Toledo Astronomical Association
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Dark Matter or Modified Gravity?

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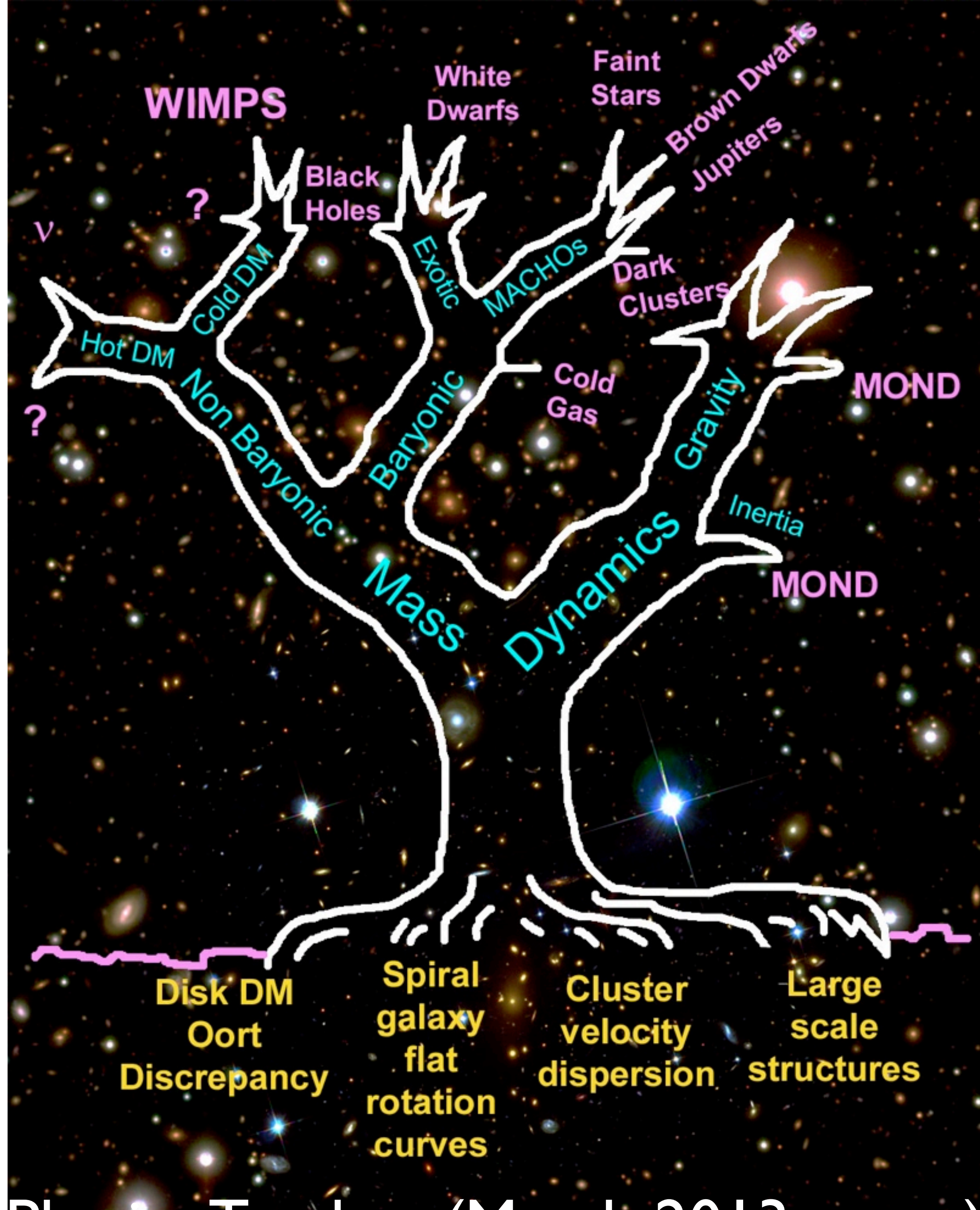


Physics Teacher (March 2013 cover)

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

It's what we know for sure that just aint so.

\- Mark Twain

A few things we know for sure...

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

$$F = ma$$

which basically means

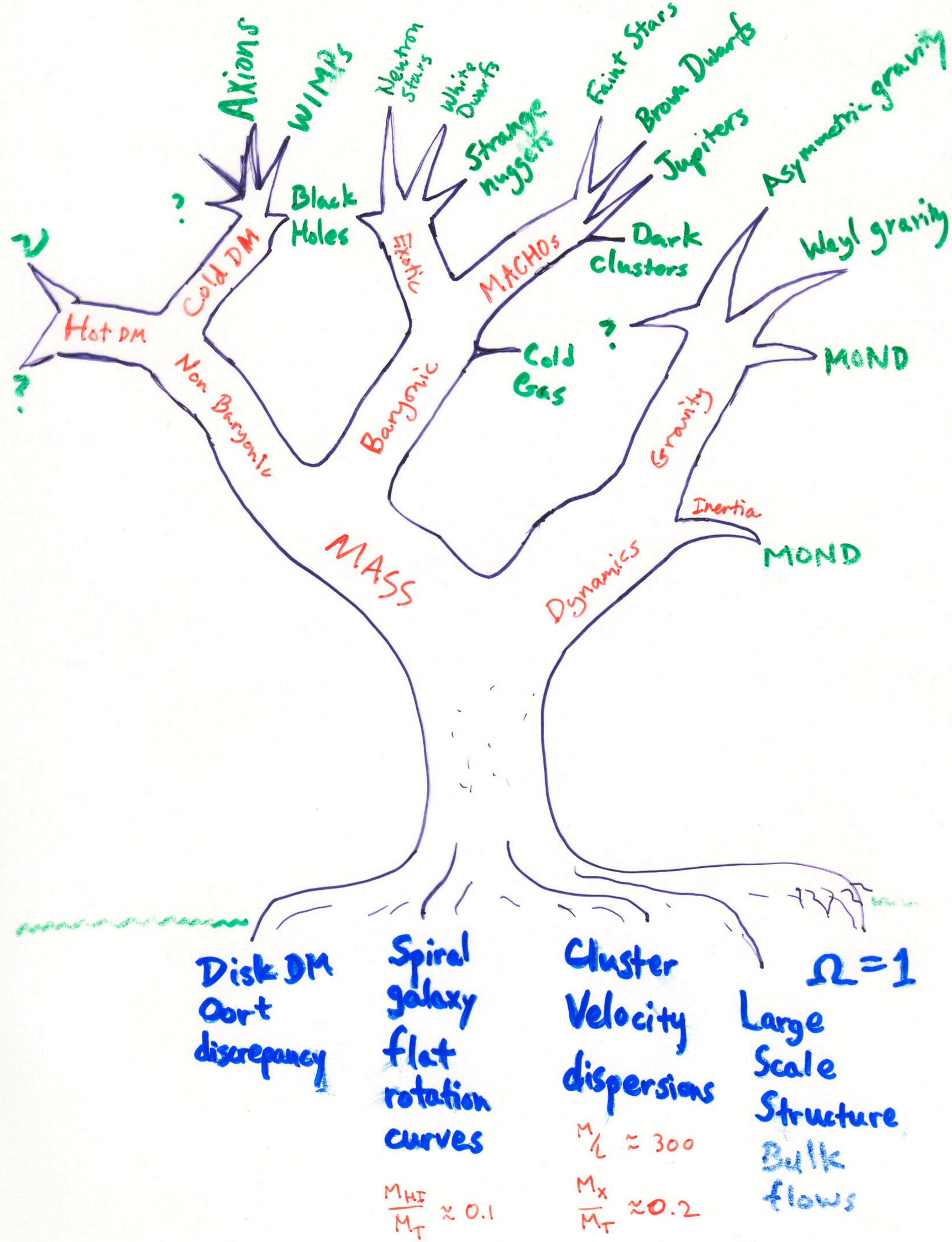
$$mV^2/R = GMm/R^2$$

i.e,

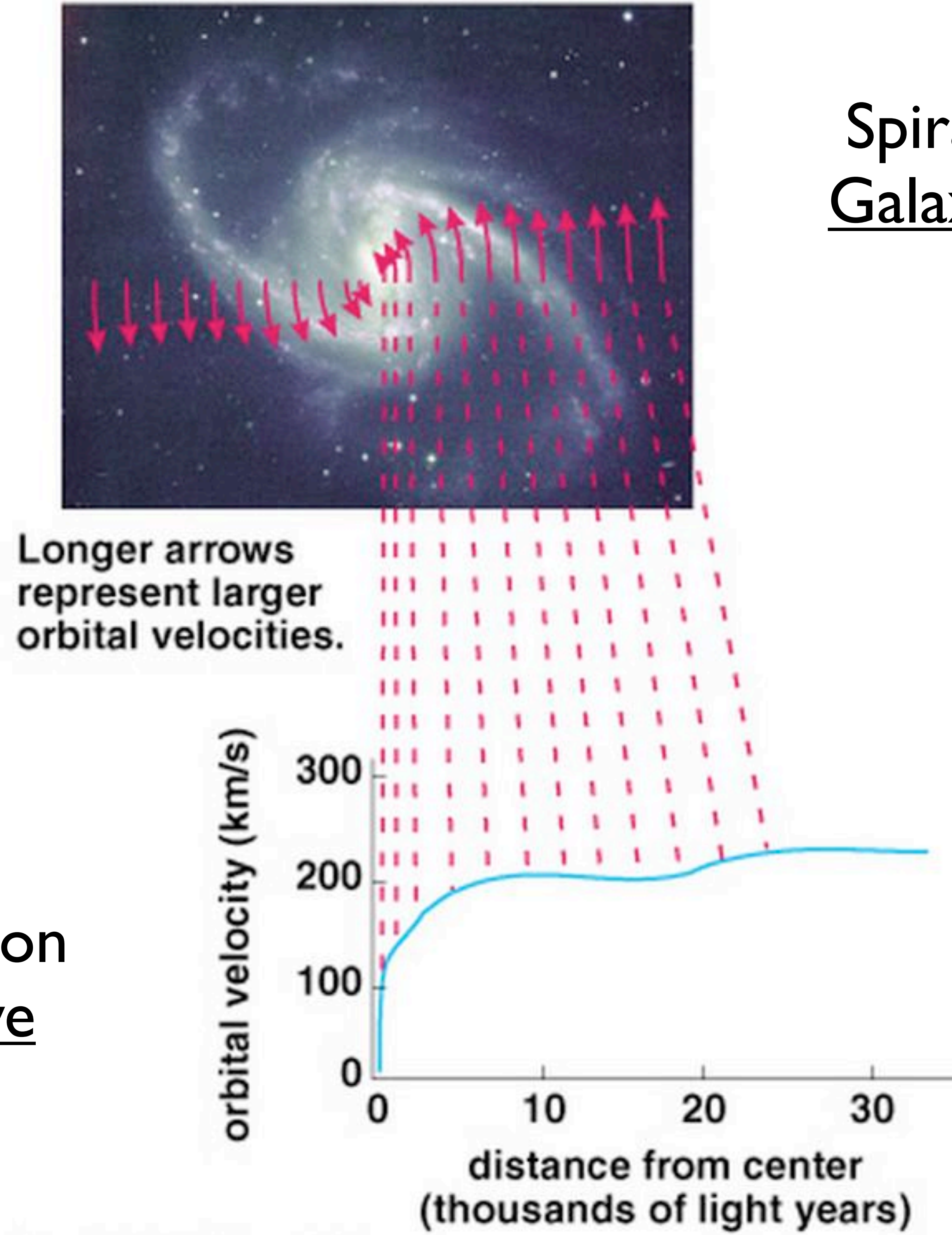
$$V^2 = GM/R$$

ergo...

The universe is filled with nonbaryonic cold dark matter.

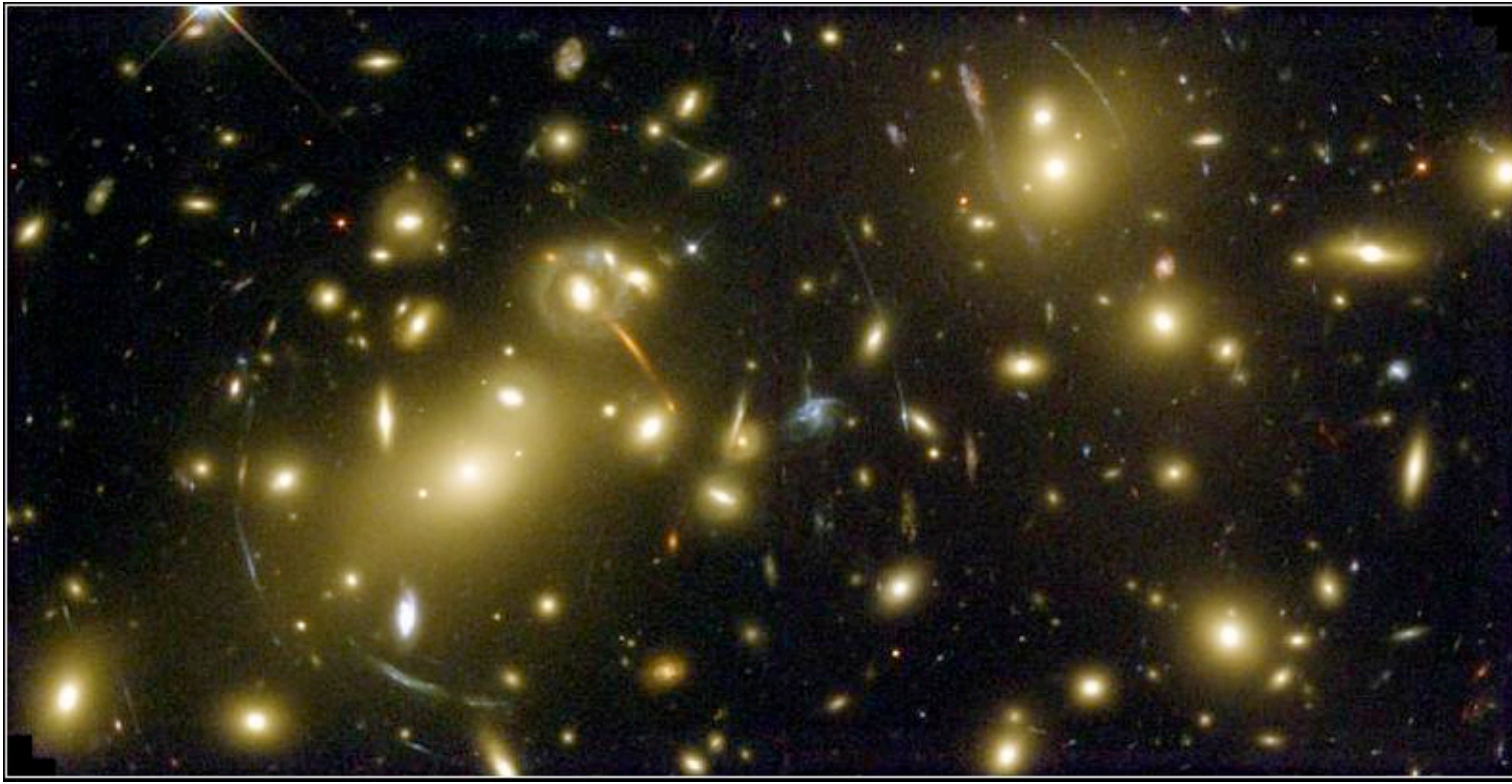

Axions
WIMPs
Neutron Stars
White Dwarfs
Faint Stars
Brown Dwarfs
Jupiters
Asymmetric gravity
Strange nuggets
Black Holes
Dark Clusters
Weyl gravity
?
?
?
?
Cold DM
Hot DM
Exotic
MACHOs
Cold Gas
MOND
Non Baryonic
Baryonic
Gravity
Inertia
MOND
MASS
Dynamics
Disk DM
Oort discrepancy
Spiral galaxy flat rotation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

