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The Los Cabos Lectures

Dark Matter Halos

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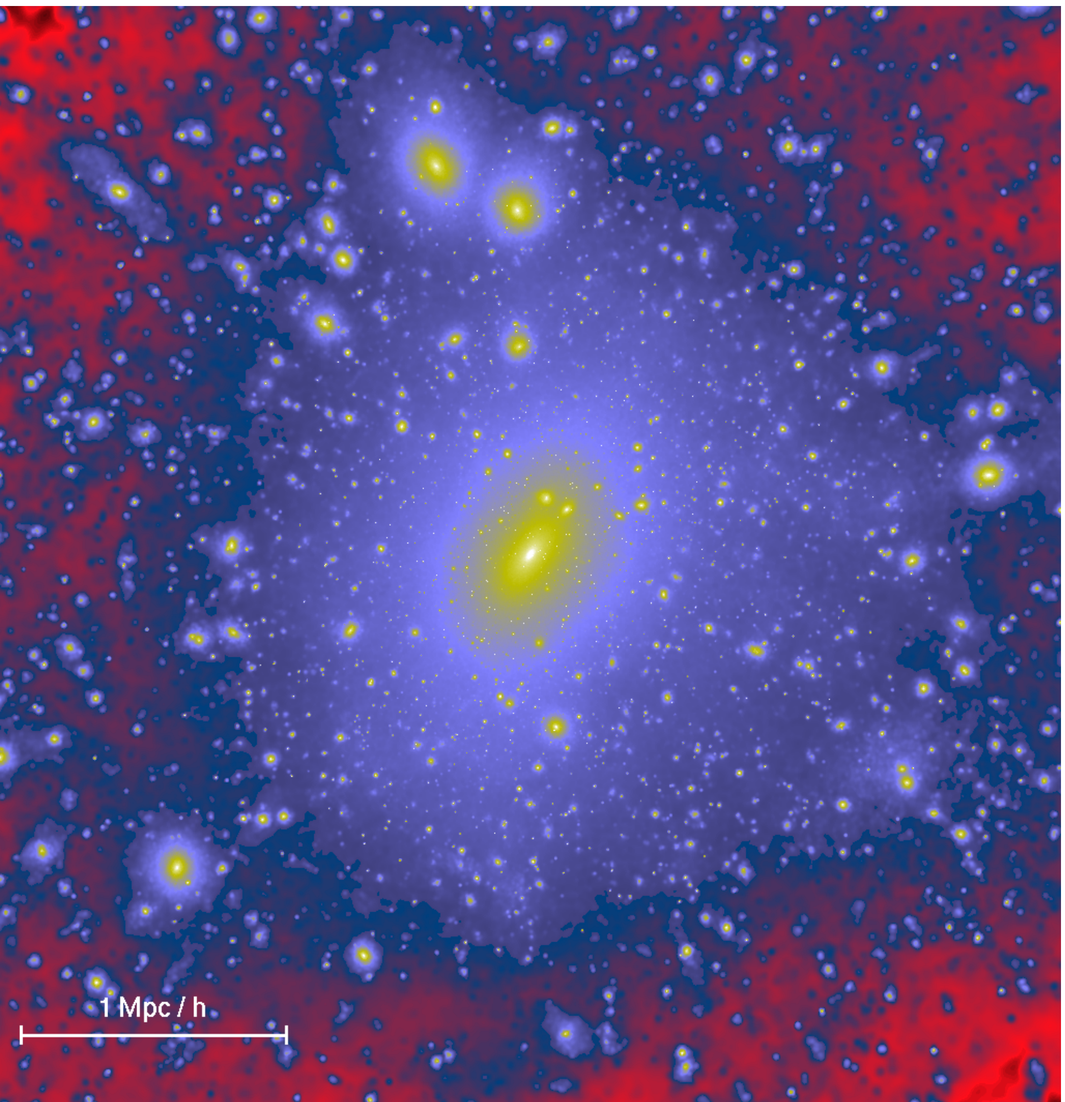
Dark matter halos are the basic units of nonlinear structure

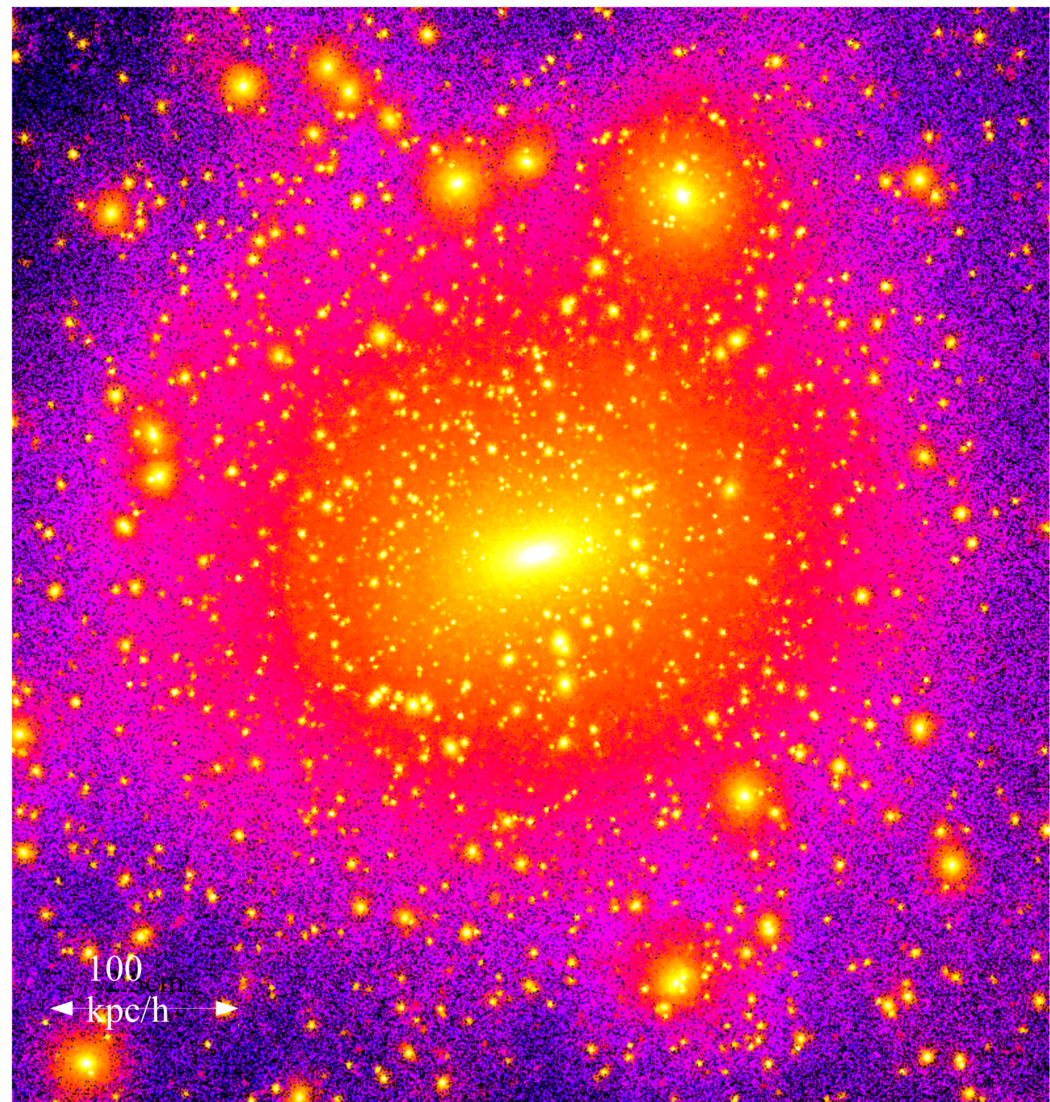
- Is all dark matter part of some halo?
- Was this always the case?
- How do halos grow? accretion? merging?
- How are they distributed?
- What is their internal structure?
  - -- density profile
  - -- shape
  - -- subhalo population – mass/radial distributions, evolution
  - -- caustics
- How do these 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



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

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 the largest mass M 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 $M_s(k_c)$

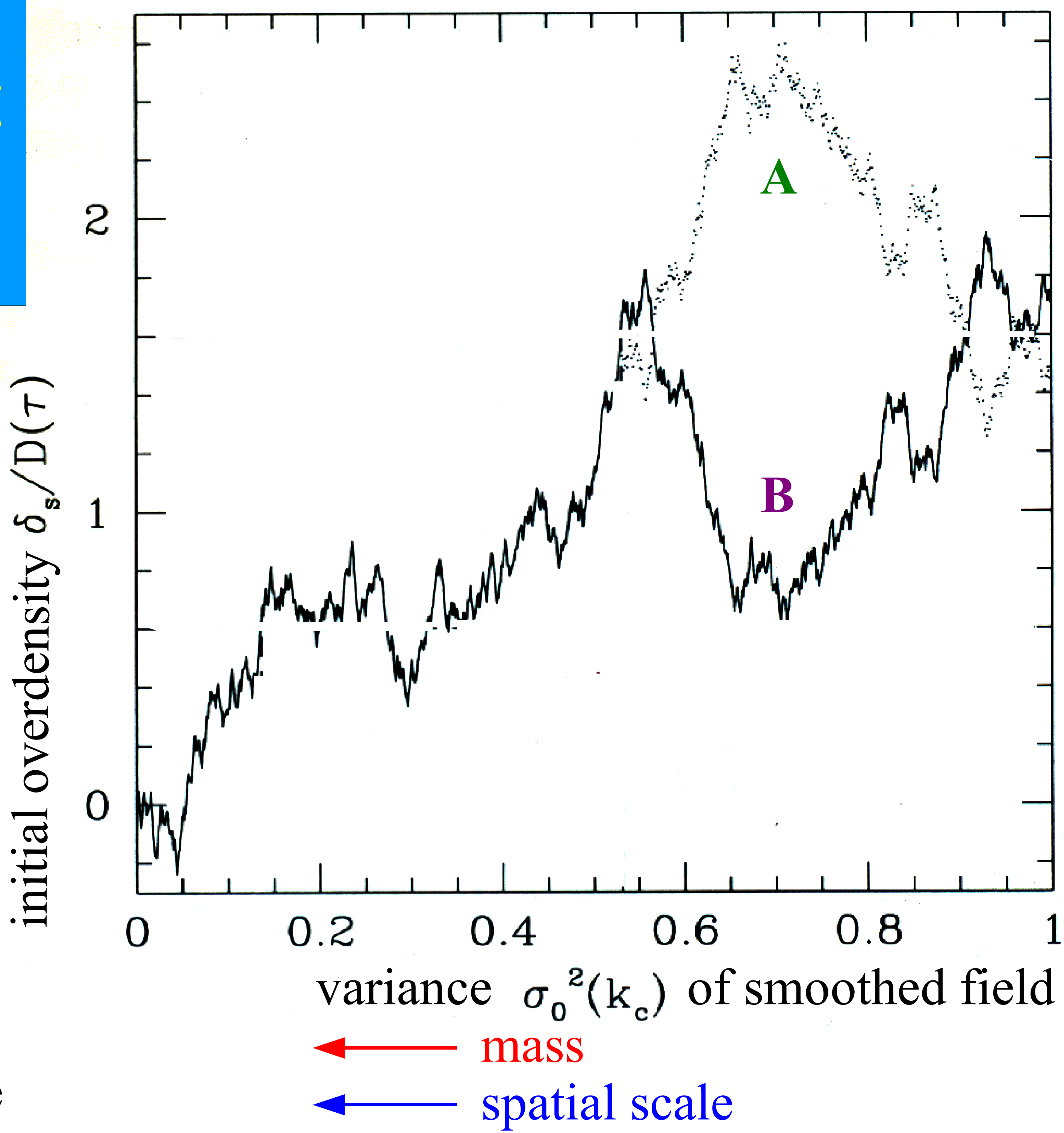
$$\rightarrow \quad n(M, z)\, dM = \frac{-\rho_o}{\sqrt{(2\pi)}\, M^2} \frac{\delta_c}{D\,\sigma_o} \frac{d \ln \sigma_o^2}{d \ln M} \exp -\frac{1}{2}\left(\frac{\delta_c}{D\,\sigma_o}\right)^2$$

