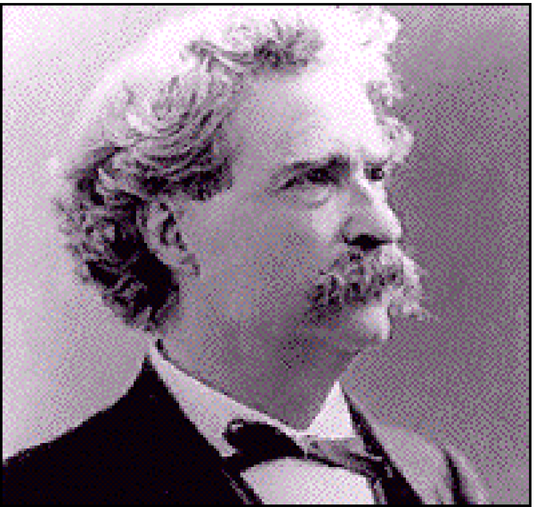
ROE, Edinburgh, 20 April 2006

Observational Constraints on the Acceleration Discrepancy Problem

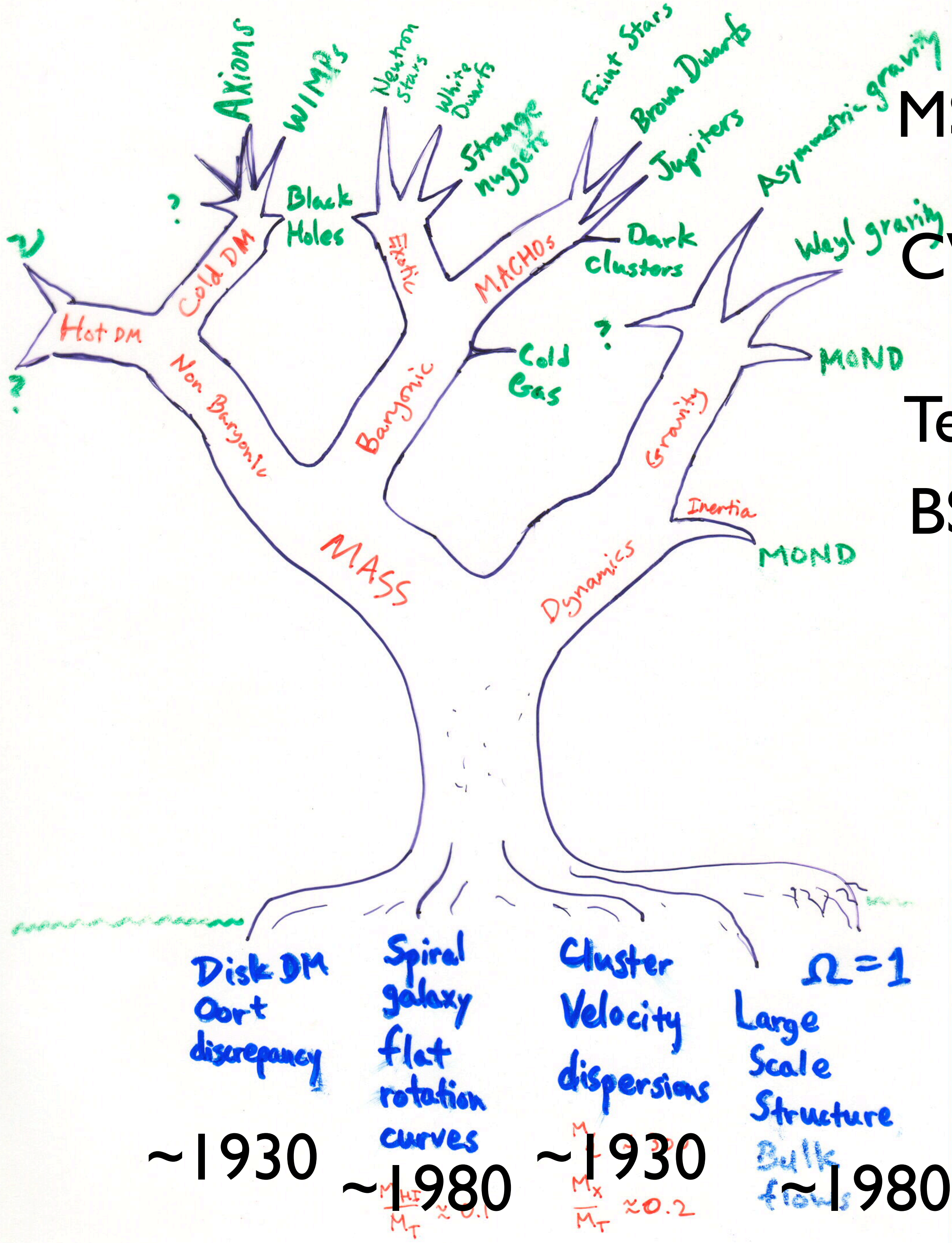
Stacy McGaugh
University of Maryland

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

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



- Mark Twain



MSTG

CWG

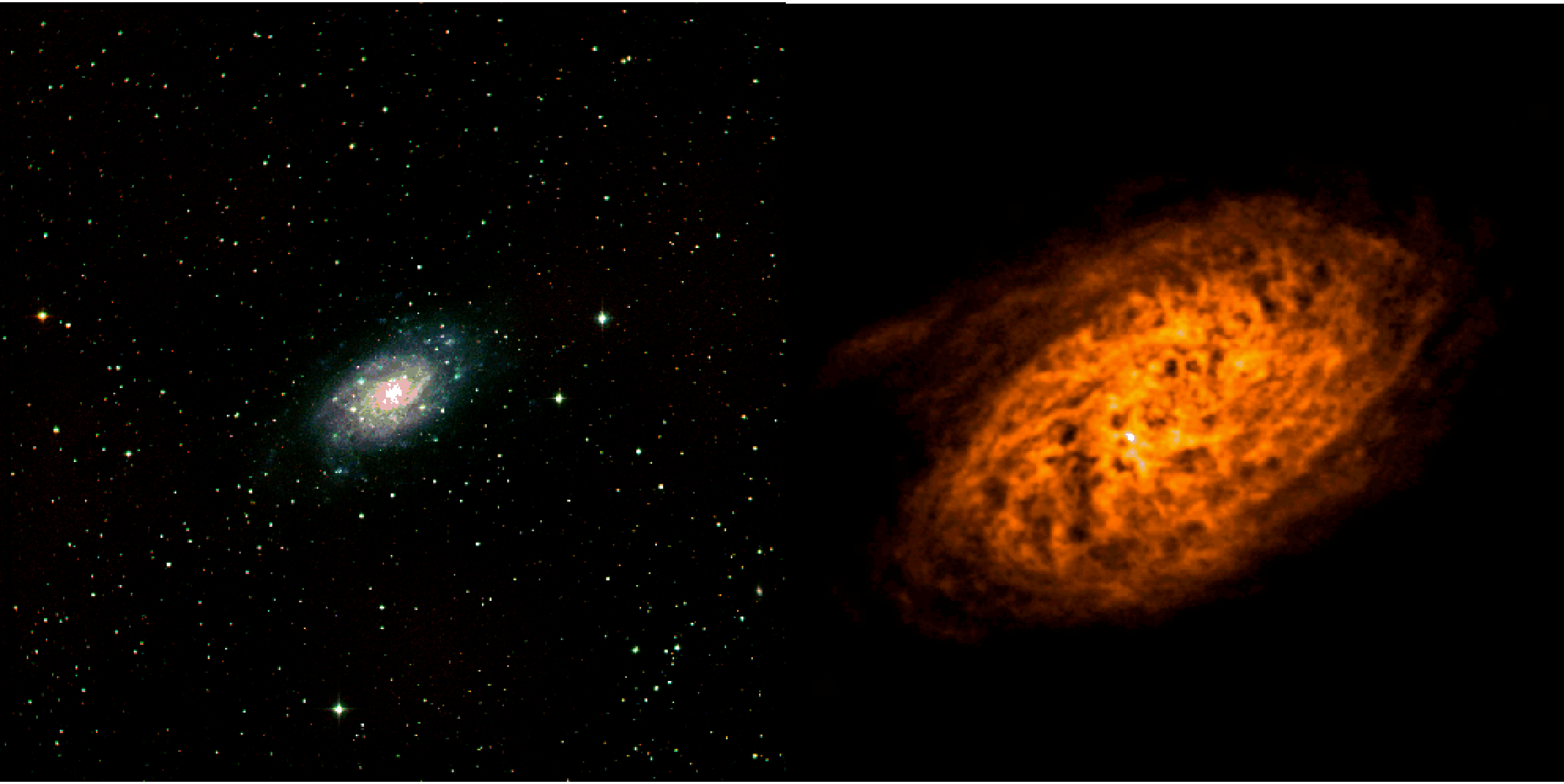
TeVeS

BSTV

?

~1930 ~1980 ~1930 ~1980

NGC 2403

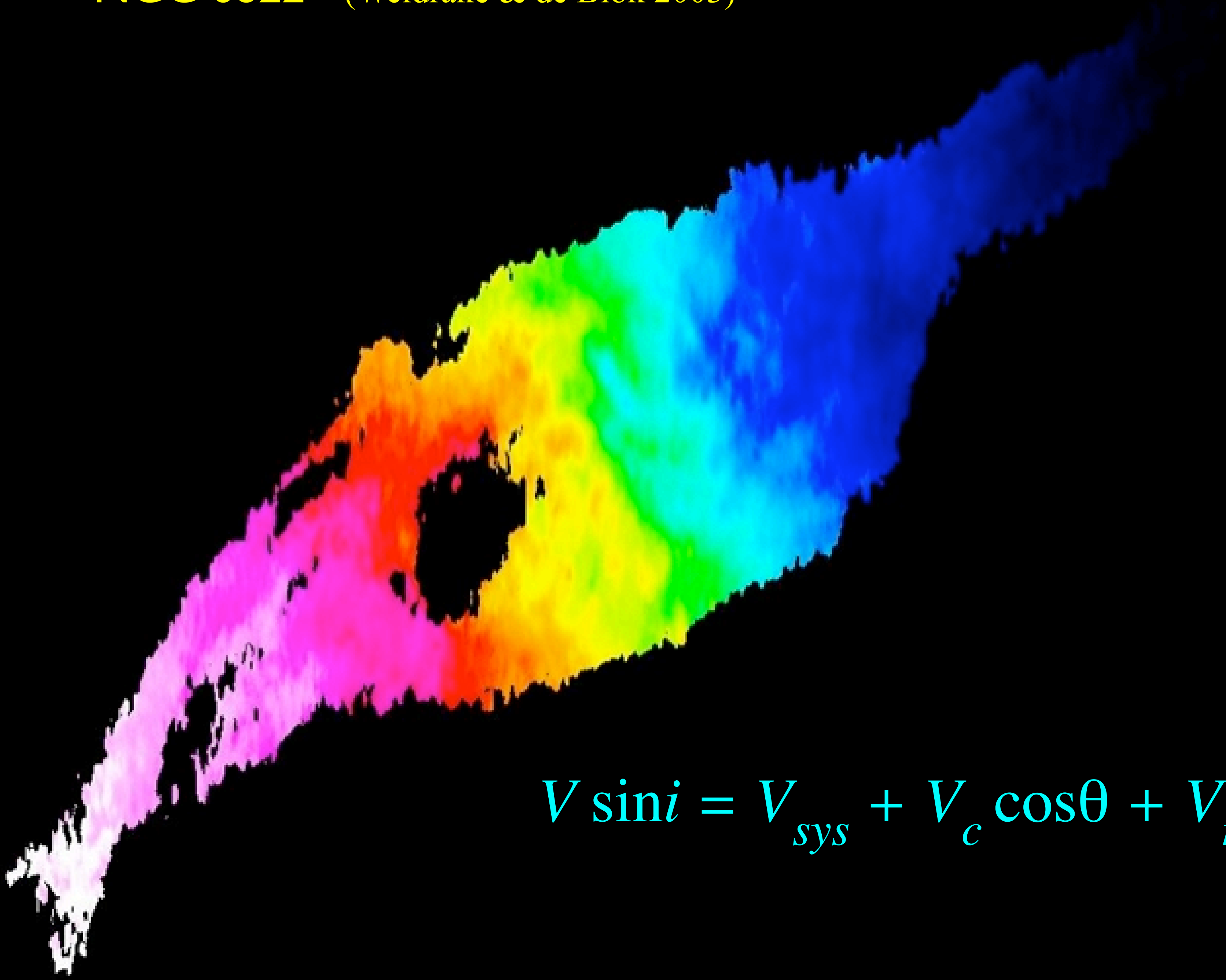


Stars

HI gas

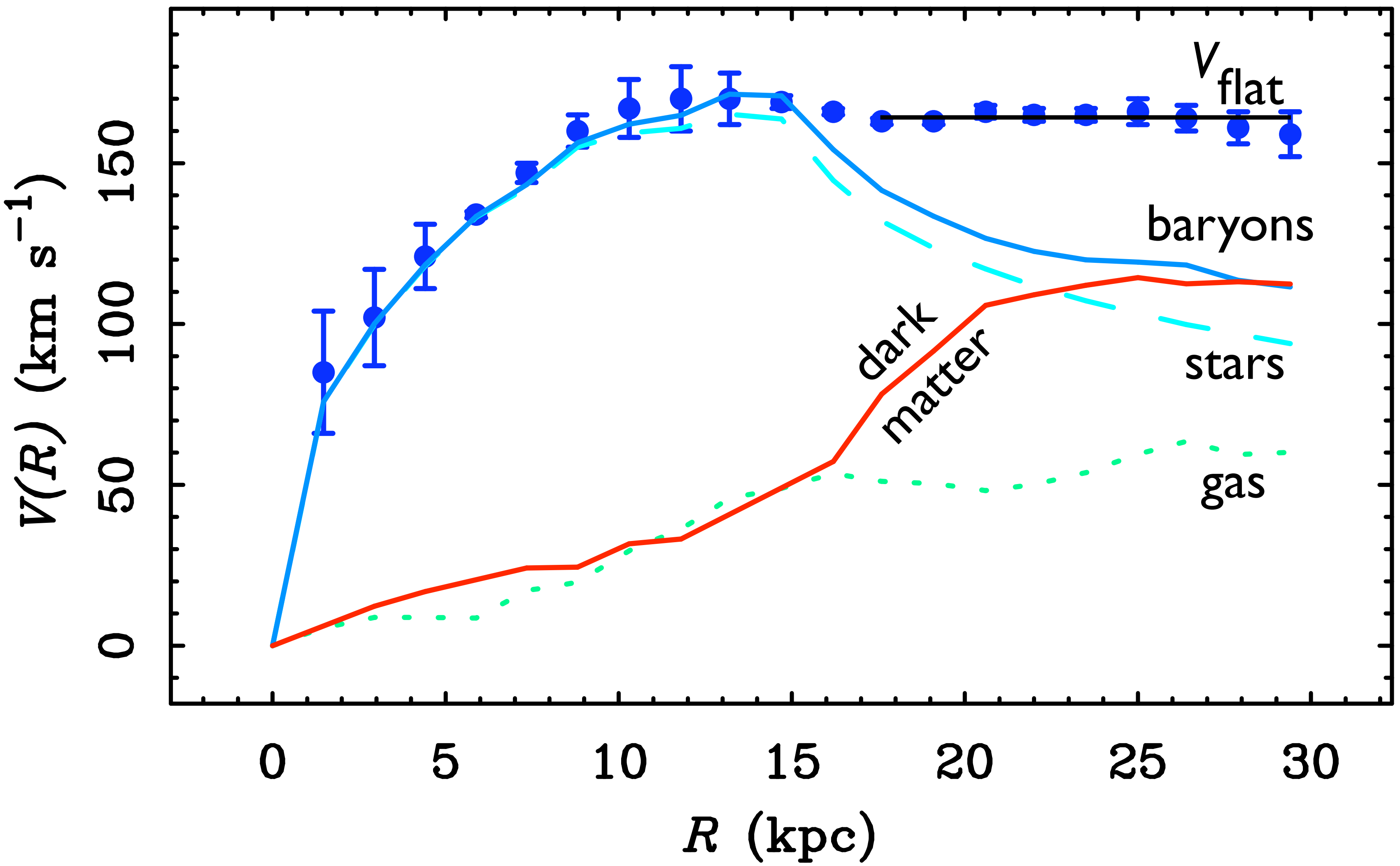
Fraternali, Oosterloo, Sancisi, & van Moorsel 2001, ApJ, 562, L47

NGC 6822 (Weldrake & de Blok 2003)

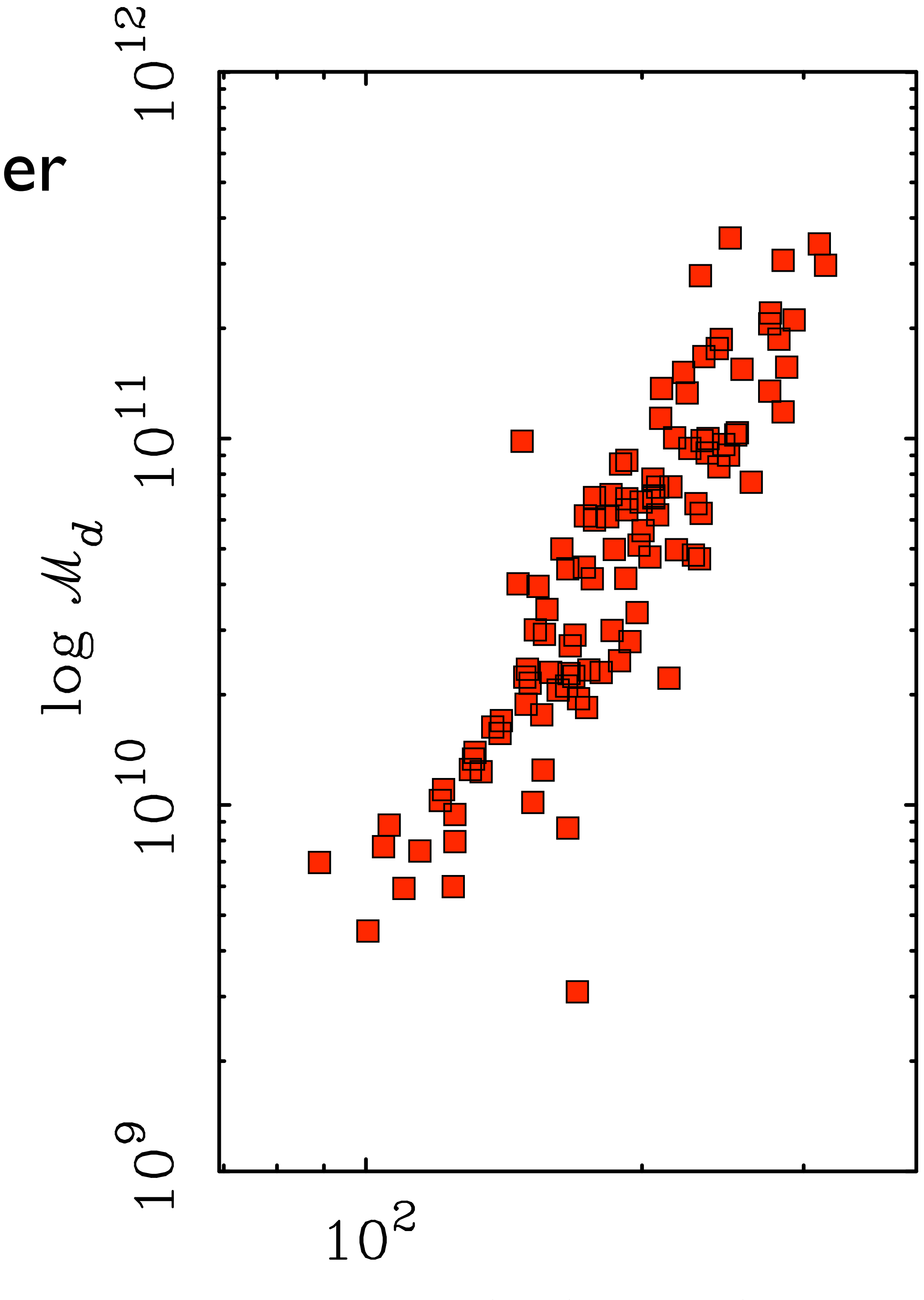


$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

NGC 6946: $\mathcal{M}_*/L_B = 1.1\ \mathcal{M}_\odot/L_\odot$



Tully-Fisher relation between luminosity/mass and rotation speed



Bothun et al. (1985)
H-band

TF Relation

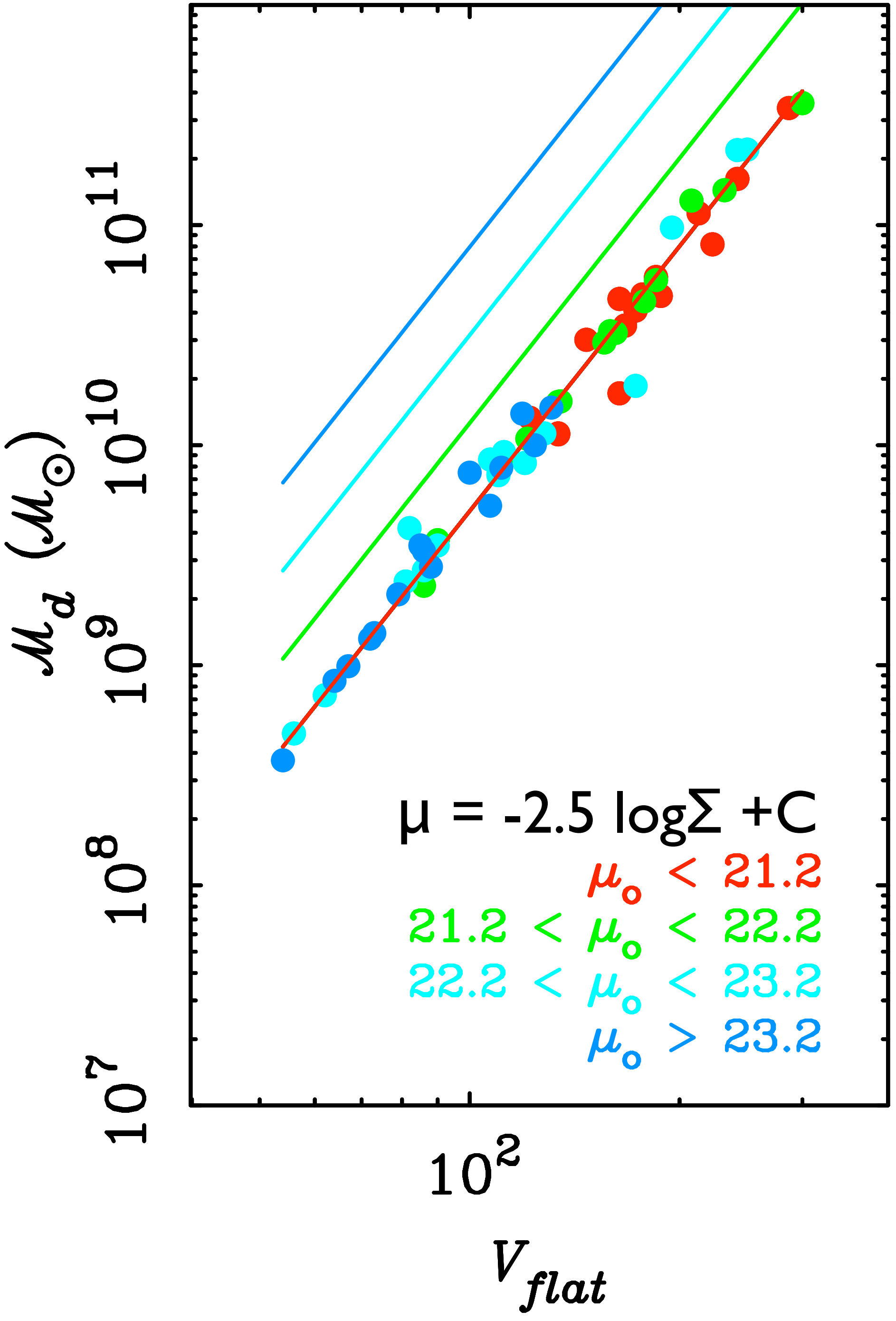
Newton says

$V^2 = GM/R$.