Spiral Galaxy

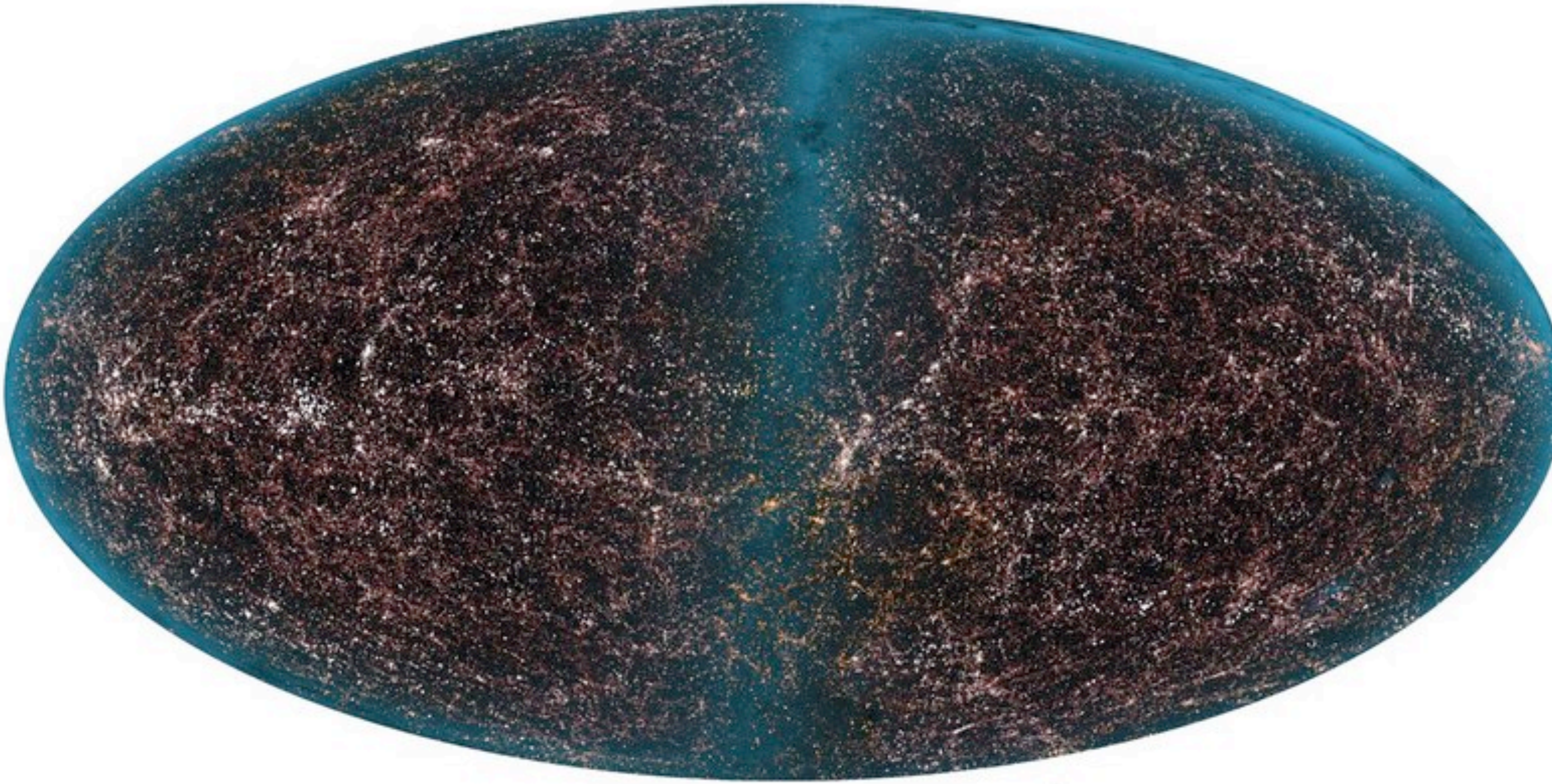


Rotation Curve

Galaxy Cluster



Large Scale Structure



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

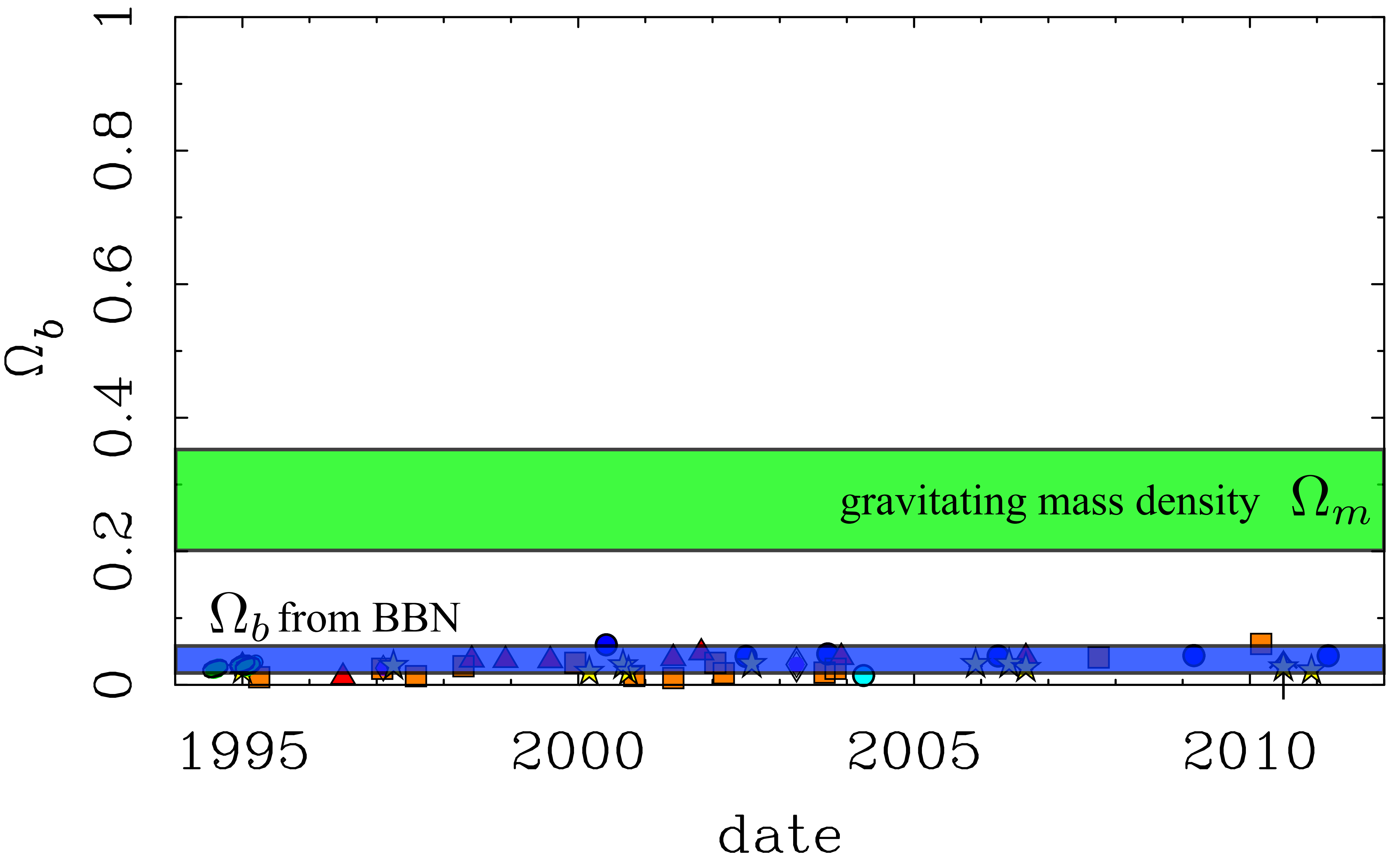
doesn't interact with light, so quite invisible.

Two big motivations:

1) total mass outweighs normal mass from BBN

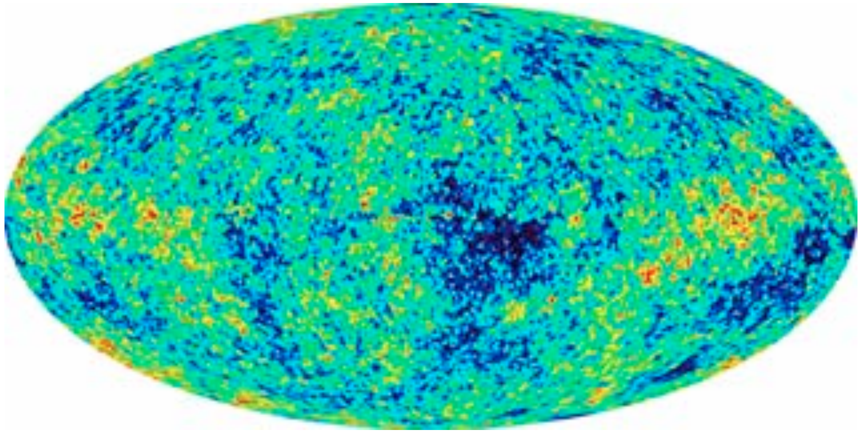
2) needed to grow cosmic structure

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



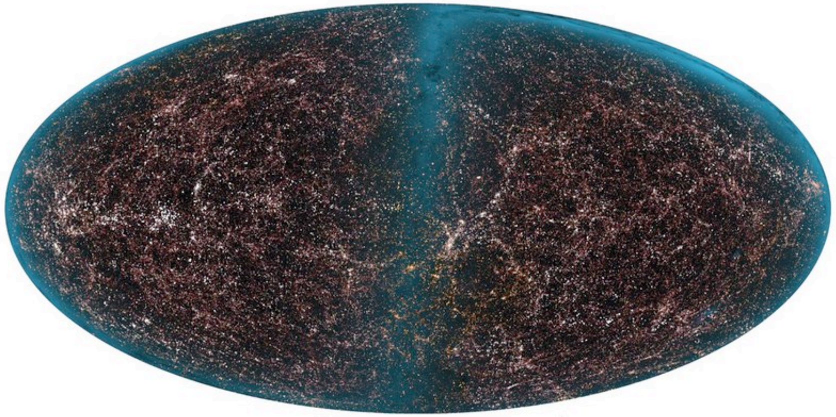
(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

t = 1.8 x 10^5 yr



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

t = 1.4 x 10^{10} yr



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

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

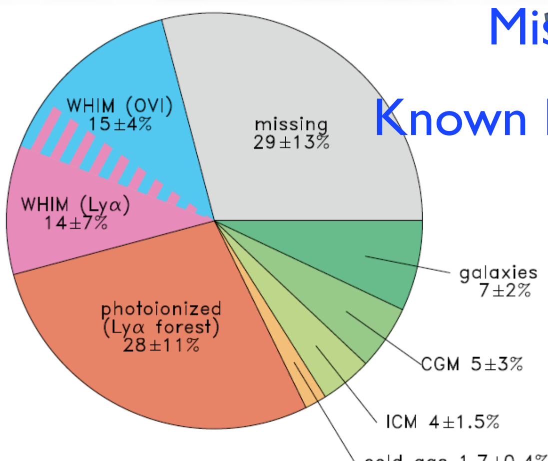
Dark matter is commonly thought to be a new particle called a WIMP

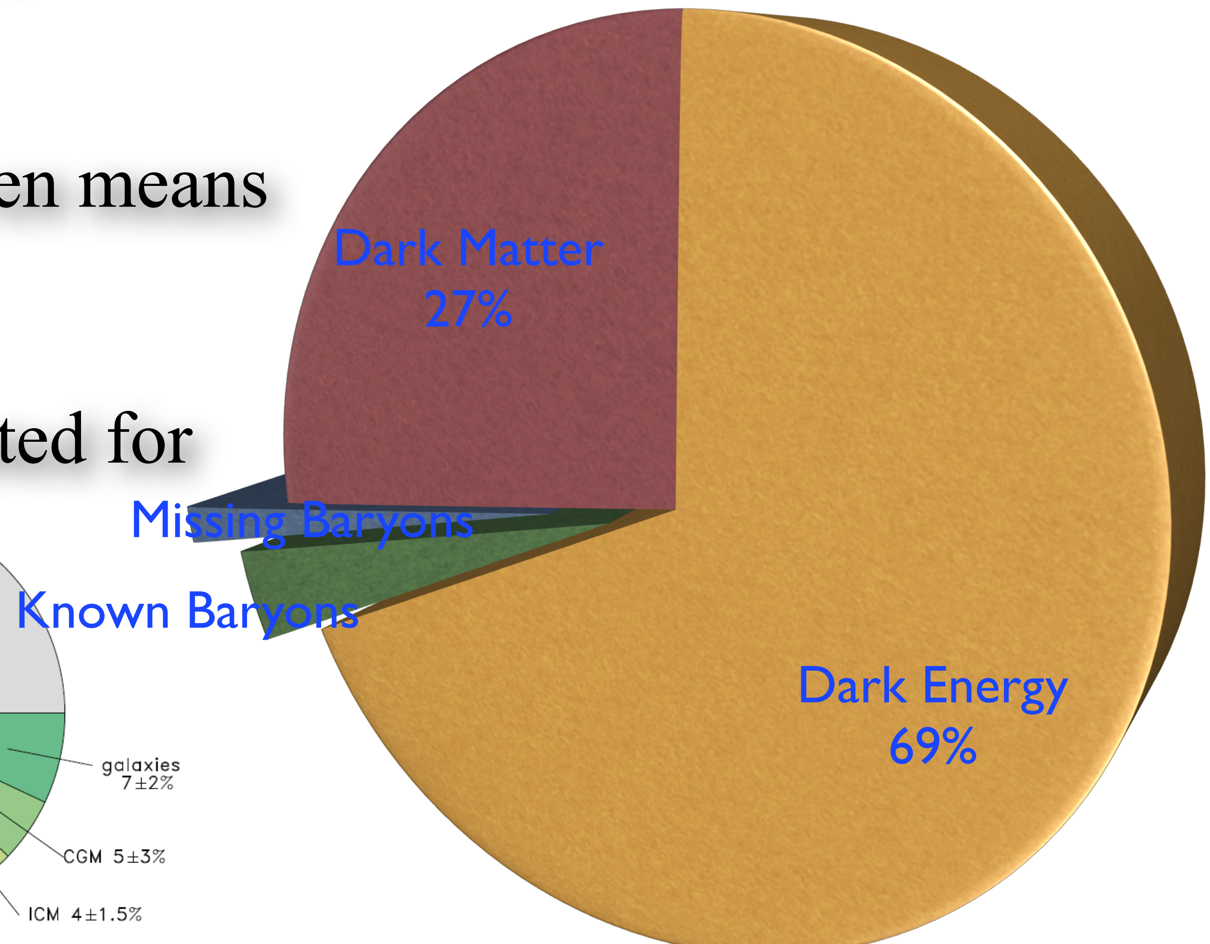
Cosmology only works with

- non-baryonic cold dark matter
  - whatever it is (e.g., WIMPs)

- dark energy
  - whatever that even means

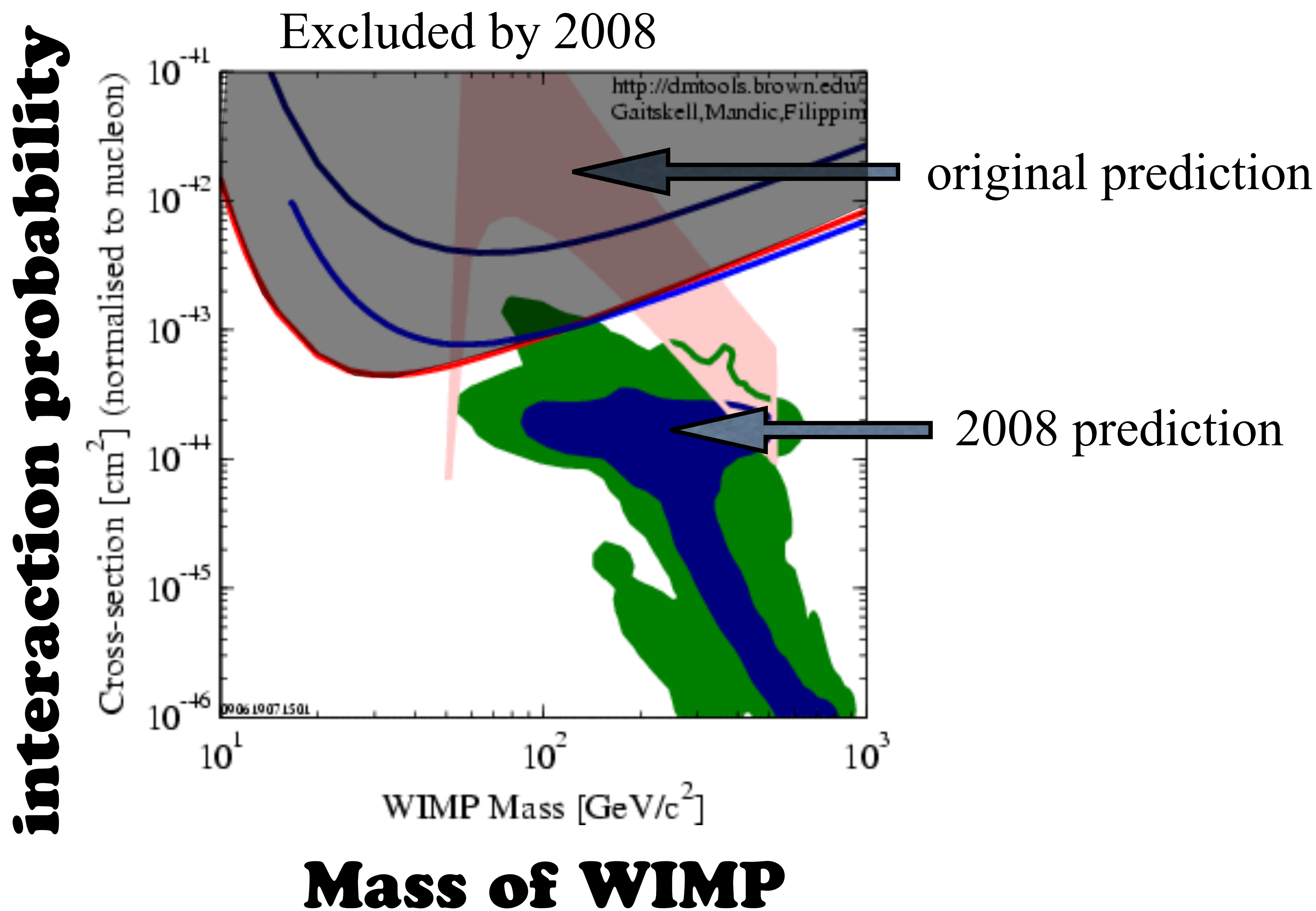
- dark baryons
  - 29% not accounted for



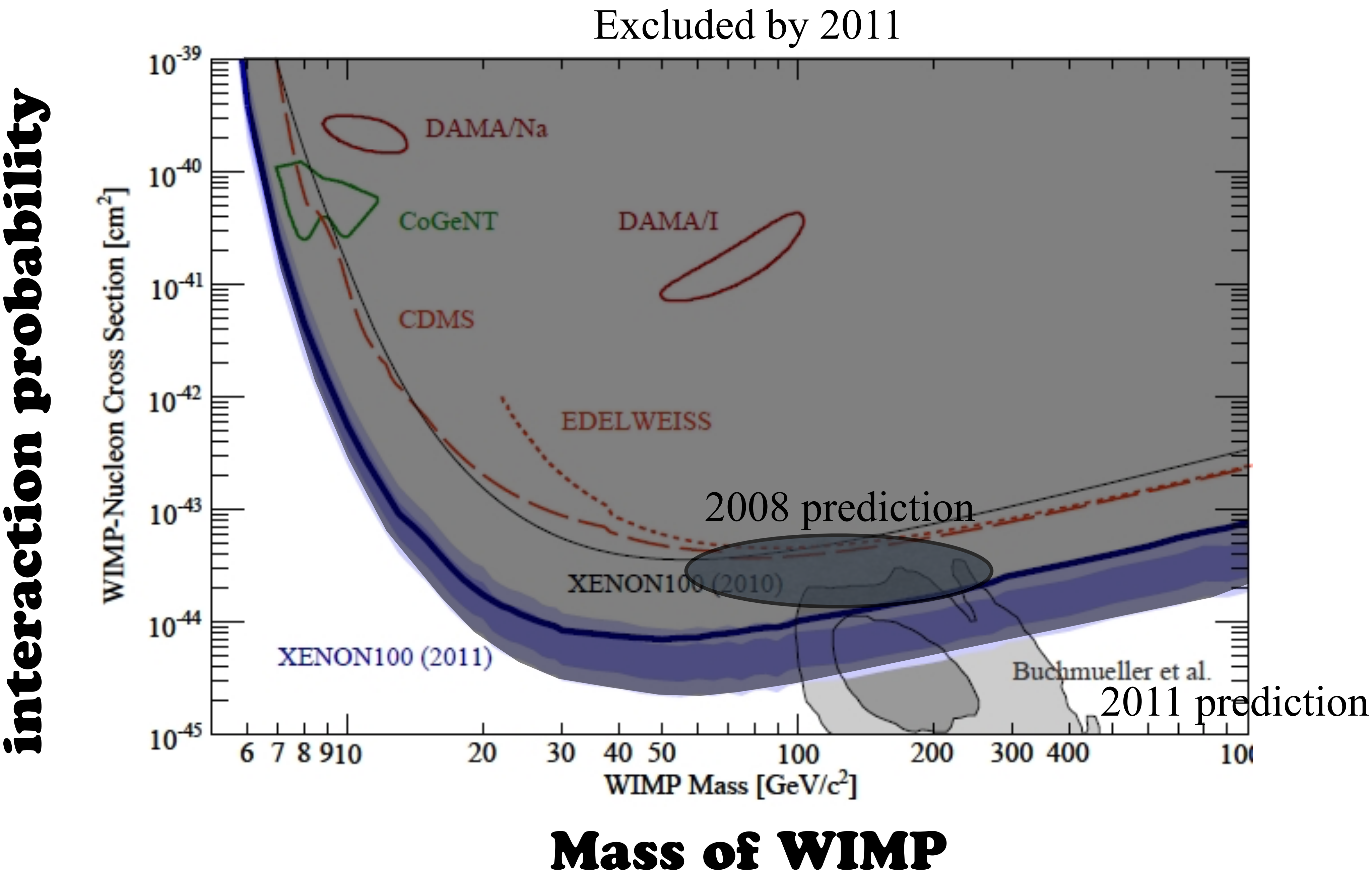


We have direct knowledge of only 3.5% of the total mass-energy density of the universe

