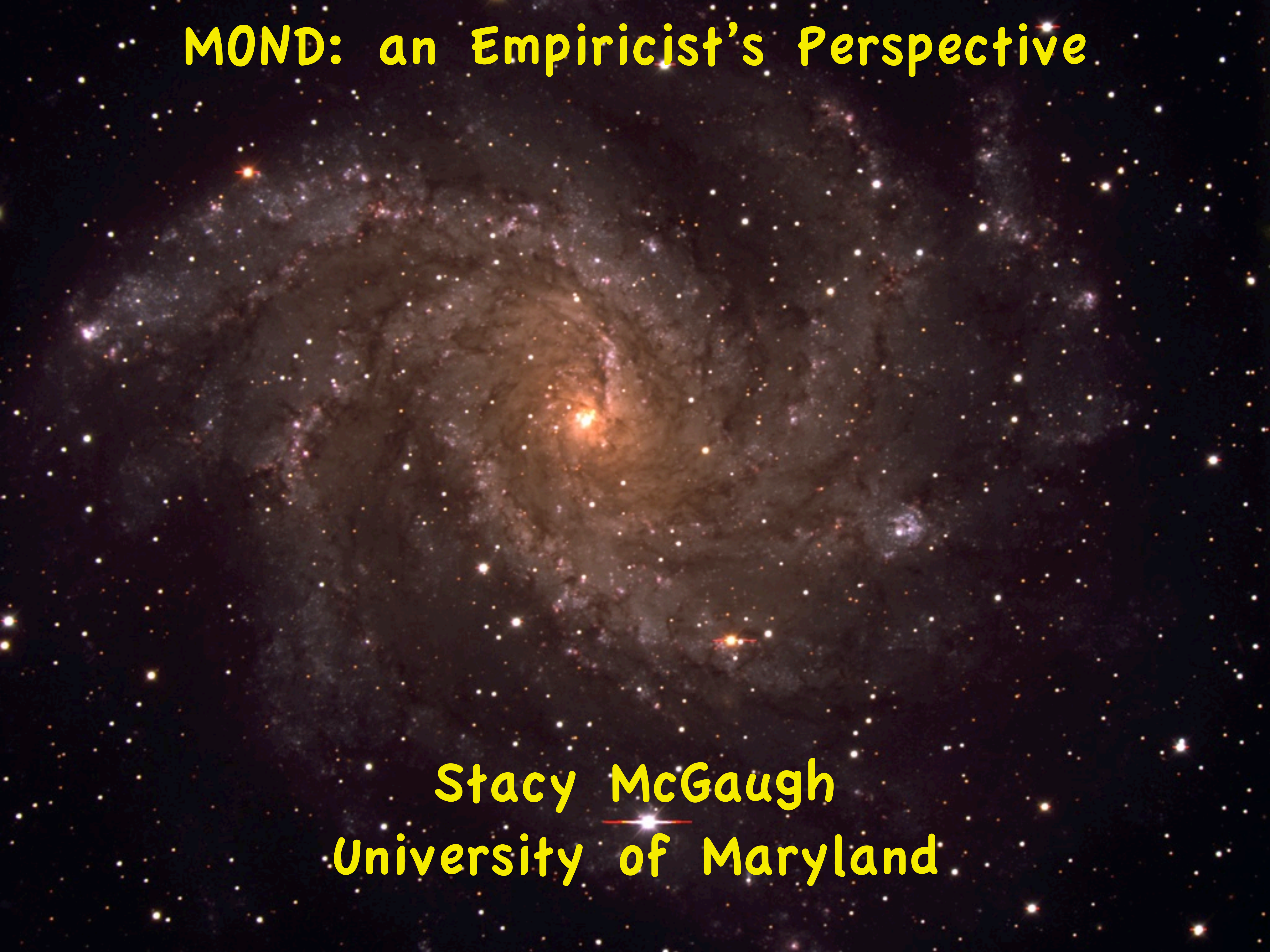
MOND: an Empiricist's Perspective



Stacy McGaugh
University of Maryland

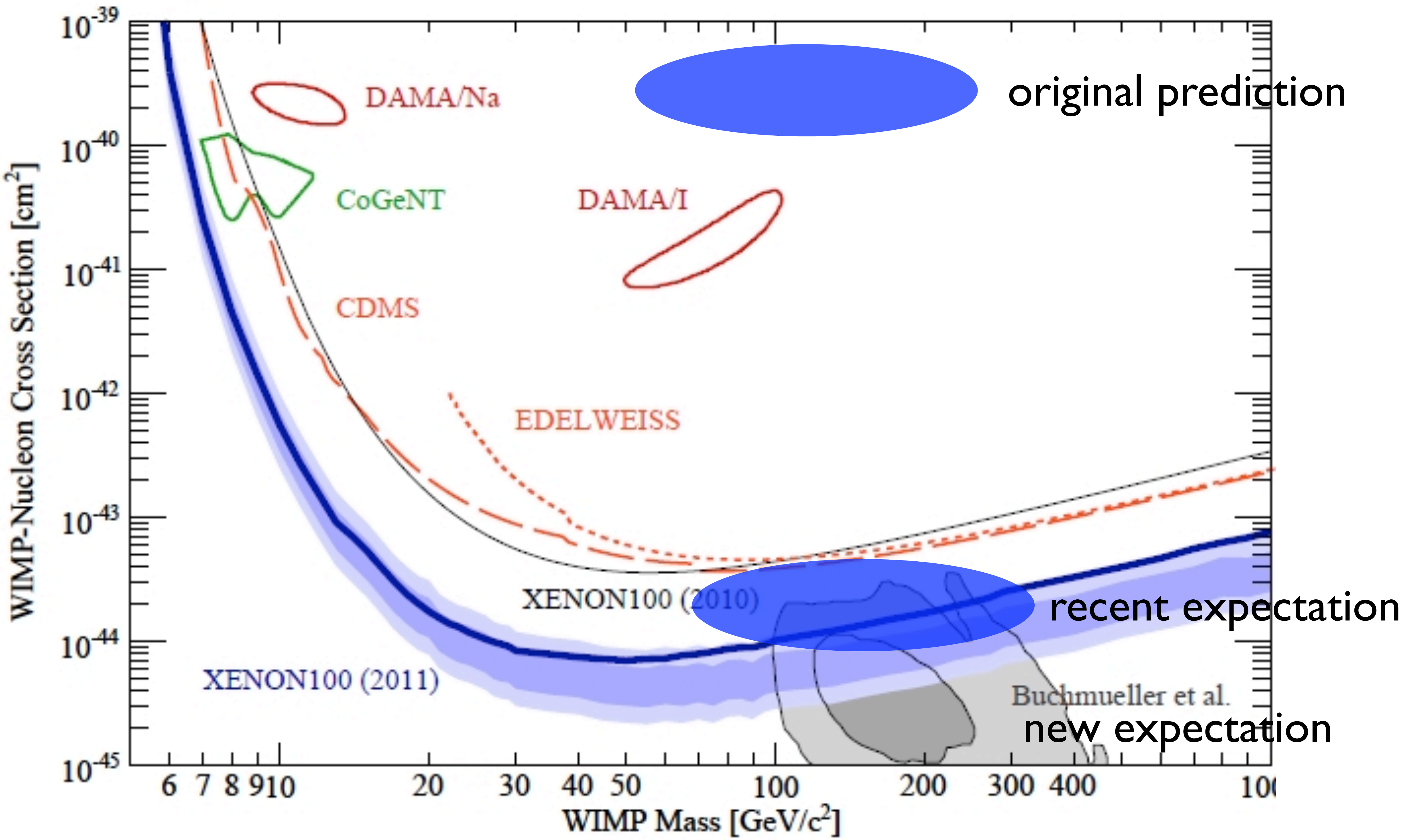
A Field of Two Attitudes

- **ΛCDM is obviously correct**
  - CMB, LSS, etc. “cosmology solved!” (Turner 1998)
  - considering alternatives is a waste of time
- **ΛCDM is obviously wrong**
  - cusp/core, missing satellites, no direct detection of CDM, DE just another fudge
  - much more reasonable to consider alternatives if ΛCDM is falsified
    - ...if that is even possible

I reckon you wouldn't even be human bein's if you didn't have some pretty strong personal feelin's about nuclear combat.

Heck, I reckon you wouldn't even be human beings if you didn't have some pretty strong personal feelings about cosmology.

WIMP detection experiments



- WIMPs have been excluded at > 95% c.l. Repeatedly.
- Usual fix has been to make more massive the particle through which WIMPs interact, thus lowering their interaction cross-section.
  - Use to be the usual weak force carriers.
  - Now down to WIMPs that exchange Higgs particles.

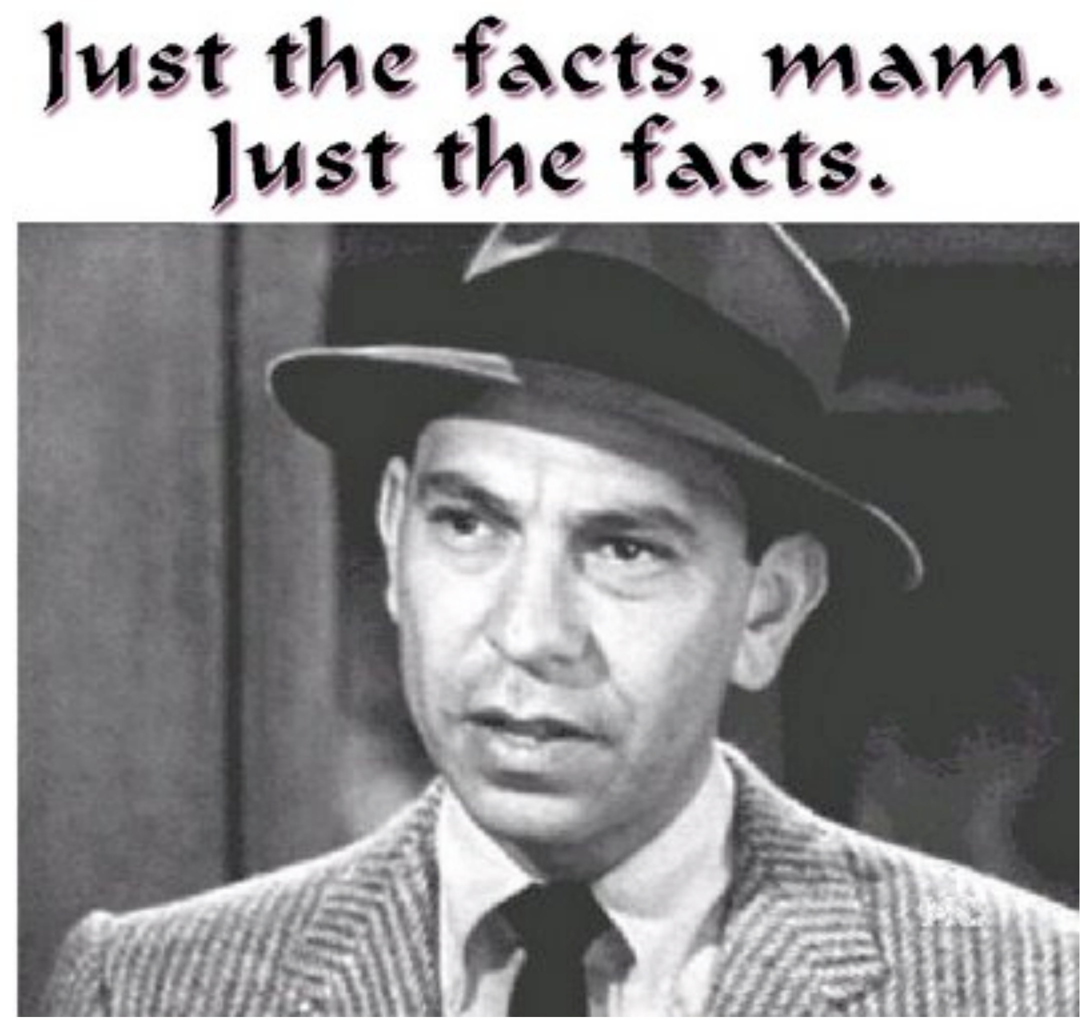
One can imagine DM particles that don't interact with anything but gravity. Might be true, but isn't falsifiable. Tuning the interaction cross-section ever-further down is *the express elevator to hell.*

3 Laws of Galactic Rotation

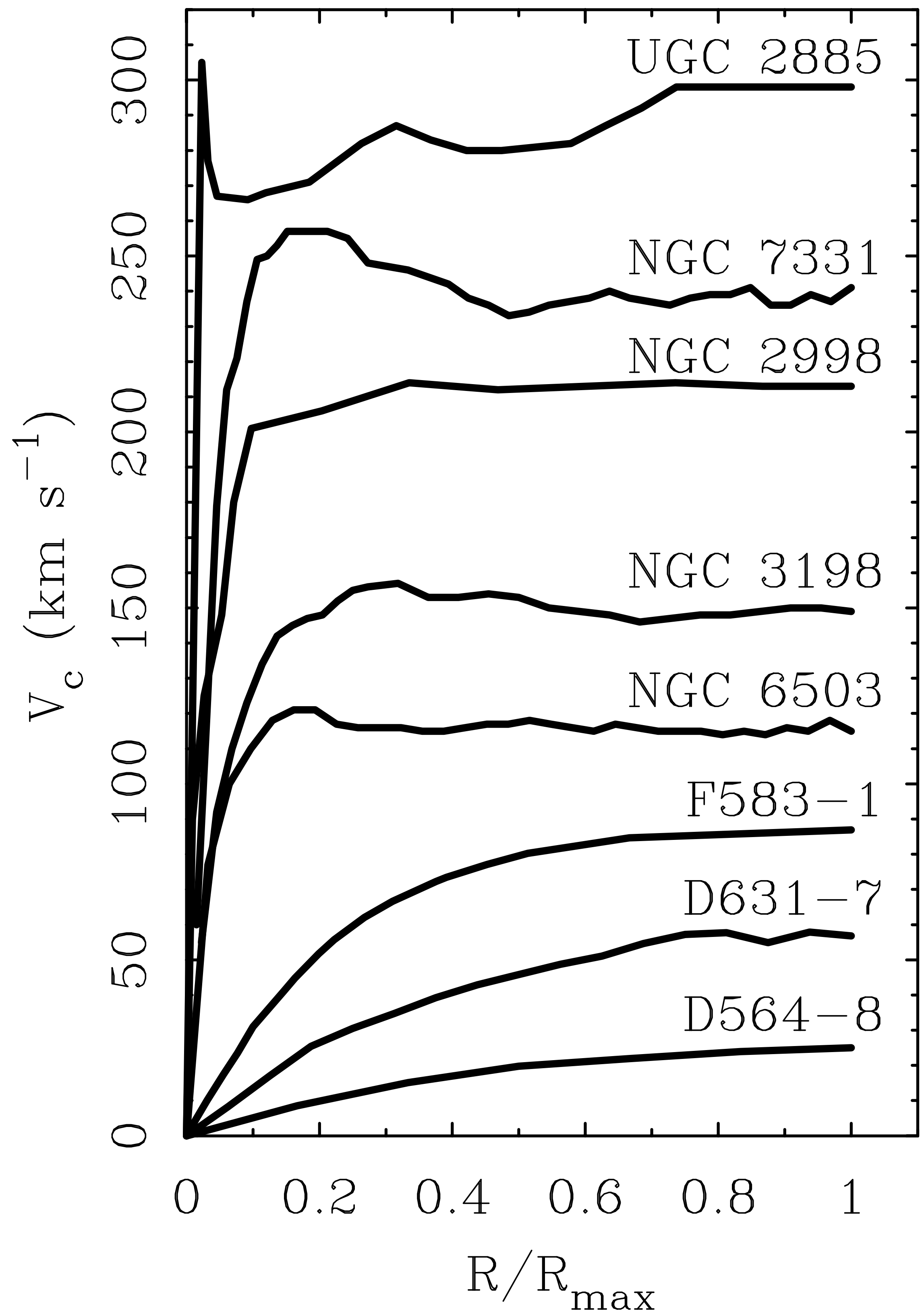
1. Rotation curves tend towards asymptotic flatness

2. Baryonic mass scales as the fourth power of rotation velocity (Baryonic Tully-Fisher)

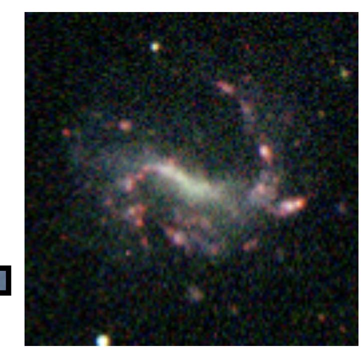
3. Gravitational force correlates with baryonic surface density

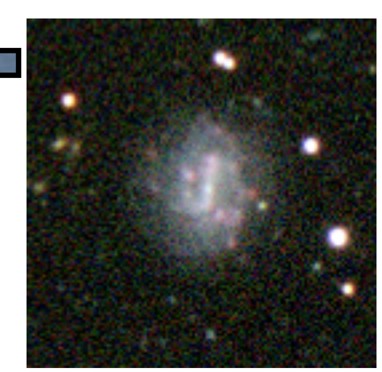


1. Flat rotation curves



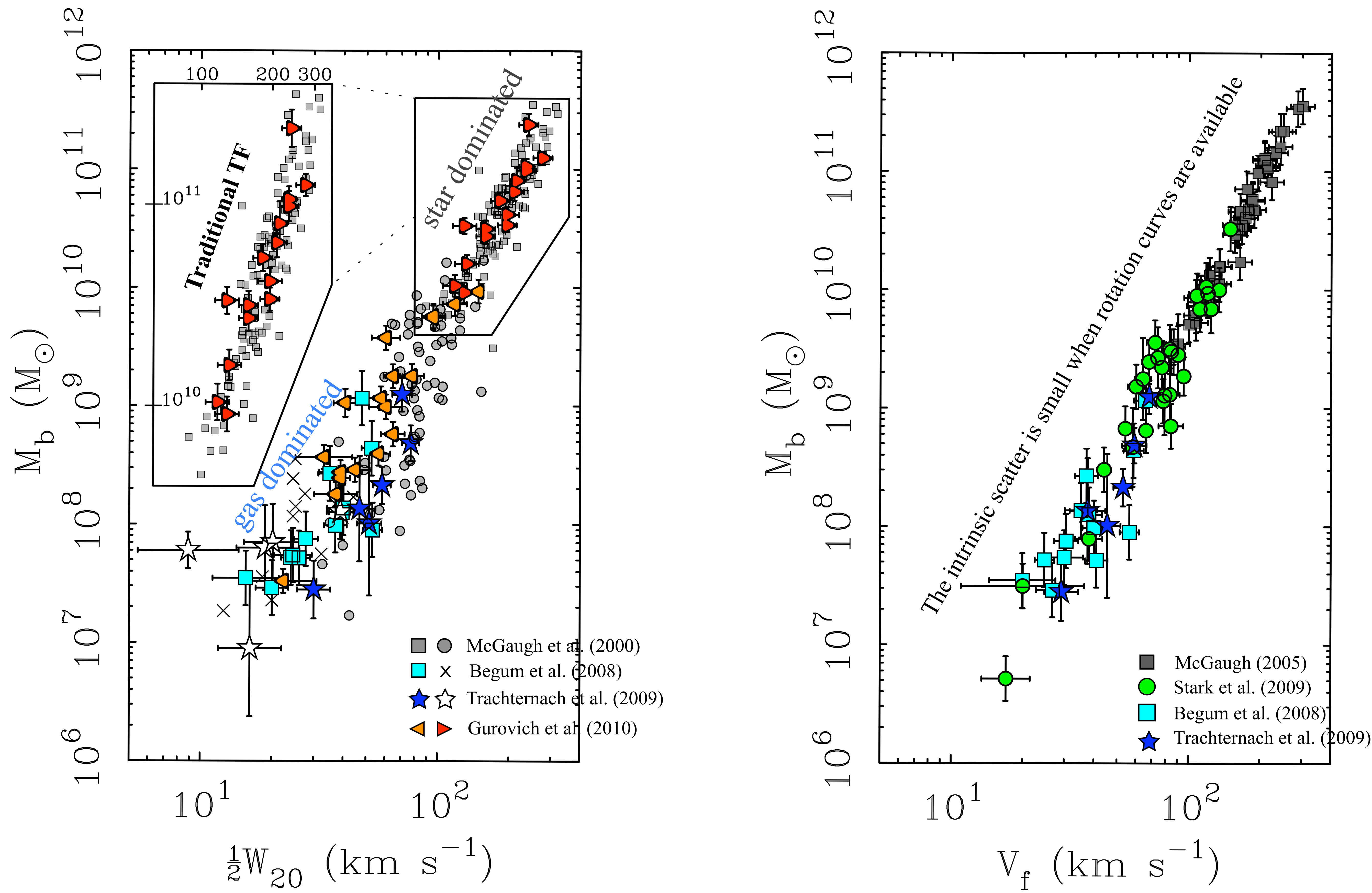
star dominated HSB



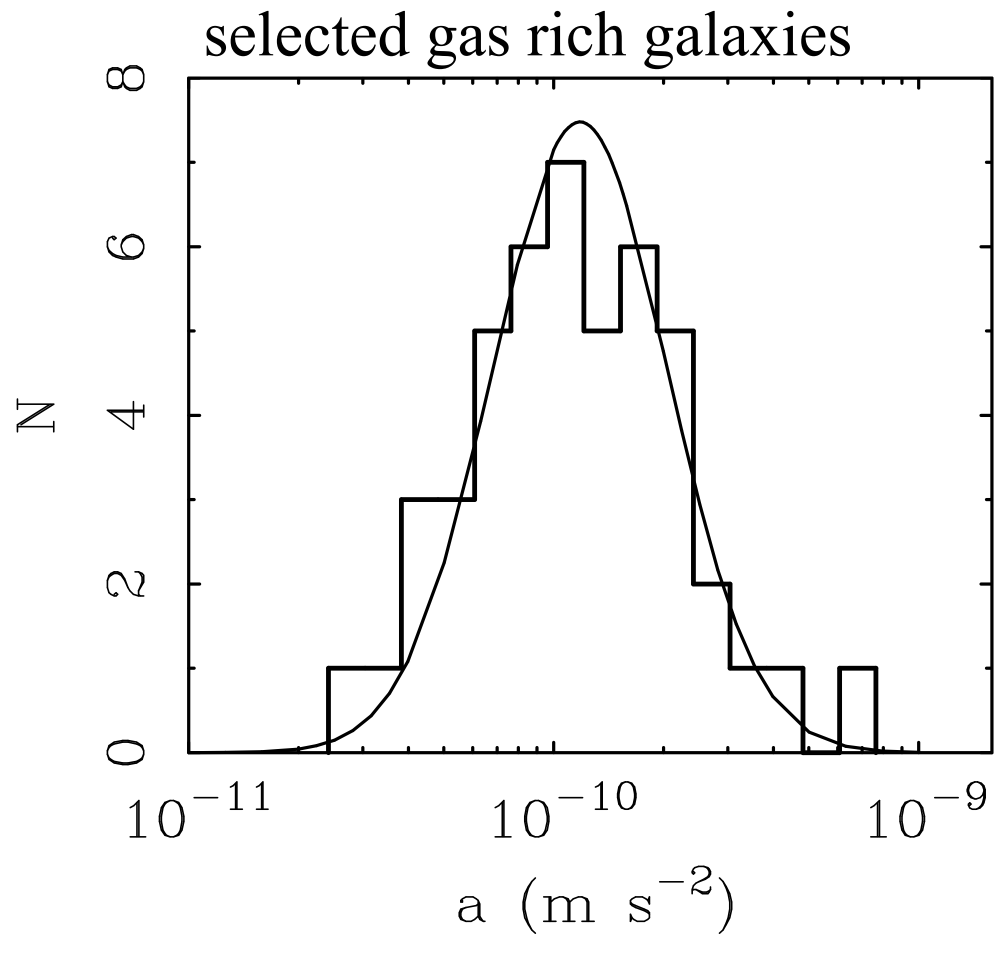


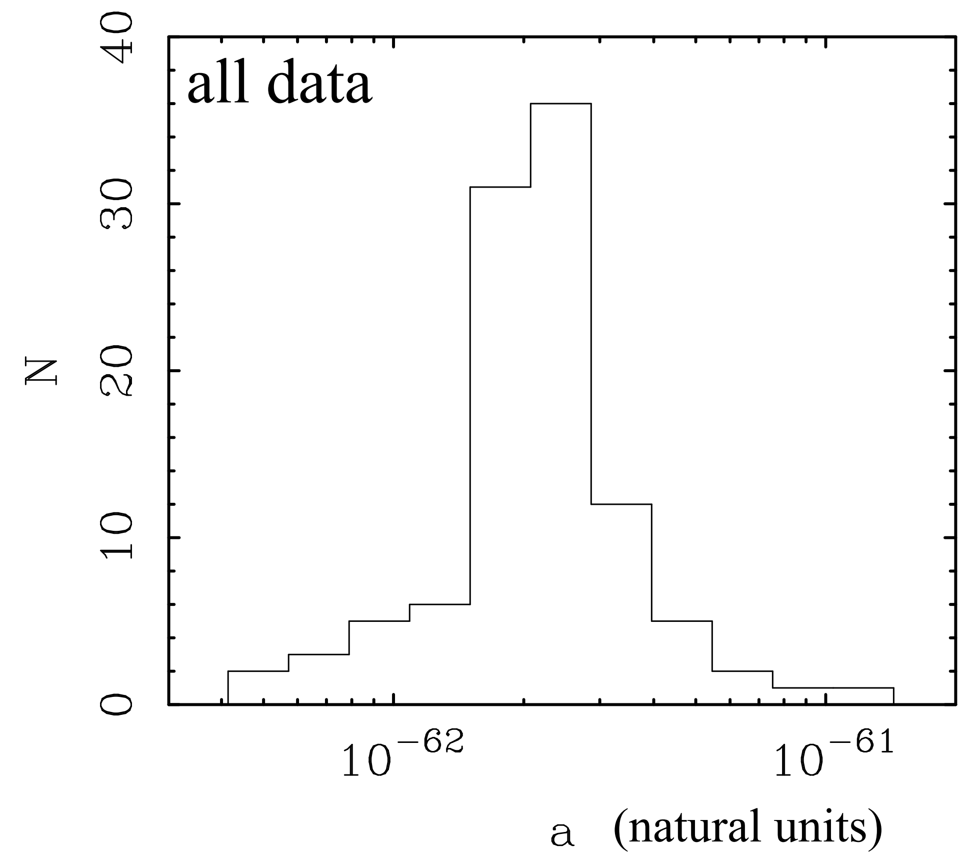
gas dominated LSBs

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



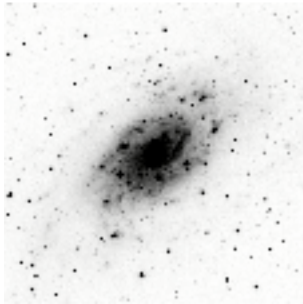
The data specify a particular acceleration scale: $a = \dfrac{V_f^4}{GM_b}$