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

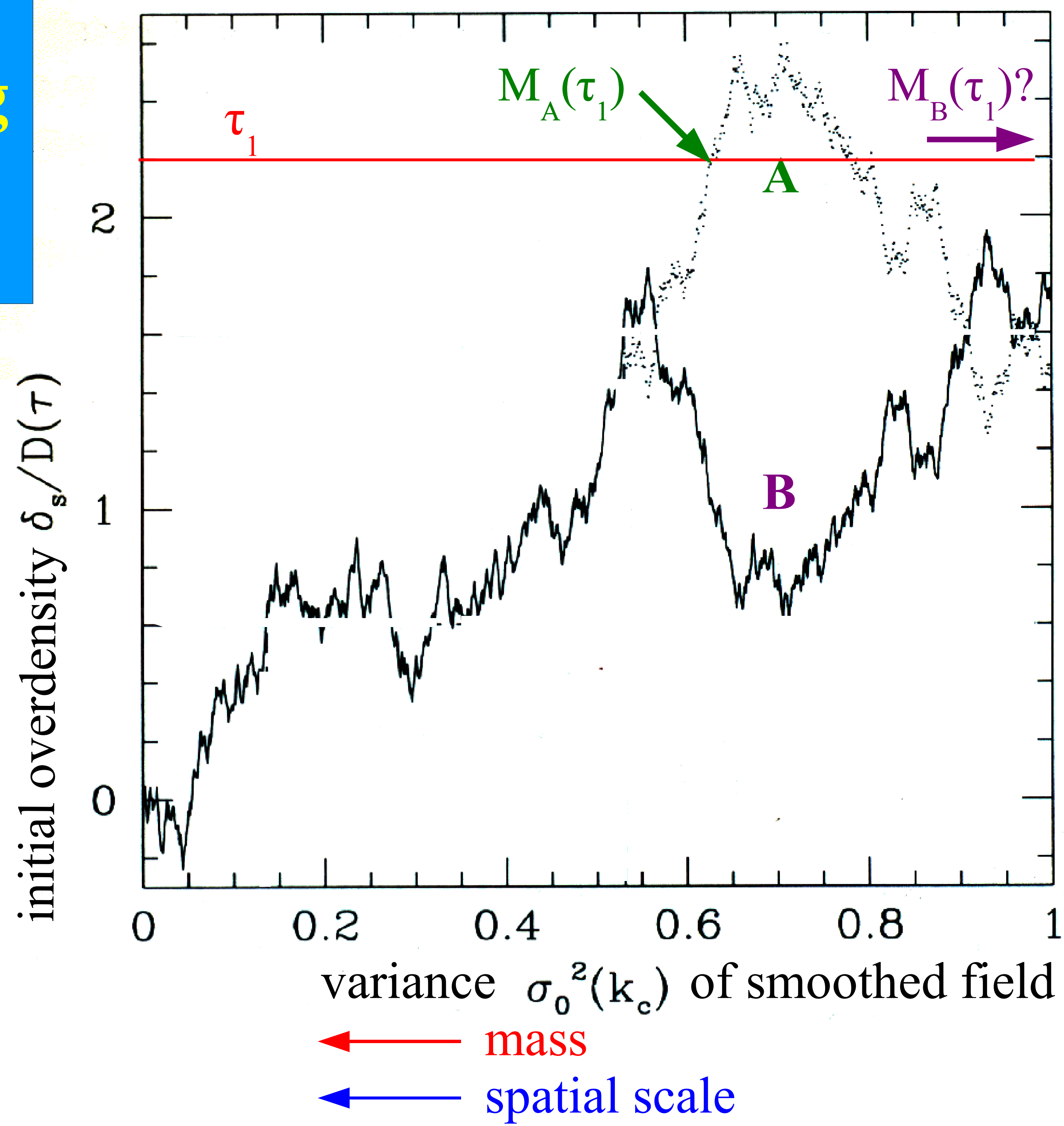


Overdensity vs smoothing at a given position

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

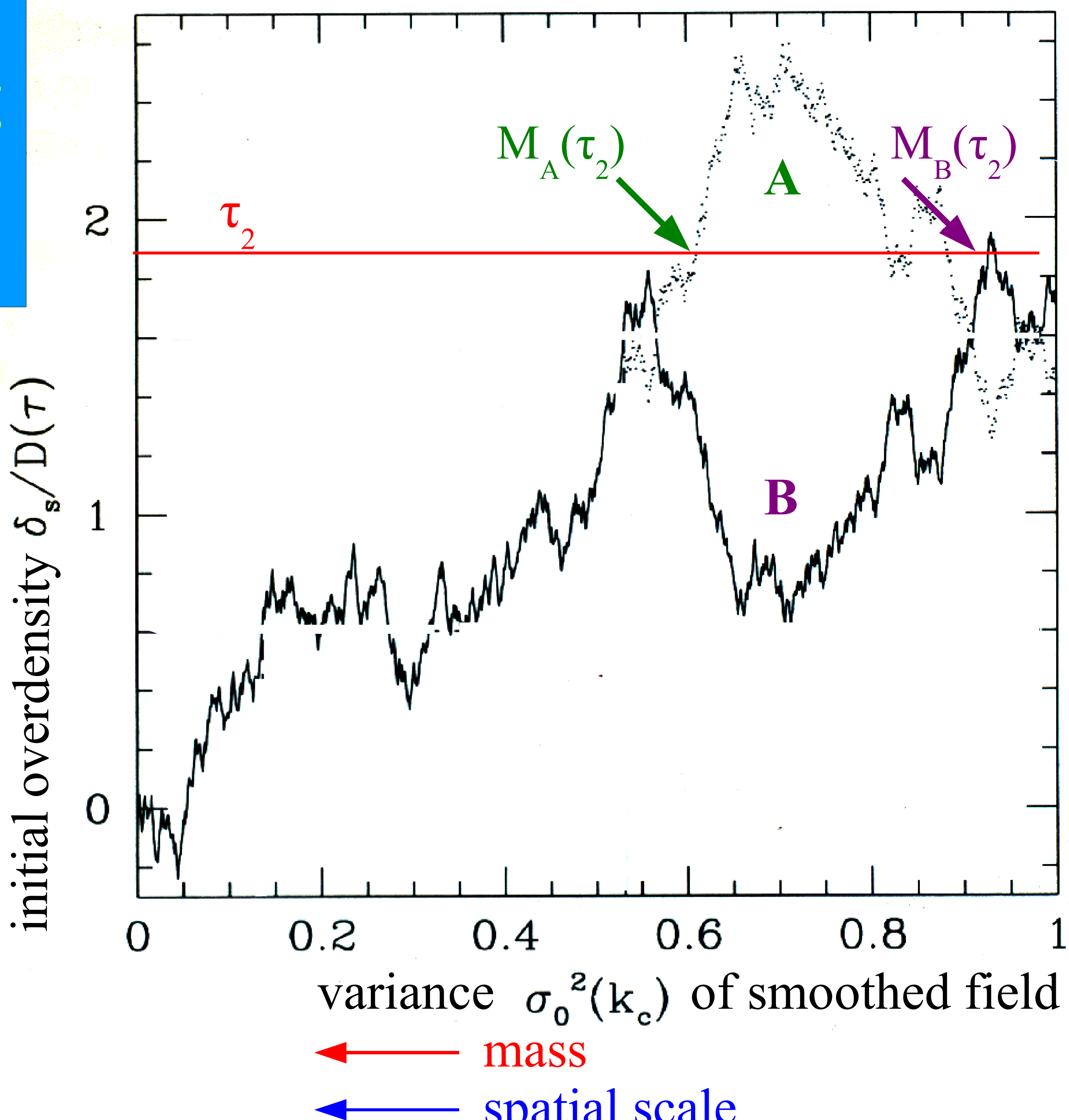


Overdensity vs smoothing at a given position

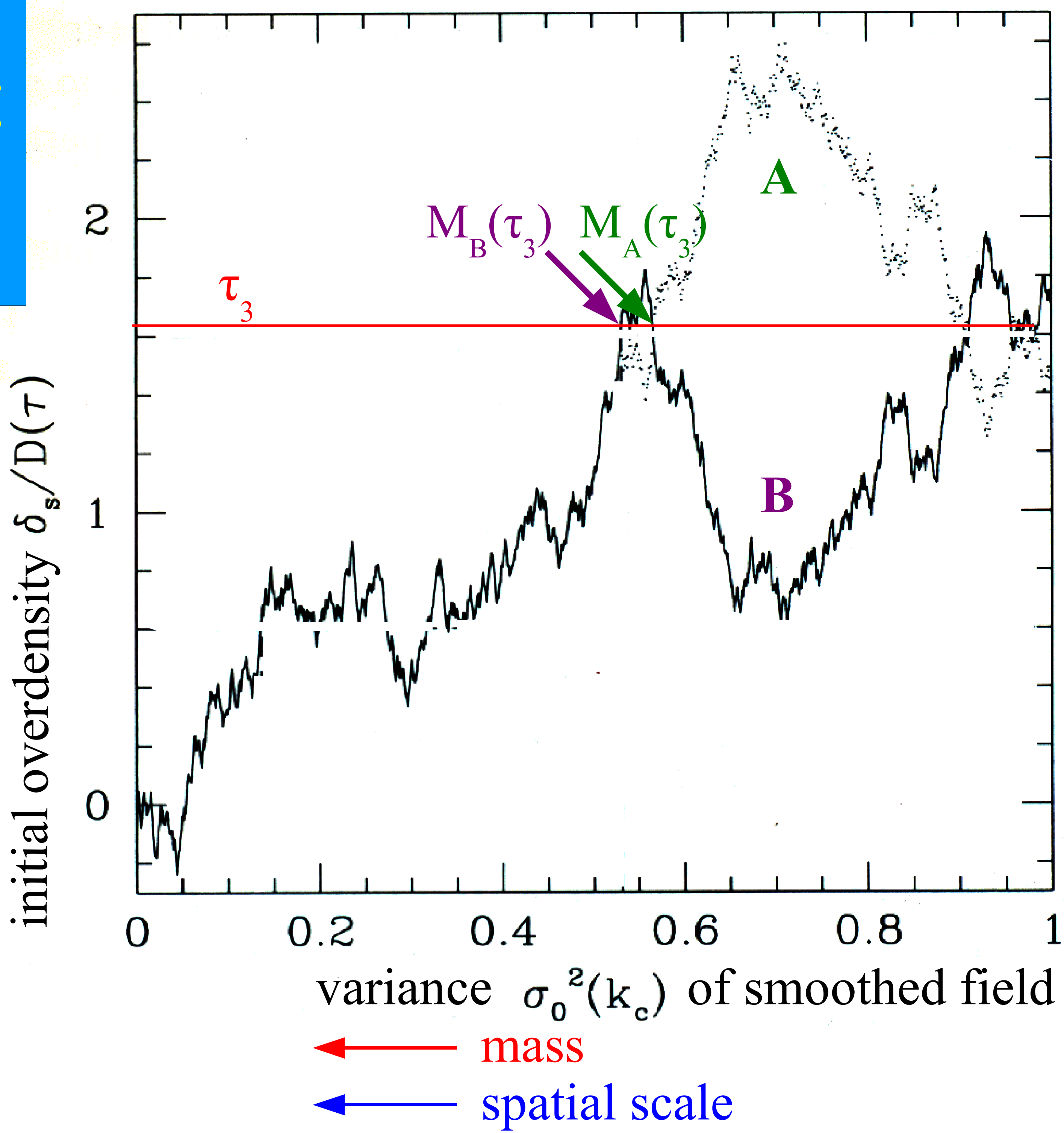
Later, at time τ_2

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

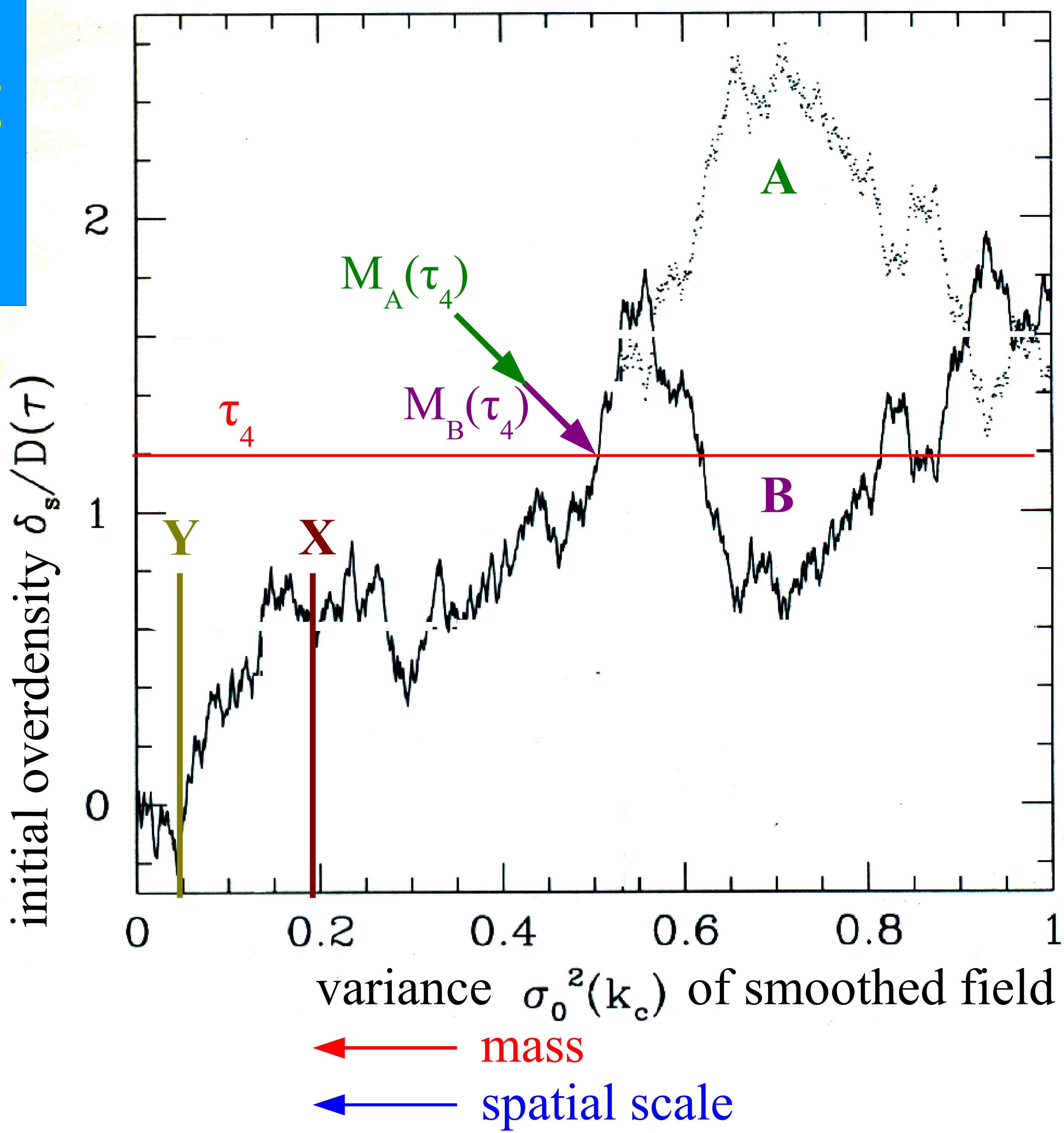
Overdensity vs smoothing at a given position

Still later, e.g. τ_4

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

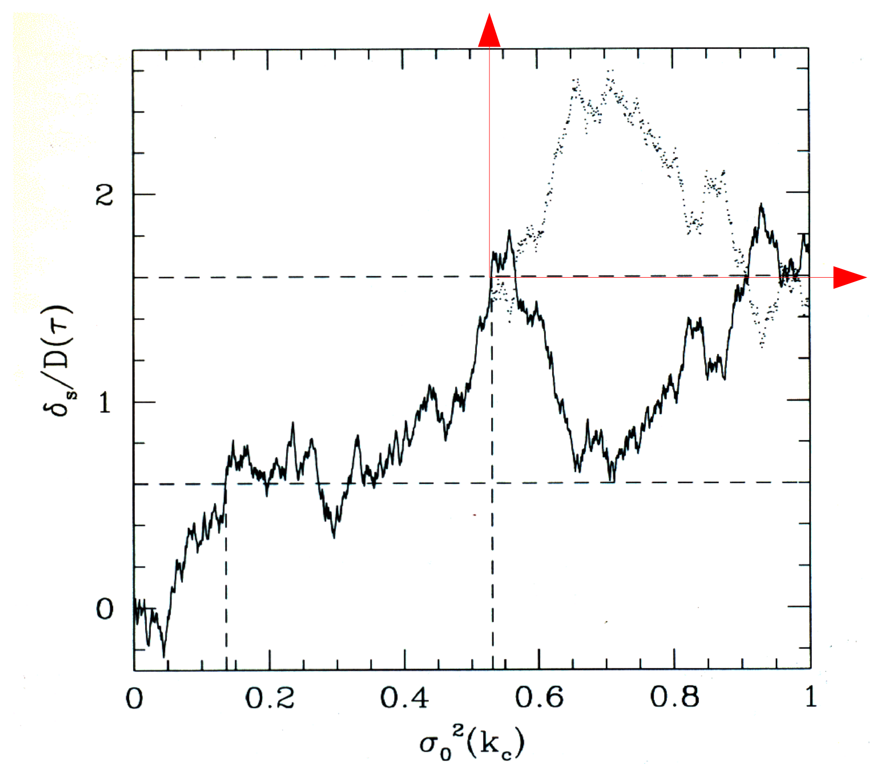
On scale X they are embedded in a high density region.