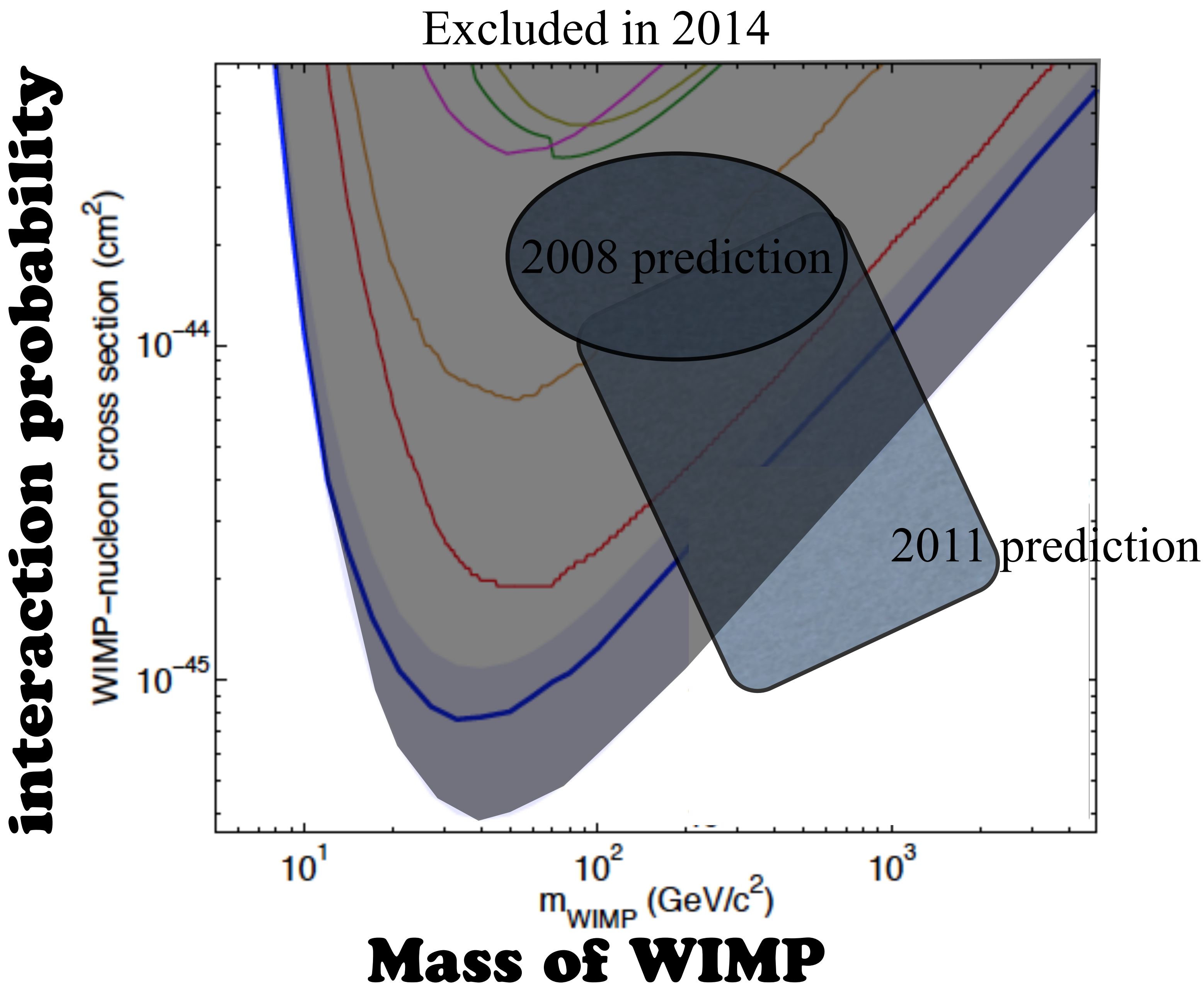
Dark matter is commonly thought to be a new particle called a WIMP



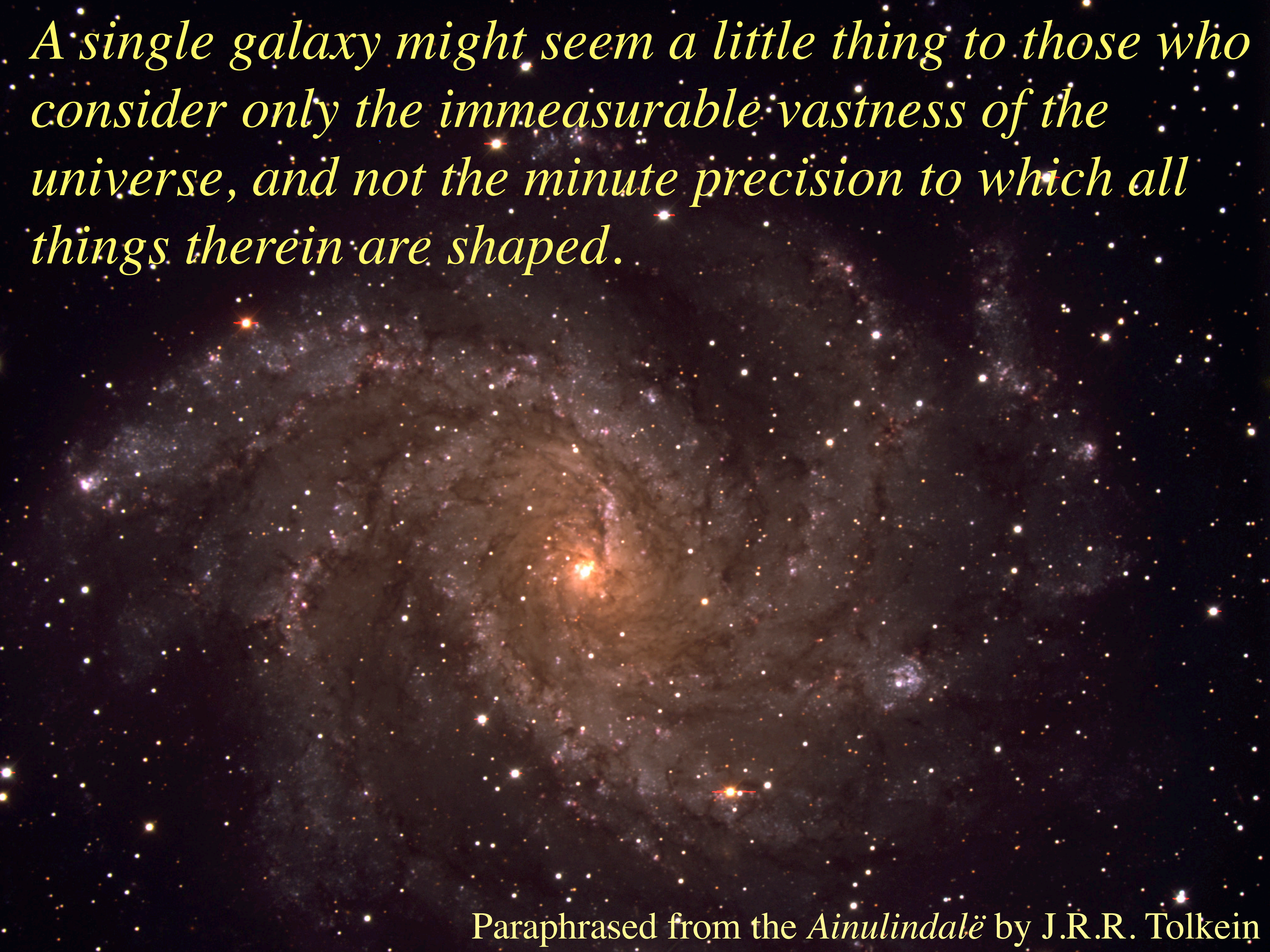
WIMP detection experiments



Excluded by 2011
interaction probability
WIMP-Nucleon Cross Section [cm²]
DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS
2008 prediction
XENON100 (2010)
XENON100 (2011)
Buchmueller et al.
2011 prediction
WIMP Mass [GeV/c²]
Mass of WIMP

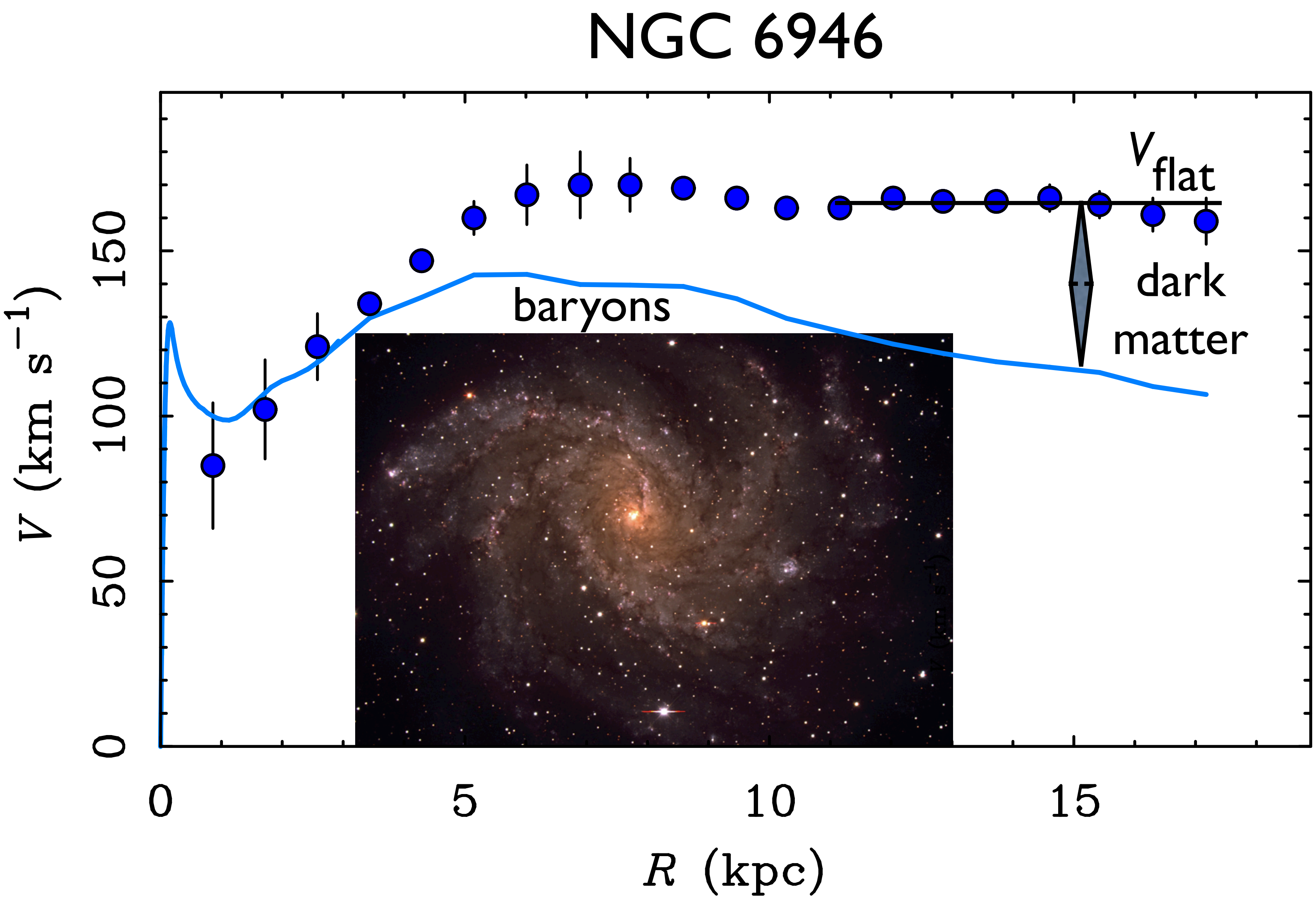


Excluded in 2014
2008 prediction
2011 prediction
interaction probability
WIMP–nucleon cross section (cm^2)
10^{-44}
10^{-45}
10^1
10^2
10^3
m_{WIMP} (GeV/c^2)
Mass of WIMP



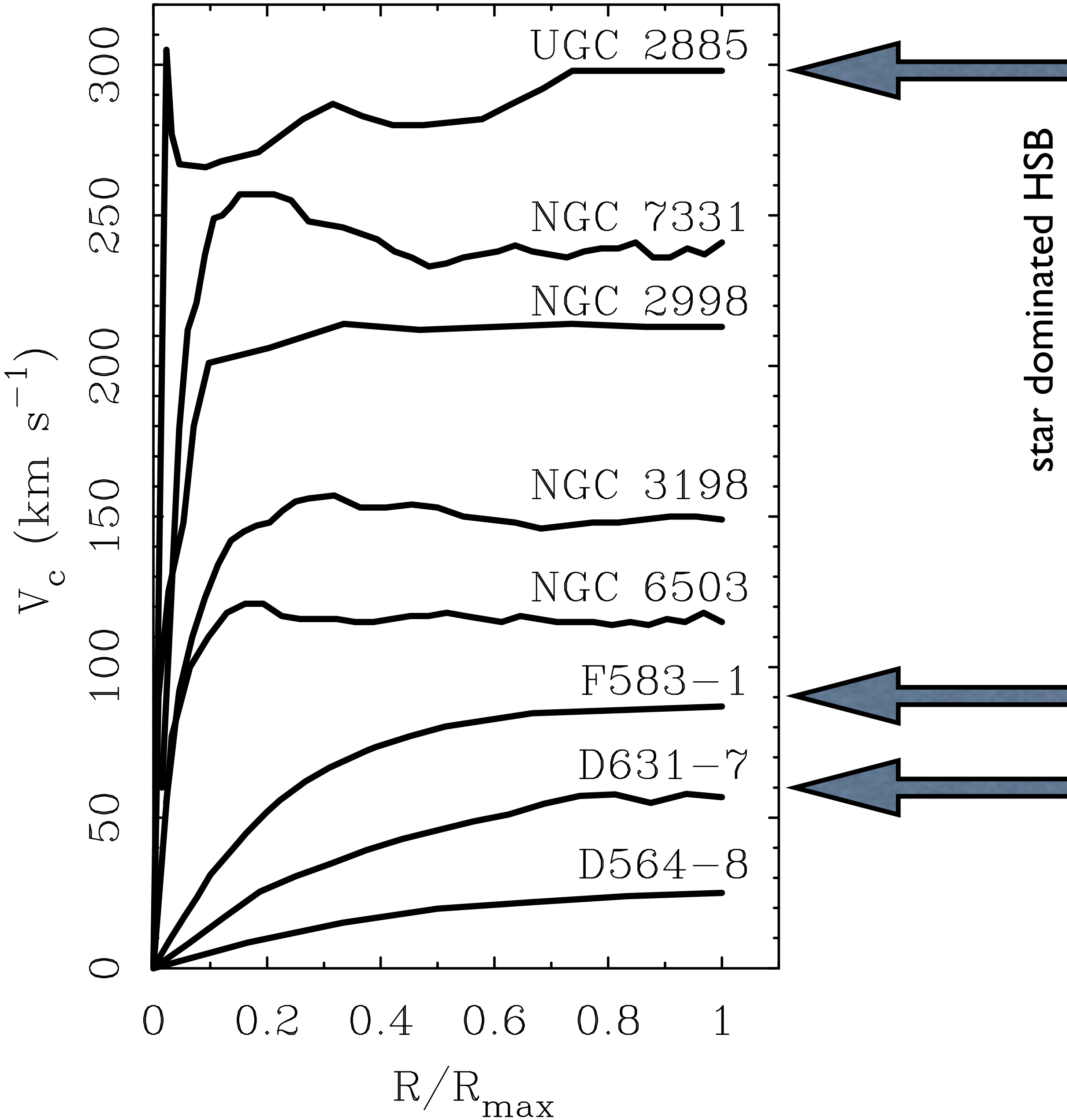
A single galaxy might seem a little thing to those who consider only the immeasurable vastness of the universe, and not the minute precision to which all things therein are shaped.

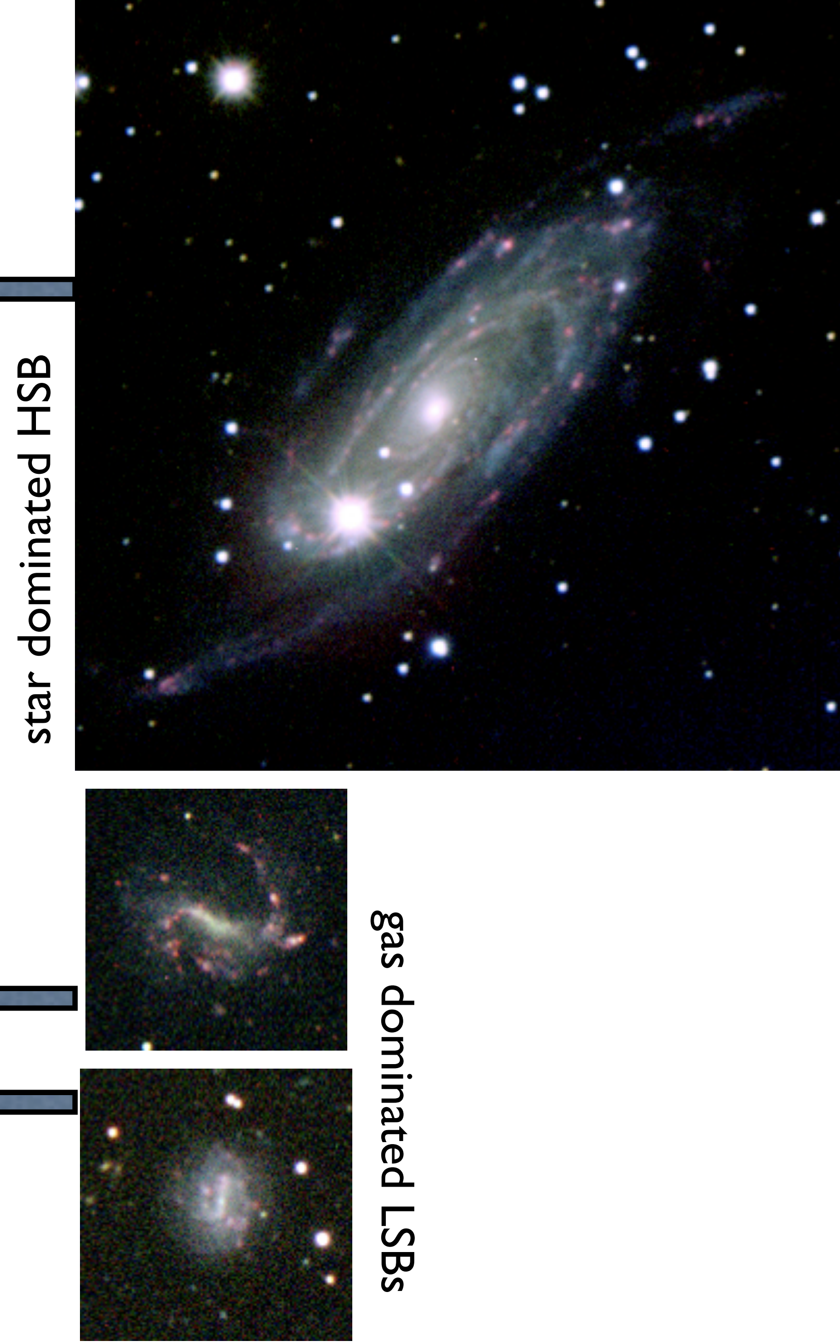
Paraphrased from the *Ainulindalë* by J.R.R. Tolkein



