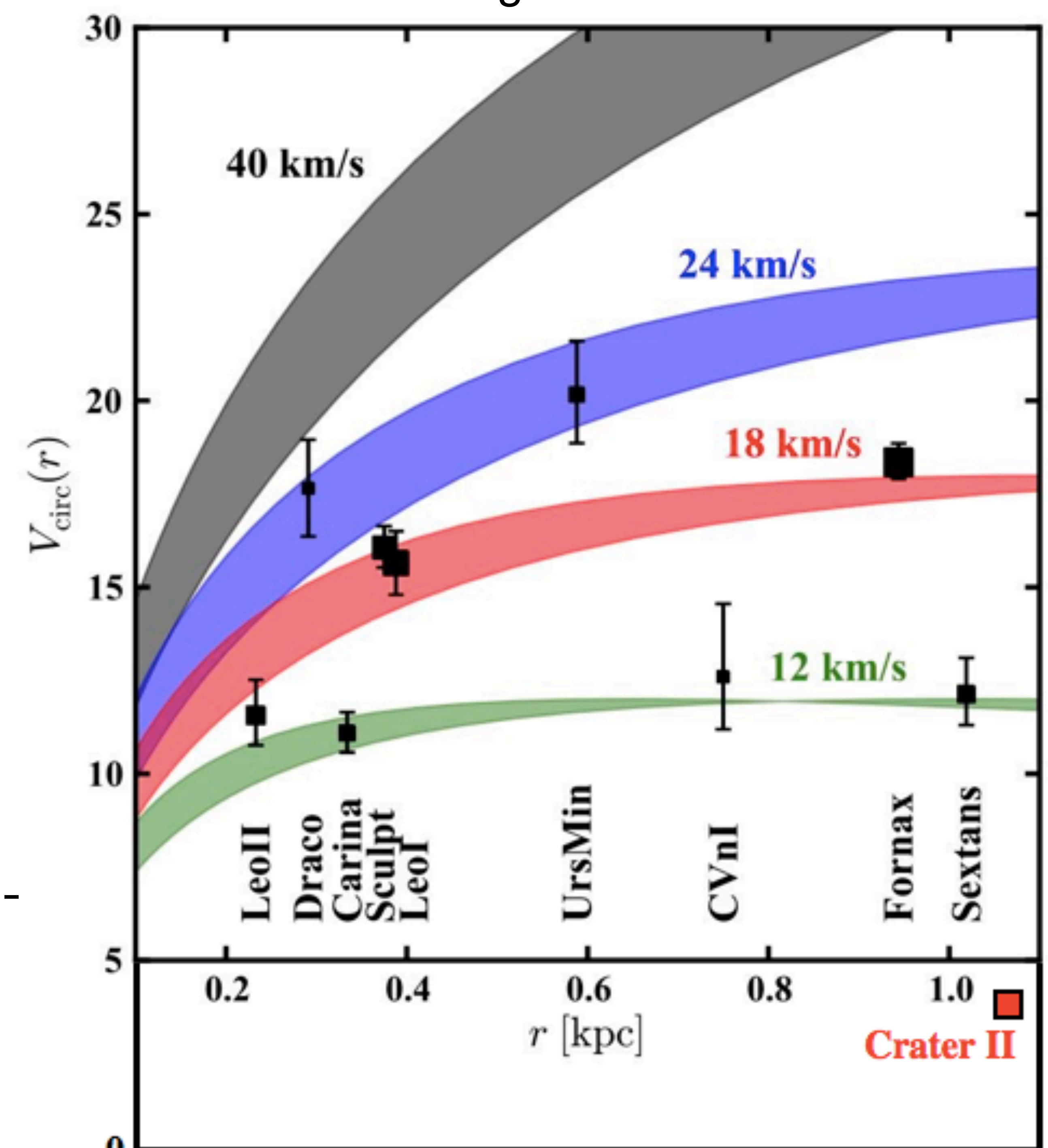
Subsequently observed: 2.7 ± 0.3 km/s
(Caldwell et al. 2017, ApJ, 839, 20)

