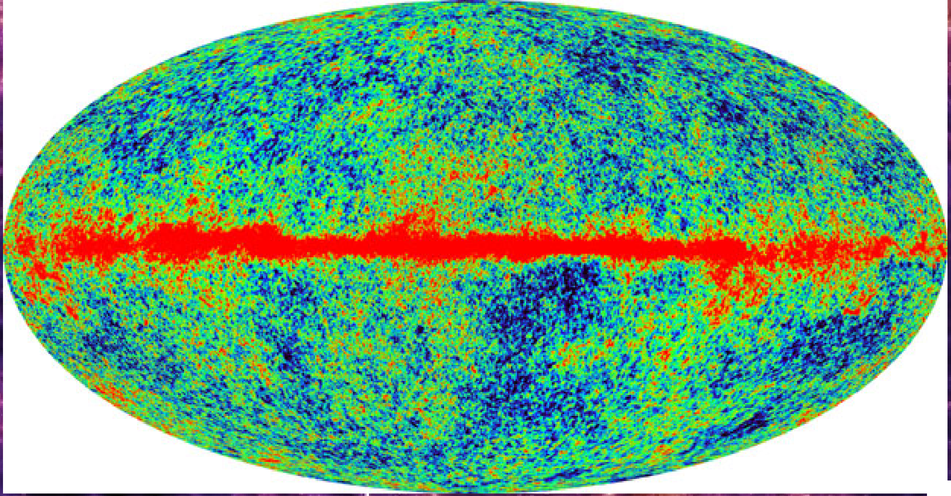
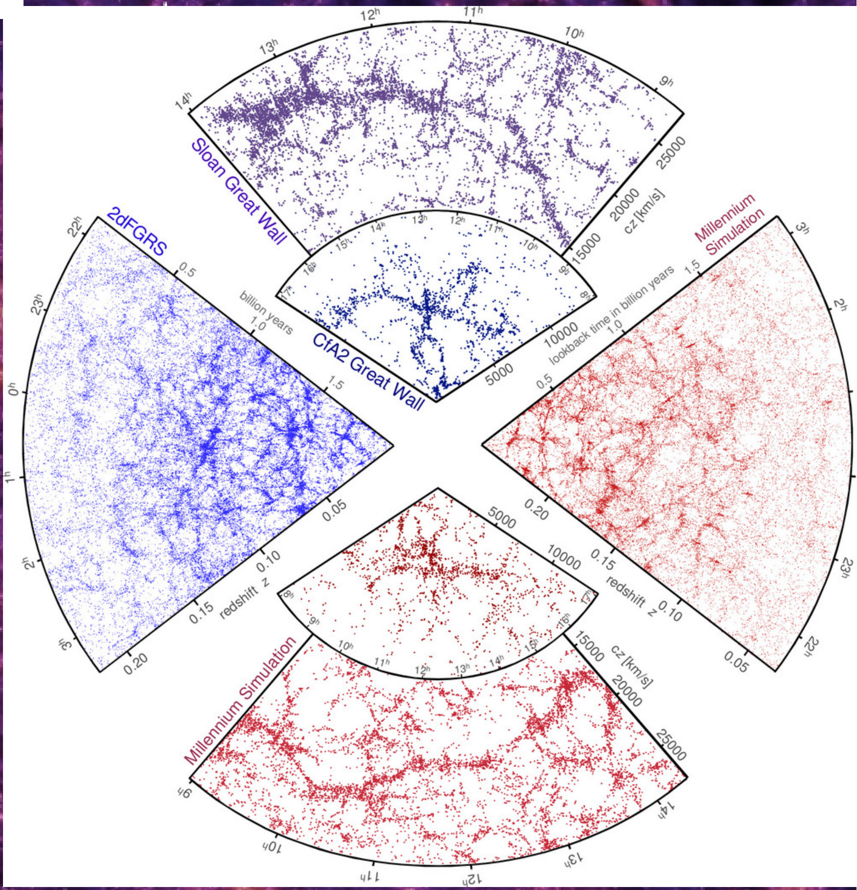
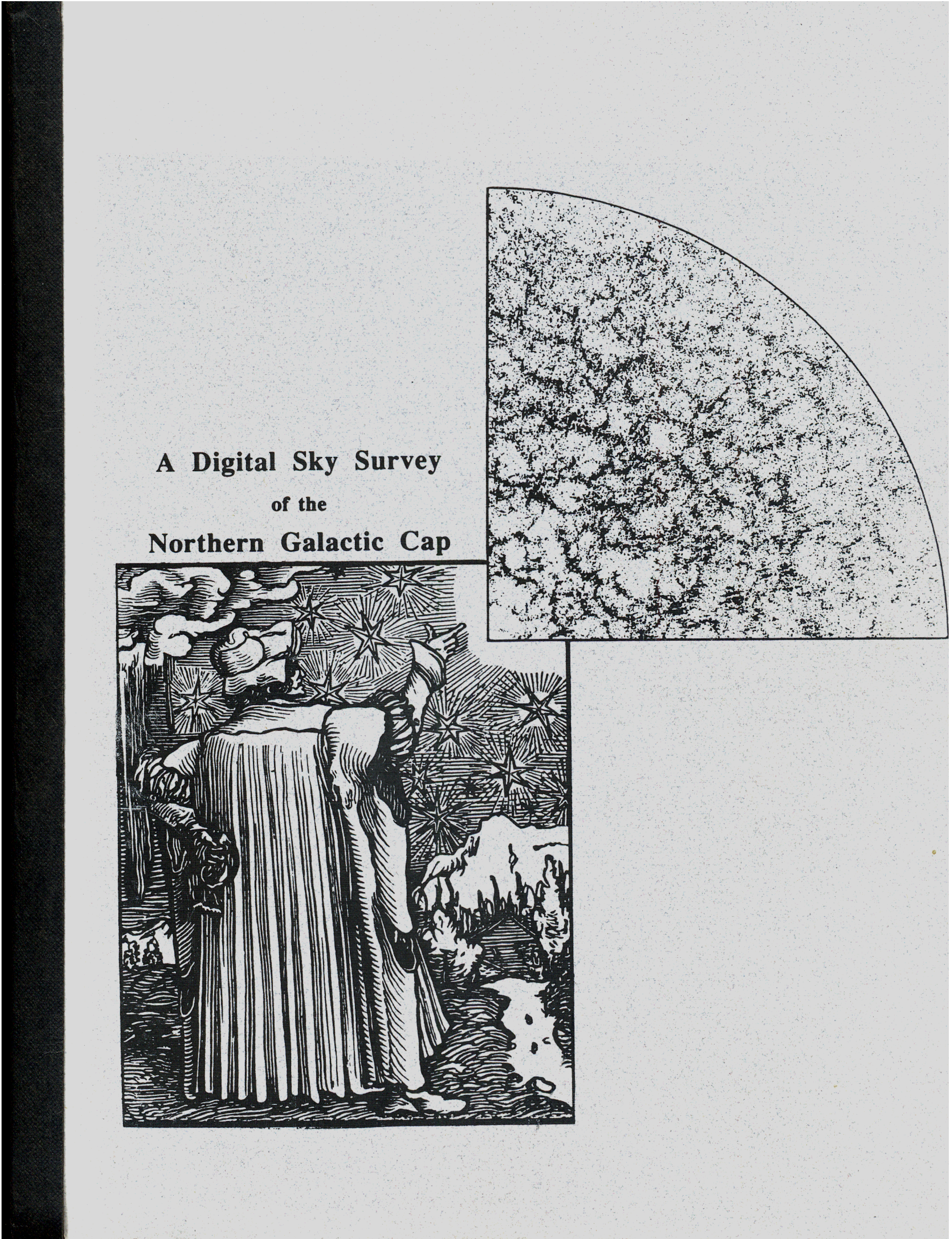


SDSS Symposium
Chicago
August 2008



Cosmic structure formation

Simon White
Max Planck Institut für Astrophysik



The Grey Book

(SDSS proposal to the NSF, 1993)

Grey Book Science Goals – Large Scale Structure

- Has structure grown through gravitational instability?
- What are the properties/origin of the primordial fluctuations?
- What is the dark matter?
- What are the values of Ω and Λ?

- How did galaxies form?
- What physics, other than gravity, played a role?
- What determines galaxy luminosity, size, color, morphology?
- What is the relation between the galaxy and mass distributions?

"Because galaxies are the markers by which we trace large scale structure, we cannot address the first category of questions without simultaneously addressing the second, especially the final question about galaxies and mass."

Grey Book Methods to achieve Science Goals

Survey Design

- Large-sky area, covering full north Galactic cap
  localised window function for P(k) measurements
- Full sampling of area both for photometry and spectroscopy
  sensitivity to *morphology* of large scale structure
- 5-band photometry to enable photo-z's
  increase volume and depth surveyed

Statistical tools

- Power spectra, correlation functions, redshift space distortions
- High order correlations, counts, void studies, morphology/topology
- Large scale flows
- Cluster abundance and evolution, cluster morphology
- QSO metal line clustering

MISSING! Ly α forest, gravitational lensing

LETTERS TO NATURE (1990)

The cosmological constant and cold dark matter

G. Efstathiou, W. J. Sutherland & S. J. Maddox

Department of Physics, University of Oxford, Oxford OX1 3RH, UK

THE cold dark matter (CDM) model[1–4] for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work[5–8] suggests that there is more cosmological structure on very large scales ($l > 10\ h^{-1}$ Mpc, where h is the Hubble constant H_0 in units of 100 km s^{-1} Mpc^{-1}) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

In 1993 there were no measures
- of CMB doppler peaks
- of an accelerated expansion
- of LBG's/Madau plots

Nevertheless, the ΛCDM model was already the *de facto* standard because of LSS studies

(There were also no exoplanets, star streams, Dark Energy or concordance cosmology!)

LETTERS TO NATURE (1990)

The cosmological constant and cold dark matter

G. Efstathiou, W. J. Sutherland & S. J. Maddox

Department of Physics, University of Oxford, Oxford OX1 3RH, UK

THE cold dark matter (CDM) model[1–4] for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work[5–8] suggests that there is more cosmological structure on very large scales ($l > 10\ h^{-1}$ Mpc, where h is the Hubble constant H_0 in units of 100 km s^{-1} Mpc^{-1}) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

LETTERS TO NATURE (1995)

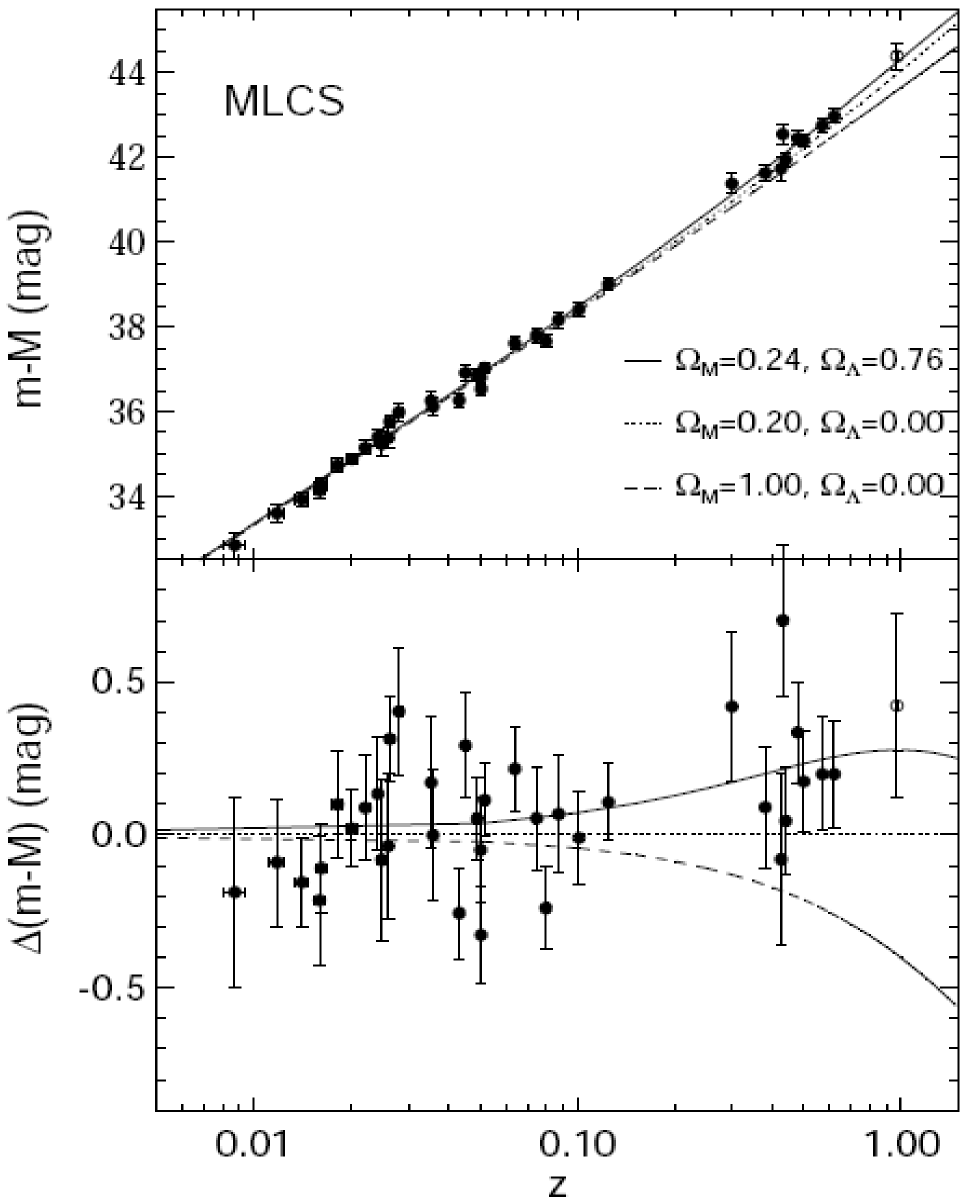
The observational case for a low-density Universe with a non-zero cosmological constant

J. P. Ostriker* & Paul J. Steinhardt†

* Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544, USA
† Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

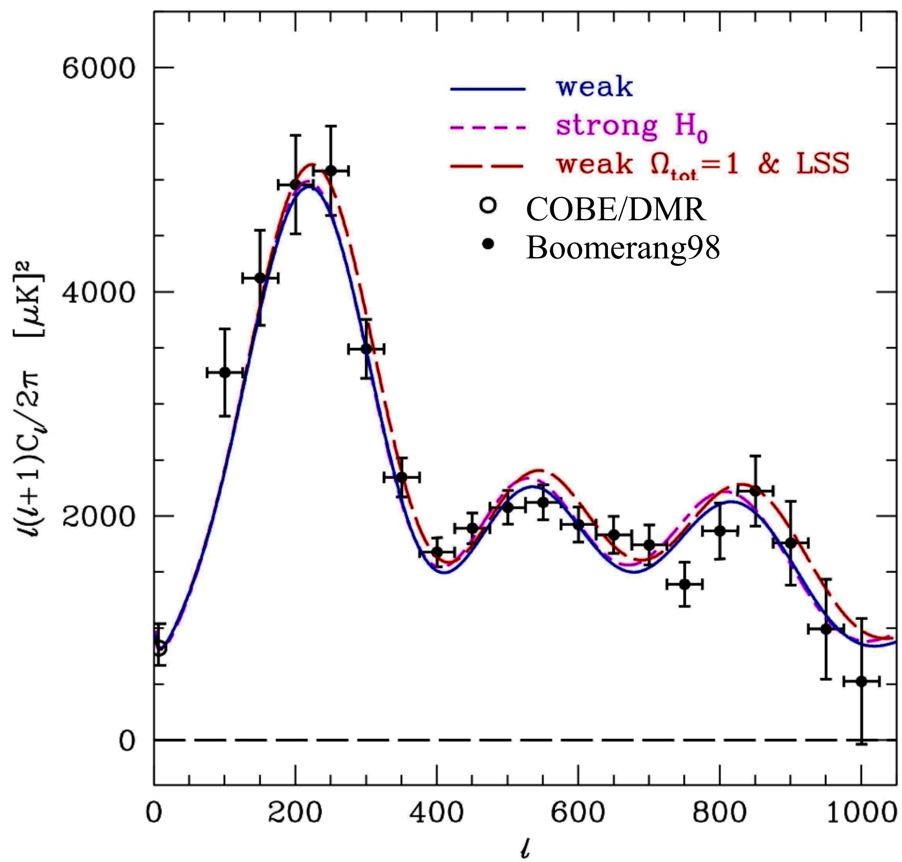
OBSERVATIONS are providing progressively tighter constraints on cosmological models advanced to explain the formation of large-scale structure in the Universe. These include recent determinations of the Hubble constant[1–3] (which quantifies the present expansion rate of the Universe) and measurements of the anisotropy of the cosmic microwave background[4,5]. Although the limits imposed by these diverse observations have occasionally led to suggestions[6] that cosmology is facing a crisis, we show here that there remains a wide range of cosmological models in good concordance with these constraints. The combined observations point to models in which the matter density of the Universe falls well below the critical energy density required to halt its expansion. But they also permit a substantial contribution to the energy density from the vacuum itself (a positive 'cosmological constant'), sufficient to recover the critical density favoured by the simplest inflationary models. The observations do not yet rule out the possibility that we live in an ever-expanding 'open' Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favoured.

