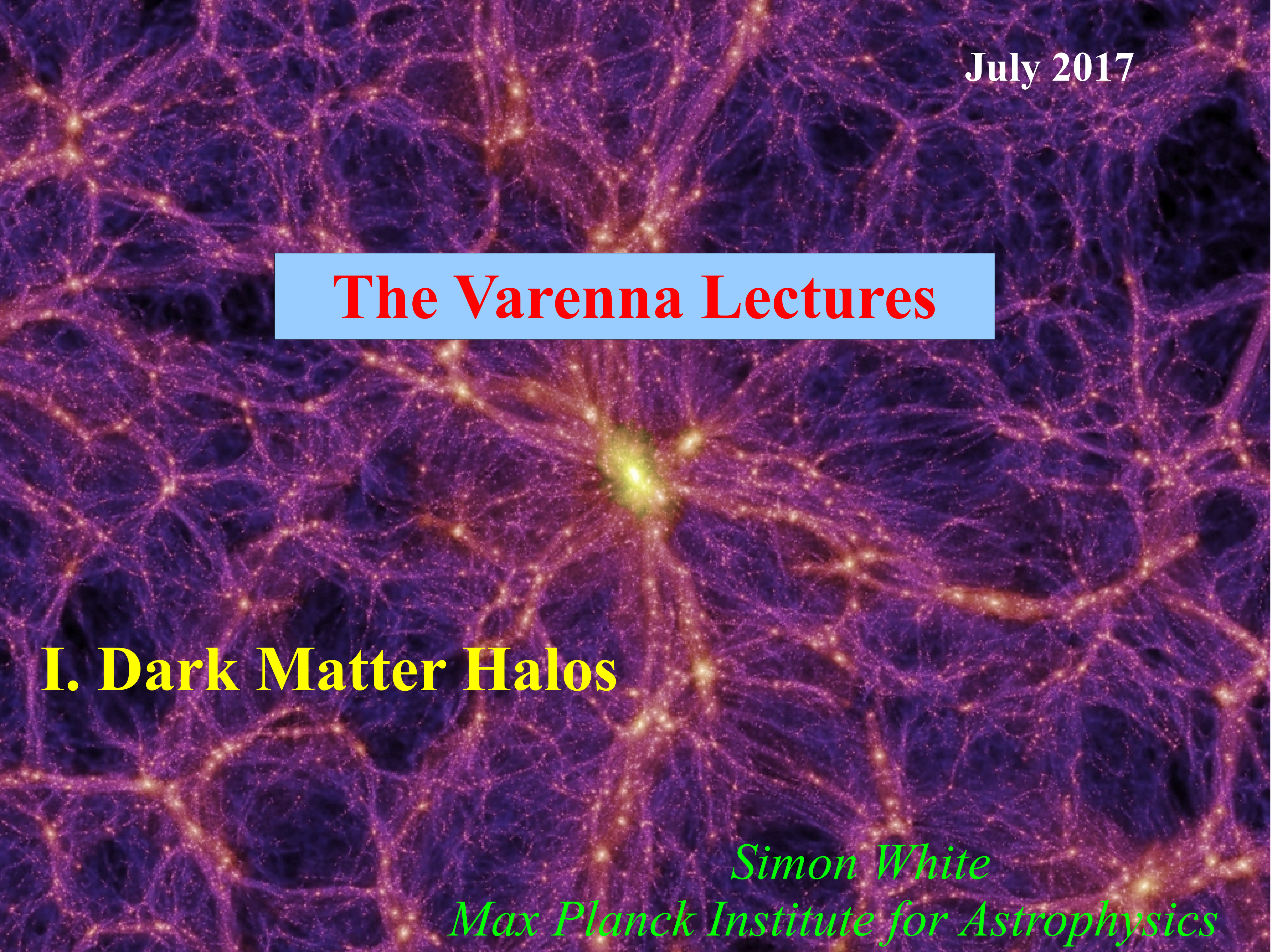


July 2017

The Varenna Lectures

I. Dark Matter Halos

Simon White
Max Planck Institute for Astrophysics

Dark matter halos are the basic units of nonlinear structure

Is all dark matter part of some halo?

Was this always the case?

How do halos grow? accretion? merging?

How are they distributed? (Relation to large-scale structure?)

What is their internal structure?

-- density profile

-- shape

-- subhalo population – mass/radial distributions, evolution

-- caustics

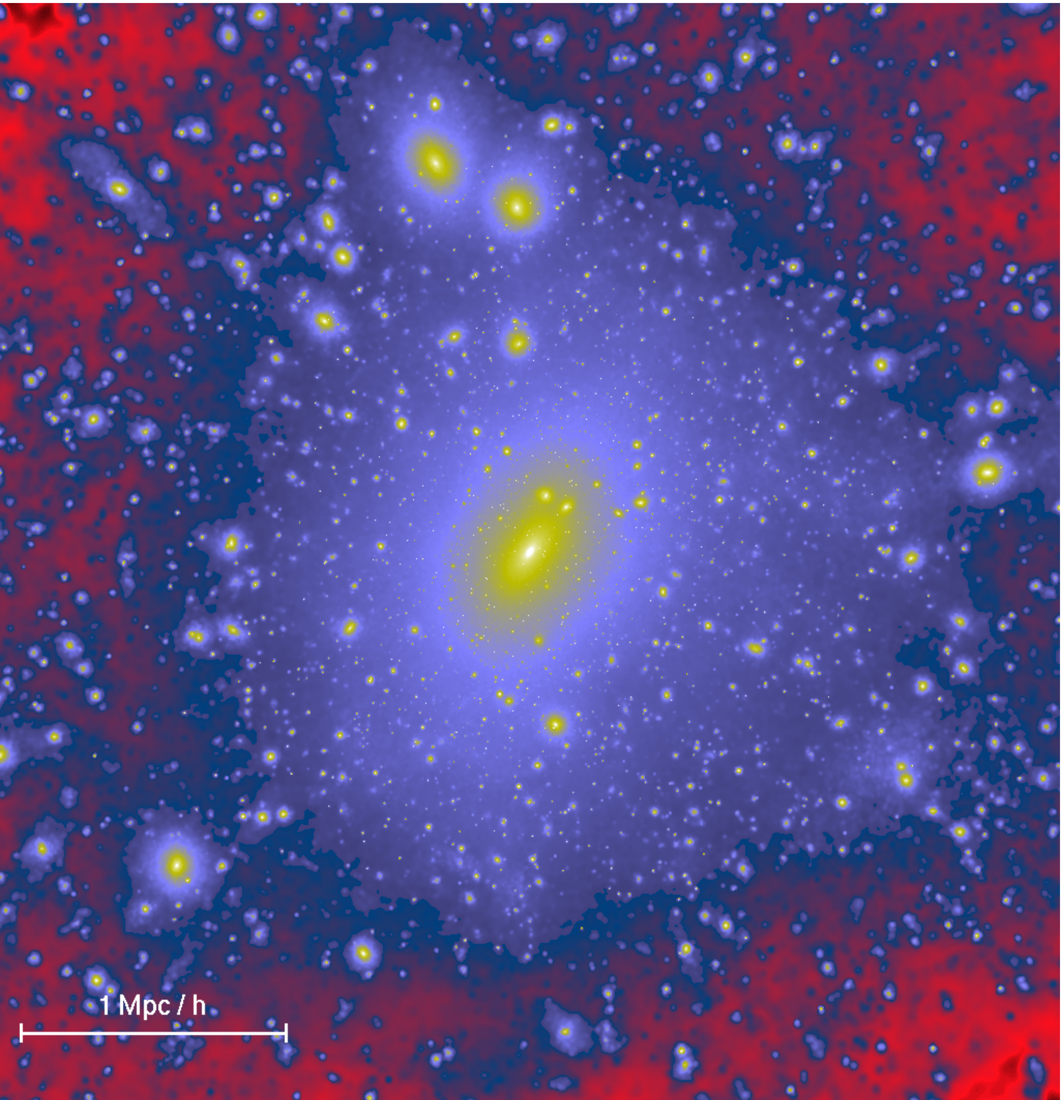
How do these properties affect DM detection experiments?

How can they be used to test the standard paradigm?

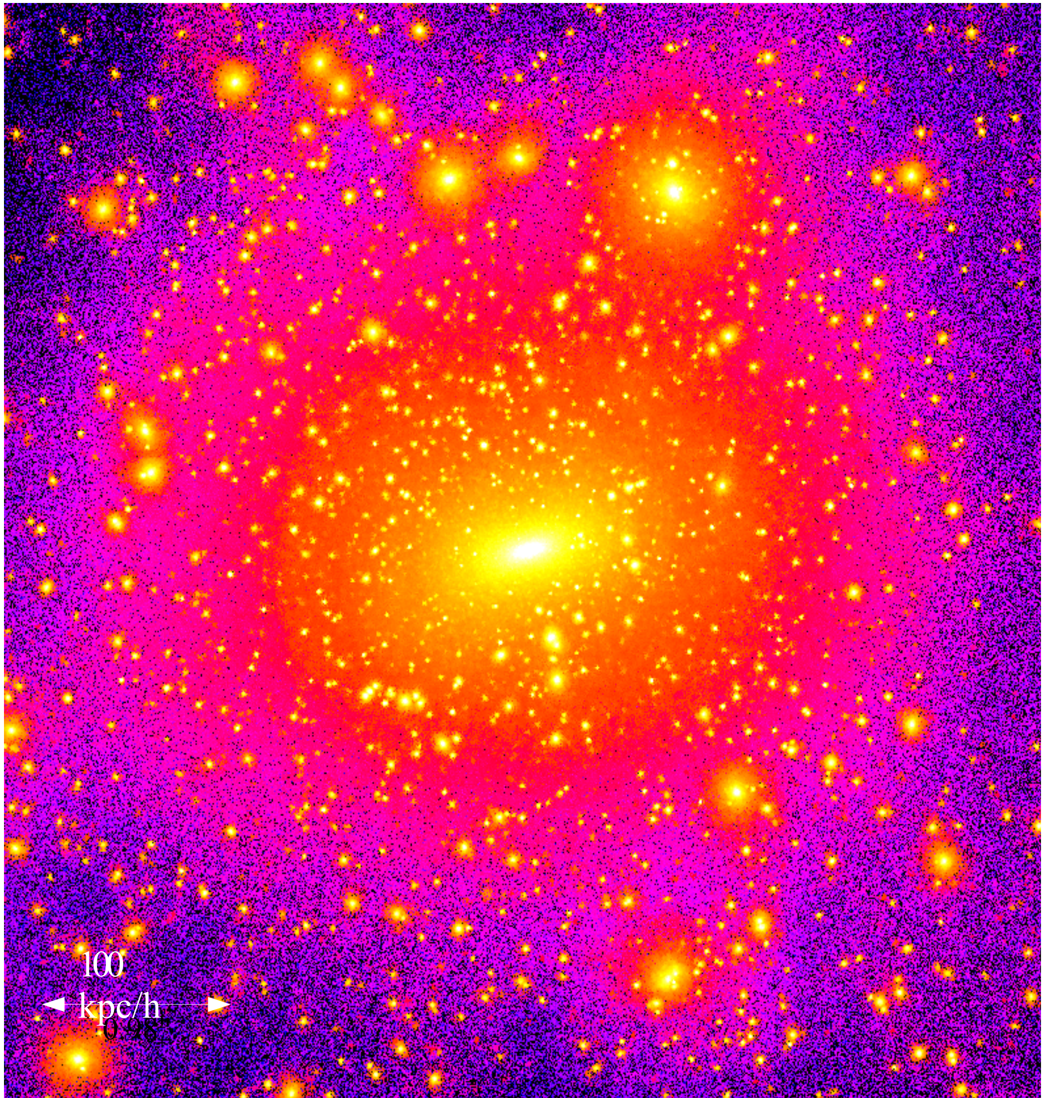
How do they affect/are they affected by the baryonic matter

ΛCDM halos

A rich galaxy cluster halo
Springel et al 2001



A 'Milky Way' halo
Power et al 2002



Excursion set model for structure formation

In linear theory in a dust universe

$$\delta(\mathbf{x}, z) = D(z)\,\delta_o(\mathbf{x}) = (2\pi)^{-3/2} D(z) \int d^3k\, \delta_{\mathbf{k}} \exp(-i\,\mathbf{k.x})$$

where we define D(0) = 1

Consider the smoothed density field

$$\delta_s(\mathbf{x}, z; k_c) = (2\pi)^{-3/2} D(z) \int_{|\mathbf{k}|<k_c} d^3k\, \delta_{\mathbf{k}} \exp(-i\,\mathbf{k.x})$$

and define $\langle \delta_s(\mathbf{x}, z; k_c)^2 \rangle_{\mathbf{x}} = D^2(z)\,\sigma_o^2(k_c)$, $M_s = 6\pi^2 \rho_o k_c^{-3}$

As k_c grows from 0 to ∞, the smoothing mass decreases from ∞ to 0, and $\delta_s(\mathbf{x}, z; k_c)$ executes a random walk

For a <u>gaussian</u> linear overdensity field

$$\Delta\delta_s = \delta_s(\mathbf{x}, z; k_c + \Delta k_c) - \delta_s(\mathbf{x}, z; k_c)$$

is <u>independent</u> of δ_s and has variance $D^2 \Delta\sigma_o^2$

---- A Markov random walk ----

The "Press &Schechter" Ansatz

A uniform spherical "top hat" perturbation virialises when its extrapolated linear overdensity is $\delta_c \approx 1.69$

Assume that at redshift z, the mass element initially at **x** is part of a virialised object with mass M = the largest value for which

$$\delta_s(\mathbf{x}, z; k_c(M)) \geq \delta_c$$

This is the Markov walk's <u>first upcrossing</u> of the <u>barrier</u> $\delta_s = \delta_c$

The fraction of all points with first upcrossing below k_c is then the fraction of cosmic mass in objects with mass above $M_s(k_c)$

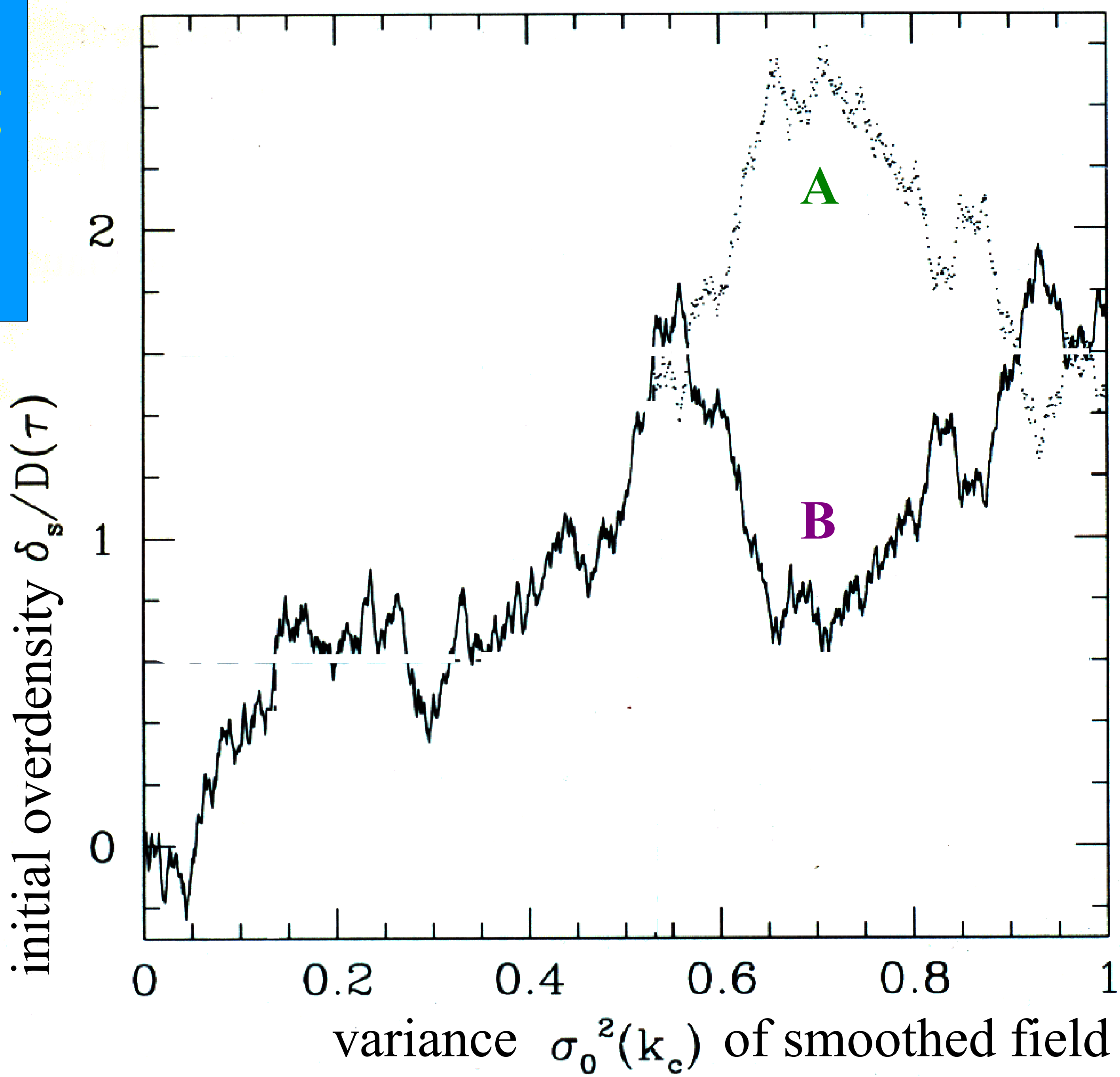
$$\rightarrow \quad n(M, z)\, dM = \frac{-\rho_o}{\sqrt{(2\pi)}\, M^2} \frac{\delta_c}{D\,\sigma_o} \frac{d \ln \sigma_o^{\,2}}{d \ln M} \exp -\frac{1}{2}\left(\frac{\delta_c}{D\,\sigma_o}\right)^2$$

Overdensity vs smoothing at a given position

If the density field is smoothed using a sharp filter in k-space, then each step in the random walk is independent of all earlier steps

A Markov process

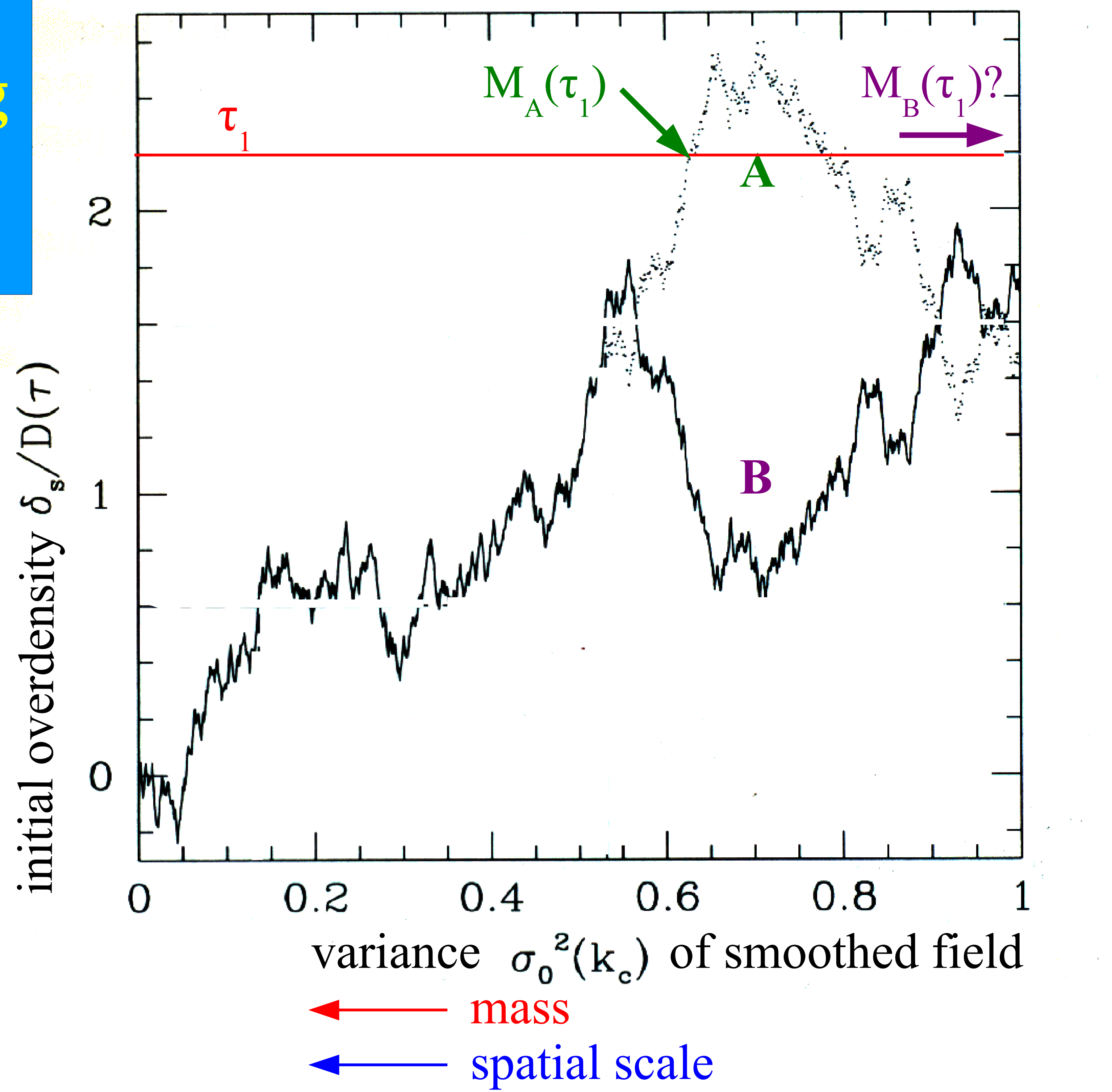
The walks shown at positions A and B are equally probable



← mass

← spatial scale

Overdensity vs smoothing at a given position

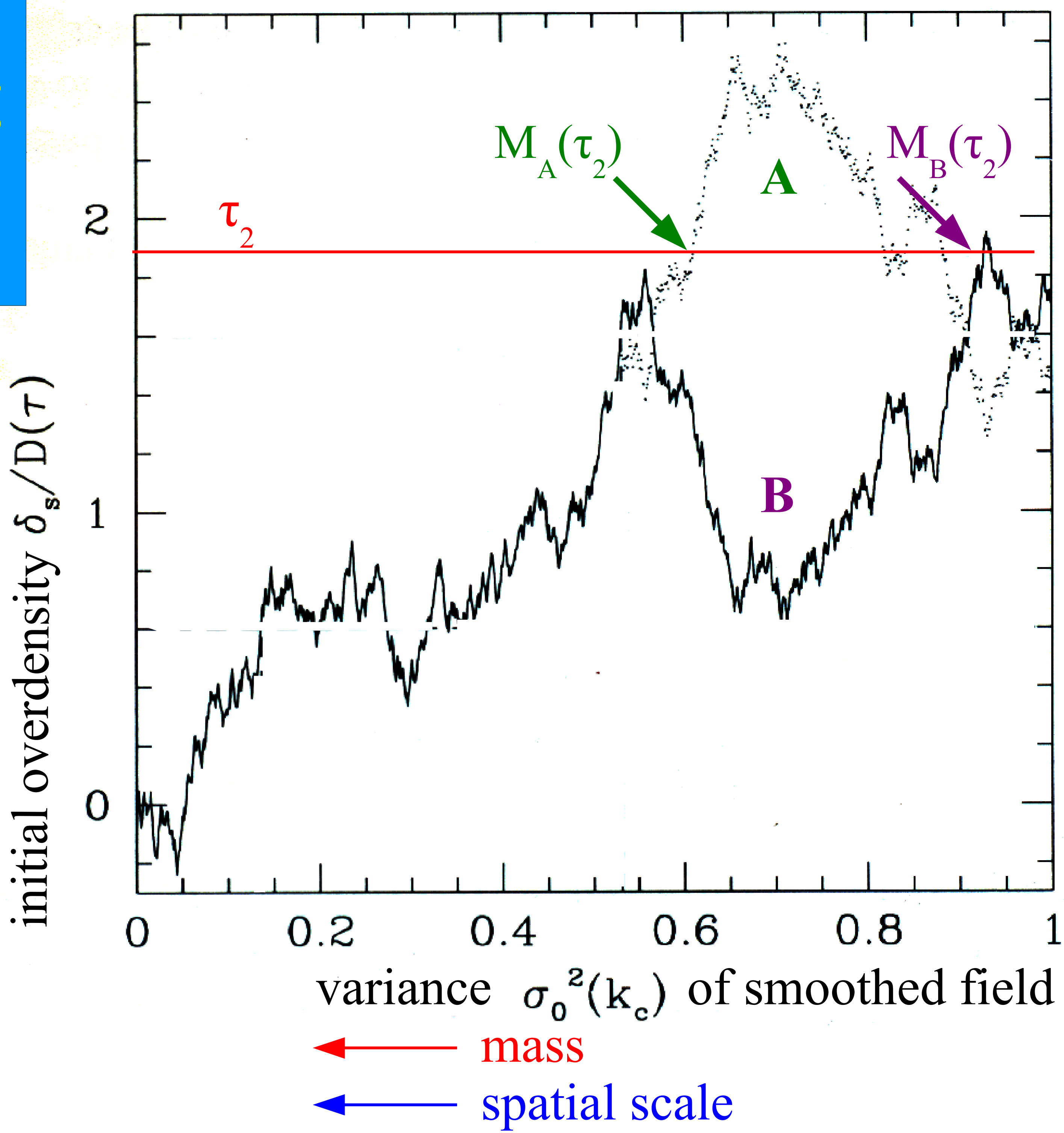


At an early time τ_1

A is part of a quite massive halo

B is part of a very low mass halo or no halo at all

Overdensity vs smoothing at a given position



Later, at time τ_2

A's halo has grown slightly by accretion

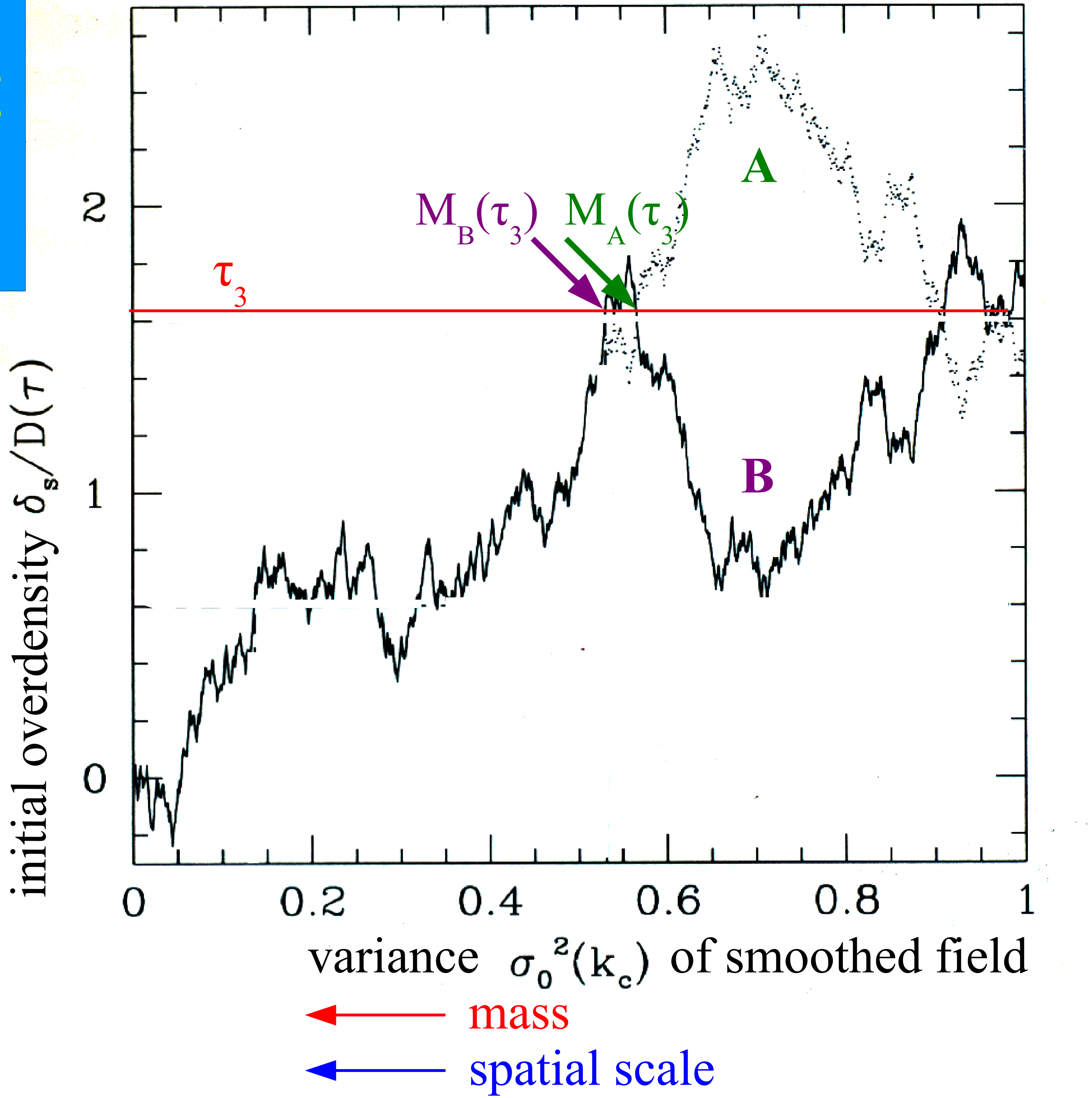
B is now part of a moderately massive halo

Overdensity vs smoothing at a given position

A bit later, time τ_3

A's halo has grown further by accretion

B's halo has merged again and is now more massive than **A**'s halo

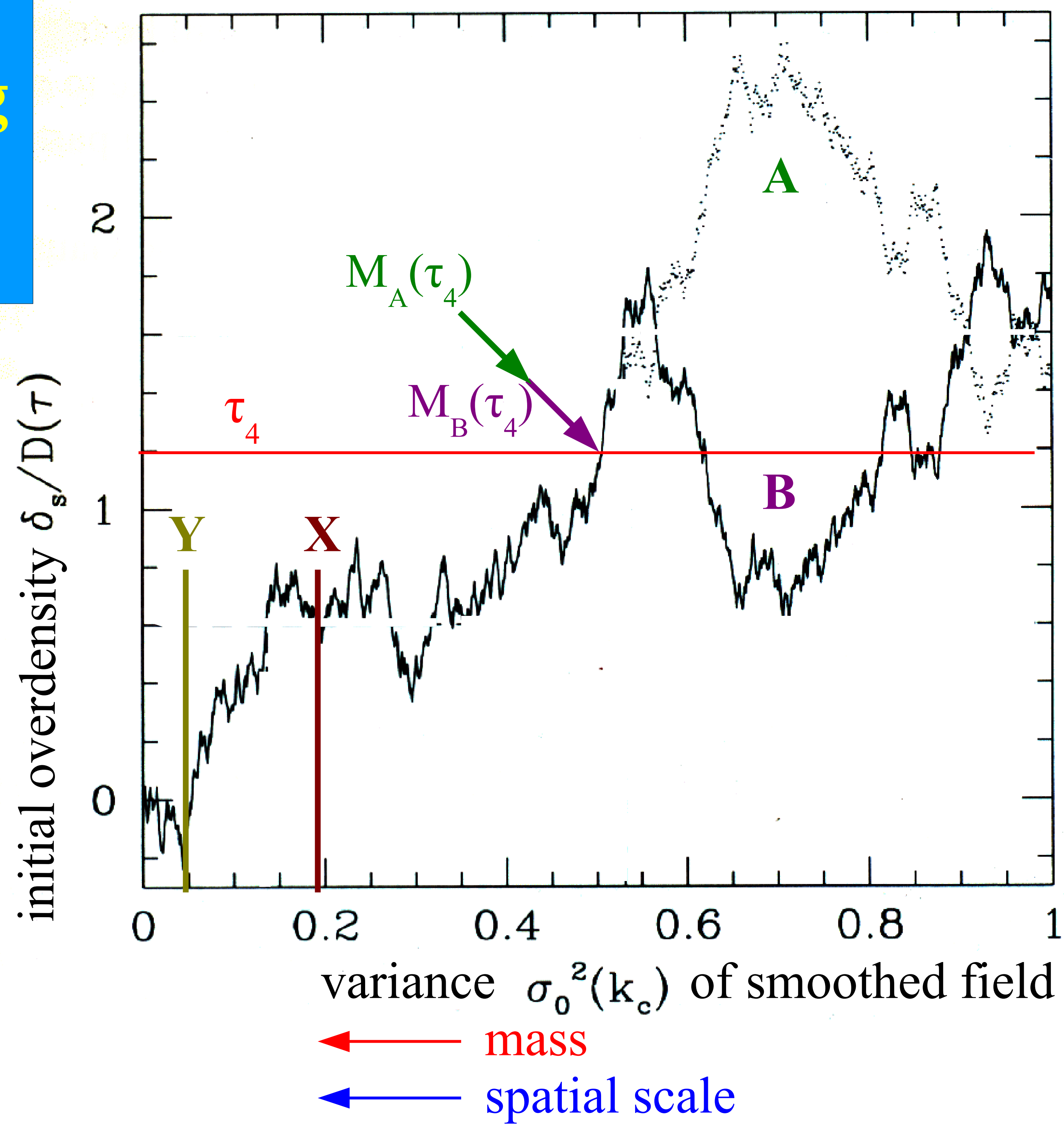


Overdensity vs smoothing at a given position

Still later, e.g. τ_4

A and **B** are part of halos which follow identical merging/ accretion histories

On scale **X** they are embedded in a high density region.
On larger scale **Y** in a low density region



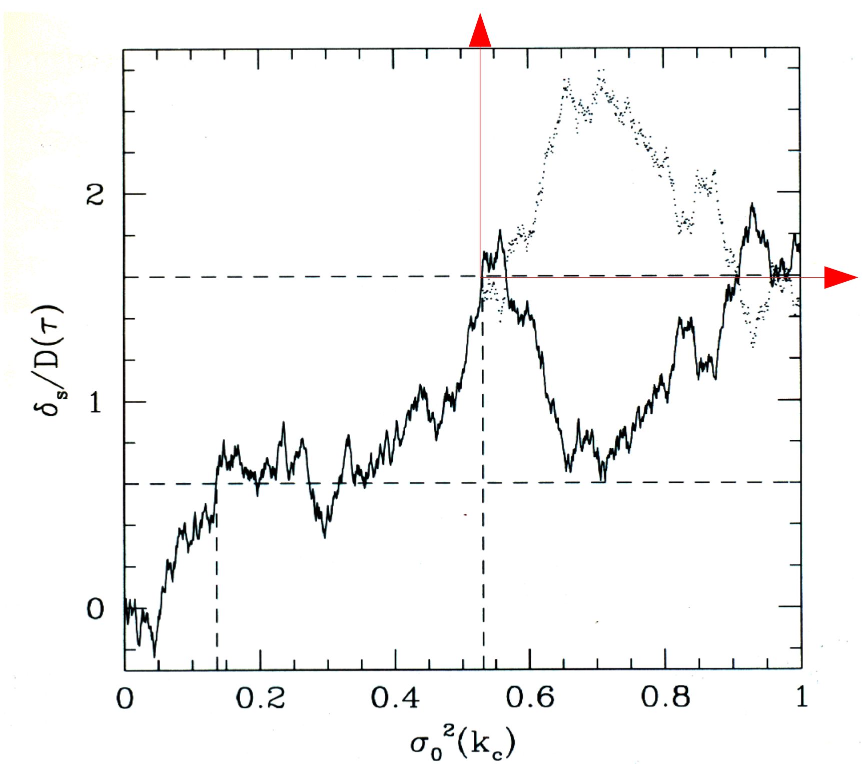
Consequences of the Markov nature of EPS walks

The assembly history of a halo is <u>independent</u> of its future

The assembly history of a halo is <u>independent</u> of its environment

The internal structure of a halo is <u>independent</u> of its environment

The mass distribution of progenitors of a halo of given M and z is obtained simply by changing the origin to $\sigma_o^2(M)$ and $\delta_c/D(z)$

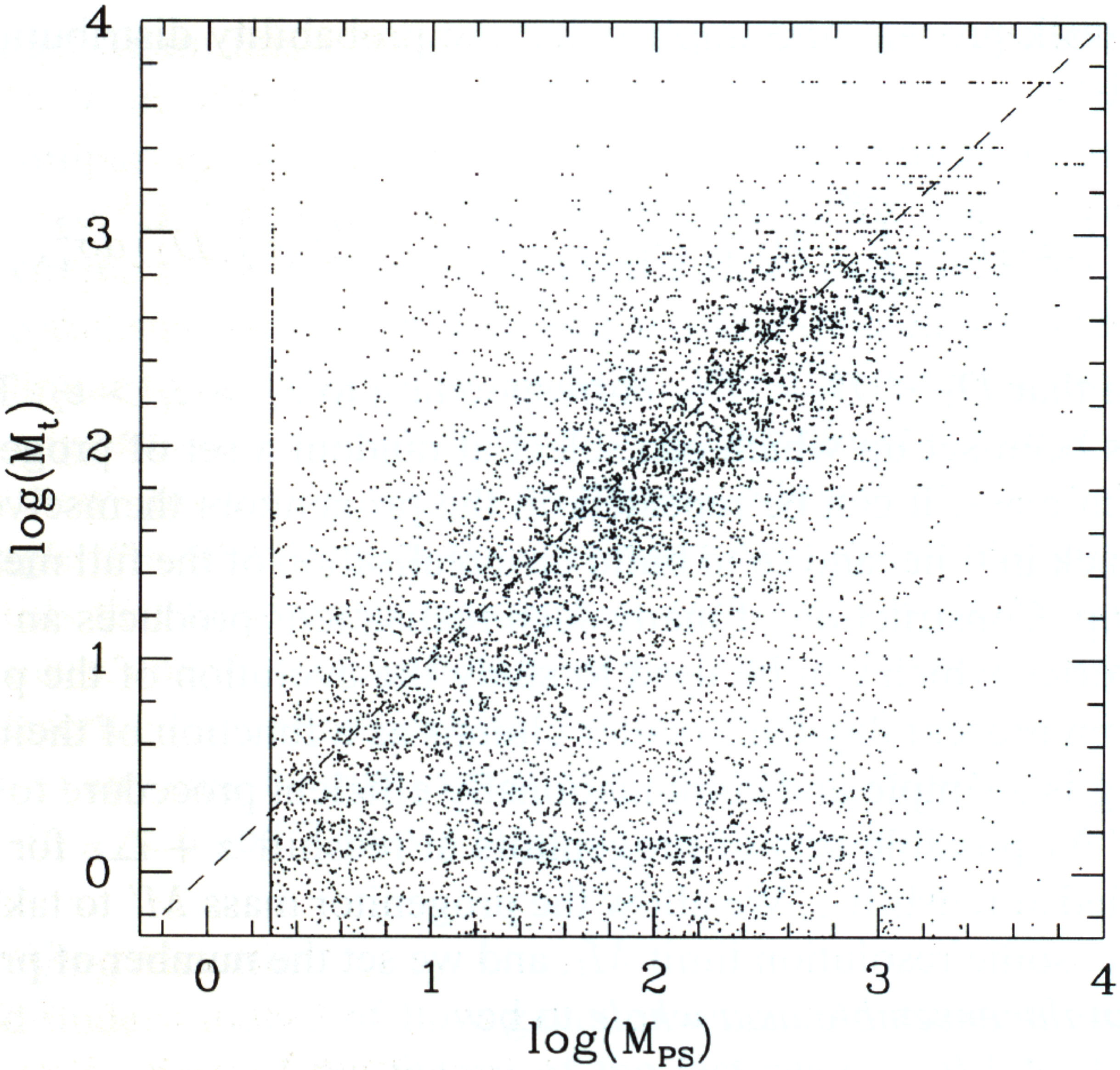


The resulting formulae can be used to obtain descendant distributions and merger rates

A similar argument gives formulae for the clustering bias of halos

Does it work point by point?