On larger scale Y in a low density region



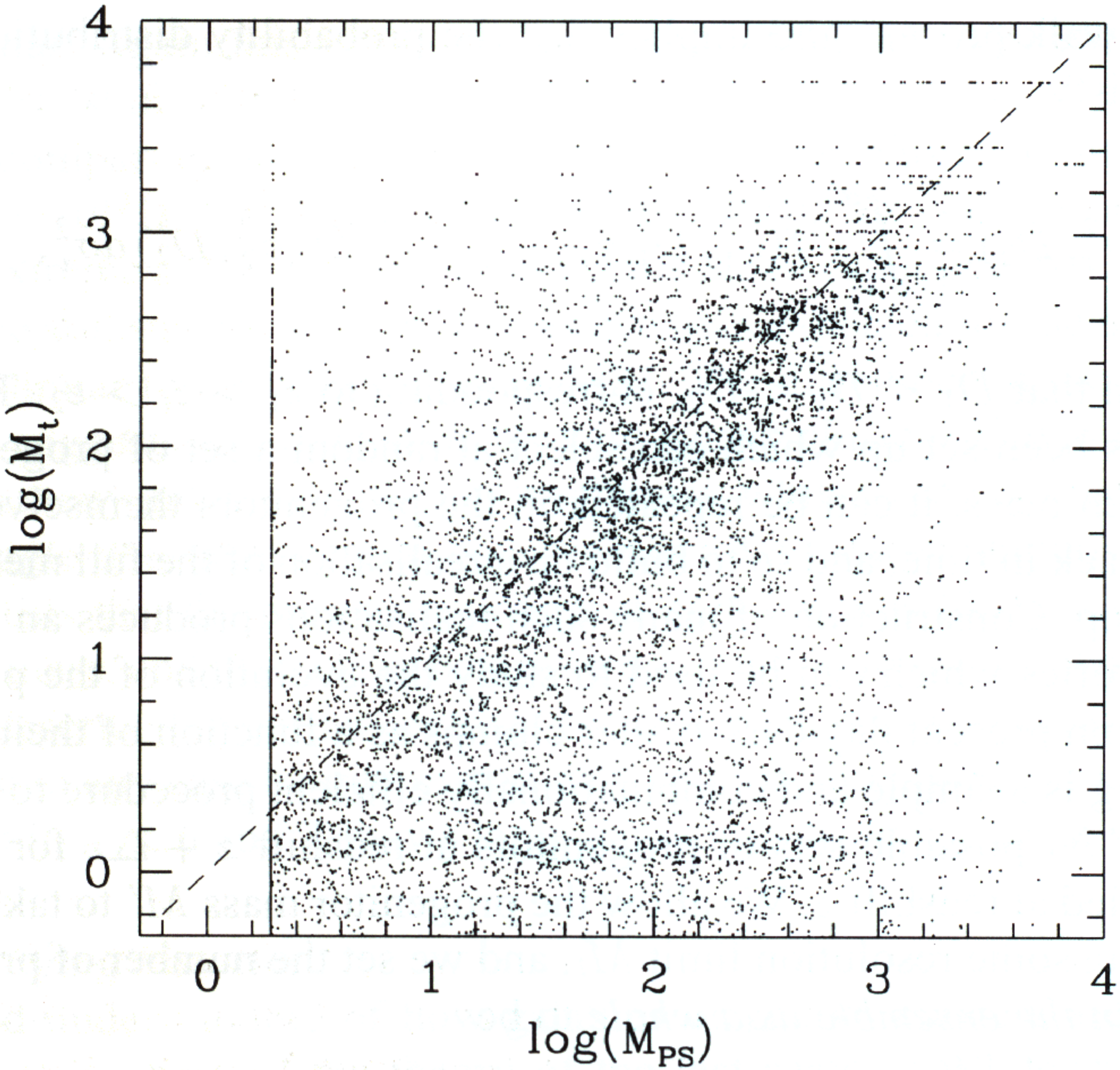
Consequences of the Markov nature of EPS walks

- 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?

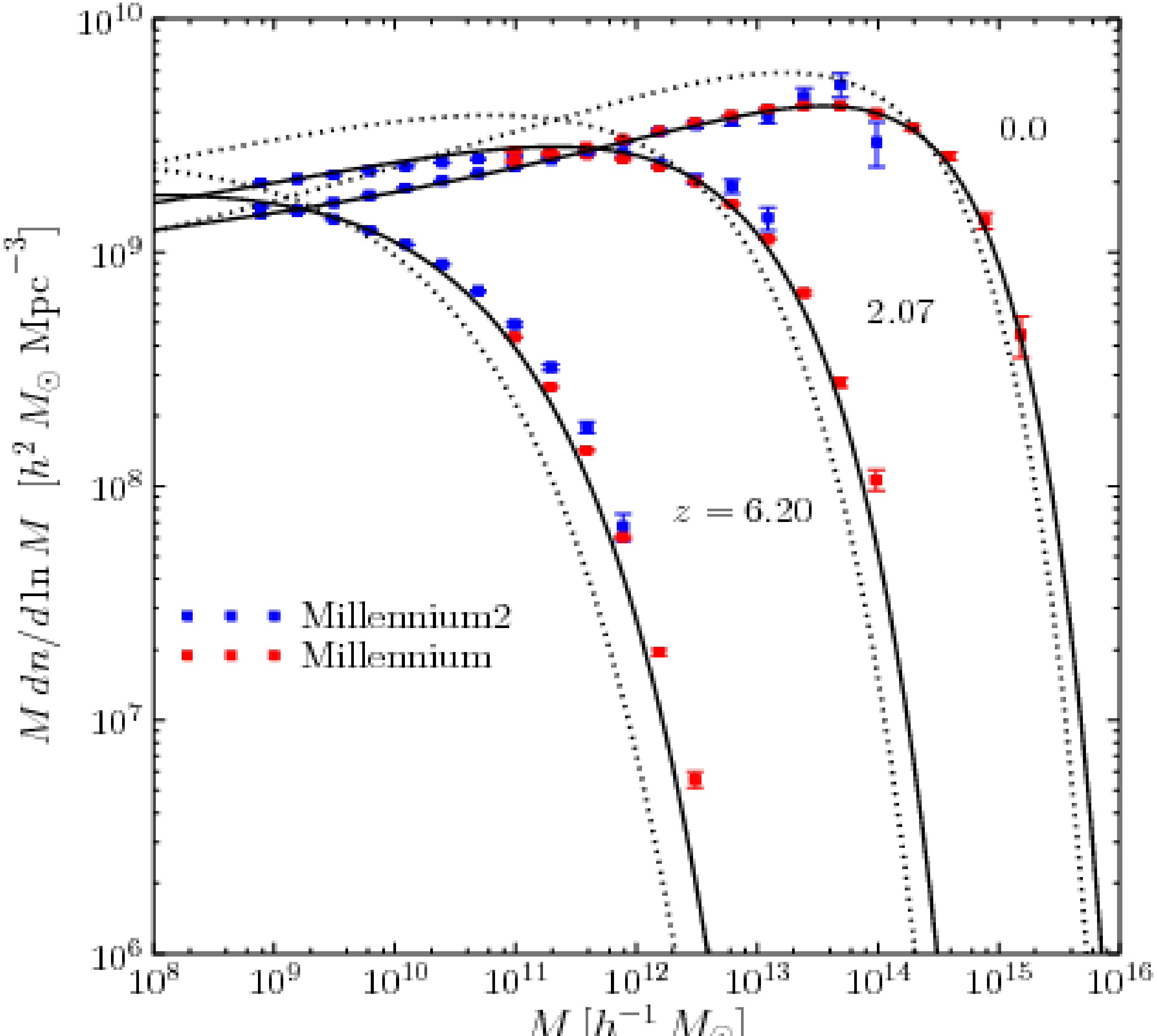
Mass of the halo in which the particle is actually found



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

Does it work statistically?

