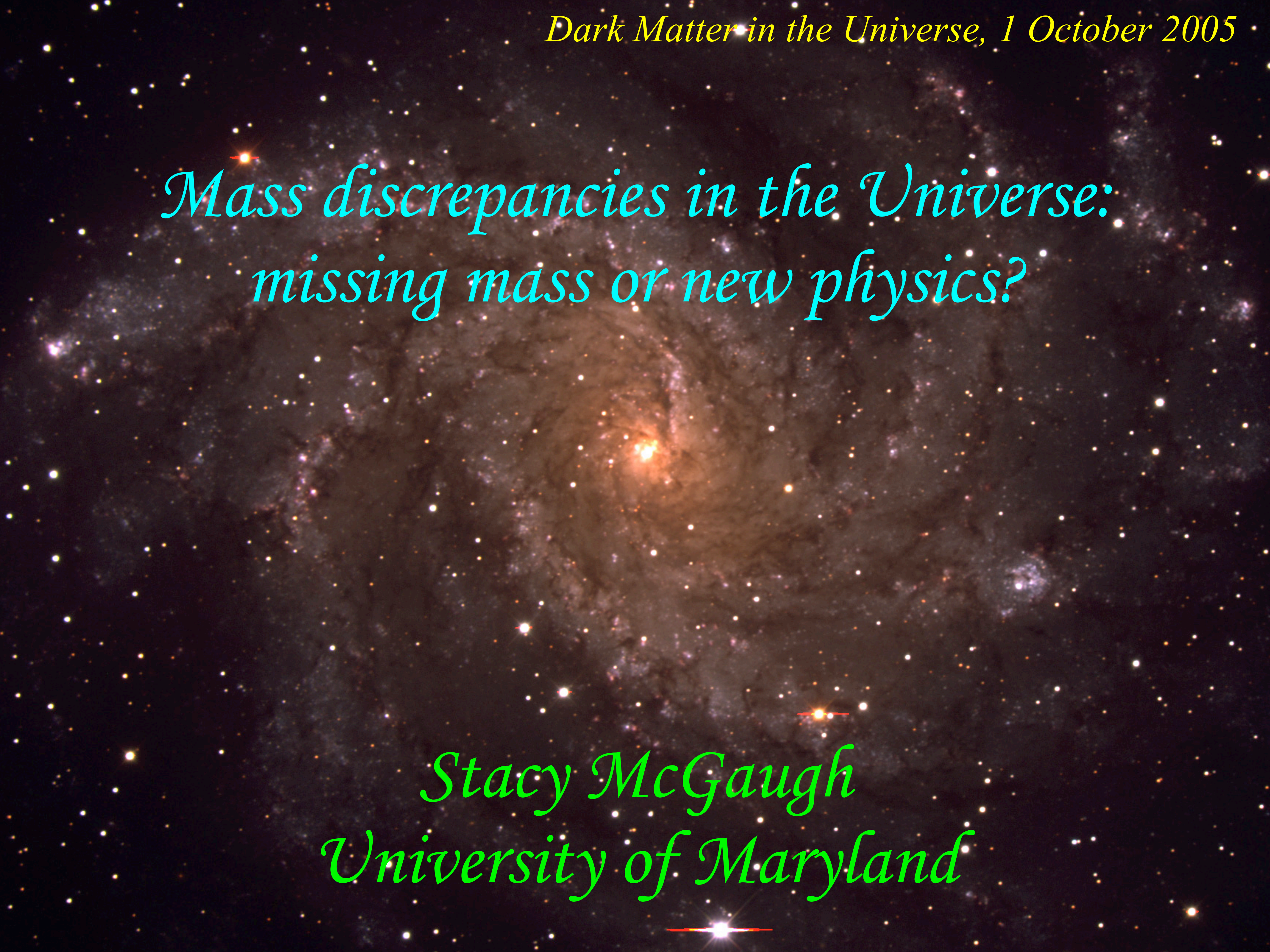
Dark Matter in the Universe, 1 October 2005

Mass discrepancies in the Universe: missing mass or new physics?

Stacy McGaugh
University of Maryland



Ancient Cosmology: A Flat Earth

Here there be dragons!

d Map of Hecataeus of Miletus (c. 500 BC)


...full of galaxies!

The modern idea for the origin of this expanding universe is called the

Three Pillars of the

BIG BANG

- Expanding Universe
- Primordial Nucleosynthesis

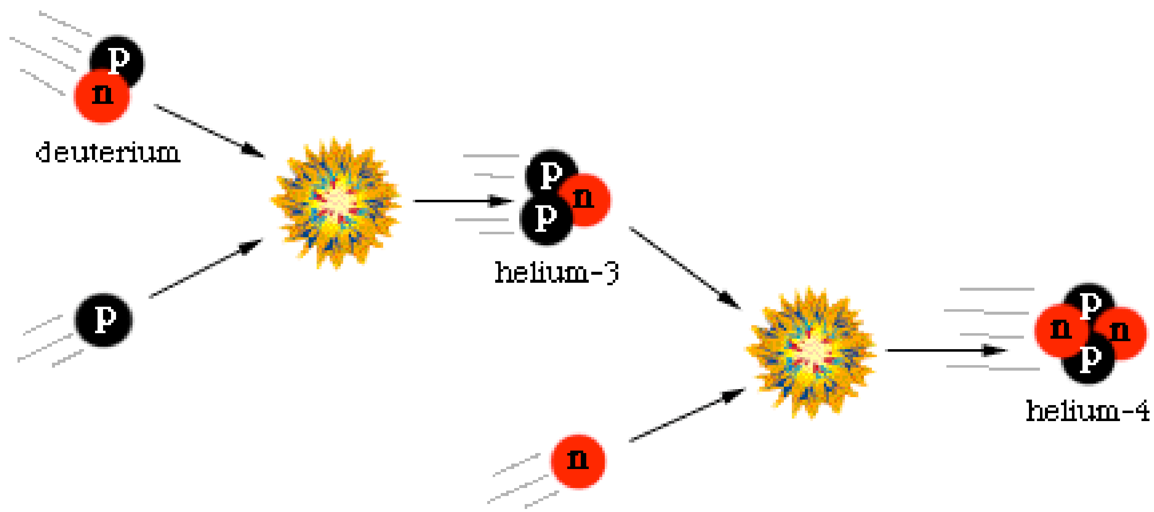
  Origin of the Light Elements (H, He, Li)
- Relic Radiation Field

  The Cosmic Microwave Background

Primordial Nucleosynthesis:

Gamow

When the universe is just a few minutes old, the Temperature and Density are just right for it to be one Big Nuclear Furnace:

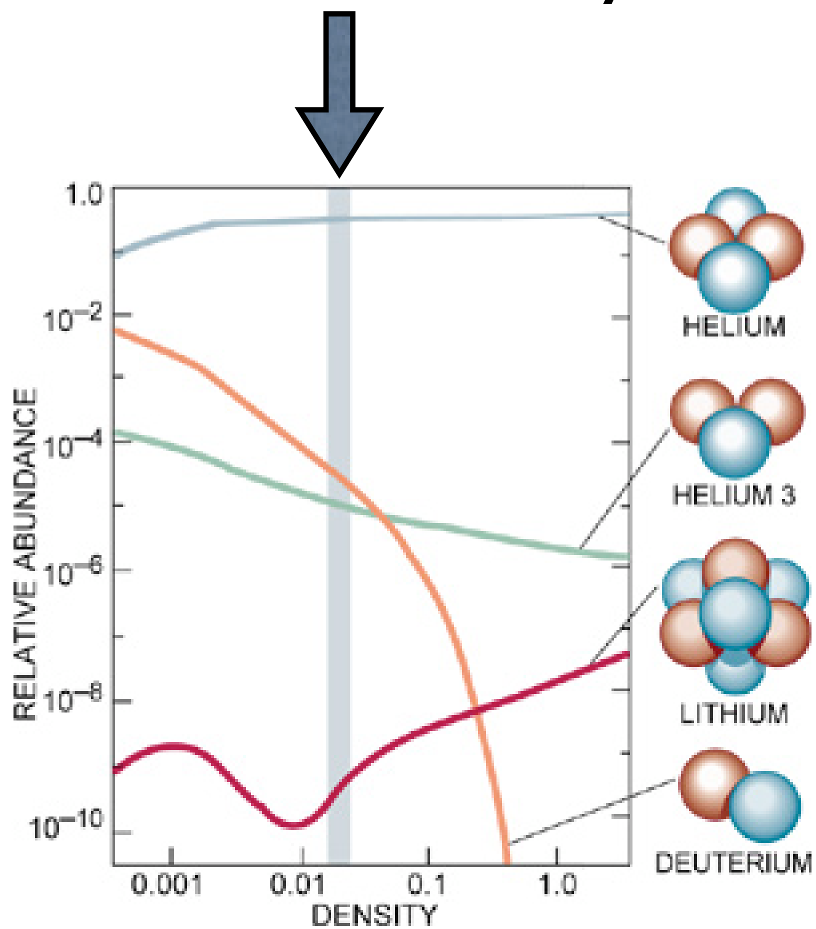


The light elements
Hydrogen, Helium, and Lithium
are made at this time.

The amount of each element to emerge from the big bang depends on the amount of raw material (protons + neutrons = "baryons")

Measured abundances point to a modest amount of "normal" baryonic matter

$$\Omega_b \approx 0.04$$



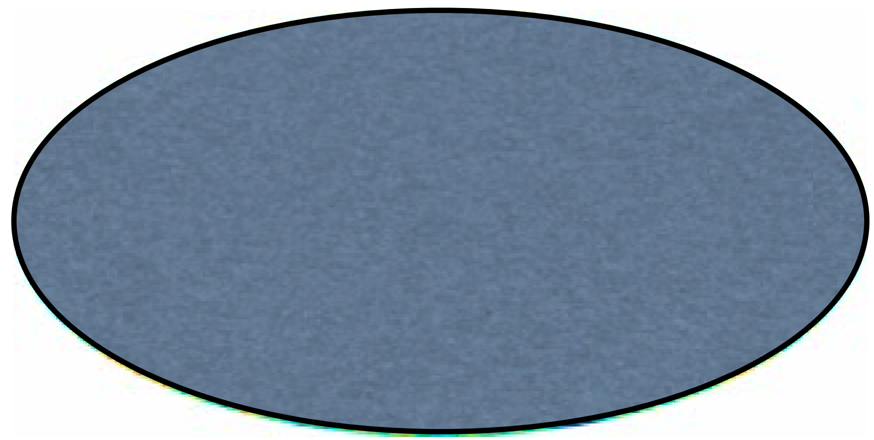
<u>Relic Radiation Field:</u>

The residual heat of the Big Bang should leave an echo - a relic glow of the cosmic fireball.

This was discovered in 1963; now called the Cosmic Microwave Background

Wilson Penzias

Nobel Prize



The universe has cooled off - it is now just 2.7 degrees above absolute zero.

Baby picture of the Universe (only 180,000 years old)

- The Expanding Universe
- Primordial Nucleosynthesis
- a Relic Radiation Field

all fit beautifully with the idea of a
Hot Big Bang which makes sense in terms of
Einstein's theory of General Relativity.

Just need to know two numbers...

$$H_0 \ \& \ \Omega_m$$

and we know everything.

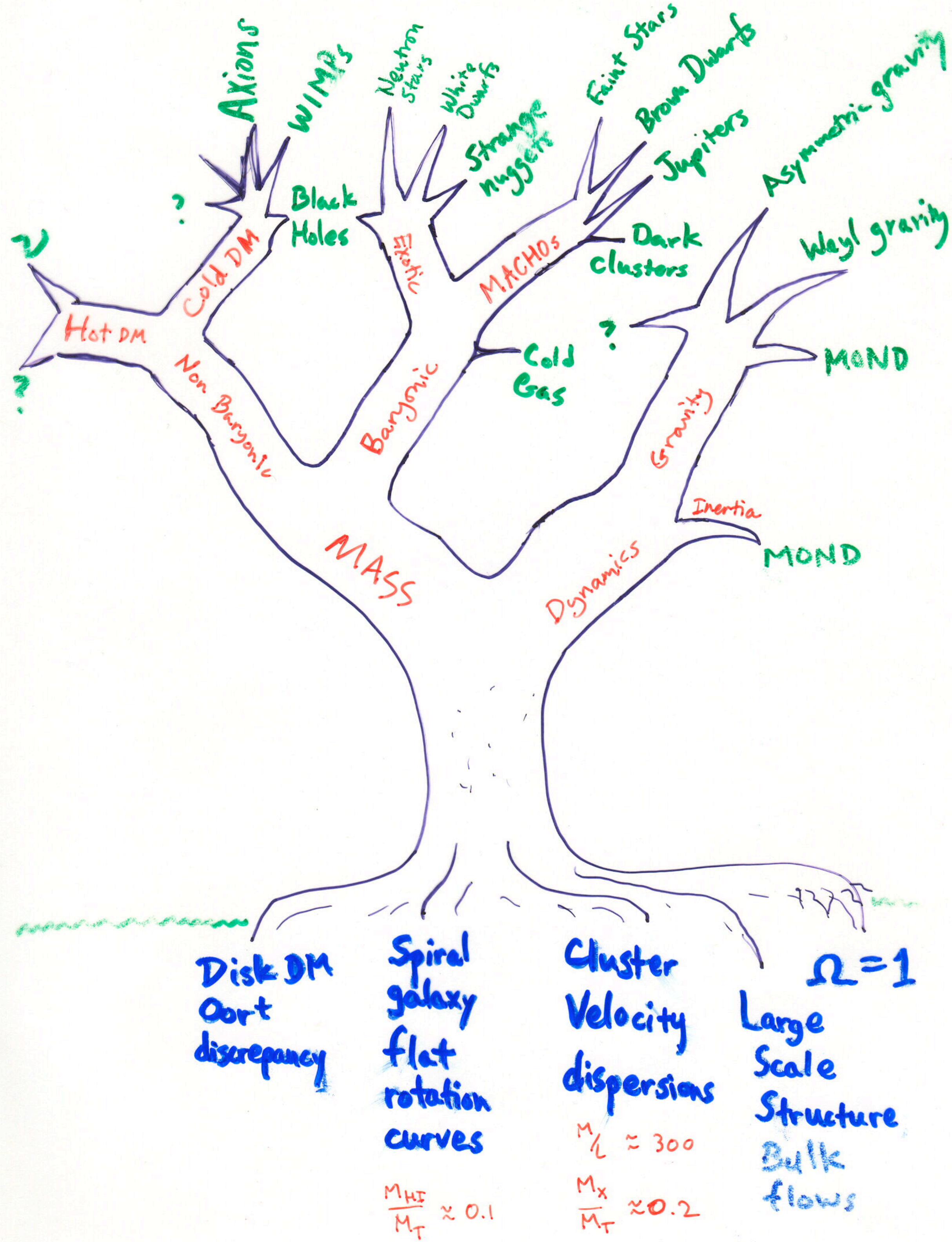
How many tooth fairies should a theory be allowed?

But there is more:

- Dark Matter
- Dark Energy

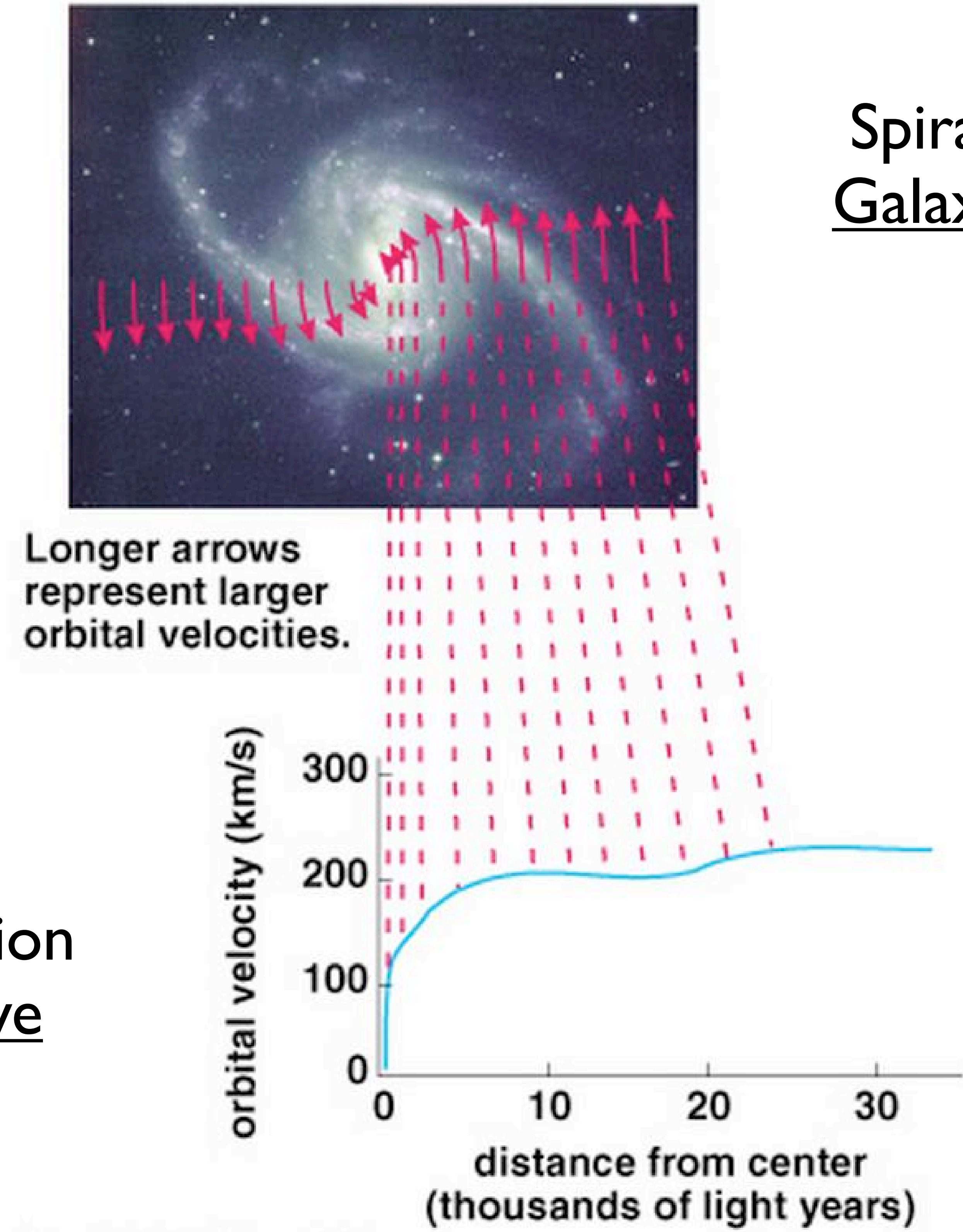
so maybe we need a few more numbers:

$$\Omega_b \ \Omega_\Lambda \ \sigma_8 \ n$$

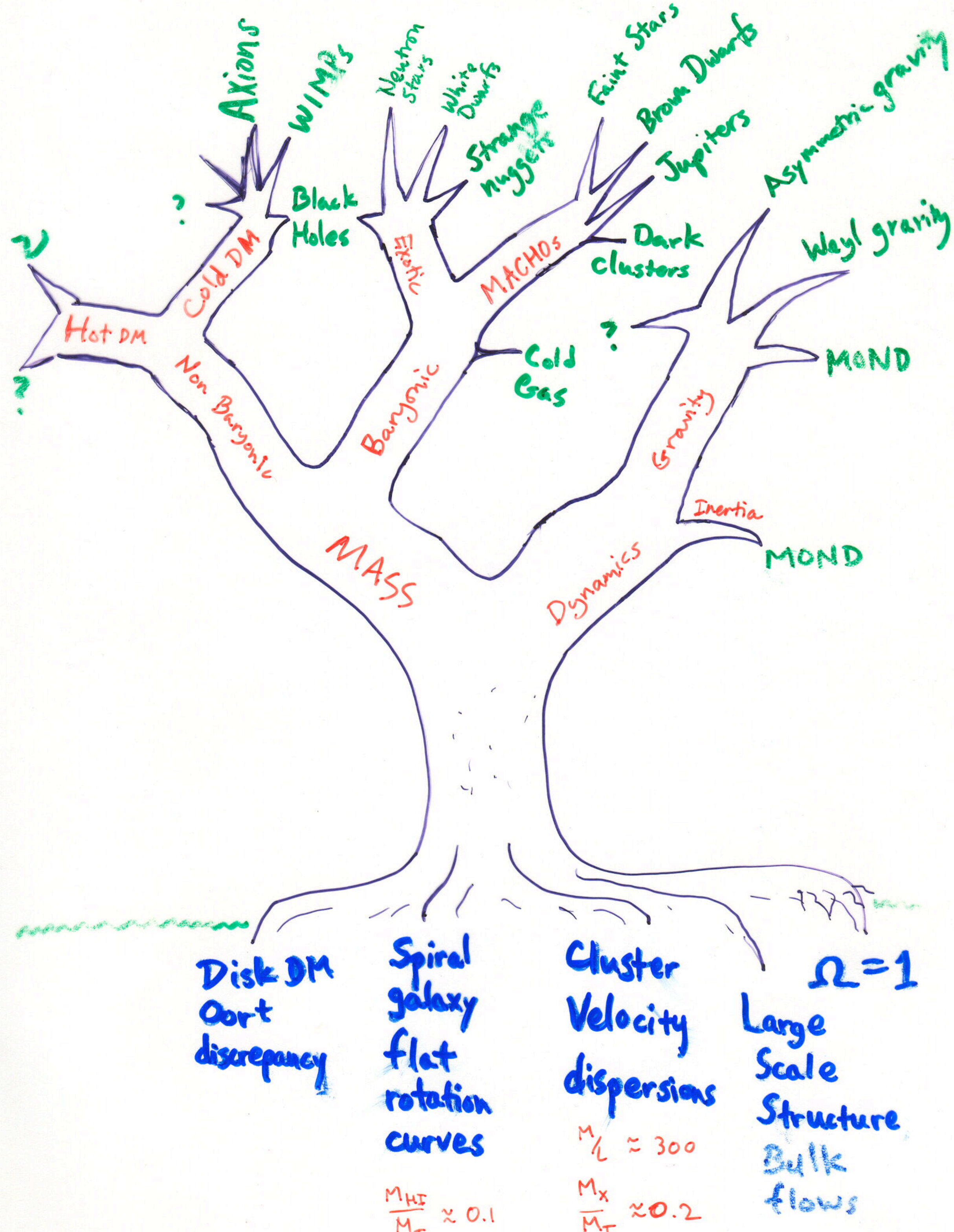


Axions
WIMPs
Neutron Stars
White Dwarfs
Faint Stars
Brown Dwarfs
Jupiters
Asymmetric gravity
Strange nuggets
Black Holes
Dark Clusters
Weyl gravity
Cold DM
Exotic
MACHOs
Hot DM
Cold Gas
MOND
Non Baryonic
Baryonic
Gravity
Inertia
MOND
MASS
Dynamics
Disk DM
Oort discrepancy
Spiral galaxy flat rotation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

Spiral Galaxy



Rotation Curve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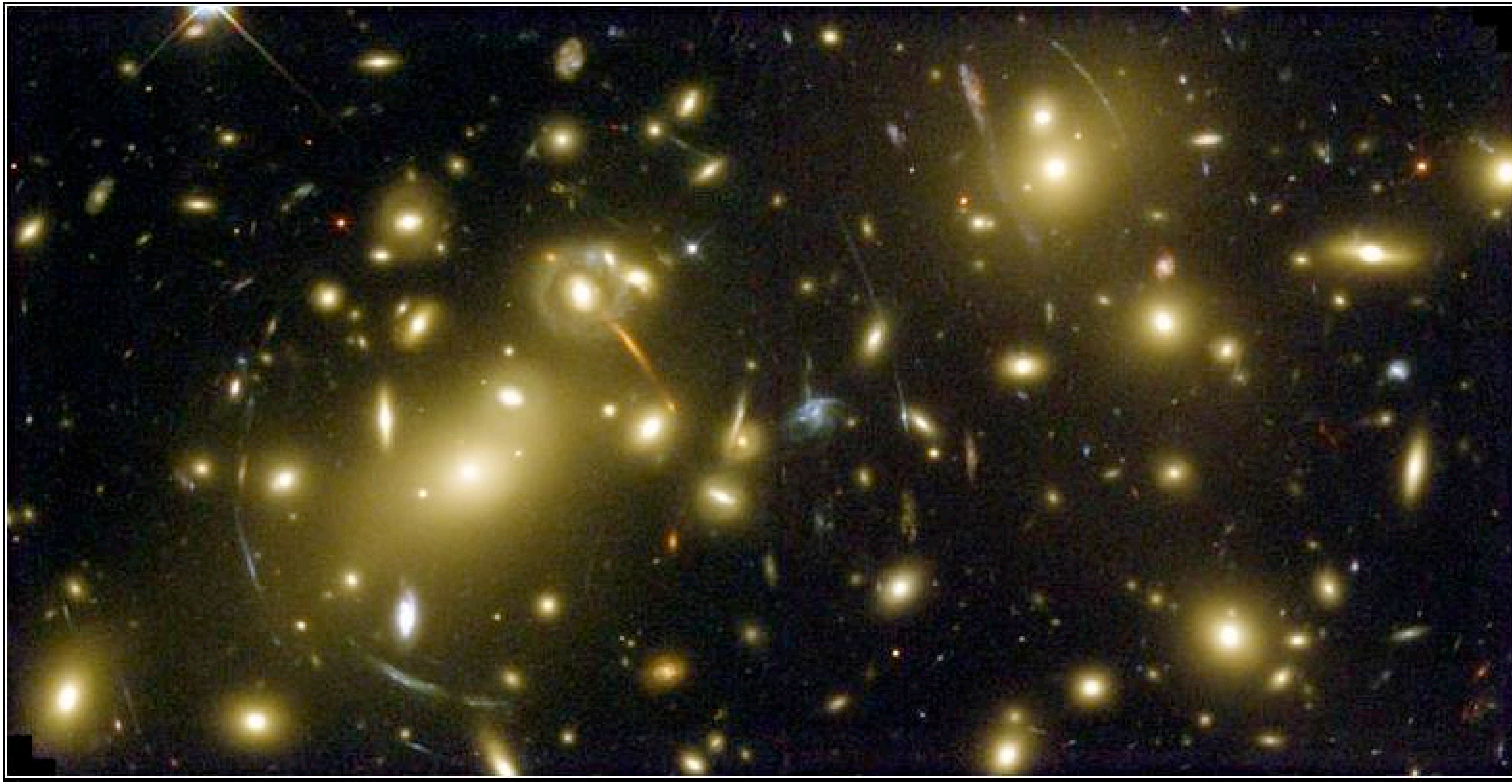
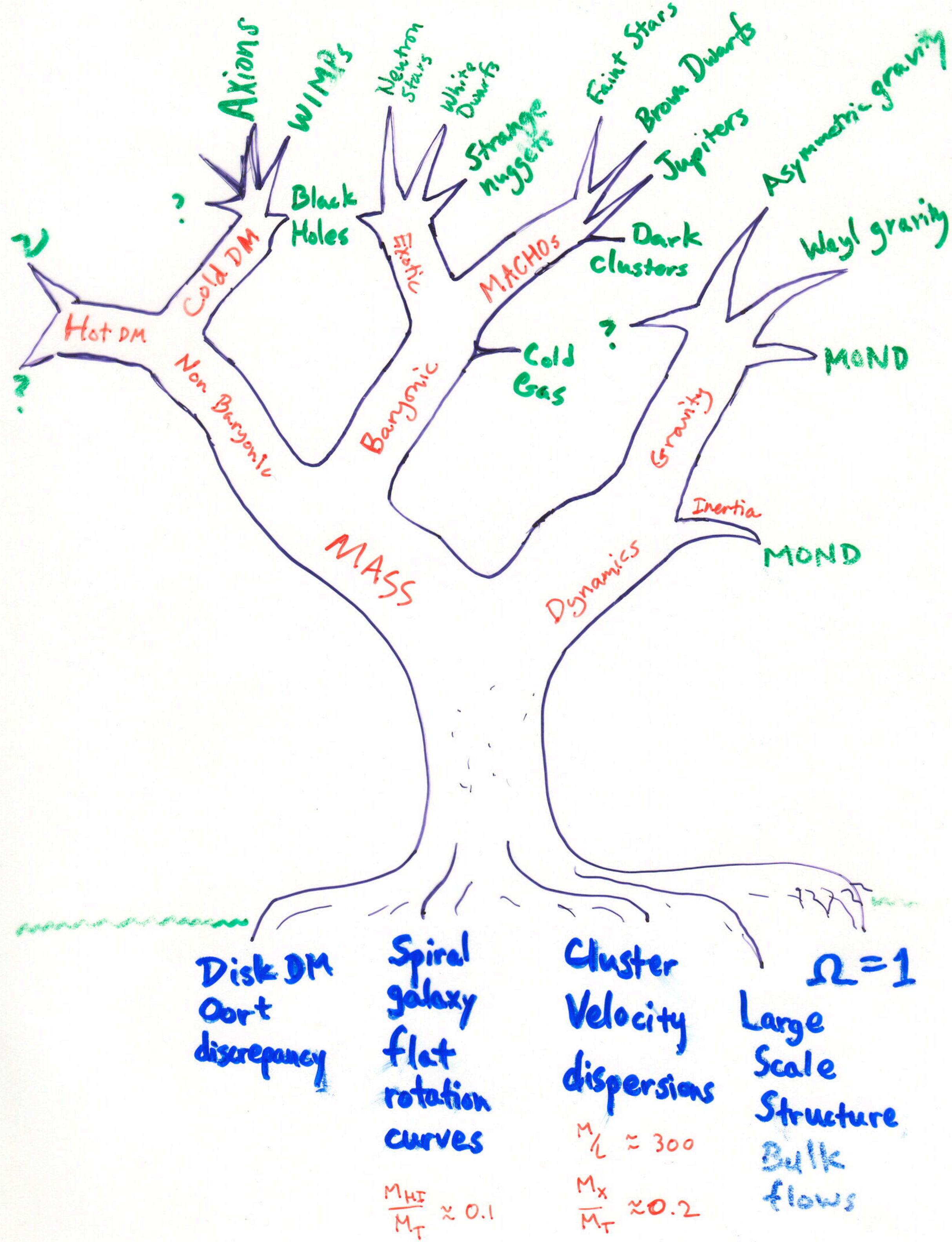
Galaxy Cluster





