Dark Matter and Gravity in the Universe

"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

Crawley Astronomical Society
19 March 2021

Stacy McGaugh
Case Western Reserve University
Est. 1826

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

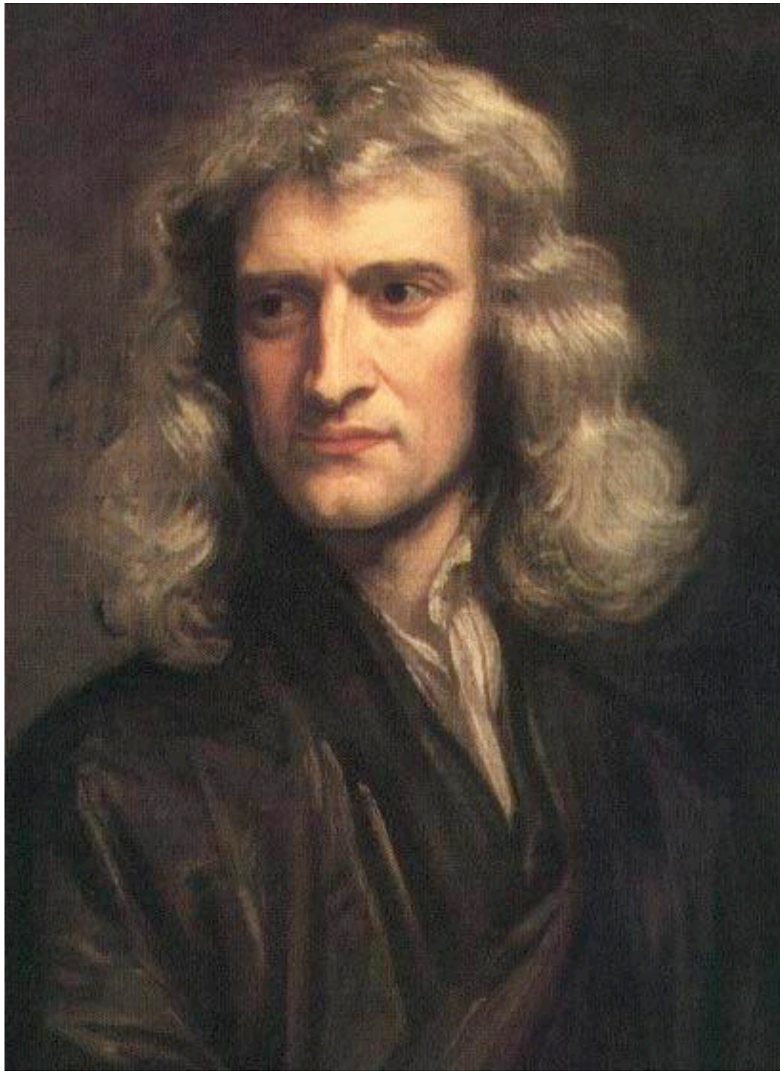
- Josh Billings
(paraphrased)
c. 1874

A few things we know for sure...

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

which basically means

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



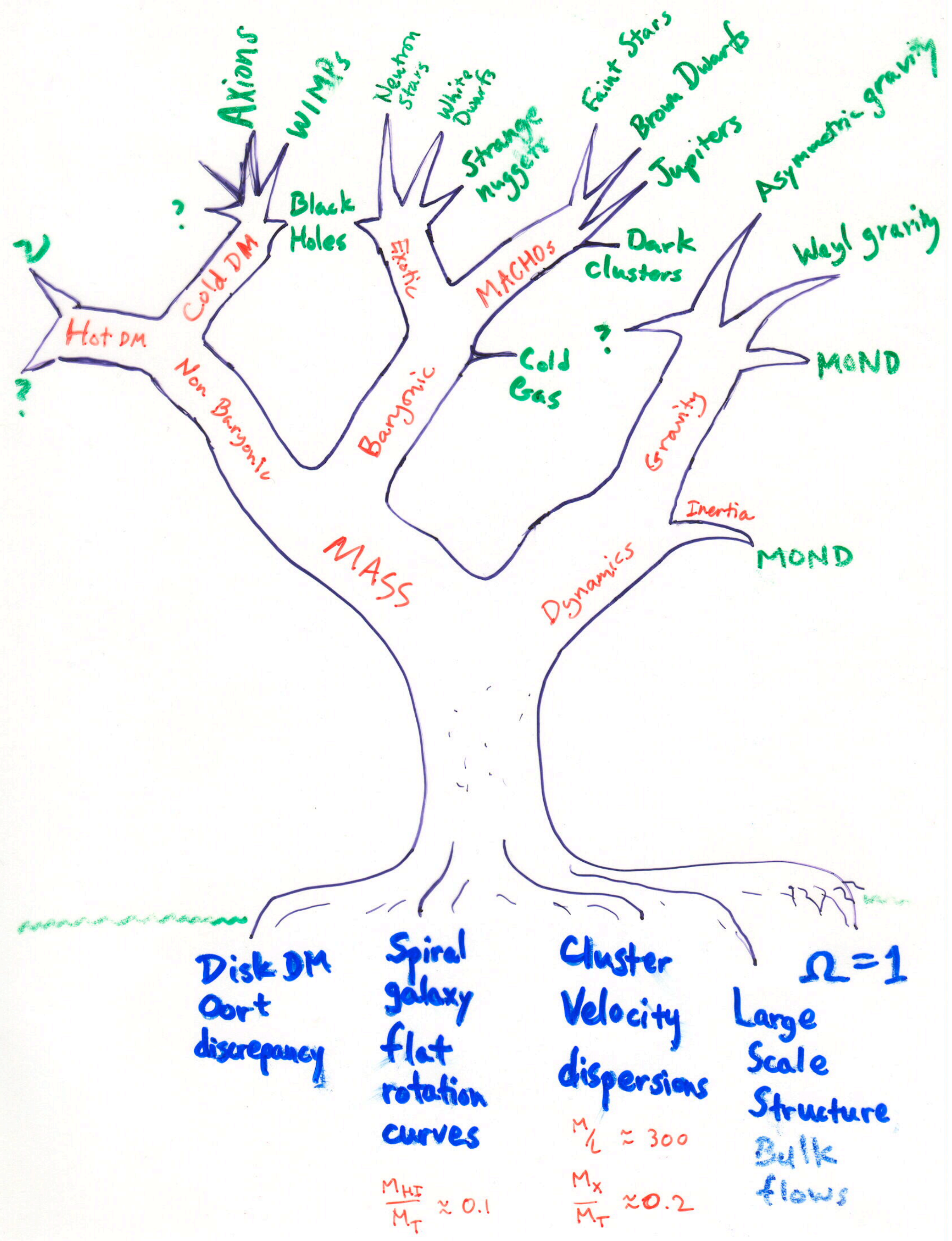
ergo...

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

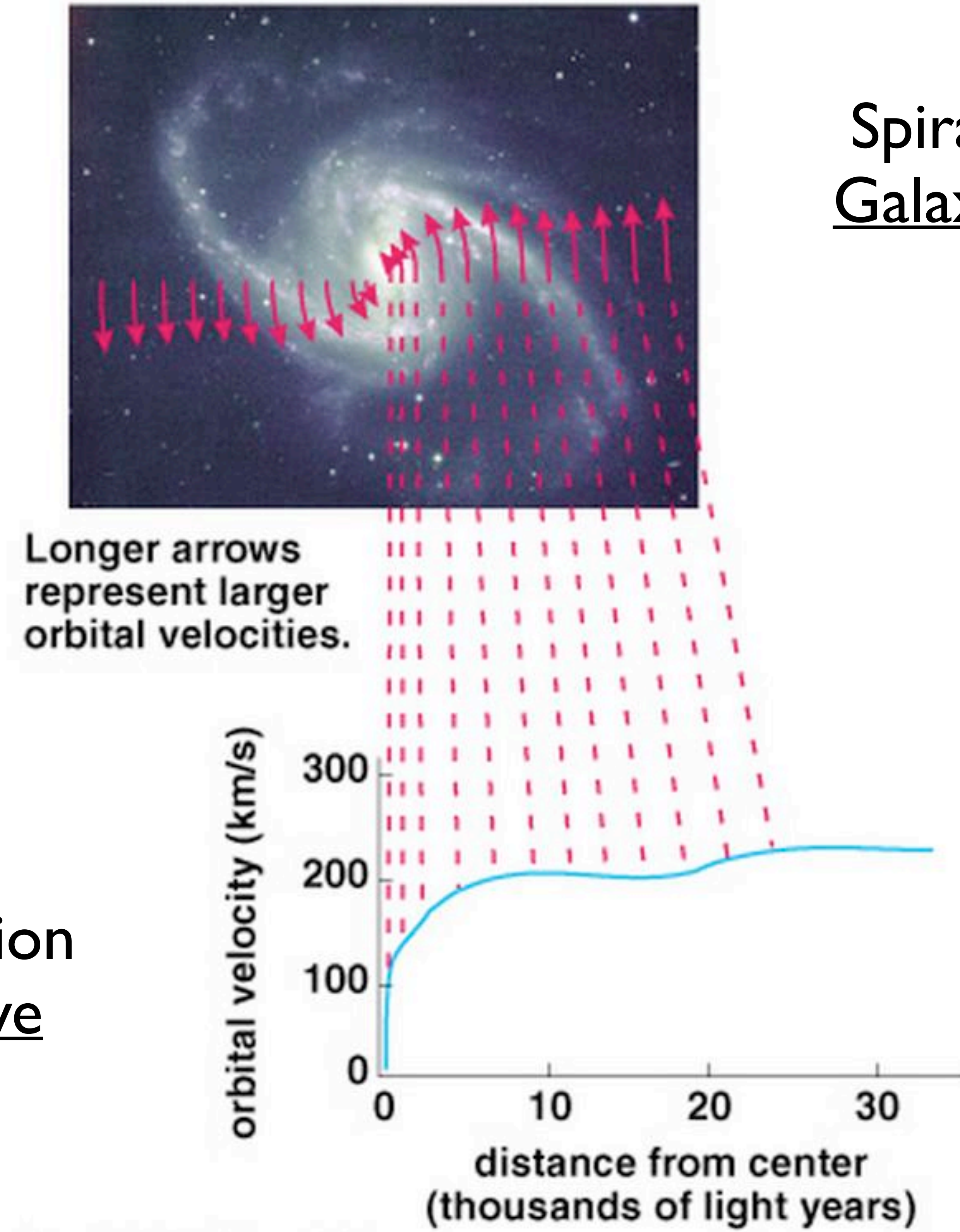
The Dark Matter tree

Hypothesized solutions

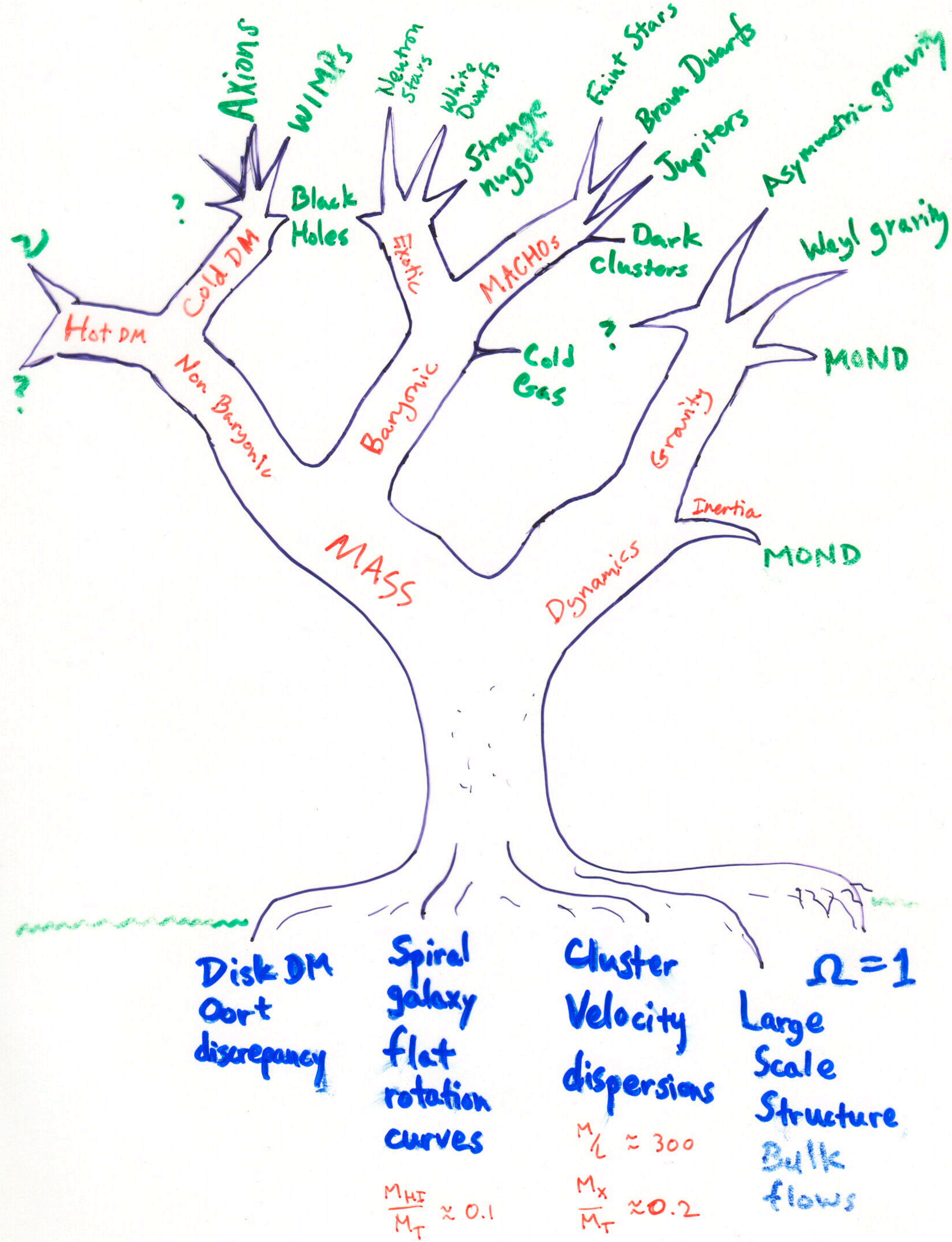
Roots of the problem



Spiral Galaxy

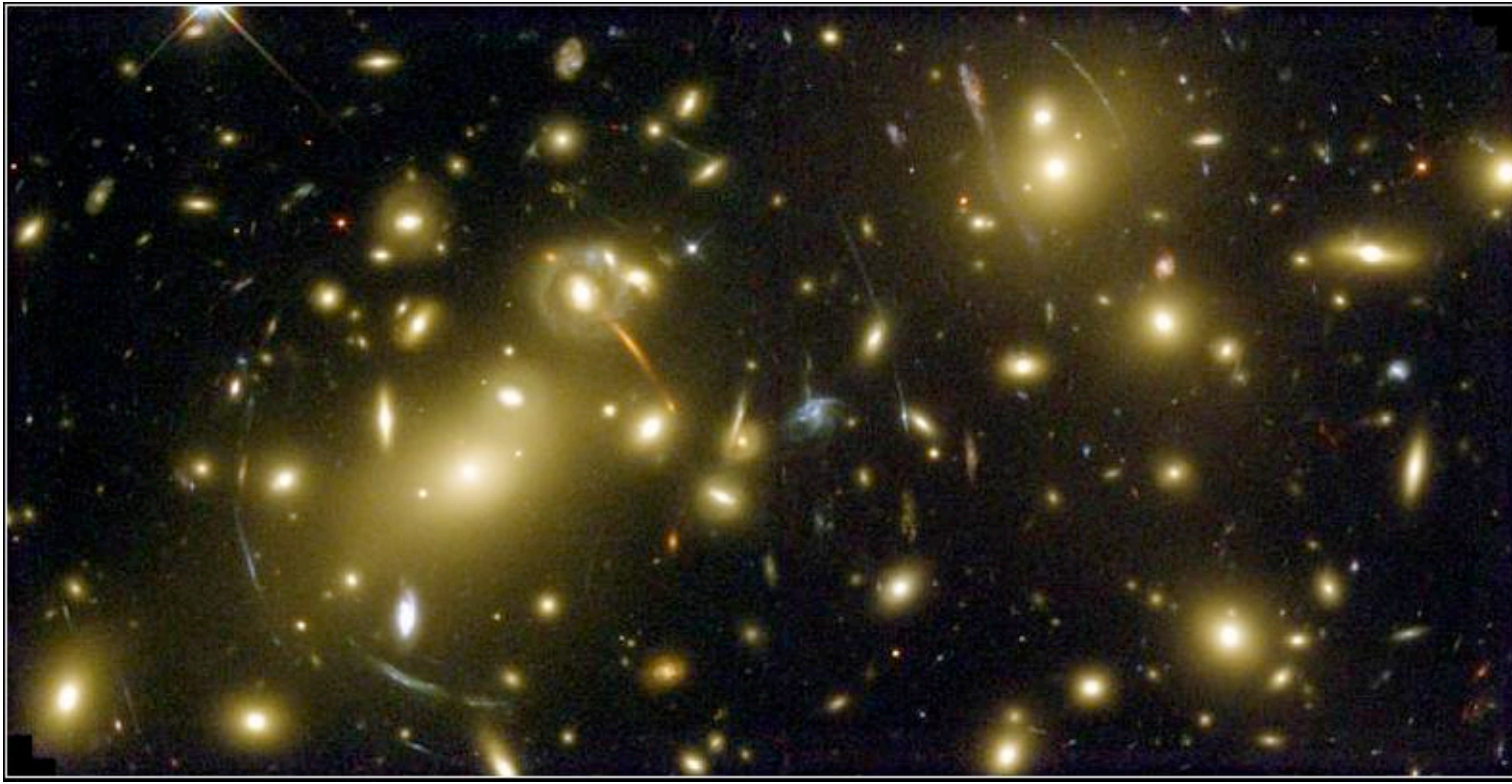


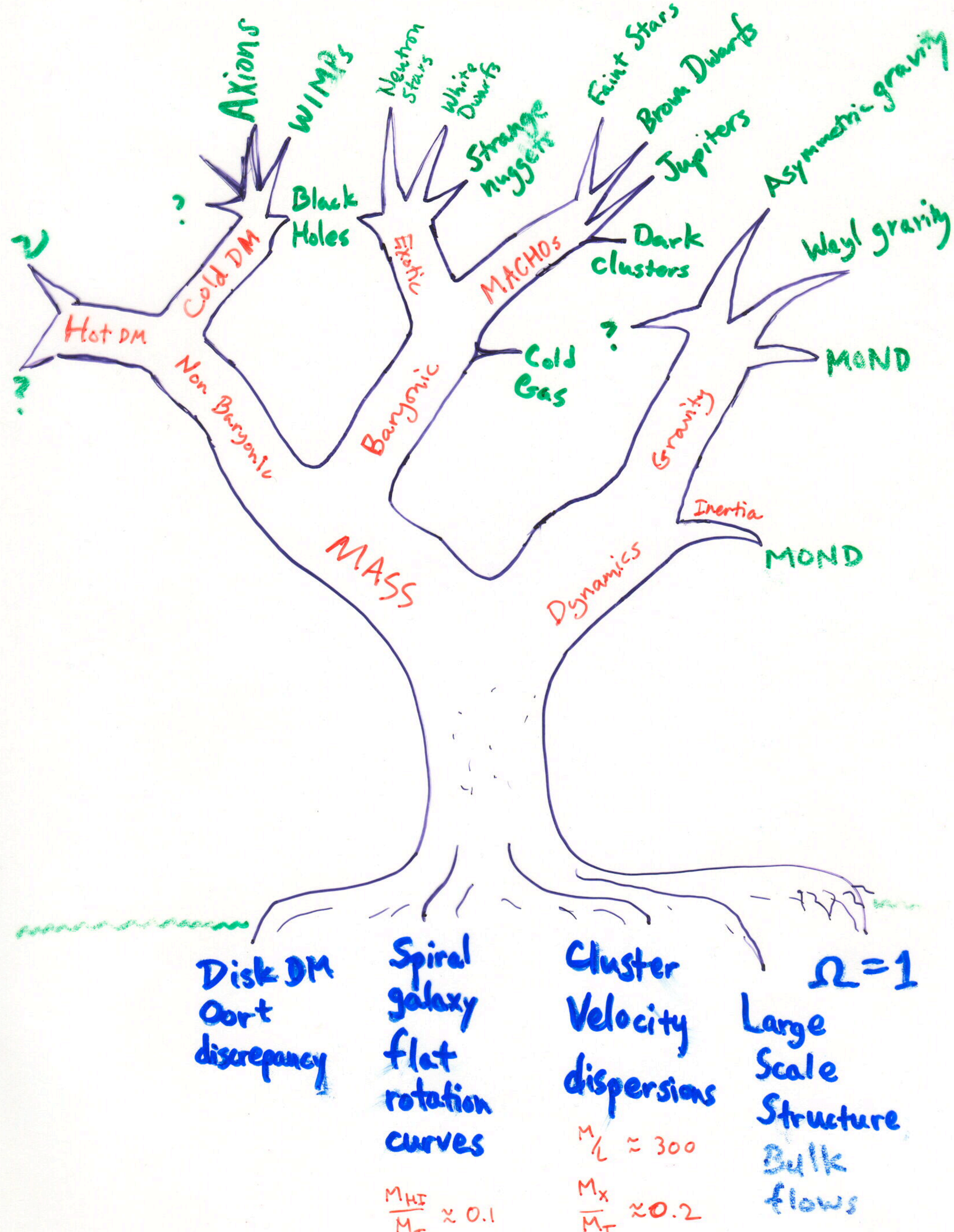
Rotation Curve



Axions
WIMPs
Neutron stars
White Dwarfs
Faint Stars
Brown Dwarfs
Jupiters
Asymmetric gravity
Strange nuggets
Black Holes
Dark clusters
Weyl gravity
Cold DM
Exotic
MACHOs
Hot DM
Cold Gas
MOND
Non Baryonic
Baryonic
Gravity
Inertia
MOND
MASS
Dynamics
Disk DM
Oort discrepancy
Spiral galaxy flat rotation curves
$\frac{M_{HI}}{M_T} \approx 0.1$
Cluster Velocity dispersions
$M/L \approx 300$
$\frac{M_X}{M_T} \approx 0.2$
$\Omega = 1$
Large Scale Structure
Bulk flows

