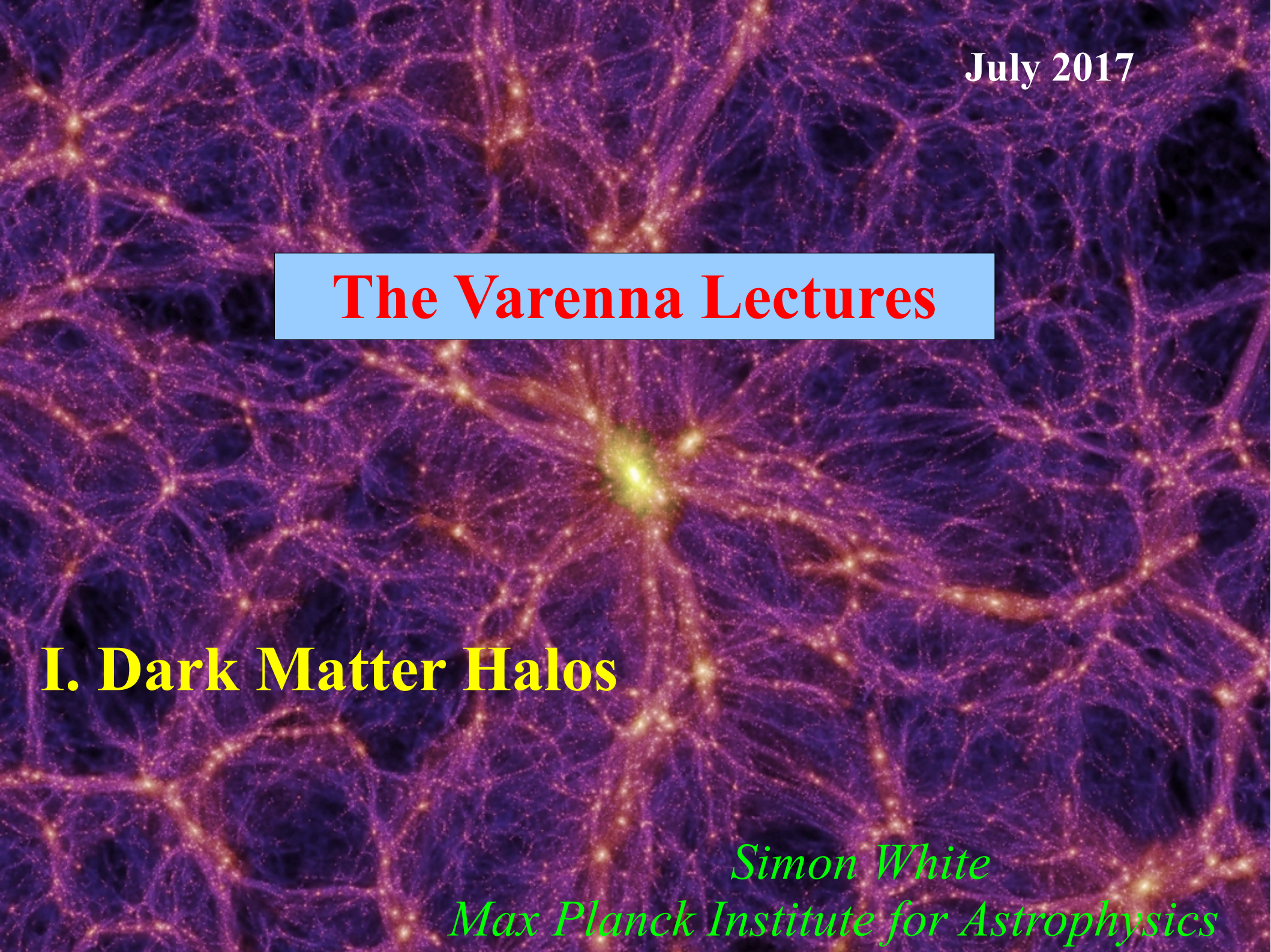


A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are depicted as thin, branching structures in shades of purple and blue, while the clusters are represented by bright, yellowish-white points of light. The overall structure is highly interconnected and fractal-like.

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

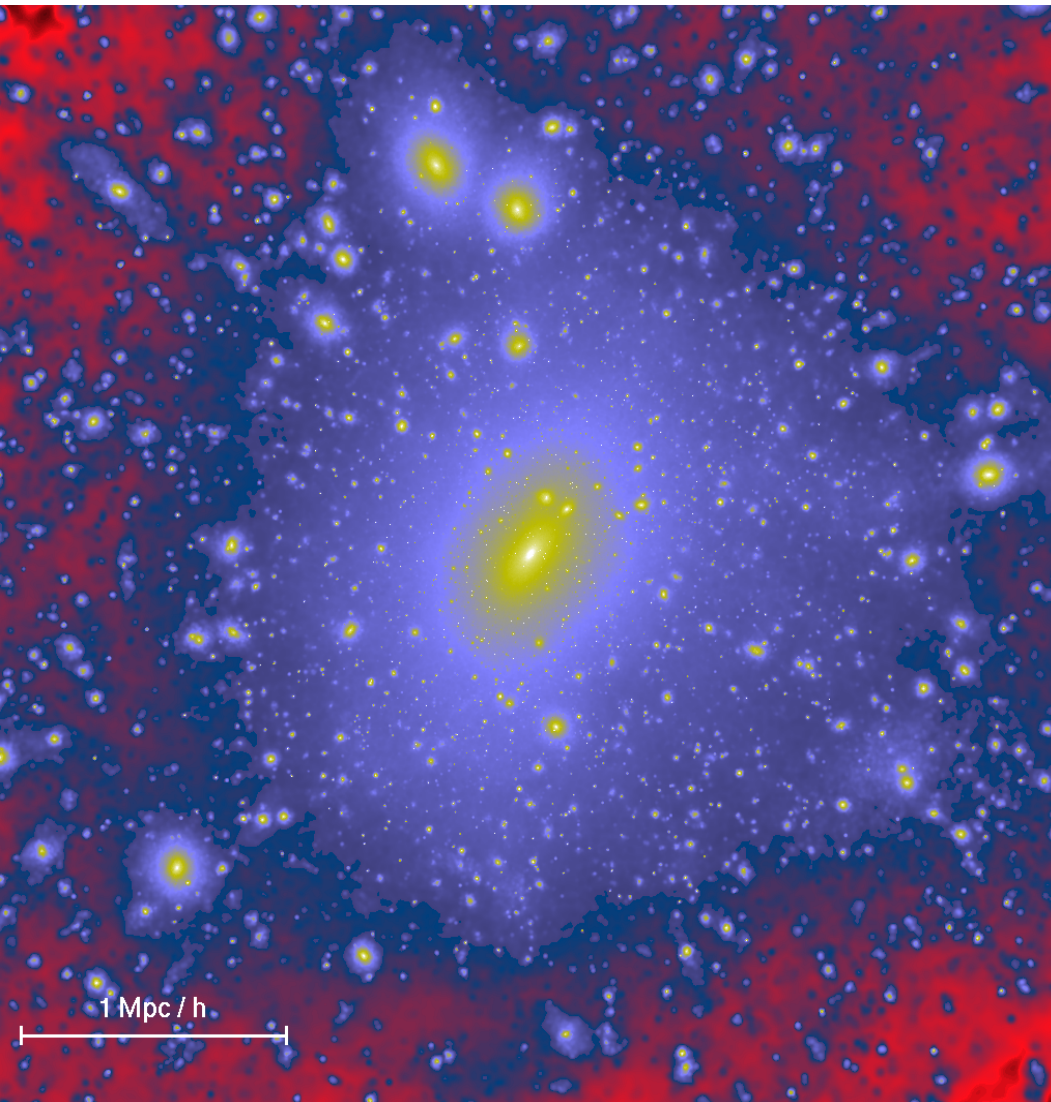
How do these properties affect DM detection experiments?

How can they be used to test the standard paradigm?

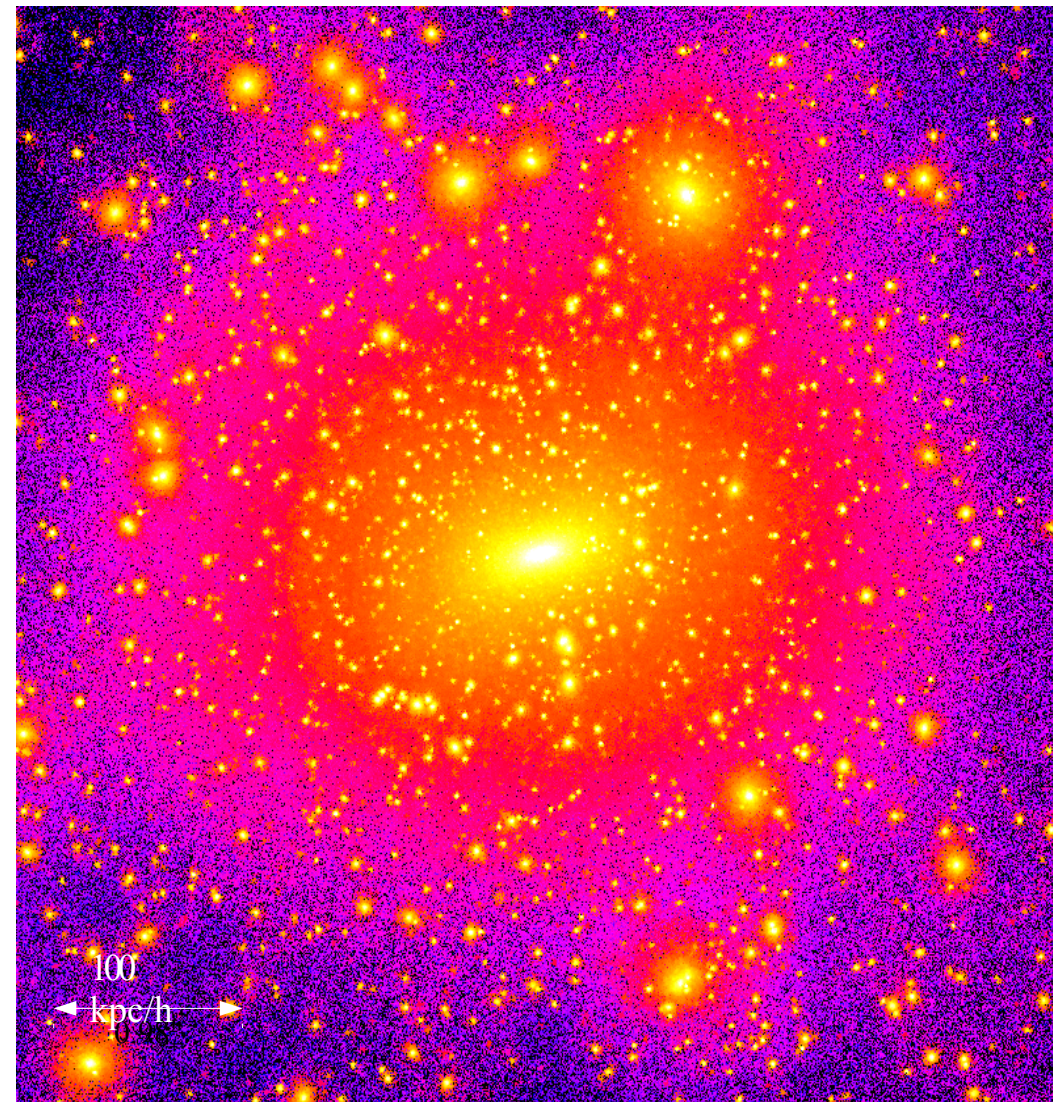
How do they affect/are they affected by the baryonic matter

