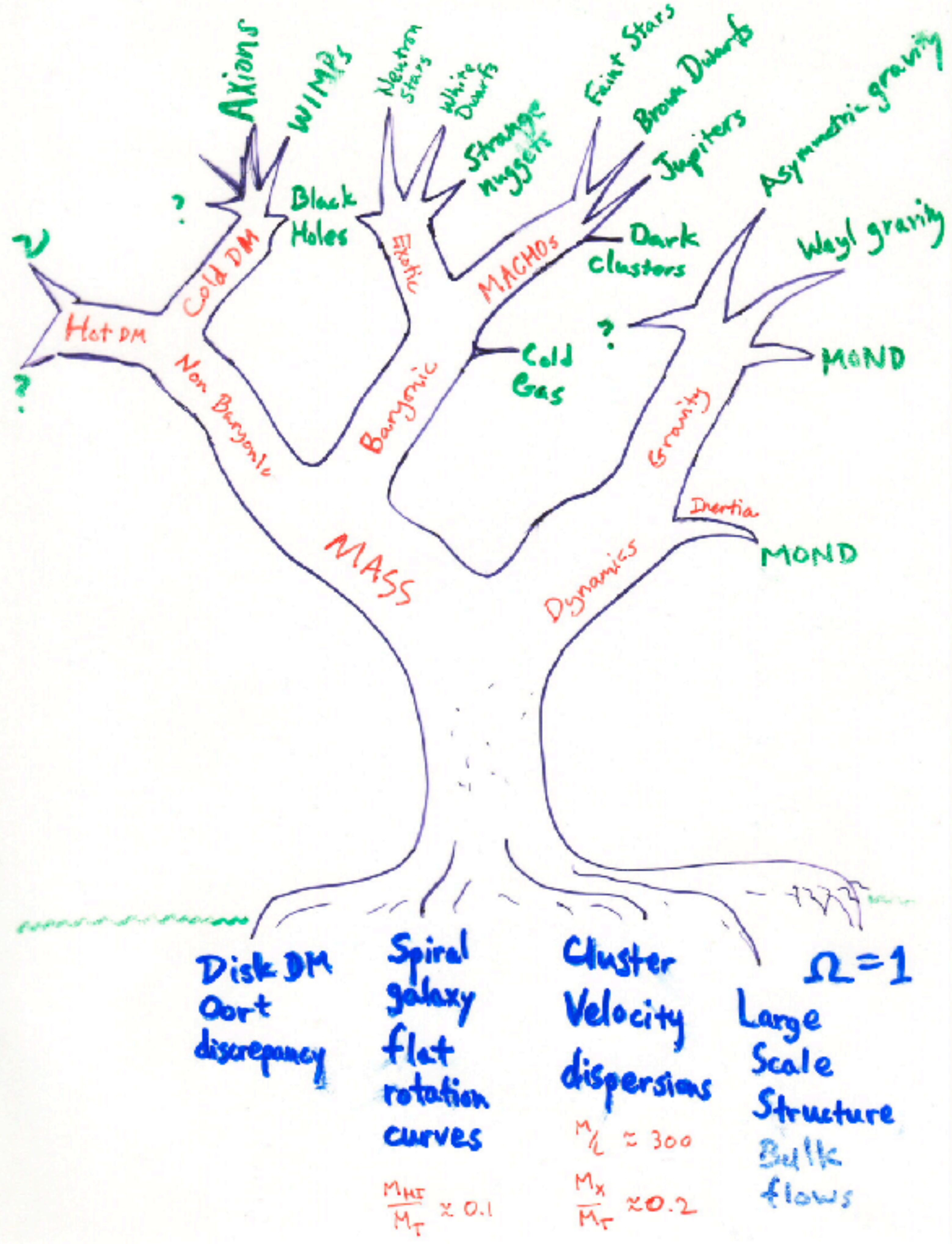
Dark Matter

ASTR 333/433

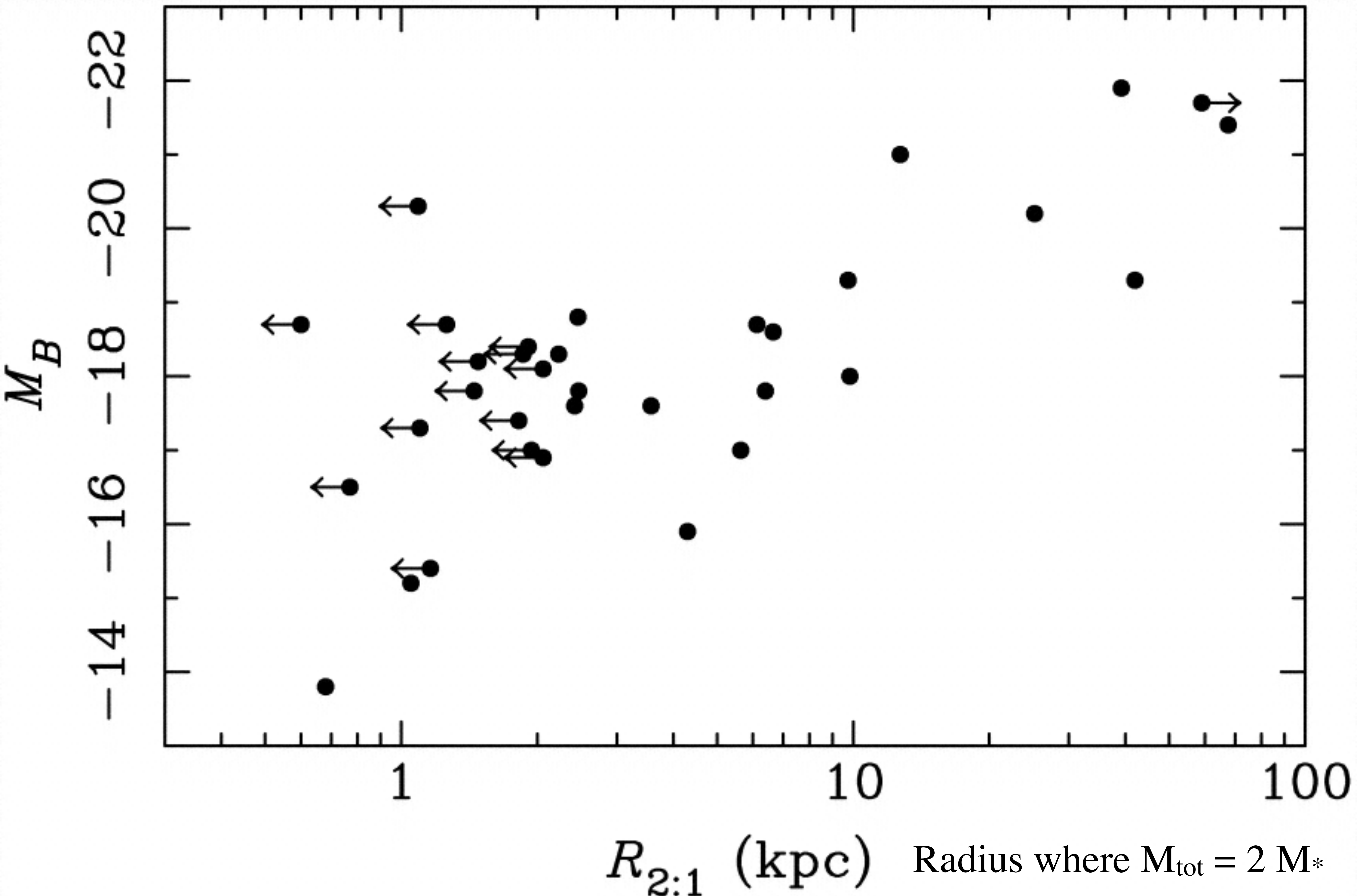
Today

Modified Gravity Theories
MOND

4/24: Homework 4 due
4/26: Exam



Not any theory will do - length scale based modifications can be immediately excluded as the discrepancy does not appear at a particular length scale.



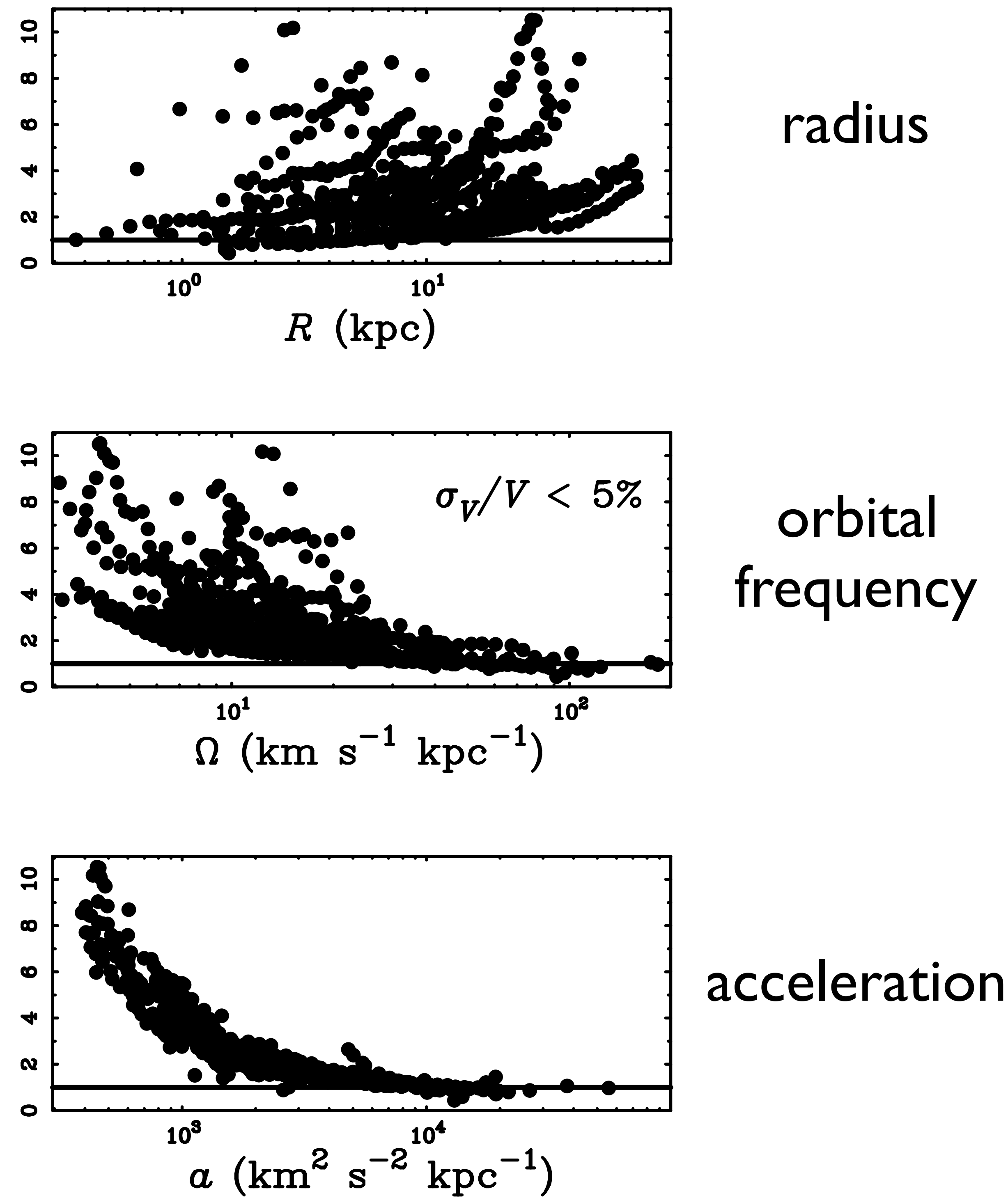
Radius where $M_{tot} = 2\ M_*$

Not just any force law...

No unique size scale in the data. Can generically exclude any modification of gravity where a change in the force law appears at a specific length scale.

There is a characteristic acceleration scale in the data

McGaugh (2004)



60 galaxies
> 600 points
(errors < 5%)

MOND

Modified Newtonian Dynamics (Milgrom 1983)

Instead of invoking dark matter, modify gravity (or inertia). Milgrom suggested a modification at a particular acceleration scale a_0

Newtonian regime

$$a = g_N \text{ for } a \gg a_0$$

MOND regime

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

MOND regime invariant under transformations $(t, \mathbf{x}) \to \lambda(t, \mathbf{x})$

Regimes smoothly joined by $$\mu\left(\frac{a}{a_0}\right) a = g_N$$

$$\mu(x) \to 1 \text{ for } x \gg 1 \qquad \mu(x) \to x \text{ for } x \ll 1 \qquad x = \frac{a}{a_0}$$

Modified Poisson equation

$$\nabla \left[\mu\left(\frac{\nabla\Phi}{a_0}\right) \nabla\Phi\right] = 4\pi G\rho$$

Derived from aquadratic Lagrangian of Bekenstein & Milgrom (1984) to satisfy energy conservation.

MOND predictions

ApJ, 270, 381

Milgrom 1983

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 [illegible] and galactic [illegible] I [illegible] Milgrom [illegible].

VIII. PREDICTIONS

The main predictions conce[illegible] lows.

1. Velocity curves calculat[illegible] 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] the same [illegible] conventional dynamics should yield a discrepancy which increases with radius in a predictable manner.

4. Effects of the [illegible] dynamics are predicted to be particularly str[illegible] dwarf [illegible] (for review of propert[illegible] Hodge [illegible] and [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 $a_{in} \ll g$, $h_{10} = 1$).

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 [illegible] advantages: (*a*) [illegible] 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 [illegible] many cases [illegible] requires [illegible] 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] $\Sigma^{-1} V_\infty^{4}$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that low surface dens[illegible] higher than [illegible] by [illegible] normal surface density gal[illegible].

We also predict that the lower the average surface density of a galaxy is, the smaller is the transition ra[illegible] scale length [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.

