Simulation constraints on the nature of Dark Matter

Simon White, Max Planck Institute for Astrophysics

The first N-body simulations of cosmic structure growth

FORMATION OF GALAXIES AND CLUSTERS OF GALAXIES BY SELF-SIMILAR GRAVITATIONAL CONDENSATION*

WILLIAM H. PRESS AND PAUL SCHECHTER
California Institute of Technology
Received 1973 August 1

ABSTRACT

We consider an expanding Friedmann cosmology containing a "gas" of self-gravitating masses. The masses condense into aggregates which (when sufficiently bound) we identify as single particles of a larger mass. We propose that after this process has proceeded through several scales, the mass spectrum of condensations becomes "self-similar" and independent of the spectrum initially assumed. Some details of the self-similar distribution, and its evolution in time, can be calculated with the linear perturbation theory. Unlike other authors, we make no ad hoc assumptions about the spectrum of long-wavelength initial perturbations: the nonlinear N-body interactions of the mass points randomize their positions and generate a perturbation to all larger scales; this should fix the self-similar distribution almost uniquely. The results of numerical experiments on 1000 bodies are presented; these appear to show new nonlinear effects: condensations can "bootstrap" their way up in size faster than the linear theory predicts.

The first N-body simulations of cosmic structure growth

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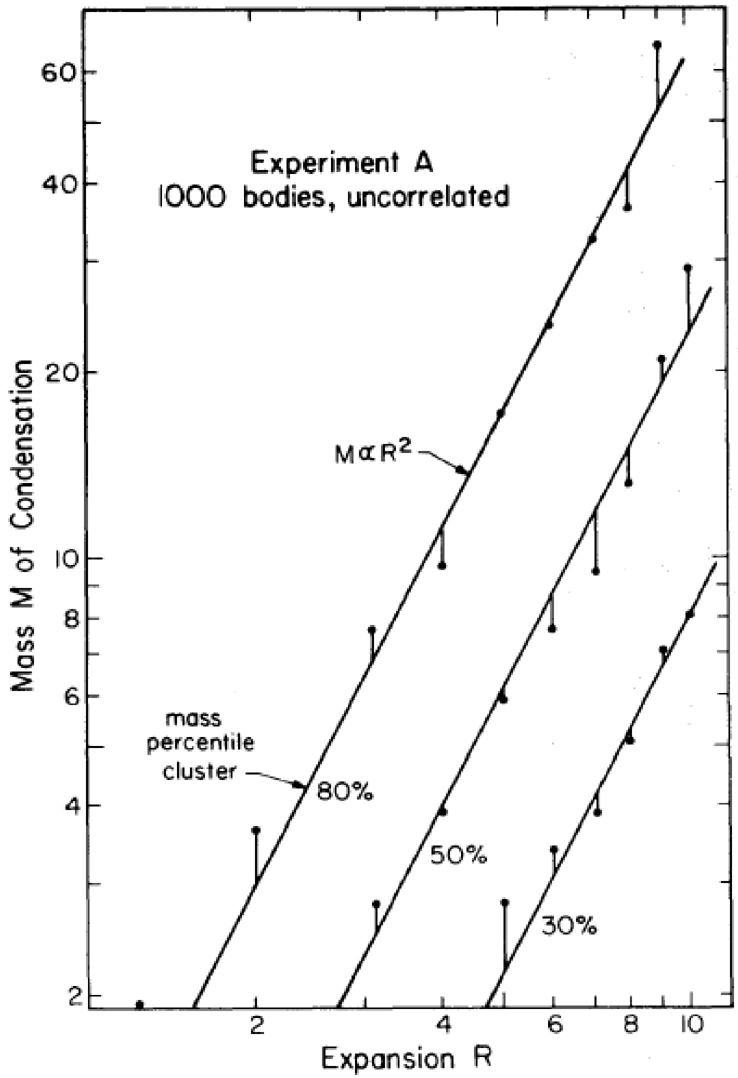

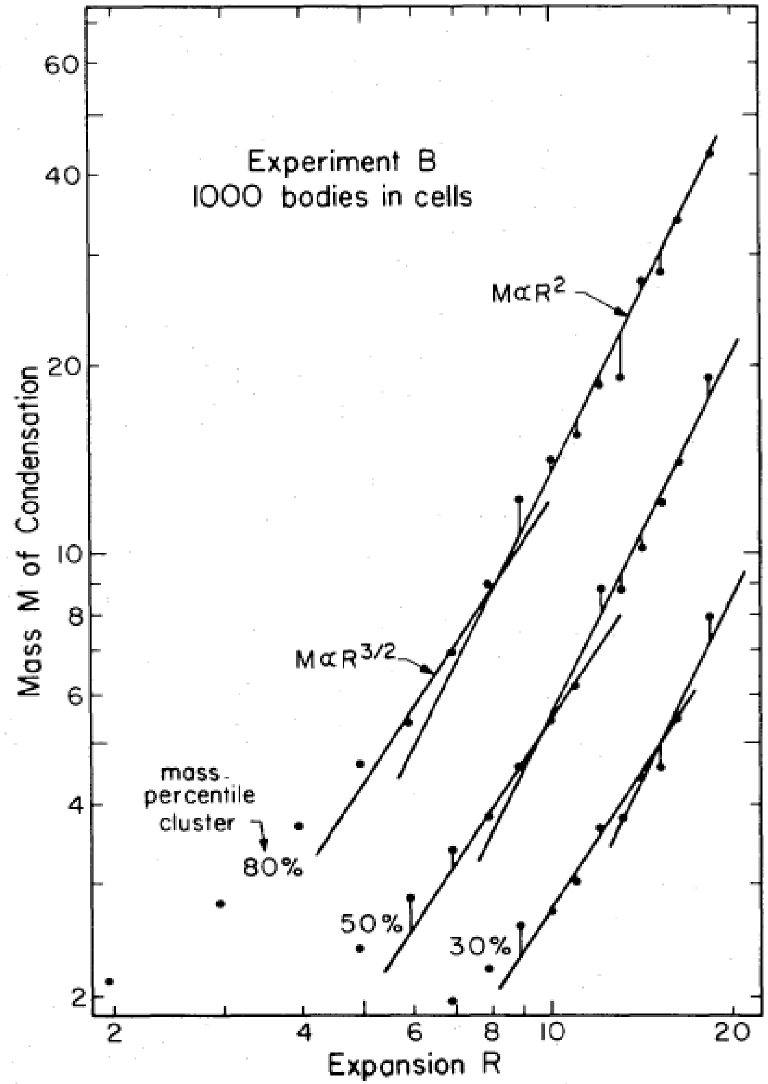

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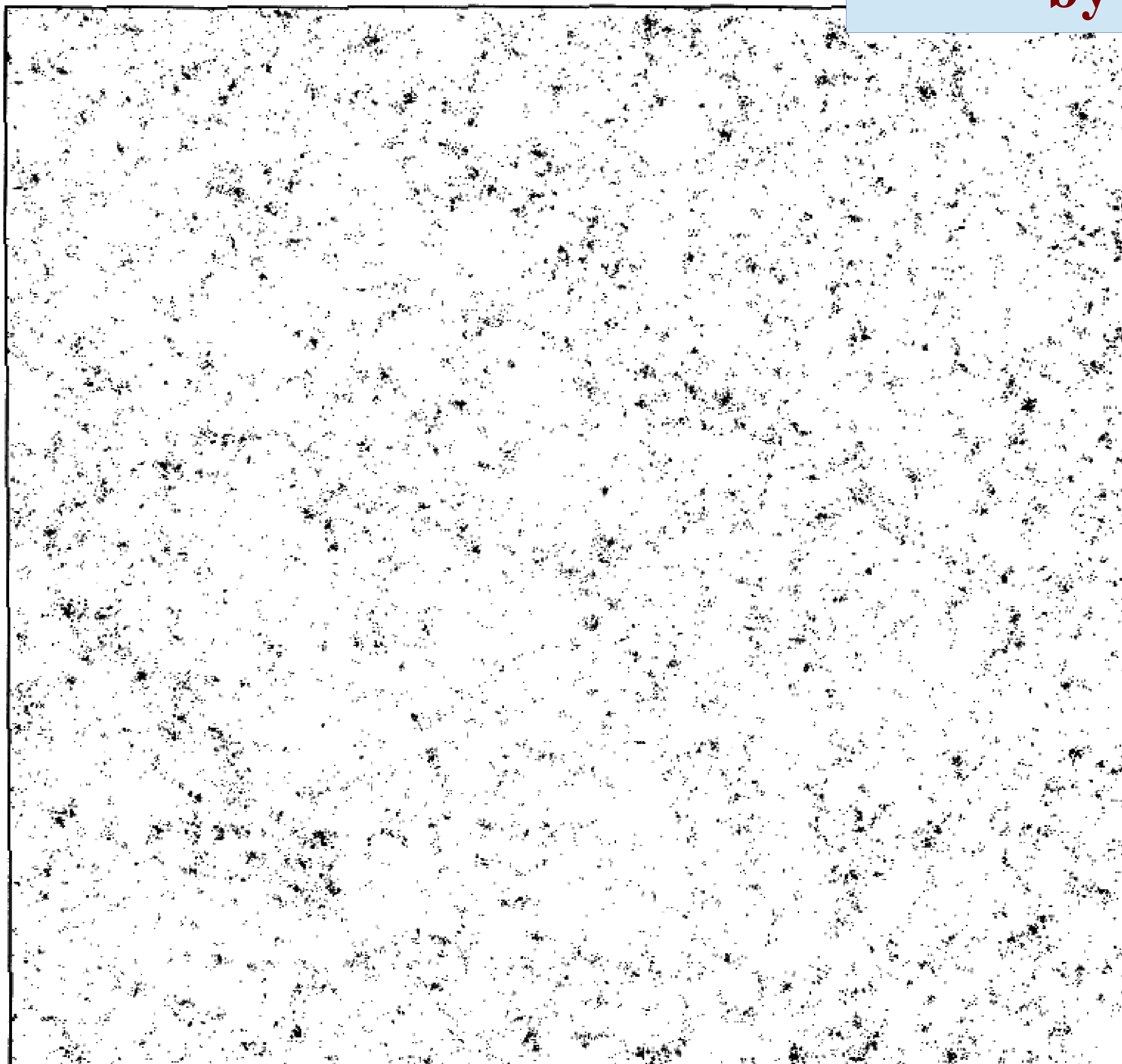
Structure formation simulations by the early 1980s

Efstathiou & Eastwood 1981

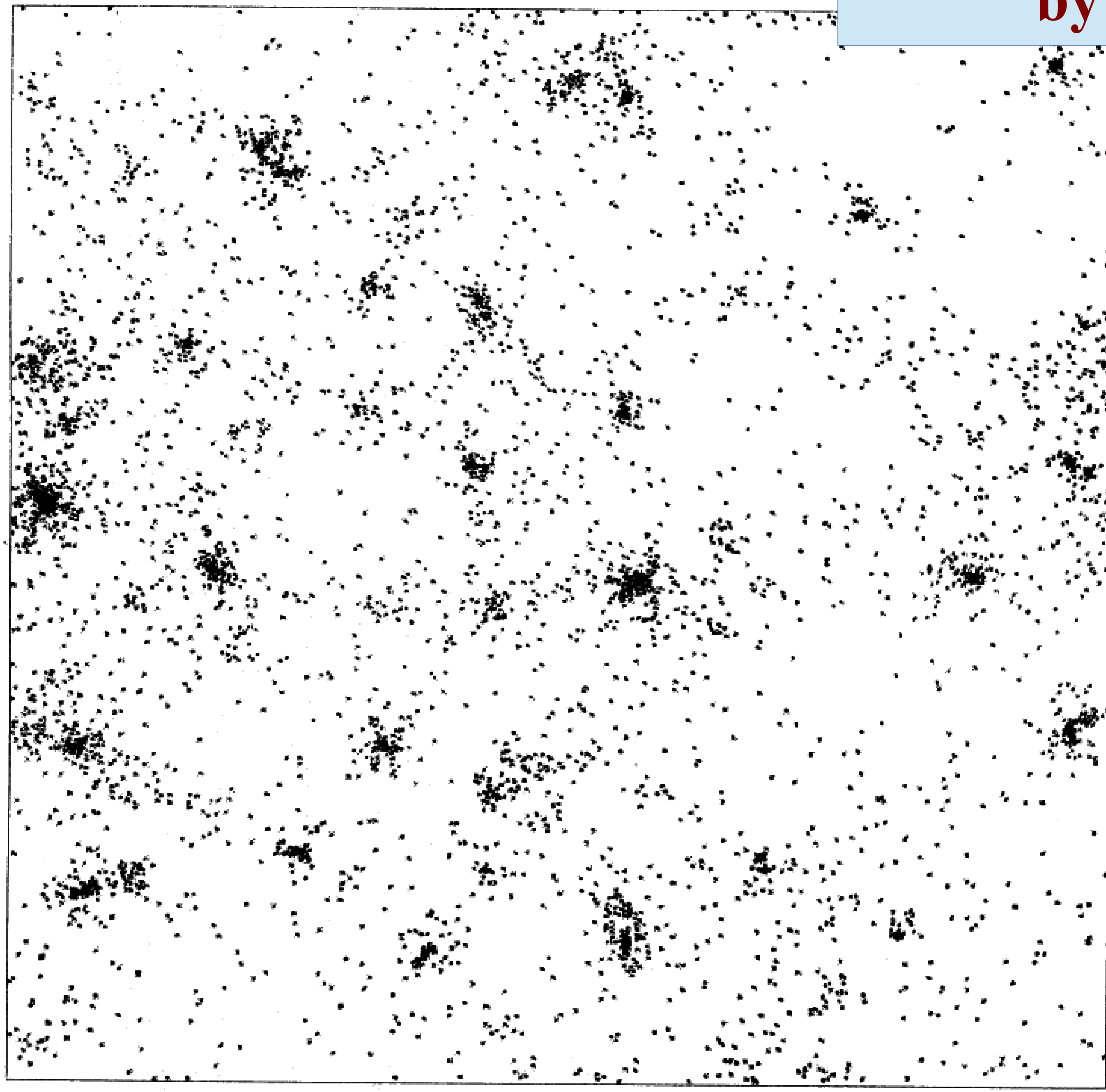


Methods developed to treat periodic “boxes” and larger particle numbers.

Studies still focused on nonlinear growth from idealized scale-free IC's...

Structure formation simulations by the early 1980s

Klypin & Shandarin 1983



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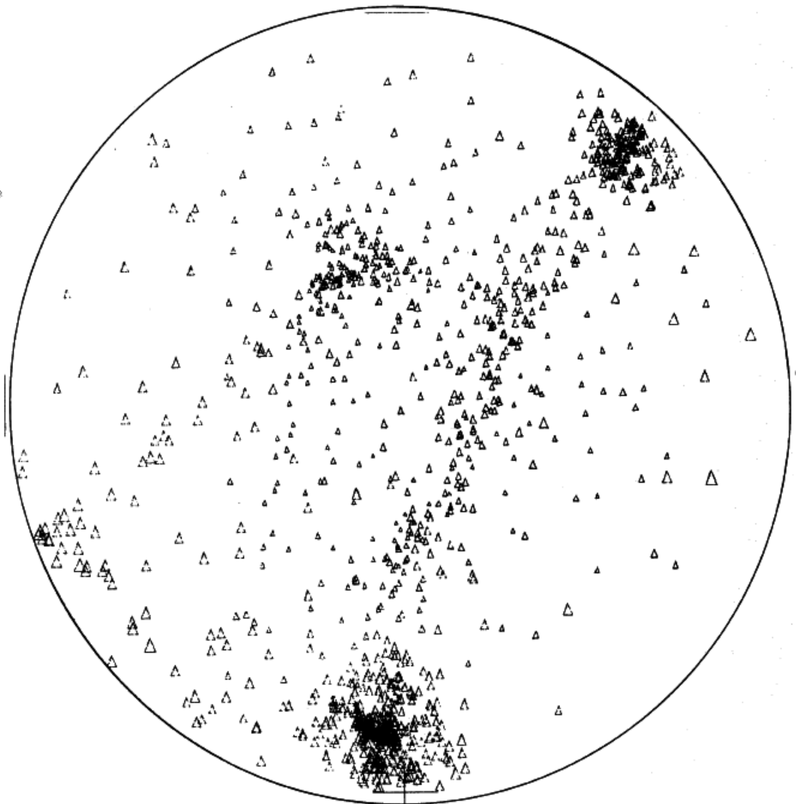

