MGADS

Modified Gravity Approaches to the Dark Sector

Empirical Tests of MOND in Galaxies

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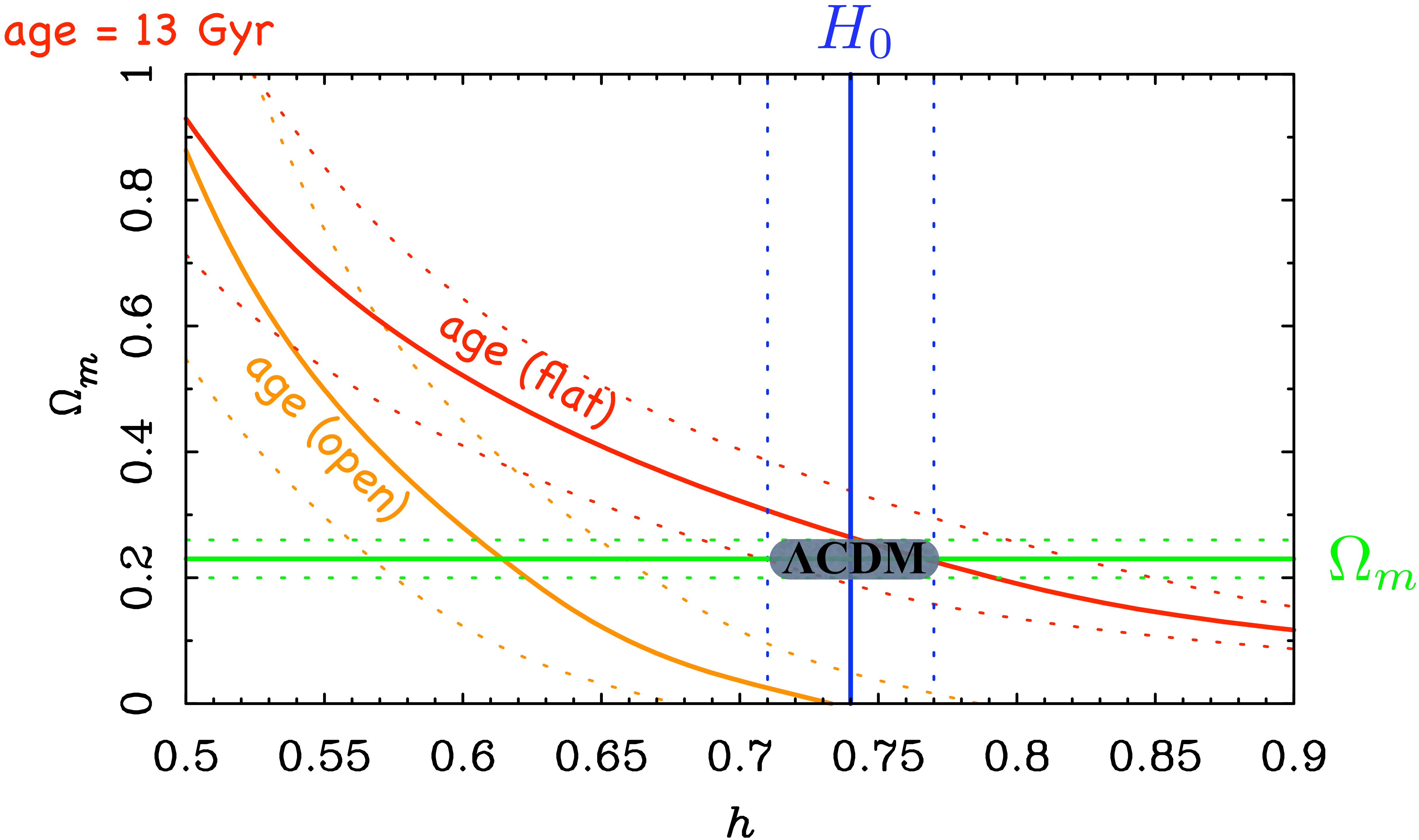
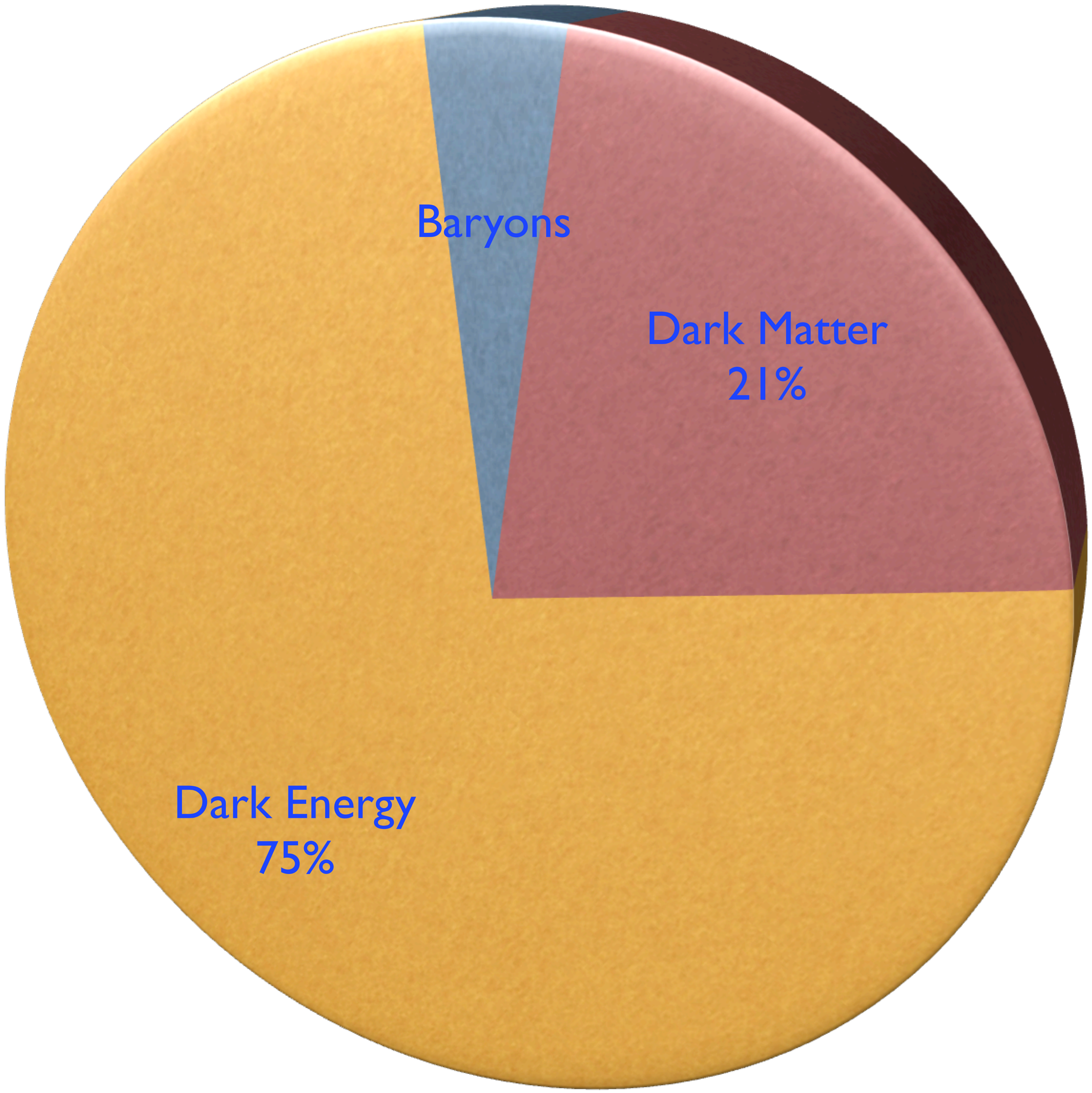
Cosmological Constraints



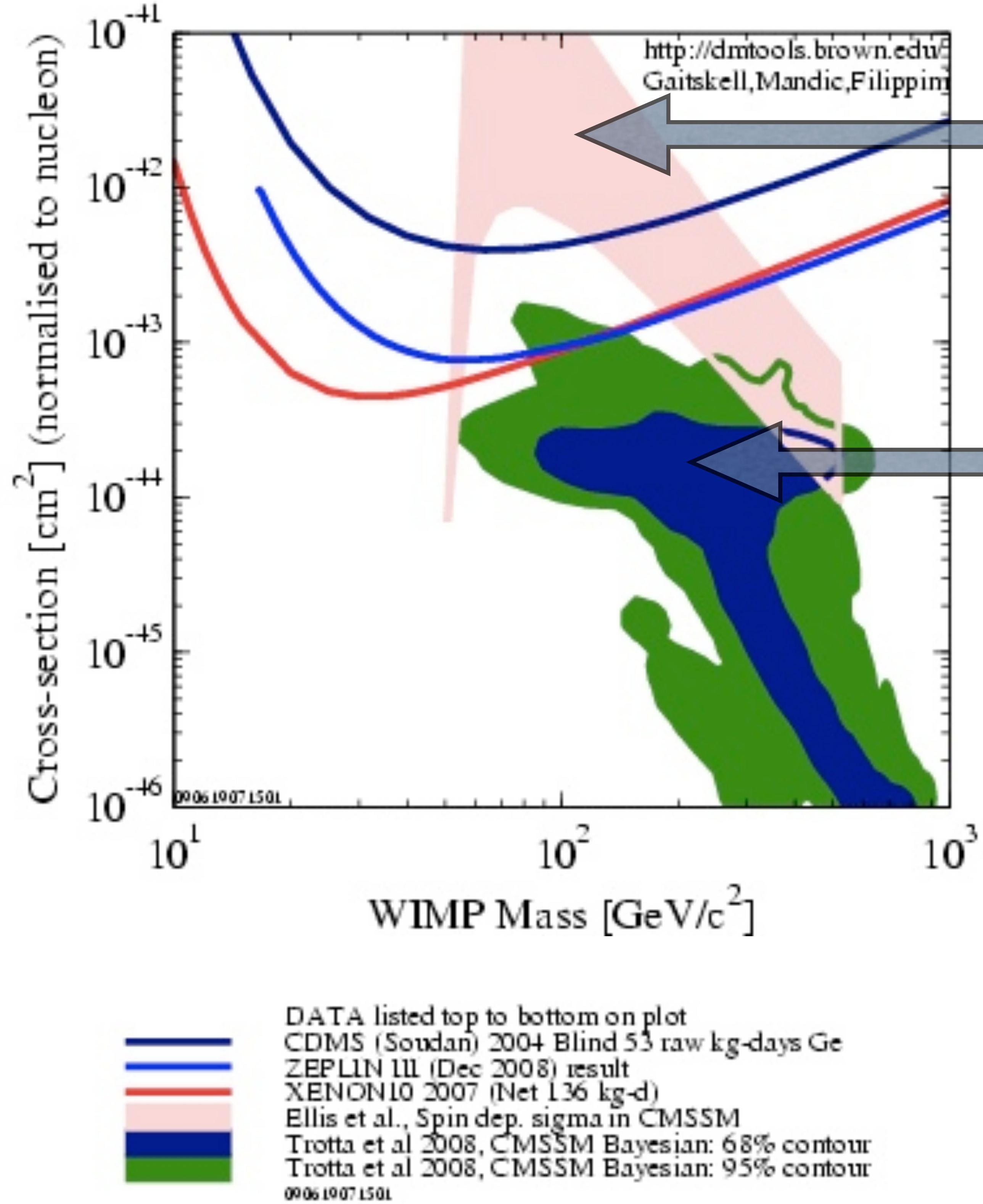
SNIa and CMB want similar numbers, so it must be true!



FLRW cosmology
only works with
• dark matter
• dark energy

We don’t know what
dark matter is and
we don’t understand
what dark energy means

Does dark matter exist?

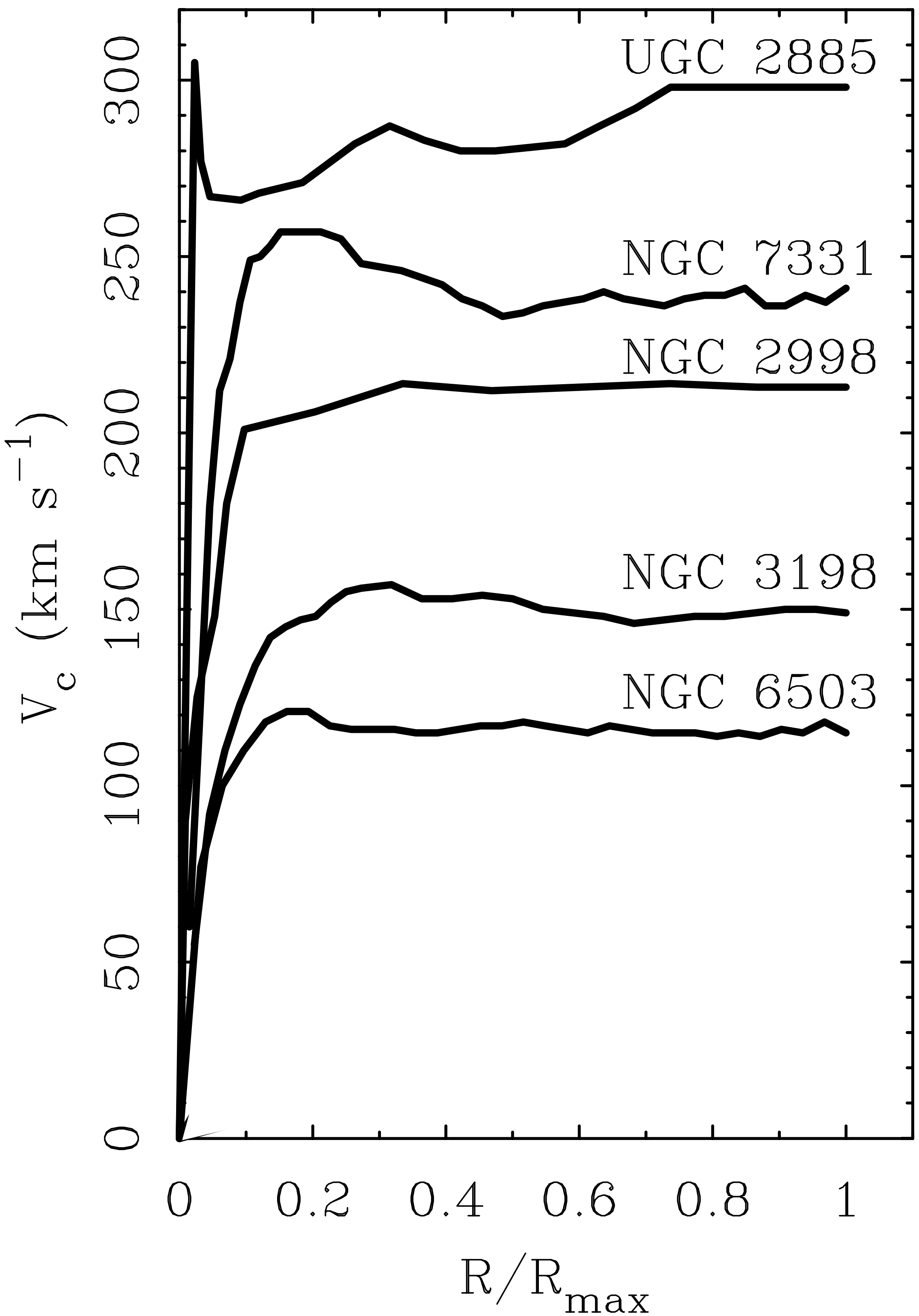


original prediction

current expectation

But we behave like we're pretty darn sure that dark matter is made of WIMPs.

Rotation curves of spirals

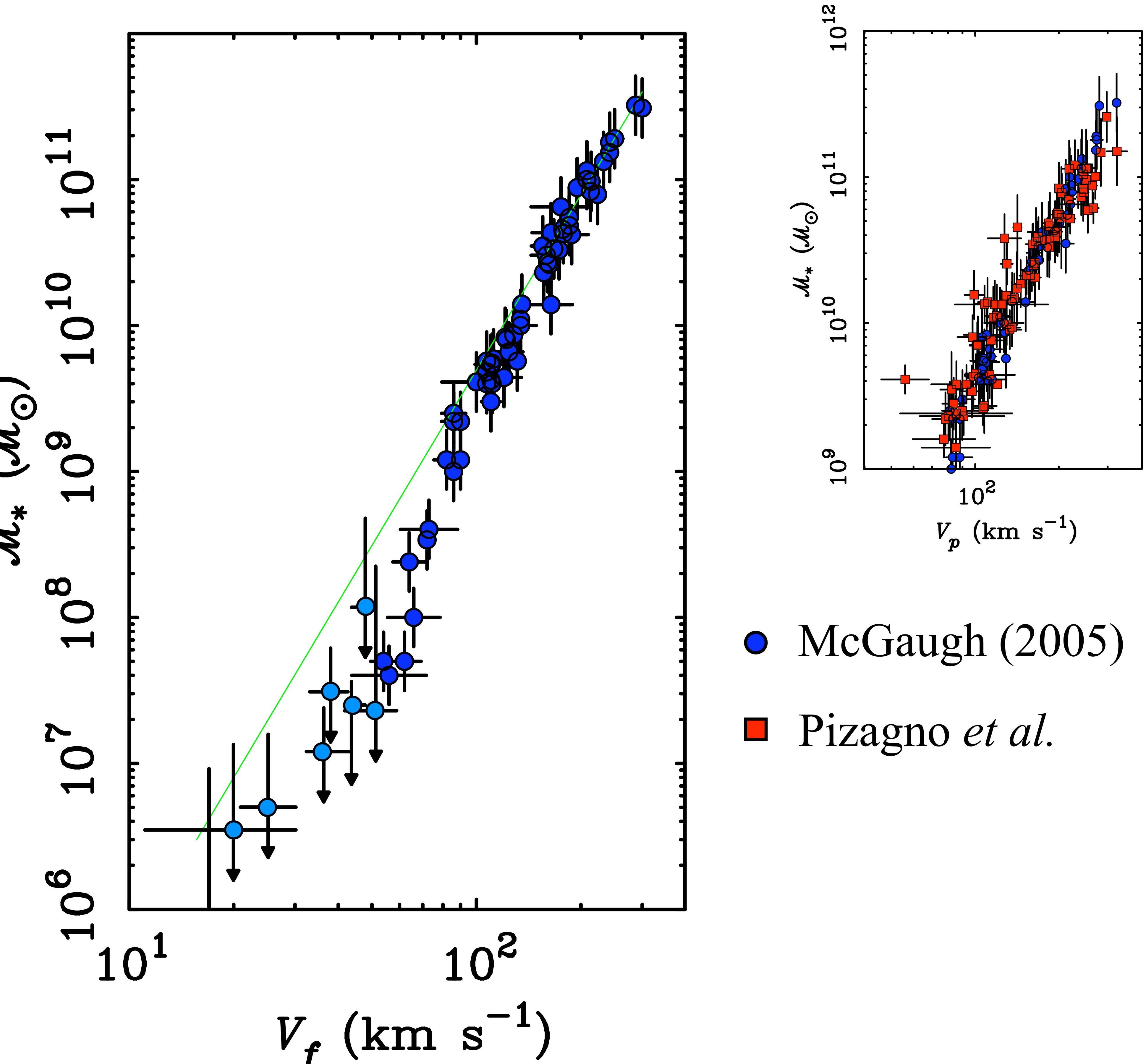


Interpretation in terms of dark matter leads to fine-tuning problems.

Global Relation: Tully-Fisher Relation

Stars only

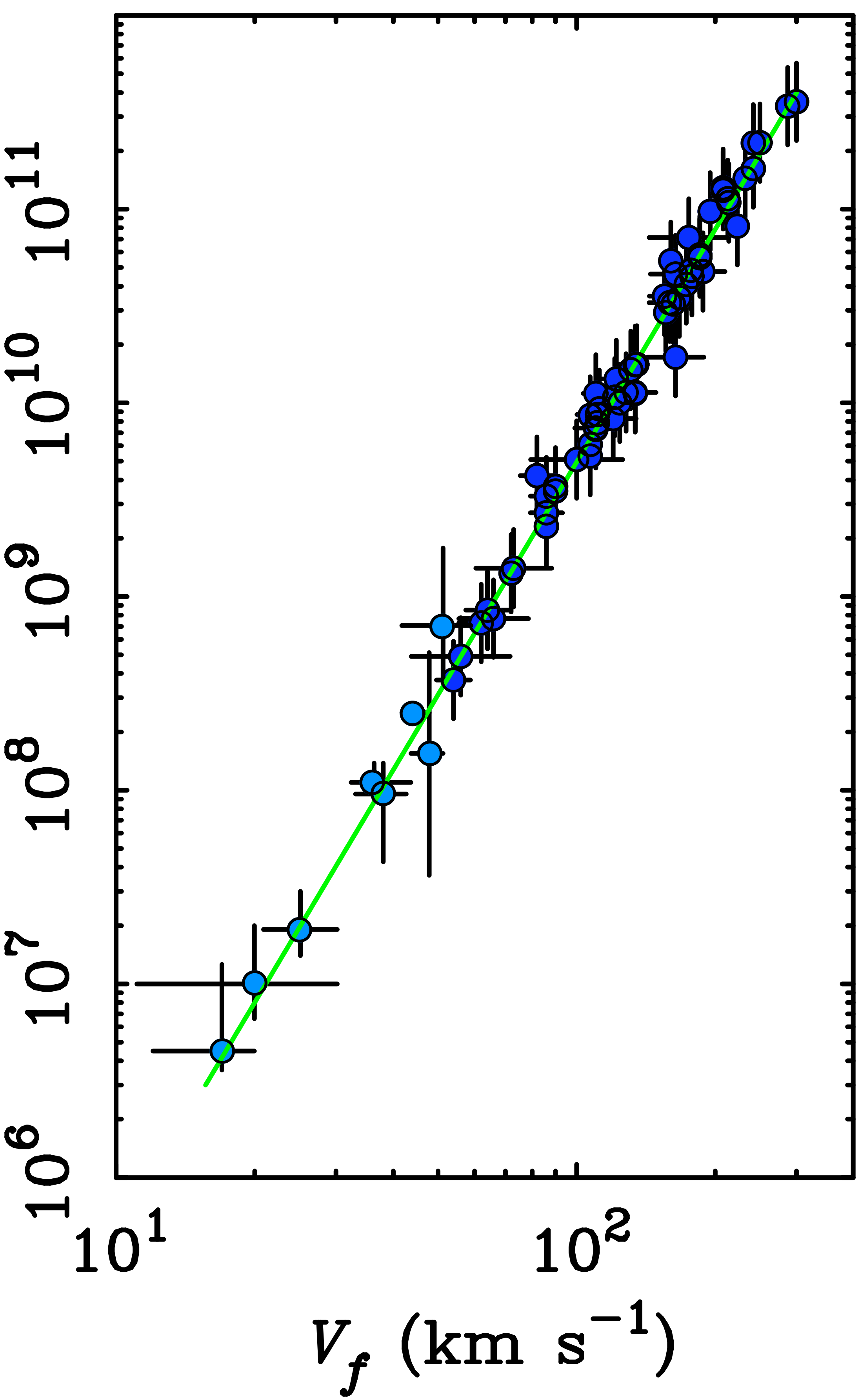
$M_\star = \Upsilon_\star L$

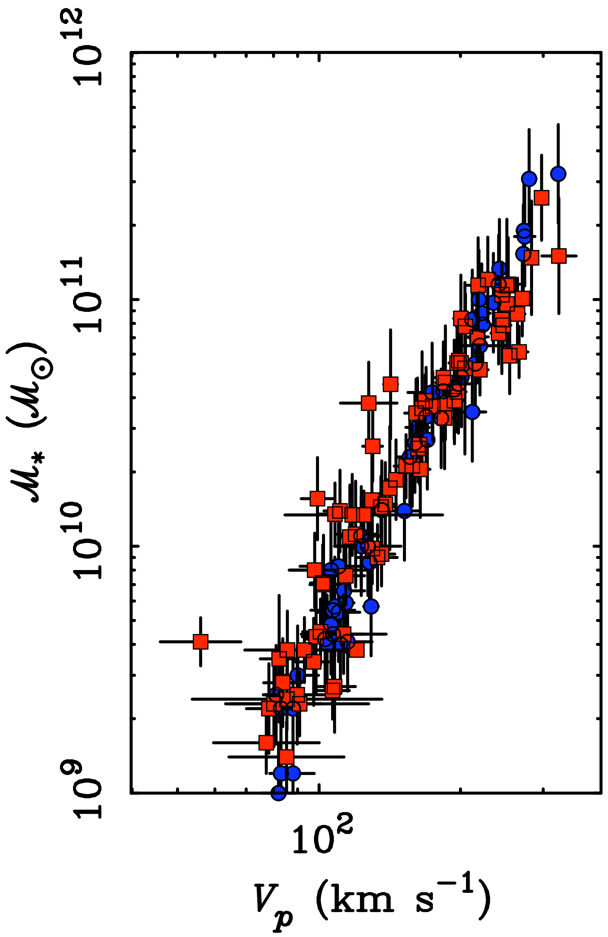


Global Relation: Baryonic Tully-Fisher

Stars plus gas

$$M_b = M_\star + M_{gas}$$





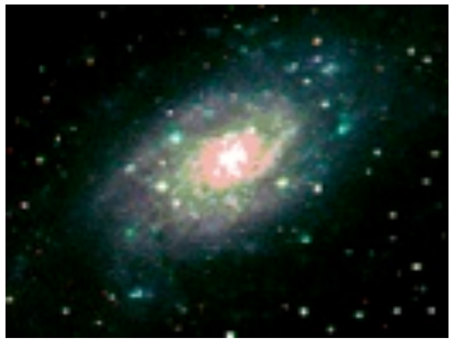
line:

$$\log M_b = 4 \log V_f + 1.7$$

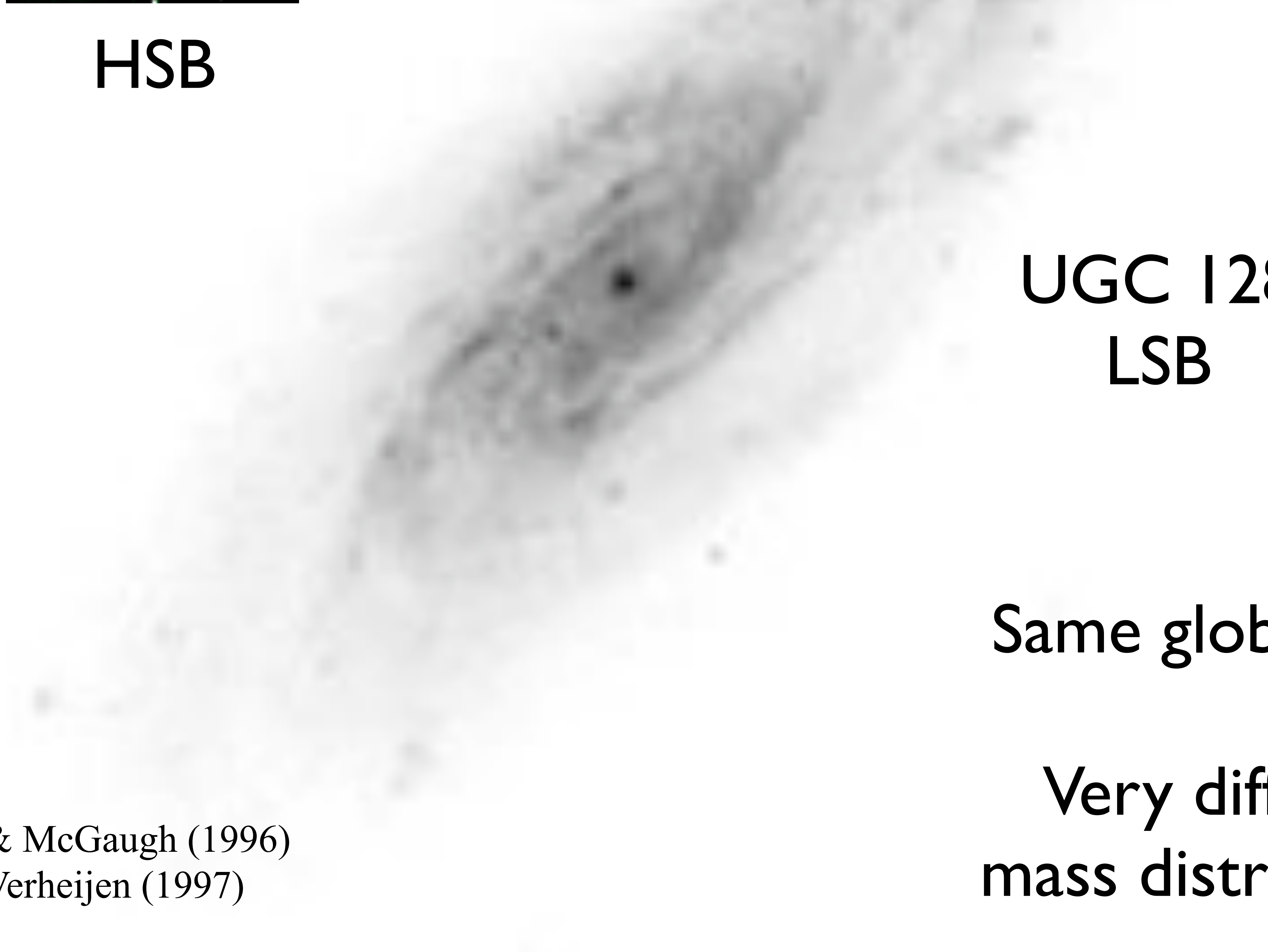
(McGaugh 2005)

Implies no other substantial reservoirs of baryonic mass.