Riess et al 1998

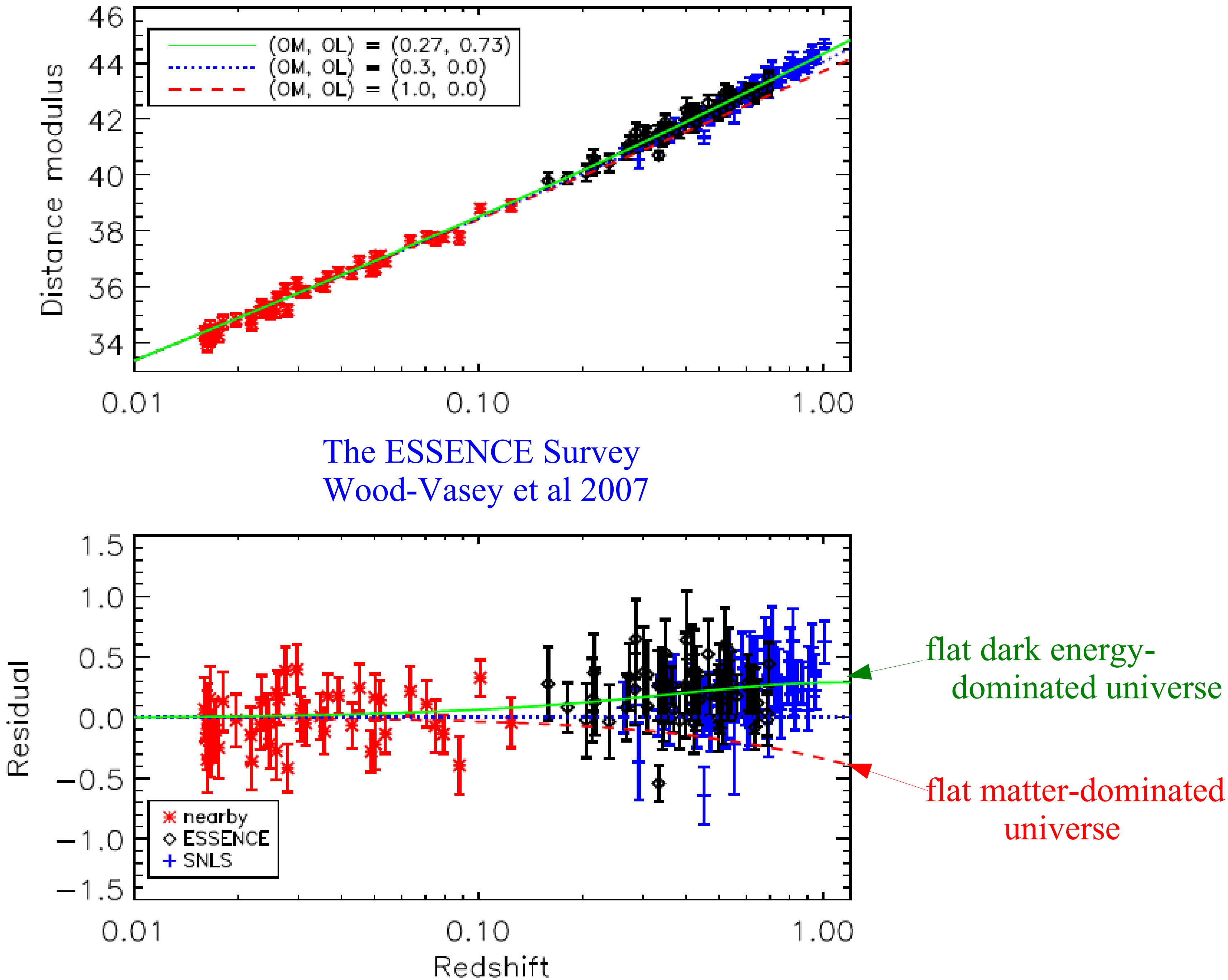


The expansion is accelerating

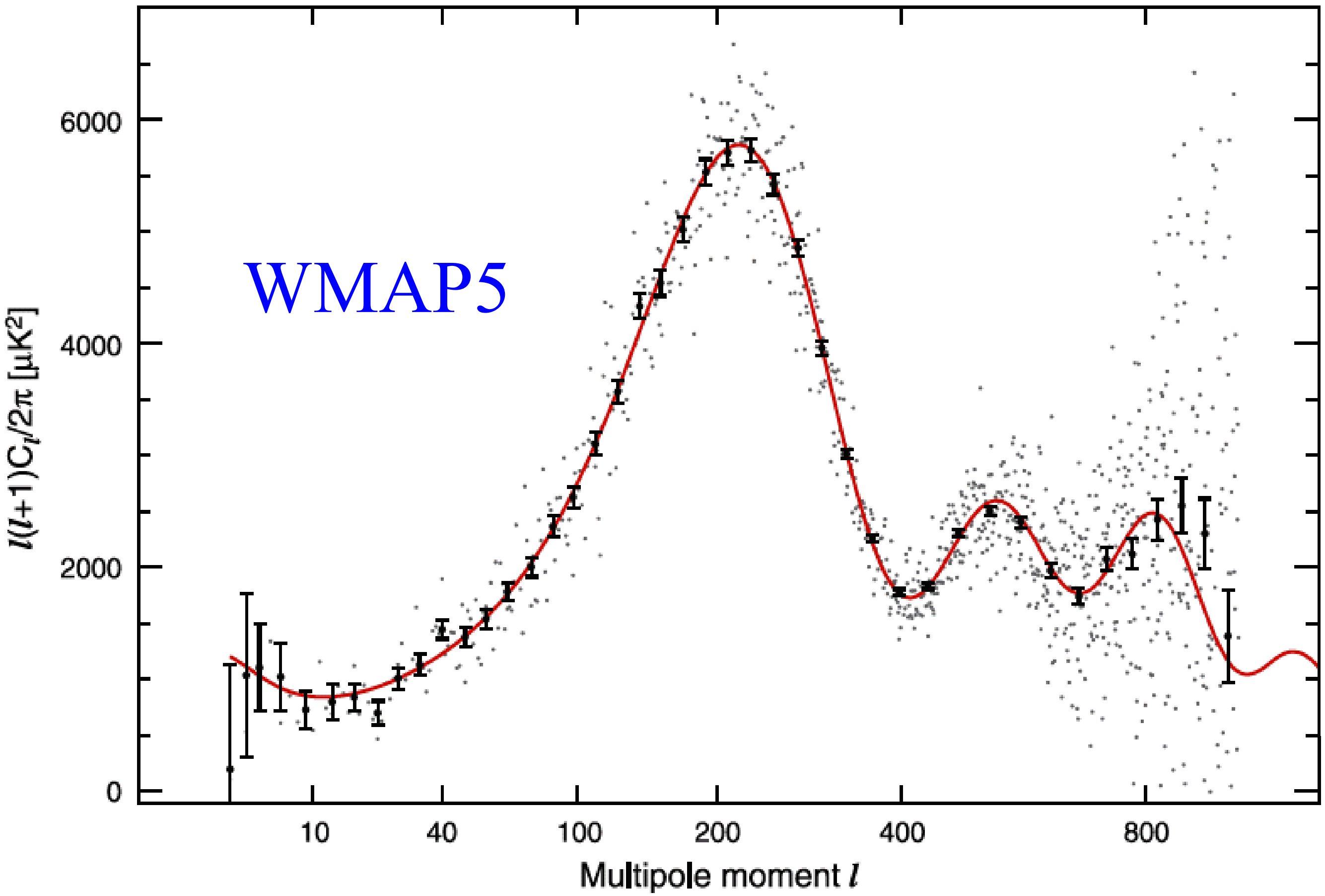
Netterfield et al 2002

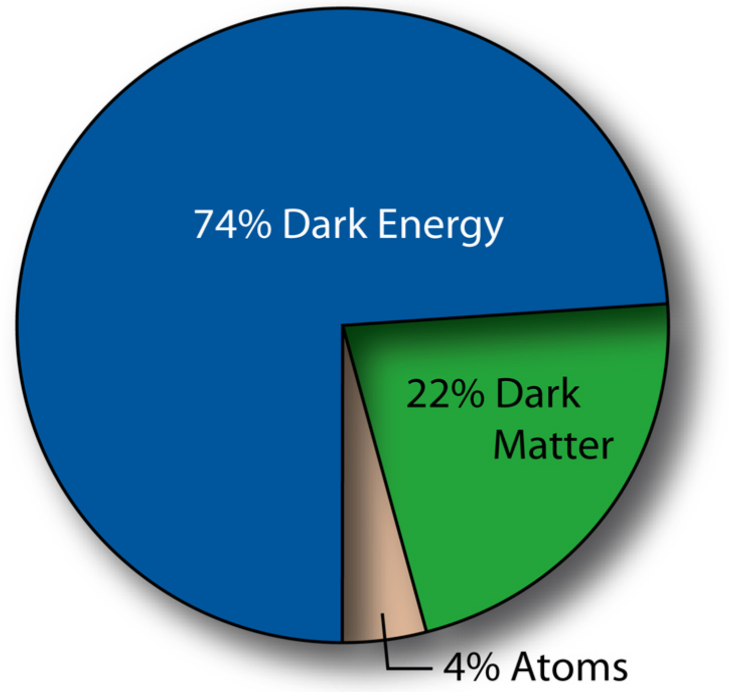


The Universe is flat

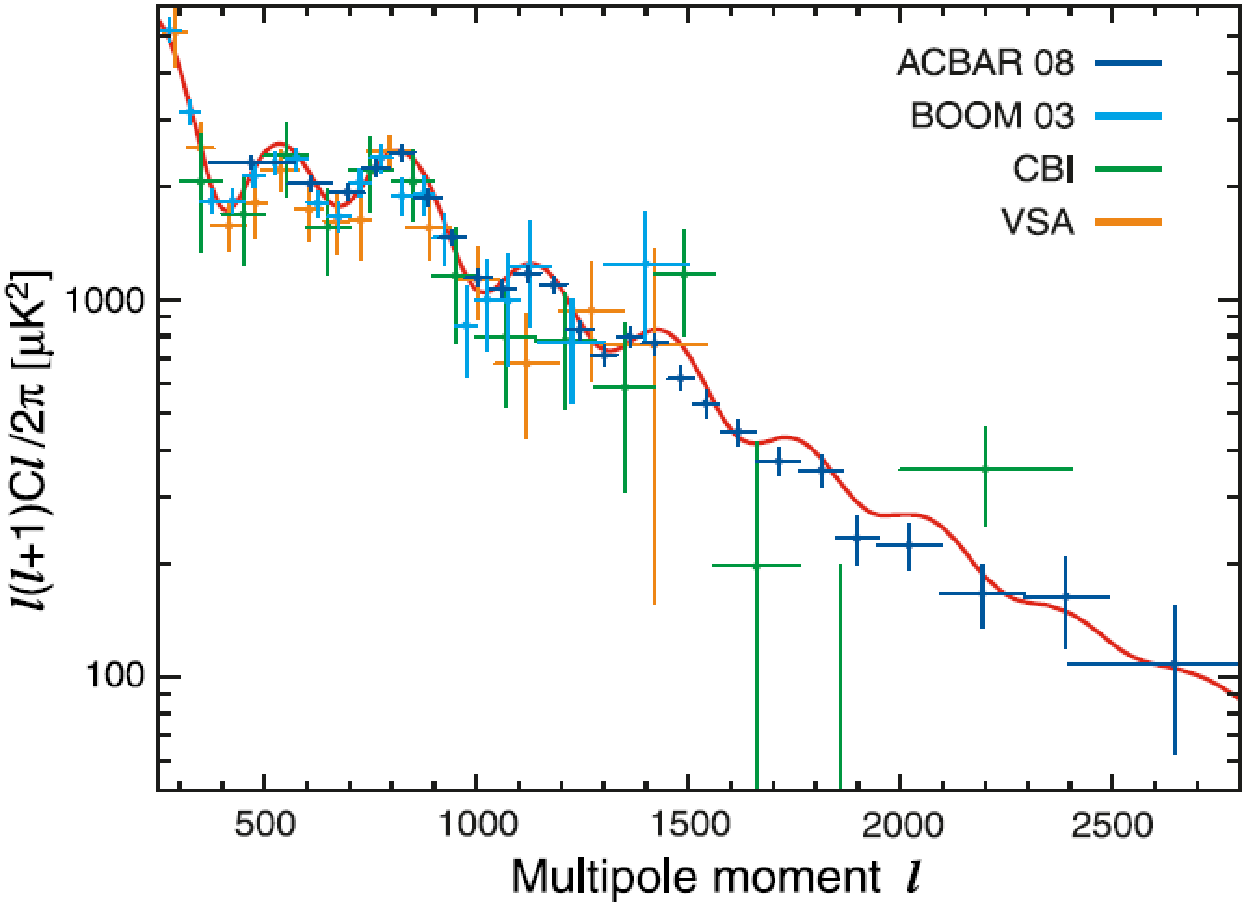


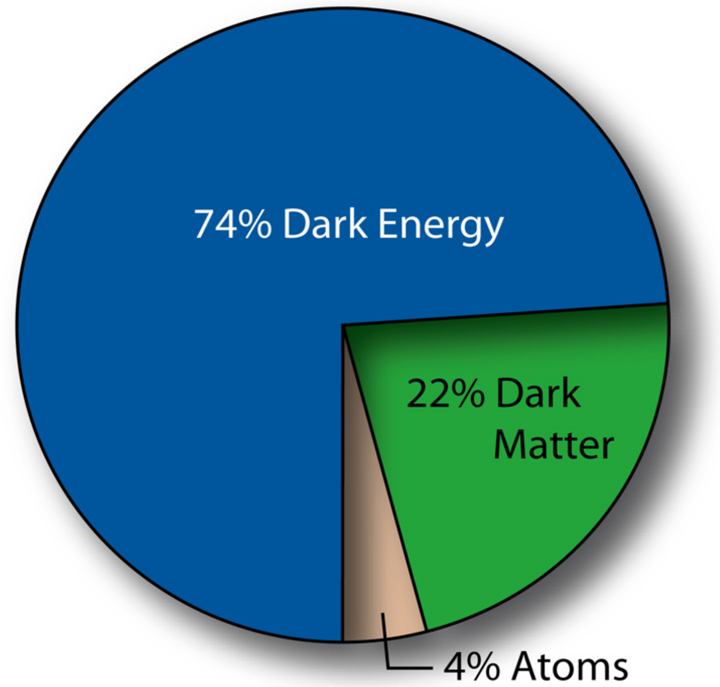
46
44
42
40
38
36
34
Distance modulus
(OM, OL) = (0.27, 0.73)
(OM, OL) = (0.3, 0.0)
(OM, OL) = (1.0, 0.0)
0.01
0.10
1.00
The ESSENCE Survey
Wood-Vasey et al 2007
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Residual
nearby
ESSENCE
SNLS
0.01
0.10
1.00
Redshift
flat dark energy-
dominated universe
flat matter-dominated
universe