Equivalently,

$\Sigma = M/R^2$

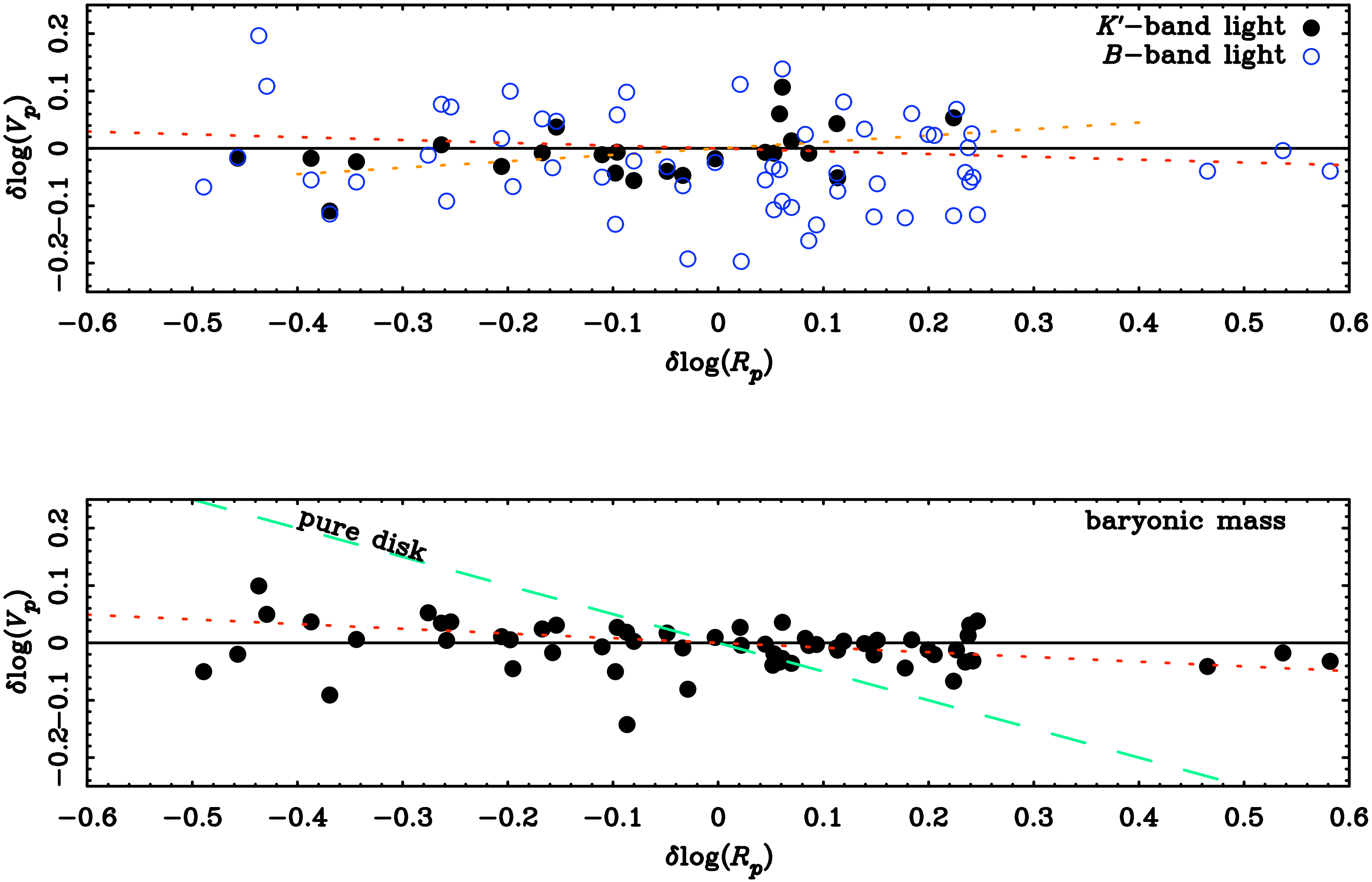
$V^4 = G^2 M\Sigma$



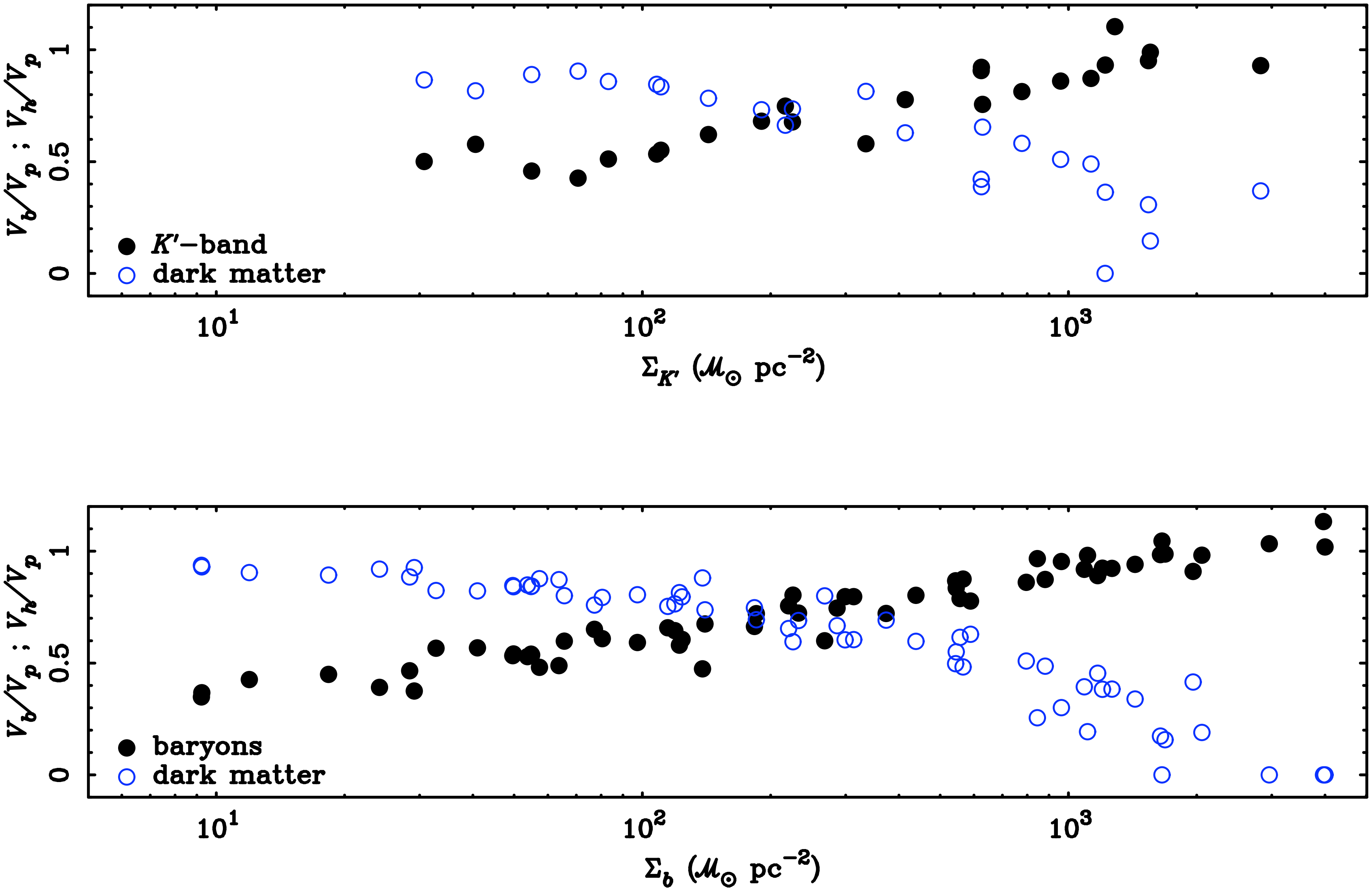
Therefore

Different Σ *should* mean different TF normalization.

No Residuals from TF rel'n



Requires fine balance between dark & baryonic mass



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

Renzo's Rule:

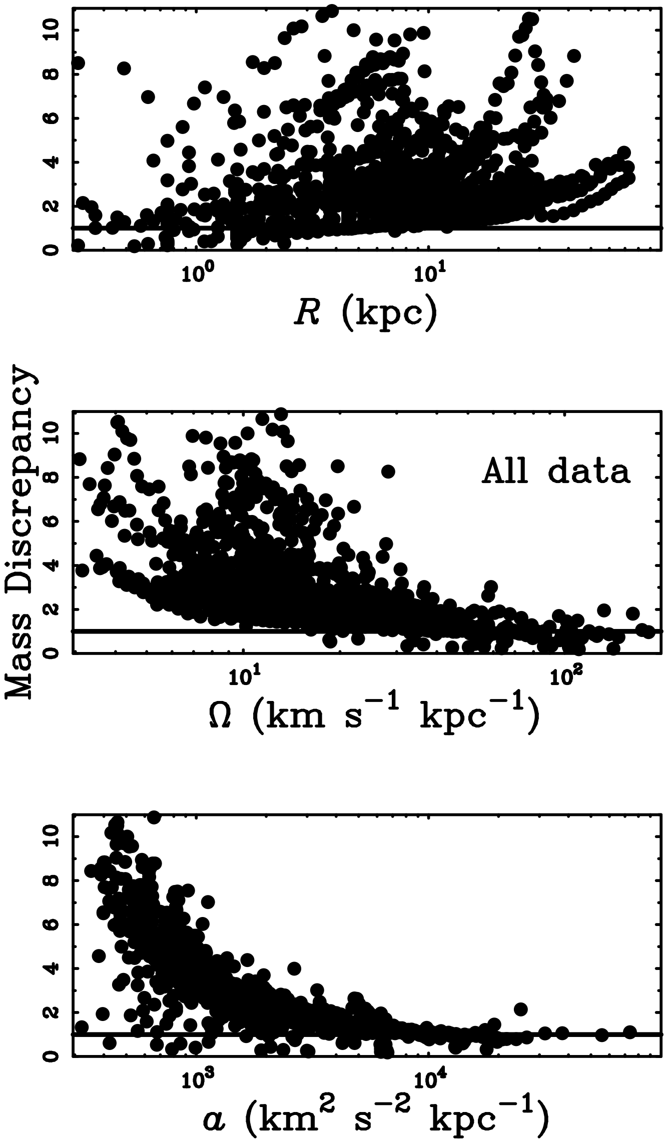
"When you see a feature in the light, you see a corresponding feature in the rotation curve."

(Sancisi 1995, private communication)

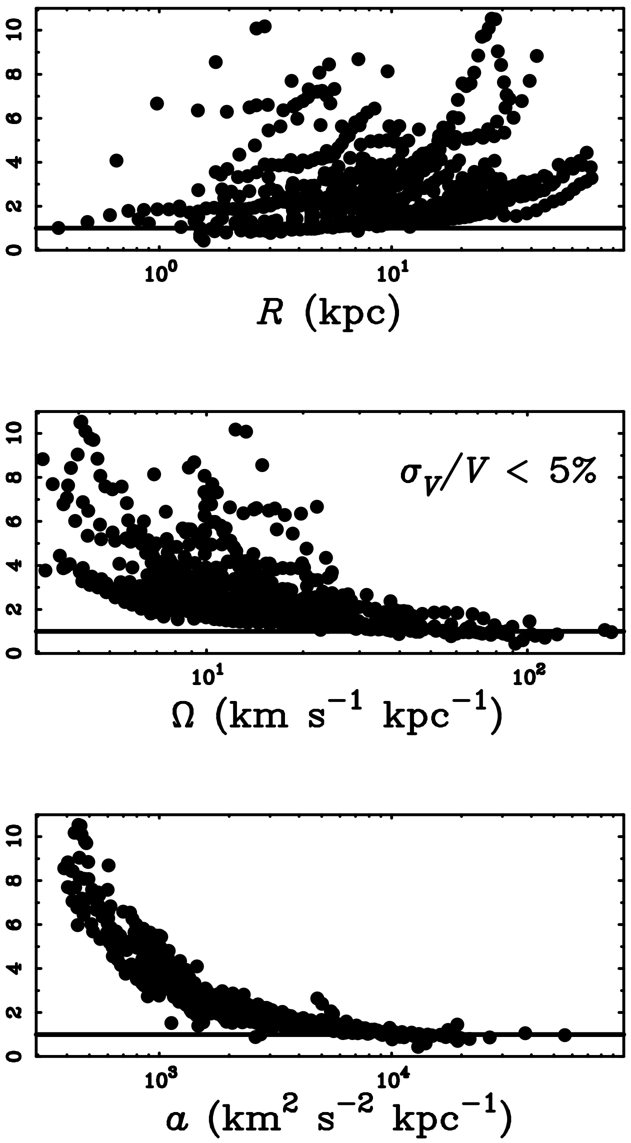
The distribution of mass is coupled to the distribution of light.

Quantify by defining the Mass Discrepancy:

$$\mathcal{D} = \frac{V^2}{V_b^2} = \frac{V^2}{\Upsilon_\star v_\star^2 + V_g^2}$$



74 galaxies
> 1000 points
(all data)

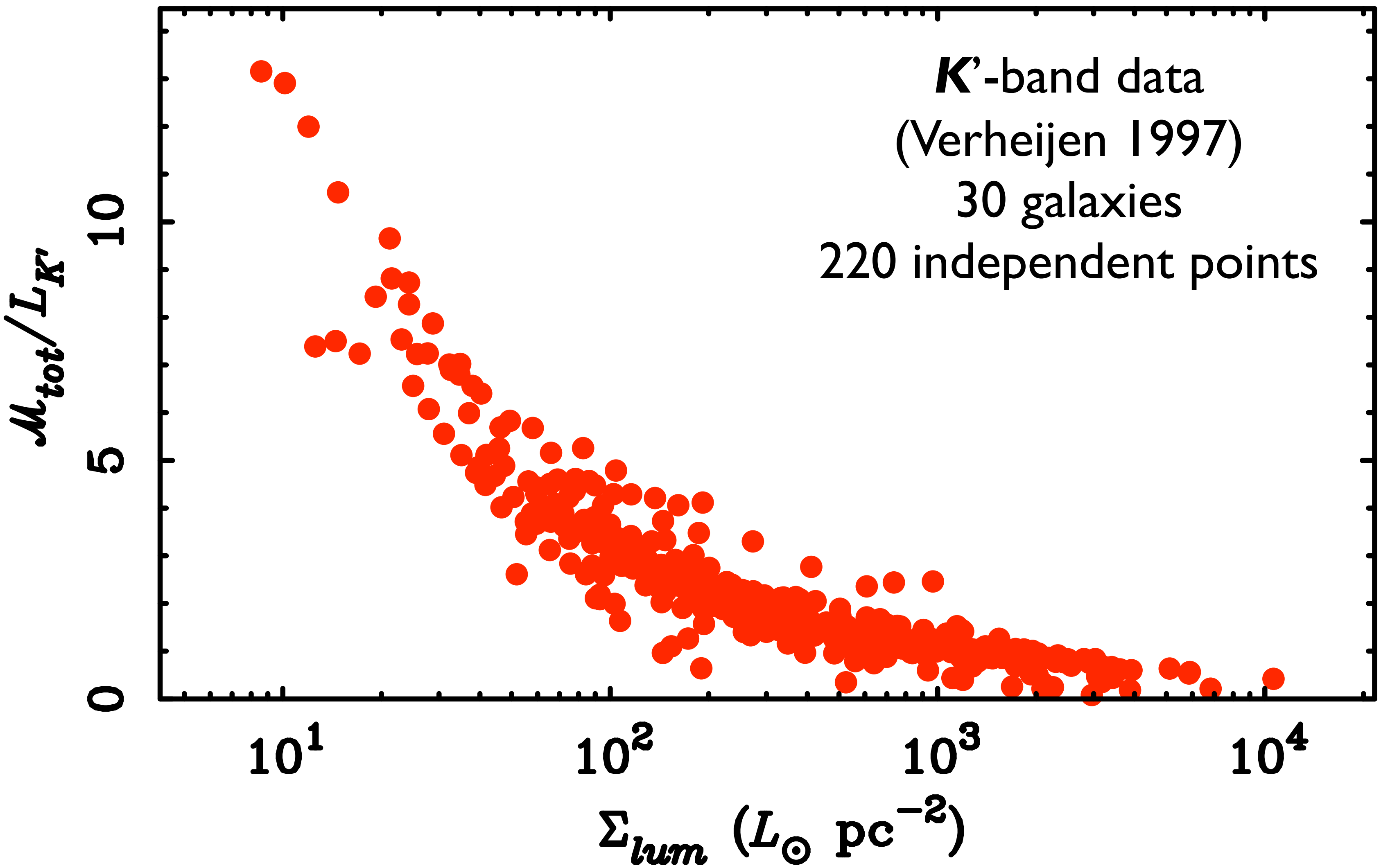


radius

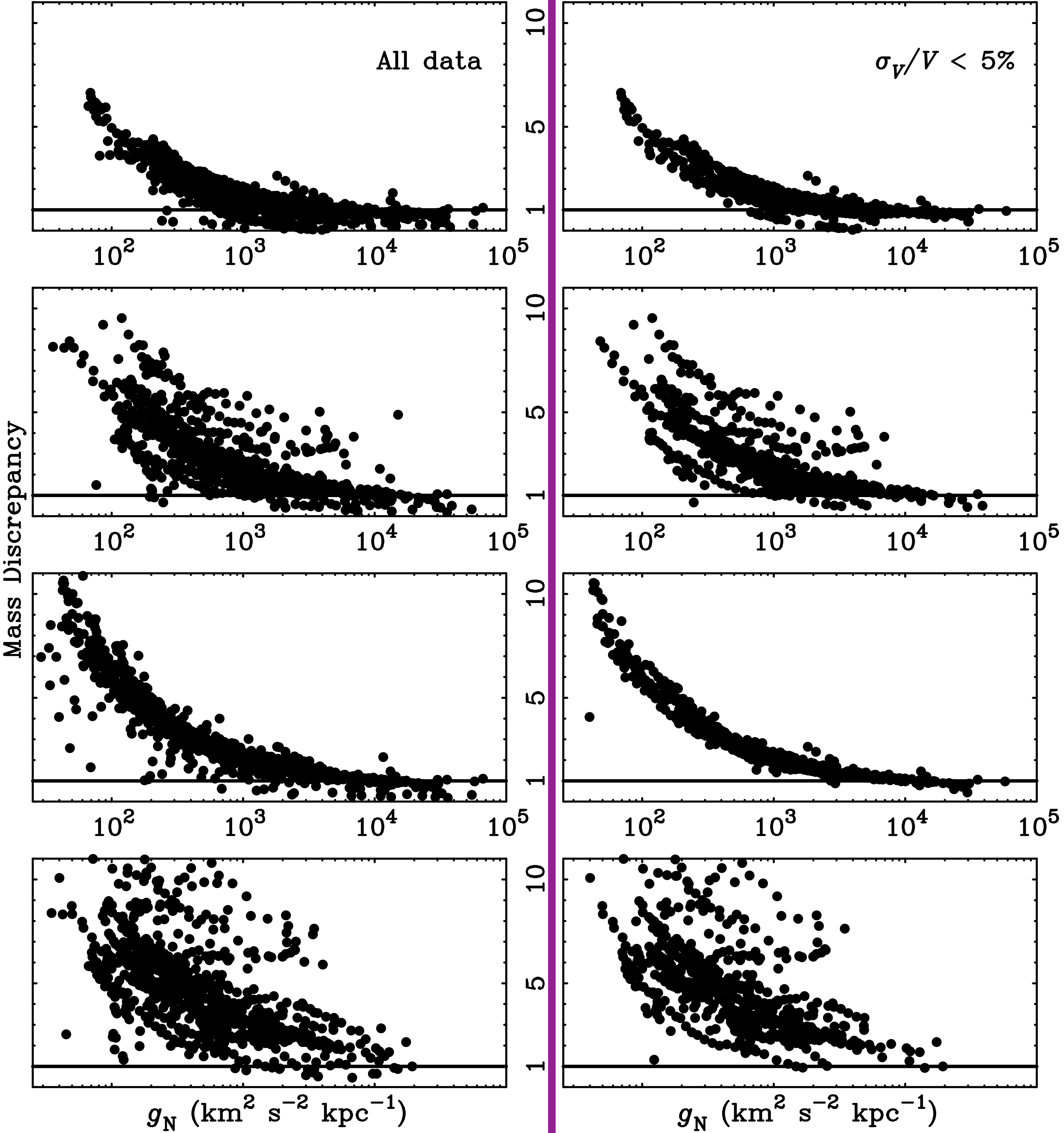
orbital
frequency

acceleration

60 galaxies
> 600 points
(errors < 5%)


K'-band data
(Verheijen 1997)
30 galaxies
220 independent points
$\mathcal{M}_{tot}/L_{K'}$
0
5
10
10^1
10^2
10^3
10^4
Σ_{lum} ($L_\odot$ pc^{-2})

Different choices of Stellar Mass-to-Light Ratio



MOND

MOdified Newtonian Dynamics

introduced by Moti Milgrom in 1983

instead of dark matter, suppose the force law changes such that

$$\text{for } \; a >> a_o, \; a \Rightarrow g_N$$

$$\text{for } \; a << a_o, \; a \Rightarrow \sqrt{(g_N a_o)}$$

where

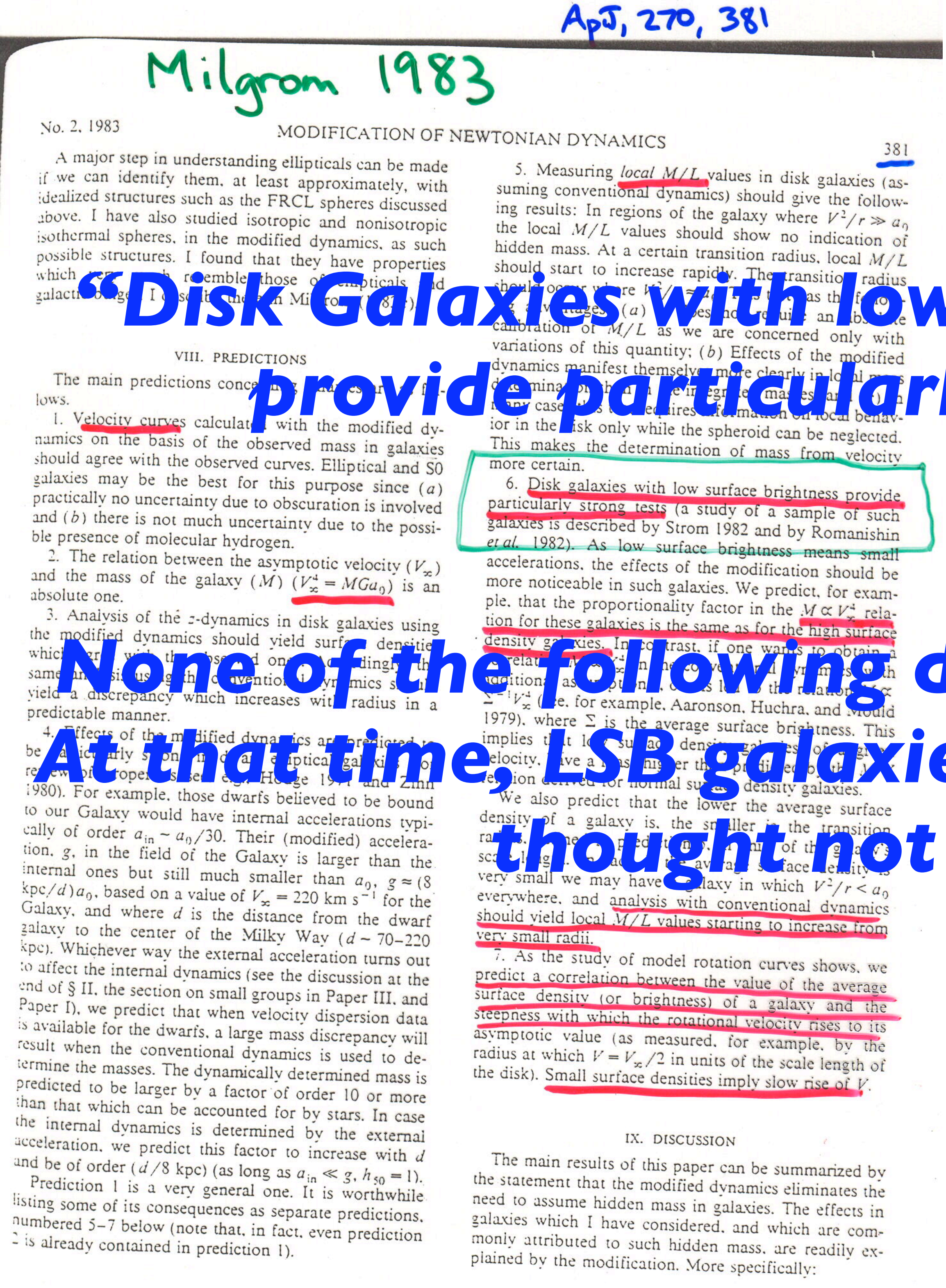
$$g_N = GM/R^2$$

is the usual Newtonain acceleration.
More generally, these limits are connected by a smooth interpolation fcn $\mu(a/a_o)$ so that

$$\mu(a/a_o)\, a = g_N\,.$$

MOND can be interpreted as a modification of either inertia (F = ma) or gravity (the Poisson eqn).

MOND predictions



ApJ, 270, 381

Milgrom 1983

A major step in understanding ellipticals can be made if we can identify them, at least approximately, with idealized structures such as the FRCL spheres discussed above. I have also studied isotropic and nonisotropic isothermal spheres, in the modified dynamics, as such possible structures. I found that they have properties which [illegible] resemble those of [illegible] and galacti[illegible] I [illegible] Milgrom [illegible]

VIII. PREDICTIONS

The main predictions conce[illegible] follows.

