Cosmic Flights of Fancy: Mass and the Gravity that Moves It

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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

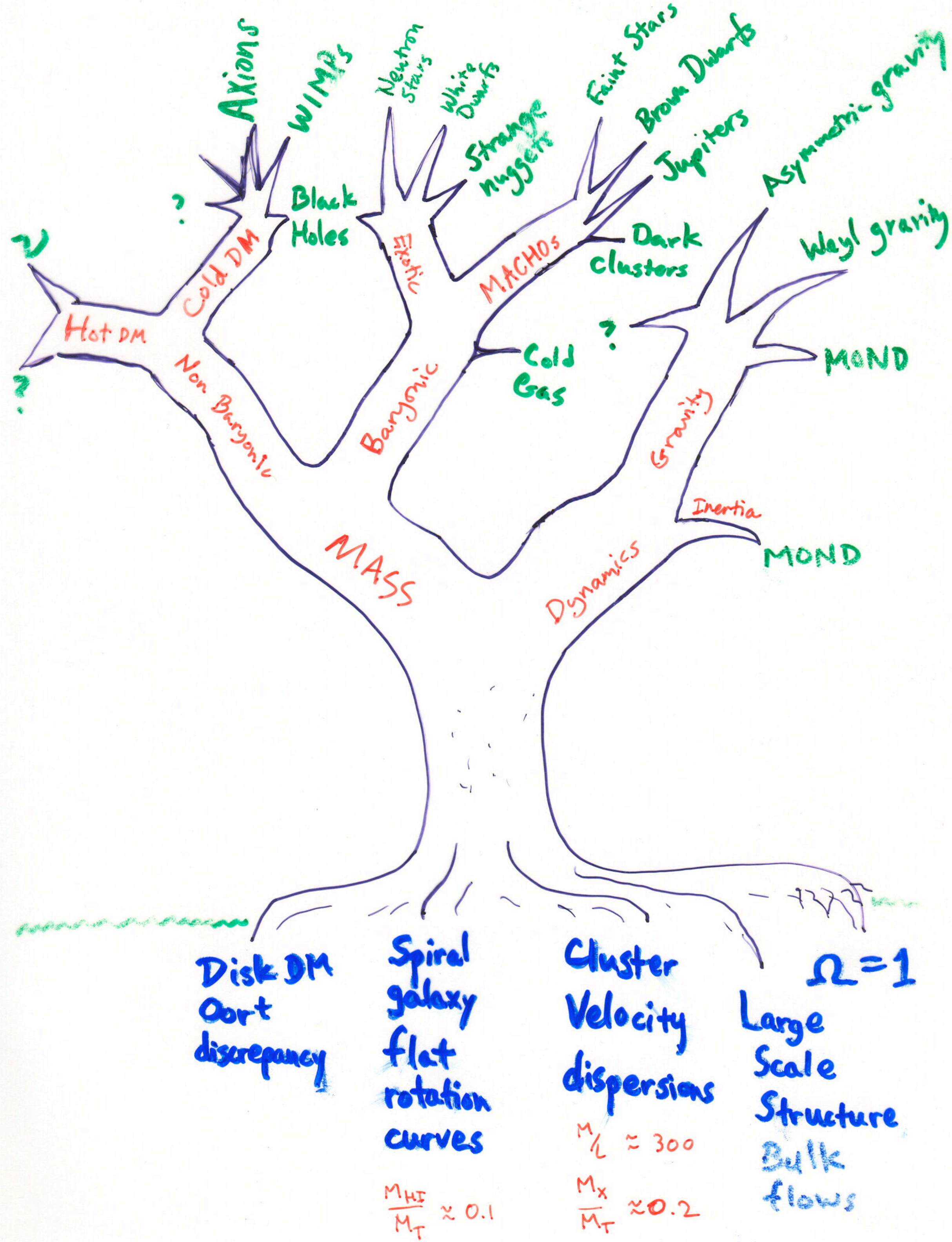
$$mV^2/R = GMm/R^2$$

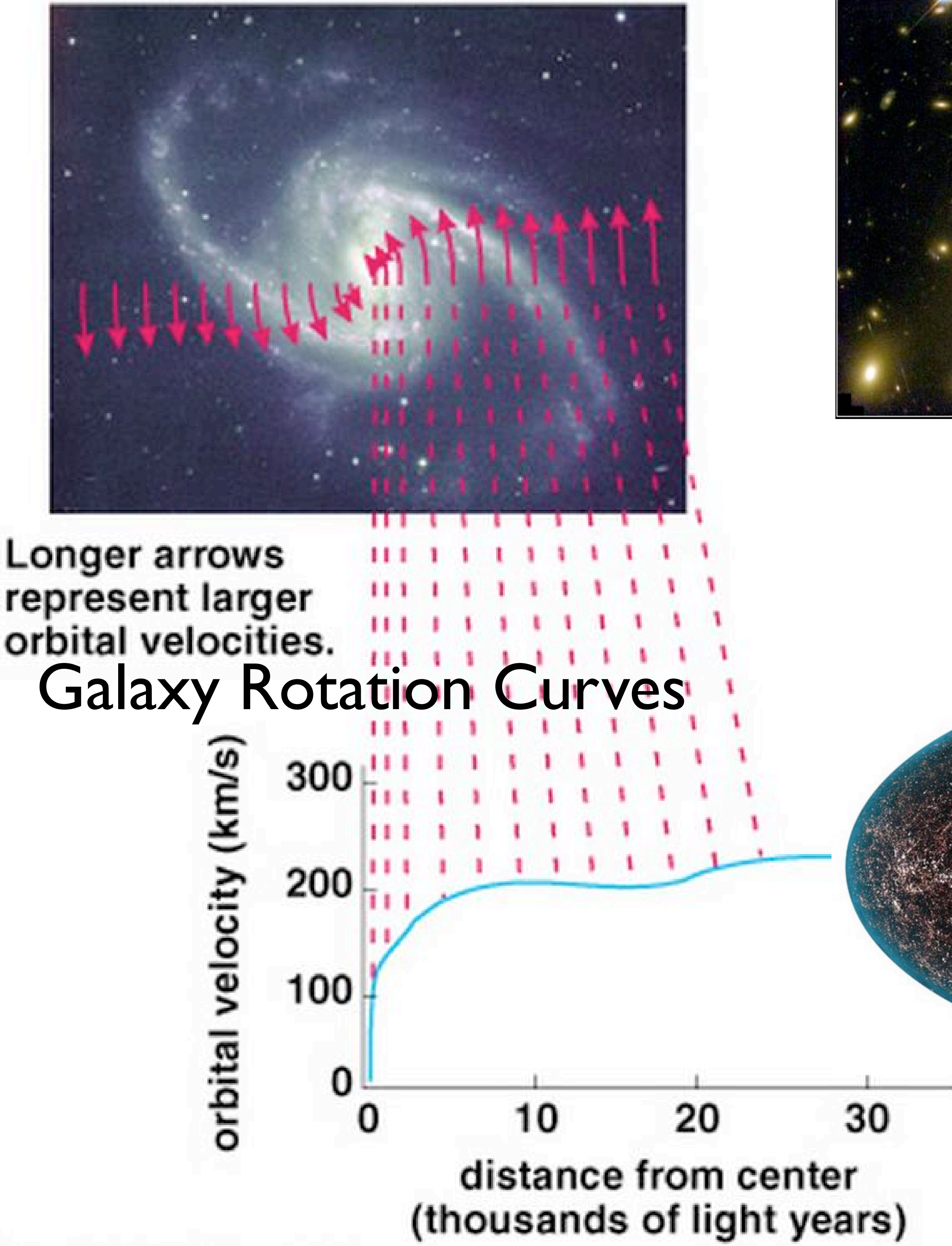
i.e,

$$V^2 = GM/R$$

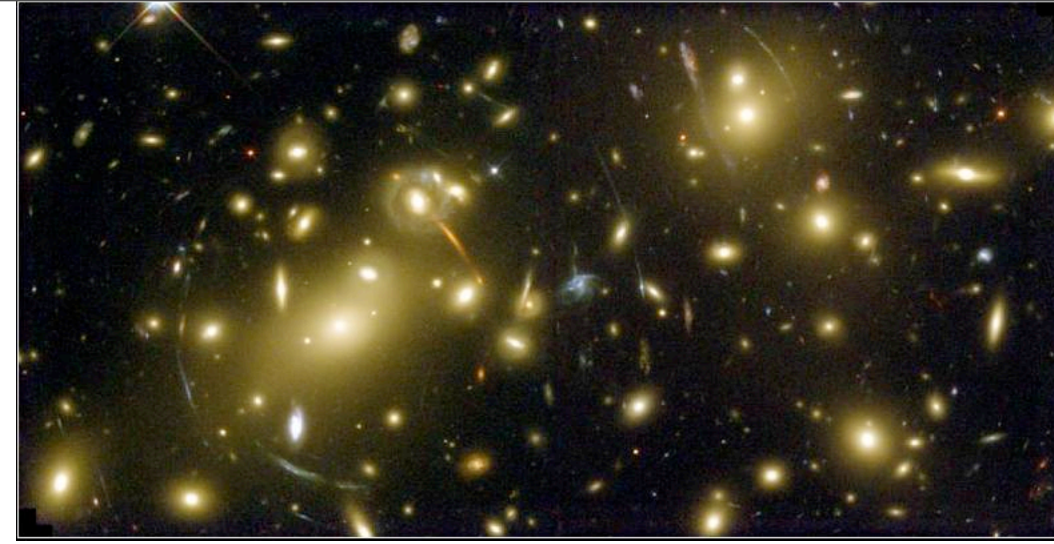
ergo...

The universe is filled with nonbaryonic cold dark matter.


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

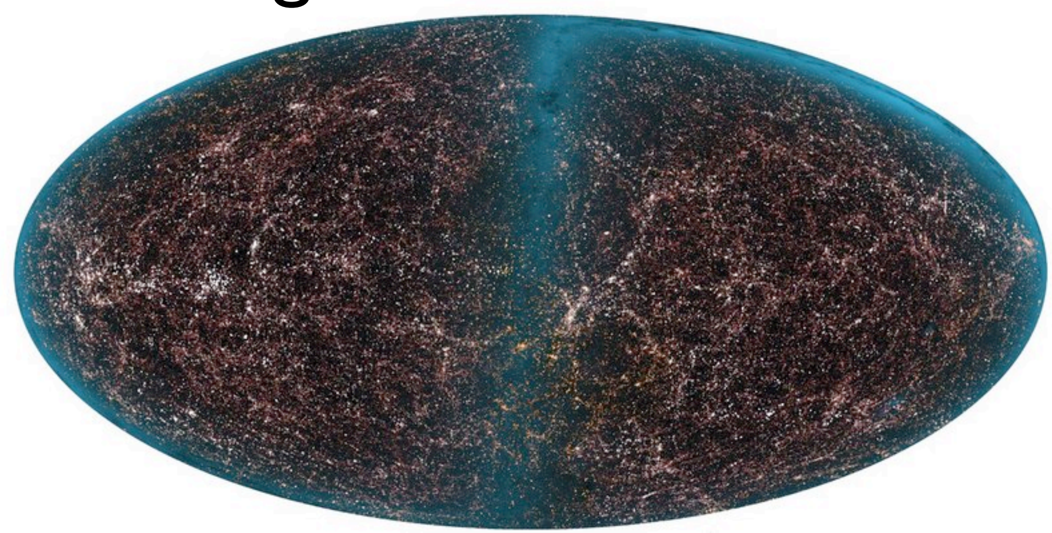


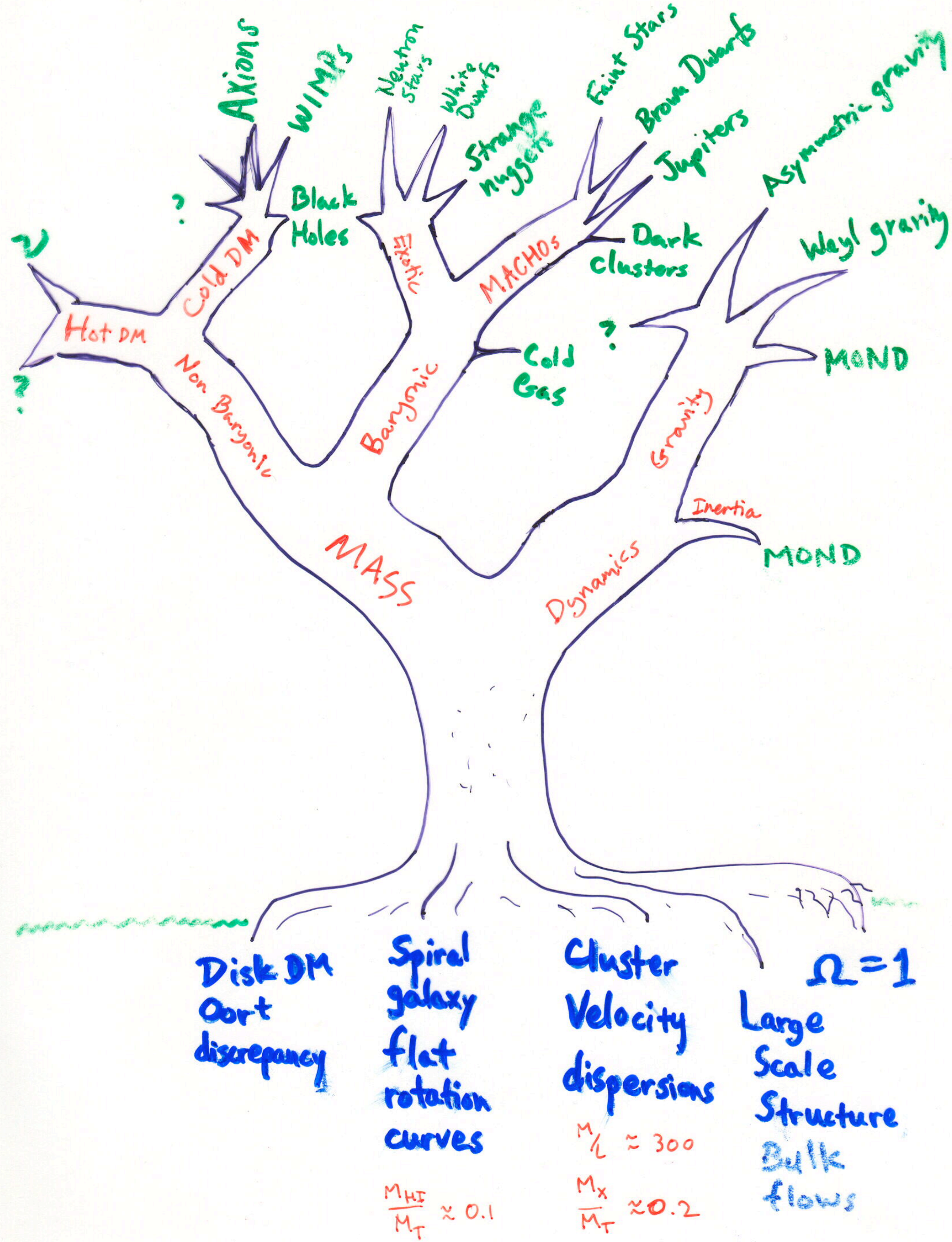
Galaxy Rotation Curves



Galaxy Clusters

Large Scale Structure

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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

What is the Dark Matter?

Baryonic Dark Matter

Normal things:

very faint stars, brown dwarfs

other hard-to-see objects (planets, gas)

Hot Dark Matter

neutrinos - got mass, but not enough

✔ **Cold Dark Matter**

Some new fundamental particle

doesn't interact with light, so quite invisible.

Two big motivations:

1) total mass outweighs normal mass from BBN

2) needed to grow cosmic structure

(1)

Normal baryonic mass = 4% of total

from Primordial Nucleosynthesis

Total mass density = 27% of total

from gravity

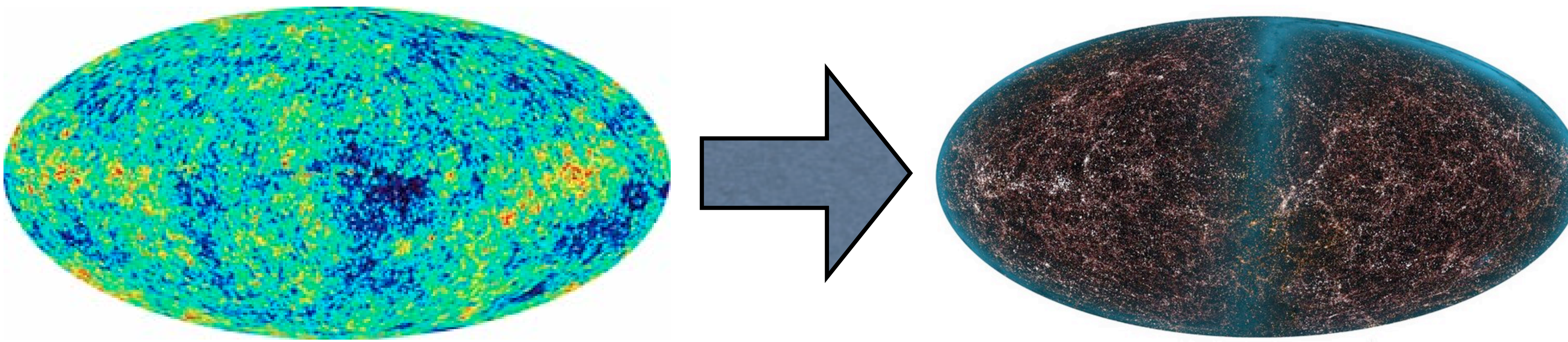
gravitating mass >> normal mass

Most of the mass needs to be
in some brand new form!

(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

t = 1.4 x 10^{10} yr



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

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

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

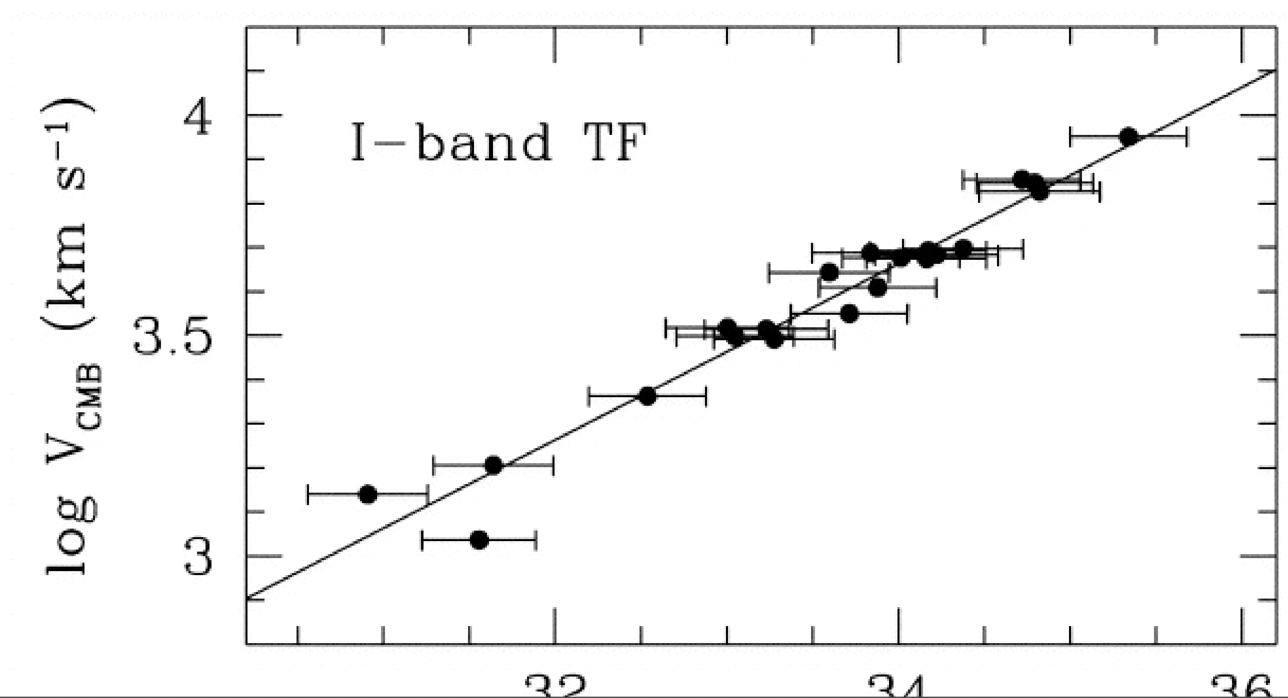
Both (1) and (2) hold only when gravity is normal.

Dark Energy

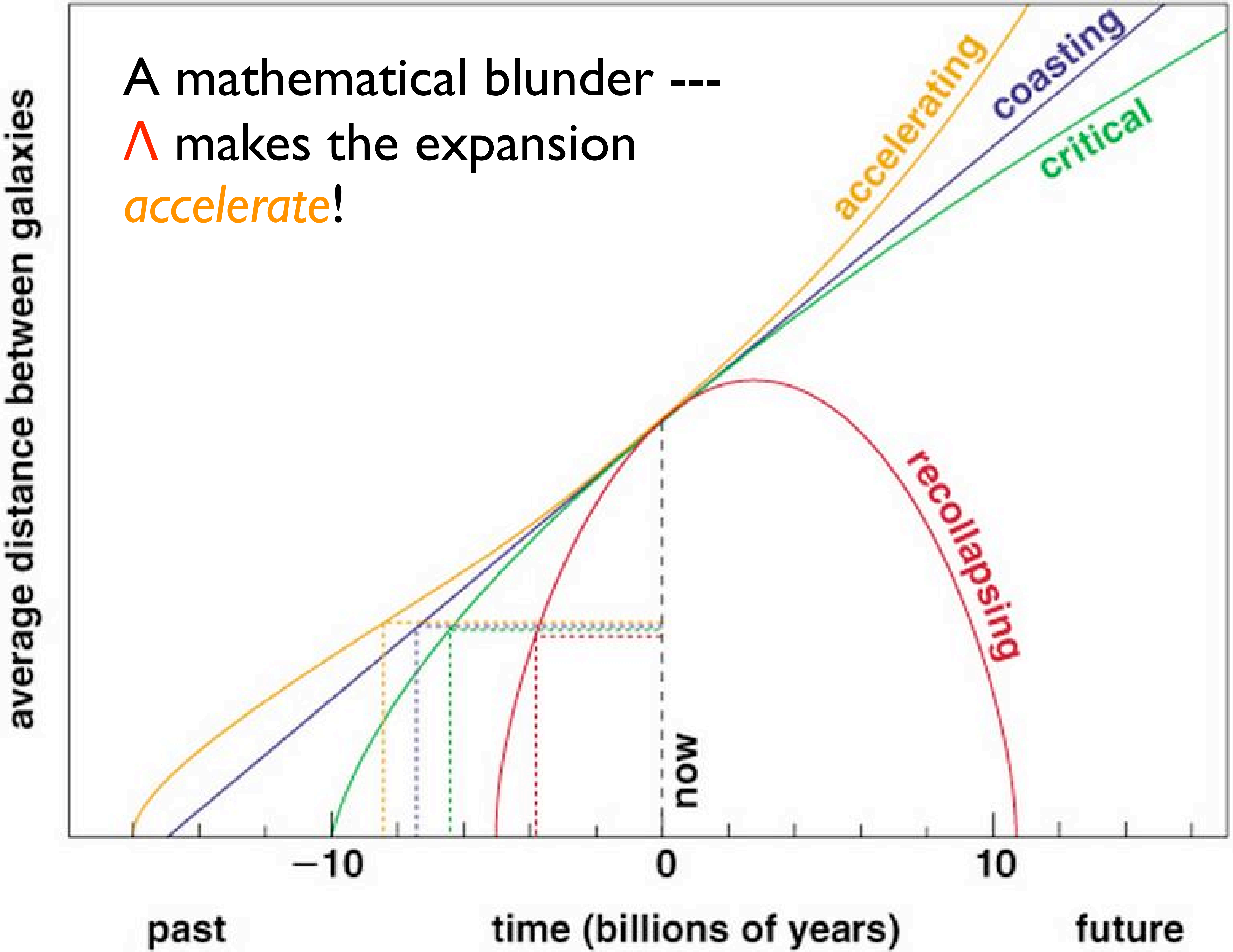
Einstein's greatest blunder?

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

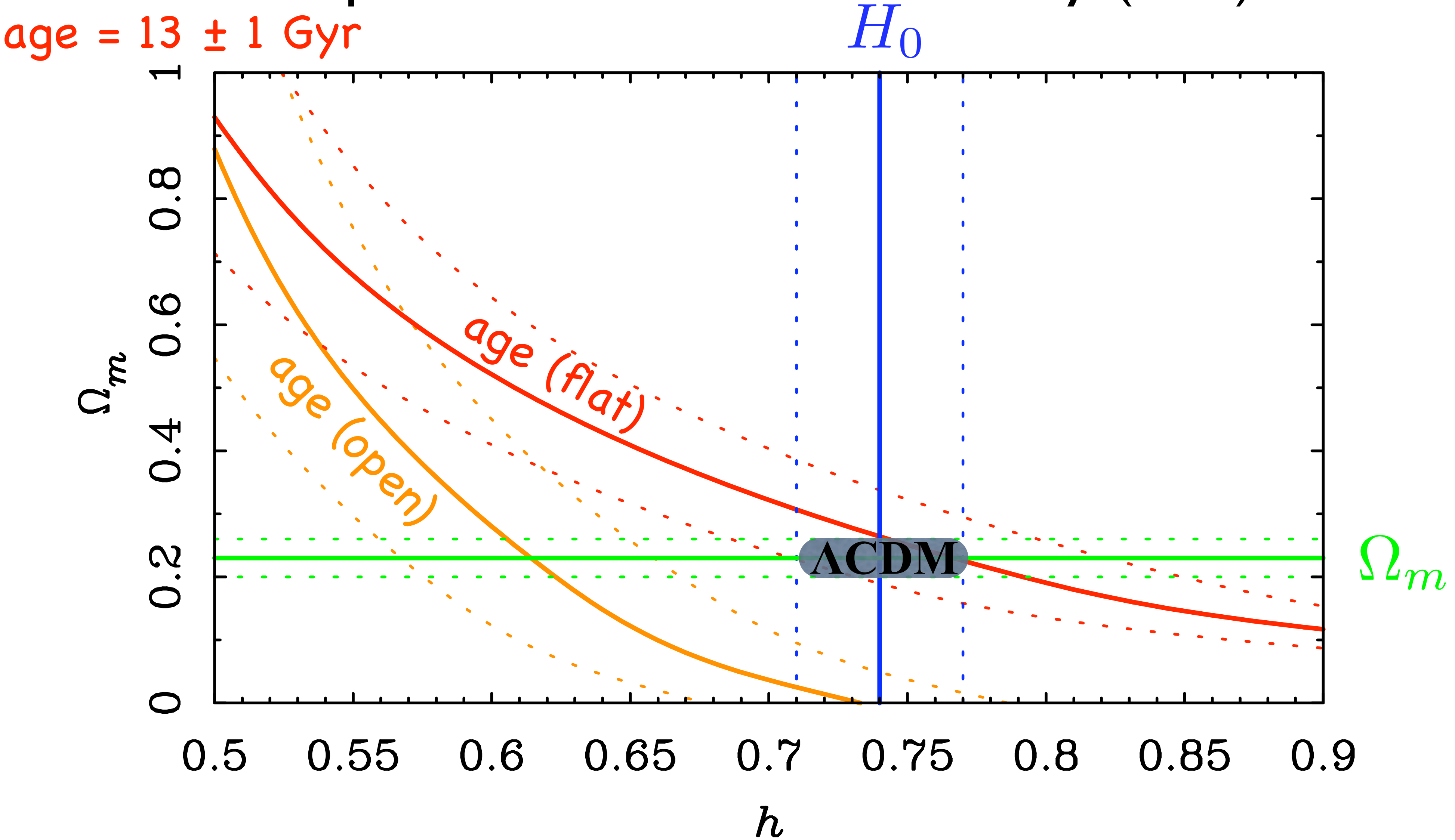
Einstein's intention was to keep the universe static. But it does expand!



A mathematical blunder ---
Λ makes the expansion
accelerate!