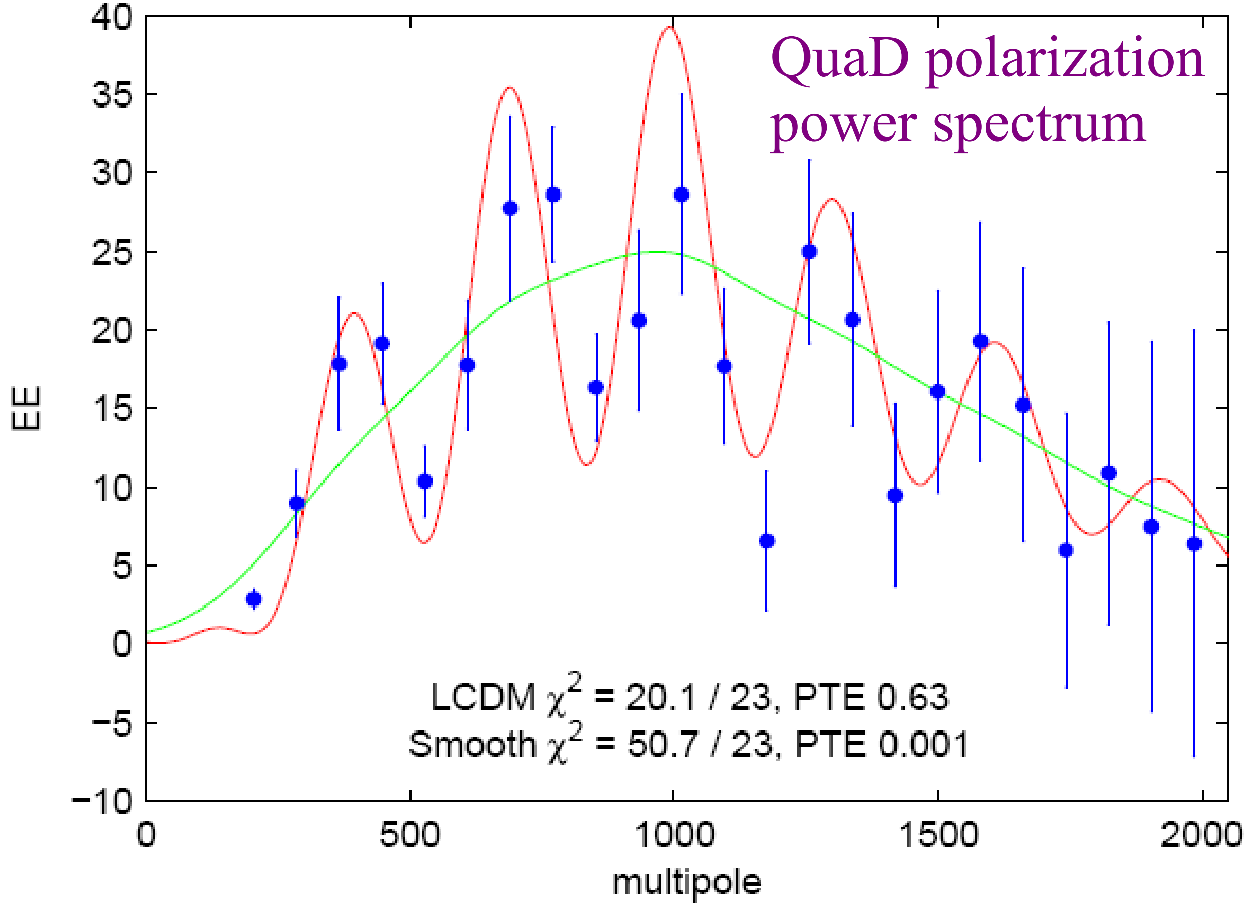


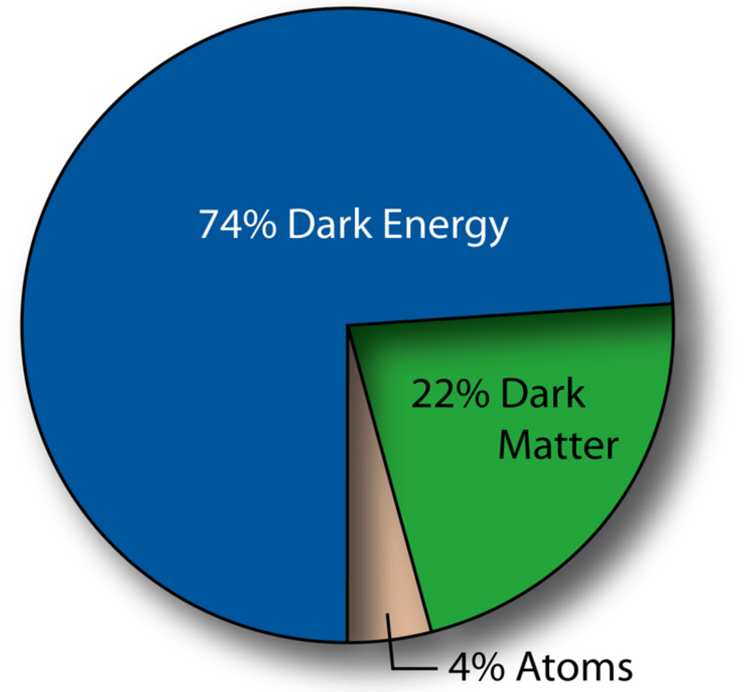
parameter	symbol	WMAP-5 alone	WMAP-5 + BAO + SNe	comment
CMB temperature	T_{CMB}	2.728 ± 0.004 K	–	from (Fixsen *et al.* 1996)
total matter density	Ω_{tot}	$1.099\ ^{+0.100}_{-0.085}$	1.0052 ± 0.0064	
matter density	Ω_{m0}	0.258 ± 0.03	0.279 ± 0.015	assuming spatial flatness
baryon density	Ω_{b0}	0.0441 ± 0.0030	0.0462 ± 0.0015	here and below
cosmological constant	$\Omega_{\Lambda 0}$	0.742 ± 0.03	0.721 ± 0.015	
Hubble constant	h	$0.719\ ^{+0.026}_{-0.027}$	0.701 ± 0.013	
power-spectrum normalisation	σ_8	0.796 ± 0.036	0.817 ± 0.026	
age of the Universe in Gyr	t_0	13.69 ± 0.13	13.73 ± 0.12	
decoupling redshift	z_{dec}	1087.9 ± 1.2	1088.2 ± 1.1	
reionisation optical depth	τ	0.087 ± 0.017	0.084 ± 0.016	
spectral index	n_{s}	$0.963\ ^{+0.014}_{-0.015}$	$0.960\ ^{+0.014}_{-0.013}$	





parameter	symbol	WMAP-5 alone	WMAP-5 + BAO + SNe	comment
CMB temperature	$T_{\rm CMB}$	2.728 ± 0.004 K	–	from (Fixsen *et al.* 1996)
total matter density	$\Omega_{\rm tot}$	$1.099\ ^{+0.100}_{-0.085}$	1.0052 ± 0.0064	
matter density	$\Omega_{\rm m0}$	0.258 ± 0.03	0.279 ± 0.015	assuming spatial flatness
baryon density	$\Omega_{\rm b0}$	0.0441 ± 0.0030	0.0462 ± 0.0015	here and below
cosmological constant	$\Omega_{\Lambda 0}$	0.742 ± 0.03	0.721 ± 0.015	
Hubble constant	h	$0.719\ ^{+0.026}_{-0.027}$	0.701 ± 0.013	
power-spectrum normalisation	σ_8	0.796 ± 0.036	0.817 ± 0.026	
age of the Universe in Gyr	t_0	13.69 ± 0.13	13.73 ± 0.12	
decoupling redshift	$z_{\rm dec}$	1087.9 ± 1.2	1088.2 ± 1.1	
reionisation optical depth	τ	0.087 ± 0.017	0.084 ± 0.016	
spectral index	$n_{\rm s}$	$0.963\ ^{+0.014}_{-0.015}$	$0.960\ ^{+0.014}_{-0.013}$	





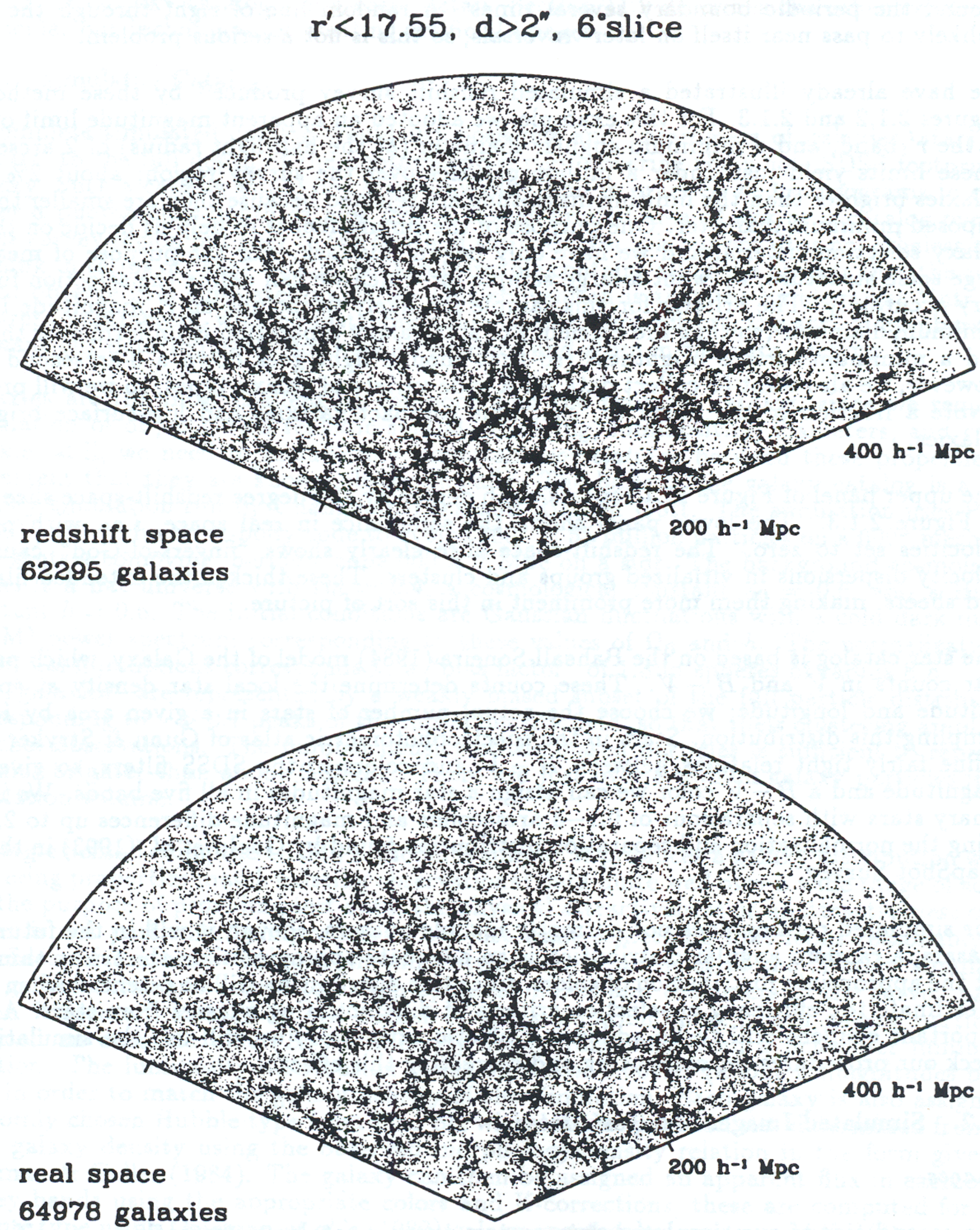
parameter	symbol	WMAP-5 alone	WMAP-5 + BAO + SNe	comment
CMB temperature	$T_{\rm CMB}$	2.728 ± 0.004 K	–	from (Fixsen *et al.* 1996)
total matter density	$\Omega_{\rm tot}$	$1.099^{+0.100}_{-0.085}$	1.0052 ± 0.0064	
matter density	$\Omega_{\rm m0}$	0.258 ± 0.03	0.279 ± 0.015	assuming spatial flatness
baryon density	$\Omega_{\rm b0}$	0.0441 ± 0.0030	0.0462 ± 0.0015	here and below
cosmological constant	$\Omega_{\Lambda 0}$	0.742 ± 0.03	0.721 ± 0.015	
Hubble constant	h	$0.719^{+0.026}_{-0.027}$	0.701 ± 0.013	
power-spectrum normalisation	σ_8	0.796 ± 0.036	0.817 ± 0.026	
age of the Universe in Gyr	t_0	13.69 ± 0.13	13.73 ± 0.12	
decoupling redshift	$z_{\rm dec}$	1087.9 ± 1.2	1088.2 ± 1.1	
reionisation optical depth	τ	0.087 ± 0.017	0.084 ± 0.016	
spectral index	$n_{\rm s}$	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$	

Grey Book Simulations

Park & Gott 1993

PM with N = 5.5×10^7, ε = 1 Mpc,

$\Omega_m = 0.4$, $\Omega_\Lambda = 0.6$, $\sigma_8 = 0.76$

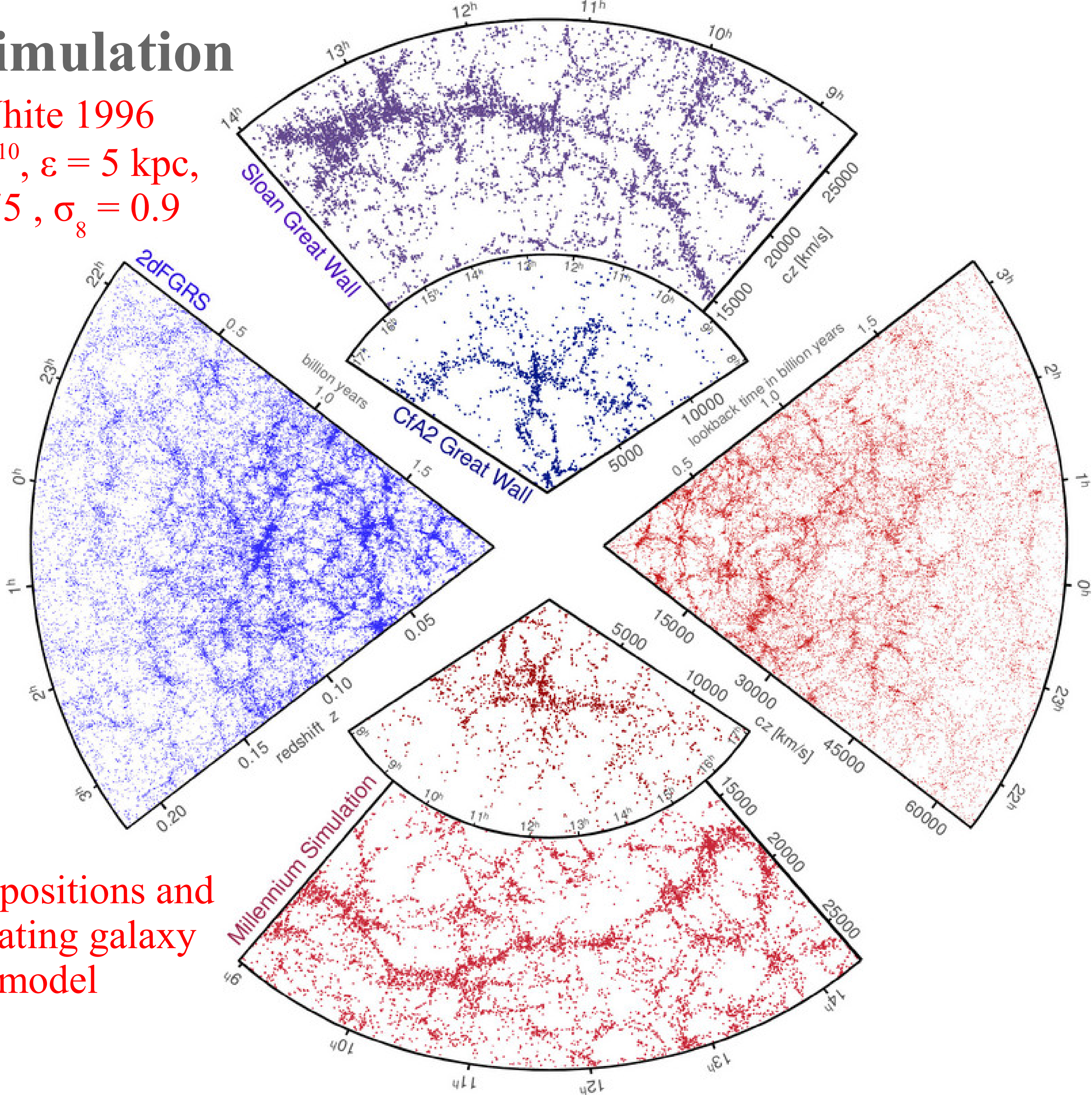


Galaxy luminosities, positions and velocities from a statistical bias recipe

Figure 11.1 Slices from a simulation of the SDSS redshift survey. The upper panel (repeated from Figure 2.1.3) shows a 6 degree by 130 degree slice in redshift space – each point represents a galaxy, plotted at the distance indicated by its redshift. The lower panel shows the same slice in real space, with no peculiar velocity effects.

