# 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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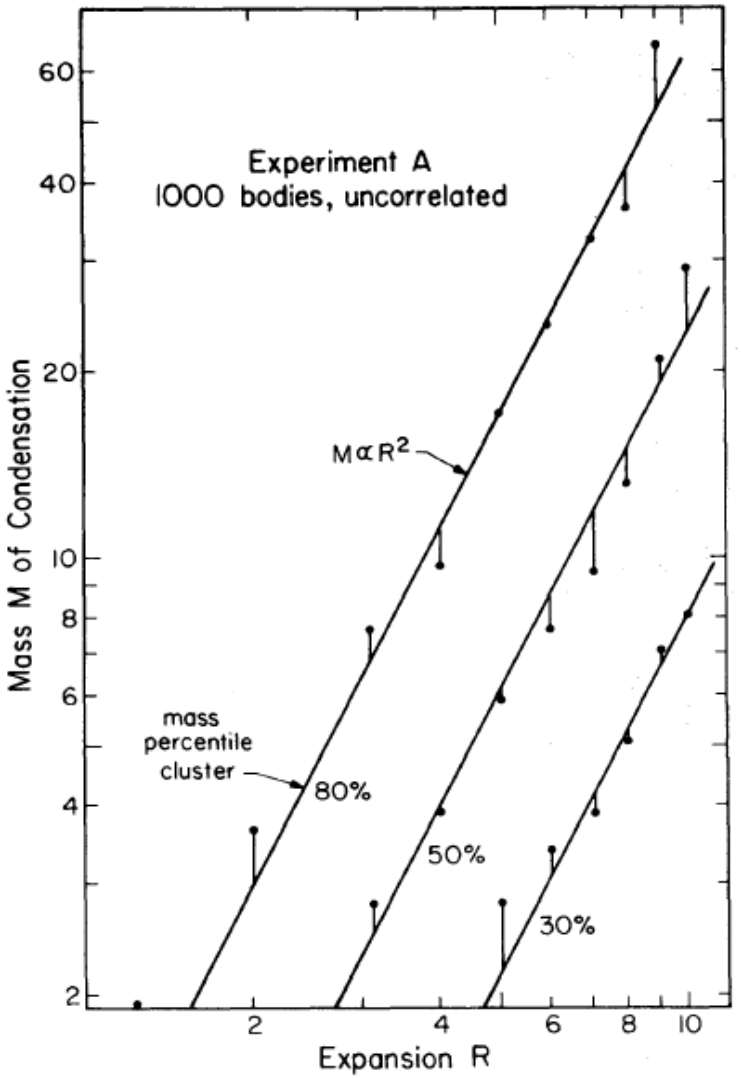


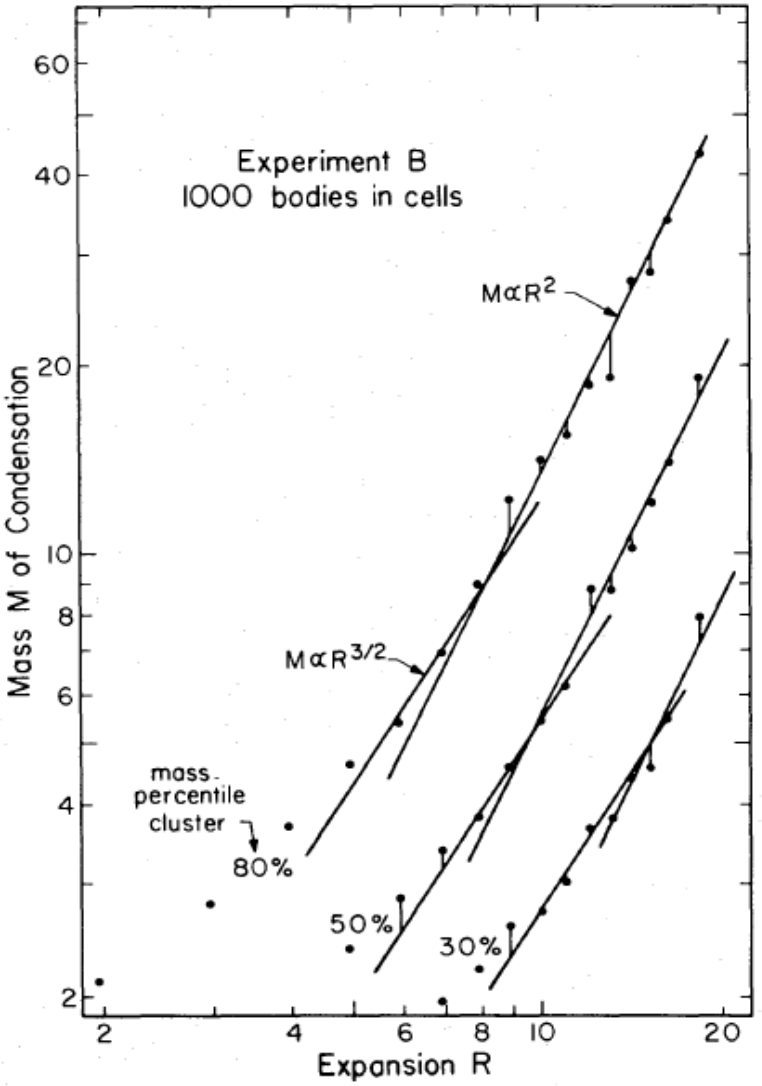


BY

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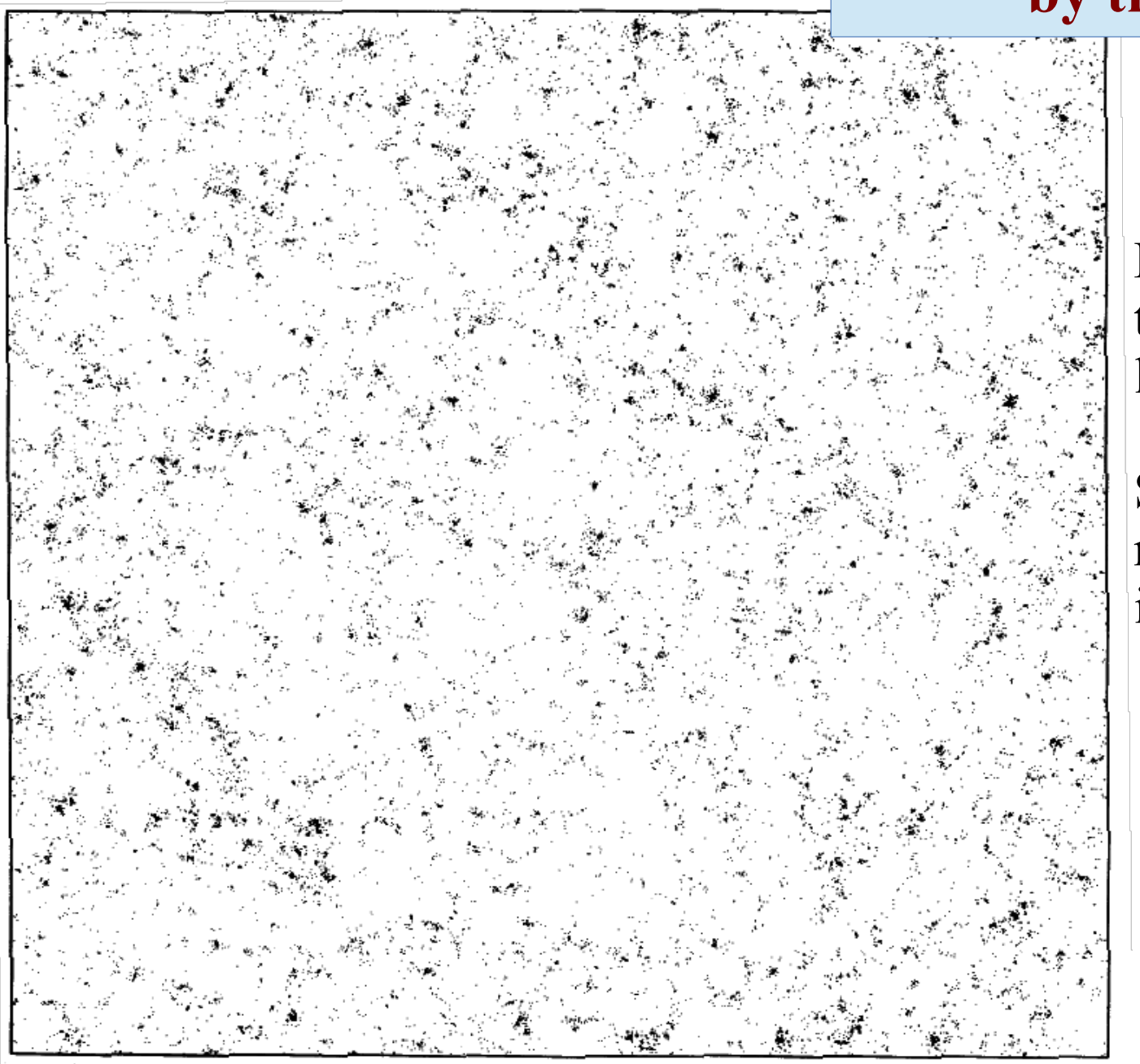
Efstathiou & Eastwood 1981

# Structure formation simulations by the early 1980s



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

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

Klypin & Shandarin 1983

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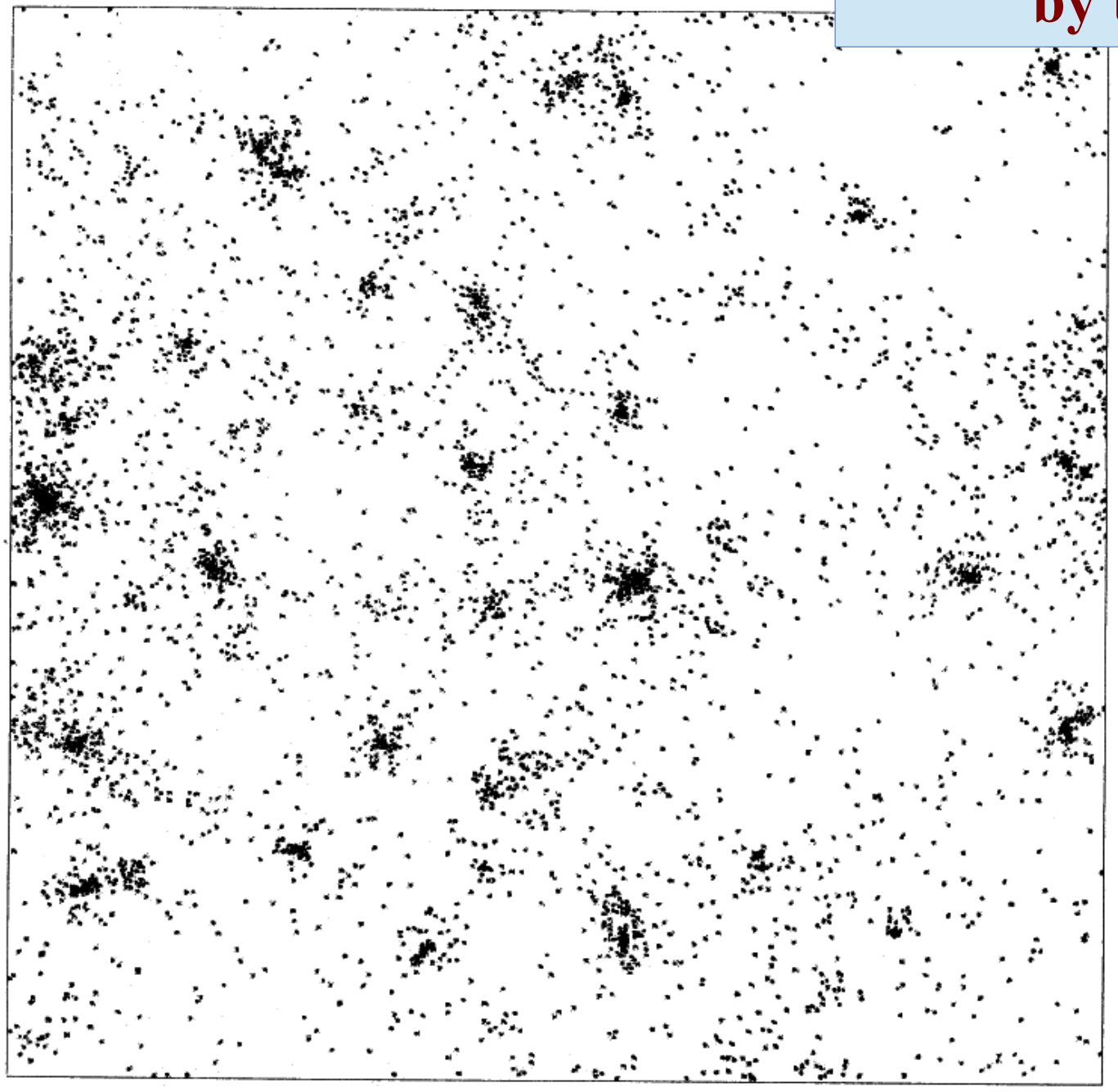

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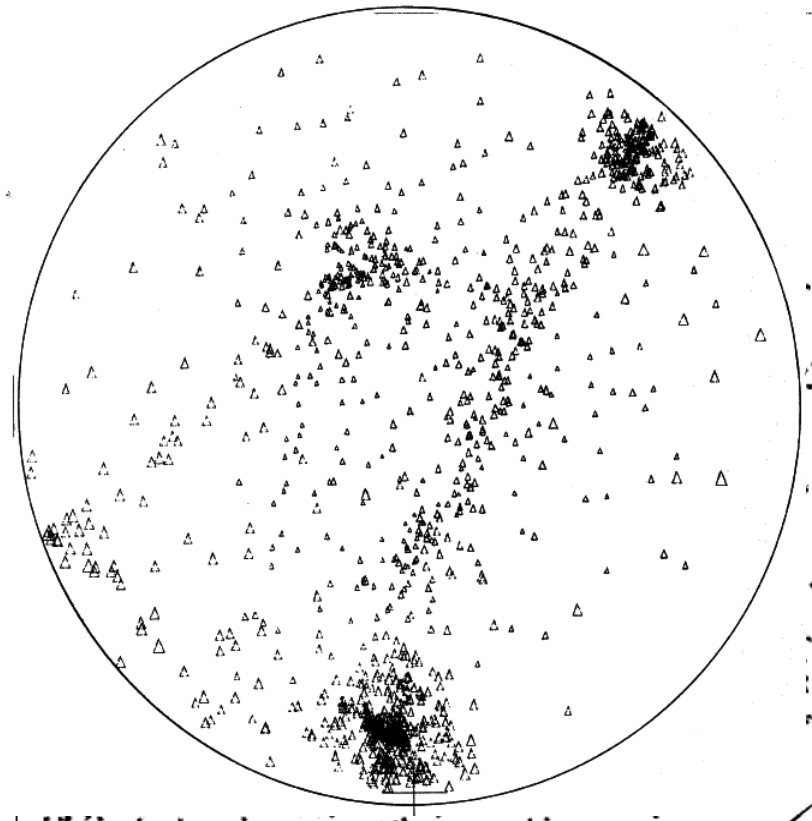

