Seeing Through Dark Matter

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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

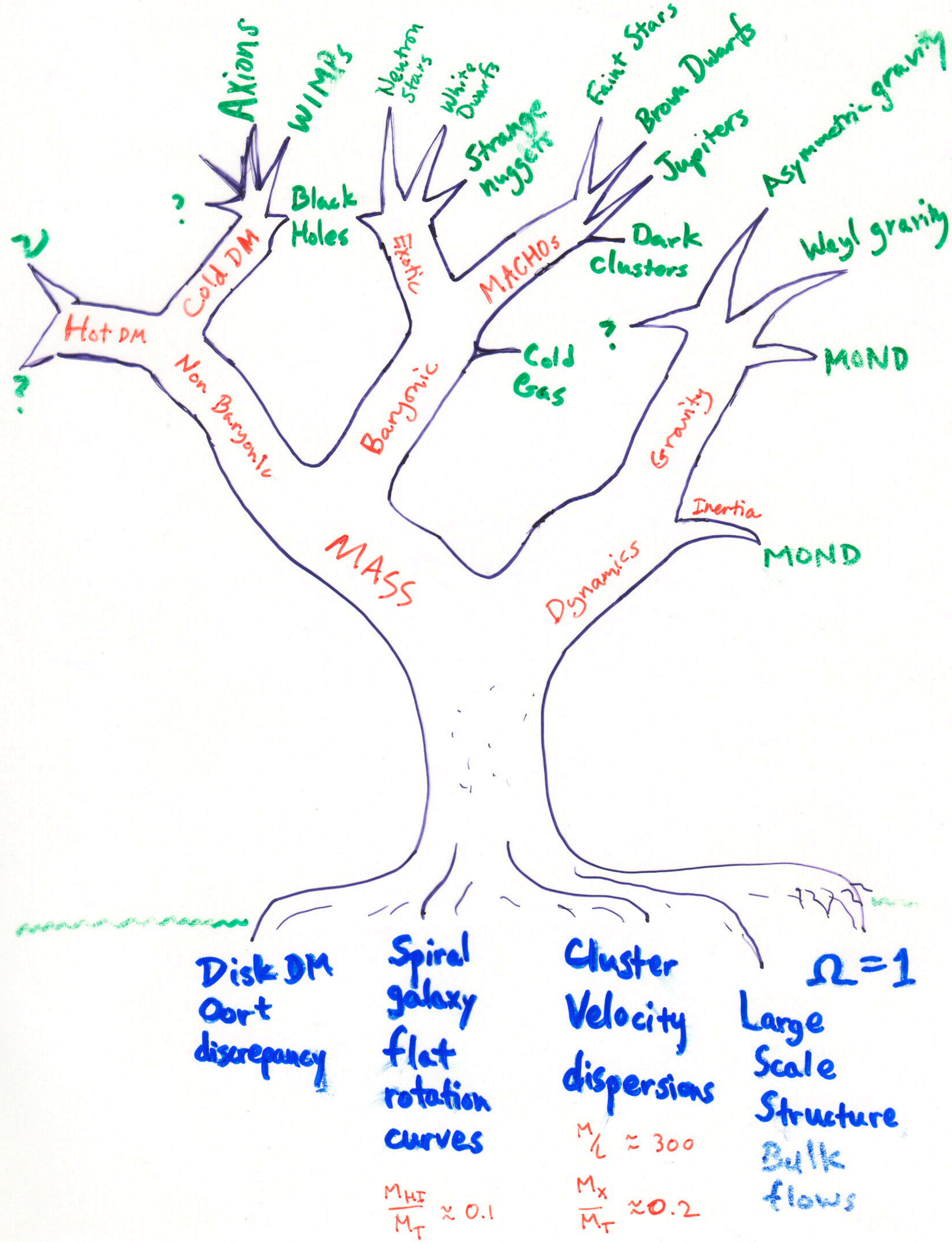
$$mV^2/R = GMm/R^2$$

i.e,

$$V^2 = GM/R$$

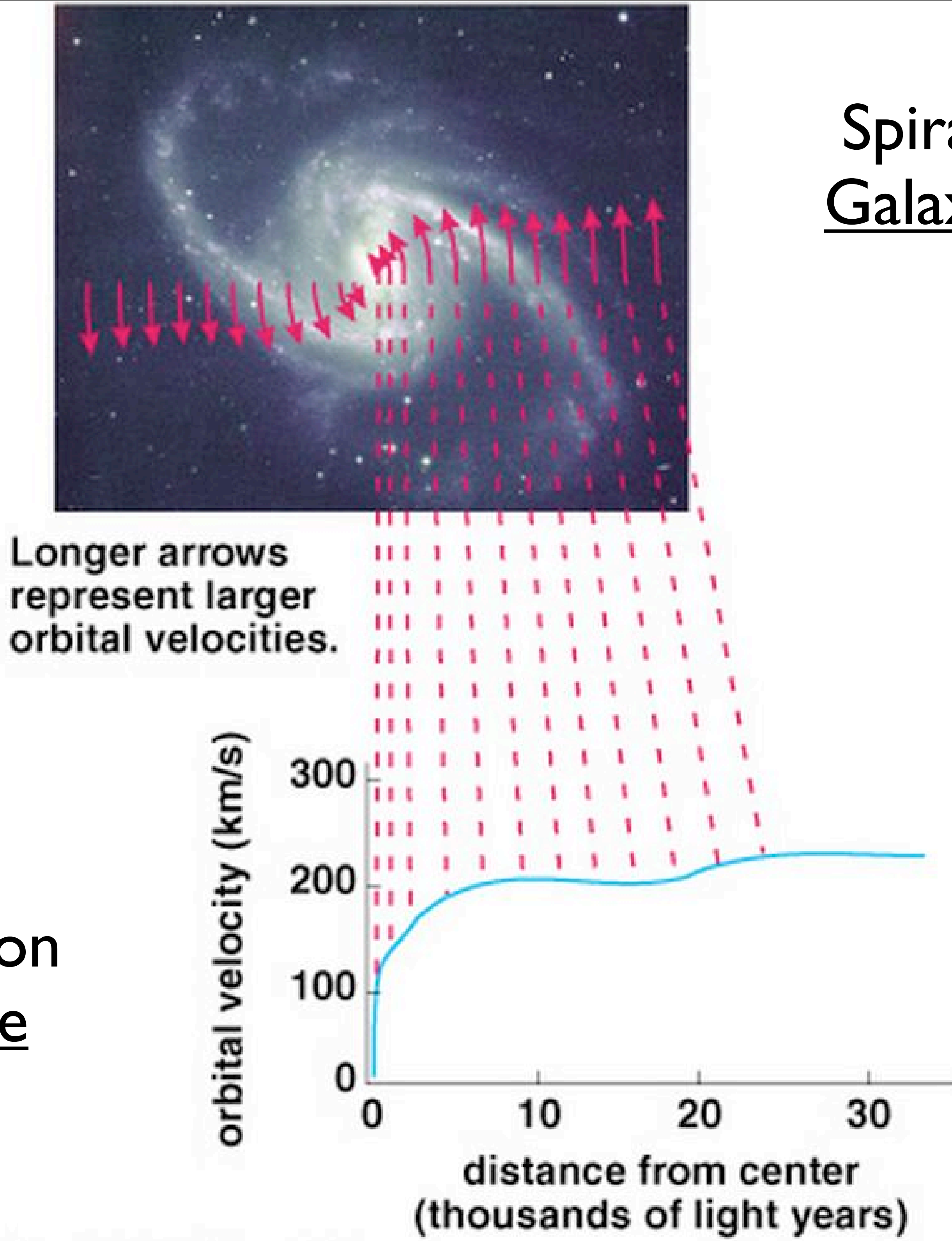
ergo...

The universe is filled with nonbaryonic cold dark matter.

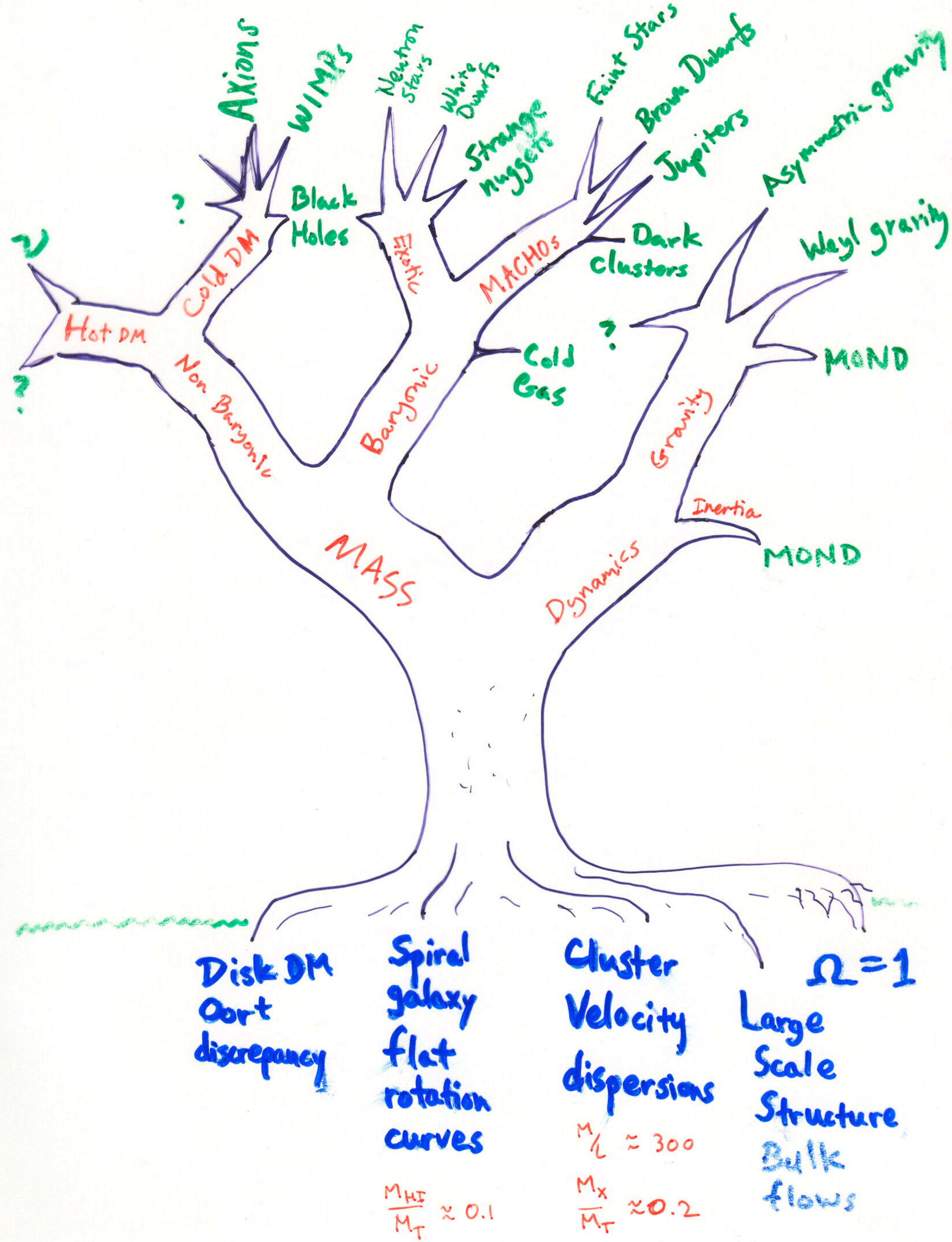


Axions
WIMPs
Neutron Stars
White Dwarfs
Faint Stars
Brown Dwarfs
Jupiters
Asymmetric gravity
Strange nuggets
Black Holes
Dark Clusters
Weyl gravity
Cold DM
Exotic
MACHOs
Hot DM
?
?
?
?
Cold Gas
MOND
Non Baryonic
Baryonic
Gravity
Inertia
MOND
MASS
Dynamics
Disk DM Oort discrepancy
Spiral galaxy flat rotation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

Spiral
Galaxy



Rotation
Curve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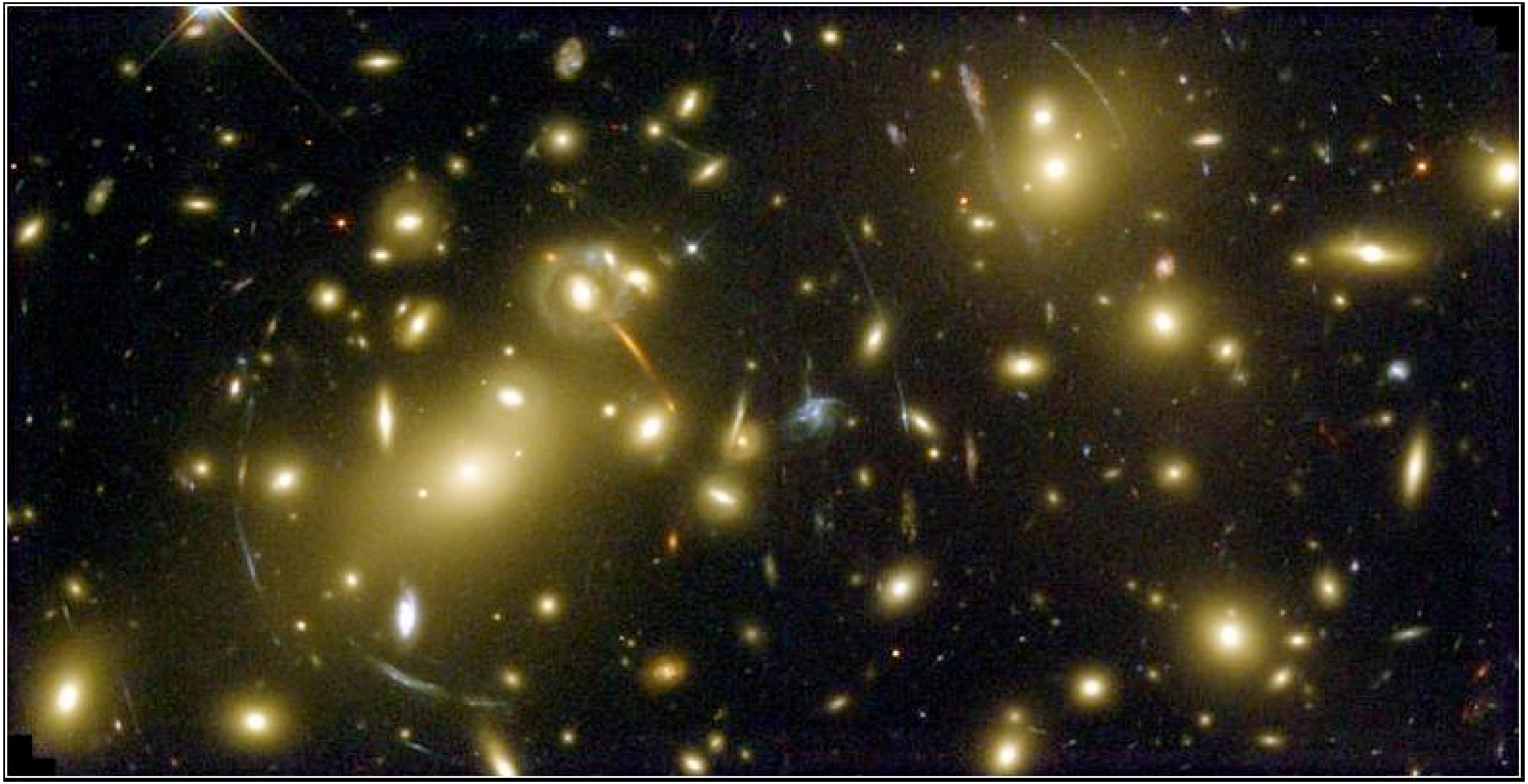
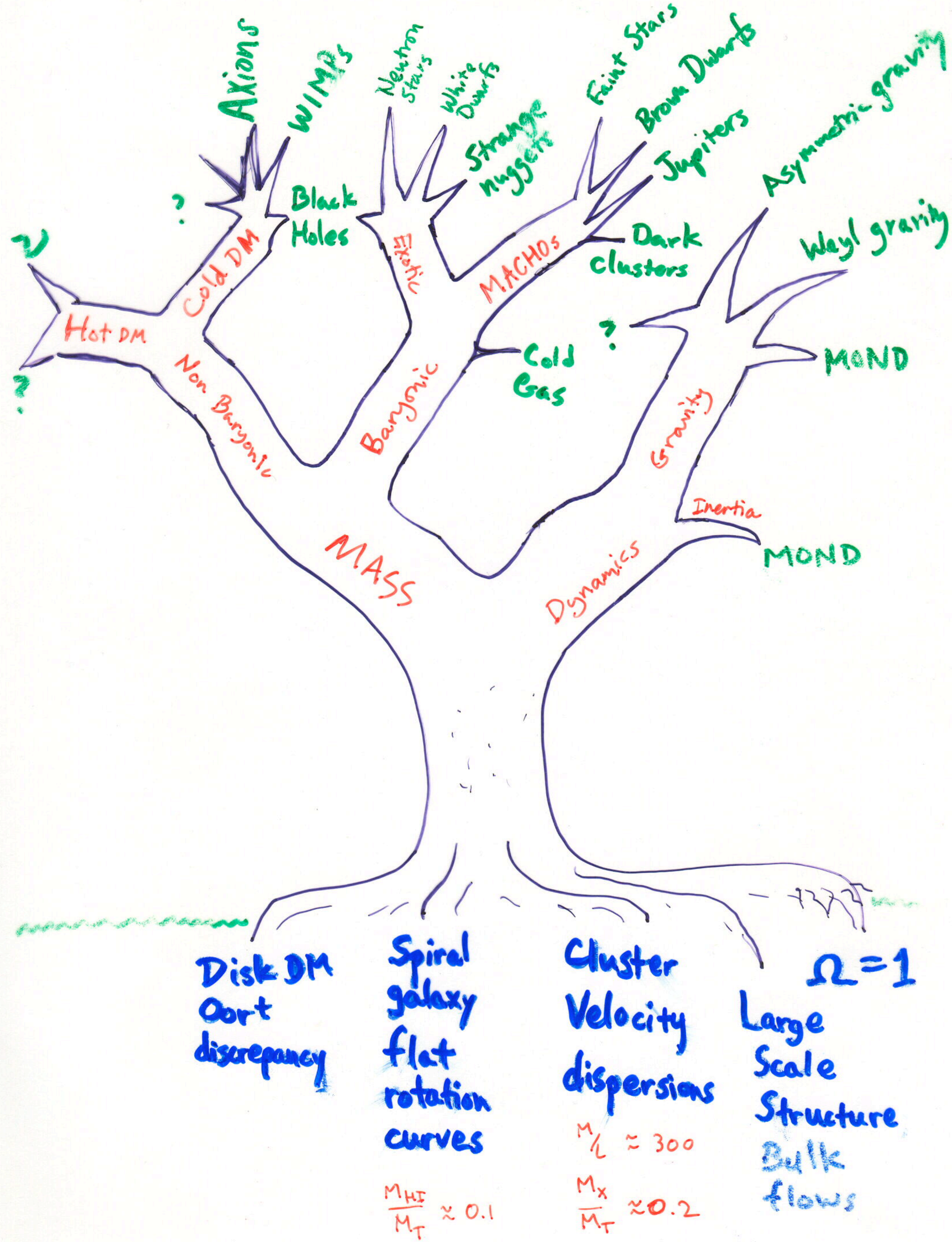
Large Scale Structure
Bulk flows

Galaxy Cluster

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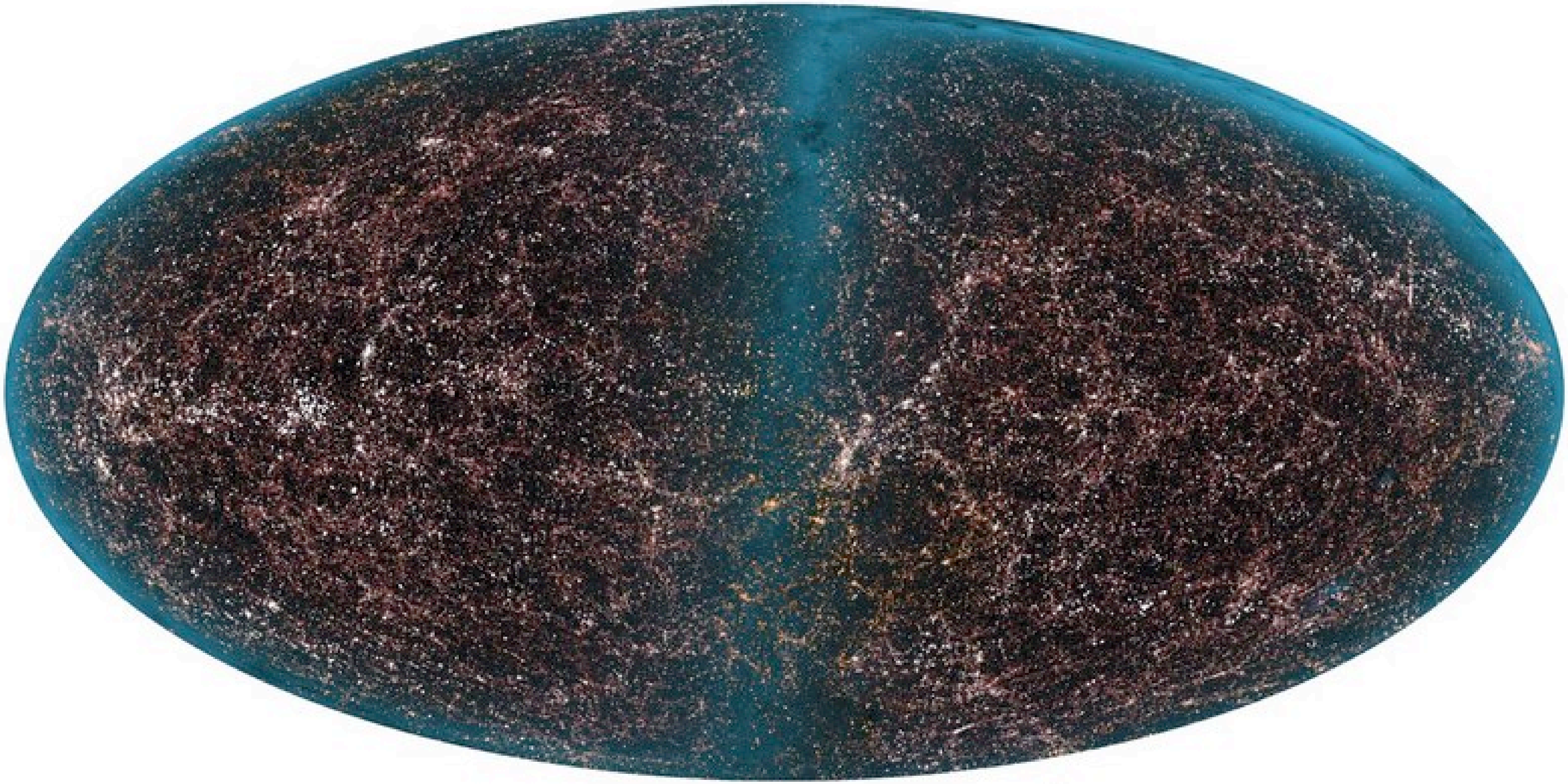
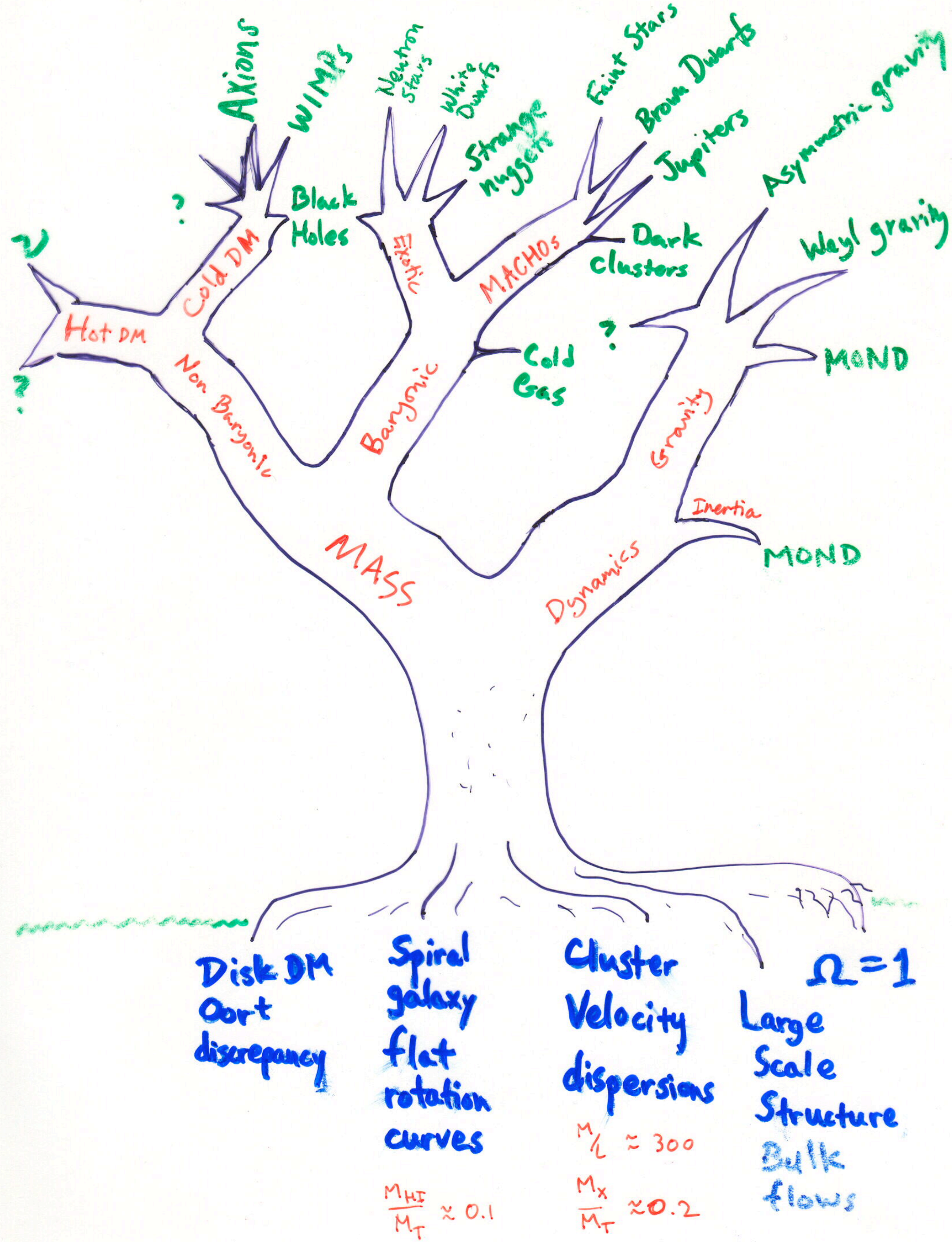
Large Scale Structure