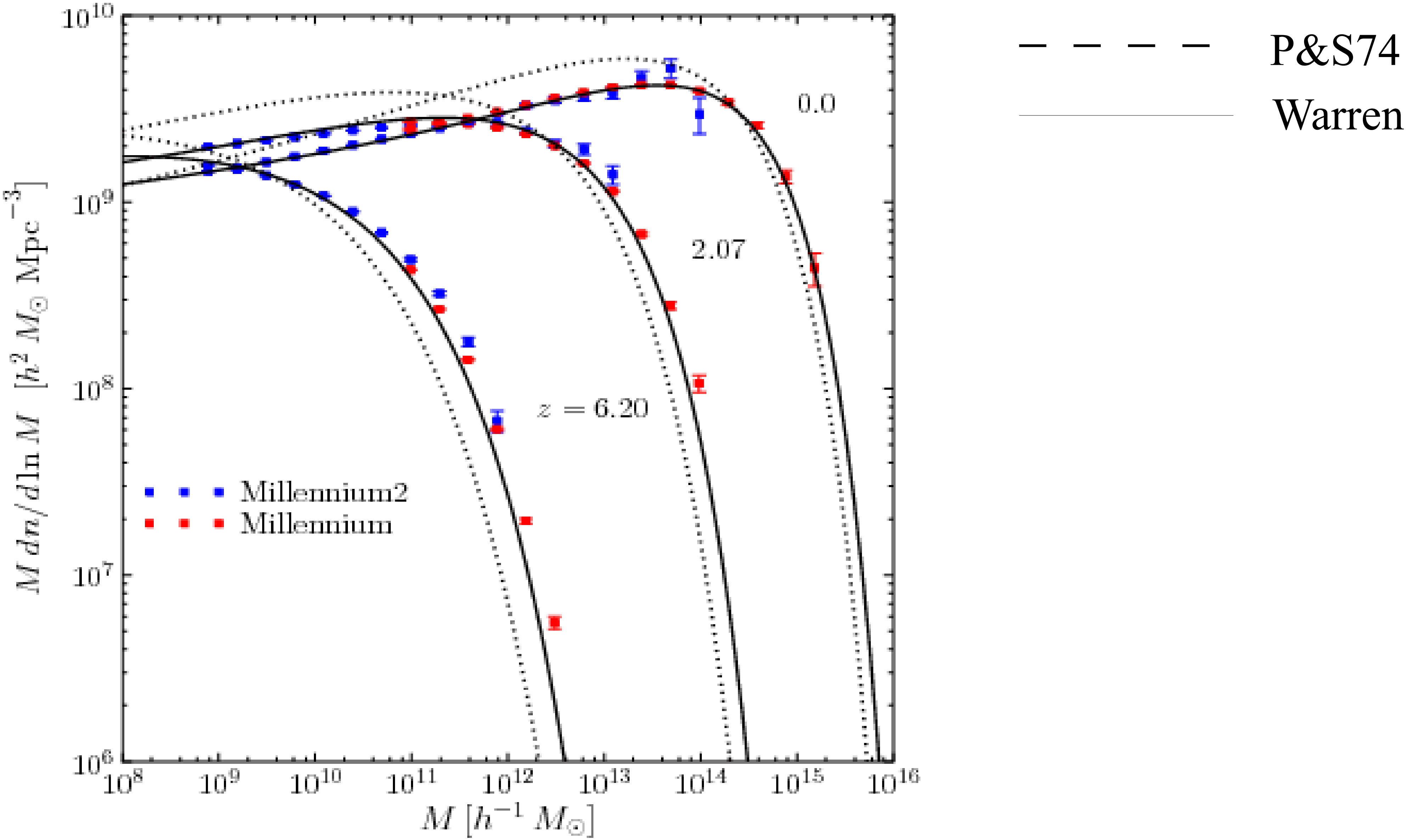
Mass of the halo in which the particle is actually found



Halo mass predicted for each particle by its own sharp k-space random walk

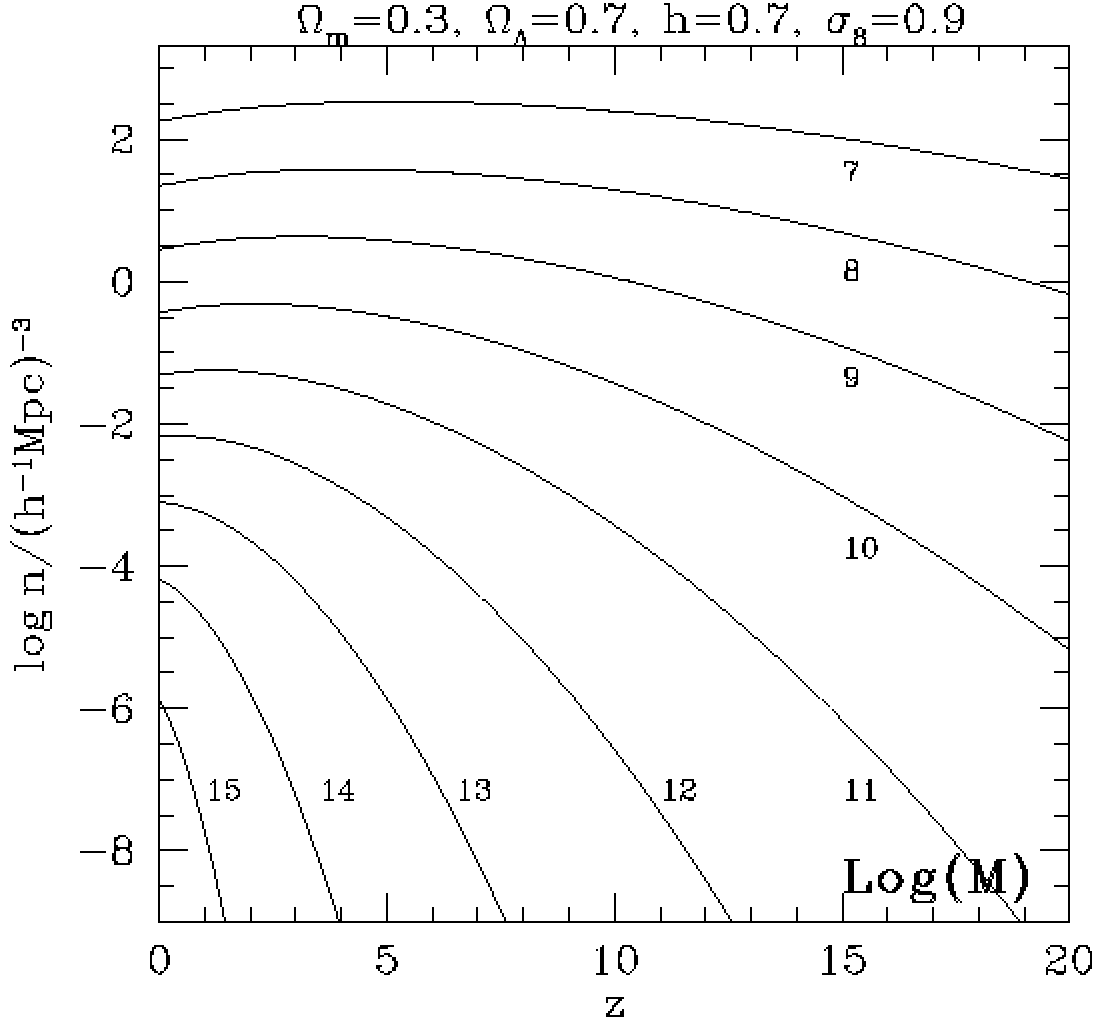
Does it work statistically?

Boylan-Kolchin et al 2009



Evolution of halo abundance in ΛCDM

Mo & White 2002



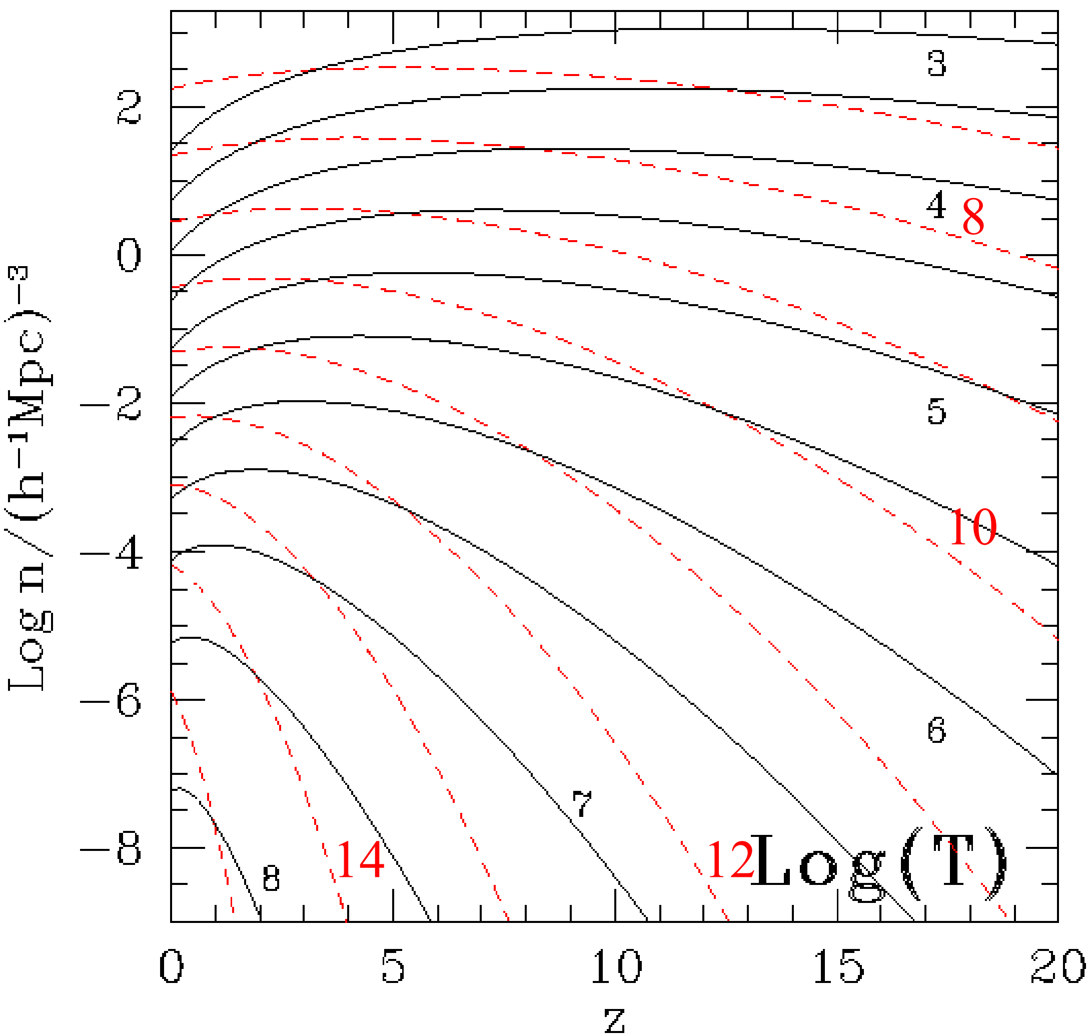
Abundance of rich cluster halos drops rapidly with z

Abundance of Milky Way mass halos drops by less than a factor of 10 to z=5

$10^9 M_\odot$ halos are almost as common at z=10 as at z=0

Evolution of halo abundance in ΛCDM

Mo & White 2002



Temperature increases with both mass and redshift

$$T \propto M^{2/3}(1+z)$$

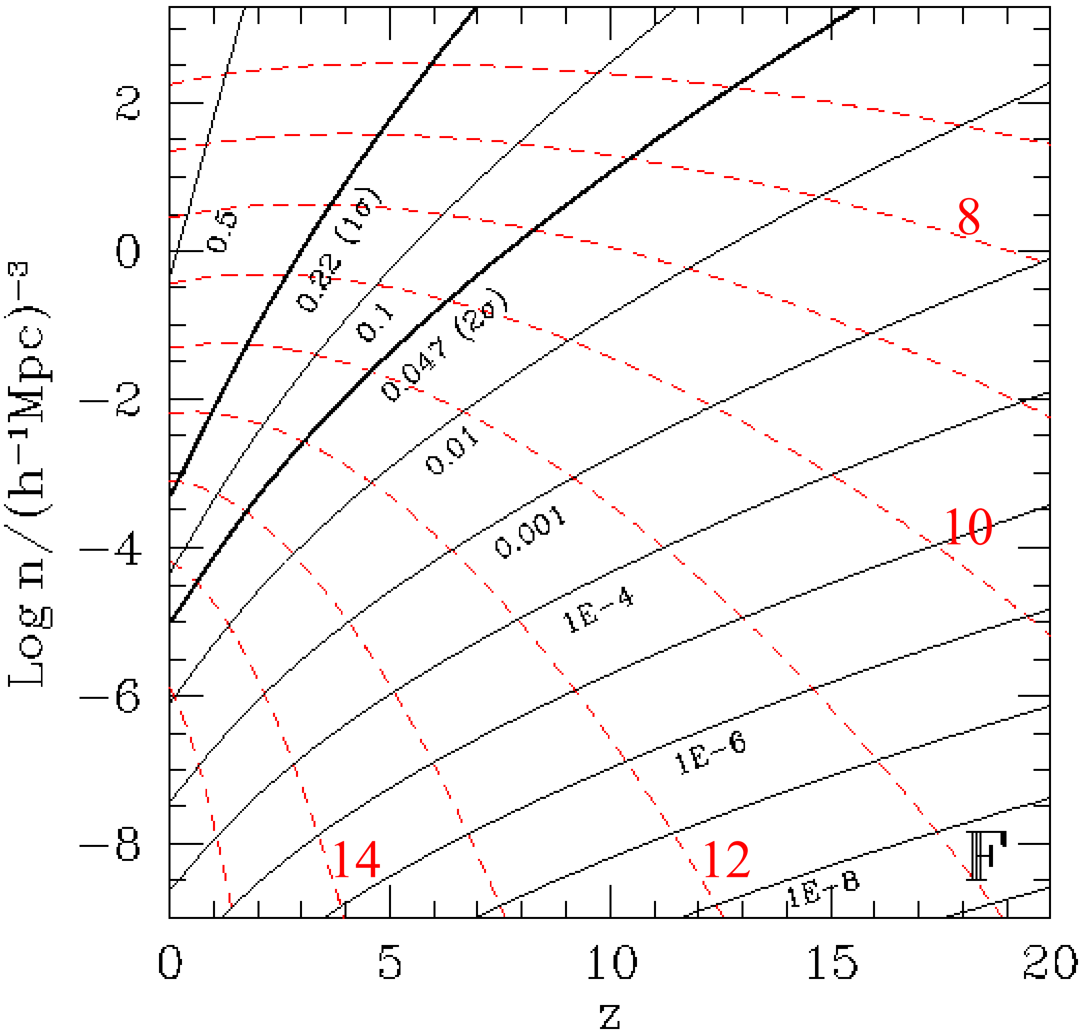
Halos with virial temperature $T = 10^7$ K are as abundant at $z = 2$ as at $z=0$

Halos with virial temperature $T = 10^6$ K are as abundant at $z = 8$ as at $z=0$

Halos of mass $>10^{7.5} M_\odot$ have $T > 10^4$ K at $z=20$ and so can cool by H line emission

Evolution of halo abundance in ΛCDM

Mo & White 2002



Half of all mass is in halos more massive than $10^{10}M_\odot$ at z=0, but only 10% at z=5, 1% at z=9 and 10^{-6} at z=20

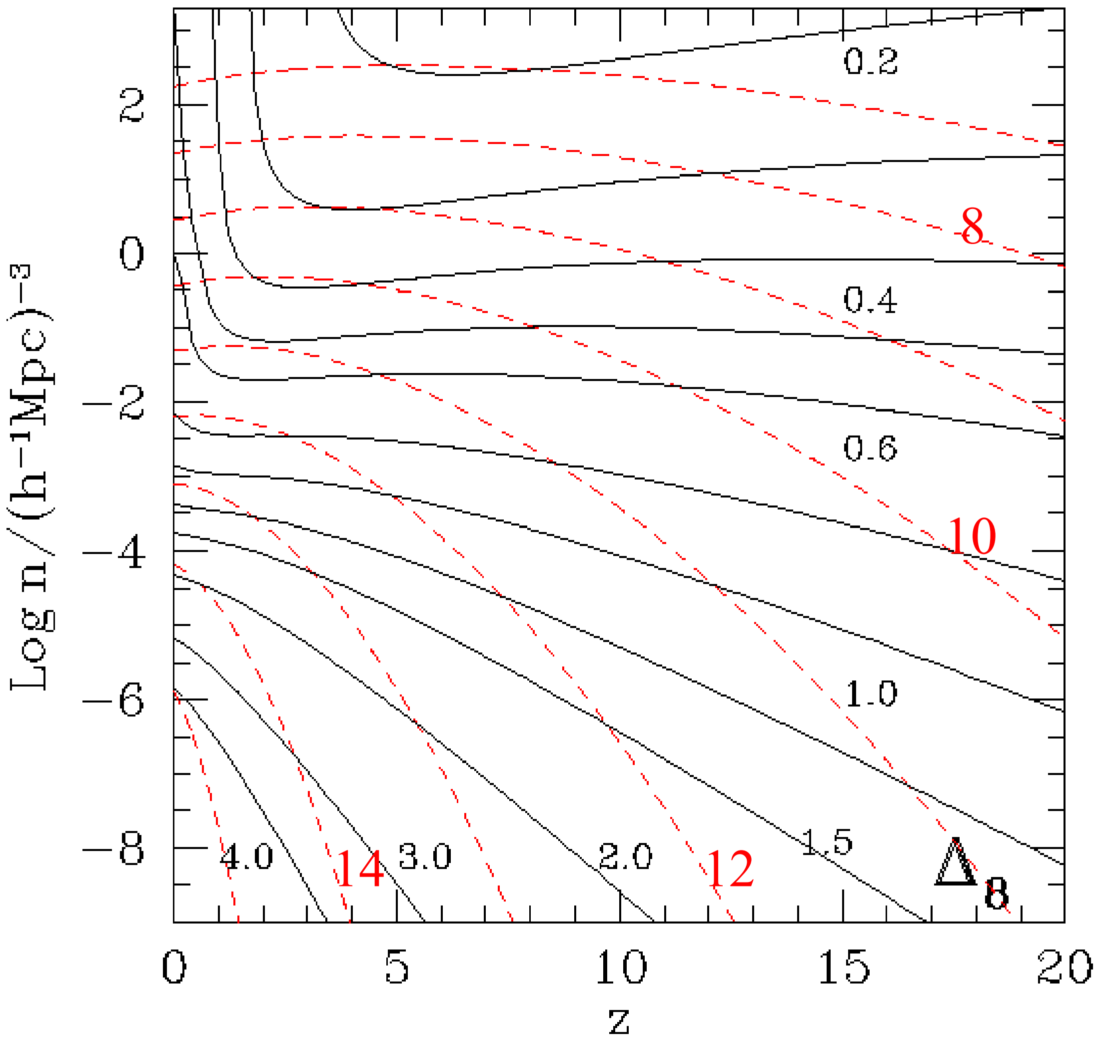
1% of all mass is in halos more massive than $10^{15}M_\odot$ at z=0

40% of all mass at z=0 is in halos which cannot confine photoionised gas

1% of all mass at z=15 is in halos hot enough to cool by H line emission

Evolution of halo abundance in ΛCDM

Mo & White 2002



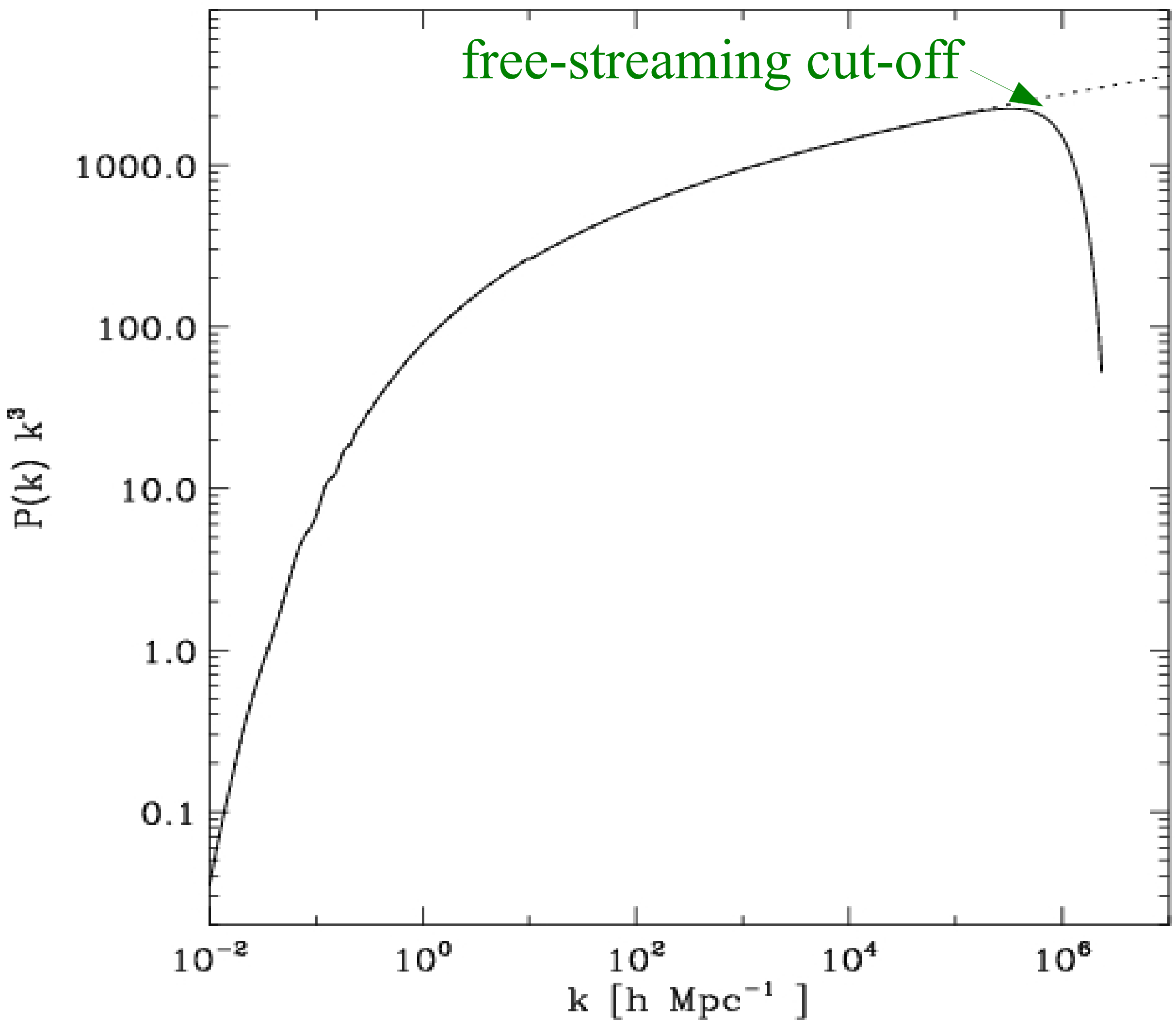
Halos with the abundance of L_* galaxies at z=0 are equally strongly clustered at all z < 20

Halos of given mass or virial temperature are more clustered at *higher* z

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo et al 2009



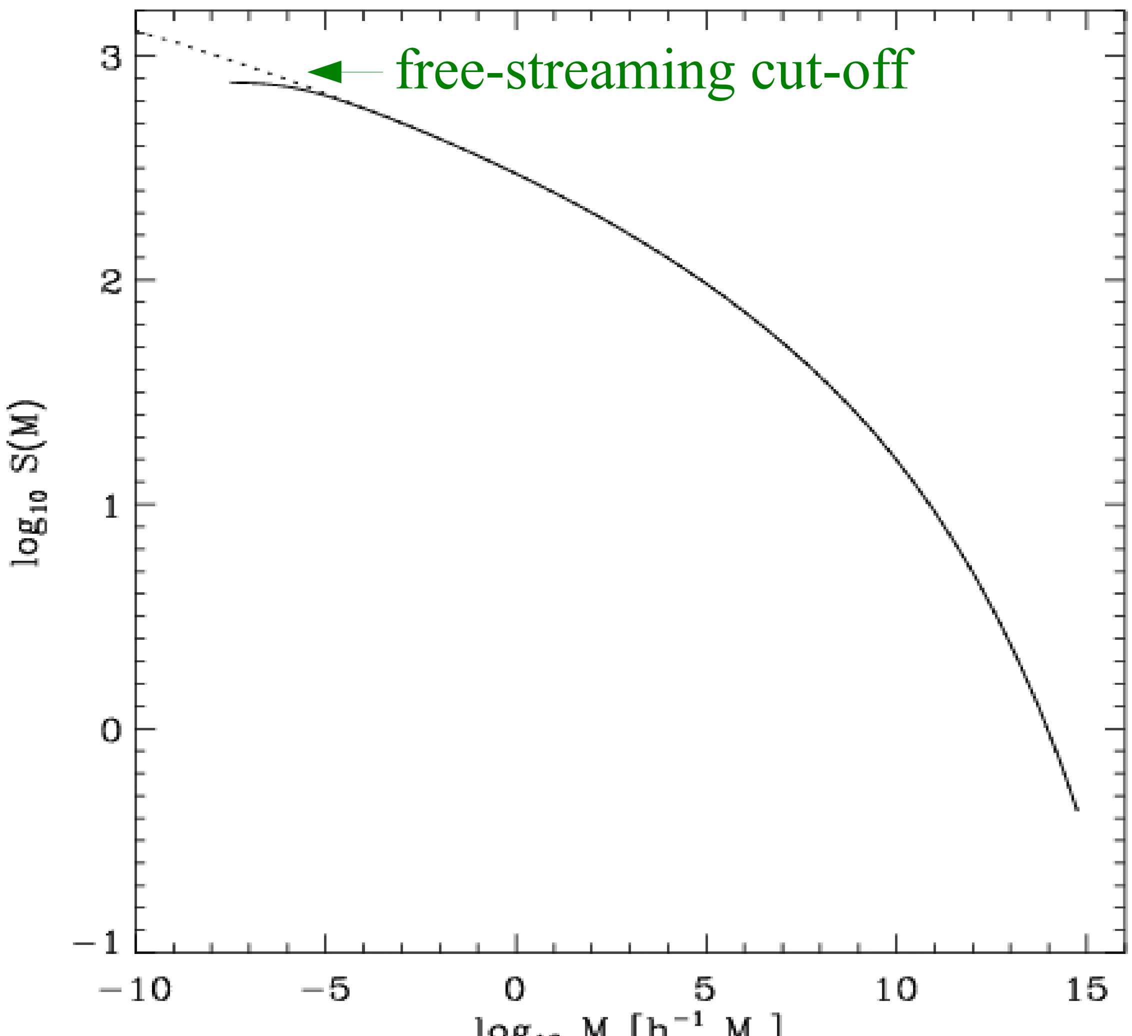
The linear power spectrum in "power per octave" form

Assumes a 100GeV wimp following Green et al (2004)

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo et al 2009

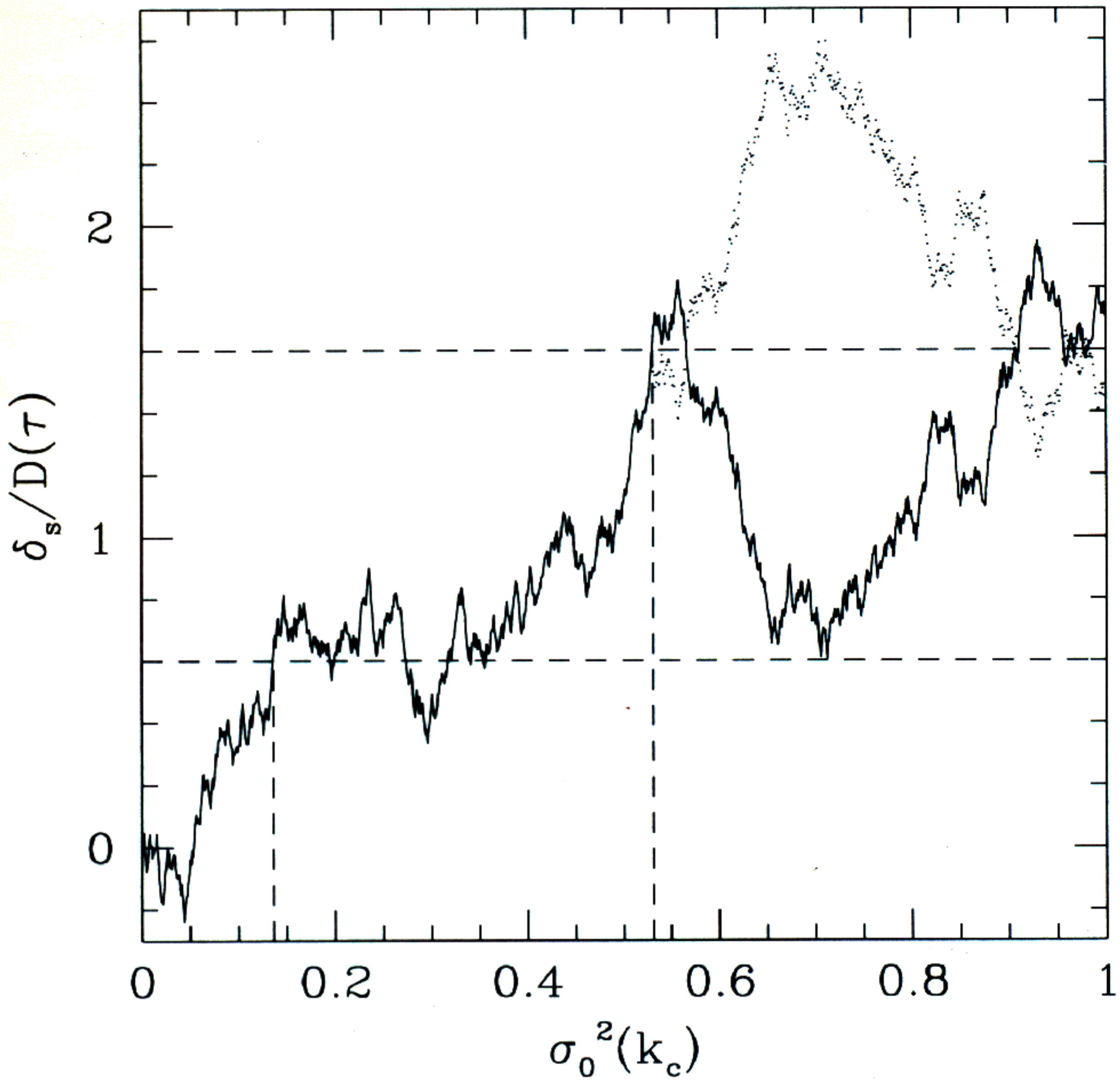


Variance of linear density fluctuation within spheres containing mass M, extrapolated to z = 0

As $M \rightarrow 0$, $S(M) \rightarrow 720$

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$



If these Markov random walks are scaled so the maximum variance is 720 and the vertical axis is multiplied by √720, then they represent complete halo assembly histories for random CDM particles.