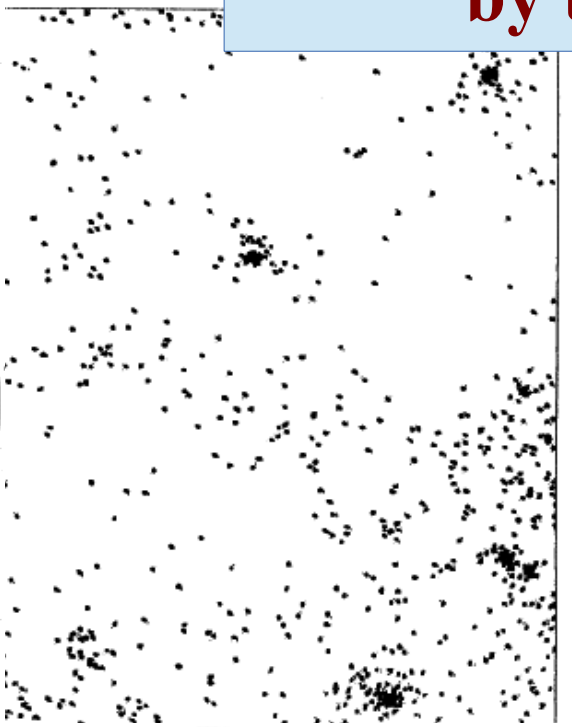

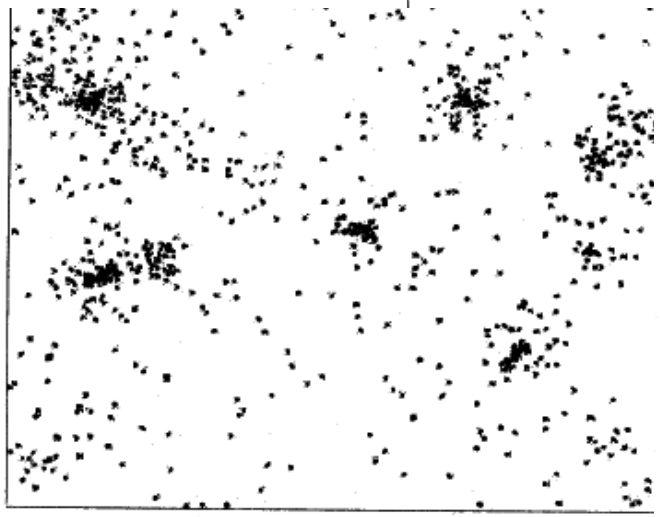

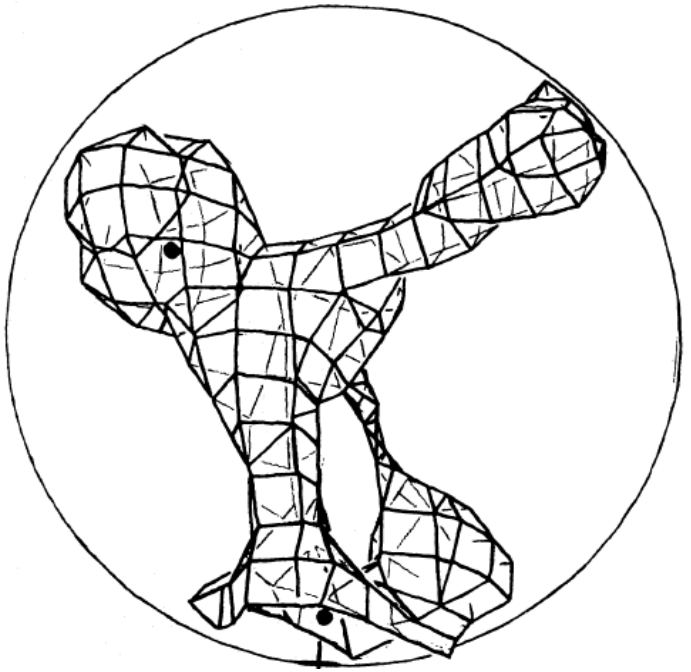

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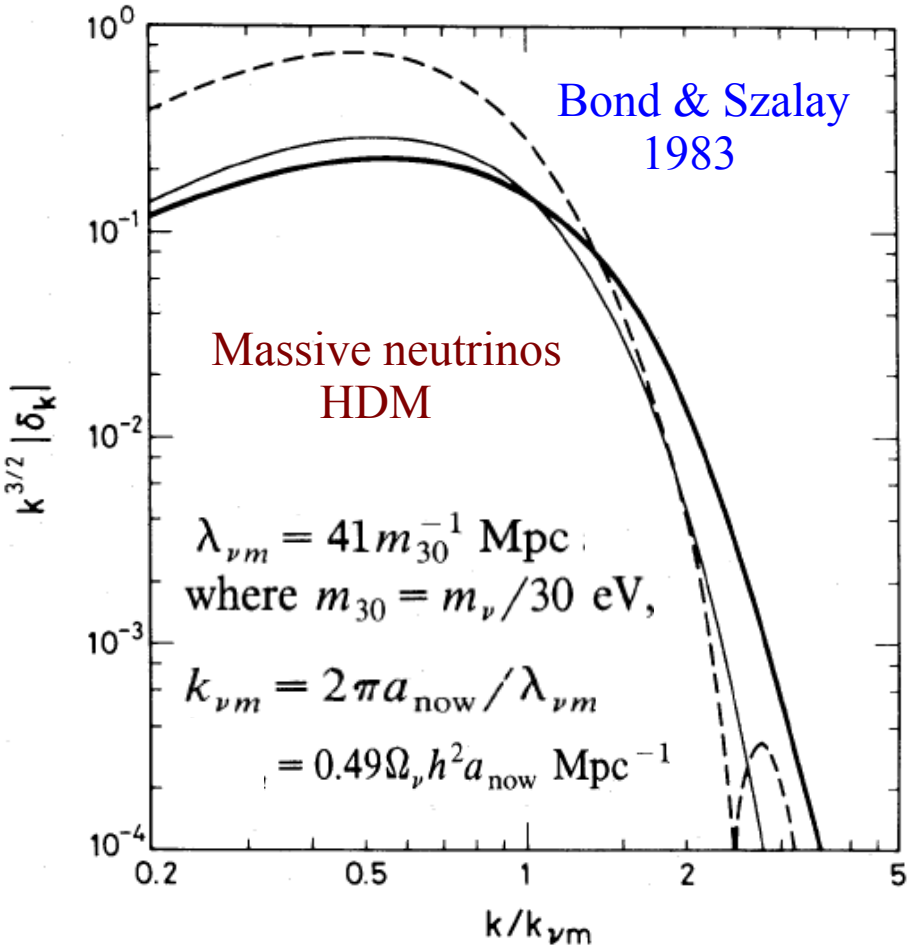
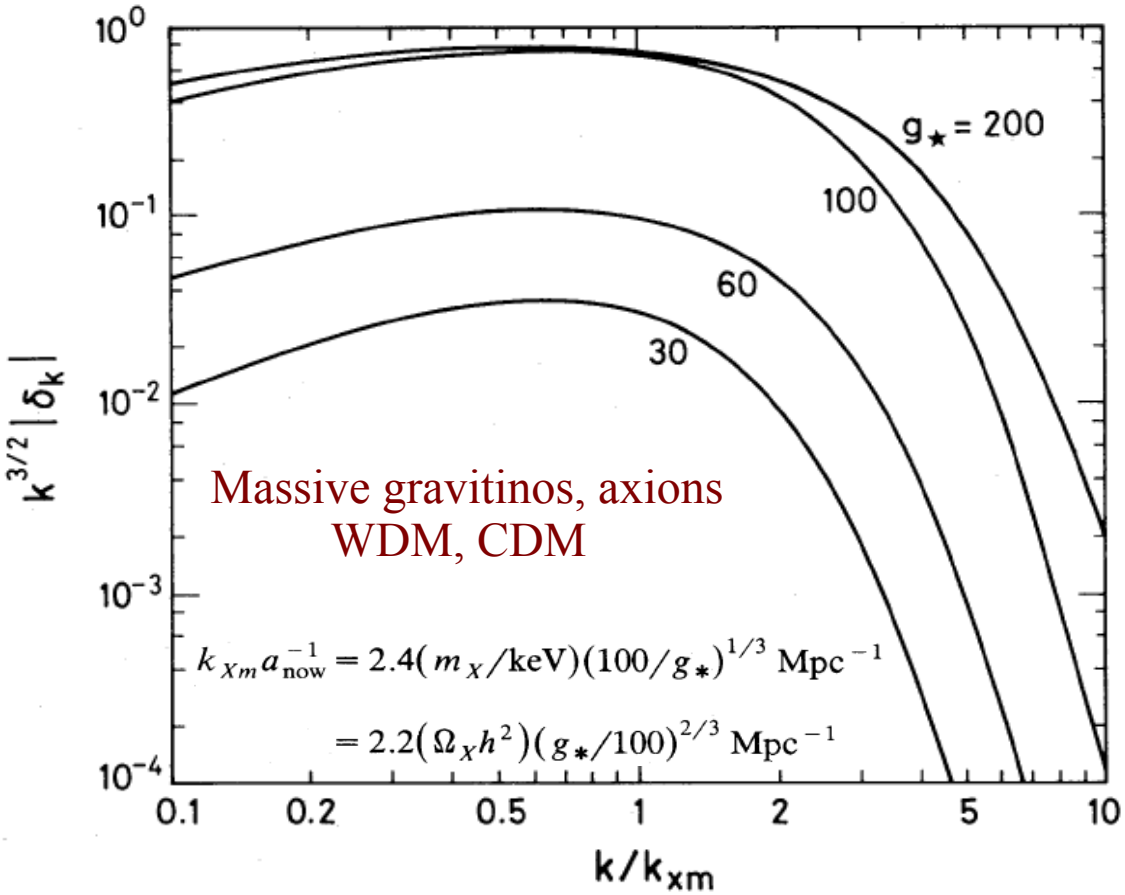
# Calculation of precise linear IC's for particle DM

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

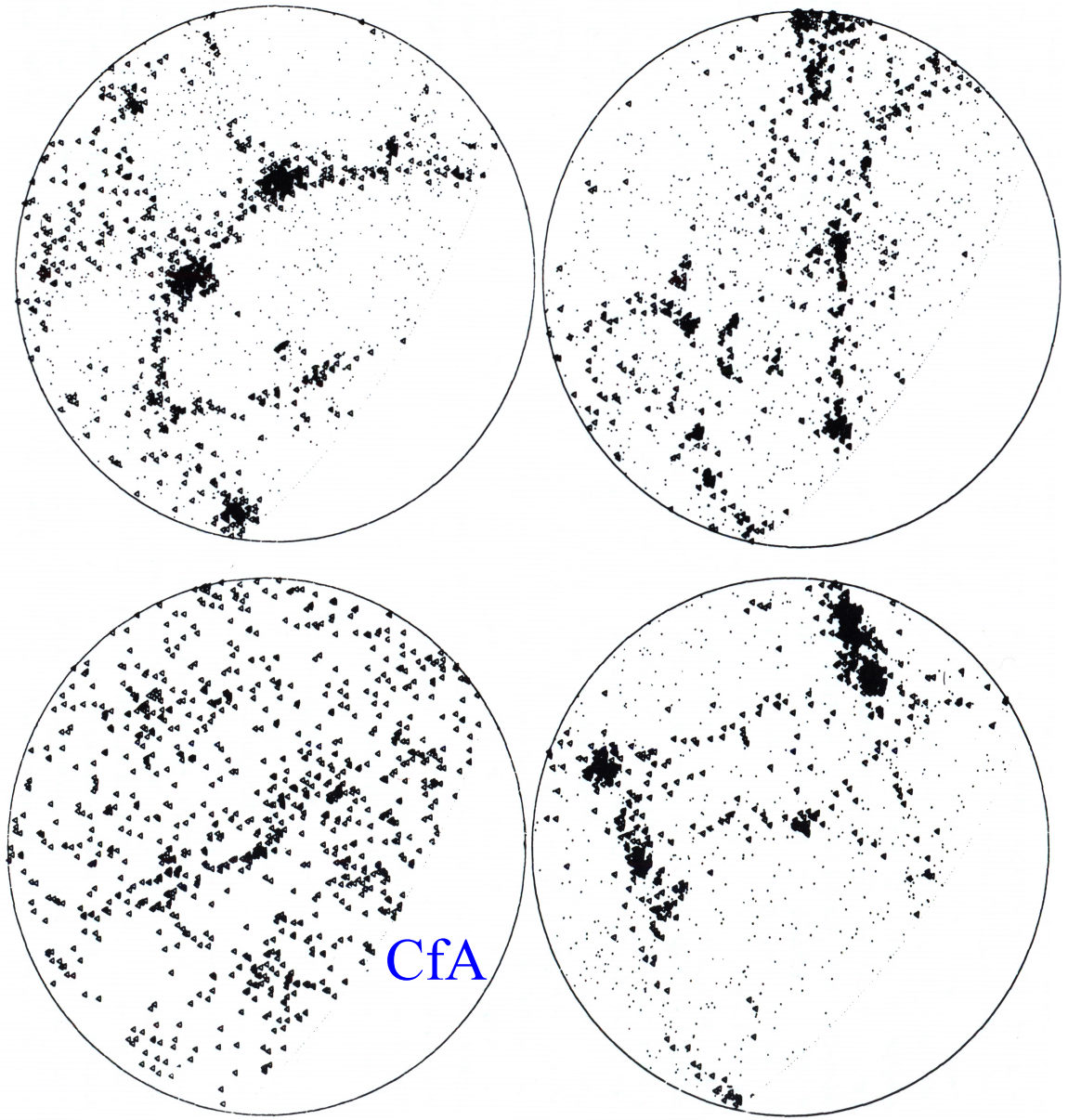
  → precise initial conditions for nonlinear structure formation



# 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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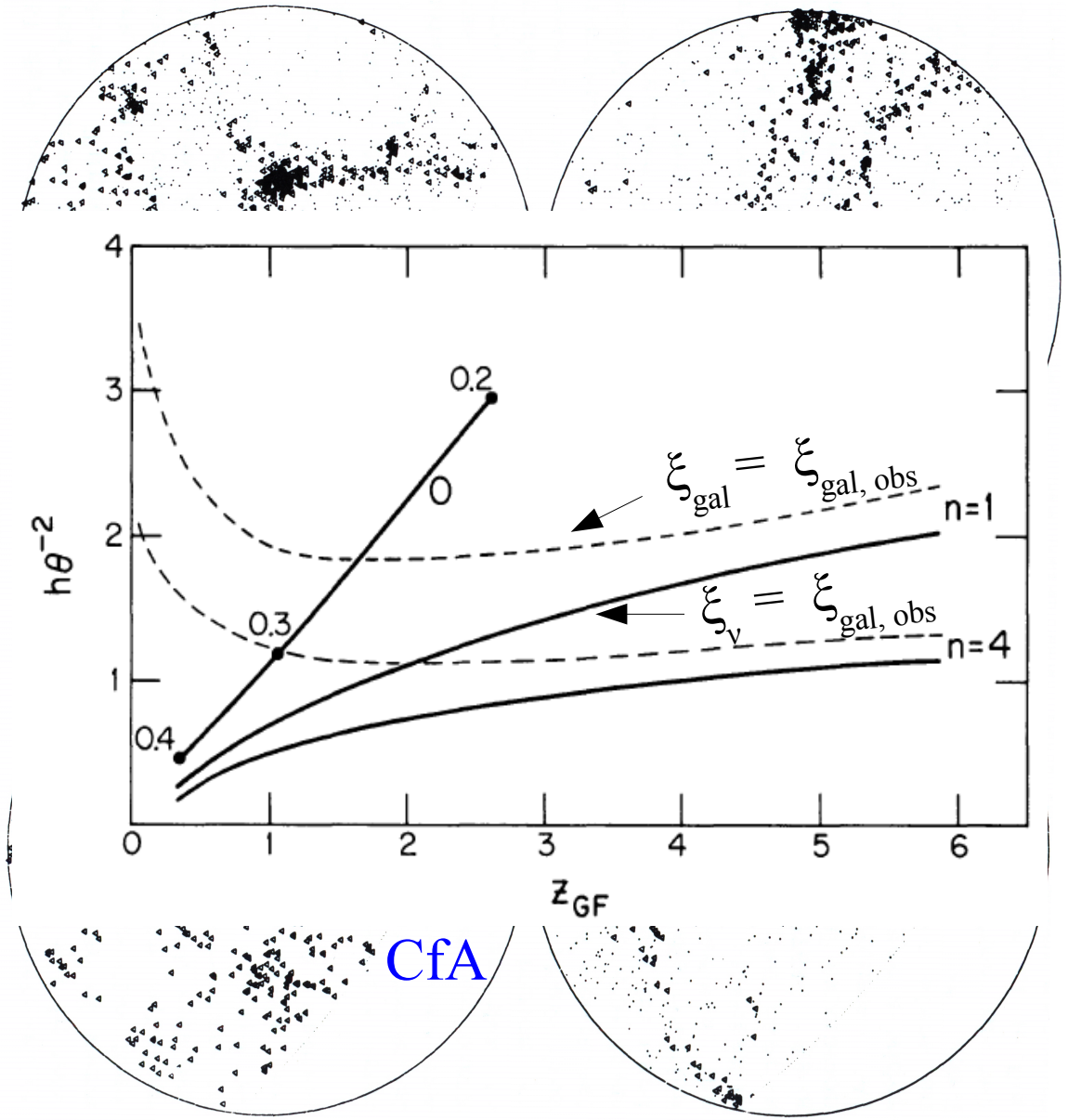



New algorithms to represent ν-dominated IC's, allowed N-body exploration of nonlinear growth