NGC 2403



HSB

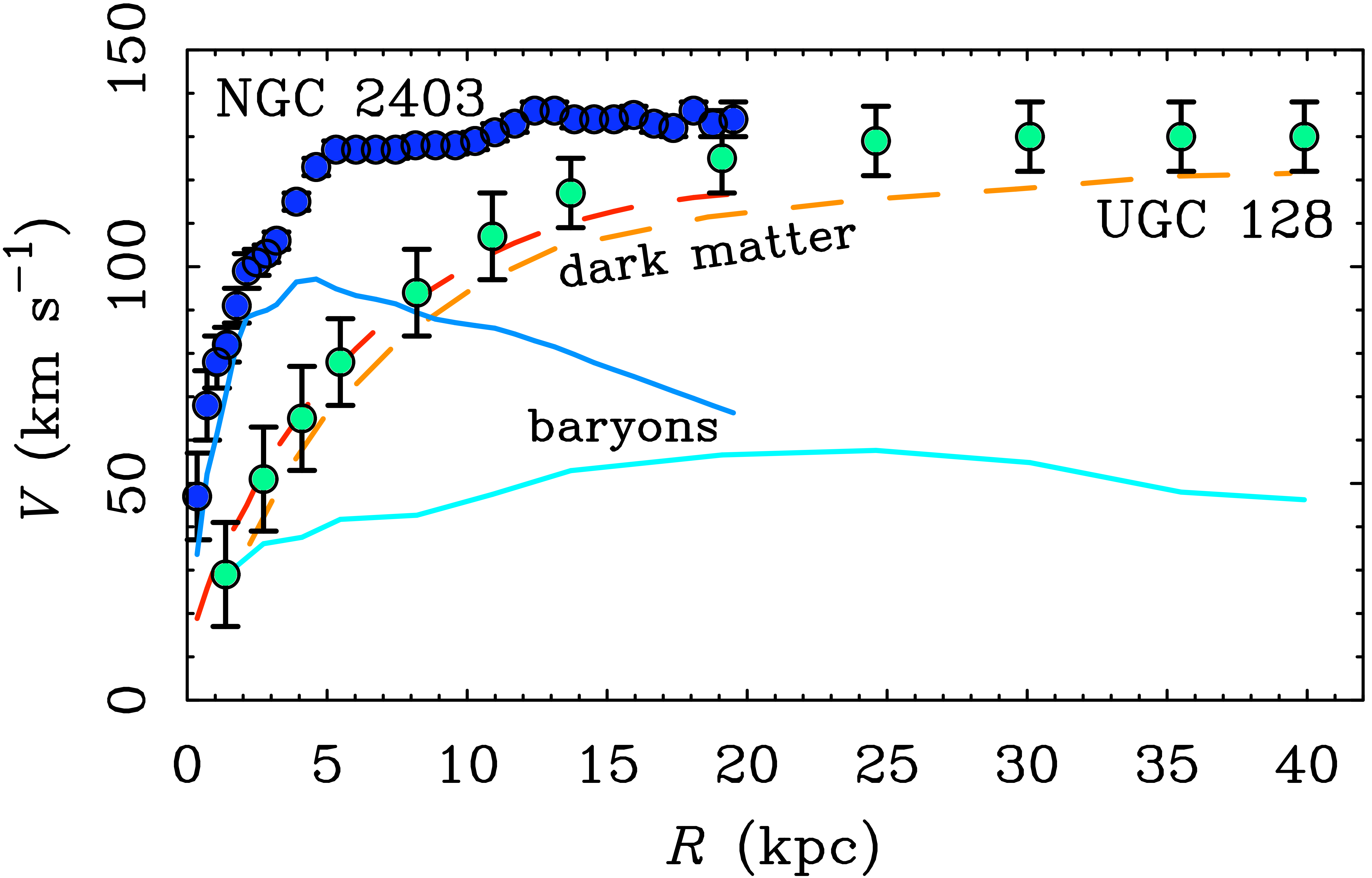


UGC 128
LSB

Same global M_b,V

Very different
mass distributions

de Blok & McGaugh (1996)
Tully & Verheijen (1997)



NGC 2403
UGC 128
dark matter
baryons
V (km s^{-1})
R (kpc)
0
50
100
150
0
5
10
15
20
25
30
35
40

TF Relation

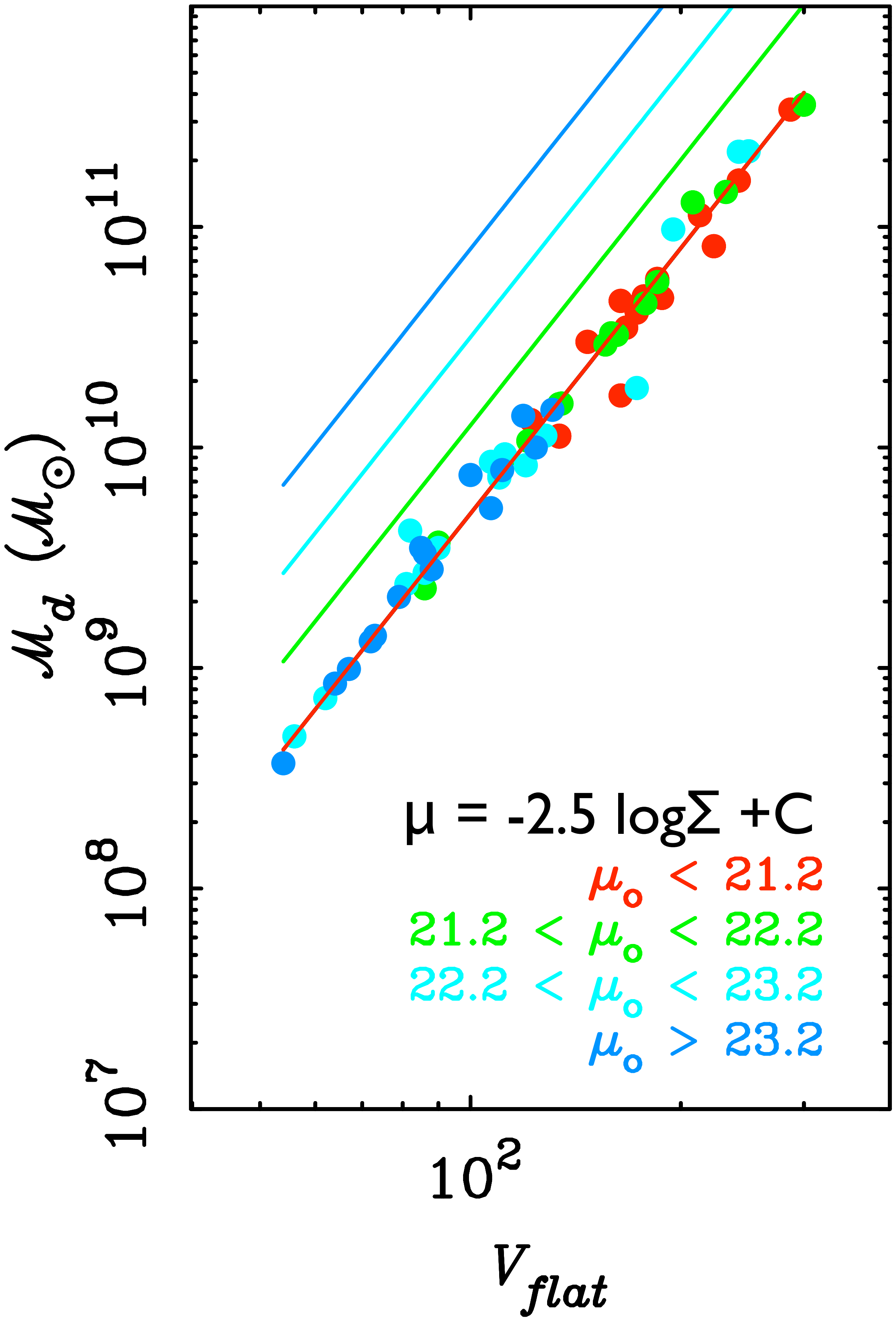
<u>Newton says</u>

$V^2 = GM/R$.

Equivalently,

$\Sigma = M/R^2$

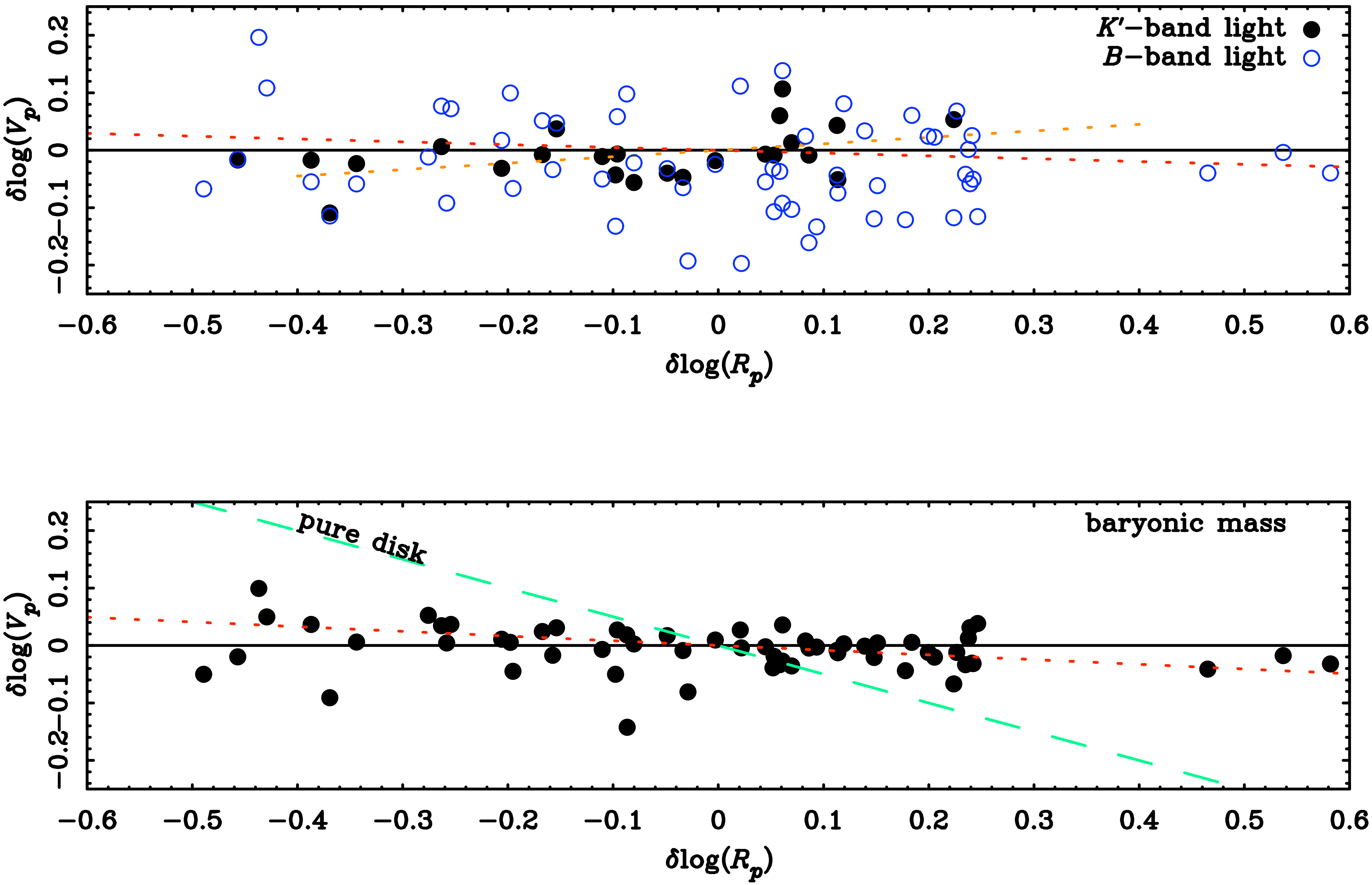
$V^4 = G^2 M\Sigma$



<u>Therefore</u>

Different Σ *should* mean different TF normalization.

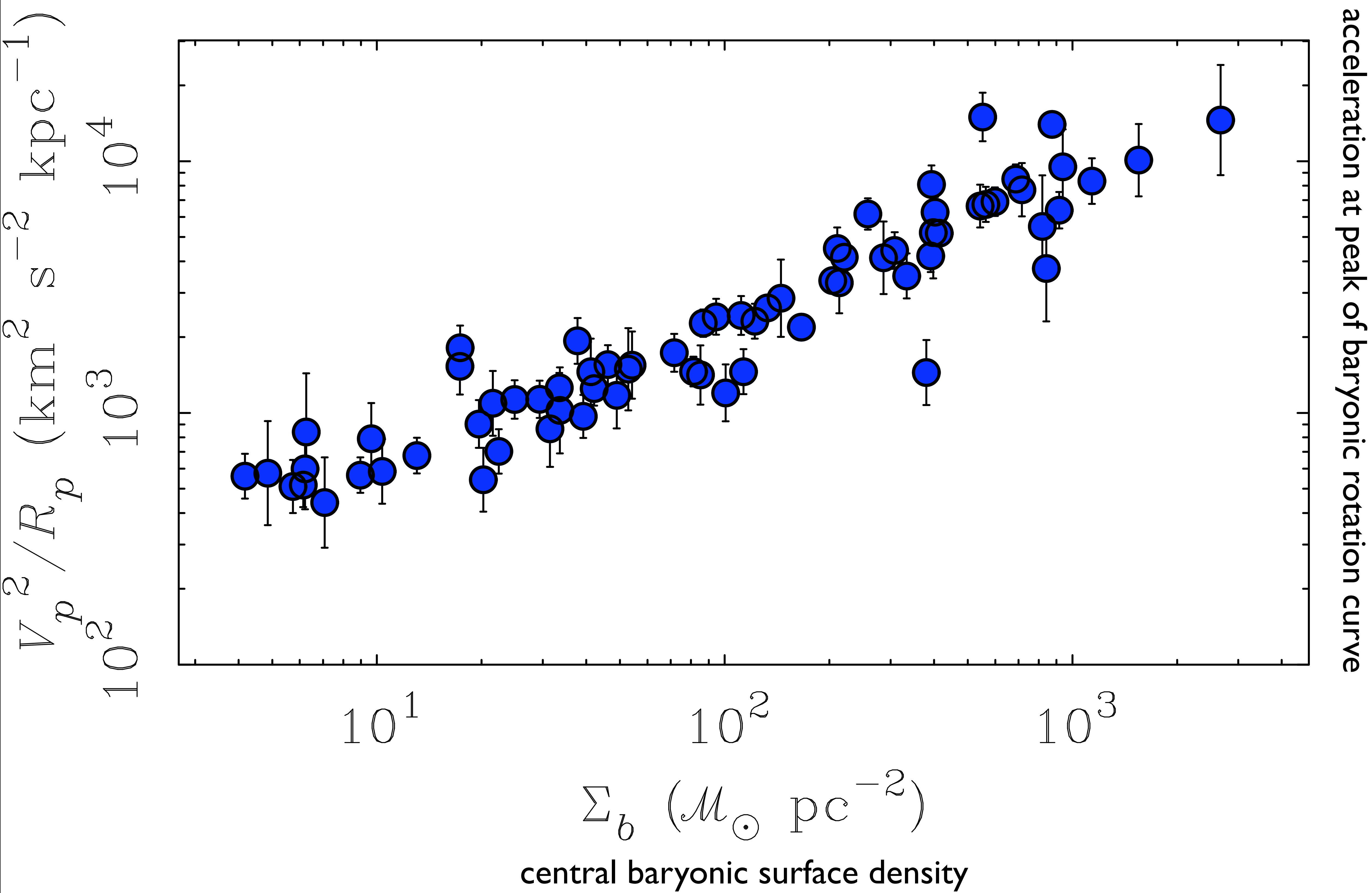
No Residuals from TF rel'n



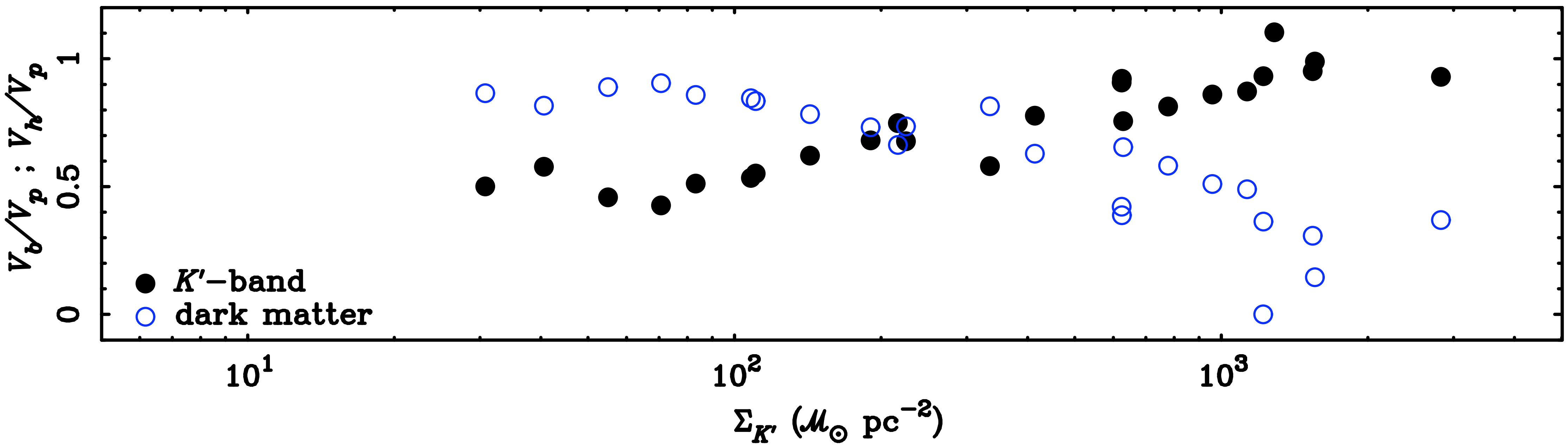
Sometimes interpreted to mean that dark matter dominates over disk mass

Acceleration related to baryonic surface density

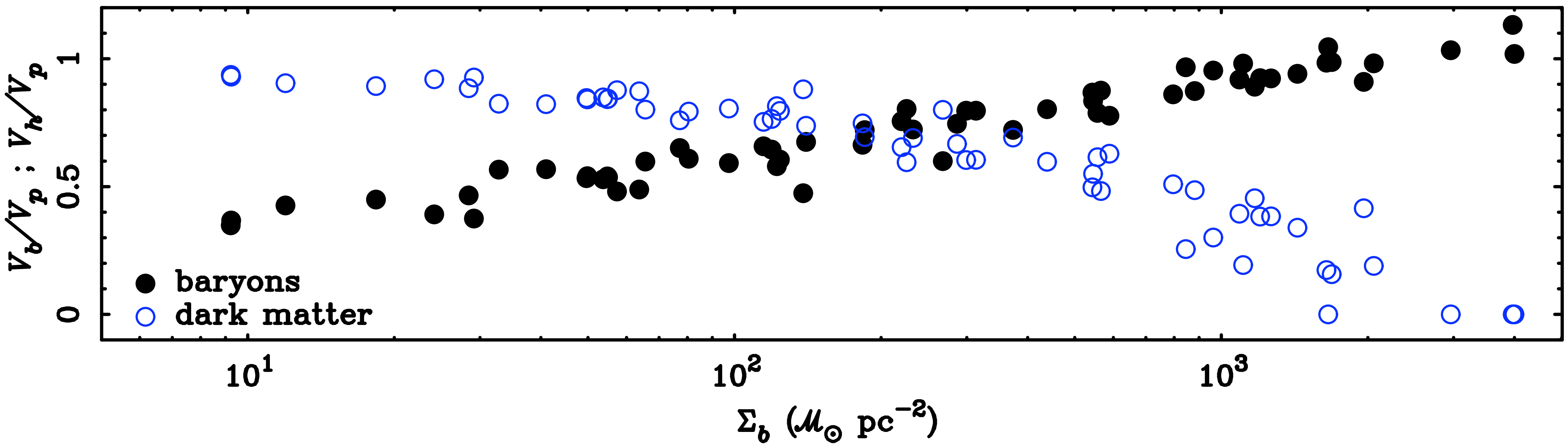
Baryons important to dynamics - dark matter does not dominate.
A contradiction to purely Newtonian dynamics?



Fine-tuning unavoidable



Phys. Rev. Lett. 95, 171302 (2005)



“...working on the thing can drive you mad.”

MOND

$$a \gg a_0 \qquad a \to g_N$$

$$a \ll a_0 \qquad a \to \sqrt{g_N a_o}$$

$$a_0 \approx 1\,\text{Å}\,\text{s}^{-2}$$

$$\mu \to 1 \qquad a \gg a_0$$

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

$$\mu \to \frac{a}{a_0} \qquad a \ll a_0$$

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 [illegible] galactic bulge[illegible]

VIII. PREDICTIONS

The main predictions conc[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 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 $V_\infty = 220\ \mathrm{km\ s^{-1}}$ 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 $a_{in} \ll g$, $h_{s0} = 1$).

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 rapid[illegible]. The transitio[illegible] radius [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 [illegible] ior 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.

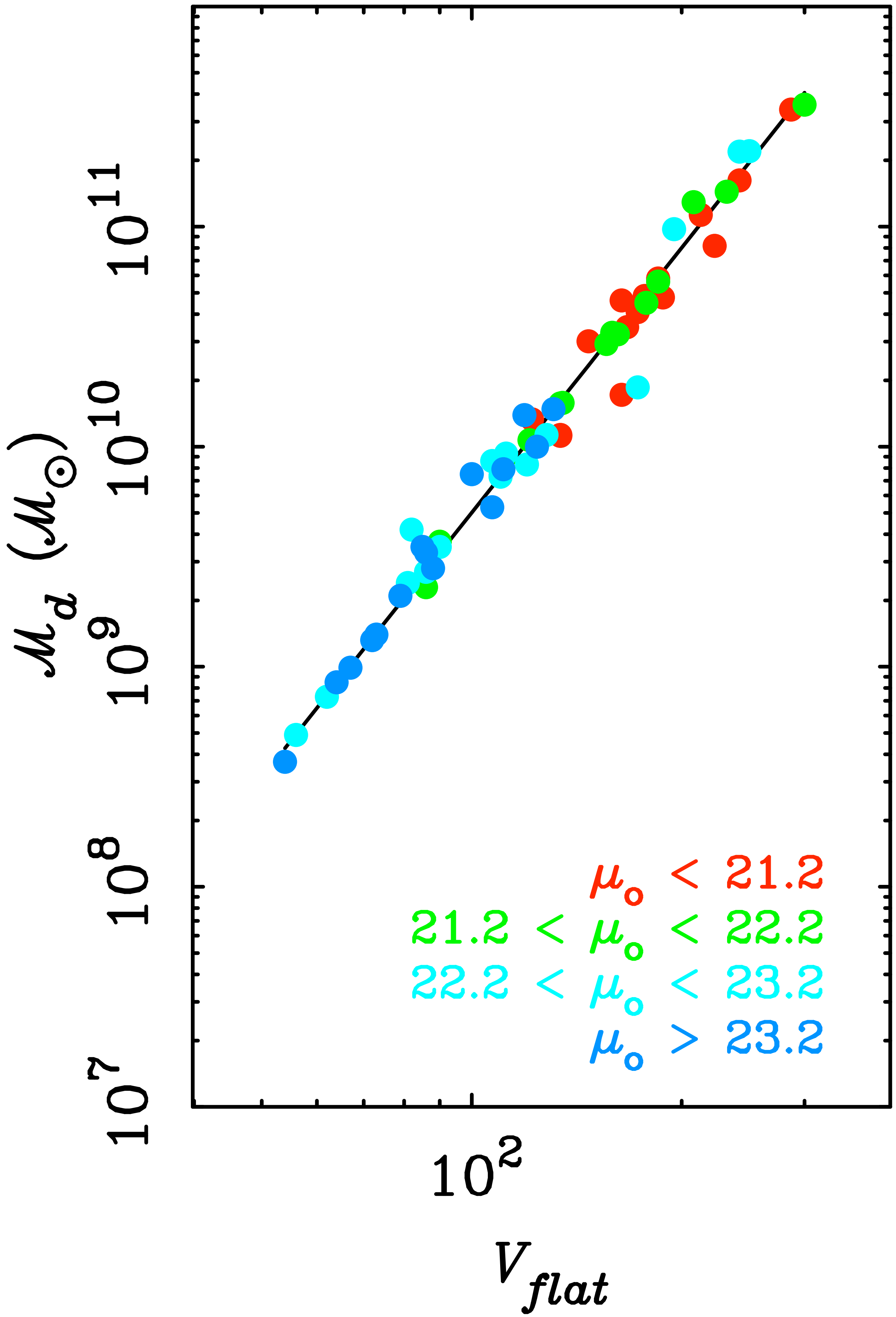
IX. DISCUSSION

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:

MOND predictions

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



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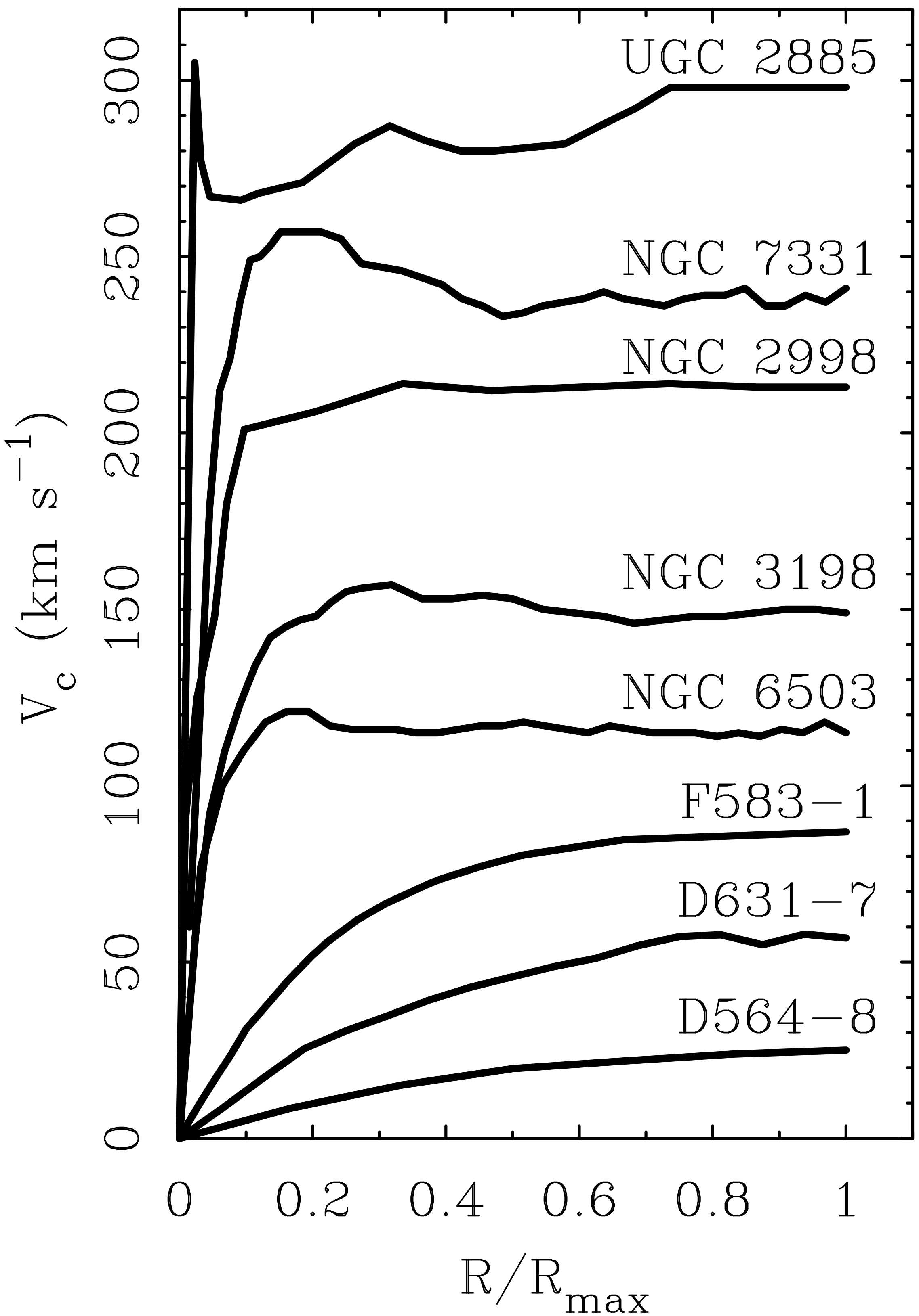
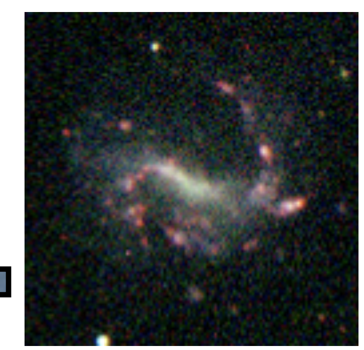
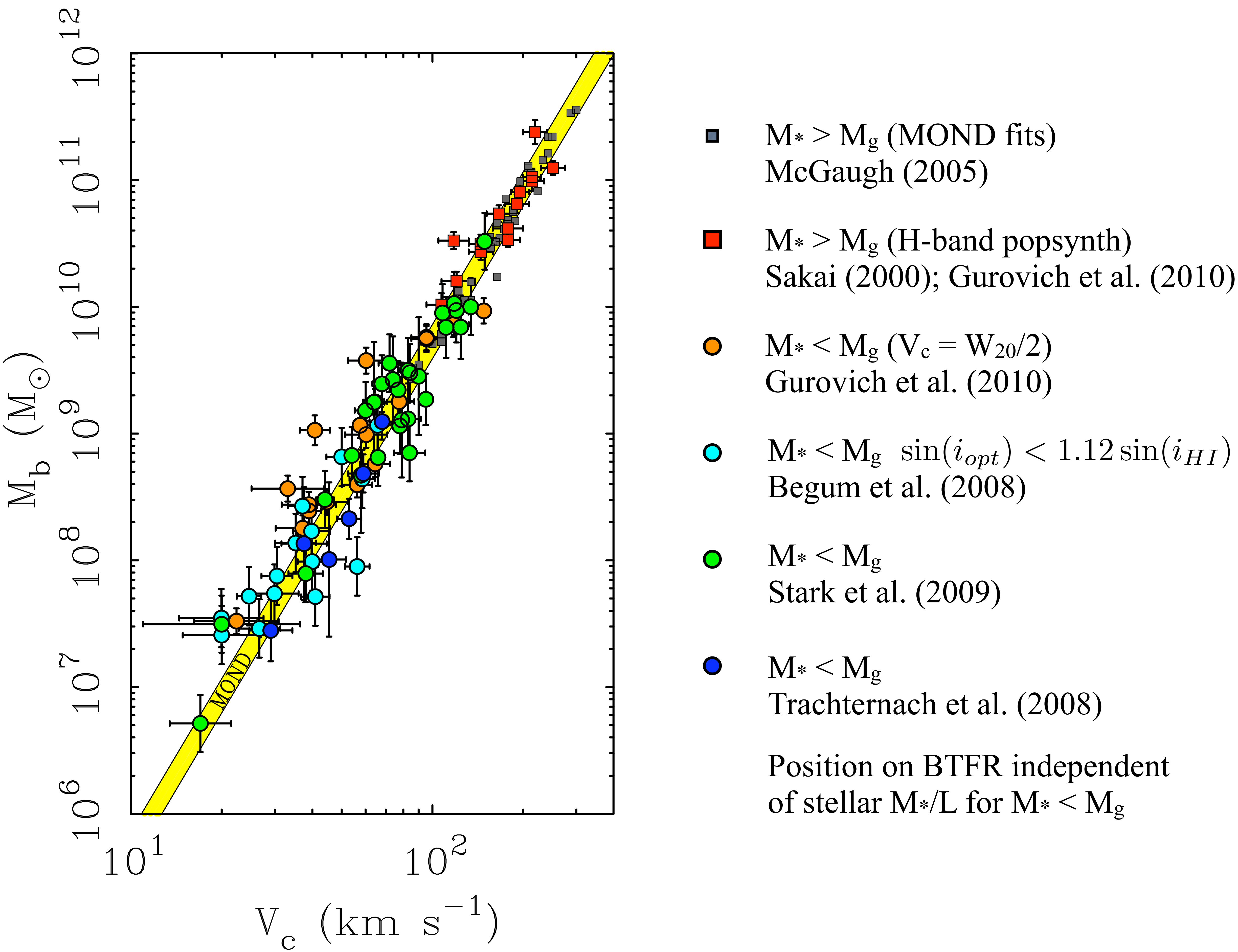
Rotation curves of spirals
and low mass dIrrs with $M_* < M_g$.