Boylan-Kolchin et al 2009

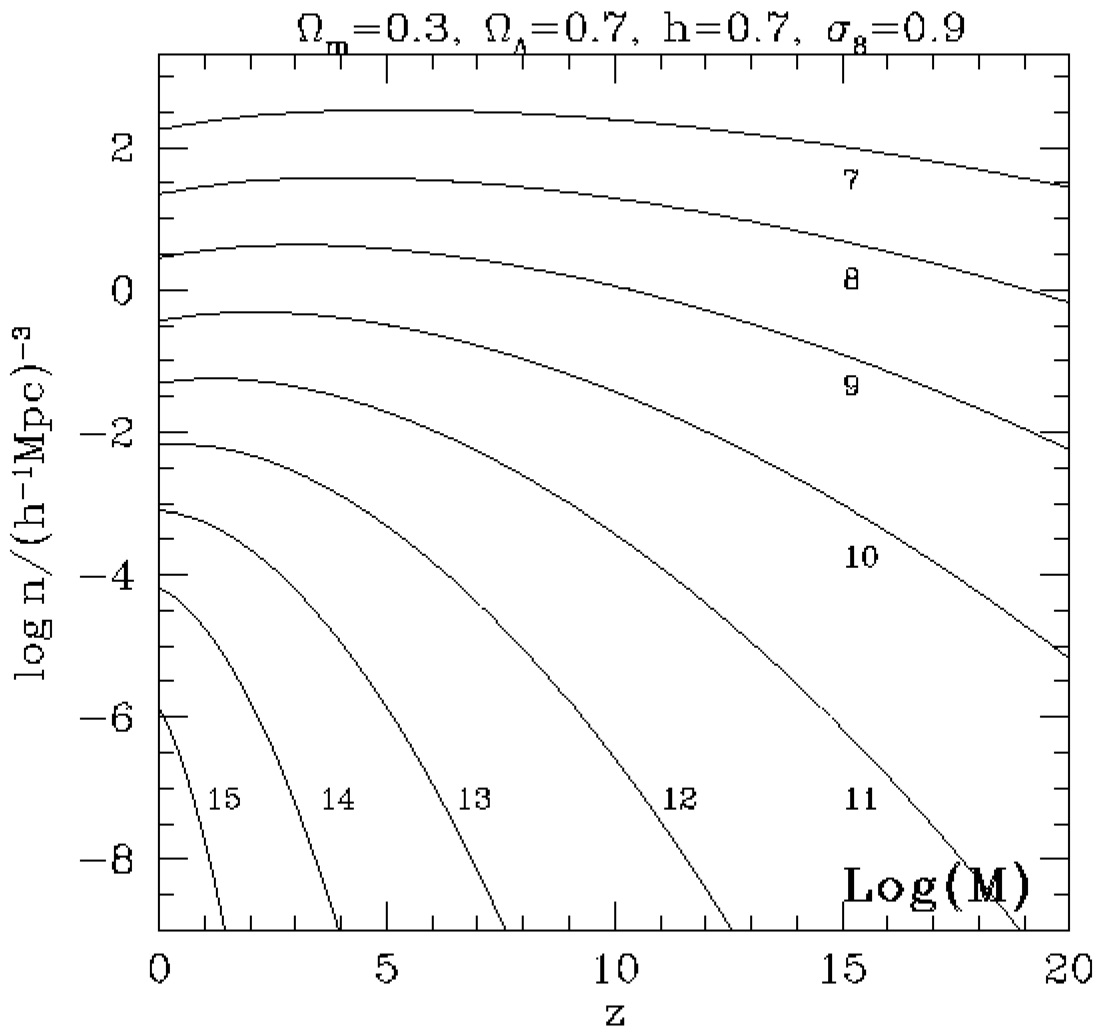


P&S74

Warren

Evolution of halo abundance in ΛCDM

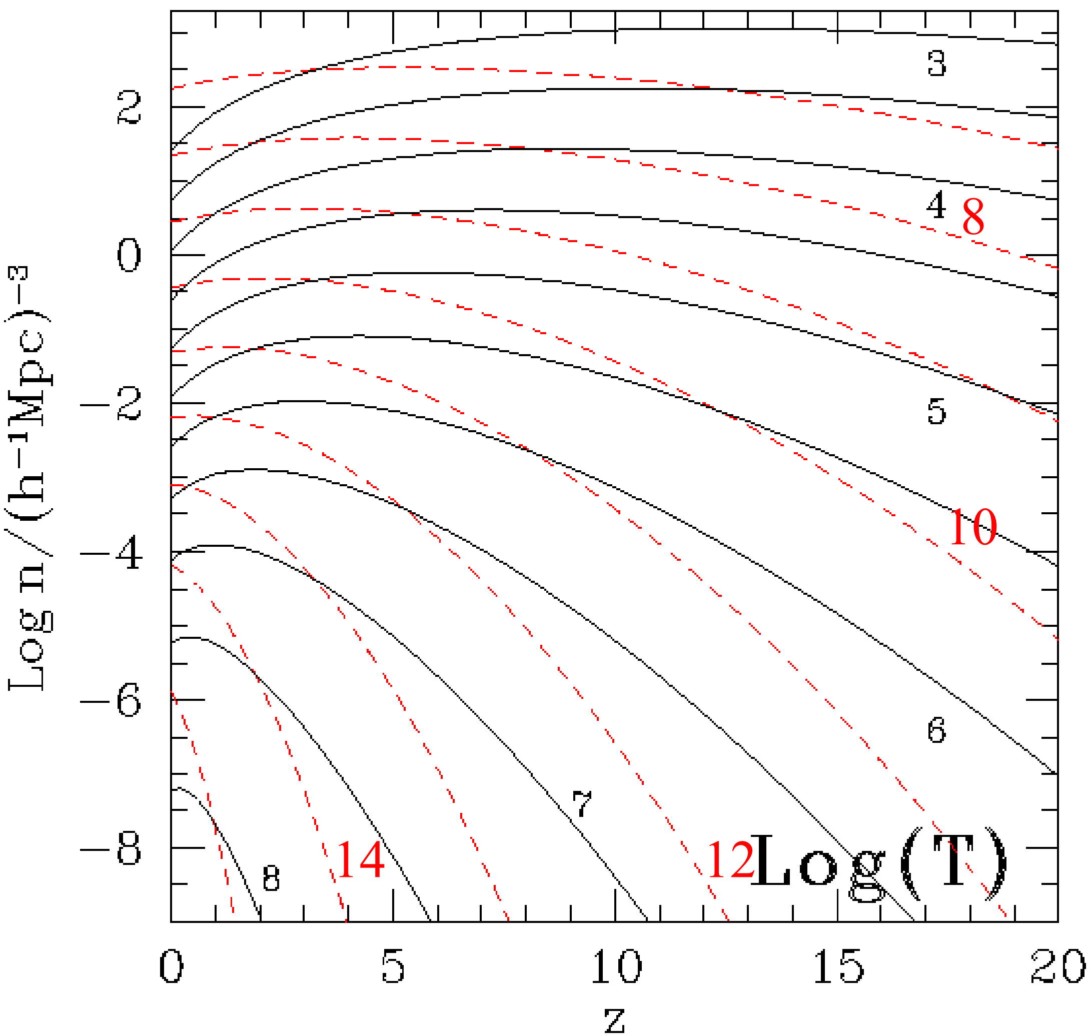
Mo & White 2002



- 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

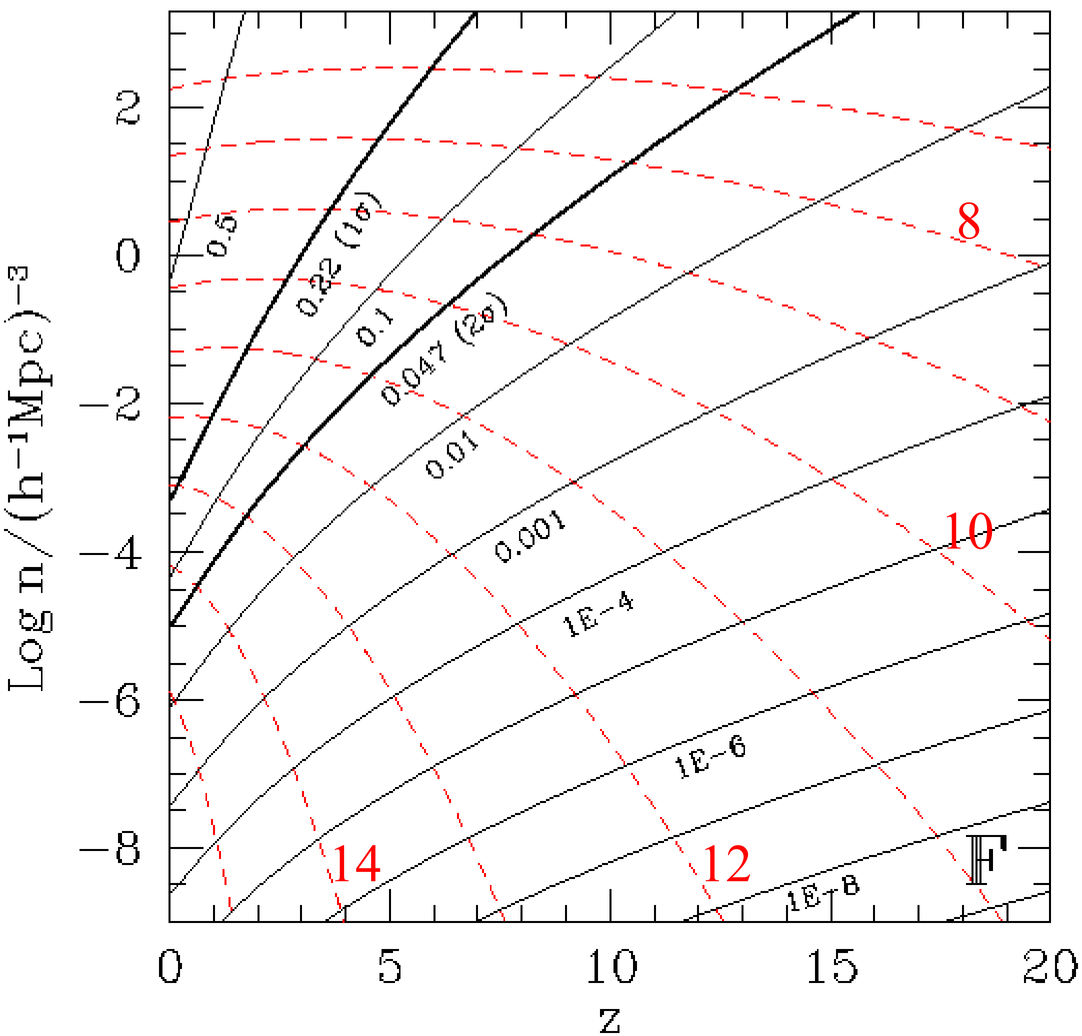
Mo & White 2002



- 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

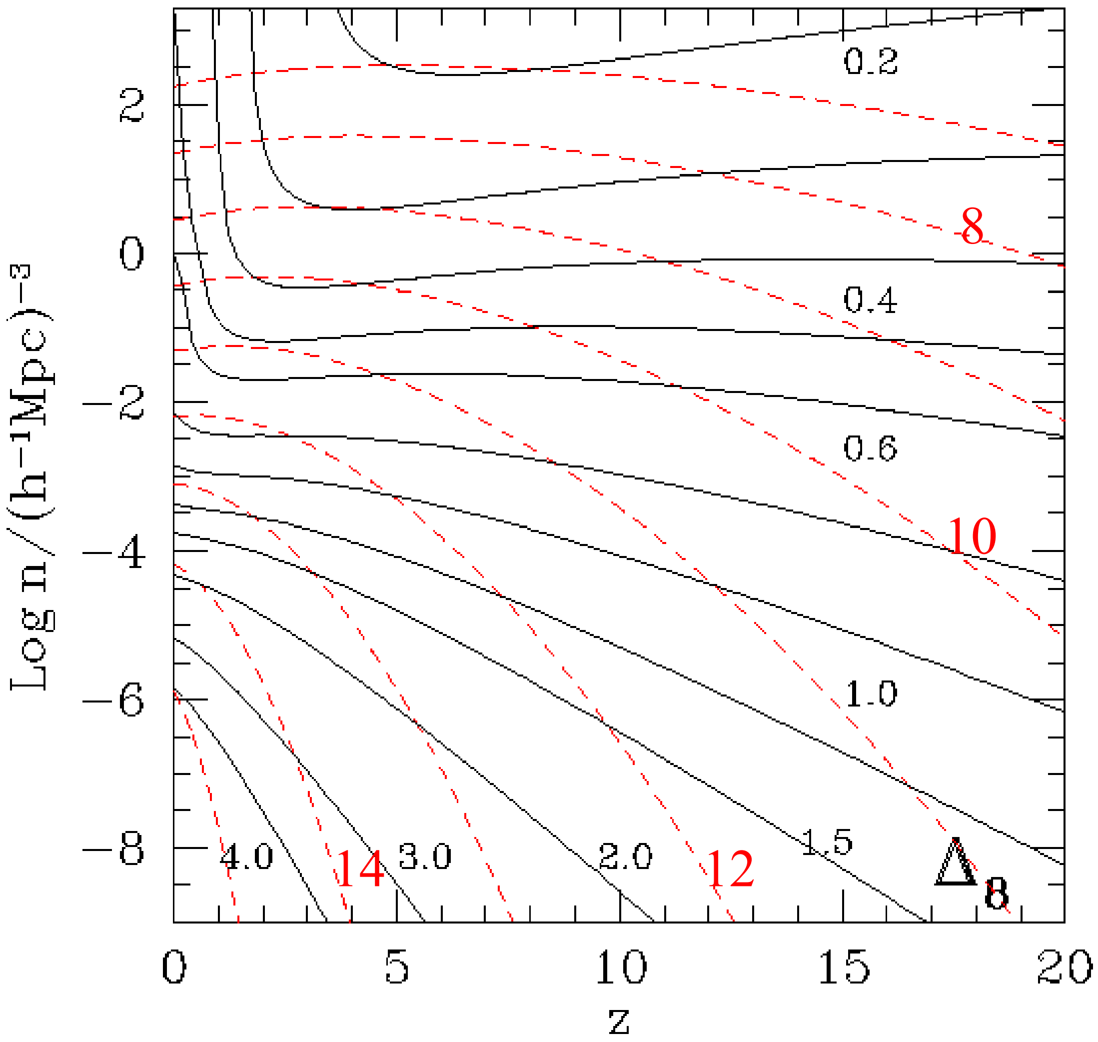
Mo & White 2002



- 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

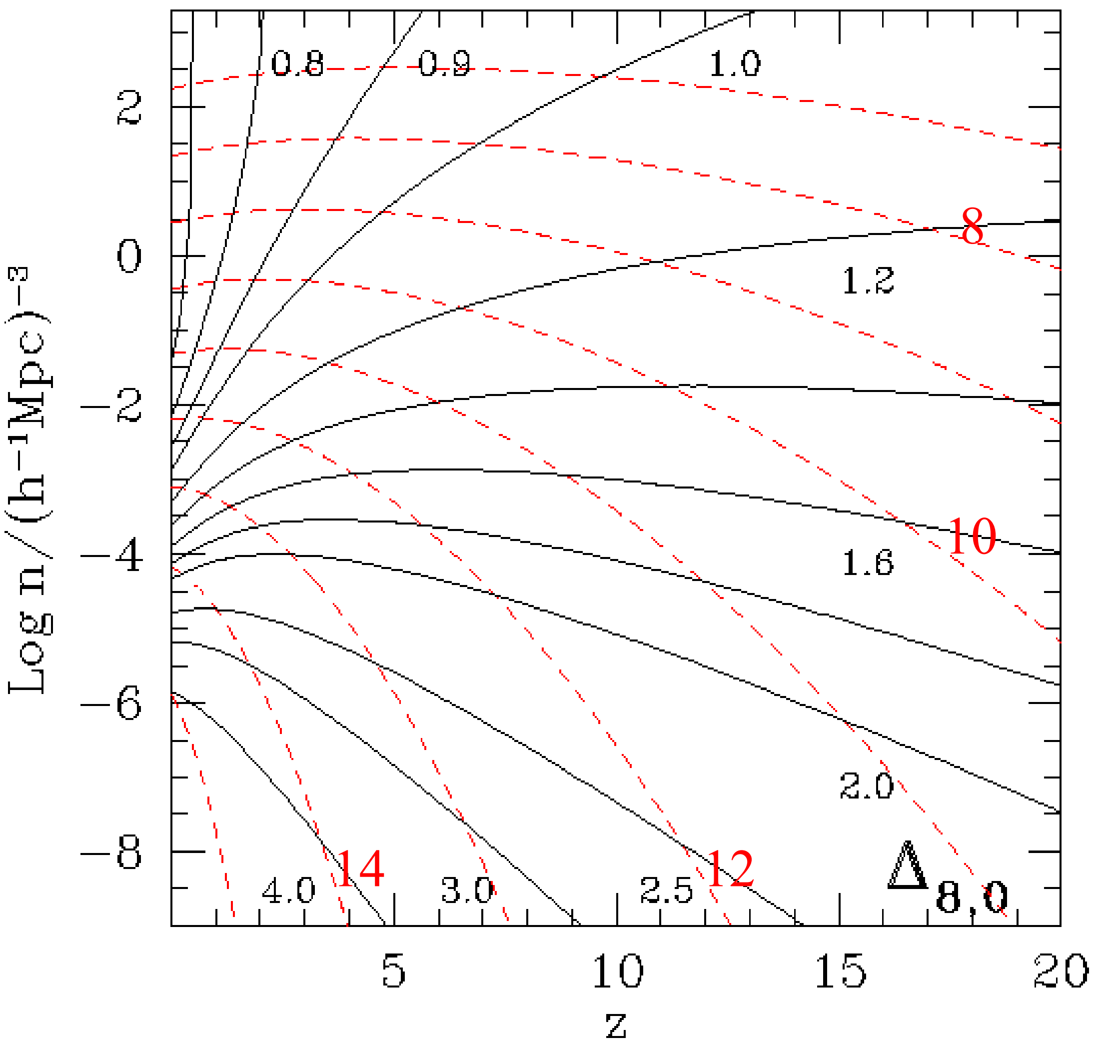
Mo & White 2002



- 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

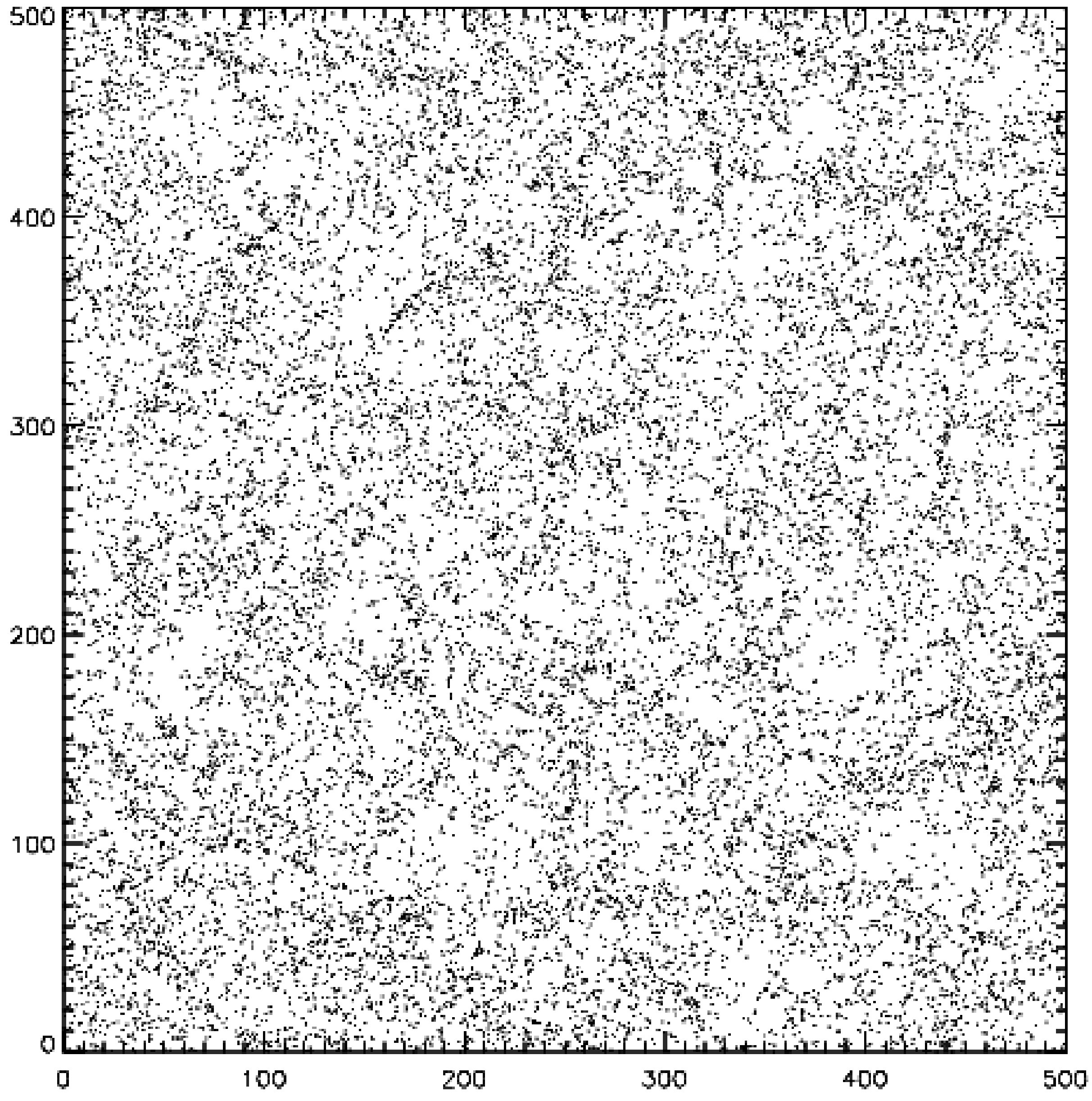
Evolution of halo abundance in ΛCDM

Mo & White 2002



- The remnants (stars and heavy elements) from all star-forming systems at z>6 are today more clustered than L_* galaxies
- The remnants of objects which at any z > 2 had an abundance similar to that of present-day L_* galaxies are today more clustered than L_* galaxies

Does halo clustering depend on formation history?

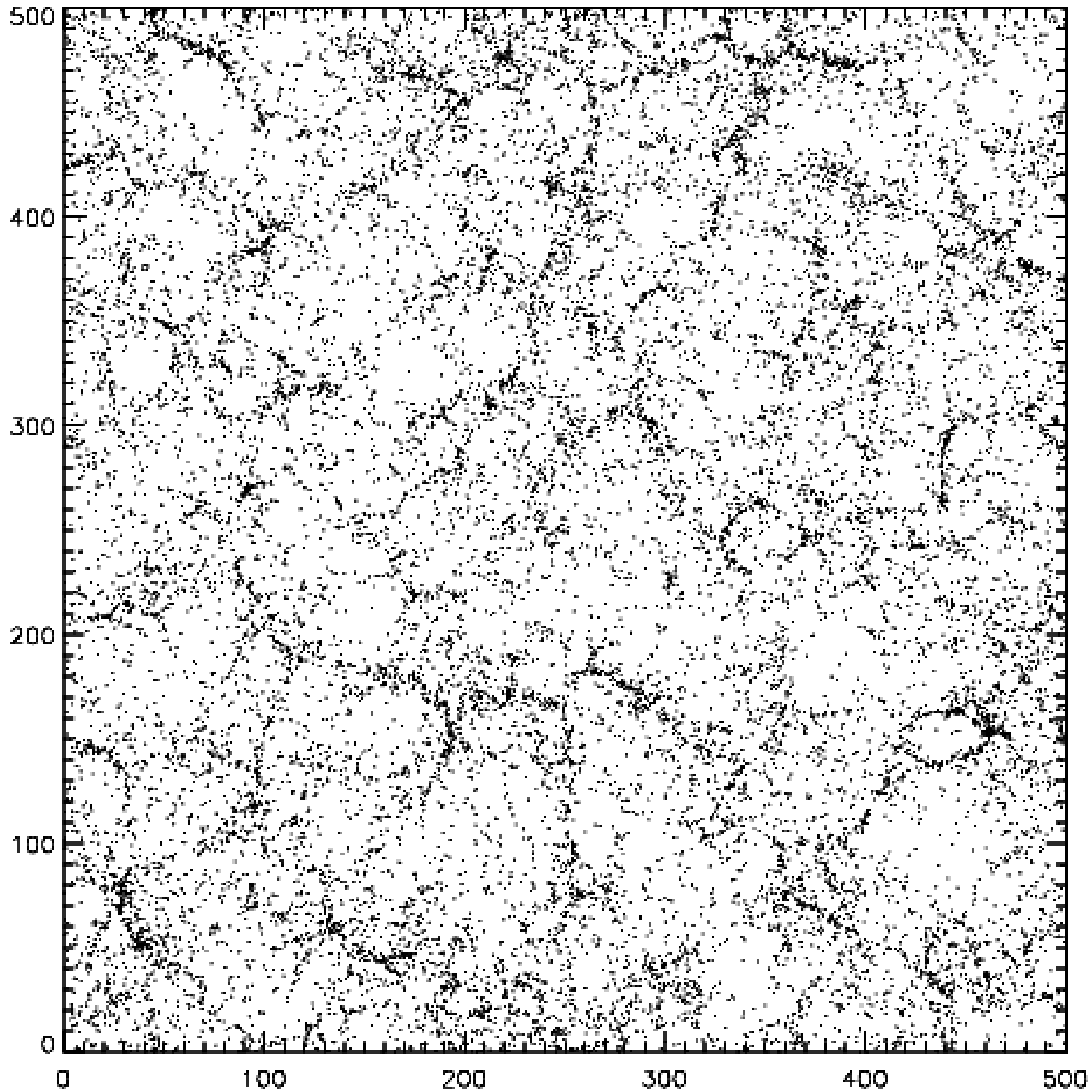


Gao, Springel & White 2005

The 20% of halos with the *lowest* formation redshifts in a 30 Mpc/h thick slice

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

Does halo clustering depend on formation history?