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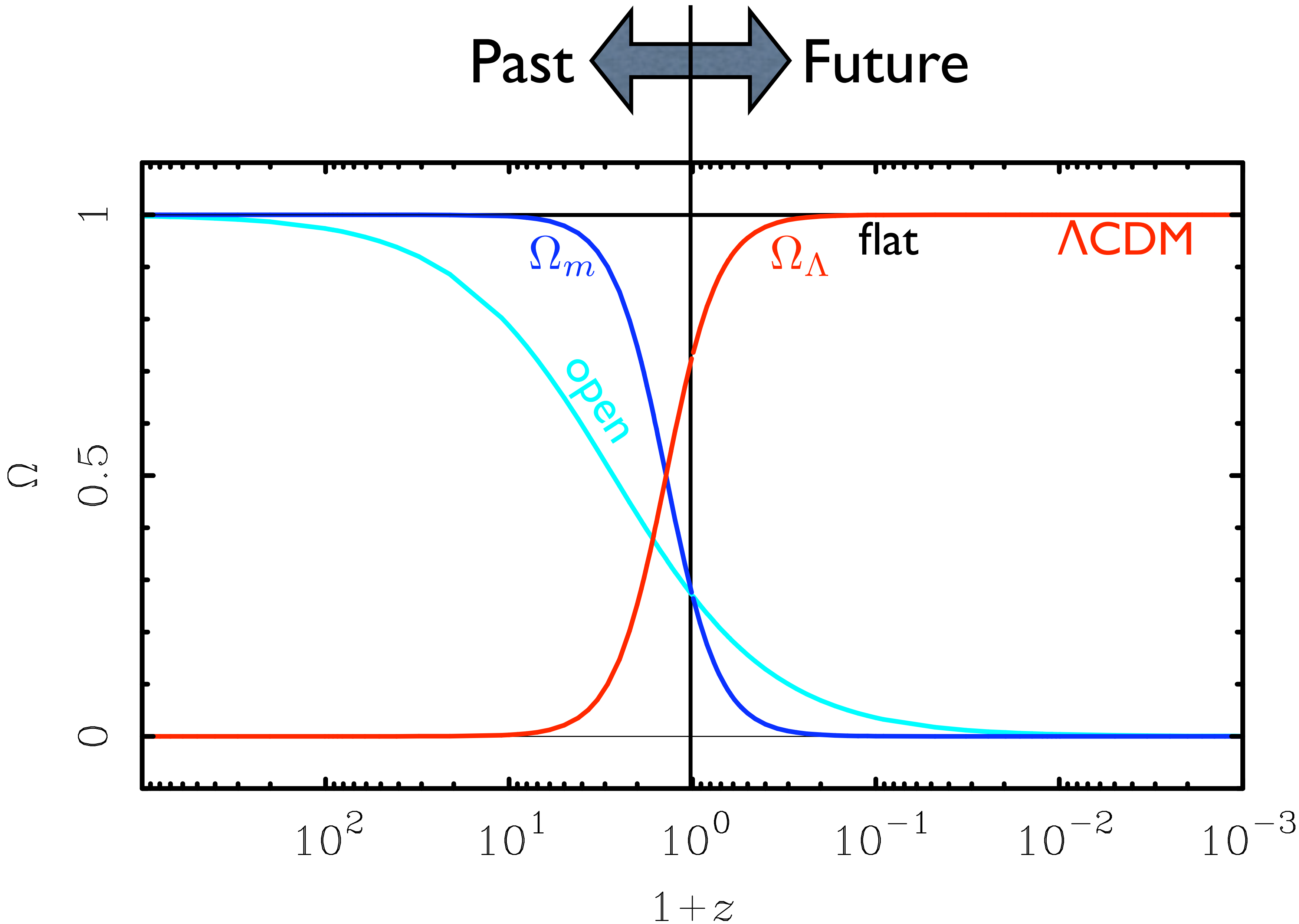
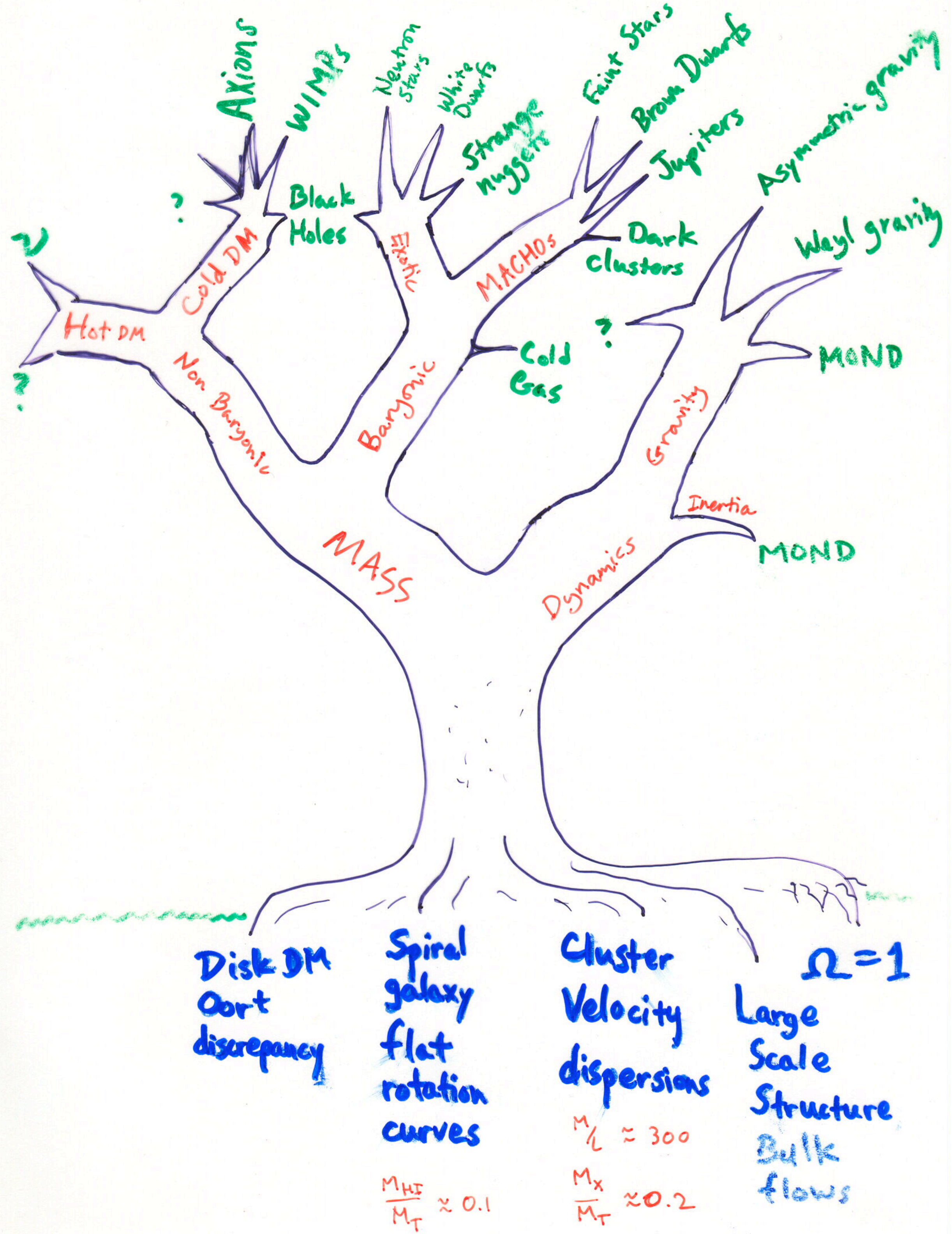


Past
Future
1
0.5
0
Ω
Ω_m
Ω_Λ
flat
ΛCDM
open
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$1+z$



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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
(phase space constraint)

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:

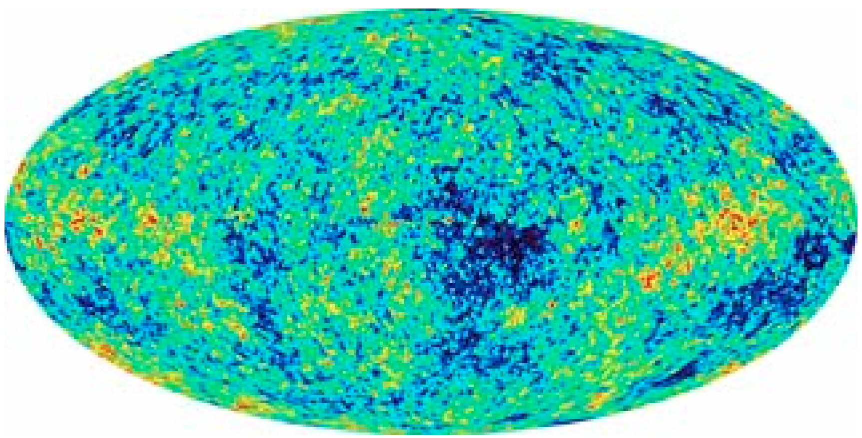
1) total mass outweighs normal mass from BBN

$$\Omega_m \approx 6\Omega_b$$

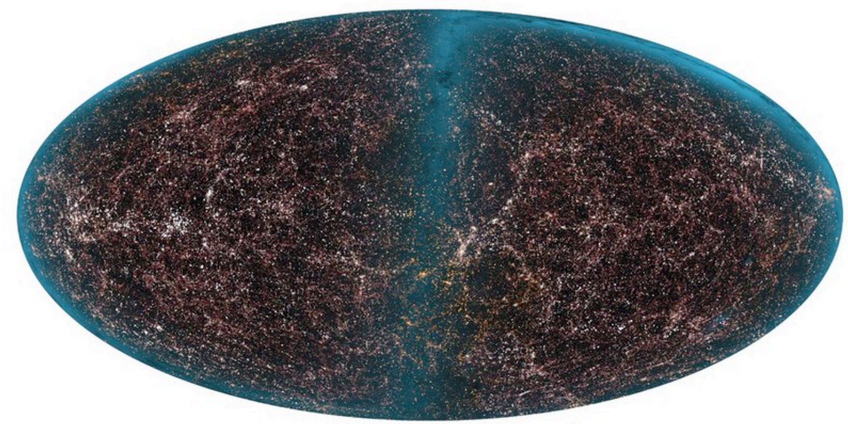
2) needed to grow cosmic structure

(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.

$t = 1.8 \times 10^5$ yr



$t = 1.4 \times 10^{10}$ yr



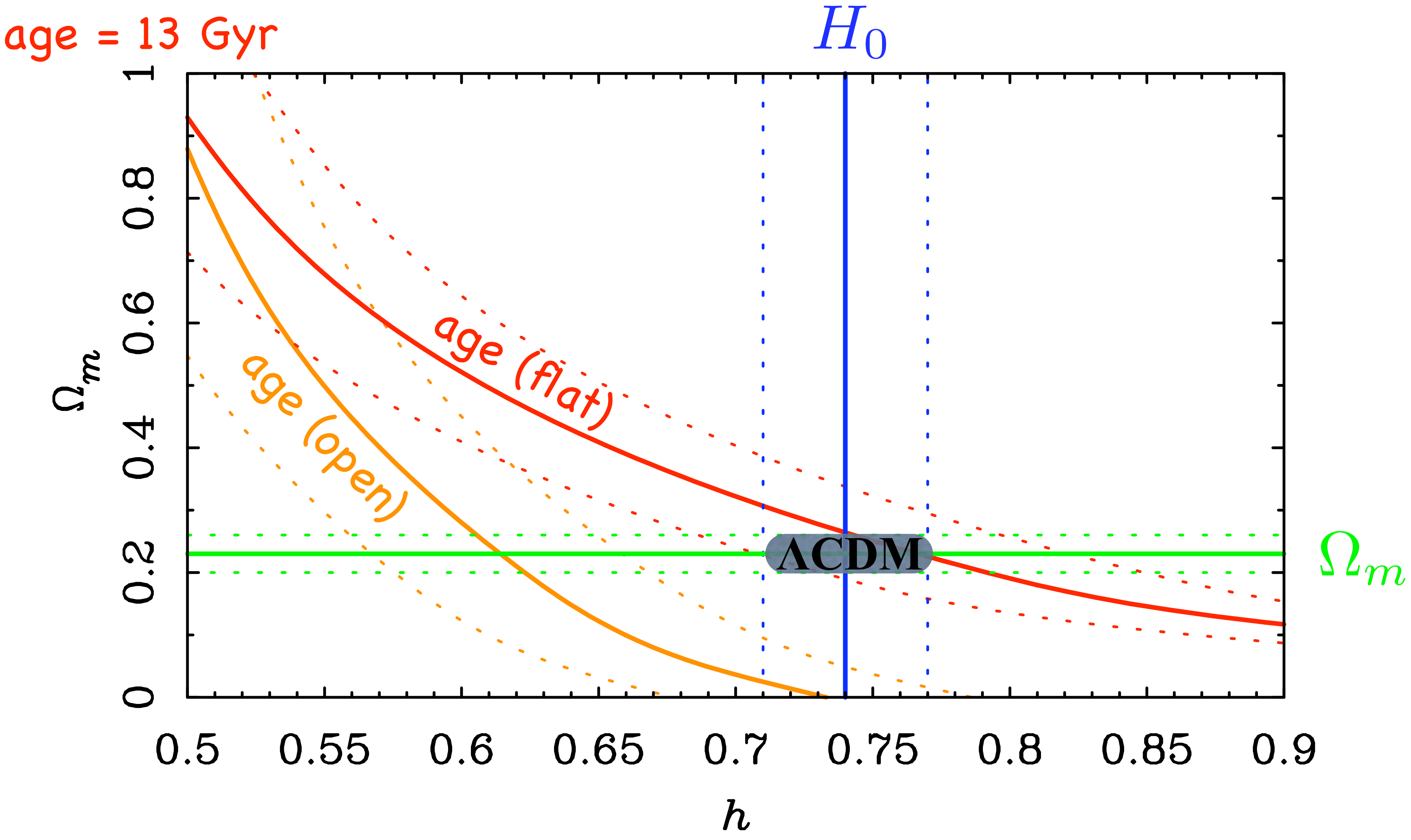
very smooth: $\delta\rho/\rho \sim 10^{-5}$

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

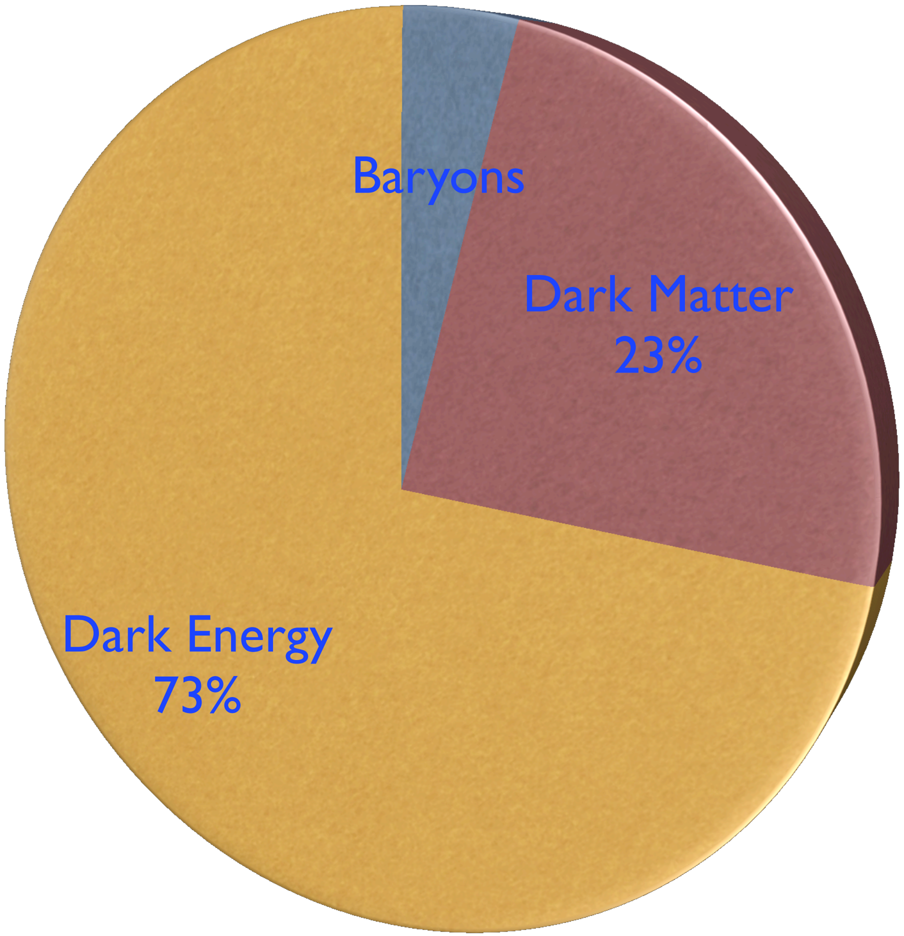
$$\delta\rho/\rho \propto t^{2/3}$$

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

Constraints predating SN, CMB



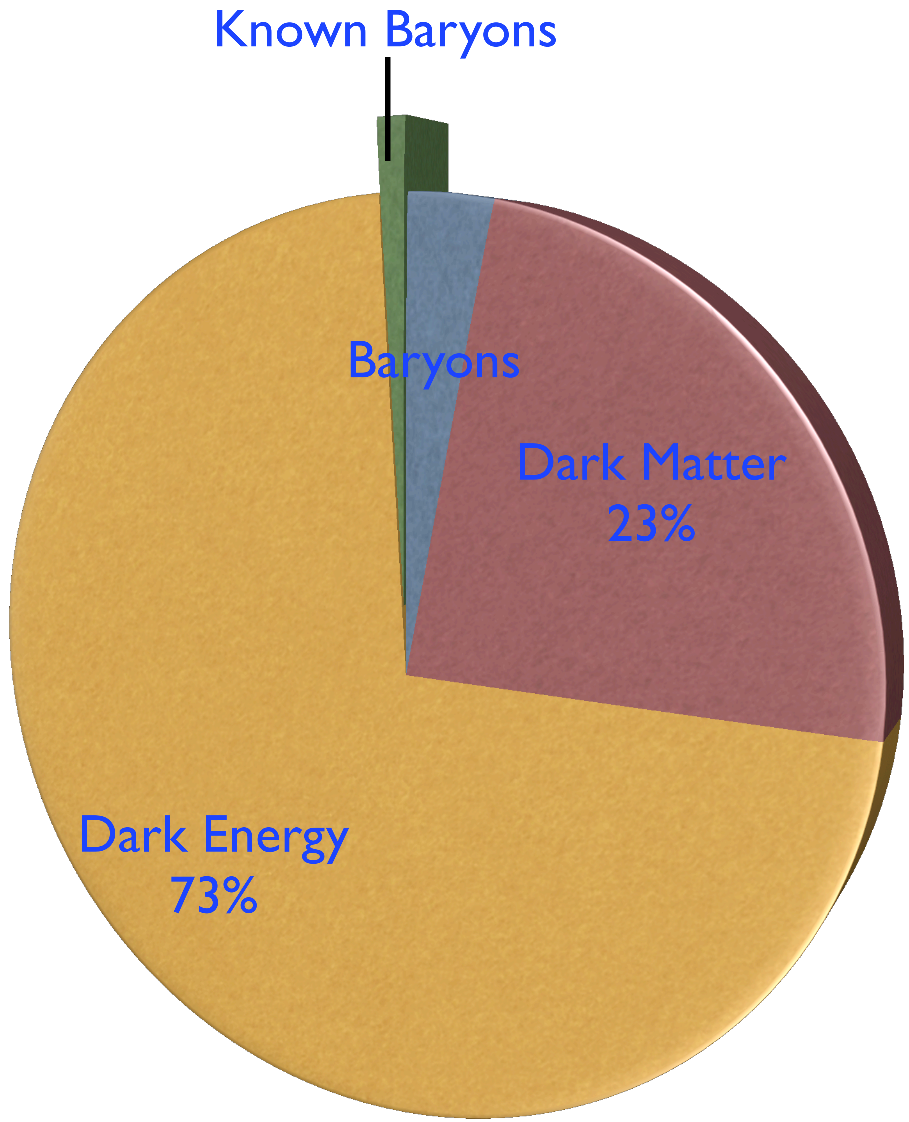
ΛCDM



Pros - Invisible Matter

- Apparently required by wide array of data
- Provides self-consistent cosmology
- Explains large scale structure
- ΛCDM model parameters well constrained

We have direct knowledge of < 1% of this stuff.



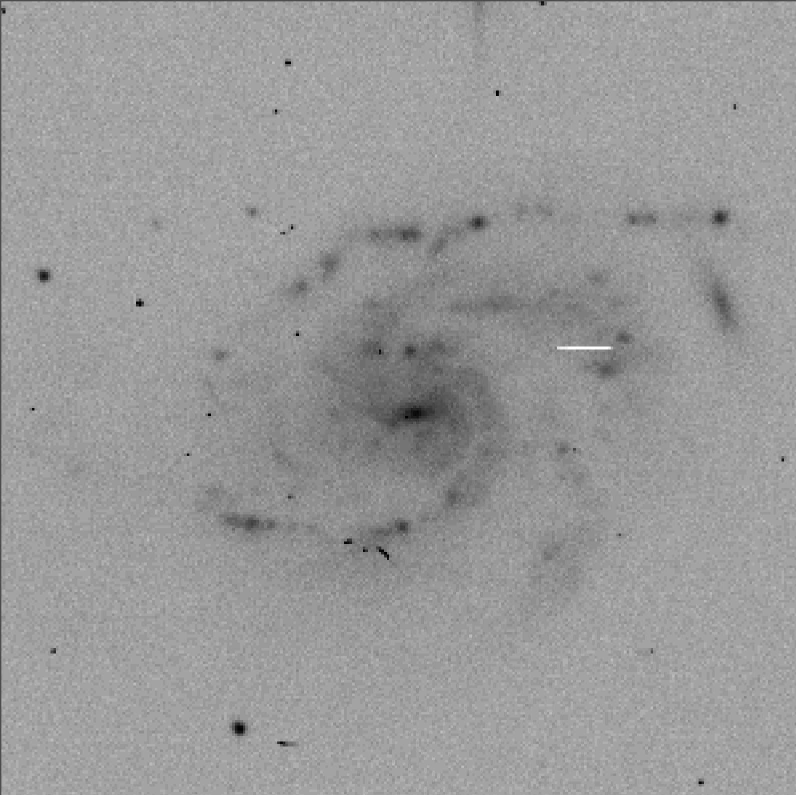
"Cosmologists are often wrong, but never in doubt"

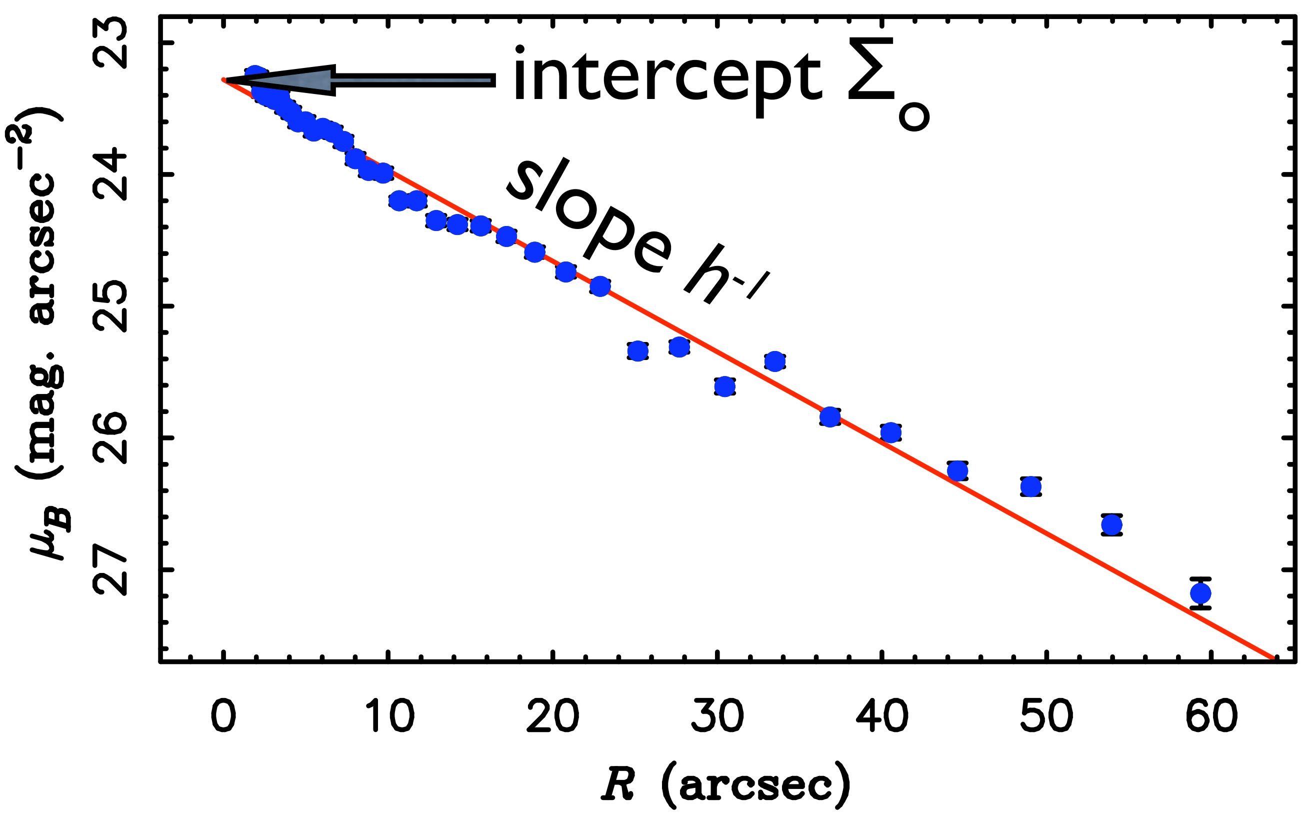
- Lev Landau

On Galaxy Scales...

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

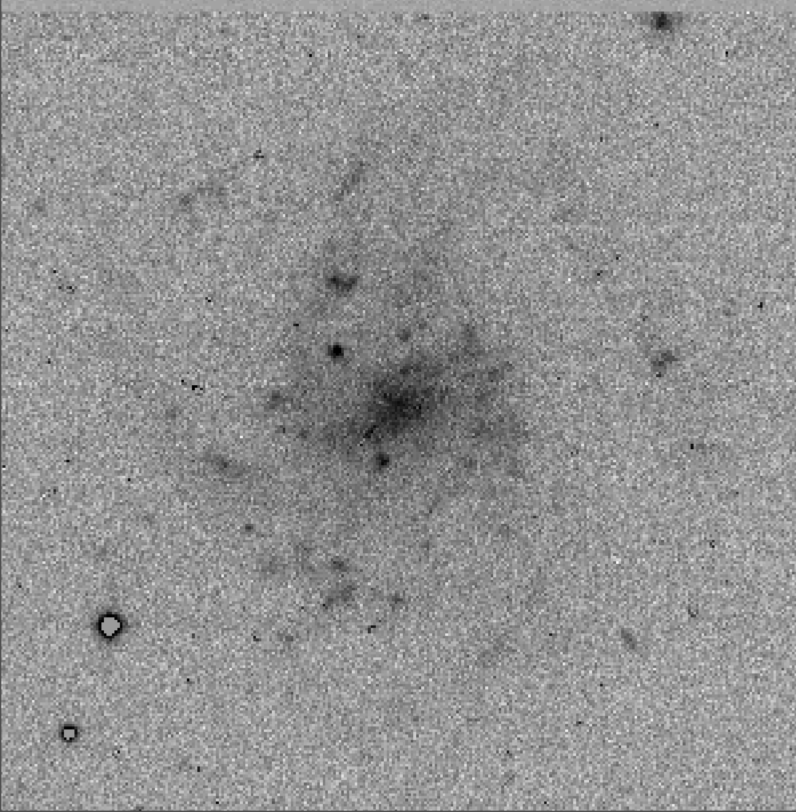
High Surface Brightness (HSB)





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

Azimuthally averaged light distribution typically exponential for spiral disks.

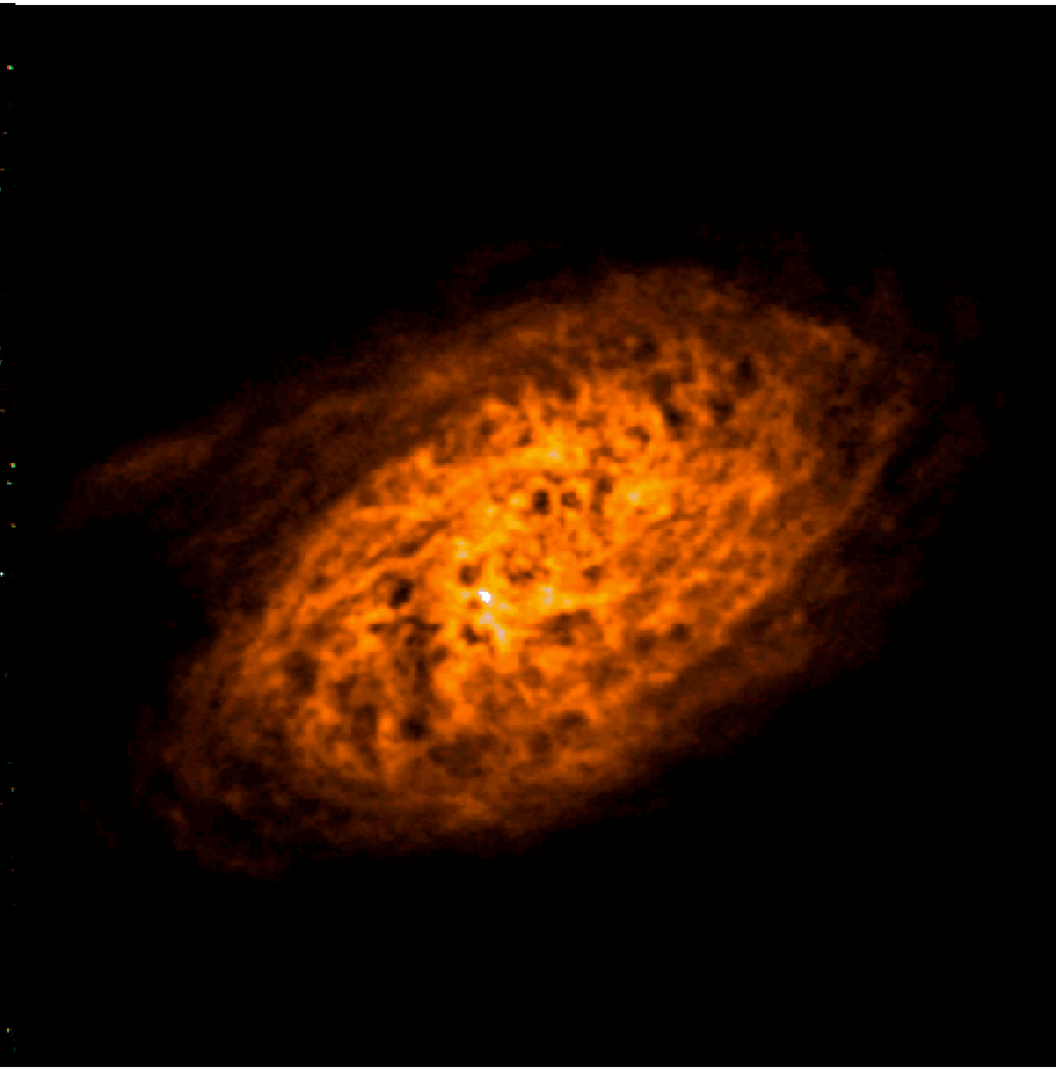


Low Surface Brightness (LSB)