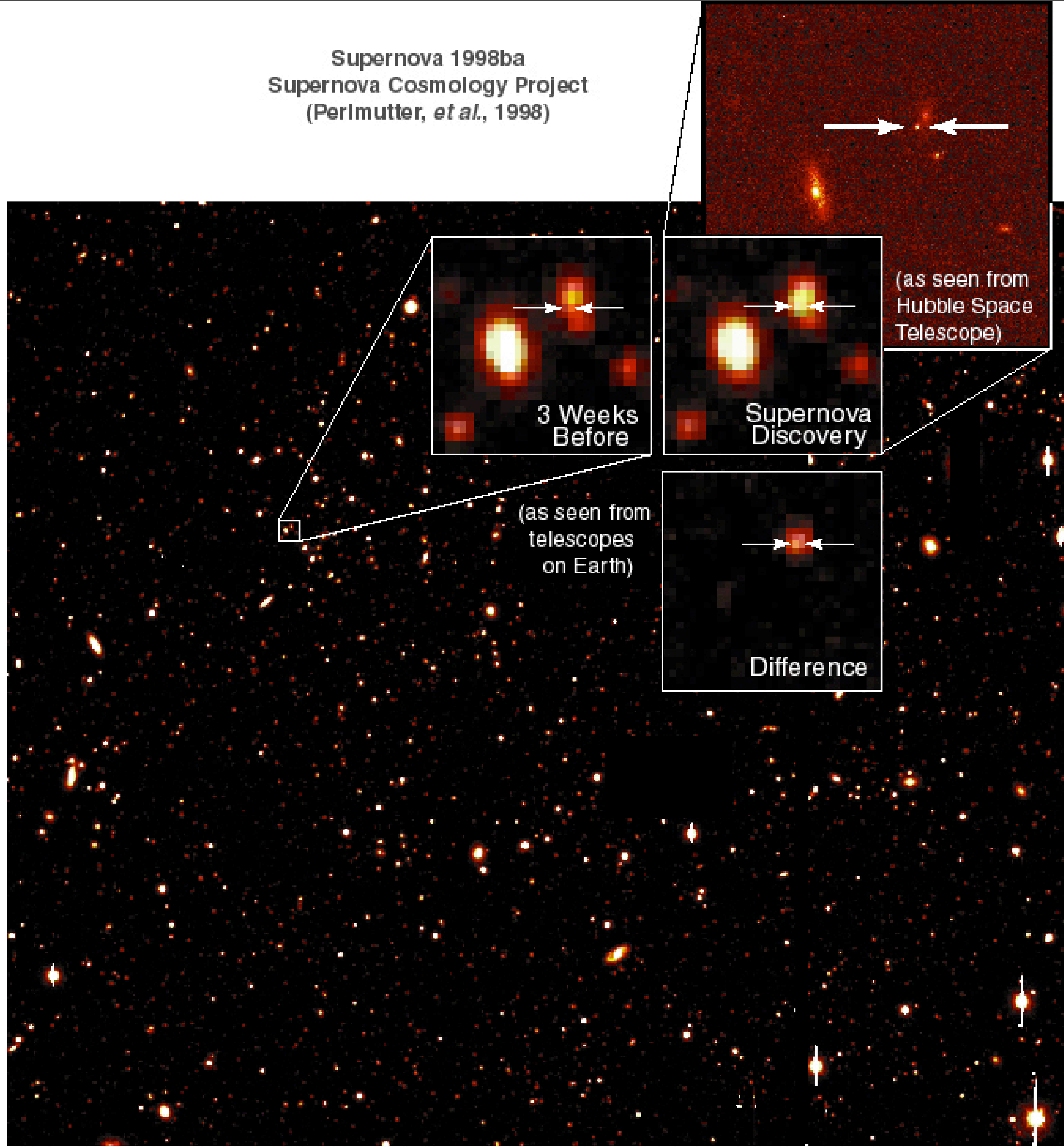
The Search for Two (or Three) Numbers
Expansion Rate & Mass Density (& Λ)



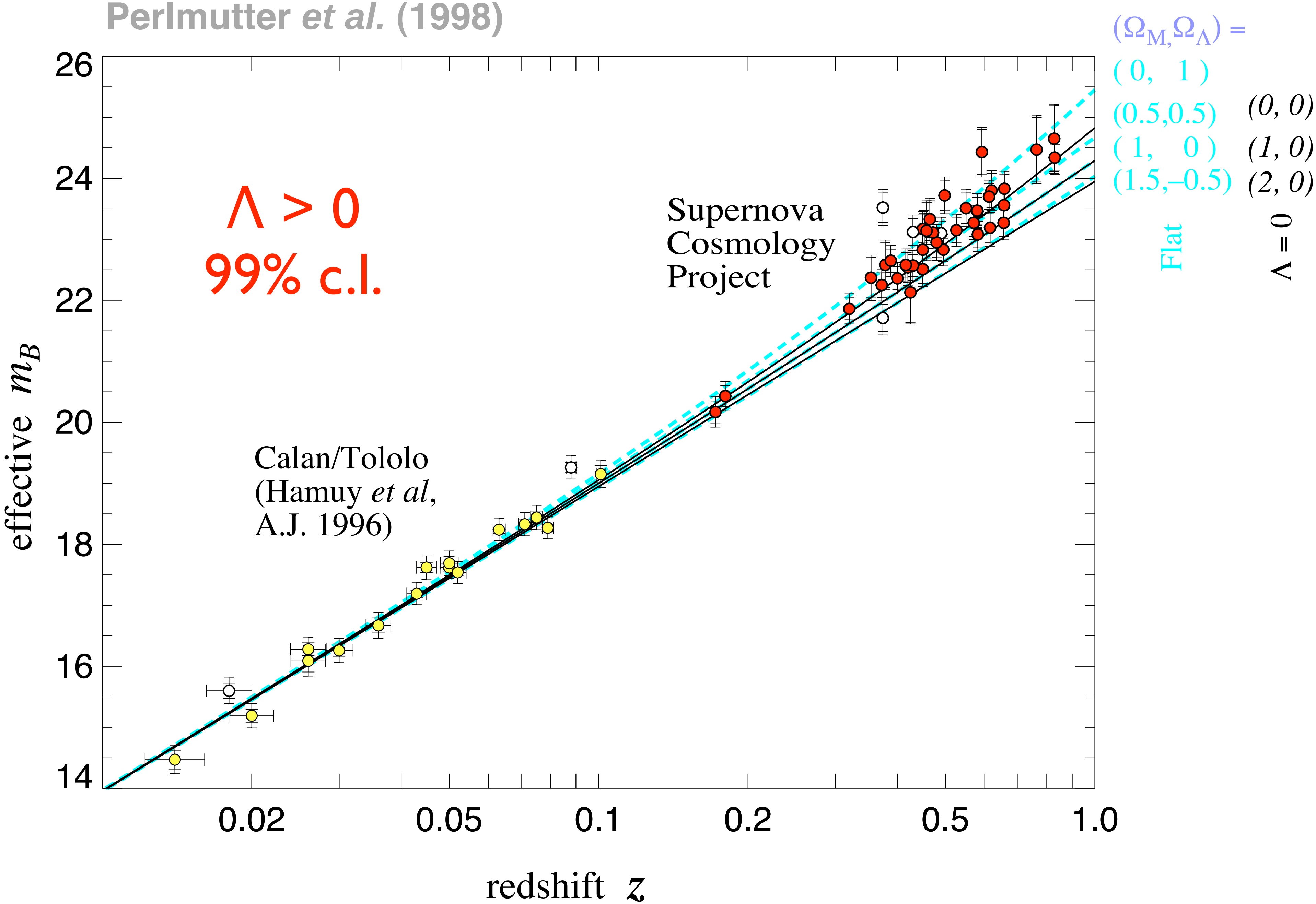
Other hints as well:

"...these number count data favor a flat, low-density $\Omega_m \approx 0.2$ universe with a nonzero cosmological constant." (Yoshi & Peterson 1995, ApJ, 444, 15)

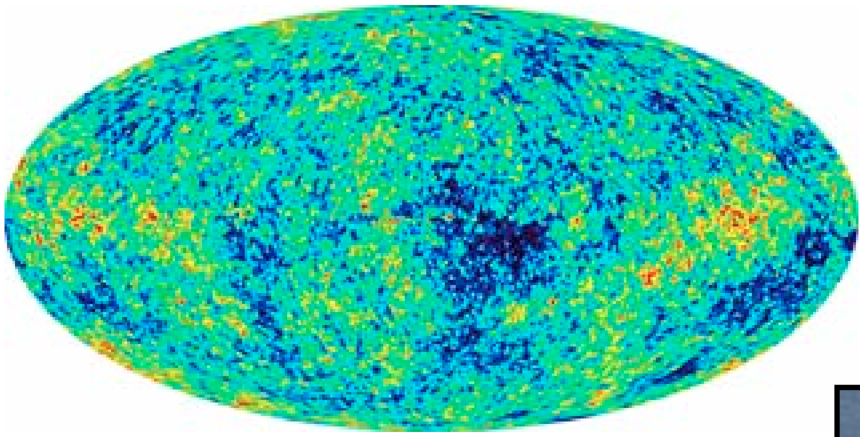
Several lines of evidence suggest that the expansion of the universe is indeed accelerating!



Supernova Cosmology Project
Perlmutter *et al.* (1998)

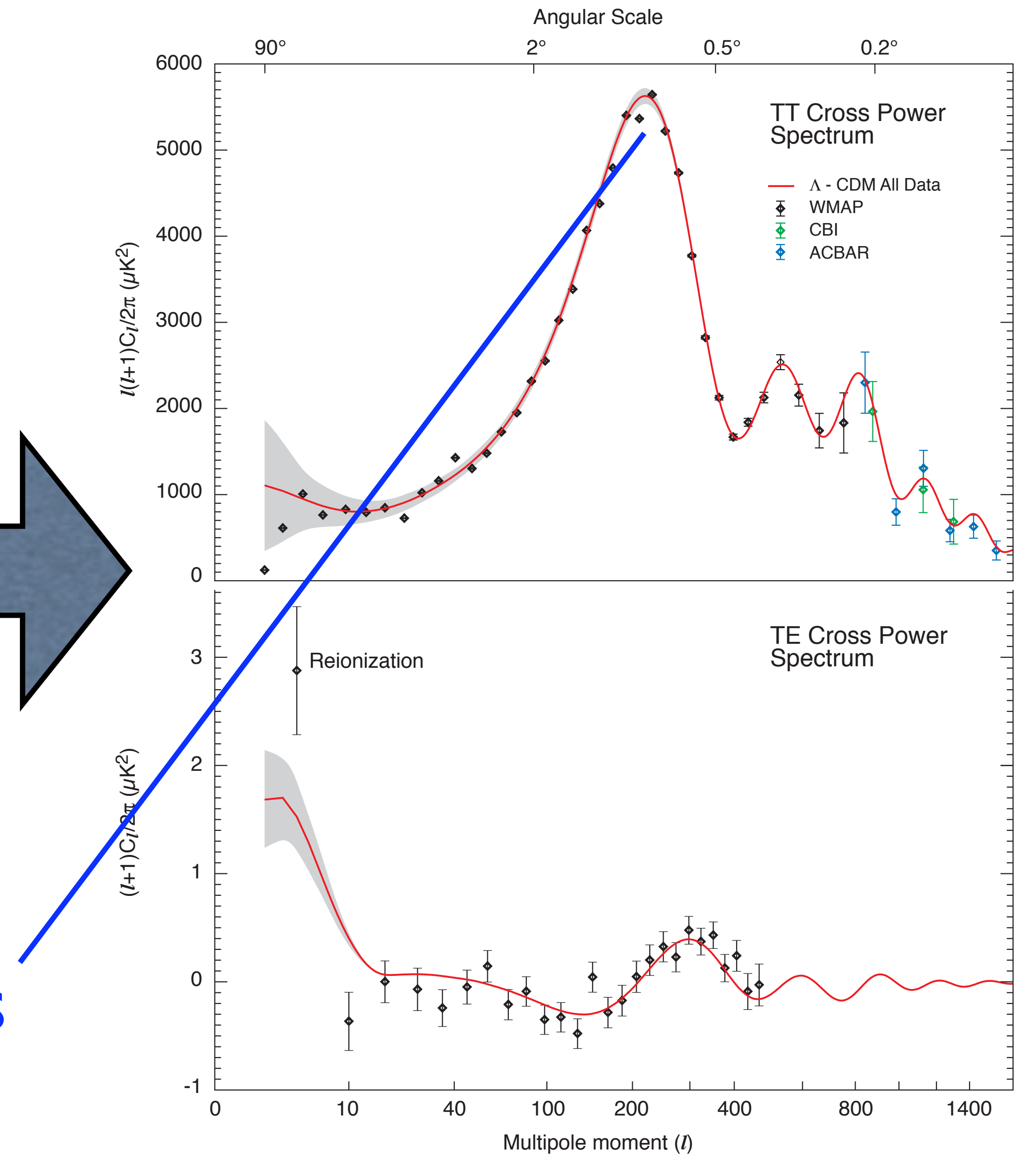


In flat universe: Ω_M = 0.28 [± 0.085 statistical] [± 0.05 systematic]



WMAP

Cosmic Background Radiation



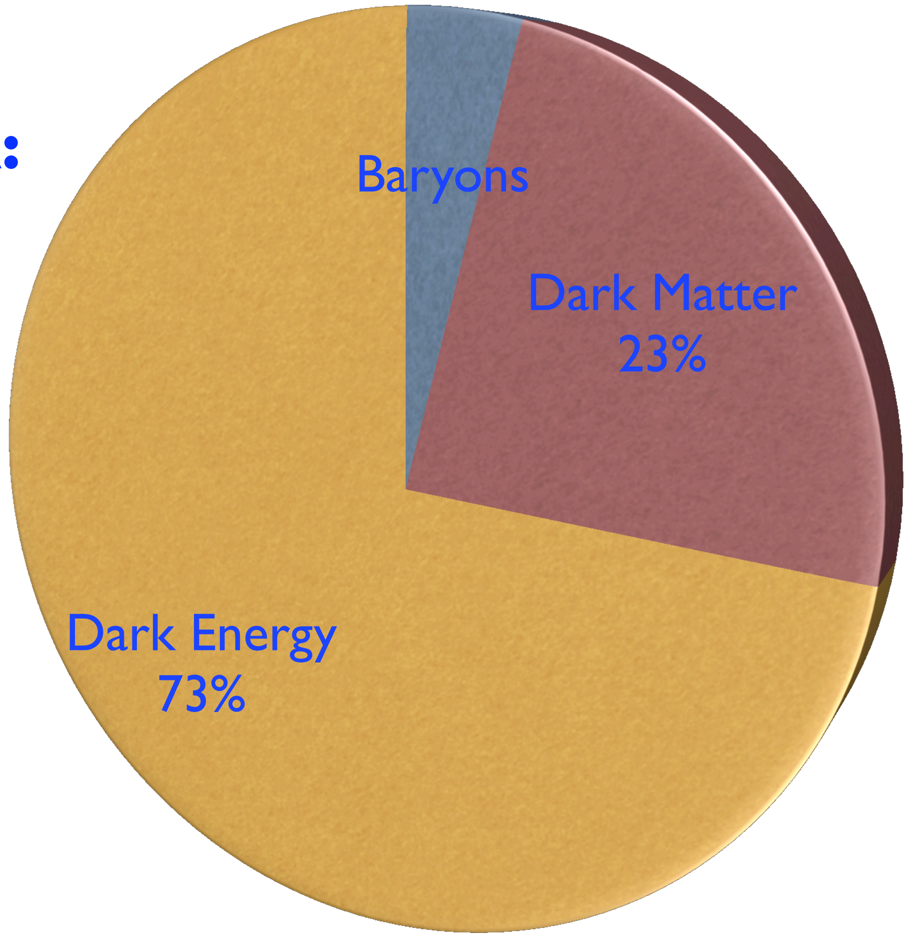
Position of first peak implies

$\Omega_m + \Omega_\Lambda \approx 1$

$\Omega_m < 1$, so again, $\Lambda > 0$

Cosmological Mass-Energy Budget

THE ANSWER:



Hot Big Bang
+
Dark Energy
+
Dark Matter

is now called

"ΛCDM"

"The only interesting problem left in cosmology is the value of the exponent of the dark energy equation of state."

- L. Krauss (2004)

"The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.... Our future discoveries must be looked for in the sixth place of decimals."

- A. Michelson (1894)

"Cosmologists are often wrong, but never in doubt"

- Lev Landau

Things we know for sure in cosmology:

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"

- Lev Landau

Things we know for sure in cosmology:

2003:

$$\Omega_m = 0.27$$

$$\Omega_\Lambda = 0.73$$

$$\Omega_b h^2 = 0.0224$$

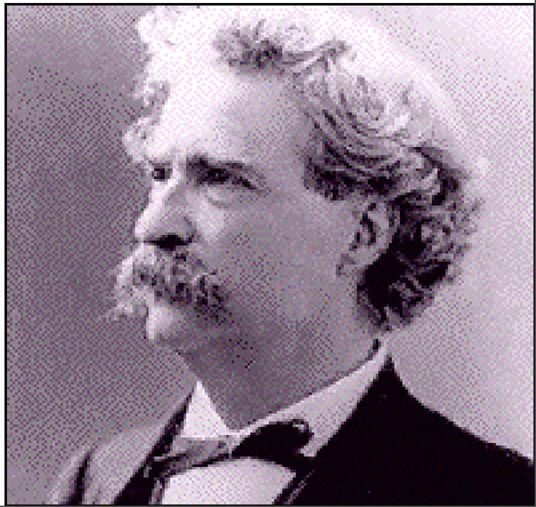
$$H_o = 72 \text{ km/s/Mpc}$$

Dark Matter = Cold Dark Matter

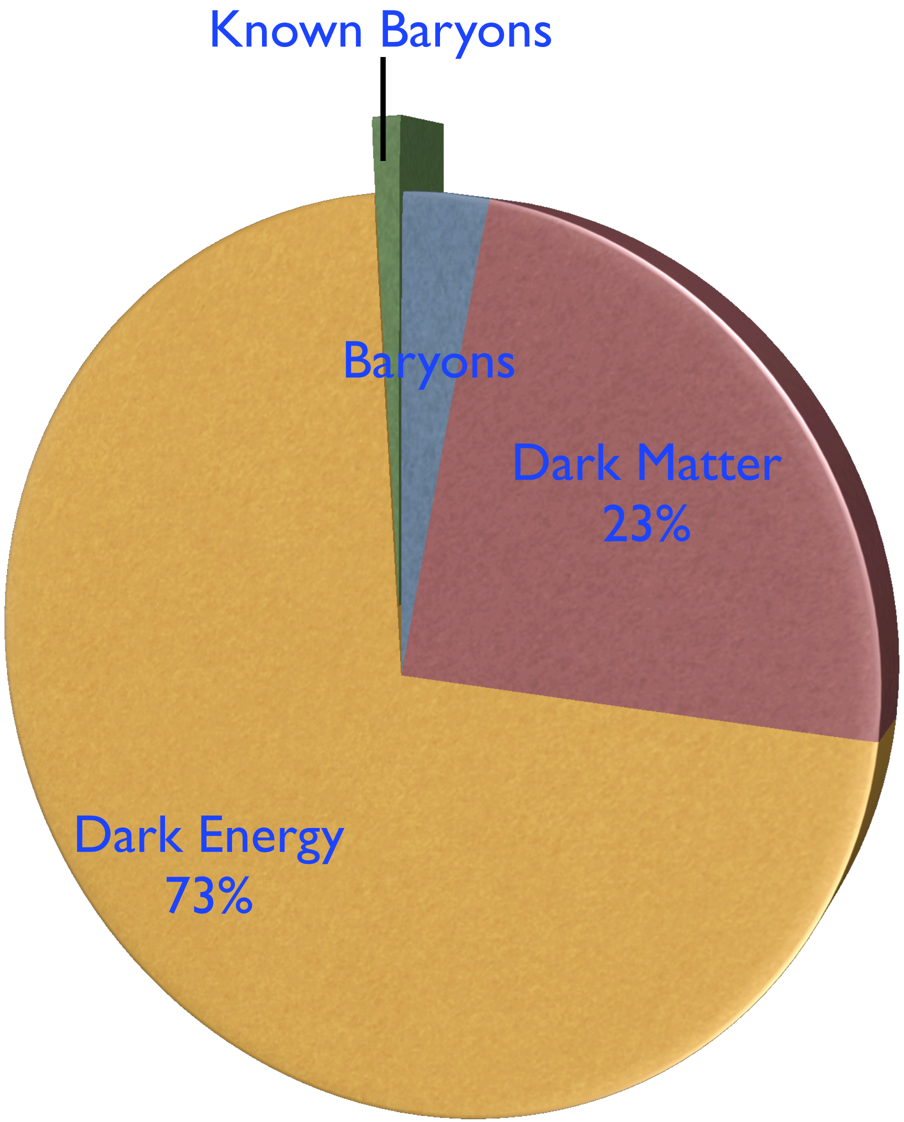
... or maybe Warm Dark Matter

or Self-Interacting Dark Matter

What did I say?



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



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

CDMS Collaboration **arXiv:0802.3530**

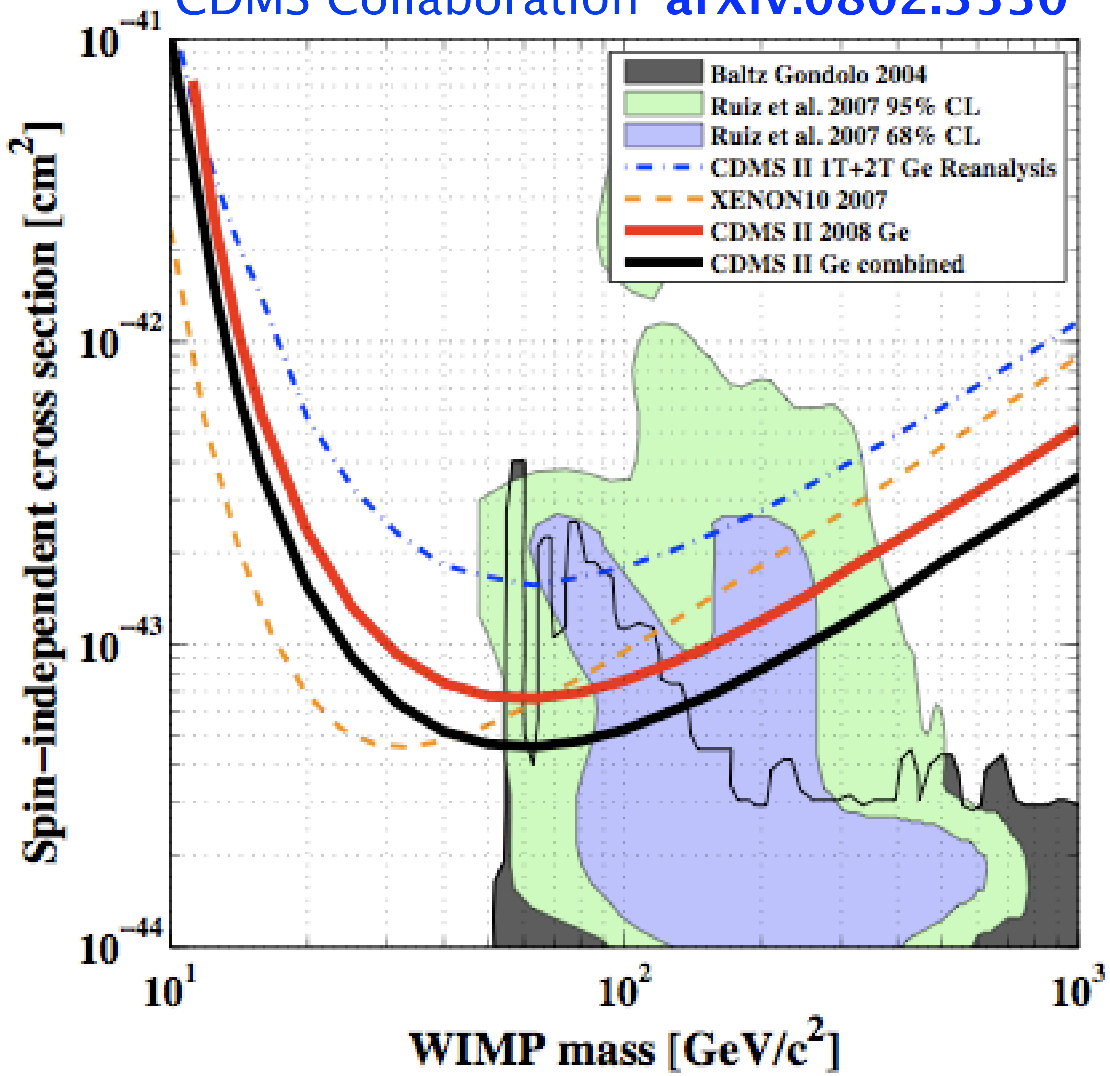
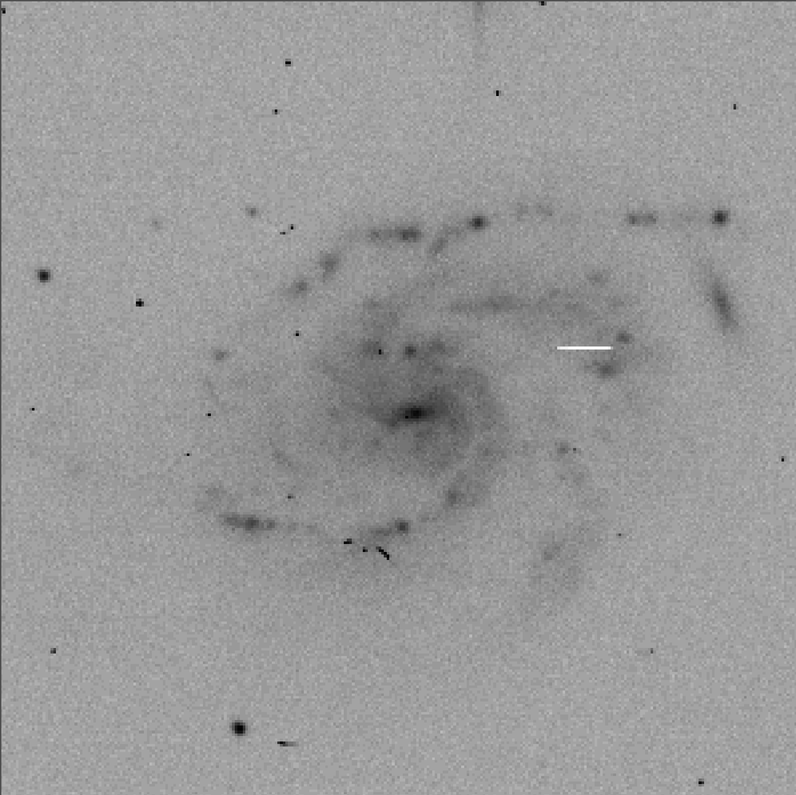


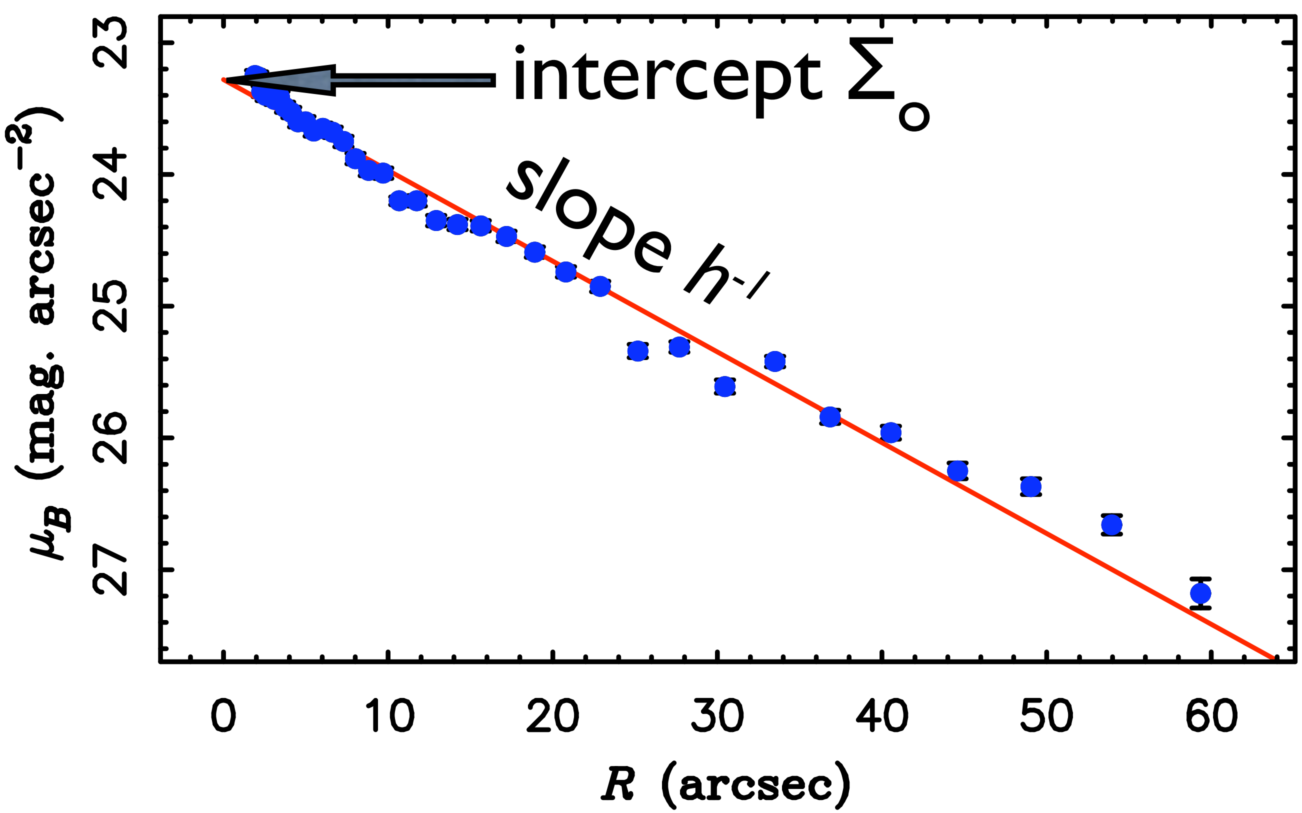
FIG. 4: Spin-independent WIMP-nucleon cross section upper limits (90% C.L.) versus WIMP mass. The upper curve (dash-dot) is the result of a re-analysis [17] of our previously published data. The upper solid line represents the limit derived from our new data set. The combined CDMS limit

On Galaxy Scales...

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

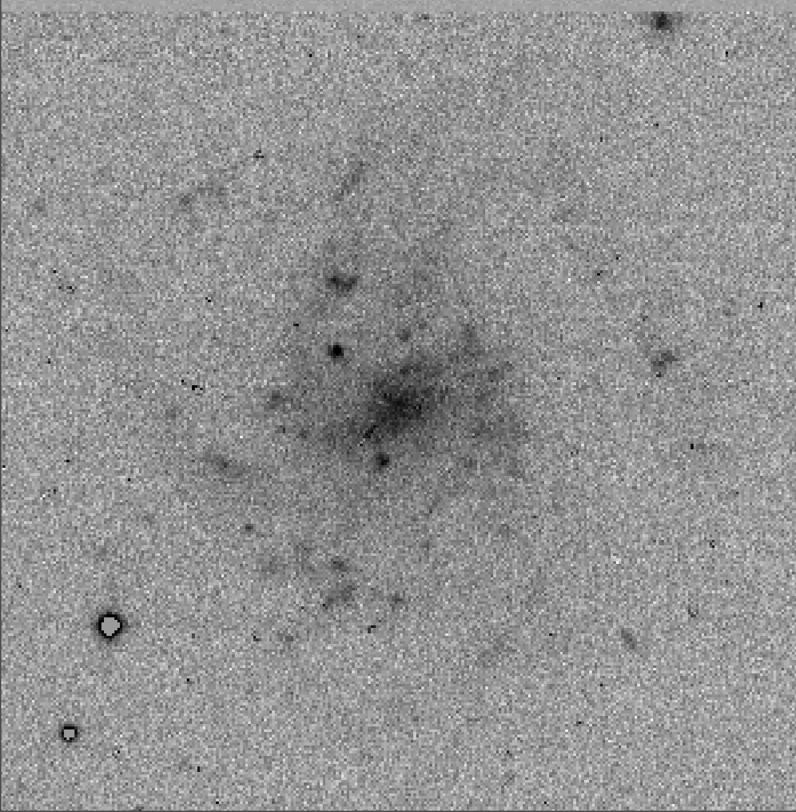
High Surface Brightness (HSB)





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

Azimuthally averaged light distribution typically exponential for spiral disks.