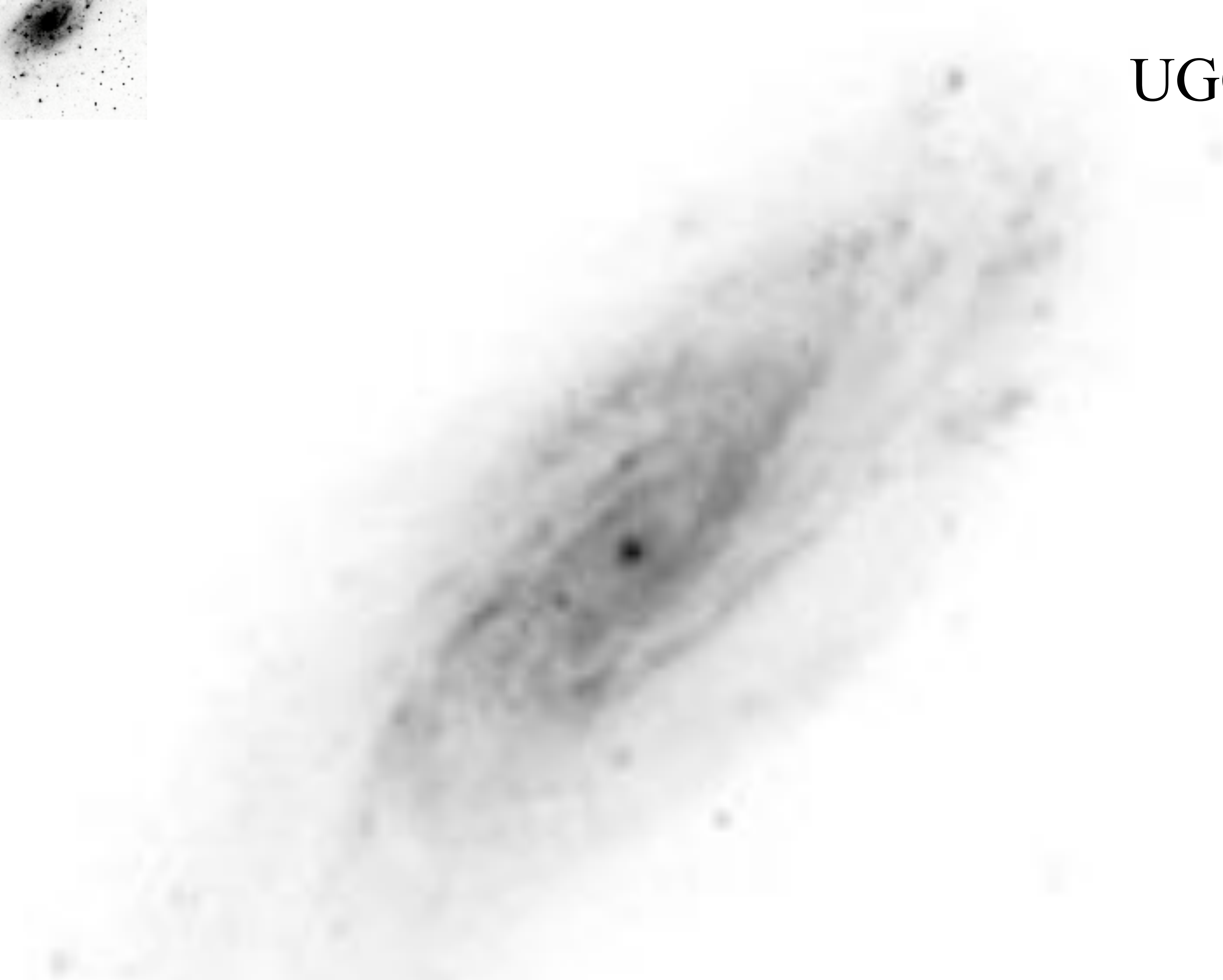
histogram: data
line: distribution expected from observational uncertainties.

The data are consistent with zero intrinsic scatter.



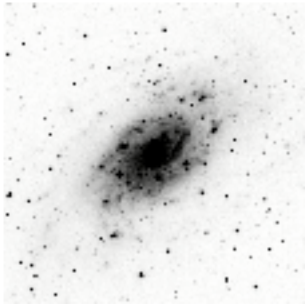
NGC 2403

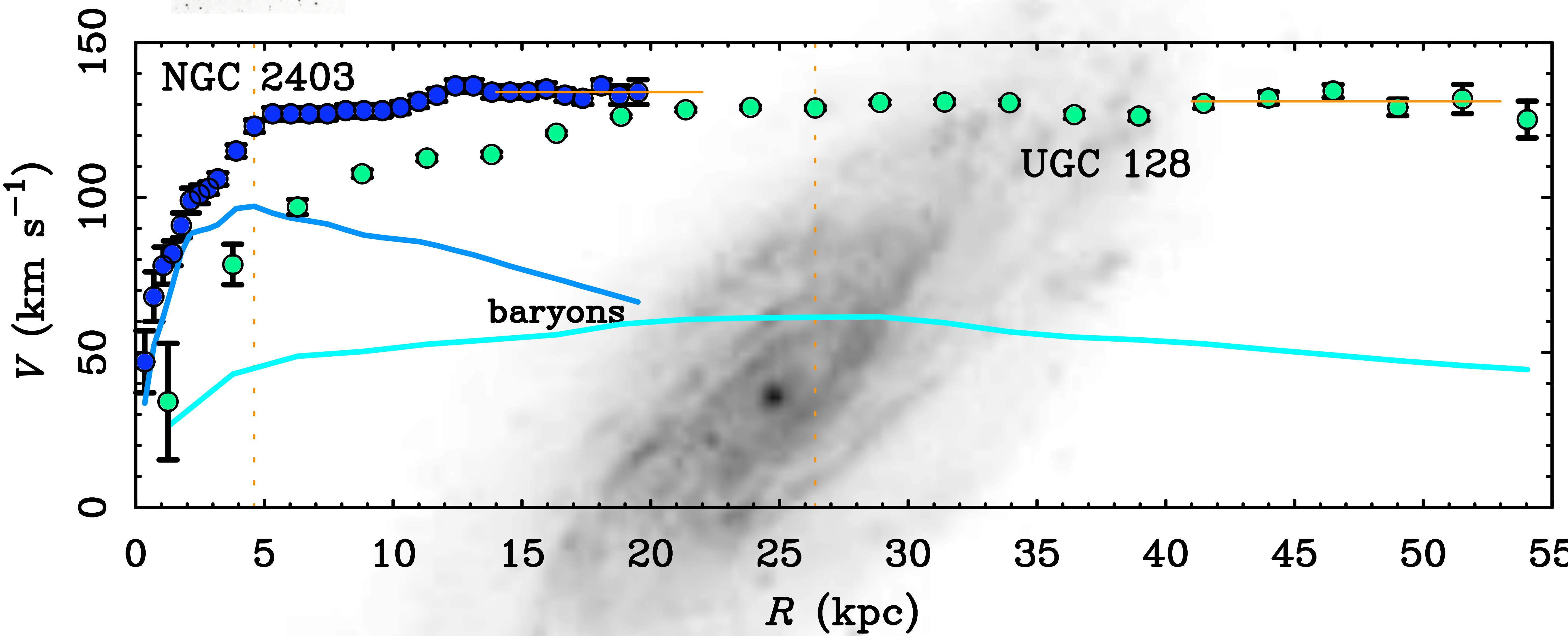
UGC 128



The BTFR is just the zeroth moment, as it were - total baryonic mass vs. characteristic circular velocity. There is more information in the distribution of mass.

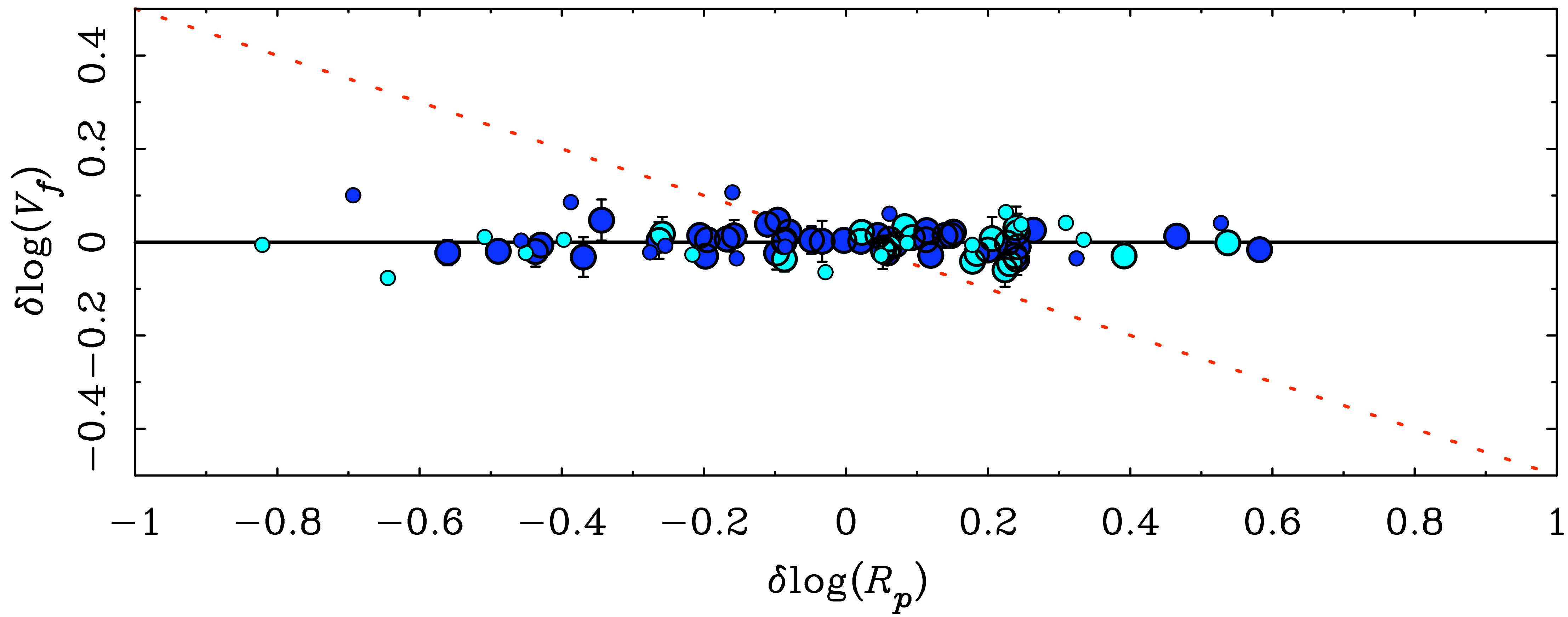
No residuals from TF with size or surface density





Same (M,V) but very different size and surface density

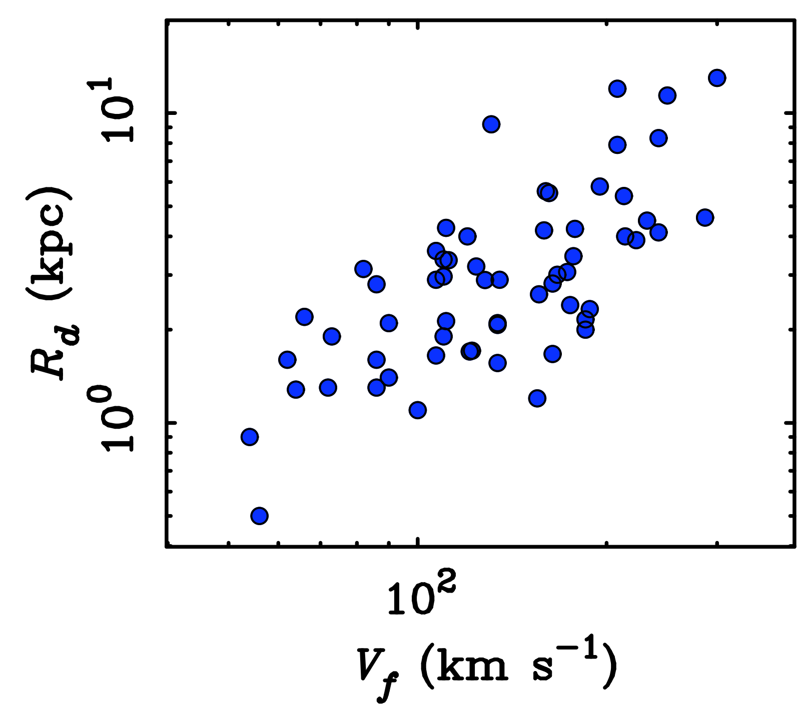
which is strange, since $V^2 = \frac{GM}{R}$



No residuals from TF with size or surface density for disks

$$V^2 = \frac{GM}{R} \quad \rightarrow \frac{\delta \log(V)}{\delta \log(R)} = -\frac{1}{2}$$ expected slope (dotted line)

Note: large range in size at a given mass or velocity



For disk galaxies

Newton says: $$\frac{V^2}{R} = \frac{GM}{R^2} = G(\Sigma_b + \Sigma_{DM})$$

surface density $$\Sigma = \frac{M}{R^2}$$

So we infer that $\Sigma_{DM} \gg \Sigma_b$

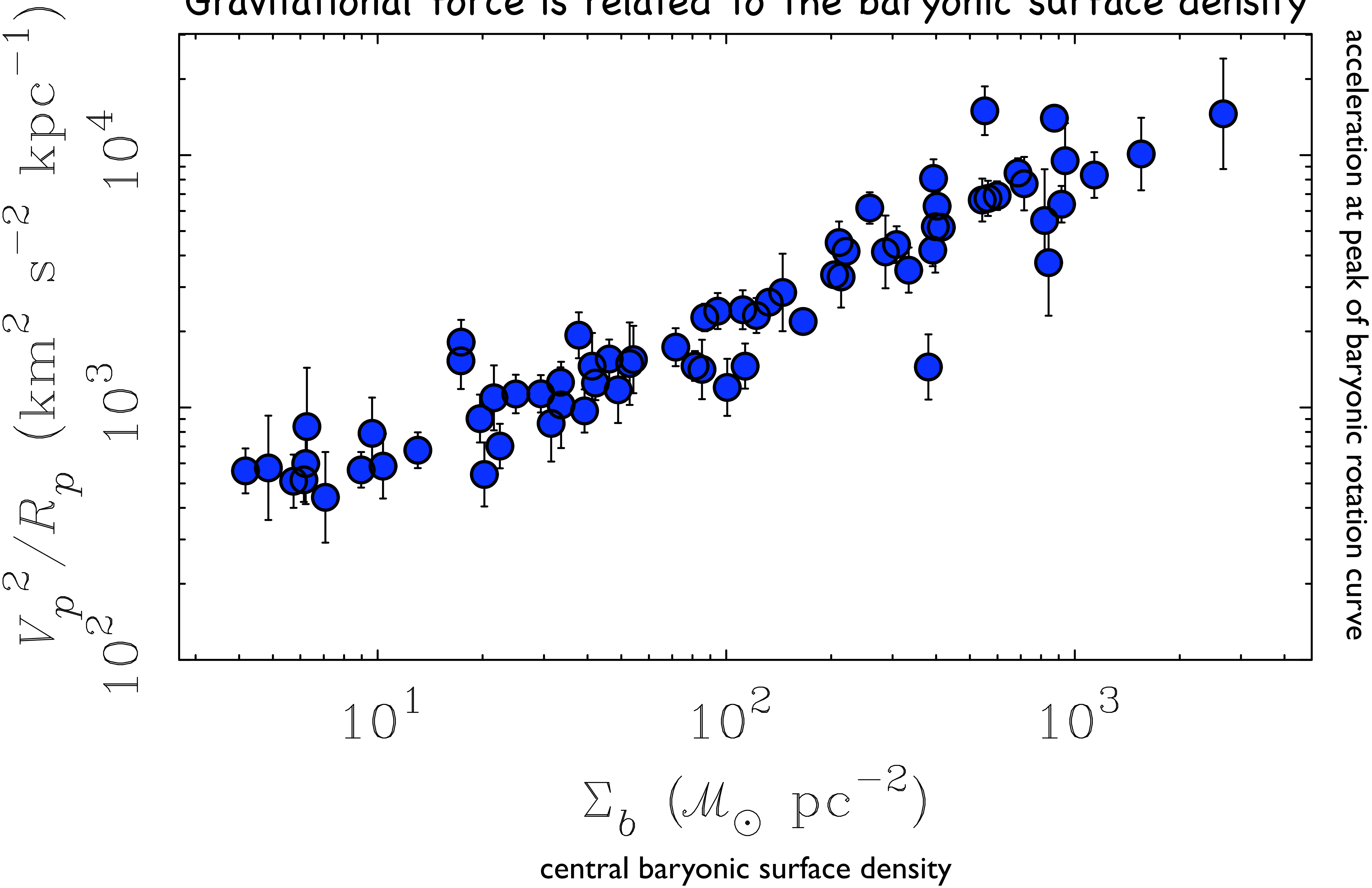
(i.e., that all disks are dark matter dominated)
in order to explain the lack of TF residuals with
luminous size R_p

There is still more information in the mass distribution...

Just looking at the peak radius

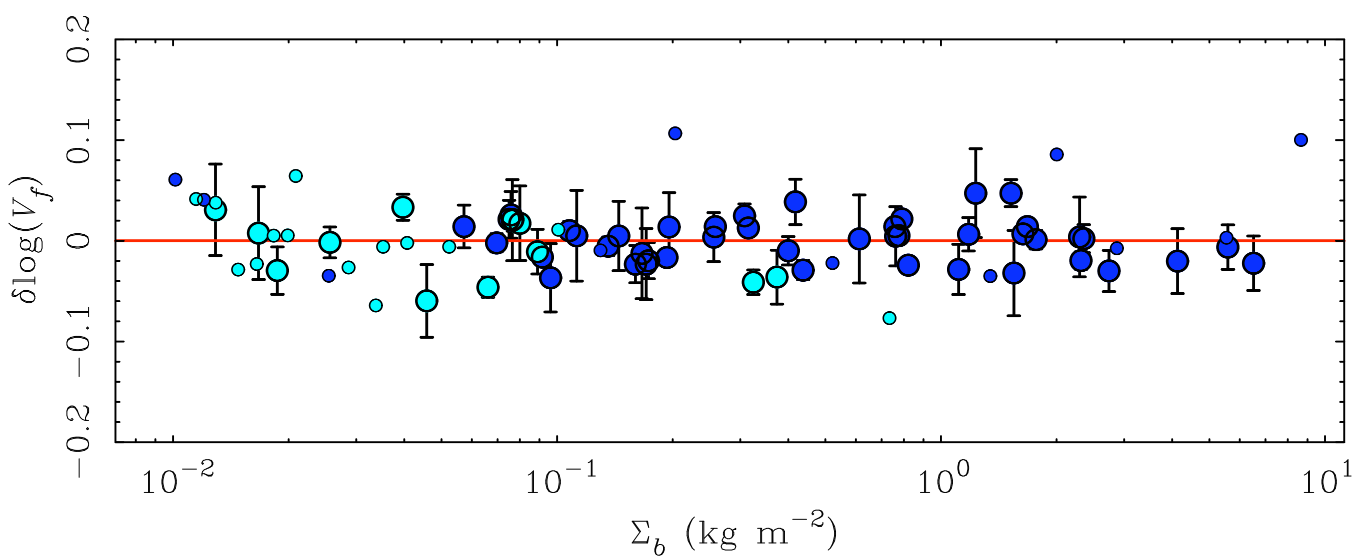
$$a \sim \Sigma_b^{1/2}$$

Gravitational force is related to the baryonic surface density



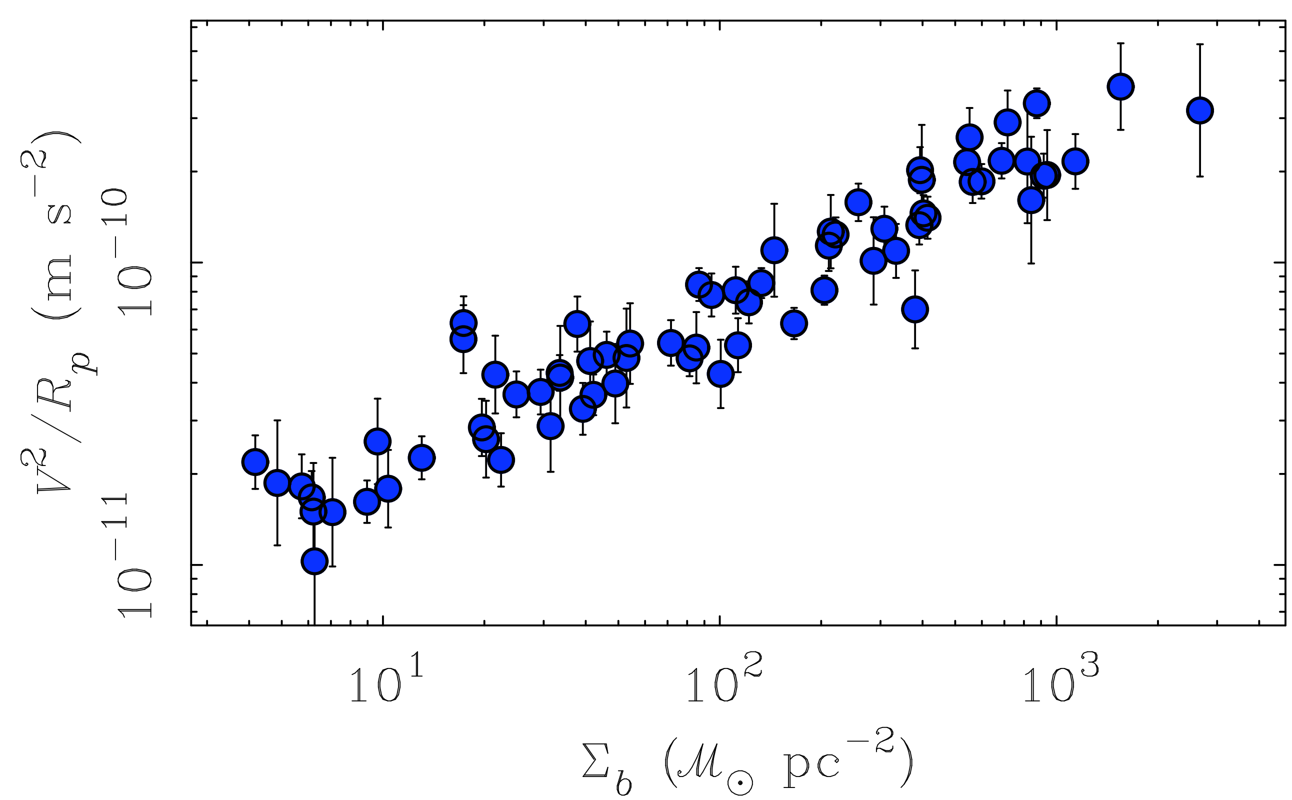
But wait - before we decided $\Sigma_b \ll \Sigma_{DM}$

Now it has to matter. Is this a contradiction?



