The Mass Discrepancy Problem: New Physics in Matter or Gravity?

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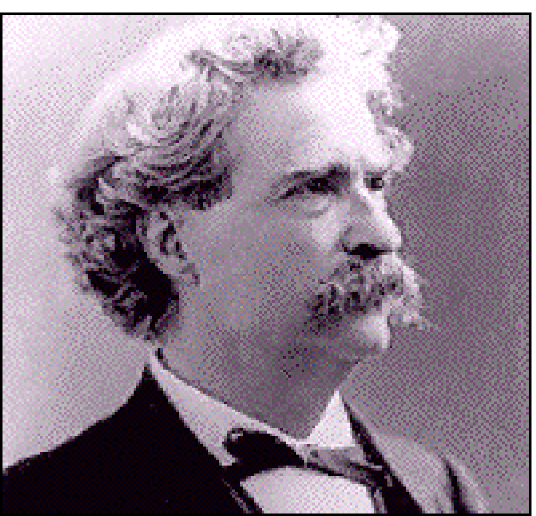
What gets us into trouble is not what we don't know.

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

- Mark Twain



A few things we know for sure...

$$\nabla^2\Phi = 4\pi G\rho$$
$$F = ma$$

which basically means

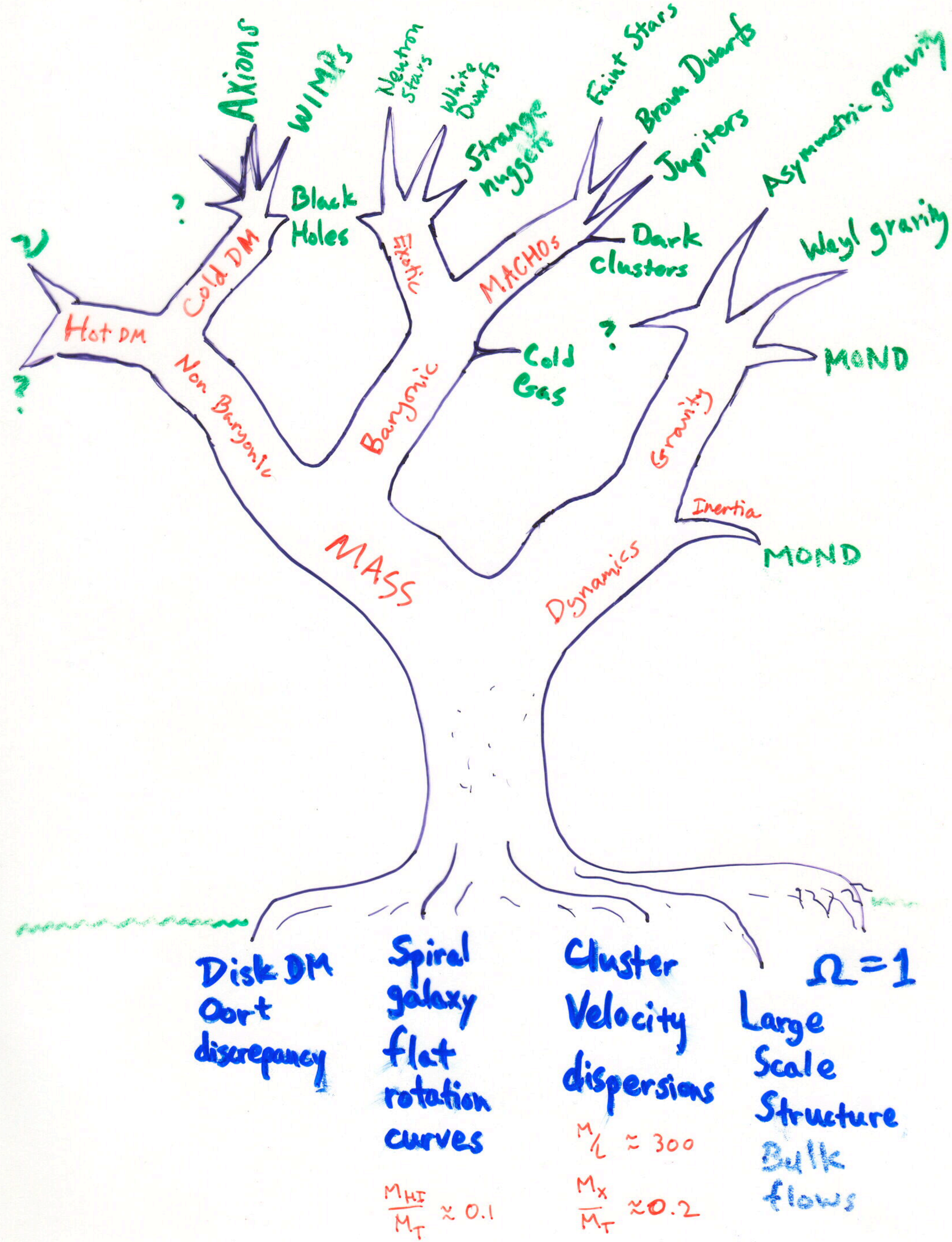
$$mV^2/R = GMm/R^2$$

i.e,

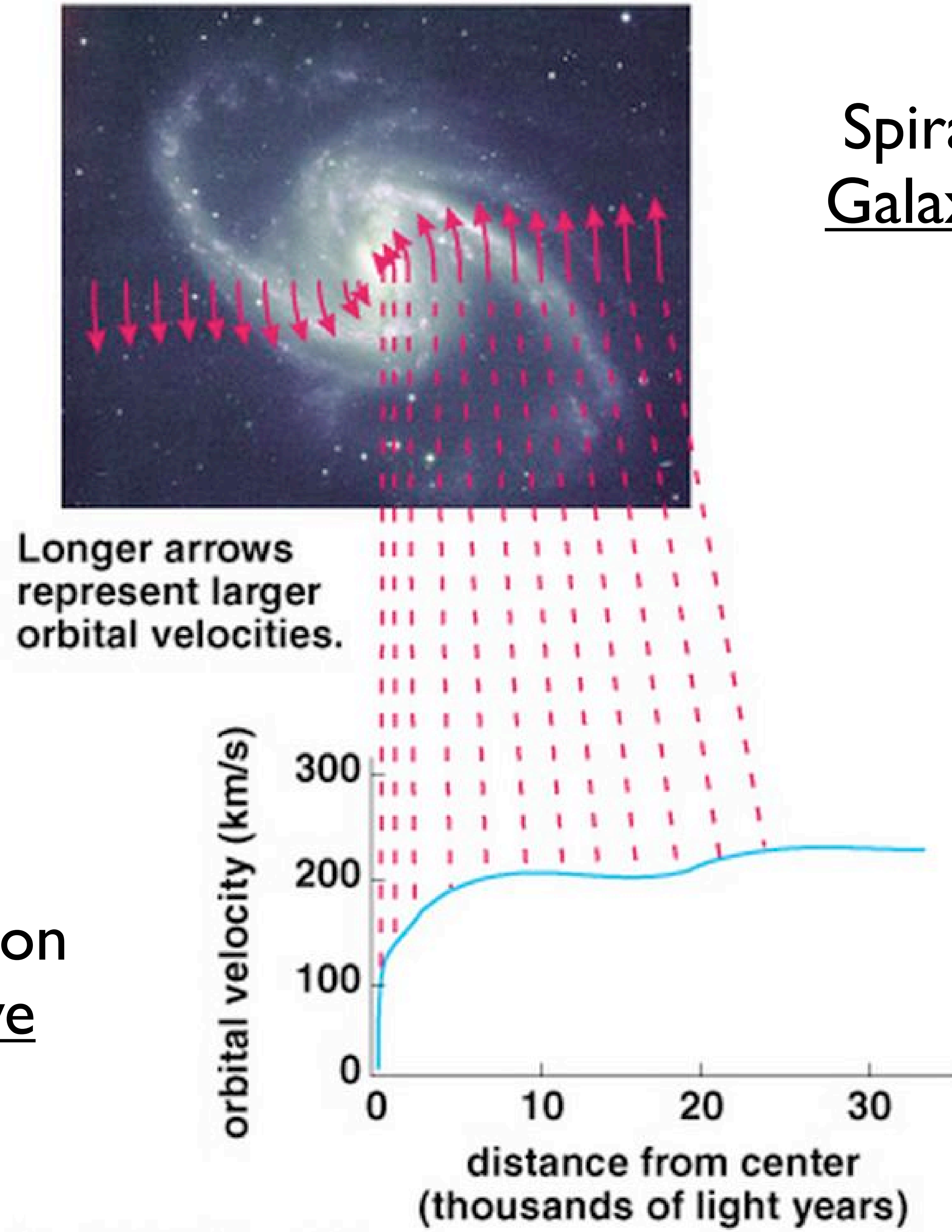
$$V^2 = GM/R$$

ergo...

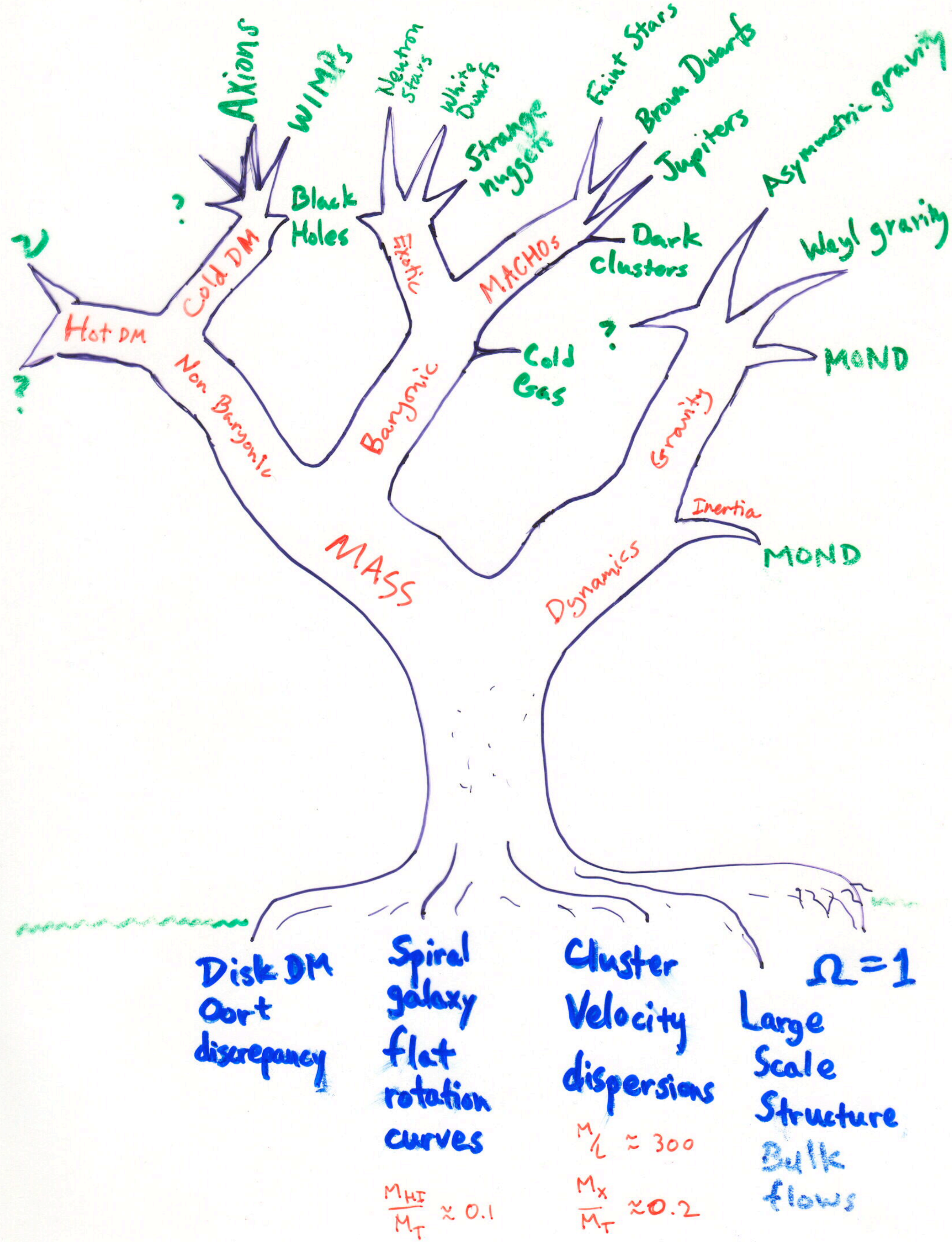
The universe is filled with nonbaryonic cold dark matter.


Axions
WIMPs
Neutron Stars
White Dwarfs
Faint Stars
Brown Dwarfs
Jupiters
Asymmetric gravity
Strange nuggets
Black Holes
Dark Clusters
Weyl gravity
?
?
?
Cold DM
Exotic
MACHOs
Hot DM
Cold Gas
?
MOND
Non Baryonic
Baryonic
Gravity
Inertia
MOND
MASS
Dynamics
Disk DM
Oort discrepancy
Spiral galaxy flat rotation curves
Cluster Velocity dispersions
Ω = 1
Large Scale Structure
Bulk flows
M/L ≈ 300
M_HI/M_T ≈ 0.1
M_X/M_T ≈ 0.2

Spiral Galaxy



Rotation Curve



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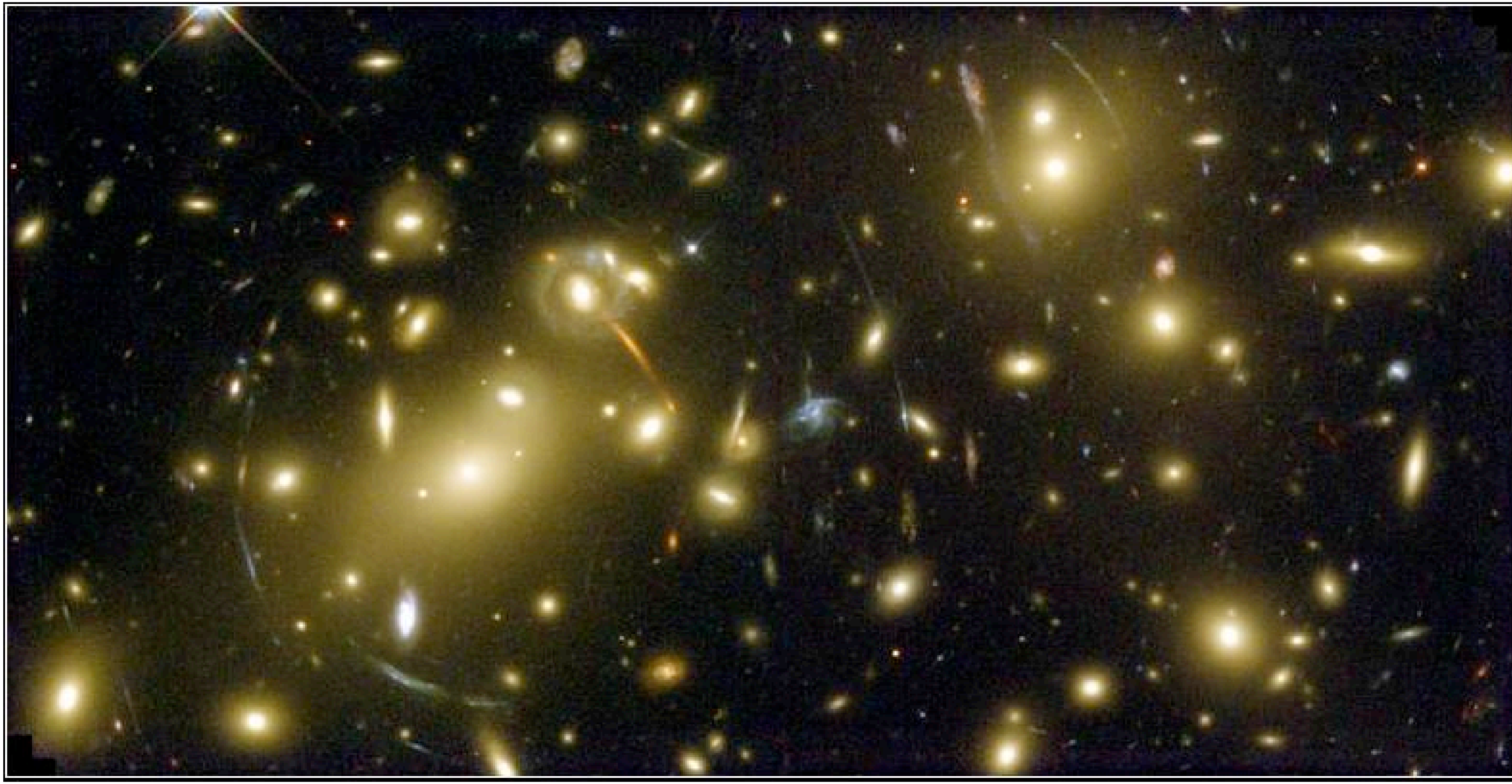
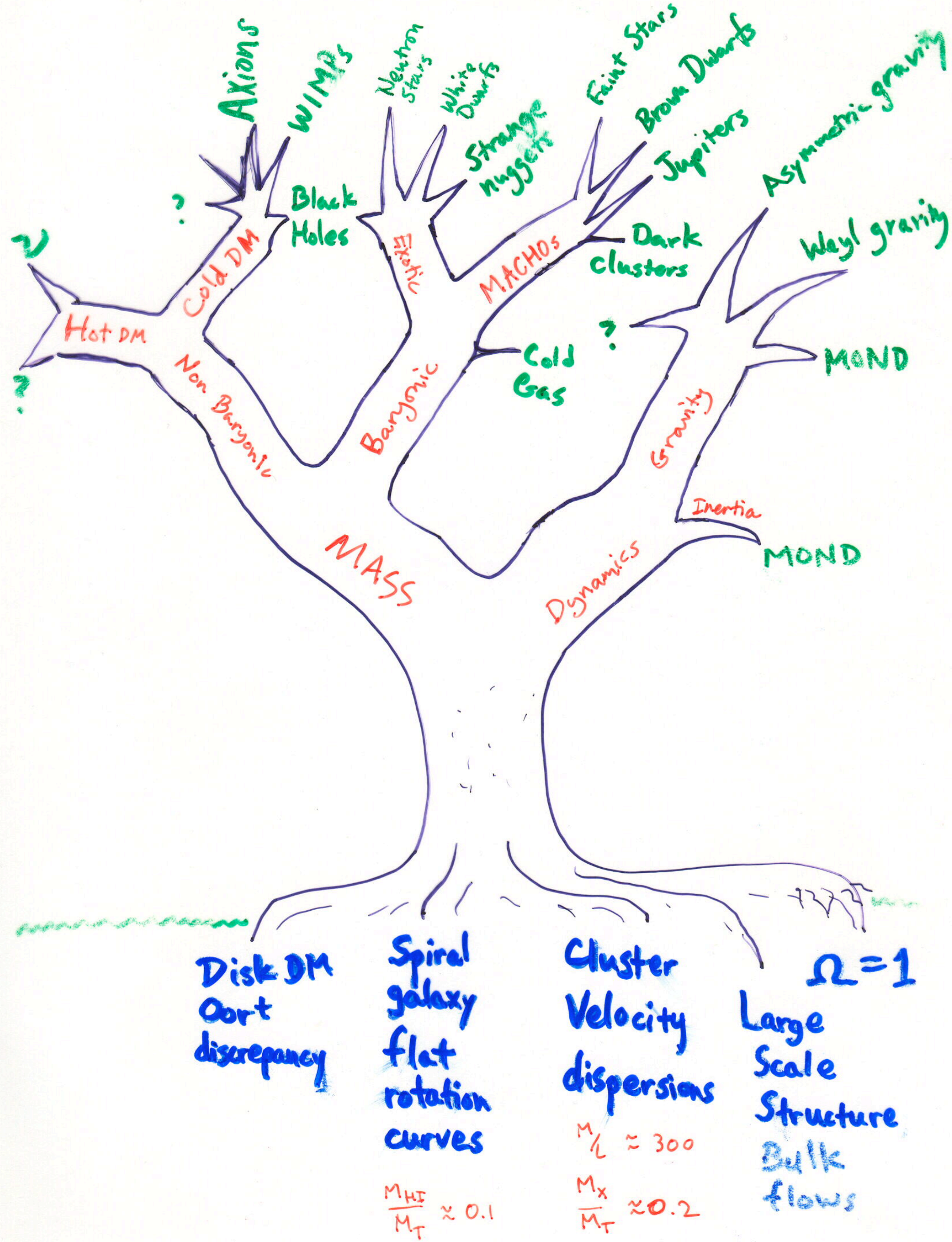
Bulk flows

Galaxy Cluster





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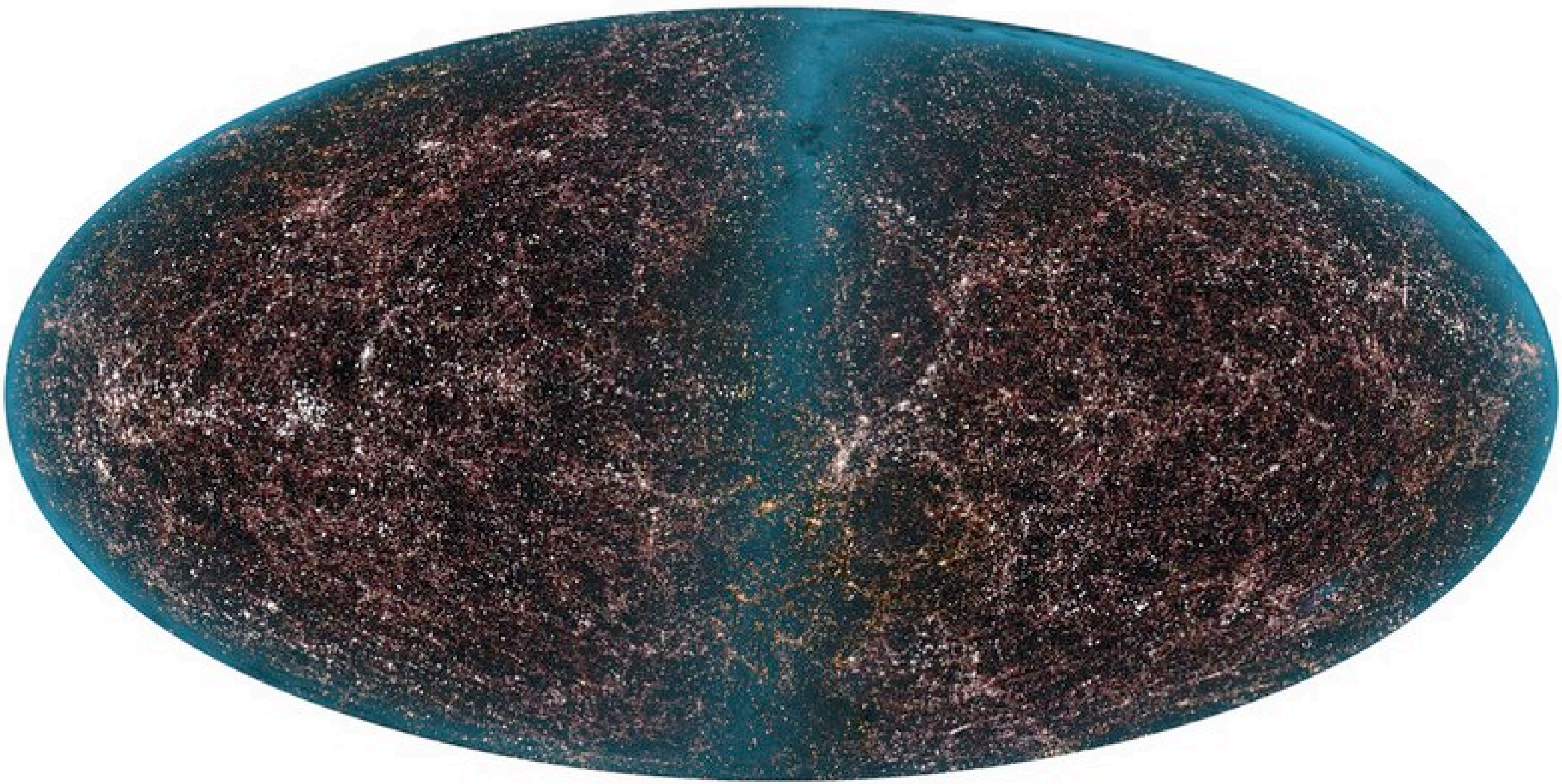