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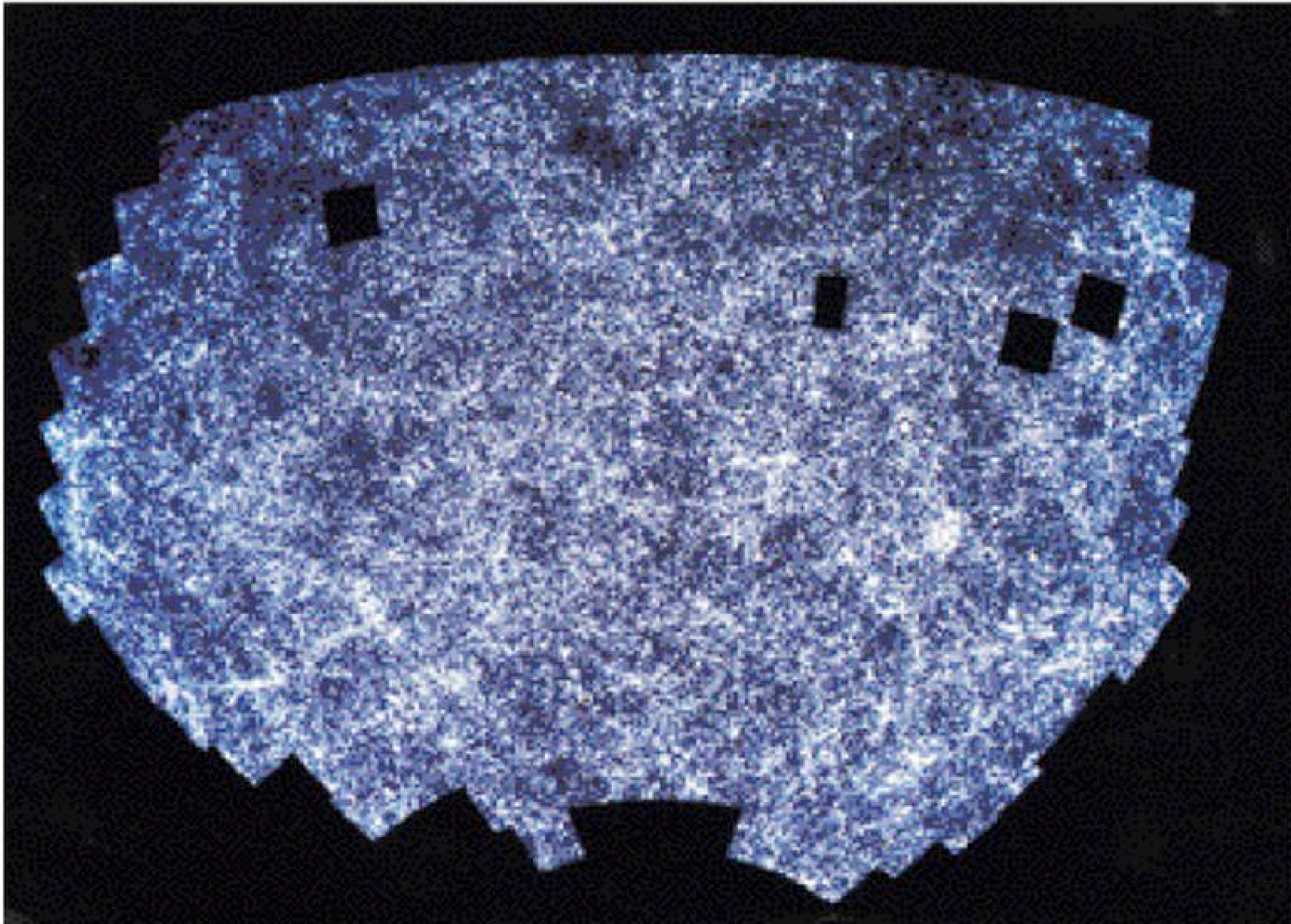
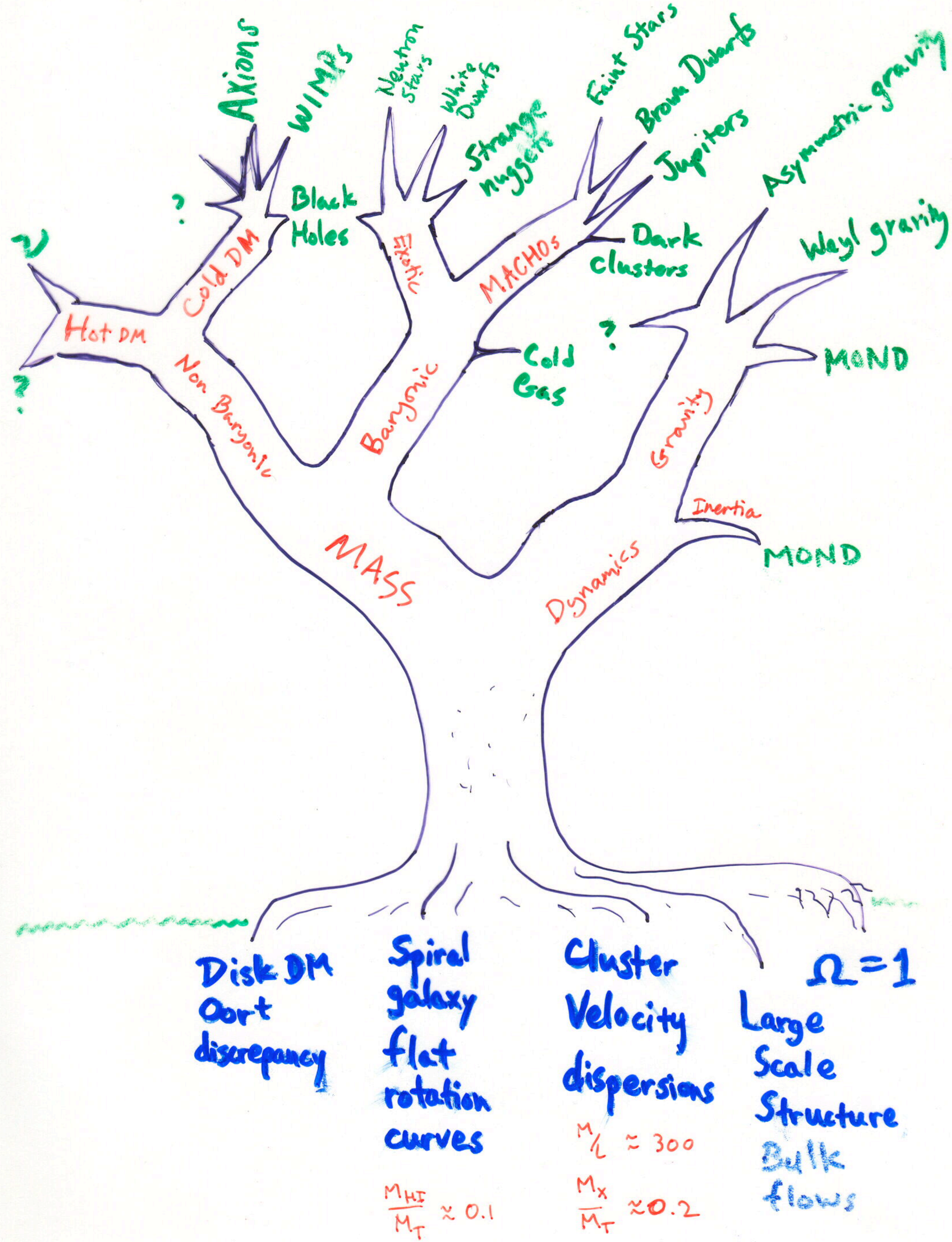
Large Scale Structure





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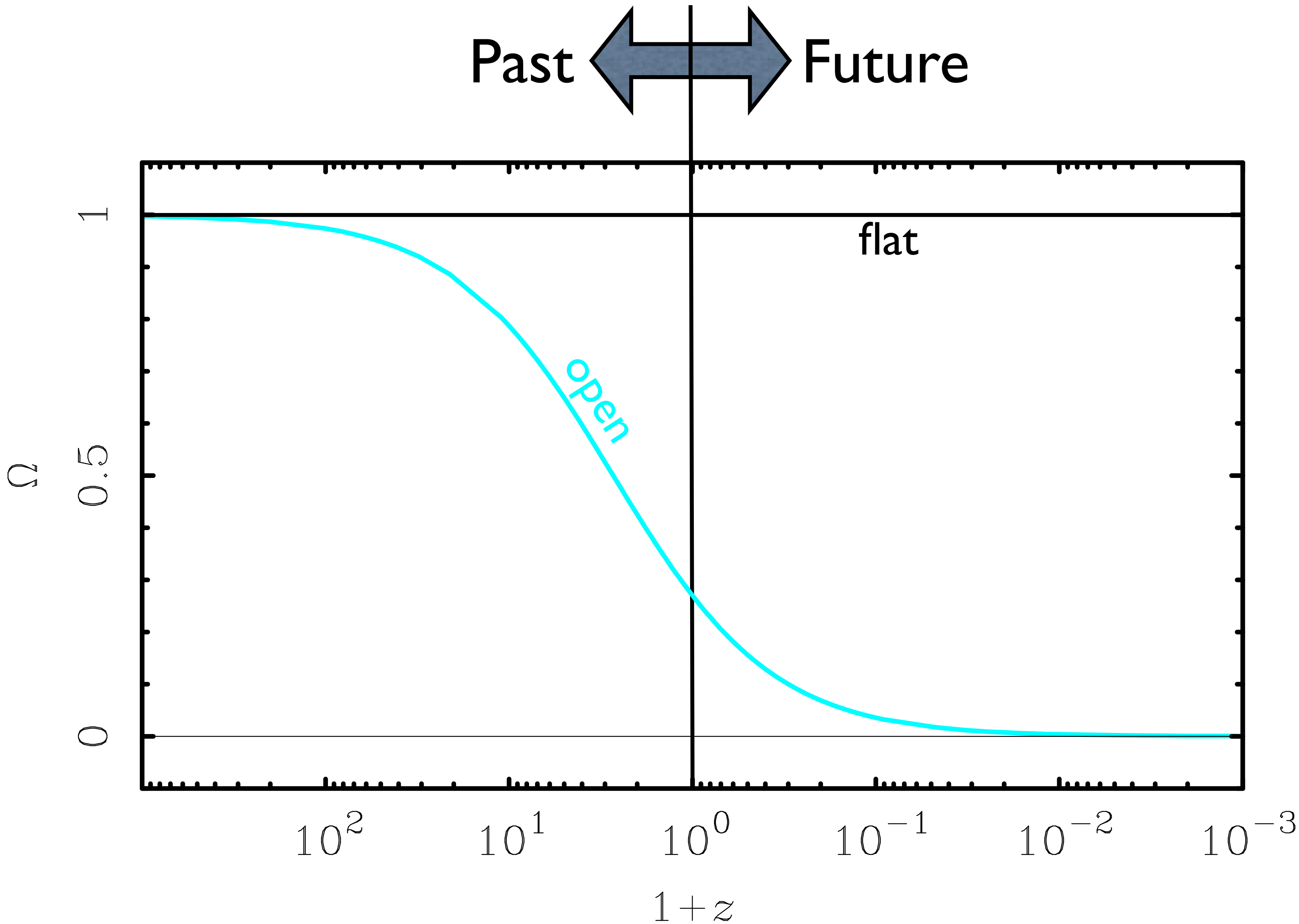
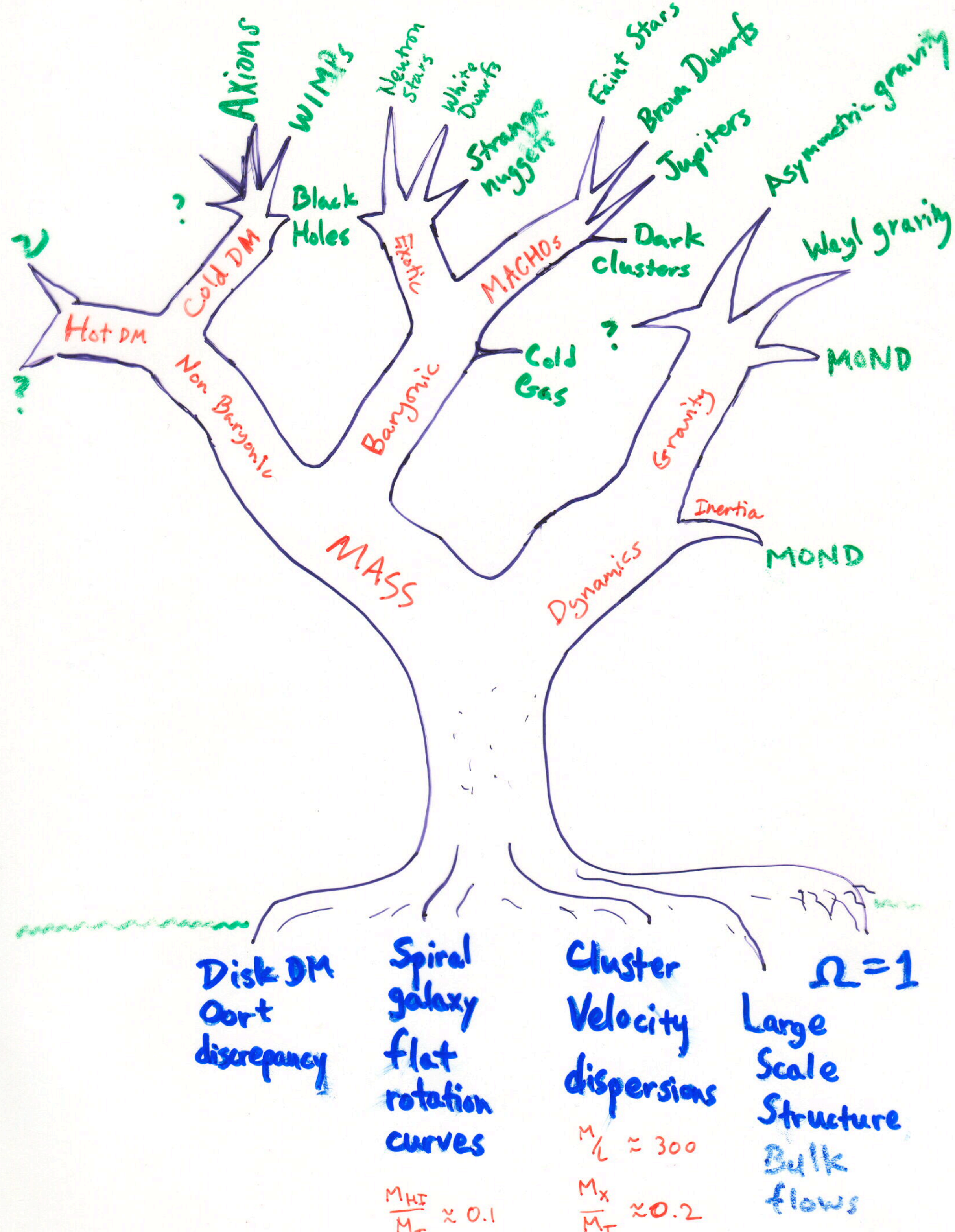


Coincidence Problem solved iff $\Omega_m = 1$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Large Scale Structure
Bulk flows

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 $\Omega_b \approx 0.04$

from Primordial Nucleosynthesis

Total mass density $\Omega_m \approx 0.25$

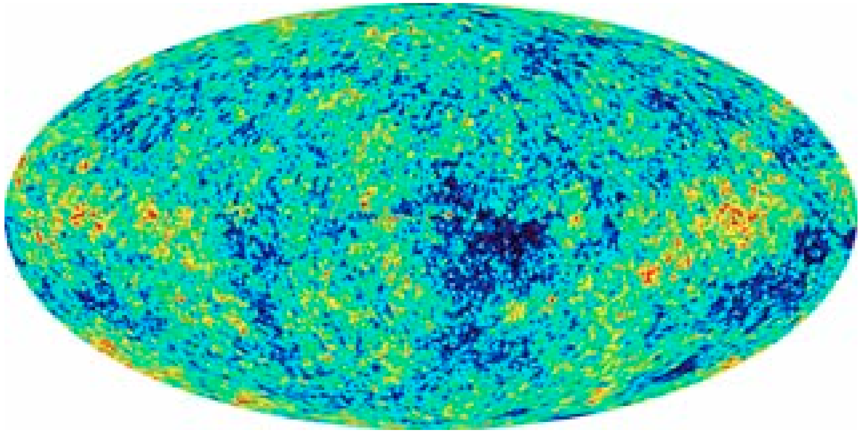
from gravity

gravitating mass > normal mass

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

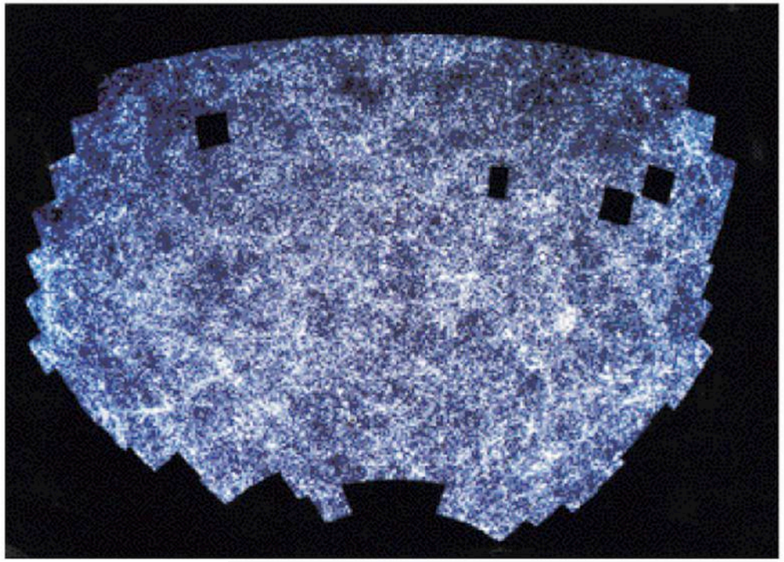
(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