Galaxy Cluster





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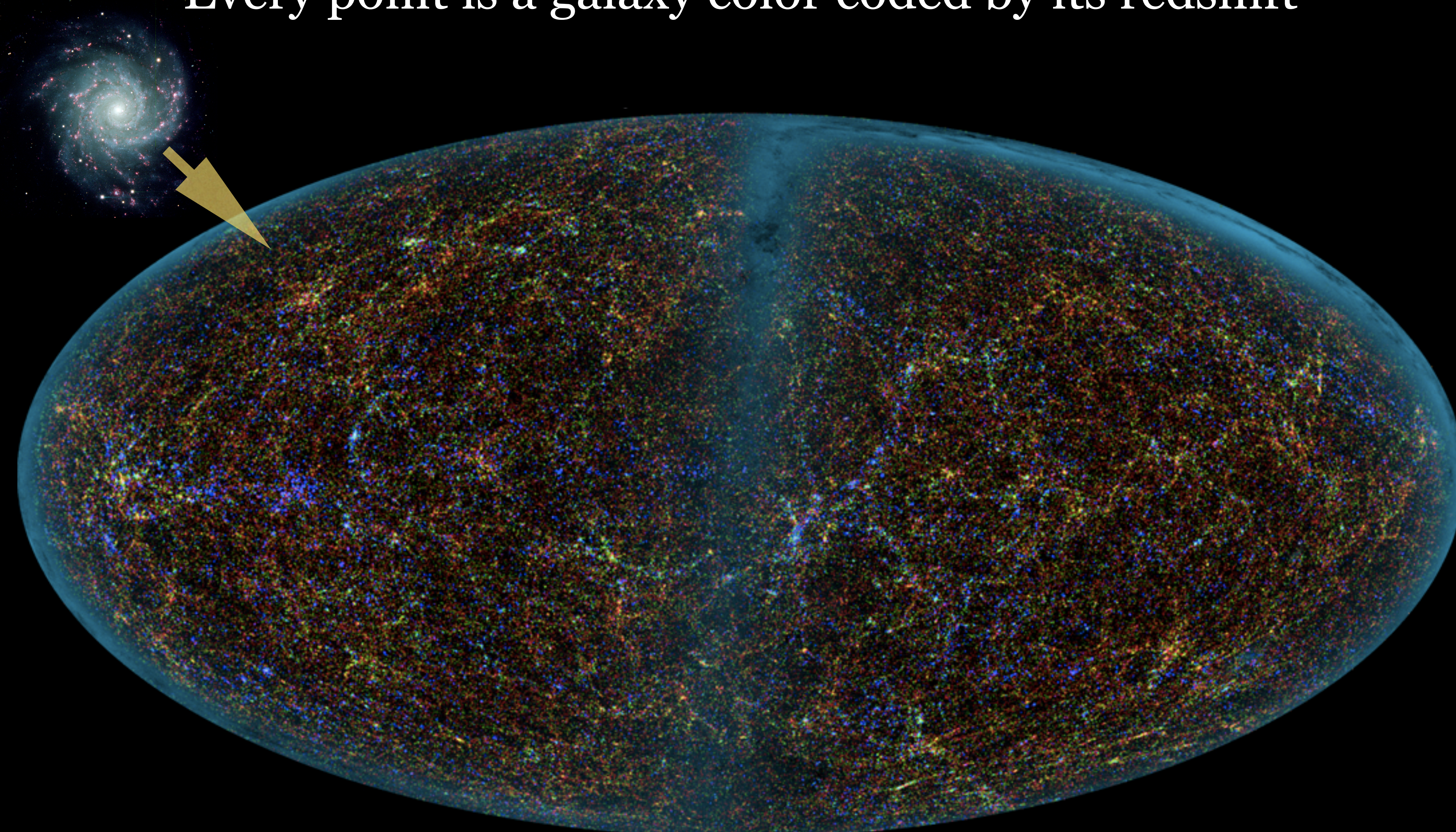
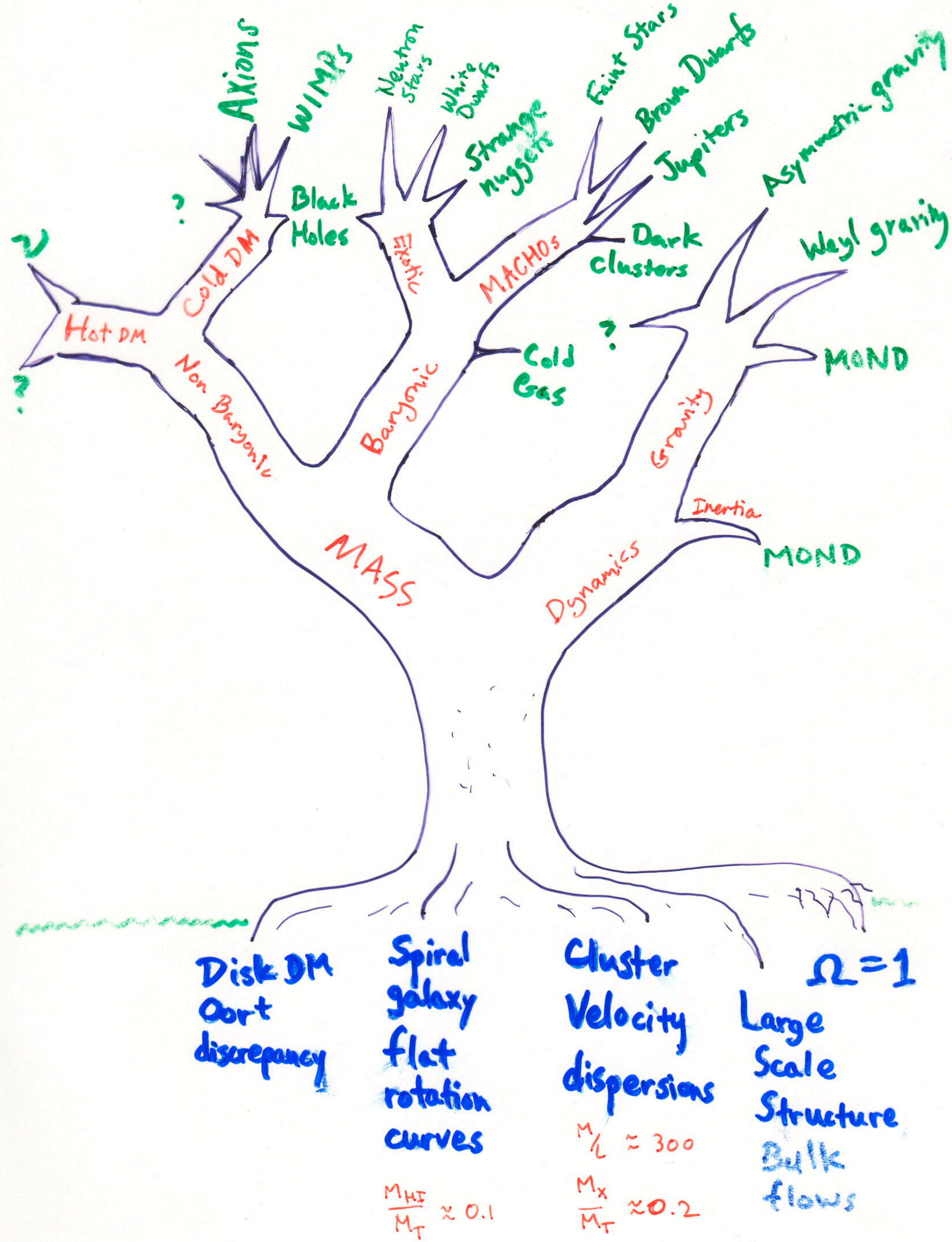
M_HI / M_T ≈ 0.1
M_X / M_T ≈ 0.2

Large Scale Structure

This is a map of the entire sky
Every point is a galaxy color coded by its redshift



2MASS galaxy survey



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What is the Dark Matter?

Baryonic Dark Matter

Normal things:

very faint stars, brown dwarfs

other hard-to-see objects (planets, gas)

Hot Dark Matter

neutrinos - got mass, but not enough

✔ **Cold Dark Matter**

Some new fundamental particle

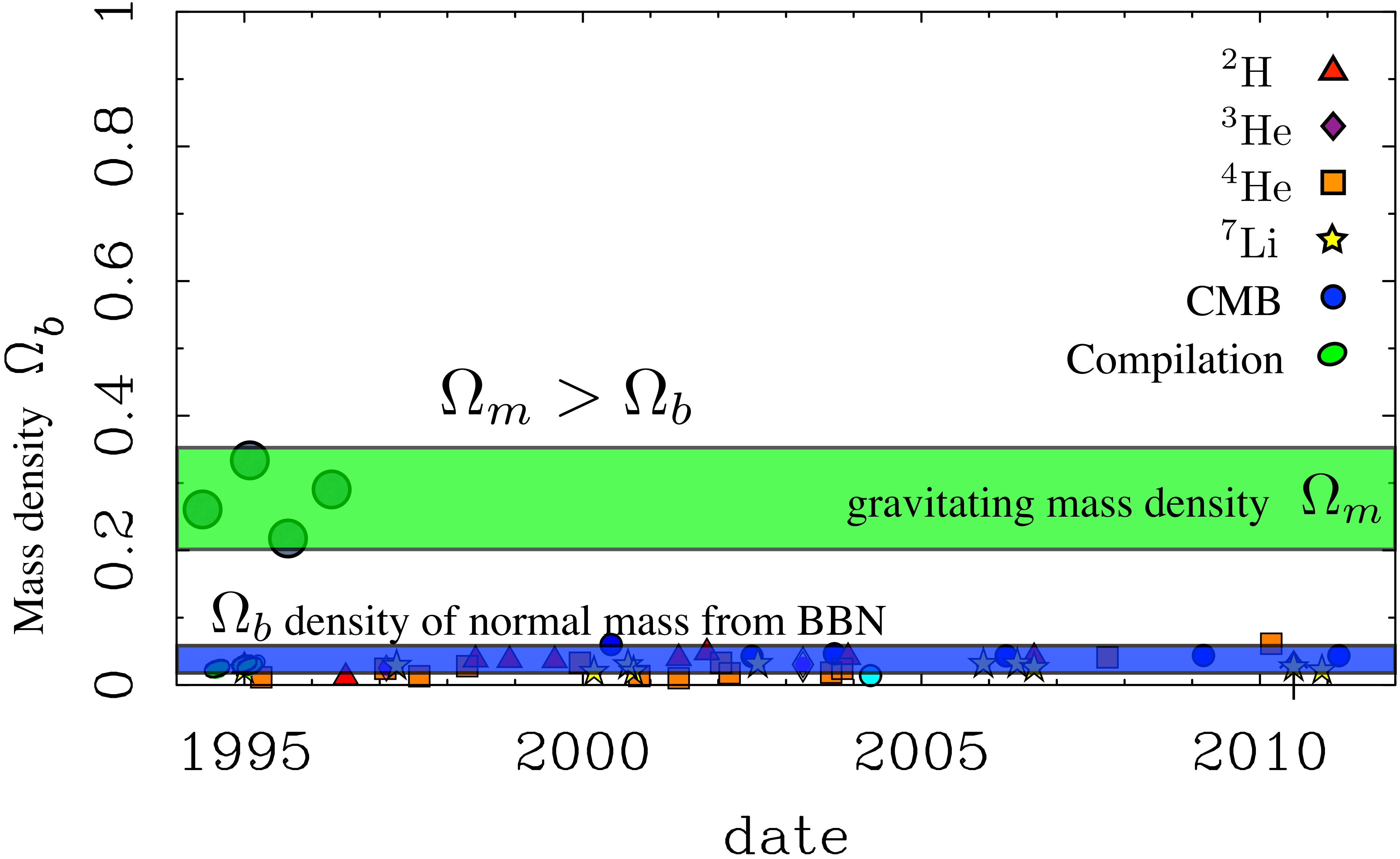
doesn't interact with light, so quite invisible.

Two big motivations:

1) total mass outweighs normal mass from BBN

2) needed to grow cosmic structure

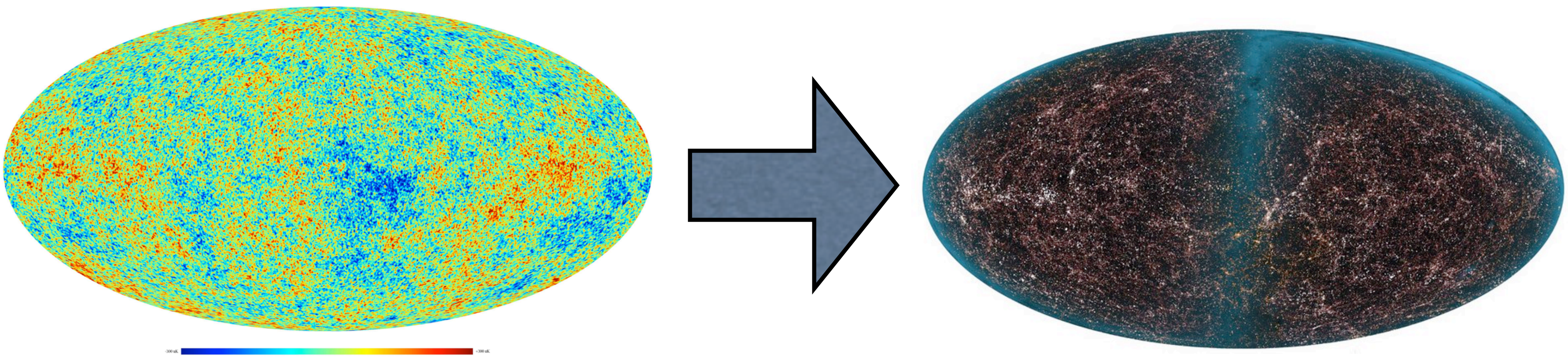
(I) There is more gravitating mass than Big Bang Nucleosythesis allows in normal matter



(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 x 10^5 yr

t = 1.4 x 10^{10} yr



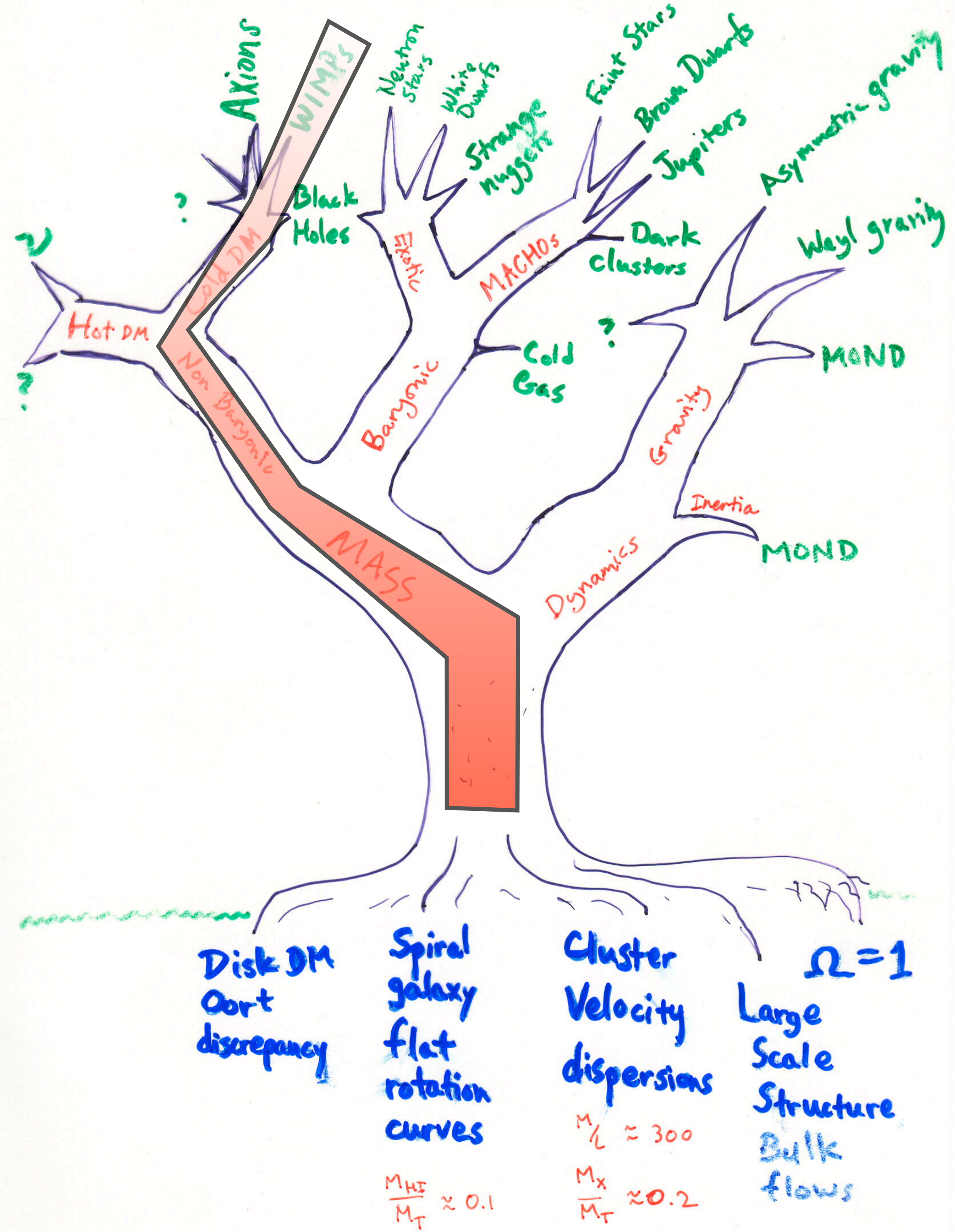
very smooth: $\delta\rho/\rho \sim 10^{-5}$

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

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

Both (1) and (2) hold only when gravity is normal.

Amongst all hypothesized solutions, WIMPs* are the odds-on favorite.



