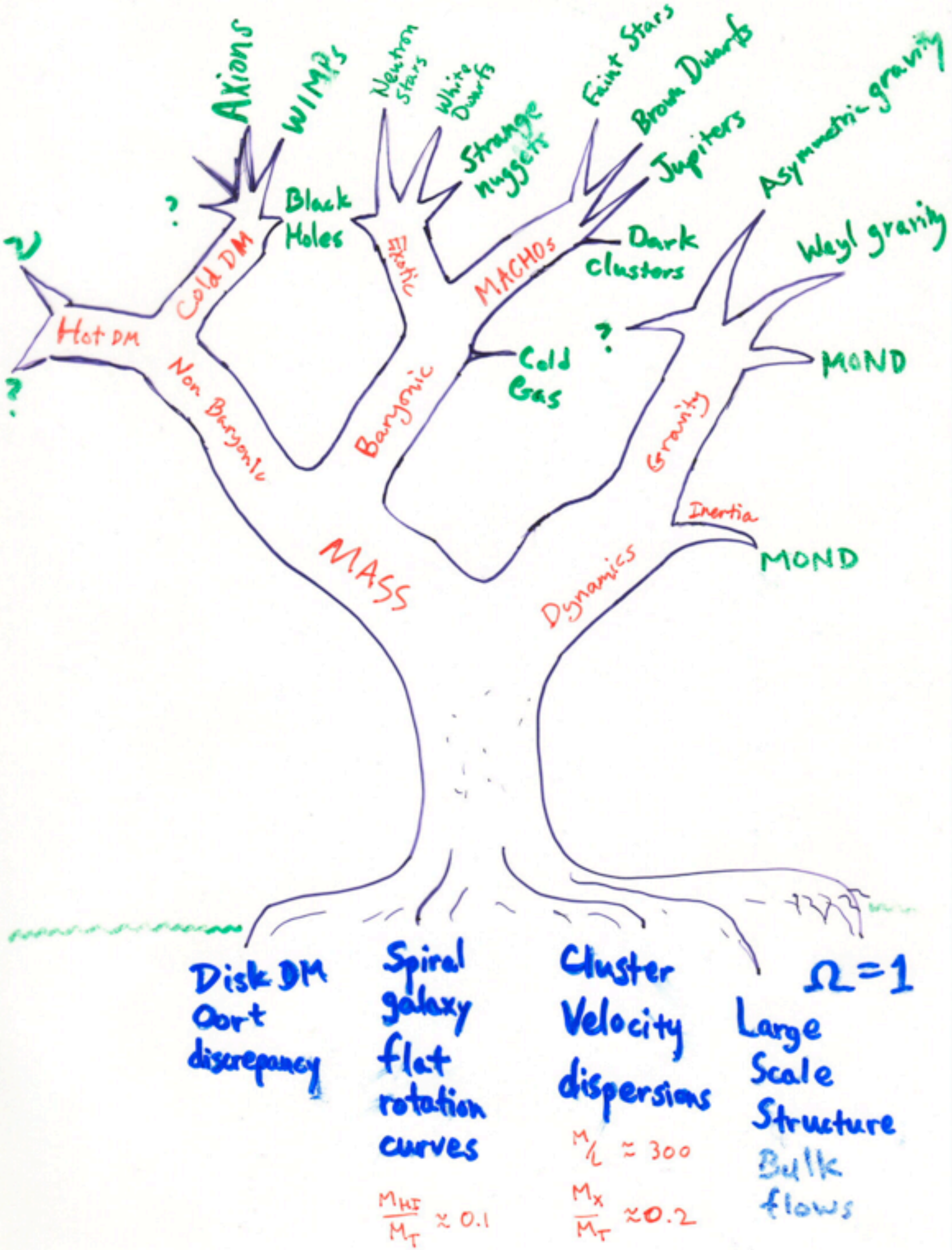
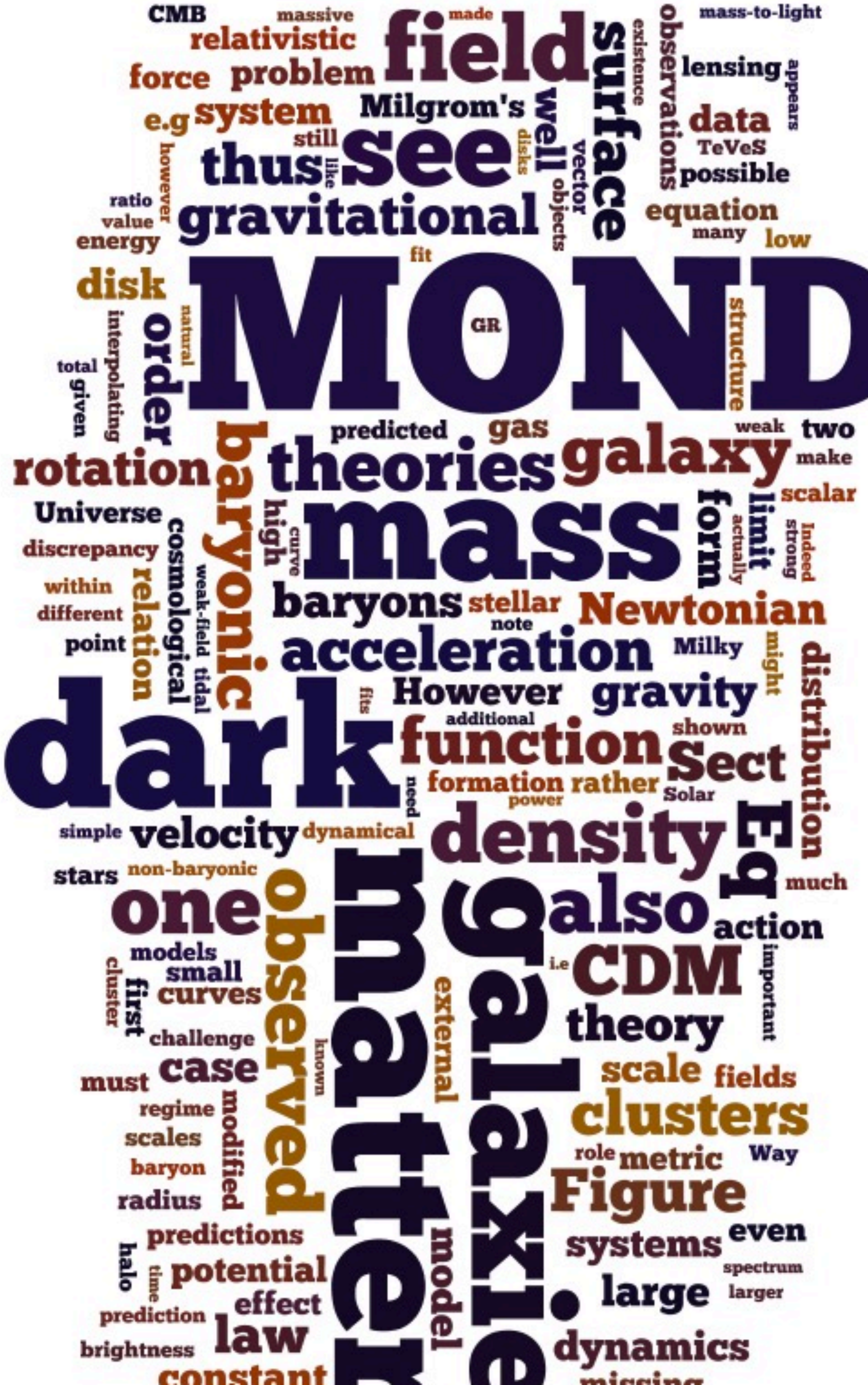


MOND

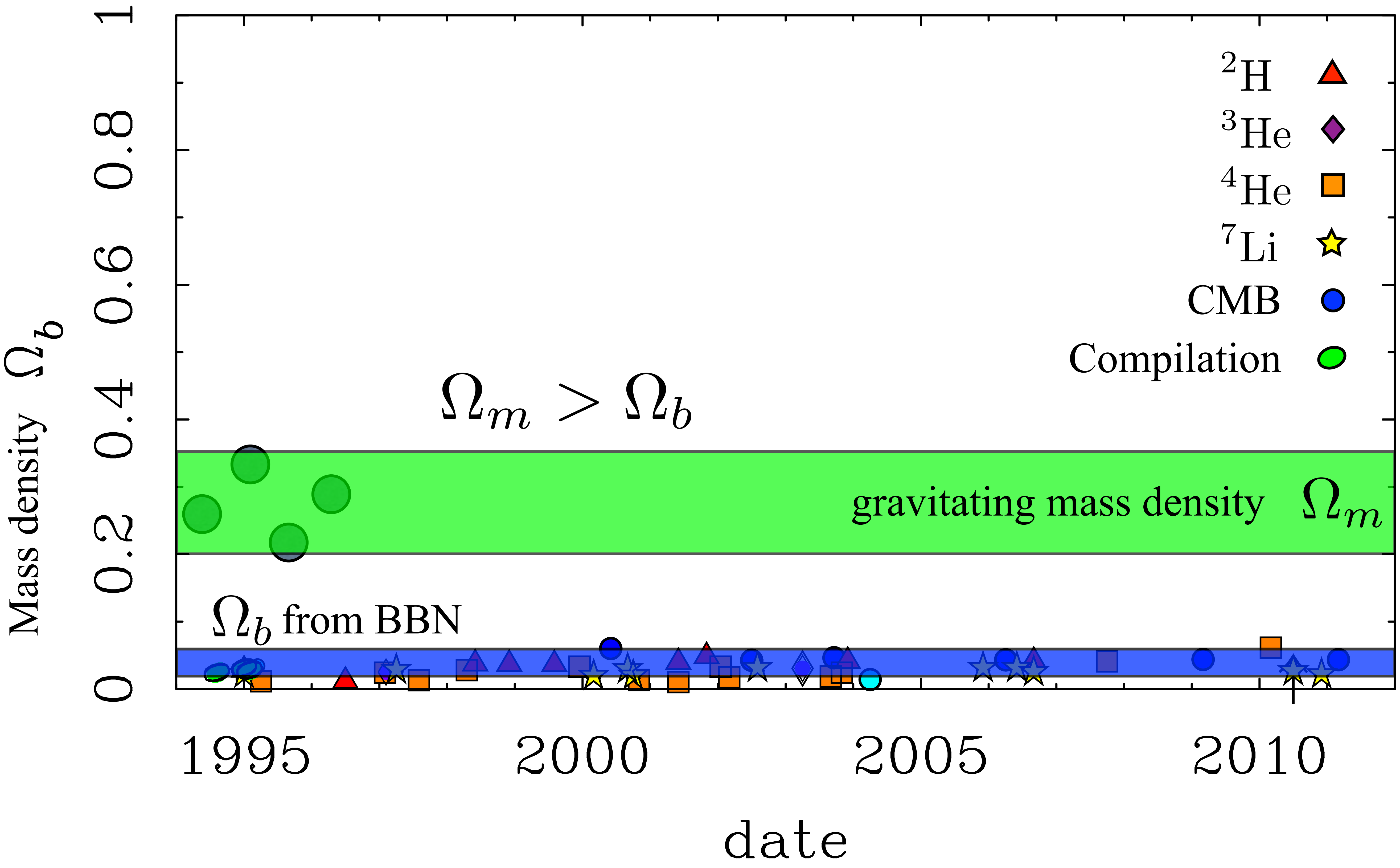
Stacy McGaugh
Case Western Reserve



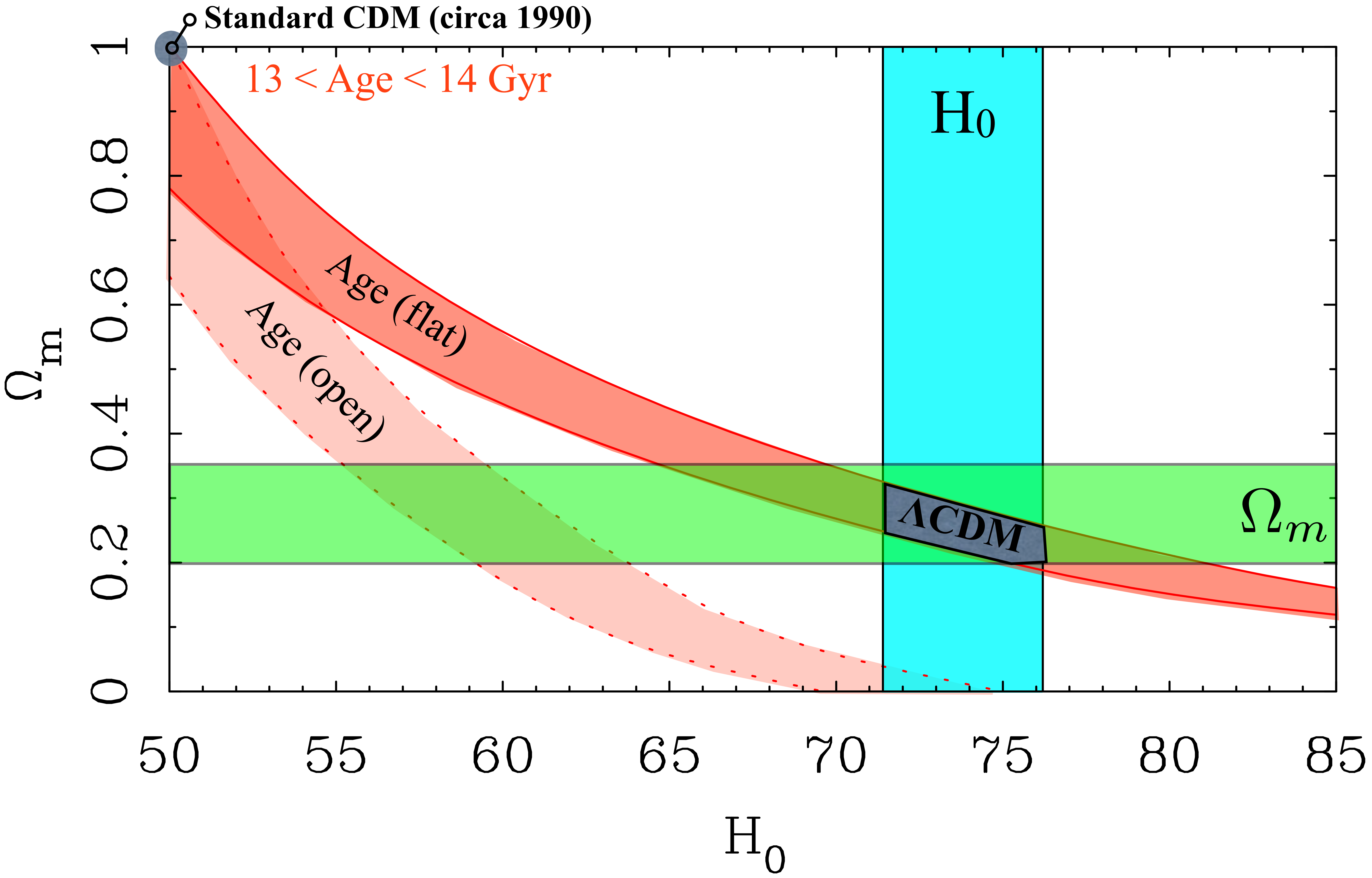
Famaey & McGaugh 2012

Silk & Mamon 2012

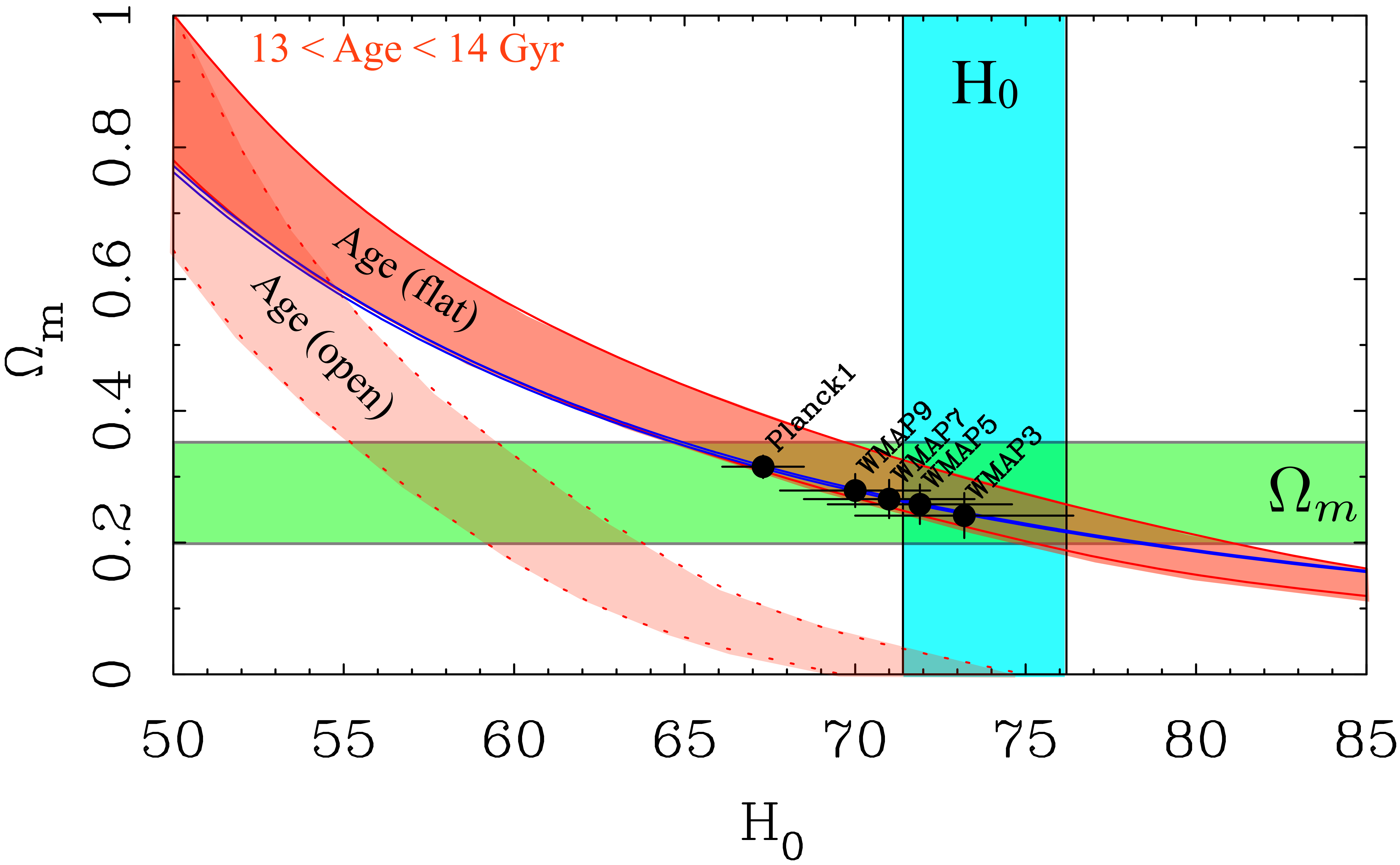
(1) Must have non-baryonic cold dark matter: There's more mass than BBN allows in baryons



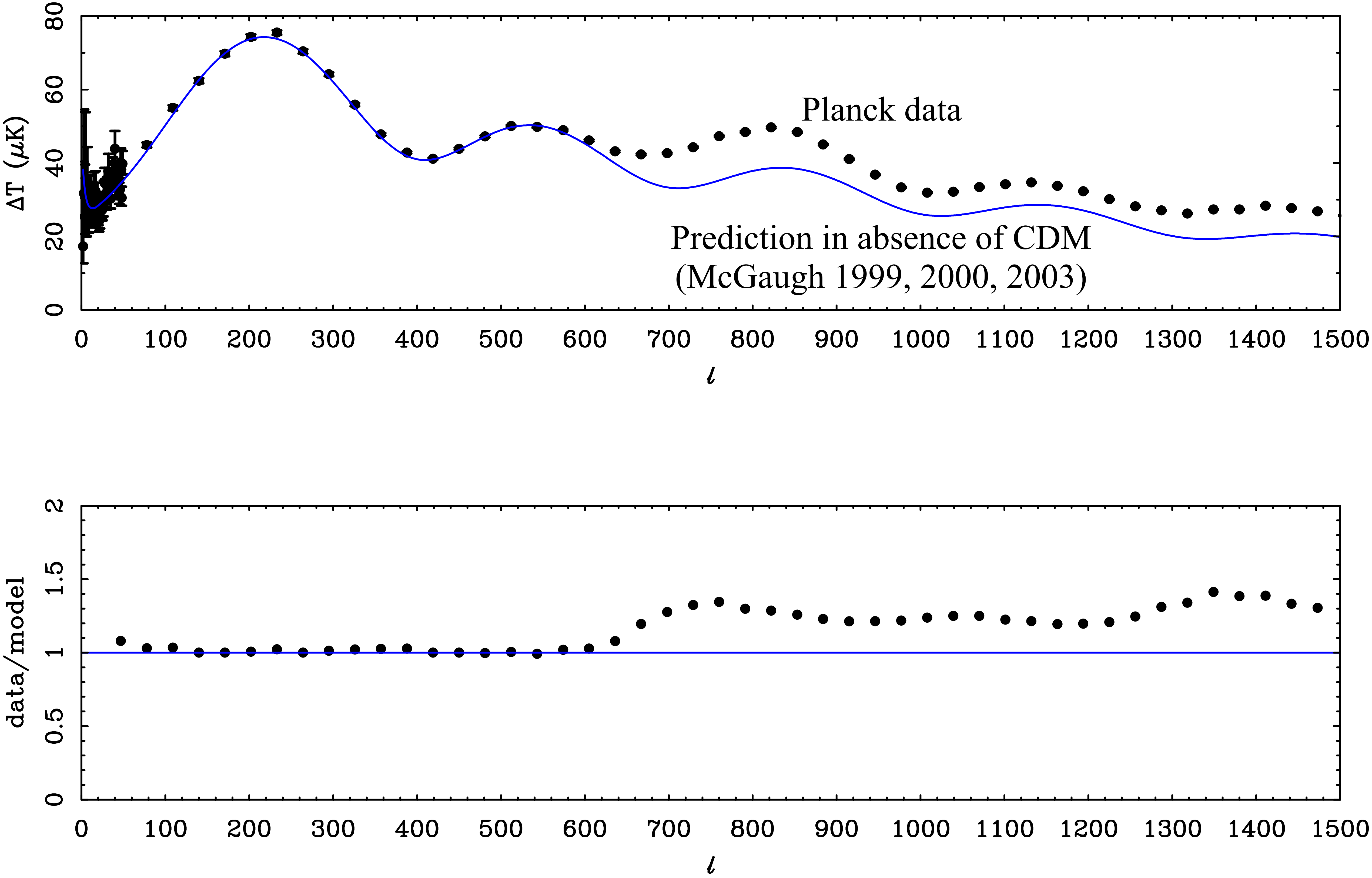
Constraints predating SN, CMB (circa 1995)

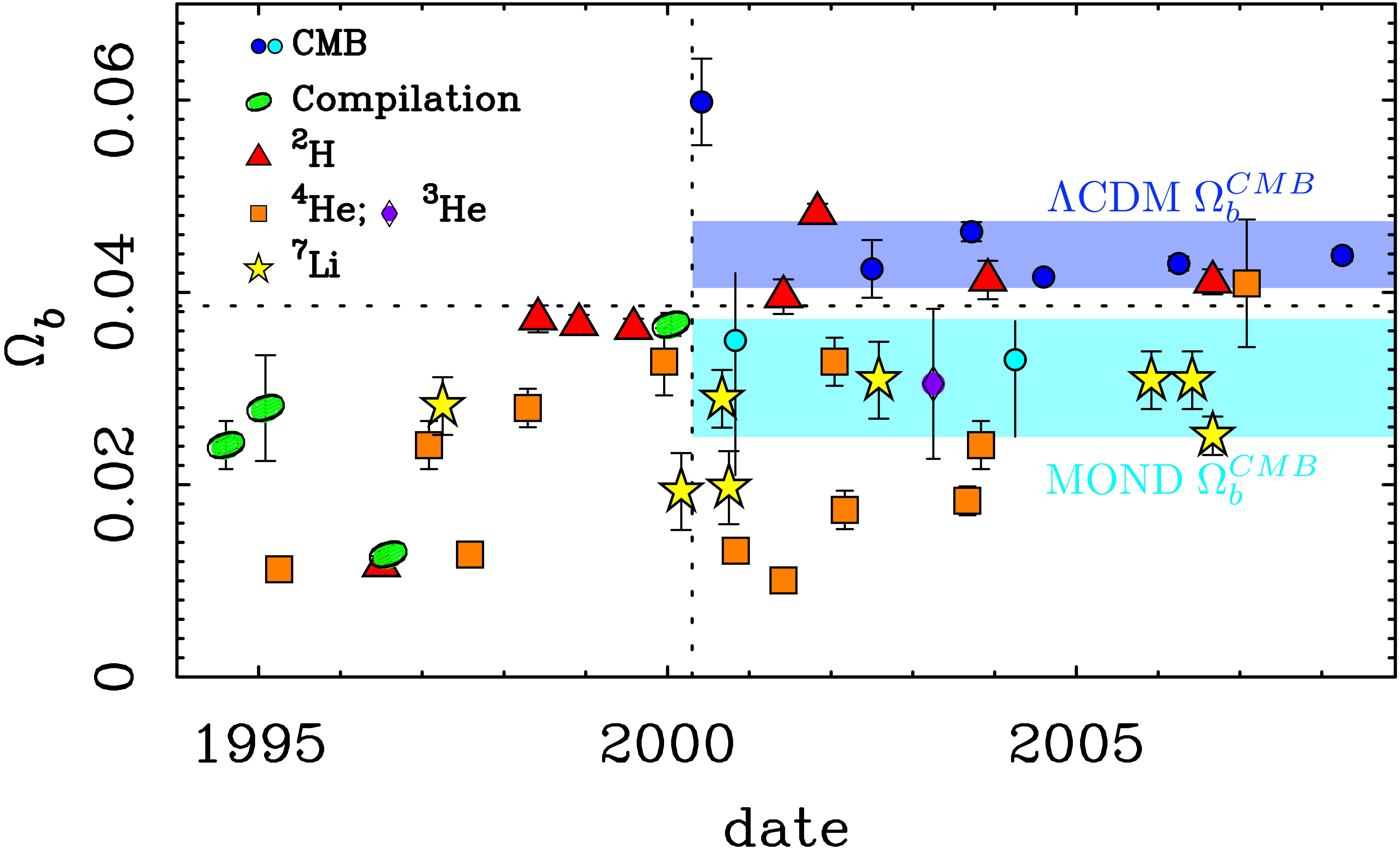


2013 Planck constraint: $\Omega_m h^3 = 0.0959 \pm 0.0006$



CMB power spectrum

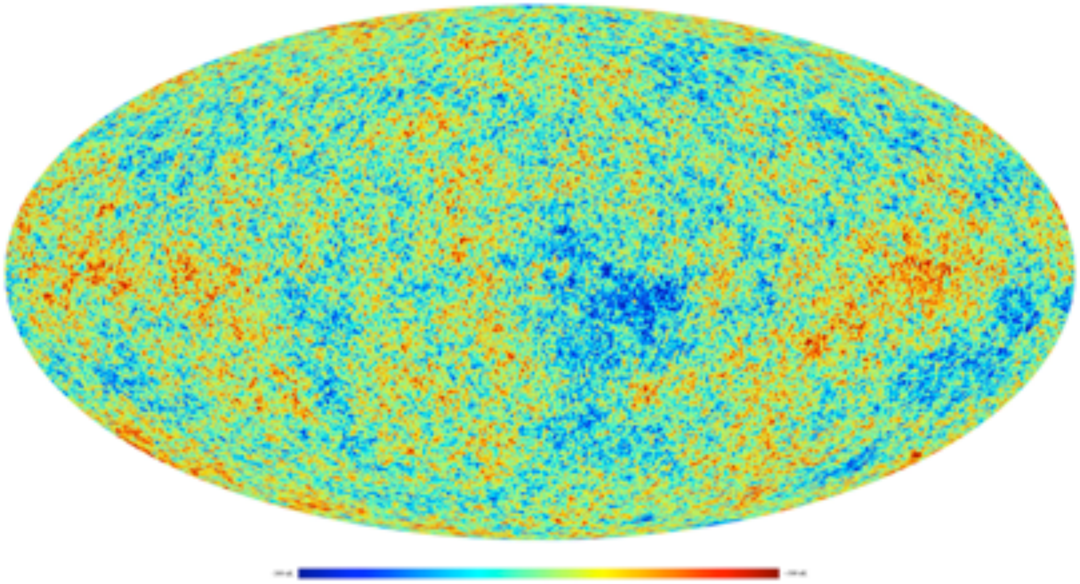




Baryon density measurements by various methods. The dark blue band is from fits to the CMB in ΛCDM. The light blue band is the range implied in MOND (2004, ApJ, 611, 26). The latter is consistent with independent measurements of all isotopes of the light elements, excepting only deuterium measurements published after CMB measurements became available.