t = 1.8 x 10^5 yr



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

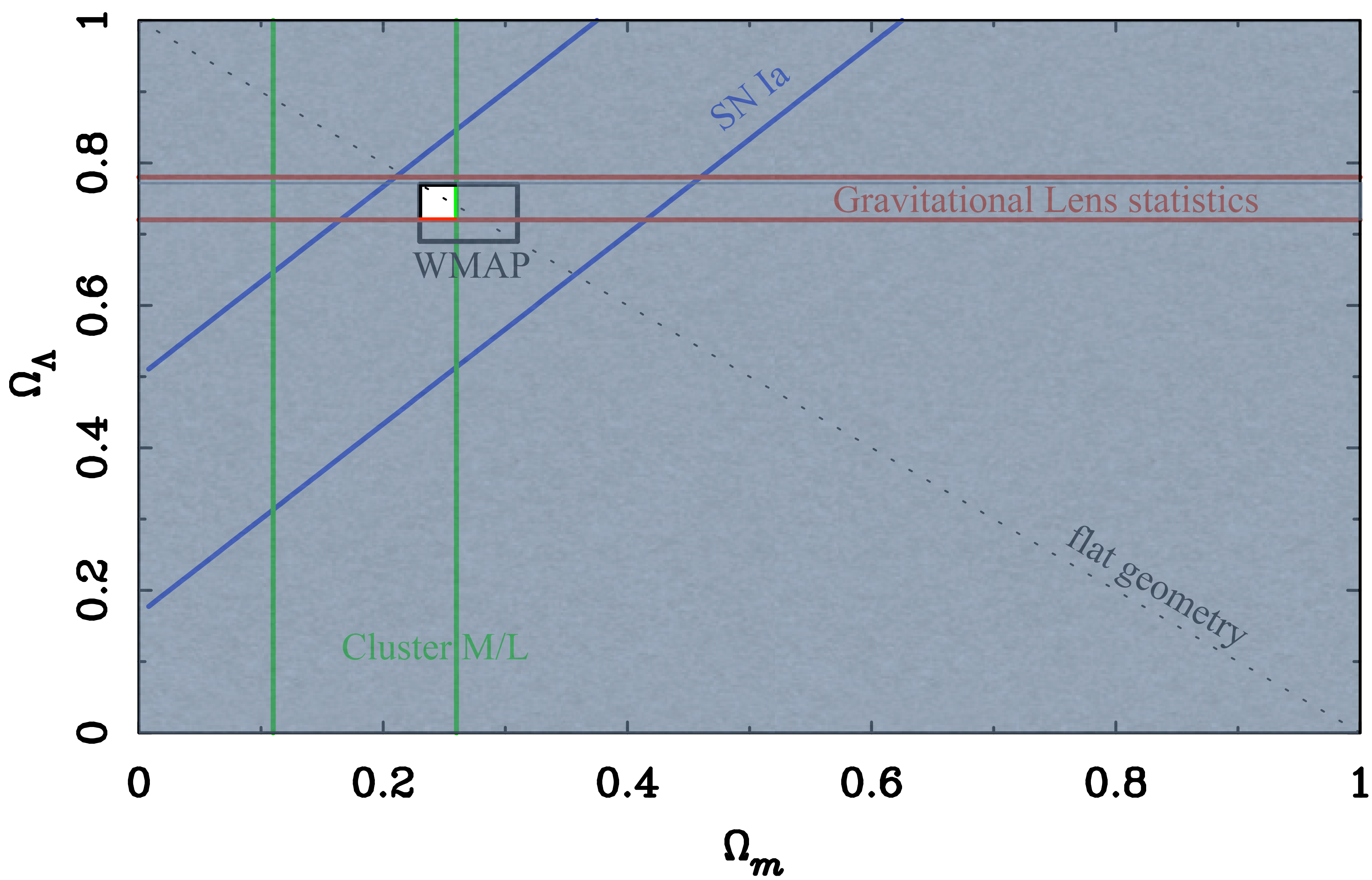
t = 1.4 x 10^{10} yr



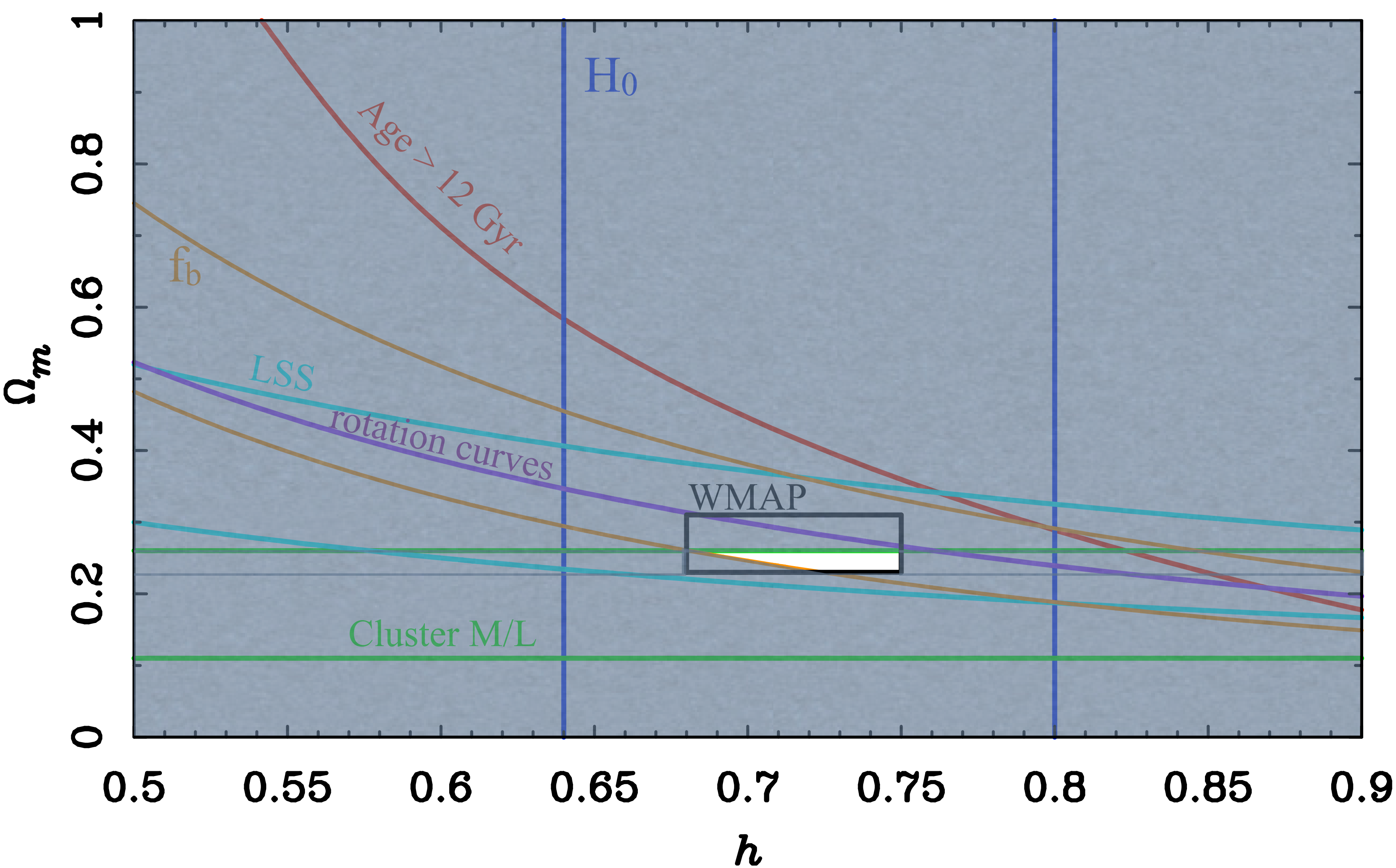
very lumpy: $\delta\rho/\rho \sim 1$

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

Cosmic parameters now constrained by multiple independent data sets



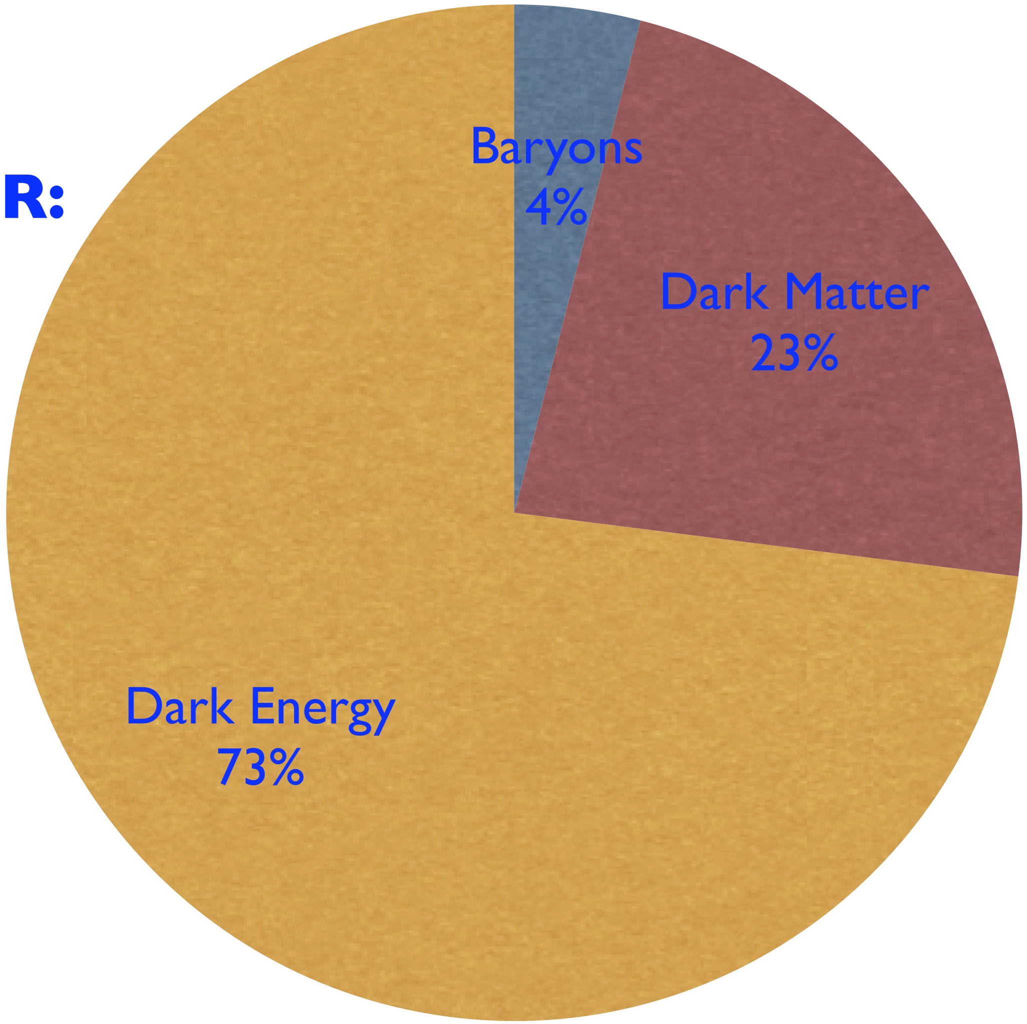
Cosmic parameters now constrained by multiple independent data sets



Is open window the right answer?
Or merely the least improbable?

Cosmological Mass-Energy Budget

THE ANSWER:



Hot Big Bang
+
Dark Energy
+
Dark Matter

is now called

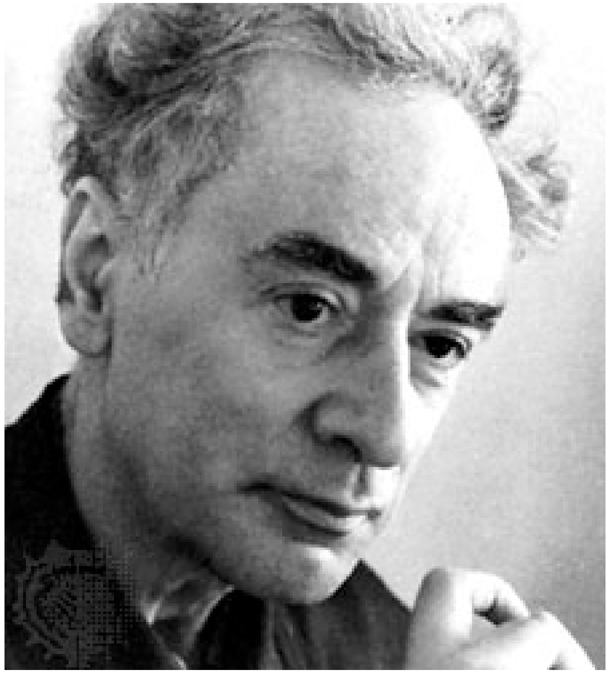
"ΛCDM"

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

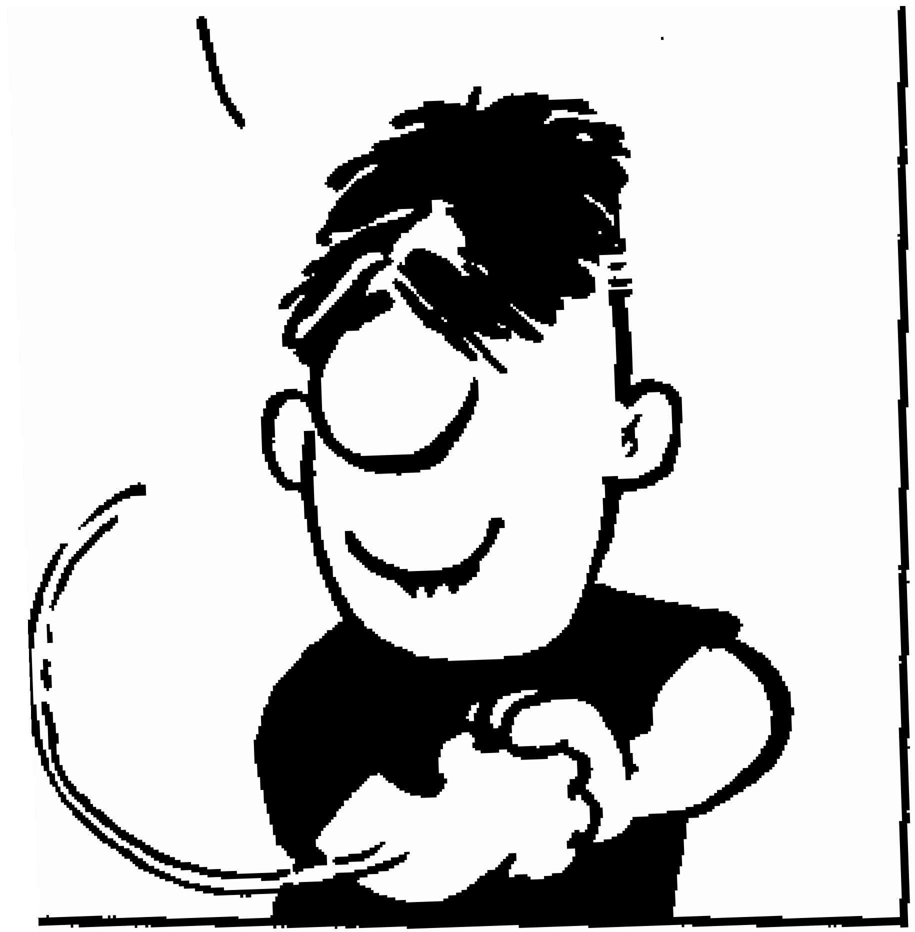
L. Krauss (2004)

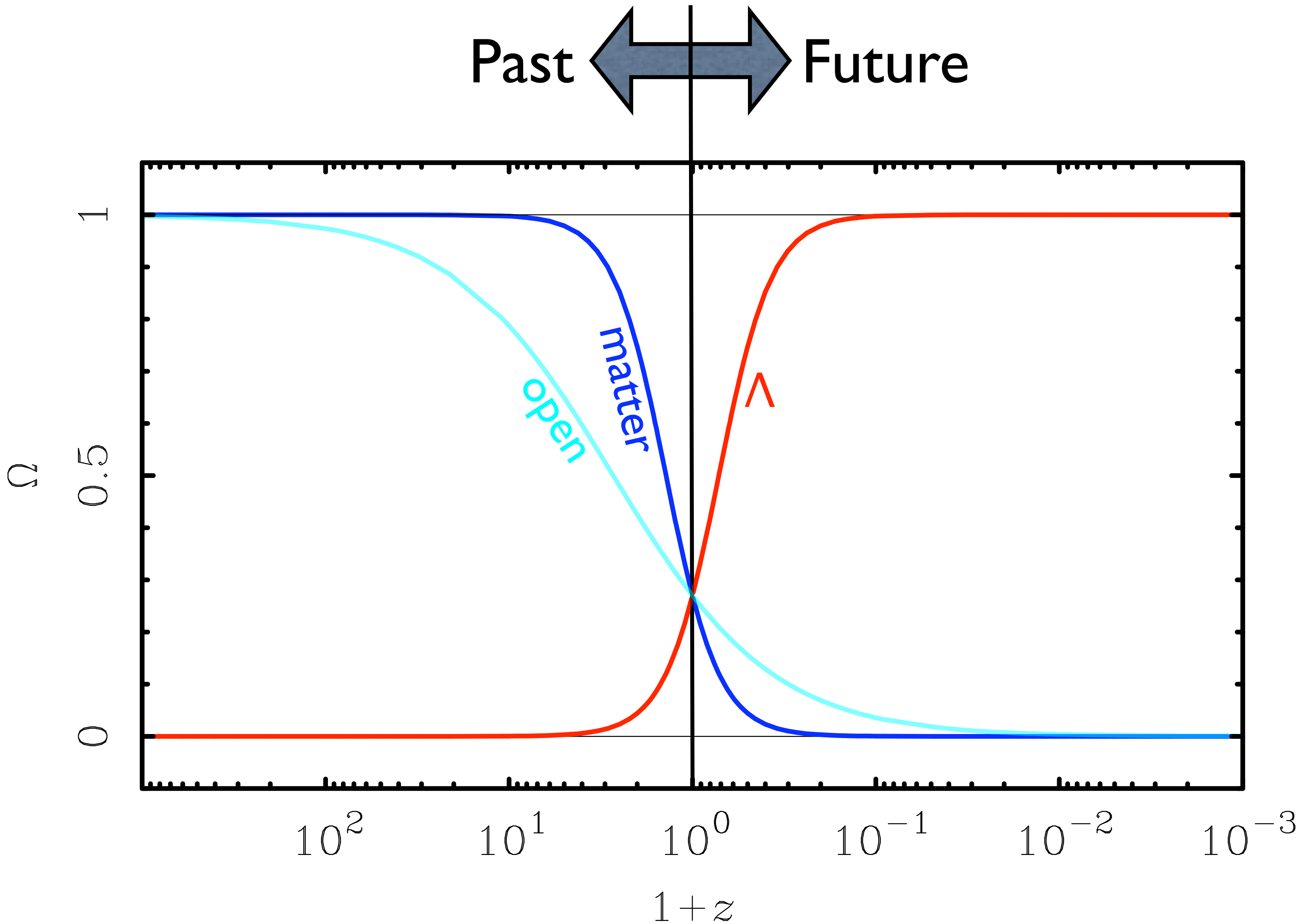
"The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.... Our future discoveries must be looked for in the sixth place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

- A. Michelson (1894)



You got a problem with ΛCDM?



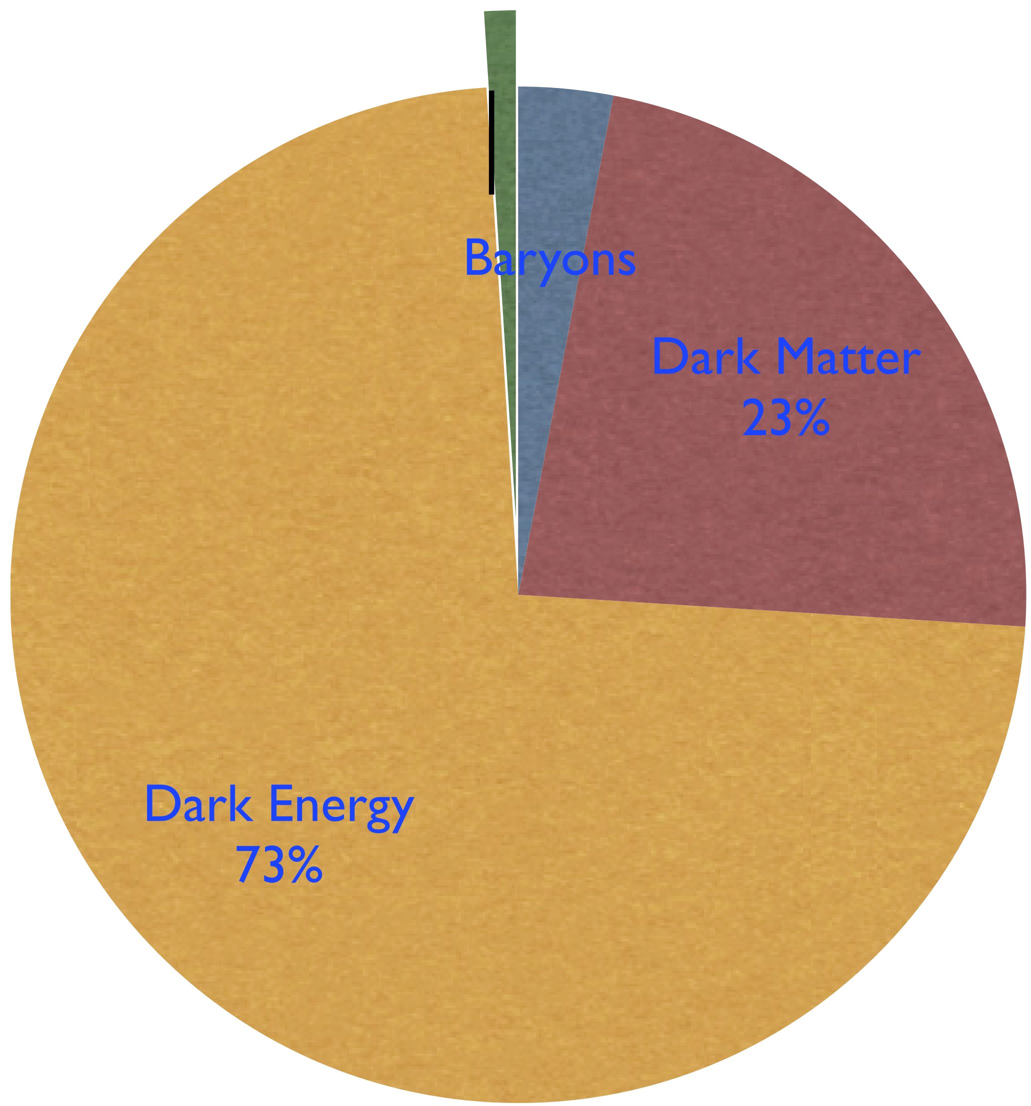


Coincidence Problem has gotten *worse*

Coincidence Problem

Anthropomorphic Arguments

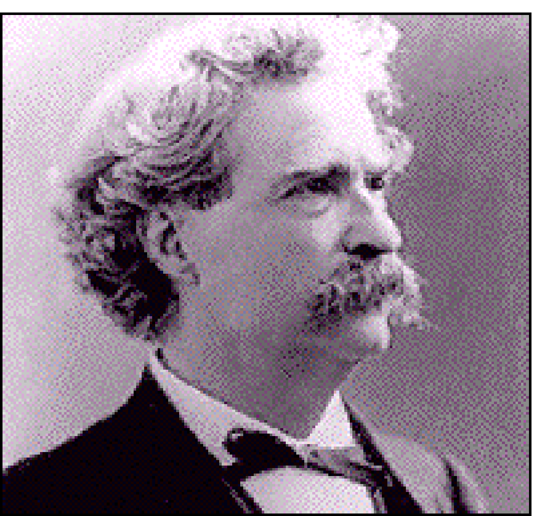
We have direct knowledge of < 1% of this stuff.



Do these the Dark components really exist?

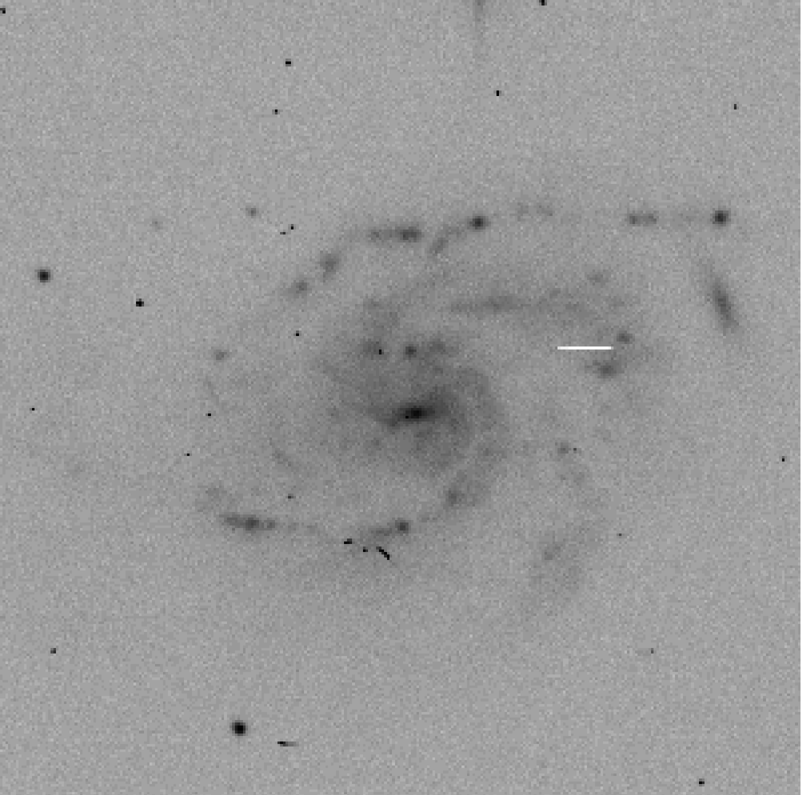
What gets us into trouble is not what we don't know.

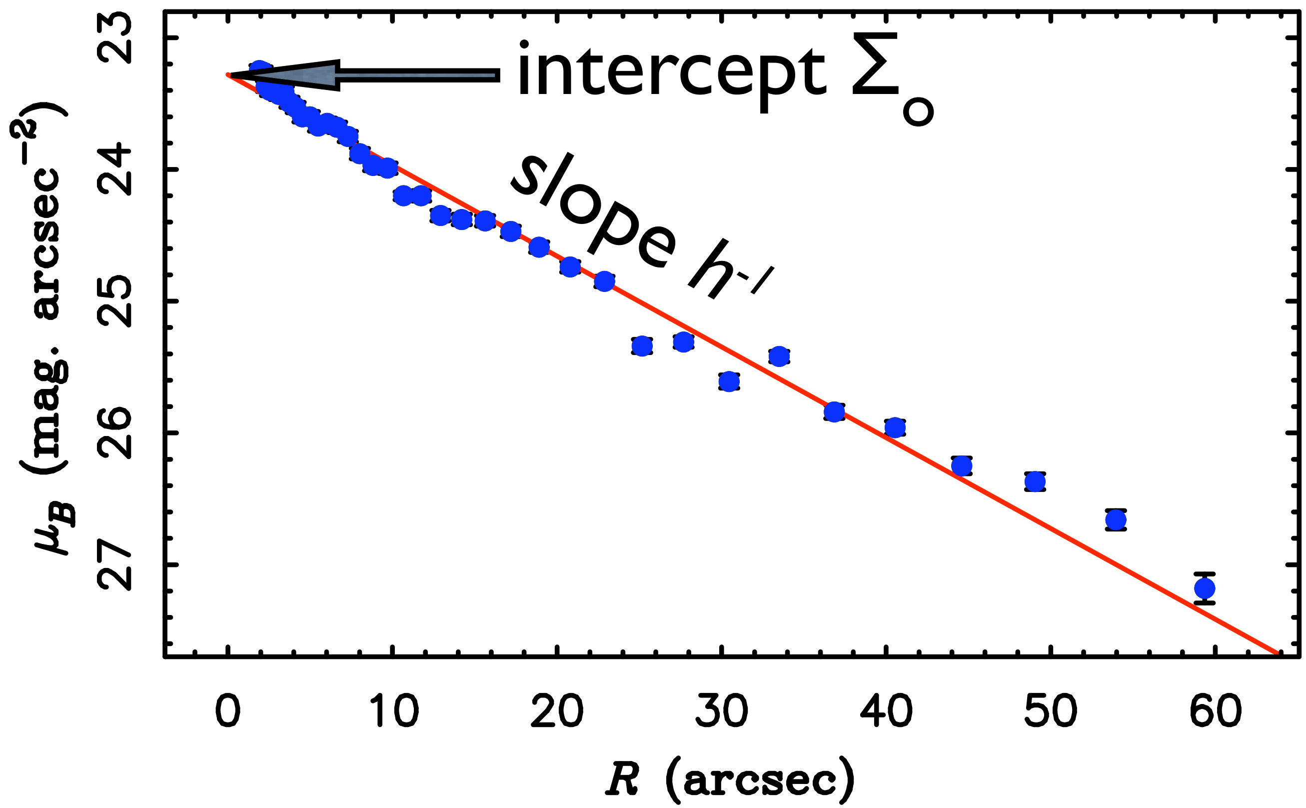
It's what we know for sure that just aint so.



