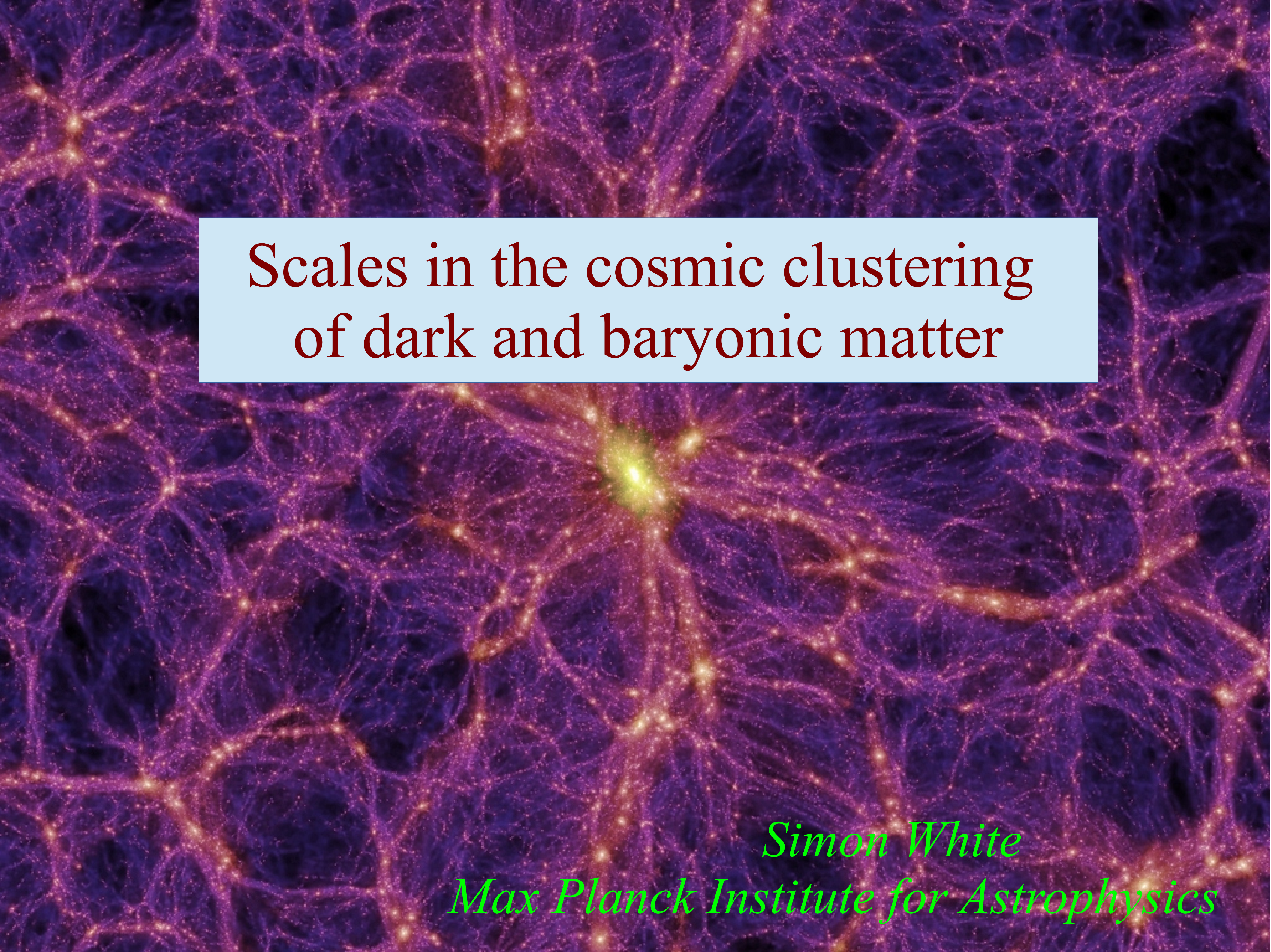
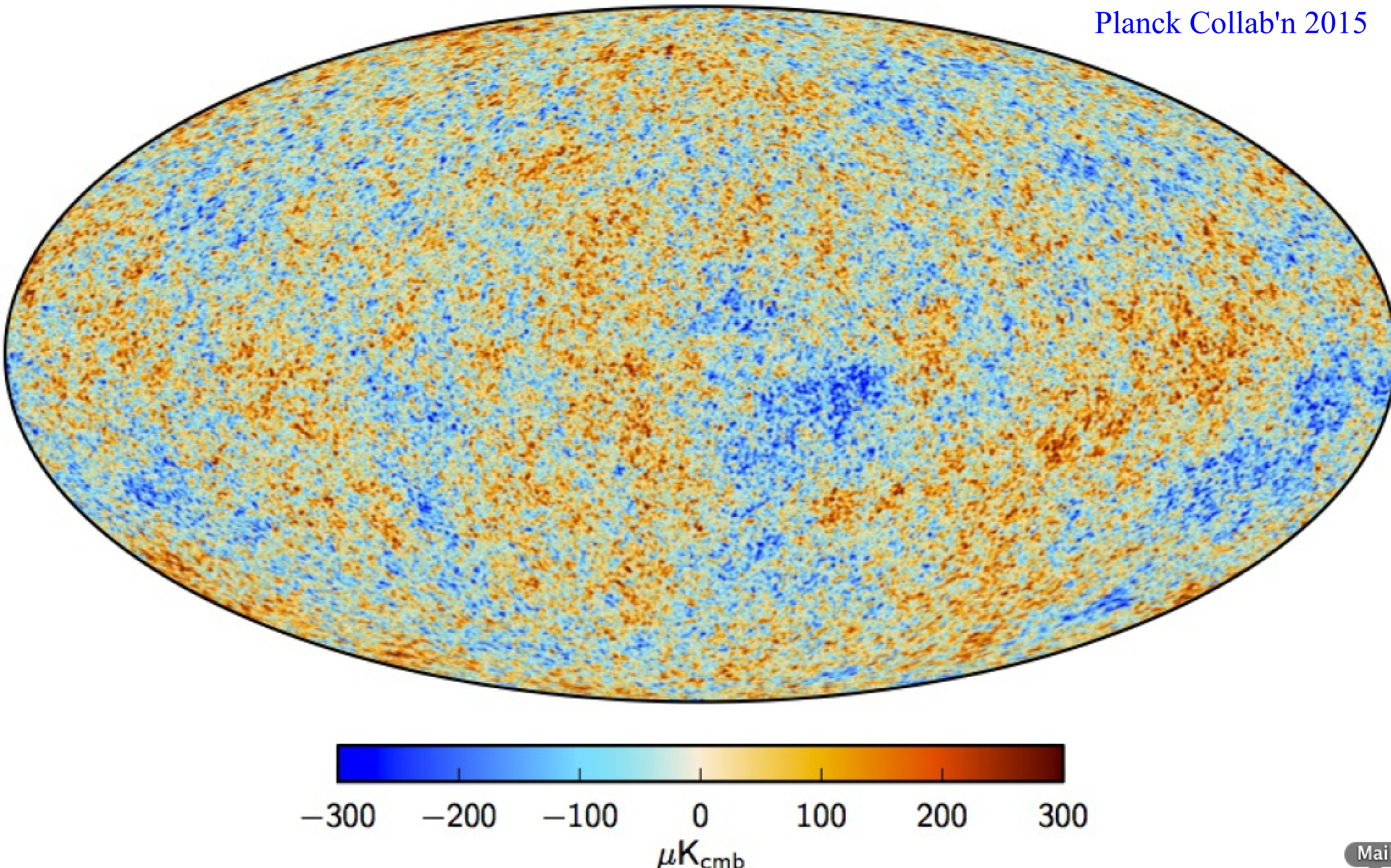


Scales in the cosmic clustering of dark and baryonic matter

Simon White
Max Planck Institute for Astrophysics

CMB map from the full *Planck* mission

Planck Collab'n 2015



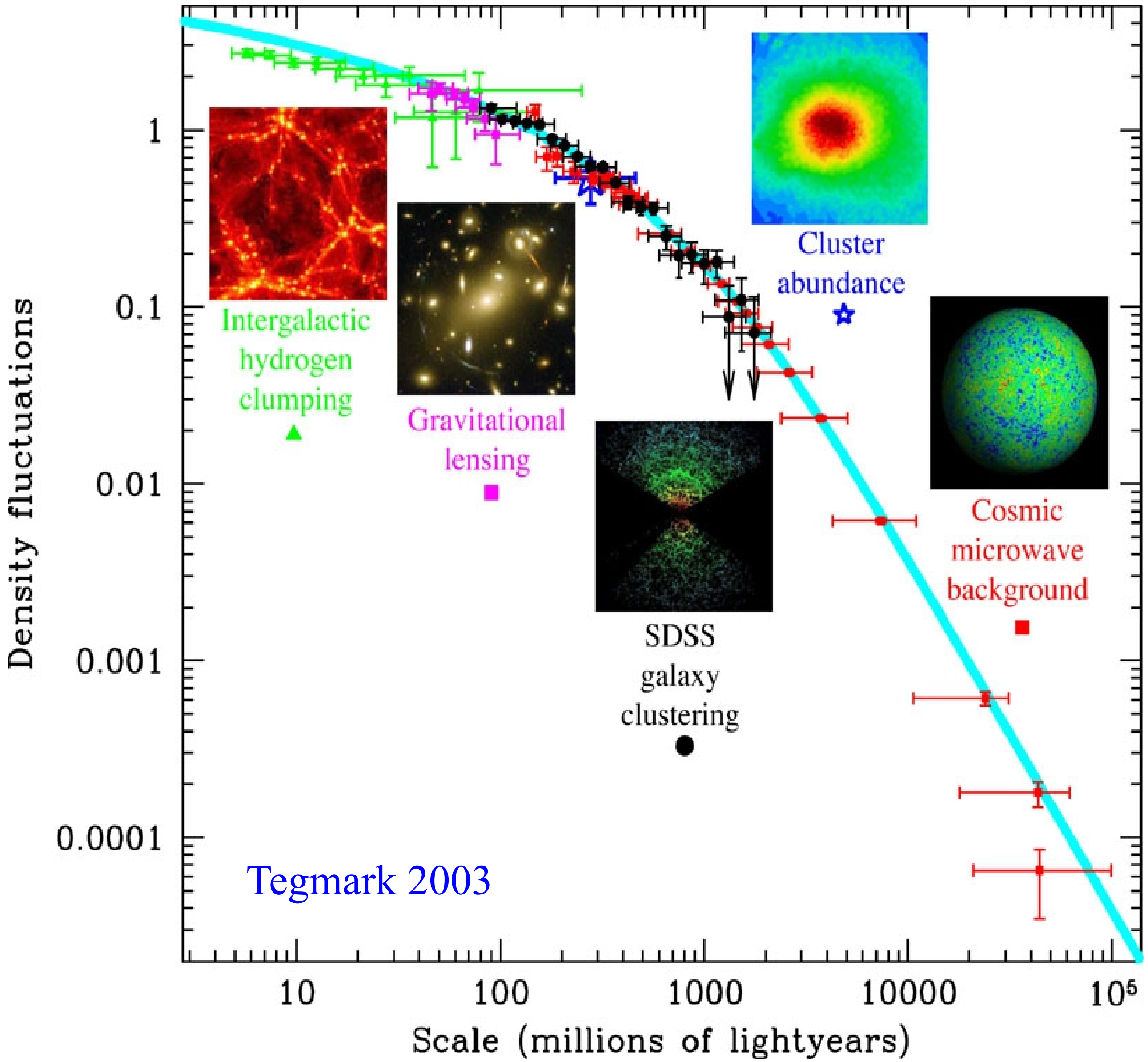
Mail

The six parameters of the base ΛCDM model

Planck Collab'n 2015

Parameter	TT+lowP 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04077 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.079 ± 0.017	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.094 ± 0.034	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049	0.9667 ± 0.0040

The Equipartition Scale



The size of the cosmological horizon at the redshift of matter-radiation equality sets the scale of the bend in the matter power spectrum.

$$\lambda_{eq} \propto k_{eq}^{-1} \propto (\Omega_m h^2)^{-1}$$

The equipartition scale as motivator for ΛCDM

letters to nature

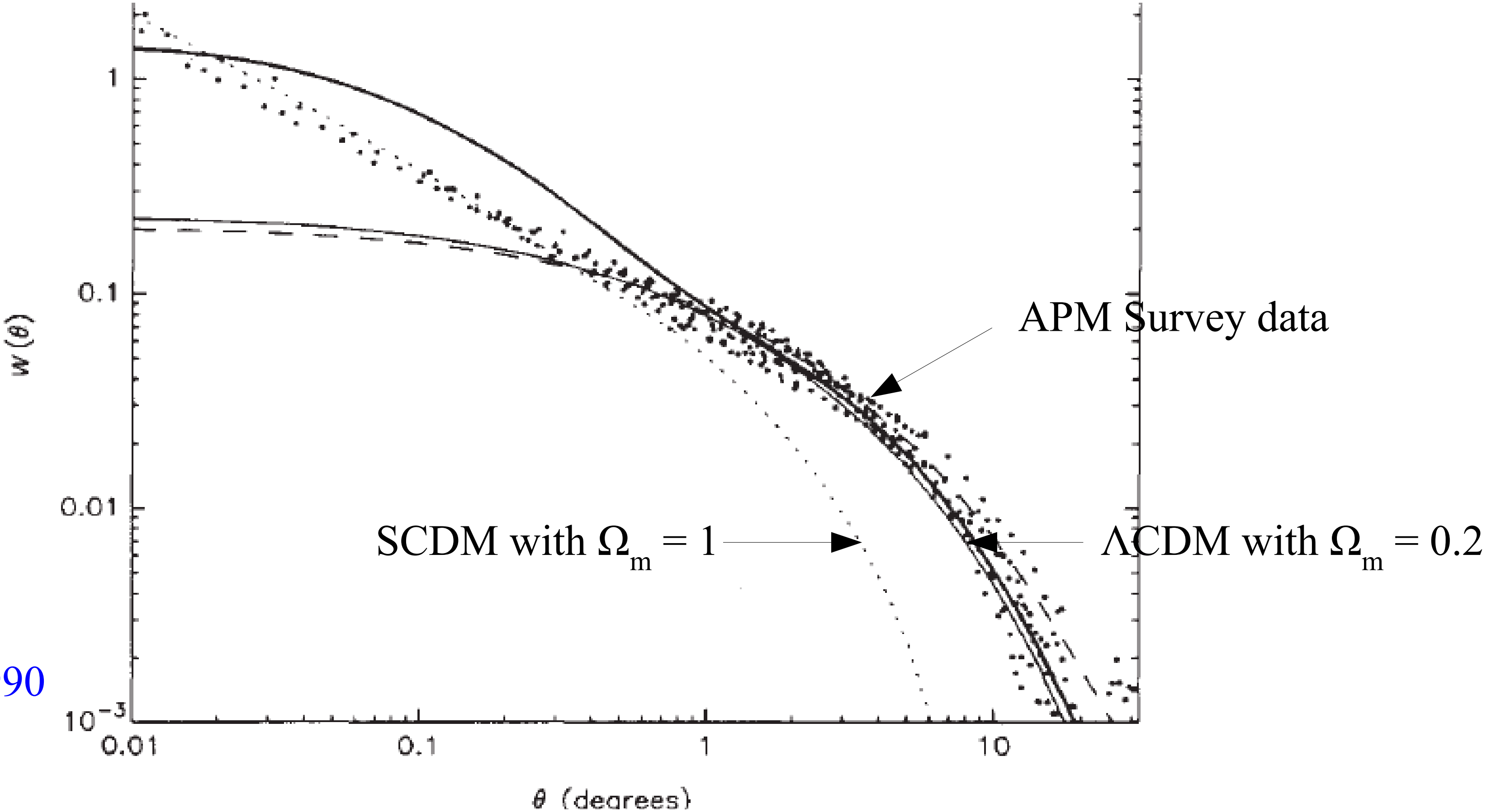
Nature **348**, 705 - 707 (27 December 1990); doi:10.1038/348705a0

The cosmological constant and cold dark matter

G. EFSTATHIOU, W. J. SUTHERLAND & S. J. MADDOX

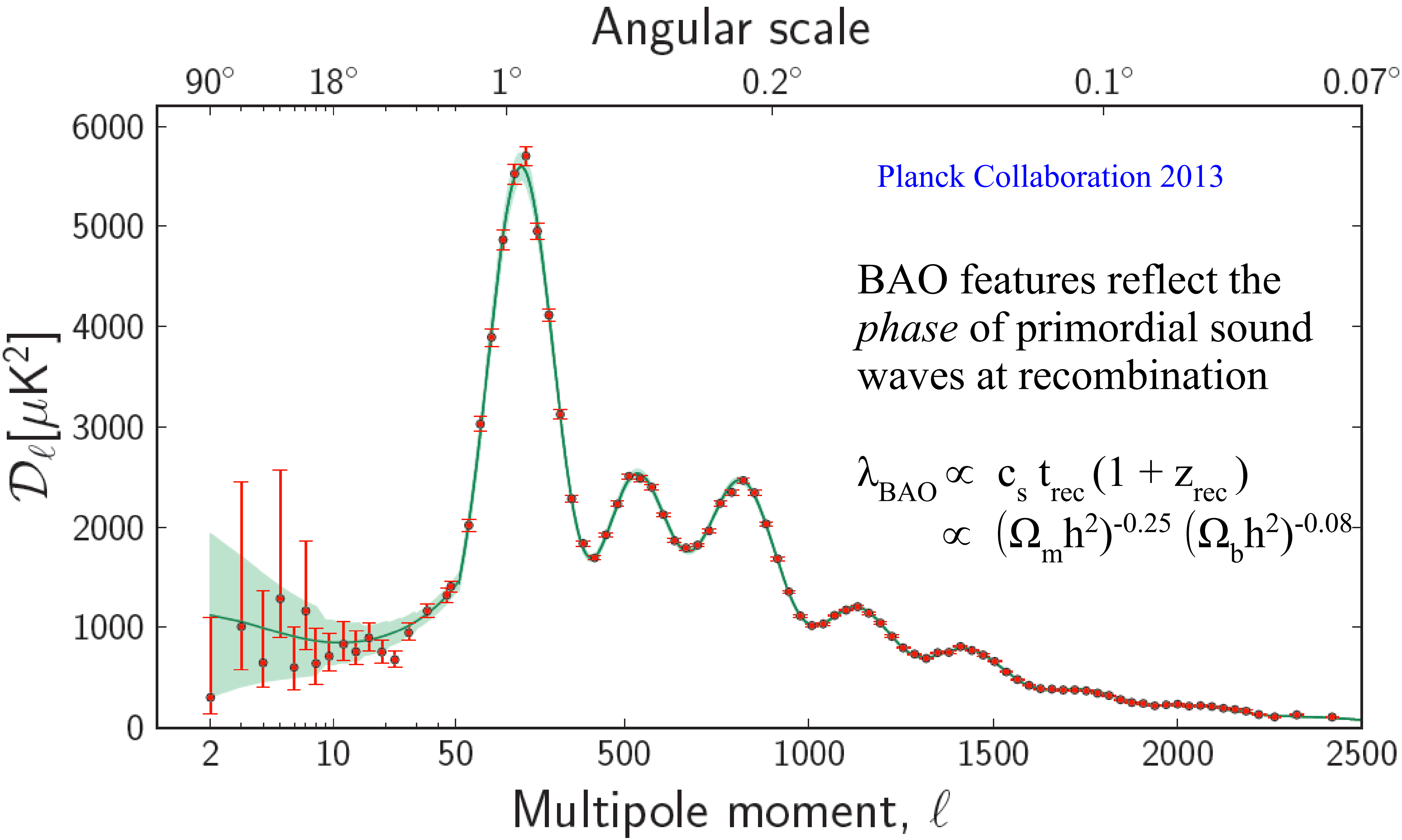
Department of Physics, University of Oxford, Oxford 0X1 3RH, UK

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.