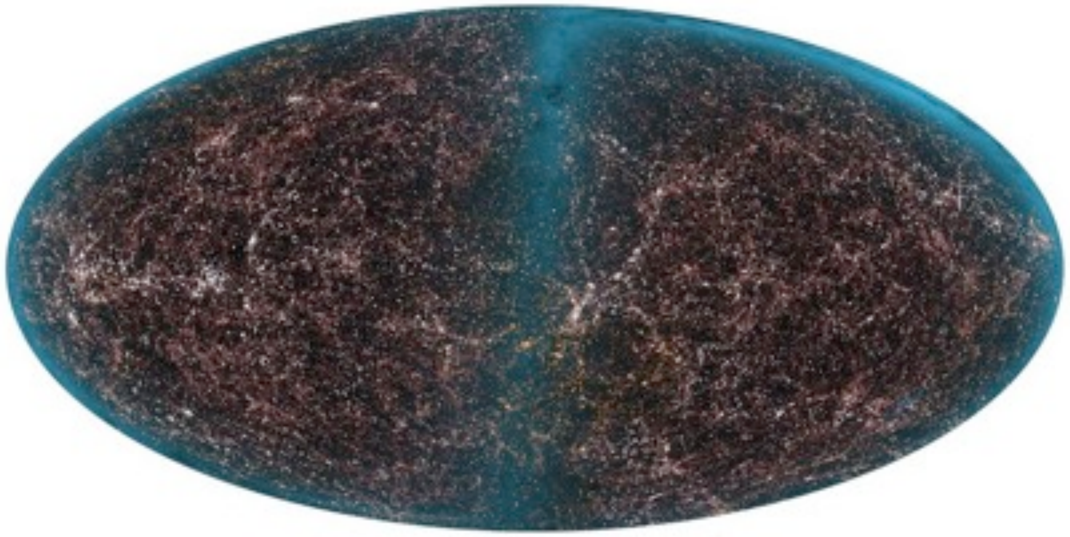
(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

t = 3.8 x 10^5 yr



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

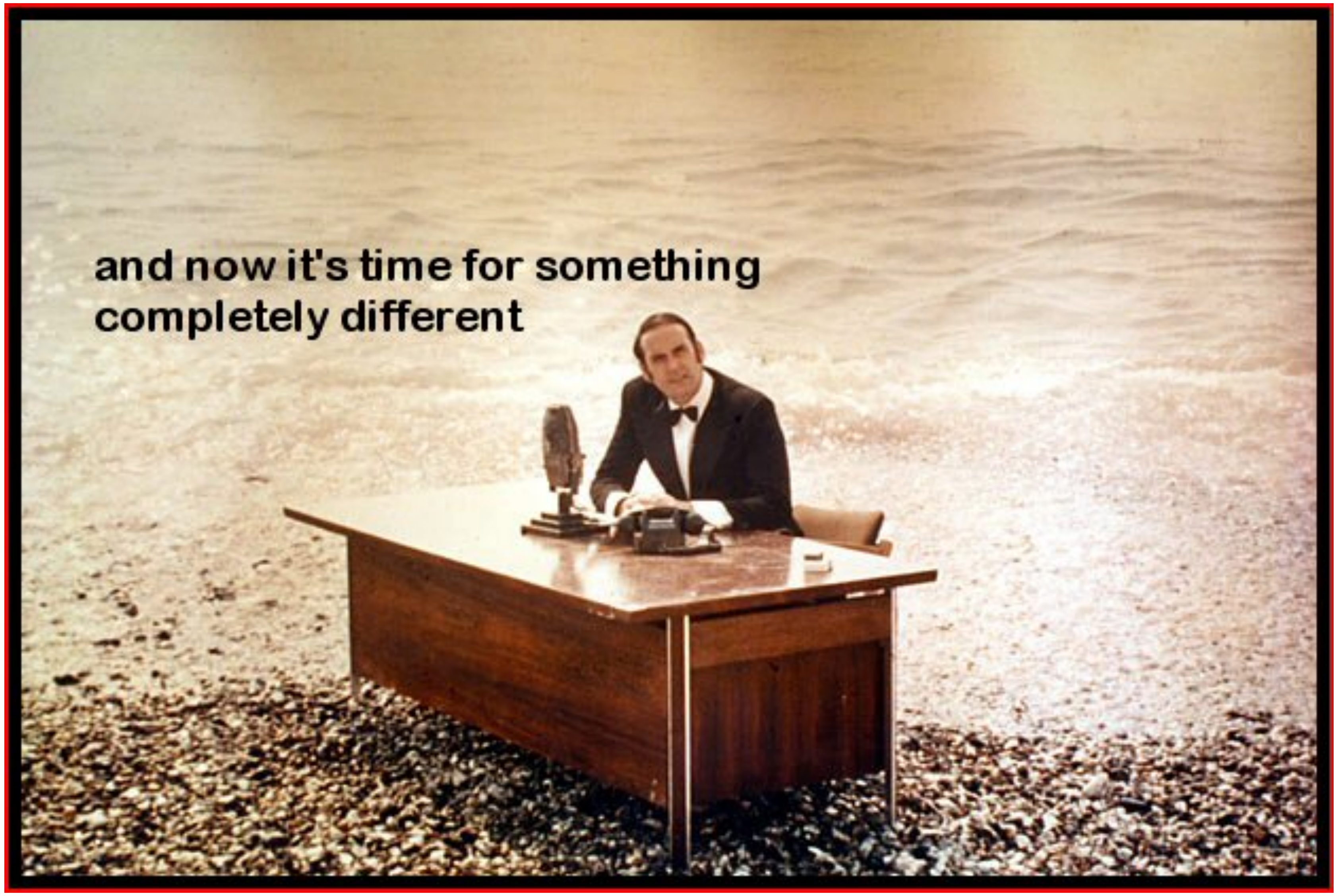
t = 1.4 x 10^{10} yr



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

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

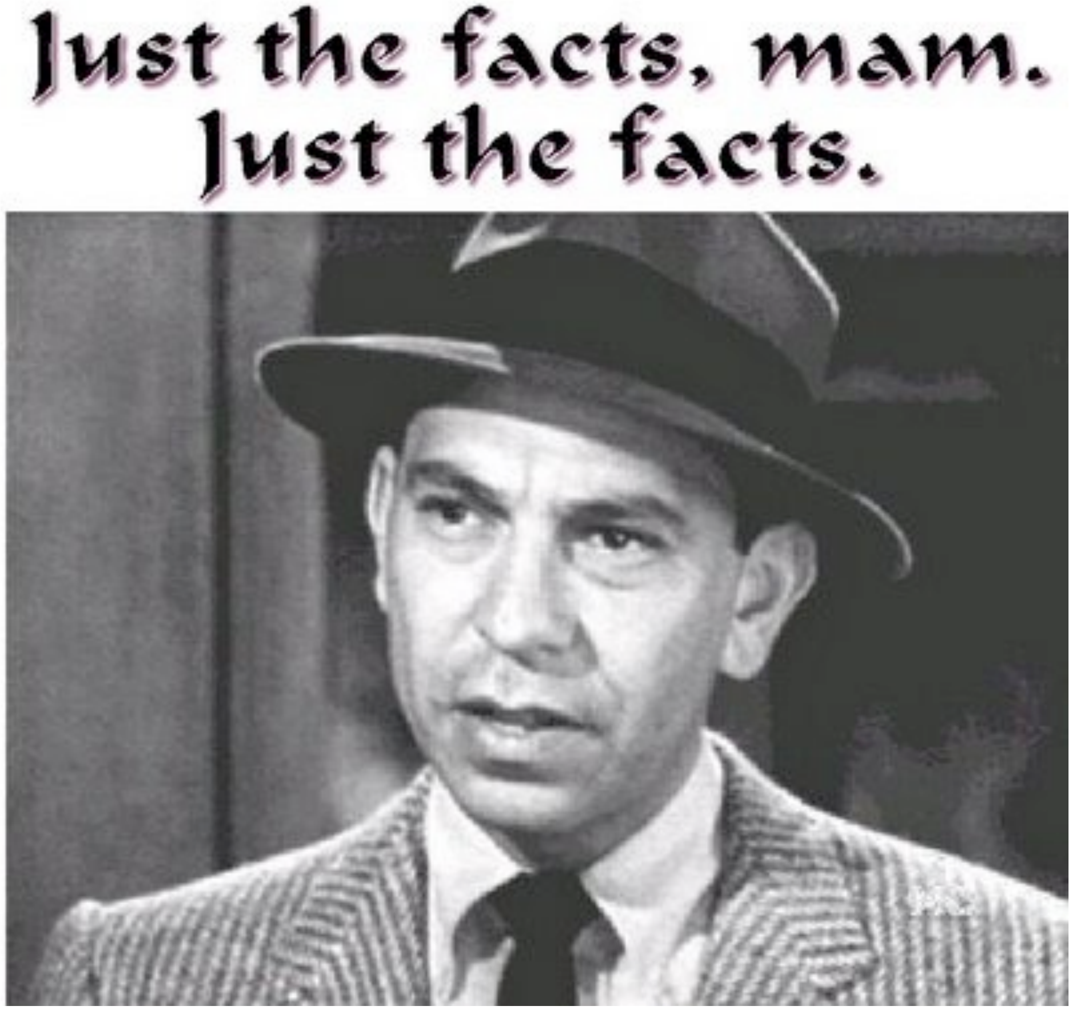
Both (1) and (2) hold only when gravity is normal.


and now it's time for something
completely different

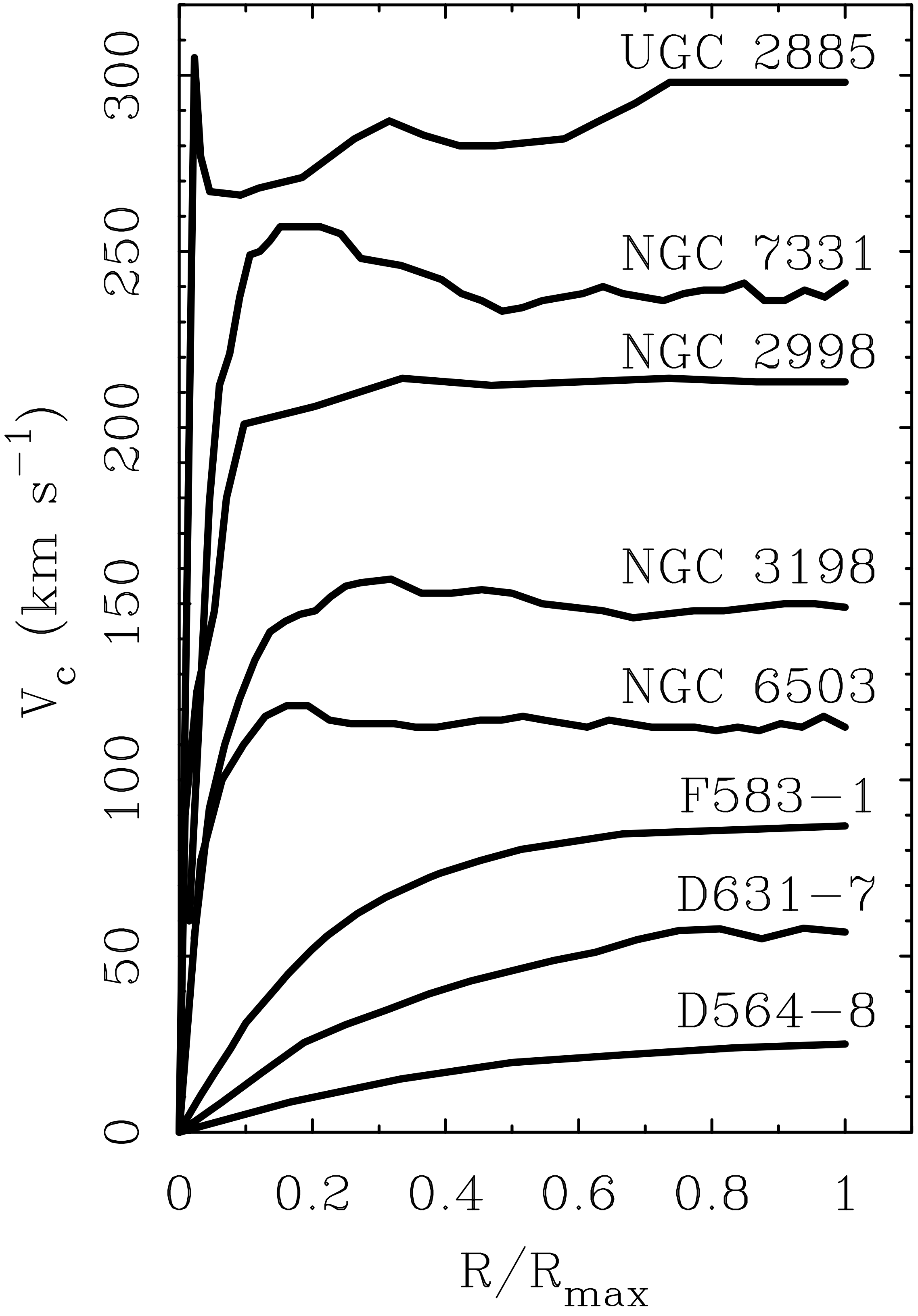
3 Laws of Galactic Rotation

1. Rotation curves tend towards asymptotic flatness $V_f \rightarrow \text{constant}$
2. Baryonic mass scales as the fourth power of rotation velocity (Baryonic Tully-Fisher) $M_b \propto V_f^4$
3. Gravitational force correlates with baryonic surface density

$$-\frac{\partial \Phi}{\partial R} \propto \Sigma_b^{1/2}$$



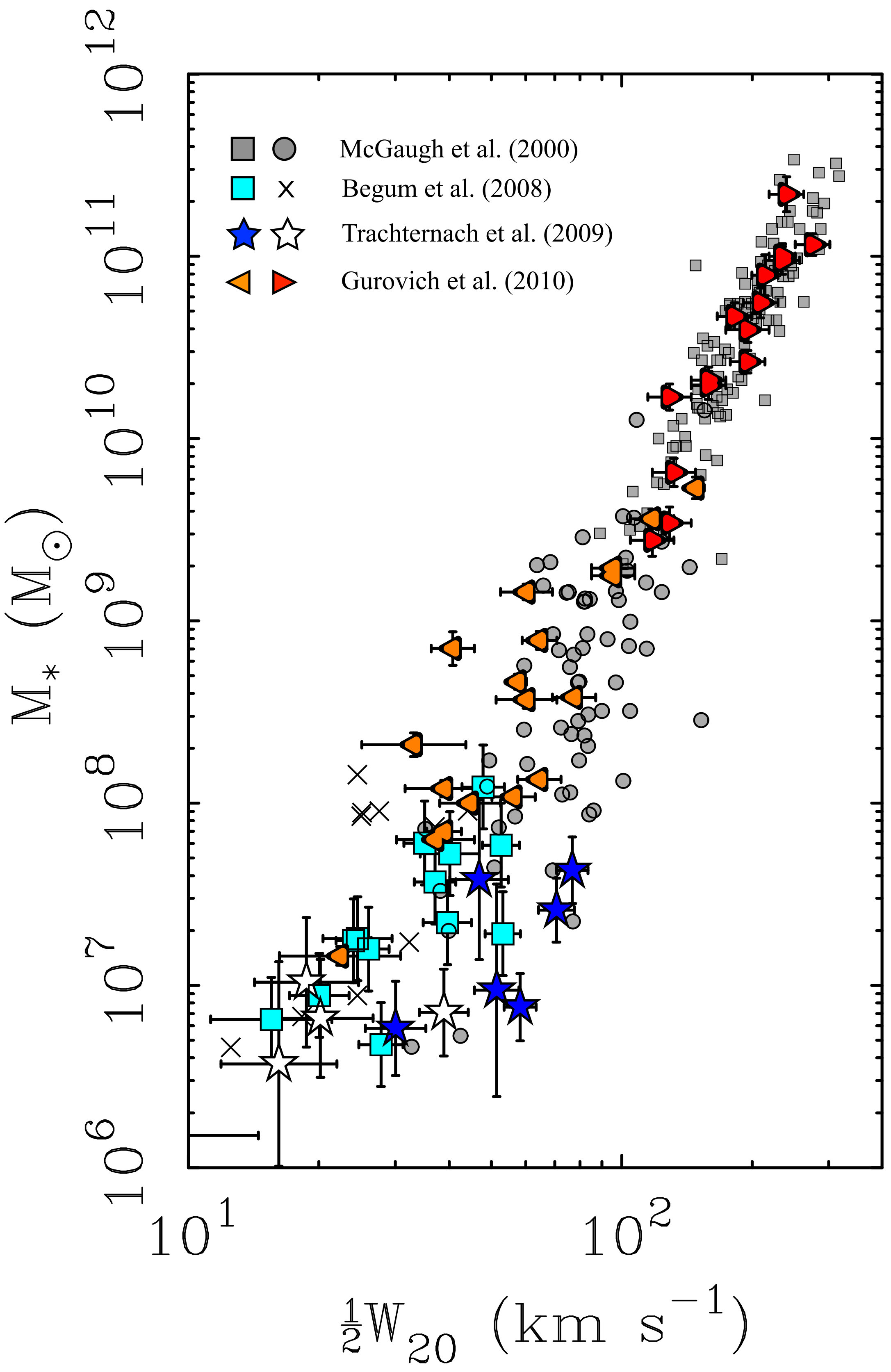
1. Flat rotation curves



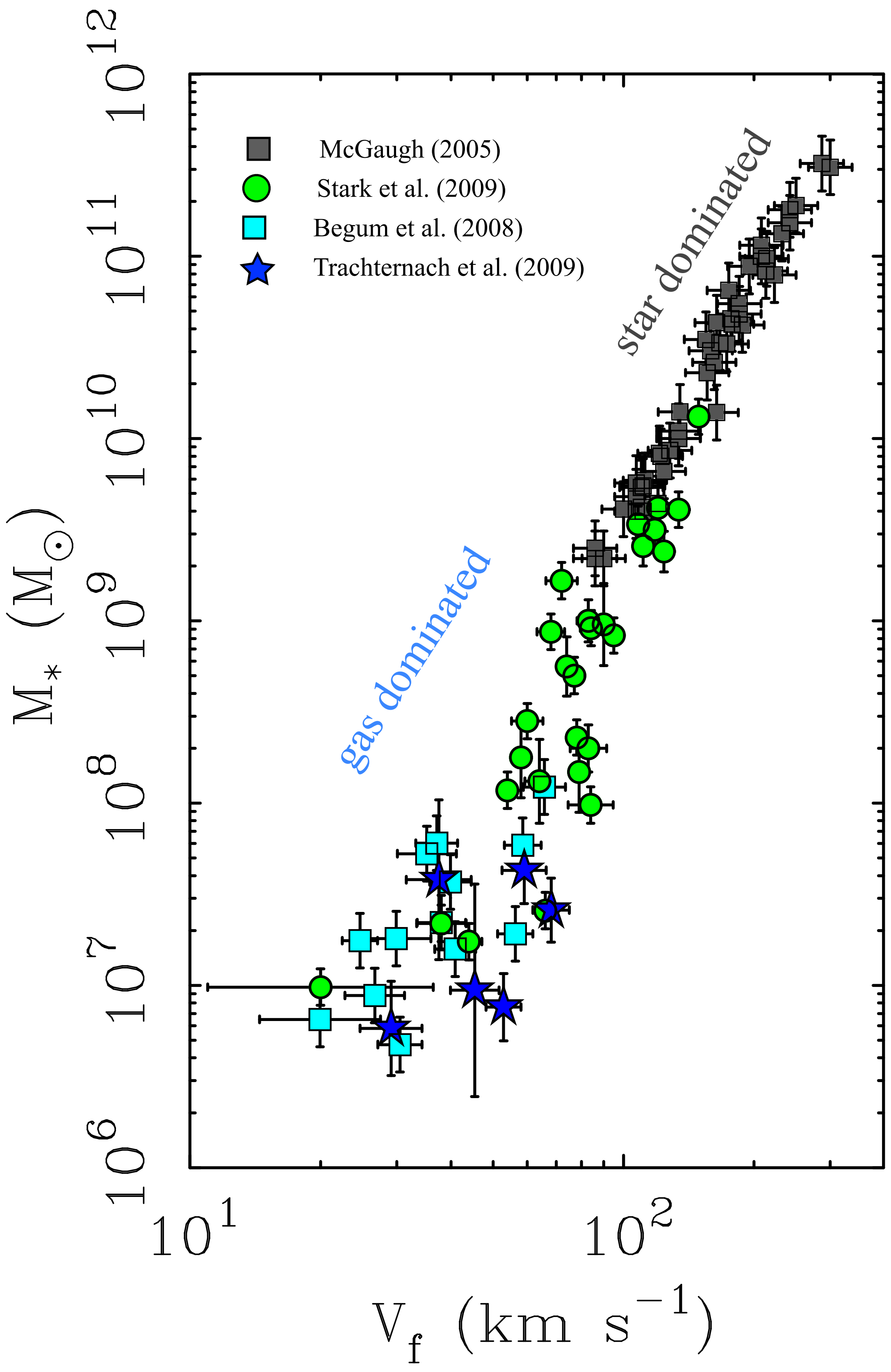
star dominated HSB

gas dominated LSBs

Stellar Mass Tully-Fisher relation



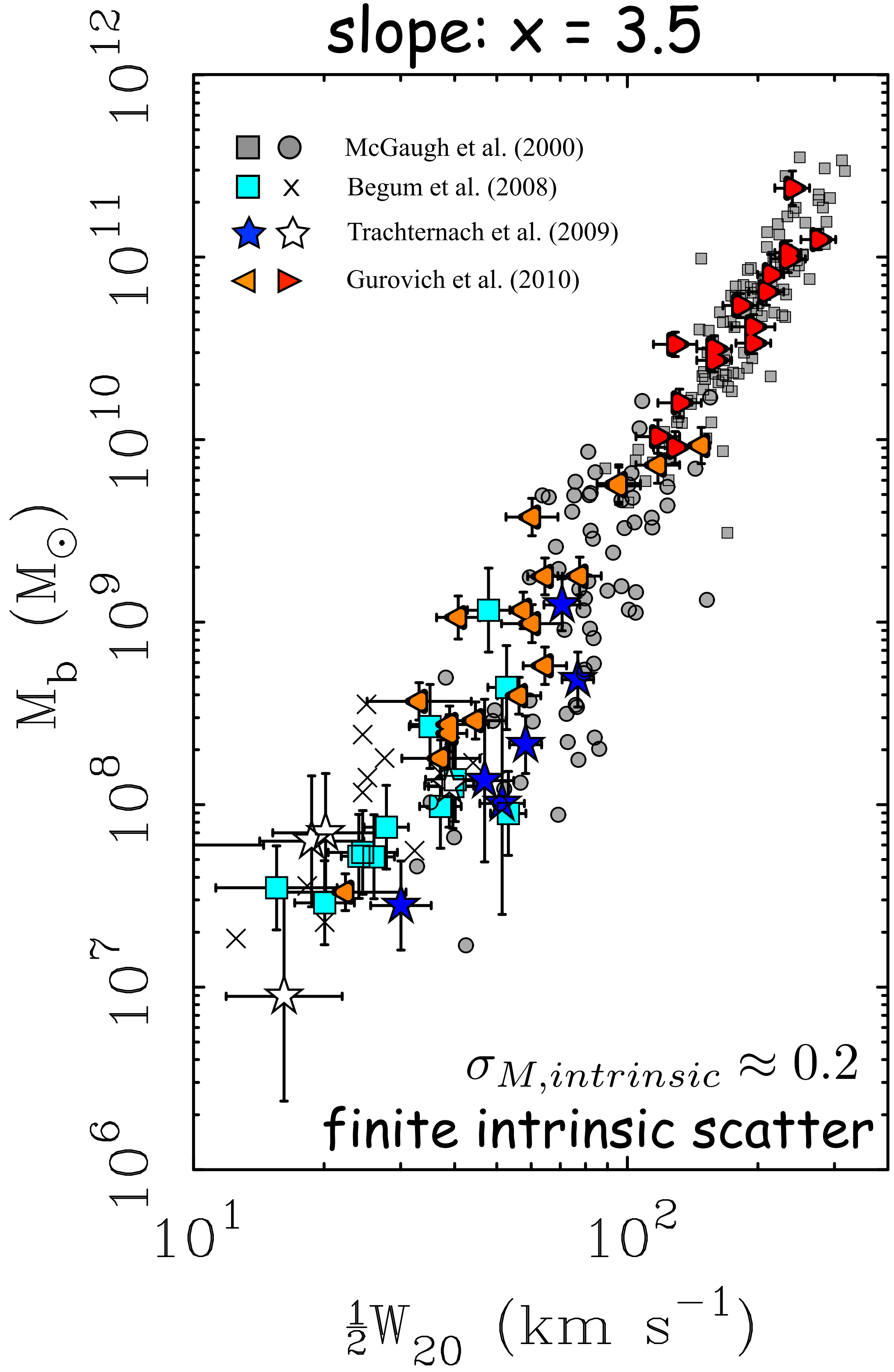
line-width



outer (flat) velocity

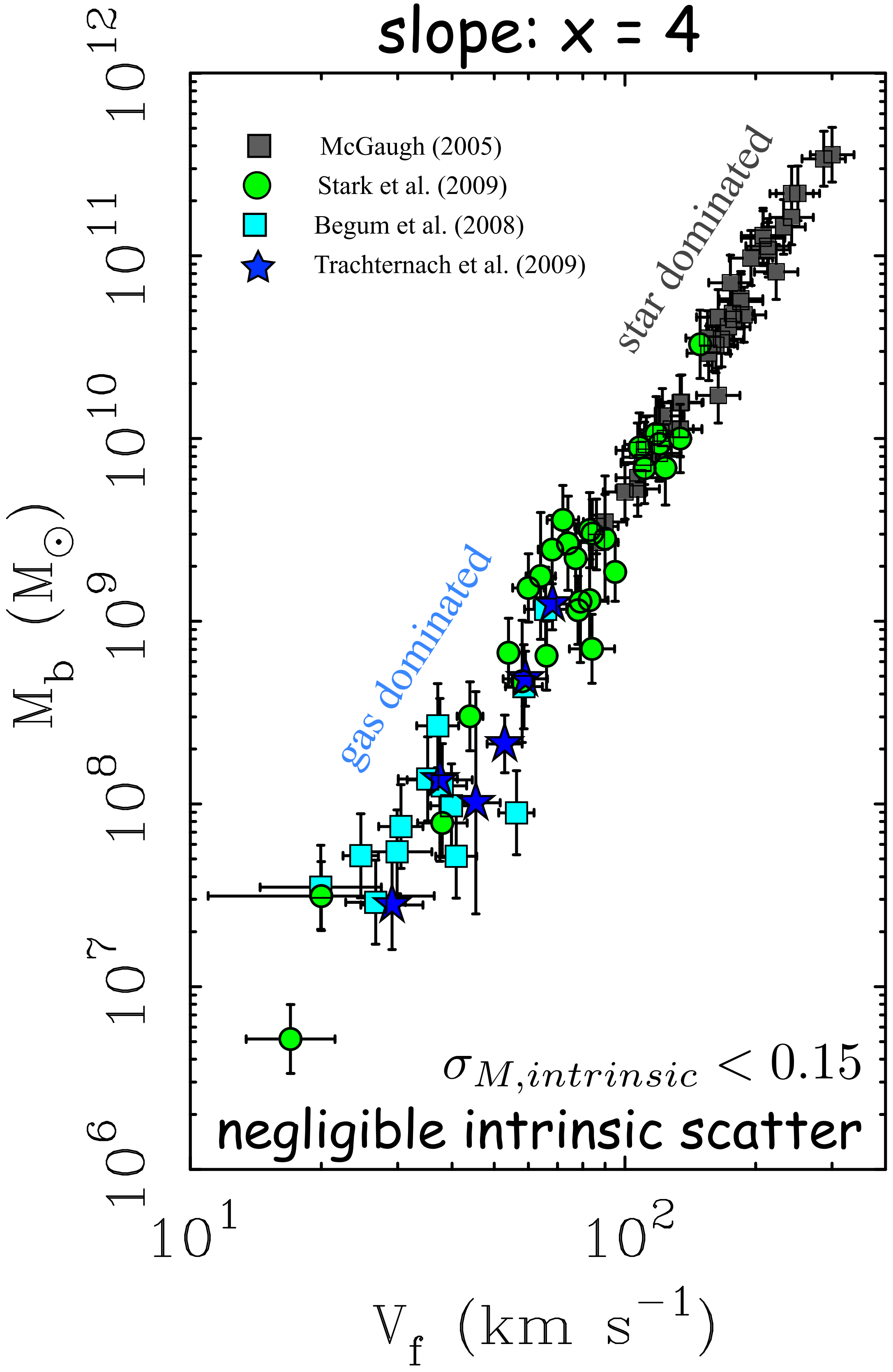
2. Baryonic Tully-Fisher relation: $M_b = 47\ V^4$

slope: x = 3.5



line-width

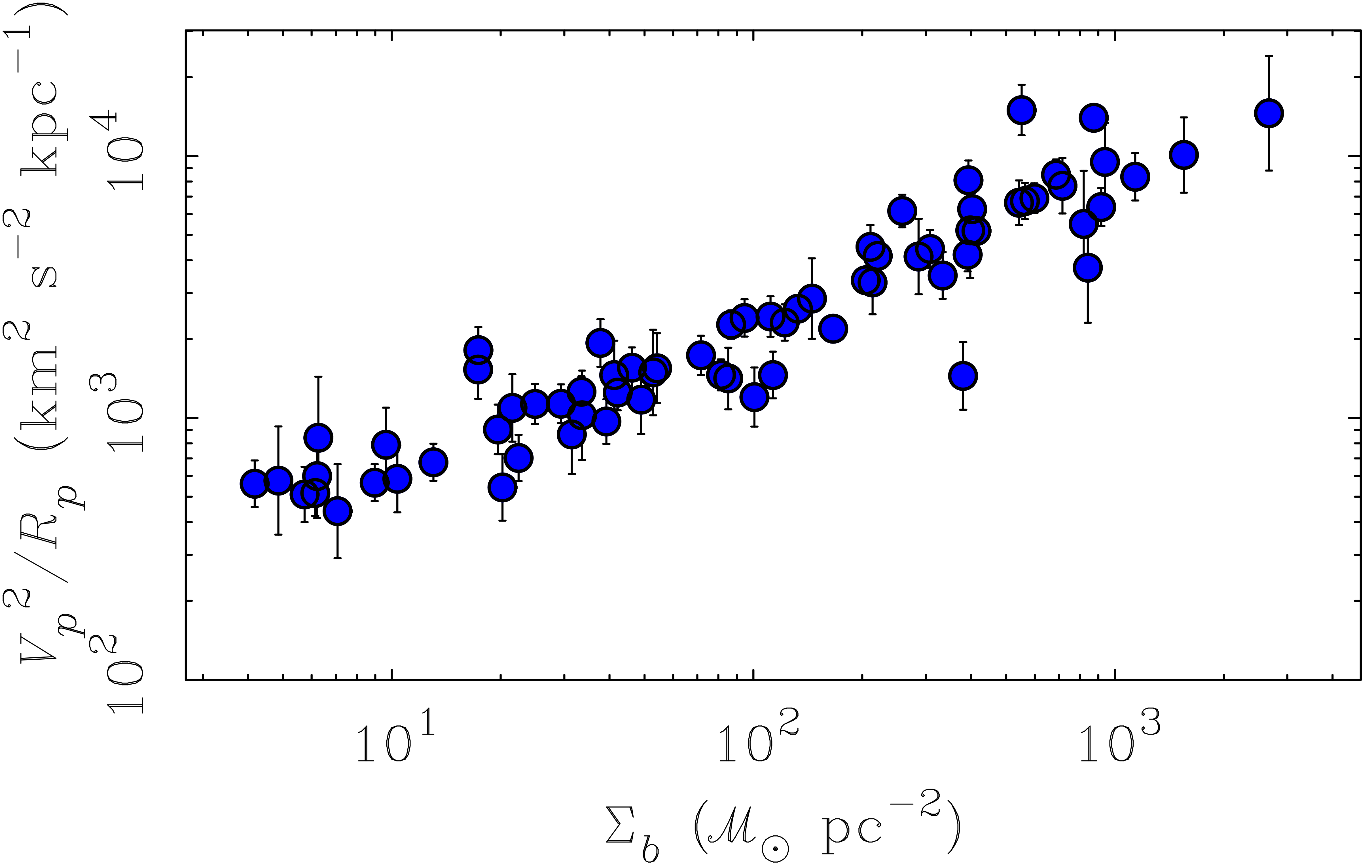
slope: x = 4



outer (flat) velocity

3. Gravitational force correlates with baryonic surface density

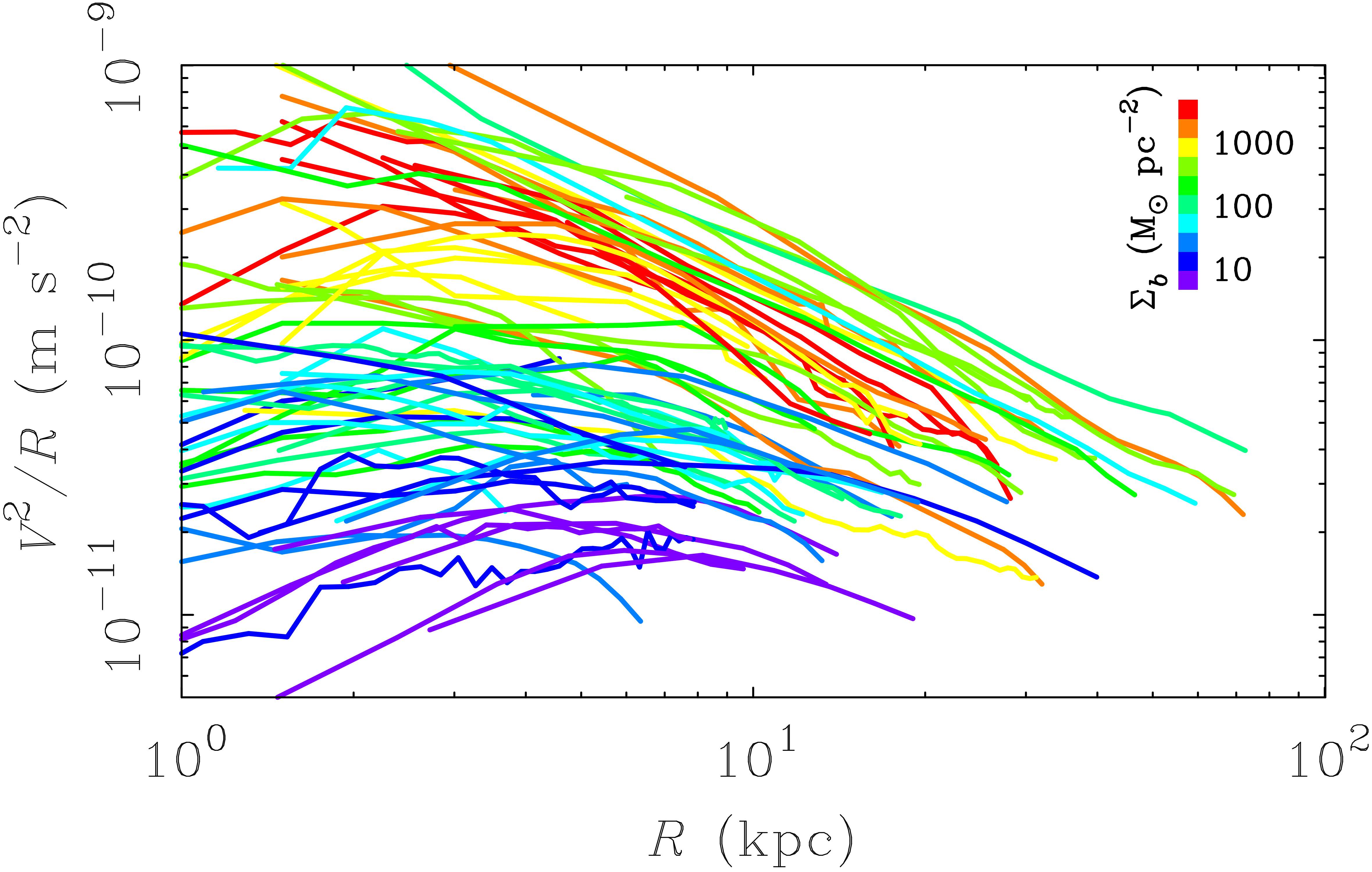
$$a \sim \Sigma_b^{1/2}$$



acceleration at peak of baryonic rotation curve

central baryonic surface density

The baryonic surface density correlates with acceleration

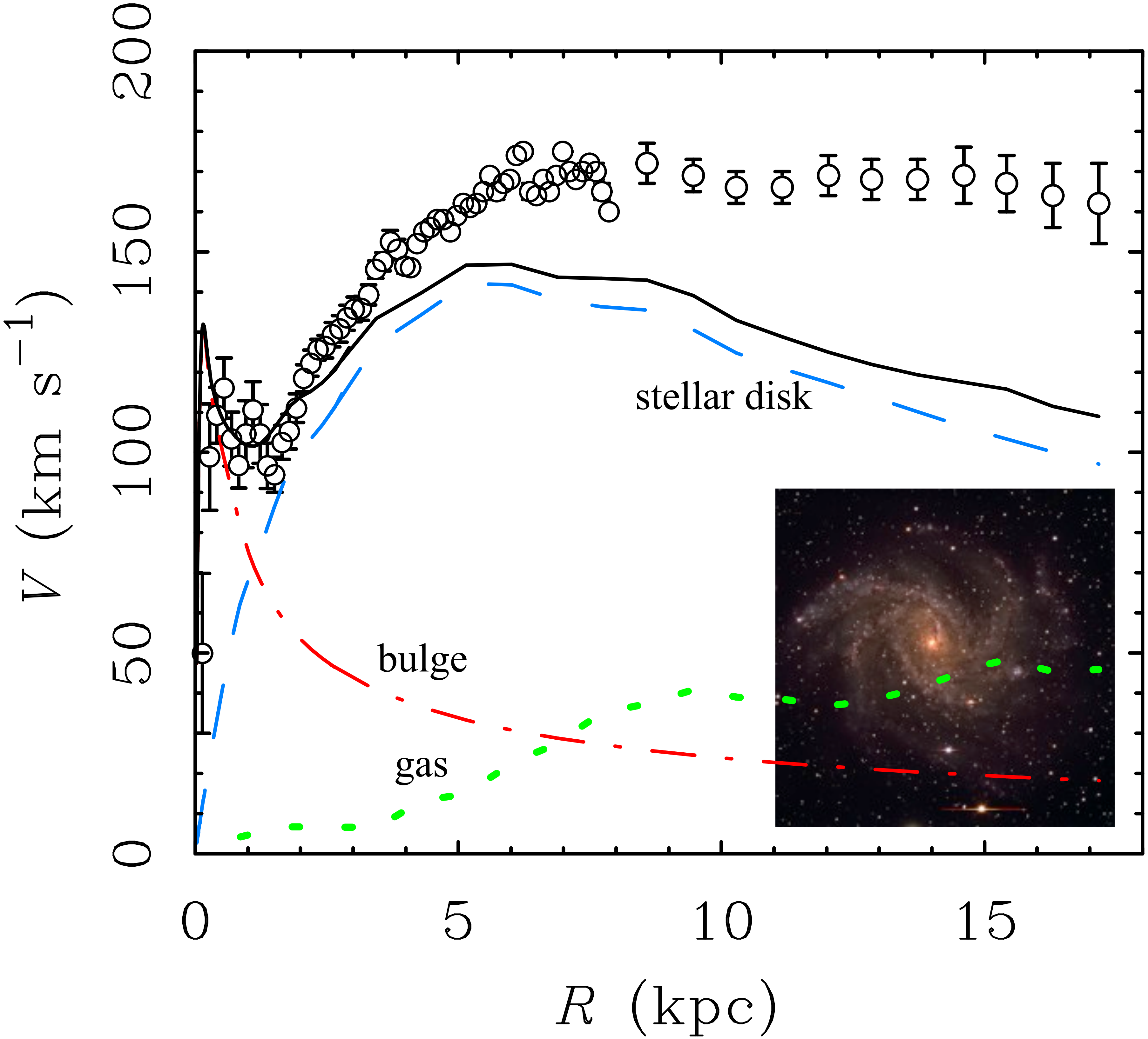


(gravitational force per unit mass) at all radii

Includes bumps & wiggles - Renzo's Rule:

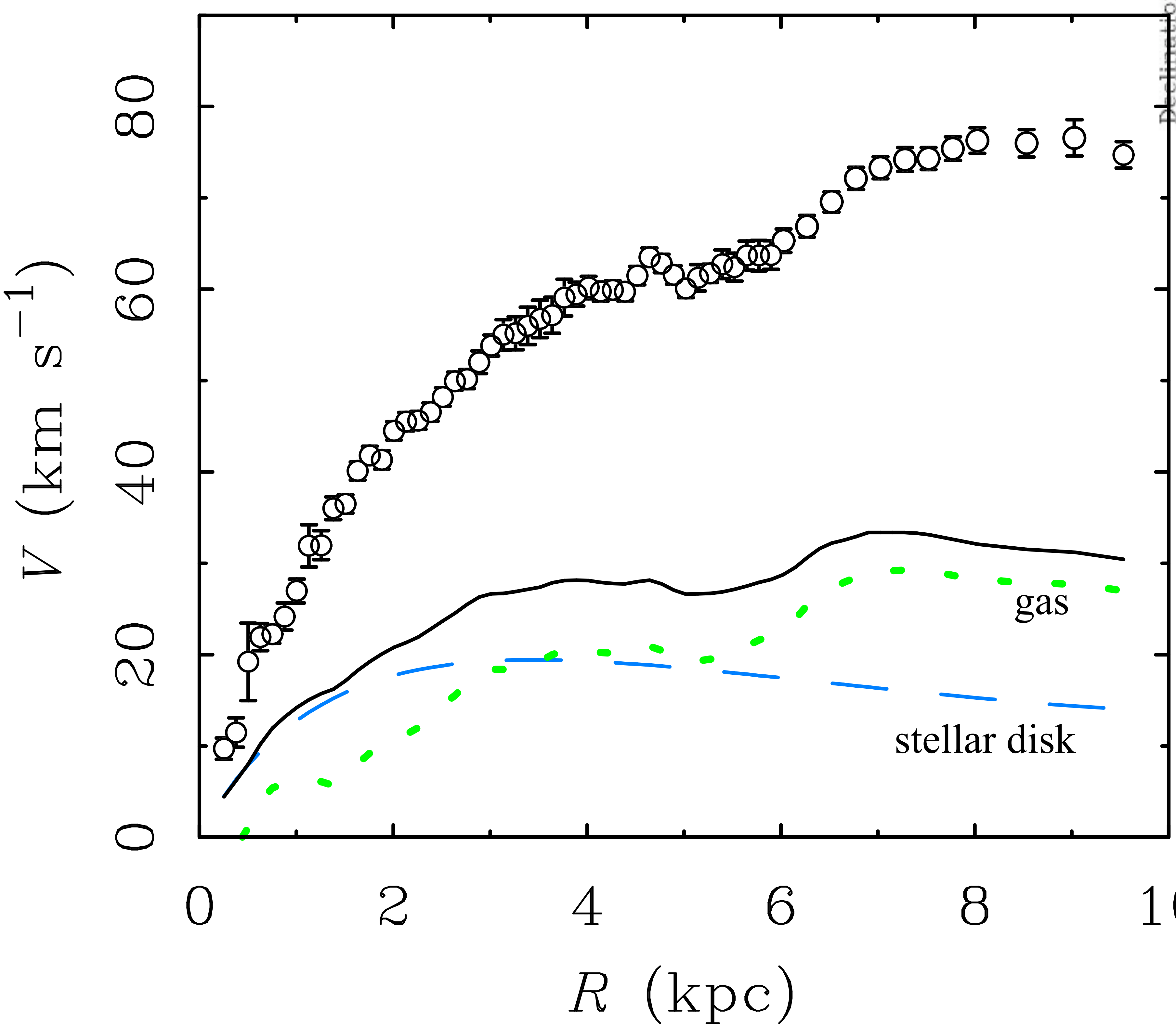
"When you see a feature in the light, you see a corresponding feature in the rotation curve."

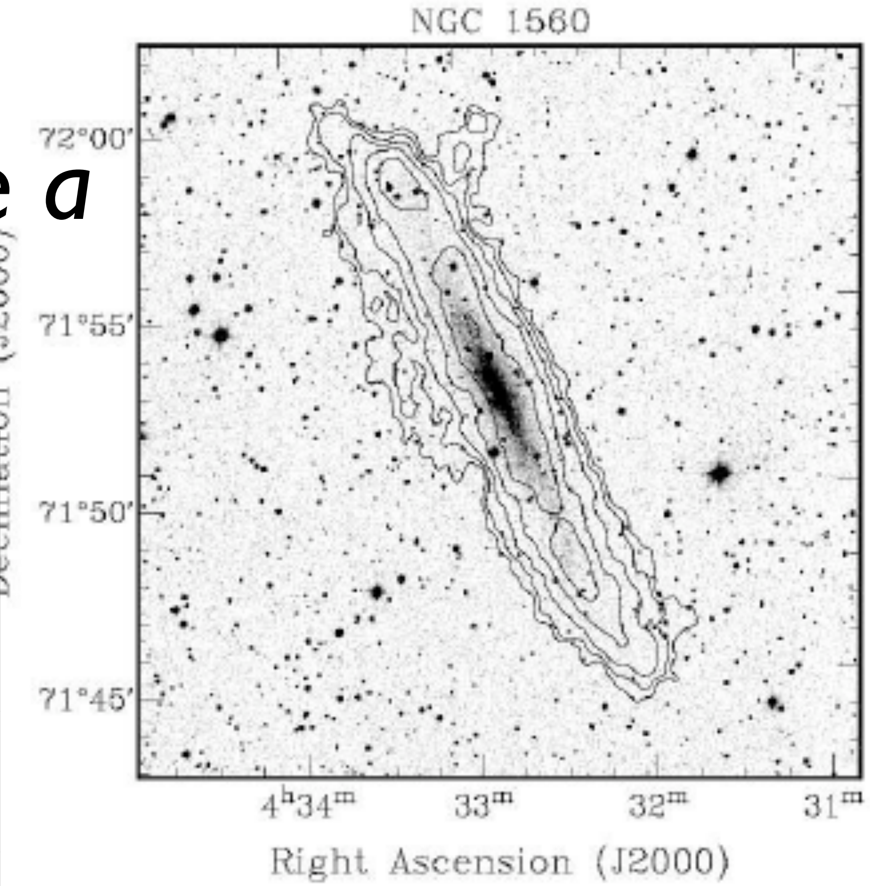
In NGC 6946, a tiny bulge (just 4% of the total light) leaves a distinctive mark.



Renzo's Rule works in LSBs too.

"When you see a feature in the light, you see a corresponding feature in the rotation curve."

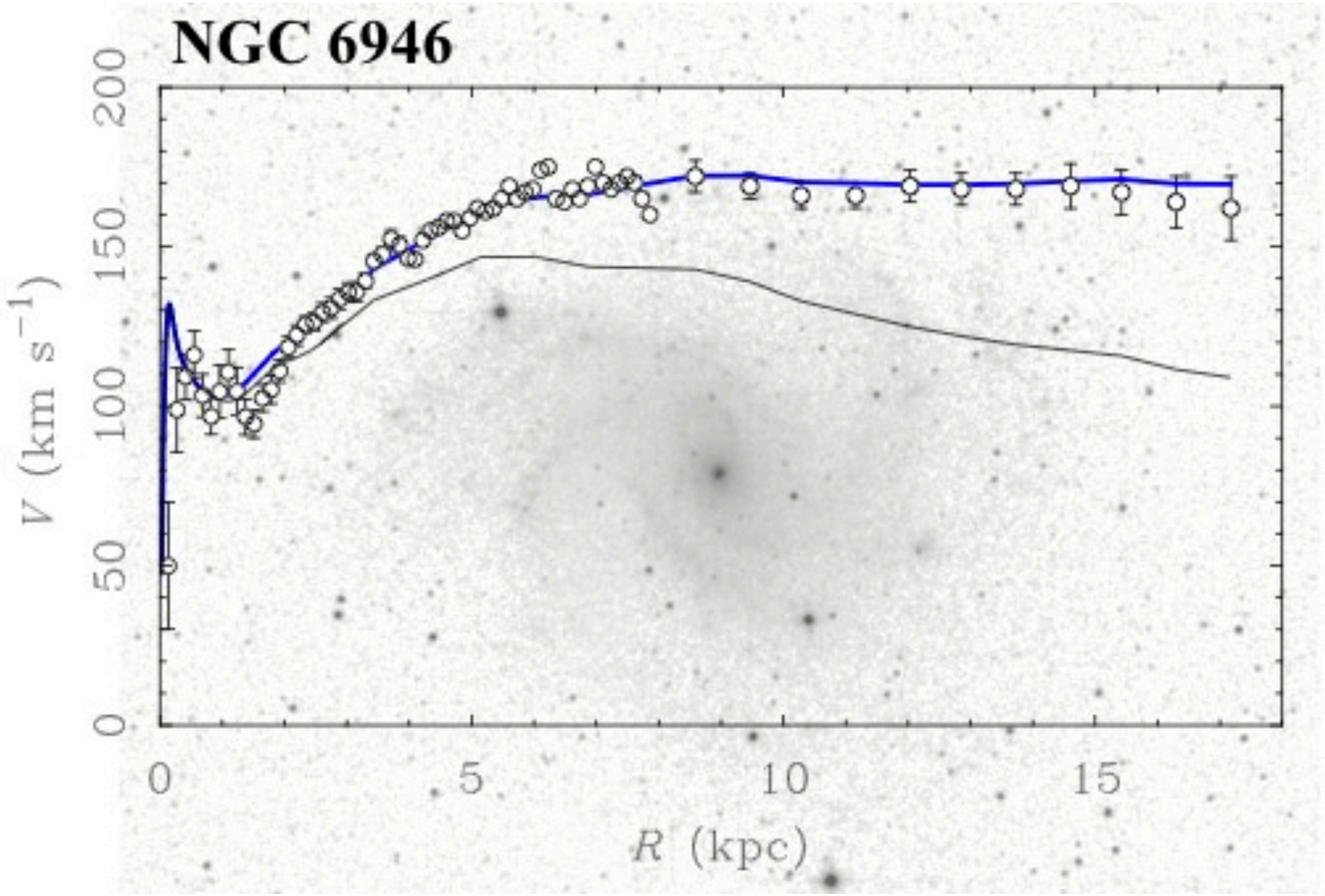


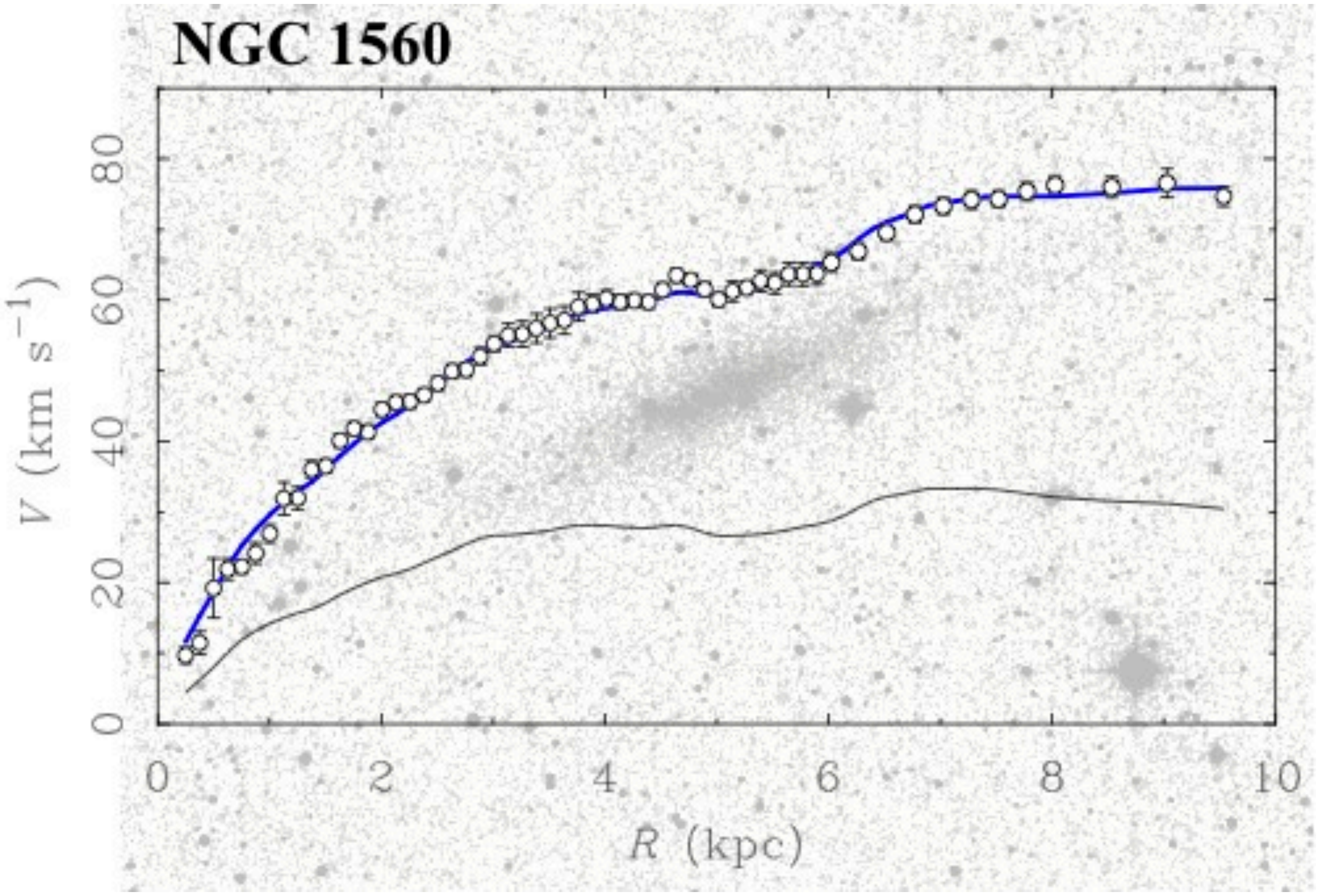


Gentile et al. (2010)

In NGC 1560, a marked feature in the gas is reflected in the kinematics, even though dark matter should be totally dominant.

The baryon distribution maps to the observed rotation





even in galaxies with large mass discrepancies

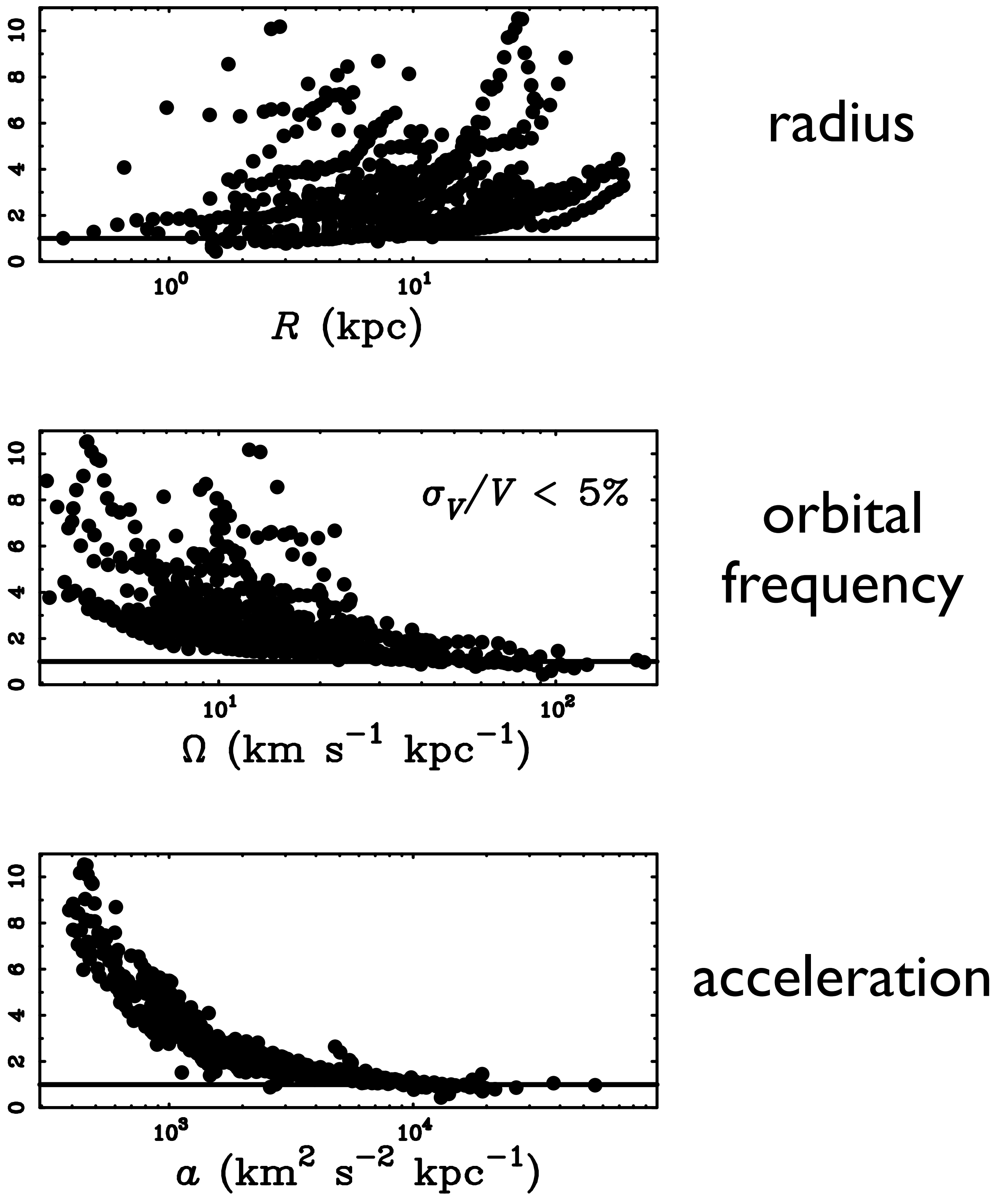
FALSIFIABILITY

Not just any force law will do

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%)

3 Laws of Galactic Rotation

1. Rotation curves tend towards asymptotic flatness
2. Baryonic mass scales as the fourth power of rotation velocity (Baryonic Tully-Fisher)
3. Gravitational force correlates with baryonic surface density

No theory so far - just data.

Can always be interpreted in terms of dark matter (with sufficient fine-tuning).

Might stem more naturally from a universal force law.

MOND

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 $(t, \mathbf{x}) \rightarrow \lambda(t, \mathbf{x})$

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

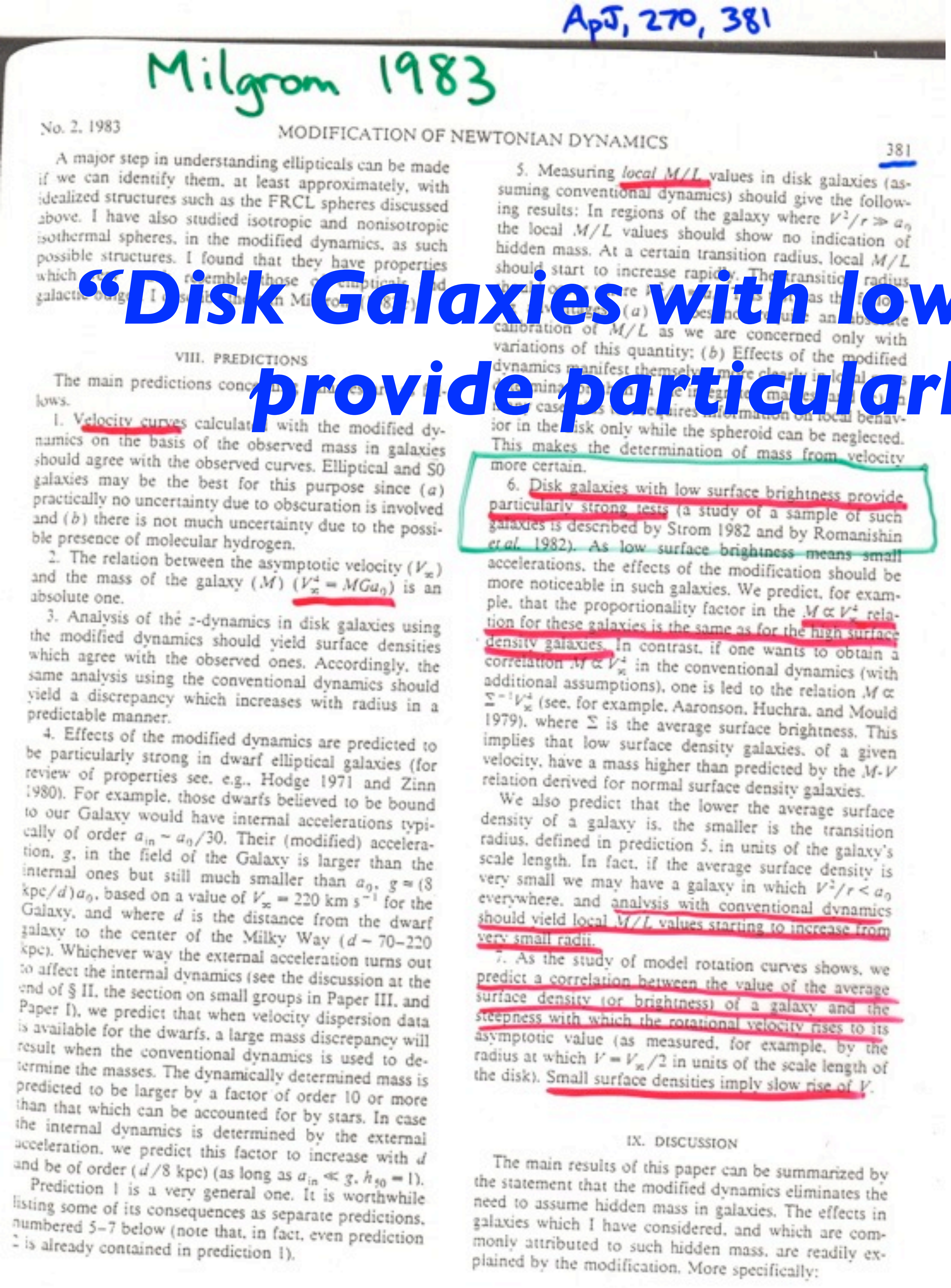
$$\mu(x) \rightarrow 1 \text{ for } x \gg 1 \qquad \mu(x) \rightarrow x \text{ for } x \ll 1 \qquad x = \frac{a}{a_0}$$

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 of ellipticals and galactic bulges. I describe them in Milgrom ([illegible]).

VIII. PREDICTIONS

The main predictions conc[illegible] 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 agree with the observed ones. Accordingly, the same analysis using 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, $g \approx (8\ \mathrm{kpc}/d)a_0$, 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 [illegible] This has the following advantages: (*a*) [illegible] 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 determinations than in integrated masses and (*c*) in many cases this 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 correlation $M \propto V_\infty^4$ in the conventional dynamics (with additional assumptions), one is led to the relation $M \propto \Sigma^{-1}V_\infty^4$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that low surface density galaxies, of a given velocity, have a mass higher than predicted by the M-V 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, defined in prediction 5, in units of the galaxy's scale length. In fact, if the 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.

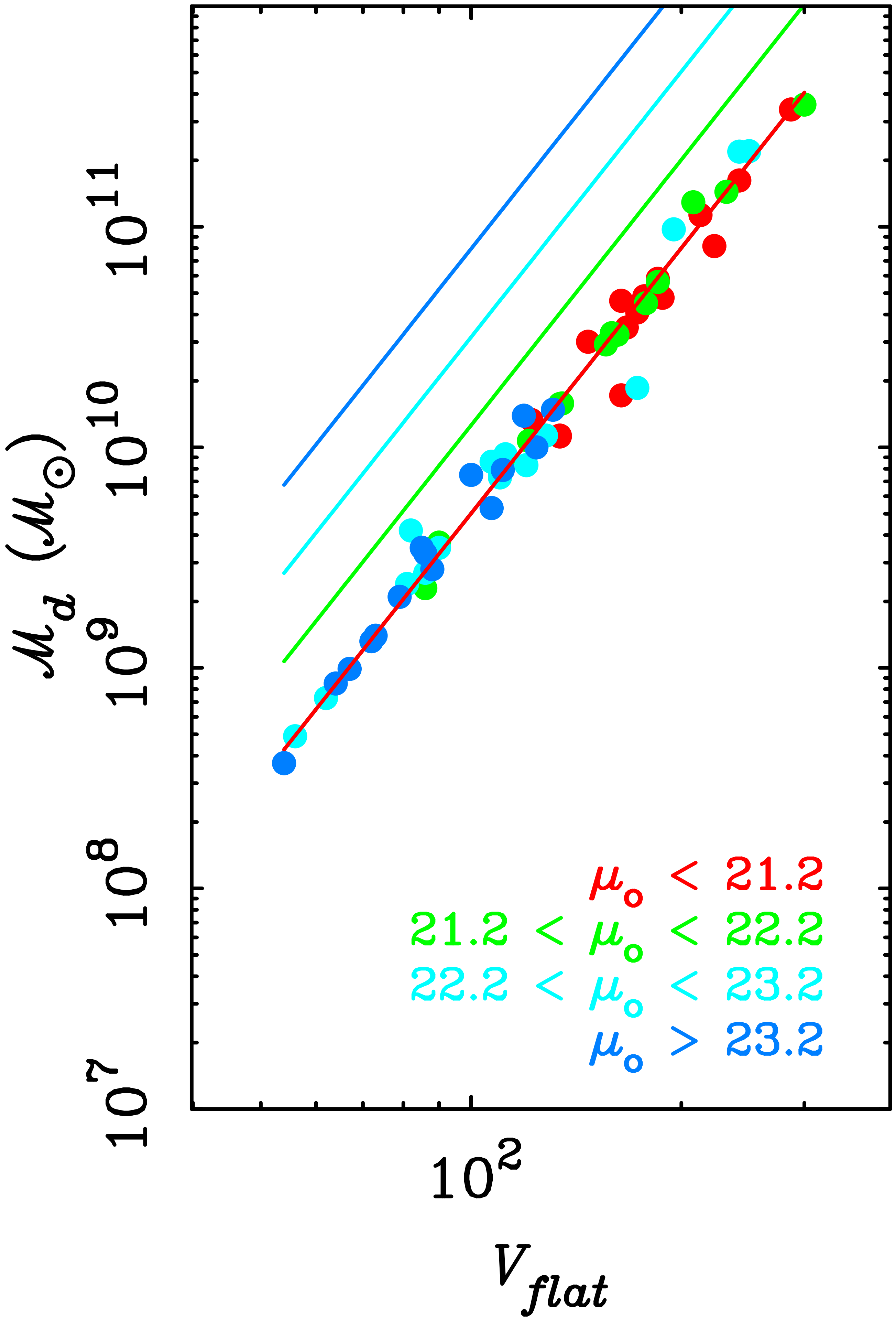
7. As the study of model rotation curves shows, we predict a correlation between the value of the average surface density (or brightness) of a galaxy and the steepness with which the rotational velocity rises to its asymptotic value (as measured, for example, by the radius at which $V = V_\infty/2$ in 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:

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

- 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

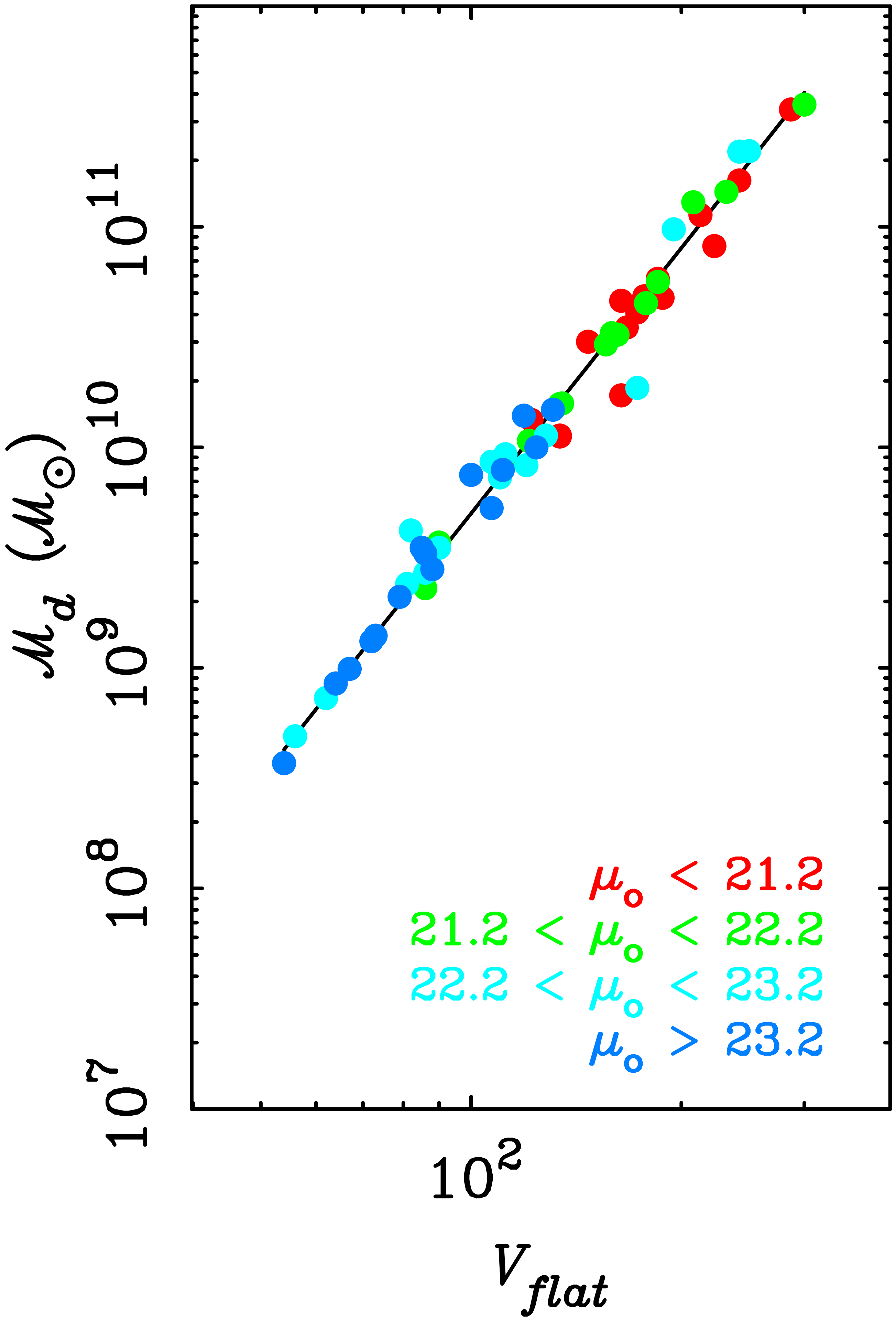


My prediction

Newton said

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

so galaxies of fixed mass should shift off the TF reln depending on their radius / surface brightness