Λ CDM 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

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

where we define $D(0) = 1$

Consider the smoothed density field

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

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

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 gaussian linear overdensity field

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

is independent 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 $\mathbf{x}$ 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 first upcrossing of the barrier $\delta_s = \delta_c$

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

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

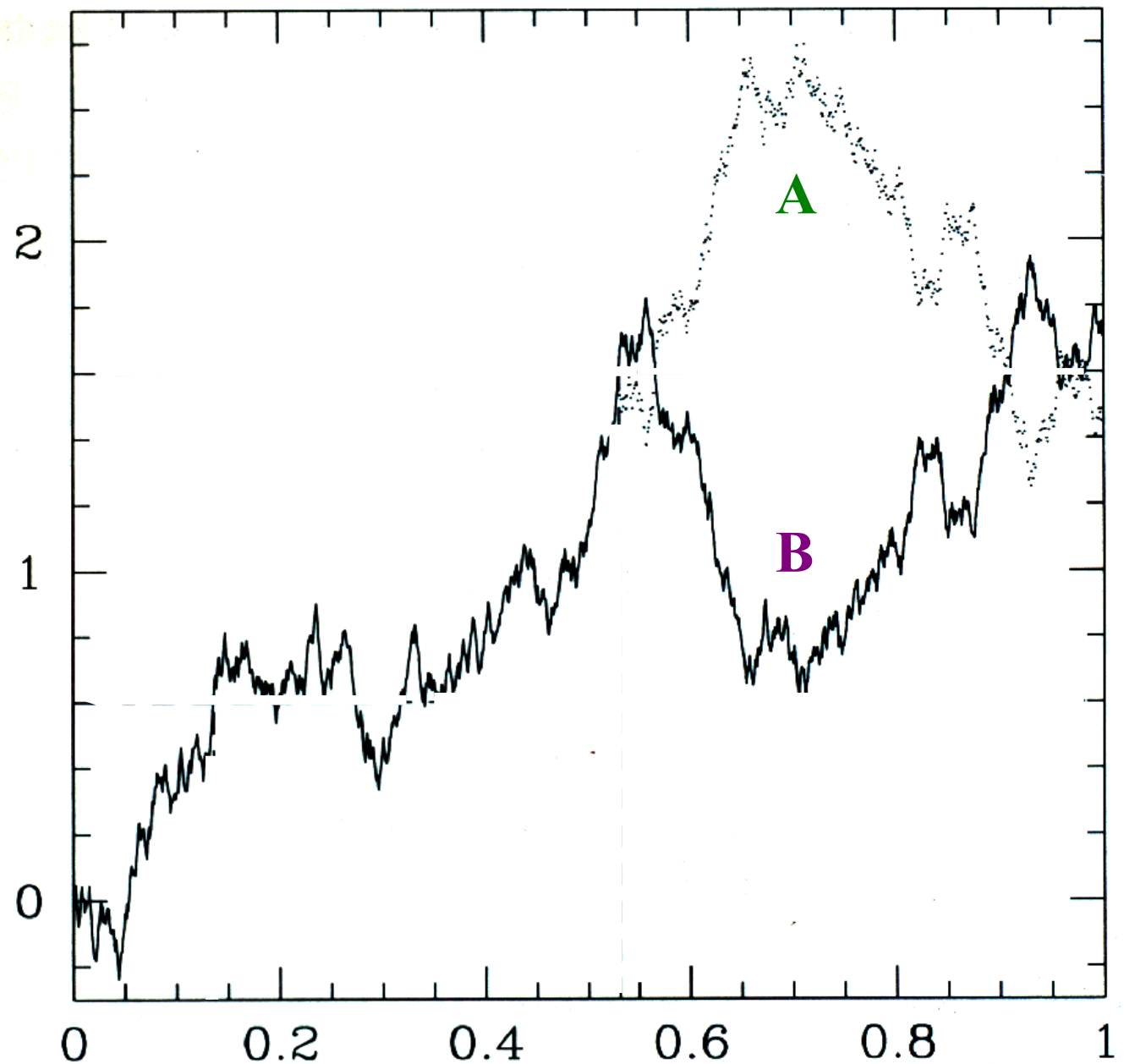
Overdensity vs smoothing at a given position

