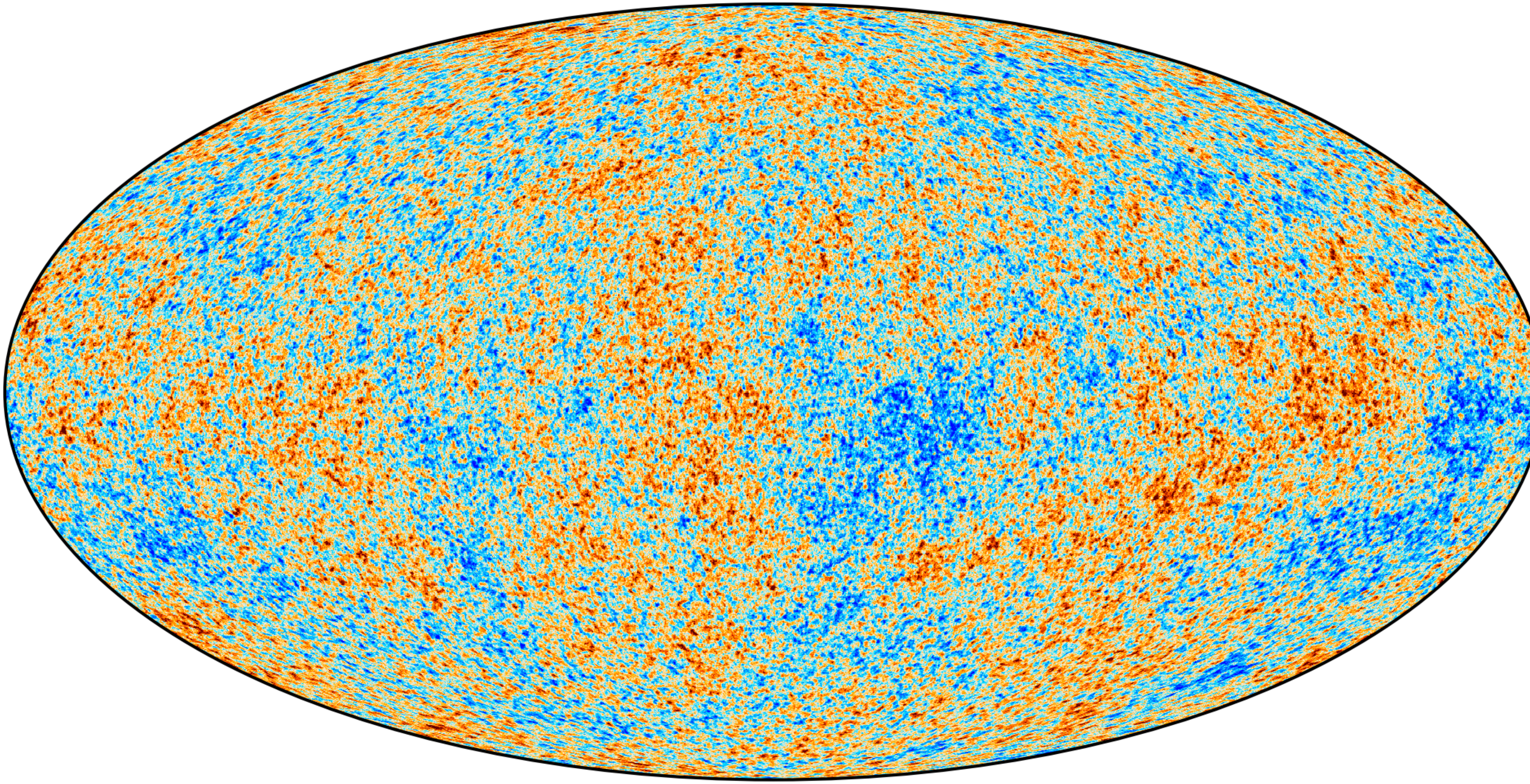
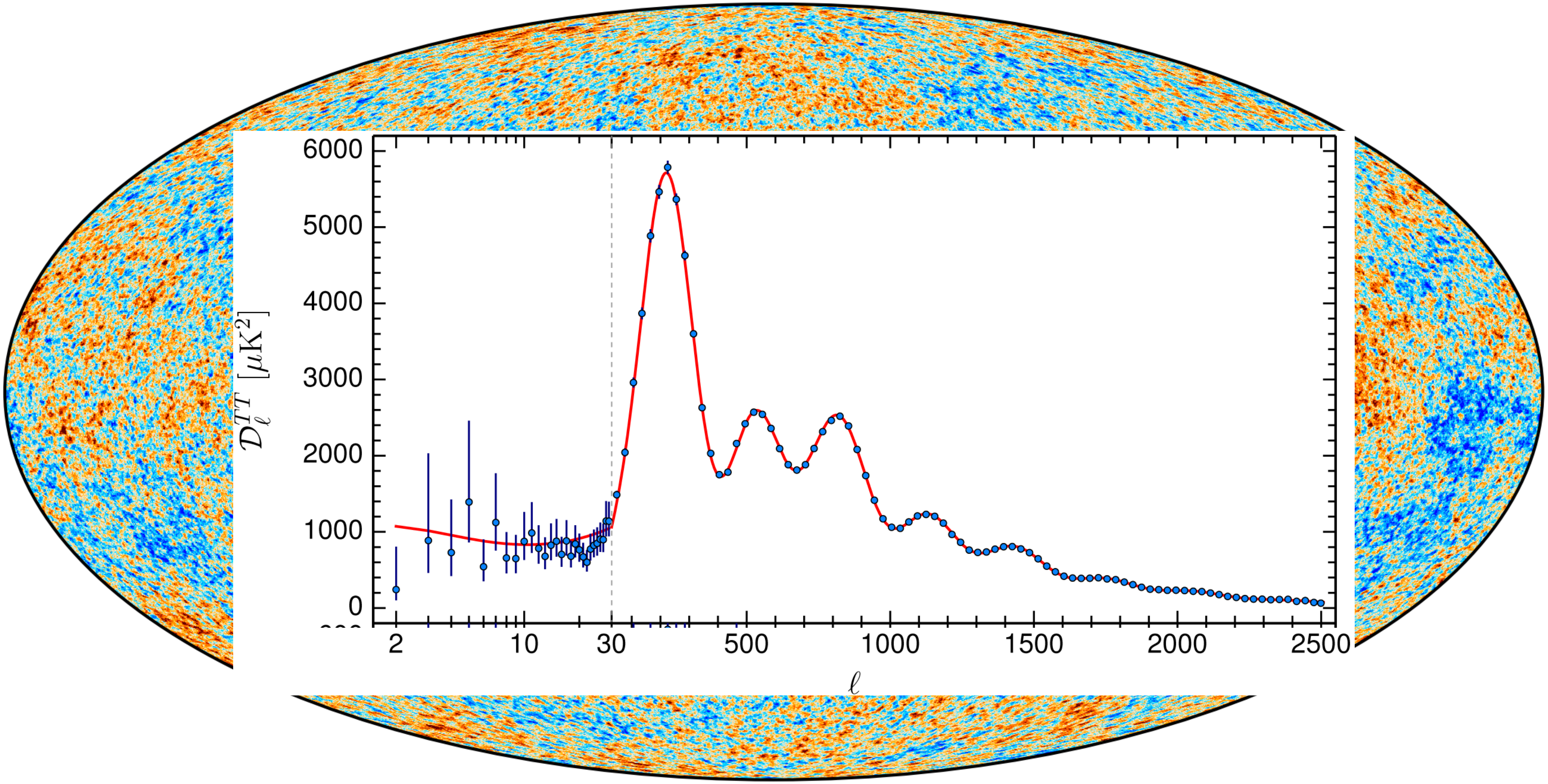
Stars, Planets and Galaxies 2018
Harnack House, Berlin