MOND predictions

- The Tully-Fisher Relation
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  - ✓ 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
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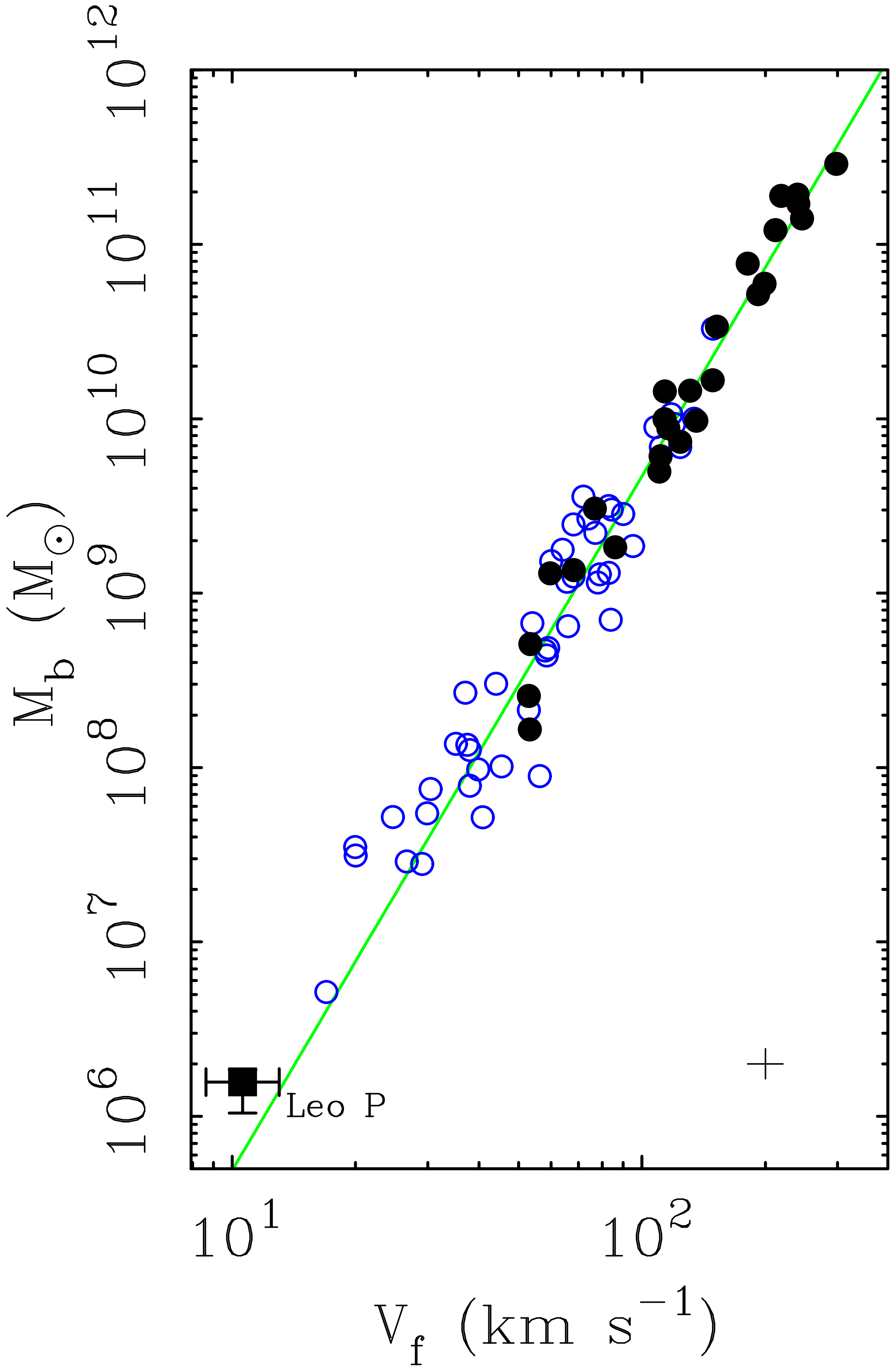
Baryonic Tully-Fisher relation



M_* from near-IR observations + population synthesis models

● **star dominated**

$M_* > M_g$

○ **gas dominated**

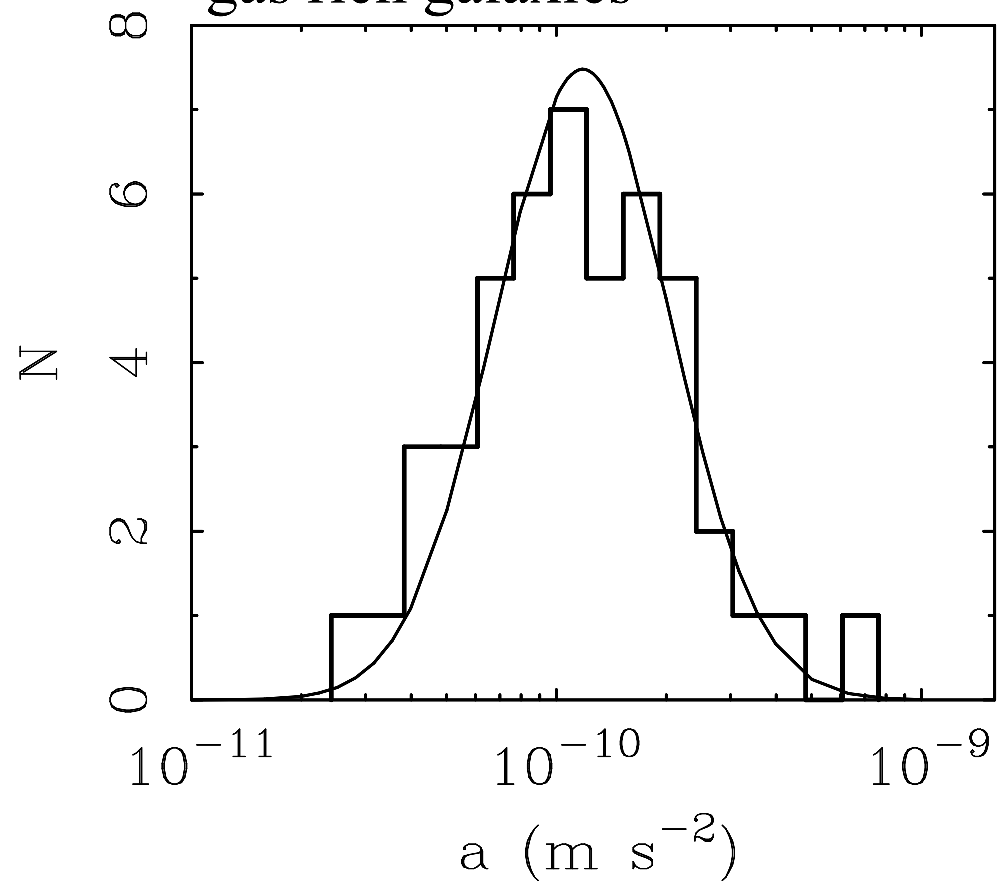
$M_* < M_g$

M_g from HI observations

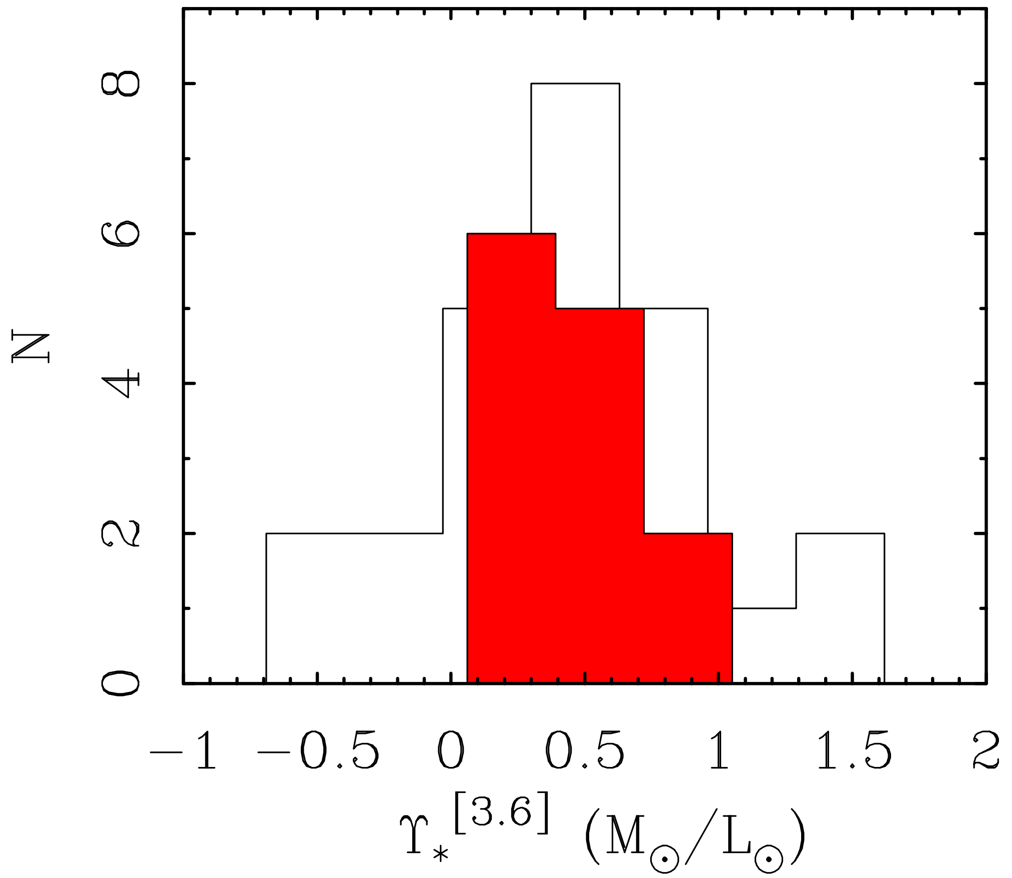
MOND

no free parameters

The data specify a particular acceleration scale: $\mathrm{a} = \frac{V_f^4}{G M_b}$



gas rich galaxies

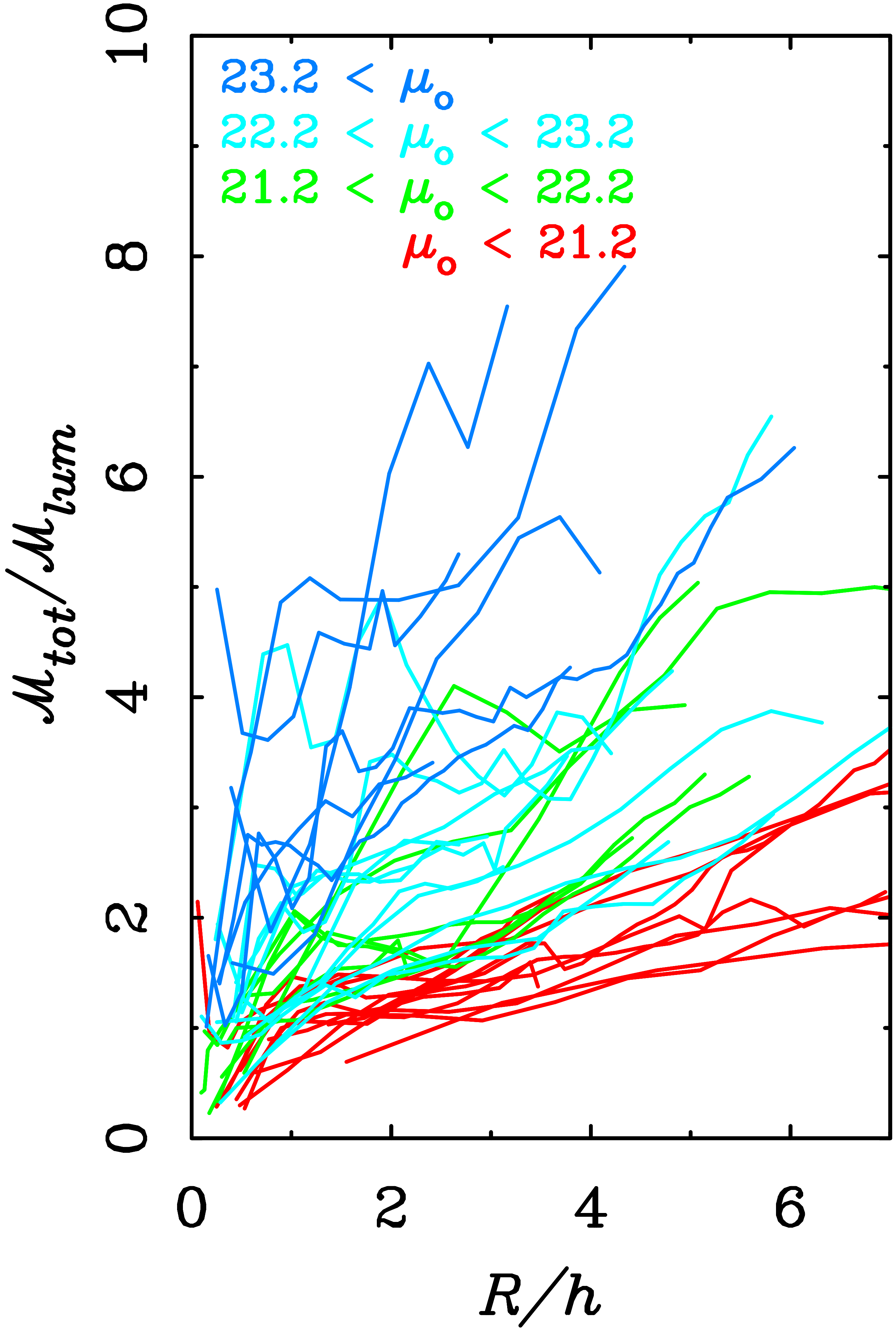


star dominated galaxies

[3.6] mass-to-light ratios

histogram: data
line: distribution expected from observational uncertainties.

The data are consistent with zero intrinsic scatter (< 0.15 dex in mass).



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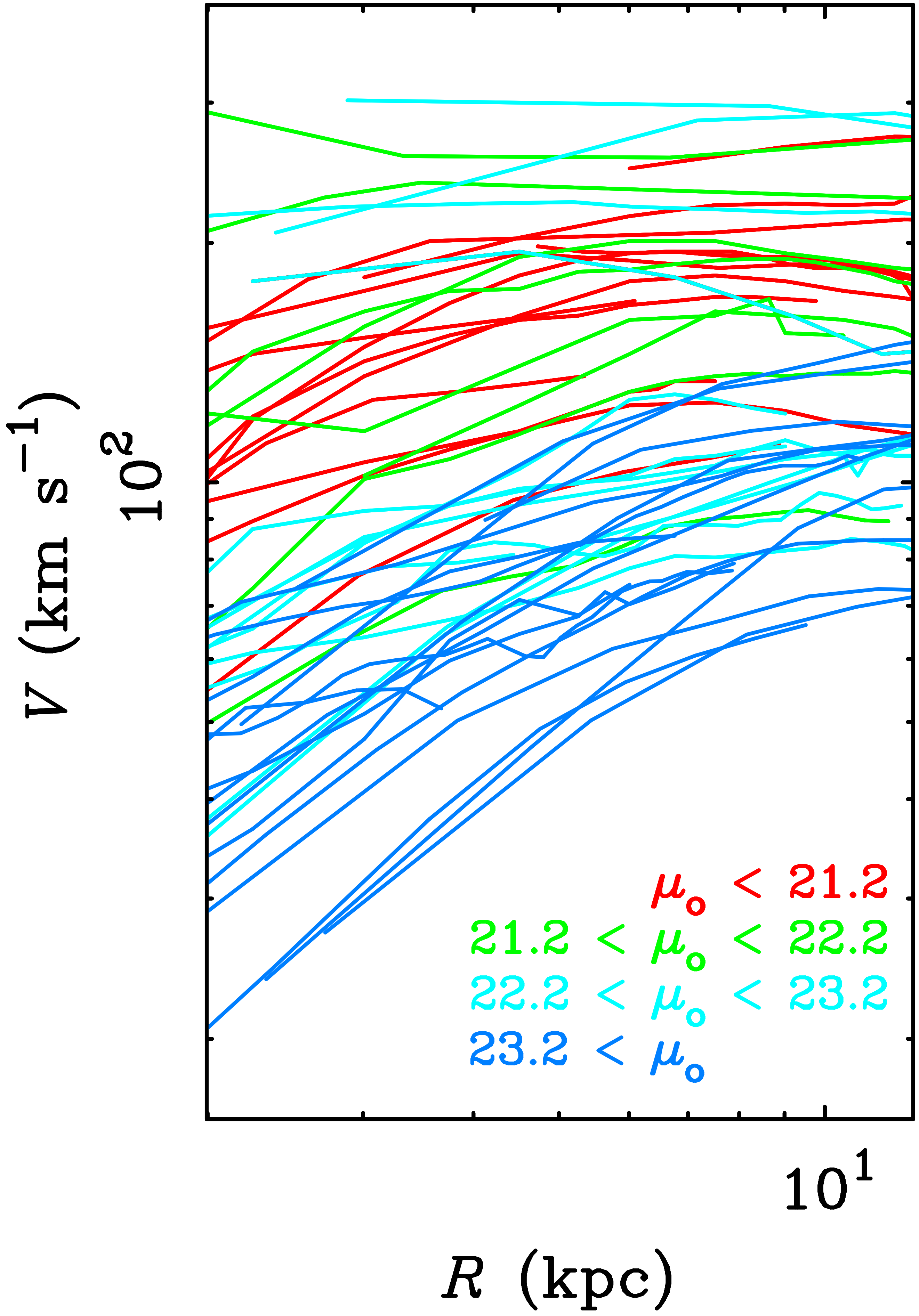

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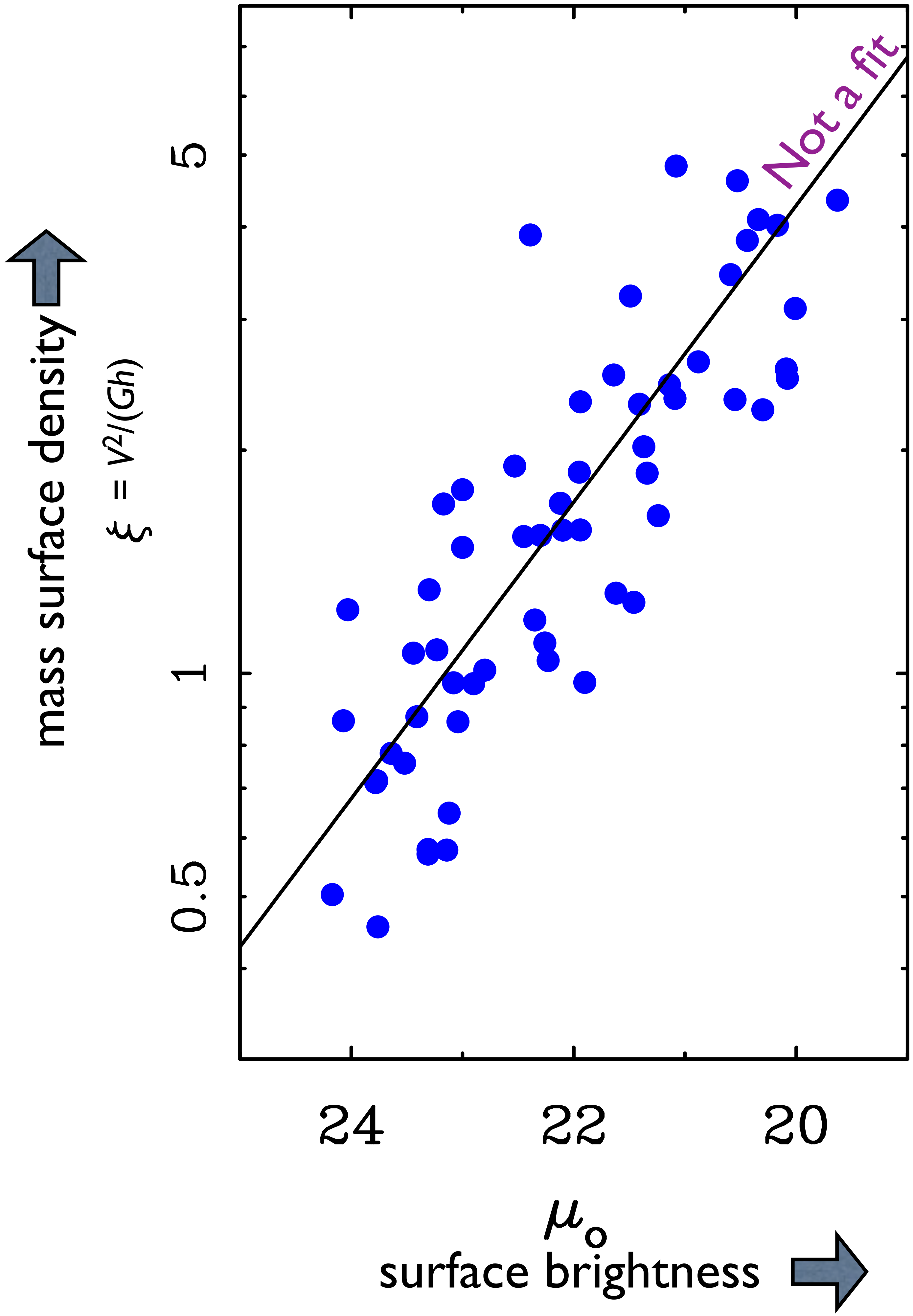

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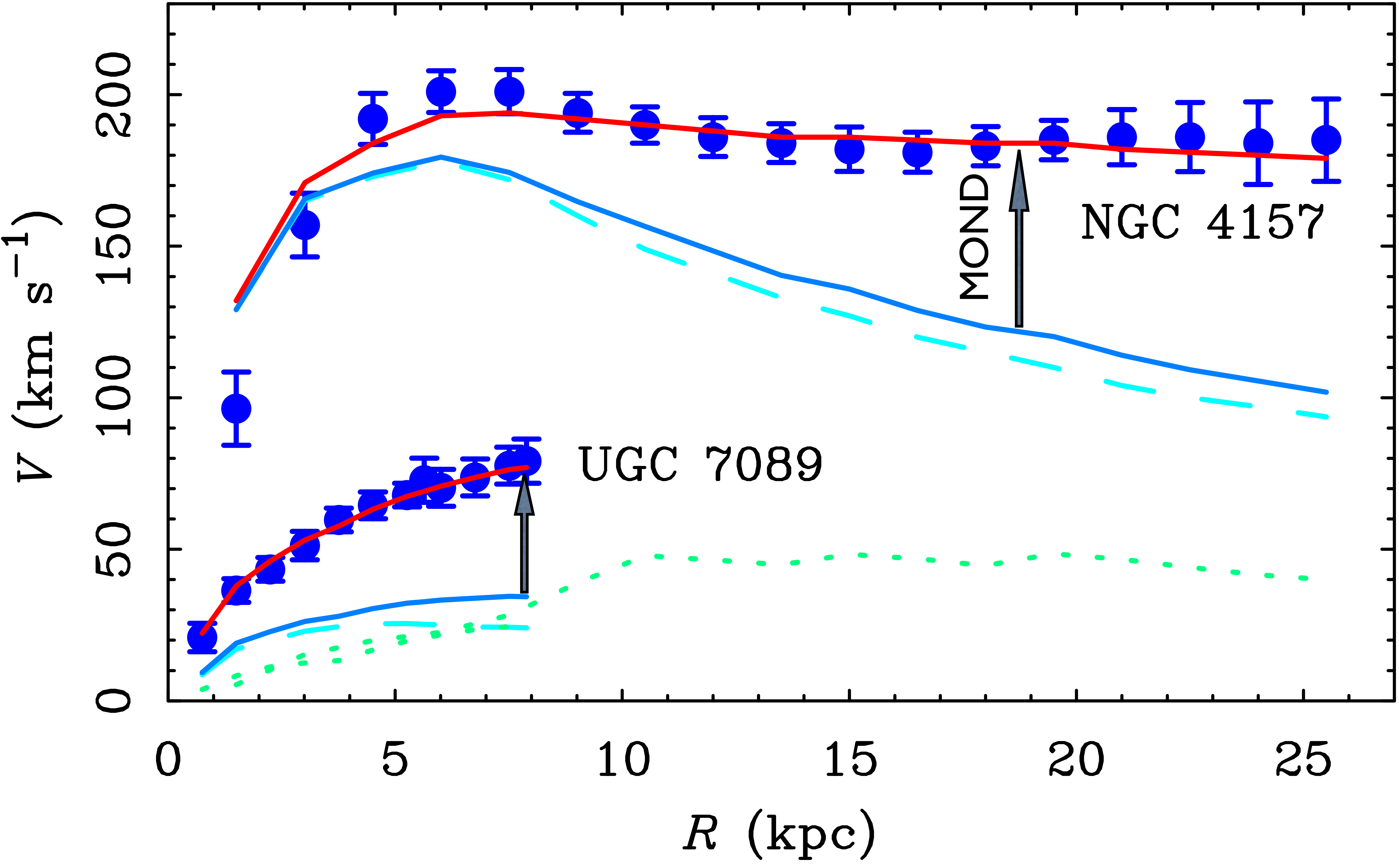
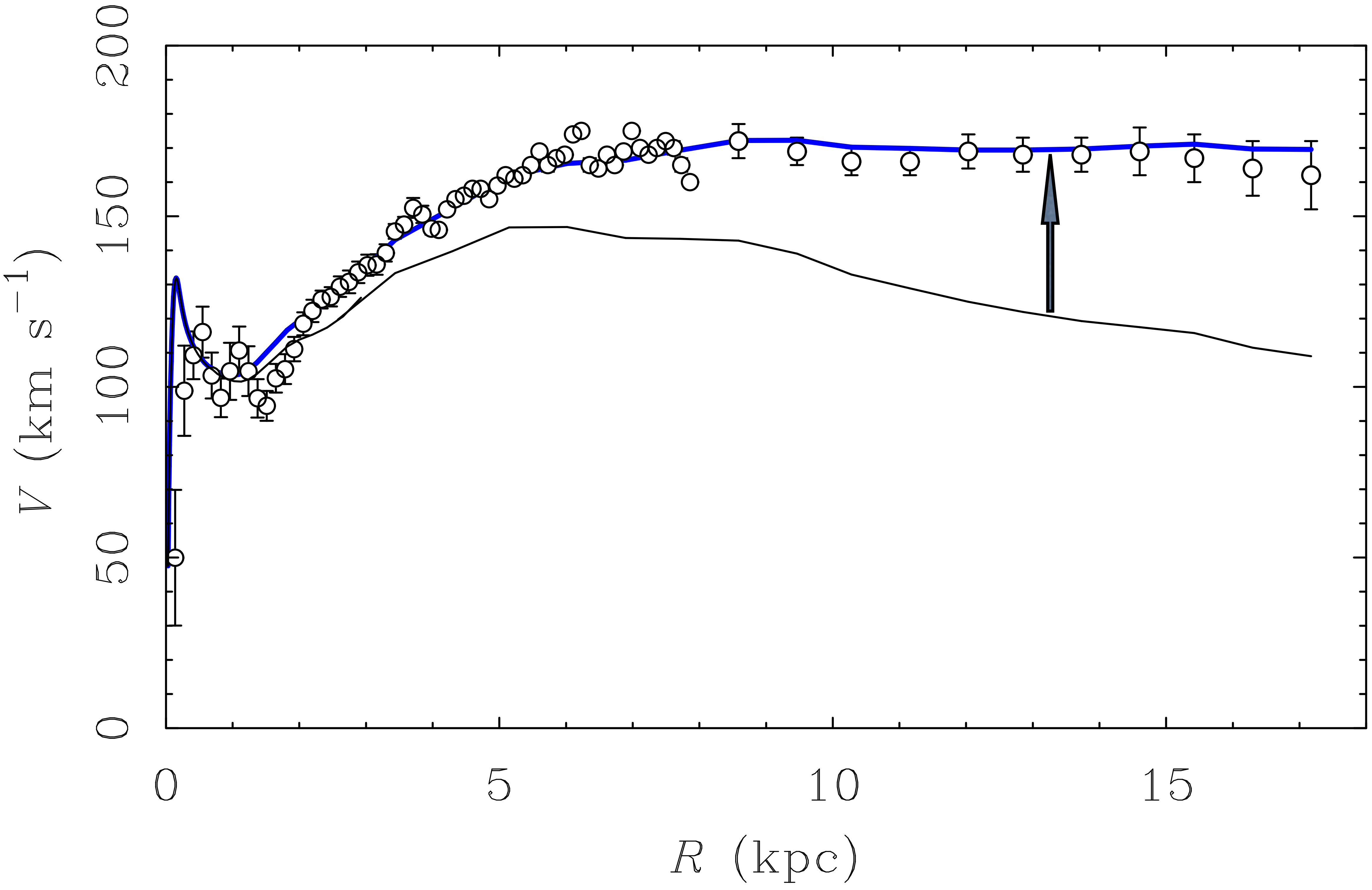
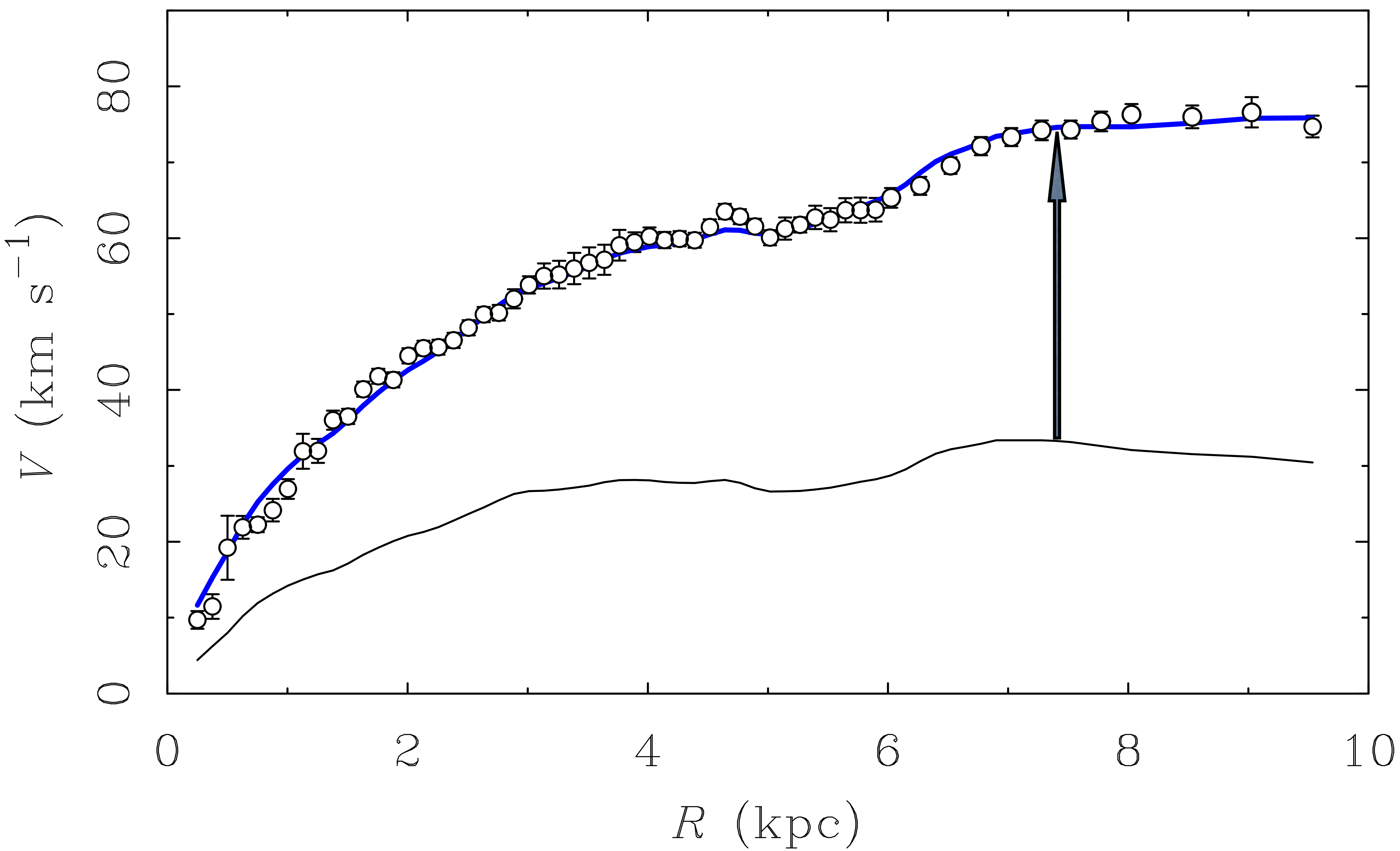