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

No acceptable combination of cosmological and ν parameters,

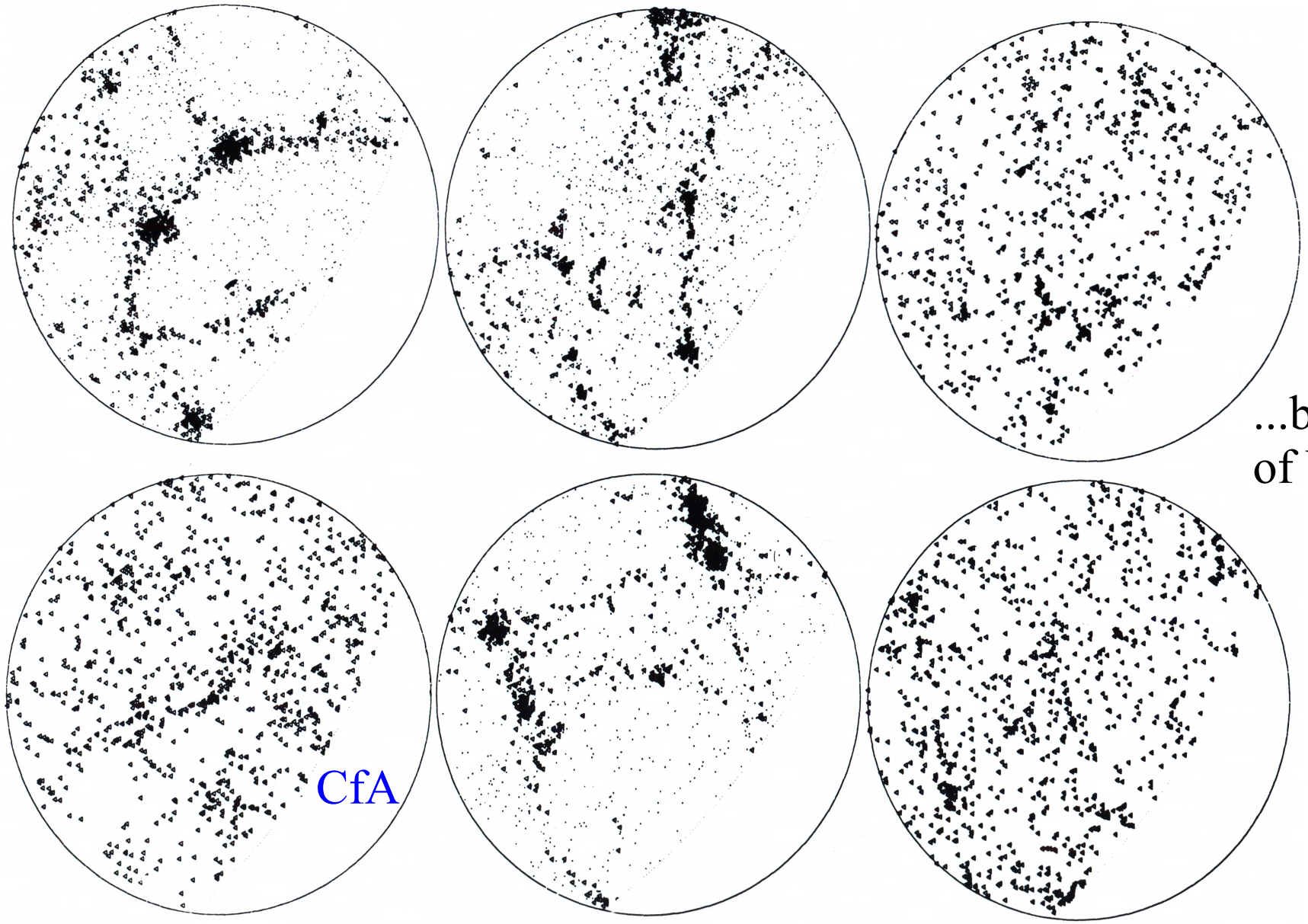
$$\Omega,\ h,\ n,\ N_{\nu},\ z_{CF}$$

could produce galaxy clustering as weak as observed

→ DM cannot be made of any known WIMP

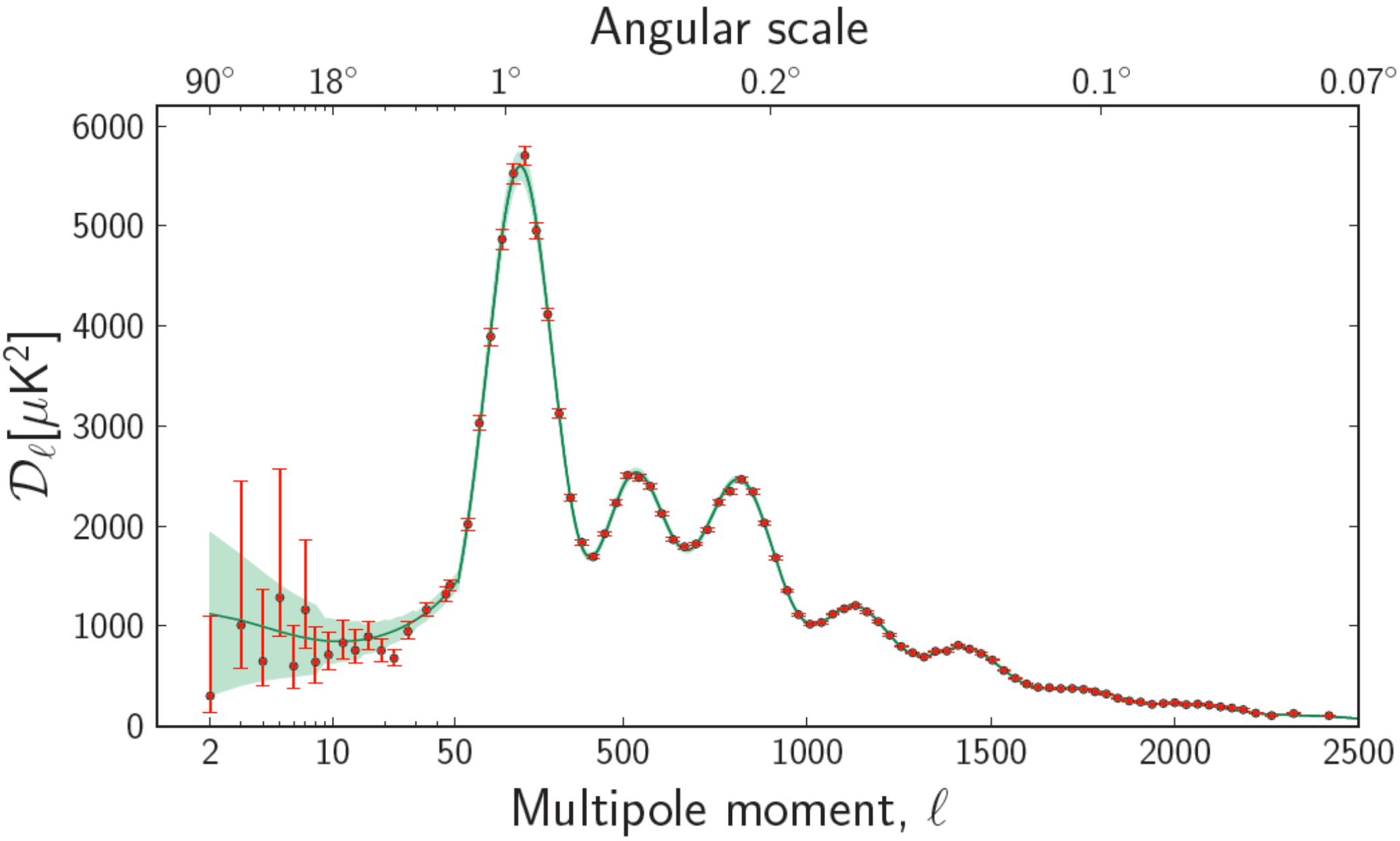
# The exclusion of neutrinos as a DM candidate

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

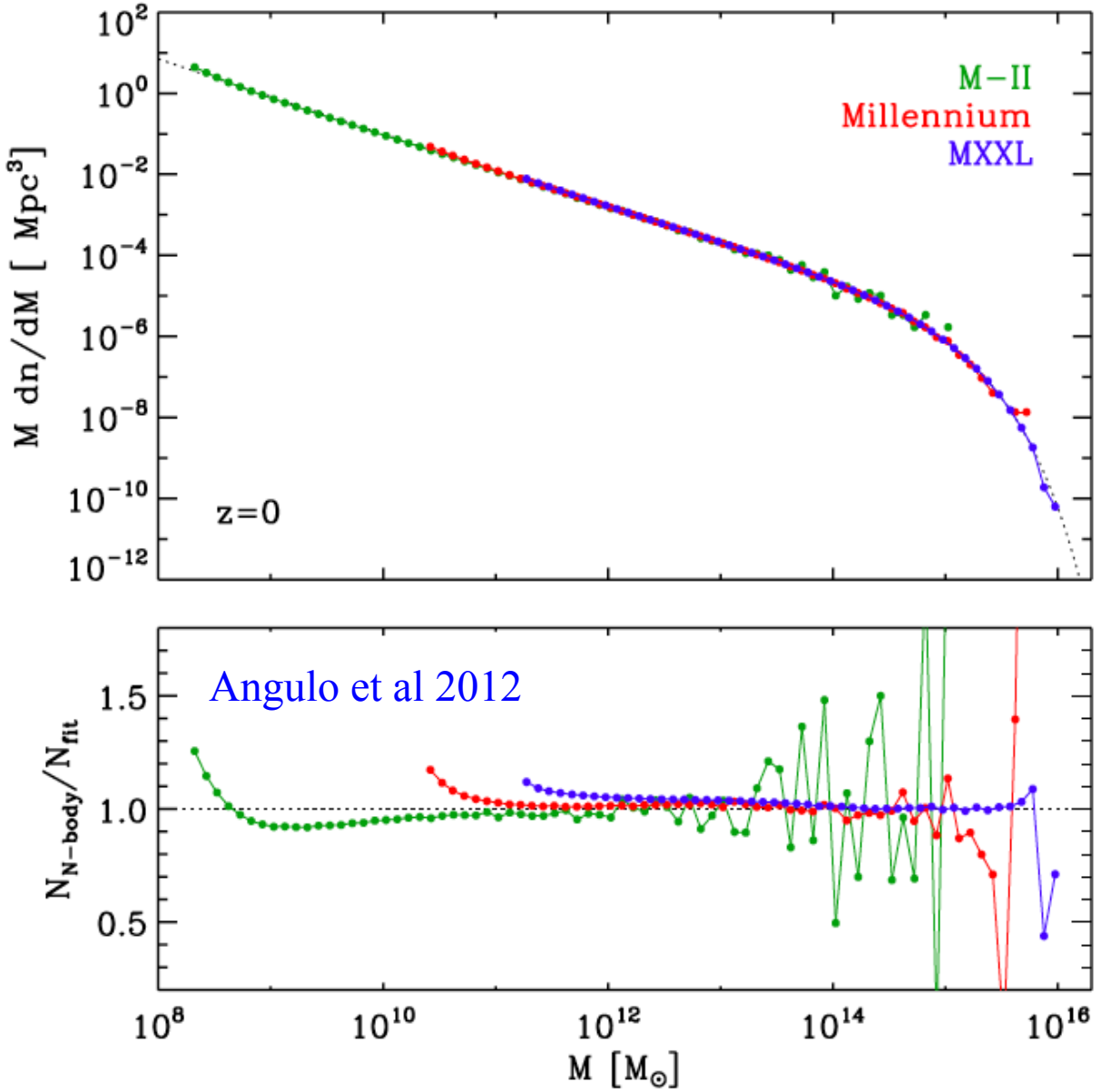
| | *Planck*+WP | |
|---|---|---|
| Parameter | Best fit | 68% limits |
| $\Omega_b h^2$ . . . . . | 0.022032 | $0.02205 \pm 0.00028$ |
| $\Omega_c h^2$ . . . . . | 0.12038 | $0.1199 \pm 0.0027$ |
| $\Omega_\Lambda$ . . . . . | 0.6817 | $0.685^{+0.018}_{-0.016}$ |

At recombination 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

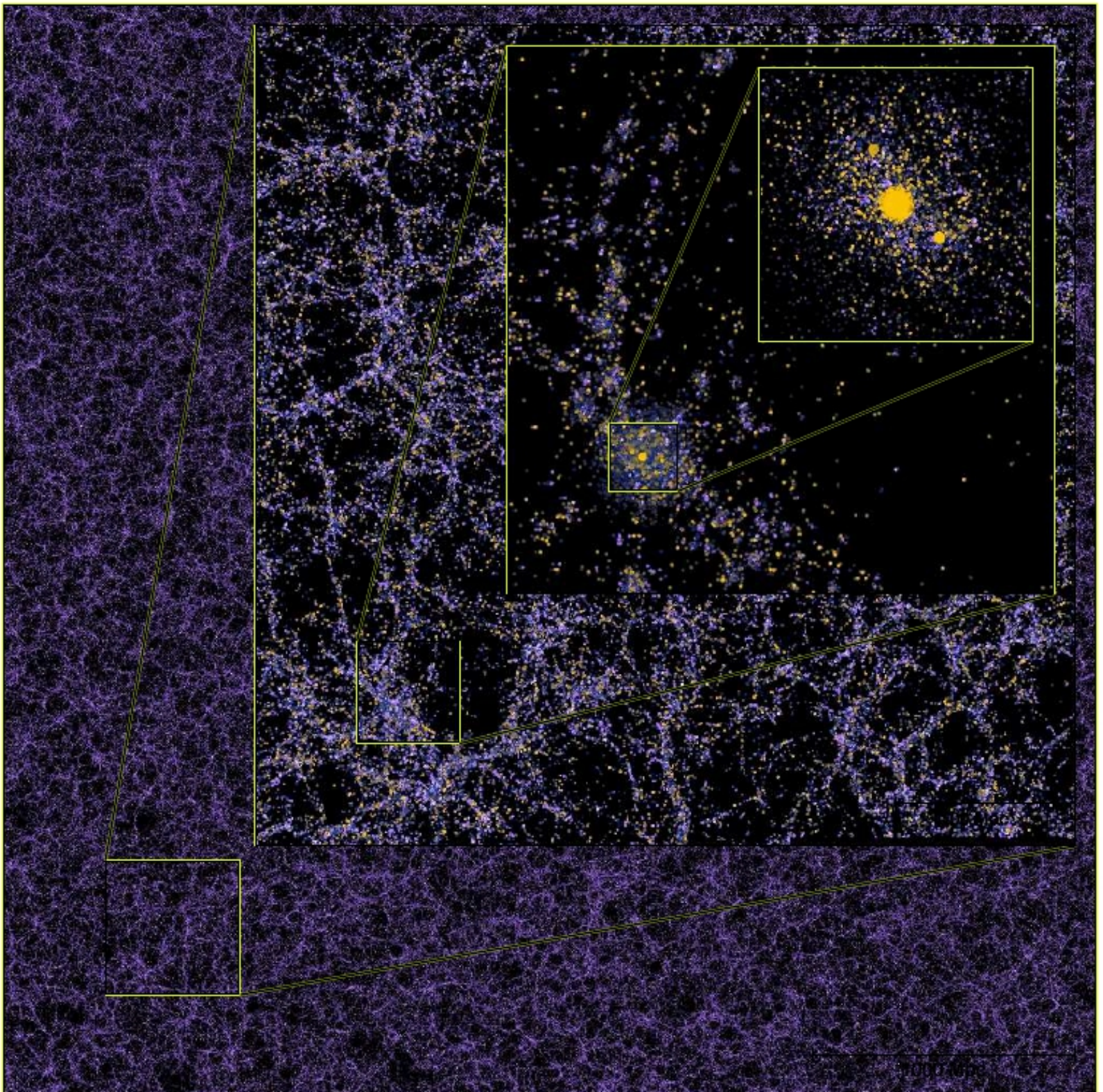
| | *Planck*+WP+highL+BAO | |
|---|---|---|
| Parameter | Best fit | 95% limits |
| $\Omega_K$ . . . . . | 0.0009 | $-0.0005^{+0.0065}_{-0.0066}$ |
| $\Sigma m_\nu$ [eV] . . . . . | 0.000 | $< 0.230$ |
| $N_{\rm eff}$ . . . . . | 3.22 | $3.30^{+0.54}_{-0.51}$ |

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

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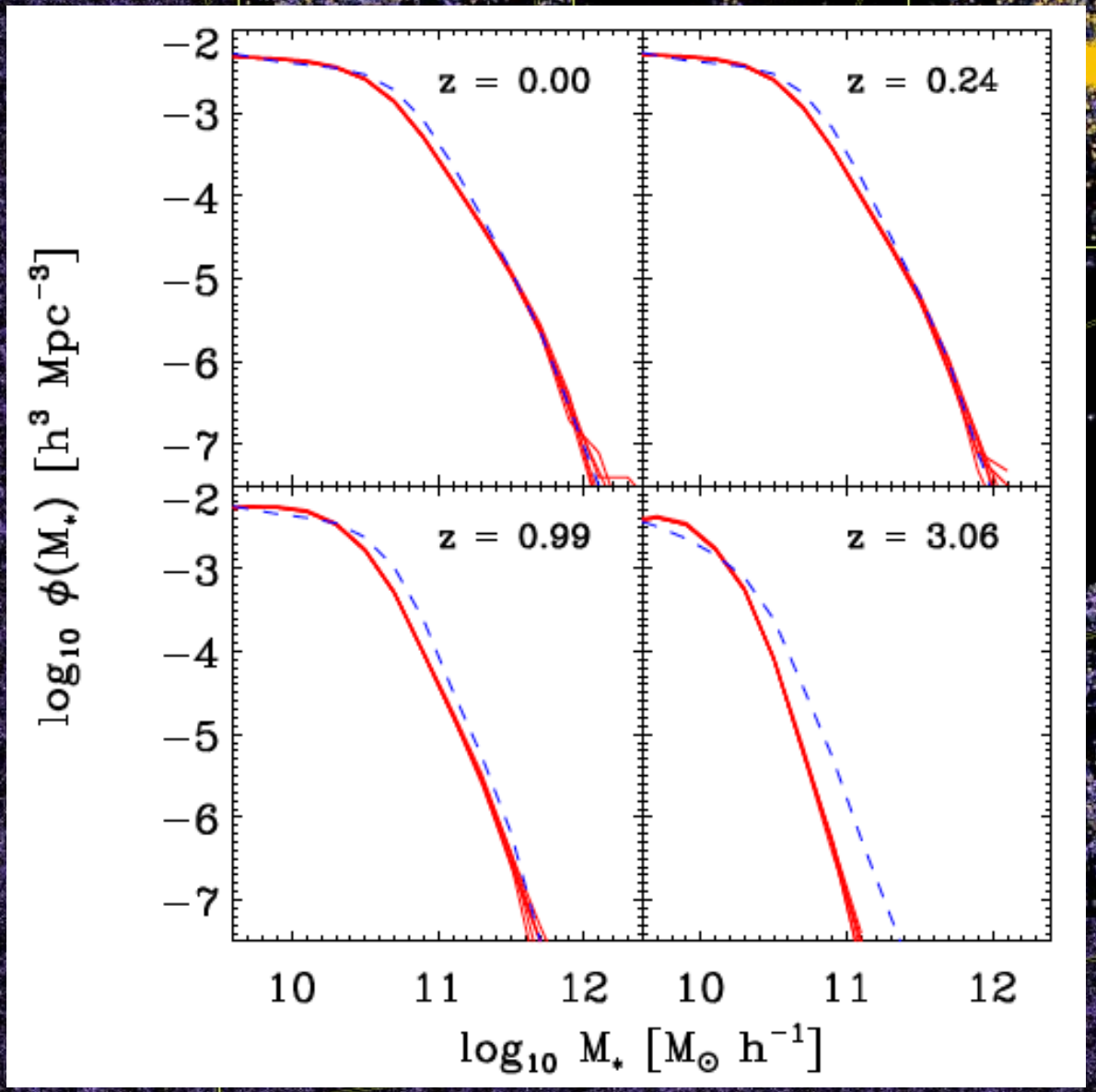