The imprint of the initial conditions on large-scale structure

Simon White
Max Planck Institute for Astrophysics

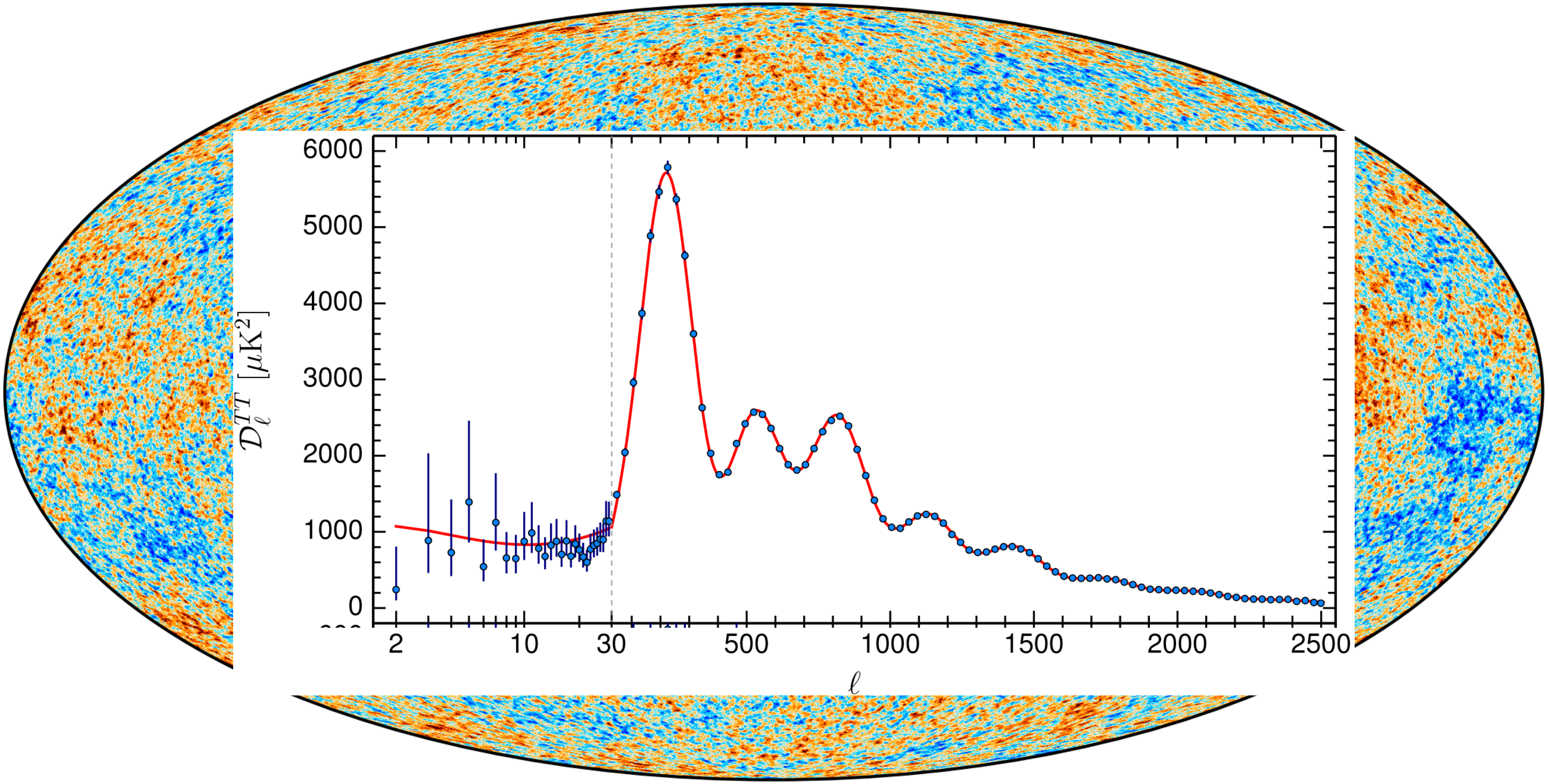


The Planck map of T_{CMB} – the initial conditions for all structure growth



The Planck map of T_{CMB} – the initial conditions for all structure growth

A pure gaussian random field – fully specified by its power spectrum



The Planck map of T_{CMB} – the initial conditions for all structure growth

A pure gaussian random field – fully specified by its power spectrum

The observed spectrum is well fit by a 6-parameter flat ΛCDM model for the contents of the hi-z universe and the origin of all structure.

The six parameters of the minimal ΛCDM model

Planck Collaboration 2013

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

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A 40σ detection of nonbaryonic DM using *only* z ~1000 data!

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A 40σ detection of nonbaryonic DM using *only* z ~1000 data!

86σ in 2015 using *Planck* data alone!!

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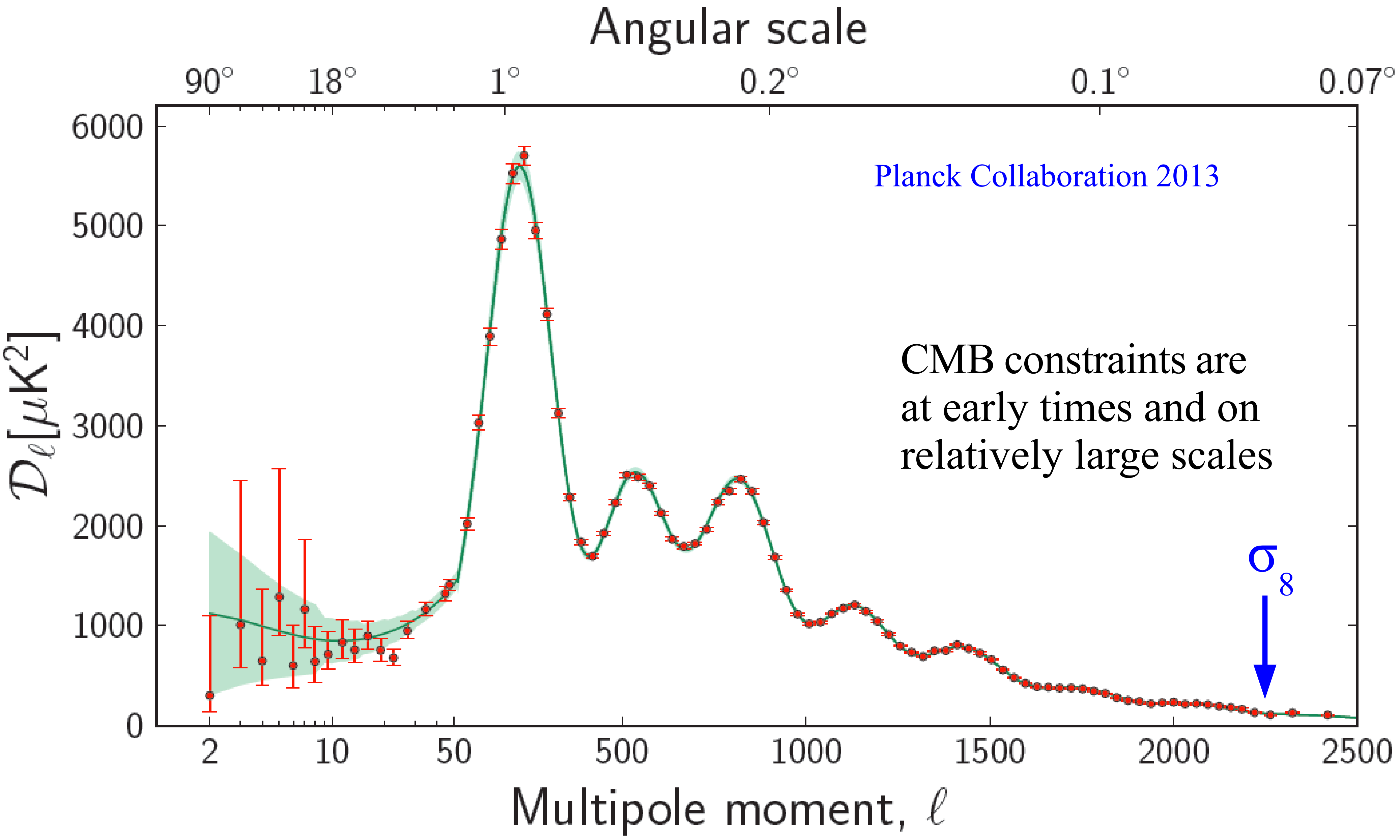
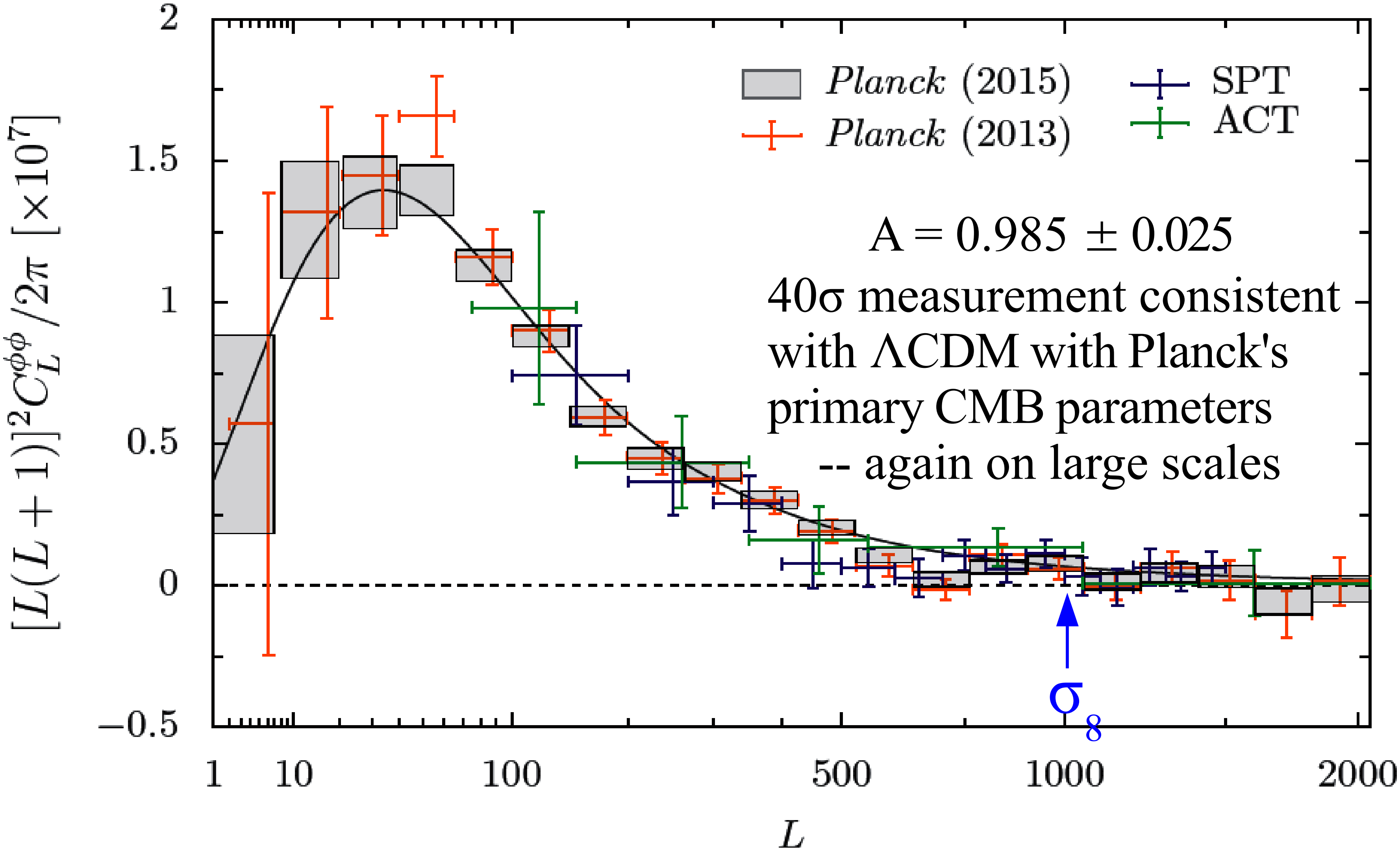
Information content of the *Planck* CMB map