- Mark Twain

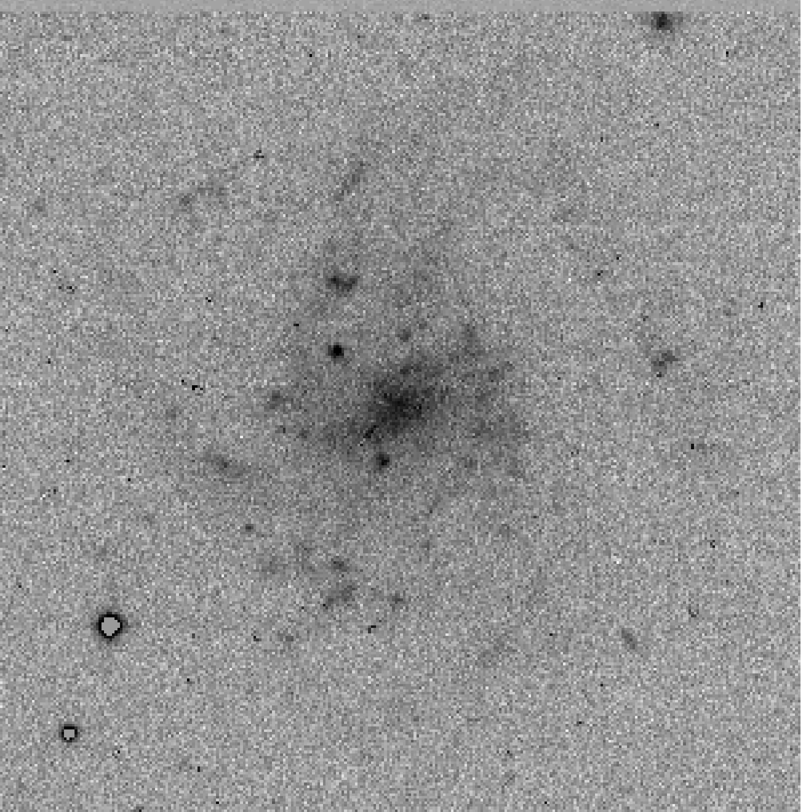
High Surface Brightness (HSB)



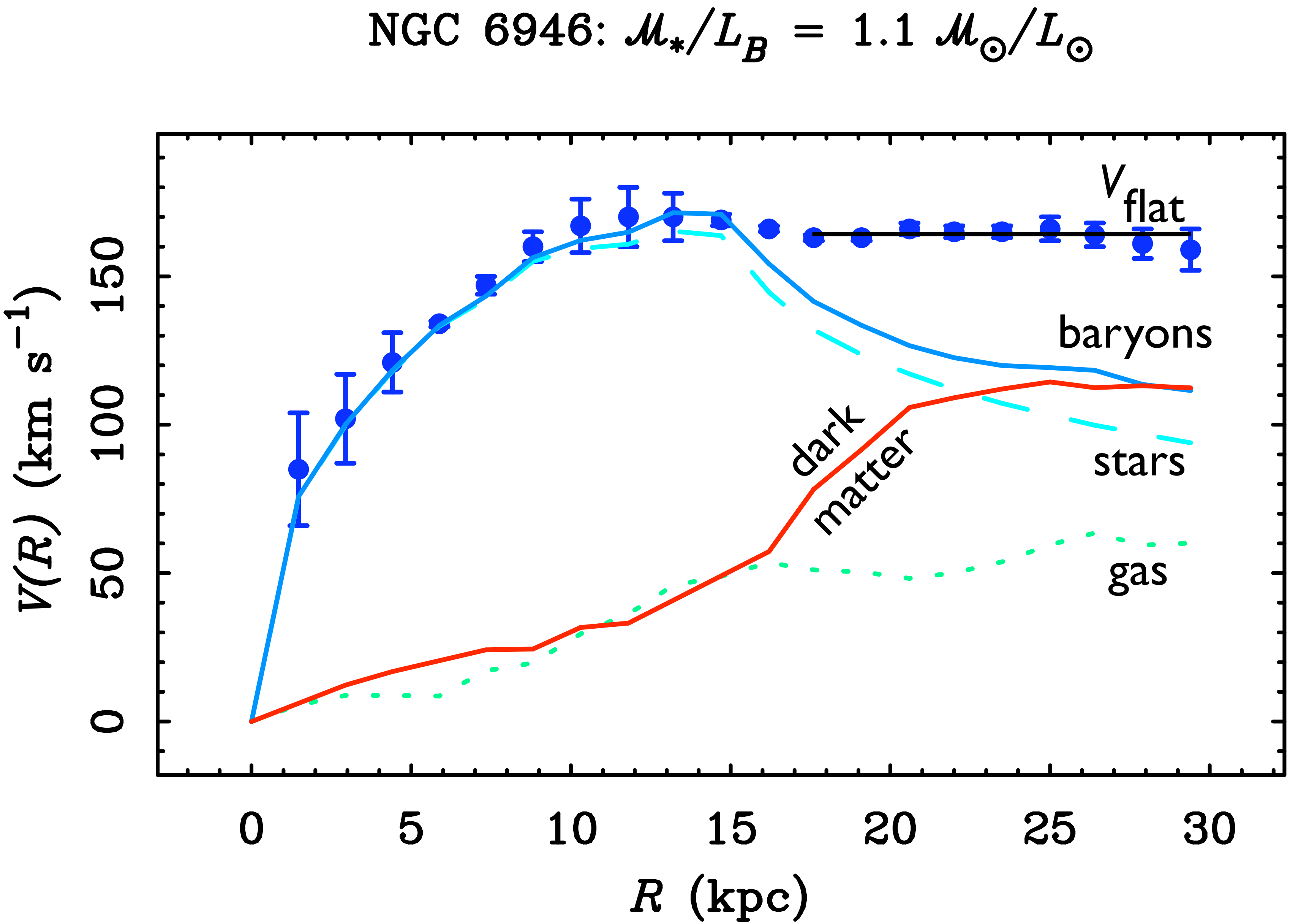


$$\Sigma(R) = \Sigma_o \, e^{-R/h}$$

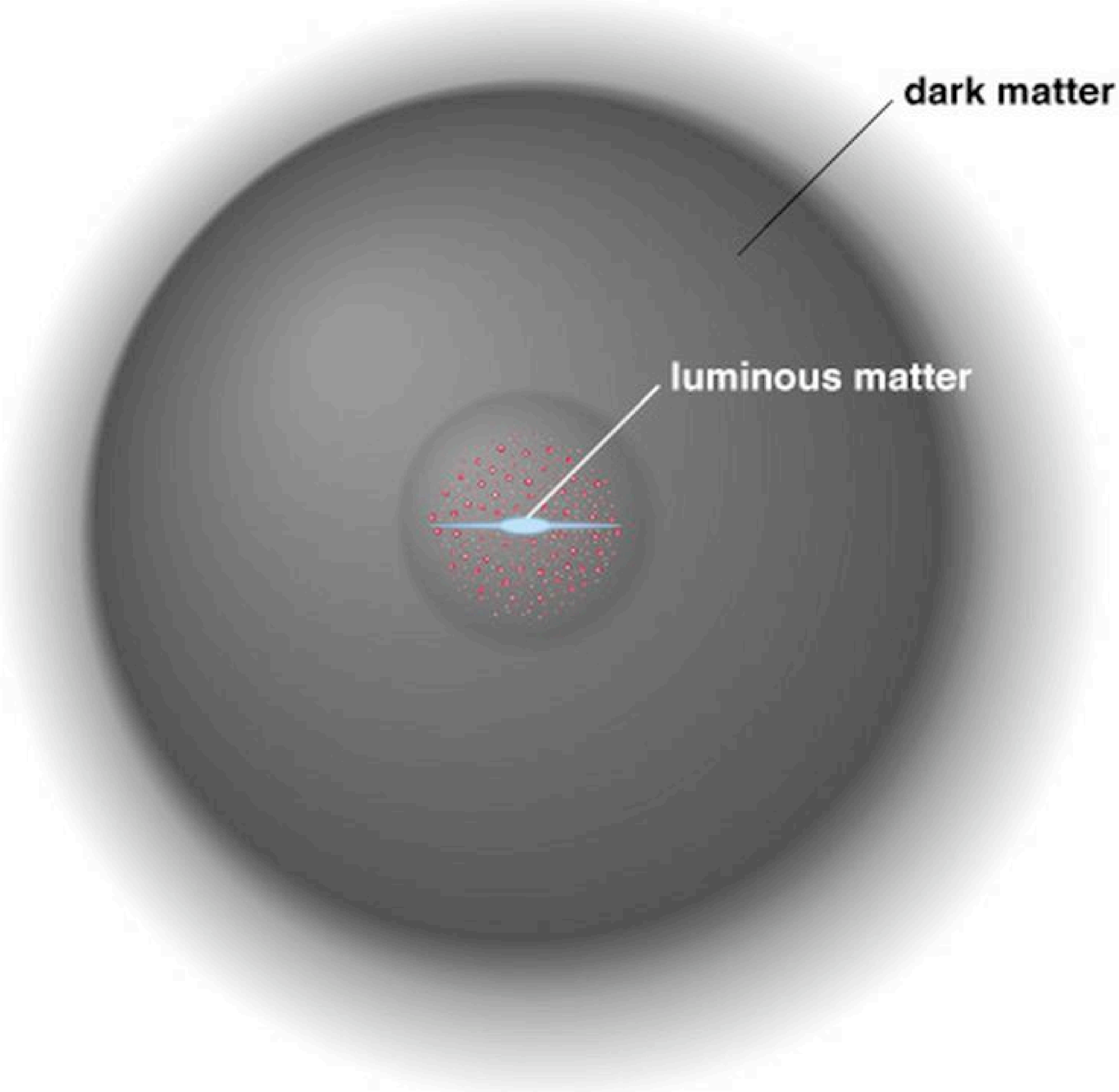
Azimuthally averaged light distribution typically exponential for spiral disks.



Low Surface Brightness (LSB)



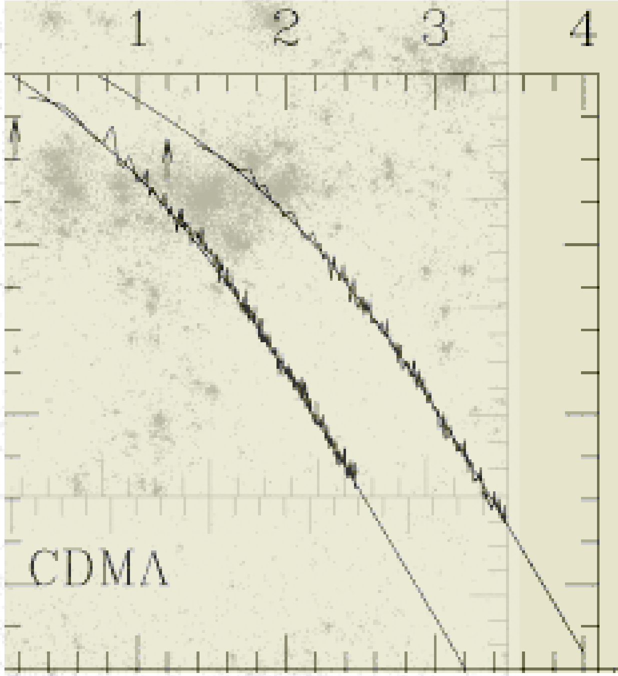
NGC 6946: $\mathcal{M}_*/L_B = 1.1\ \mathcal{M}_\odot/L_\odot$
V_{flat}
baryons
dark matter
stars
gas
0
50
100
150
$V(R)$ (km s^{-1})
0
5
10
15
20
25
30
R (kpc)


dark matter
luminous matter

Dark Matter Halos in Cosmology

Simulations of structure formation find a characteristic halo form (the "NFW halo"):

$$\rho(r) = \delta_c \rho_c / [(r/r_s)(1+r/r_s)^2]$$

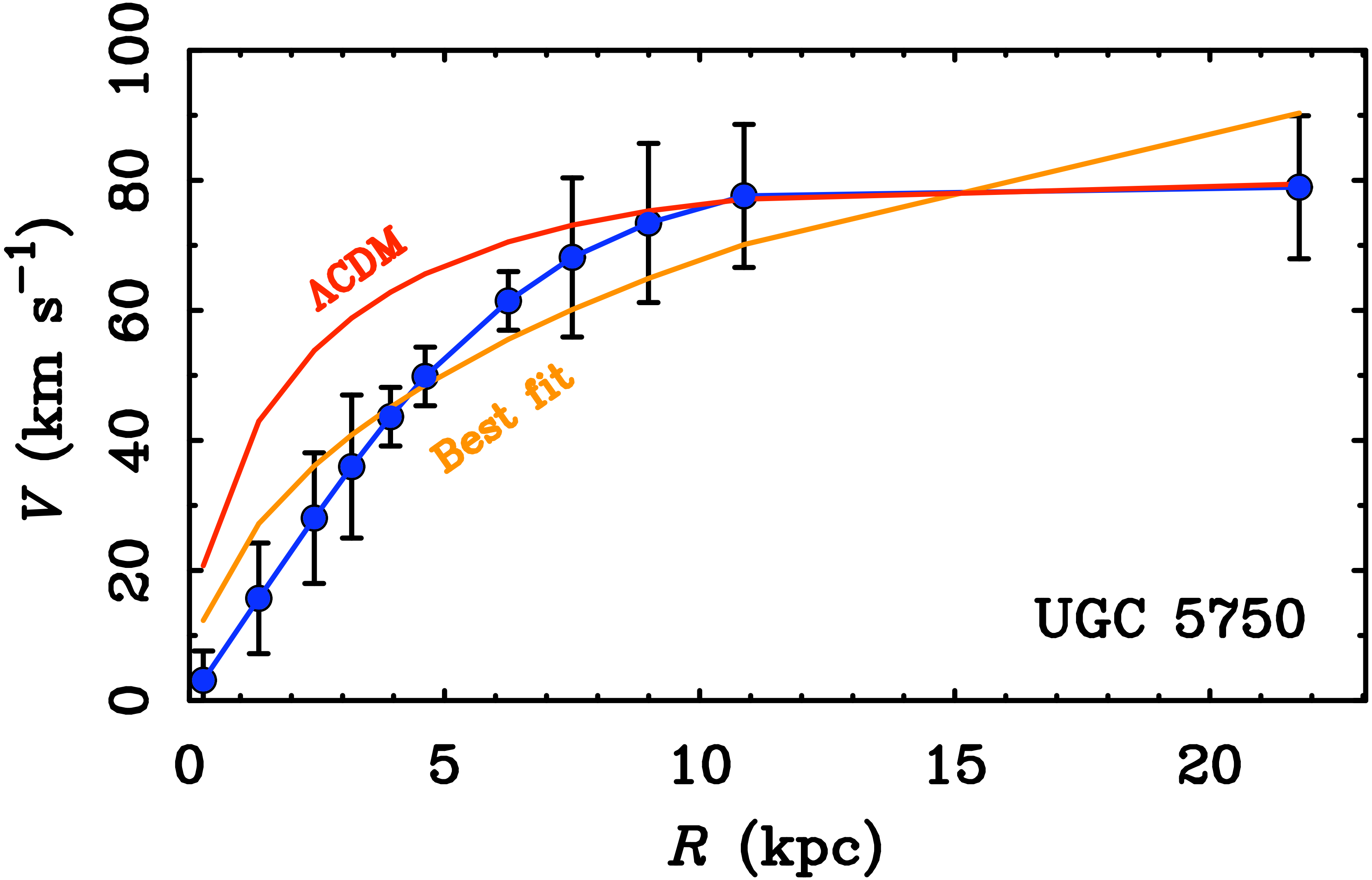


note: $\rho(r) \sim r^{-1}$ at small radii

$$V^2(r) = V^2_{200}[\ln(1+cx)-cx/(1+cx)]/\{x[\ln(1+c)-c/(1+c)]\}$$

with $x = r/r_{200}$ and $c = r_{200}/r_s$

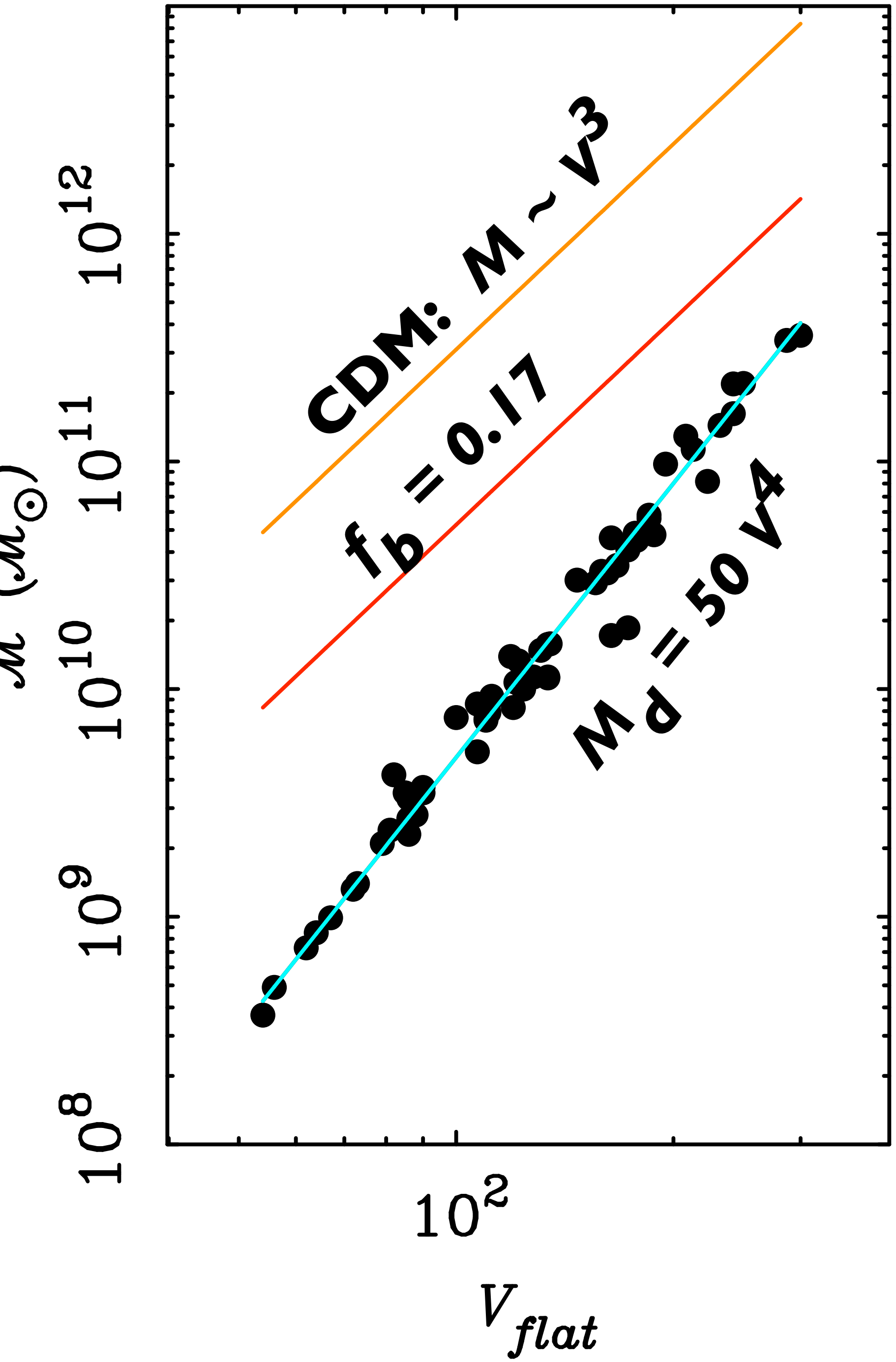
Predicts mass-velocity relation and rotation curve shape.



ΛCDM predicts: c = 10; V_{200} = 67 km/s

Best NFW fit: c = 2.6; V_{200} = 123 km/s

CDM TF Relation



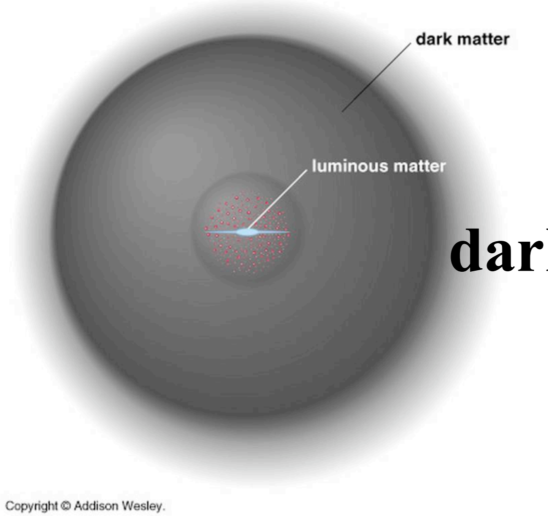
The **Frenk Principle**: "If the Cold Dark Matter Model does not agree with observations, there must be physical processes, no matter how bizarre or unlikely, that can explain the discrepancy."

The **Strong Frenk Principle**: (2 versions)

1: "The physical processes must be the most bizarre and unlikely..."

2: "If we are incapable of finding any physical processes to explain the discrepancy between CDM models and observations, then observations are wrong."

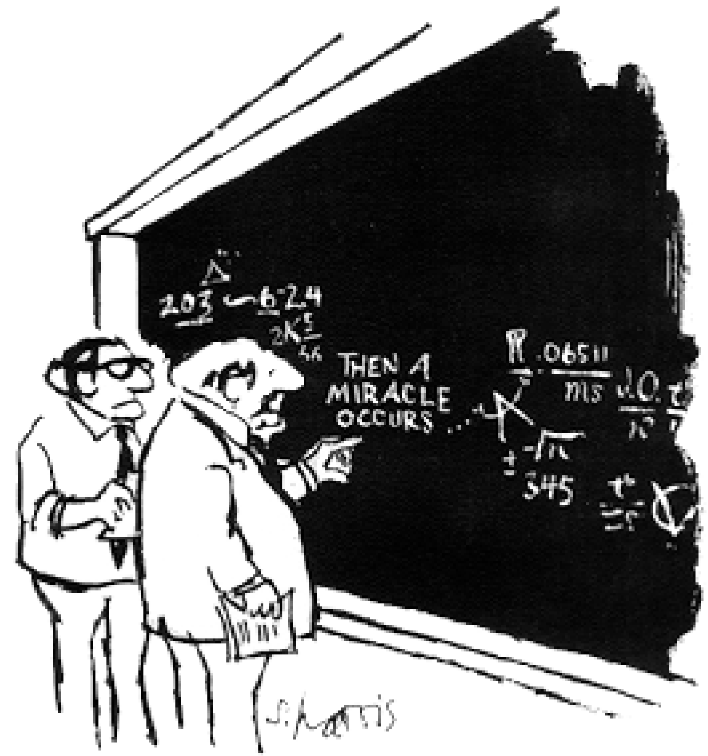
- George Efstathiou



step 1: dark matter halo

step 2: feedback? gastrophysics?

step 3: a real galaxy



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

Tully-Fisher Relation

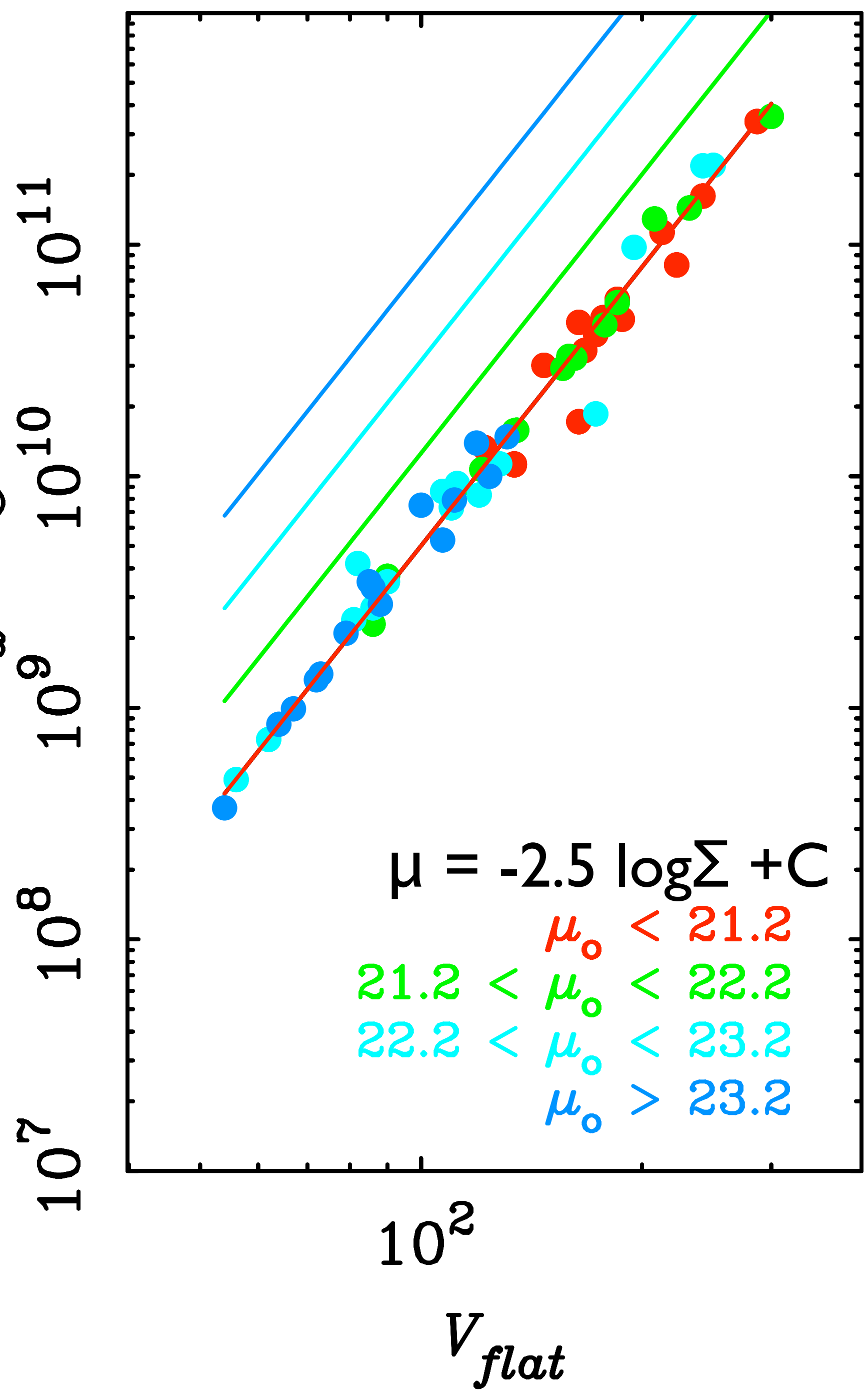
<u>Newton says</u>

$V^2 = GM/R$.