Consistent with a priori MOND prediction

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

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

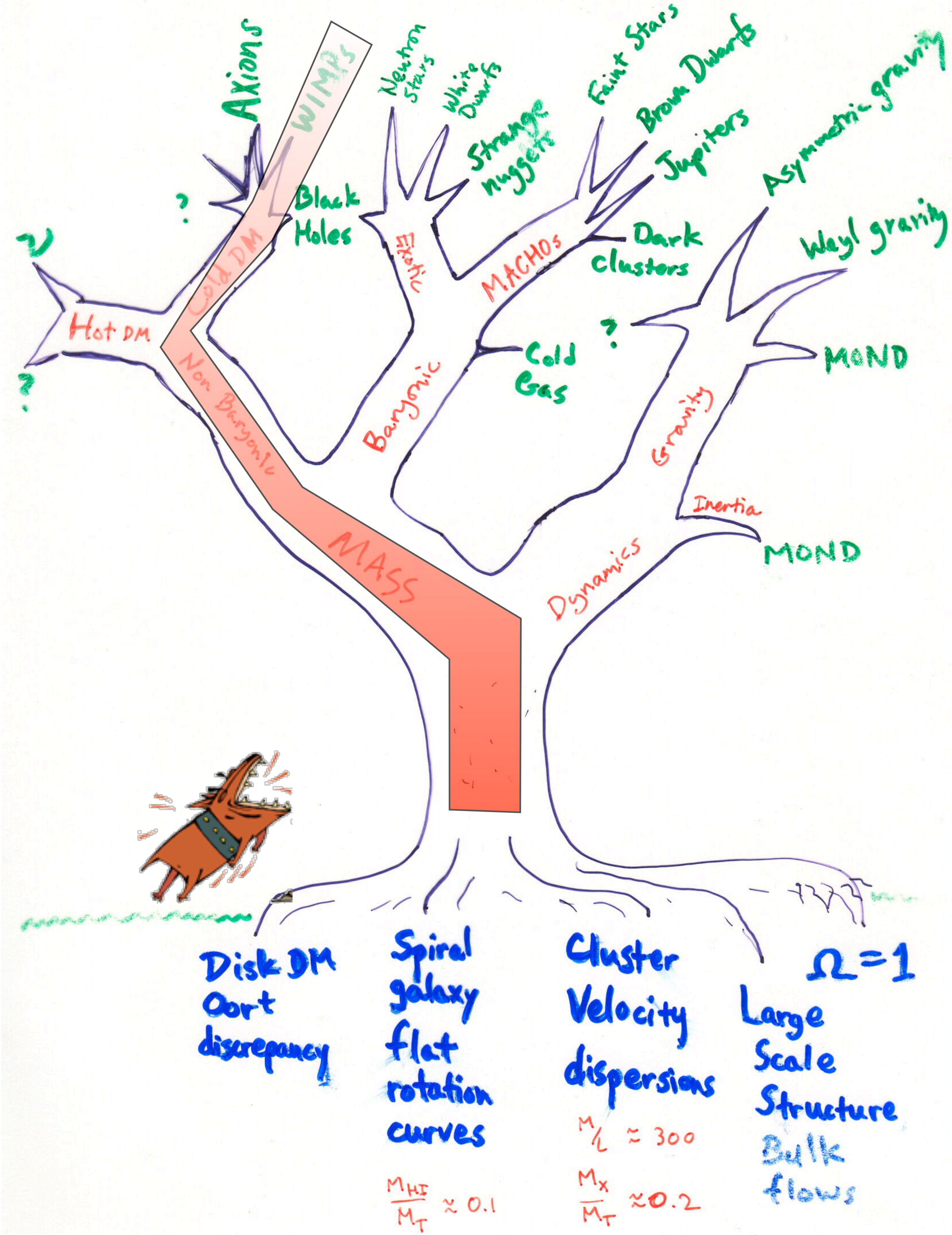
"Too Big To Fail"



Predictions made in advance of observation are the gold standard in science.
MOND has had *many* more successful *a priori* predictions than dark matter based theories.

Why does MOND get *any* prediction right?