$N = 3 \times 10^{11}$

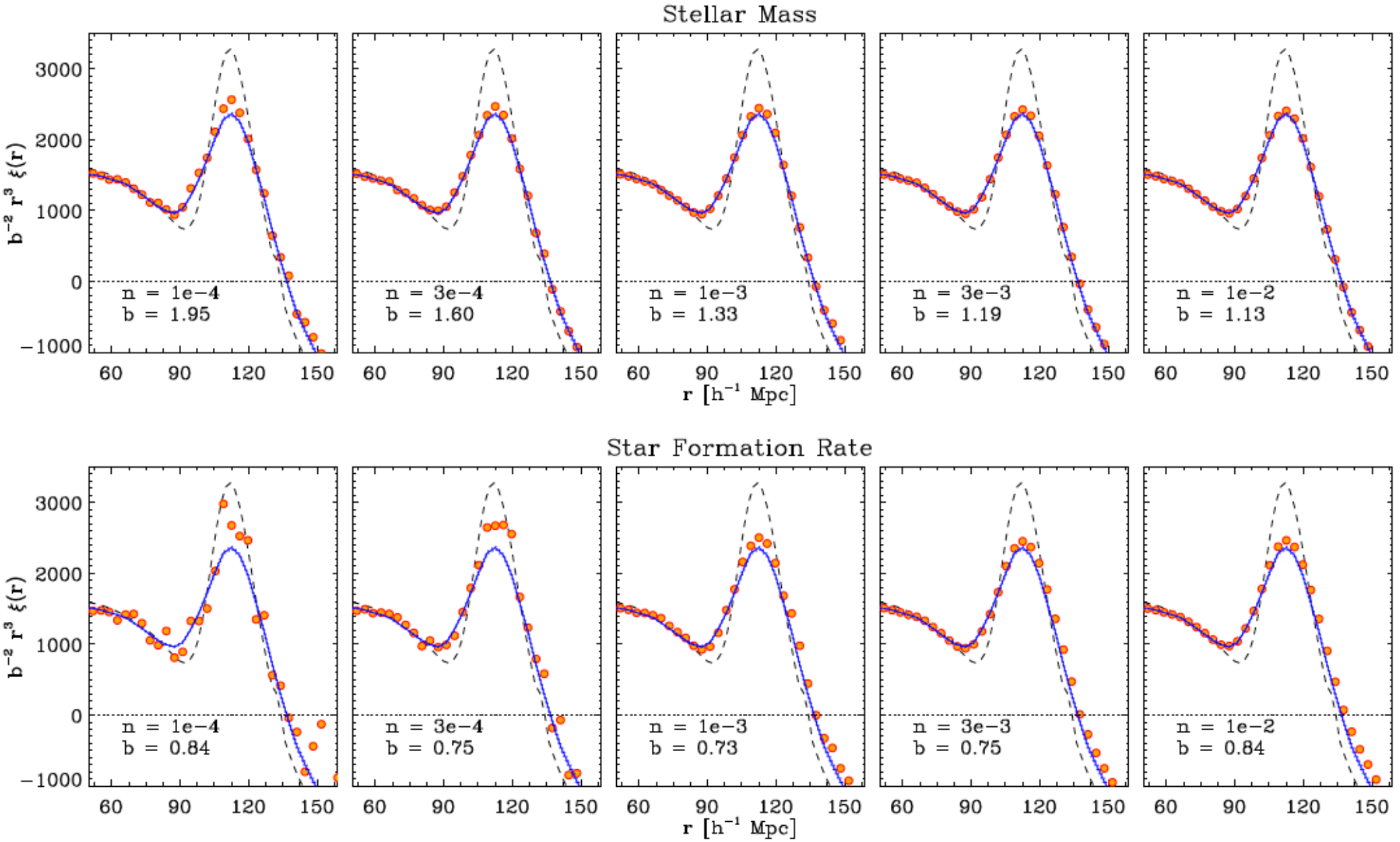
$L = 4.3$ Gpc

Simulates the formation of ~1 billion galaxies directly

Results converge with Millennium for brighter galaxies

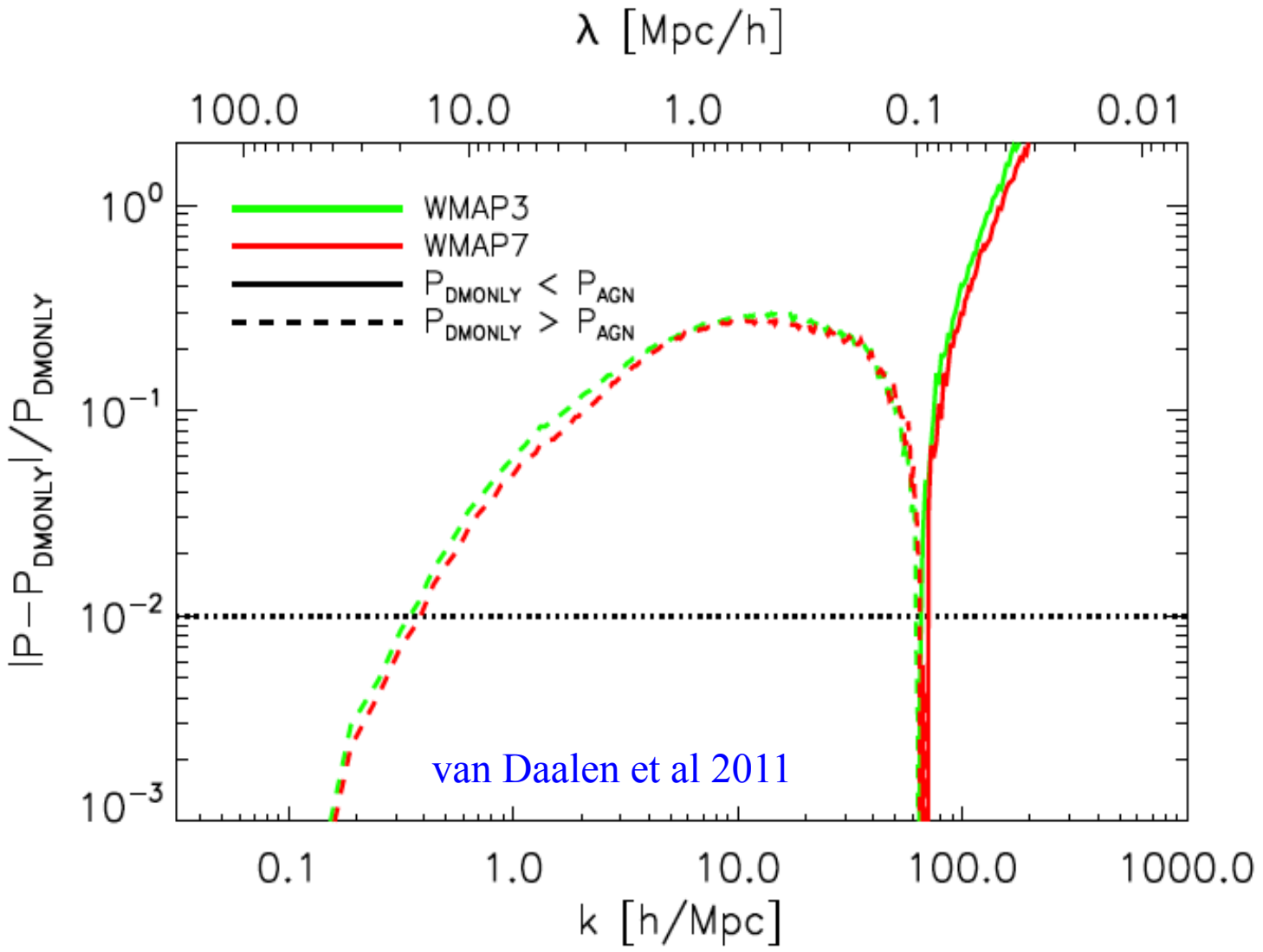
Angulo et al 2012

# Distortions of BAO feature in the galaxy population



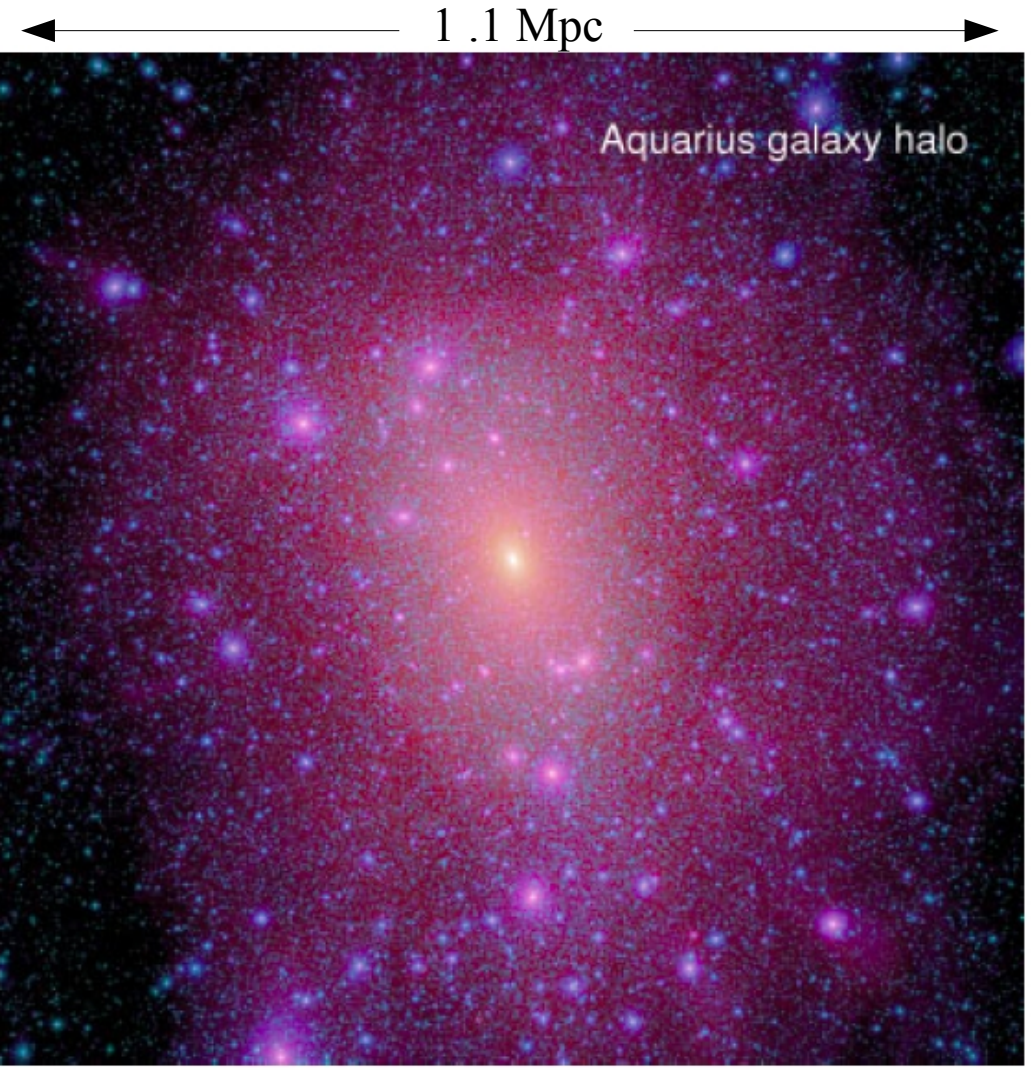

Small but measurable shifts for different selection methods

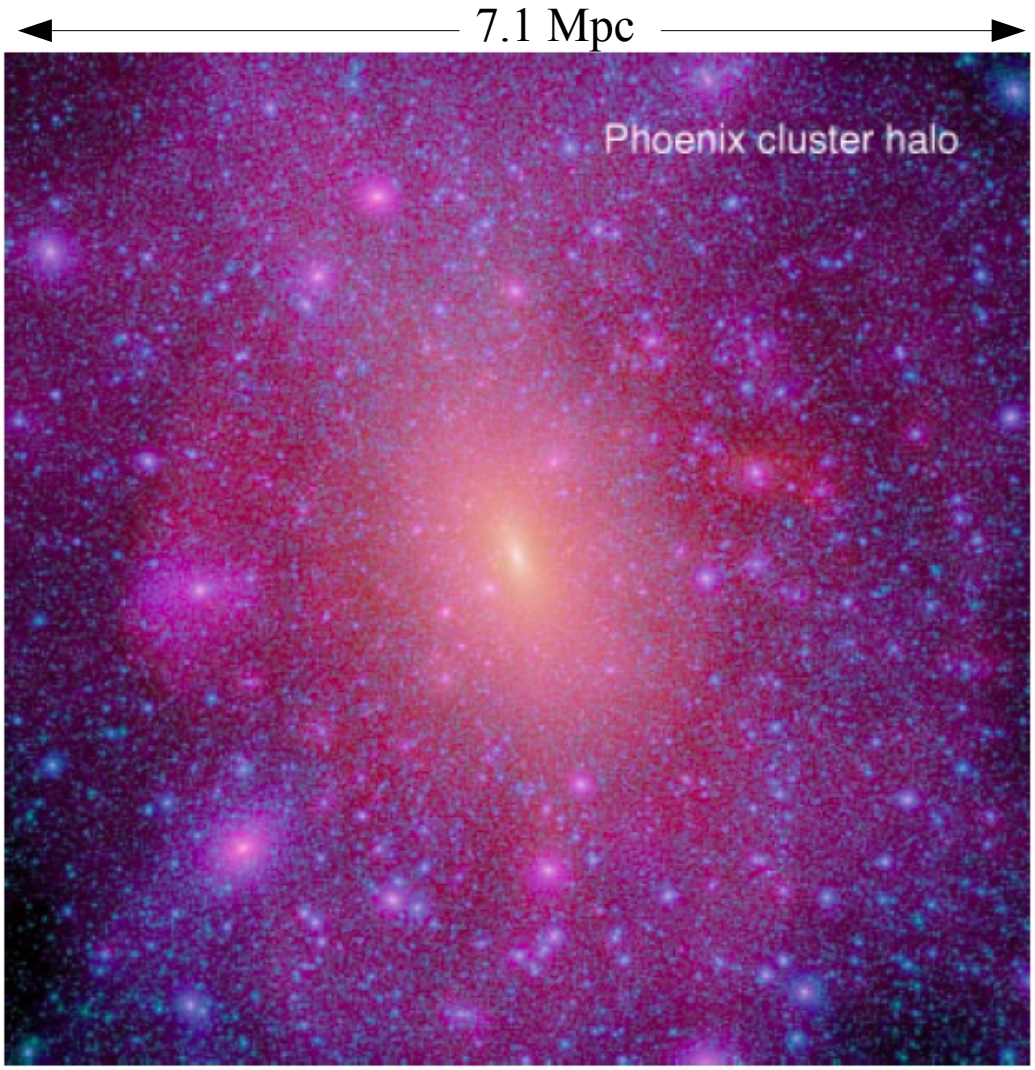
Angulo et al 2013




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

# All ΛCDM halos look similar

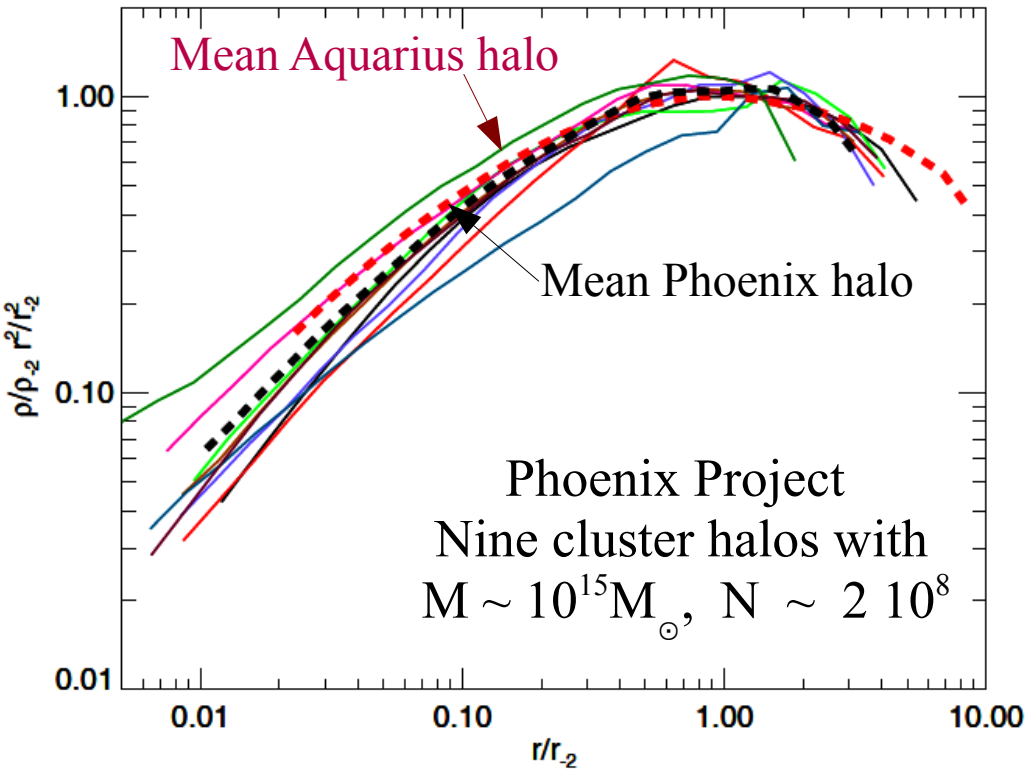


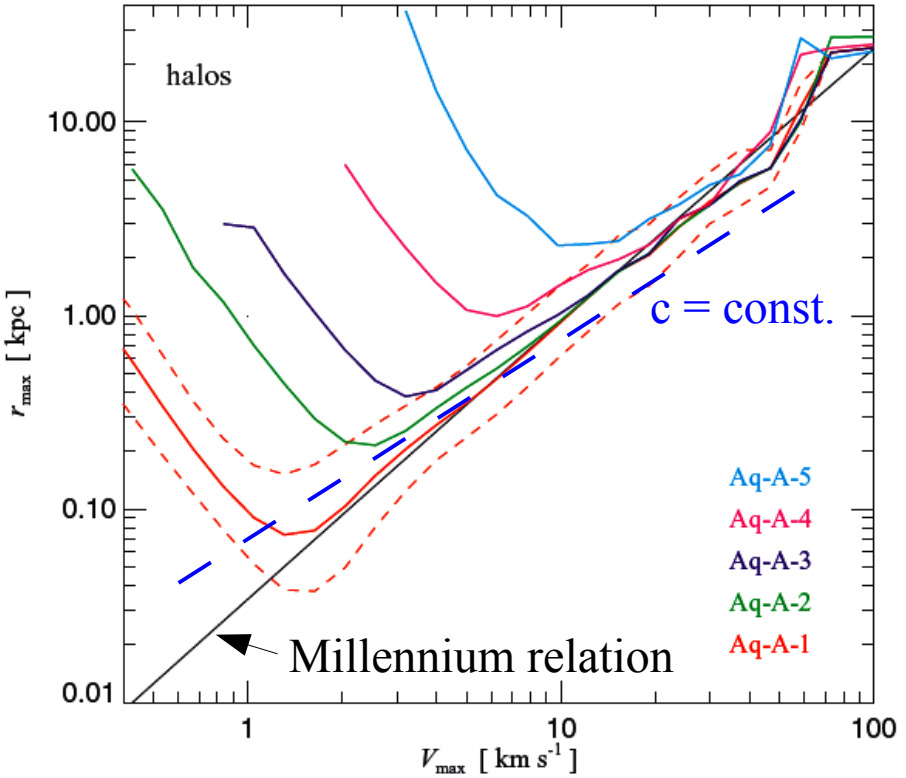

- Cuspy -- radial density profiles are fit by NFW/Einasto models
- Triaxial -- equidensity contours with a/c > 2 are common
- Substructure – mainly at large radii with up to tens of percent of the mass