*<u>**WIMP**</u>

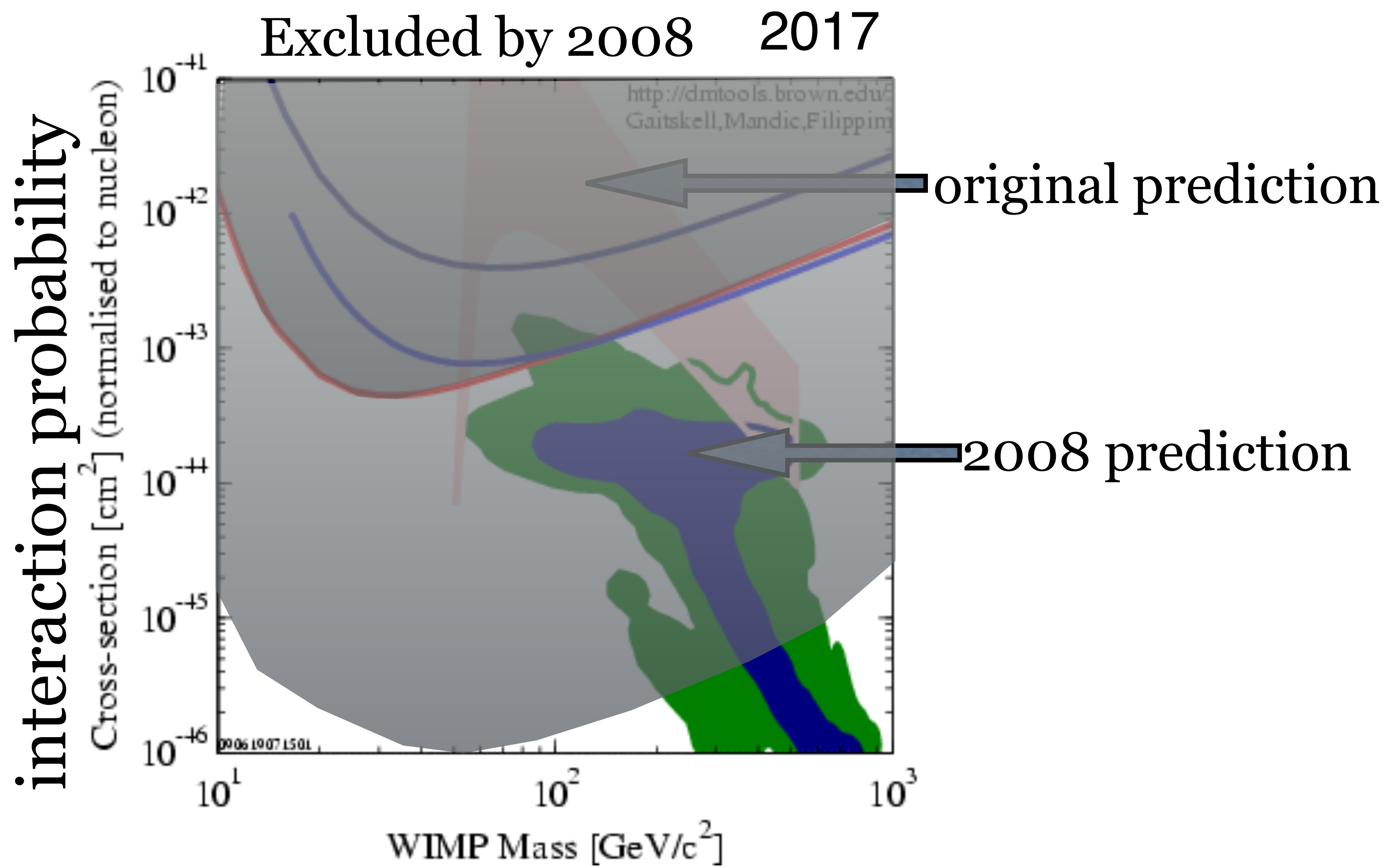
Weakly
Interacting
Massive
Particle

WIMPs have been such favorites that we have long acted as if we knew ***for sure*** that this was the correct answer.

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

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

WIMPs are hiding

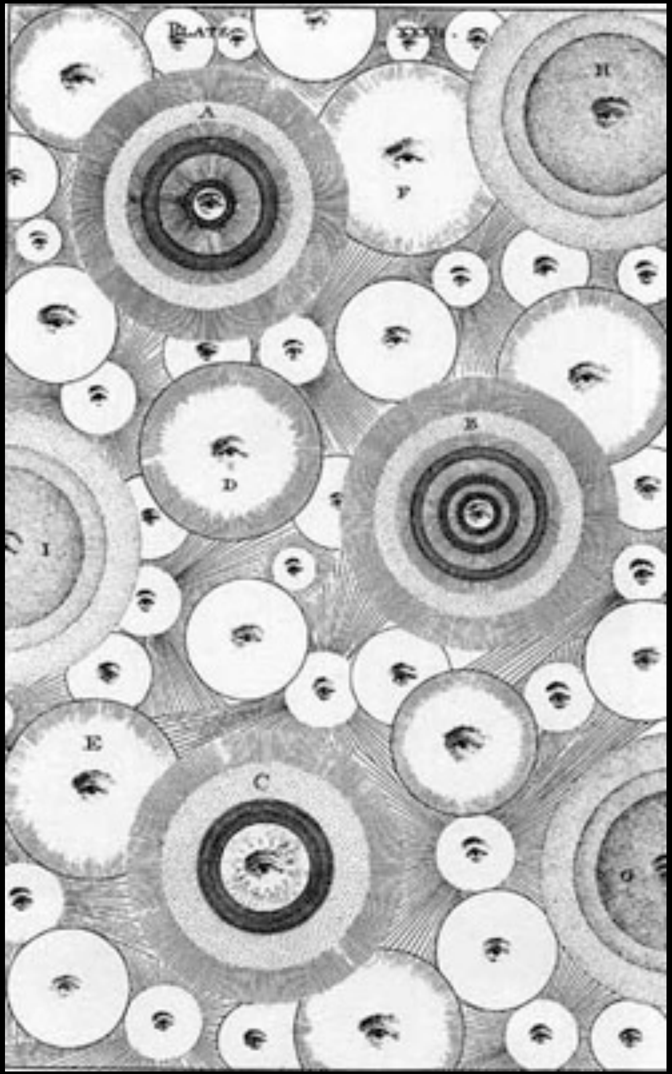


Mass of WIMP

WIMP detection experiments

We've been here before

By the end of the 19th century, people were convinced that the Milky Way was the entirety of creation, an island universe embedded in an indefinite void.



"No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintain any single nebula to be a star system of coordinate rank with the Milky Way. A practical certainty has been attained that the entire contents, stellar and nebular, of the sphere belong to one mighty aggregation" [i.e., the Milky Way]

- Agnes Mary Clerke (1890)

Popular History of Astronomy during the Nineteenth Century

Curtis-Shapley Debate
(the "Great Debate" - 1920)

Shapley

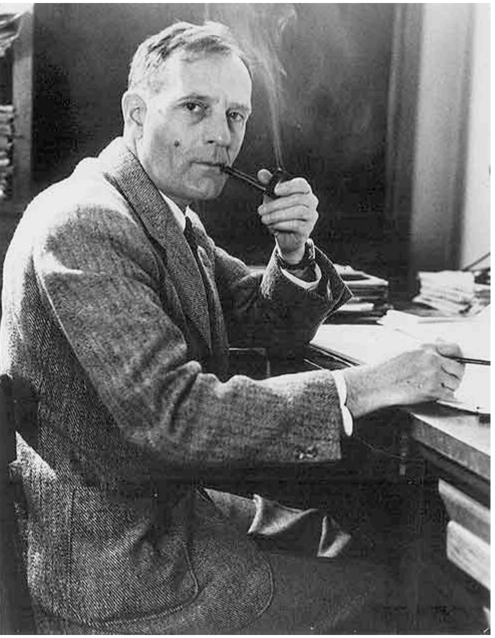
The Milky Way is big; we are not near the center

Other nebulae are clouds of gas within the Milky Way

Curtis

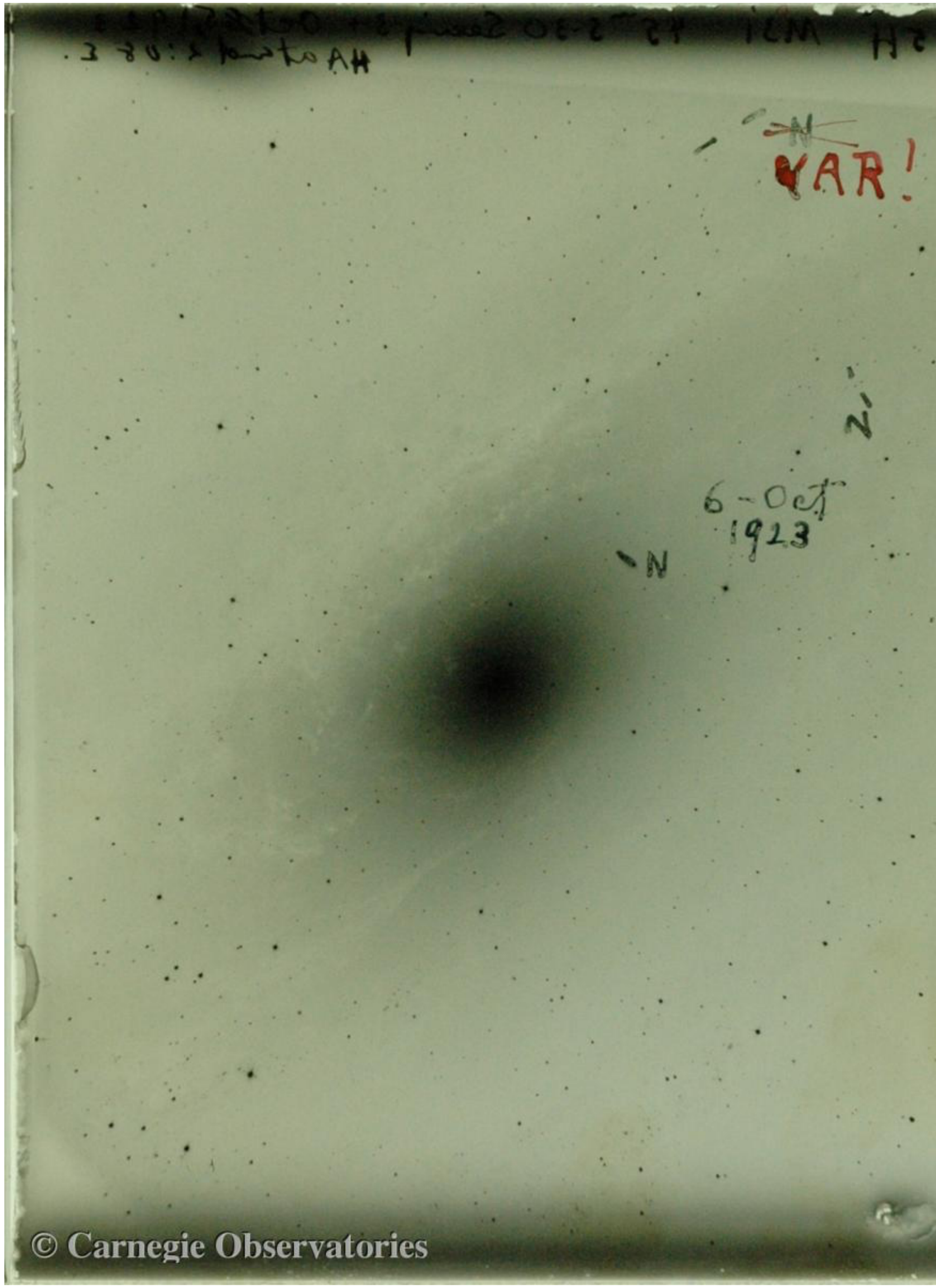
The Milky Way is small; we happen to be near the center

The spiral nebulae are "island universes" comparable to the Milky Way



Hubble

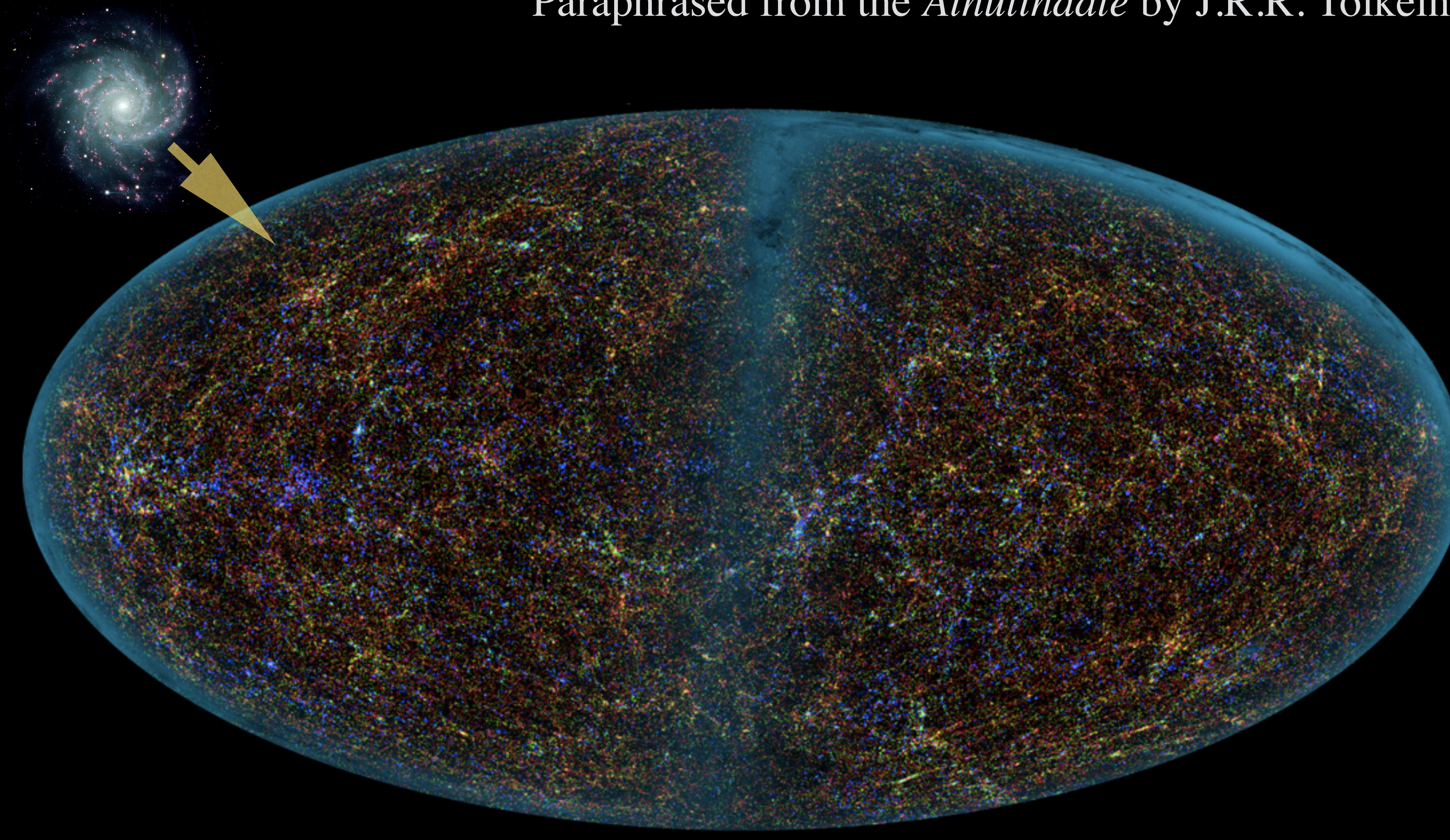
1929

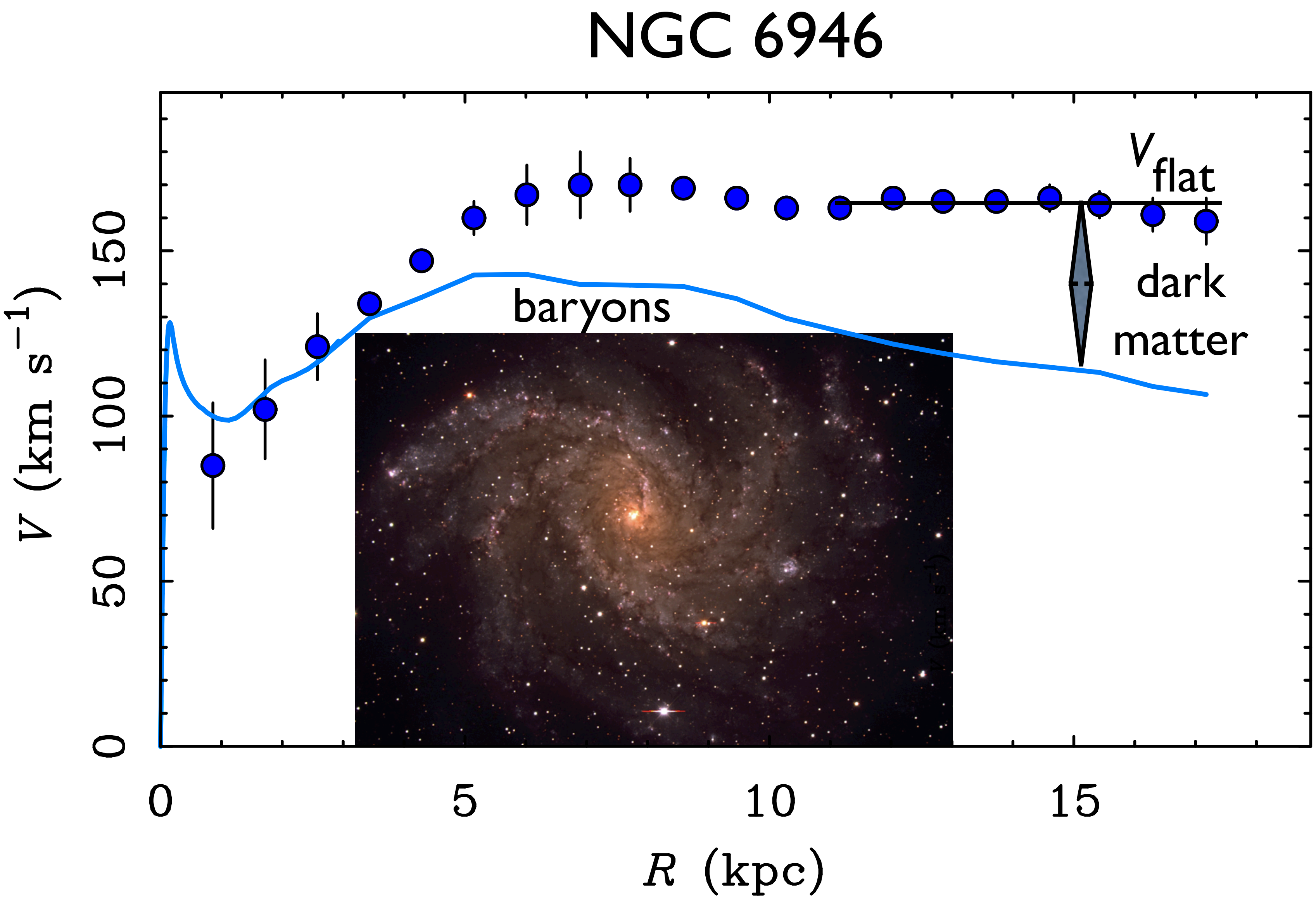


- Showed that galaxies were distant systems, comparable in size to the Milky Way
  - settled the Great Debate after ten years.

A single galaxy might seem a little thing to those who consider only the immeasurable vastness of the universe, and not the minute precision to which all things therein are shaped.