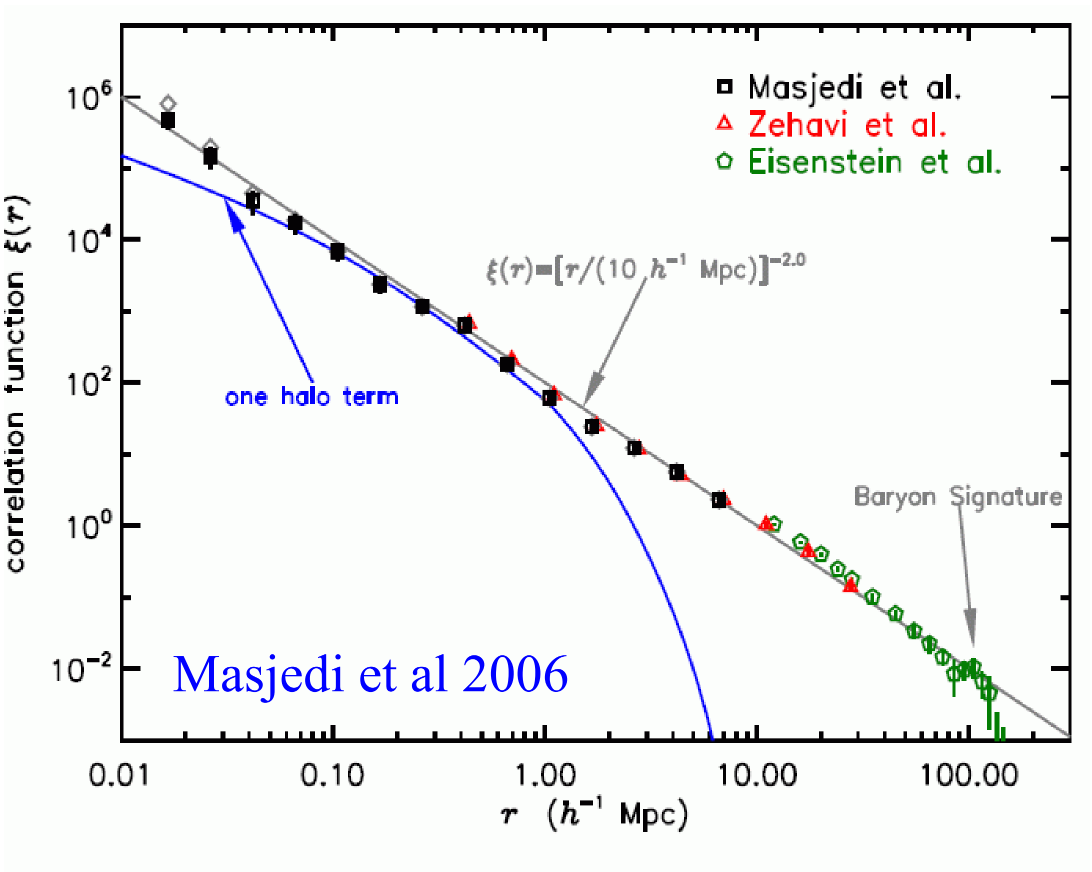
Millennium Simulation

Springel, Frenk & White 1996
TreePM with $N = 10^{10}$, $\varepsilon = 5$ kpc,
$\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $\sigma_8 = 0.9$

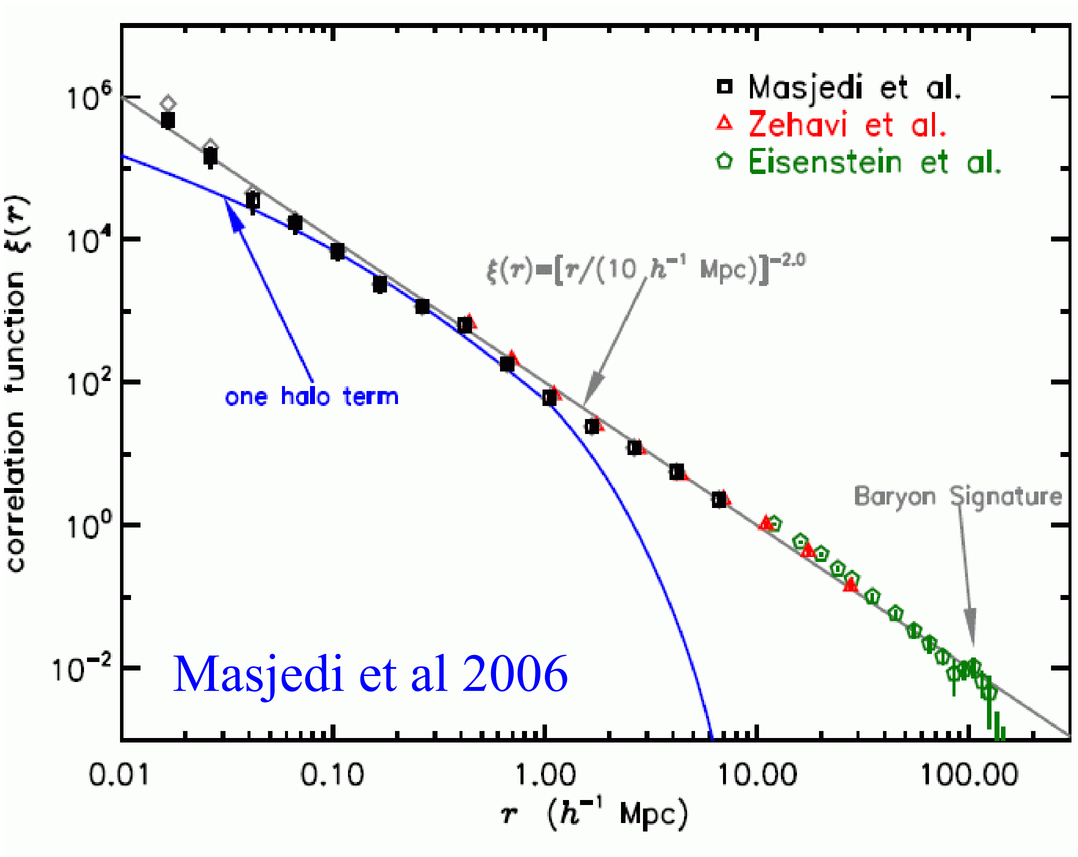


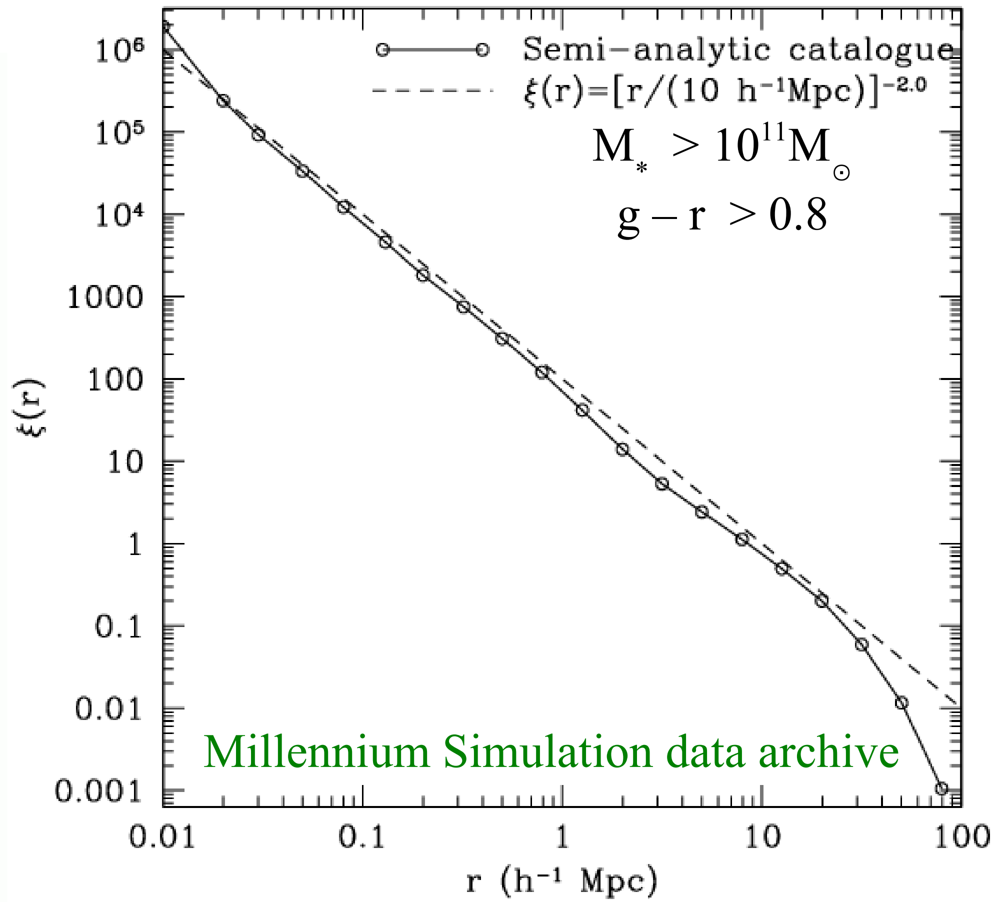
Galaxy luminosities, positions and velocities from simulating galaxy formation within the model

SDSS estimates "classical" clustering measures with extraordinary precision: e. g. LRG correlations....



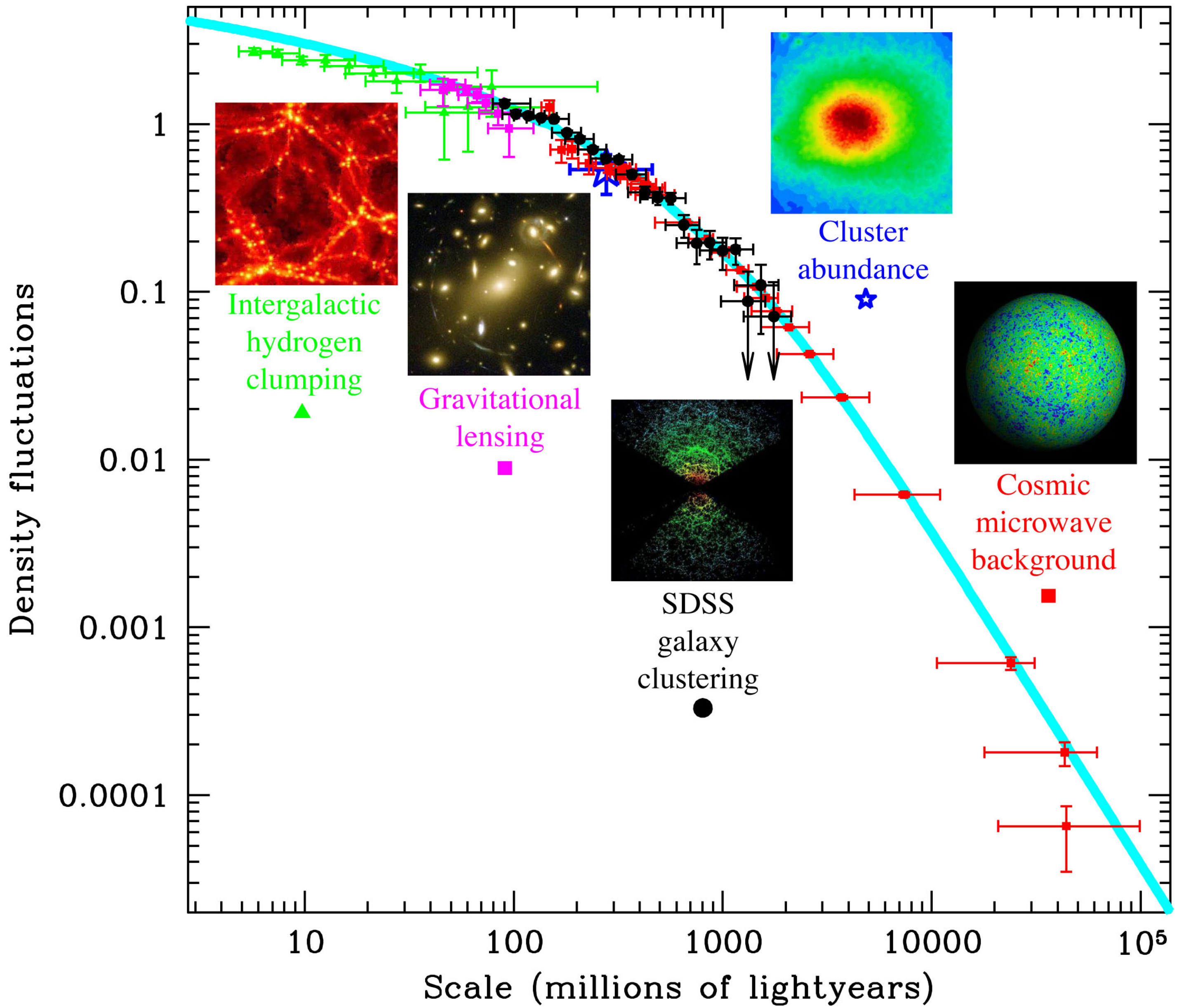
SDSS estimates "classical" clustering measures with extraordinary precision: e. g. LRG correlations....





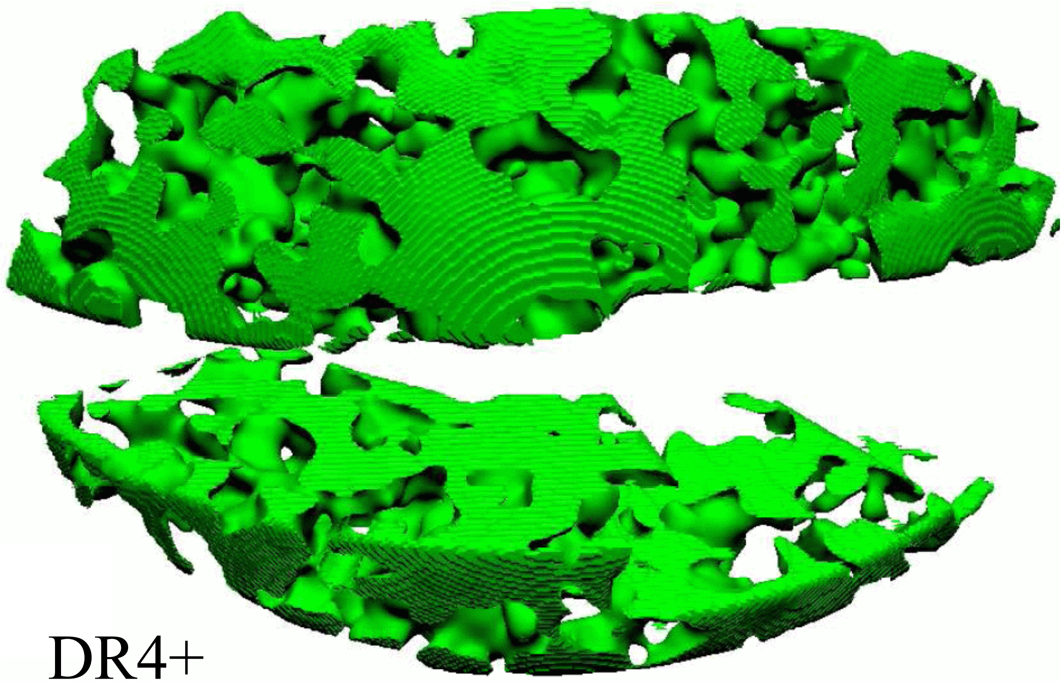
....so they constrain galaxy and structure formation strongly on both linear and nonlinear scales

The Tegmark representation of power spectrum data (2006)