# All ΛCDM halos look similar ...but not identical

Gao et al 2012

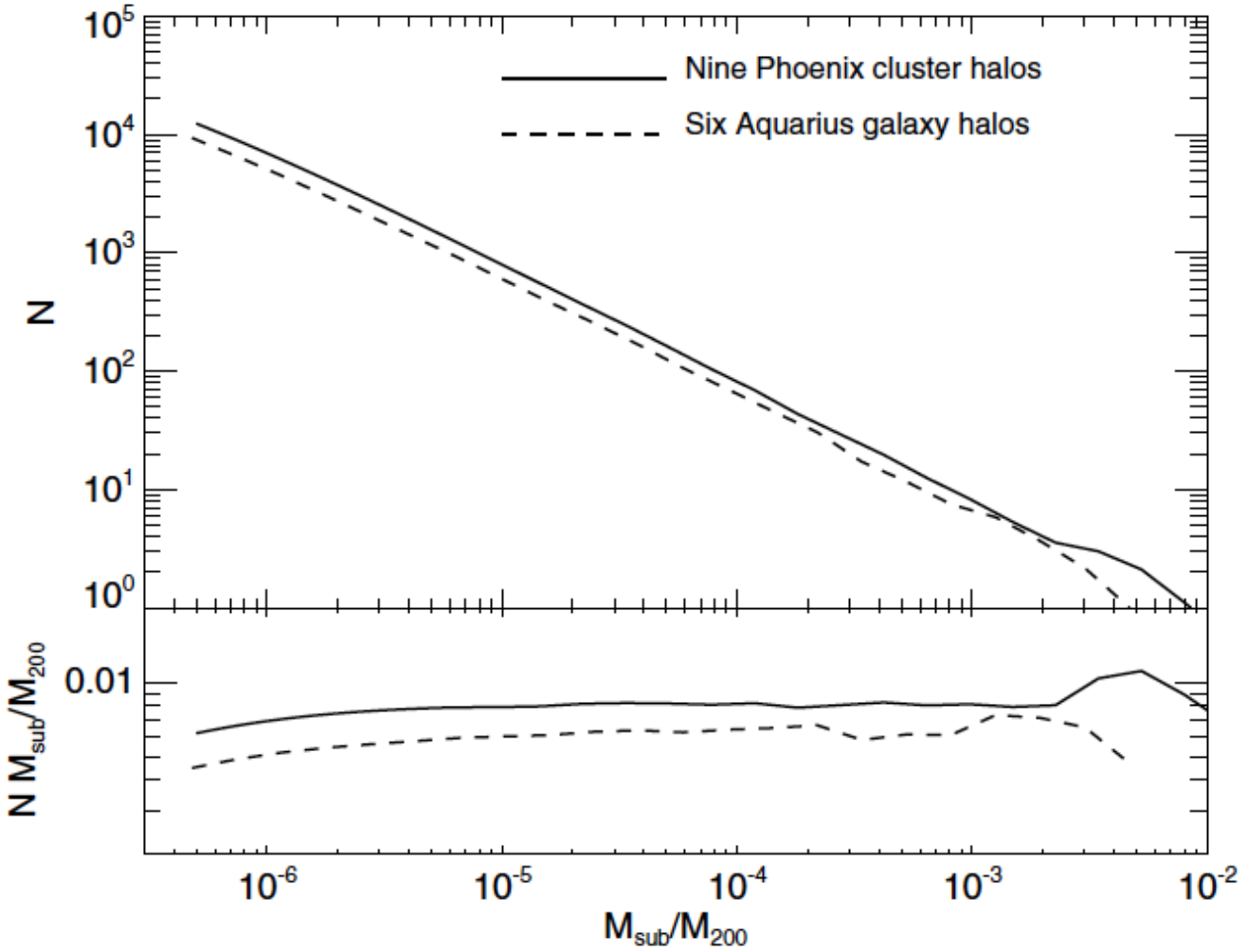



Springel et al 2008

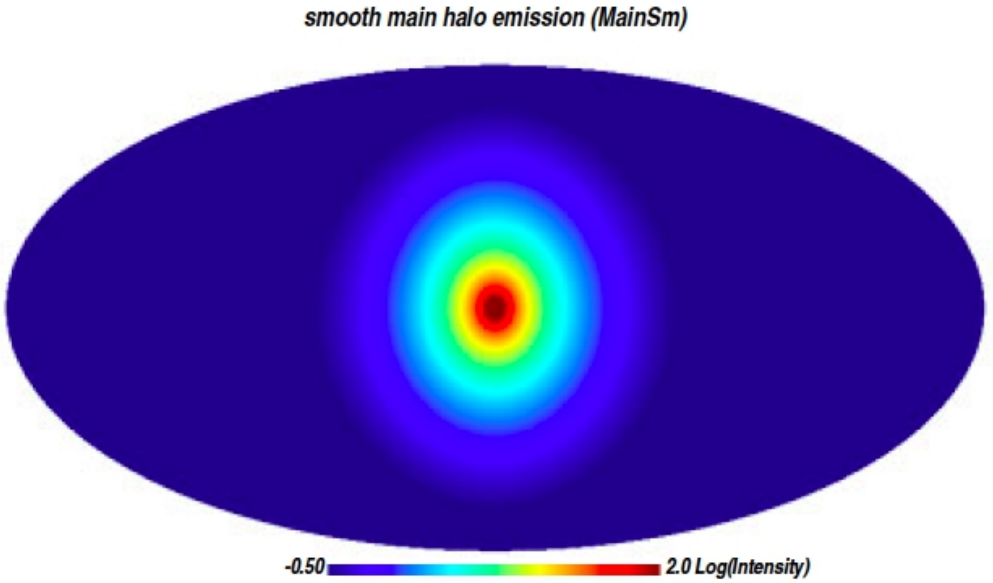


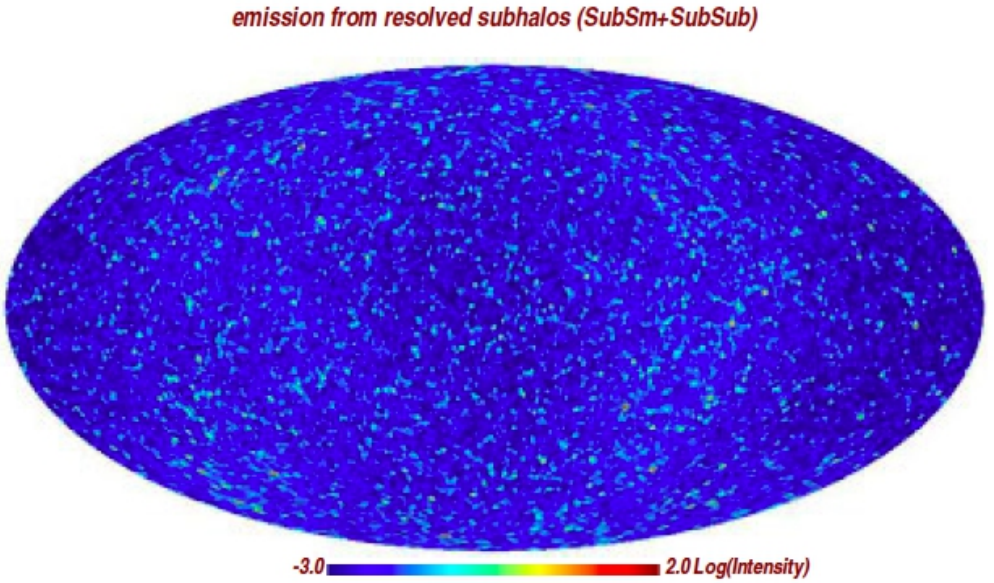

- The scatter in profile <u>shape</u> between halos of given mass is large compared to dependence of mean shape on mass
- The dependence of concentration (mean density → annihilation efficiency) on mass is significant, but not measured to very low mass

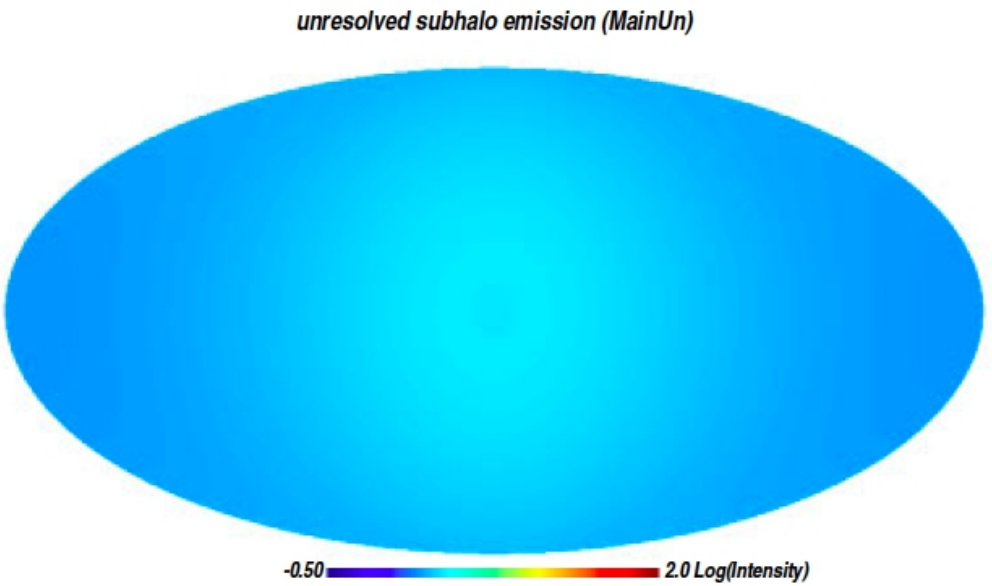
# All ΛCDM halos look similar also in their substructure

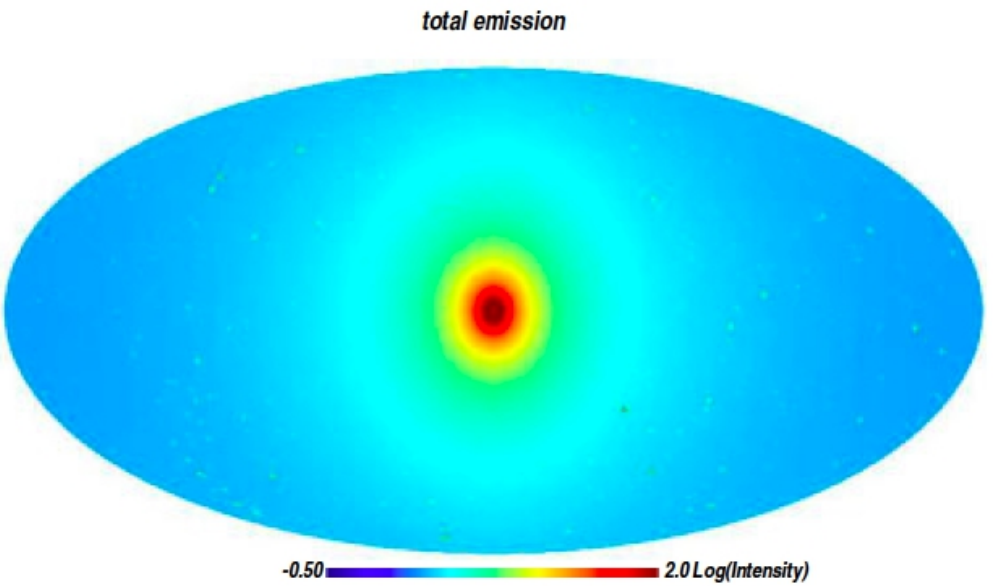



- Galaxy halos have slightly less substructure than cluster halos
- Both have roughly equal total mass in each decade of subhalo mass
- Total mass in subhalos of *any* mass is still quite uncertain



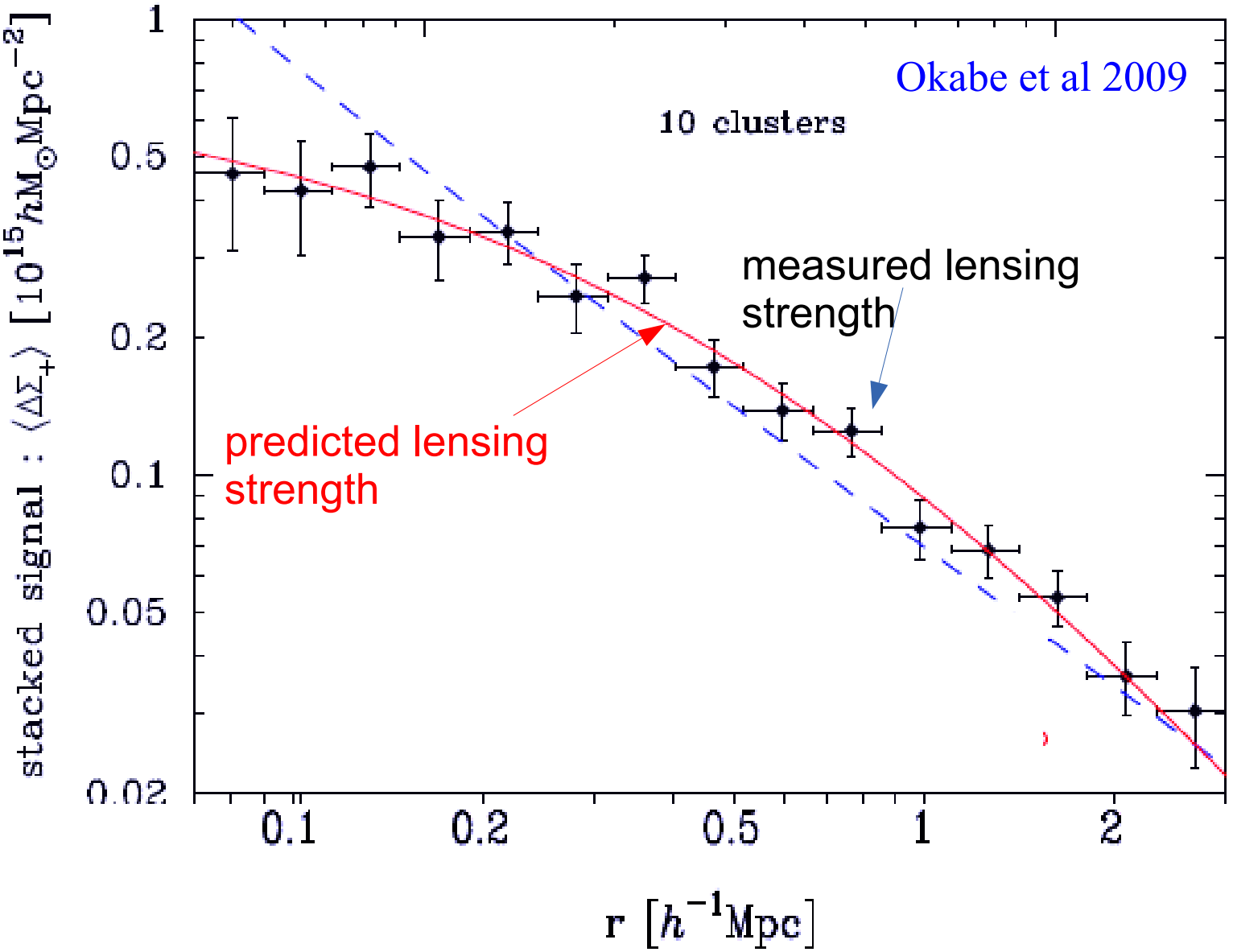




- Halo annihilation flux dominated by that from unresolved small halos but this is nearly uniform over the sky
- Flux from the Galactic centre dominates that from resolved subhalos by a large factor, but relative detectability depends critically on noise sources

# Dark matter halos – issues?

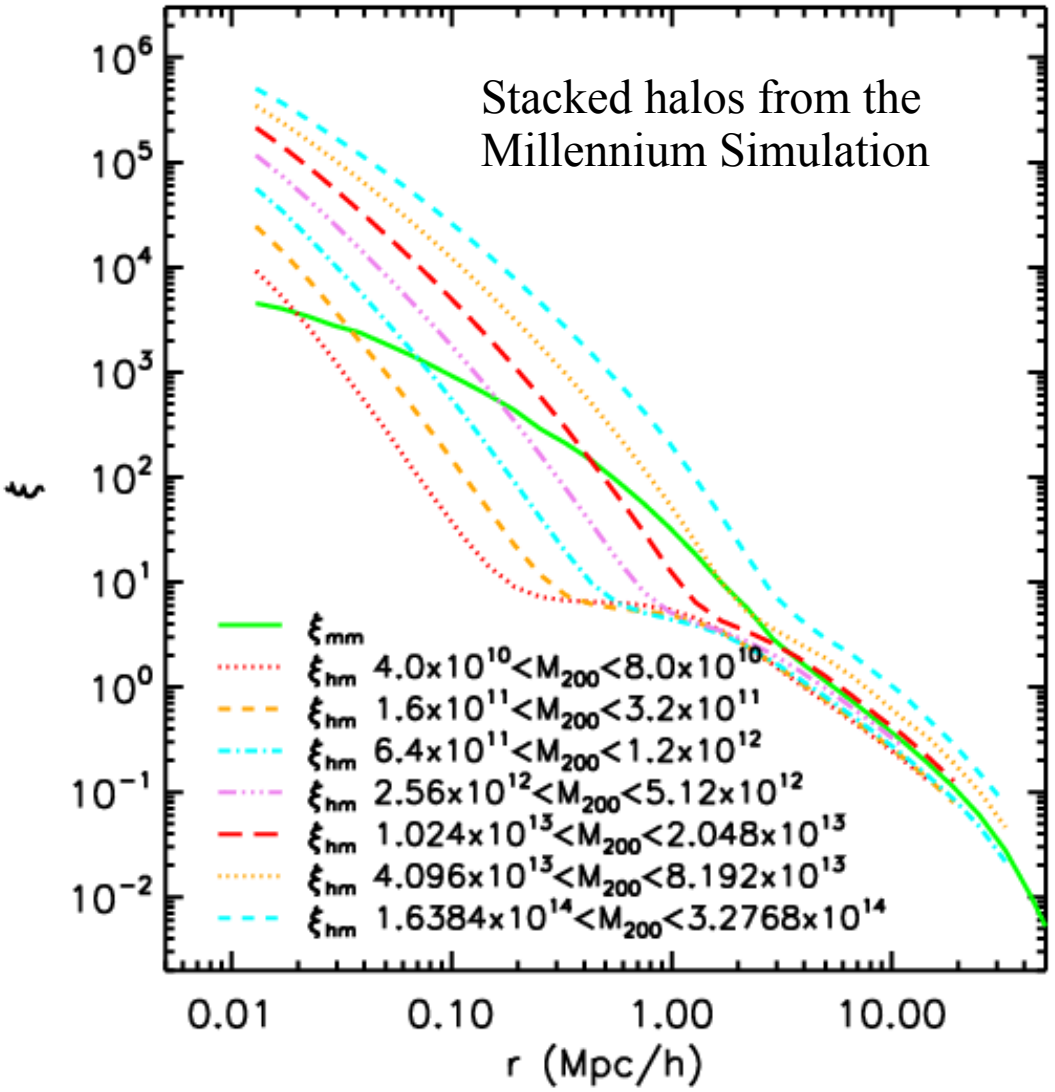
- Profiles as predicted?
  - NFW over the bulk of the mass?
  - Central cusps? (nature of DM?)