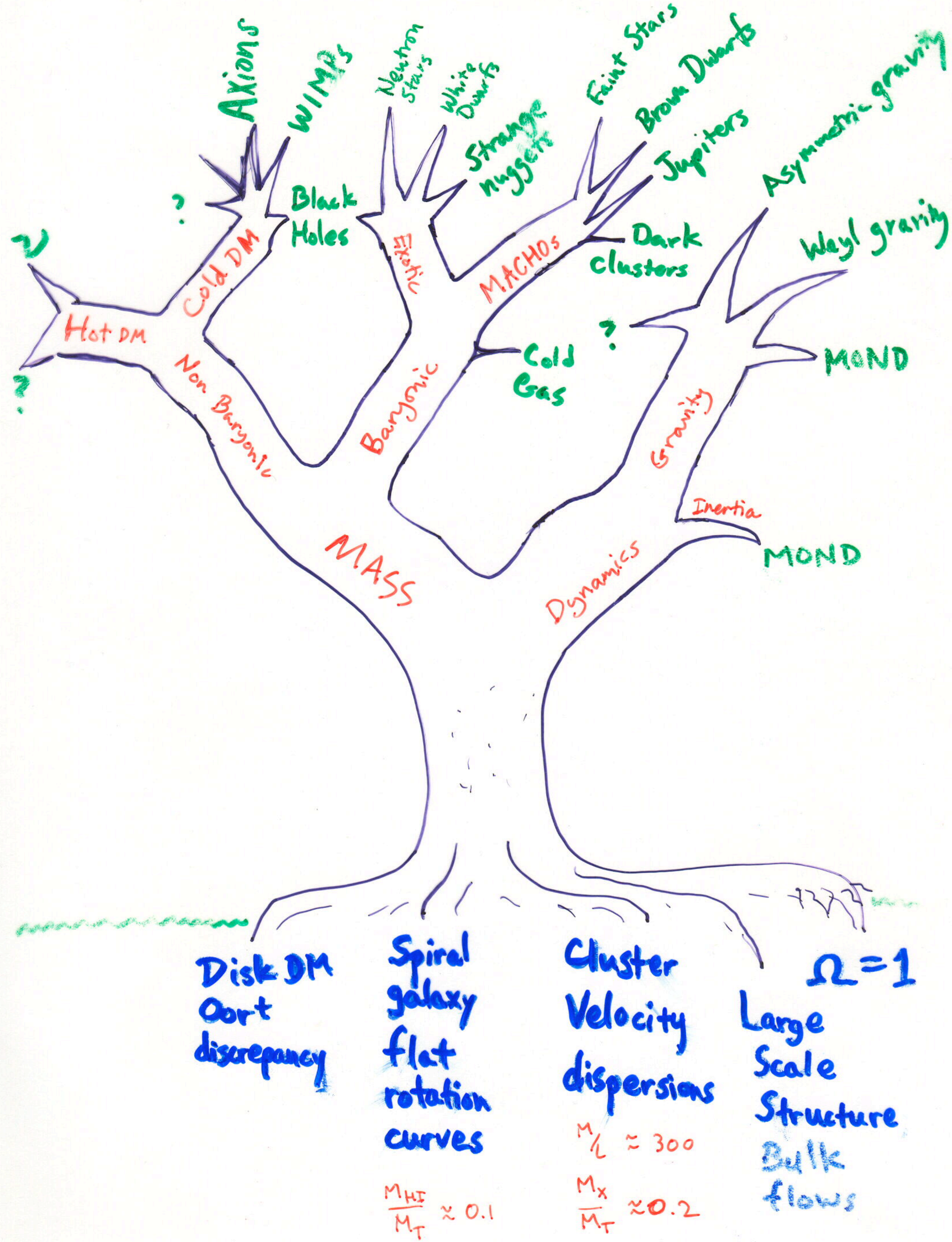

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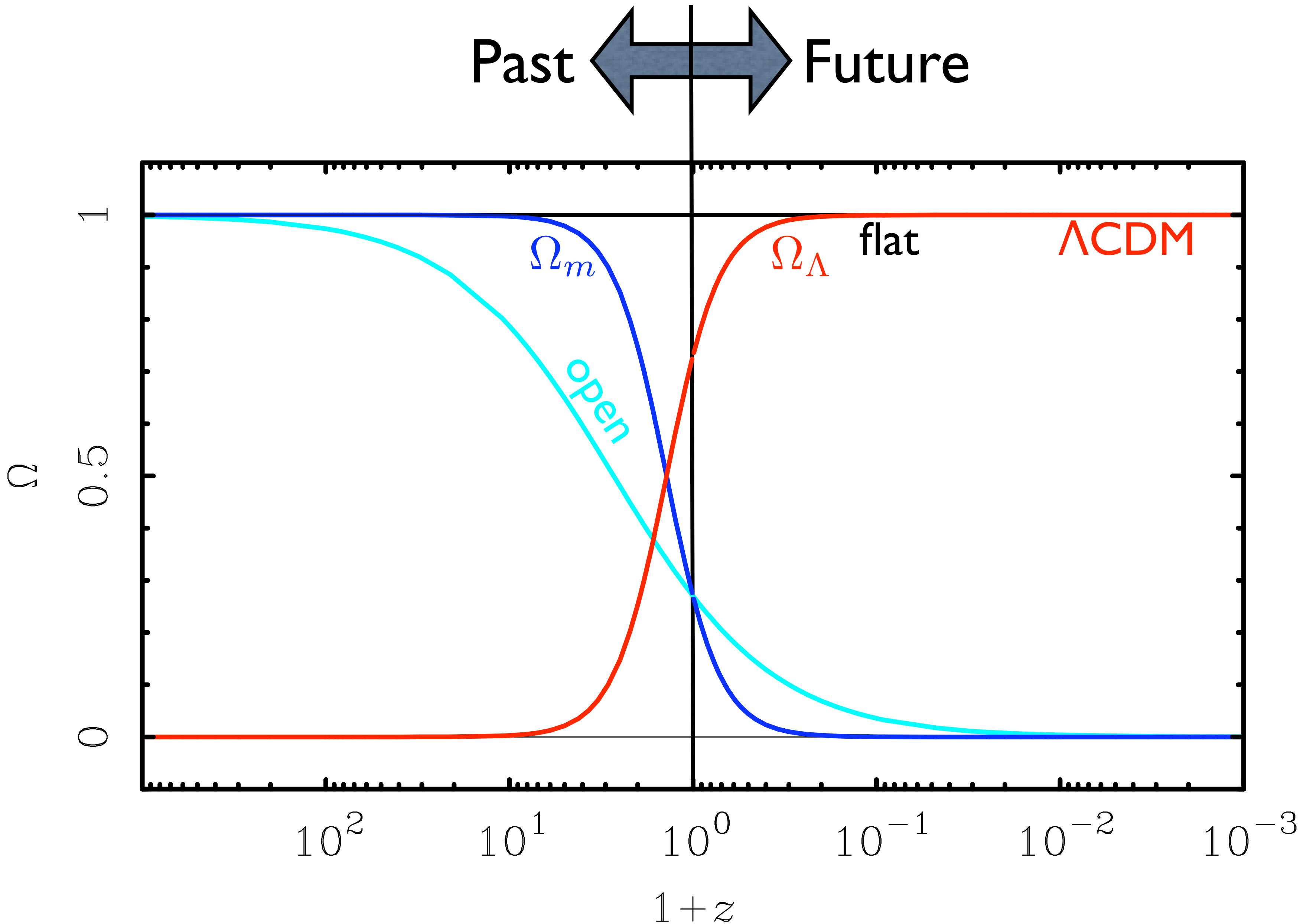
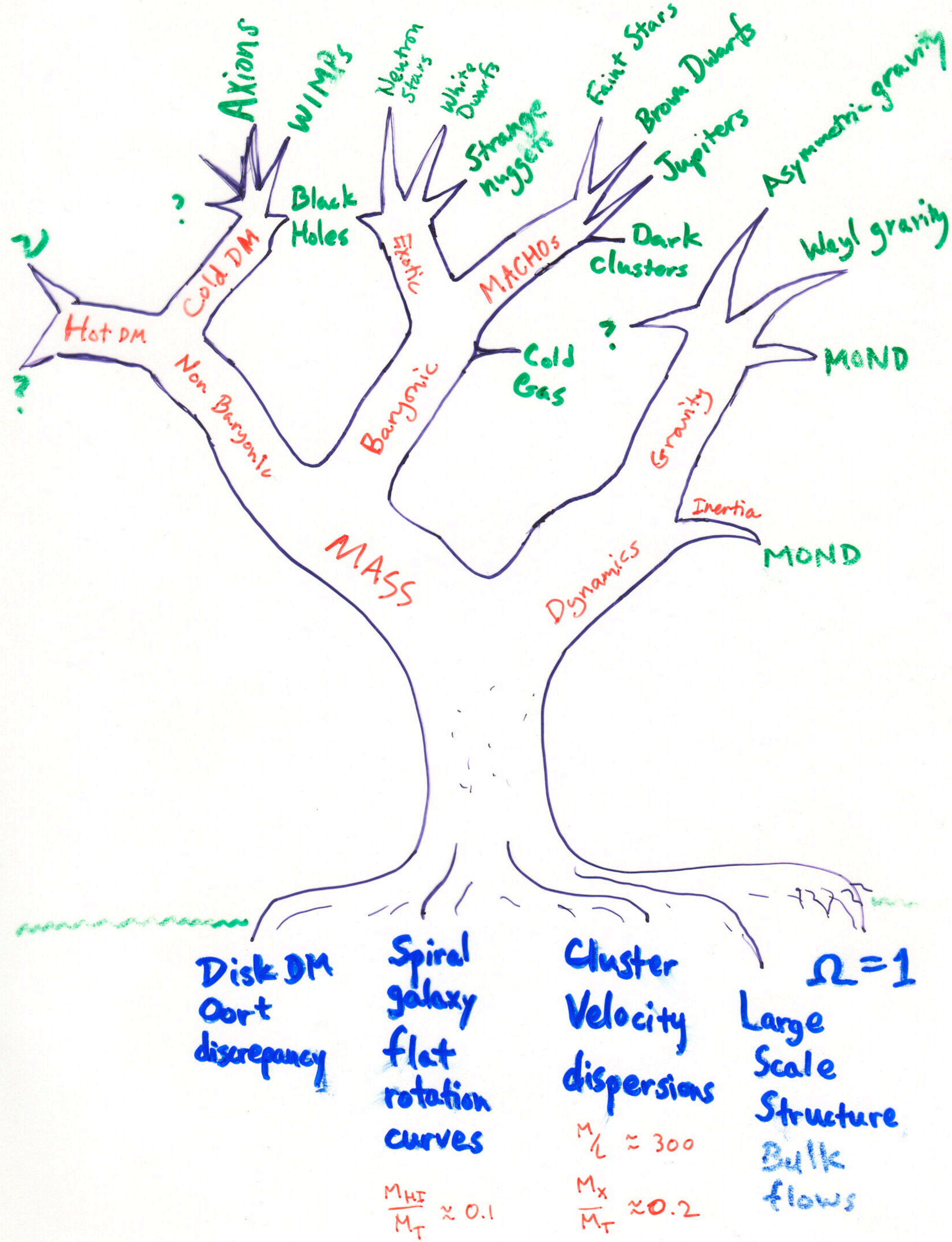


Past
Future
Ω_m
Ω_Λ
flat
ΛCDM
open
1
0.5
0
Ω
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$1+z$



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Pruning the tree

Baryonic Dark Matter

Many candidates:
brown dwarfs
Jupiters
very faint stars
very cold molecular gas
warm (~10^5 K) ionized gas

Can usually figure out a way to detect them: most have been ruled out.

Pruning the tree

Hot Dark Matter

Obvious candidate:
neutrinos

neutrinos got mass!...
...but not enough.

Also
- neutrinos suppress structure formation
- can't crowd together closely enough

Pruning the tree

Cold Dark Matter

Some new particle, usually assumed to be **WIMPs** (Weakly Interacting Massive Particle)

don't interact electromagnetically, so very dark.

Two big motivations:

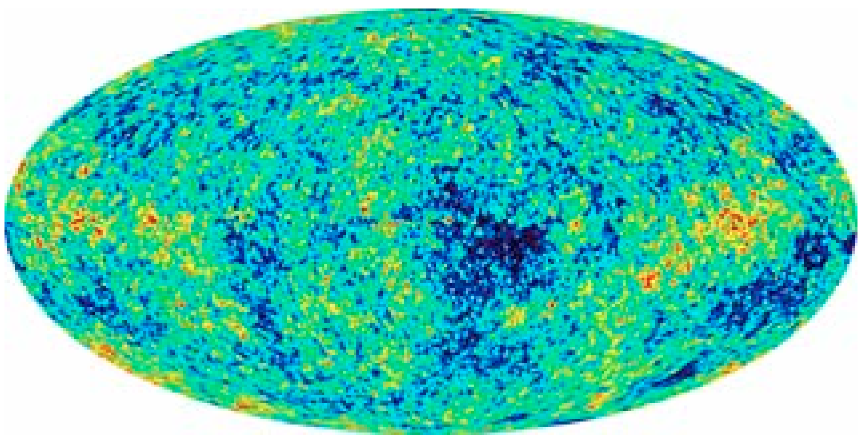
1) total mass outweighs normal mass from BBN

$$\Omega_m \approx 6\Omega_b$$

2) needed to grow cosmic structure

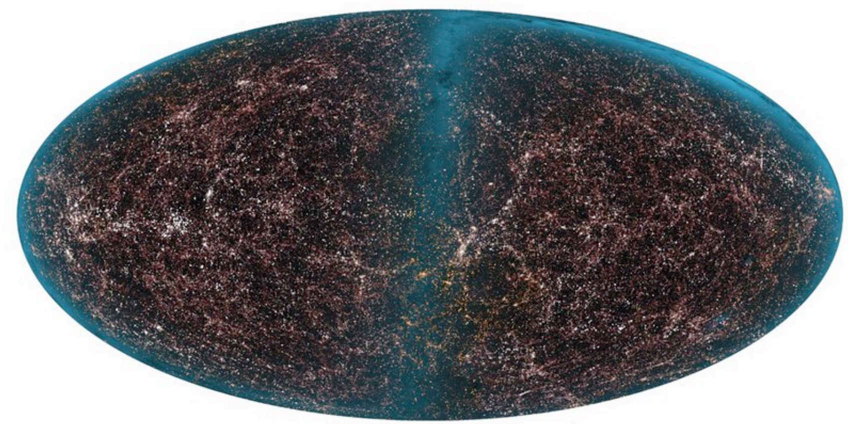
(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

t = 1.8 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.

"Cosmologists are often wrong, but never in doubt"

- Lev Landau

Things we know for sure in cosmology:

pre-1990:

$$\Omega_m = 1.00$$

$$\Omega_\Lambda = 0.00$$

$$\Omega_b h^2 = 0.0125$$

$$H_o = 50 \text{ km/s/Mpc}$$

Dark Matter = Cold Dark Matter

"Cosmologists are often wrong, but never in doubt"

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Things we know for sure in cosmology:

2006:

$$\Omega_m = 0.24$$

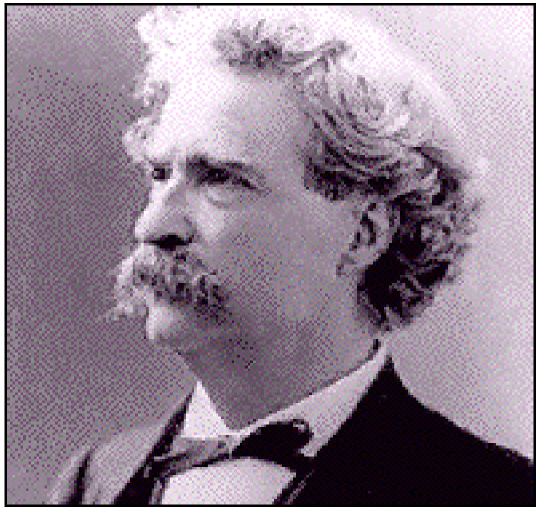
$$\Omega_\Lambda = 0.76$$

$$\Omega_b h^2 = 0.0223$$

$$H_o = 73 \text{ km/s/Mpc}$$

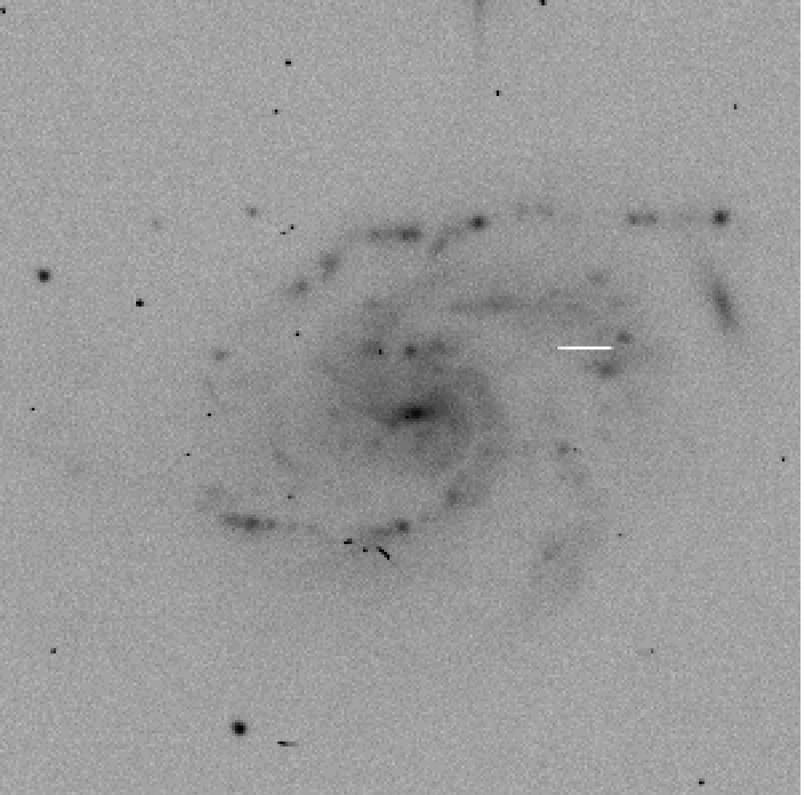
Dark Matter = Cold Dark Matter

What did I say?

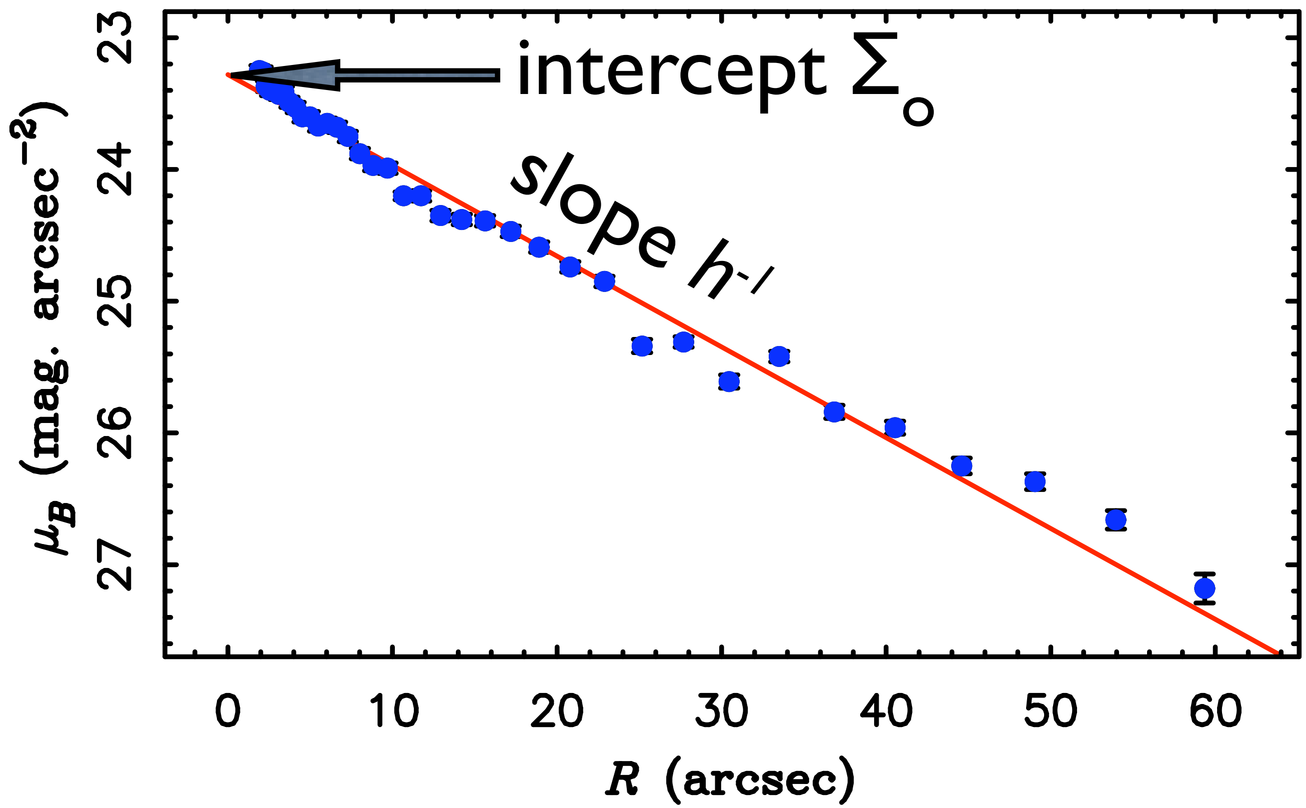


On Galaxy Scales...

- Measure rotation velocity; find
- Properties depend systematically on
  - Total Baryonic Mass
  - Baryon Distribution
  - Acceleration

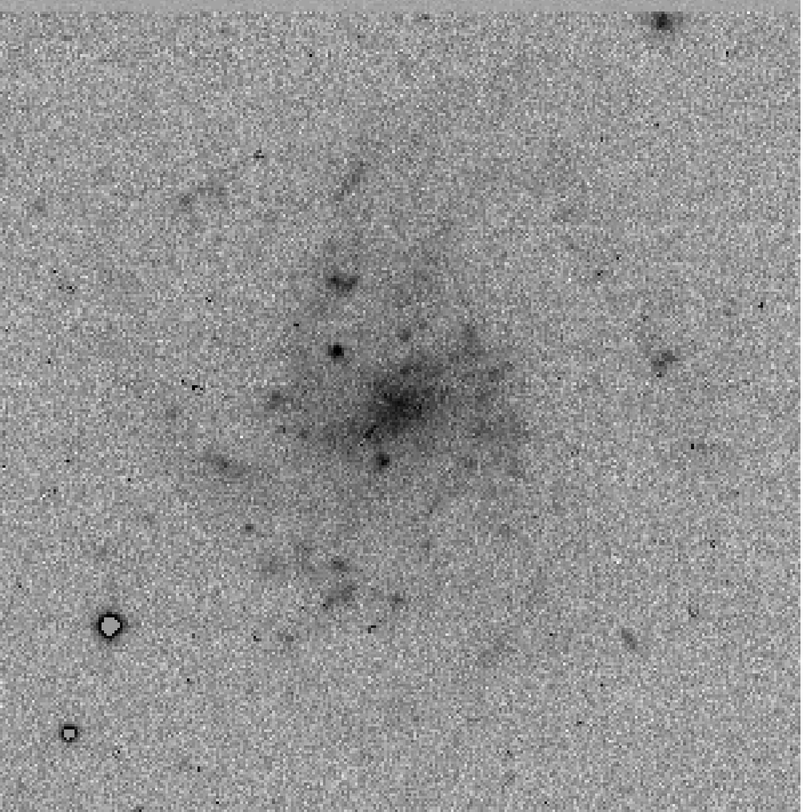


High Surface Brightness (HSB)



$$\Sigma(R) = \Sigma_o \, e^{-R/h}$$

Azimuthally averaged light distribution typically exponential for spiral disks.