Equivalently,

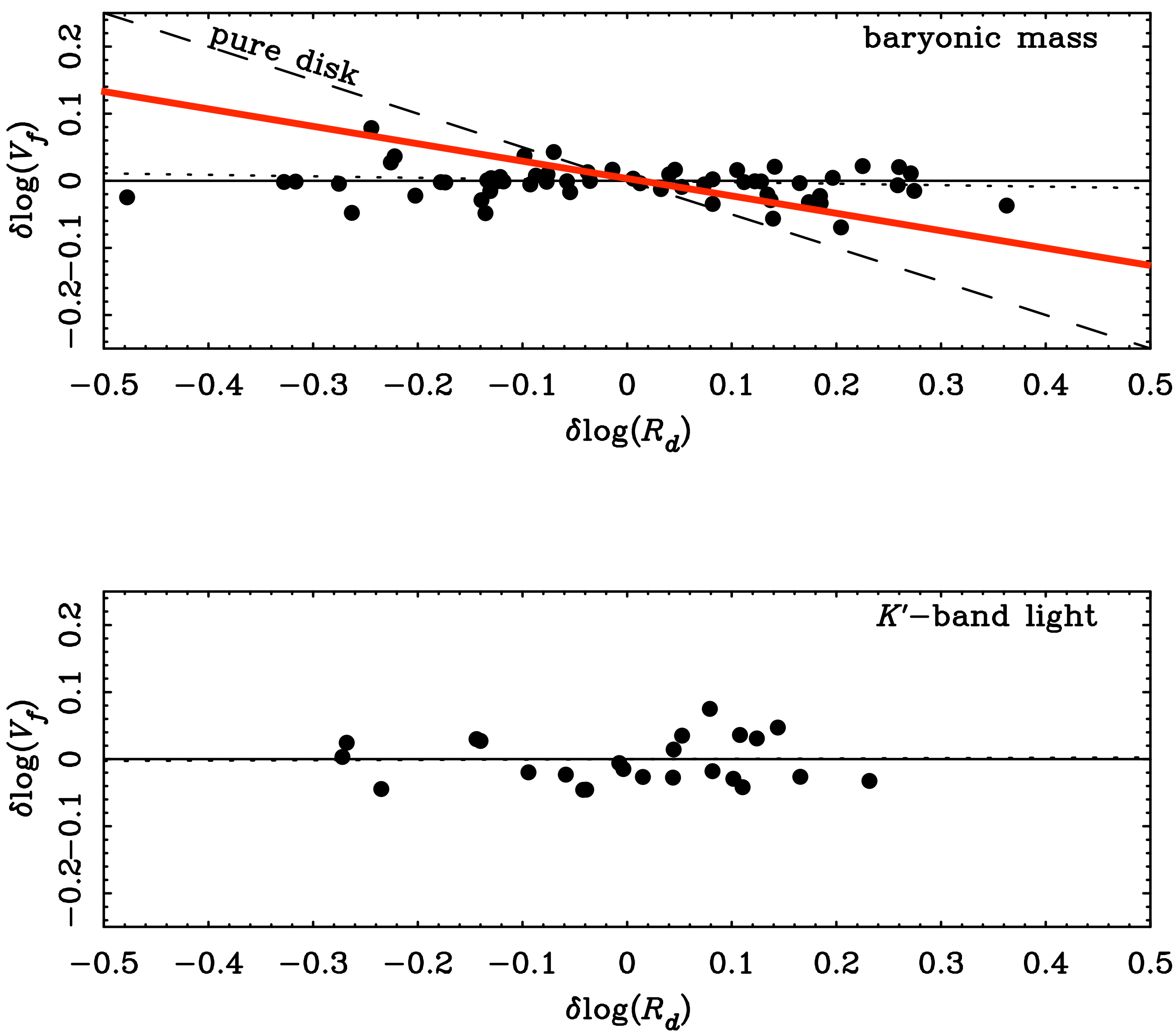
$\Sigma = M/R^2$

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

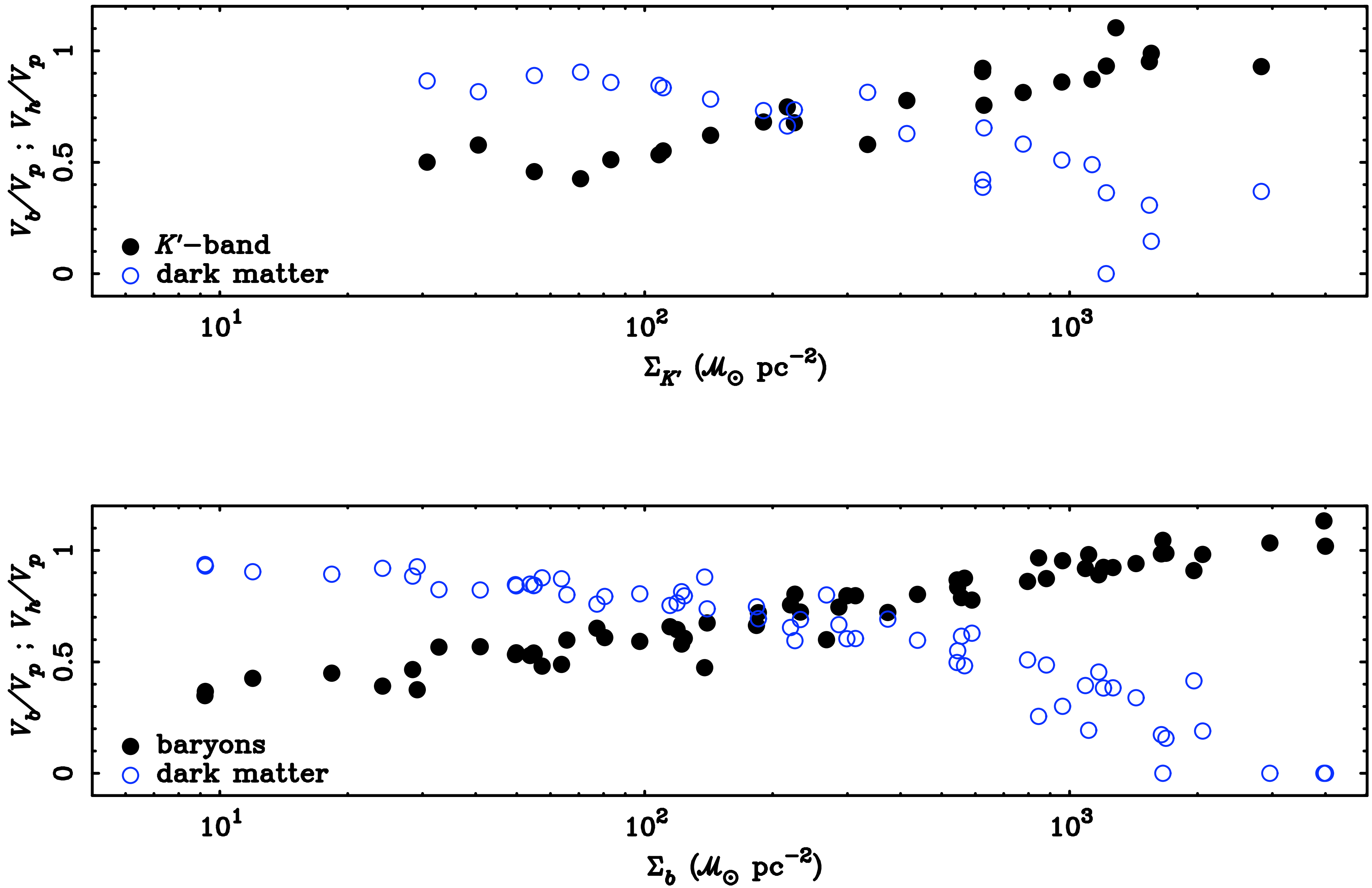


<u>Therefore</u>

Galaxies of different surface brightnesses *should* form distinct Tully-Fisher sequences.

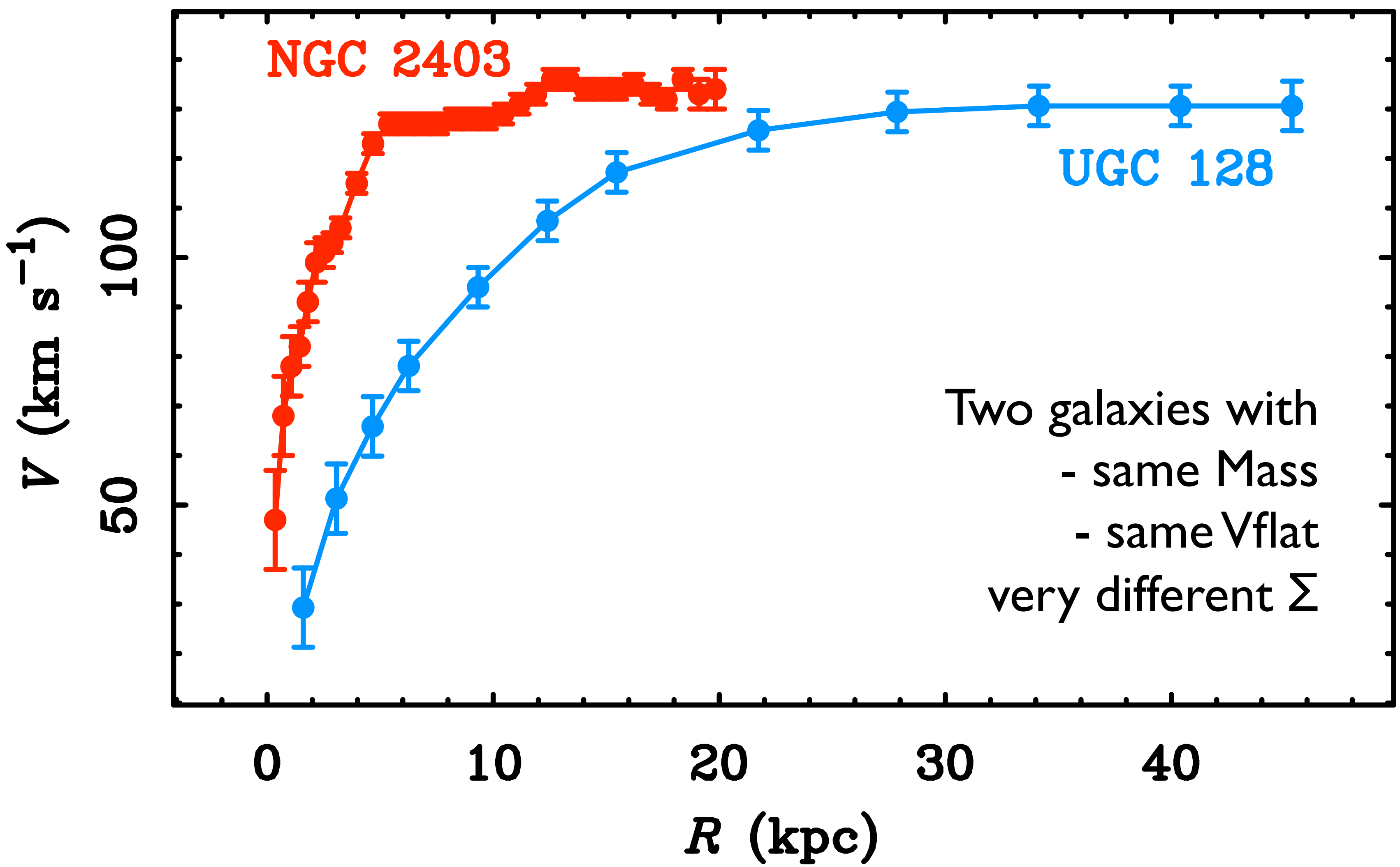


Dutton et al. (2005)

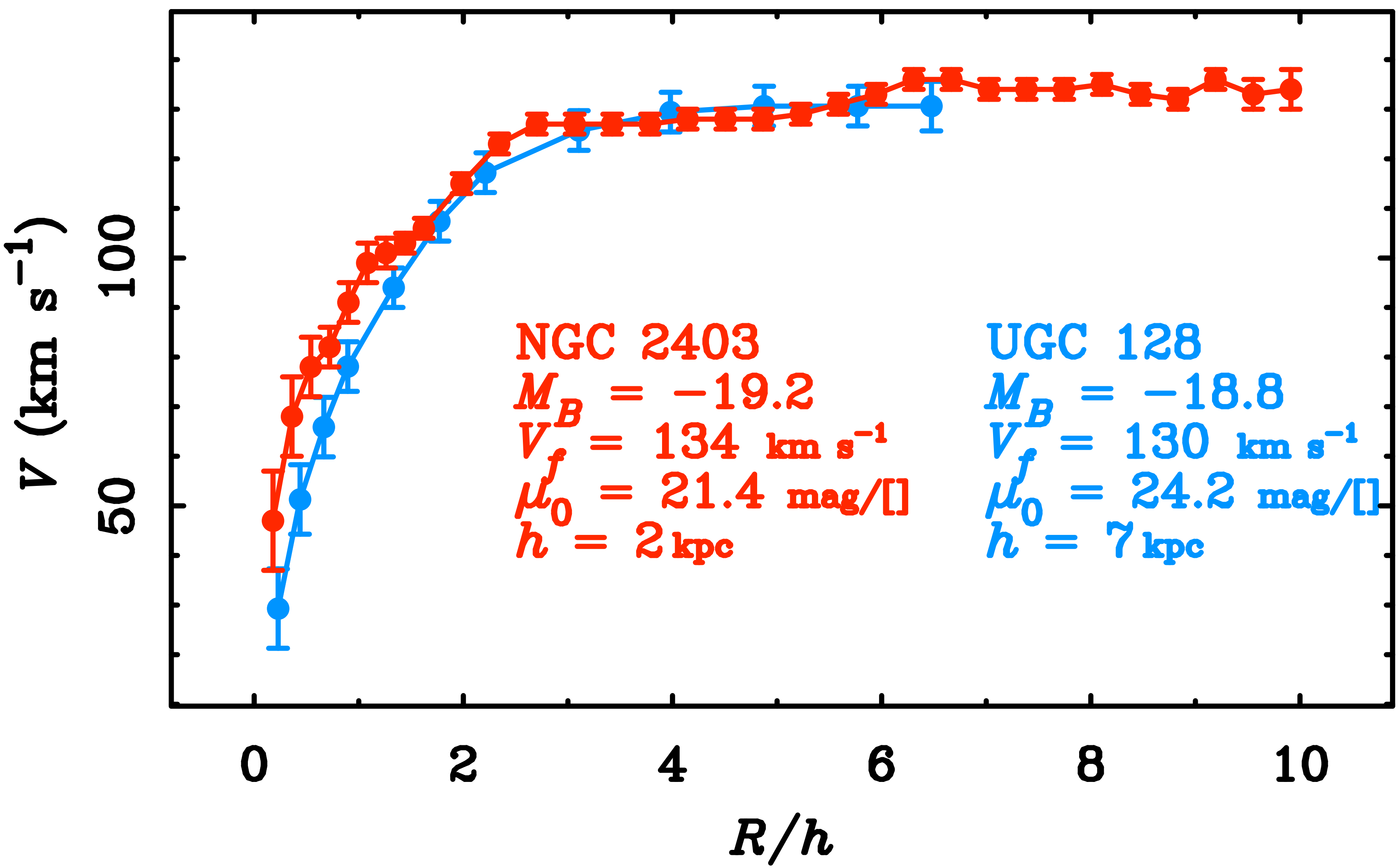


fine-tuning unavoidable

Galaxies which are indistinguishable in TF:



Radius measured by size of *visible* disk



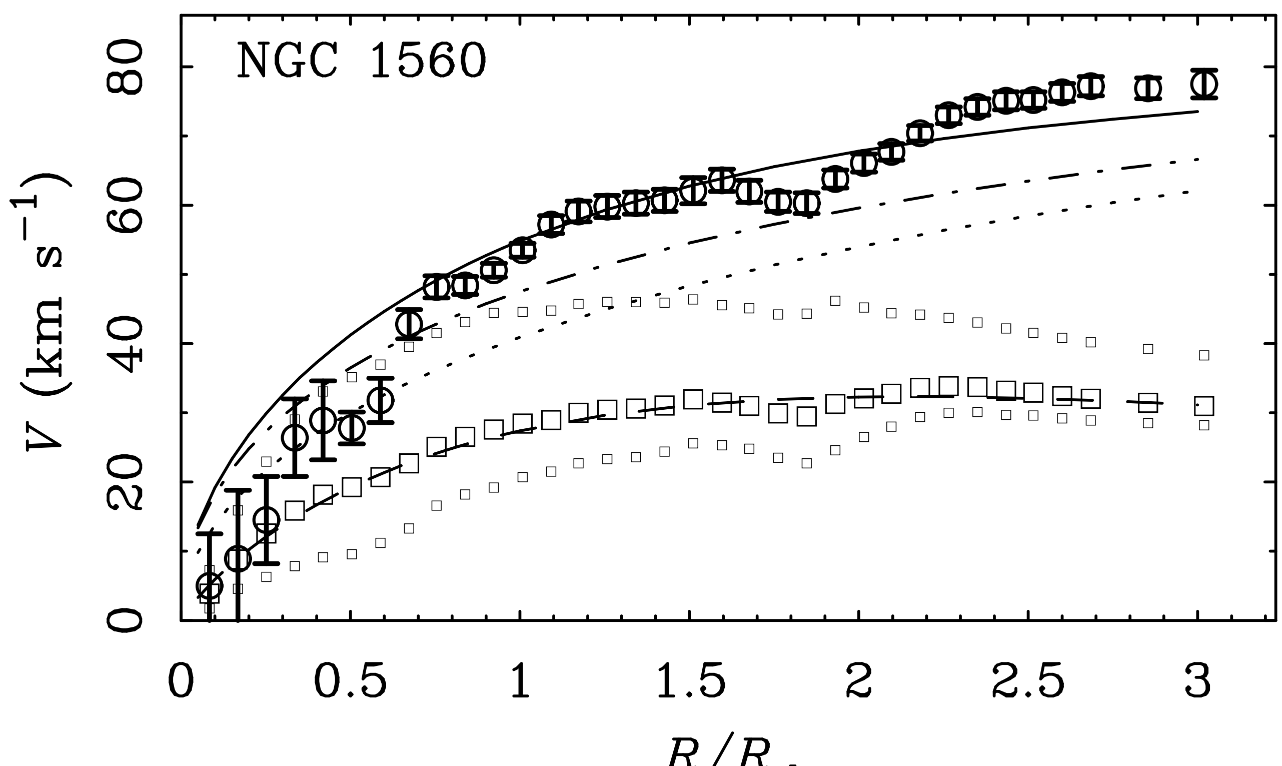
Dynamics knows about the distribution of light as well as the total mass.

Renzo's Rule:

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

(Sancisi 1995, private communication
2003, published in IAU proceedings)

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



MOND

MOdified Newtonian Dynamics

introduced by Moti Milgrom in 1983

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

$$\mu(a/a_0)\, a = g_N\,.$$

Above a critical acceleration a_0 everything is normal.
Below that scale, gravity in effect becomes stronger.

$$a_0 = 1.2 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

ApJ, 270, 381

Milgrom 1983

MOND predictions

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 conc[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] densitie[illegible] [illegible] yield a discrepancy which increases with radius in a predictable manner.

4. Effects of the m[illegible] are predict[illegible] to be particularly stro[illegible] review of propert[illegible] 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, $g \approx (8$ 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 V^2/r [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] requires information on local behavior in the disk only while the spheroid can be neglected. This makes the determination of mass from velocity more certain.

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

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 [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

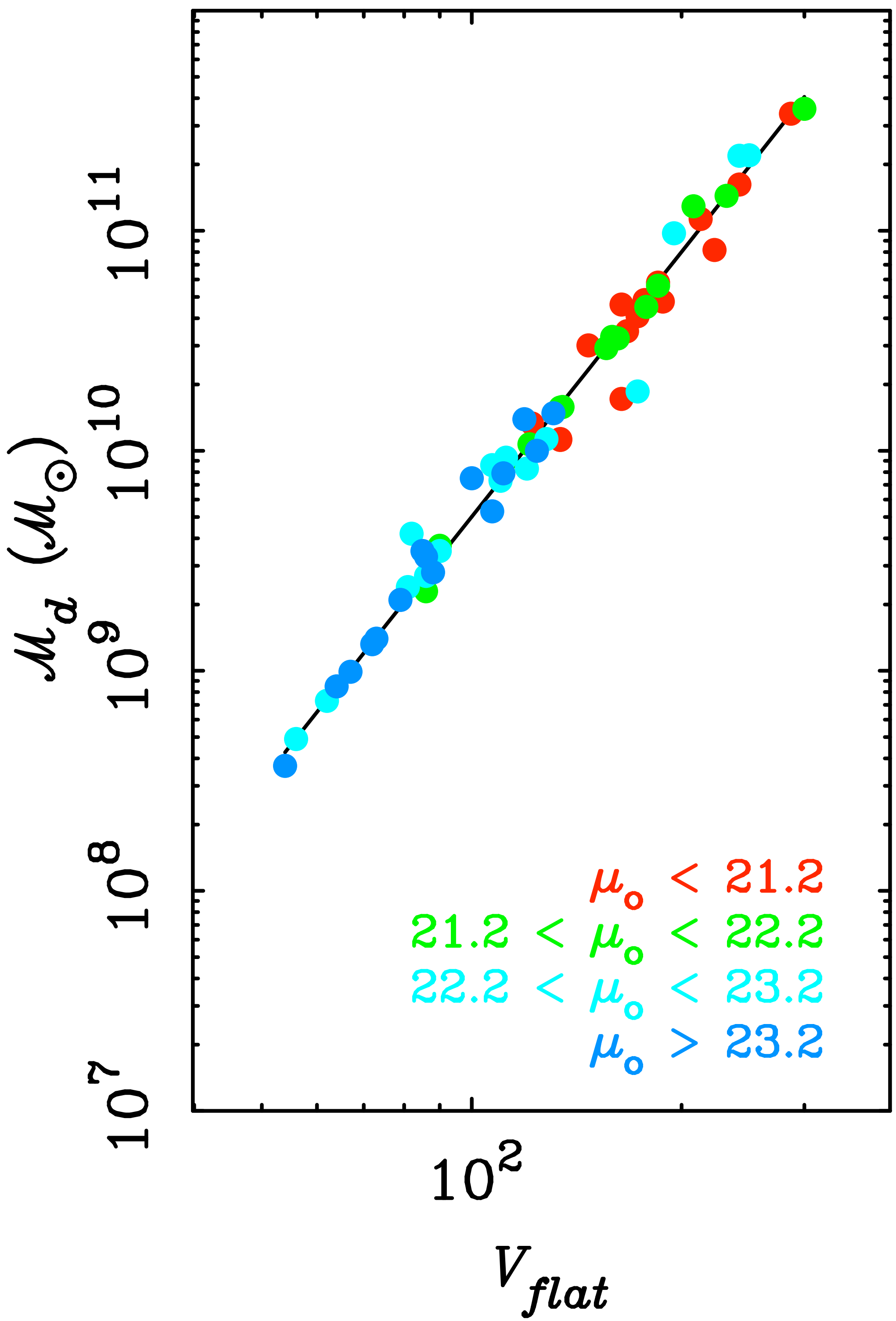
The main results of this paper can be summarized by the statement that the modified dynamics eliminates the need to assume hidden mass in galaxies. The effects in galaxies which I have considered, and which are commonly attributed to such hidden mass, are readily explained by the modification. More specifically:

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

- 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

None of the following data existed in 1983.

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



MOND predictions

- The Tully-Fisher Relation
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  - ✔ Normalization = $1/(a_0G)$
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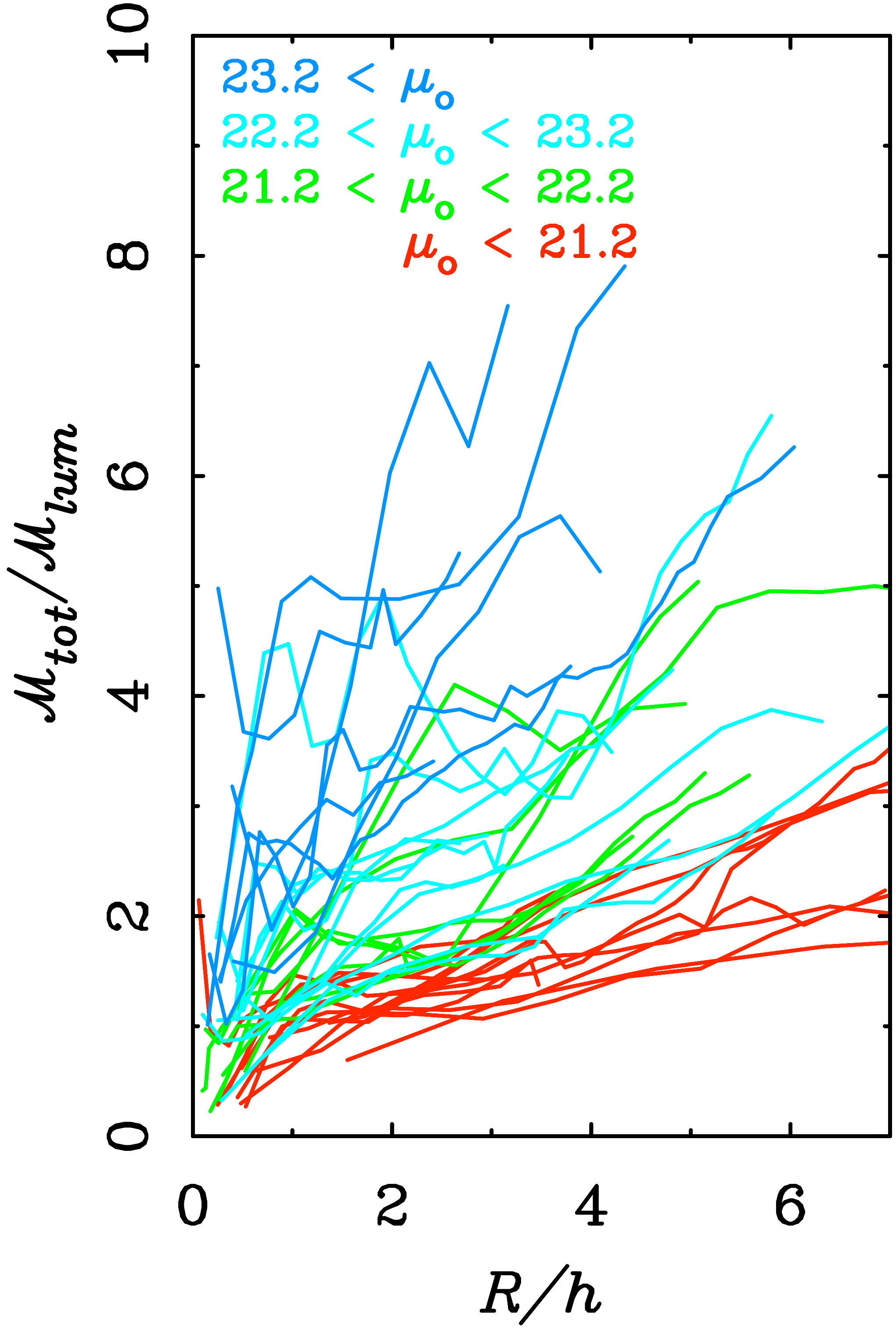