Efstathiou et al 1990

The BAO scale in the *Planck* CMB map

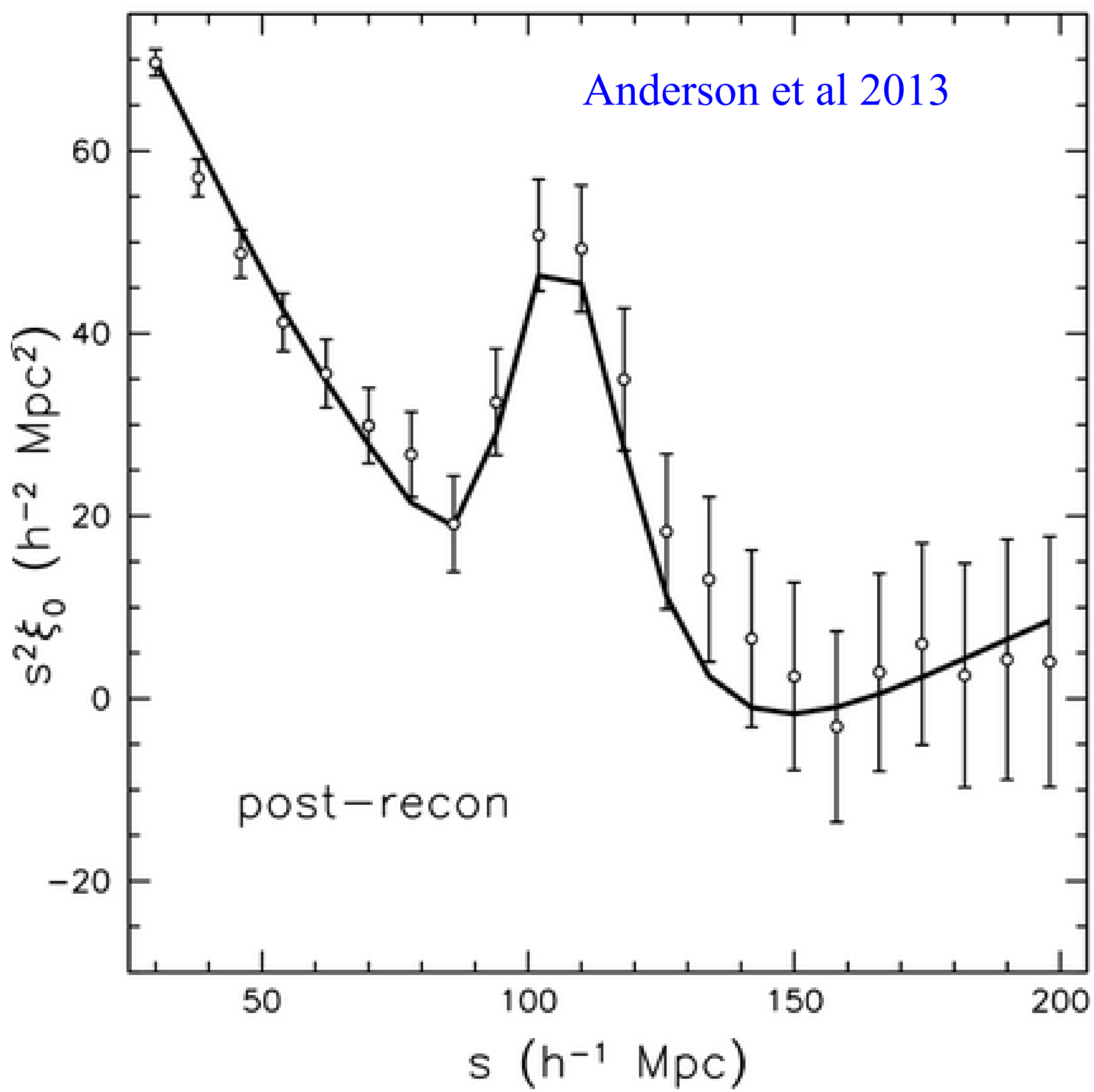


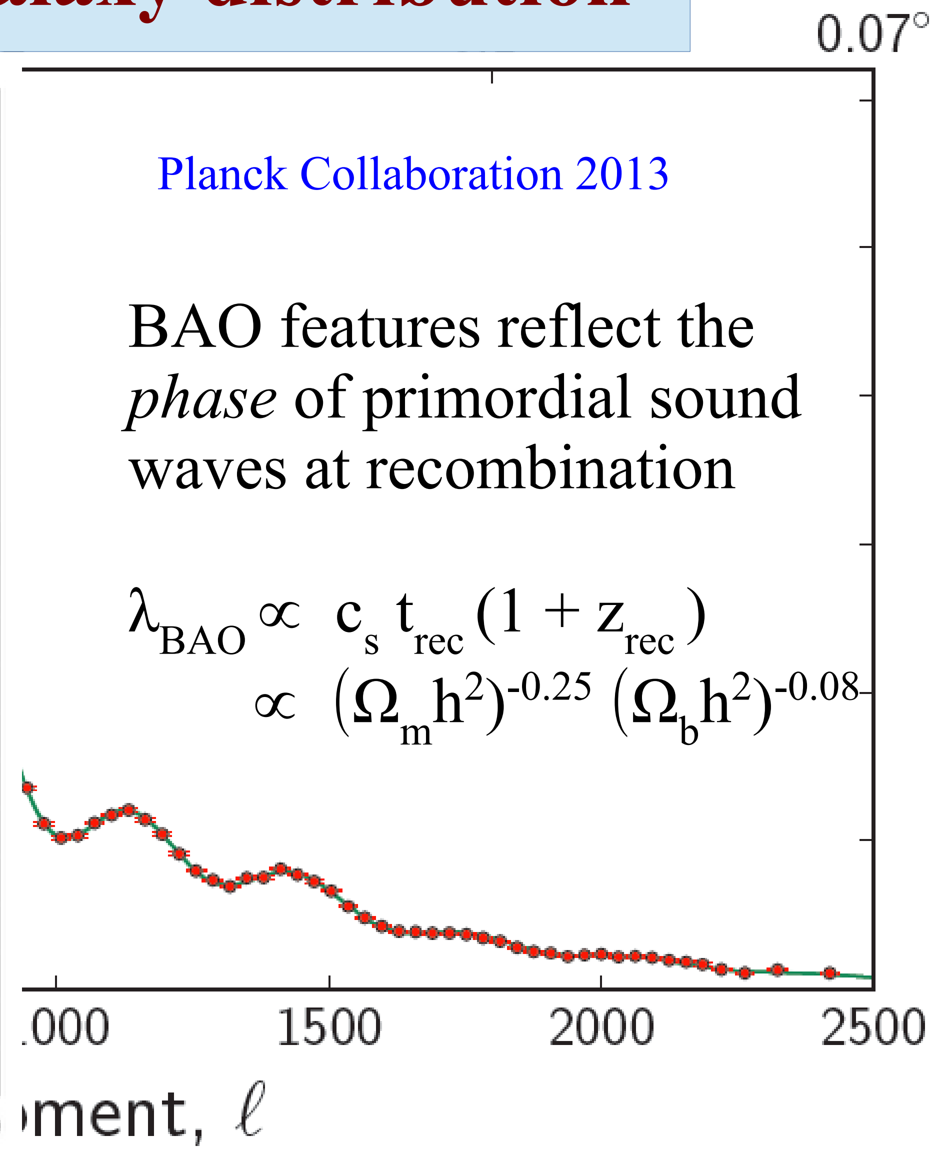
BAO features reflect the *phase* of primordial sound waves at recombination

$$\lambda_{BAO} \propto c_s \, t_{rec} (1 + z_{rec}) \propto (\Omega_m h^2)^{-0.25} (\Omega_b h^2)^{-0.08}$$

The BAO scale in the *Planck* CMB map

...and in the BOSS galaxy distribution





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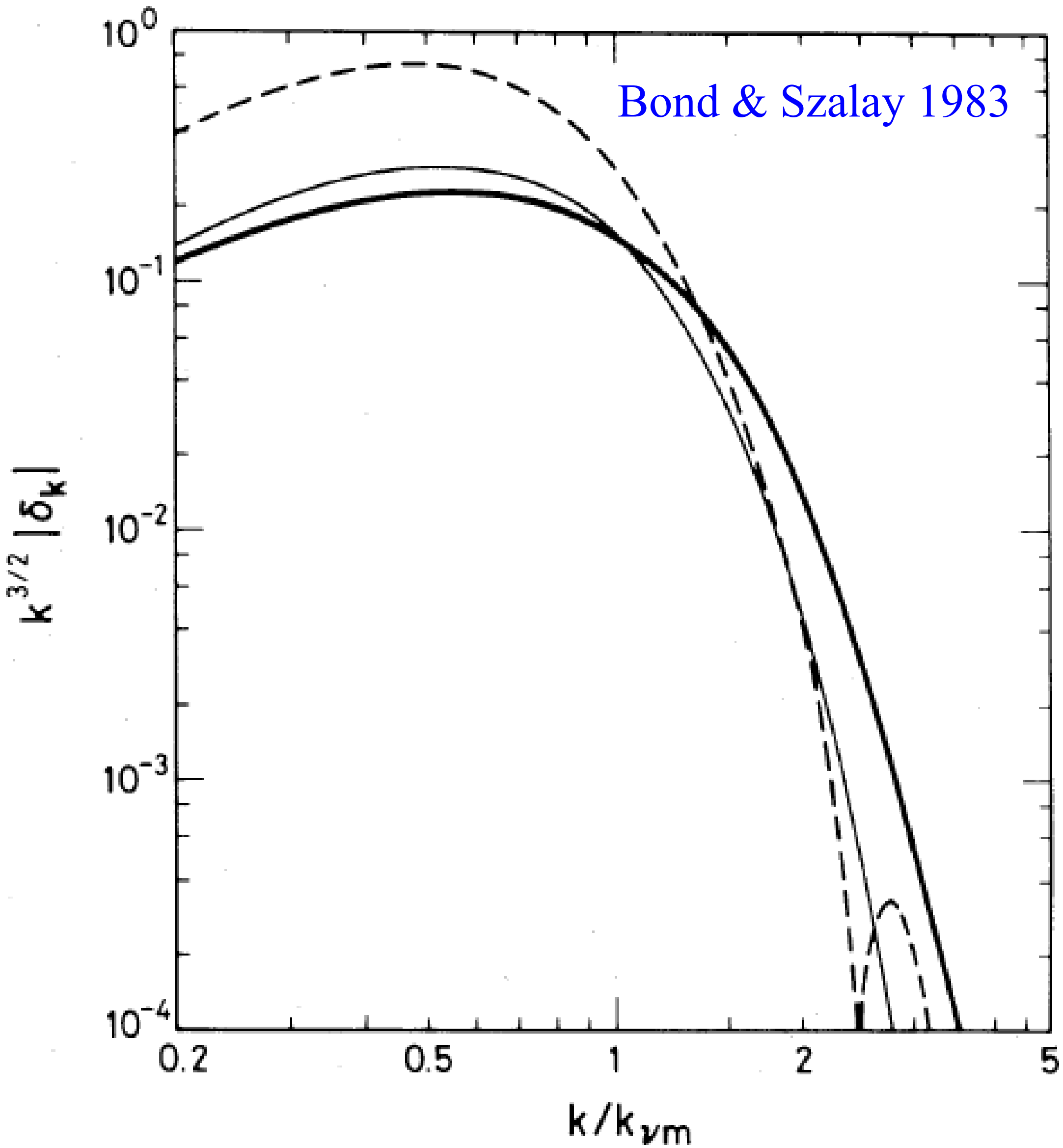
The dark matter free-streaming scale



Free-streaming of DM particles while still relativistic erases small-scale structure in the ICs

$\lambda_{fs} \propto c\, t_{non.rel.} (1 + z_{non\text{-}rel.})$

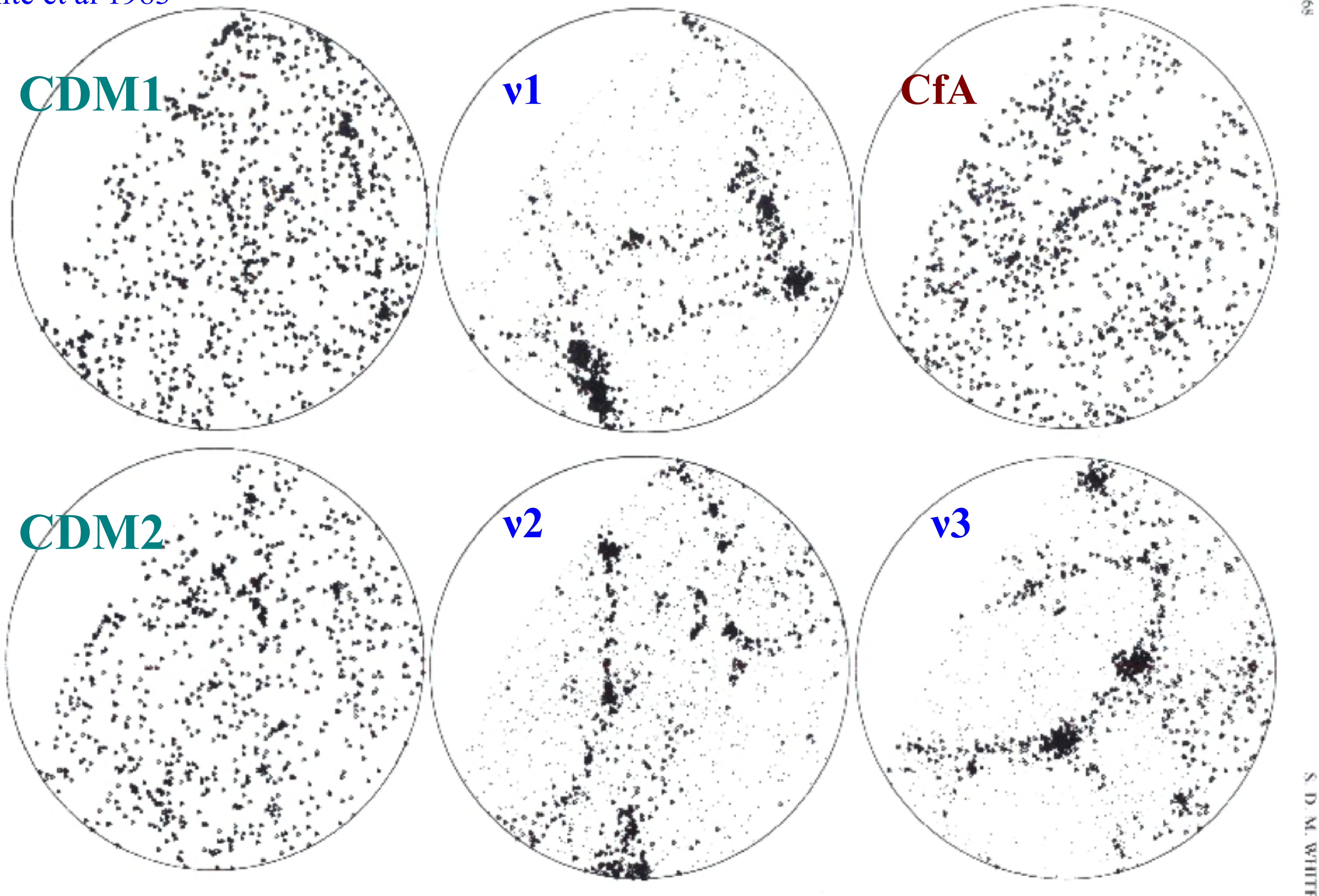
with

$1 + z_{non\text{-}rel.} = m_x\, c^2/kT_{cmb}$

Together with $n\, m_x \propto \Omega_m h^2$, this ties the density of dark matter to a characteristic, mass-dependent spatial scale

The exclusion of massive neutrinos as the dark matter

White et al 1983



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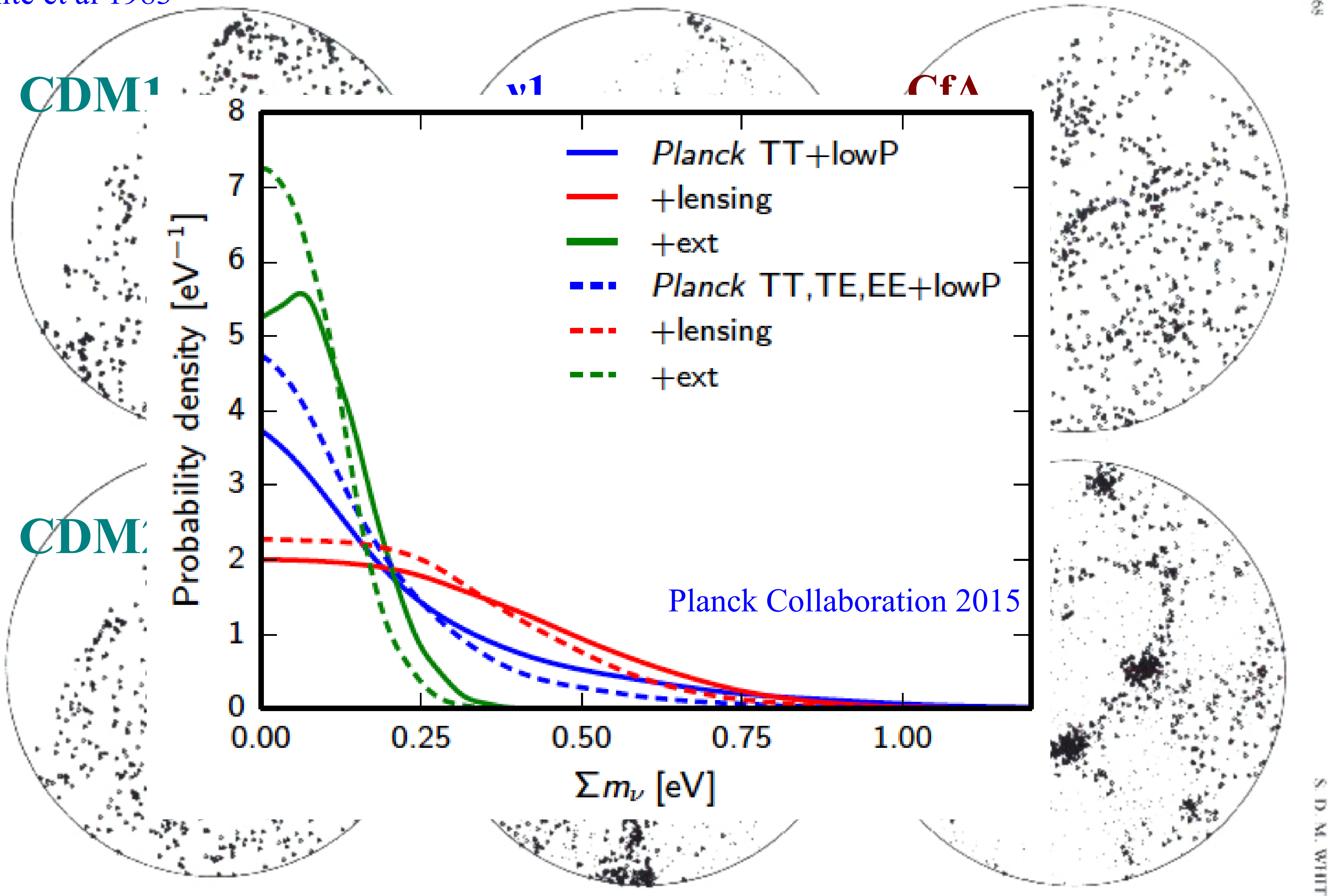
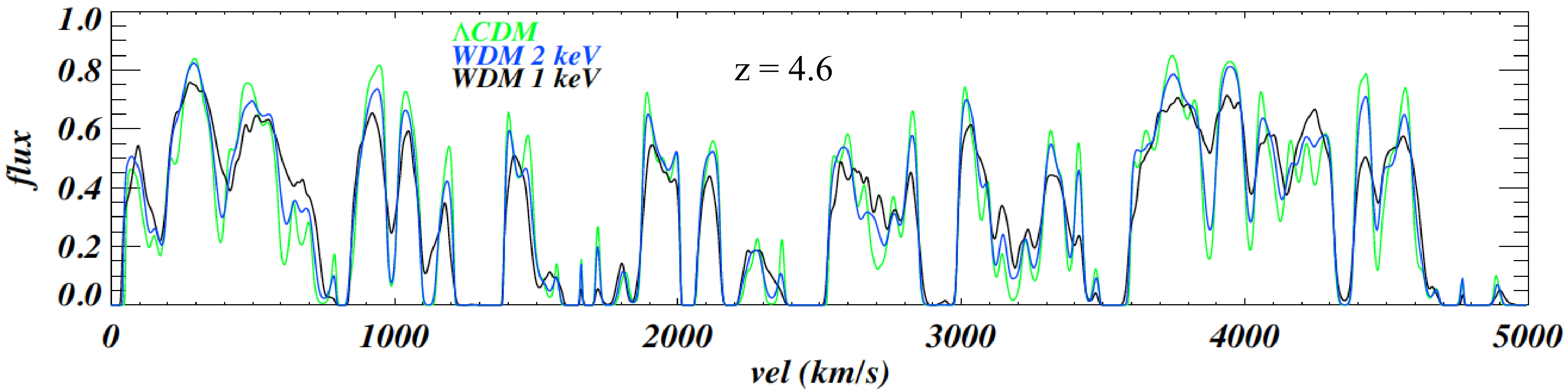