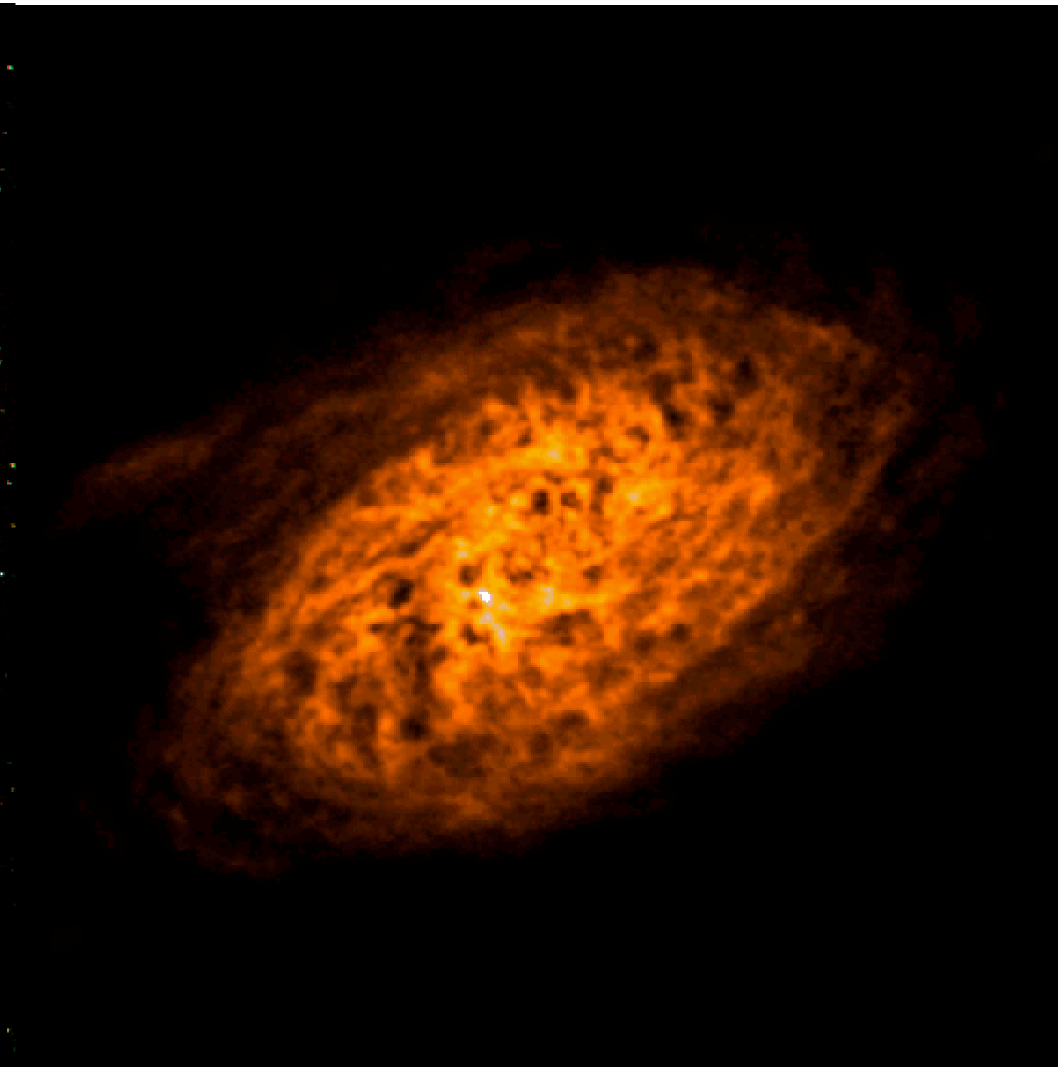


Low Surface Brightness (LSB)

NGC 2403

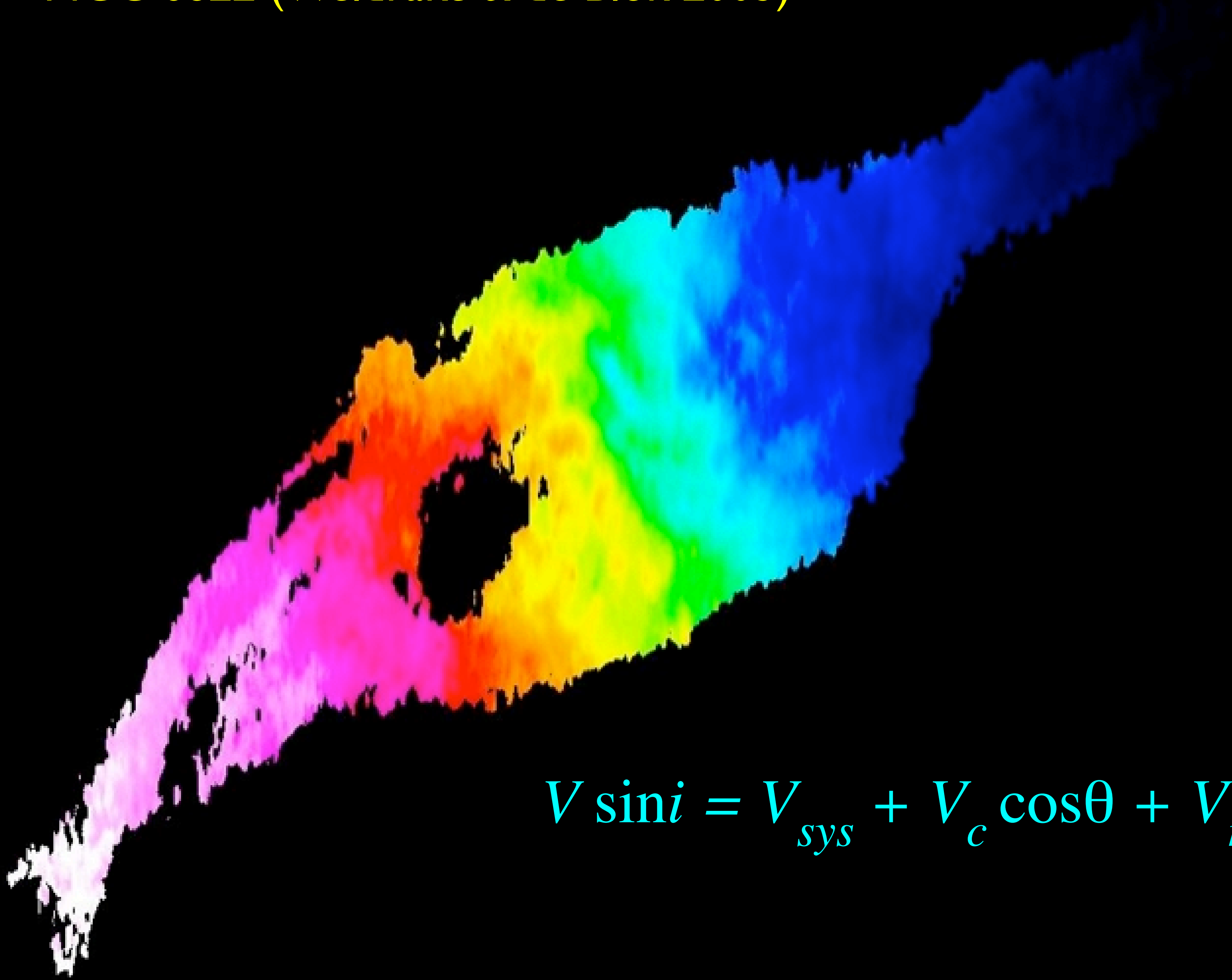
Stars

HI gas



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

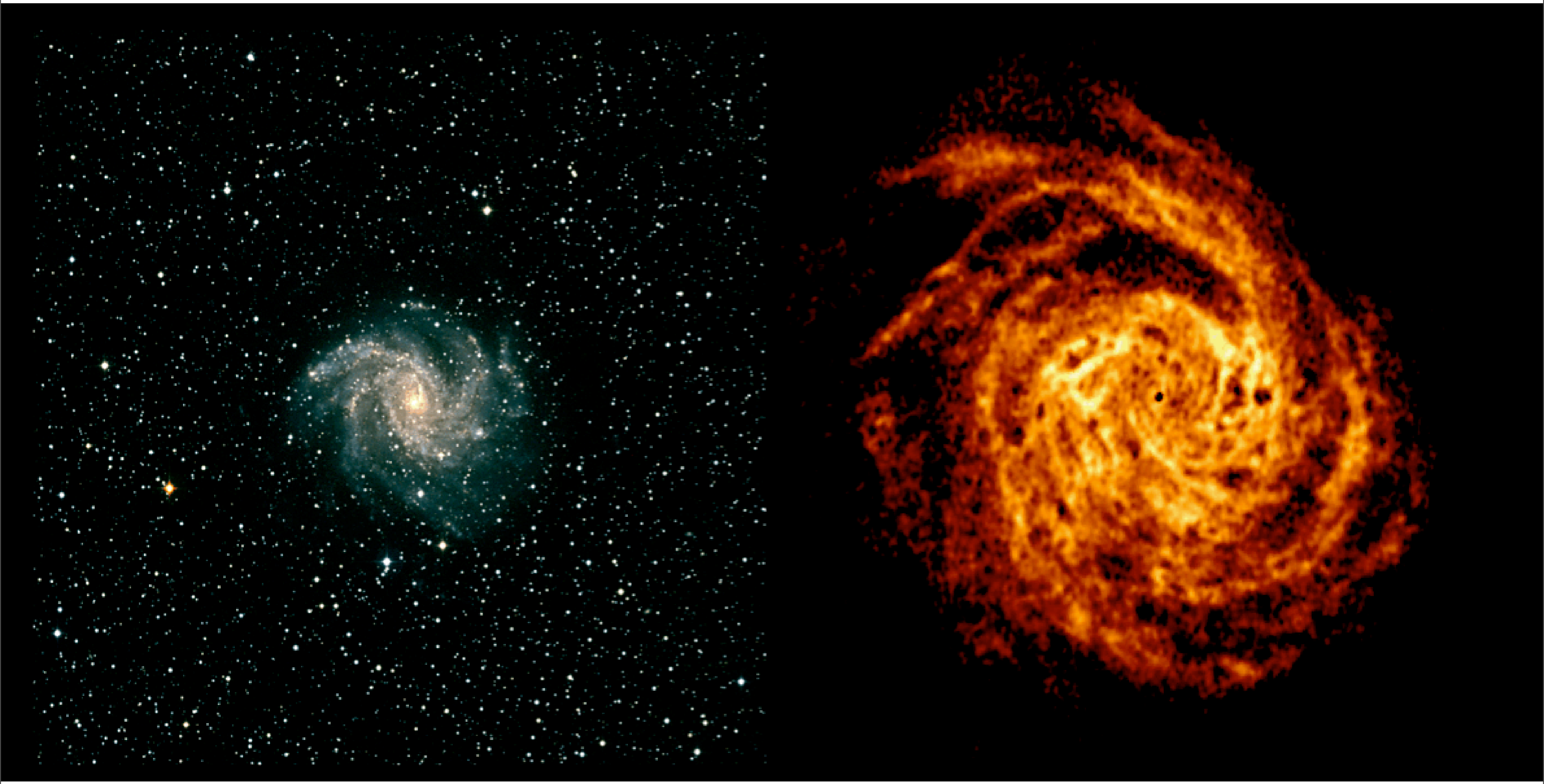
NGC 6822 (Weldrake & de Blok 2003)



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

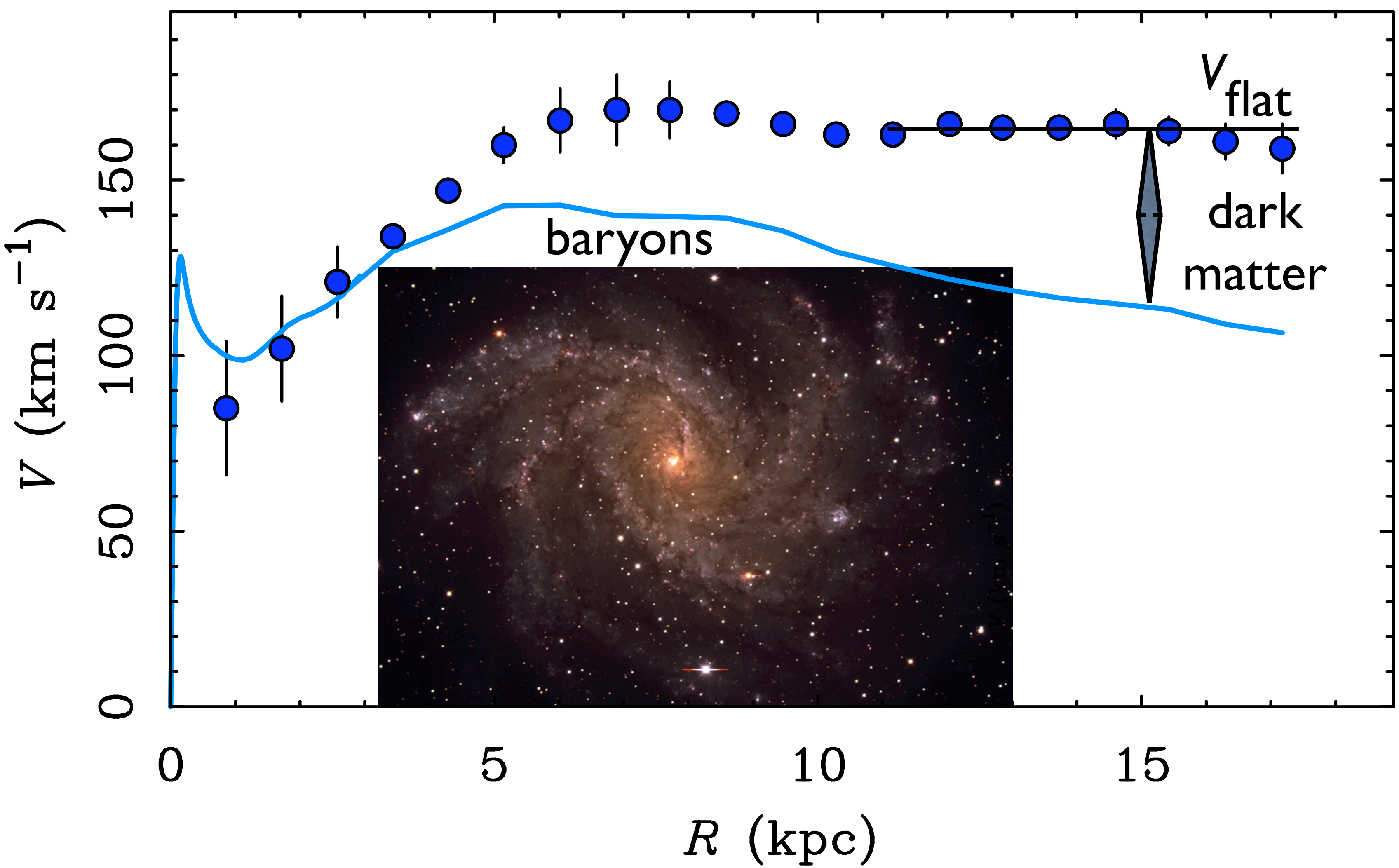
NGC 6946

Stars | HI gas



Boomsma 2005

NGC 6946



TF Relation

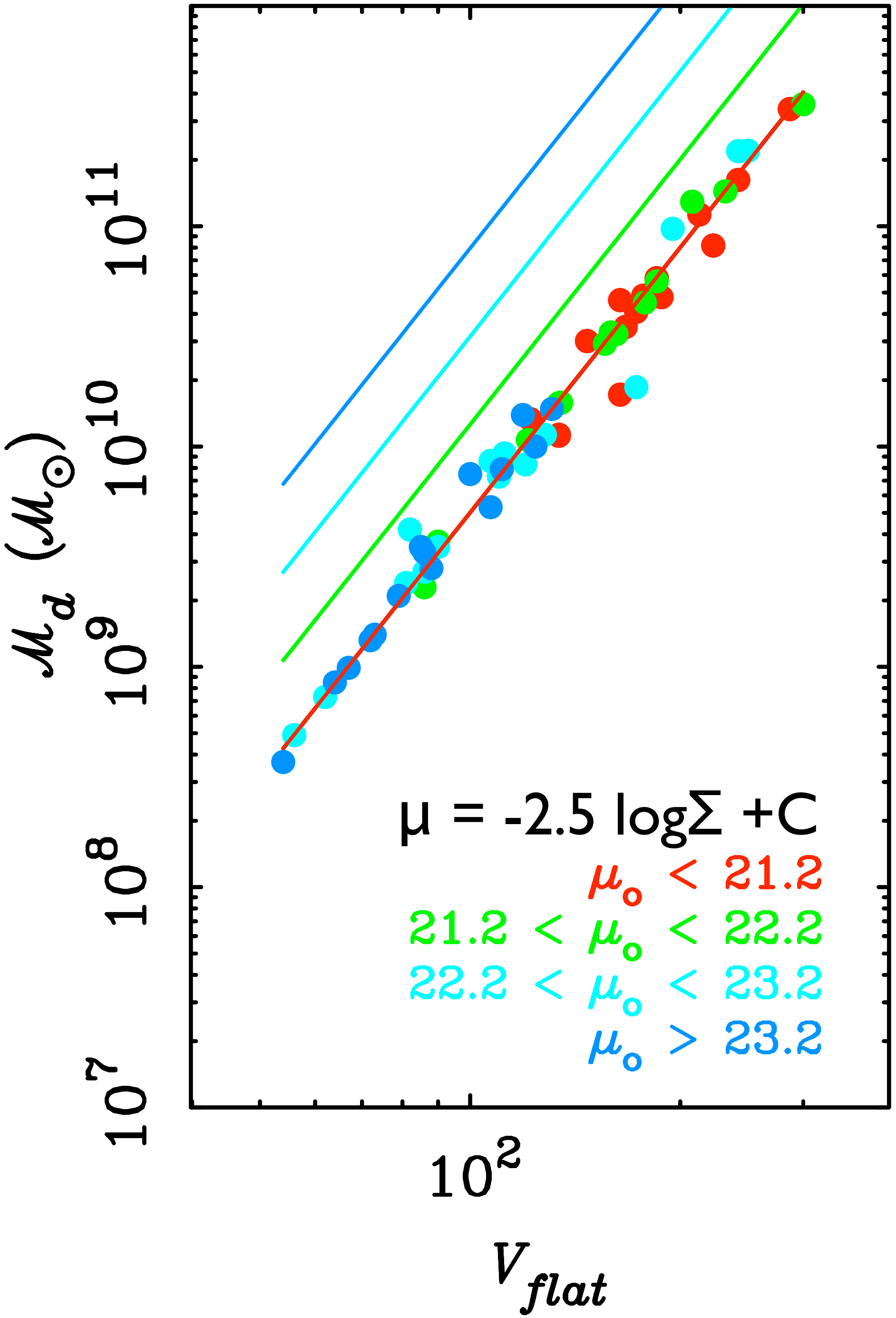
<u>Newton says</u>

$V^2 = GM/R$.

Equivalently,

$\Sigma = M/R^2$

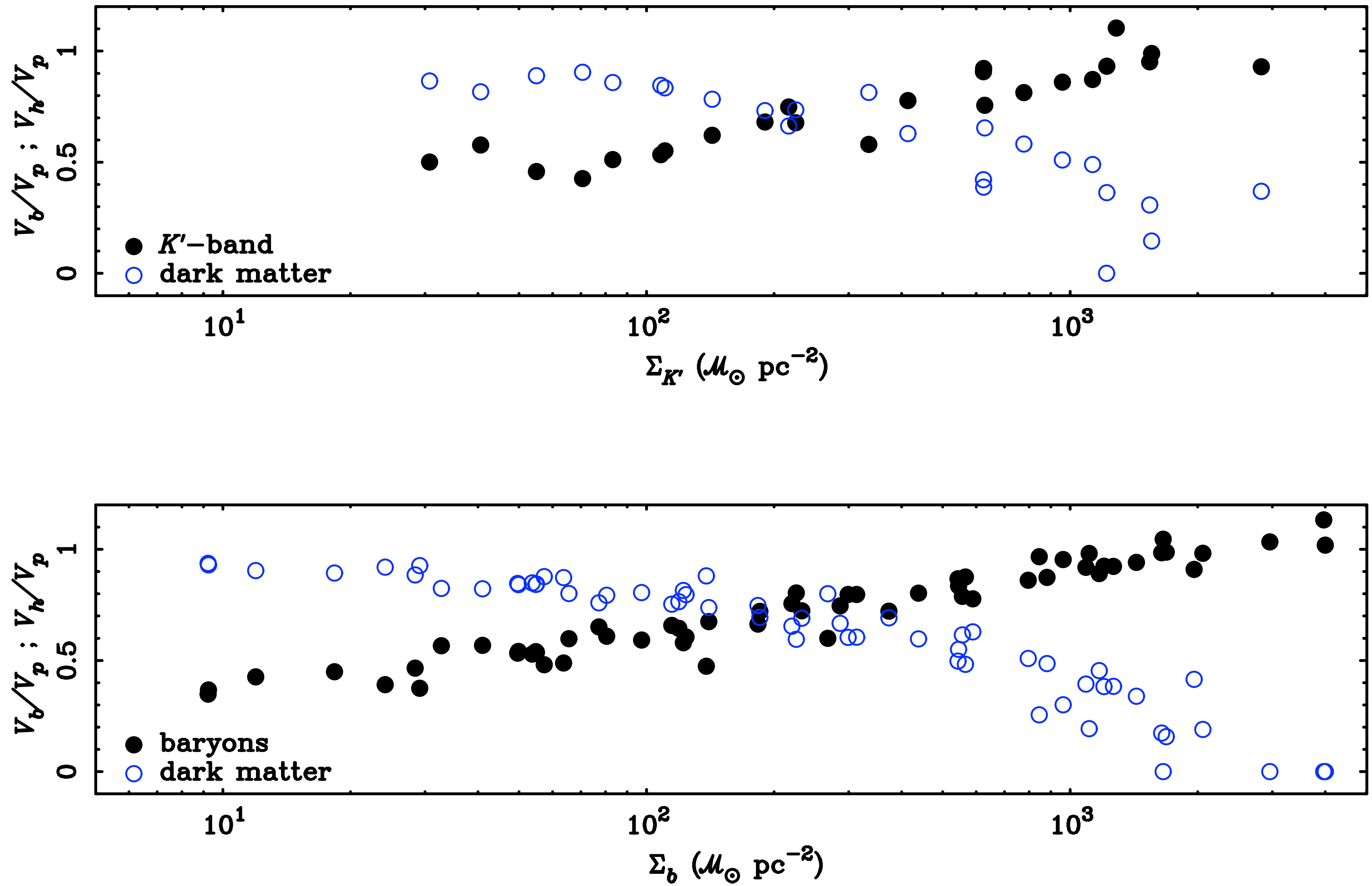
$V^4 = G^2 M \Sigma$



<u>Therefore</u>

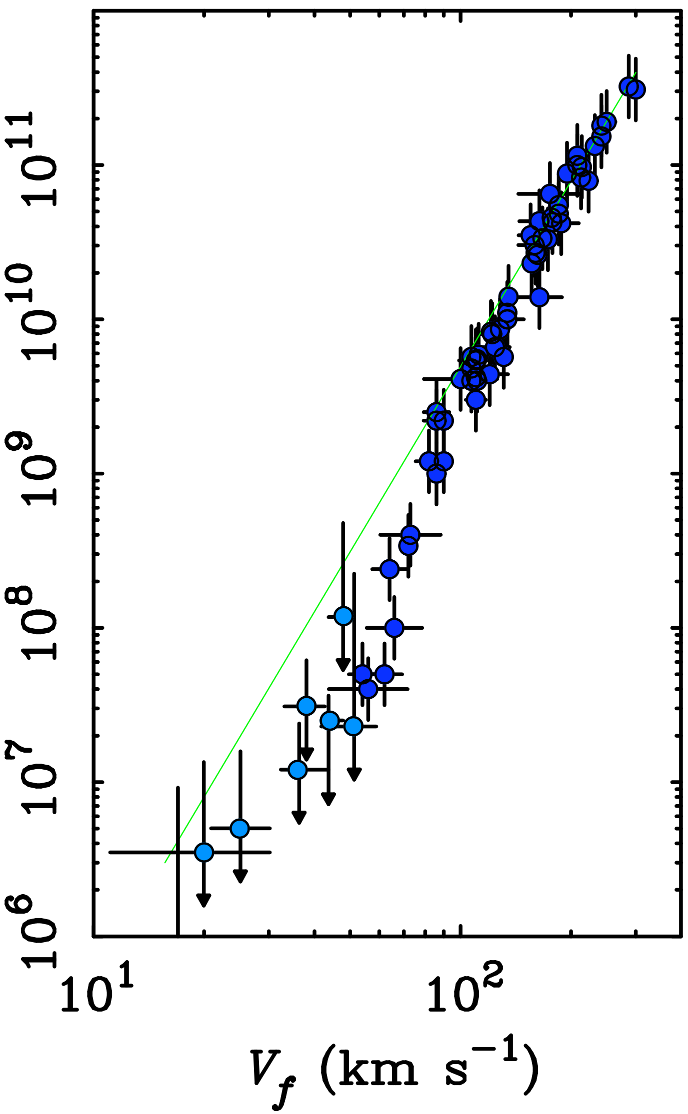
Different Σ *should* mean different TF normalization.

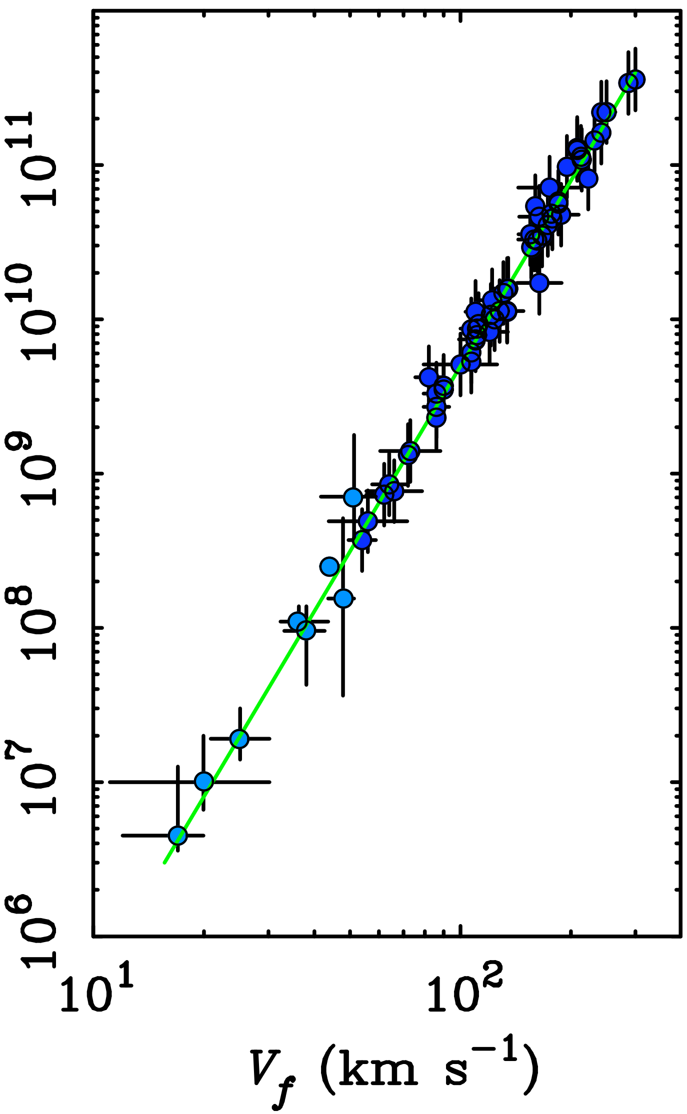
Requires fine balance between dark & baryonic mass