CMB constraints are at early times and on relatively large scales

Late-time mass fluctuations from CMB lensing

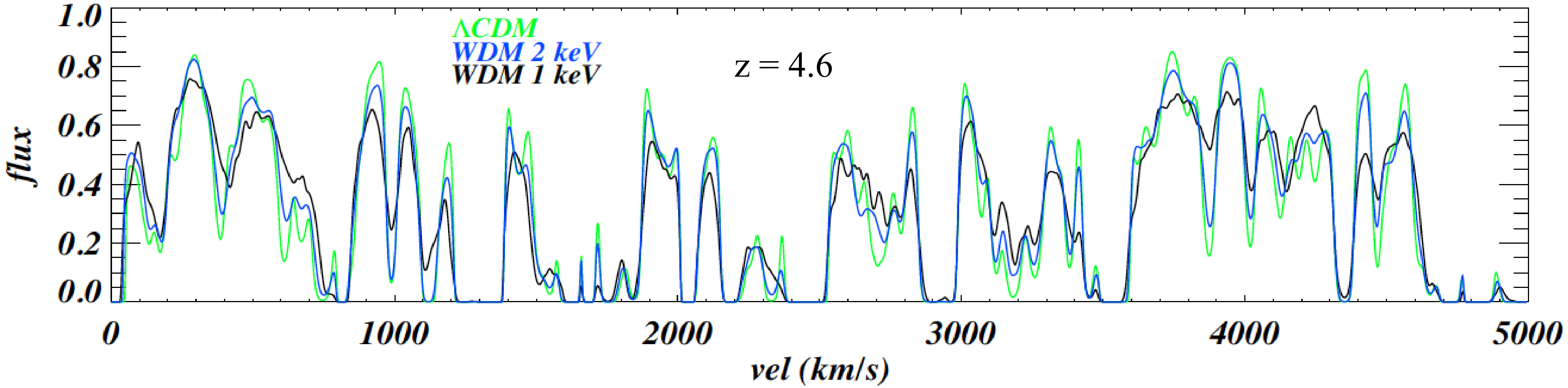


The lensing signal in the CMB pattern is imprinted at $0.5 < z < 2.5$

→ gravitational structure growth since $z \sim 1000$ is as expected

Ly α forest spectra and small-scale initial structure

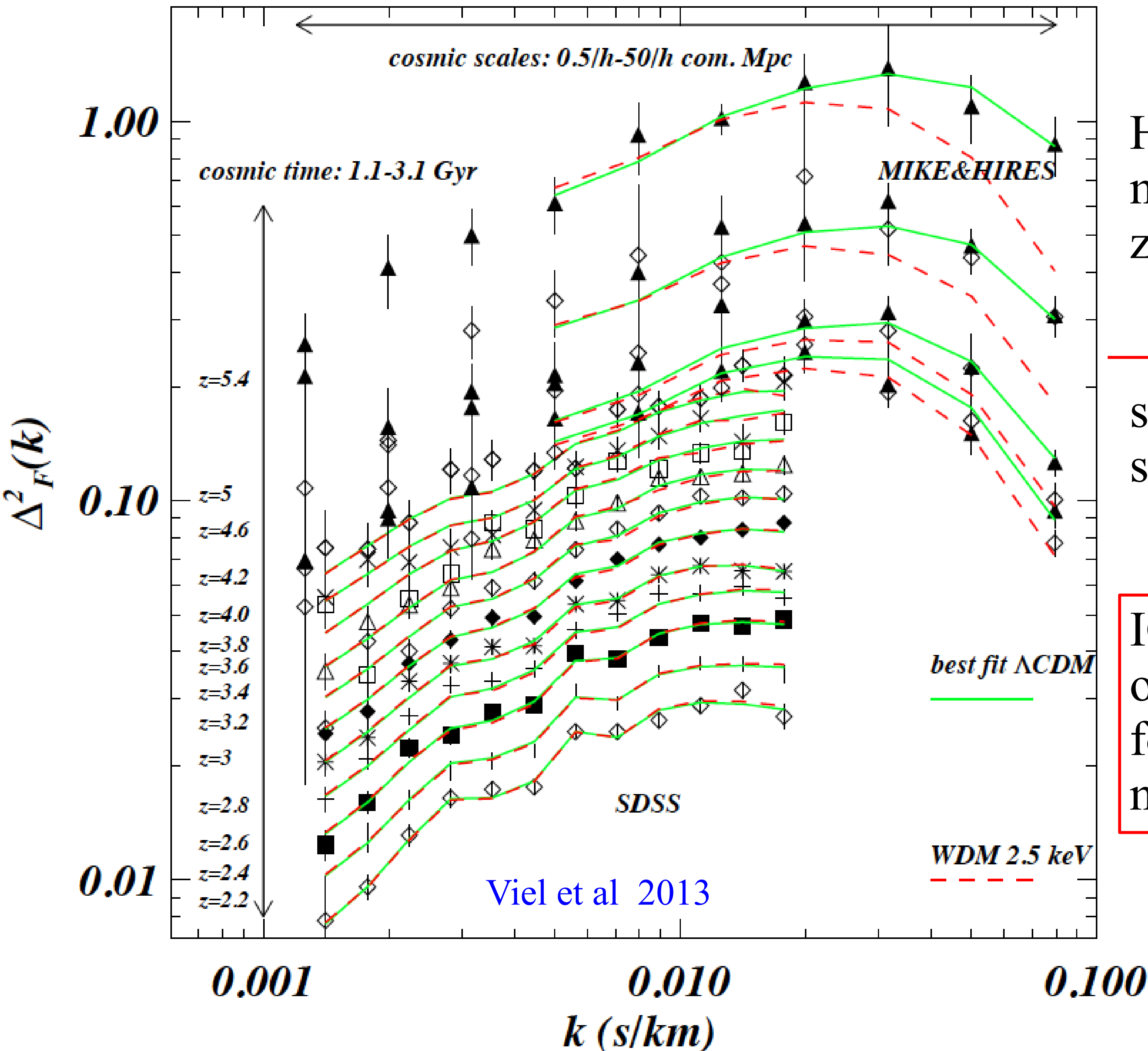
Viel, Becker, Bolton & Haehnelt 2013



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

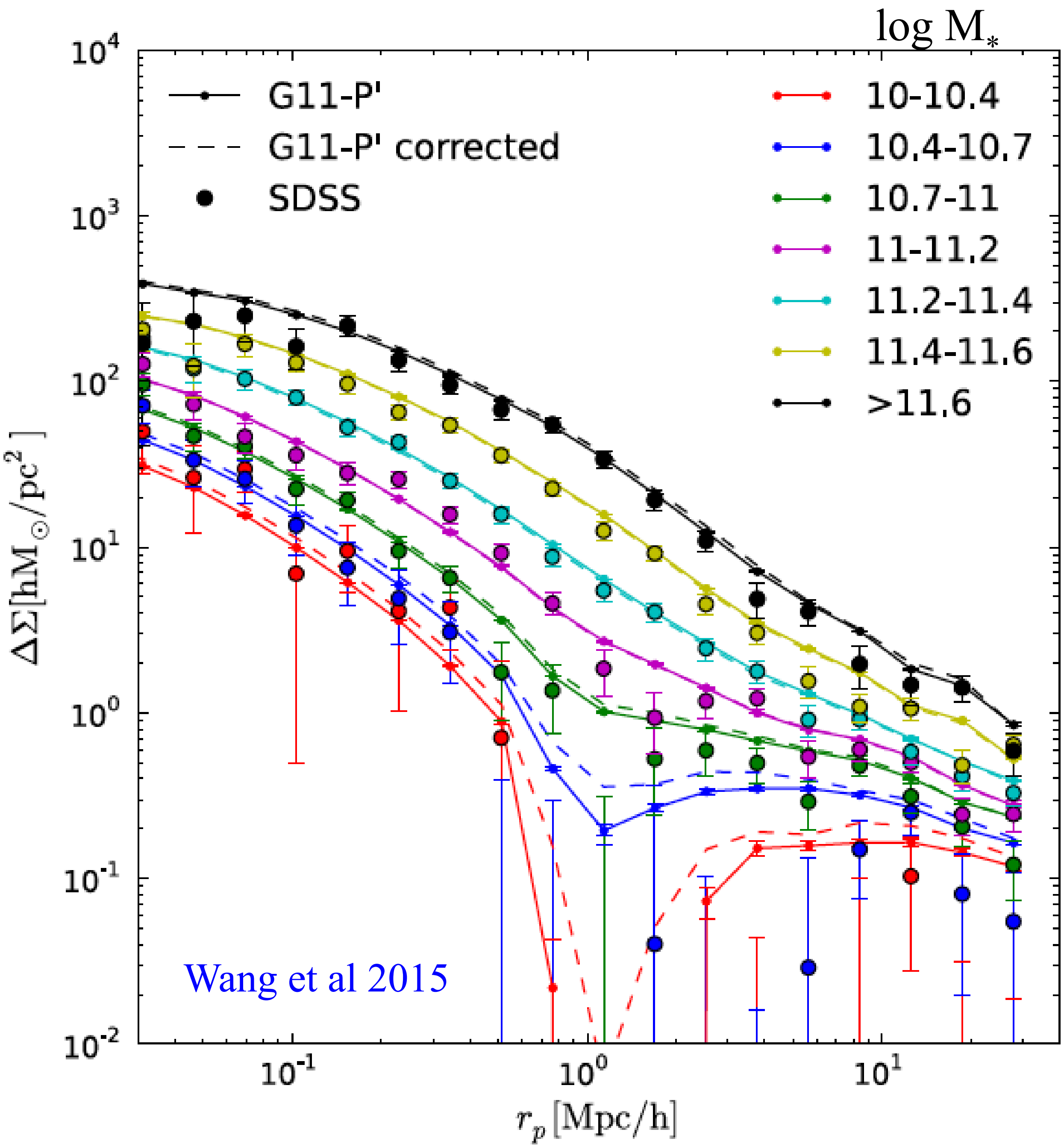


High-resolution spectra match ΛCDM up to z = 5.4

→ WDM can affect the structure only of the smallest galaxies

IC's are well measured on all scales relevant for the formation of the main galaxy population