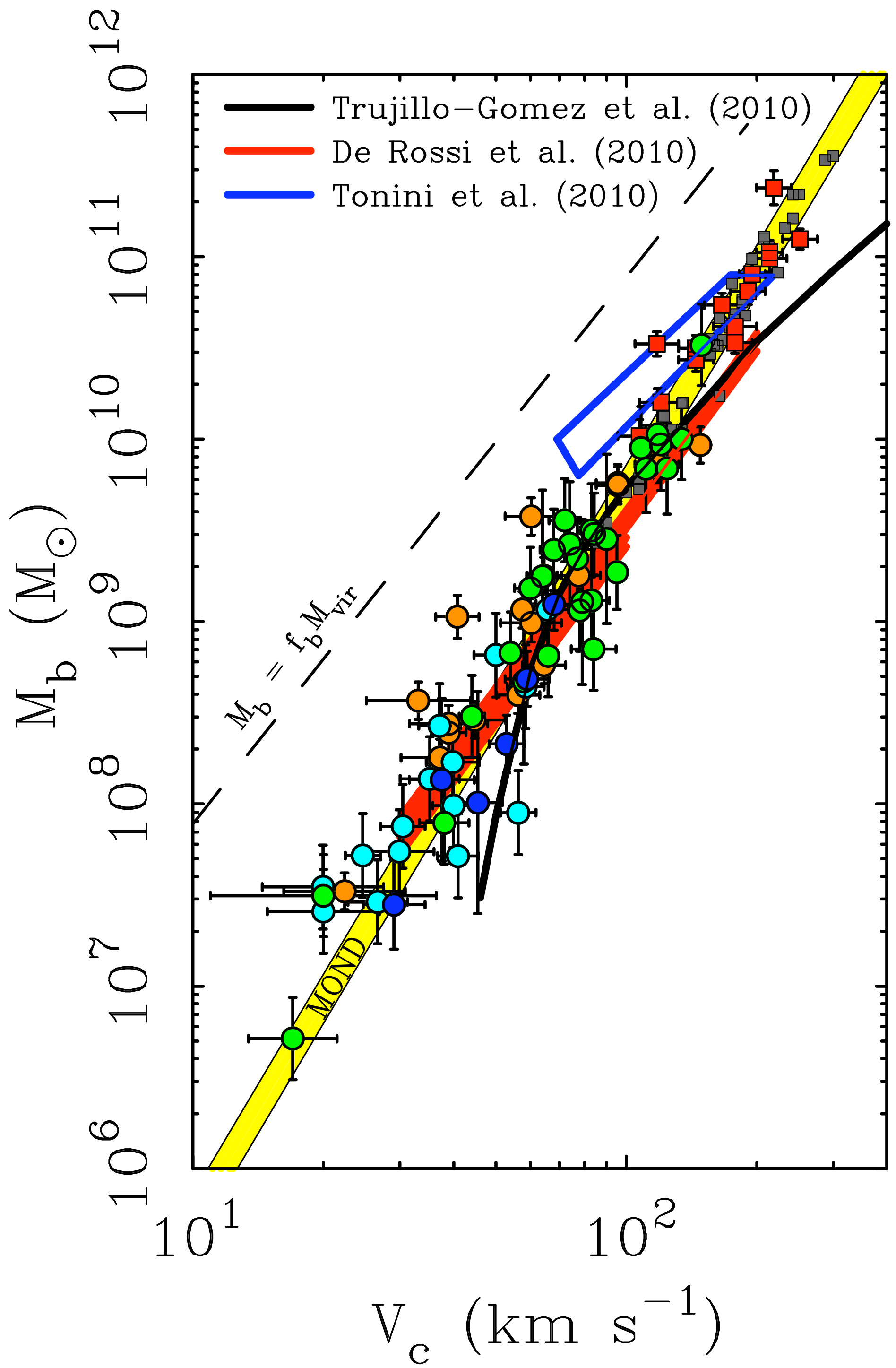
Rotation curves of
late type disks
(Sd, Sm, Irr)

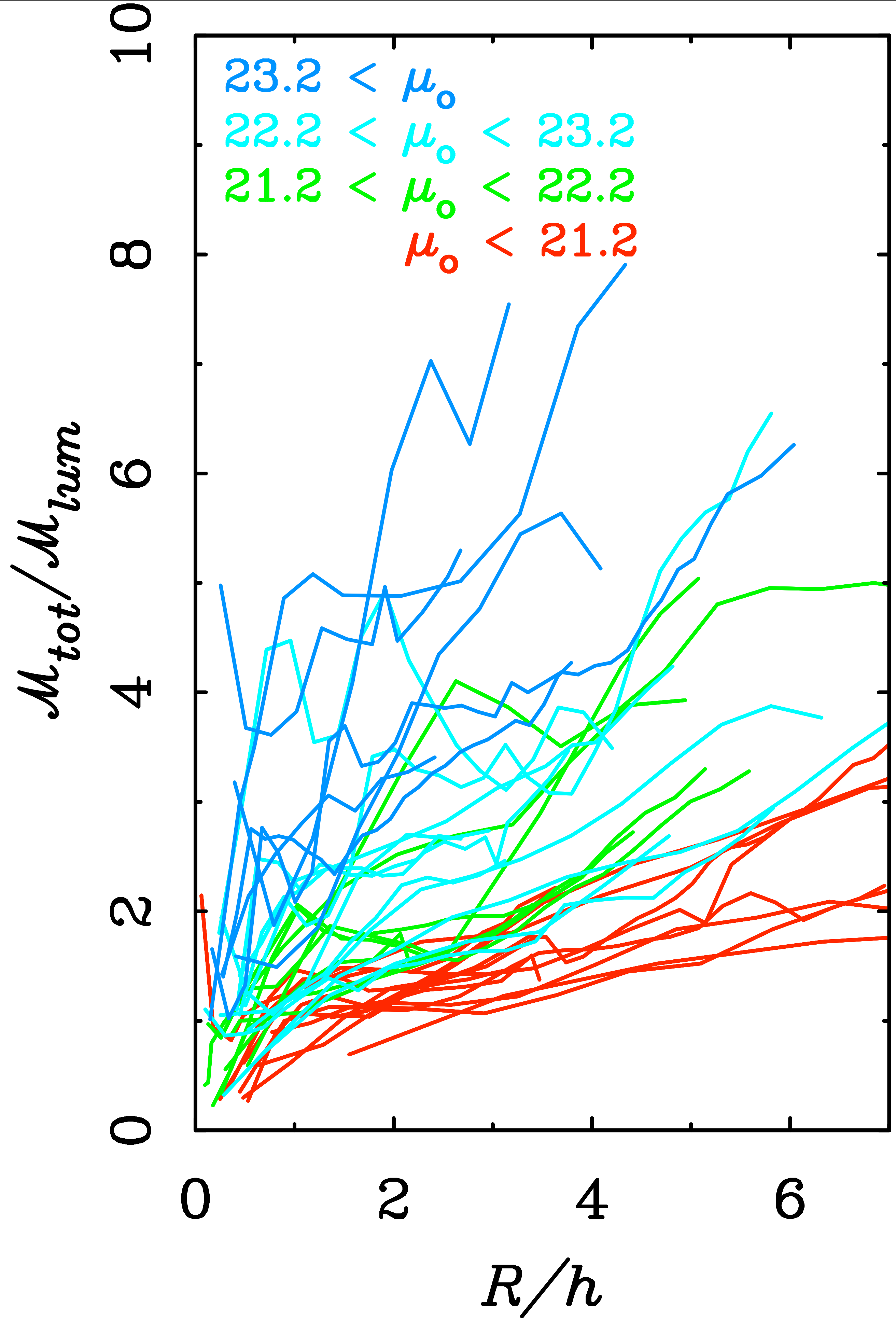
Kuzio de Naray et al.
(2006, 2008, 2009);
Trachternach et al.
(2009)



10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
M_b ($M_\odot$)
10^{1}
10^{2}
V_c (km s^{-1})
MOND
$M_* > M_g$ (MOND fits)
McGaugh (2005)
$M_* > M_g$ (H-band popsynth)
Sakai (2000); Gurovich et al. (2010)
$M_* < M_g$ ($V_c = W_{20}/2$)
Gurovich et al. (2010)
$M_* < M_g$ $\sin(i_{opt}) < 1.12 \sin(i_{HI})$
Begum et al. (2008)
$M_* < M_g$
Stark et al. (2009)
$M_* < M_g$
Trachternach et al. (2008)
Position on BTFR independent
of stellar M_*/L for $M_* < M_g$

- MOND accurately predicts the BTF location of gas dominated galaxies with zero free parameters.
- CDM does not do this.





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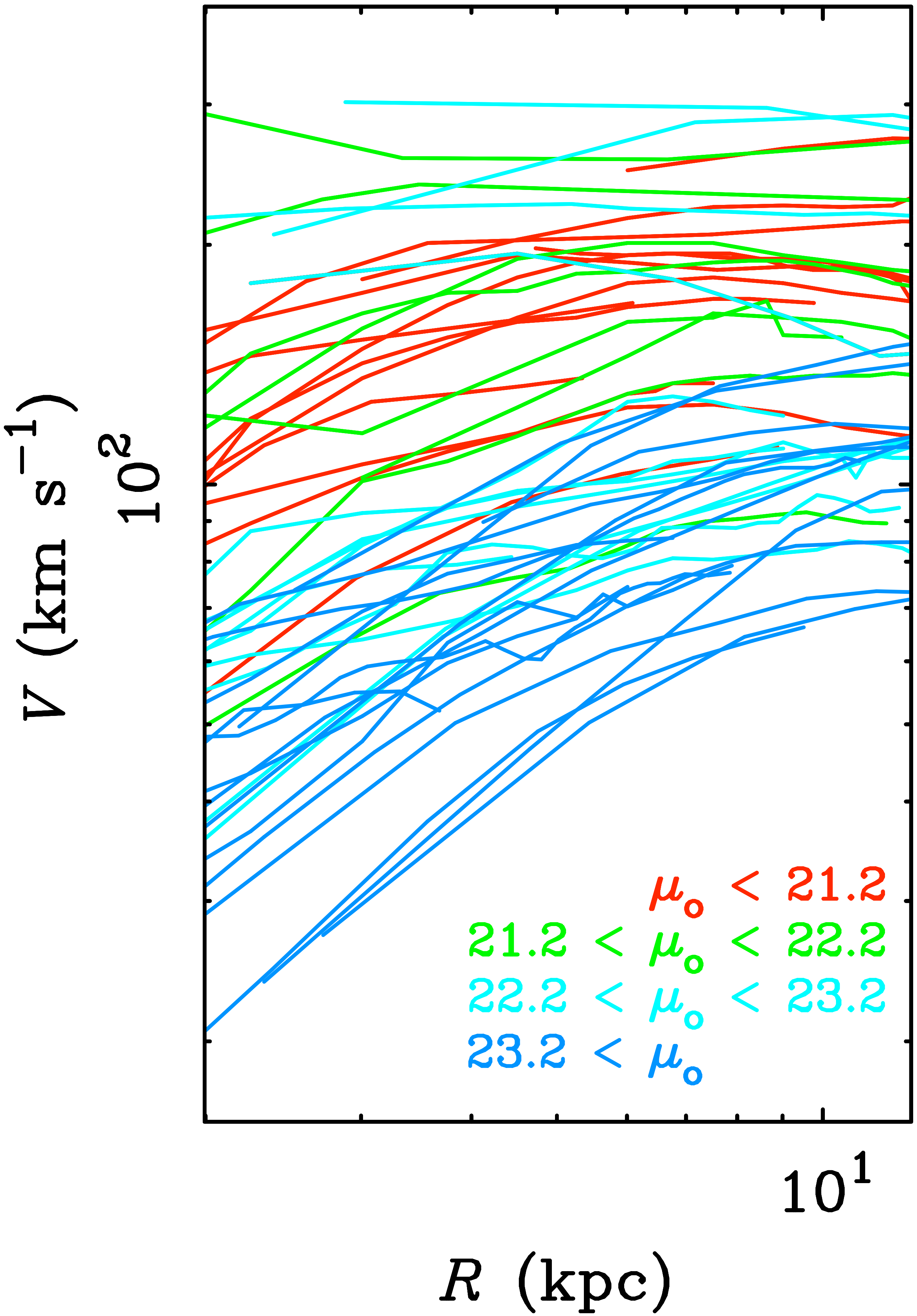

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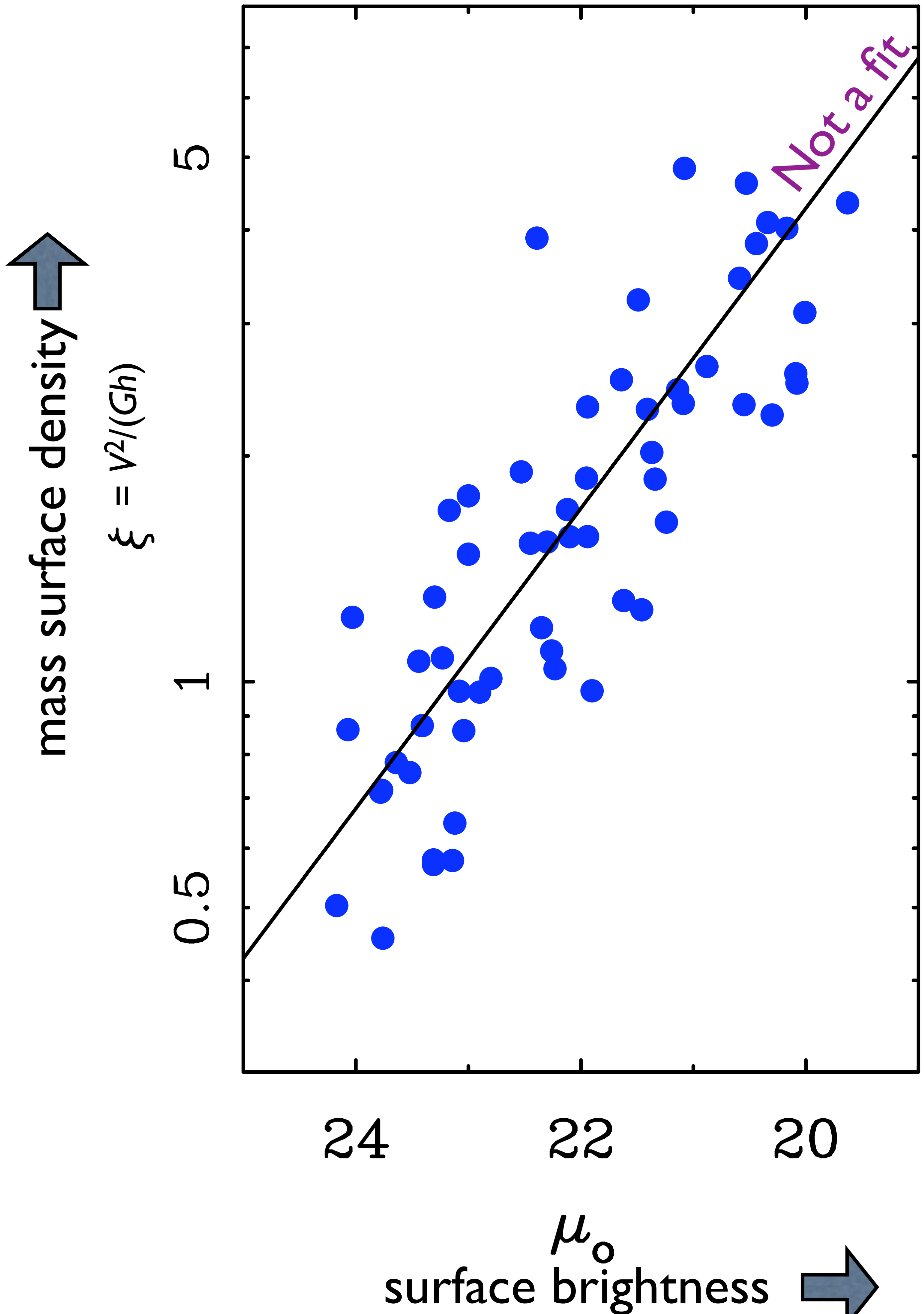

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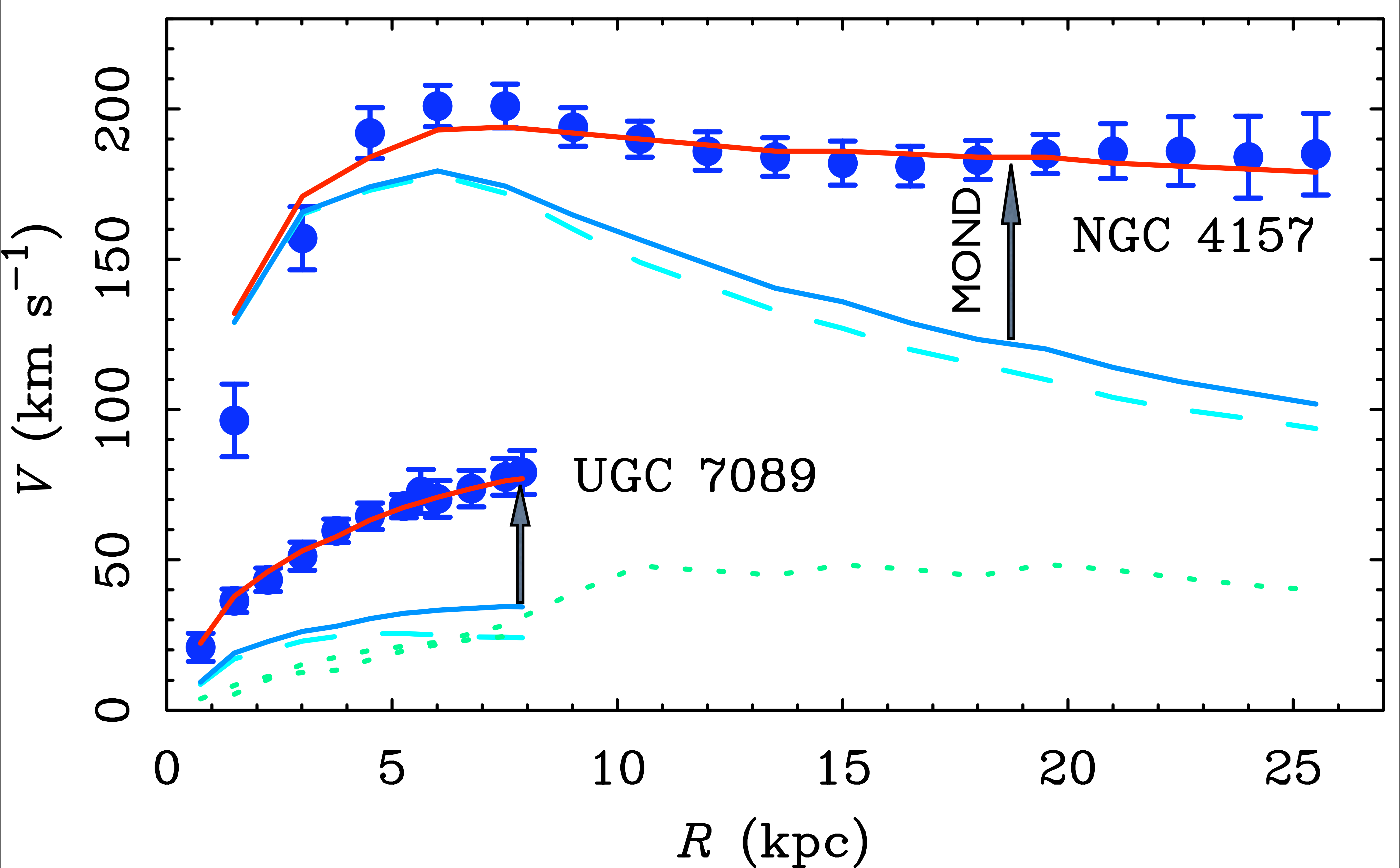
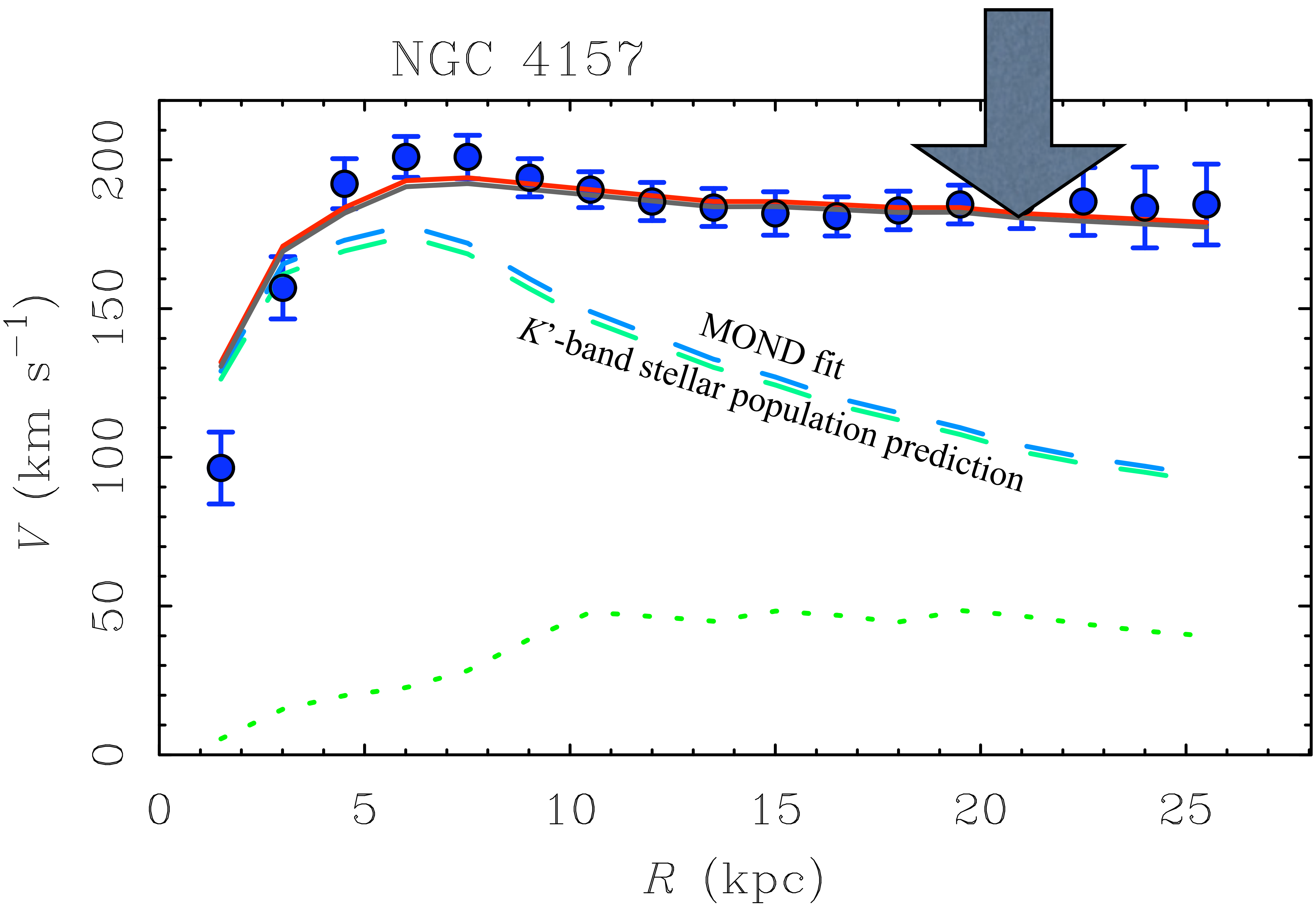
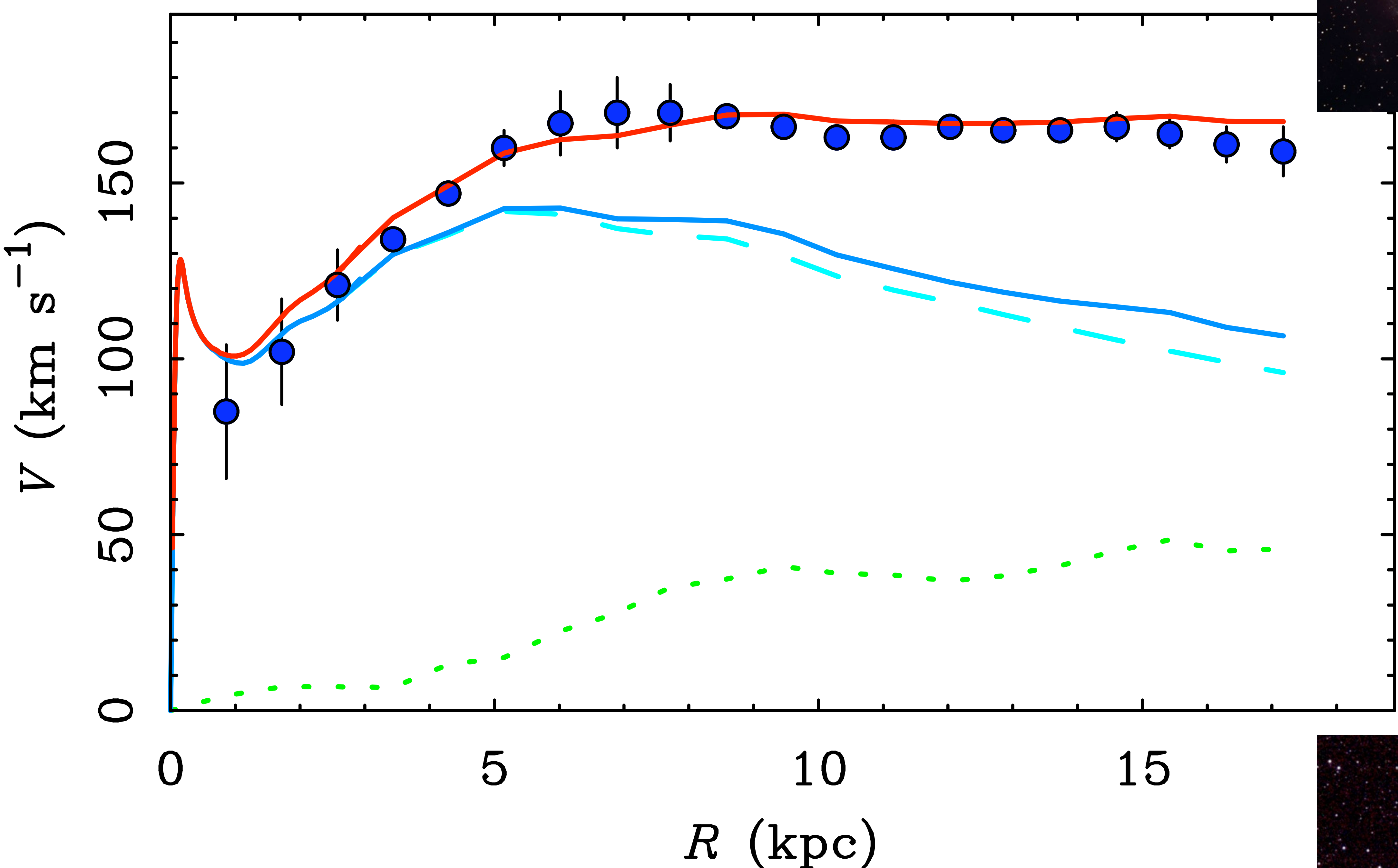