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

initial overdensity $\delta_s/D(\tau)$



variance $\sigma_0^2(k_c)$ of smoothed field

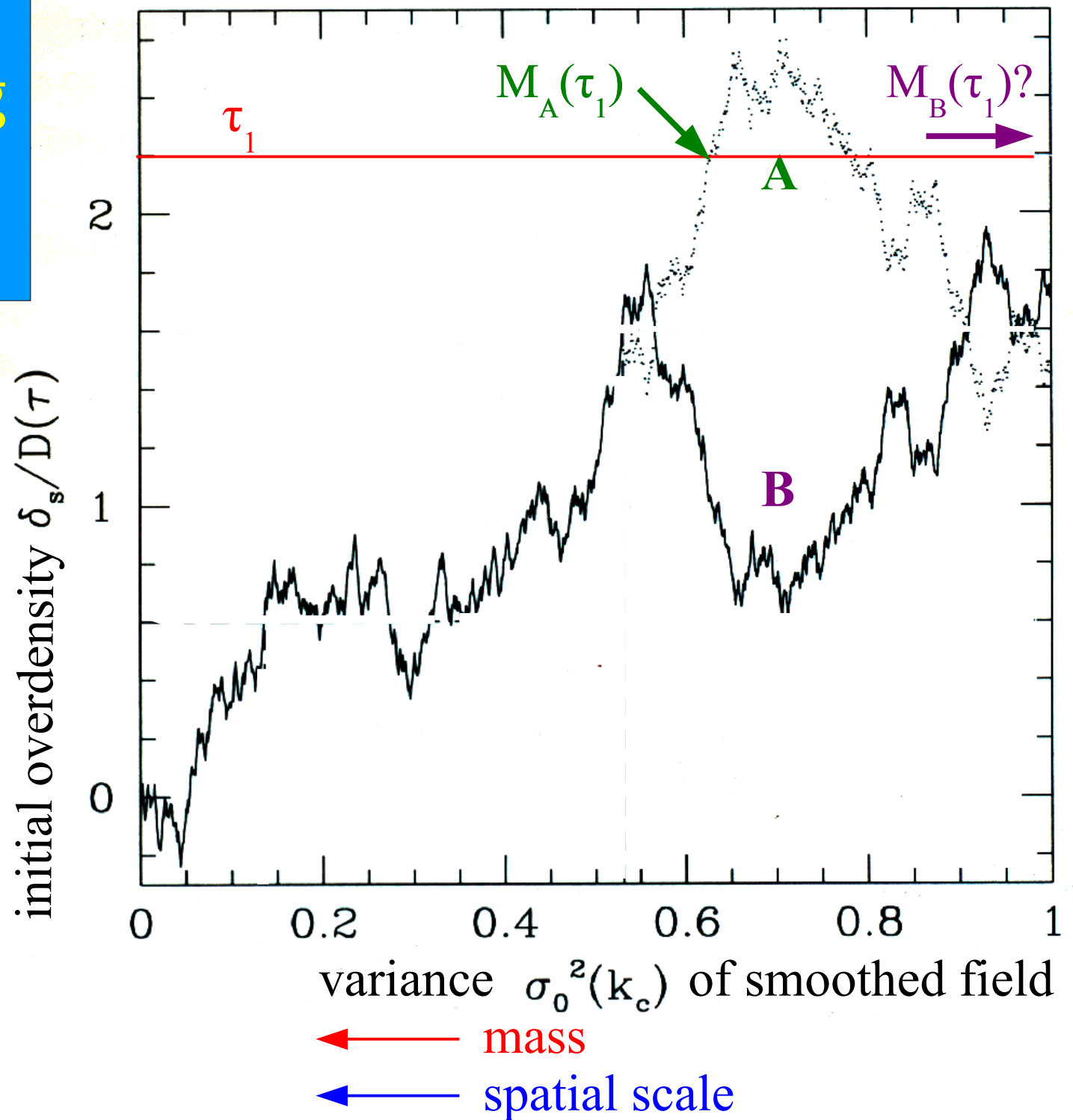
← mass

← 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

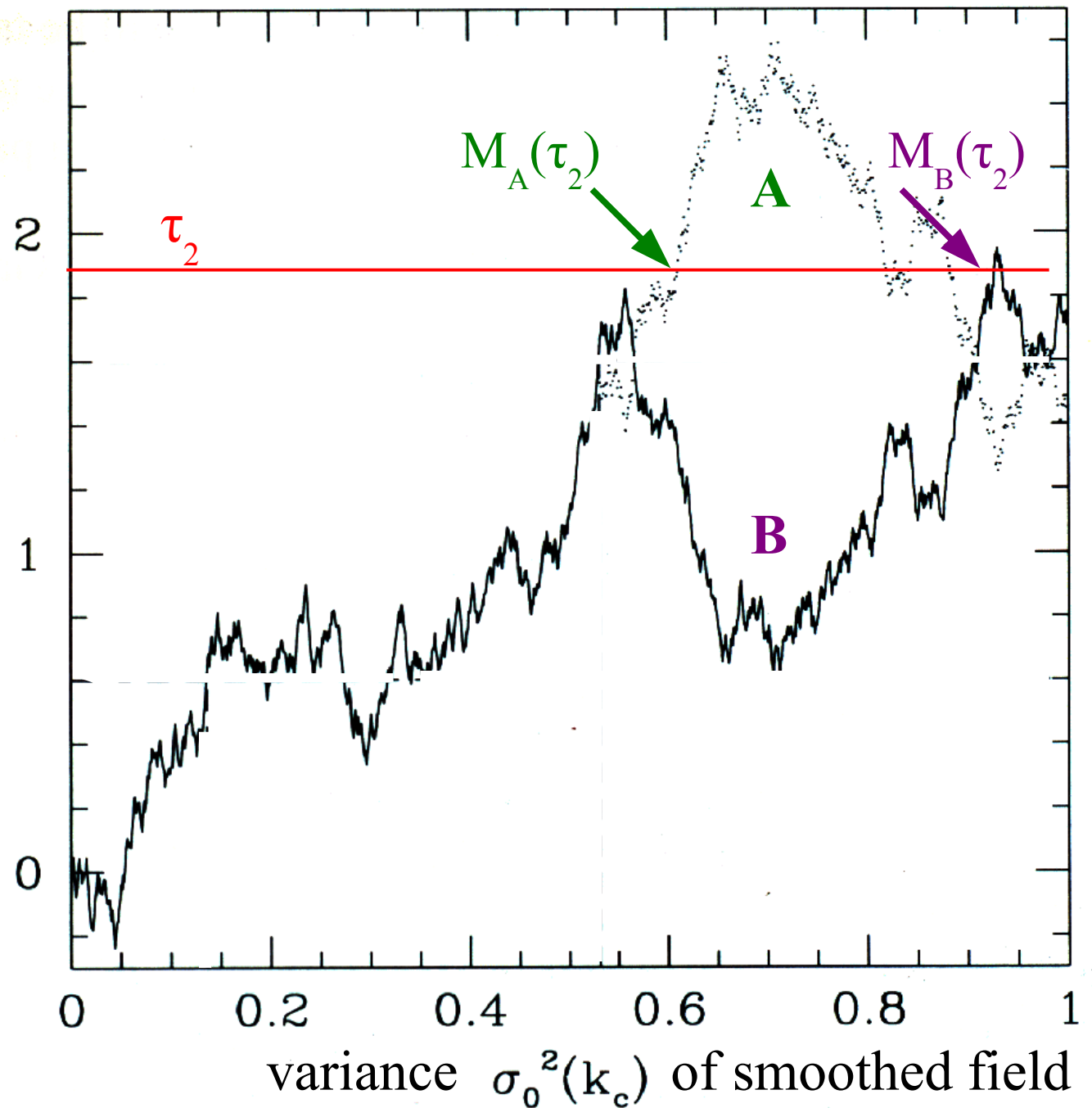


Overdensity vs smoothing at a given position

Later, at time τ_2
A's halo has grown
slightly by accretion

B is now part of a
moderately massive
halo

initial overdensity $\delta_s/D(\tau)$



← mass

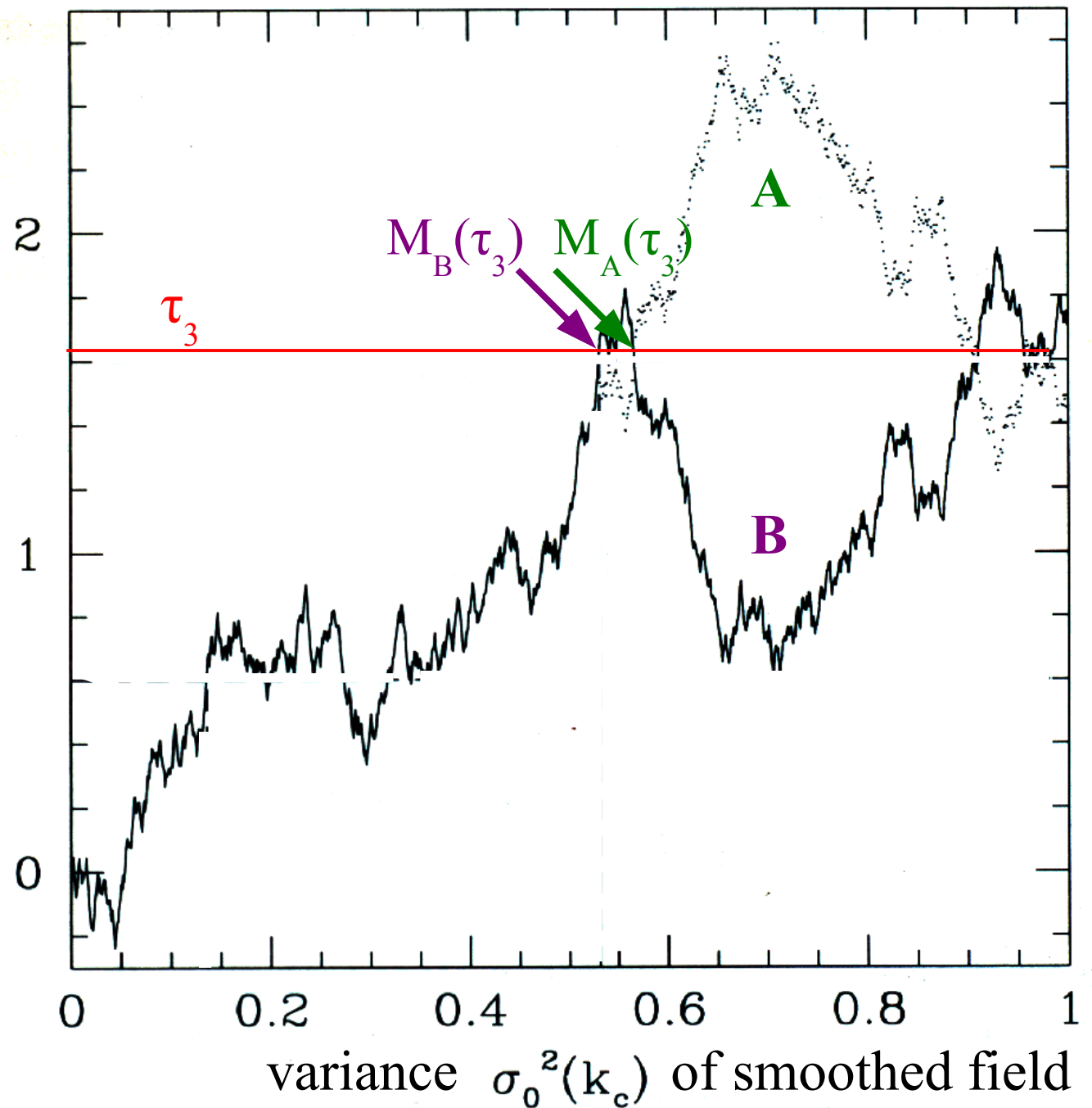
← spatial scale

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

initial overdensity $\delta_s/D(\tau)$



← mass

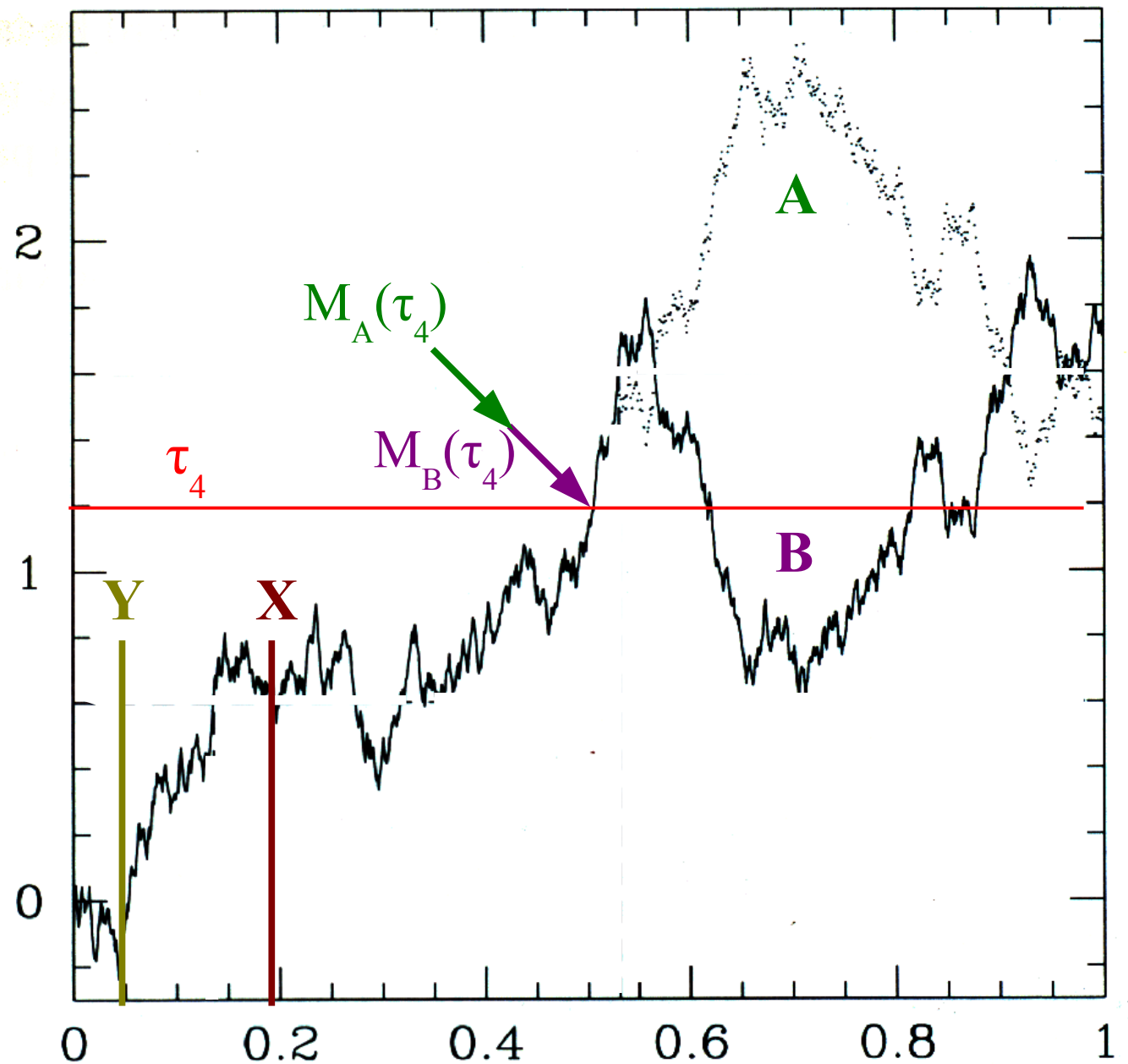
← spatial scale

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

initial overdensity $\delta_s/D(\tau)$



variance $\sigma_0^2(k_c)$ of smoothed field

← mass

← spatial scale

Consequences of the Markov nature of EPS walks

The assembly history of a halo is independent of its future

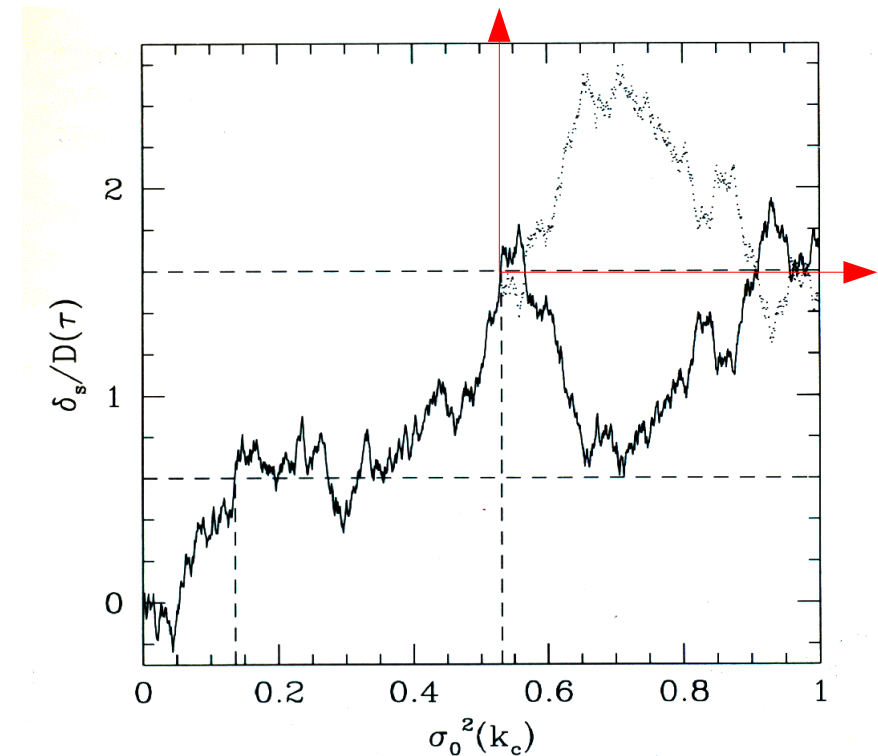
The assembly history of a halo is independent of its environment

The internal structure of a halo is independent of its environment

The mass distribution of progenitors of a halo of given M and z is obtained simply by changing the origin to $\sigma_0^2(M)$ and $\delta_c/D(z)$