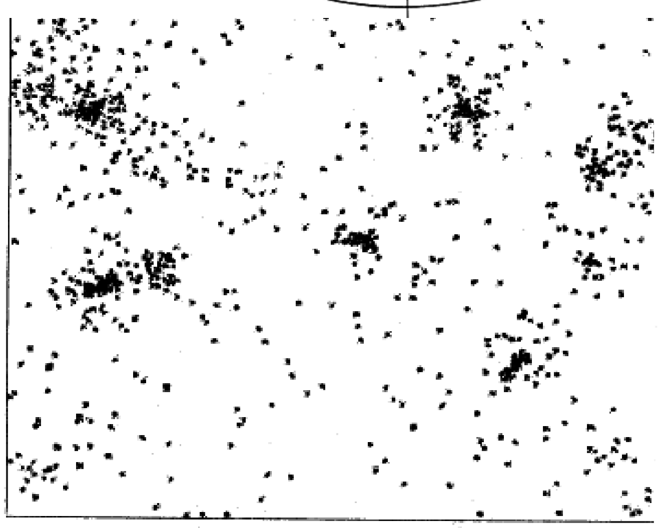

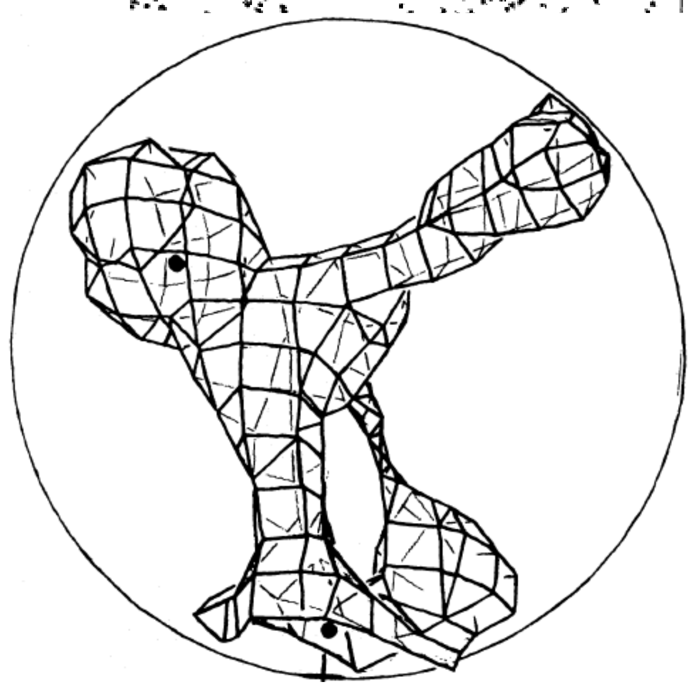

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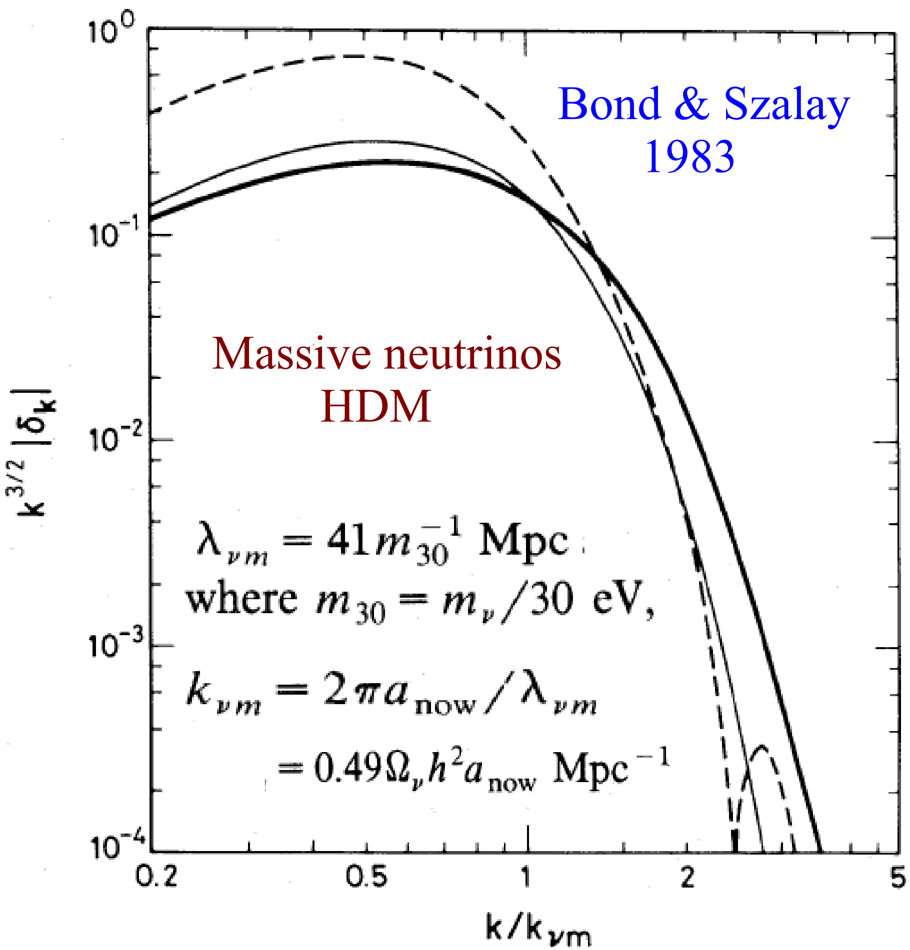
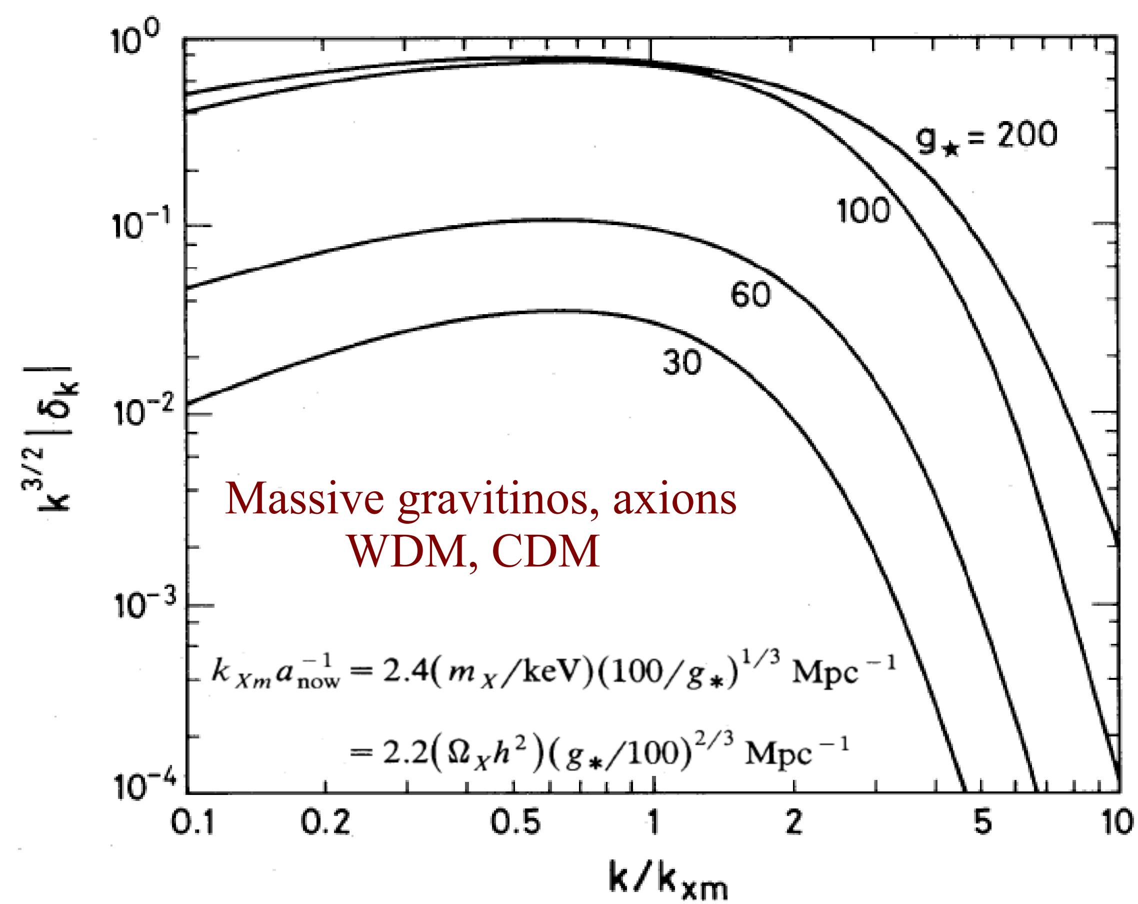
Calculation of precise linear IC's for particle DM

- Lyubimov et al (1980) apparent measurement of 30 eV mass for ν_e
- Boltzmann linear transfer calculations for massive ν's and exotic WIMPs

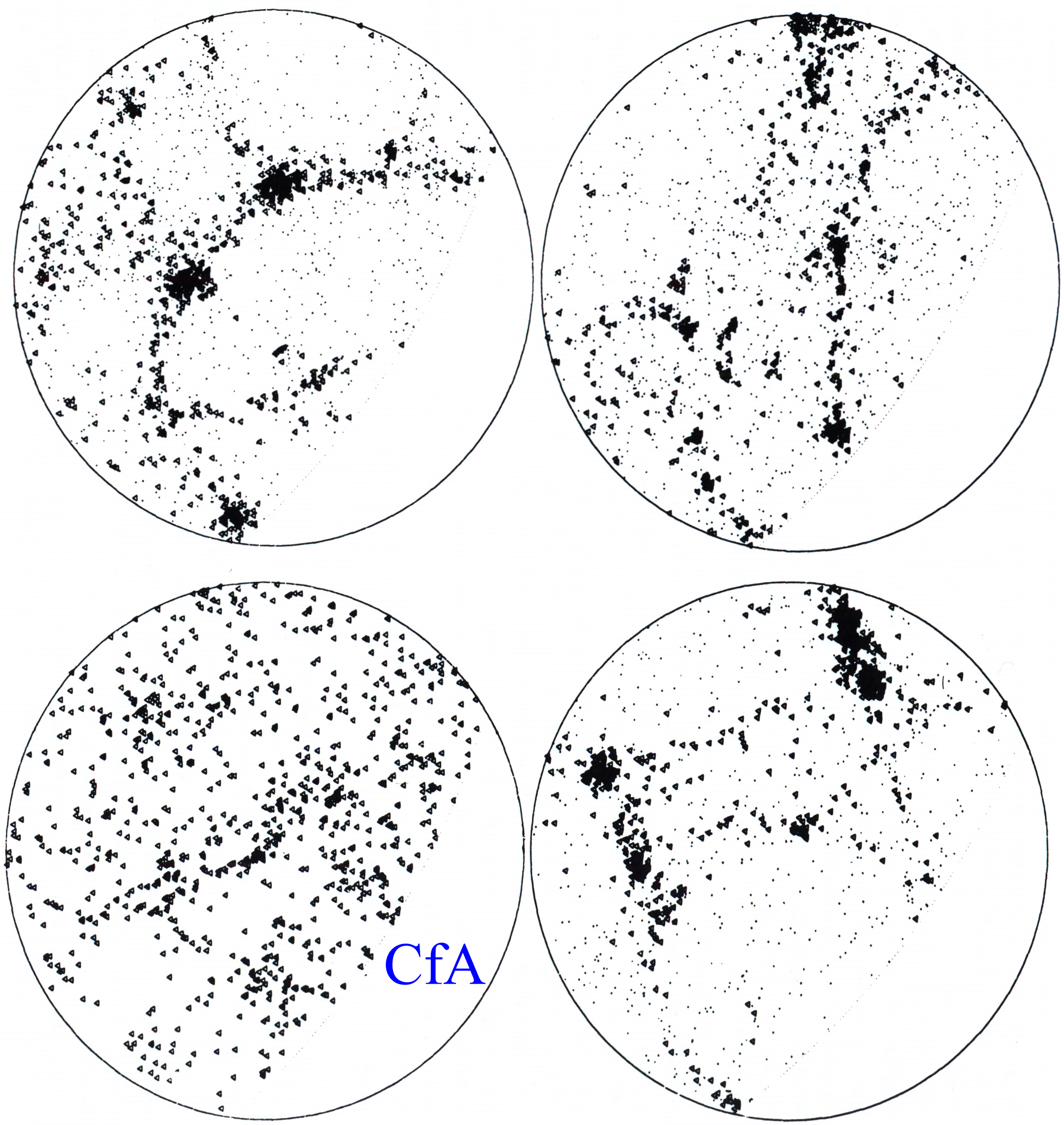
  → precise initial conditions for nonlinear structure formation





The exclusion of neutrinos as a DM candidate

White, Frenk & Davis 1983



New algorithms to represent ν-dominated IC's, allowed N-body exploration of nonlinear growth

First structures were massive pancakes and filaments in which galaxies could form

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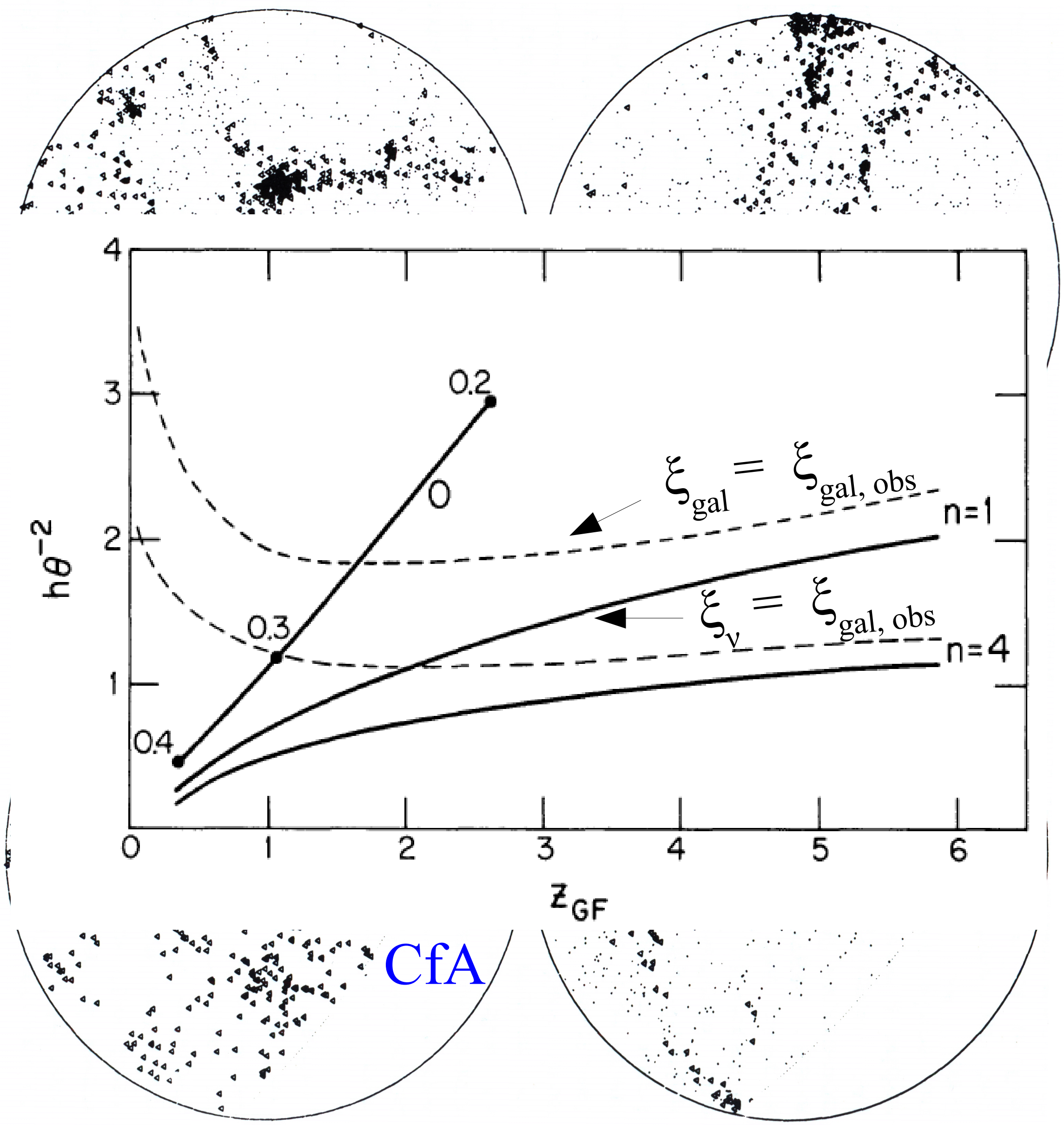


New algorithms to represent ν-dominated IC's, allowed N-body exploration of nonlinear growth

First structures were massive pancakes and filaments in which galaxies could form