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

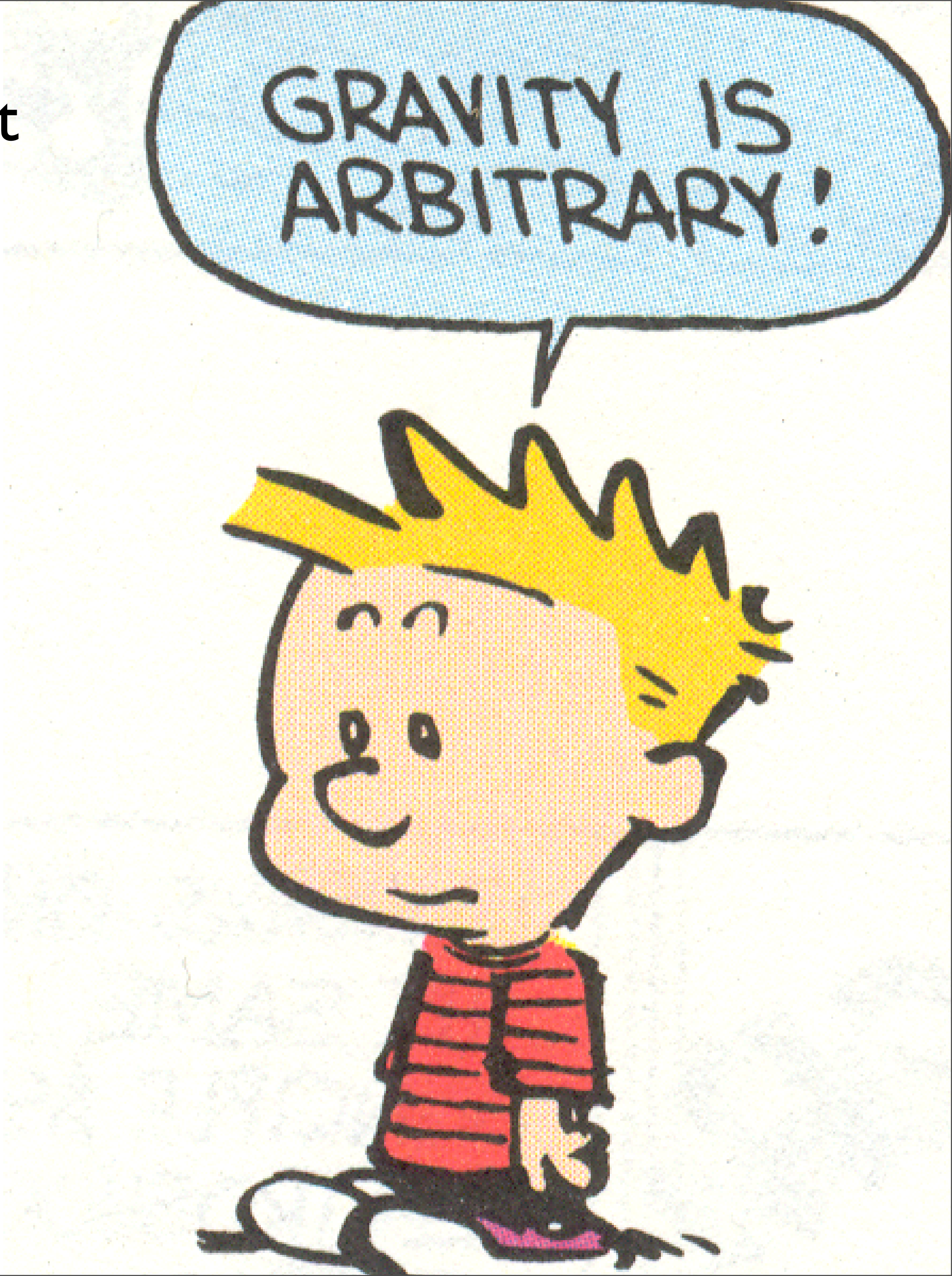
Baryonic Tully-Fisher Relation





Depends only on ordinary mass

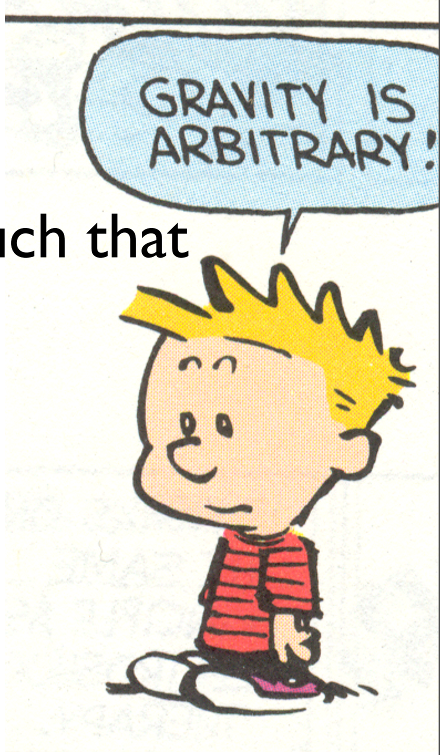
One begins to worry that



MOND

MOdified Newtonian Dynamics

introduced by Moti Milgrom in 1983



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

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

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

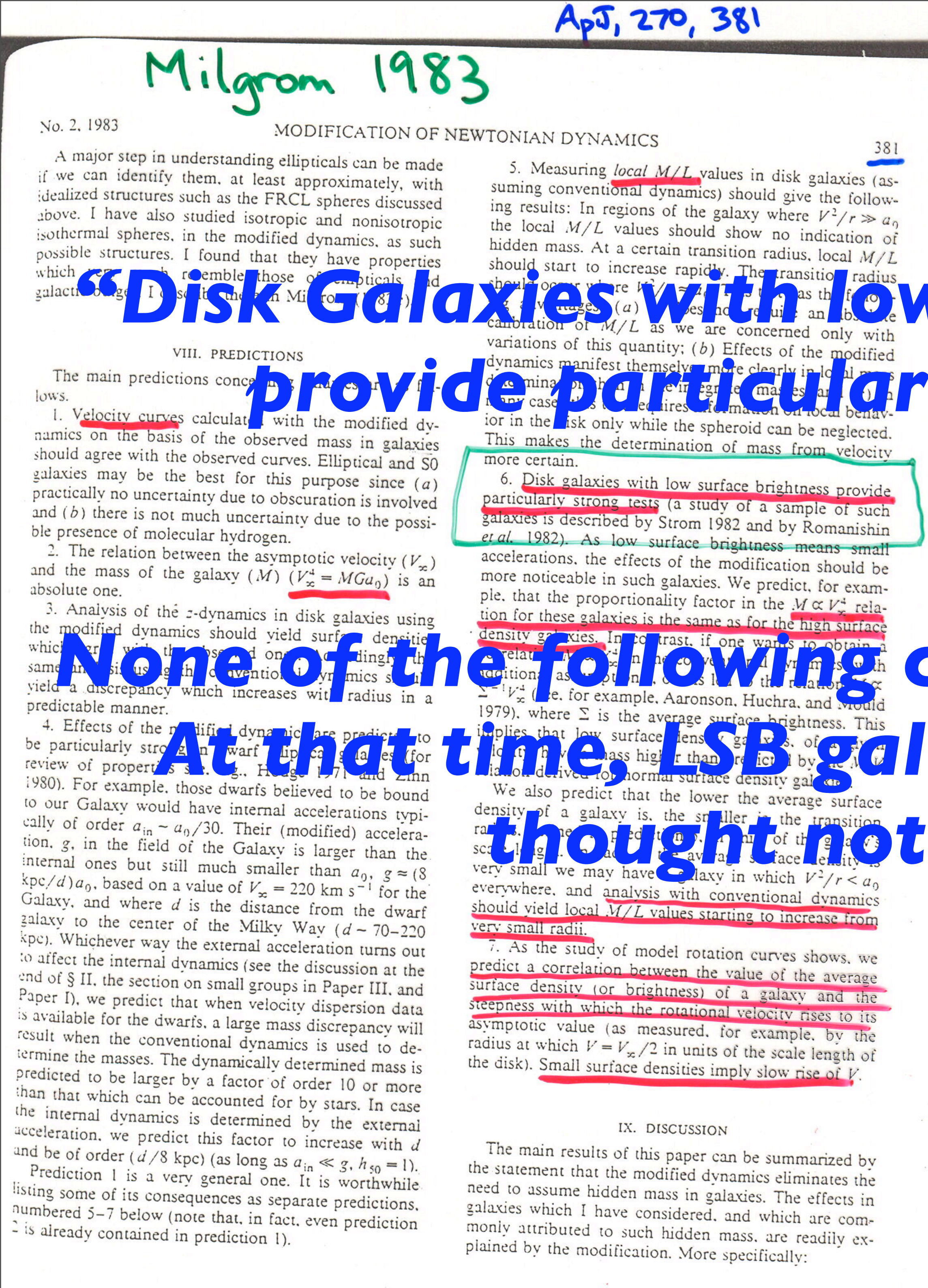
where

$$g_N = GM/R^2$$

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 [illegible] resemble those of [illegible] and galacti[illegible] I [illegible] Mi[illegible].

VIII. PREDICTIONS

The main predictions conce[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 surf[illegible] densitie[illegible] whic[illegible] same [illegible] yield a discrepancy which increases wit[illegible] radius in a predictable manner.

4. Effects of the m[illegible] dyna[illegible] to be particularly stro[illegible] review of propert[illegible] 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 transitio[illegible] radius [illegible] (*a*) [illegible] calibration of M/L as we are concerned only with variations of this quantity; (*b*) Effects of the modified dynamics manifest themselve[illegible] more clearly in lo[illegible] [illegible] ior 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 [illegible] $\Sigma^{-1} V_\infty^4$ ([illegible]e, for example, Aaronson, Huchra, and Mould 1979), where Σ is the average surface brightness. This implies that low surface [illegible] [illegible] normal surface density gal[illegible].

We also predict that the lower the average surface density of a galaxy is, the sm[illegible]ller [illegible] the transition ra[illegible] very small we may have [illegible]laxy 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:

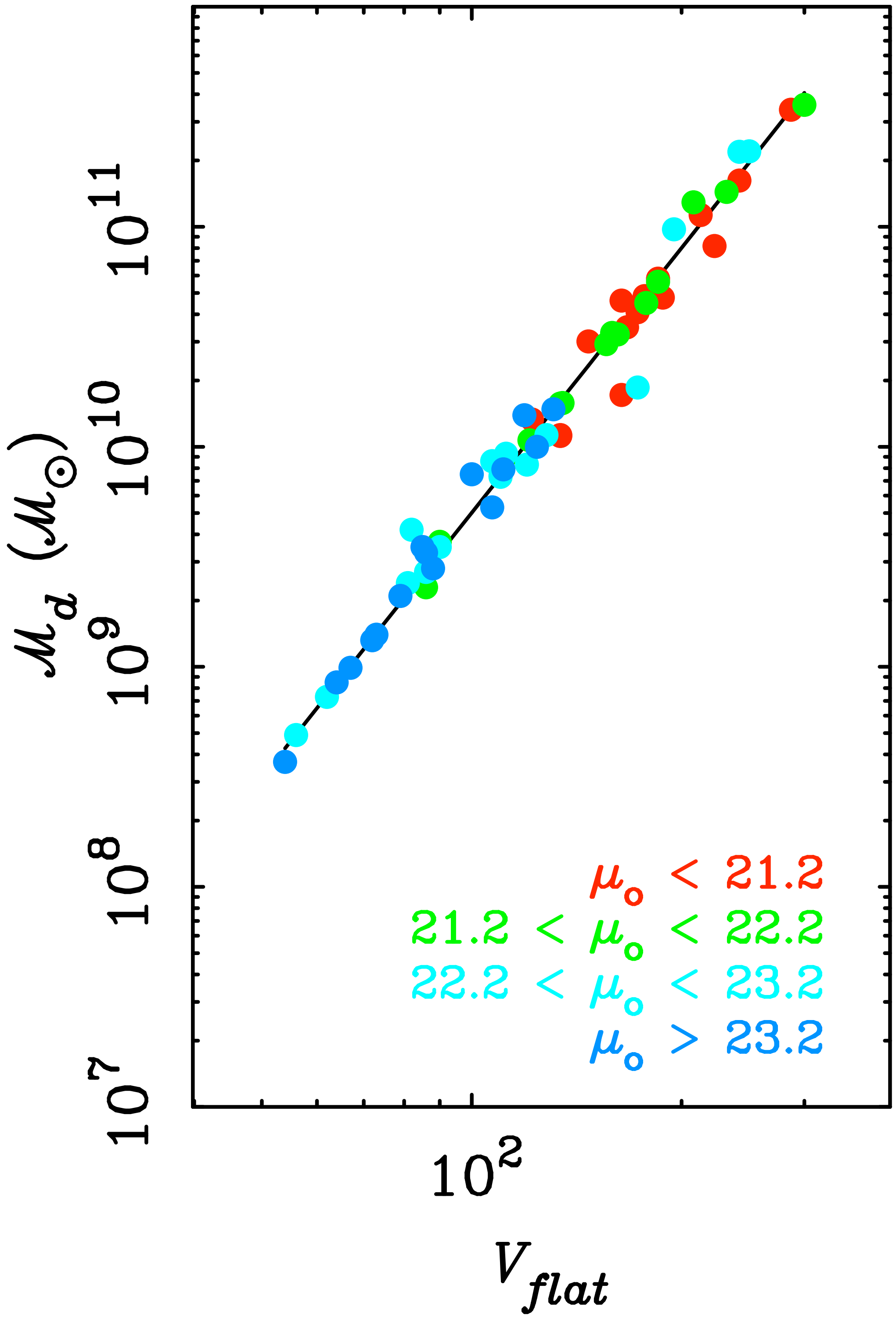
MOND predictions

- The Tully-Fisher Relation
  - Slope = 4
  - Normalization = 1/(a_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 Galaxies with low surface brightness provide particularly strong tests"

None of the following data existed in 1983.

At that time, LSB galaxies were widely thought not to exist.



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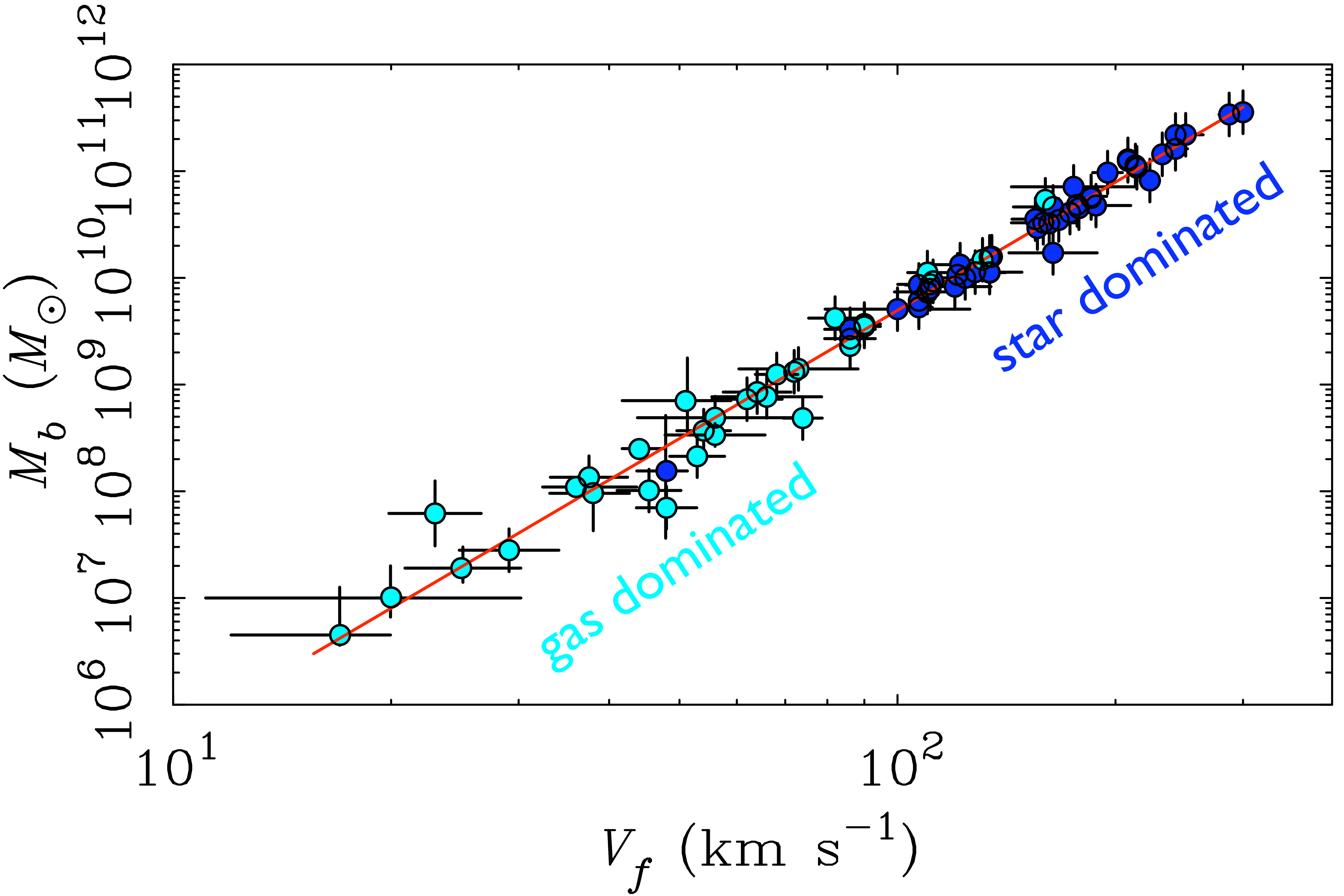
In MOND limit of low acceleration

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

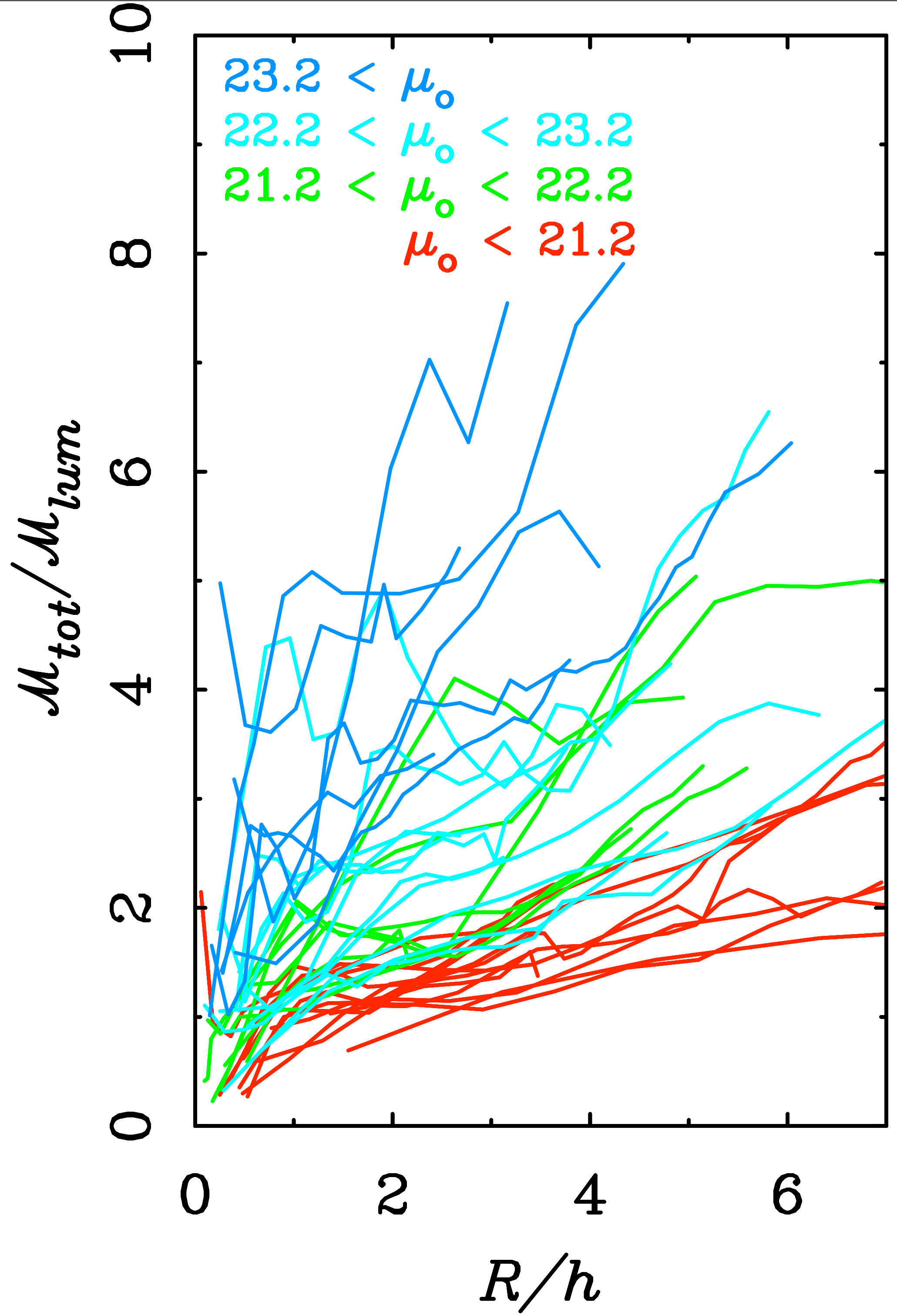
$$\frac{V^2}{R} = \sqrt{\frac{GM}{R^2} a_0}$$

$$V^4 = a_0 GM$$

observed TF!



M_b ($M_\odot$)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^1
10^2
V_f (km s^{-1})
gas dominated
star dominated



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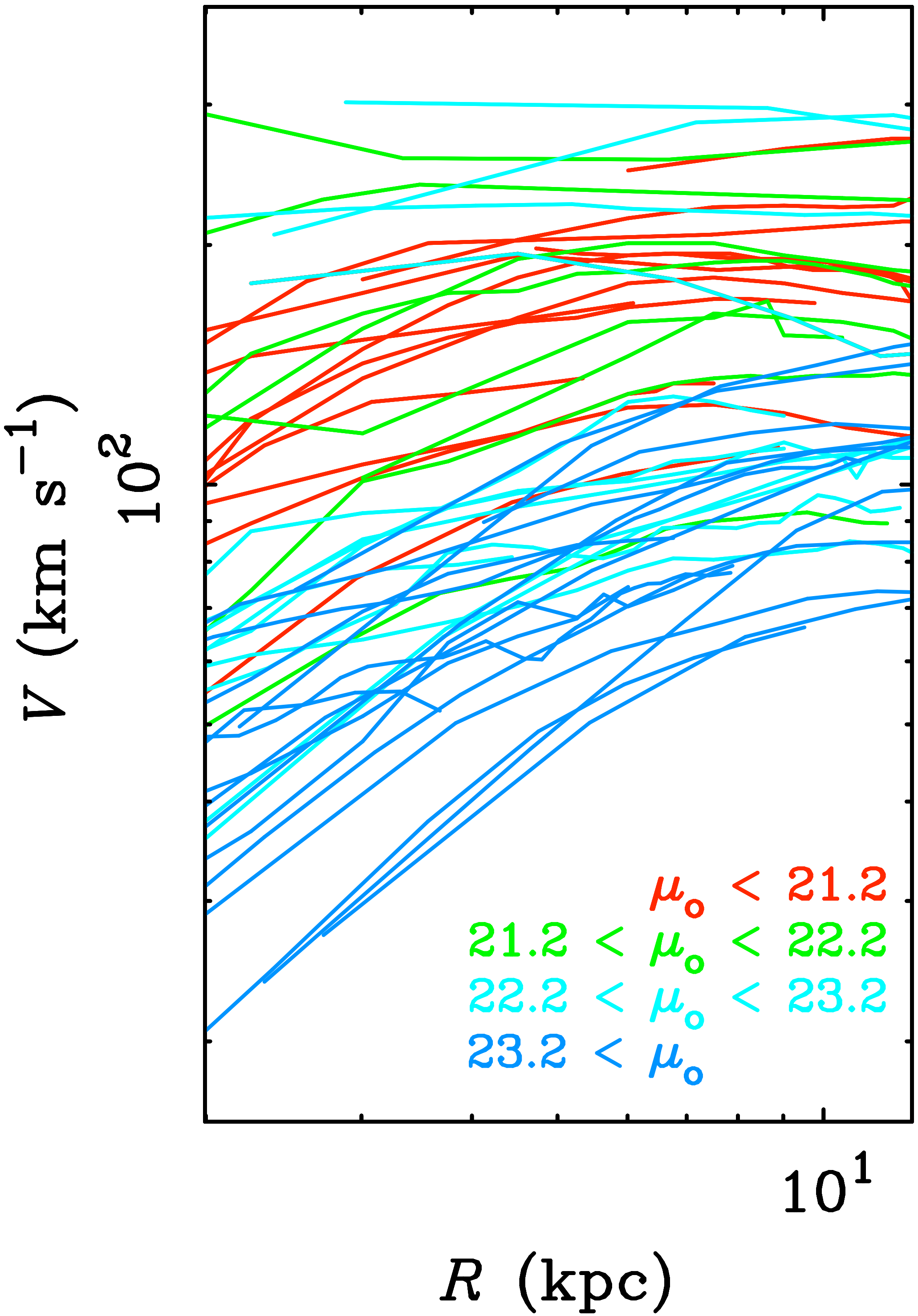

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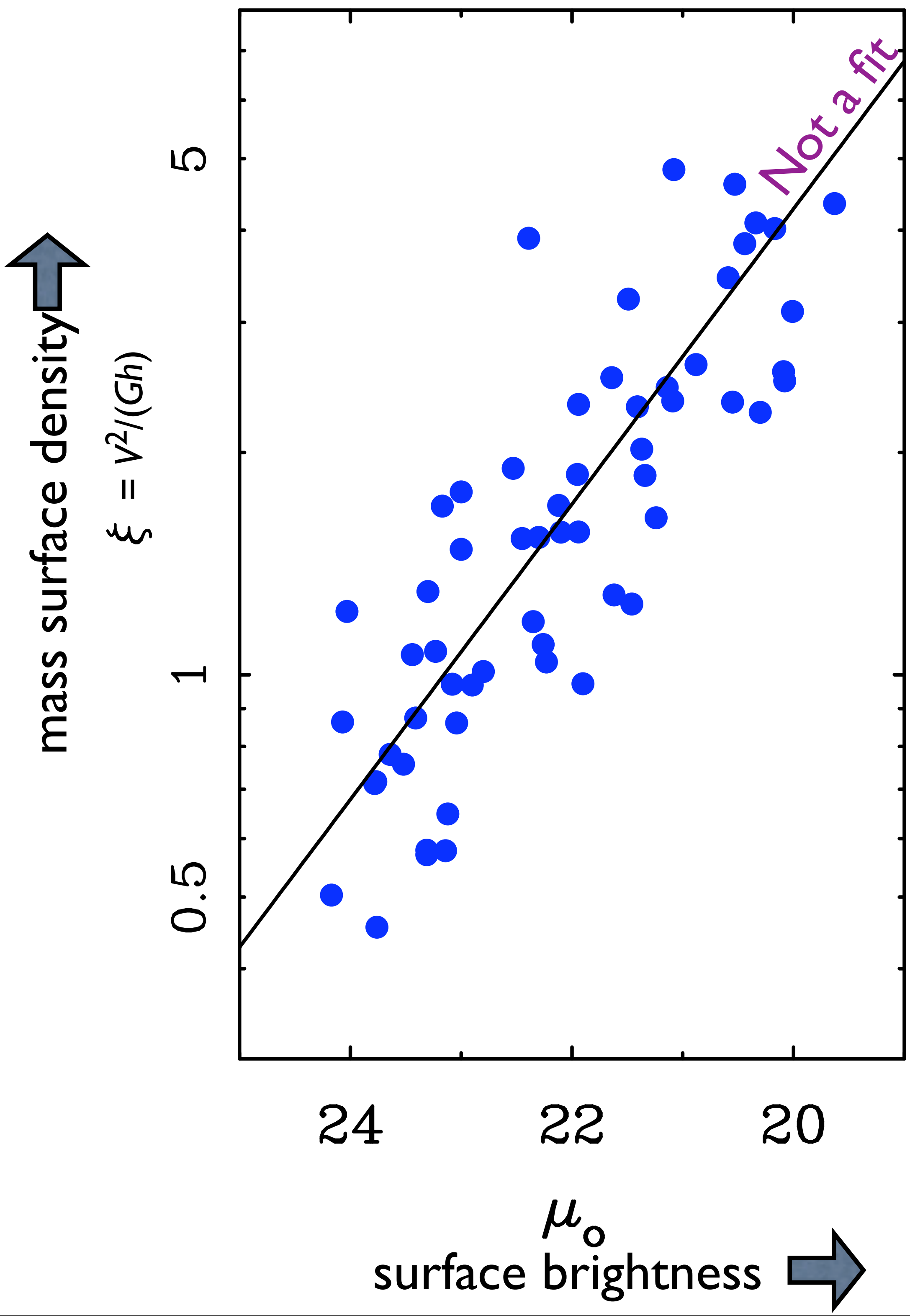