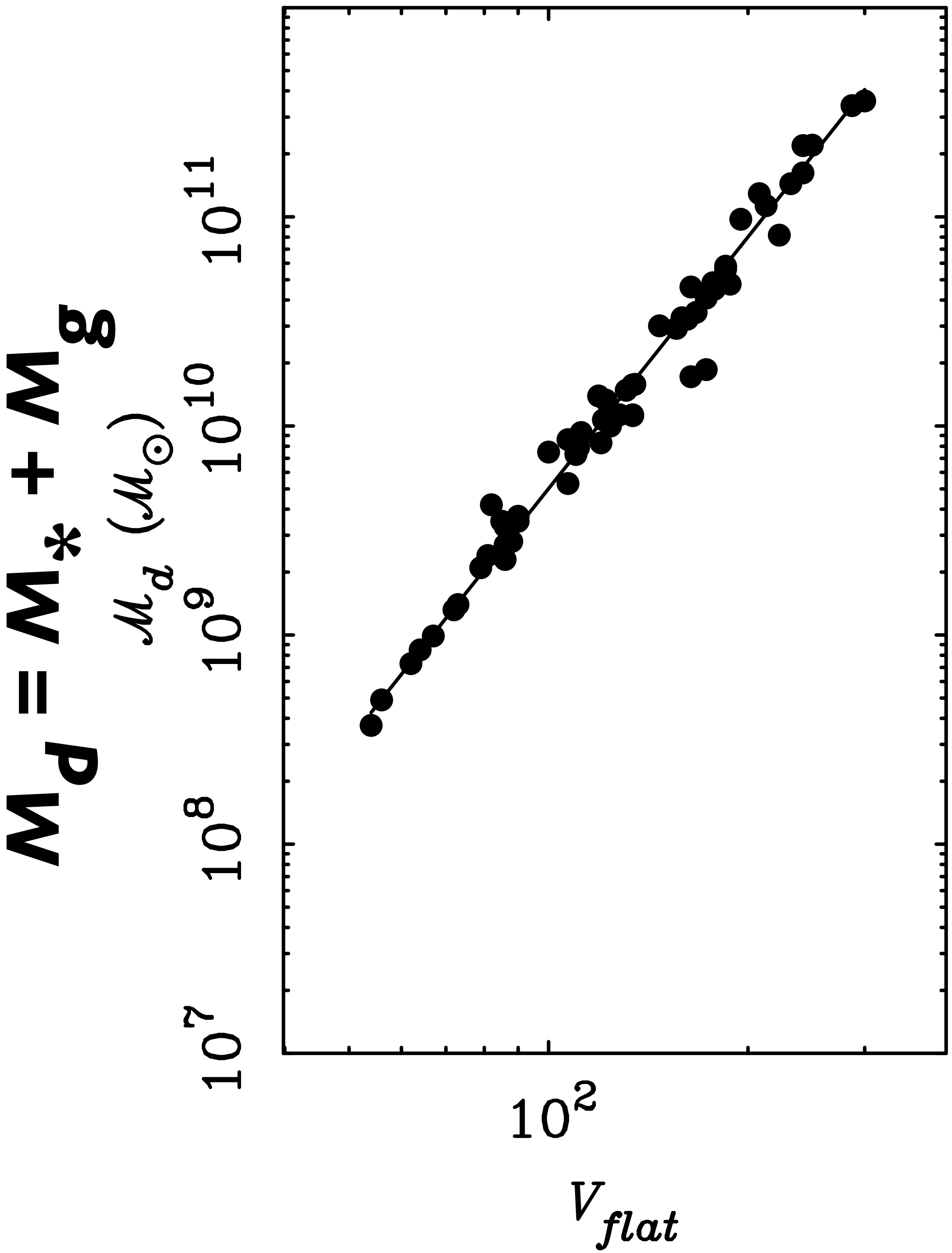
Solve Poisson equation numerically to obtain V(r) for observed baryon distribution

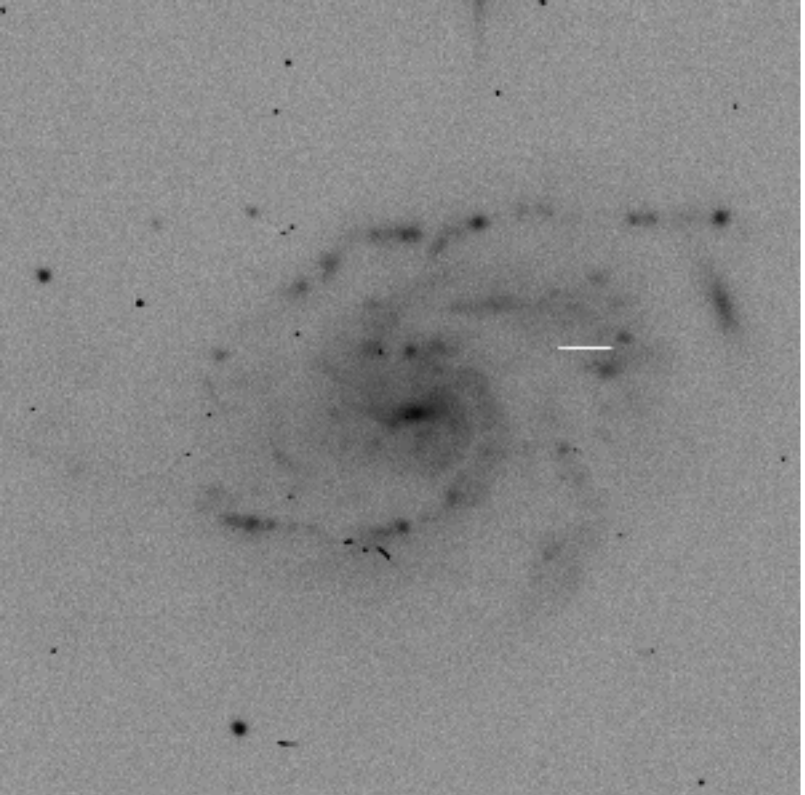
Flat rotation curves





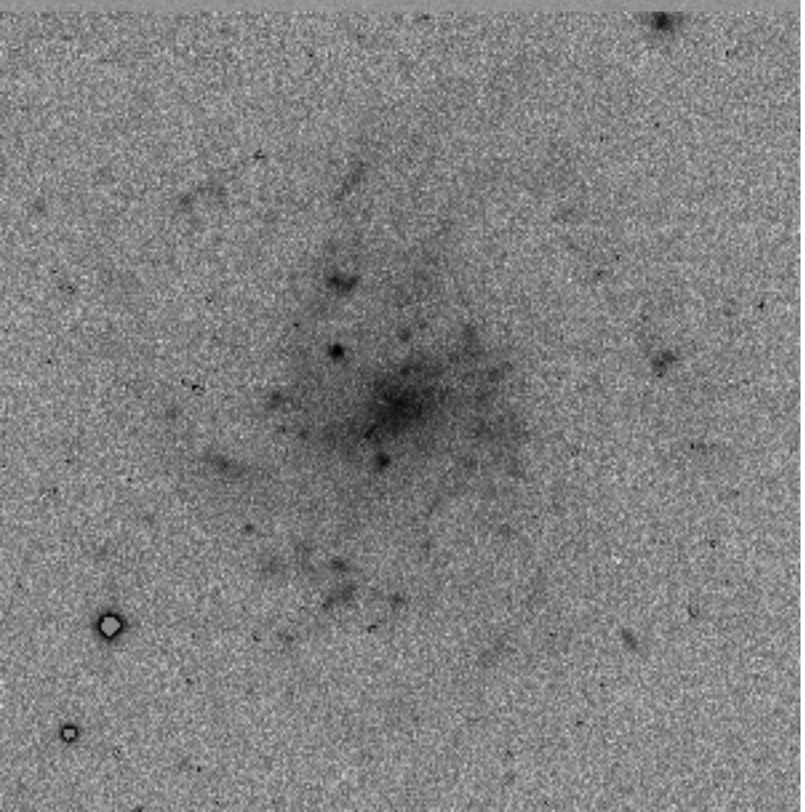
Tully-Fisher Relation





Some galaxies are

High Surface Brightness (HSB)



Others are

Low Surface Brightness (LSB)

Tully-Fisher Relation

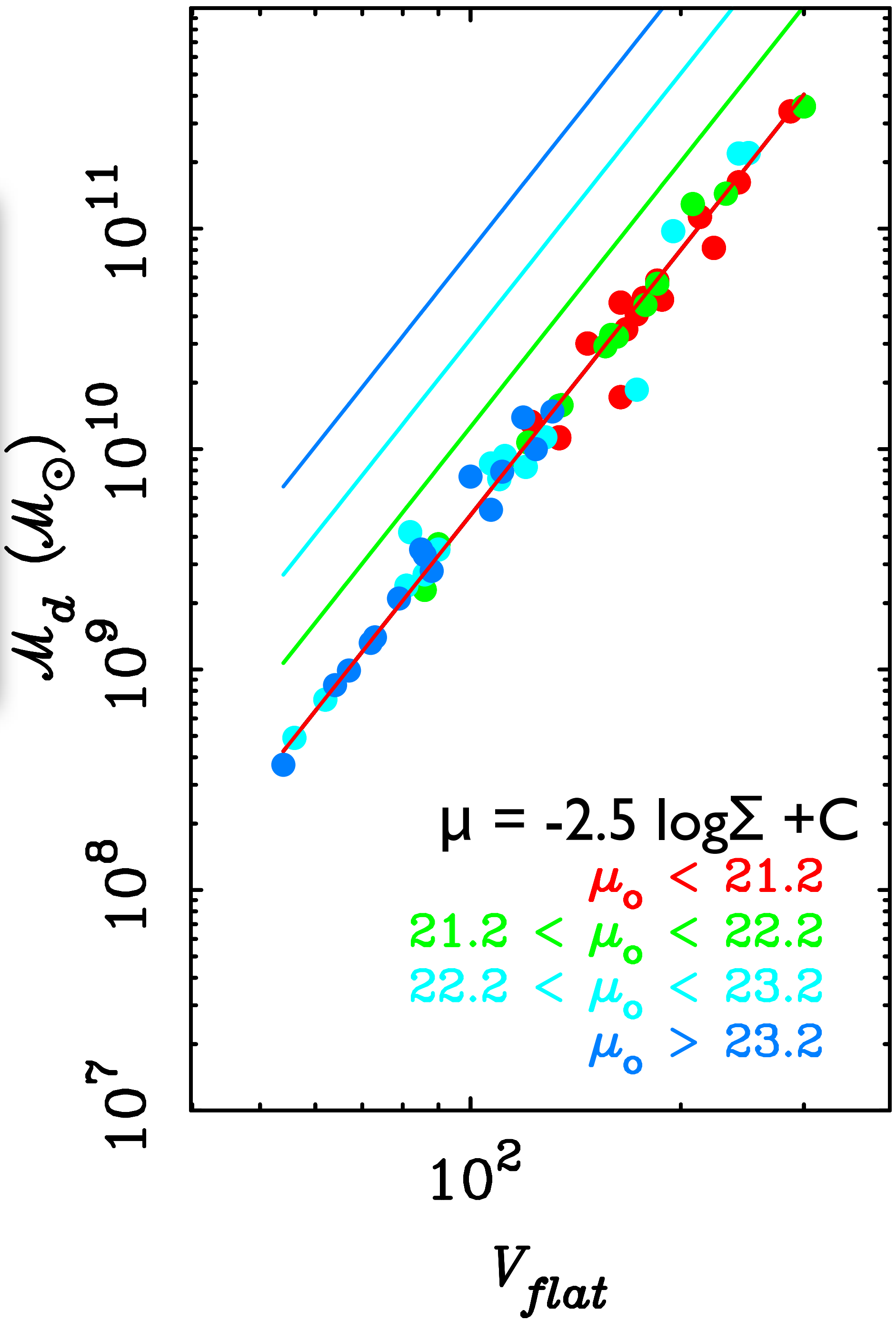
Newton says

$V^2 = GM/R$.

Equivalently,

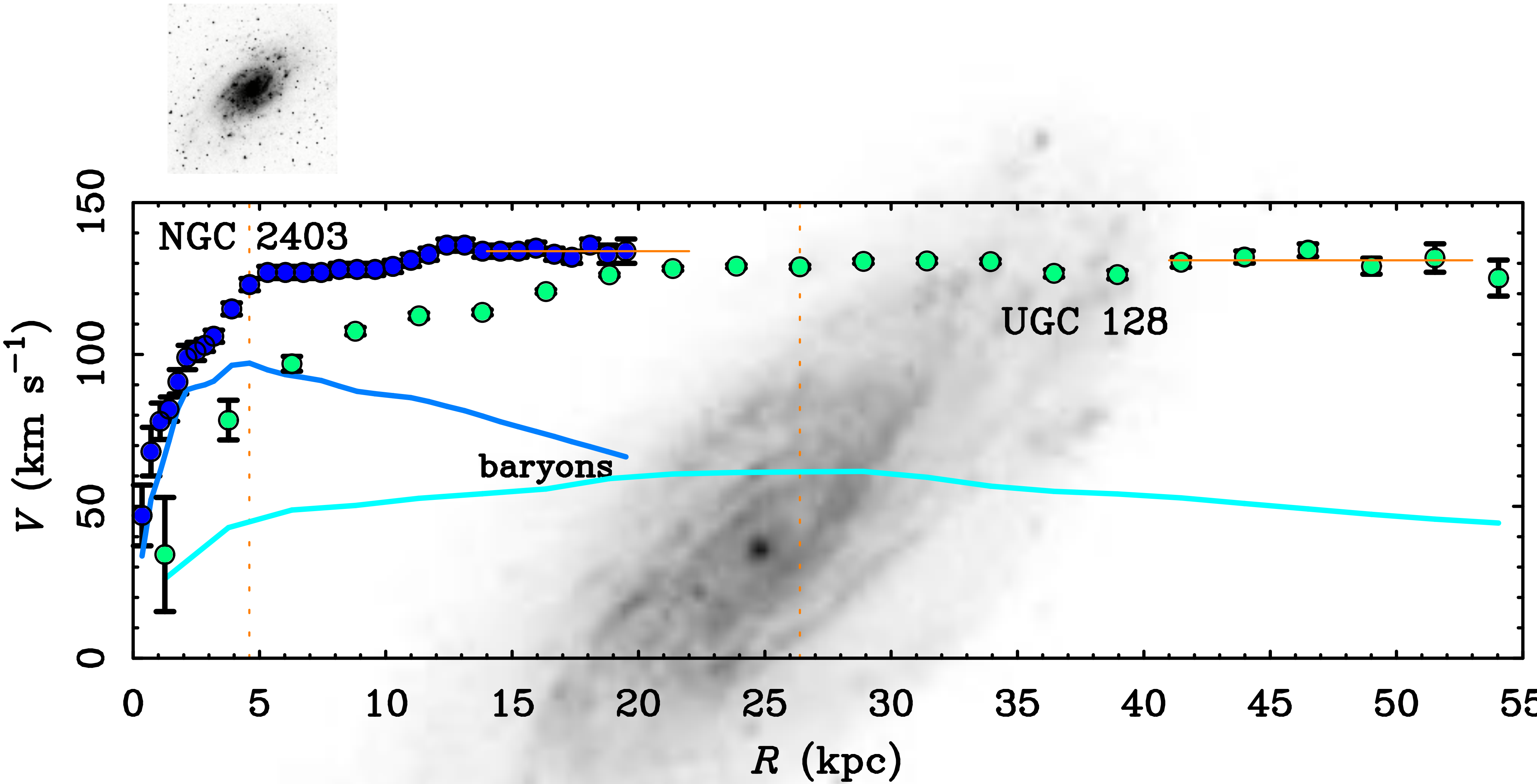
$\Sigma = M/R^2$

$V^4 = G^2 M \Sigma$

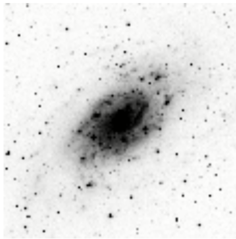


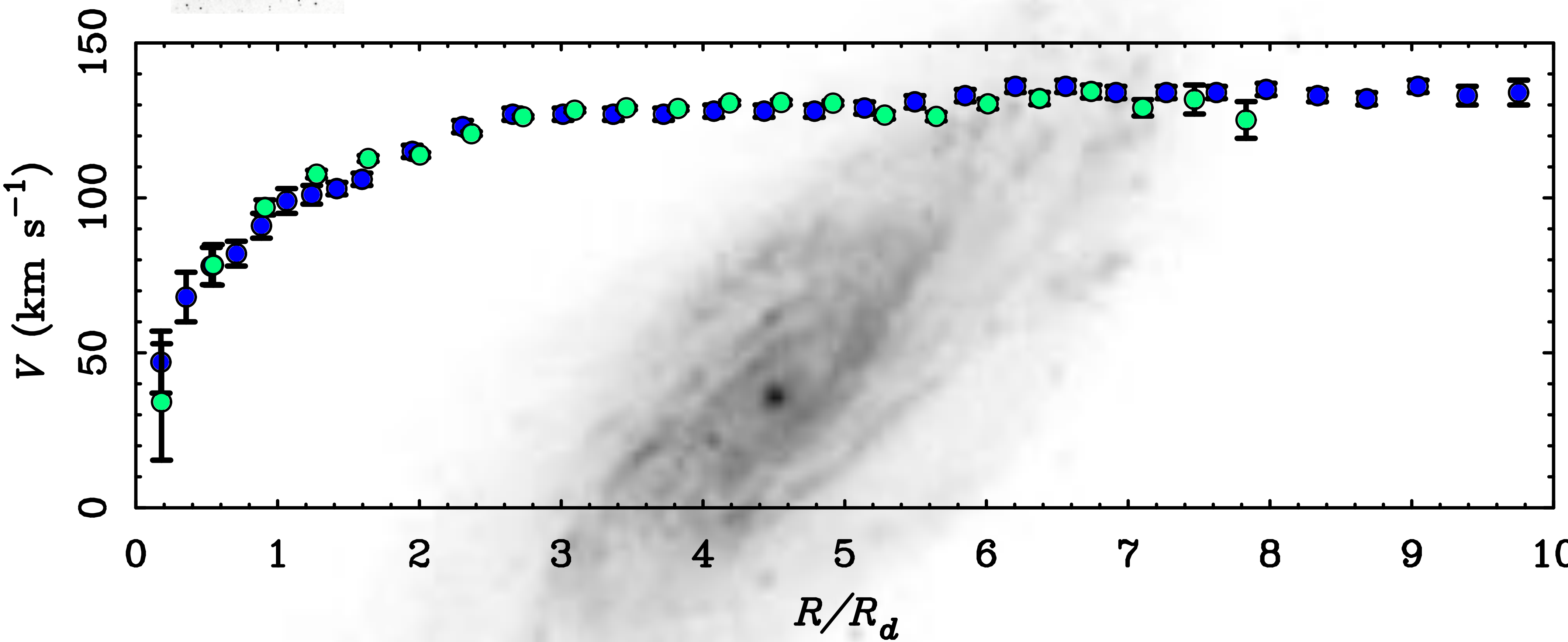
Therefore

Galaxies of different surface brightnesses *should* form distinct Tully-Fisher sequences.



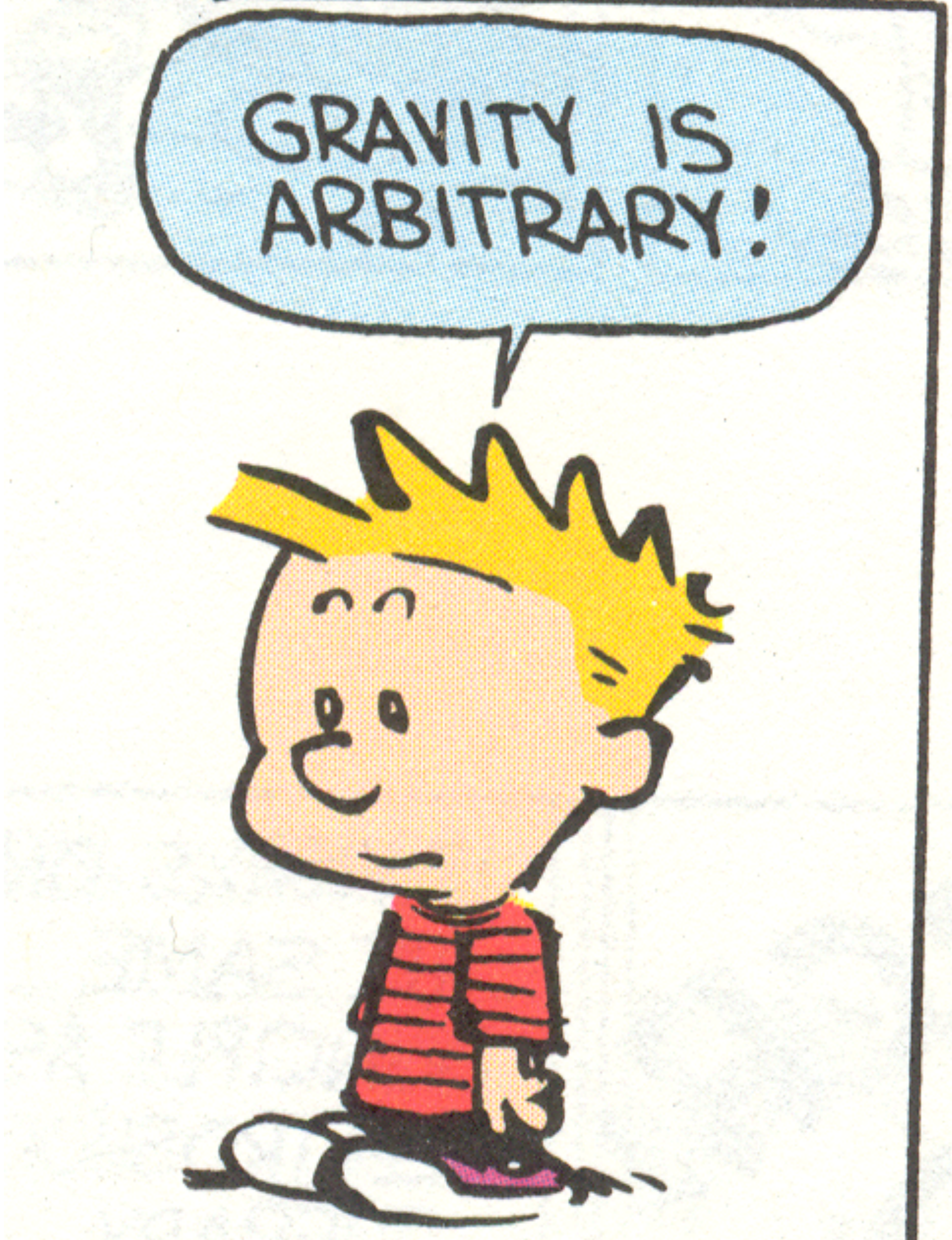
Radius in physical units (kpc)





Radius normalized by size of disk.