# Comparison of predicted/observed lensing



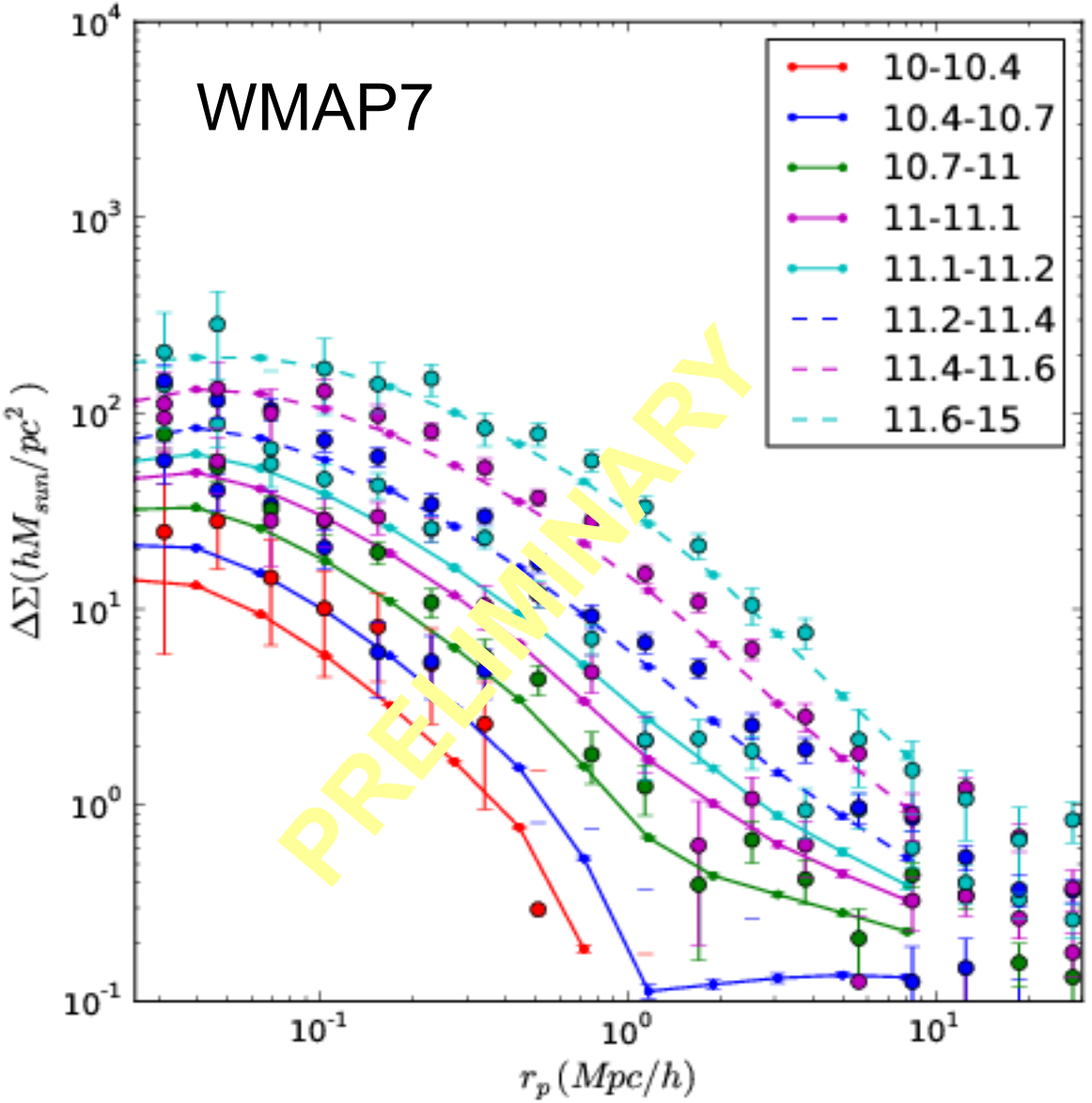
# Mean density profiles of dark halos to large radius

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



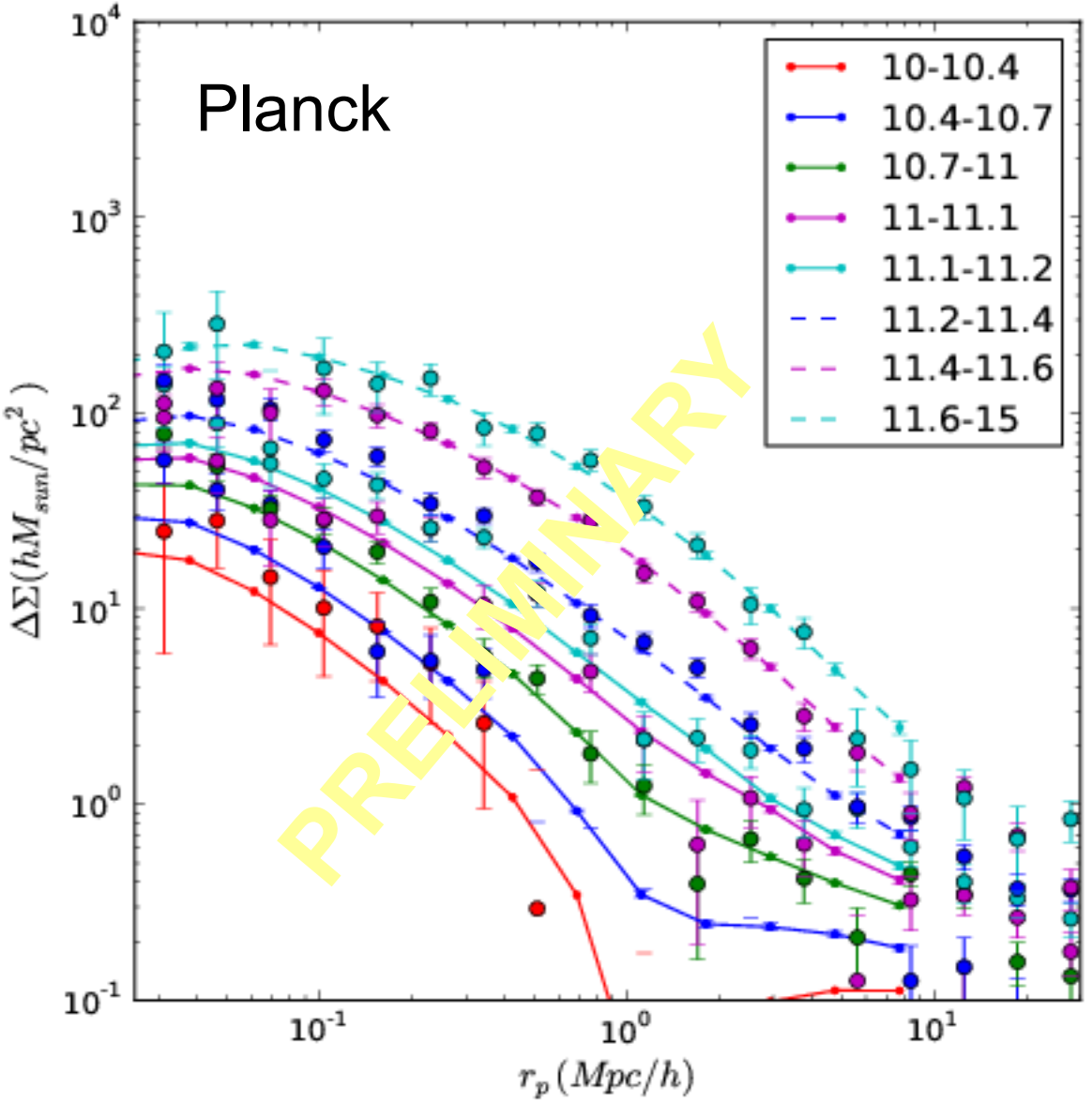

Wang, Mandelbaum et al, in prep.

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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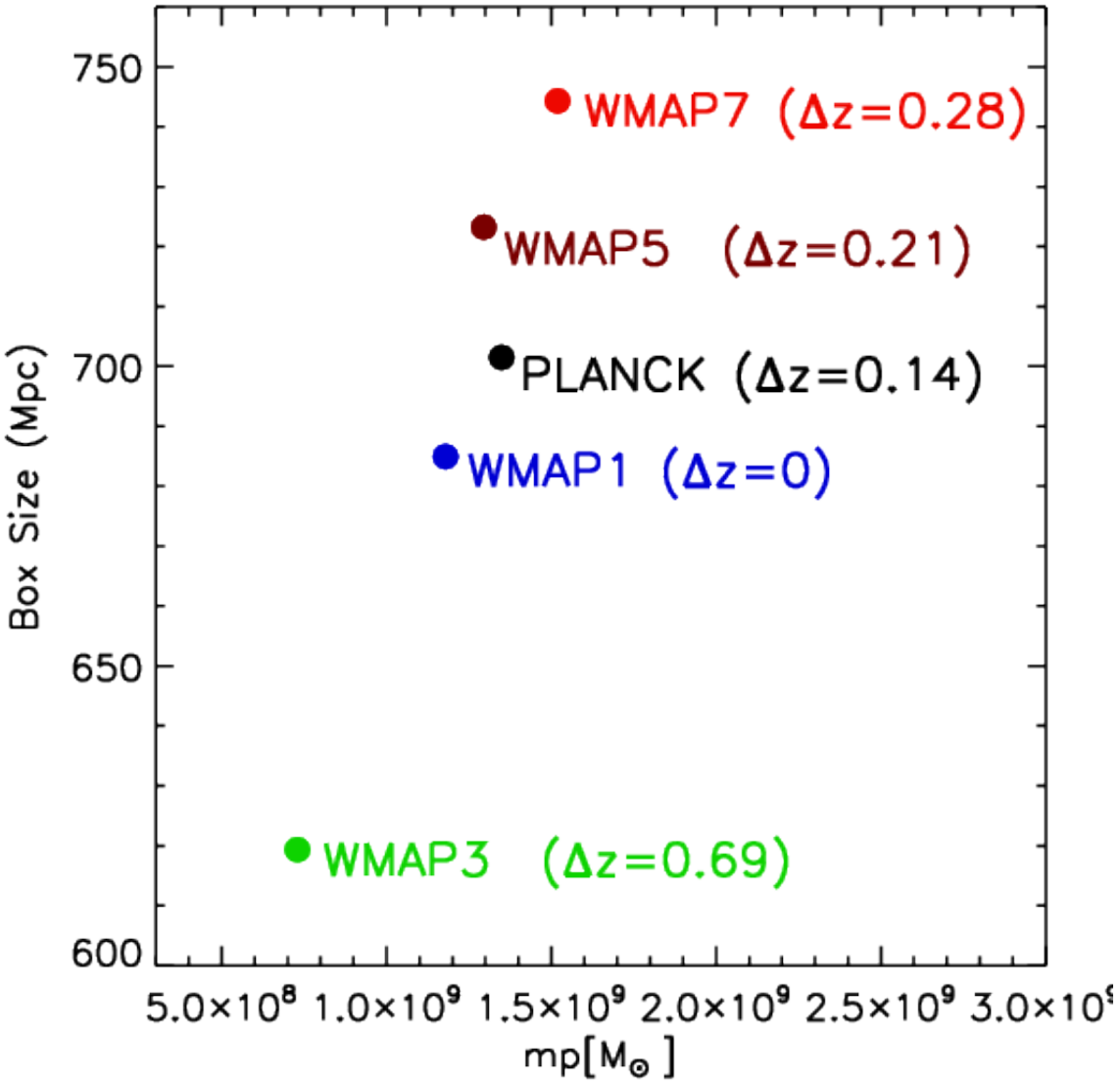
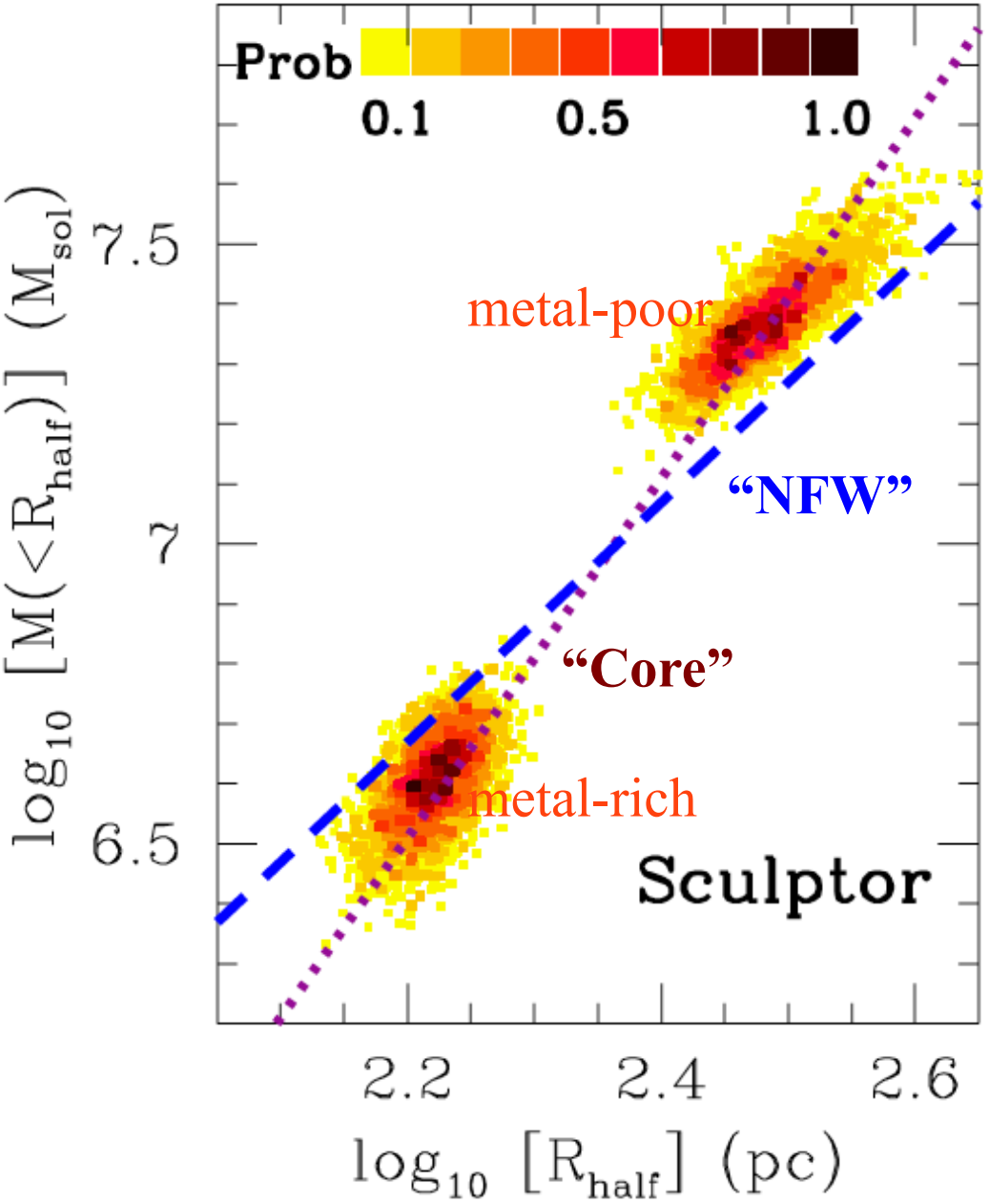
# Effect of changing cosmology on structure growth




Scalings needed to adapt the MS to changing CMB cosmologies

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

# Dark matter halos – issues?

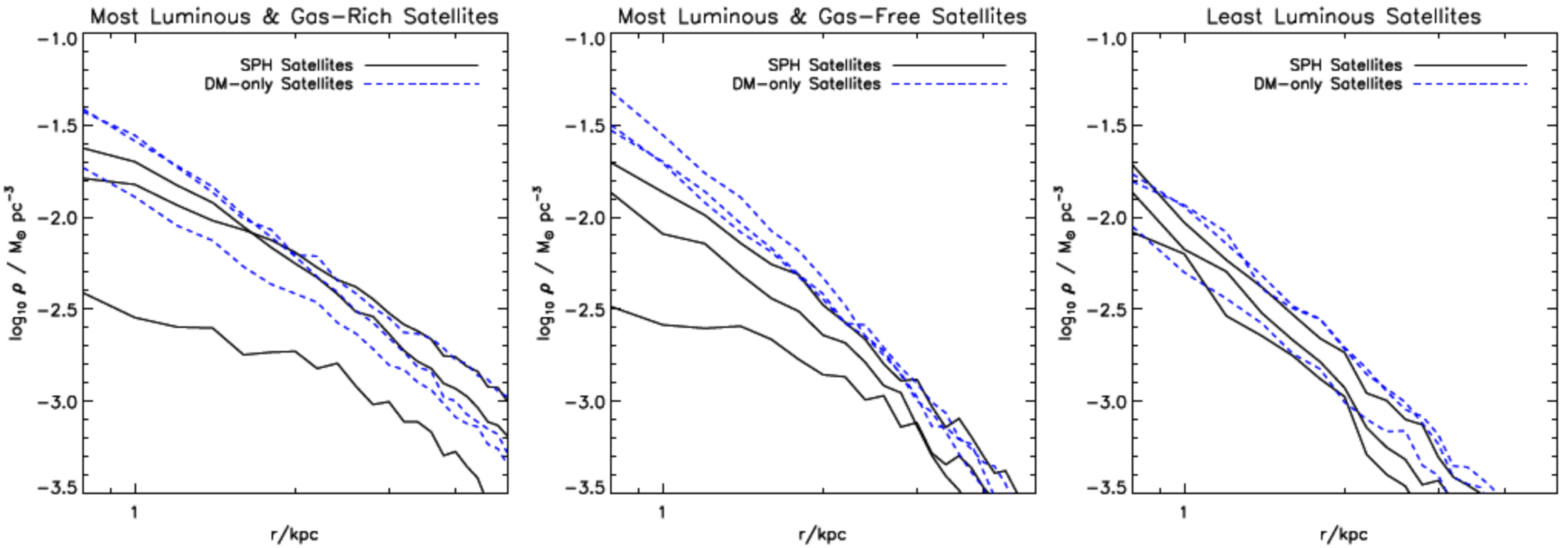



Sculptor (and also Fornax) has two well defined populations. Metal-rich stars are clearly more centrally concentrated and have lower velocity dispersion than metal-poor stars. Assuming