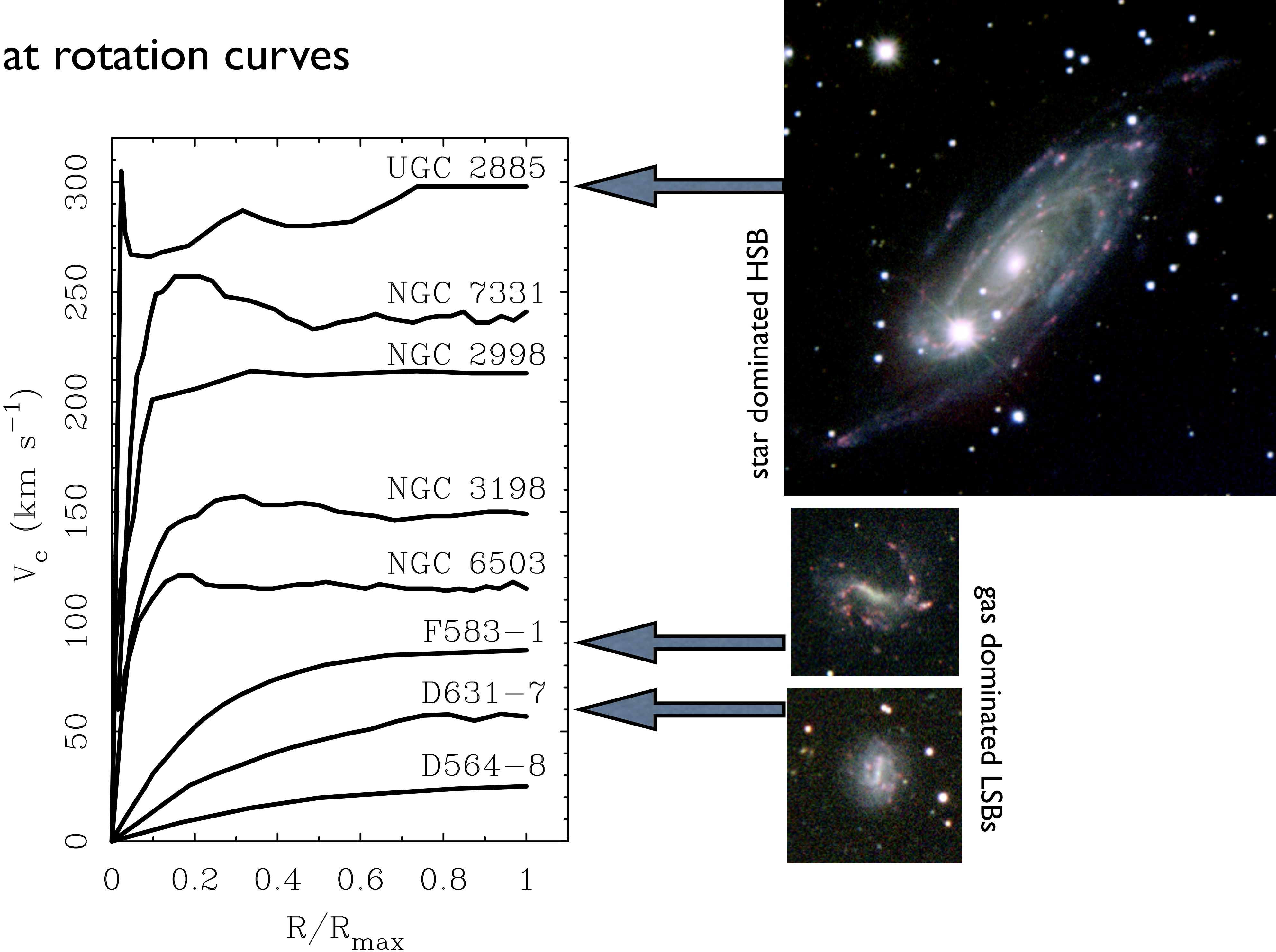
Paraphrased from the *Ainulindalë* by J.R.R. Tolkein



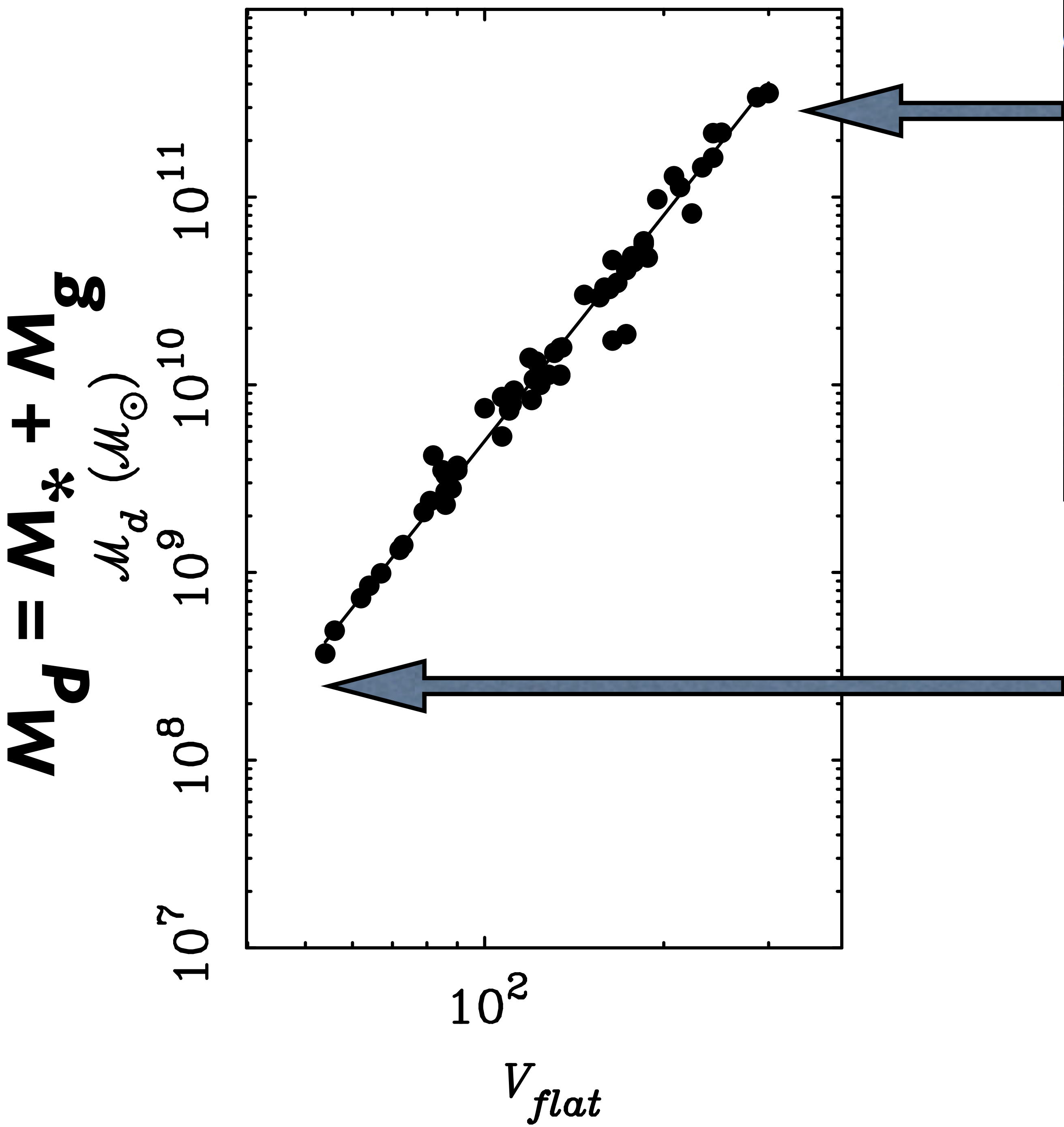


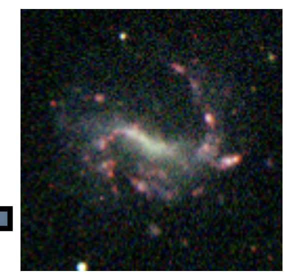
Solve Poisson equation numerically to obtain V(r) for observed baryon distribution

Flat rotation curves

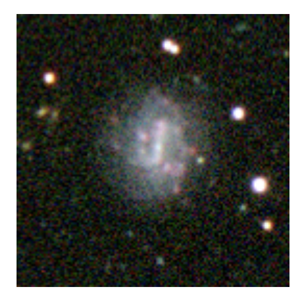


Tully-Fisher Relation

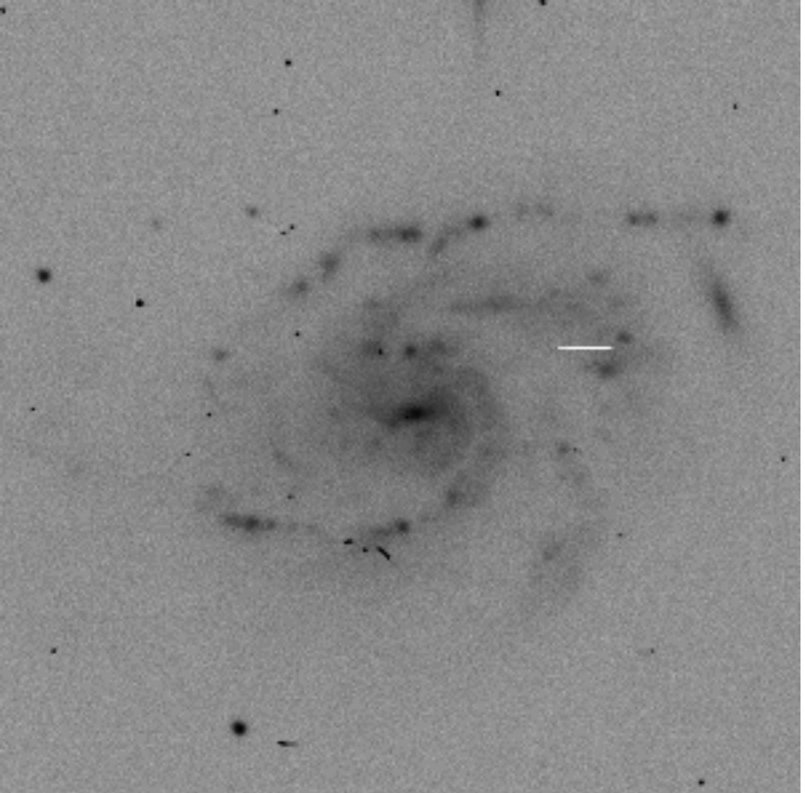




Big galaxies rotate fast

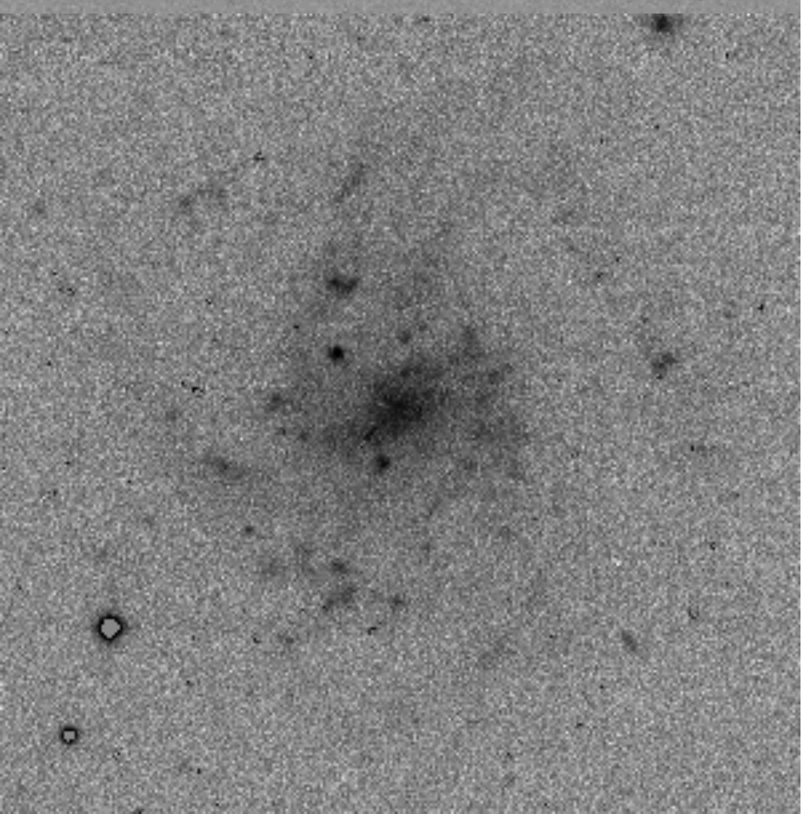


Small galaxies rotate slowly



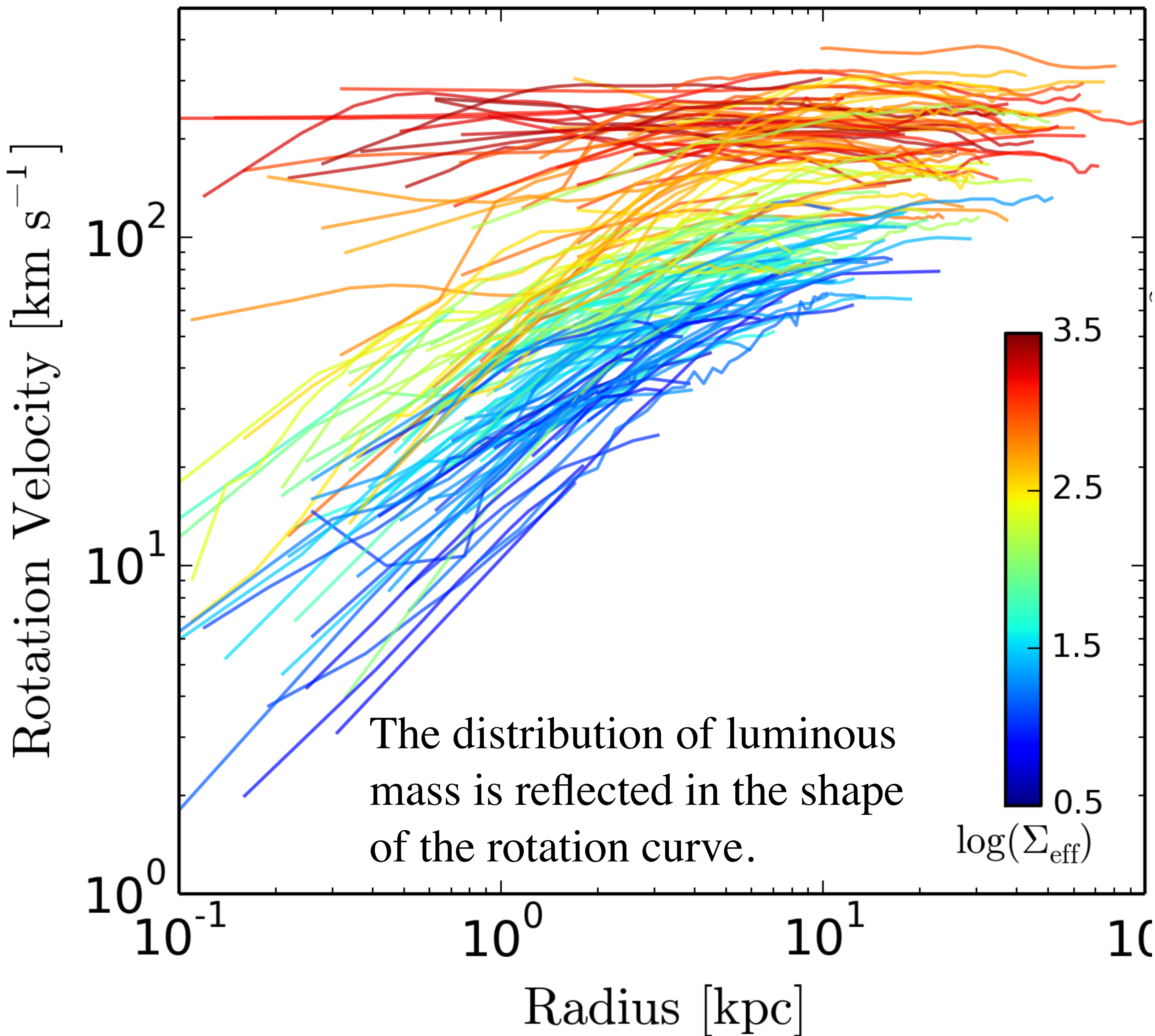
Some galaxies are

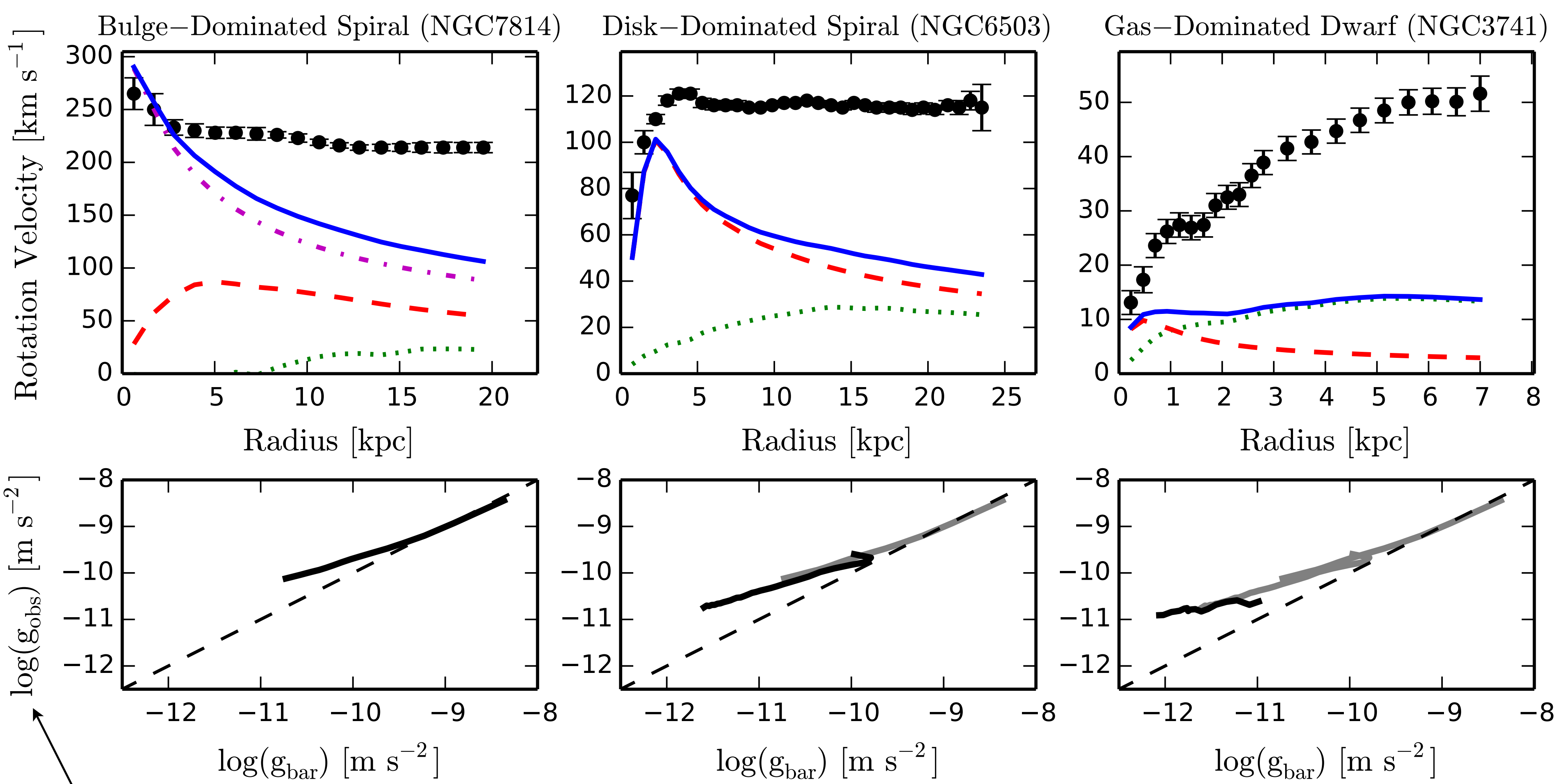
High Surface Brightness (HSB)



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]
The distribution of luminous mass is reflected in the shape of the rotation curve.
3.5
2.5
1.5
0.5
log(Σ_{eff})