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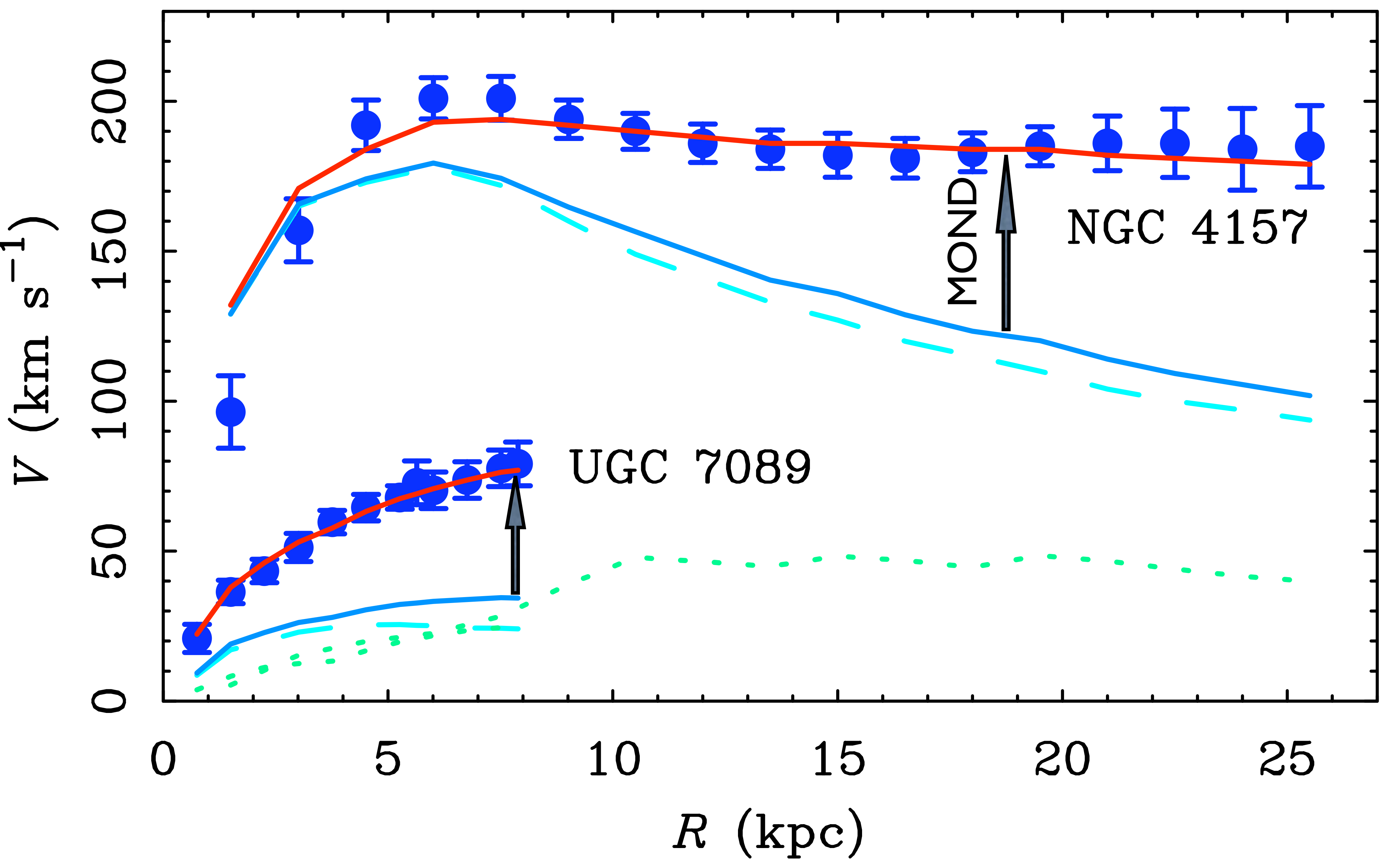
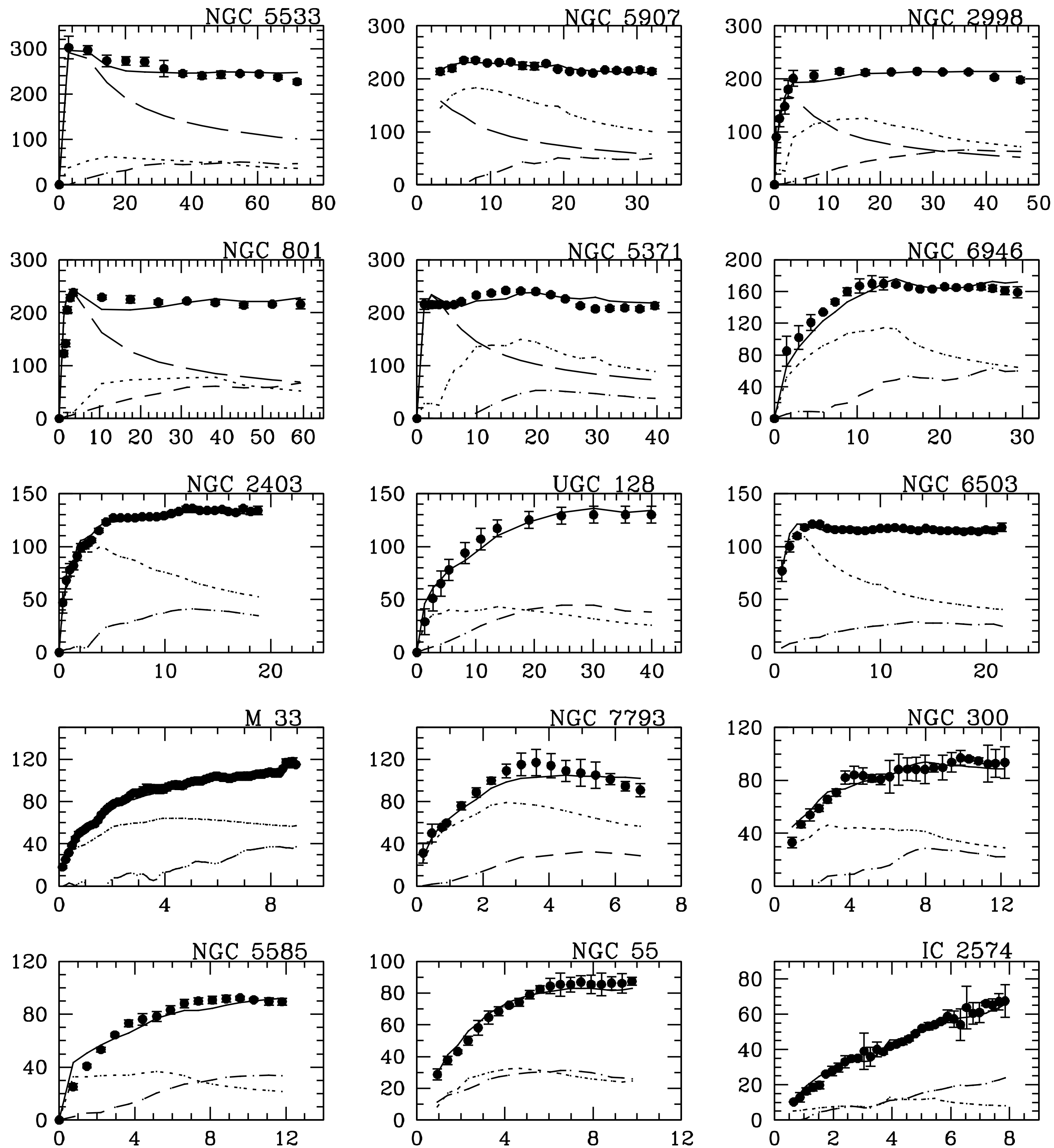
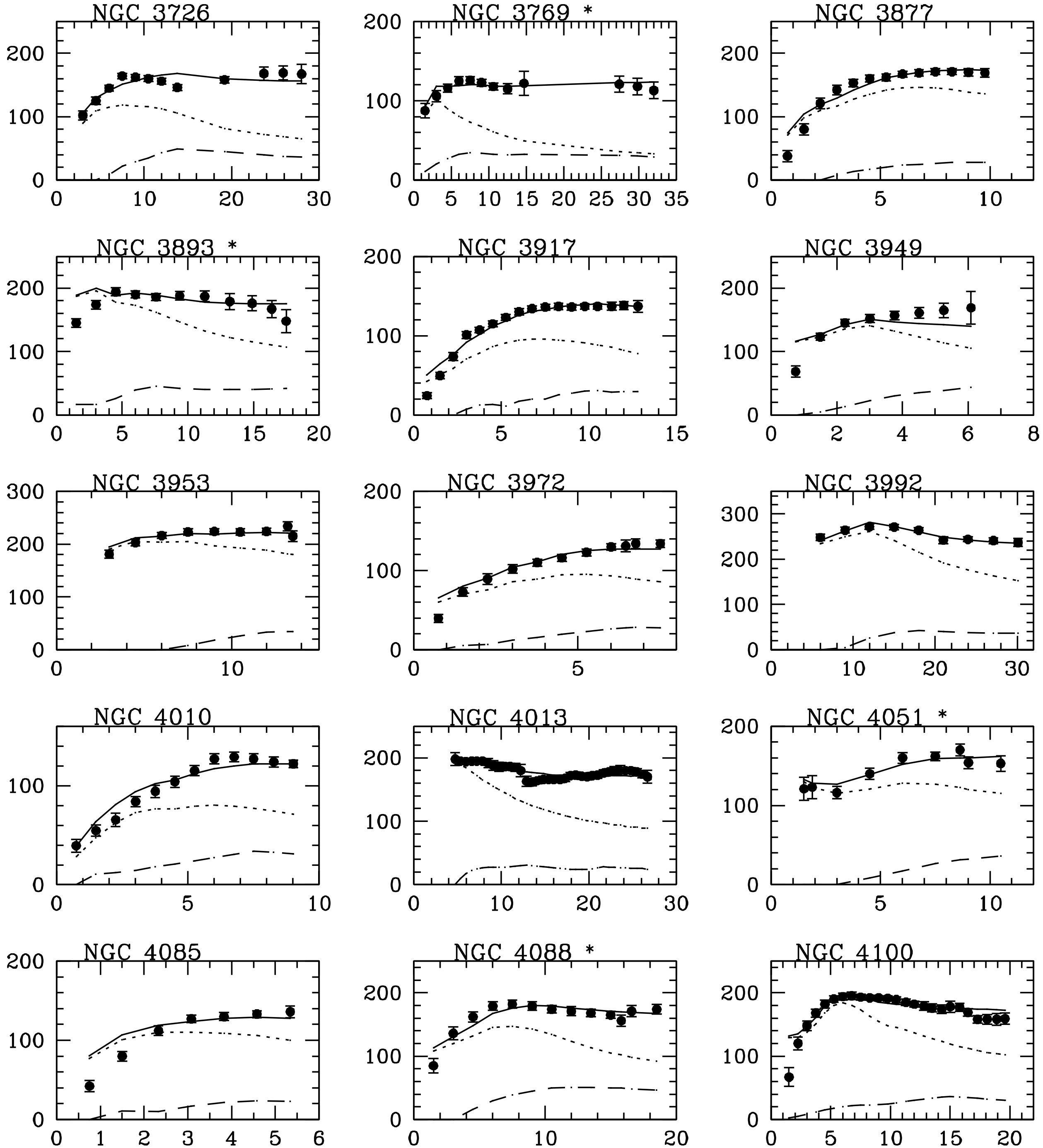


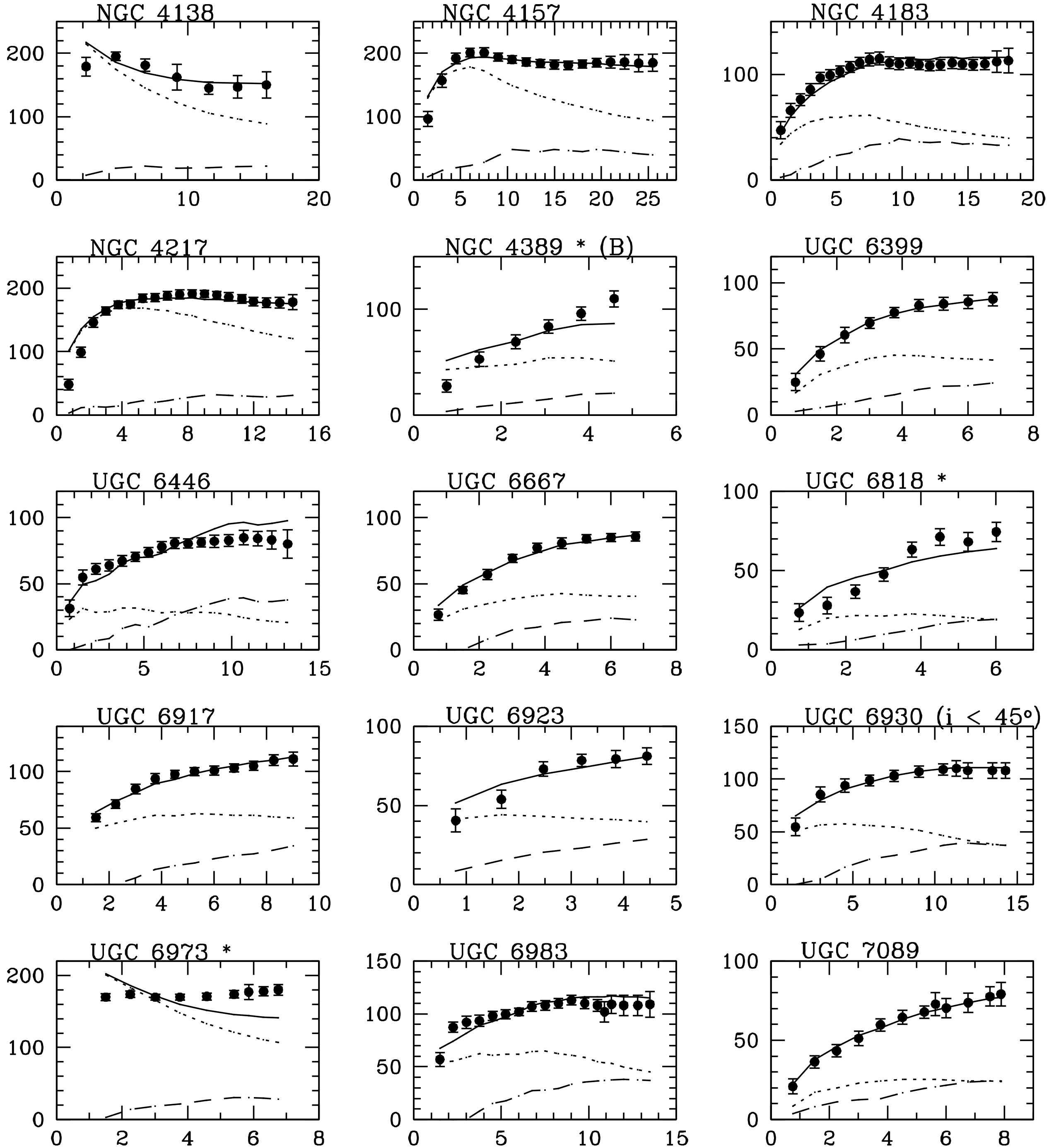
V (km s−1)
R (kpc)
0
50
100
150
200
0
5
10
15
20
25
MOND
NGC 4157
UGC 7089

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



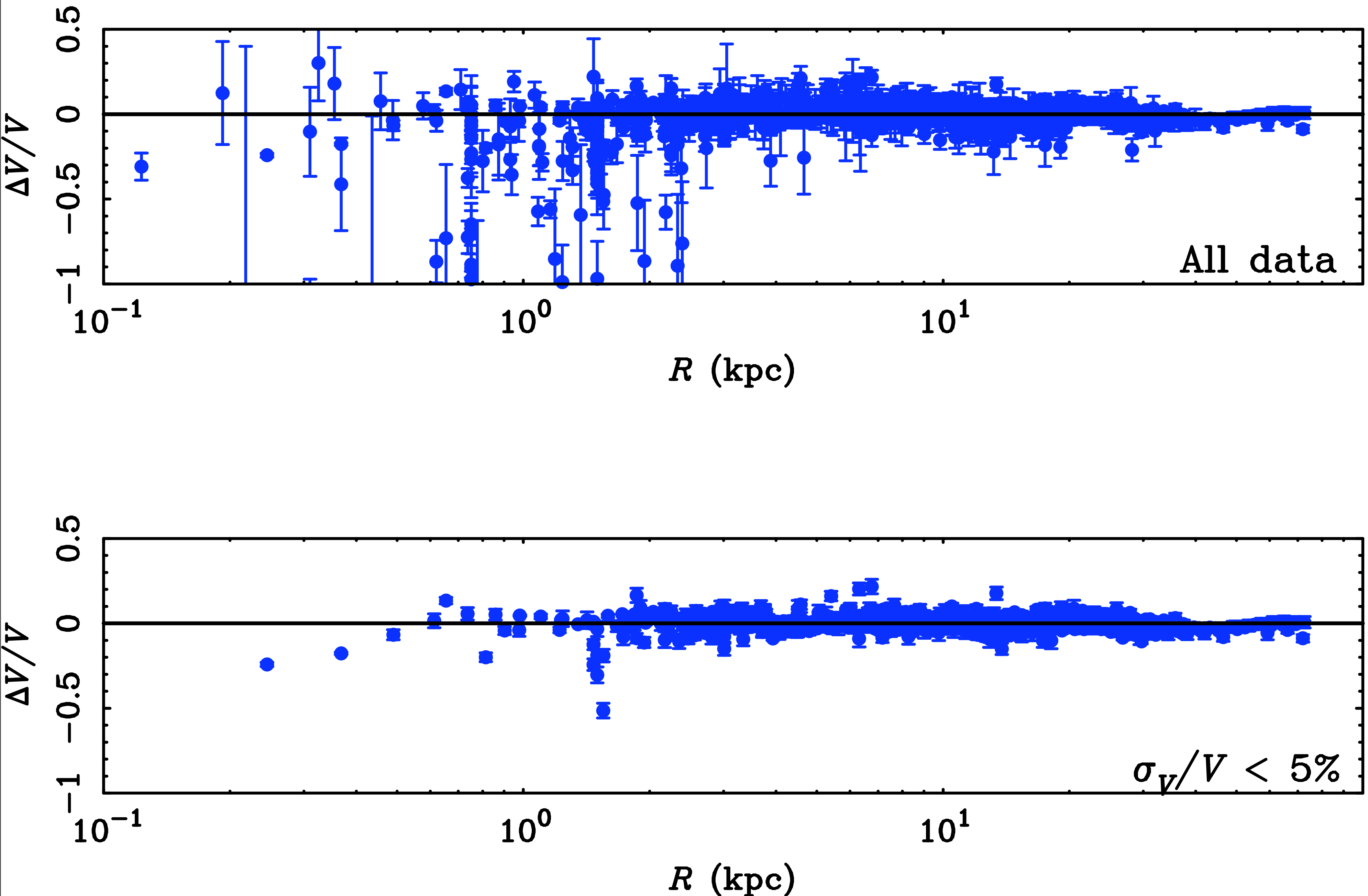
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



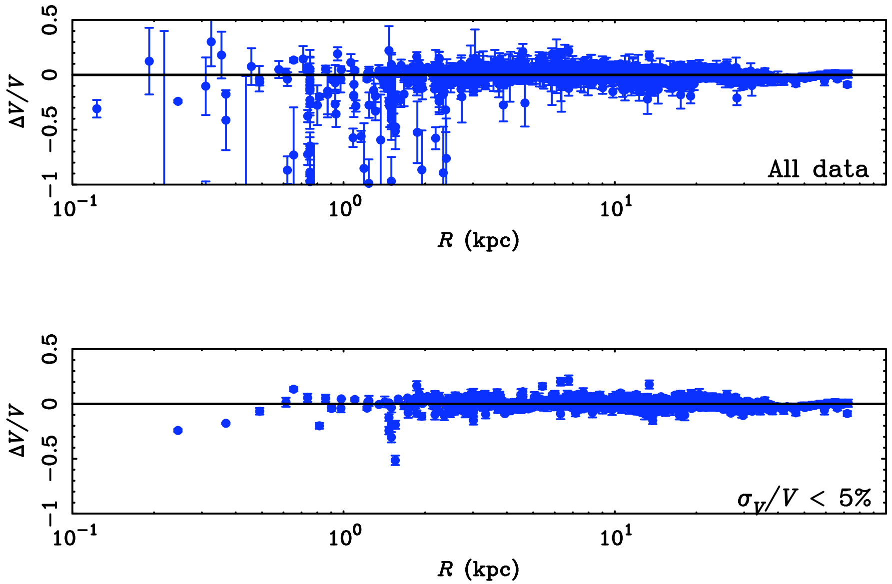


Sanders & McGaugh 2002, *ARA&A*, **40**, 263

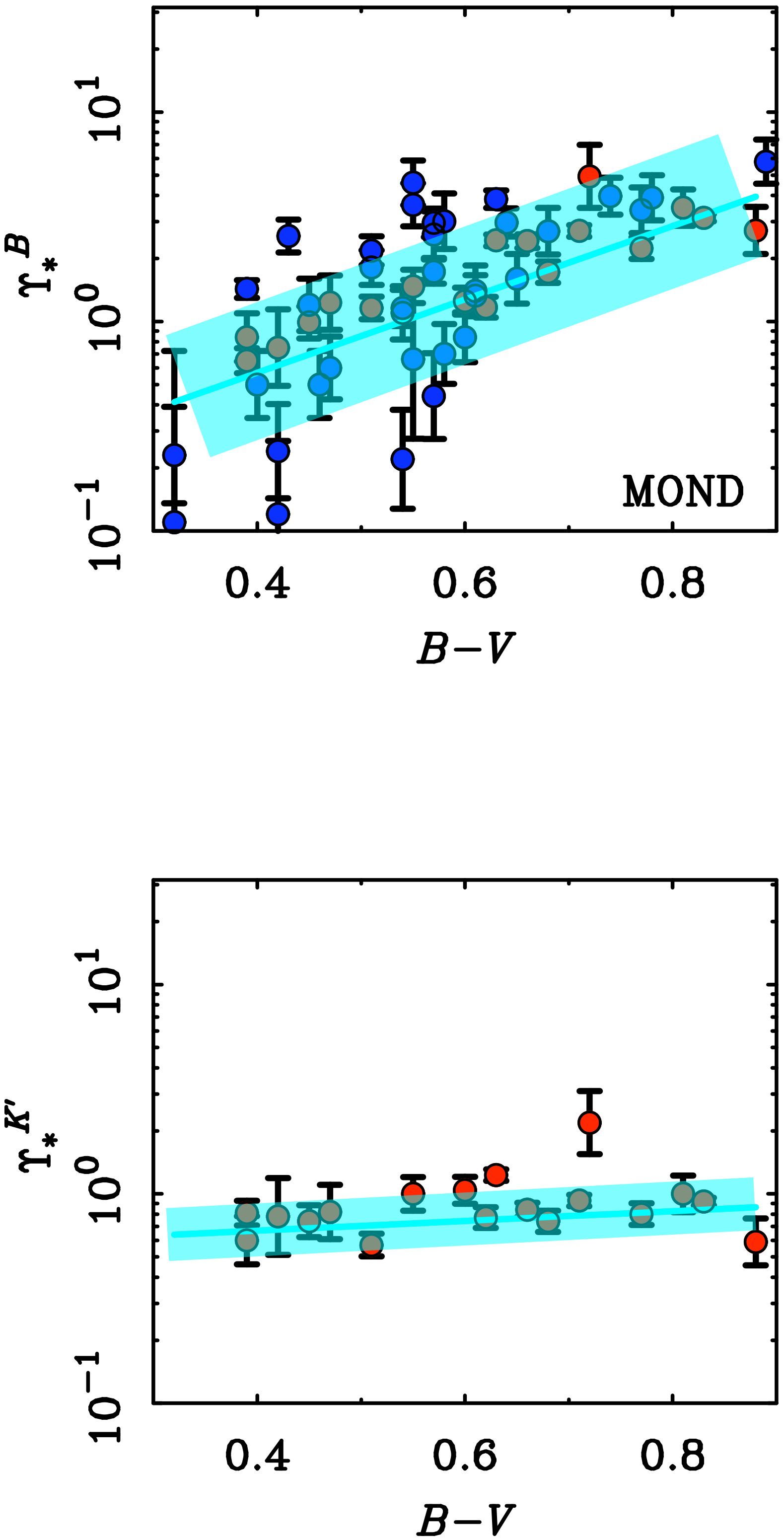
Residuals of MOND fits



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 = $1/(a_0 G)$
  - ✔ 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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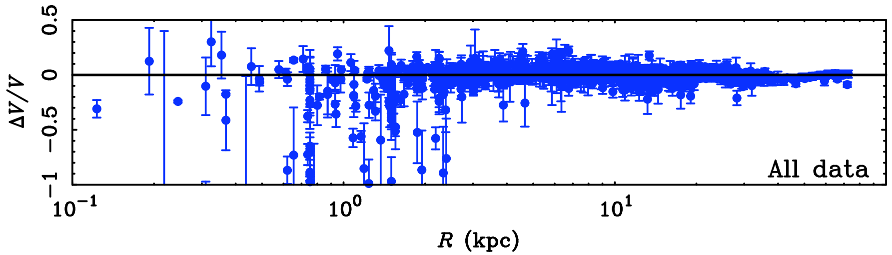
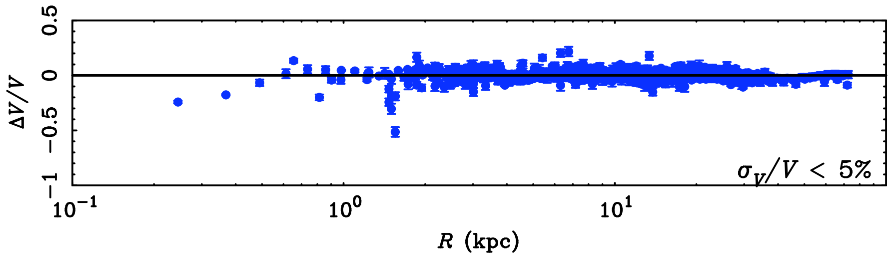
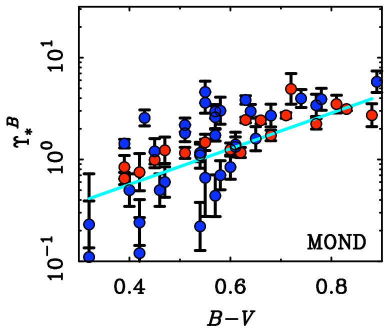
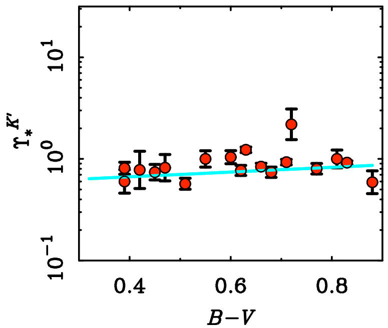
- ✔ Detailed Rotation Curve Fits
- ✔ Stellar Population Mass-to-Light Ratios



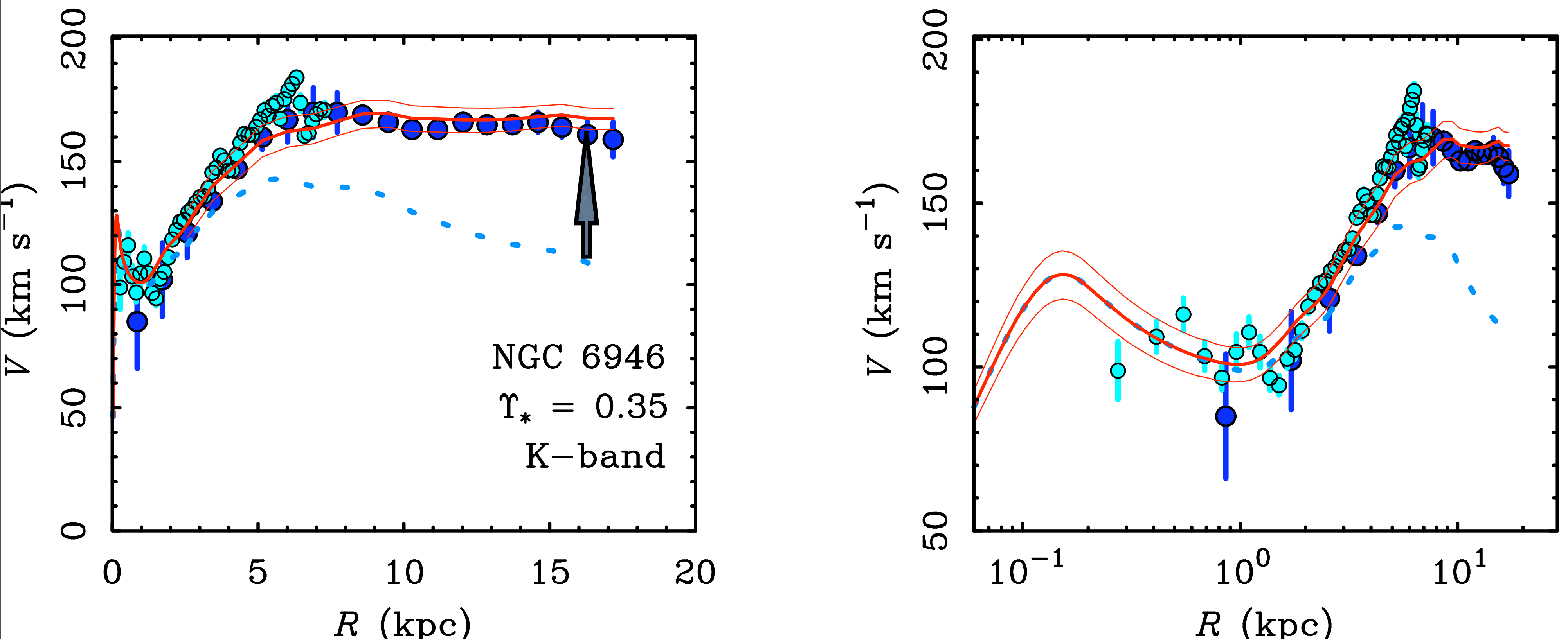






Renzo's Rule:

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

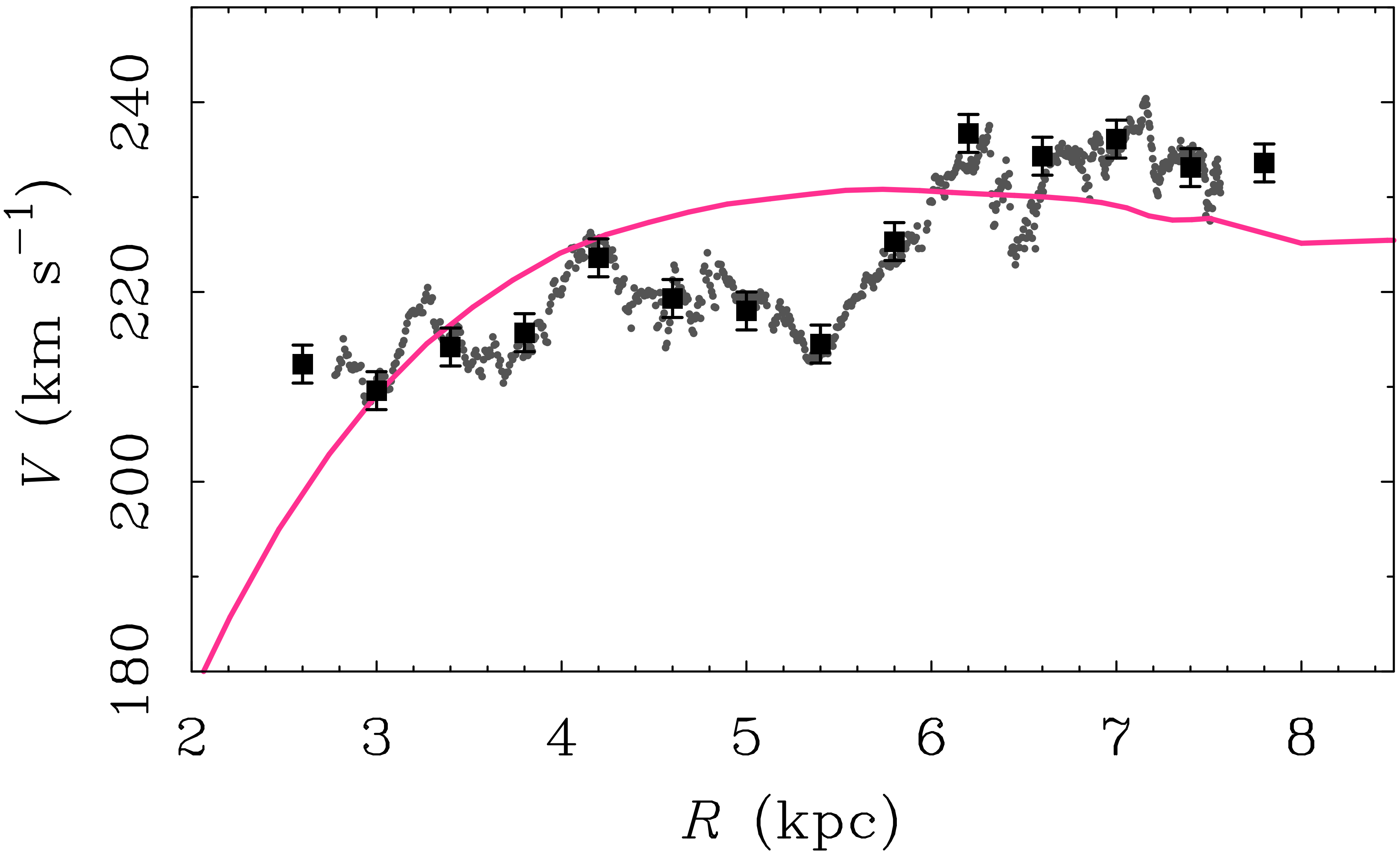


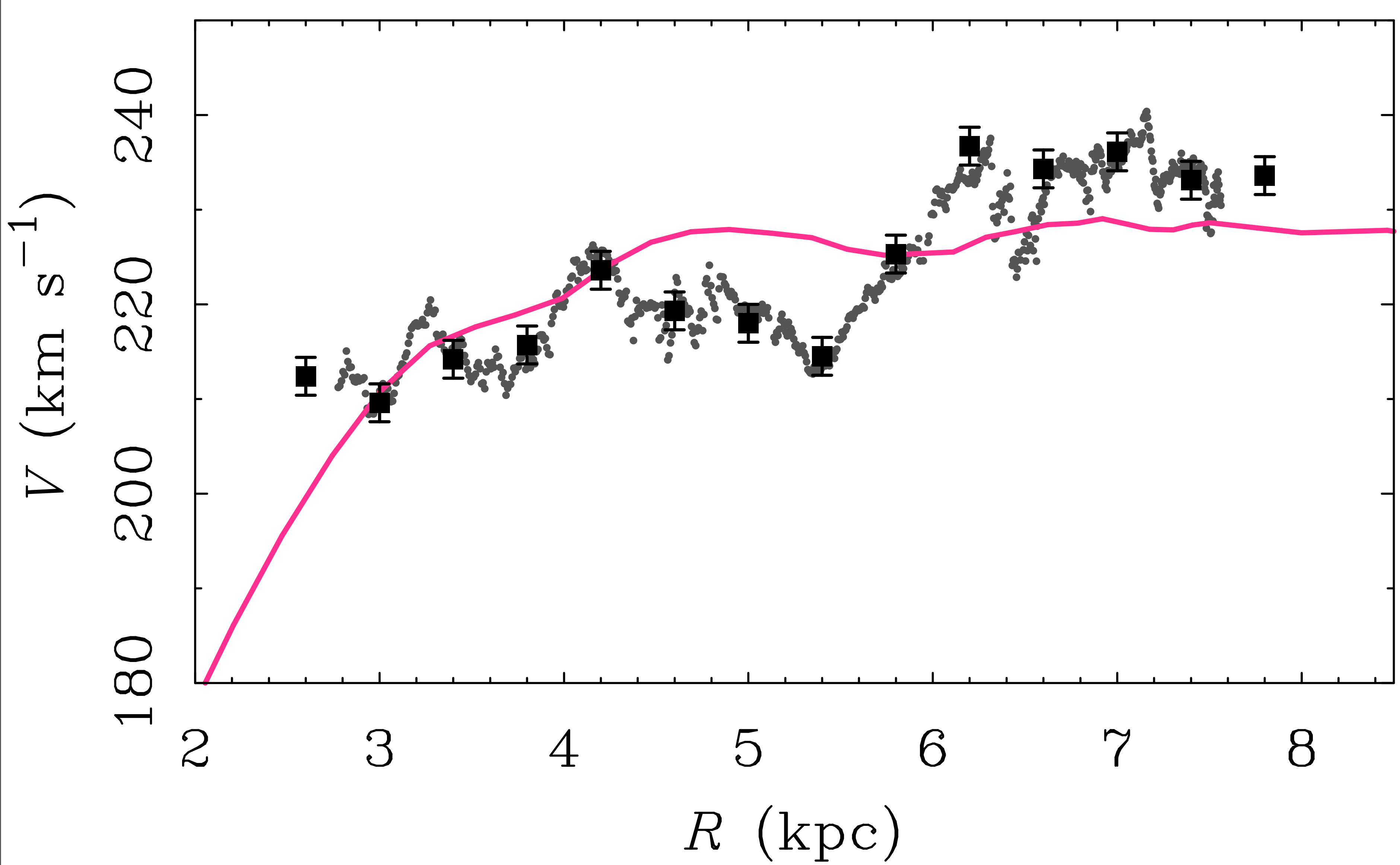
$$\Upsilon_\star^K = 0.35\ M_\odot / L_\odot$$