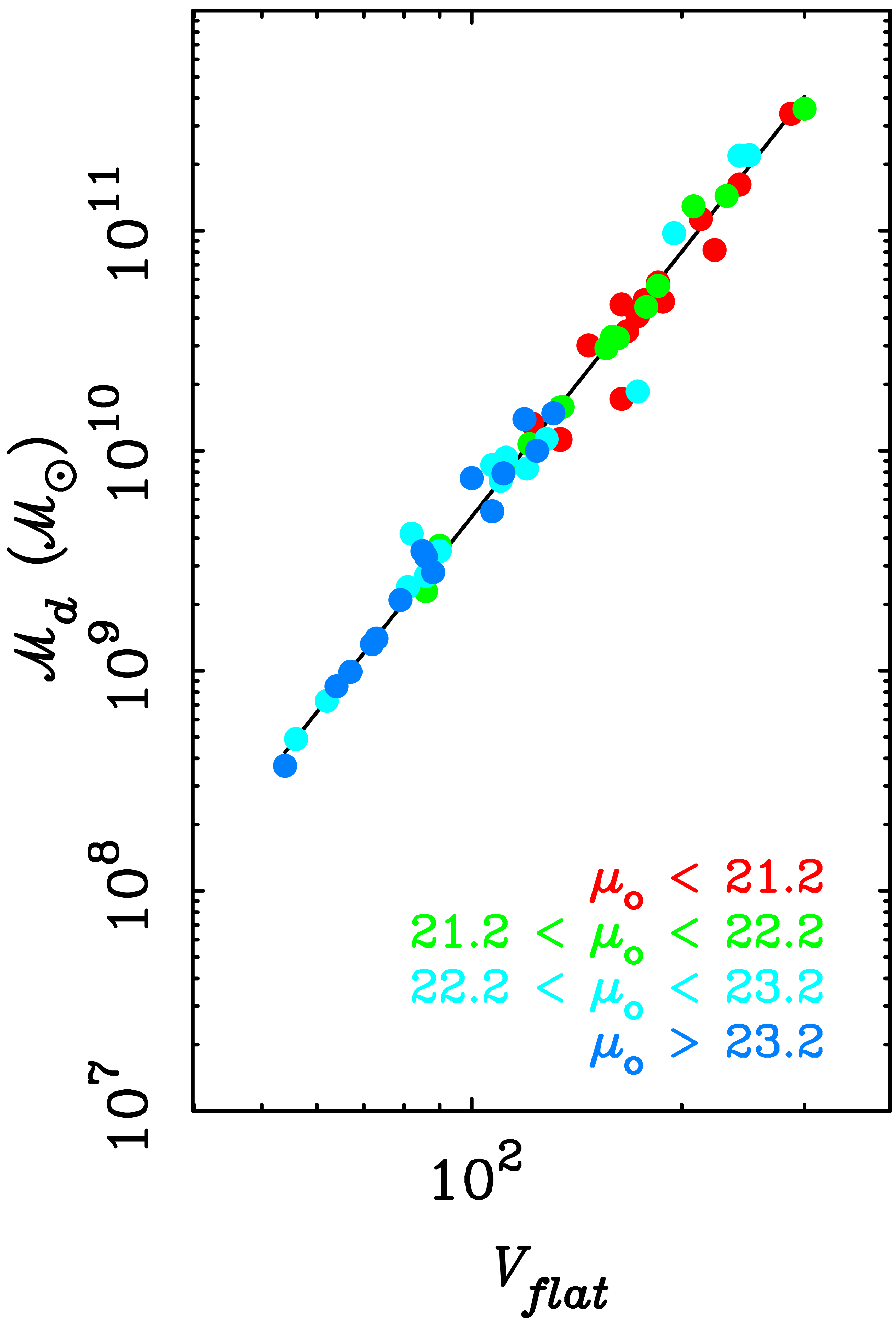
IX. DISCUSSION

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”

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

- 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



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
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In MOND limit of low acceleration

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

$$\frac{V^2}{R} = \sqrt{\frac{GM}{R^2} a_0}$$

$$V^4 = a_0 GM$$

observed TF!

Why?
Physics of the BTFR scaling relation

dark matter

halos: $M_{tot} \propto V^3$

baryons: $M_d \propto V^x$

$x \geq 3$ depending on $m_d(V)$

Should depend on disk scale length, unless all disks submaximal

Should work as long as object not tidally disrupted

MOND

$$M_{tot} = M_b = \frac{V^4}{a_0 G}$$

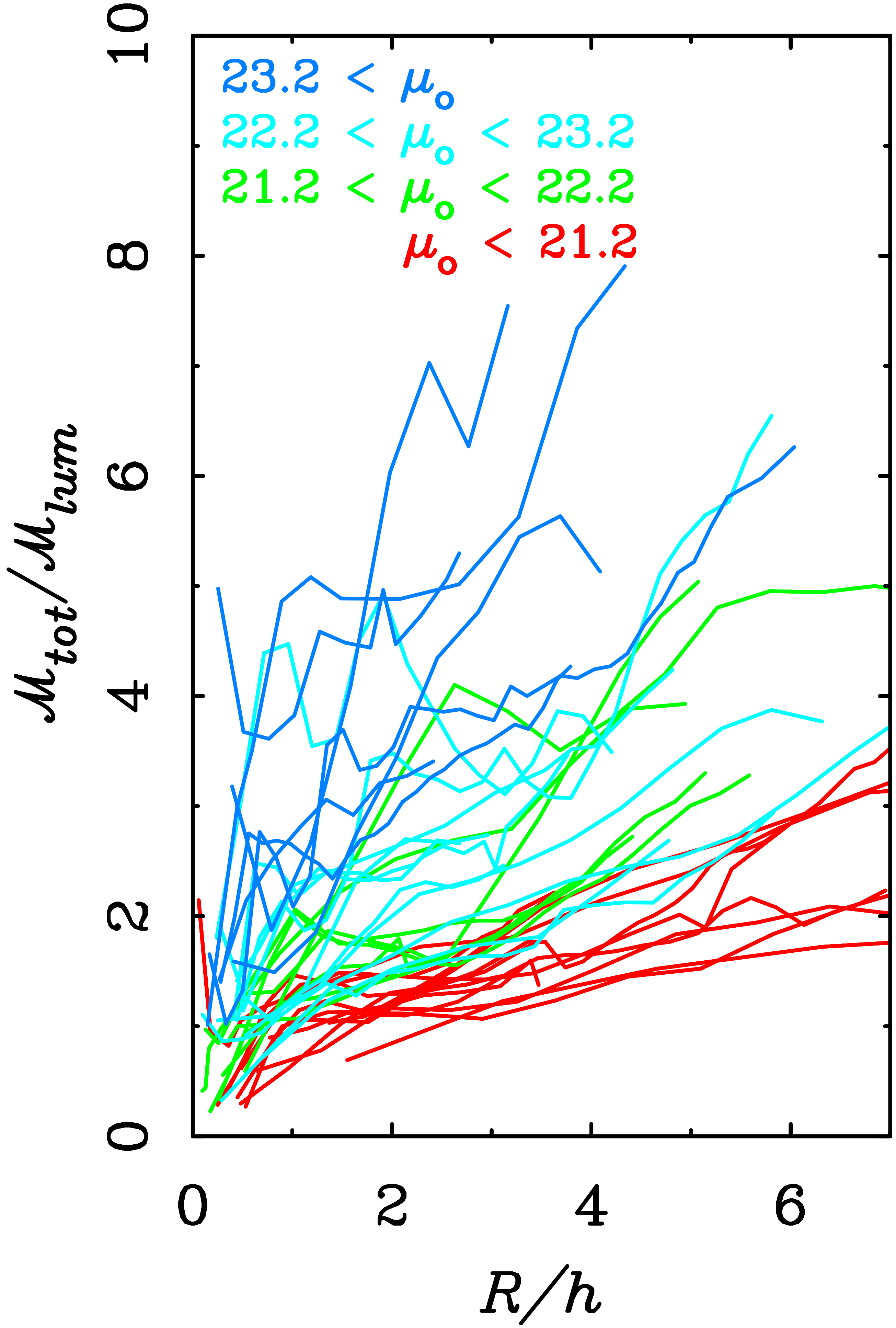
an absolute consequence of the force law for $a \ll a_0$:

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

Newtonian regime:
$\mu \to 1$ for $g \gg a_0$ so $g = g_N$

MOND regime:
$\mu \to g/a_0$ for $g \ll a_0$ so $g = \sqrt{g_N a_0}$

Should only work for objects in MOND regime



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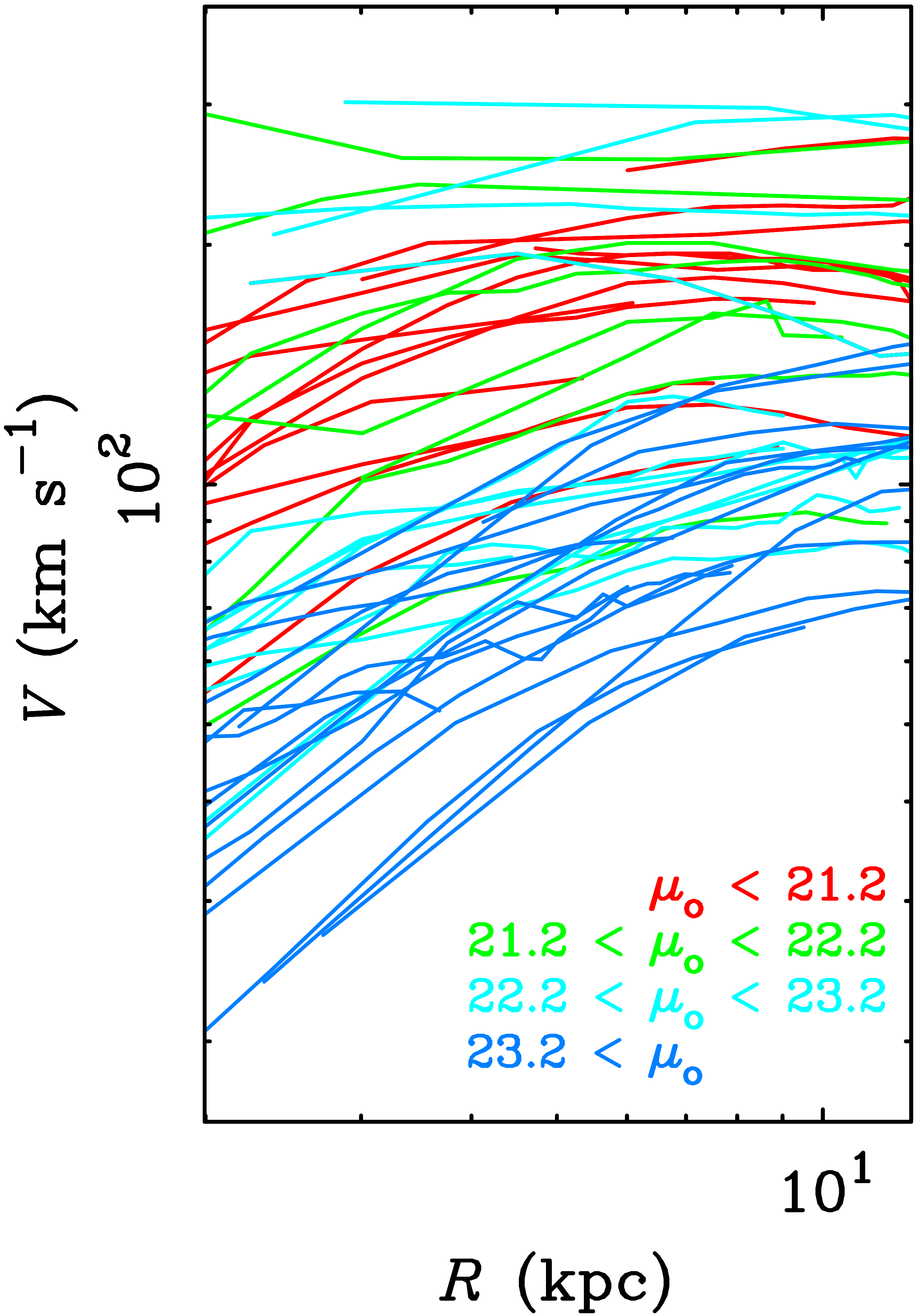

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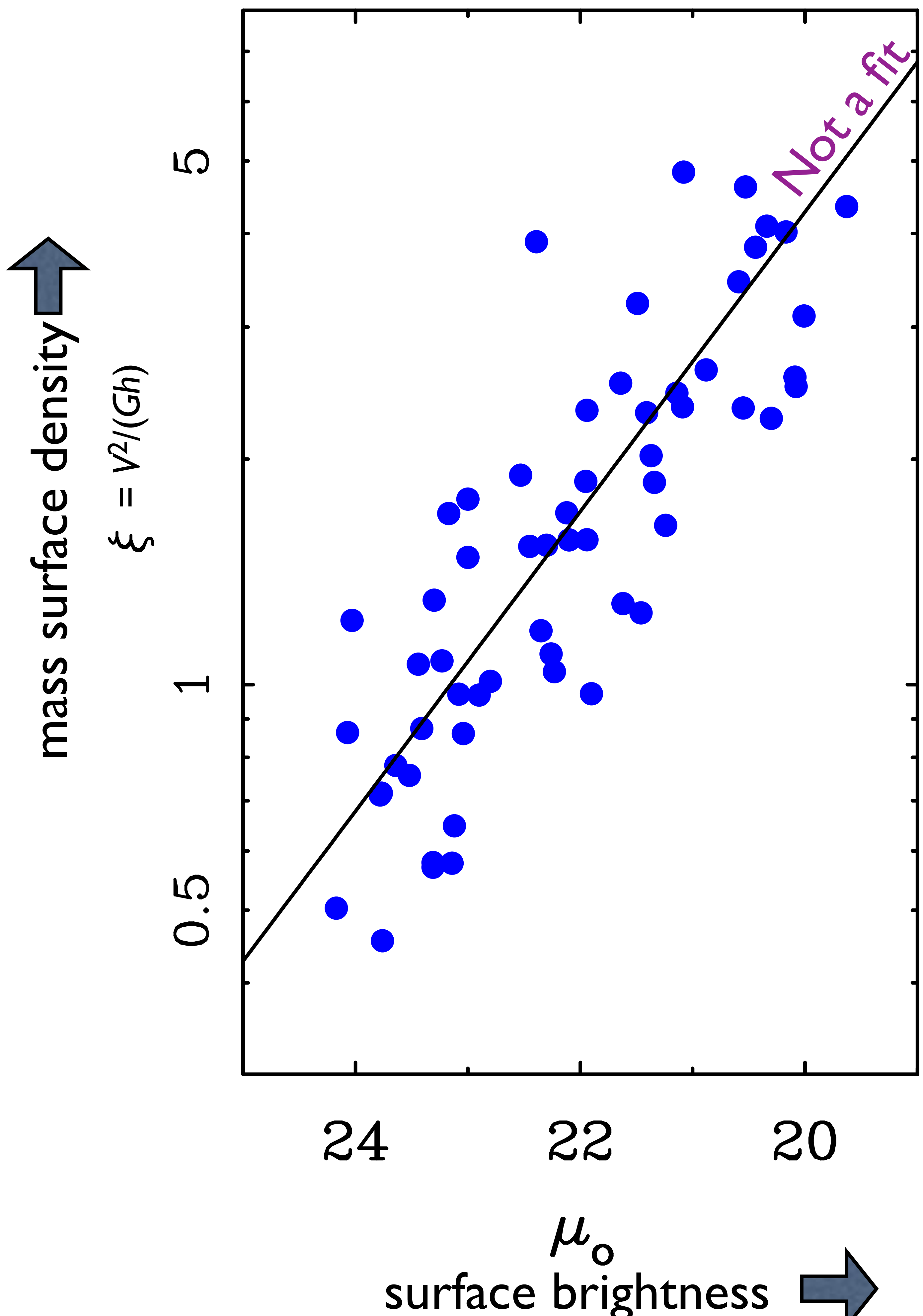