Mean mass profiles around low-redshift galaxies

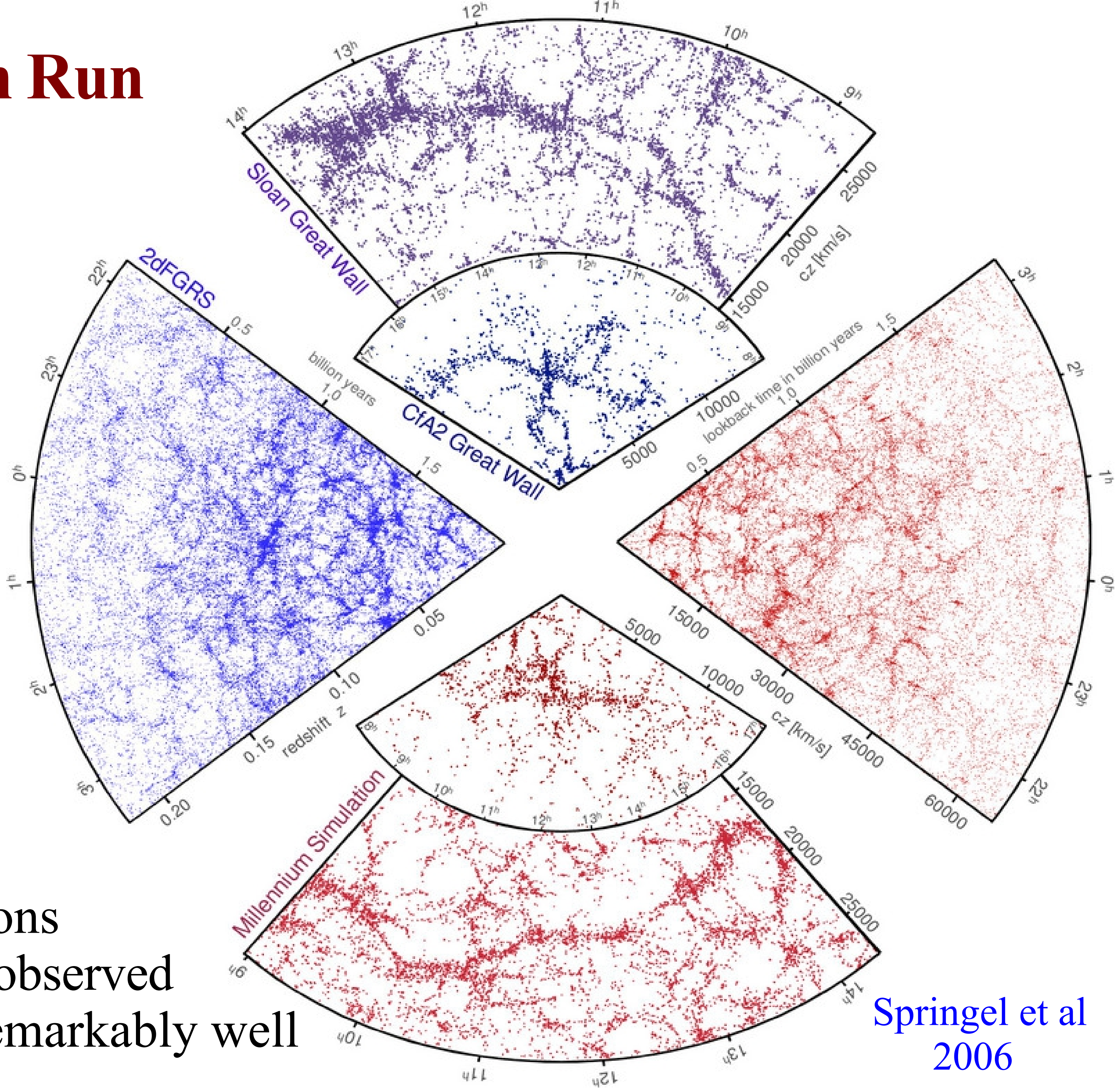


Points are mean weak lensing profiles around SDSS "central" galaxies as a function of their stellar mass.

Lines are from a <u>simulation</u> of the formation of the galaxy population within ΛCDM, assuming Planck parameters.

No simulation parameters were adjusted for this comparison, but the agreement depends on the <u>astrophysical</u> modelling, i.e. which galaxies are put in which halos

Millennium Run 2005



Such simulations reproduce the observed cosmic web remarkably well

Springel et al 2006

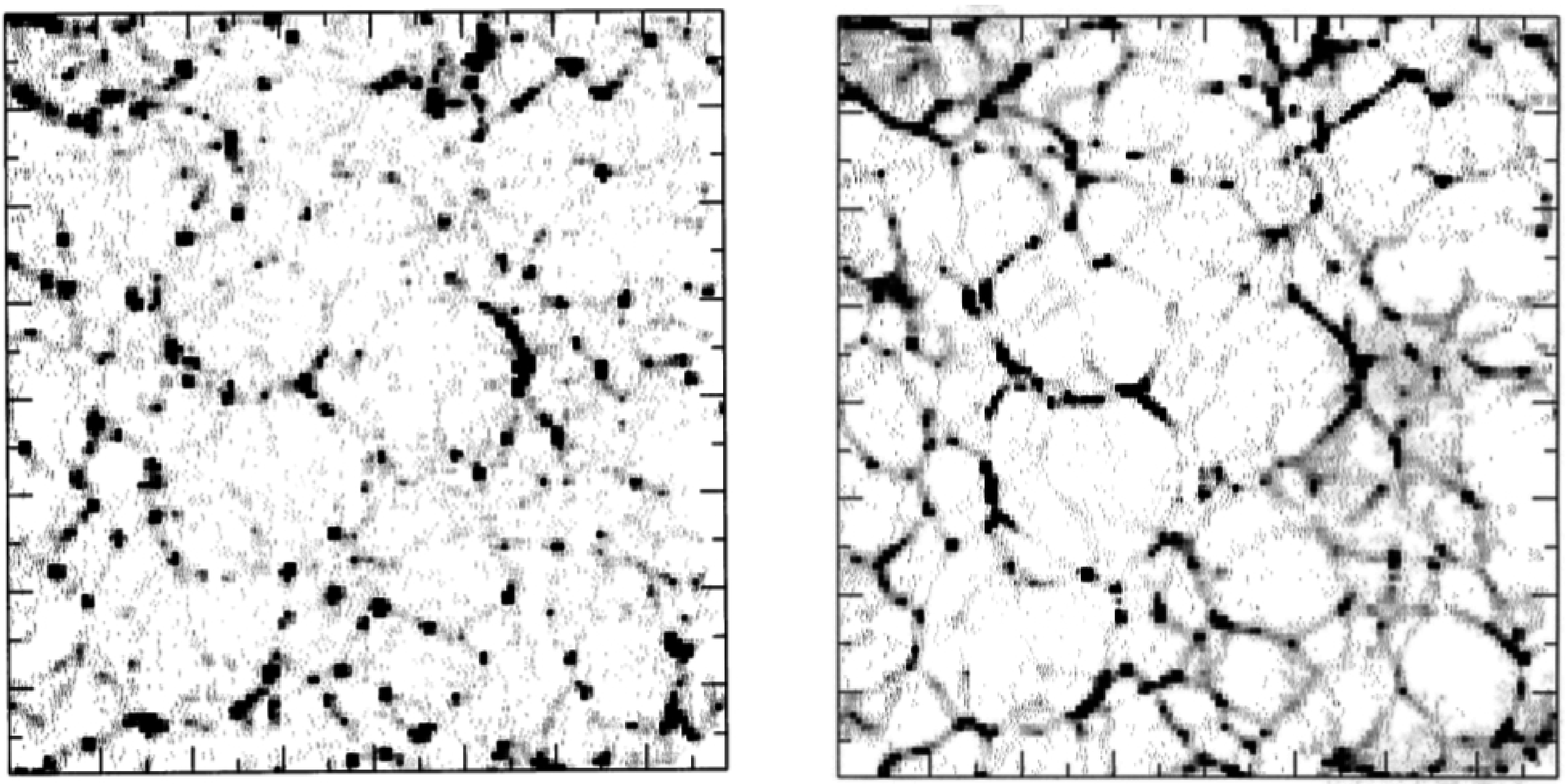
Large-scale structure from linear theory + adhesion

In linear theory: $\delta(\mathbf{q}, t) = b(t)\,\delta_o(\mathbf{q}) \longrightarrow \mathbf{x}(\mathbf{q},t) = \mathbf{q} - b(t)\nabla\Phi_o$

This is known as the “Zel'dovich approximation”

“Adhesion” assumes matter to stick at shocks, conserving M and **P**

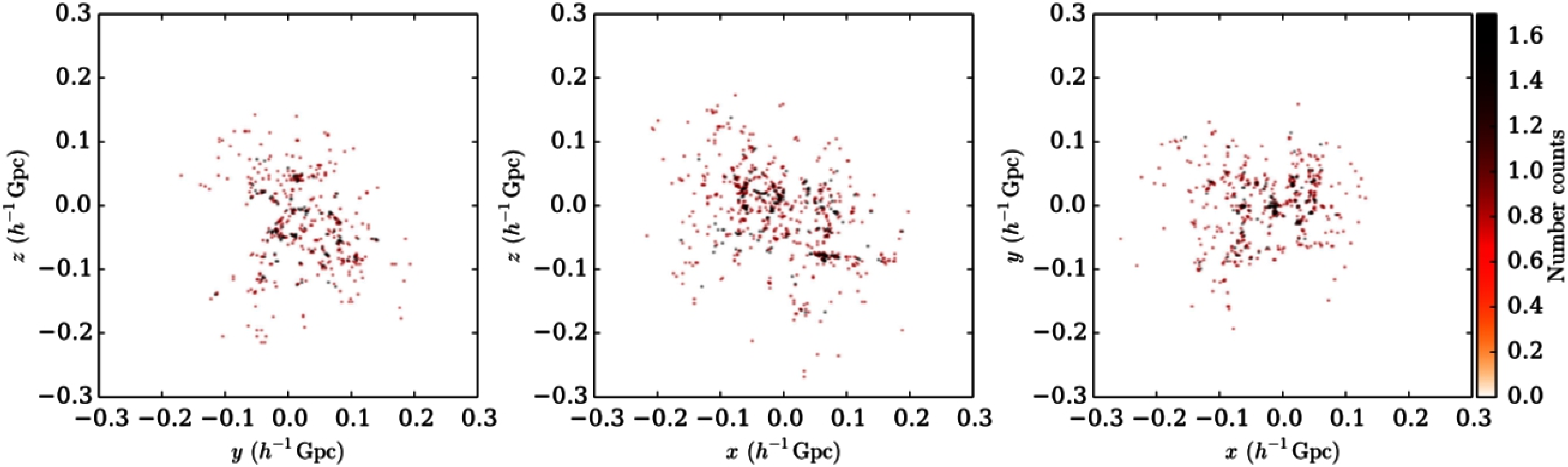
Together they reproduce the cosmic web simply as “amplified IC's”