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

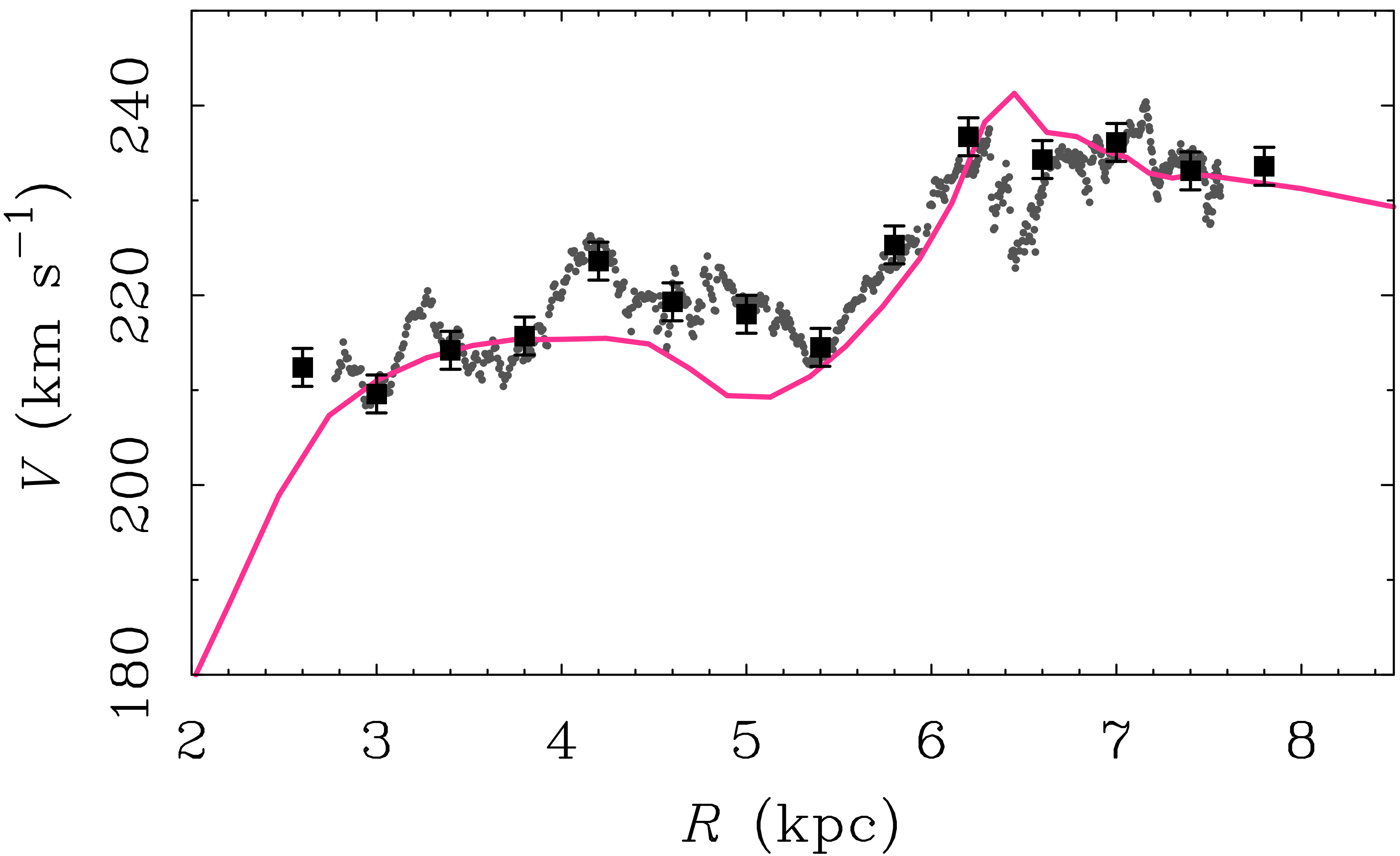
What about our own Galaxy?

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

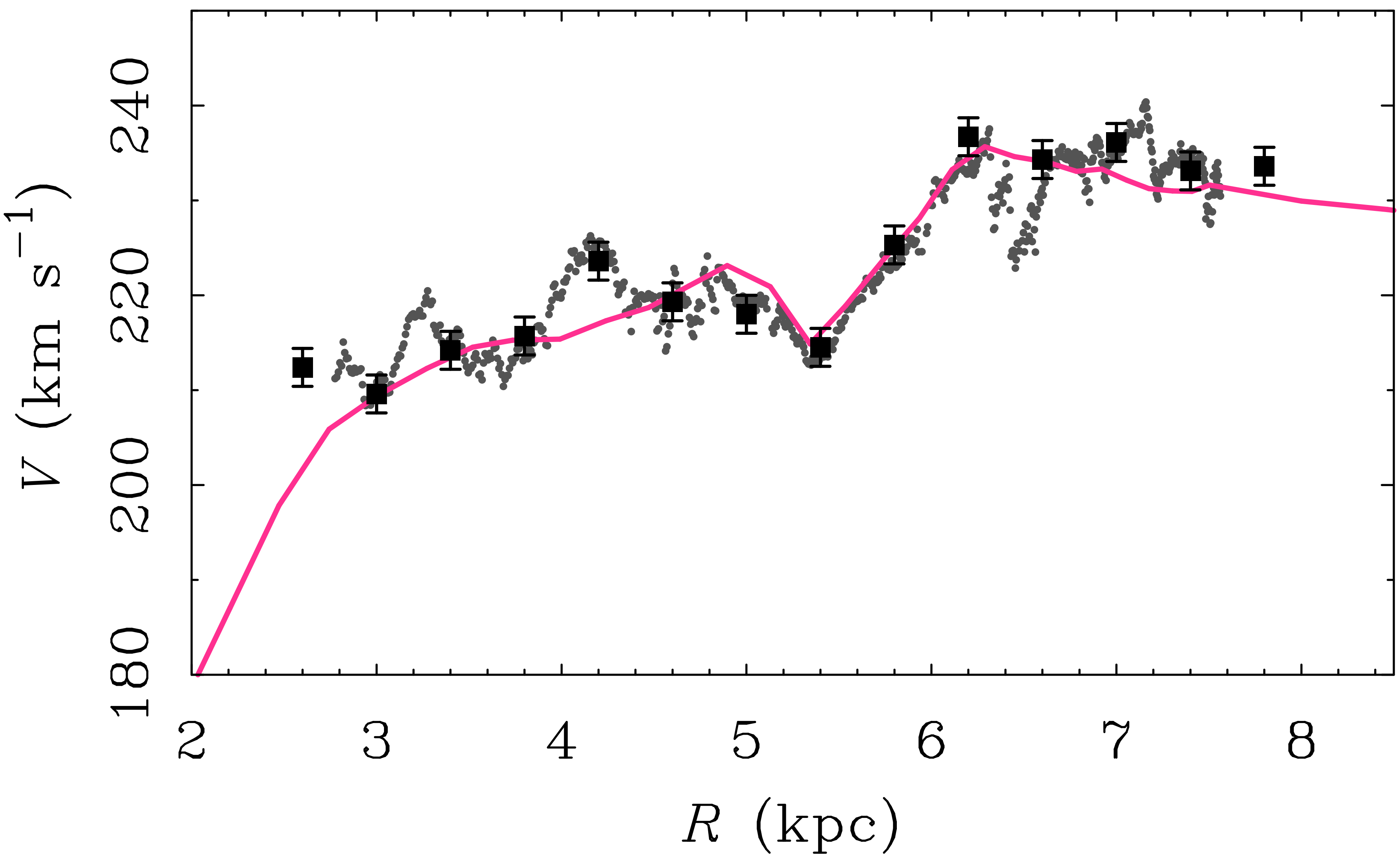




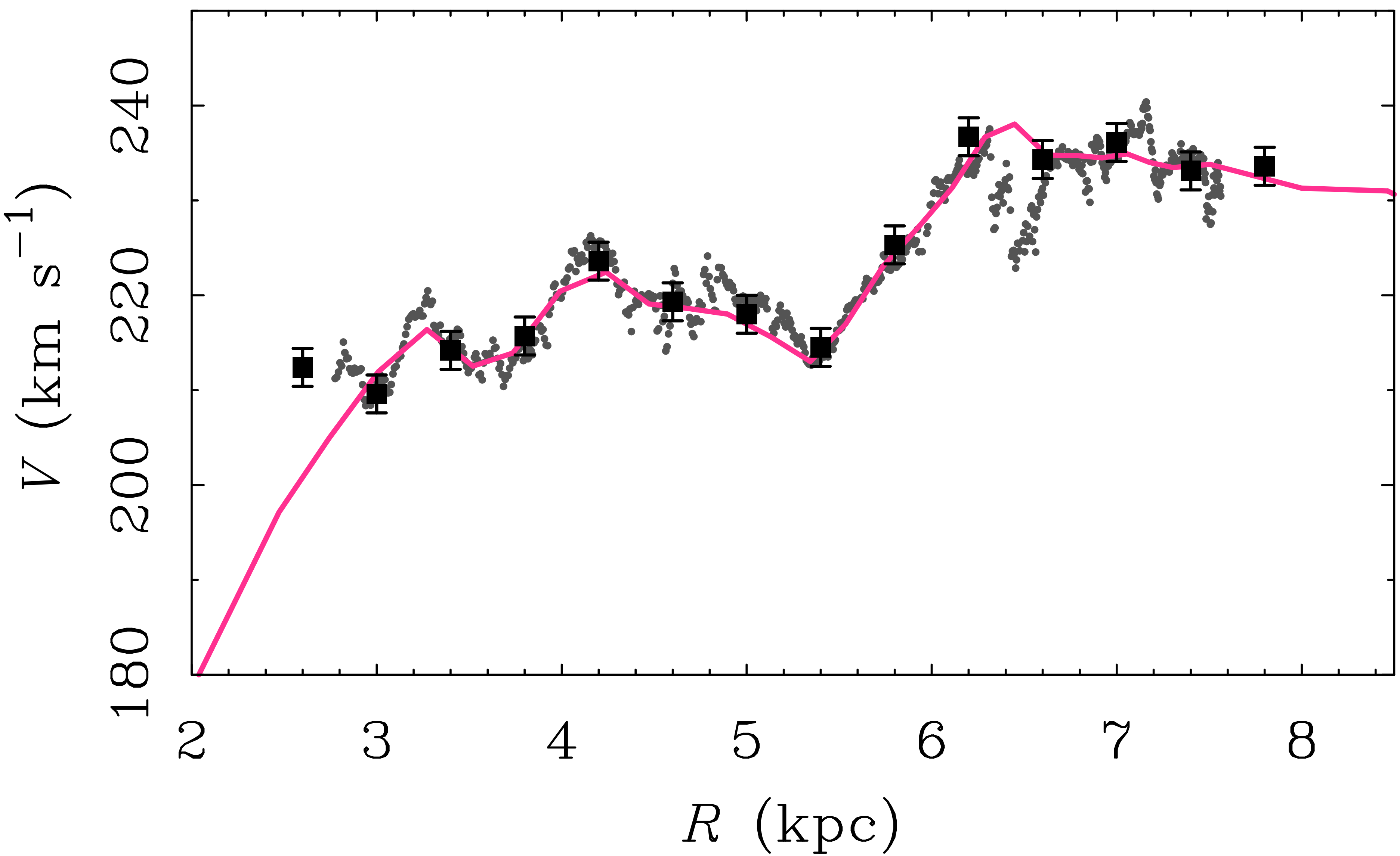
180
200
220
240
V (km s^{-1})
2
3
4
5
6
7
8
R (kpc)



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

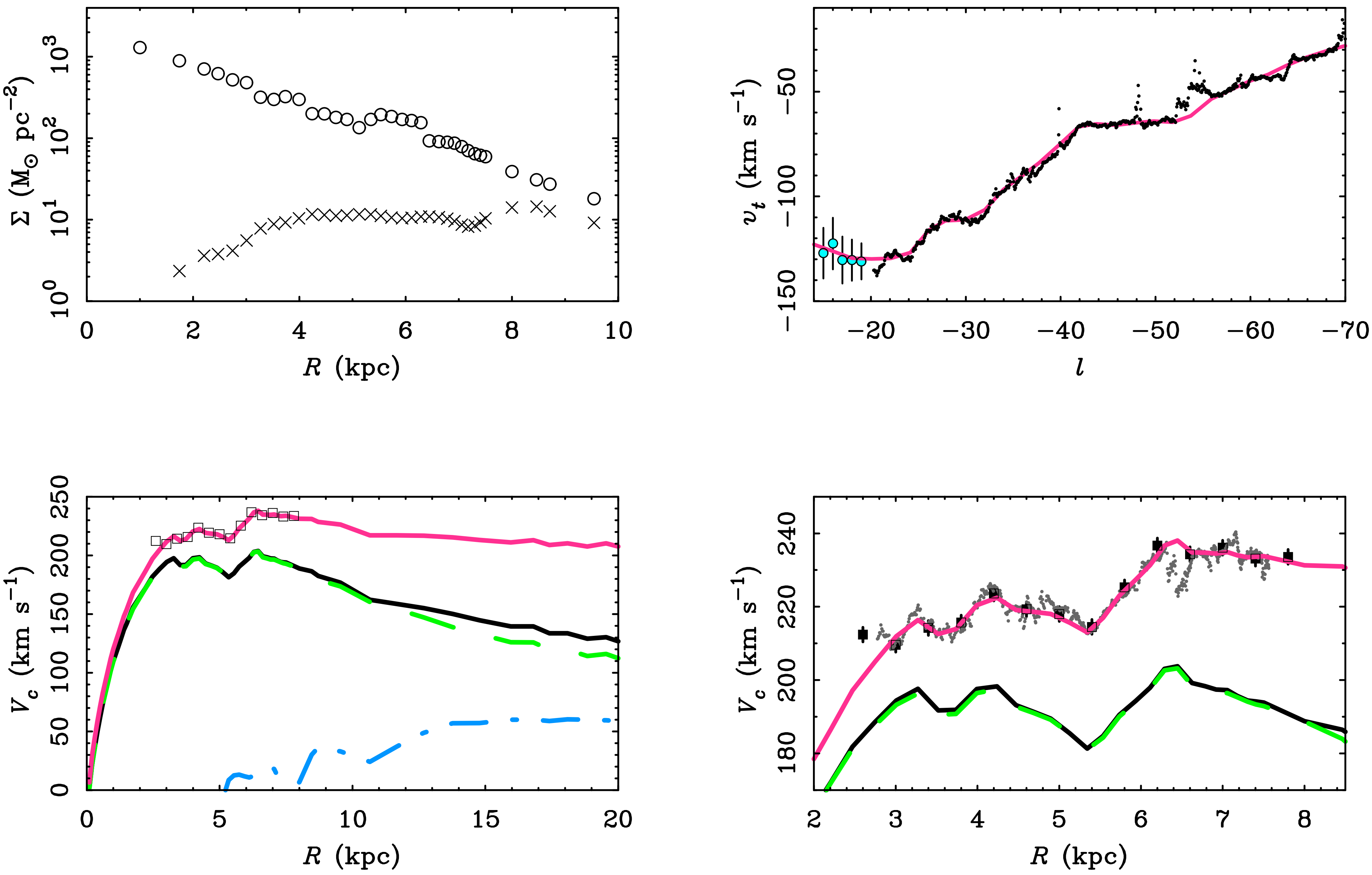


V (km s^{-1})
180
200
220
240
2
3
4
5
6
7
8
R (kpc)

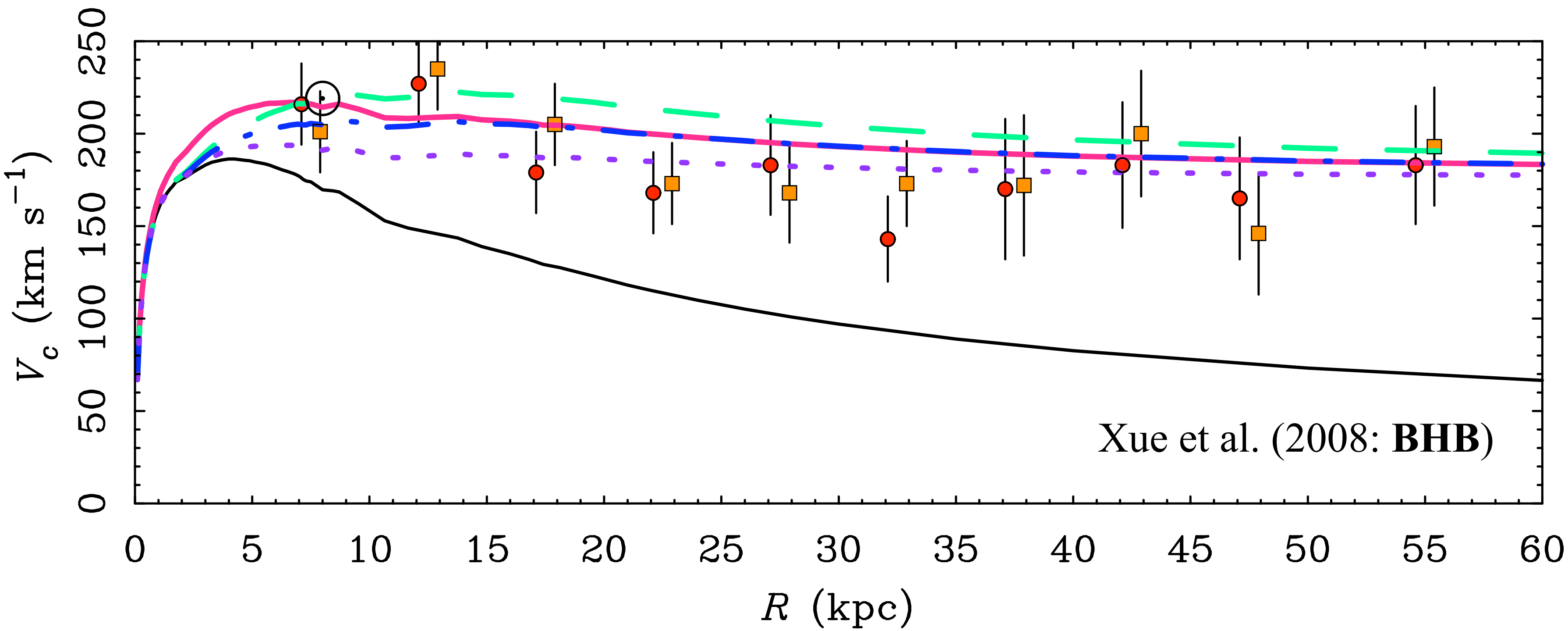


180
200
220
240
V (km s^{-1})
2
3
4
5
6
7
8
R (kpc)

MONDian Milky Way

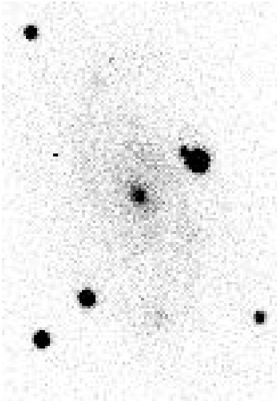


Get outer rotation curve with no fitting



Different lines represent different assumed interpolation functions

Disk Masses from Density Waves



LSB galaxies got spiral arms!

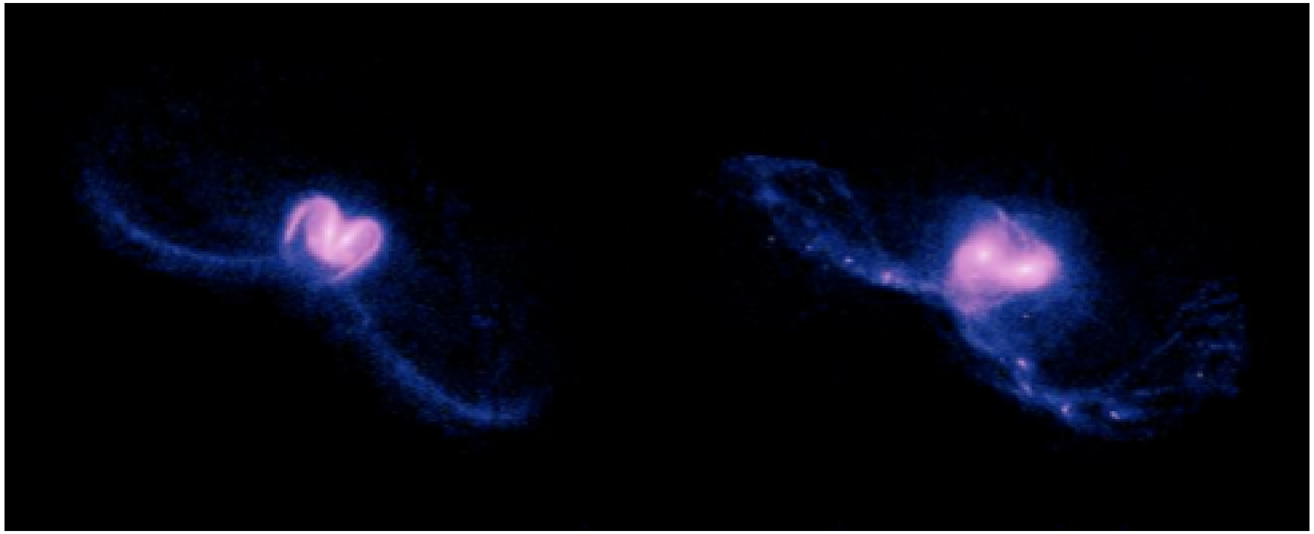
Need very massive disks to drive spiral density waves in LSBs, as anticipated by McGaugh & de Blok (1998), *ApJ*, 499, 66

DISK STABILITY MAKES MORE SENSE IN MOND

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

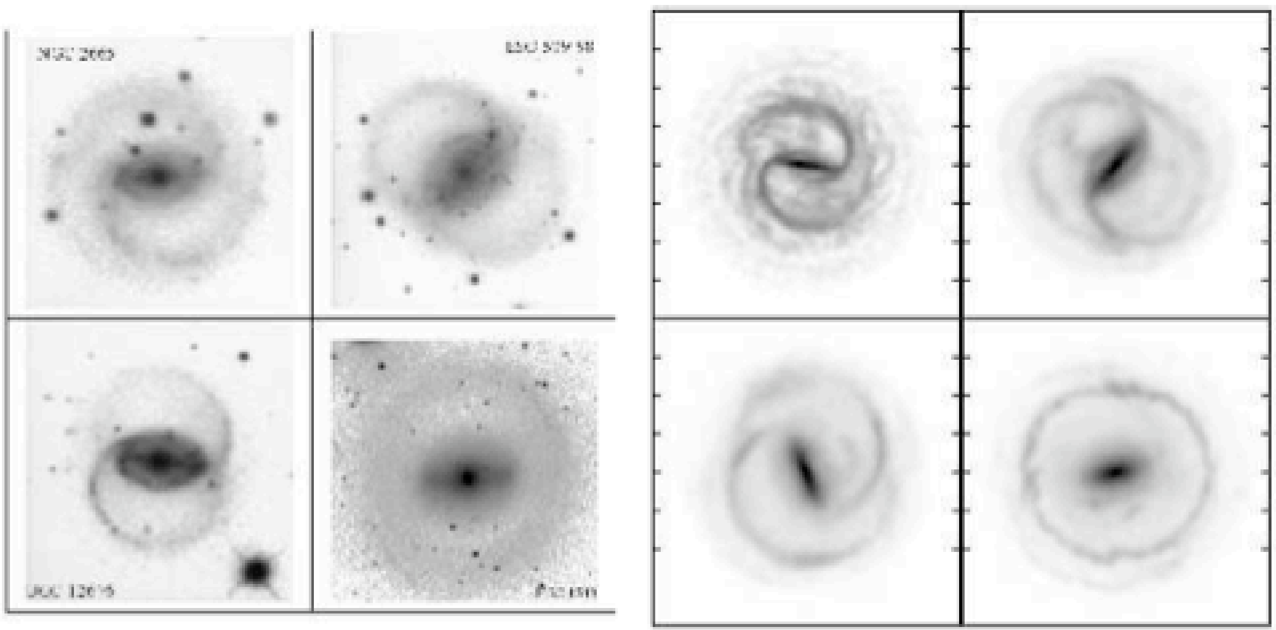
Big $(M/L)_*$'s!

from B. Fuchs, astro-ph/0209157



Tiret & Combes

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

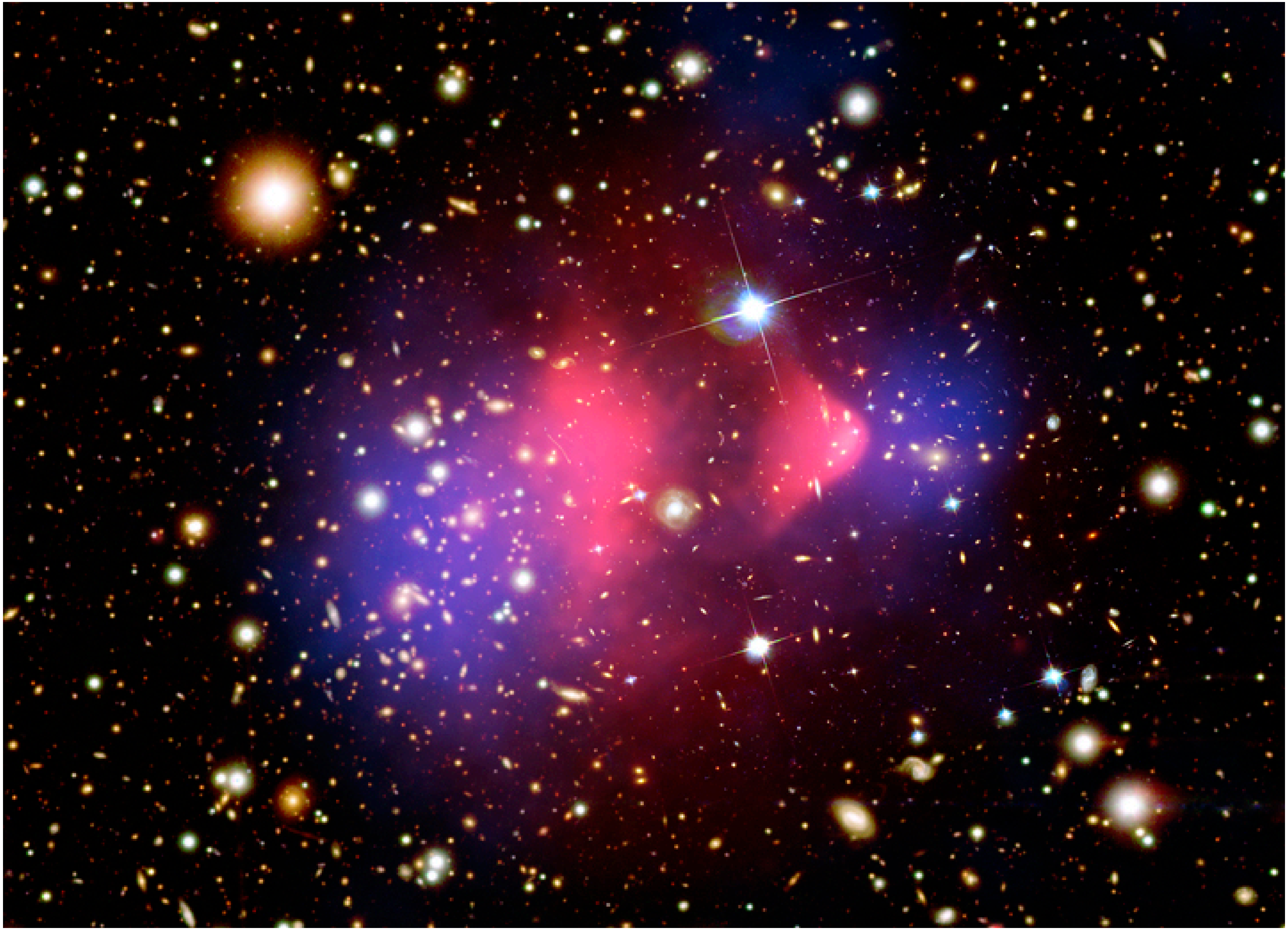


. Several examples showing the morphological structures of NGC 2665, ESO 509-98, UGC 12646 and NGC 1543 anel) compared to simulated galaxies in MOND (bottom panel). Rings and pseudo-rings structures are well uced with modified gravity.