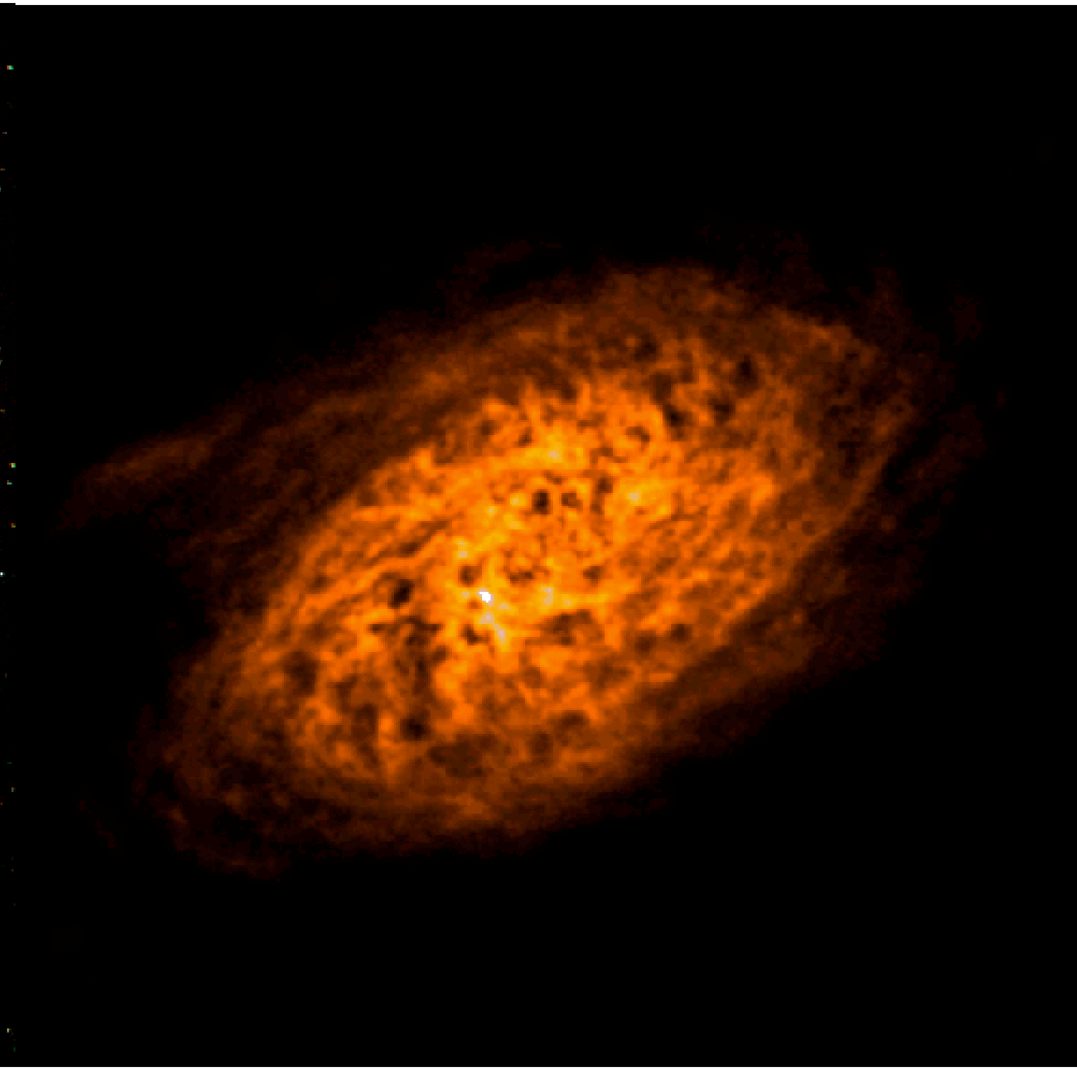


Low Surface Brightness (LSB)

NGC 2403

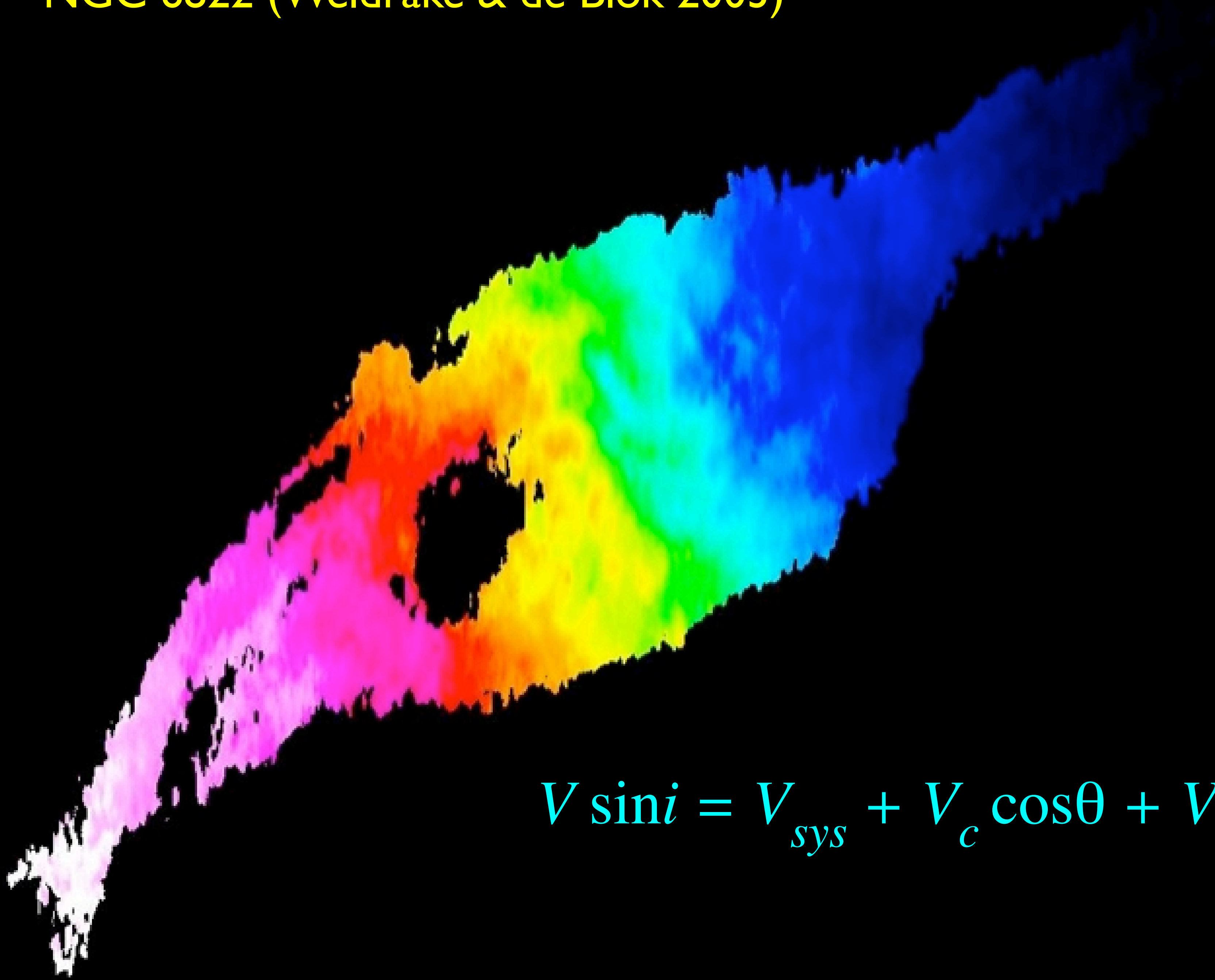
Stars

HI gas



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

NGC 6822 (Weldrake & de Blok 2003)

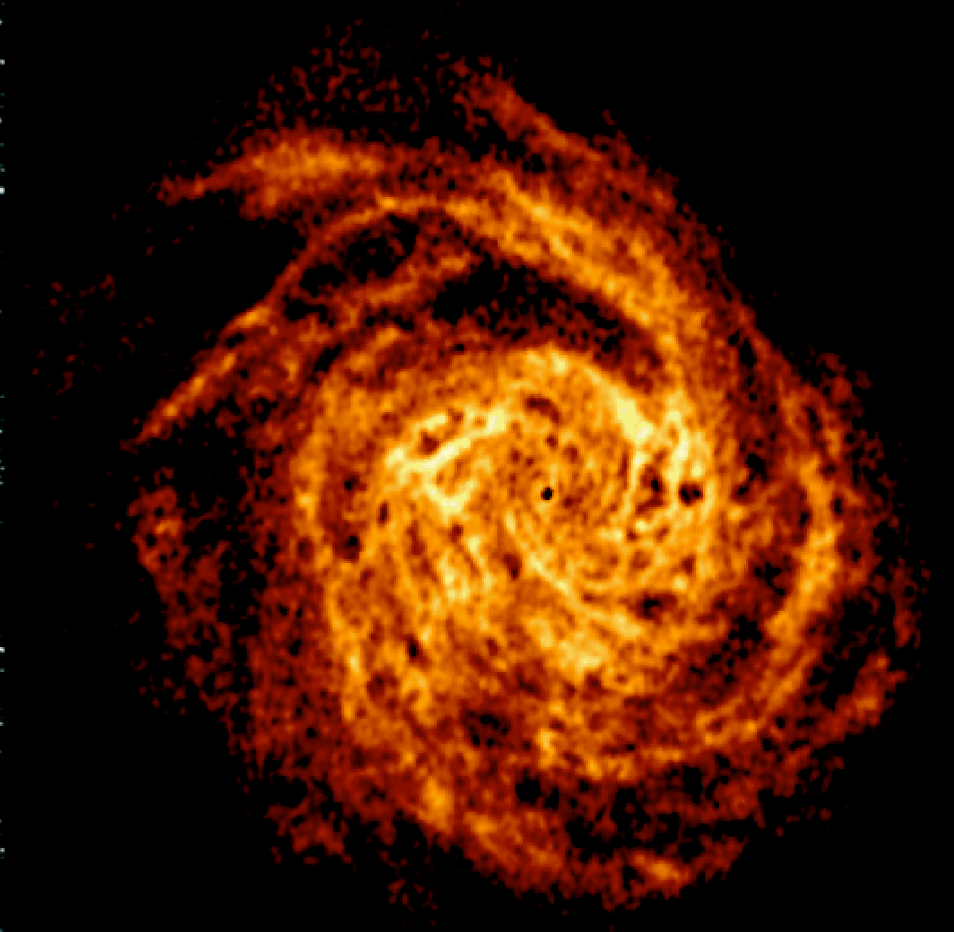


$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

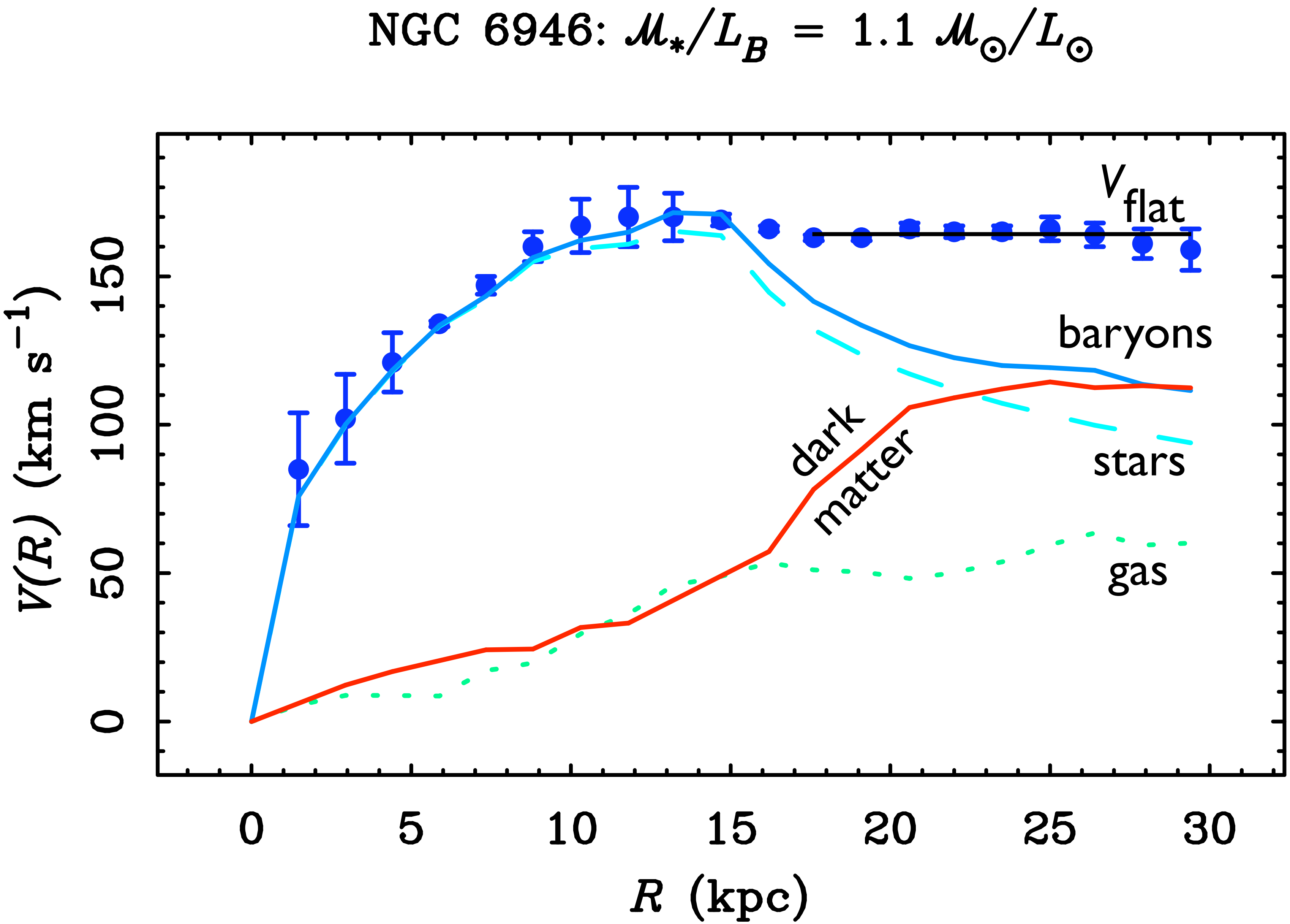
NGC 6946

Stars

HI gas

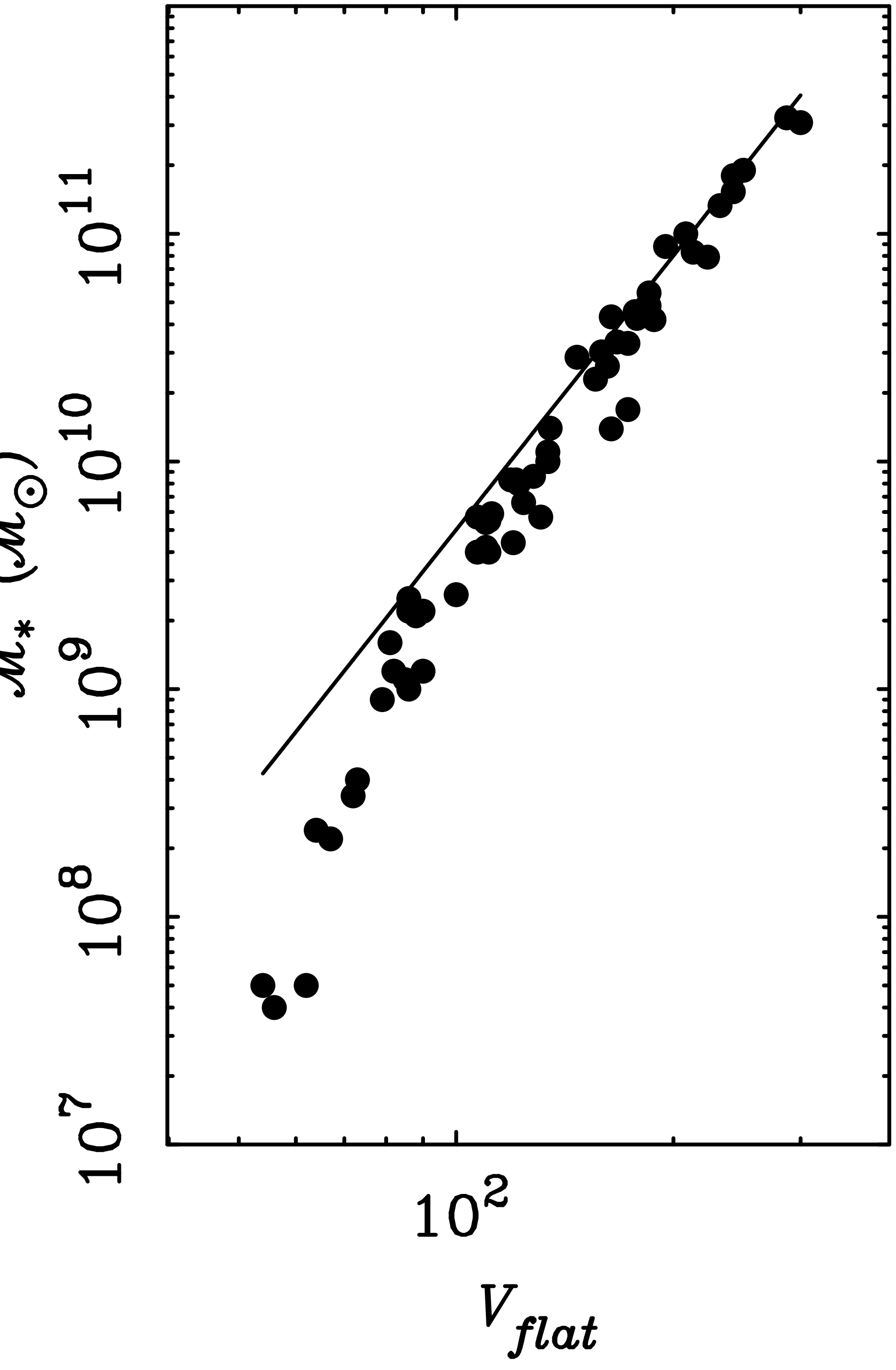


Boomsma 2005


NGC 6946: $\mathcal{M}_*/L_B = 1.1\ \mathcal{M}_\odot/L_\odot$
V_{flat}
baryons
dark matter
stars
gas
$V(R)$ (km s^{-1})
0
50
100
150
0
5
10
15
20
25
30
R (kpc)