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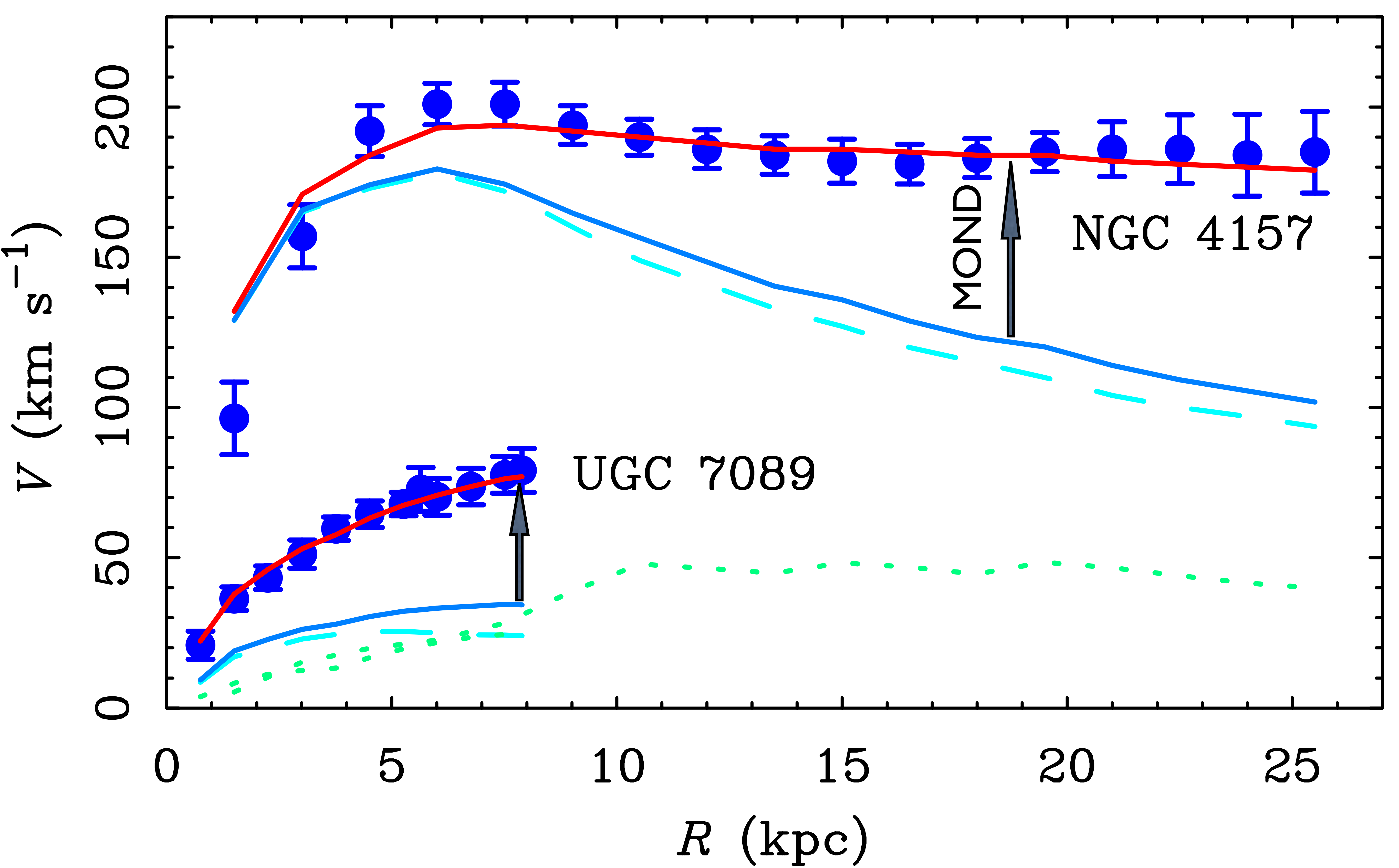
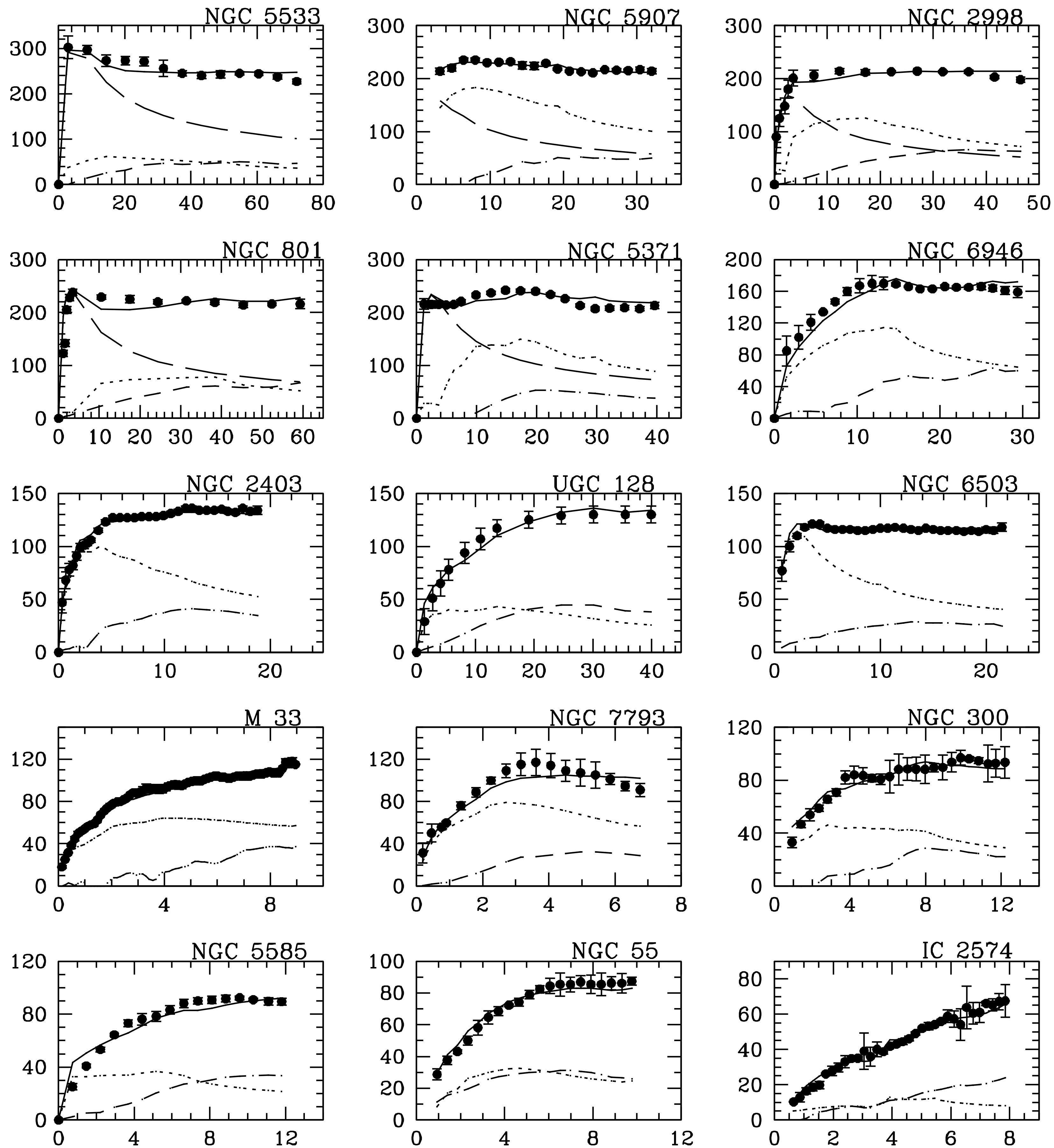
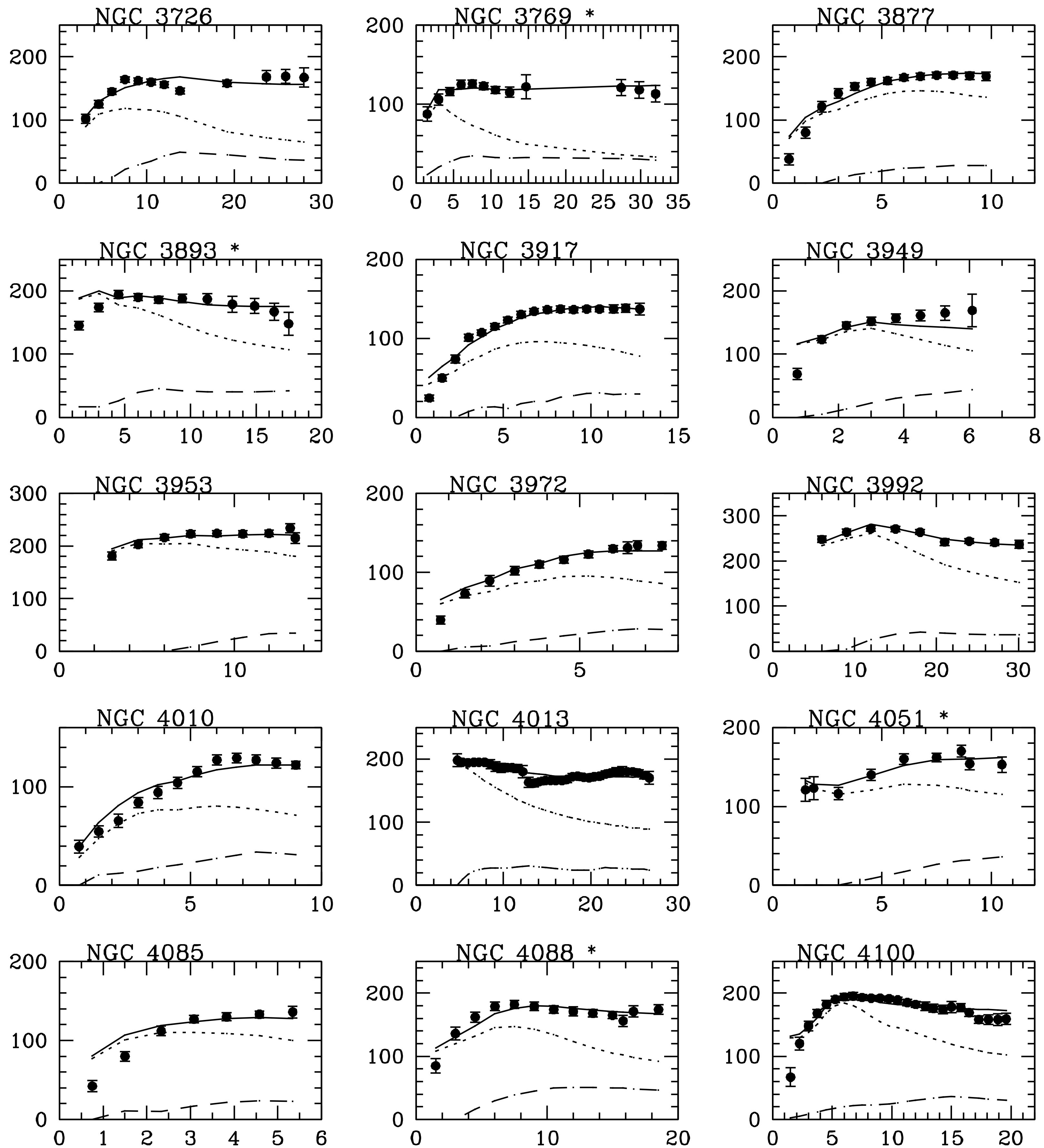


V (km s⁻¹)
R (kpc)
NGC 4157
UGC 7089
MOND
0
5
10
15
20
25
0
50
100
150
200

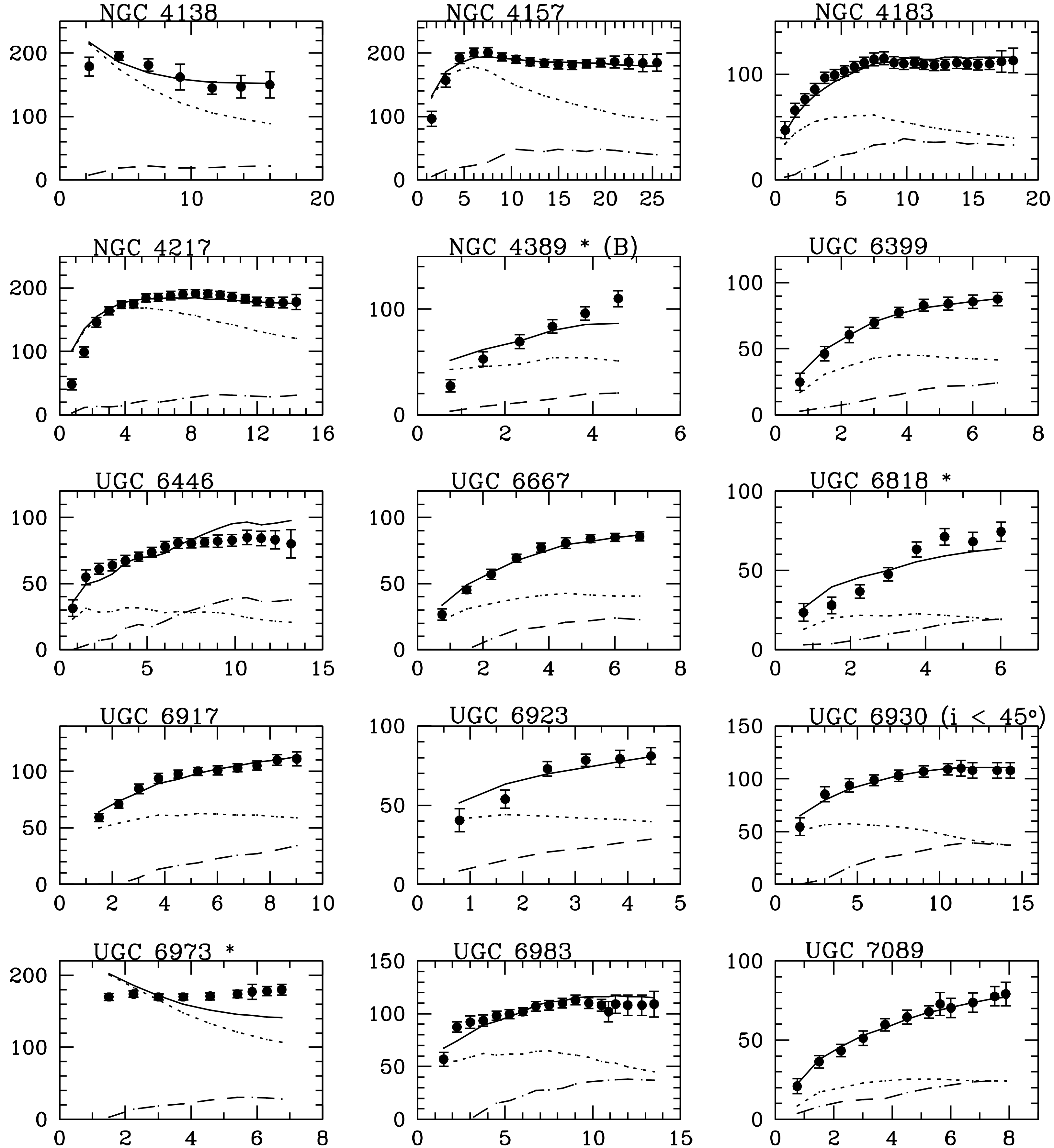
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