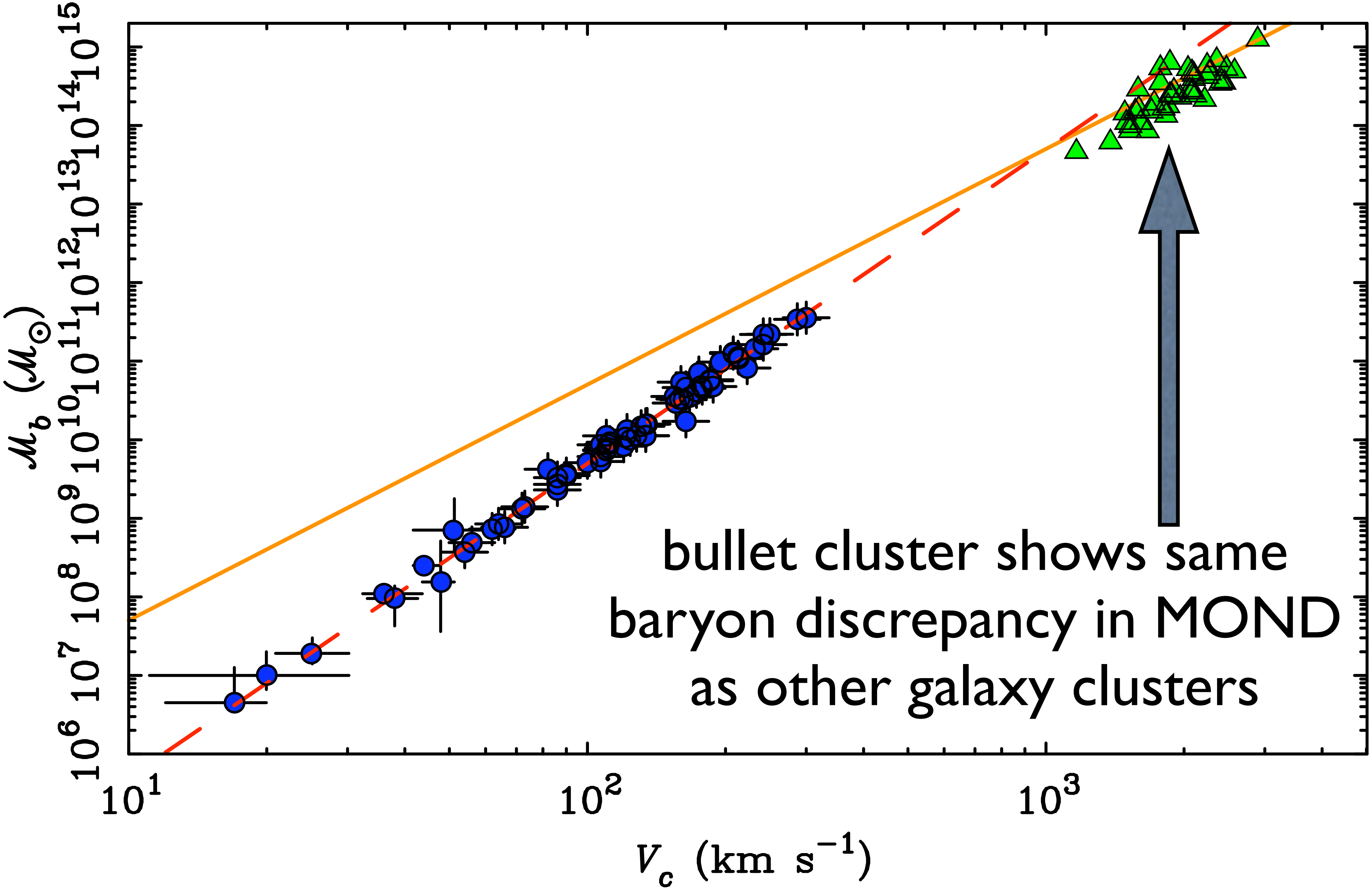
What are the downsides?

- 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 Bekenstein (2004)
- Does it survive other tests? Clusters problematic

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



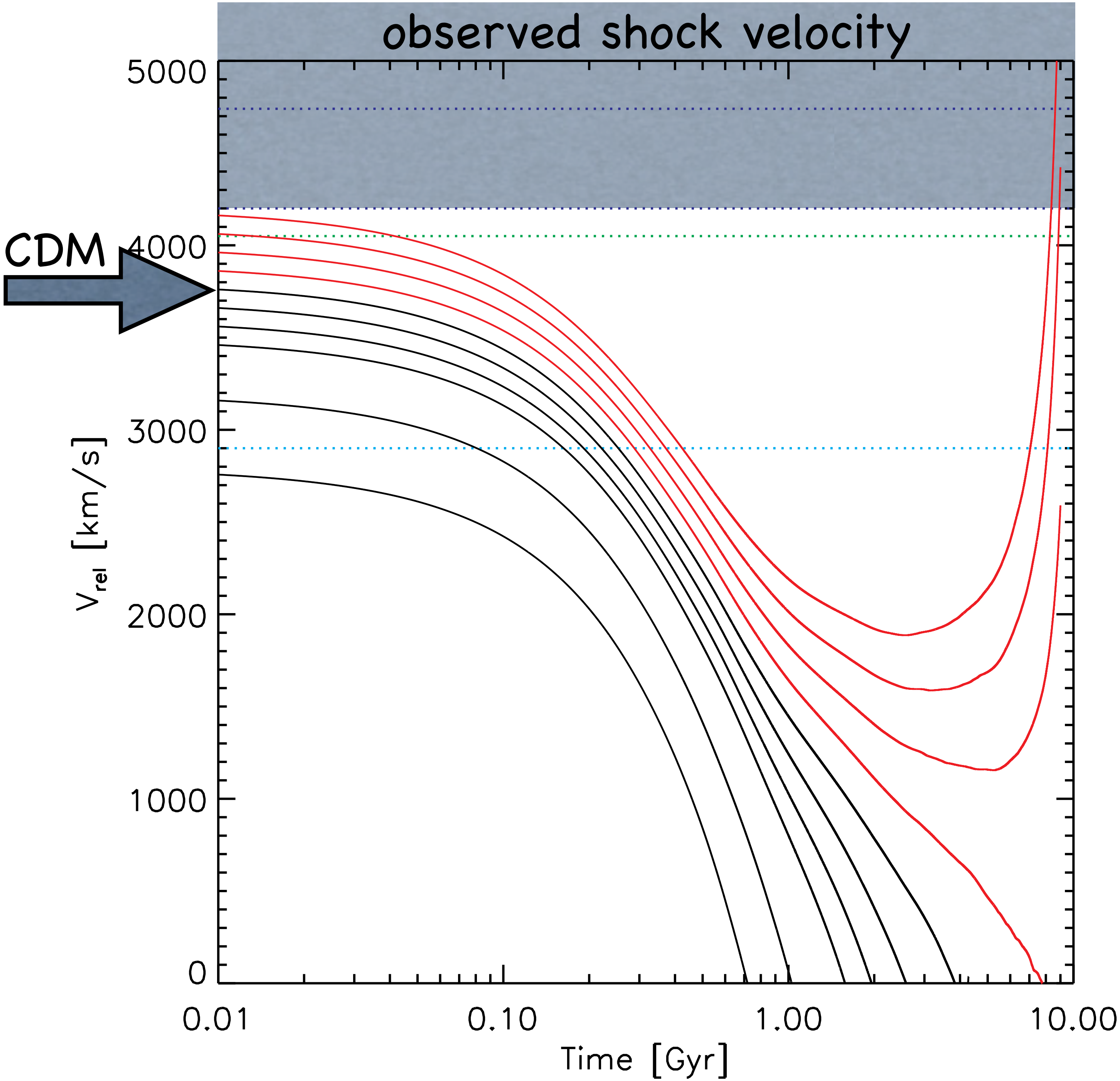
direct proof of dark matter?



MOND suffers a missing mass problem!

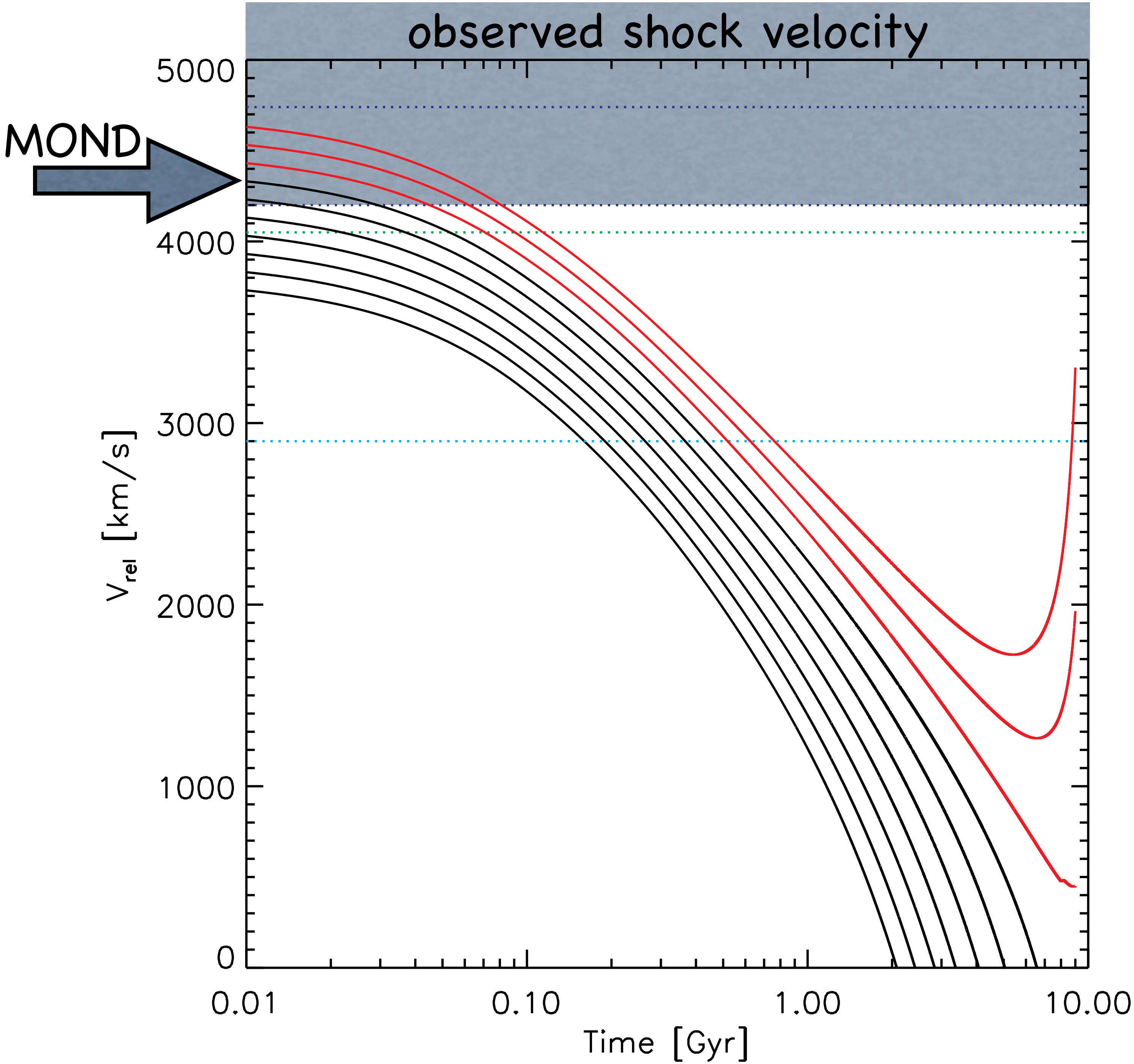
unseen baryons? heavy neutrinos?

bullet cluster collision velocity



Angus & McGaugh (2008) [arXiv:0704.0381]

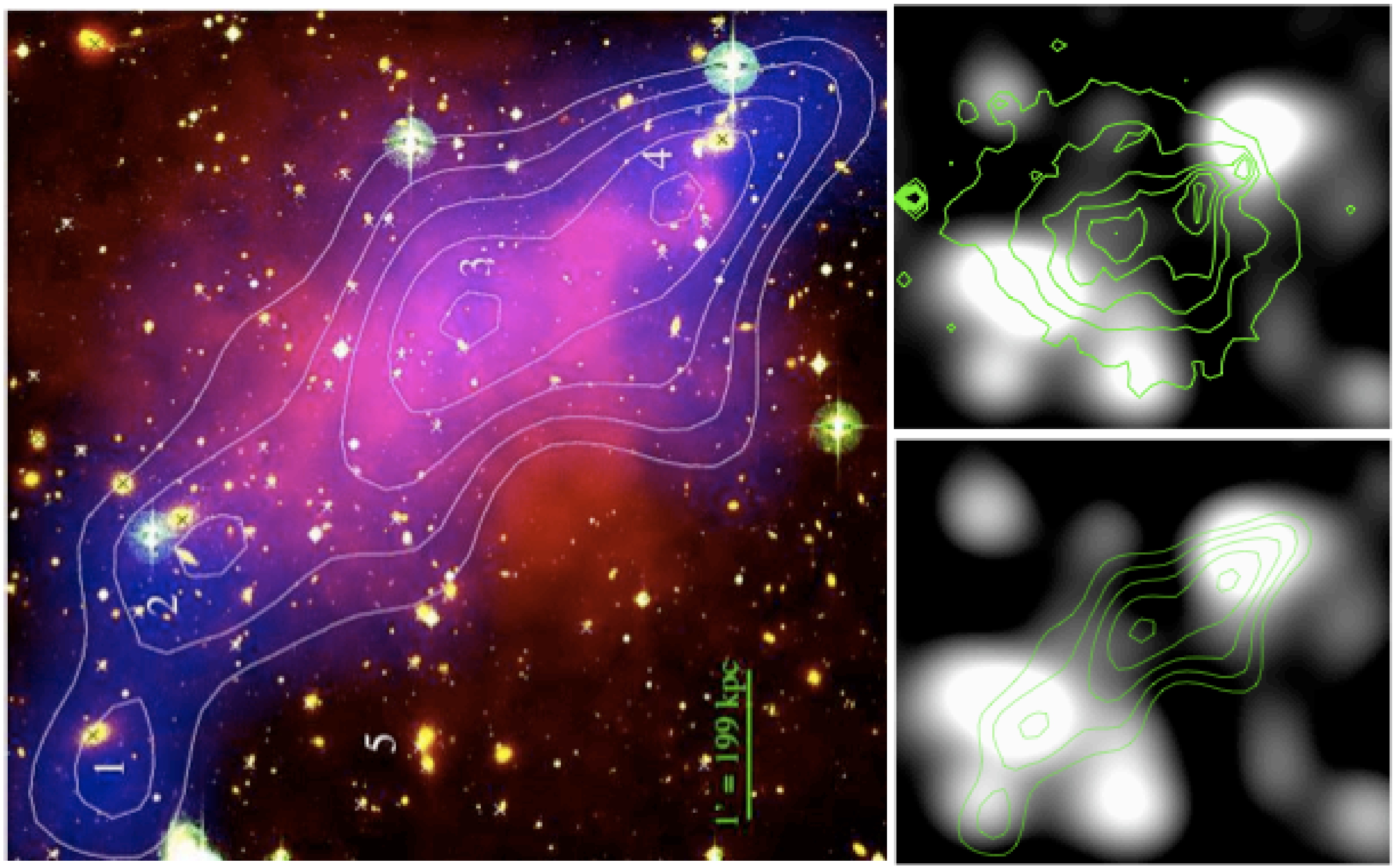
bullet cluster collision velocity

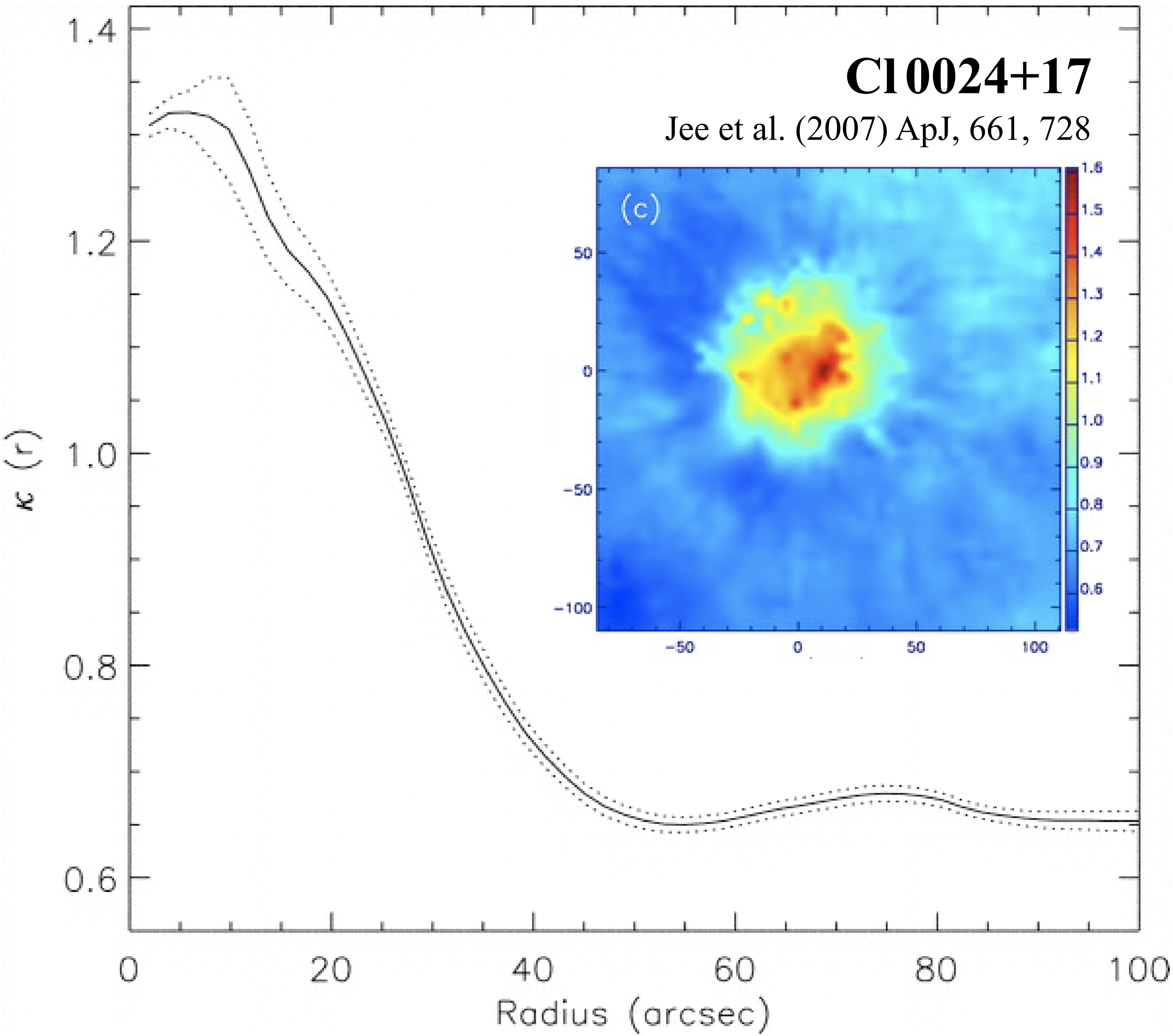


Angus & McGaugh (2008) [arXiv:0704.0381]

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

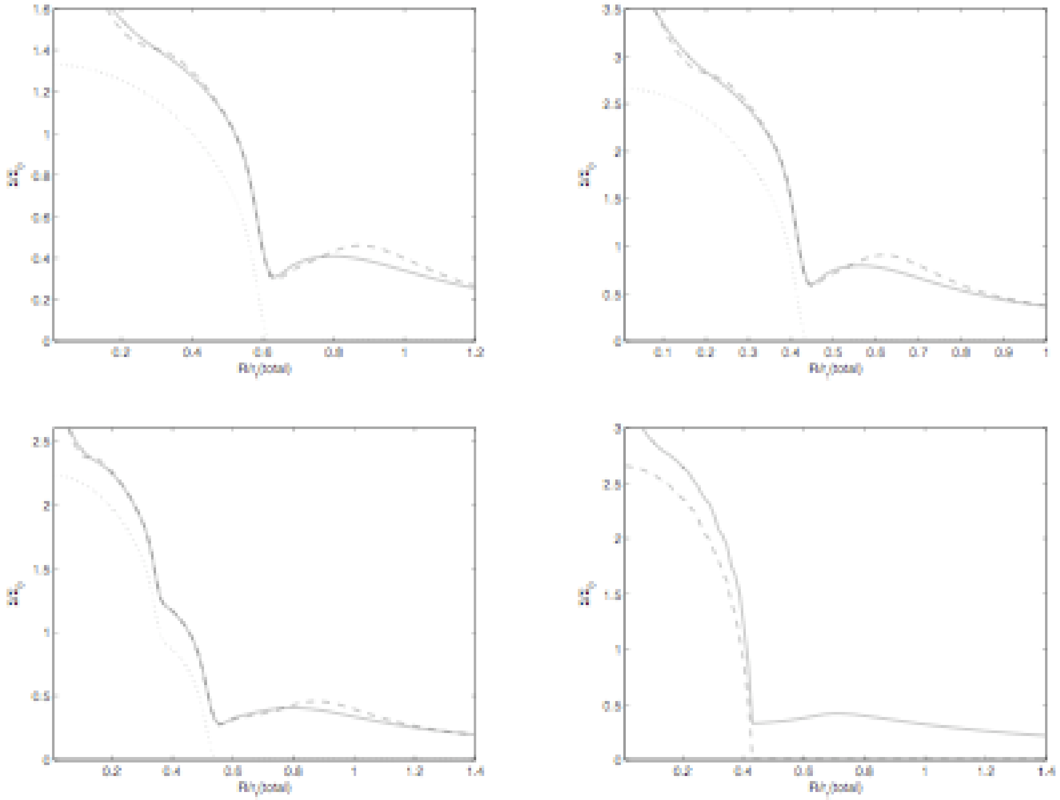


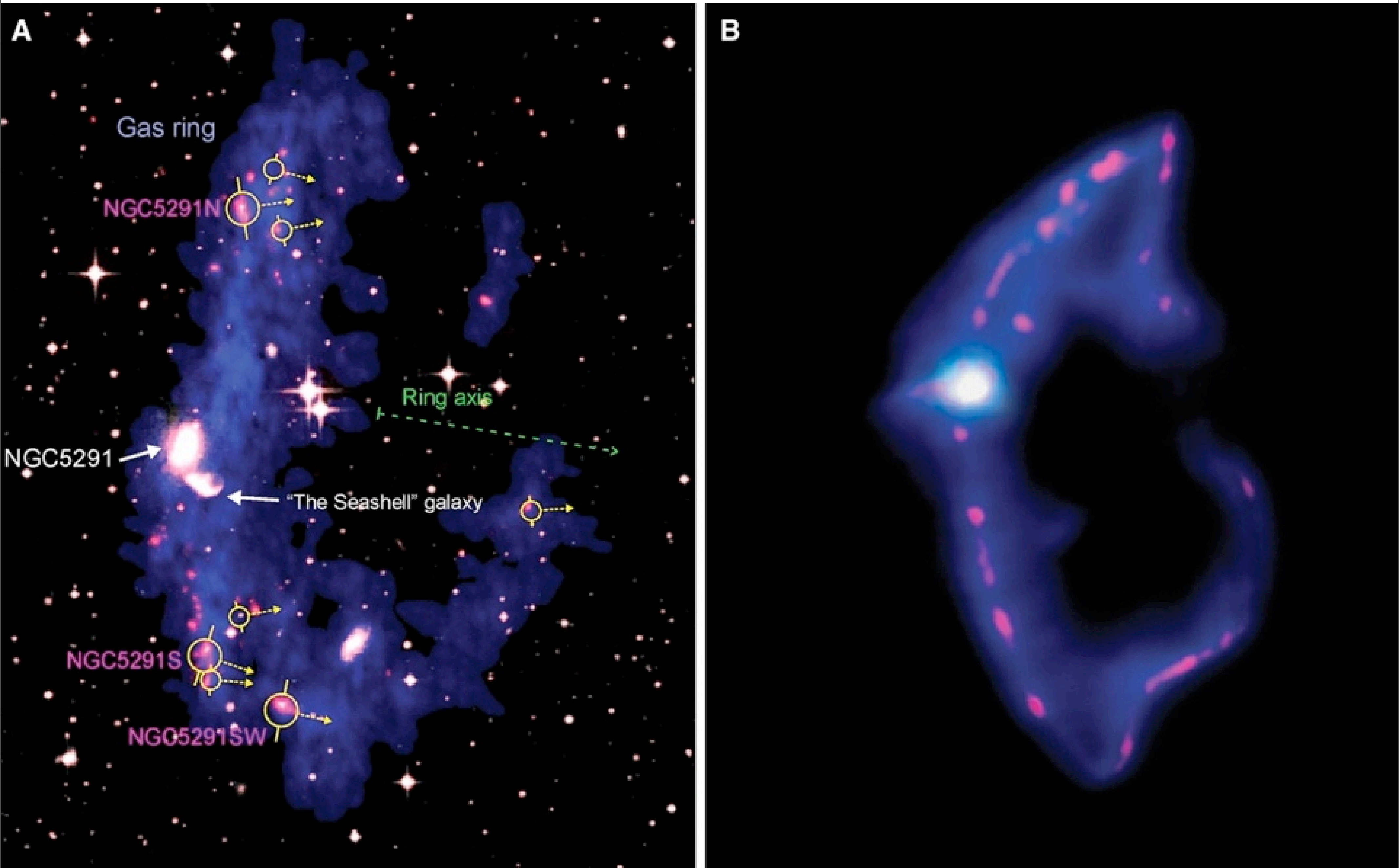
Fig. 6.— The total projected Surface density in units of Σ_0. Upper left: for a single sphere of constant density with a radius that is 0.6 the transition radius. Upper right: for two spheres of constant density far apart from each other along the line of sight, each has a radius that is 0.6 of its own 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).

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

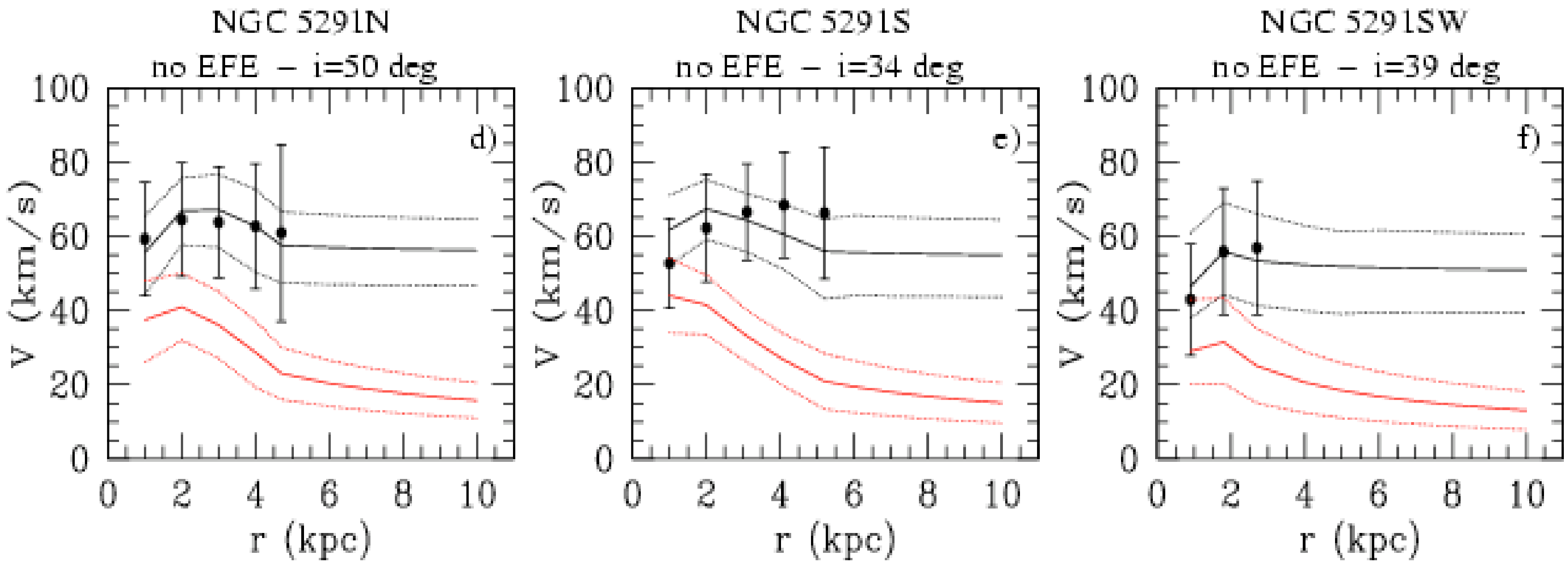
There can be a feature around the transition radius, depending on the interpolation function.