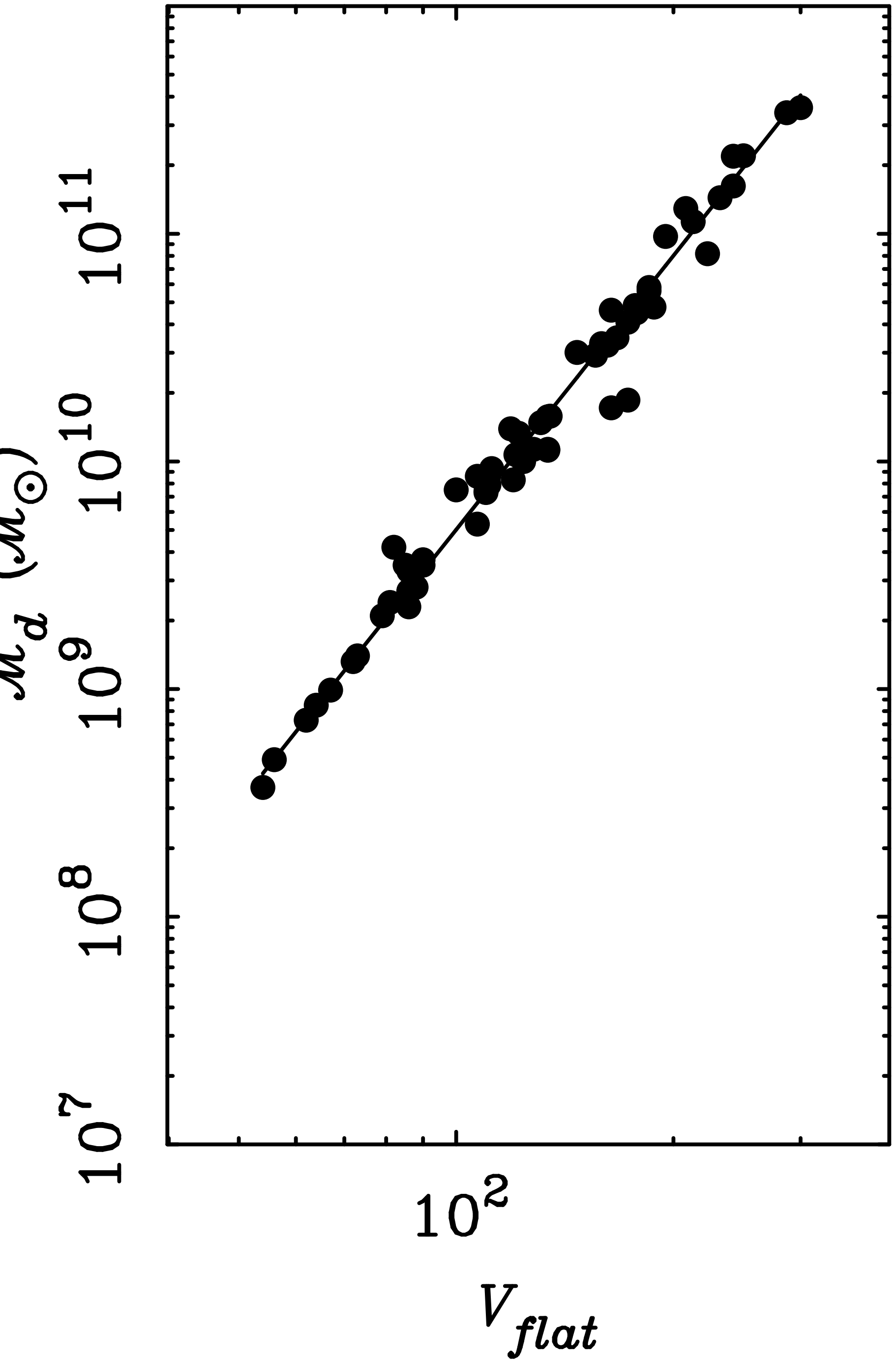
Tully-Fisher Relation

$M_* = (M/L)_* L$

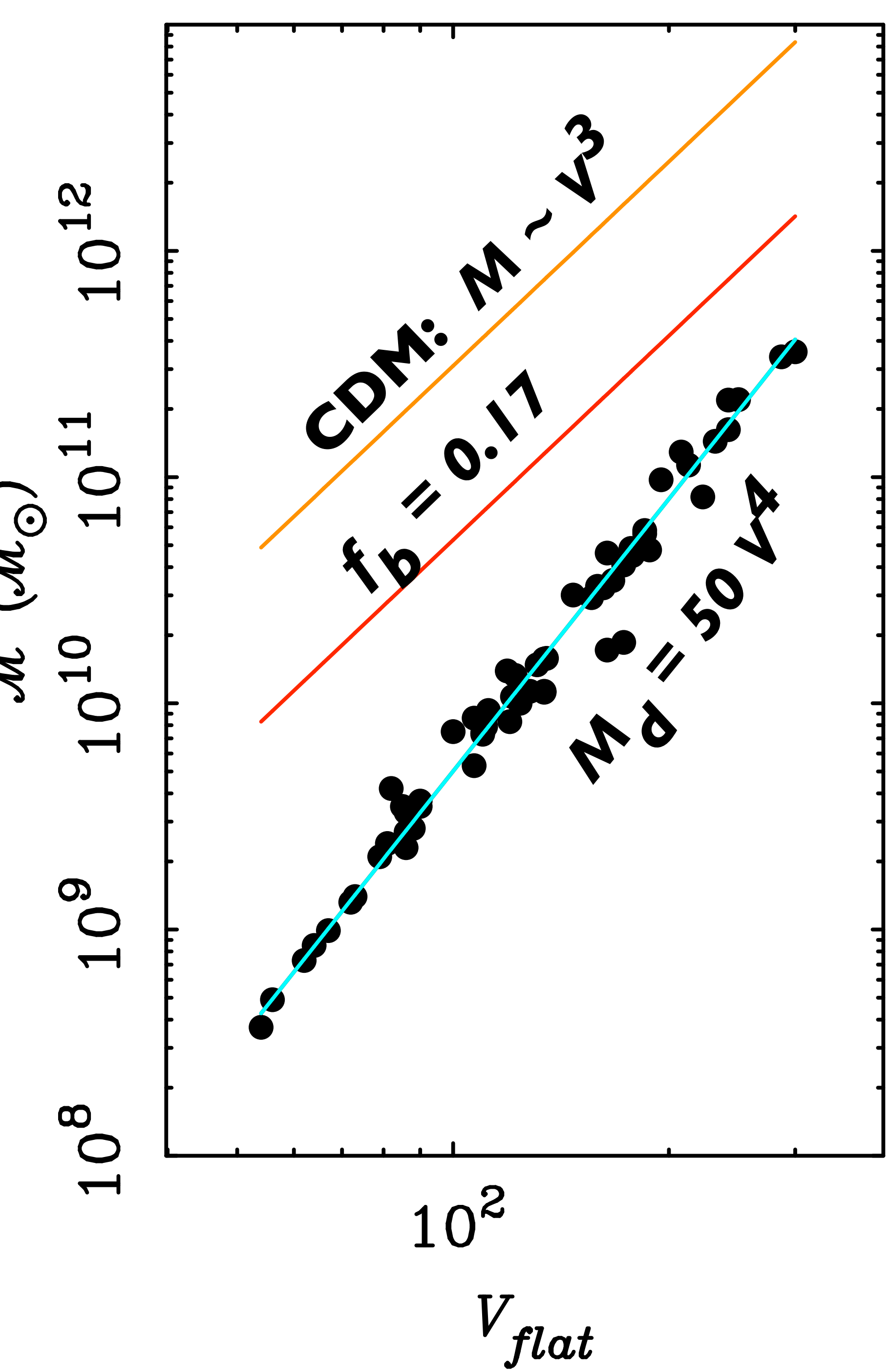


Baryonic Tully-Fisher Relation

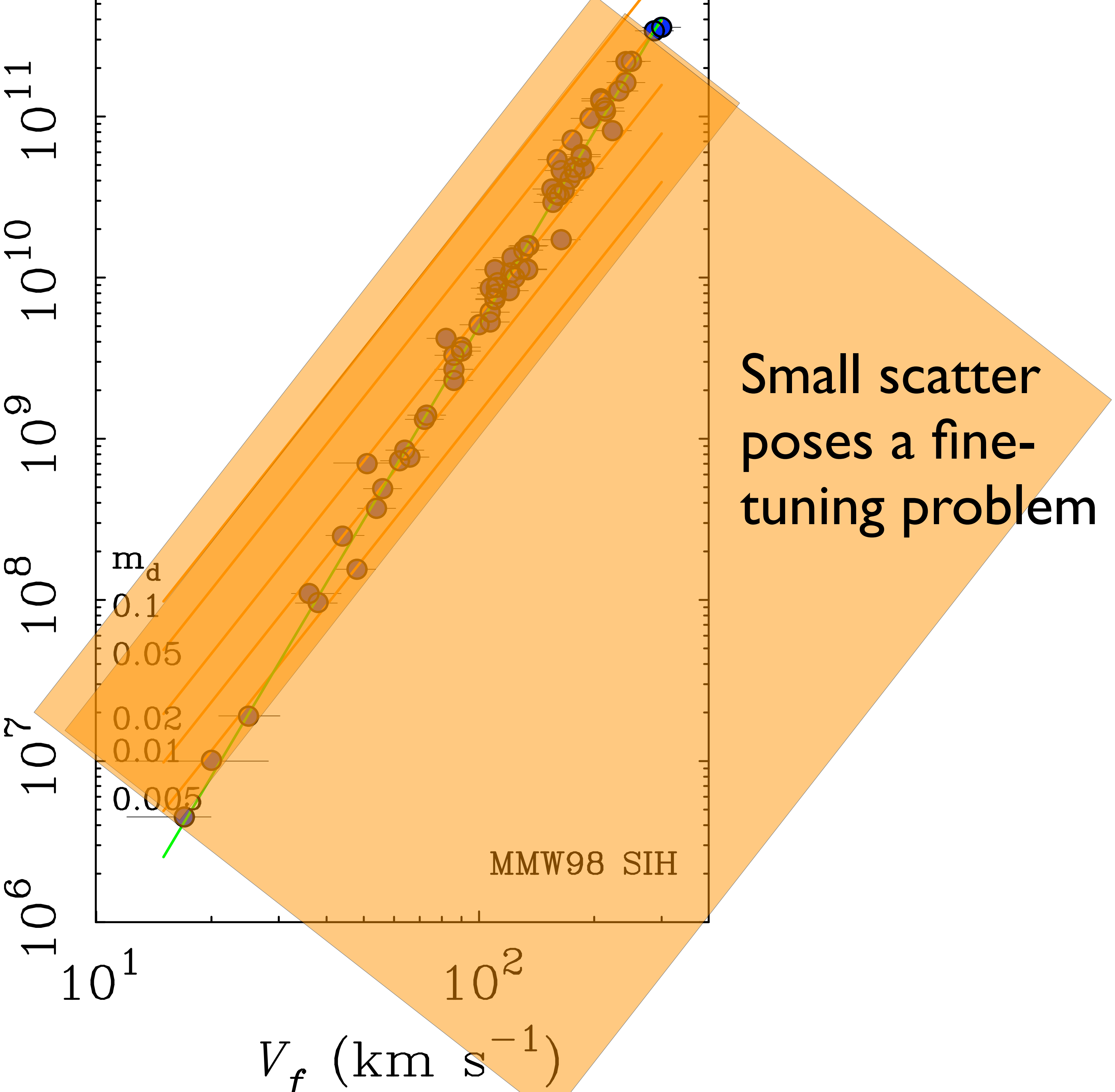
$M_d = M_* + M_g$



CDM TF Relation



Slope and normalization wrong



$$m_d = \frac{\mathcal{M}_{disk}}{\mathcal{M}_{tot}}$$

$$(m_d \leq f_b)$$

Small scatter poses a fine-tuning problem

TF Relation

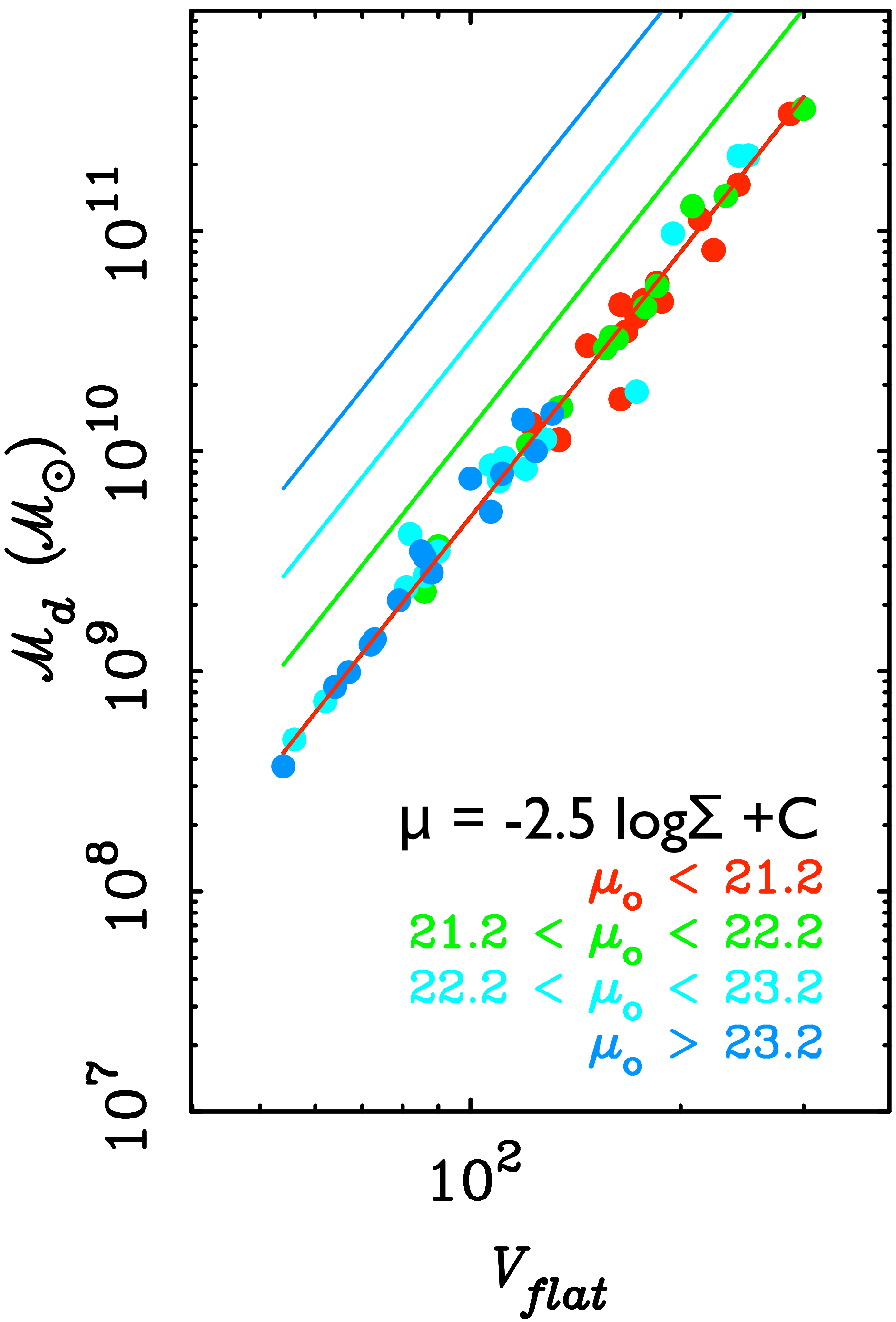
<u>Newton says</u>

$V^2 = GM/R$.

Equivalently,

$\Sigma = M/R^2$

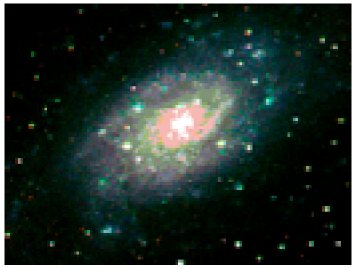
$V^4 = G^2 M \Sigma$

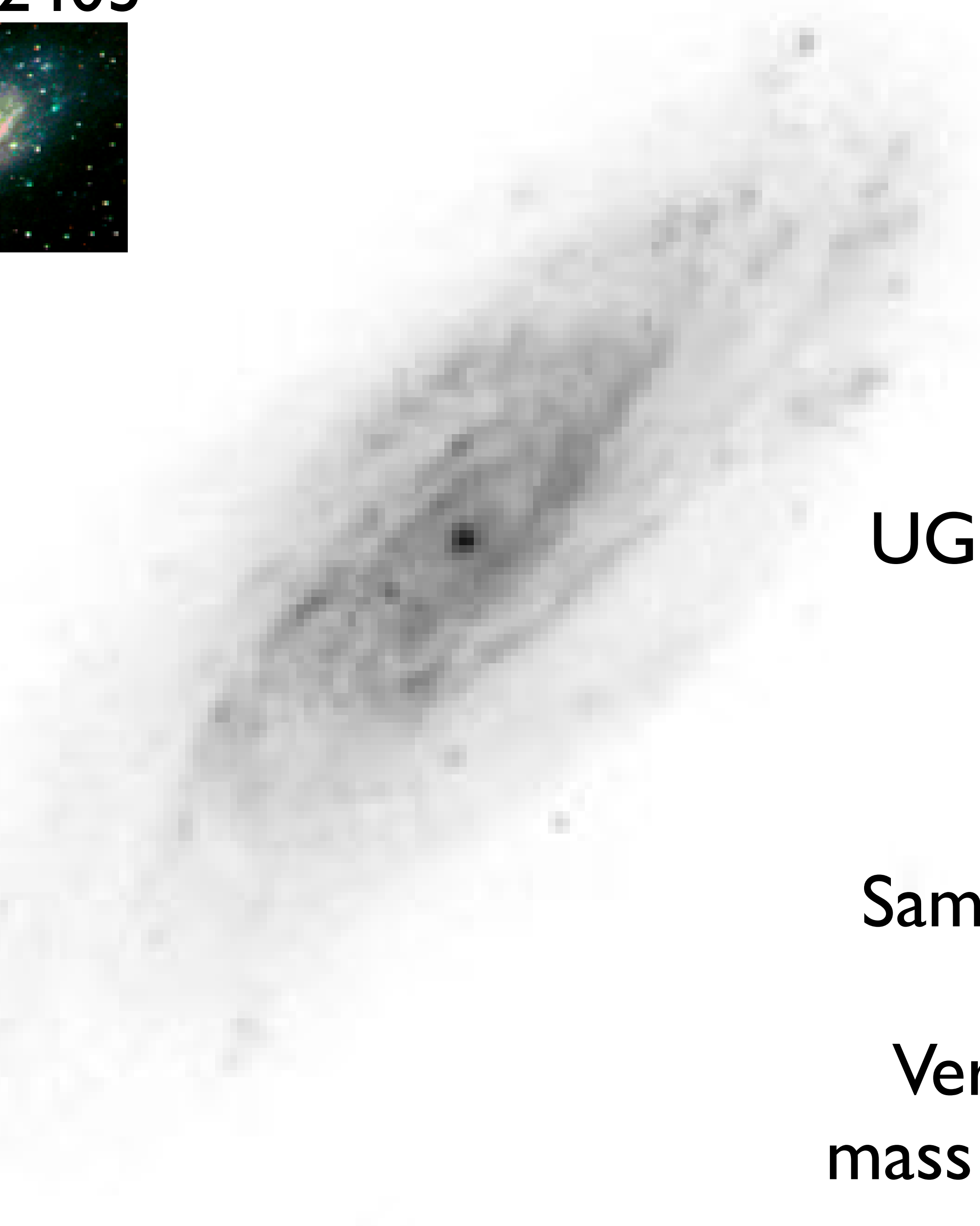


<u>Therefore</u>

Different Σ *should* mean different TF normalization.

NGC 2403

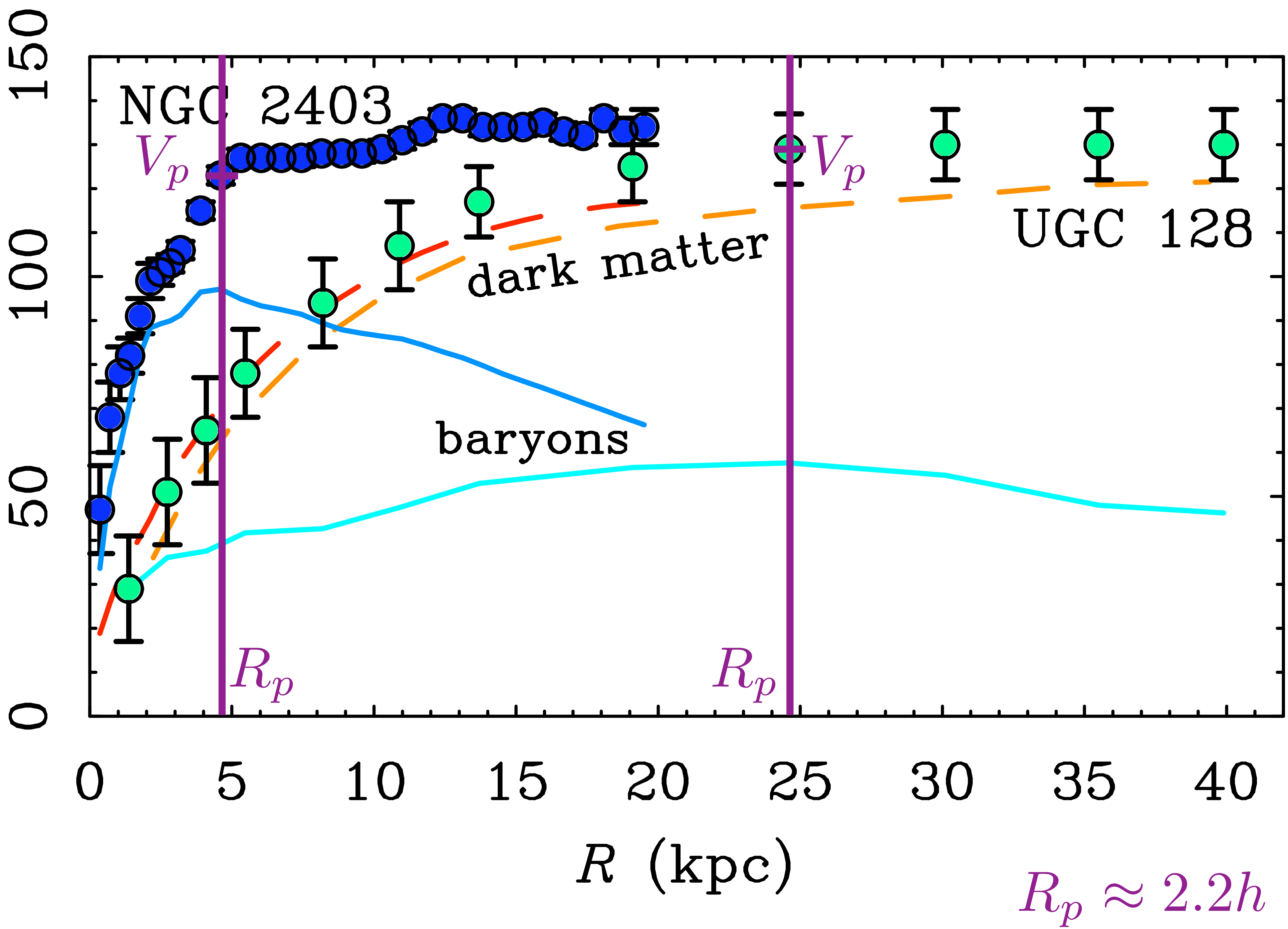




UGC 128

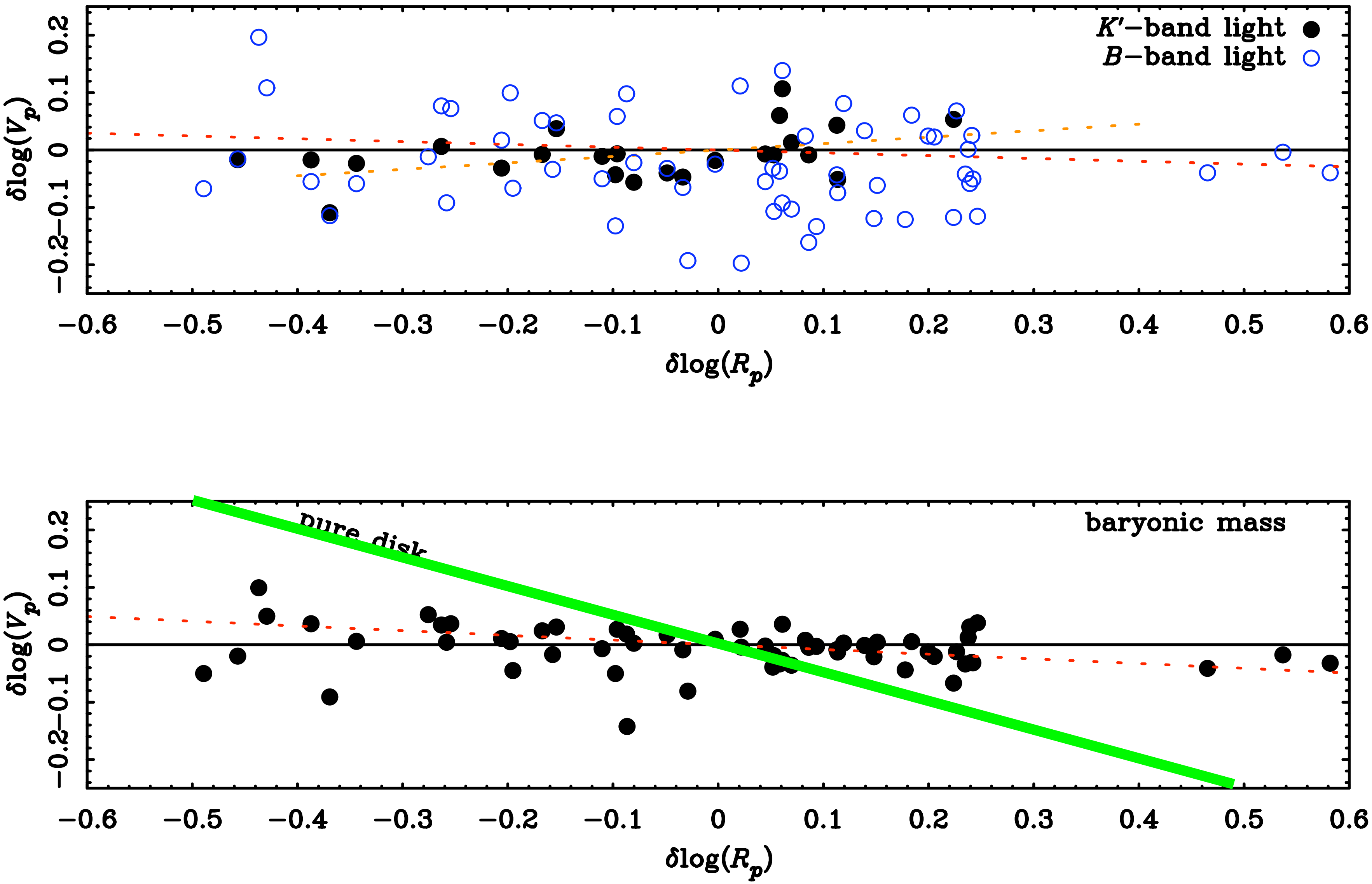
Same global L,V

Very different
mass distributions



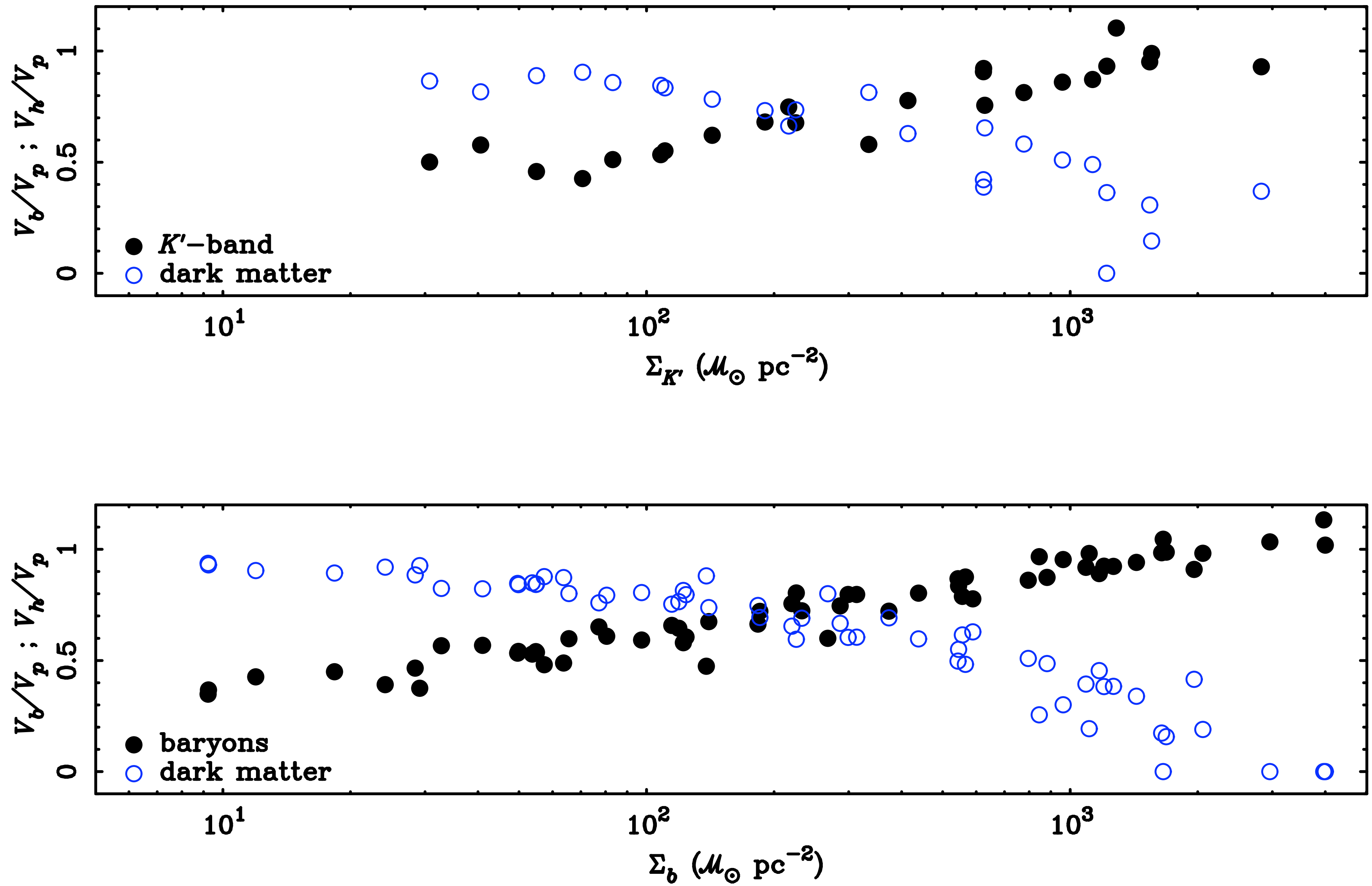
150
100
50
0
NGC 2403
V_p
V_p
UGC 128
dark matter
baryons
R_p
R_p
0
5
10
15
20
25
30
35
40
R (kpc)
$R_p \approx 2.2h$