Melott, Shandarin & Weinberg 1994

Reconstructing the Local DM distribution and its IC's at z=1000

Lavaux & Jasche 2016



Orthogonal slices through the observed SDSS galaxy distribution

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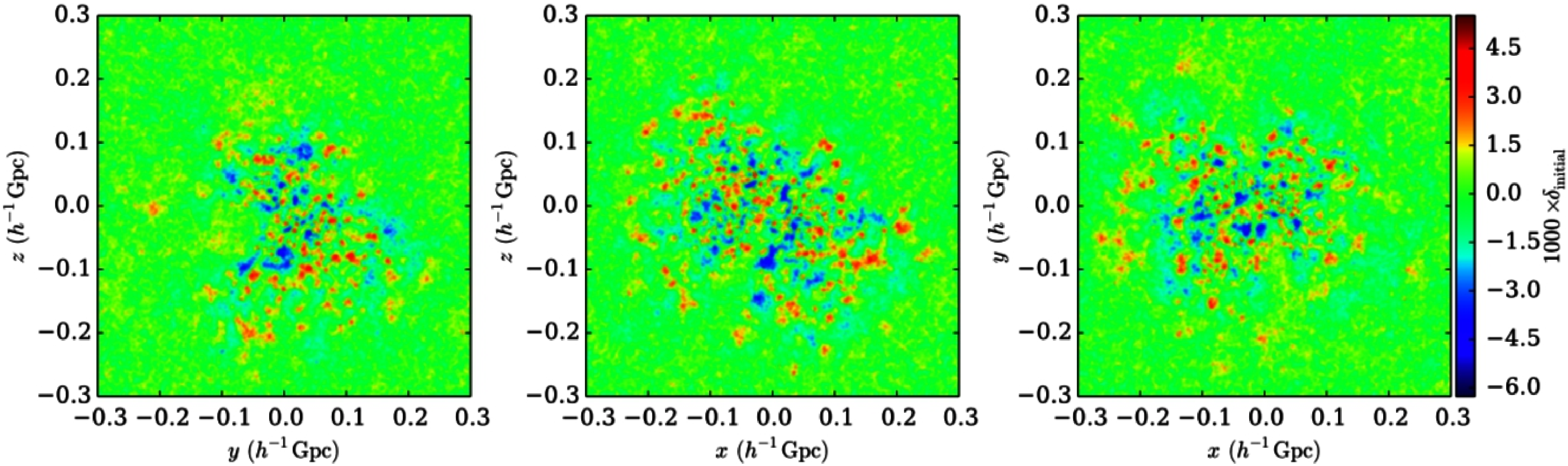

Orthogonal slices through the observed SDSS galaxy distribution

Mean of 10000 linear density distributions at z=1000 which evolve to produce z=0 DM distributions consistent with SDSS + Poisson sampling

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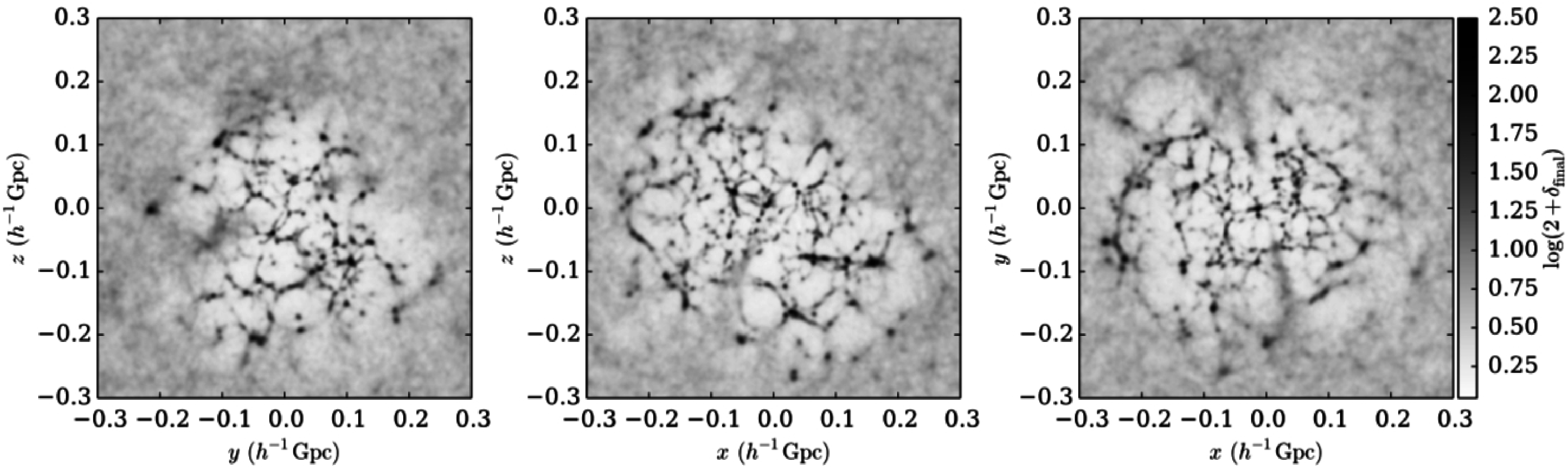

Orthogonal slices through the observed SDSS galaxy distribution

Mean of 10000 linear density distributions at z=1000 which evolve to produce z=0 DM distributions consistent with SDSS + Poisson sampling

Mean of the z=0 set of 1000 DM distributions produced by gravitational evolution from these initial conditions

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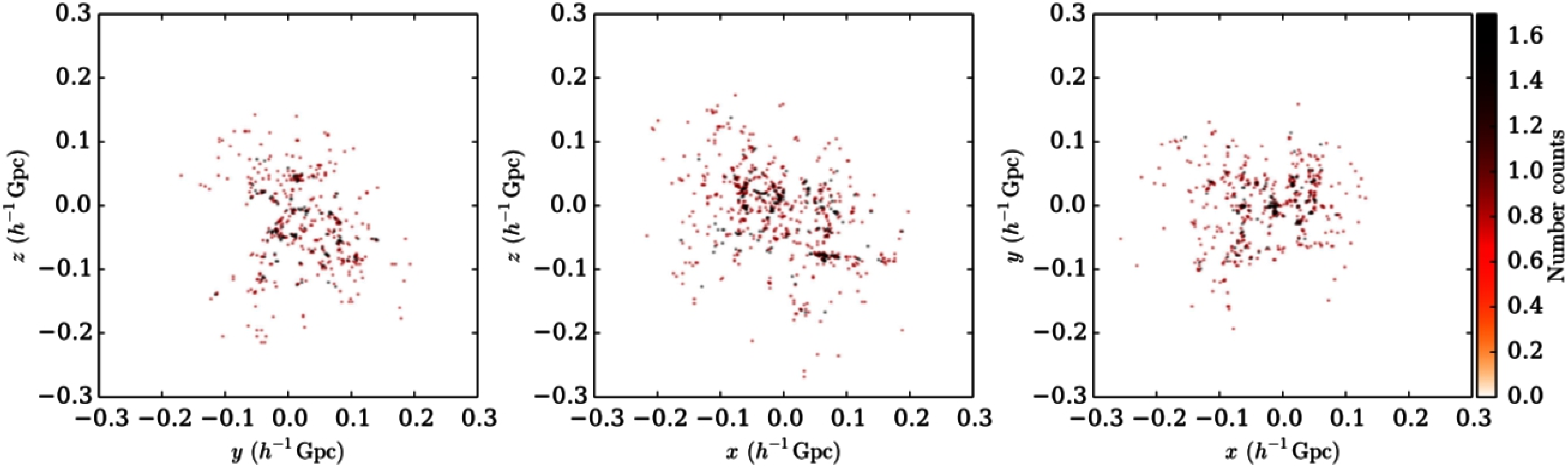


Orthogonal slices through the observed SDSS galaxy distribution

Mean of 10000 linear density distributions at z=1000 which evolve to produce z=0 DM distributions consistent with SDSS + Poisson sampling

Mean of the z=0 set of 1000 DM distributions produced by gravitational evolution from these initial conditions

Positions and masses of observed rich clusters are quite well matched

The IC's also determine the z=0 distribution of halos

Consider the linear density field smoothed with a filter enclosing M

$$\delta_s(\mathbf{x}, t; M) = \int d^3x' \, \delta(\mathbf{x'}, t) \, F(|\mathbf{x} - \mathbf{x'}|; M)$$

<u>Press-Schechter Ansatz</u>: At time t the mass element from initial position **x** is part of a halo of mass given by the largest M for which $\delta_s(\mathbf{x}, t; M) > \delta_{thresh}$ for some threshold δ_{thresh}

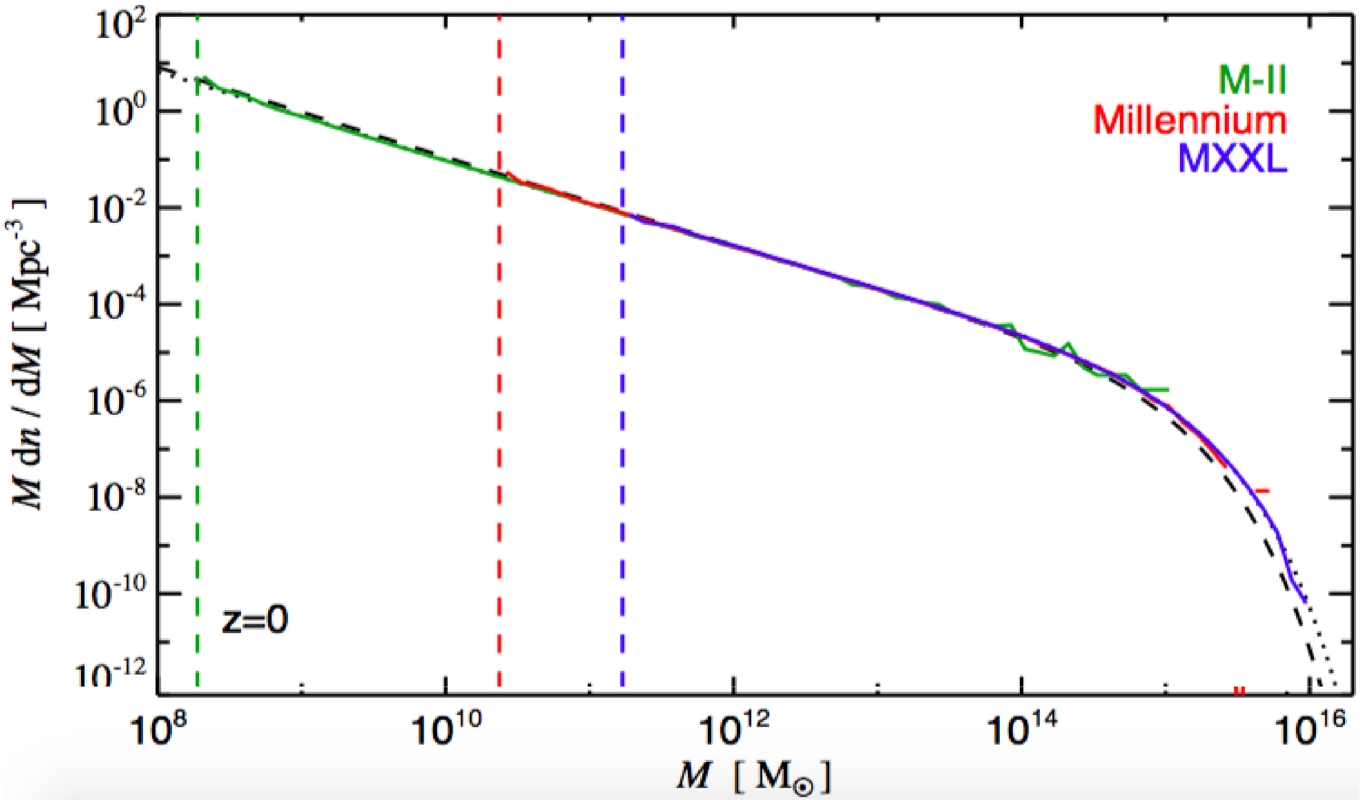
→ For suitably chosen F and δ_{thresh} this reproduces simulated