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


GRAVITY IS ARBITRARY!

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

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 [illegible] resemble those of ellipticals [illegible] galacti[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[illegible] densities which [illegible] with those [illegible] ding [illegible] same [illegible] conventional dynamics [illegible] 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 ellipticals [illegible] for review of propert[illegible] 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 $V_\infty = 220$ 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 [illegible] determina[illegible] many cases [illegible] 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 [illegible] relat[illegible] additional as[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[illegible] galaxies [illegible] mass high[illegible] than [illegible] derived [illegible] normal surface density gal[illegible]

We also predict that the lower the average surface density of a galaxy is, the smaller [illegible] the transition ra[illegible] very small we may have [illegible] 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

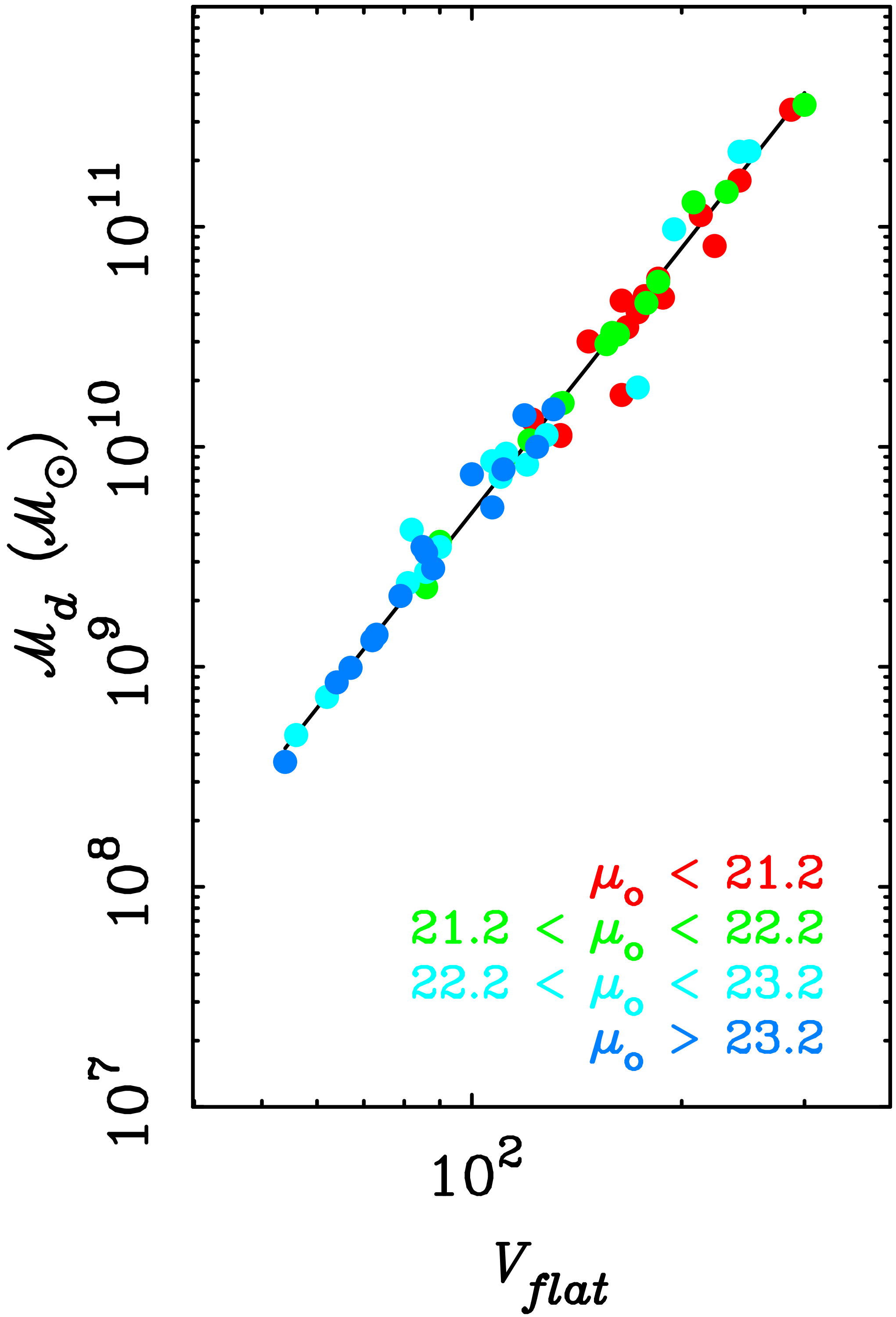
The main results of this paper can be summarized by the statement that the modified dynamics eliminates the need to assume hidden mass in galaxies. The effects in galaxies which I have considered, and which are commonly attributed to such hidden mass, are readily explained by the modification. More specifically:

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

- 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

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

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



MOND predictions

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  - ✔ Slope = 4
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  - ✔ Fundamentally a relation between Disk Mass and V_{flat}
  - ✔ No Dependence on Surface Brightness !
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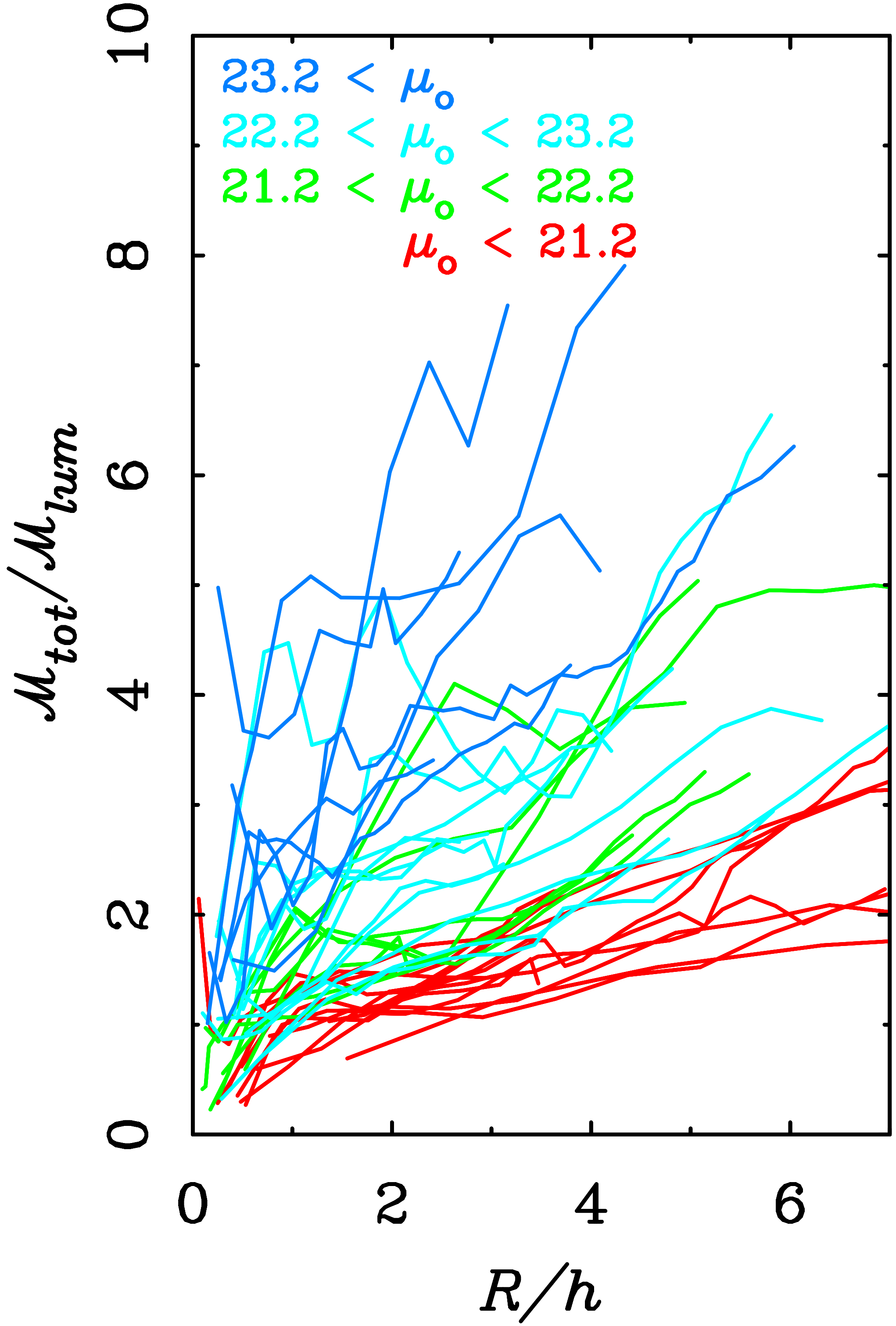

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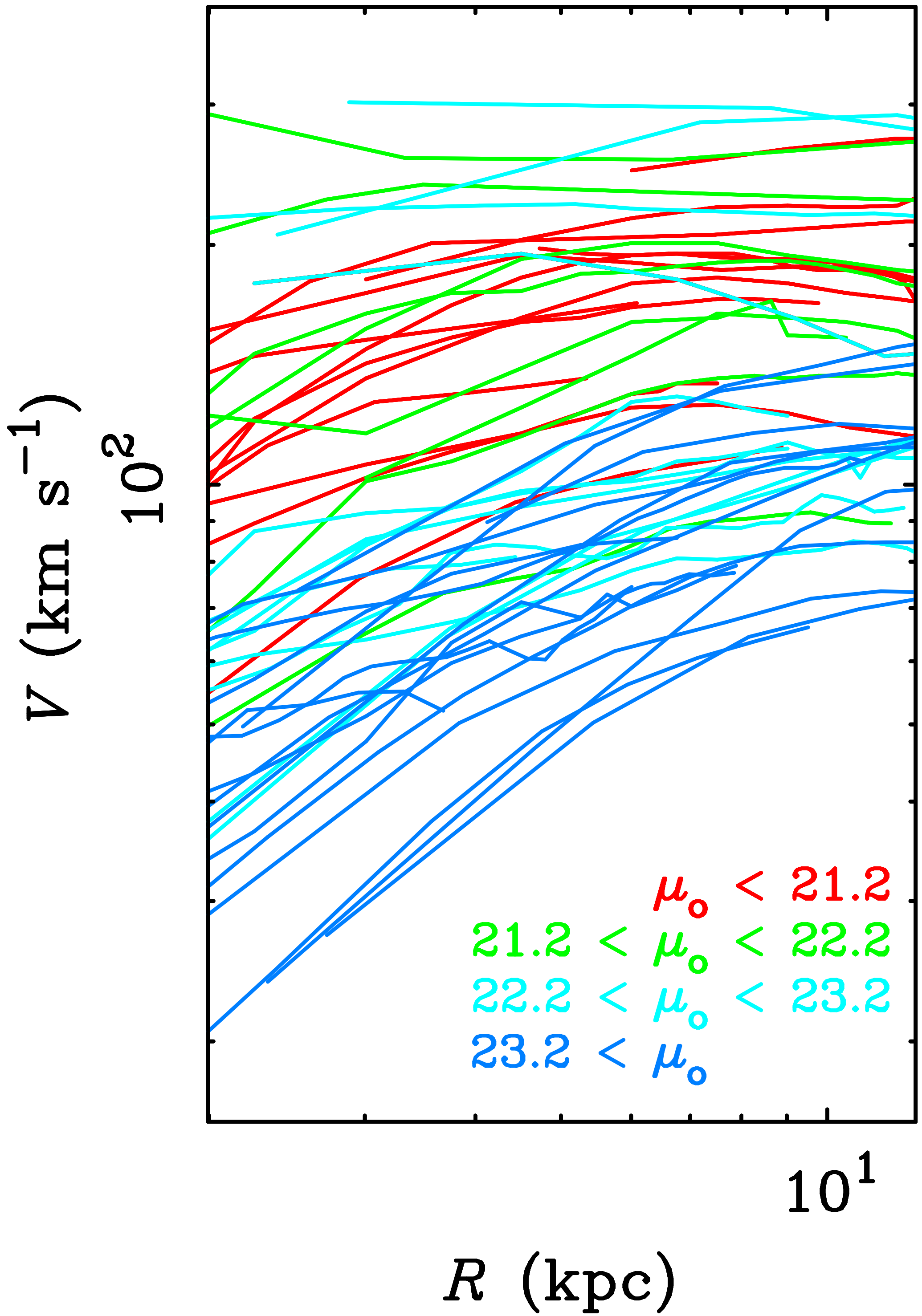

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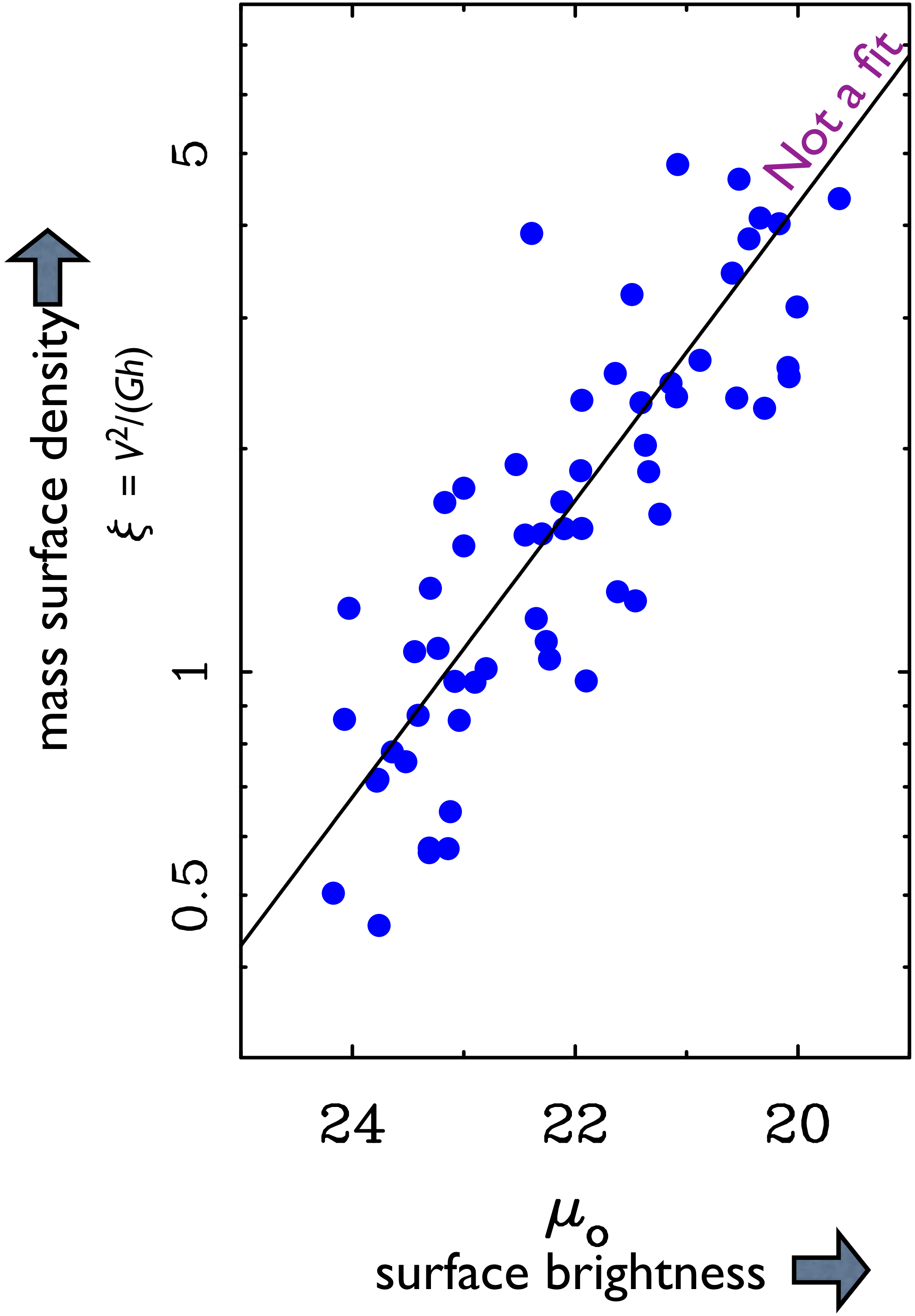