No Residuals from TF rel'n



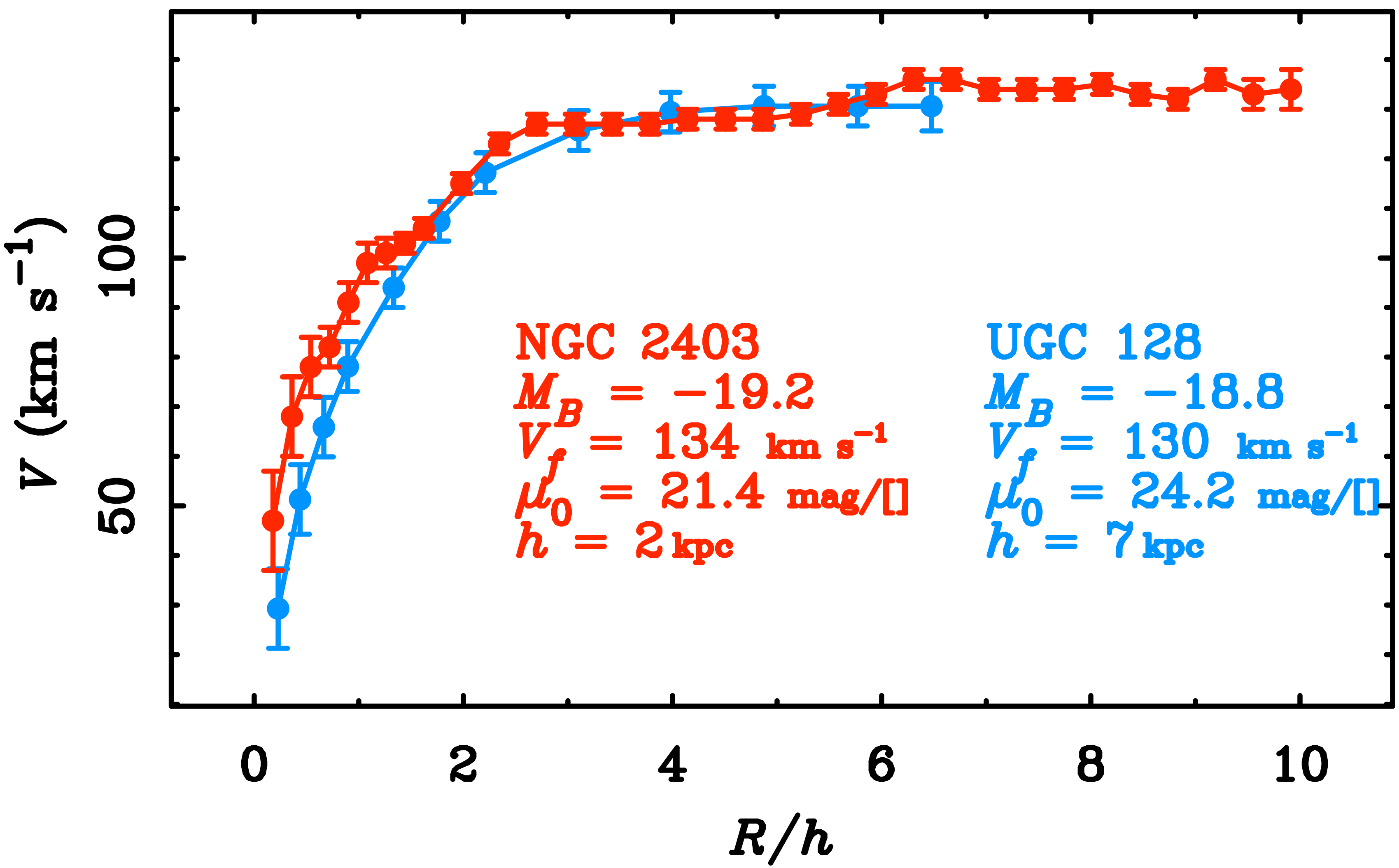
Not even where disk contribution is maximal

Requires fine balance between dark & baryonic mass



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

Radius measured by disk scale length *h*



Dynamics knows about the distribution of light as well as the total mass.

Renzo's Rule:

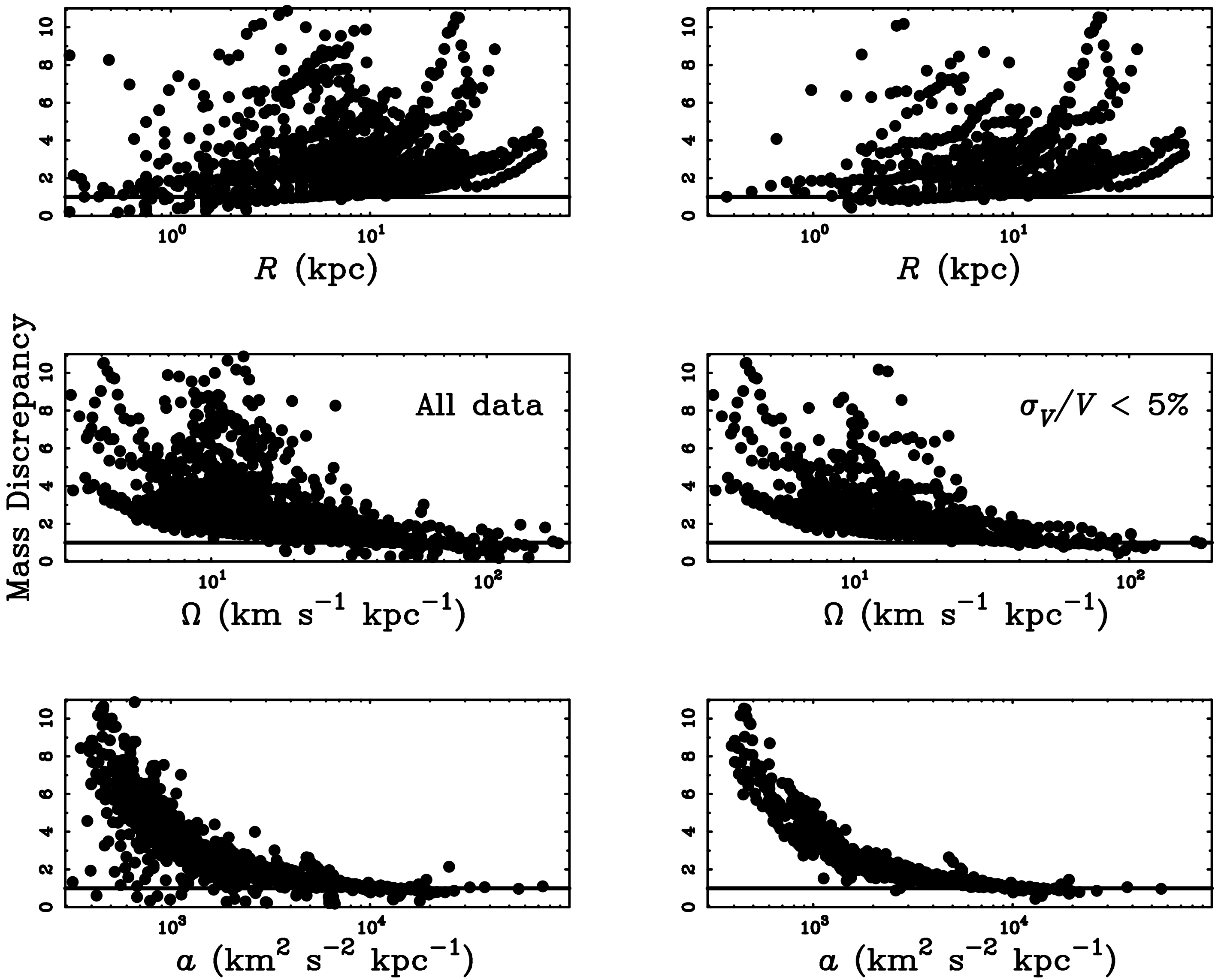
"When you see a feature in the light, you see a corresponding feature in the rotation curve."

(Sancisi 1995, private communication)

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

Quantify by defining the Mass Discrepancy:

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



radius

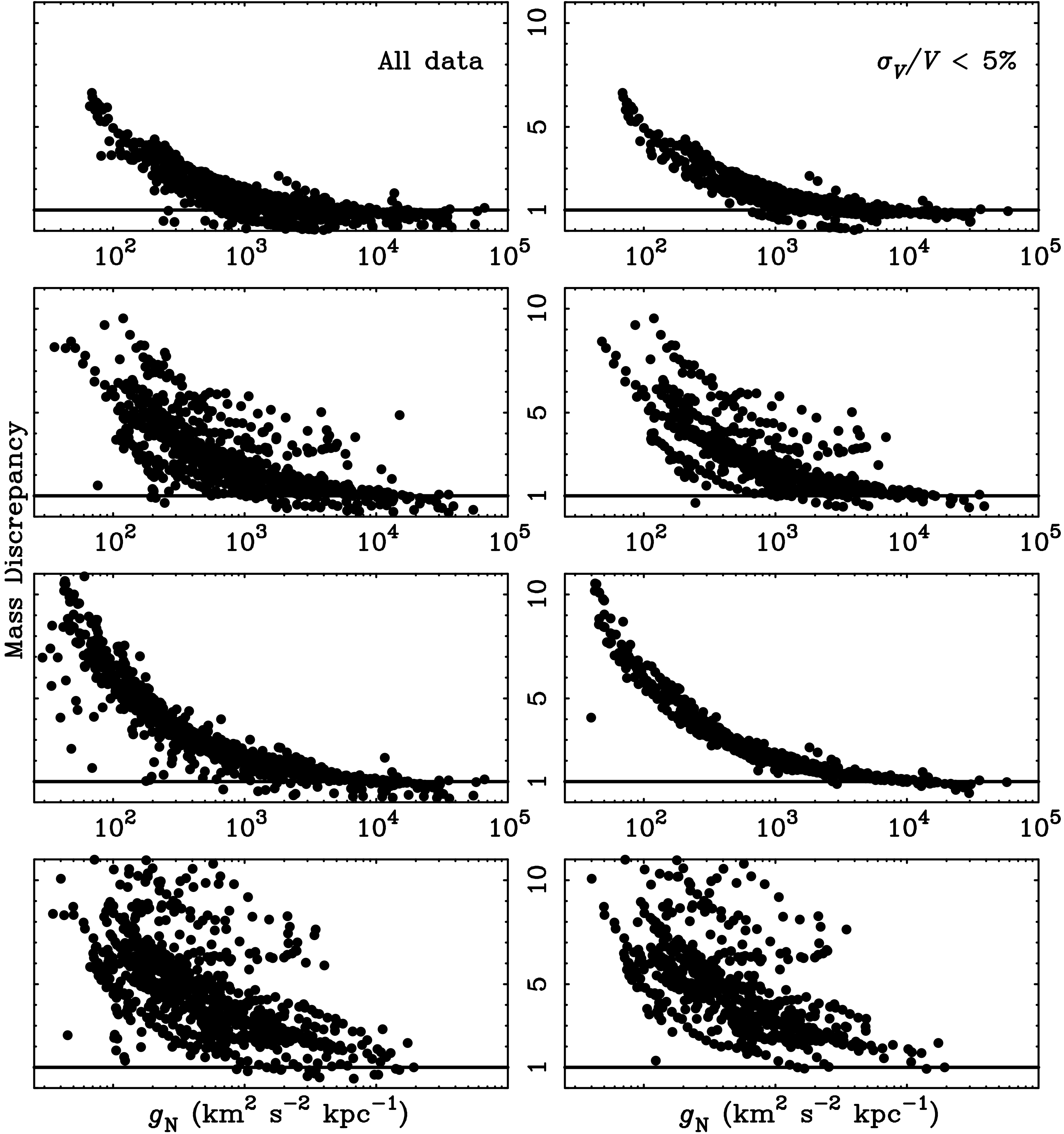
orbital frequency

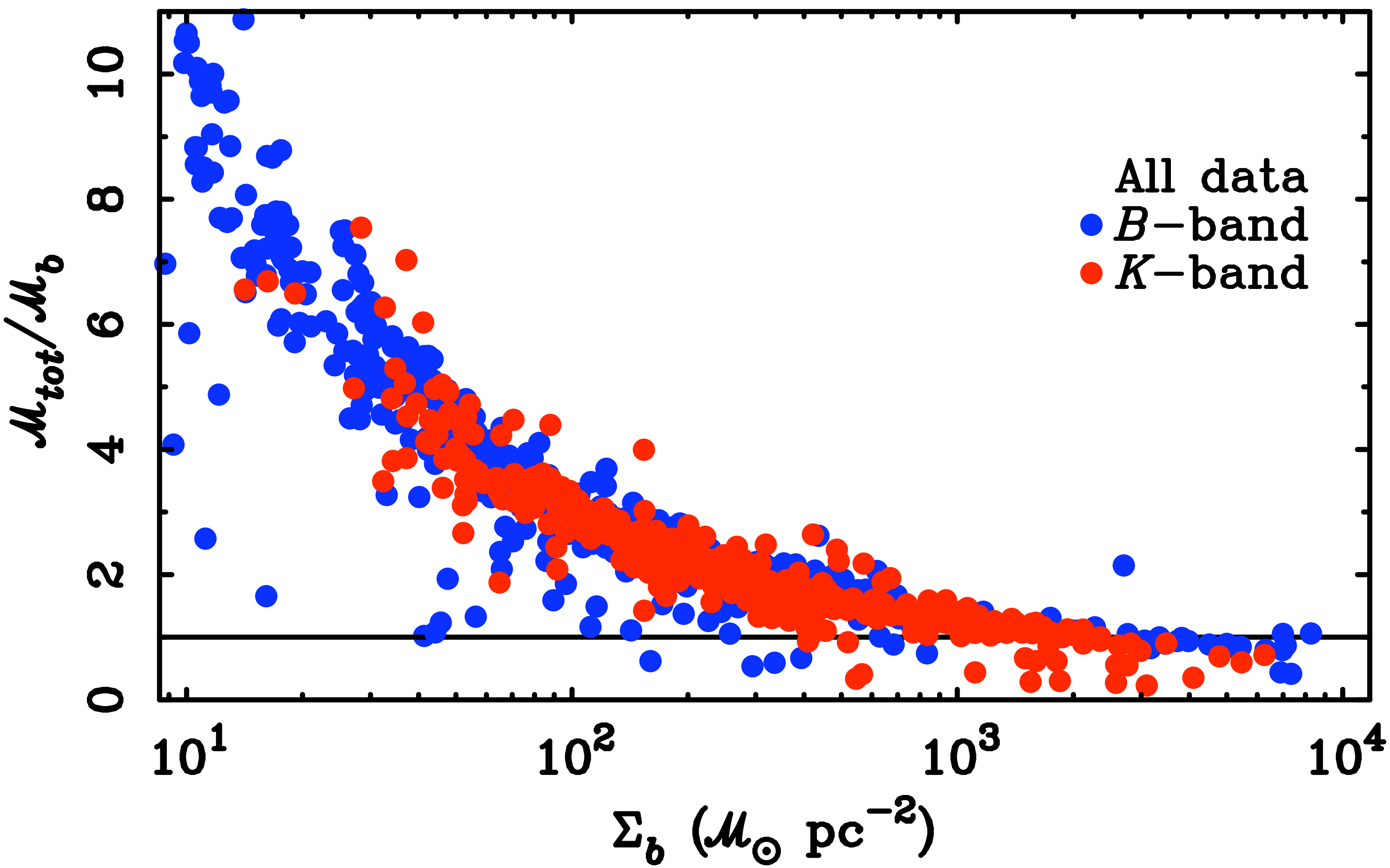
acceleration

74 galaxies
> 1000 points
(all data)

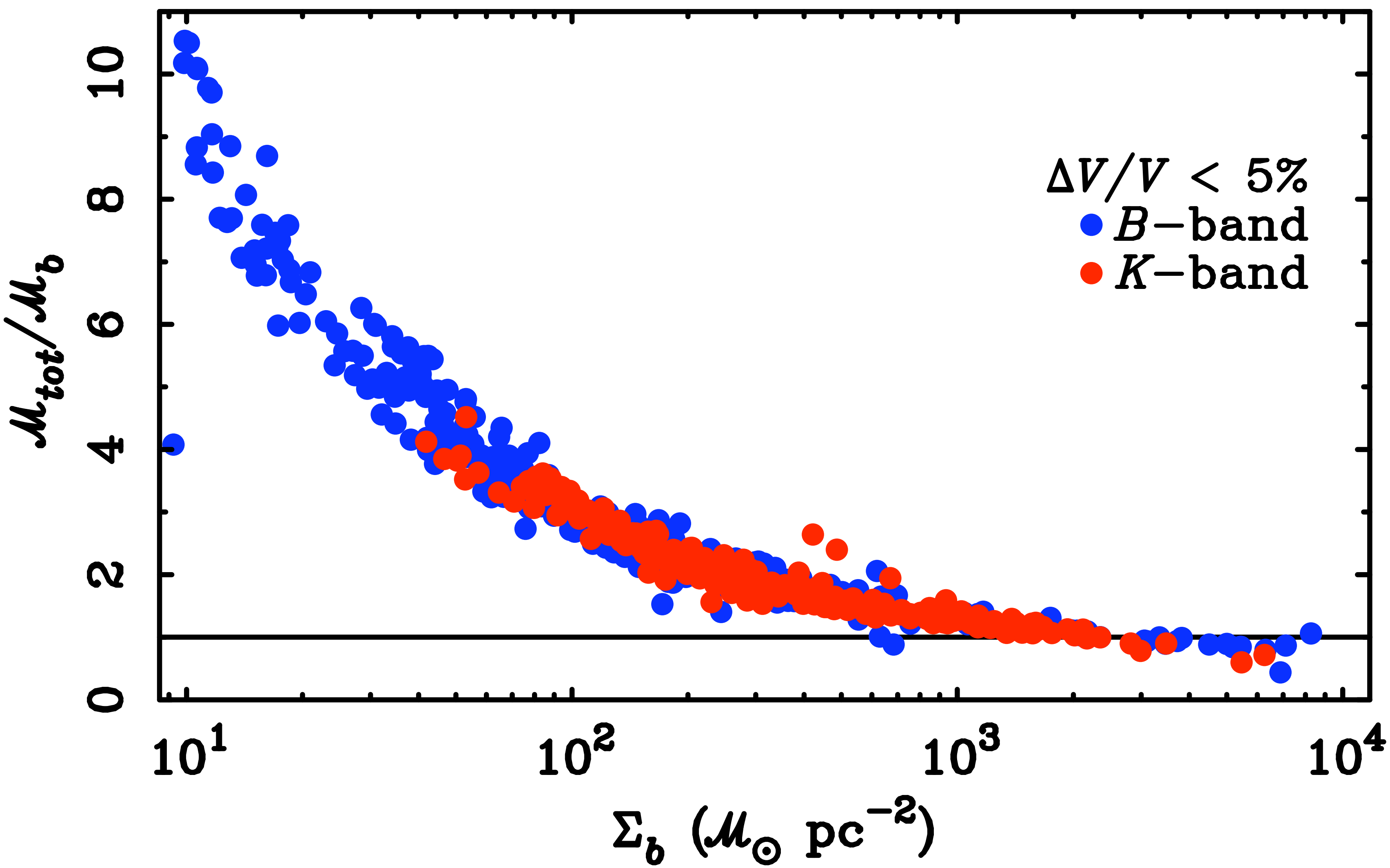
60 galaxies
> 600 points
(errors < 5%)

Different choices of Stellar Mass-to-Light Ratio





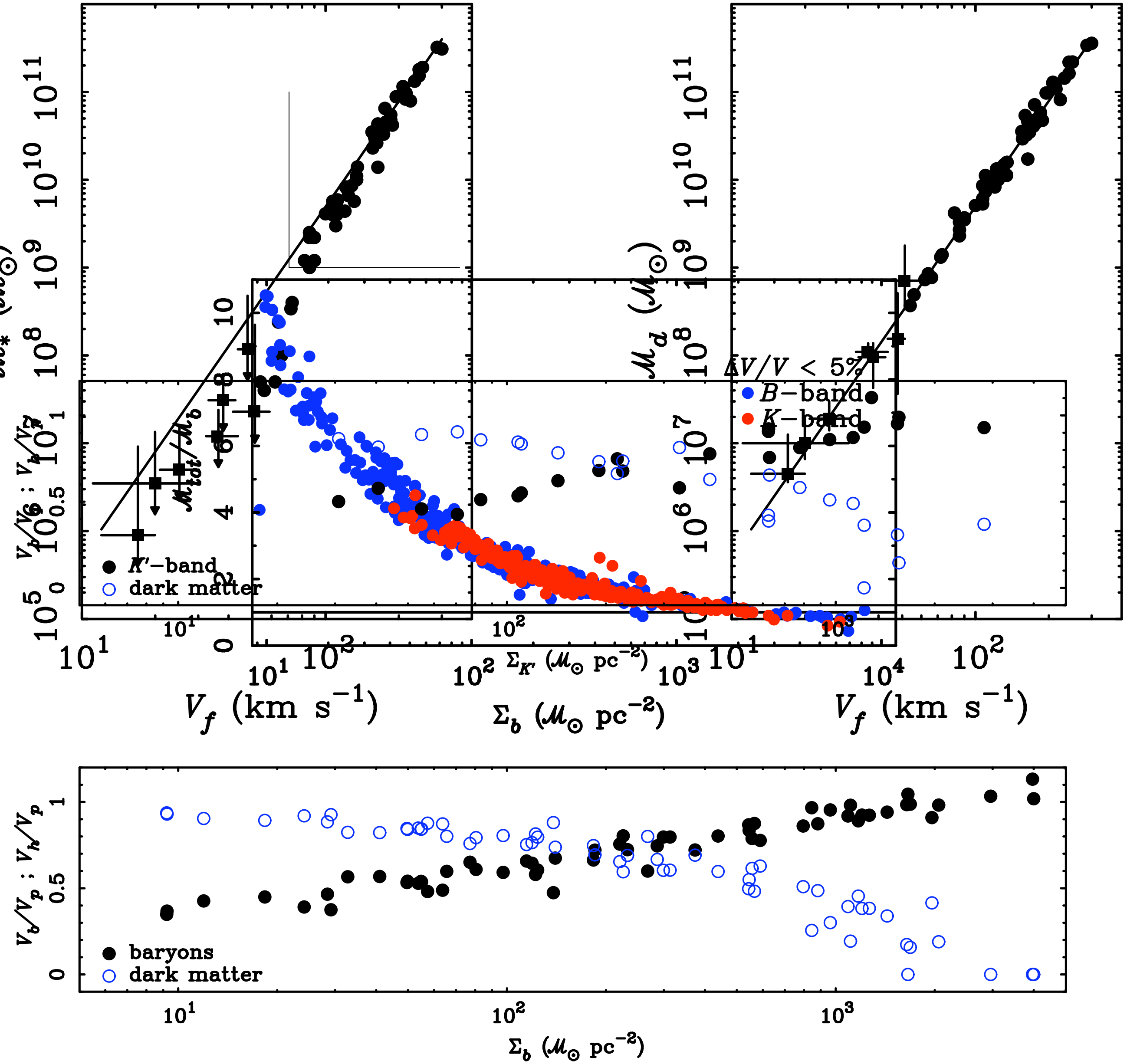
All data
B−band
K−band
$\mathcal{M}_{tot}/\mathcal{M}_b$
Σ_b ($\mathcal{M}_\odot$ pc^{-2})
0
2
4
6
8
10
10^1
10^2
10^3
10^4



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

Unexplained Correlations

- Tully-Fisher relation
- Mass discrepancy-acceleration relation
- dark matter/baryon see-saw



MOND

MOdified Newtonian Dynamics

introduced by Moti Milgrom in 1983

tead 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 ellipticals and galactic [illegible]

VIII. PREDICTIONS

The main predictions conce[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 surf[illegible] densities which [illegible] the same [illegible] 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 [illegible] (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, $g \approx (8\ \text{kpc}/d)a_0$, 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] (a) [illegible] calibration of M/L as we are concerned only with variations of this quantity; (b) Effects of the modified dynamics manifest themselves more clearly in local [illegible] many cases [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 [illegible] $\Sigma^{-1}V_\infty^4$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that [illegible] 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 [illegible] 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.