No acceptable combination of cosmological and ν parameters,

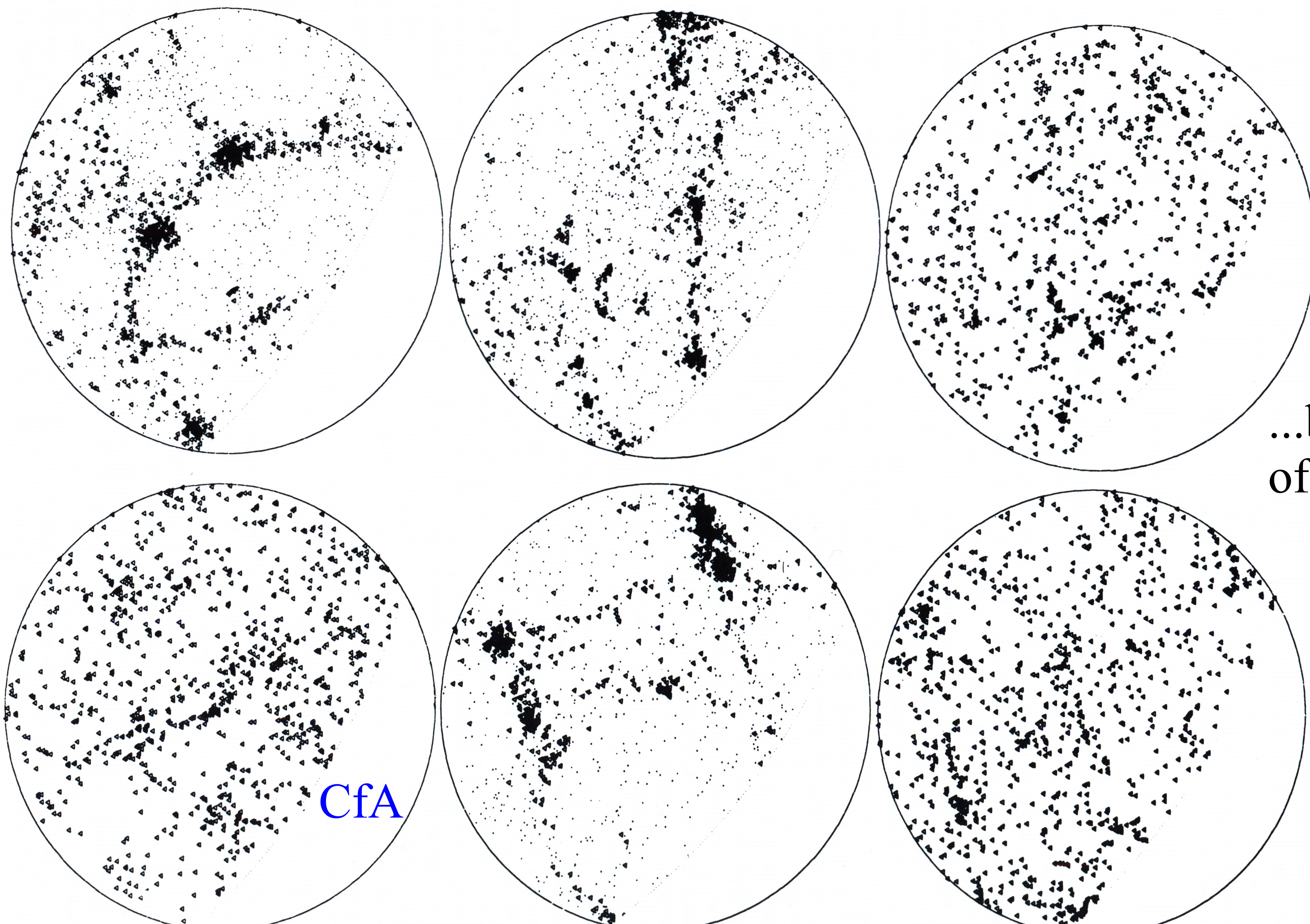
$\Omega,\ h,\ n,\ N_\nu,\ z_{CF}$

could produce galaxy clustering as weak as observed

→ DM cannot be made of any known WIMP

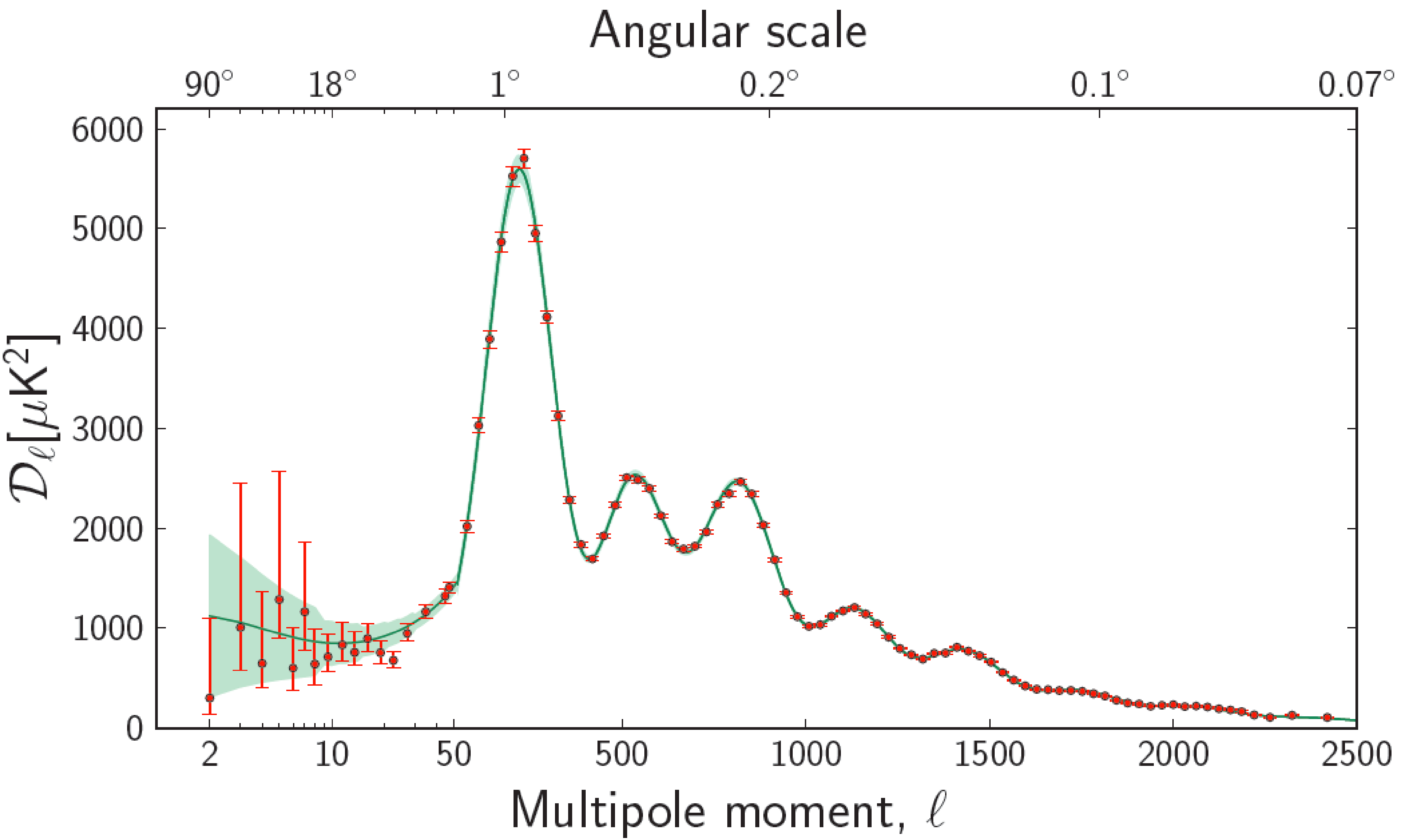
The exclusion of neutrinos as a DM candidate

Davis et al 1985



...but a new kind of WIMP could work well CDM!

Planck CMB power spectrum from 2.5 surveys



Planck+ parameters and the nature of DM

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$

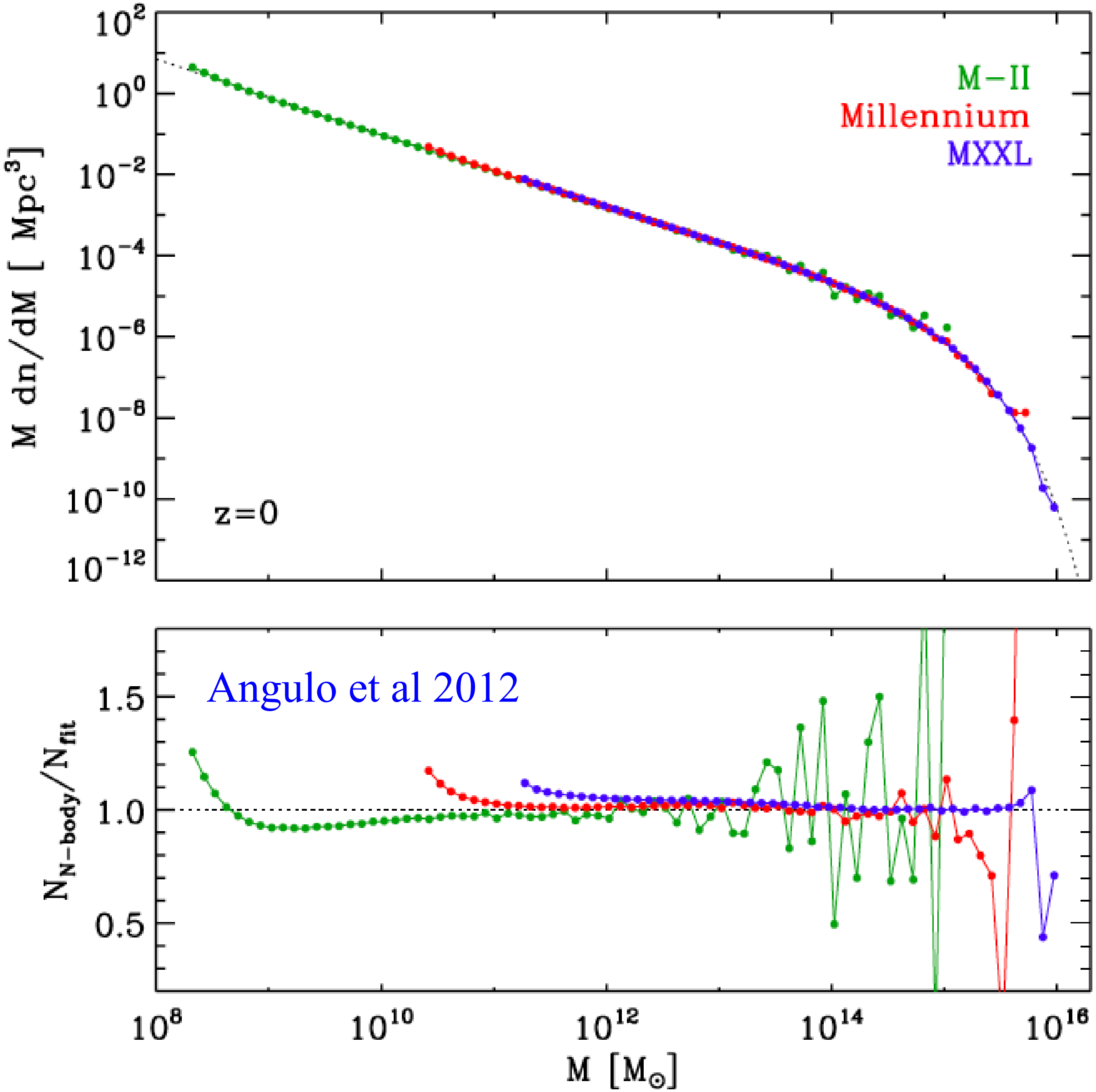
At <u>recombination</u> DM was 84.5 ± 2.5 % of all mass, baryons 15.5%

The stars and gas in today's galaxies are a small fraction of all baryons

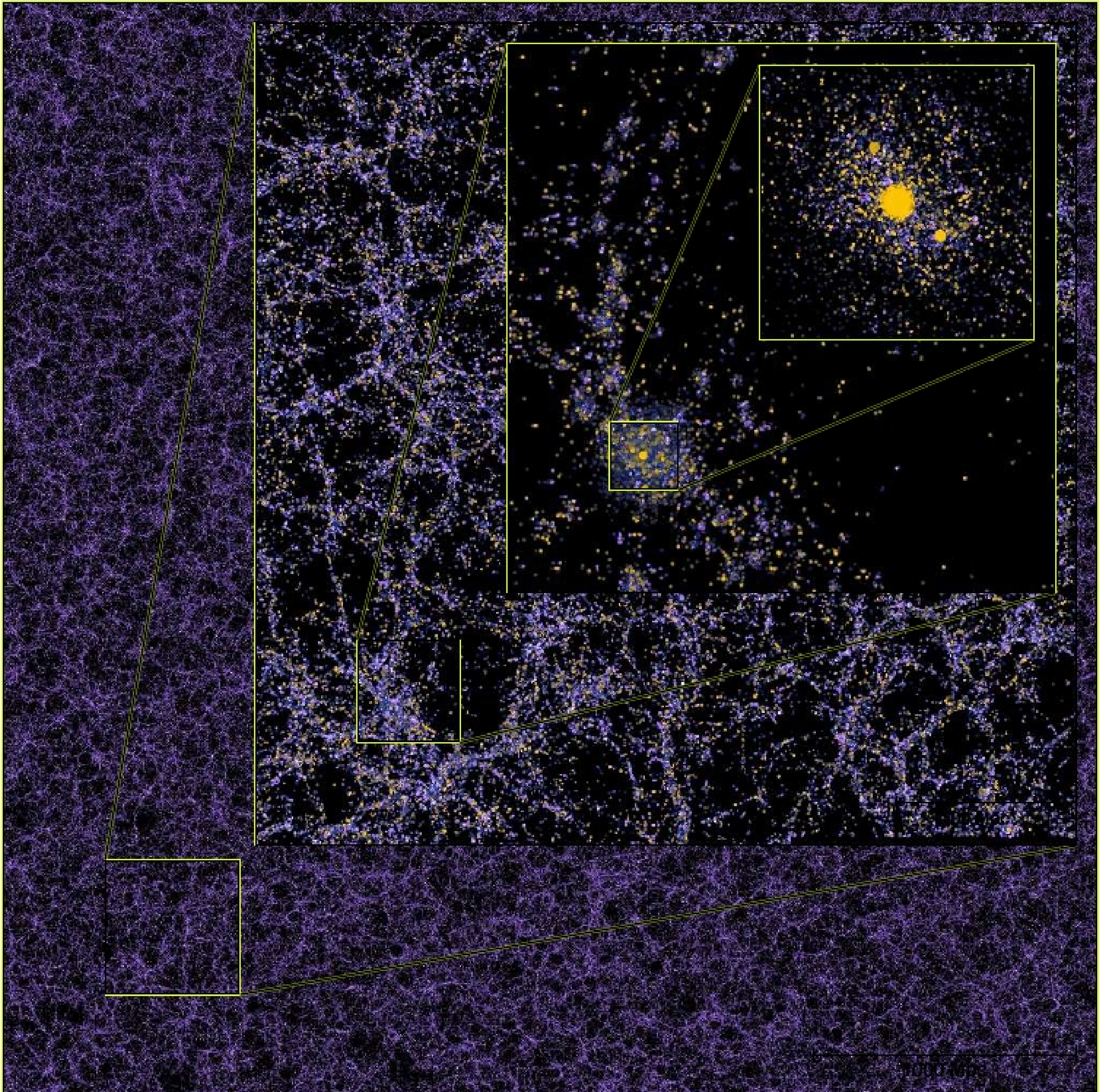
Parameter	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 95% limits
Ω_K	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.000	< 0.230
$N_{\rm eff}$	3.22	$3.30^{+0.54}_{-0.51}$

Neutrinos account for at most a few percent of the DM

Precision simulations for cosmology?



- Halo abundances are available to few percent accuracy over 7 orders of magnitude in mass
- Differences in definition of "halo" can shift n(M) by tens of percent
- ~40% of DM is not in a halo with $M > 10^8 M_\odot$ -- lensing?
- Baryonic processes can affect halo structure