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] ones. [illegible] same [illegible] conventio[illegible] yield a discrepancy which increases wit[illegible] radius in a predictable manner.

4. Effects of th[illegible] dynamics are predicted to be [illegible] elliptical galaxies [illegible] Hodge 19[illegible] 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, $g \approx (8 \text{ kpc}/d)a_0$, based on a value of $V_\infty = 220 \text{ km s}^{-1}$ 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 [illegible] as the fo[illegible] advantages: (*a*) [illegible] an abs[illegible] calibration of M/L as we are concerned only with variations of this quantity; (*b*) Effects of the modified dynamics manifest themselve[illegible] clearly in local [illegible] than in the integrated masses [illegible] many case[illegible] requires information on local behavior in the disk only while the spheroid can be neglected. This makes the determination of mass from velocity more certain.

6. Disk galaxies with low surface brightness provide particularly strong tests (a study of a sample of such galaxies is described by Strom 1982 and by Romanishin *et al.* 1982). As low surface brightness means small accelerations, the effects of the modification should be more noticeable in such galaxies. We predict, for example, that the proportionality factor in the $M \propto V_\infty^4$ relation for these galaxies is the same as for the high surface density galaxies. In contrast, if one wants to obtain a [illegible] additiona[illegible] the relation [illegible] $\Sigma^{-1}V_\infty^4$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies th[illegible] density [illegible] velocity, have a [illegible] normal su[illegible] density galaxies.

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

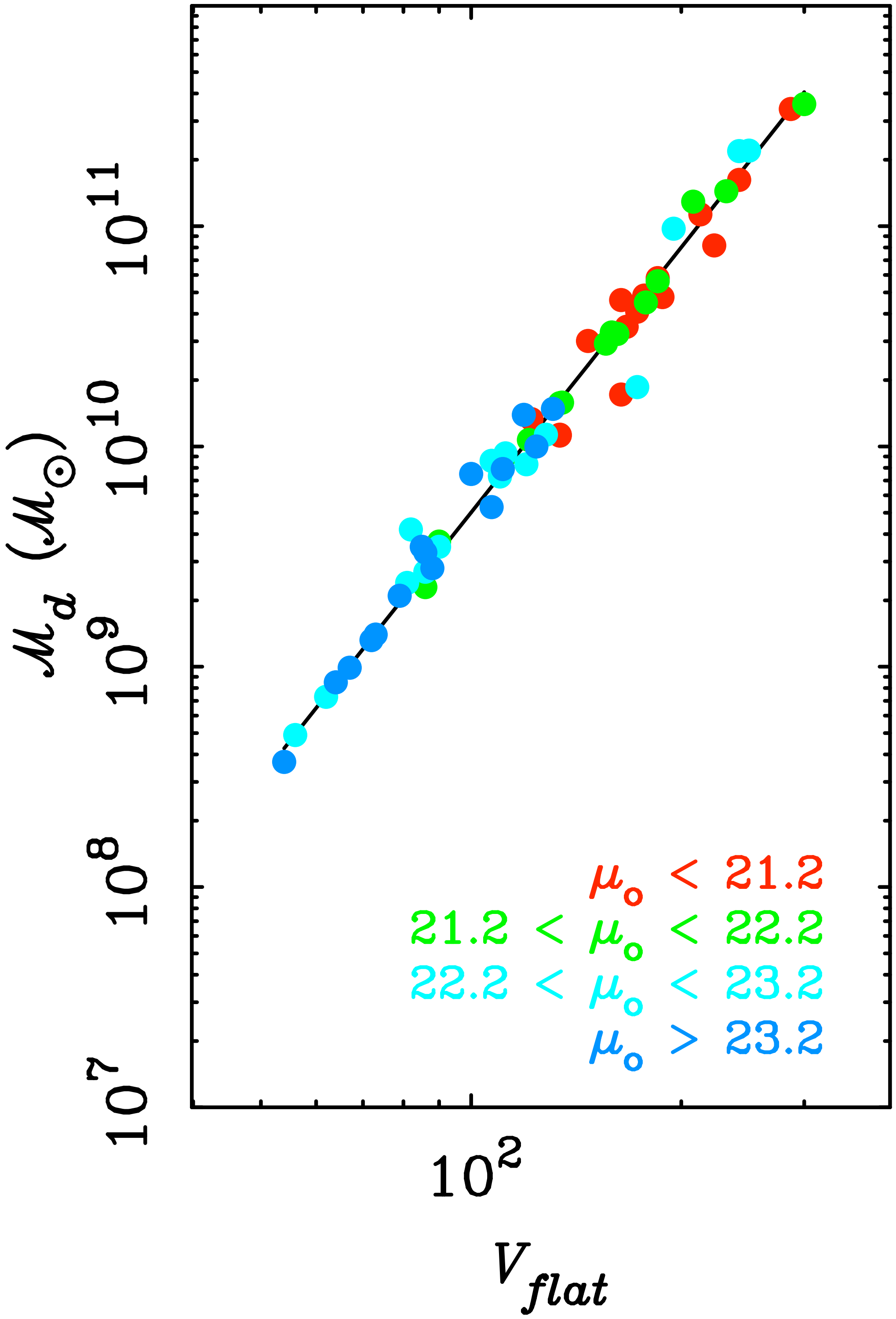
IX. DISCUSSION

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

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



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- Surface Density ~ Surface Brightness
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Test TF slope by extrapolation to very low velocities:

(McGaugh 2005)

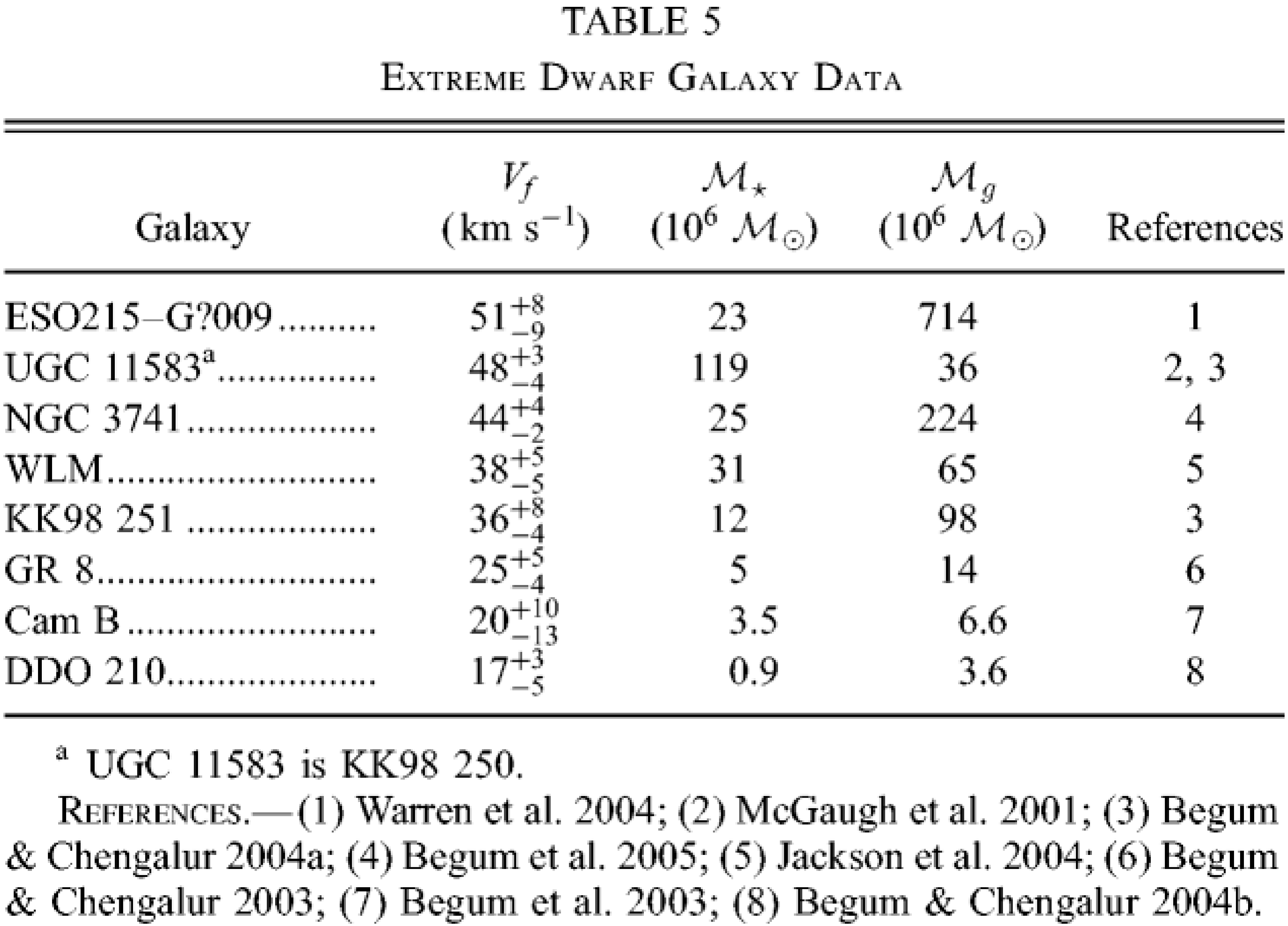


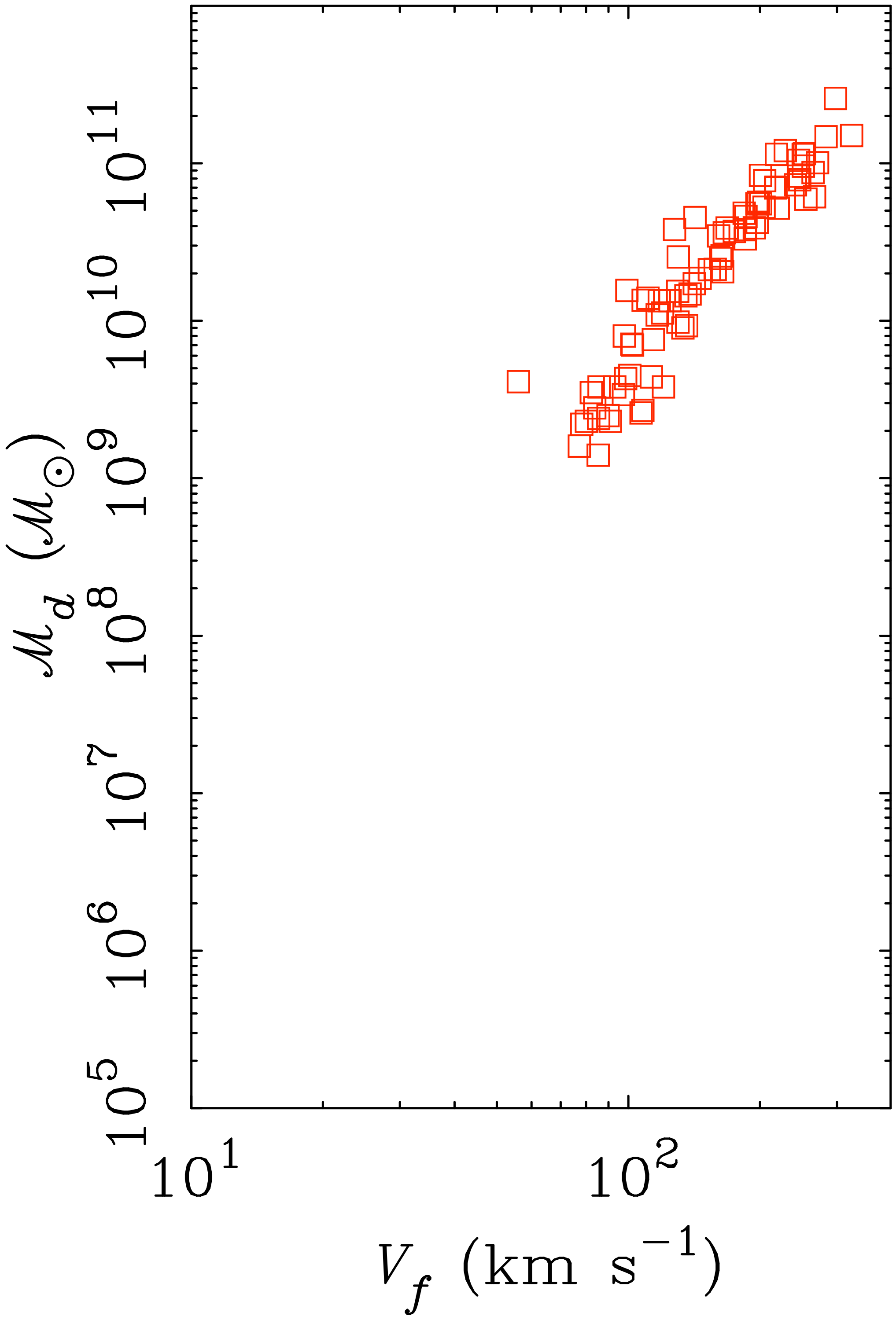
TABLE 5

EXTREME DWARF GALAXY DATA

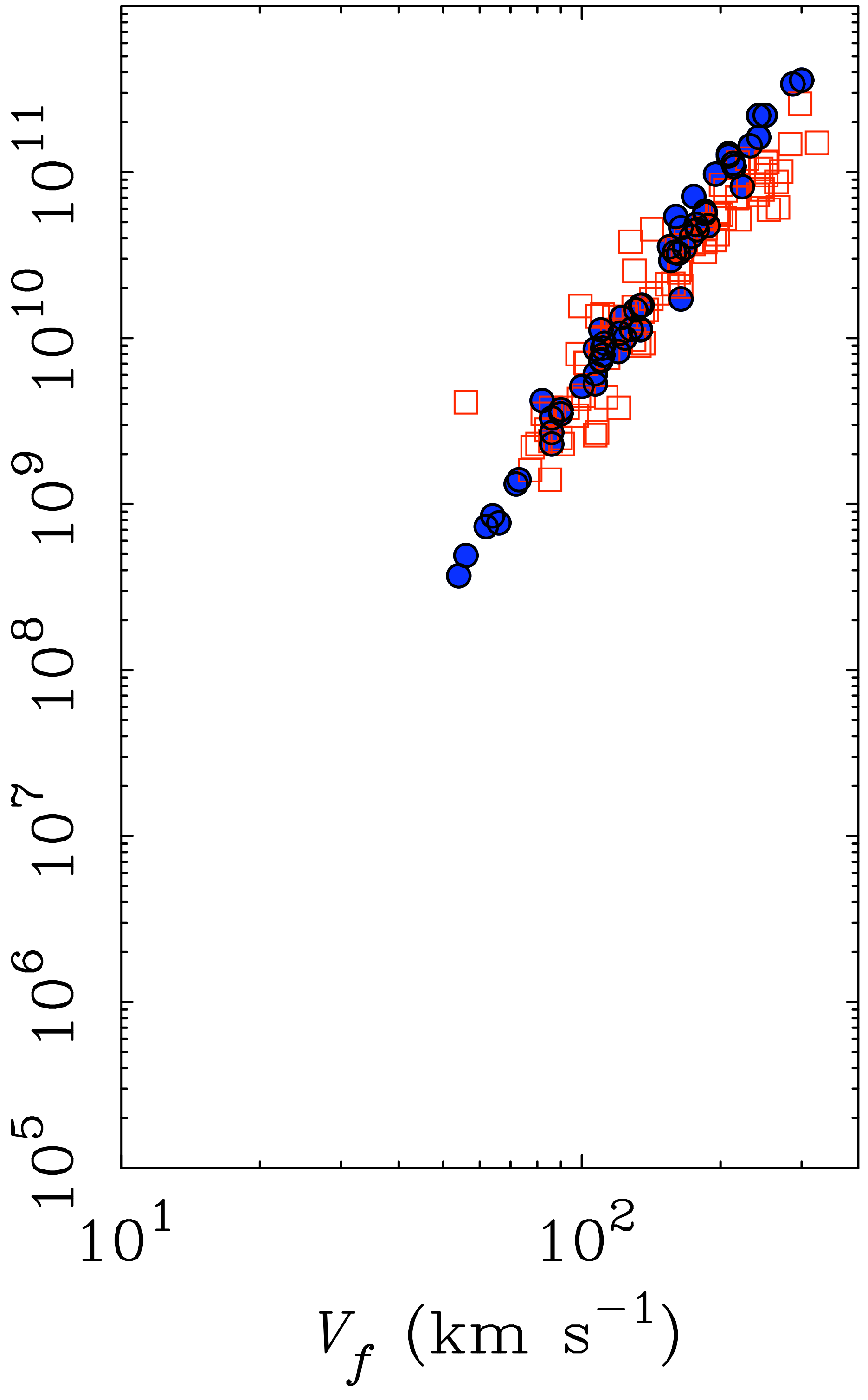
Galaxy	V_f (km s^{-1})	$\mathcal{M}_\star$ (10^6 $\mathcal{M}_\odot$)	$\mathcal{M}_g$ (10^6 $\mathcal{M}_\odot$)	References
ESO215–G?009..........	51^{+8}_{-9}	23	714	1
UGC 11583[a]................	48^{+3}_{-4}	119	36	2, 3
NGC 3741....................	44^{+4}_{-2}	25	224	4
WLM...........................	38^{+5}_{-5}	31	65	5
KK98 251	36^{+8}_{-4}	12	98	3
GR 8............................	25^{+5}_{-4}	5	14	6
Cam B	20^{+10}_{-13}	3.5	6.6	7
DDO 210.....................	17^{+3}_{-5}	0.9	3.6	8

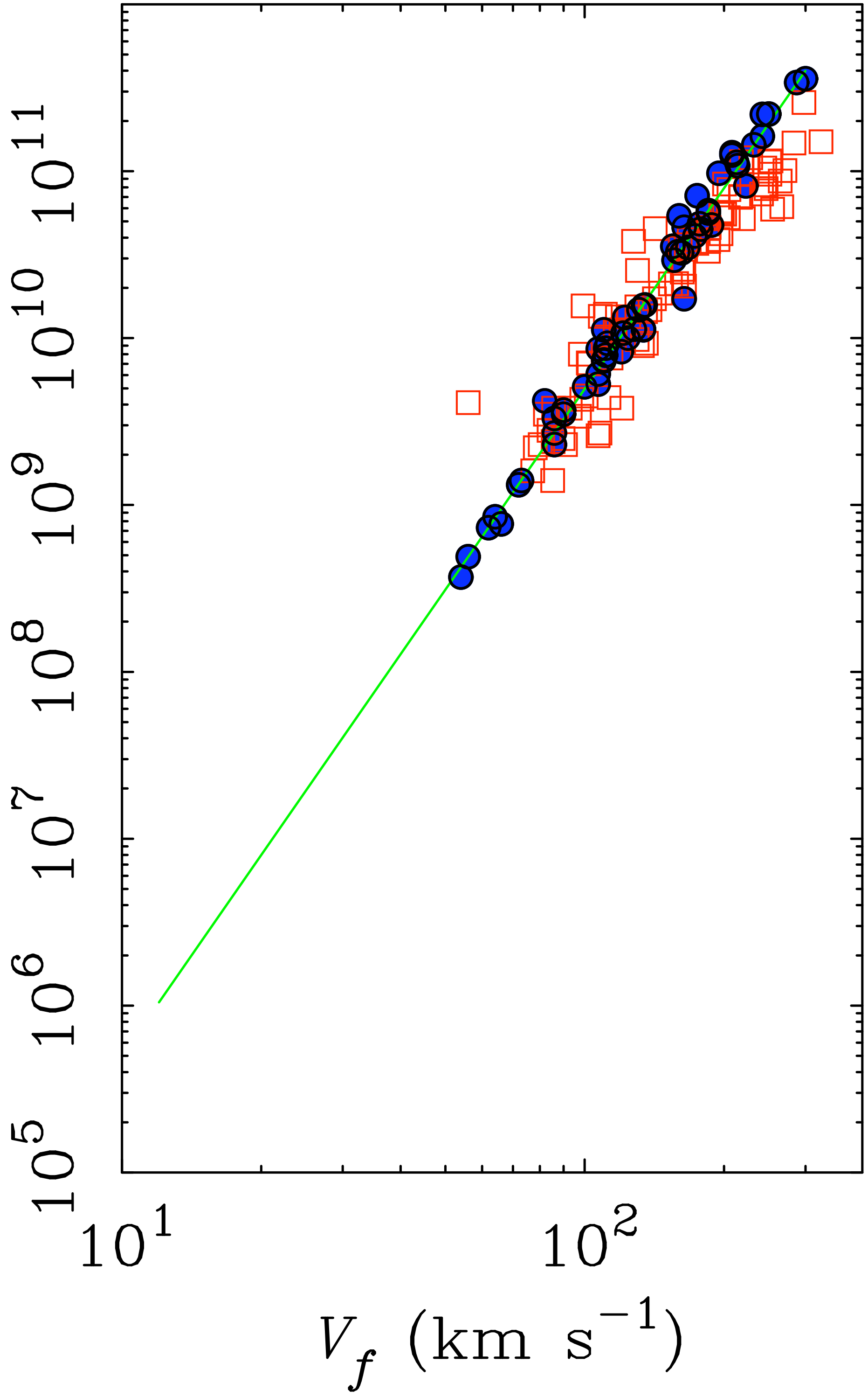
[a] UGC 11583 is KK98 250.

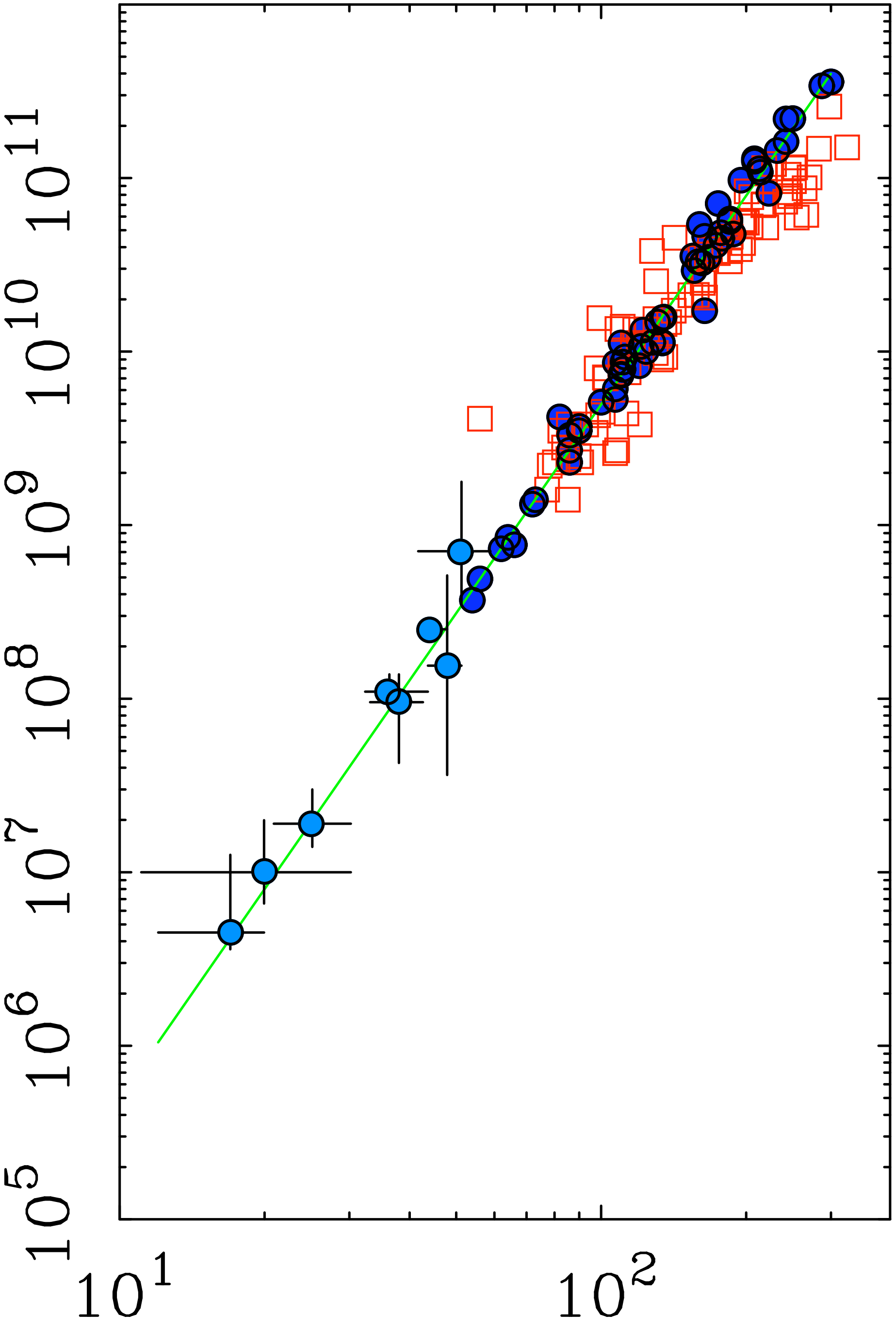
REFERENCES.—(1) Warren et al. 2004; (2) McGaugh et al. 2001; (3) Begum & Chengalur 2004a; (4) Begum et al. 2005; (5) Jackson et al. 2004; (6) Begum & Chengalur 2003; (7) Begum et al. 2003; (8) Begum & Chengalur 2004b.