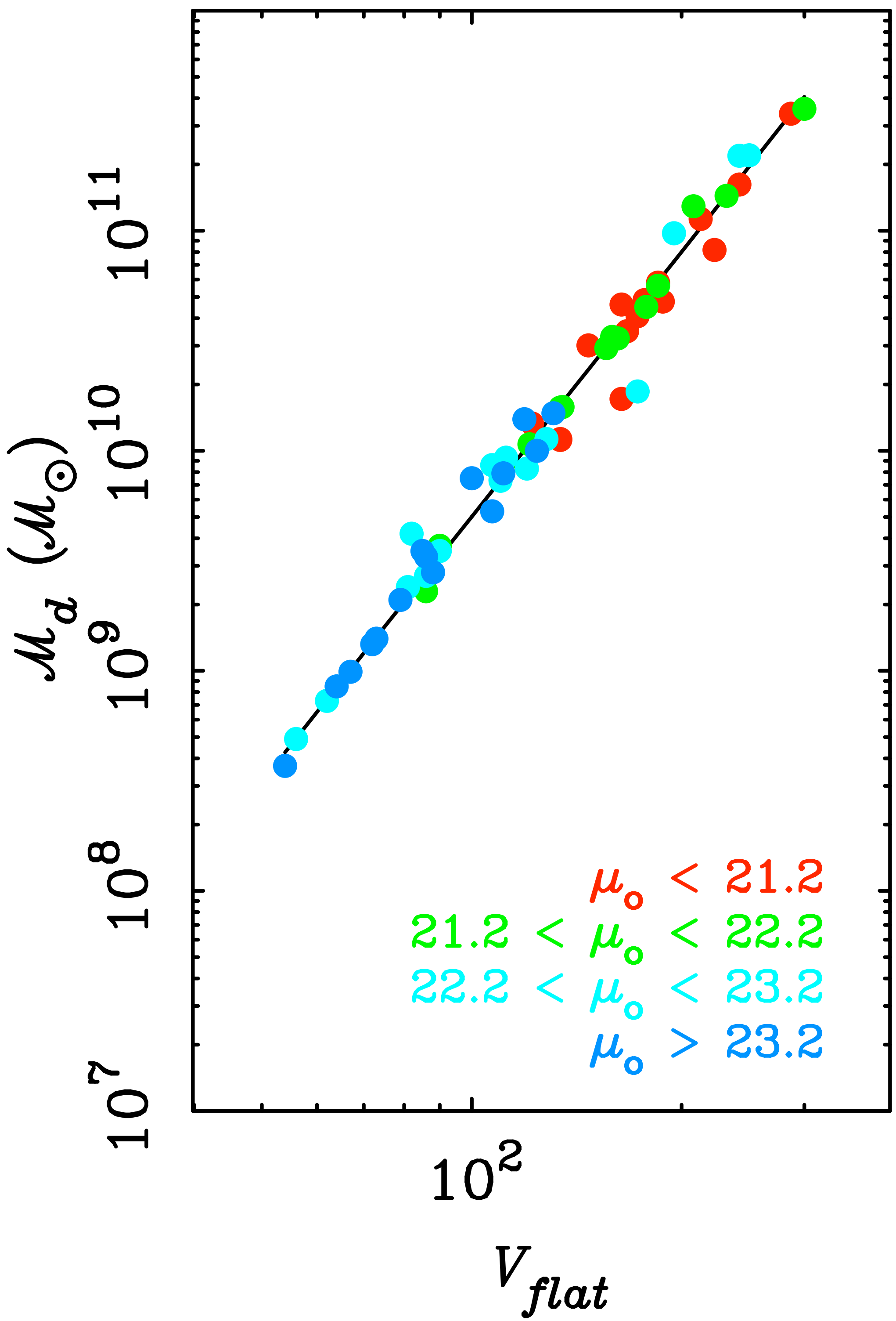
IX. DISCUSSION

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

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



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
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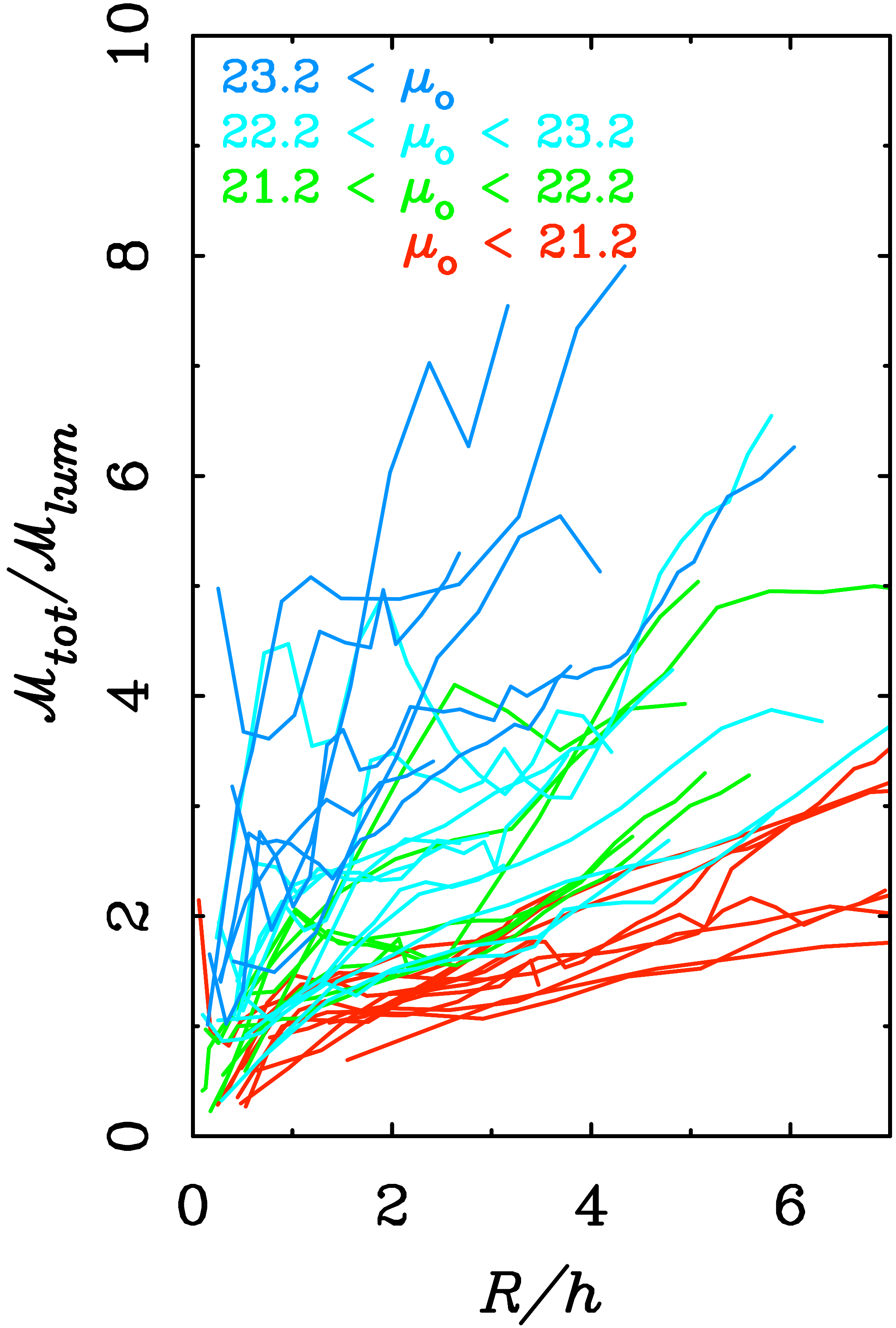
In MOND limit of low acceleration

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

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

$$V^4 = a_0 GM$$

observed TF!



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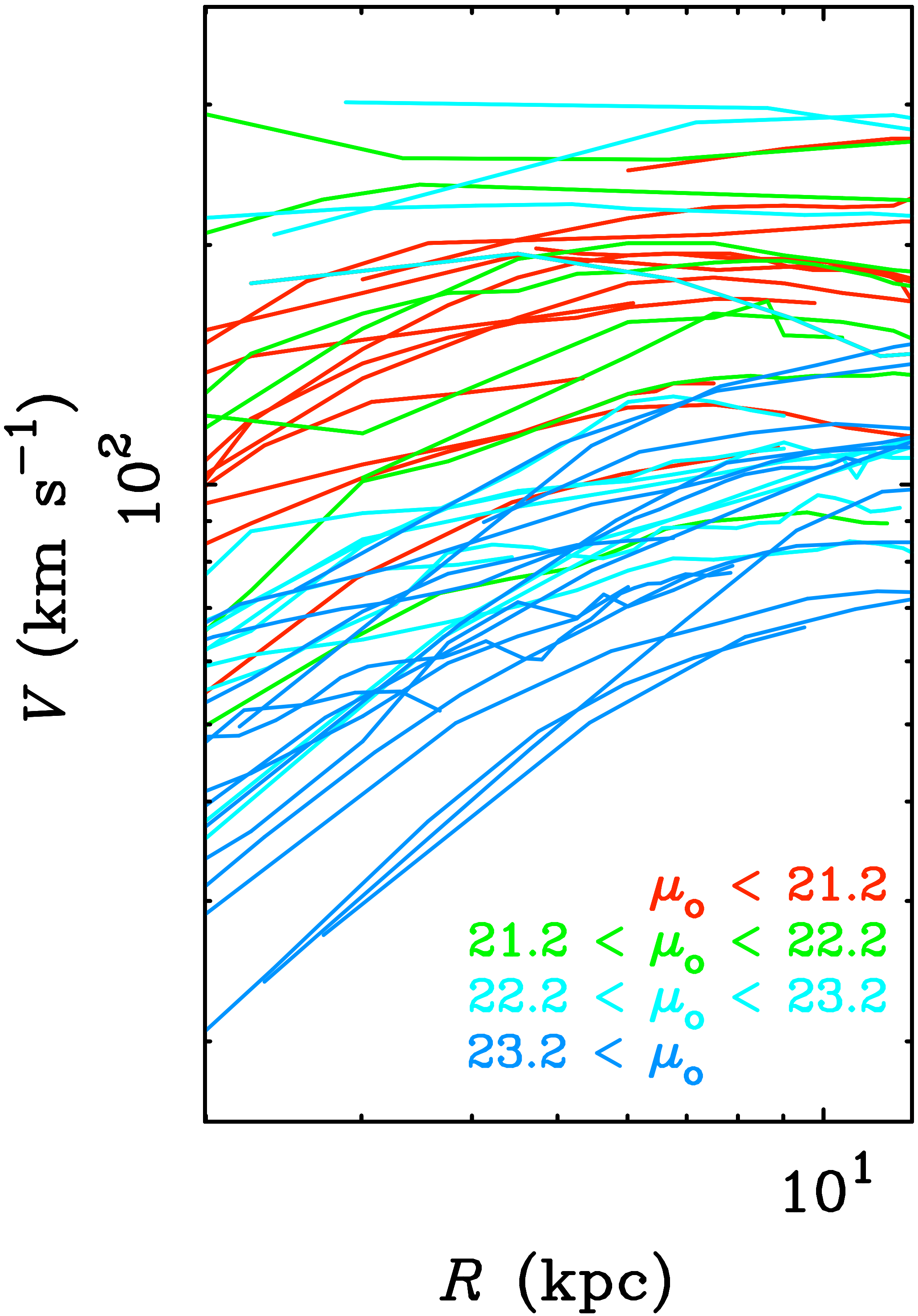

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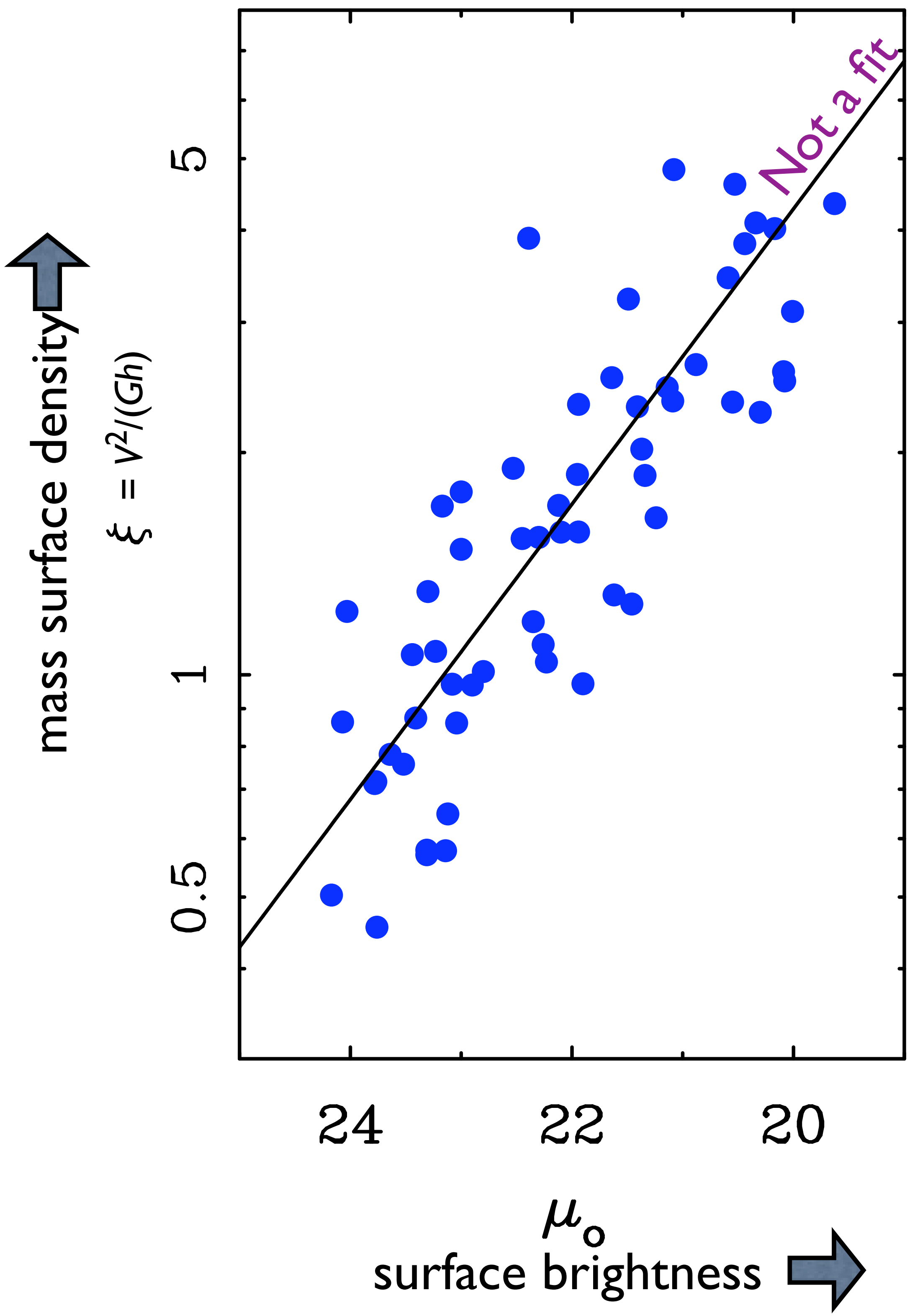