Ly α forest spectra and small-scale initial structure

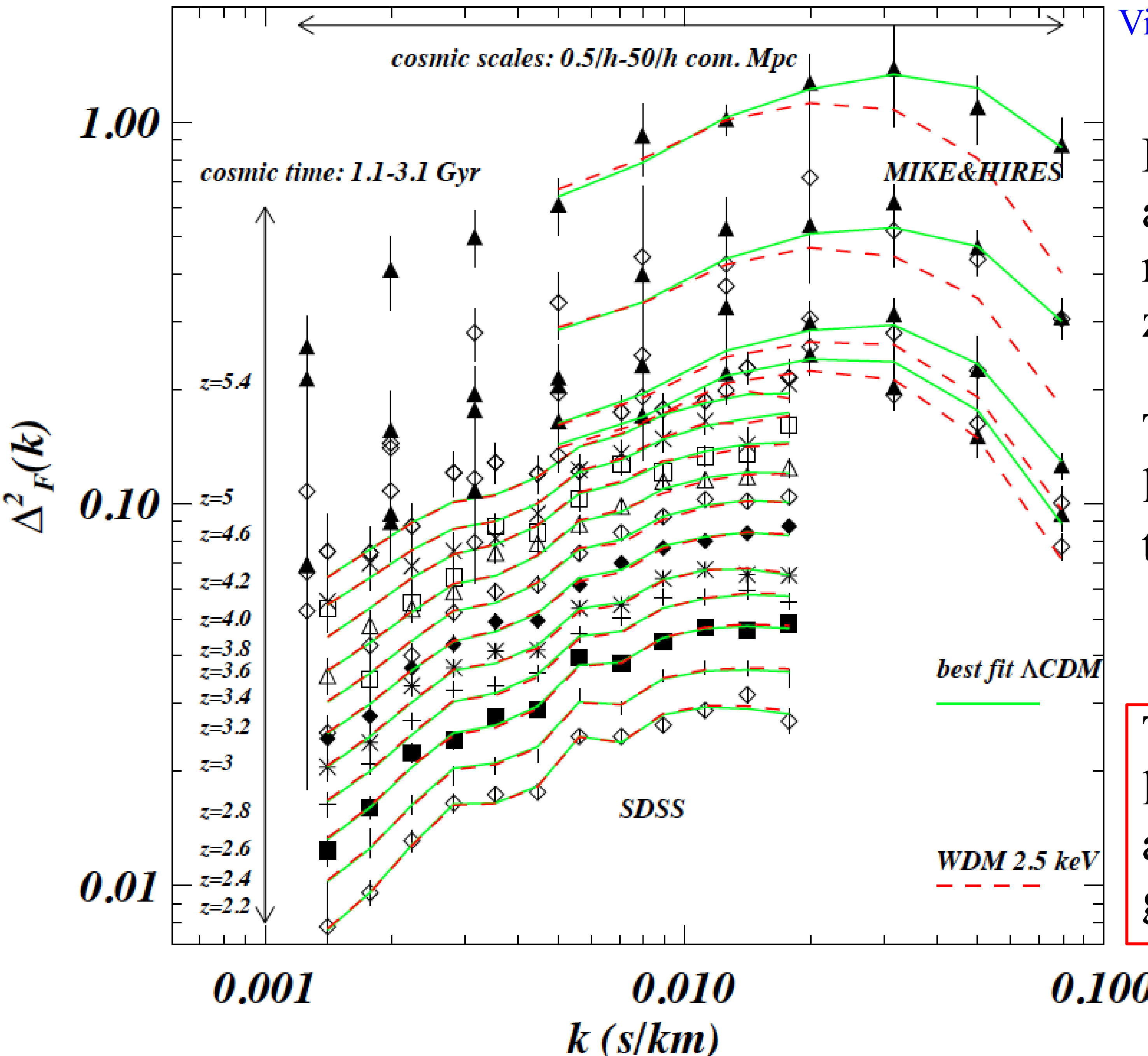
Viel, Becker, Bolton & Haehnelt 2013



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

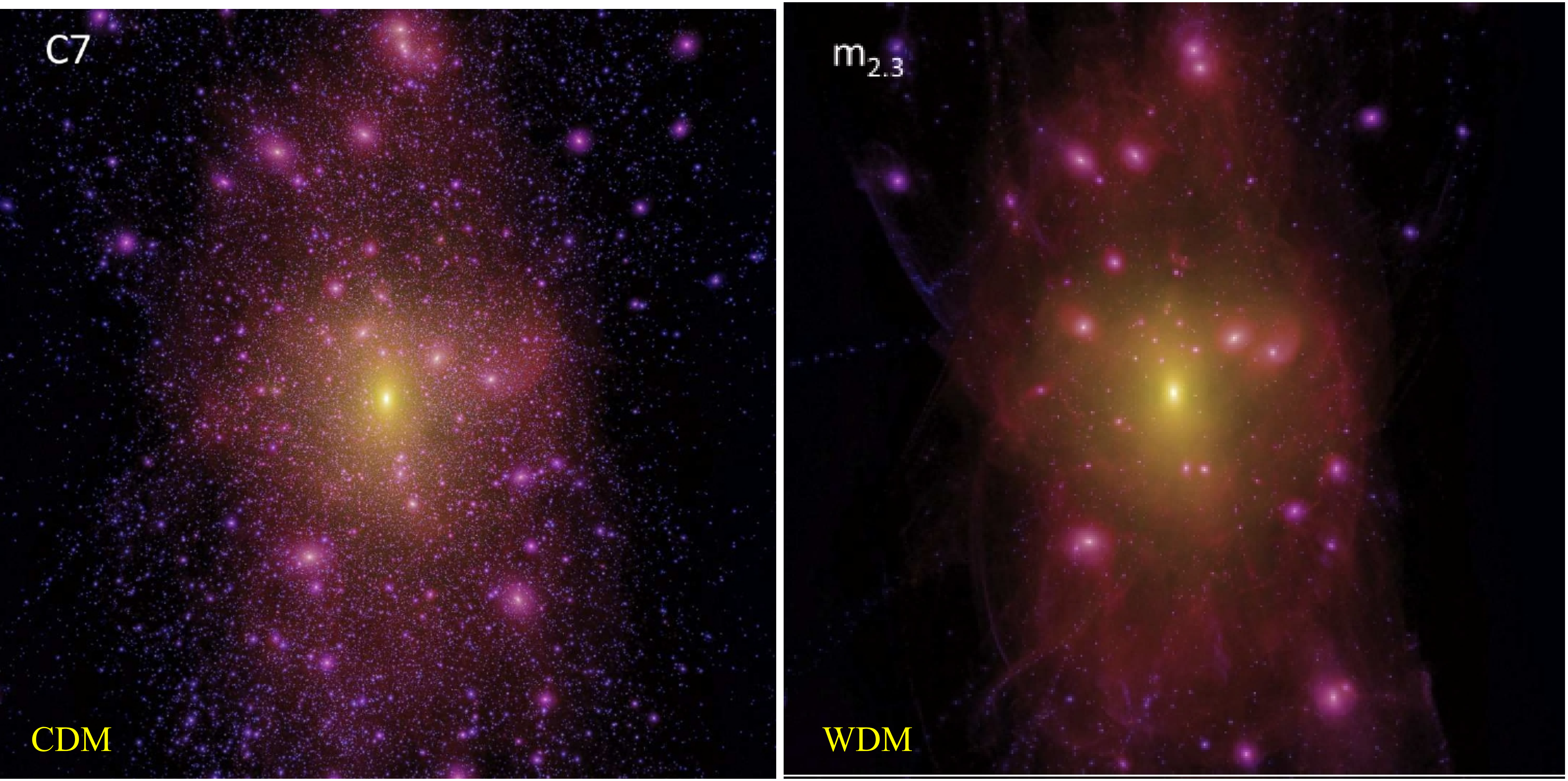
This places a 2σ lower limit on the mass of a thermal relic

$m_{WDM} > 3.3$ keV

This lower limit is too large for WDM to have a big effect on dwarf galaxy structure

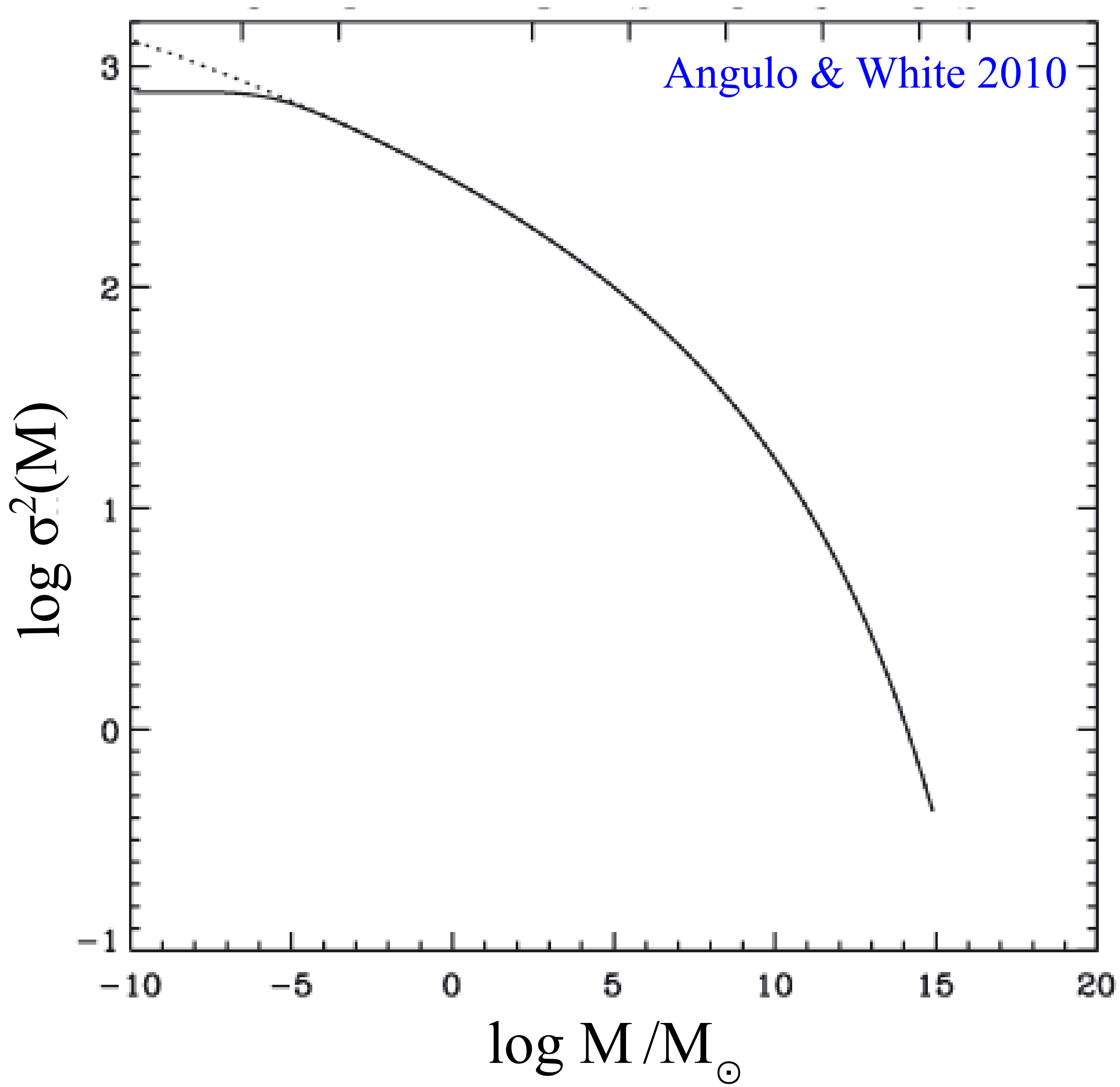
Dark matter effects on galaxy formation?

Lovell et al 2013.



"Milky Way" halos in CDM and WDM. Note, the Ly α forest 2σ lower limit gives a limiting halo mass 3 times *smaller* than assumed here. The IC's are ~ΛCDM on essentially all scales relevant to galaxies

Evolution of the scale of nonlinearity



At late times small-scale structure is nonlinear while large-scales remain "linear"

The (mass) scale of nonlinearity is conventionally defined by

$$\sigma(M_*(z)) = 1.68\, b(z),$$

b(z) is the linear growth factor, σ(M) the *rms* linear fluctuation in spheres of mean mass M

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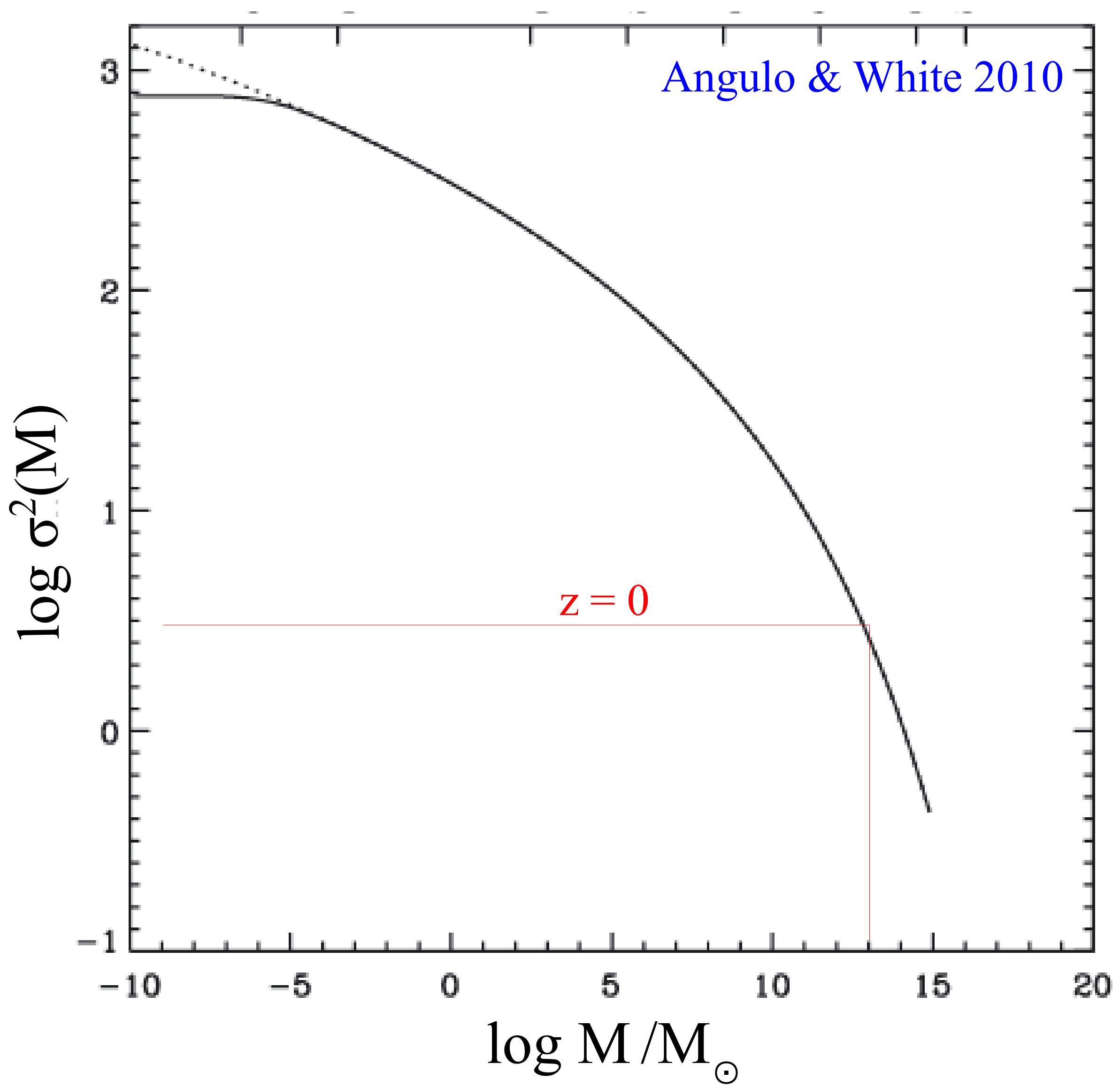