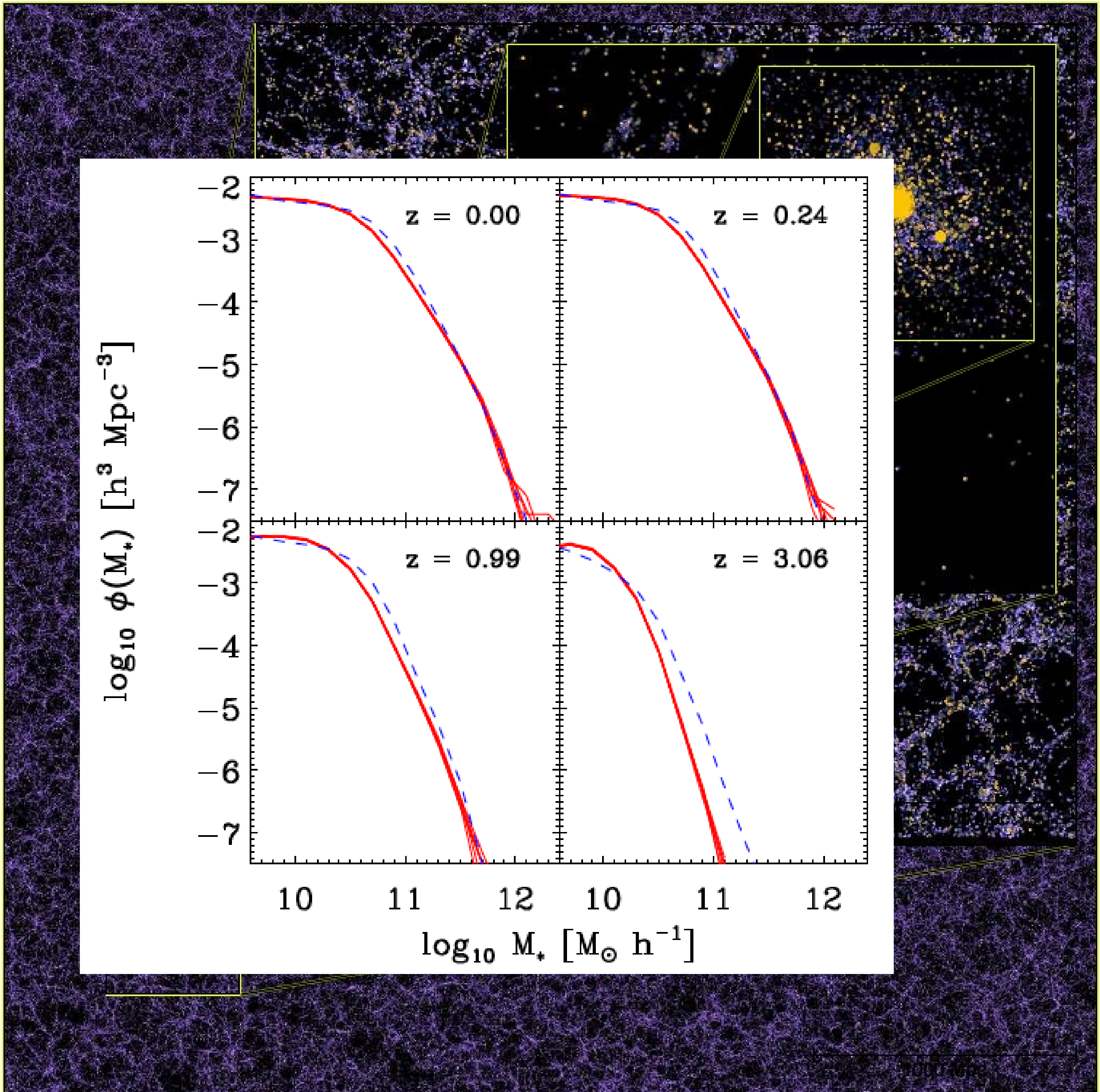
M-XXL

$N = 3 \times 10^{11}$

$L = 4.3$ Gpc

Simulates the formation of ~1 billion galaxies directly

Angulo et al 2012



M-XXL

$N = 3 \times 10^{11}$

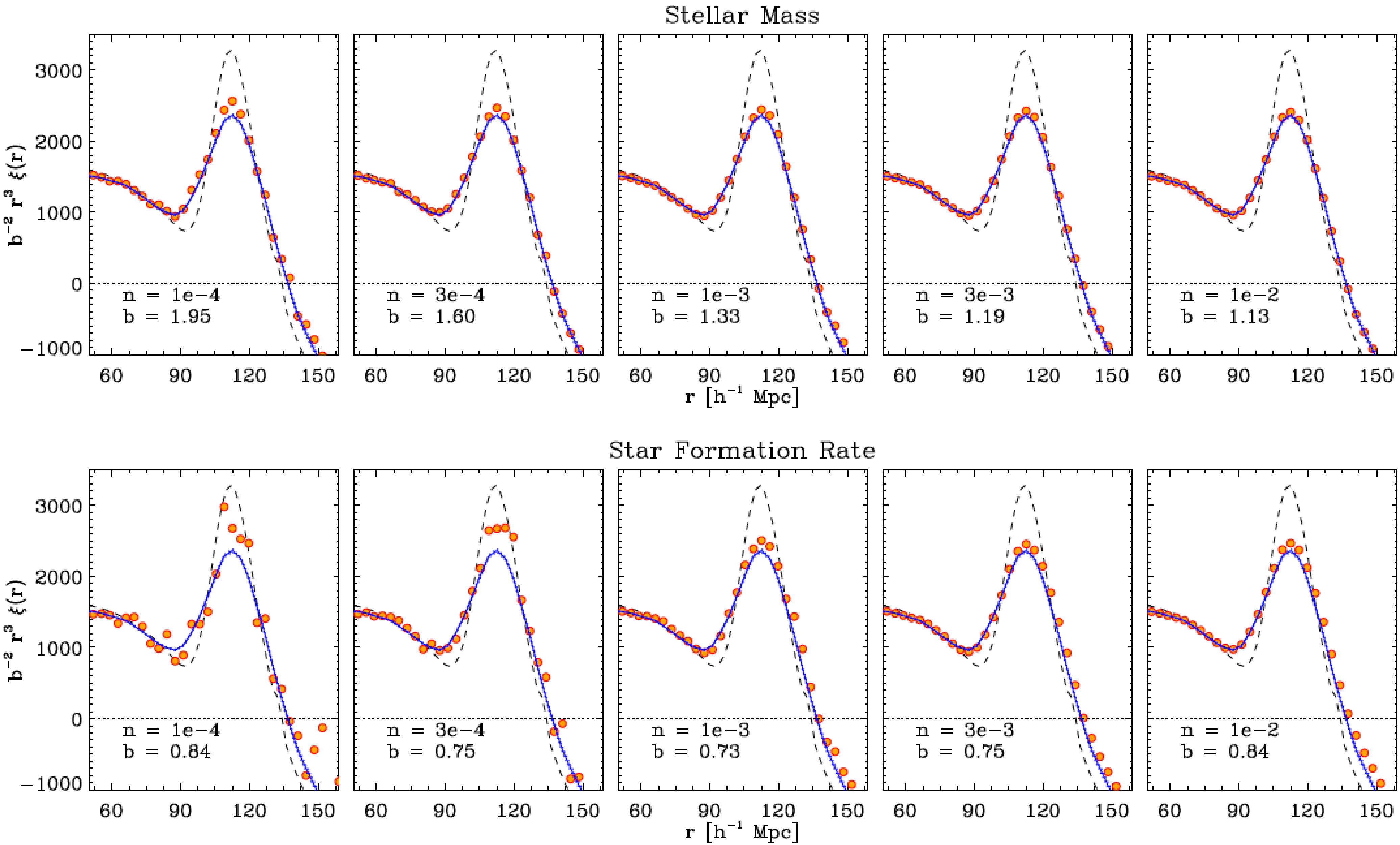
$L = 4.3$ Gpc

Simulates the formation of ~1 billion galaxies directly

Results converge with Millennium for brighter galaxies

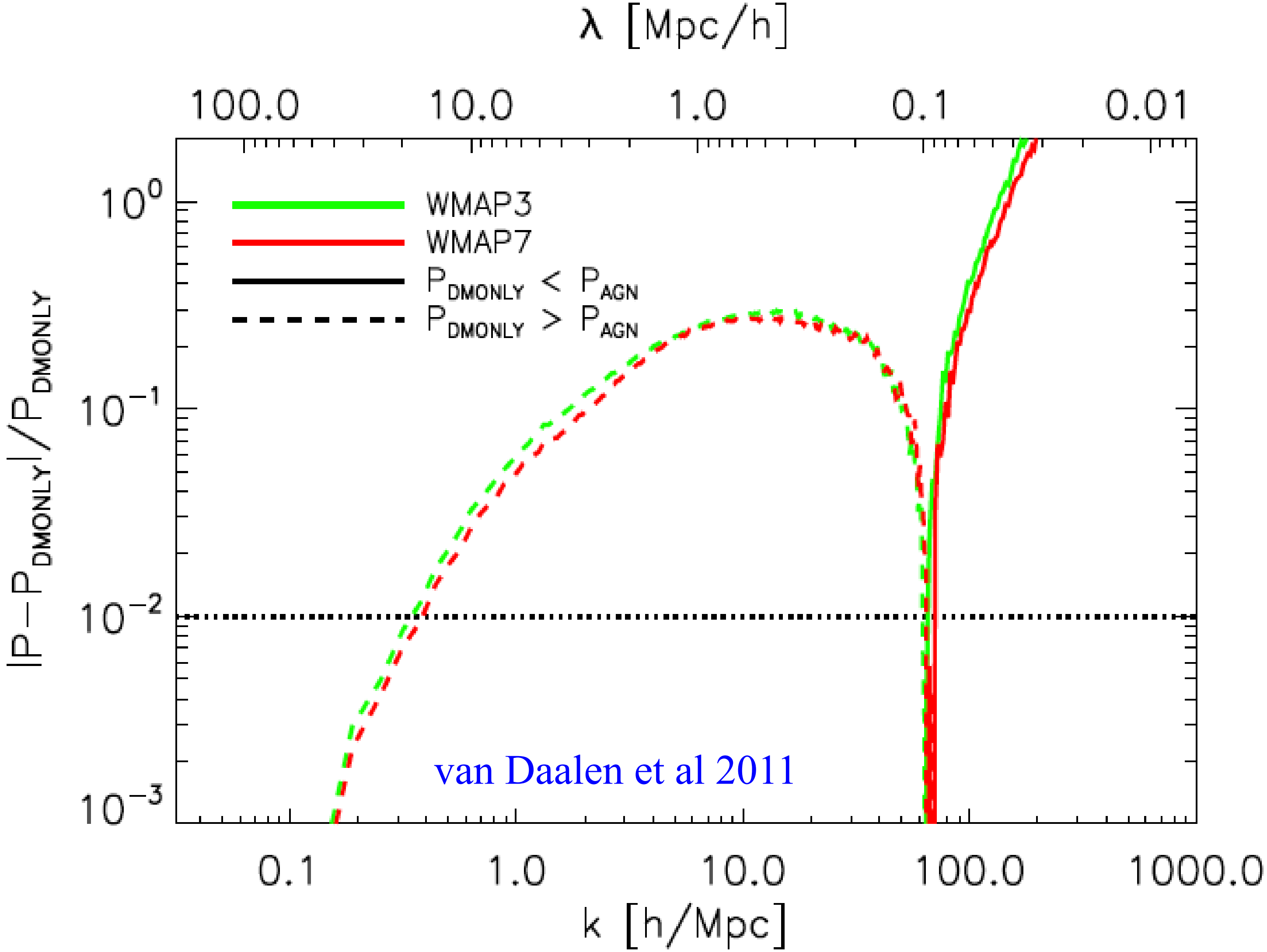
Angulo et al 2012

Distortions of BAO feature in the galaxy population



Angulo et al 2013

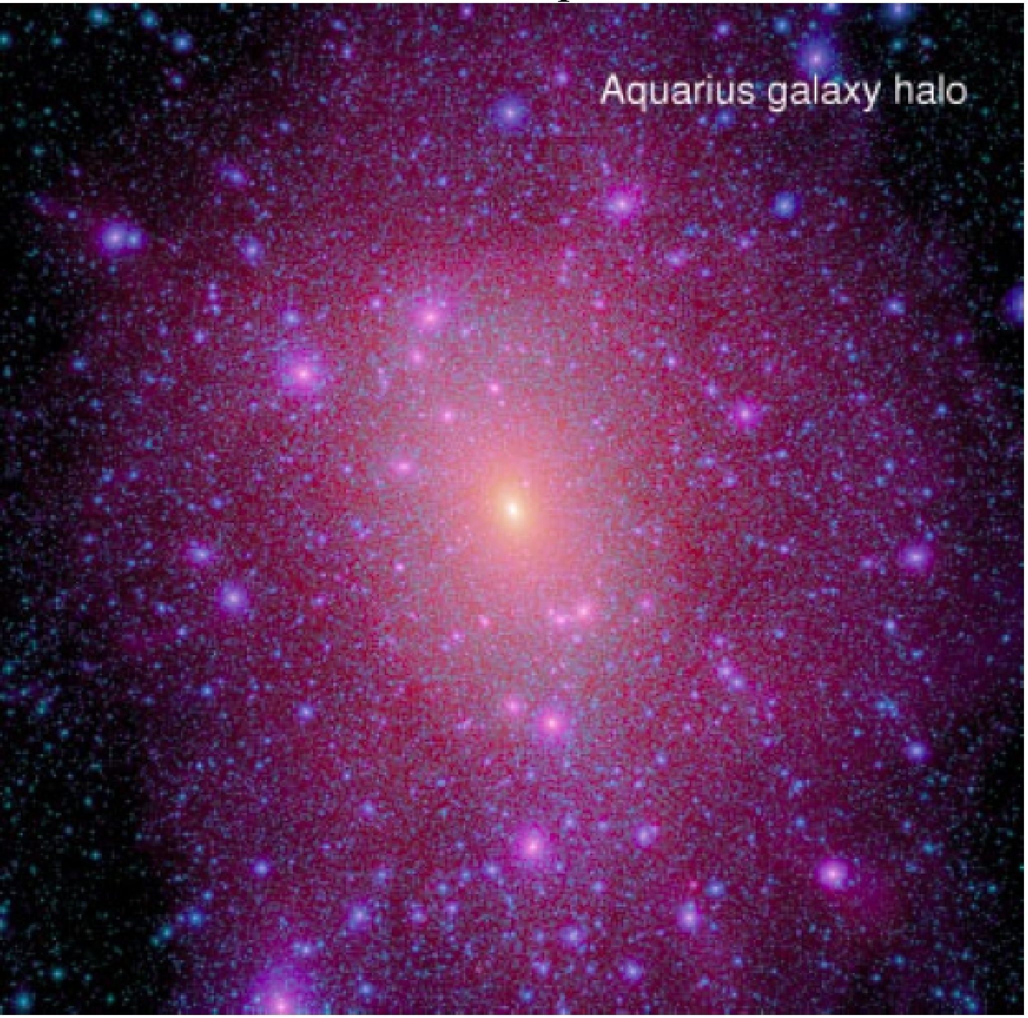
Small but measurable shifts for different selection methods



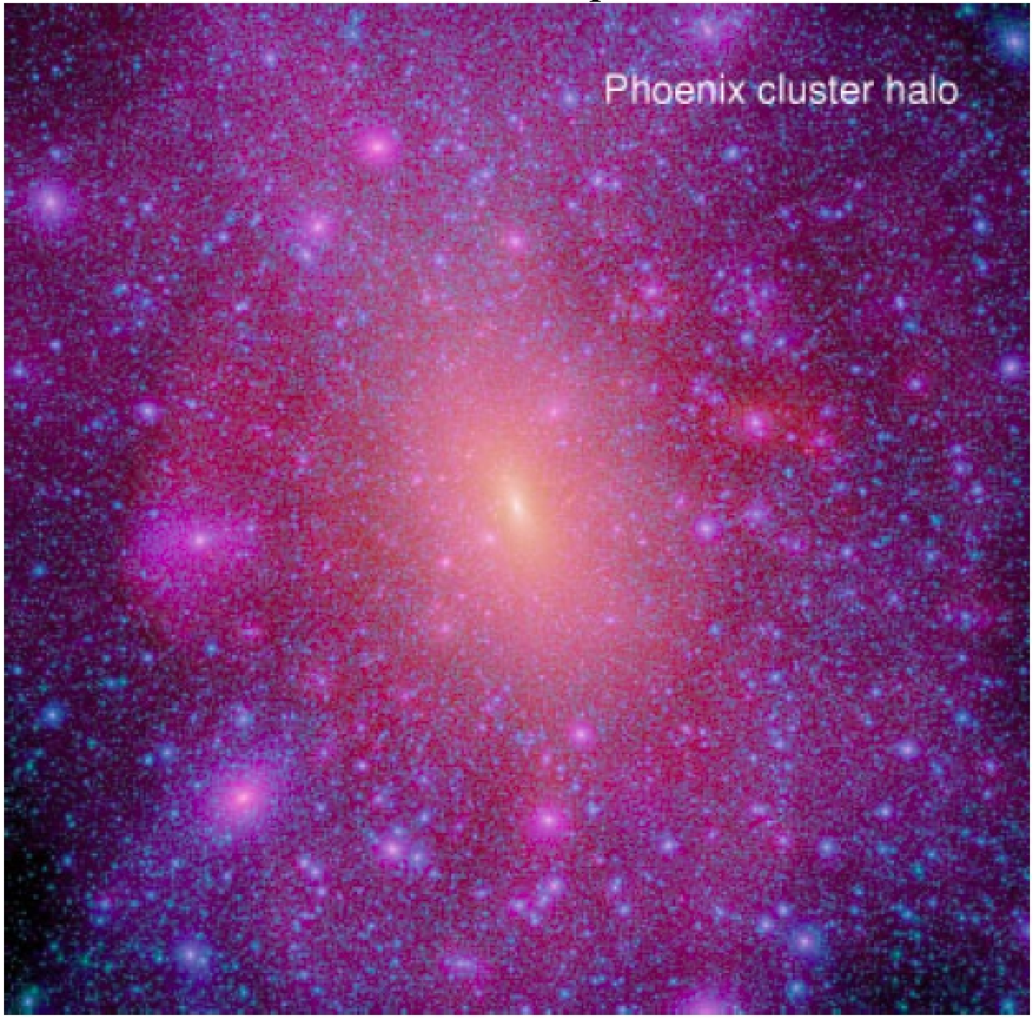
Feedback effects in a realistic galaxy formation model affect the mass power spectrum at the several percent level even at λ ~ 10 Mpc
This poses a problem for "precision" cosmology

All ΛCDM halos look similar

1 .1 Mpc



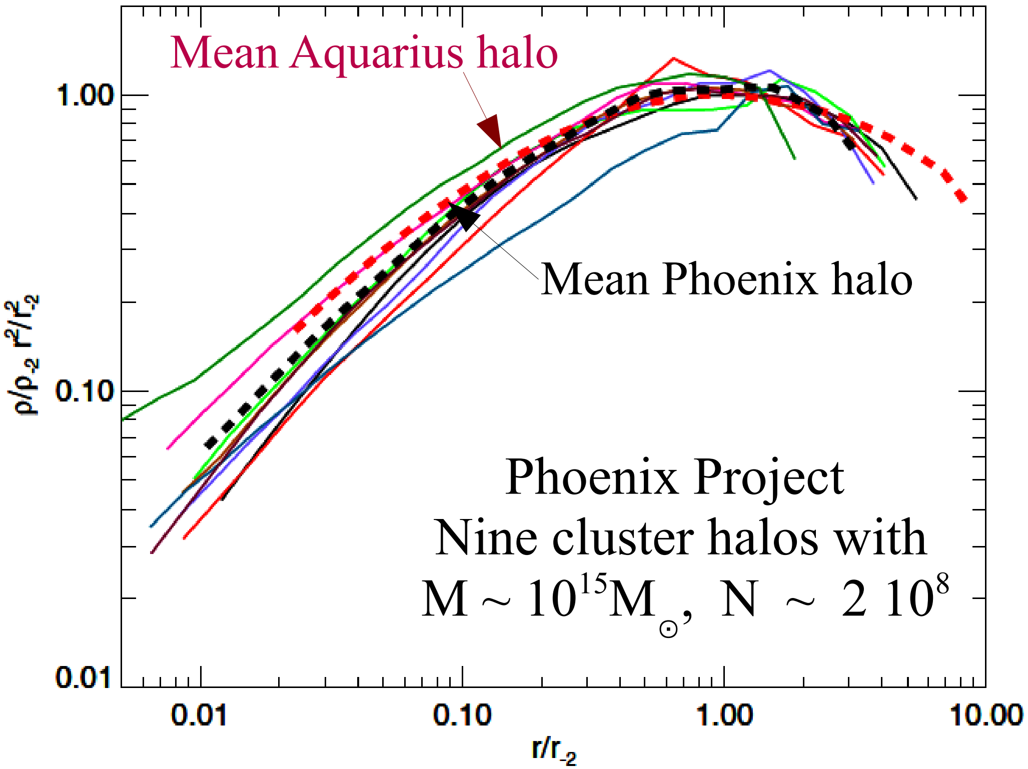
7.1 Mpc



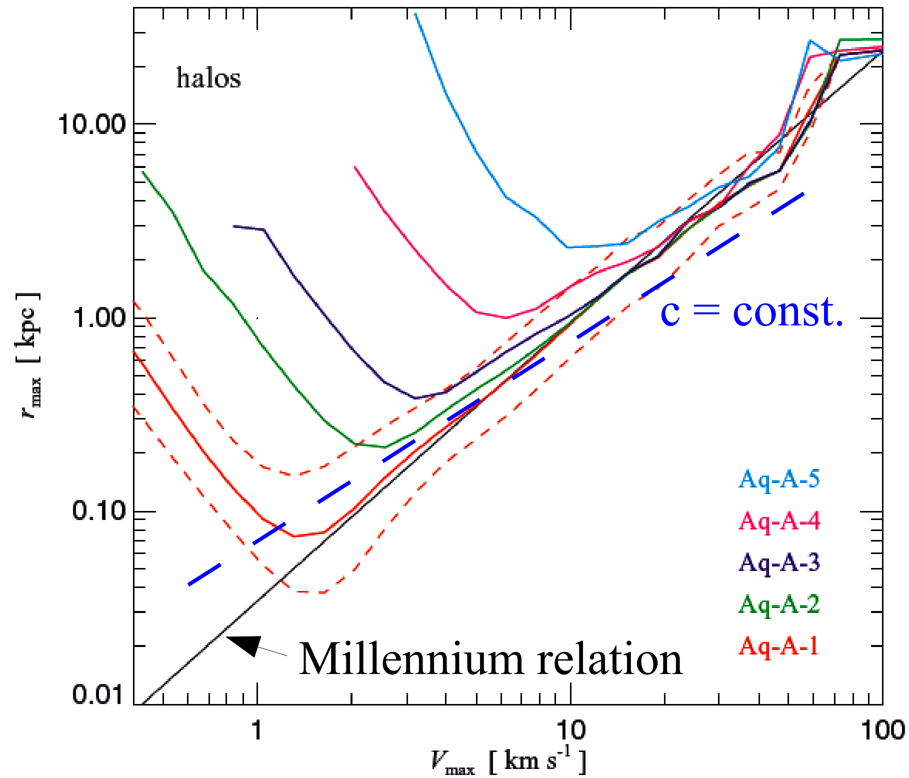
- Cuspy -- radial density profiles are fit by NFW/Einasto models
- Triaxial -- equidensity contours with a/c > 2 are common
- Substructure – mainly at large radii with up to tens of percent of the mass