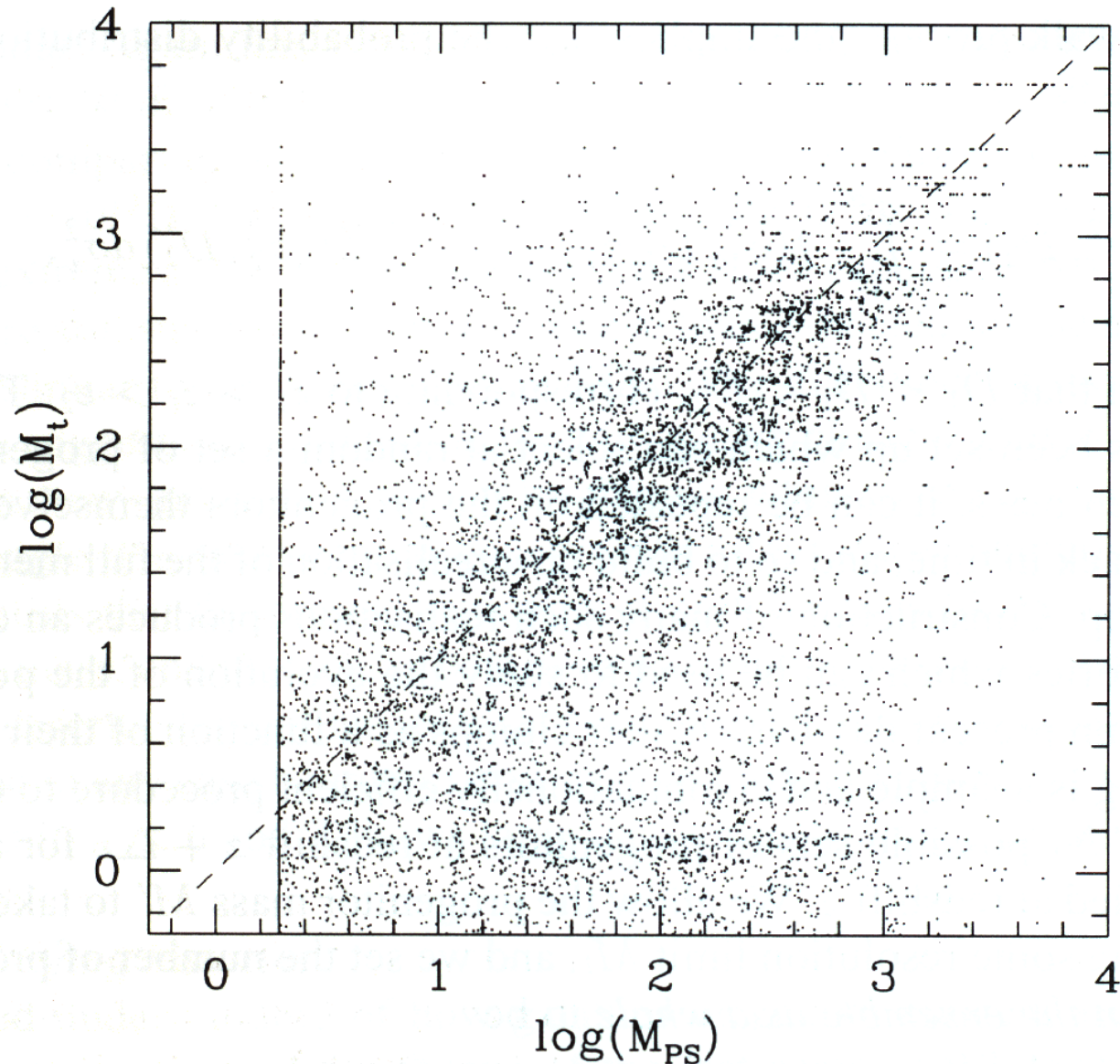
The resulting formulae can be used to obtain descendant distributions and merger rates

A similar argument gives formulae for the clustering bias of halos



Does it work point by point?

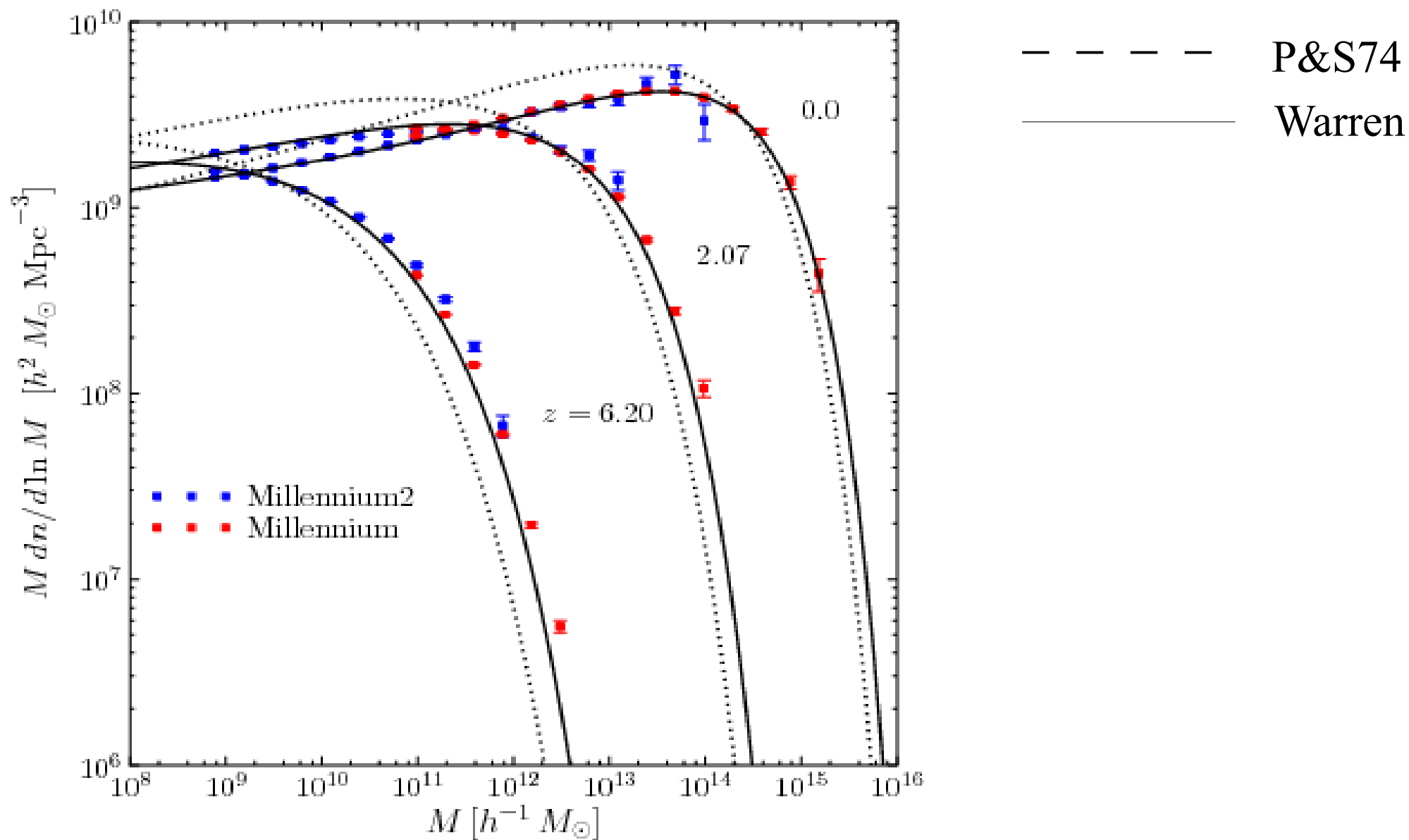
Mass of the
halo in which
the particle is
actually found



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

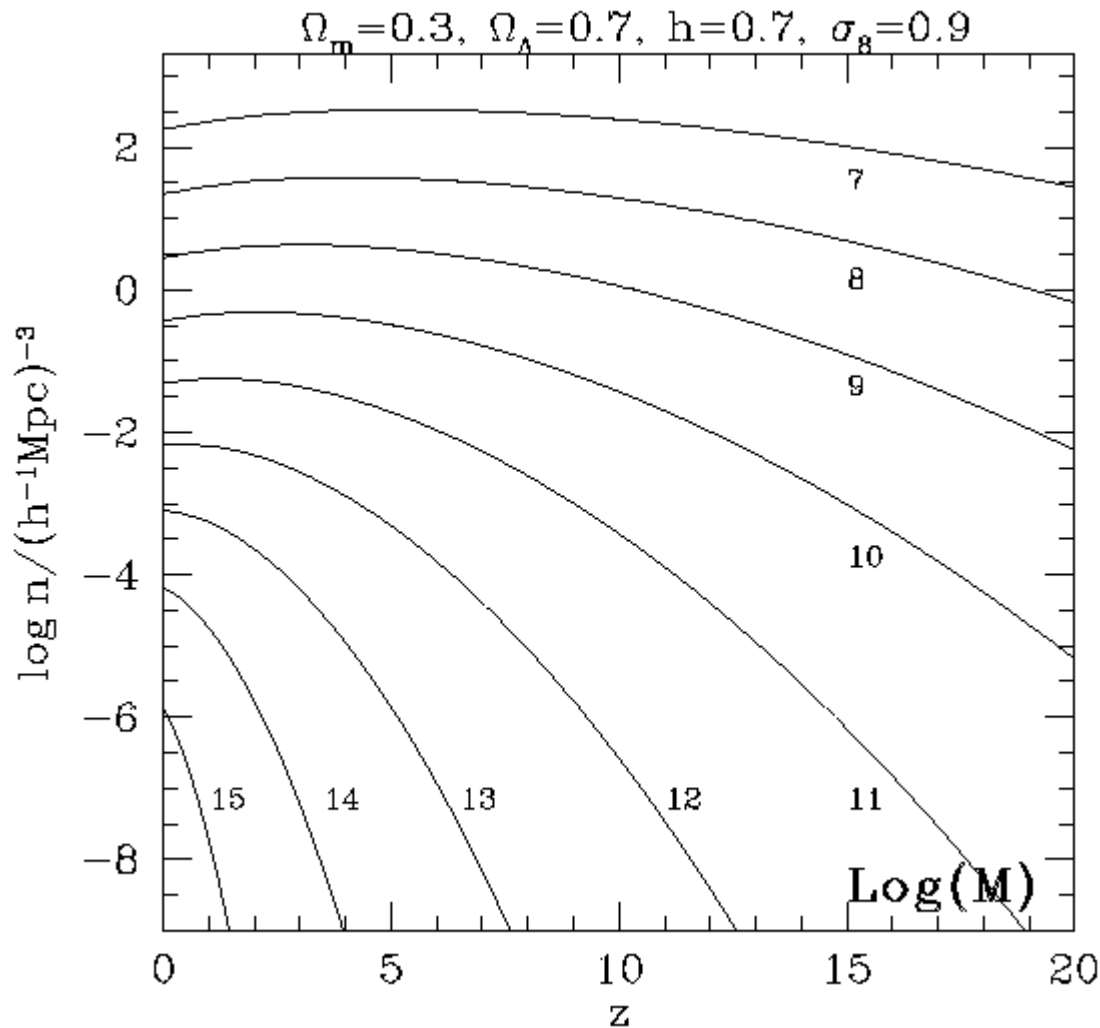
Does it work statistically?