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

independent quantities

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

acceleration from rotation curve

acceleration from baryon distribution

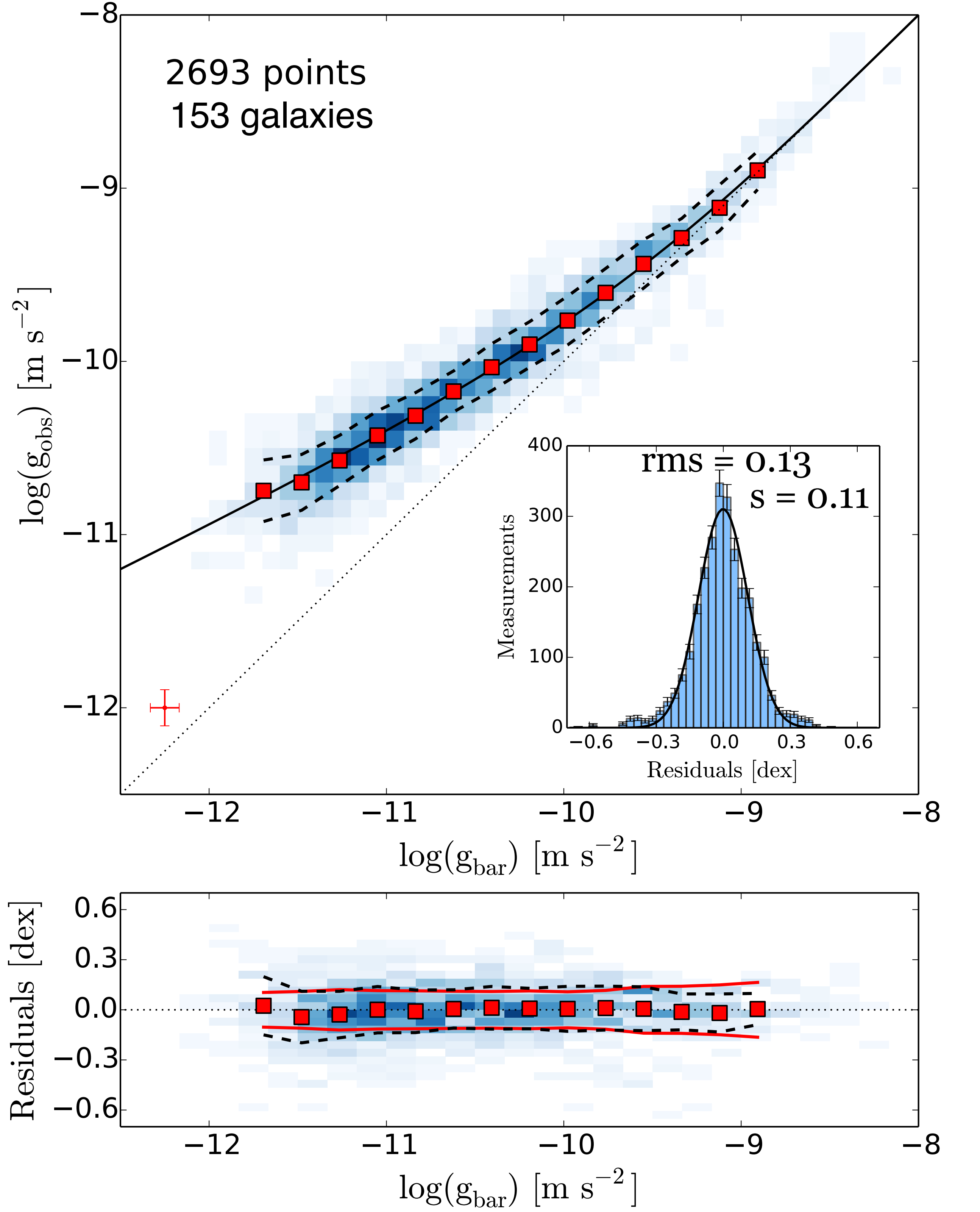
All galaxies obey the same

Radial Acceleration Relation

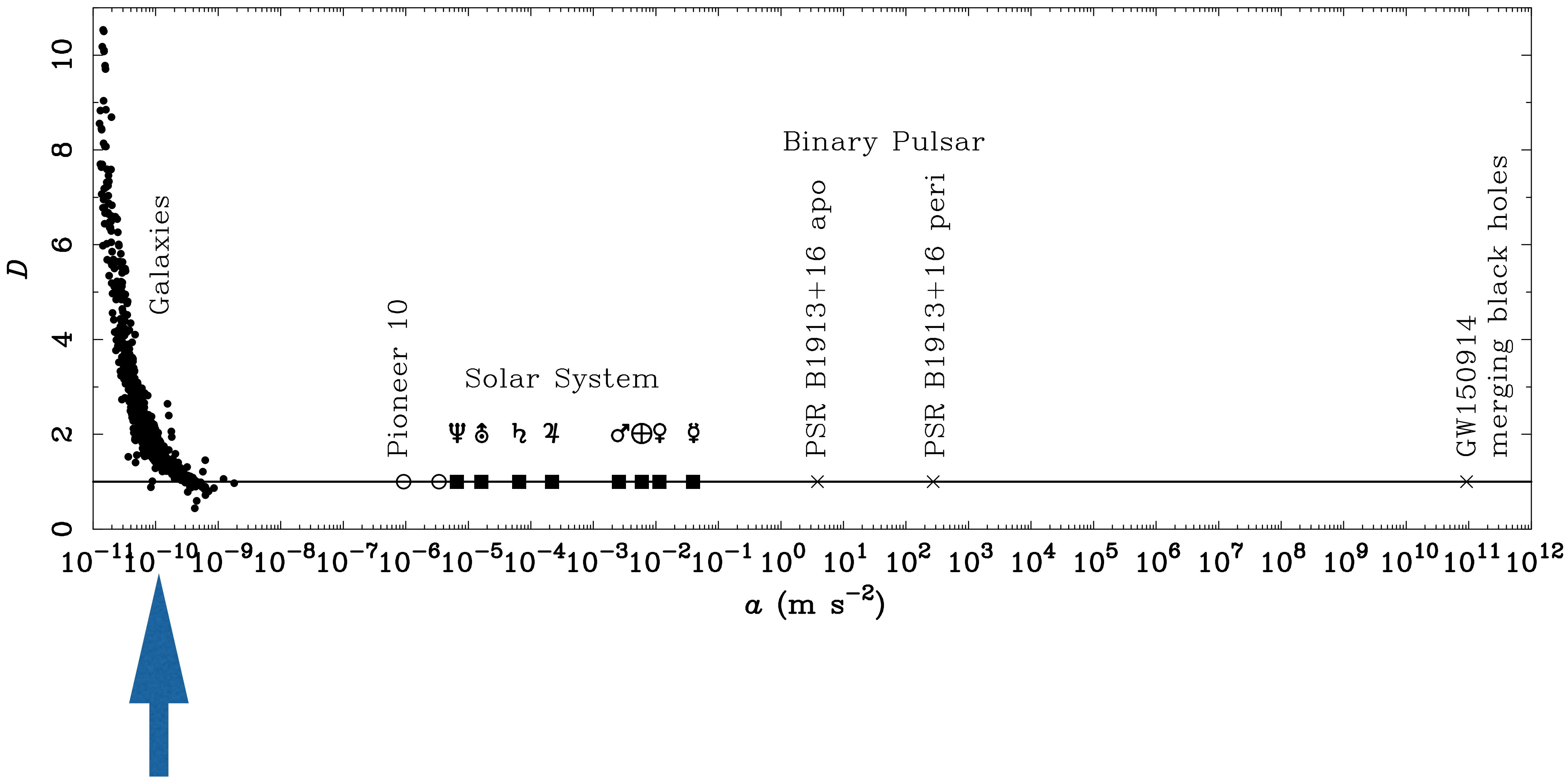
The tail of normal matter wags the dark matter dog

critical acceleration scale

10^{-10} m/s/s



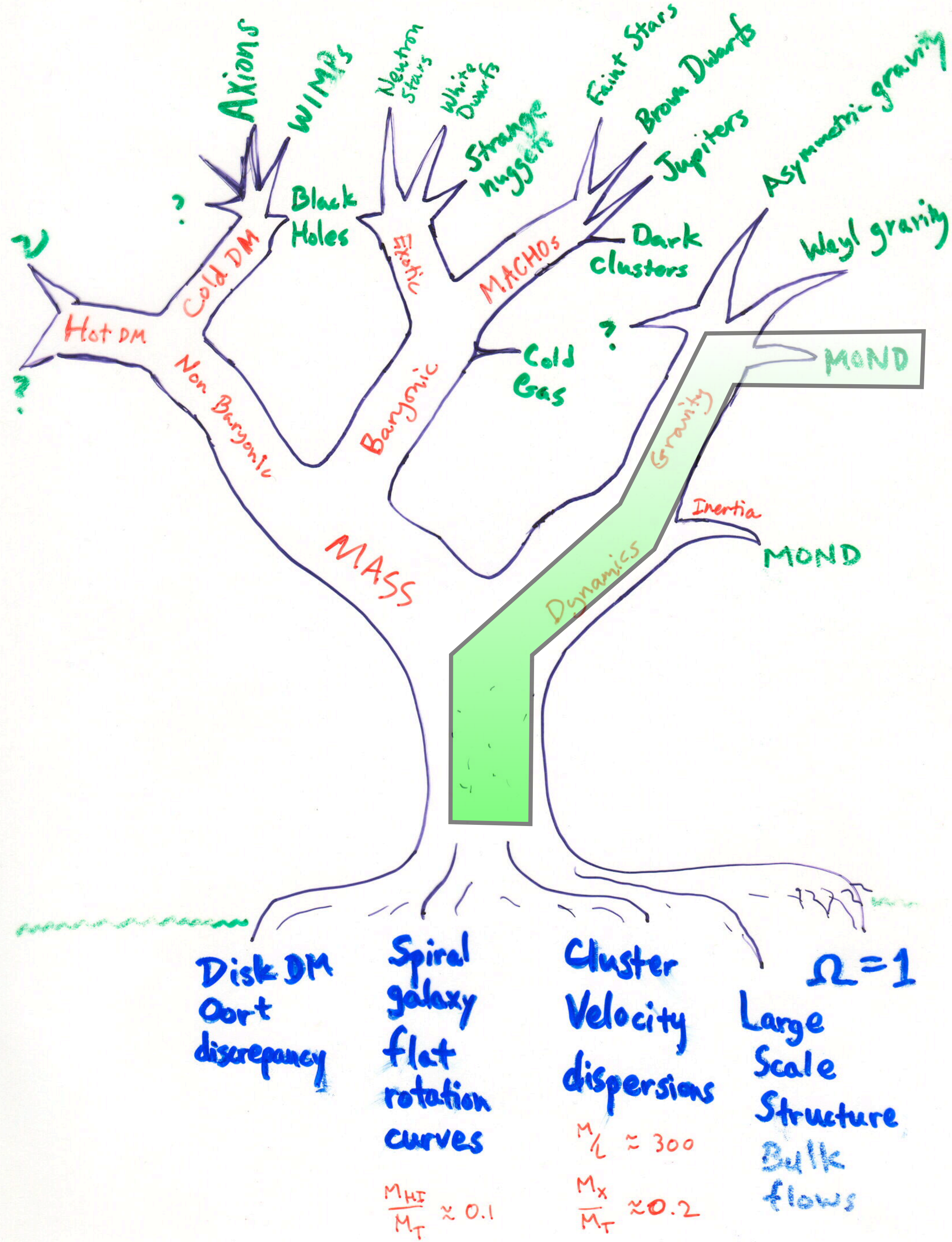
The mass discrepancy as a function of acceleration



We only infer the need for dark matter below a critical acceleration scale

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

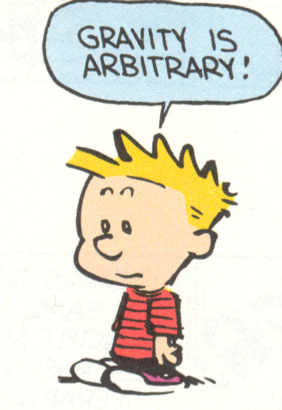
This theory modifies gravity instead of invoking dark matter.



MOND

MOdified Newtonian Dynamics

introduced by Moti Milgrom in 1983



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.

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

$$a \rightarrow \sqrt{g_N a_0} \quad \text{for} \quad a < a_0$$

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

"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.

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 resemble those of ellipticals and galactic bulges. I ... results in Milgrom ...

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 ... the ... on ... same ... 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, $g \approx (8 \text{ kpc}/d) a_0$, 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/r ... as th... advantages (a) ... an abs... 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 ... many cases ... 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.

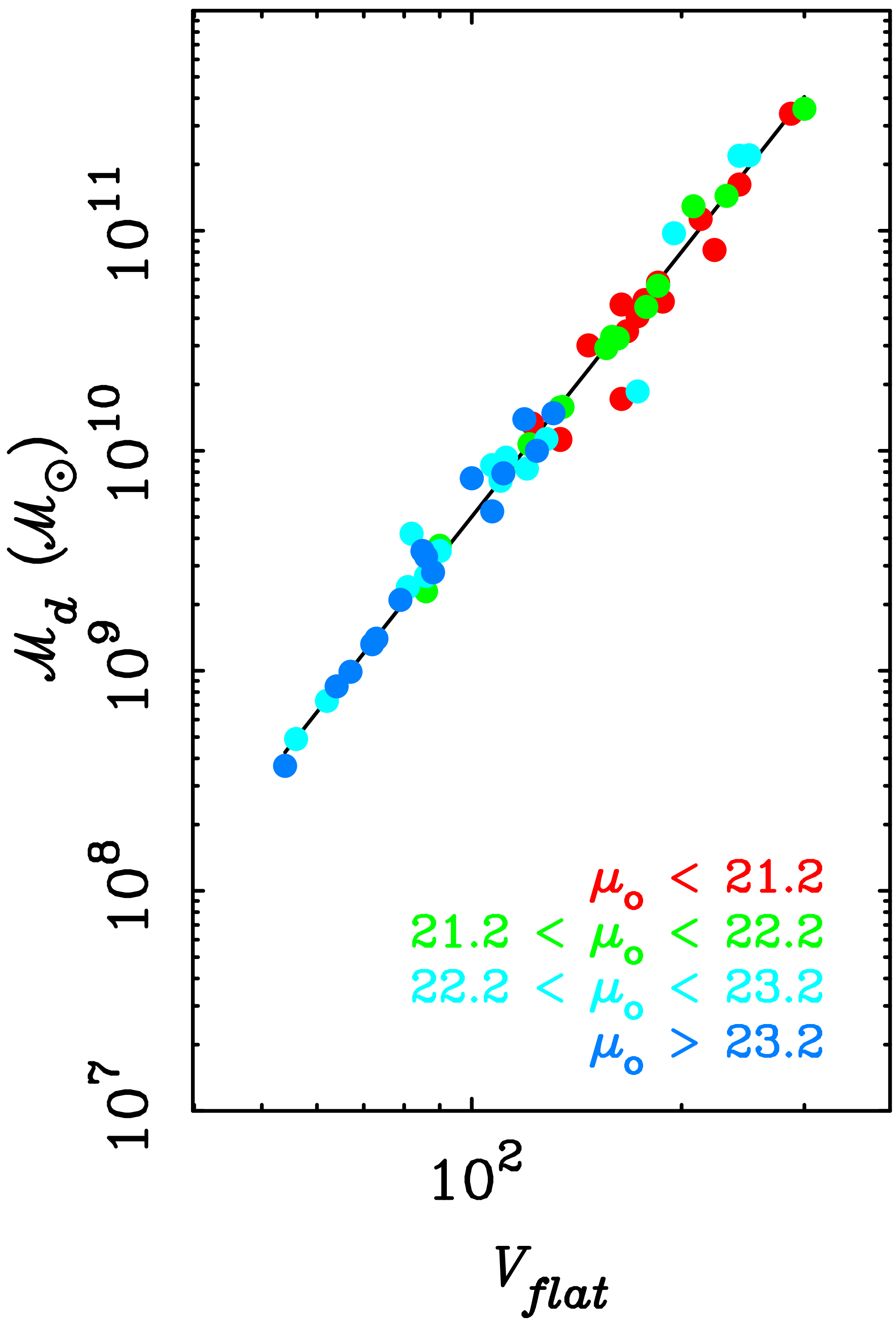
6. Disk galaxies with low surface brightness provide particularly strong tests (a study of a sample of such galaxies is described by Strom 1982 and by Romanishin *et al.* 1982). As low surface brightness means small accelerations, the effects of the modification should be more noticeable in such galaxies. 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 ... relat... additional as... the relation ... $\Sigma^{-1} V_\infty^4$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that low surface density galaxies, of ... mass higher than predicted by ... 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 ... sc... 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:



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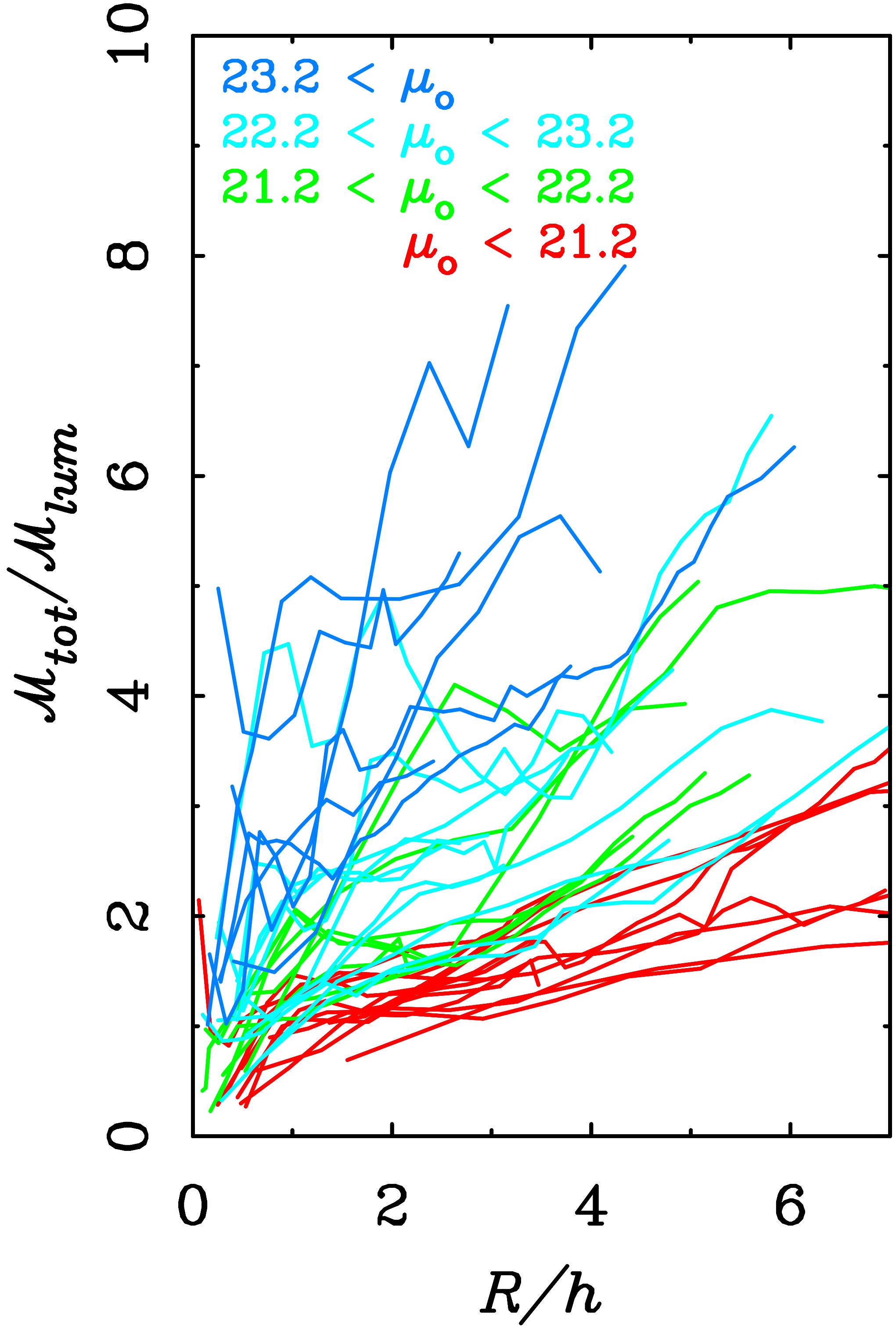