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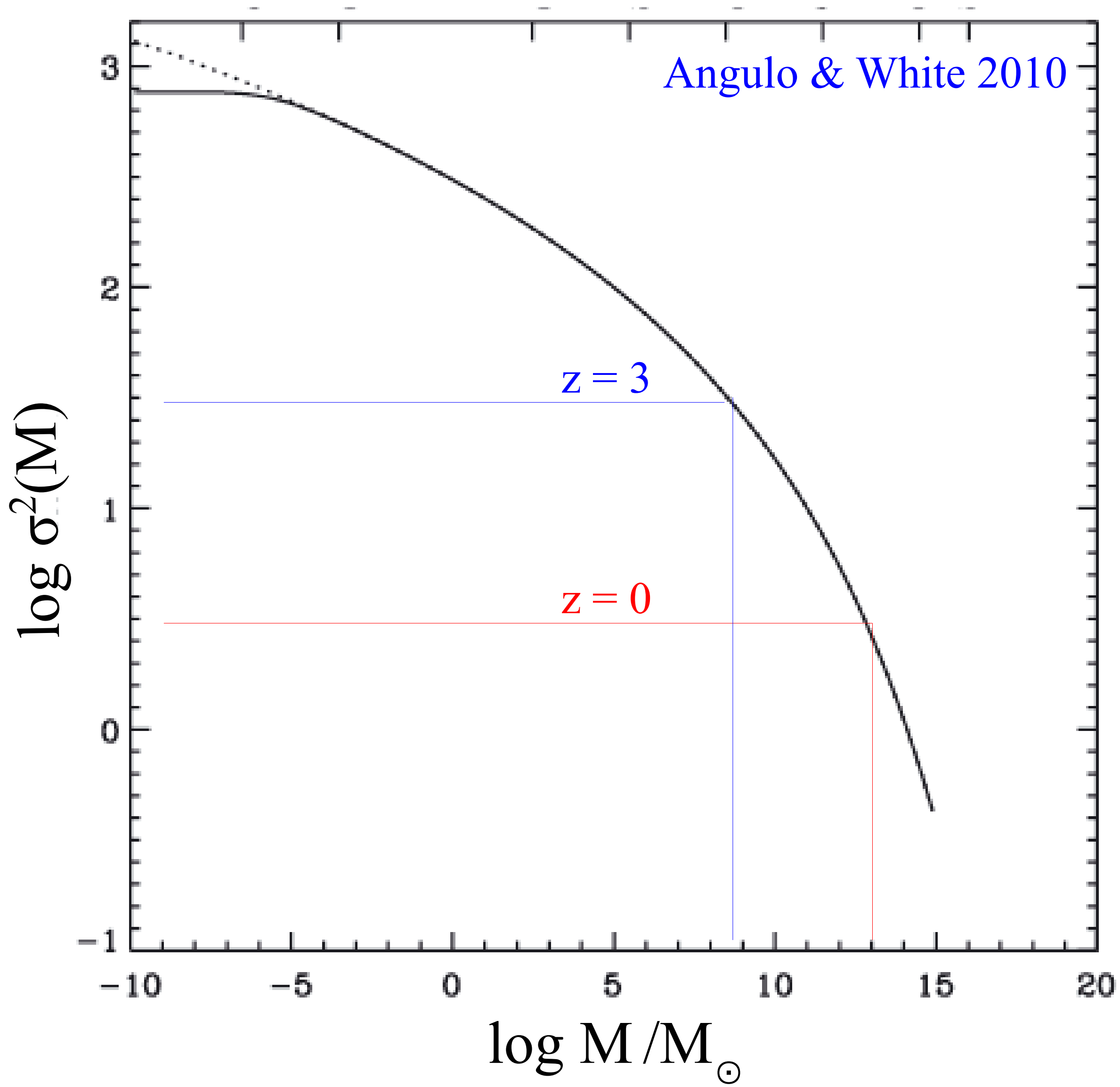

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$\sim$ 9. at z = 3

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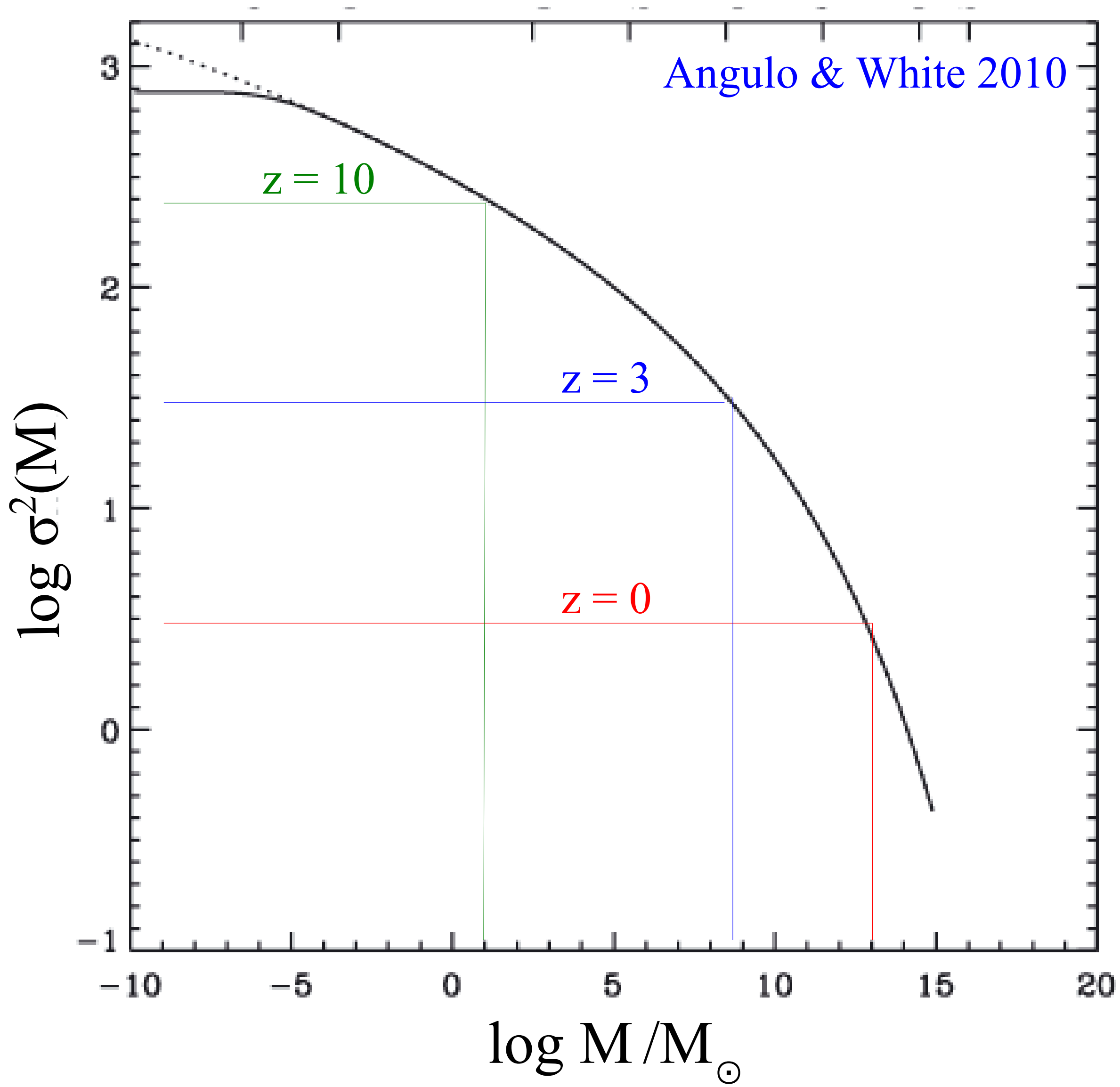

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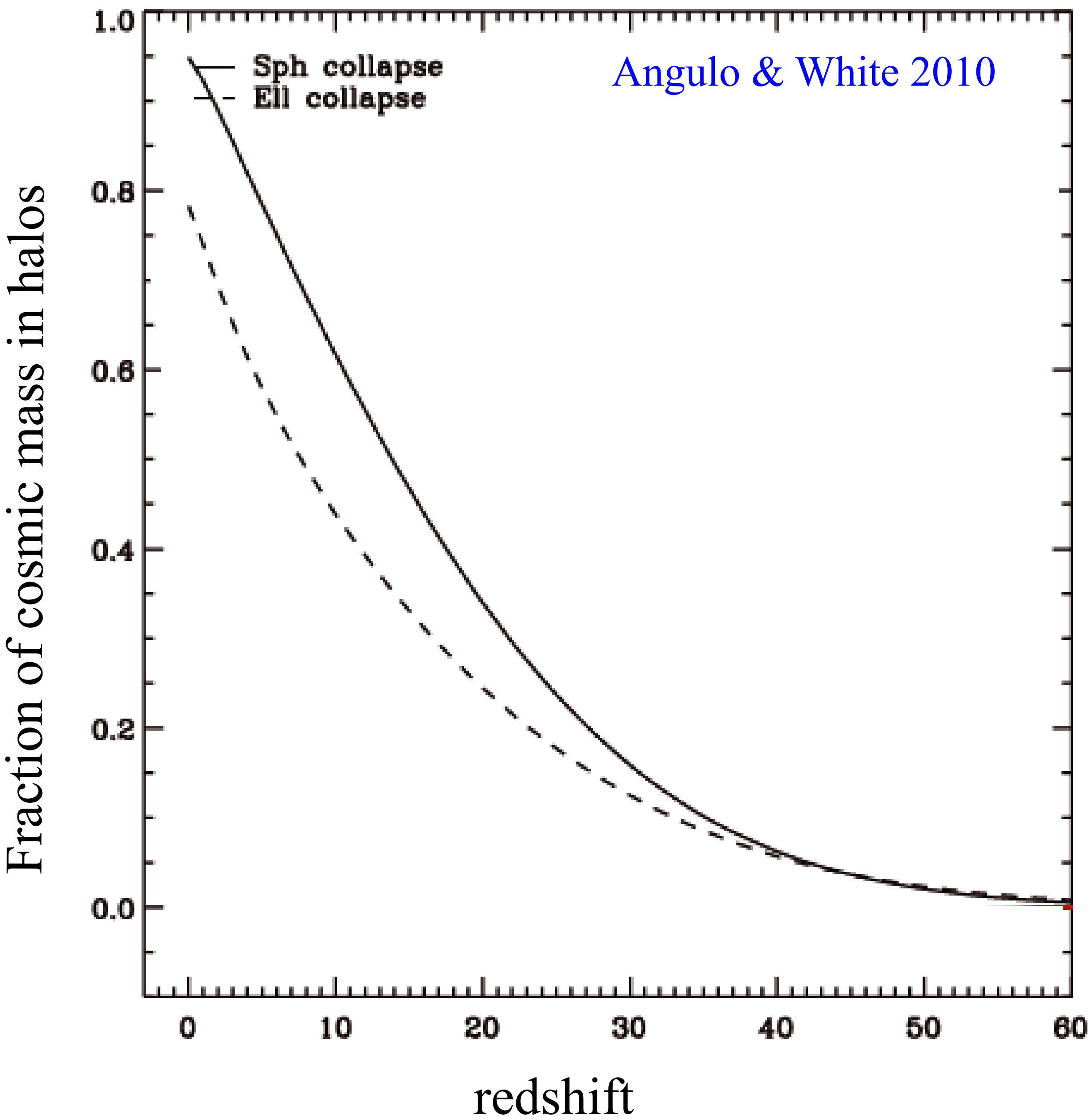
$\sim$ 9. at z = 3

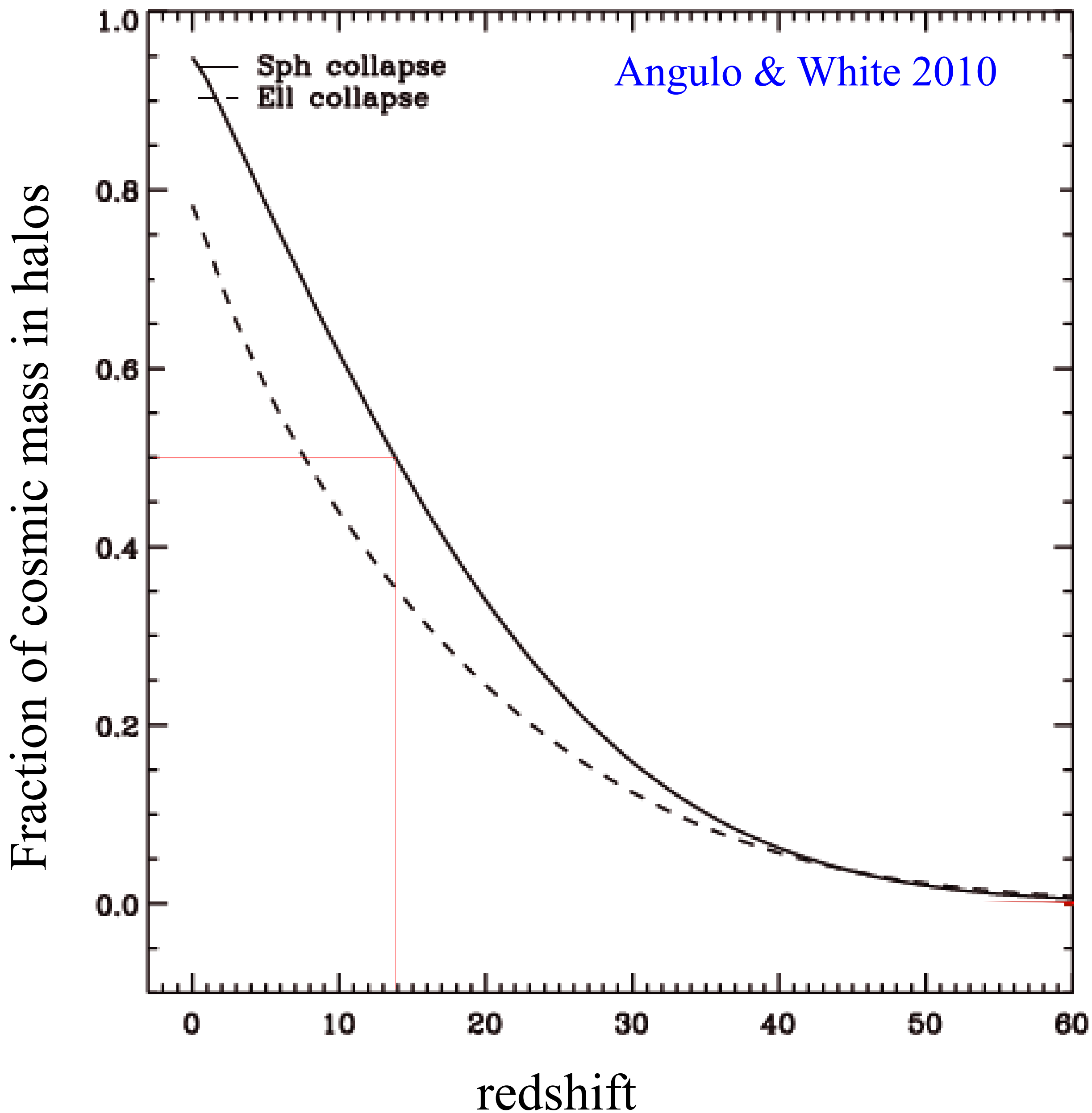
$\sim$ 1. at z = 10

Evolution of the scale of nonlinearity



At high redshift most cosmic mass is not part of <u>any</u> halo, even of Earth mass

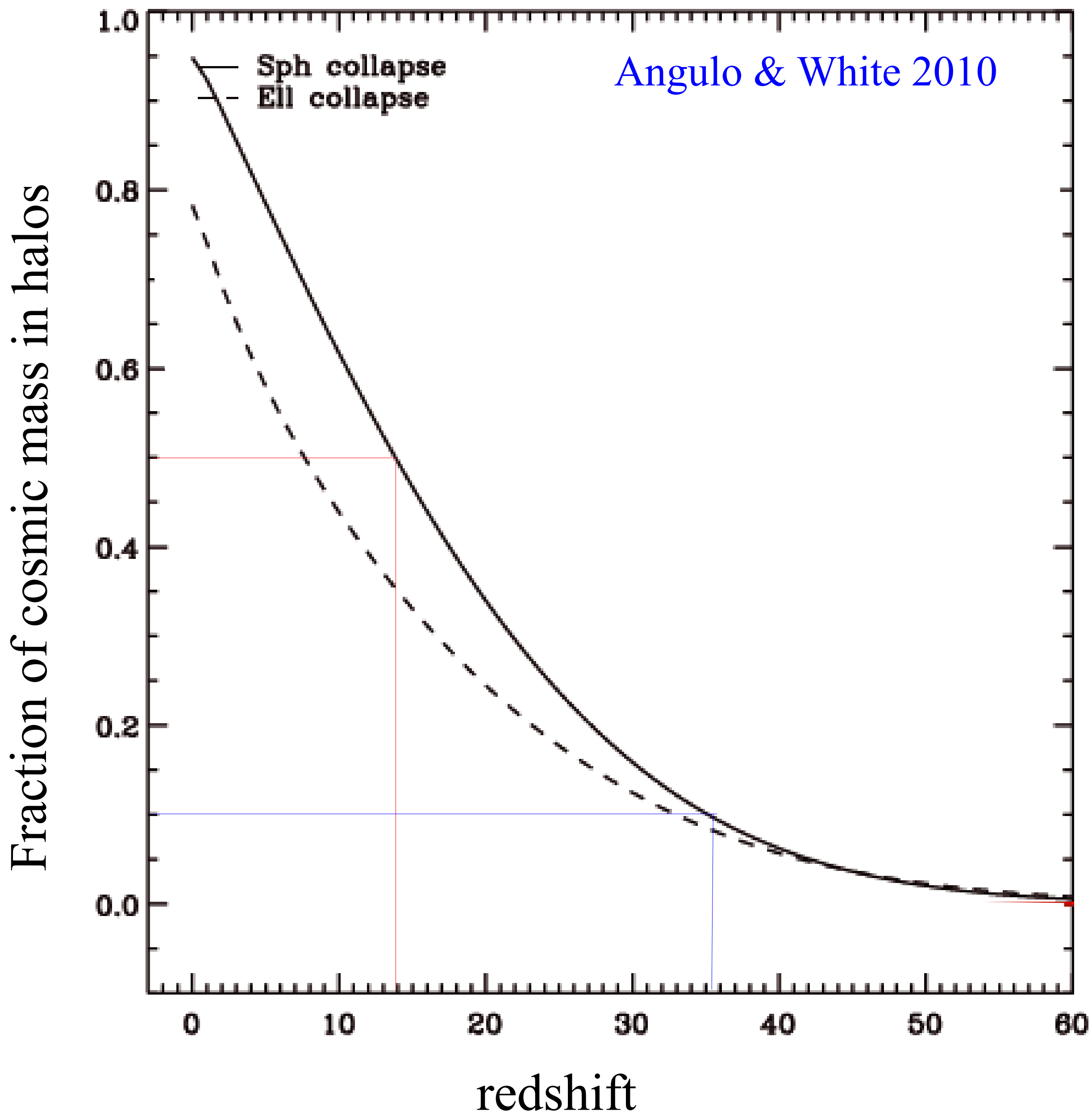
Evolution of the scale of nonlinearity



At high redshift most cosmic mass is not part of any halo, even of Earth mass

At z > 14, more than half of all mass is diffuse

Evolution of the scale of nonlinearity



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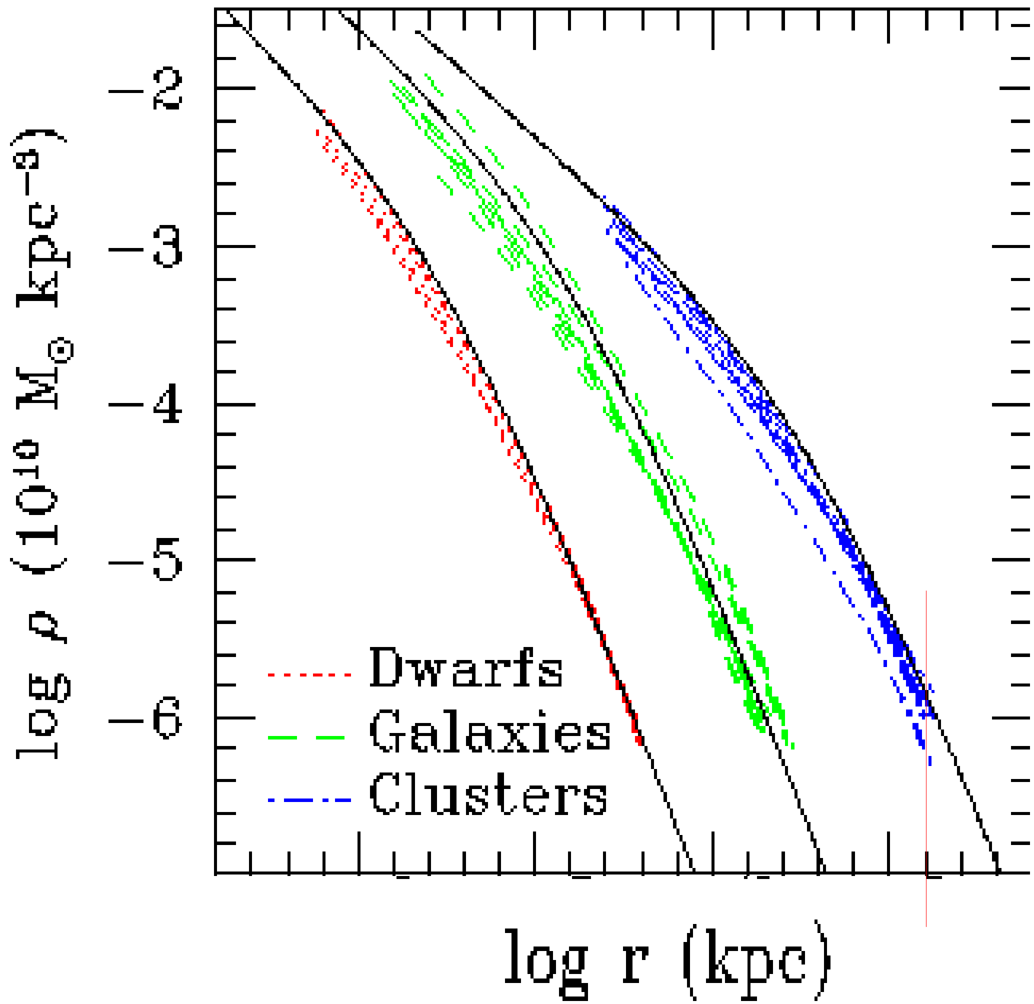
At z > 14, more than half of all mass is diffuse