Boylan-Kolchin et al 2009



Evolution of halo abundance in Λ CDM

Mo & White 2002



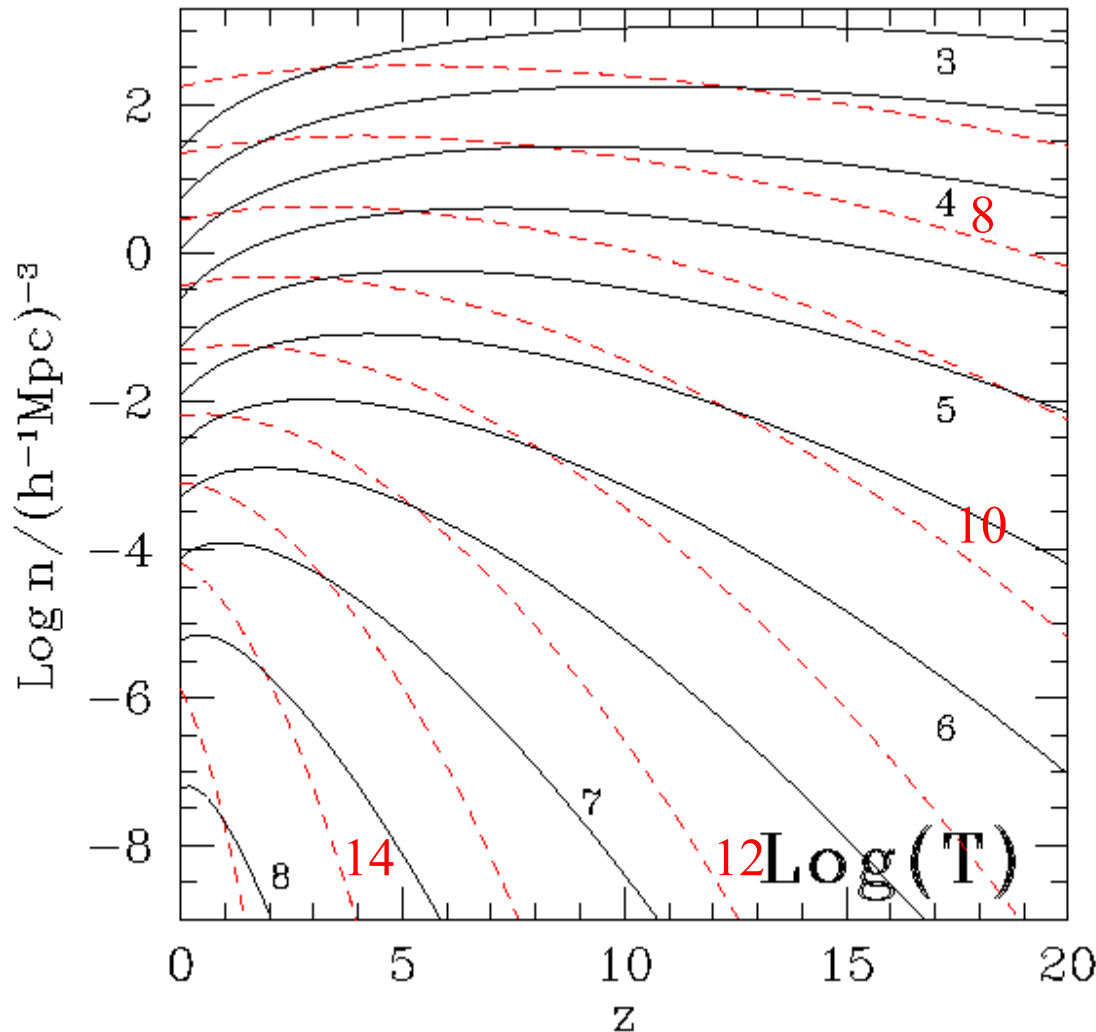
Abundance of rich cluster halos drops rapidly with z

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 Λ CDM

Mo & White 2002



Temperature increases with both mass and redshift

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

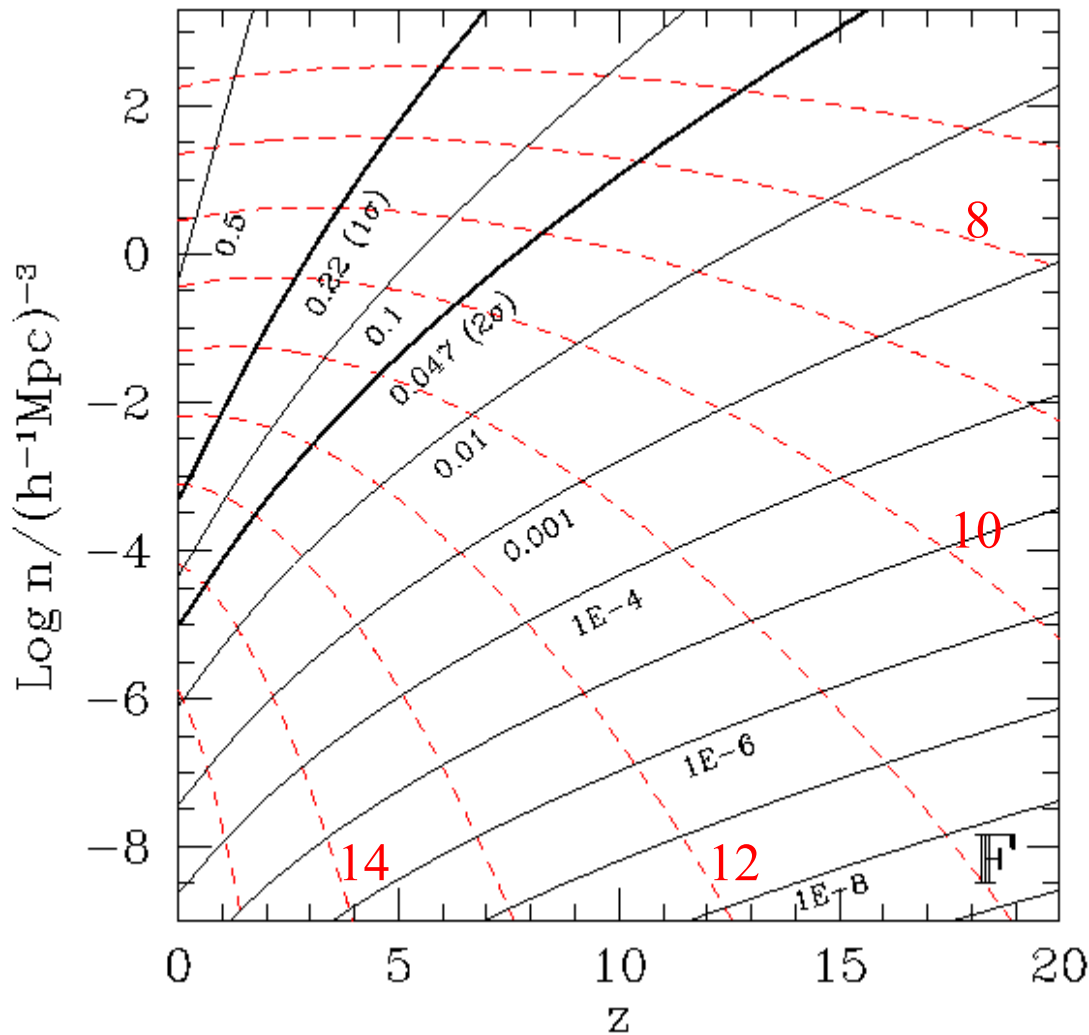
Halos with virial temperature $T = 10^7$ K are as abundant at $z = 2$ as at $z=0$

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 Λ CDM

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 $z=20$

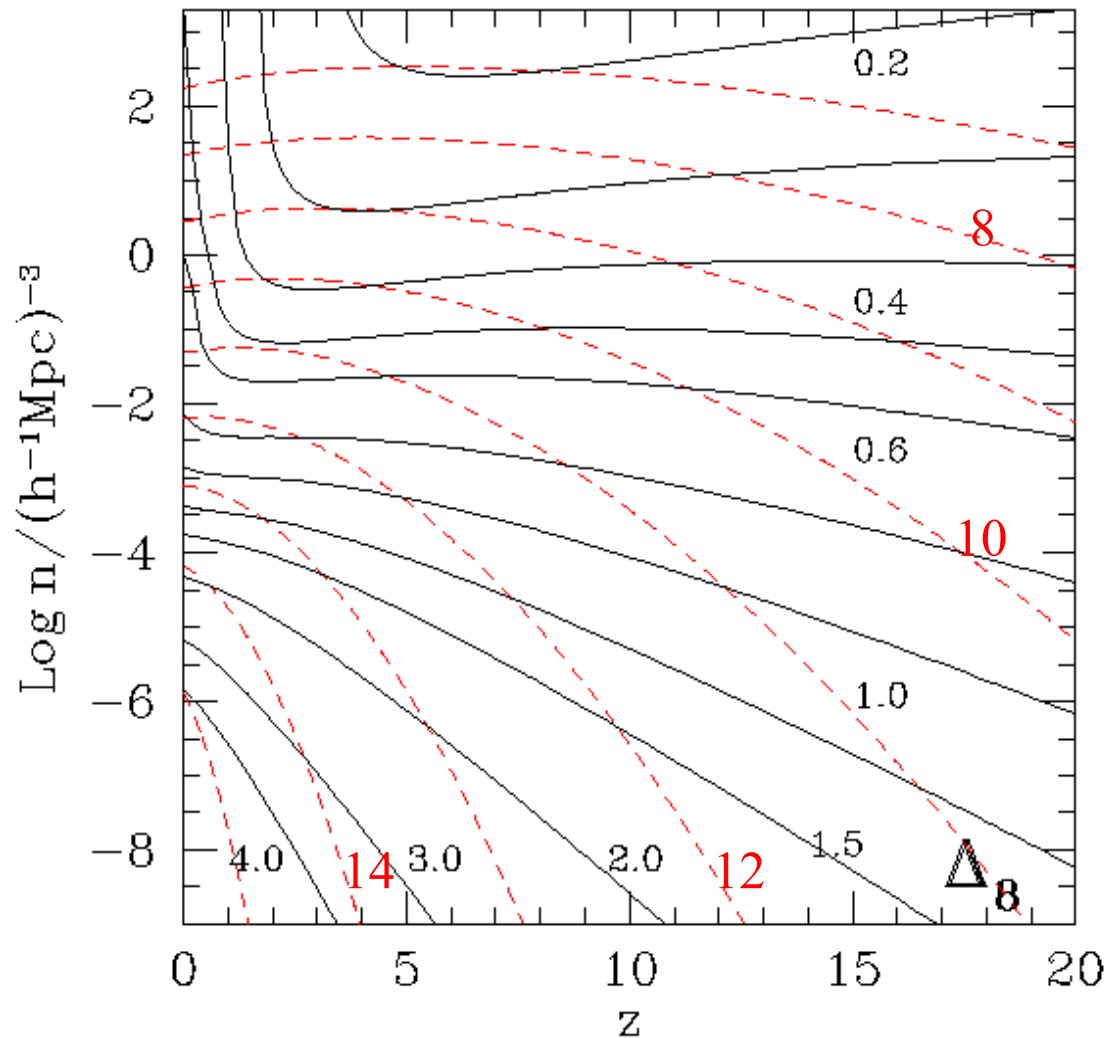
1% of all mass is in halos more massive than $10^{15} M_{\odot}$ at $z=0$