All ΛCDM halos look similar ...but not identical

Gao et al 2012

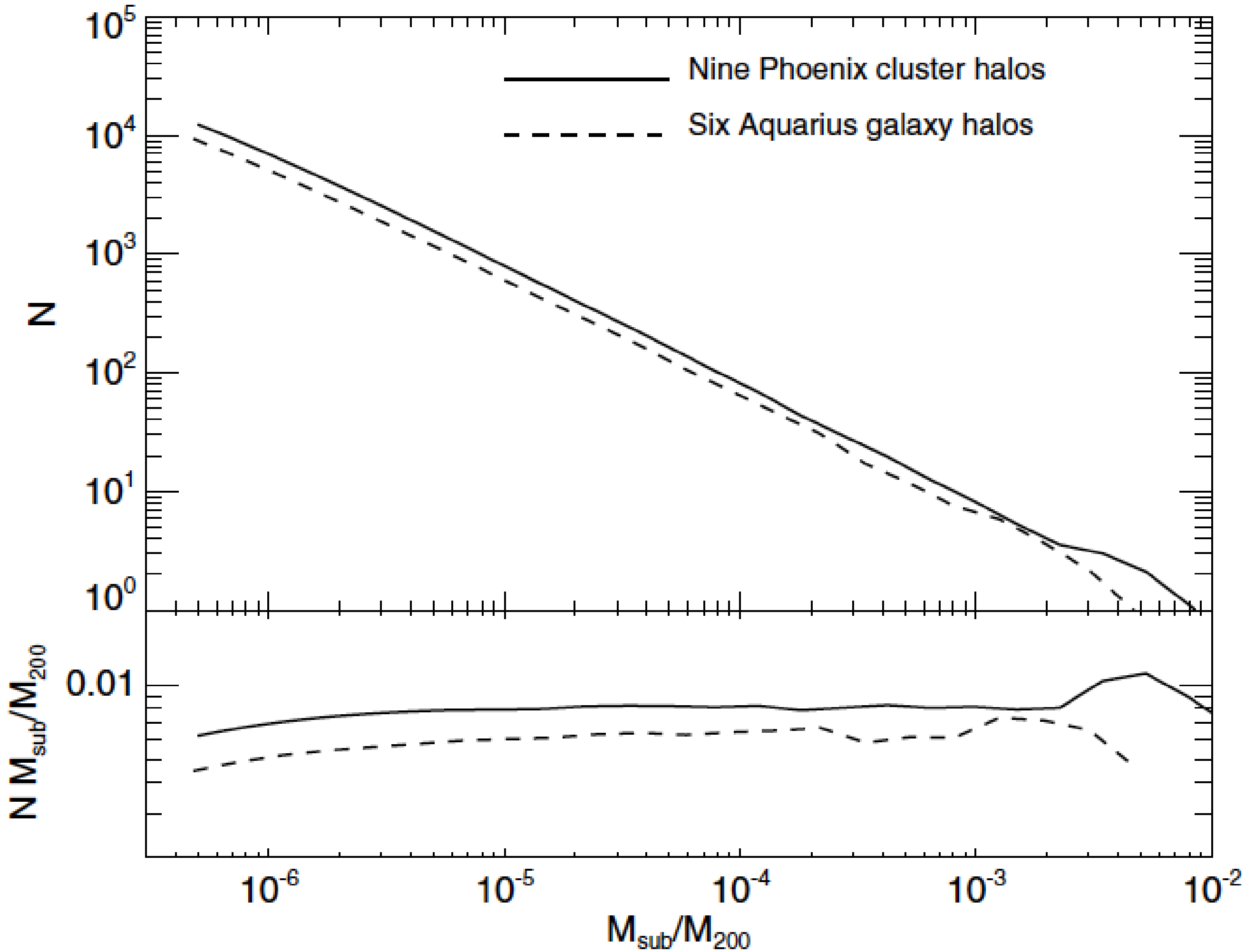


Springel et al 2008

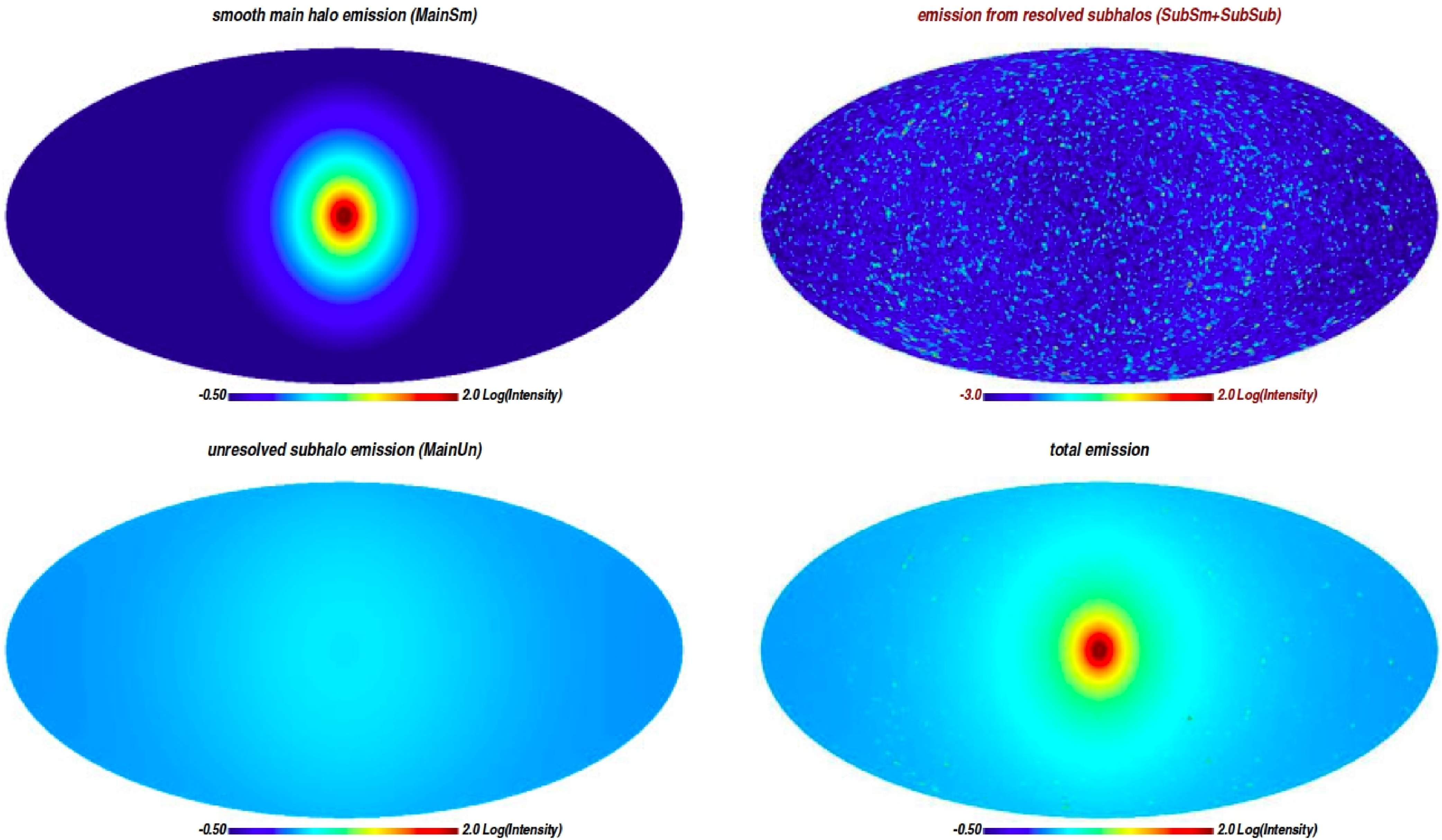


- The scatter in profile <u>shape</u> between halos of given mass is large compared to dependence of mean shape on mass
- The dependence of concentration (mean density → annihilation efficiency) on mass is significant, but not measured to very low mass

All ΛCDM halos look similar also in their substructure



- Galaxy halos have slightly less substructure than cluster halos
- Both have roughly equal total mass in each decade of subhalo mass
- Total mass in subhalos of *any* mass is still quite uncertain

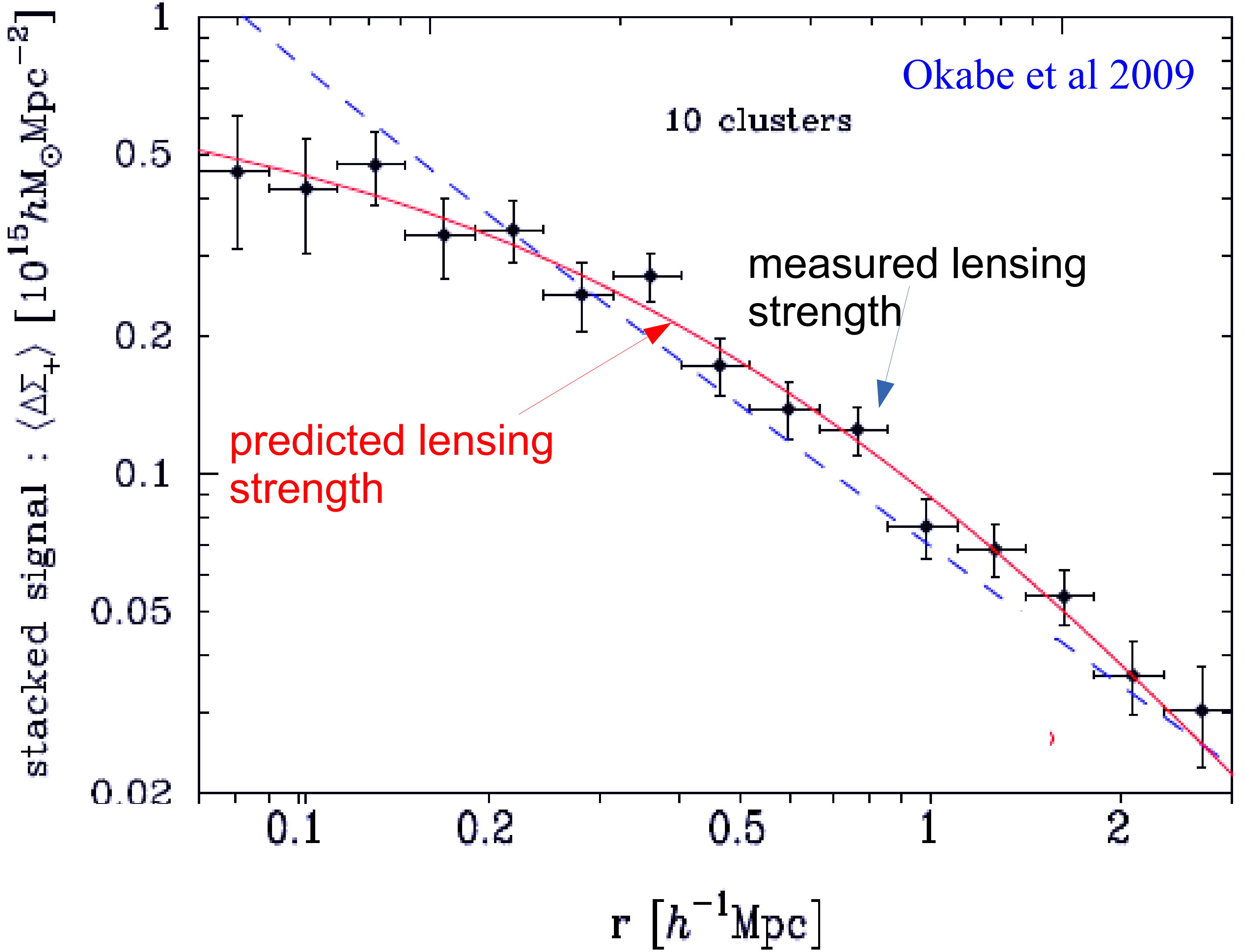


- Halo annihilation flux dominated by that from unresolved small halos but this is nearly uniform over the sky
- Flux from the Galactic centre dominates that from resolved subhalos by a large factor, but relative detectability depends critically on noise sources

Dark matter halos – issues?

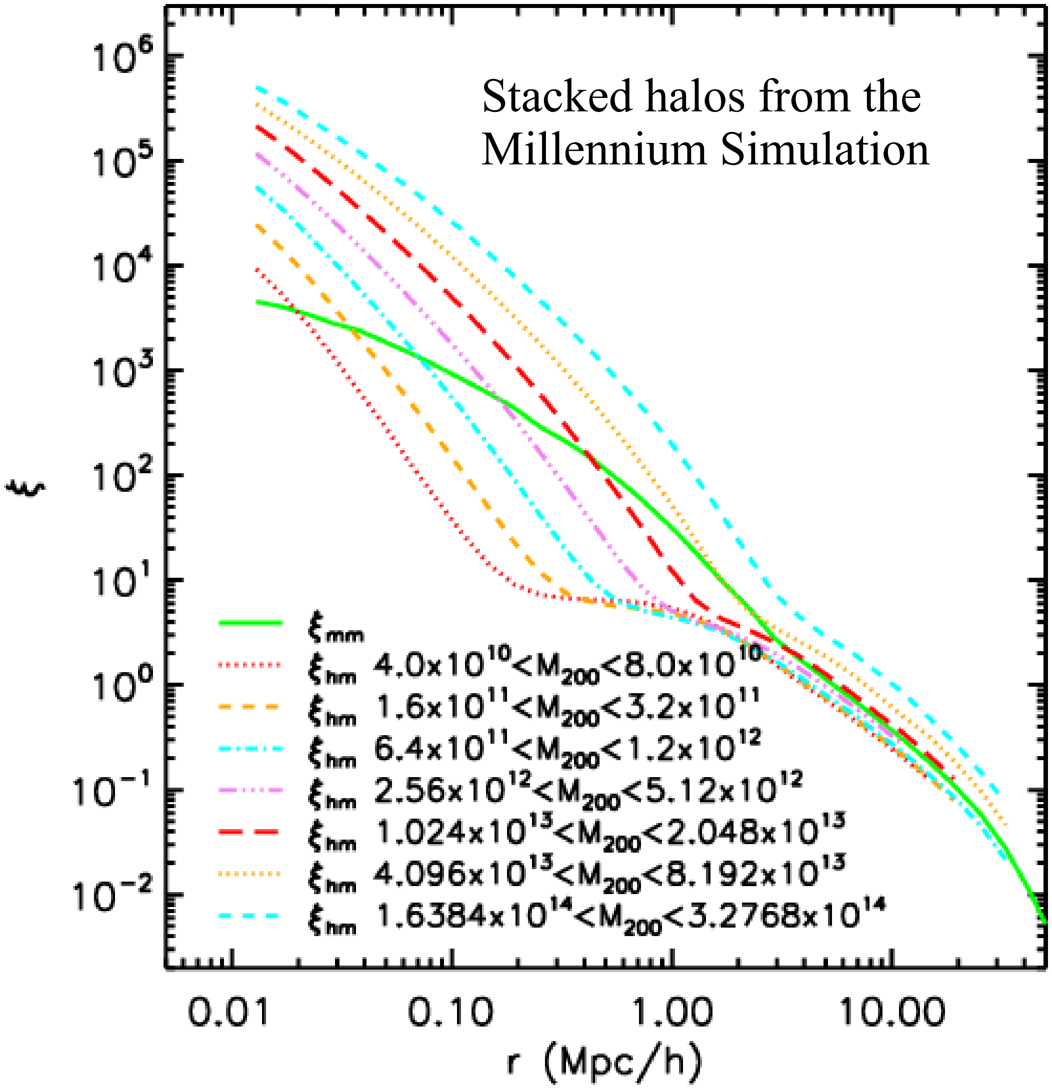
- Profiles as predicted?
  NFW over the bulk of the mass?
  Central cusps? (nature of DM?)

Comparison of predicted/observed lensing



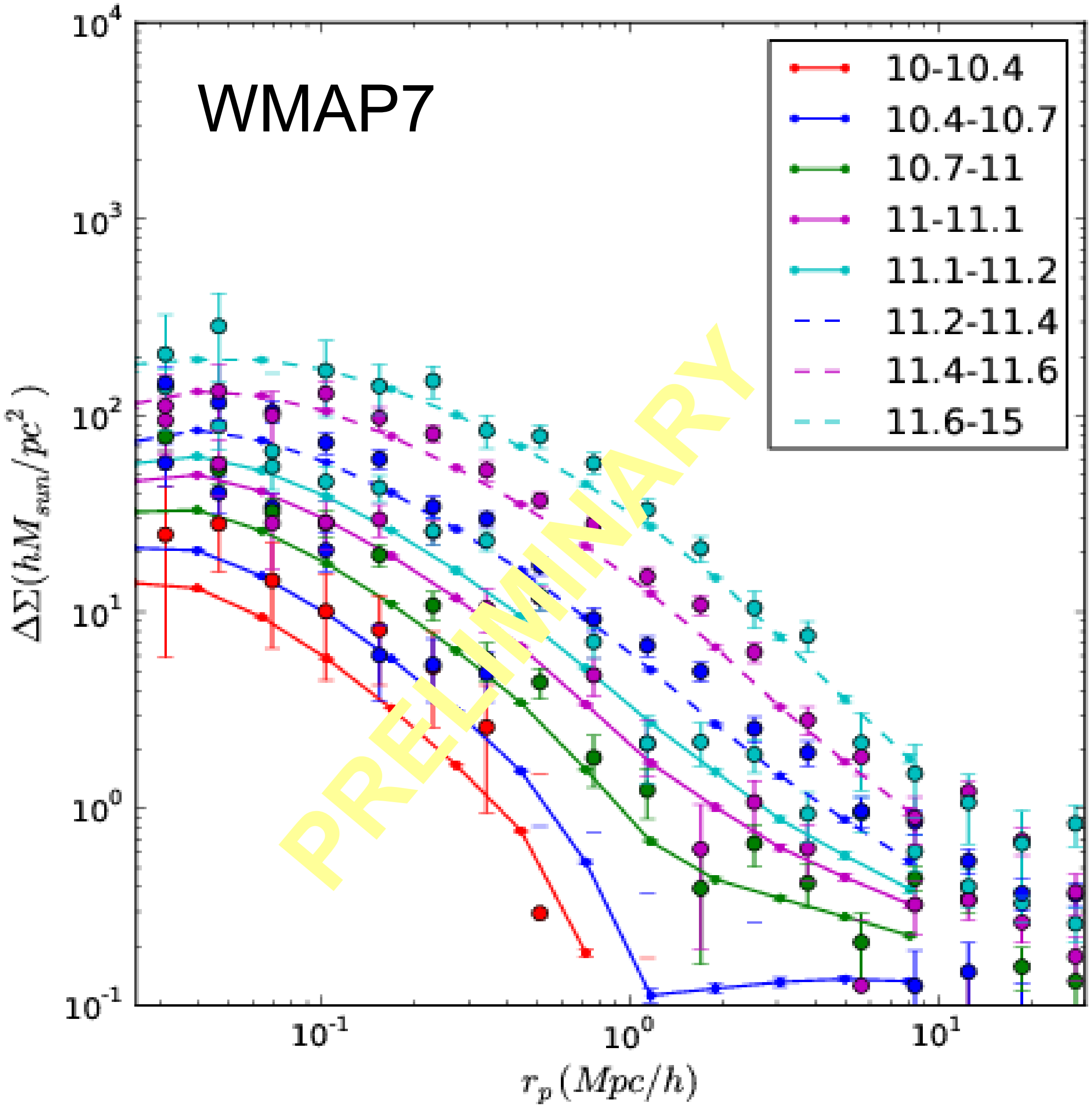
Mean density profiles of dark halos to large radius

Hayashi & White 2007



- Fit by an NFW or Einasto profile on small scales
- Fit by a biased *linear* 2-point correlation function on large scales
- A sharp transition!