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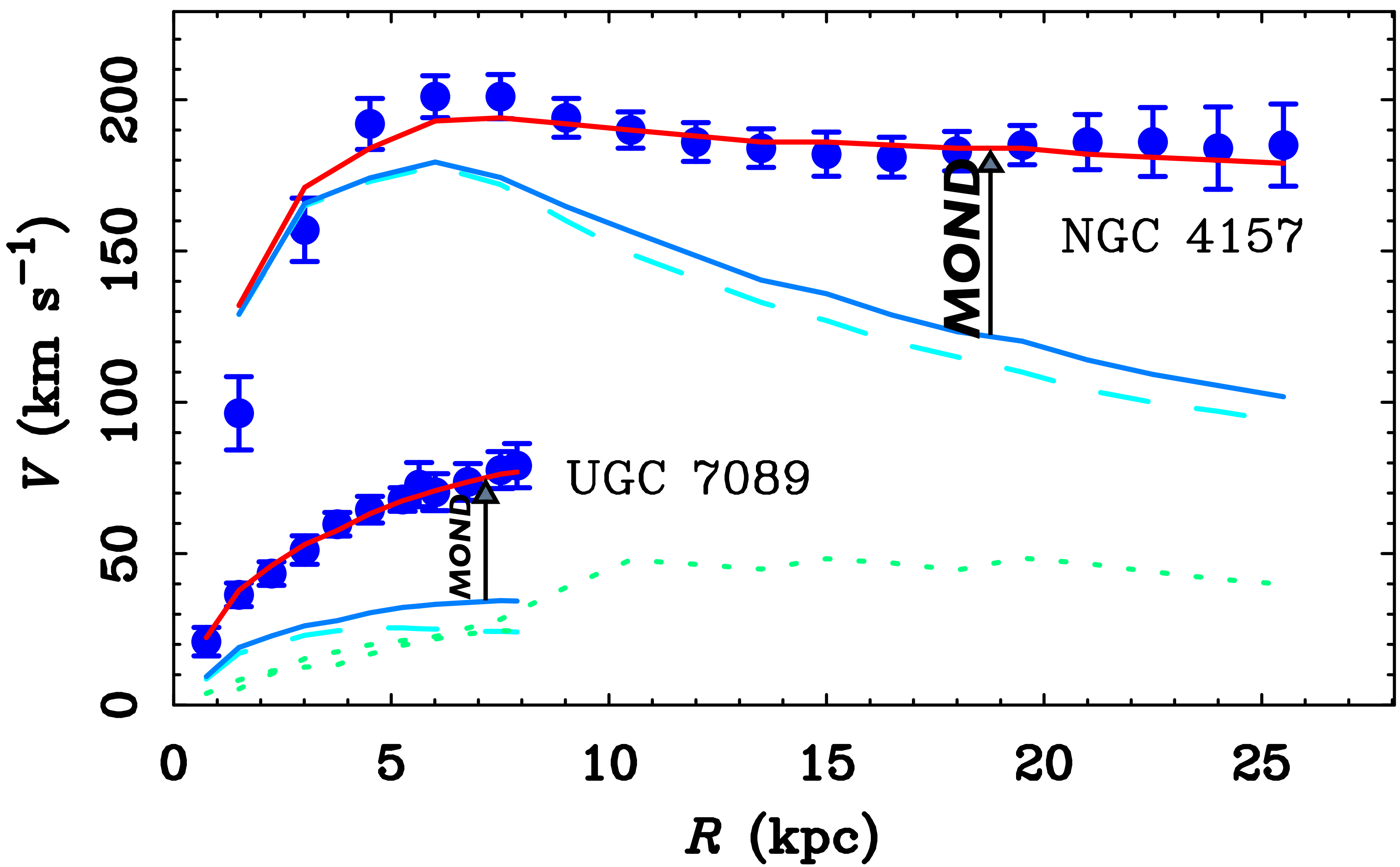
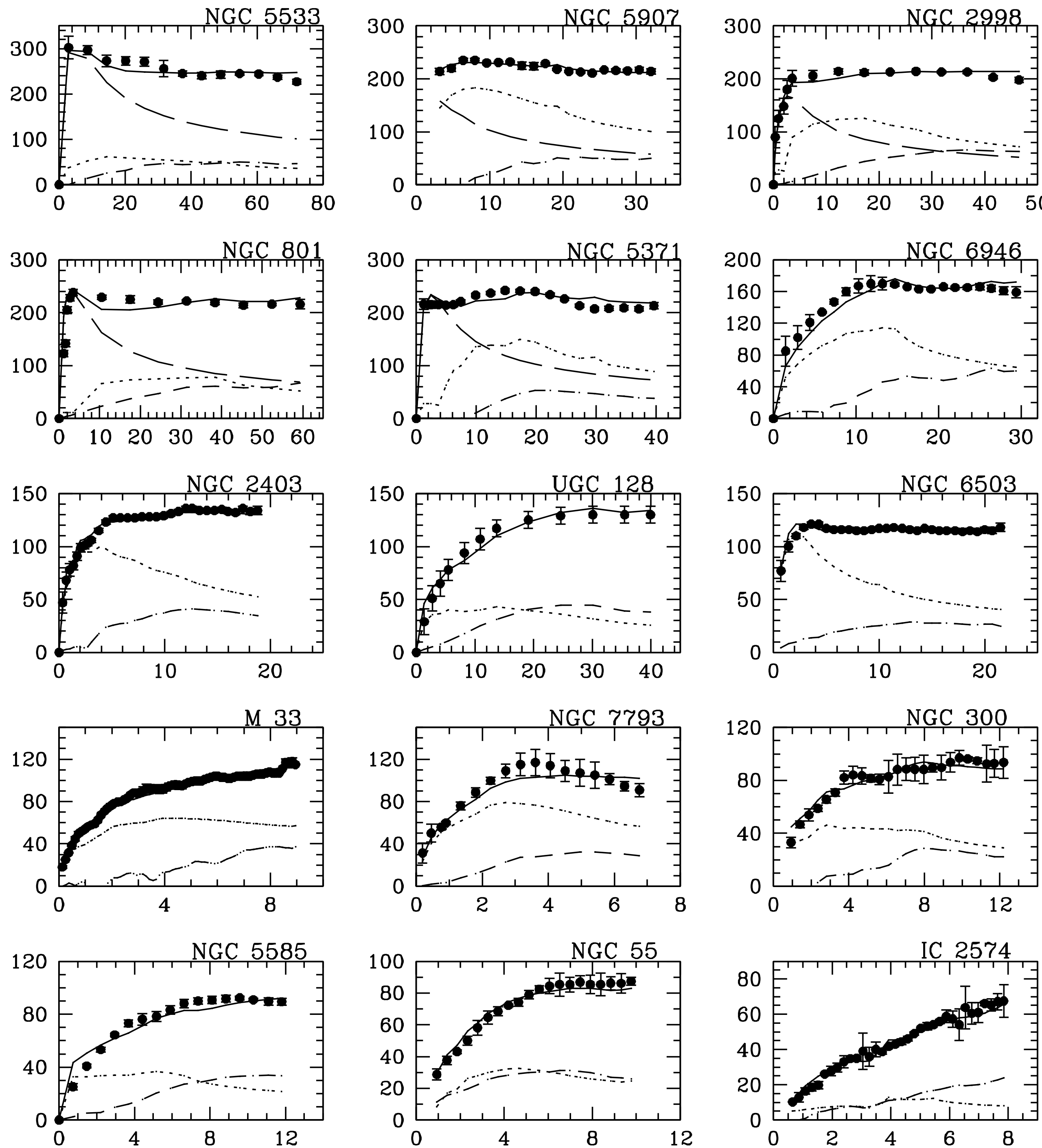
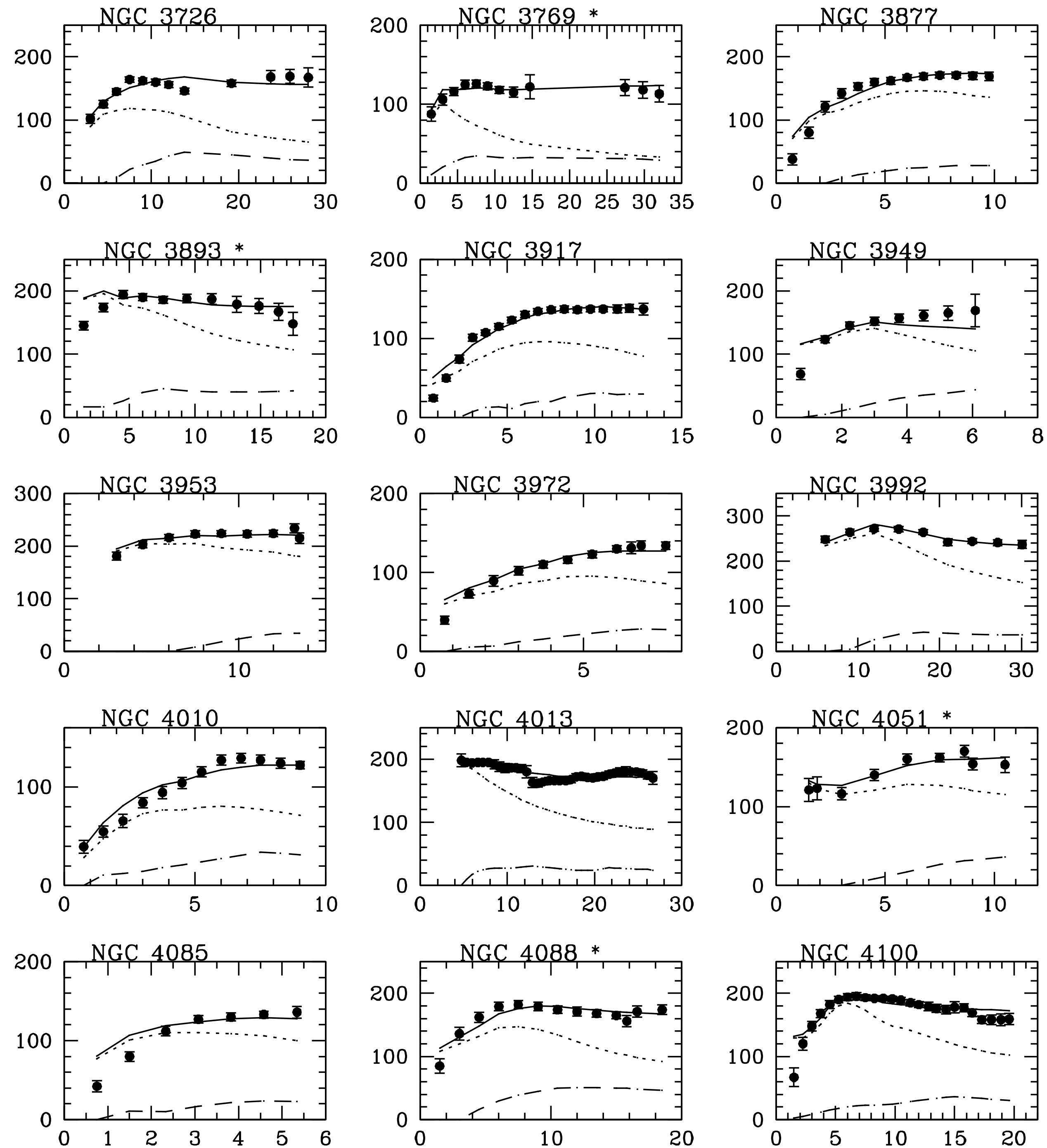


NGC 4157
UGC 7089
MOND
MOND
V (km s^-1)
R (kpc)
0
50
100
150
200
0
5
10
15
20
25

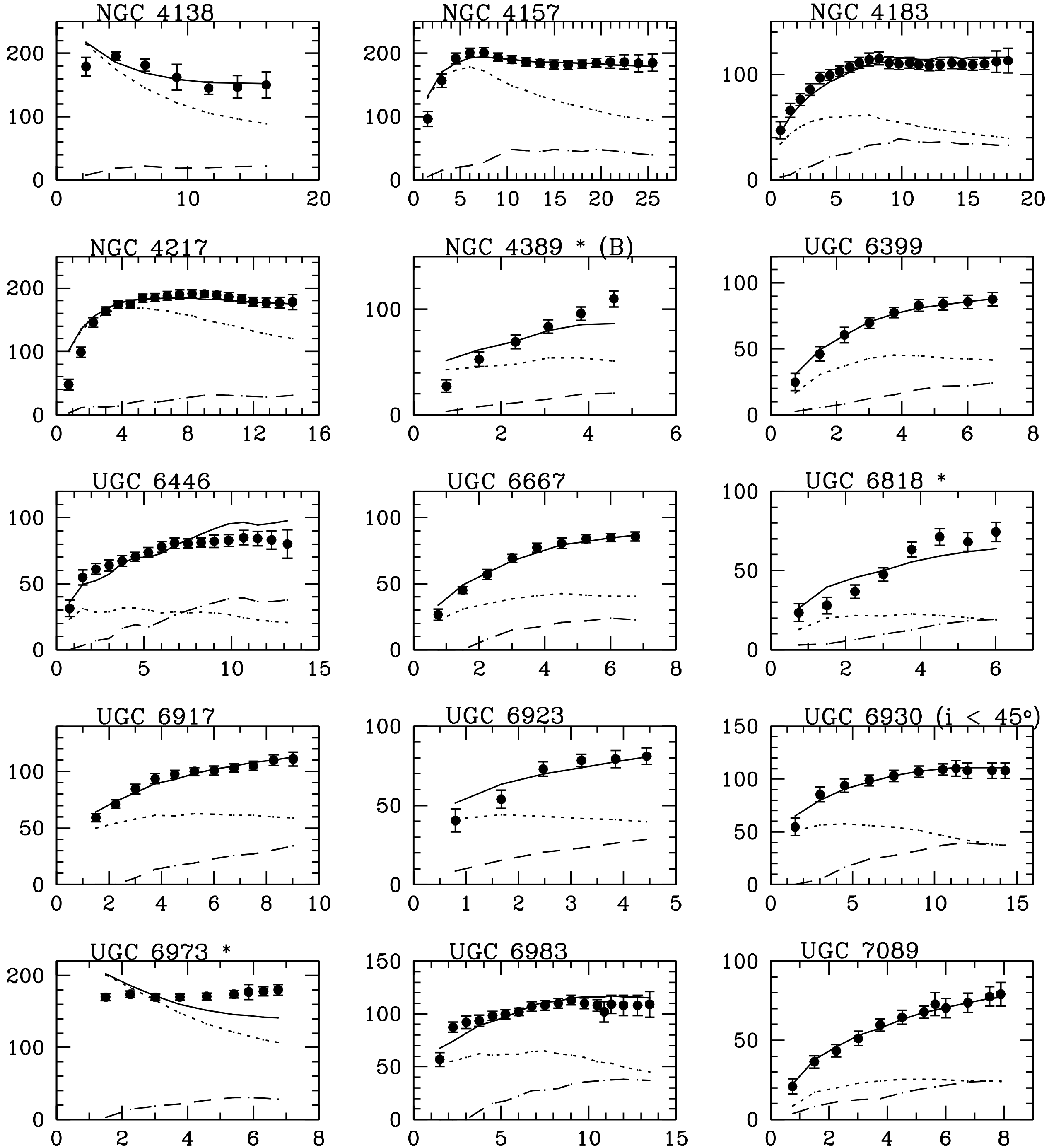
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



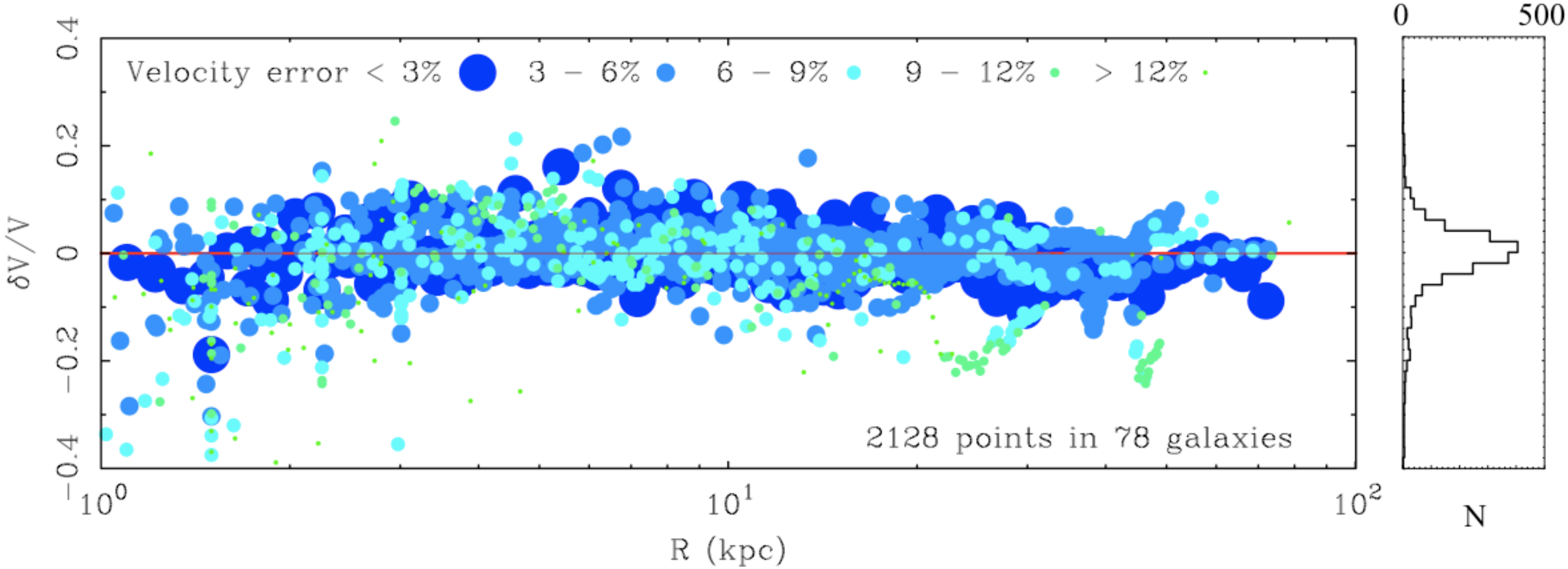
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



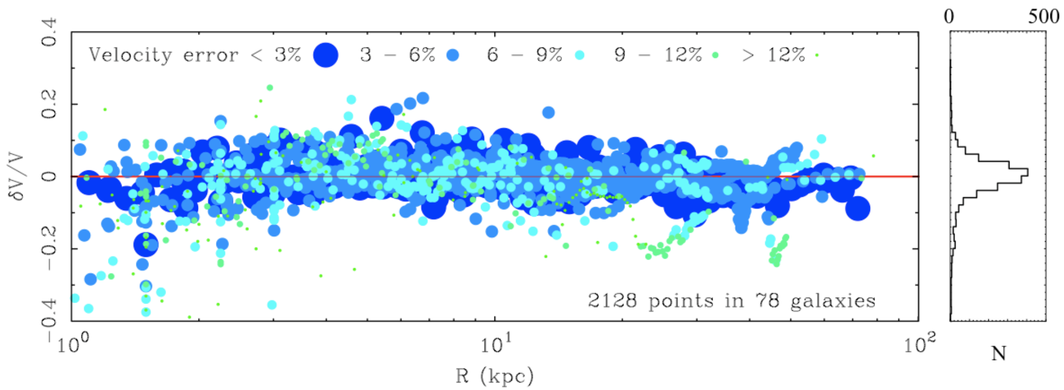
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



