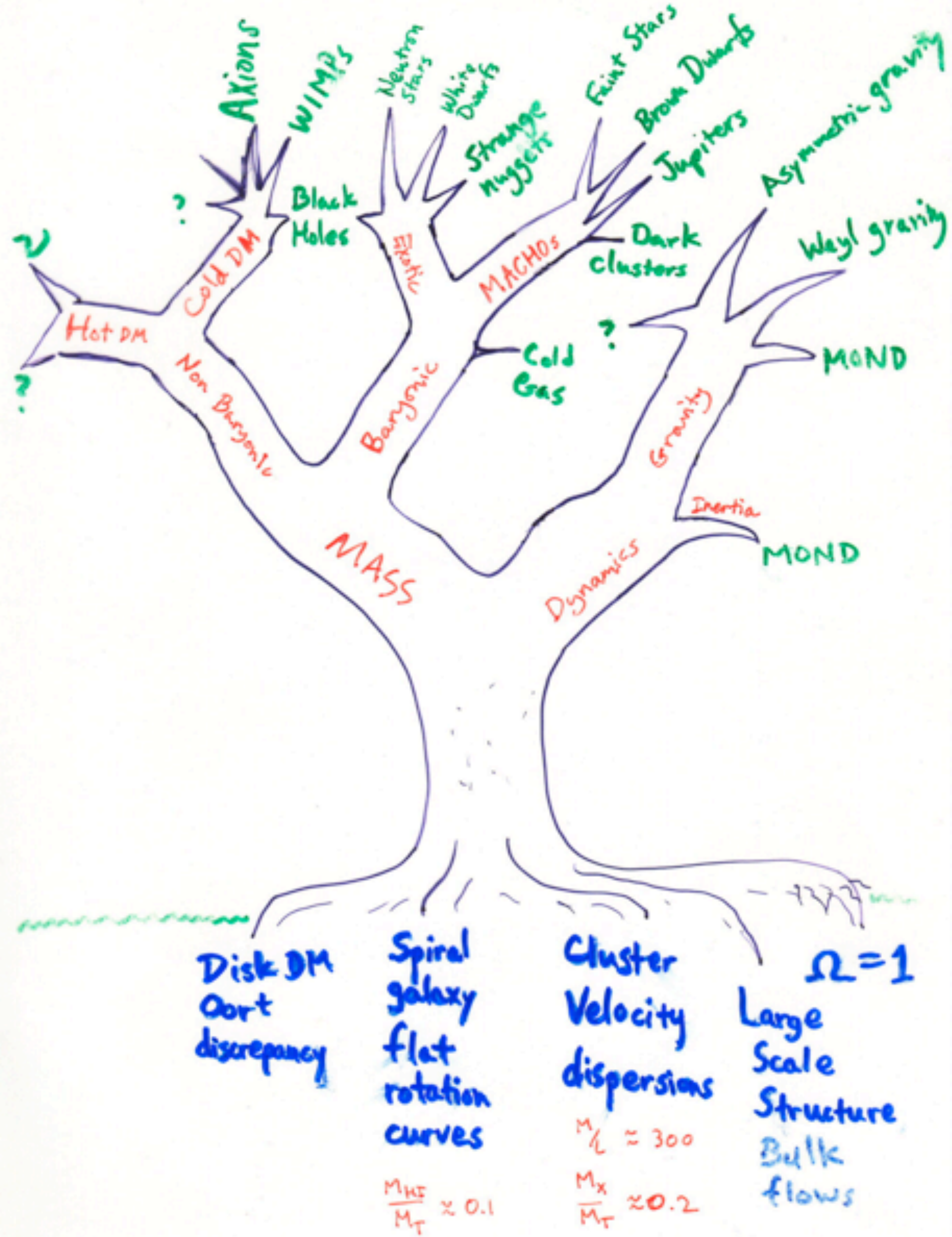
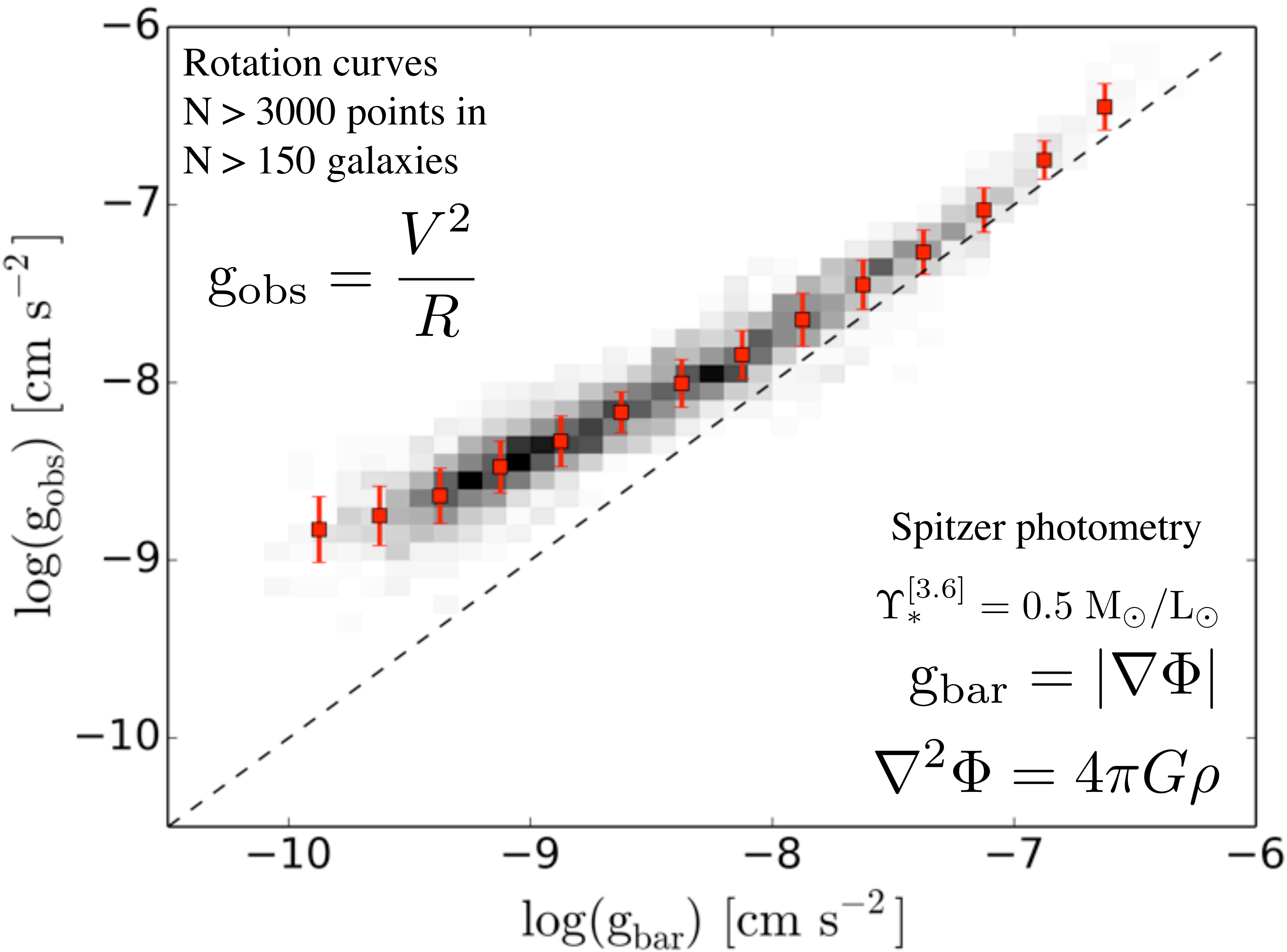
Today:

- MOND
- Review

Next time: **Exam**





Rotation curves
N > 3000 points in
N > 150 galaxies
$g_{obs} = \frac{V^2}{R}$
Spitzer photometry
$\Upsilon_*^{[3.6]} = 0.5\ M_\odot/L_\odot$
$g_{bar} = |\nabla\Phi|$
$\nabla^2\Phi = 4\pi G\rho$
$\log(g_{obs})\ [\mathrm{cm\ s^{-2}}]$
$\log(g_{bar})\ [\mathrm{cm\ s^{-2}}]$
−6
−7
−8
−9
−10

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

$a = g_N$ for $a \gg a_0$

MOND regime

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

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

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

$\mu(x) \rightarrow 1$ for $x \gg 1$ $\quad$ $\mu(x) \rightarrow x$ for $x \ll 1$ $\quad$ $x = \dfrac{a}{a_0}$

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.

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 and galactic [illegible] in Milgrom [illegible].

VIII. PREDICTIONS

The main predictions conc[illegible] fol-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 observed ones. [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 stro[illegible] dwarf [illegible] (for review of propert[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, $g \approx (8\ \mathrm{kpc}/d)a_0$, 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 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 [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] case [illegible] requires [illegible] 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 wa[illegible] to obtain a [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] [illegible] higher than [illegible] for 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] 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

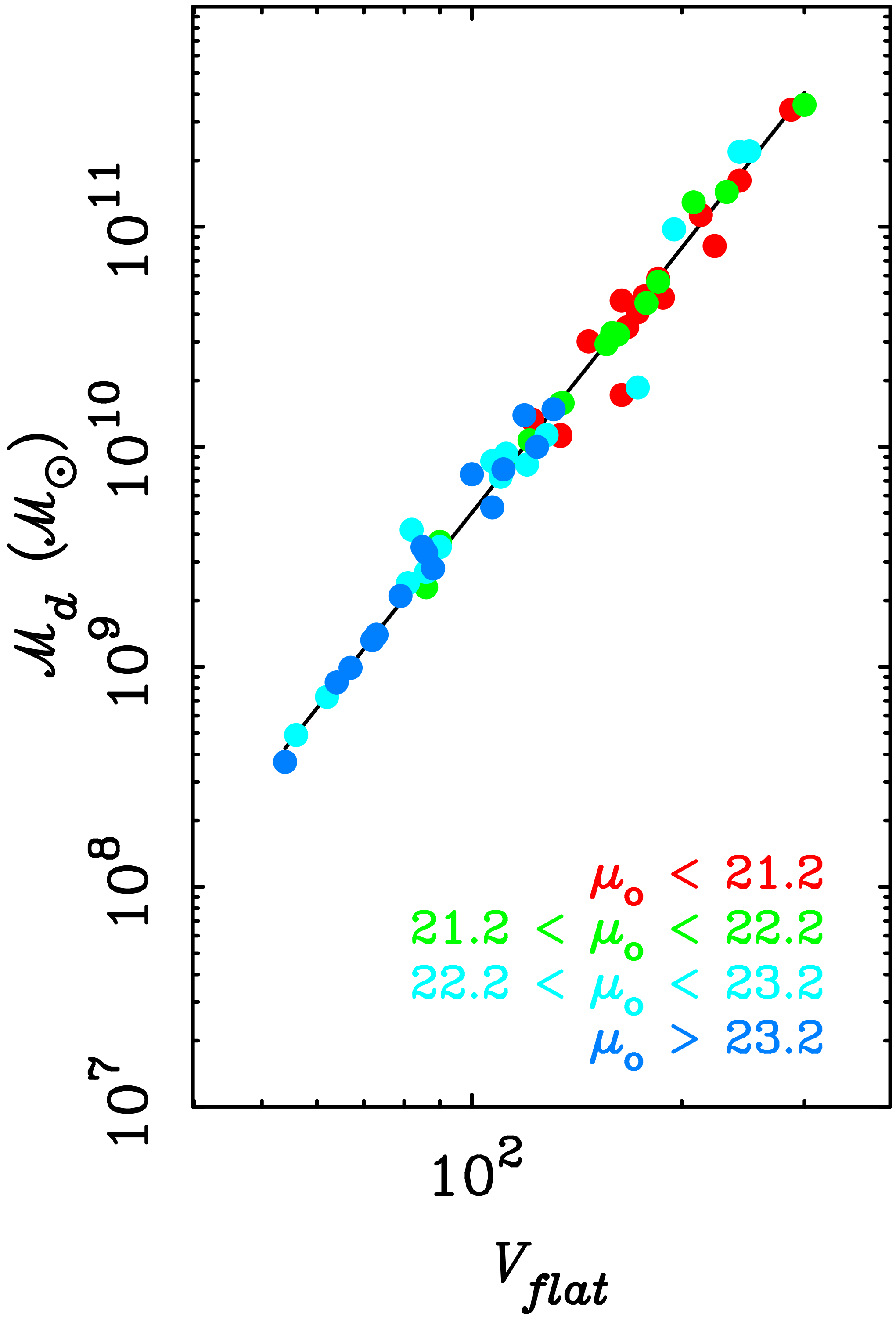
The main results of this paper can be summarized by the statement that the modified dynamics eliminates the need to assume hidden mass in galaxies. The effects in galaxies which I have considered, and which are commonly attributed to such hidden mass, are readily explained by the modification. More specifically:

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.



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In MOND limit of low acceleration

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

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

$$V^4 = a_0 GM$$

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

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

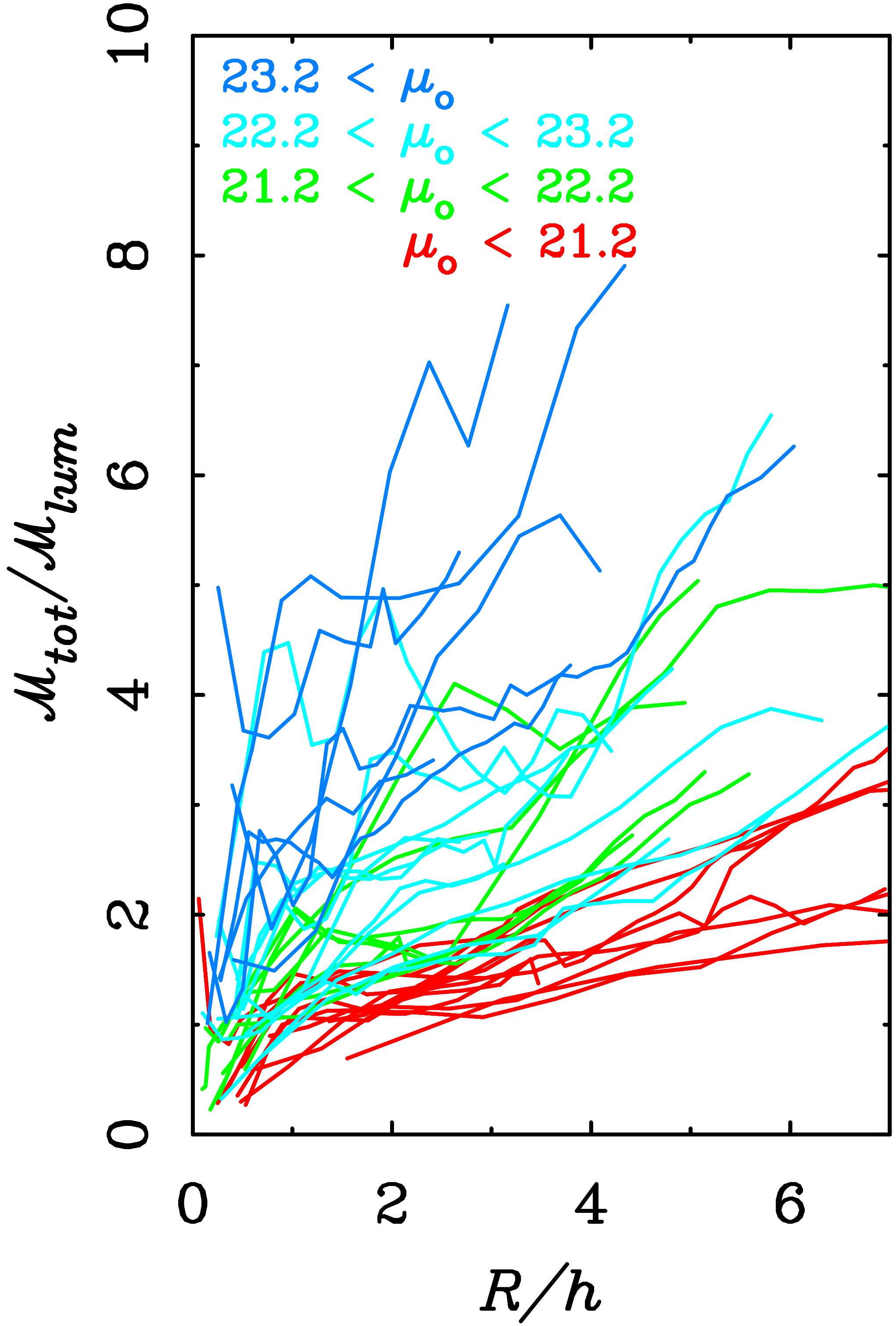
an absolute consequence of the force law for a << a_0:

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

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

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

Should only work for objects in MOND regime



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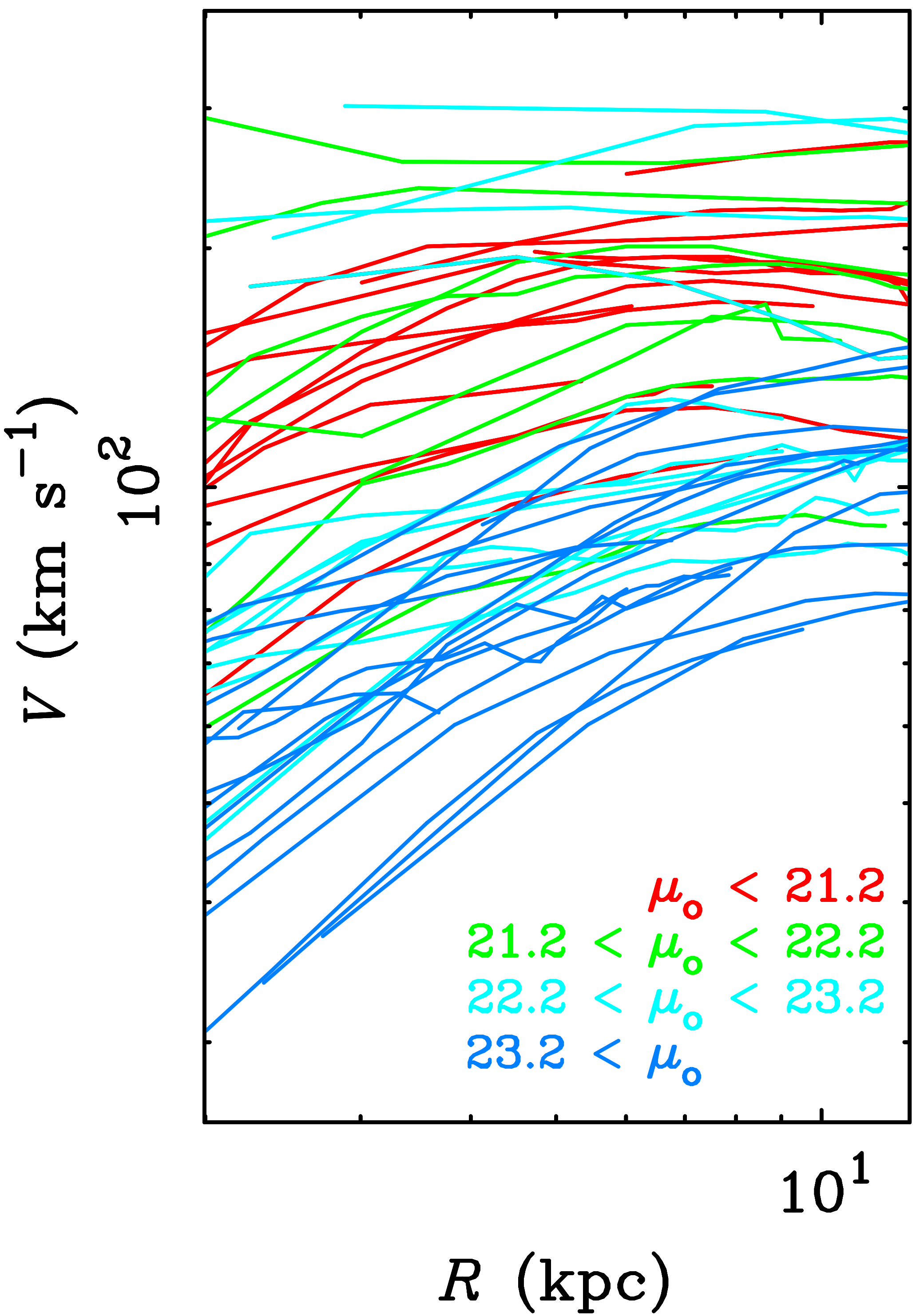