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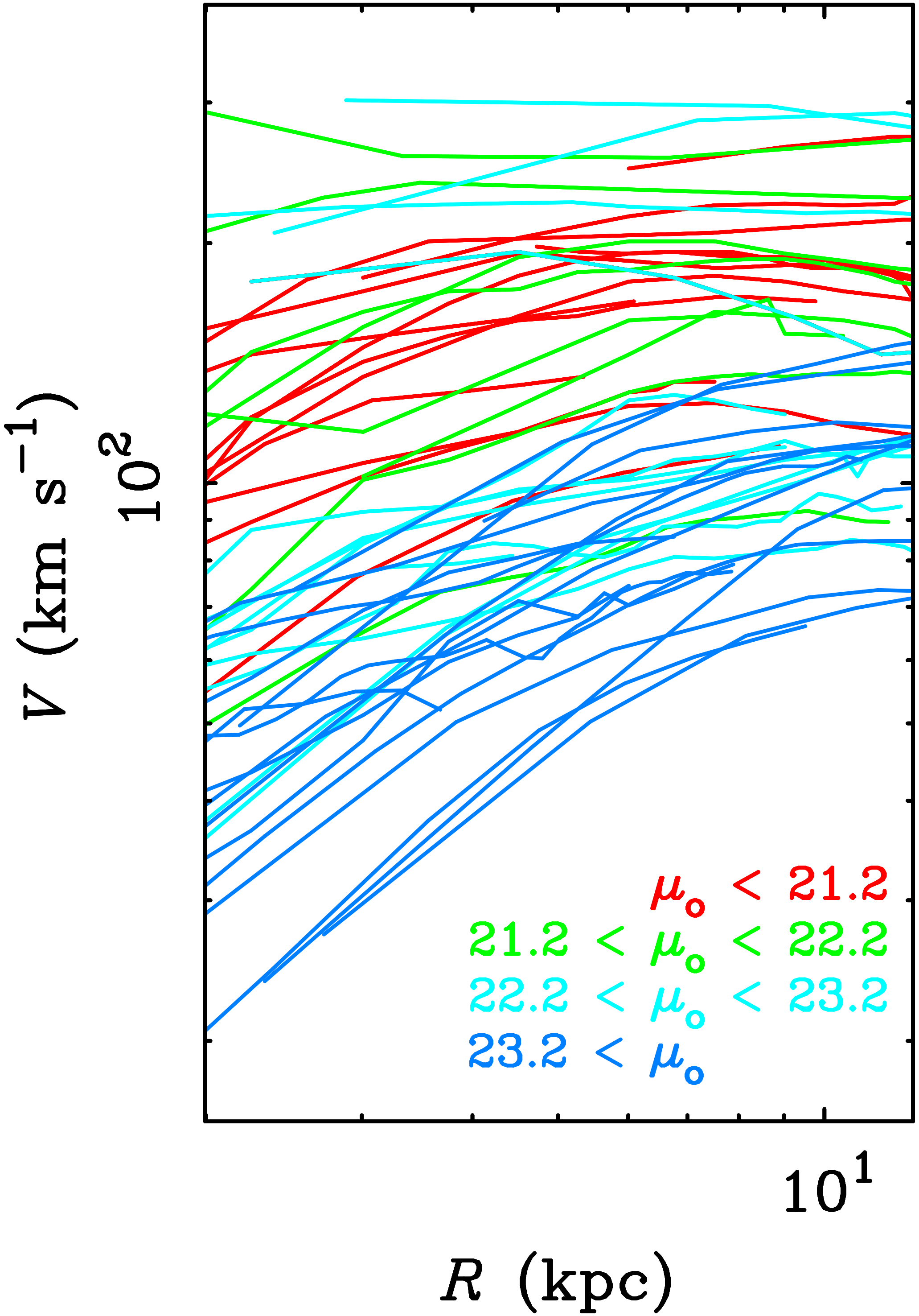

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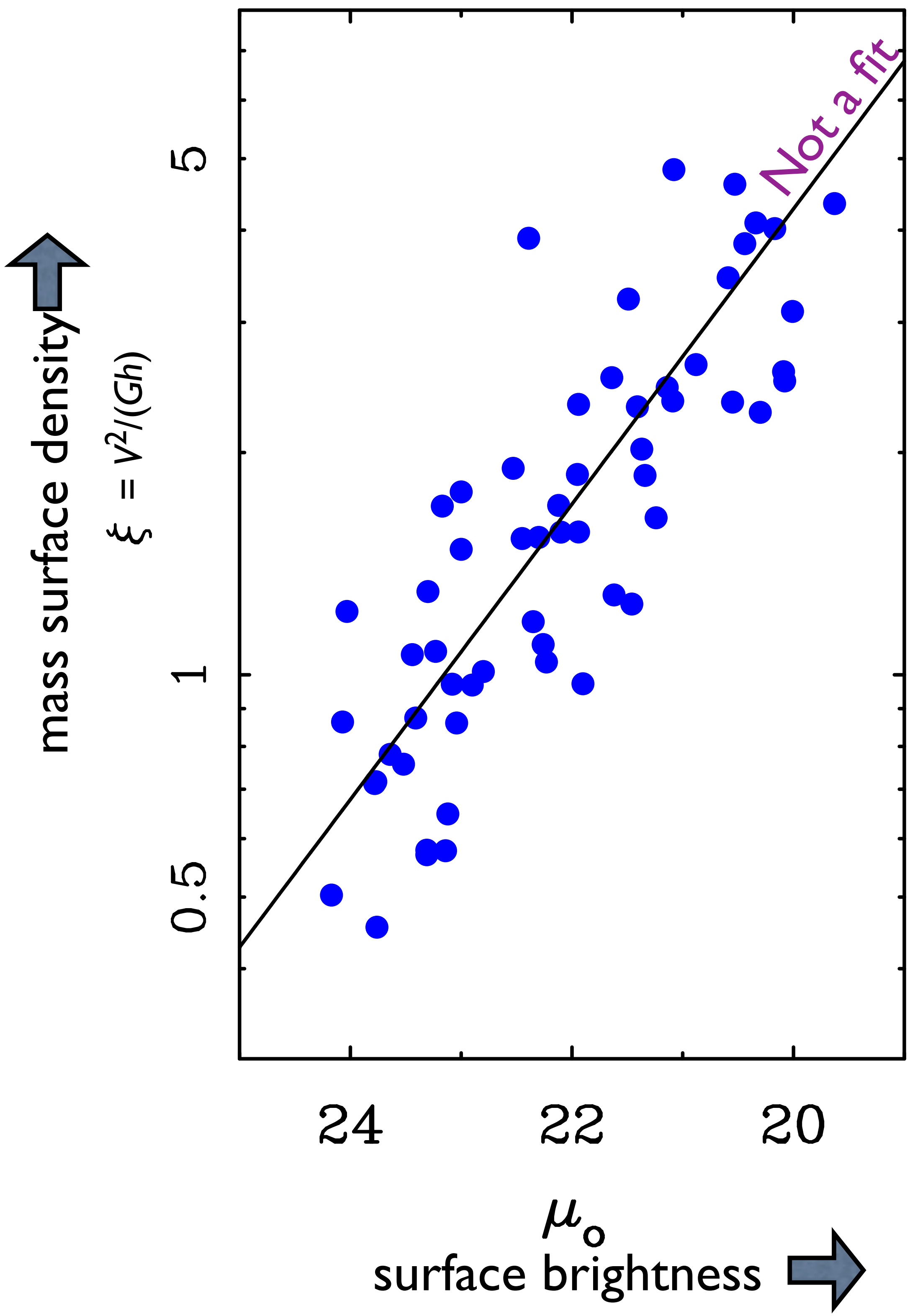

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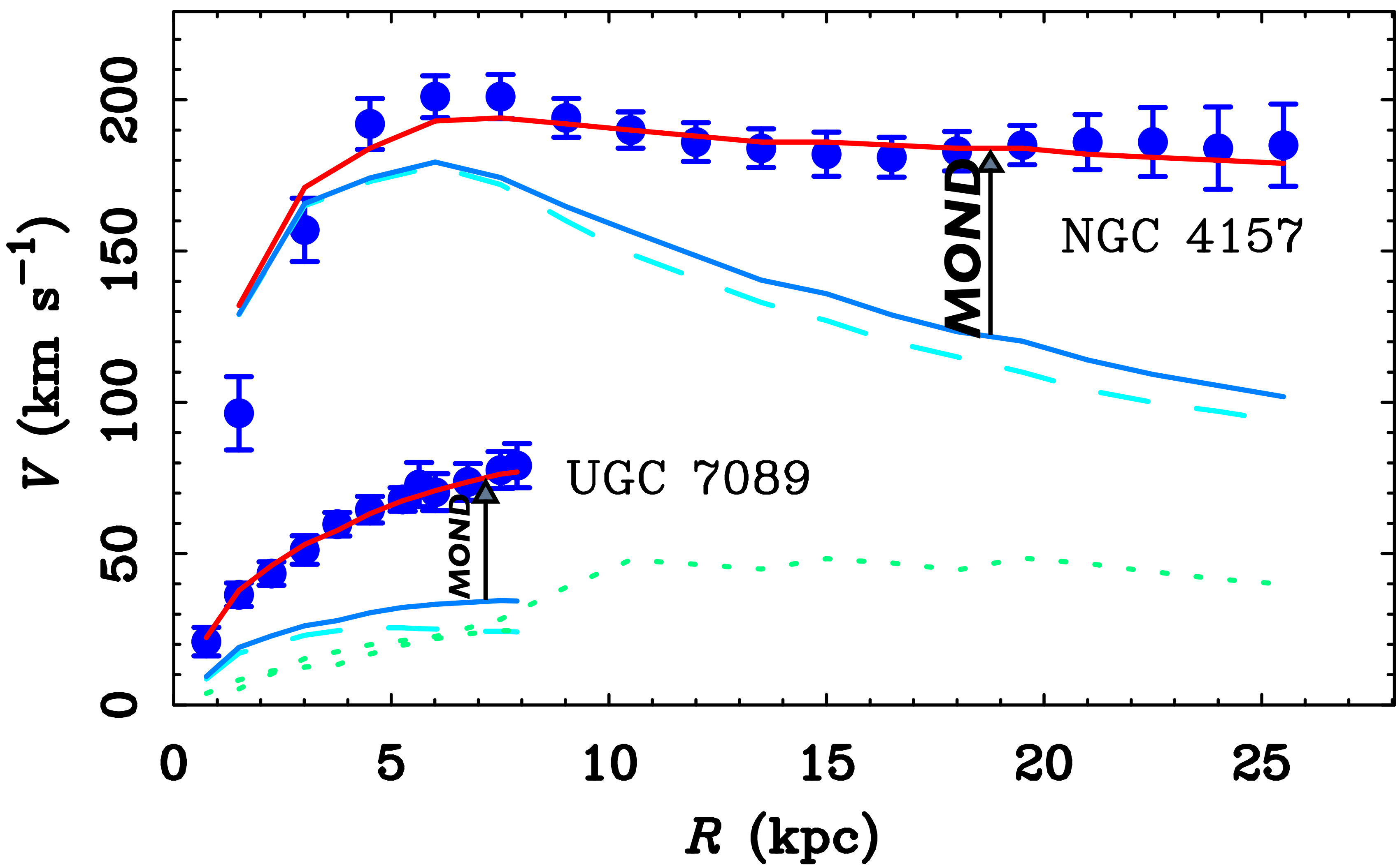
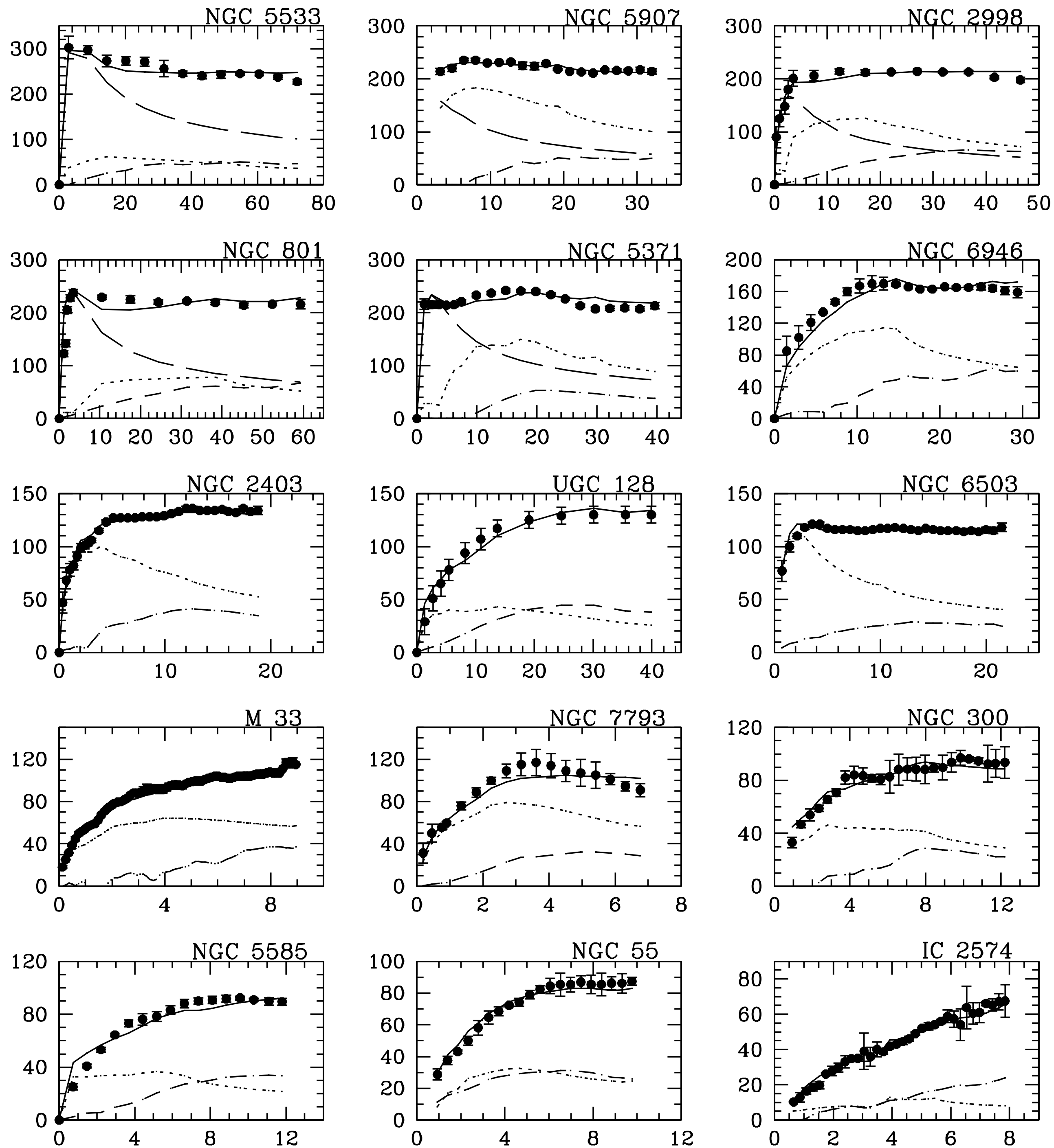
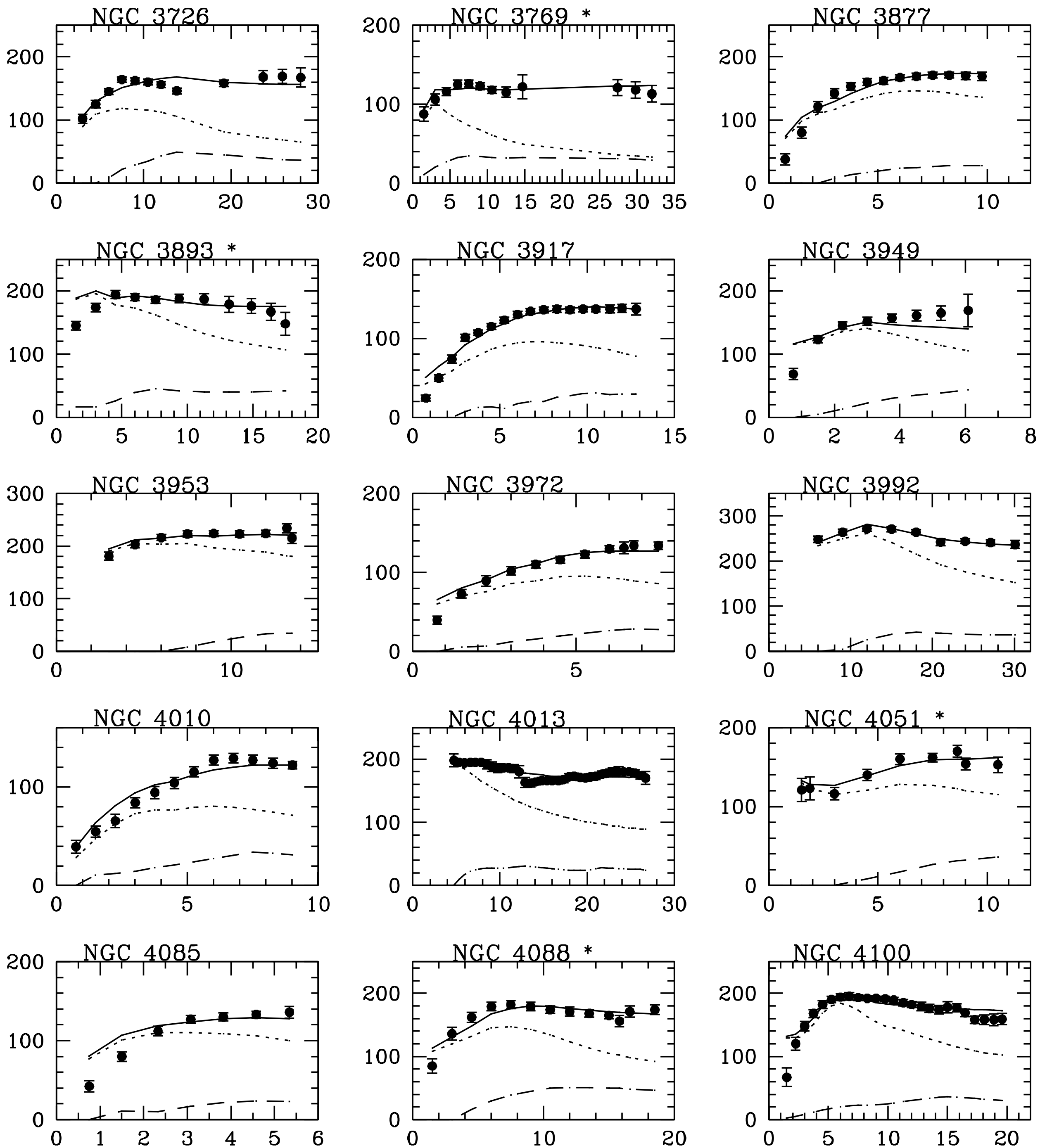


NGC 4157
UGC 7089
MOND
MOND
V (km s^{-1})
R (kpc)
0
50
100
150
200
0
5
10
15
20
25