V (km s^{-1})
R (kpc)
0
50
100
150
200
0
5
10
15
20
25
NGC 4157
UGC 7089
MOND

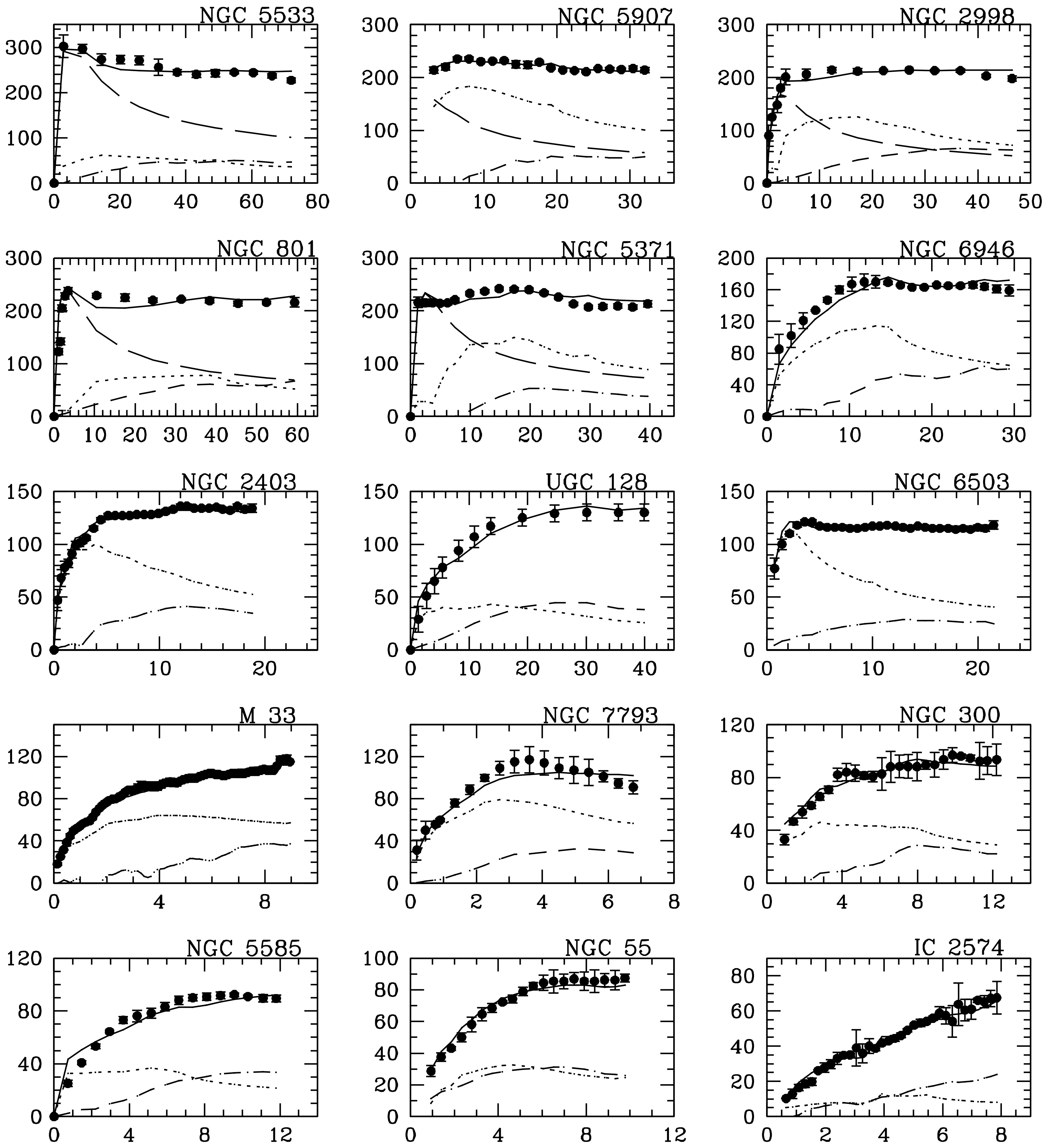
NGC 6946

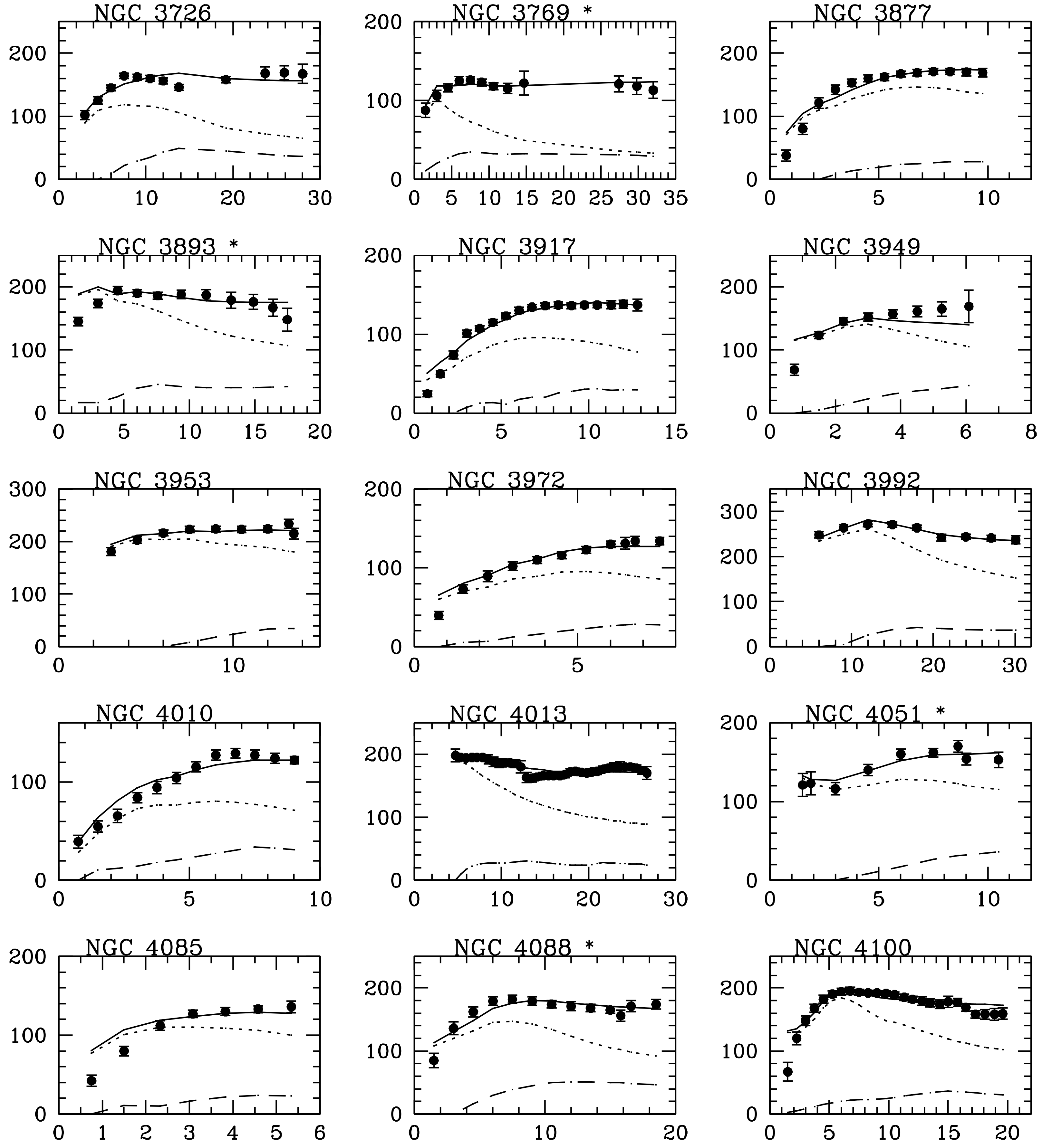


NGC 1560



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




NGC 3726
NGC 3769 *
NGC 3877
NGC 3893 *
NGC 3917
NGC 3949
NGC 3953
NGC 3972
NGC 3992
NGC 4010
NGC 4013
NGC 4051 *
NGC 4085
NGC 4088 *
NGC 4100
0
100
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25
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6
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1
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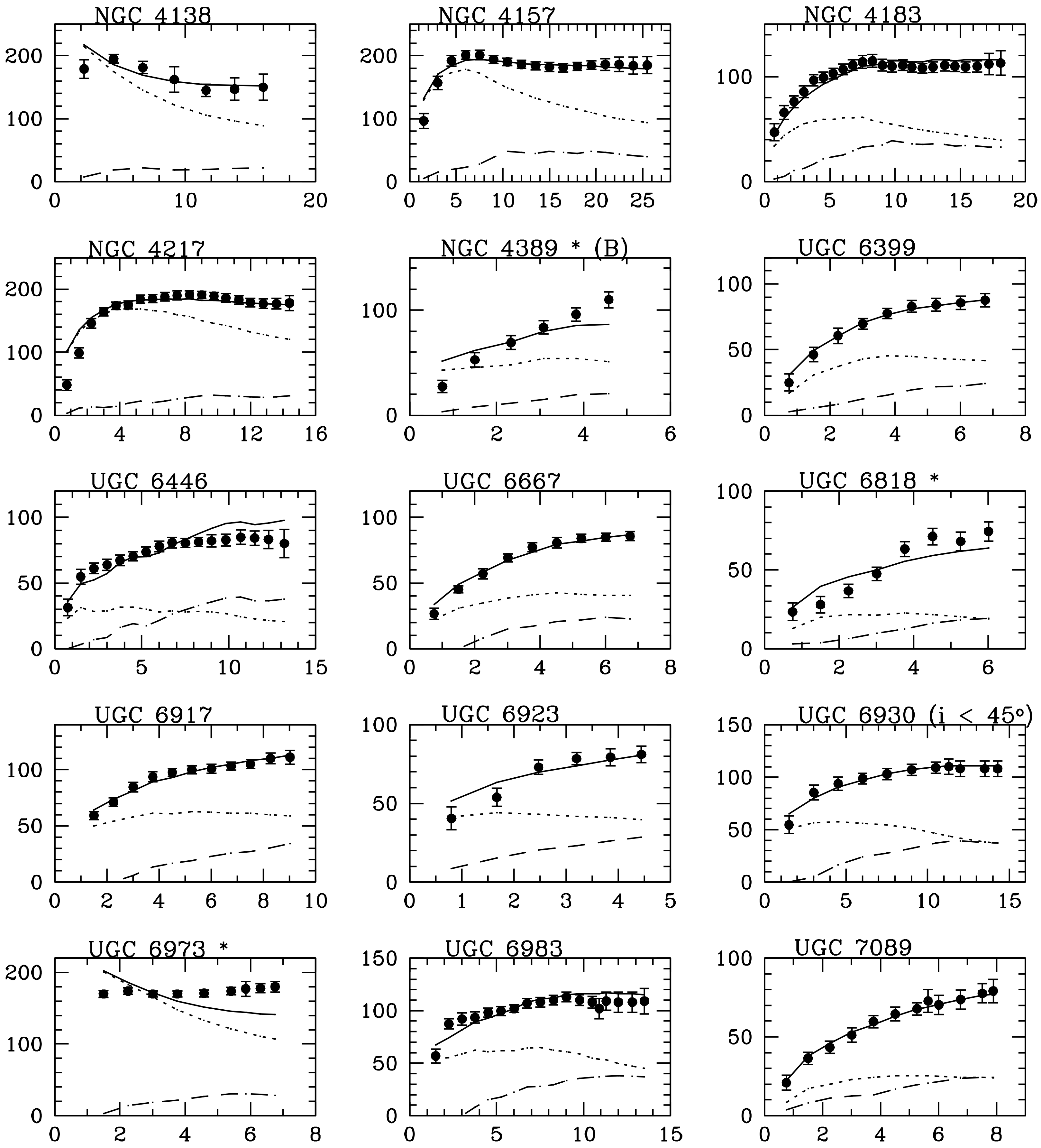
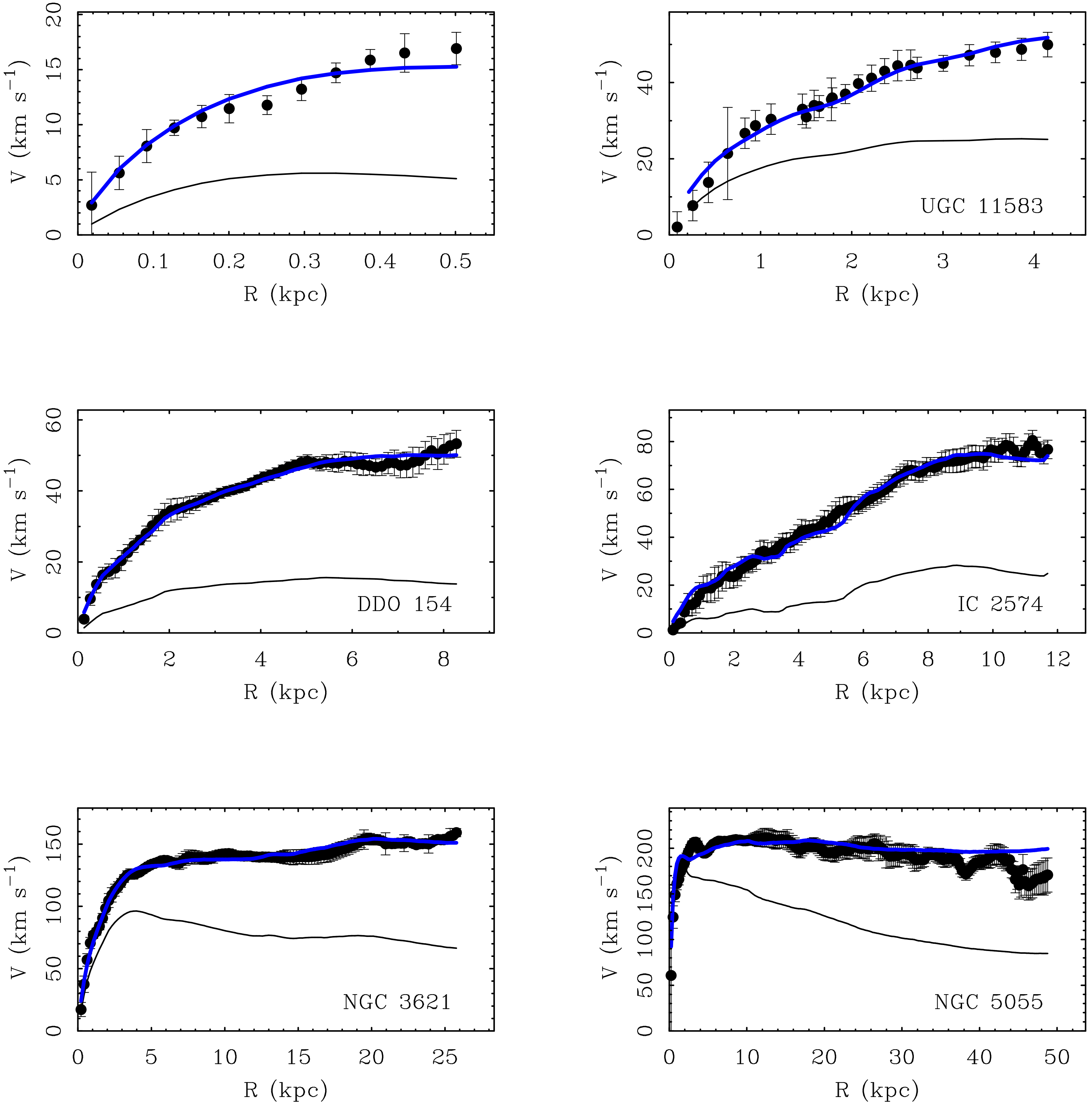
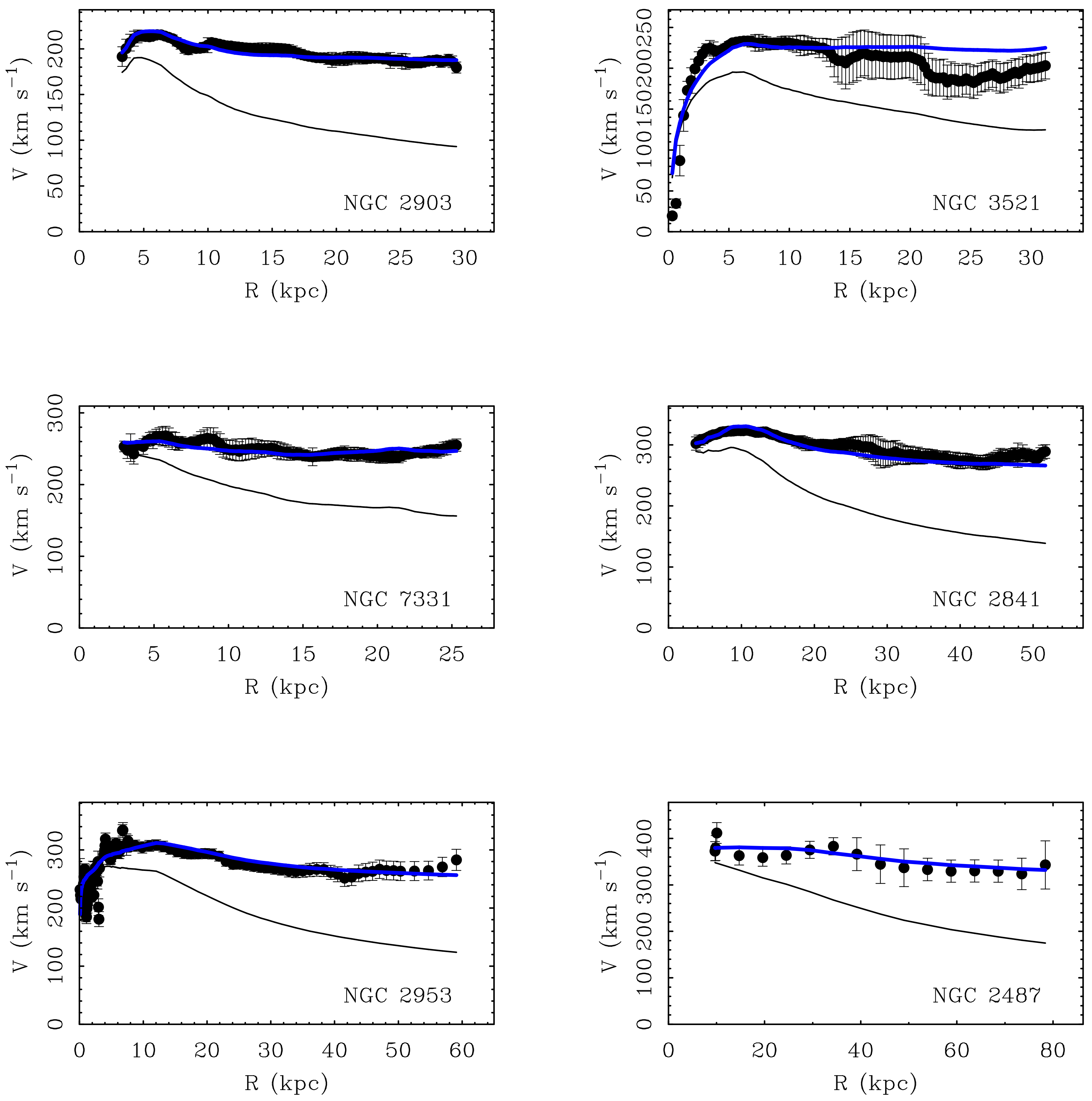
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



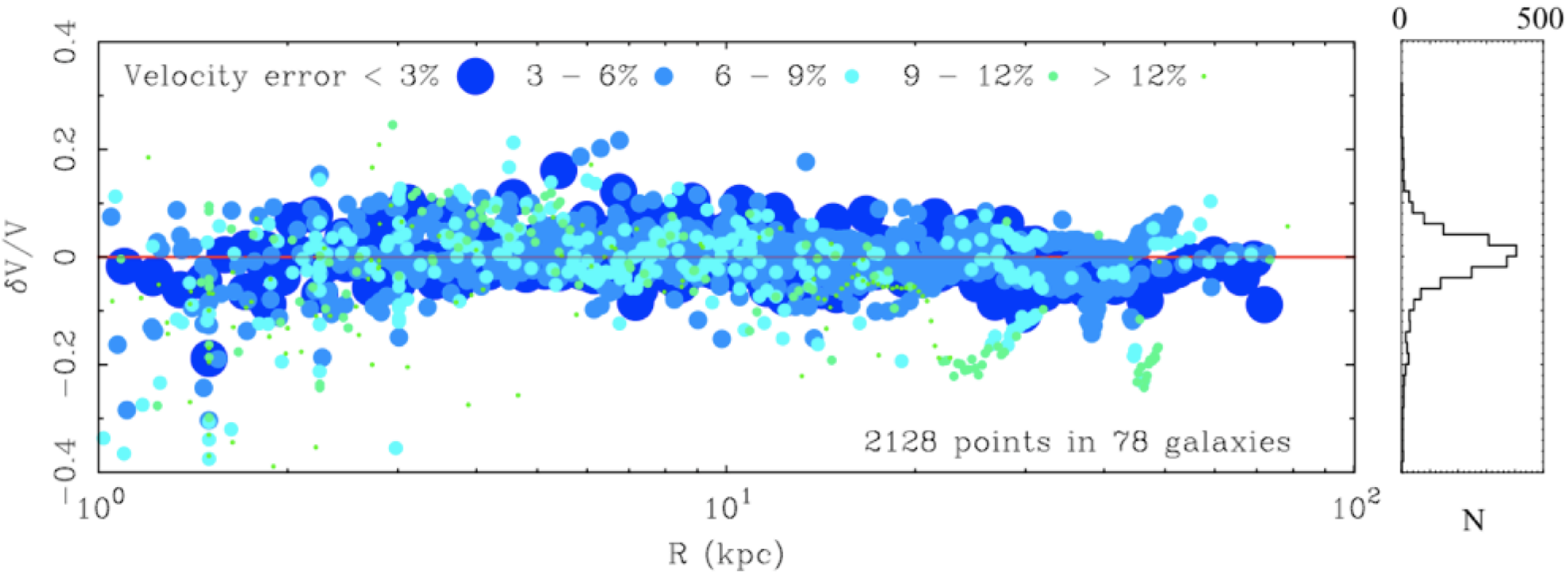
Famaey & McGaugh 2011



Famaey & McGaugh 2011

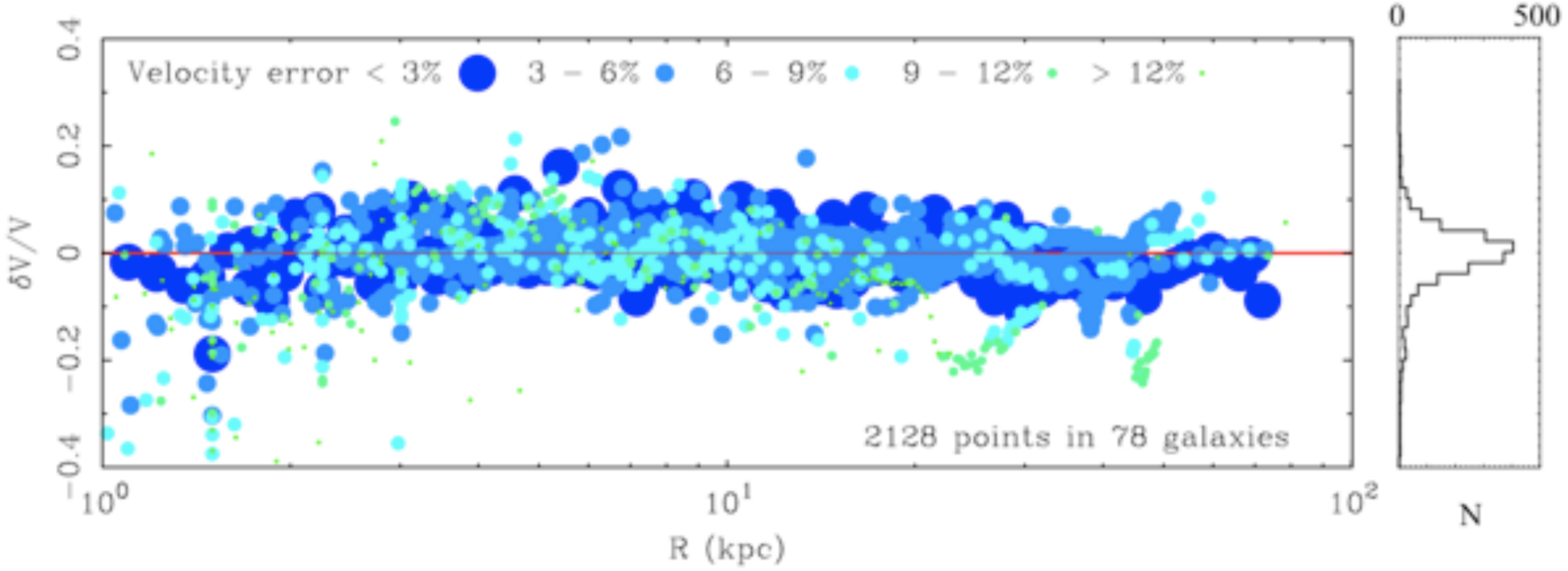


Residuals of MOND fits

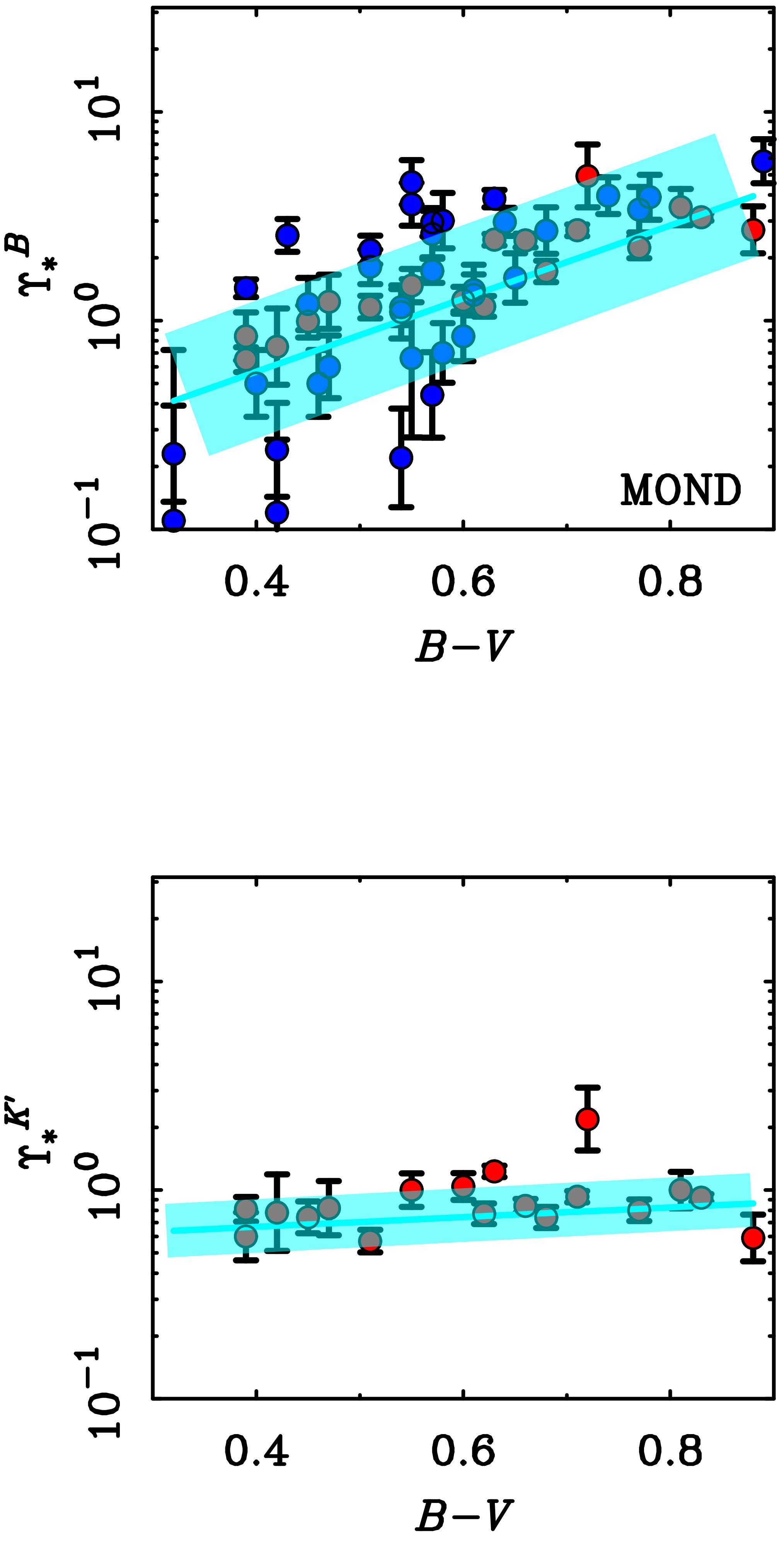


The data are consistent with a single effective force law in disk galaxies.