V (km s^{-1})
R (kpc)
NGC 4157
UGC 7089
MOND
0
50
100
150
200
0
5
10
15
20
25

predictive power: zero free parameters



NGC 6946 - small bulge predicted



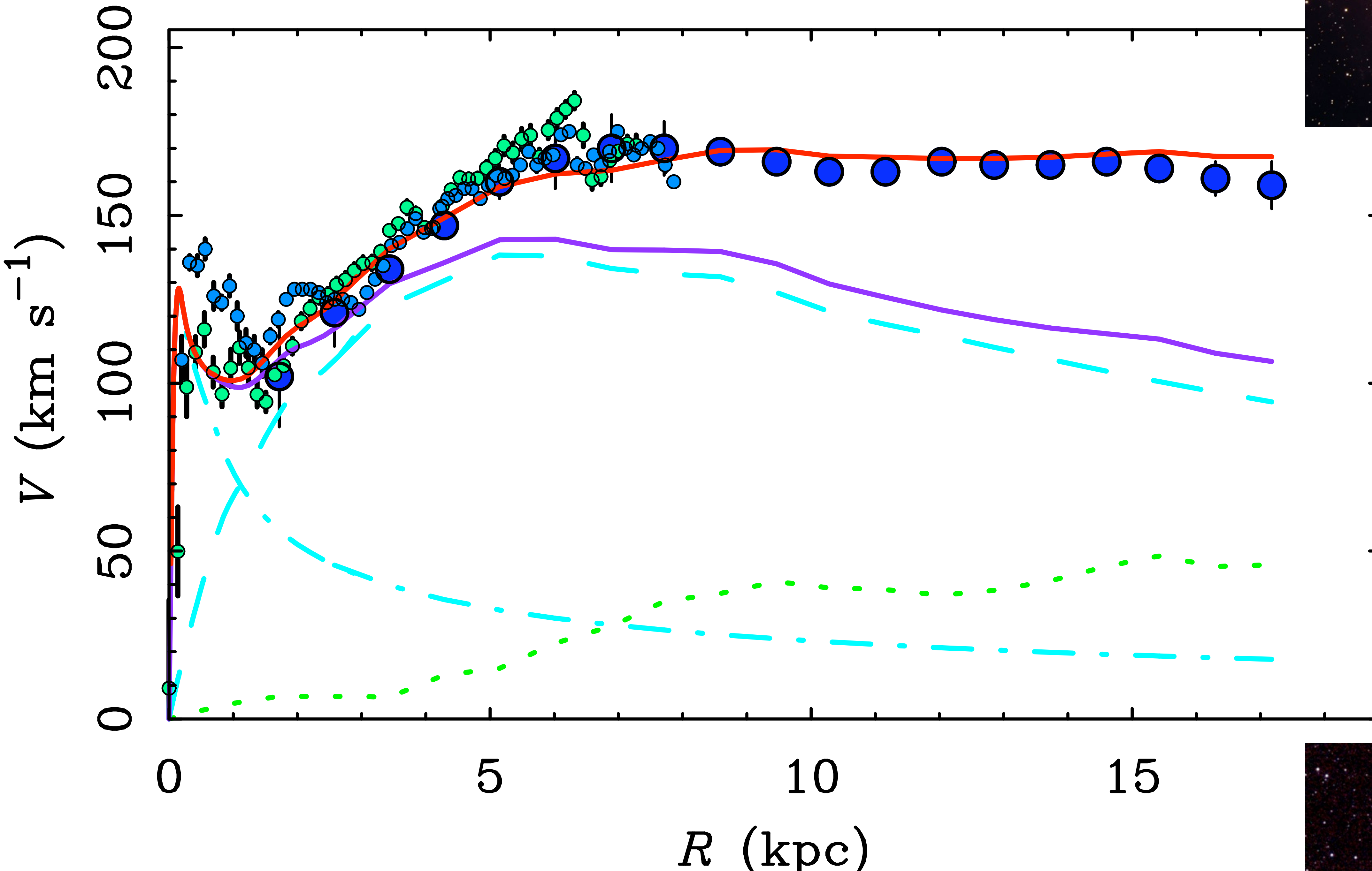
optical

near-IR

Renzo's Rule:

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

NGC 6946 - small bulge observed



optical

near-IR

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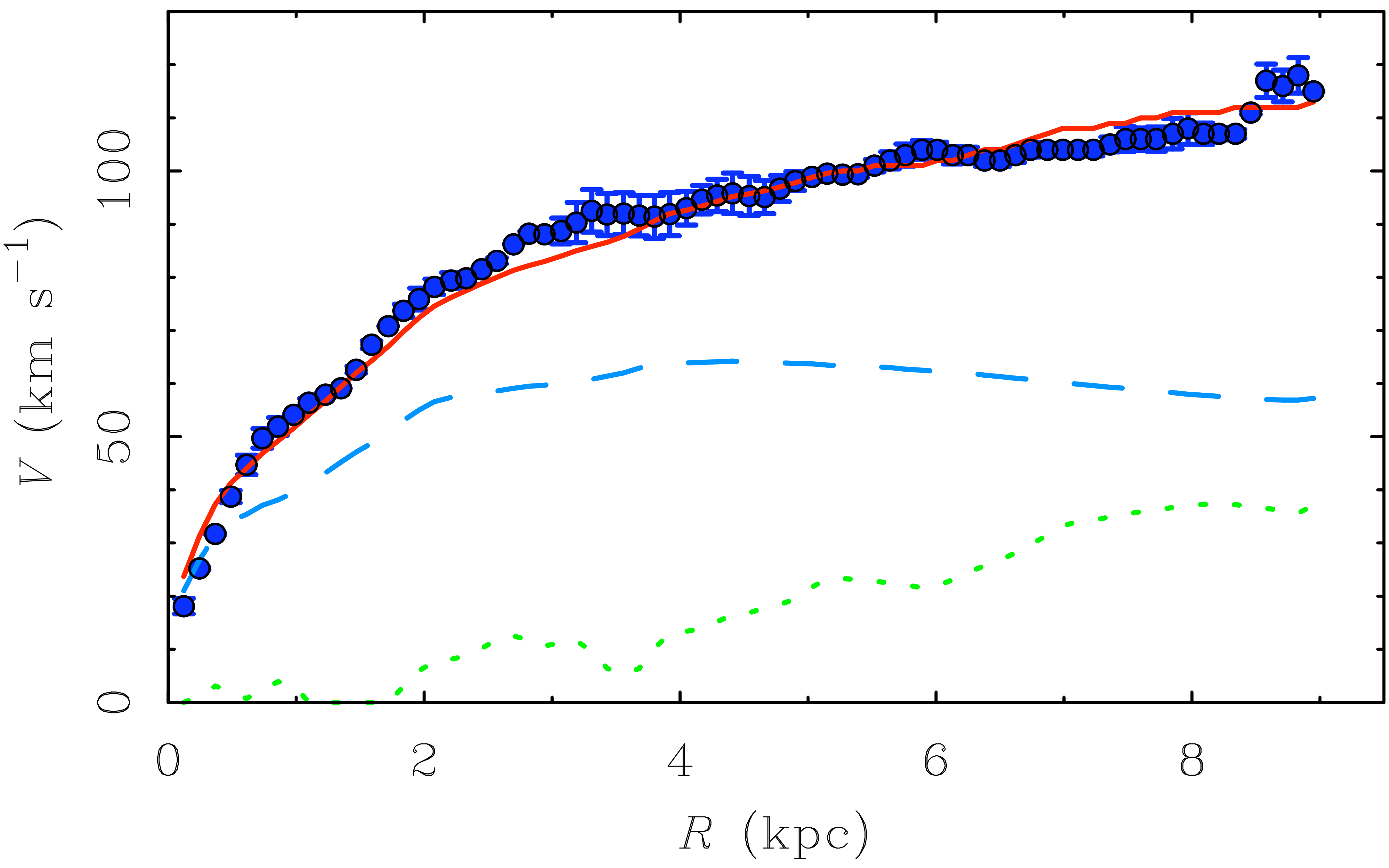
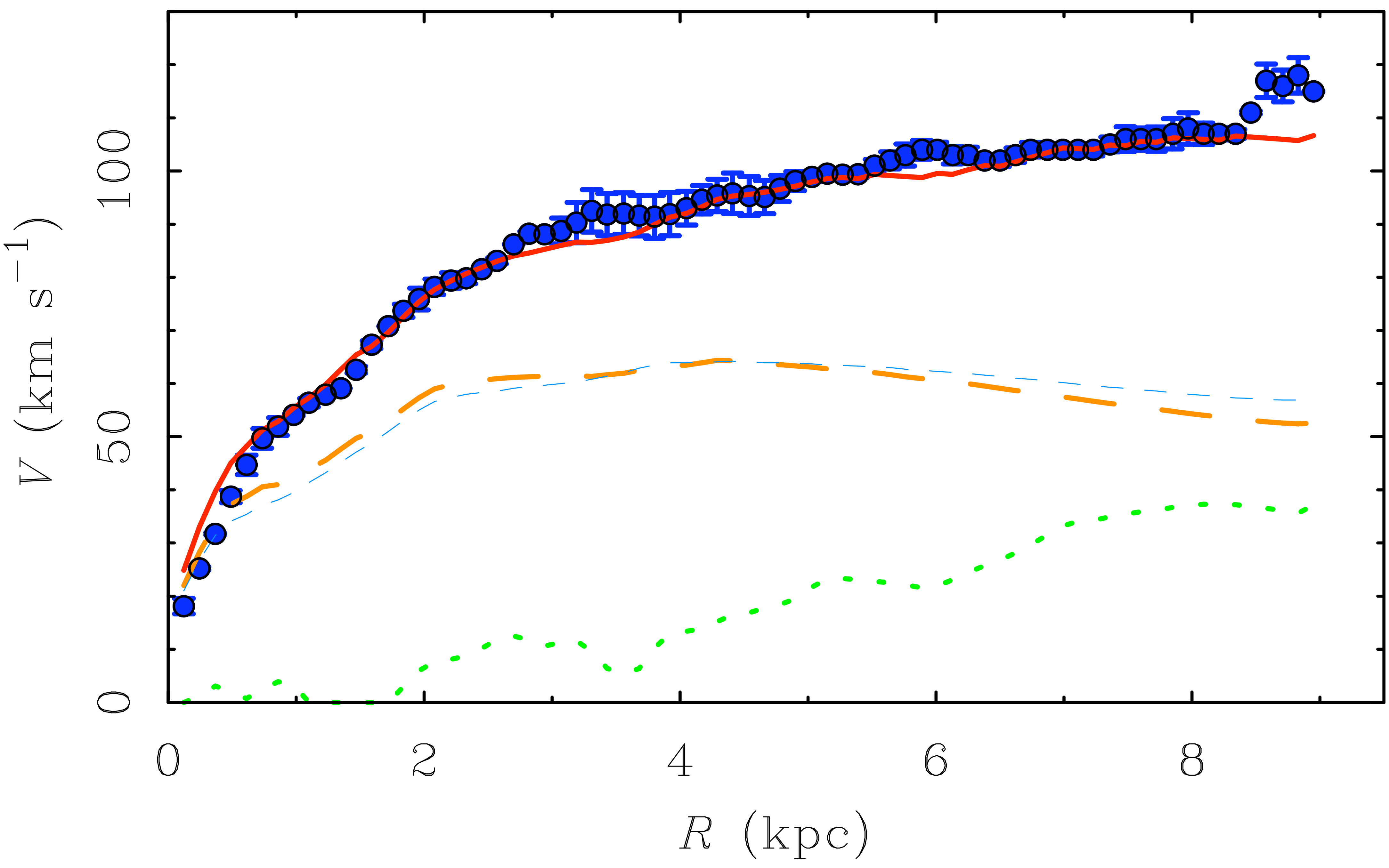
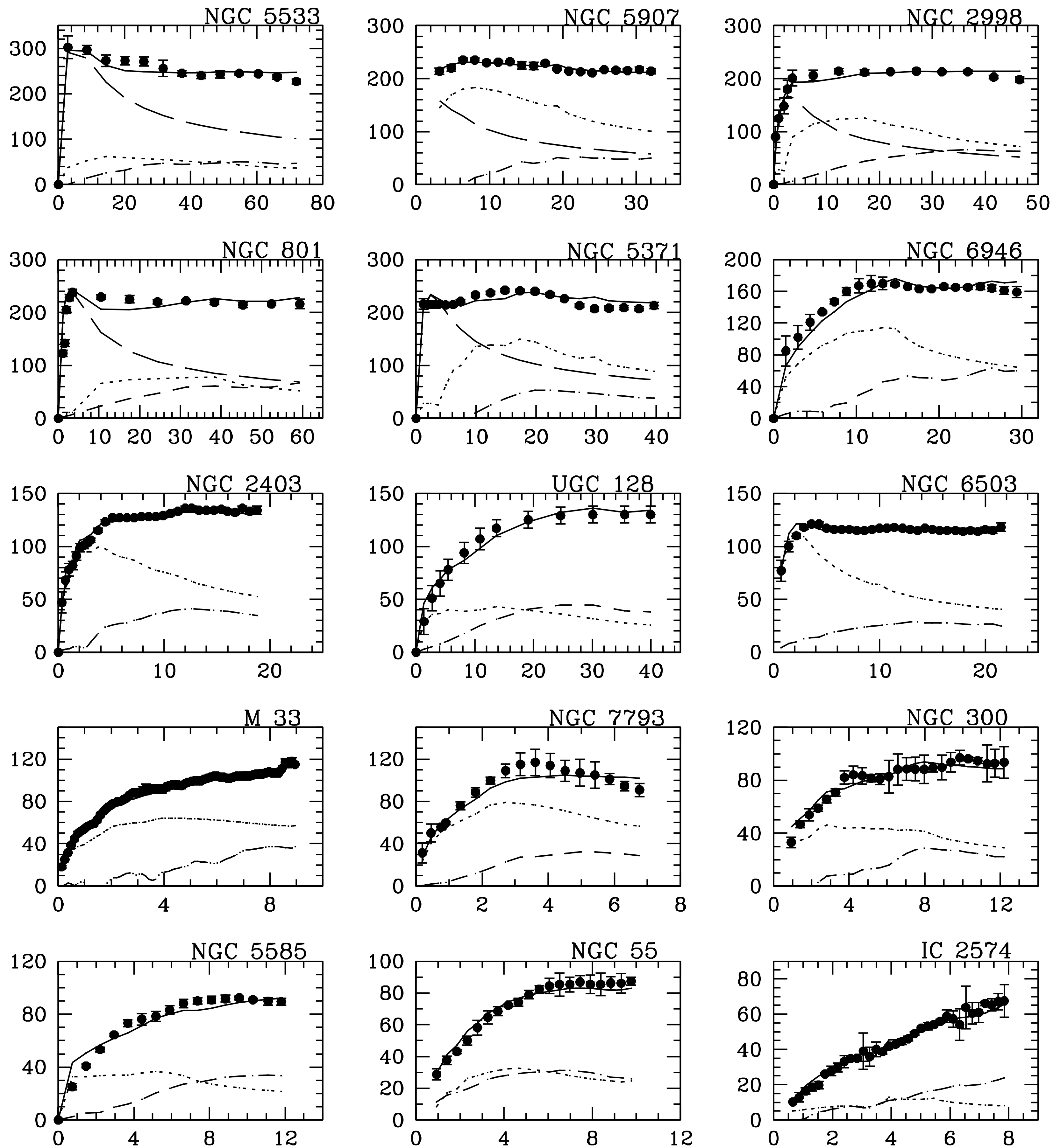
M33

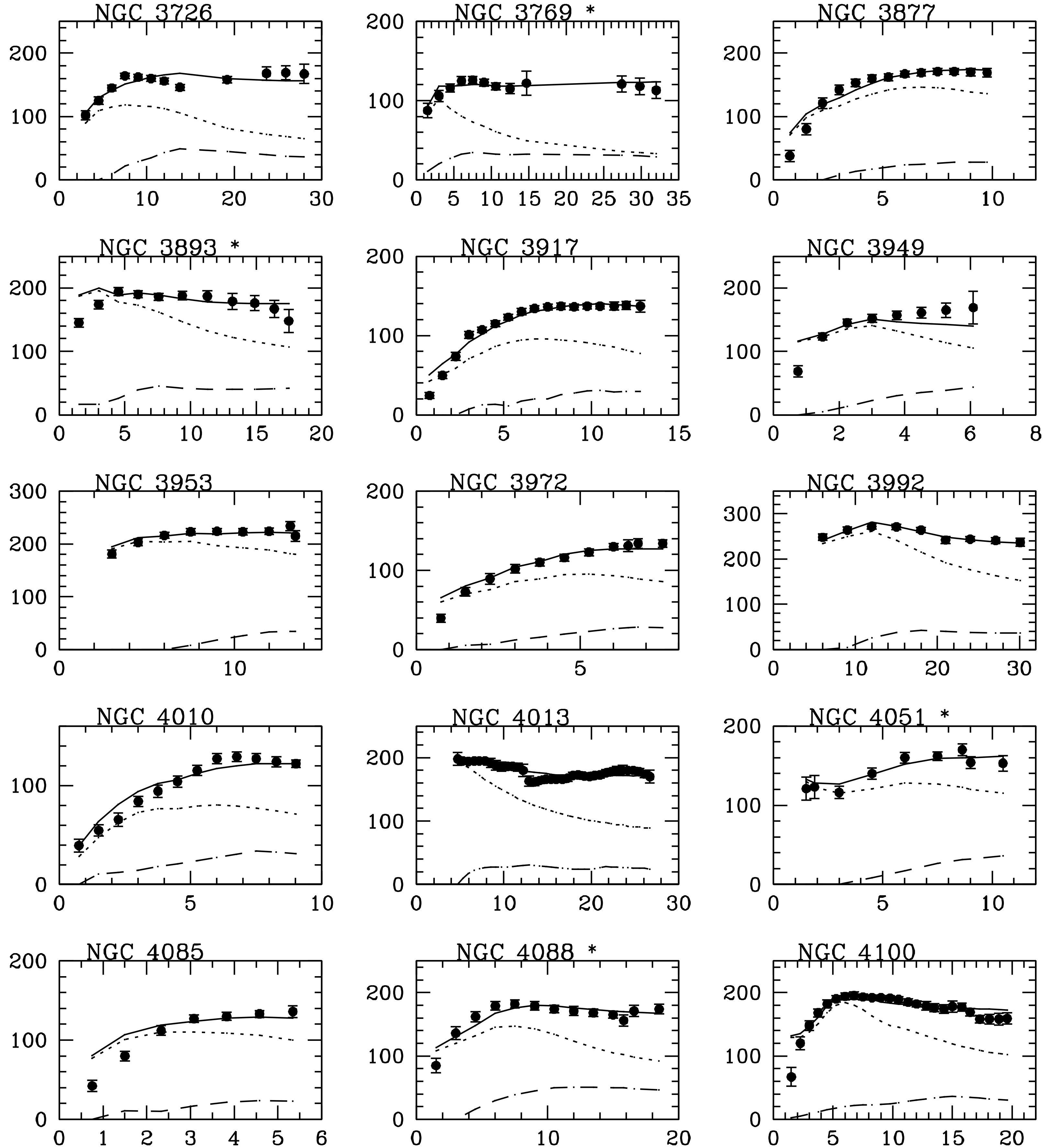


M33 color gradient corrected



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





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

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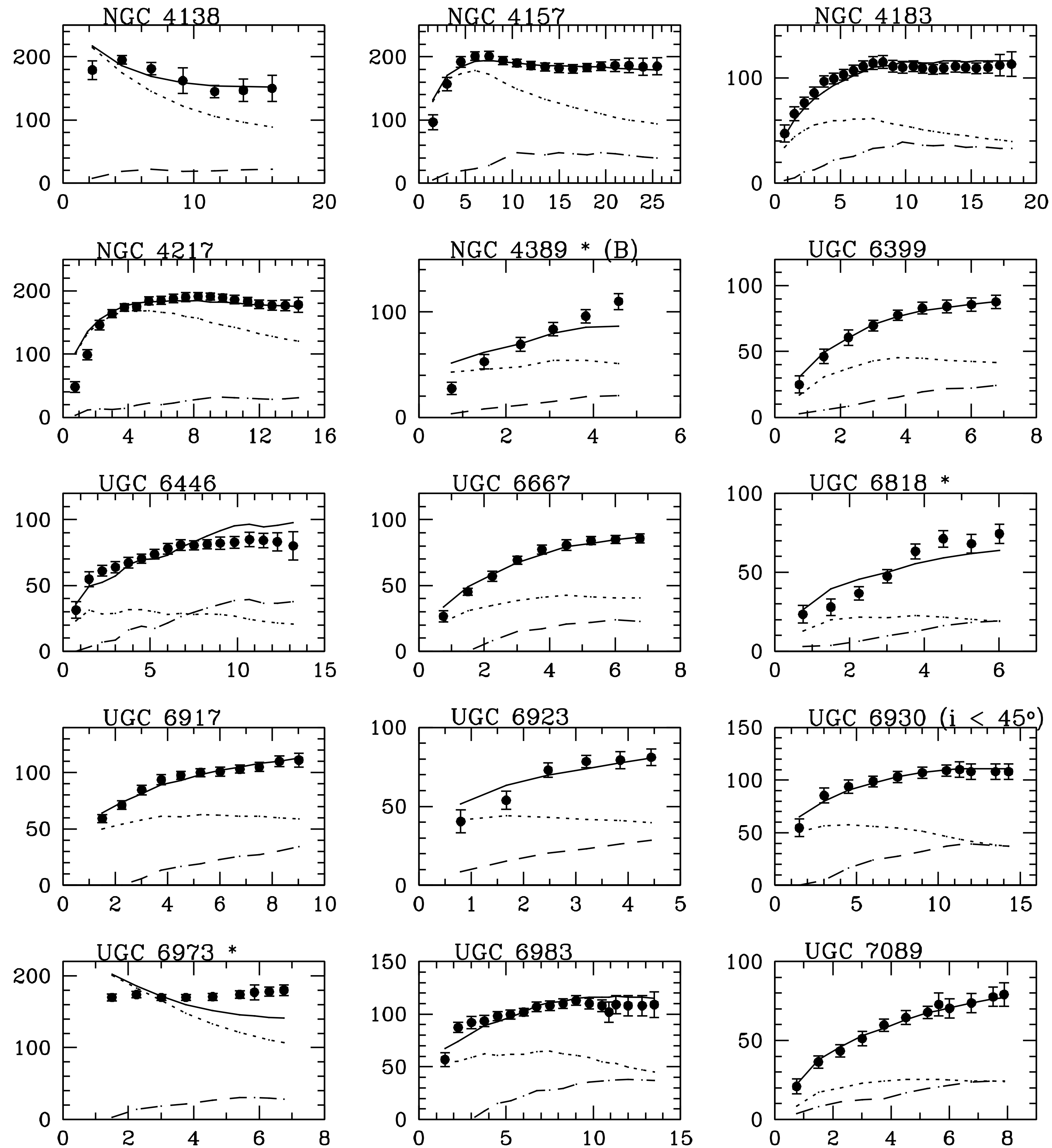
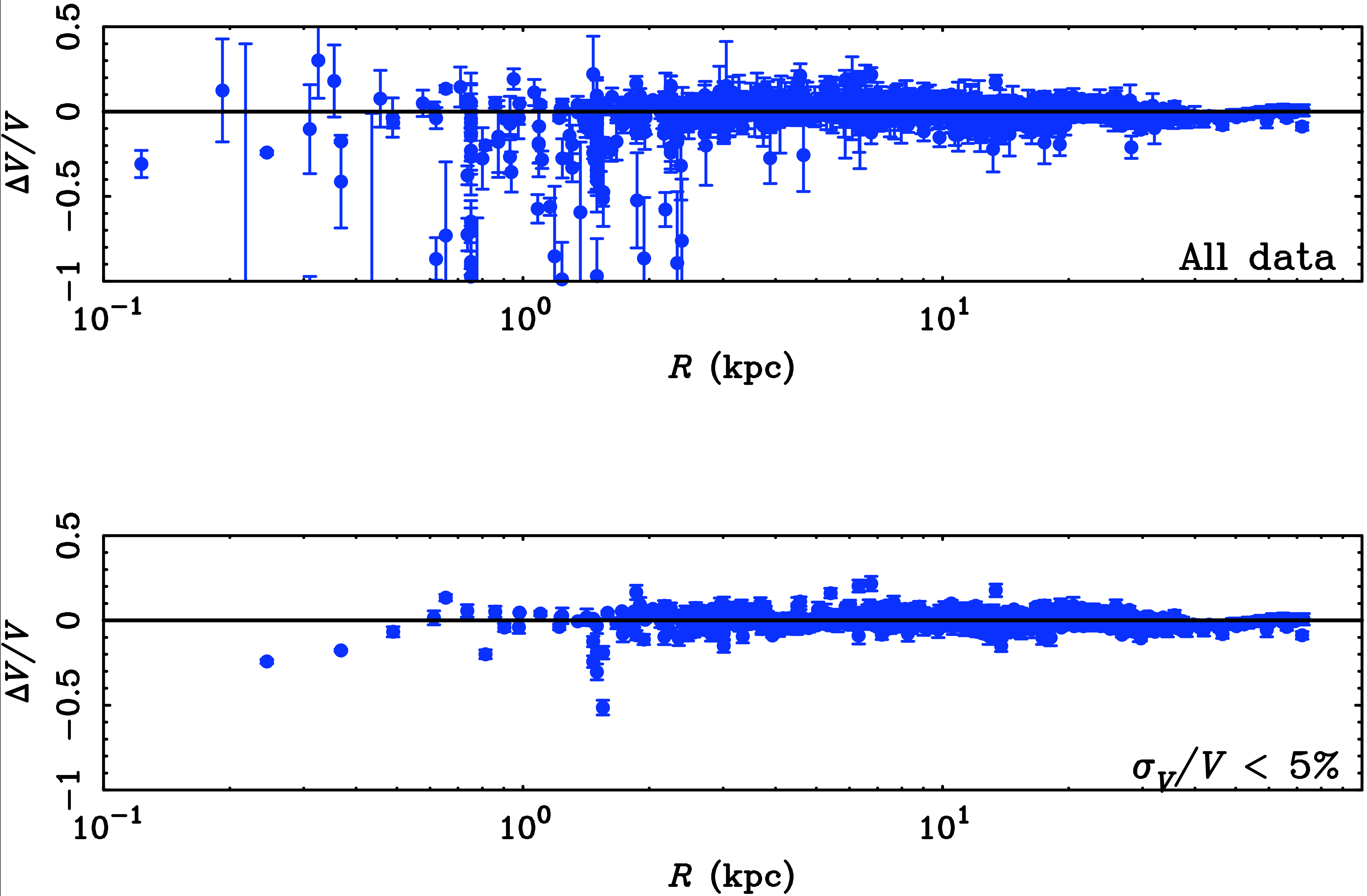
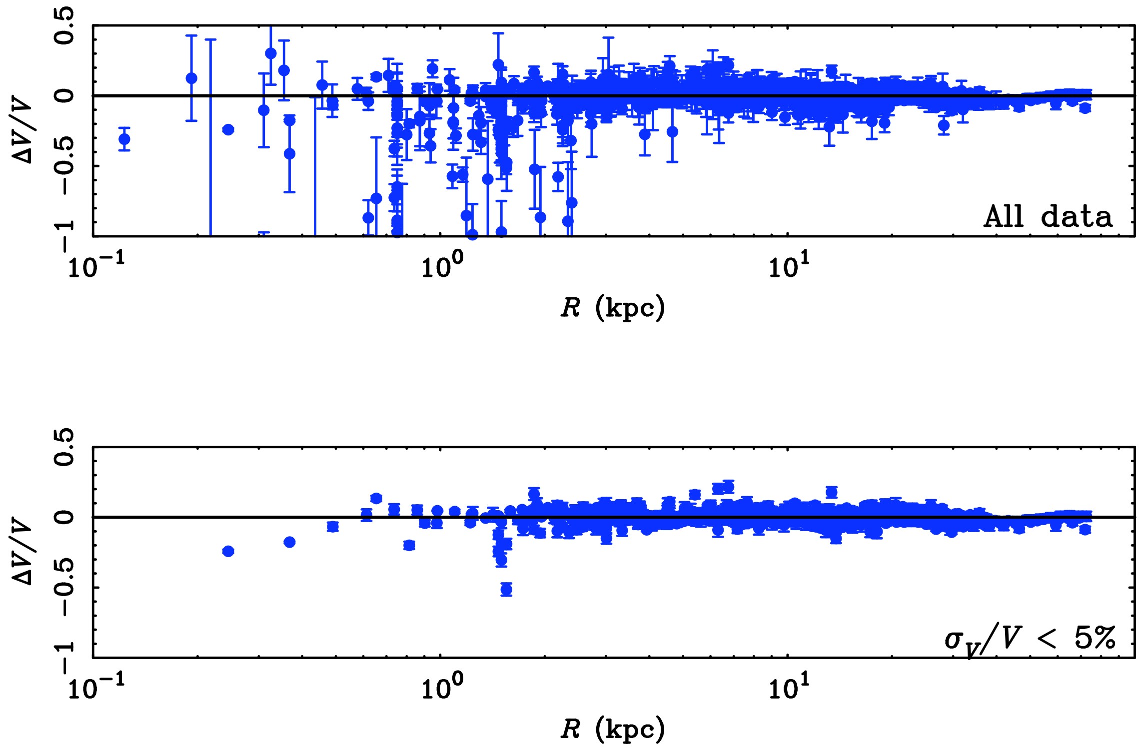