At z > 35, more than 90% of all mass is diffuse

The characteristic scale of dark matter halos

Navarro, Frenk & White 1996



$N_{200} \sim 7 \times 10^3$

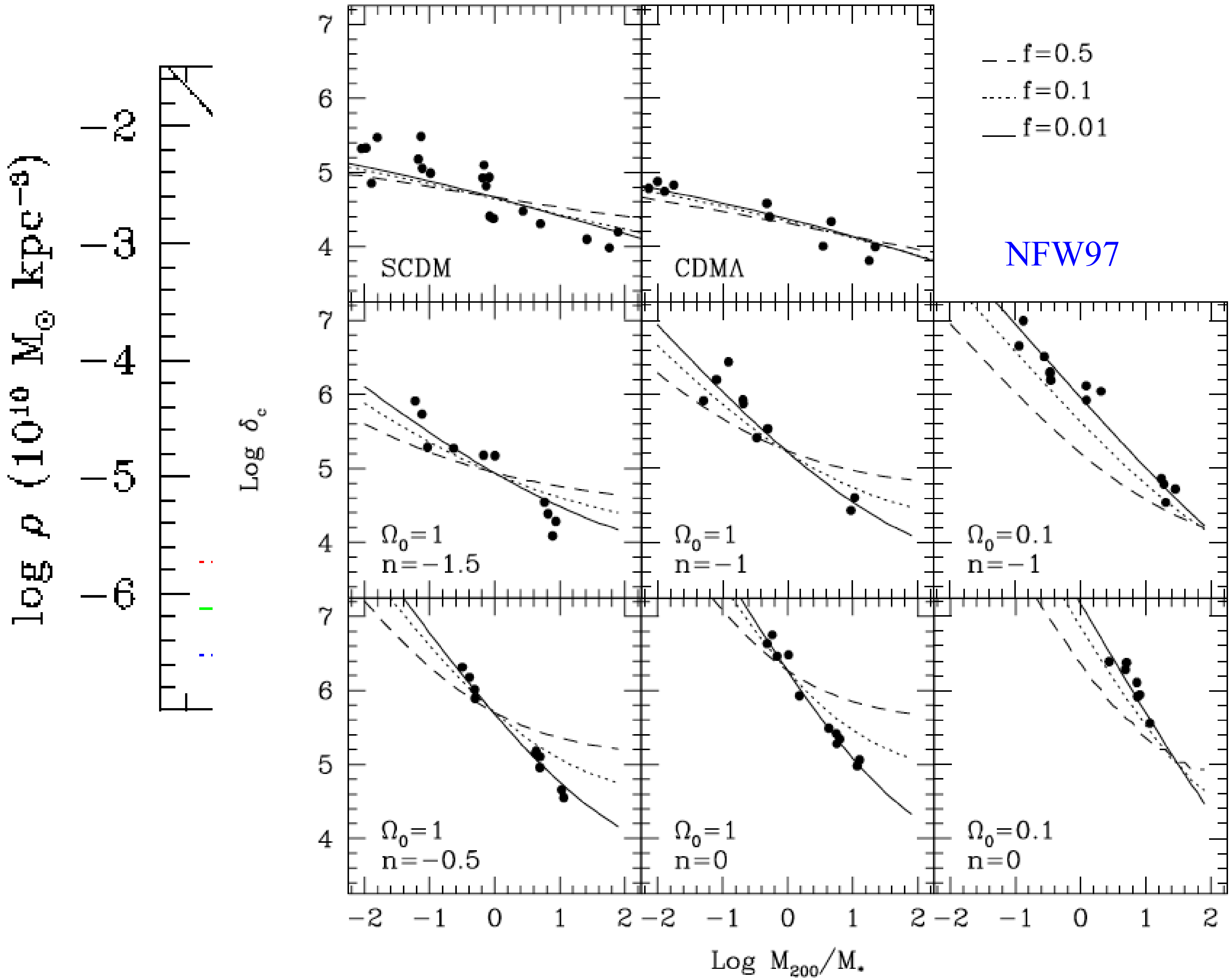
The average dark matter density of a dark halo depends similarly on distance from halo centre in halos of all masses at all times in all cosmologies

-- a universal profile shape --

$$\rho(r)/\rho_{crit} \approx \delta\ r_s / r(1 + r/r_s)^2$$

More massive halos have lower characteristic densities, reflecting a lower cosmic mean density at the time of formation

The characteristic scale of dark matter halos



NFW97

atter density
ds similarly
o centre in
t all times

e shape --

$(1 + r/r_s)^2$

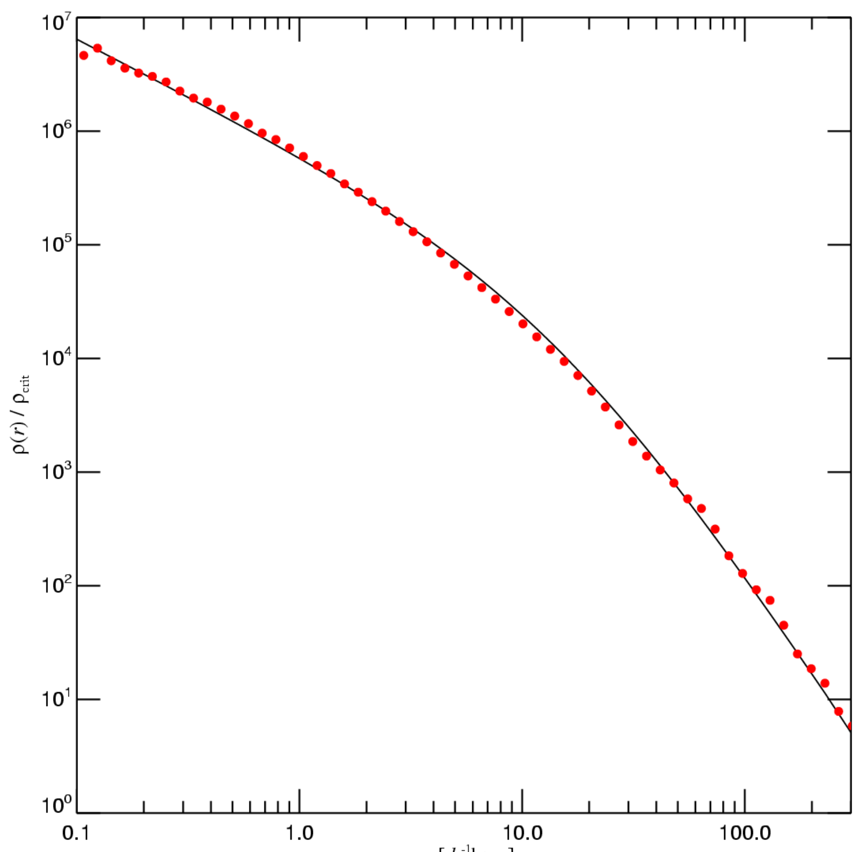
have lower
es,
smic mean
f formation

600 kpc

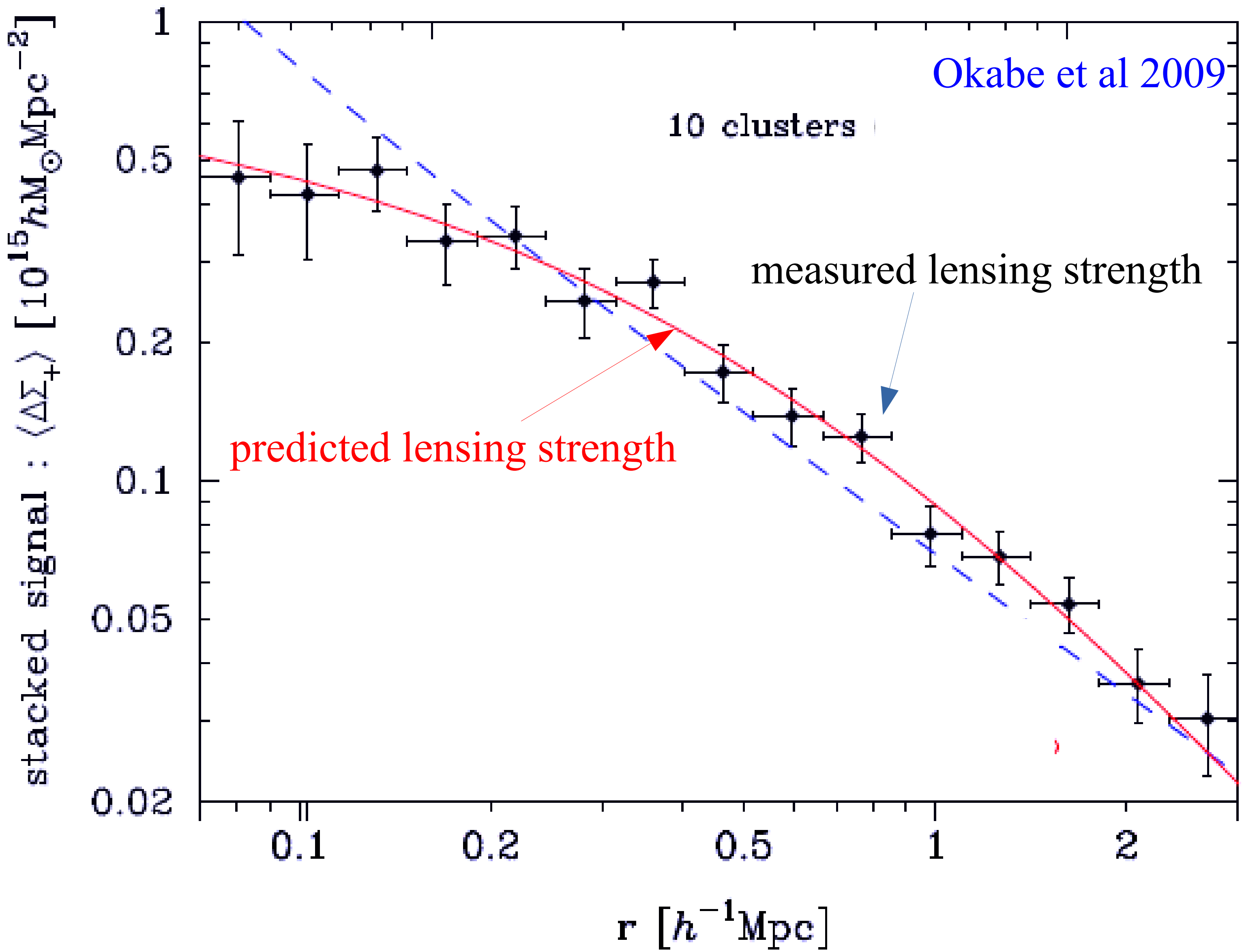
A high-resolution Milky Way halo

Navarro et al 2006

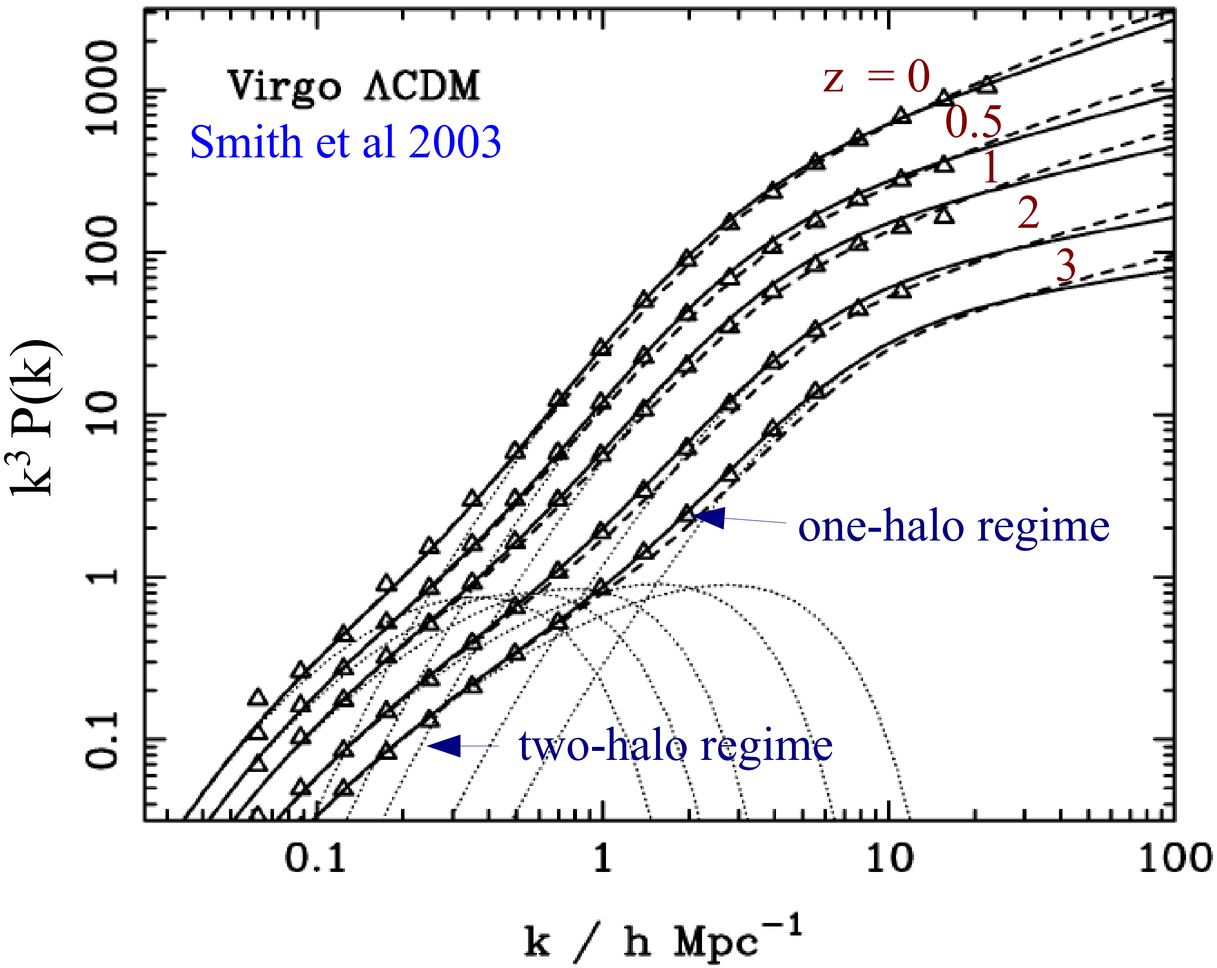
$$N_{200} \sim 3 \times 10^7$$



Comparison of lensing strength measured around real galaxy clusters to that predicted by simulations of structure formation



The nonlinear scale in the overall mass distribution

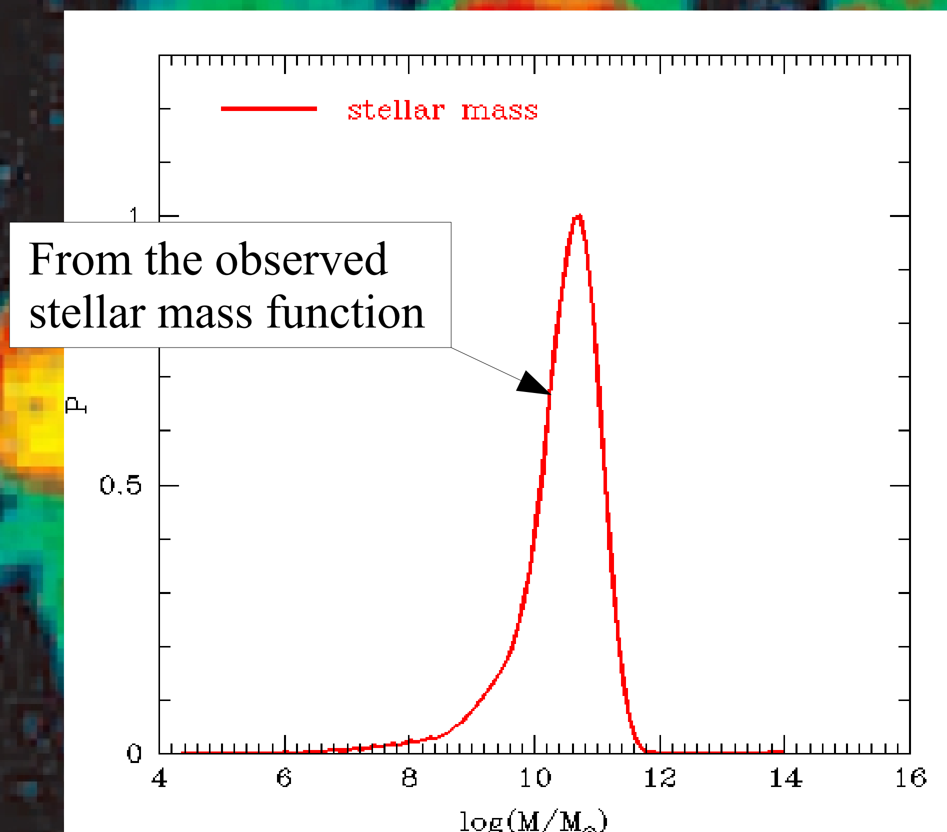


When cosmic structure is characterised using P(k) or ξ(r), small scales are dominated by the internal structure of halos and large scales by the spatial distribution of halos

The transition is quite gentle in such 2-point statistics

A sharp characteristic scale for galaxies

Most stars are in galaxies similar in mass to the Milky Way



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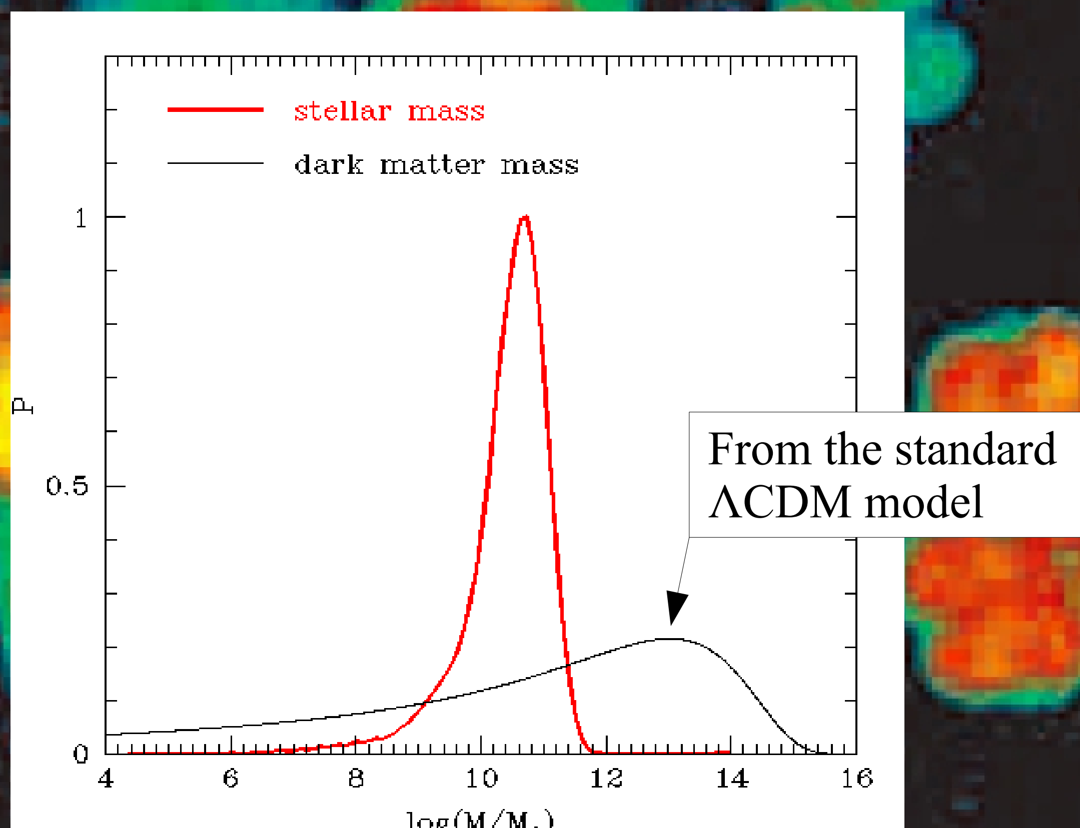
Dark matter is *much* more broadly distributed across halos