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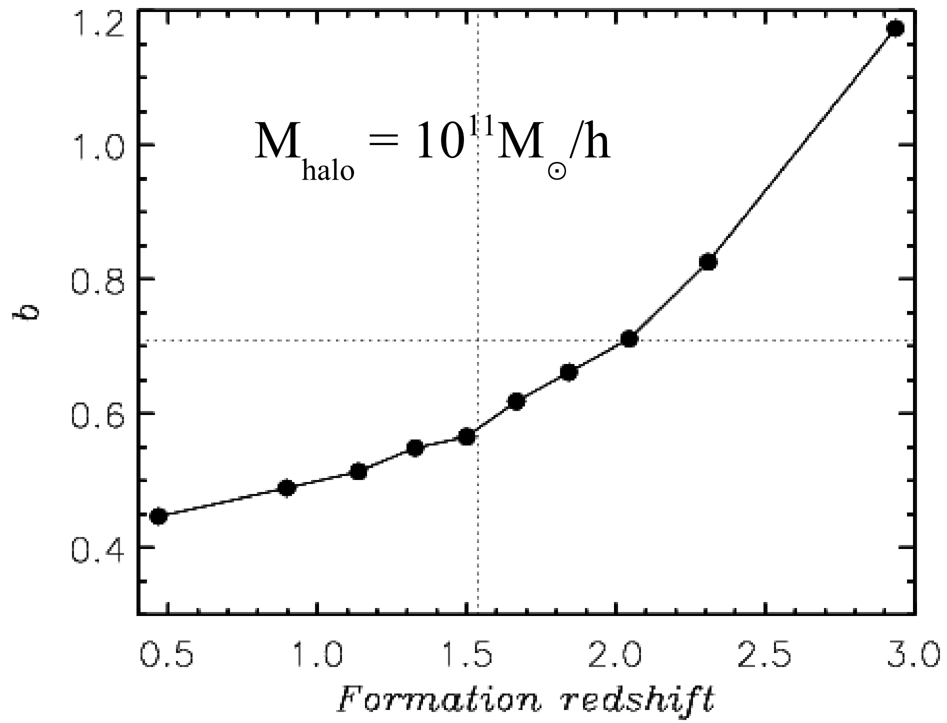
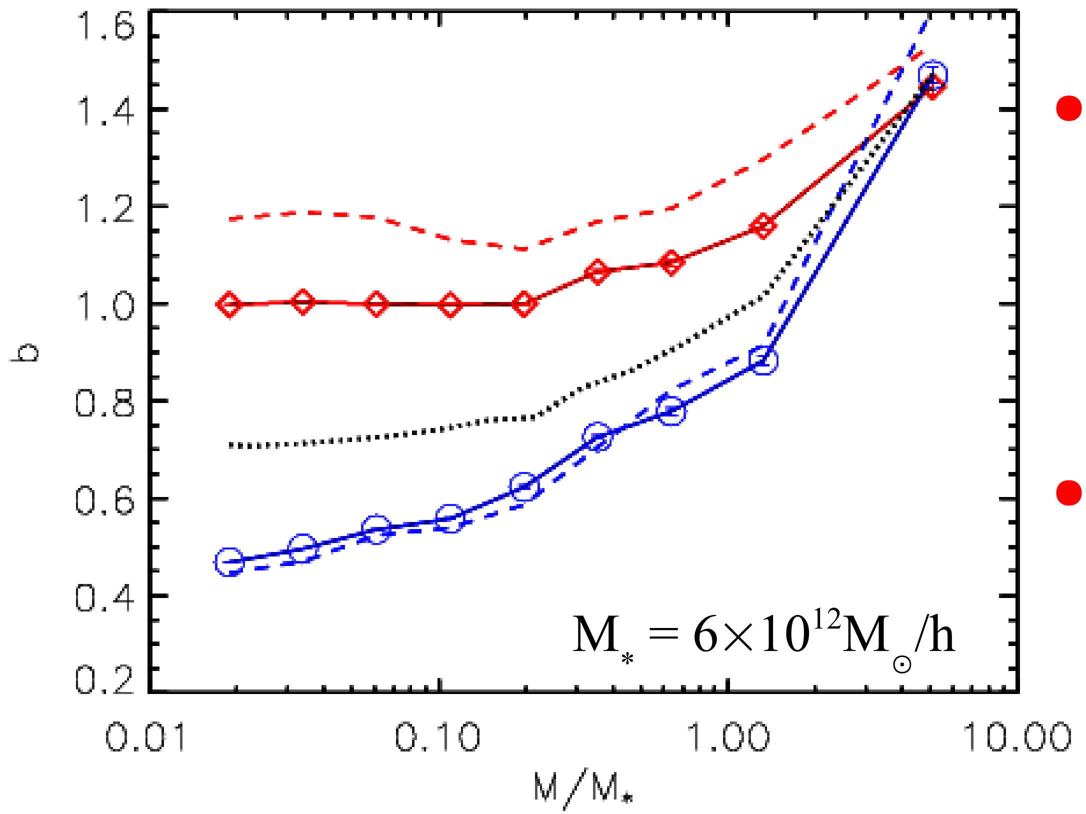
Halo bias as a function of mass and formation time



Gao, Springel & White 2005

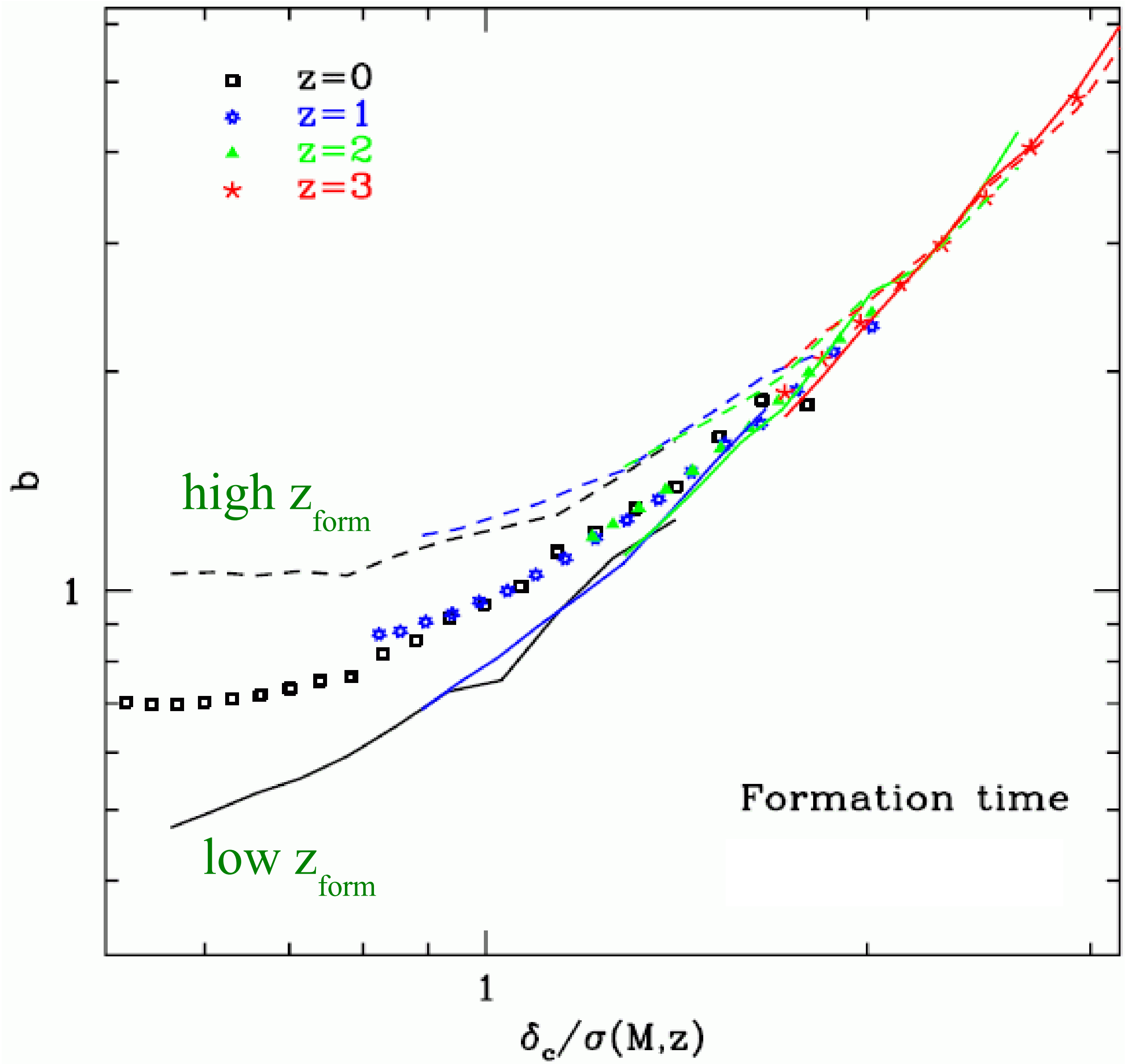
- Bias increases smoothly with formation redshift



- The dependence on formation redshift is strongest at low mass
- This dependence is consistent *neither* with excursion set theory *nor* with HOD models

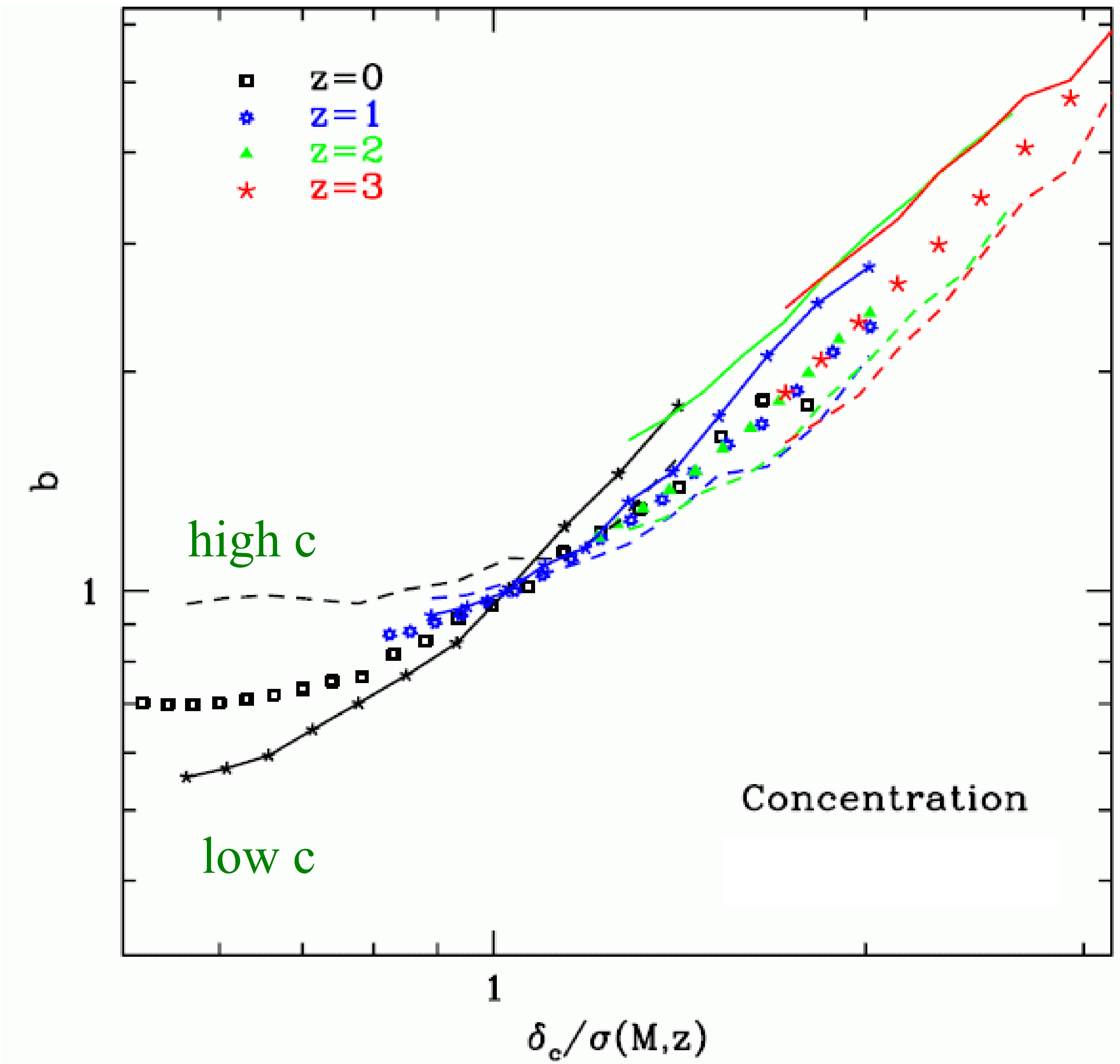
Bias as a function of ν and formation time