Residuals of MOND fits



MOND predictions



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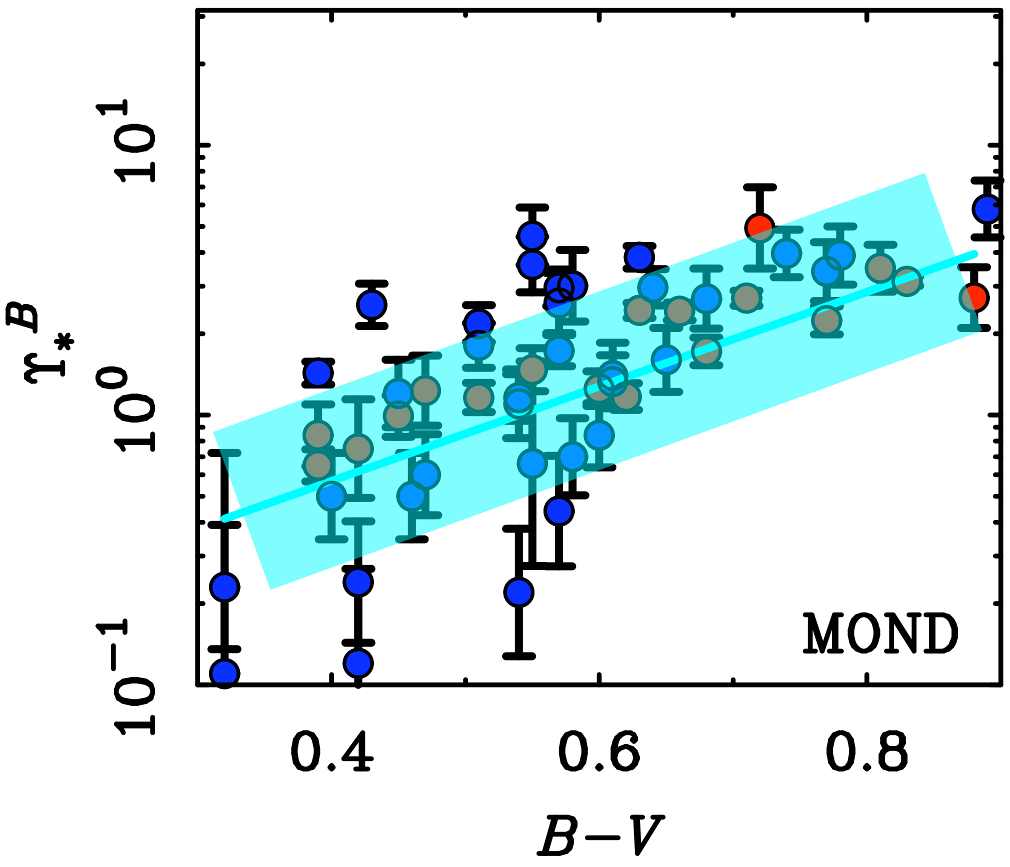
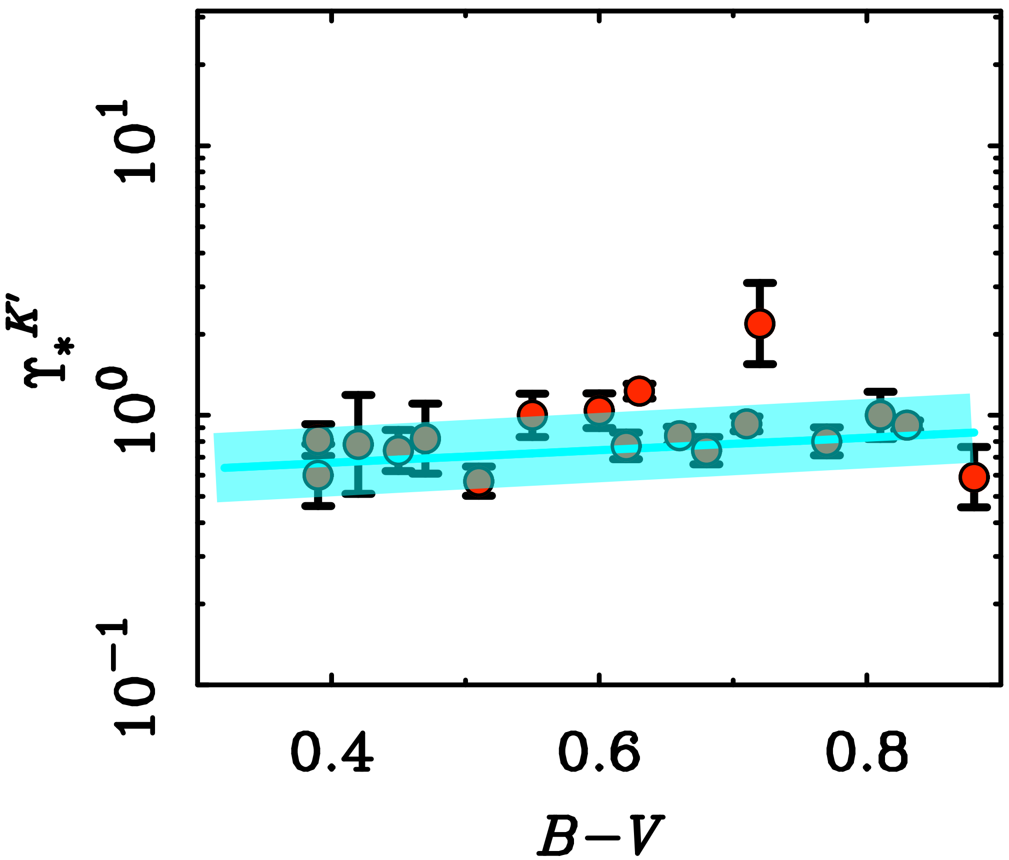
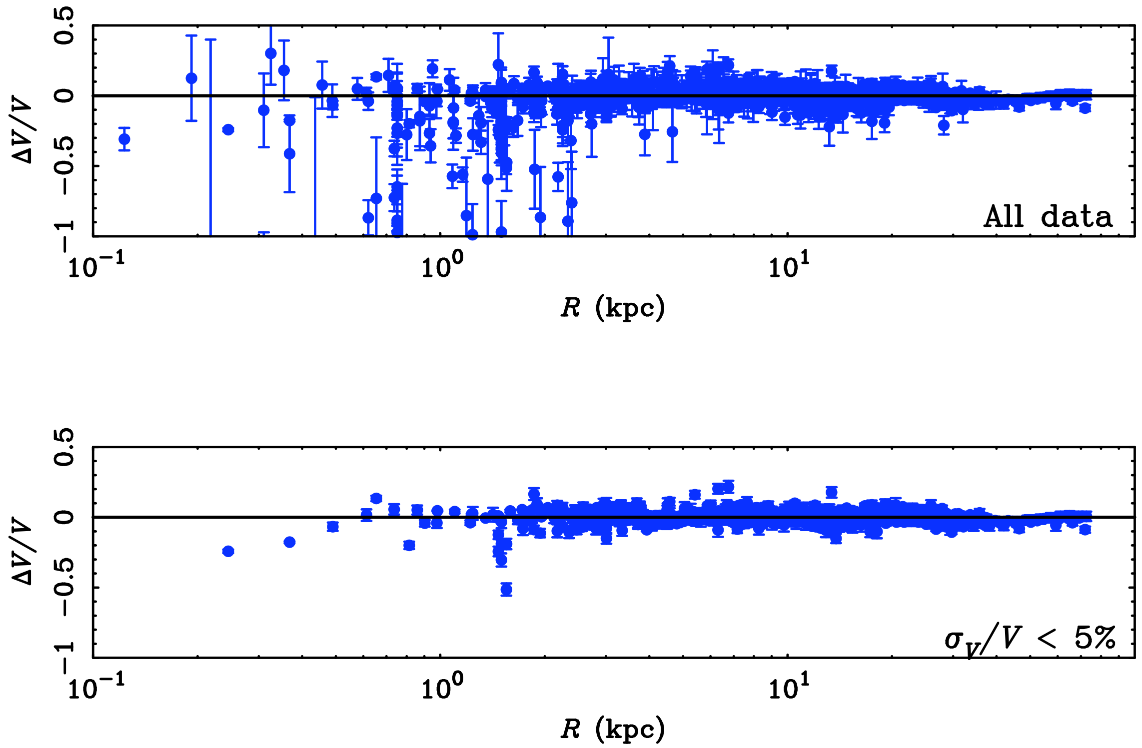


Line: stellar population model
(mean expectation)



MOND predictions



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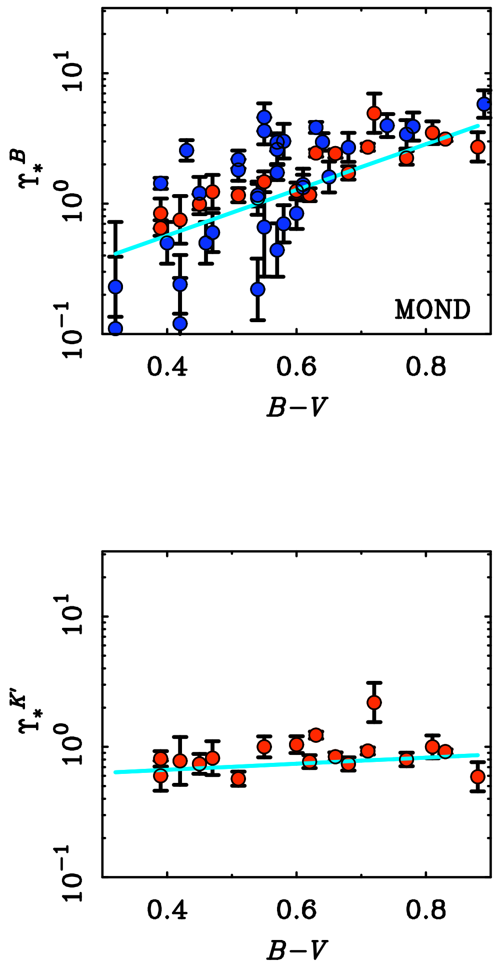
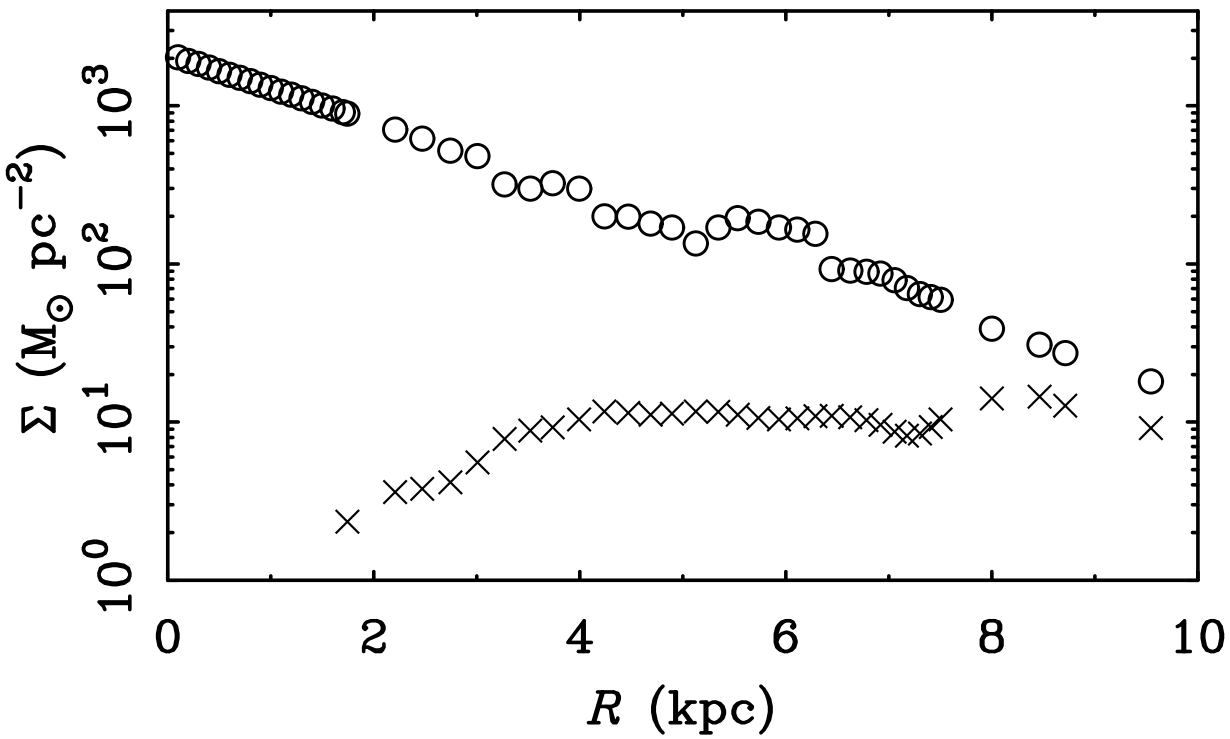
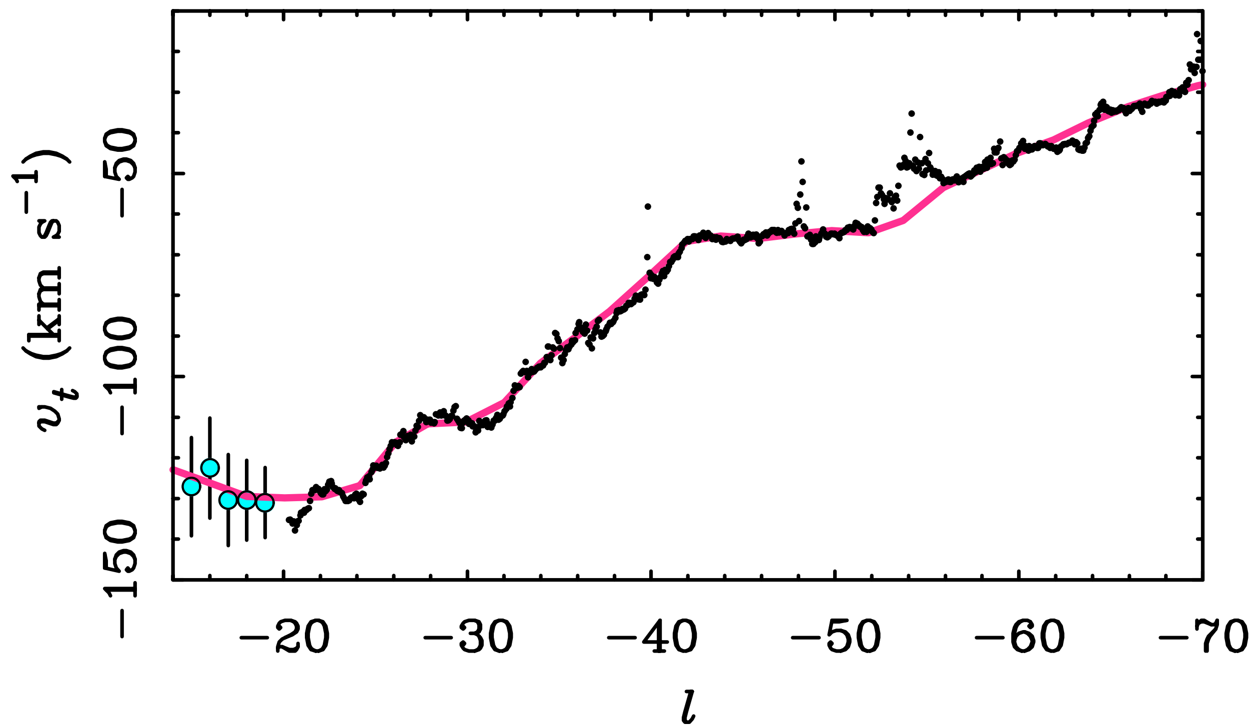


Can we reverse the procedure?

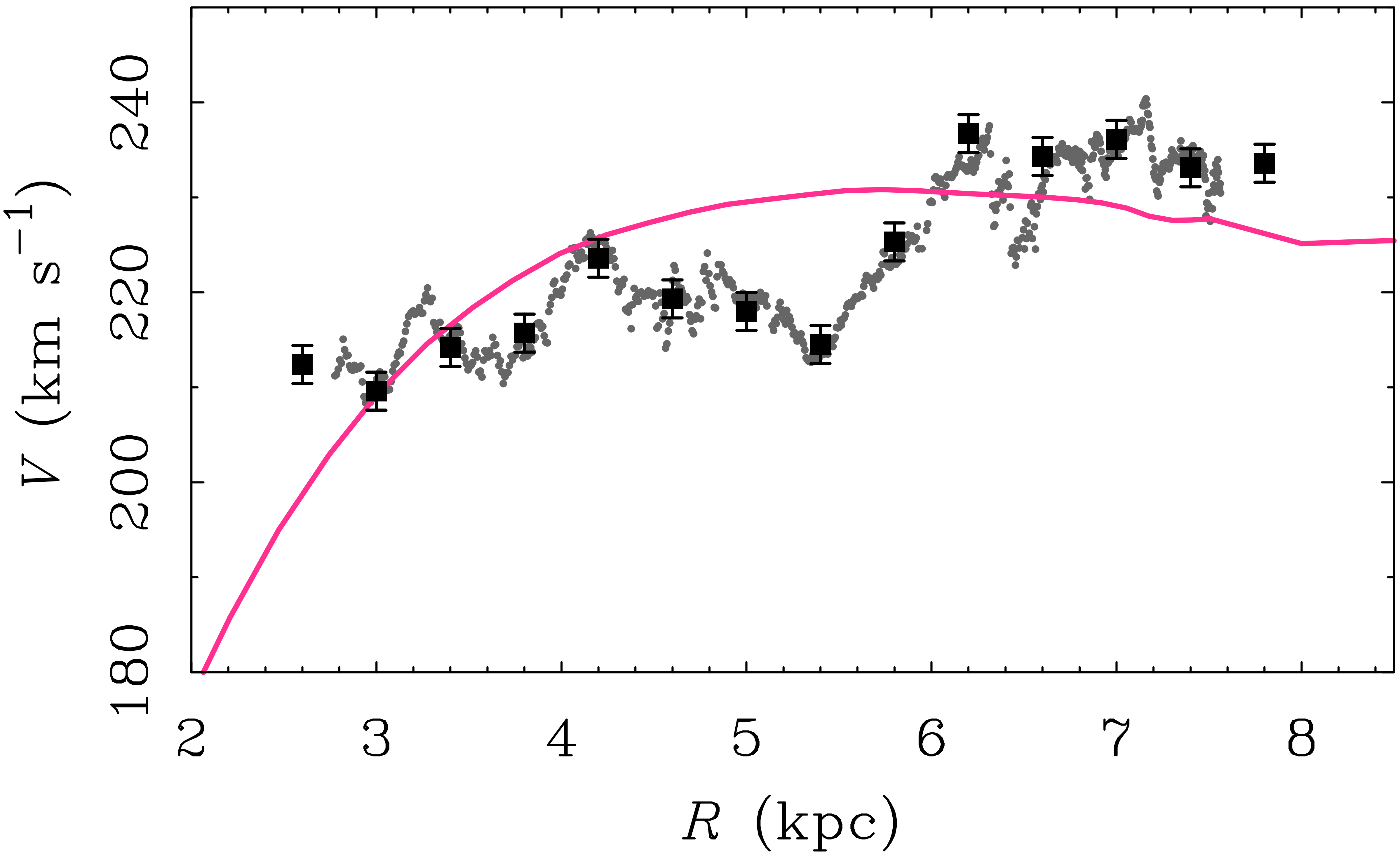
Rather than fitting rotation curves given the photometry, can we infer the baryonic mass distribution from the rotation curve?



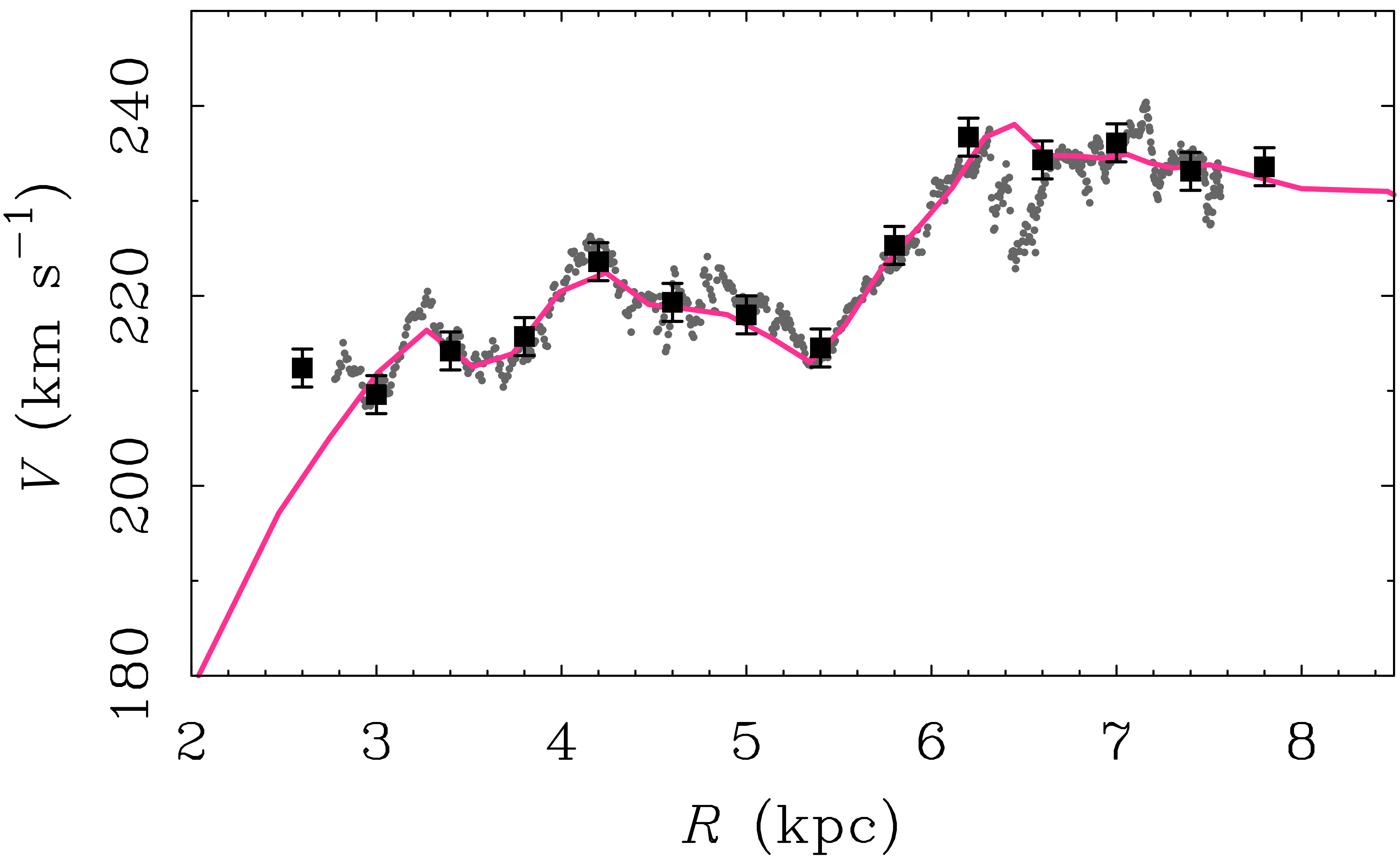
Milky Way terminal velocities



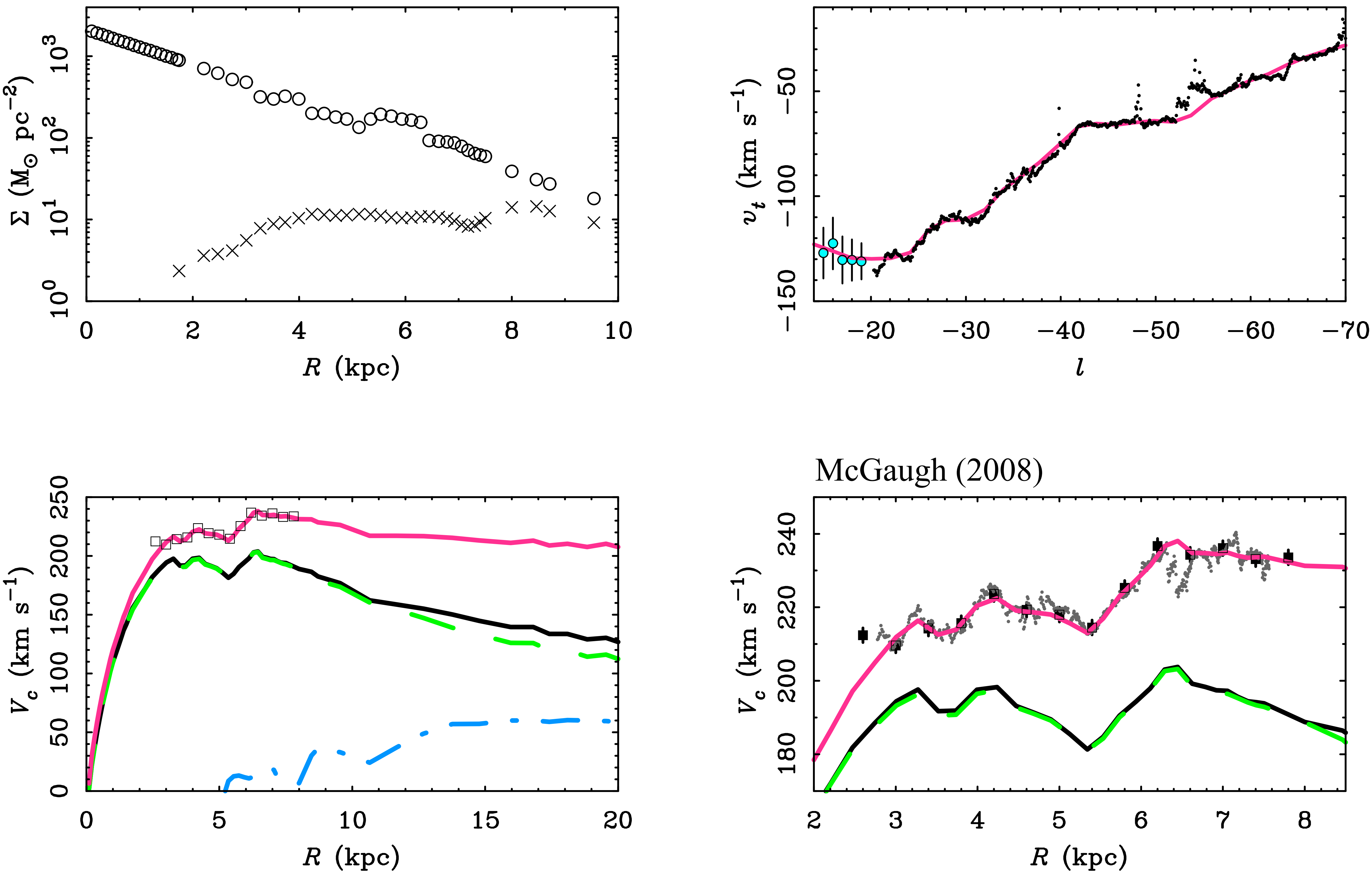
initial guess

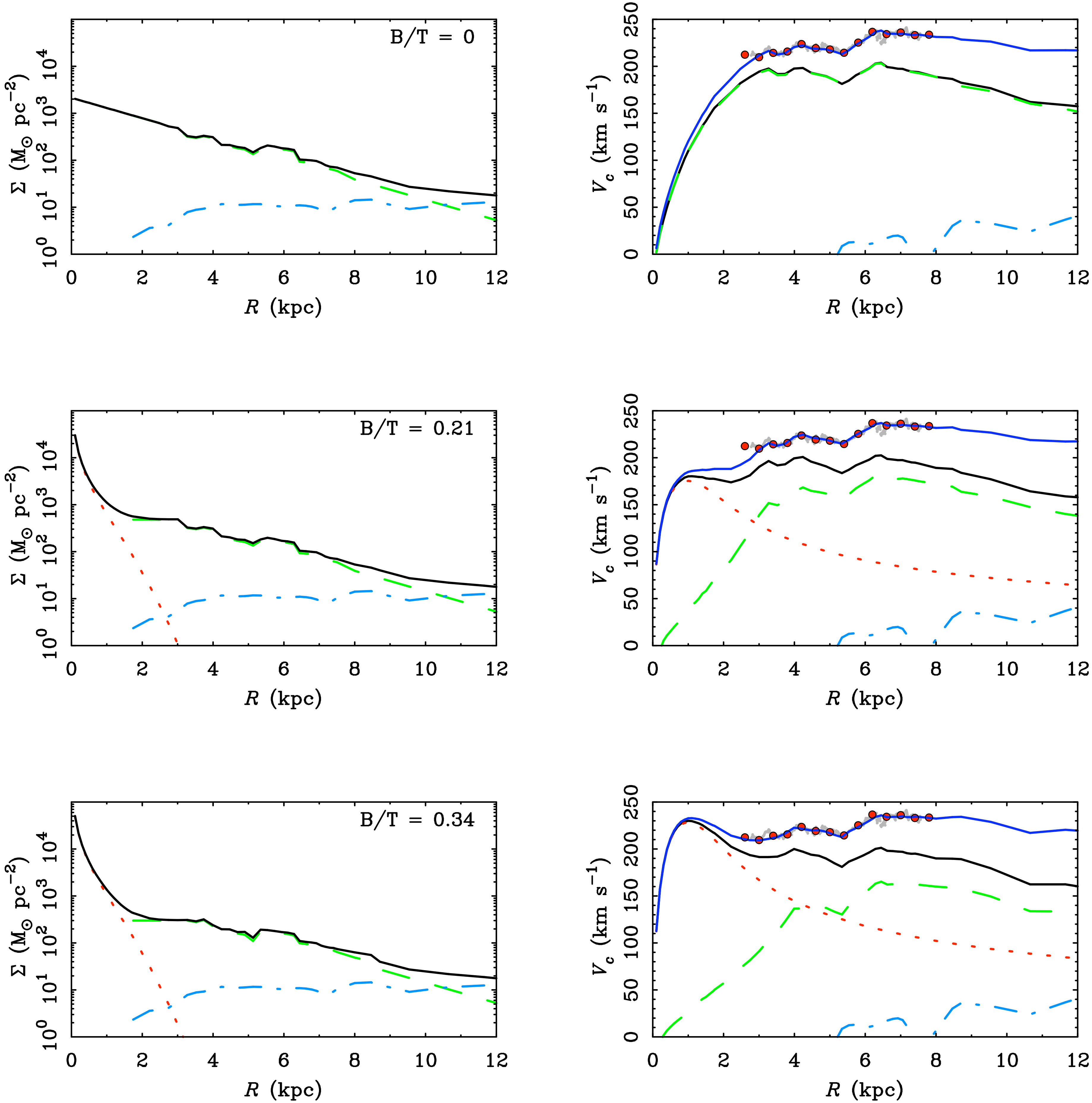


final fit



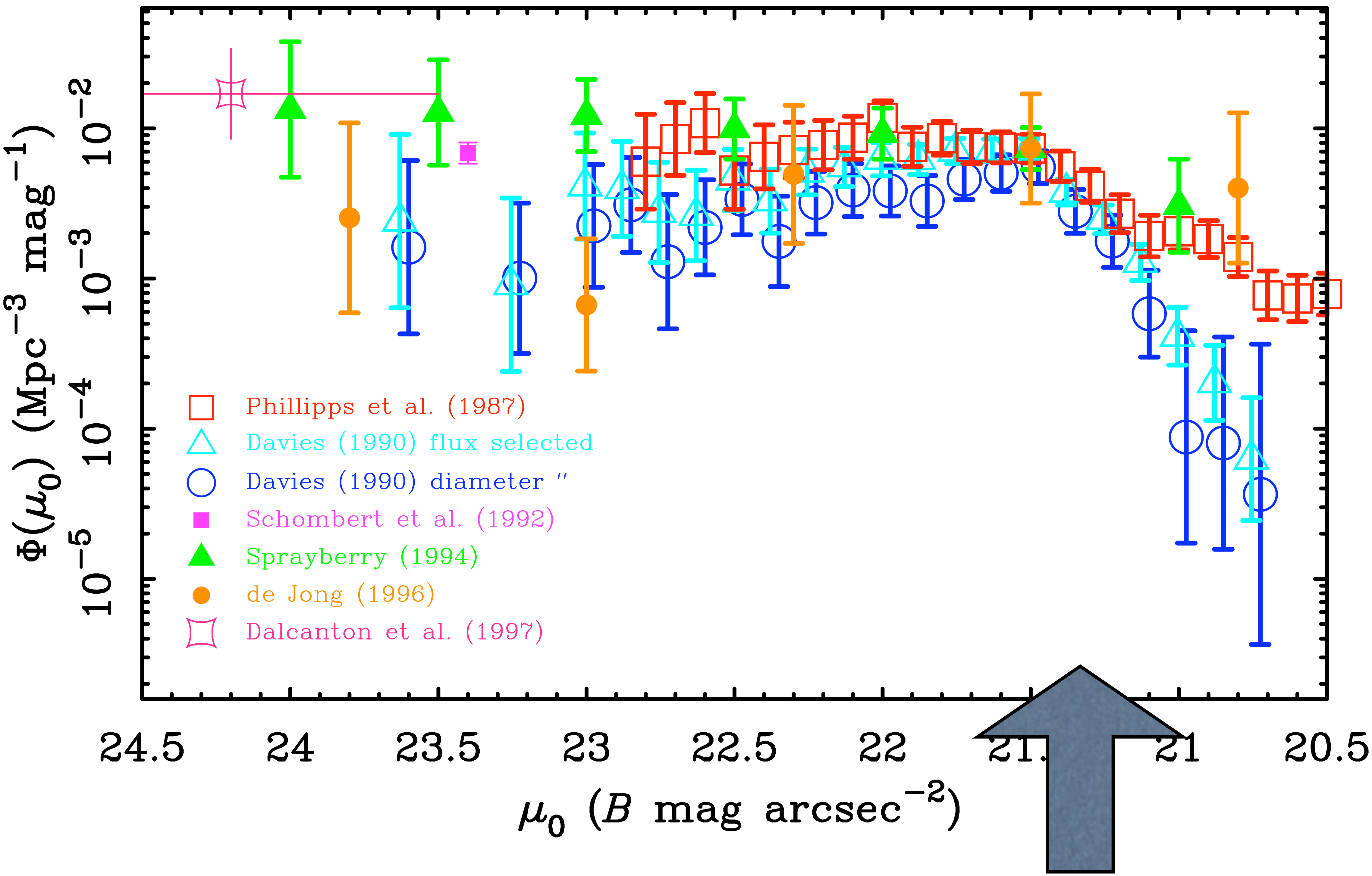
Obtain plausible mass profile; predictions testable with GAIA