MOND predictions

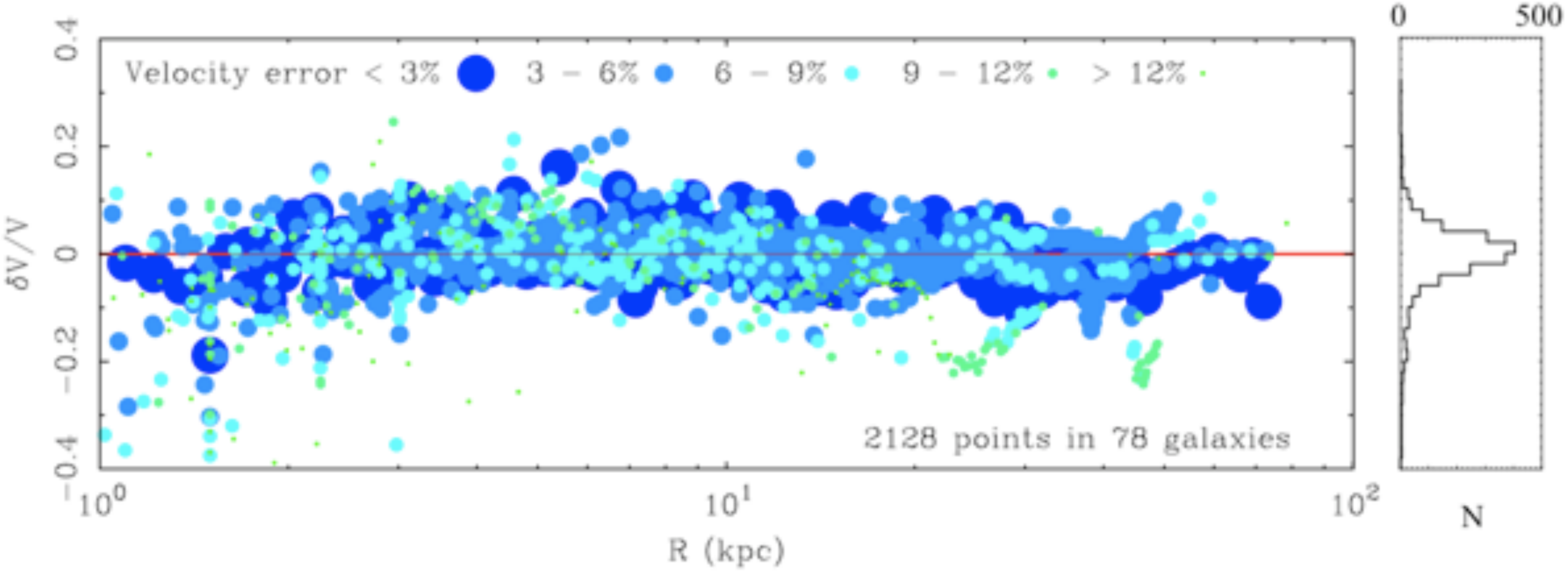


- The Tully-Fisher Relation
  - ✔ Slope = 4
  - ✔ Normalization = $1/(a_0G)$
  - ✔ Fundamentally a relation between Disk Mass and V_{flat}
  - ✔ No Dependence on Surface Brightness
- ✔ Dependence of conventional M/L on radius and surface brightness
- ✔ Rotation Curve Shapes
- ✔ Surface Density ~ Surface Brightness
- ✔ Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios



Line: stellar population model
(mean expectation)

MOND predictions



- The Tully-Fisher Relation
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  - ✓ Fundamentally a relation between Disk Mass and V_{flat}
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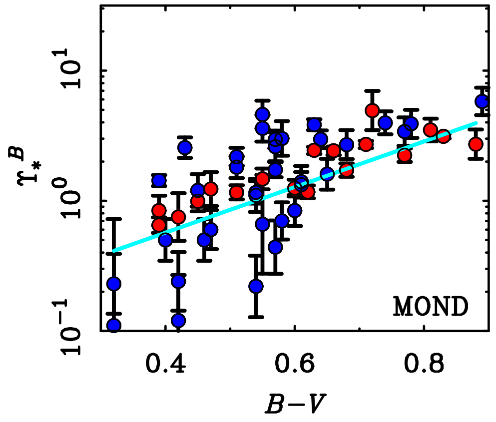
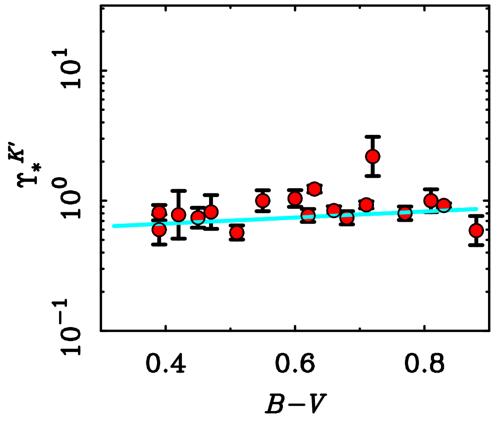
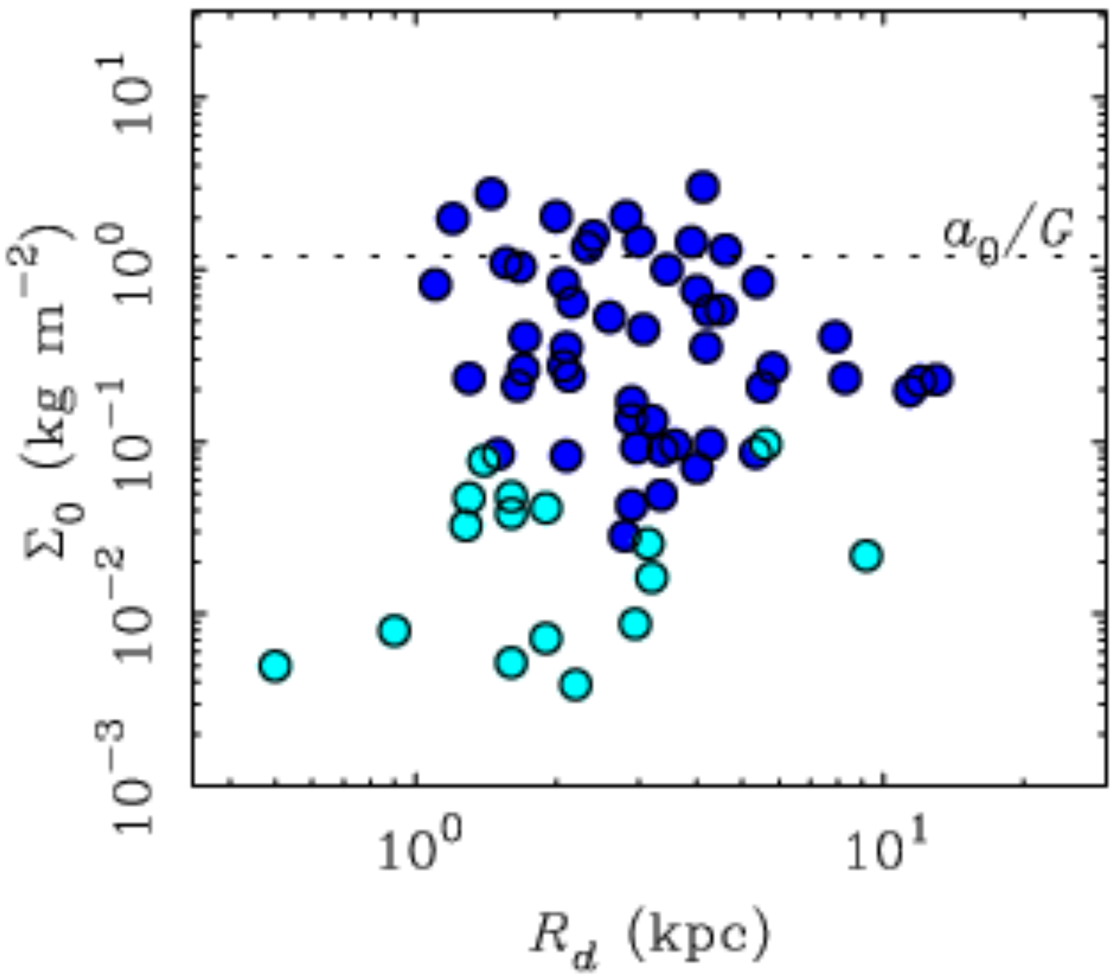


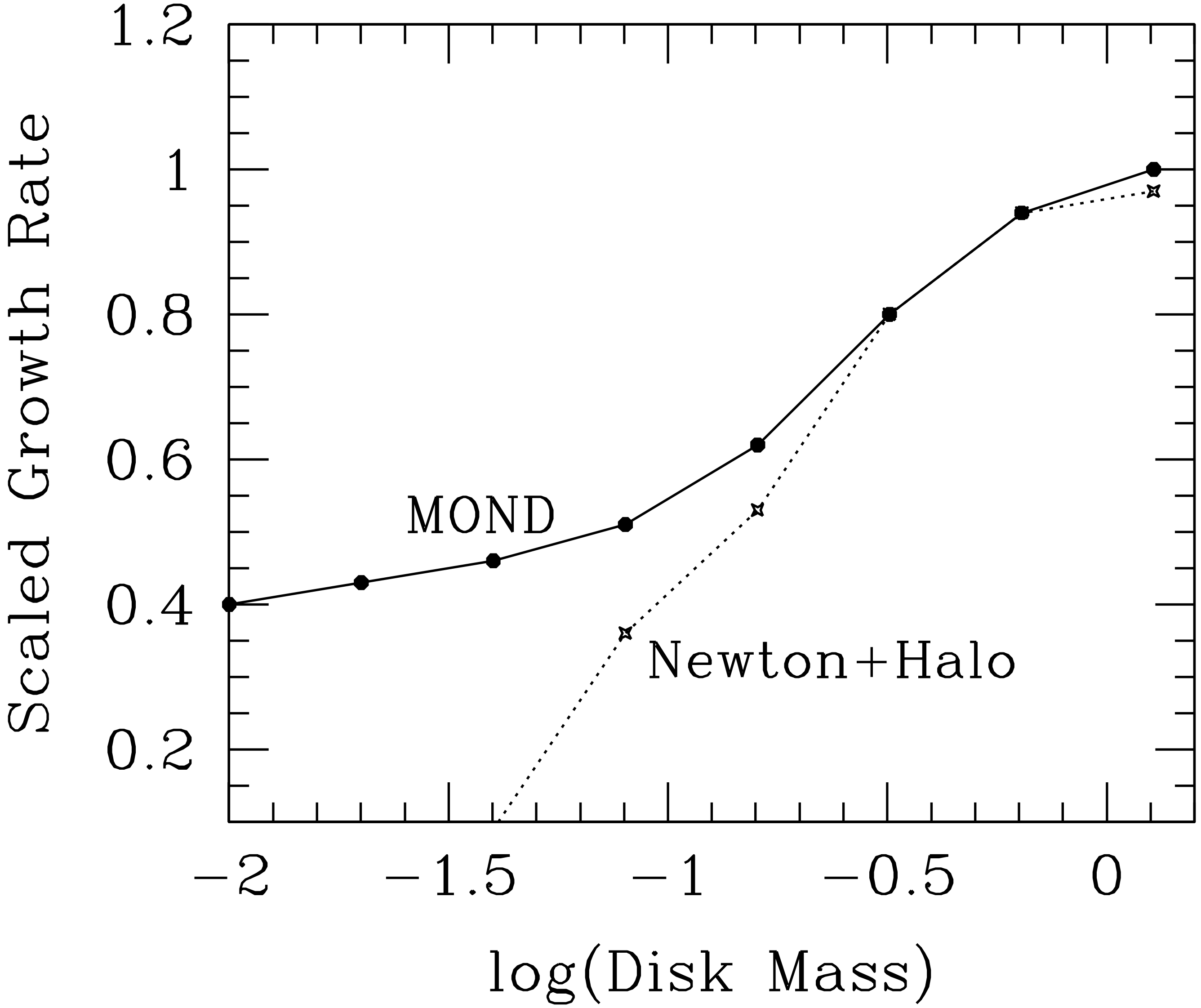


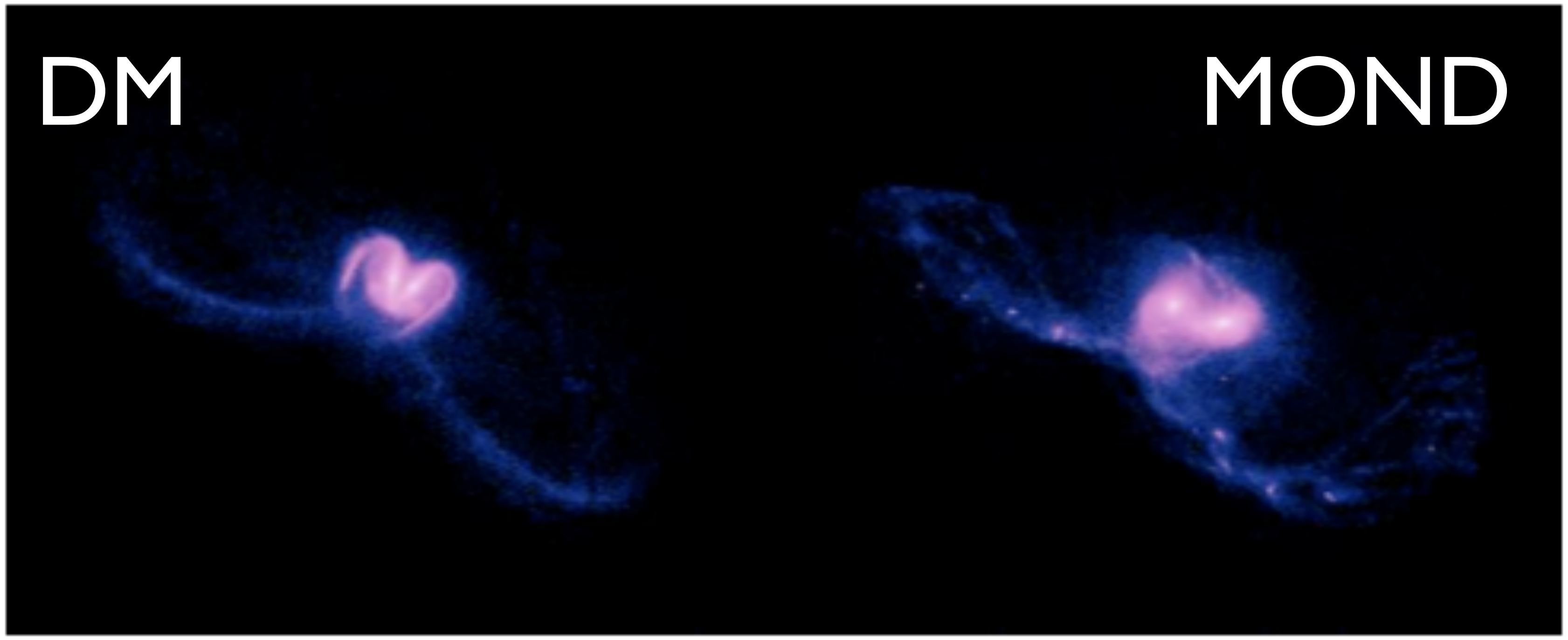
What else?

Disk Stability



The maximum surface density
of disks is set by the MOND scale

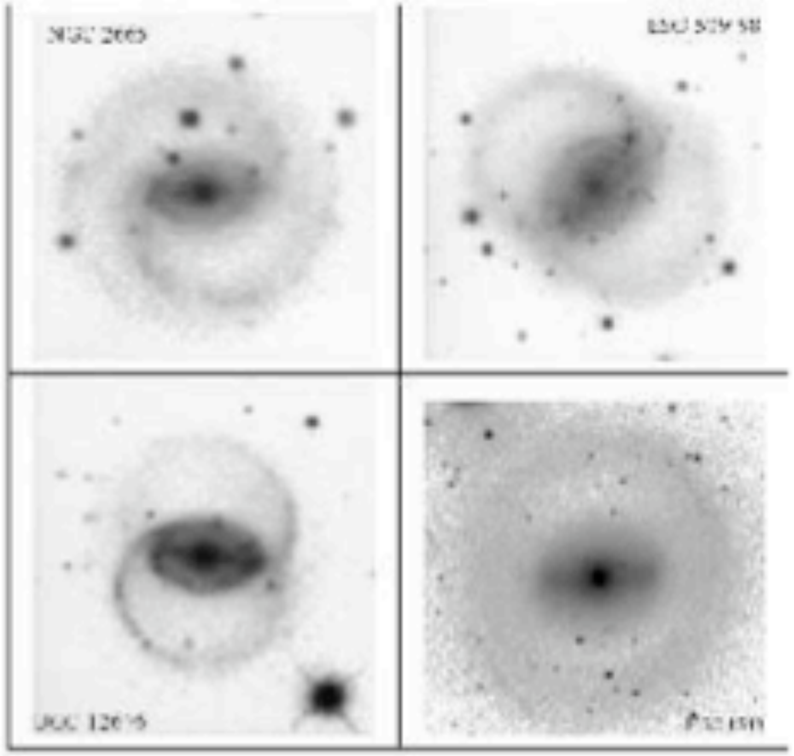




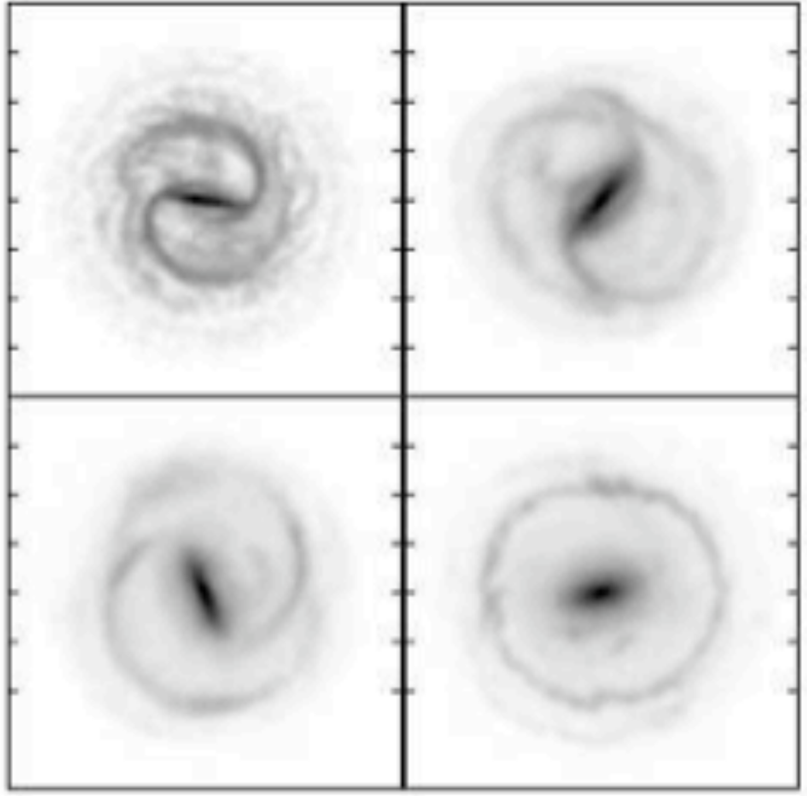
Tiret & Combes

Fig. 5. Simulations of the Antennae galaxies in the DM model (left) and MOND model(right).

real galaxies

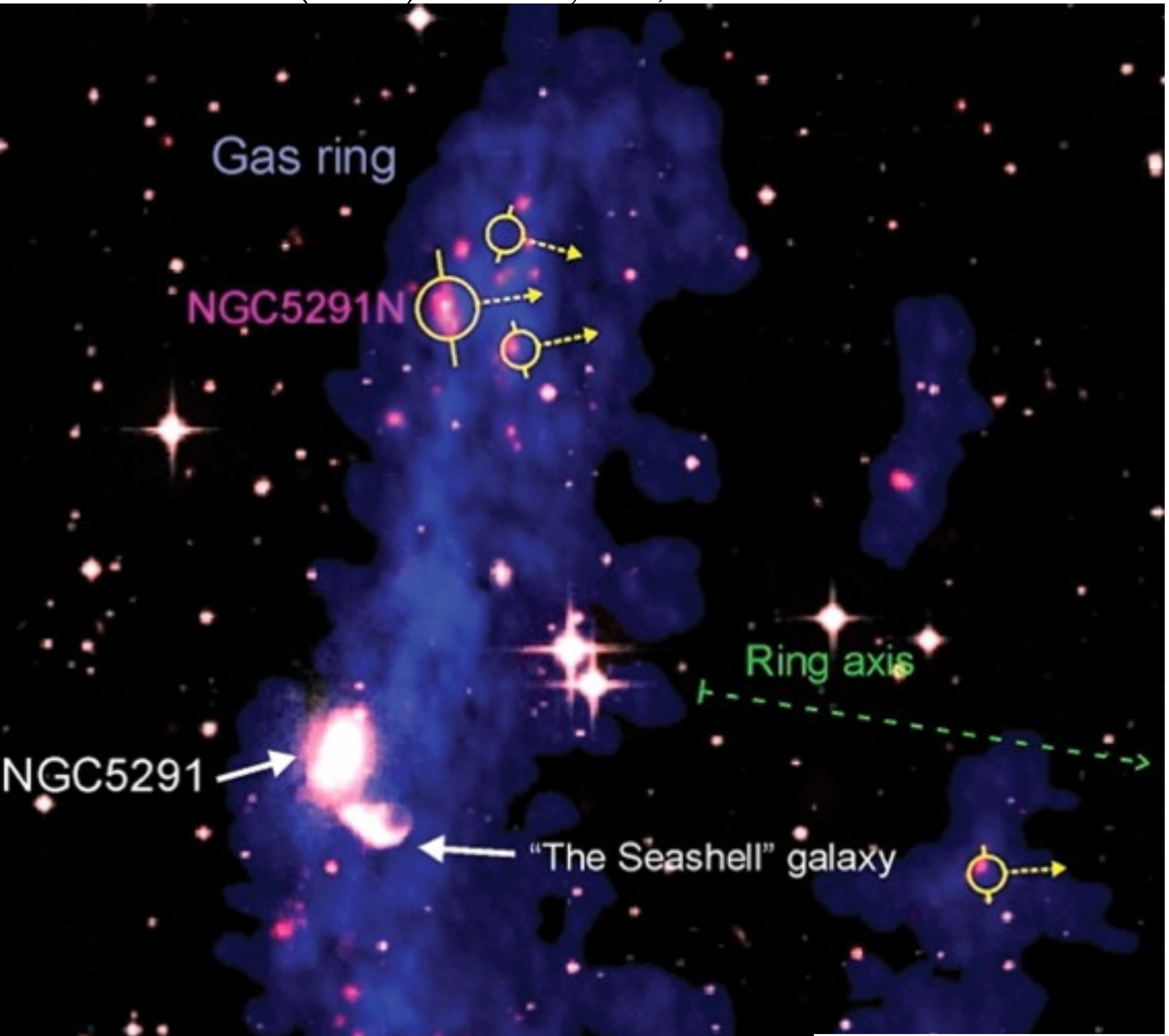


MOND simulation



. Several examples showing the morphological structures of NGC 2665, ESO 509-98, UGC 12646 and NGC 1543 anel) compared to simulated galaxies in MOND (bottom panel). Rings and pseudo-rings structures are well uced with modified gravity.

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

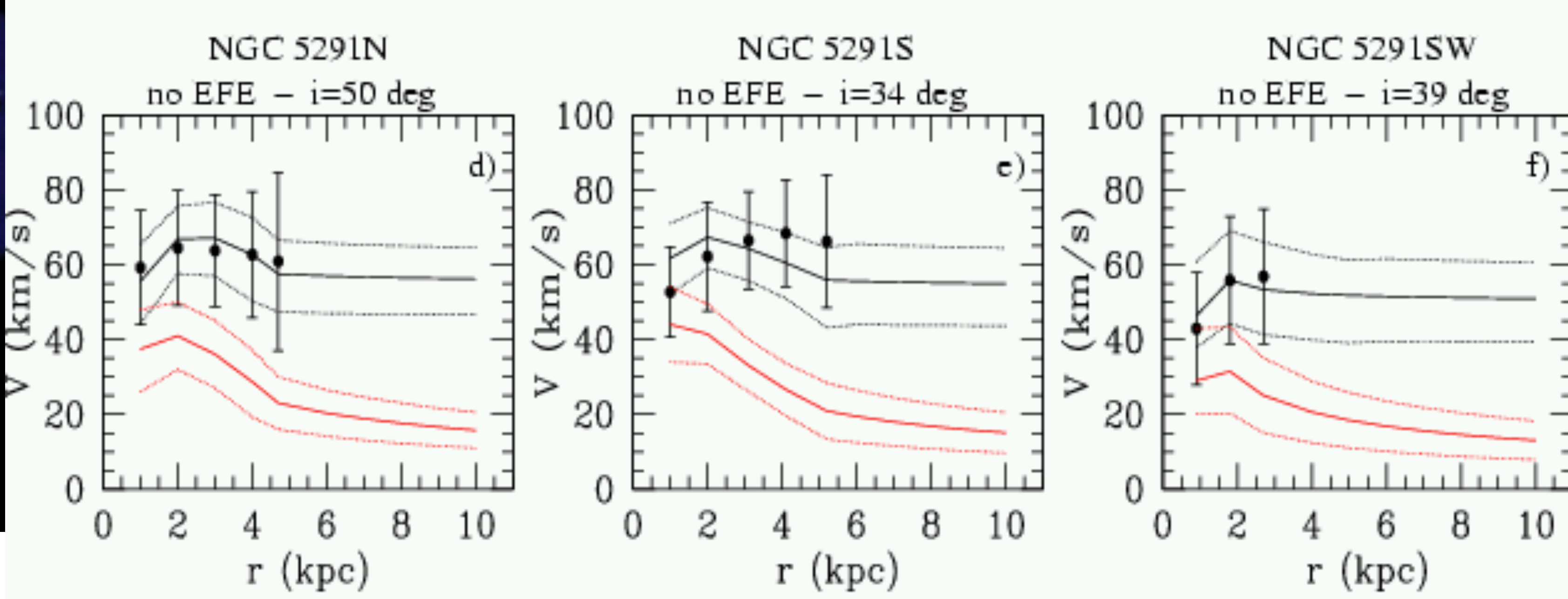


Tidal dwarfs

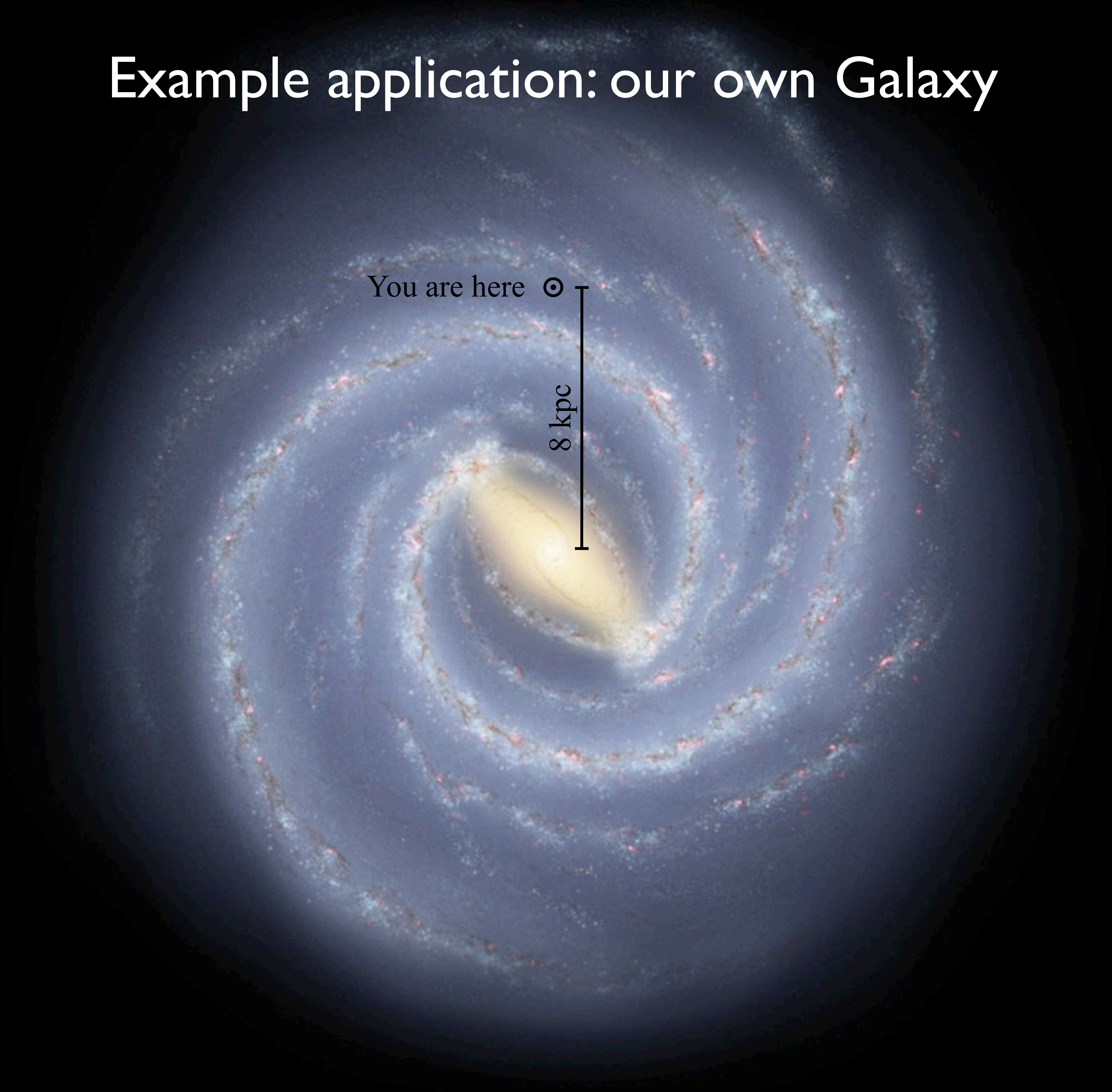
Should be devoid of dark matter in LCDM

Must evince a mass discrepancy in MOND

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

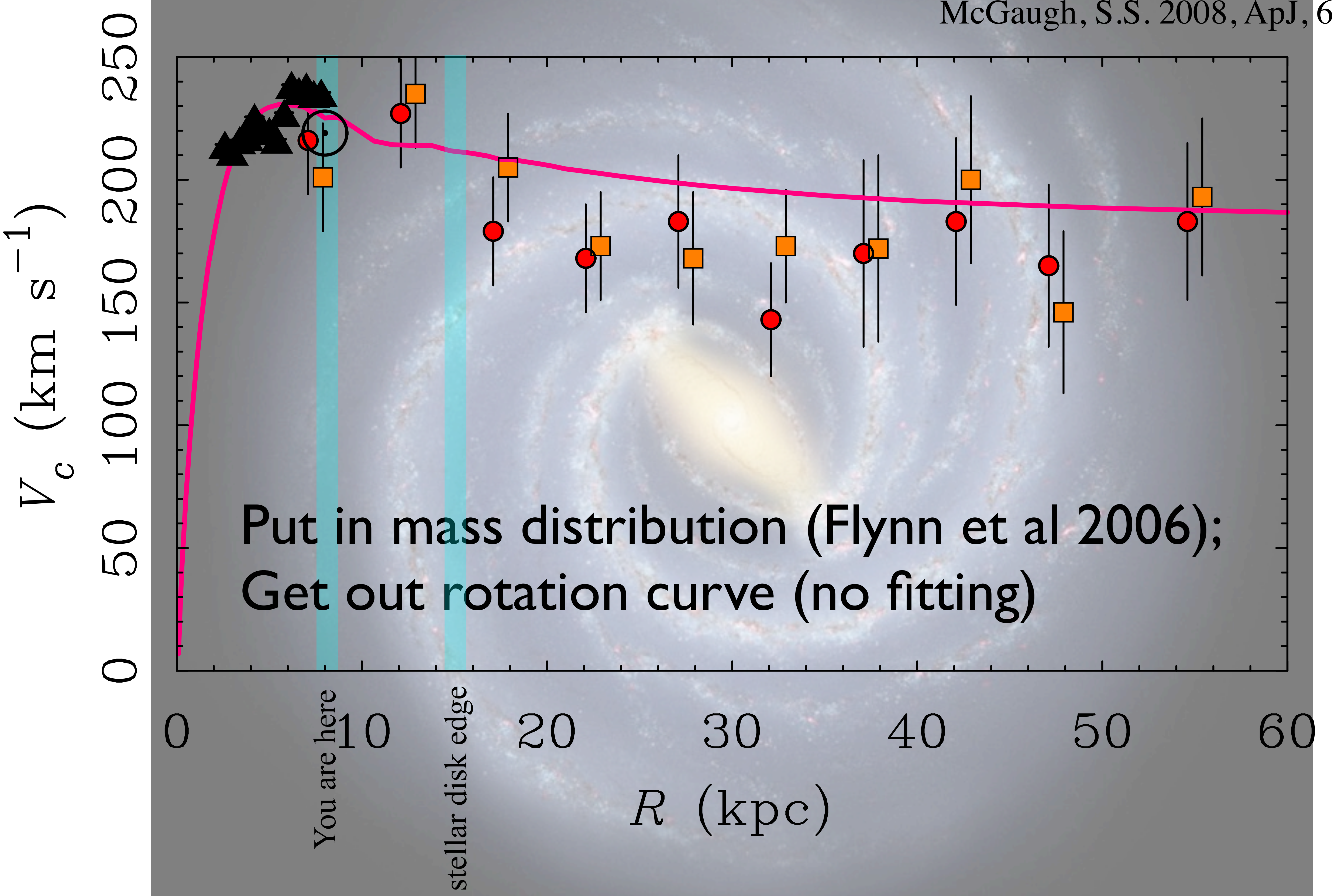


Example application: our own Galaxy



Example application: our own Galaxy

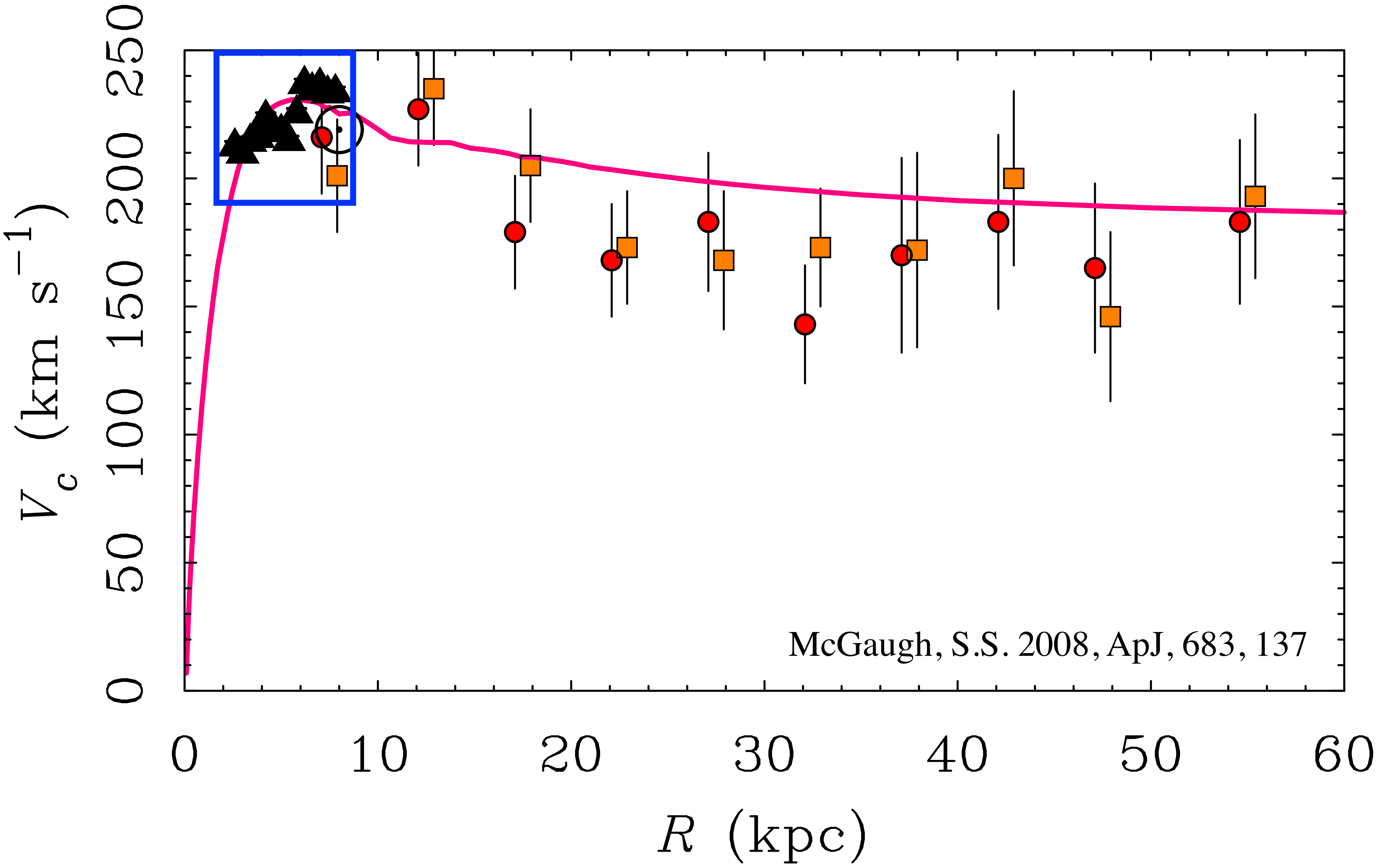
McGaugh, S.S. 2008, ApJ, 683, 137



Put in mass distribution (Flynn et al 2006);
Get out rotation curve (no fitting)