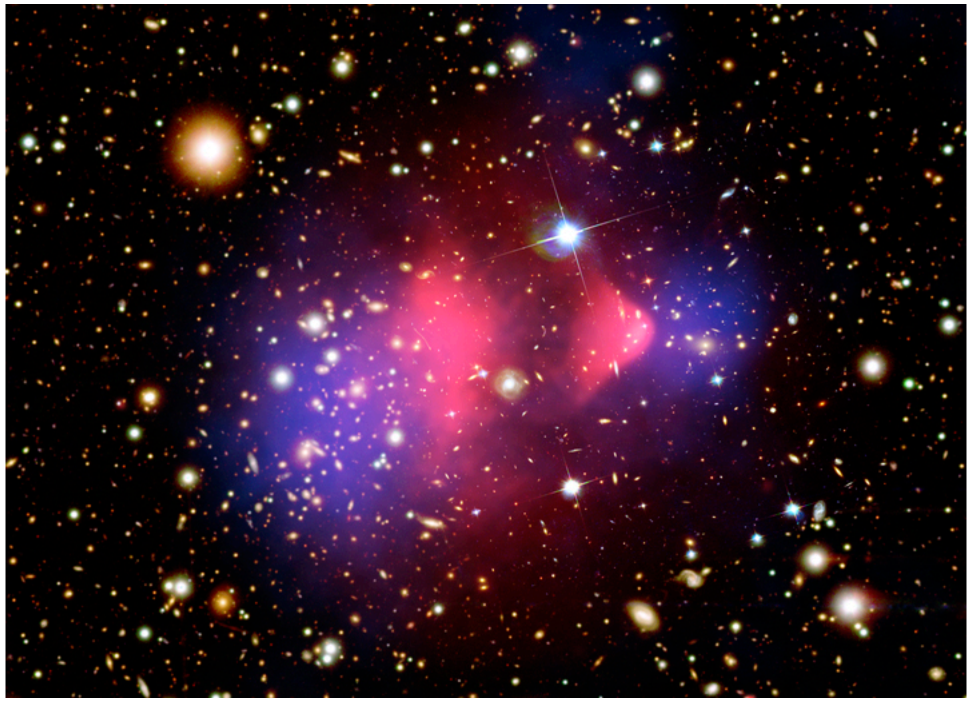
Have we been barking up the wrong side of the tree?



I find your lack of faith disturbing.

- You don’t know the Power of the Dark Side
- Can MOND explain large scale structure?
- Can it provide a satisfactory cosmology?
- Can it be reconciled with General Relativity?