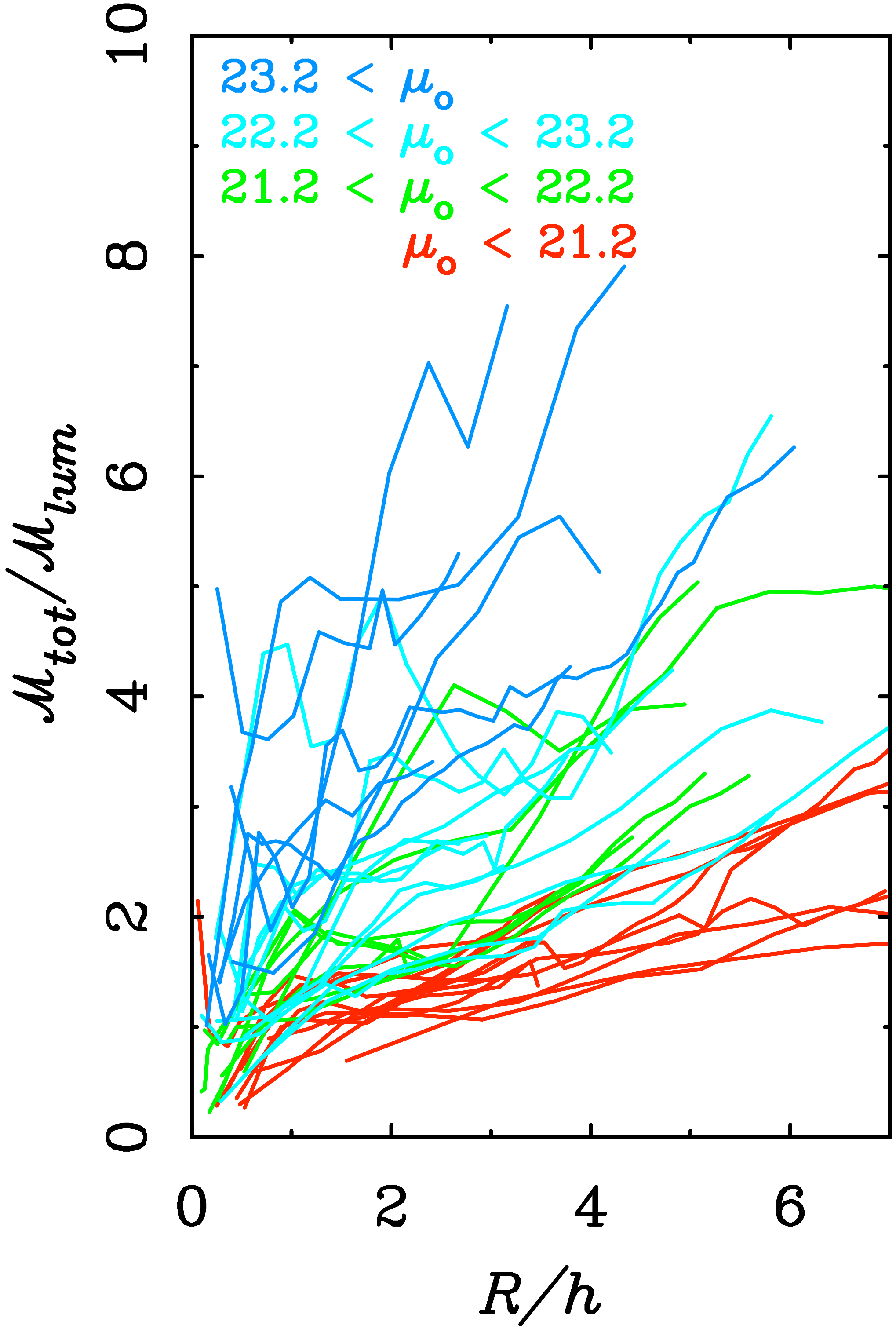


Pizagno et al. (2005)


$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^1
10^2
V_f (km s^{-1})


$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^1
10^2
V_f (km s^{-1})


$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^1
10^2
V_f (km s^{-1})



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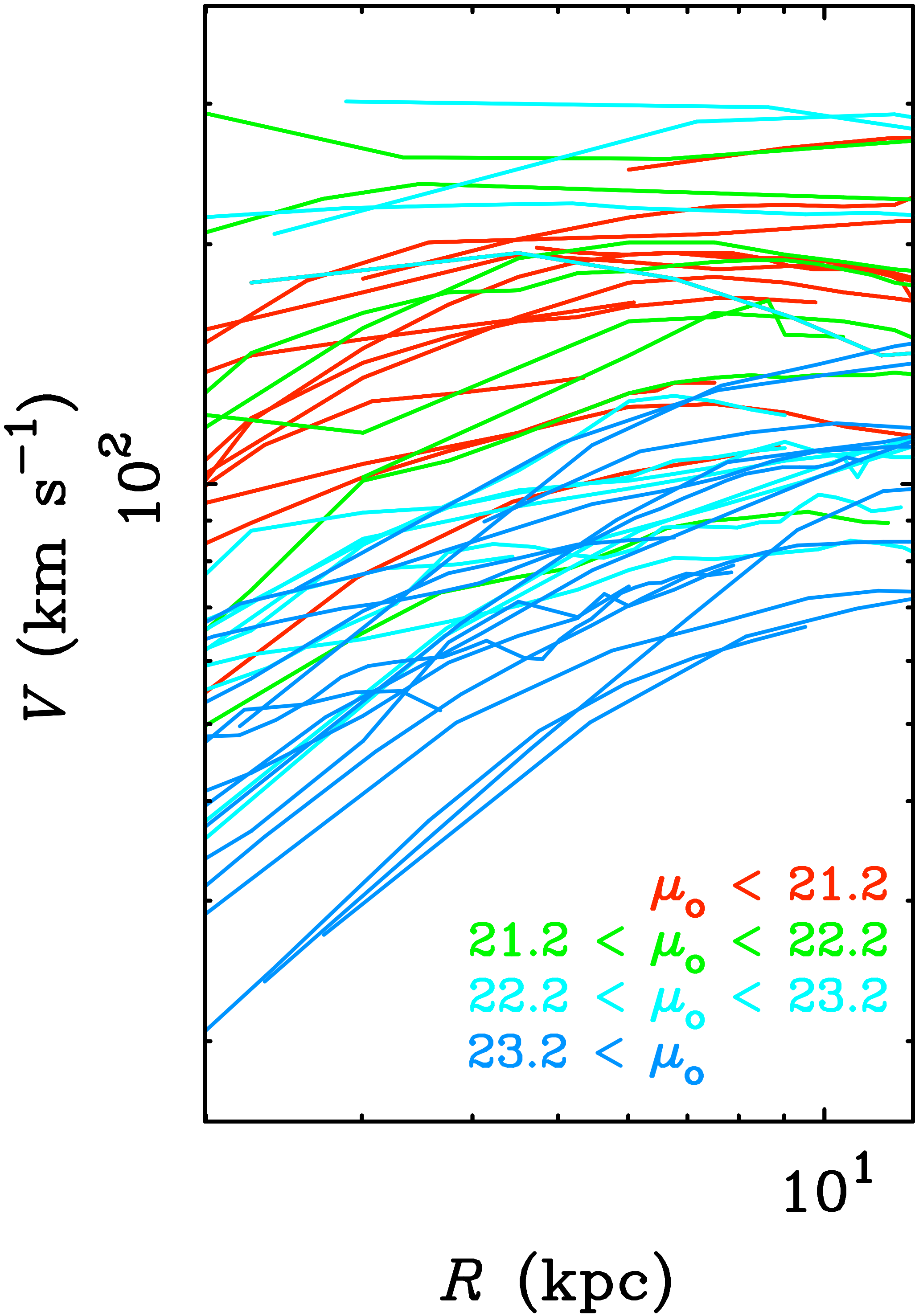

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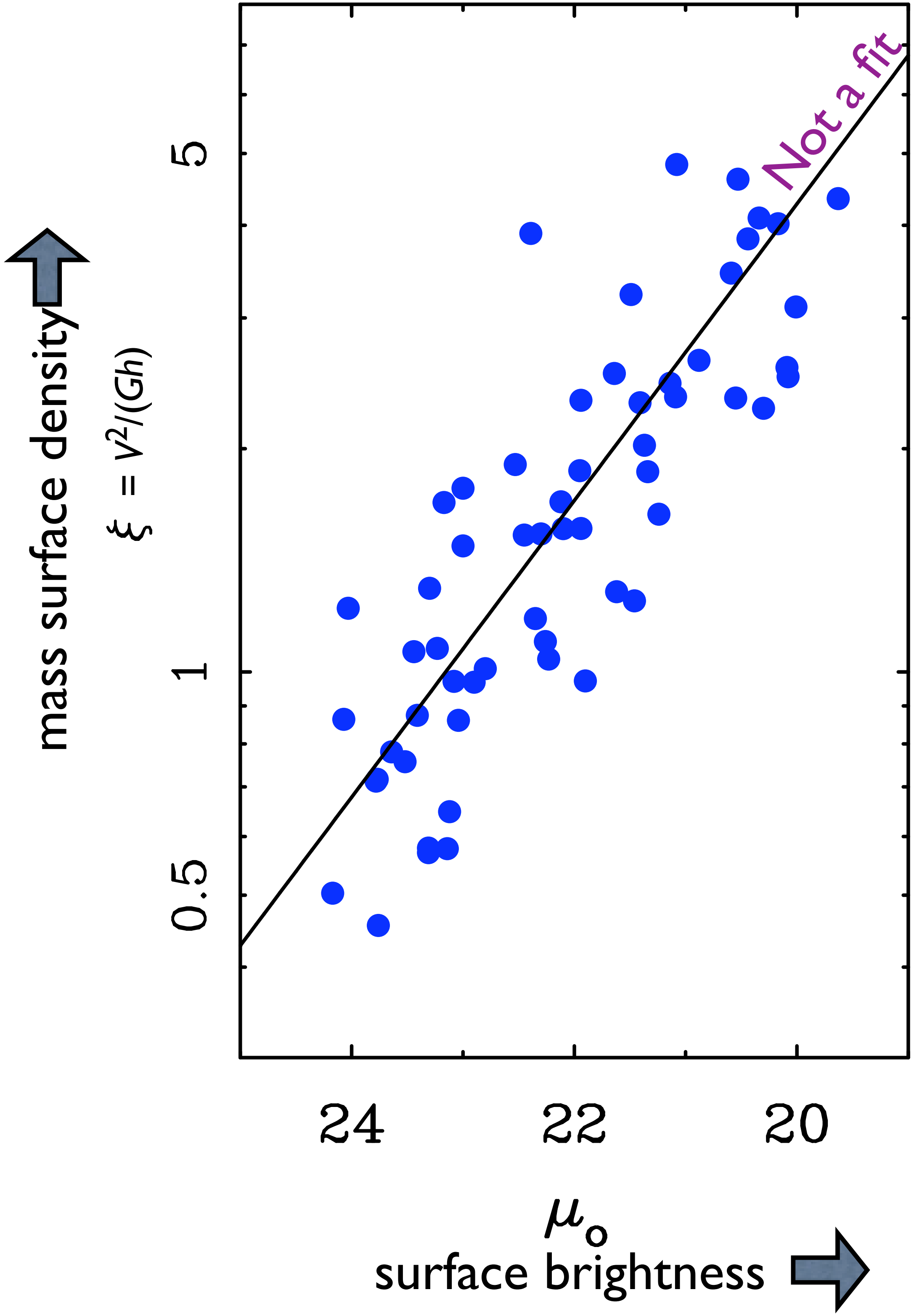

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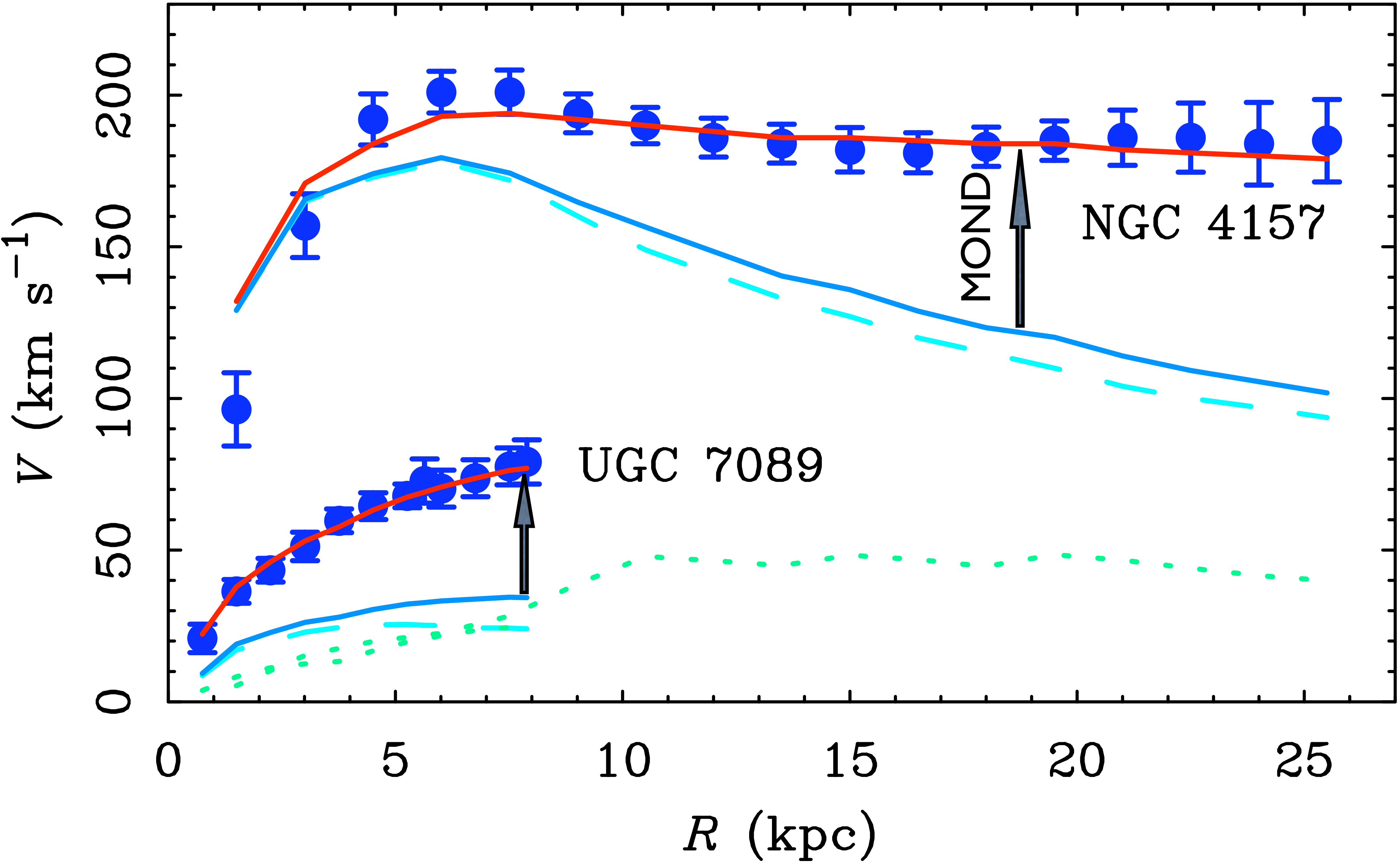
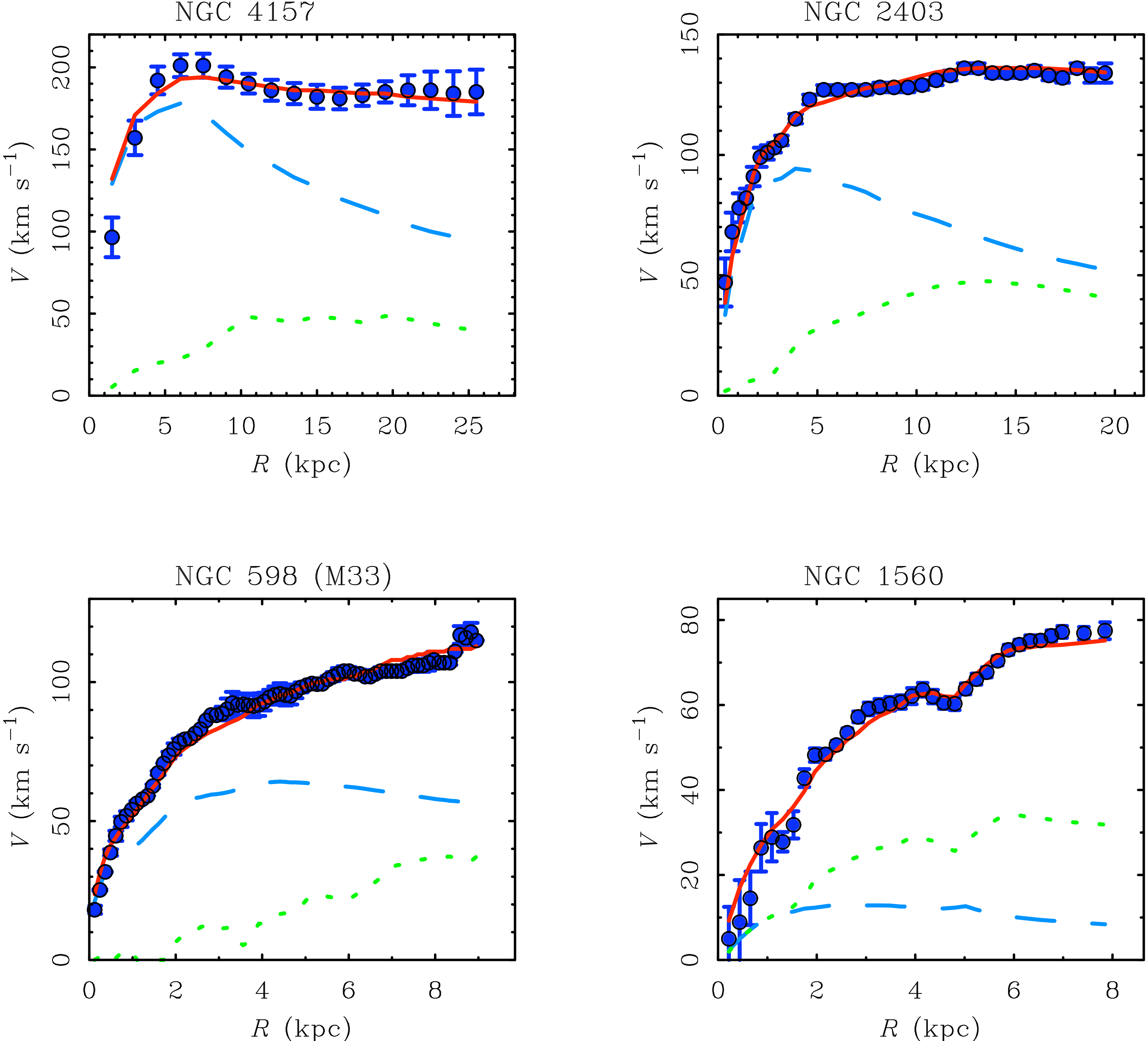
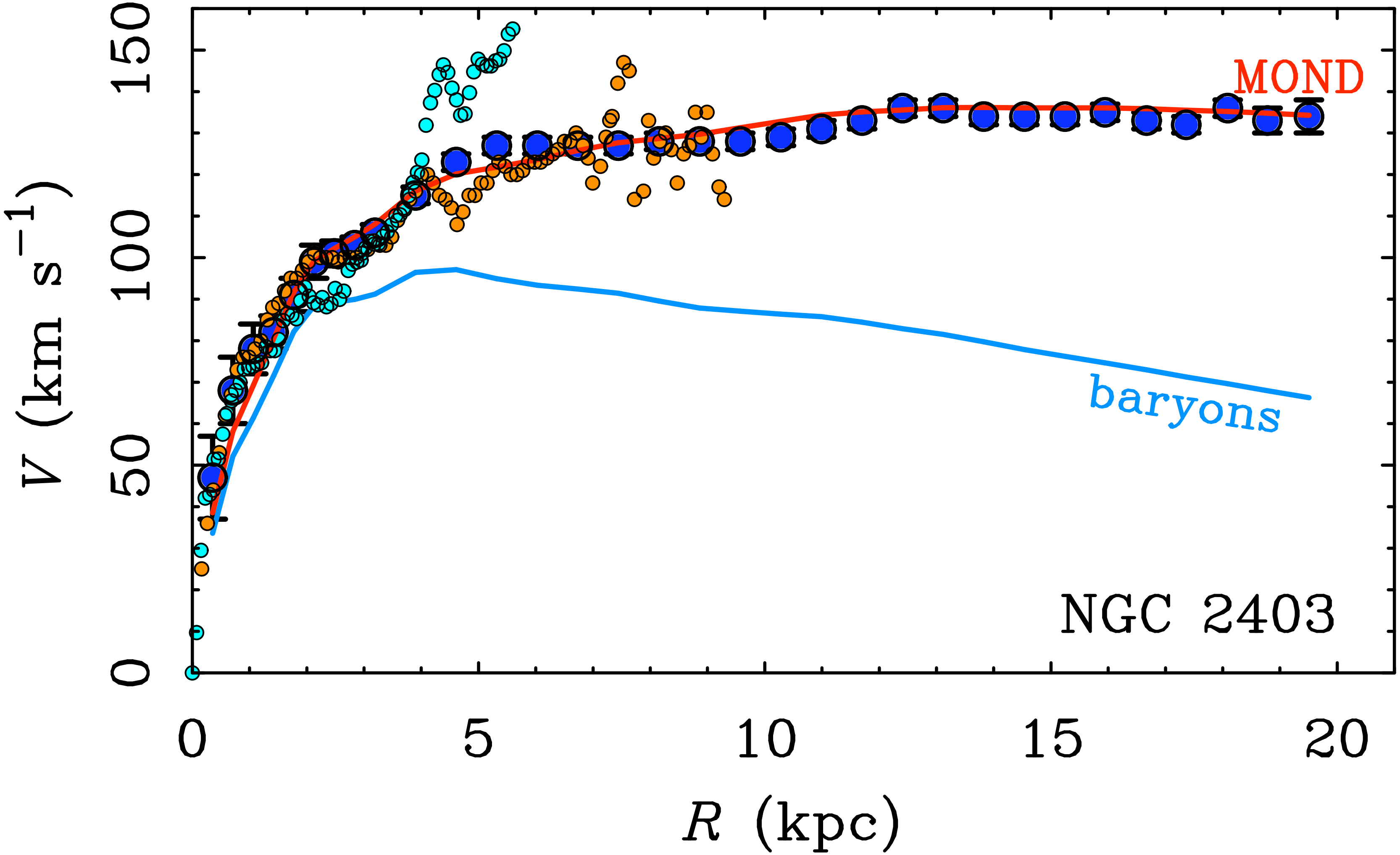