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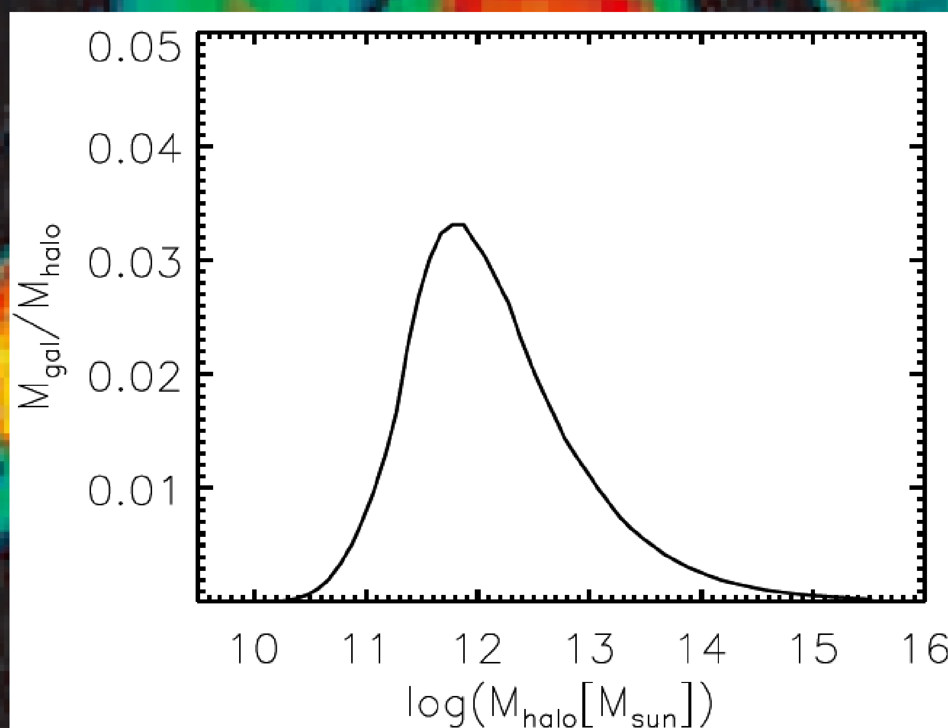
→ Galaxy to halo mass ratio varies *strongly* with mass

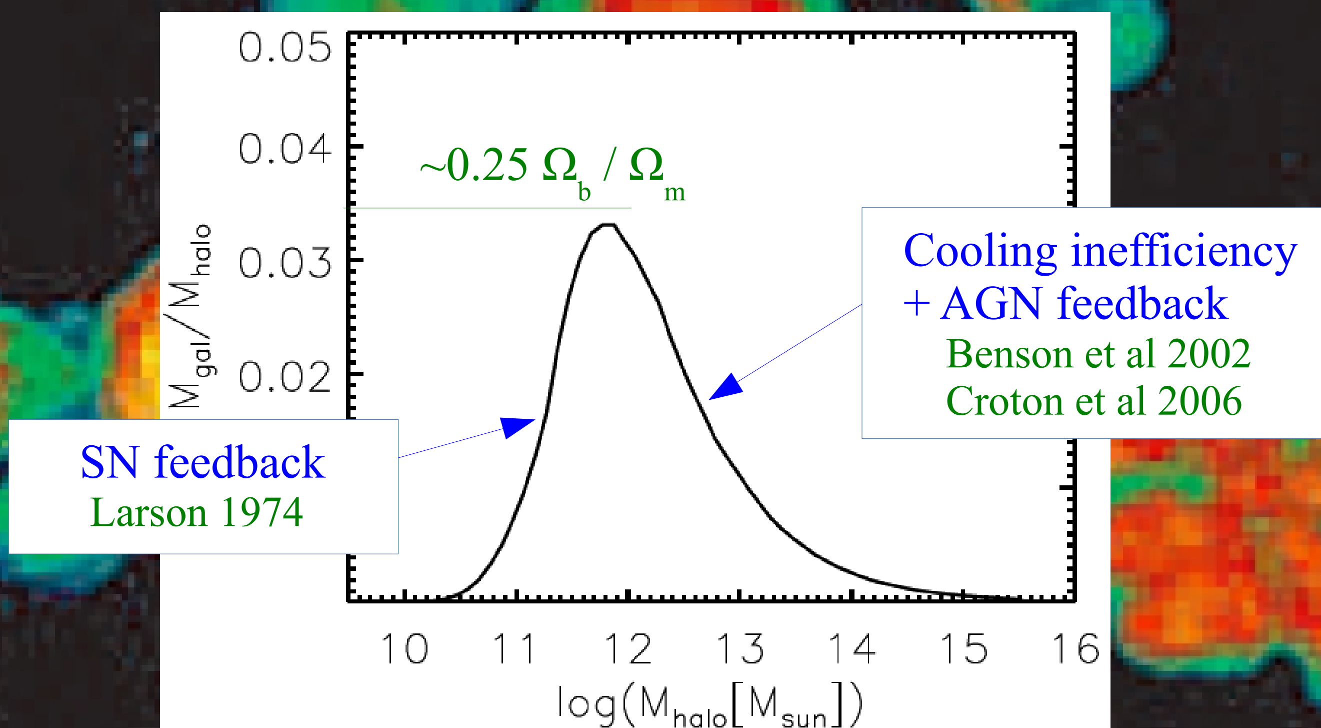


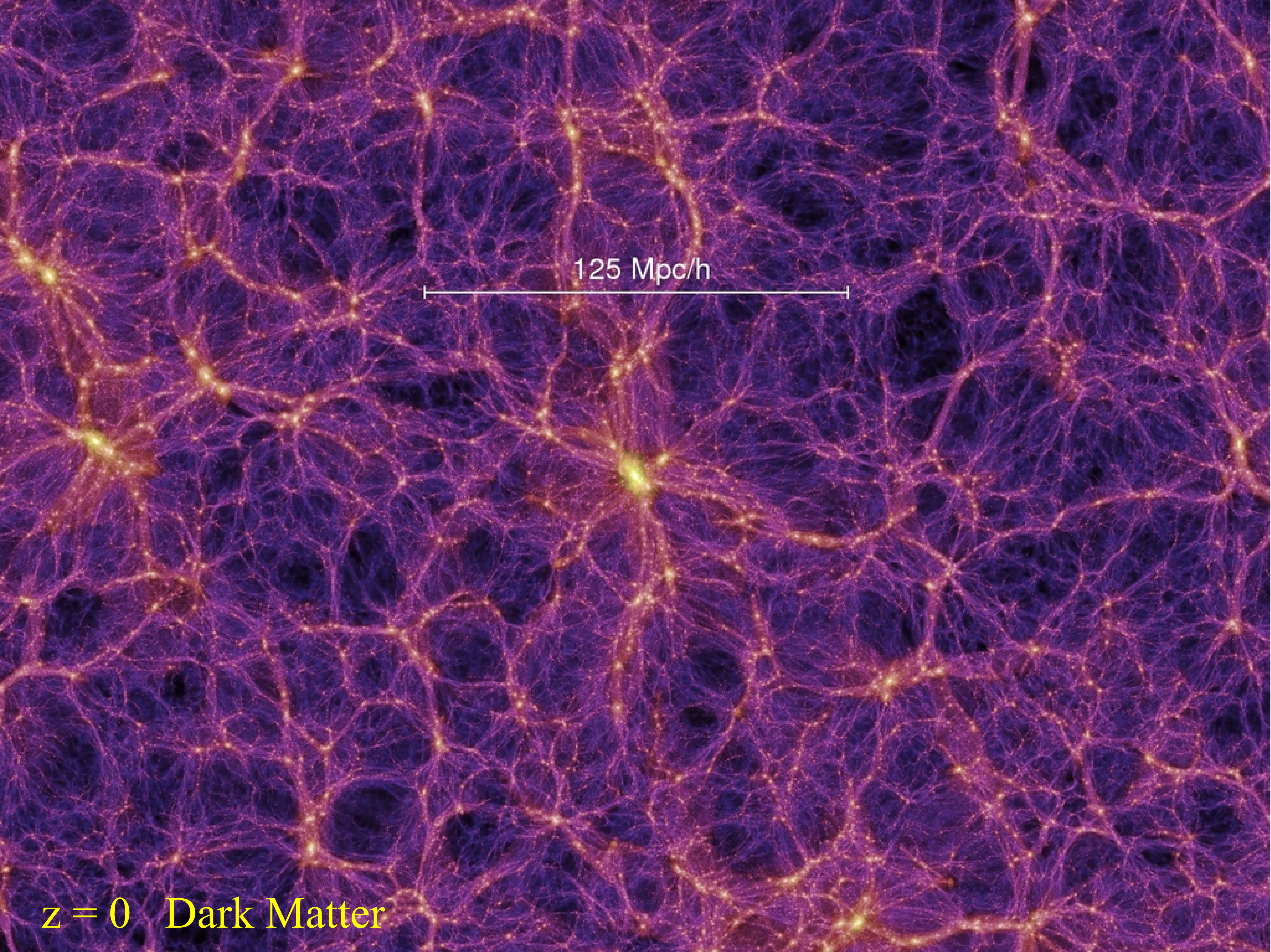
A sharp characteristic scale for galaxies

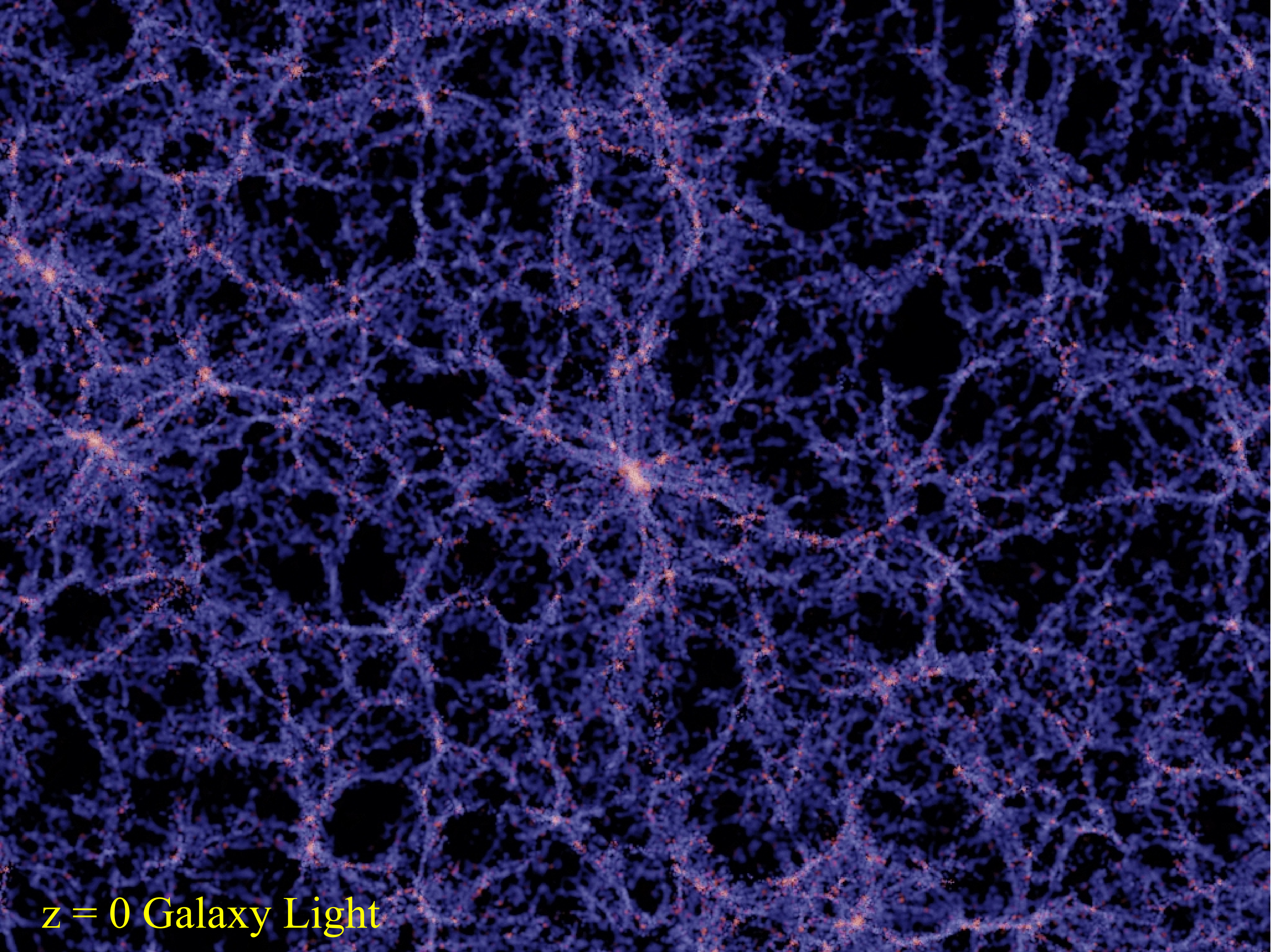
Most stars are in galaxies similar in mass to the Milky Way
Dark matter is *much* more broadly distributed across halos

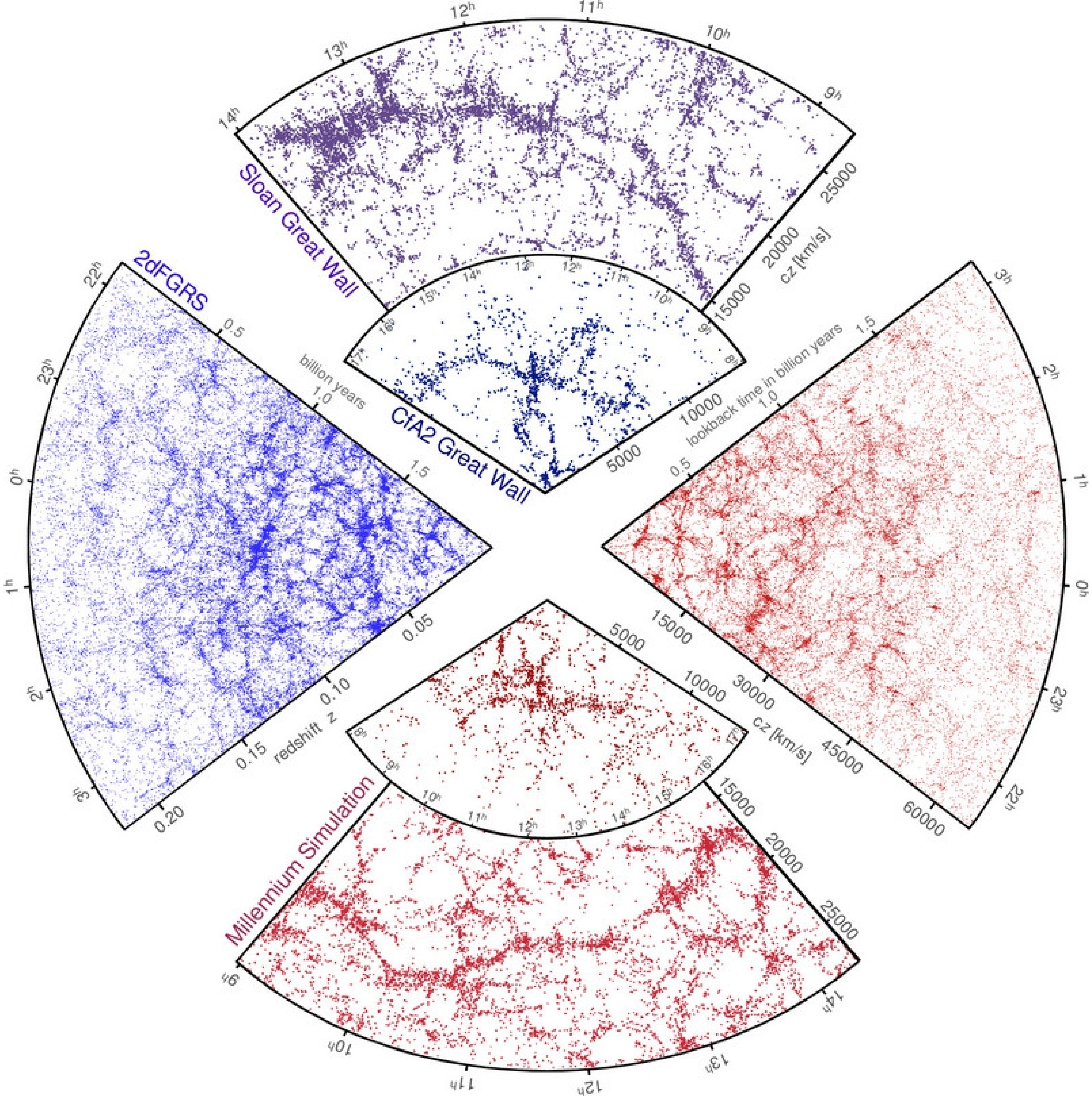
→ Halo to galaxy mass ratio varies *strongly* with mass