Gao & White 2007



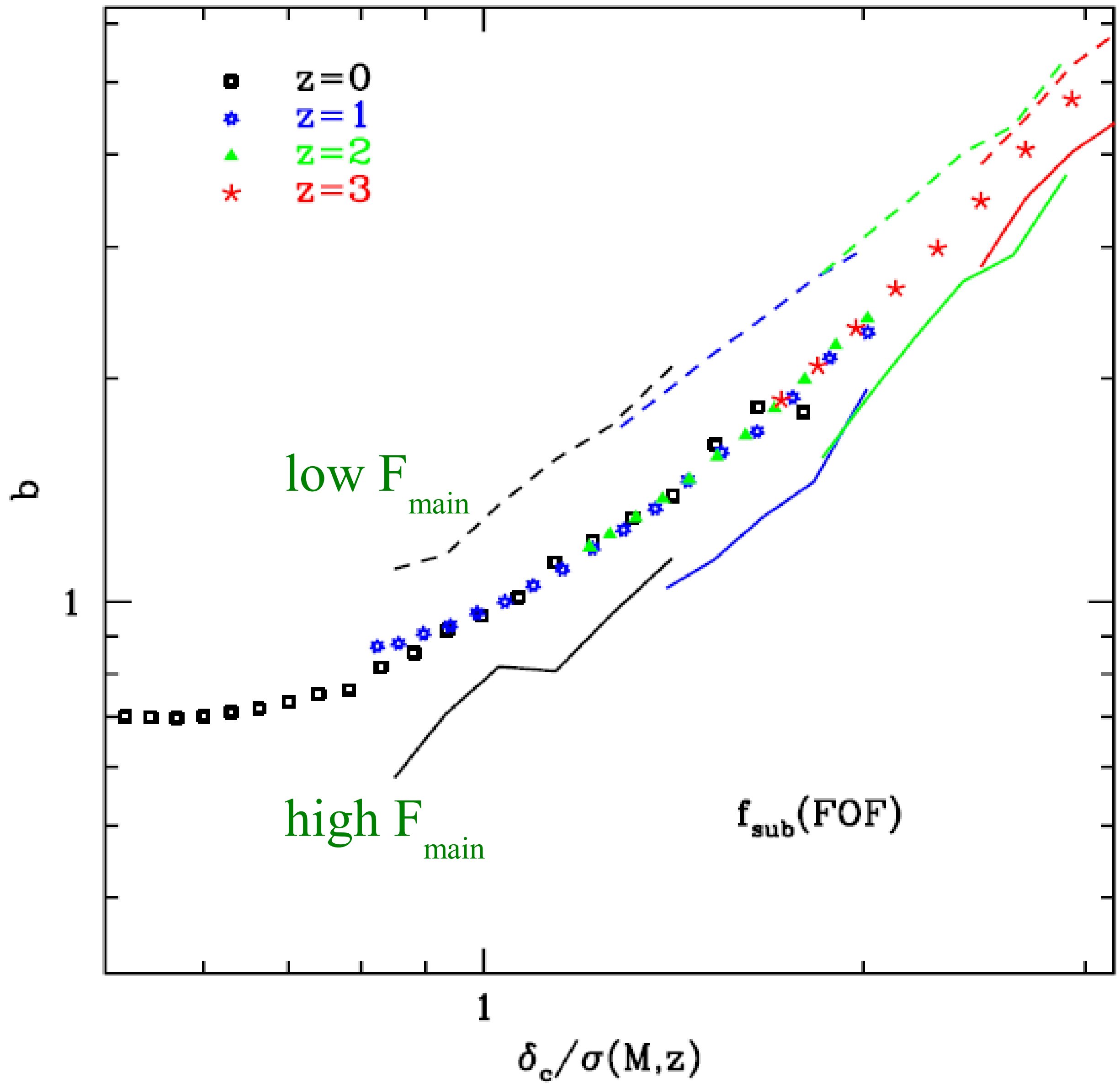
Bias as a function of ν and concentration

Gao & White 2007



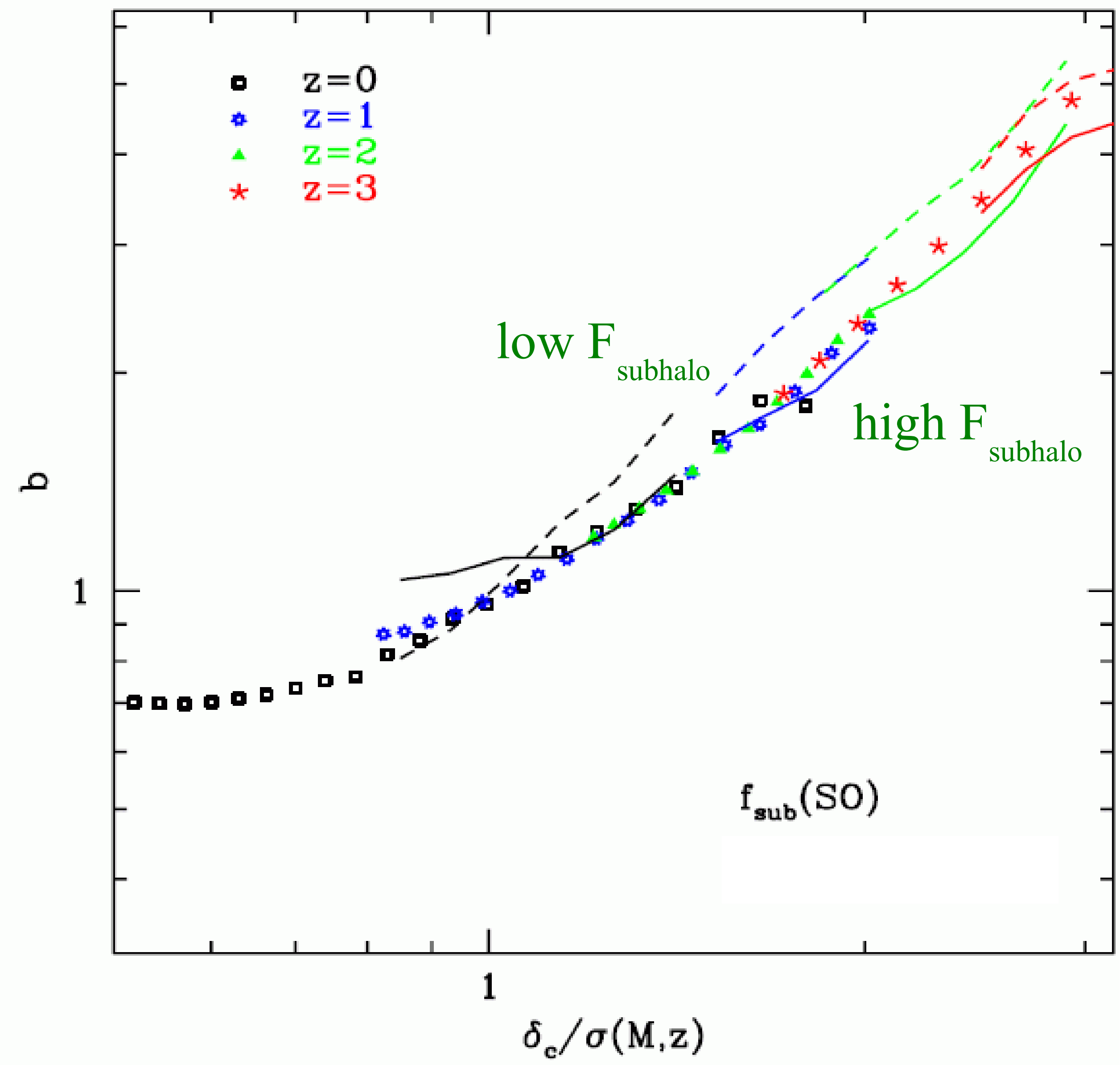
Bias as a function of ν and main halo mass fraction

Gao & White 2007



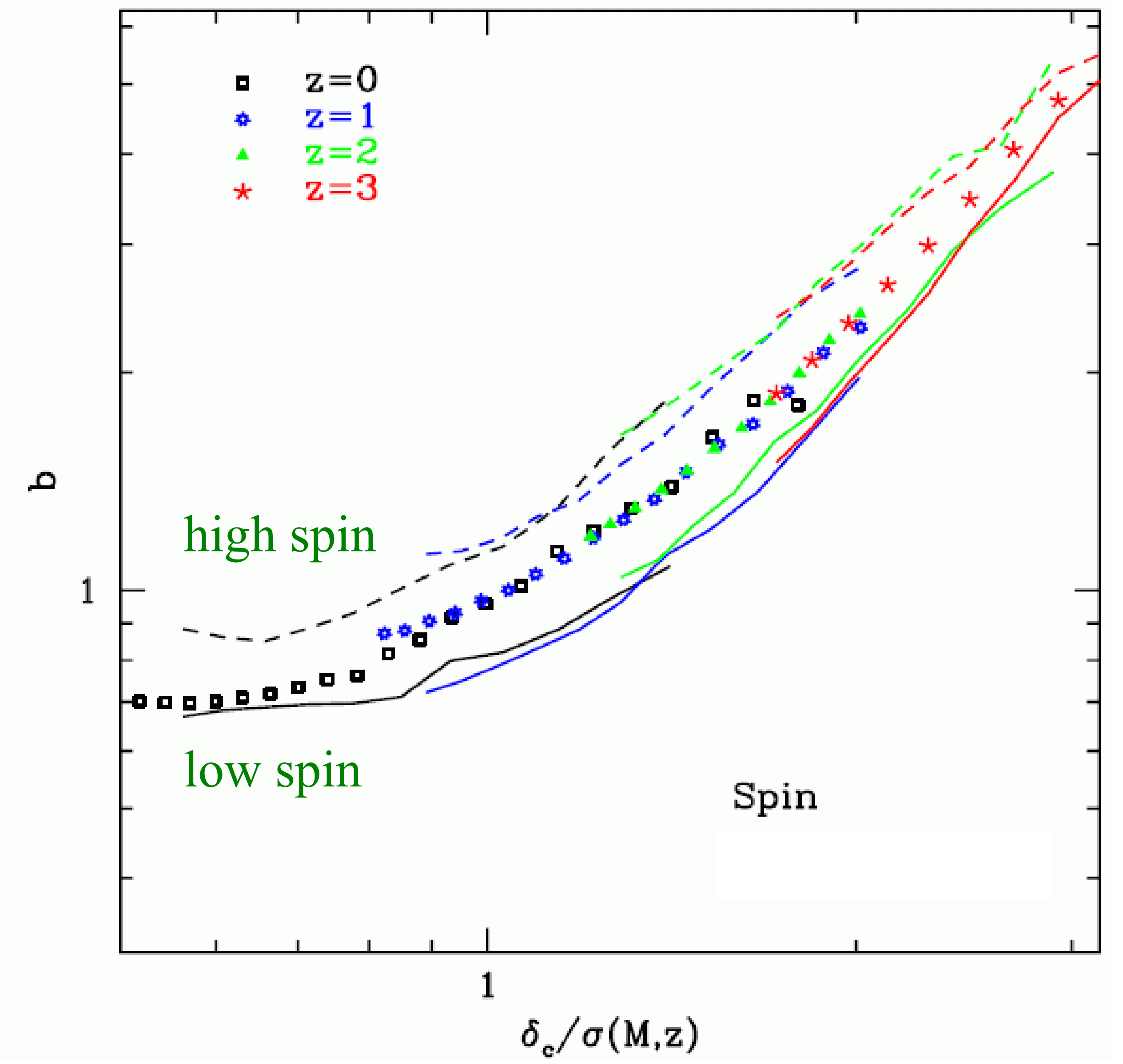
Bias as a function of ν and subhalo mass fraction

Gao & White 2007



Bias as a function of ν and spin

Gao & White 2007



Halo assembly bias: conclusions

The large-scale bias of halo clustering relative to the dark matter depends on halo mass through $\nu = \delta_c / D(z)\, \sigma_o(M)$ and also on

- -- formation time
- -- concentration
- -- substructure content
- -- spin

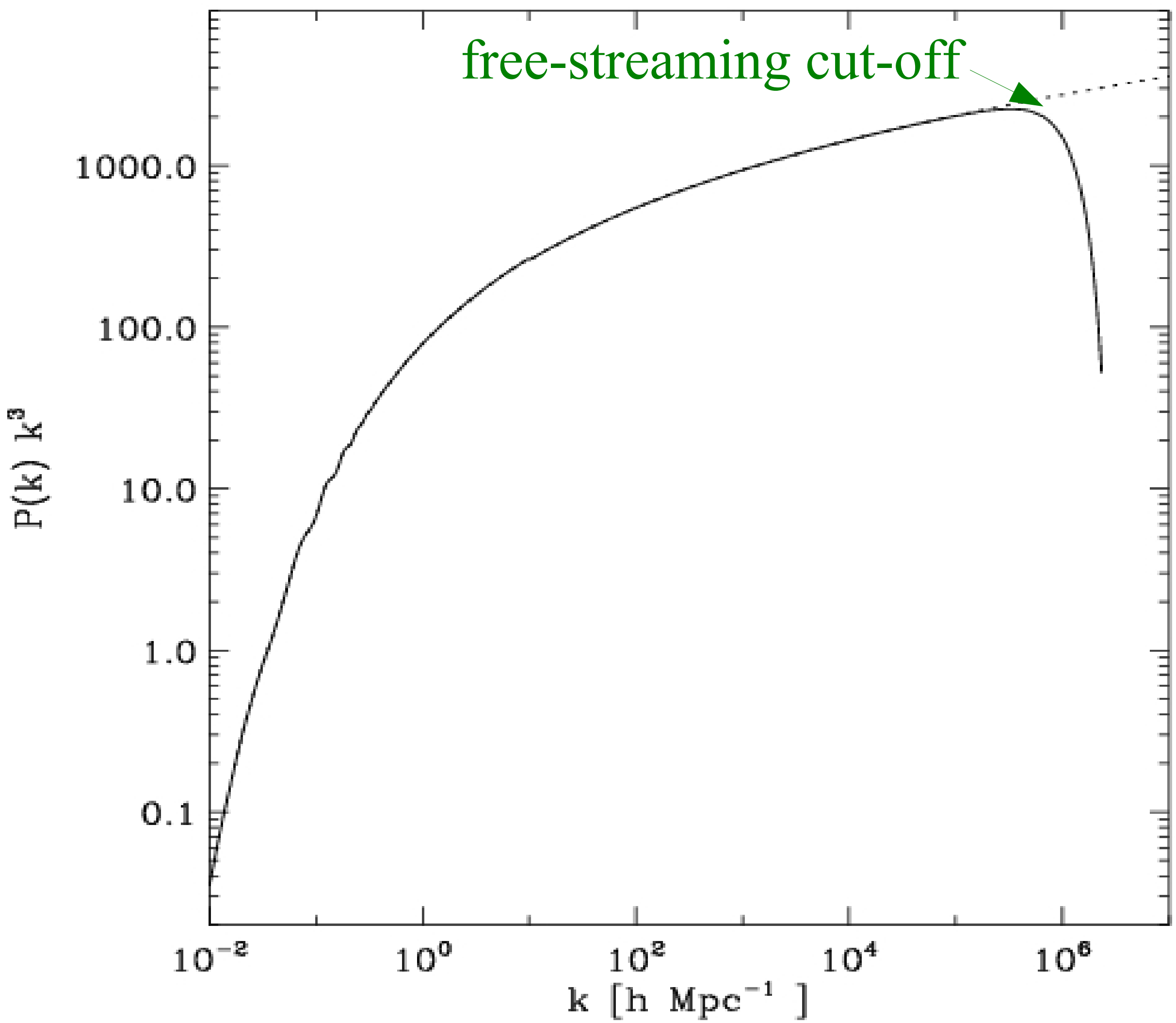
The dependences on these assembly variables are different and <u>cannot</u> be derived from each other, e.g. more concentrated halos are more strongly clustered at low mass but less strongly clustered at high mass; rapidly spinning halos are more strongly clustered by equal amounts at all masses.