NGC 2403

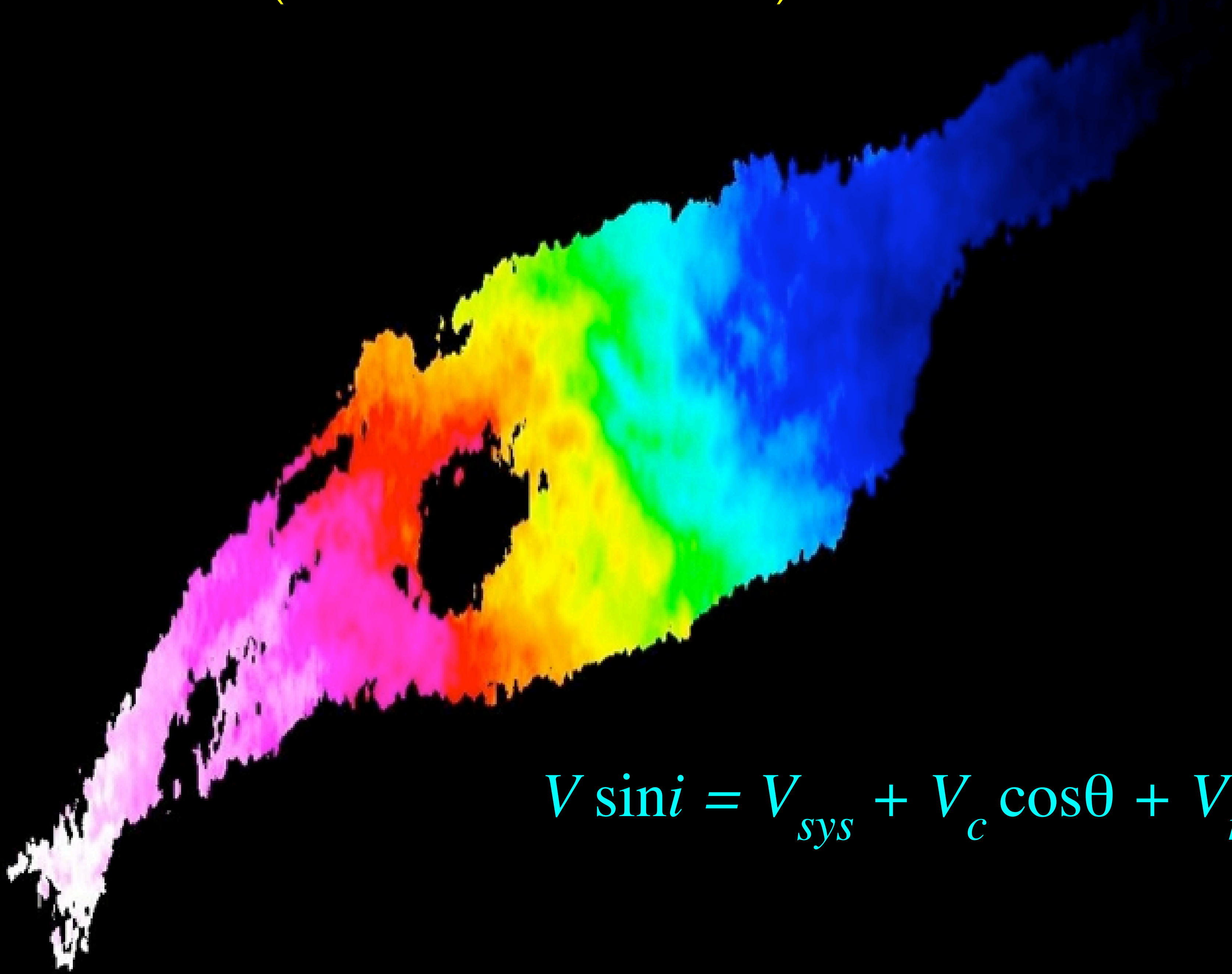
Stars

HI gas



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

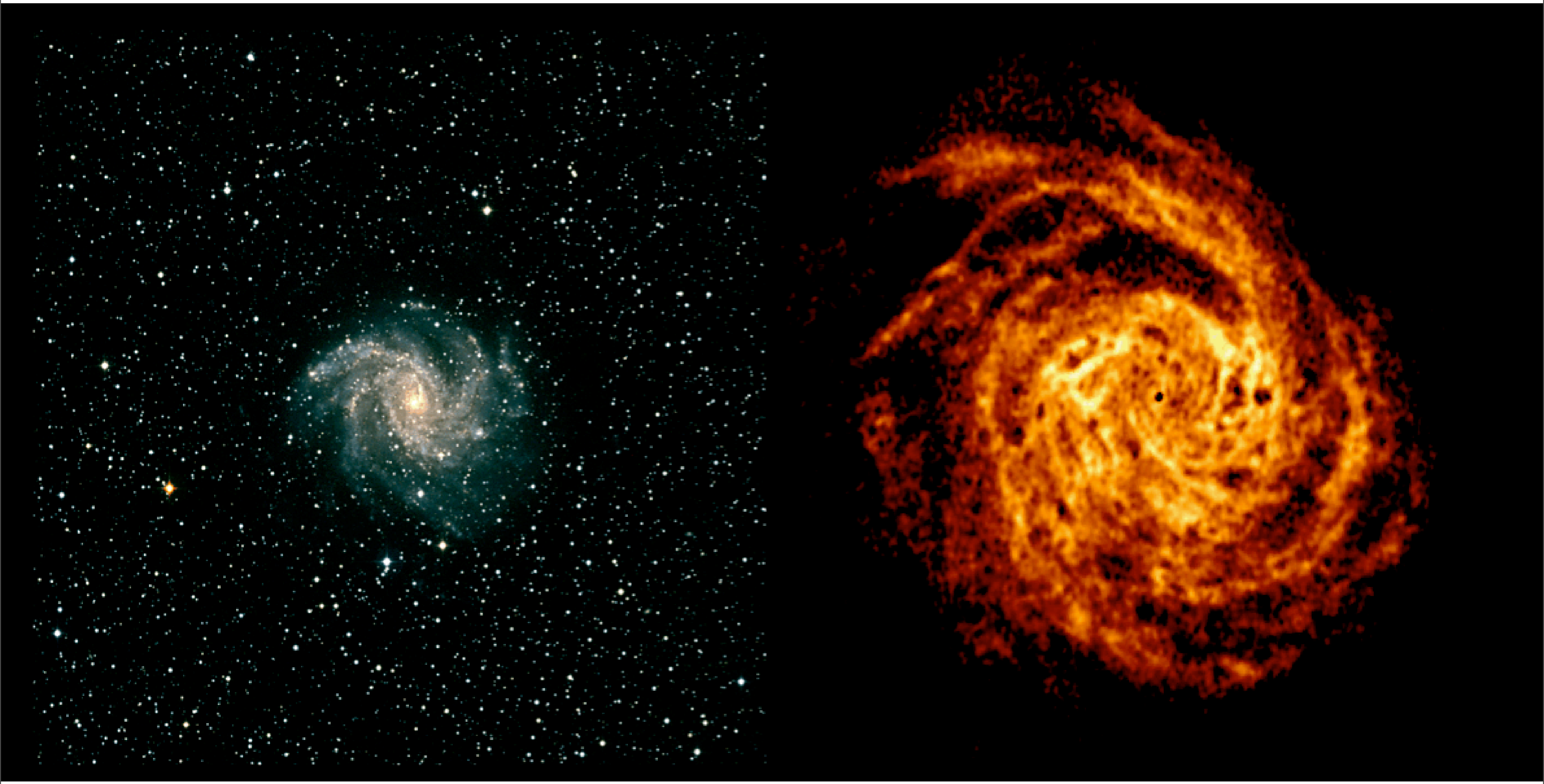
NGC 6822 (Weldrake & de Blok 2003)



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

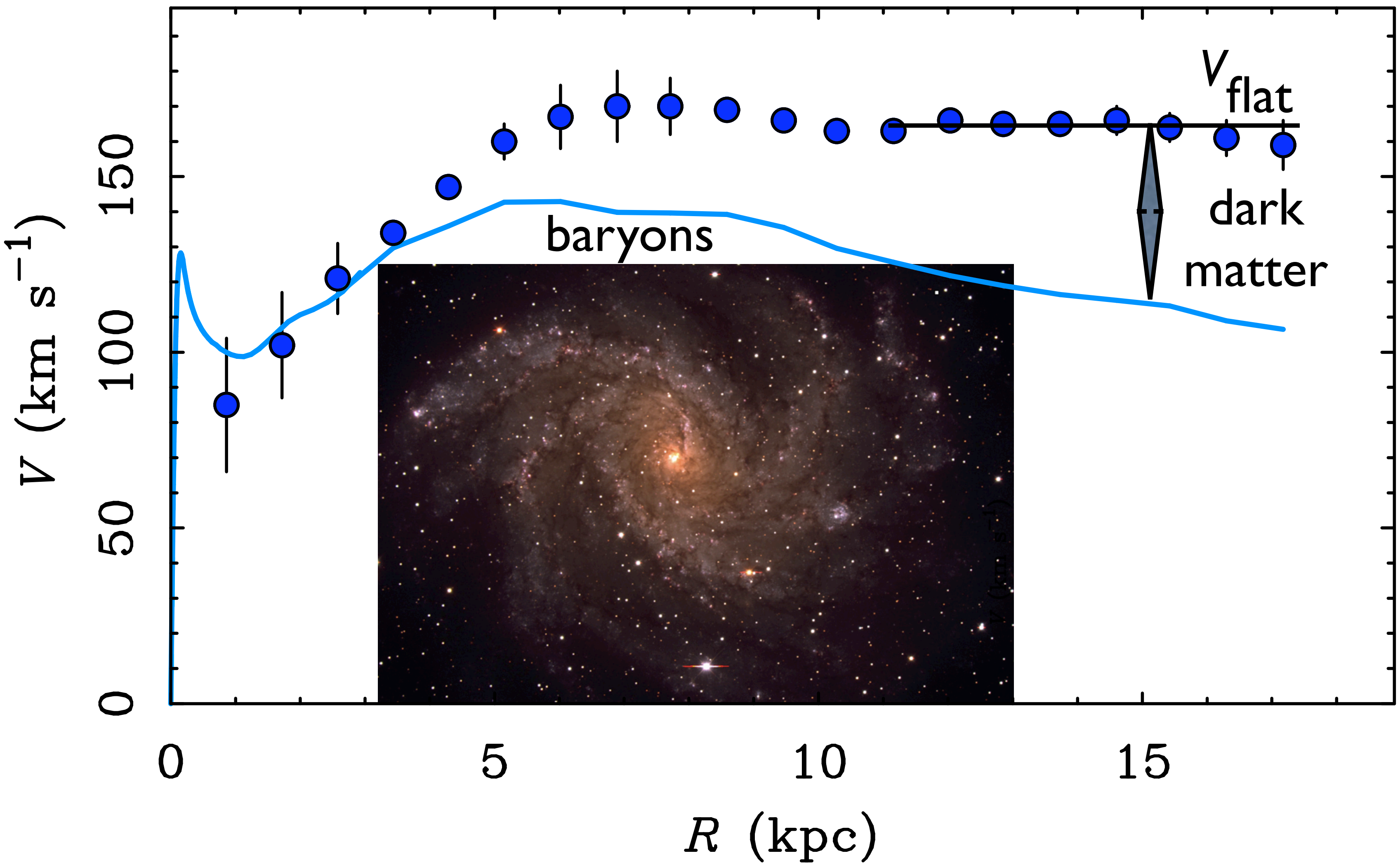
NGC 6946

Stars | Hı gas



Boomsma 2005

NGC 6946



TF Relation

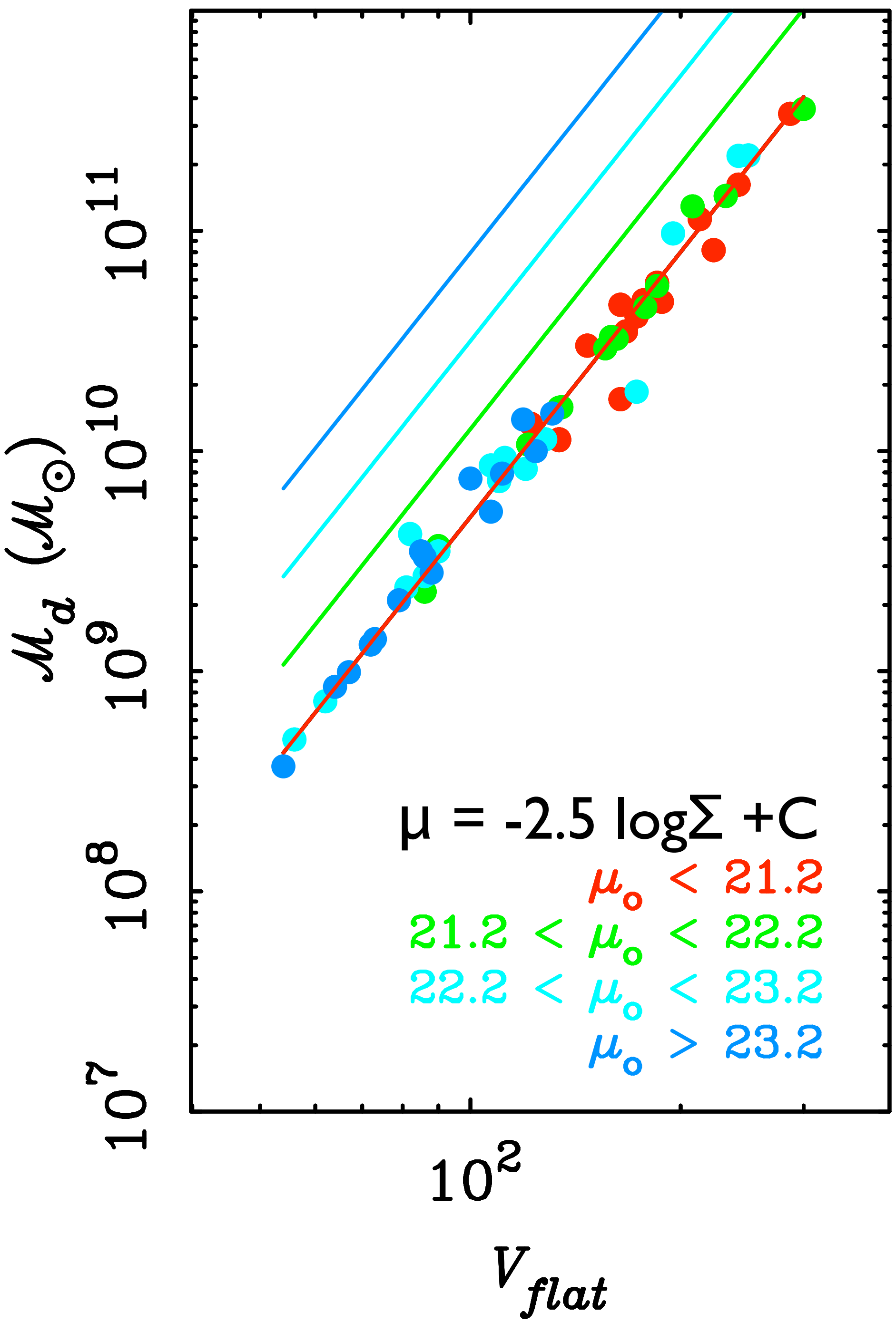
<u>Newton says</u>

$V^2 = GM/R$.

Equivalently,

$\Sigma = M/R^2$

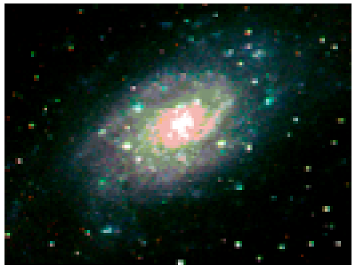
$V^4 = G^2 M \Sigma$

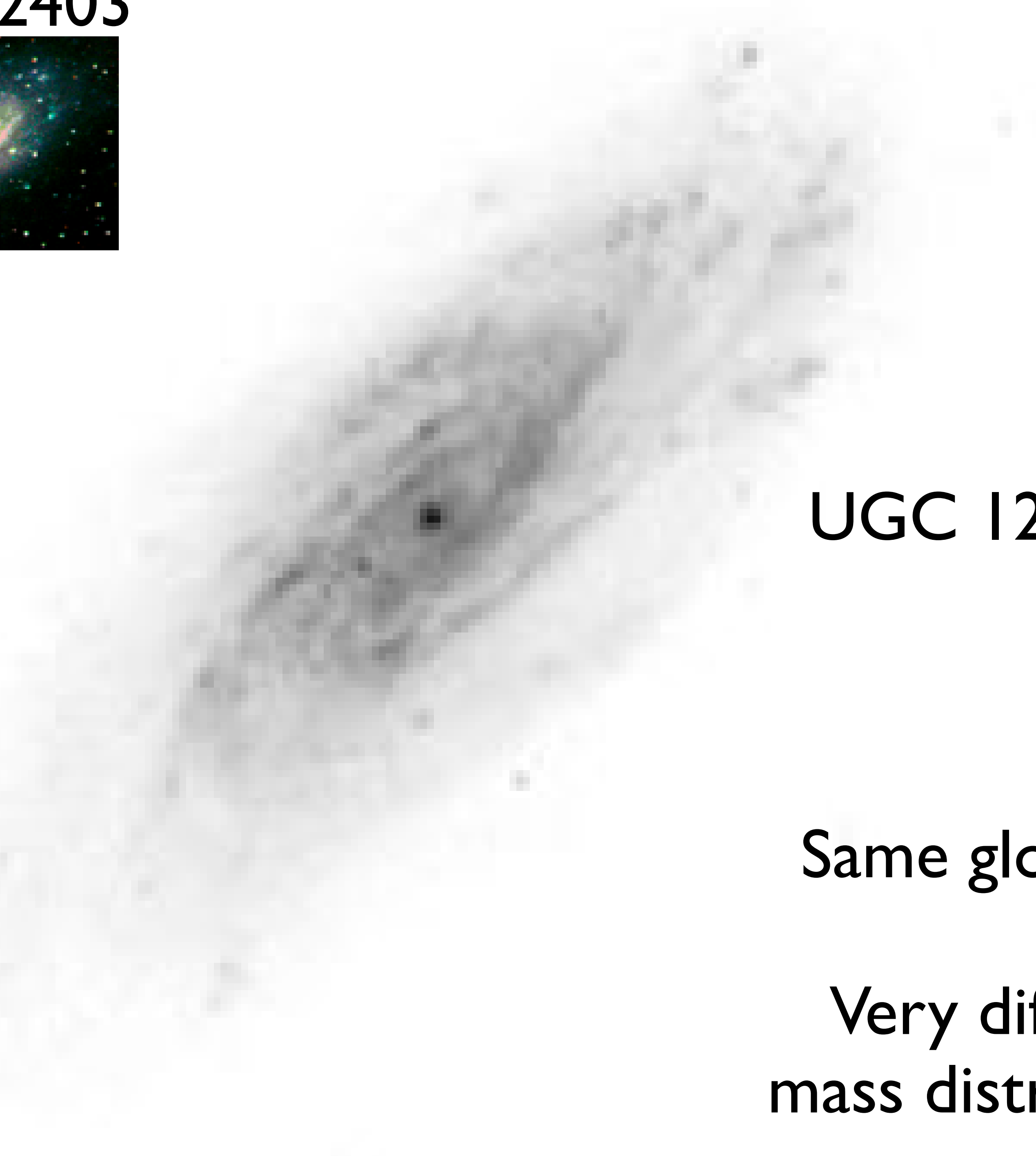


<u>Therefore</u>

Different Σ *should* mean different TF normalization.

NGC 2403

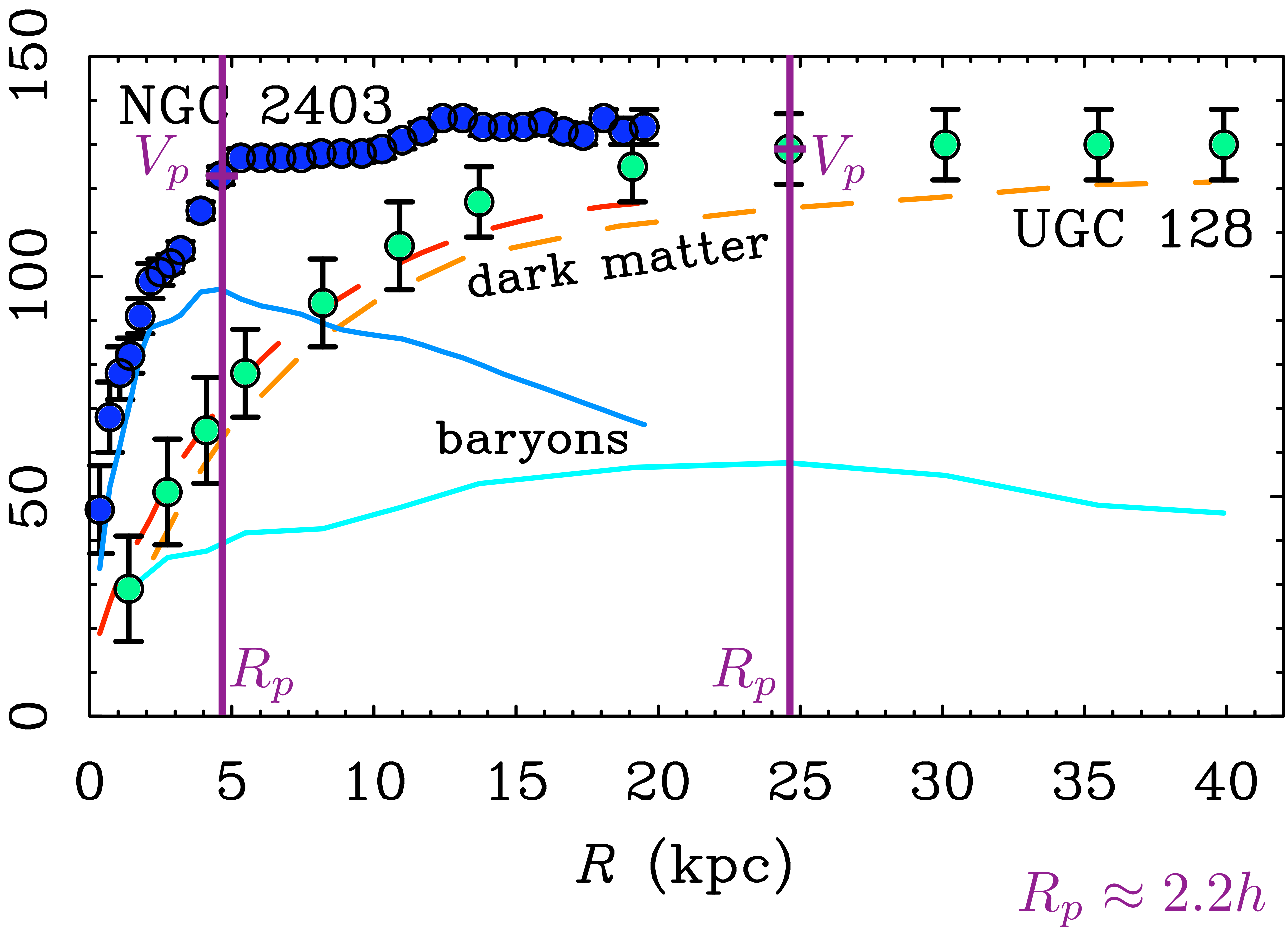




UGC 128

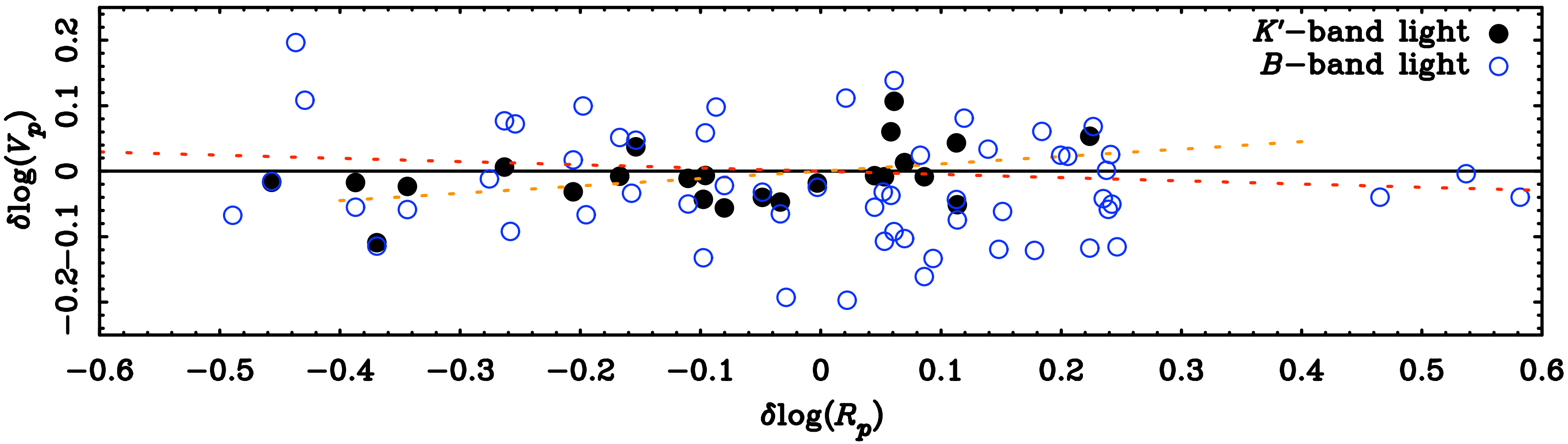
Same global L,V

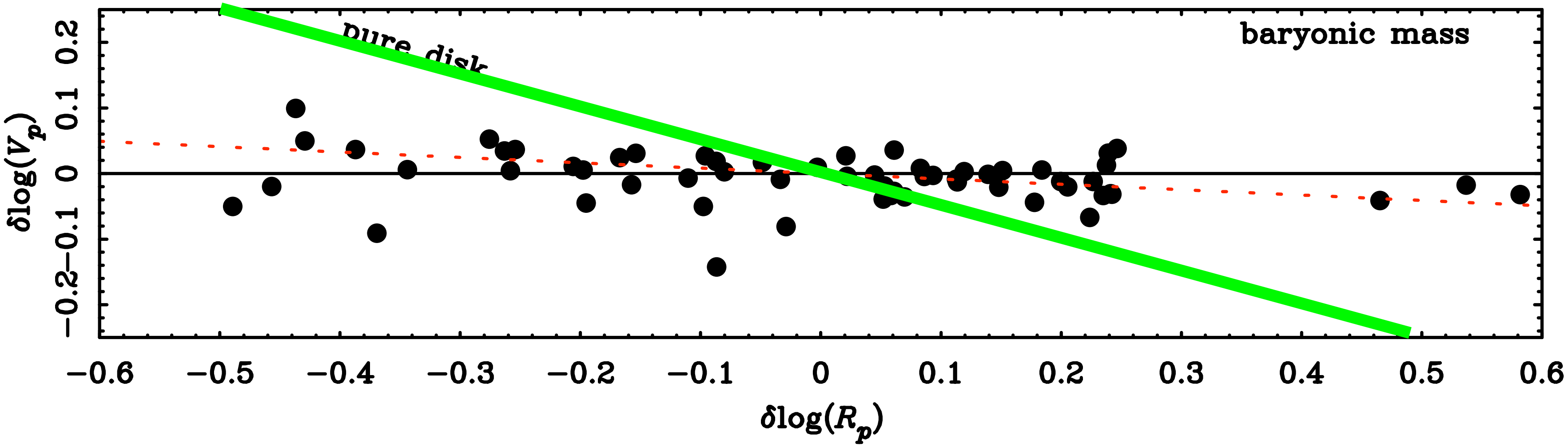
Very different
mass distributions



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

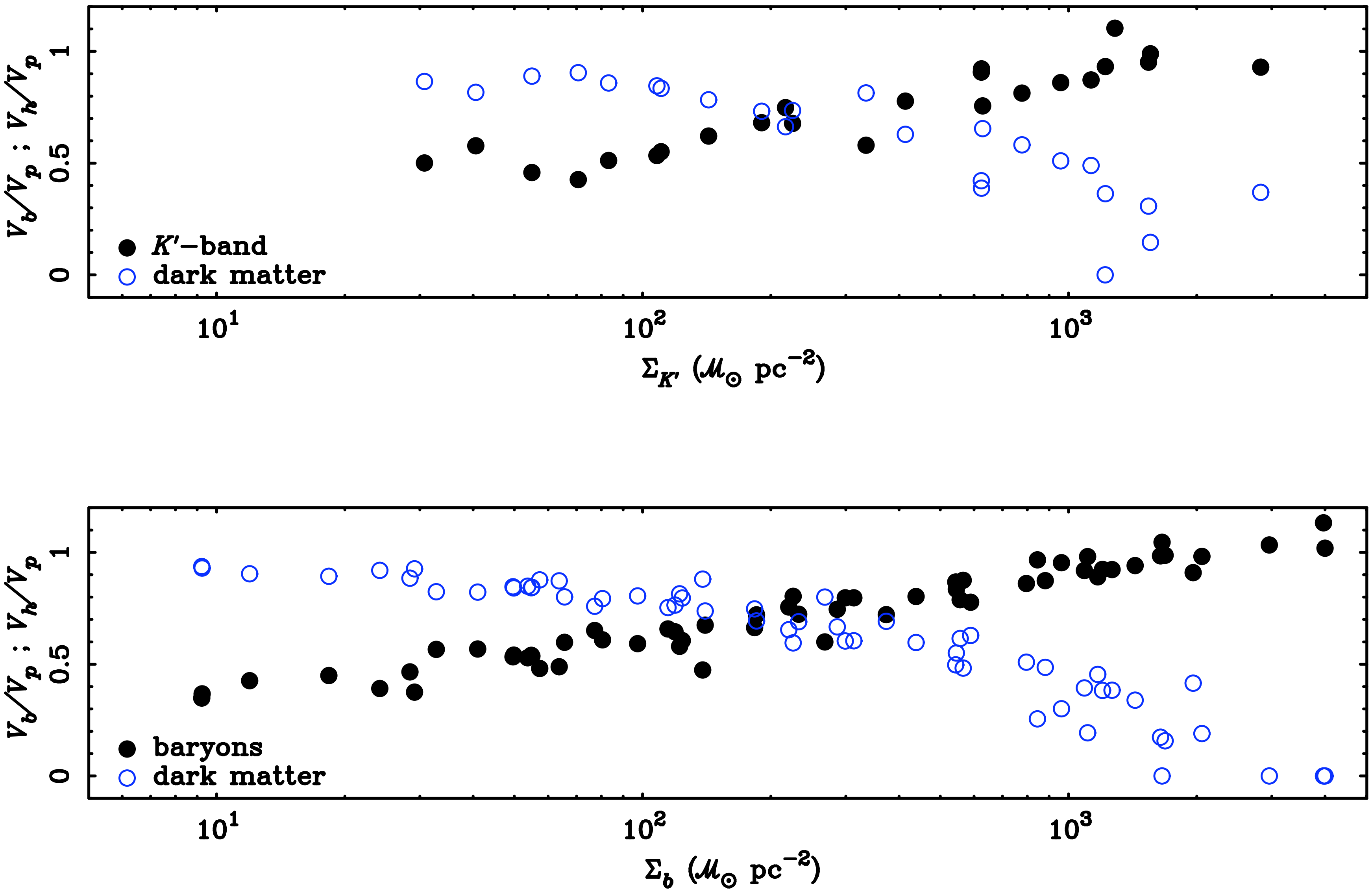
No Residuals from TF rel'n





Not even where disk contribution is maximal

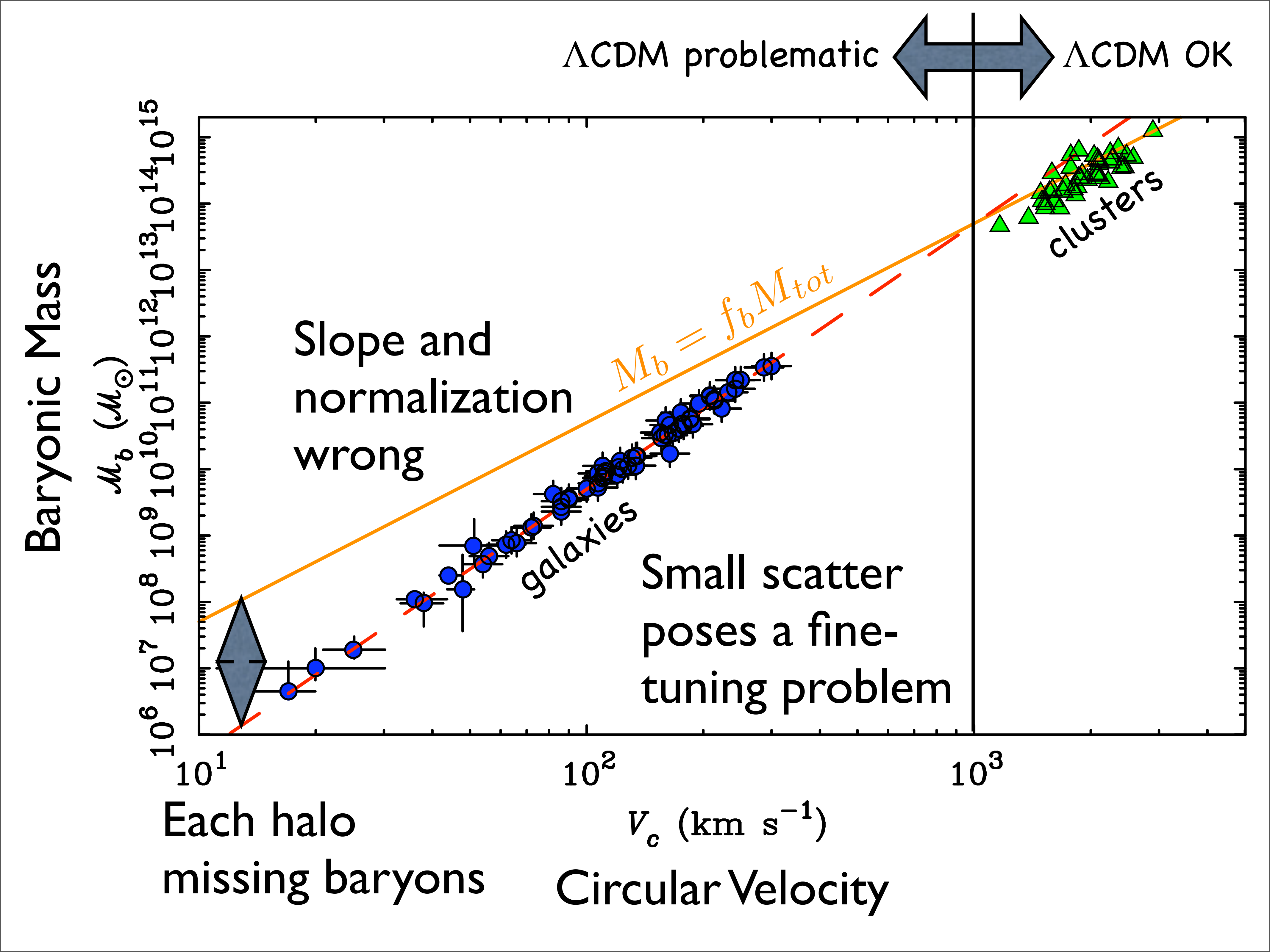
Requires fine balance between dark & baryonic mass



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

Cons - Invisible Matter

- Serious fine-tuning problems
- Halo-by-halo missing baryon problem
- Cusp/core problem
- Missing satellite problem
- Do dark matter particles actually exist?