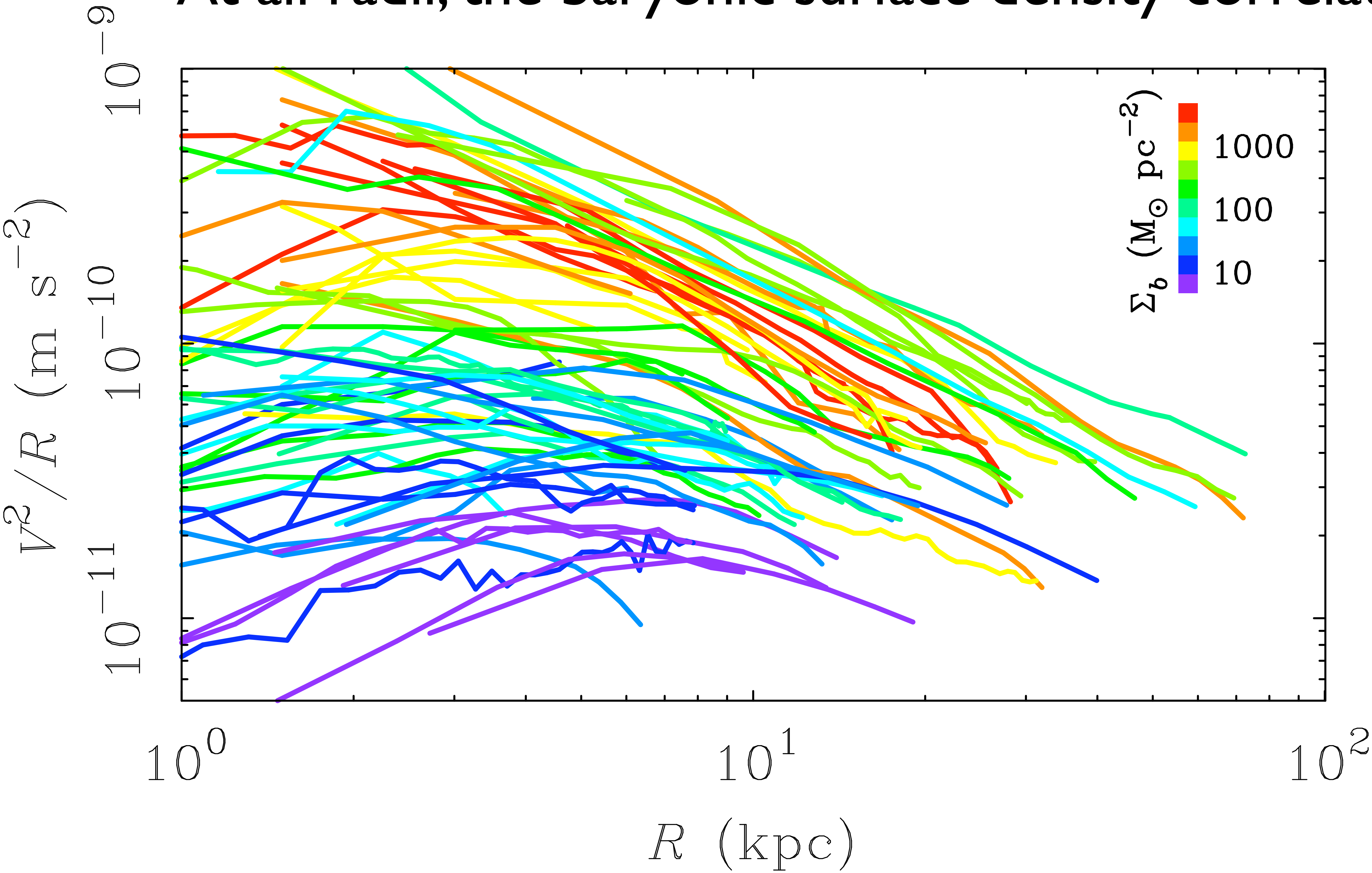
Lack of TF residuals says baryon distribution does not matter.

Correlation of dynamical force with observed surface density says the baryon distribution does matter.



$$\frac{V^2}{R} = G\left(\Sigma_b + \Sigma_{DM}\right)$$

At all radii, the baryonic surface density correlates

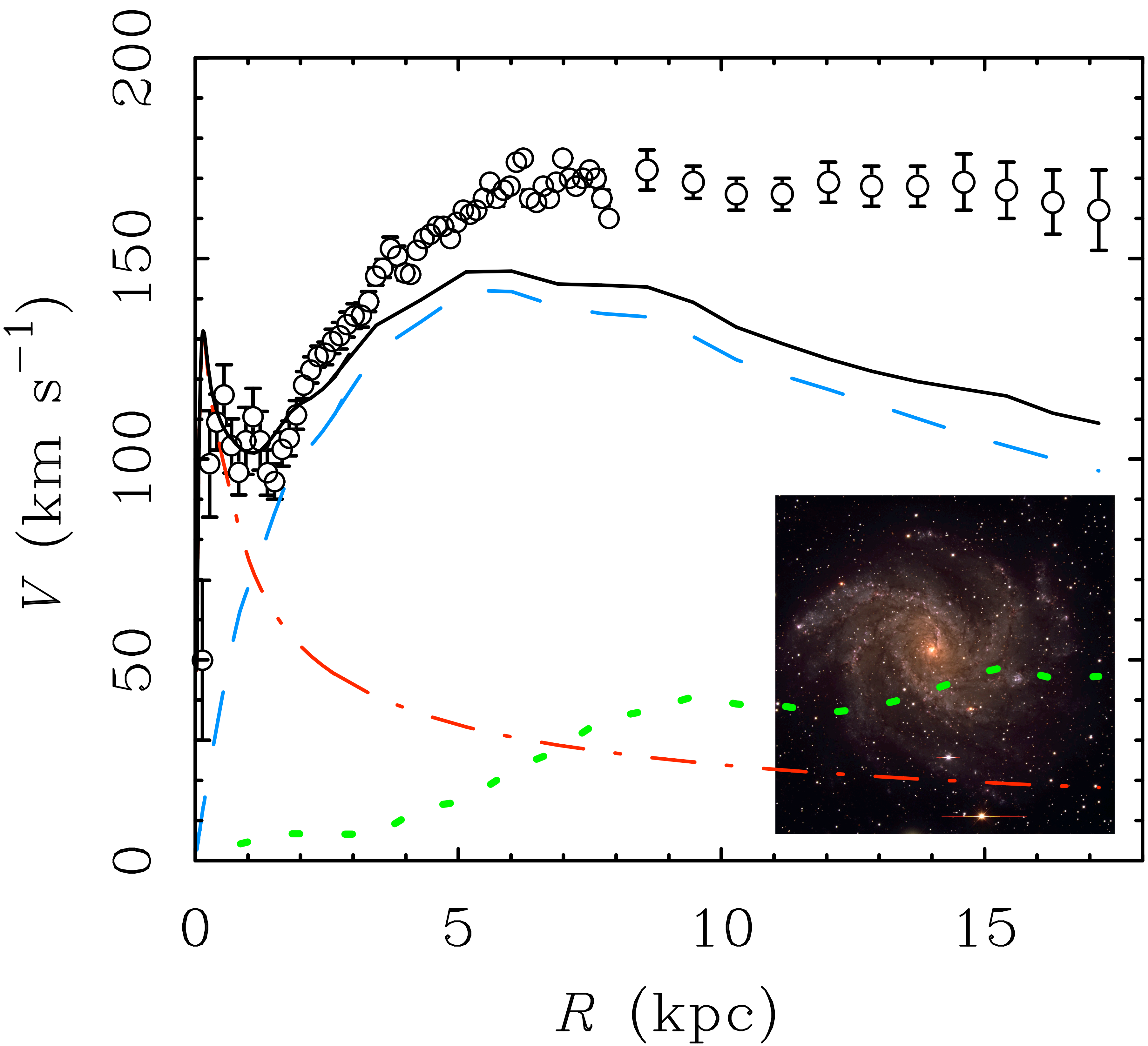


with the acceleration (gravitational force per unit mass)

Renzo's Rule: (2004 IAU; 1995 private communication)

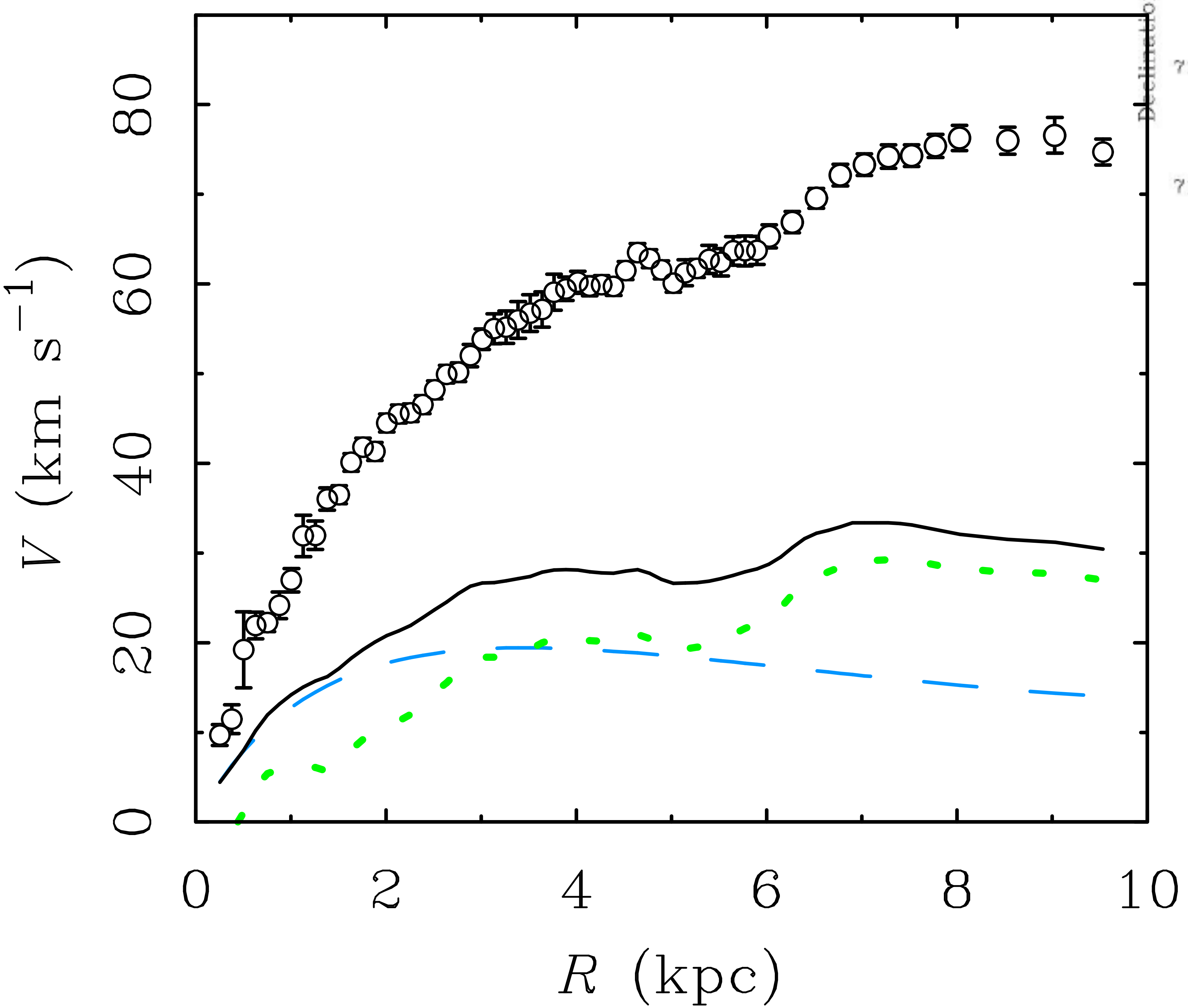
"When you see a feature in the light, you see a corresponding feature in the rotation curve."

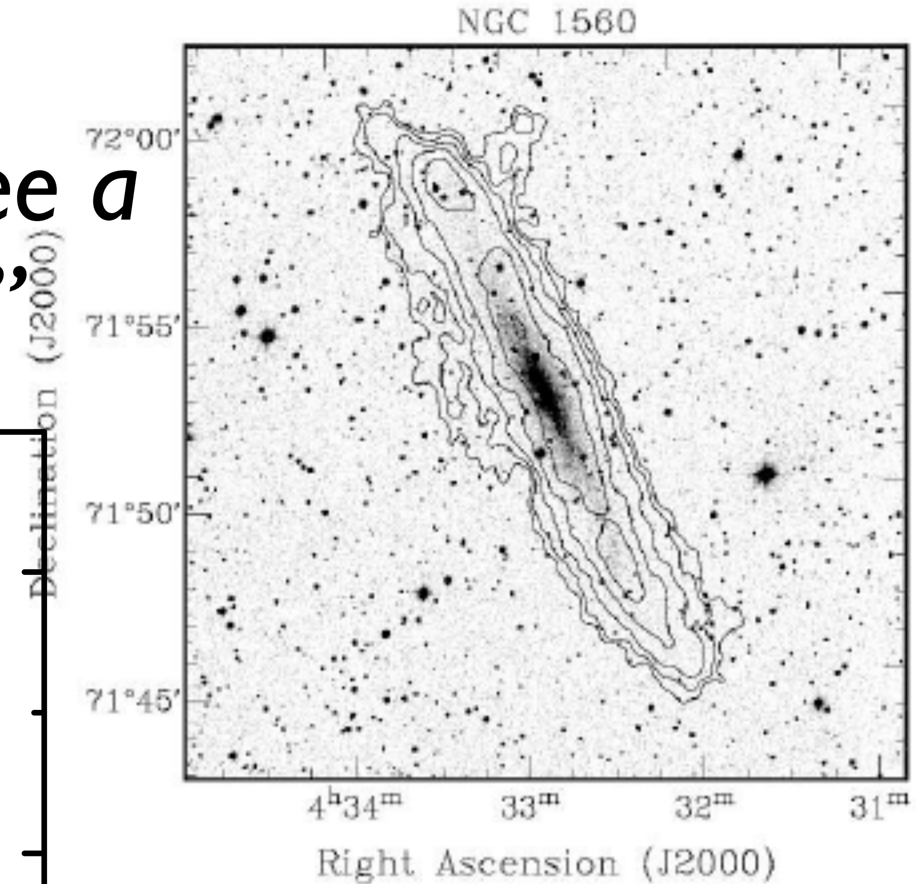
In NGC 6946, a tiny bulge (just 4% of the total light) leaves a distinctive mark.



Renzo's Rule:

"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.

Renzo's Rule:

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

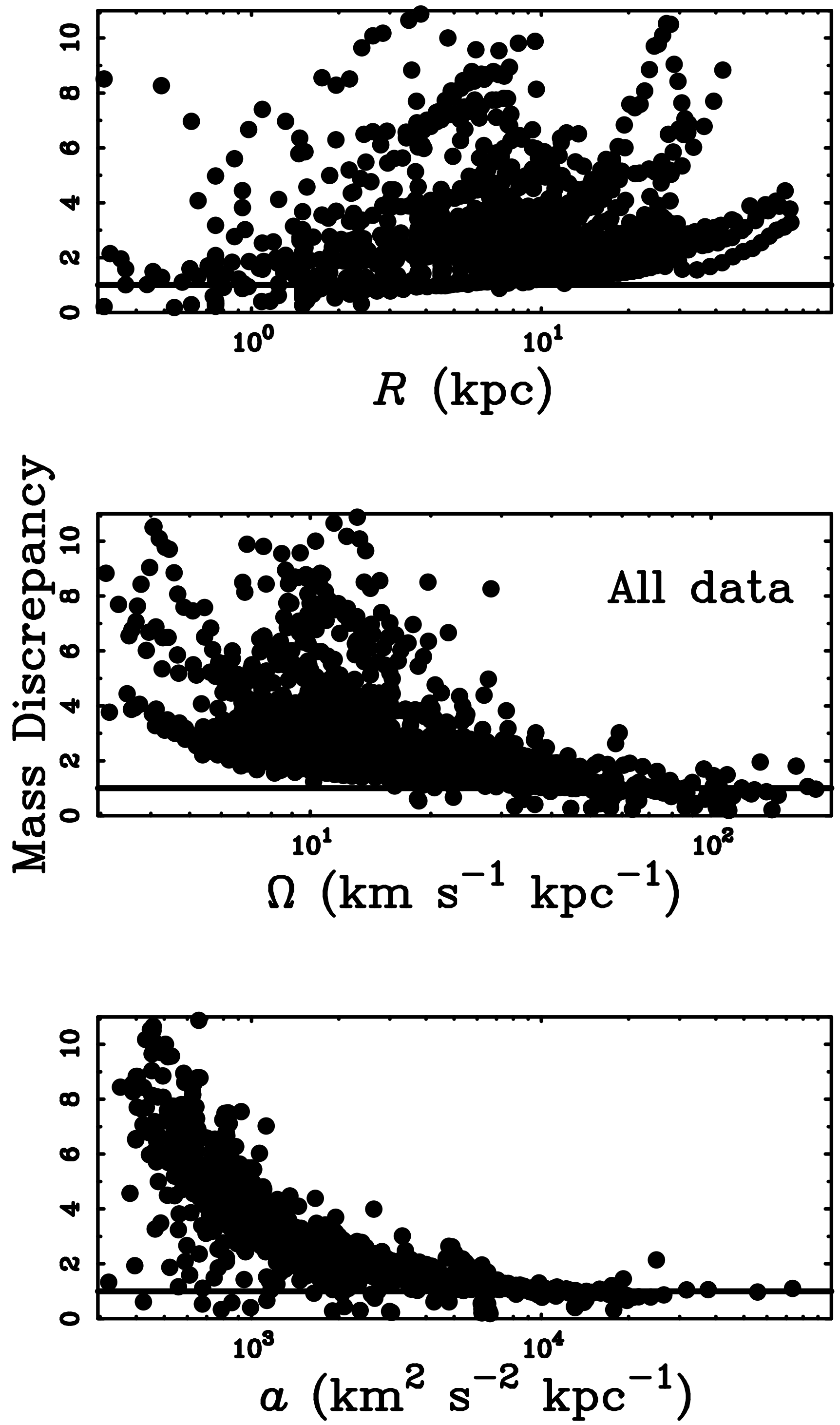
The distribution of mass is coupled to the distribution of light.