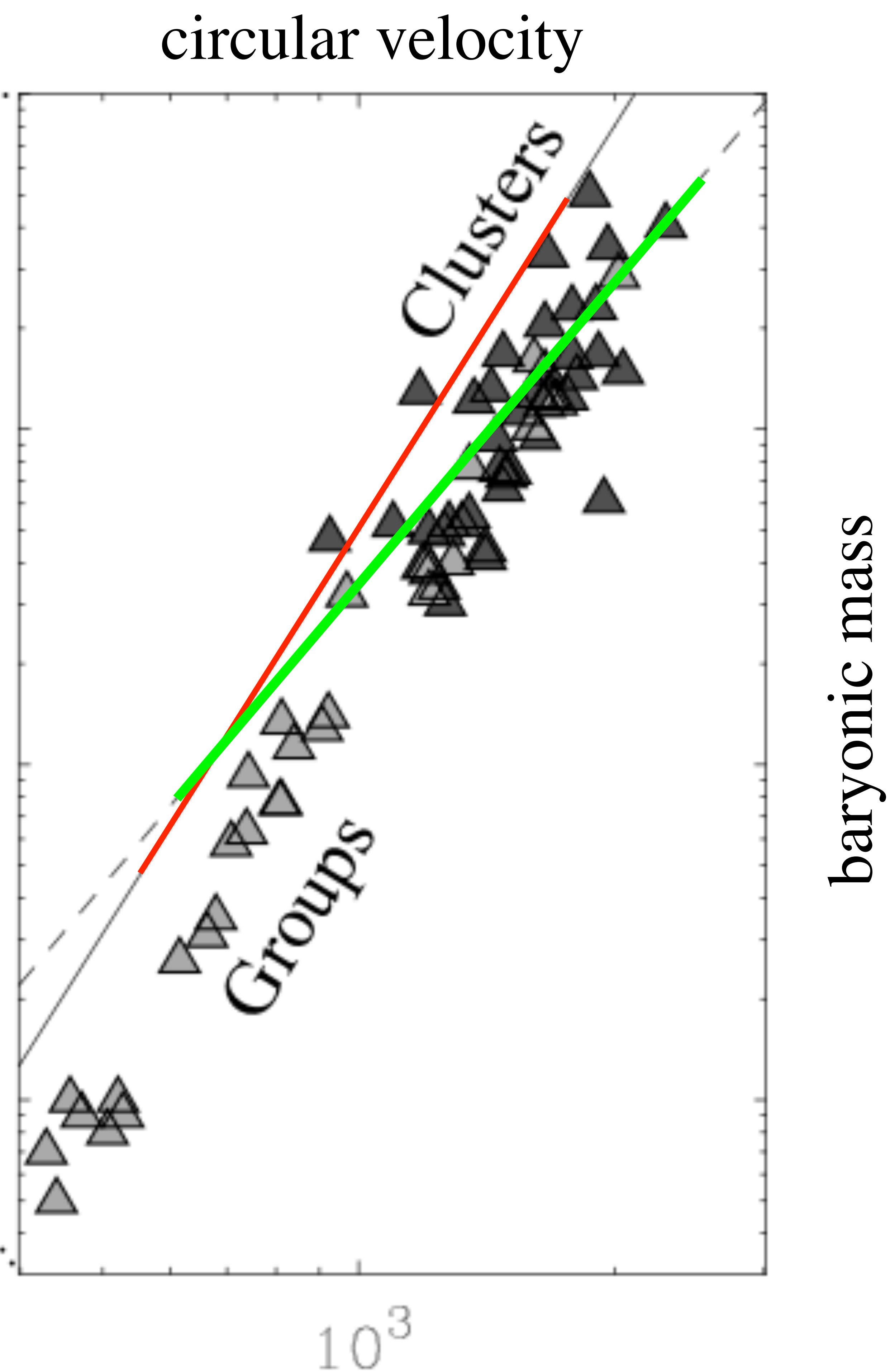
1E 0657-56 - the “bullet” cluster



Clusters of galaxies are a nagging problem

Observational Test	Successful	Promising	Unclear	Problematic
Rotating Systems				
solar system			X	
galaxy rotation curve shapes	X			
surface brightness $\propto \Sigma \propto a^2$	X			
galaxy rotation curve fits	X			
fitted M_*/L	X			
Tully-Fisher Relation				
baryon based	X			
slope	X			
normalization	X			
no size nor Σ dependence	X			
no intrinsic scatter	X			
Galaxy Disk Stability				
maximum surface density	X			
spiral structure in LSBGs	X			
thin & bulgeless disks		X		
Interacting Galaxies				
tidal tail morphology		X		
dynamical friction			X	
tidal dwarfs	X			
Spheroidal Systems				
star clusters			X	
ultrafaint dwarfs			X	
dwarf Spheroidals	X			
ellipticals	X			
Faber-Jackson relation	X			
Clusters of Galaxies				
dynamical mass				X
velocity (bulk & collisional)		X		
Gravitational Lensing				
strong lensing	X			
weak lensing				X
Cosmology				
expansion history			X	
geometry			X	
big bang nucleosynthesis	X			
Structure Formation				
galaxy power spectrum			X	
empty voids		X		
early structure		X		
Background Radiation				
first:second acoustic peak	X			
second:third acoustic peak				X
detailed fit				X
early re-ionization	X			