Star formation efficiency is reduced at both low *and* high halo mass



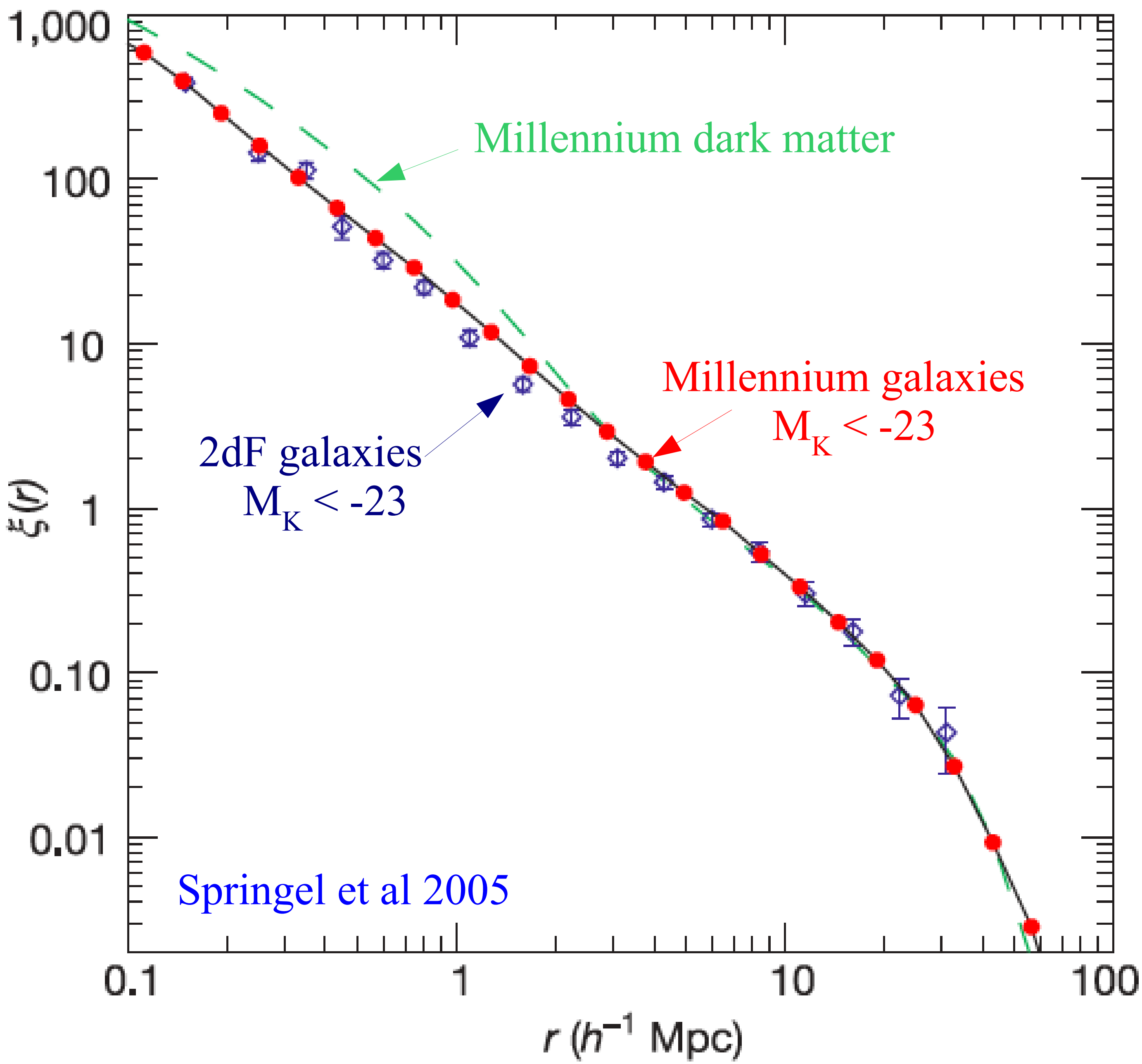

125 Mpc/h
z = 0 Dark Matter


z = 0 Galaxy Light



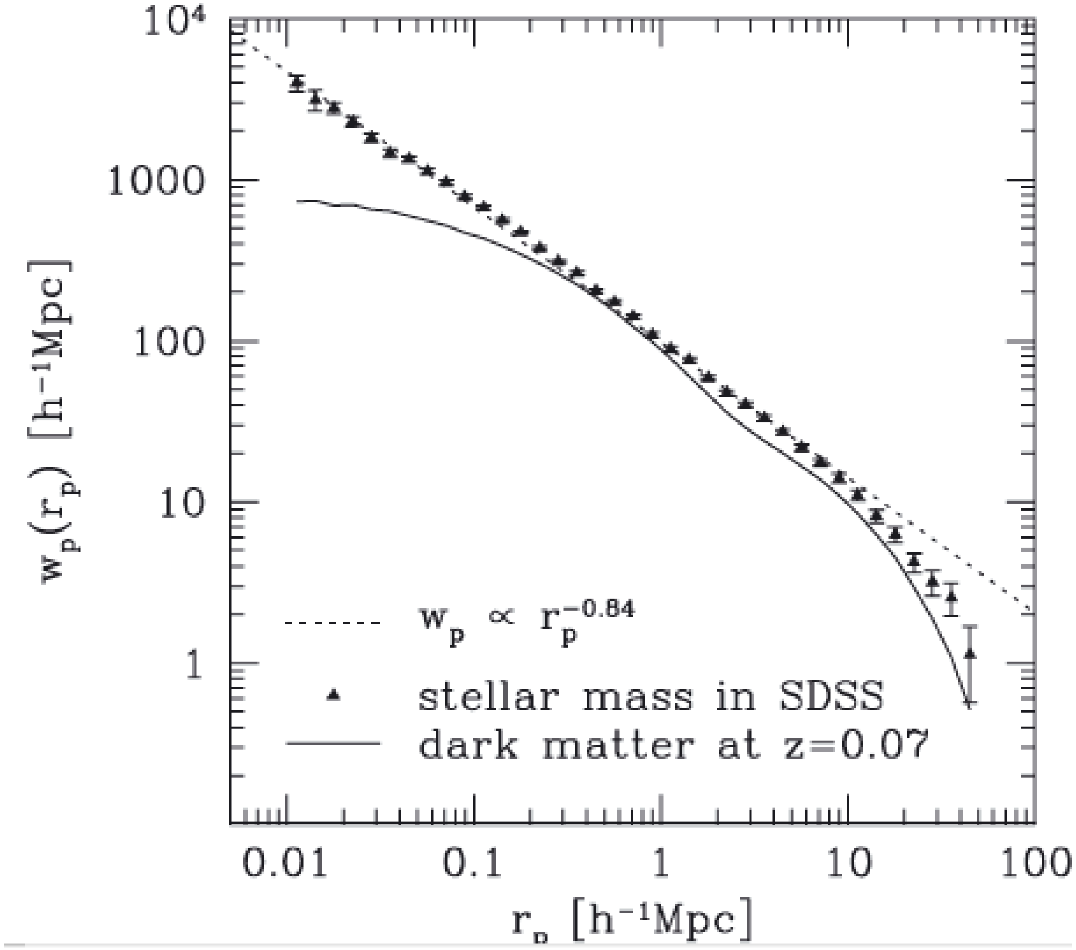
Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
cz [km/s]
billion years
lookback time in billion years
redshift z

The nonlinear scale in the galaxy distribution?



The nonlinear scale in the galaxy distribution?

Li & White 2009



In the present universe, the auto-correlation of stellar mass is very close to a power law over <u>three orders of magnitude</u> in spatial scale

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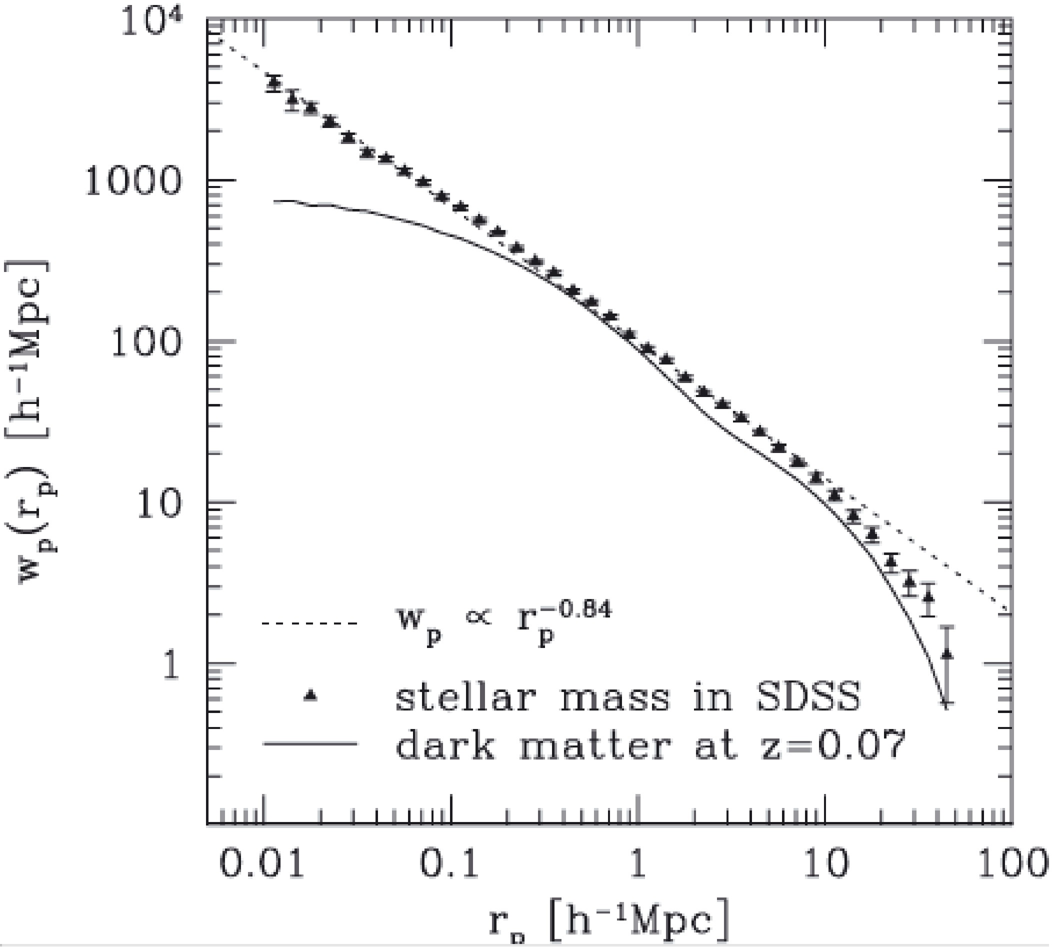

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The predicted function for dark matter is <u>far</u> from a power law over this same range of scales

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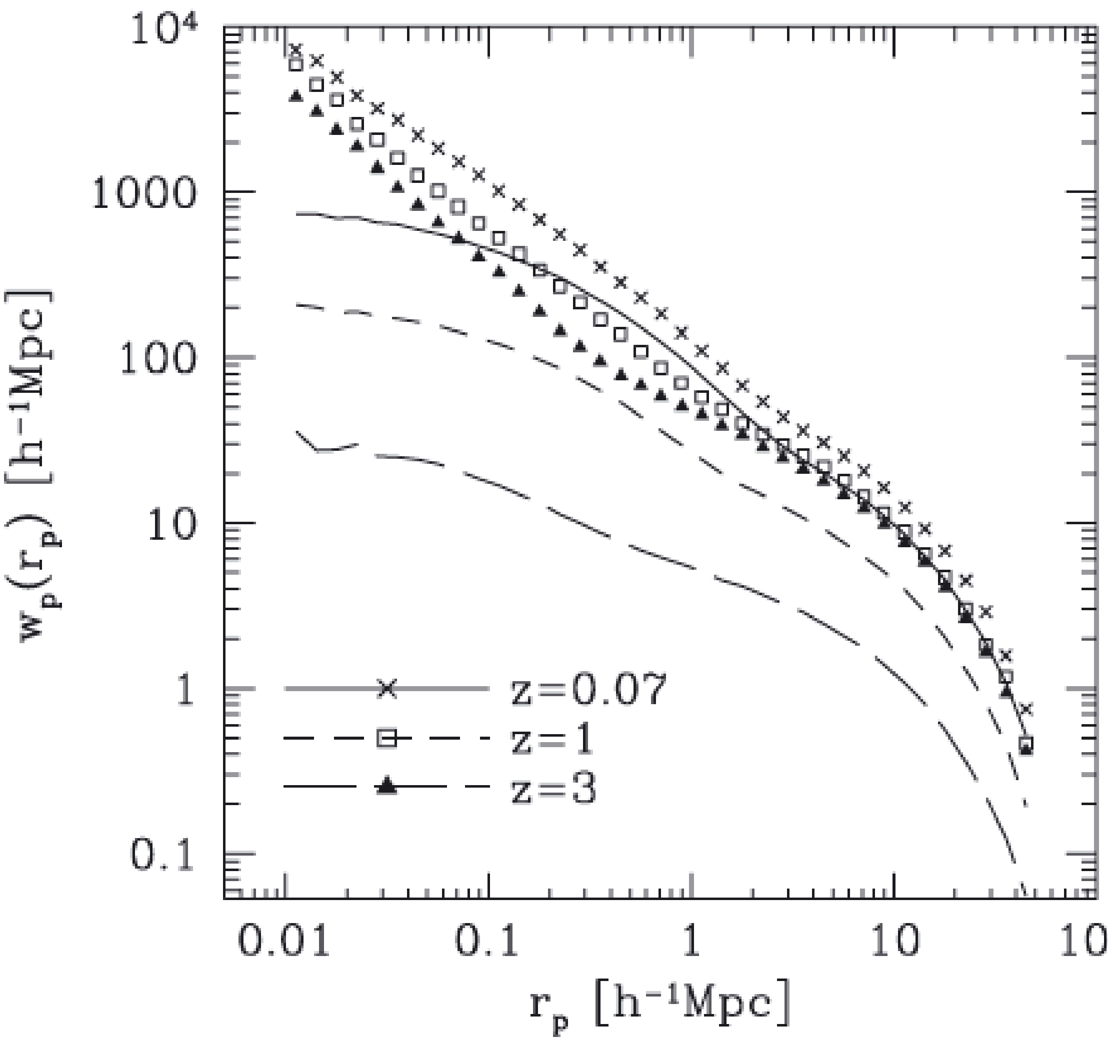

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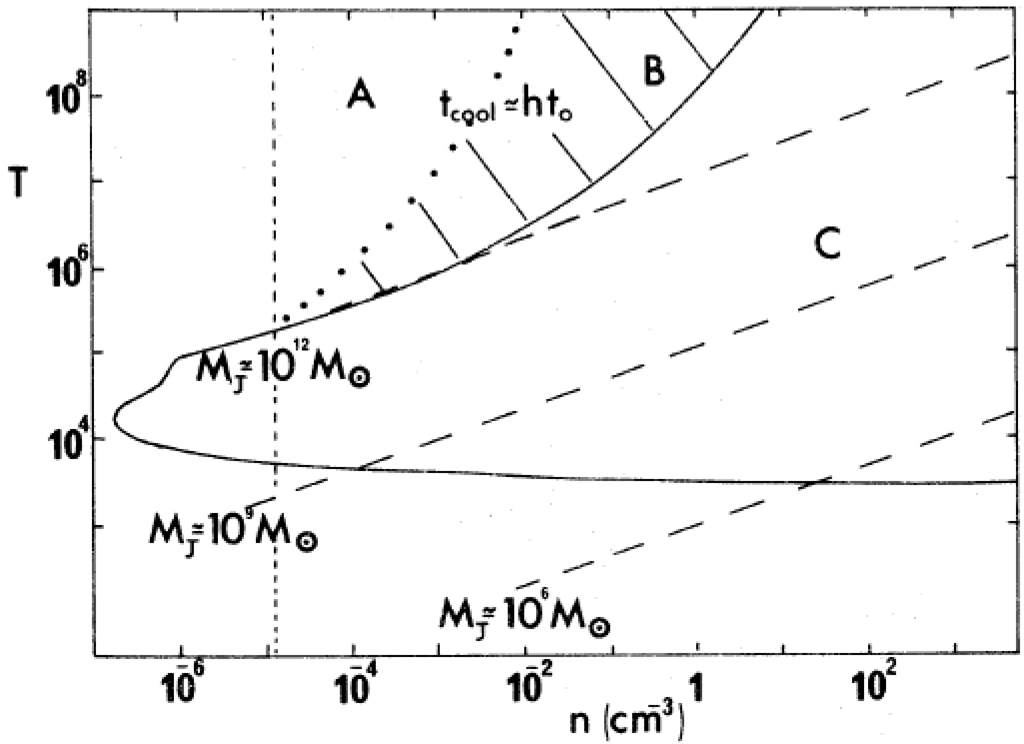
The predicted function for dark matter is <u>far</u> from a power law over this same range of scales

Simulations predict the power law for stellar mass <u>only</u> at z = 0

Apparently it's a coincidence!

The origin of the galaxy scale



Rees & Ostriker 1977
Silk 1977
Binney 1977

When gas clouds of galactic mass collapse:

(i) shocks are radiative and collapse unimpeded, when $t_{cool} < t_{dyn}$

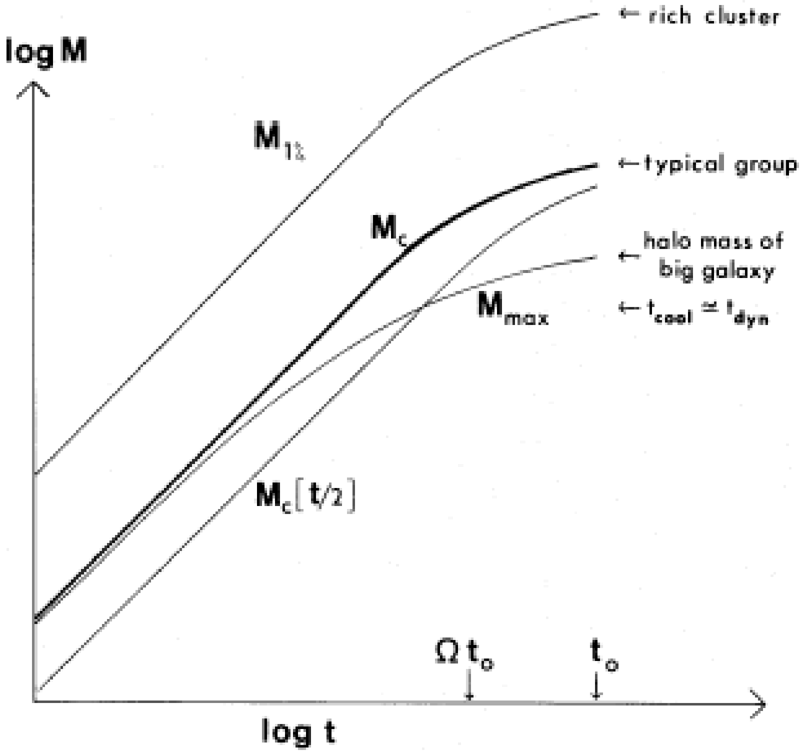
(ii) shocks are non-radiative and collapse arrested, when $t_{cool} > t_{dyn}$

where quantities are estimated at virial equilibrium

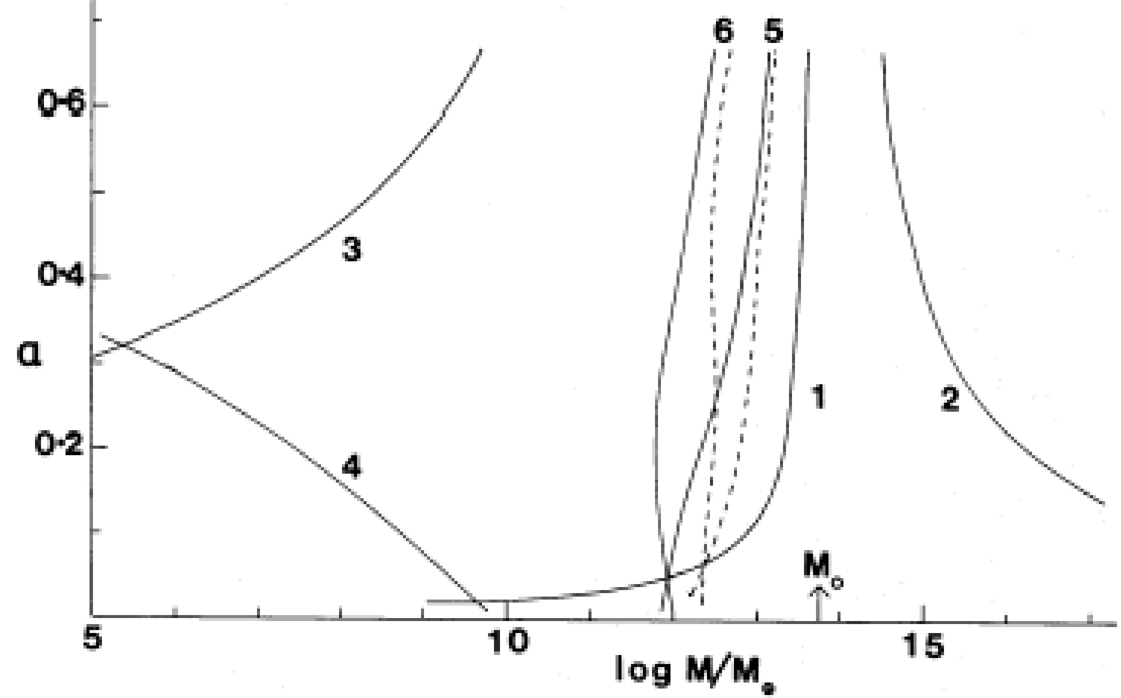
Galaxies form in case (i) since fragmentation is possible