- Halo mass functions, $n(M, t)$
- Halo clustering on large scale, $\xi(r; M, t)$
- Halo assembly histories, $P\{M_1, t_1 \mid M_0, t_0\}$, $t_1 < t_0$

The properties of z=0 halos are directly encoded in the z=1000 IC's

The (simulated) dark halo mass function

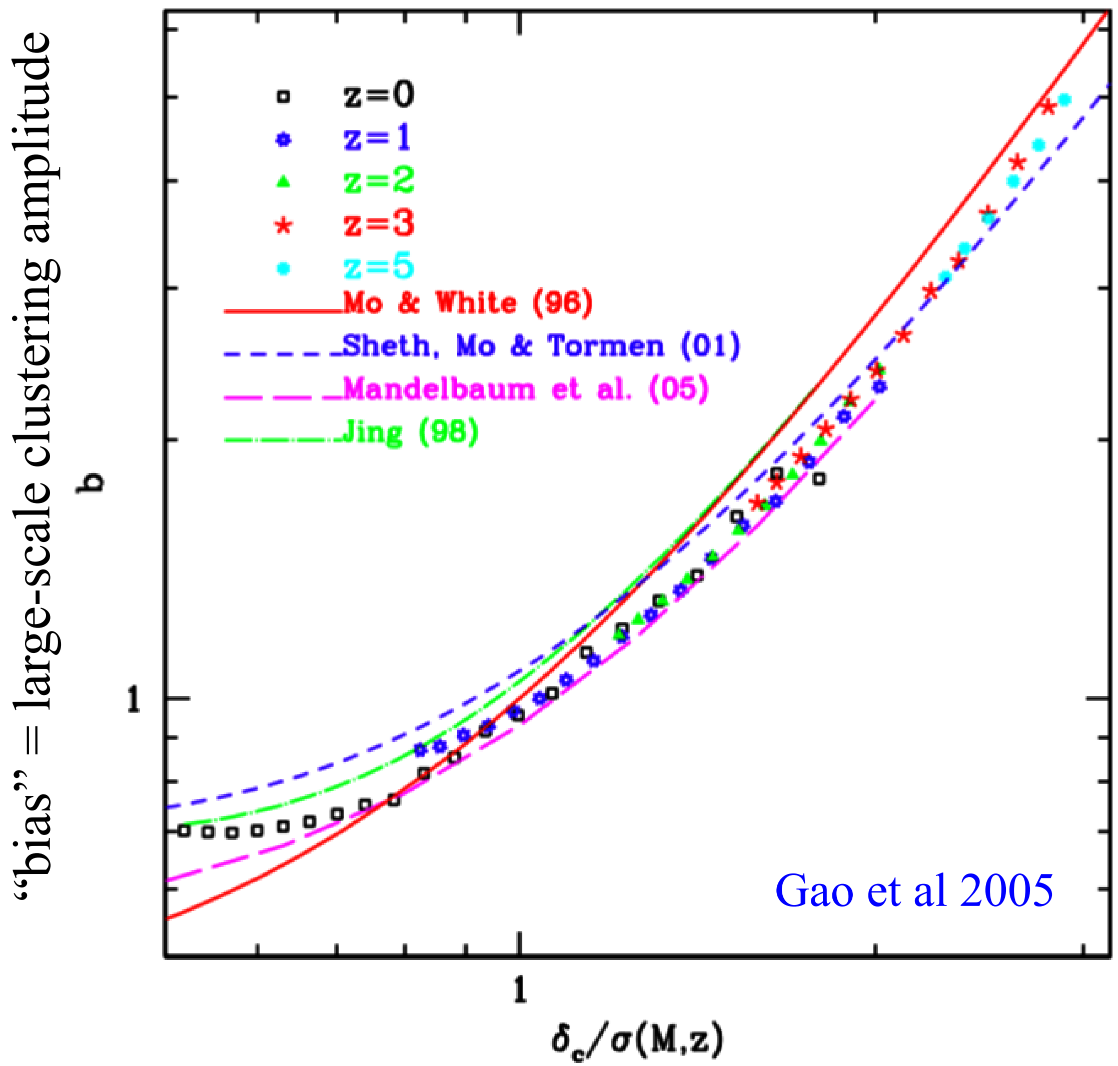
Angulo et al 2012



Simulations are well converged over 8 orders of magnitude in mass

A function of PS type can fit (also as a function of t) to ~10%

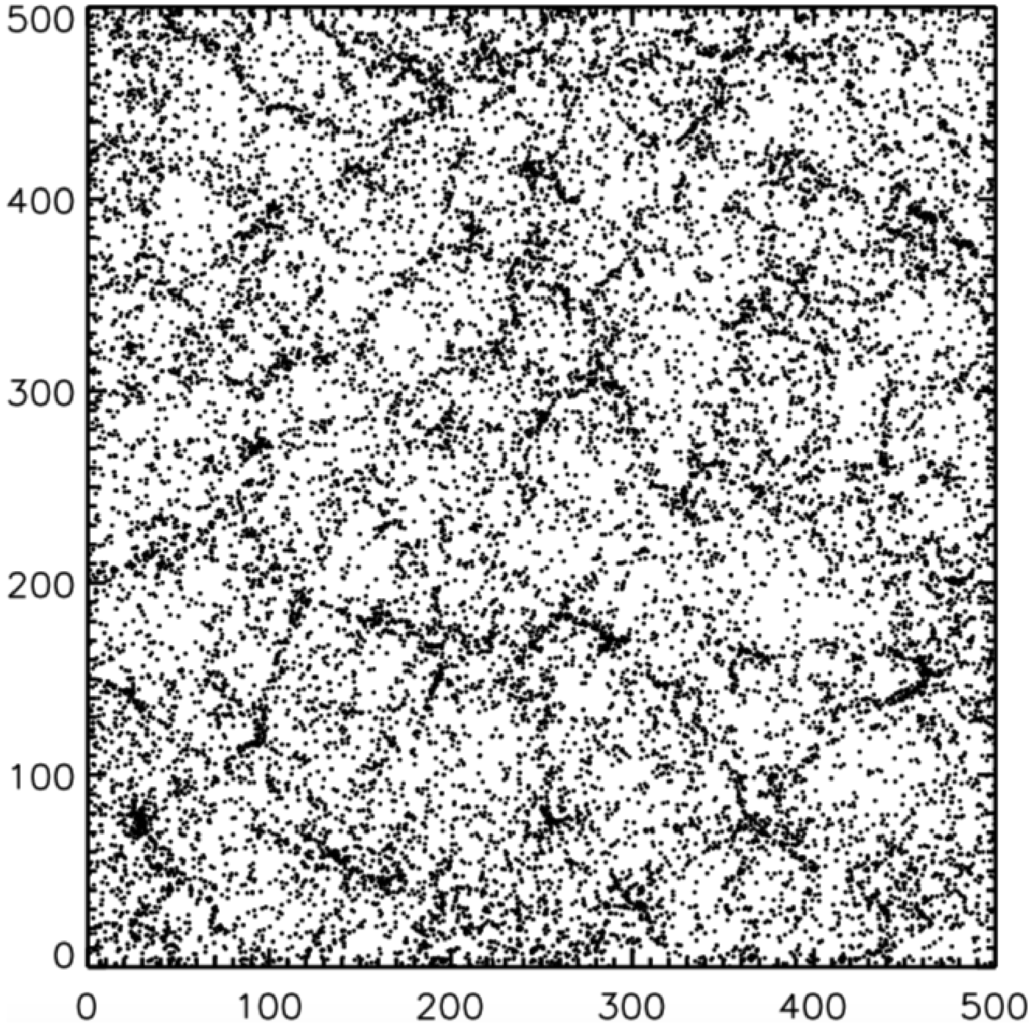
The clustering of (simulated) dark halos



The large-scale clustering of (simulated) halos as a function of M and t is also well fit by PS predictions......