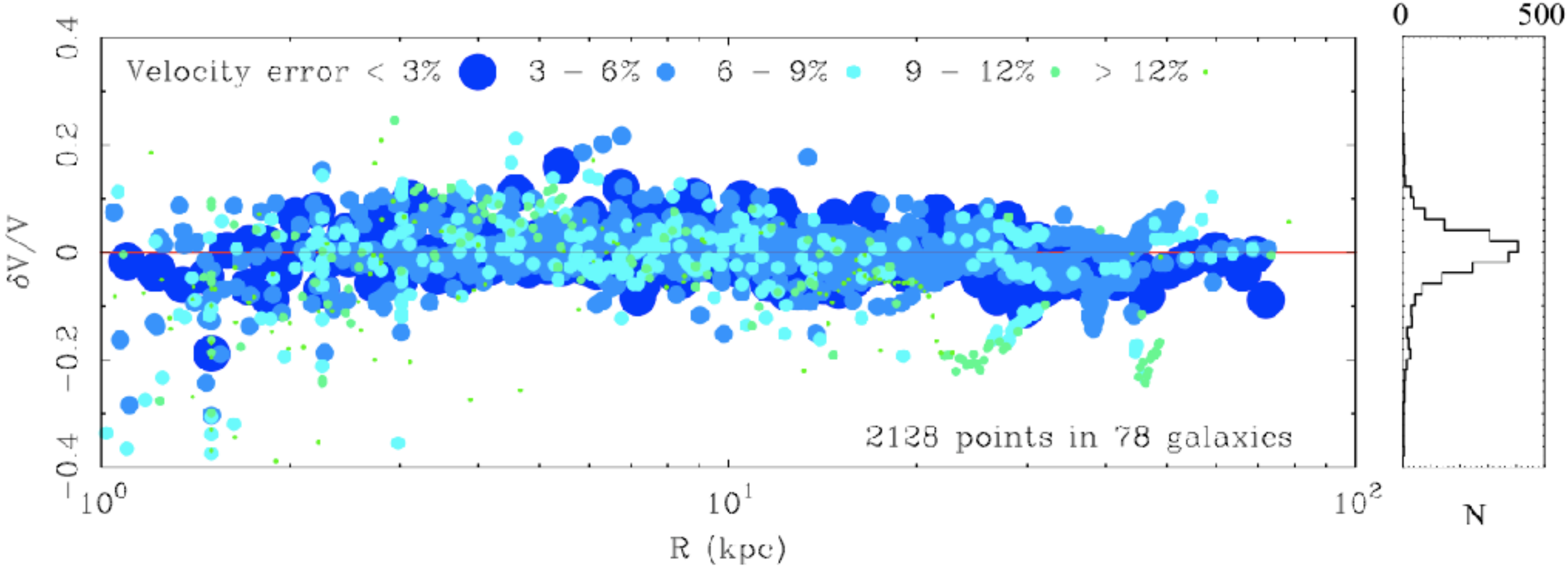
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



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

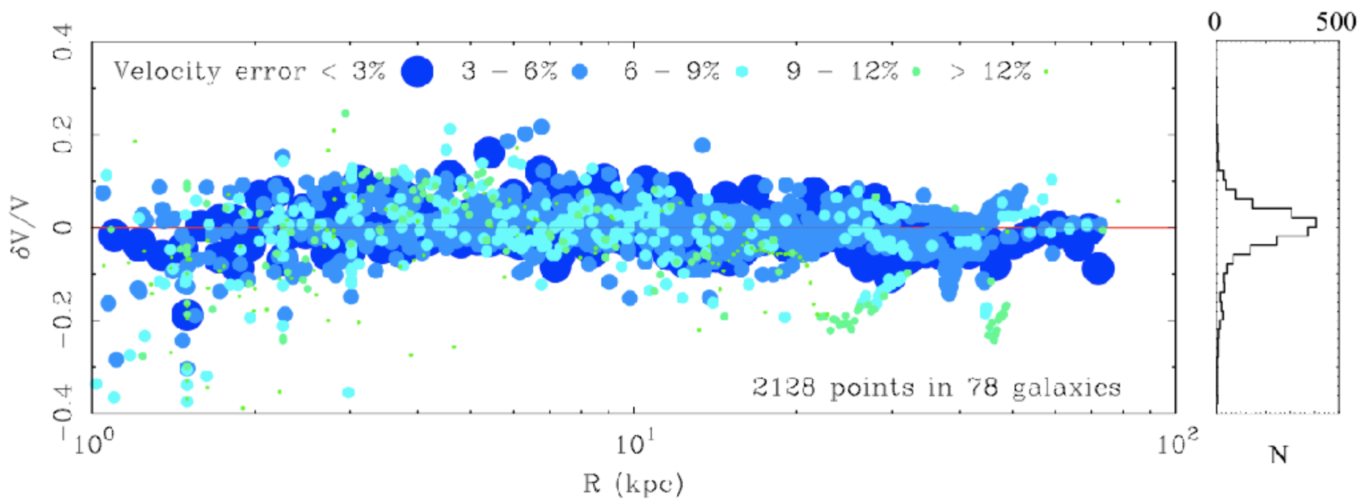


Residuals of MOND fits



Famaey, B., & McGaugh, S.S. 2012, L
Reviews in Relativity, 15, 10

MOND predictions



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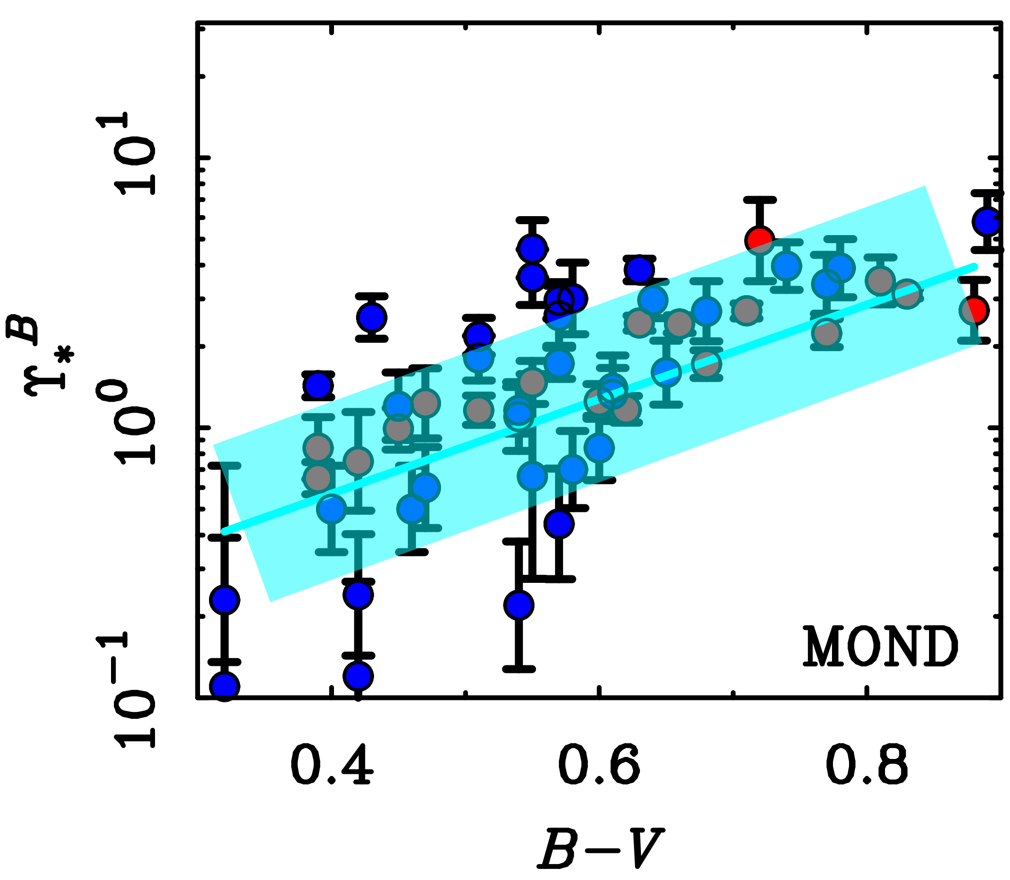
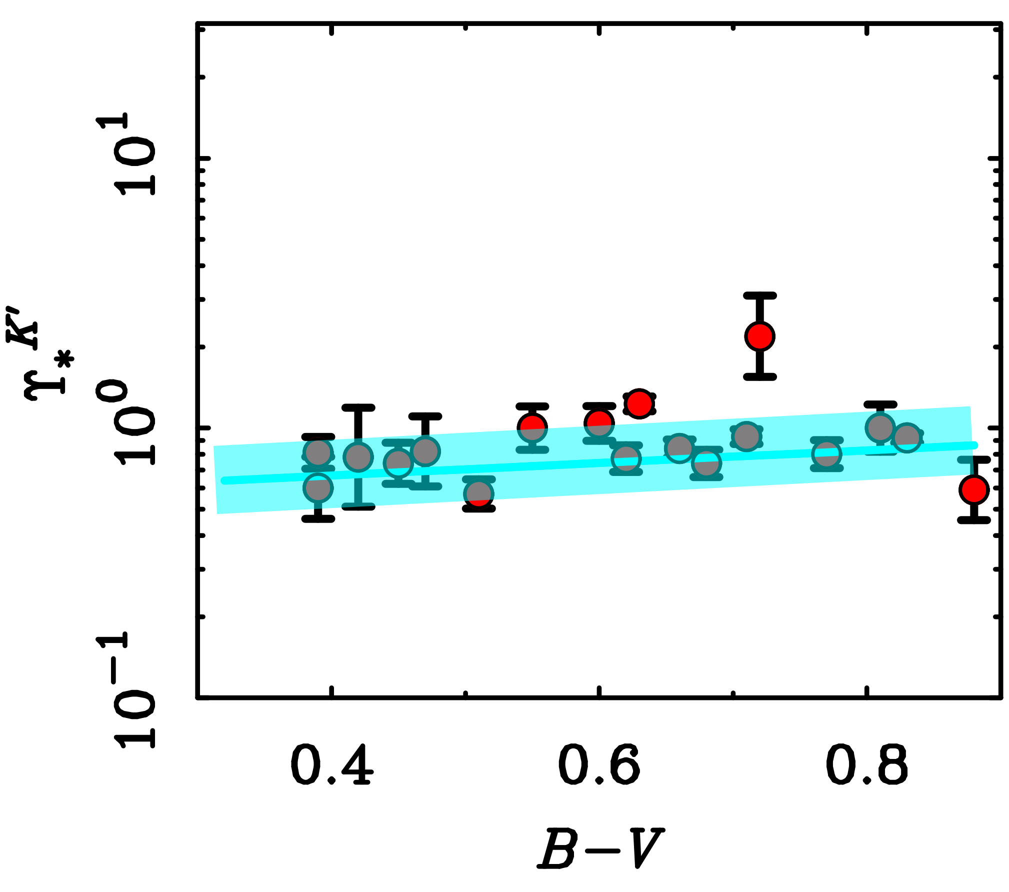
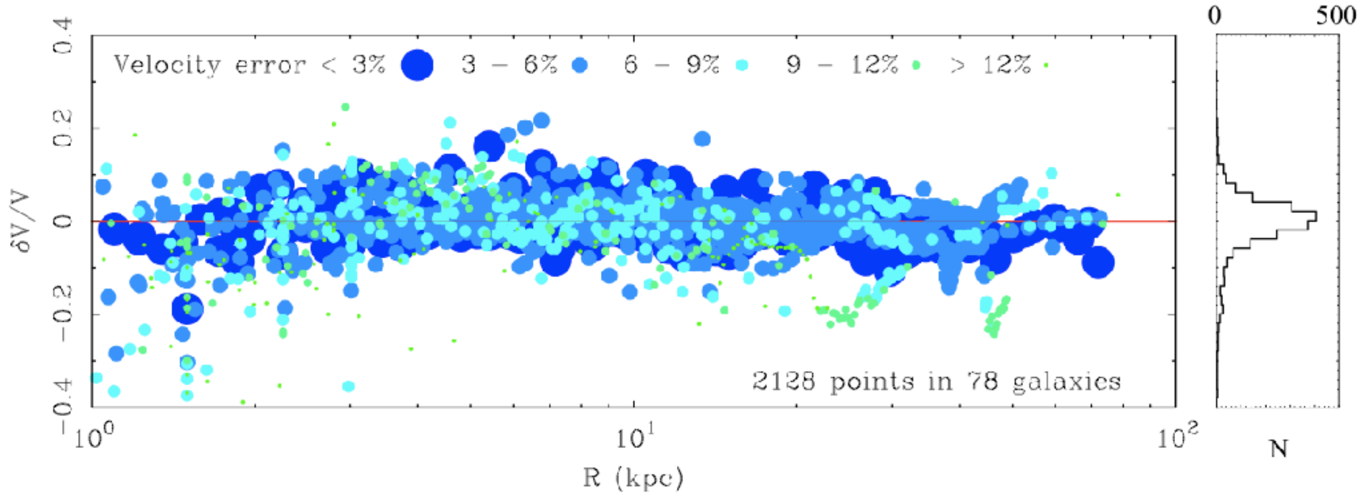


Line: stellar population model
(mean expectation)