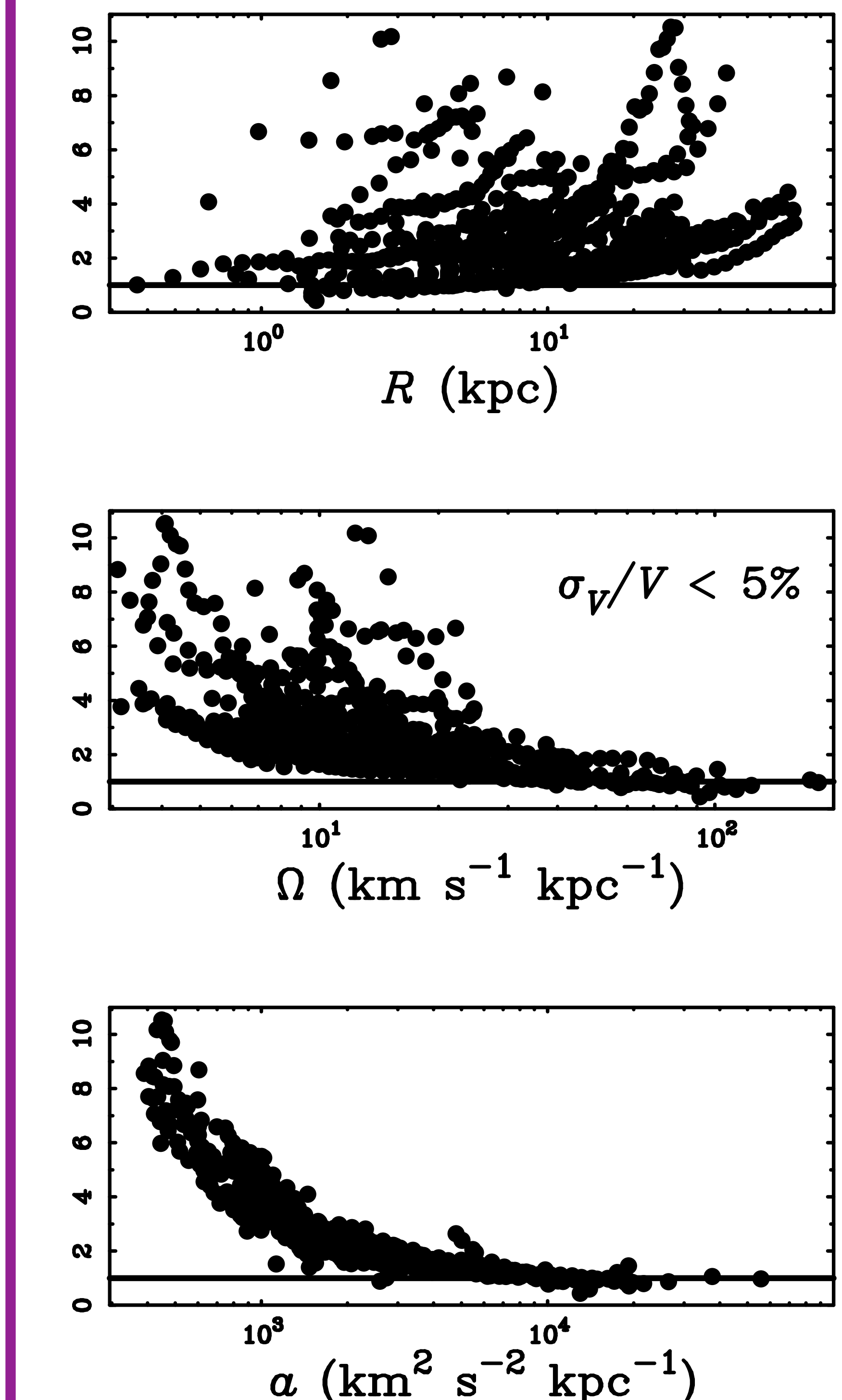
Quantify by defining the Mass Discrepancy:

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

The Mass Discrepancy correlates with acceleration and baryonic surface density

McGaugh (2004)





radius

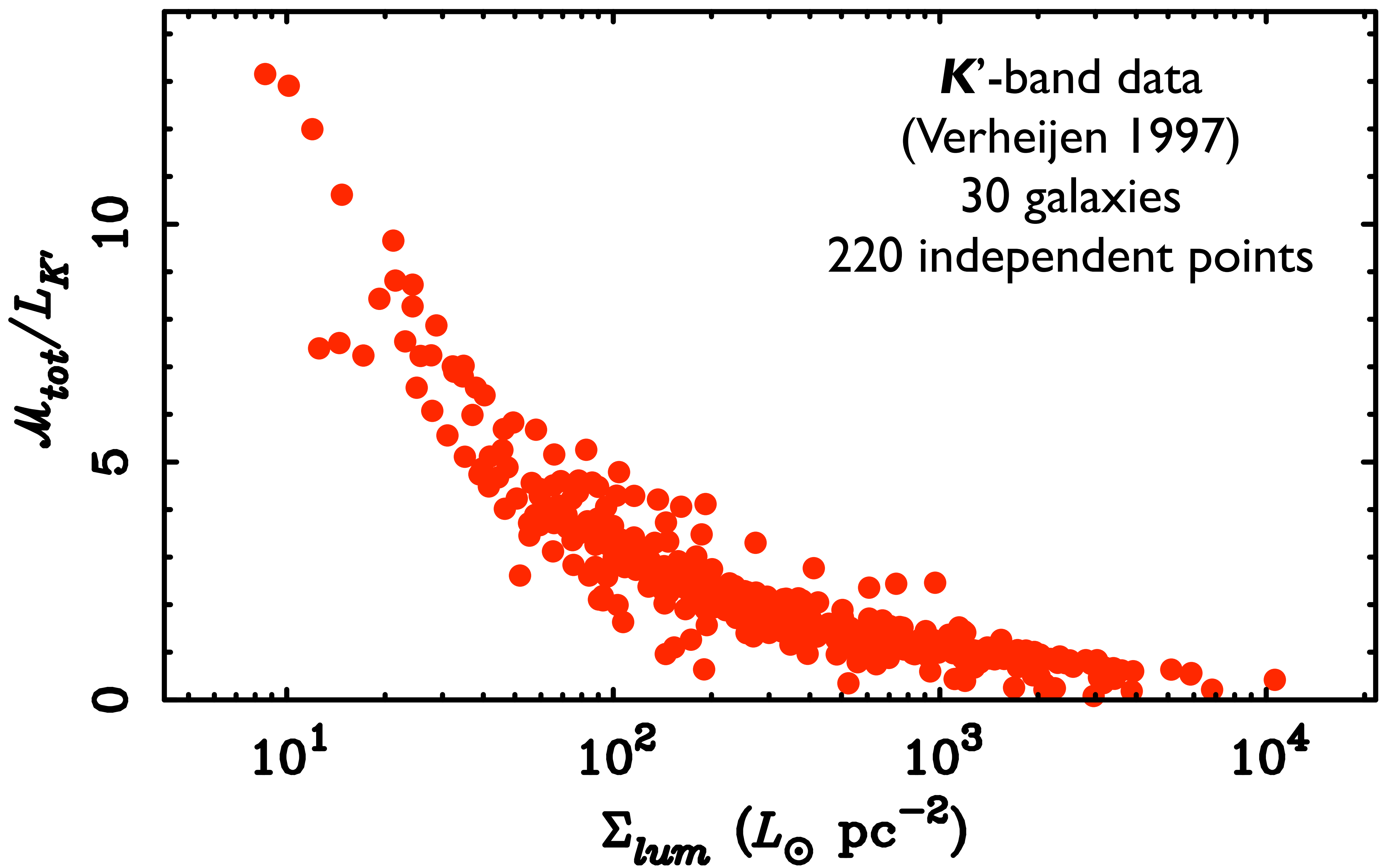
orbital frequency

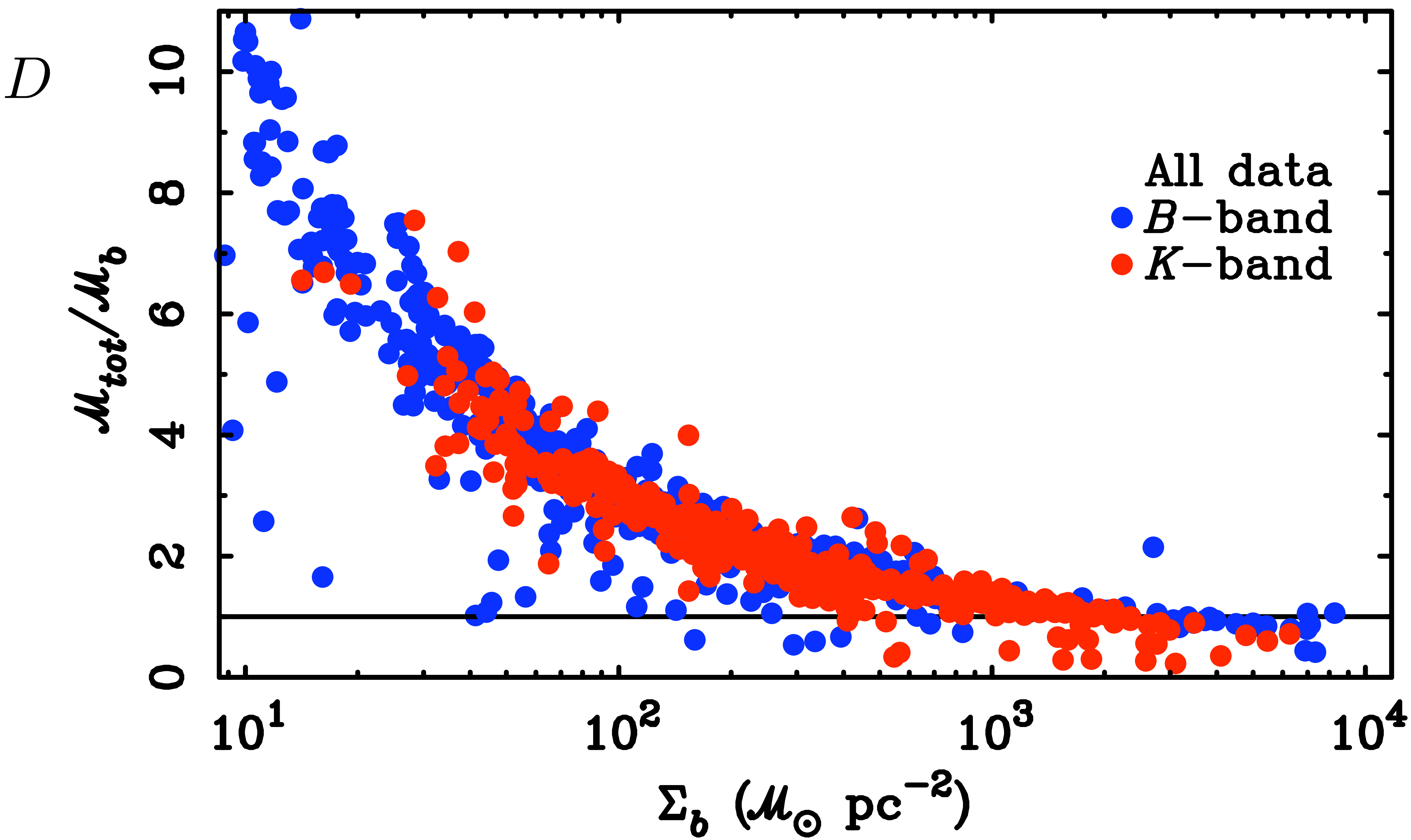
acceleration

74 galaxies
> 1000 points
(all data)

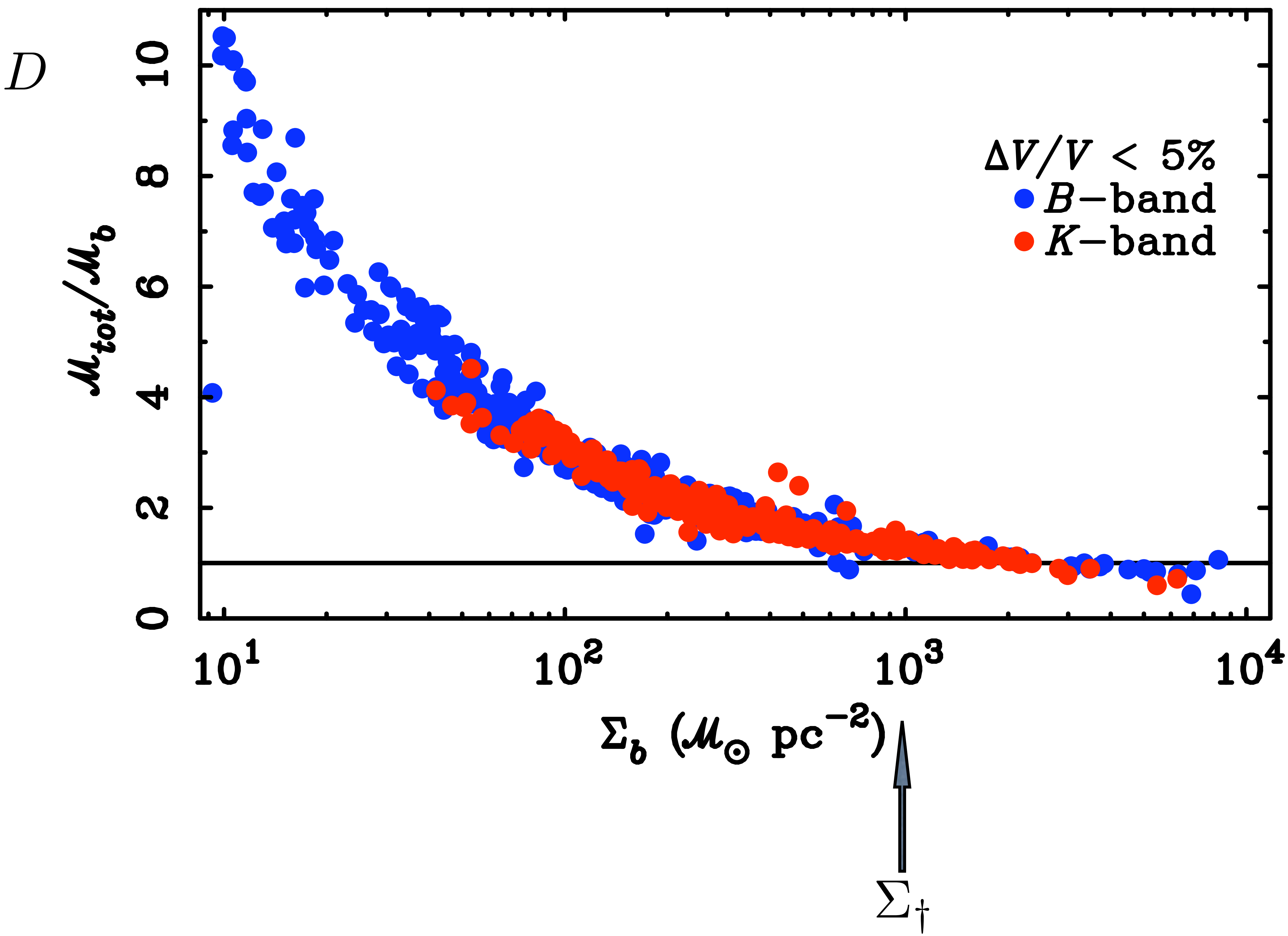
60 galaxies
> 600 points
(errors < 5%)

Can see the effect directly in the data with no assumption on M*/L





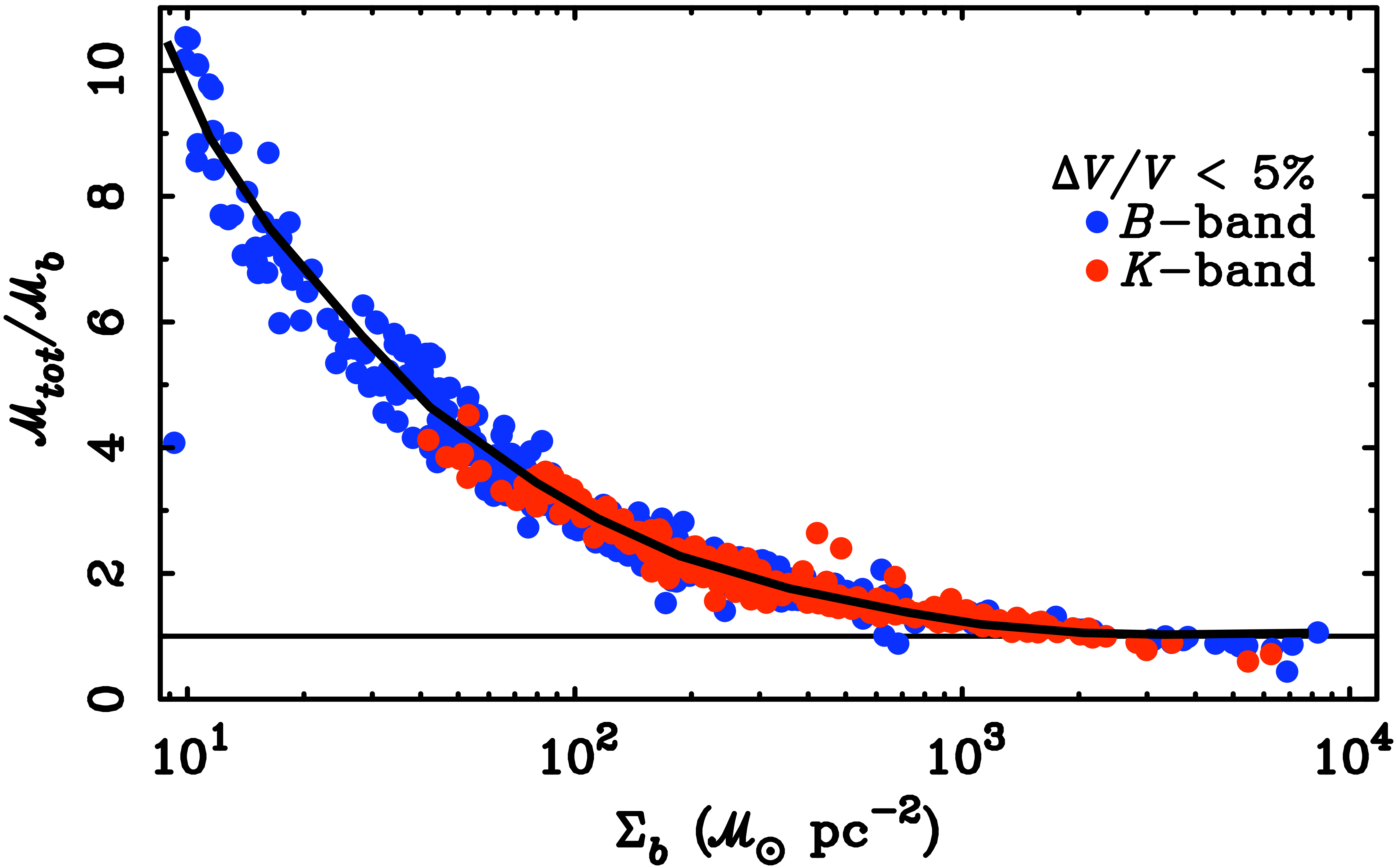
D
All data
B−band
K−band
$\mathcal{M}_{tot}/\mathcal{M}_b$
0
2
4
6
8
10
10^1
10^2
10^3
10^4
Σ_b ($\mathcal{M}_\odot$ pc^{-2})



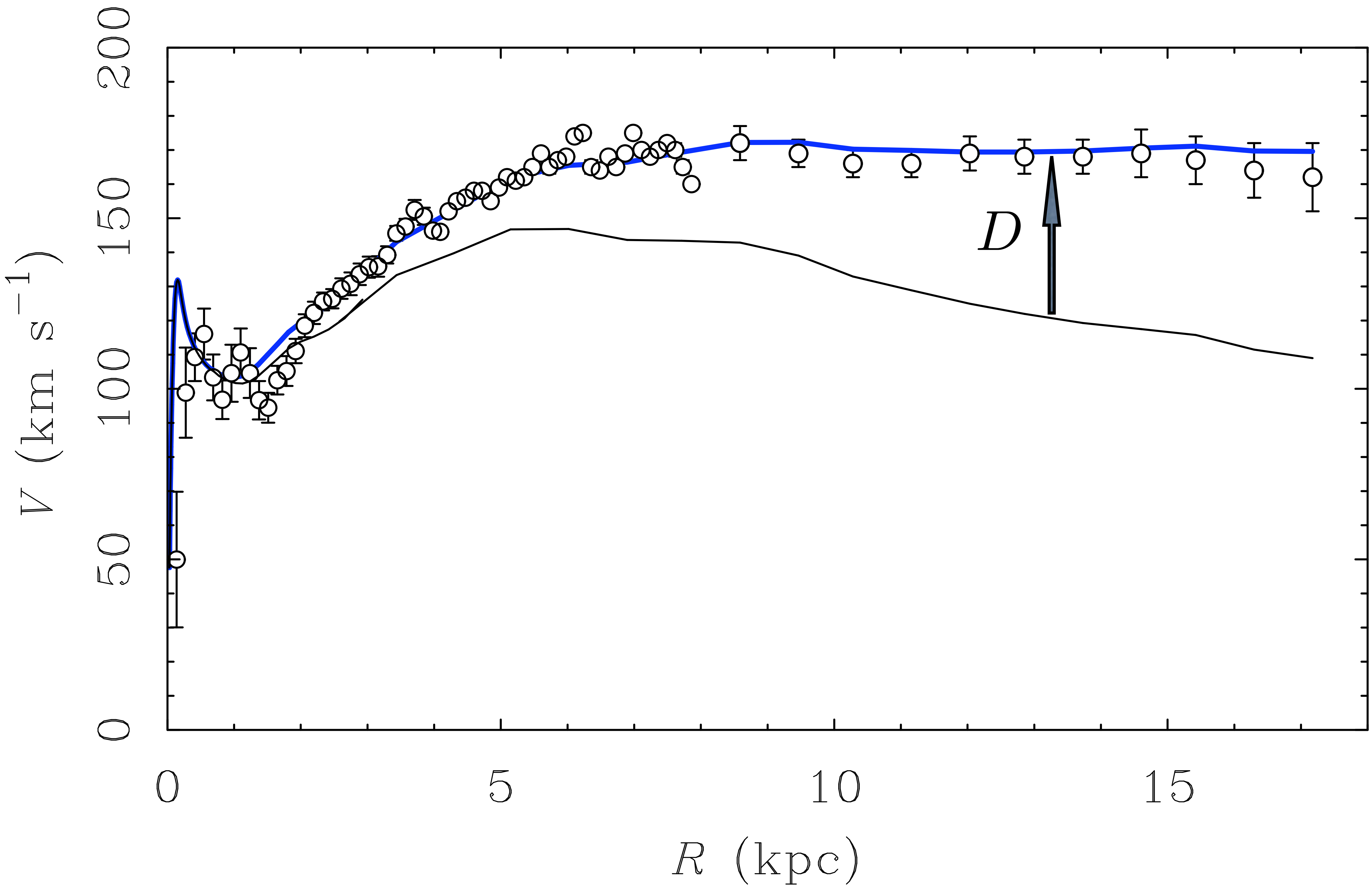
D
ΔV/V < 5%
B−band
K−band
$\mathcal{M}_{tot}/\mathcal{M}_b$
Σ_b ($\mathcal{M}_\odot$ pc^{-2})
$\Sigma_\dagger$
0
2
4
6
8
10
10^1
10^2
10^3
10^4

Can fit a fcn to the data $D(\Sigma/\Sigma_\dagger)$ or $D(a/a_0)$

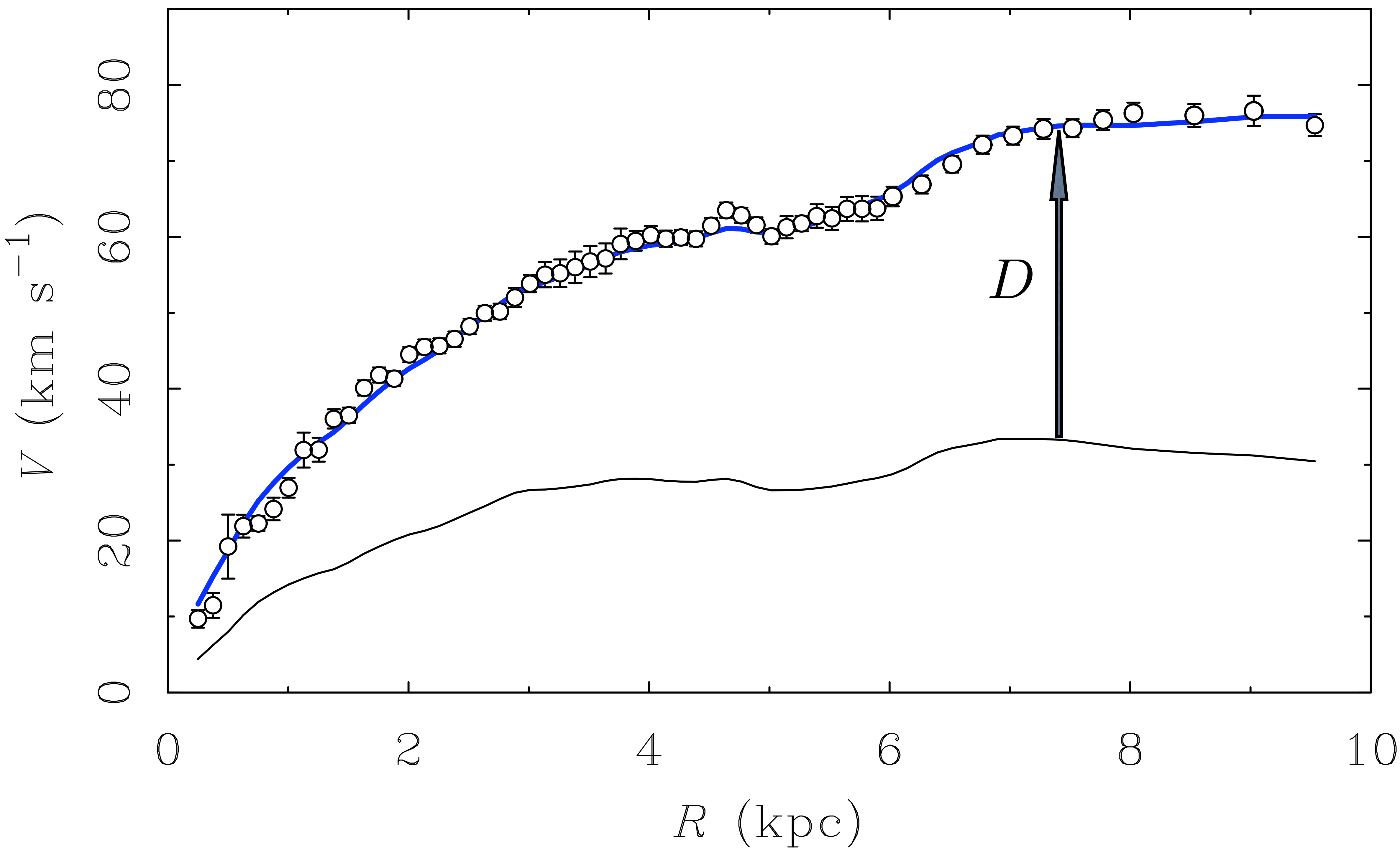
D



and use it to map between V_b and V_{tot}.