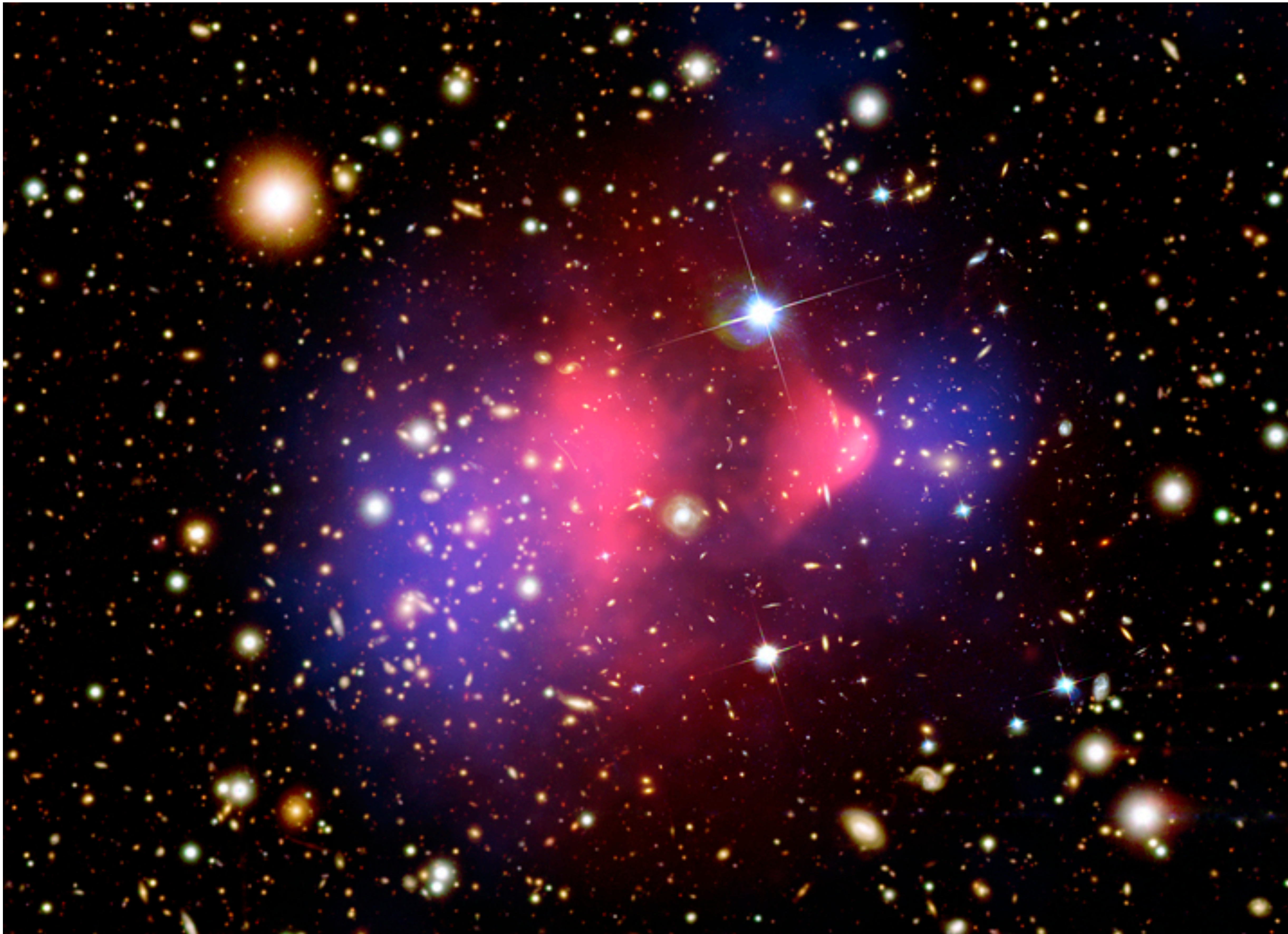
Table 1: *Observational tests of MOND.*



MOND suffers a missing mass problem!

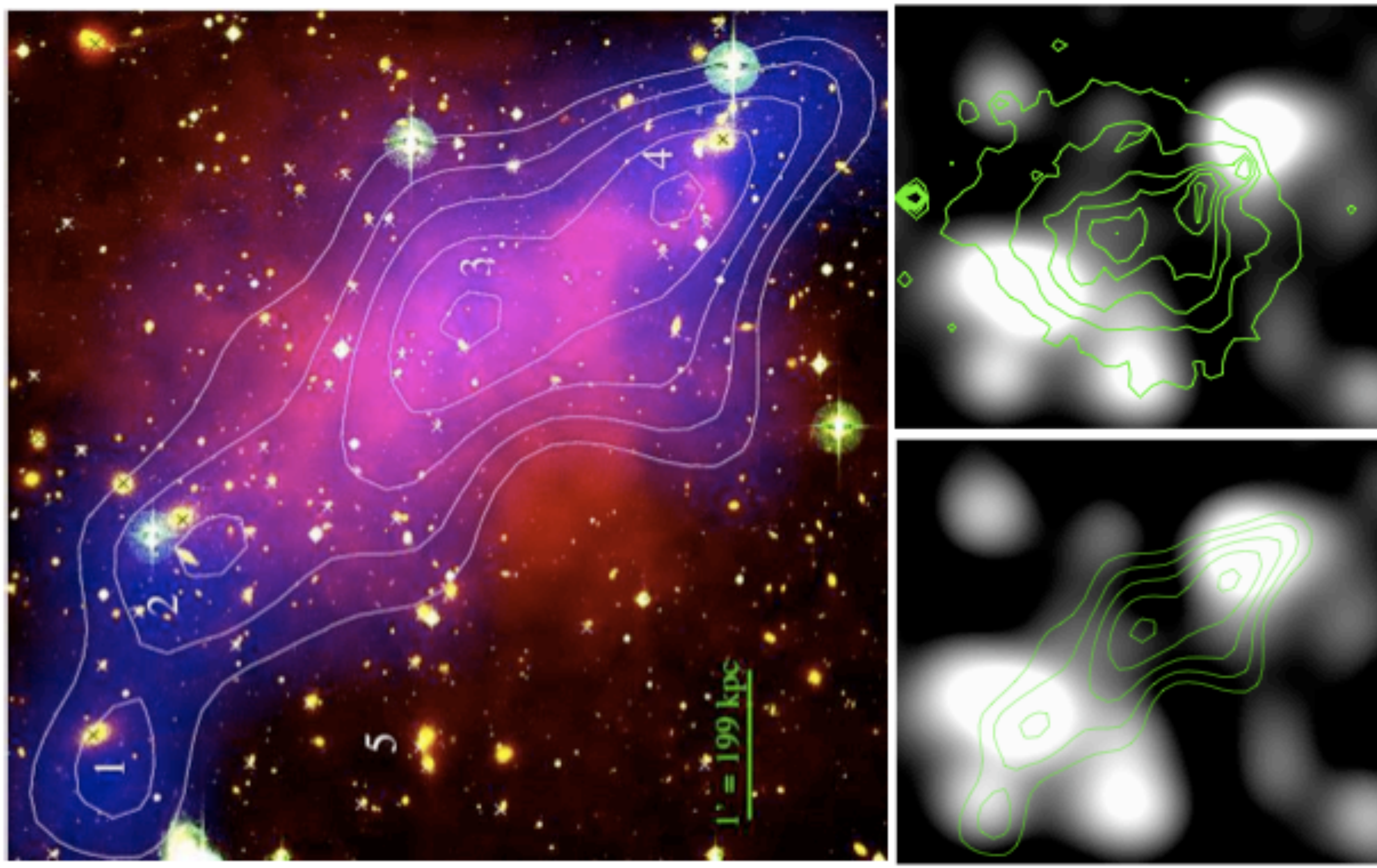
Clusters should be on red line; are closer to green line