Comparison of predicted/observed lensing



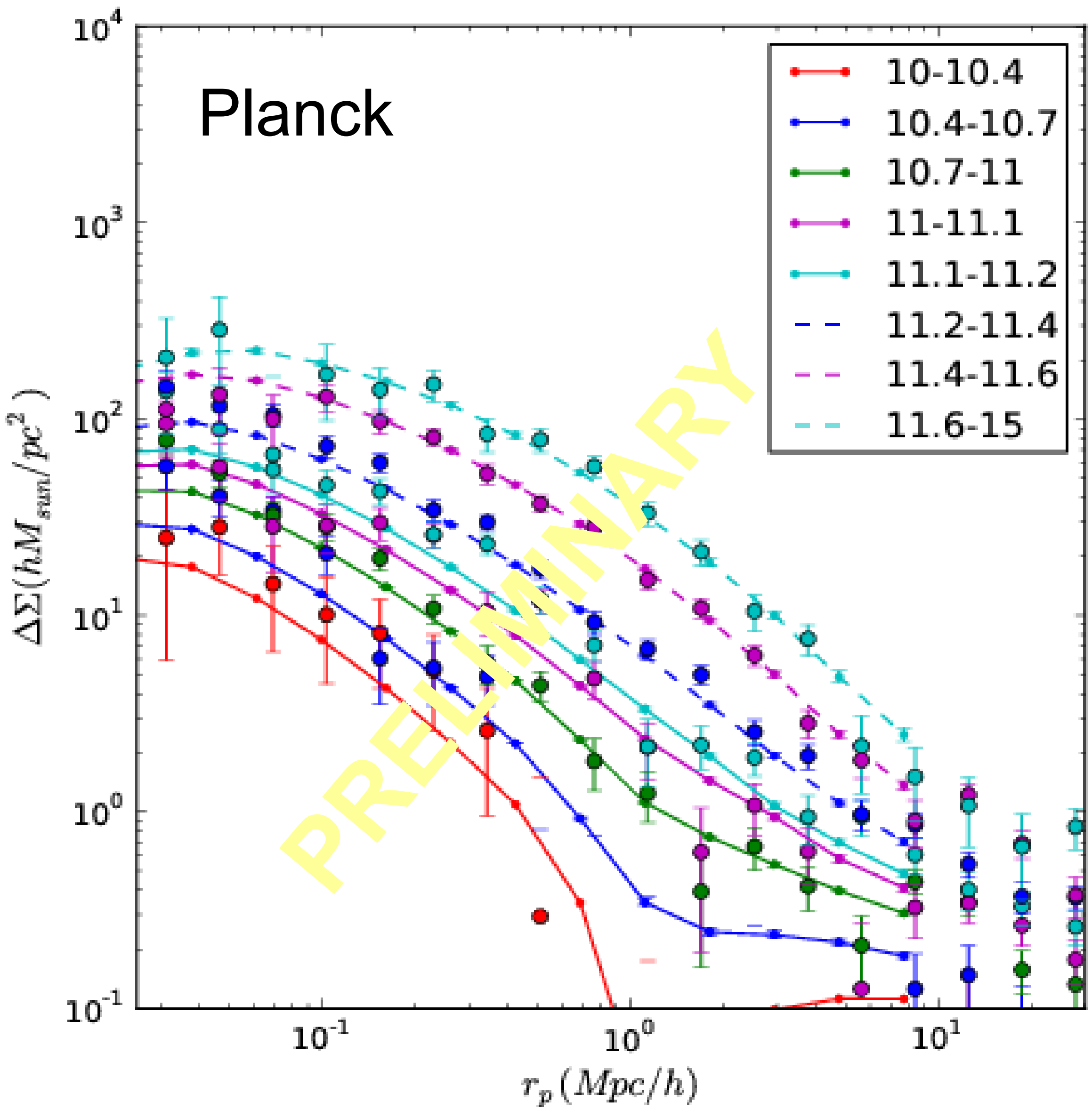
Wang, Mandelbaum et al, in prep.

Stacked weak lensing signal around Locally Brightest Galaxies in the SDSS/DR7 in bins of LBG stellar mass.

Dashed lines are similarly selected samples from the Guo et al (2013) galaxy formation simulation for a WMAP7 cosmology

A “no parameters” test!

Comparison of predicted/observed lensing



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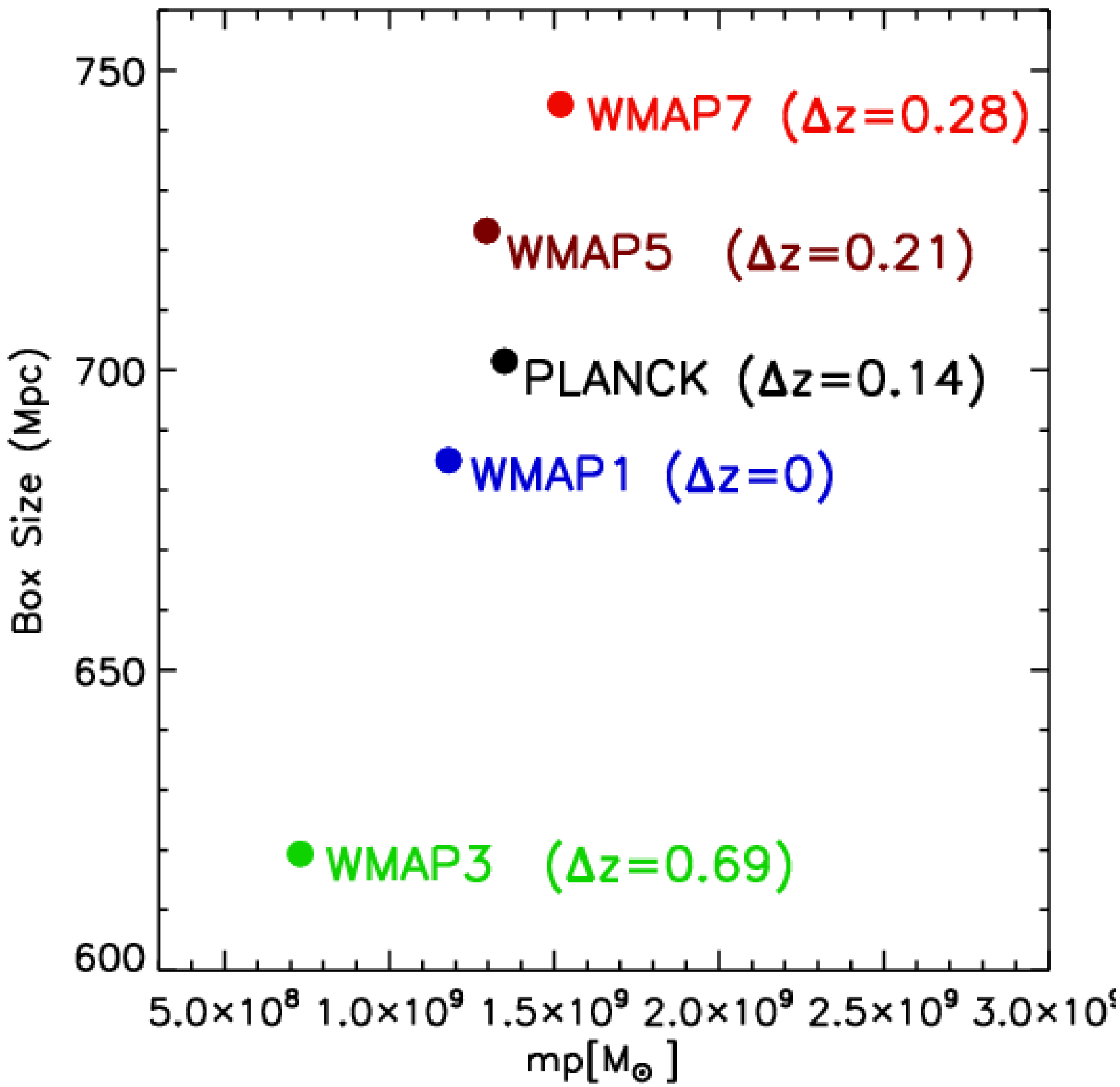
A “no parameters” test!

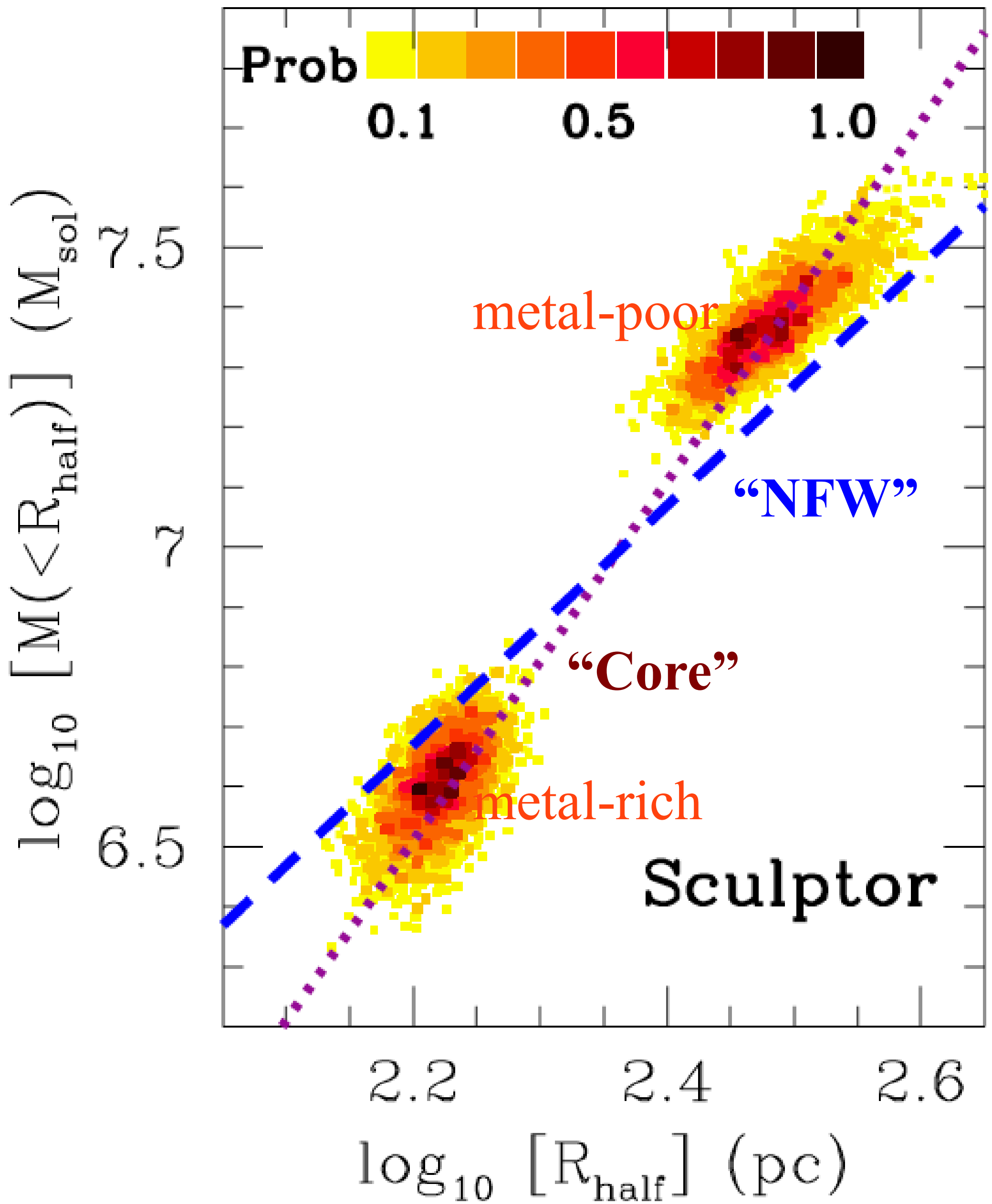
Effect of changing cosmology on structure growth



Scalings needed to adapt the MS to changing CMB cosmologies

(see Angulo & White (2010) for details of the scaling method)

Dark matter halos – issues?

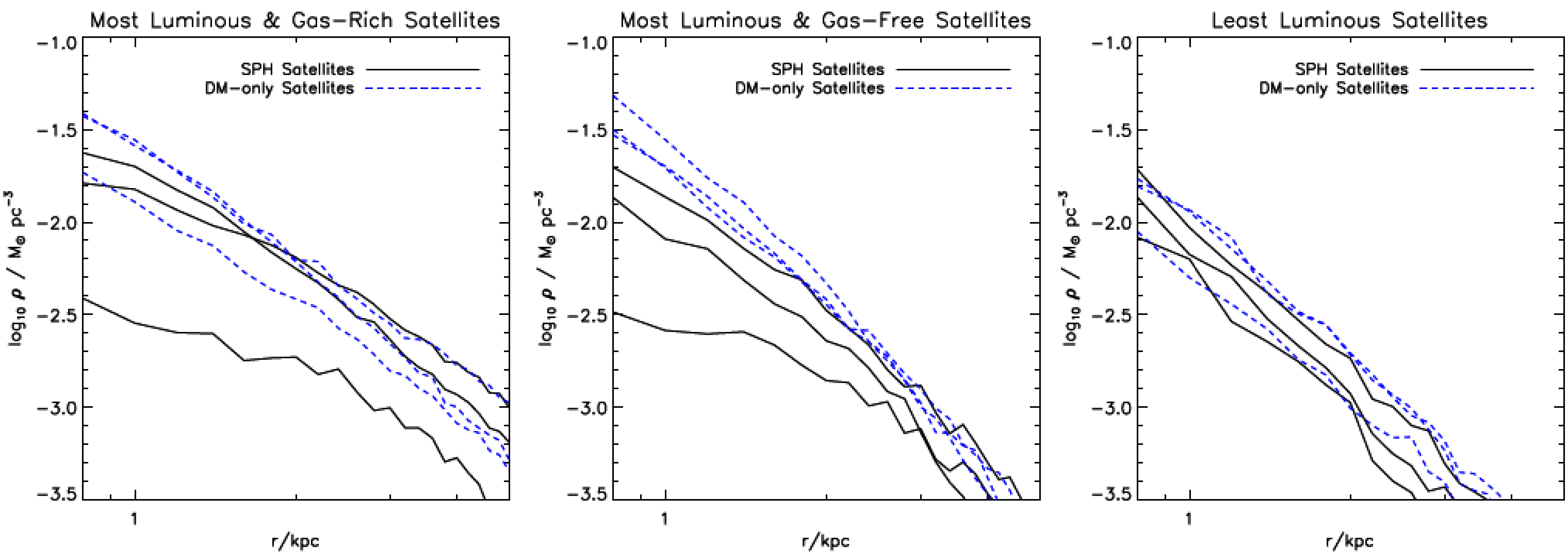


Sculptor (and also Fornax) has two well defined populations. Metal-rich stars are clearly more centrally concentrated and have lower velocity dispersion than metal-poor stars. Assuming

$$M(r_{1/2,\mathrm{proj}}) = C_W\, r_{1/2,\mathrm{proj}}\, \sigma^2_{\mathrm{l.o.s.}} / G$$

with $C_W \approx 2.5$, Walker & Penarrubia (2011) exclude NFW mass distributions

Dark matter halos – issues?

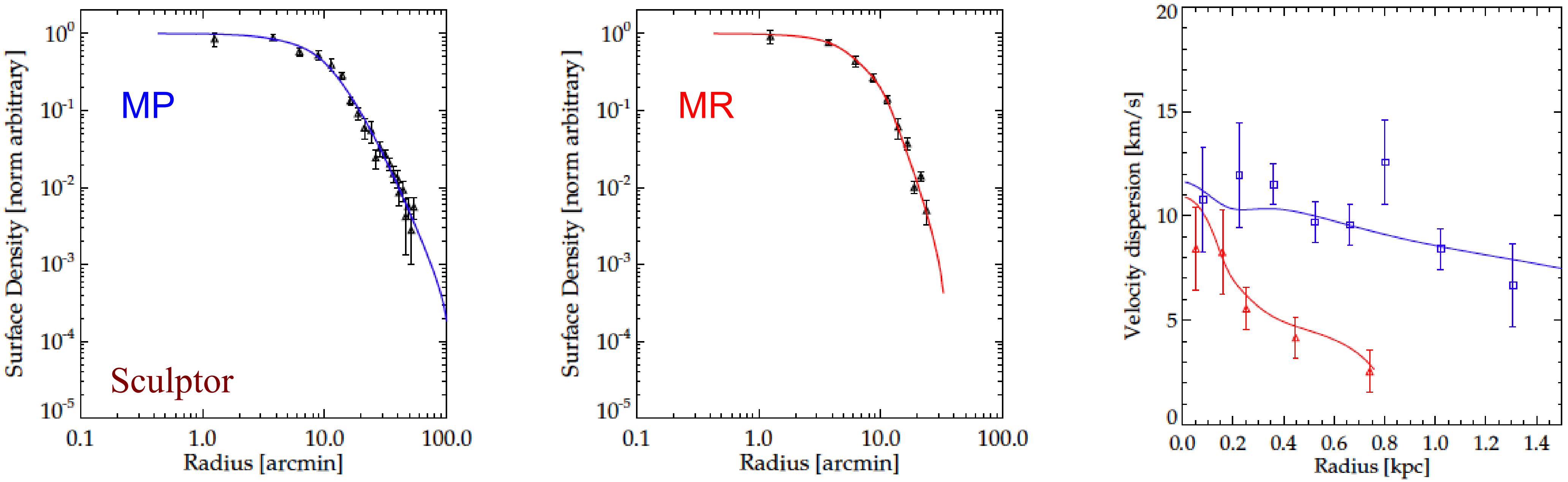


SPH simulations by Zolotov et al (2012) suggest dynamics associated with star formation may "flatten" cores in more massive dwarfs

Do dSph's have enough stars for this to be important?

Dark matter halos – issues?