The clustering of (simulated) dark halos

Gao et al 2005



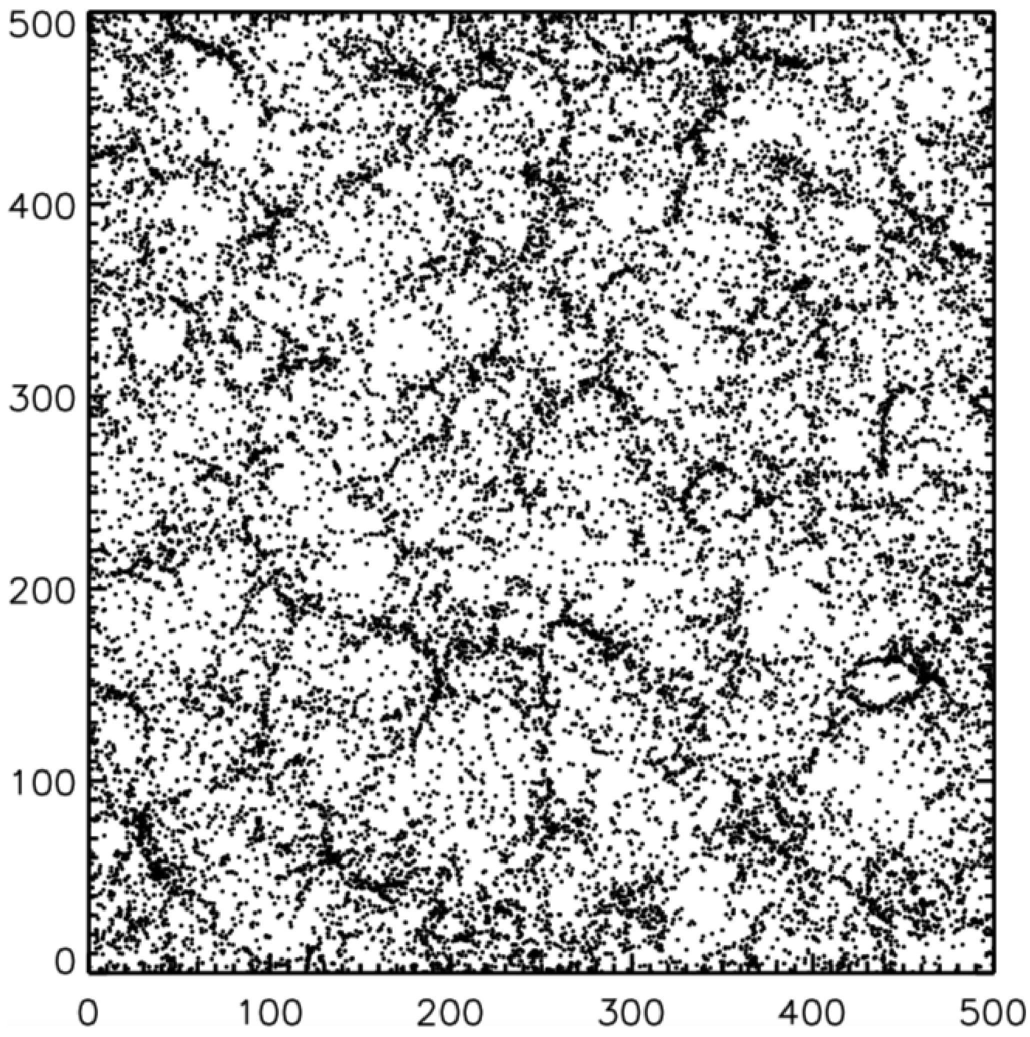
Halos of mass $\sim 2 \times 10^{11} M_\odot$ in a 30 Mpc/h thick slice

A random 20% of all halos shown

......but dependences on halo formation time (concentration, spin, shape...) are not. This is known as **AssemblyBias**

The clustering of (simulated) dark halos

Gao et al 2005



Halos of mass $\sim 2 \times 10^{11}\ M_\odot$ in a 30 Mpc/h thick slice

The earliest forming 20% of halos

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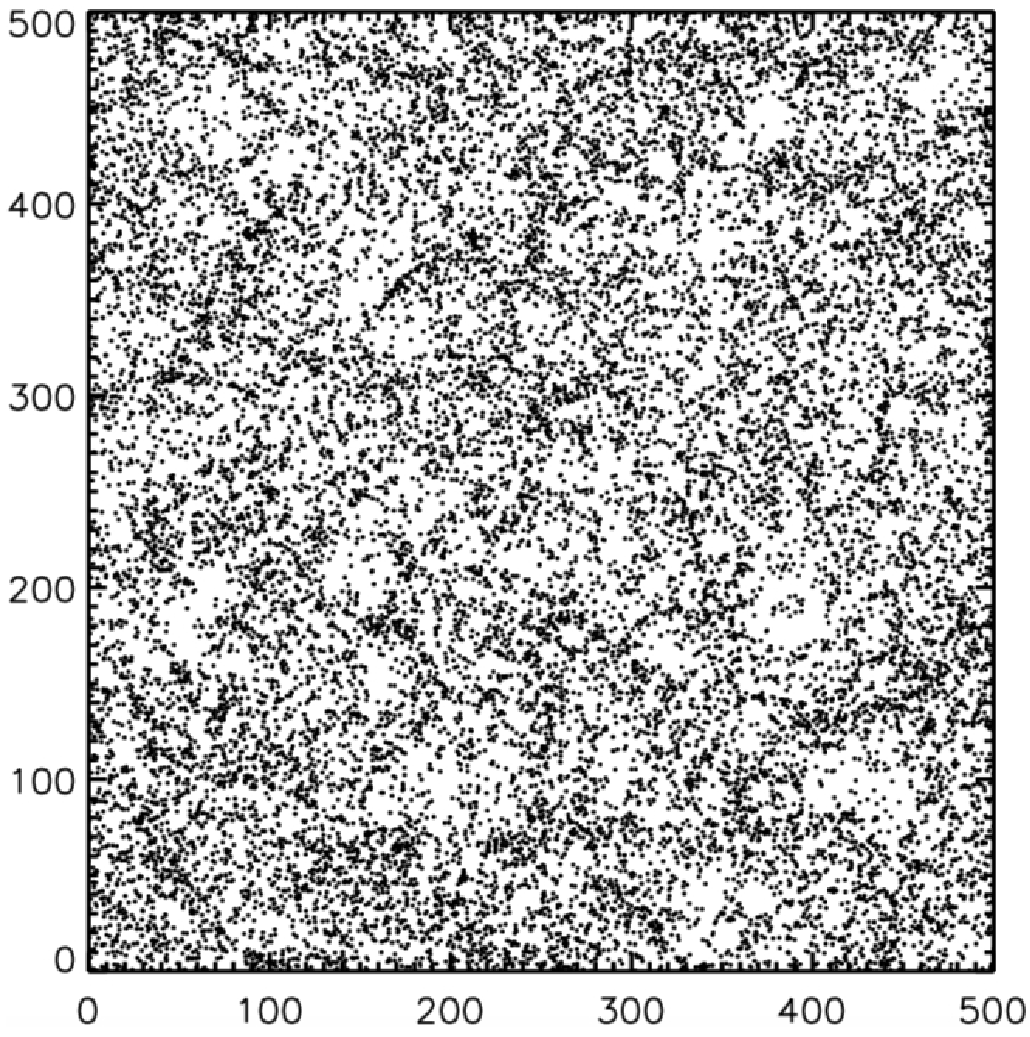
Gao et al 2005



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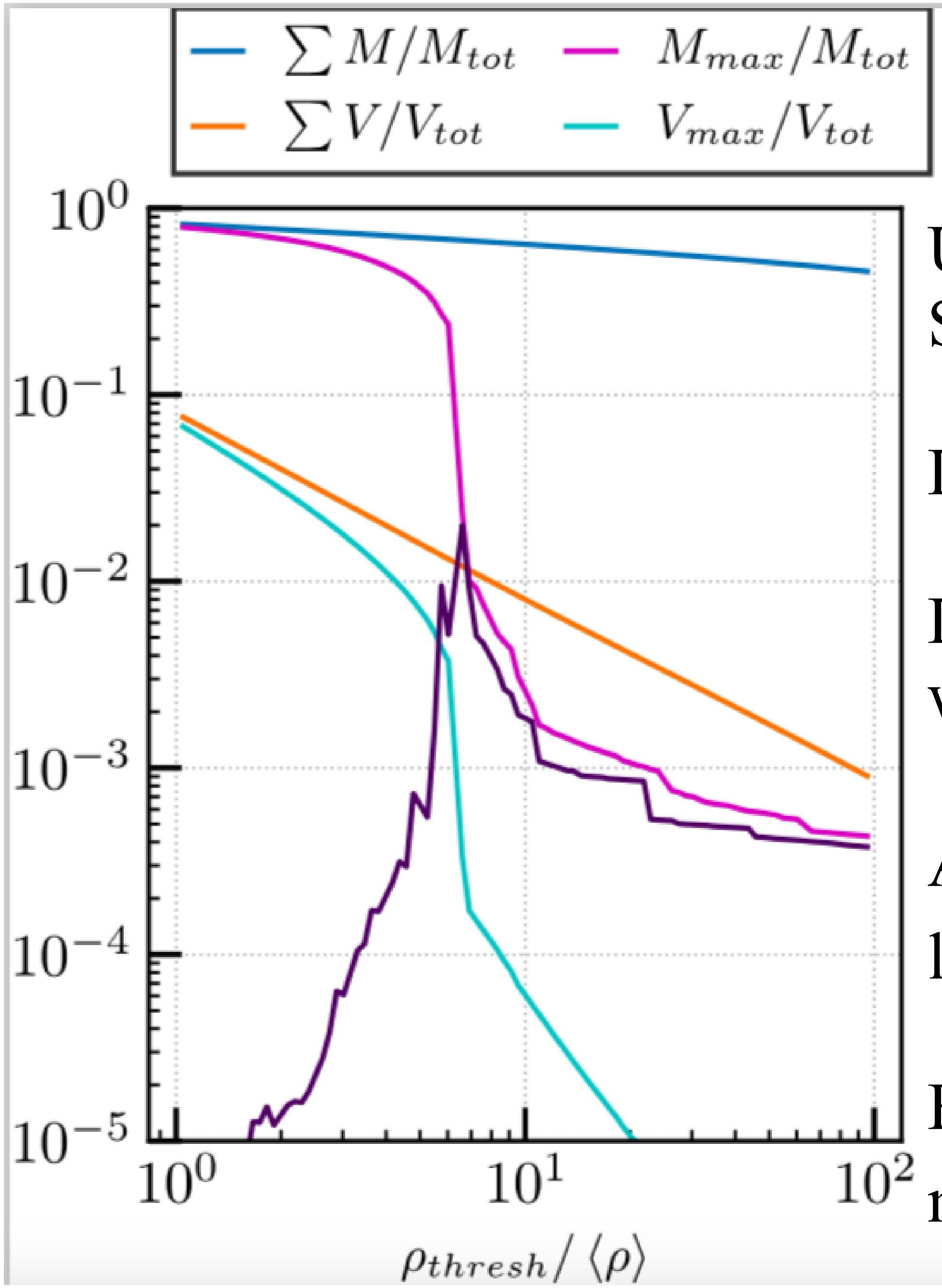
Defining the cosmic web at high resolution