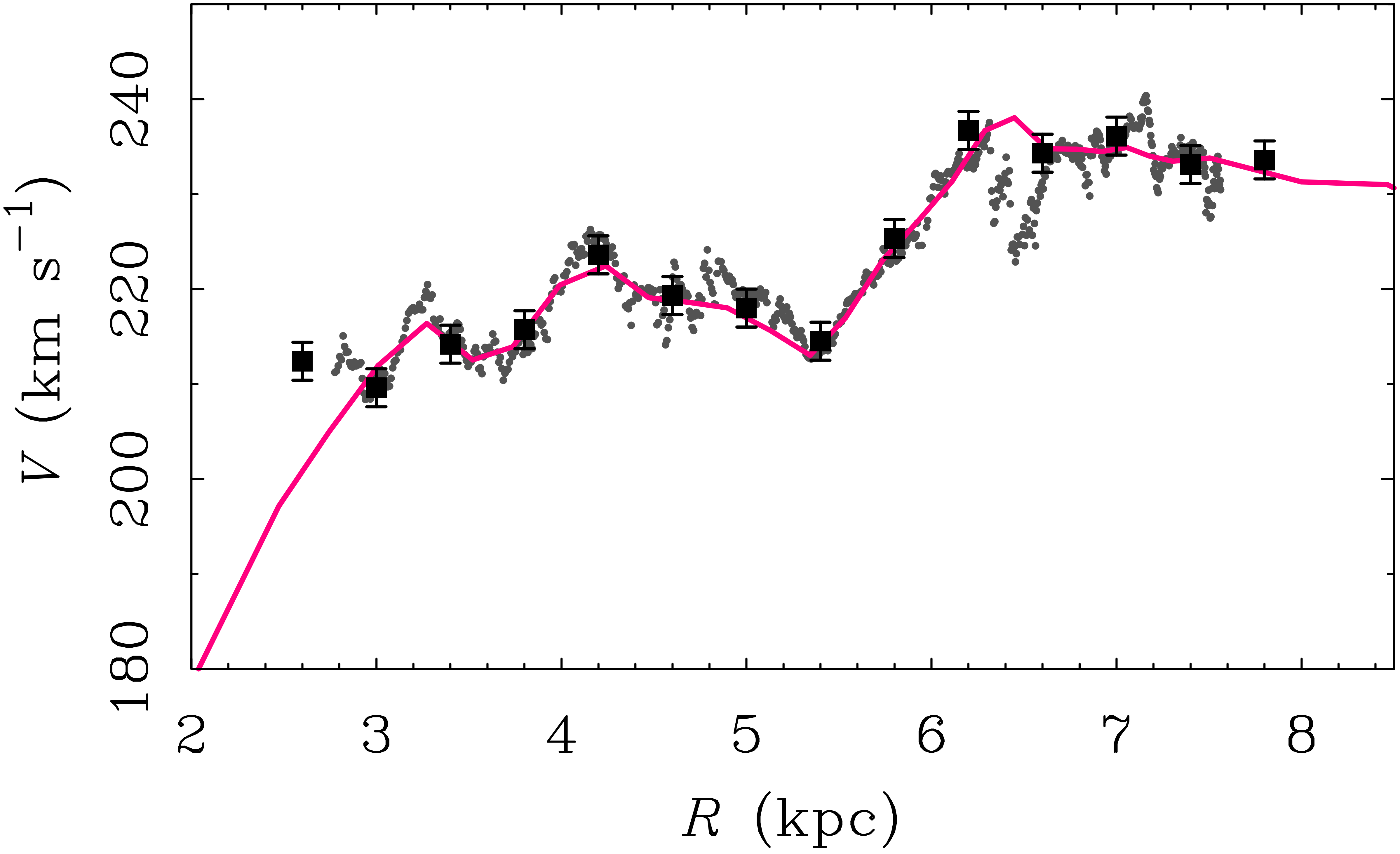
Luna et al. (2006: **CO**); McClure-Griffiths & Dickey (2007: **HI**); Xue et al. (2008: **BHB**)

Can we do better fitting the details of the terminal velocity curve?

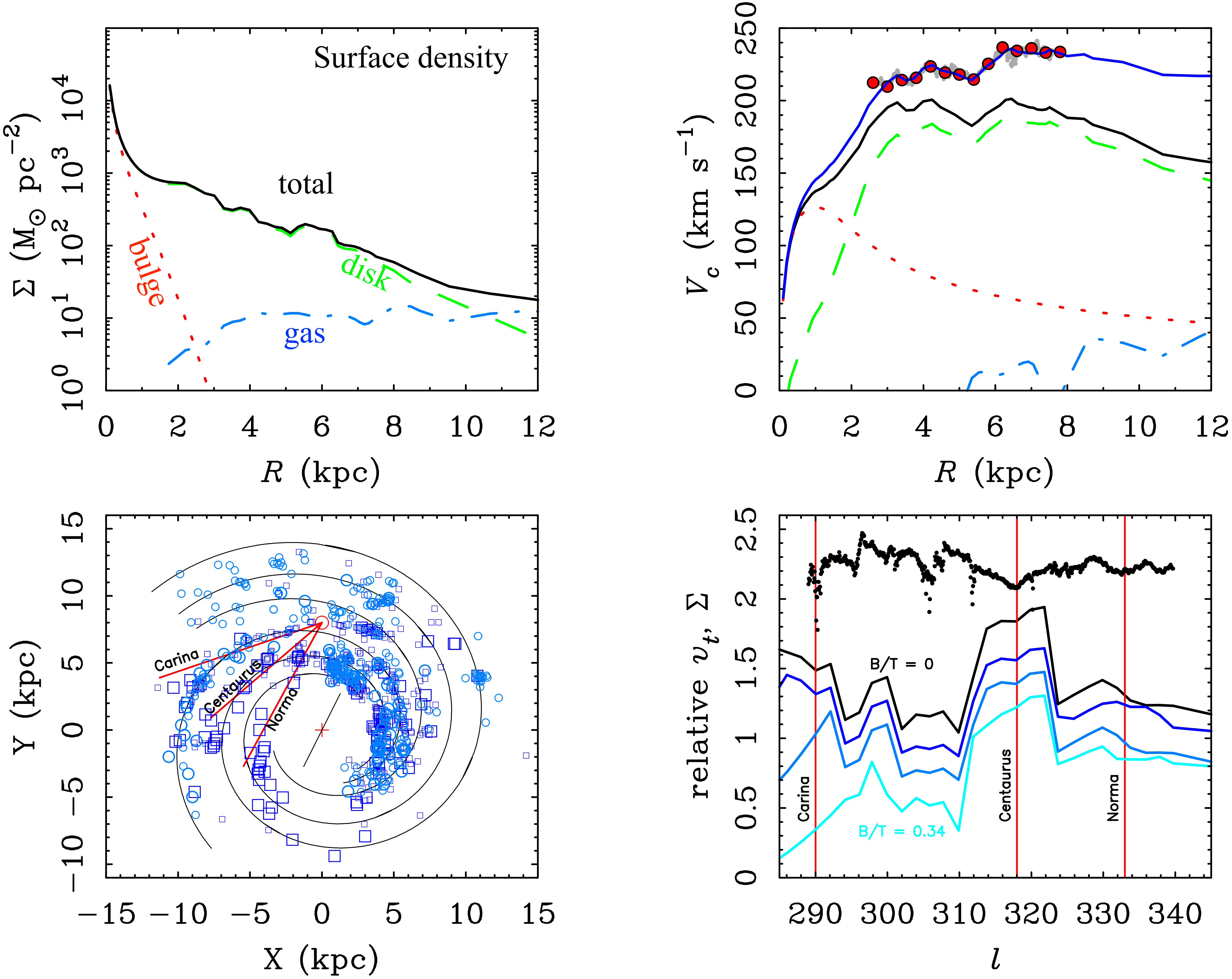


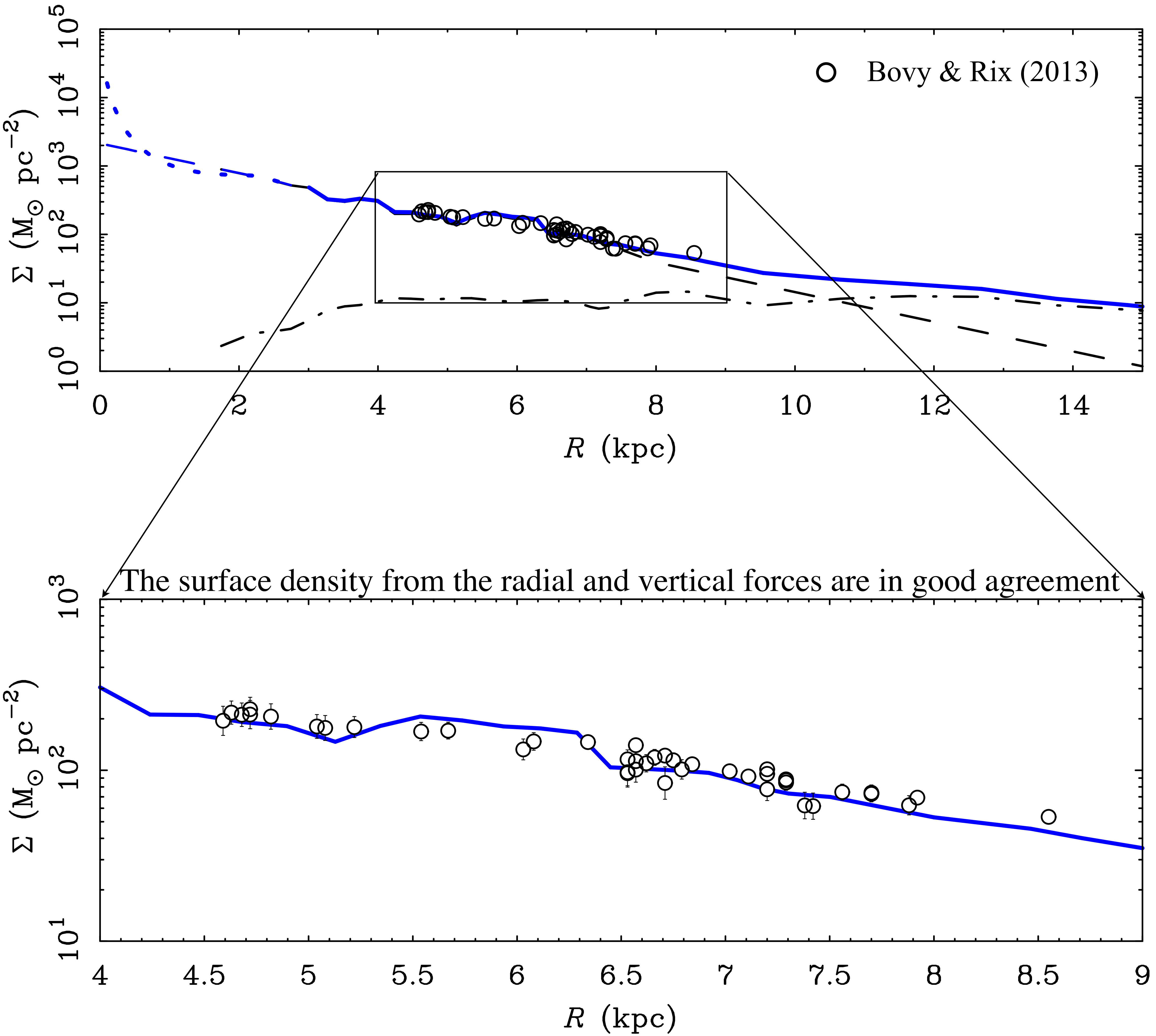
Luna et al. (2006: **CO**); McClure-Griffiths & Dickey (2007: **HI**); Xue et al. (2008: **BHB**)

Fitting the details of the terminal velocity curve

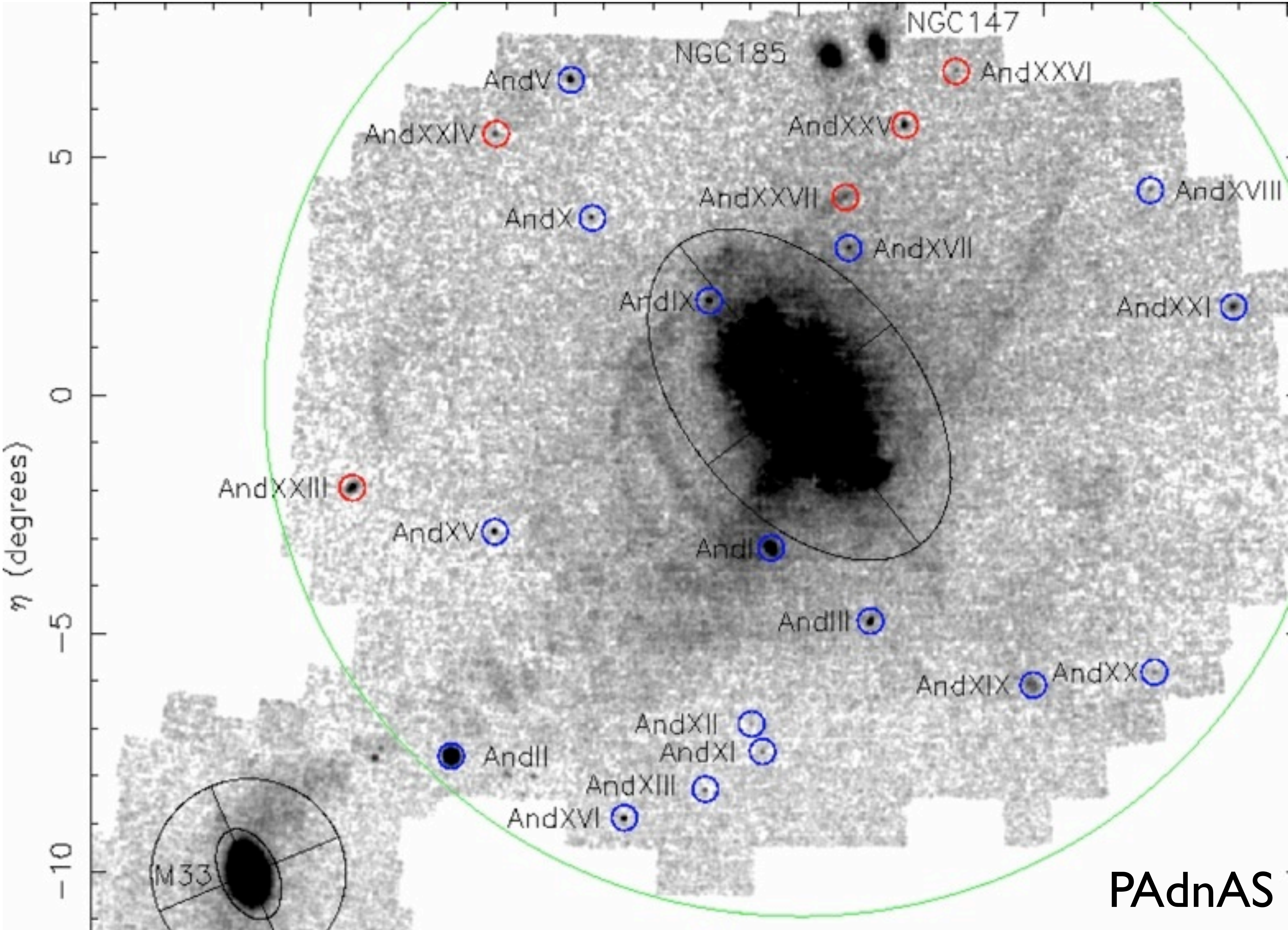


Fitting the details of the terminal velocity curve uncovers details of Milky Way structure: the inferred density enhancement corresponds to the Centaurus spiral arm.

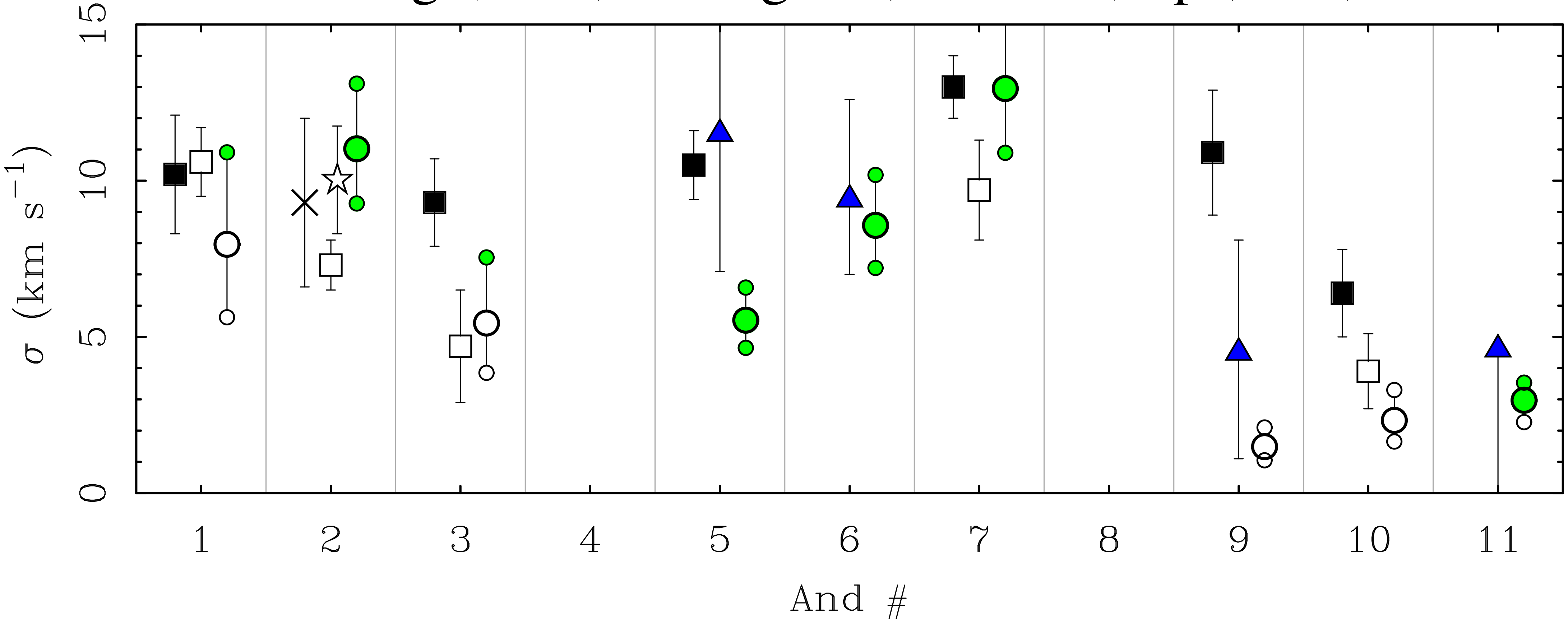



Bovy & Rix (2013)
Σ ($M_\odot$ pc^{-2})
10^0
10^1
10^2
10^3
10^4
10^5
0
2
4
6
8
10
12
14
R (kpc)
The surface density from the radial and vertical forces are in good agreement
Σ ($M_\odot$ pc^{-2})
10^1
10^2
10^3
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
R (kpc)

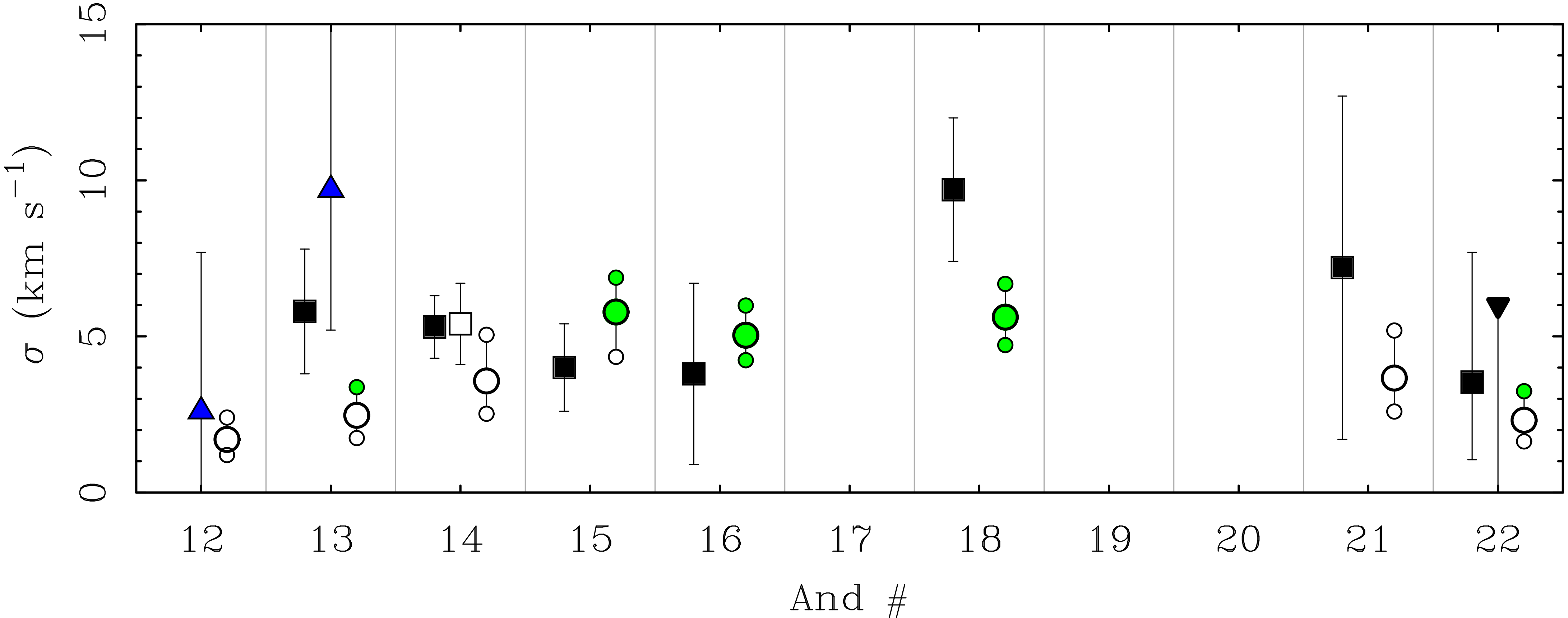
A new test: the dwarf satellites of Andromeda



McGaugh, S.S., & Milgrom, M. 2013, ApJ, 766, 22



Use MOND to predict dwarf's velocity dispersions



McGaugh, S.S., & Milgrom, M. 2013, ApJ, 766, 22

Completely *a priori* predictions for 10 dwarfs

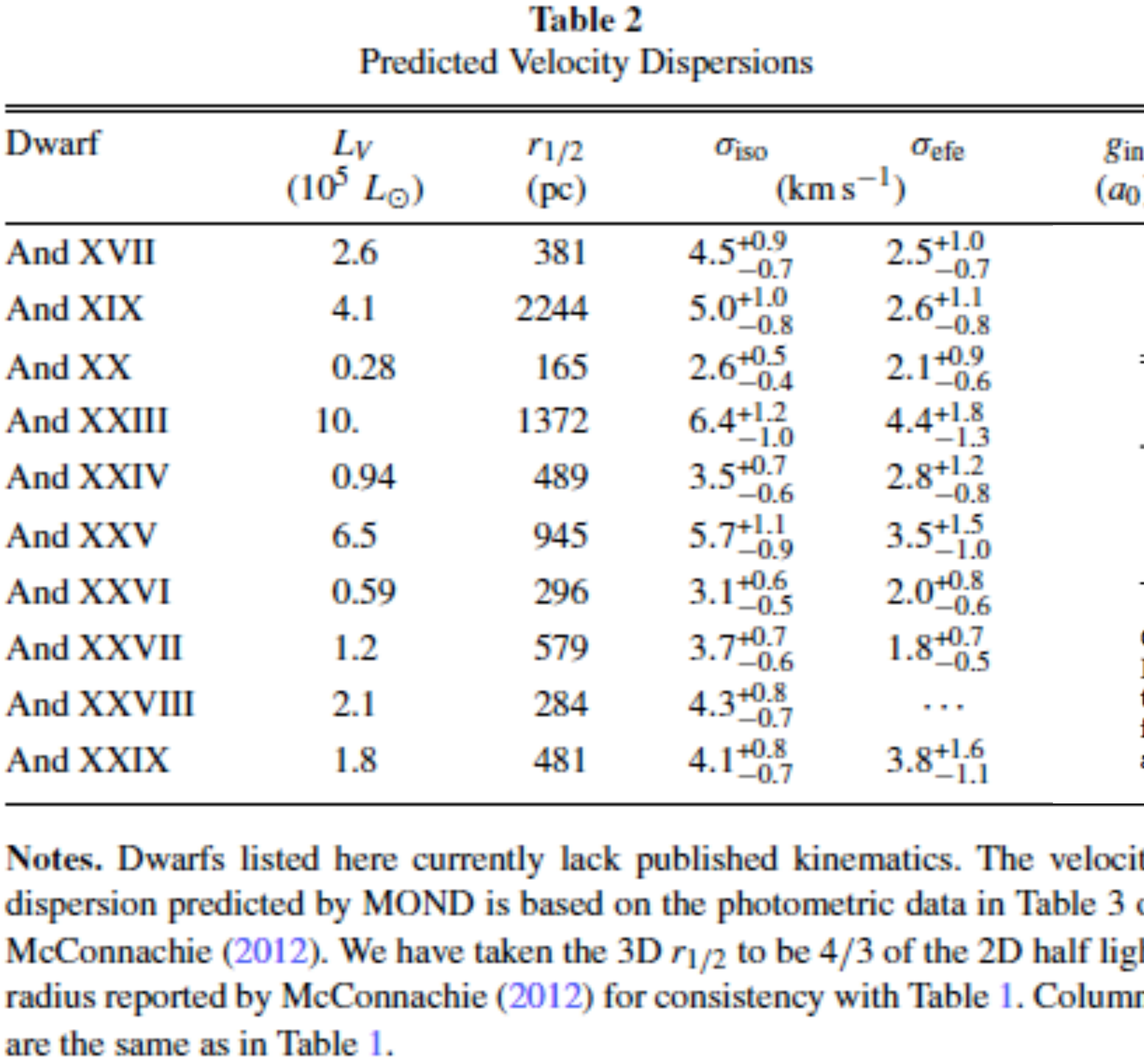


Table 2
Predicted Velocity Dispersions

Dwarf	L_V ($10^5\ L_\odot$)	$r_{1/2}$ (pc)	$\sigma_{\rm iso}$ (km s^{-1})	$\sigma_{\rm efe}$ (km s^{-1})	$g_{\rm in}$ (a_0)
And XVII	2.6	381	$4.5^{+0.9}_{-0.7}$	$2.5^{+1.0}_{-0.7}$	
And XIX	4.1	2244	$5.0^{+1.0}_{-0.8}$	$2.6^{+1.1}_{-0.8}$	
And XX	0.28	165	$2.6^{+0.5}_{-0.4}$	$2.1^{+0.9}_{-0.6}$	
And XXIII	10.	1372	$6.4^{+1.2}_{-1.0}$	$4.4^{+1.8}_{-1.3}$	
And XXIV	0.94	489	$3.5^{+0.7}_{-0.6}$	$2.8^{+1.2}_{-0.8}$	
And XXV	6.5	945	$5.7^{+1.1}_{-0.9}$	$3.5^{+1.5}_{-1.0}$	
And XXVI	0.59	296	$3.1^{+0.6}_{-0.5}$	$2.0^{+0.8}_{-0.6}$	
And XXVII	1.2	579	$3.7^{+0.7}_{-0.6}$	$1.8^{+0.7}_{-0.5}$	
And XXVIII	2.1	284	$4.3^{+0.8}_{-0.7}$	...	
And XXIX	1.8	481	$4.1^{+0.8}_{-0.7}$	$3.8^{+1.6}_{-1.1}$	

Notes. Dwarfs listed here currently lack published kinematics. The velocity dispersion predicted by MOND is based on the photometric data in Table 3 of McConnachie (2012). We have taken the 3D $r_{1/2}$ to be 4/3 of the 2D half light radius reported by McConnachie (2012) for consistency with Table 1. Columns are the same as in Table 1.

and 3 more

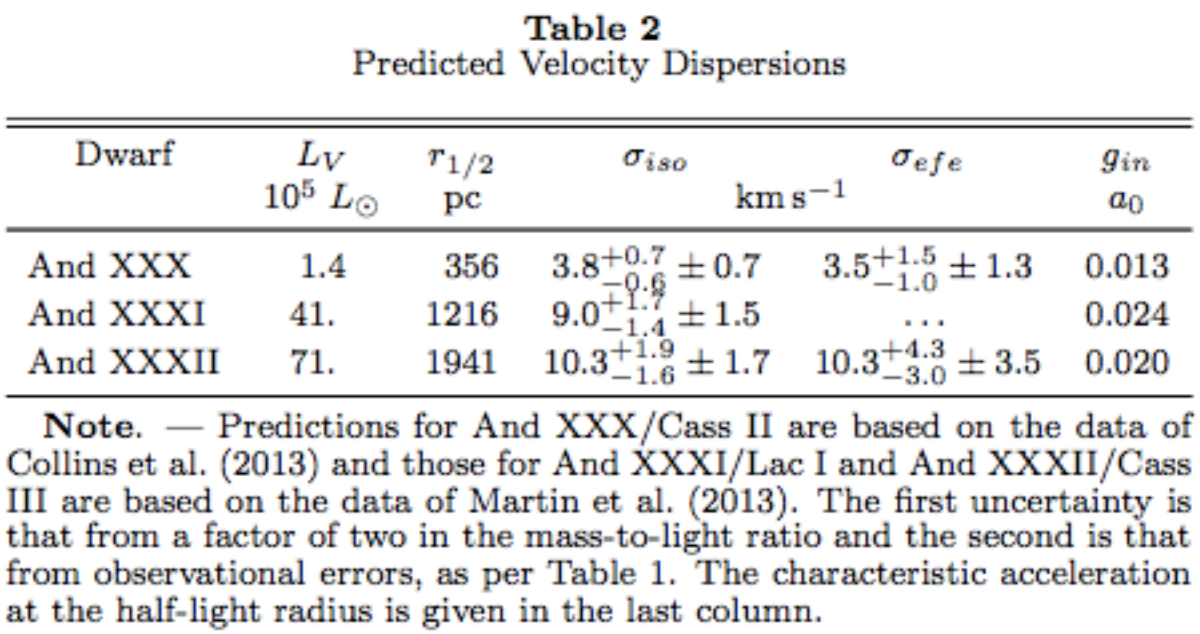


Table 2
Predicted Velocity Dispersions

Dwarf	L_V $10^5\ L_\odot$	$r_{1/2}$ pc	σ_{iso} km s^{-1}	σ_{efe} km s^{-1}	g_{in} a_0
And XXX	1.4	356	$3.8^{+0.7}_{-0.6} \pm 0.7$	$3.5^{+1.5}_{-1.0} \pm 1.3$	0.013
And XXXI	41.	1216	$9.0^{+1.7}_{-1.4} \pm 1.5$	...	0.024
And XXXII	71.	1941	$10.3^{+1.9}_{-1.6} \pm 1.7$	$10.3^{+4.3}_{-3.0} \pm 3.5$	0.020