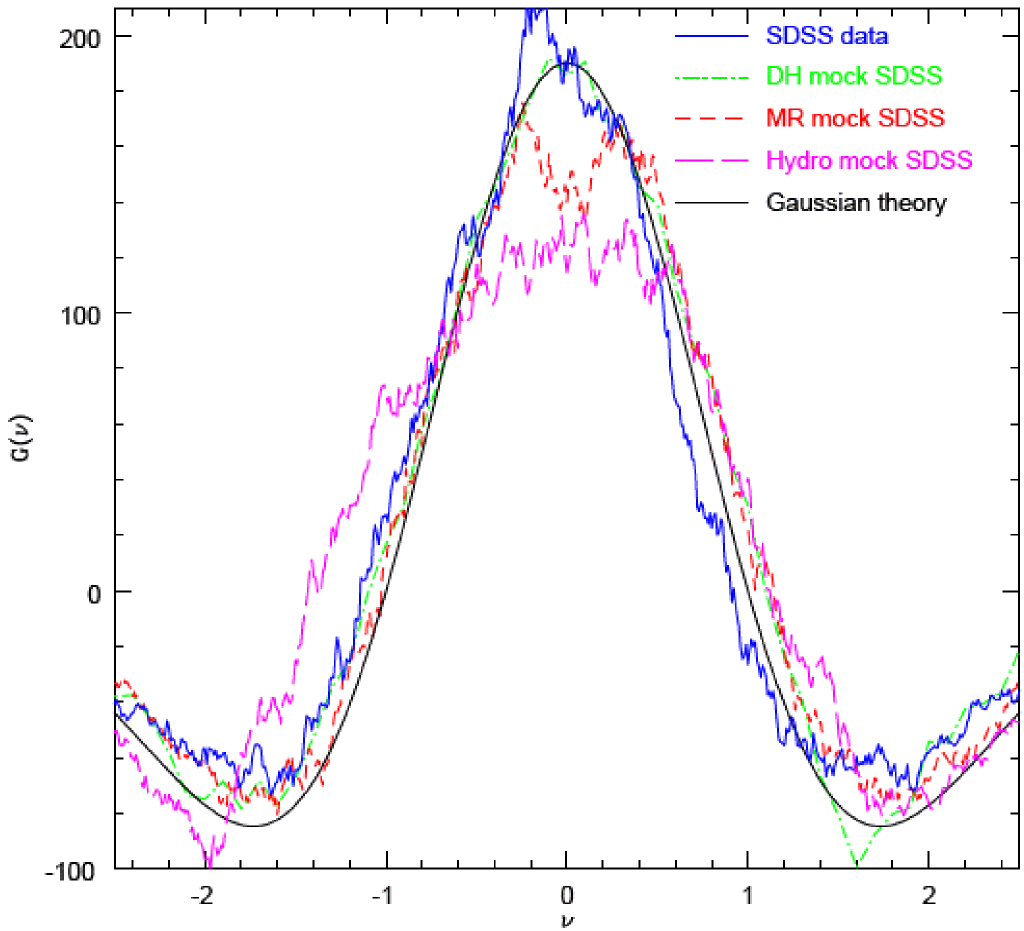


SDSS enables a good measurement of the topology of LSS

Gott et al 2008

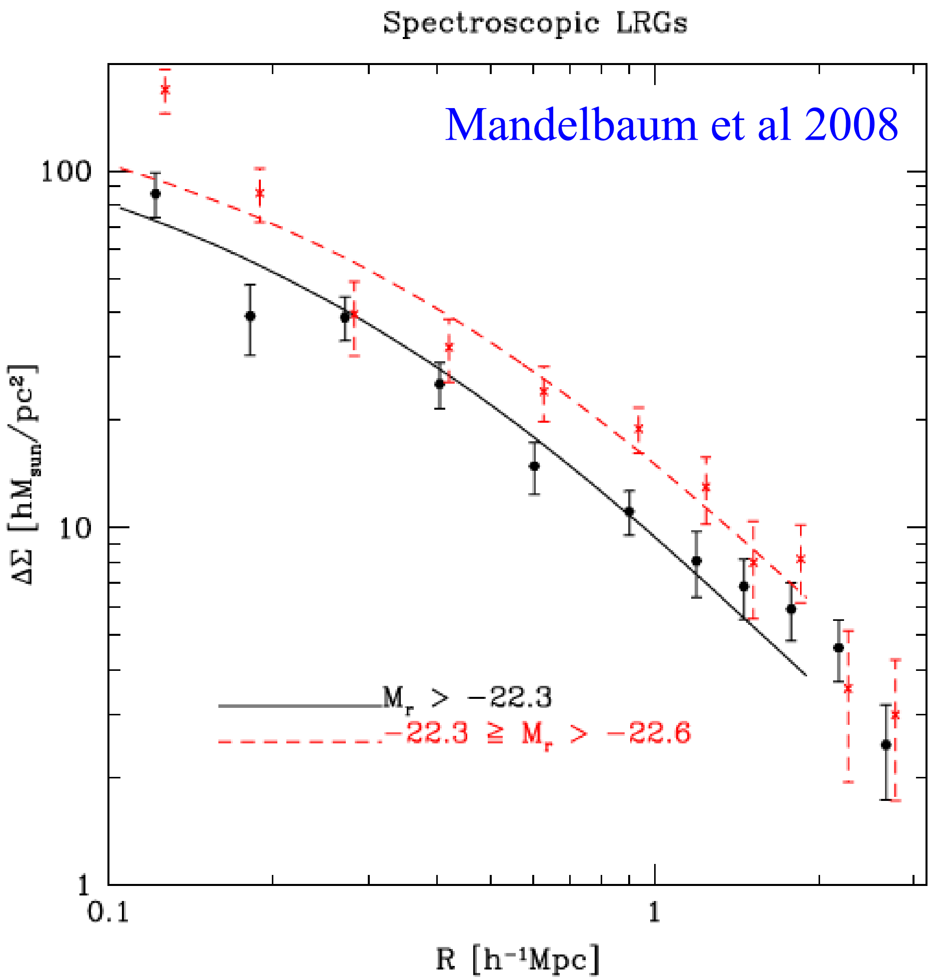


DR4+
6 Mpc/h smoothing

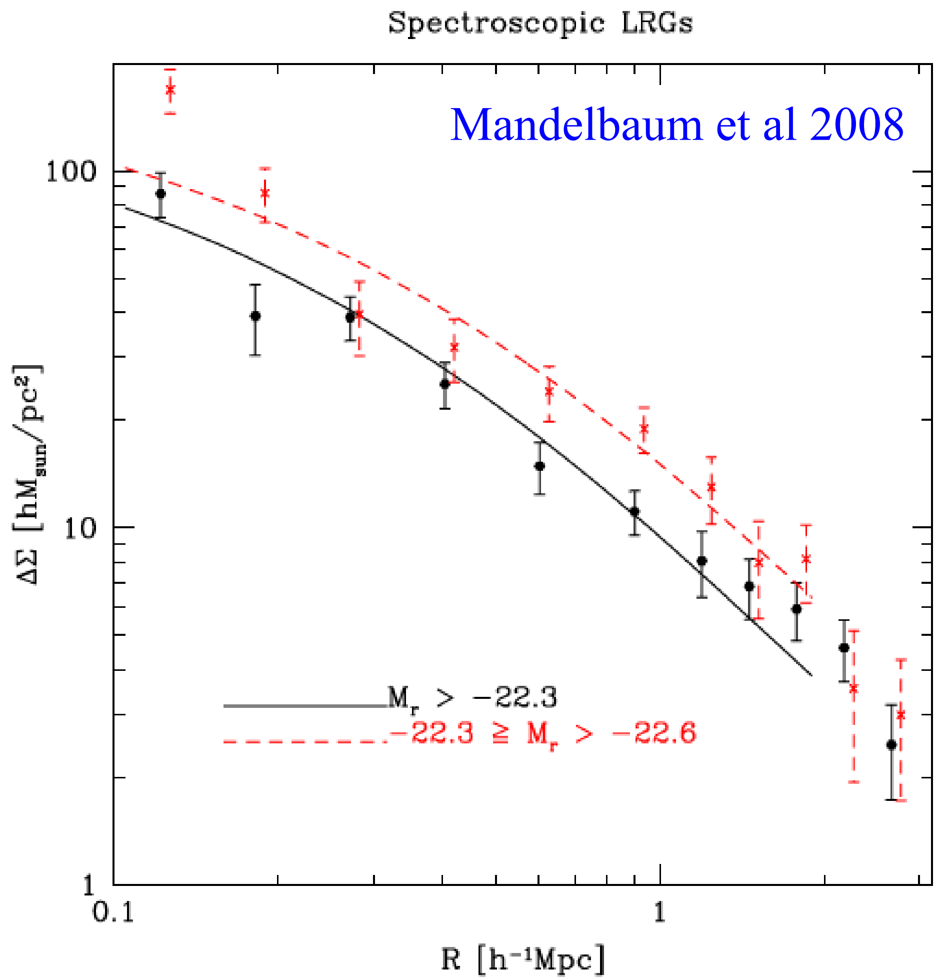


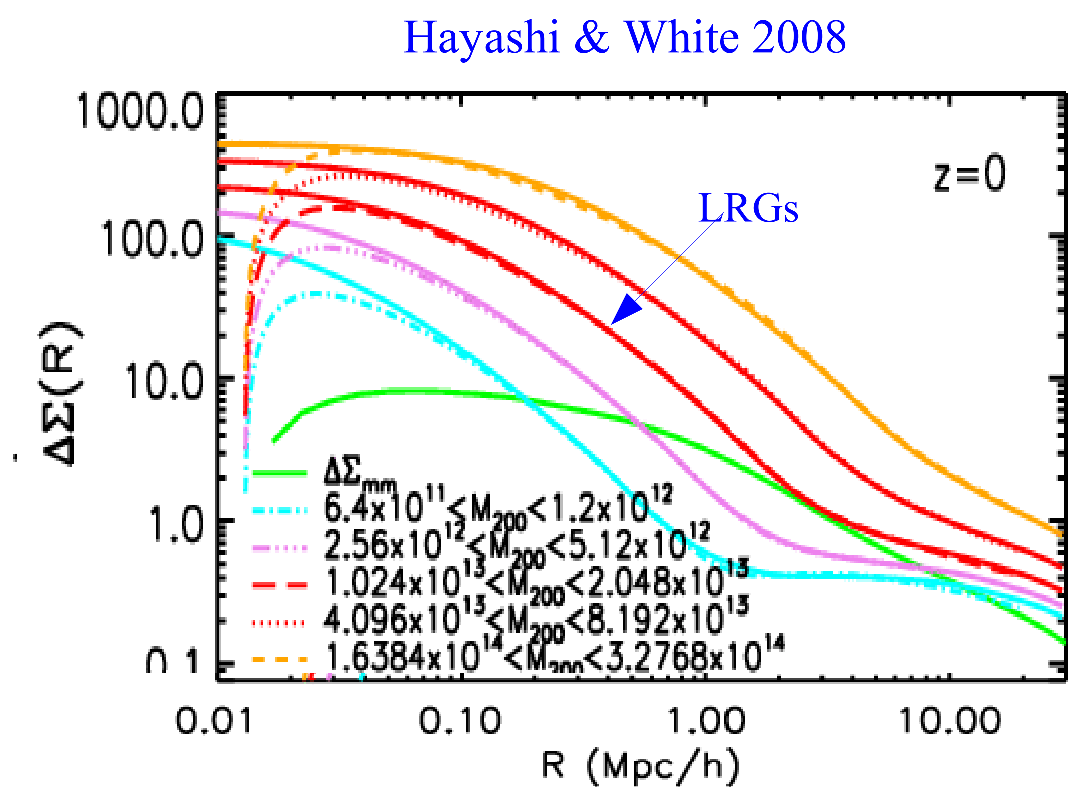
Genus curve agrees well in amplitude and shape with ΛCDM predictions, but it shows a shift to negative ν whereas the simulations show a slight shift towards positive ν

Galaxy-galaxy lensing around isolated LRGs gives the mean surface density profile of their halos: $\Delta\Sigma = \overline{\Sigma}(r_p) - \Sigma(r_p)$



Galaxy-galaxy lensing around isolated LRGs gives the mean surface density profile of their halos: $\Delta\Sigma = \overline{\Sigma}\,(r_p) - \Sigma\,(r_p)$

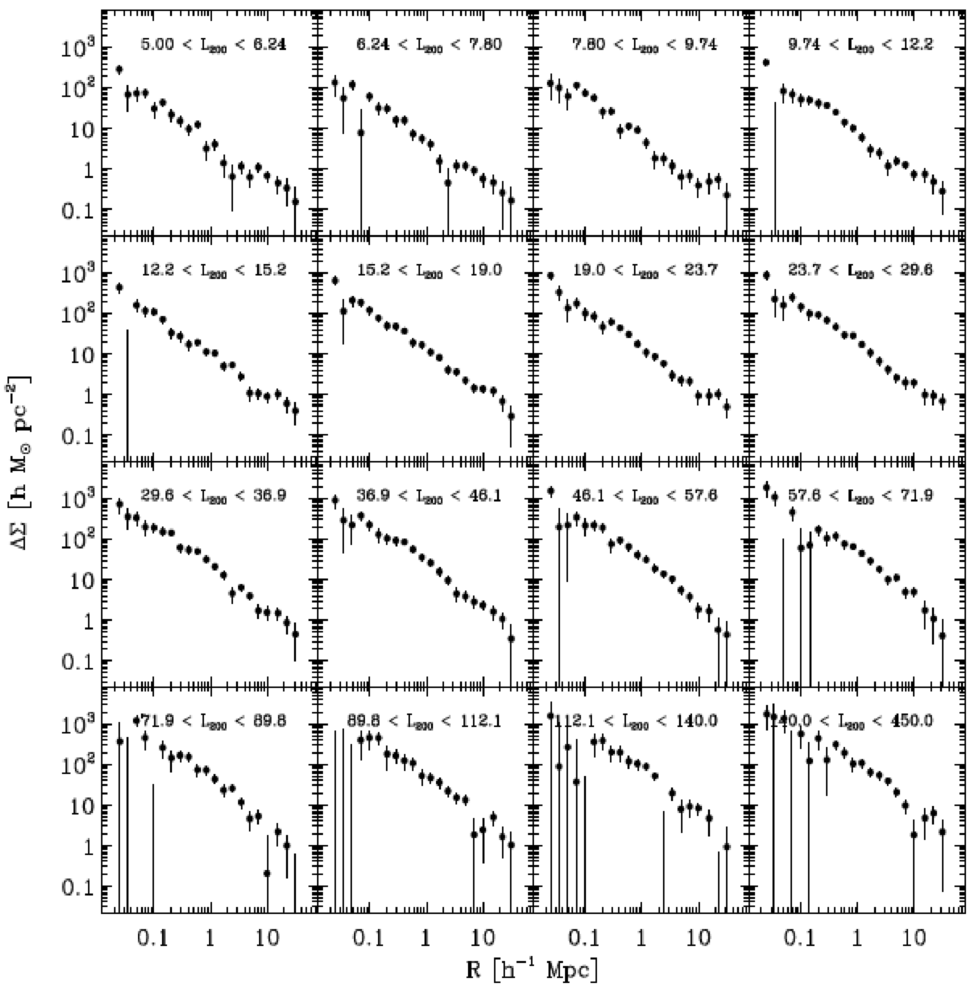




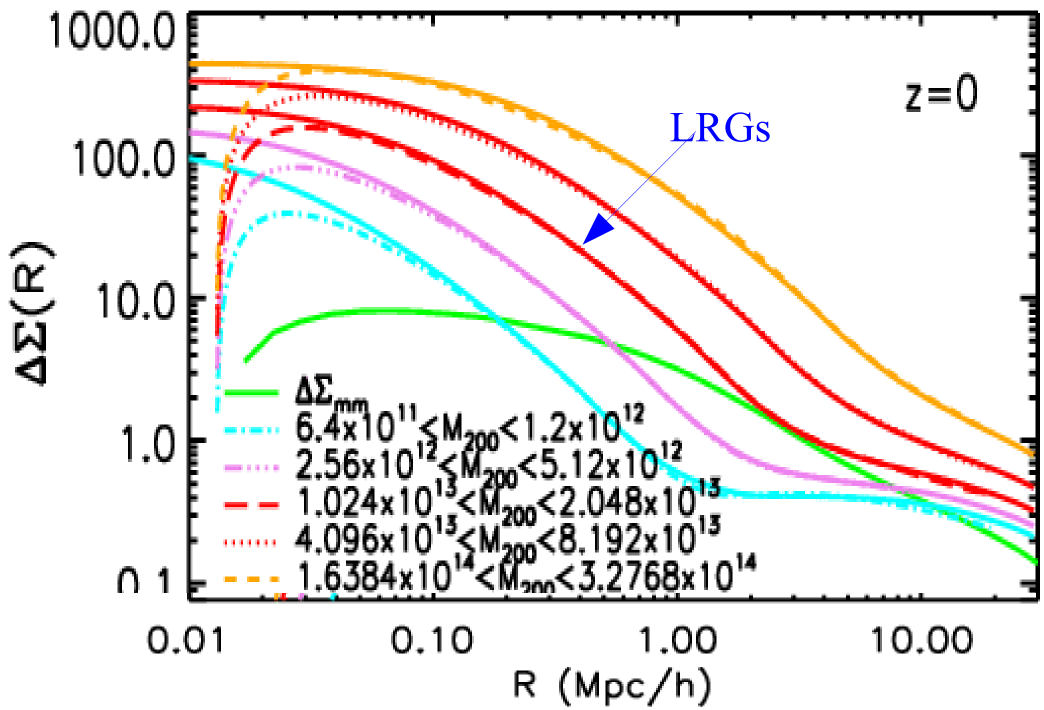
Profile is a good match to ΛCDM expectation -- strong features are expected at larger radii which scale with halo mass