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 Λ CDM

Mo & White 2002

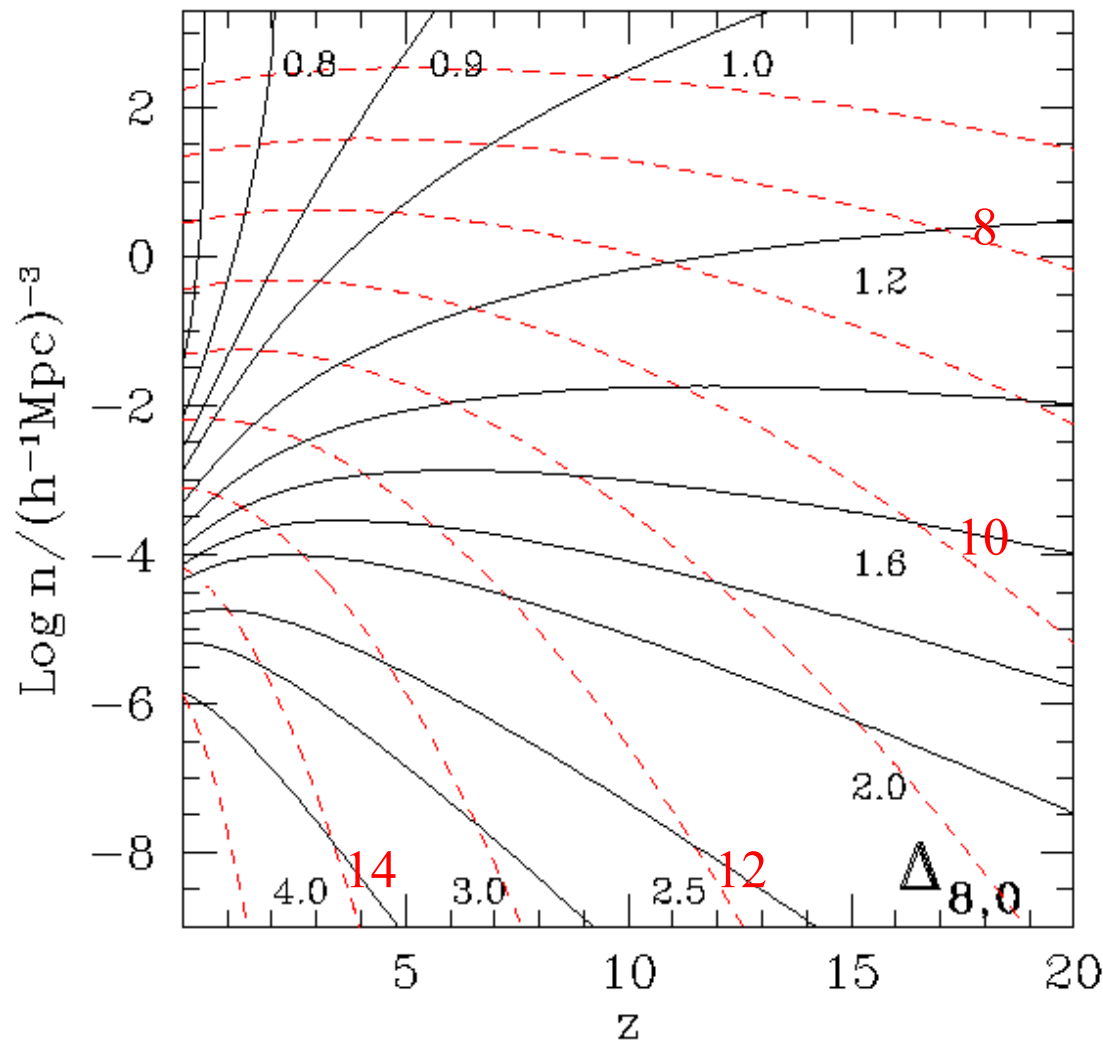


Halos with the abundance of L_* galaxies at $z=0$ are equally strongly clustered at all $z < 20$

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

Evolution of halo abundance in Λ CDM

Mo & White 2002



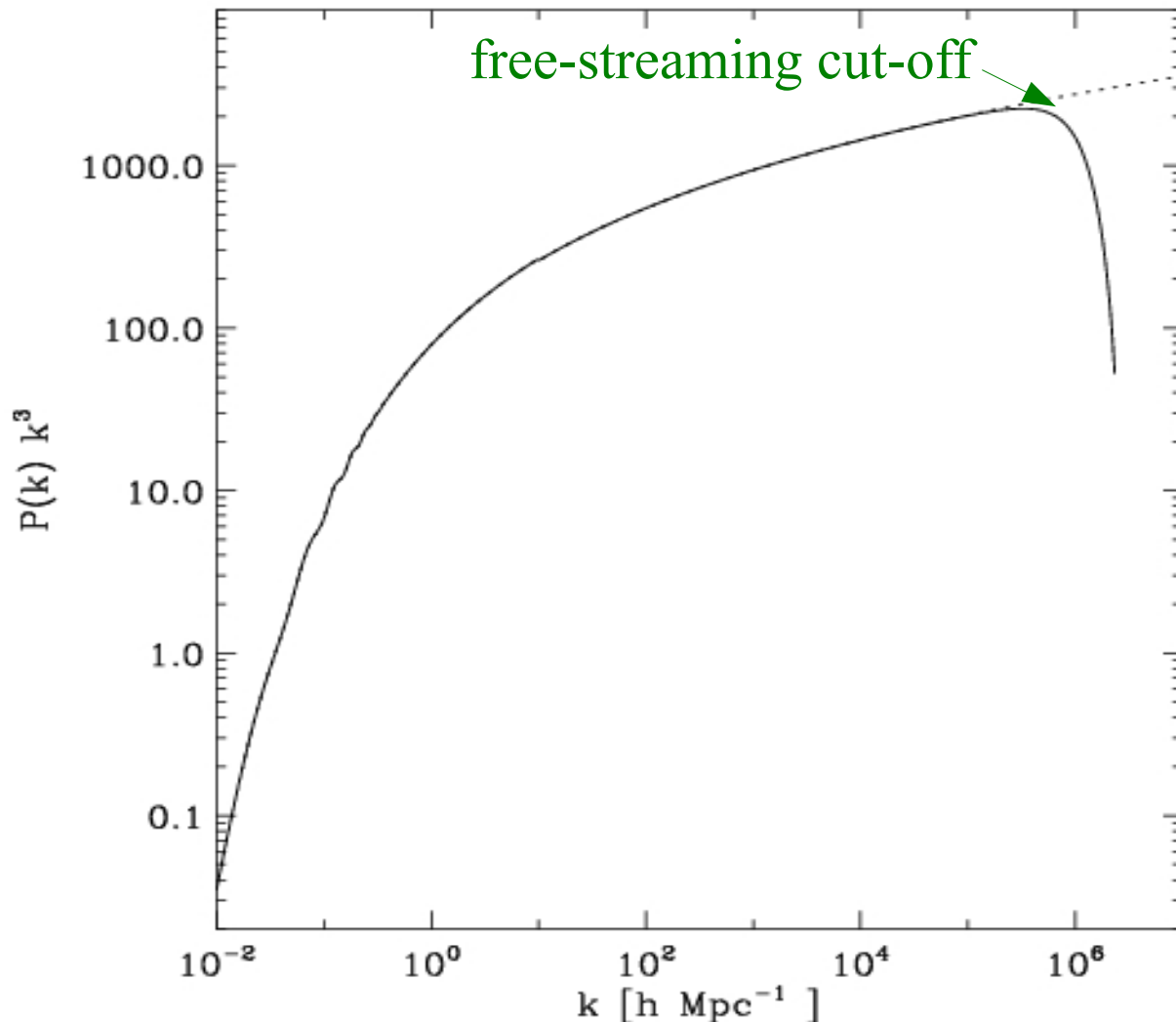
The remnants (stars and heavy elements) from all star-forming systems at $z > 6$ are today more clustered than L_* galaxies

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

EPS statistics for the standard Λ CDM cosmology

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

Angulo et al 2009



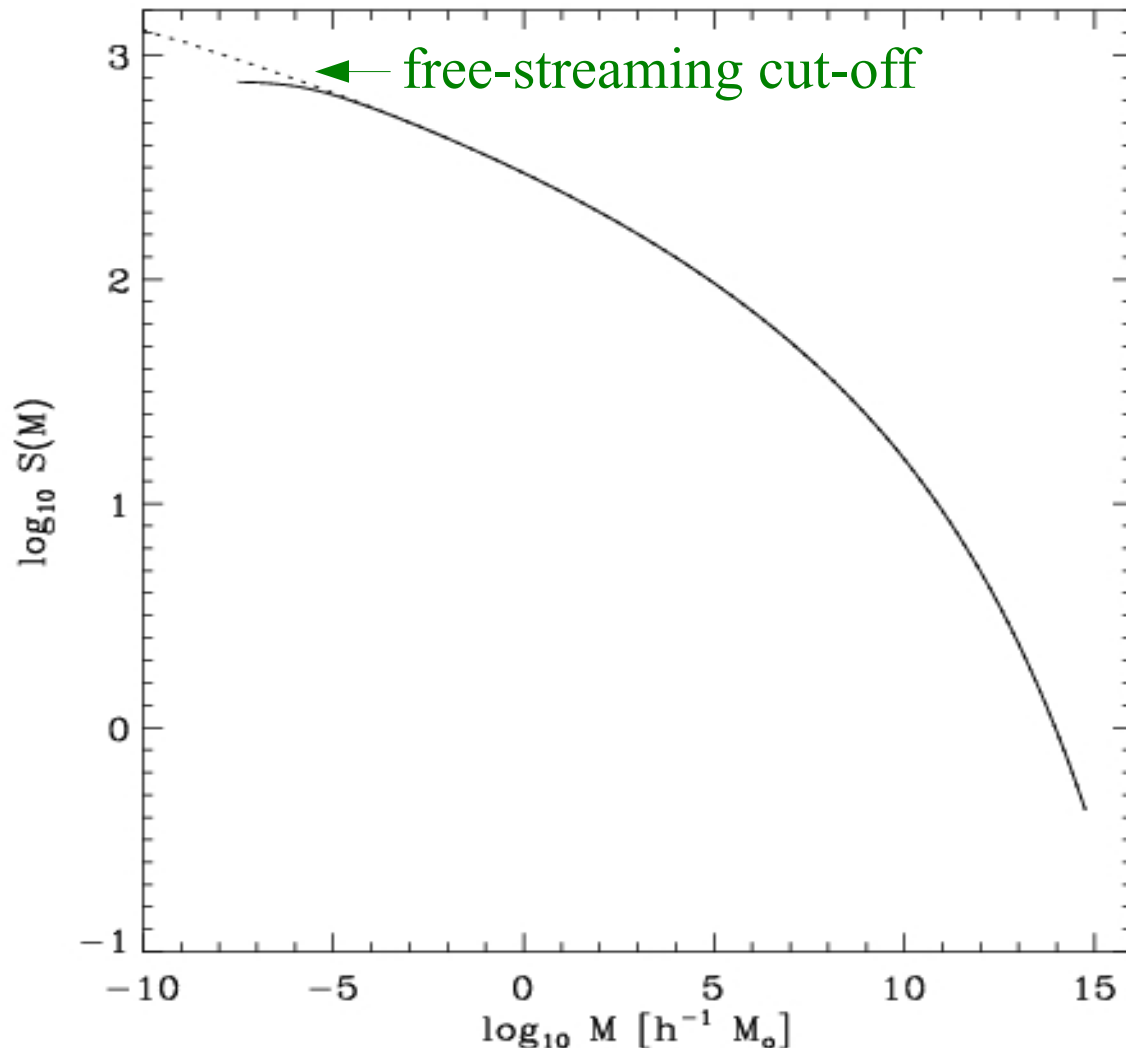
The linear power spectrum in “power per octave” form