These dependences are likely to be reflected in <u>galaxy</u> bias

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)

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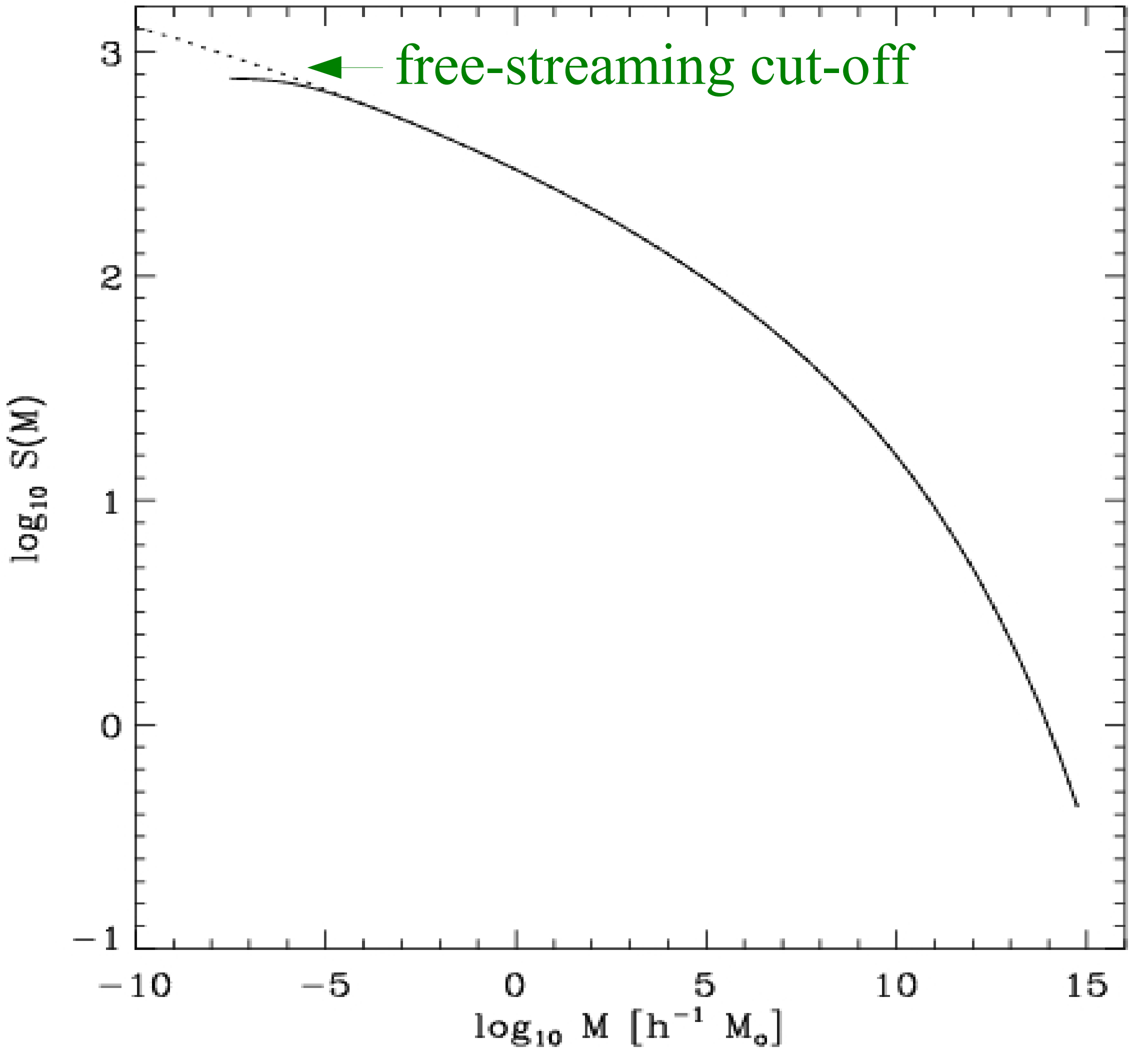

Variance of linear density fluctuation within spheres containing mass M, extrapolated to z = 0

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

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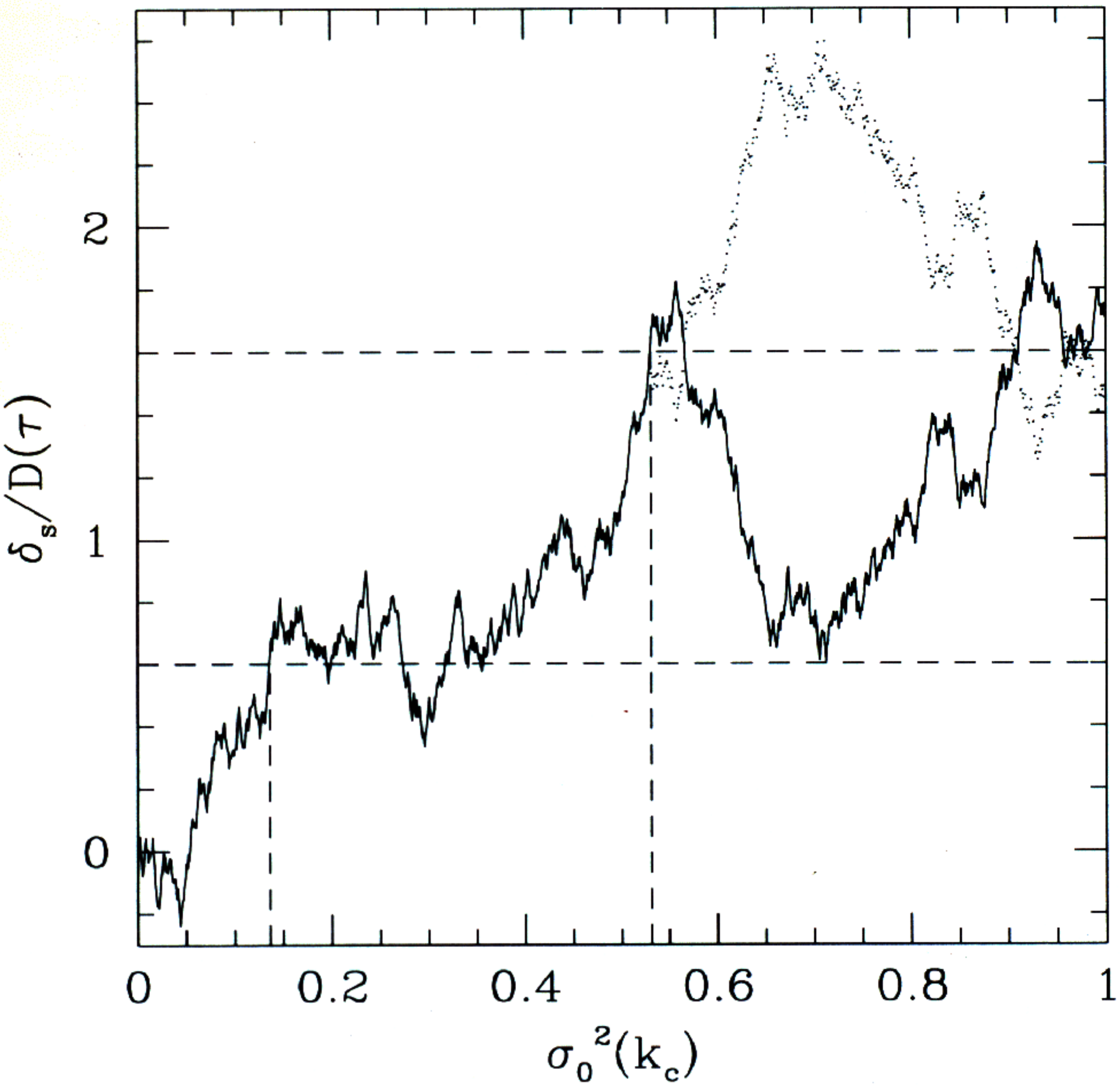

If these Markov random walks are scaled so the maximum variance is 720 and the vertical axis is multiplied by √720, then they represent halo assembly histories for random CDM particles.

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

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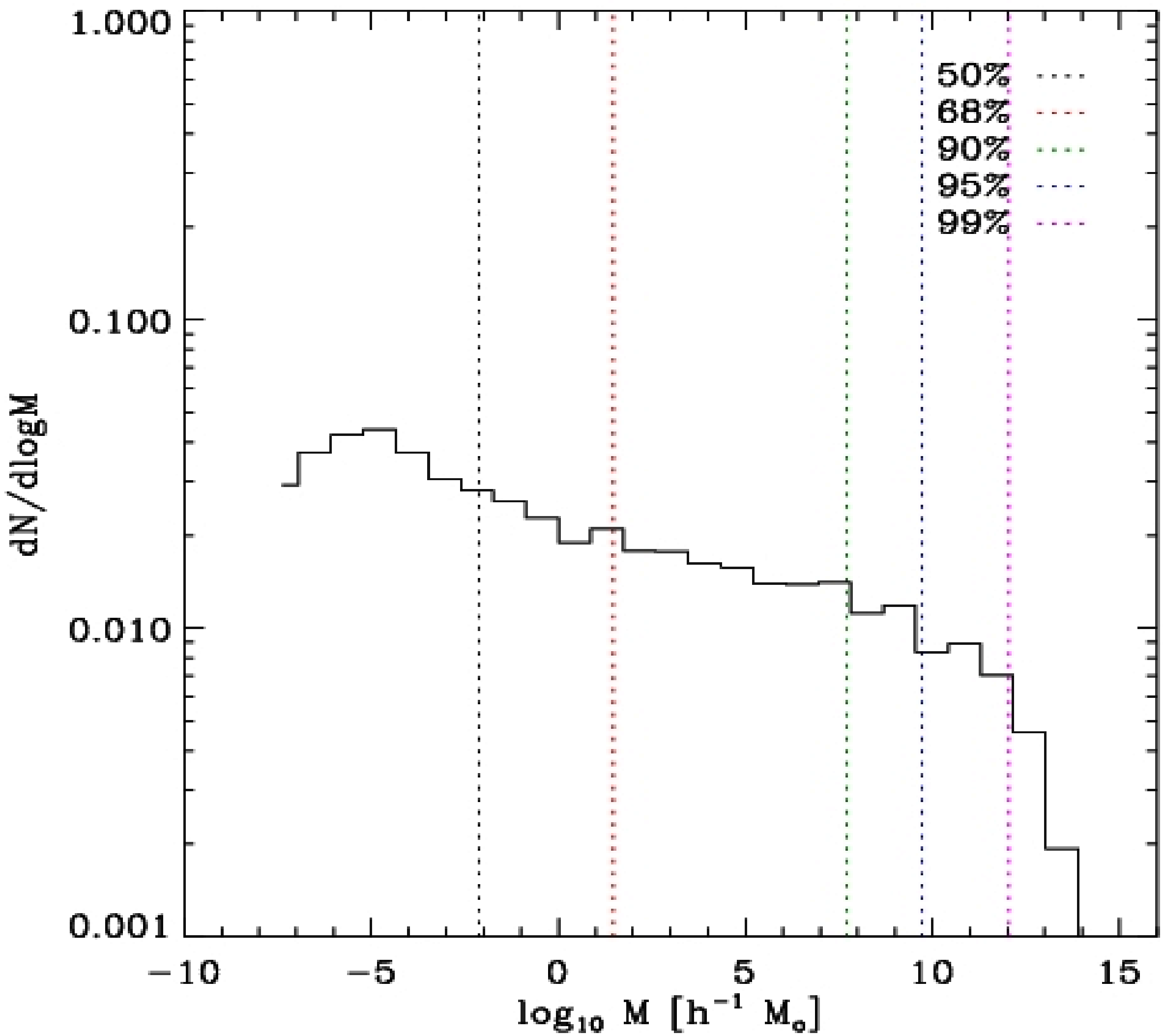

Distribution of the masses of the <u>first</u> halos for a random set of dark matter particles

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

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

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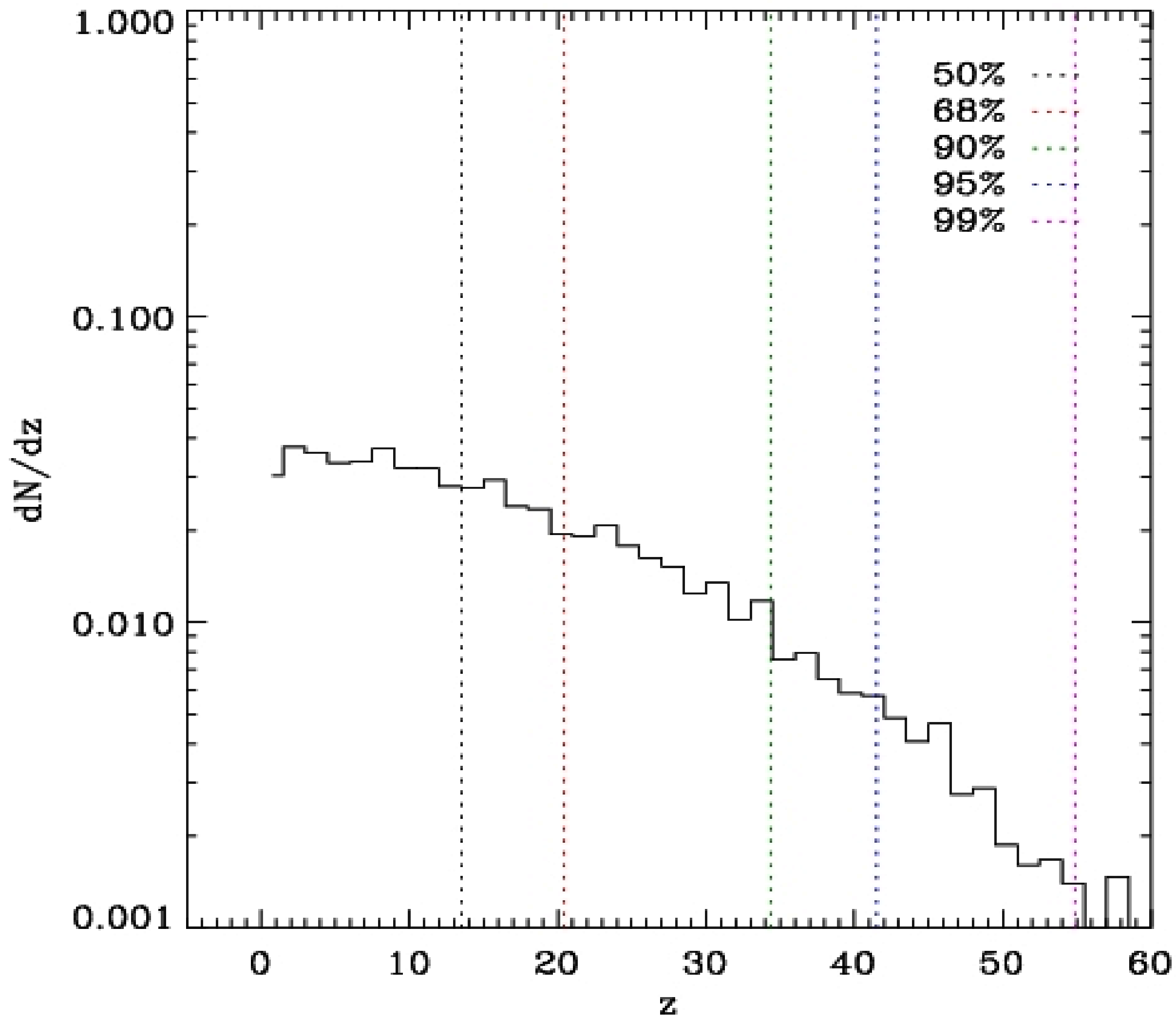

Distribution of the collapse redshifts of the first halos for a random set of dark matter particles