The bullet cluster shows this discrepancy in dramatic fashion:
the mass (blue) is segregated from most of the known baryons (red).



Mahdavi et al. (2007) arXiv:0706.3048

Abell 520 - Counter-example to bullet cluster
with a mass peak devoid of galaxies

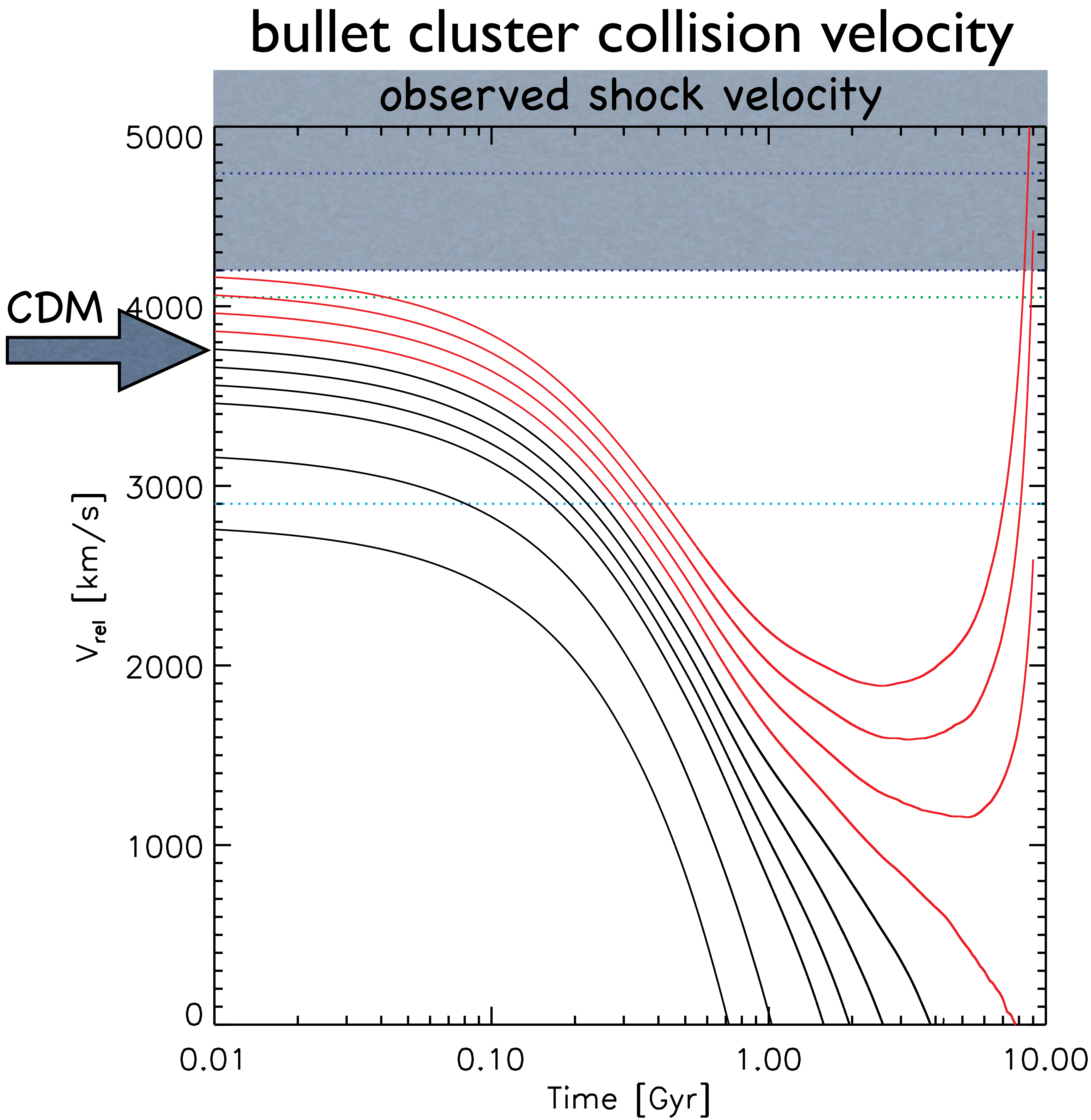


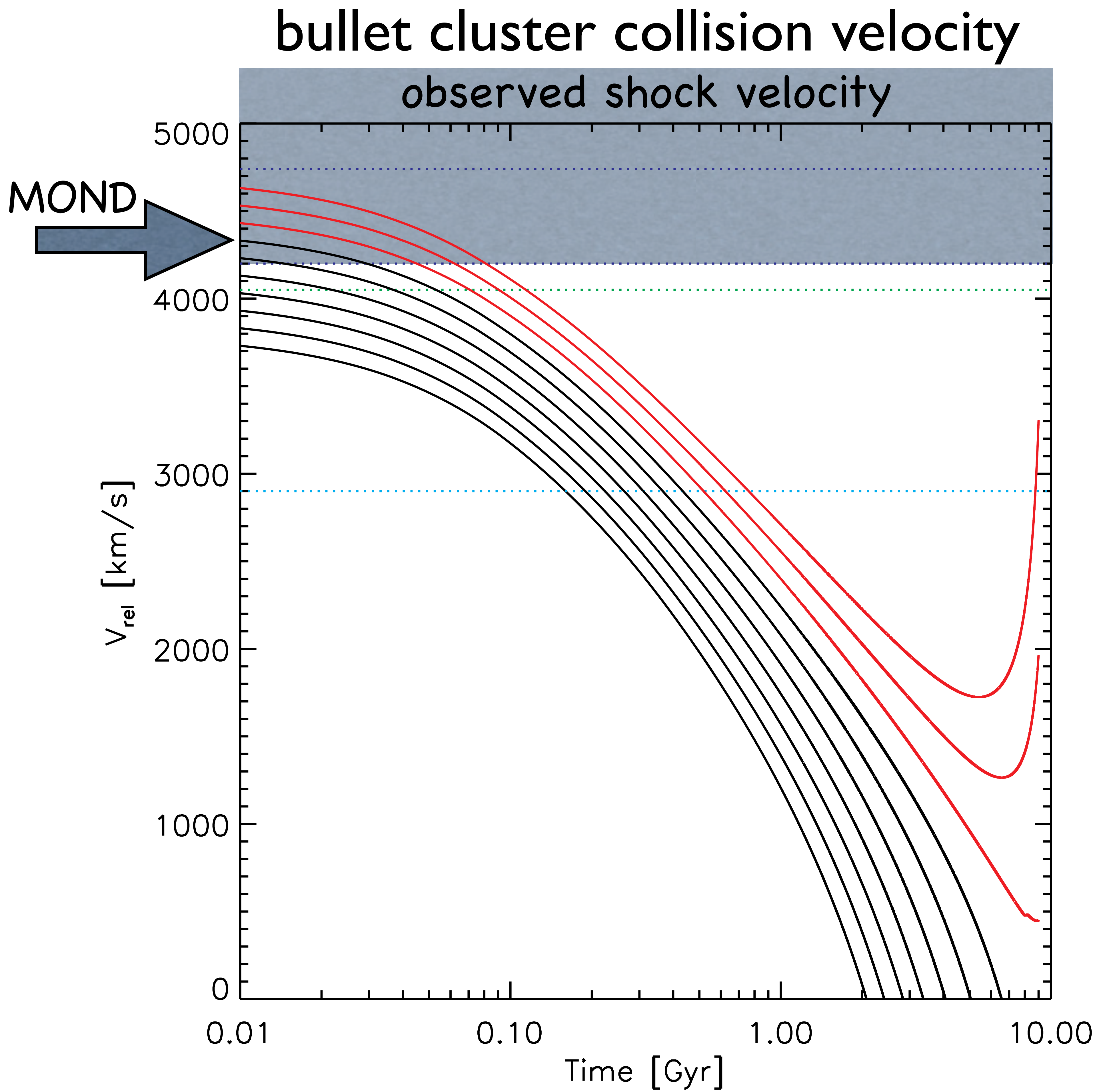
We don't understand clusters in either theory

The bullet cluster is widely cited as falsifying MOND.