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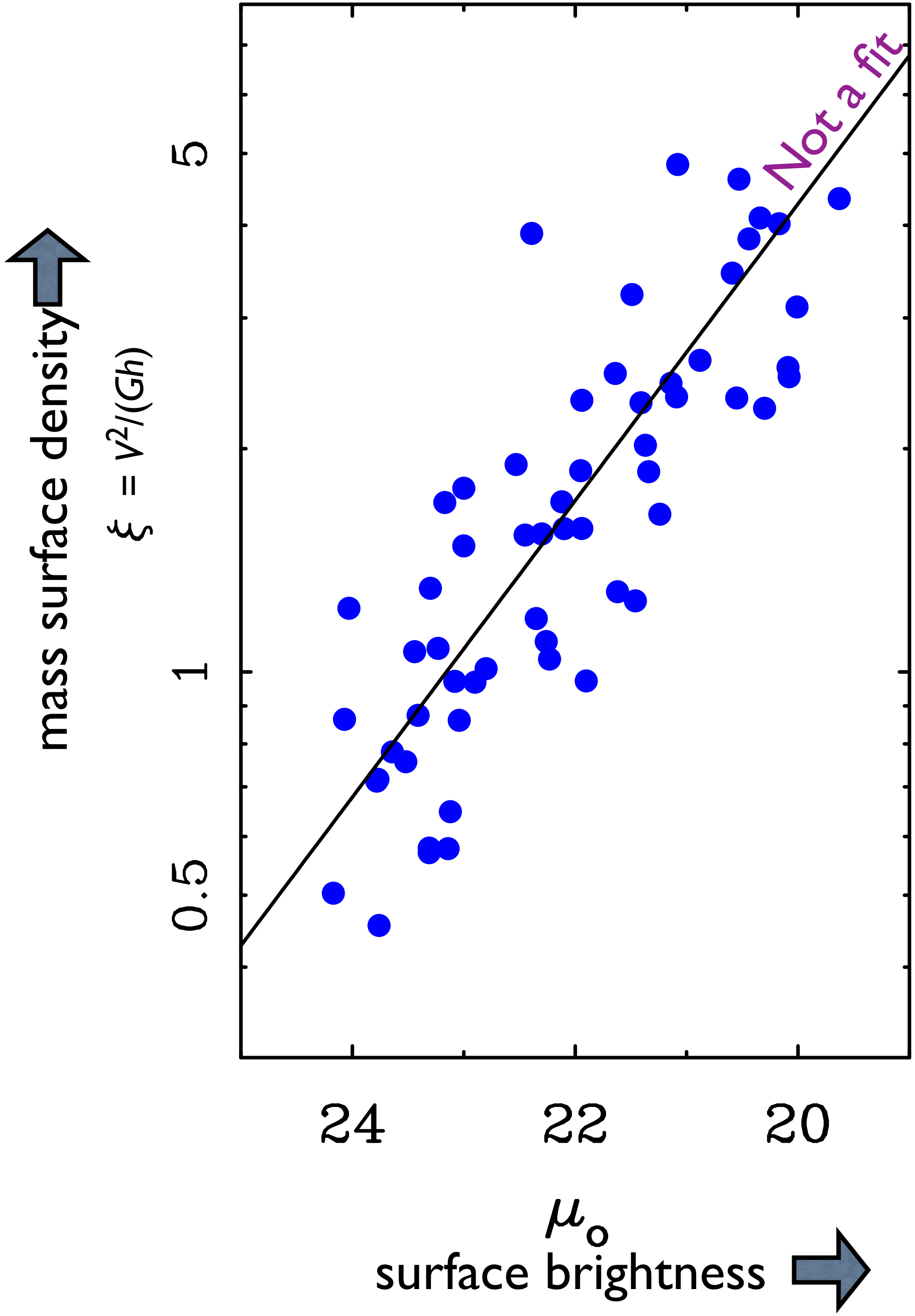

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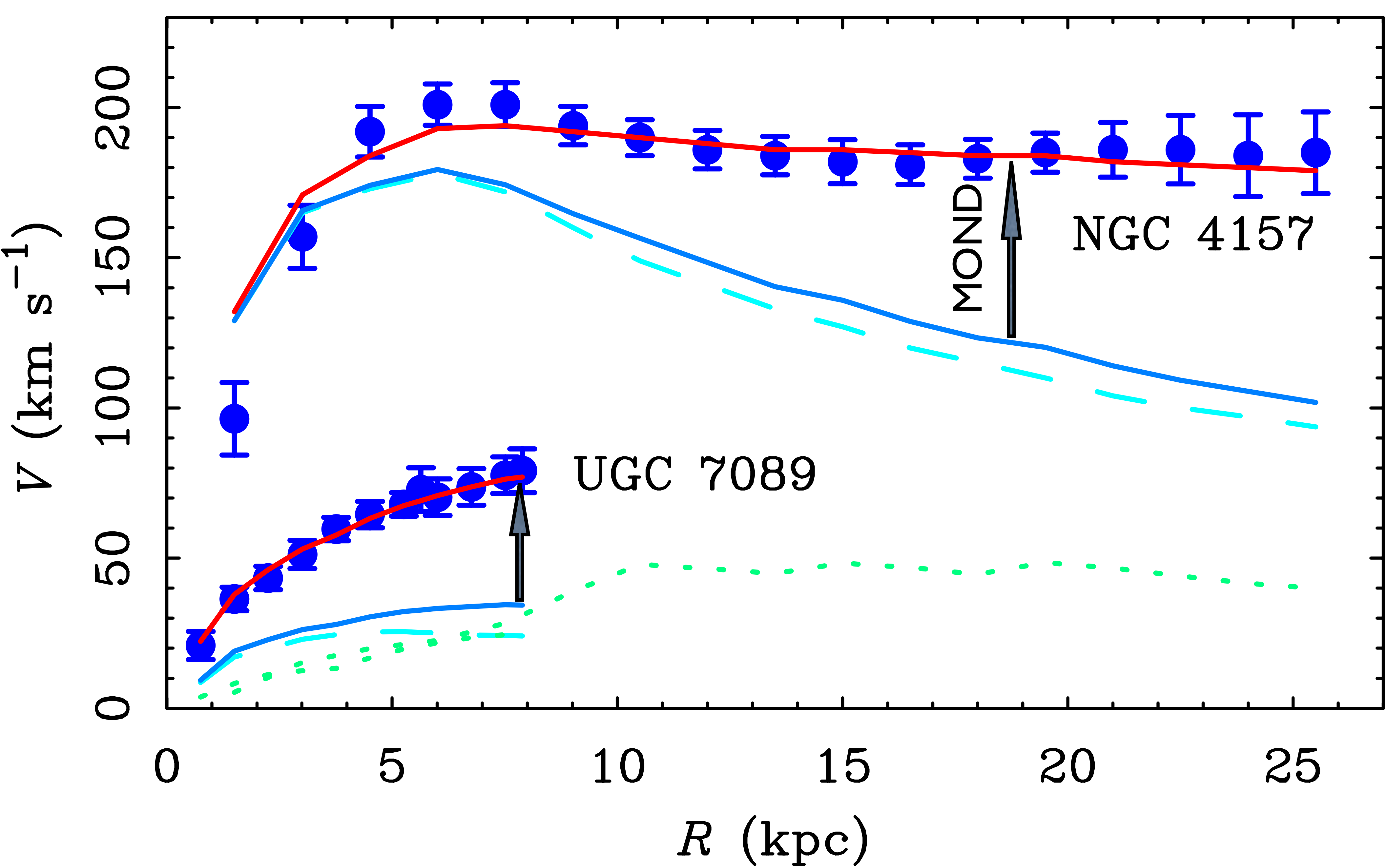
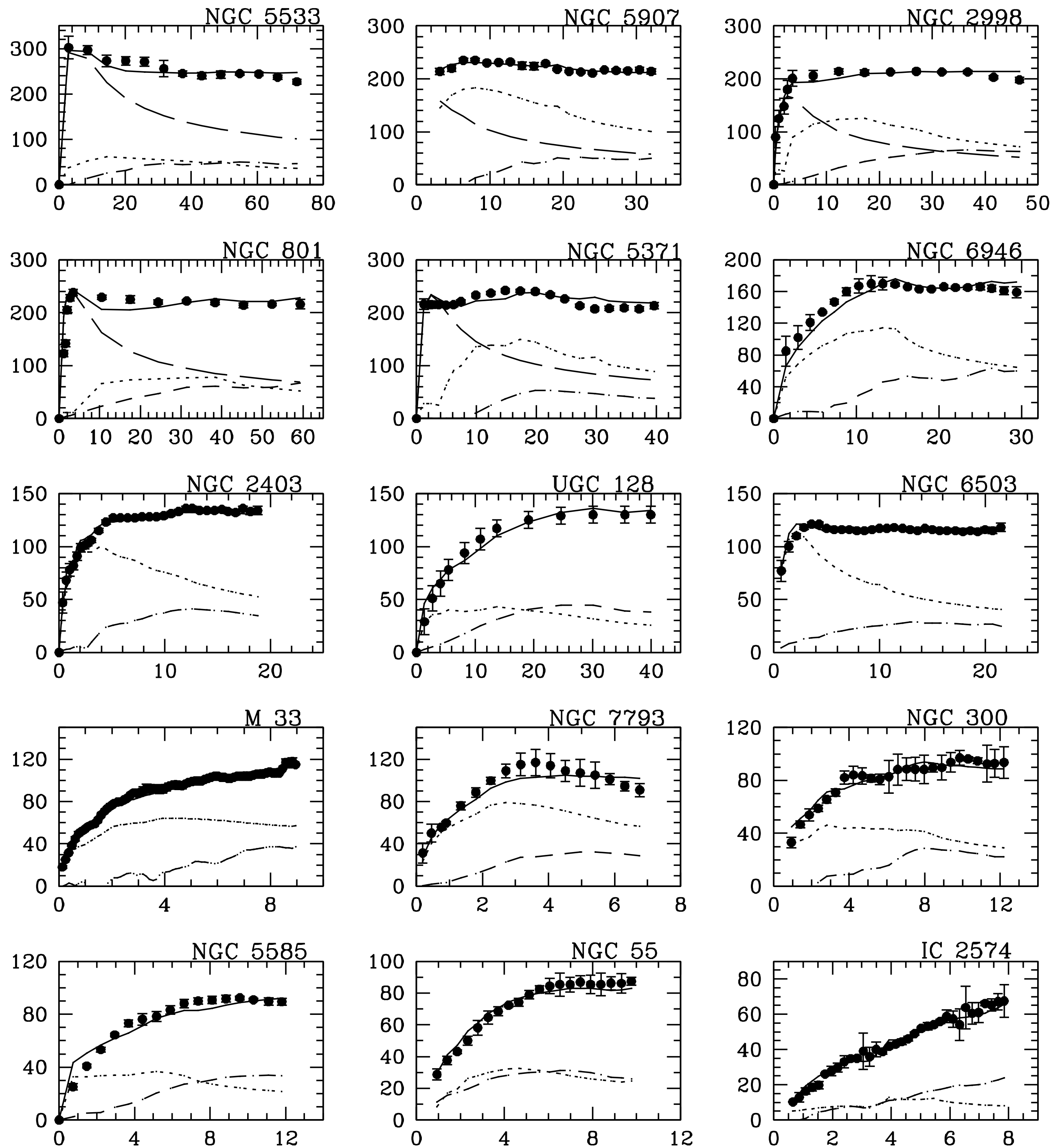
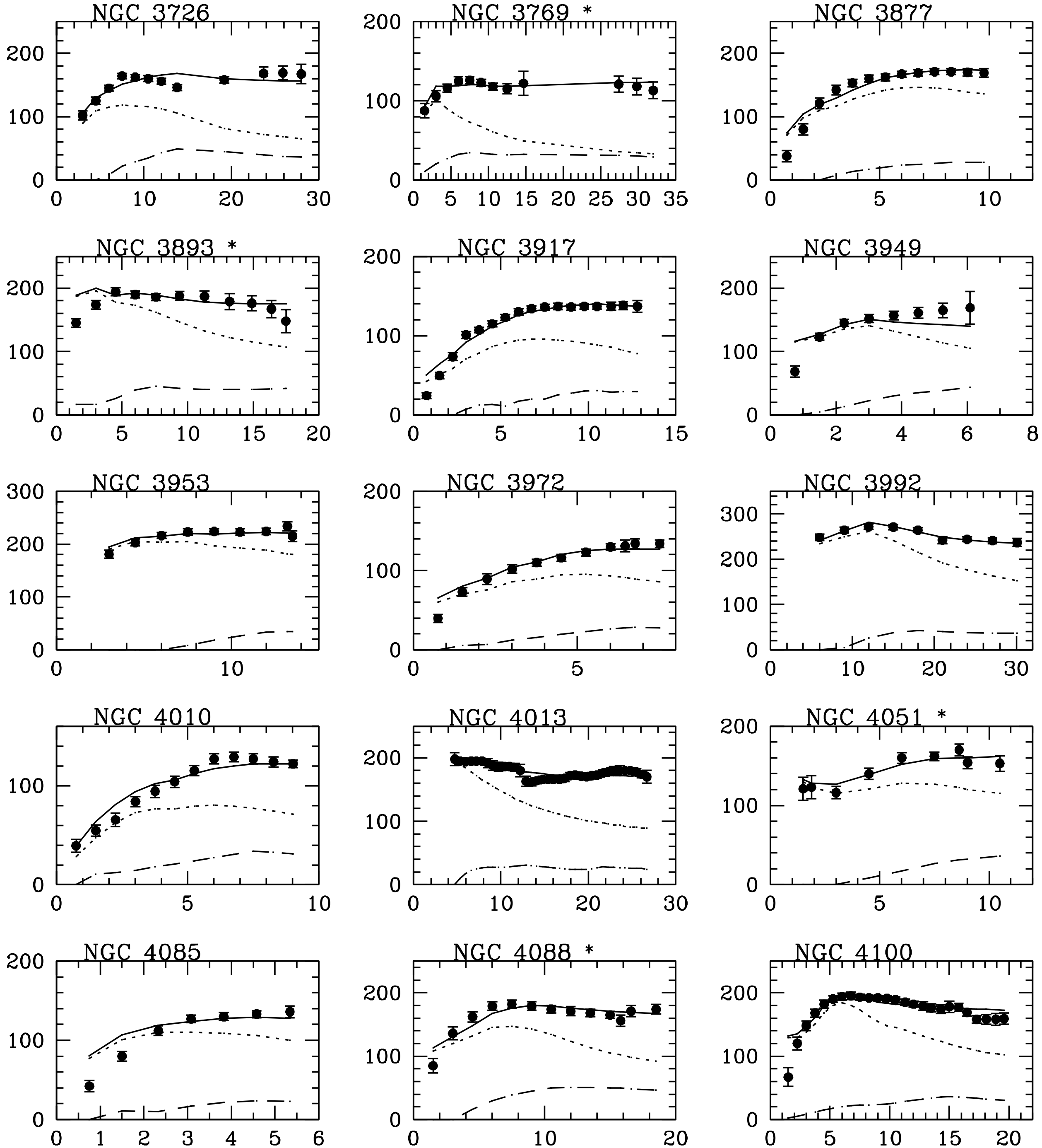