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

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

# Dark matter halos – issues?

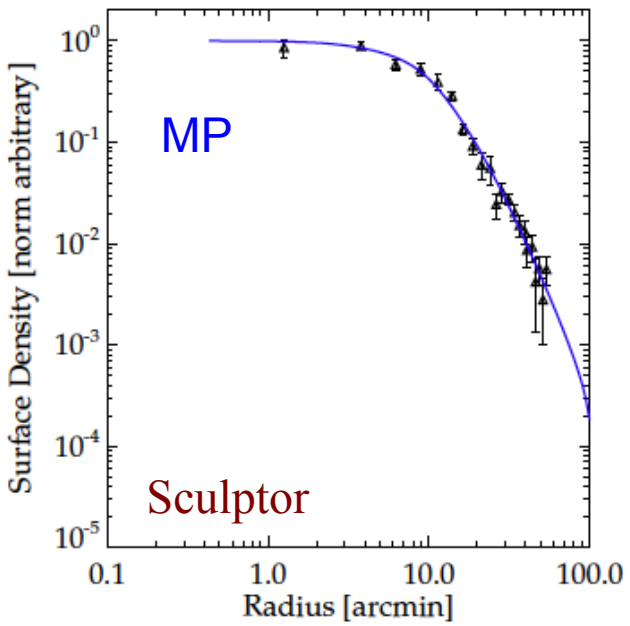


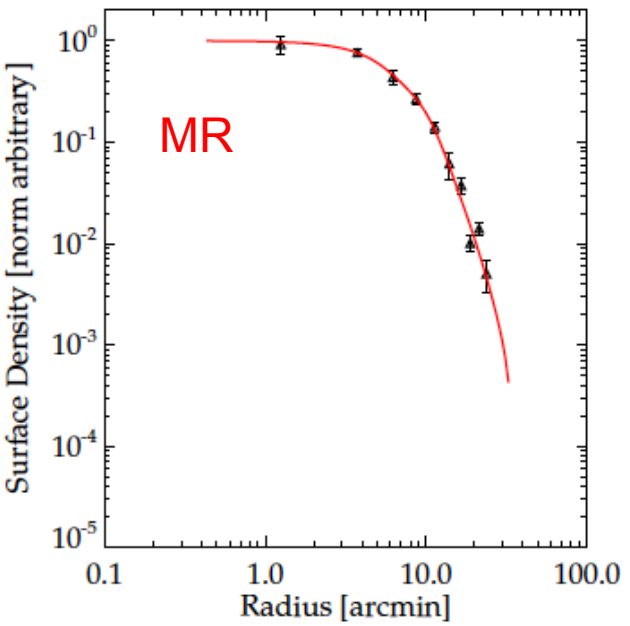

SPH simulations by Zolotov et al (2012) suggest dynamics associated with star formation may “flatten” cores in more massive dwarfs

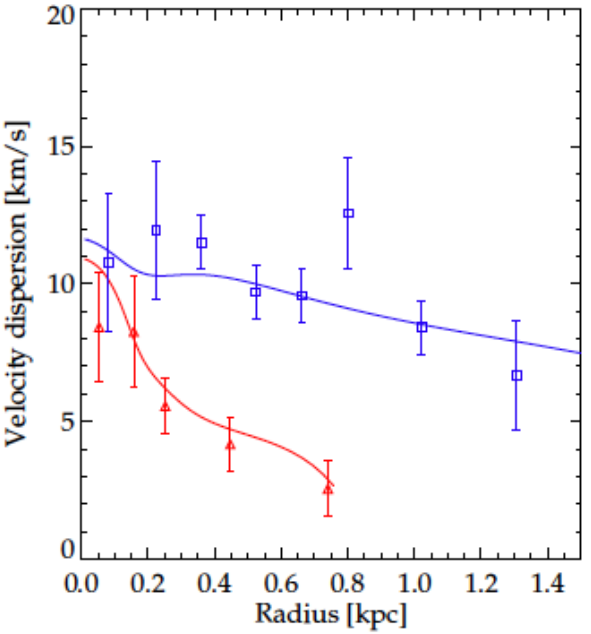
Do dSph's have enough stars for this to be important?

# Dark matter halos – issues?

Strigari et al 2013, in prep.



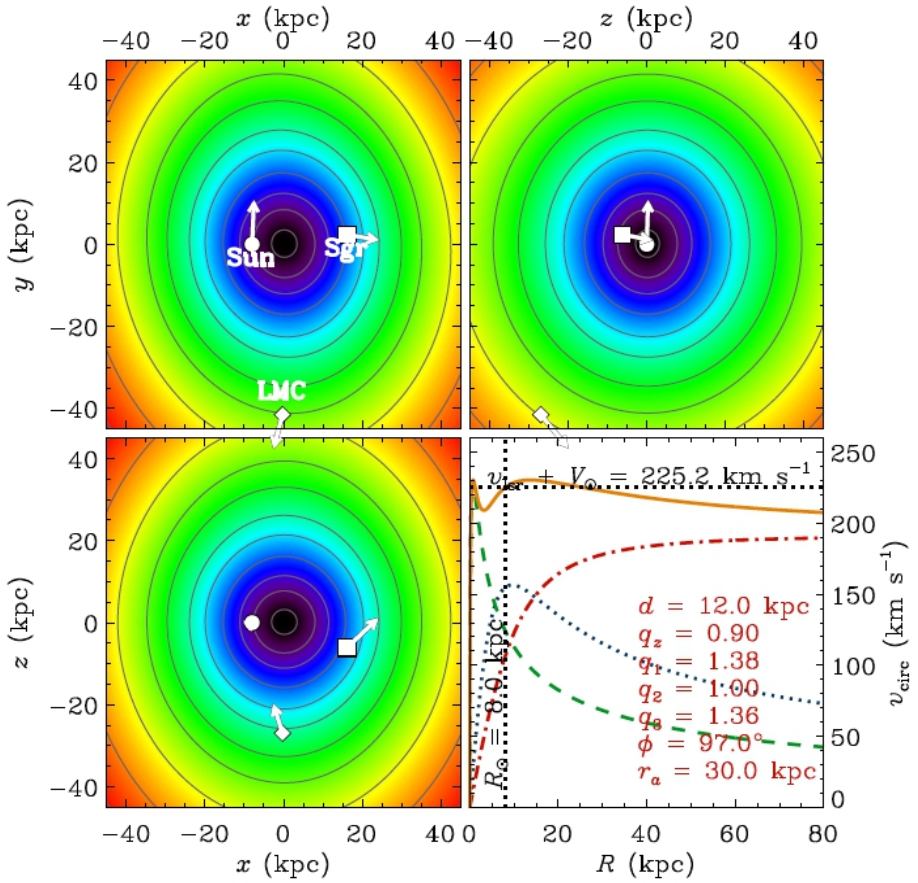

The counts and dispersion profiles of the MR and MP populations in Sculptor *can* be well fit (in a $\chi^2$ sense) as equilibria defined by simple anisotropic distribution functions within a single NFW potential.
The required NFW parameters are consistent with ΛCDM subhalos

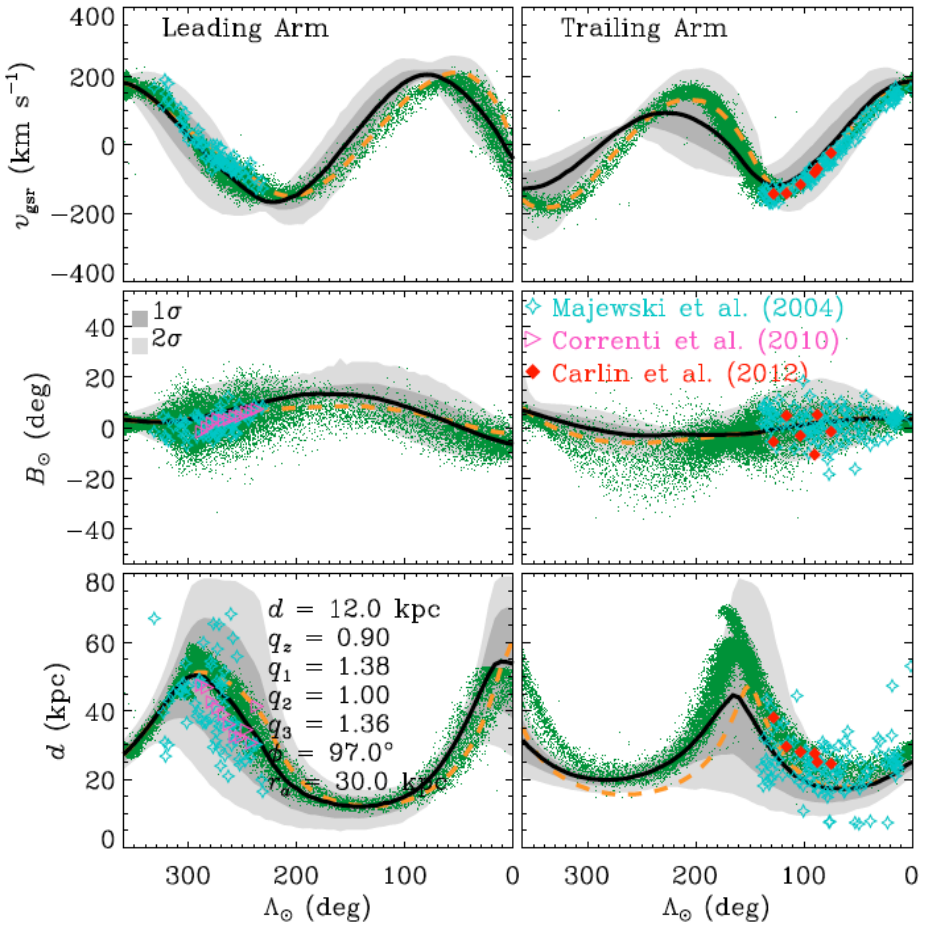
# Dark matter halos – issues?

- 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?

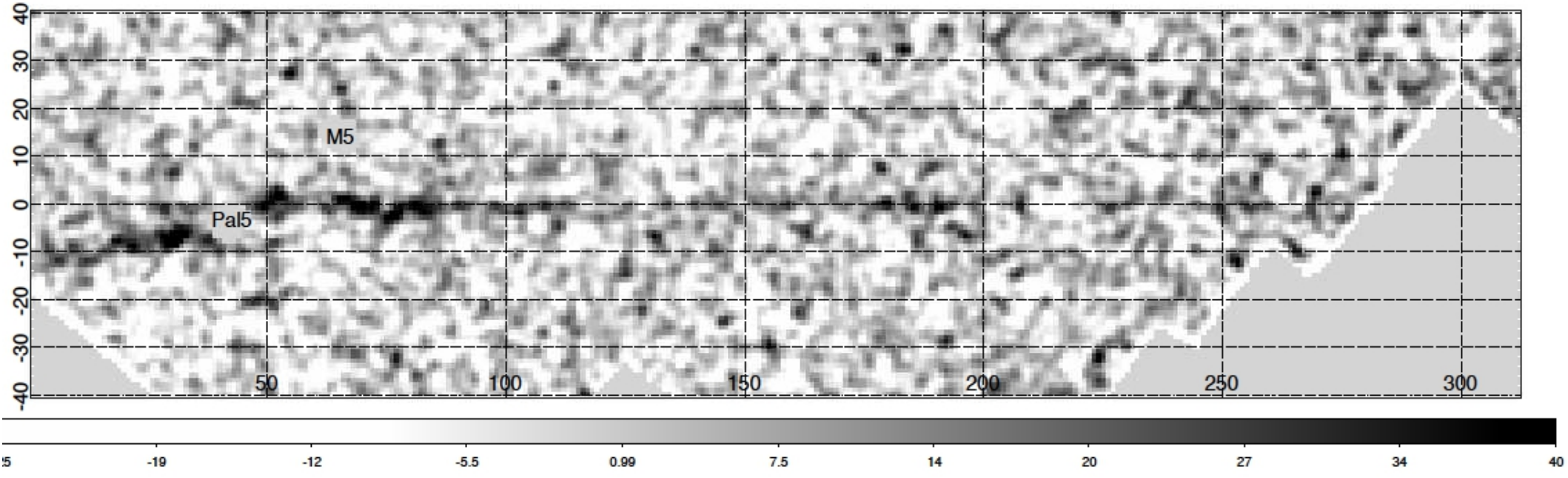
- Profiles as predicted?
  - NFW over the bulk of the mass?
  - Central cusps? (nature of DM)

- 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?

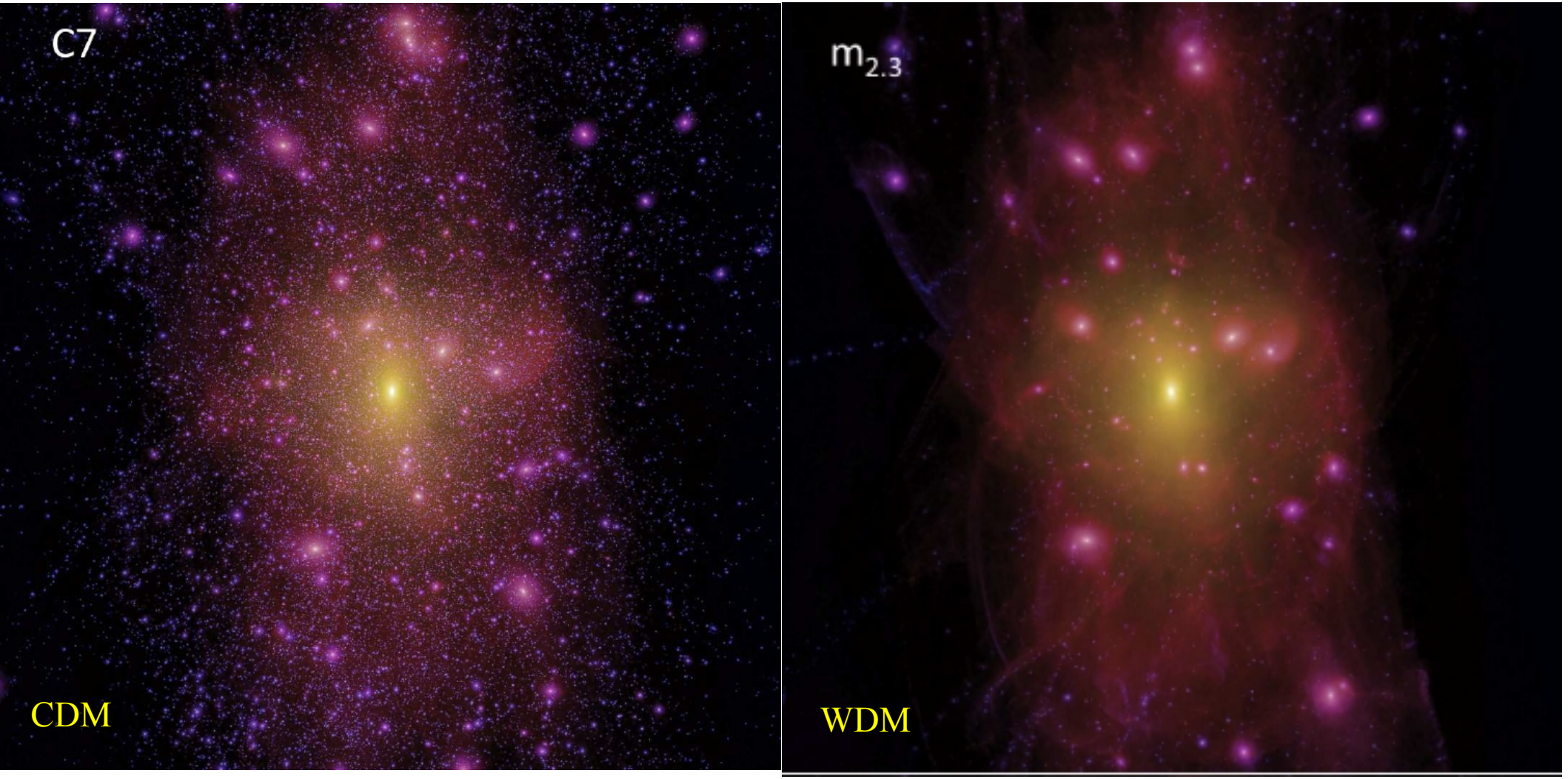
Carlberg, Grillmair & Hetherington 2013




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.

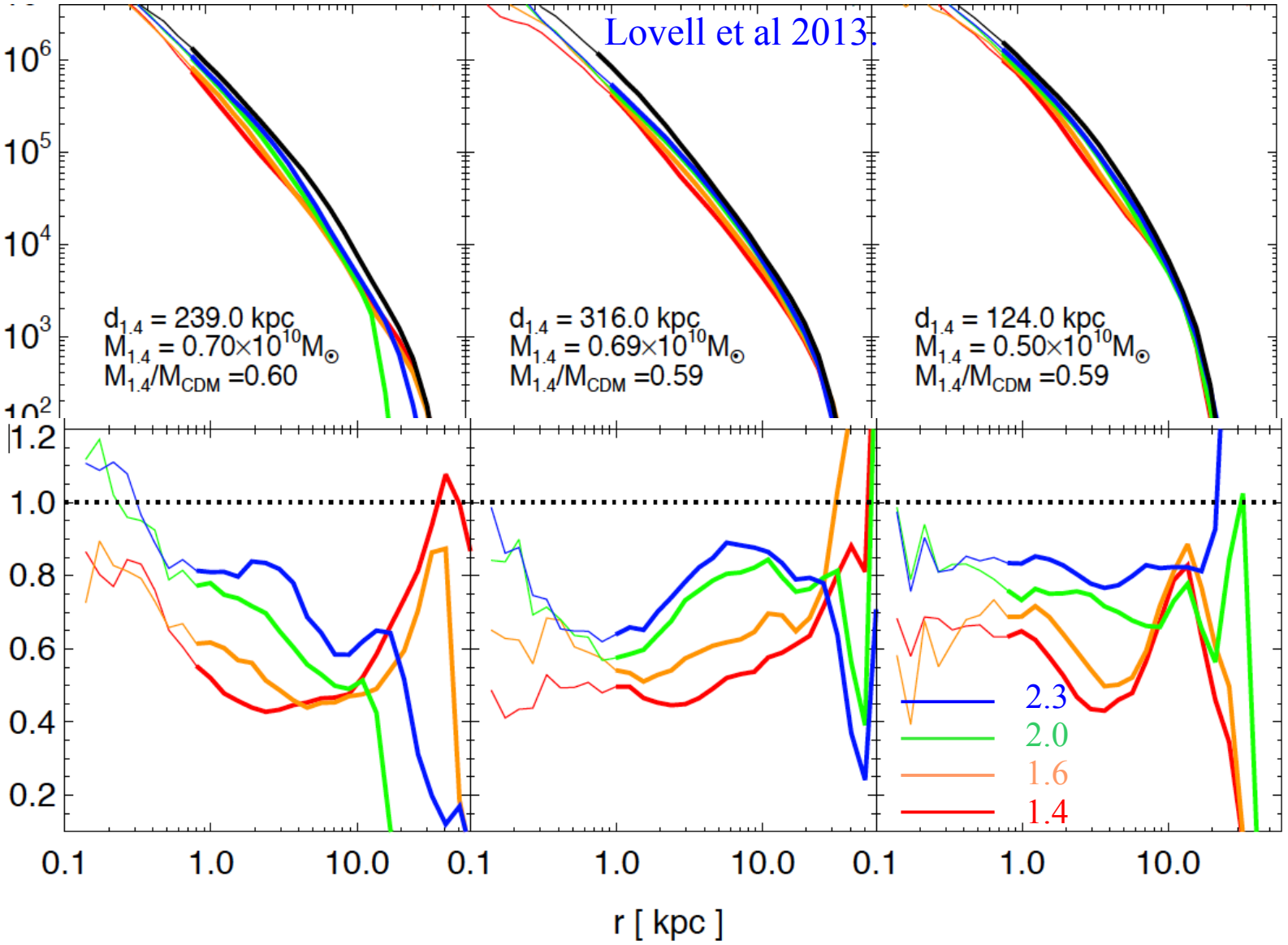
# Dark matter halos – issues?