Allowing for a significant bulge component implies that the Milky Way has a Type II disk

Other tests - e.g., disk stability (Milgrom 1989)



$$G\Sigma_* = a_0$$

disk stability

Brada & Milgrom (1998)

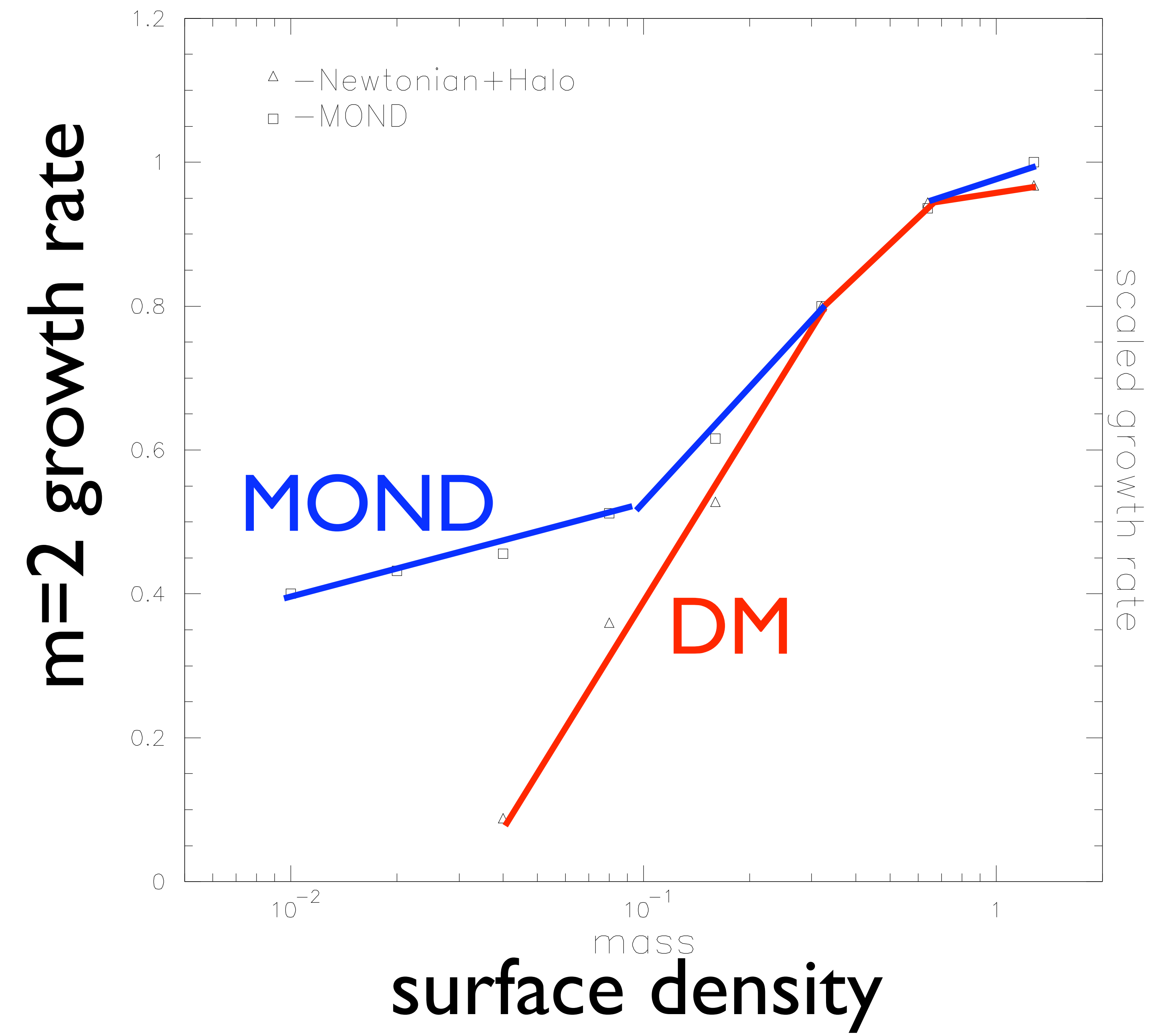
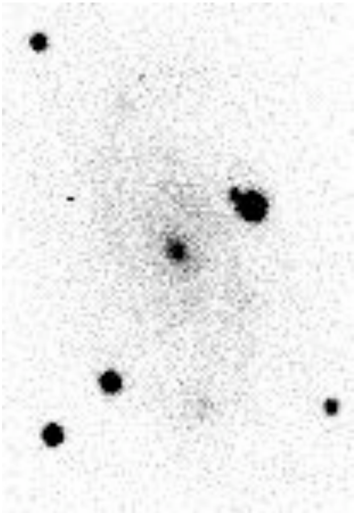
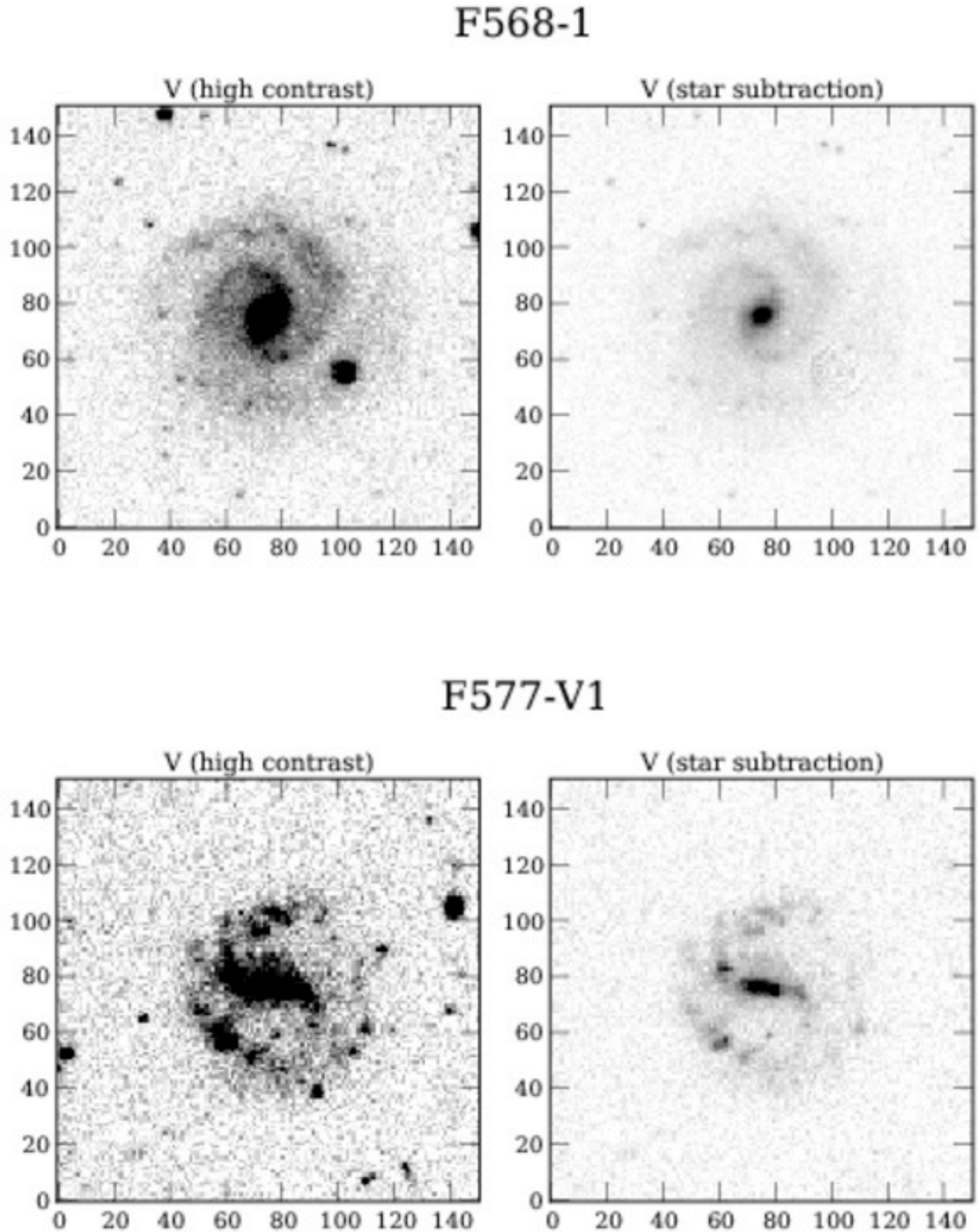


Figure 11: The growth rate, in units of the dynamical time, for the m=2 mode as a function of the total mass of the disk. □ MOND, △ Newtonian + Halo.

m	Q	time step scaling	Growth rate		halo mass at R=1
			MOND	Newt+DM	



LSB galaxies
got spiral arms!



To explain this, we anticipate the need for very massive disks to drive spiral density waves in LSBs

McGaugh & de Blok (1998), *ApJ*, **499**, 66

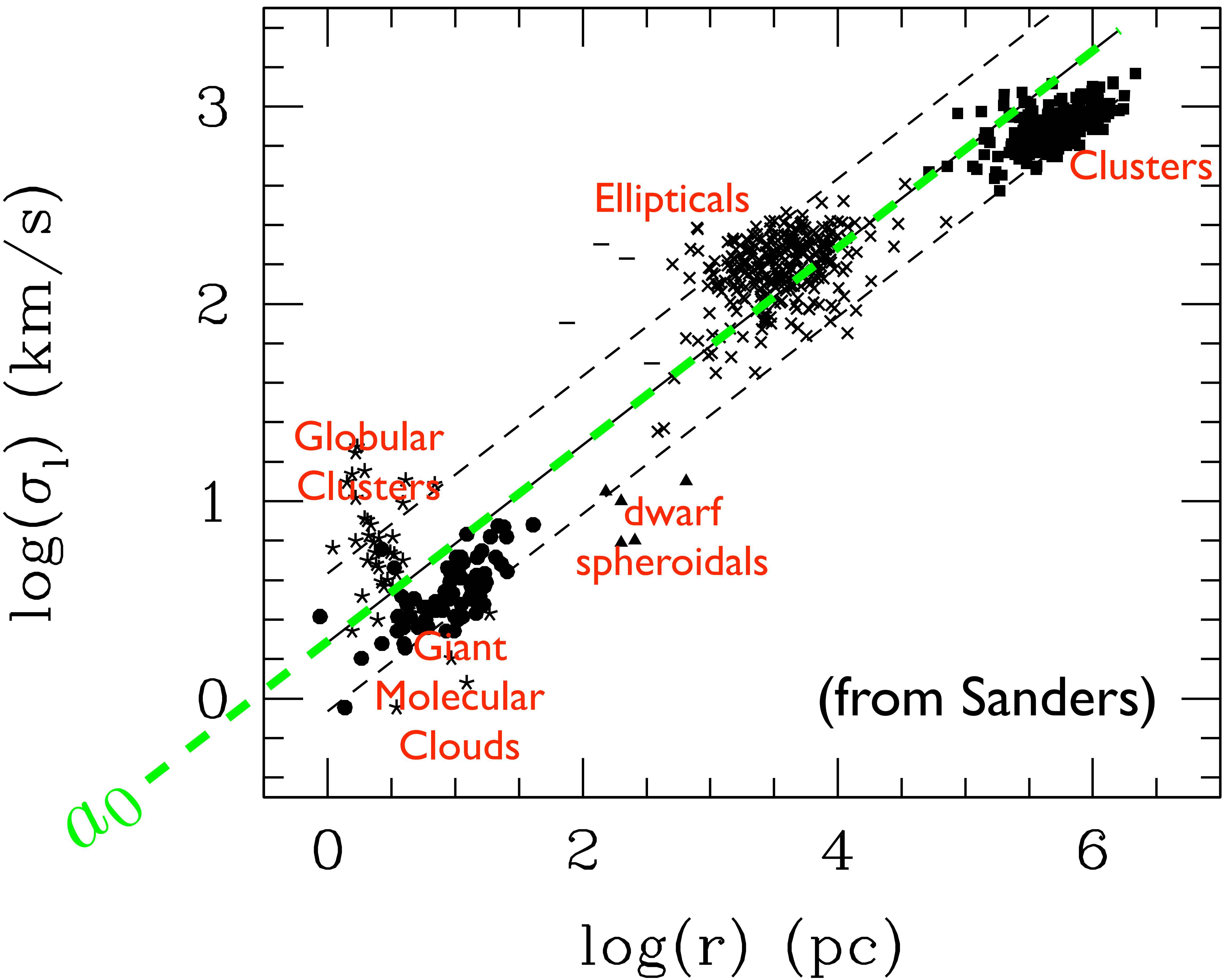
Disk Masses from Density Waves

Galaxy	$(M/L)_*$	AUTHOR
F568-1	14	FUCHS
F568-3	7	FUCHS
F568-6	11	FUCHS
F568-V1	16	FUCHS
UGC 128	4	FUCHS
UGC 1230	6	FUCHS
UGC 6614	8	FUCHS
ESO 14-40	4	FUCHS
ESO 206-140	4	FUCHS
ESO 302-120	1.7	FUCHS
ESO 425-180	2.4	FUCHS
ESO 186-550	7.5	SABUROVA
ESO 206-140	8.8	SABUROVA
ESO 234-130	5.7	SABUROVA
ESO 400-370	9	SABUROVA

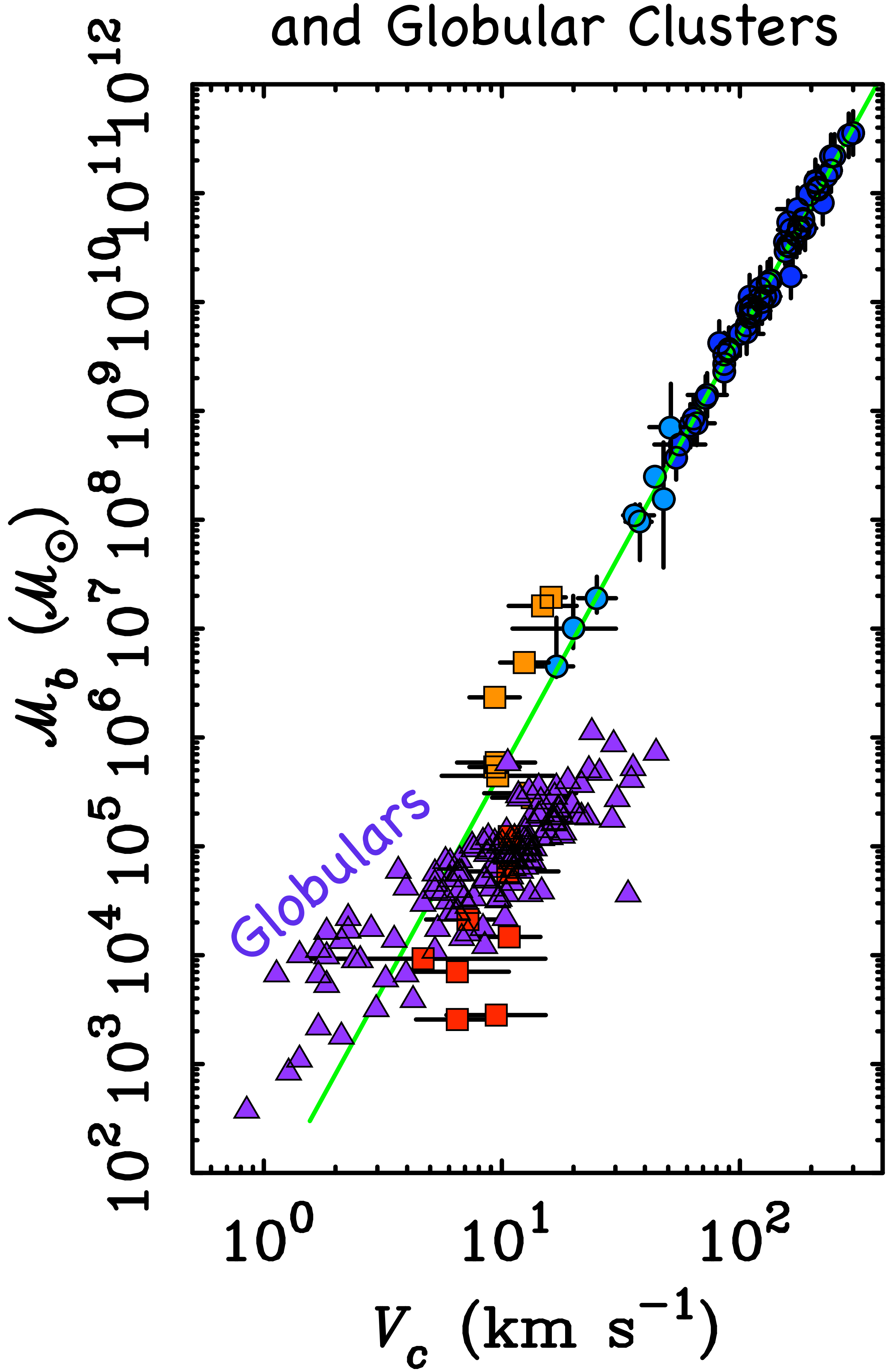
Big $(M/L)_*$'s!

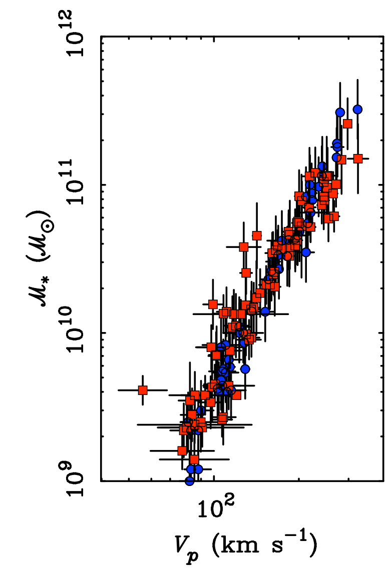
Conventional analysis overestimates M_*/L, as expected

Other tests - other systems



with LG dwarf Spheroidals
and Globular Clusters





Mateo (1998)

Simon & Geha (2007)

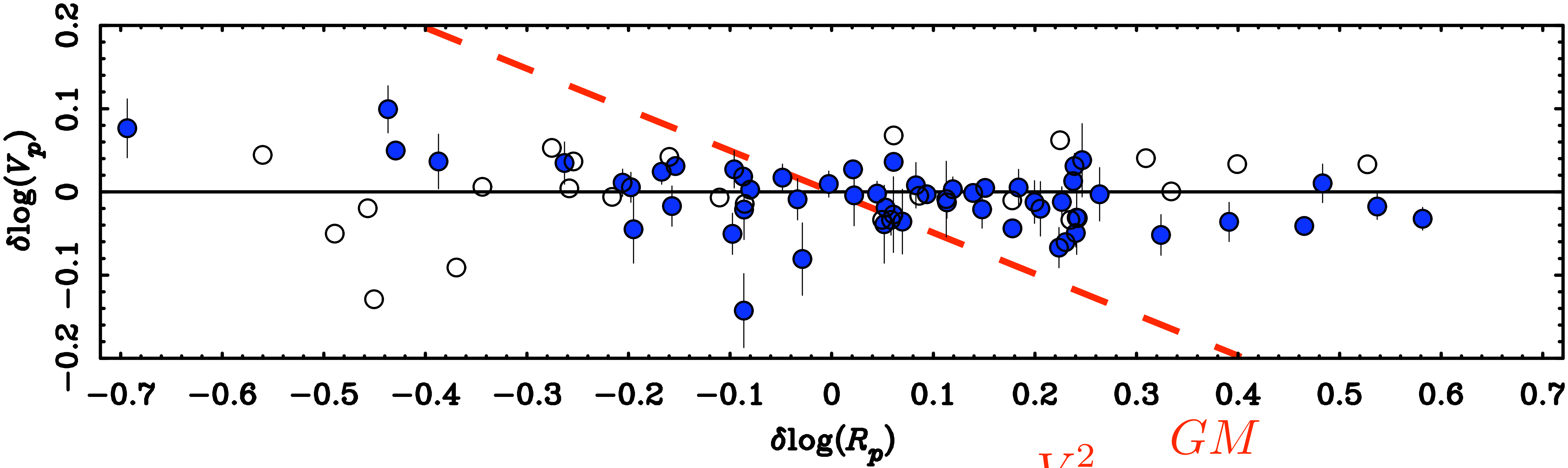
Gnedin et al. (2002)

Assumes

$$\Upsilon_\star = 1$$

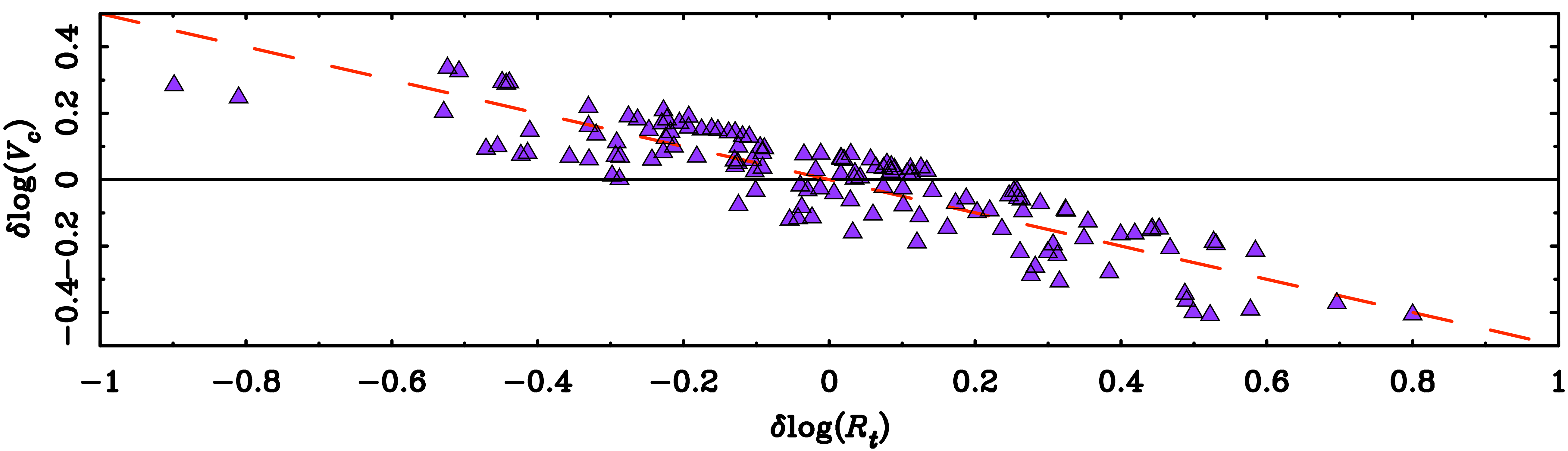
$$V_c = \sqrt{2}\sigma$$

No scale length residuals for Galaxies...



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

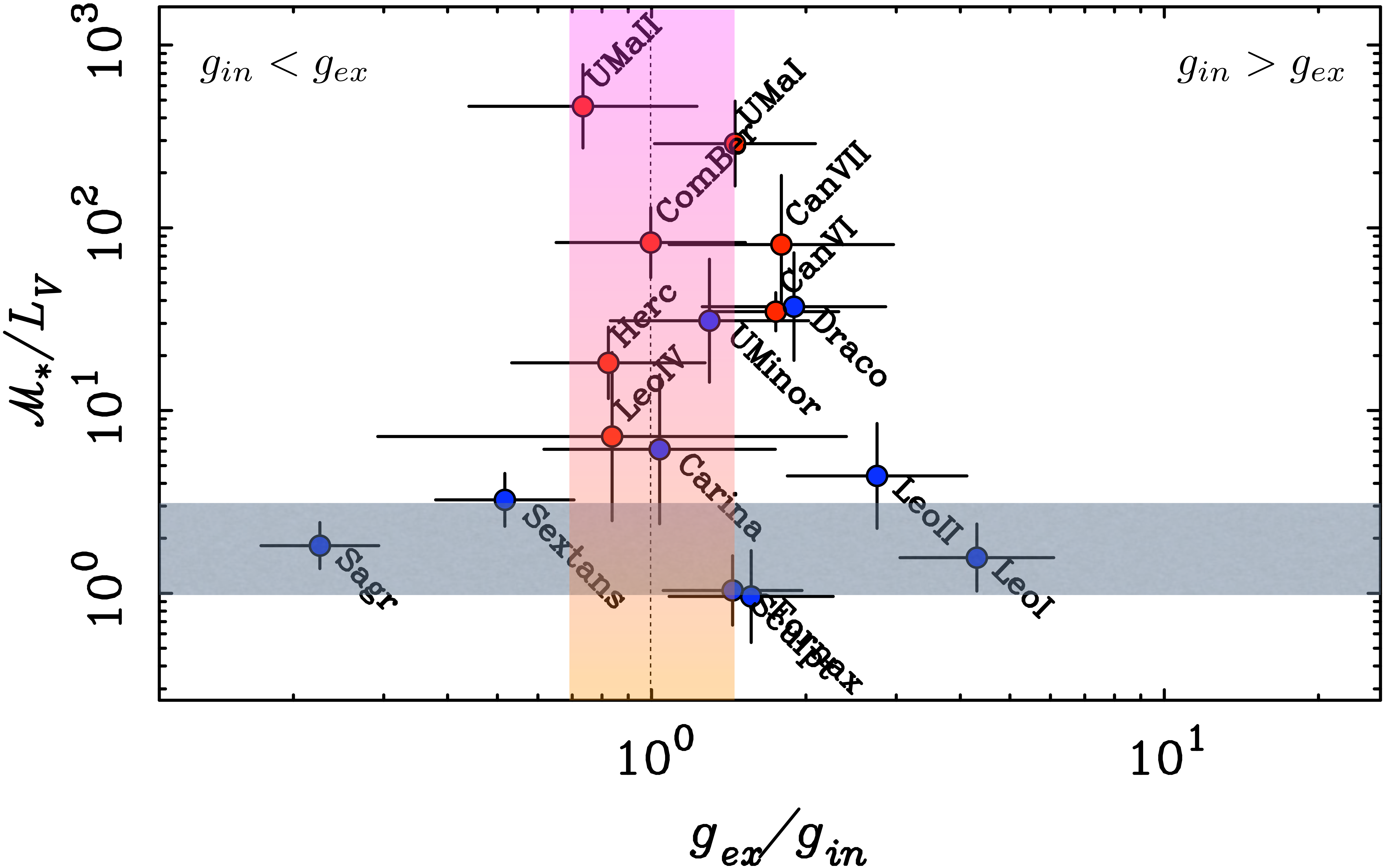
...but there are for Globular Clusters



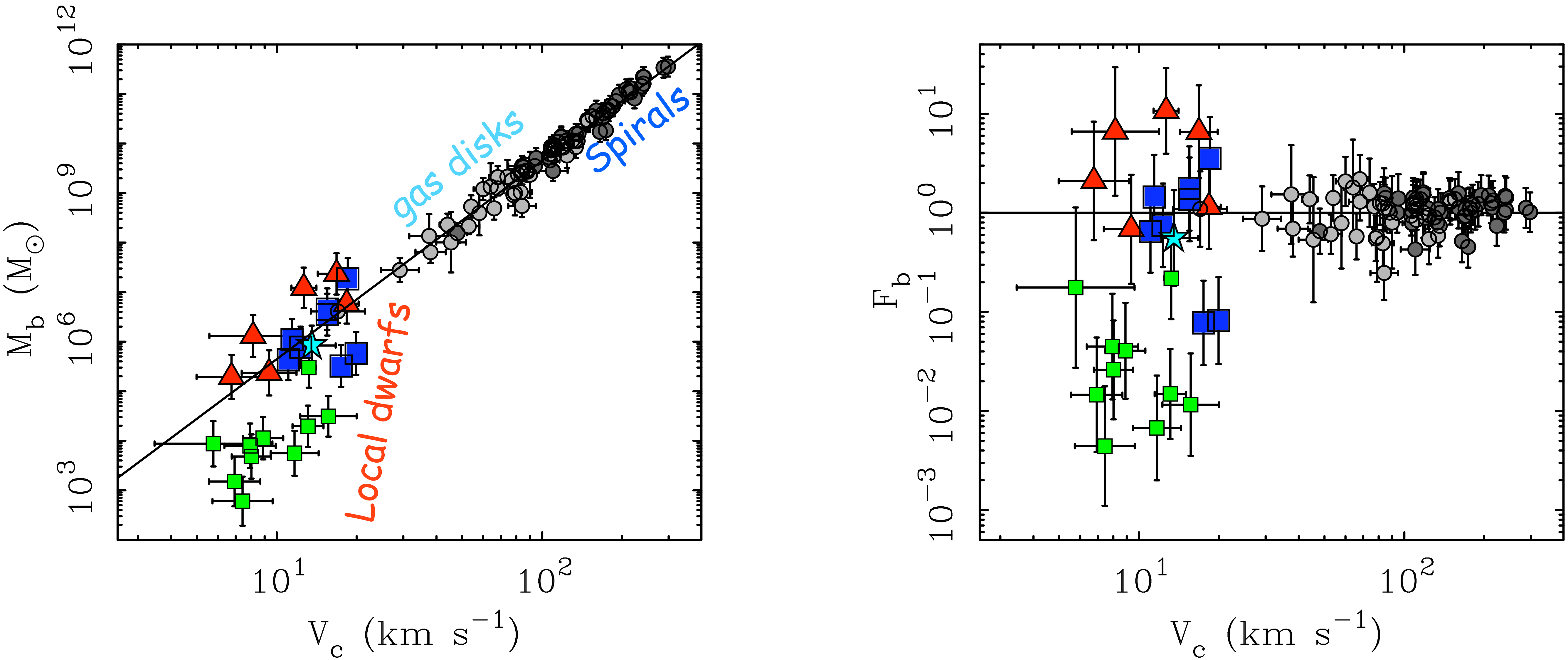
Newton works (as he should in high density systems)