But it is a big problem for dark matter too.

The collision speed is too fast in dark matter - must invoke special pleading.

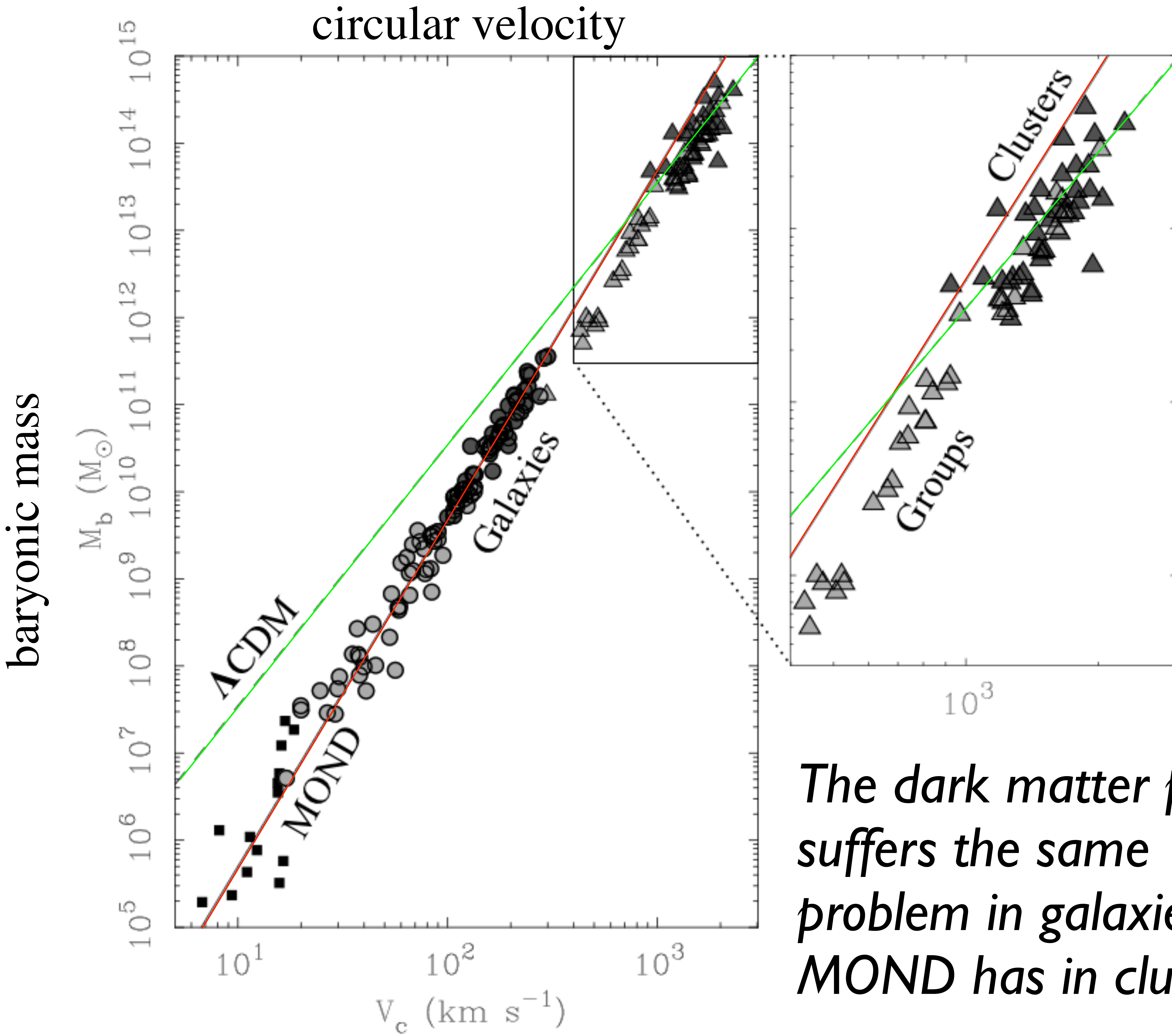




The bullet cluster is widely cited as falsifying MOND.

But it is a big problem for dark matter too.

The collision speed is natural in MOND



The dark matter picture suffers the same problem in galaxies that MOND has in clusters!

Logical possibilities

- ΛCDM is fine; puzzling observations will be explained … somehow
- MOND gets predictions right because there is something to it --- dark matter doesn't exist.
- We have no clue what is going on.