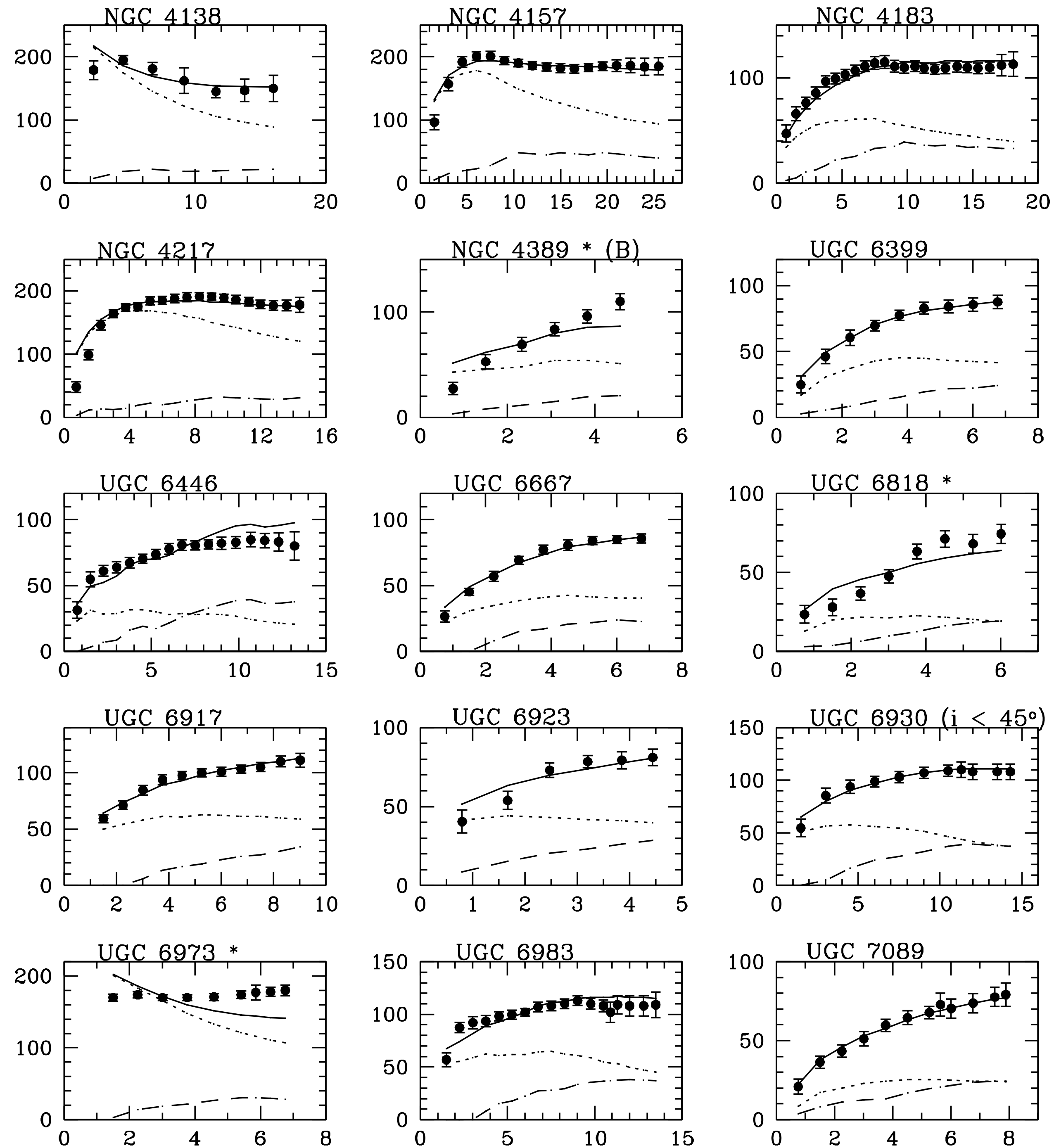
V (km s⁻¹)
R (kpc)
0
50
100
150
200
0
5
10
15
20
25
NGC 4157
UGC 7089
MOND

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



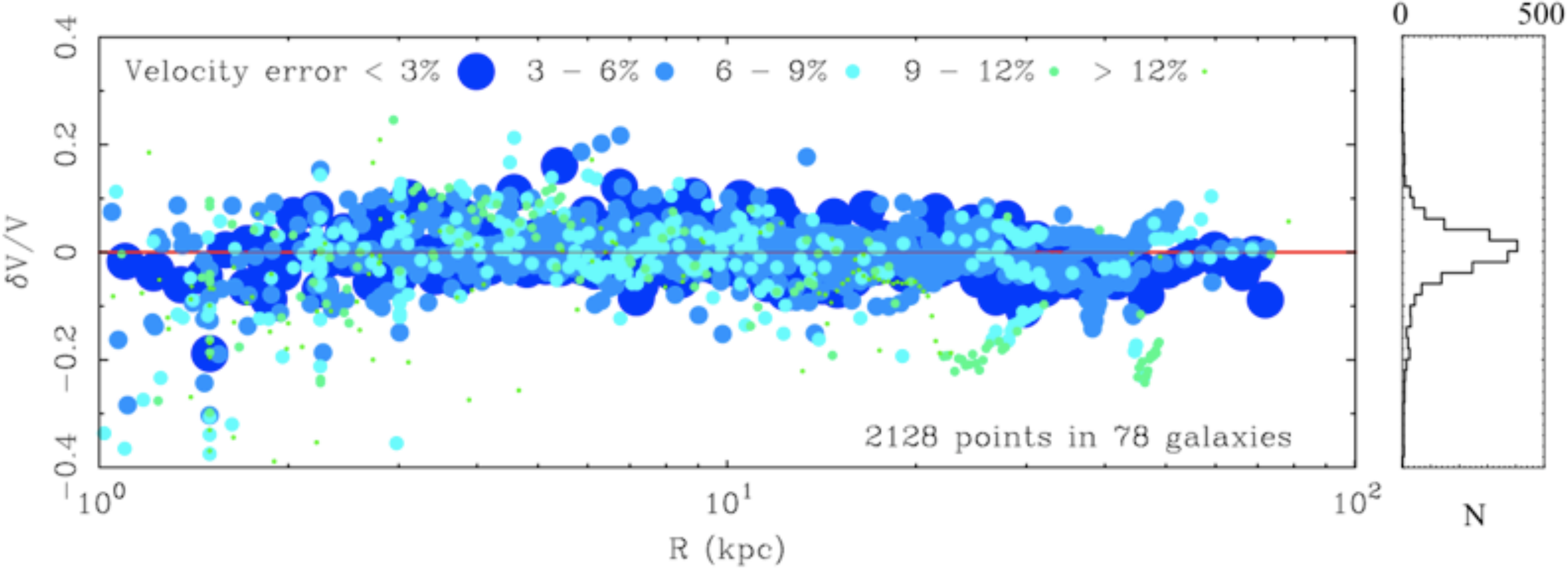
Sanders & McGaugh 2002, *ARA&A*, **40**, 263