Residuals of MOND fits



MOND predictions



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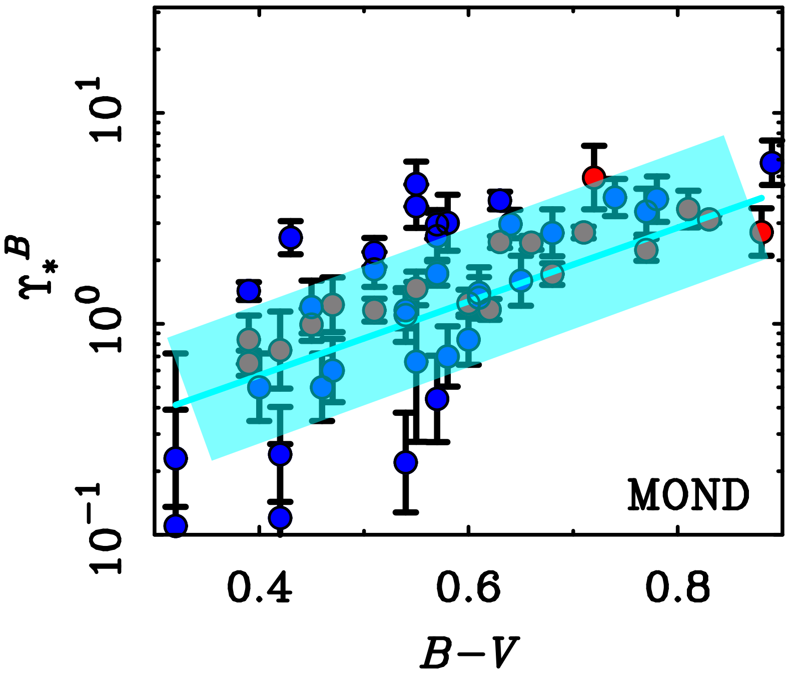
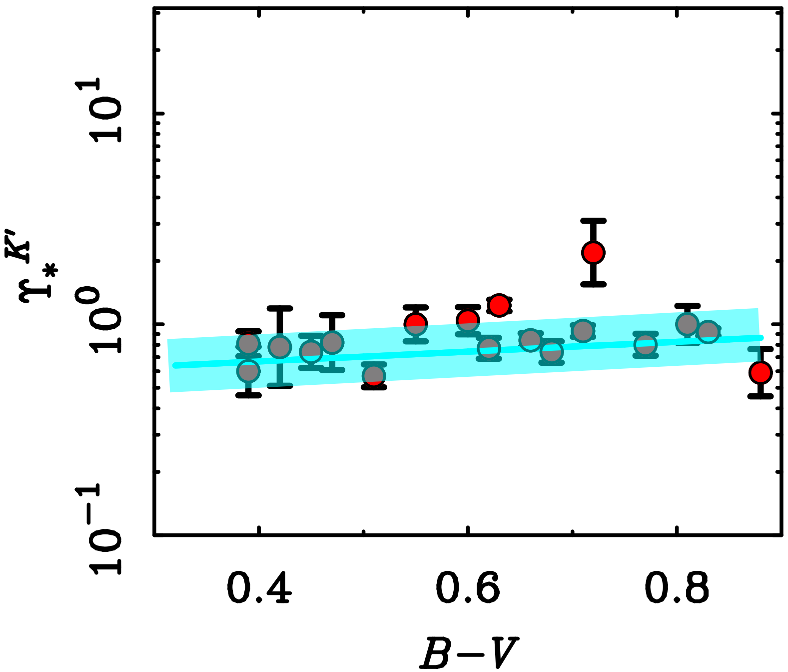
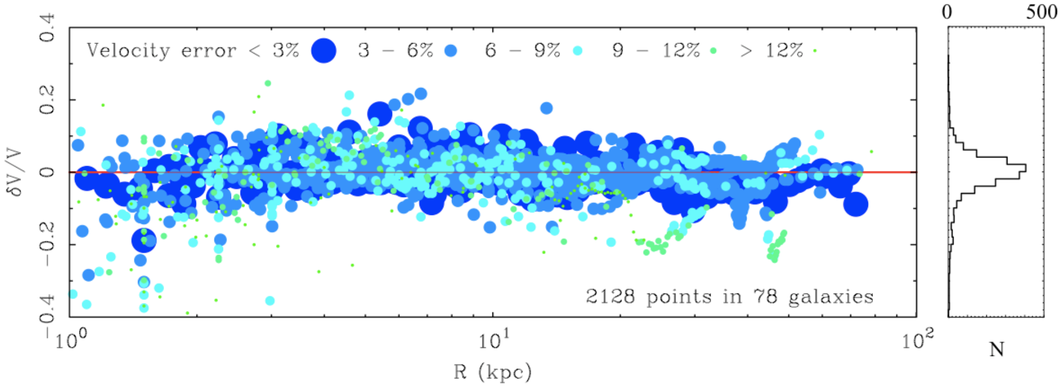
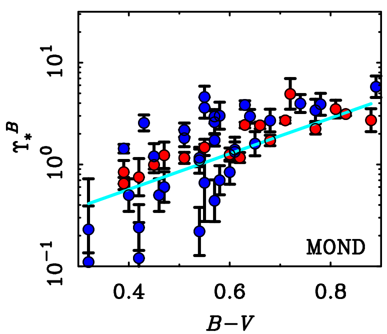


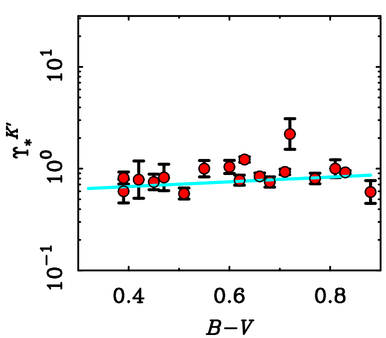
Line: stellar population model
(mean expectation)



MOND predictions







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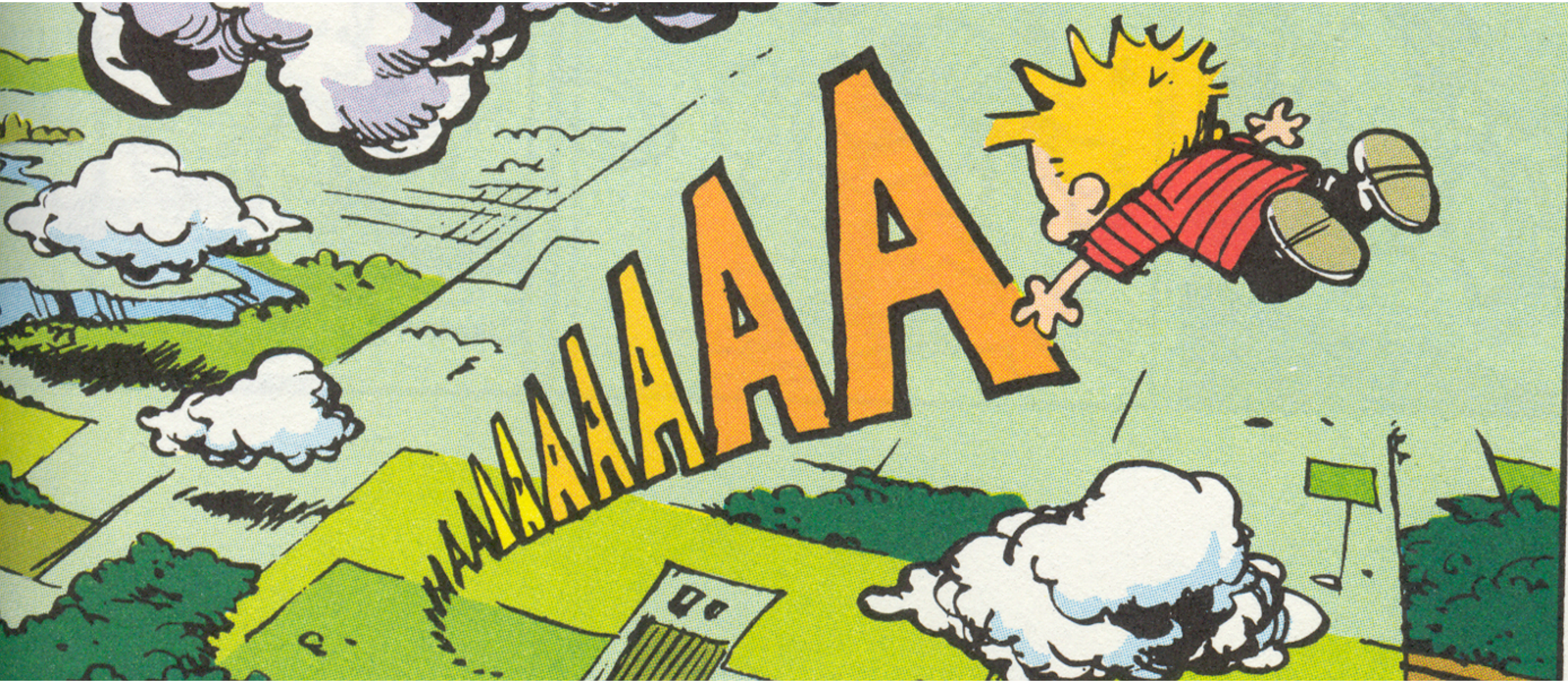
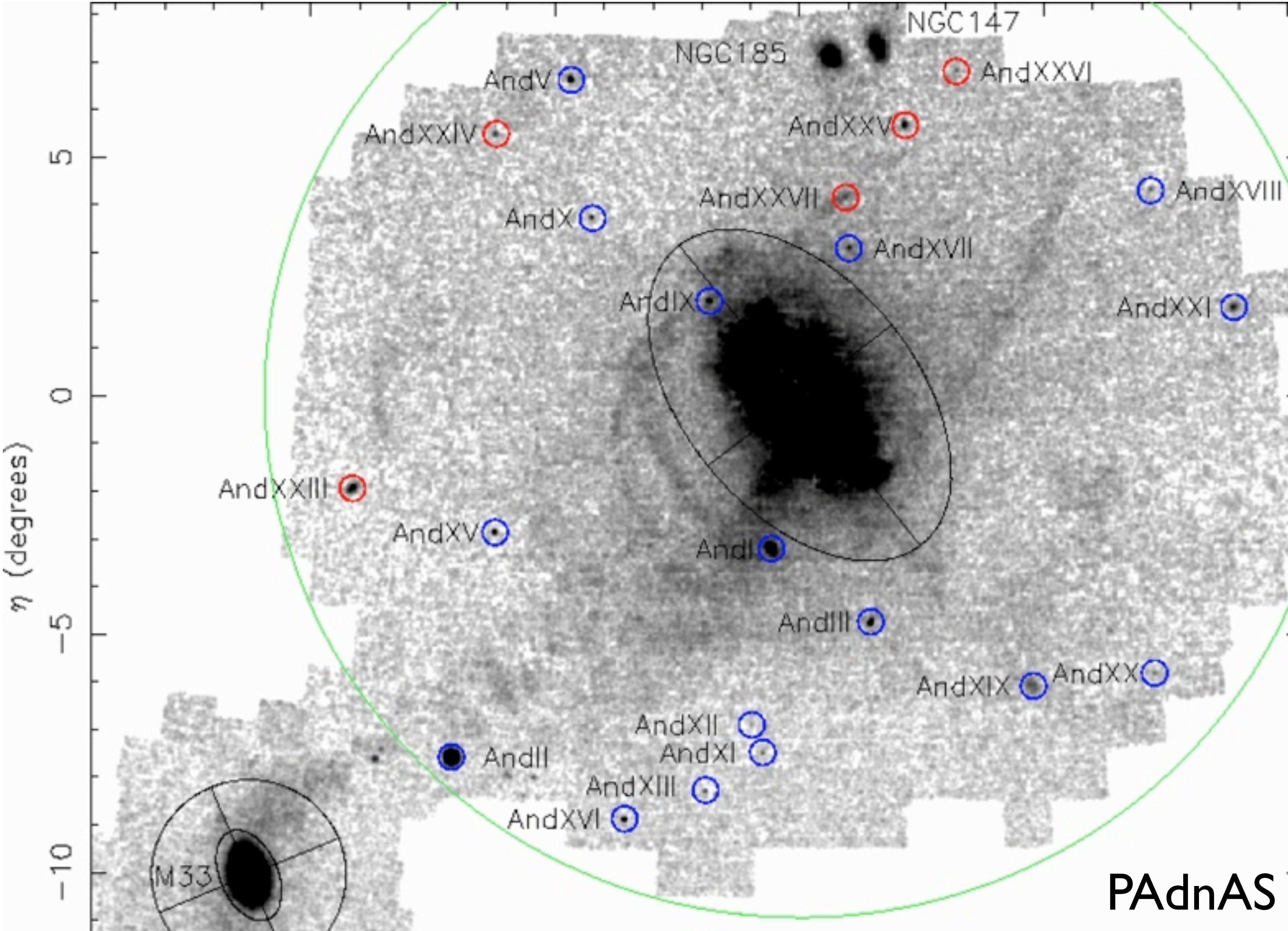
Are you suggesting that there is no dark matter?

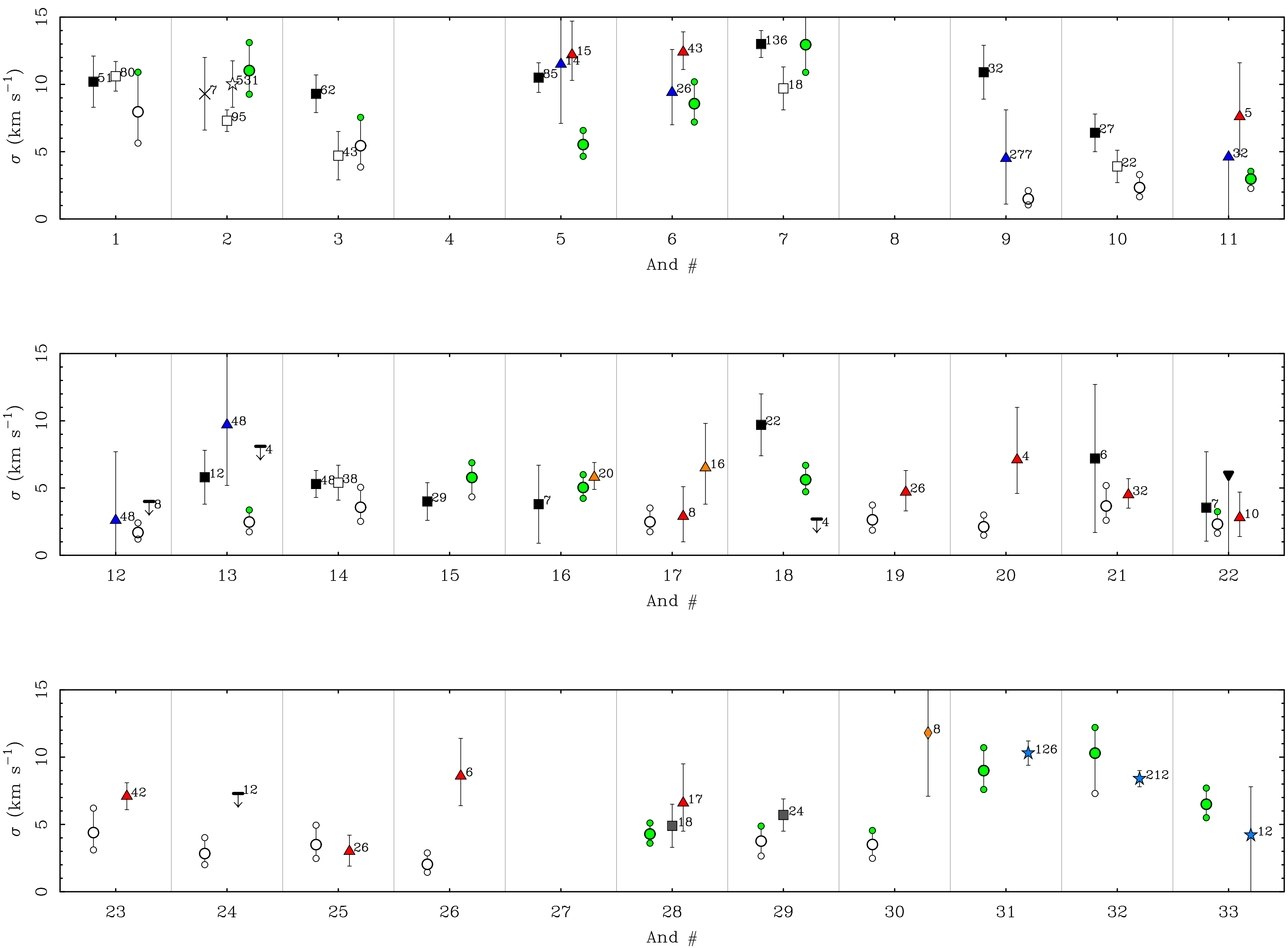
What does MOND do to cosmology?



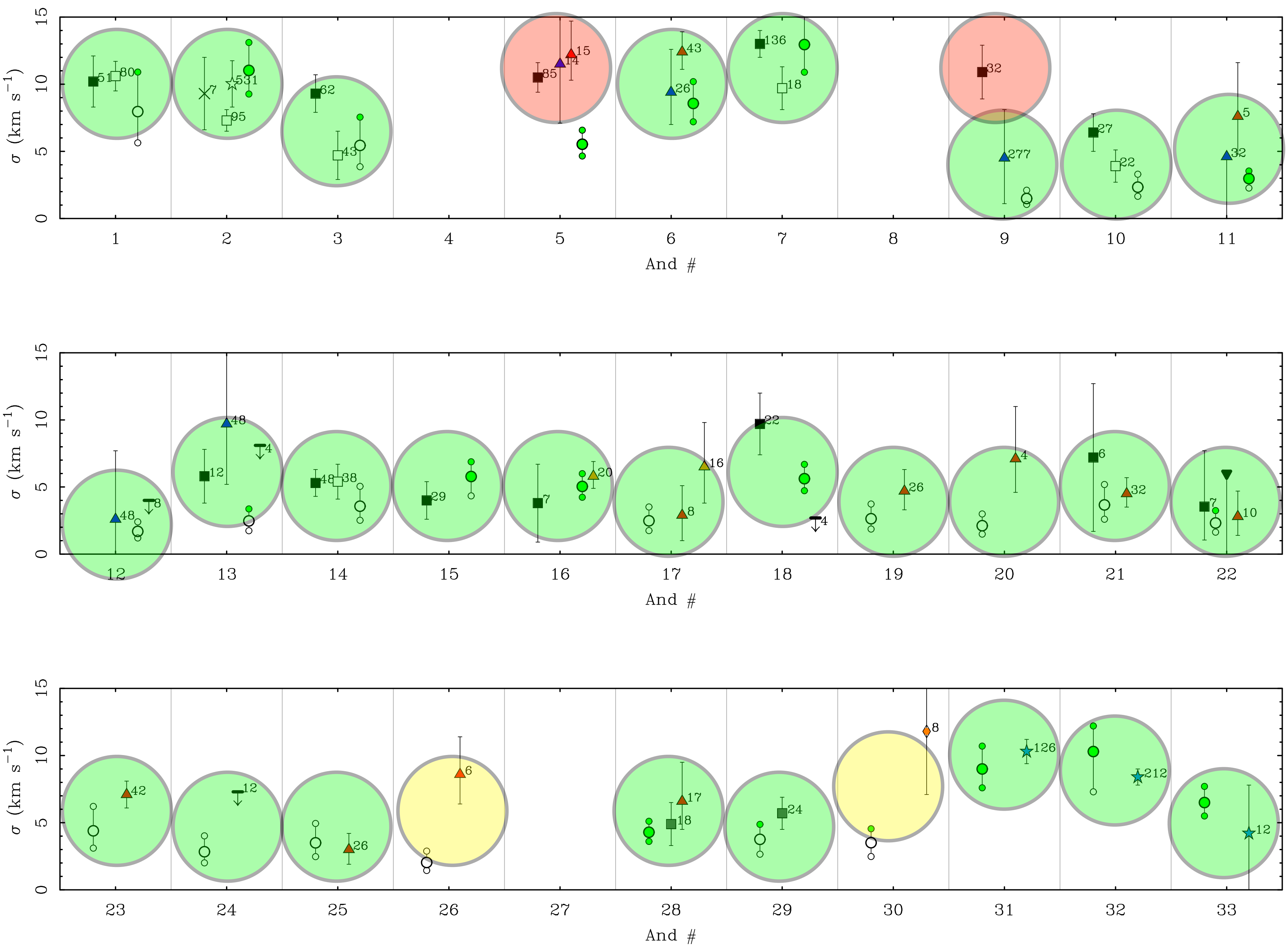
A new test: the dwarf satellites of Andromeda