V (km s−1)
R (kpc)
D
0
50
100
150
200
0
5
10
15



0
20
40
60
80
V (km s^{-1})
0
2
4
6
8
10
R (kpc)
D

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

$a \gg a_0$ $\quad a \to g_N$

$$a_0 \approx 10^{-10}\,\mathrm{m\,s^{-2}} \sim cH_0 \sim c\Lambda^{1/2}$$

$a \ll a_0$ $\quad a \to \sqrt{g_N a_o}$ $\quad \Longrightarrow \quad a_0 GM = V_f^4$

Milgrom (1983)

modified inertia (F=ma)
OR modified gravity

Bekenstein & Milgrom (1984): $\nabla \cdot [\mu(|\nabla\phi|/a_0)\nabla\phi] = 4\pi G\rho$

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

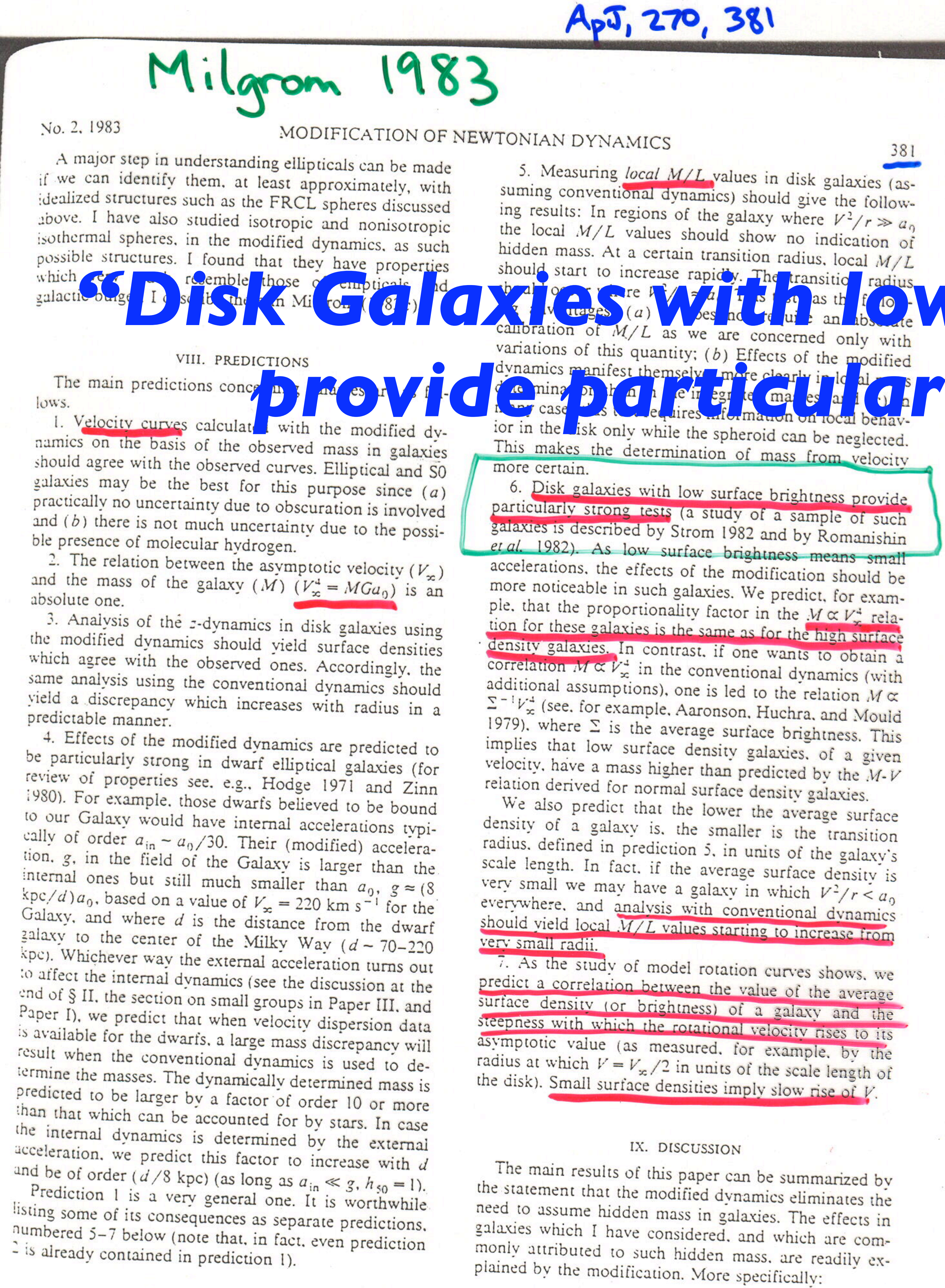
$\mu \to 1 \qquad a \gg a_0$

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

Relativistic extensions: TeVeS, bimetric gravity, ???

Always emotions MOND is.

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 o[illegible]ticals and galactic bulge[illegible]. I [illegible]s[illegible] the[illegible]n Mi[illegible]ro[illegible] (1[illegible]8[illegible]).

VIII. PREDICTIONS

The main predictions conc[illegible] [illegible]es ar[illegible] f[illegible]lows.

1. Velocity curves calculat[illegible] with the modified dynamics on the basis of the observed mass in galaxies should agree with the observed curves. Elliptical and S0 galaxies may be the best for this purpose since (a) practically no uncertainty due to obscuration is involved and (b) there is not much uncertainty due to the possible presence of molecular hydrogen.

2. The relation between the asymptotic velocity (V_∞) and the mass of the galaxy (M) ($V_\infty^4 = MGa_0$) is an absolute one.

3. Analysis of the z-dynamics in disk galaxies using the modified dynamics should yield 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 $a_{in} \ll g$, $h_{50} = 1$).

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 rapid[illegible]. The[illegible] transitio[illegible] radius [illegible] [illegible]re [illegible] [illegible] as th[illegible] f[illegible]lo[illegible] [illegible]ntages (a) [illegible]es n[illegible] [illegible]u[illegible]e an [illegible]bs[illegible]te calibration of M/L as we are concerned only with variations of this quantity; (b) Effects of the modified dynamics [illegible]anifest themselv[illegible] m[illegible]re cl[illegible]rly i[illegible] lo[illegible]al [illegible] d[illegible]mina[illegible] [illegible] [illegible]e i[illegible]egr[illegible] ma[illegible]es a[illegible] [illegible] [illegible]n [illegible] case[illegible] [illegible]requires information on local behavior in the [illegible]isk 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.

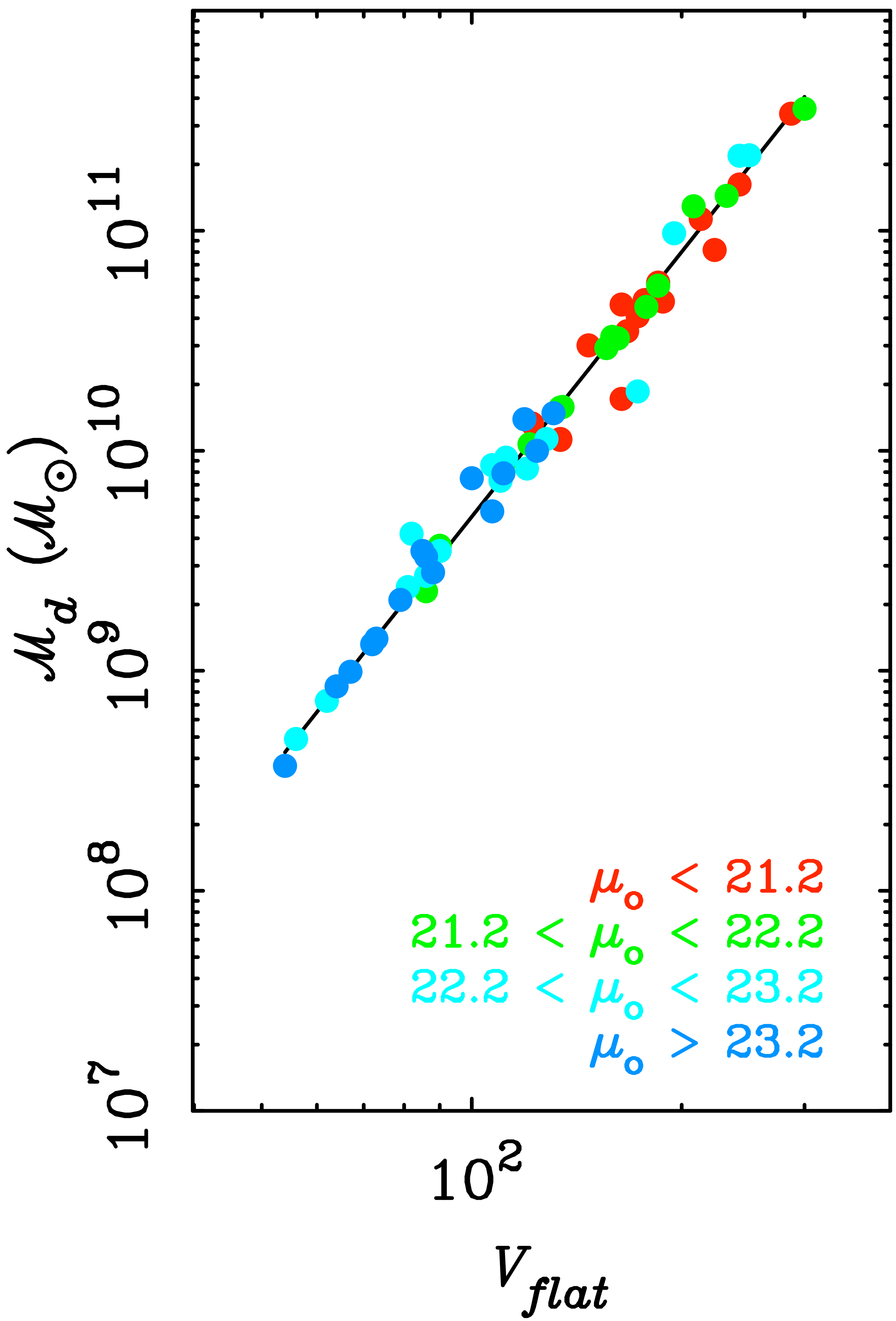
7. As the study of model rotation curves shows, we predict a correlation between the value of the average surface density (or brightness) of a galaxy and the steepness with which the rotational velocity rises to its asymptotic value (as measured, for example, by the radius at which $V = V_\infty/2$ in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

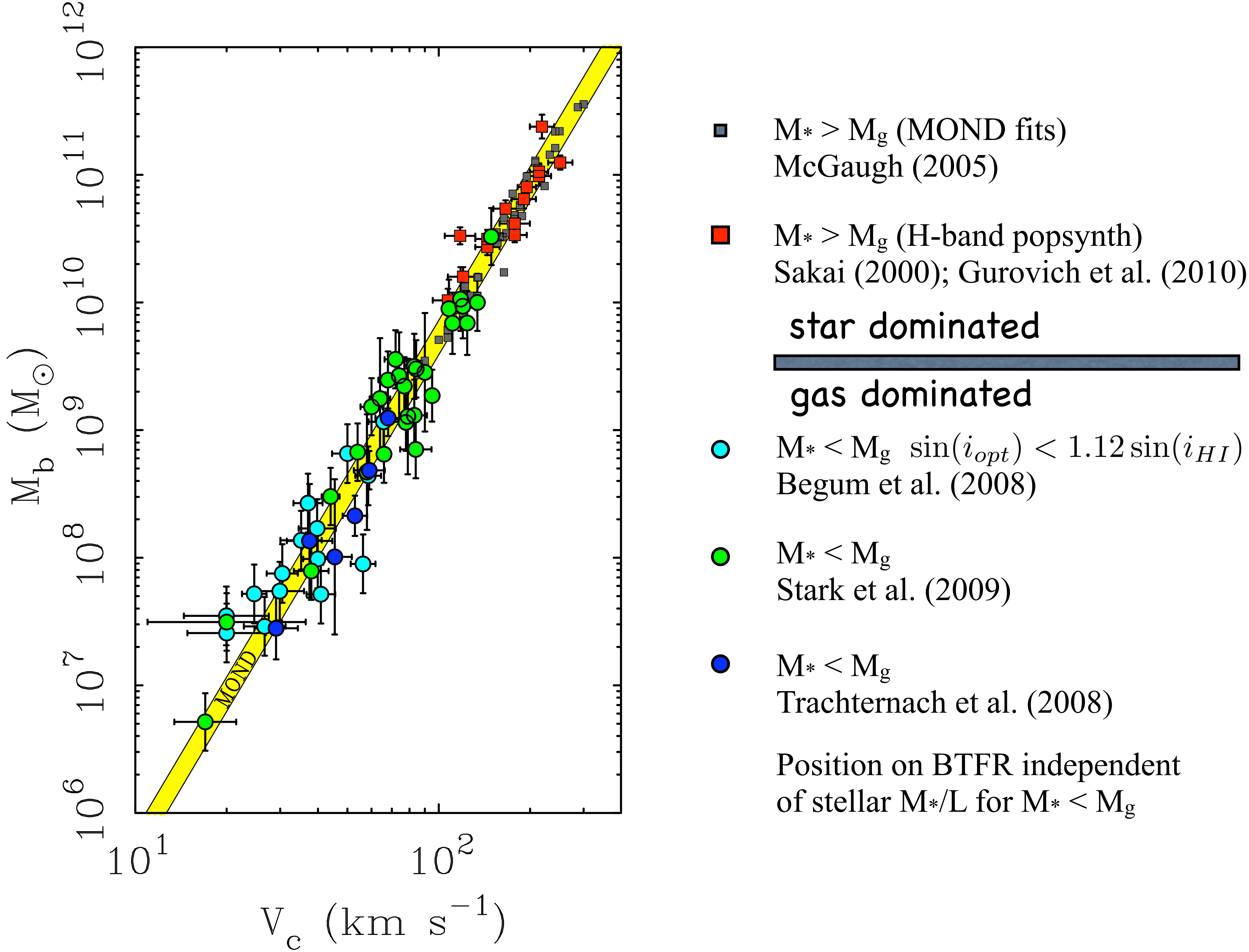
“Disk Galaxies with low surface brightness provide particularly strong tests”

- 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

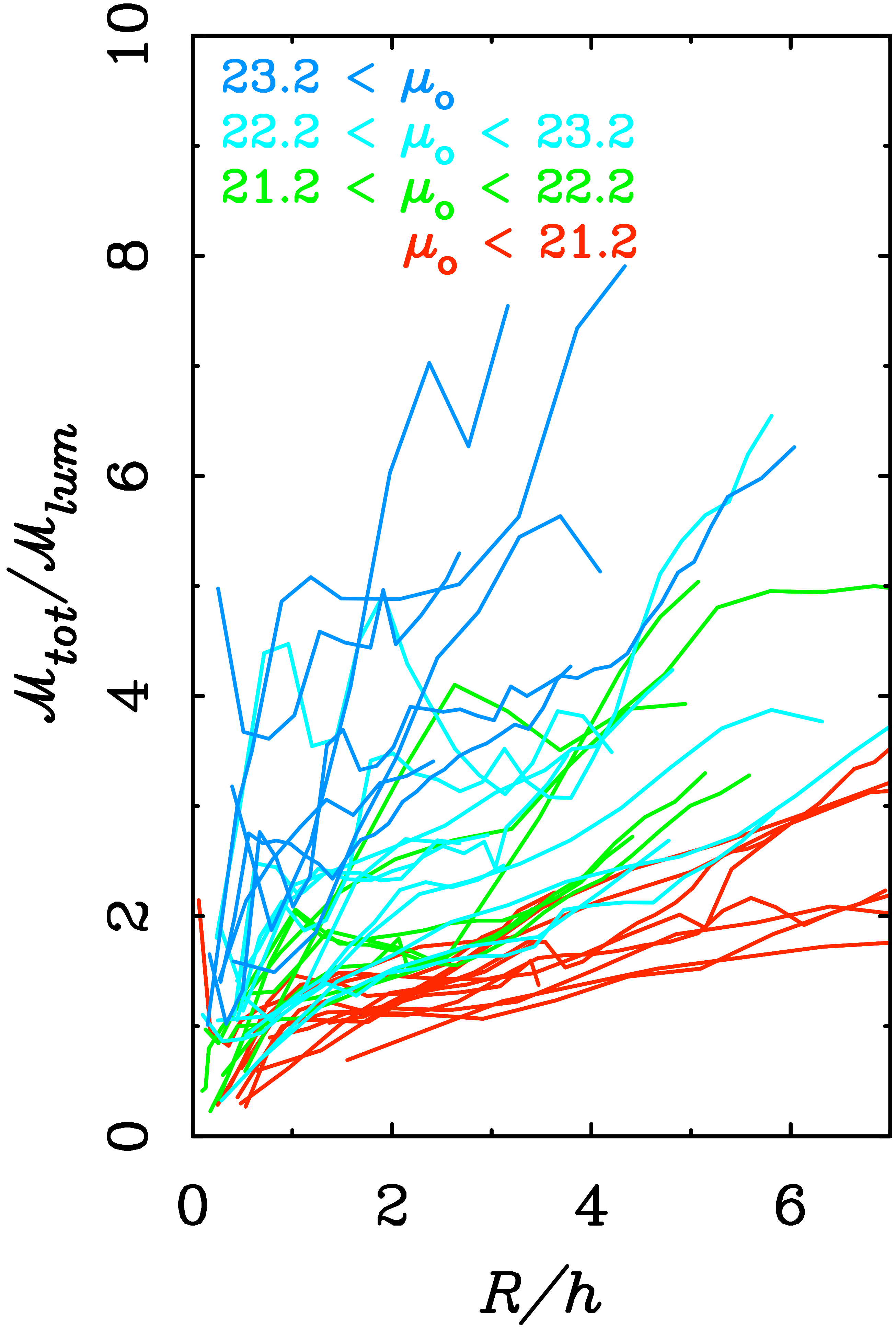


MOND predictions

- 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

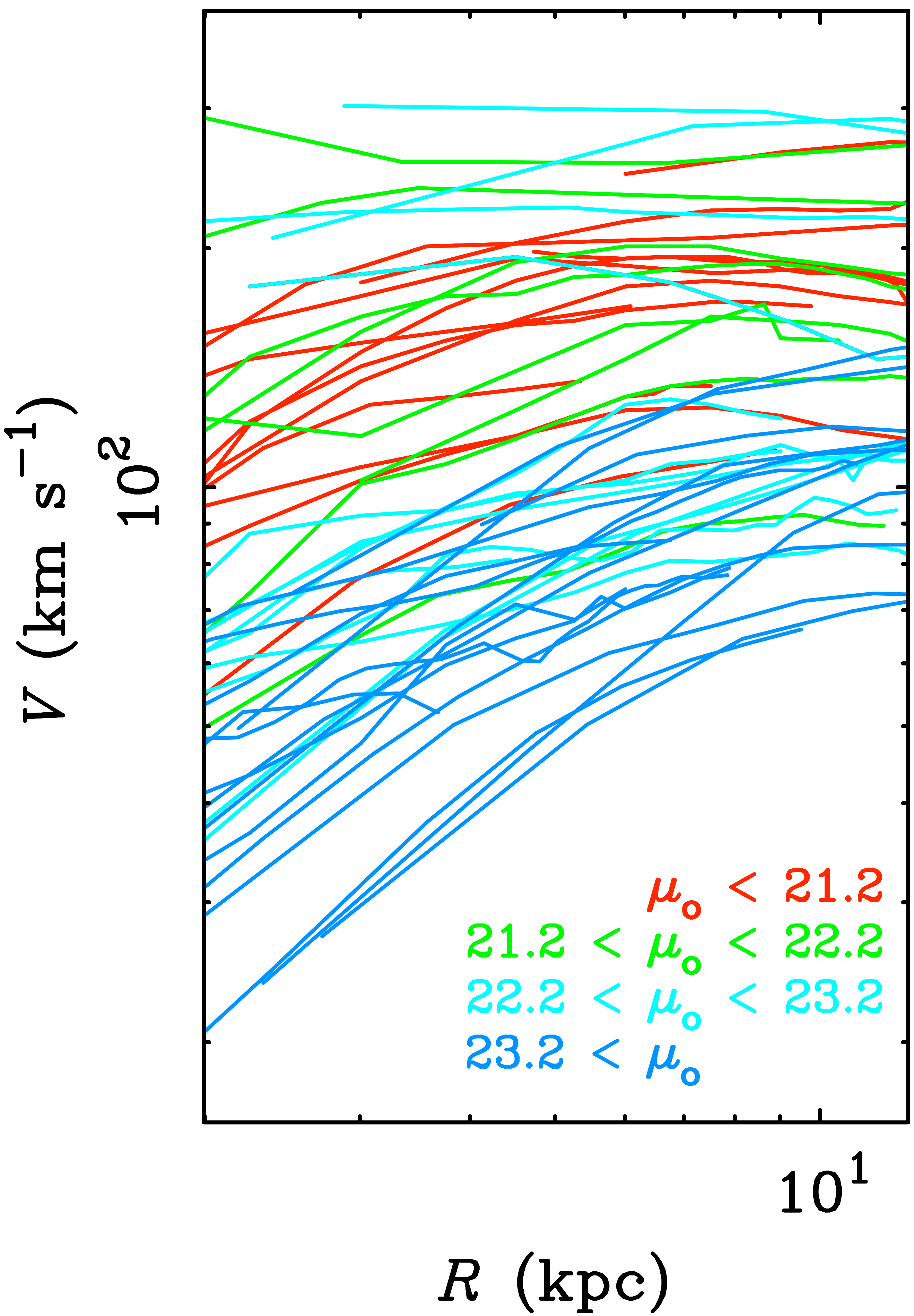


$M_b\ (M_\odot)$
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{1}
10^{2}
$V_c\ (\mathrm{km\ s^{-1}})$
MOND
$M_* > M_g$ (MOND fits)
McGaugh (2005)
$M_* > M_g$ (H-band popsynth)
Sakai (2000); Gurovich et al. (2010)
star dominated
gas dominated
$M_* < M_g$ $\sin(i_{opt}) < 1.12 \sin(i_{HI})$
Begum 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 $M_* < M_g$