ΛCDM problematic
ΛCDM OK
Baryonic Mass
$\mathcal{M}_b$ ($\mathcal{M}_\odot$)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
$M_b = f_b M_{tot}$
clusters
Slope and normalization wrong
galaxies
Small scatter poses a fine-tuning problem
10^1
10^2
10^3
V_c (km s^{-1})
Each halo missing baryons
Circular Velocity

Cons - Invisible Matter

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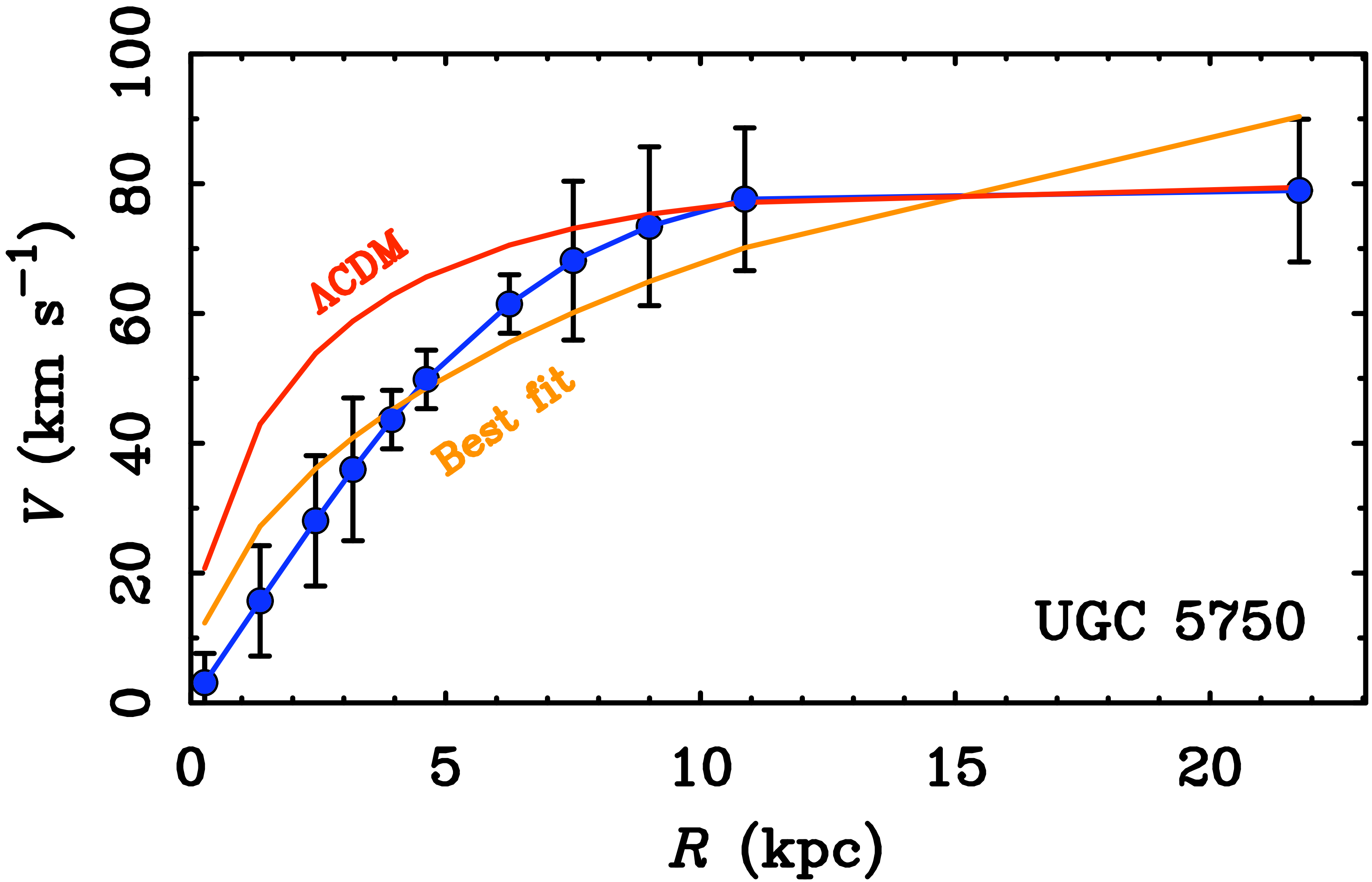
cusp/core problem



ΛCDM predicts too much dark mass at small radii

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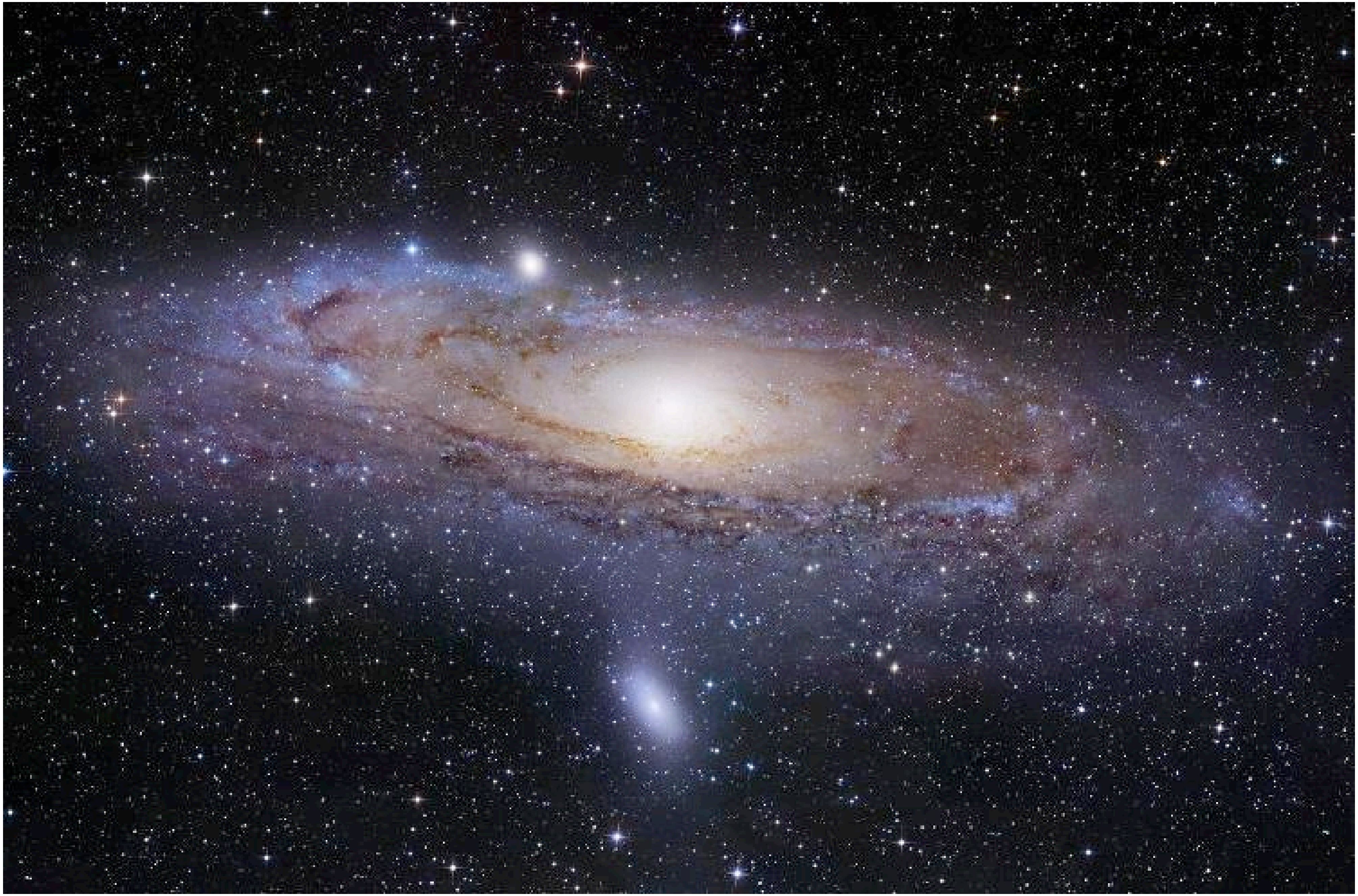
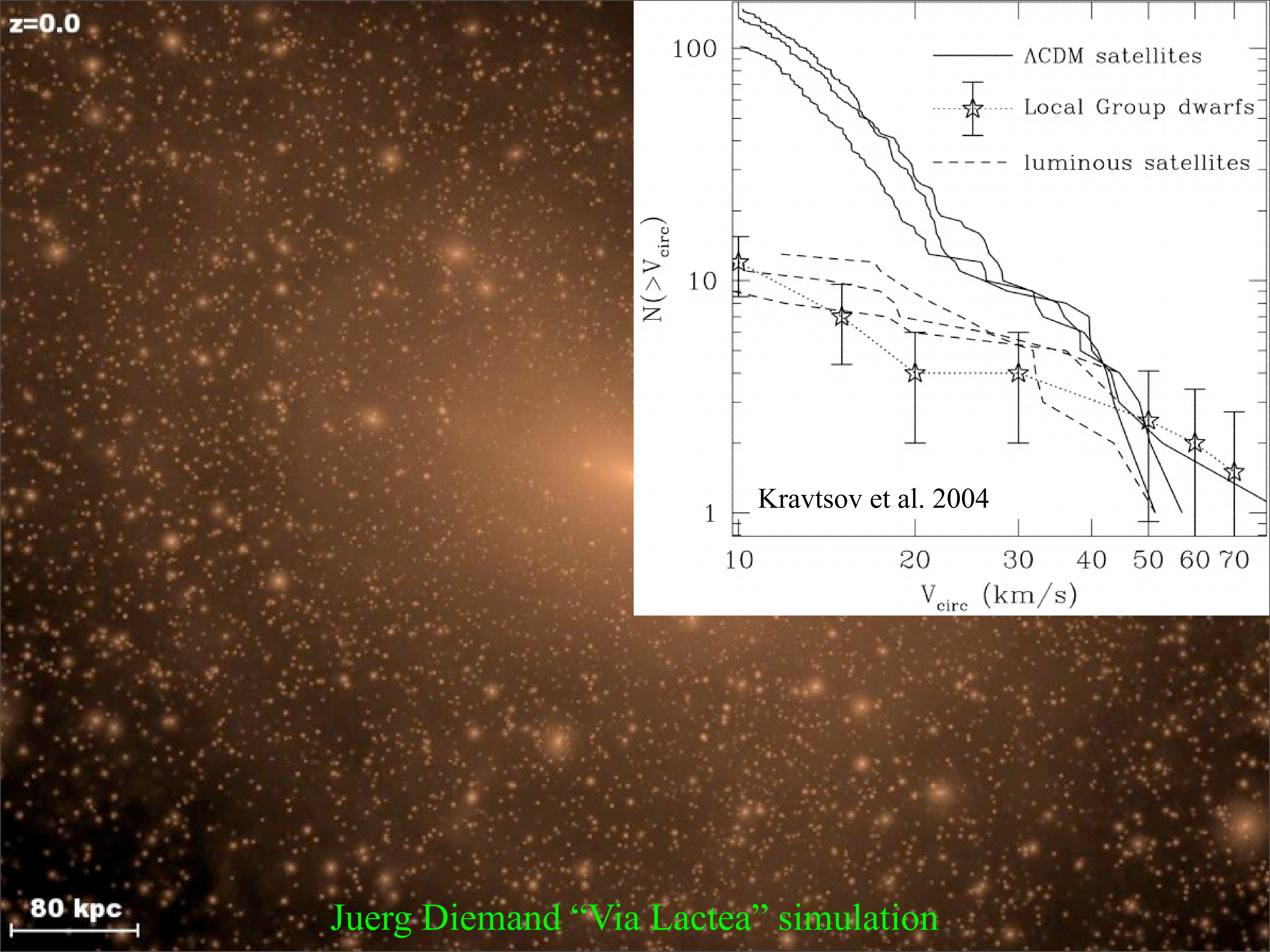
M31 (Gendler)





Juerg Diemand "Via Lactea" simulation

Cons - Invisible Matter

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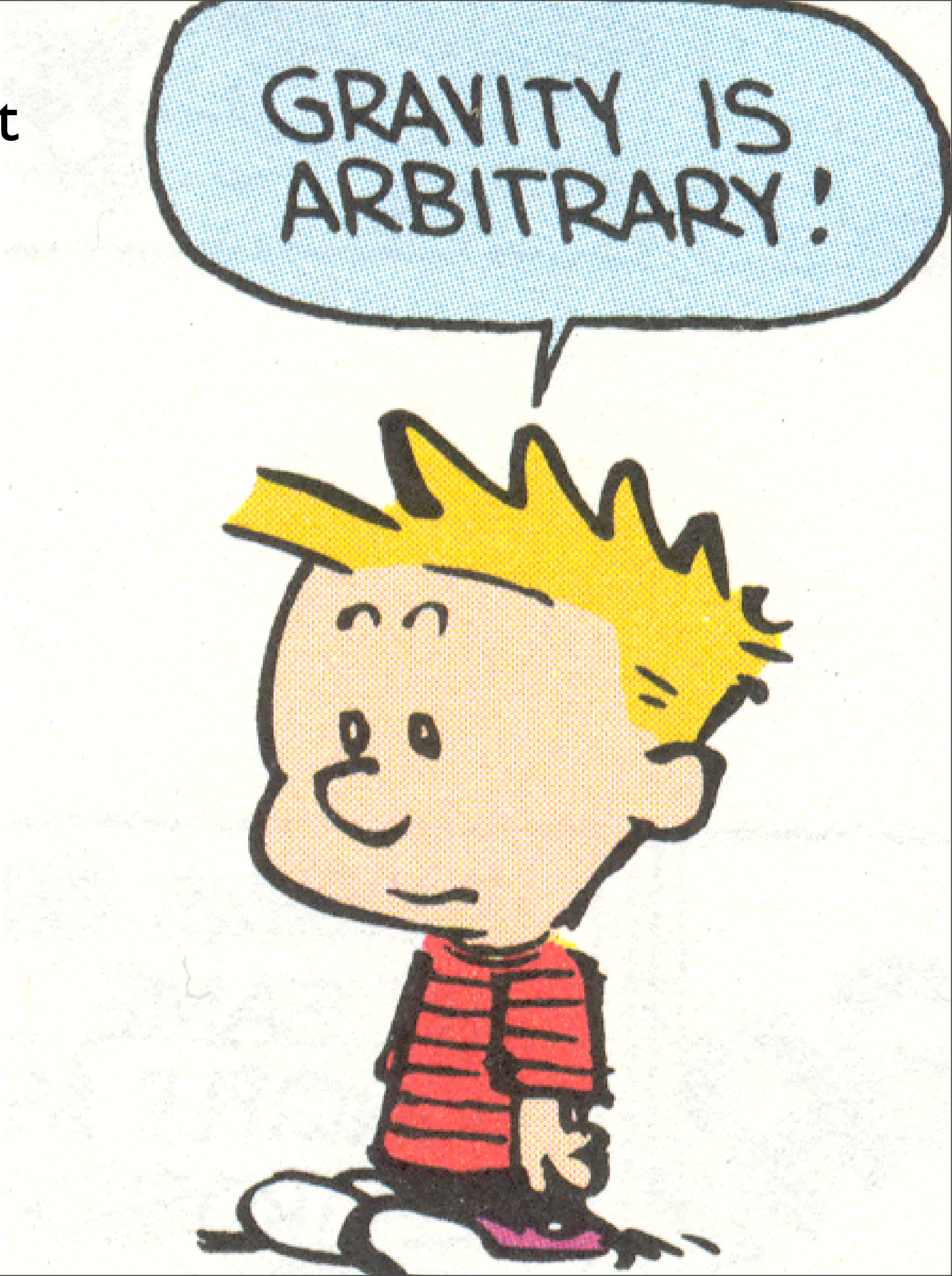
CDMS, LHC, & GLAST ***should*** *all see something* ***soon***

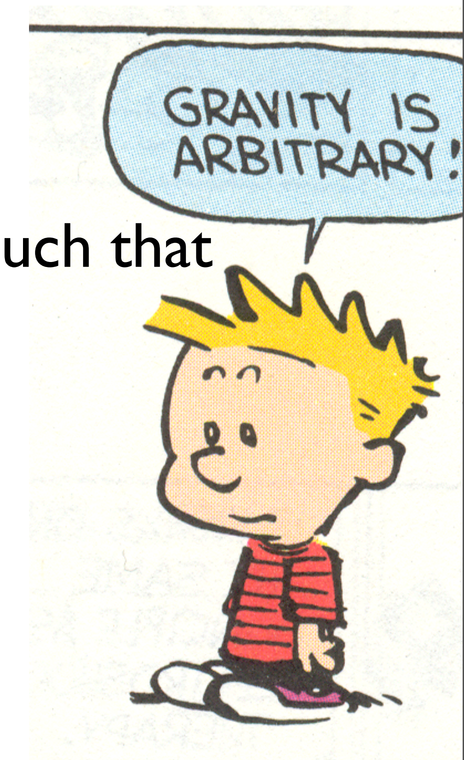
One begins to worry that



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).

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 … resemble those of ellipticals and galactic … I … in Mi…

VIII. PREDICTIONS

The main predictions conce… 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… densities … same … conventional dynamics should yield a discrepancy which increases with radius in a predictable manner.

4. Effects of the modified dynamics are … e.g., Hodge 1971 and Zinn 1980). For example, those dwarfs believed to be bound to our Galaxy would have internal accelerations typically of order $a_{in} \sim a_0/30$. Their (modified) acceleration, g, in the field of the Galaxy is larger than the internal ones but still much smaller than a_0, $g \approx (8\ \mathrm{kpc}/d)a_0$, based on a value of $V_\infty = 220$ km s^{-1} for the Galaxy, and where d is the distance from the dwarf galaxy to the center of the Milky Way ($d \sim 70$–220 kpc). Whichever way the external acceleration turns out to affect the internal dynamics (see the discussion at the end of § II, the section on small groups in Paper III, and Paper I), we predict that when velocity dispersion data is available for the dwarfs, a large mass discrepancy will result when the conventional dynamics is used to determine the masses. The dynamically determined mass is predicted to be larger by a factor of order 10 or more than that which can be accounted for by stars. In case the internal dynamics is determined by the external acceleration, we predict this factor to increase with d and be of order (d/8 kpc) (as long as $a_{in} \ll g$, $h_{50} = 1$).

Prediction 1 is a very general one. It is worthwhile listing some of its consequences as separate predictions, numbered 5–7 below (note that, in fact, even prediction 2 is already contained in prediction 1).

5. Measuring local M/L values in disk galaxies (assuming conventional dynamics) should give the following results: In regions of the galaxy where $V^2/r \gg a_0$ the local M/L values should show no indication of hidden mass. At a certain transition radius, local M/L should start to increase rapidly. The transition radius should occur where … (a) … calibration of M/L as we are concerned only with variations of this quantity; (b) Effects of the modified dynamics manifest themselves more clearly in local mass determina… many cases … 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 … additional … $\Sigma^{-1}V_\infty^4$ (see, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that low surface density galaxies … velocity … 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 … 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

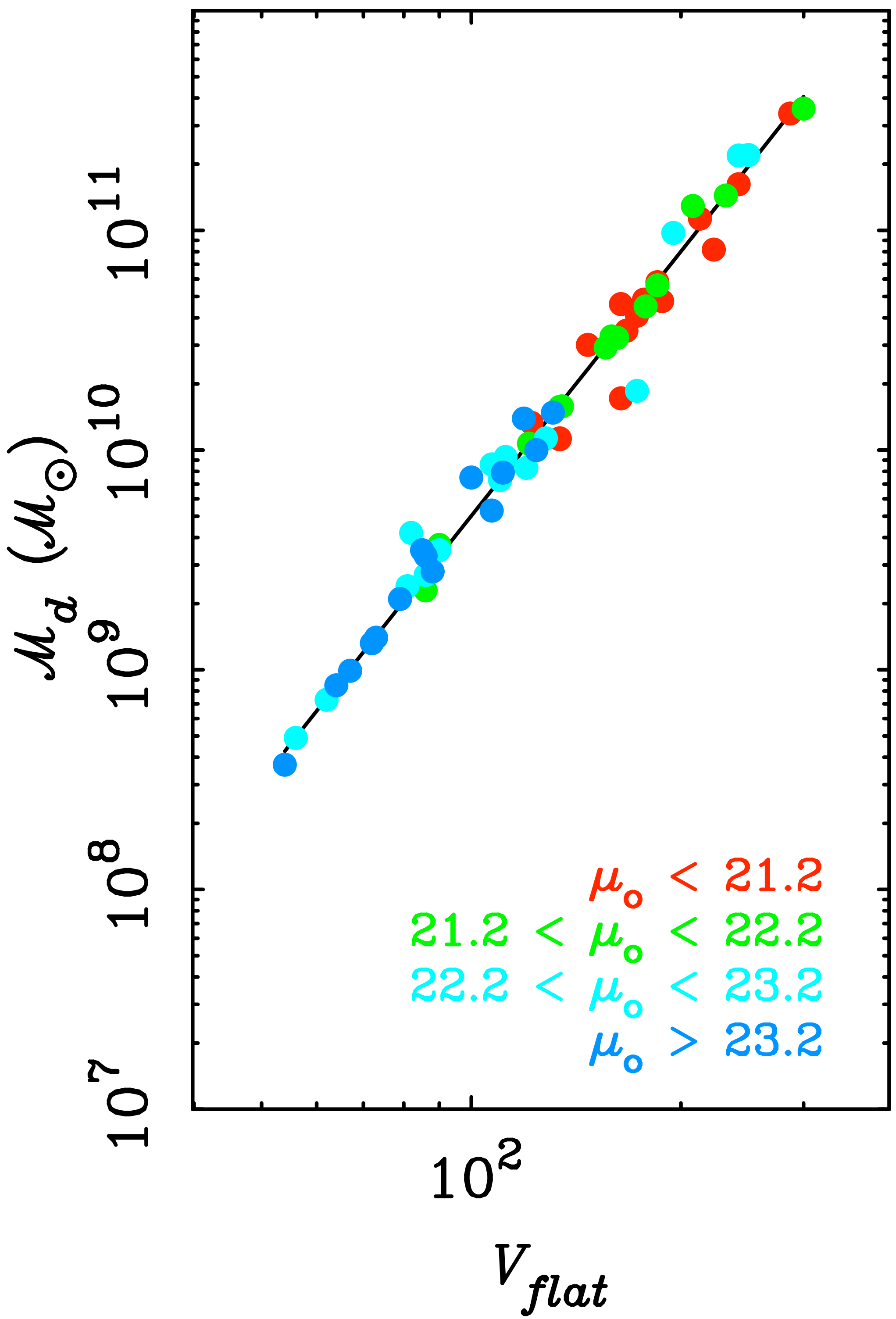
The main results of this paper can be summarized by the statement that the modified dynamics eliminates the need to assume hidden mass in galaxies. The effects in galaxies which I have considered, and which are commonly attributed to such hidden mass, are readily explained by the modification. More specifically:

MOND predictions

- 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

"Disk Galaxies with low surface brightness provide particularly strong tests"

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



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- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
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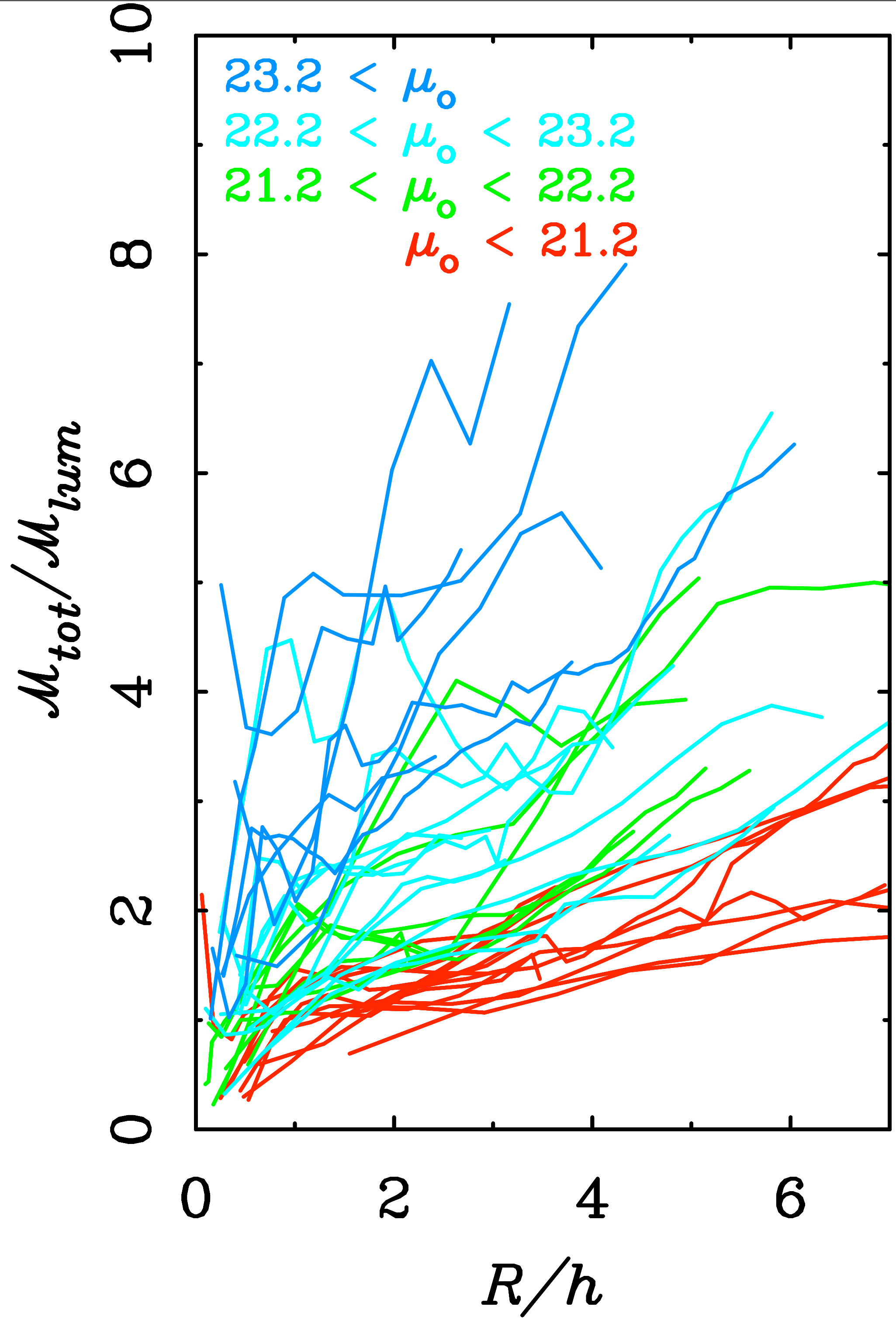
In MOND limit of low acceleration

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

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

$$V^4 = a_0 GM$$

observed TF!