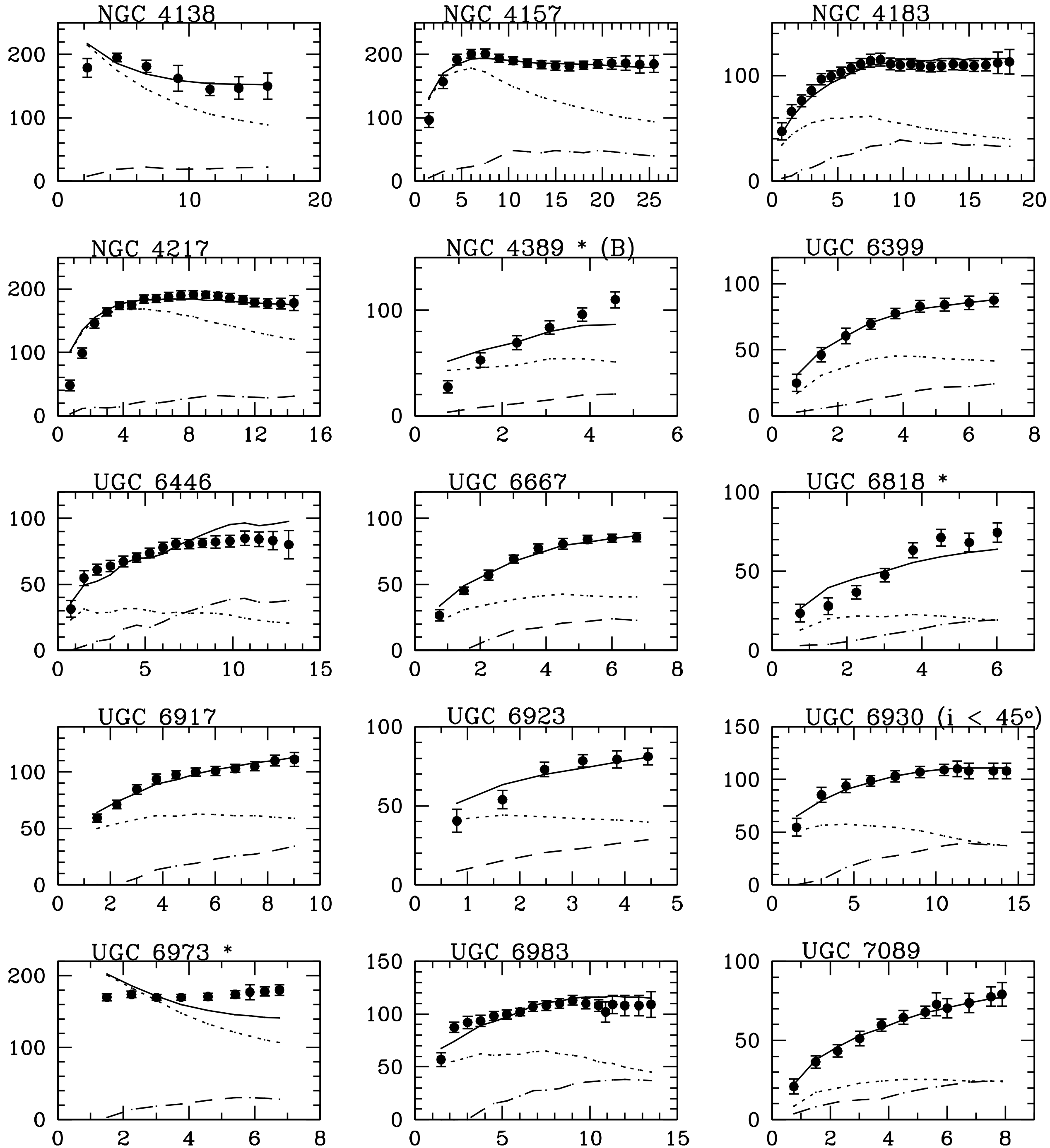
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



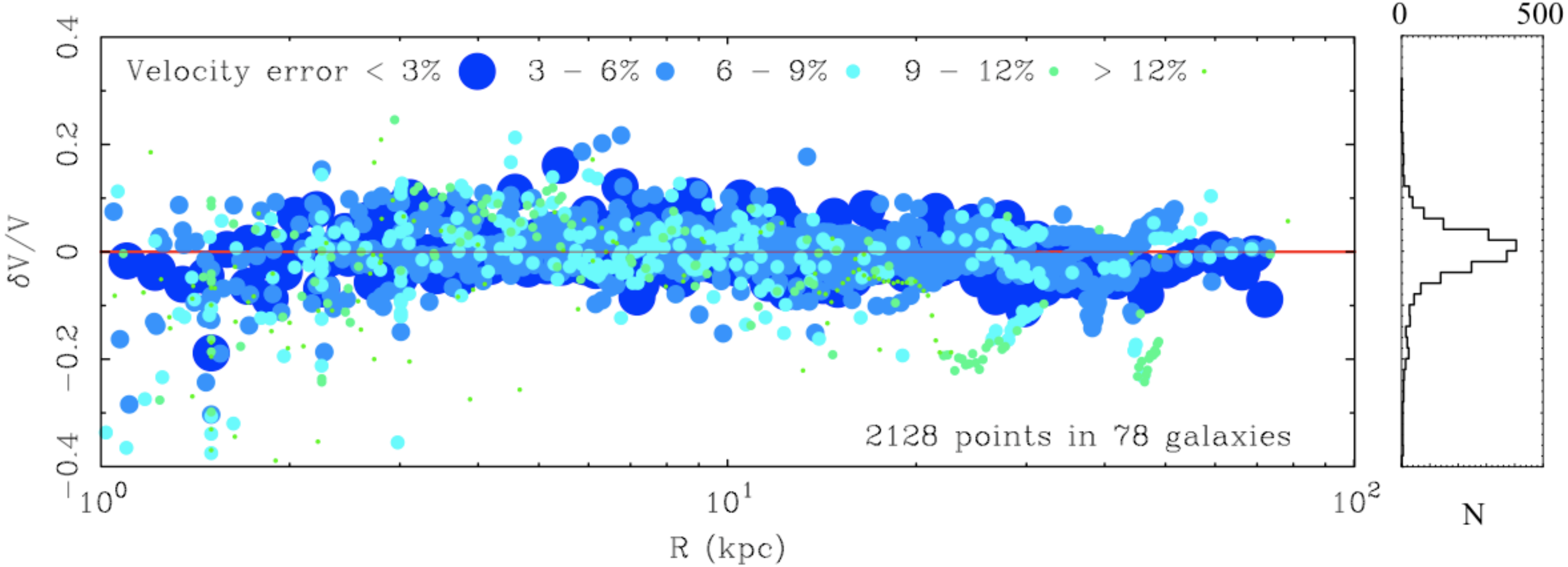
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



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



Residuals of MOND fits



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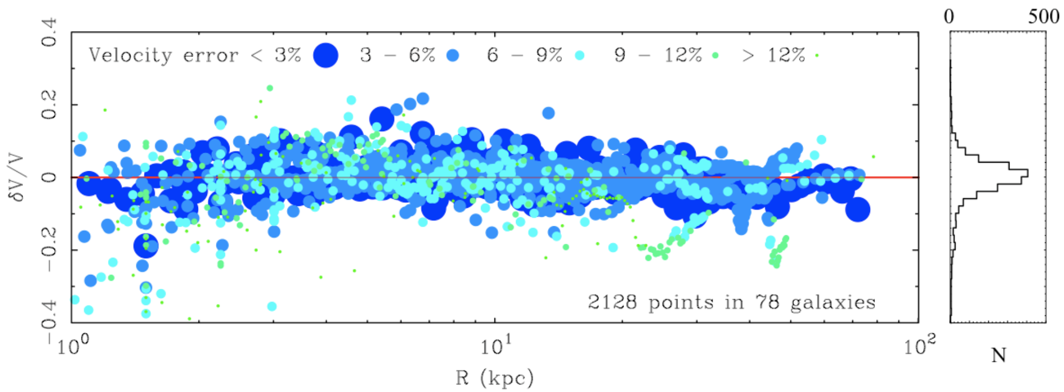
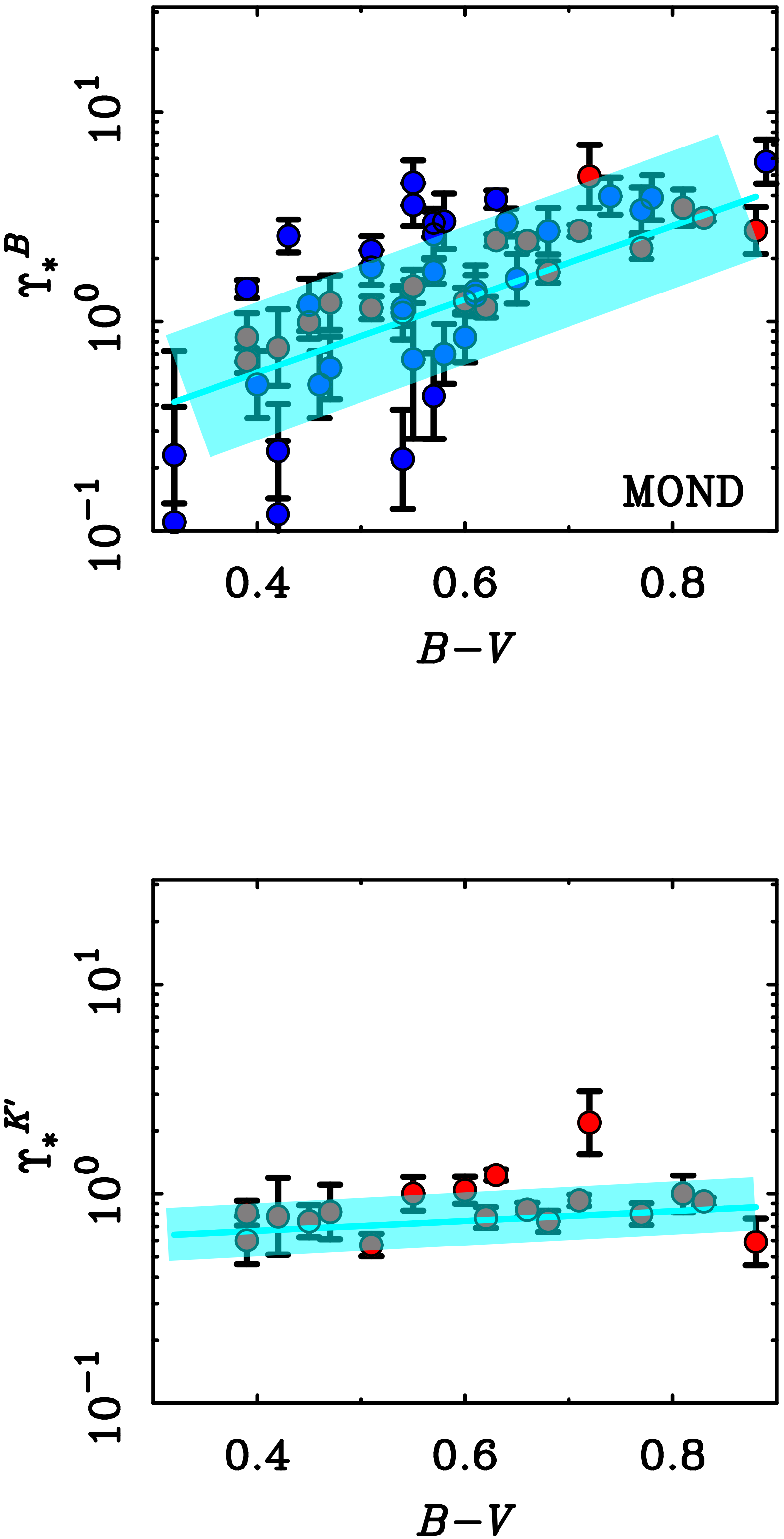
- ✔ Rotation Curve Shapes
- ✔ Surface Density ~ Surface Brightness
- ✔ Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios

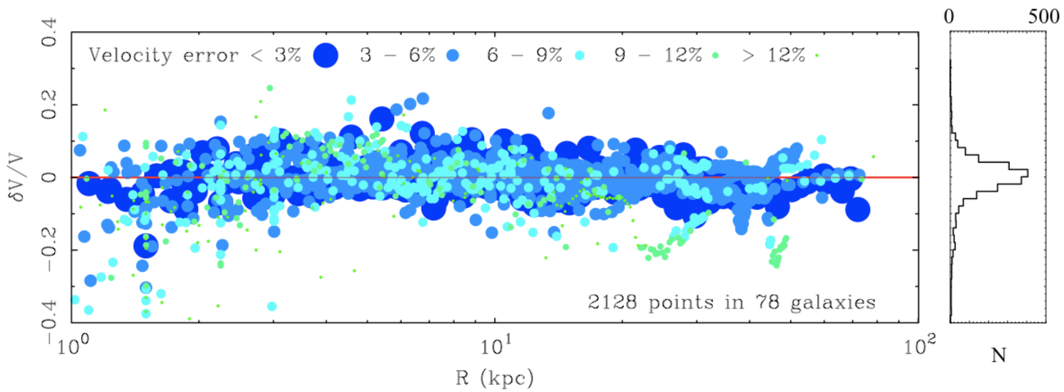


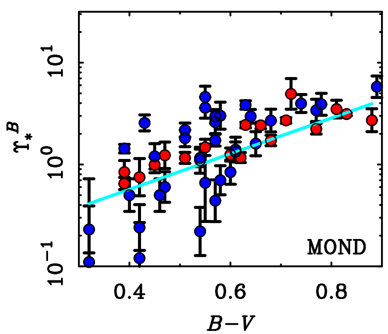


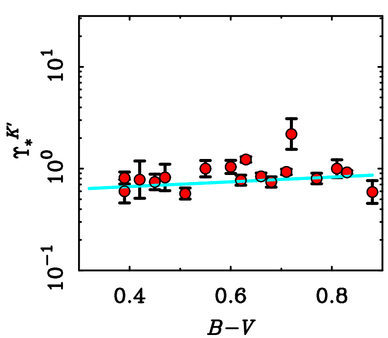
Line: stellar population model
(mean expectation)

MOND predictions

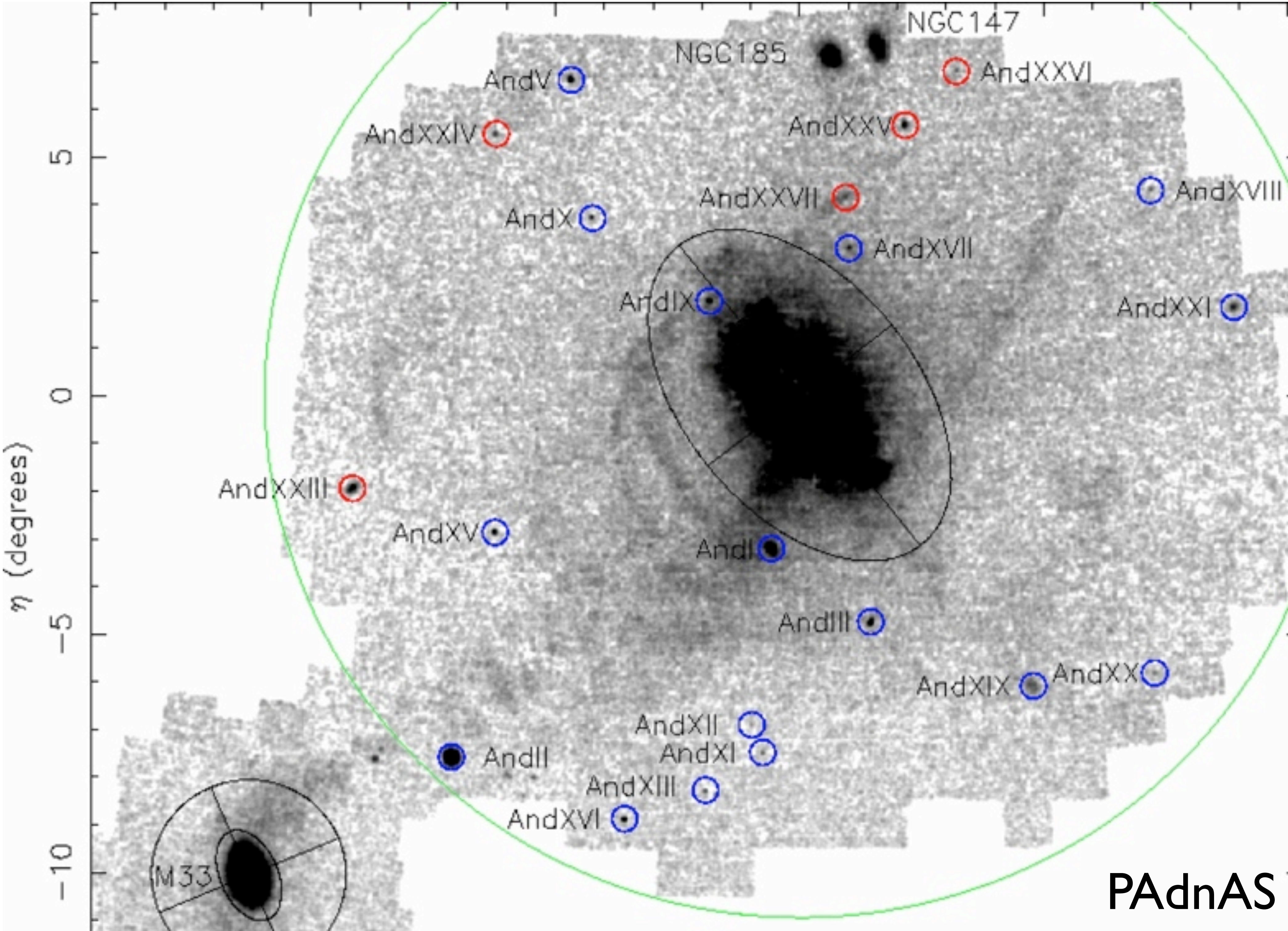
- The Tully-Fisher Relation
  - Slope = 4
  - Normalization = $1/(a_0 G)$
  - Fundamentally a relation between Disk Mass and V_{flat}
  - No Dependence on Surface Brightness
- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
- Surface Density ~ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios



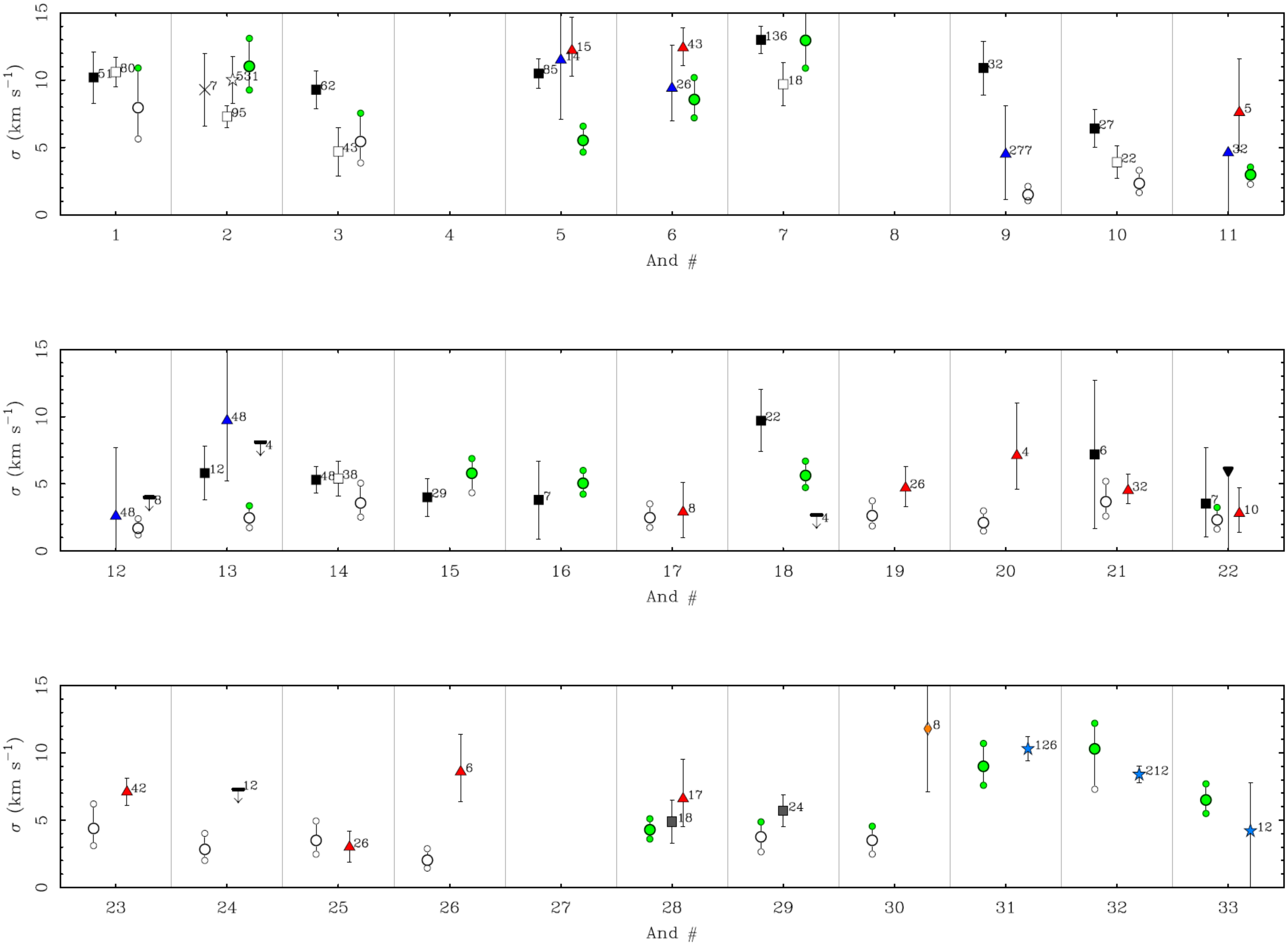




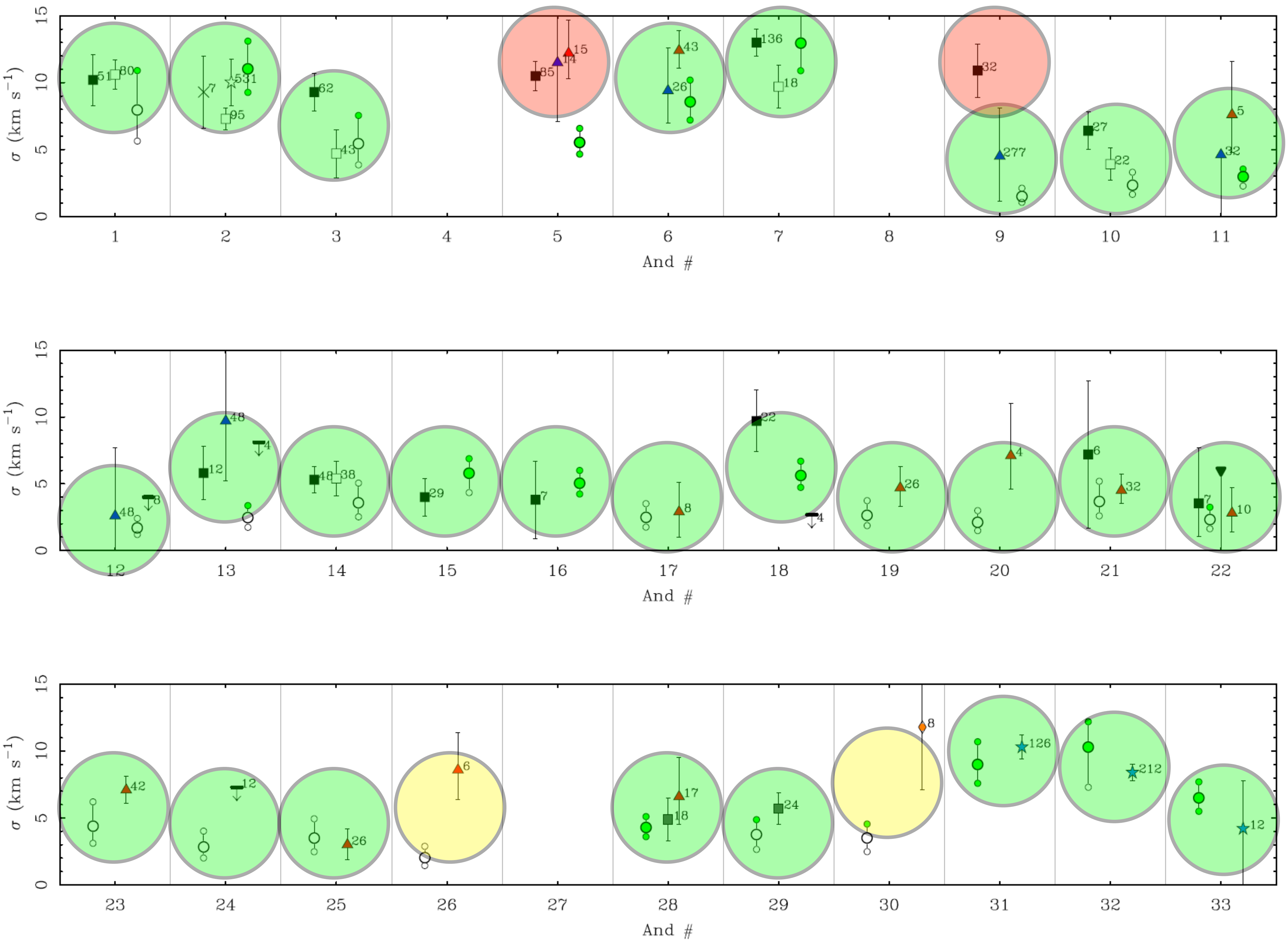
A new test: the dwarf satellites of Andromeda



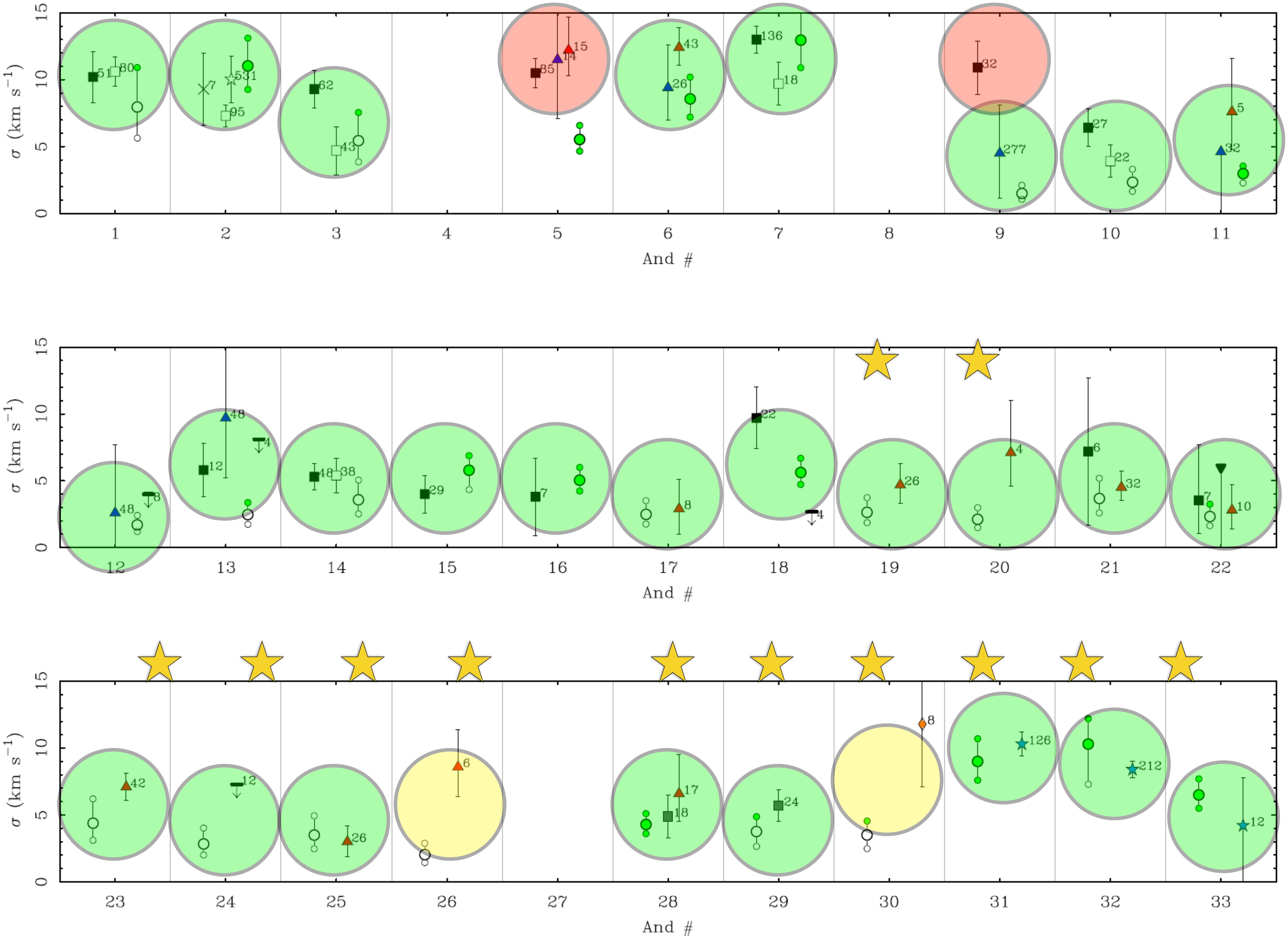
PAdnAS



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

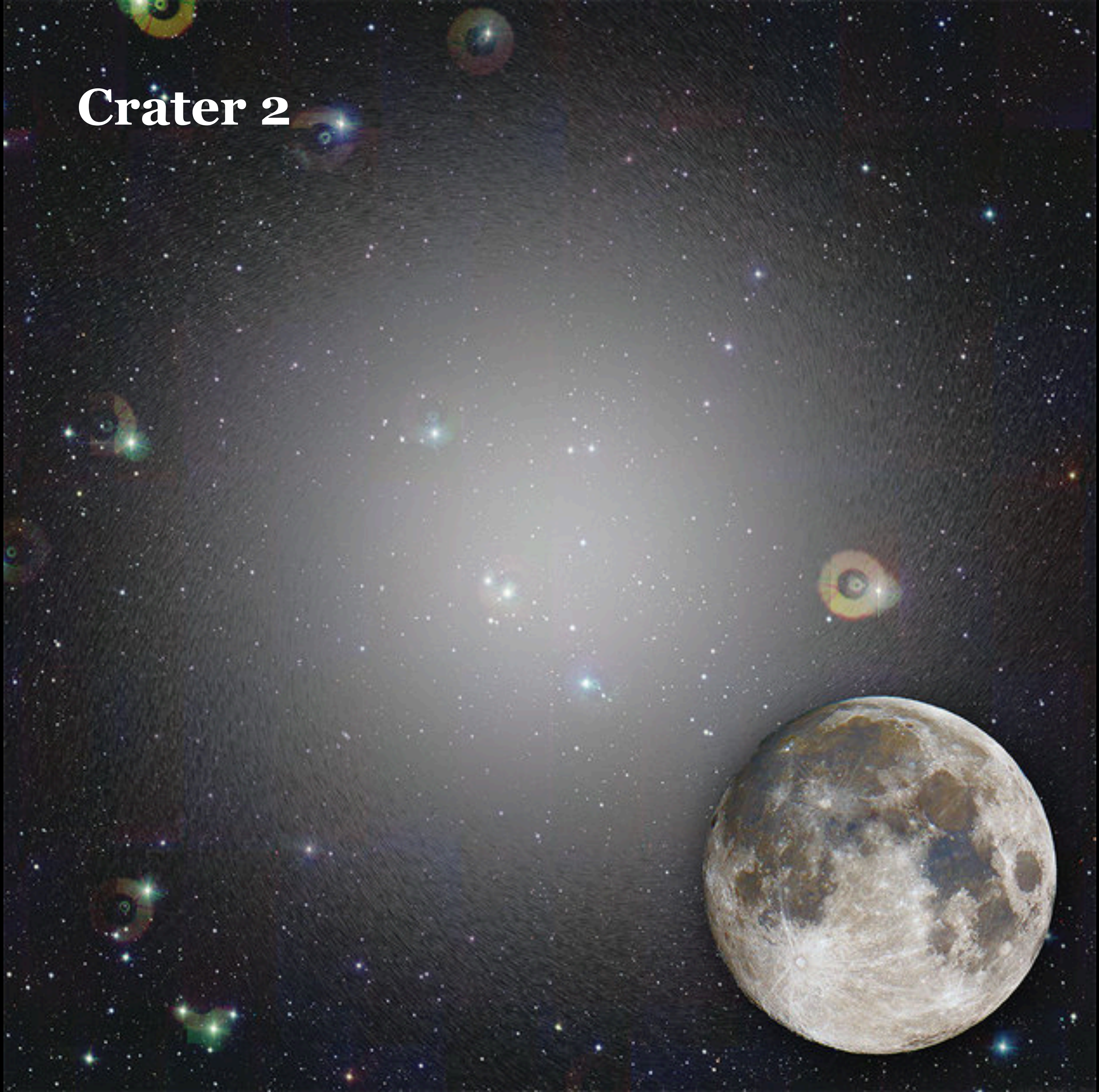


Velocity dispersions of M31 dwarfs correctly predicted (a priori in many cases) by MOND.



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

Crater 2



MOND

Crater 2

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

$$L_V = 1.6 \times 10^5 \; L_\odot$$
$$r_h = 1066 \; \text{pc}$$

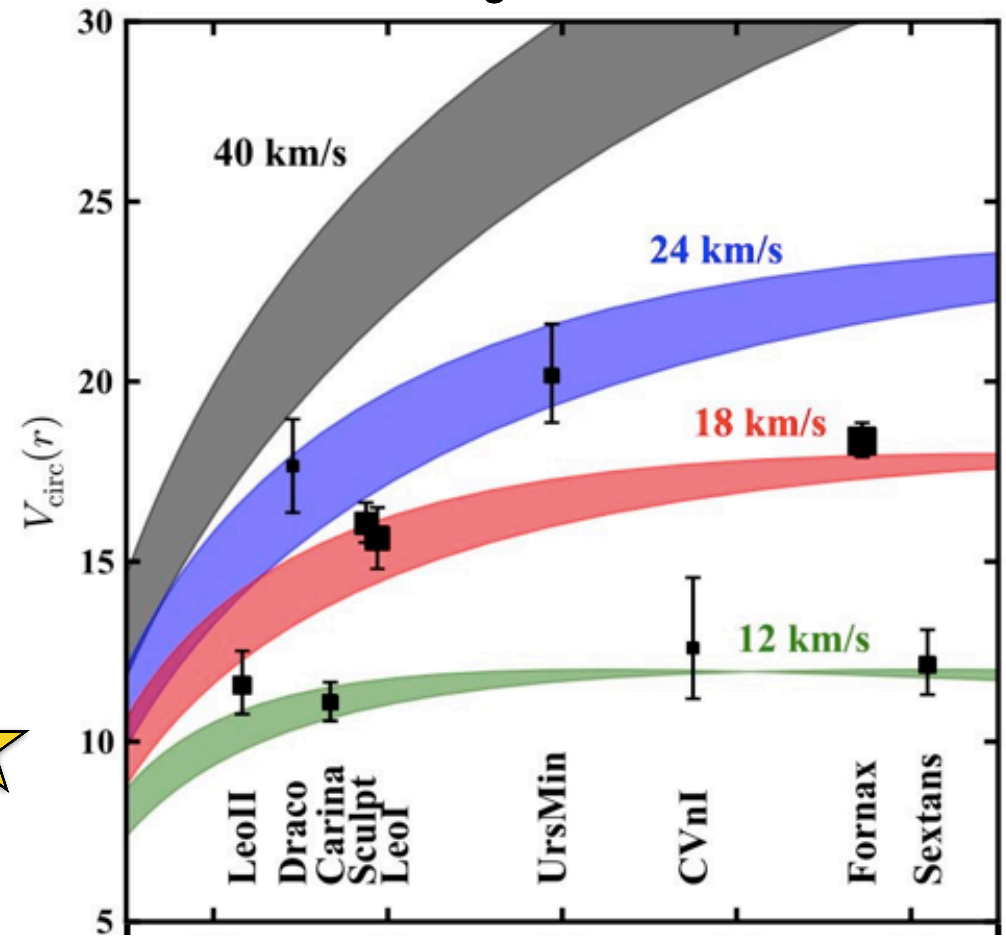
LCDM anticipates **10 - 17** km/s
(abundance matching; size-v. disp. rel'n)

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

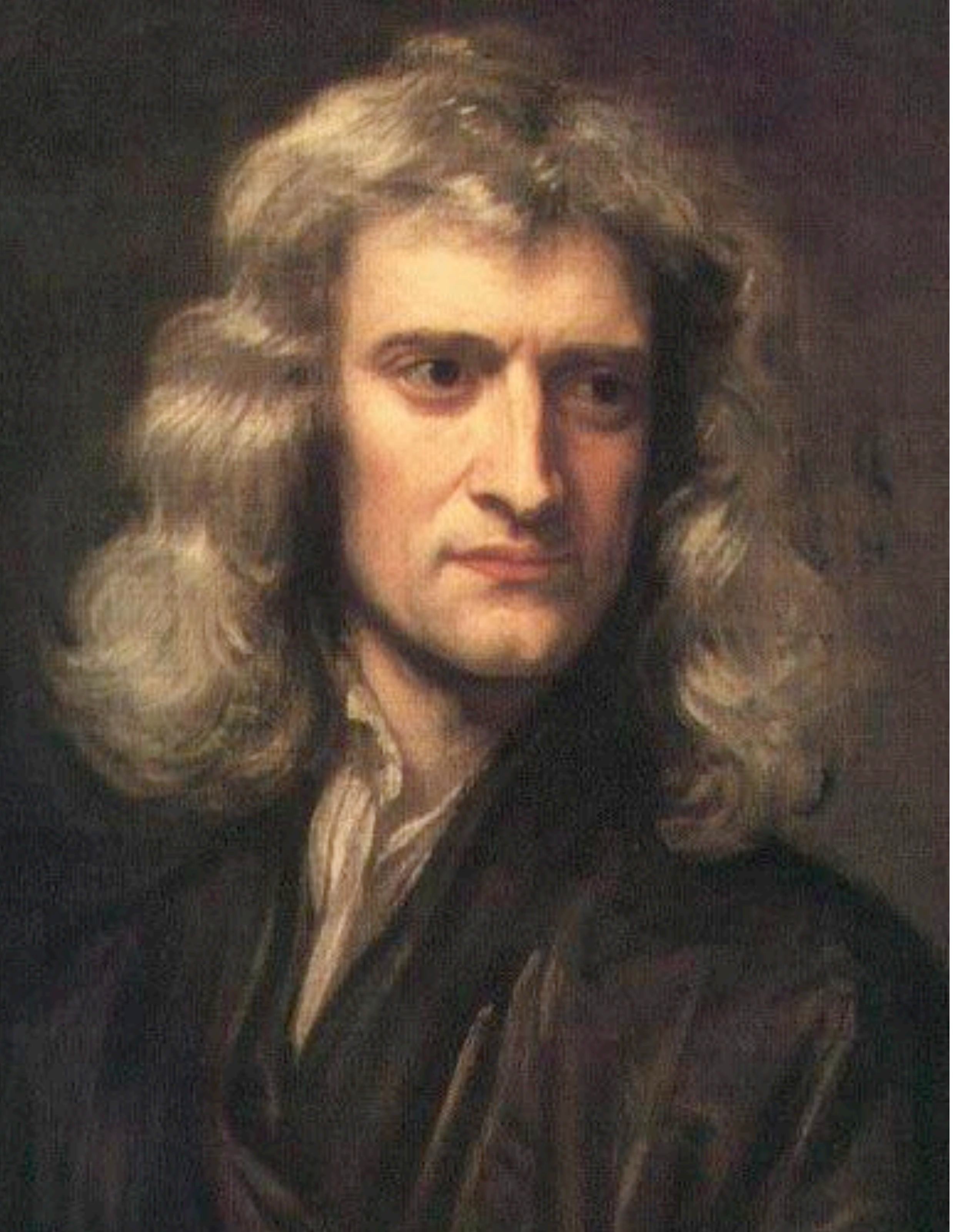
Subsequently observed: **2.7** ± 0.3 km/s
(Caldwell et al. arXiv:1612.06398)

Consistent with a priori MOND prediction ☆

Boylan-Kolchin et al. (2012) MNRAS, 422, 1203
"Too Big To Fail"



Why does MOND get this - or *any* - prediction right?



Everything happens *as if*

$$F = m\underline{g_N} = \frac{GMm}{r^2}$$

Except in galaxies, where everything happens *as if*

$$\frac{V^2}{r} = \sqrt{\underline{g_N}a_0}$$

↑ centripetal acceleration

What? No dark matter!
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?

Scientific discourse

Dark Matter does too exist. Or not.