Primordial cooling curve → characteristic mass $\sim 10^{12}\,M_\odot$

Towards a “modern” theory



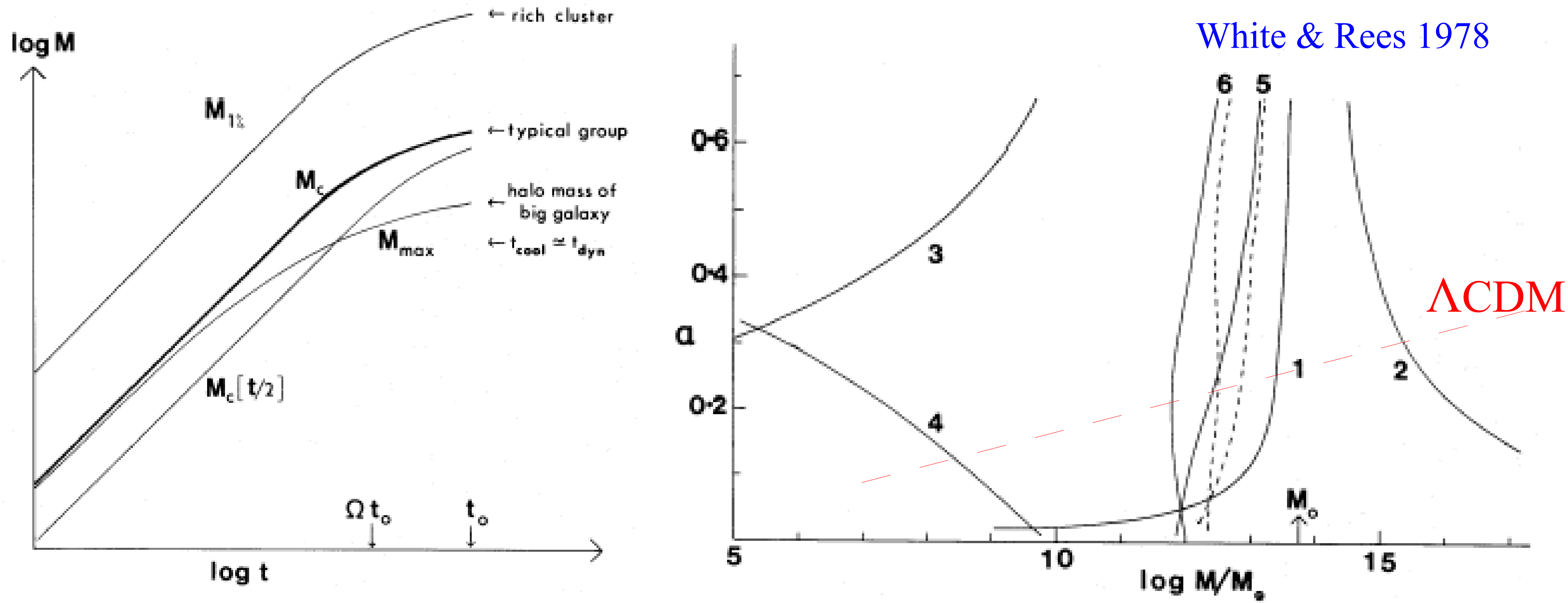
White & Rees 1978



Adding : (i) dark matter, (ii) hierarchical clustering, (iii) feedback
- -- cooling always rapid for small masses and early times
- -- only biggest galaxies sit in cooling flows
- -- feedback *à la* Larson (1974) needed to suppress small galaxies

A good model: $\Omega_m = 0.20$, $\Omega_{gas} / \Omega_{DM} = 0.20$, $\alpha = 1/3$ (n = -1)

Towards a "modern" theory



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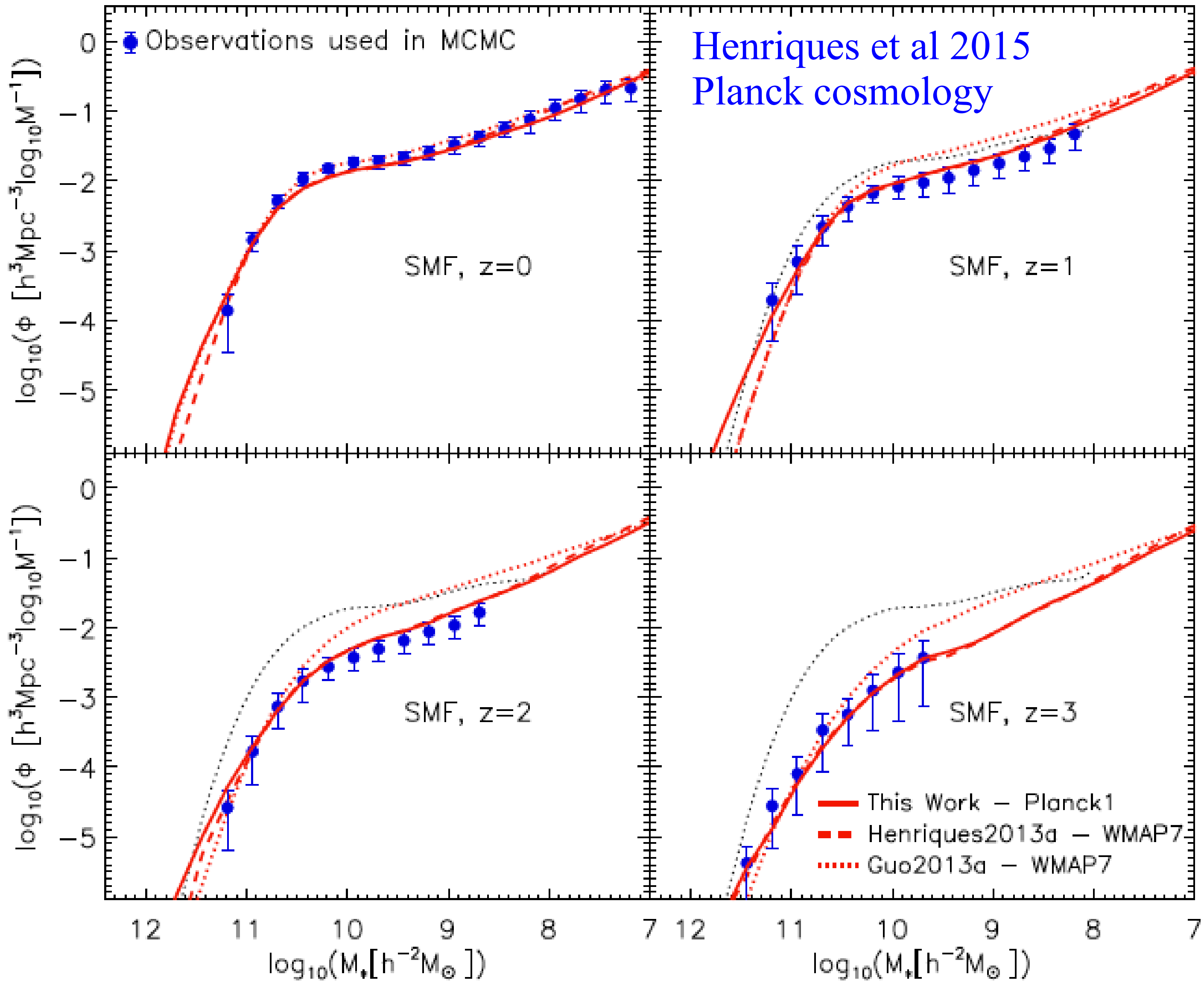
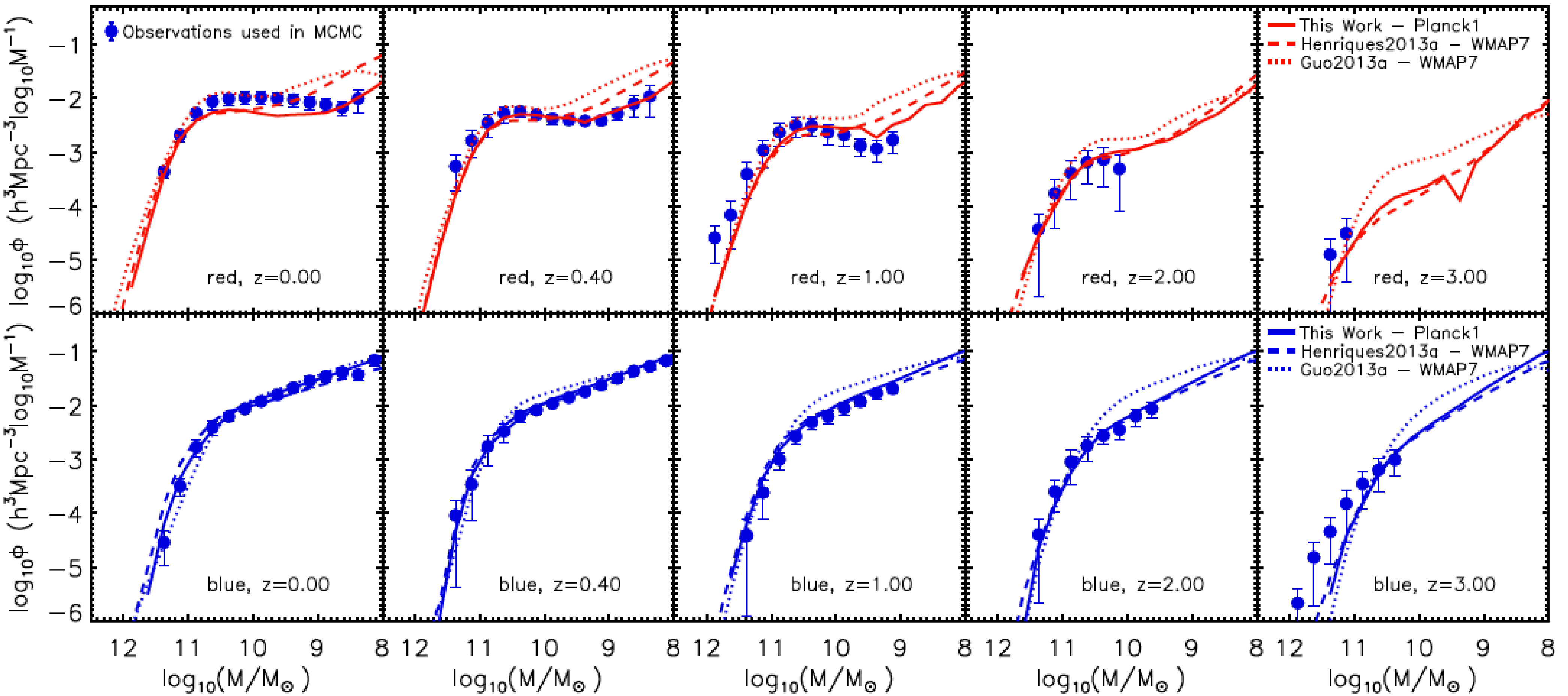


Changing the assumed timescale for reincorporation of wind ejecta

$$t_{\mathrm{return}} = \mathrm{const.} / H(z)\, V_{\mathrm{halo}} \longrightarrow t_{\mathrm{return}} = \mathrm{const.} / M_{\mathrm{halo}}$$

allows a good fit to data at all redshifts for the same # of parameters

Henriques et al 2015, Planck cosmology



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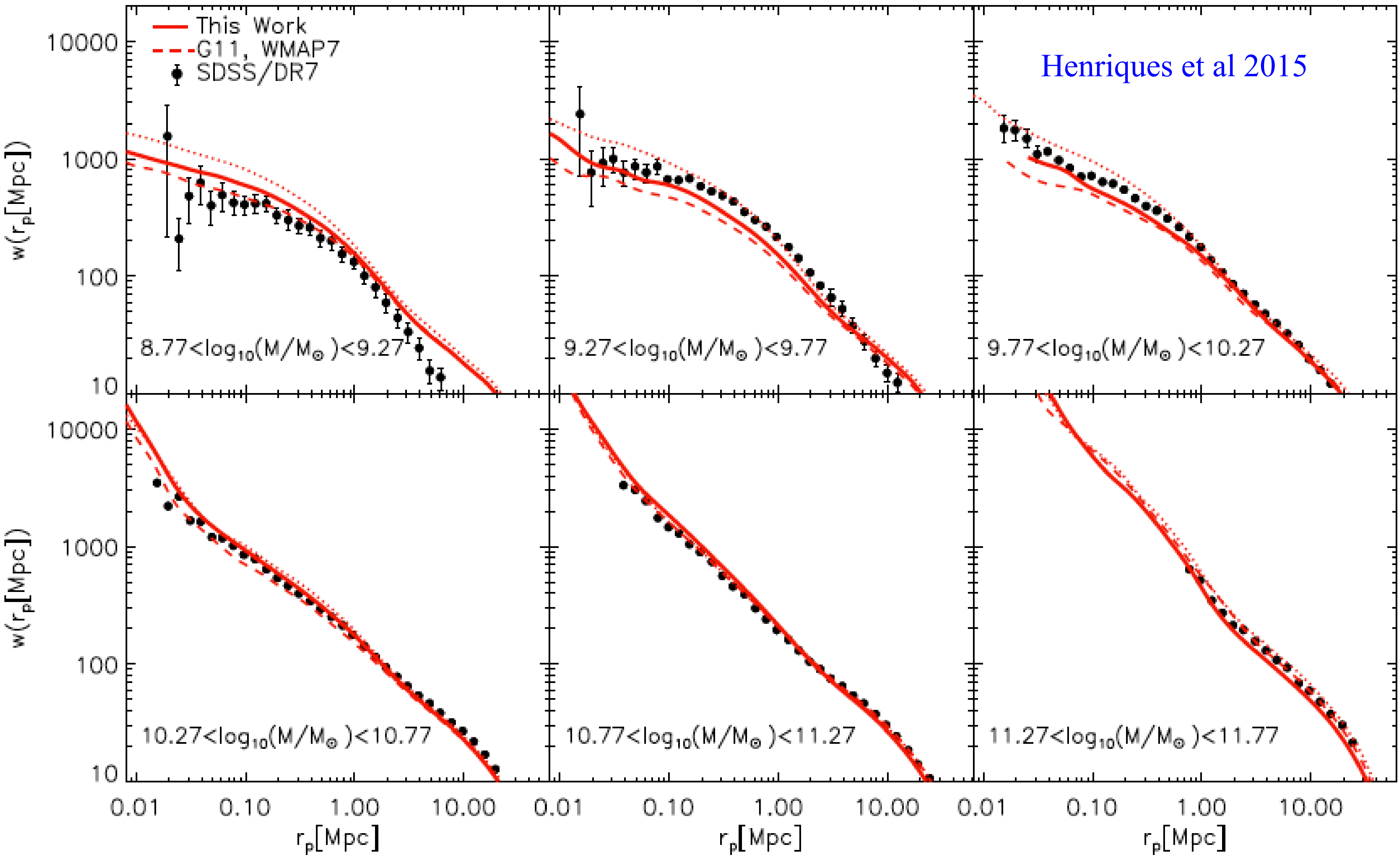
Clustering predictions of the new simulations



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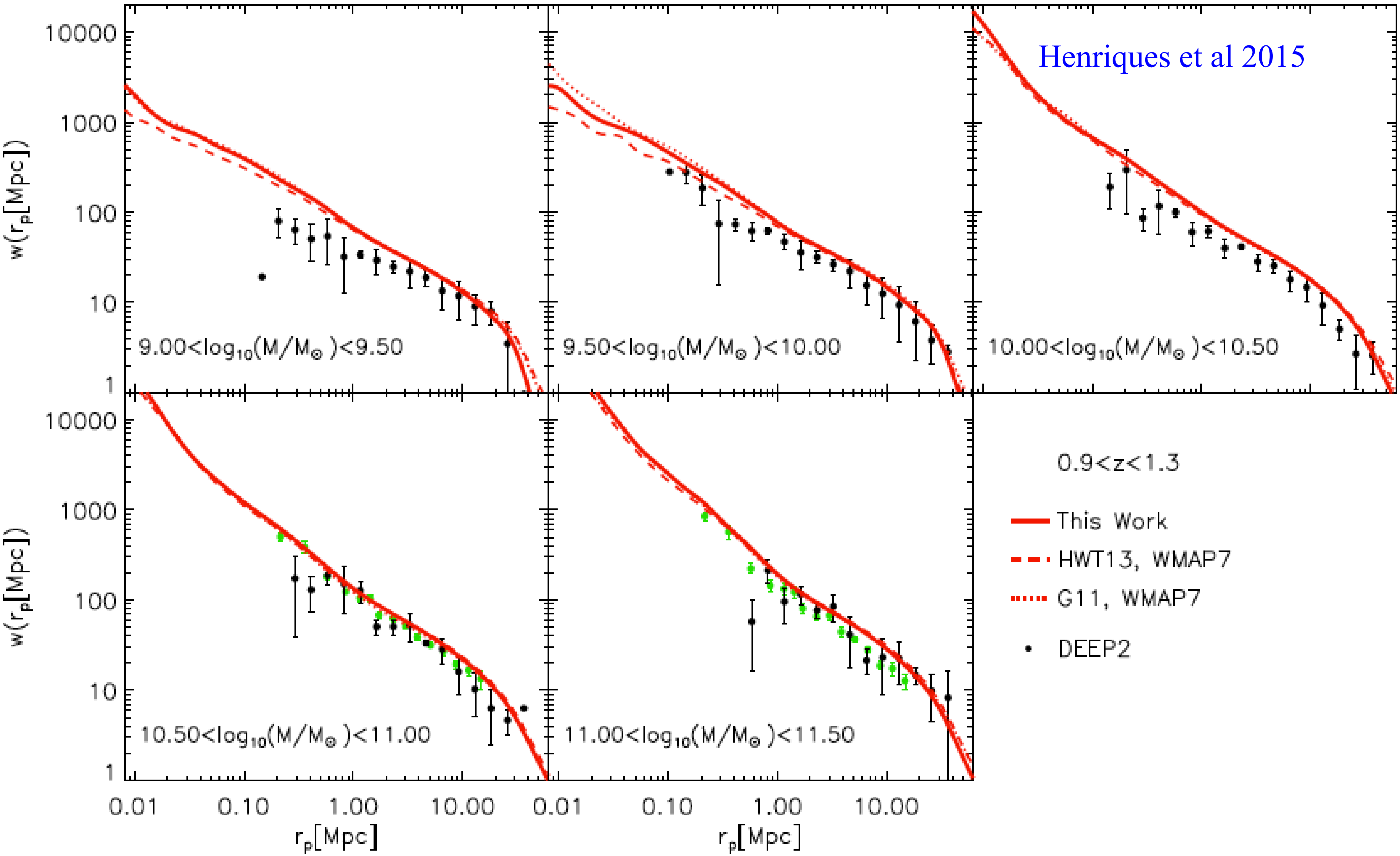

Conclusions

- Characteristic physical scales are less evident in the distribution of galaxies than of dark matter or the CMB, but are still measurable
- The apparently "fractal" distribution of galaxies at low redshift is a coincidence
- No scale characterising the *nature* of dark matter (or dark energy) has so far been seen
- The sharp characteristic mass scale of galaxies reflects baryonic physics acting within the hierarchically aggregating mass distribution