Galaxy-galaxy lensing around isolated LRGs gives the mean surface density profile of their halos: $\Delta\Sigma = \overline{\Sigma}(r_p) - \Sigma(r_p)$

Sheldon et al 2008



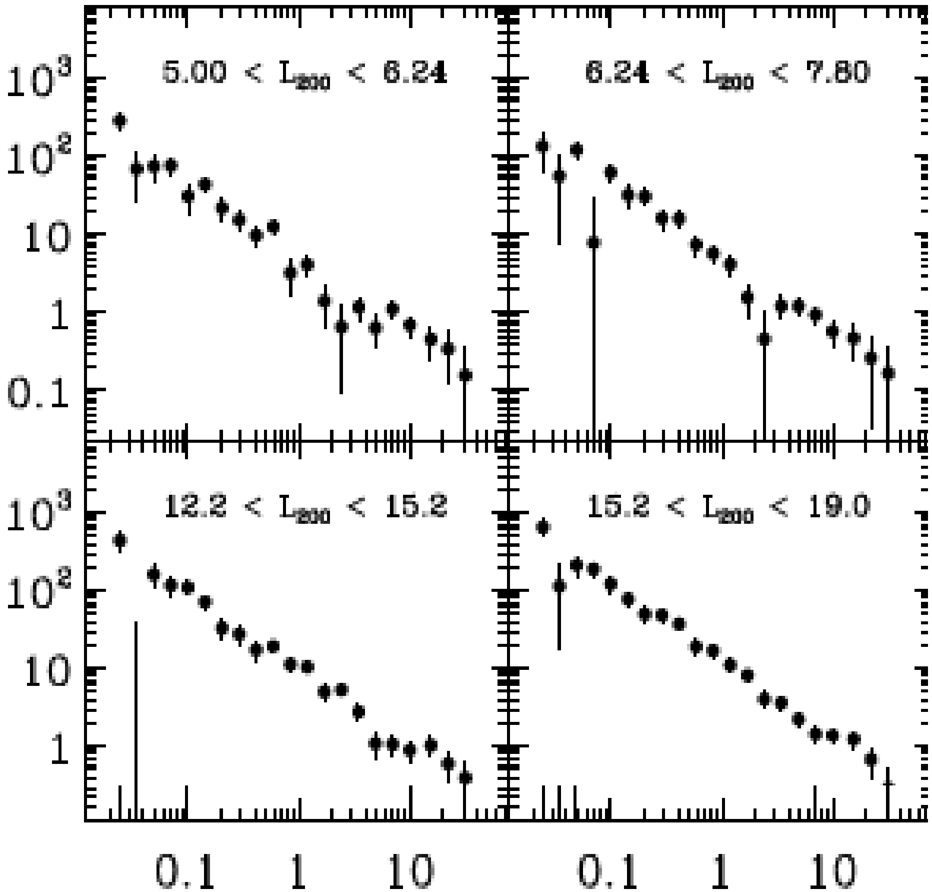
Hayashi & White 2008



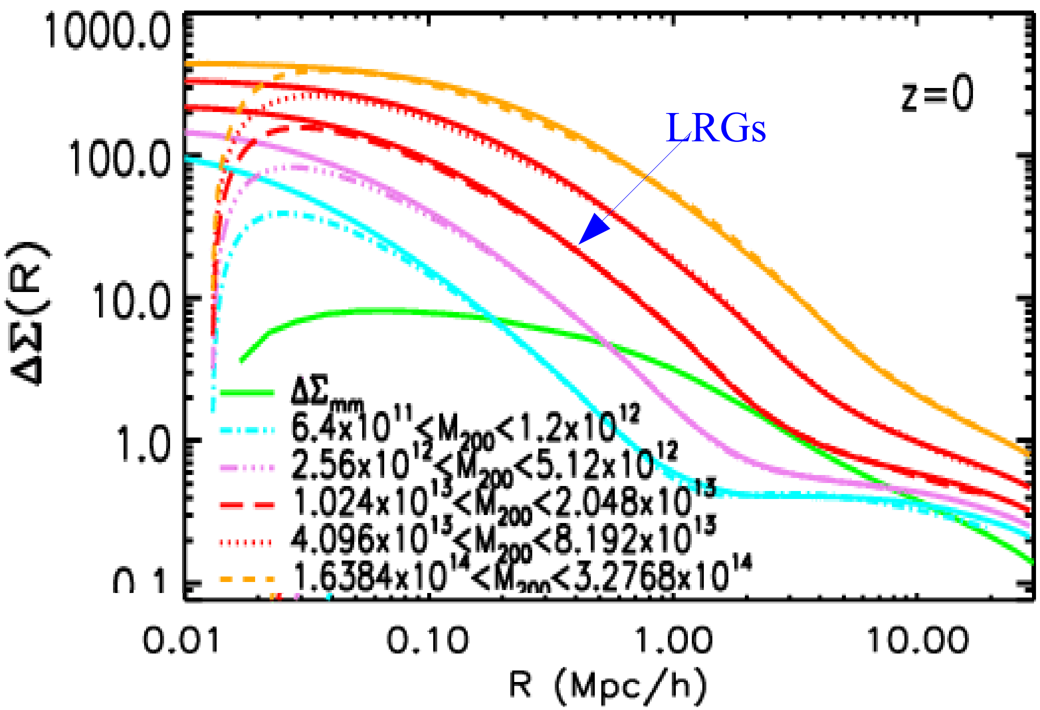
Profile is a good match to ΛCDM expectation -- strong features are expected at larger radii which scale with halo mass

Galaxy-galaxy lensing around isolated LRGs gives the mean surface density profile of their halos: $\Delta\Sigma = \overline{\Sigma}\,(r_p) - \Sigma\,(r_p)$

Sheldon et al 2008

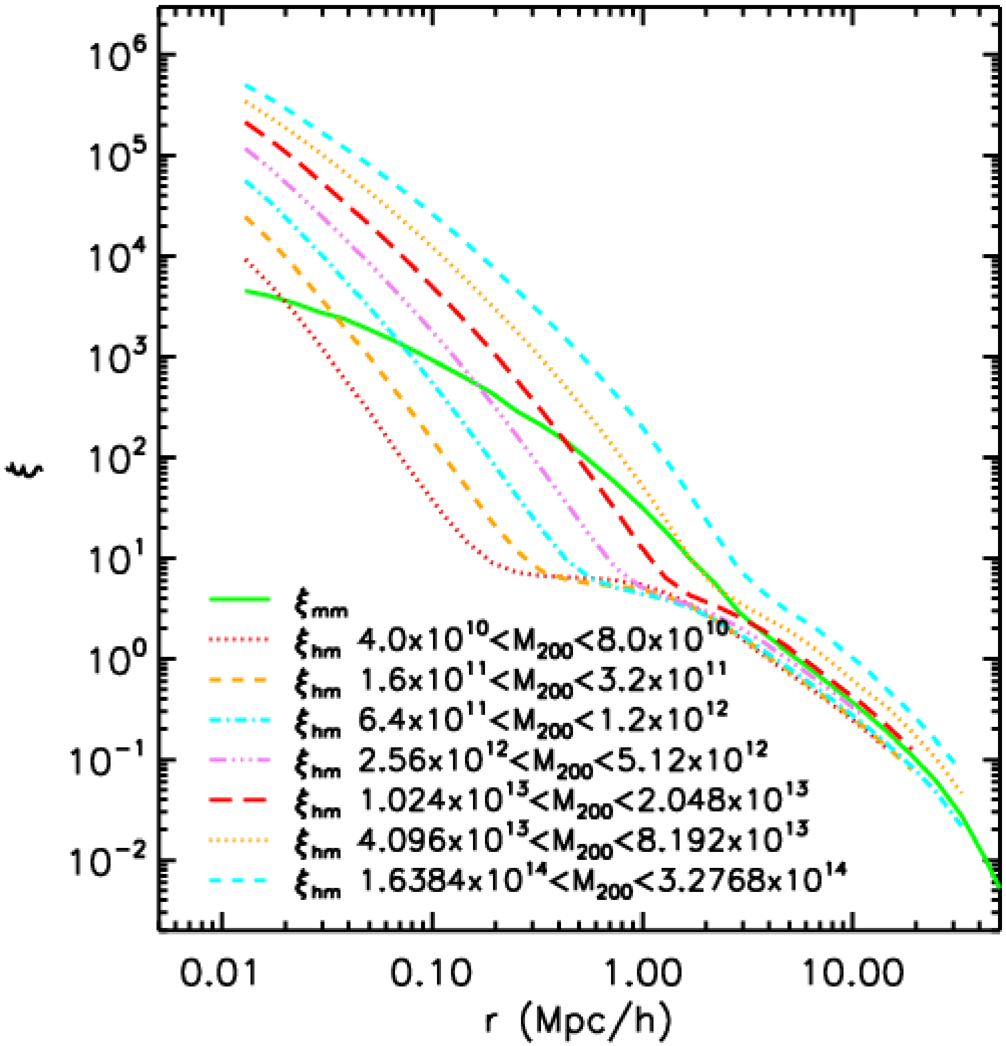


Hayashi & White 2008

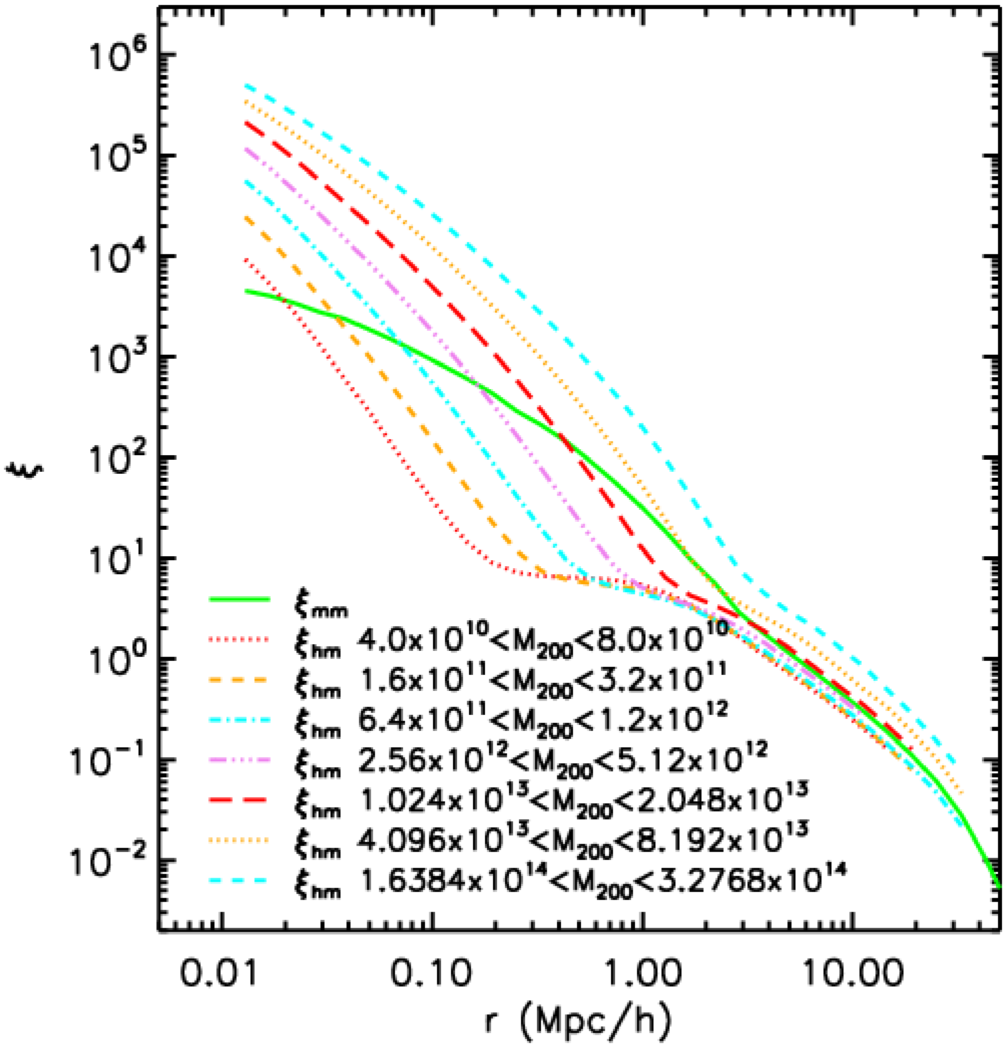


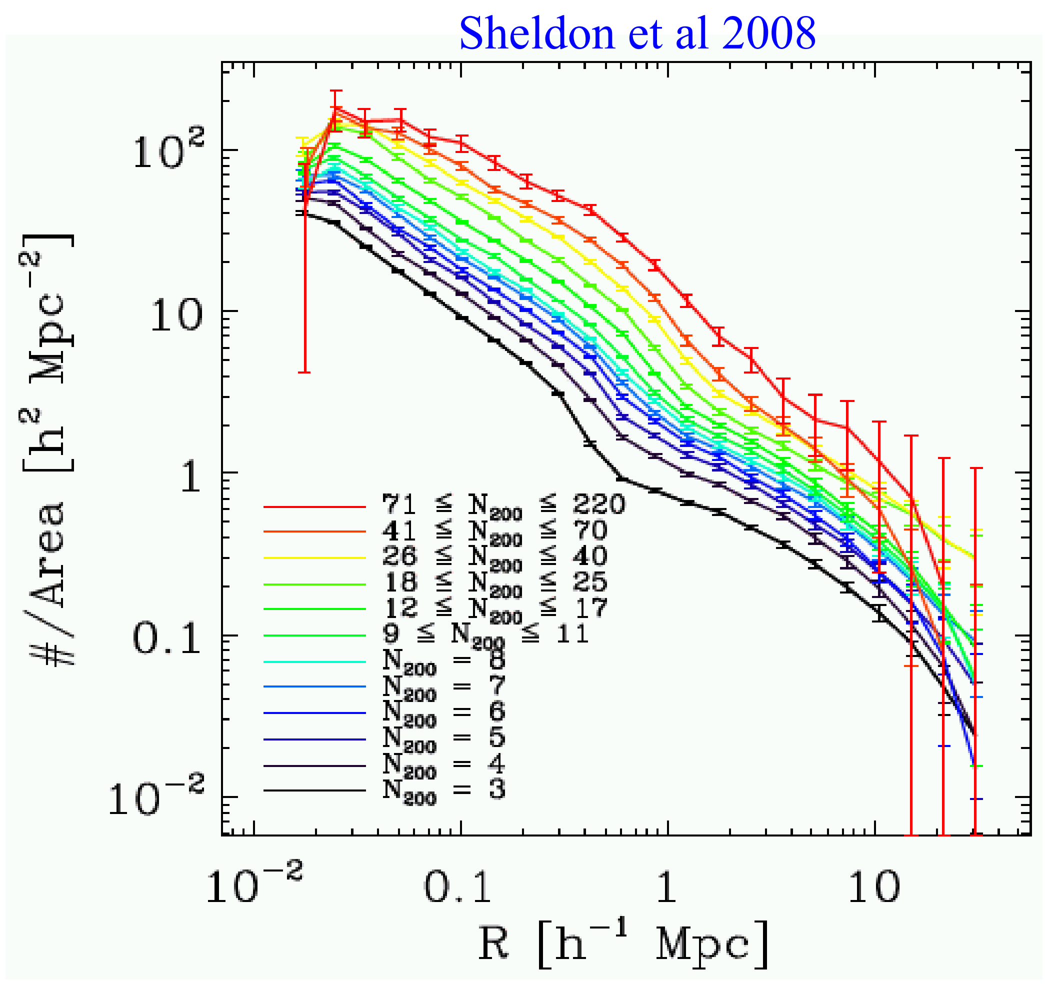
Profile is a good match to ΛCDM expectation -- strong features are expected at larger radii which scale with halo mass

Mean ΛCDM density profiles break sharply at the 1-halo 2-halo transition -- a clear indicator of dark matter over MOND?