MOND predictions



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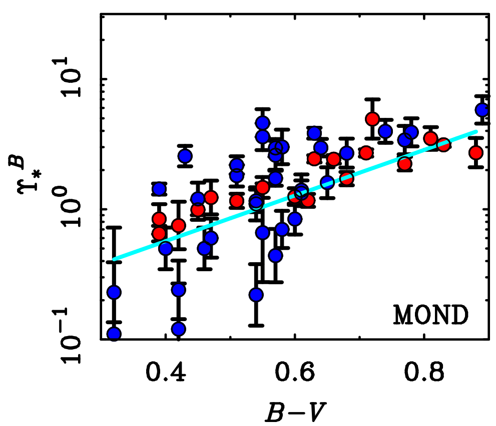

- ✔ Dependence of conventional M/L on radius and surface brightness
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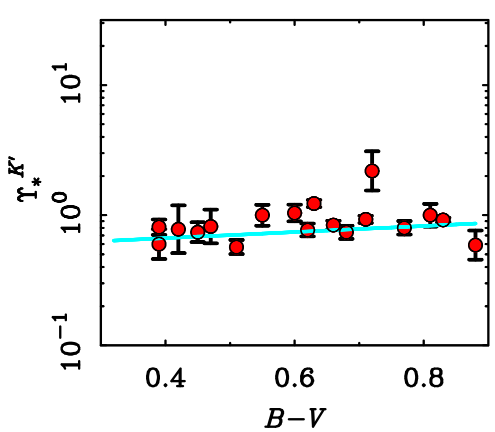


Newtonian regime

$g_{in} > a_0$ $\qquad M = \frac{RV^2}{G}$

e.g., surface of the Earth

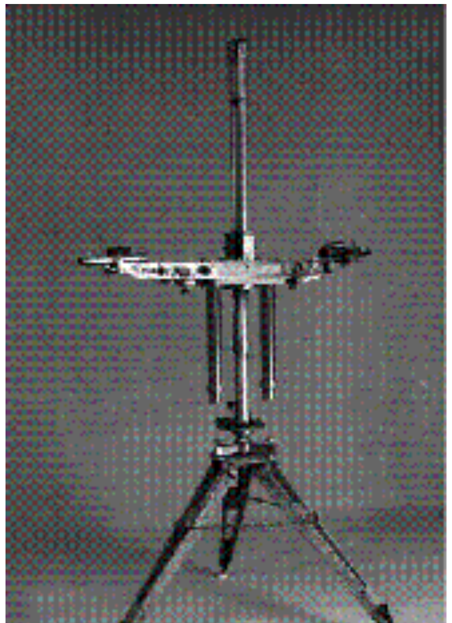
MOND regime

$g_{in} < a_0$ $\qquad M = \frac{V^4}{a_0 G}$

e.g., remote dwarf Leo I

External Field dominant Newtonian regime

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

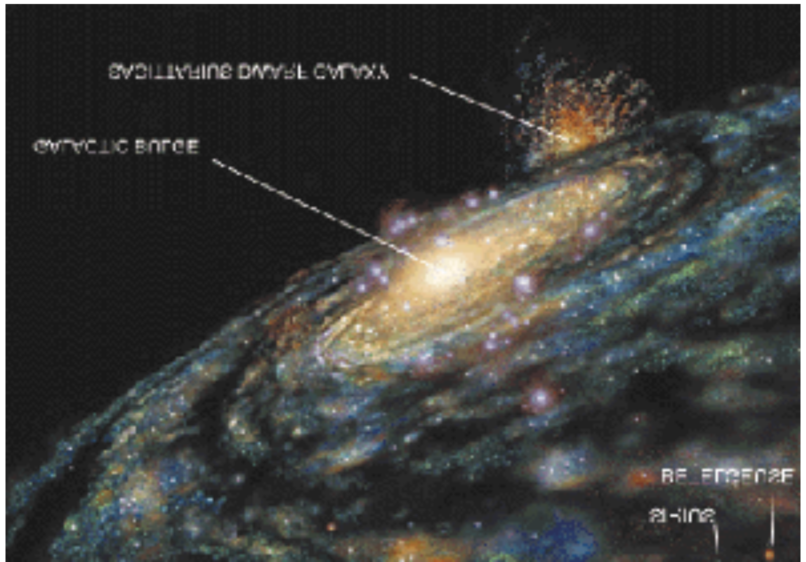


e.g., Eotvos-type experiment on the surface of the Earth

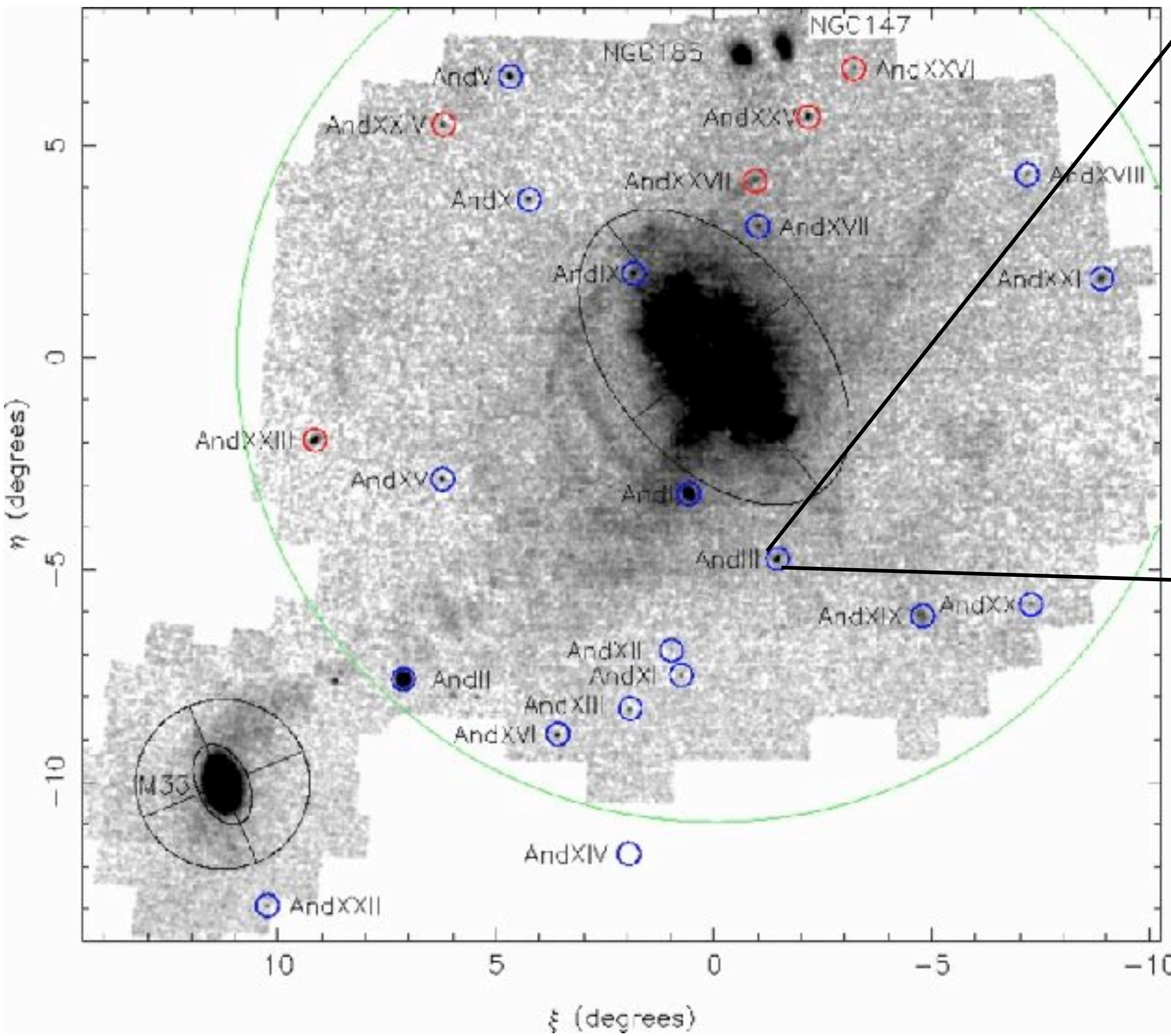
External Field dominant quasi-Newtonian regime

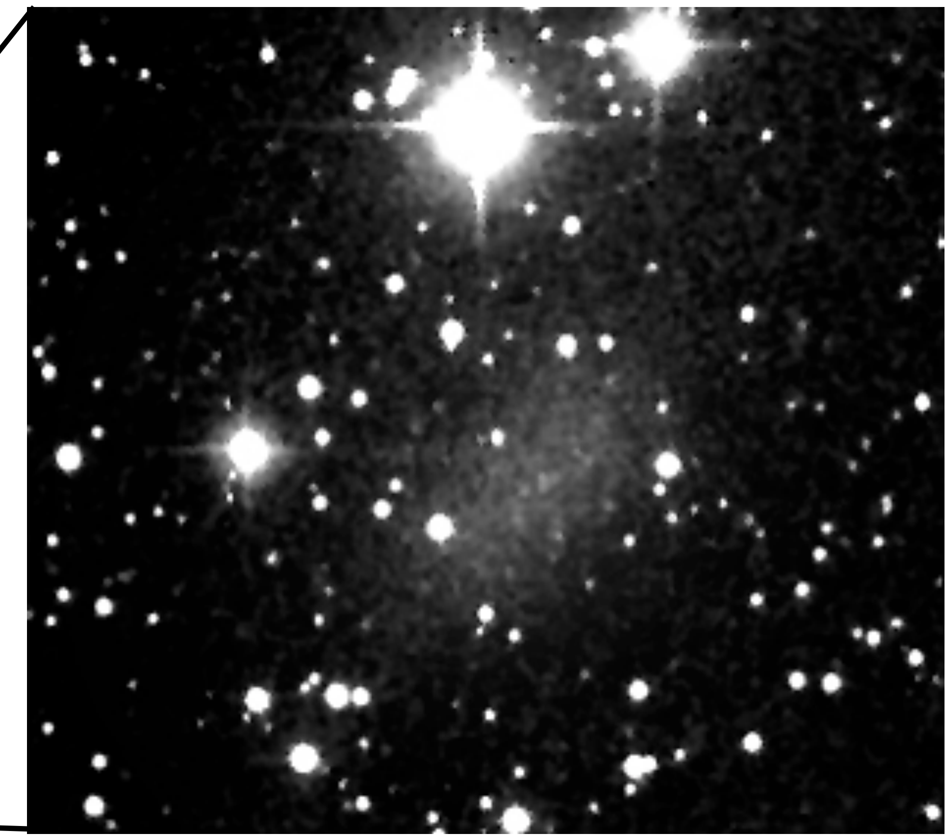
$g_{in} < g_{ex} < a_0$ $\qquad M = \frac{a_0}{g_{ex}} \frac{RV^2}{G}$