An ensemble of walks thus represents the probability distribution of assembly histories

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

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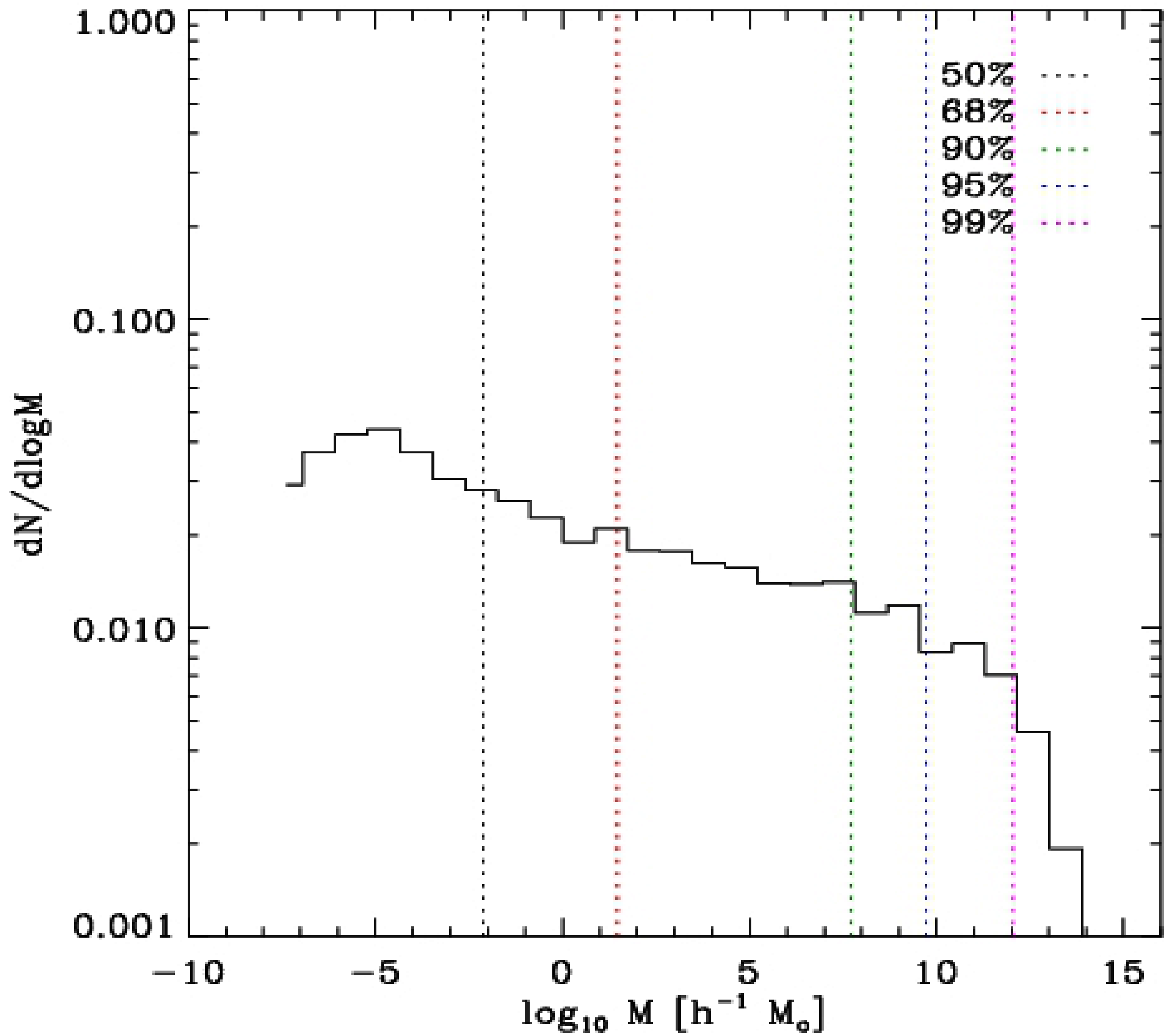


Distribution of the masses of the <u>first</u> halos for a random set of dark matter particles

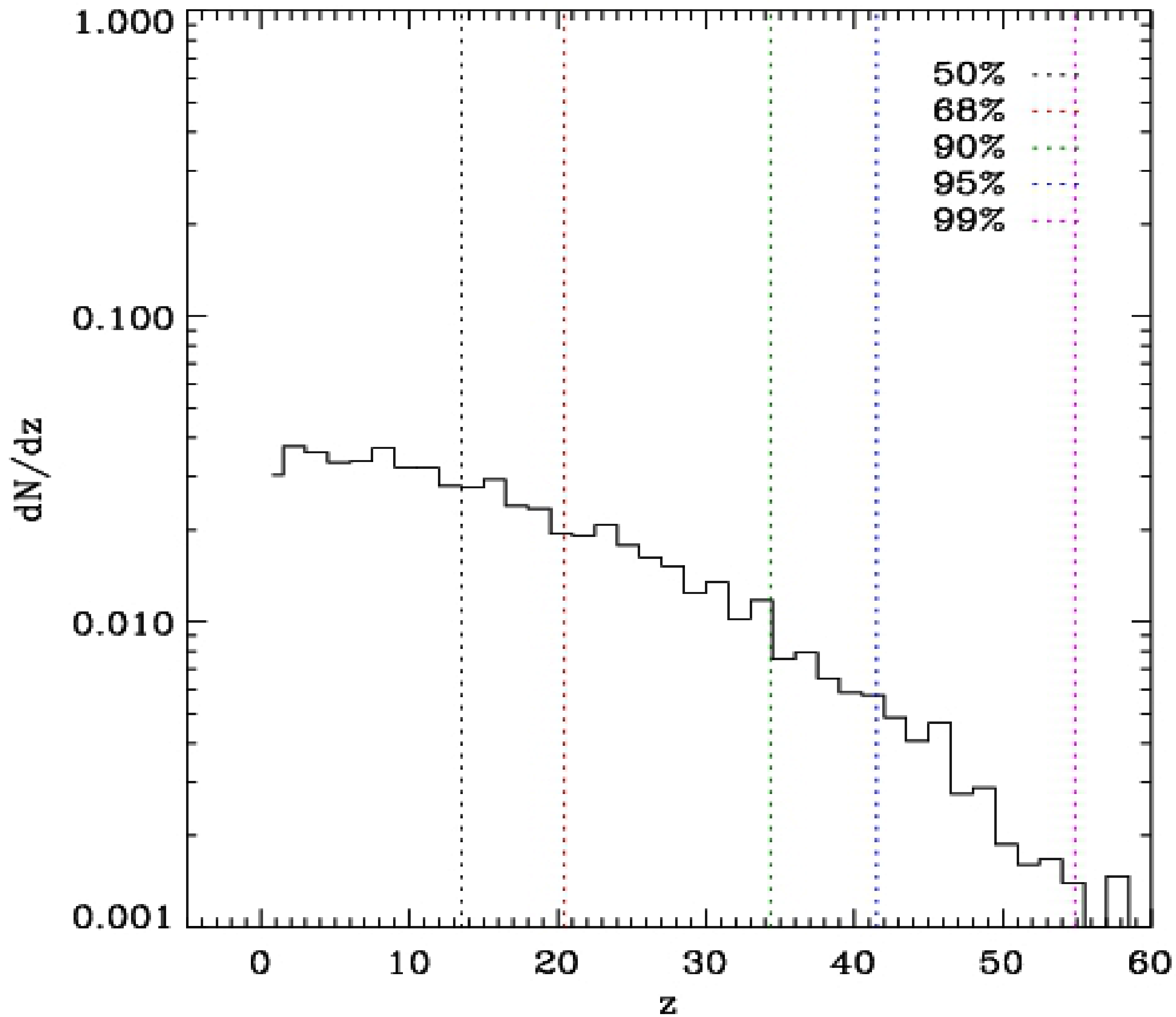
The median is $10^{-2} M_\odot$

For 10% of the mass the first halo has $M > 10^7 M_\odot$

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo et al 2009



Distribution of the collapse redshifts of the first halos for a random set of dark matter particles

The median is z = 13

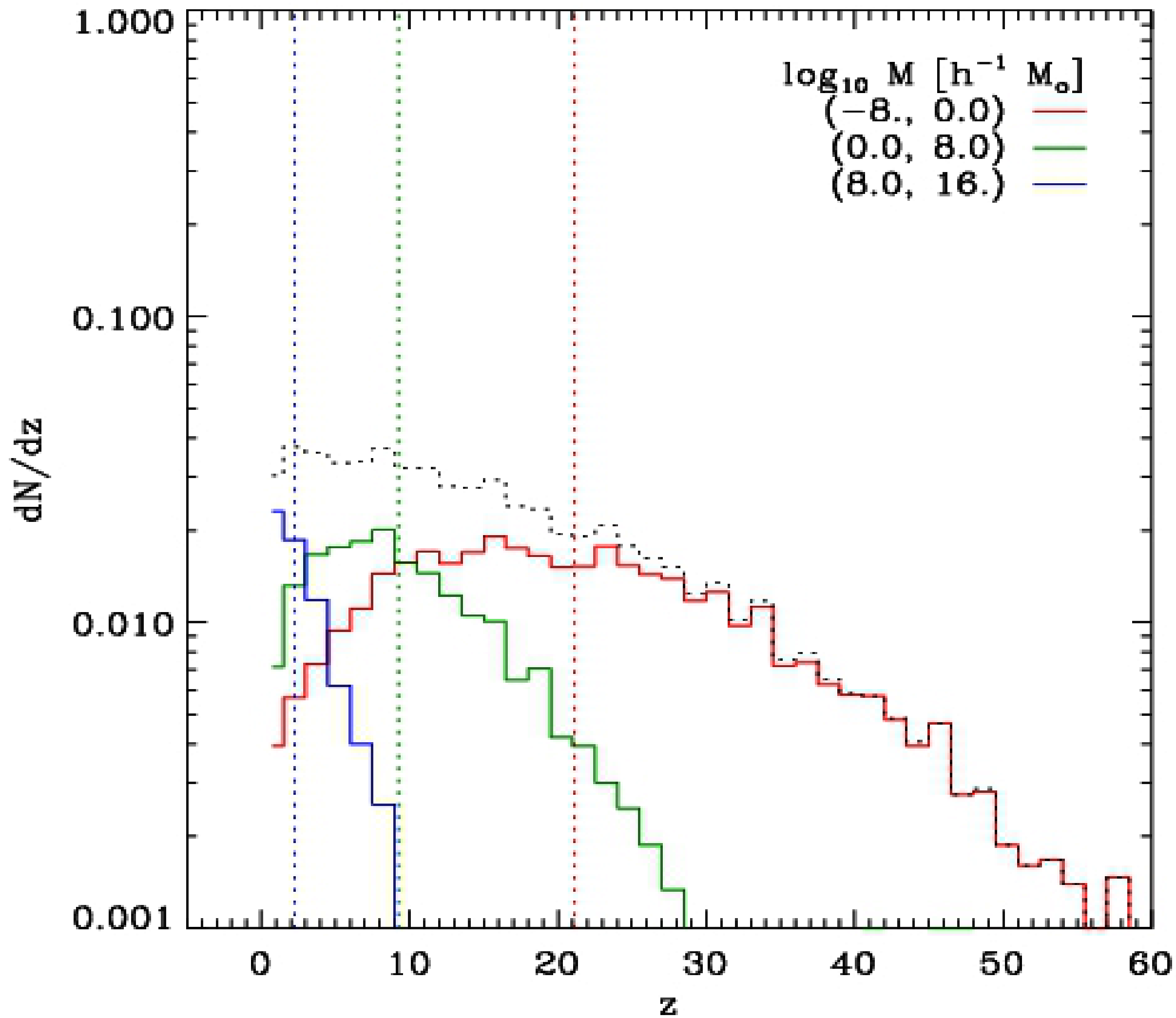
For 10% of the mass the first halo collapses at z > 34

For 1% at z > 55

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo et al 2009



Distribution of the collapse redshifts of the first halos for dark matter particles split by the mass of the first object

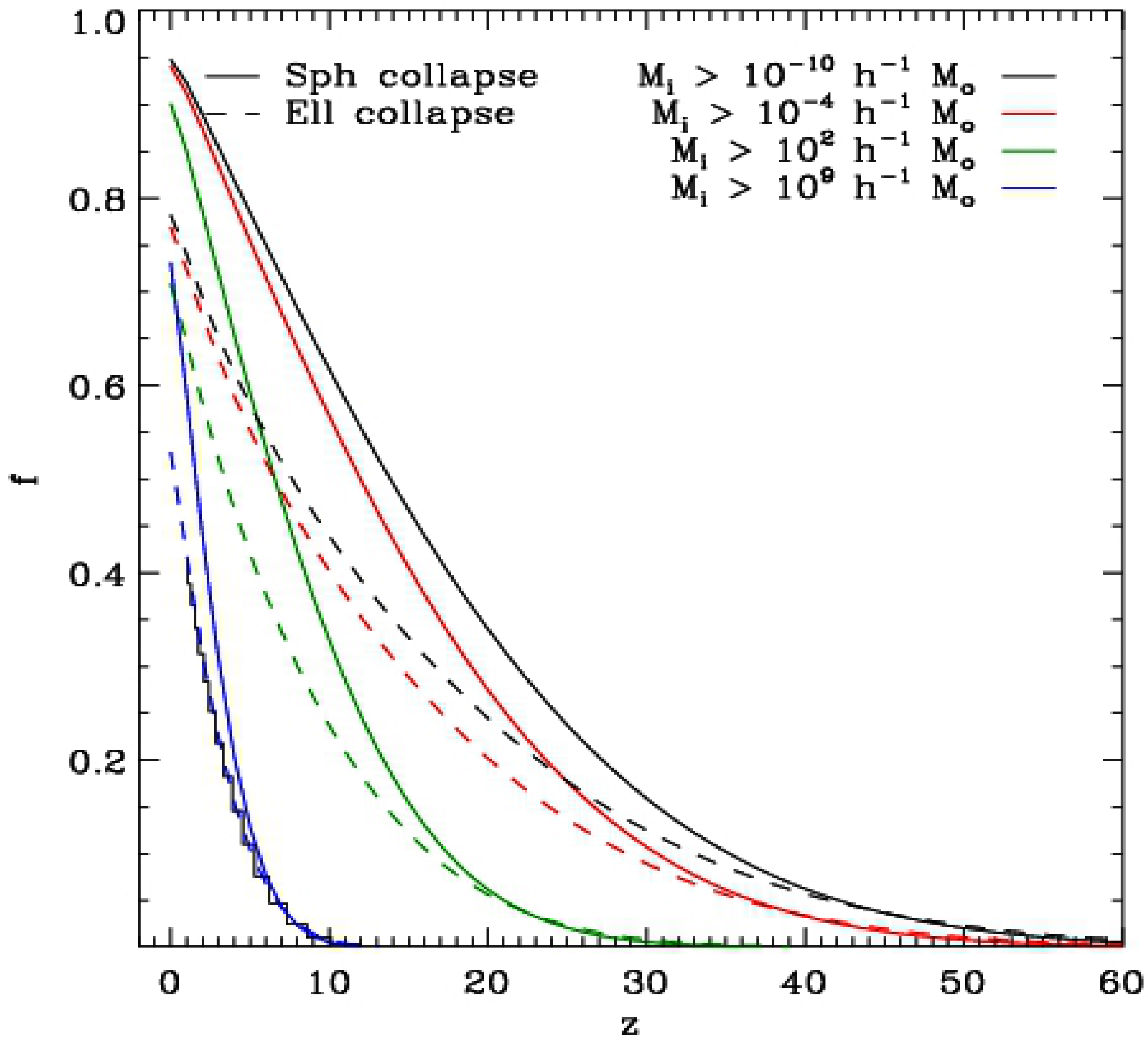
The high redshift tail is entirely due to matter in small first halos

For first halo masses below a solar mass, the median collapse redshift is z = 21

EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, n=1, $\sigma_8 = 0.9$

Angulo et al 2009



Total mass fraction in halos

At z = 0 about 5% (Sph) or 20% (Ell) of the mass is still diffuse

Beyond z = 50 almost all the mass is diffuse

Only at z < 2 (Sph) or z<0.5 (Ell) is most mass in halos with $M > 10^8 M_\odot$ The "Ell" curve agrees with simulations

EPS halo assembly: conclusions

The typical first halo is much more massive than the free streaming mass

First halos typically collapse quite late $z \sim 13$

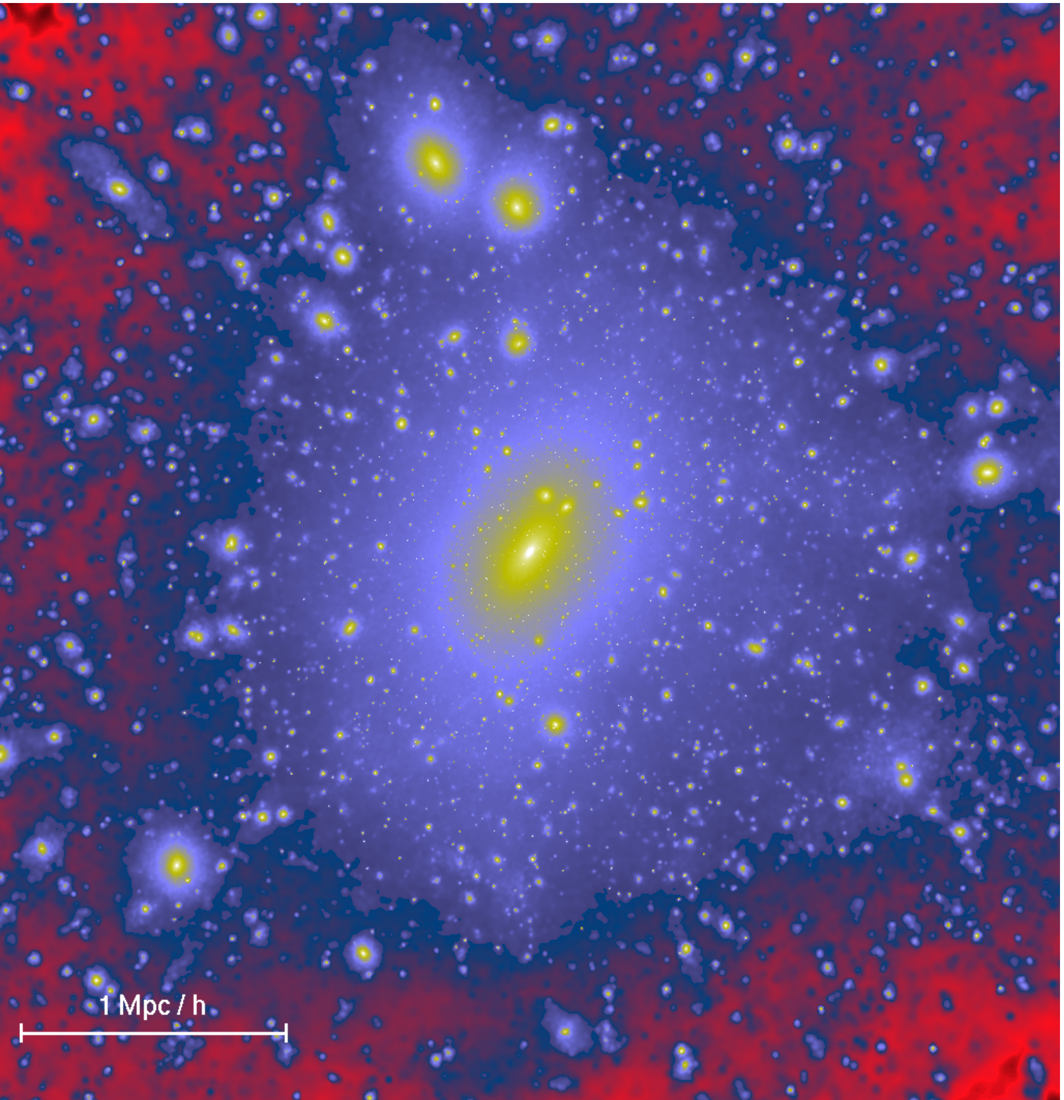
Halo growth occurs mainly by accretion of much smaller halos

There are rather few "generations" of accretion/merger events

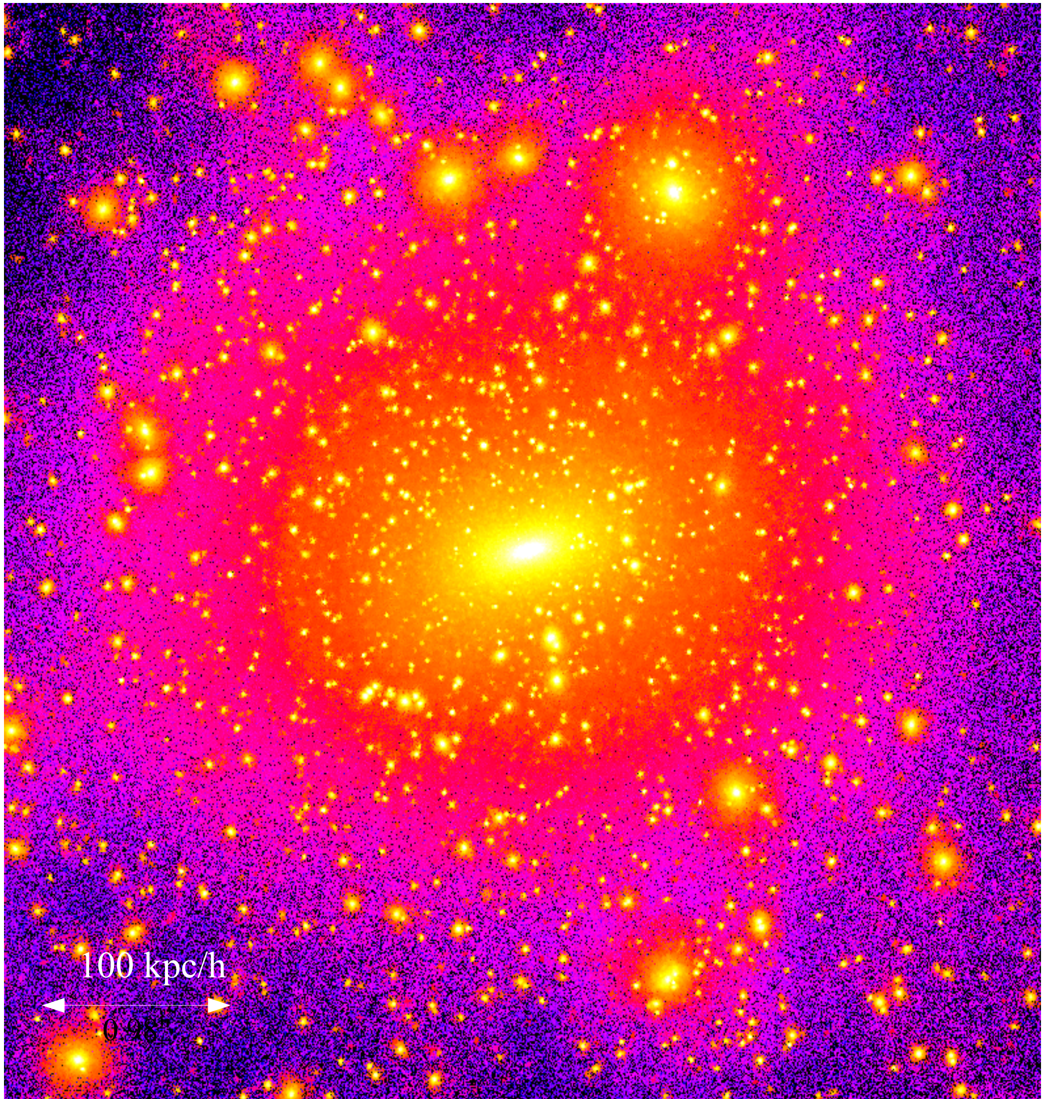
Major mergers are not a major part of the growth of most halos

The dark matter structure of ΛCDM halos

A rich galaxy cluster halo
Springel et al 2001



A 'Milky Way' halo
Power et al 2002



ΛCDM galaxy halos (without galaxies!)

Halos extend to ~10 times the 'visible' radius of galaxies and contain ~10 times the mass in the visible regions

Halos are not spherical but approximate triaxial ellipsoids

- more prolate than oblate
- axial ratios greater than two are common

"Cuspy" density profiles with outwardly increasing slopes

$-d \ln \varrho / d \ln r = \gamma$ with $\gamma < -2.5$ at large r

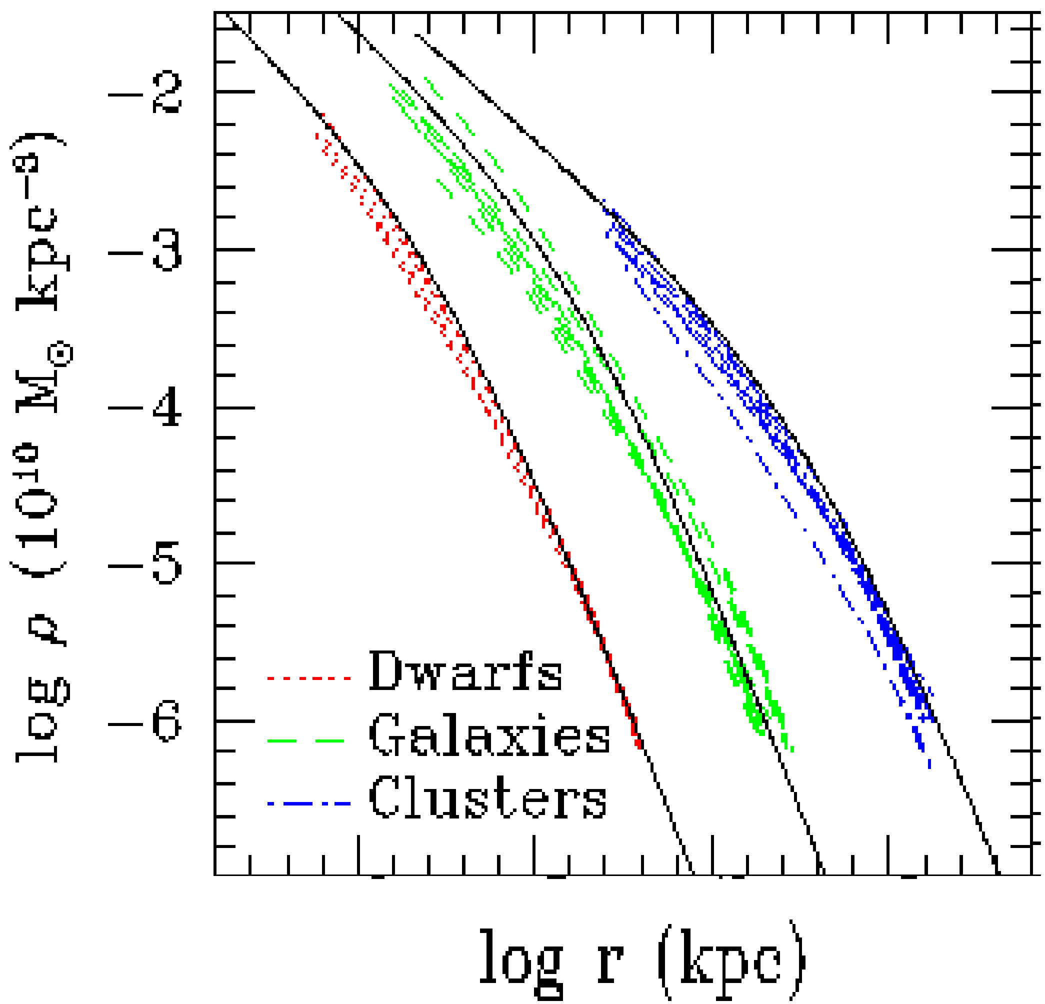
$\gamma > -1.2$ at small r

Substantial numbers of self-bound subhalos contain ~10% of the halo's mass and have $dN/dM \sim M^{-1.9}$

→ Most substructure mass is in the most massive subhalos

Density profiles of dark matter halos

Navarro, Frenk & White 1996



The average dark matter density of a dark halo depends on distance from halo centre in a very similar way in halos of all masses at all times

-- a universal profile shape --

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

Less massive halos and halos that form earlier have higher densities (bigger δ)

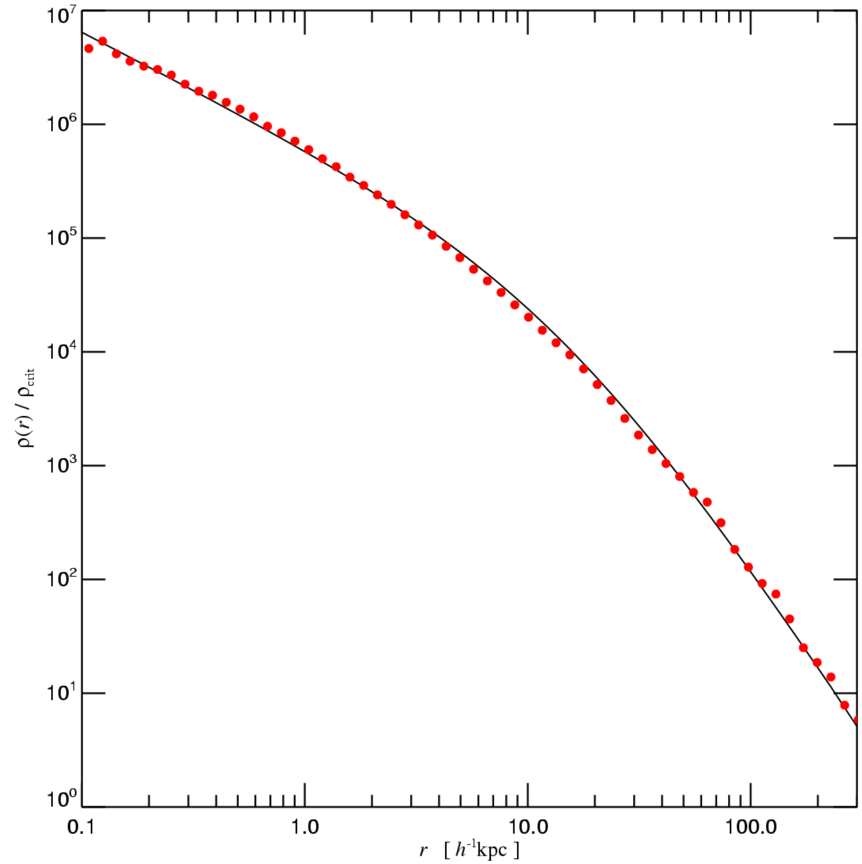
Concentration $c = r_{200} / r_s$ is an alternative density measure

Beware variety of definitions!

NFW profiles may not be pretty....

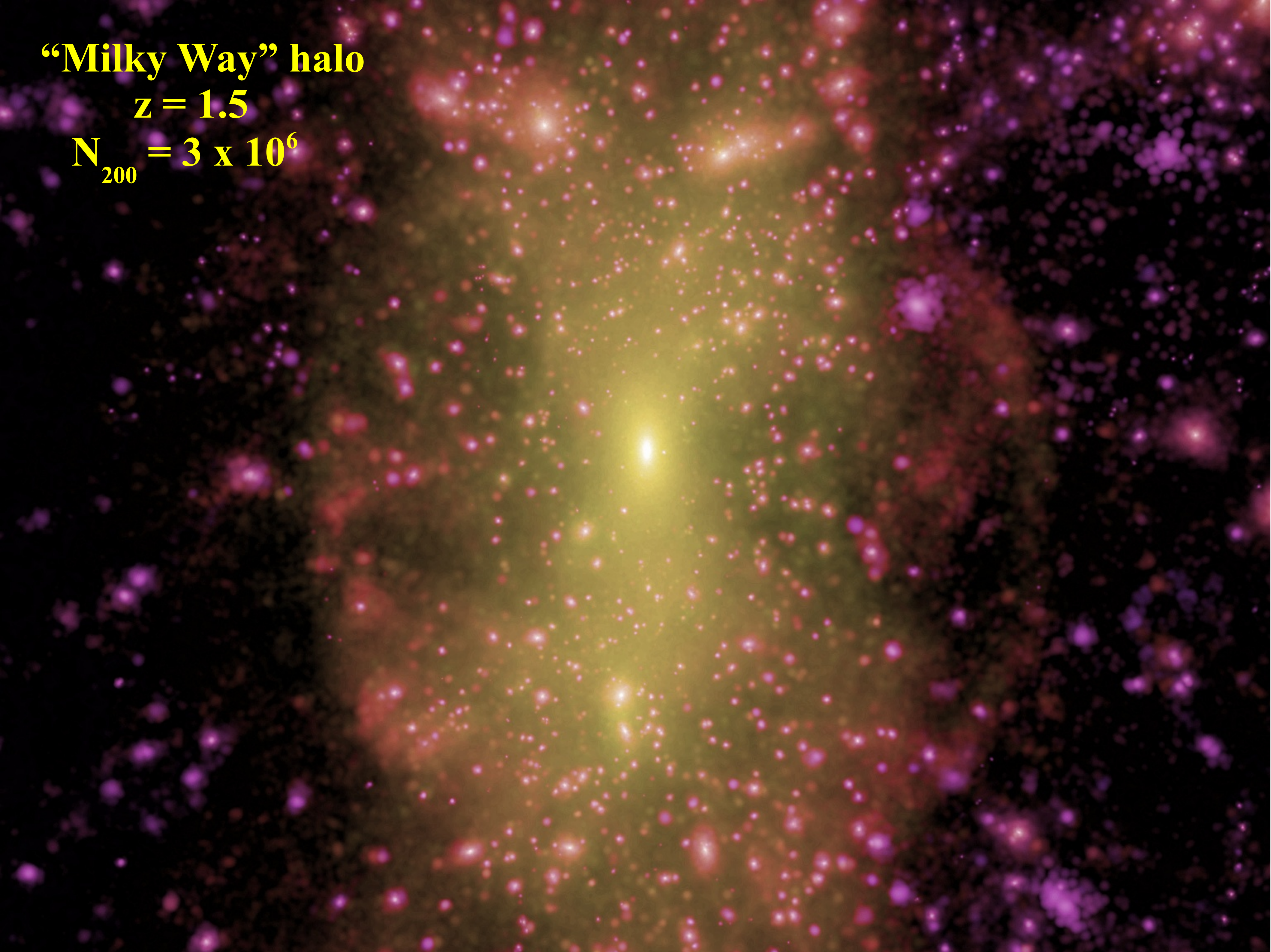
...but they work surprisingly well

600 kpc



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

Navarro et al 2006

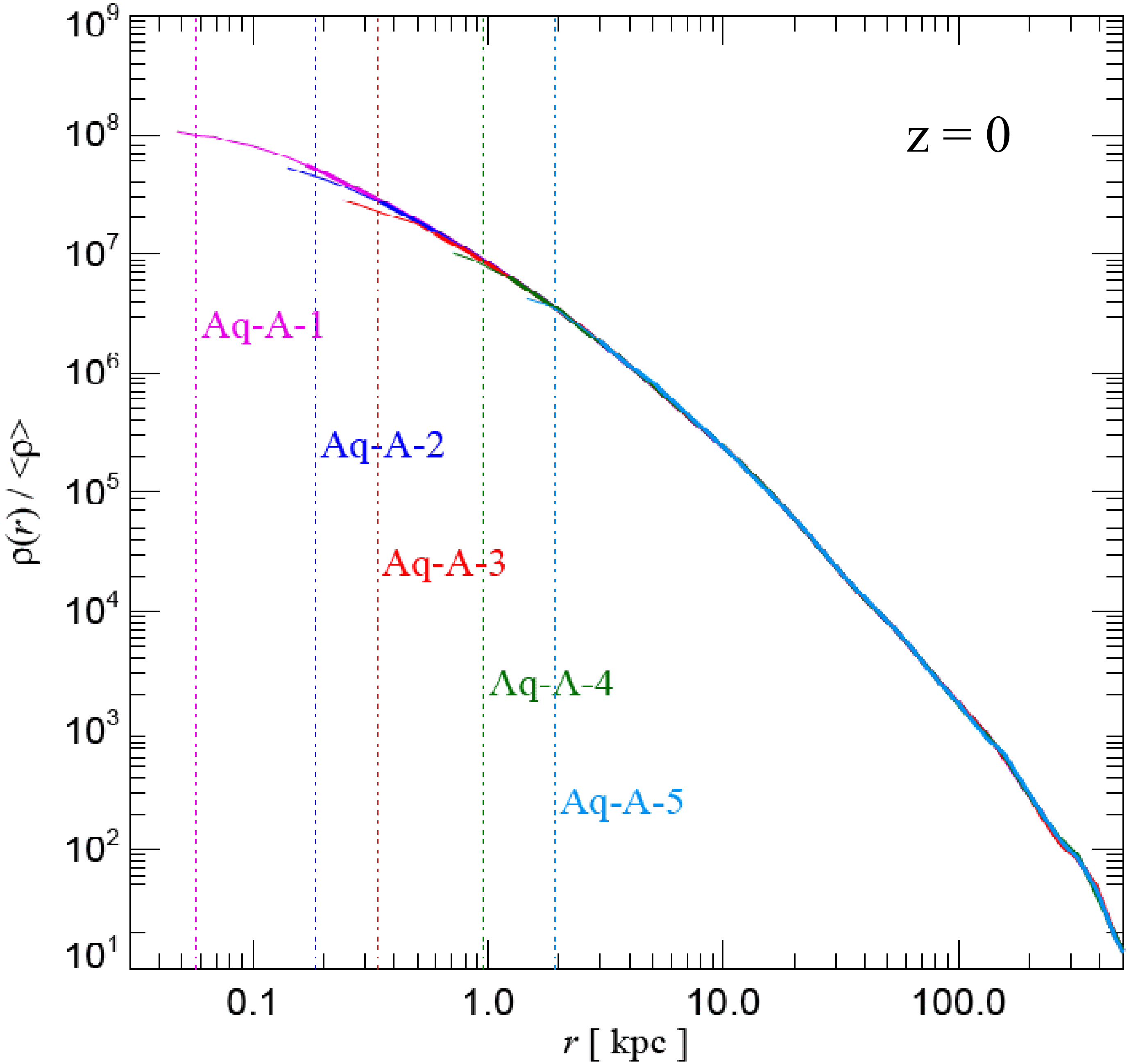

"Milky Way" halo
z = 1.5
N200 = 3 x 10^6


"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



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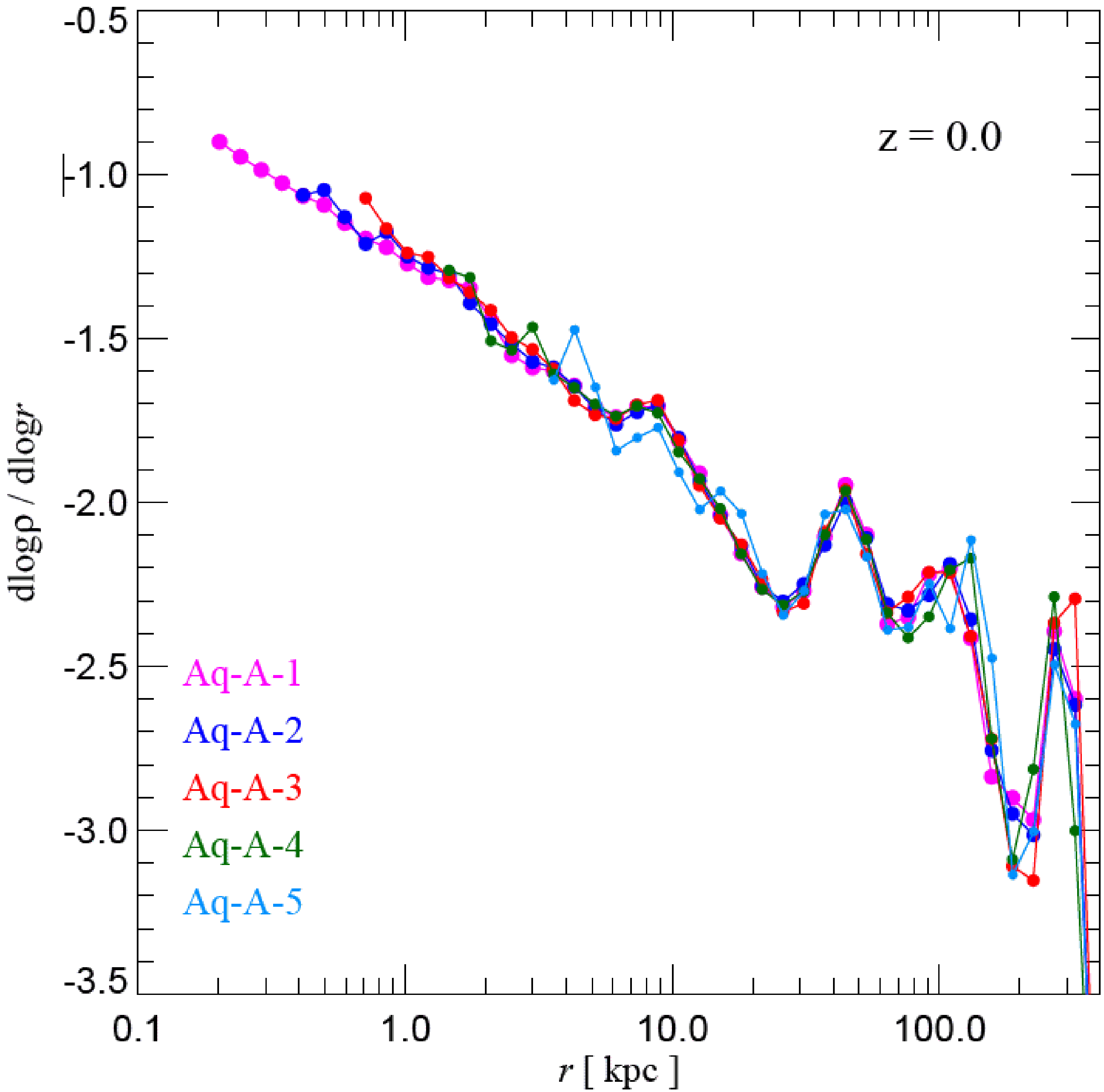
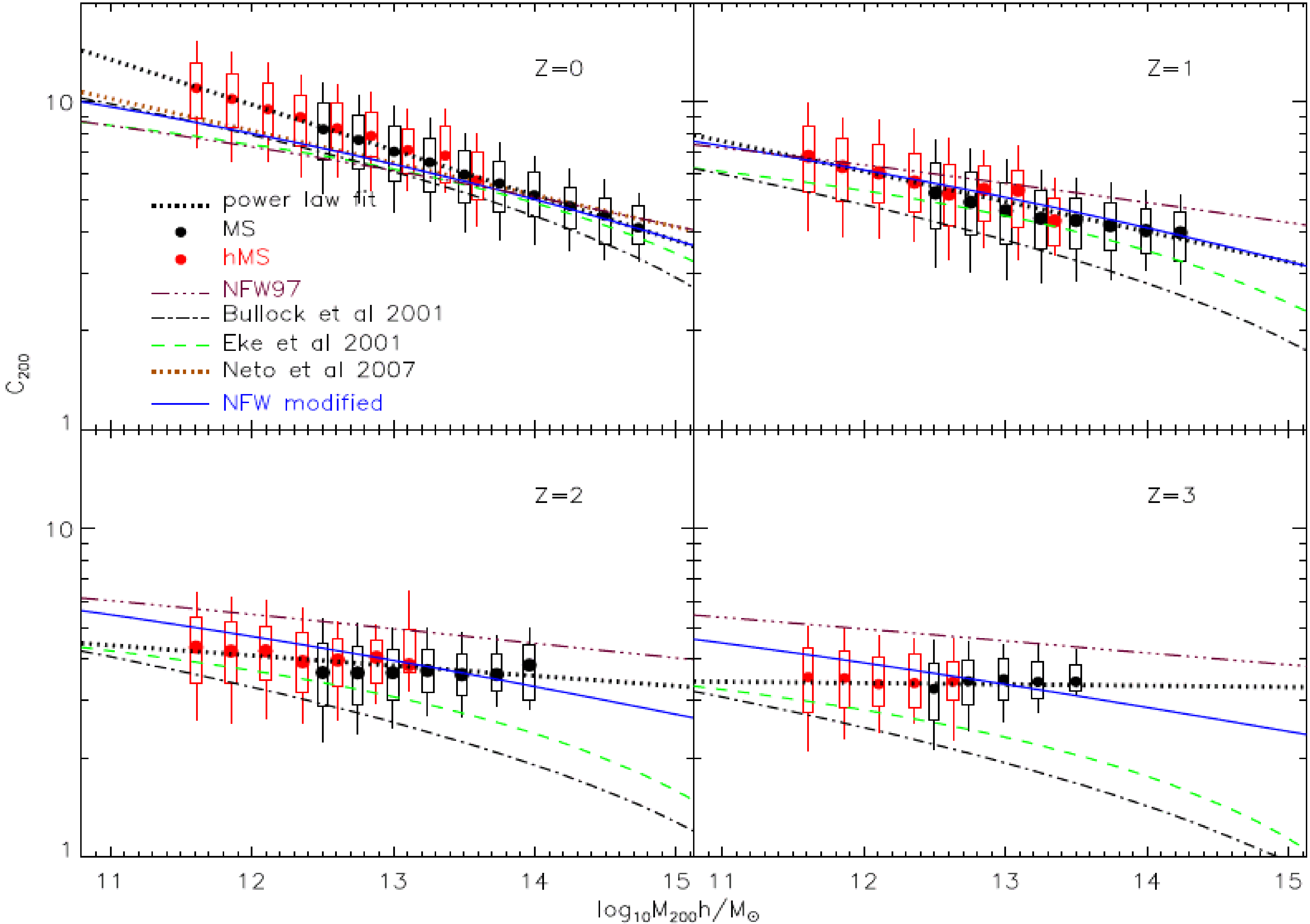