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

EPS statistics for the standard Λ CDM cosmology

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

Angulo et al 2009

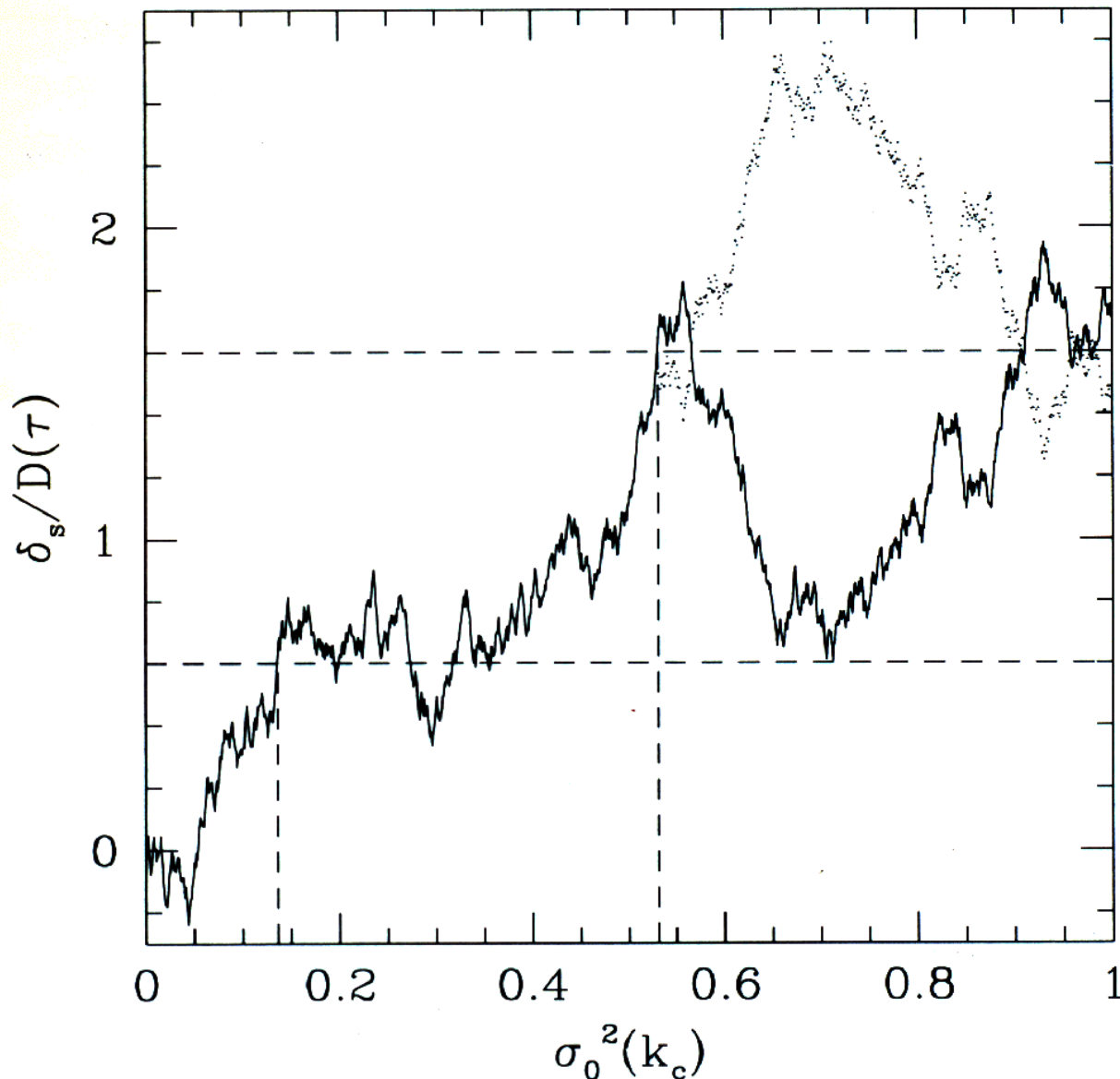


Variance of linear density fluctuation within spheres containing mass M , extrapolated to $z = 0$

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

EPS statistics for the standard Λ CDM cosmology

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



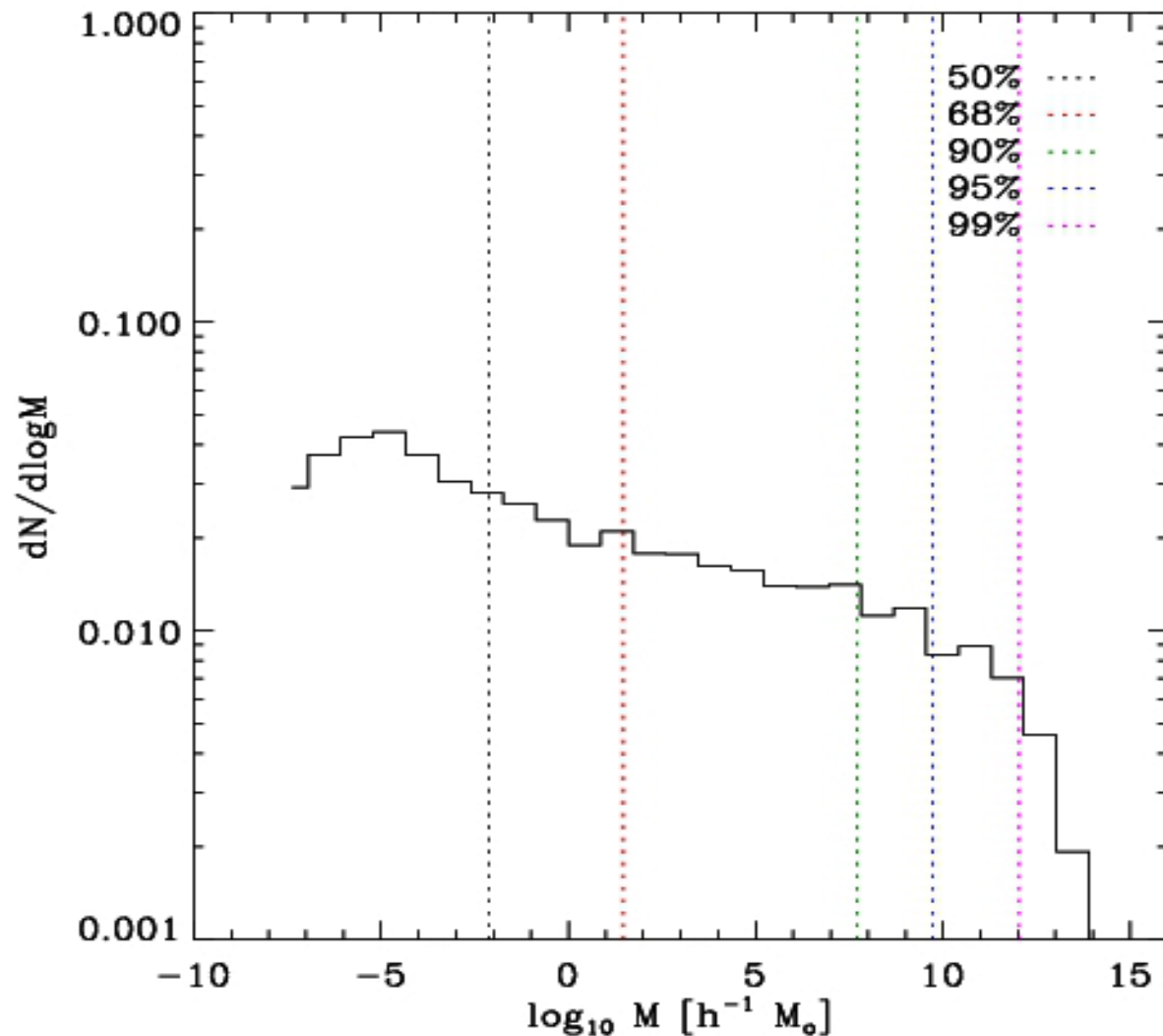
If these Markov random walks are scaled so the maximum variance is 720 and the vertical axis is multiplied by $\sqrt{720}$, then they represent complete halo assembly histories for random CDM particles.

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

EPS statistics for the standard Λ CDM 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 masses of the first halos for a random set of dark matter particles

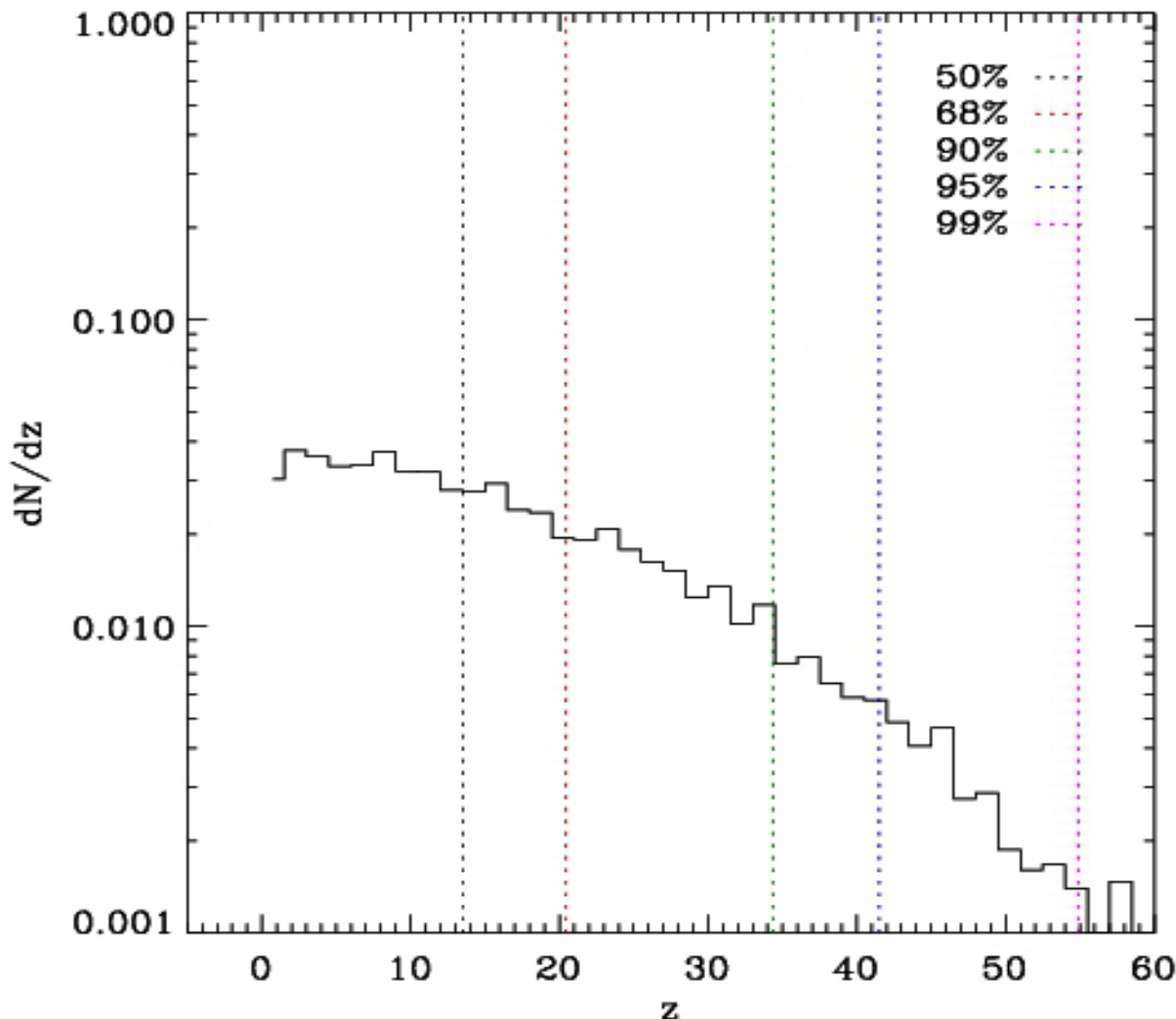
The median is $10^{-2} M_\odot$

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

EPS statistics for the standard Λ CDM 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 $z = 13$