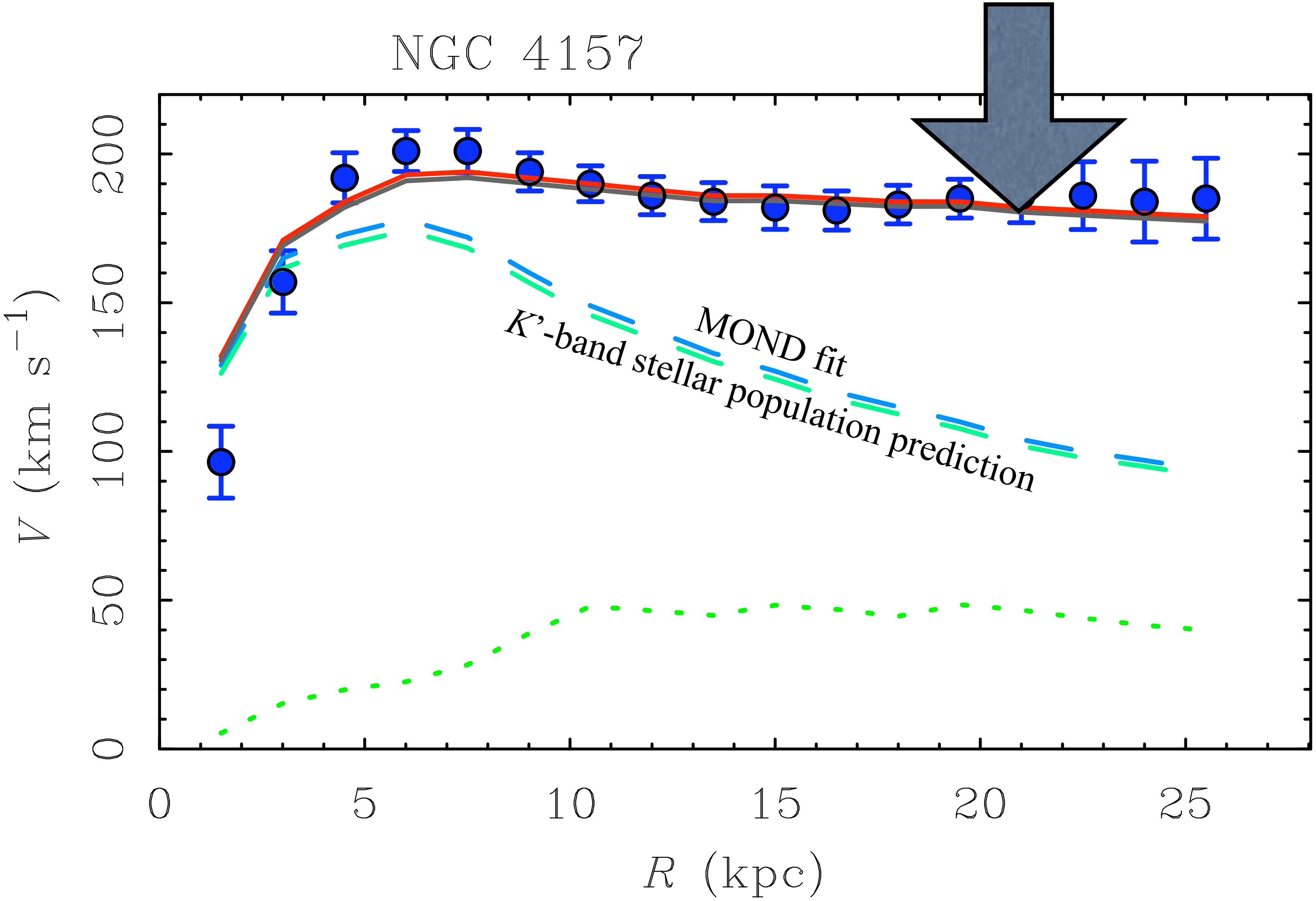
V (km s^{-1})
0
50
100
150
200
R (kpc)
0
5
10
15
20
25
MOND
NGC 4157
UGC 7089


NGC 4157
NGC 2403
NGC 598 (M33)
NGC 1560
V (km s^{-1})
R (kpc)
0
50
100
150
200
0
5
10
15
20
25
0
2
4
6
8
20
40
60
80

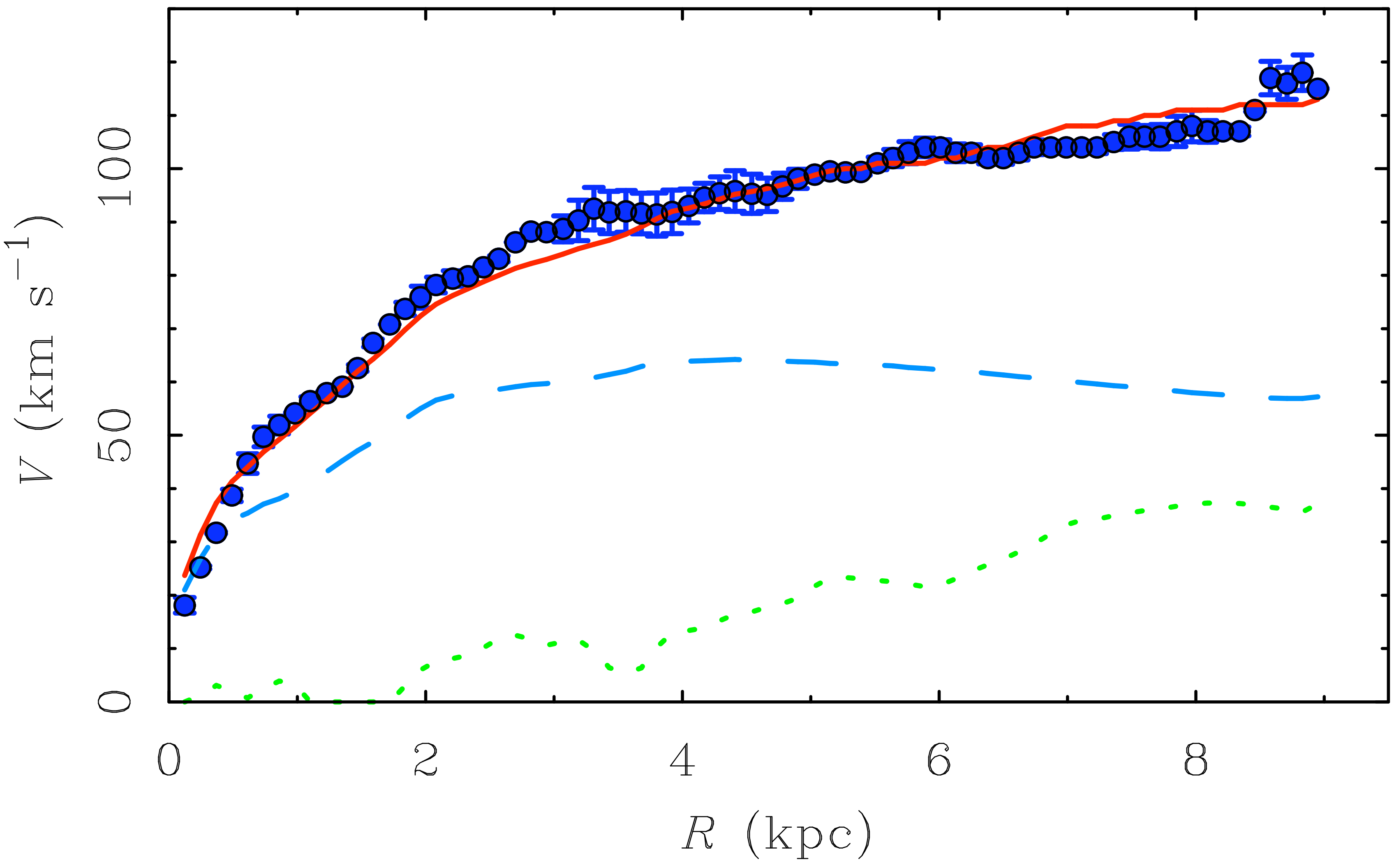


● Begeman (1987): HI data
● Blais-Ouellette et al. (2004) Hα Fabry-Perot
● Daigle et al. (2006) Hα Fabry-Perot

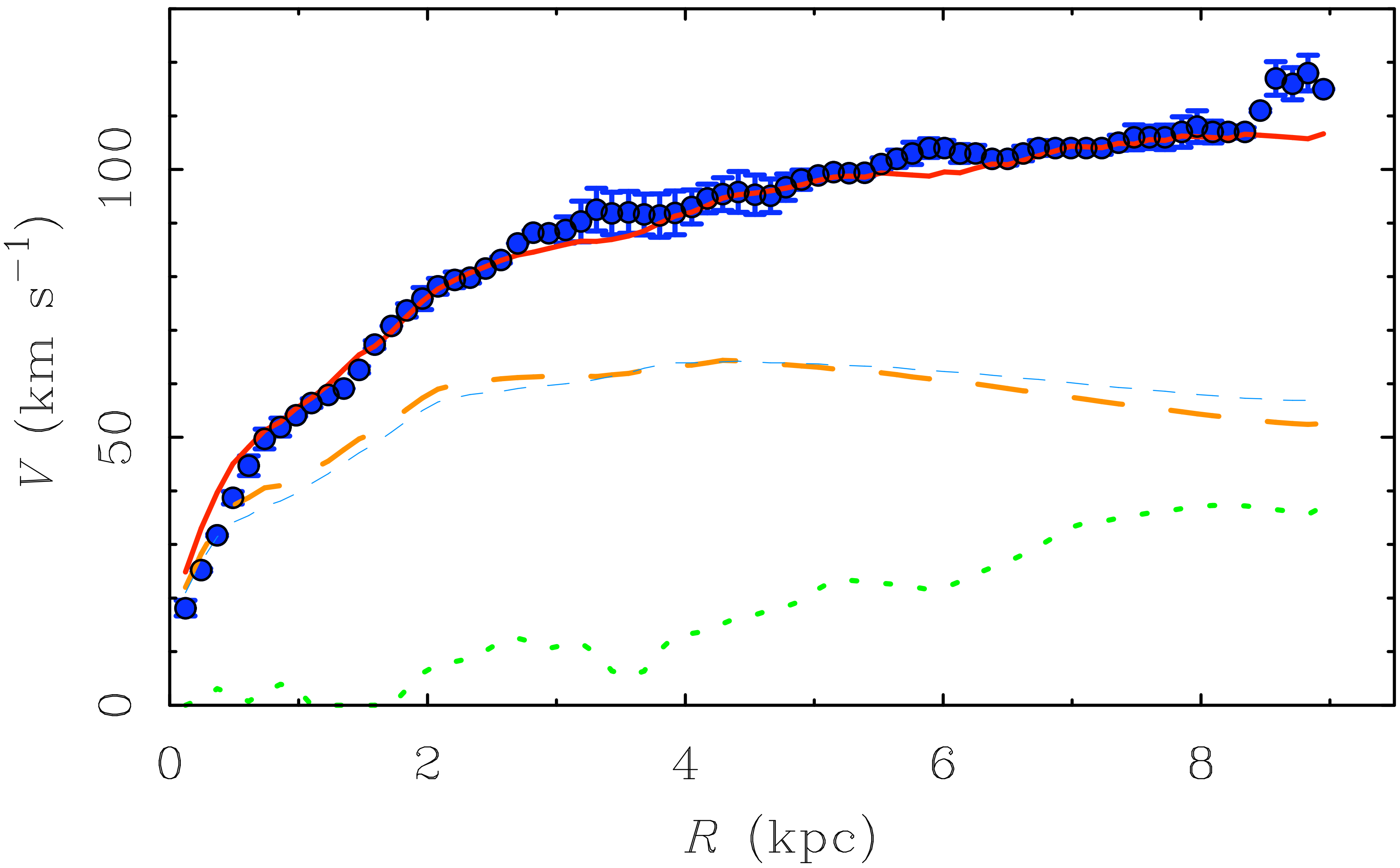
predictive power: zero free parameters



M33

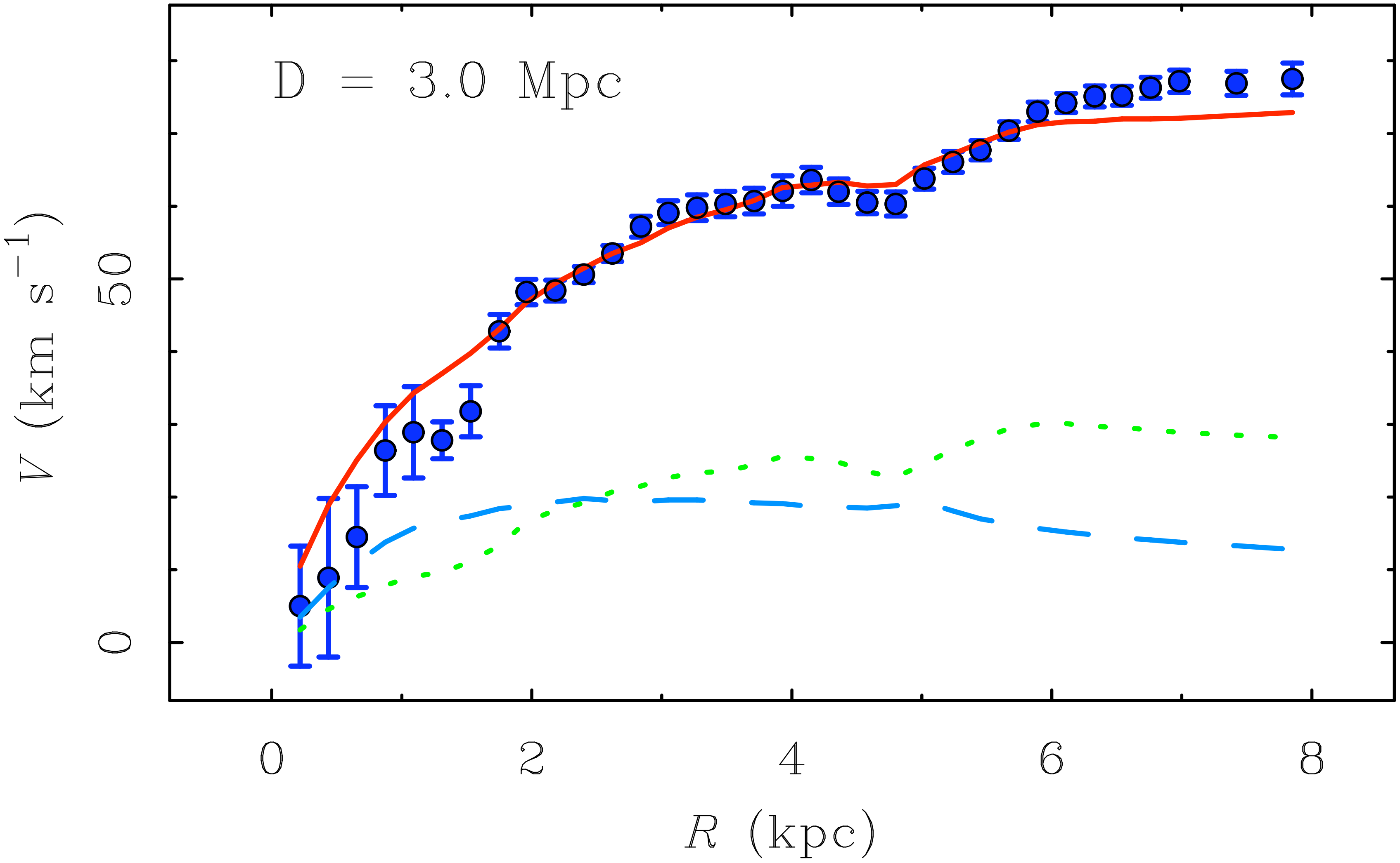


M33 color gradient corrected



Begeman, Broeils, & Sanders (1991)

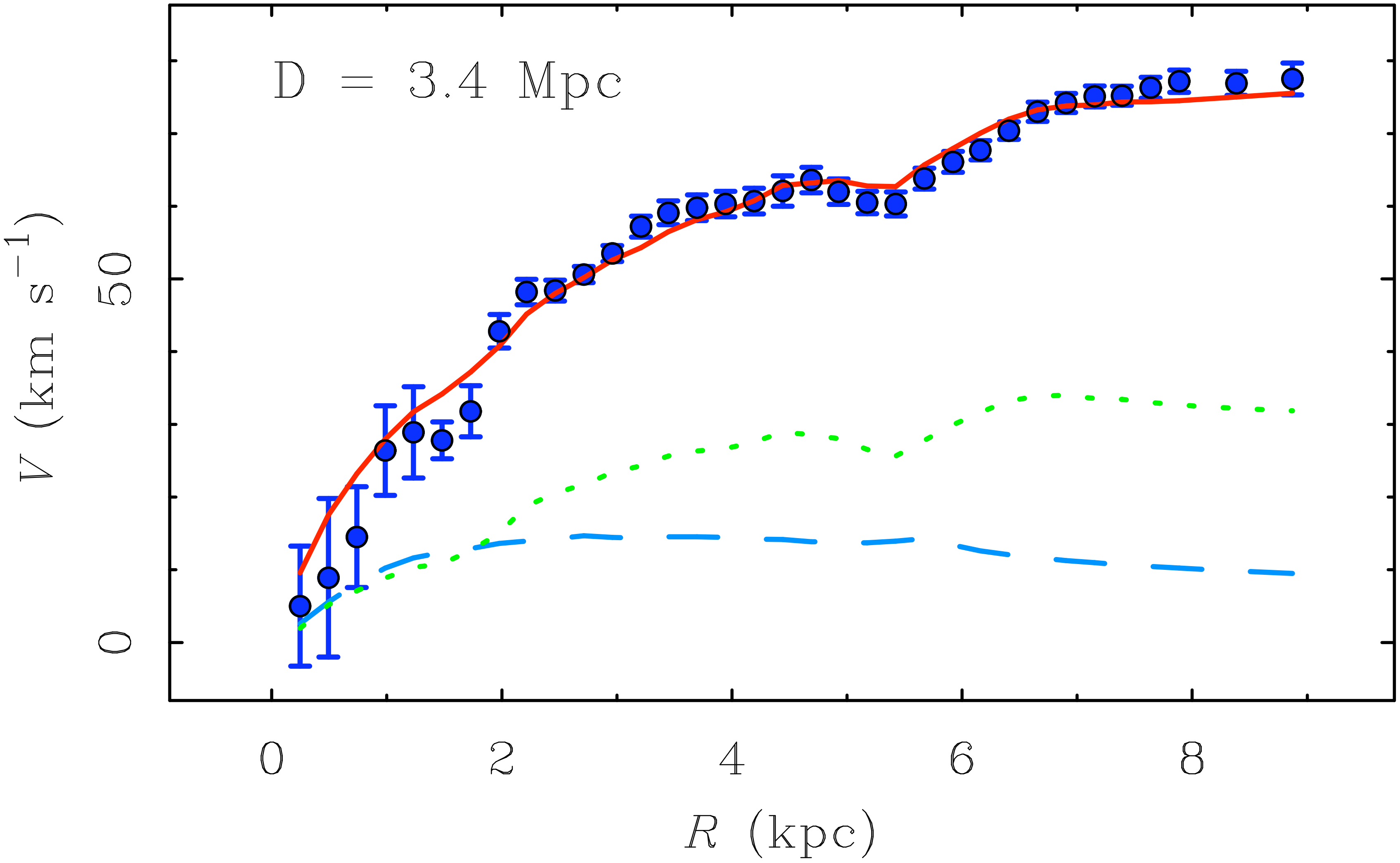
NGC 1560



$\Upsilon_* = 0.97$

Begeman, Broeils, & Sanders (1991)

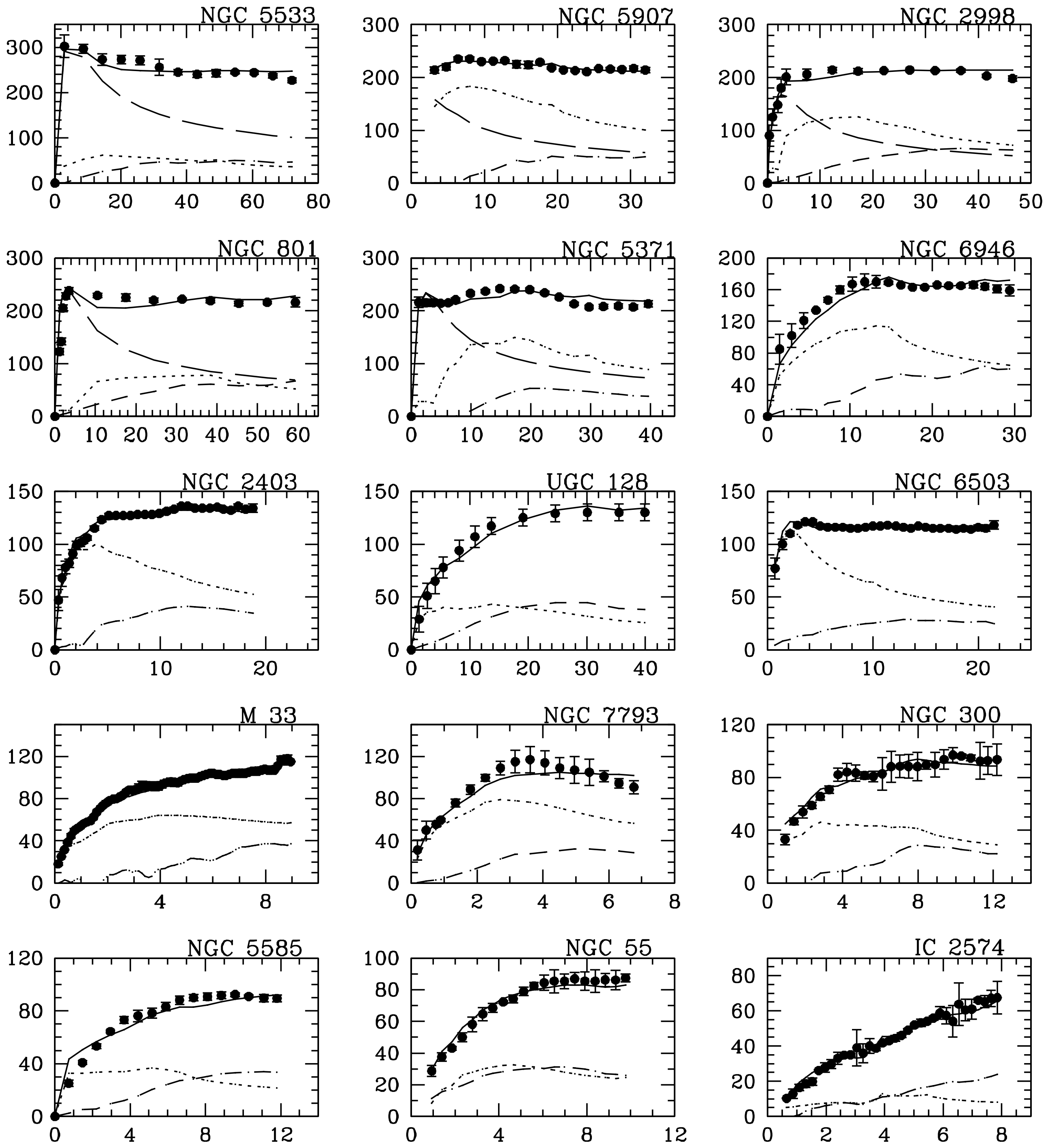
NGC 1560



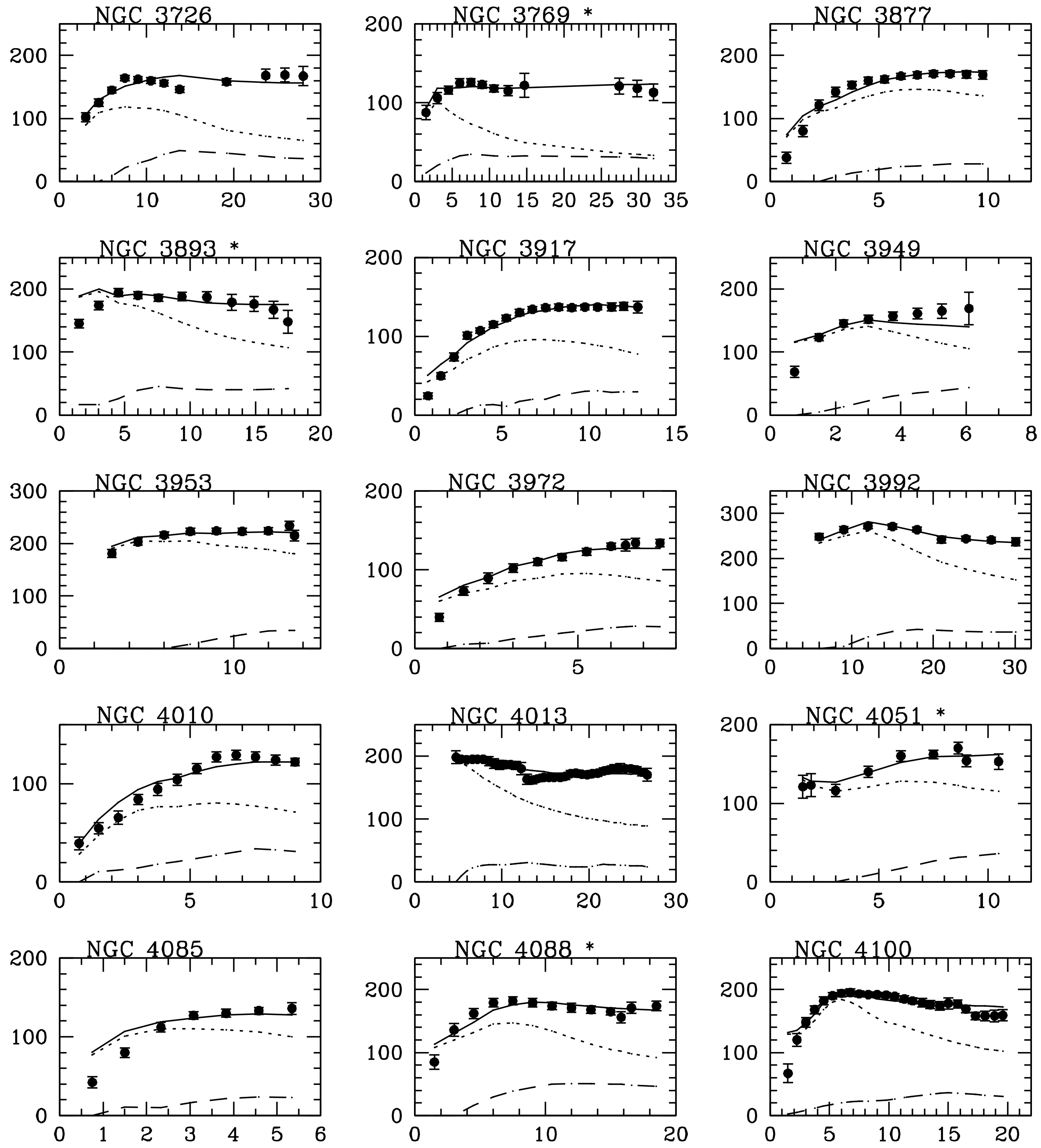
modern D = 3.45 Mpc (TRGB)
(Karachentsev *et al.* 2004)