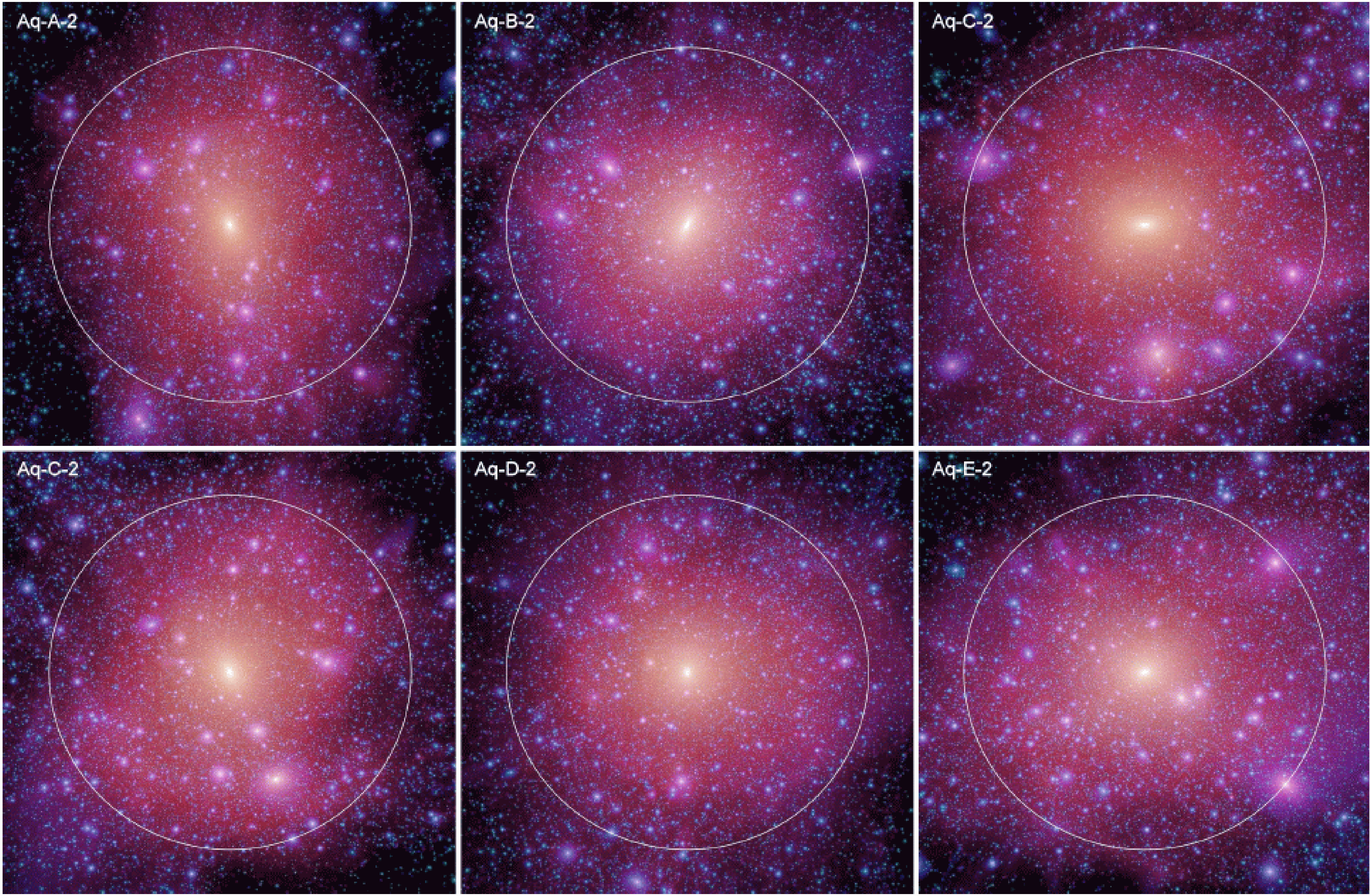
Concentration scatter and trend with M and z

Gao et al 2008



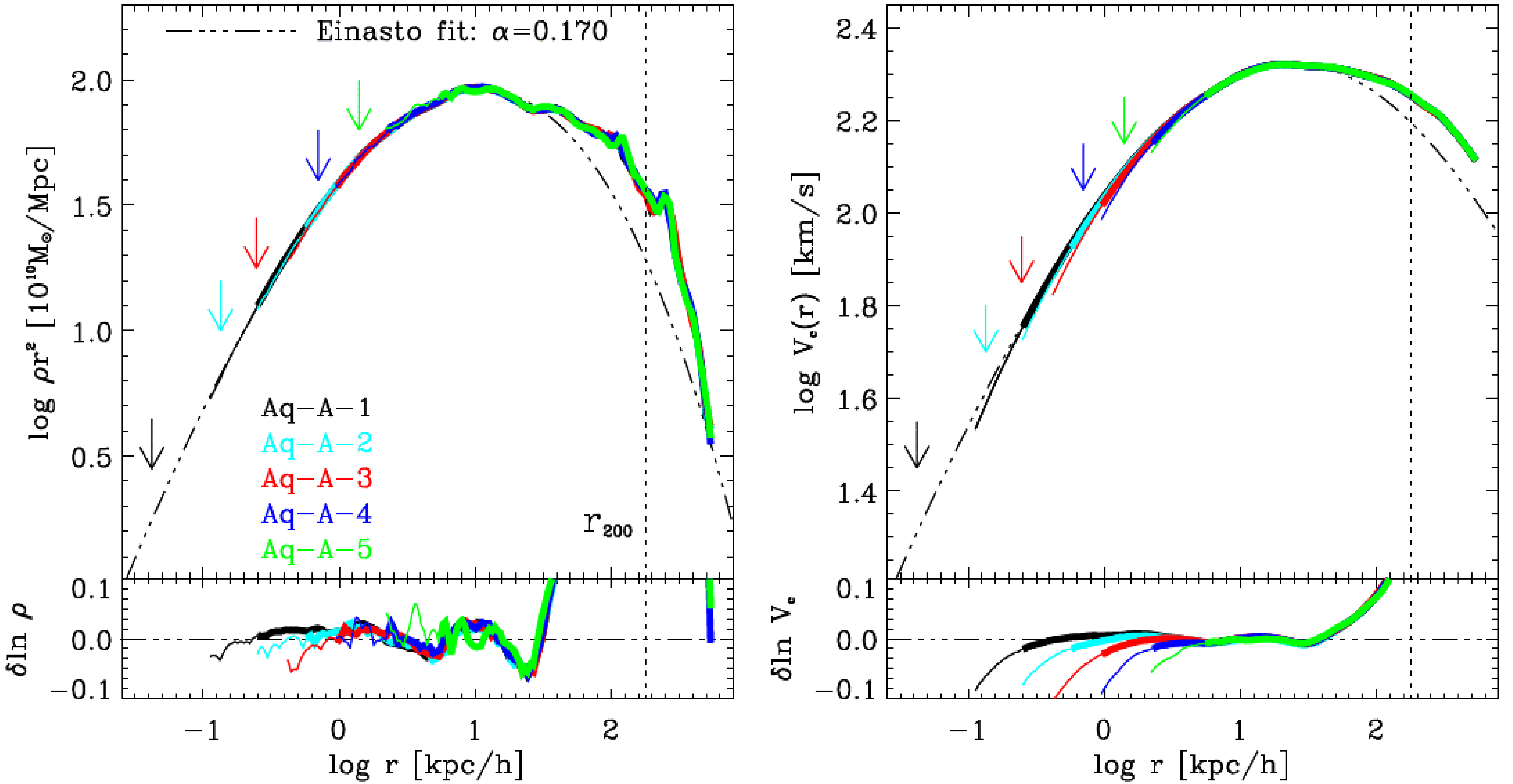
The Aquarius halos

Springel et al 2008



The Einasto profile fits the inner cusps

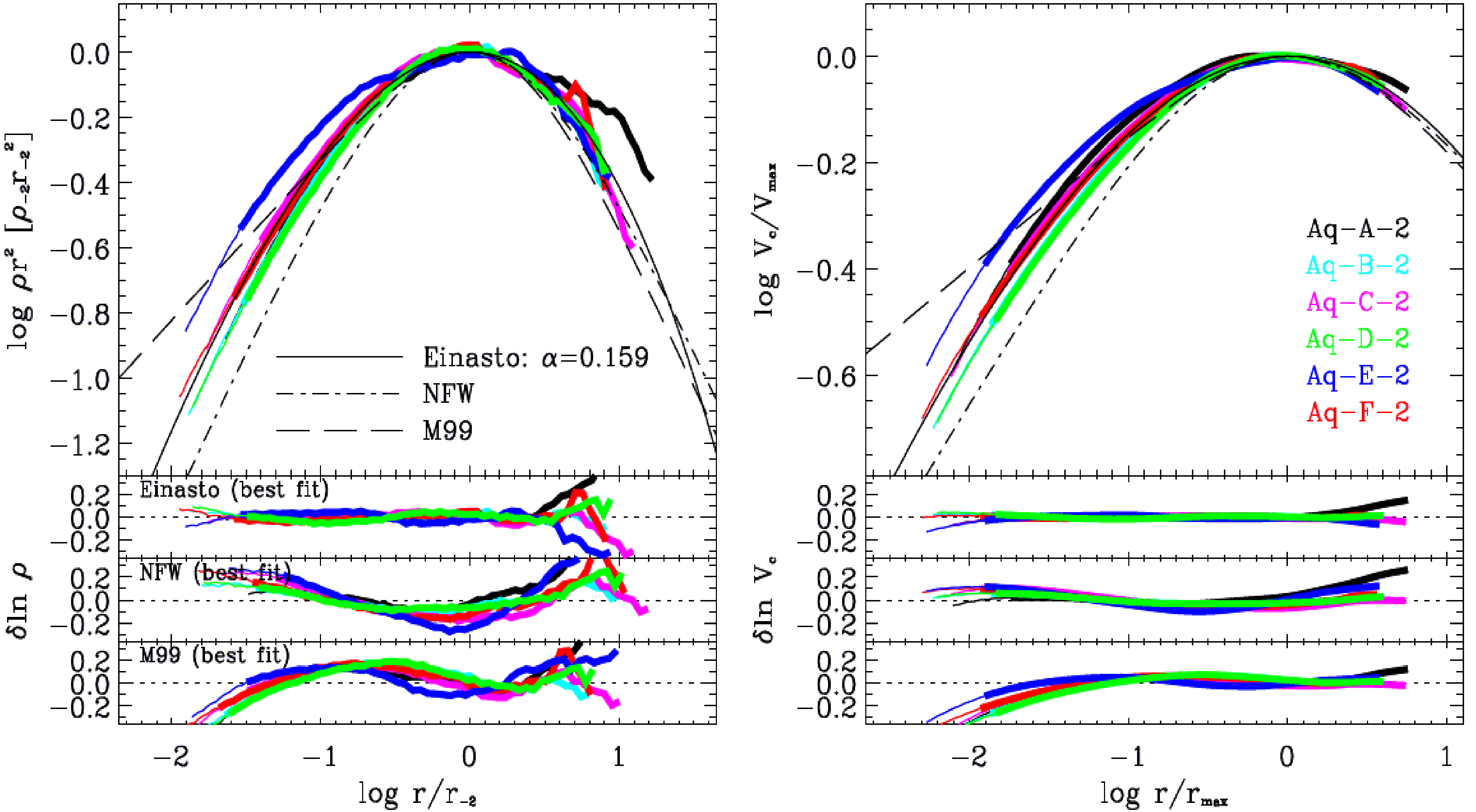
Navarro et al 2009



Einasto's (1965) profile: $\ln \rho(r)/\rho_{-2} = -2/\alpha \;[(r/r_{-2})^{\alpha} - 1]$

The Einasto profile fits the inner cusps

Navarro et al 2009



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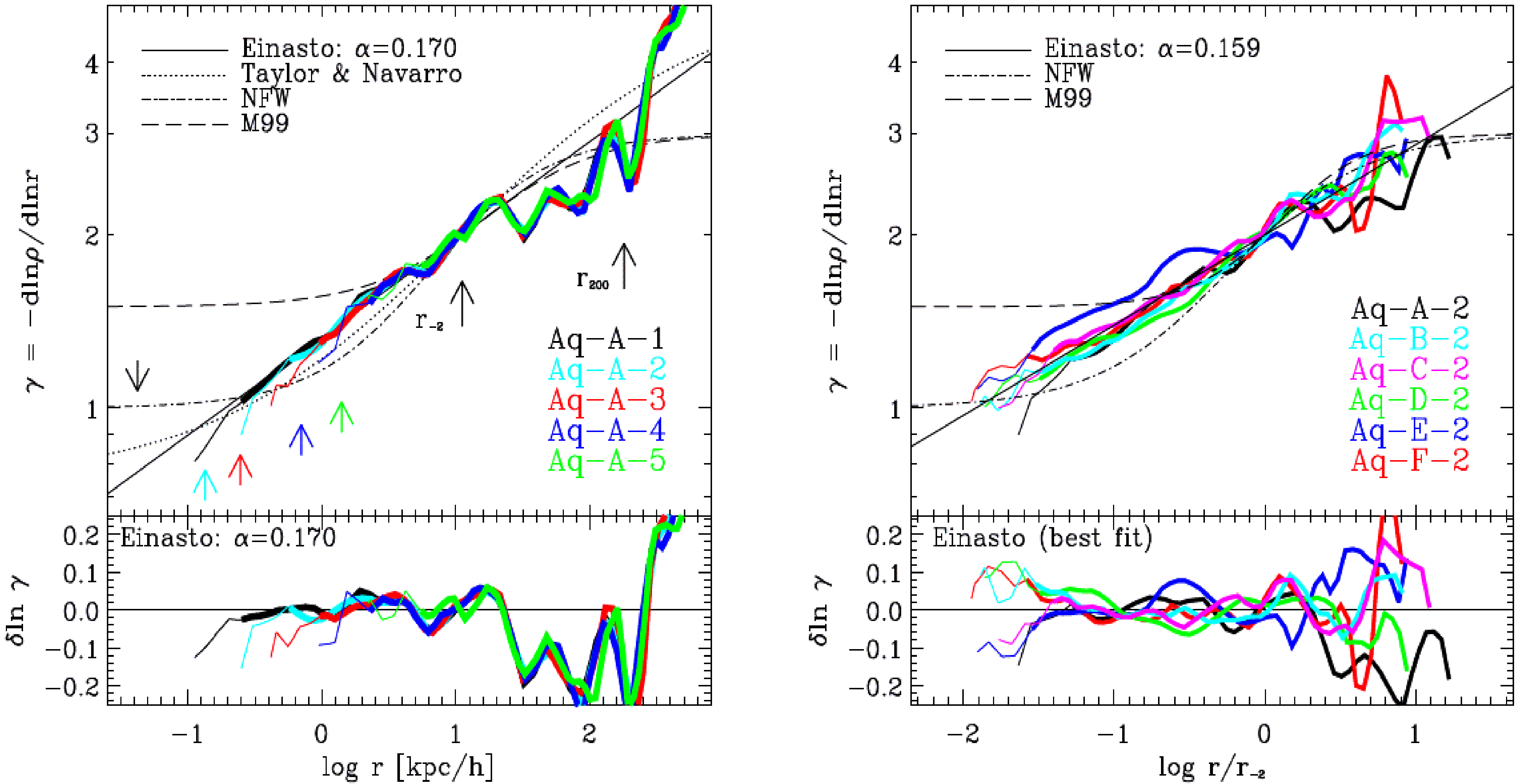
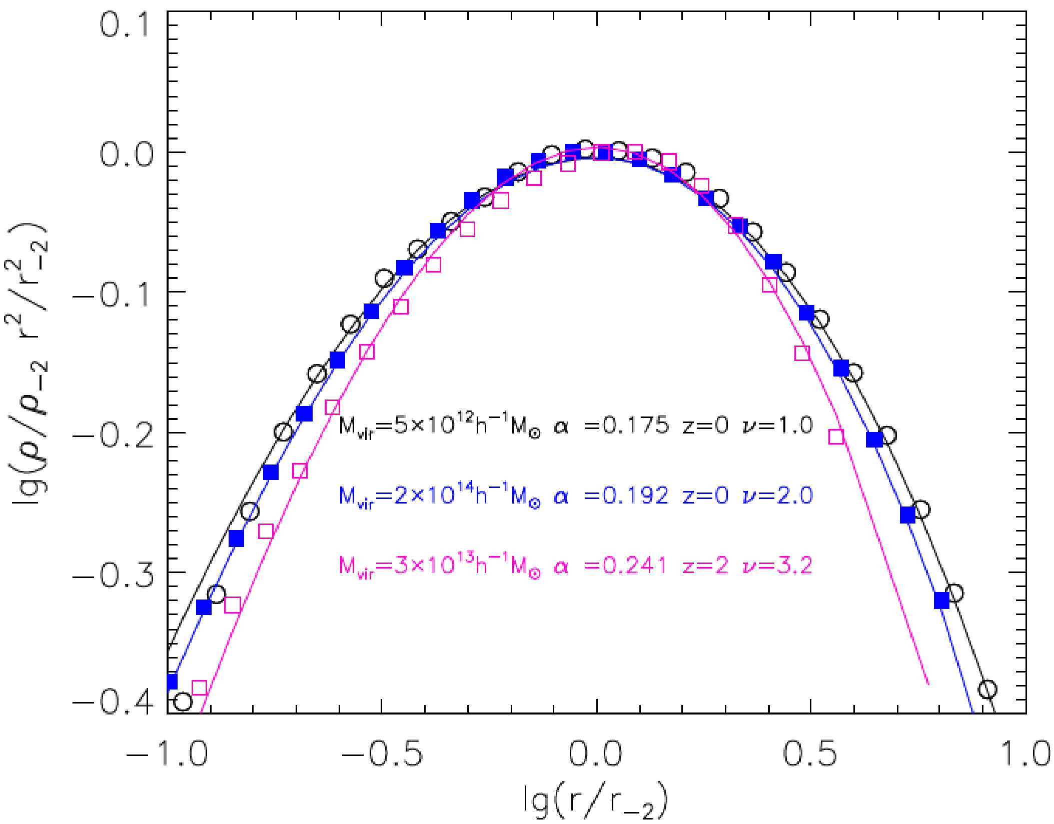


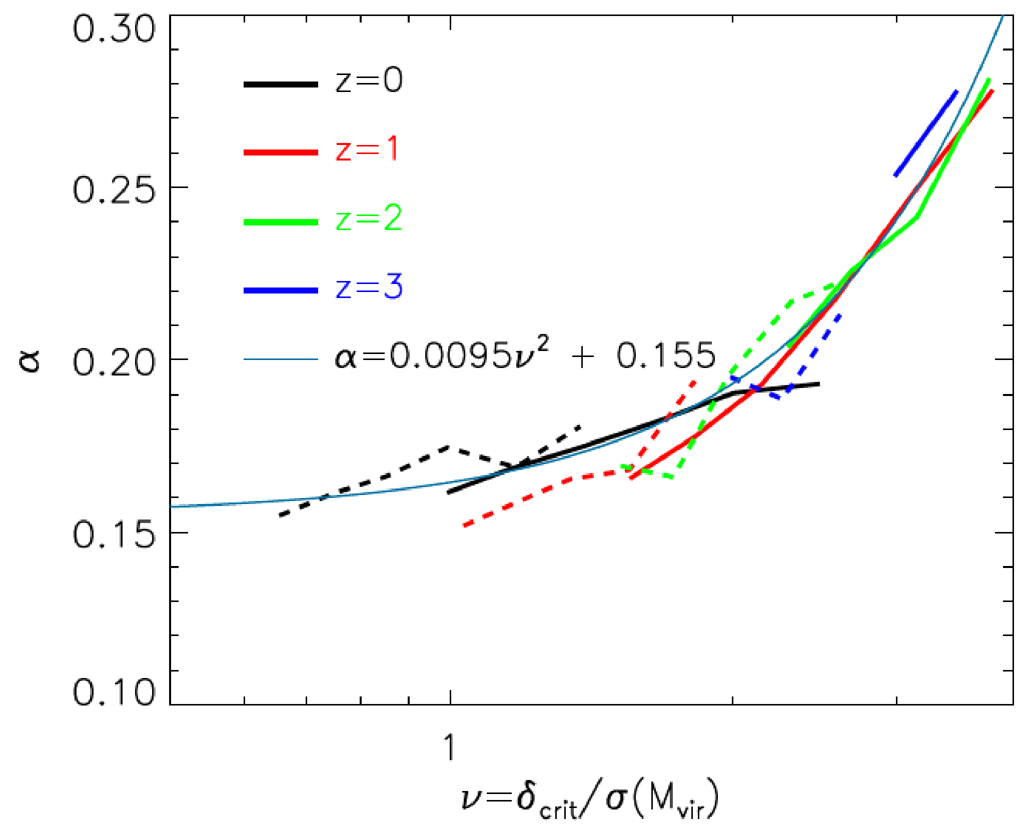
Einasto's (1965) profile: $\ln \rho(r)/\rho_{-2} = -2/\alpha \; [(r/r_{-2})^{\alpha} - 1]$

The Einasto α varies with mass

Gao et al 2008

Results for stacked halos in the Millennium run





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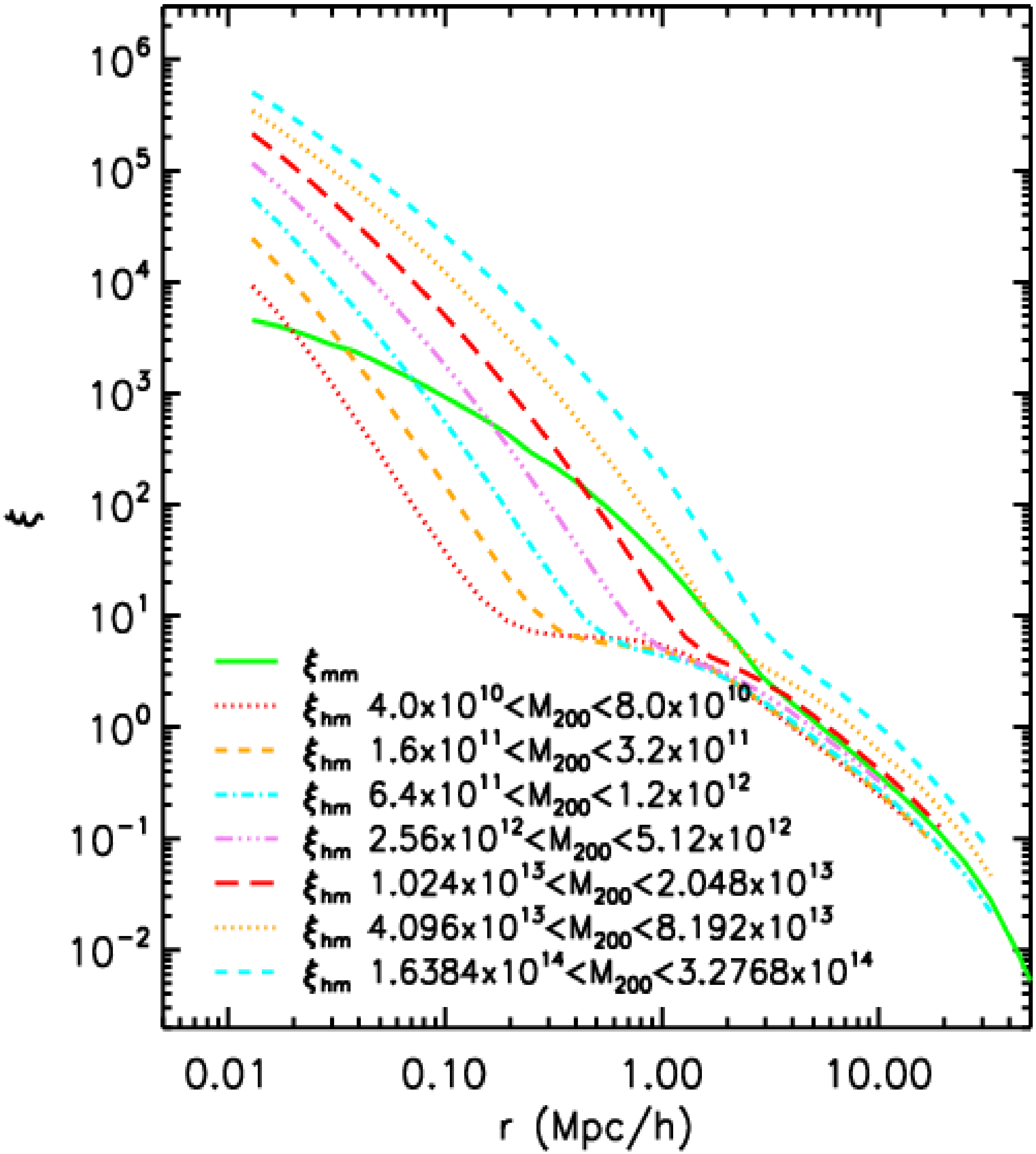


Mean profiles to much larger radii

Hayashi & White 2008

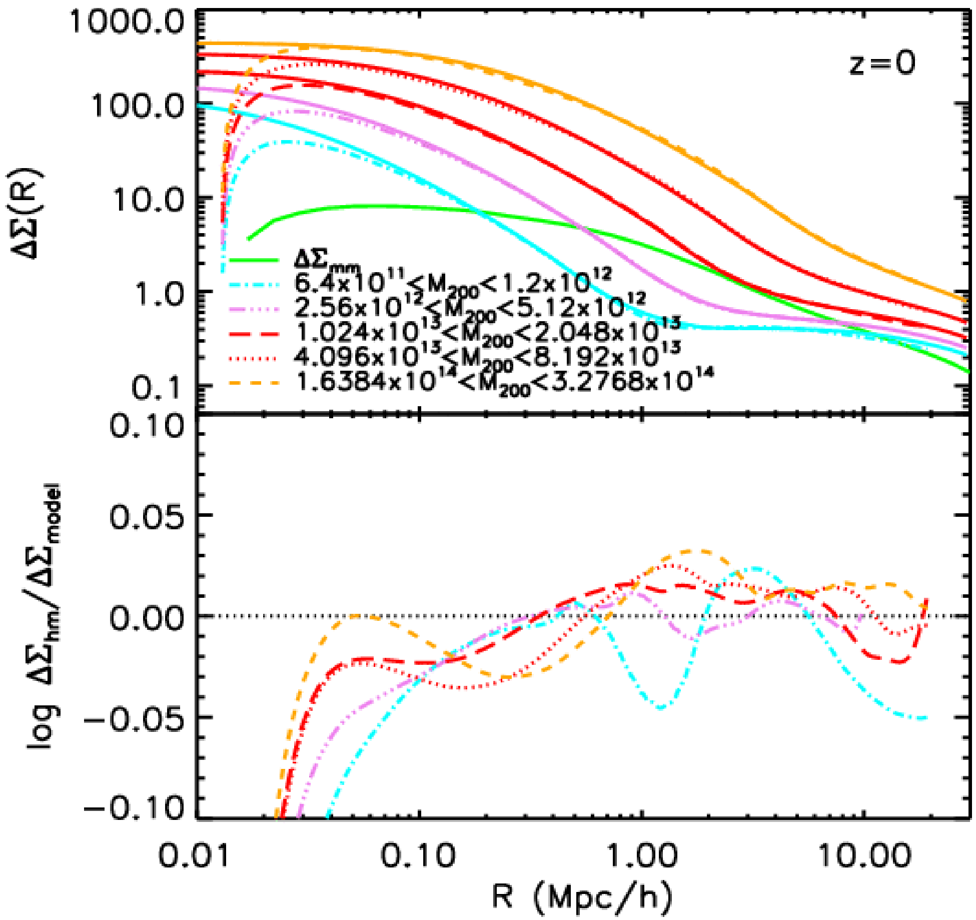
At large radii, the mean density profile $\bar{\rho}(r) \propto \xi_{lin}(r)$, the *linear* mass correlation function

To a good approximation

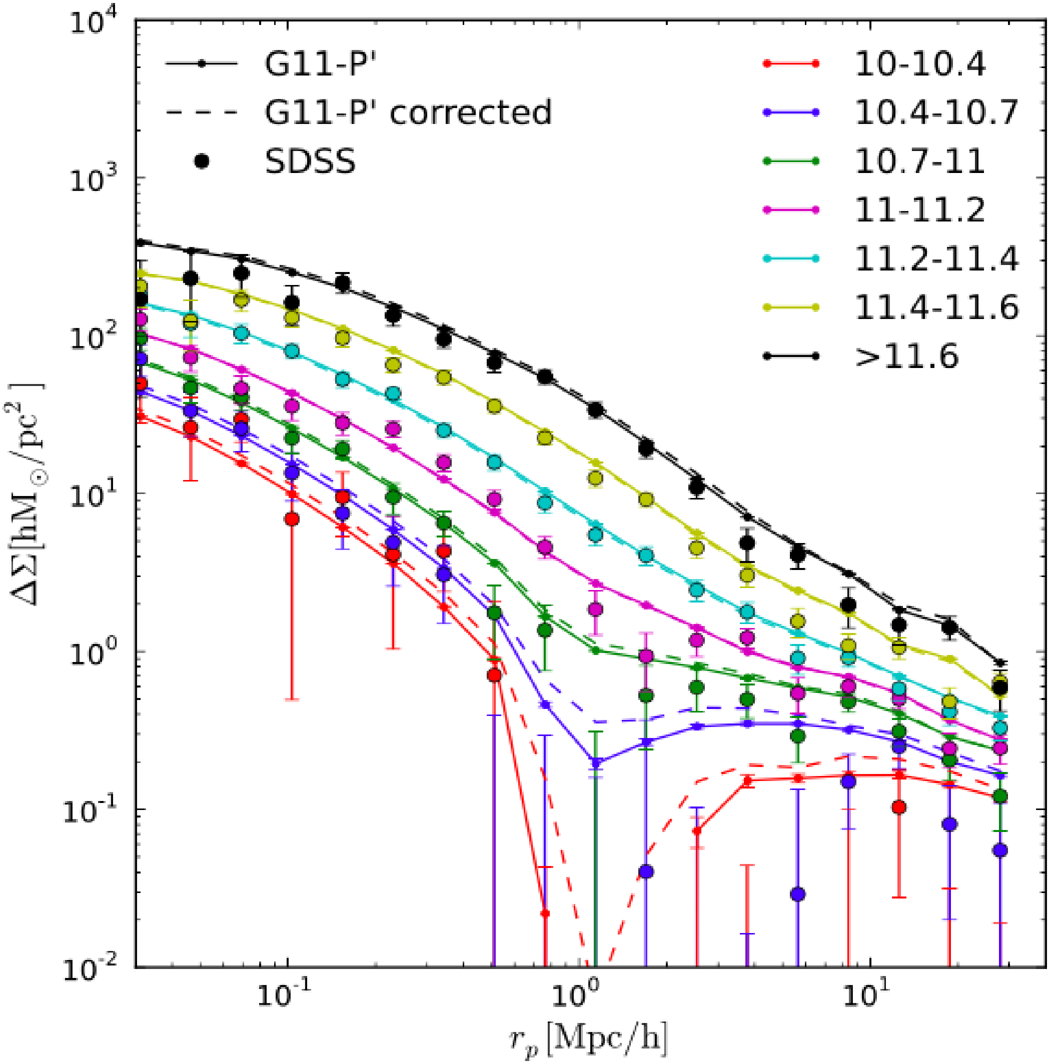
$$\bar{\rho}(r) = \max[\, \rho_{Ein}(r), b\, \xi_{lin}(r) \,]$$

A lensing test of the DM paradigm?