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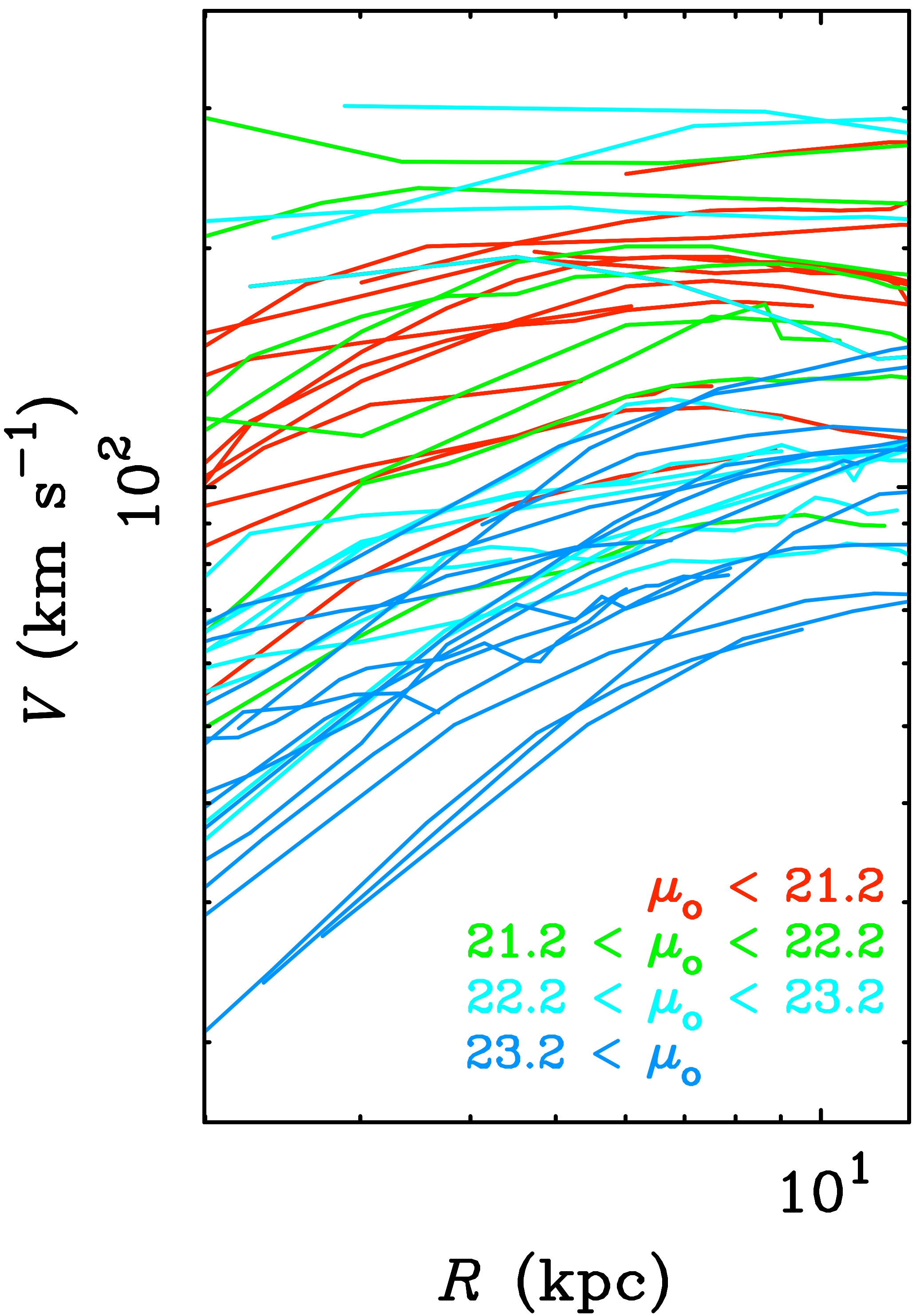
- Stellar Population Mass-to-Light Ratios



MOND predictions

- The Tully-Fisher Relation
  - ✔ Slope = 4
  - ✔ Normalization = $1/(a_0 G)$
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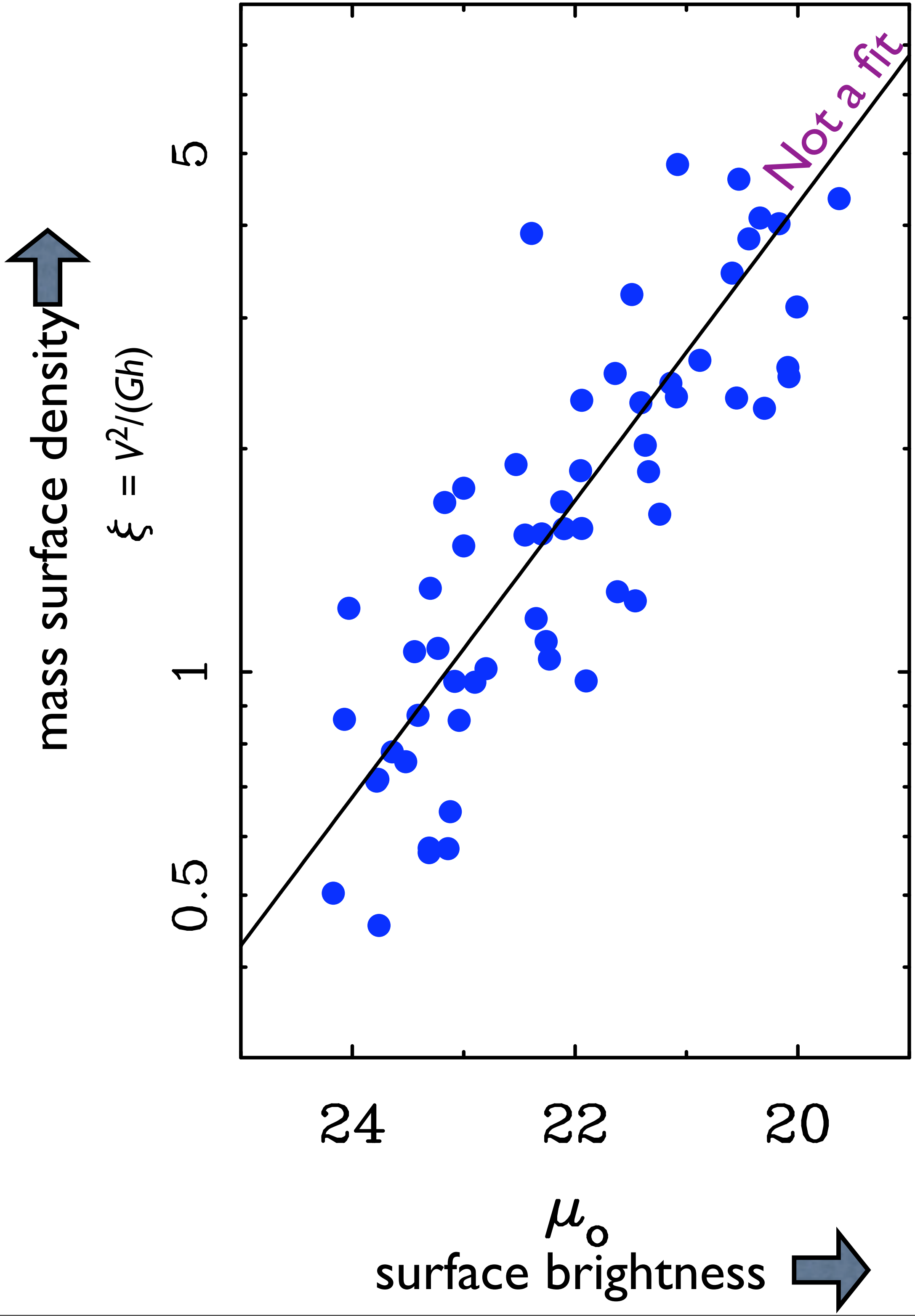

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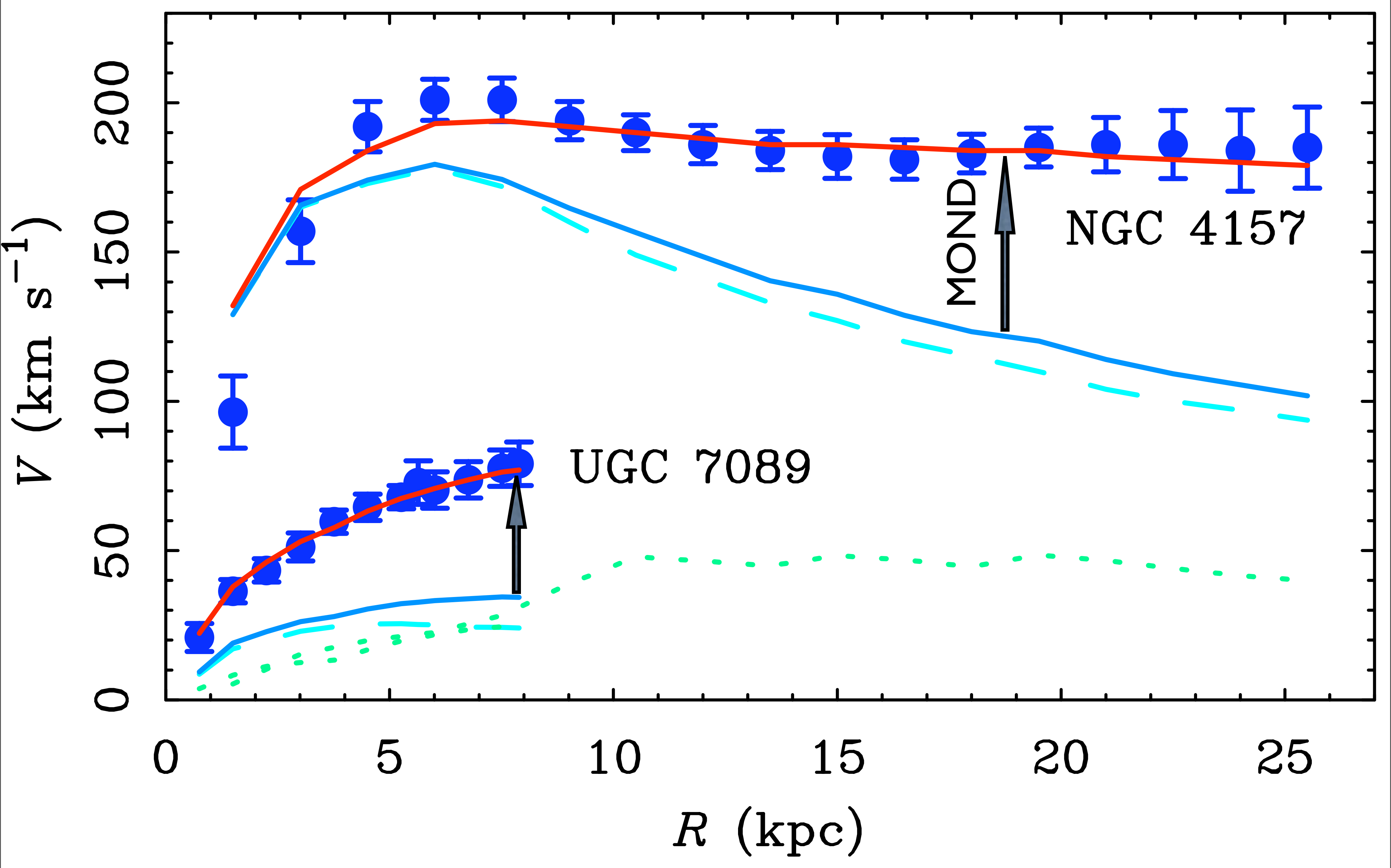
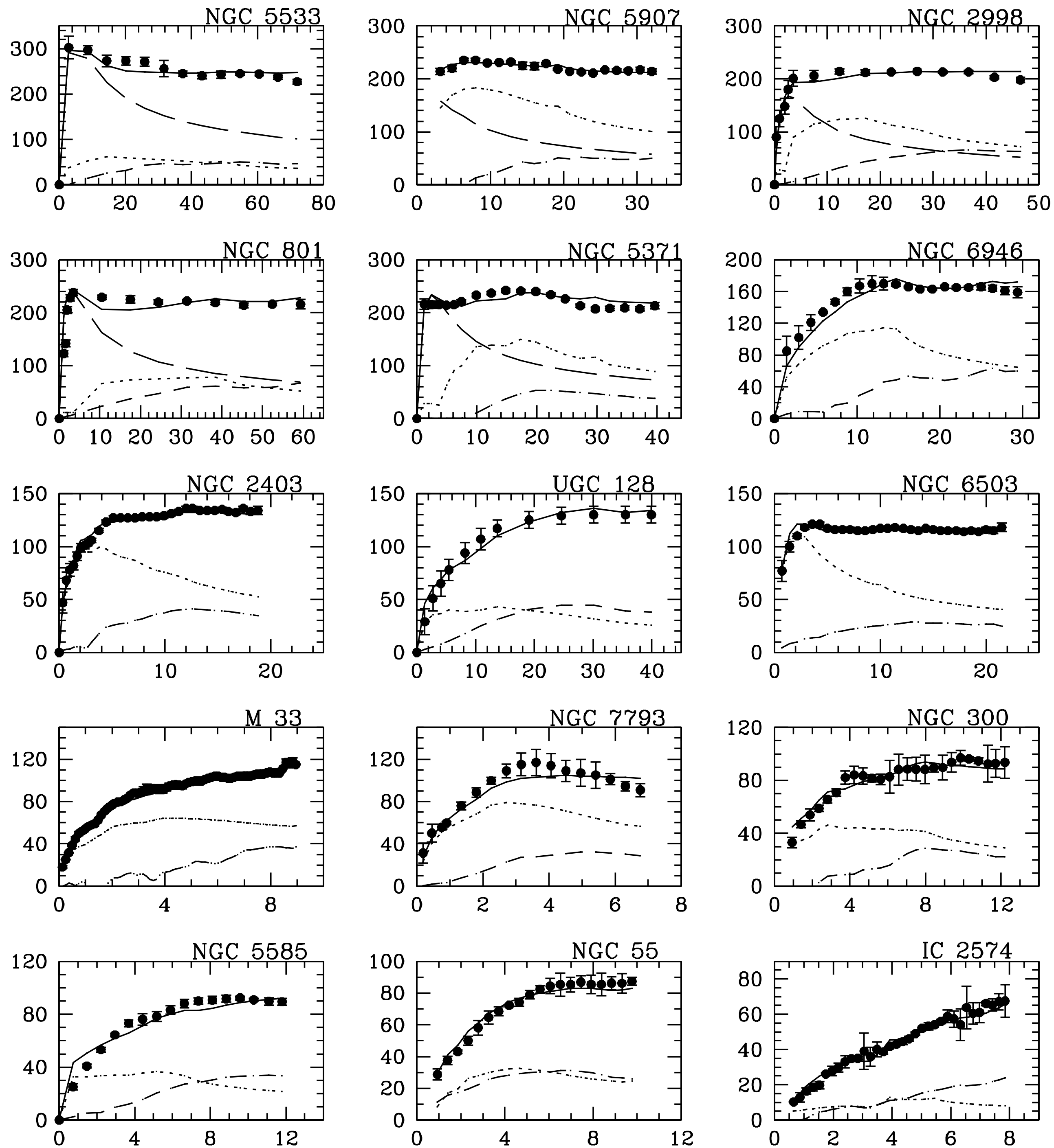
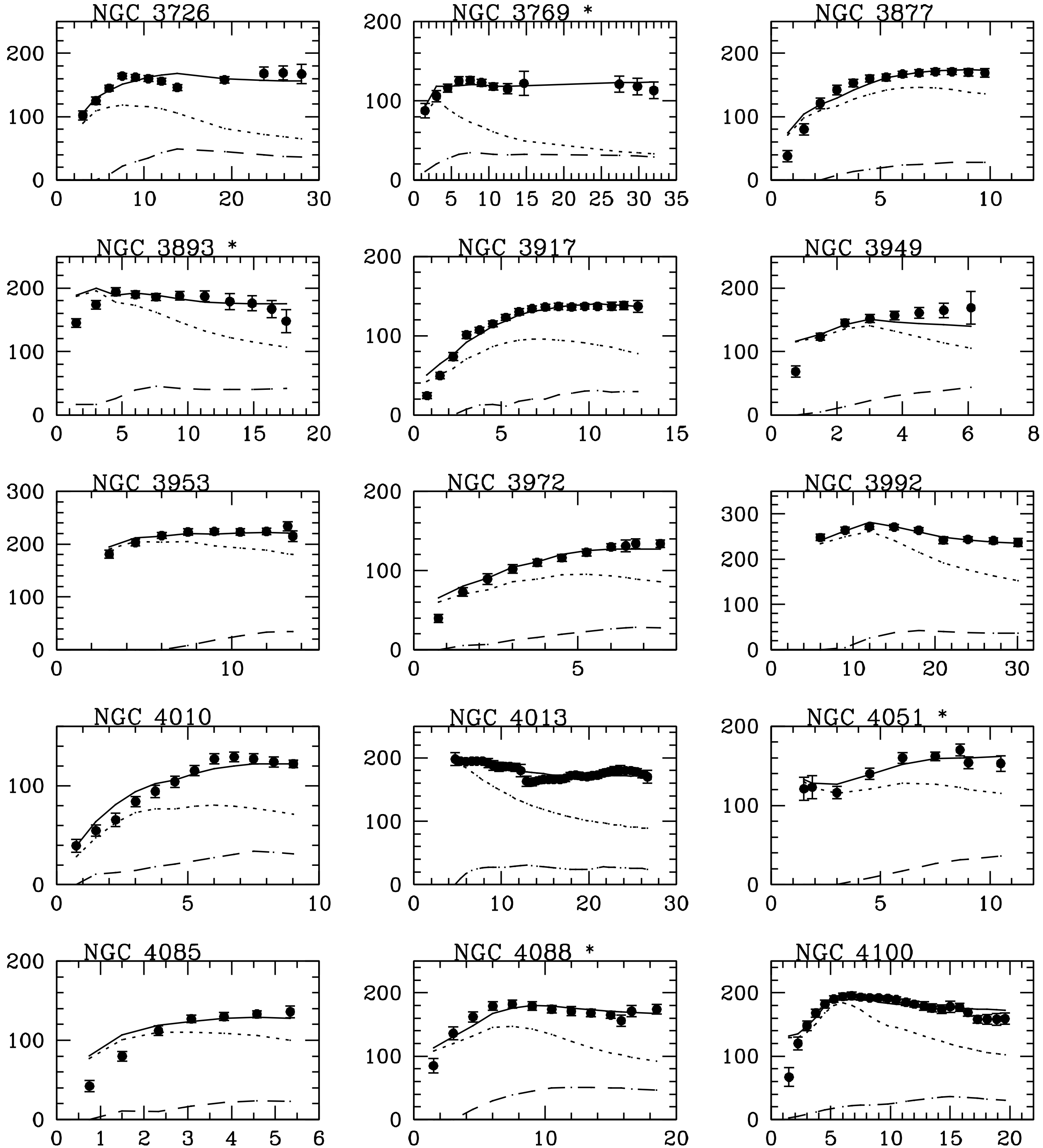


V (km s^{-1})
0
50
100
150
200
R (kpc)
0
5
10
15
20
25
MOND
NGC 4157
UGC 7089

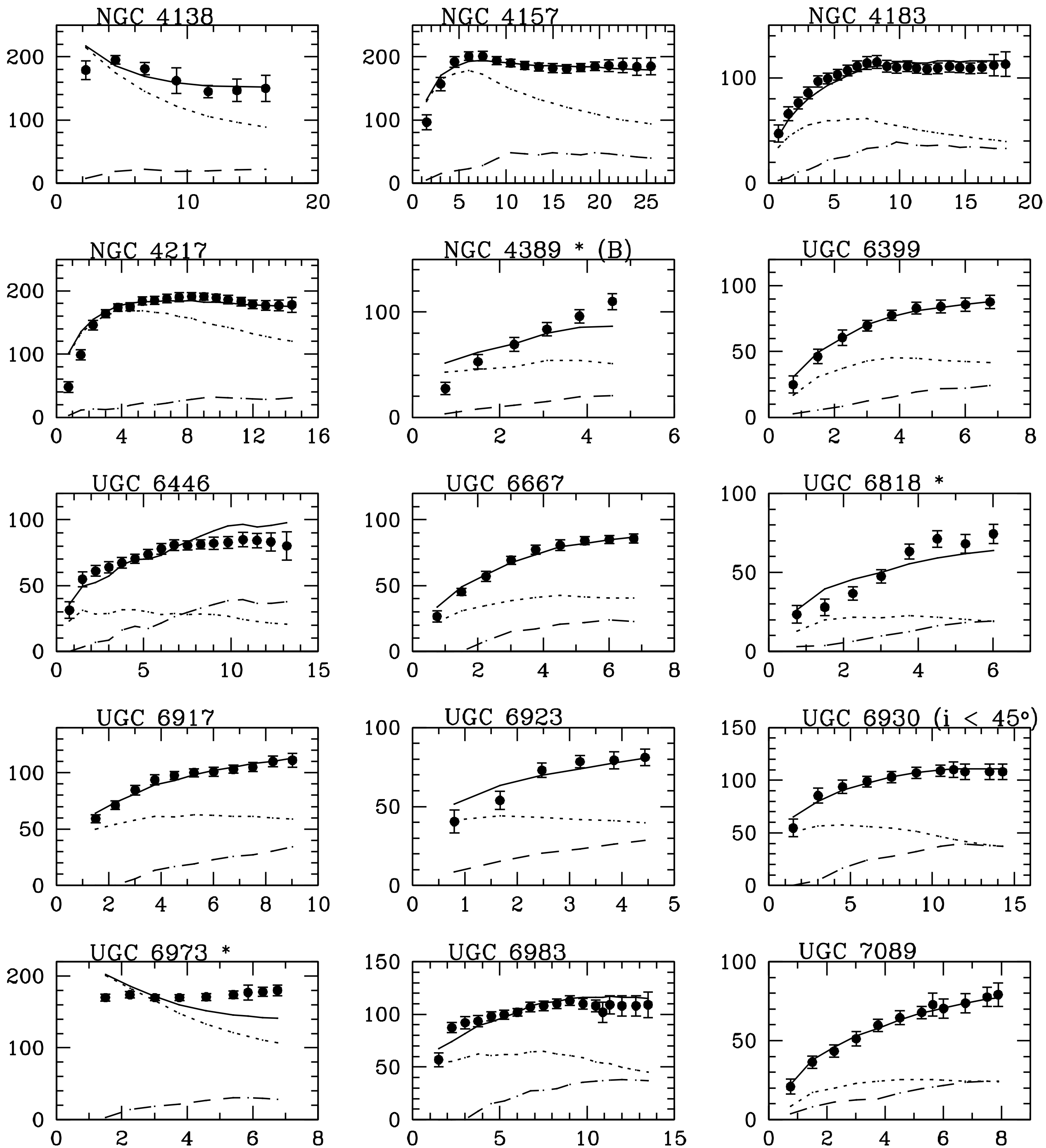


Sanders & McGaugh 2002, *ARA&A*, **40**, 263

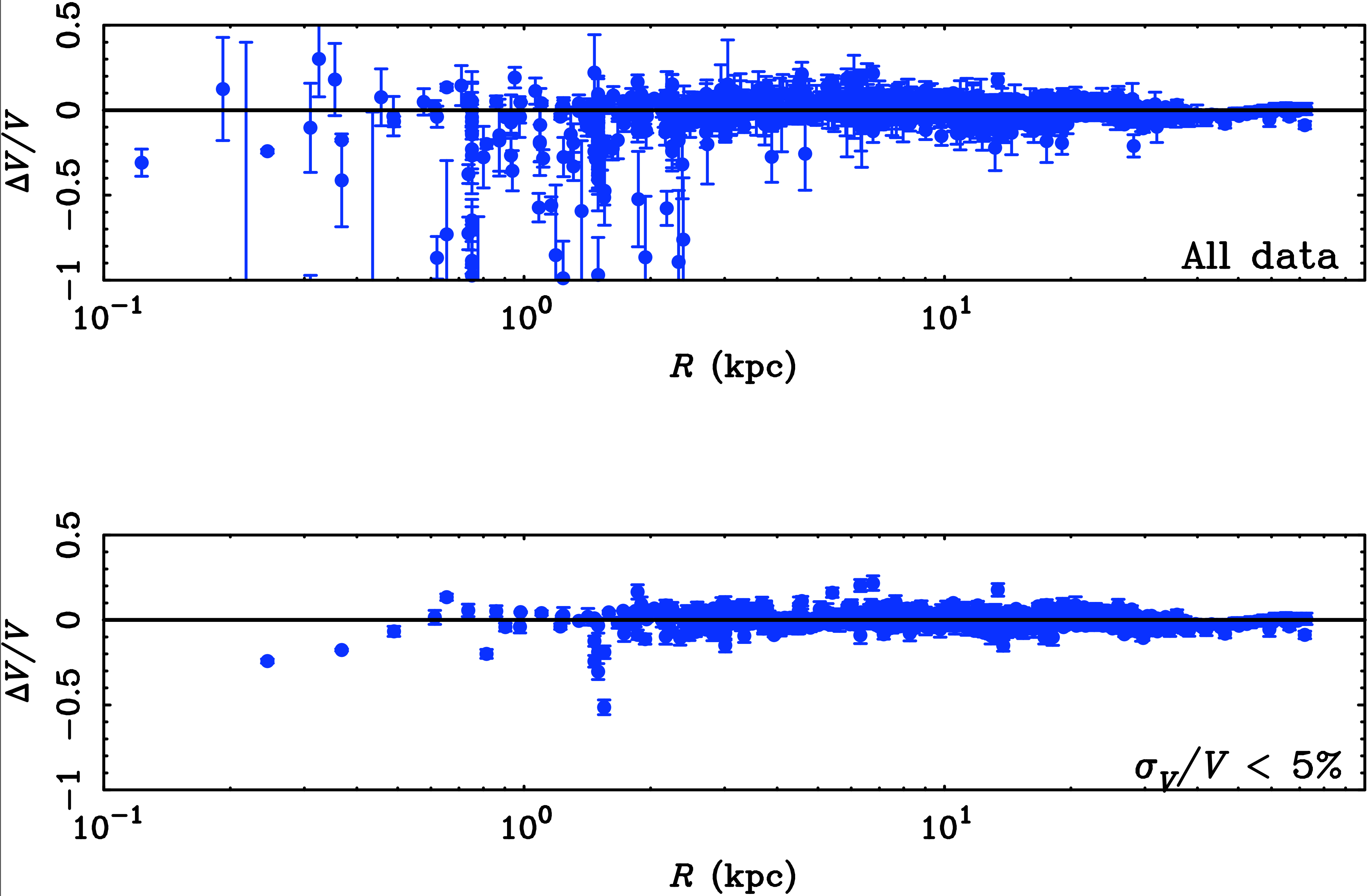


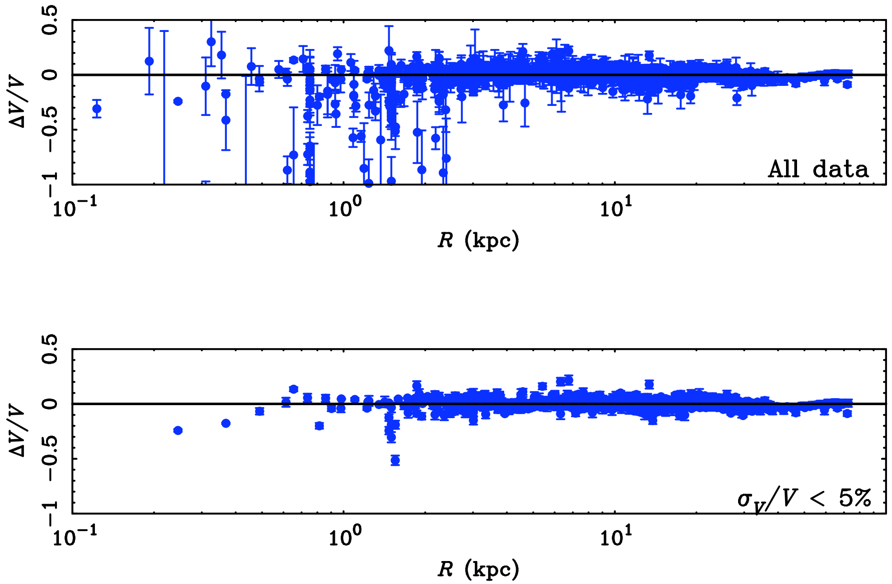
Sanders & McGaugh 2002, *ARA&A*, **40**, 263