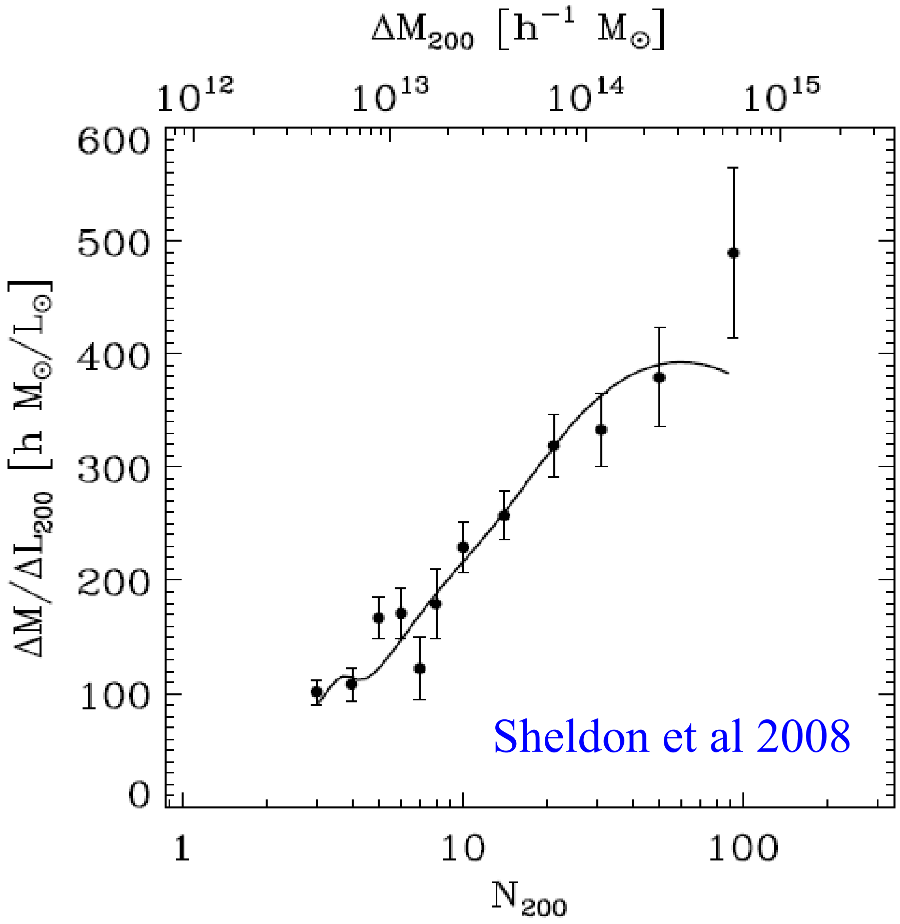
Mean ΛCDM density profiles break <u>sharply</u> at the 1-halo 2-halo transition -- a clear indicator of dark matter over MOND?



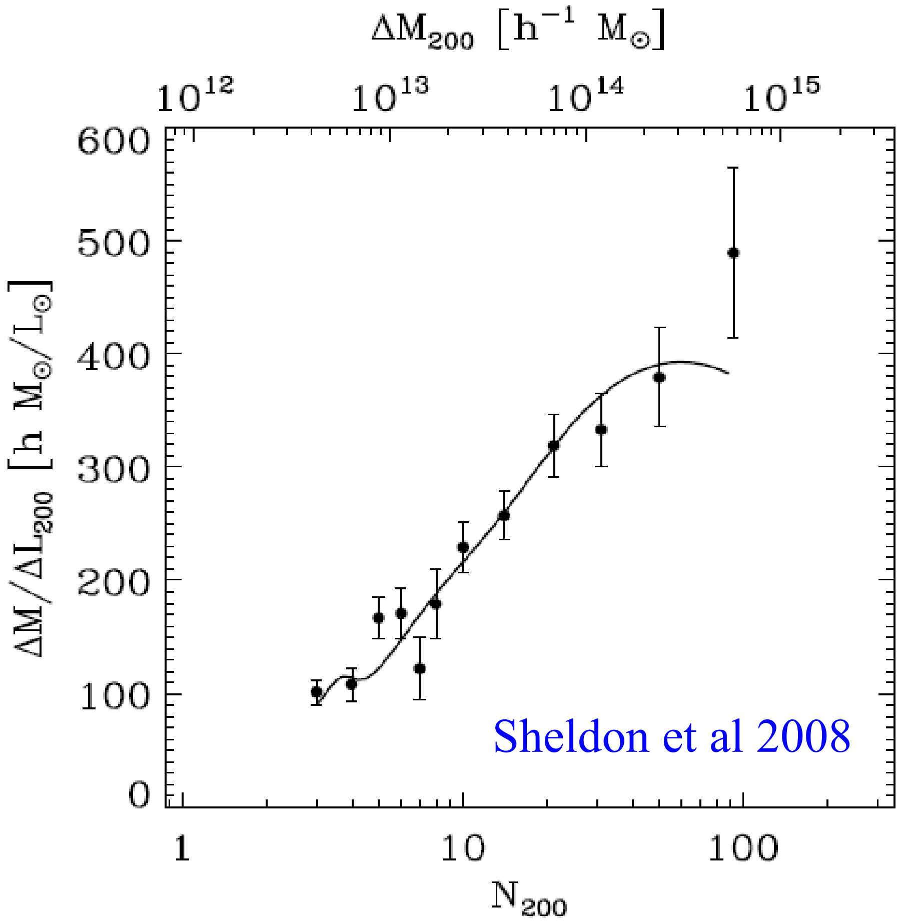


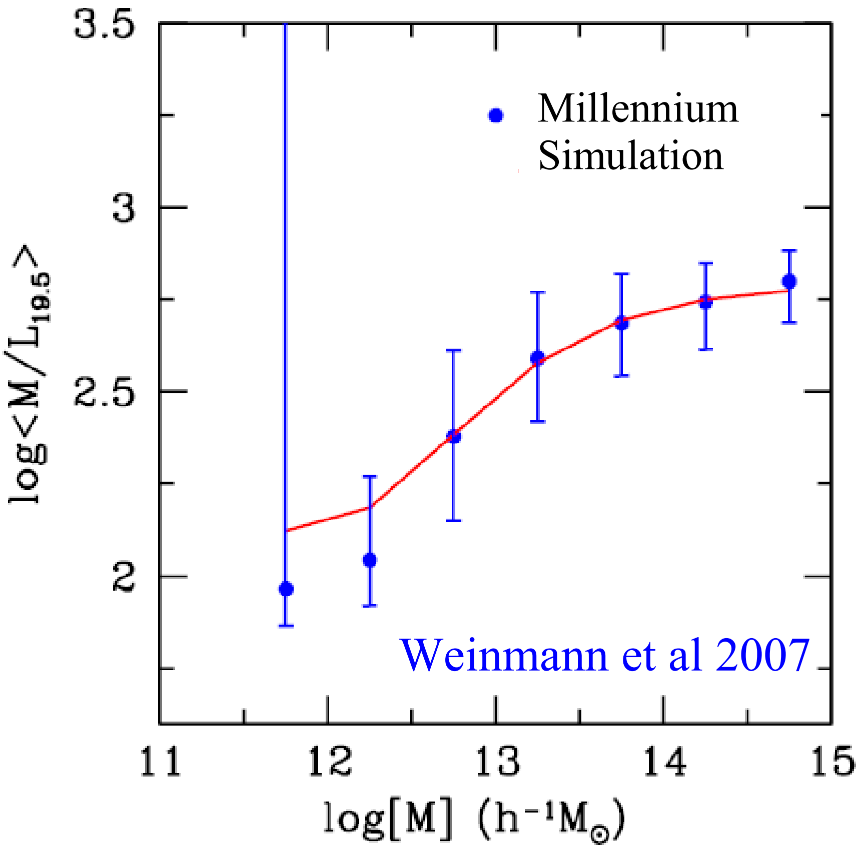
Maybe – or maybe not!

...at least, a direct, high S/N measure of M/L as a function of M_{halo} ...



...at least, a direct, high S/N measure of M/L as a function of M_{halo} ...





...which agrees well with that in ΛCDM simulations of galaxy formation

(Near) future tests of the structure formation model

- Tests of gaussianity

  ---morphology, high-order correlations, cluster mass function

- Tests of gravity

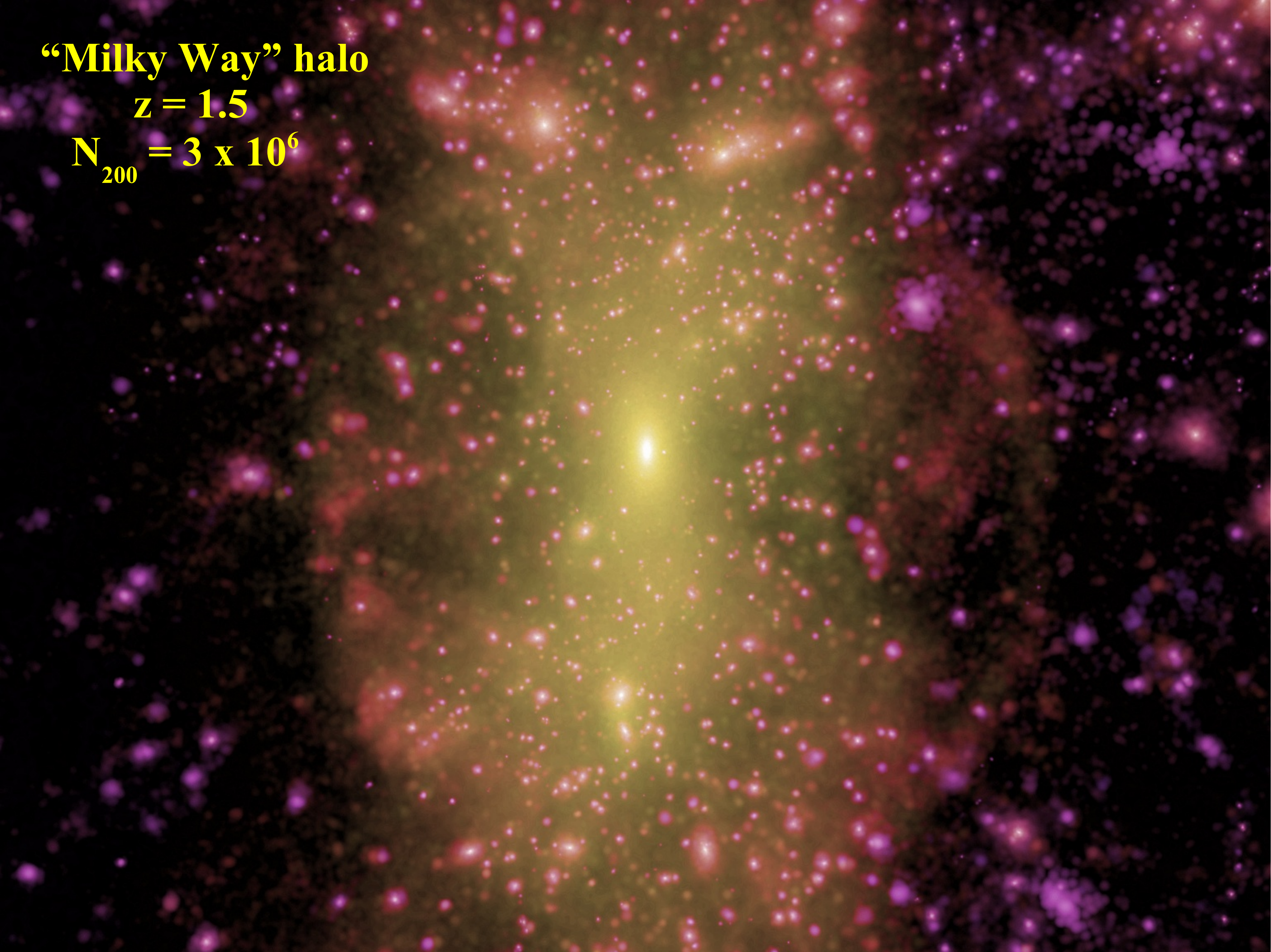
  ---halo shapes and density profiles (vs MOND, or coupled models)