Hayashi & White 2008



Wang et al 2016



Halo profiles: conclusions

The NFW formula fits spherically averaged profiles of most objects to within 10% out to at least 2 r_s

The characteristic density (or concentration) varies with mass, redshift and cosmology

The Einasto formula fits better – its additional shape parameter varies systematically with mass

There is no indication of *any* "asymptotic inner power law"

The scatter among halos is larger than the Einasto-NFW difference

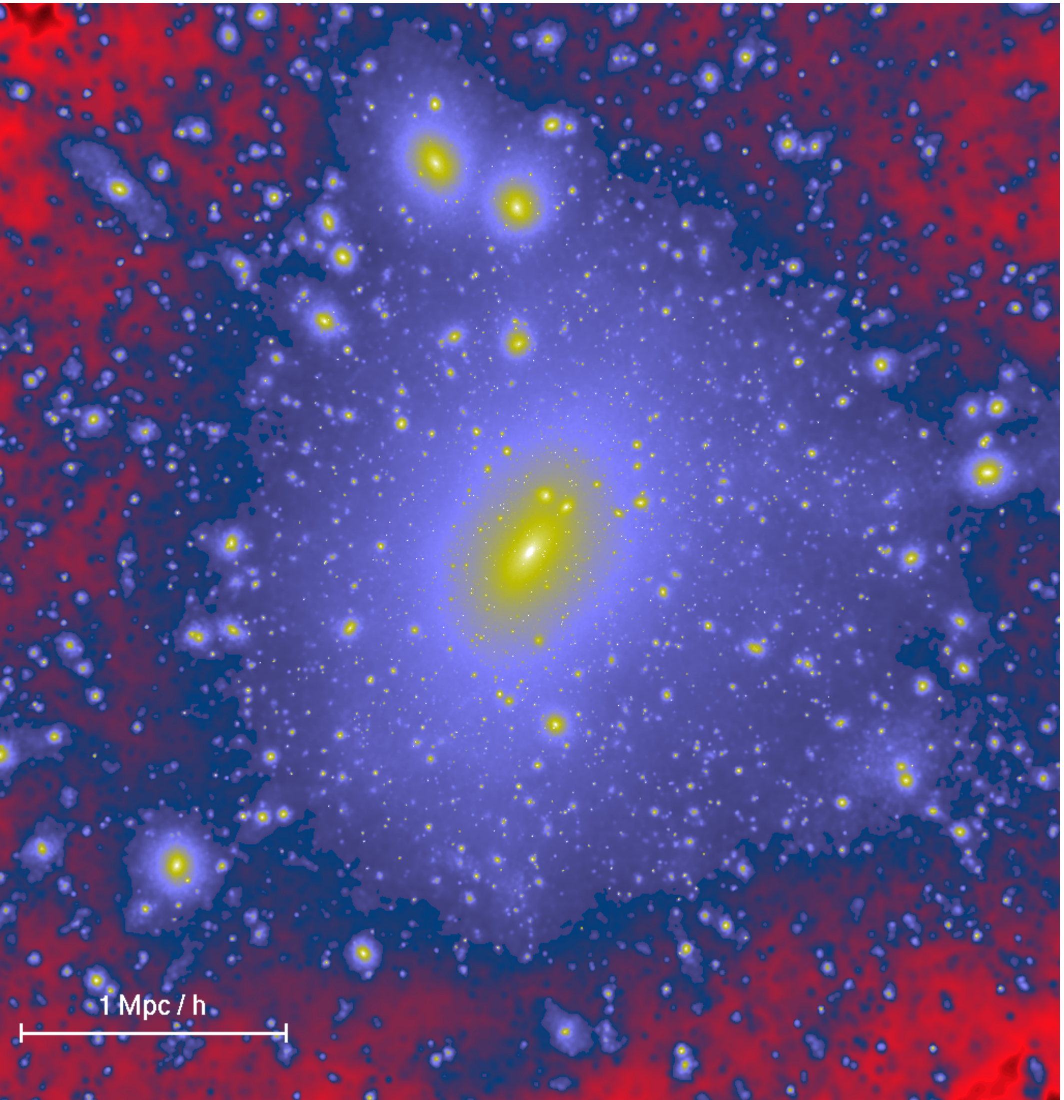
Mean profiles change shape dramatically for $\delta < 10$ (i.e. at large *r*)

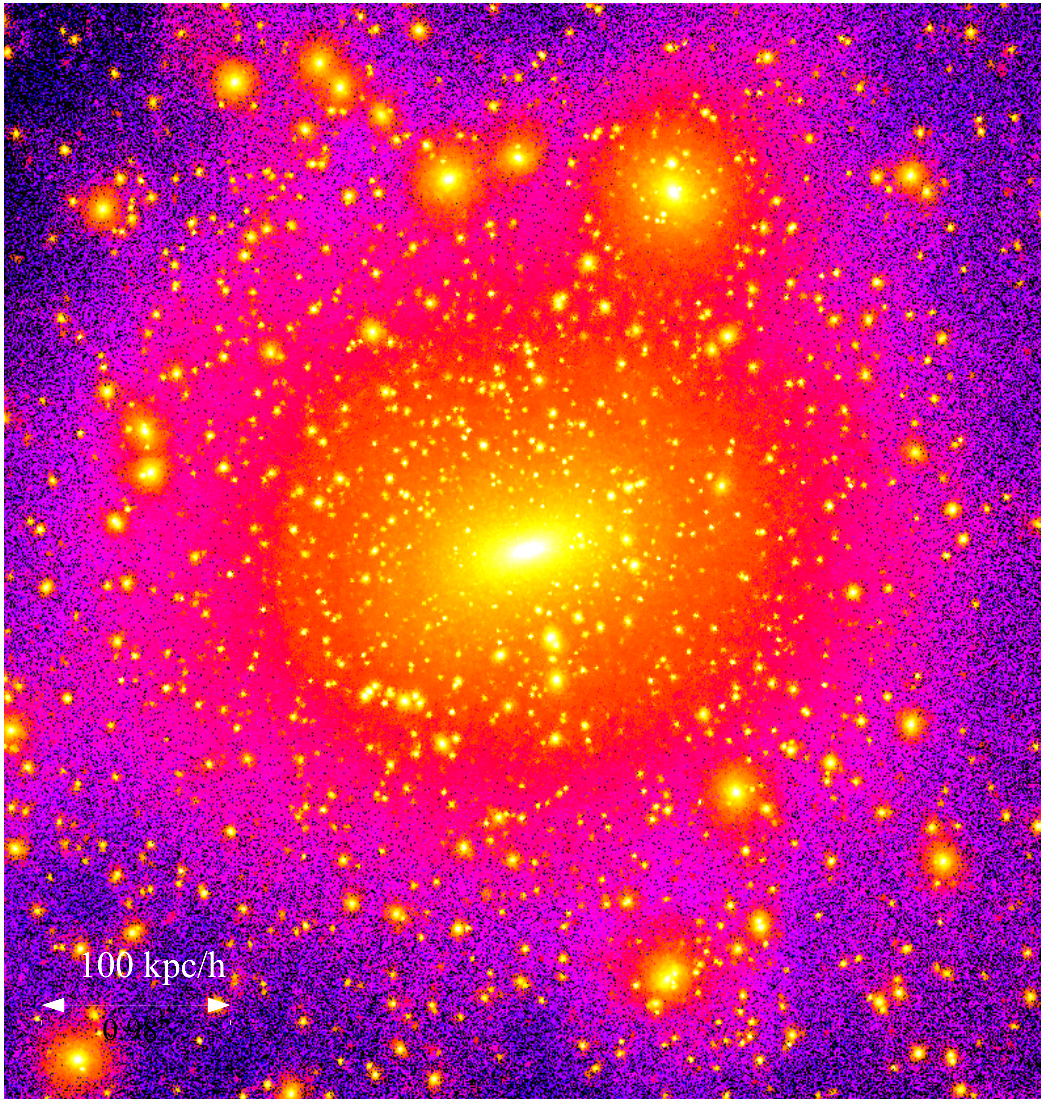
This shape change is observed directly through weak gravitational lensing, confirming ΛCDM predictions at <u>large</u> halo radius

The dark matter structure of ΛCDM halos

A rich galaxy cluster halo
Springel et al 2001

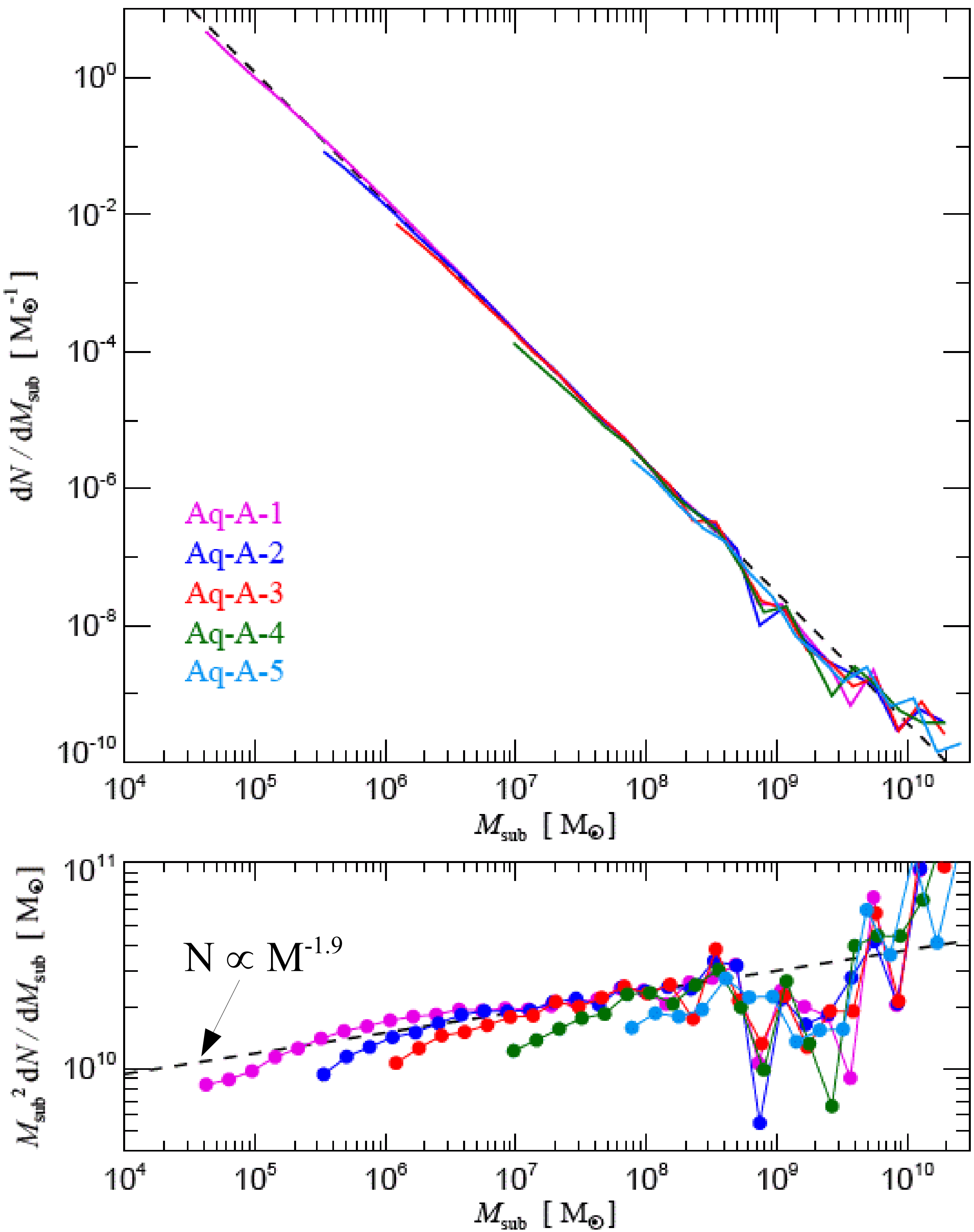
A 'Milky Way' halo
Power et al 2002





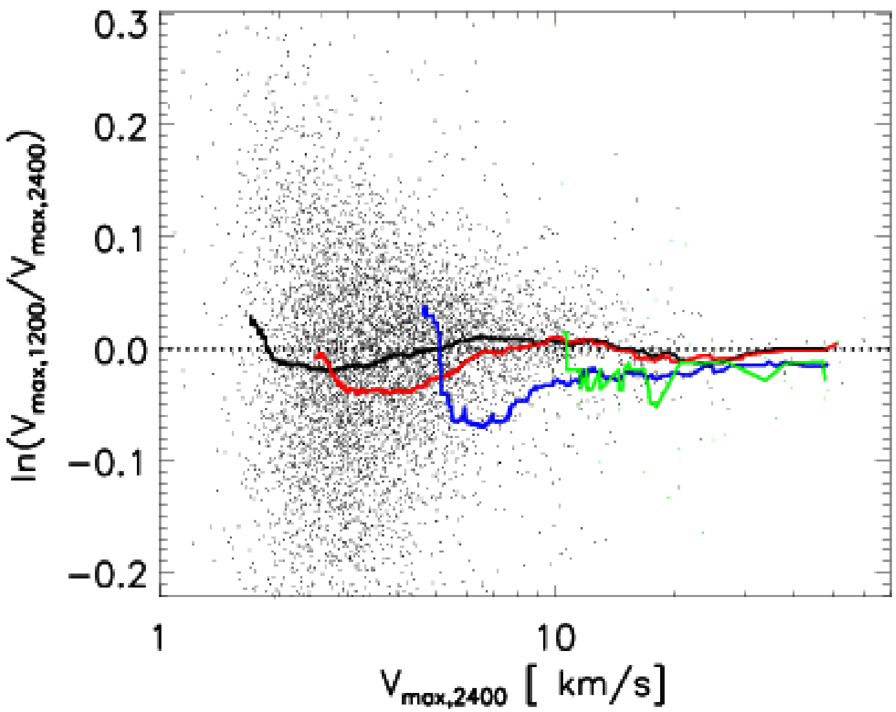
How well does substructure converge?

Springel et al 2008

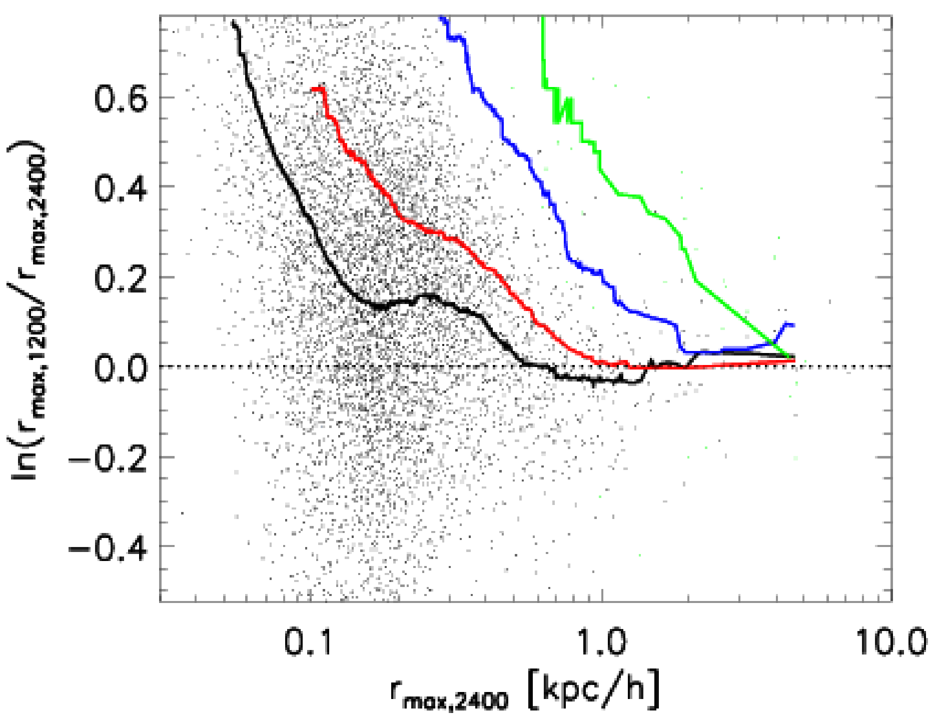


How well does substructure converge?

Aquarius Project: Springel et al 2008



Convergence in the size and maximum circular velocity for individual subhalos cross-matched between simulation pairs.



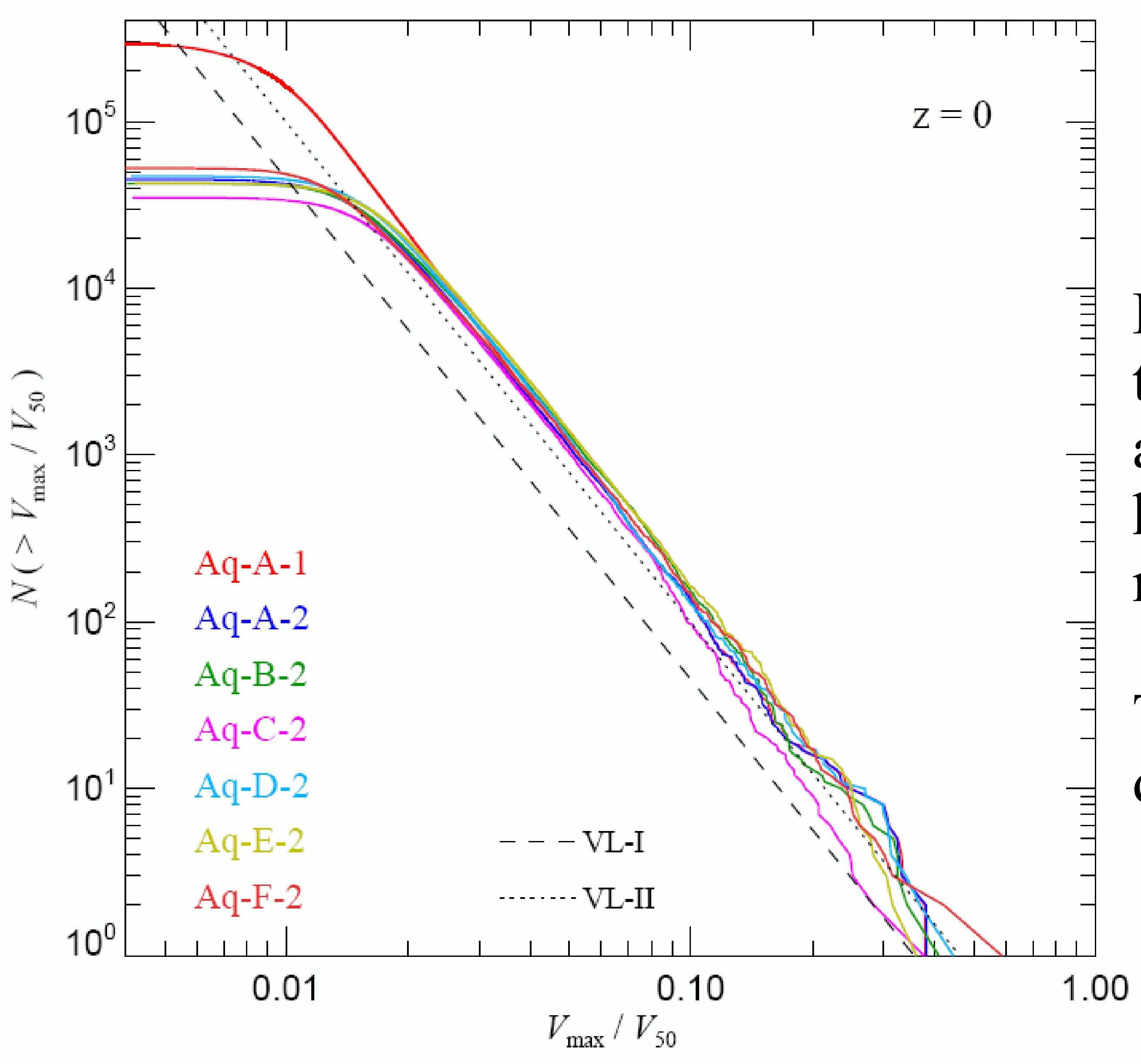
Biggest simulation gives convergent results for

$$V_{max} > 1.5 \text{ km/s}$$

$$r_{max} > 165 \text{ pc}$$

Much smaller than the halos inferred for even the faintest dwarf galaxies

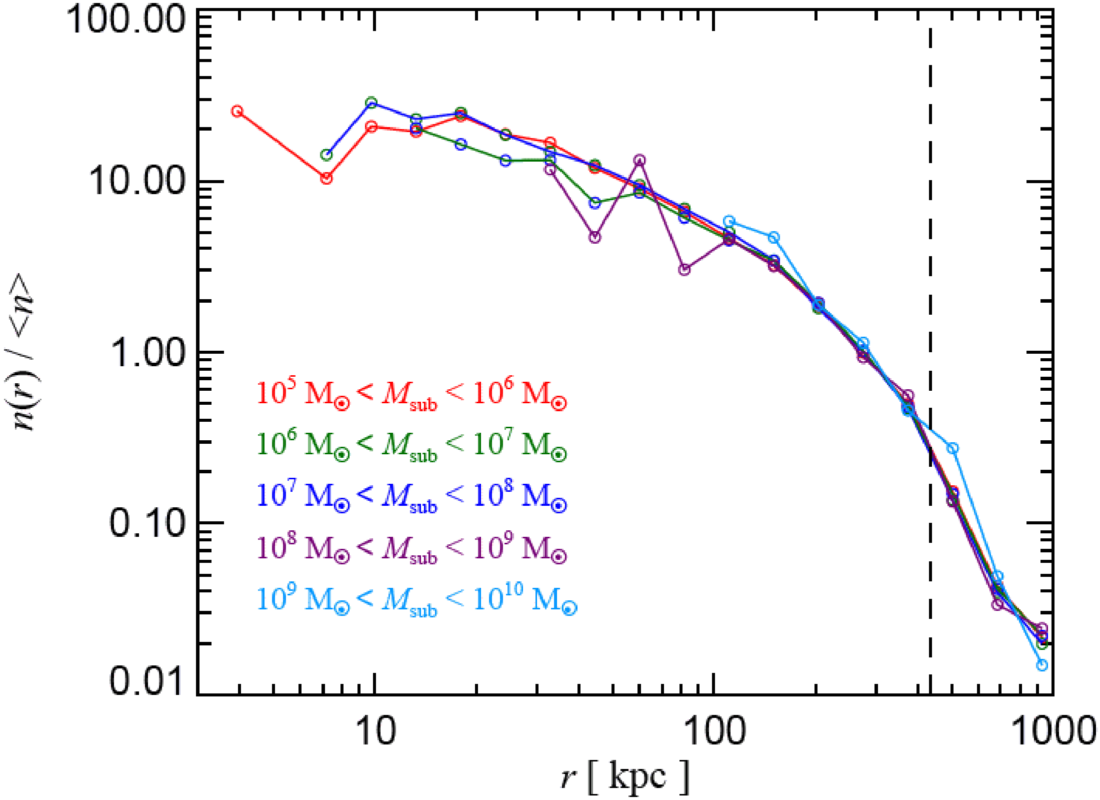
How uniform are subhalo populations?

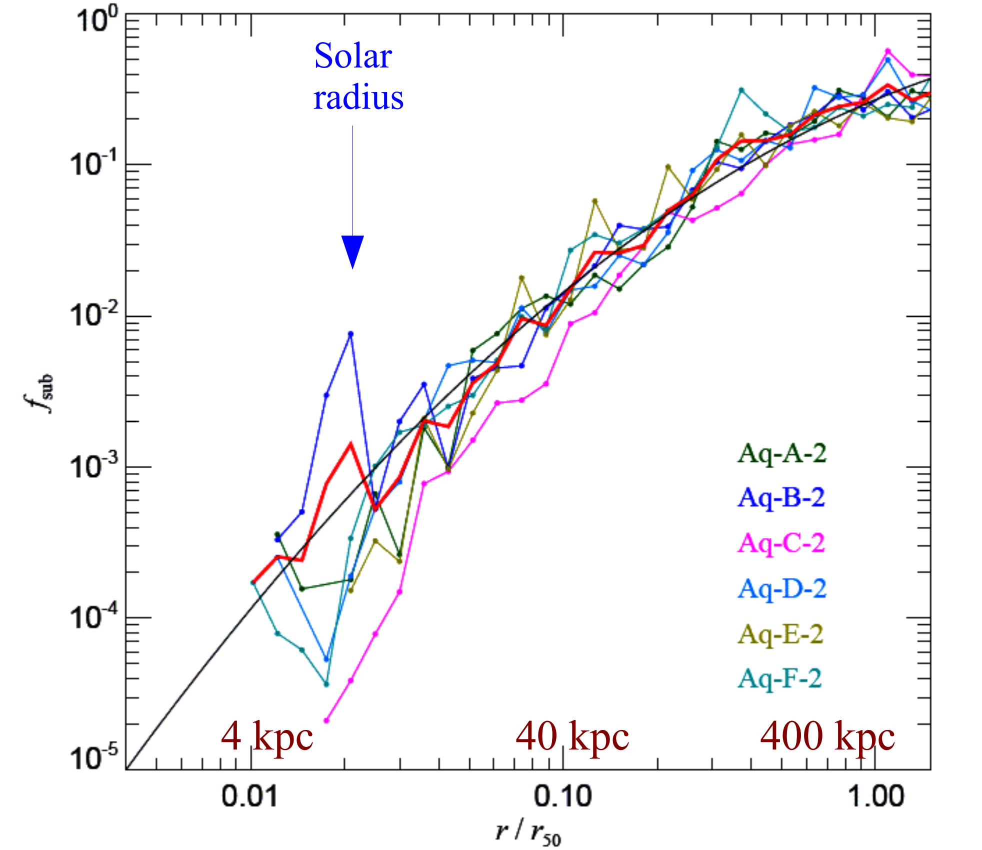


Springel et al 2008

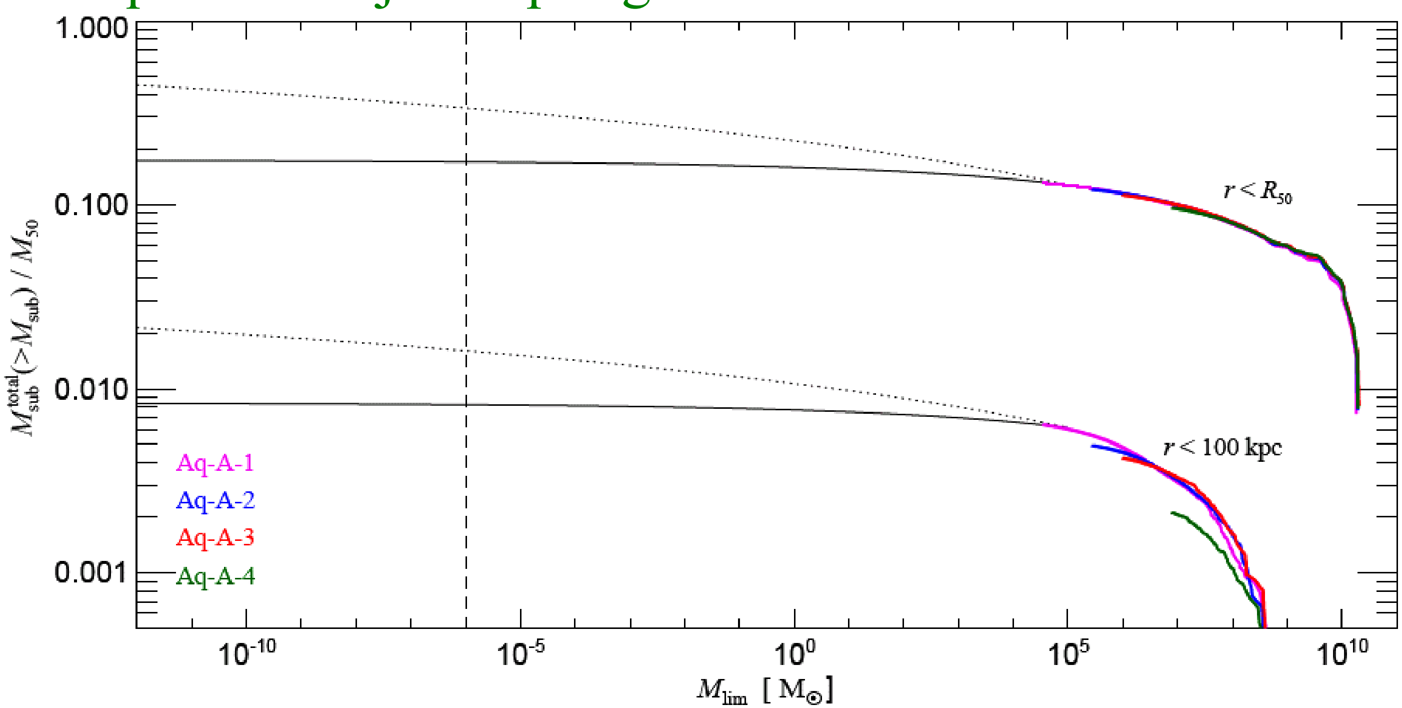
For the six Aquarius halos, the scatter in subhalo abundance is Poisson at high mass and ~20% at low mass

The Via Lactea simulations differ significantly





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

Substructure: conclusions

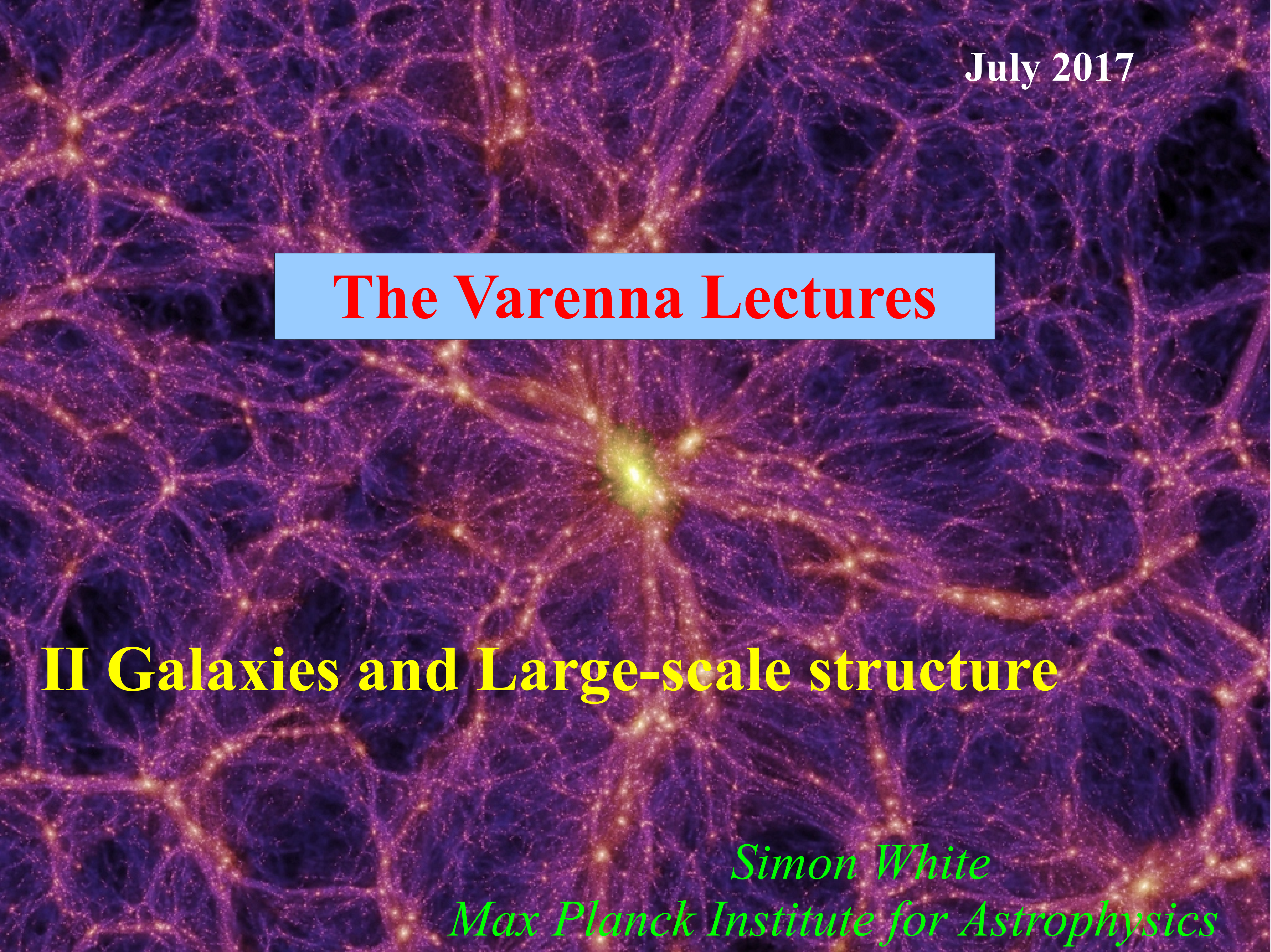
Substructure is primarily in the outermost parts of halos

The radial distribution of subhalos is almost mass-independent

Subhalo populations scale (almost) with the mass of the host

The subhalo mass distribution converges only weakly at small m

Subhalos contain a small fraction of the mass in the inner halo



July 2017

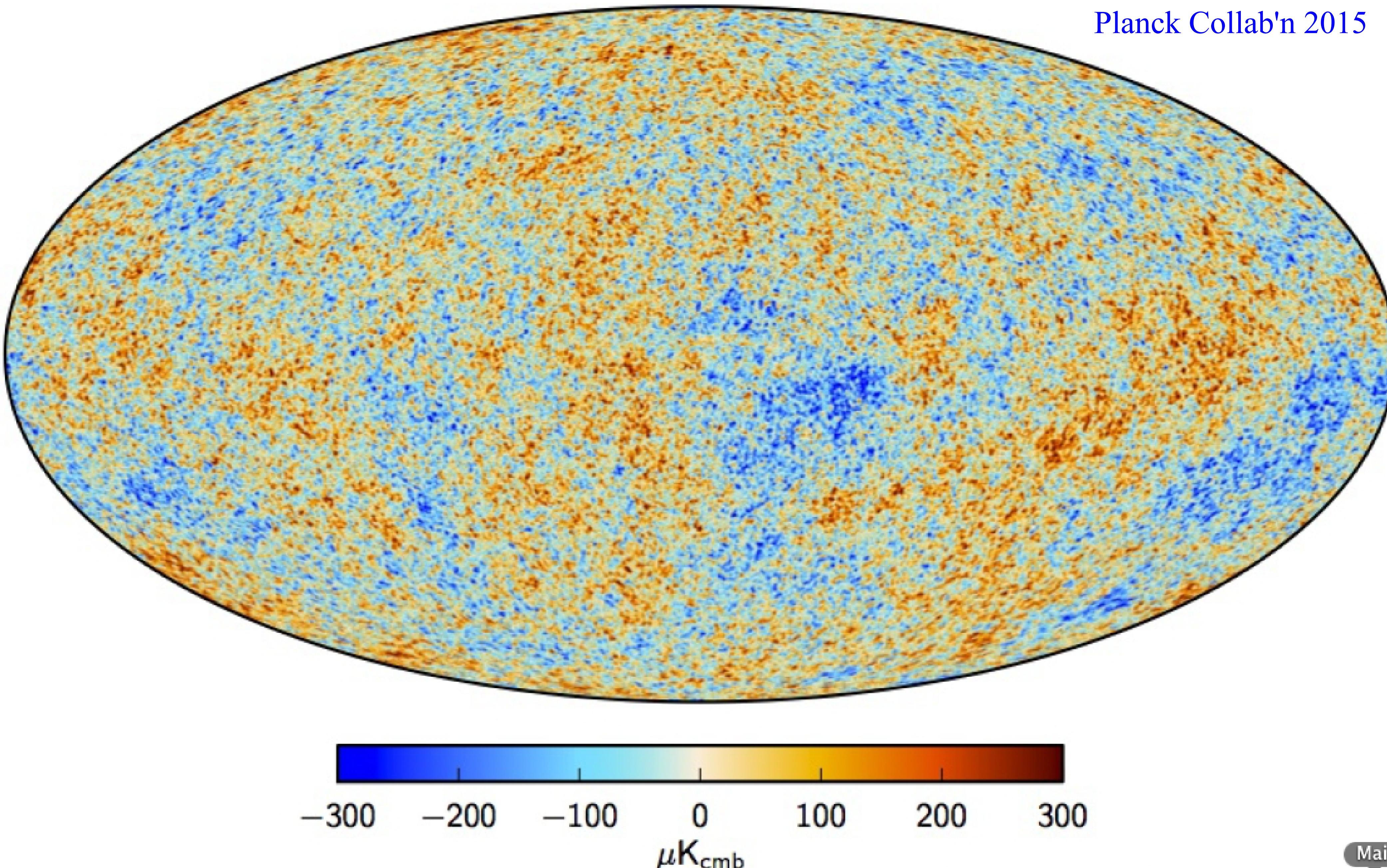
The Varenna Lectures

II Galaxies and Large-scale structure

Simon White
Max Planck Institute for Astrophysics

CMB map from the full *Planck* mission

Planck Collab'n 2015

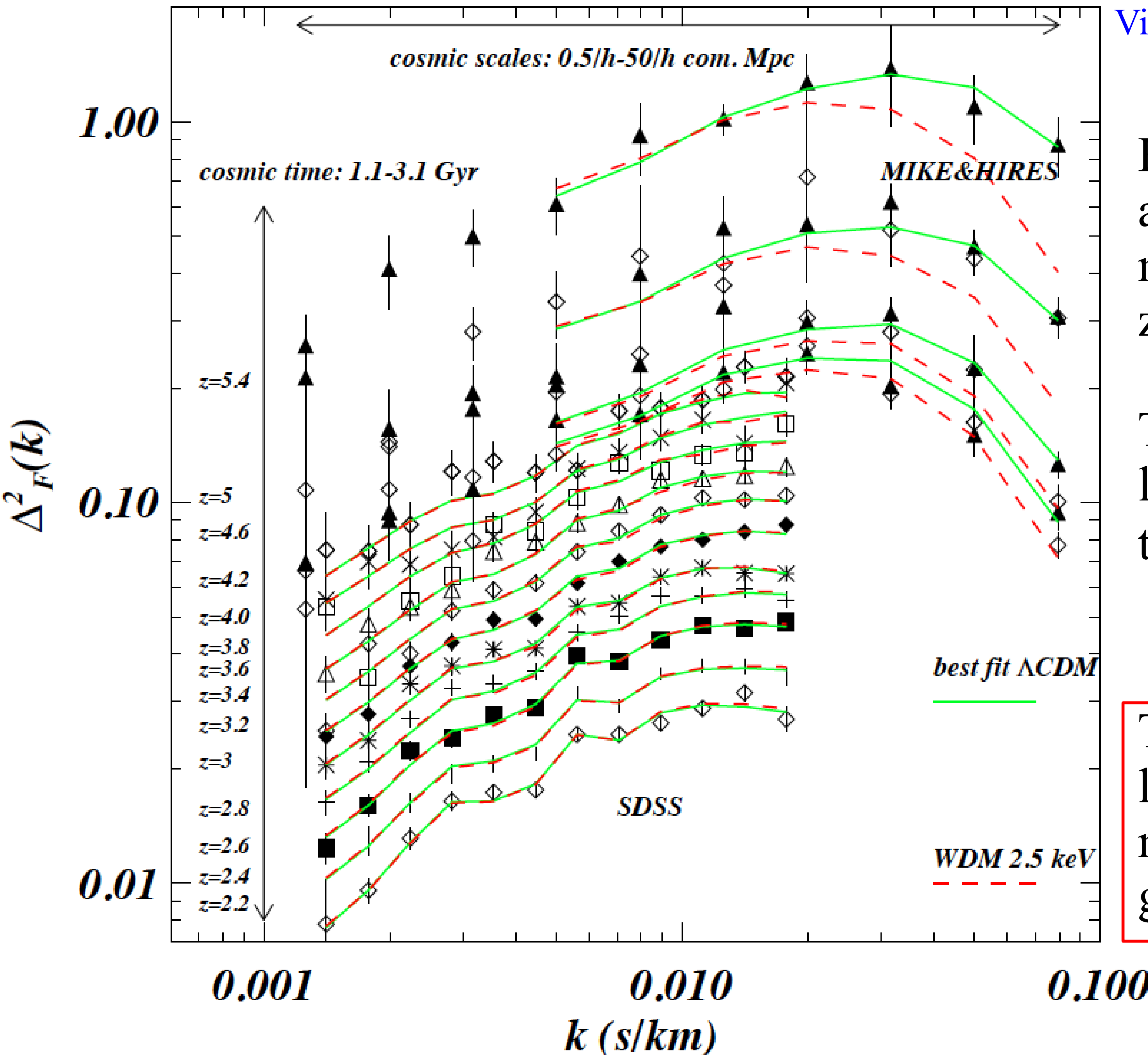


The six parameters of the base ΛCDM model

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

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 much effect on dwarf galaxy structure

Cosmology and galaxy formation

- The geometry is flat to better than 0.5%
- Baryon and CDM densities, H_0 and σ_8 are known to $\sim$1%
- Initial P(k) is ΛCDM with $n \sim 0.97$ down to subgalactic scales
- Initial non-gaussianities and $\Sigma\, m_\nu$ are both small

Cosmology and galaxy formation

- The geometry is flat to better than 0.5%
- Baryon and CDM densities, H_0 and σ_8 are known to ~1%
- Initial P(k) is ΛCDM with n ~ 0.97 down to subgalactic scales
- Initial non-gaussianities and $\Sigma\, m_\nu$ are both small
- Late-time expansion history – BAO signal in galaxies – w(z)
- Late-time growth factor – z-space distortions – mod.grav., ν masses
- Dwarf galaxy core structure / Ly α forest – WDM / SIDM / fuzzy DM
- Signatures of DE interactions with DM? with ν's? with baryons?

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Does galaxy formation distort or mask these signals at the 1% level?

Making predictions for galaxies (accurately?)

Simulations are ***required*** to show that nonlinear effects are under control and to represent realistic observational surveys

Making predictions for galaxies (accurately?)

Simulations are *required* to show that nonlinear effects are under control and to represent realistic observational surveys

- Are the initial conditions well enough represented?
- Is the volume large enough to control cosmic variance?
- Can the code follow growth sufficiently well?
- Is galaxy formation represented at a sufficient level by:

Making predictions for galaxies (accurately?)