Strigari et al 2013, in prep.



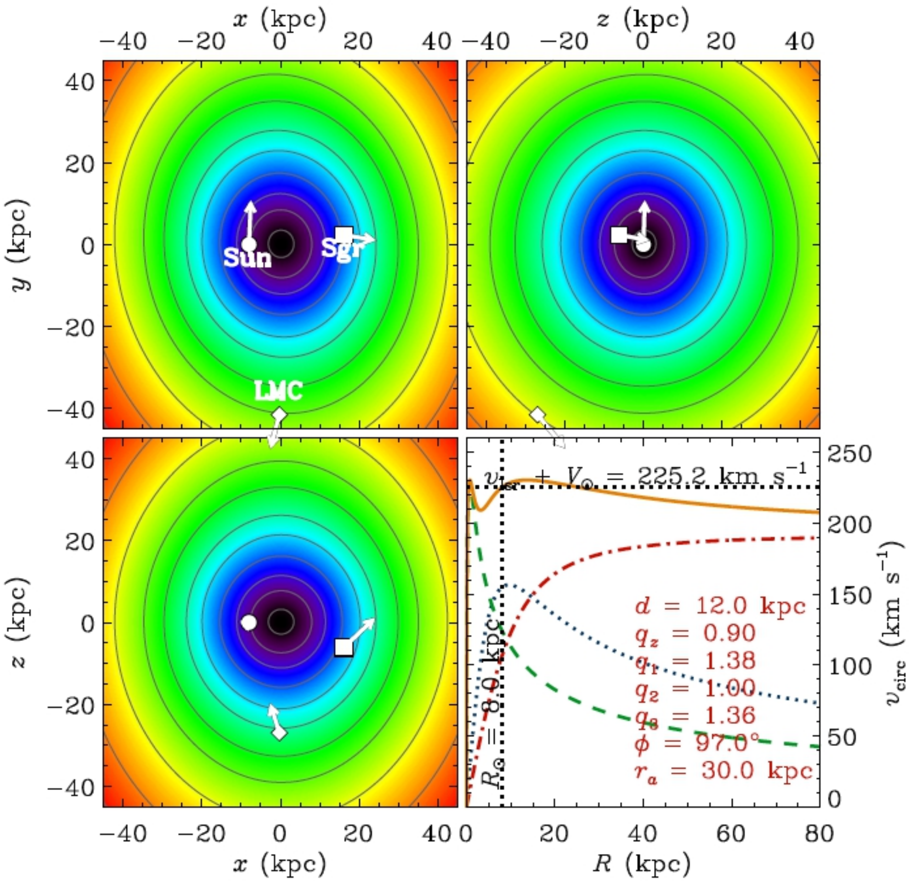
The counts and dispersion profiles of the MR and MP populations in Sculptor *can* be well fit (in a χ^2 sense) as equilibria defined by simple anisotropic distribution functions within a single NFW potential.
The required NFW parameters are consistent with ΛCDM subhalos

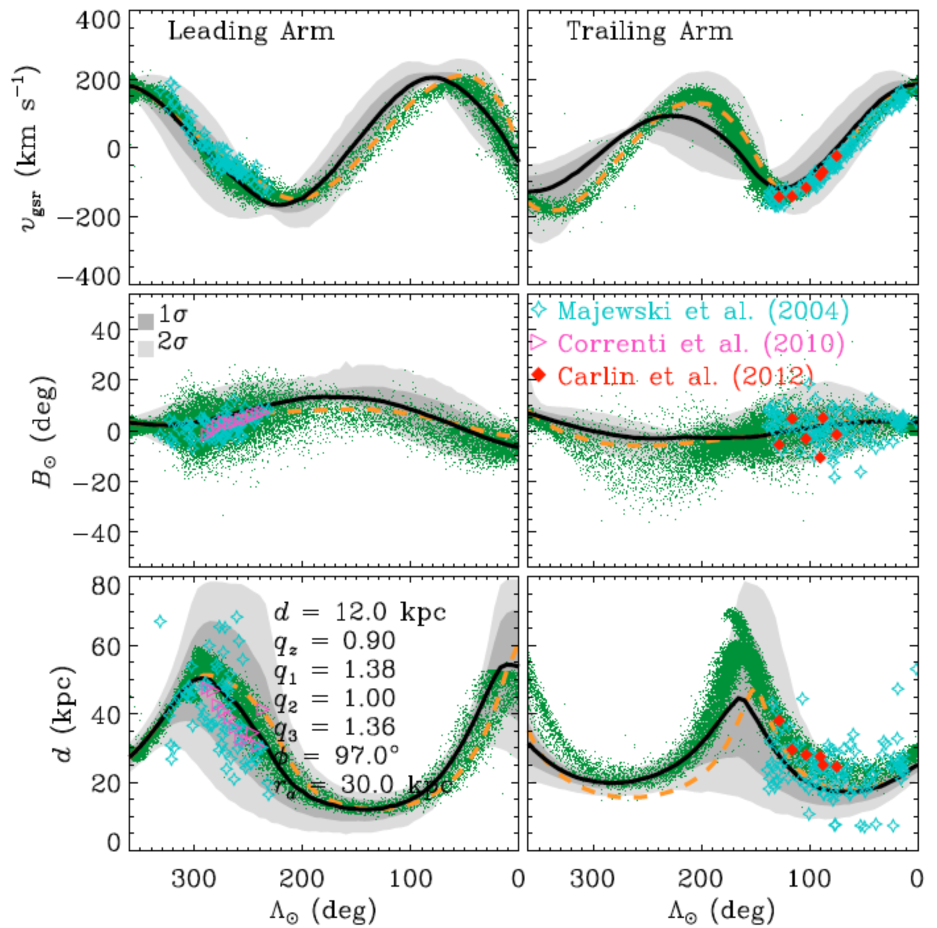
Dark matter halos – issues?

- Profiles as predicted?
  NFW over the bulk of the mass?
  Central cusps? (nature of DM?)

- Shapes as predicted?
  Shapes from lensing (individual clusters? stacked galaxies?)
  Orbits of the streams in the MW or M31 halos

Dark matter halos – issues?





Matching kinematics of both leading and trailing arms of Sagittarius can be accomplished by a potential which is oblate at r << 30 kpc and triaxial at r >> 30kpc. The LMC can have a significant effect.

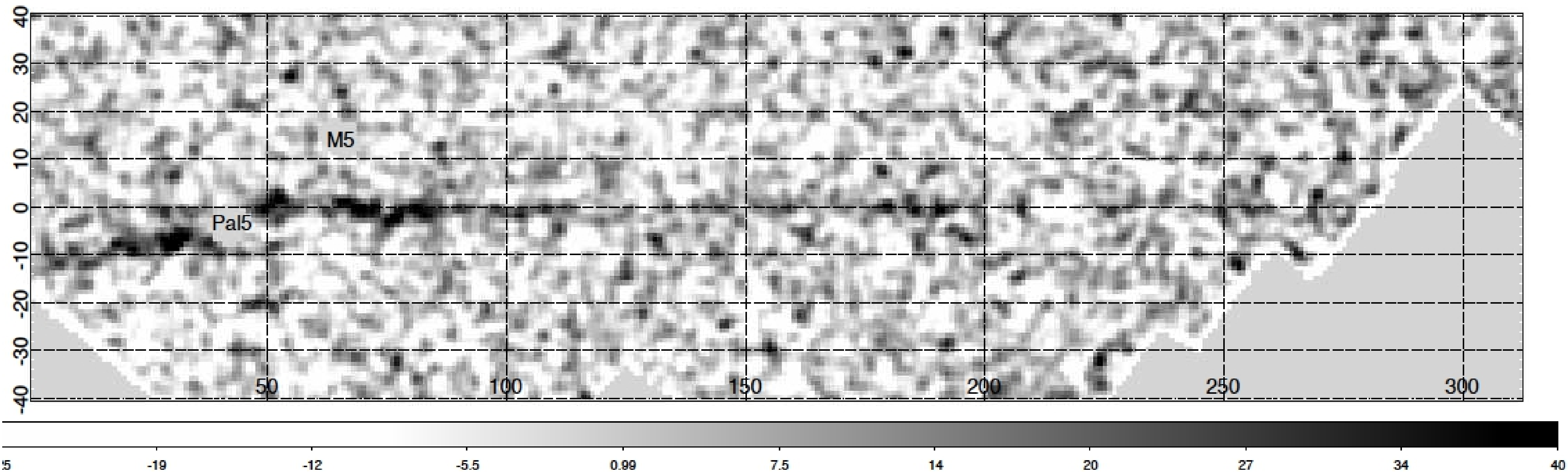
(Vera-Ciro & Helmi 2013)

Dark matter halos – issues?

- Profiles as predicted?
  - NFW over the bulk of the mass?
  - Central cusps? (nature of DM)
- Shapes as predicted?
  - Shapes from lensing (individual clusters? stacked galaxies?)
  - Orbits of the streams in the MW or M31 halos
- Substructure as predicted?
  - Effects on disk? GCs? Streams?
  - Effects on strongly lensed background objects
  - Satellite counts – abundances, M_*–V_{max} relations

Dark matter halos – issues?

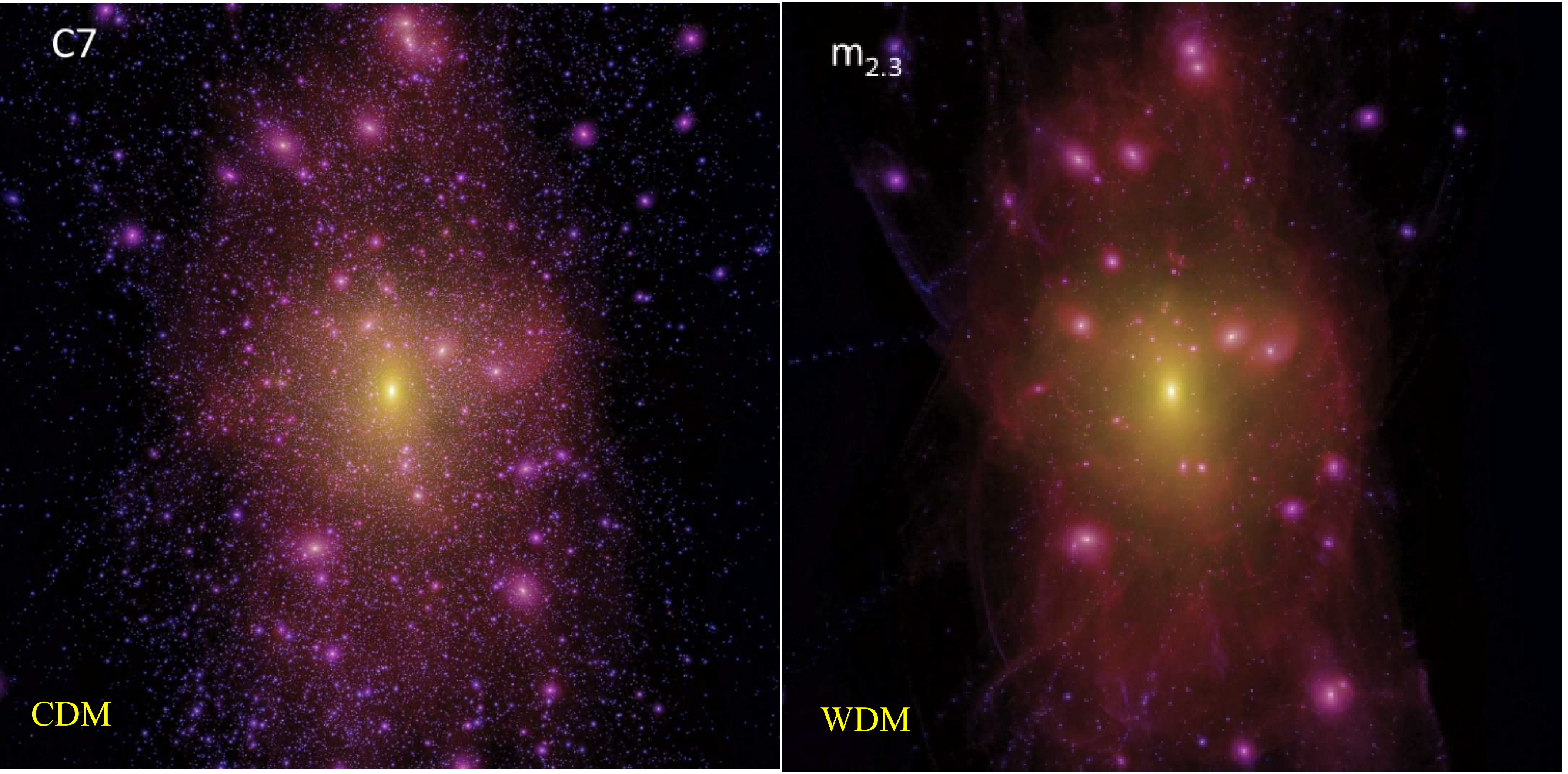
Carlberg, Grillmair & Hetherington 2013



Gaps in the Pal 5 star stream may be induced by DM subhalos
Five gaps at >99% confidence requires >1000 substructures within 30 kpc with V_{max} > 1 km/s, consistent with ΛCDM predictions.

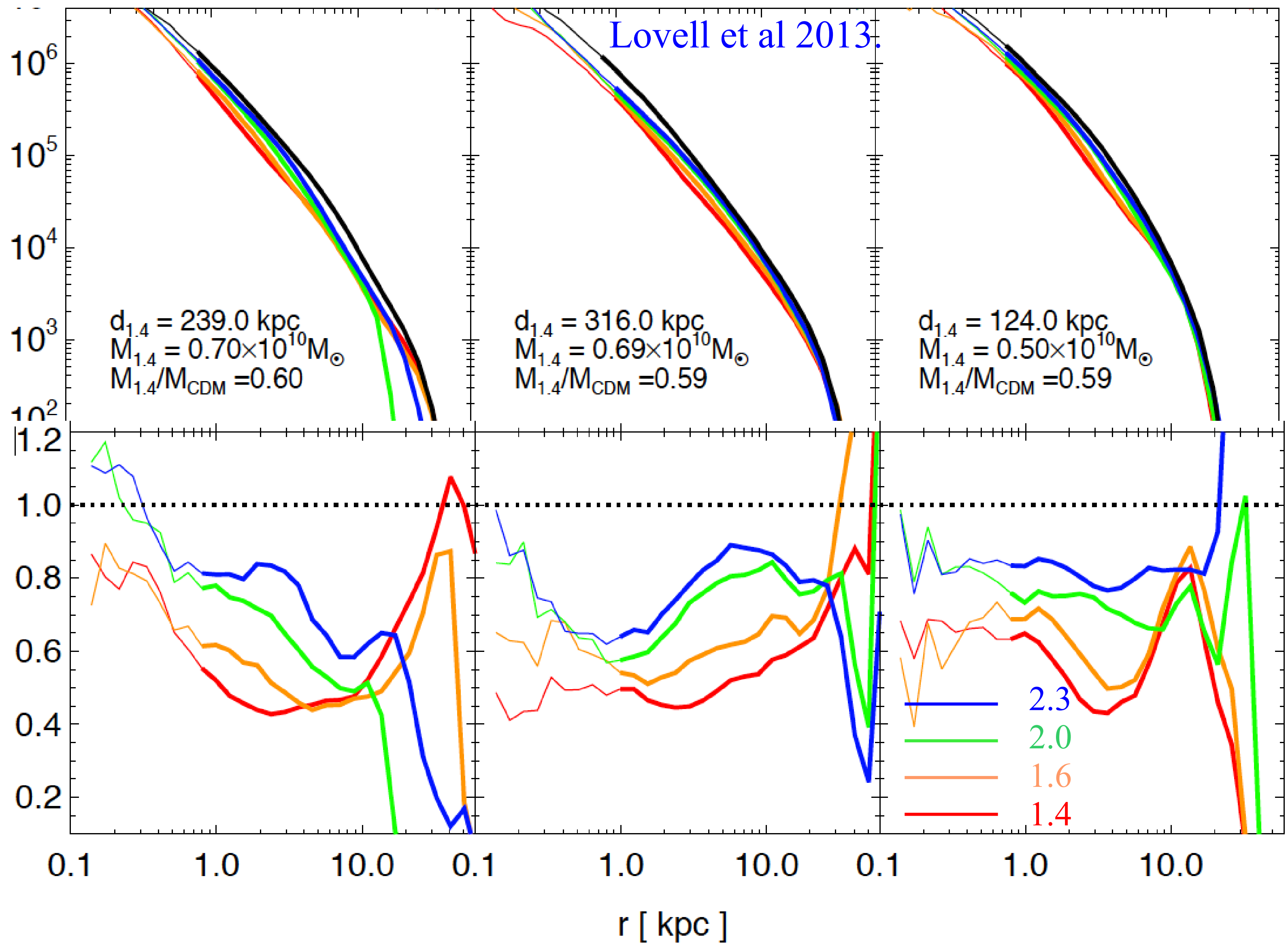
Dark matter halos – issues?

Lovell et al 2013.