e.g., nearby Sgr dwarf

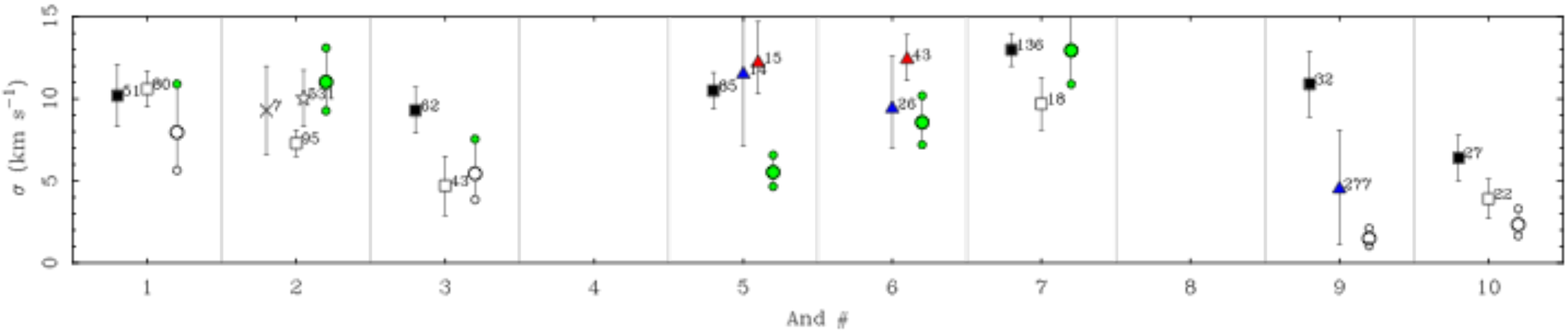


A new test: the dwarf satellites of Andromeda

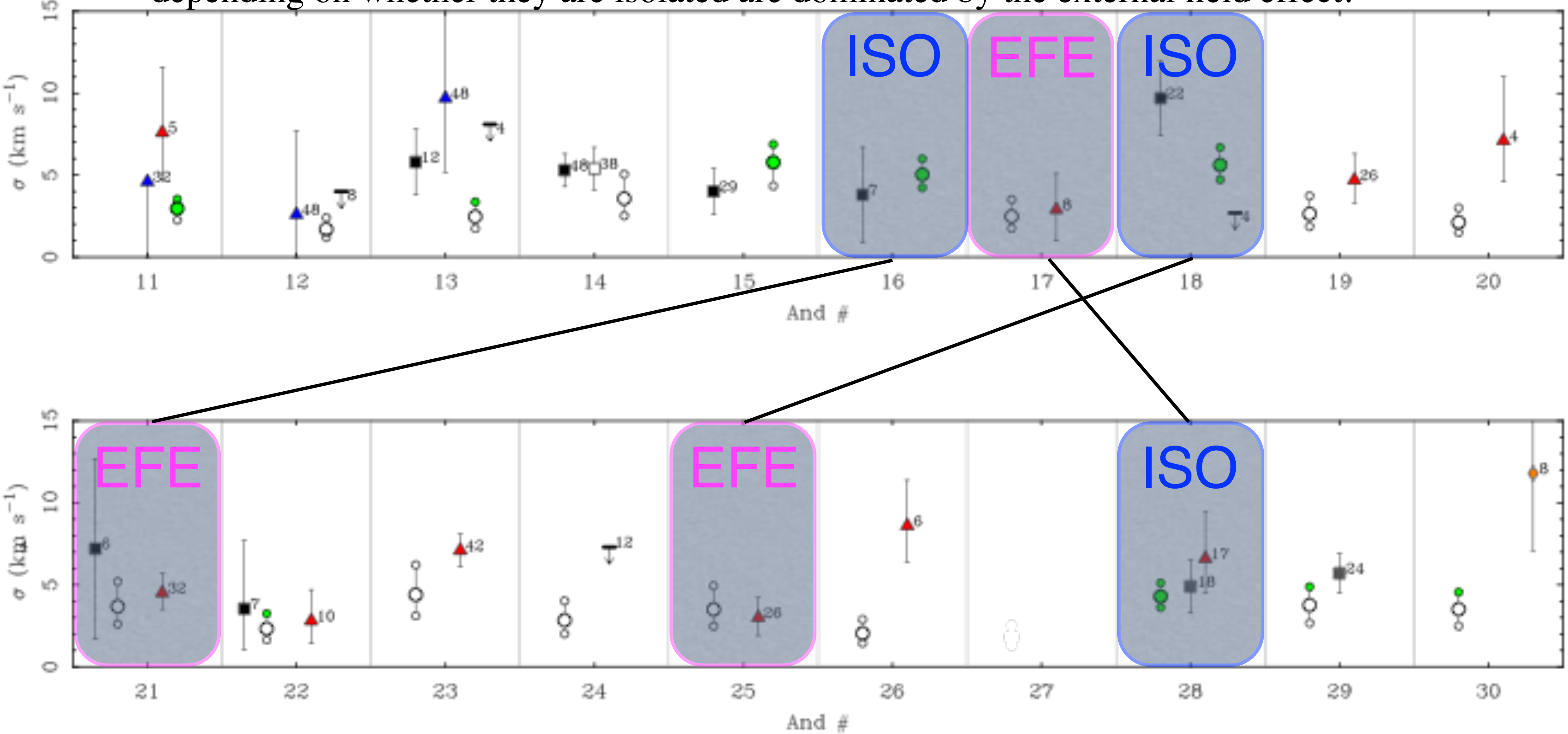




Use MOND to predict the velocity of stars within each dwarf

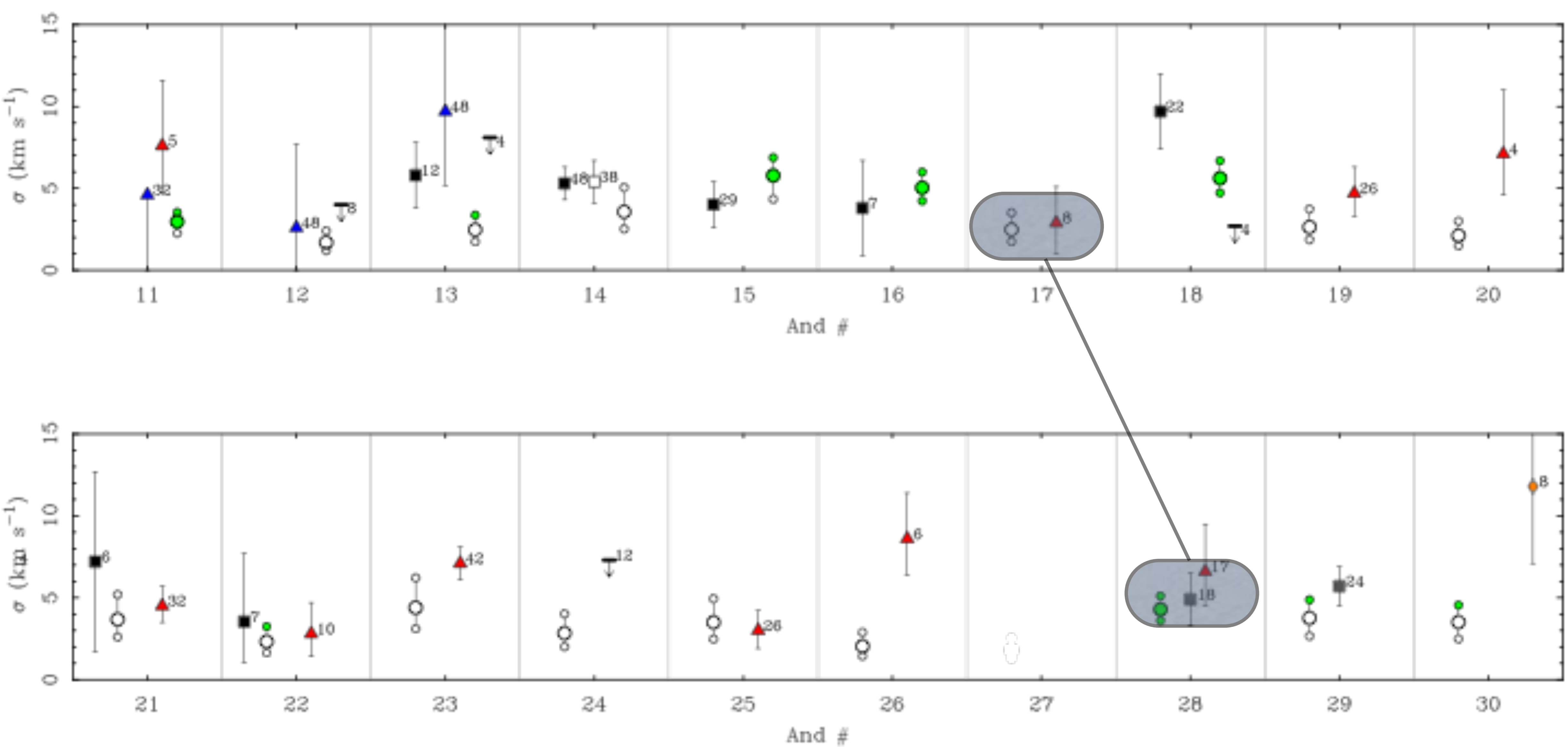


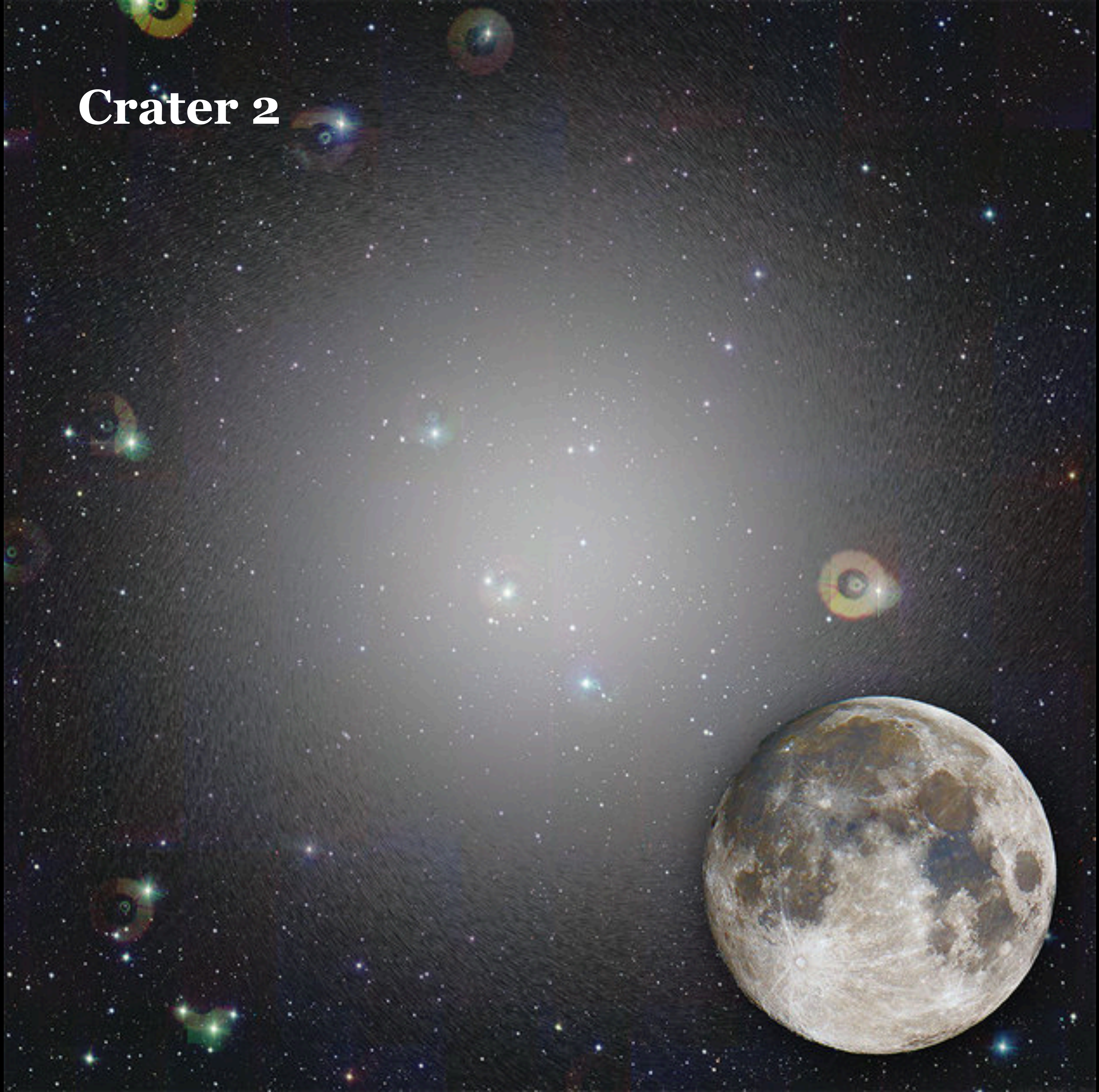
Pairs of photometrically identical dwarfs should have different velocity dispersion depending on whether they are isolated are dominated by the external field effect.



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

Name	Luminosity	R$_e$	σ_{obs}	σ_{pred}	
And XVII	2.6E+05	381	2.9	2.5	EFE
And XXVIII	2.1E+05	284	4.9	4.3	isolated




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)

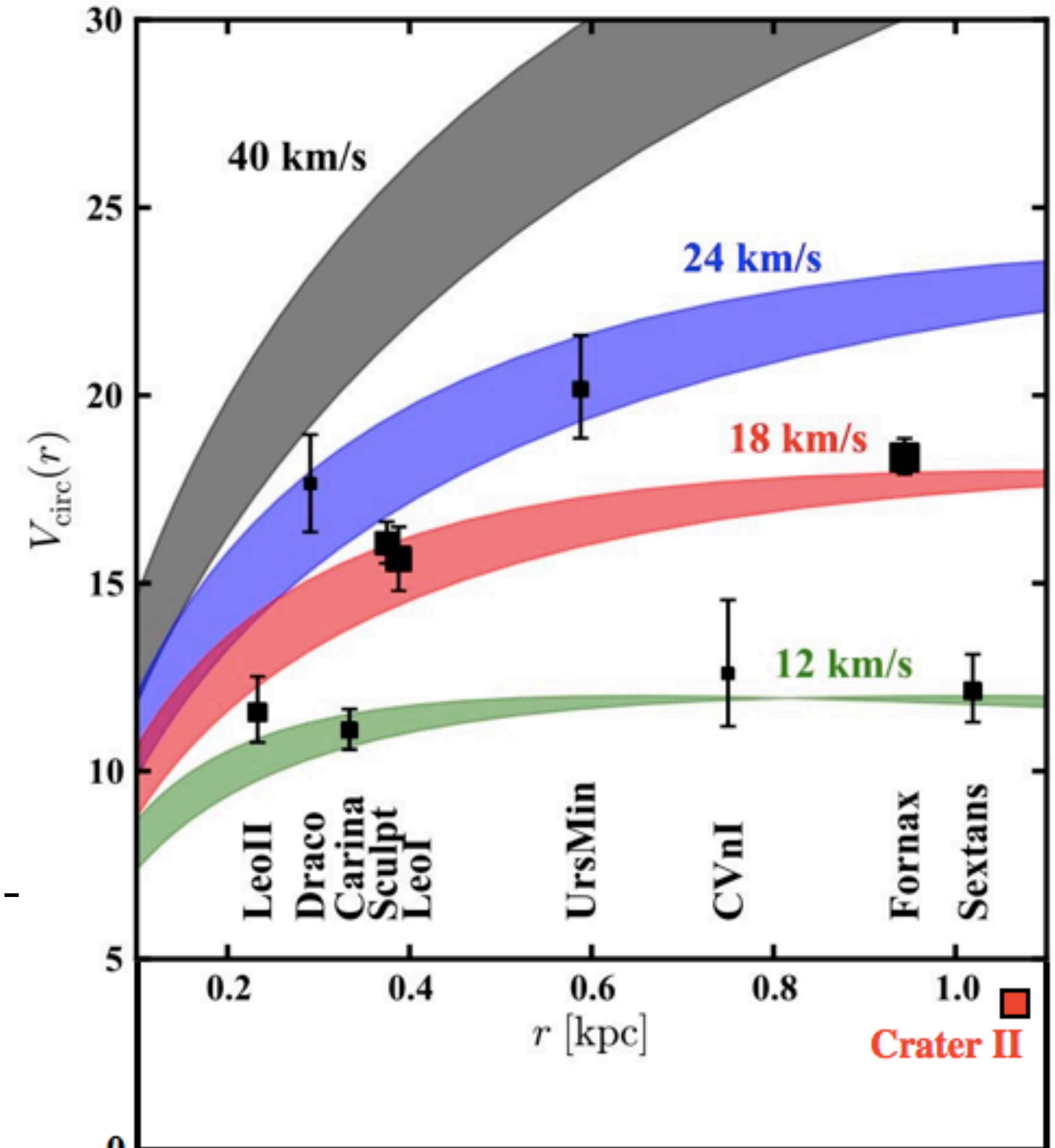
Consistent with a priori MOND prediction ★