Simulations are ***required*** to show that nonlinear effects are under control and to represent realistic observational surveys

- Are the initial conditions well enough represented?
- Is the volume large enough to control cosmic variance?
- Can the code follow growth sufficiently well?
- Is galaxy formation represented at a sufficient level by:
    - Halo occupation distribution (HOD) models
    - Subhalo abundance matching (SHAM) models
    - Semianalytic population simulations (SAM)
    - Cosmological hydrodynamical simulations

Modelling galaxies for large-scale structure

Halo Occupation Distributions (HOD)

Input: N-body simulation with halos
Fit data: Galaxy abundances and clustering at a given redshift
Output: Parameters $\boldsymbol{\alpha}$ in $P_{\boldsymbol{\alpha}}\{L_{cen}... \mid M_{halo}...\}$, $n_{\boldsymbol{\alpha}}(L_{sat}, r \mid M_{halo}...)$

Subhalo Abundance Matching (SHAM)

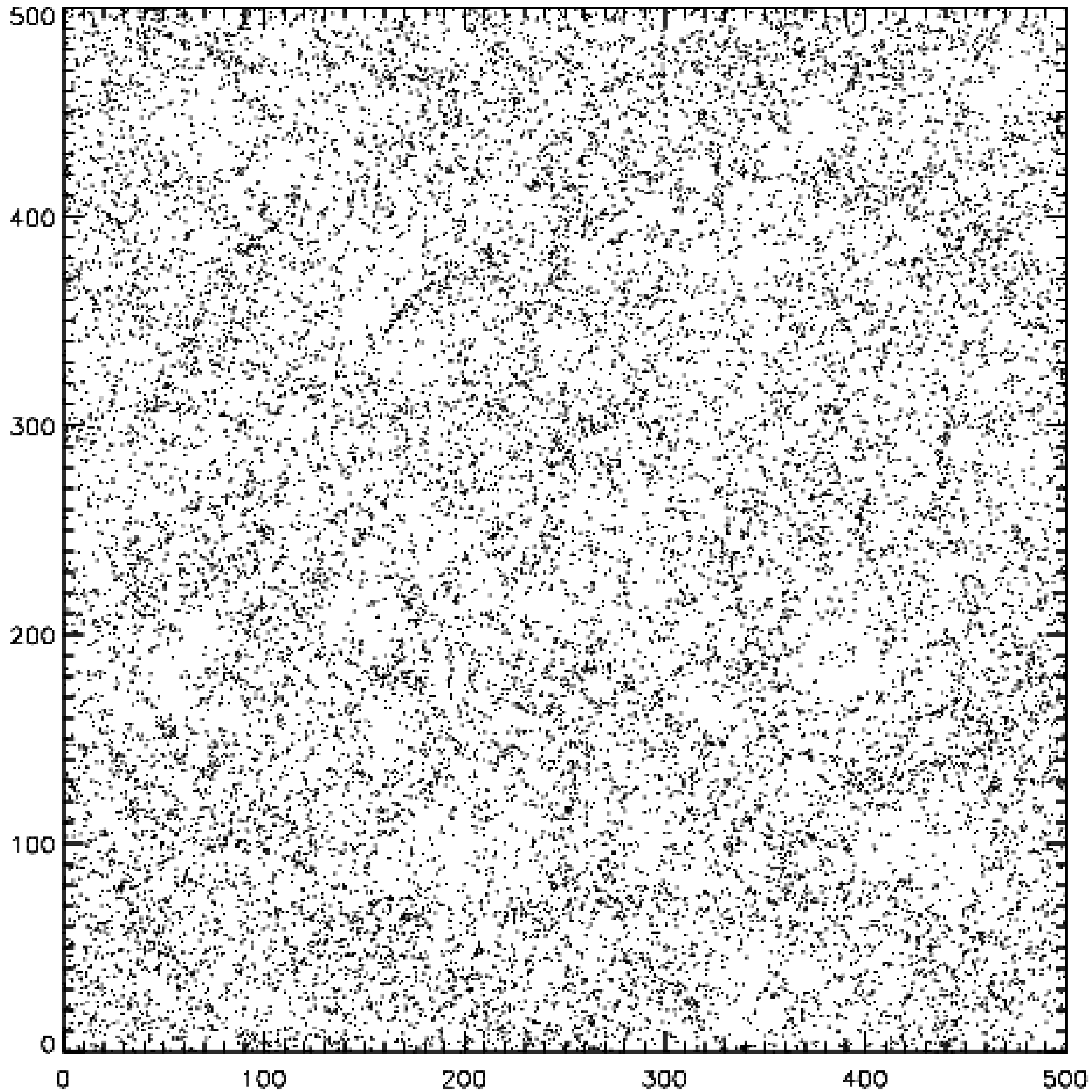
Input: N-body simulation with halos+subhalos, observed $\Phi(L)$
Fit data: Galaxy clustering at a given redshift
Output: Scatter in $L - M_{halo}$ relation, "best" estimator for M_{halo}

Semianalytic/Empirical Models (SAM)

Input: N-body simulation with halos+subhalos+merger tree
Fit data: Galaxy abundances and clustering at multiple redshifts
Output: Parameters of physical/empirical galaxy formation model

Cosmological Hydrodynamical Simulations

Halo clustering depends on formation history

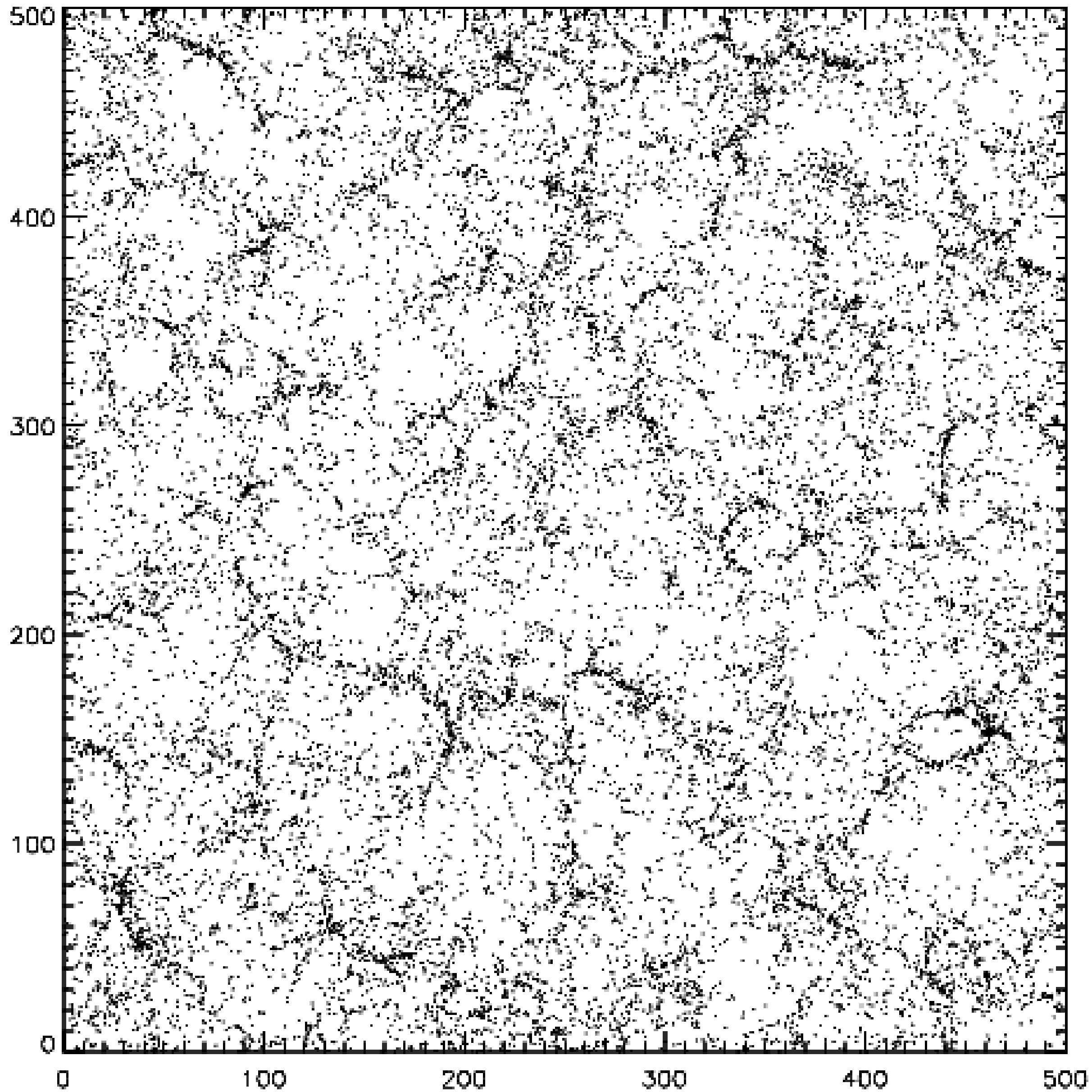


Gao, Springel & White 2005

The 20% of halos with the *latest* half-mass assembly redshifts in a 30 Mpc/h thick slice

$M_{halo} \sim 10^{11} M_{\odot}$

Halo clustering depends on formation history

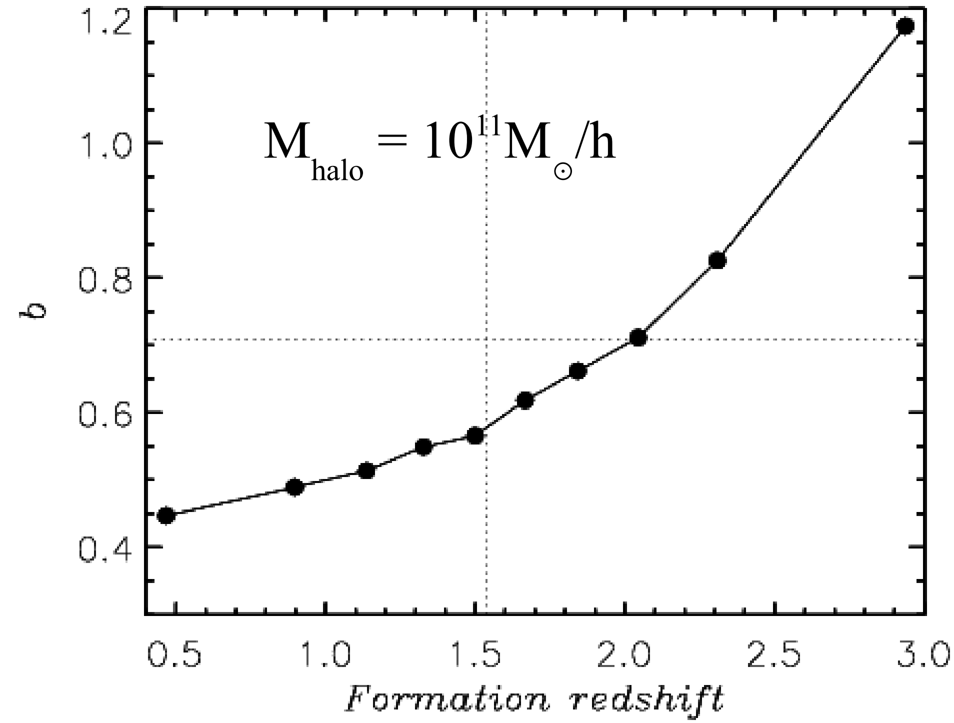


Gao, Springel & White 2005

The 20% of halos with the <u>*earliest*</u> half-mass assembly redshifts in a 30 Mpc/h thick slice

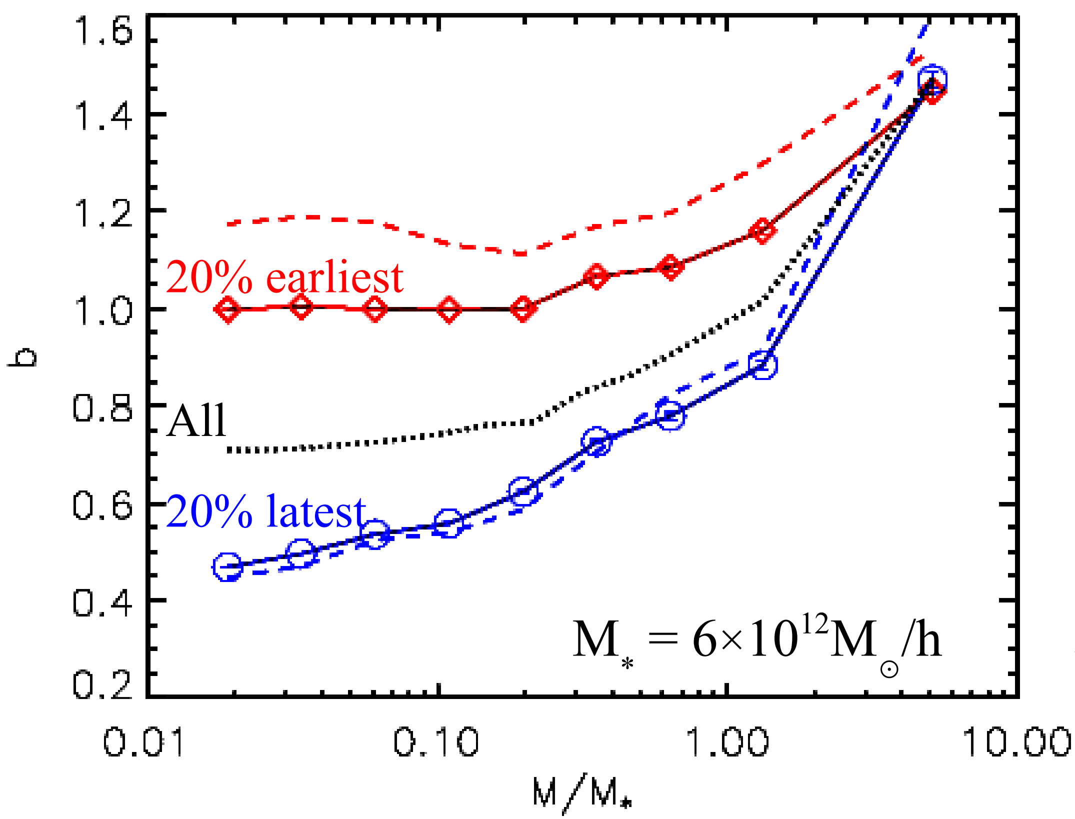
$$M_{halo} \sim 10^{11} M_{\odot}$$

Halo bias as a function of mass and formation time



Gao, Springel & White 2005

On large scales halo bias increases smoothly with formation redshift

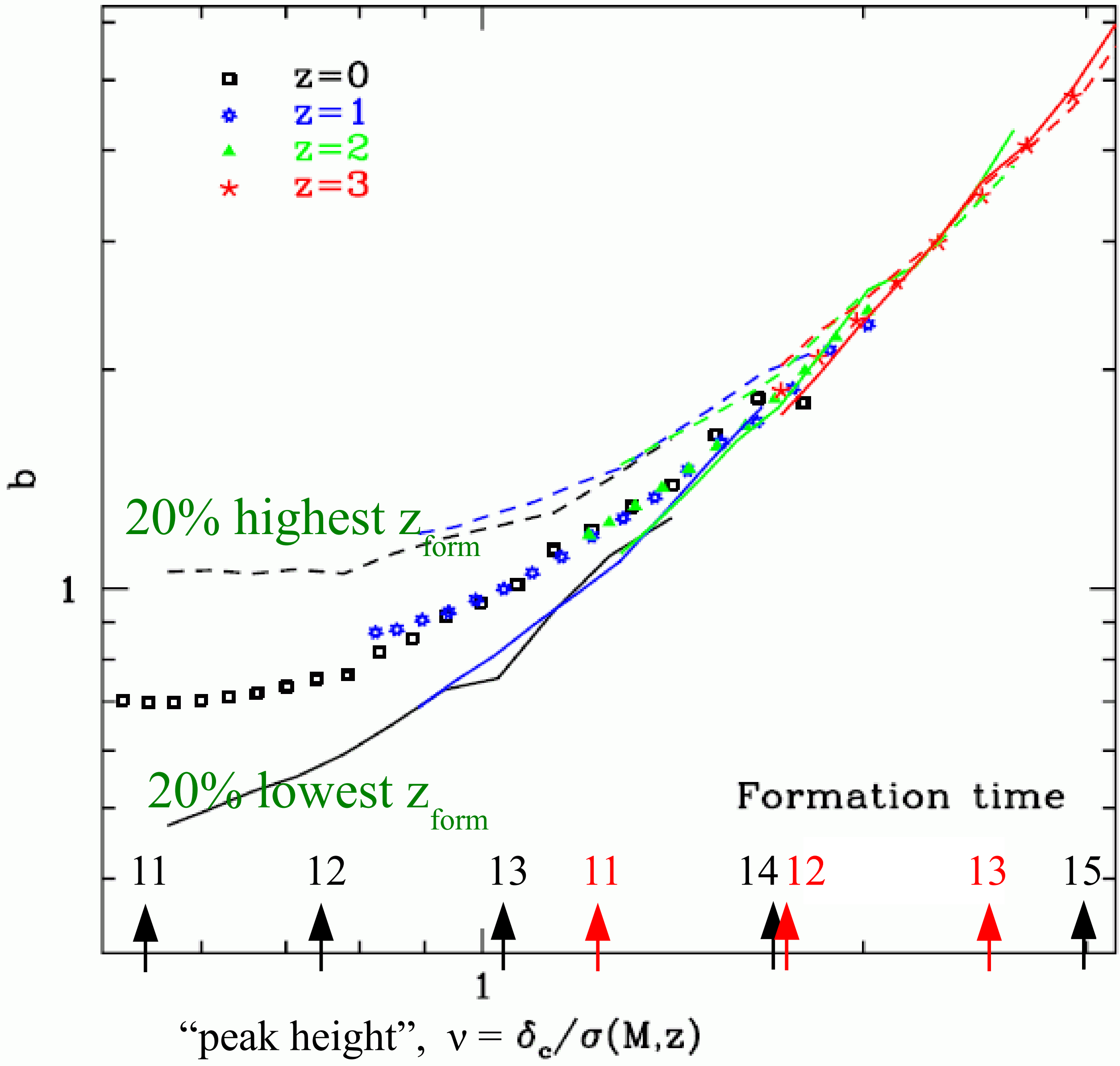


The dependence of bias on formation redshift is strongest at low mass

This behaviour is inconsistent with simple versions of excursion set theory, and of HOD and halo abundance matching models

Bias as a function of ν and formation time

Gao & White 2007



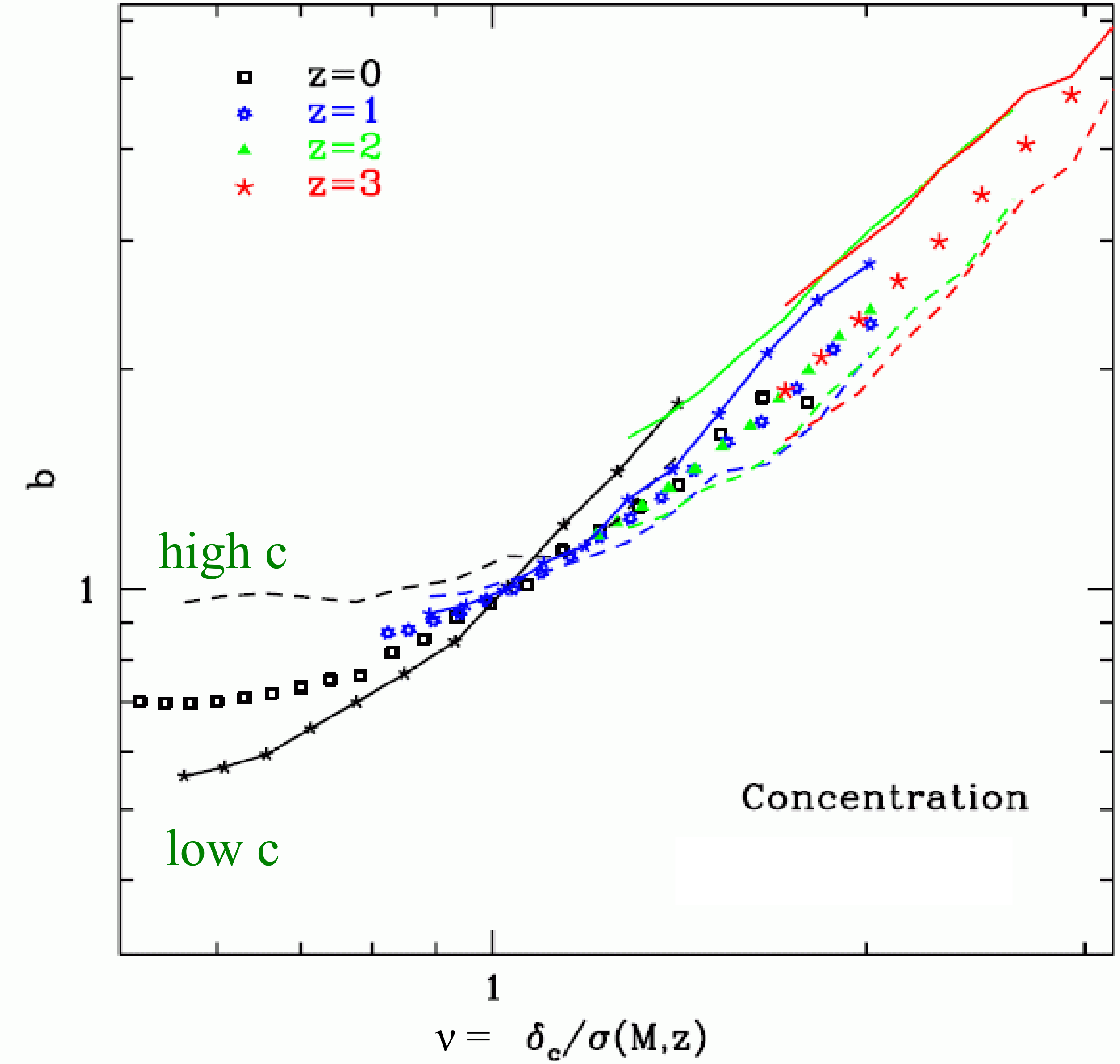
log (h M_{halo} / $M_\odot$)
at z = 0, at z = 2

Dynamic range and S/N can be increased by superposing redshifts and using halo-mass cross-correlations

The effect is a factor of two in *b* at MW halo mass but it vanishes at rich cluster mass

Bias as a function of ν and concentration

Gao & White 2007



For MW-mass halos, the bias ratio $b_{hi} / b_{lo} \sim 1.5$

For cluster mass halos, $b_{hi} / b_{lo} \sim 0.7$

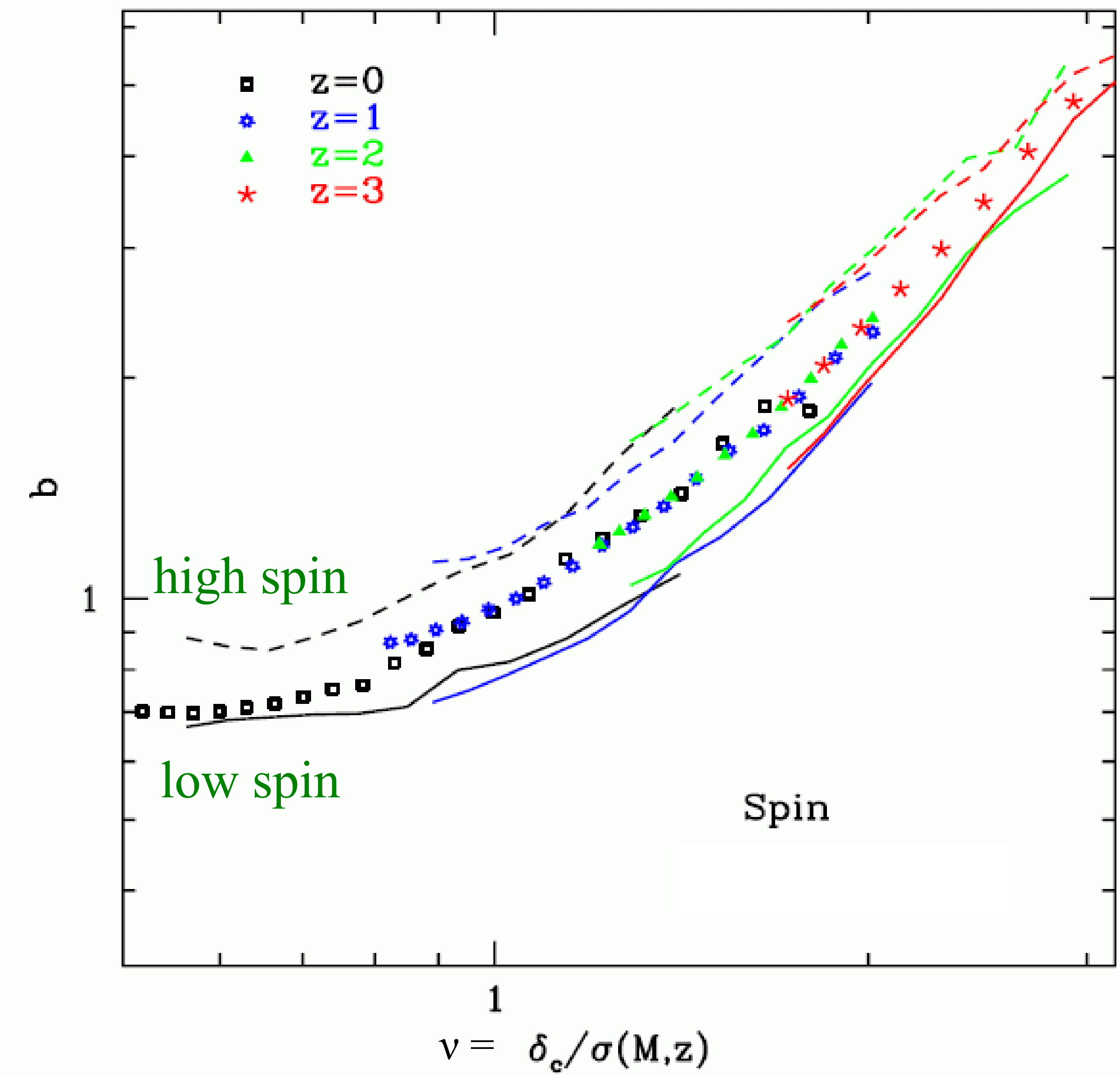
The effect vanishes for $M_{halo} \sim M_*$

Concentration is NOT an appropriate proxy for formation time when studying halo clustering.

c.f. Wechsler et al 2006

Bias as a function of ν and spin

Gao & White 2007



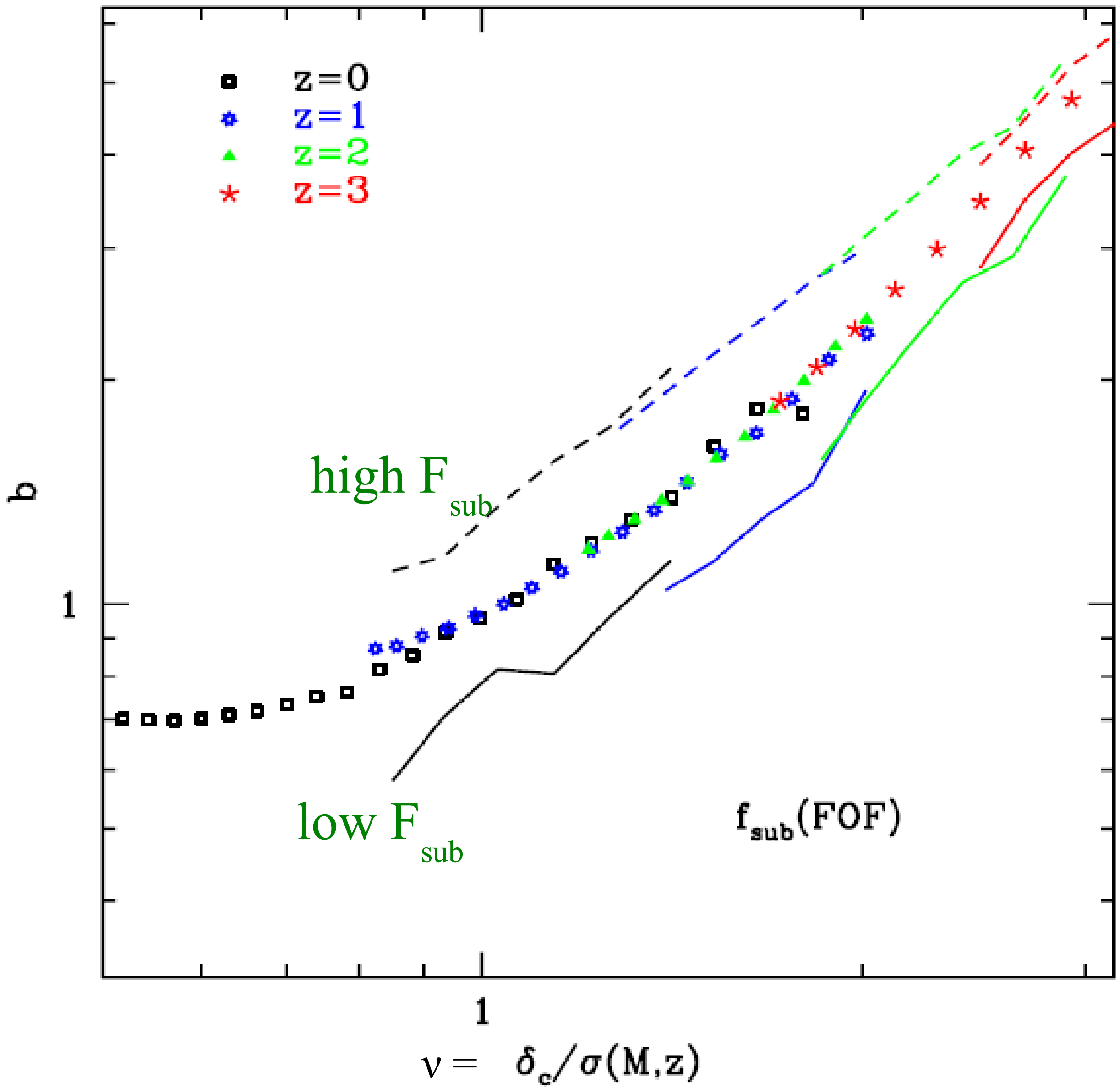
For halo spin, defined as λ' for the mass within the virial radius, the bias ratio is roughly independent of mass

$b_{hi} / b_{lo} \sim 1.4$

This behaviour differs both from that of formation time and from that of concentration

Bias as a function of ν and substructure mass fraction

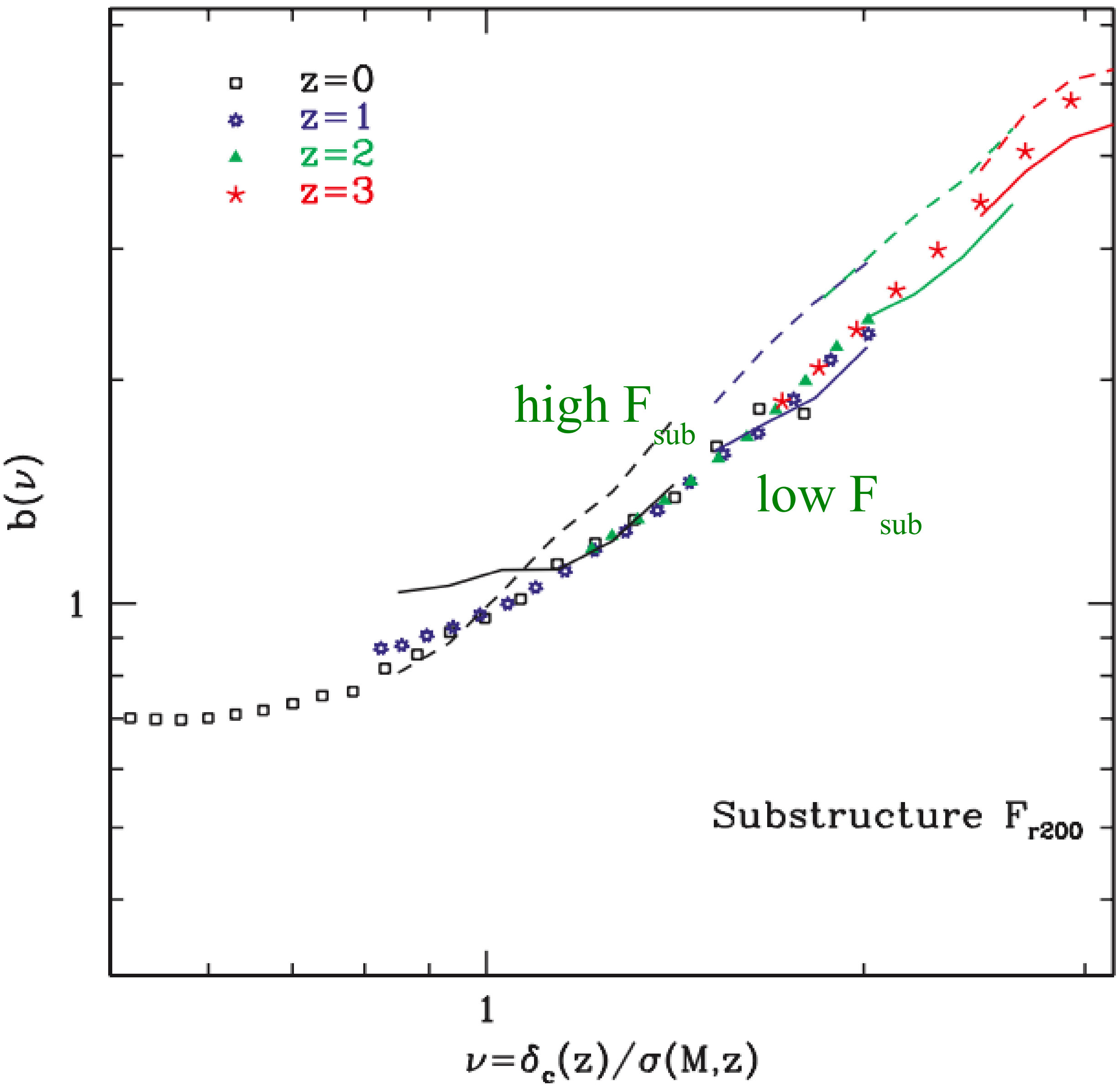
Gao & White 2007



Defining substructure mass fraction so that $1 - F_{sub}$ is the fraction of the FoF mass in the main self-bound subhalo, b_{hi} / b_{lo} varies from ~ 2 at M_* to ~1.5 at cluster mass

Bias as a function of ν and substructure mass fraction

Gao & White 2007



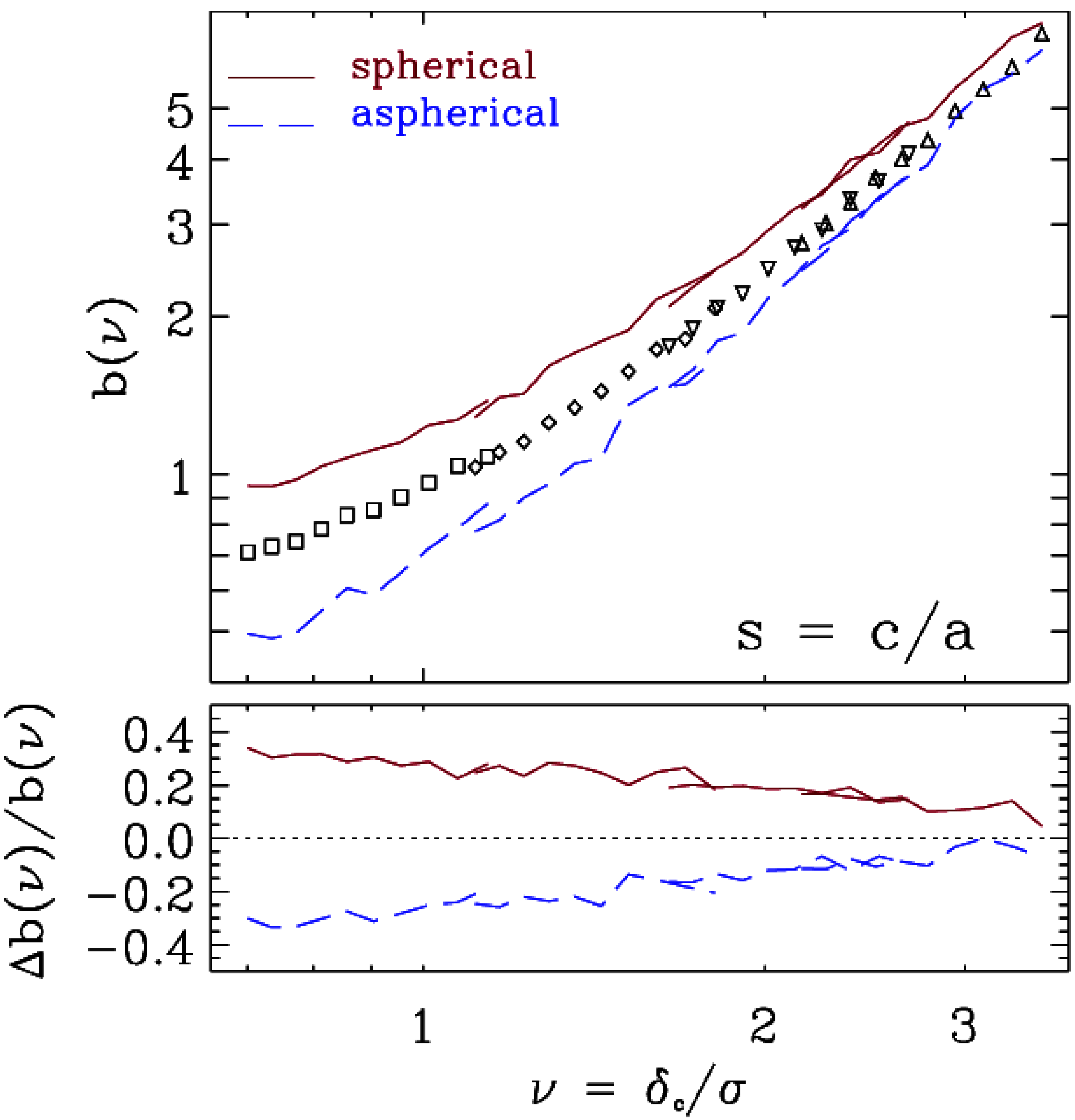
Defining substructure mass fraction so that F_{sub} is the fraction of mass in subhalos within the virial radius, the effect is much smaller, going through unity at M_*.