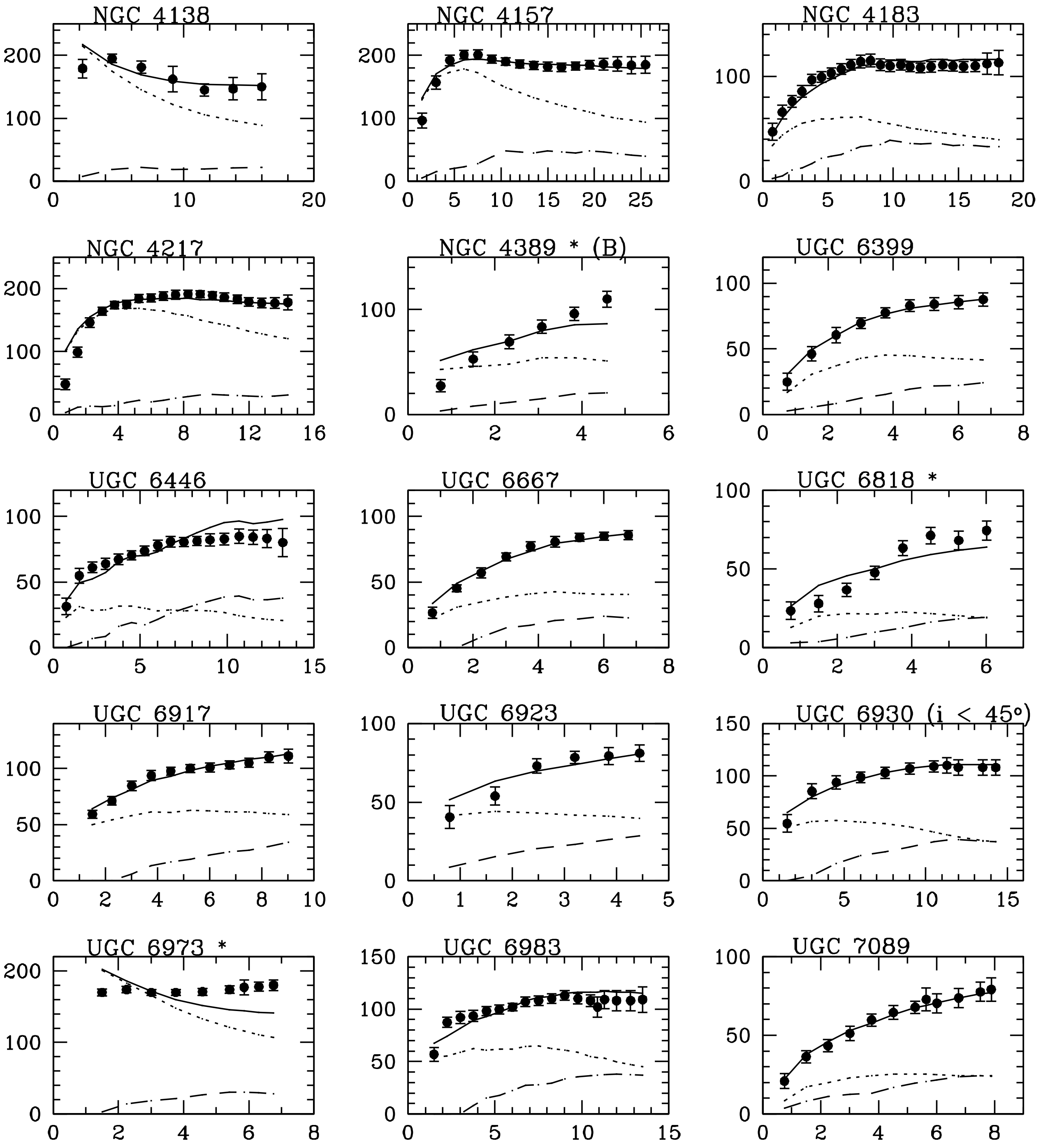
$$\Upsilon_* = 0.44$$

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

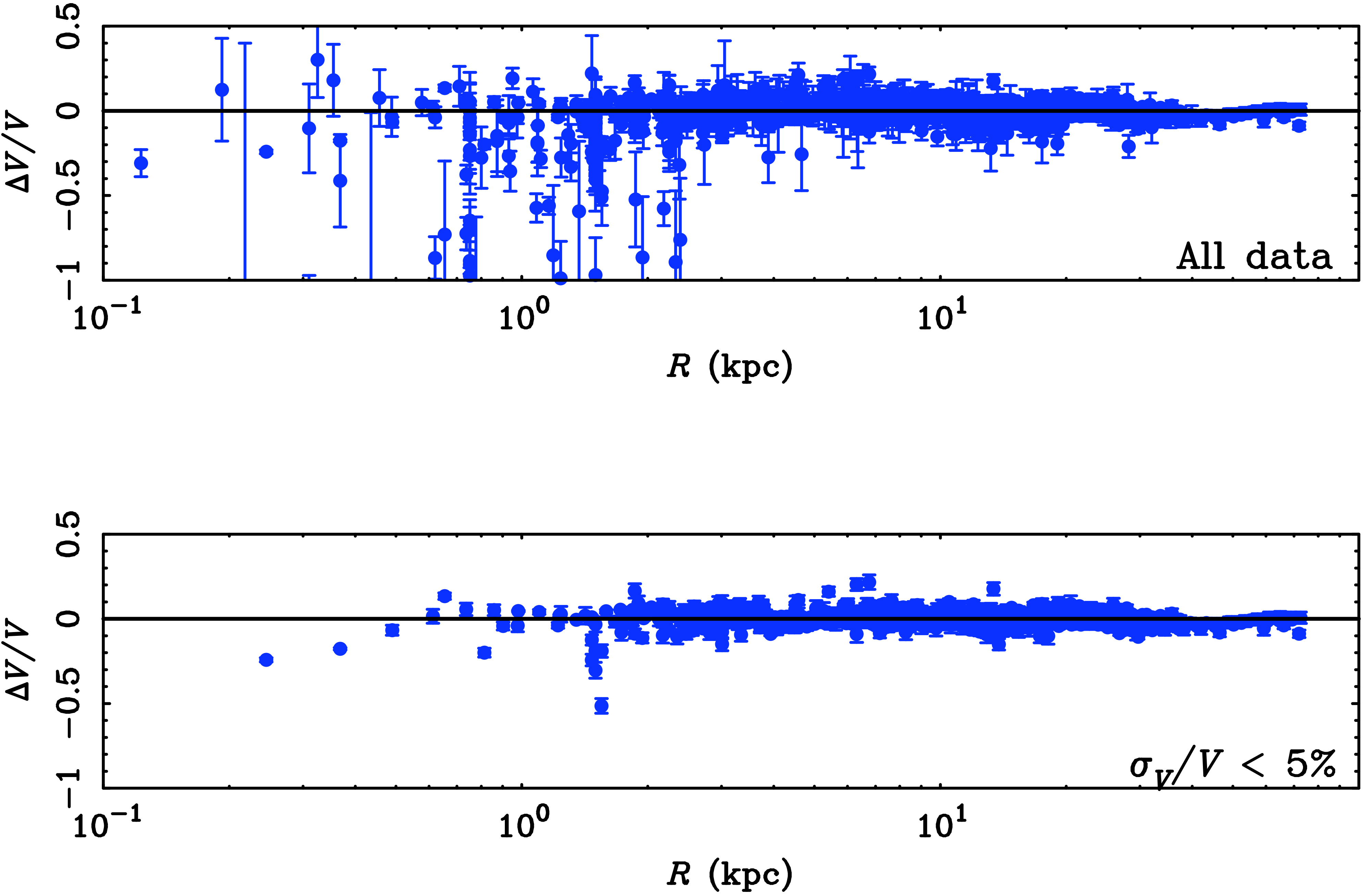


Sanders & McGaugh 2002, *ARA&A*, **40**, 263

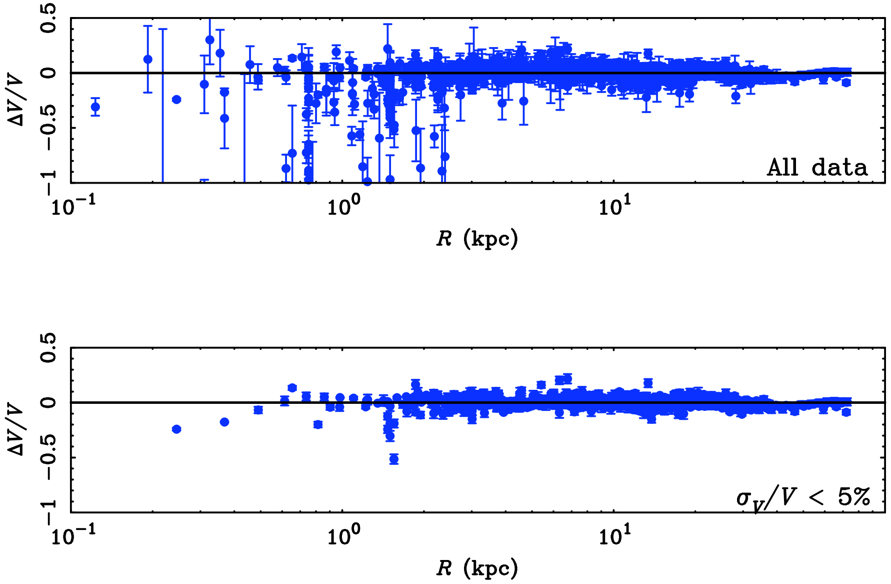



NGC 4138
NGC 4157
NGC 4183
NGC 4217
NGC 4389 * (B)
UGC 6399
UGC 6446
UGC 6667
UGC 6818 *
UGC 6917
UGC 6923
UGC 6930 (i < 45°)
UGC 6973 *
UGC 6983
UGC 7089
0
50
100
150
200
0
2
4
5
6
8
10
12
14
15
16
20
25

Residuals of MOND fits



MOND predictions



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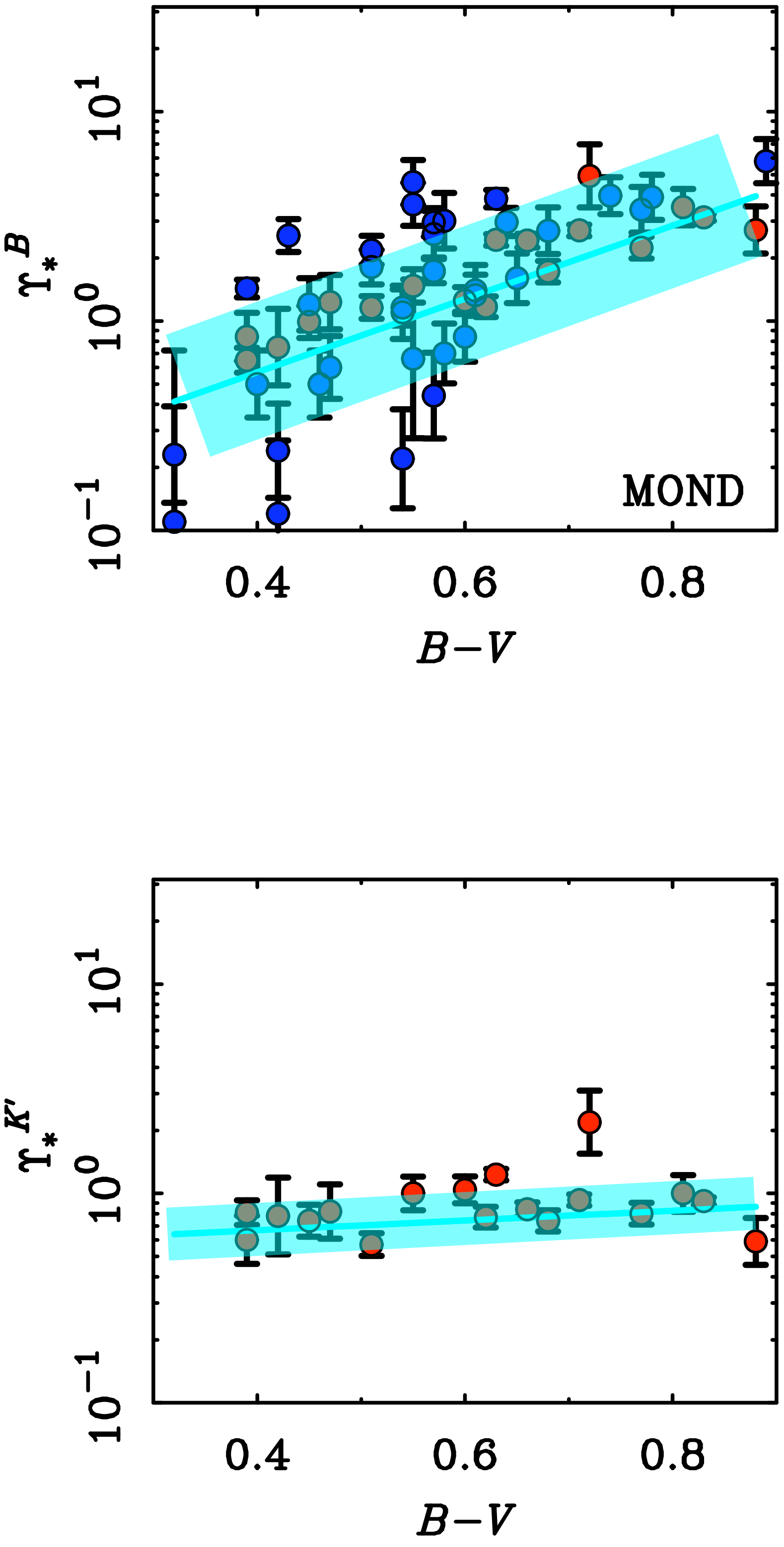
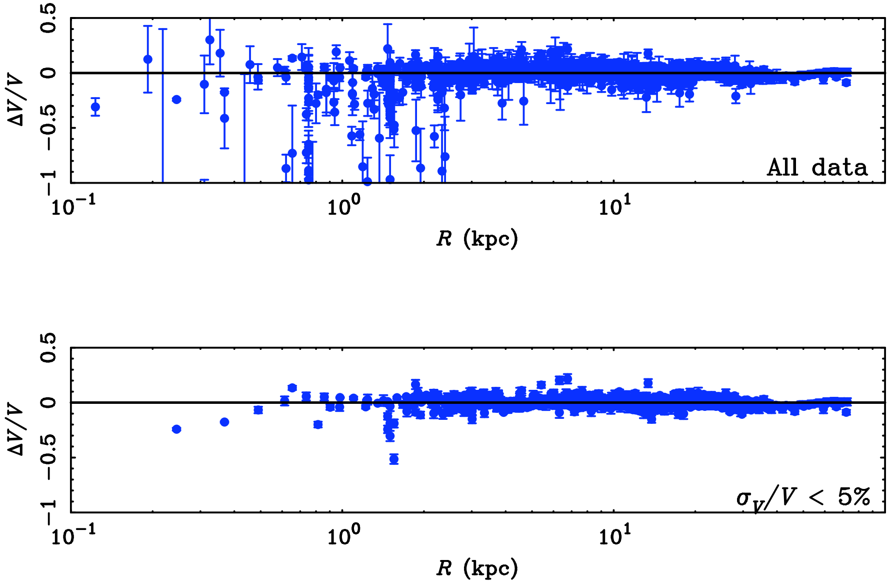
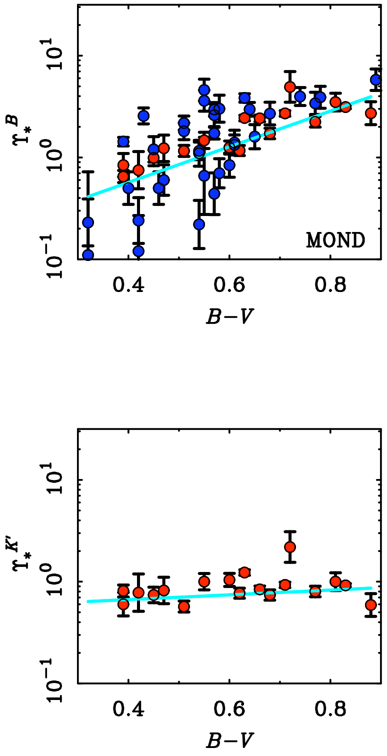


Line: stellar population model
(mean expectation)

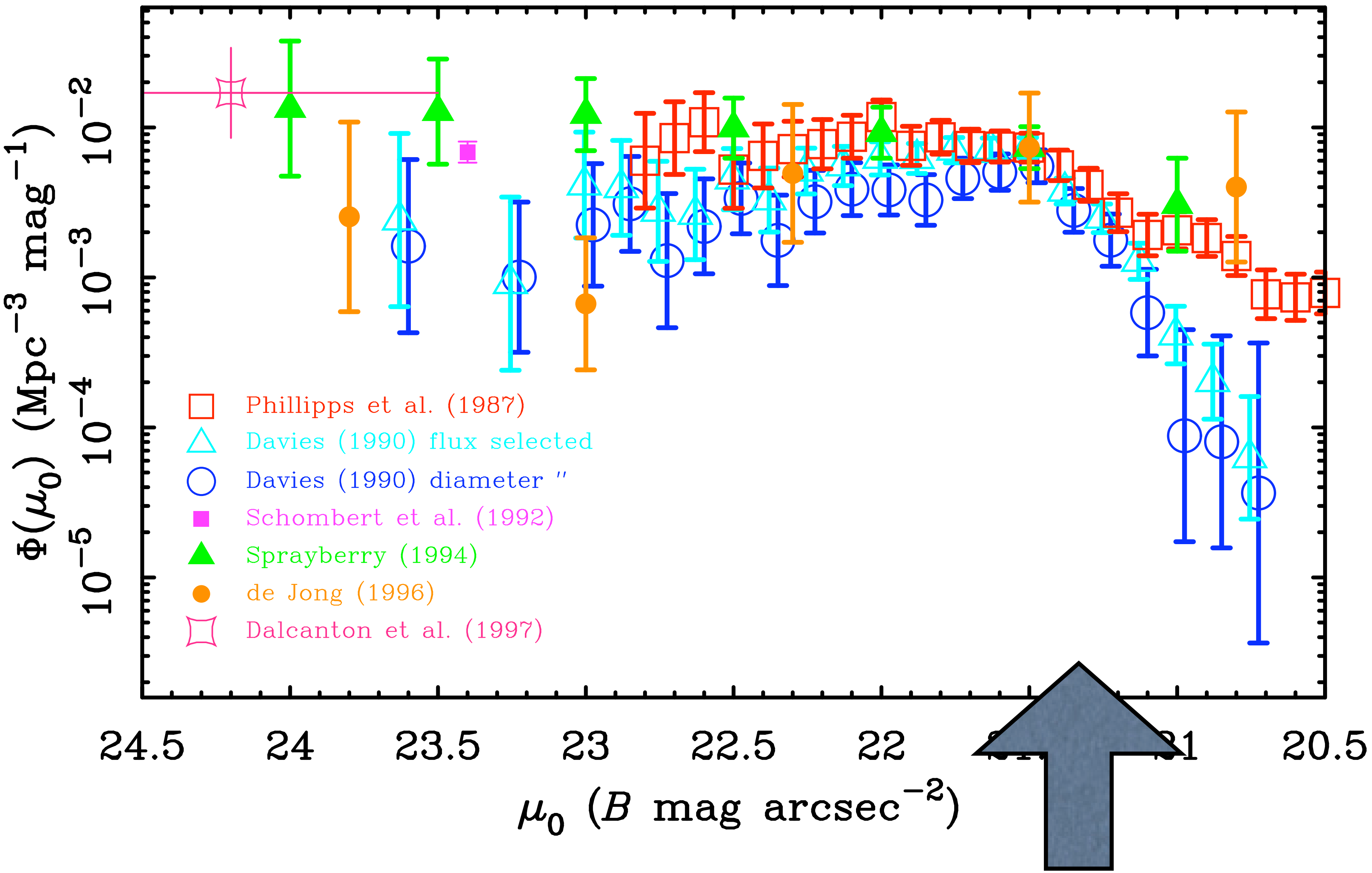




MOND predictions

- 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

disk stability limit (Milgrom 1989)



$$G\Sigma_* = a_0$$

disk stability

Brada & Milgrom (1998)

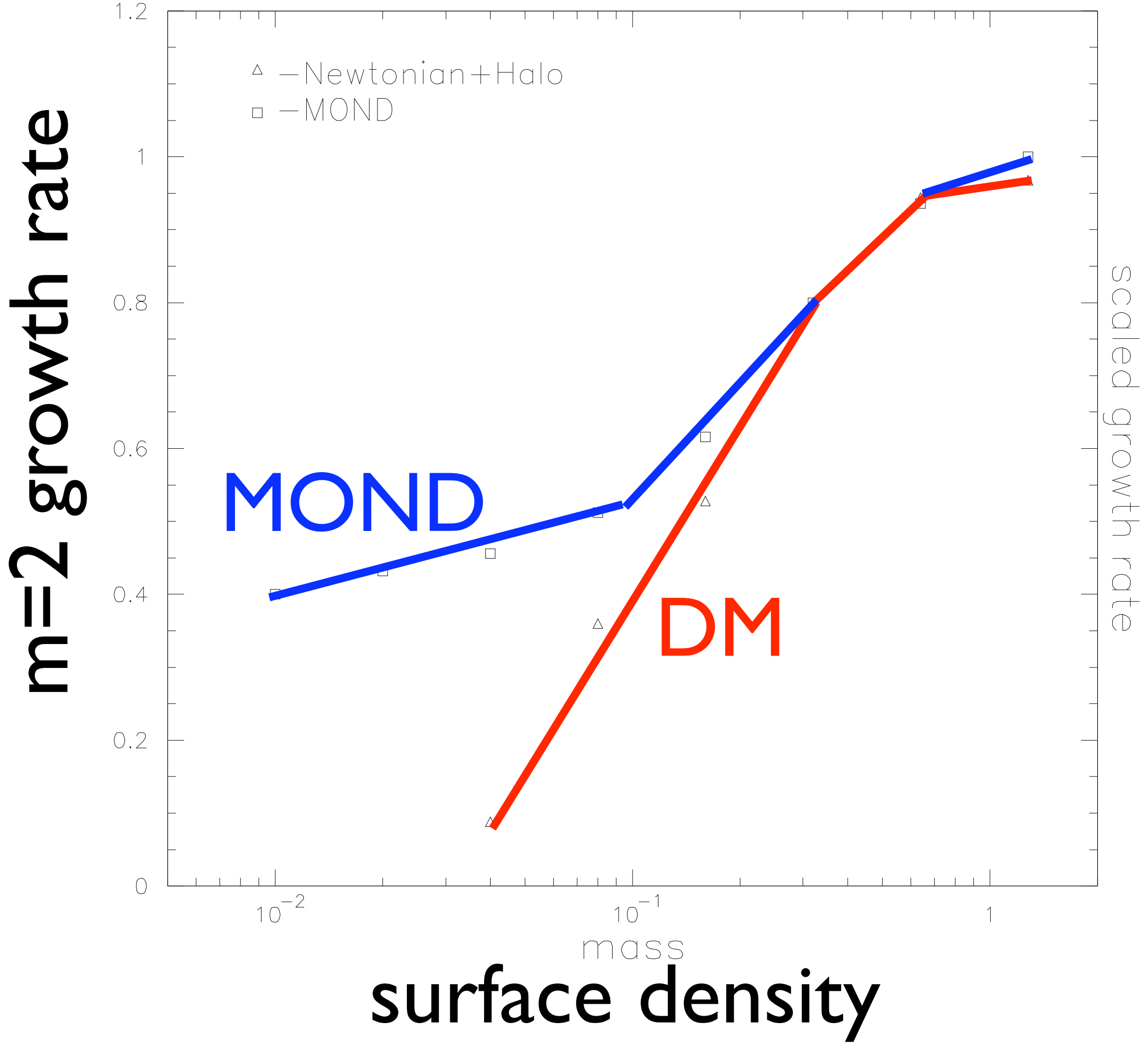
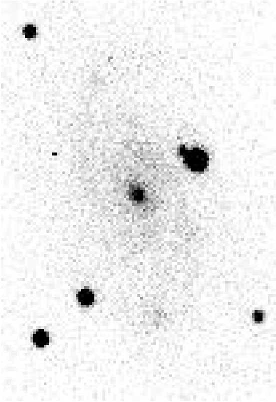


Figure 11: The growth rate, in units of the dynamical time, for the m=2 mode as a function of the total mass of the disk. □ MOND, △ Newtonian + Halo.