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

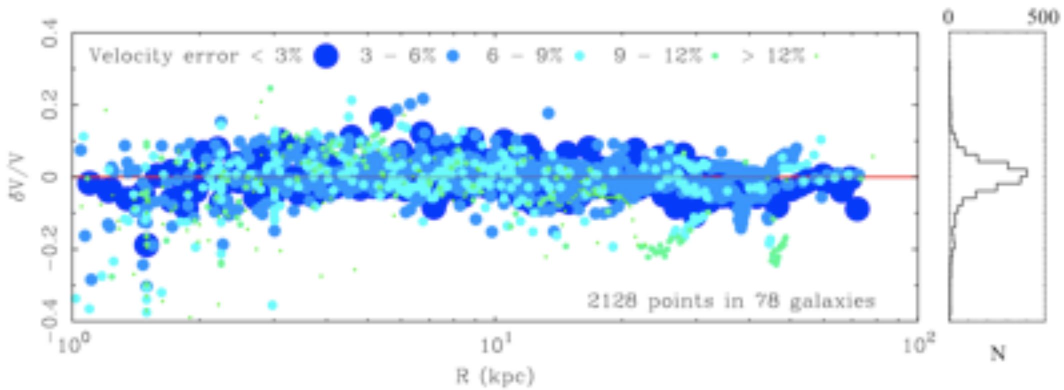
Residuals of MOND fits



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

MOND predictions

- The Tully-Fisher Relation



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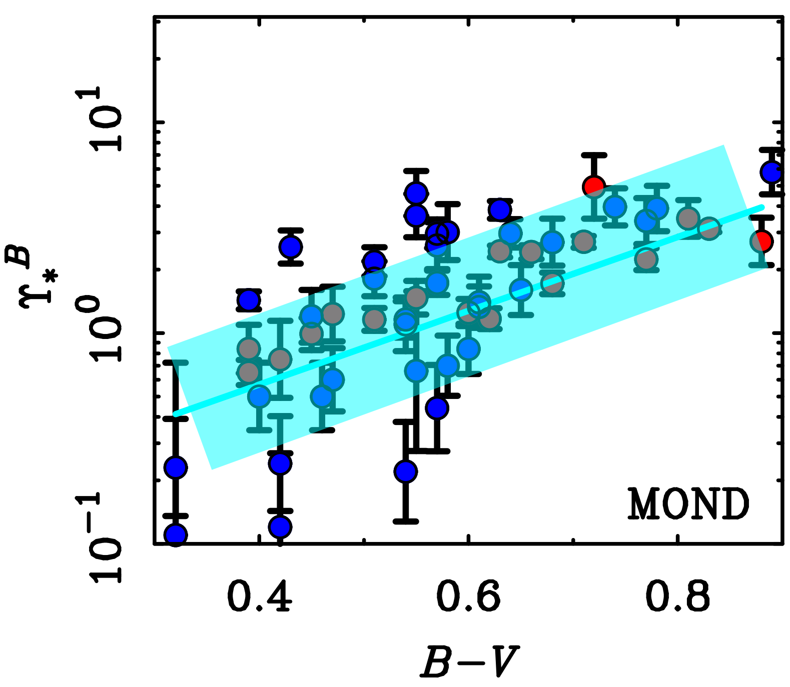
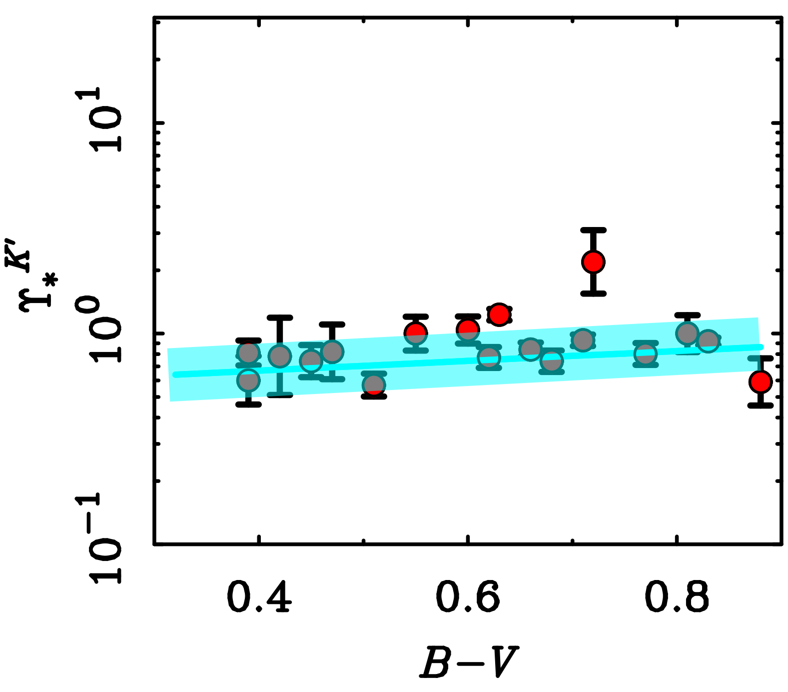
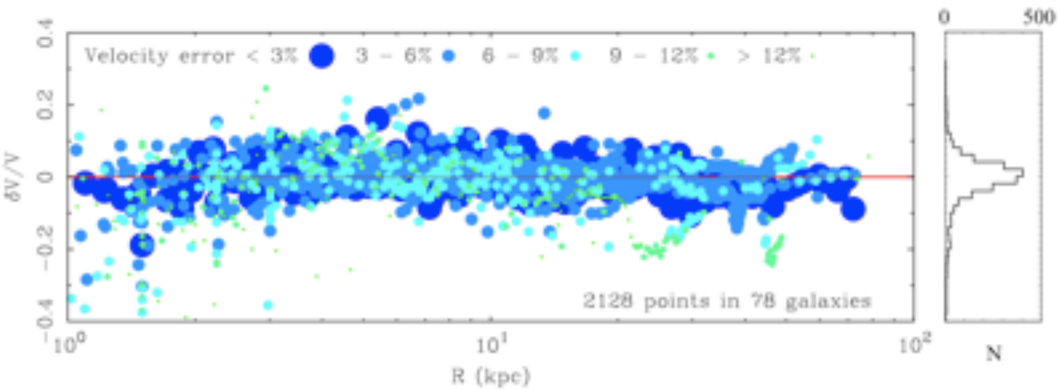
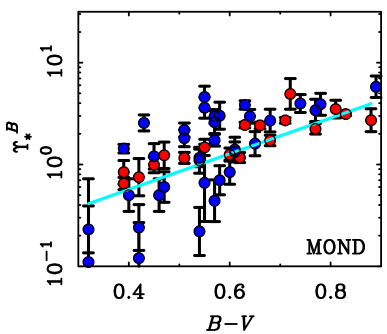


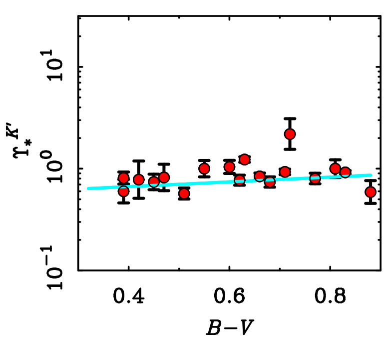
Line: stellar population model
(mean expectation)



MOND predictions







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Newtonian regime

$g_{in} > a_0$

$$M = \frac{RV^2}{G}$$

e.g., surface of the Earth

MOND regime

$g_{in} < a_0$

$$M = \frac{V^4}{a_0 G}$$

e.g., remote dwarf Leo I

External Field dominant Newtonian regime

$g_{in} < a_0 < g_{ex}$

$$M = \frac{RV^2}{G}$$

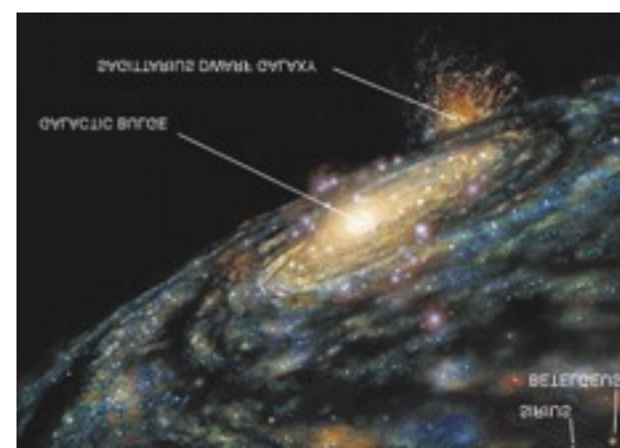
e.g., Eotvos-type experiment on the surface of the Earth