At high mass b_{hi} / b_{lo} ~ 1.2

Li et al (2008) found a similar strong dependence of assembly bias on the definition of formation time.

Bias as a function of ν and main subhalo shape

Faltenbacher & White 2010



Main subhalos which are rounder are more strongly clustered at all masses.

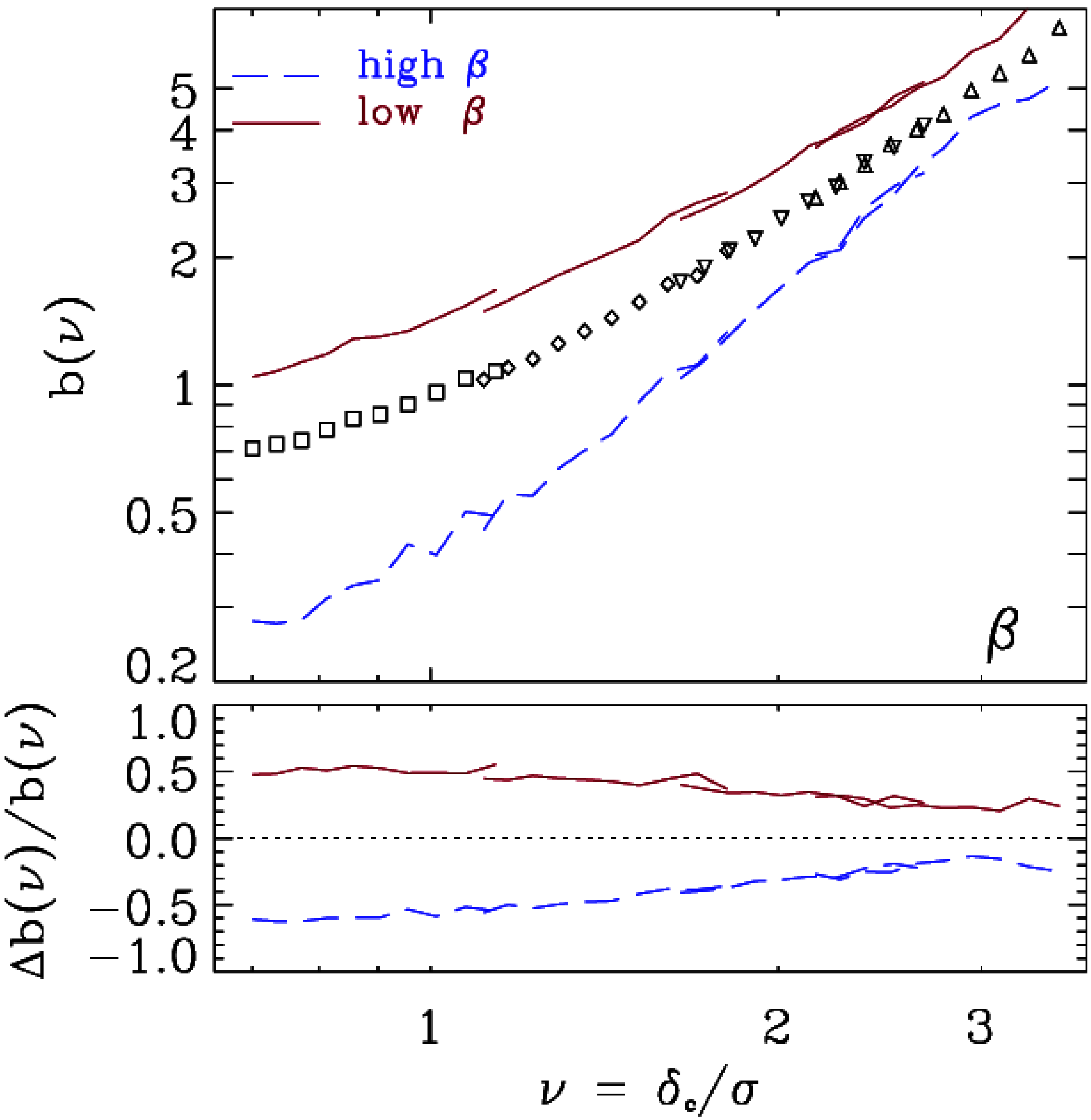
For MW-mass halos,
$b_{hi} / b_{lo} \sim 2$

For cluster mass halos,
$b_{hi} / b_{lo} \sim 1.2$

The <u>orientation</u> of the main subhalo also correlates with surrounding large-scale structure

Bias as a function of ν and velocity anisotropy

Faltenbacher & White 2010



β is equivalent to the fraction of the K.E. of the main subhalo in radial motions

For MW-mass halos,
$b_{hi} / b_{lo} \sim 0.3$

For cluster mass halos,
$b_{hi} / b_{lo} \sim 0.6$

This is the strongest of all the effects considered so far

Assembly bias and the cosmic web

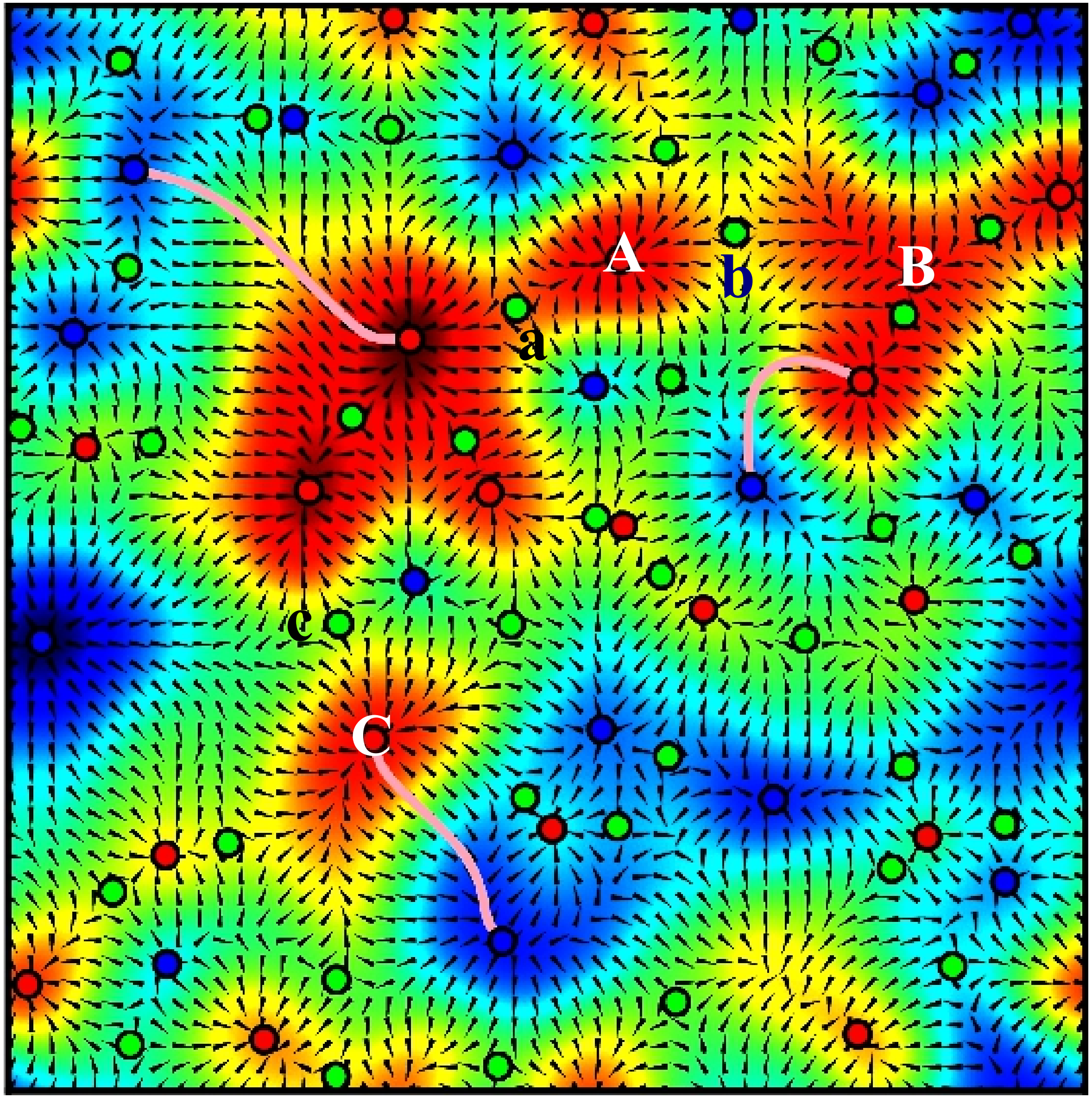


Image from T. Sousbie (2011)

Let halos be bounded by red equidensity contours and associated to their highest peak

The density at which halo **A** links to a structure with a higher peak is that at saddle point **a**

Halo **B** links at saddle point **b**

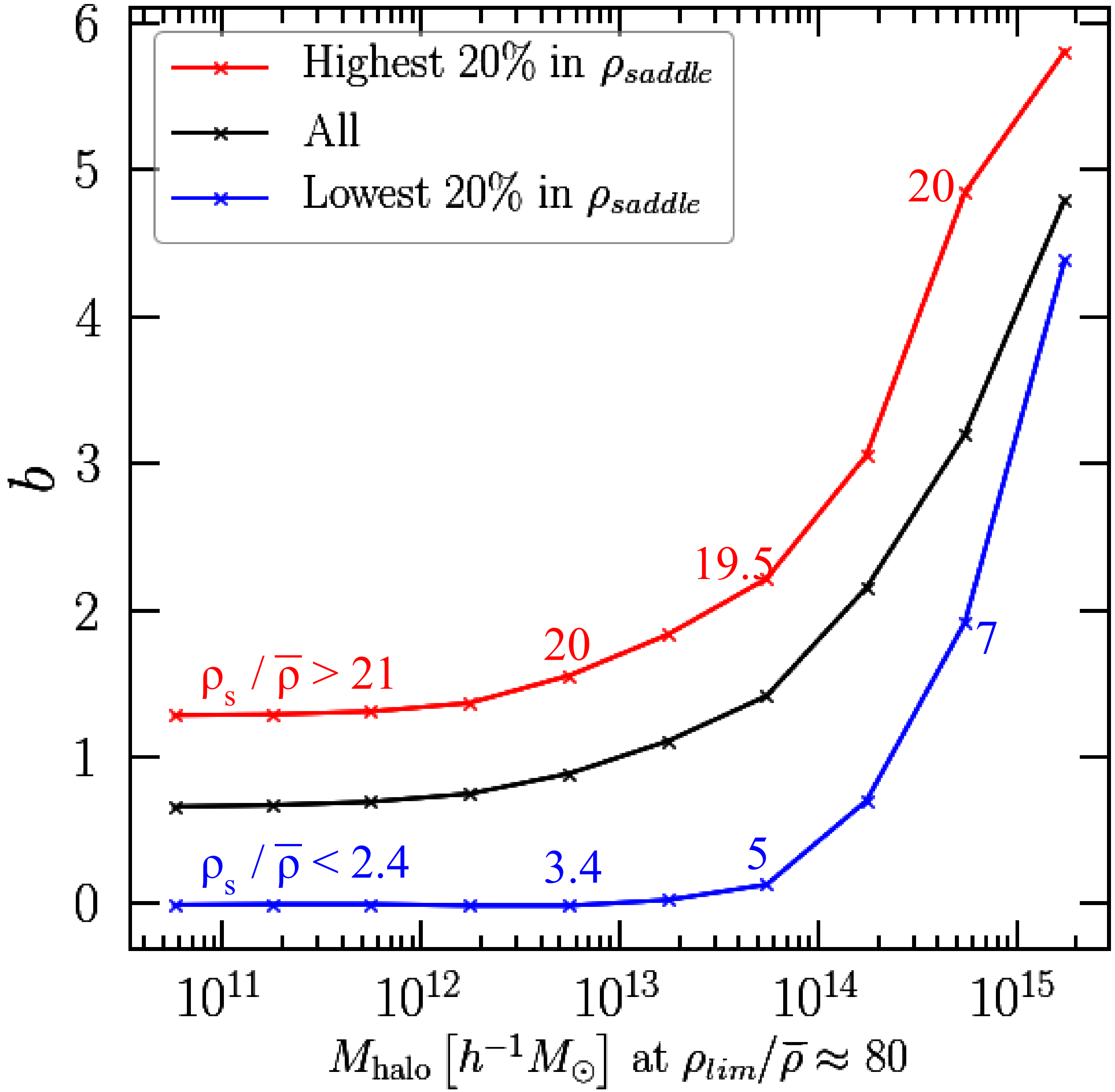
Halo **C** links at saddle point **c**

$\rho_{\mathbf{a}} > \rho_{\mathbf{b}} > \rho_{\mathbf{c}}$ in this example

The saddle point usually occurs at $< 2\,R_{halo}$

Bias as a function of mass and saddle point density

Millennium data: ρ from Voronoi tesselation



Busch et al, in prep.

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, $b_{\rm lo} = 0$!

Halos in the 20% tail with highest saddle point density are as strongly biased as those with the highest β values

Halo assembly bias: conclusions

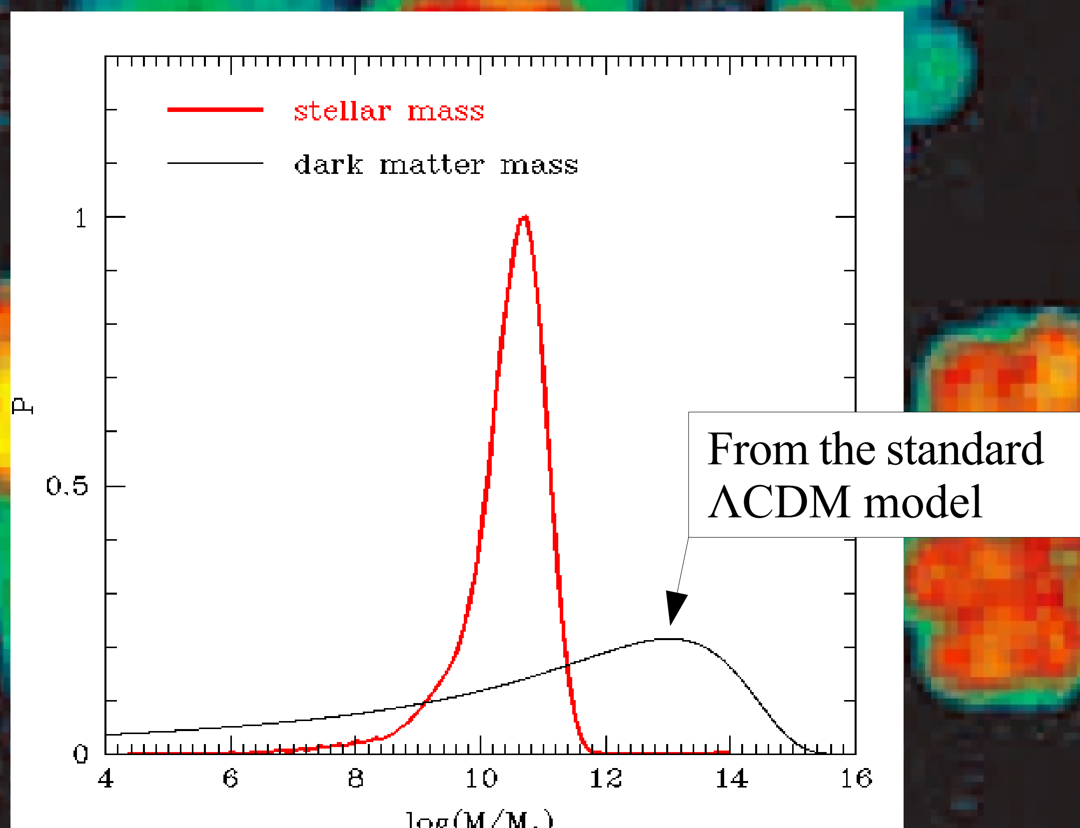
The large-scale bias of halo clustering depends not only on halo mass through $\nu = \delta_c / D(z)\, \sigma_o(M)$, but also on

- formation time
- concentration
- substructure content
- spin
- shape
- velocity anisotropy
- saddle density

The dependences on different assembly variables are different and cannot be derived from each other: $b = b(\mathrm{M}, \mathbf{A})$ with $\mathbf{A}$ multi-dimensional.

These dependences are likely to be reflected in galaxy bias

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



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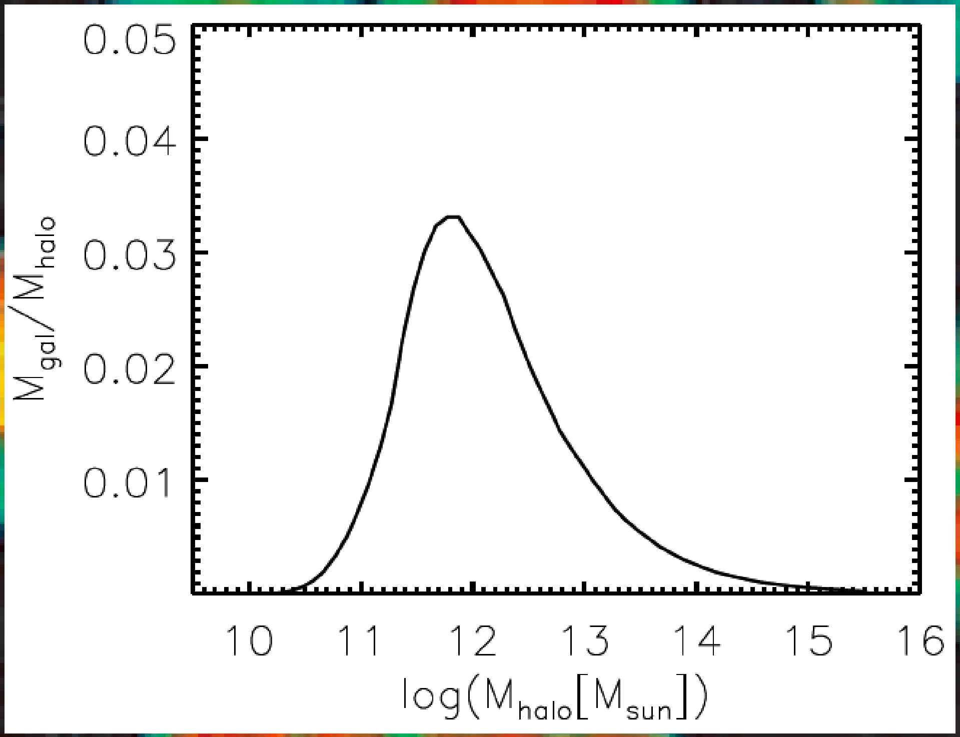
→ Galaxy to halo mass ratio varies *strongly* with mass



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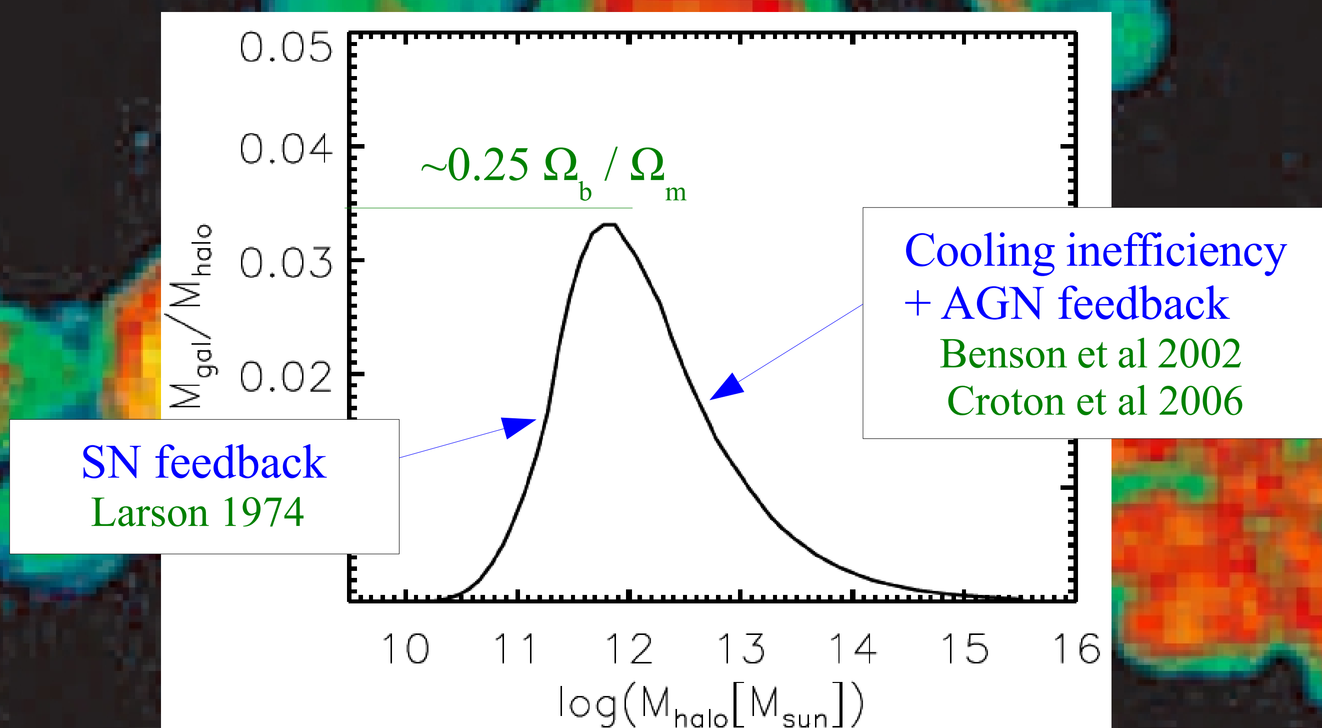
Star formation efficiency is reduced at both low *and* high halo mass



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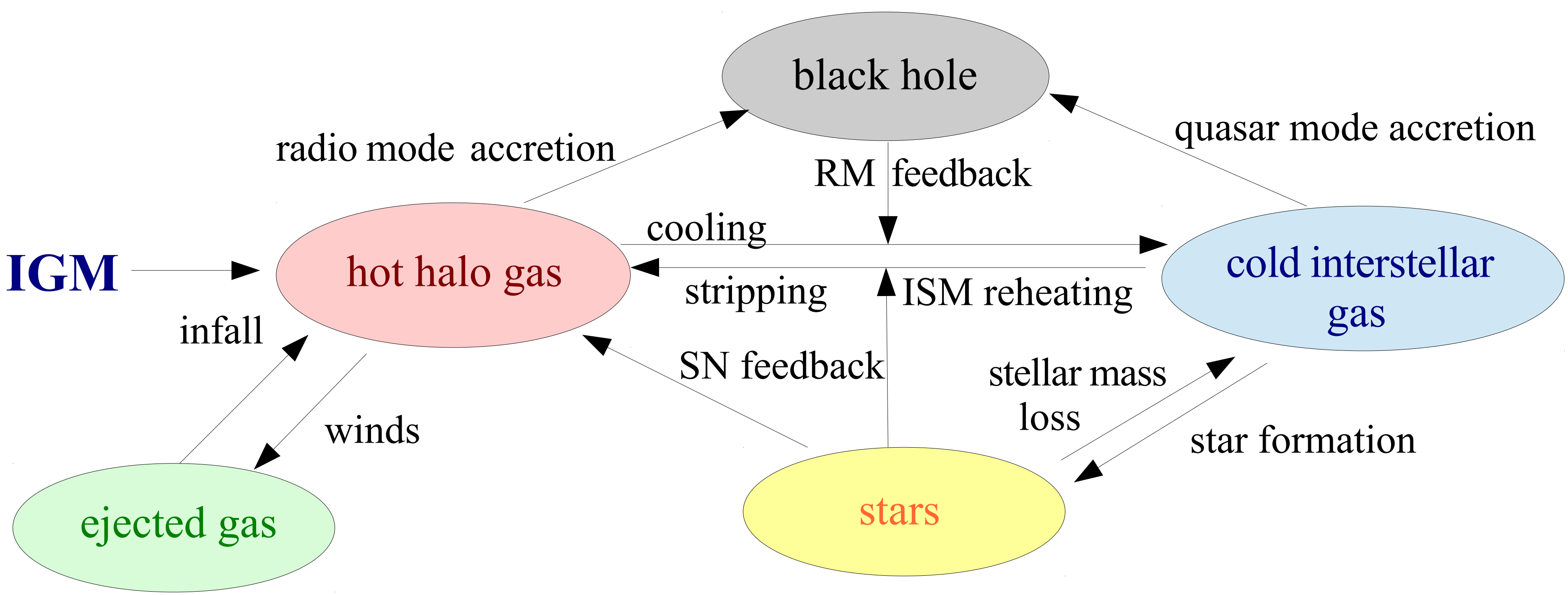
Star formation efficiency is reduced at both low *and* high halo mass

$$(\Omega_b / \Omega_m)\, M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$



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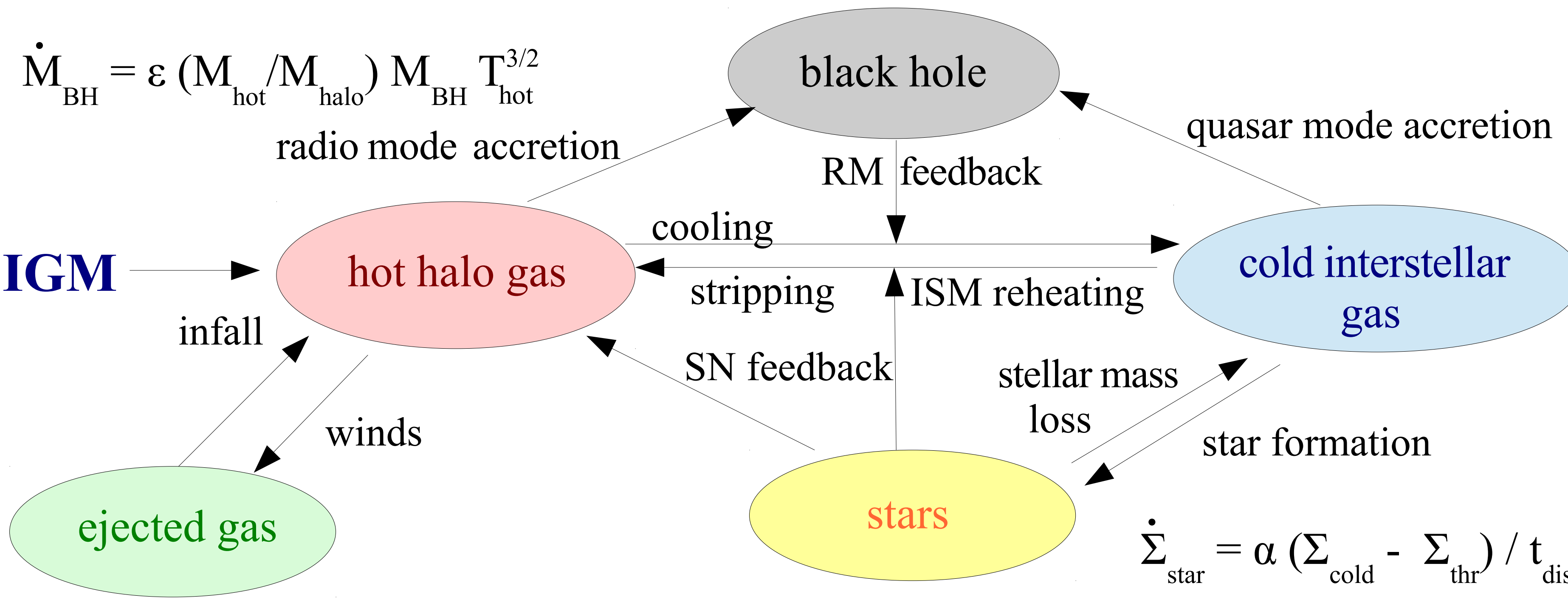
$$(\Omega_b / \Omega_m)\, M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$

$$\dot{M}_{BH} = \varepsilon\, (M_{hot}/M_{halo})\, M_{BH}\, T_{hot}^{3/2}$$



$$\dot{\Sigma}_{star} = \alpha\, (\Sigma_{cold} - \Sigma_{thr}) / t_{disk}$$

The semi-analytic programme

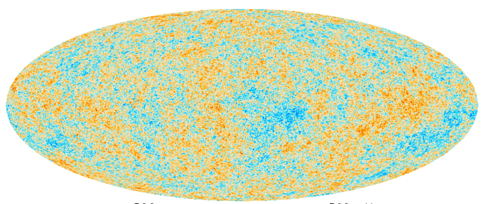
Follow the DM distribution with high-resolution simulations

- identify dark halos/subhalos at all times, building merger trees to describe their growth, internal structure and spatial distribution

Treat baryonic physics within the evolving population of DM objects using simplified physical models for processes such as

- gas cooling onto central galaxies
- star formation within these central galaxies
- central black hole growth
- generation of winds through stellar and AGN feedback
- production, expulsion and mixing of nucleosynthesis products

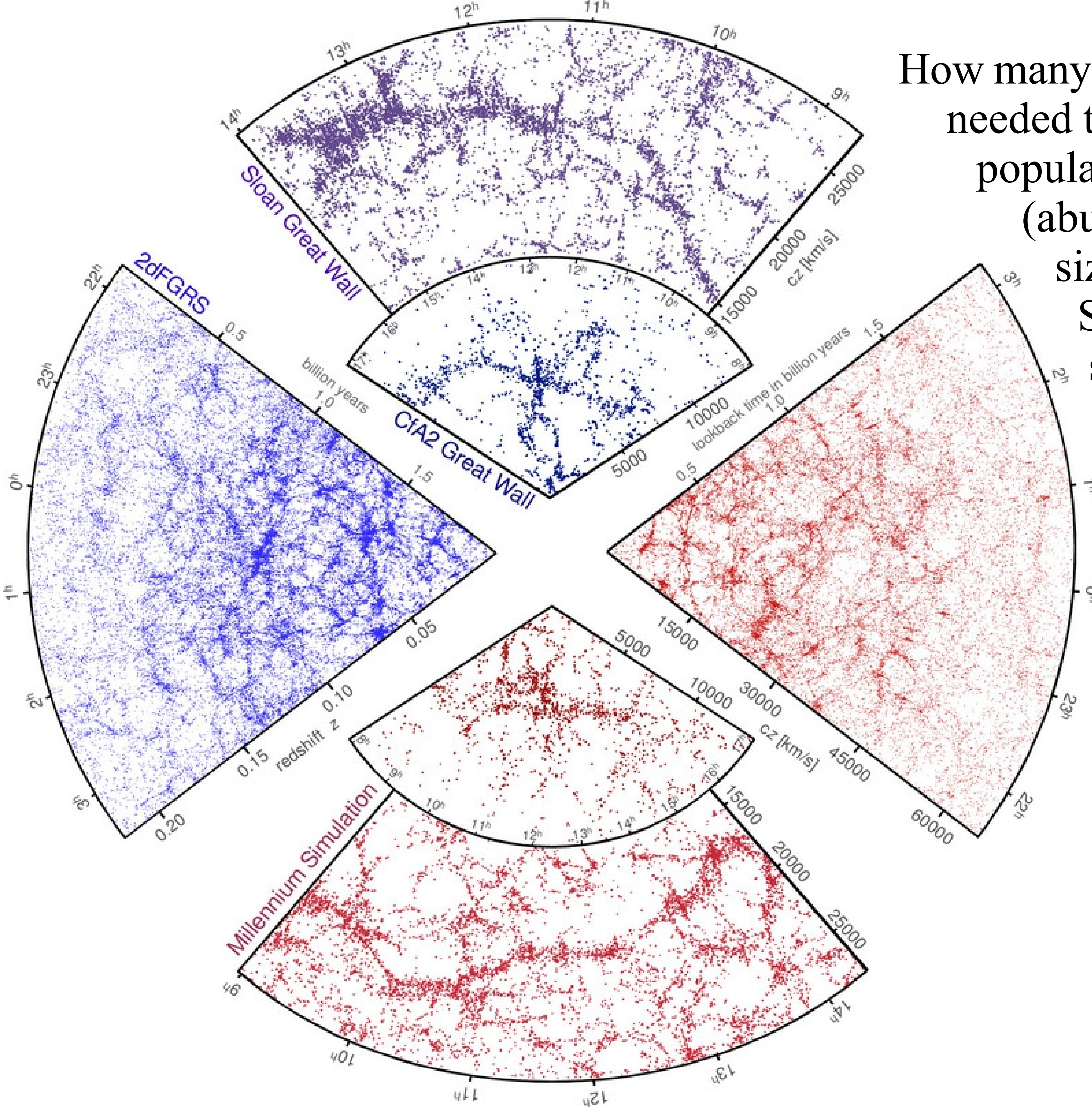
Measure the efficiencies of these processes as functions of redshift and galaxy properties by comparing model output directly with observational data

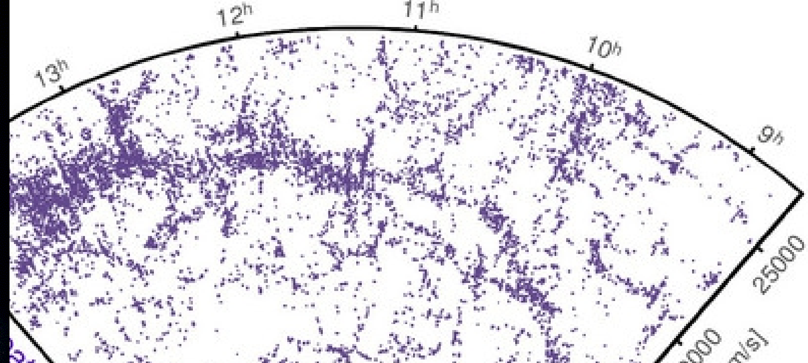
e.g.  → Ω

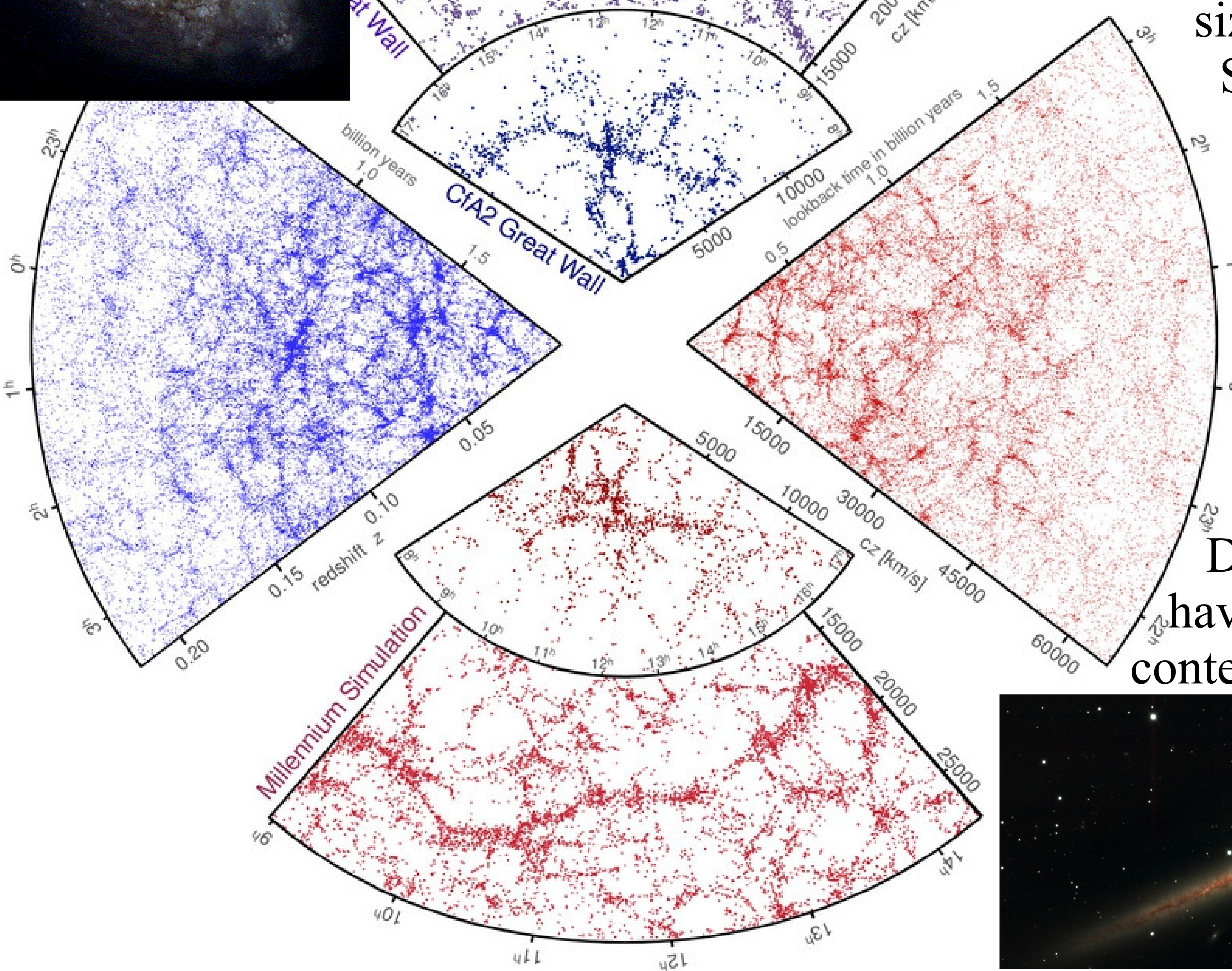
Six parameters fine-tuned to fit a single curve

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
$100\theta_{MC}$	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	$3.089^{+0.024}_{-0.027}$

How many parameters are needed to fit the galaxy population? (abundance by mass, size, gas content, SFR, B/T, AGN; scaling relations; clustering...)