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

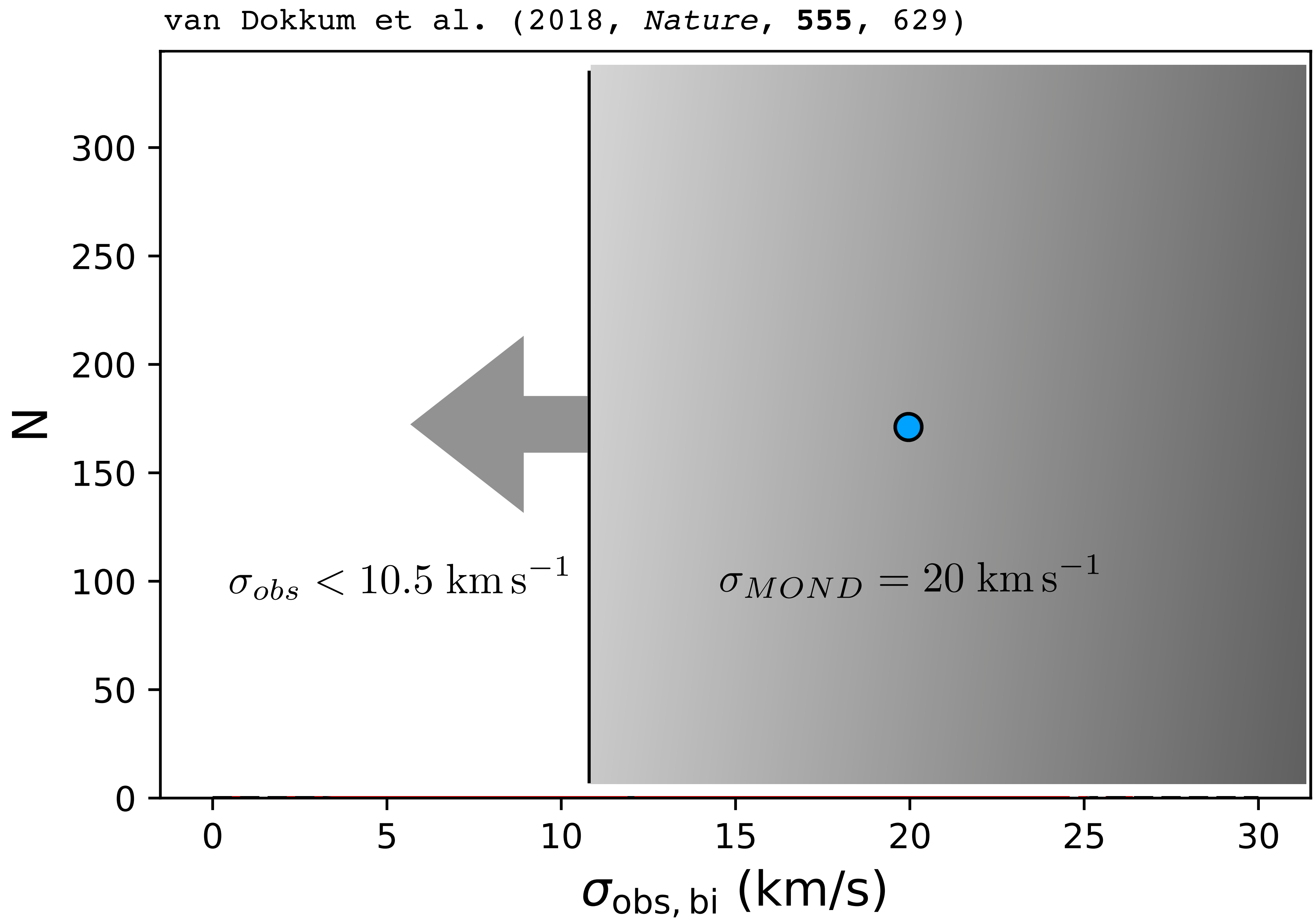
Predictions made in advance of observation are the gold standard in science. ★
MOND has had *many* more successful *a priori* predictions than dark matter based theories.

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

"Too Big To Fail"



NGC 1052-DF2



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

NGC 1052-DF2

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

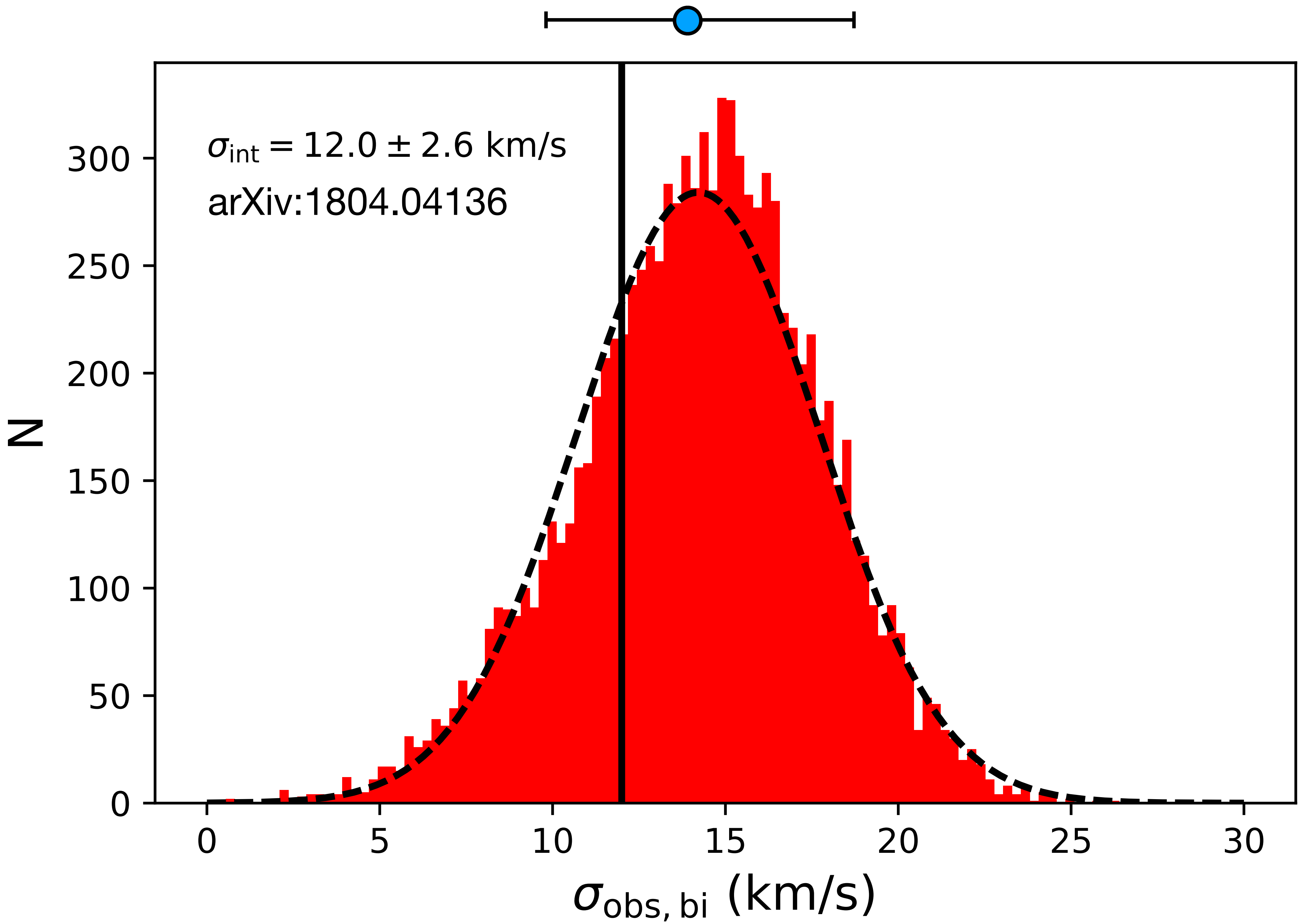


Figure 4. Results for measuring the observed biweight-midvairance dispersion from 10,000 resamples of the vD18b dataset. Here, the original velocities are perturbed within their 1 uncertainties as described in the text. The mean observed biweight for the sample comes out as $\sigma_{obs,bi} = 14.3 \pm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

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?

Review of relativistic theories containing MOND in the appropriate limit

- 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?

Famaey, B., & McGaugh, S.S. 2012, Livin
Reviews in Relativity, 15, 10

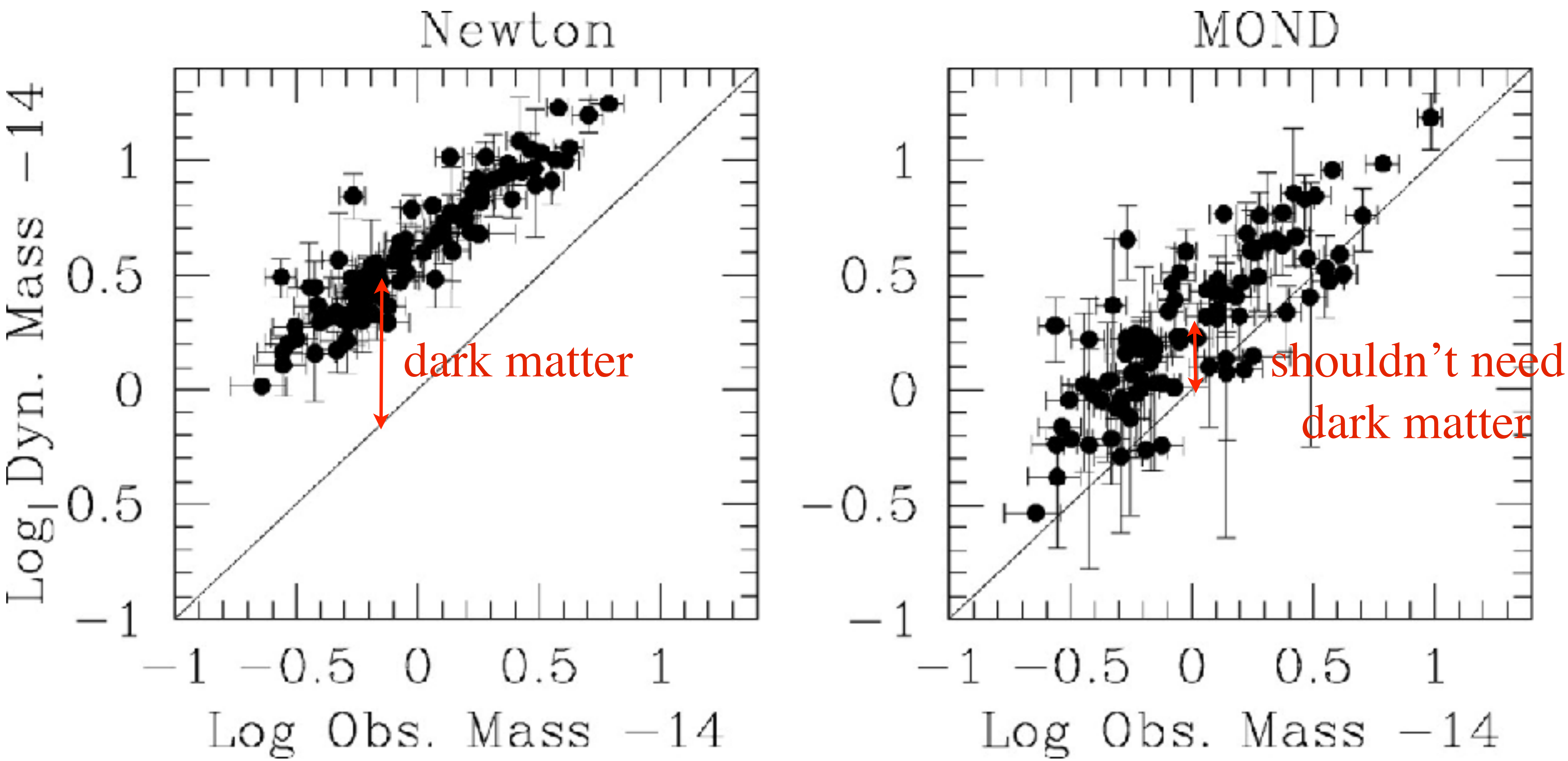
7.1 Scalar-tensor k-essence
7.2 Stratified theory
7.3 Original Tensor-Vector-Scalar theory
7.4 Generalized Tensor-Vector-Scalar theory
7.5 Bi-Scalar-Tensor-Vector theory
7.6 Non-minimal scalar-tensor formalism
7.7 Generalized Einstein-Aether theories
7.8 Bimetric theories
7.9 Dipolar dark matter
7.10 Non-local theories and other ideas
e.g., dark superfluid

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?
- Does it survive other tests?