- Tests of the nature of dark energy

  ---BAO's, cluster abundance evolution

- Tests of the nature of dark matter

  ---Ly α forest, small-scale structure

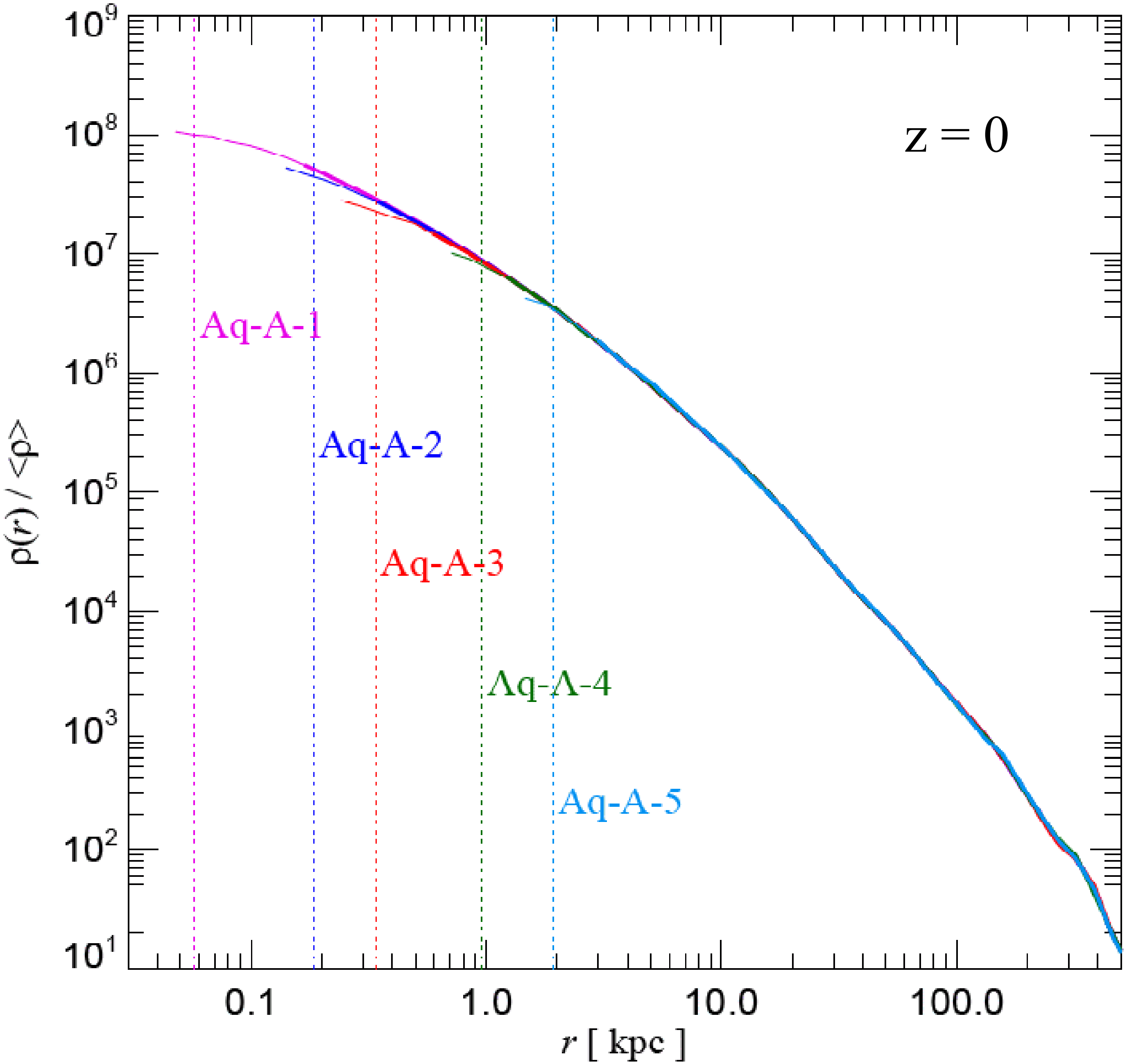

"Milky Way" halo
z = 1.5
$N_{200} = 3 \times 10^6$


"Milky Way" halo
z = 1.5
N200 = 94 x 10^6


"Milky Way" halo
z = 1.5
N200 = 750 x 10^6

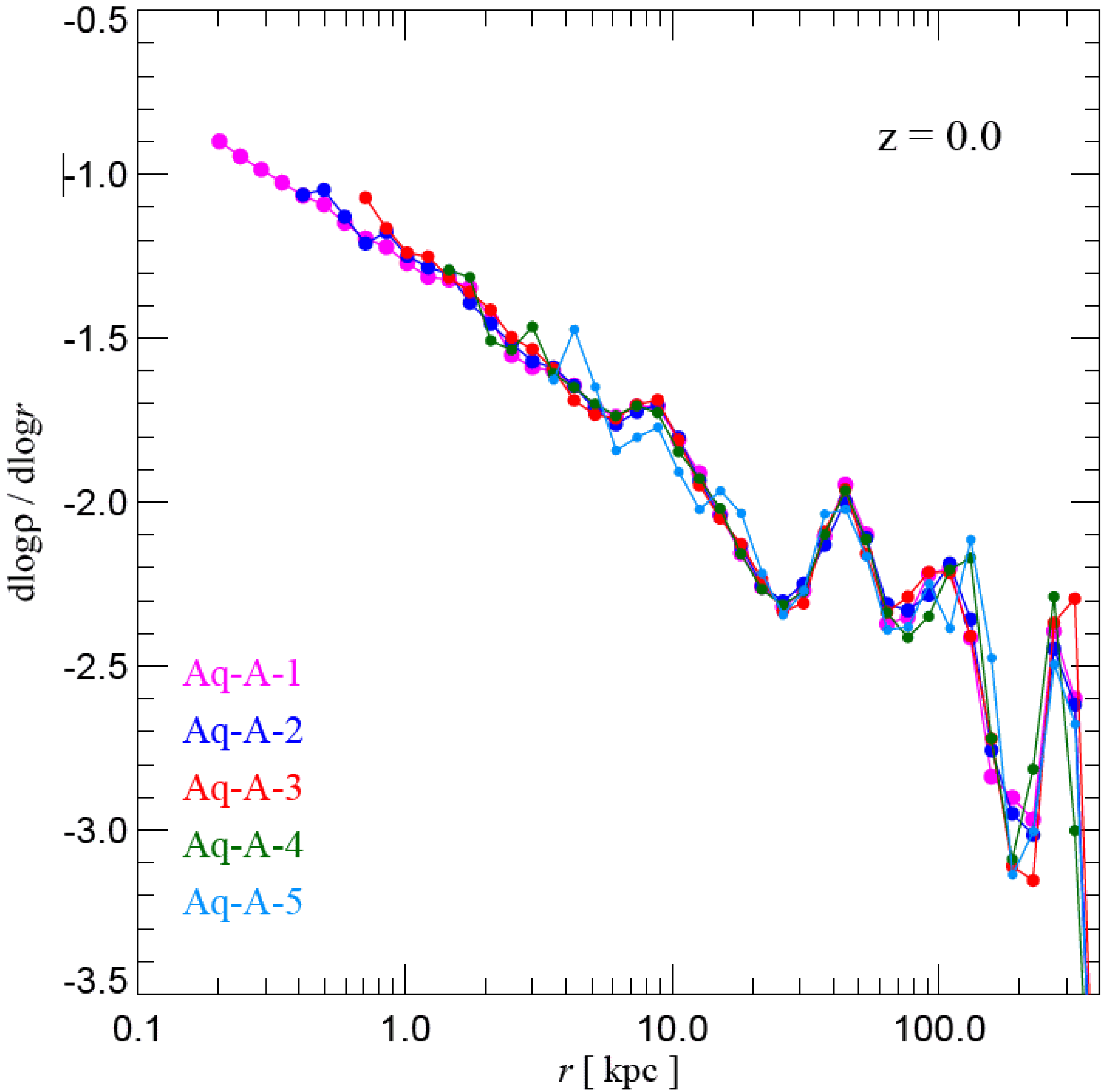
How well do density profiles converge?

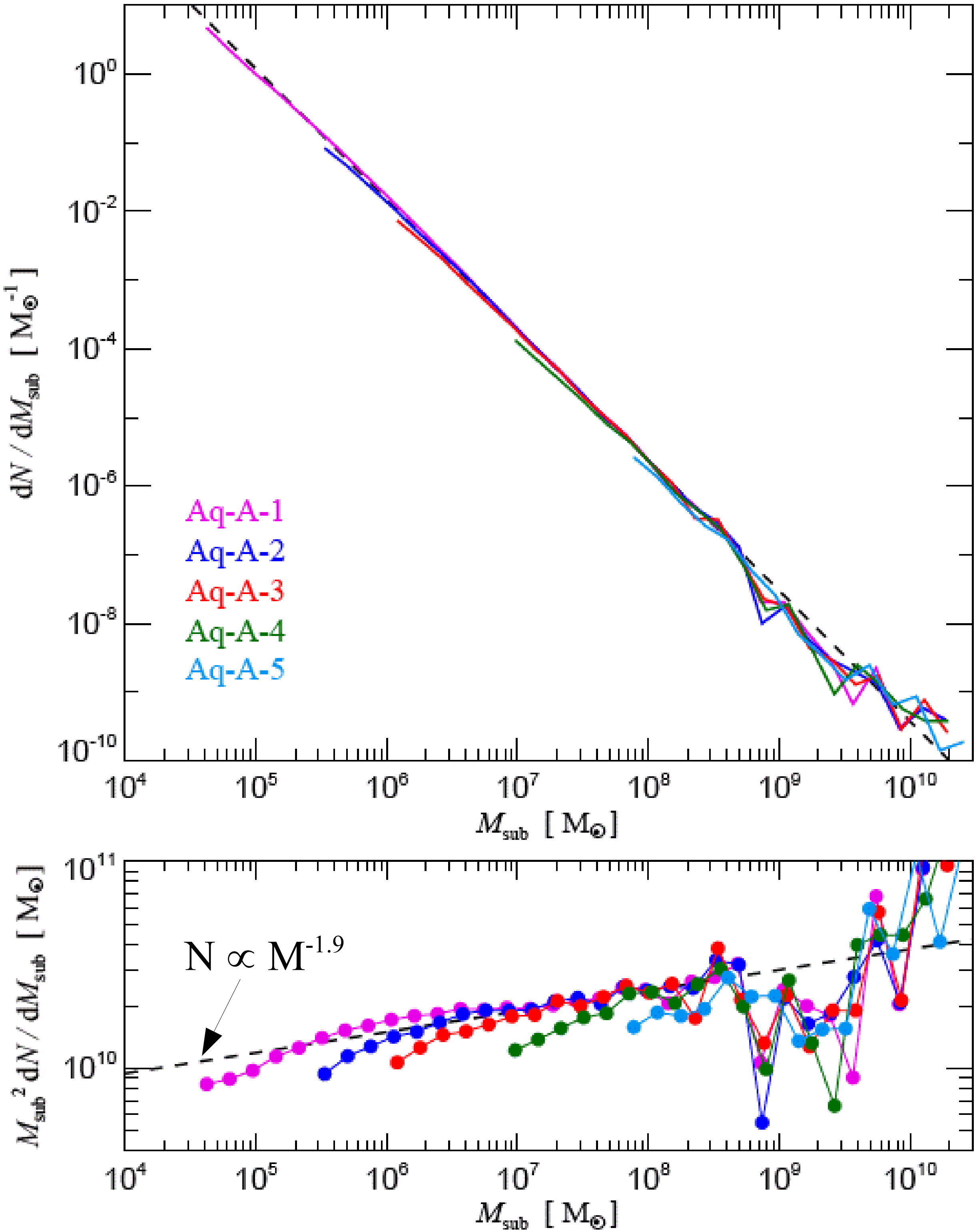
Aquarius Project: Springel et al 2008



How well do density profiles converge?

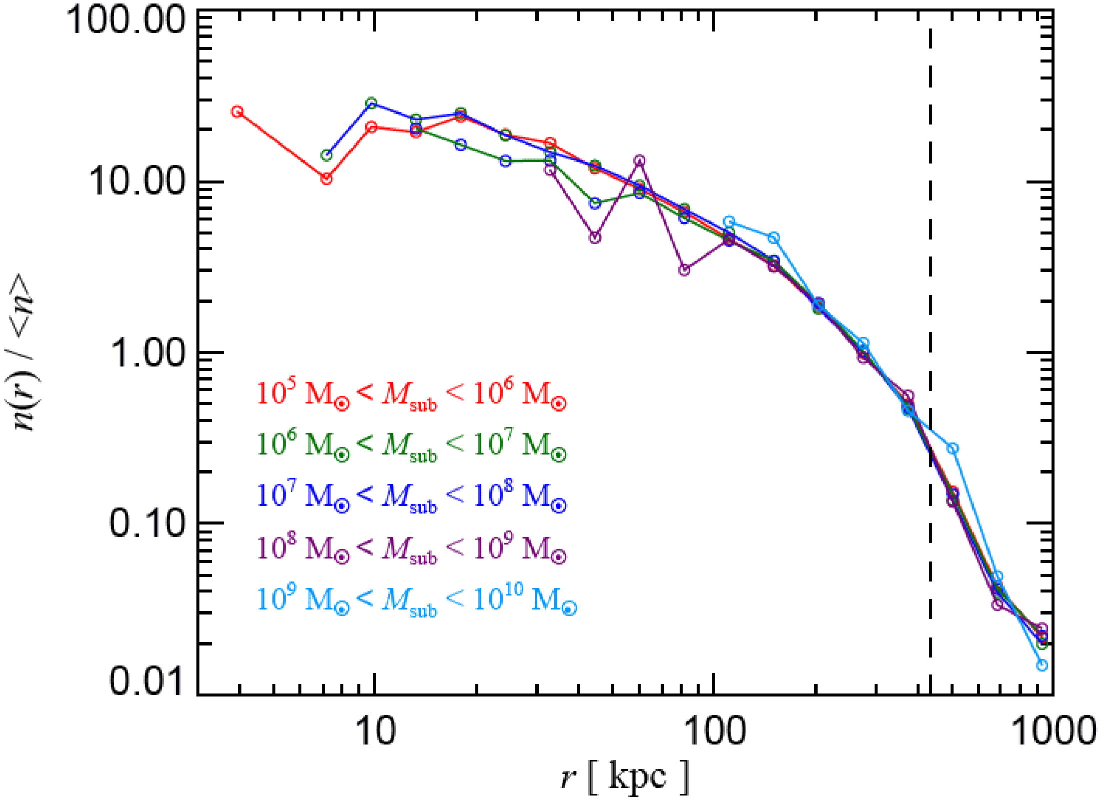
Aquarius Project: Springel et al 2008

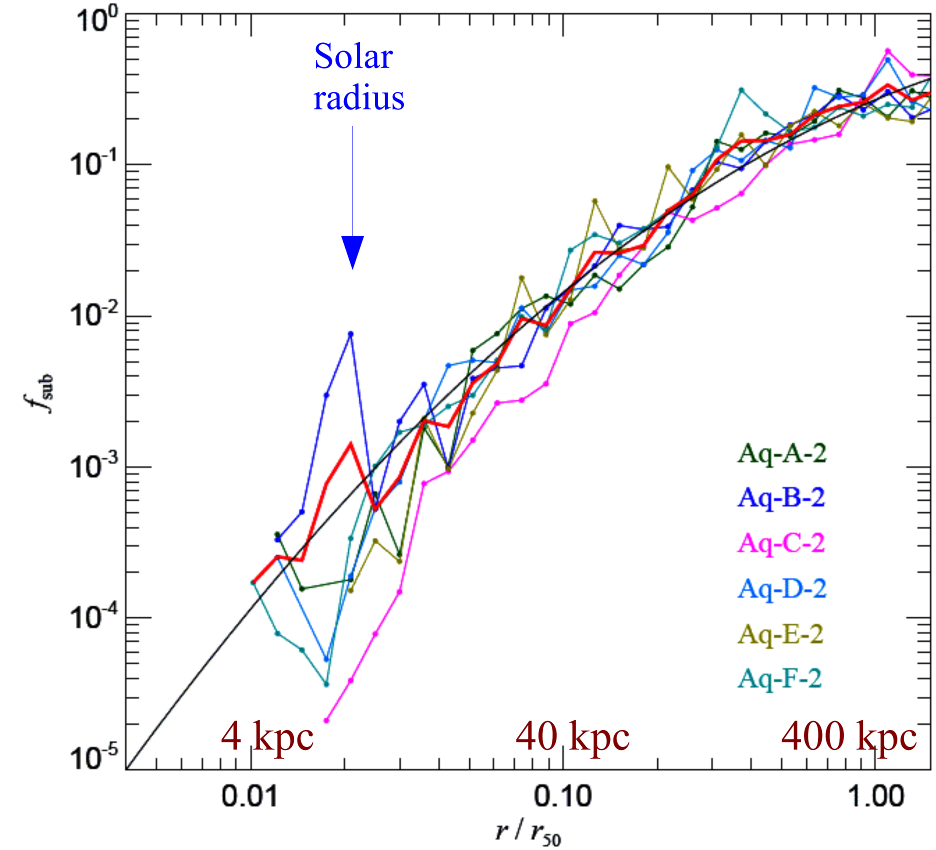




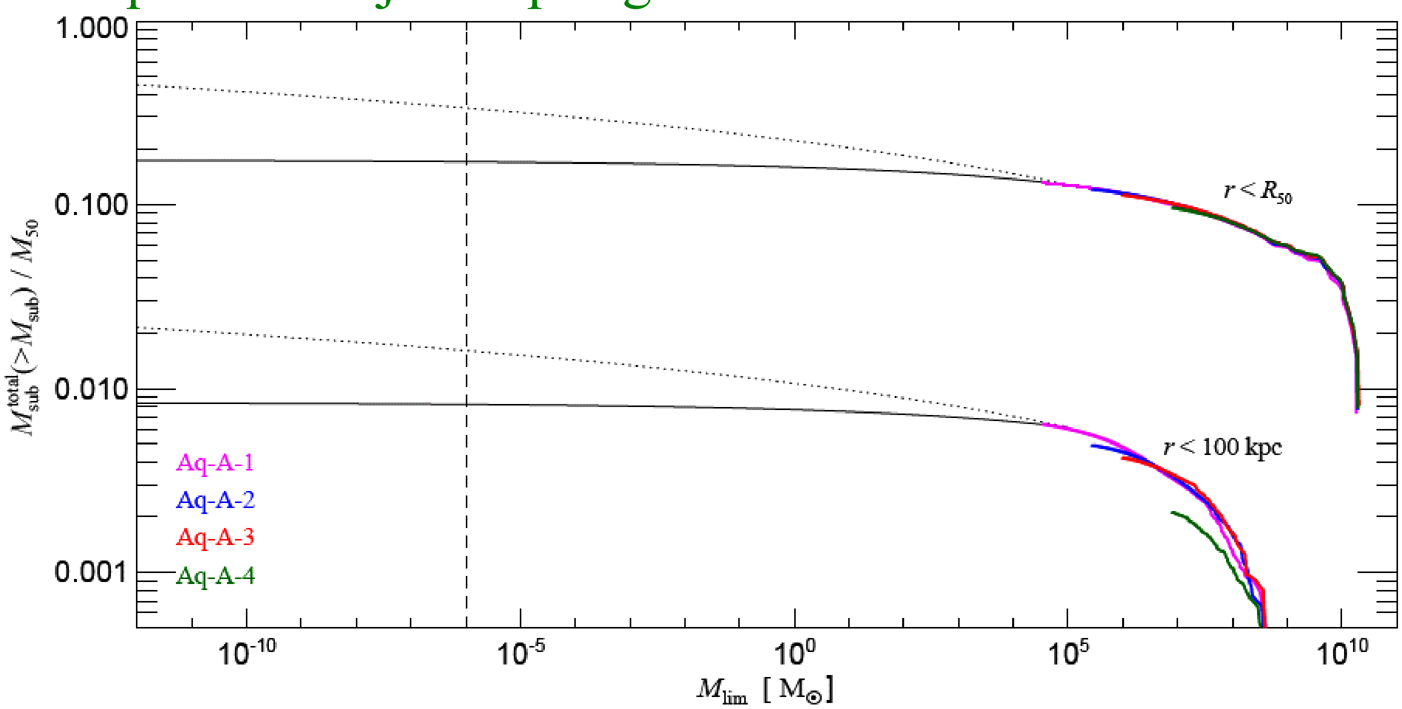
How well does substructure converge?

Aquarius Project: Springel et al 2008





Aquarius Project: Springel et al 2008



- All mass subhalos are similarly distributed
- A small fraction of the inner mass in subhalos
- <<1% of the mass near the Sun is in subhalos

Conclusions from high resolution ΛCDM simulations

- The predicted DM fraction in lumps with $M > 10^{-6} M_\odot$ is

  ~0.01 within r = 100 kpc
  ~0.001 within r = 8 kpc

- Small DM lumps should have negligible effect on the structure and orbits of inner halo objects

- The (smooth) DM near the Sun should be distributed in $> 10^5$ cold streams – indistinguishable from a smooth distribution

- DM caustics are very weak in the inner halo and have no discernible dynamical effects on observed tracers

- Caustics and small clumps (say $< 10^5 M_\odot$) make no significant contribution to the DM annihilation flux from the inner halo ($r < 100$ kpc) of our Galaxy. The most easily detectable signal will probably be that of the main diffuse halo.

Milky Way halo seen in DM annihilation radiation

Aquarius simulation: $N_{200} = 1.1 \times 10^9$