Dwarf Spheroidals

MOND M*/L OK for most classical dwarfs
but unacceptably high for ultrafaints



Residuals of dwarf Spheroidals from Baryonic Tully-Fisher Relation
McGaugh & Wolf (2010)

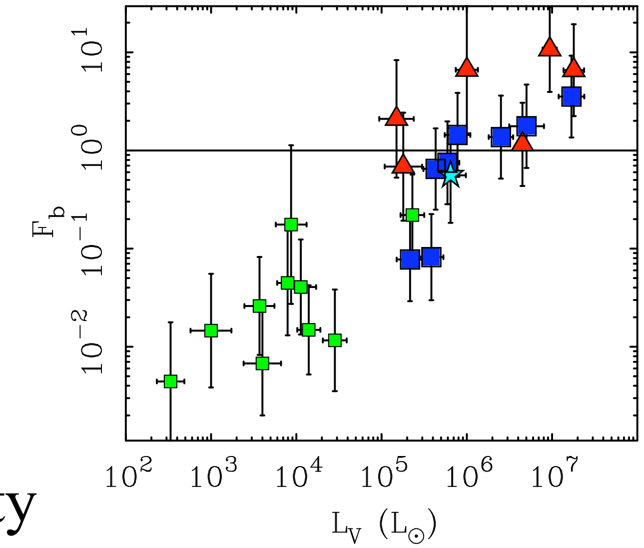


Classical dwarfs
Ultrafaint dwarfs
M31 dwarfs
Leo T (contains gas)

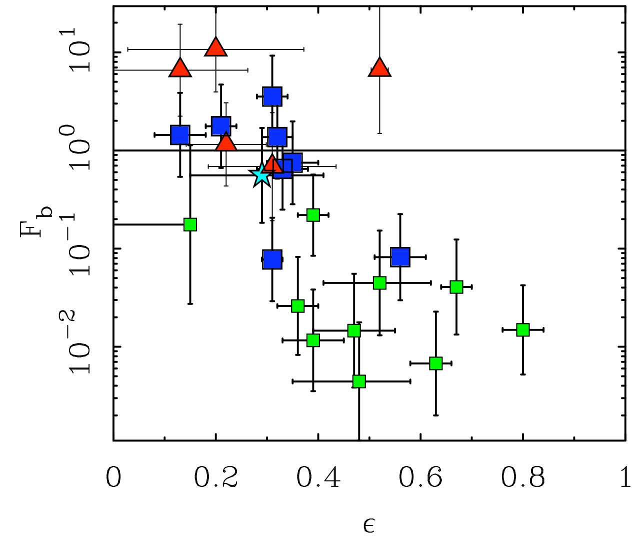
Local dwarf data: Wolf et al. (2010)
Kalirai et al. (2009; M31)
M*/L as per Mateo et al. (1998)
& Martin et al. (2008)

$$F_b = \frac{M_b}{A V_c^4}$$

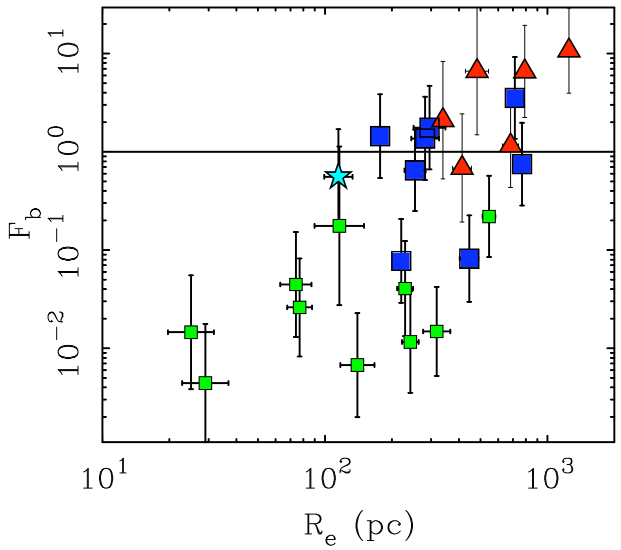
dSph BTFR residuals correlate with



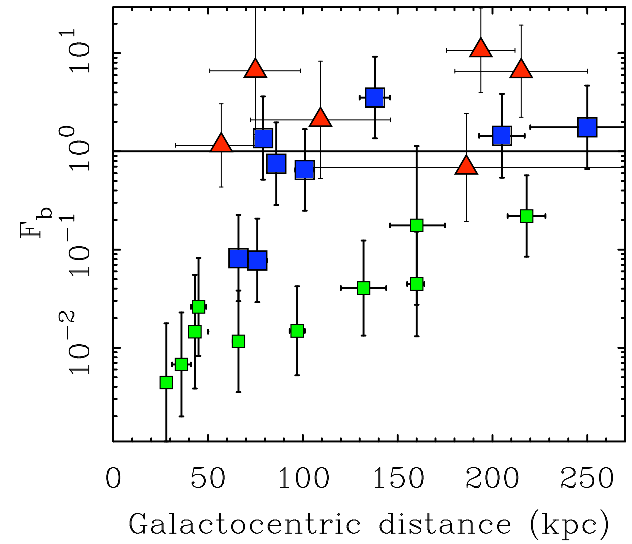
Luminosity



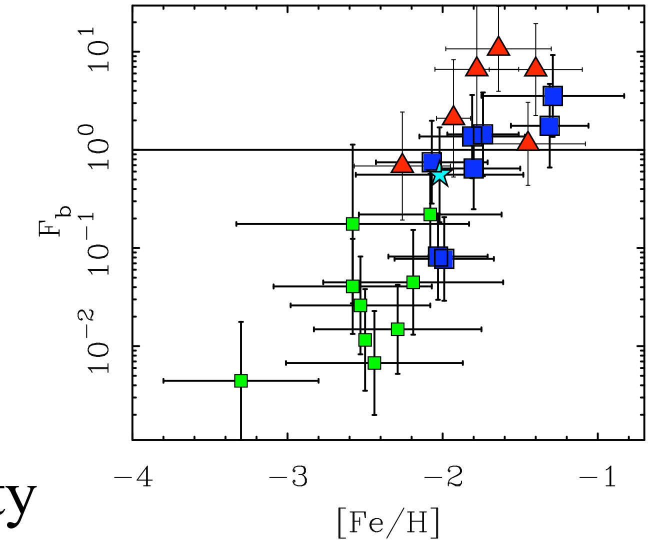
Shape



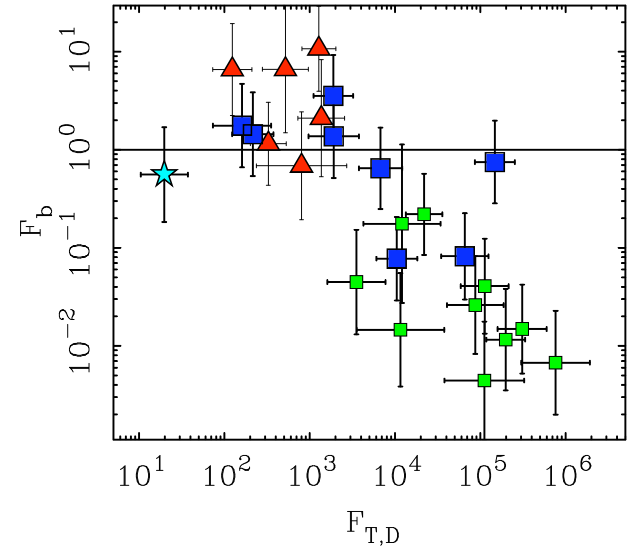
Size



Distance



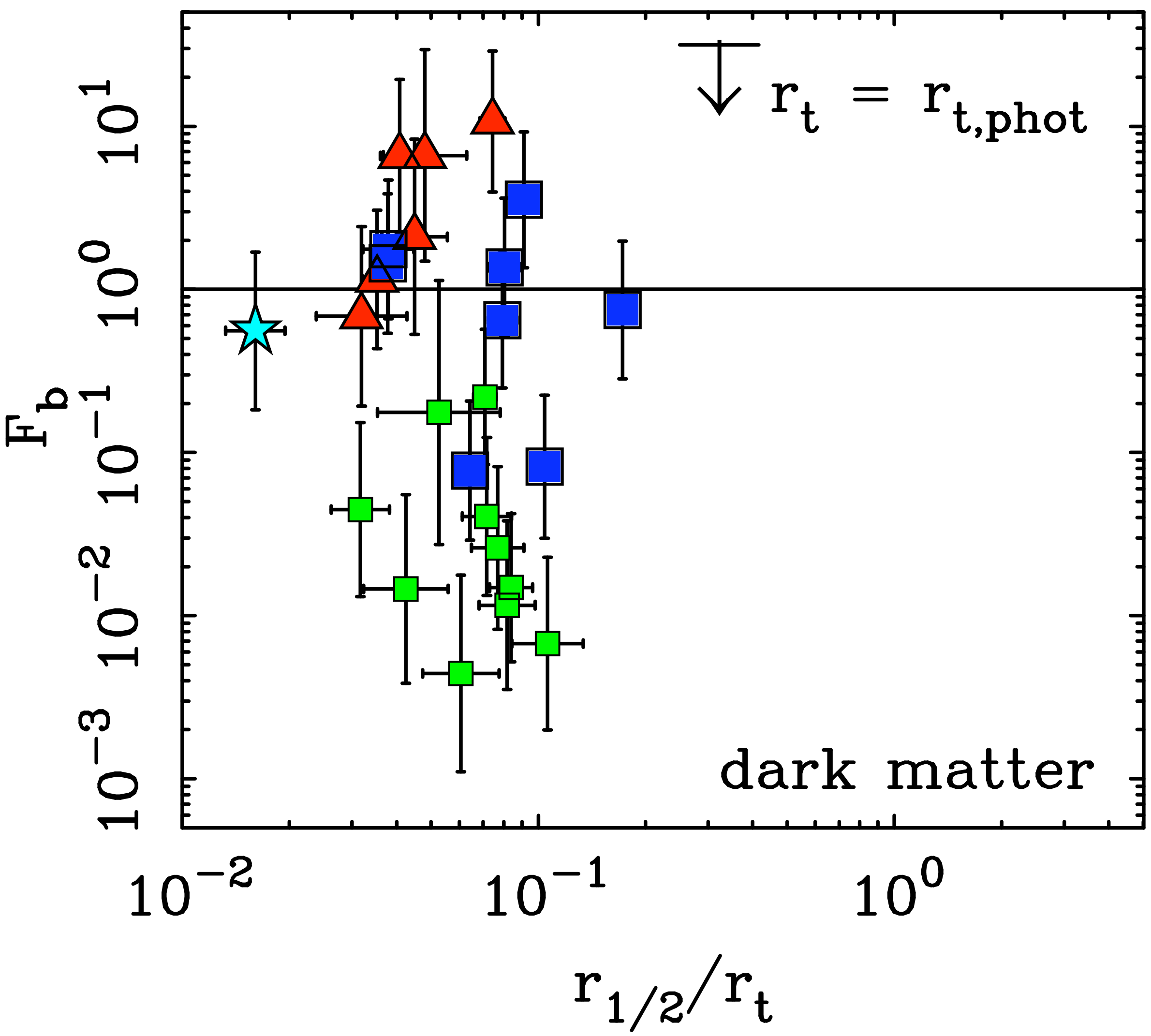
Metallicity

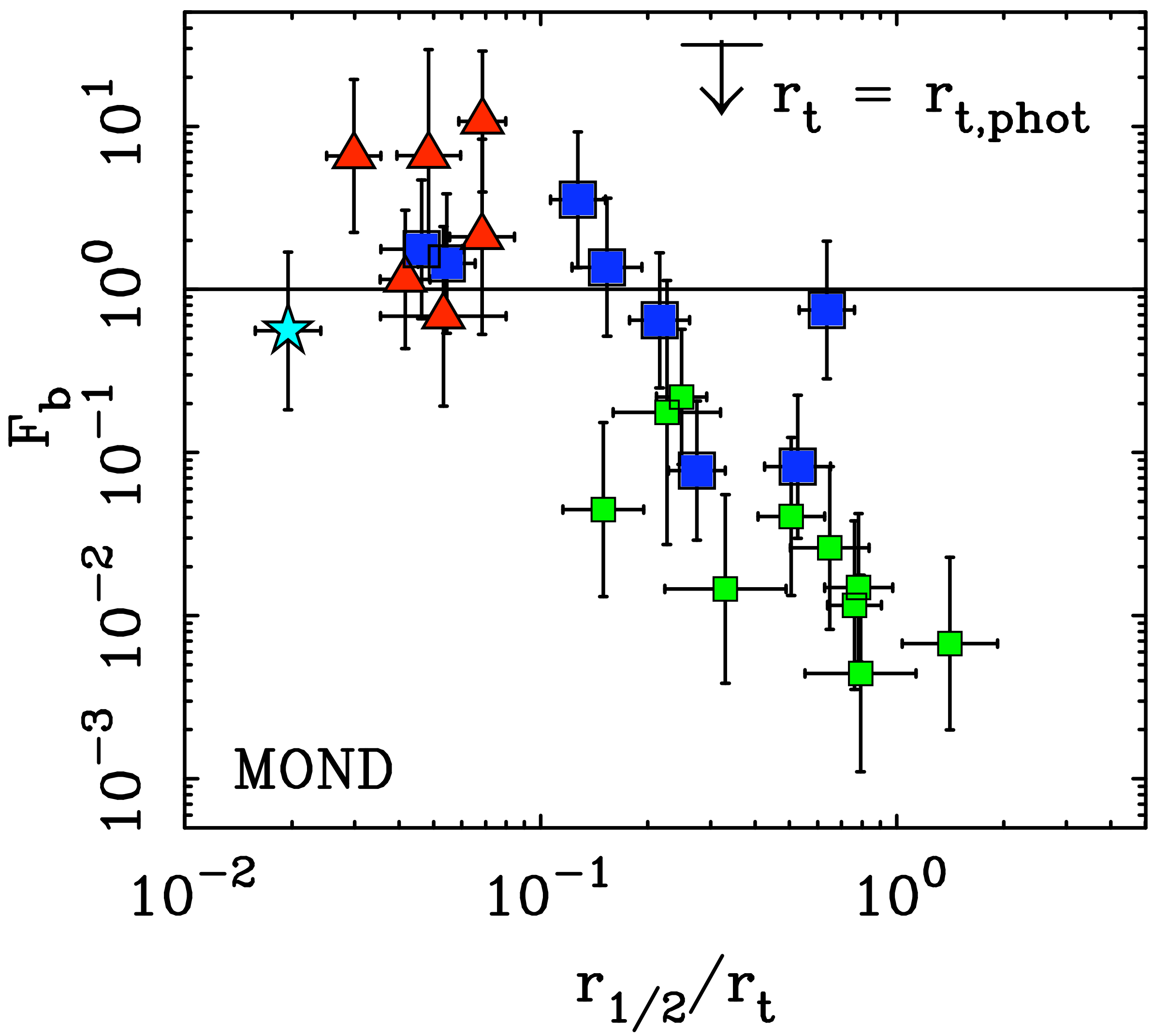


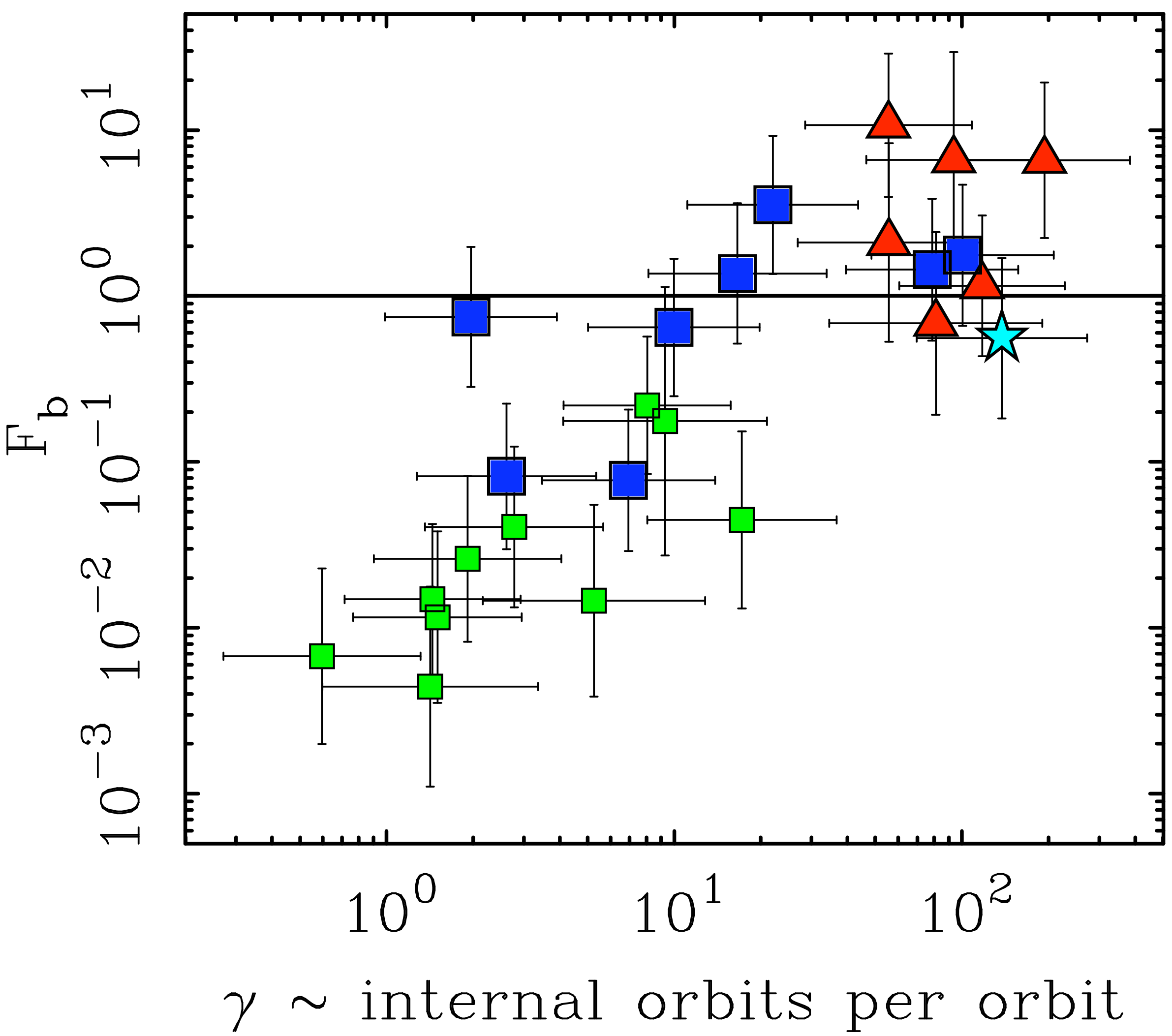
$$F_{T,D} = \frac{M}{m}\left(\frac{r}{D}\right)^3$$

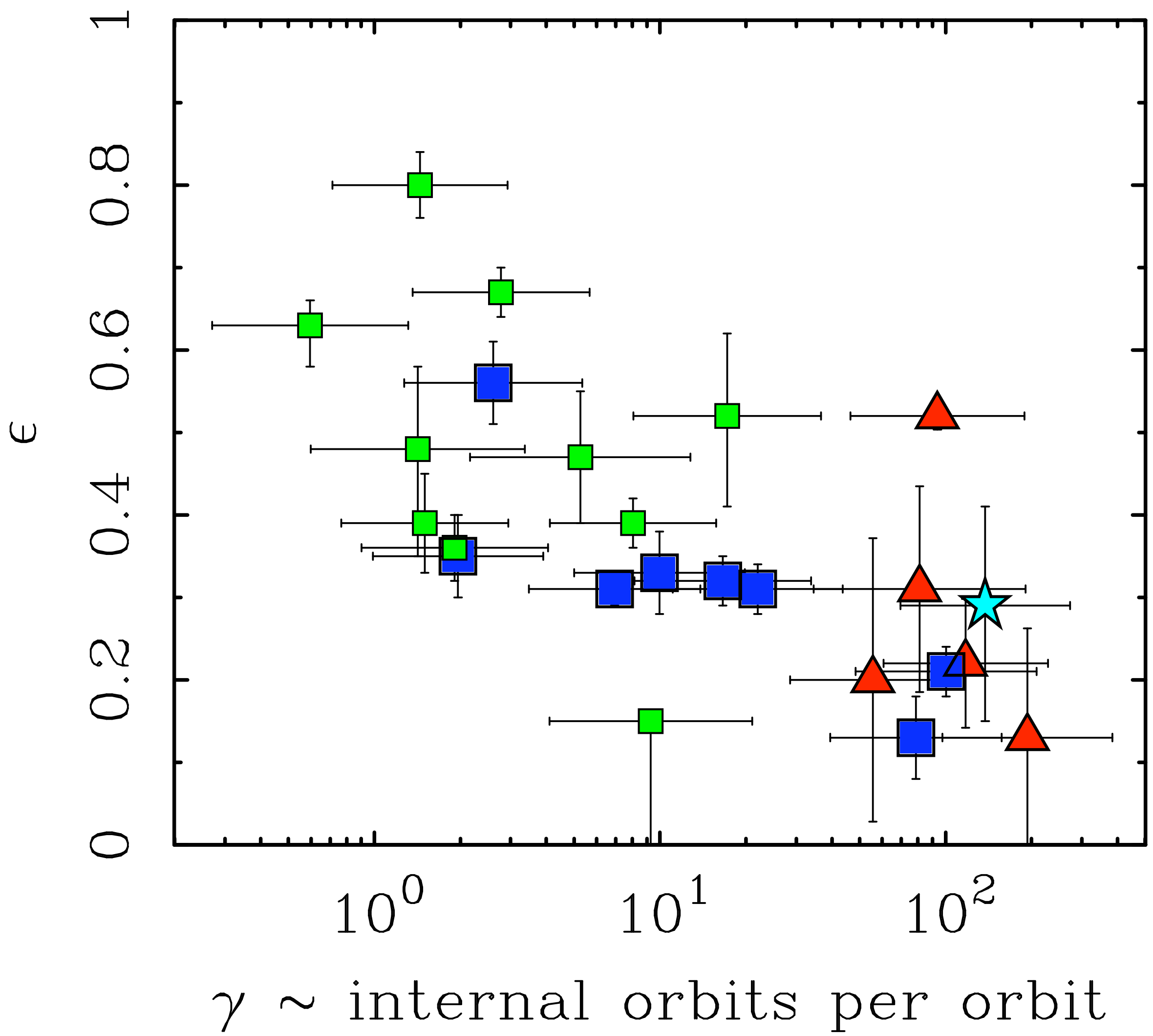
Tidal Susceptibility

tidal radii in dark matter and MOND



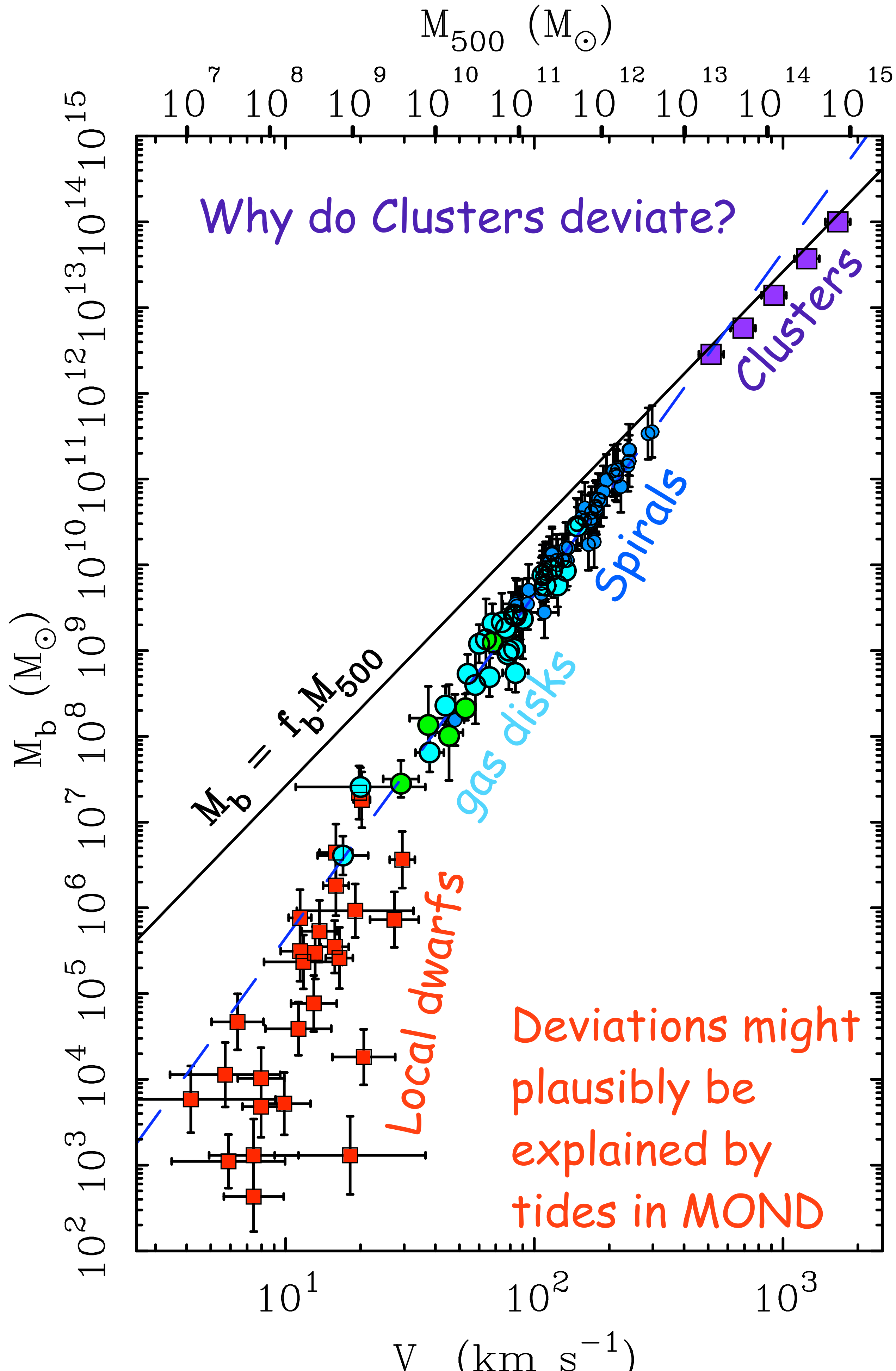






Dwarfs whose stars have little time to adjust to changes in the potential suffer the largest deviations and have more elliptical shapes.

That the ultrafaints are tidally affected by the Milky Way in MOND.
Their M*/L are overestimated by the usual equilibrium calculation.



Clusters have less baryonic mass than expected.