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



Residuals of MOND fits





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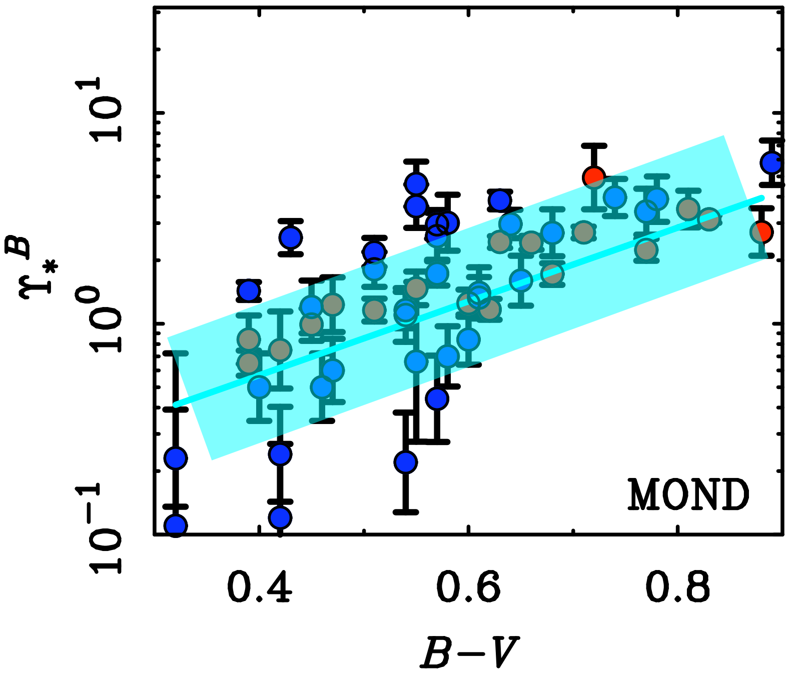
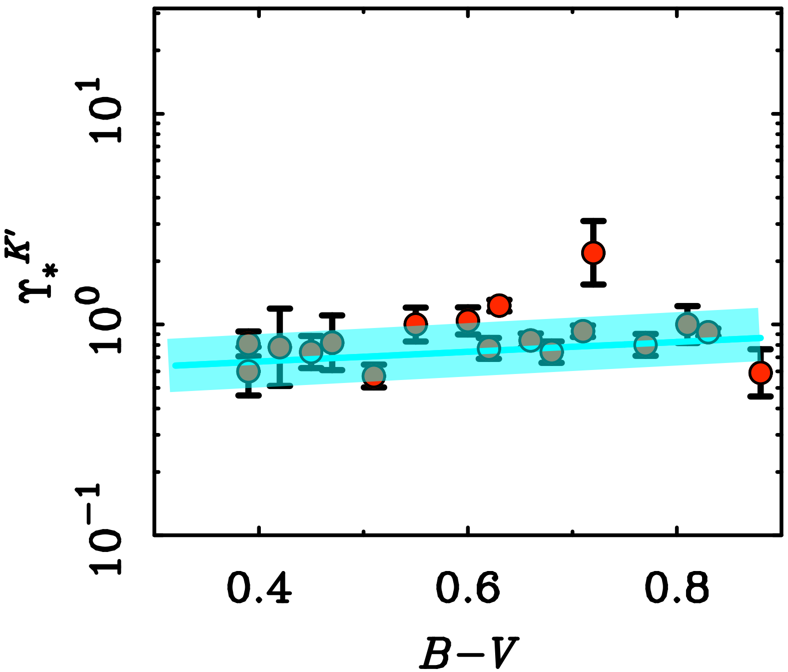
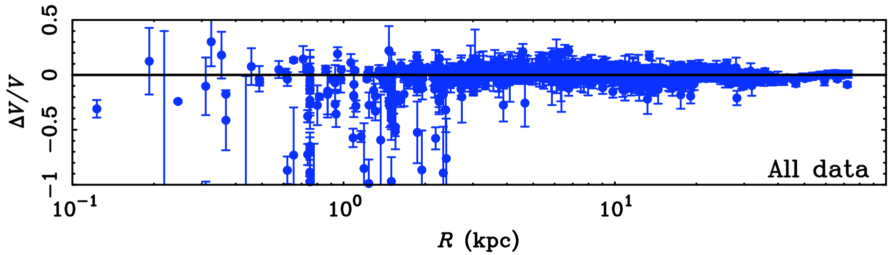
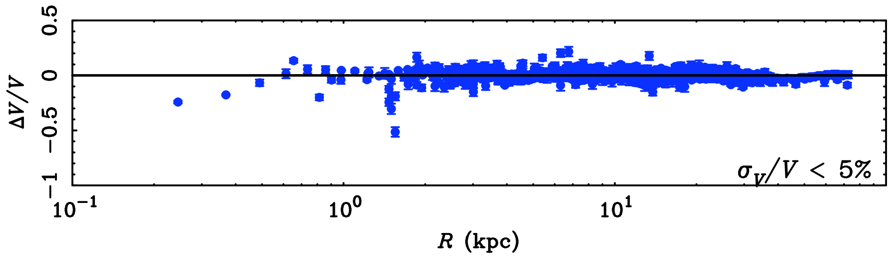


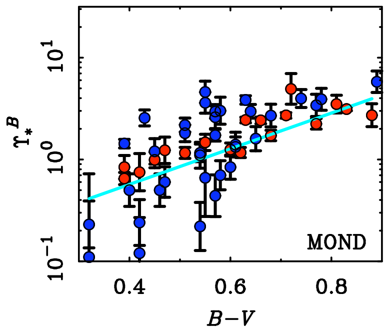
Line: stellar population model
(mean expectation)

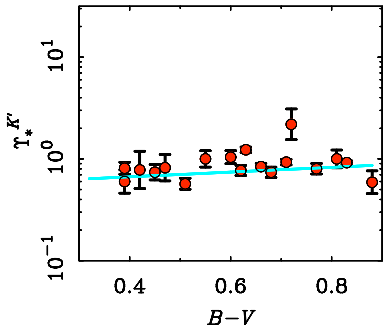


MOND predictions









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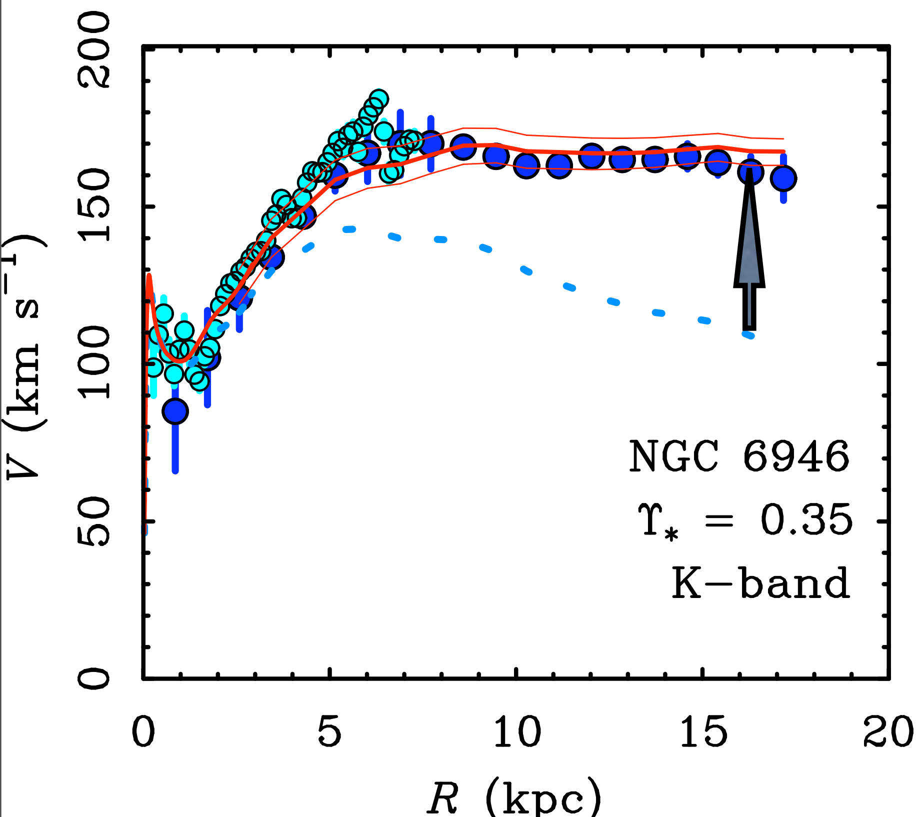
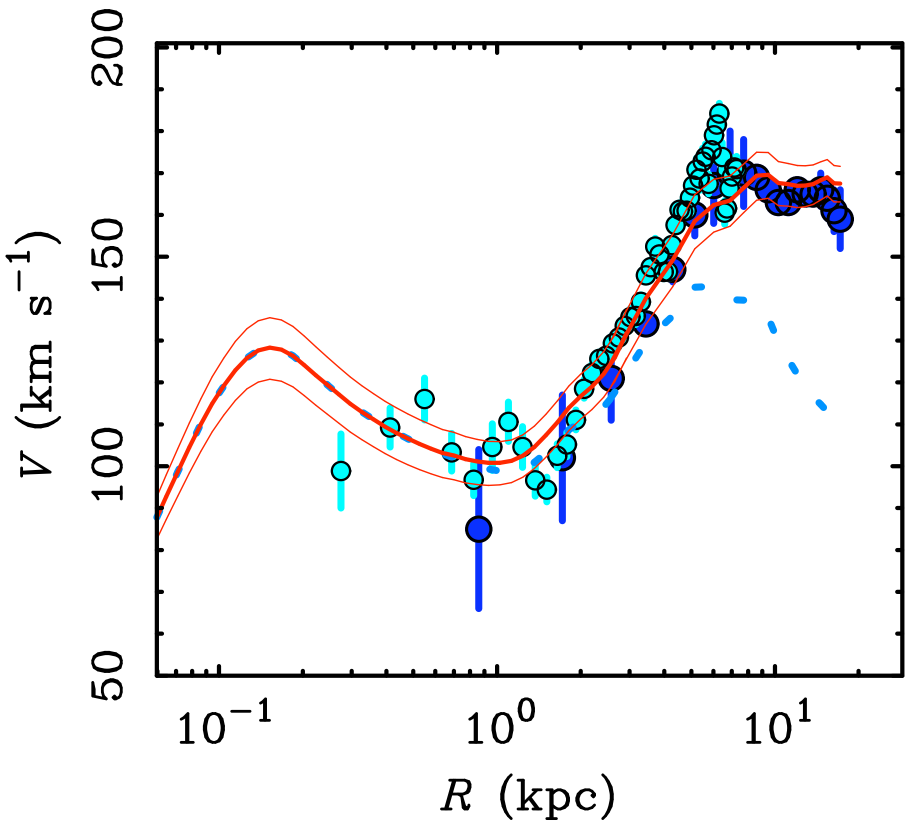
Renzo's Rule:

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

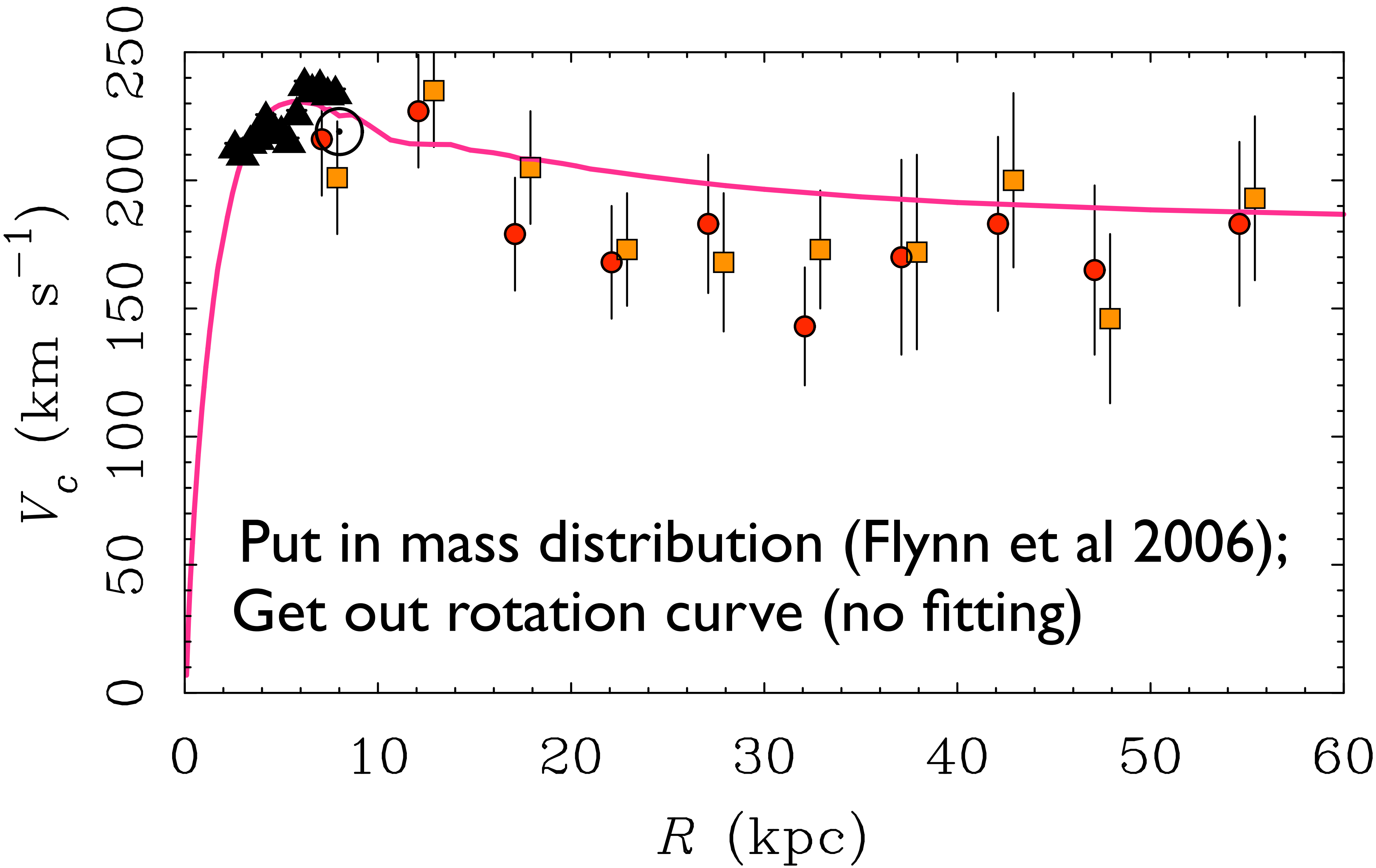




$$\Upsilon_{\star}^{K} = 0.35\ M_{\odot}/L_{\odot}$$

bang on popsynth models of Portinari et al. (2004)

What about our own Galaxy?



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

Can we do better?

Recovering surface density from rotation velocity:

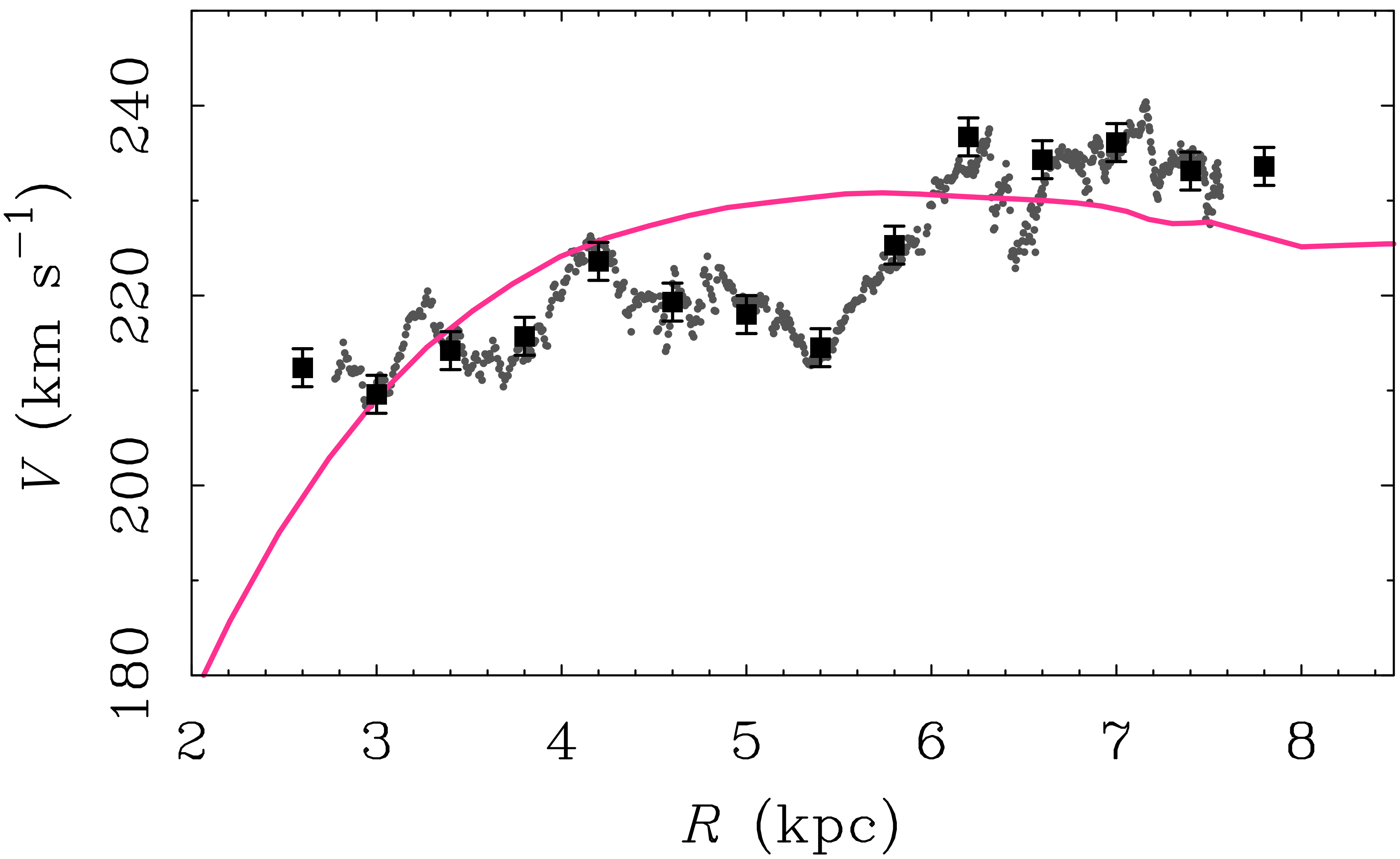
$$\Sigma(R) = \frac{V^2}{2\pi G R}$$ only works for spheres.

For disks, need

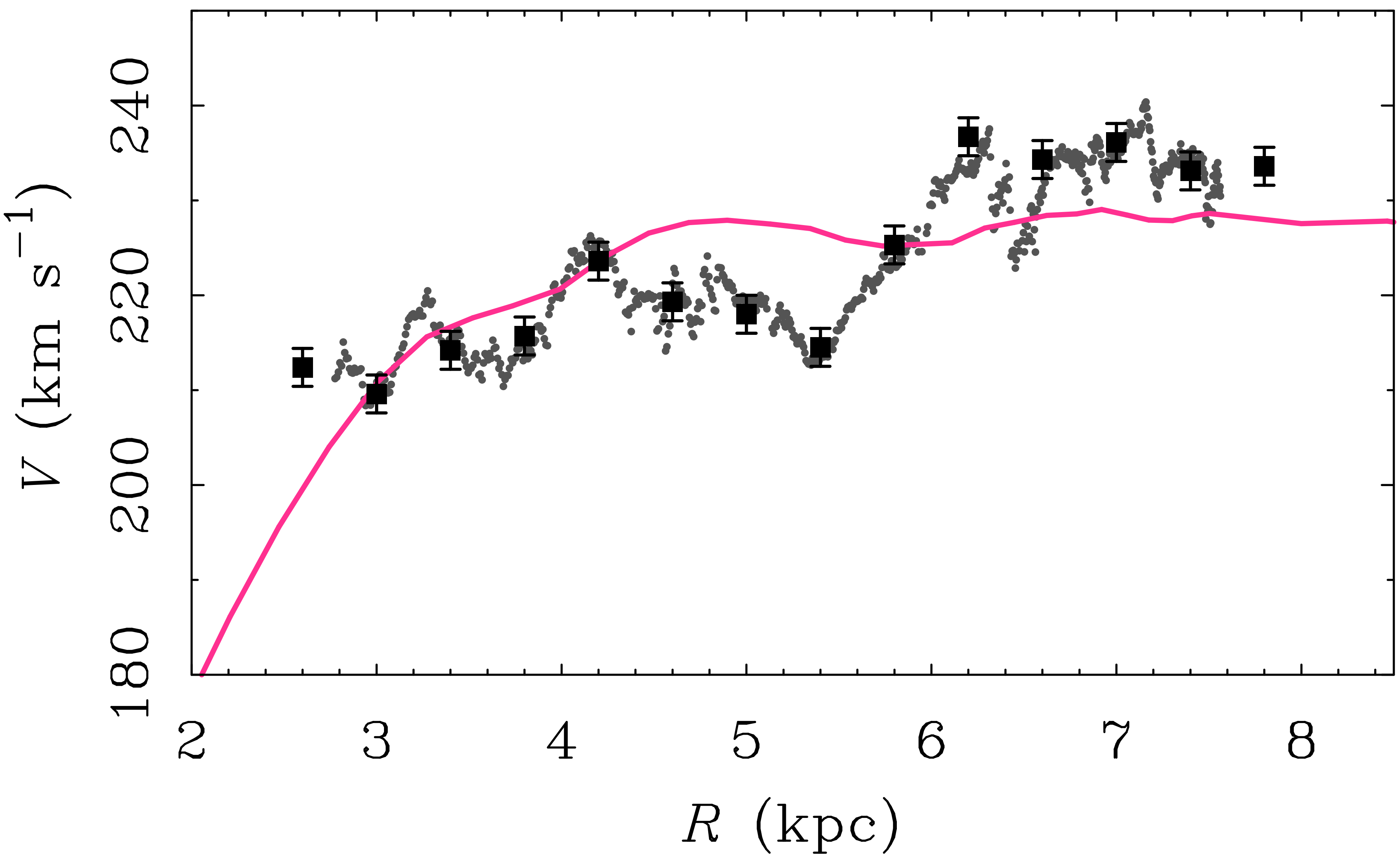
$$\Sigma(R) = \frac{1}{2\pi G}\left[\frac{1}{R}\int_0^R \frac{dV_c^2}{dr} K\left(\frac{r}{R}\right) dr + \int_R^\infty \frac{dV_c^2}{dr} K\left(\frac{R}{r}\right)\frac{dr}{r}\right]$$

which has a proclivity to blow up.

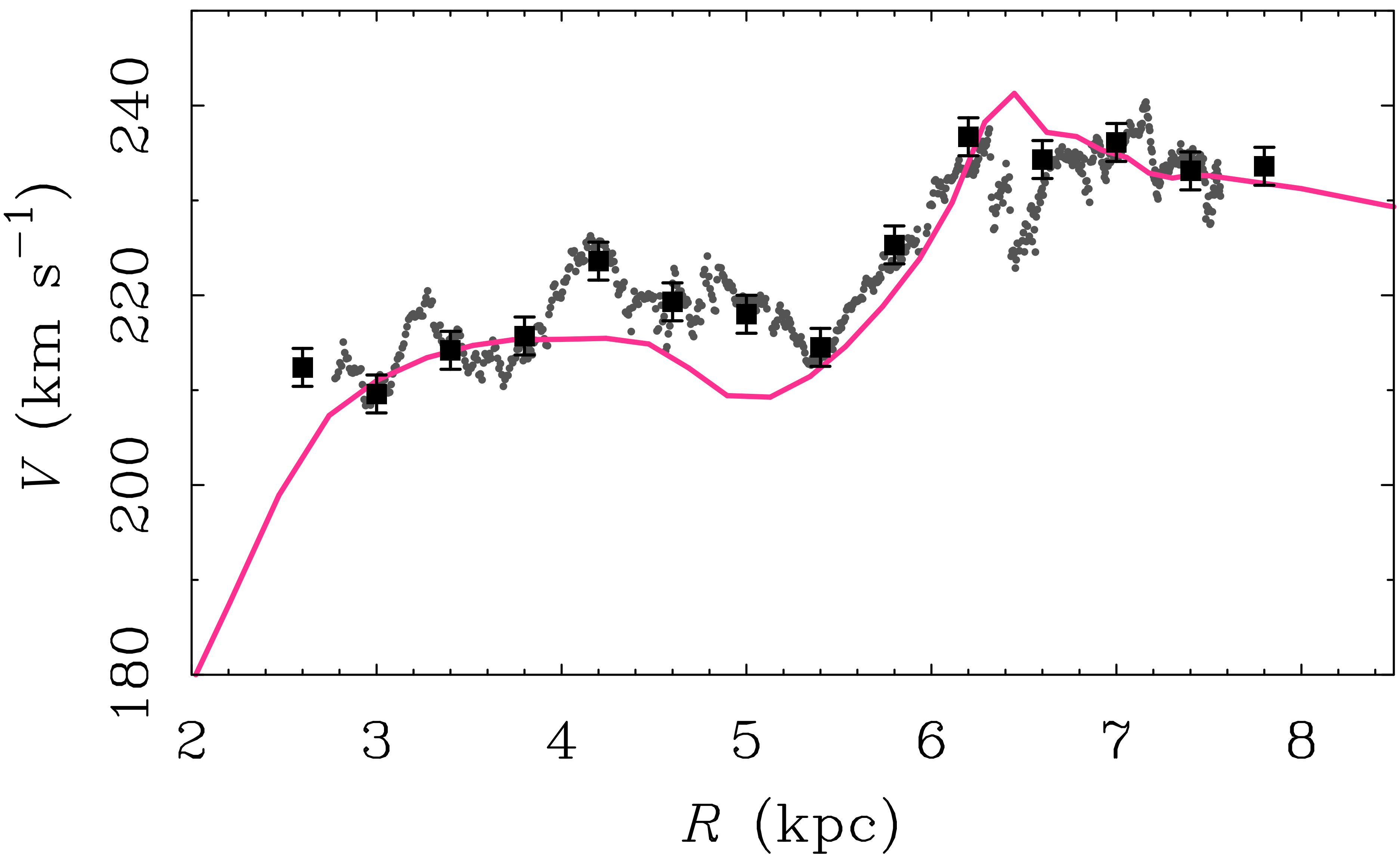
Instead, do by trial and error



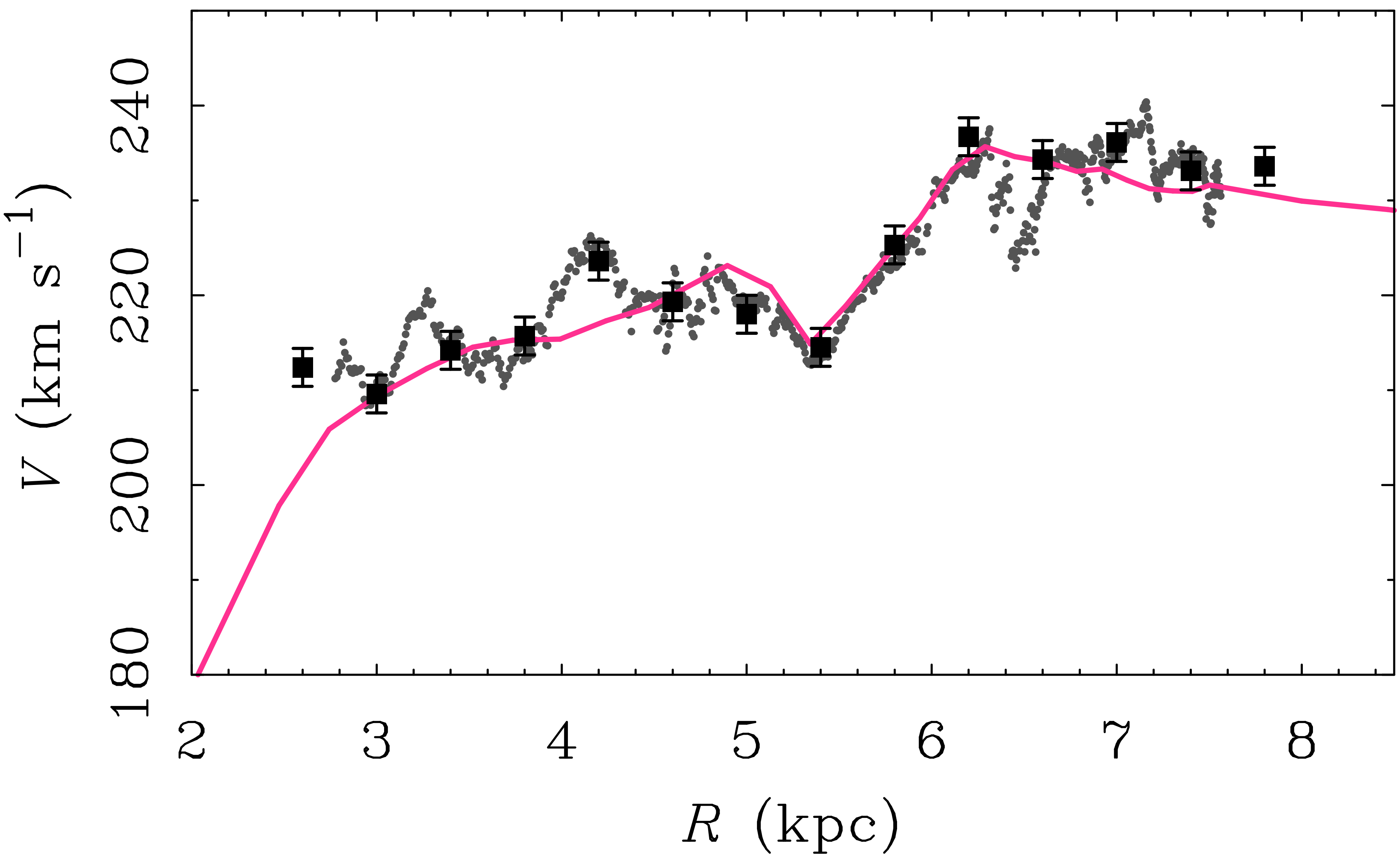
V (km s^-1)
180
200
220
240
2
3
4
5
6
7
8
R (kpc)