External Field dominant quasi-Newtonian regime

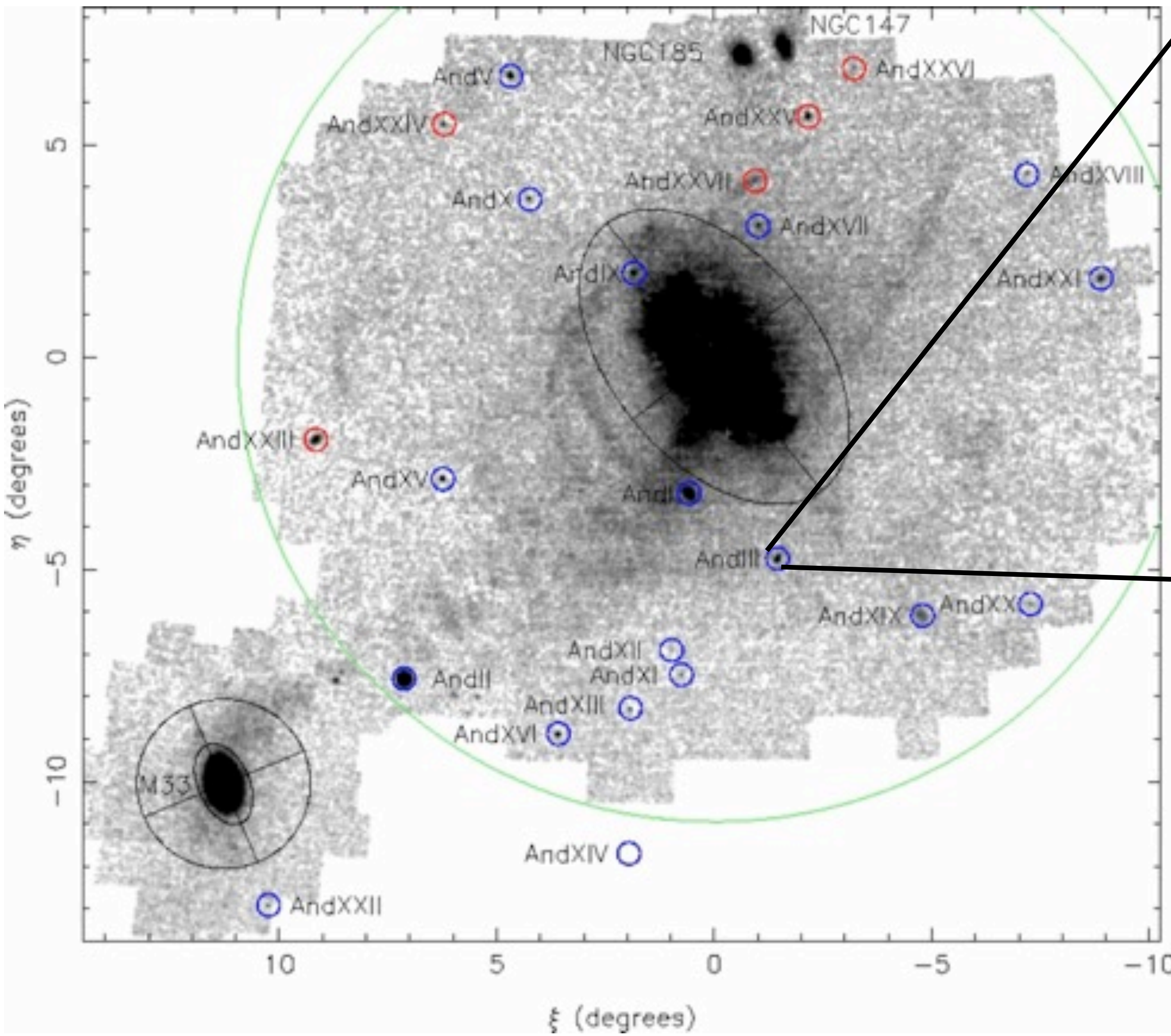
$g_{in} < g_{ex} < a_0$

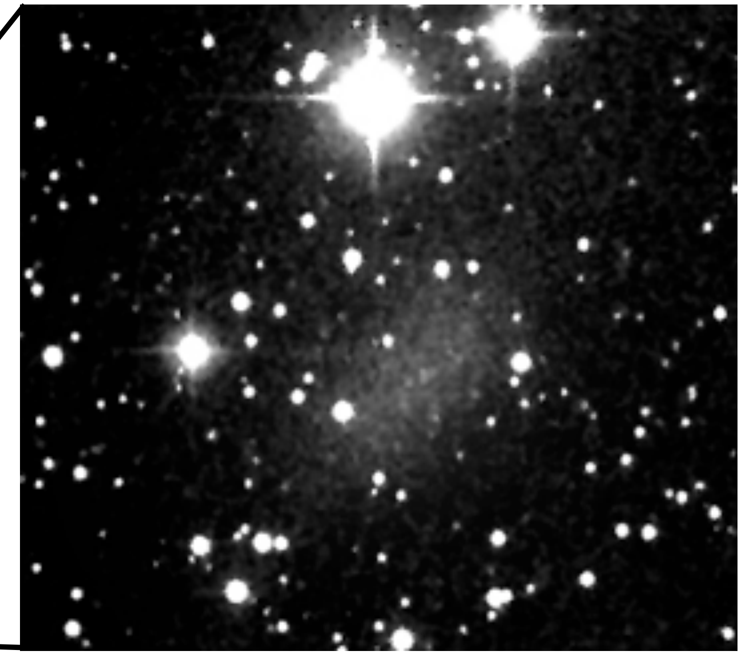
$$M = \frac{a_0}{g_{ex}} \frac{RV^2}{G}$$

e.g., nearby Sgr dwarf

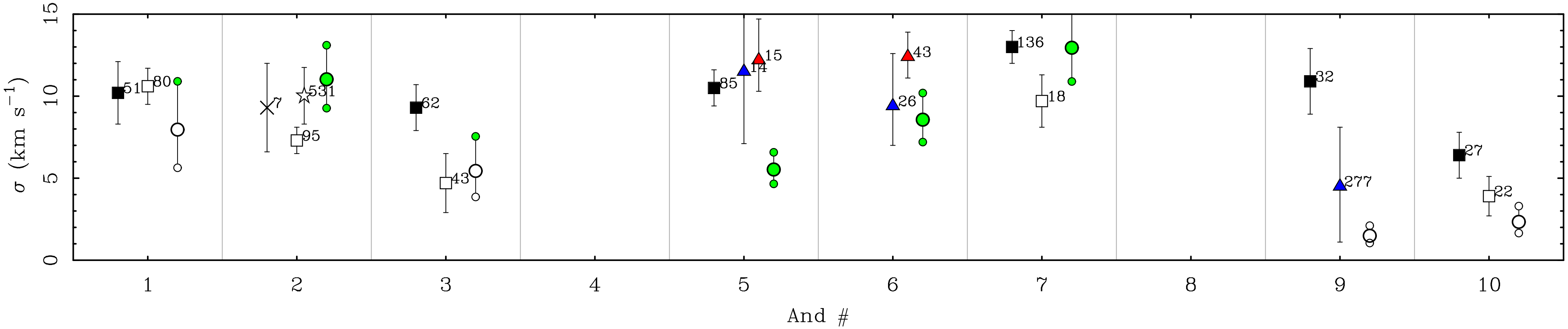


A new test: the dwarf satellites of Andromeda

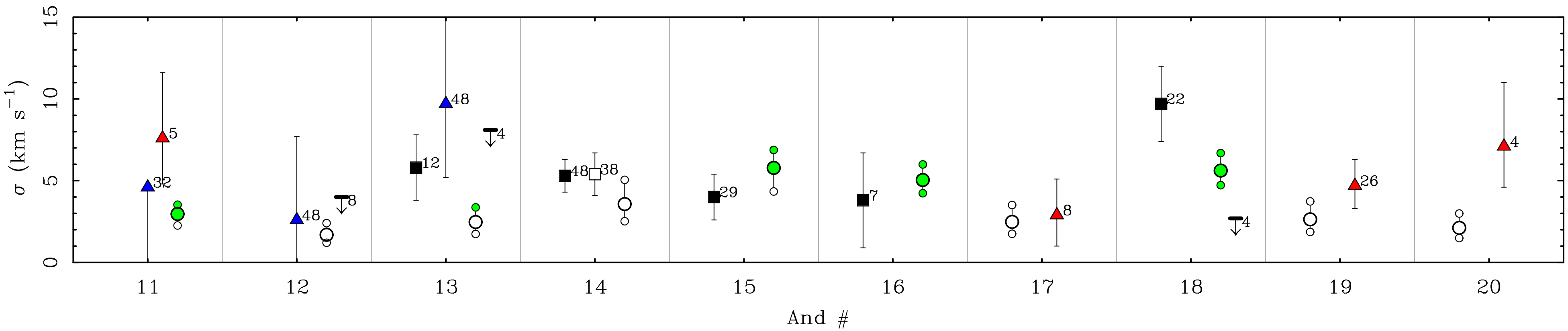


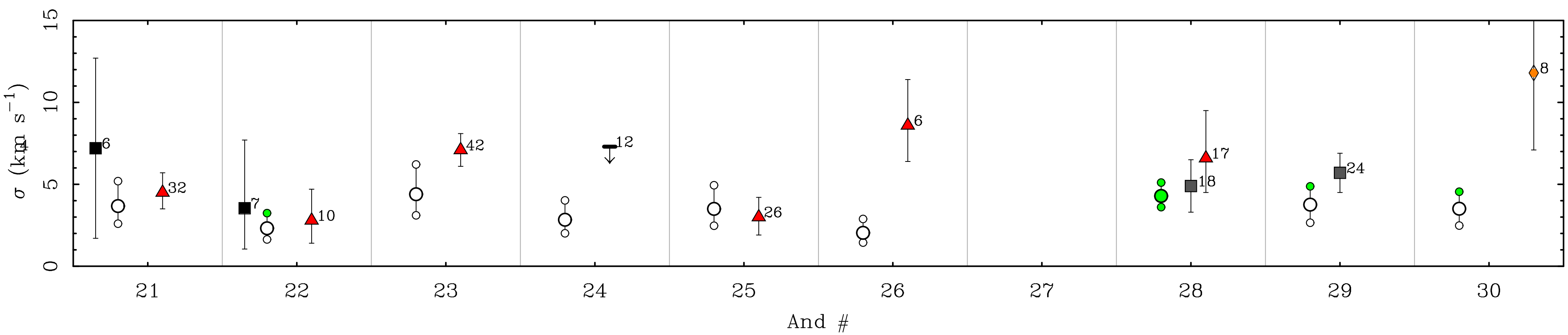


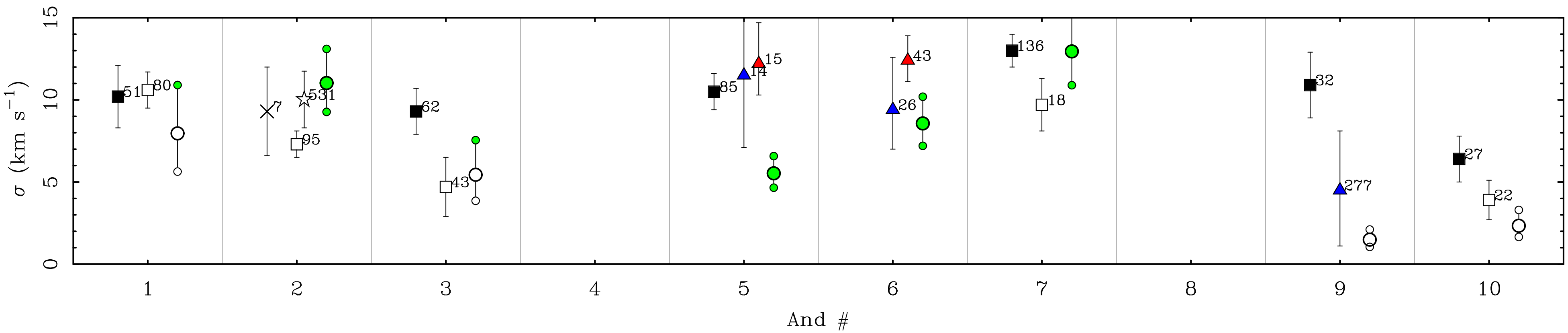
Use MOND to predict the velocity of stars within each dwarf



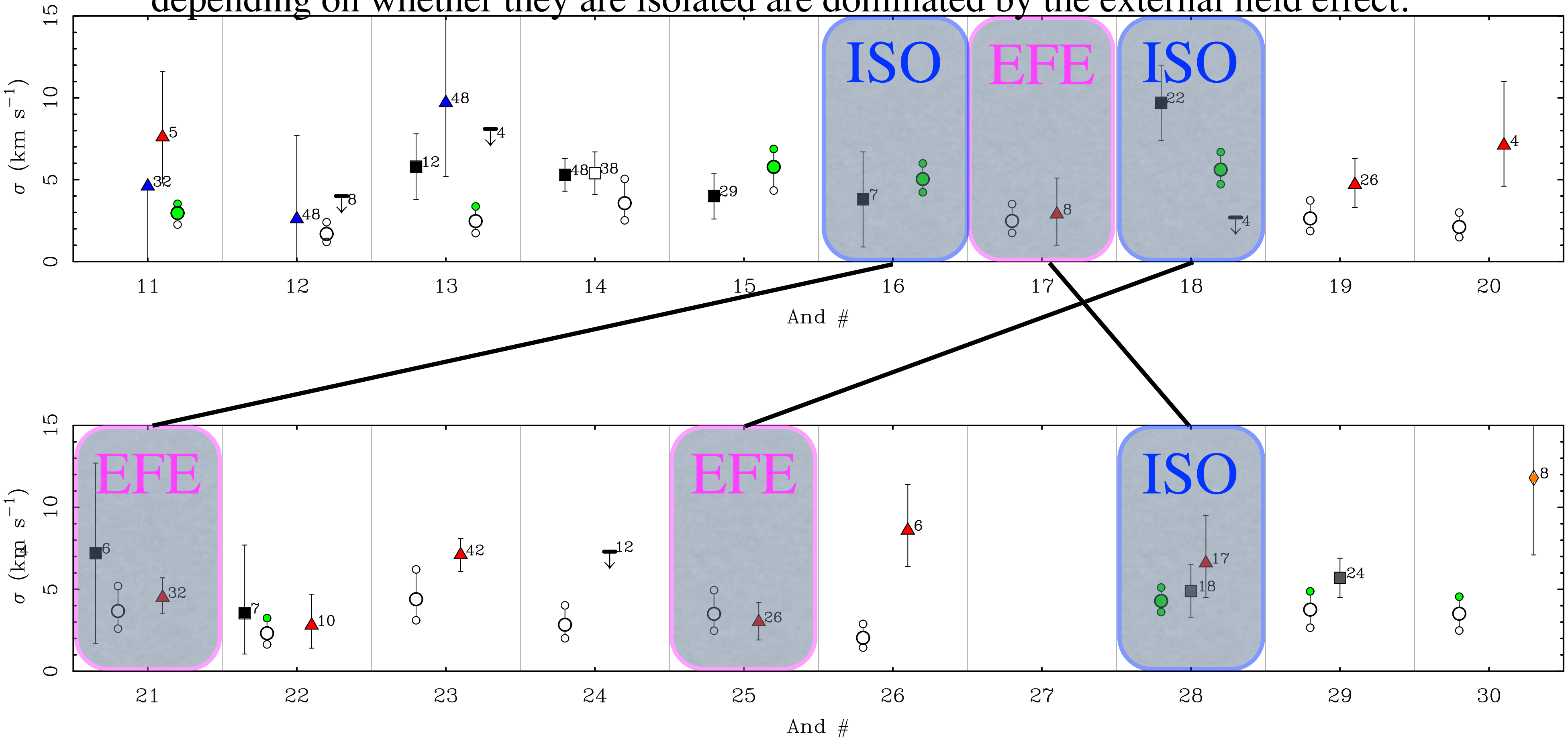
Velocity dispersions of the dwarf satellites of Andromeda