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

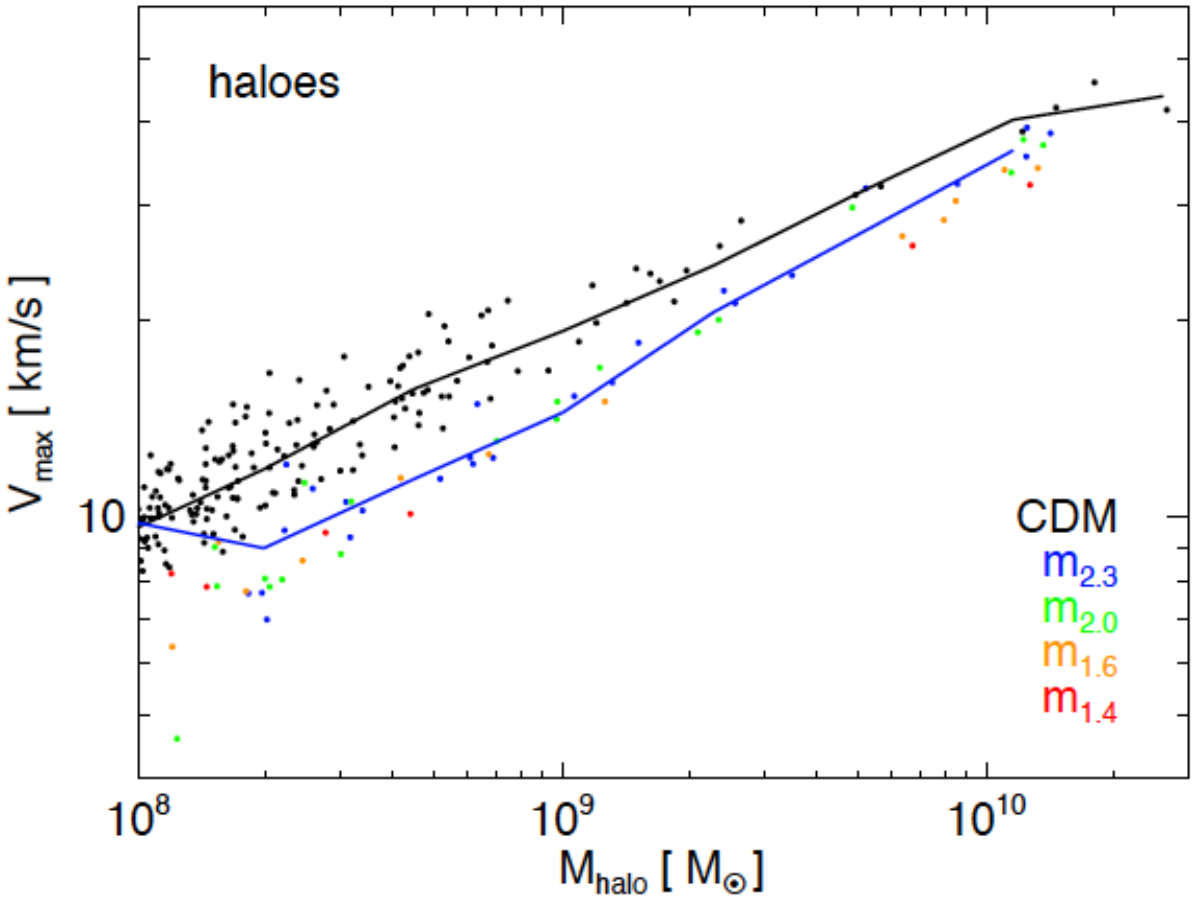
# Subhalo density profiles in WDM vs CDM




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

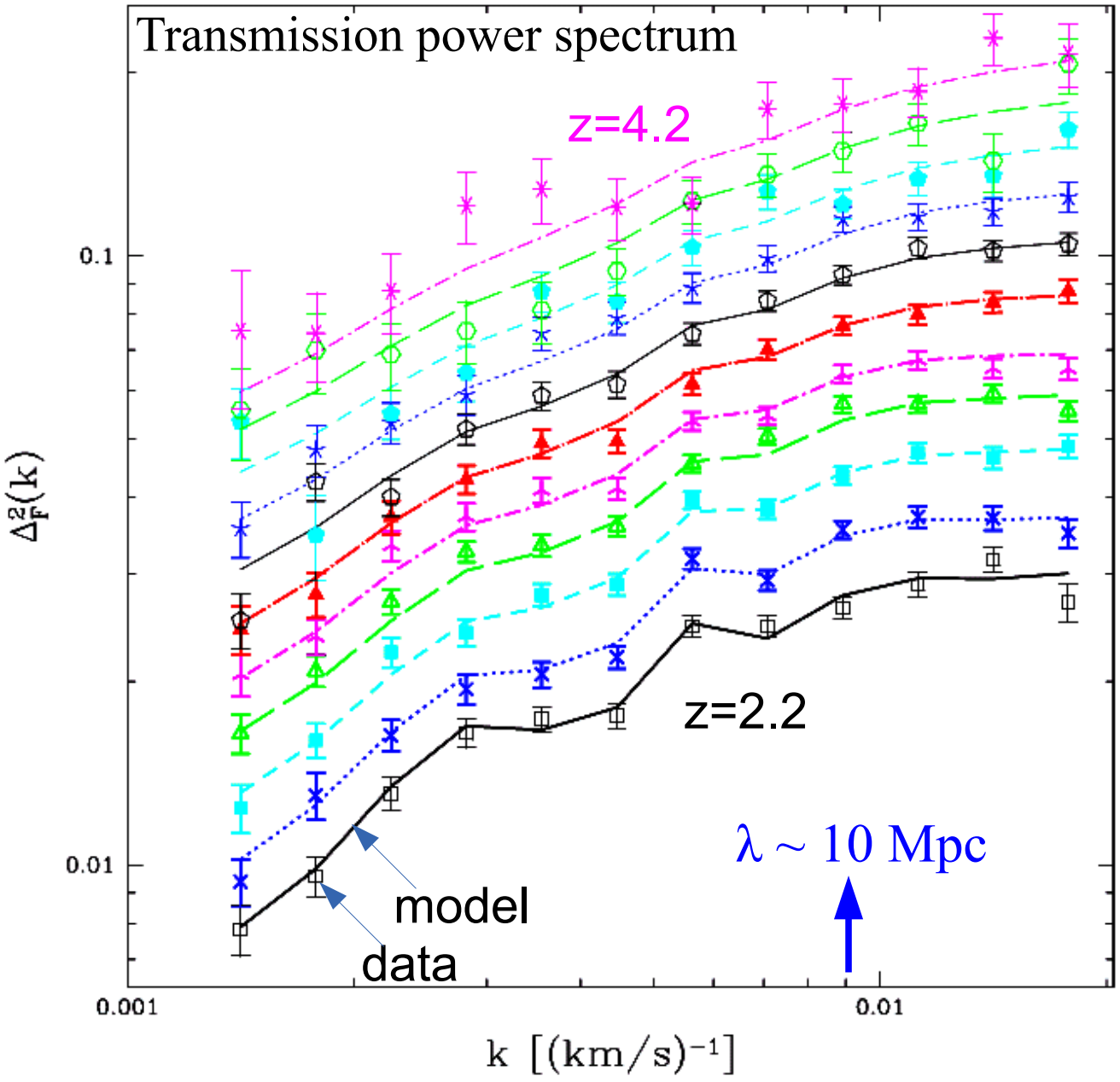
McDonald et al 2005

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

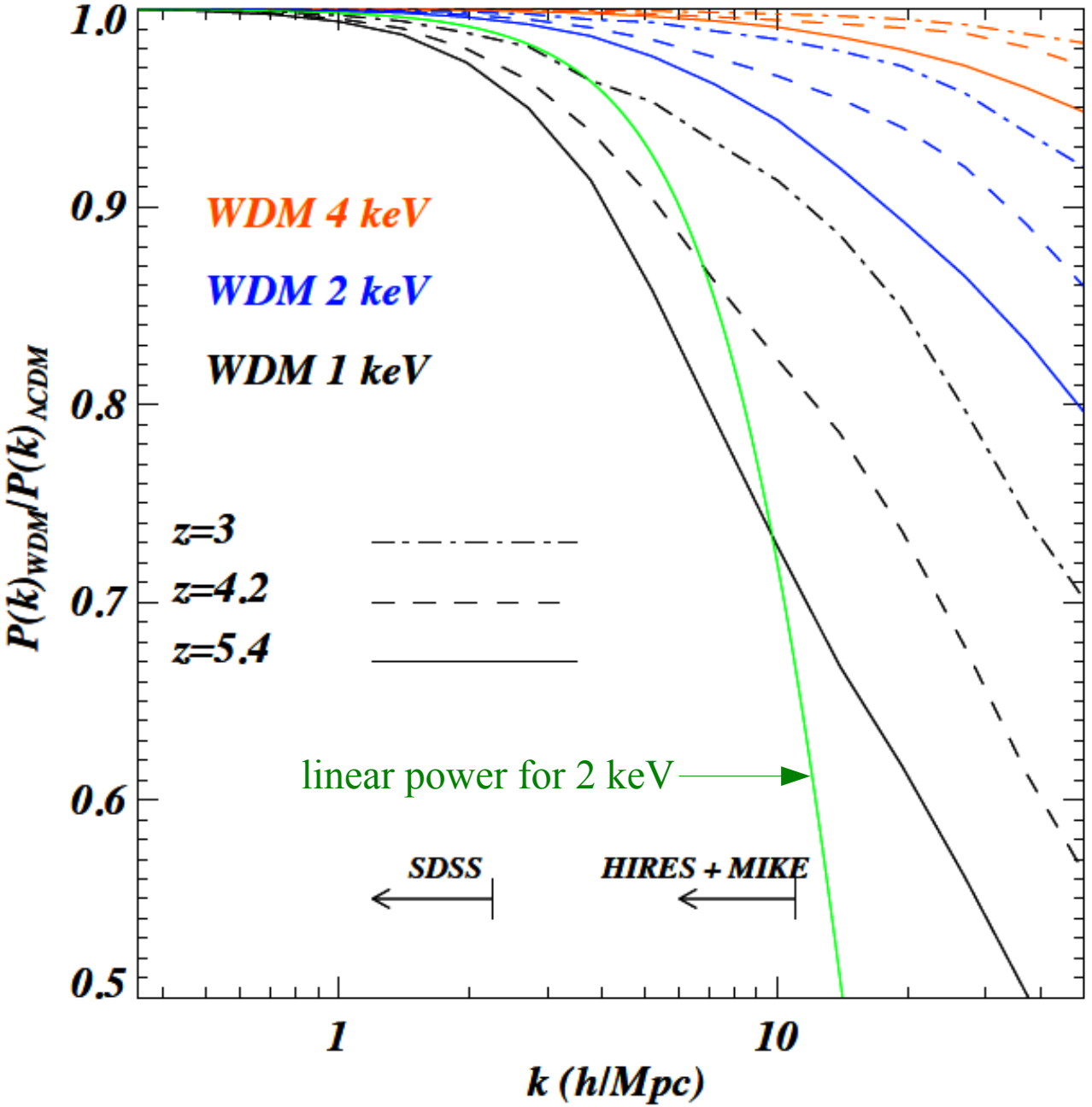
Data - 3300 SDSS quasars

Model - ΛCDM



# Matter power spectra for WDM relative to CDM

Viel, Becker, Bolton & Haehnelt 2013




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

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

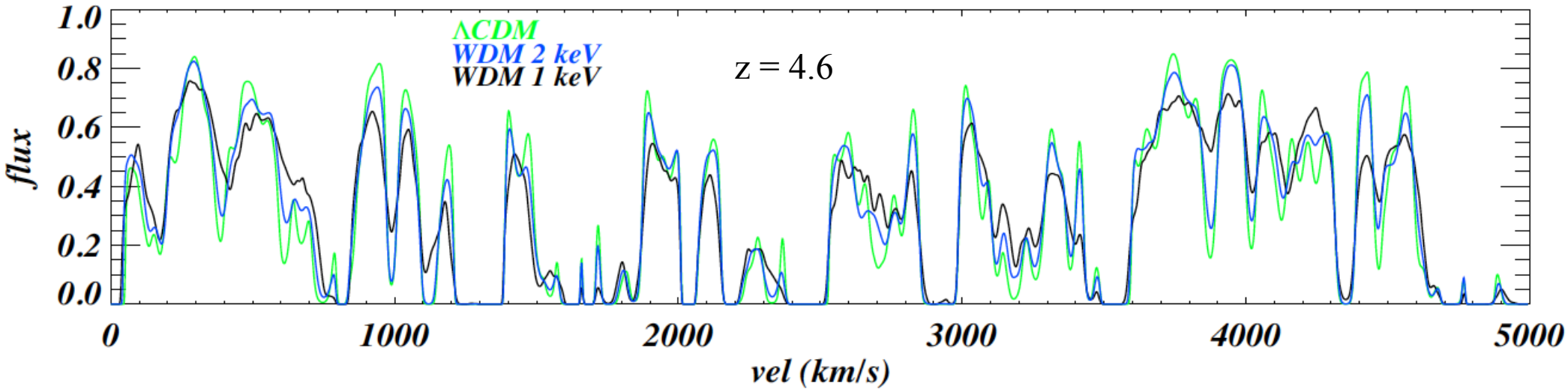
Nonlinear effects transfer power to small scales and weaken the cut-off.

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

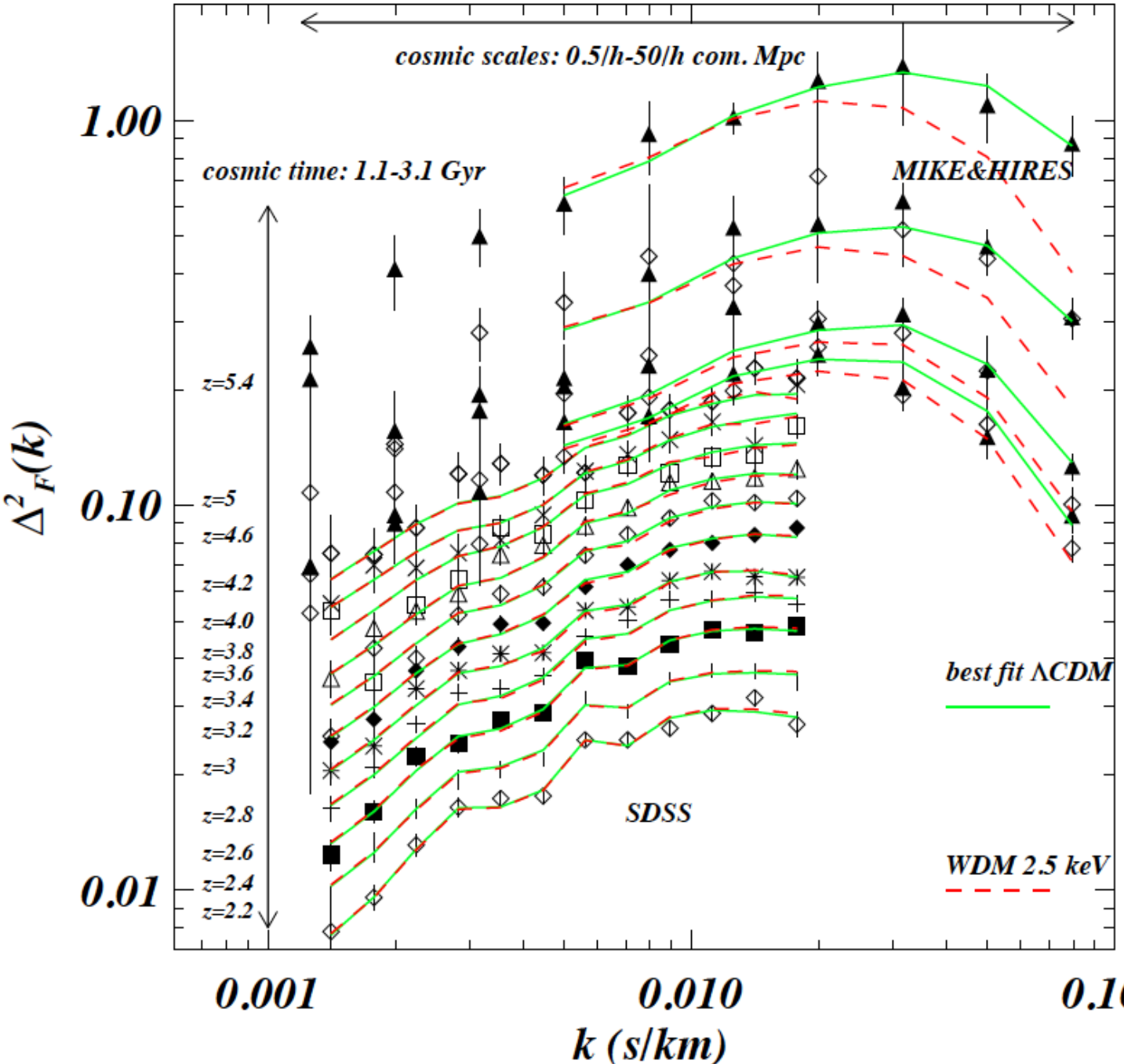
Viel, Becker, Bolton & Haehnelt 2013




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

$$m_{WDM} > 3.3 \text{ keV}$$

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