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

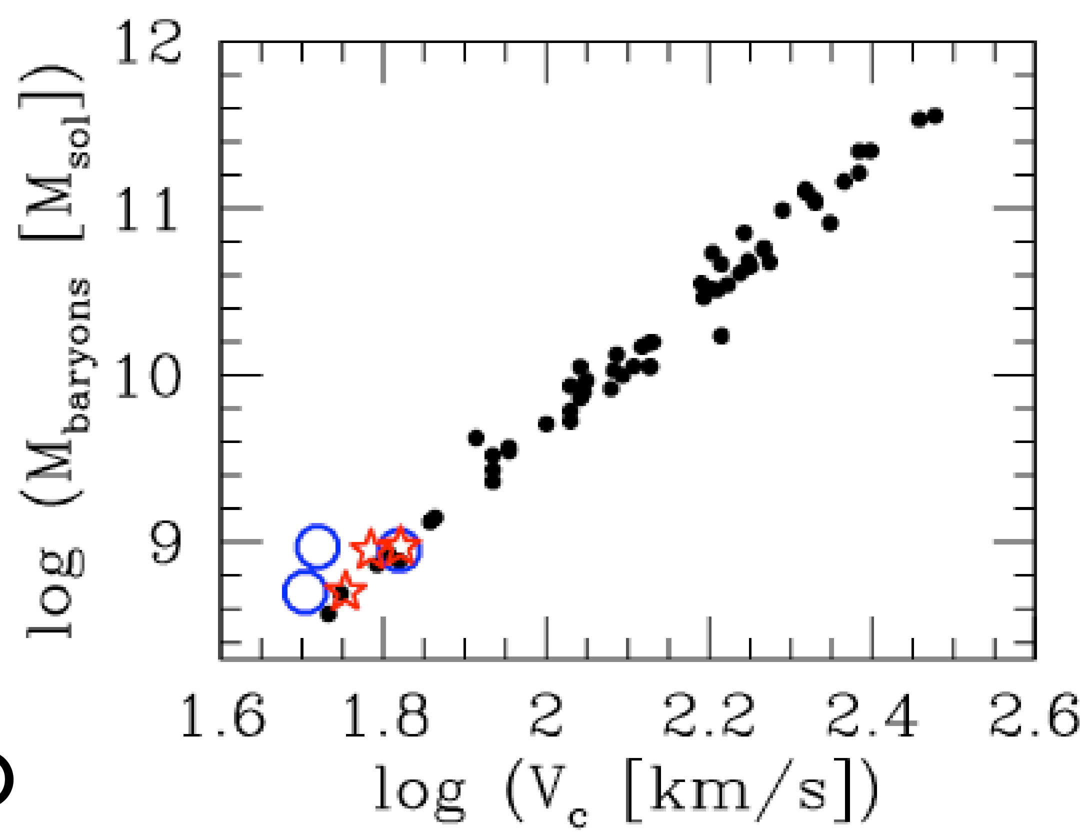
Tidal Debris Dwarfs - should be devoid of Dark Matter



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

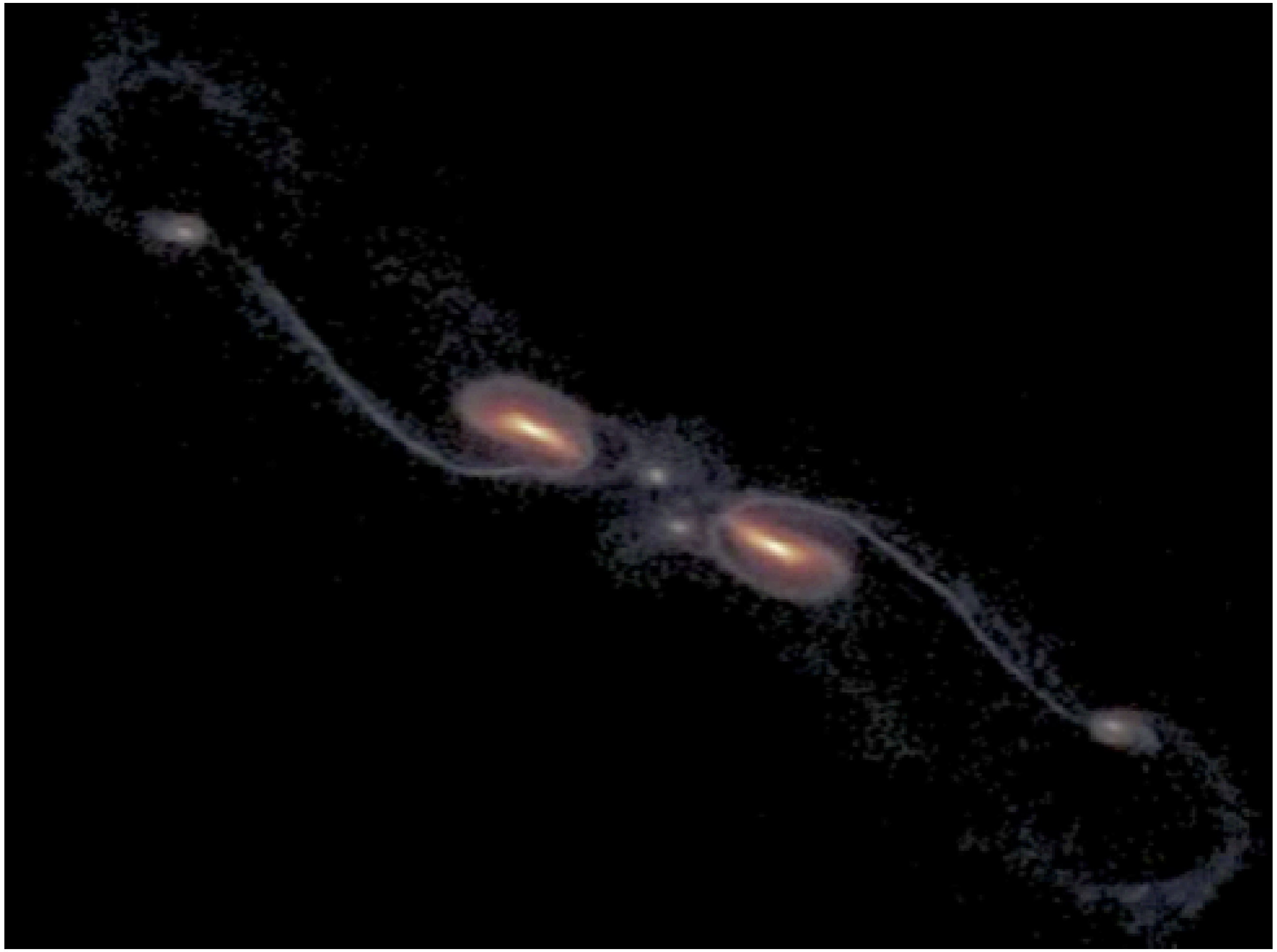


Fig. 6. Tidal dwarf formation at the tip of the tidal tail in MOND.

How else can we tell the difference?

McGaugh (1999) proposed a test for the existence of non-baryonic Cold Dark Matter in the power spectrum of the cosmic microwave background.

1st:2nd peak ratio larger w/o CDM

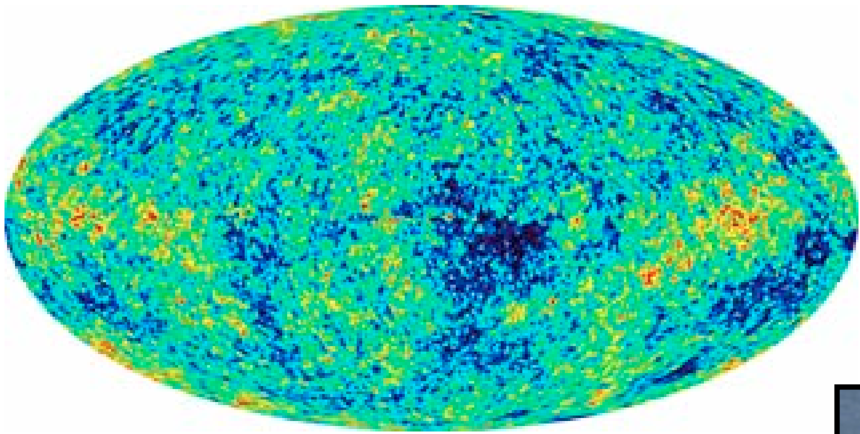
$A_{1:2} < 1.9$ (CDM) $A_{1:2} = 2.4$ (No CDM)

3rd peak lower than 2nd w/o CDM

$A_{2:3} < 1$ (CDM) $A_{2:3} > 1$ (No CDM)

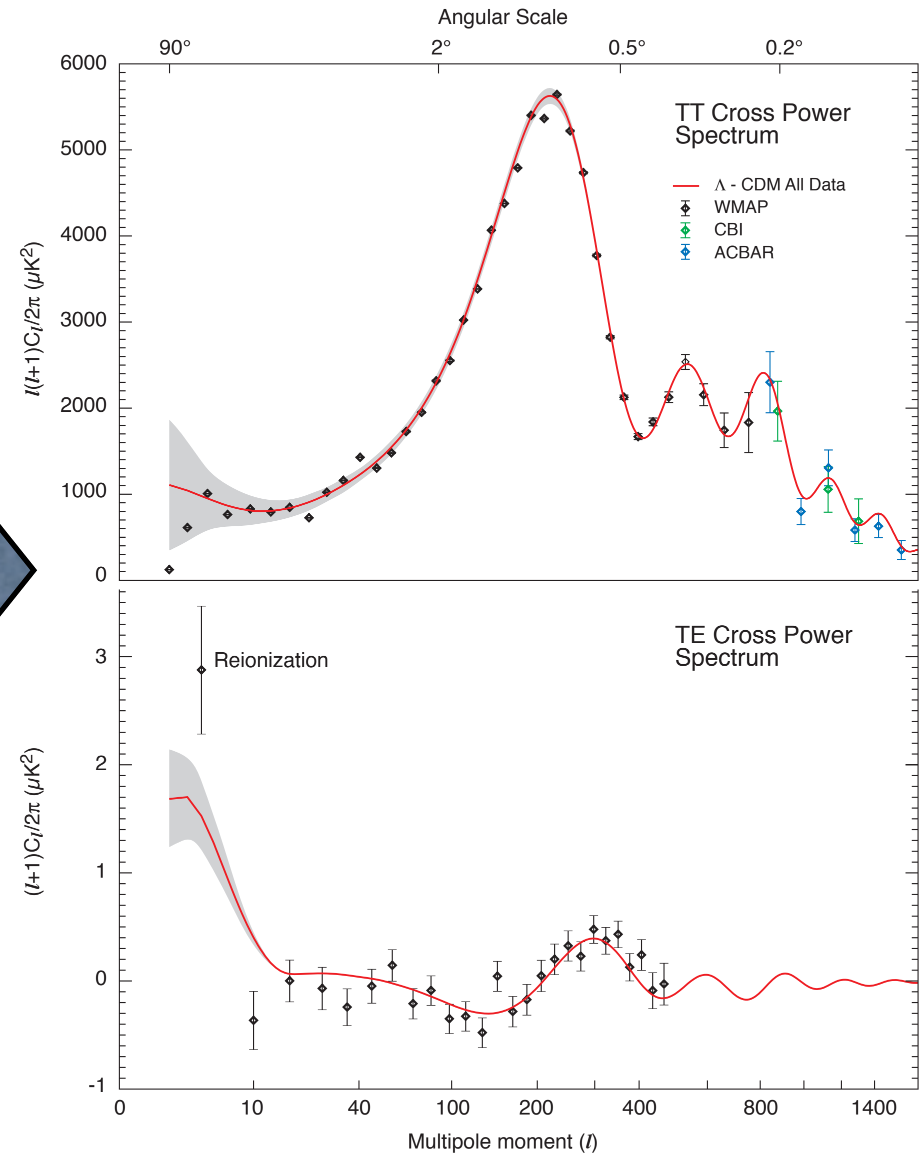
Also expect:

- enhanced ISW
- earlier reionization

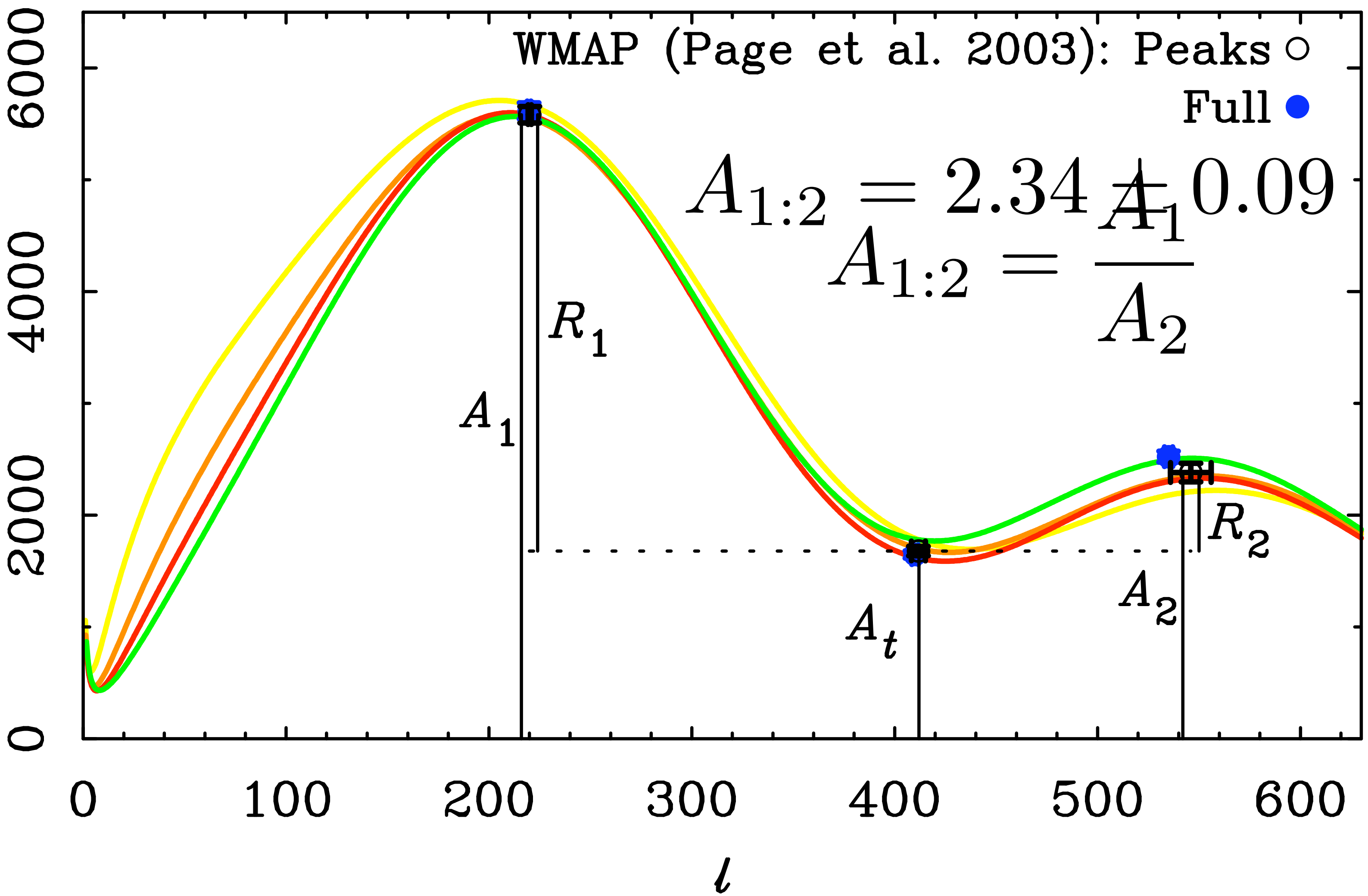


WMAP

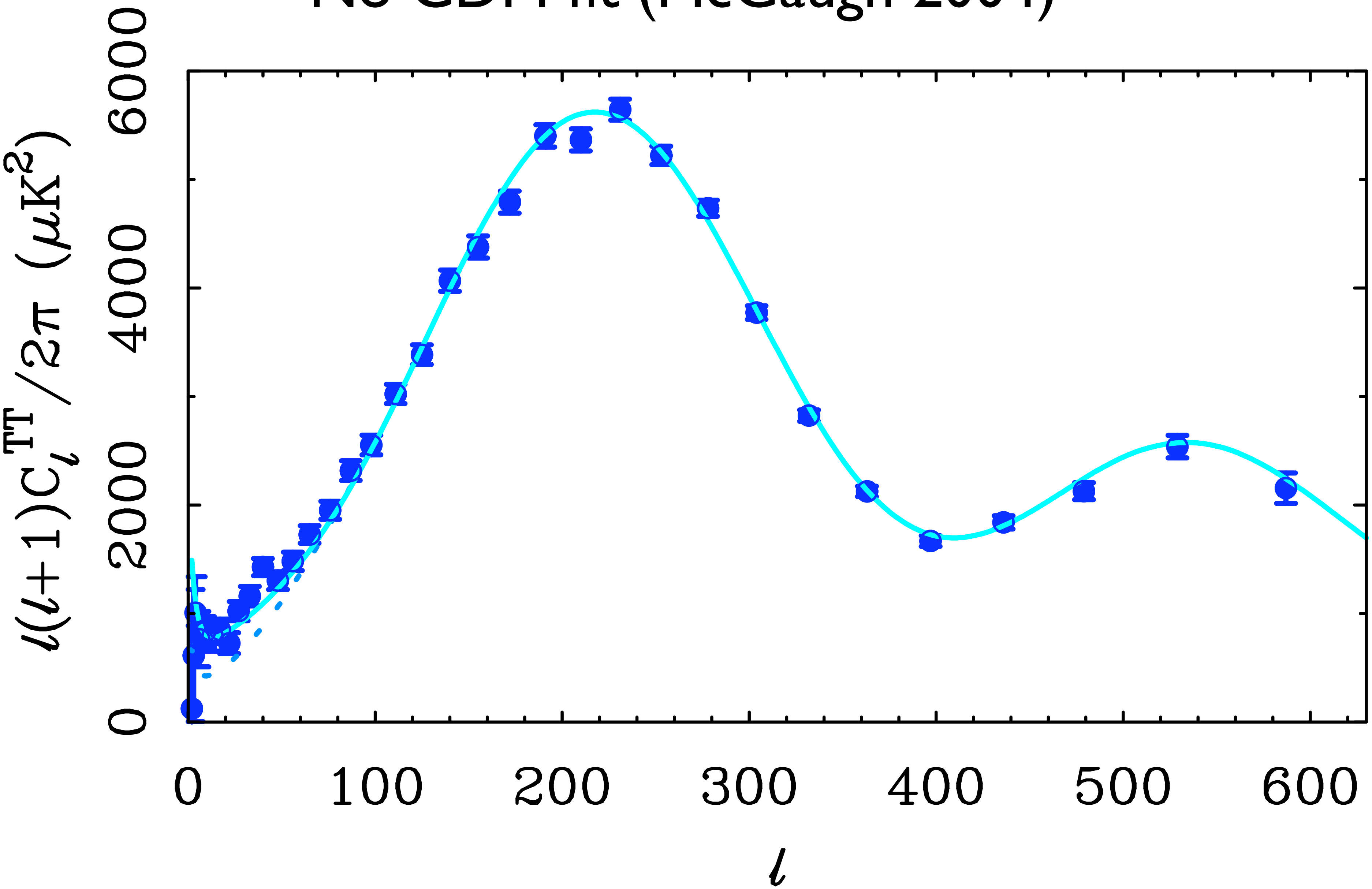
Cosmic Background Radiation



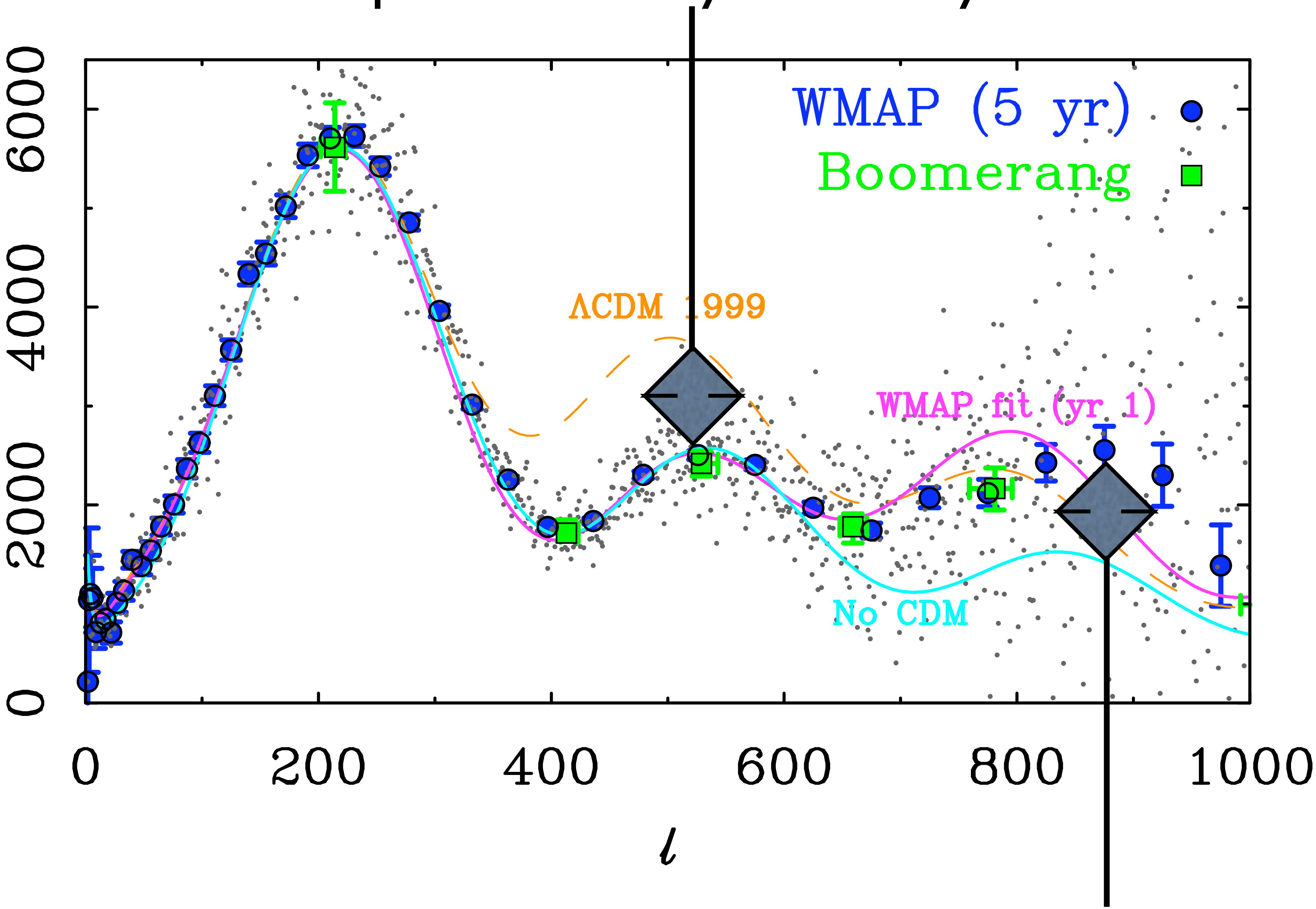
No CDM prediction (McGaugh 1999): $A_{1:2} = 2.4$



No CDM fit (McGaugh 2004)

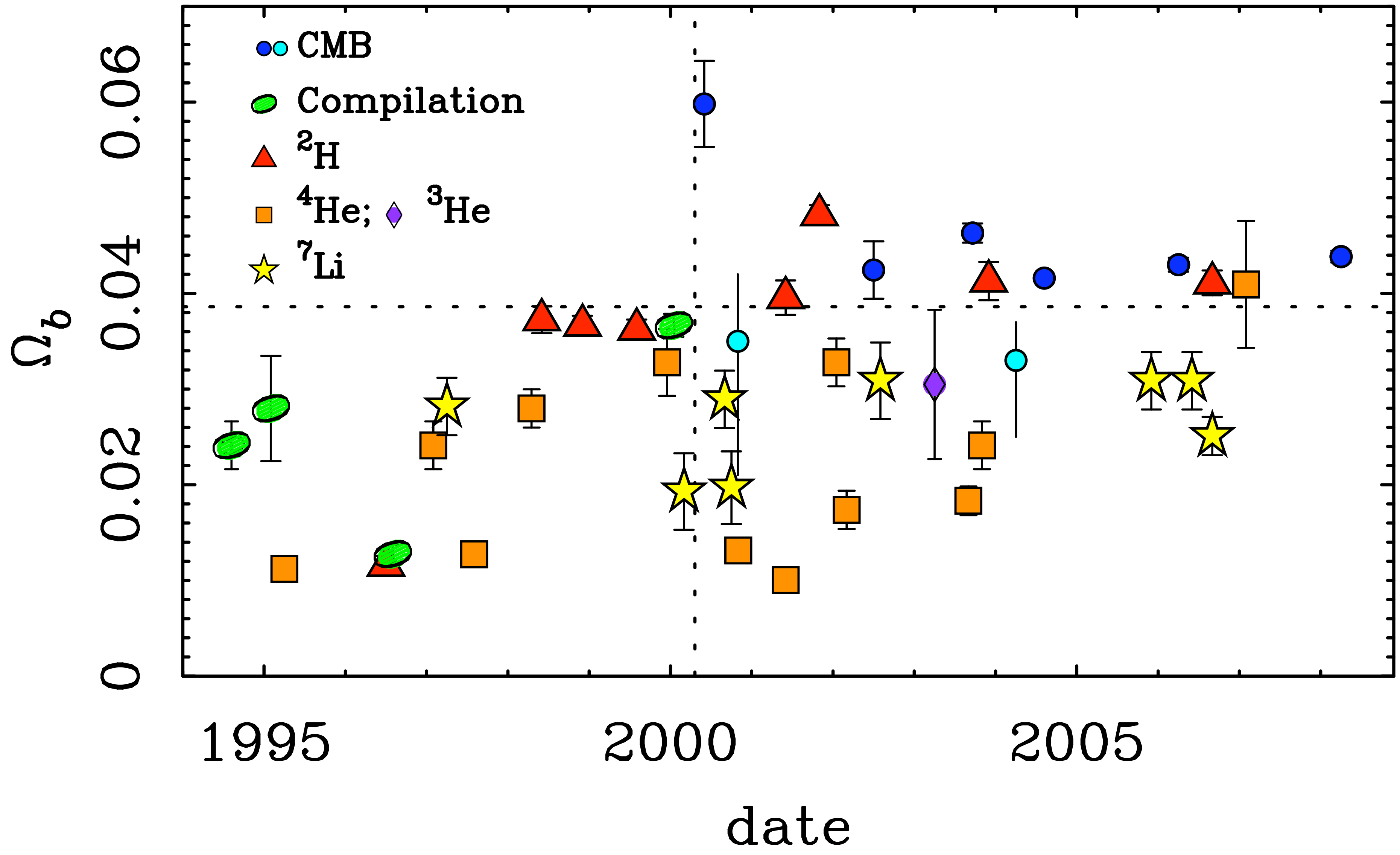


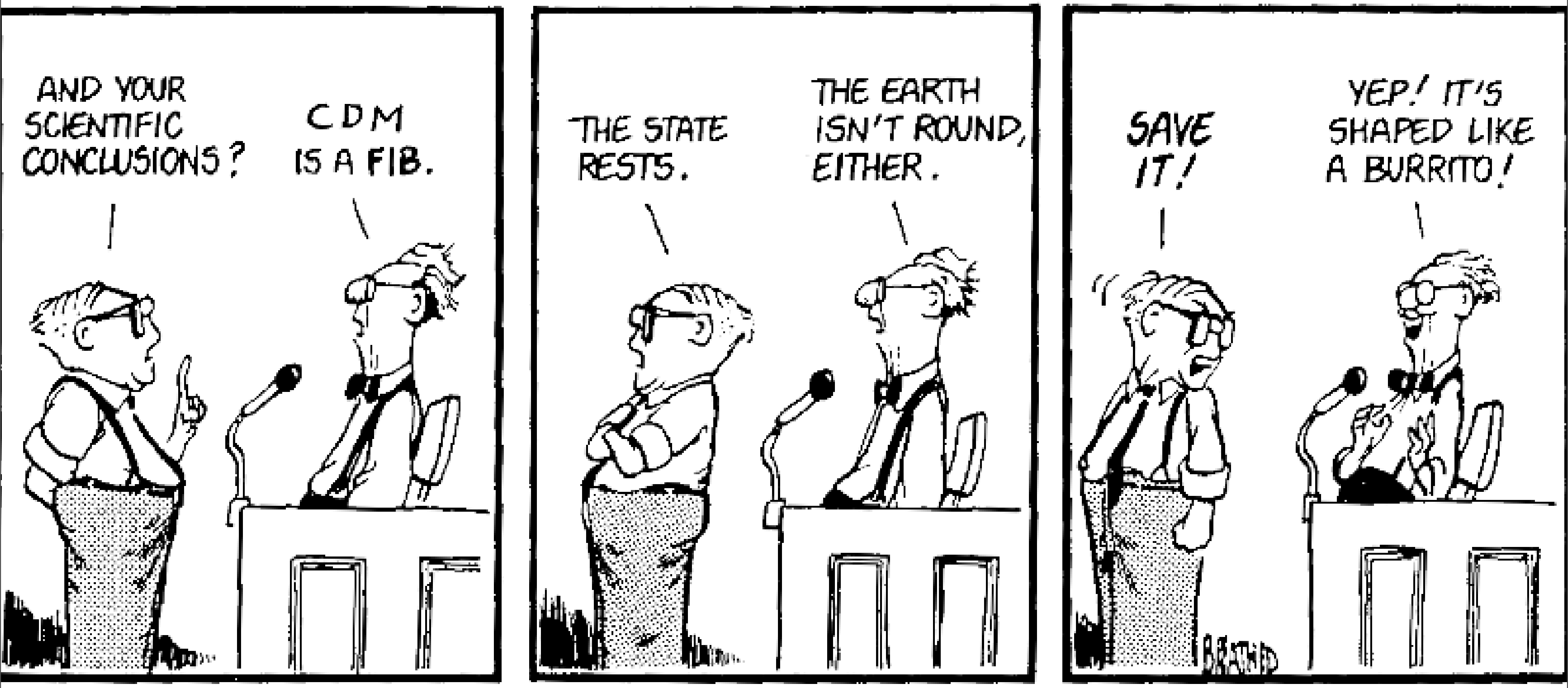
Depends on baryon density



Driving term from TeVeS? (Ferrara & Skordis 2005)

Big Bang Nucleosynthesis




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!