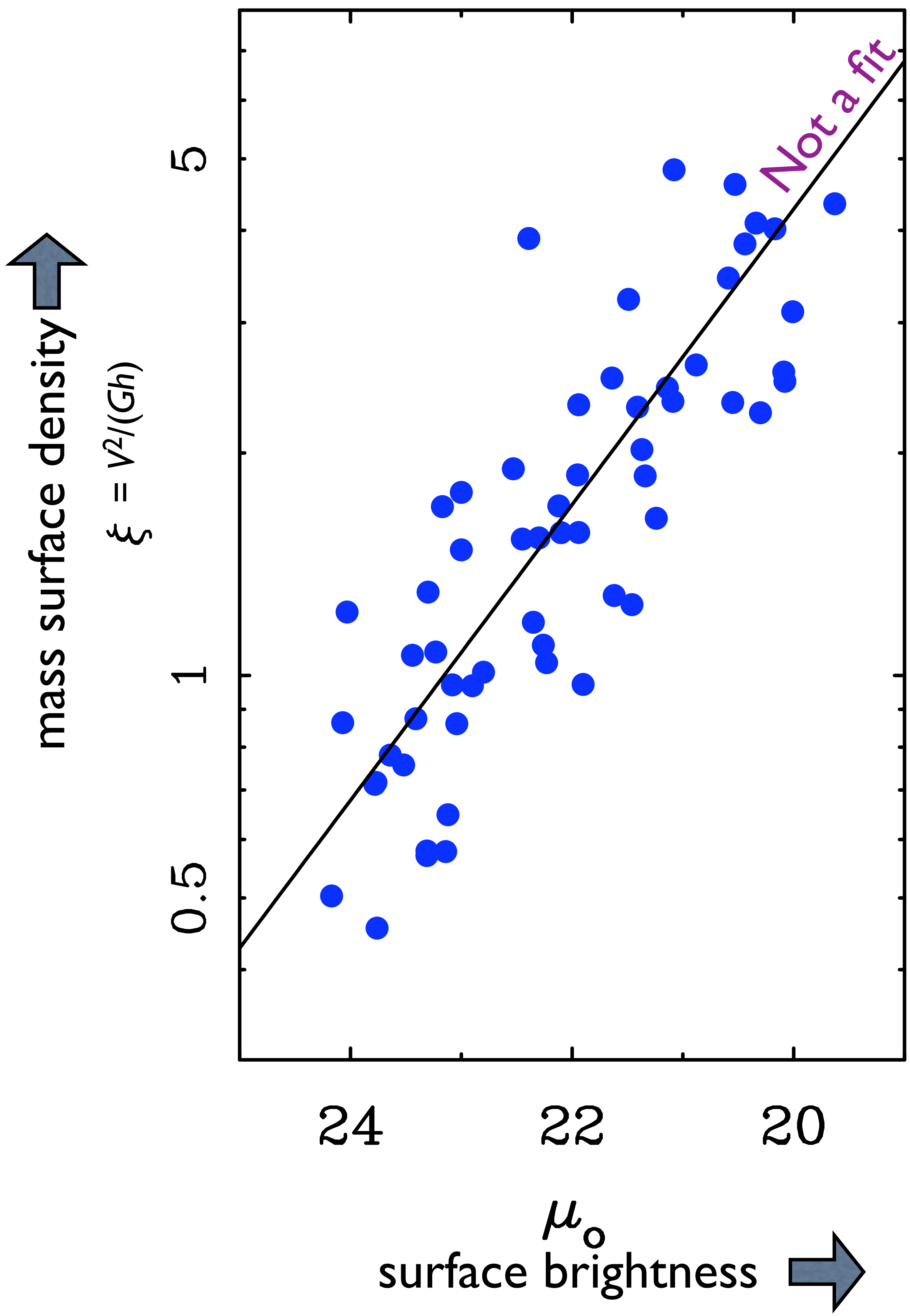
MOND predictions

- 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



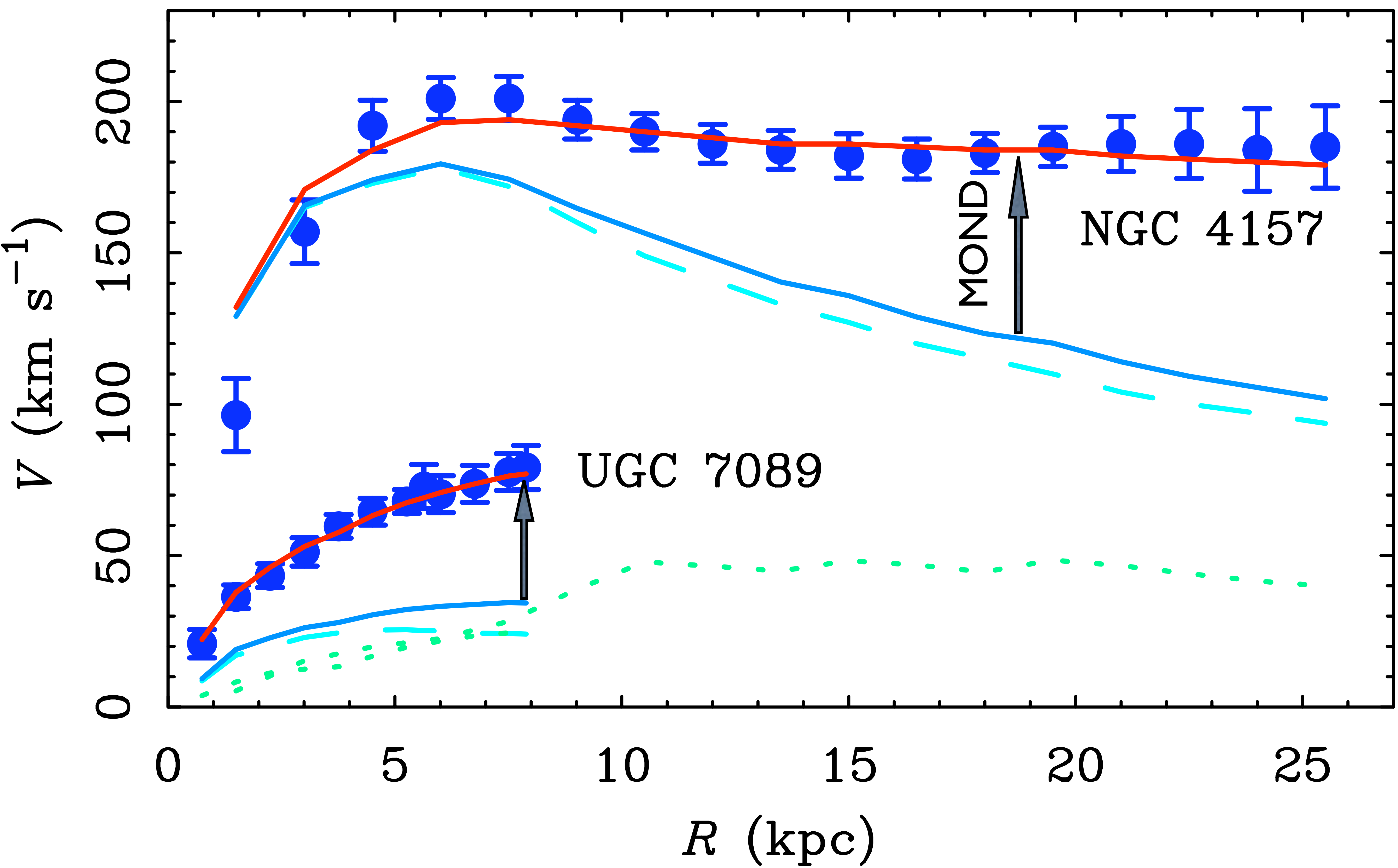
MOND predictions

- 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



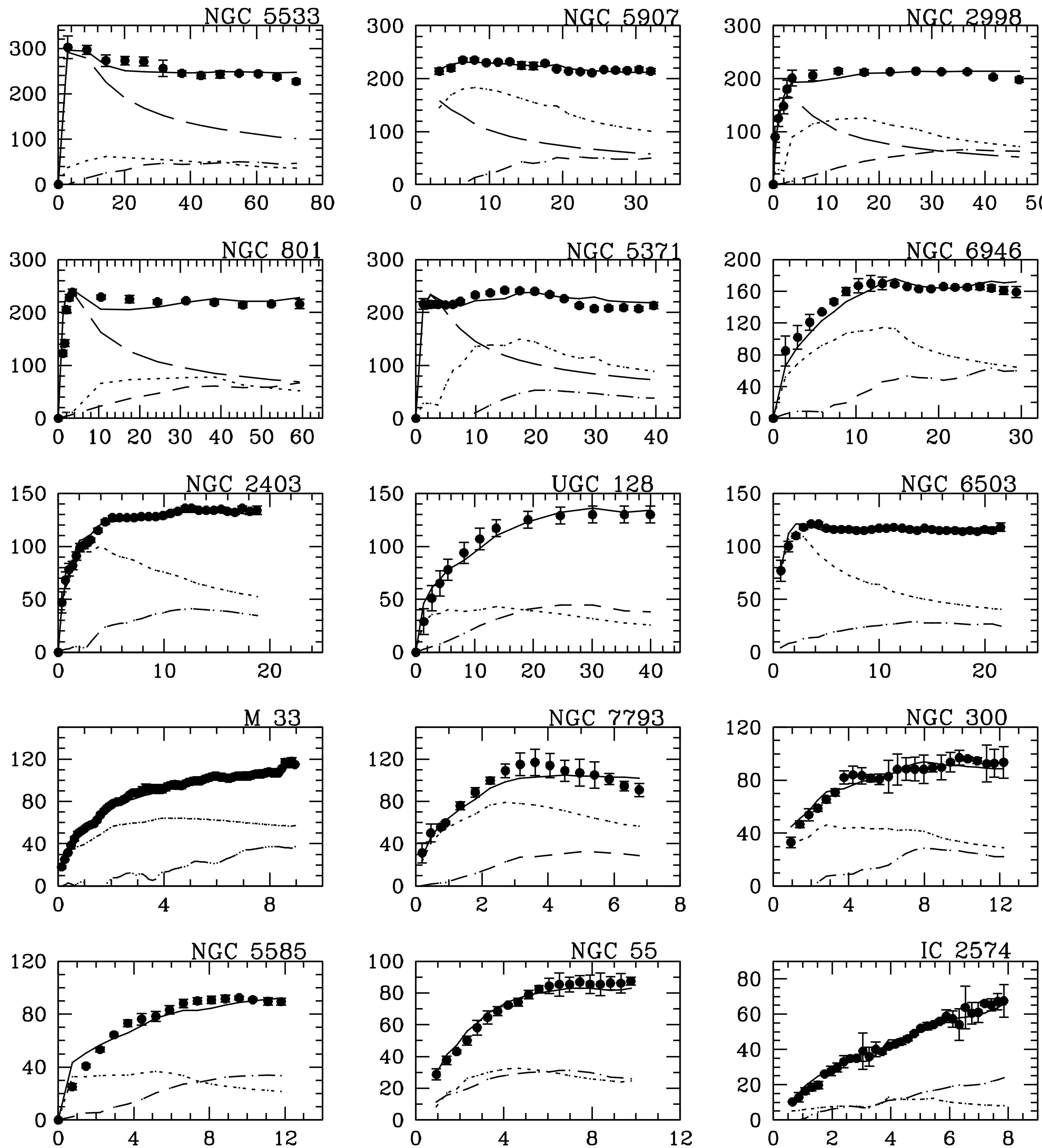
MOND predictions

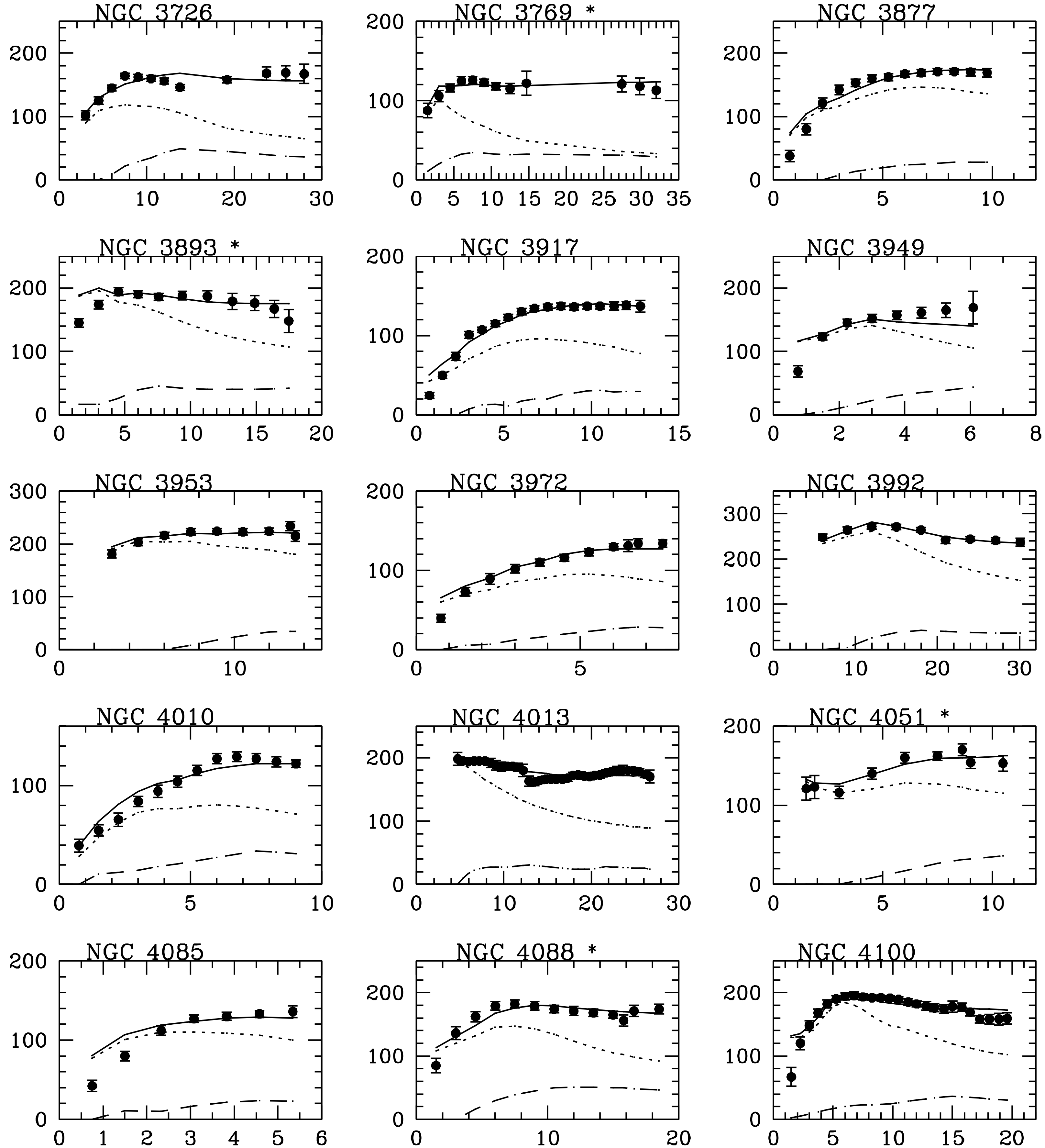
- The Tully-Fisher Relation
  - ✔ Slope = 4
  - ✔ Normalization = $1/(a_0G)$
  - ✔ Fundamentally a relation between Disk Mass and V_{flat}
  - ✔ No Dependence on Surface Brightness
- ✔ Dependence of conventional M/L on radius and surface brightness
- ✔ Rotation Curve Shapes
- ✔ Surface Density ~ Surface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



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

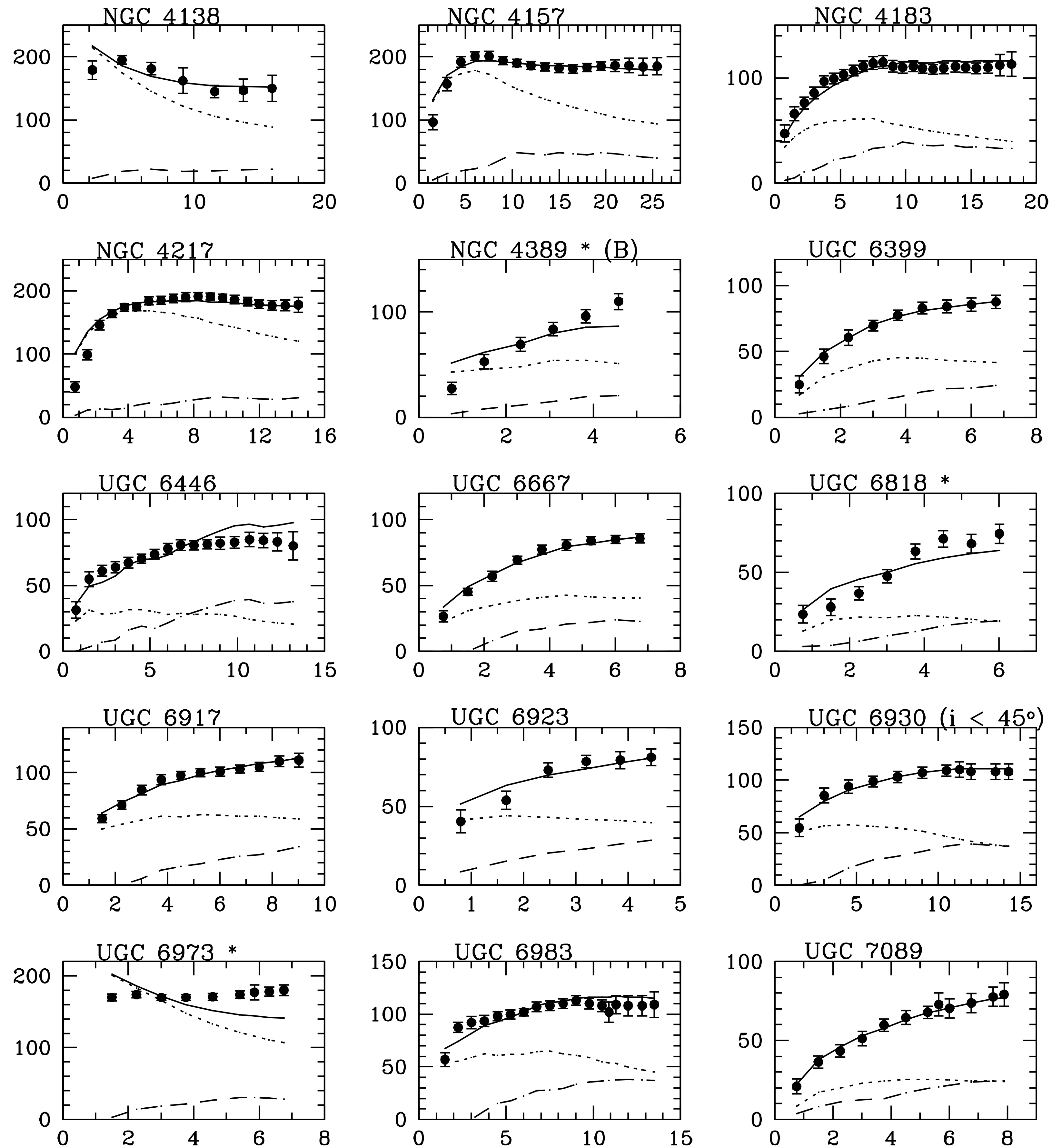
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



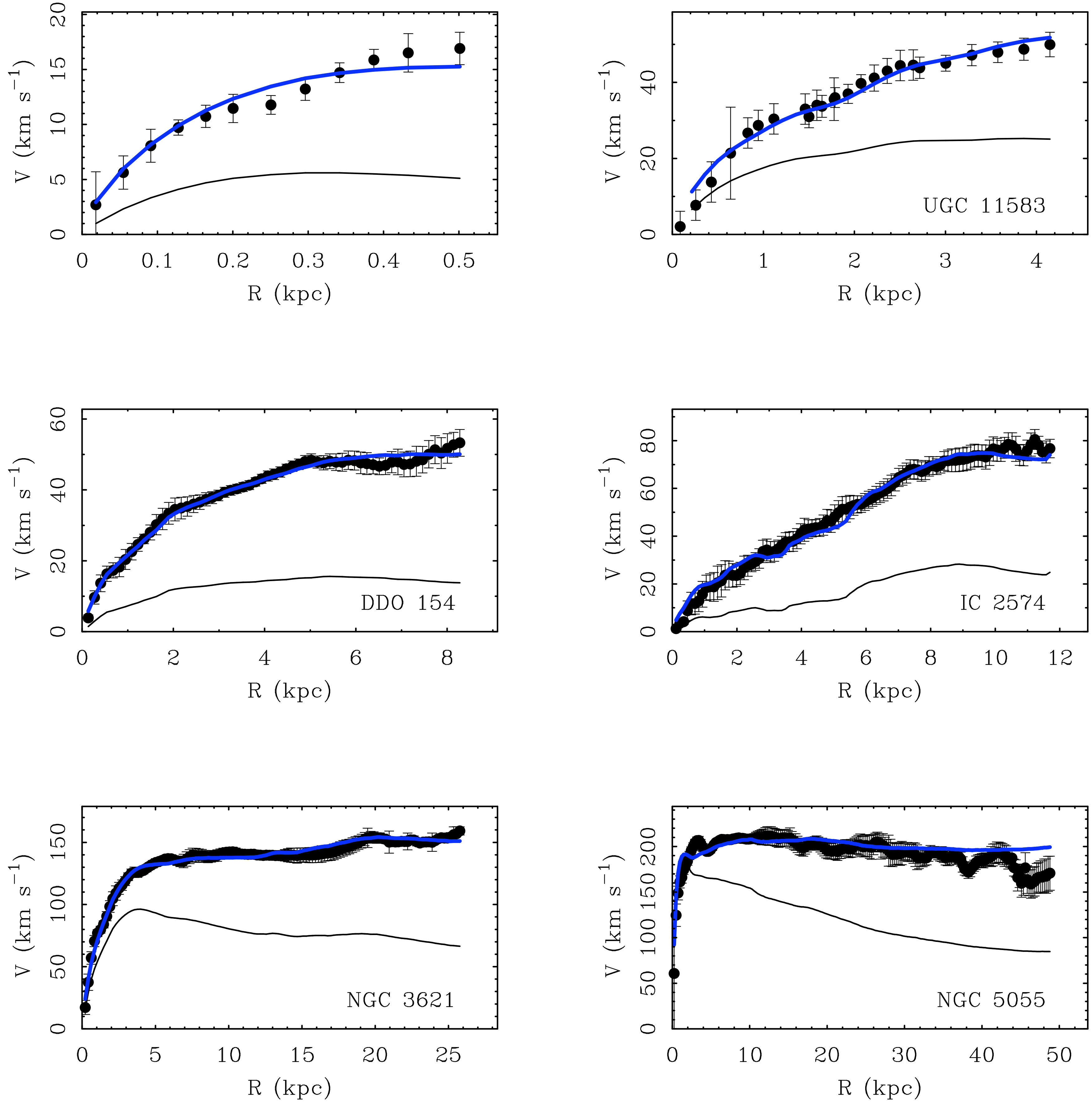


Sanders & McGaugh 2002, *ARA&A*, **40**, 263

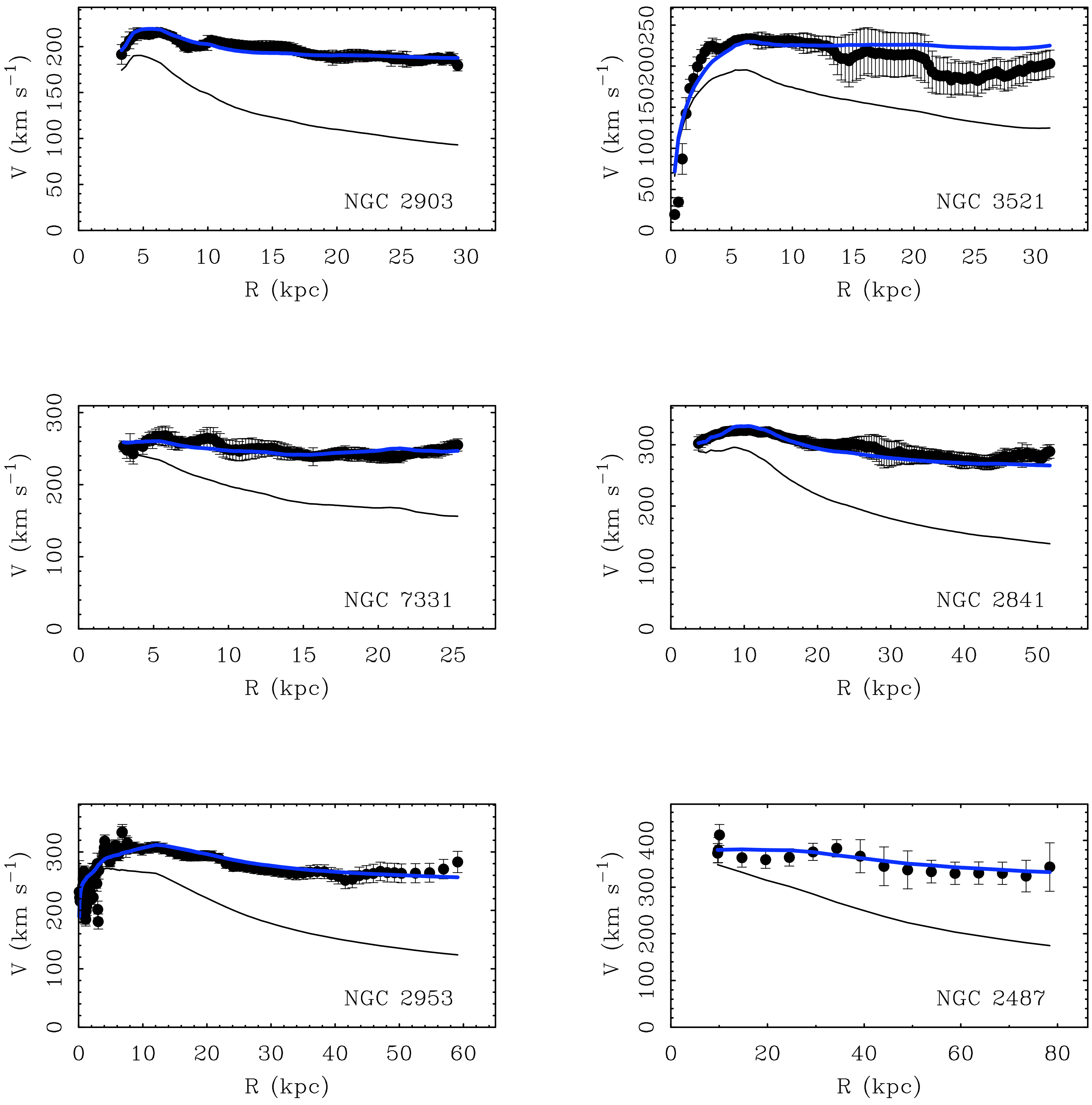
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