240
220
200
180
V (km s^{-1})
2
3
4
5
6
7
8
R (kpc)



240
220
200
180
2
3
4
5
6
7
8
V (km s^{-1})
R (kpc)



V (km s^{-1})
180
200
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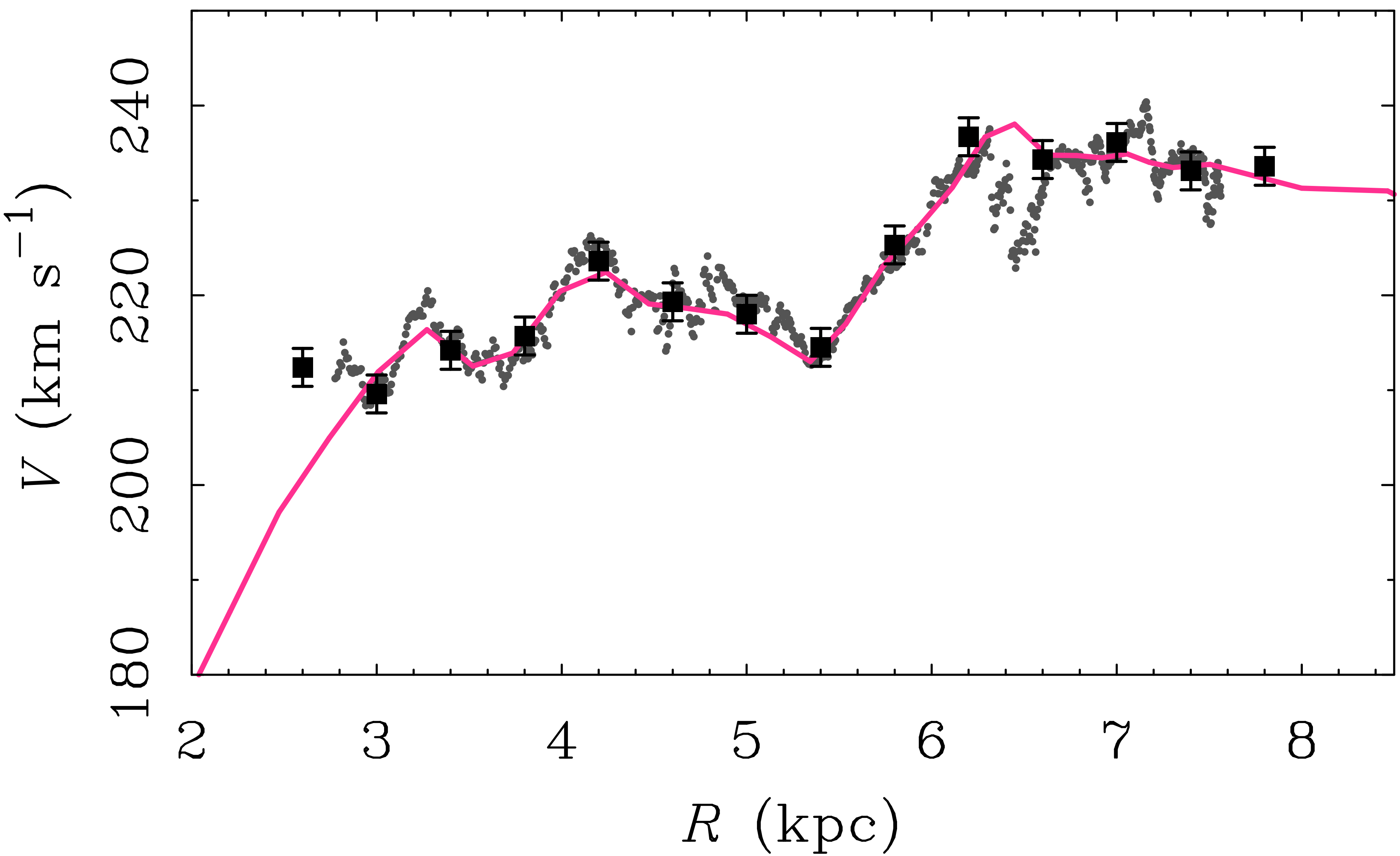
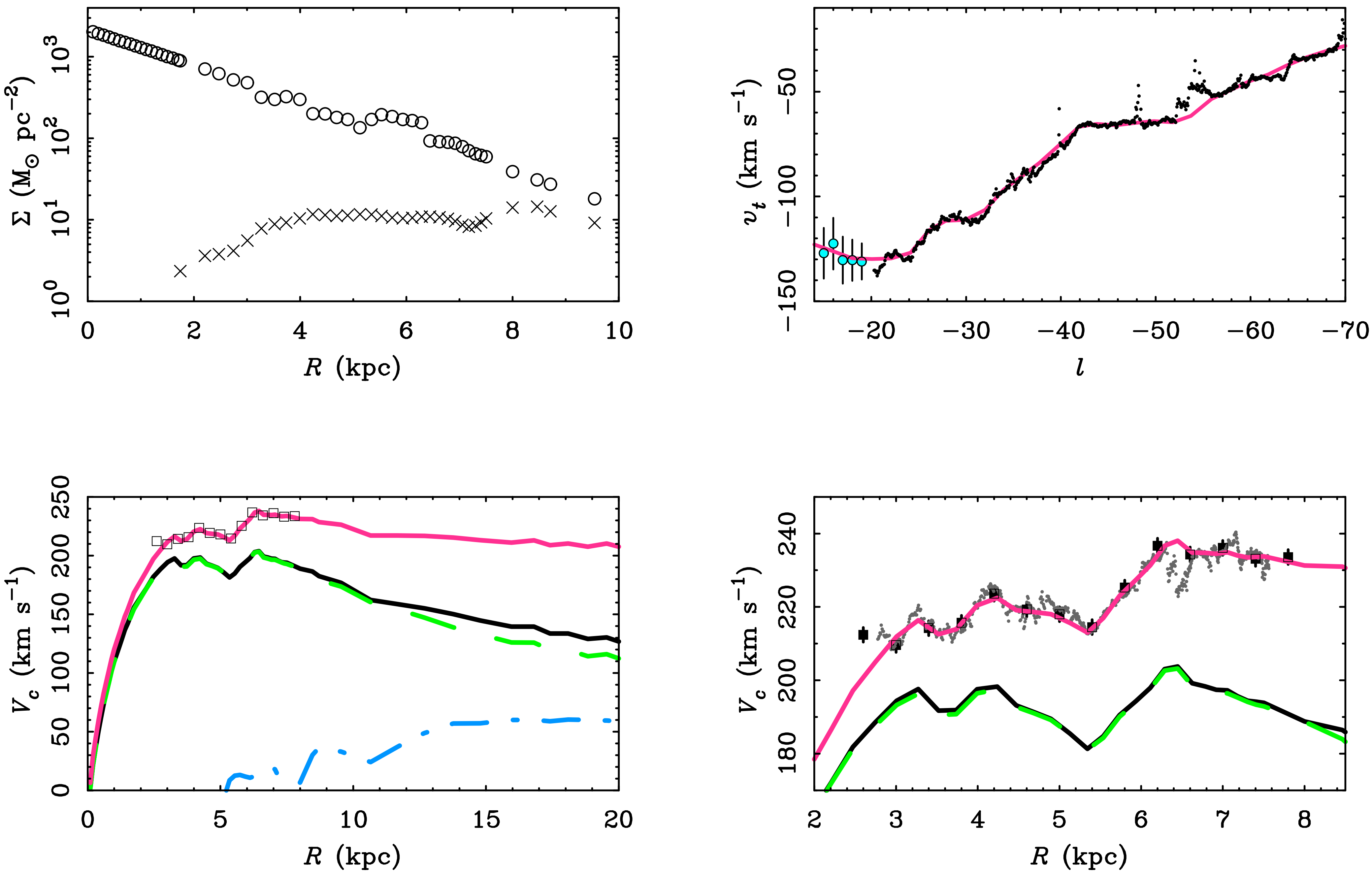
R (kpc)



V (km s^{-1})
180
200
220
240
2
3
4
5
6
7
8
R (kpc)

MONDian Milky Way



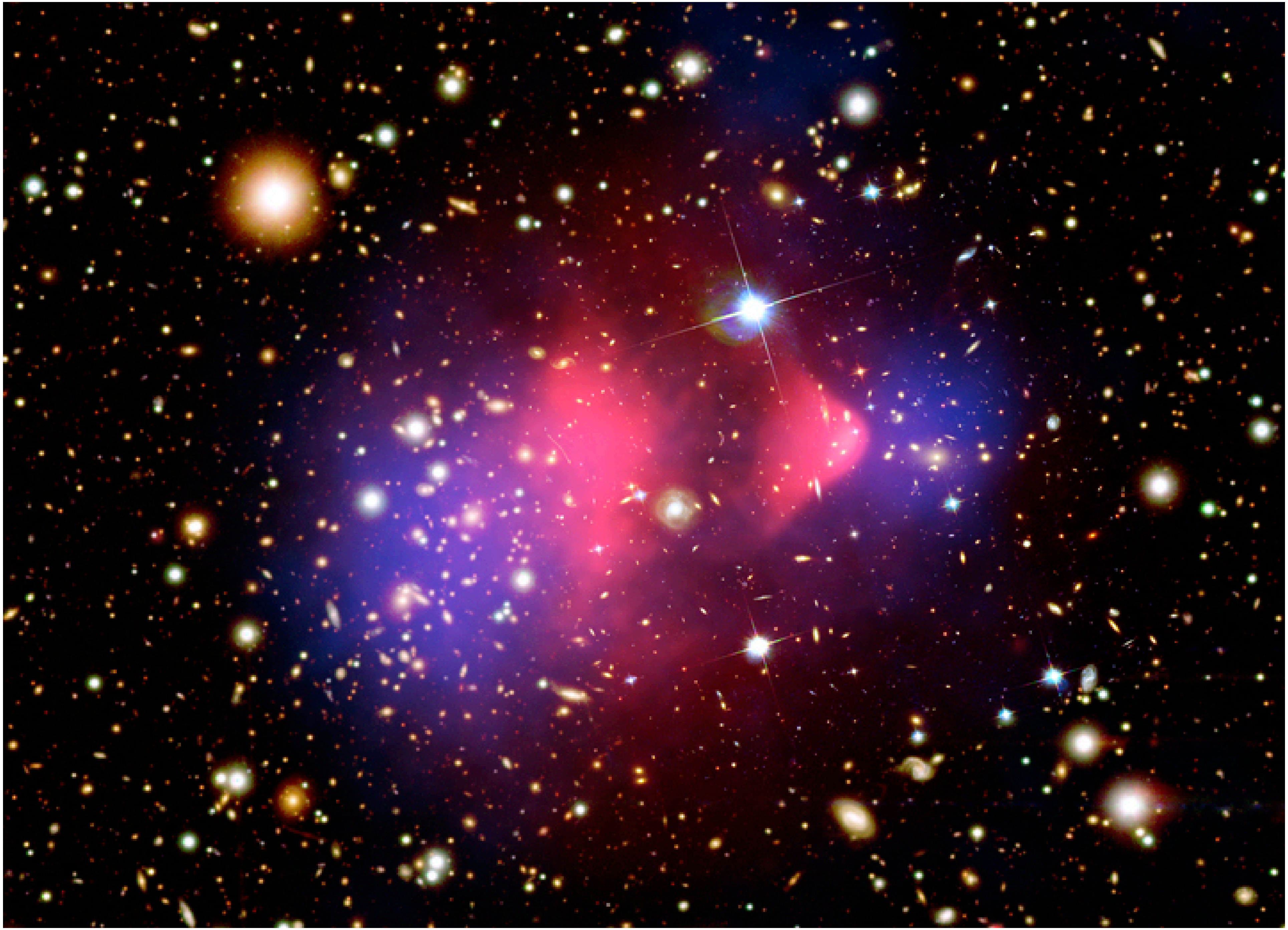
Those are the pros.

What are the cons?

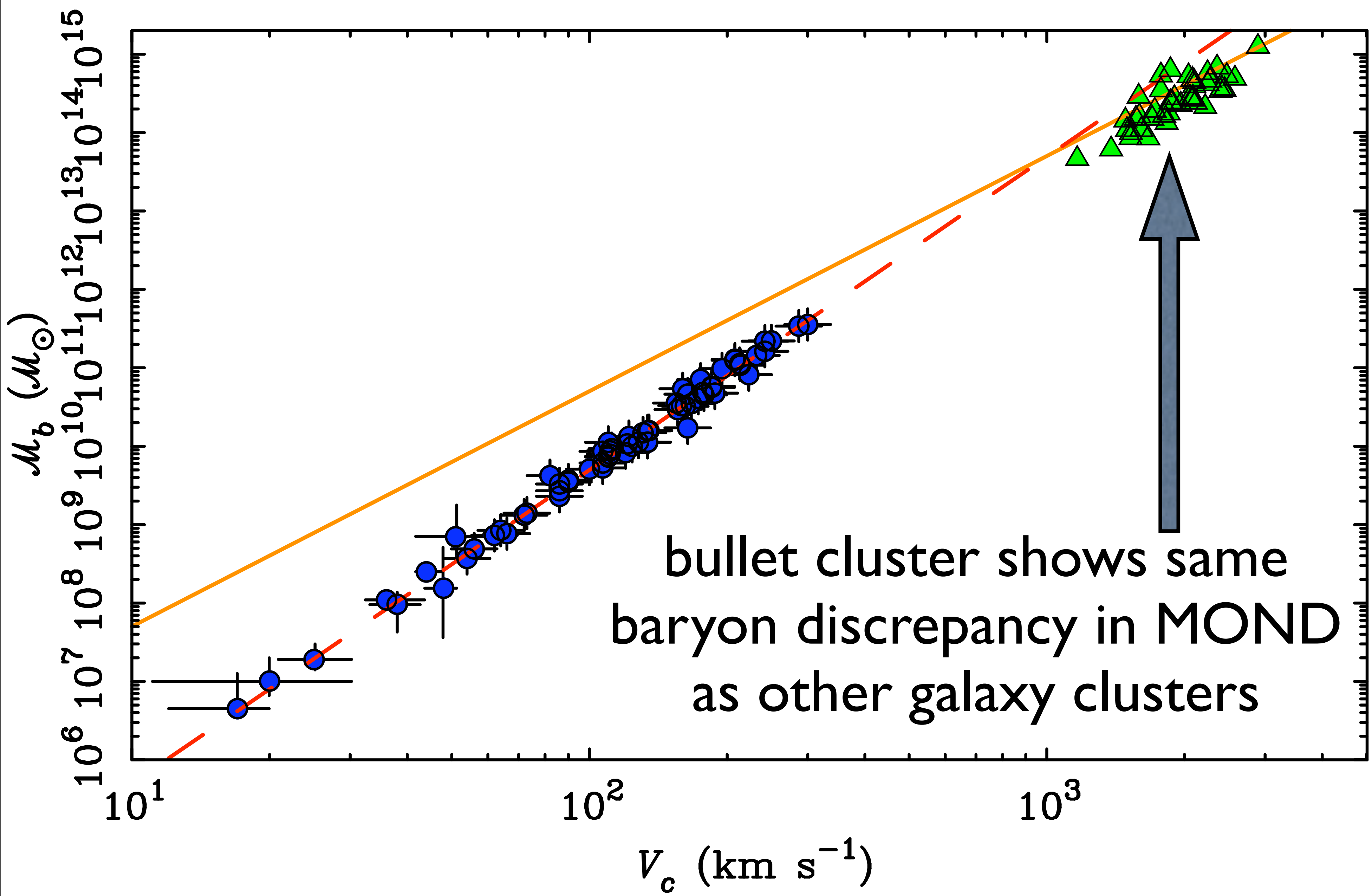
- You don't know the Power of the Dark Side
- Can MOND explain large scale structure?
- Can it provide a satisfactory cosmology?
- Can it be reconciled with General Relativity? TeVeS
- Does it survive other tests?

Clusters problematic

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



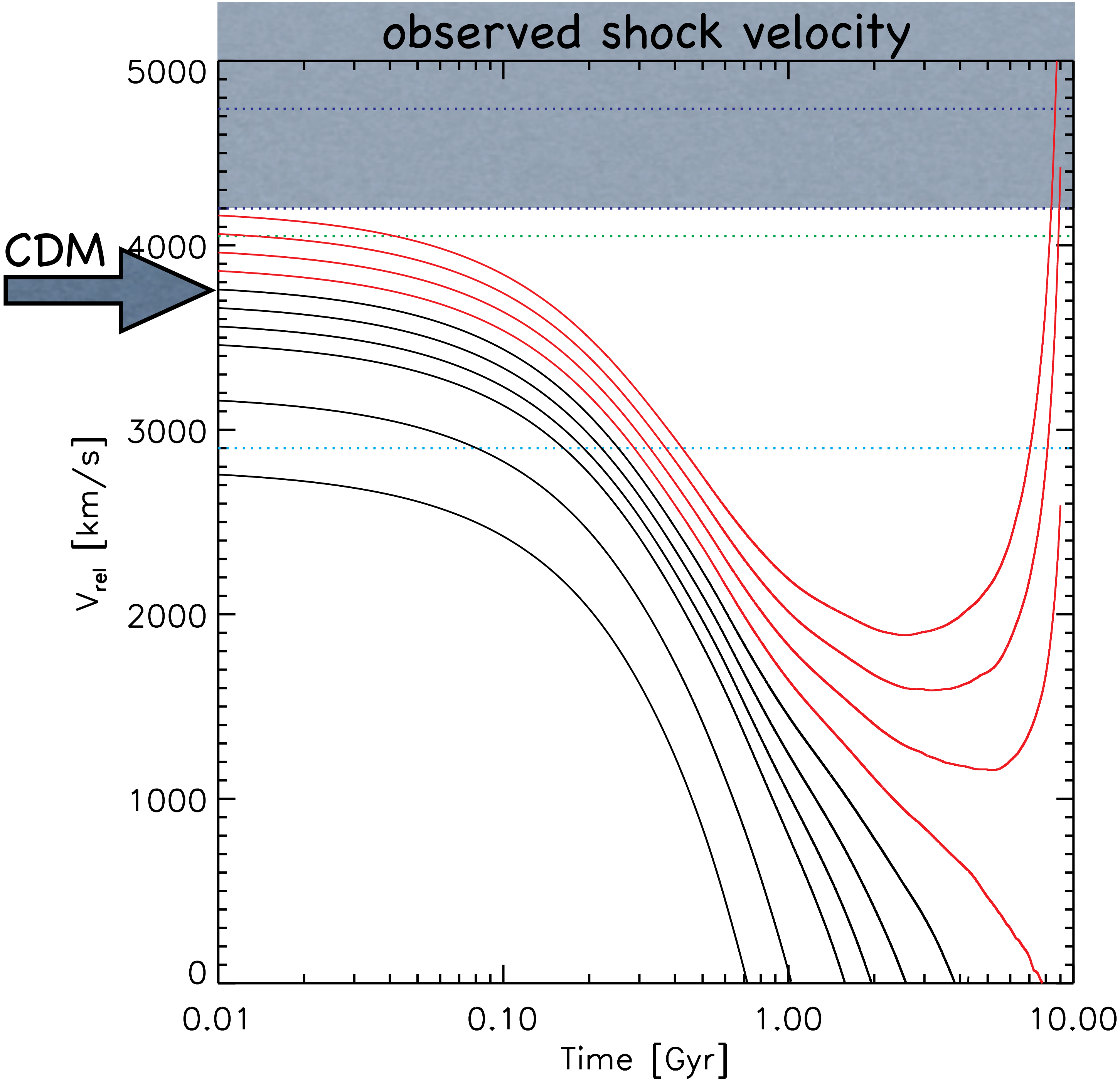
direct proof of dark matter?



MOND suffers a missing mass problem!

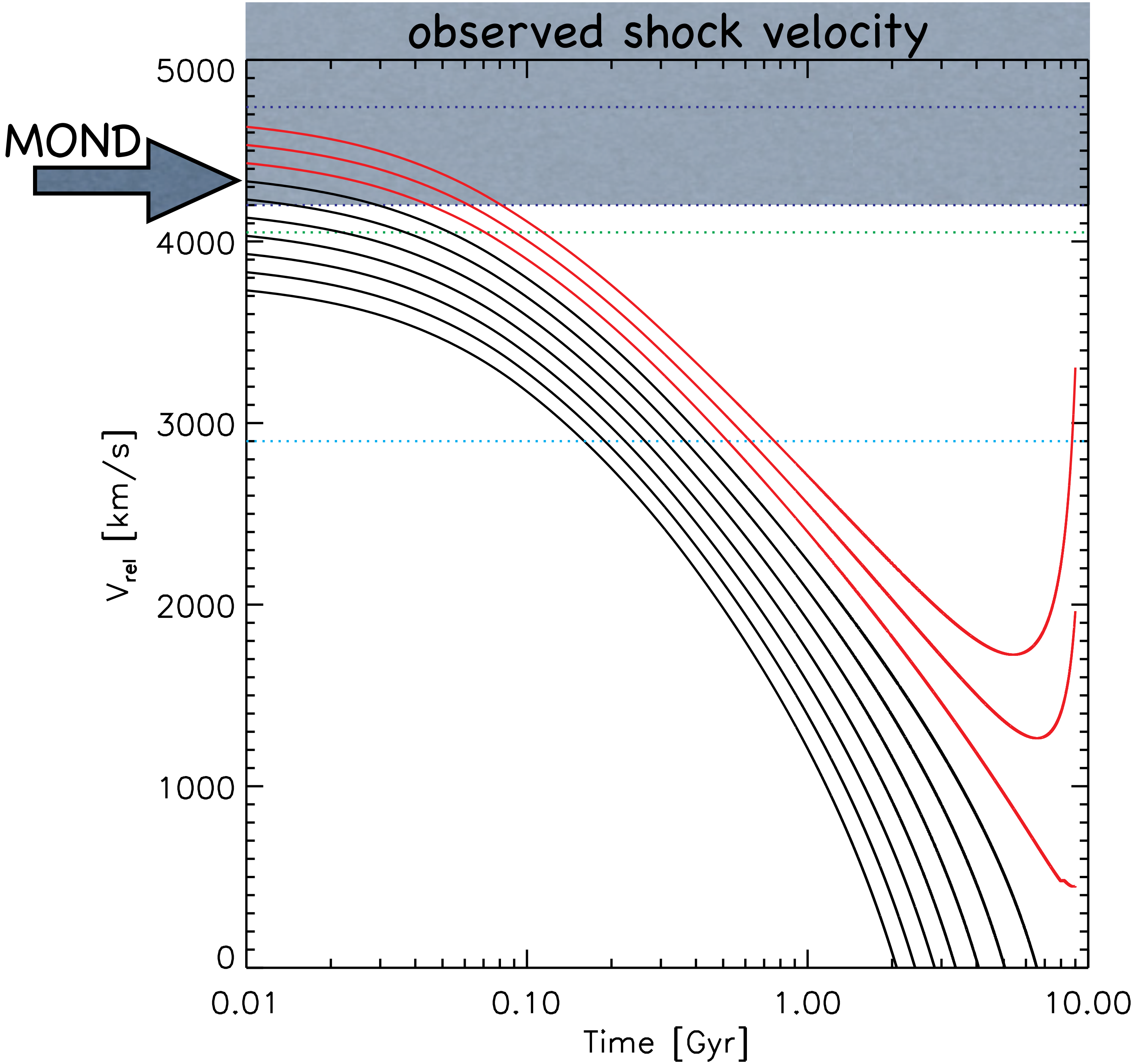
unseen baryons? heavy neutrinos?

bullet cluster collision velocity



Angus & McGaugh (2007) [arXiv:0704.0381]

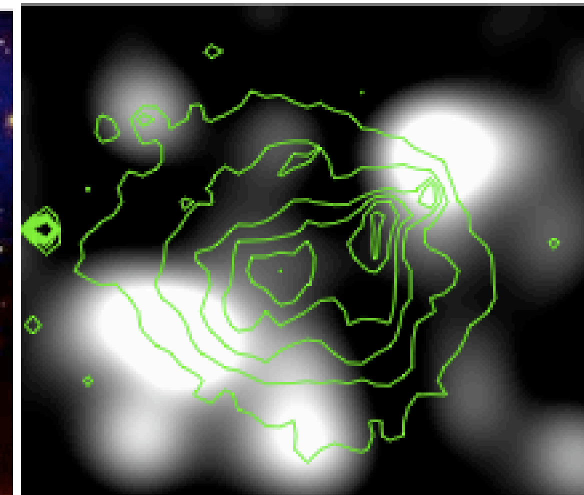
bullet cluster collision velocity

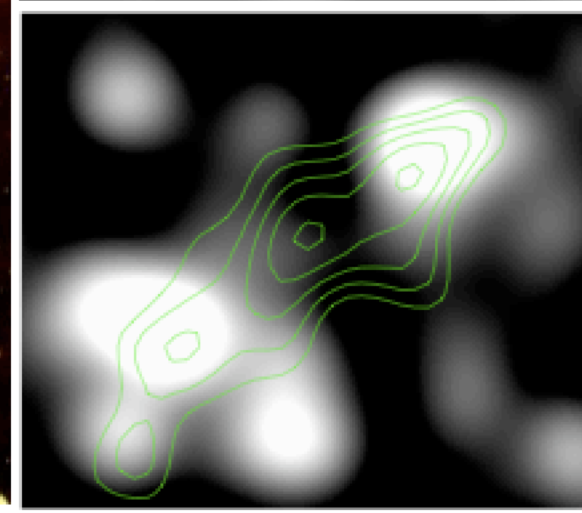


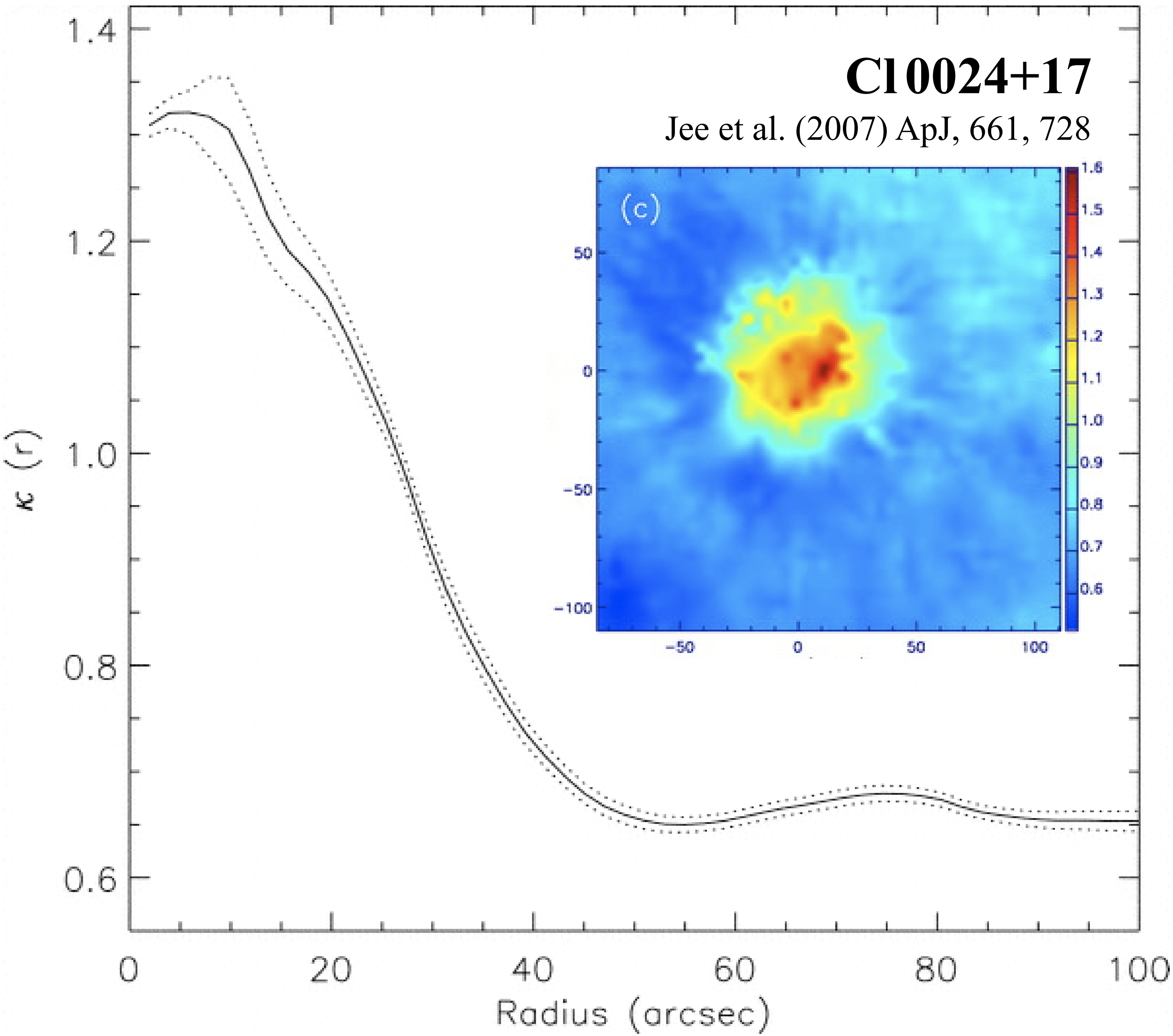
Angus & McGaugh (2007) arXiv:0704.0381

Mahdavi et al. (2007) arXiv:0706.3048

Abell 520 - Counter-example to bullet cluster
with a mass peak devoid of galaxies