A “Milky Way” halo in CDM and WDM (a “2.3 keV” sterile ν)
A mass exceeding ~1.5 keV is needed to get enough satellites

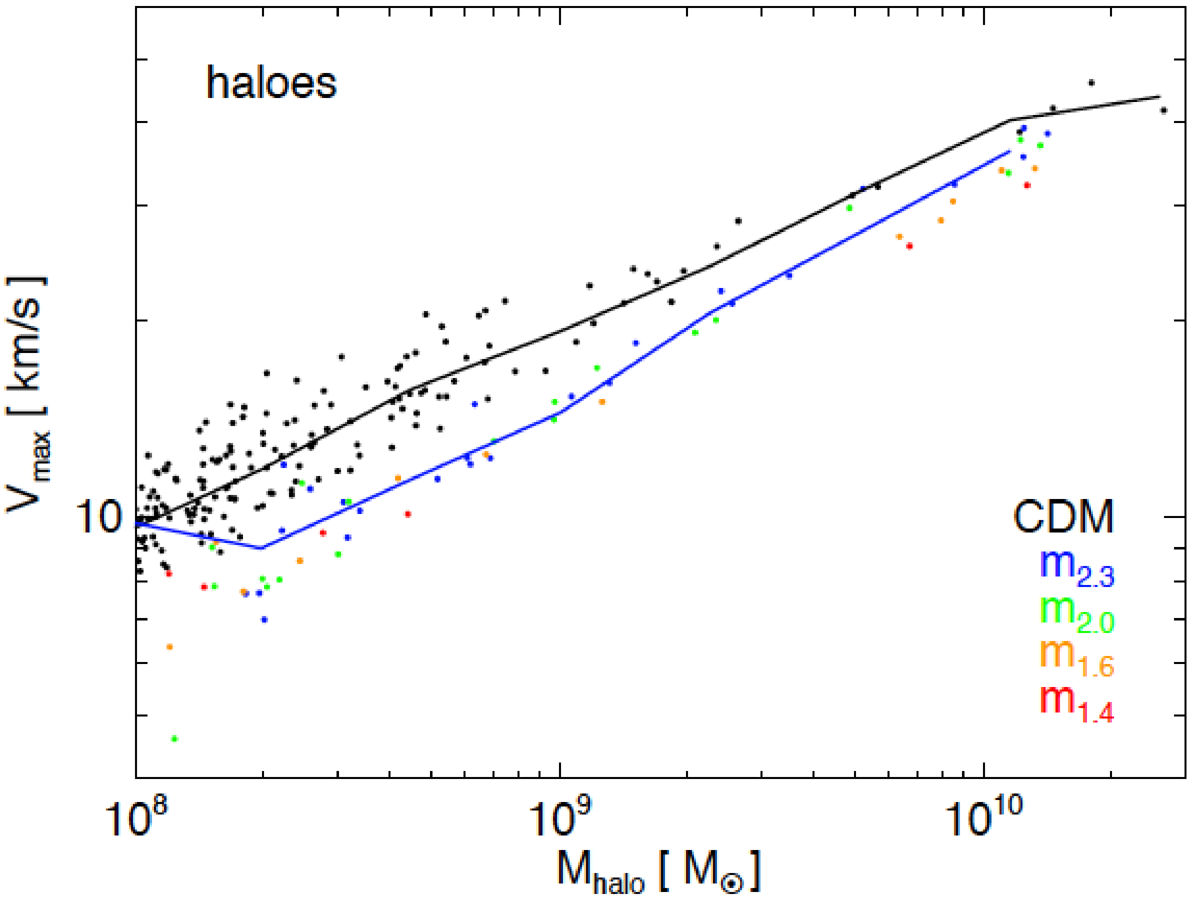
Subhalo density profiles in WDM vs CDM



WDM (sub)halos do NOT have cores. They are cuspy, as in CDM, but they are less concentrated. WDM cannot explain dwarf galaxy cores

Subhalo density profiles in WDM vs CDM

Lovell et al 2013.



Lower concentration leads to lower characteristic velocity at given subhalo mass → could help explain the low stellar velocities in (most) Milky Way dwarf satellites (the "too big to fail" problem)?

Structure in pregalactic gas at high redshift

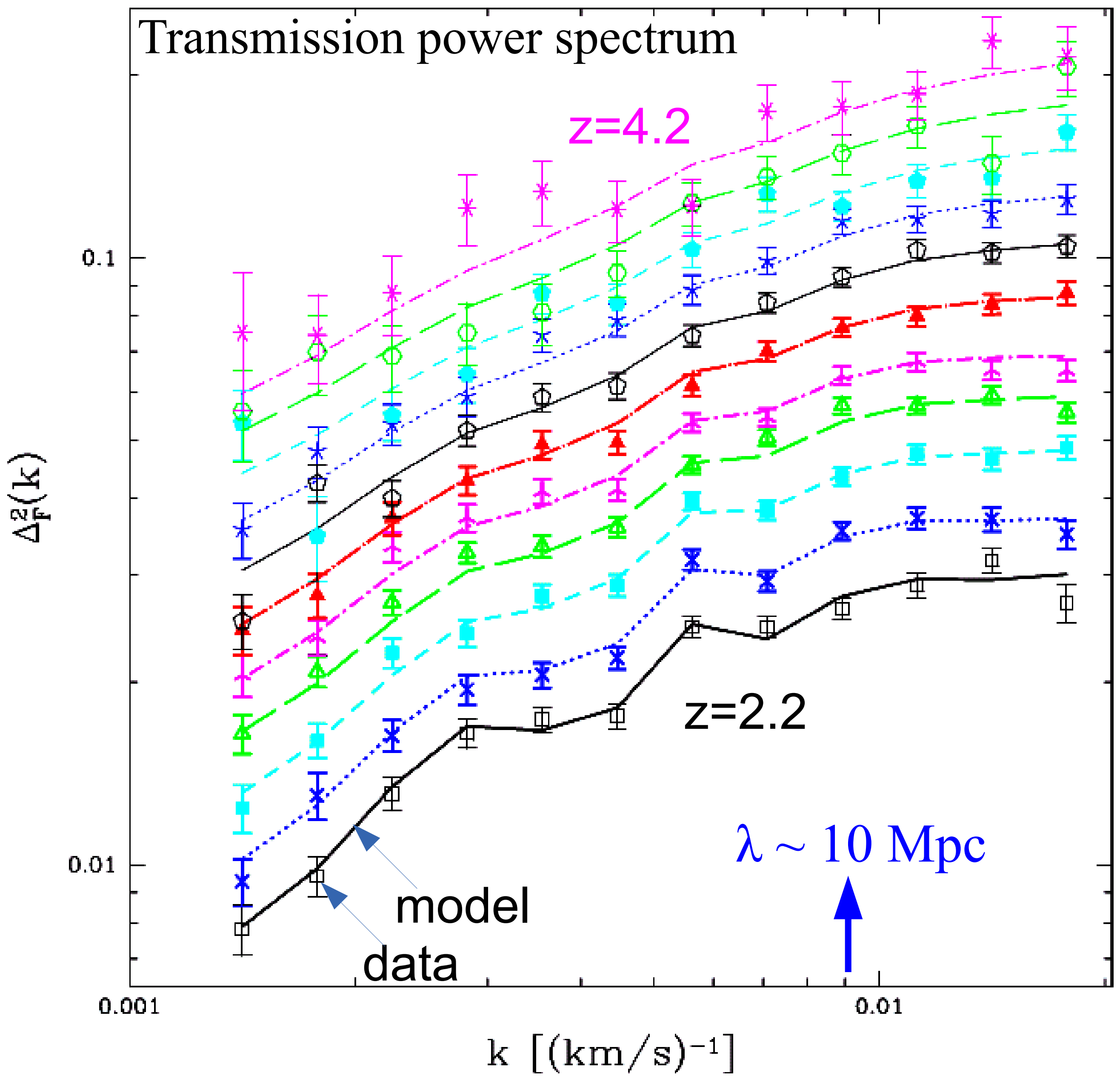
McDonald et al 2005

Diffuse intergalactic gas at high redshift can be observed through its Ly α absorption in QSO spectra

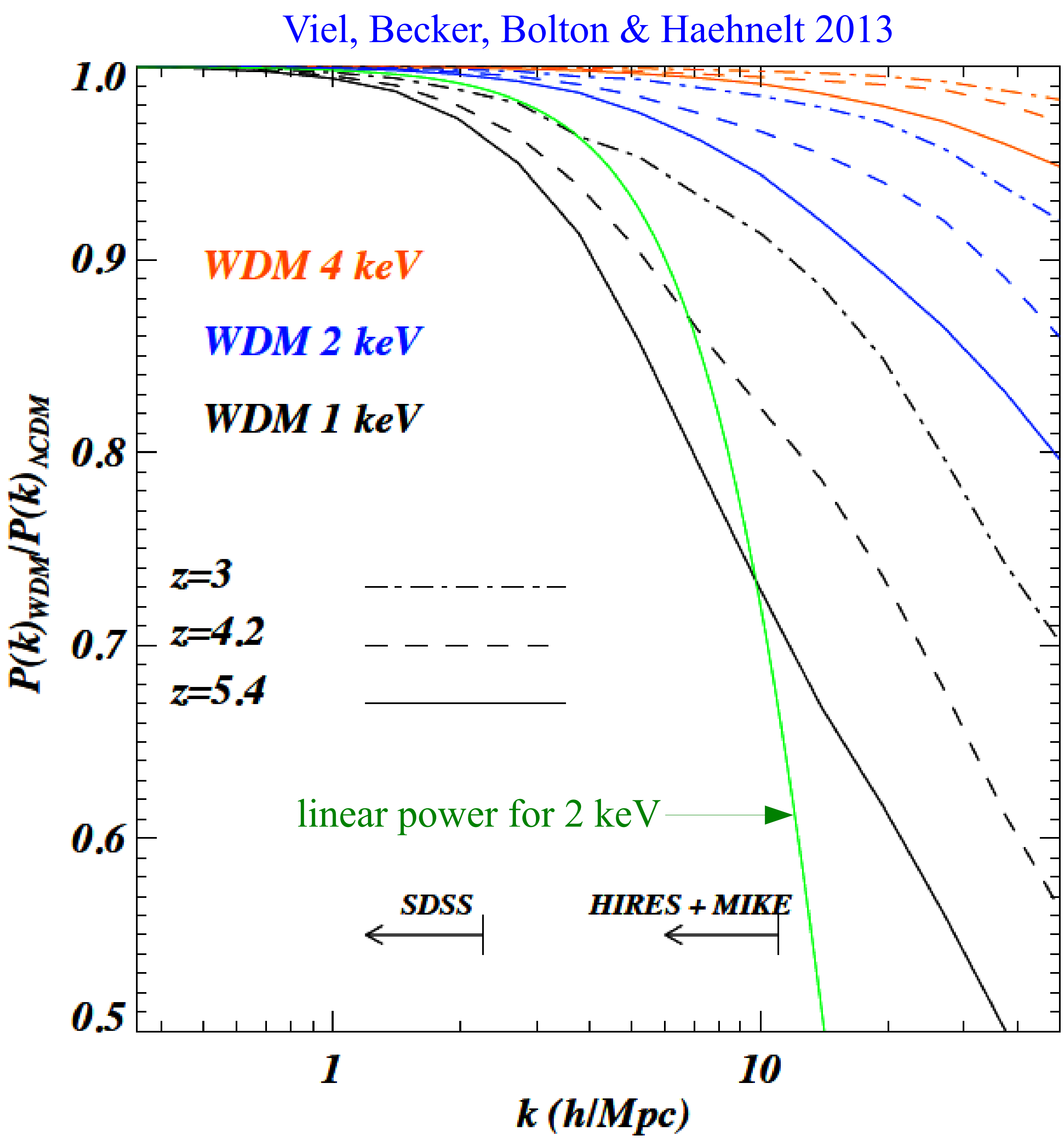
Structure in the absorption is due to fluctuations in the density and gravitationally induced velocity

Data - 3300 SDSS quasars

Model - ΛCDM



Matter power spectra for WDM relative to CDM



In linear theory, power in WDM (assuming thermal relics) is half that in CDM at

$$k_{1/2} \sim 6.5 \frac{h}{\mathrm{Mpc}} \left(\frac{m_{\mathrm{WDM}}}{1\mathrm{keV}}\right)^{1.11} \left(\frac{\Omega_{\mathrm{DM}}}{0.25}\right)^{-0.11} \left(\frac{h}{0.7}\right)^{1.22}.$$

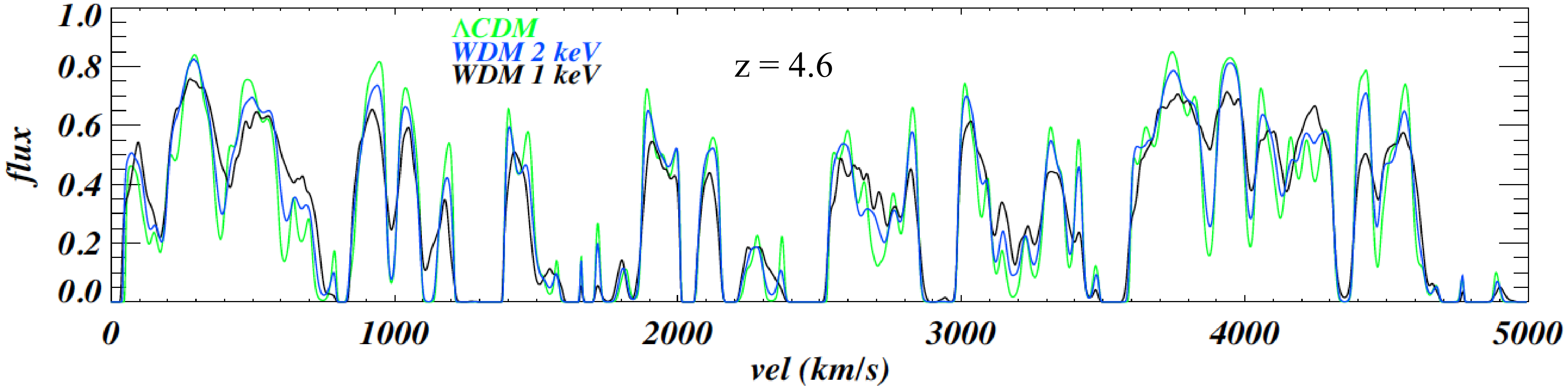
Nonlinear effects transfer power to small scales and weaken the cut-off.

The effect is already quite significant by z = 5.4

At given k, suppression is strongest at high redshift

Lyman α forest spectra for WDM relative to CDM

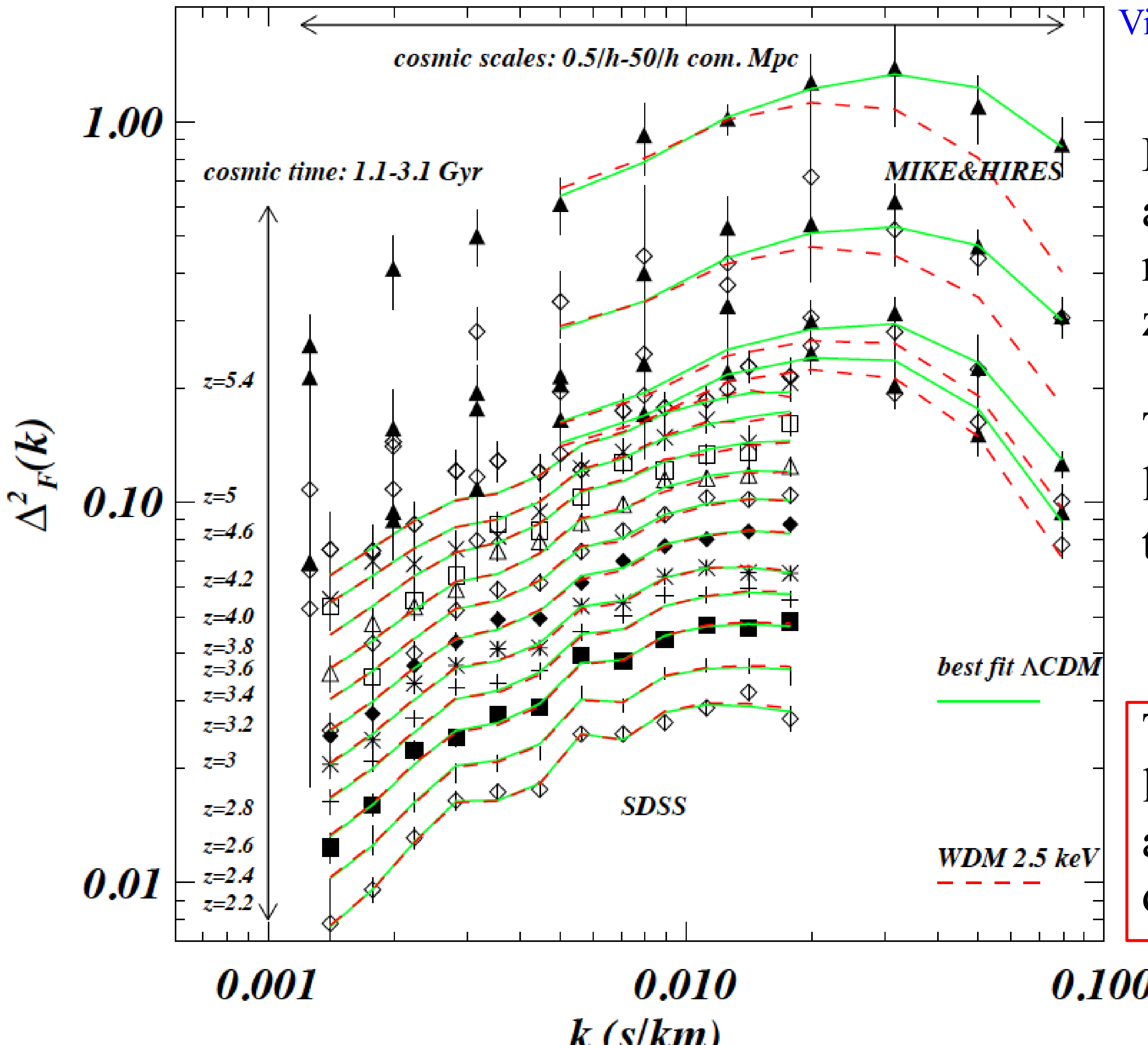
Viel, Becker, Bolton & Haehnelt 2013



Transmitted quasar flux in hydrodynamic simulations of the intergalactic medium in ΛCDM and WDM models.

High-frequency power is missing in the WDM case

Lyman α forest spectra for WDM relative to CDM



Viel, Becker, Bolton & Haehnelt 2013

High-resolution Keck and Magellan spectra match ΛCDM up to z = 5.4

This places a 2σ lower limit on the mass of a thermal relic

$m_{WDM} > 3.3$ keV

This lower limit is too large for WDM to have a significant effect on dwarf galaxy cores

Future simulation constraints on DM/DE?

- Constraints on annihilation
  - -- structure, abundance and spatial distribution of low-mass halos
  - -- formation of “dark stars”
- Collisional DM
  - -- “bullet” clusters, halos of cluster galaxies, MW satellites
  - -- shapes of halos (x-ray imaging, lensing)
- DM/DE interactions
  - -- fifth force effects (different effective G for baryons/DM)
  - -- variable DM particle mass, “decay” of DM into DE
- DE-only effects
  - -- modification of halo assembly histories/density profiles
  - -- quasi-linear/nonlinear redshift-space distortion of the density field

Take away messages?

- Neutrino DM was ruled out by simulations as soon as the linear cosmological IC's could be calculated *ab initio* and represented numerically, but CDM has been reinforced as simulations improve

- Current simulations of the nonlinear DM distribution are limited primarily by uncertainties in the treatment of baryon effects

- Apparent small-scale discrepancies with ΛCDM do not have the character expected for WDM, and Lyman α forest data now exclude WDM models which would significantly affect dwarf galaxies

- Many more complex variations in DM properties have still been explored too little to fully determine their viability/interest