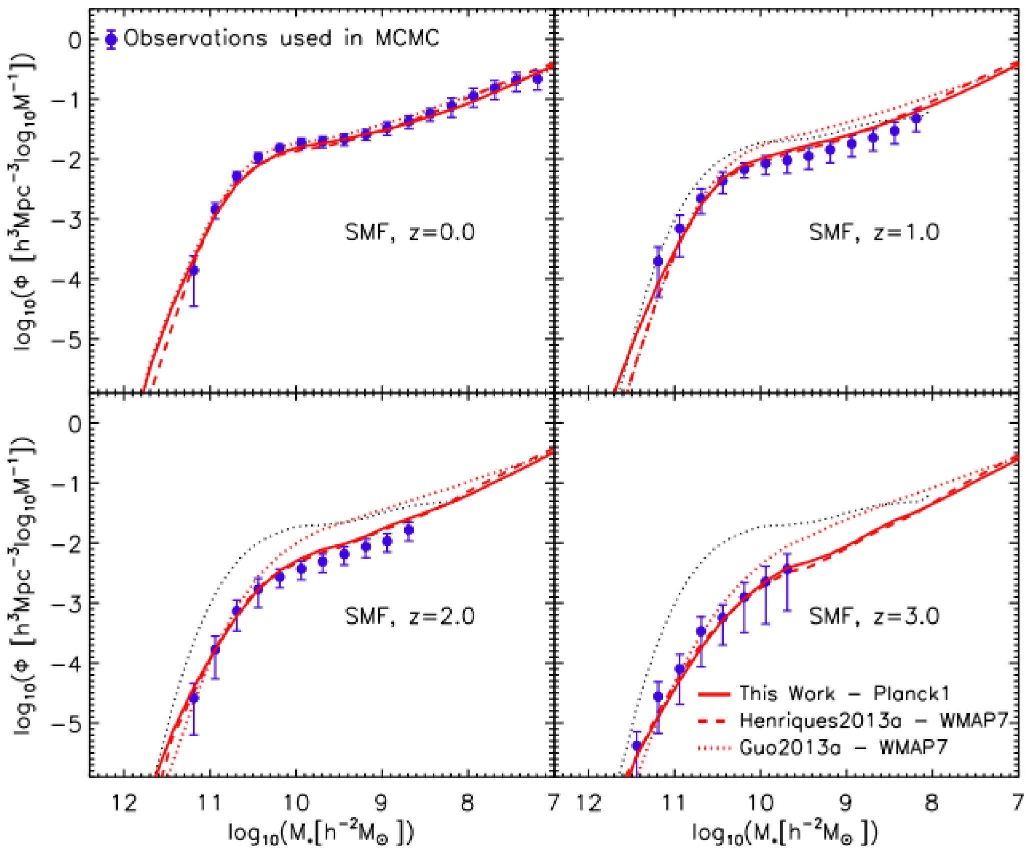




How many parameters are needed to fit the galaxy population?
(abundance by mass, size, gas content, SFR, B/T, AGN; scaling relations; clustering...)

Do the parameters have useful *physical* content?

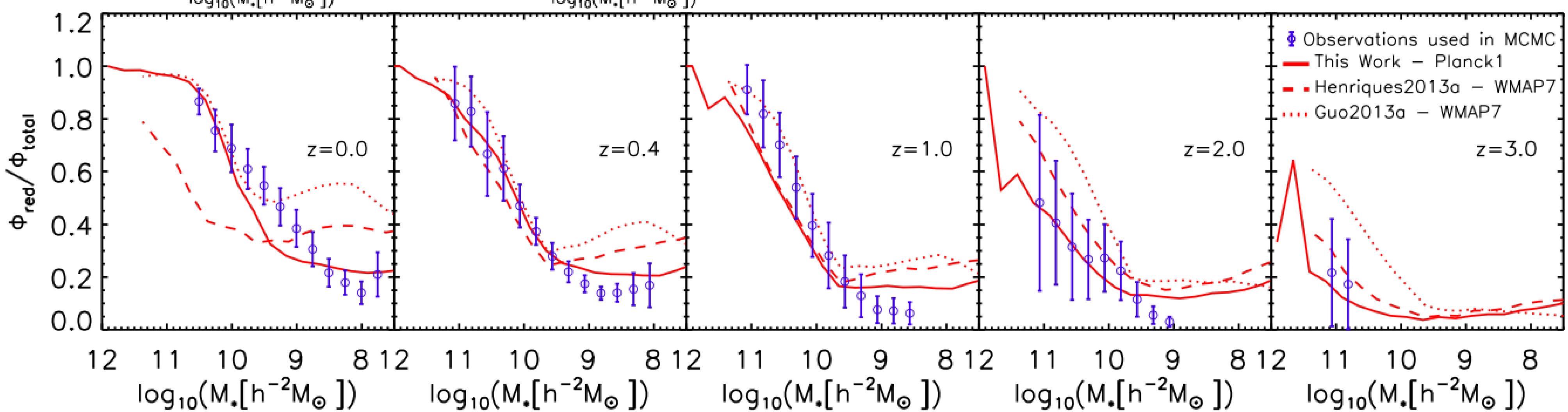
Calibrating models for (sub)halo occupation



Henriques et al (2015)

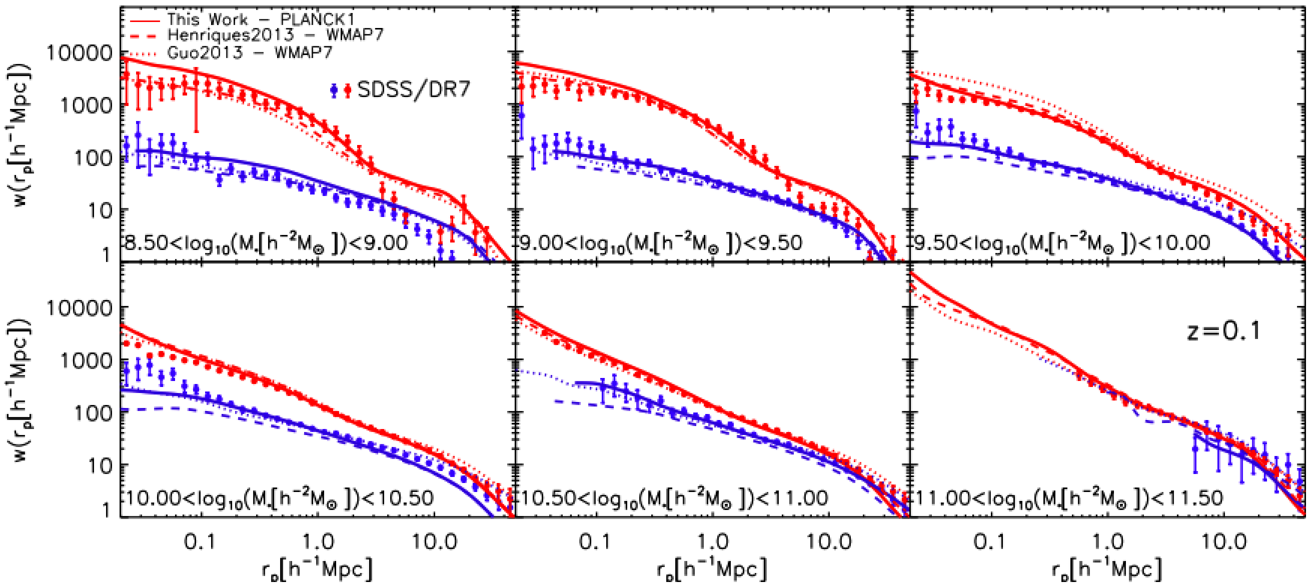
The 17 parameters of the SA subhalo occupation model constrained by MF and passive fraction observations over $0 \leq z \leq 3$ and three orders of magnitude in stellar mass

The MCMC chains show all parameters to be determined to moderate accuracy with no major degeneracies

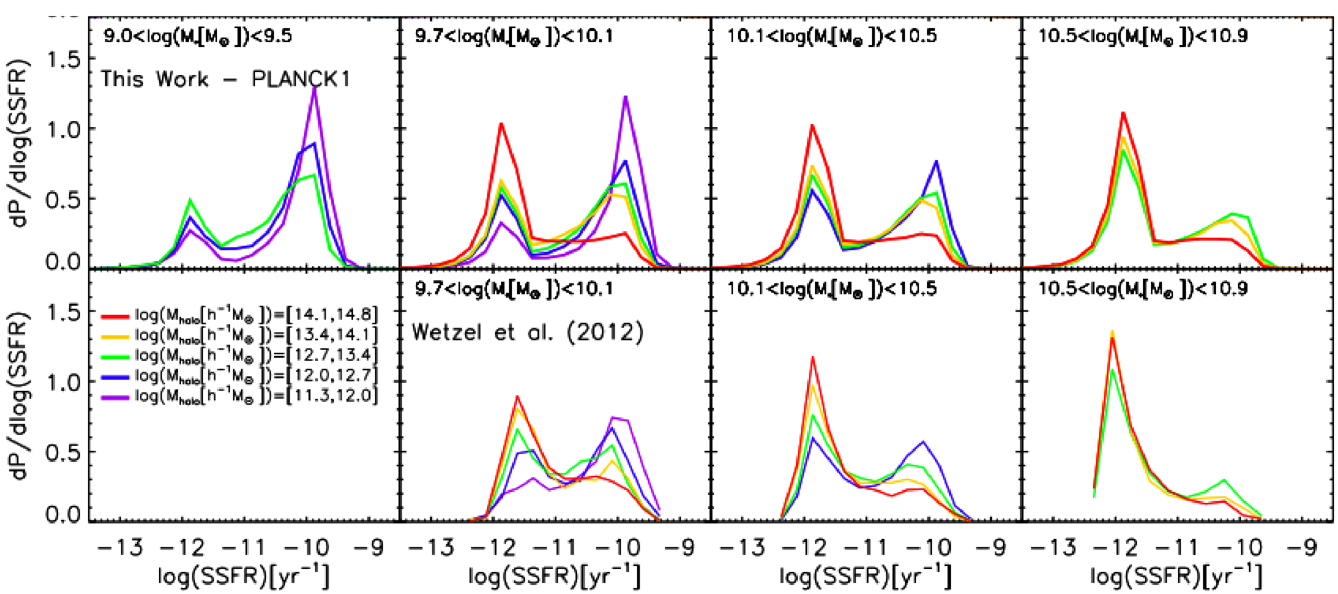


Testing semianalytic simulations

Henriques et al 2017

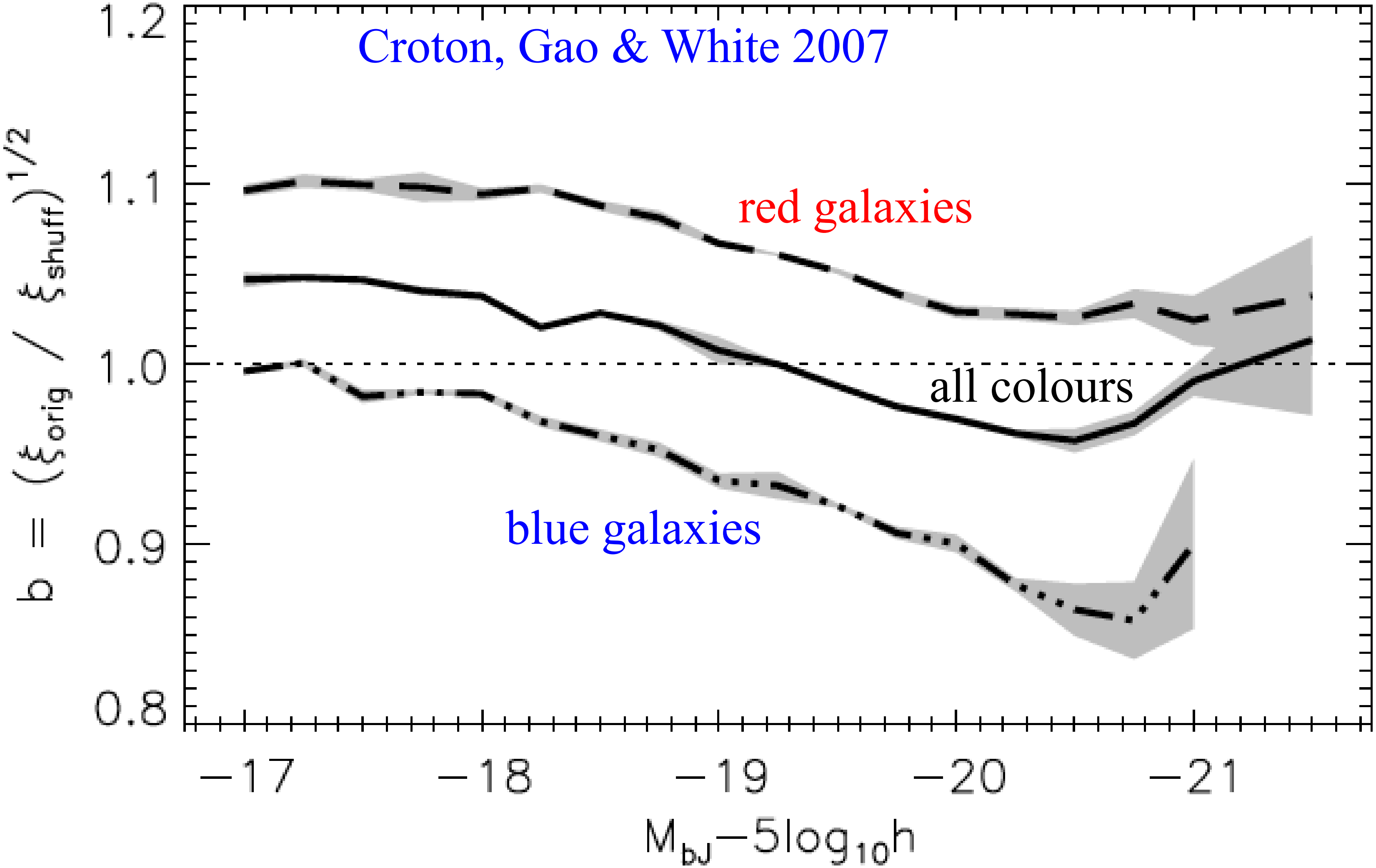


Model reproduces: w(r_p) for active/passive galaxies at r_p > 20 h^{-1} kpc and over 3 orders of magnitude in stellar mass



Variation of passive fraction with halo and stellar mass

Assembly bias in the galaxy distribution

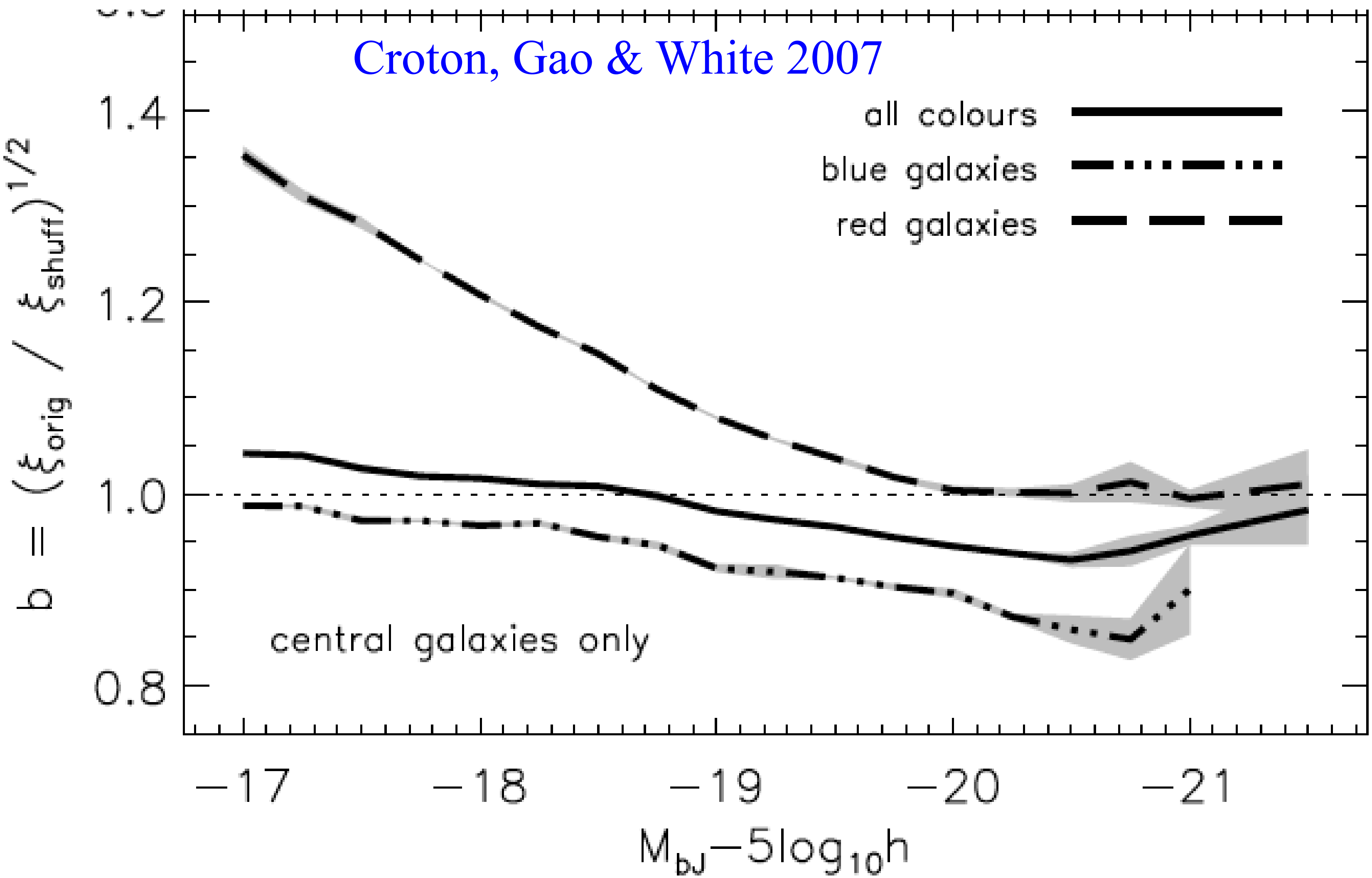


Simulated galaxy populations are <u>shuffled</u> among halos of similar mass

→ clustering differences due purely to assembly history differences

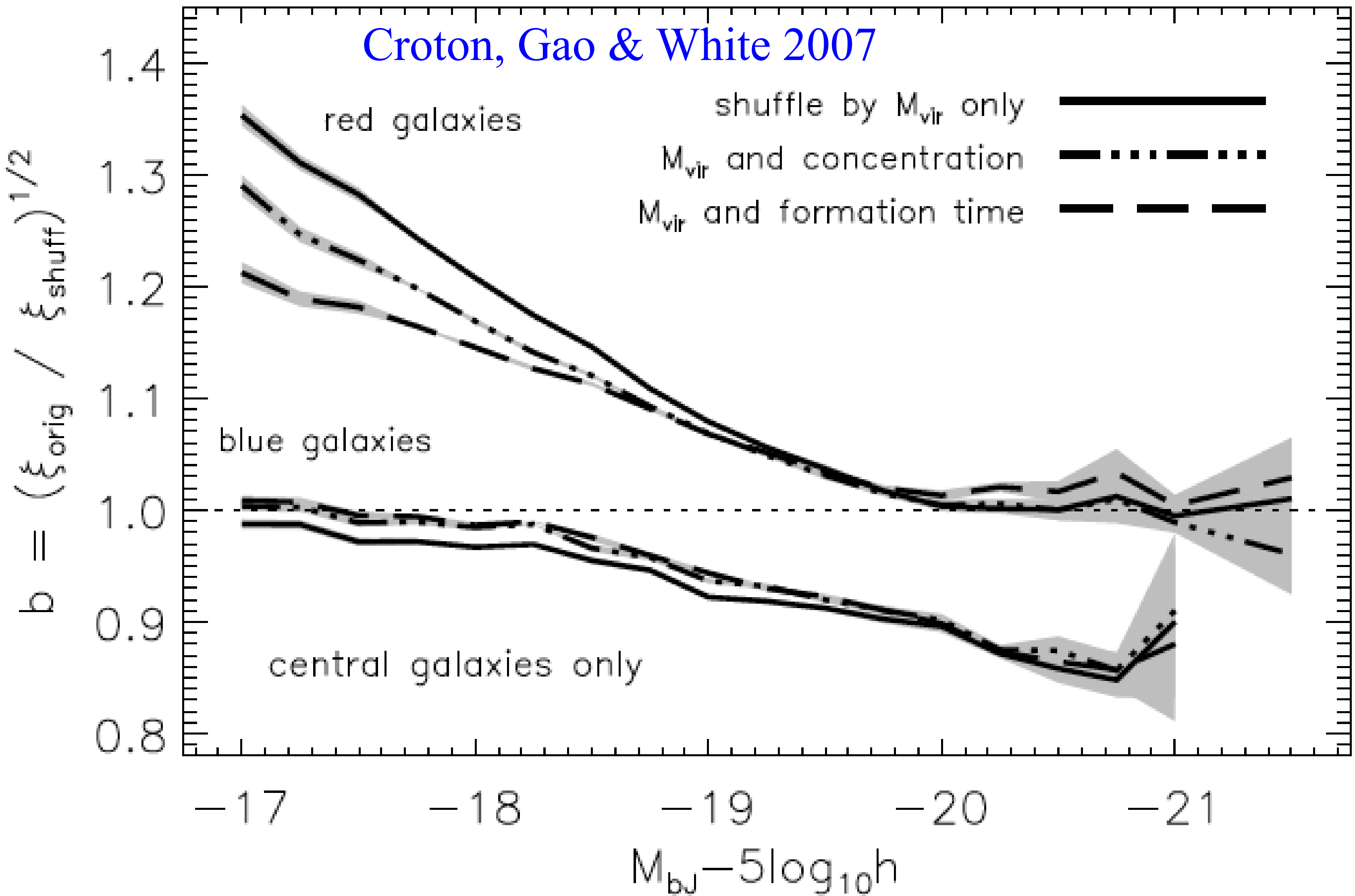
Luminosity- and colour-dependent effects at the ~10% level

Assembly bias in the galaxy distribution



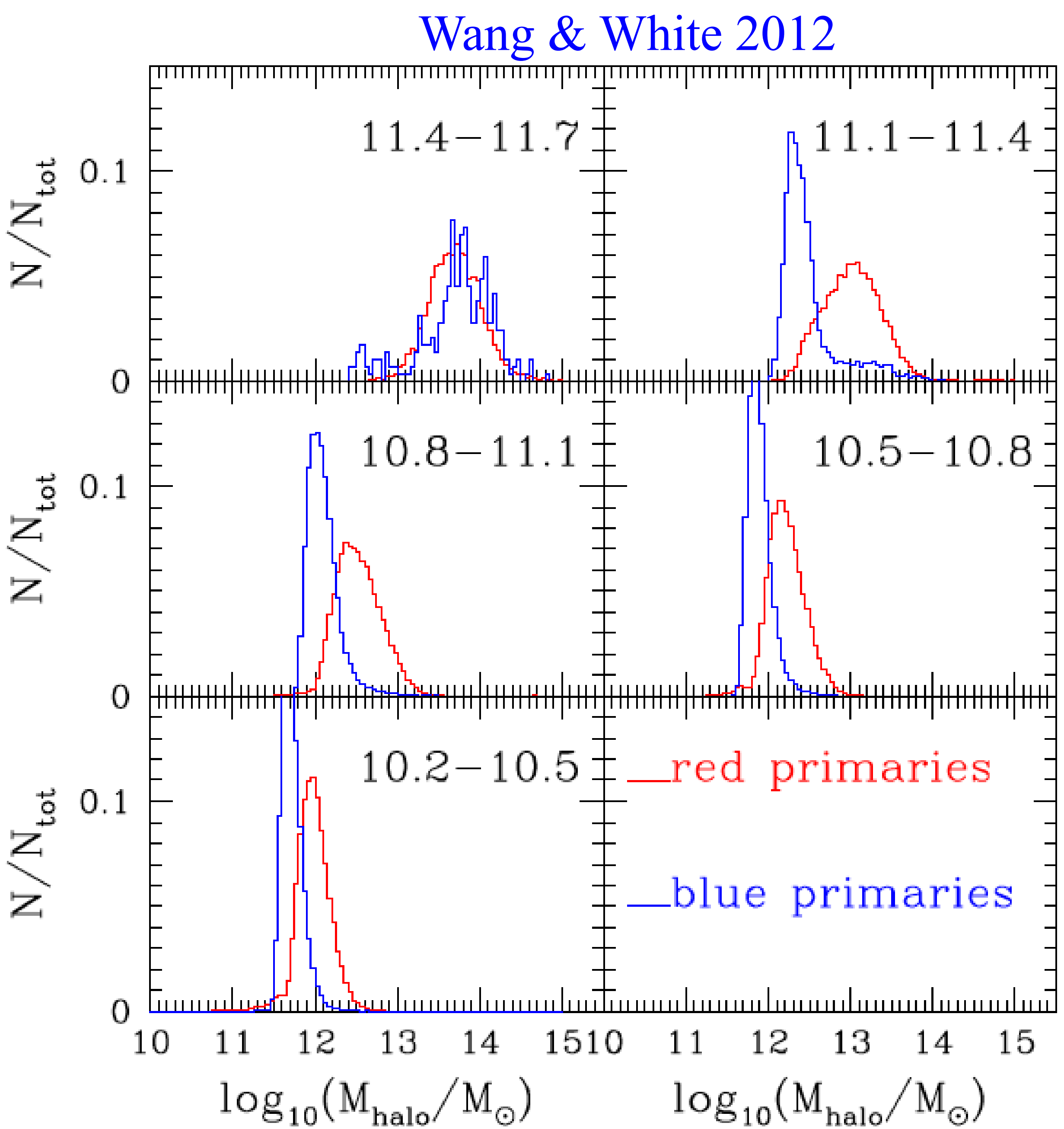
Effects are present in both central and satellite galaxy populations but differ between them

Assembly bias in the galaxy distribution



Constraining the HOD by additional halo properties (formation time, concentration) does little to reduce assembly bias effects on the galaxies

A population simulation prediction for galaxy halos



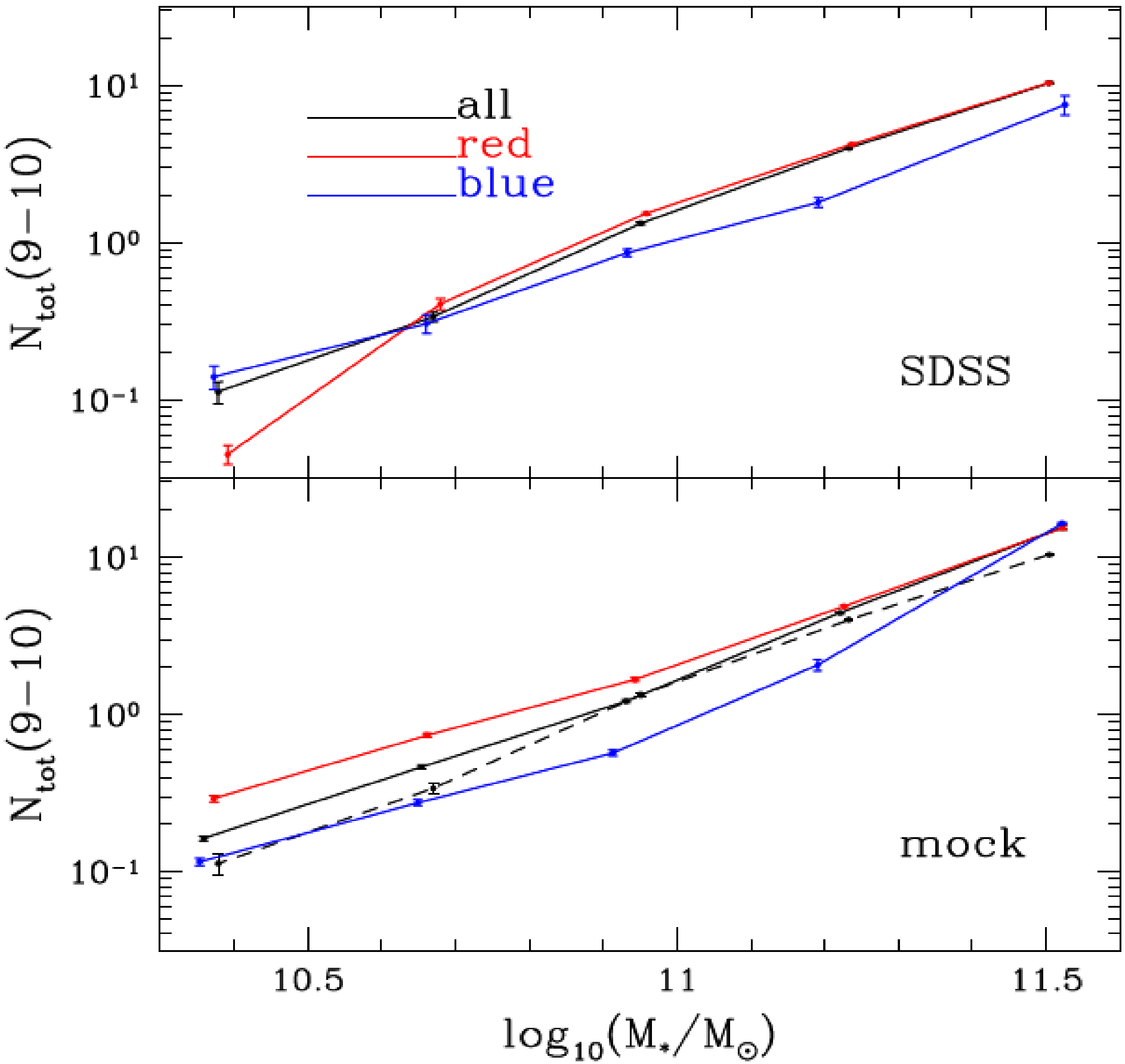
Central galaxies of a given stellar mass are predicted to have larger halo masses if they are red (passive) than if they are blue (star-forming)

This is because central galaxies stop growing after quenching but their halos do not

This effect is **not** present (by construction) in age+abundance SHAM models

A population simulation prediction for galaxy halos

Wang & White 2012

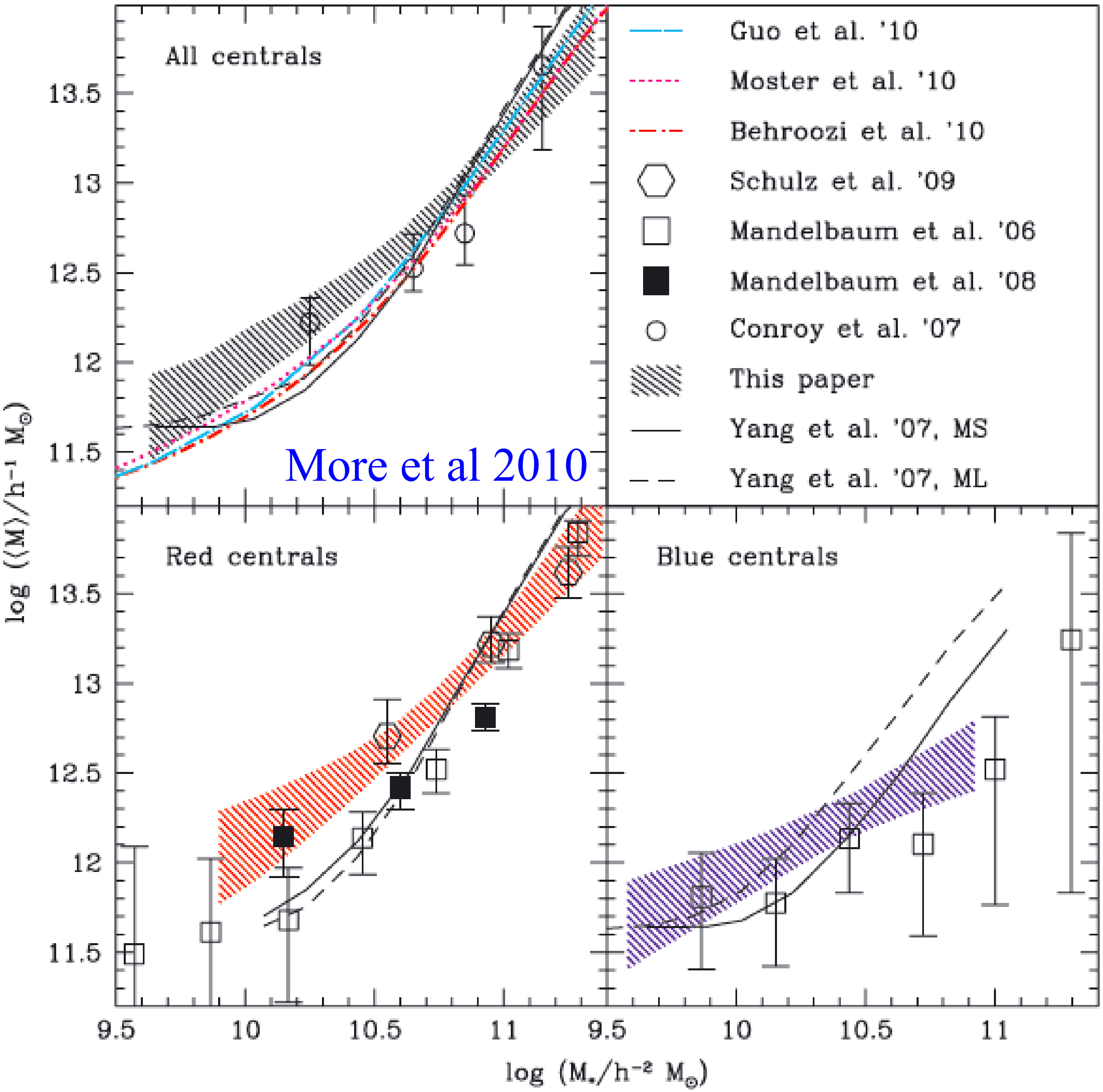


Central galaxies of a given stellar mass are predicted to have larger halo masses if they are red (passive) than if they are blue (star-forming)

This results in red centrals having more satellites than blue ones of the same stellar mass

This effect **is** seen in SDSS above Milky Way stellar mass

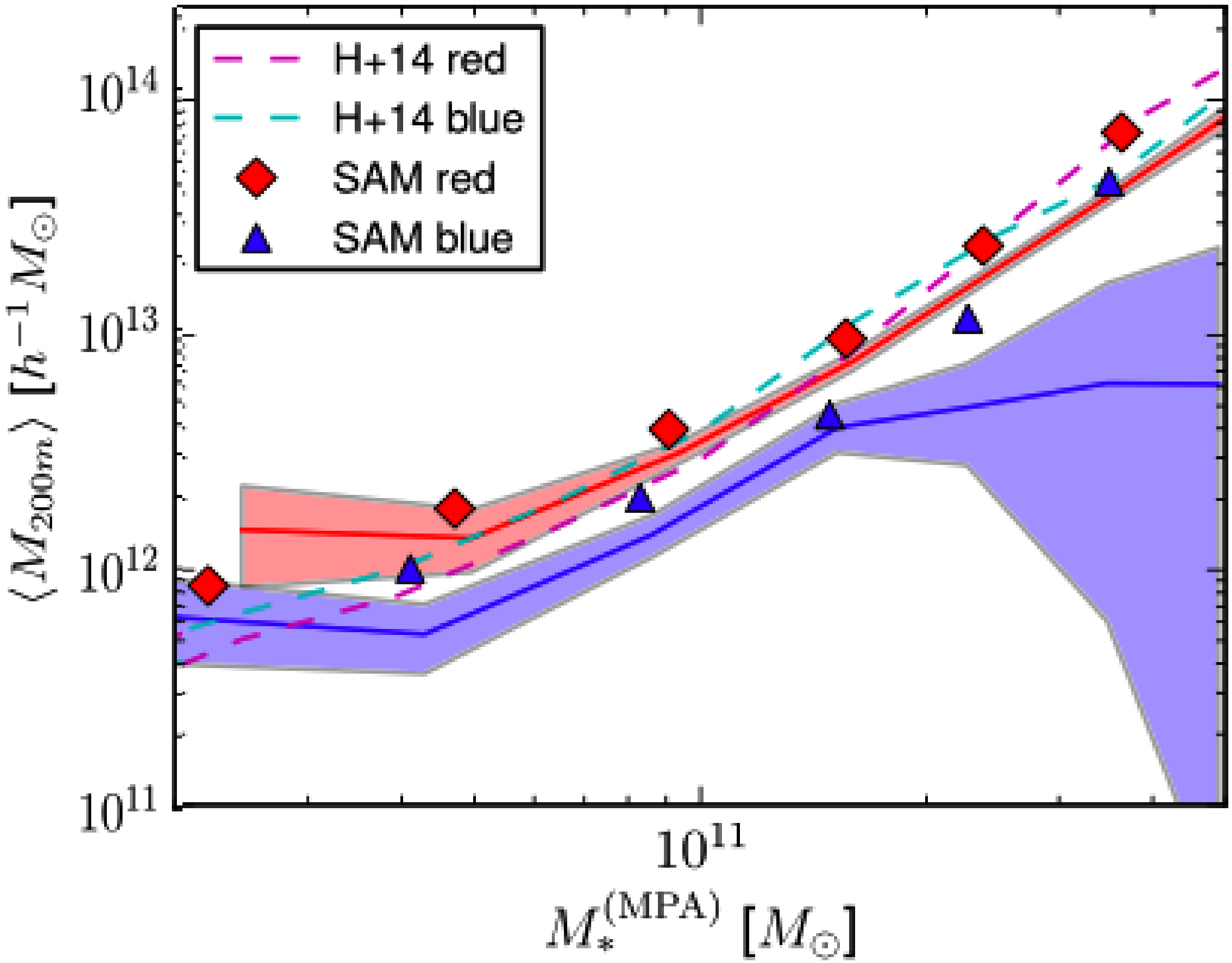
Halo mass dependence on central galaxy colour?



Blue centrals have lower mass halos than red centrals of the same stellar mass according to estimates based on the motions of satellites

Halo mass dependence on central galaxy colour?

Mandelbaum et al 2016



Blue centrals have lower mass halos than red centrals of the same stellar mass according to estimates based on the motions of satellites and on weak gravitational lensing

In summary...

Precision cosmology with galaxy surveys requires the relation between the galaxy and dark matter distributions to be known precisely

- Halo clustering depends at the 10 to 30% level on many aspects of halo structure and formation history in addition to halo mass
- This complexity carries over to the galaxy population and affects both the spatial and kinematic (peculiar velocity) properties
- Different galaxy types can have BAO features of different shape
- Halo mass depends on both colour and mass of the central galaxy
- Baryon physics can affect the lensing P(k) down to k ~ 0.3 h/Mpc

All these effects depend on the details of galaxy formation physics

None is easily included in the HOD or SHAM modelling frameworks