Cluster data: Giodini et al. (2009)

$$M_\Delta = B_\Delta V_\Delta^3$$
$$B_{500} = 1.5 \times 10^5 \ M_\odot \ \mathrm{km}^{-3} \ \mathrm{s}^3$$

Spiral data: McGaugh et al. (2005)

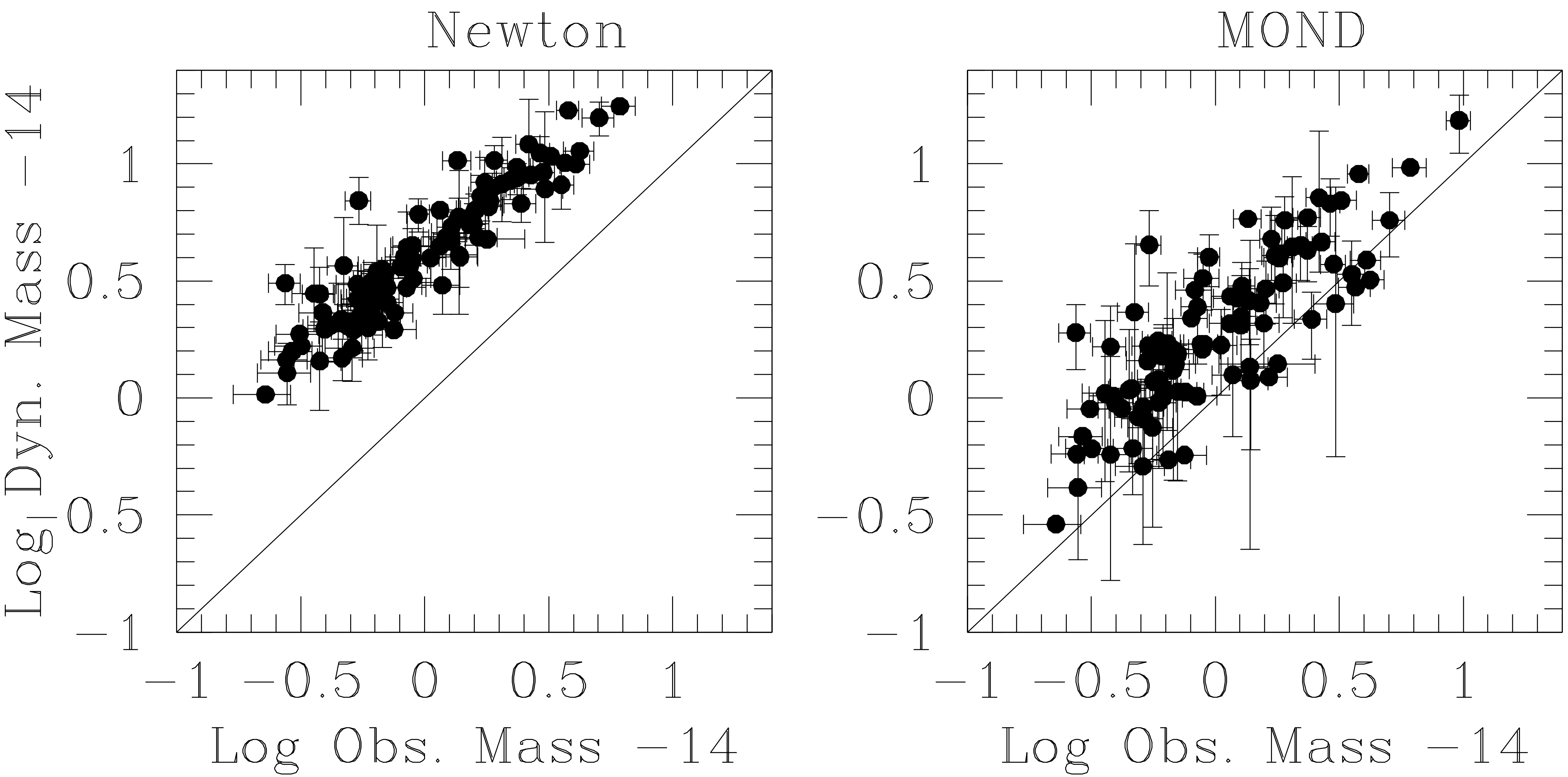
Gas dominated disks:
Stark et al. (2009)
Trachternach et al. (2009)

Local dwarf data: Walker et al. (2009)
M*/L as per Mateo et al. (1998)

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

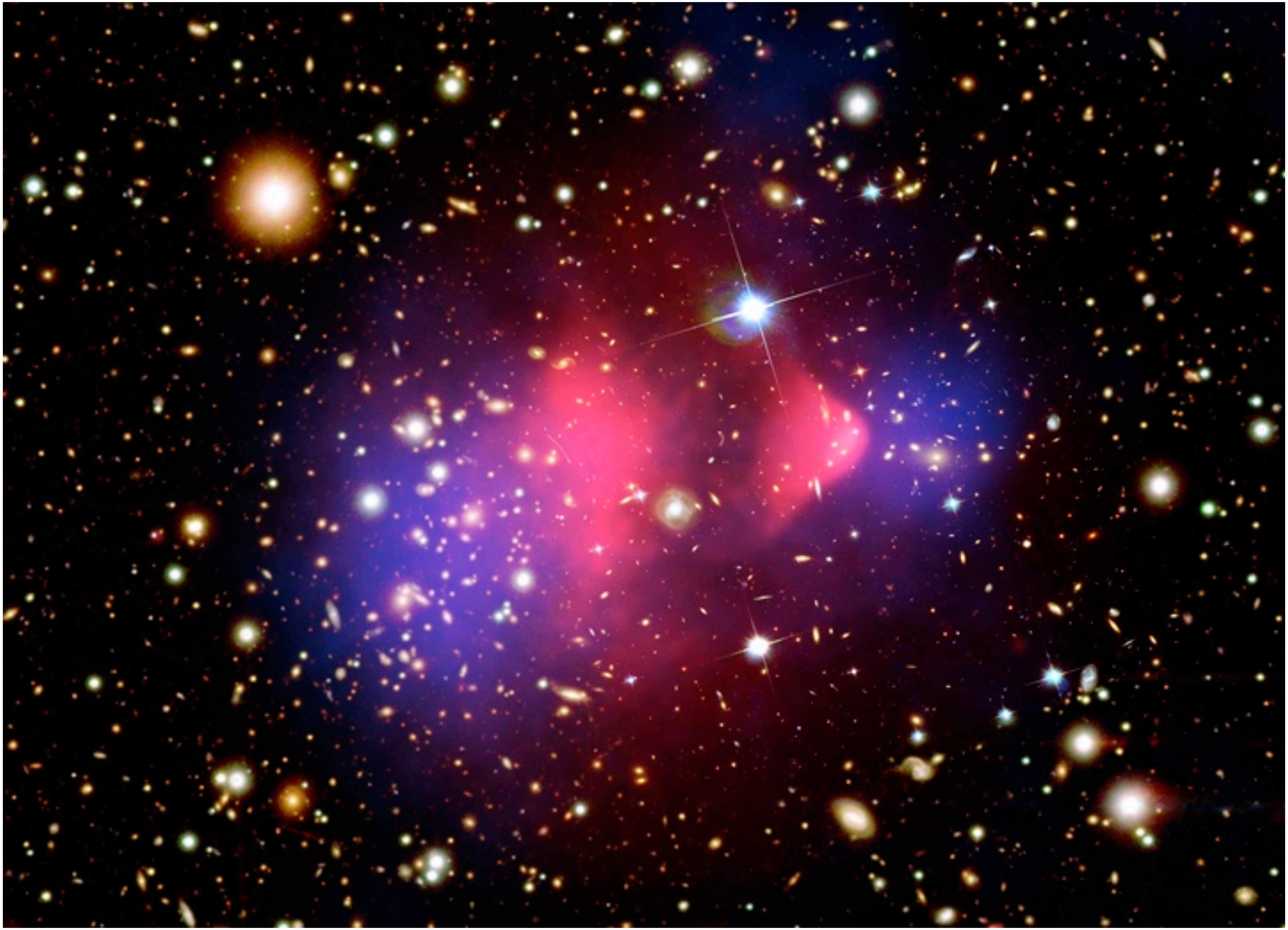
McGaugh et al. (2010)

Clusters of Galaxies

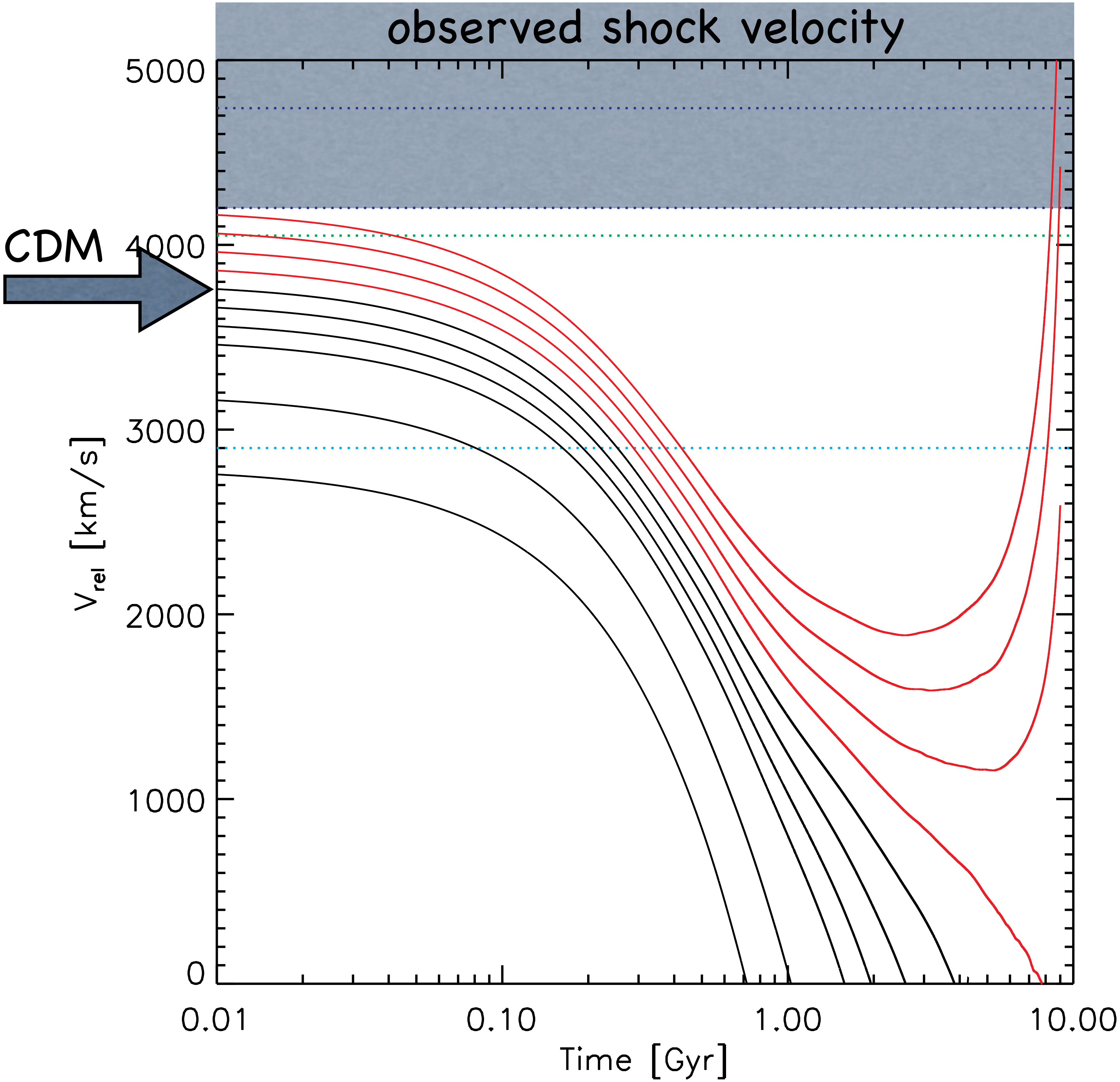


residual mass discrepancy in clusters is real...
the bullet cluster is a special case of a more general problem.

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



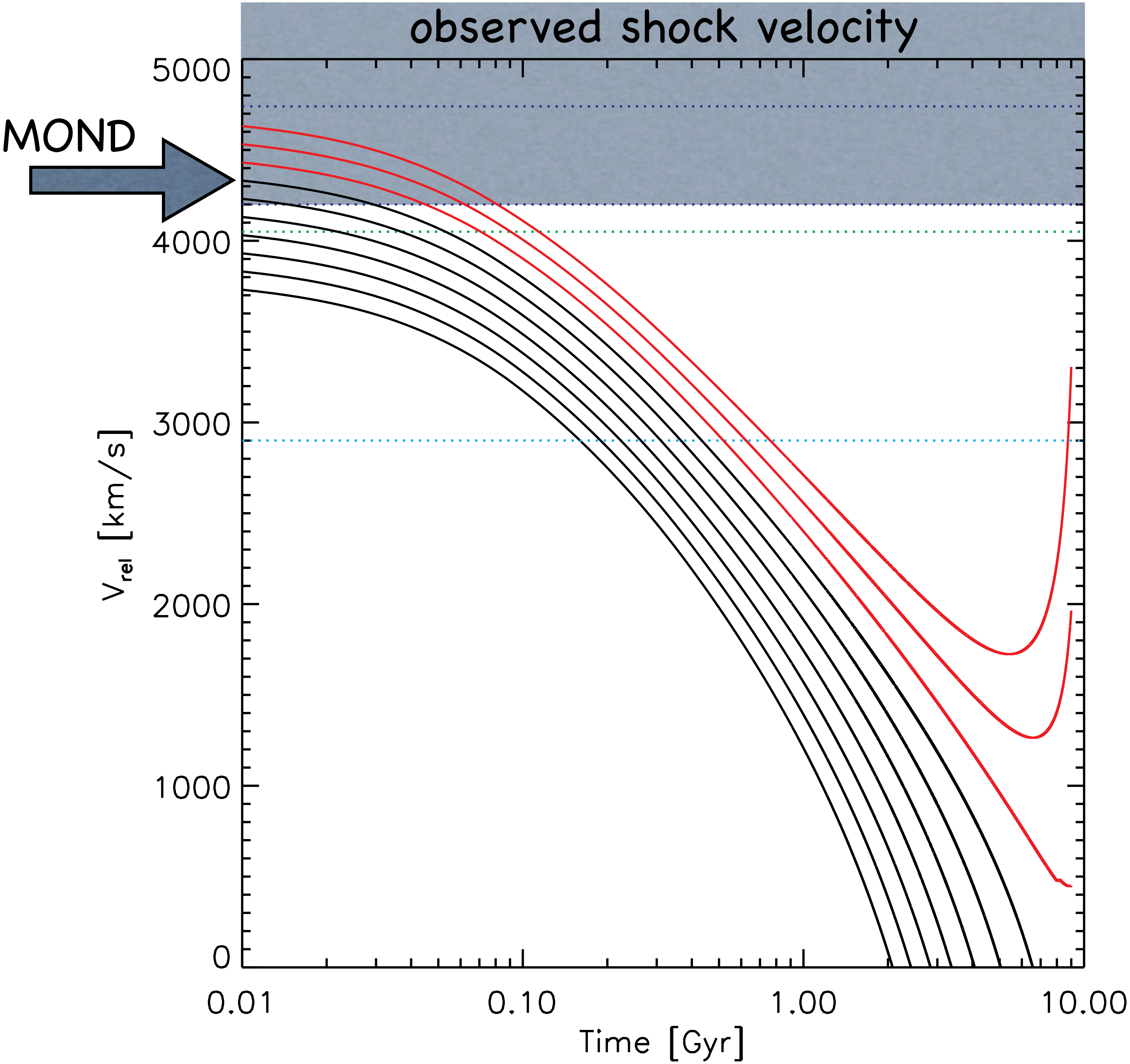
bullet cluster collision velocity



Angus & McGaugh (2008) MNRAS, 383, 417

mass discrepancy more naturally explained by CDM

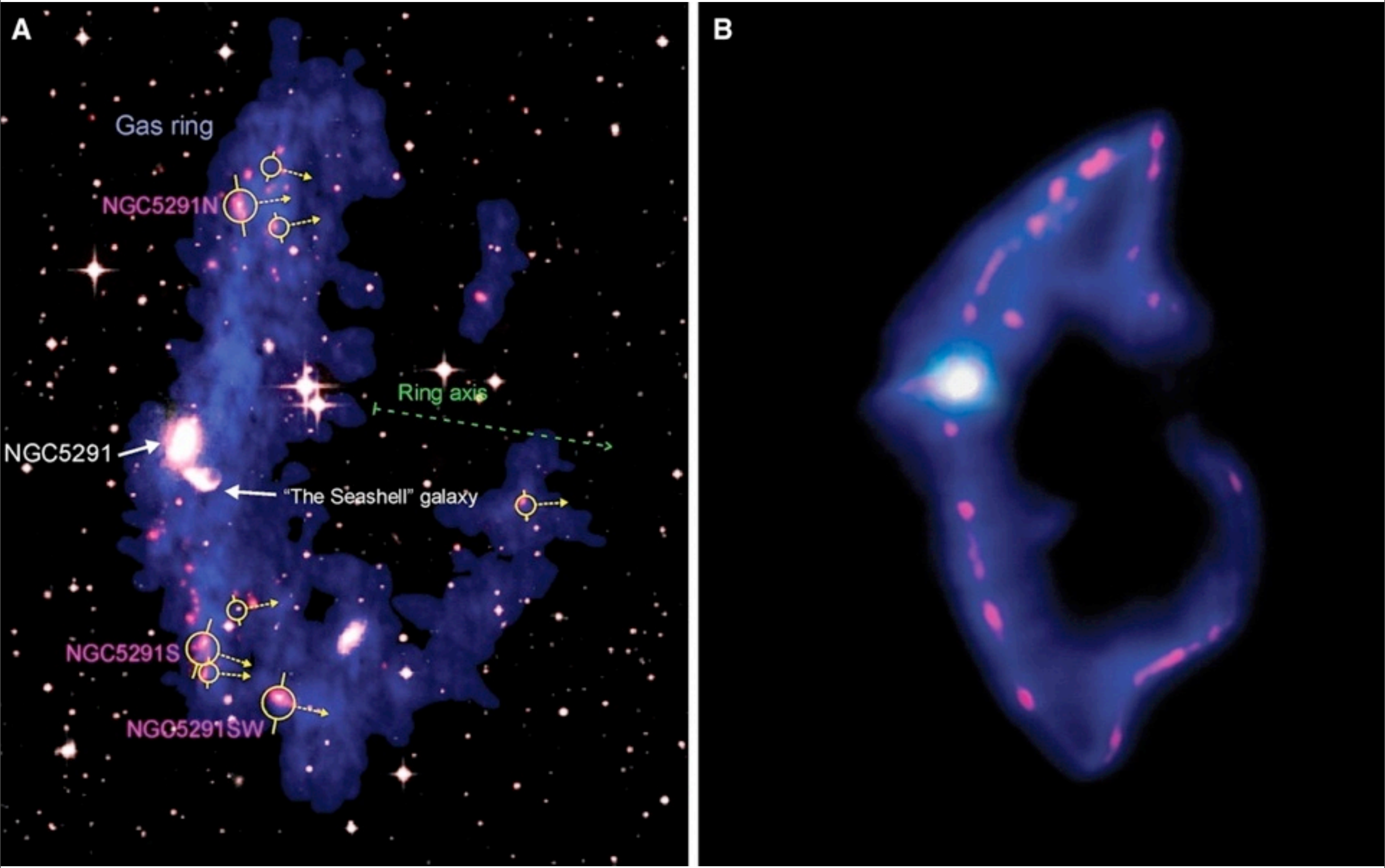
bullet cluster collision velocity



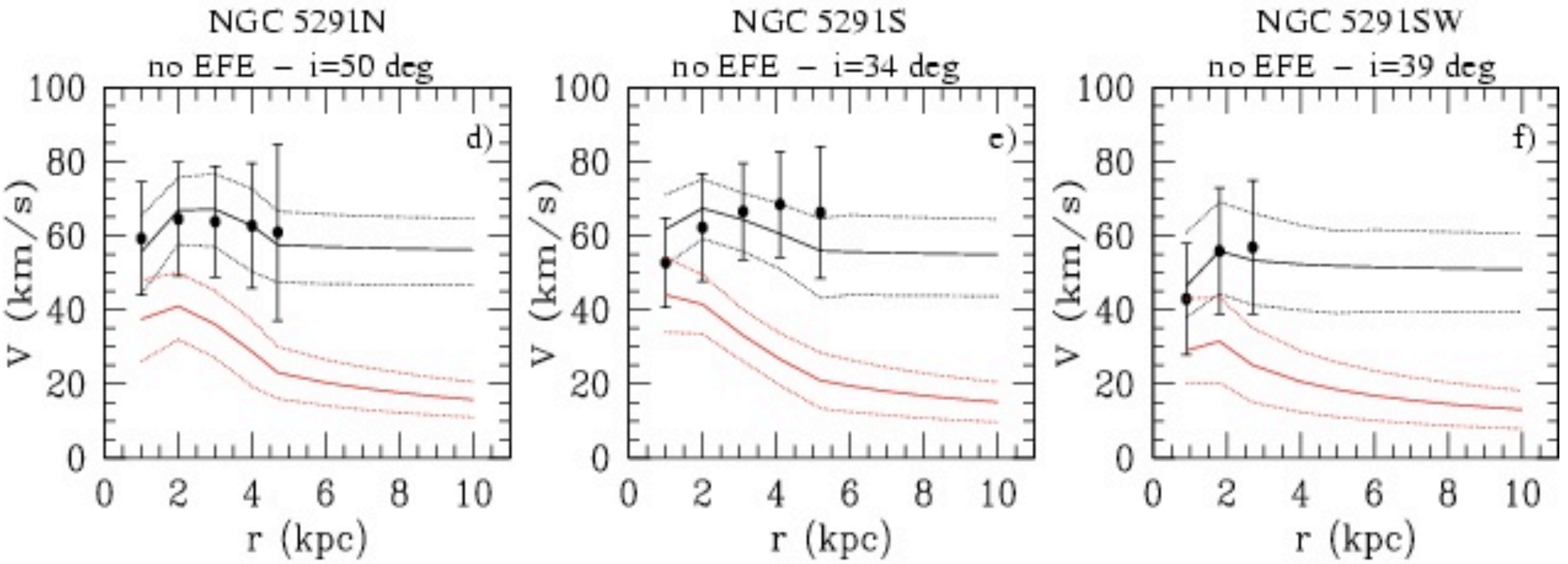
Angus & McGaugh (2008) MNRAS, 383, 417

collision velocity more naturally explained by MOND

Tidal Debris Dwarfs - should be devoid of Dark Matter

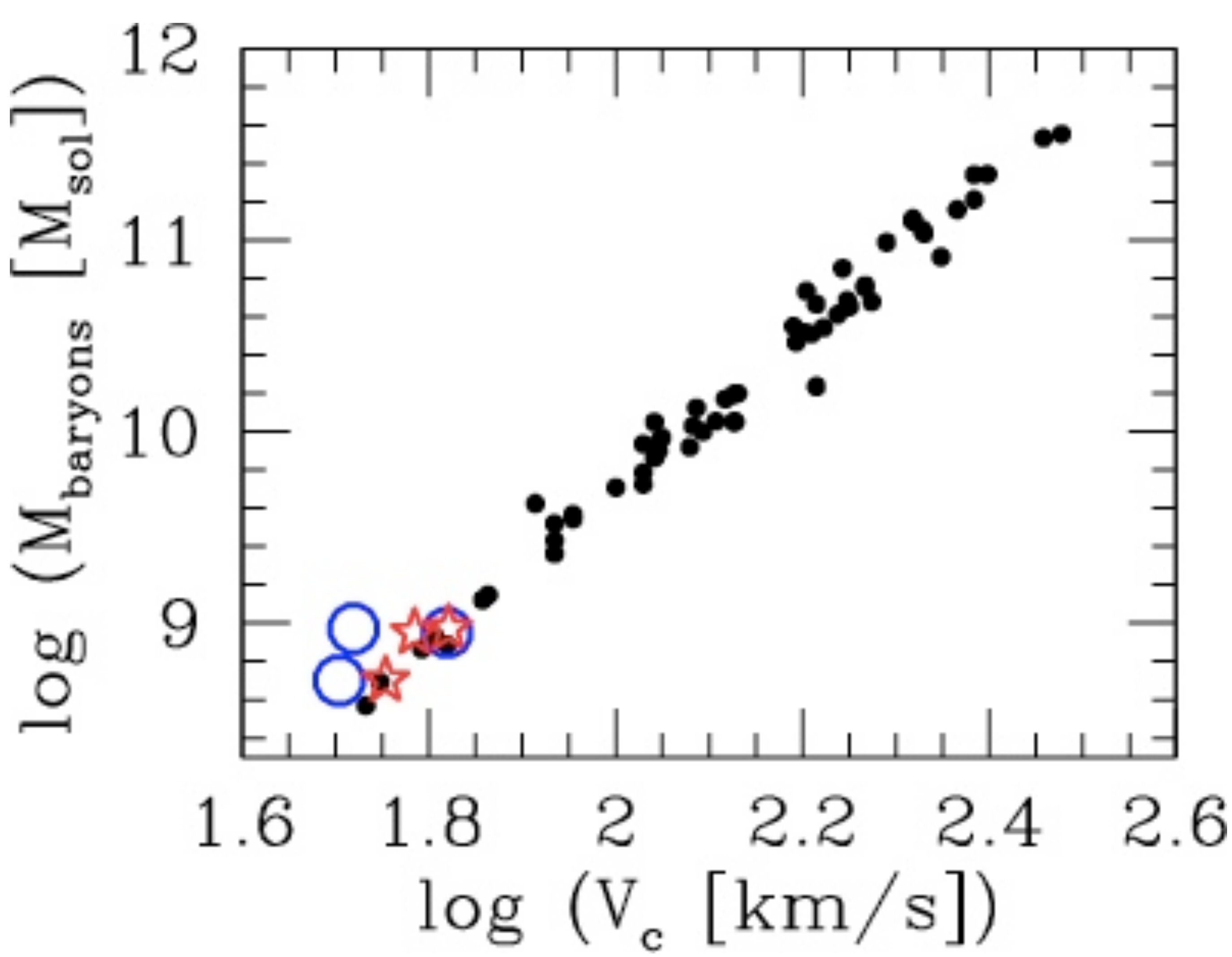


Bournaud et al. (2007) *Science*, **316**, 1166



Gentile et al. (2007)

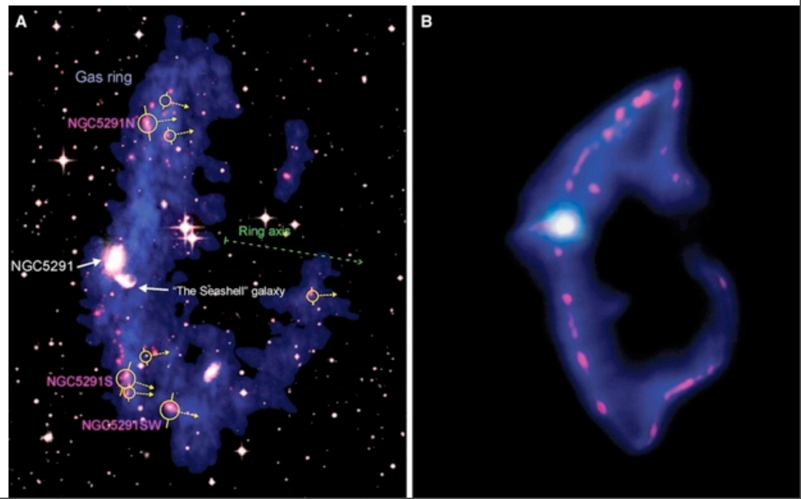
A&A, **472**, L25



Tidal dwarfs do show mass discrepancies as expected in MOND

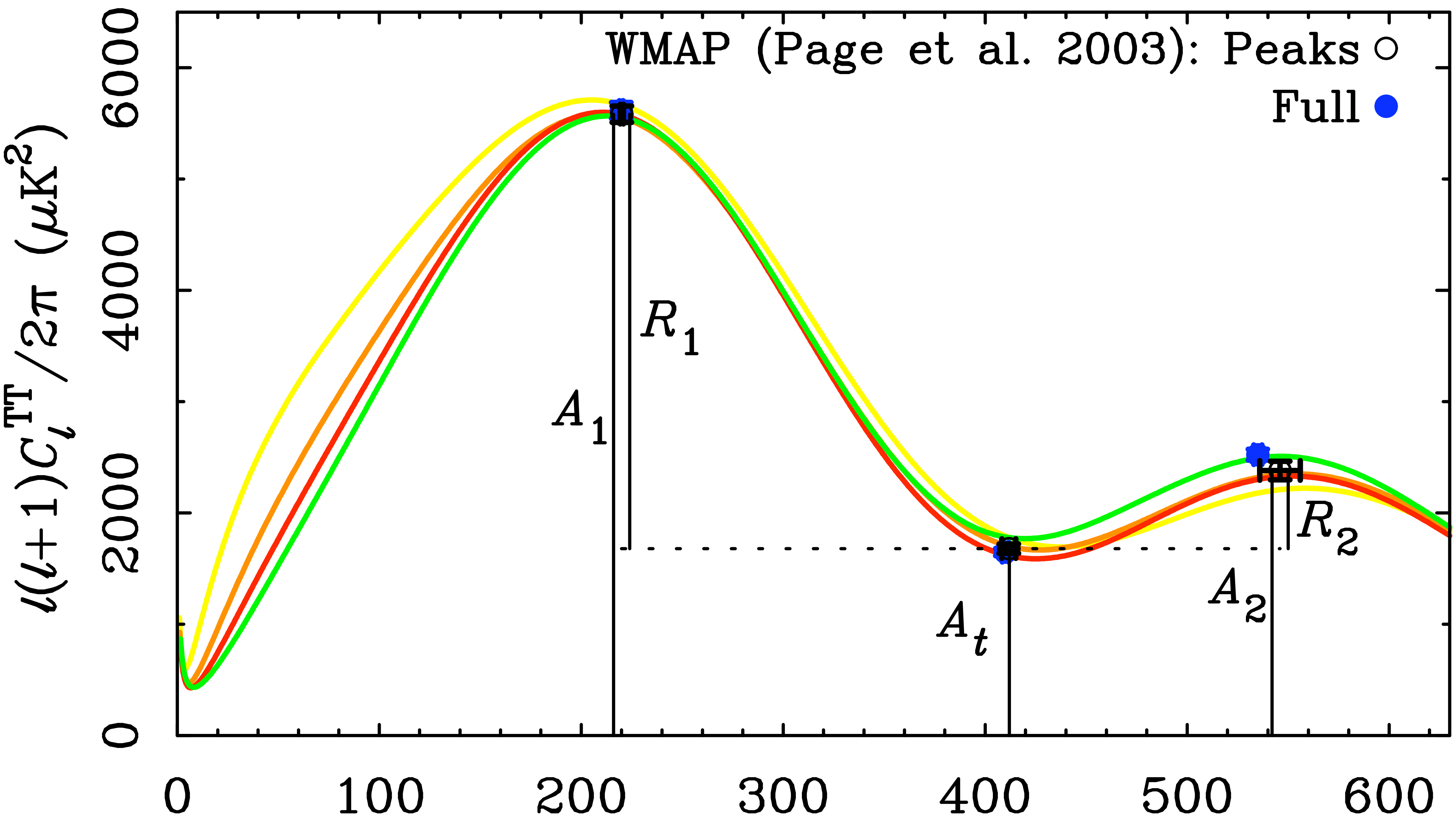
Conclusions

- MOND naturally explains a diverse array of phenomena
- Many *a priori* MOND predictions have been realized; some problems remain, especially in rich galaxy clusters
- The observed MONDian phenomenology is not naturally a part of the ΛCDM paradigm
- Can CDM be falsified???



No CDM prediction (McGaugh 1999): $A_{1:2} = 2.4$

Subsequent measurement: $A_{1:2} = 2.34 \pm 0.09$



Model	$L_{2:1}$	$A_{1:2}$	$R_{1:2}$
1999 LCDM	2.4	1.8	3.5 *
No CDM	2.6	2.4	5.4 *
WMAP Data	2.48	2.34	5.56