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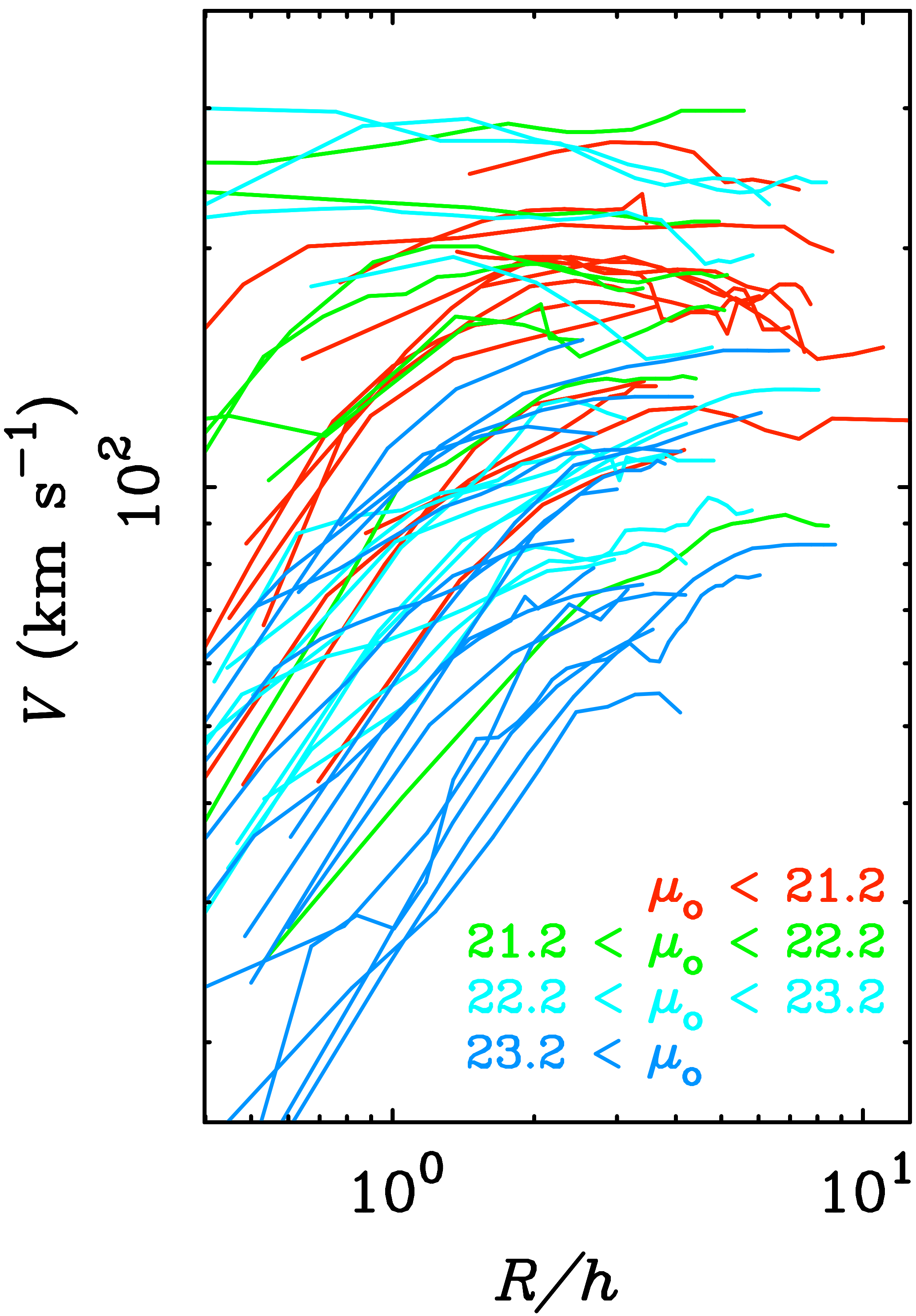

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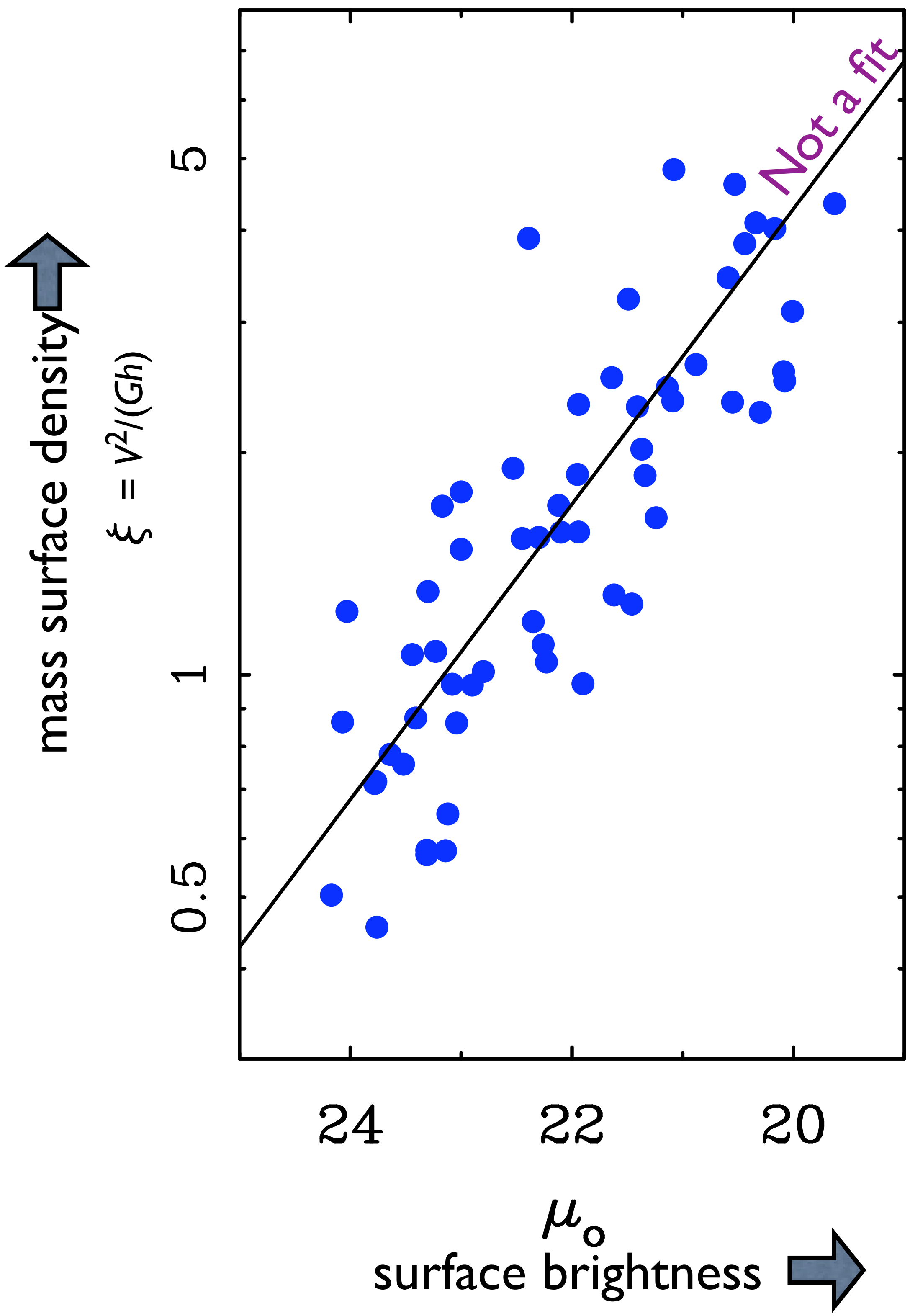

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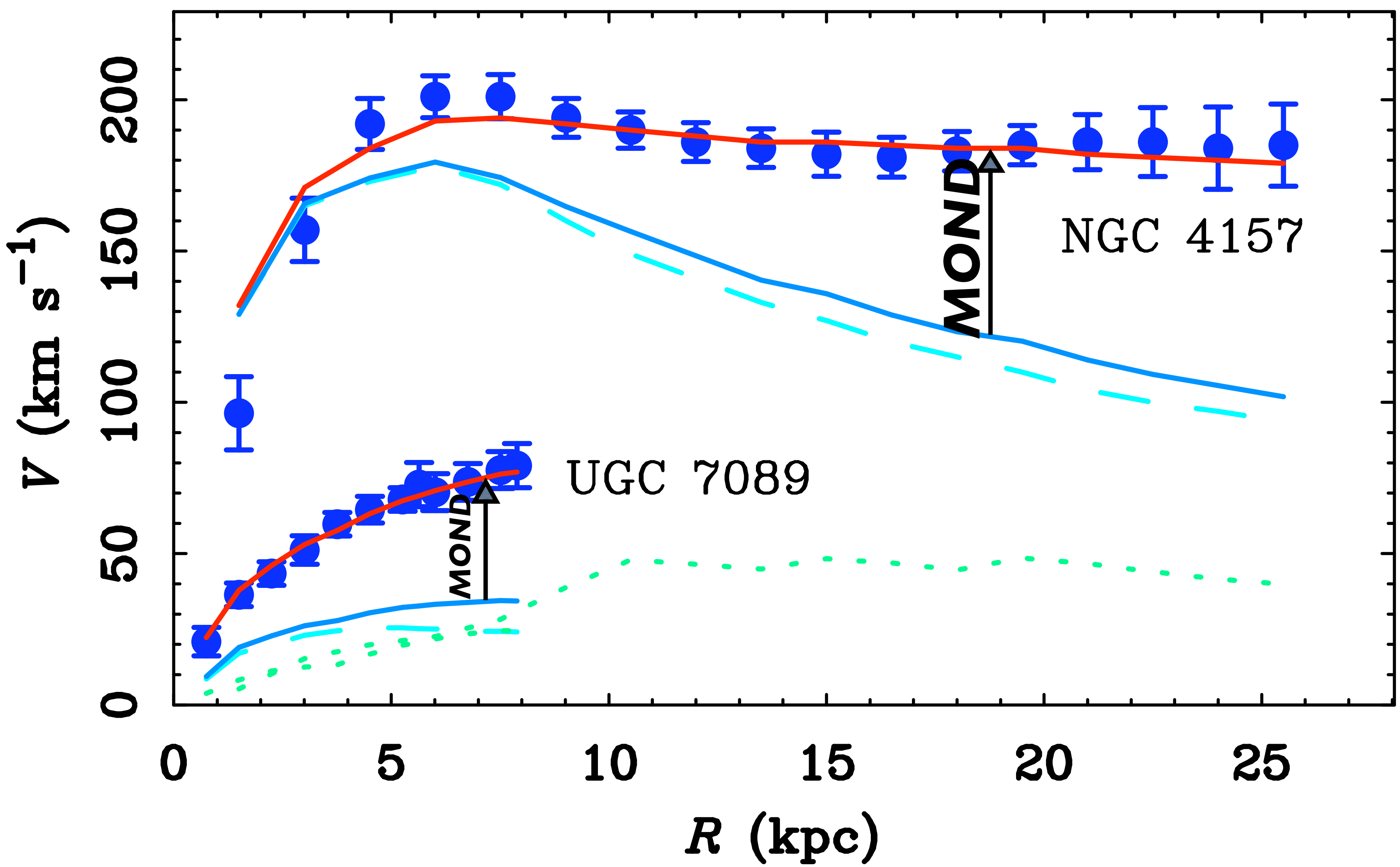
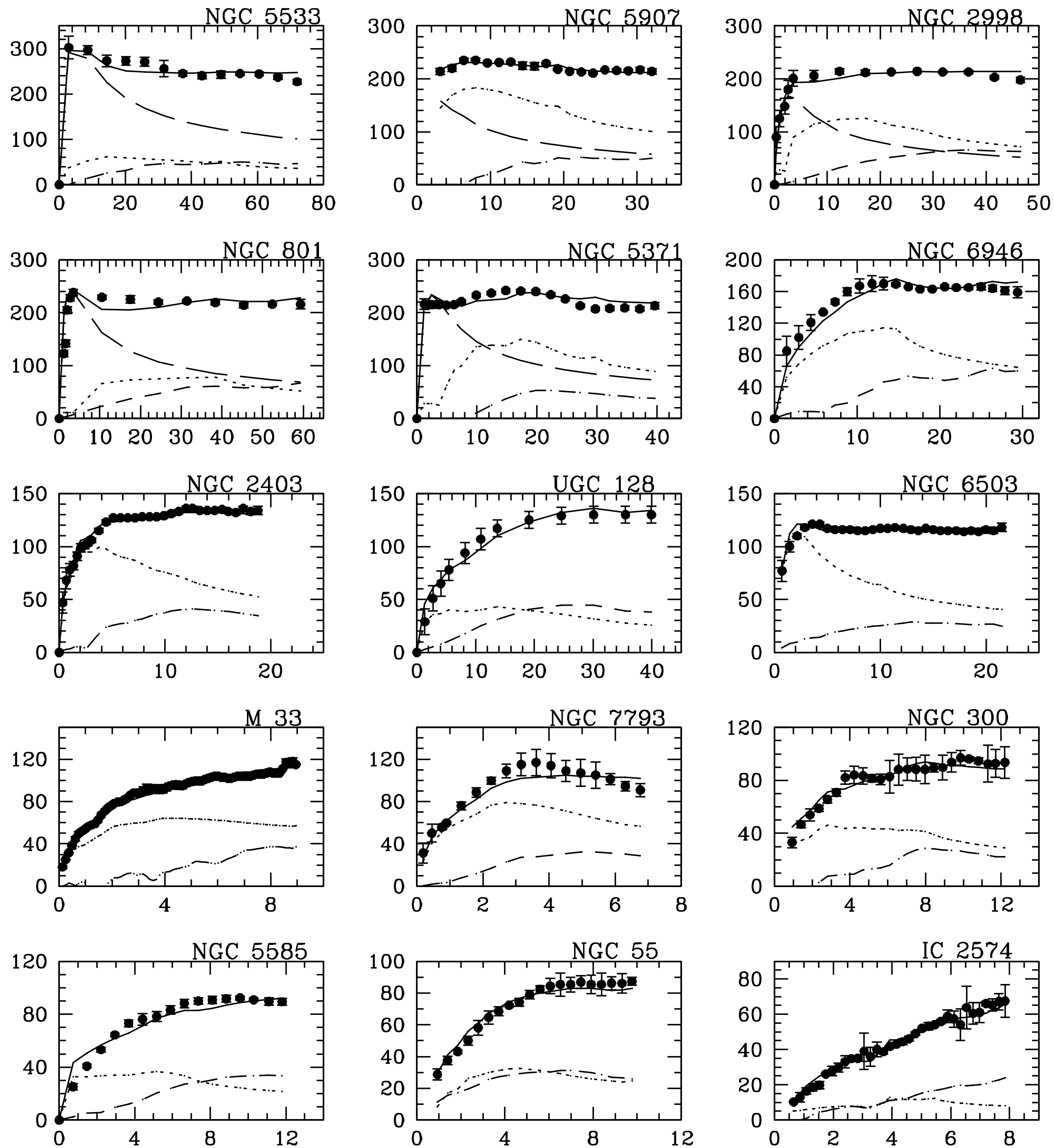
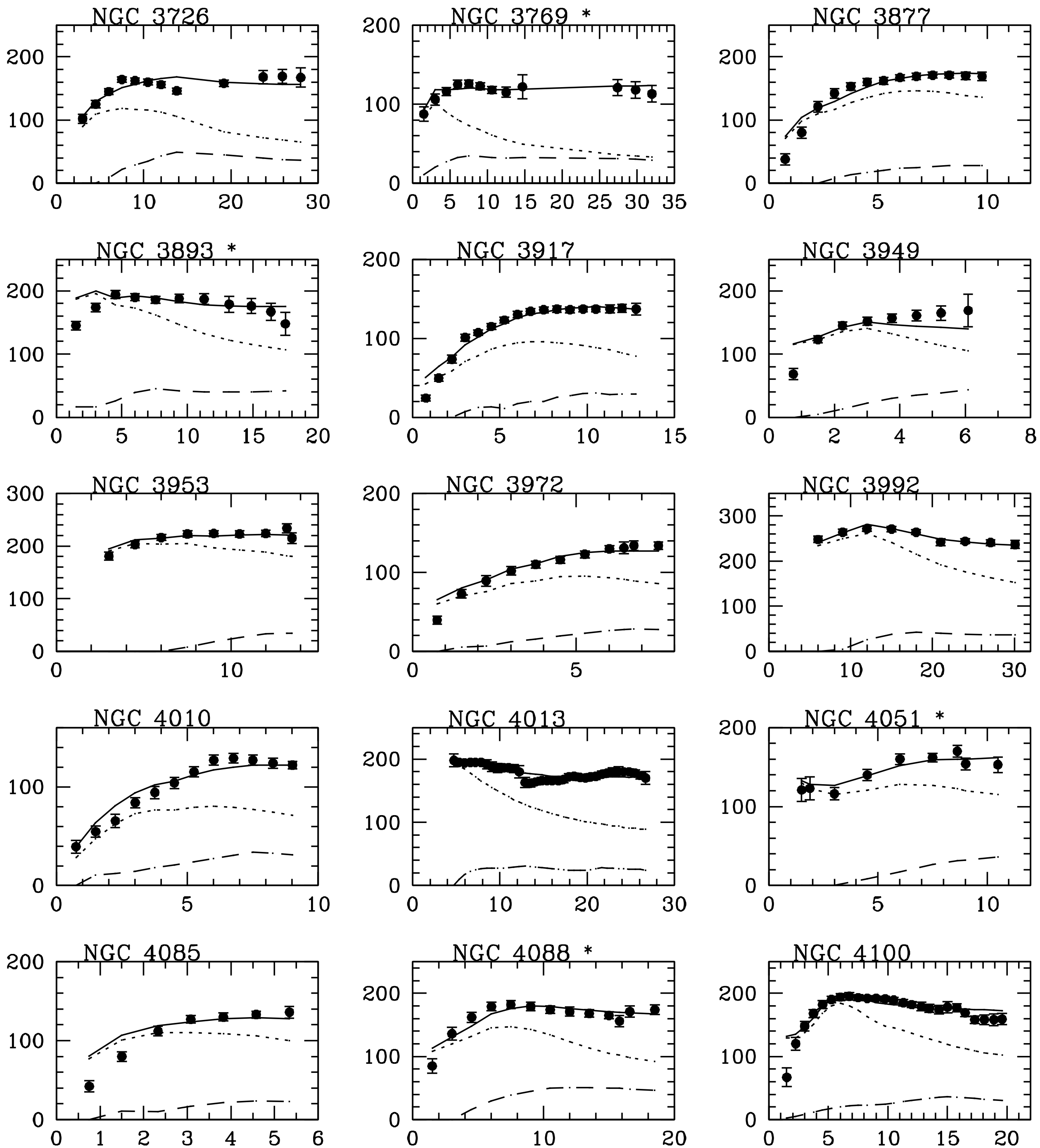


V (km s⁻¹)
R (kpc)
NGC 4157
UGC 7089
MOND
MOND
0
50
100
150
200
0
5
10
15
20
25

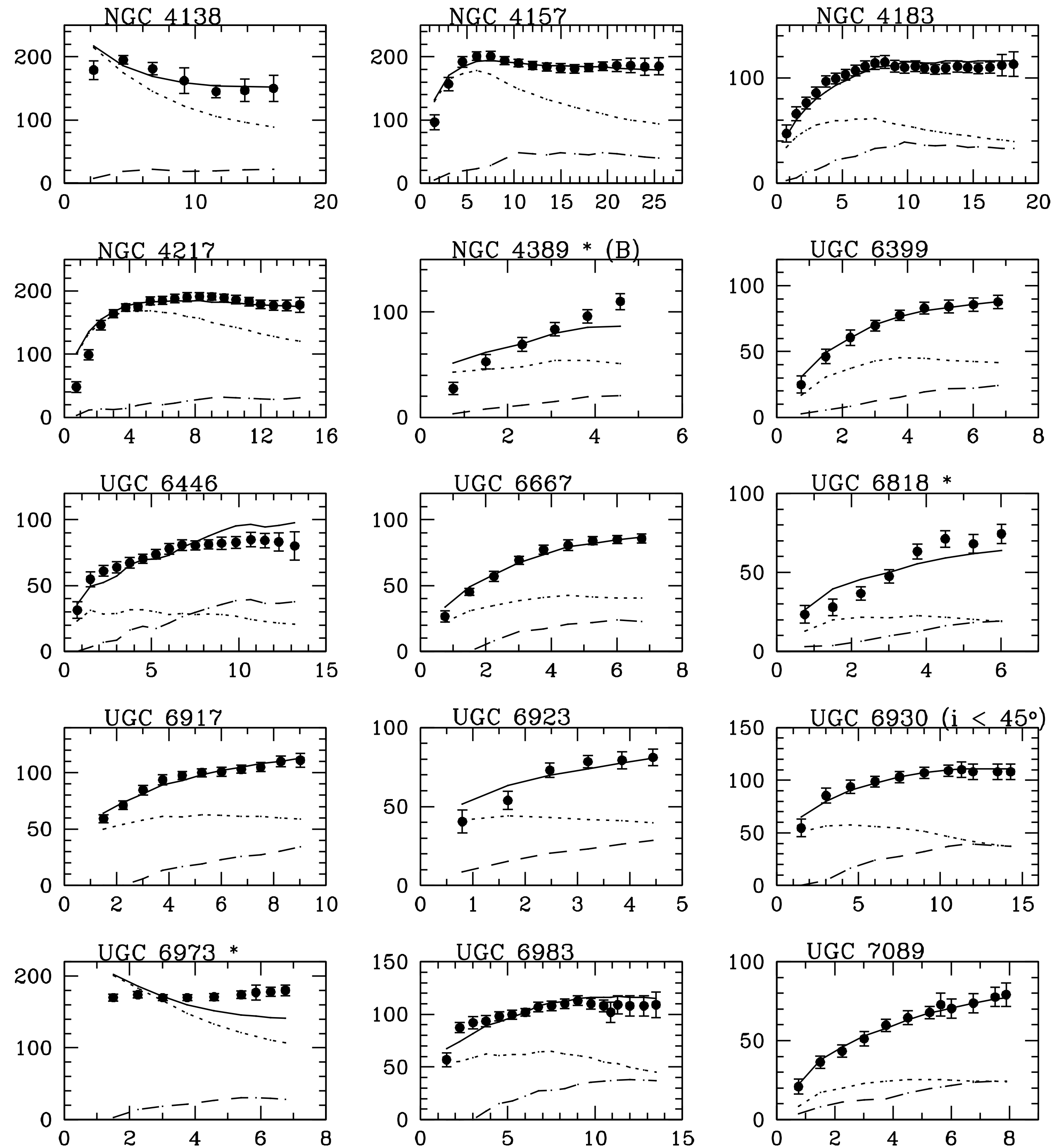


Sanders & McGaugh 2002, *ARA&A*, **40**, 263

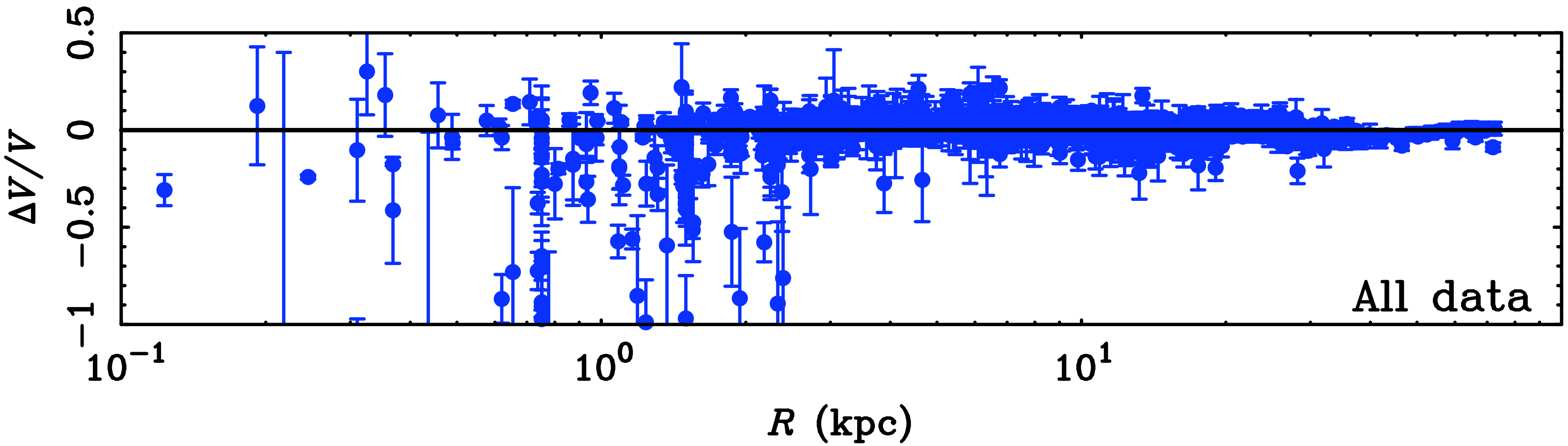
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



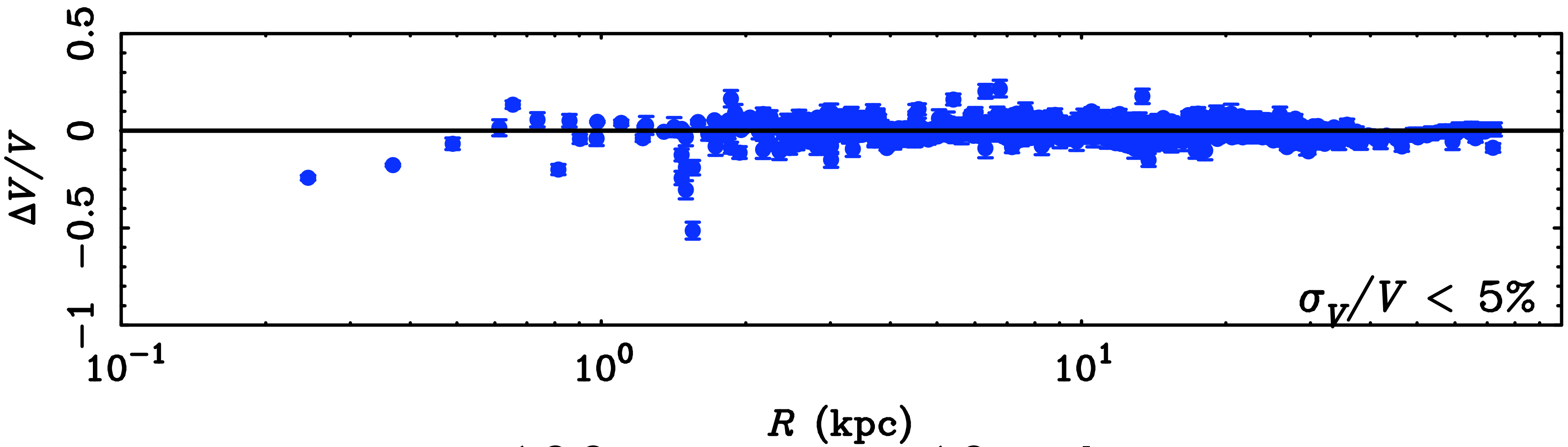
Sanders & McGaugh 2002, *ARA&A*, **40**, 263