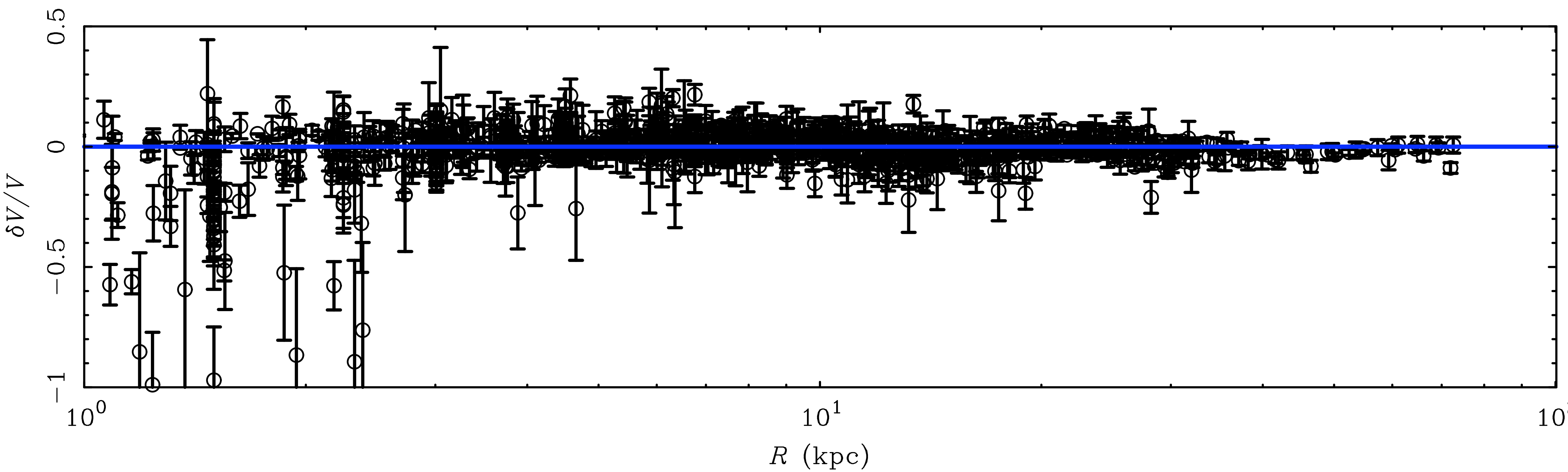
Famaey & McGaugh 2011



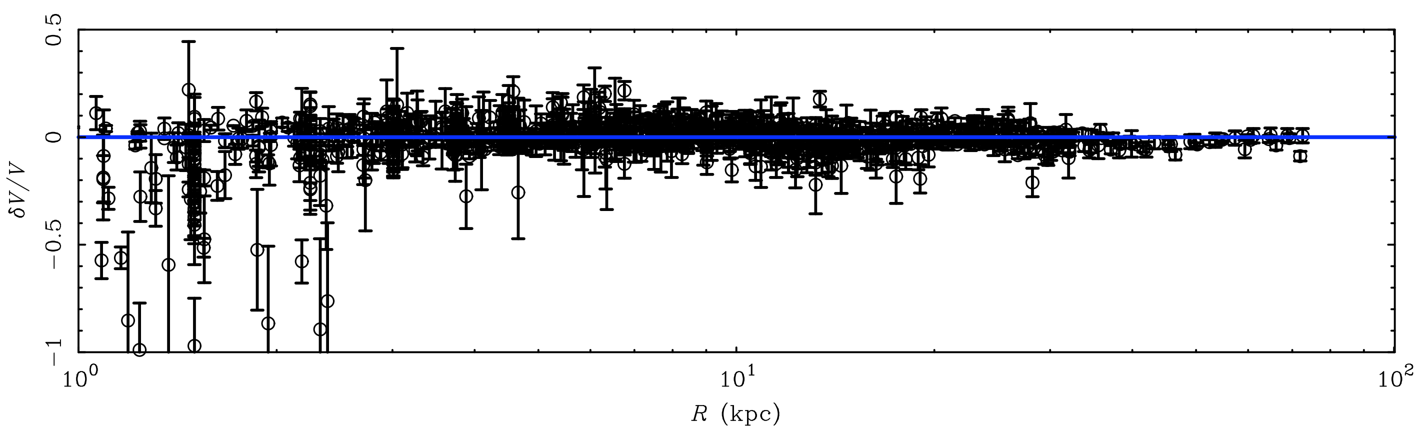
Famaey & McGaugh 2011



Residuals for 74 galaxies

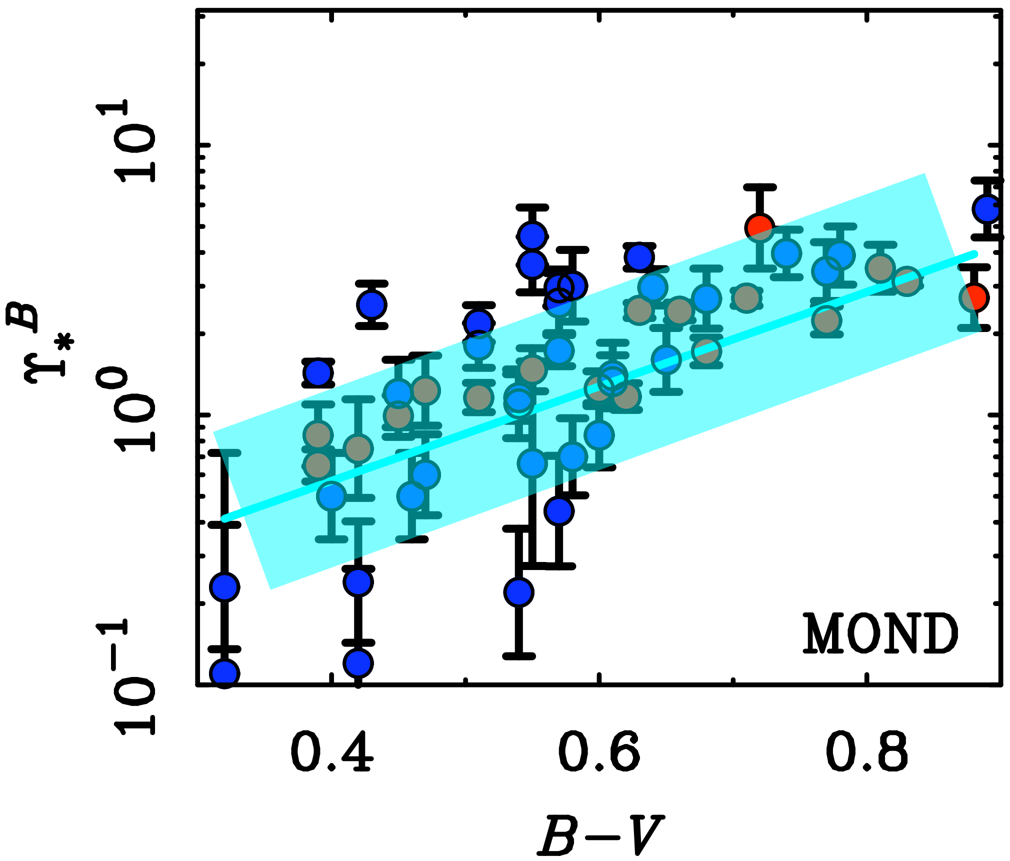


This procedure is generally successful
(including the bumps and wiggles)
given M*/L as a fit parameter

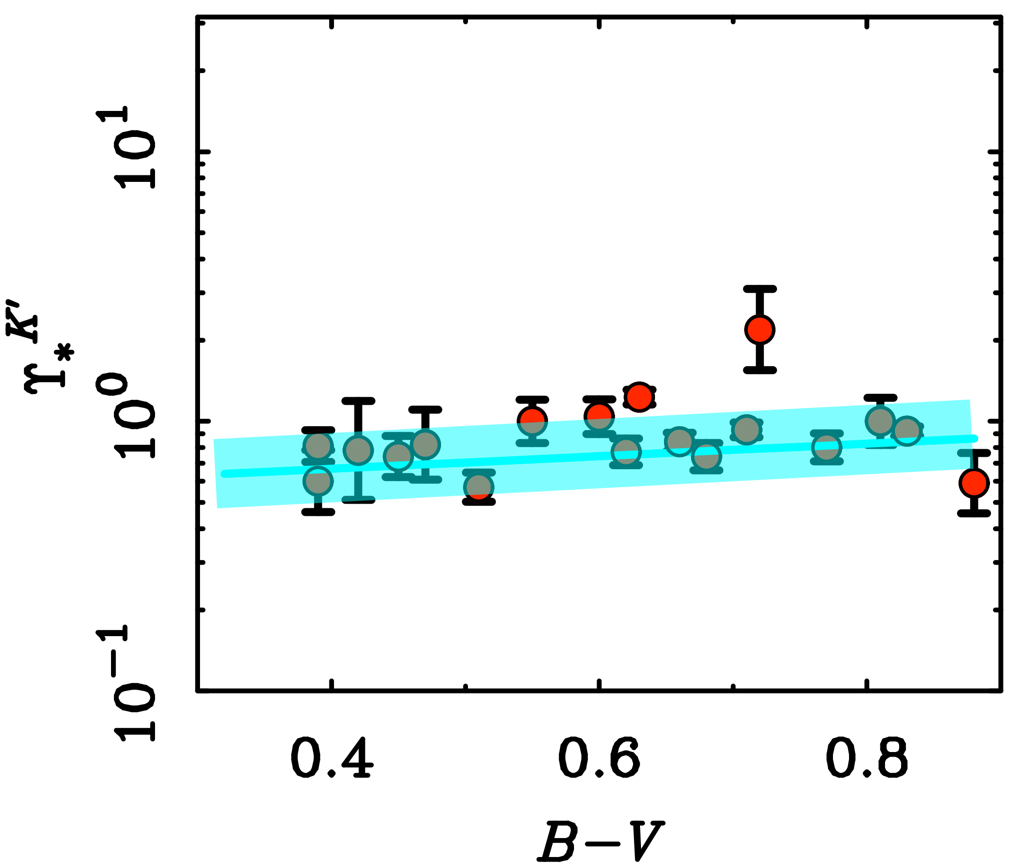


MOND predictions

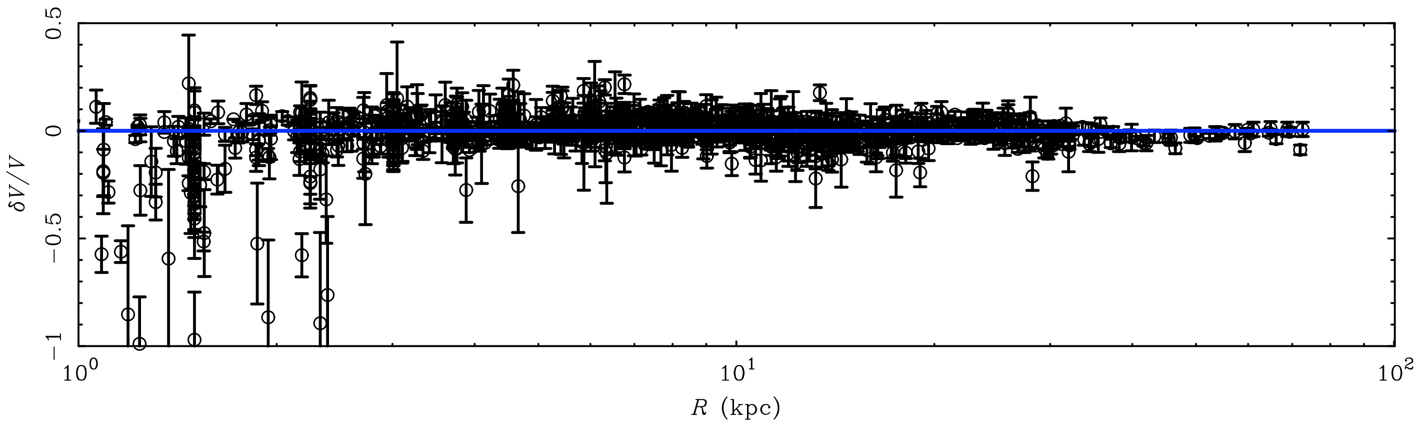
- The Tully-Fisher Relation
  - ✔ Slope = 4
  - ✔ Normalization = $1/(a_0G)$
  - ✔ Fundamentally a relation between Disk Mass and V_{flat}
  - ✔ No Dependence on Surface Brightness
- ✔ Dependence of conventional M/L on radius and surface brightness
- ✔ Rotation Curve Shapes
- ✔ Surface Density ~ Surface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



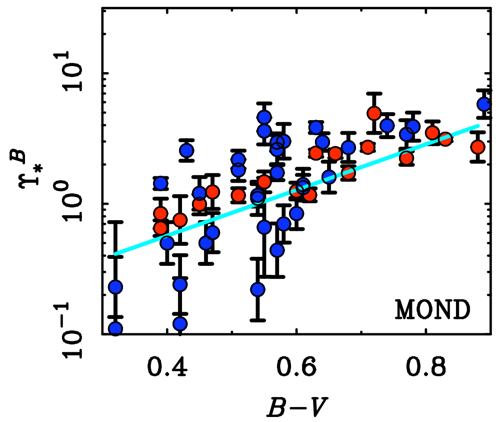
Line: stellar population model
(mean expectation)

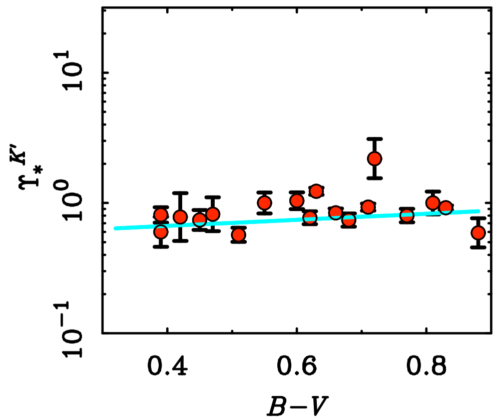


MOND predictions



- The Tully-Fisher Relation
  - ✔ 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



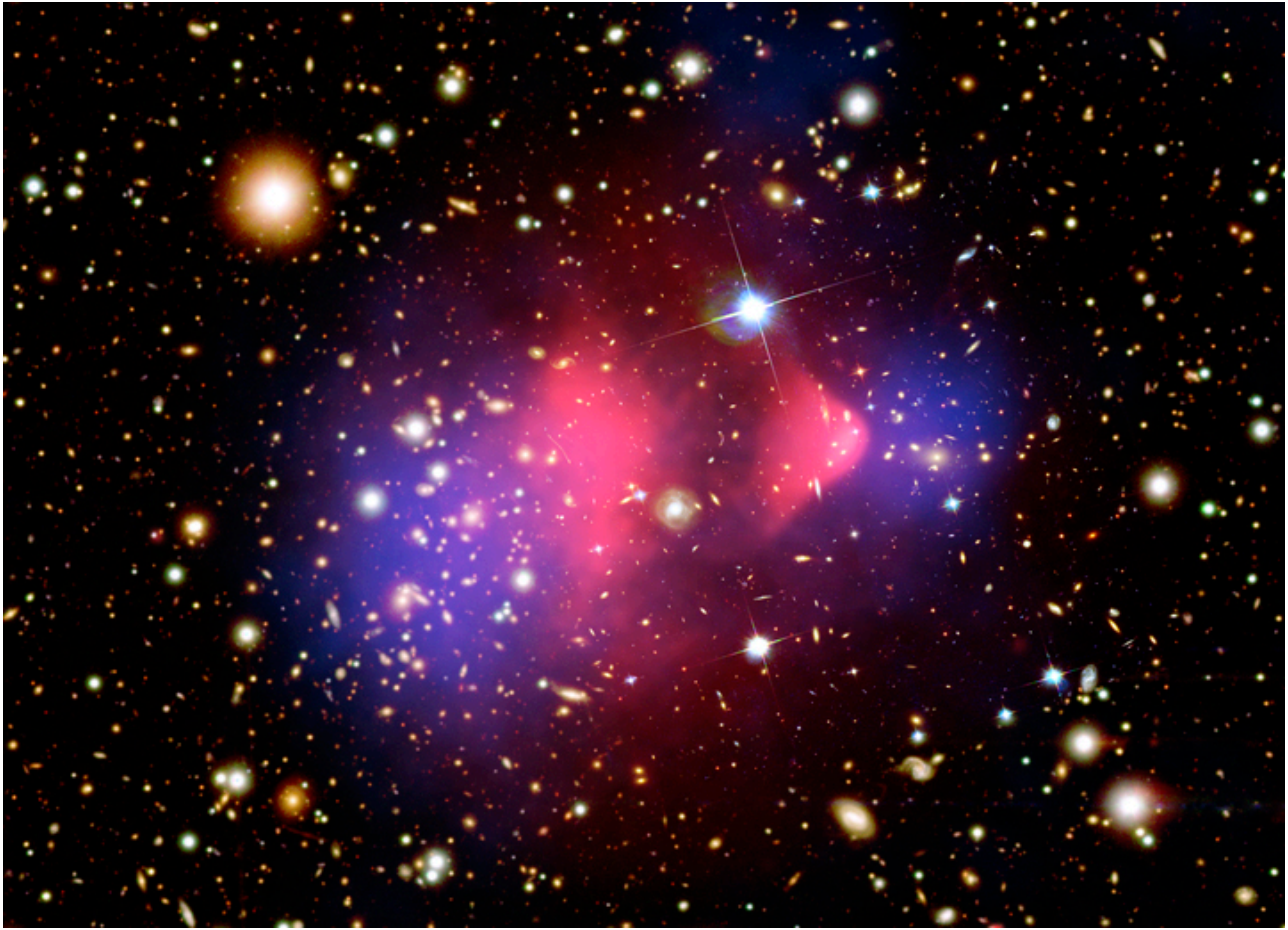


Observational Test	Successful	Promising	Unclear	Problematic
Rotating Systems				
solar system			X	
galaxy rotation curve shapes	X			
surface brightness $\propto \Sigma \propto a^2$	X			
galaxy rotation curve fits	X			
fitted M_*/L	X			
Tully-Fisher Relation				
baryon based	X			
slope	X			
normalization	X			
no size nor Σ dependence	X			
no intrinsic scatter	X			
Galaxy Disk Stability				
maximum surface density	X			
spiral structure in LSBGs	X			
thin & bulgeless disks		X		
Interacting Galaxies				
tidal tail morphology		X		
dynamical friction			X	
tidal dwarfs	X			
Spheroidal Systems				
star clusters			X	
ultrafaint dwarfs			X	
dwarf Spheroidals	X			
ellipticals	X			
Faber-Jackson relation	X			
Clusters of Galaxies				
dynamical mass				X
velocity (bulk & collisional)		X		
Gravitational Lensing				
strong lensing	X			
weak lensing				X
Cosmology				
expansion history			X	
geometry			X	
big bang nucleosynthesis	X			
Structure Formation				
galaxy power spectrum			X	
empty voids		X		
early structure		X		
Background Radiation				
first:second acoustic peak	X			
second:third acoustic peak				X
detailed fit				X
early re-ionization	X			