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

Disk Masses from Density Waves



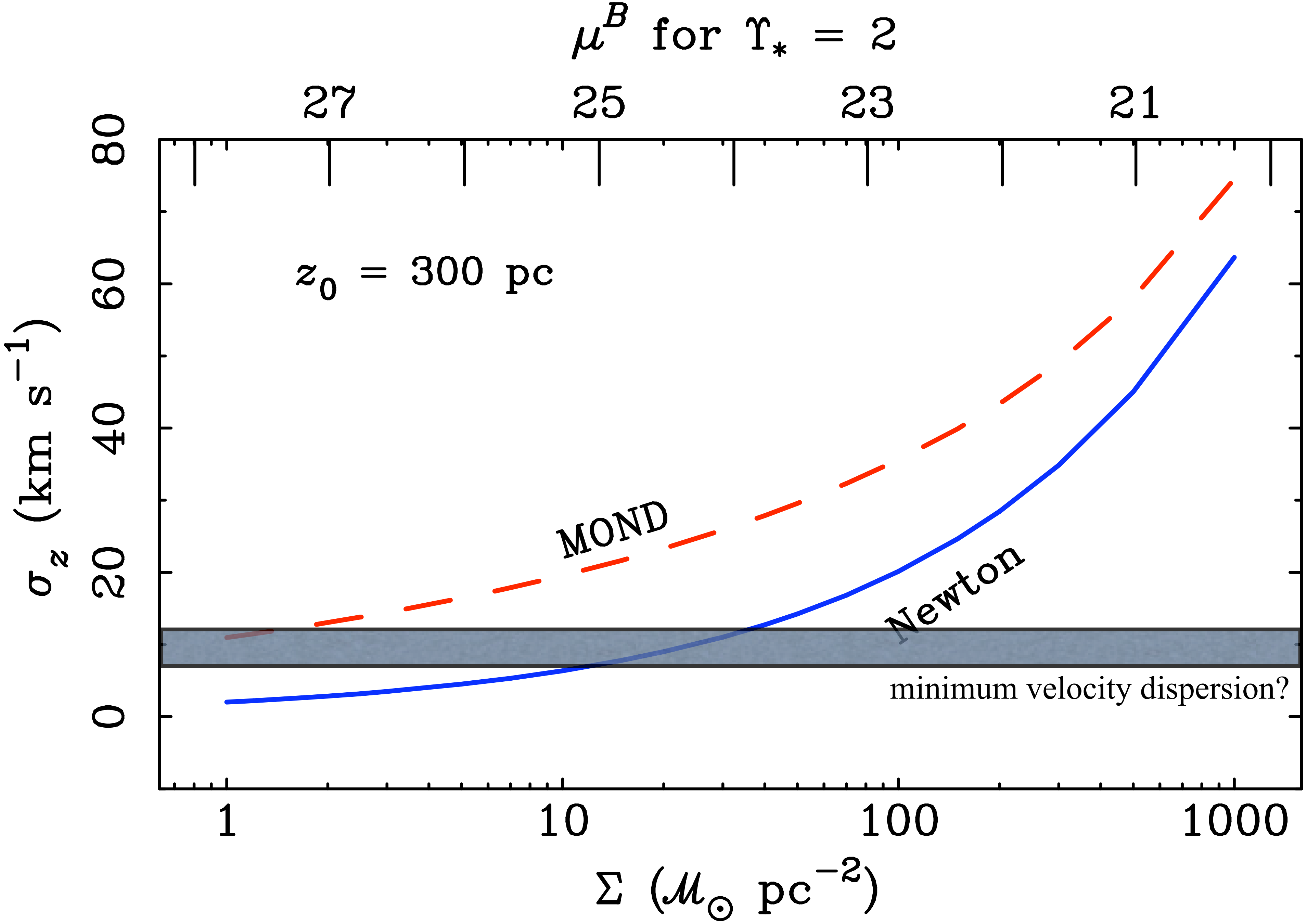
LSB galaxies
got spiral arms!

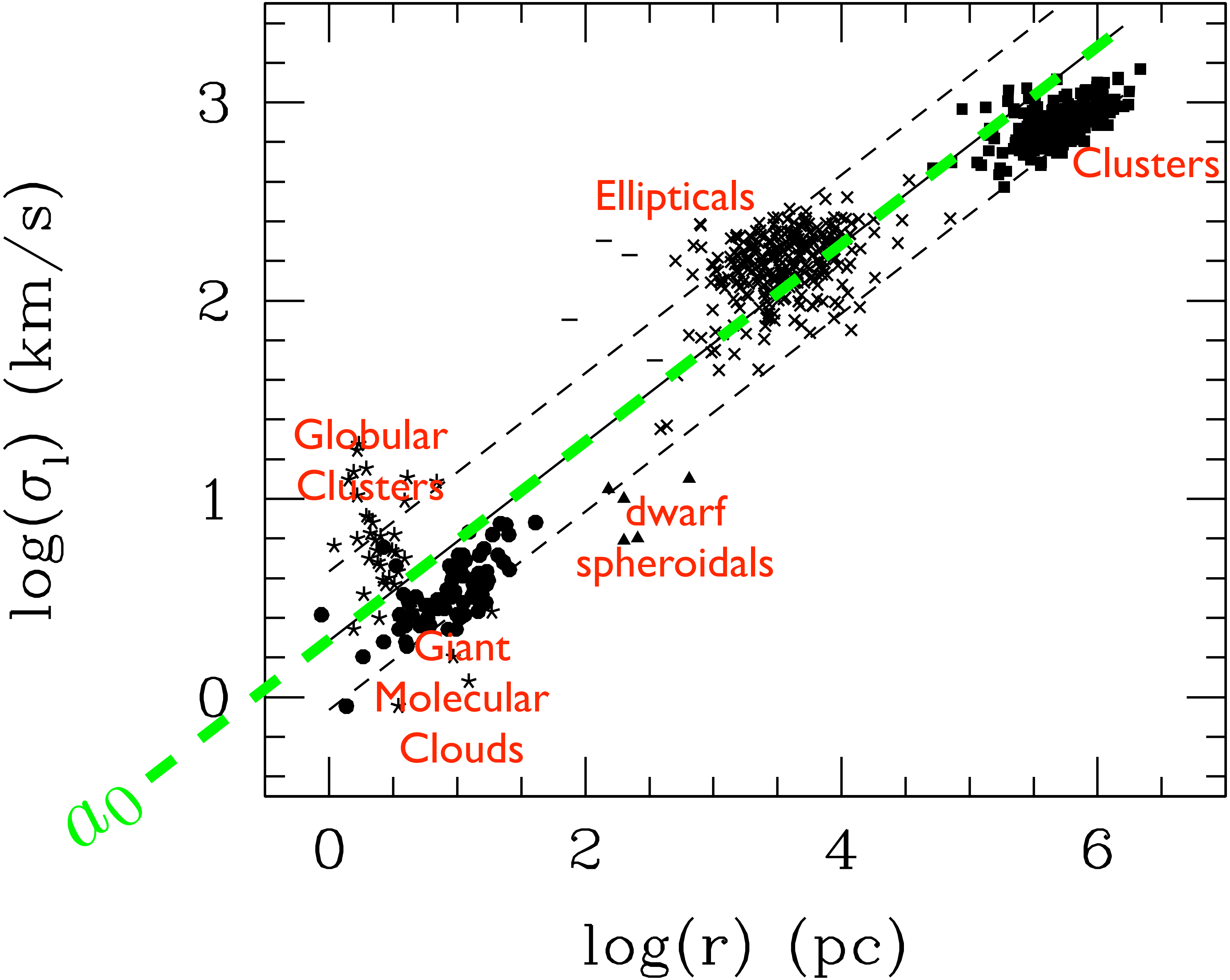
Need very massive disks to drive spiral density waves in LSBs, as anticipated by McGaugh & de Blok (1998), *ApJ*, 499, 66

Galaxy	$(M/L)_*$
F568-1	14
F568-3	7
F568-6	11
F568-V1	16
UGC 128	4
UGC 1230	6
UGC 6614	8
ESO 14-40	4
ESO 206-140	4
ESO 302-120	1.7
ESO 425-180	2.4

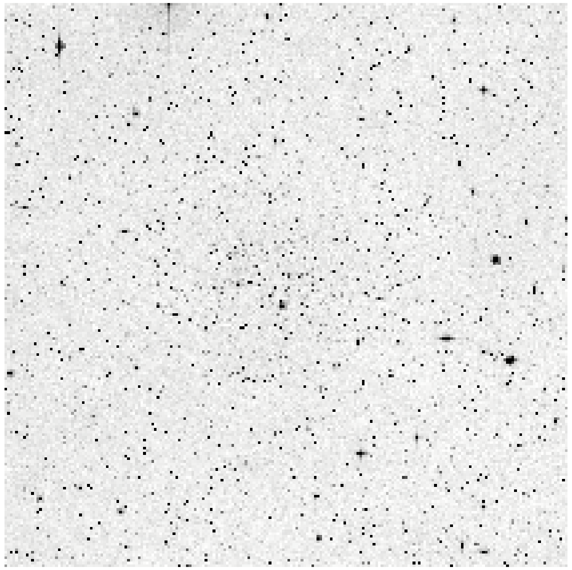
Big $(M/L)_*$'s!

from B. Fuchs, astro-ph/0209157

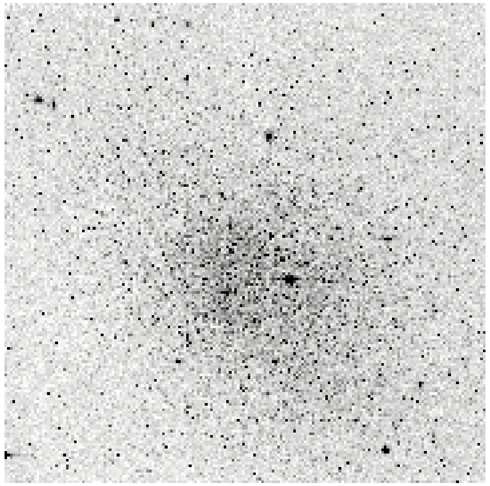

μ^B for $\Upsilon_* = 2$
27
25
23
21
80
60
40
20
0
σ_z (km s^{-1})
z_0 = 300 pc
MOND
Newton
minimum velocity dispersion?
1
10
100
1000
Σ ($\mathcal{M}_\odot$ pc^{-2})


log(σ_l) (km/s)
log(r) (pc)
0
1
2
3
0
2
4
6
Globular
Clusters
Giant
Molecular
Clouds
dwarf
spheroidals
Ellipticals
Clusters
a0

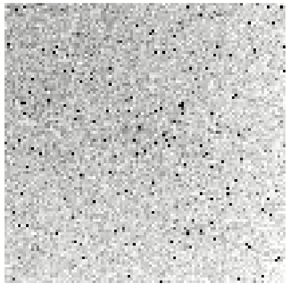
dwarf spheroidal satellites of the Milky Way



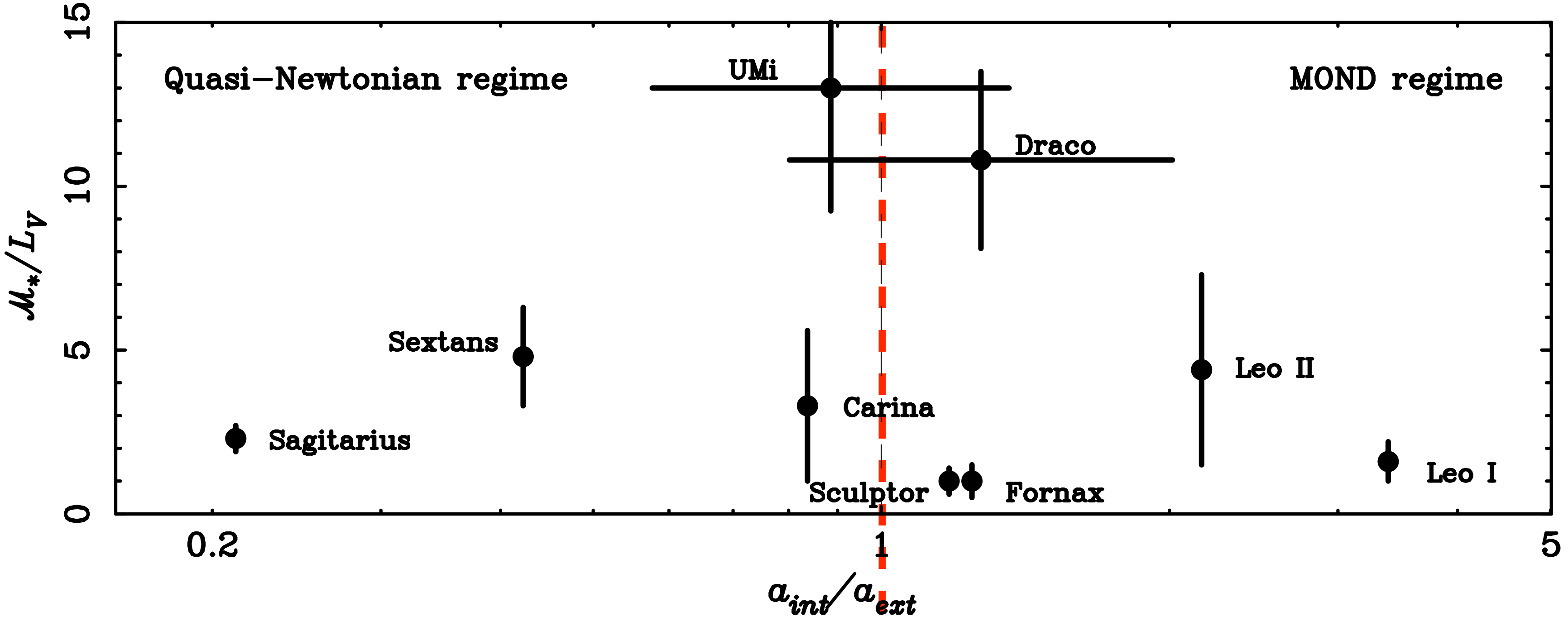
Carina



Fornax



Draco

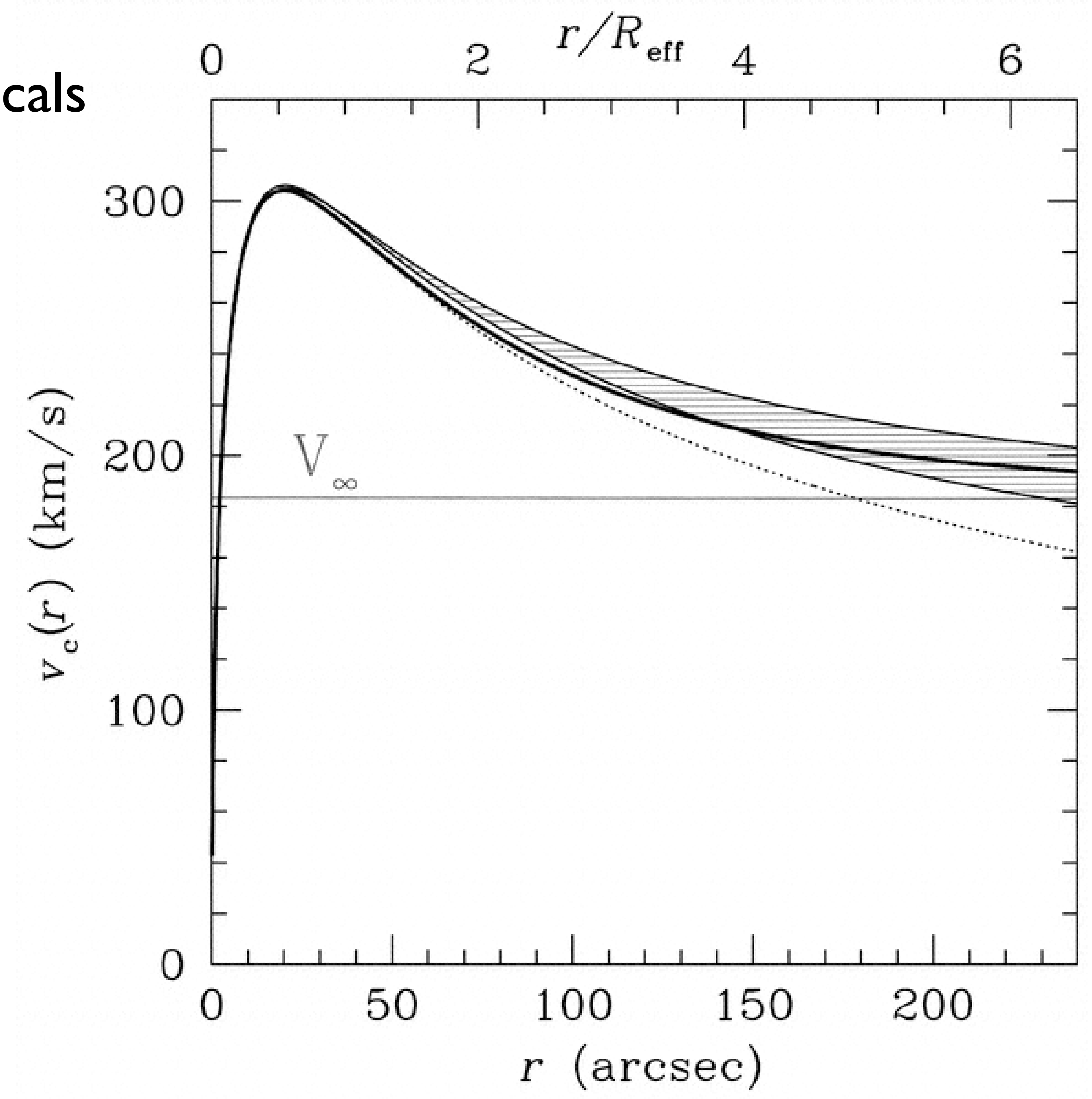


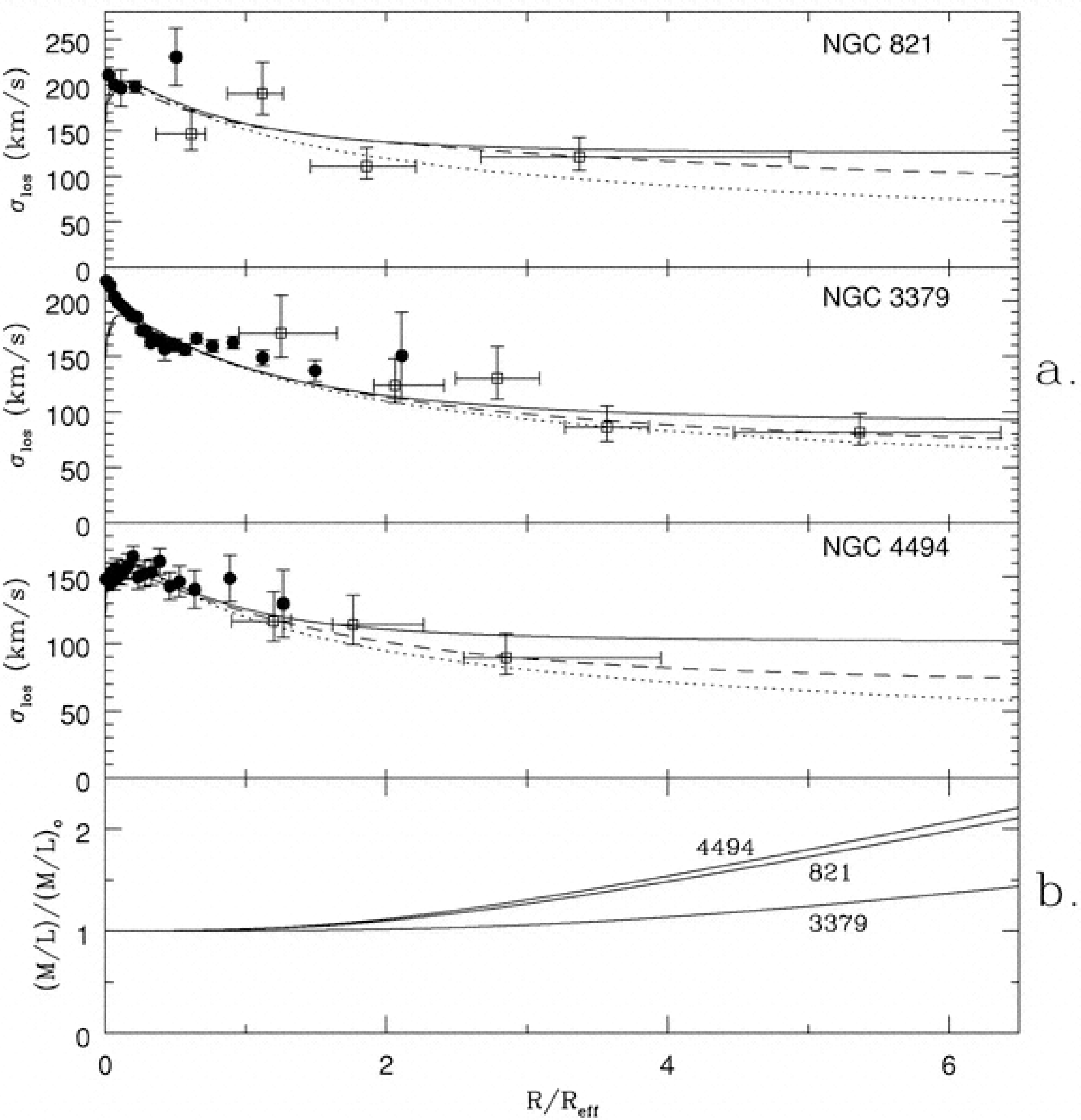
$$\mathcal{M} = \frac{2\sigma^2}{G_{eff} R_V}$$

$$\mathcal{M} = \frac{81}{4}\frac{\sigma^4}{a_0 G}$$

$$G_{eff} = \frac{G}{\mu(x)}$$

Ellipticals

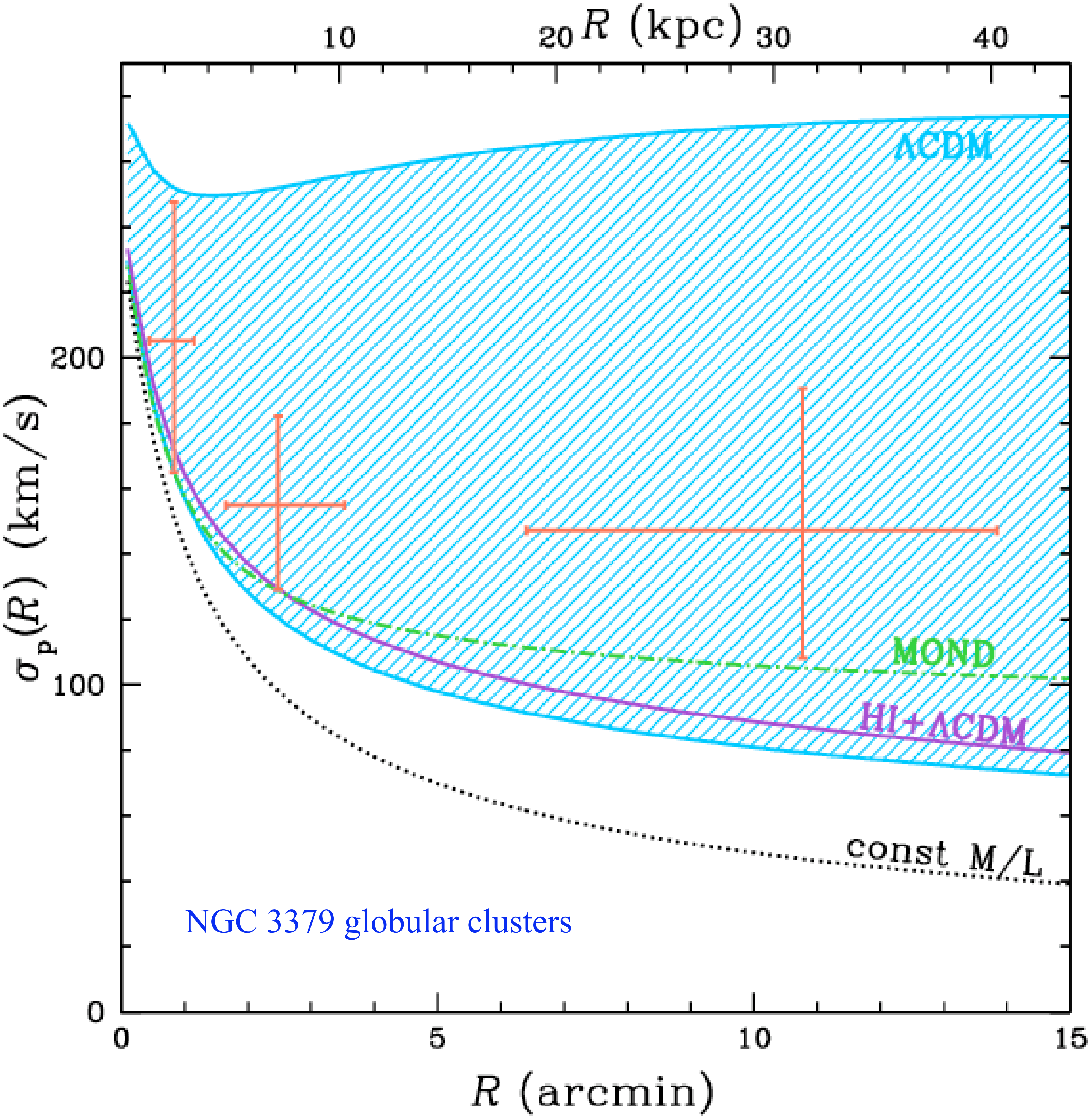




Romanowsky et al. (2003)