Cl0024+17
Jee et al. (2007) ApJ, 661, 728
(c)
κ (r)
Radius (arcsec)
1.4
1.2
1.0
0.8
0.6
0
20
40
60
80
100
50
0
−50
−100
−50
0
50
100
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6

Milgrom & Sanders (2007) arXiv:0709.2561

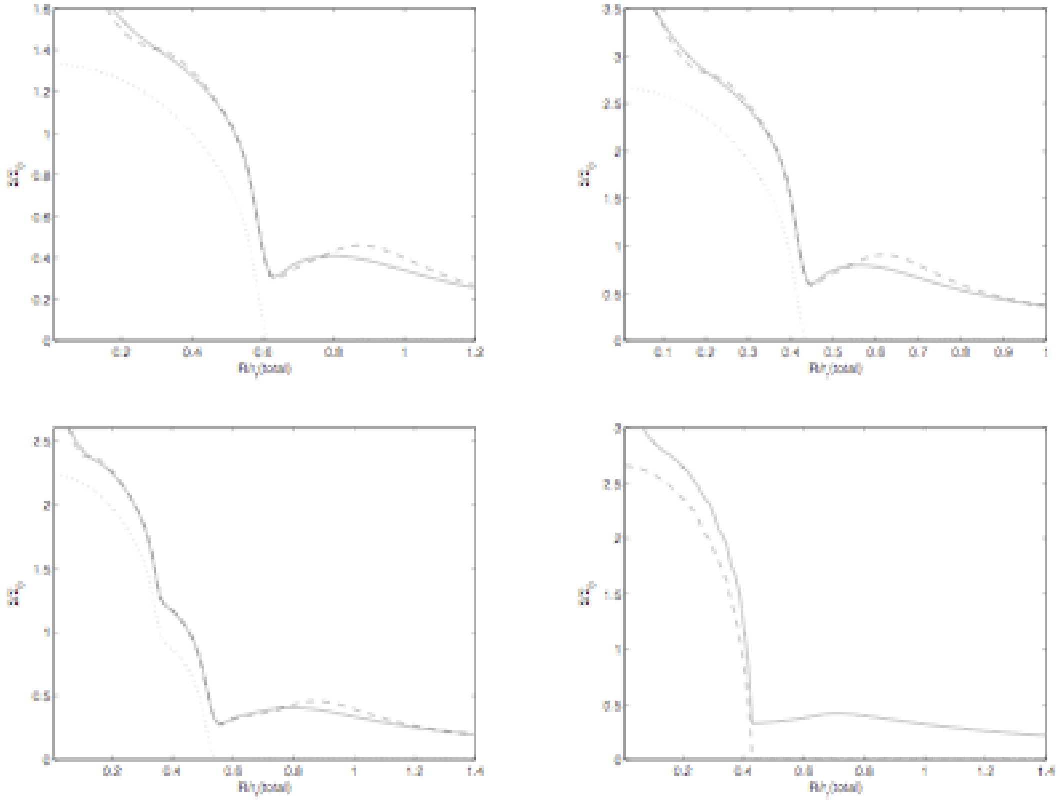


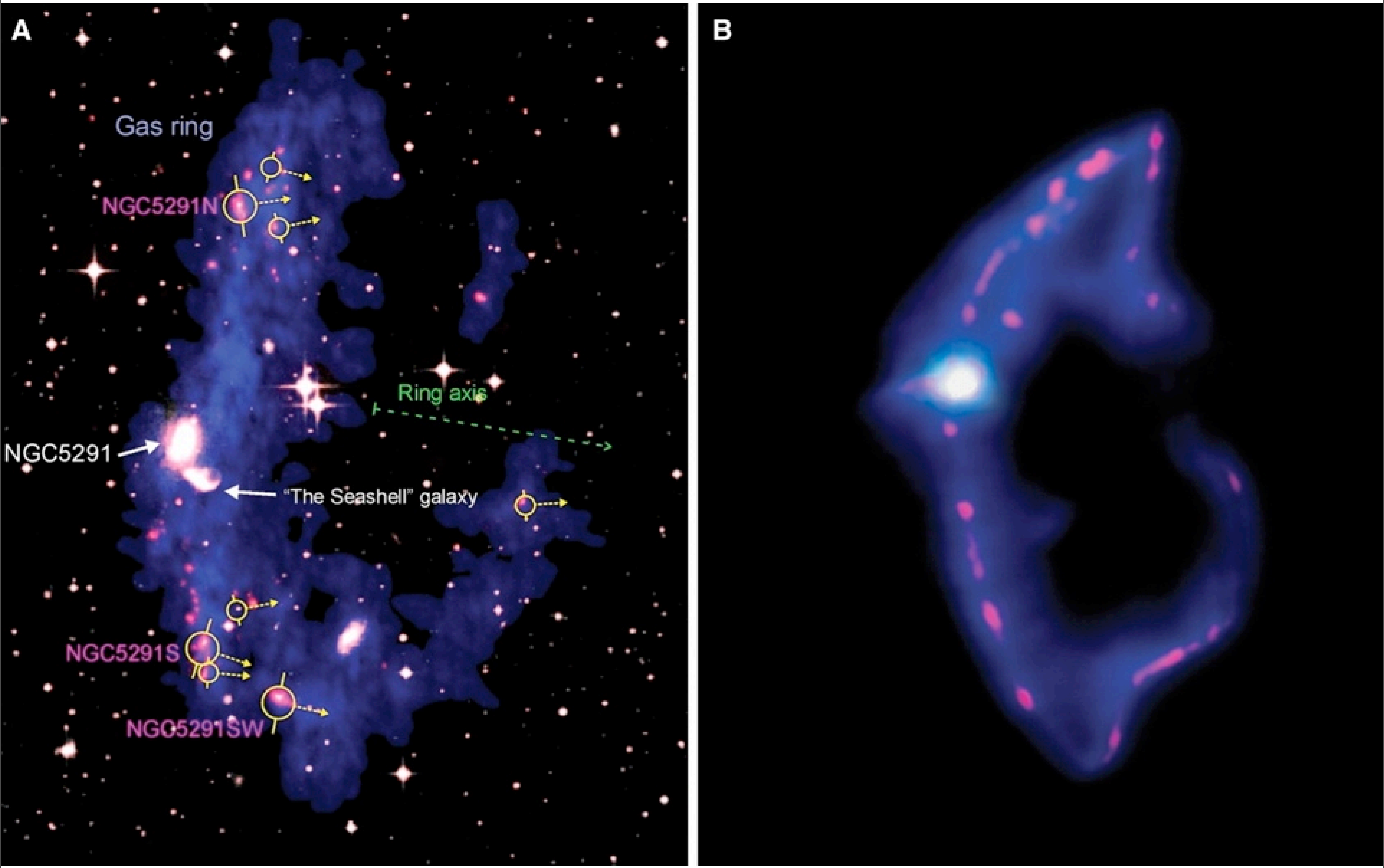
Fig. 6.— The total projected Surface density in units of Σ_0. Upper left: for a single sphere of constant density with a radius that is 0.6 the transition radius. Upper right: for two spheres of constant density far apart from each other along the line of sight, each has a radius that is 0.6 of its own transition radius. Lower left: for two concentric spheres of constant densities of masses 1 and 0.3 and radii 0.53 and 0.35 of the total transition radius. All these for two interpolating functions: $\bar{\mu}_2$ (solid) and $\bar{\mu}_3$ (dashed). In each case the baryon contribution alone is shown as the dotted line. Lower right: a dumbbell of two equal spherical masses of constant density far apart along the line of sight with μ_{10} (the source, baryon, contribution in dashed line).

$$r_t = \sqrt{\frac{GM}{a_0}}$$

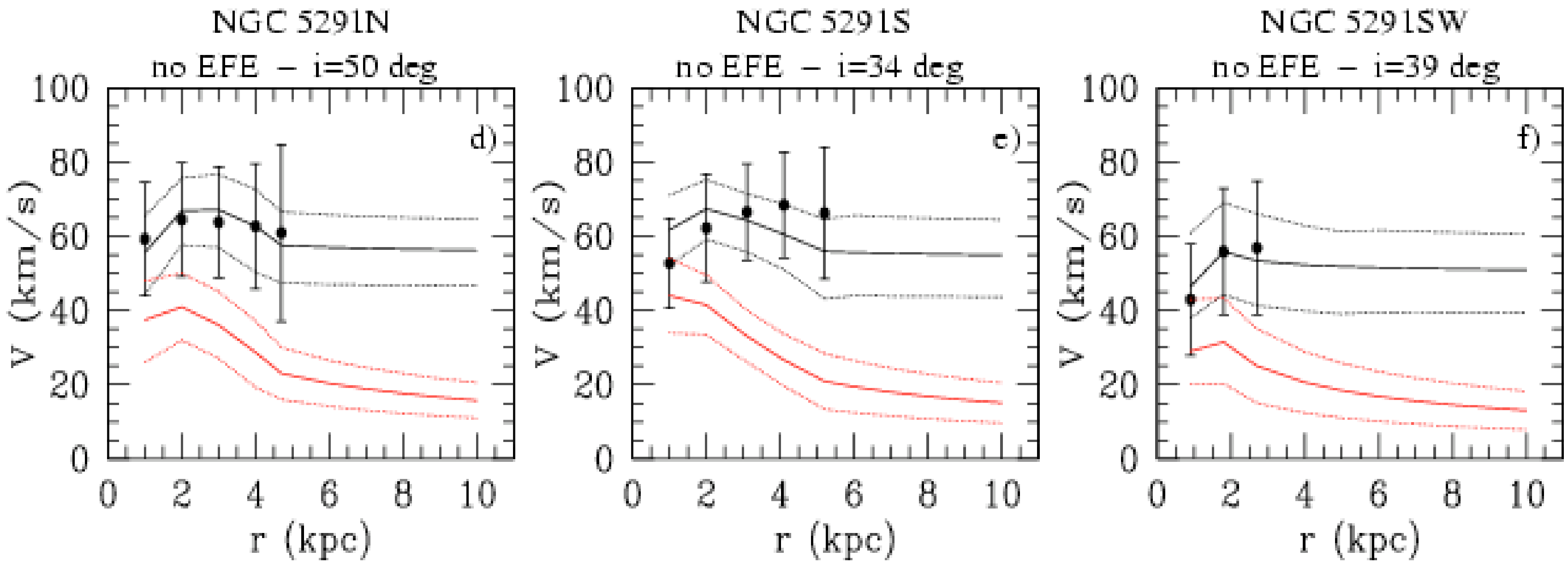
There can be an feature around the transition radius not present in the baryon distribution, depending on the interpolation function.

The ring reported by Jee et al. may be such a feature.

Tidal Debris Dwarfs - should be devoid of Dark Matter

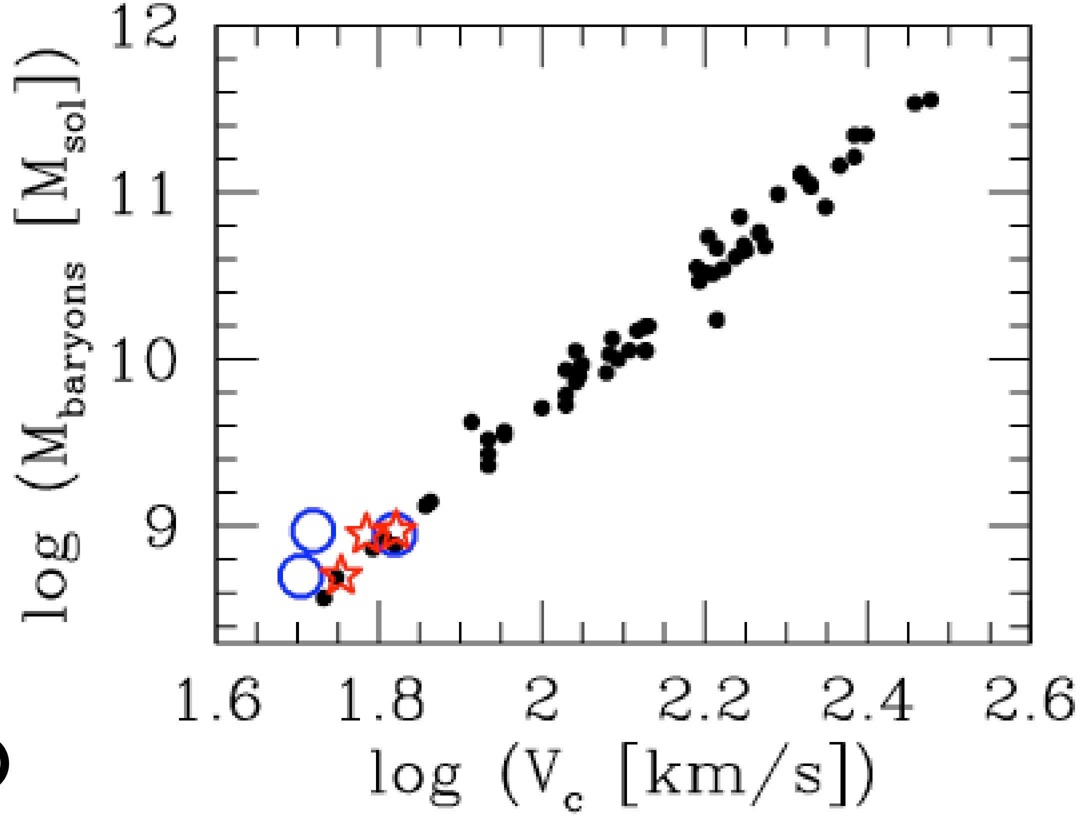


Bournaud et al. (2007) *Science*, **316**, 1166



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

Tidal dwarfs do show mass discrepancies as expected in MOND



Tiret & Combes

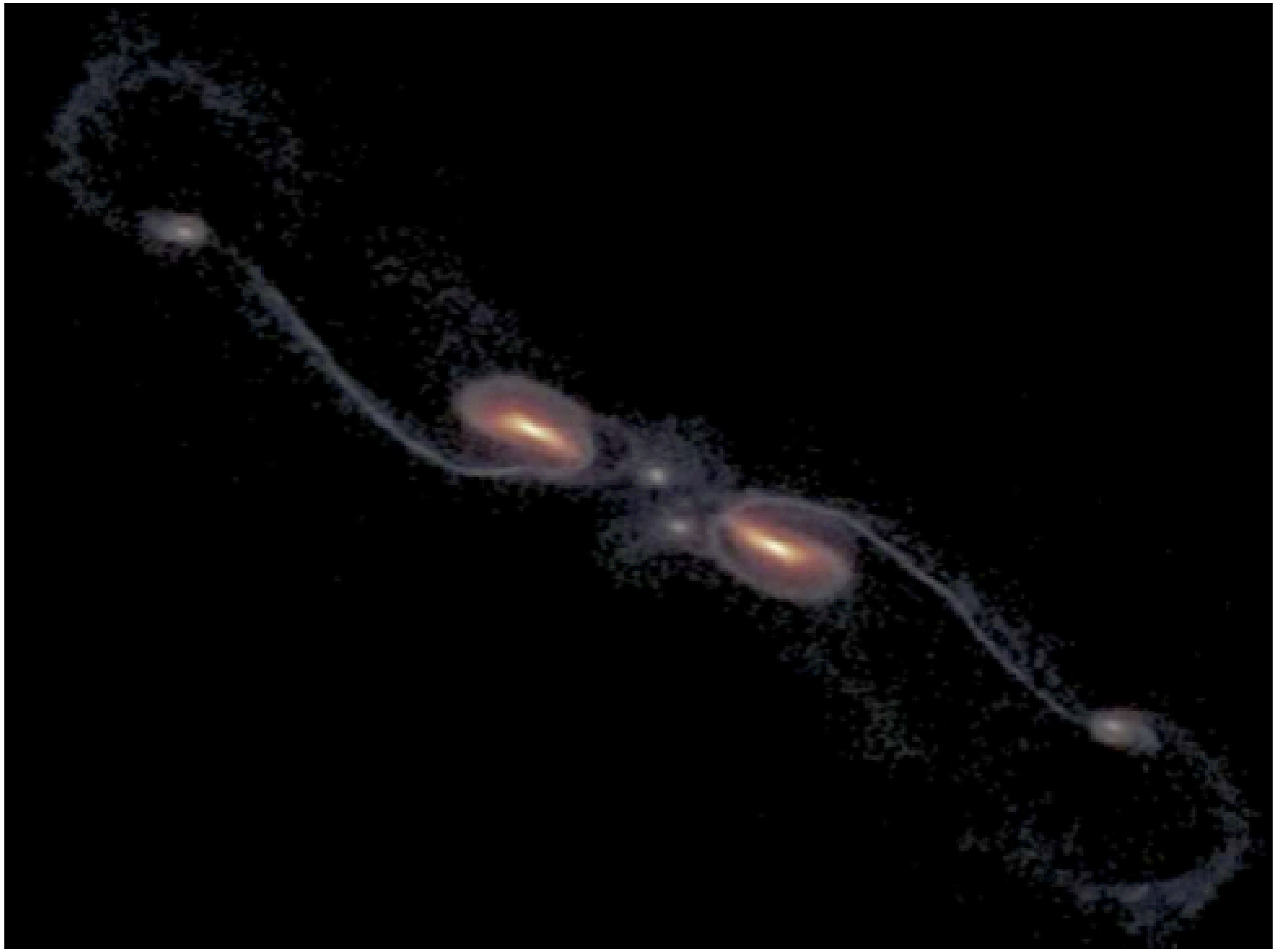
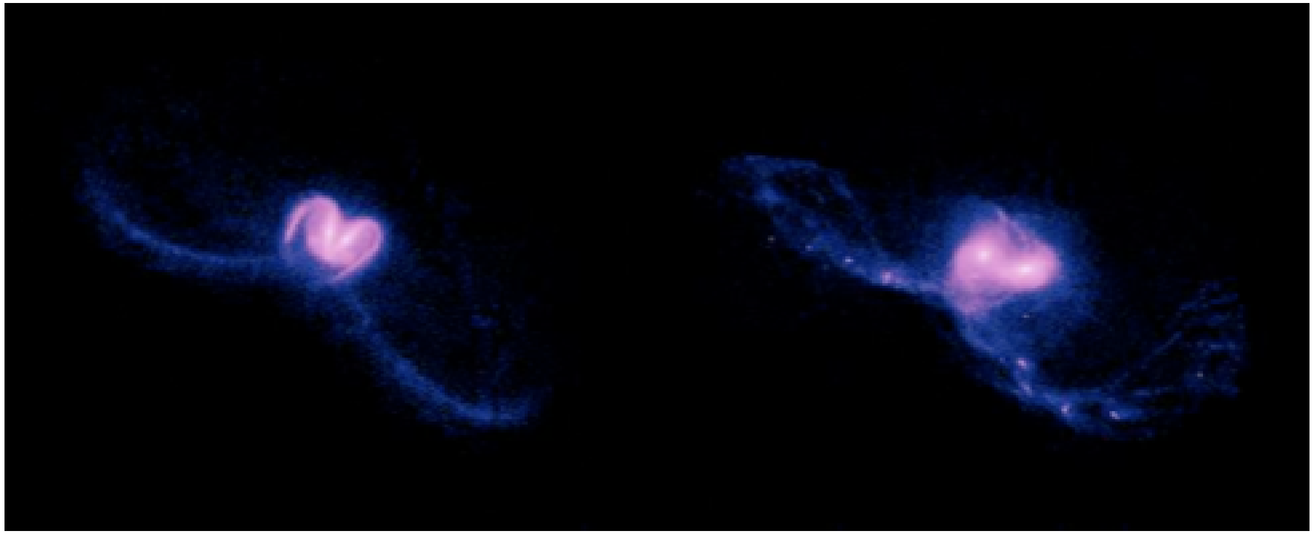
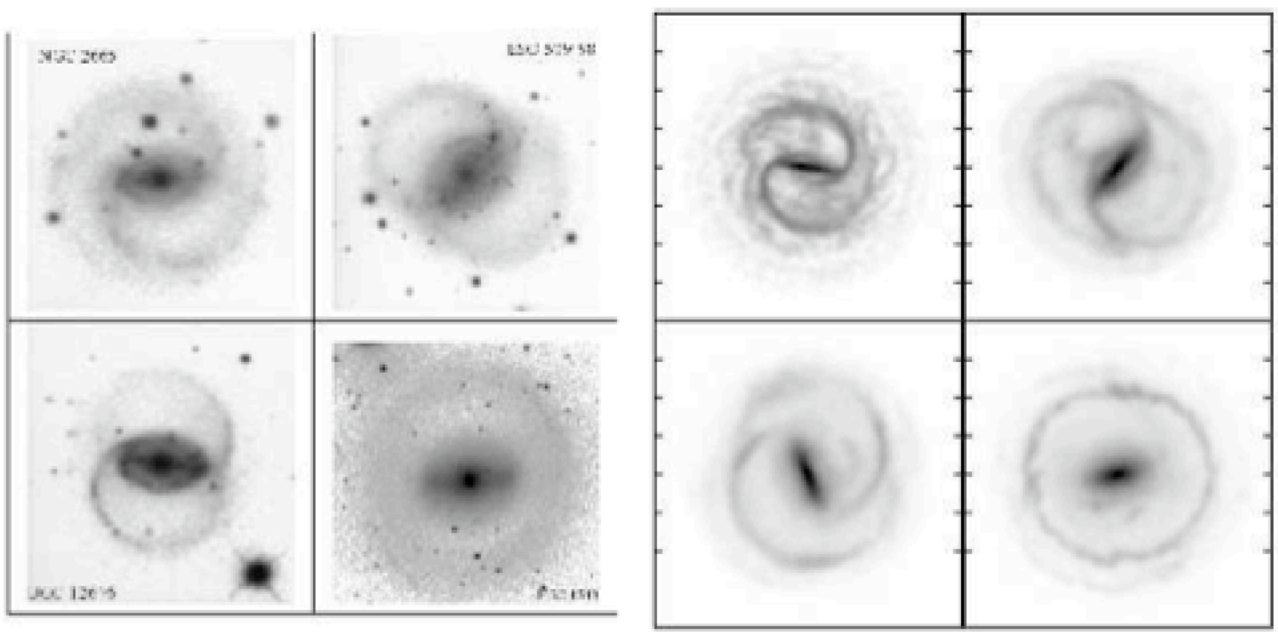


Fig. 6. Tidal dwarf formation at the tip of the tidal tail in MOND.



Tiret & Combes

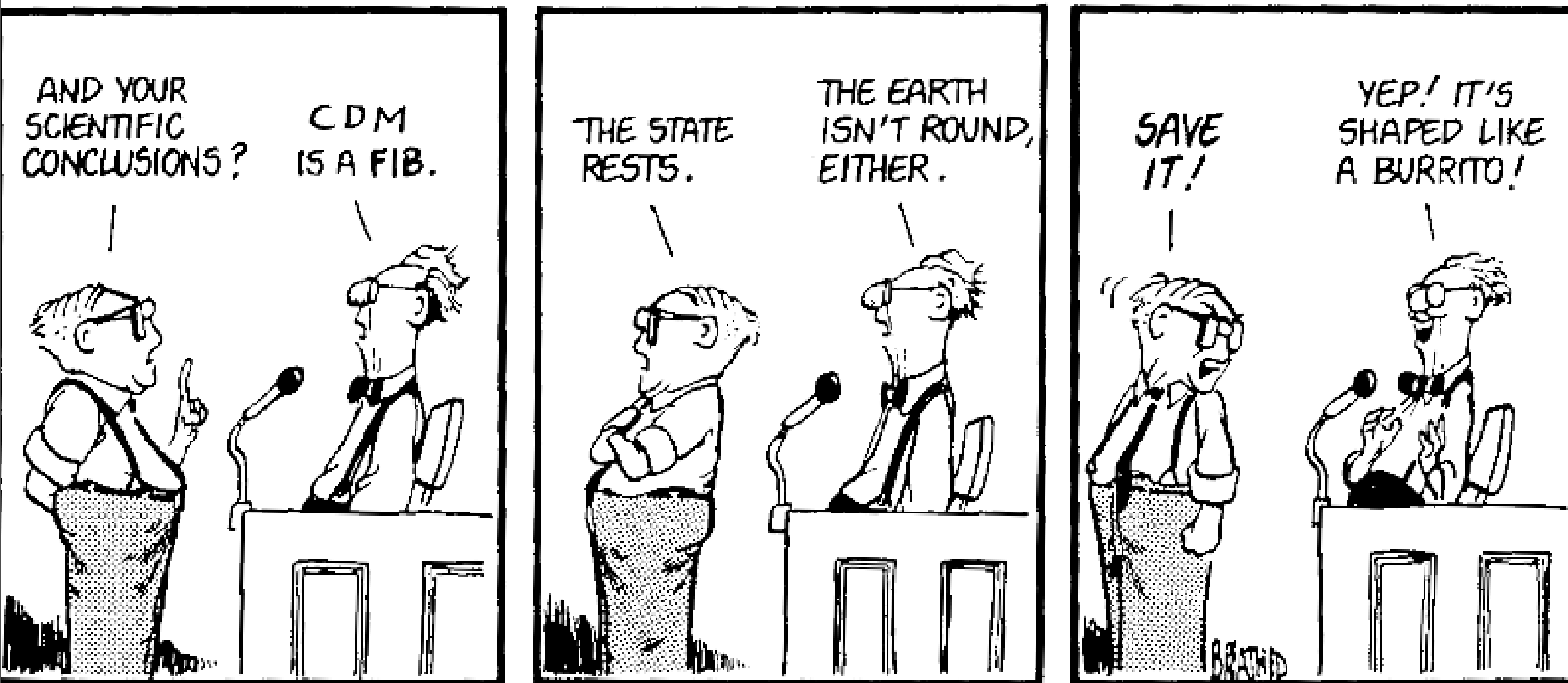
Fig. 5. Simulations of the Antennae galaxies in the DM model (left) and MOND model(right).



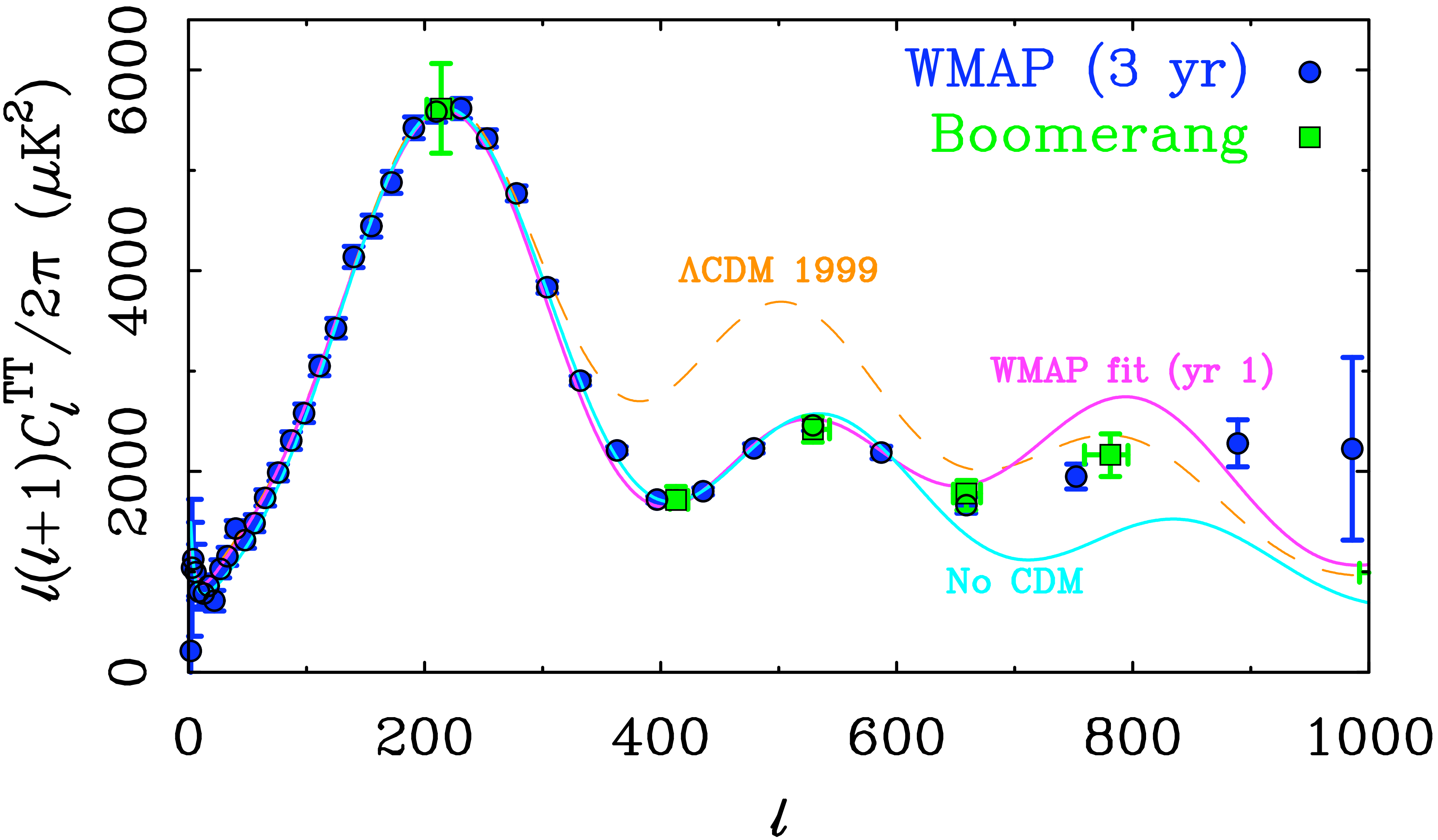
. Several examples showing the morphological structures of NGC 2665, ESO 509-98, UGC 12646 and NGC 1543 anel) compared to simulated galaxies in MOND (bottom panel). Rings and pseudo-rings structures are well uced with modified gravity.

Conclusions

- MOND naturally explains a diverse array of phenomena
- Many *a priori* MOND predictions have been realized
- Even though incomplete as a theory, MOND encapsulates an important phenomenology (Renzo's Rule)
- The observed MONDian phenomenology is not naturally a part of the ΛCDM paradigm



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!



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