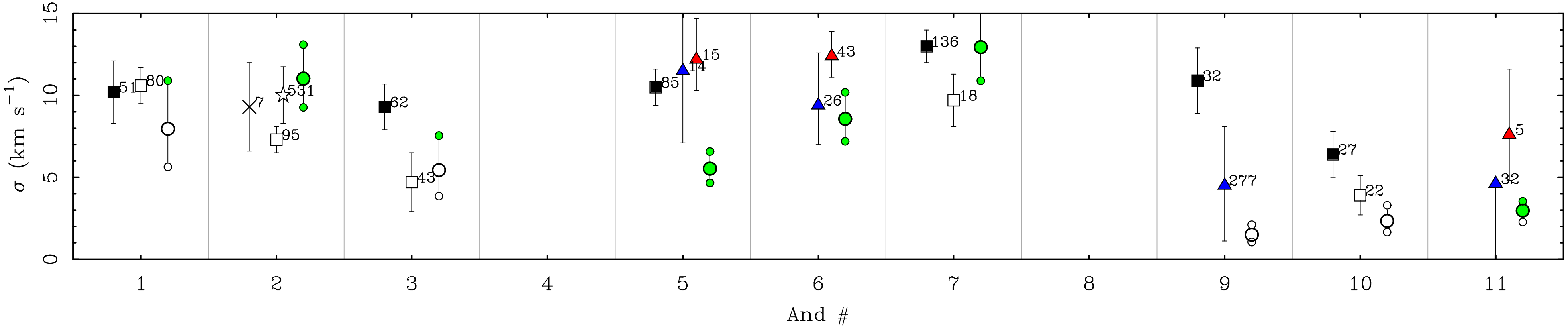
PAdnAS



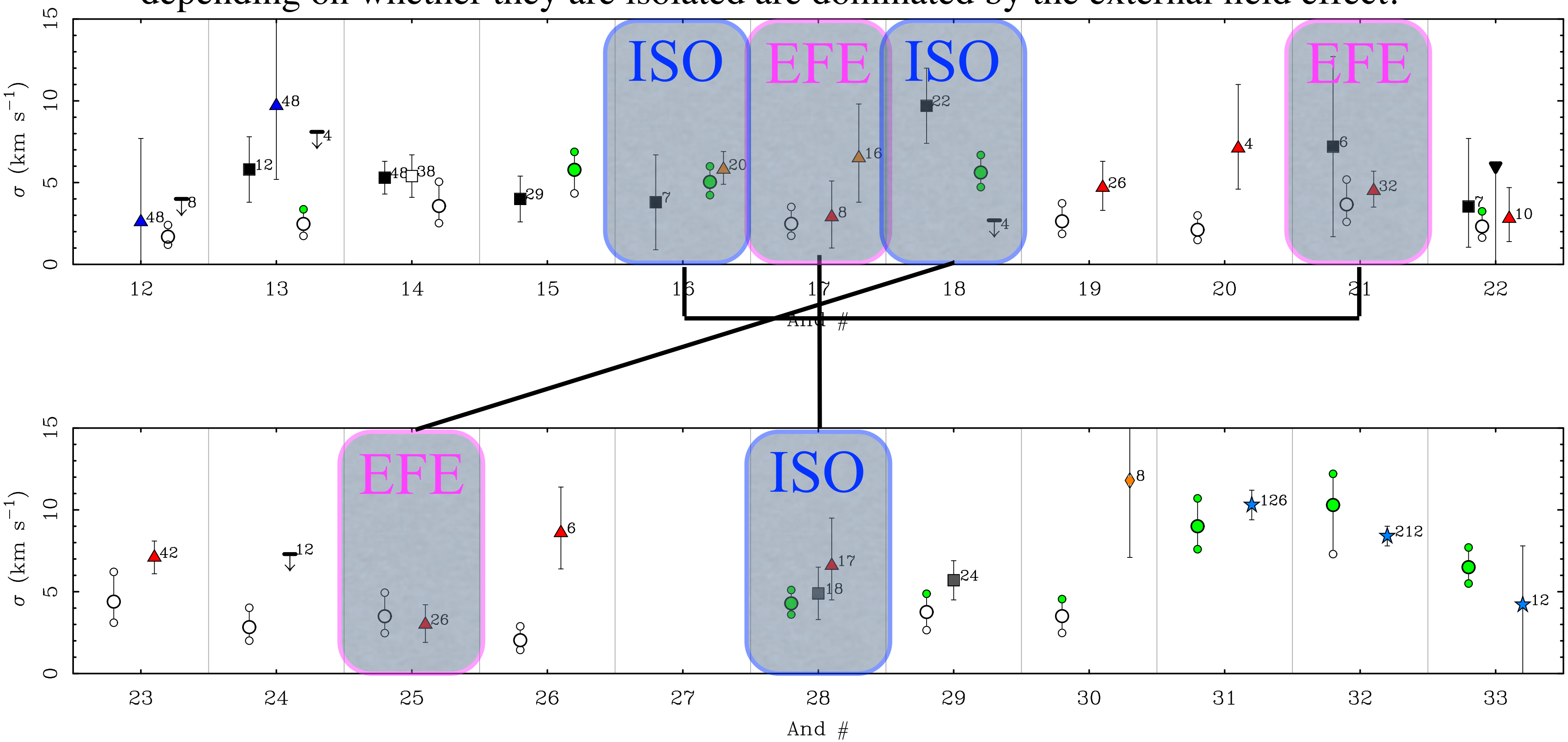
Velocity dispersions of M31 dwarfs correctly predicted (a priori in many cases) by MOND.



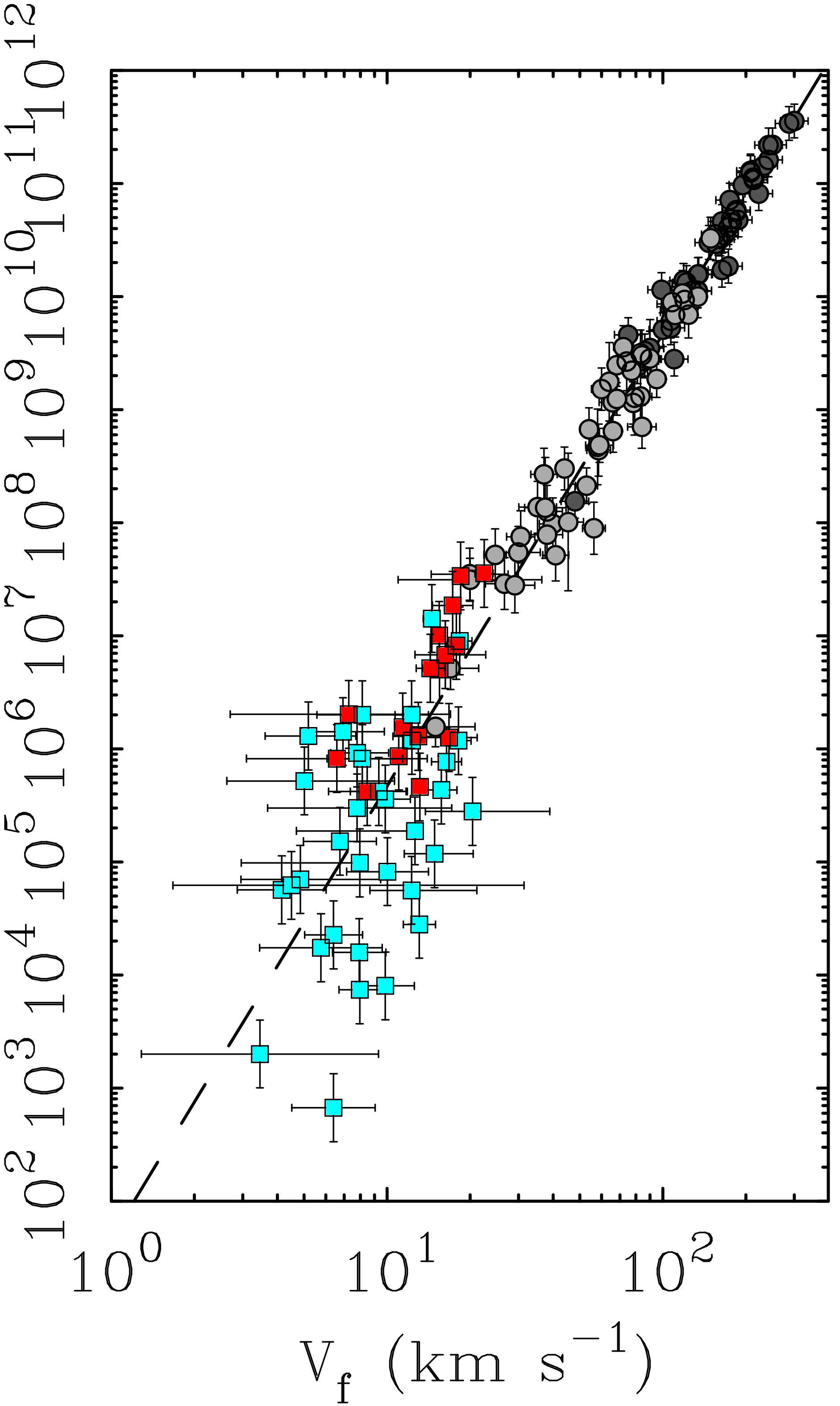
Velocity dispersions of M31 dwarfs correctly predicted (a priori in many cases) by MOND.



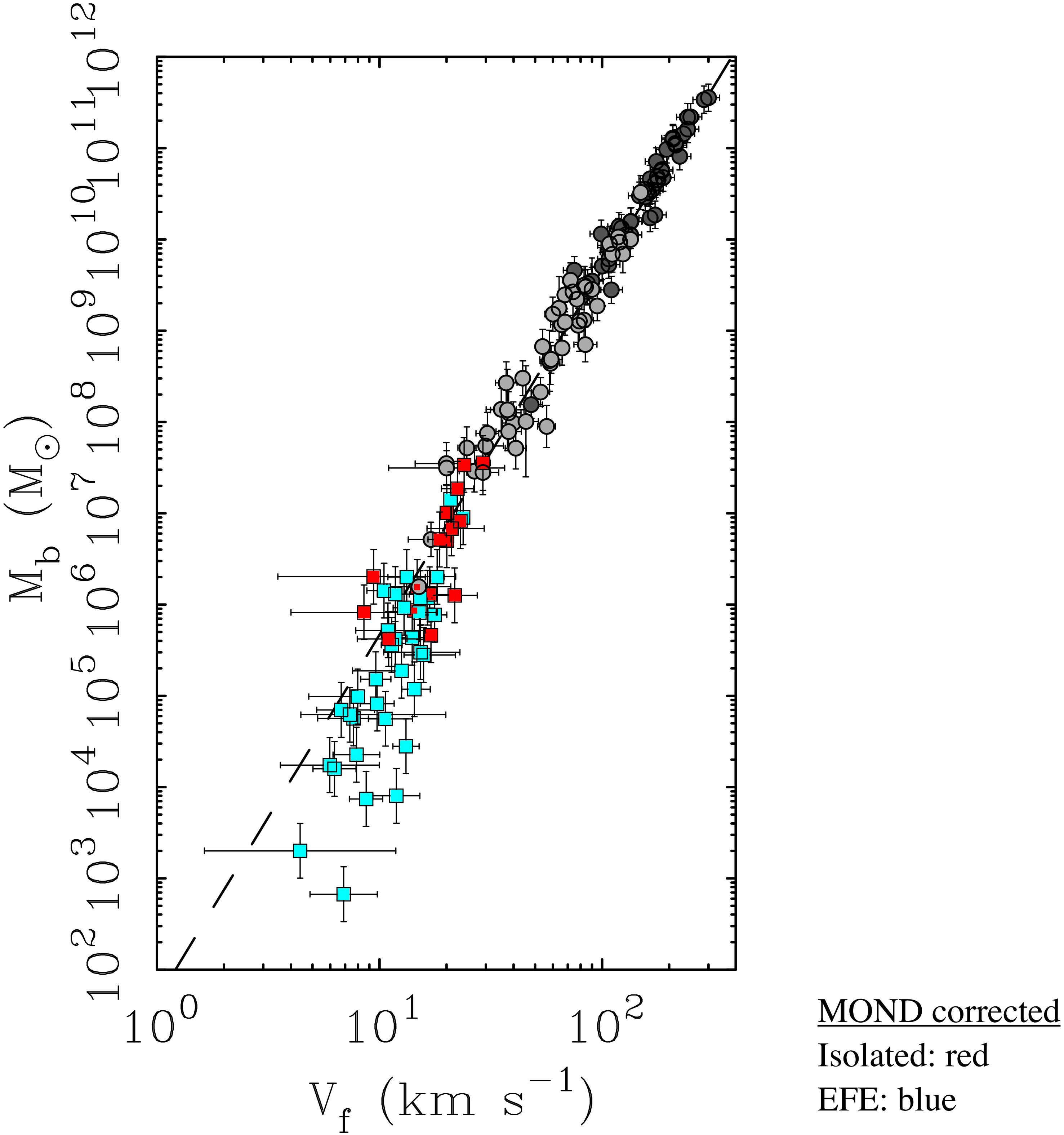
Pairs of photometrically identical dwarfs should have different velocity dispersion depending on whether they are isolated are dominated by the external field effect.



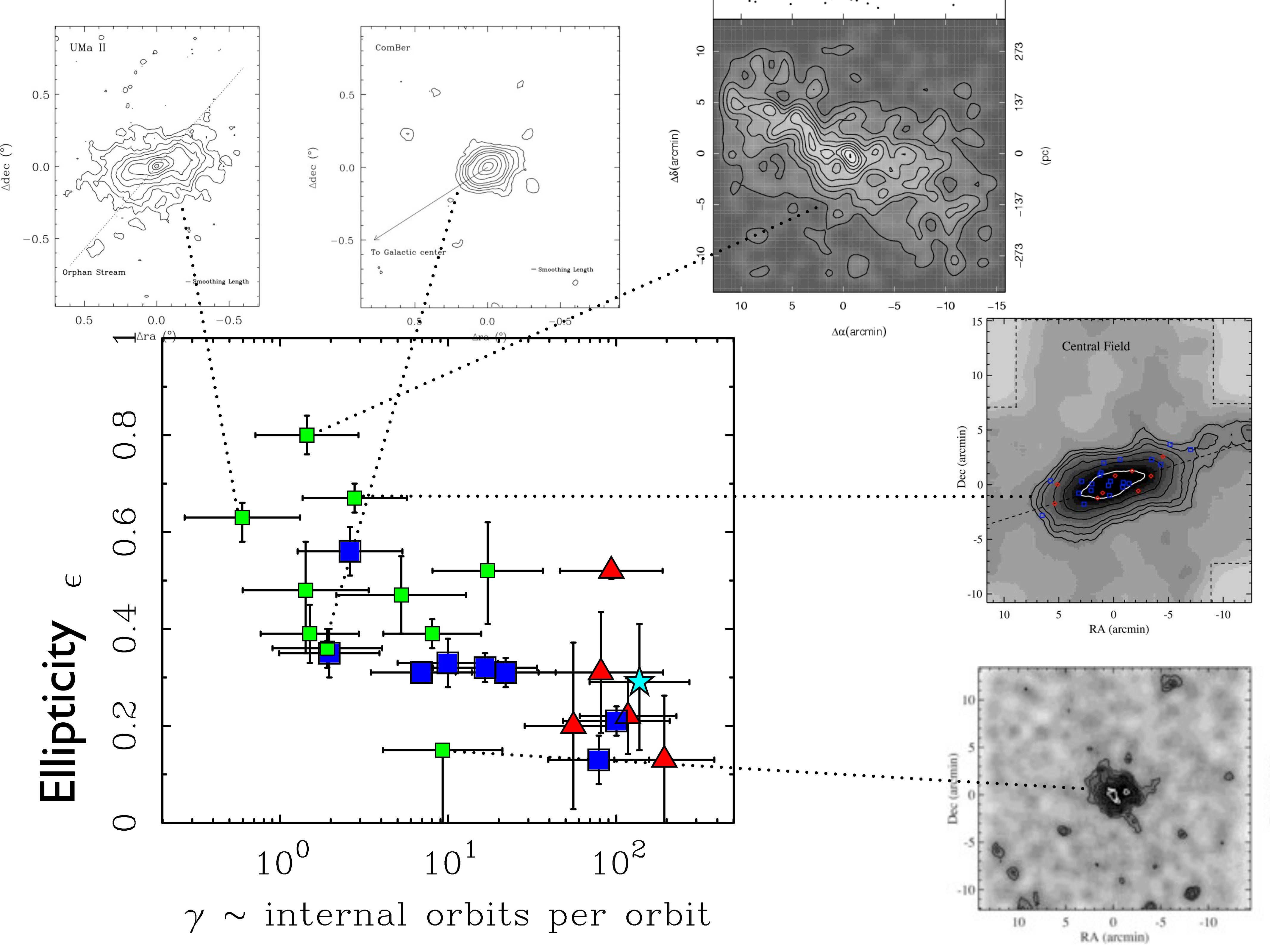
There is no EFE in dark matter - this is a unique signature of MOND.



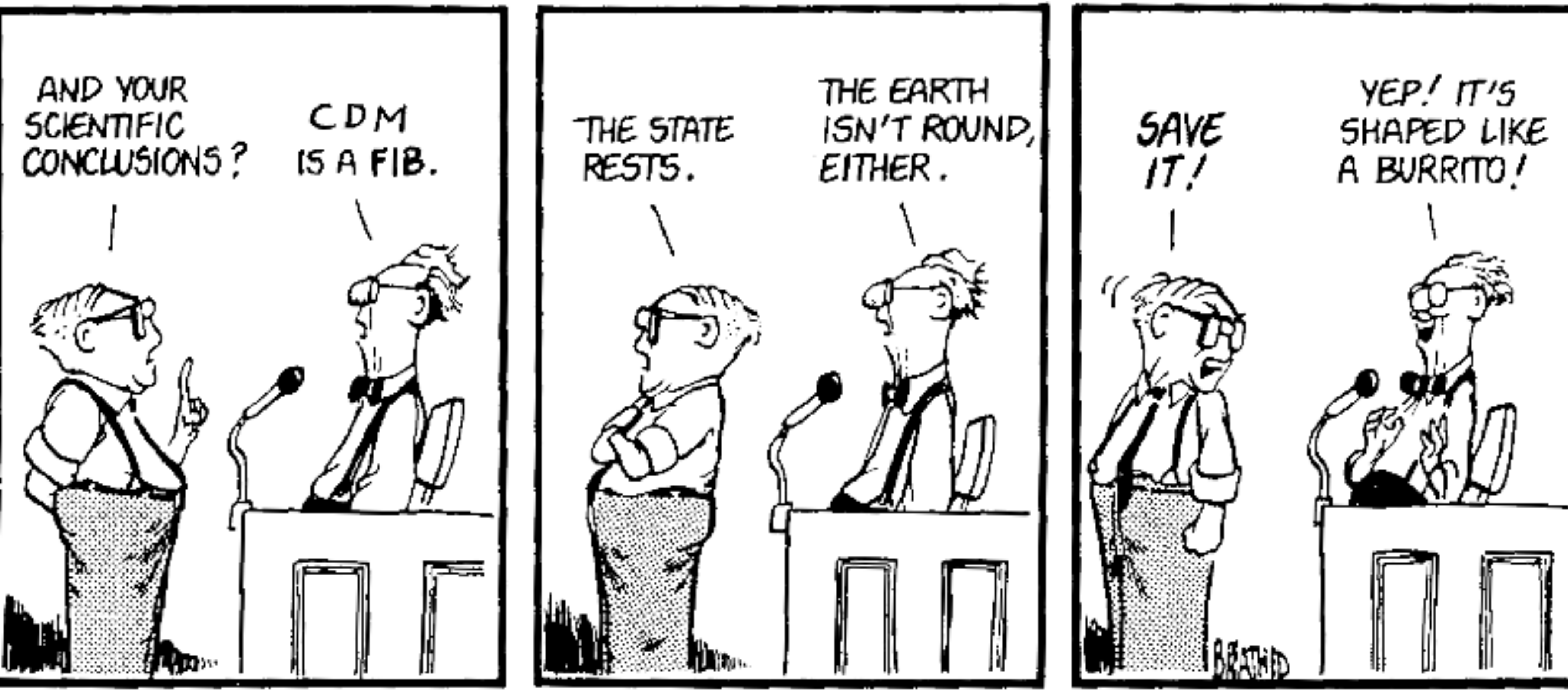
$$V_f = \sqrt{3}\sigma$$



M_b (M_⊙)
V_f (km s^-1)
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^0
10^1
10^2
MOND corrected
Isolated: red
EFE: blue



UMa II
Orphan Stream
Smoothing Length
Δdec (°)
Δra (°)
ComBer
To Galactic center
Smoothing Length
Δδ(arcmin)
Δα(arcmin)
(pc)
Central Field
Dec (arcmin)
RA (arcmin)
Ellipticity ϵ
γ ~ internal orbits per orbit


AND YOUR SCIENTIFIC CONCLUSIONS?
CDM IS A FIB.
THE STATE RESTS.
THE EARTH ISN'T ROUND, EITHER.
SAVE IT!
YEP! IT'S SHAPED LIKE A BURRITO!