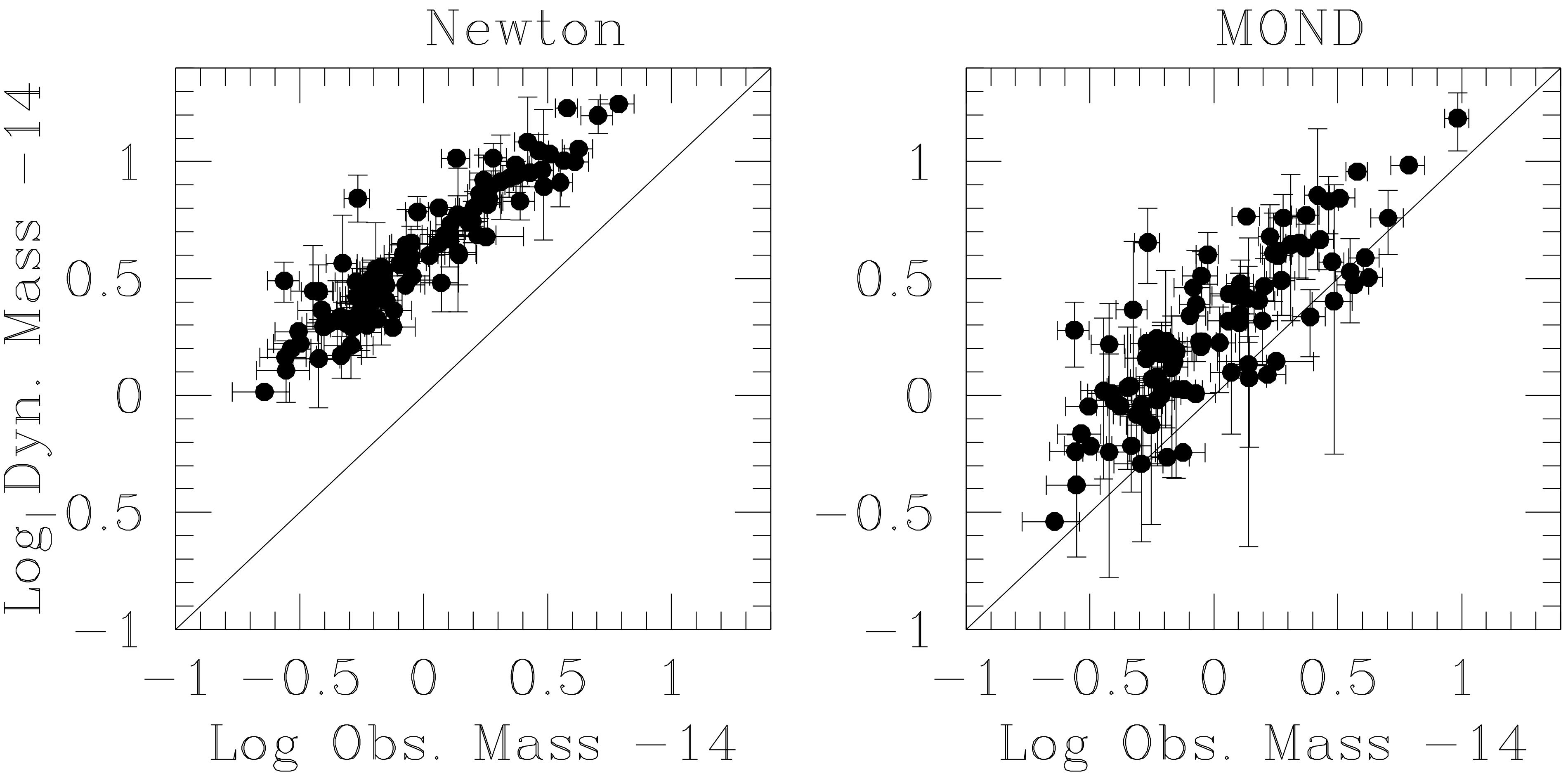
Milgrom & Sanders (2003)

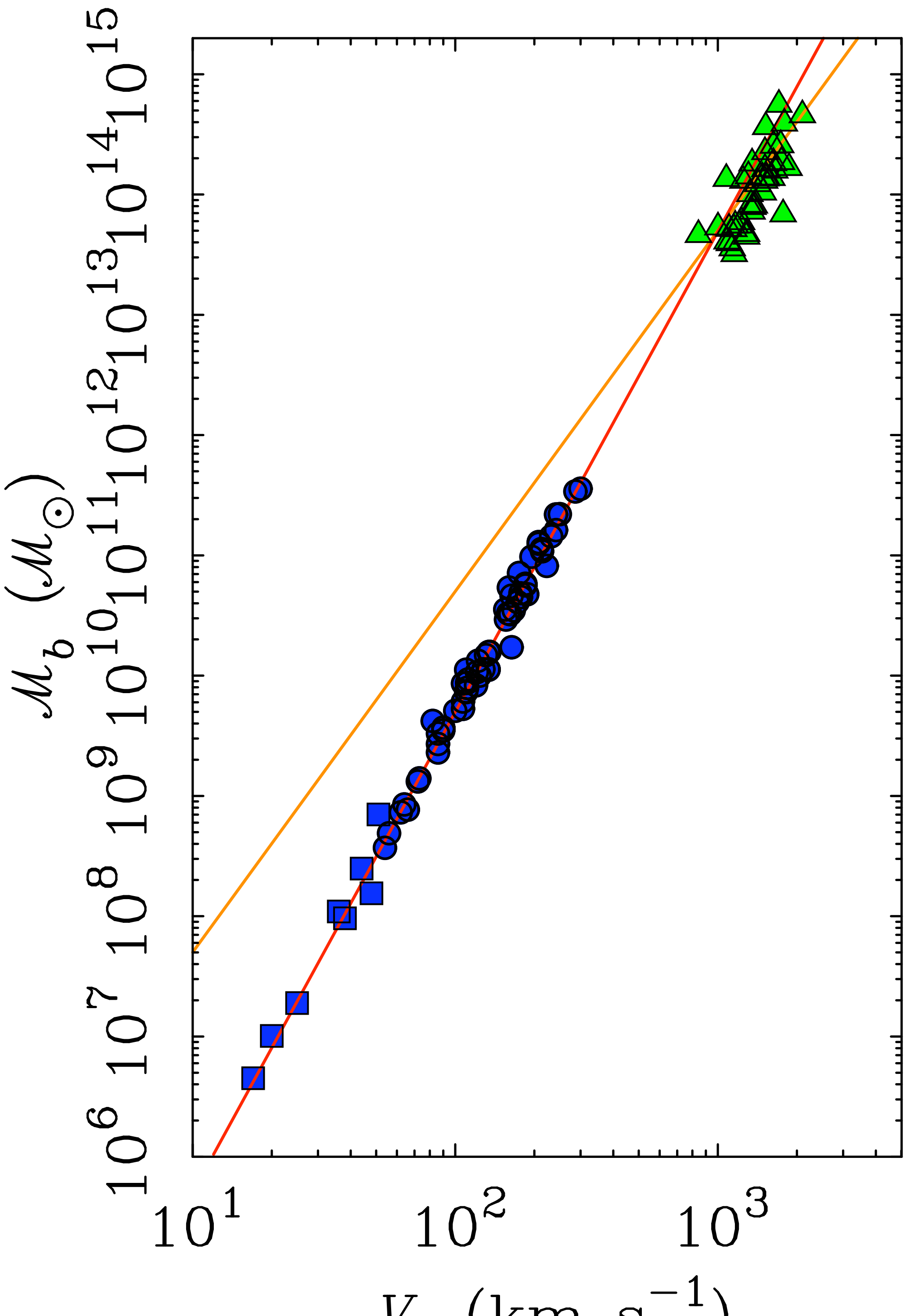
Bergond *et al.* (2006)



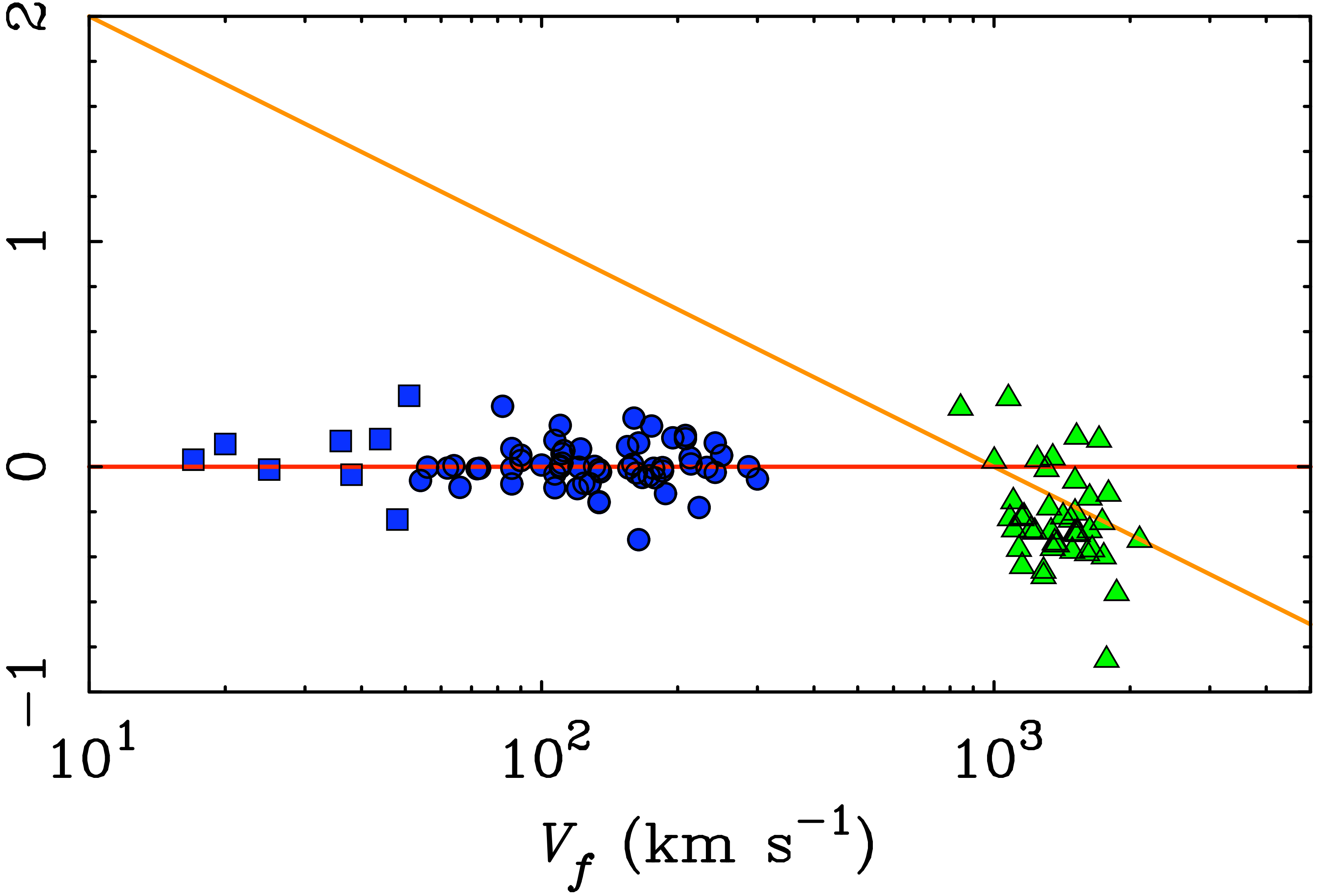
NGC 3379 globular clusters

Clusters of Galaxies

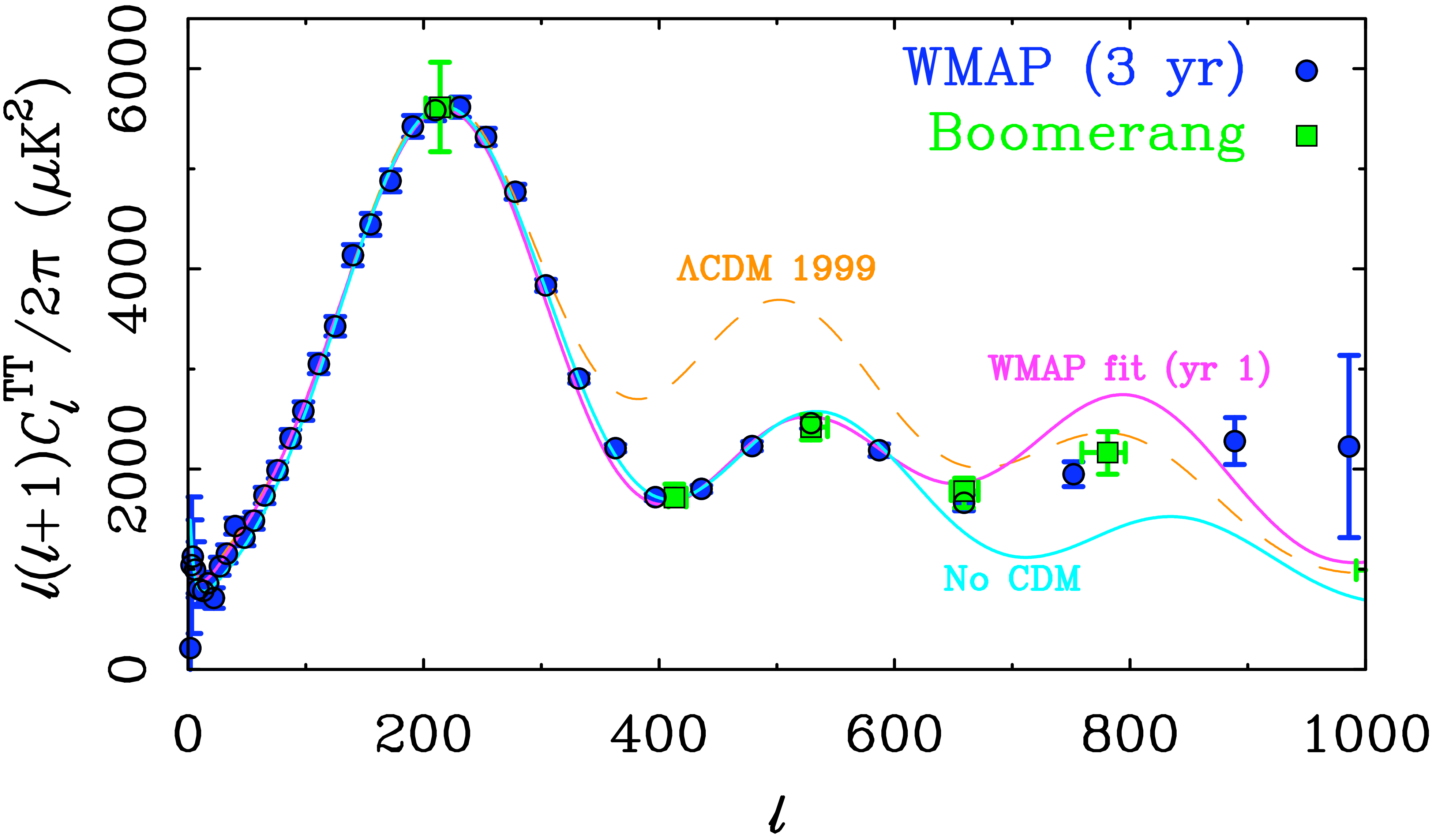




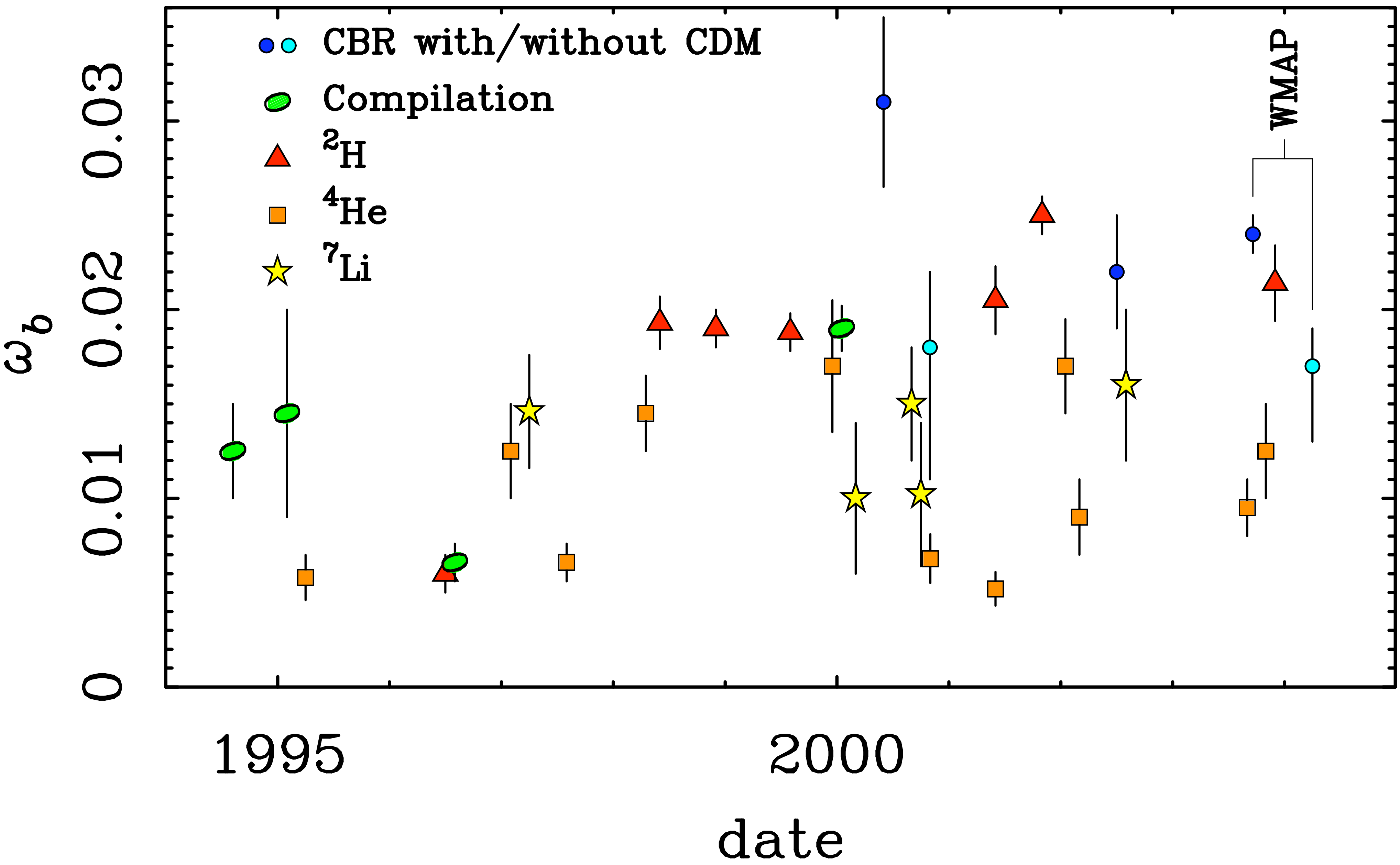
Sanders (2003)
Reiprich (2001)



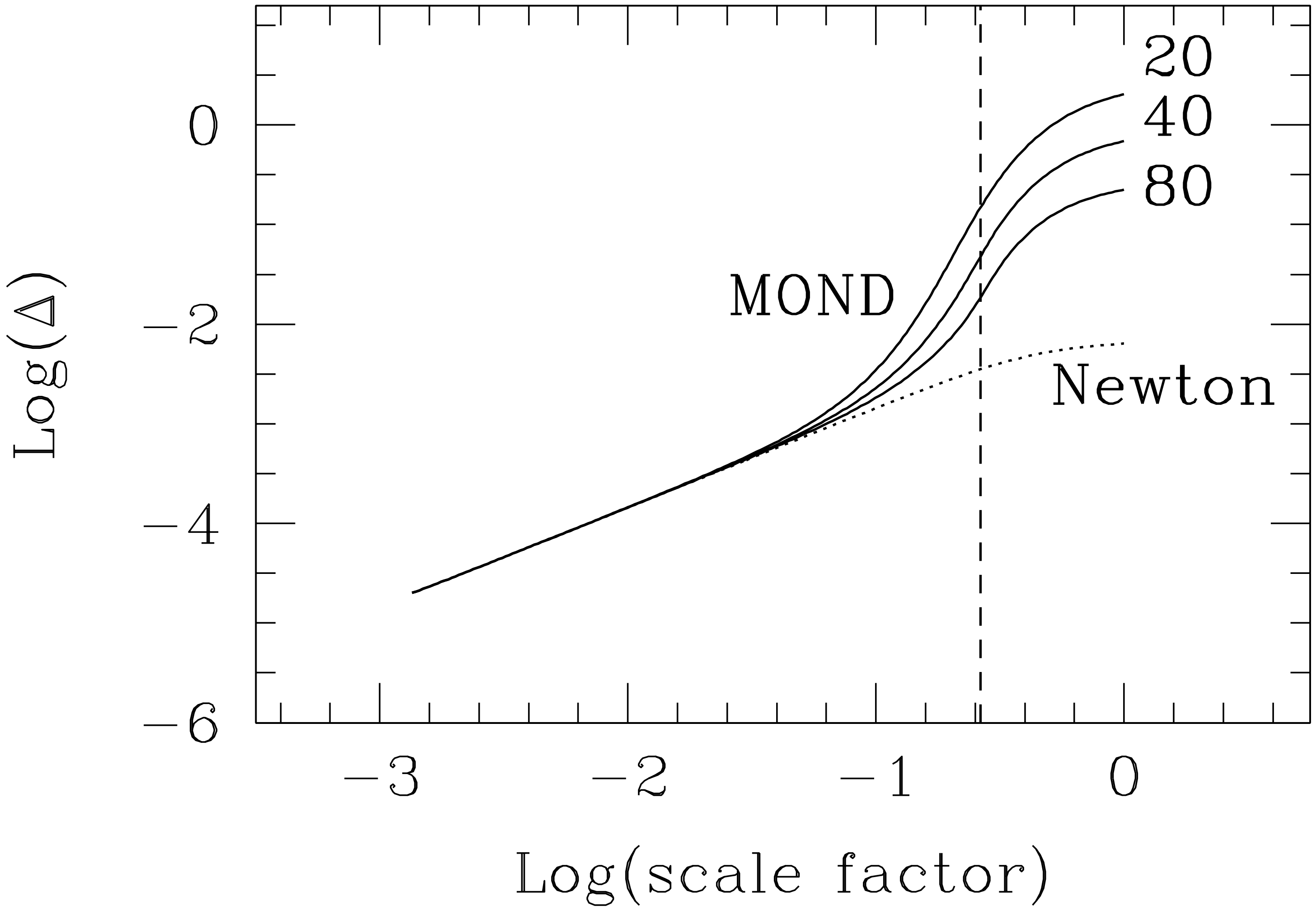
2
1
0
−1
$\delta \mathcal{M}_b / \mathcal{M}_b$
10^1
10^2
10^3
V_f (km s^{-1})


WMAP (3 yr) ●
Boomerang ■
ΛCDM 1999
WMAP fit (yr 1)
No CDM
$l(l+1)C_l^{TT}/2\pi$ (μK^2)
0
2000
4000
6000
0
200
400
600
800
1000
l

BBN: $\omega_b = \Omega_b h^2 \propto \eta_{10}$



Sanders (2001); Sanders & McGaugh (2002)
see also Nusser (2001); Kneib & Gibson (2002)



Other MOND tests

- Disk Stability
  - ✓ Freeman limit in surface brightness distribution
  - ✓ thin disks
  - ✓ velocity dispersions
  - ✓ LSB disks not over-stabilized $\sigma \approx 10\,\mathrm{km\,s^{-1}}$ at $\Sigma \approx 1\,\mathrm{M_\odot\,pc^{-2}}$

- ✓ Dwarf Spheroidals ?

- ✓ Giant Ellipticals

- ✗ Clusters of Galaxies

- ? Structure Formation

- Microwave background
  - ✓ 1st:2nd peak amplitude; BBN $\Omega_b h^2 \approx 0.017$
  - ✓ early reionization
  - ✓ enhanced ISW effect
  - ✗ 3rd peak