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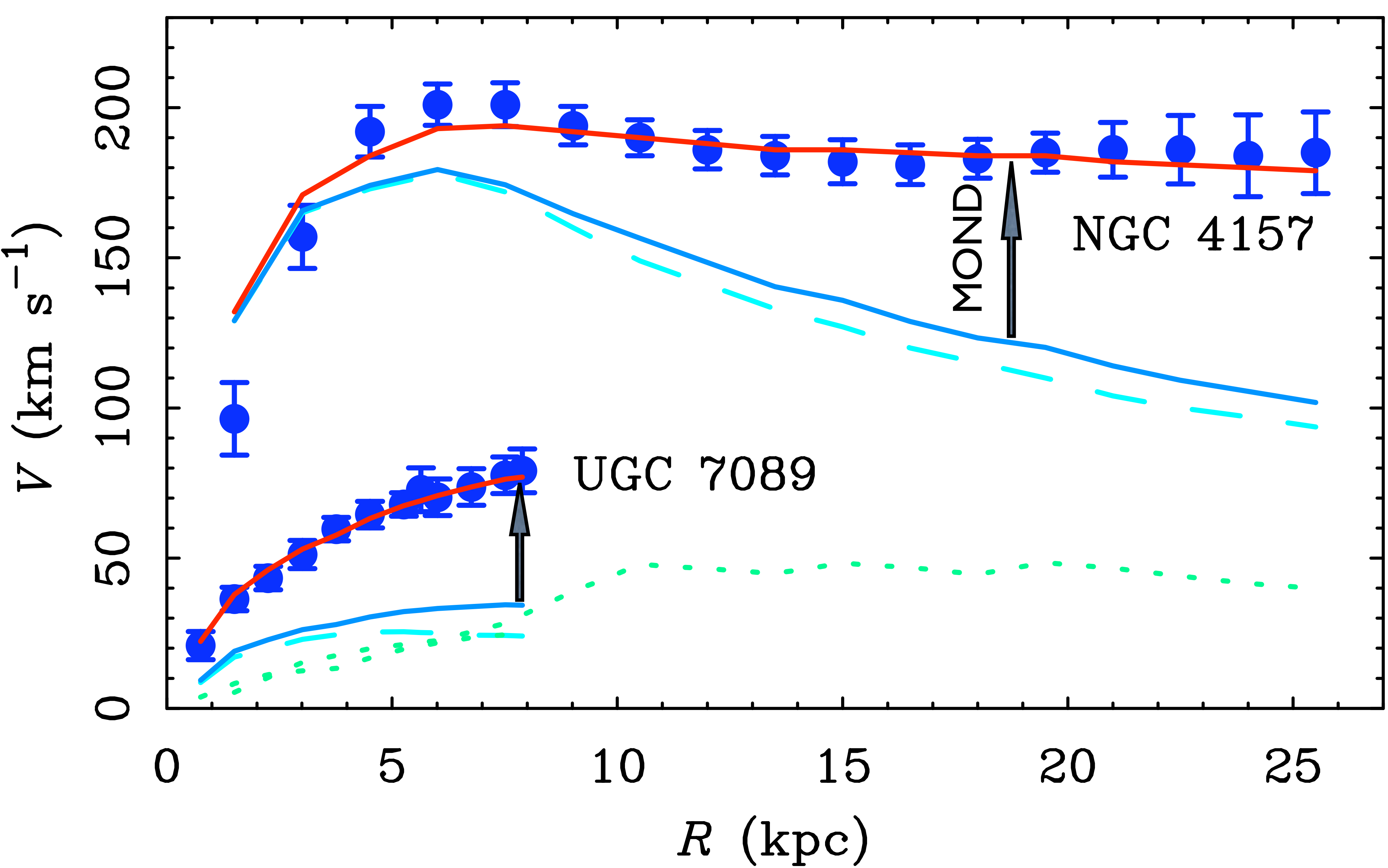
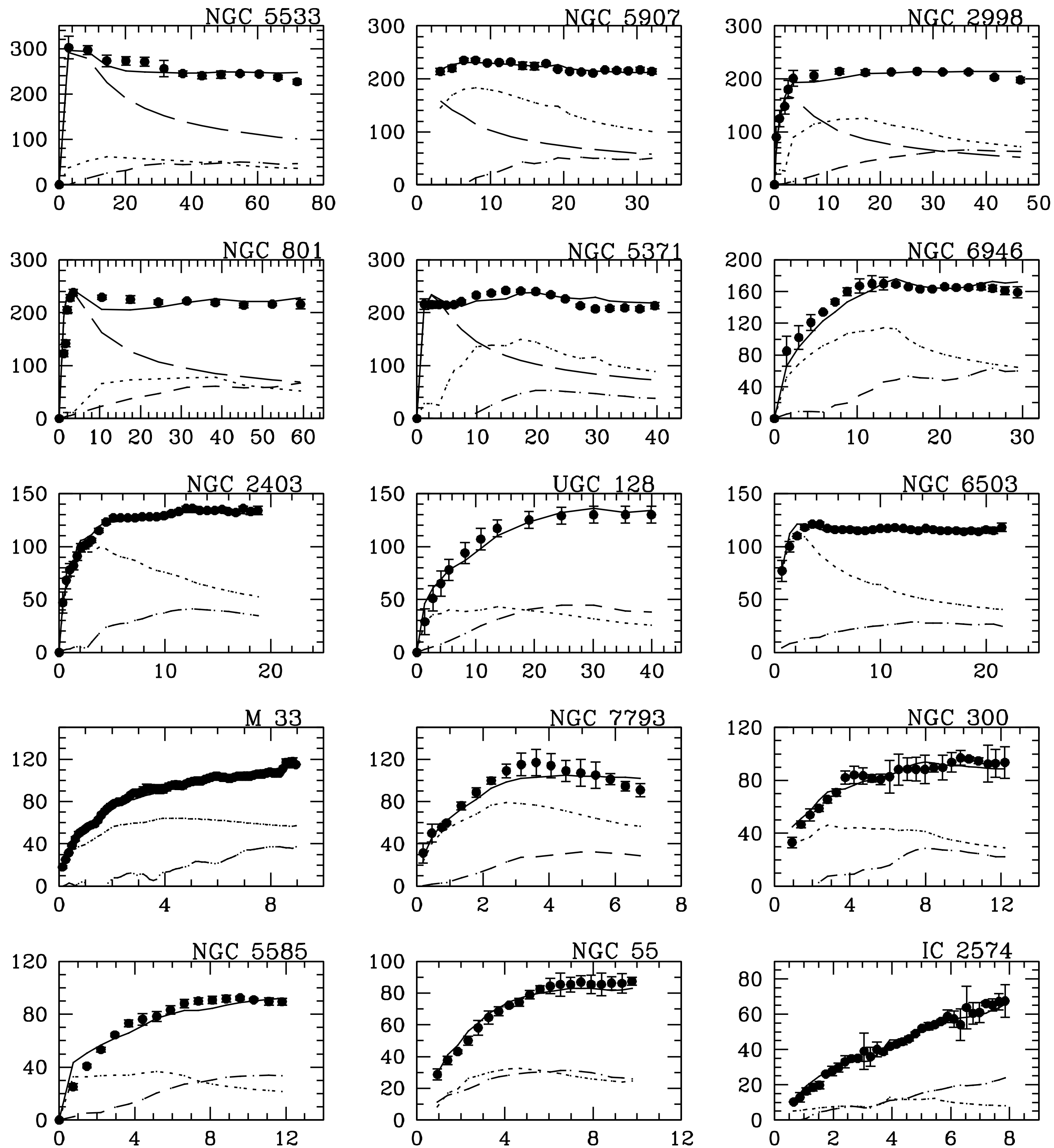
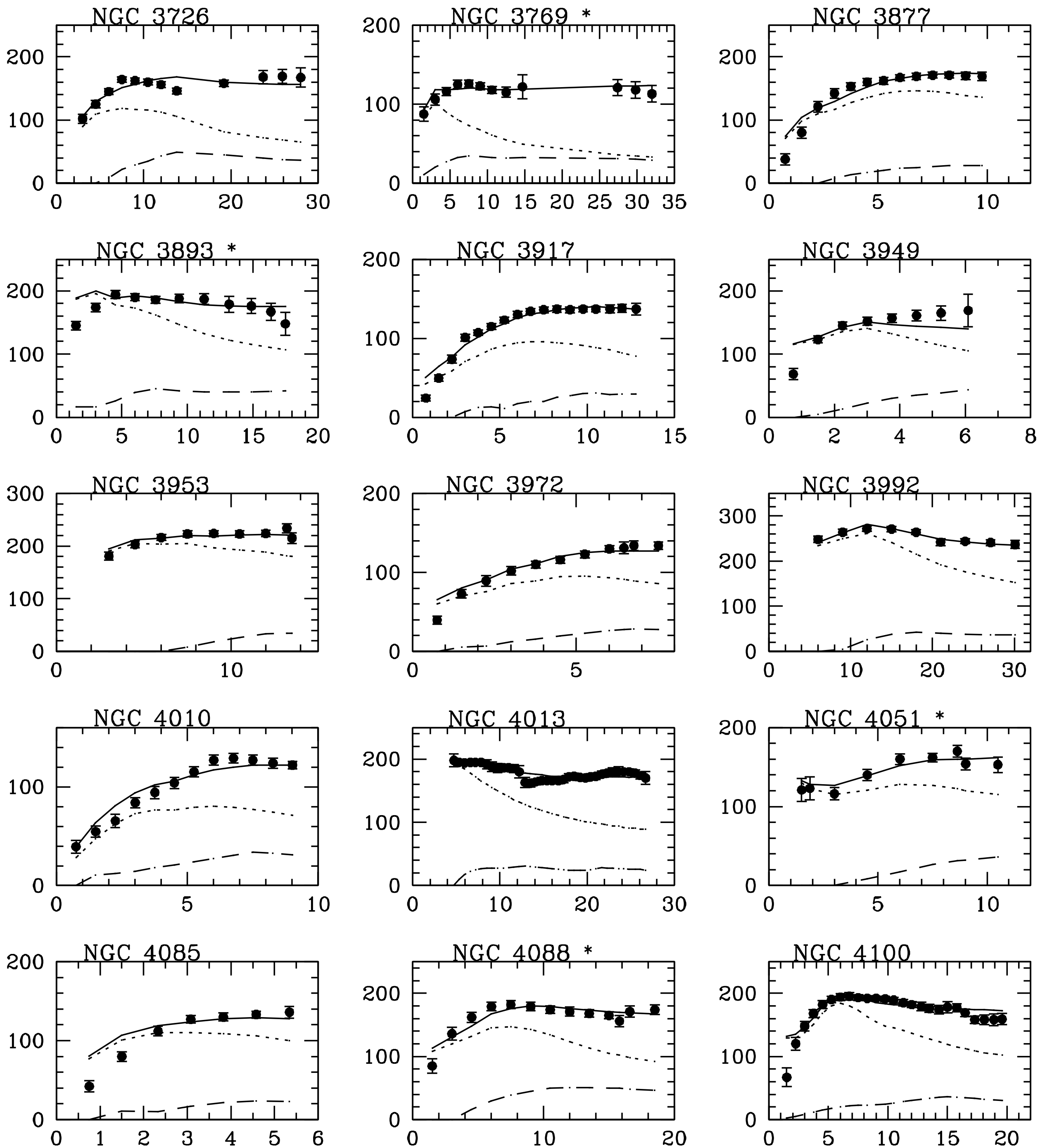


NGC 4157
UGC 7089
MOND
V (km s^{-1})
R (kpc)
0
50
100
150
200
0
5
10
15
20
25

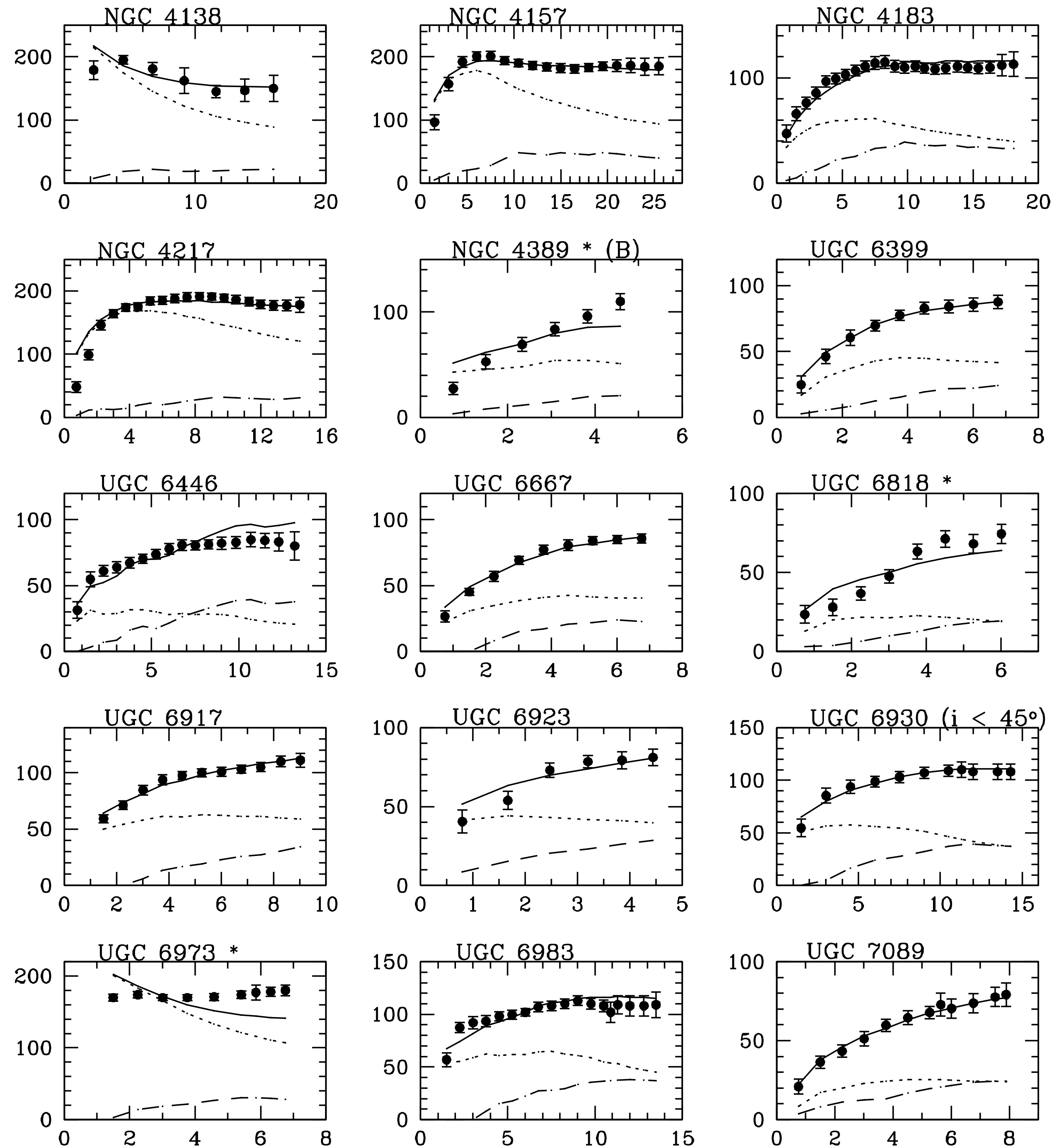
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



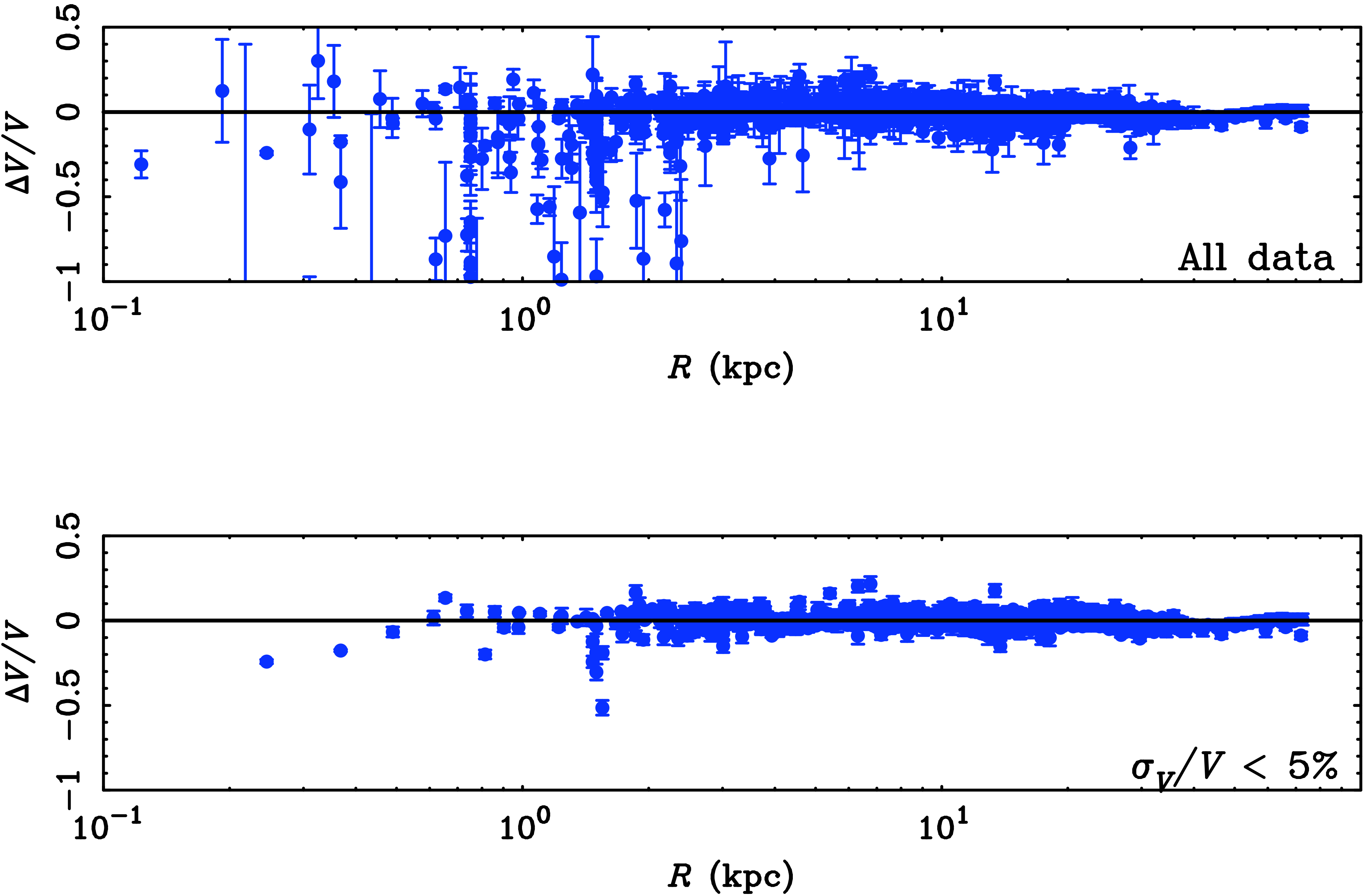
Sanders & McGaugh 2002, *ARA&A*, **40**, 263

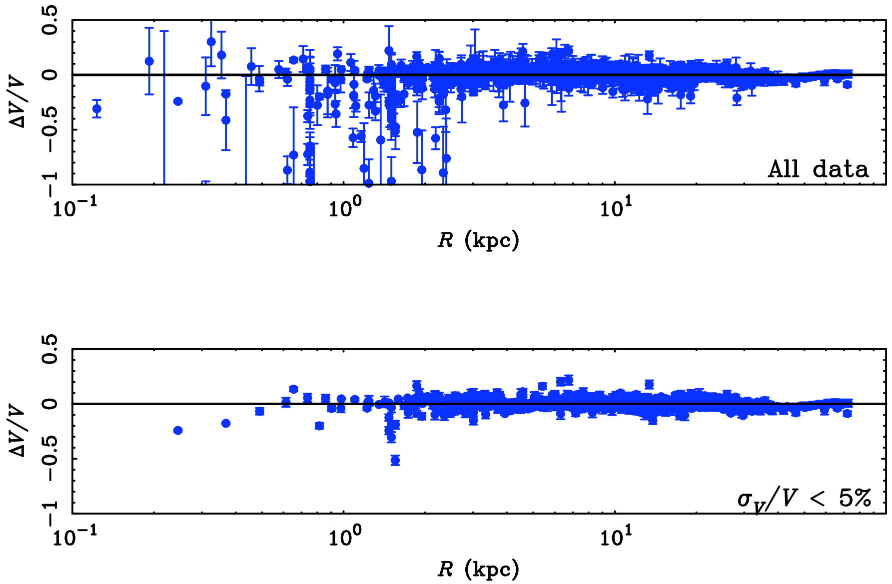


Sanders & McGaugh 2002, *ARA&A*, **40**, 263



Residuals of MOND fits





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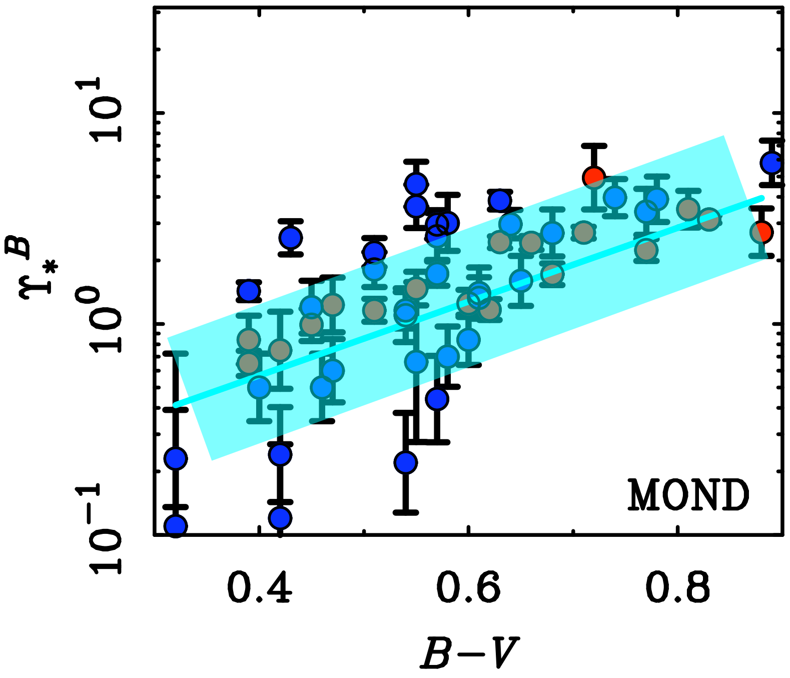
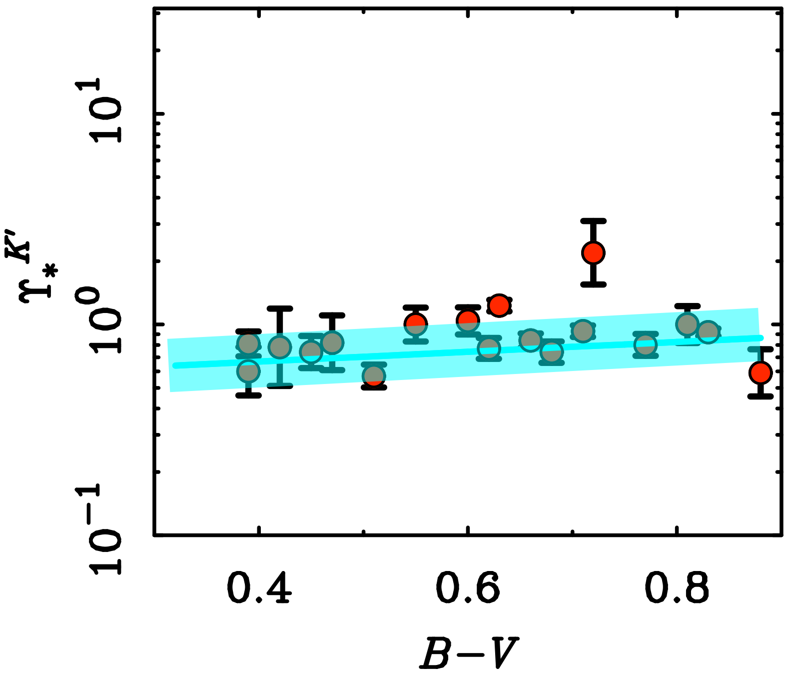
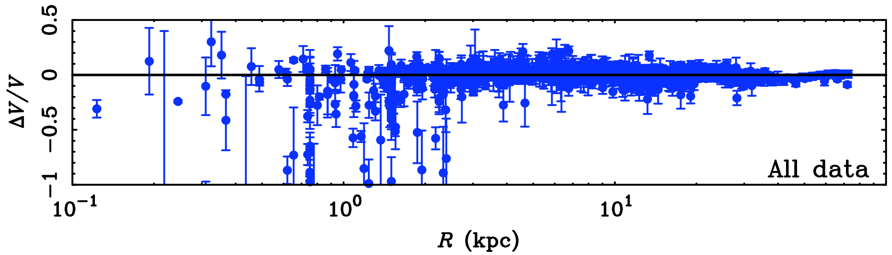
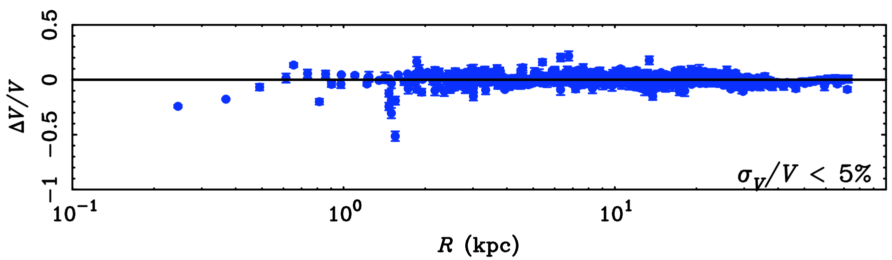


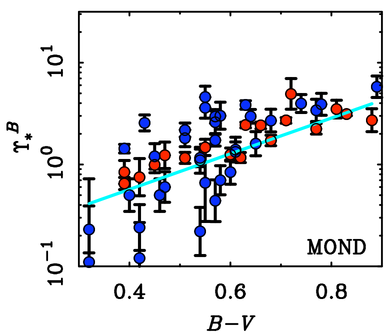
Line: stellar population model
(mean expectation)

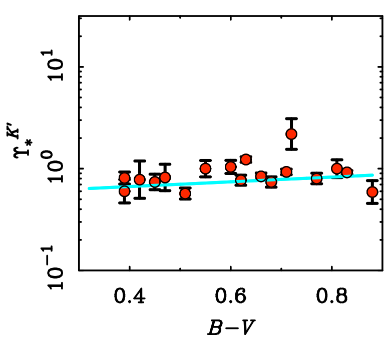


MOND predictions









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Observational Test	Dark Matter	MOND
LSBG Tully-Fisher Relation	??	+
M/L-Surface Brightness Relation	X	+
Stellar Mass to Light Ratios	NP	+
Mass Surface Densities	X	+
Local M/L	NP	+
Transition Radii	NP	+
Characteristic Accelerations	NP	+
Disk-Halo Conspiracy	X	+
Rotation Curve Shapes	X	+
Rotation Curve Rate of Rise	X	+
Rotation Curve Fits	X - NFW	+
Thin LSB Disks	X	+
Disk Stability	??	?
Dwarf Spheroidal Galaxies	NP	+
Giant Elliptical Galaxies	X	NT
Galaxy Clusters	?	??
Gravitational Lensing	?	??
Large Scale Structure	?	?
[illegible]	[illegible]	[illegible]

MOND works. *Either*

MOND is correct, or

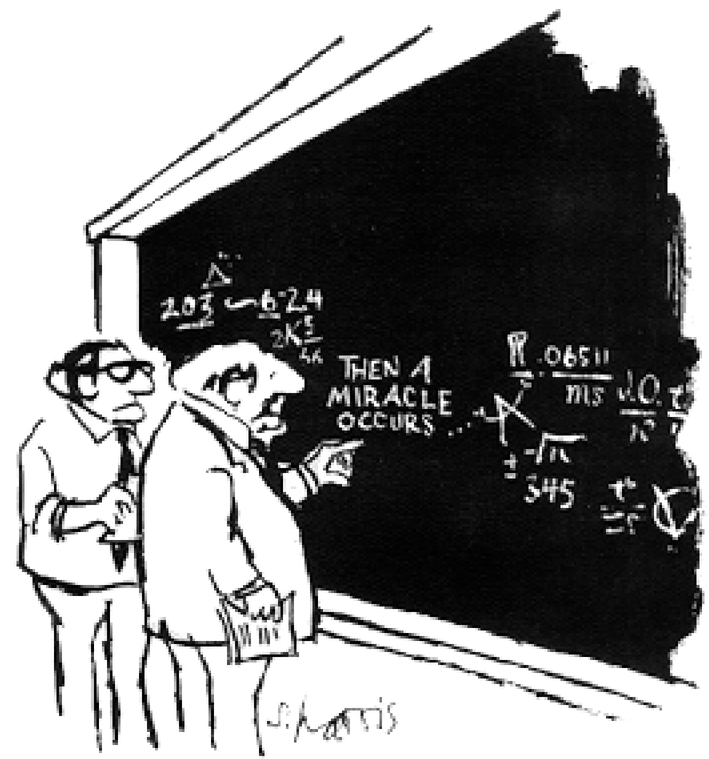
Dark Matter mimics MOND

Either way,
new physics is implicated:

- gravity?