Residuals of MOND fits

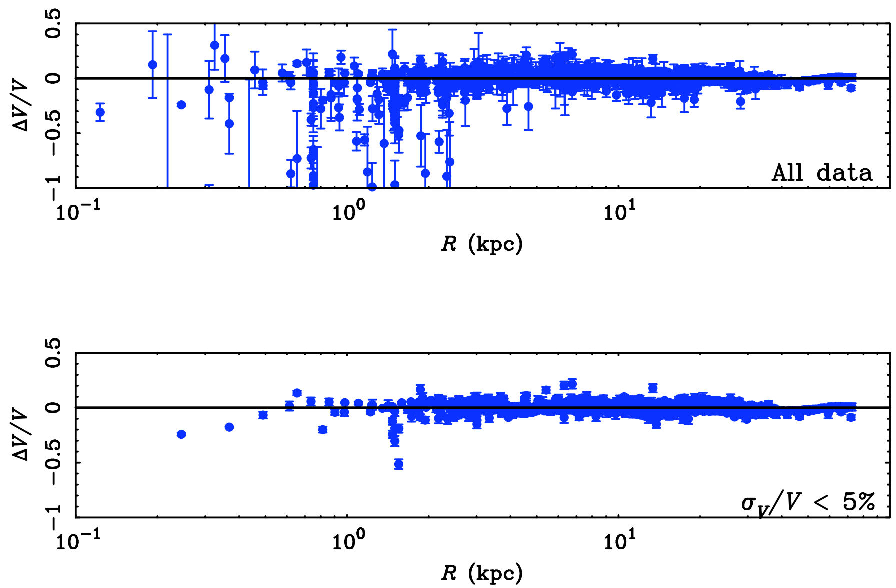


> 1000 points in 74 galaxies



> 600 points in 60 galaxies

MOND predictions



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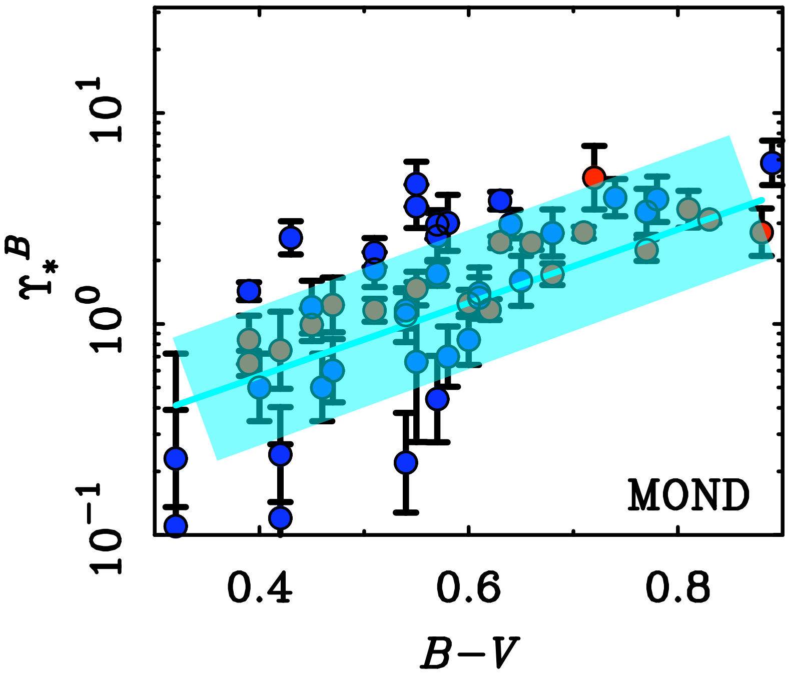
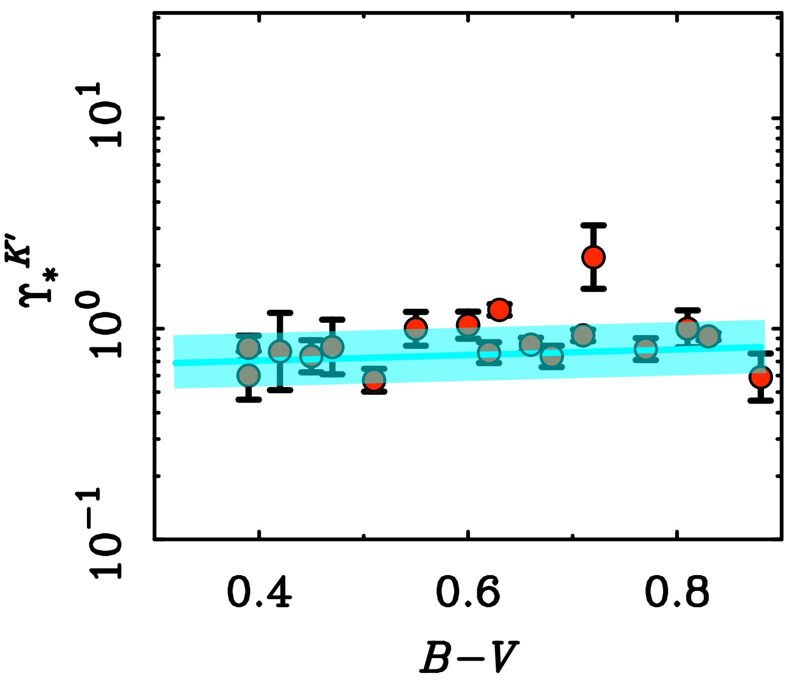
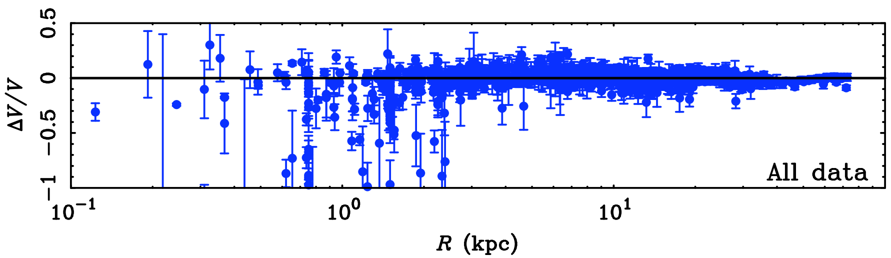


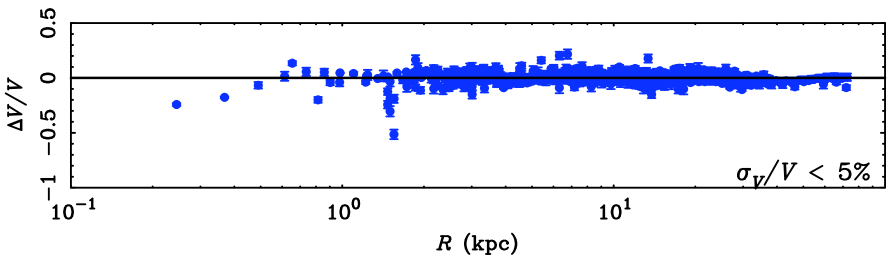


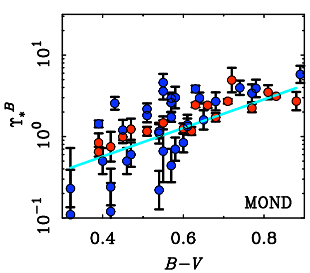
Line: stellar population model
(mean expectation)

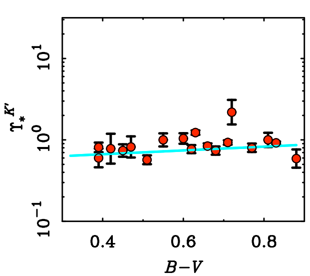
MOND reproduces
- mean normalization
- trend with color
- expected scatter

MOND predictions









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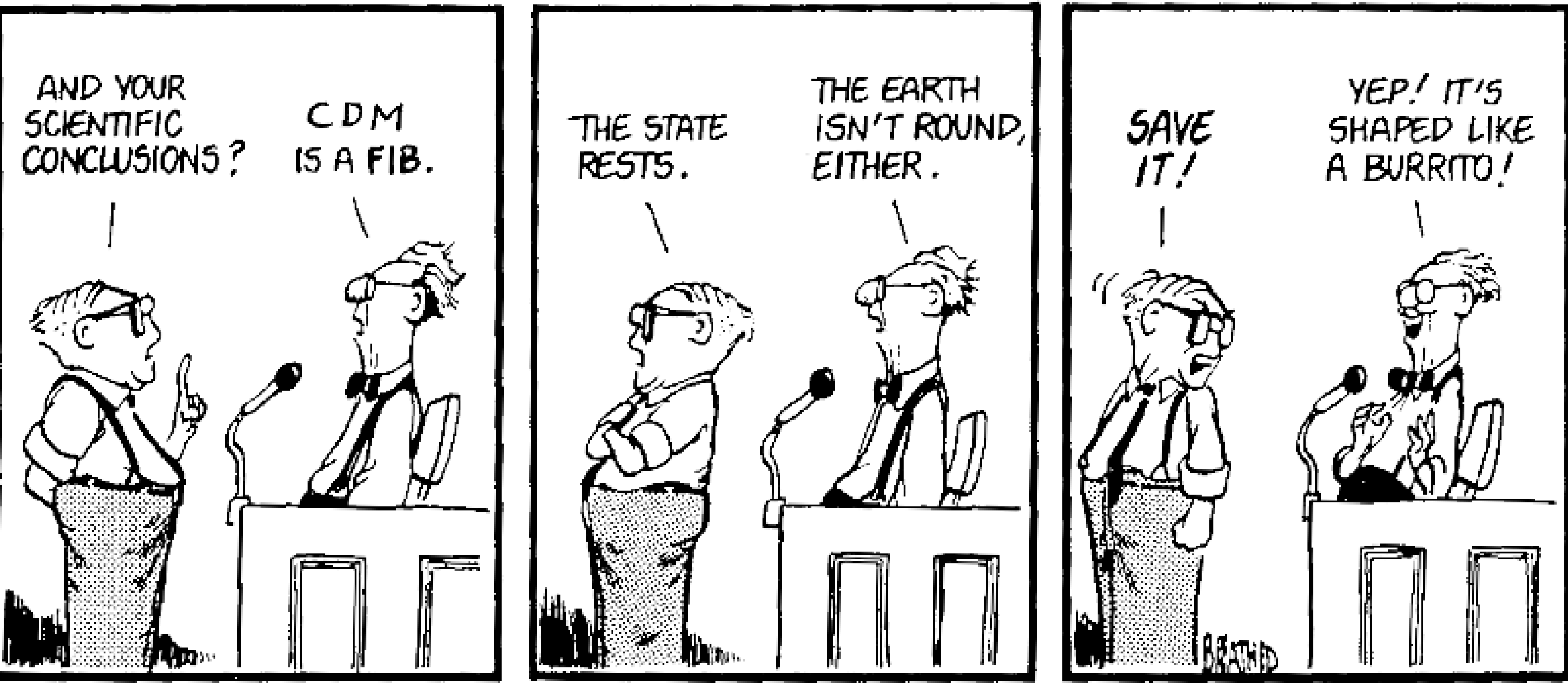

AND YOUR SCIENTIFIC CONCLUSIONS?
CDM IS A FIB.
THE STATE RESTS.
THE EARTH ISN'T ROUND, EITHER.
SAVE IT!
YEP! IT'S SHAPED LIKE A BURRITO!

Everything happens... as if the force between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

In spiral galaxies,
everything happens as if

$$\mu(a/a_0)\, a = g_N \,.$$

Other modifications fail immediately

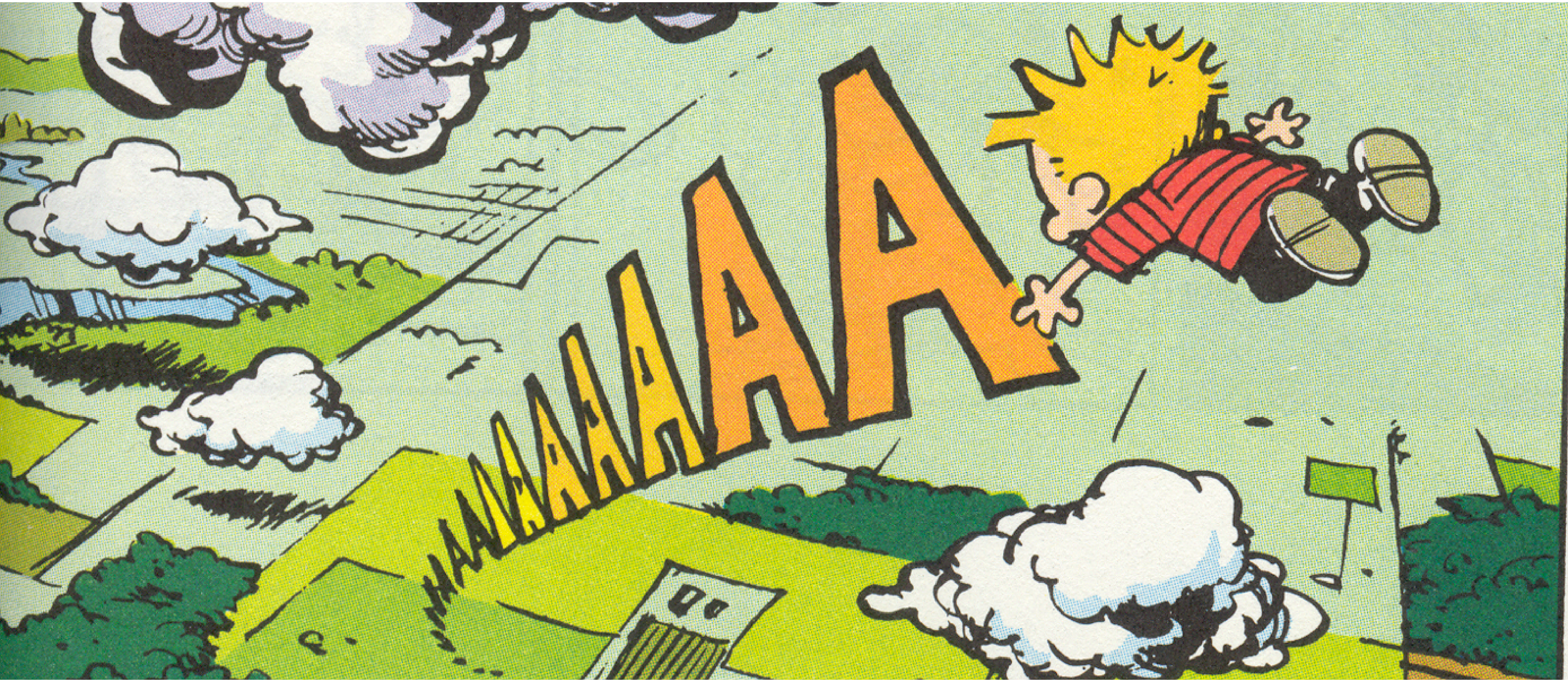
Observed behavior is simple - *seems* unlikely to originate fomr complicated baryonic gastrophysics

Are you suggesting there is no dark matter?

Distinguishing between dark matter and MOND is a nightmare

- CDM is the ultimate accommodator
  - can (and does) explain just about anything
  - not explicitly falsifiable
- MOND makes very specific predictions (delta-fcn priors)
  - about some things
  - is completely mute about others

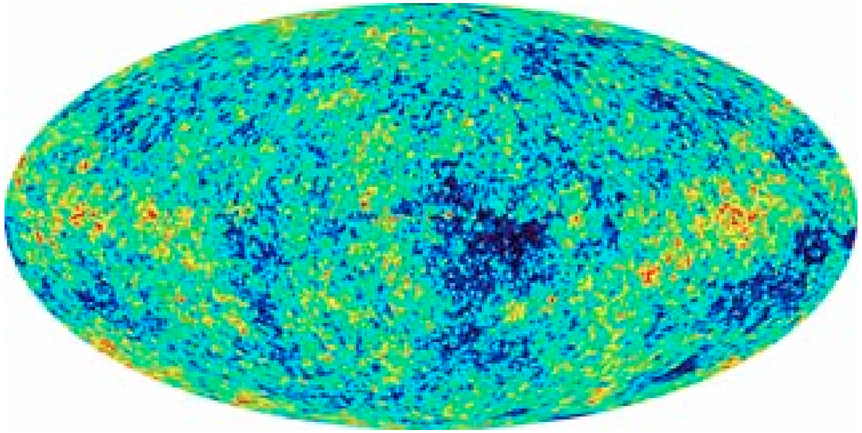
What does MOND do to cosmology?



In MOND

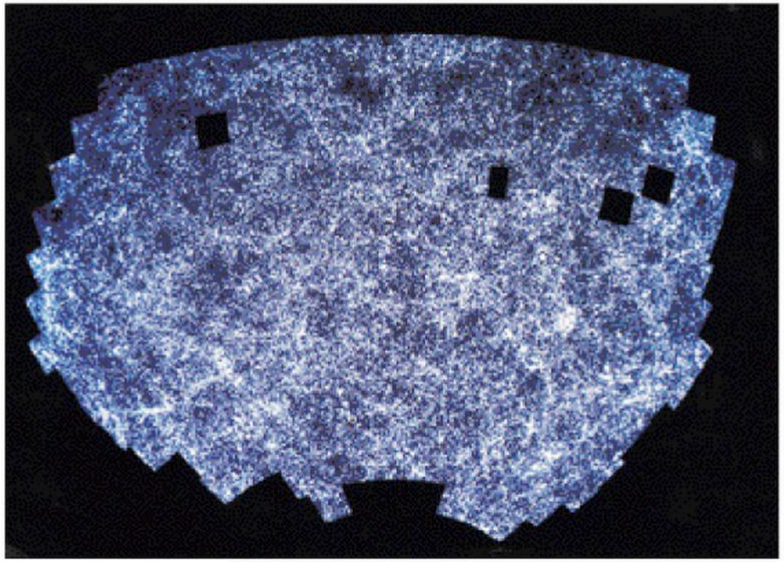
$$\Omega_b \approx \Omega_m$$

$t = 1.8 \times 10^5$ yr



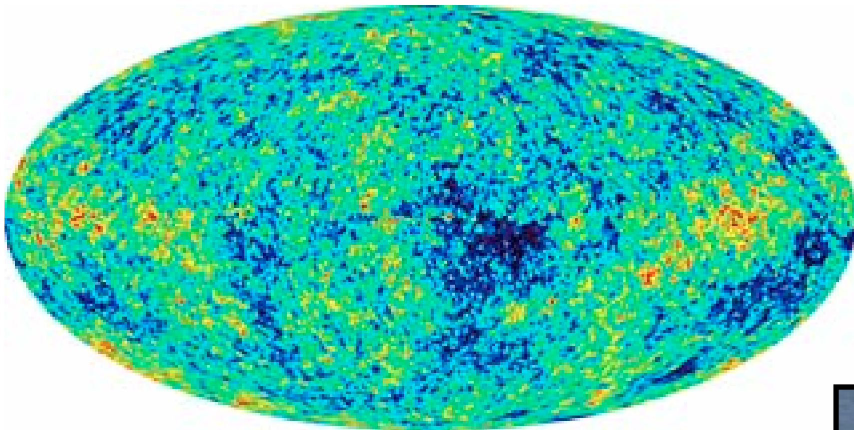
very smooth: $\delta\rho/\rho \sim 10^{-5}$