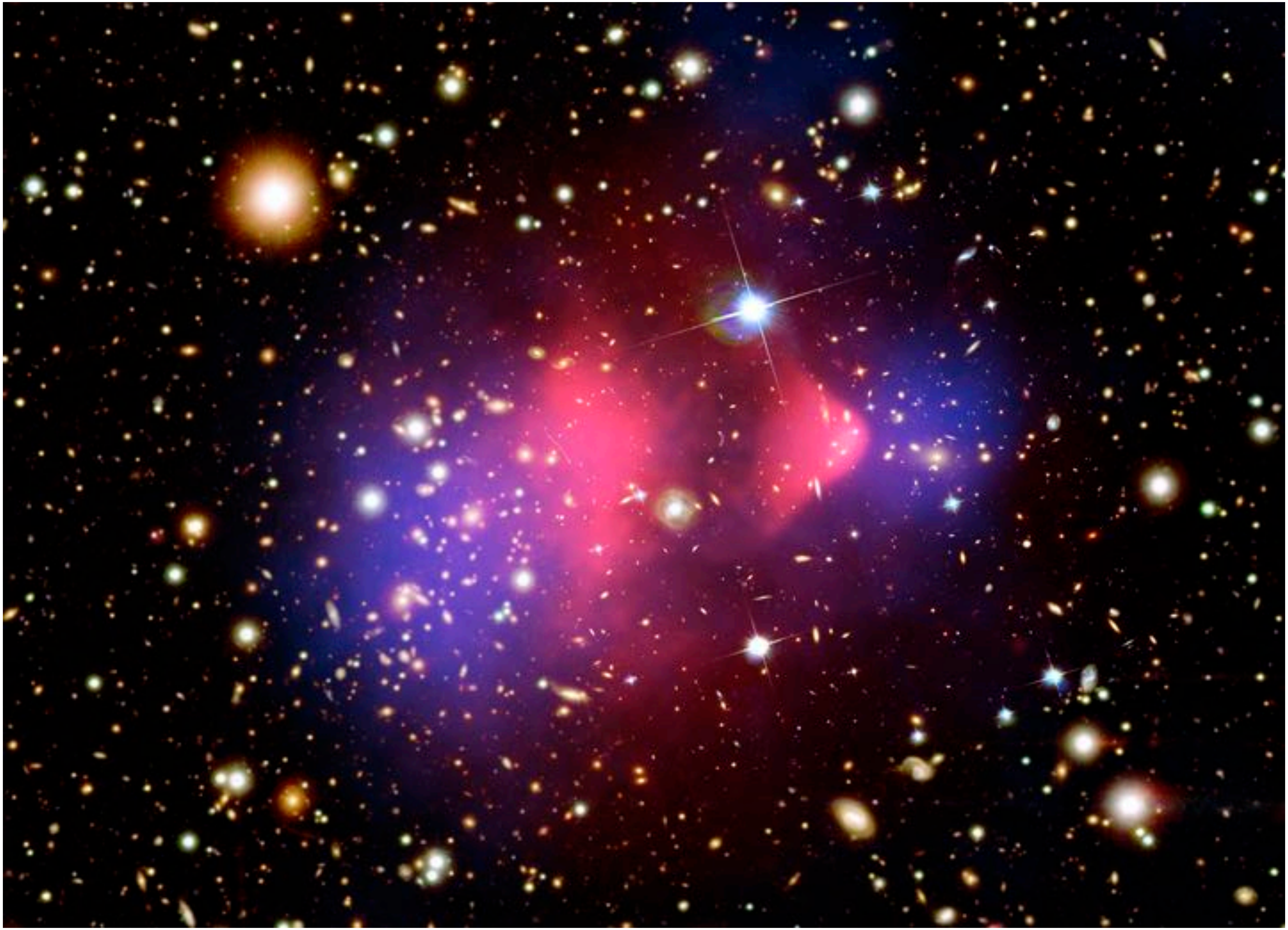
Clusters problematic

Clusters of galaxies

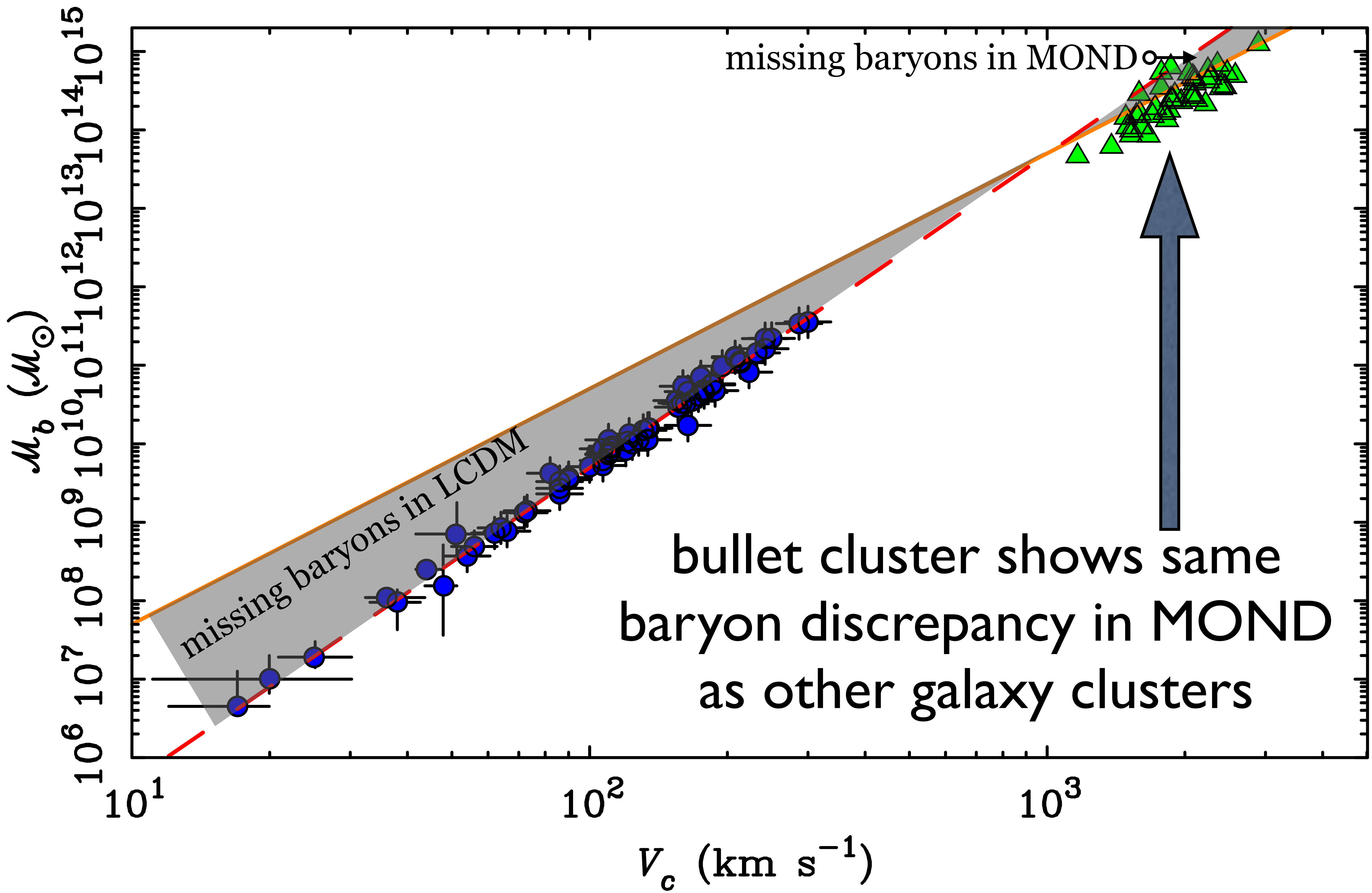


(Sanders & McGaugh 2002)

1E 0657-56 - "bullet" cluster (Clowe et al. 2006)

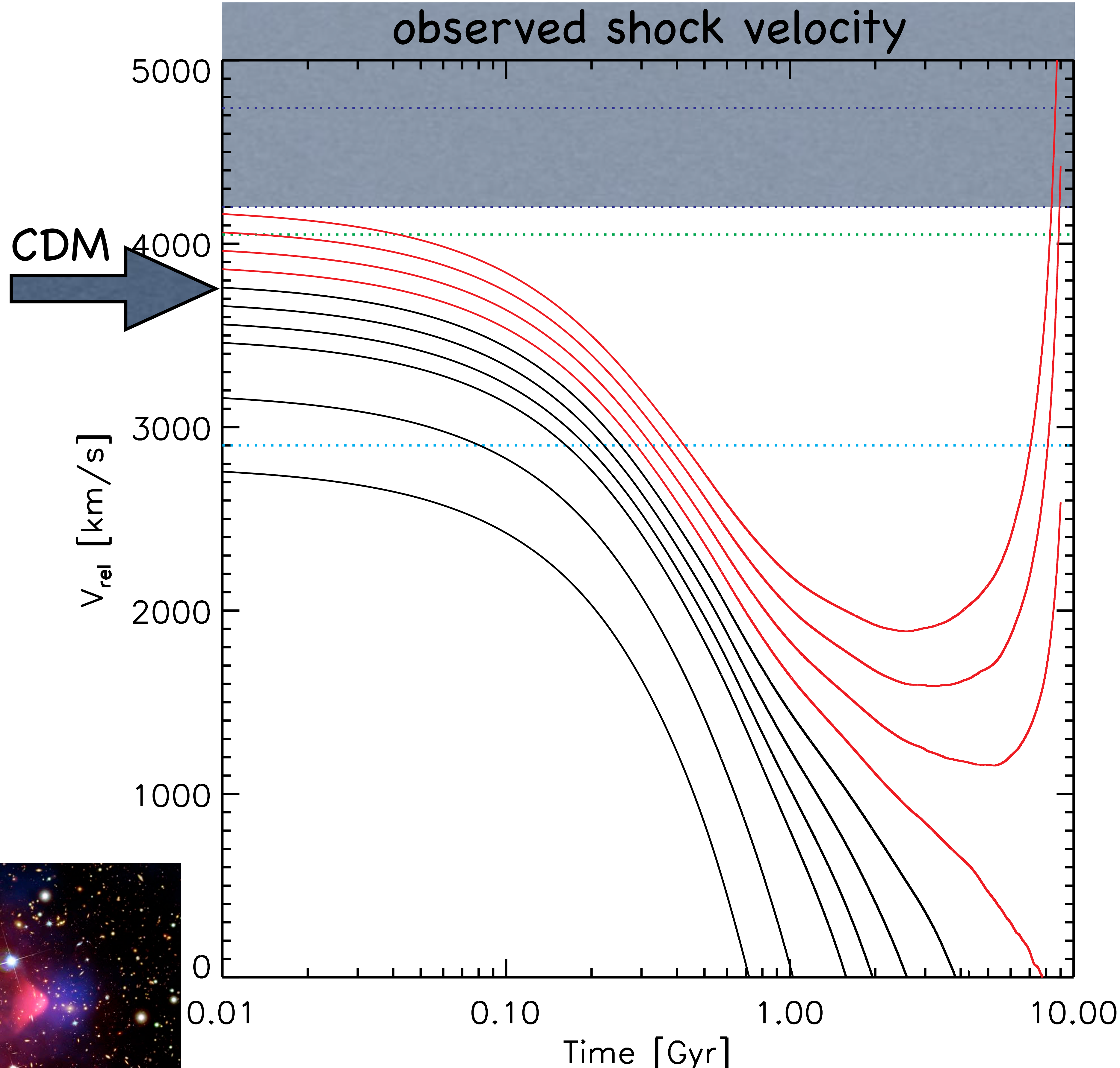


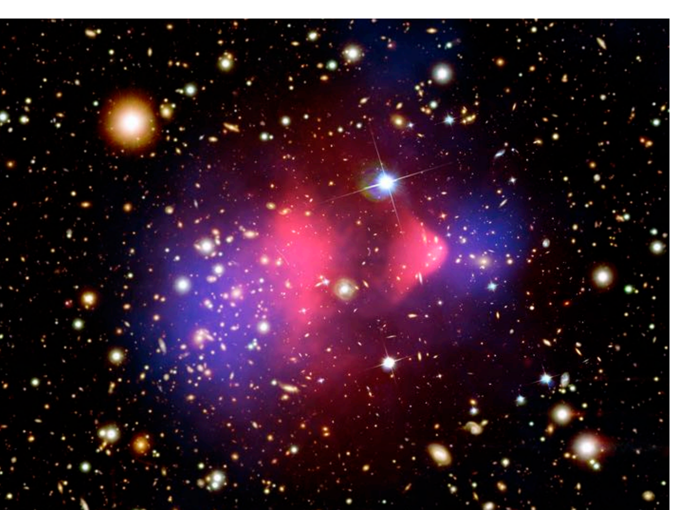
direct proof of dark matter?



missing baryons in MOND
missing baryons in LCDM
bullet cluster shows same
baryon discrepancy in MOND
as other galaxy clusters
$\mathcal{M}_b$ ($\mathcal{M}_\odot$)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^1
10^2
10^3
V_c (km s^{-1})

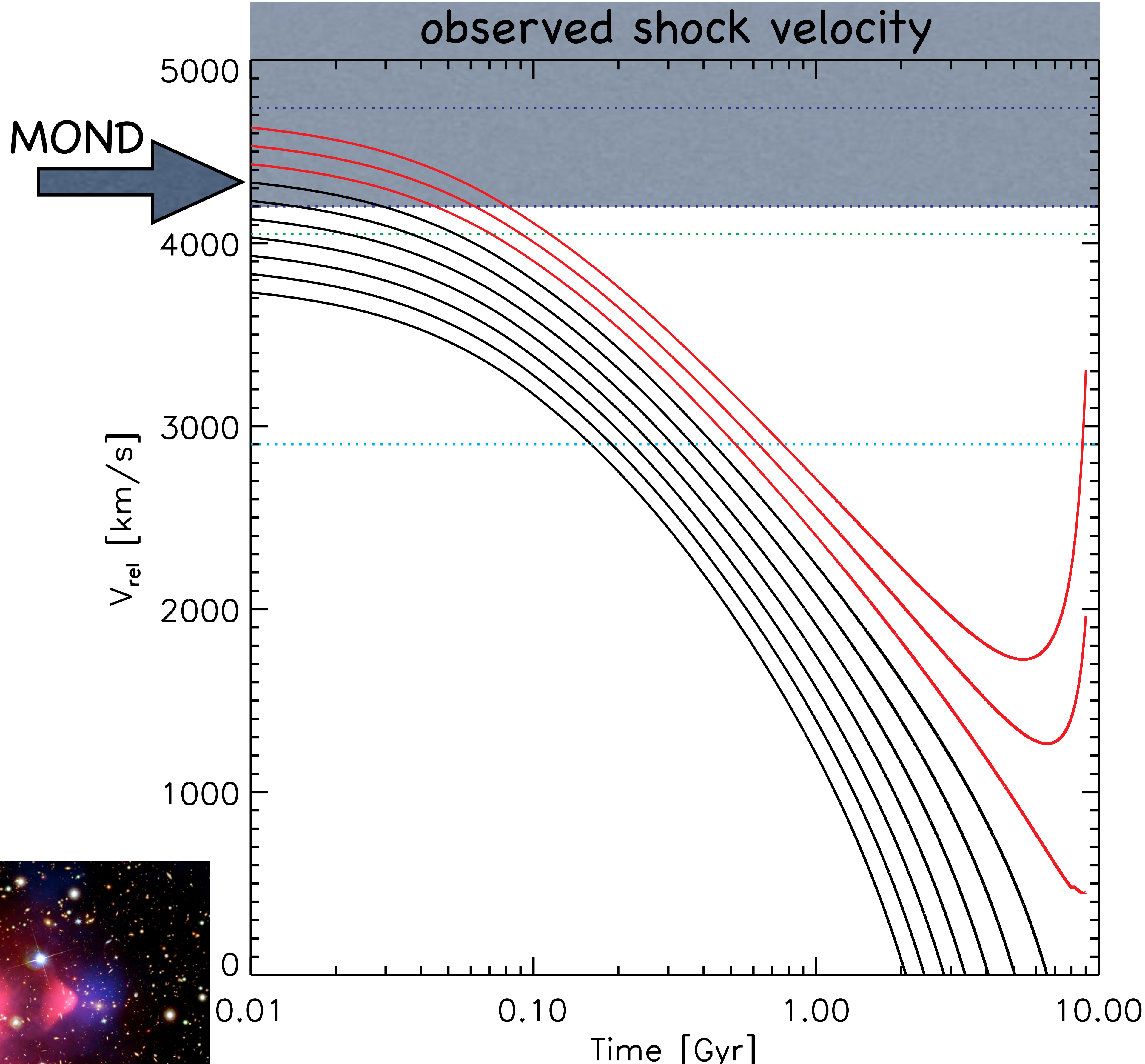
bullet cluster collision velocity

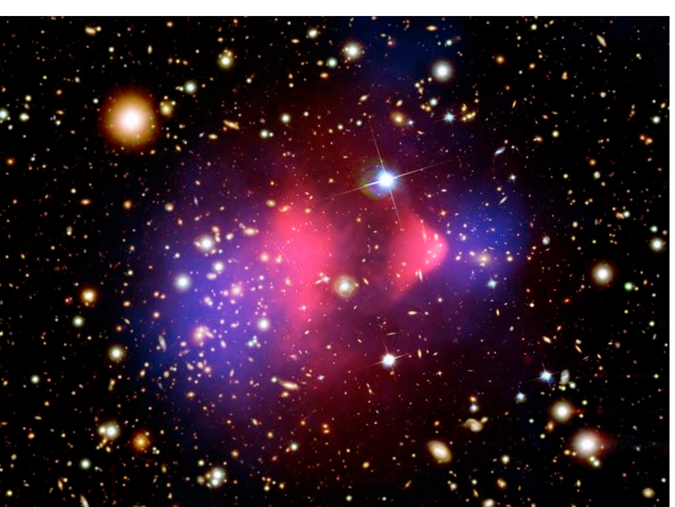




Angus & McGaugh (2008) MNRAS, 383, 417

bullet cluster collision velocity





Angus & McGaugh (2008) MNRAS, 383, 417

Bullet cluster

- Mass discrepancy more naturally explained with dark matter.
- Collision velocity more naturally explained with MOND.