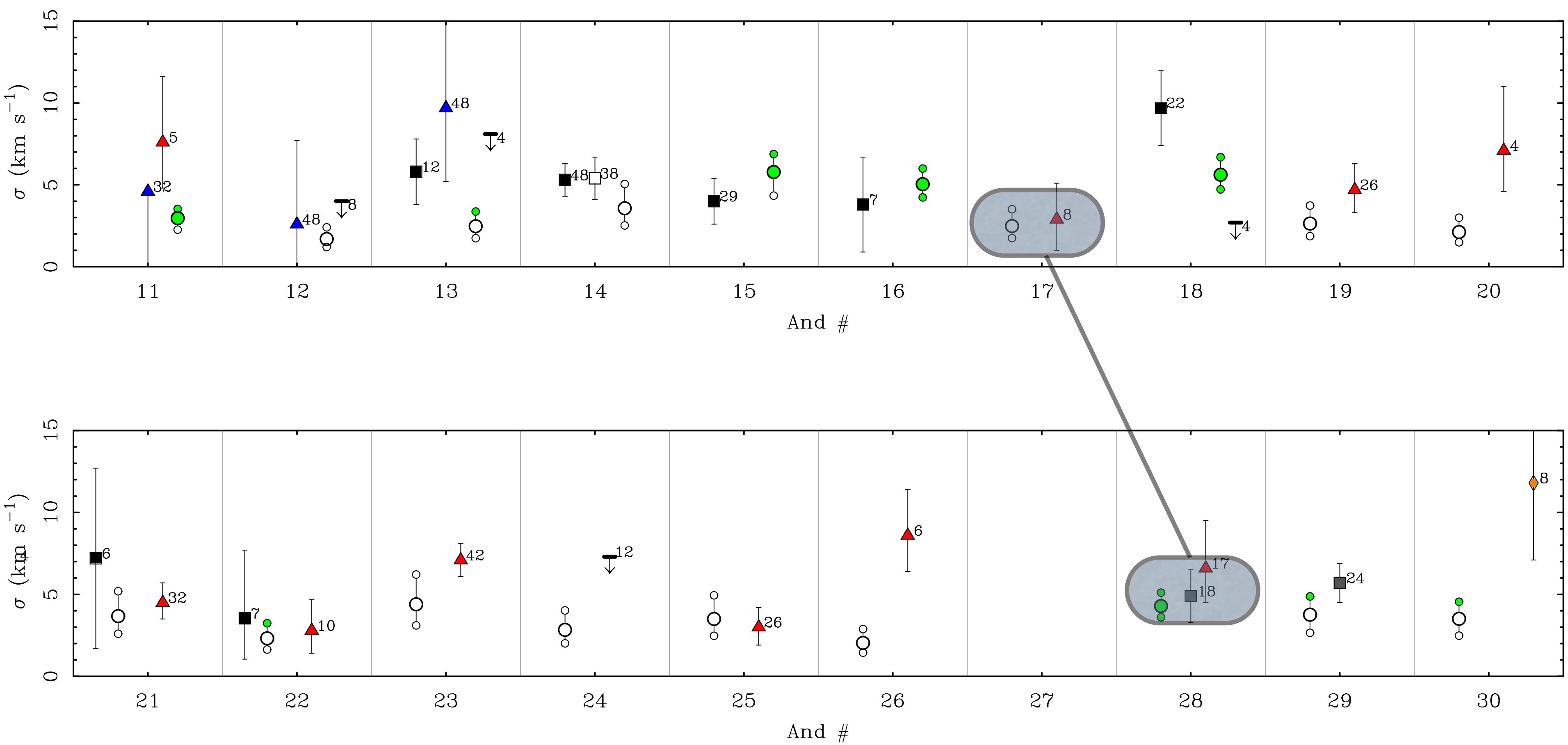


Pairs of photometrically identical dwarfs should have different velocity dispersion depending on whether they are isolated are dominated by the external field effect.

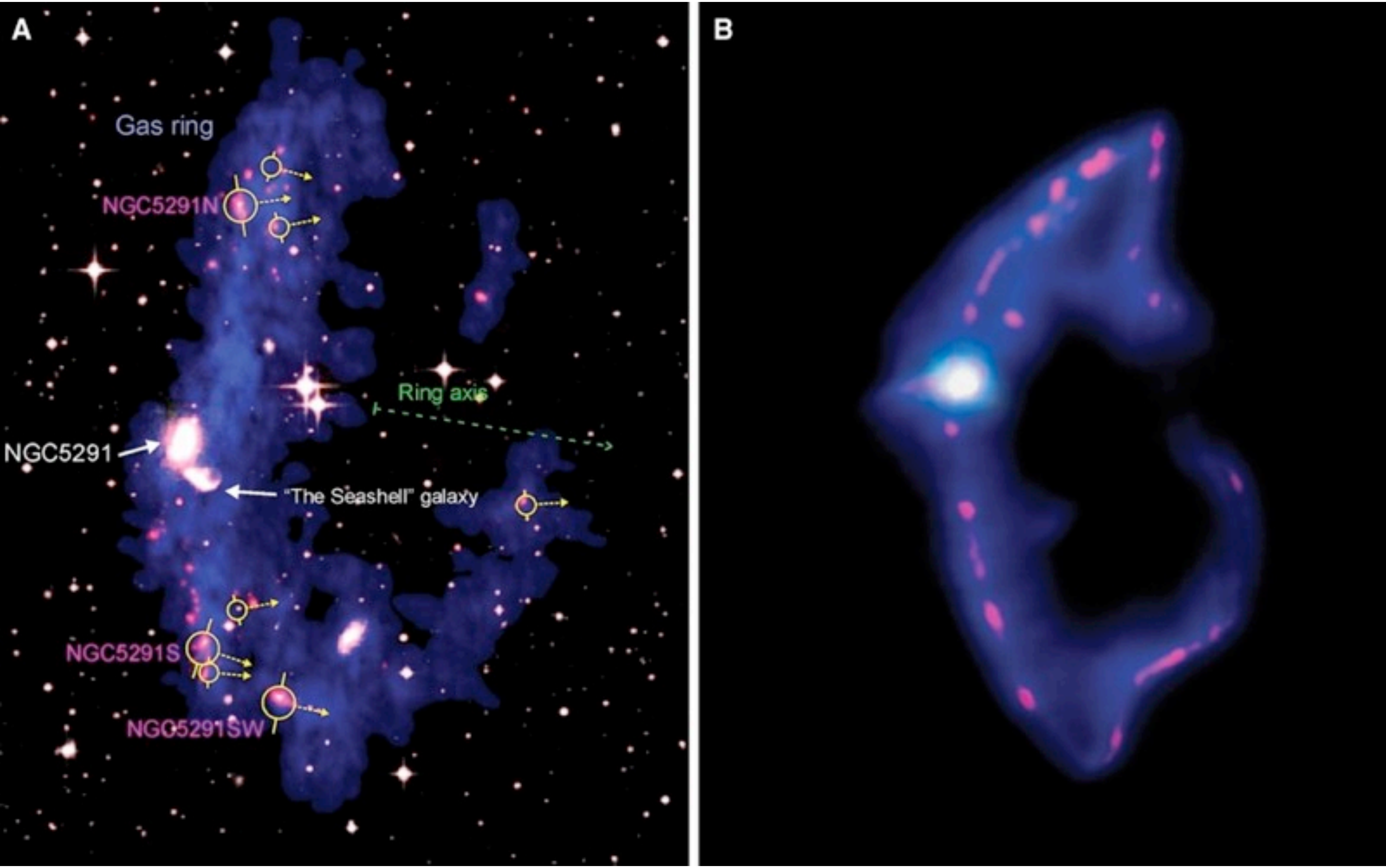


There is no EFE in dark matter - this is a unique signature of MOND.

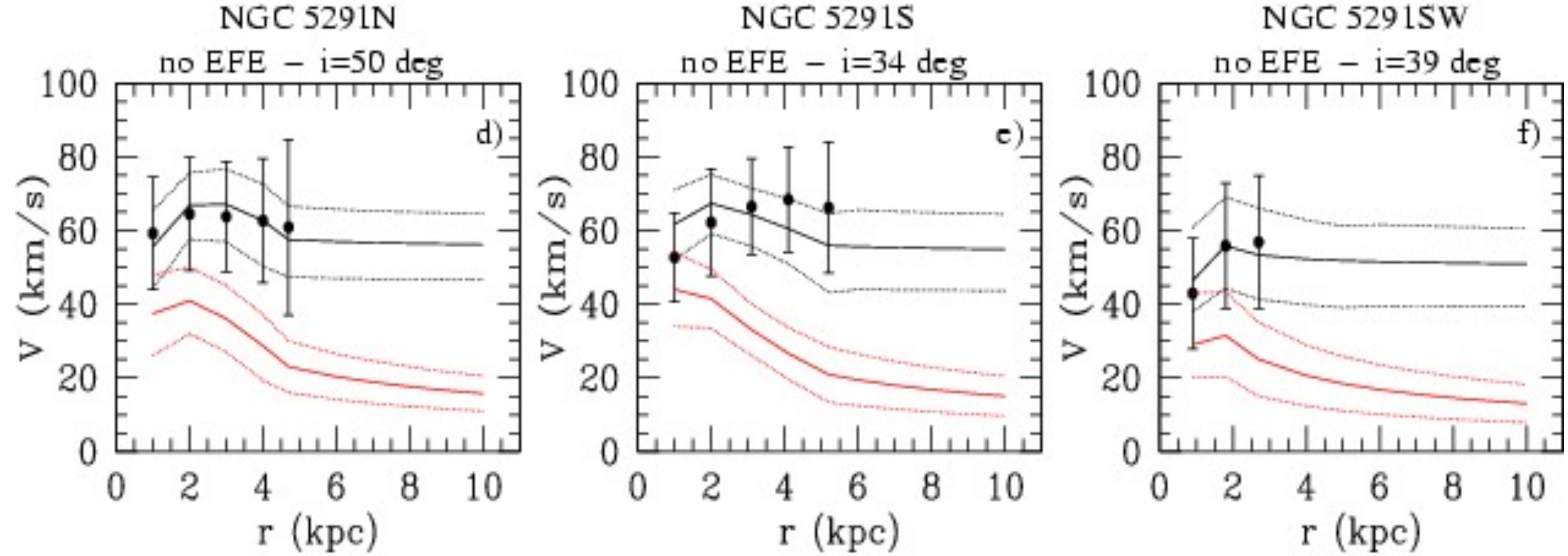
Name	Luminosity	R_e	σ_{obs}	σ_{pred}	
And XVII	2.60E+05	381	2.9	2.5	EFE
And XXVIII	2.10E+05	284	4.9	4.3	isolated