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

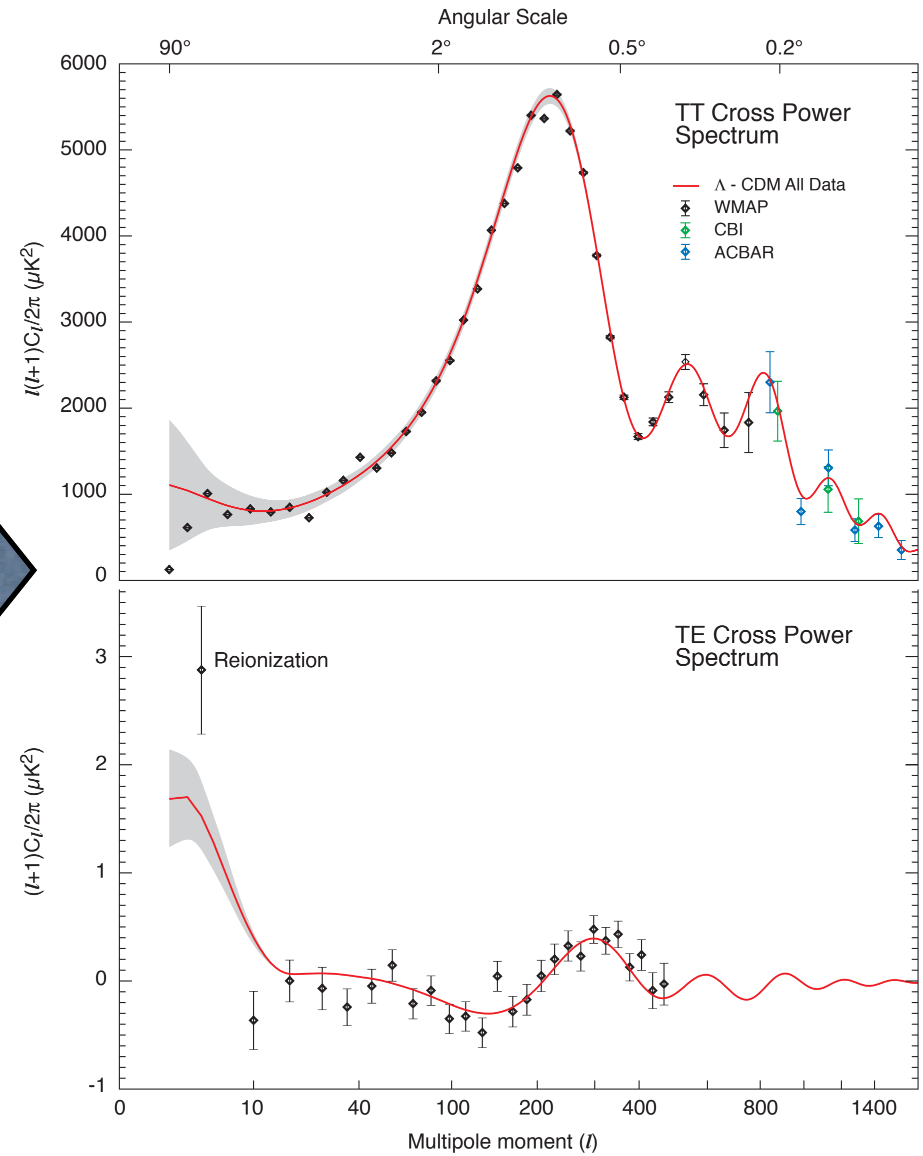


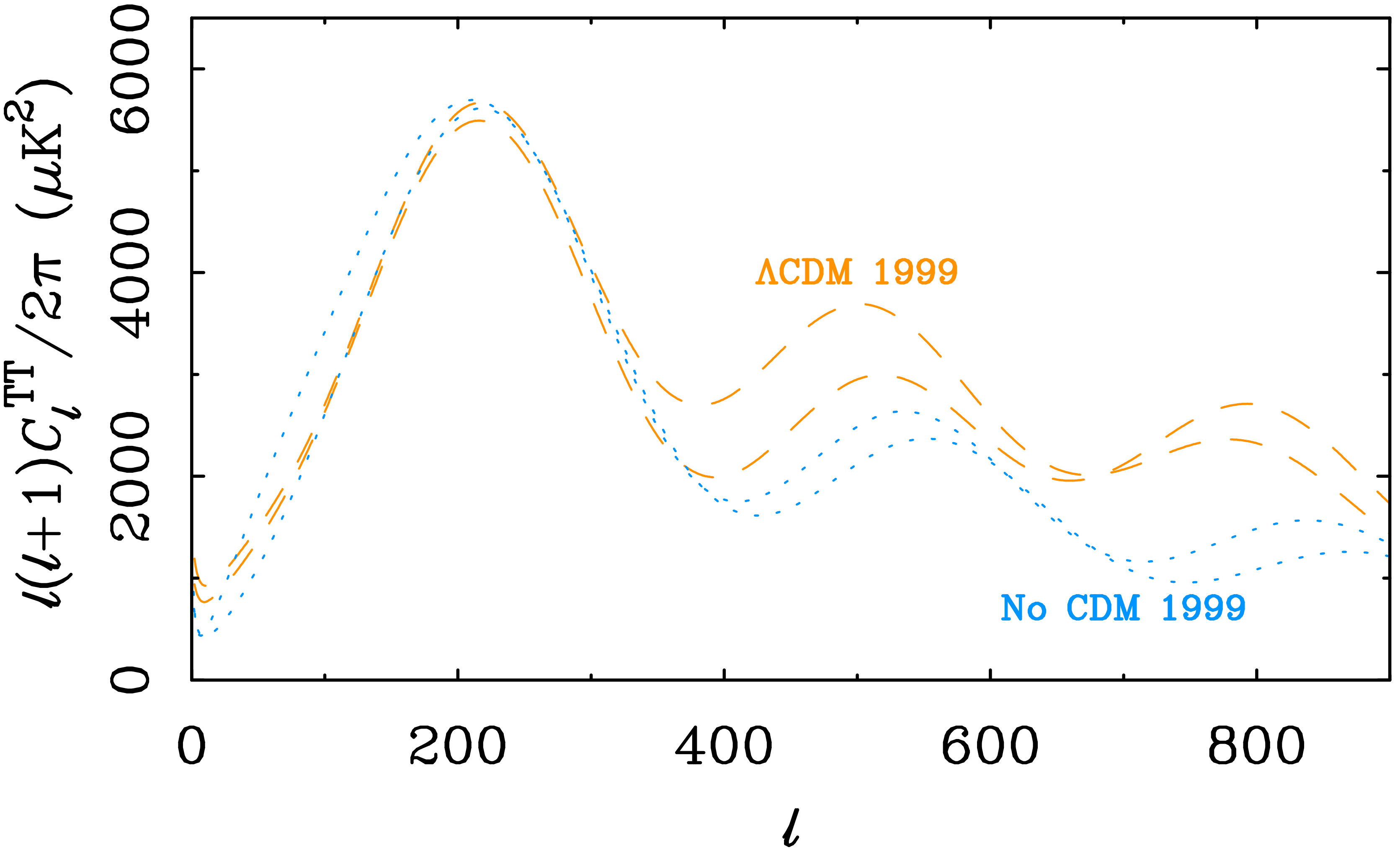
very lumpy: $\delta\rho/\rho \sim 1$

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

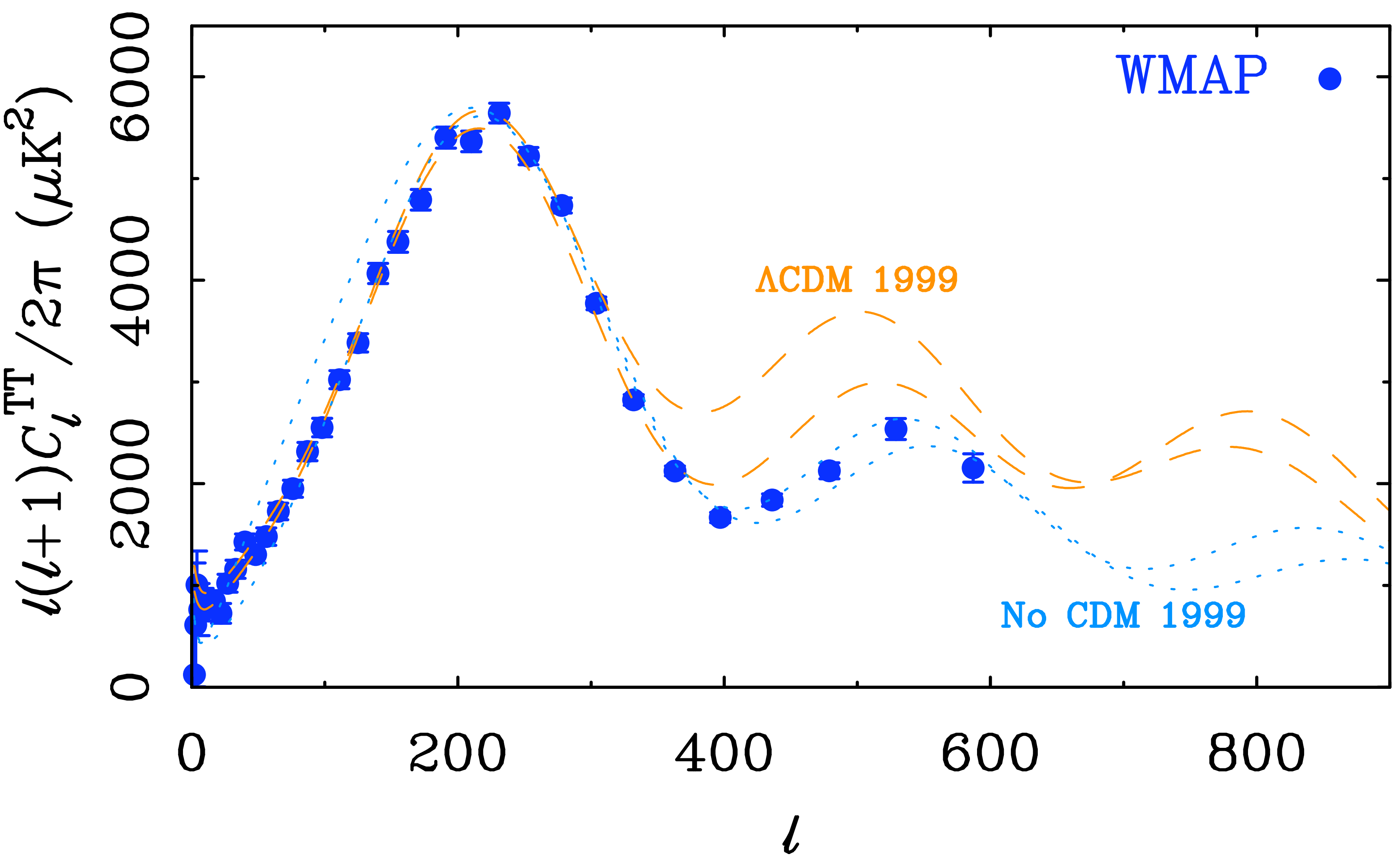


WMAP
Cosmic Background Radiation

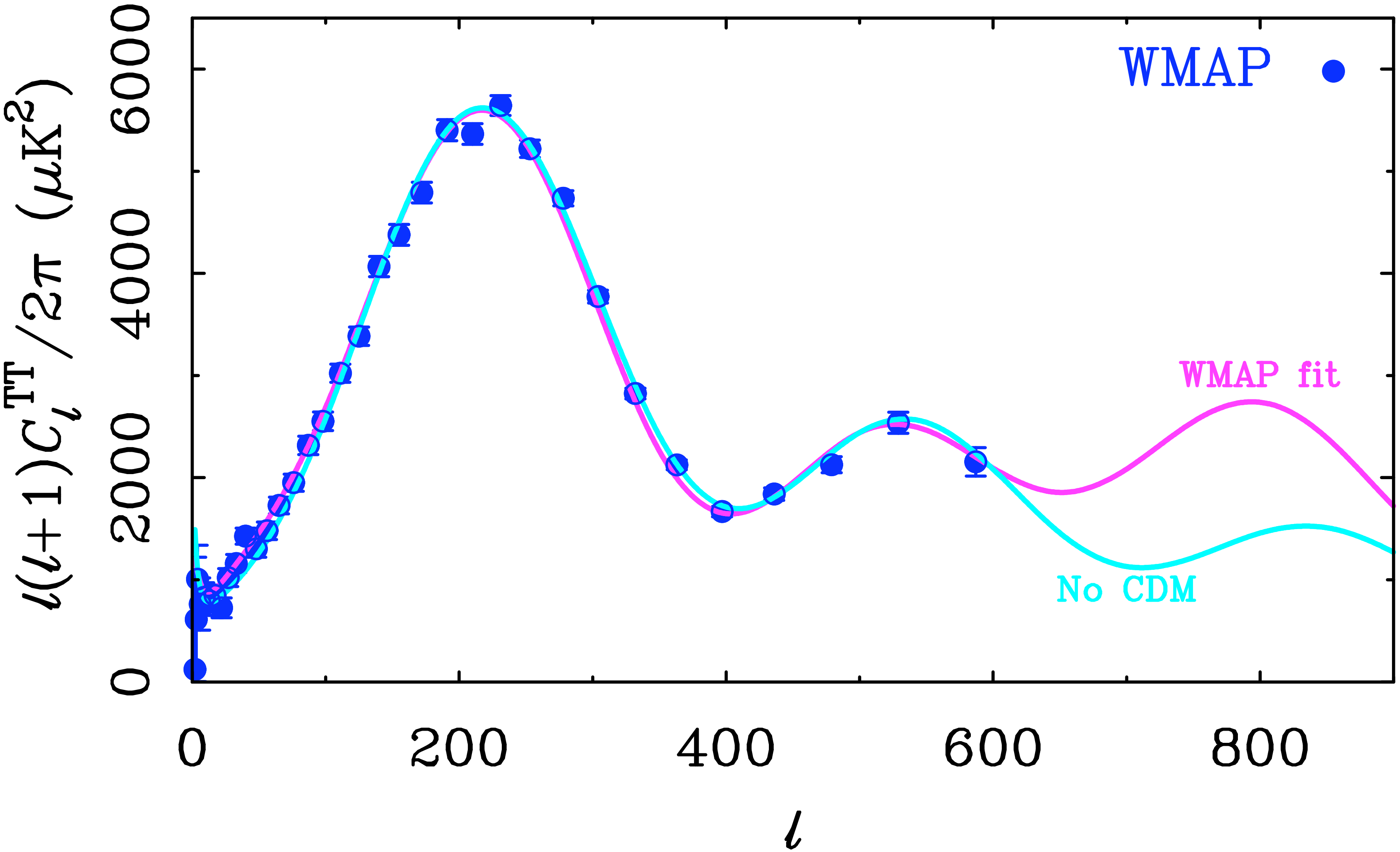




ΛCDM 1999
No CDM 1999
0
2000
4000
6000
0
200
400
600
800
$\ell(\ell+1)C_\ell^{\rm TT}/2\pi\ (\mu{\rm K}^2)$
ℓ

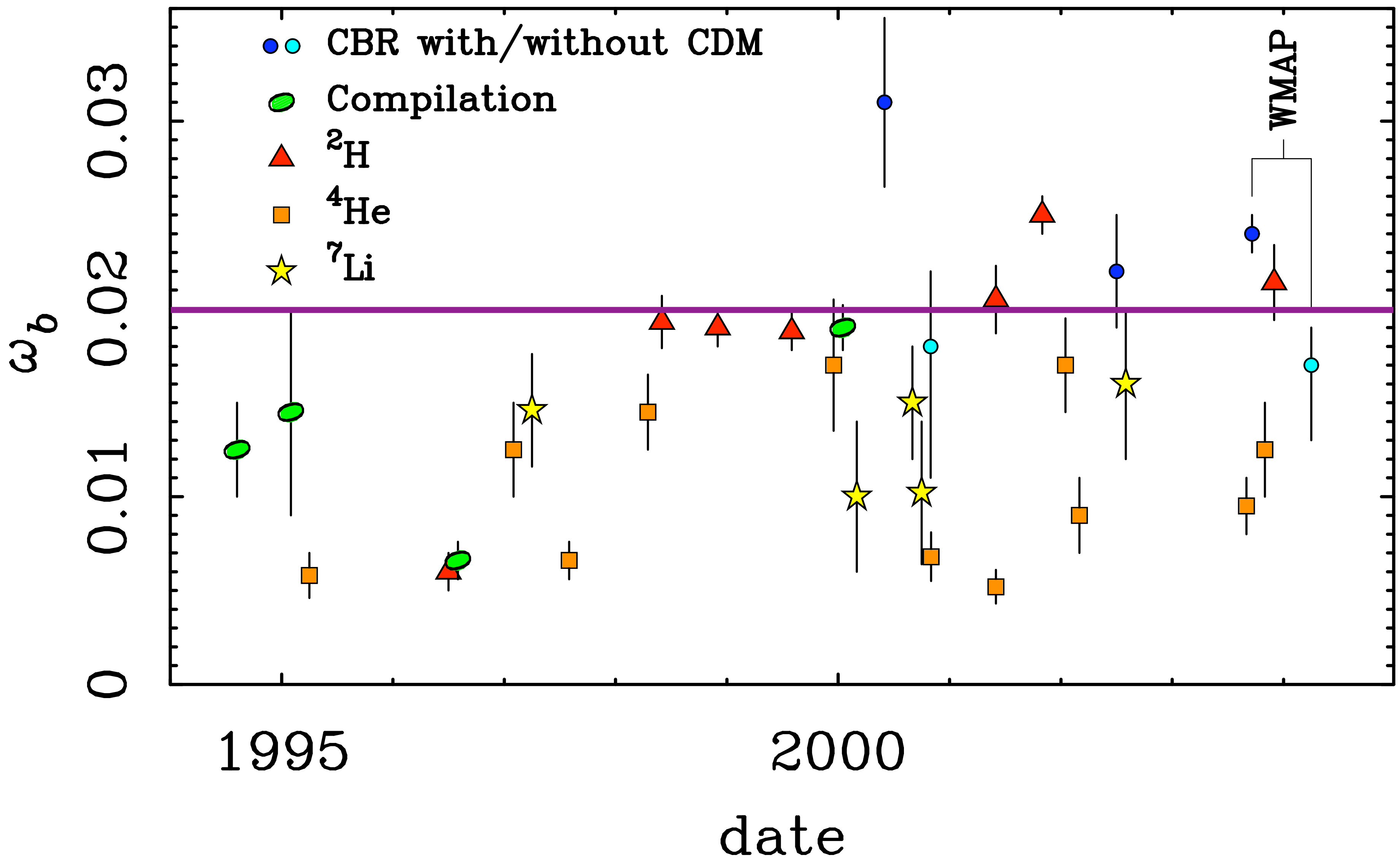


WMAP
ΛCDM 1999
No CDM 1999
$\ell(\ell+1)C_\ell^{TT}/2\pi$ (μK^2)
ℓ
0
2000
4000
6000
0
200
400
600
800

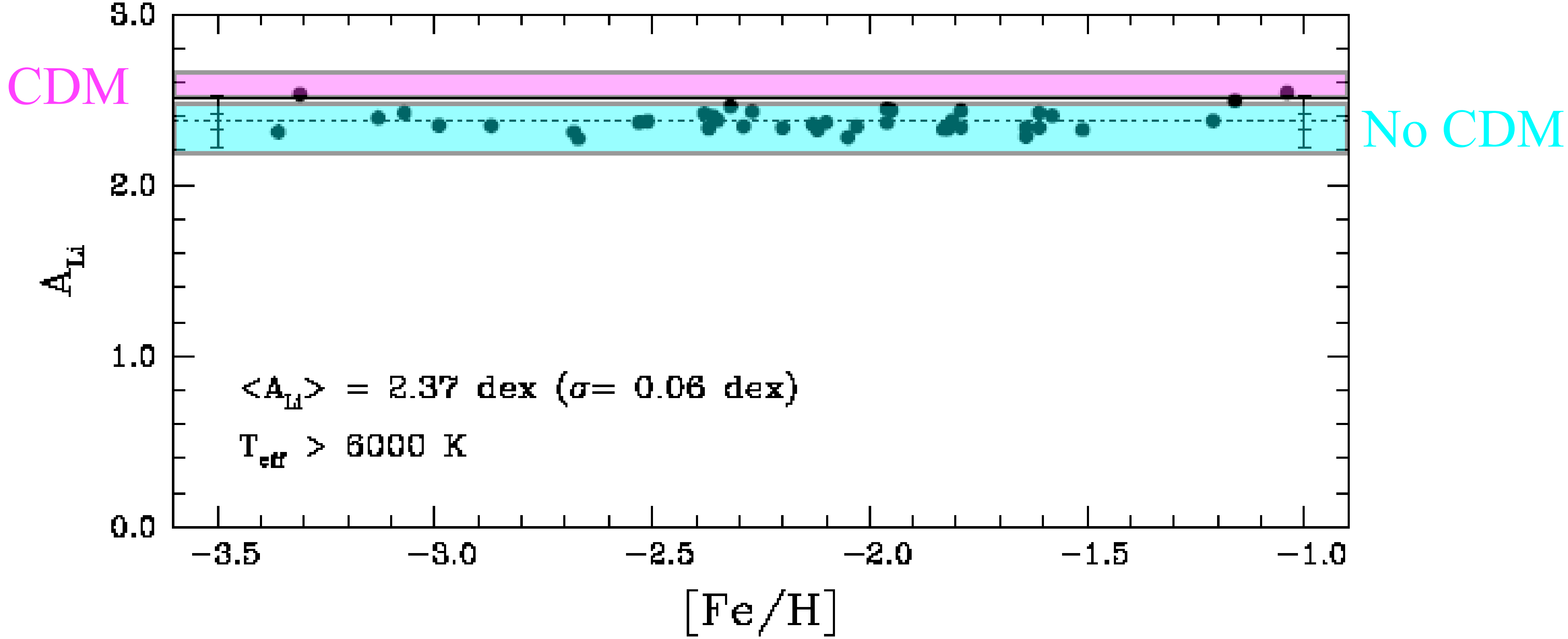


WMAP
WMAP fit
No CDM
$\ell(\ell+1)C_\ell^{TT}/2\pi$ (μK^2)
ℓ
0
2000
4000
6000
0
200
400
600
800

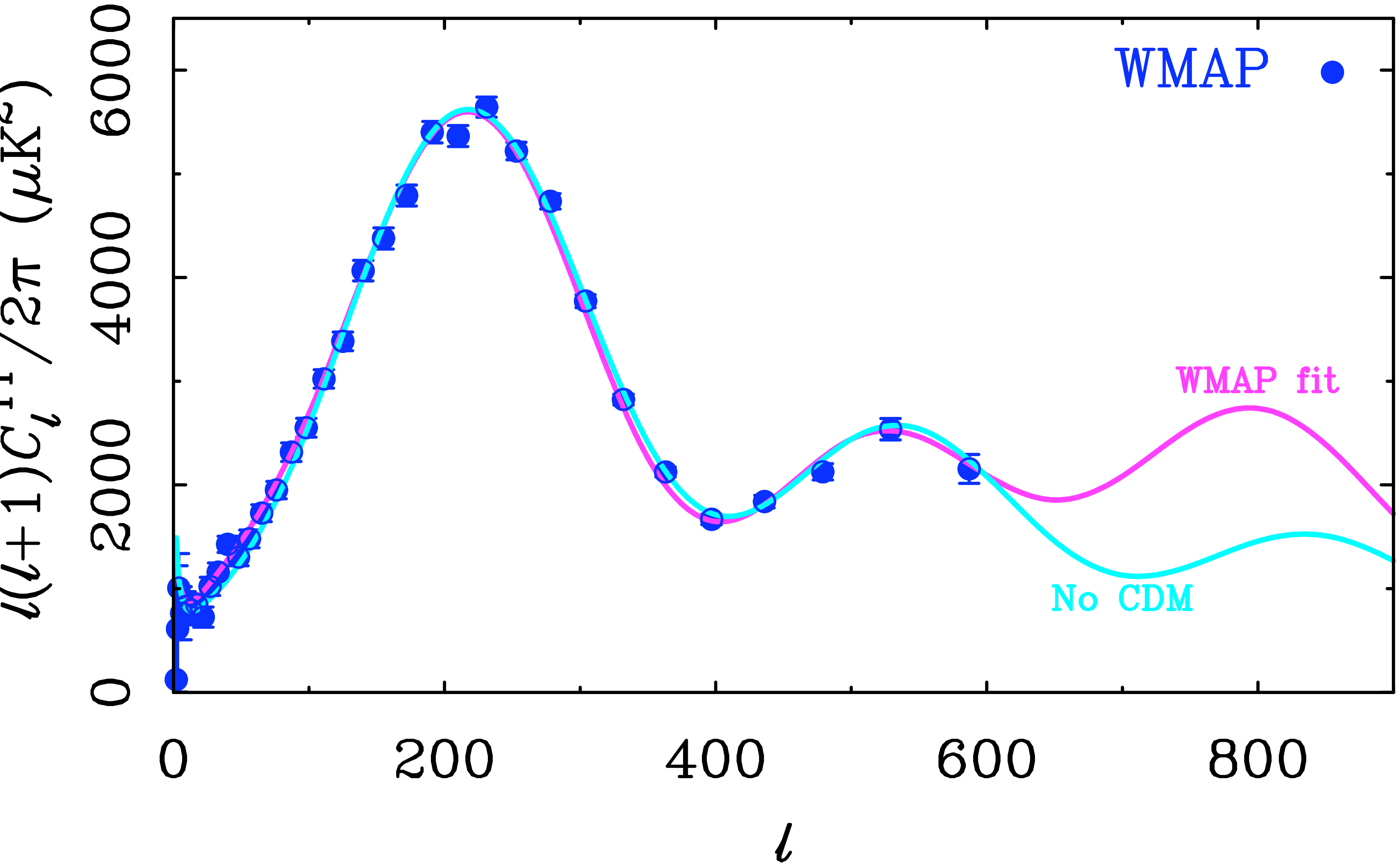
Baryon density from BBN



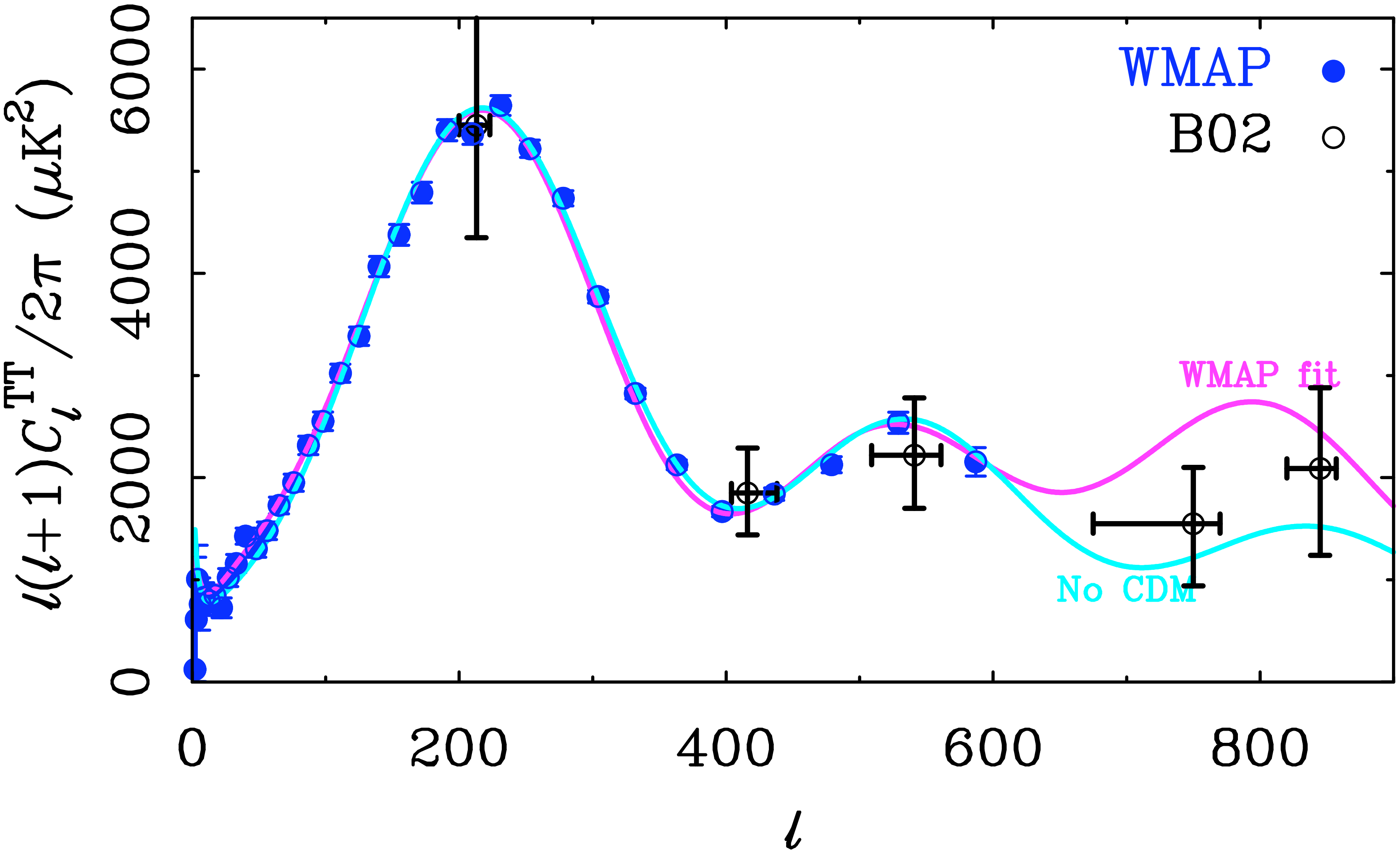
$$\omega_b = \Omega_b h^2$$



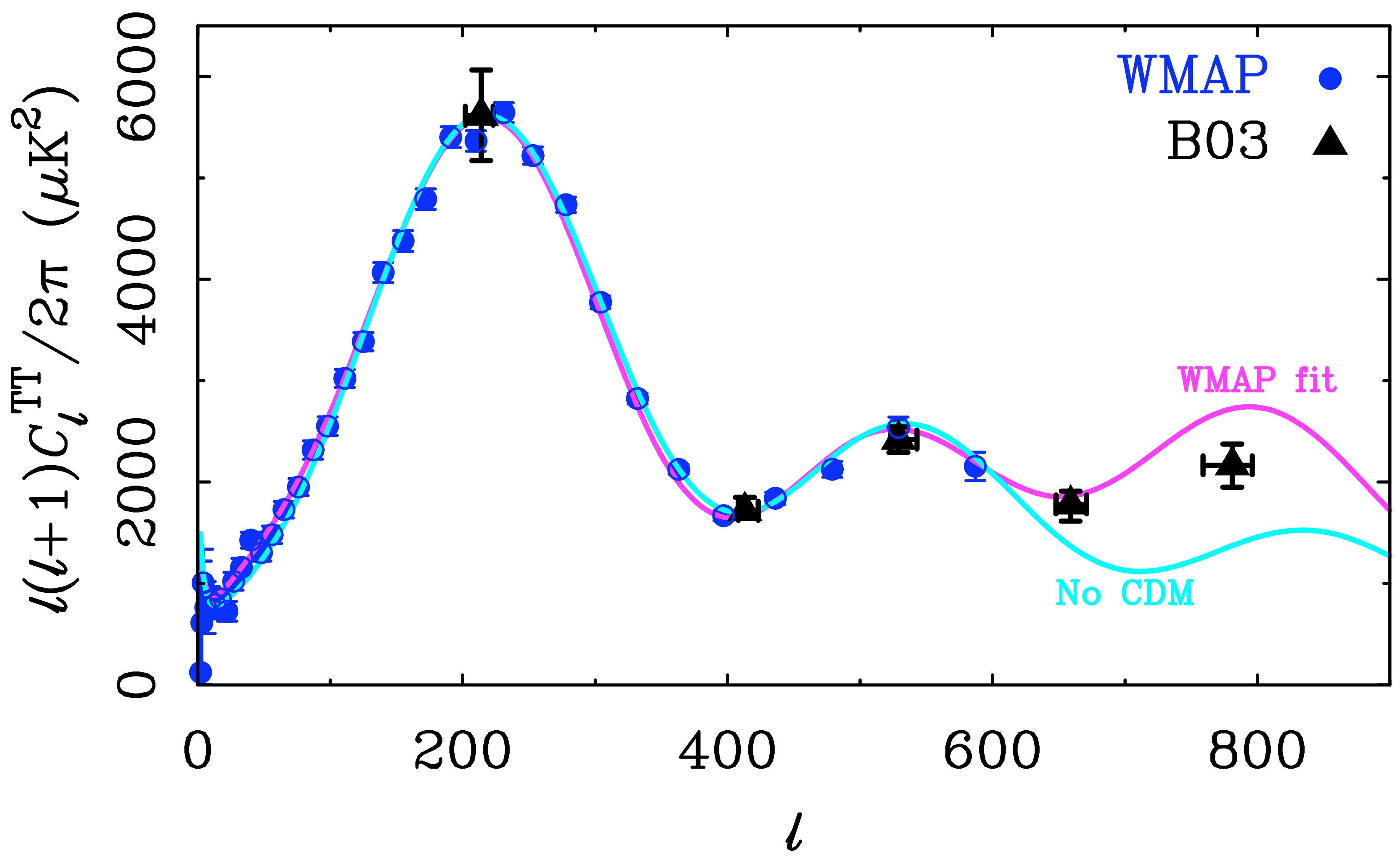
Melendez & Ramirez Astrophys.J. 615 (2004) L33



WMAP
WMAP fit
No CDM
$l(l+1)C_l^{TT}/2\pi\ (\mu K^2)$
l
0
2000
4000
6000
0
200
400
600
800



WMAP
B02
WMAP fit
No CDM
$\ell(\ell+1)C_\ell^{TT}/2\pi$ (μK^2)
ℓ
0
2000
4000
6000
0
200
400
600
800



WMAP
B03
WMAP fit
No CDM
0
2000
4000
6000
0
200
400
600
800
$\ell(\ell+1)C_\ell^{TT}/2\pi\ (\mu K^2)$
ℓ

Ways Out

- Detect Dark Matter in the laboratory
- Third peak of CBR power spectrum
- Neutrino mass (more/less than ~0.5 eV)
- Find systems MOND can't fit (clusters?)

TeVeS: Relativistic MOND?

"I think Bekenstein's March 04
paper changed the intellectual landscape. The
classic objection to McGaugh etc, that MOND is not a proper theory, is now void, and it is imperative that we discover whether Milgrom's theory is compatible with (a) CMB and (b) LSS. In view of the non-zero value of Lambda, which plainly states that minimal GR won't do, I consider that MOND now has the intellectual edge & should be taken very seriously indeed. The only problem is that I have yet to encounter someone who has taken up the challenge that Bekenstein has posed. This I feel reflects worse on the field than on MOND."

James Binney, August 3, 2004