Busch & White 2018

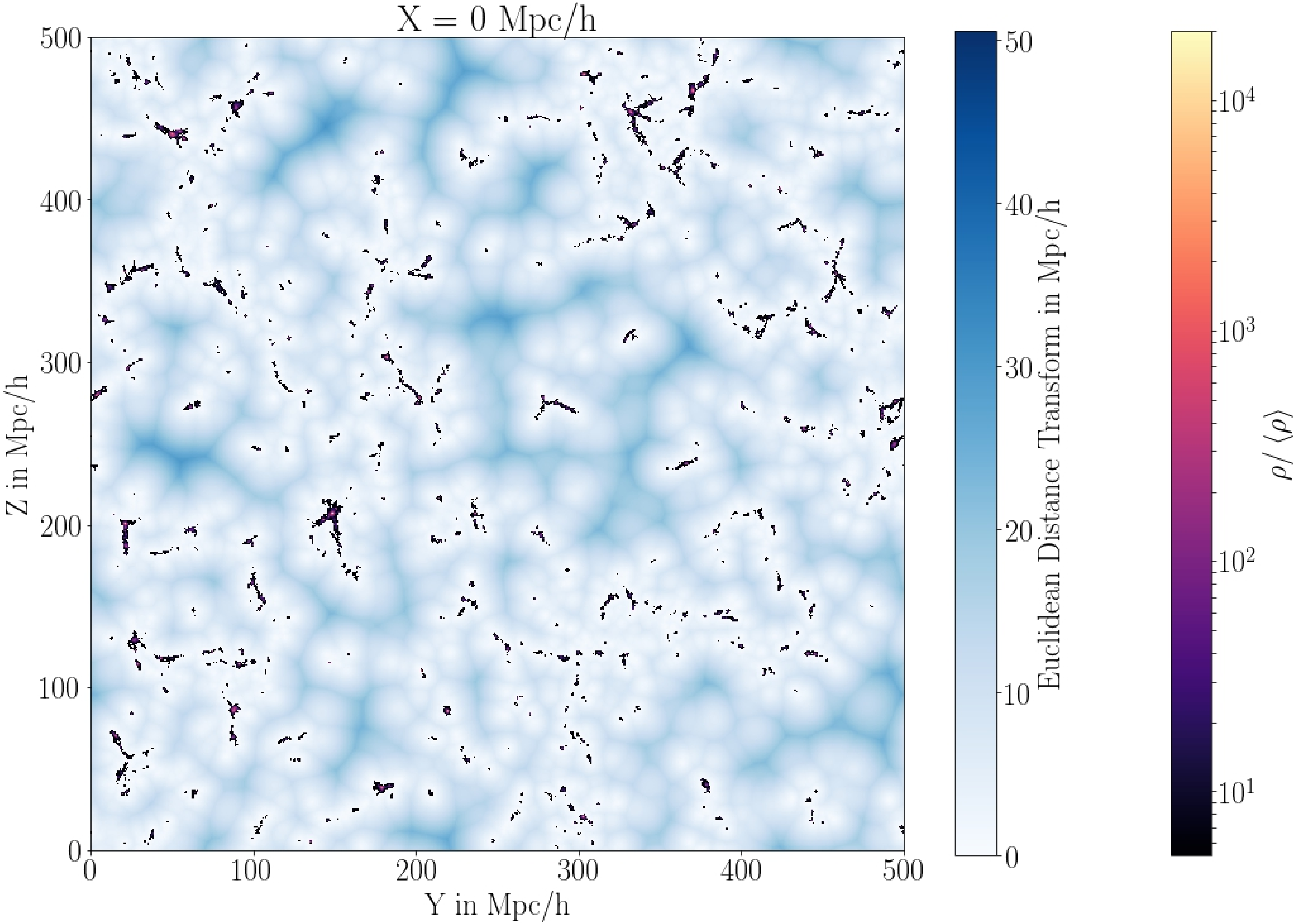
Use the 10^{10} particles in the Millennium Simulation to build a Voronoi tesselation

Define m/V as the density of each cell

Define objects as connected sets of cells with density exceeding ρ_{thresh}

As $\rho_{thresh}/\langle\rho\rangle$ drops from 10 to 5 the largest object percolates

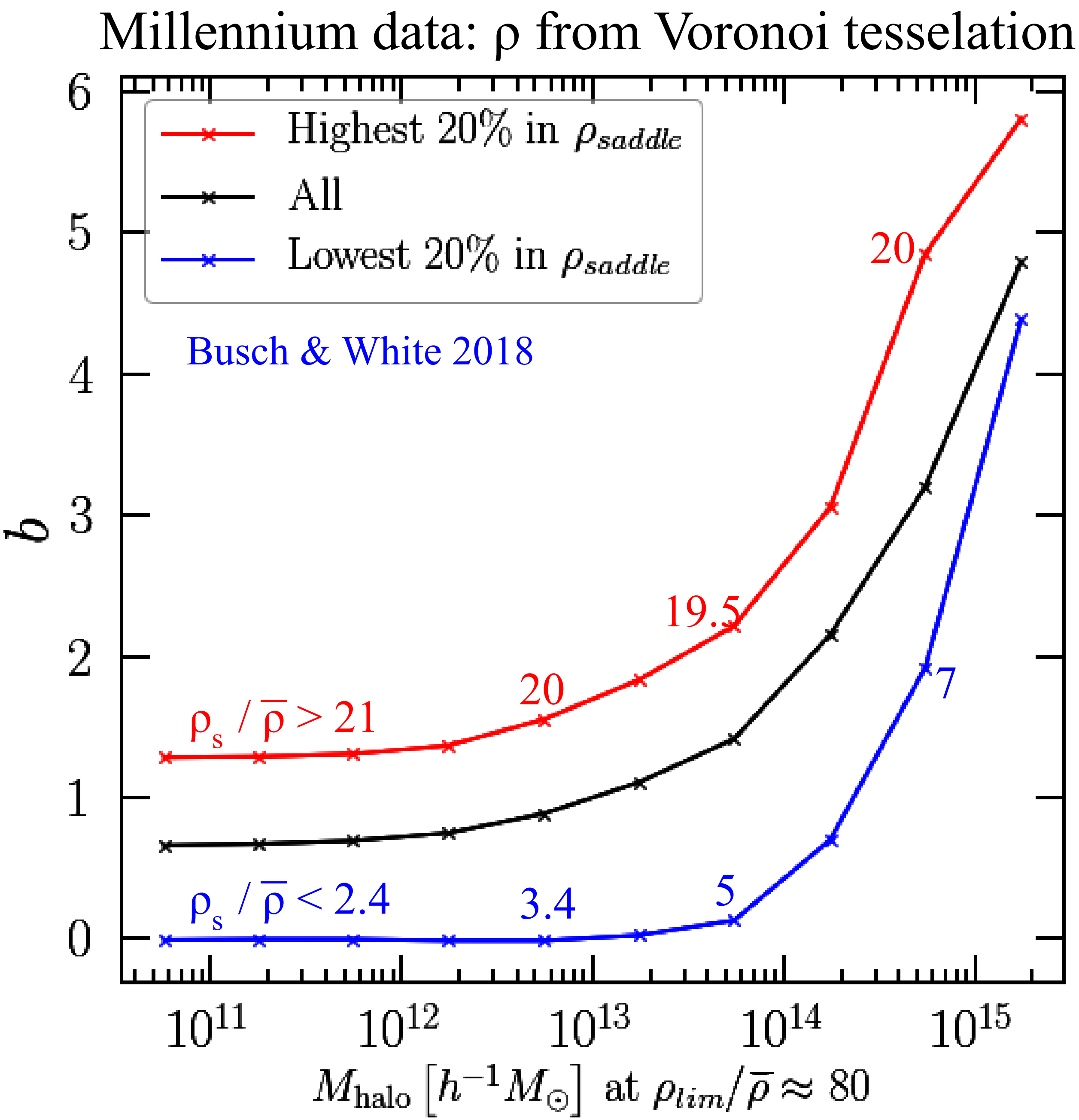
For $\rho_{thresh}/\langle\rho\rangle = 5$ it contains 35% of all mass but fills only 0.6% of the volume

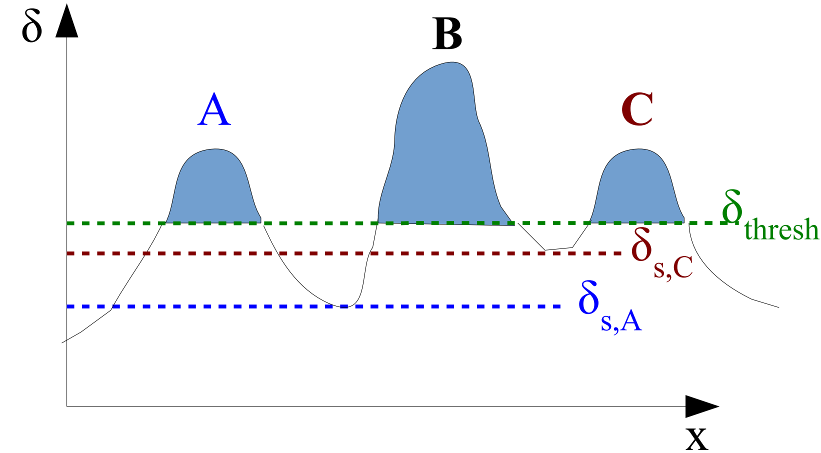


X = 0 Mpc/h
Z in Mpc/h
Y in Mpc/h
0
100
200
300
400
500
Euclidean Distance Transform in Mpc/h
0
10
20
30
40
50
$\rho/\langle\rho\rangle$
10^1
10^2
10^3
10^4

Bias as a function of mass and saddle point density

Millennium data: ρ from Voronoi tesselation





Halos in the 20% tail with smallest saddle point density are <u>uncorrelated</u> with the mass density field for halo masses like those of galaxies.
Hence, $b_{lo} = 0$!

Halos in the 20% tail with highest saddle point density are much more strongly biased than typical halos

Summary?

- Large-scale structure, the cosmic web and the spatial and mass distributions of halos can all be viewed as relatively simple distortions of the linear initial conditions
- This is because evolution is due almost entirely to gravity, and t_{dyn} / t_{Hubb} is not much less than unity
- The precisely known, gaussian nature of the IC's then translates into accurately calculable properties for halos and the cosmic web
- Galaxy formation processes occur smaller scales with shorter time-scales and more physics – then nothing is accurately calculable

Chess ⟶ Mud wrestling (Martin Rees)