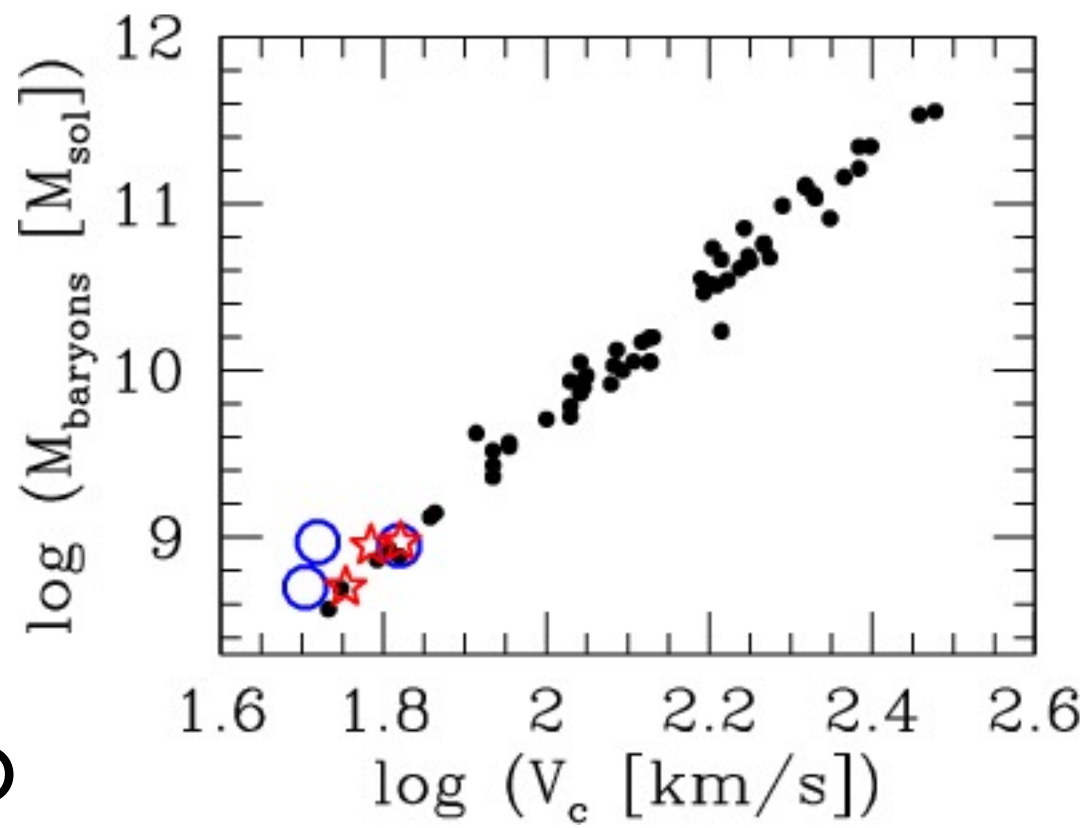
Tidal Debris Dwarfs - should be devoid of Dark Matter



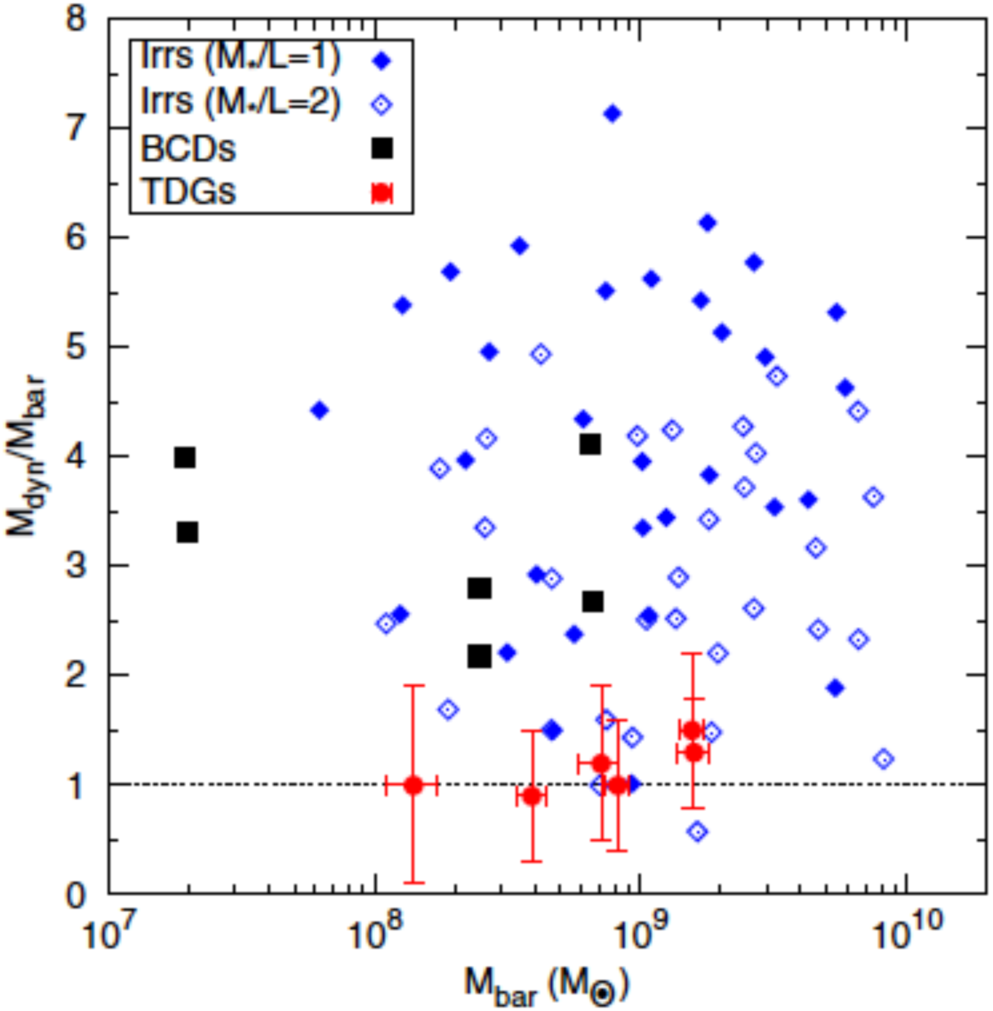
Bournaud et al. (2007) *Science*, **316**, 1166



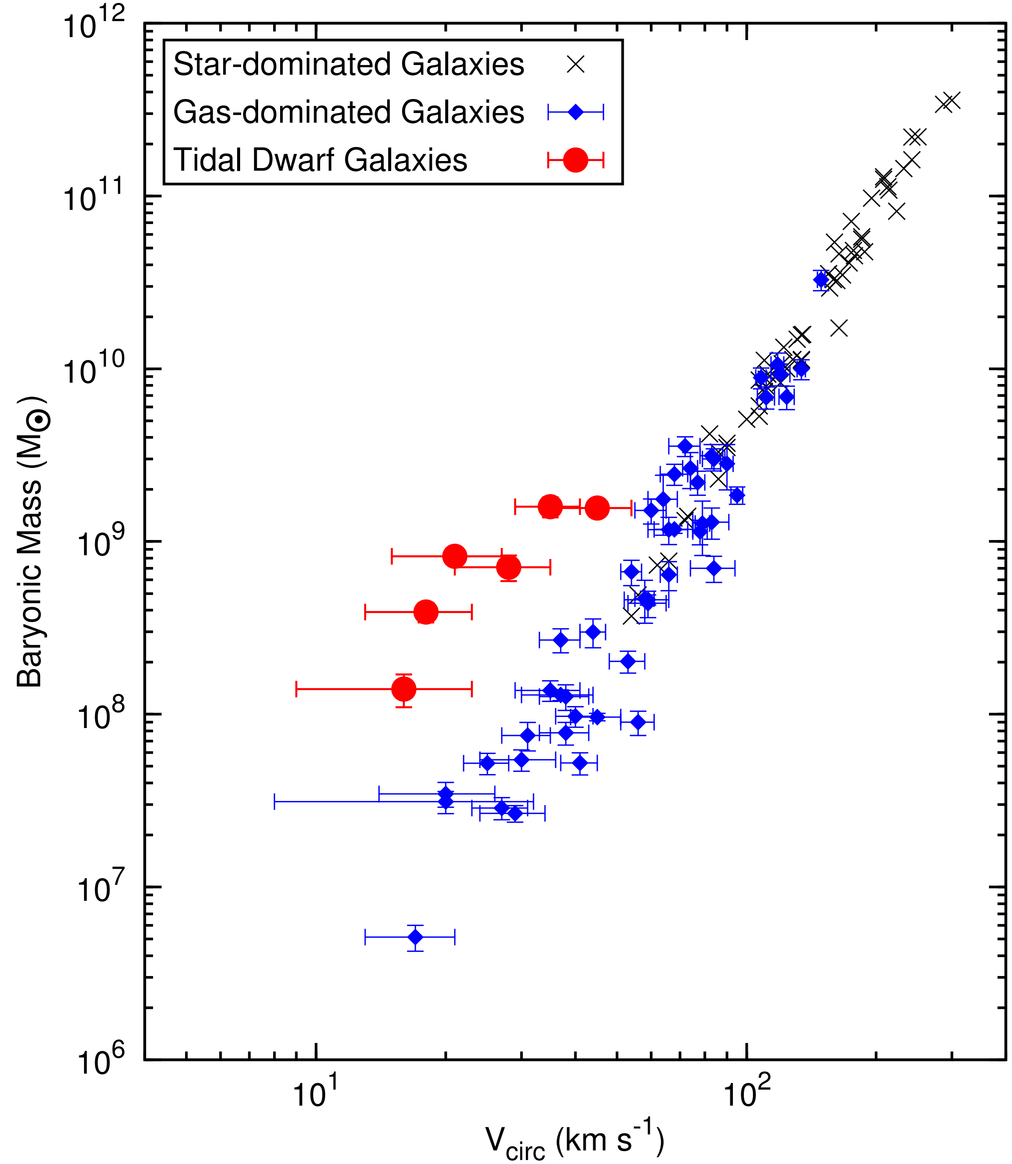
Gentile et al. (2007)
A&A, **472**, L25



Tidal dwarfs
do show mass
discrepancies as
expected in MOND



Tidal dwarfs don't show mass discrepancies as expected in CDM



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?

Questions

- Don’t know answers