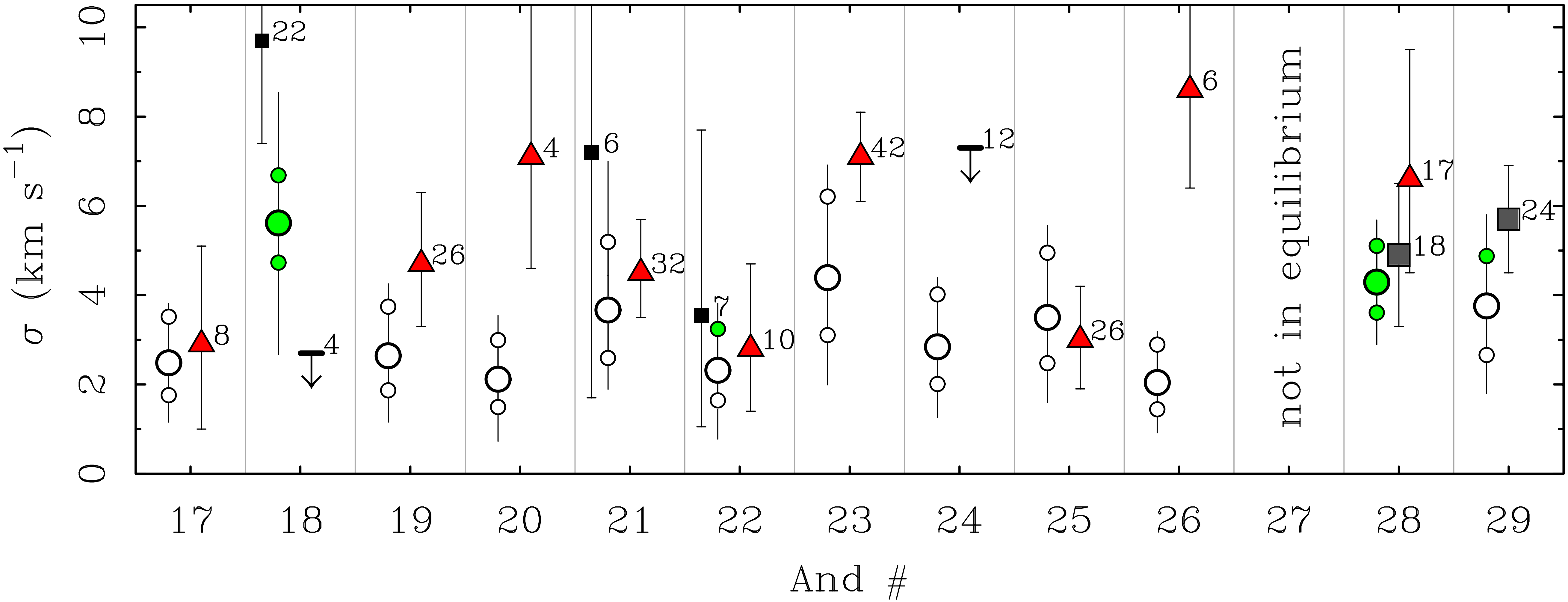
Note. — Predictions for And XXX/Cass II are based on the data of Collins et al. (2013) and those for And XXXI/Lac I and And XXXII/Cass III are based on the data of Martin et al. (2013). The first uncertainty is that from a factor of two in the mass-to-light ratio and the second is that from observational errors, as per Table 1. The characteristic acceleration at the half-light radius is given in the last column.

plus Perseus,
Cetus, & Tucana

McGaugh, S.S., & Milgrom, M. 2013, ApJ, 766, 22

McGaugh, S.S., & Milgrom, M. 2013, ApJ, 775, 139

Completely *a priori* predictions for 10 dwarfs already tested and largely confirmed



Newtonian regime

$g_{in} > a_0$

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

e.g.,
surface
of the
Earth

ISO MOND regime

$g_{in} < a_0$

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

e.g.,
remote
dwarf
Leo I

© Anglo-Australian Observatory

External Field dominant Newtonian regime

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

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

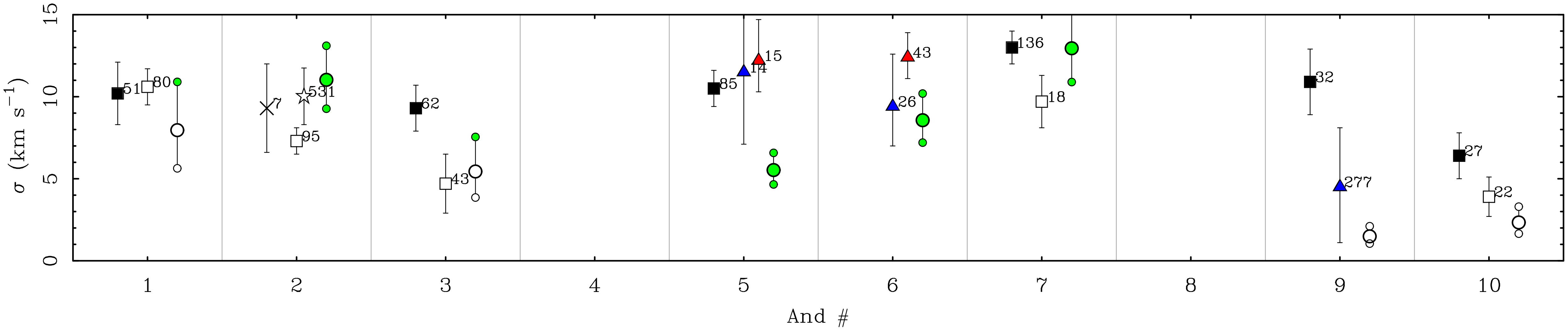
e.g.,
Eotvos-type
experiment on
the surface of
the Earth

EFE External Field dominant quasi-Newtonian regime

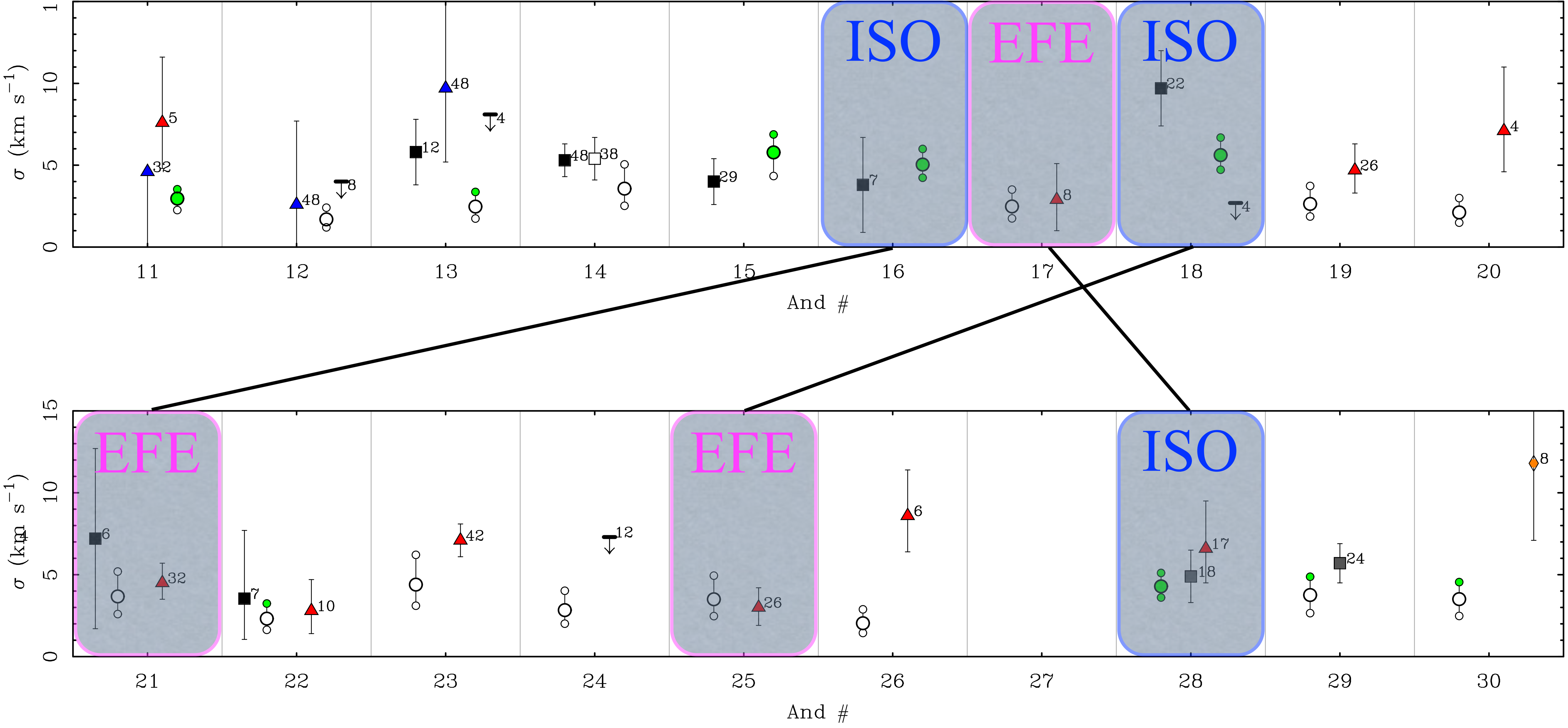
$g_{in} < g_{ex} < a_0$

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

e.g.,
nearby
dwarf
Segue 1



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



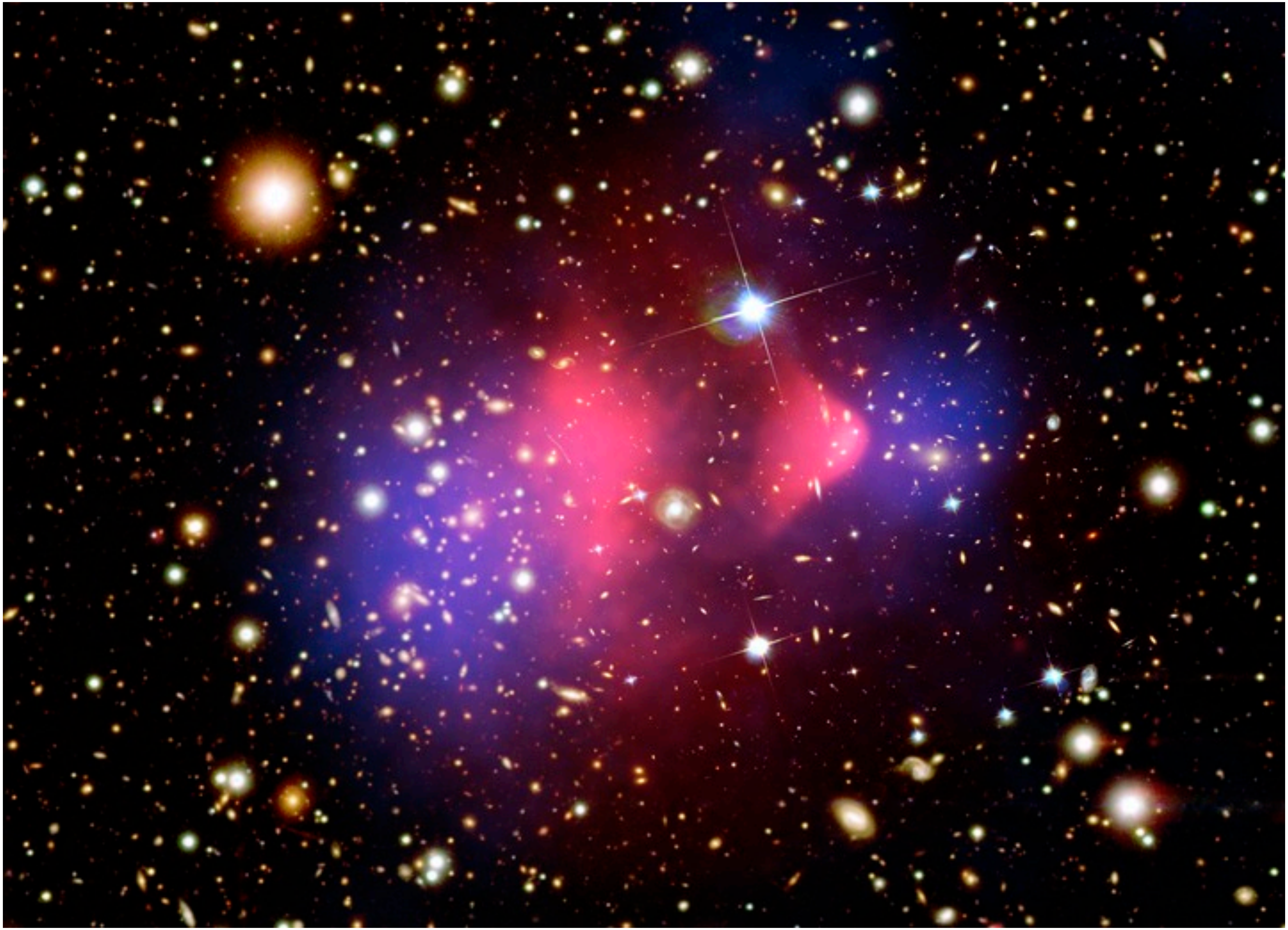
There is no EFE in dark matter - this is a unique signature of MOND.

I find your lack of faith disturbing.

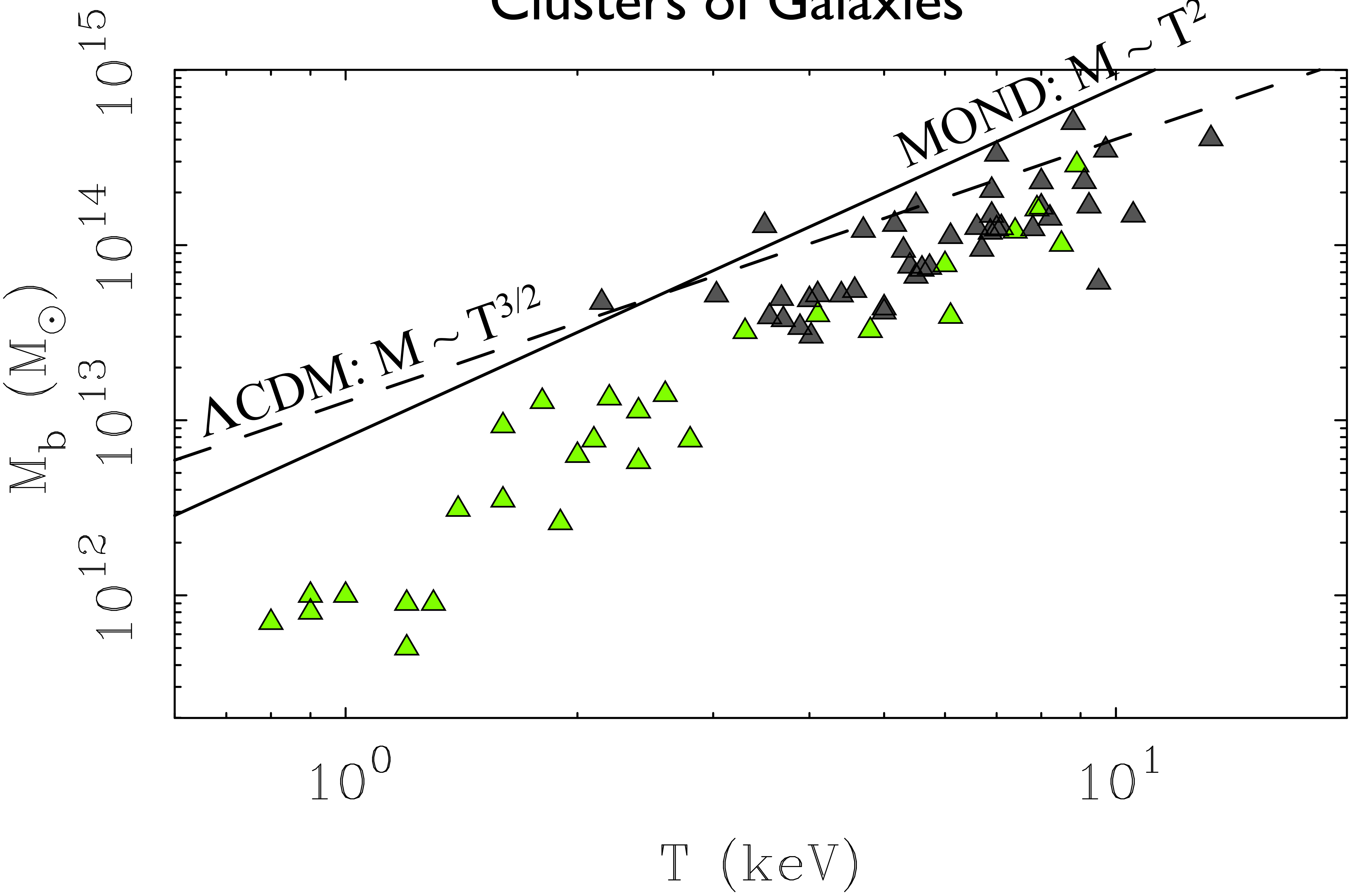
- You don’t know the Power of the Dark Side
- Can MOND explain large scale structure?
- Can it provide a satisfactory cosmology?
- Can it be reconciled with General Relativity?
- Does it survive other tests?

Clusters problematic

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

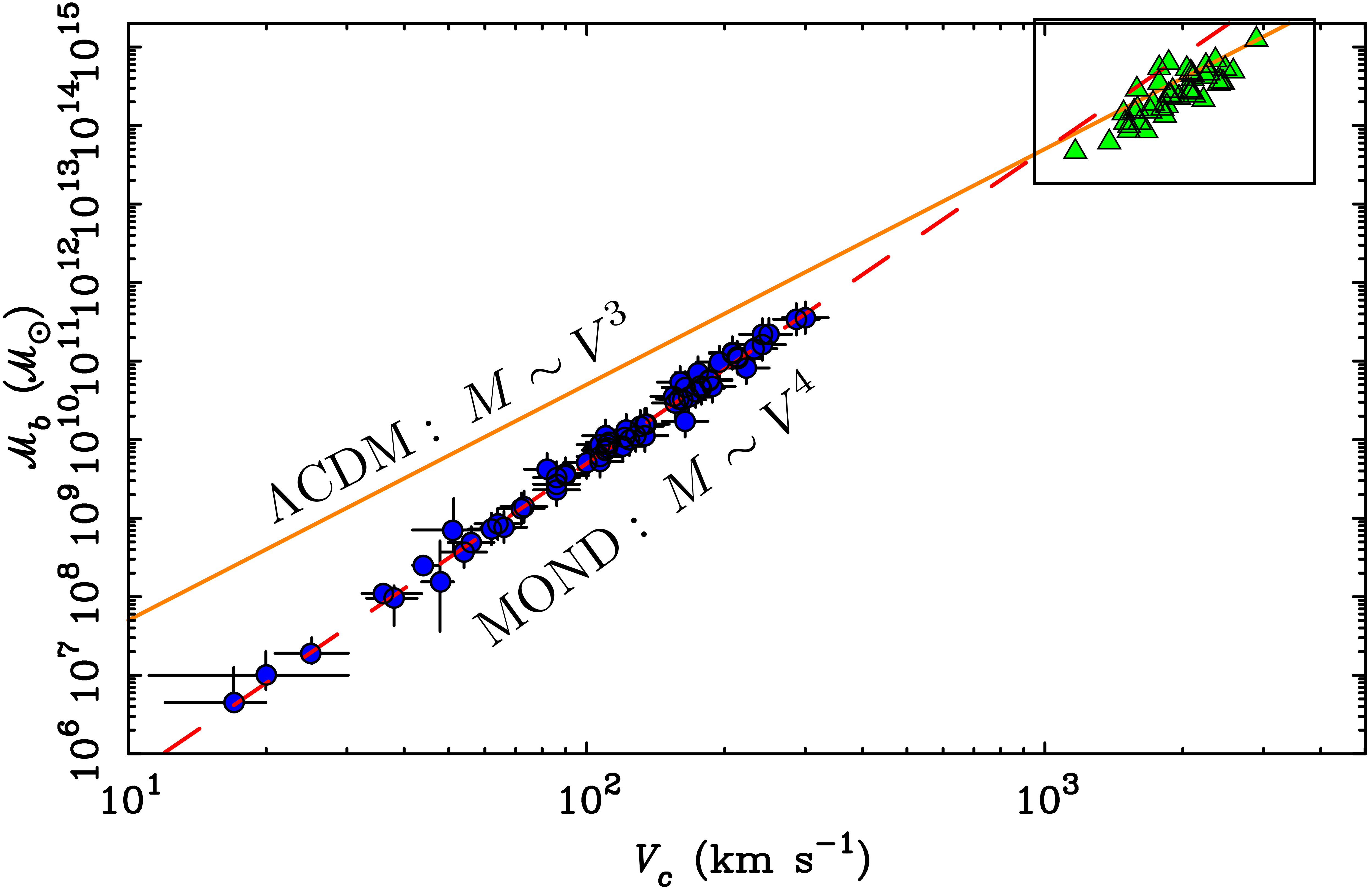


Clusters of Galaxies



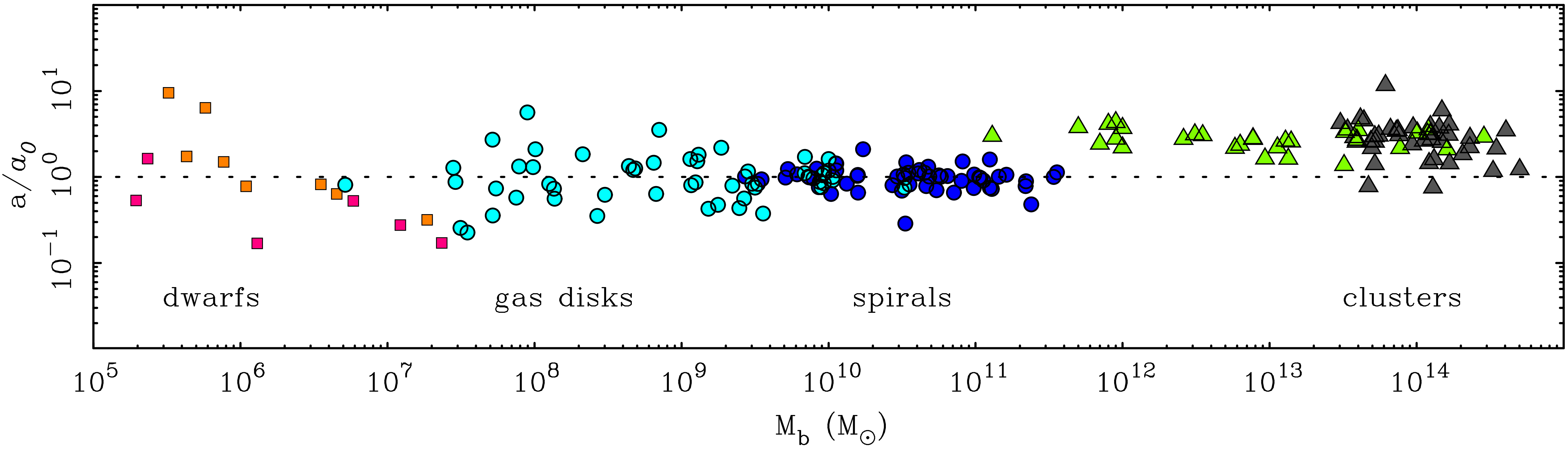
residual mass discrepancy in clusters is real...
the bullet cluster is a special case of a more general problem.

Zooming out...



$\Lambda\mathrm{CDM}: M \sim V^3$
$\mathrm{MOND}: M \sim V^4$
$\mathcal{M}_b\ (\mathcal{M}_\odot)$
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
$V_c\ (\mathrm{km\ s^{-1}})$

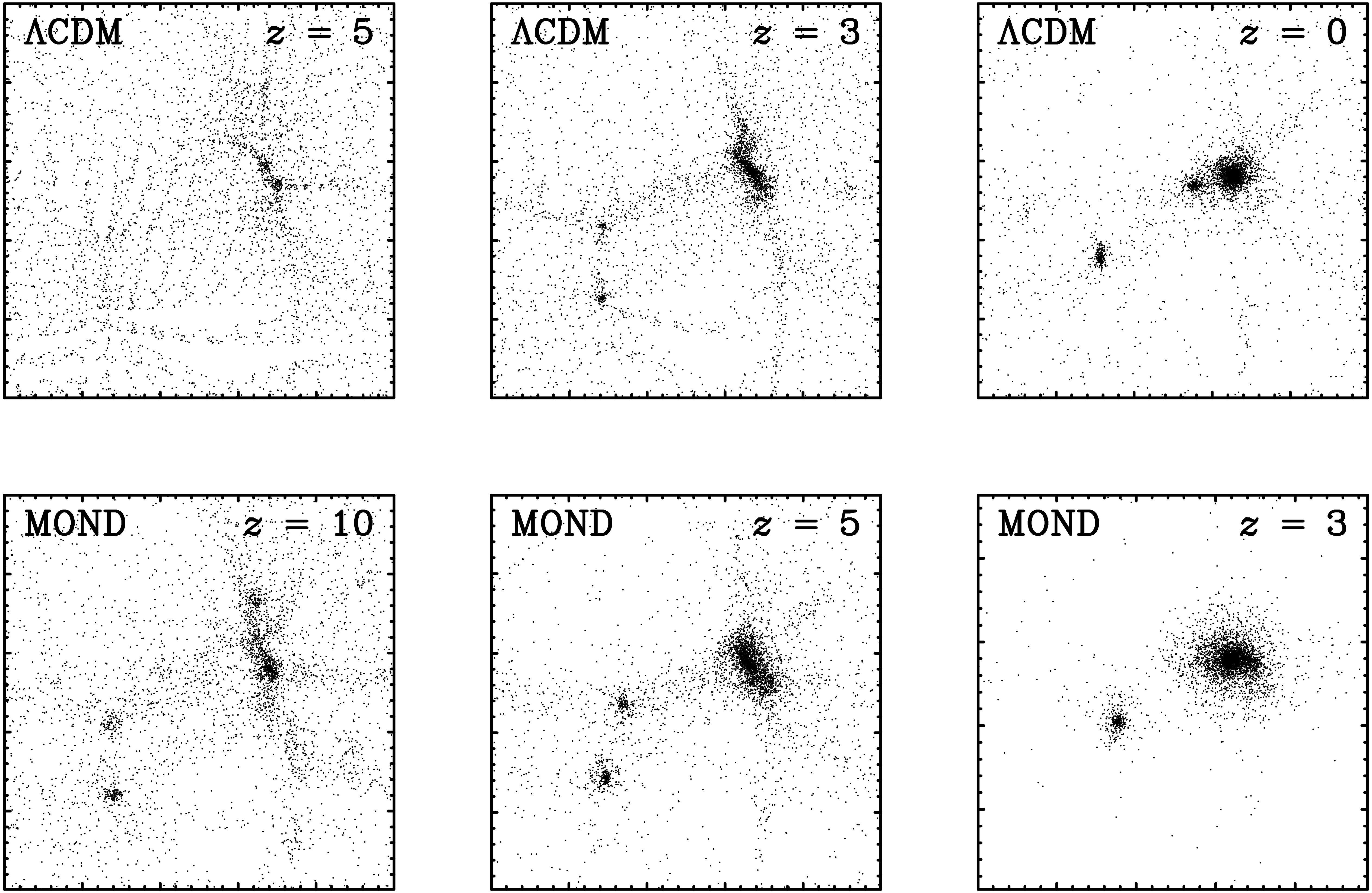
Data for groups & cluster offset from MOND prediction, but slope pretty good over many decades in baryonic mass.



$$a_0 = 1.2 \times 10^{-10}\ \mathrm{m\,s^{-2}} \approx \frac{cH_0}{2\pi} \approx c\Lambda^{1/2}$$

$$\Sigma_\dagger = 860\ \mathrm{M_\odot\,pc^{-2}}$$

Large Scale Structure



Structure forms earlier in MOND - predicted early reionization

Other MOND tests

- Disk Stability
  - ✓ Freeman limit in surface brightness distribution
  - ✓ thin disks
  - ✓ velocity dispersions
  - ✓ LSB disks not over-stabilized

- ✓ Dwarf Spheroidals

- ✓ Giant Ellipticals

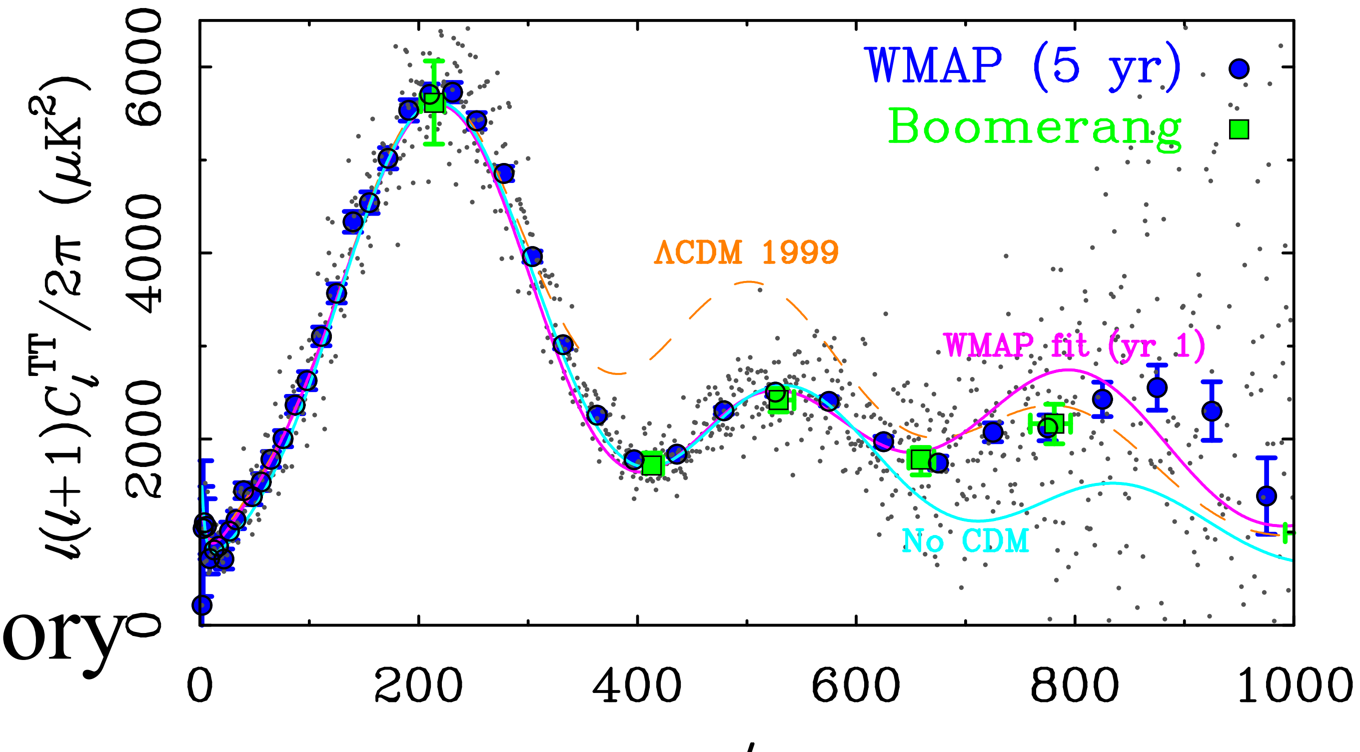
- ✗ Clusters of Galaxies

- ? Structure Formation

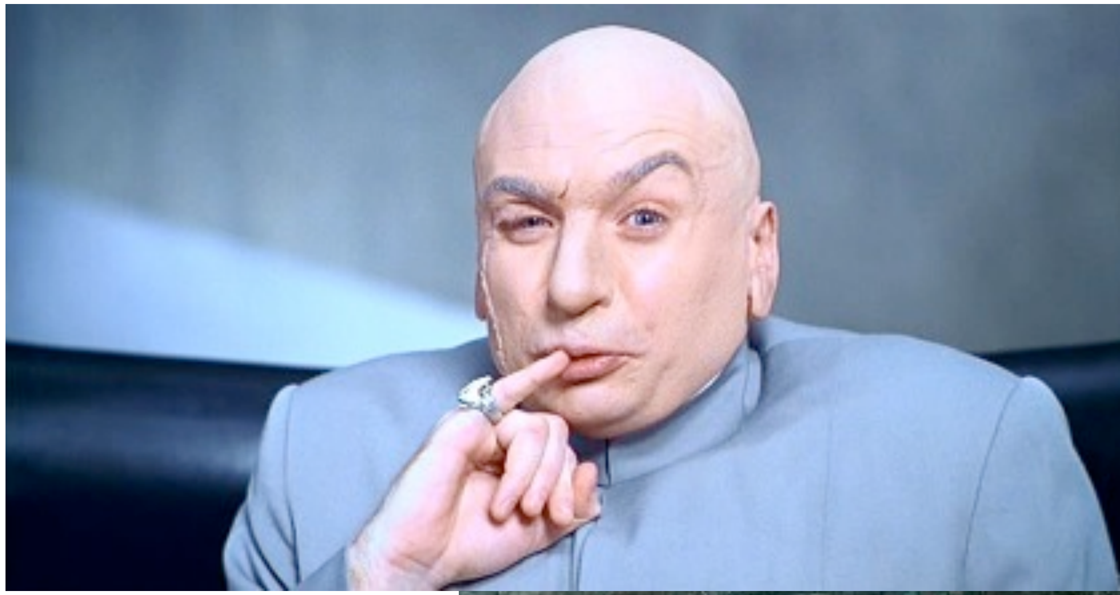
- Microwave background
  - ✓ 1st:2nd peak amplitude; BBN
  - ✓ early reionization
  - ✓ enhanced ISW/gravitational lensing
  - ✗ 3rd peak

✗ No Metric

✗ Don't know expansion history



Logical possibilities



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