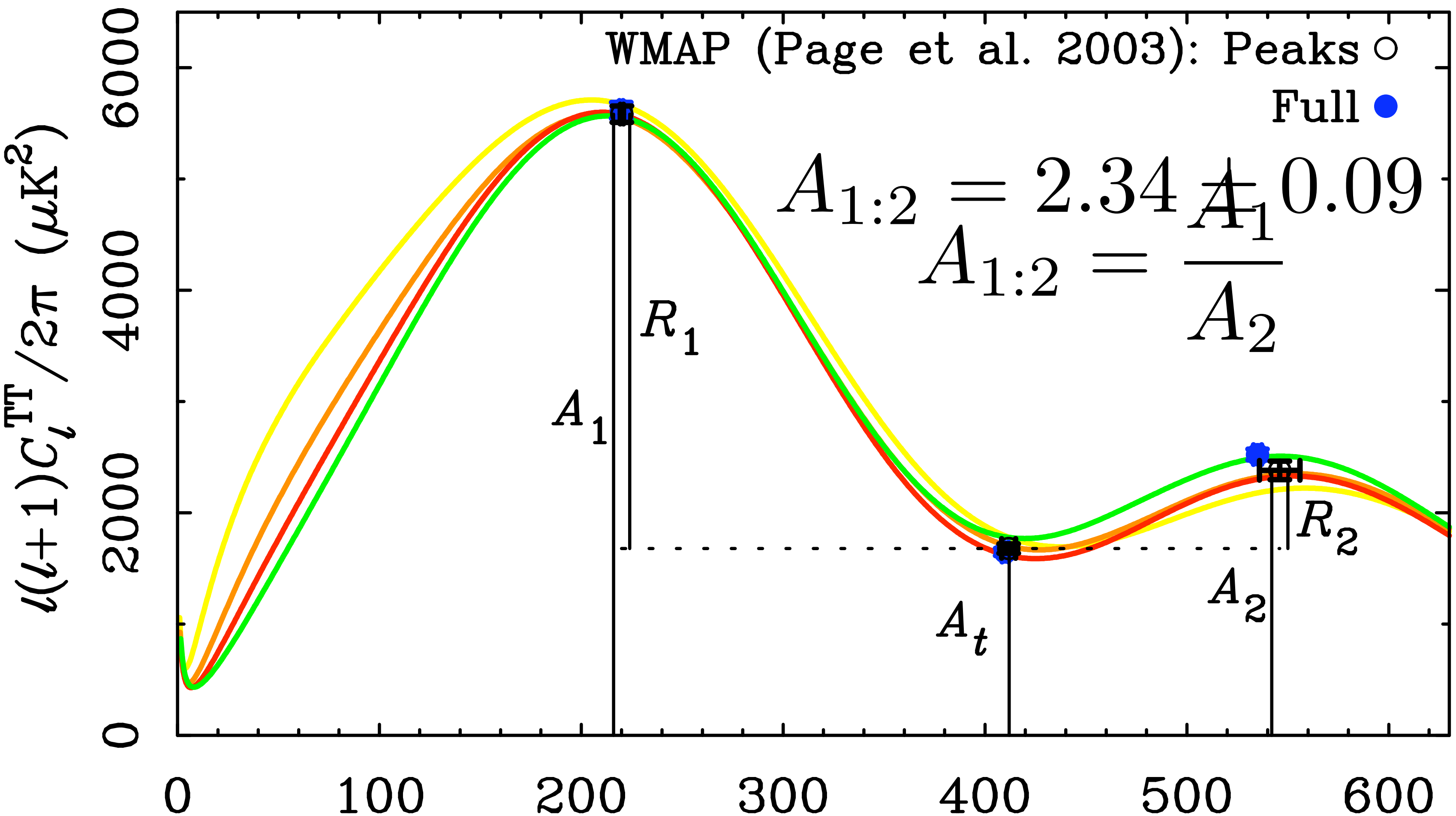
$$a_0 \sim cH_0 \sim c\Lambda^{1/2}$$

- new properties of dark matter?



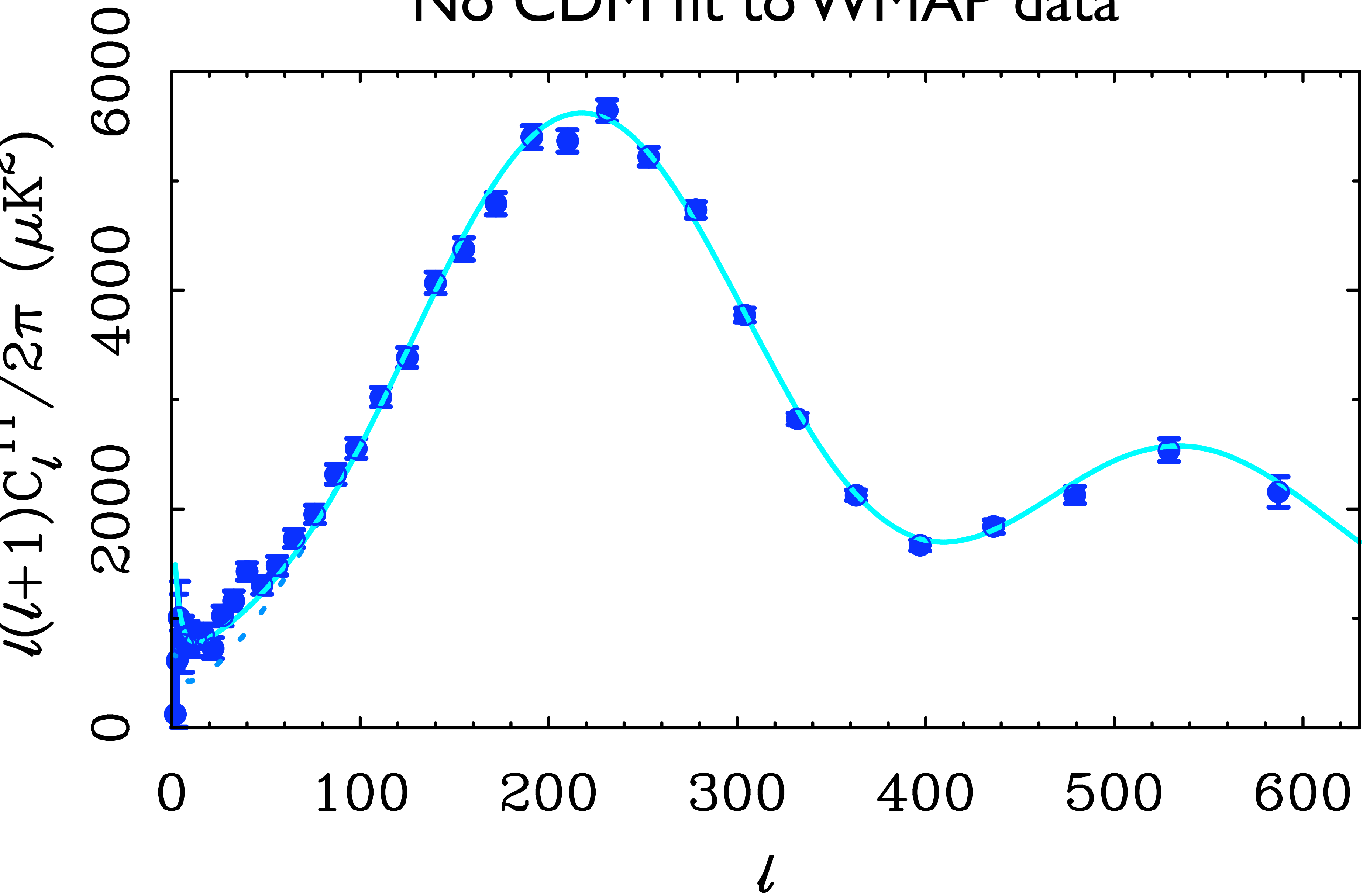
"I think you should be more explicit here in step two."

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

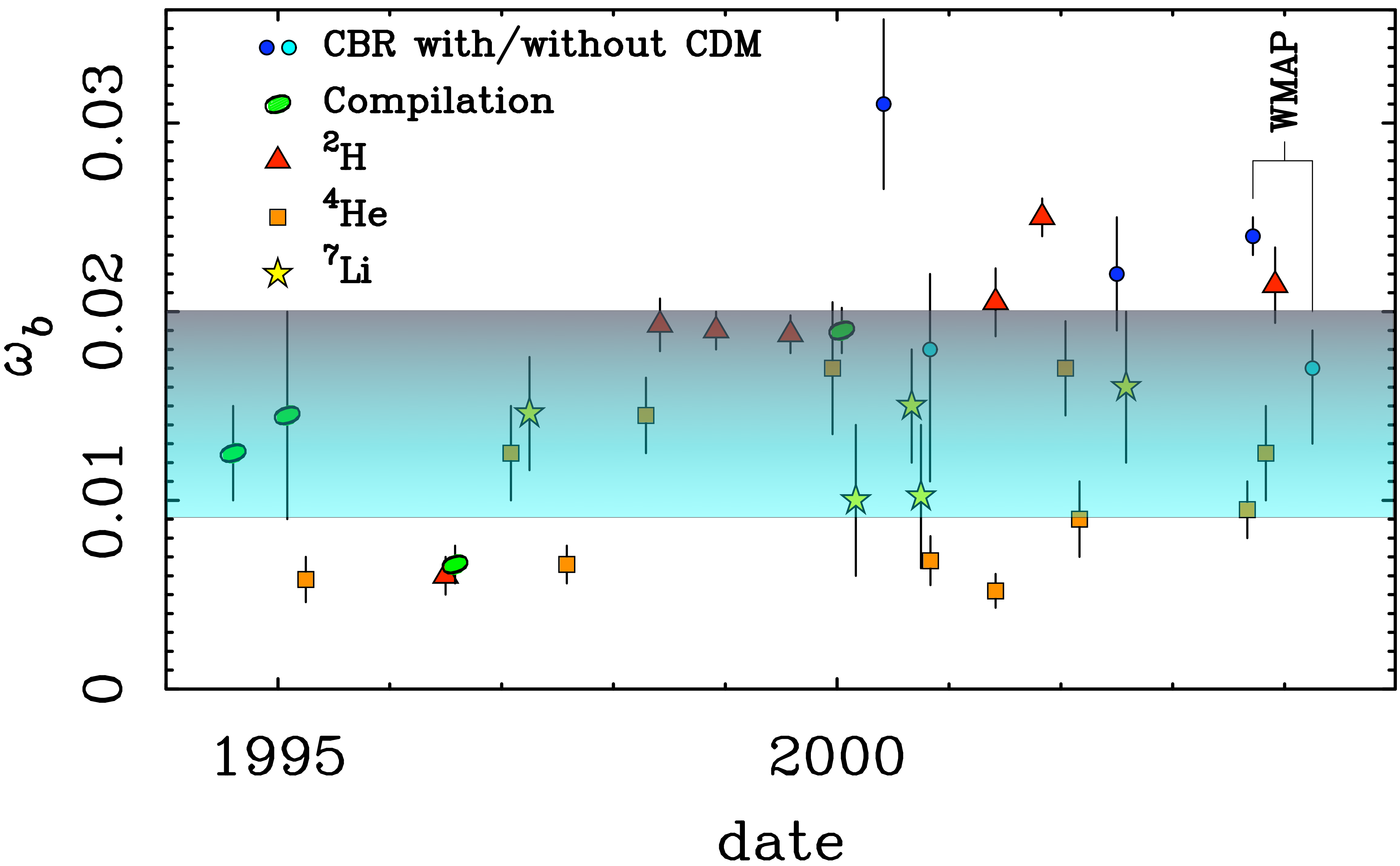


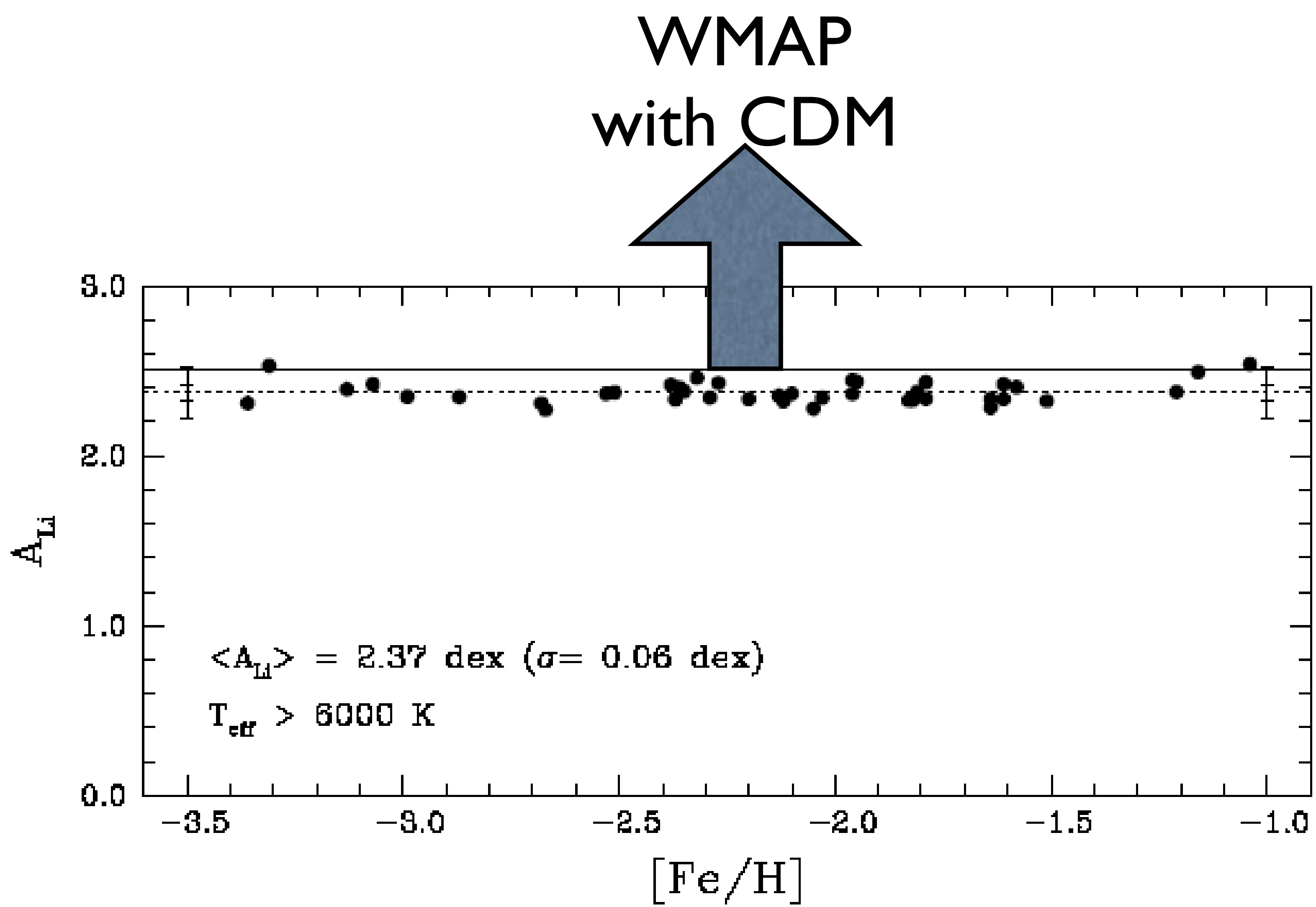
Model	$L_{2:1}$	$A_{1:2}$	$R_{1:2}$
1999 LCDM	2.4	1.8	3.5 *
No CDM	2.6	2.4	5.4 *
WMAP Data	2.48	2.34	5.56

No CDM fit to WMAP data

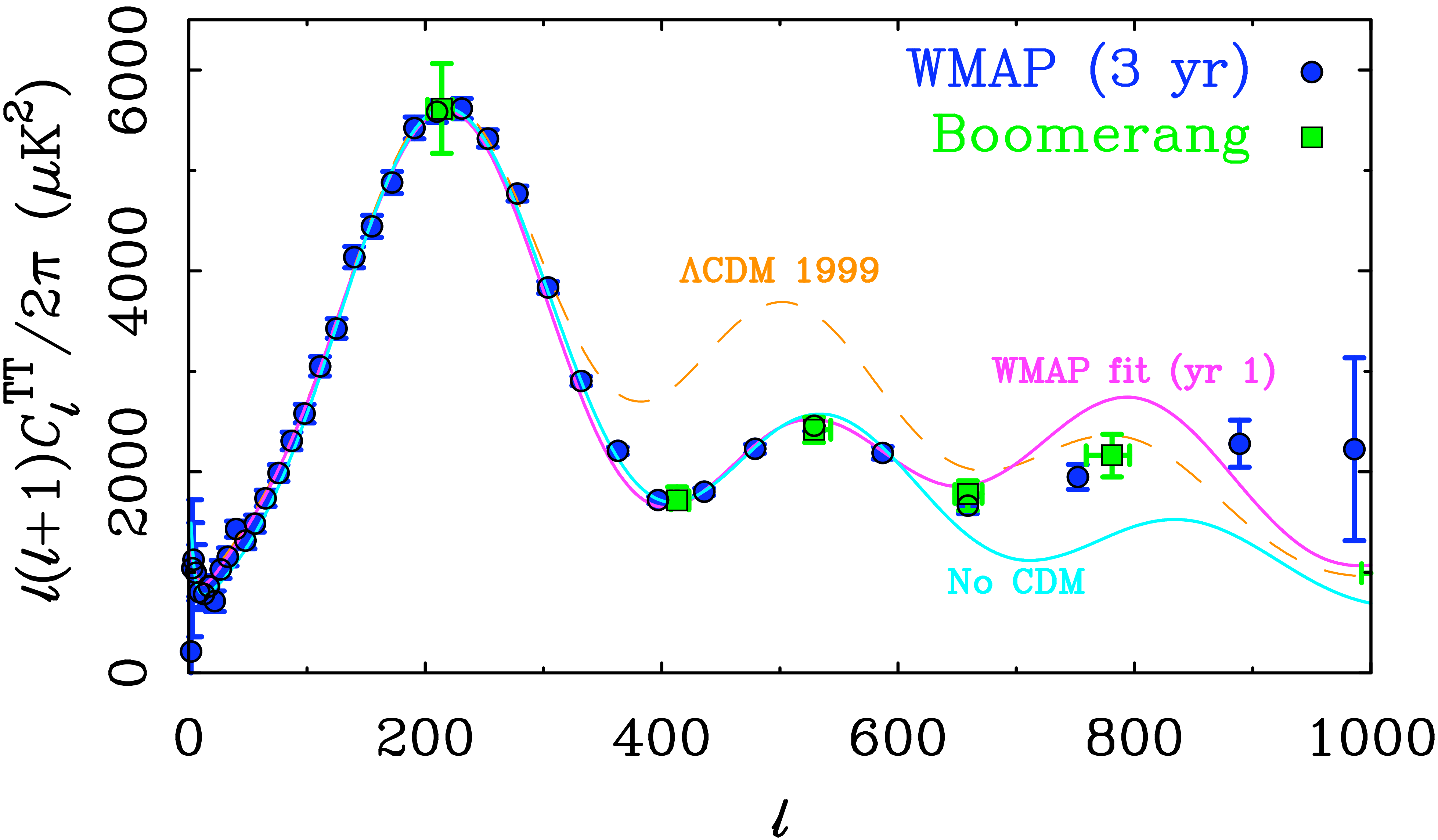


BBN: $\omega_b = \Omega_b h^2 \propto \eta_{10}$

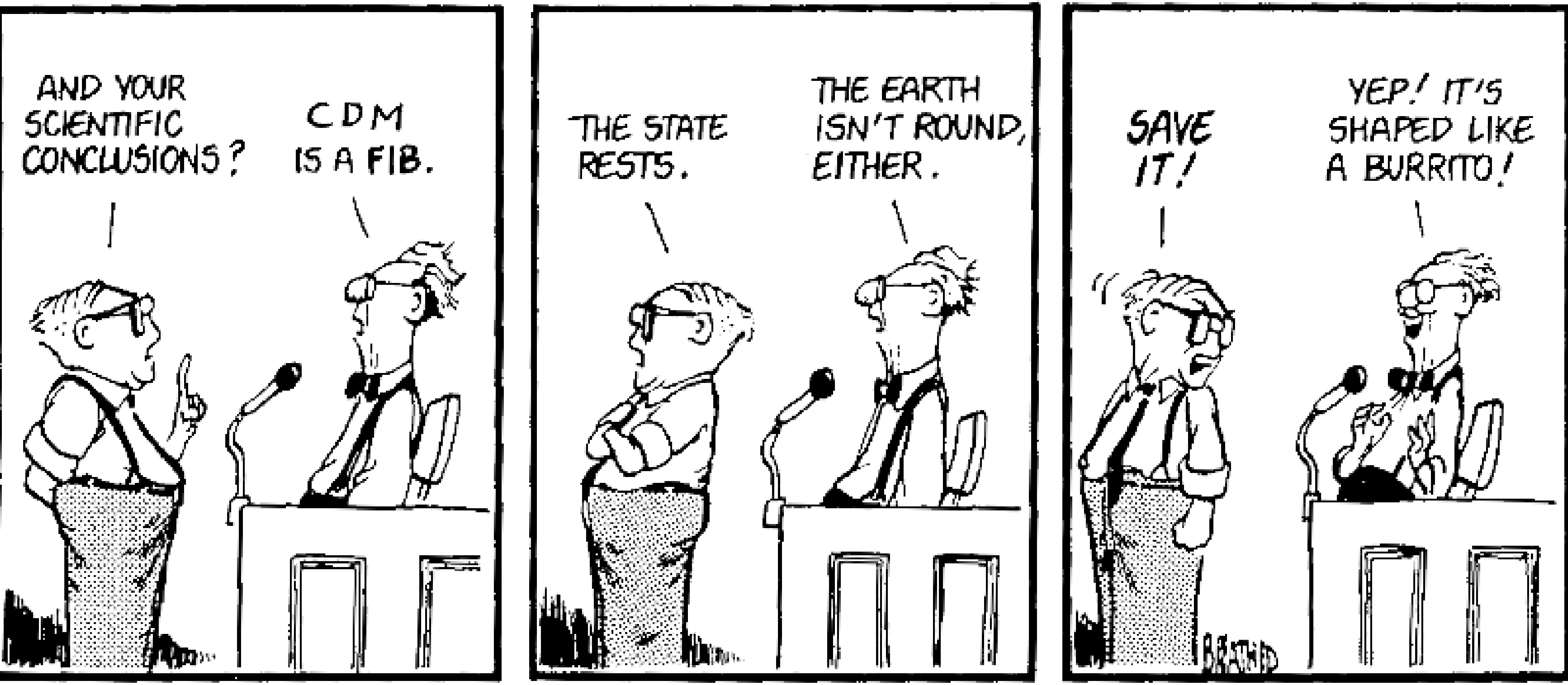




WMAP
with CDM
3.0
2.0
1.0
0.0
A_Li
<A_Li> = 2.37 dex (σ= 0.06 dex)
T_eff > 6000 K
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
[Fe/H]



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


AND YOUR SCIENTIFIC CONCLUSIONS?
CDM IS A FIB.
THE STATE RESTS.
THE EARTH ISN'T ROUND, EITHER.
SAVE IT!
YEP! IT'S SHAPED LIKE A BURRITO!
BREATHED