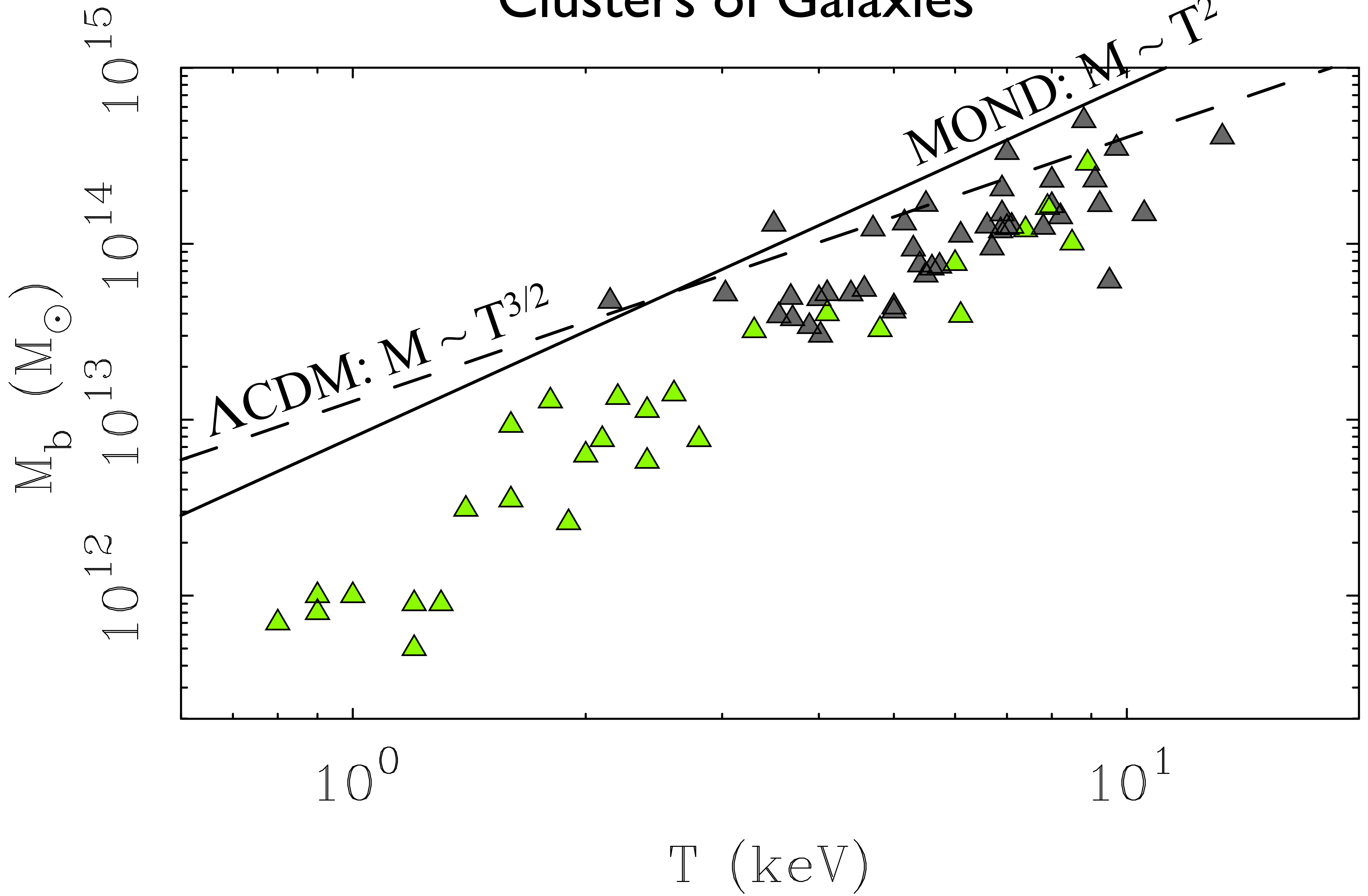
Table 1: *Observational tests of MOND.*

Famaey & McGaugh 2012

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

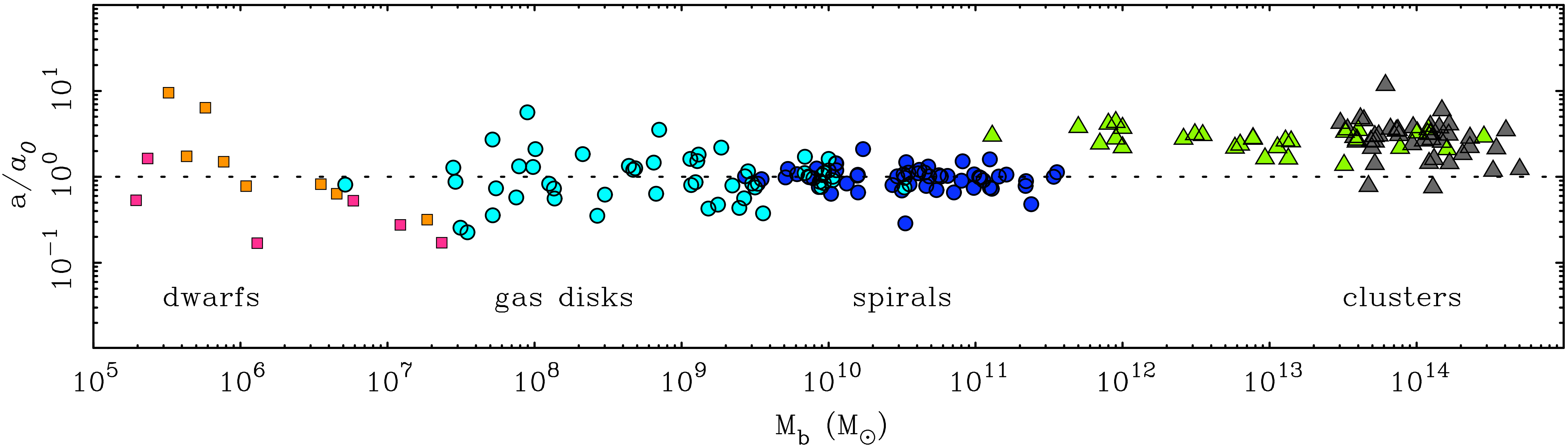


Clusters of Galaxies



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

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



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

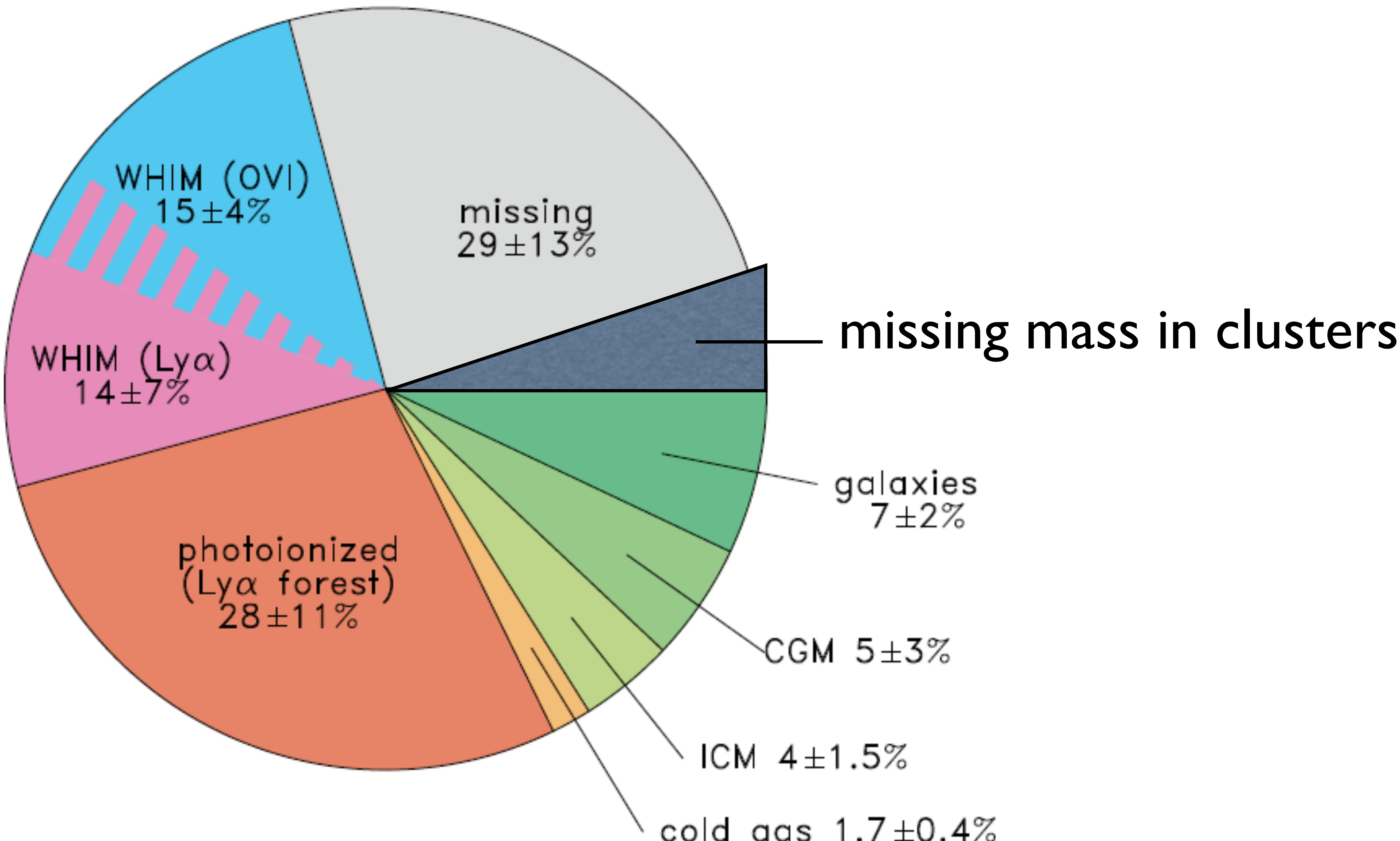
$$\Sigma_\dagger = 860\ \mathrm{M_\odot\,pc^{-2}}$$

The missing baryon problem

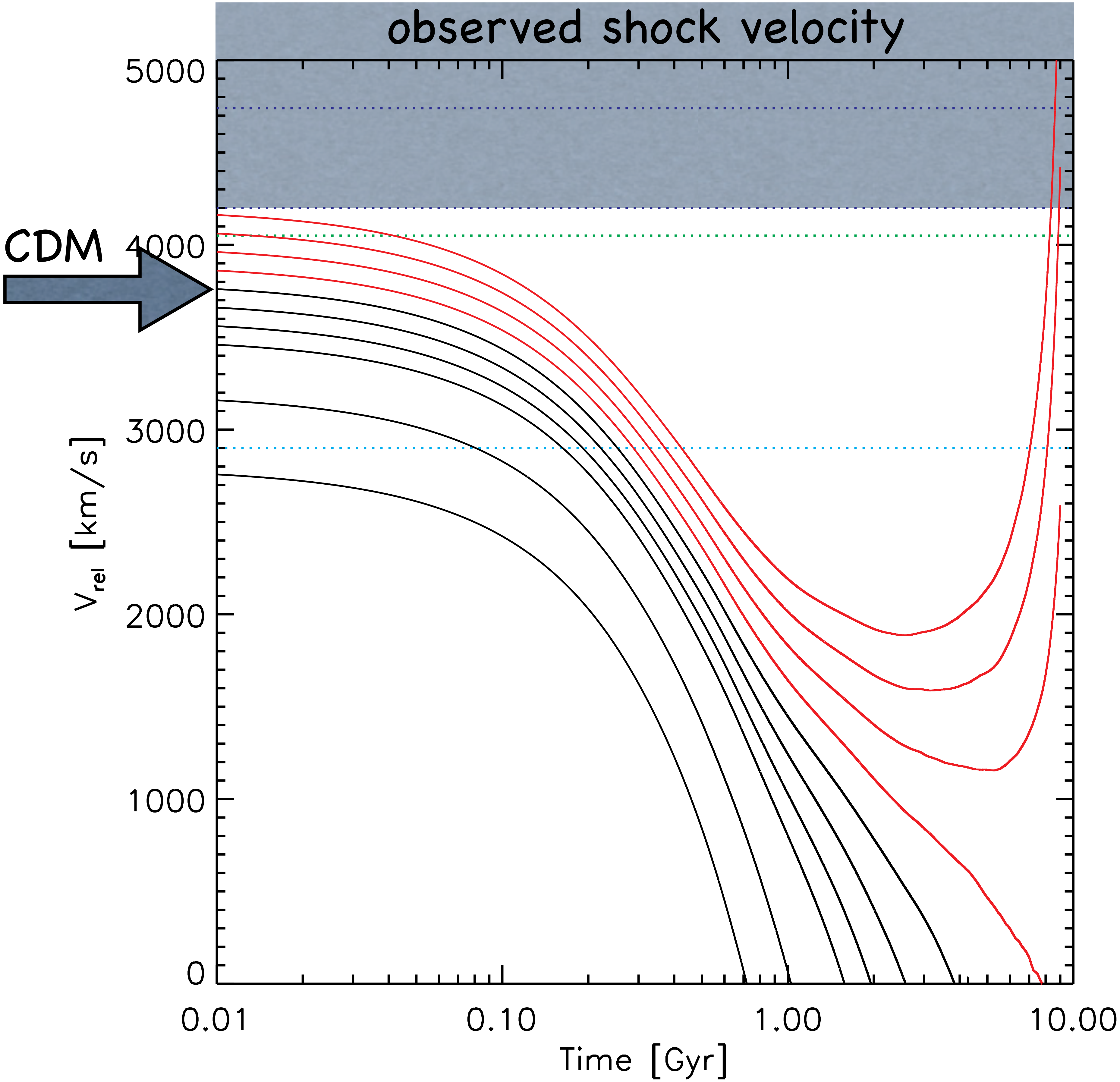
Cosmic baryon budget

(Shull et al arXiv:1112.2706)

@ $z = 0$



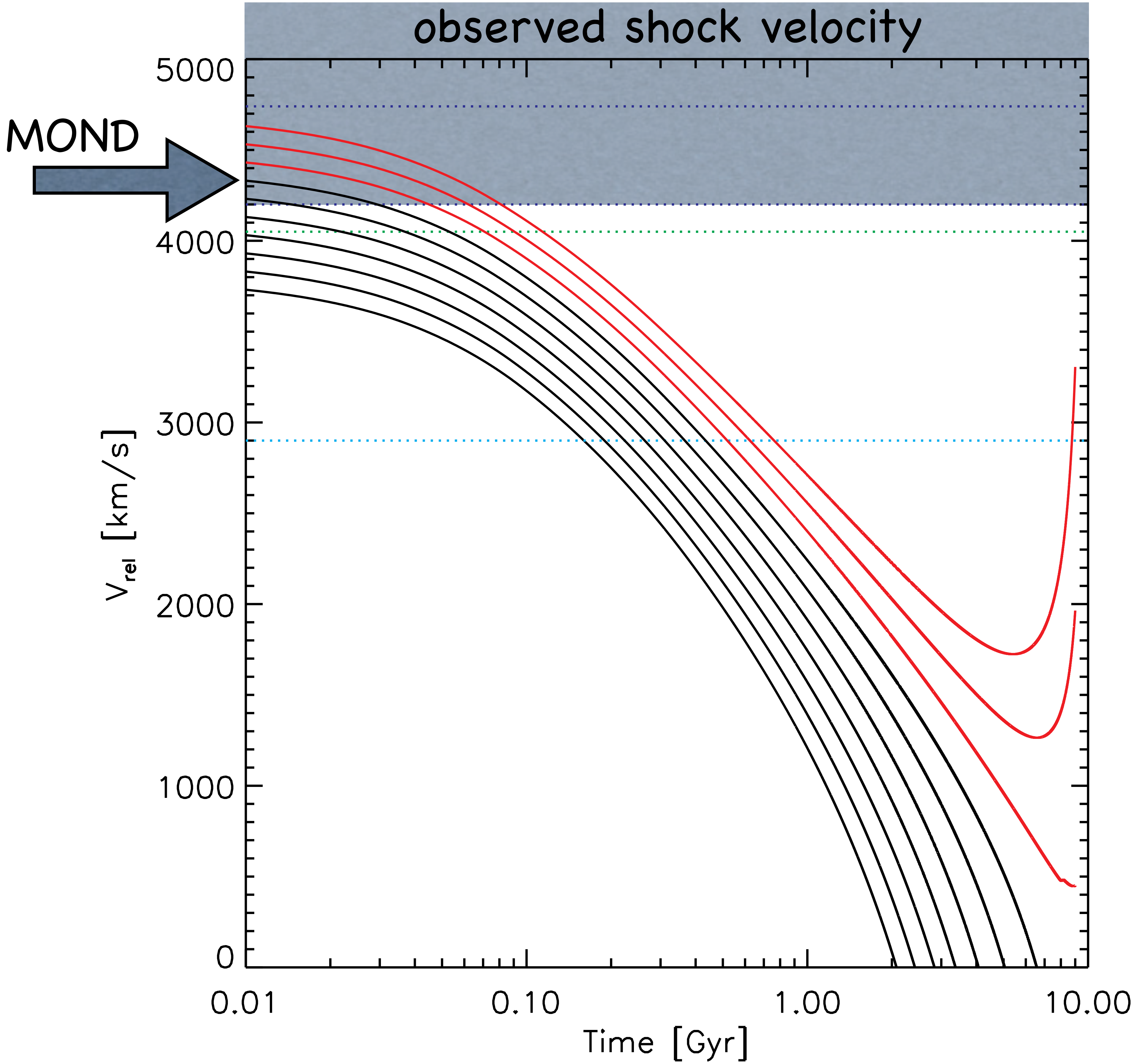
bullet cluster collision velocity



mass discrepancy more naturally explained by CDM

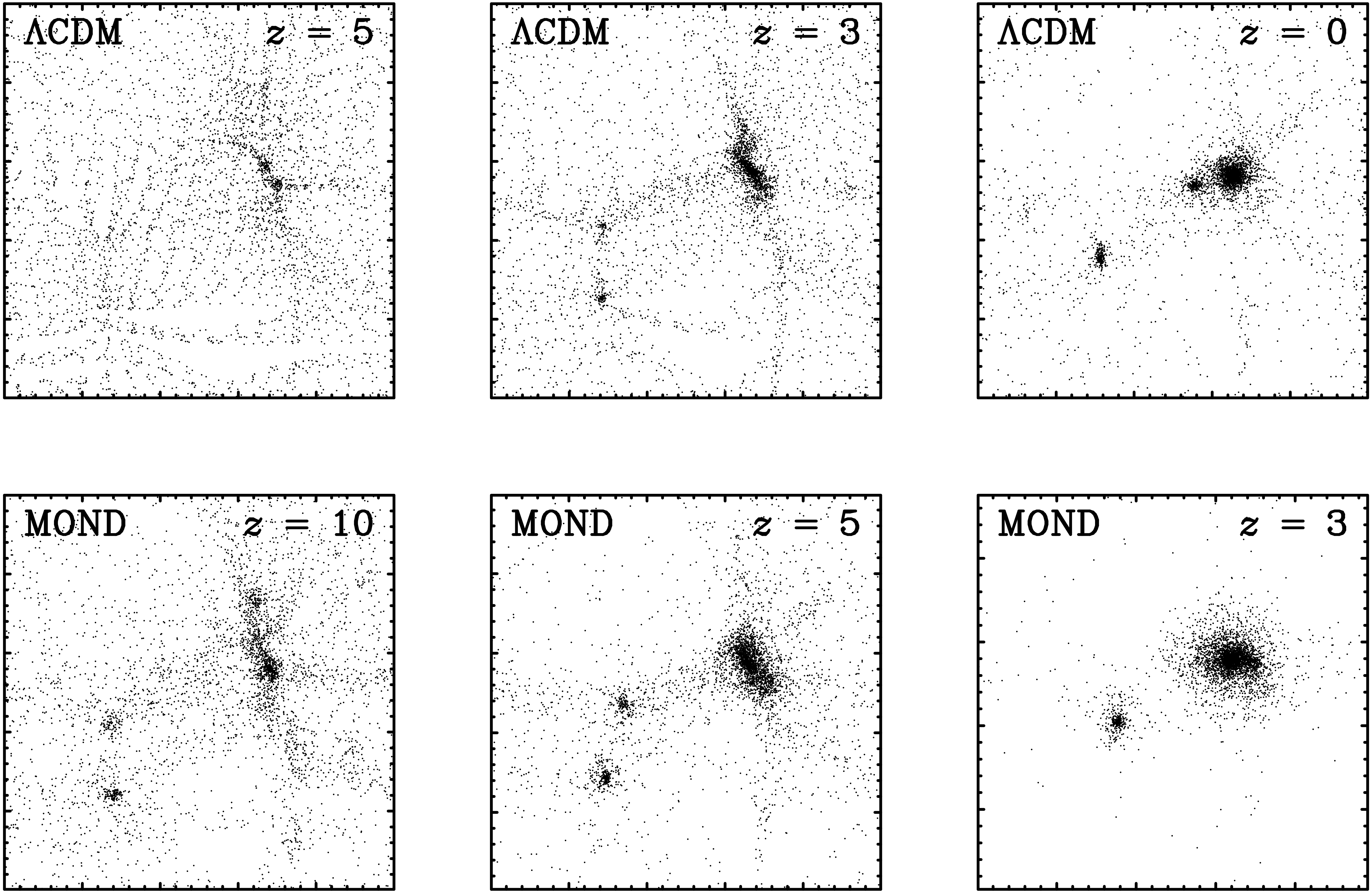
Angus & McGaugh (2008) MNRAS, 383, 417

bullet cluster collision velocity



collision velocity more naturally explained by MOND

Angus & McGaugh (2008) MNRAS, 383, 417



Expect big clusters at high redshift

Other MOND tests

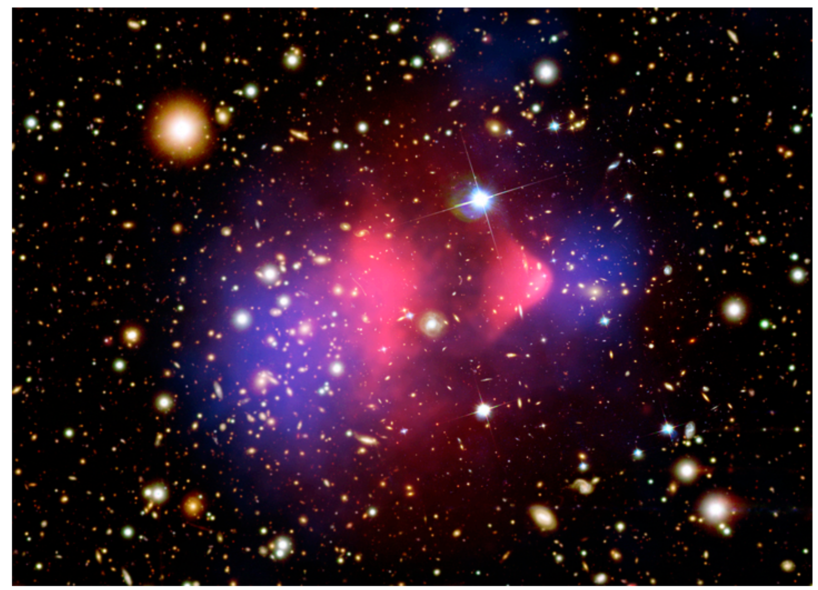
- Disk Stability
  - ✔ Freeman limit in surface brightness distribution
  - ✔ thin disks
  - ✔ velocity dispersions
  - ✔ LSB disks not over-stabilized

✔ • Dwarf Spheroidals ?

✔ • Giant Ellipticals

✗ • Clusters of Galaxies

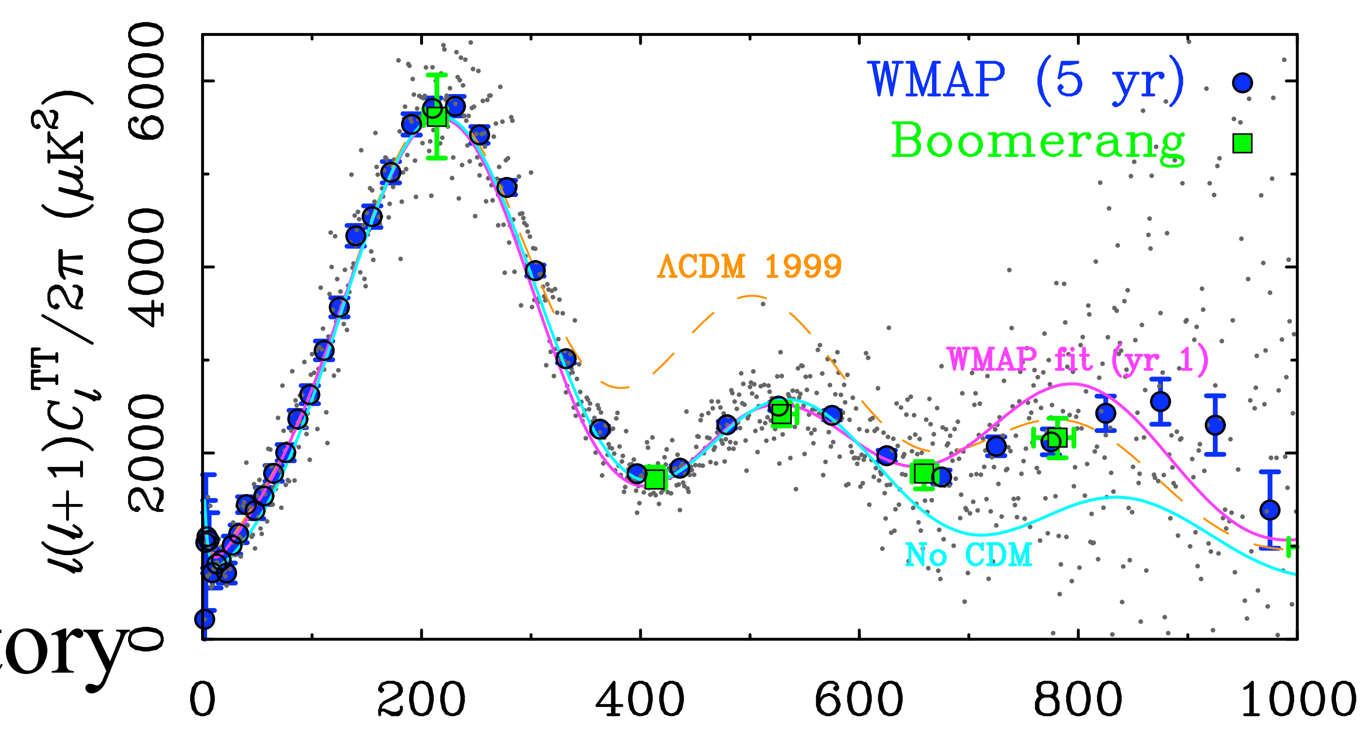
? • Structure Formation



- Microwave background
  - ✔ 1st:2nd peak amplitude; BBN
  - ✔ early reionization
  - ✔ enhanced ISW effect
  - ✗ 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.