The median is z = 13

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

For 1% at z > 55

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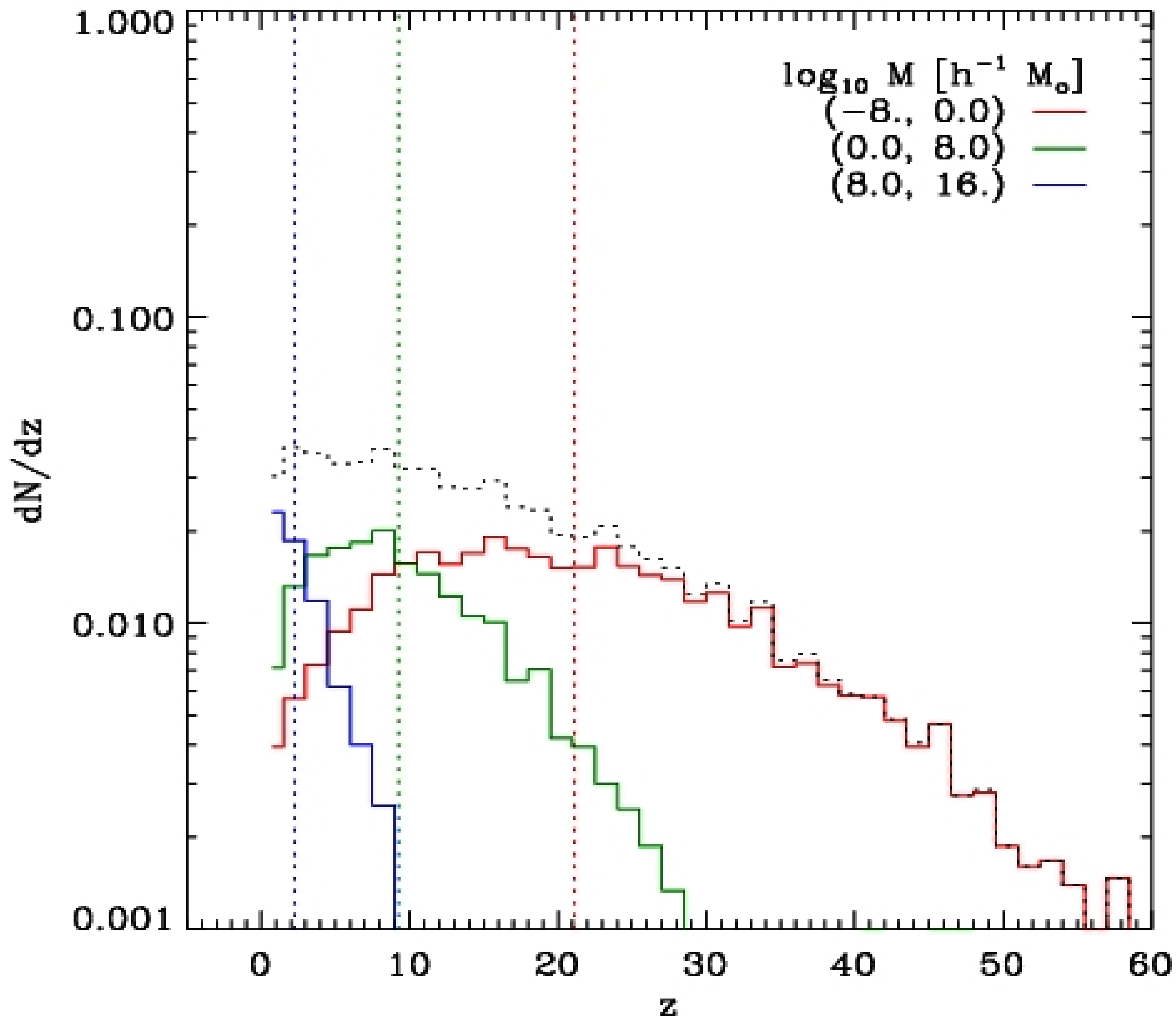

Distribution of the collapse redshifts of the <u>first</u> halos for dark matter particles split by the mass of the first object

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

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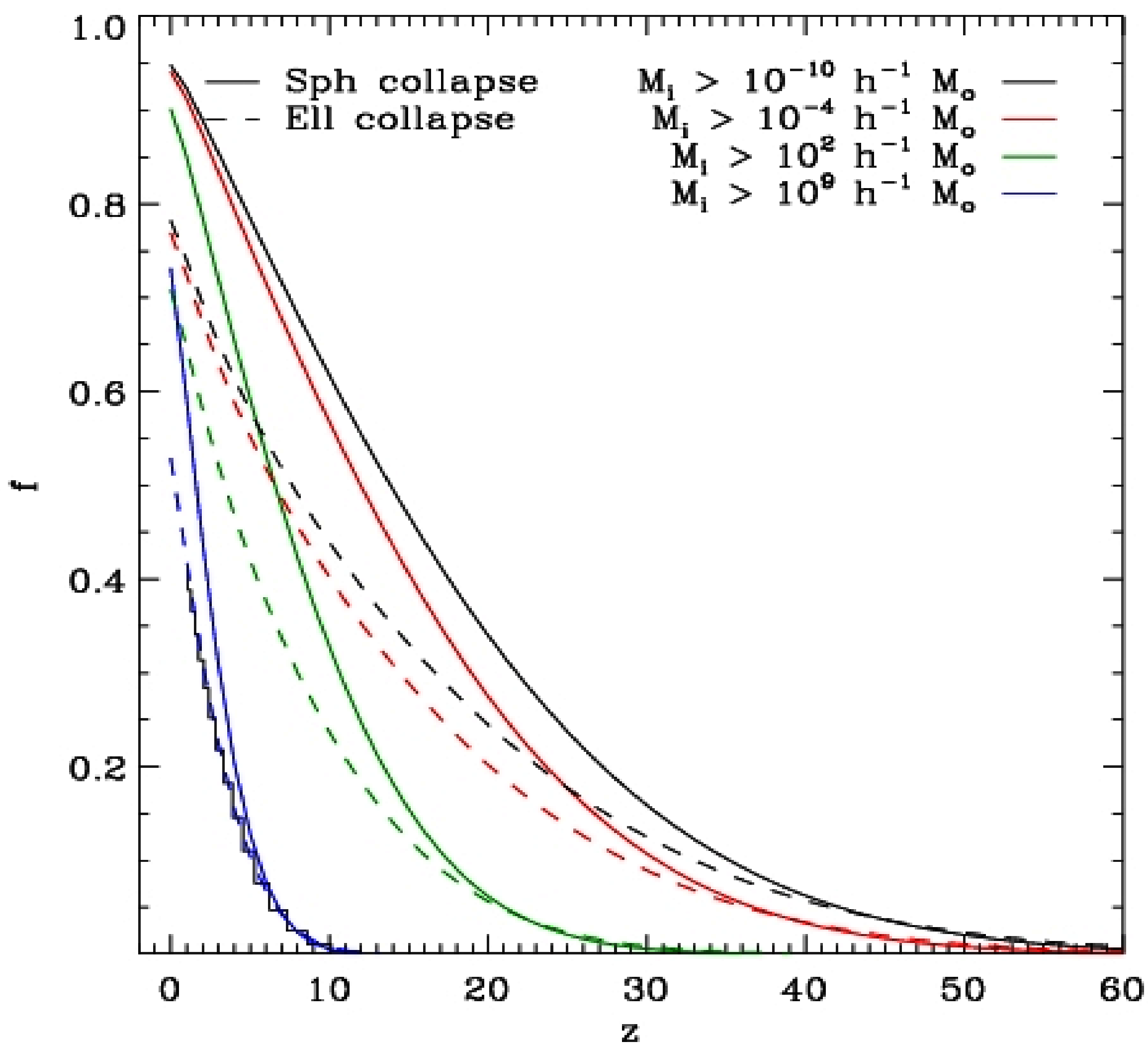

Total mass fraction in halos

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 statistics for the standard ΛCDM cosmology

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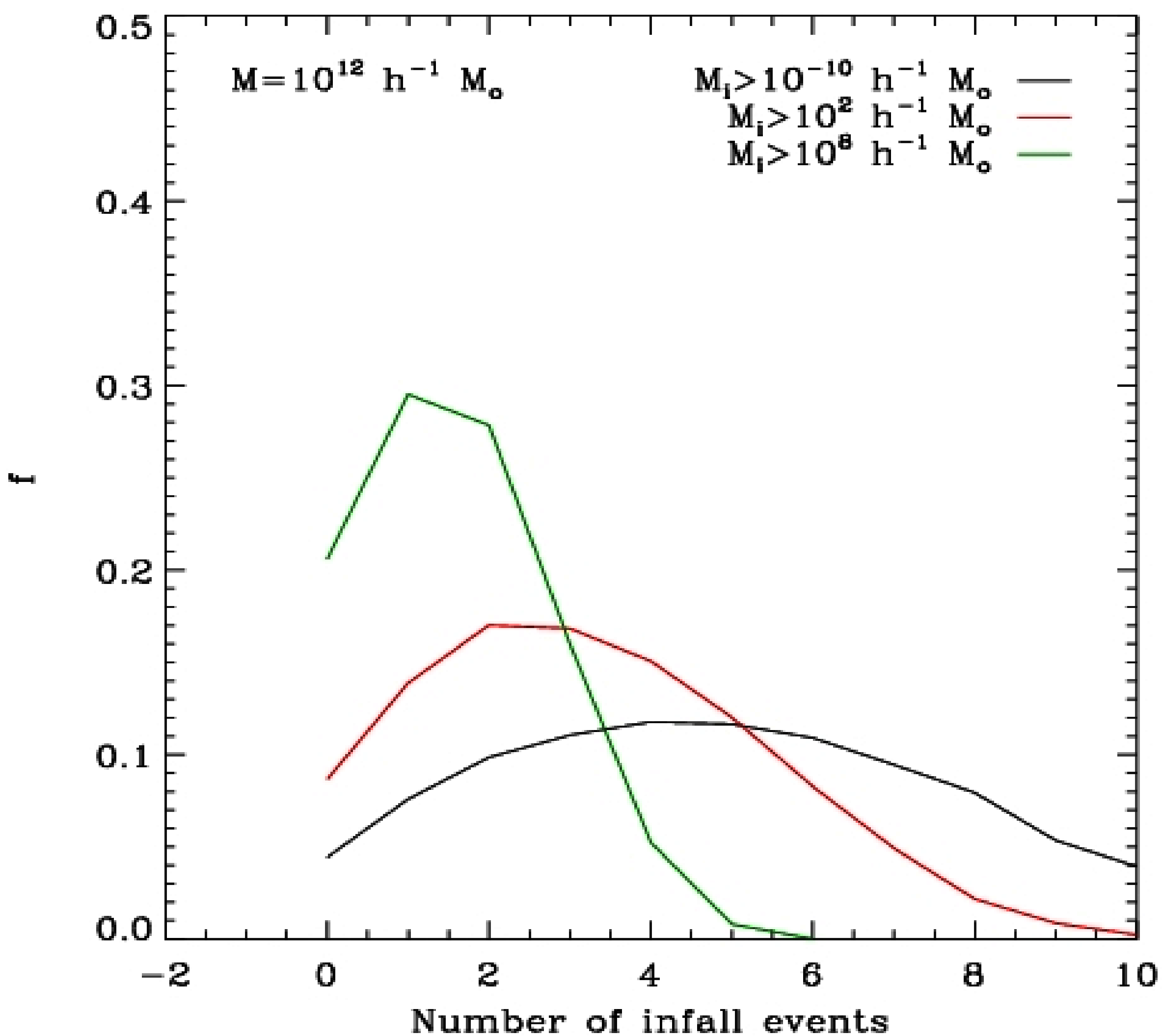

The typical mass element in a “Milky Way” halo goes through ~5 “infall events” where its halo falls into a halo bigger than itself.

Typically only one of these is as part of a halo with $M > 10^8 M_\odot$

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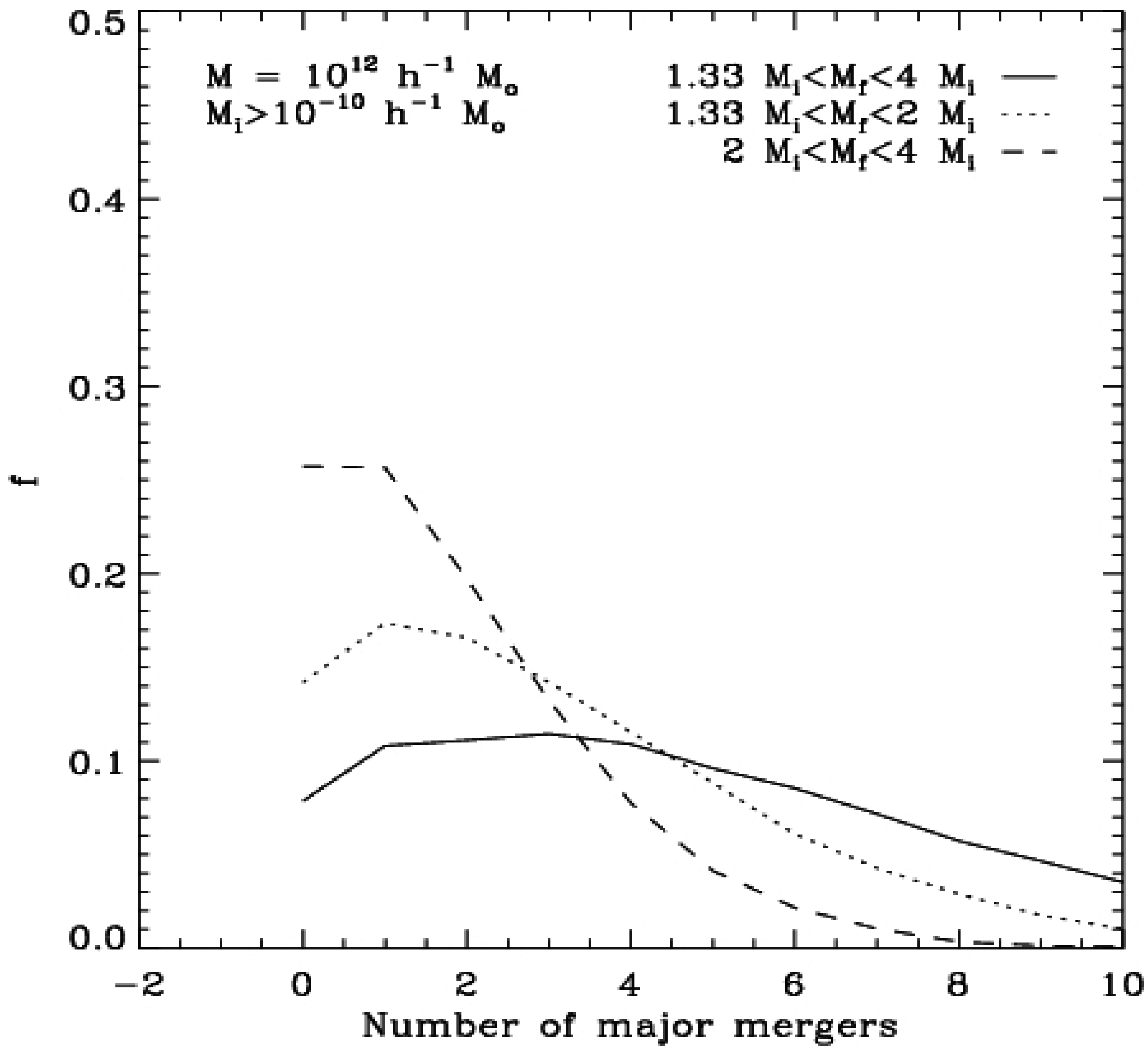

The typical mass element in a "Milky Way" halo goes through ~3 "major mergers" where the two halos are within a factor of 3 in mass

The majority of these occur when the element is part of the larger halo

EPS halo assembly: conclusions

- The typical first halo is much more massive than the free streaming mass
- First halos typically collapse quite late z ~ 15
- 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 many halos