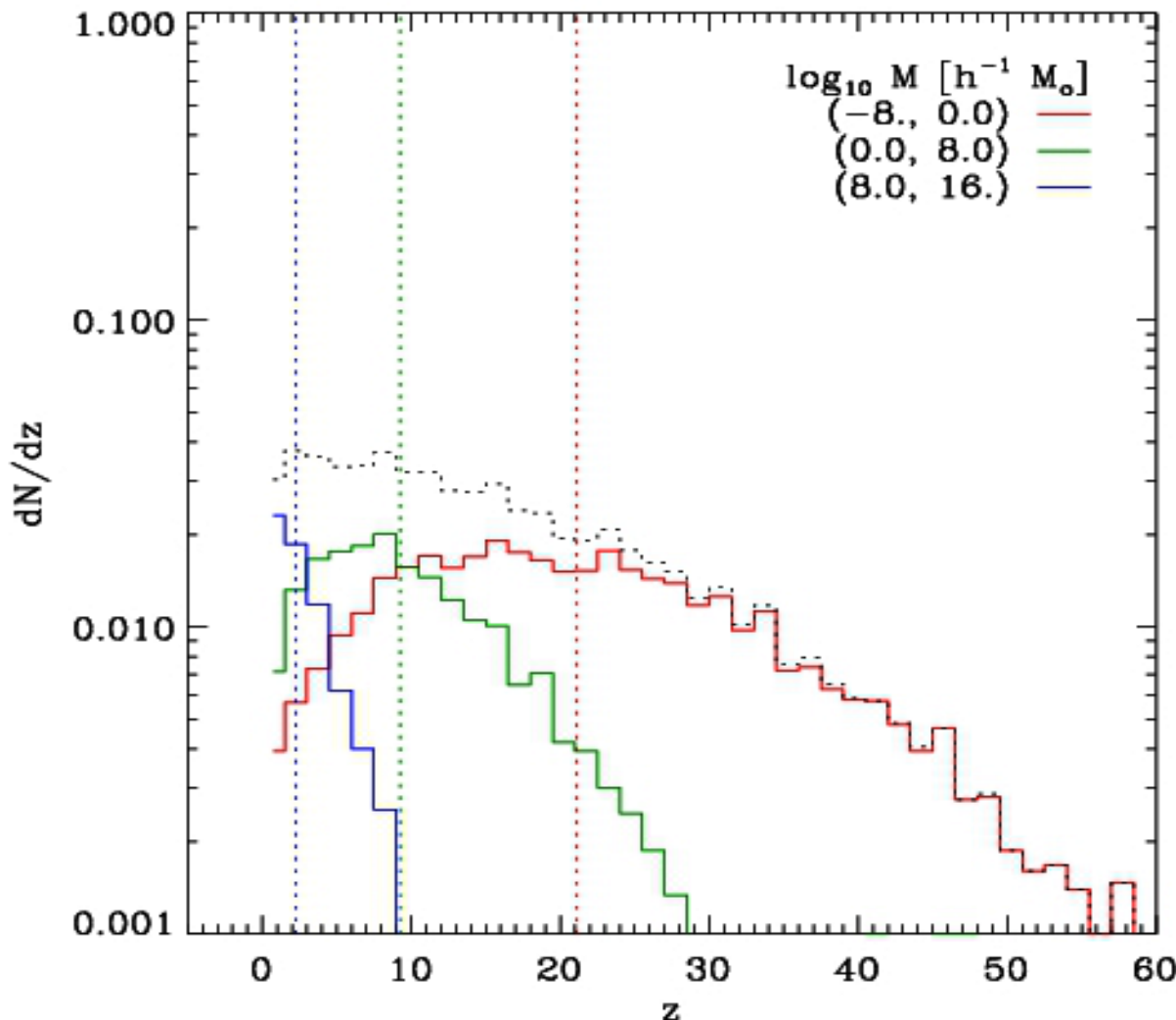
For 10% of the mass the first halo collapses at $z > 34$

For 1% at $z > 55$

EPS statistics for the standard Λ CDM 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

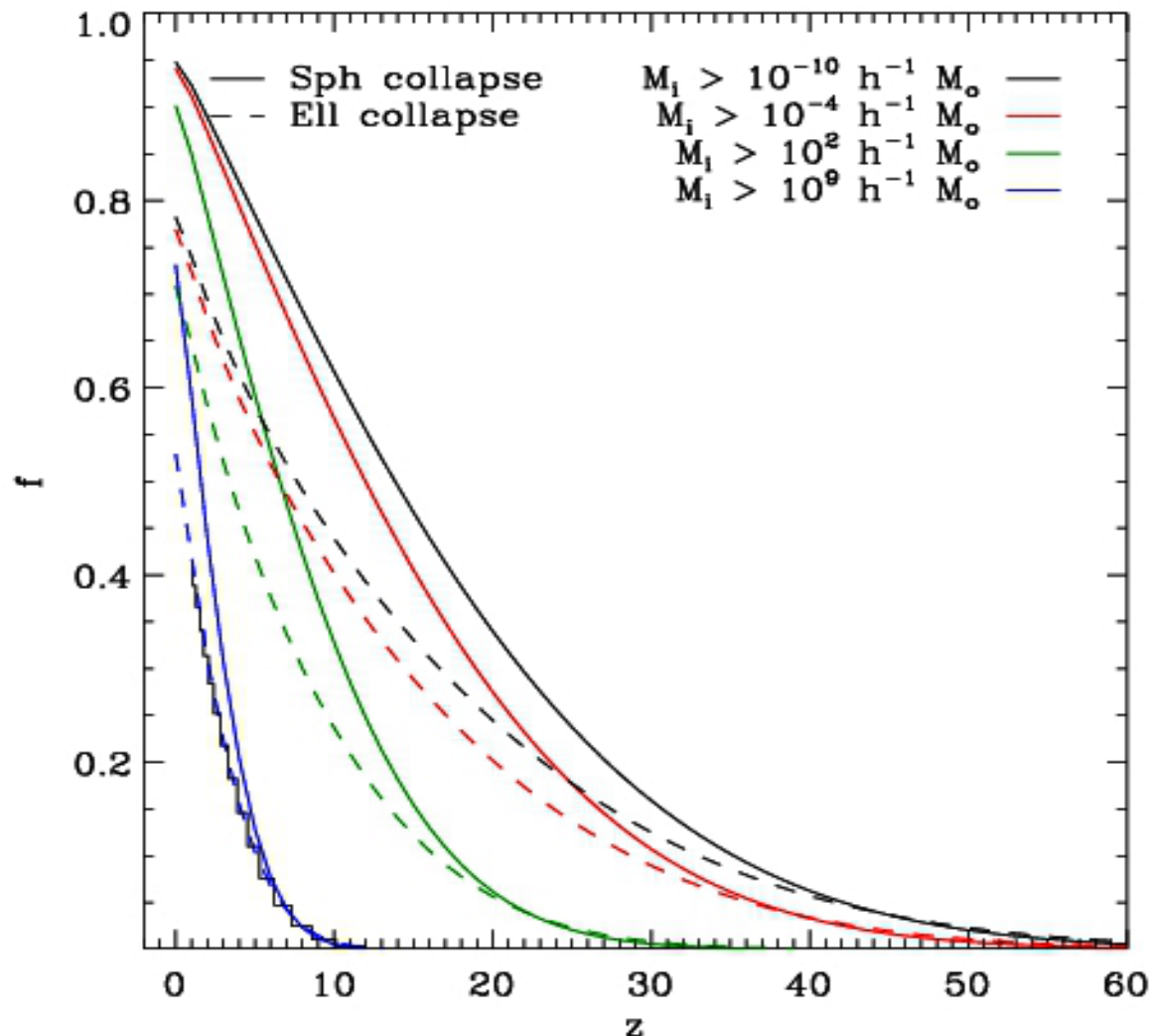
The high redshift tail is entirely due to matter in small first halos

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

EPS statistics for the standard Λ CDM 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

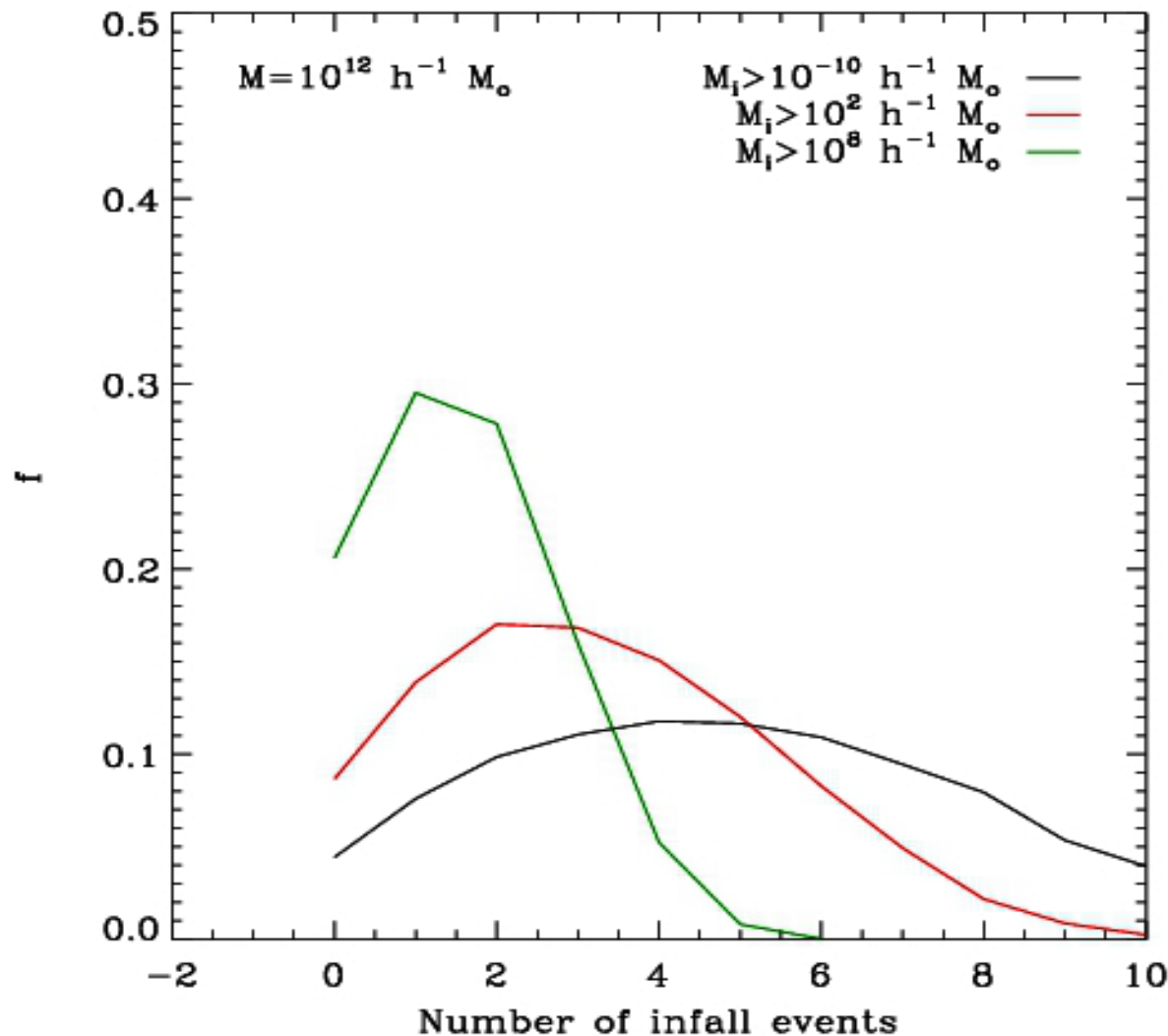
Only at $z < 2$ (Sph) or $z < 0.5$ (Ell) is most mass in halos with $M > 10^8 M_\odot$. The “Ell”

curve agrees with simulations

EPS statistics for the standard Λ CDM cosmology

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

Angulo et al 2009



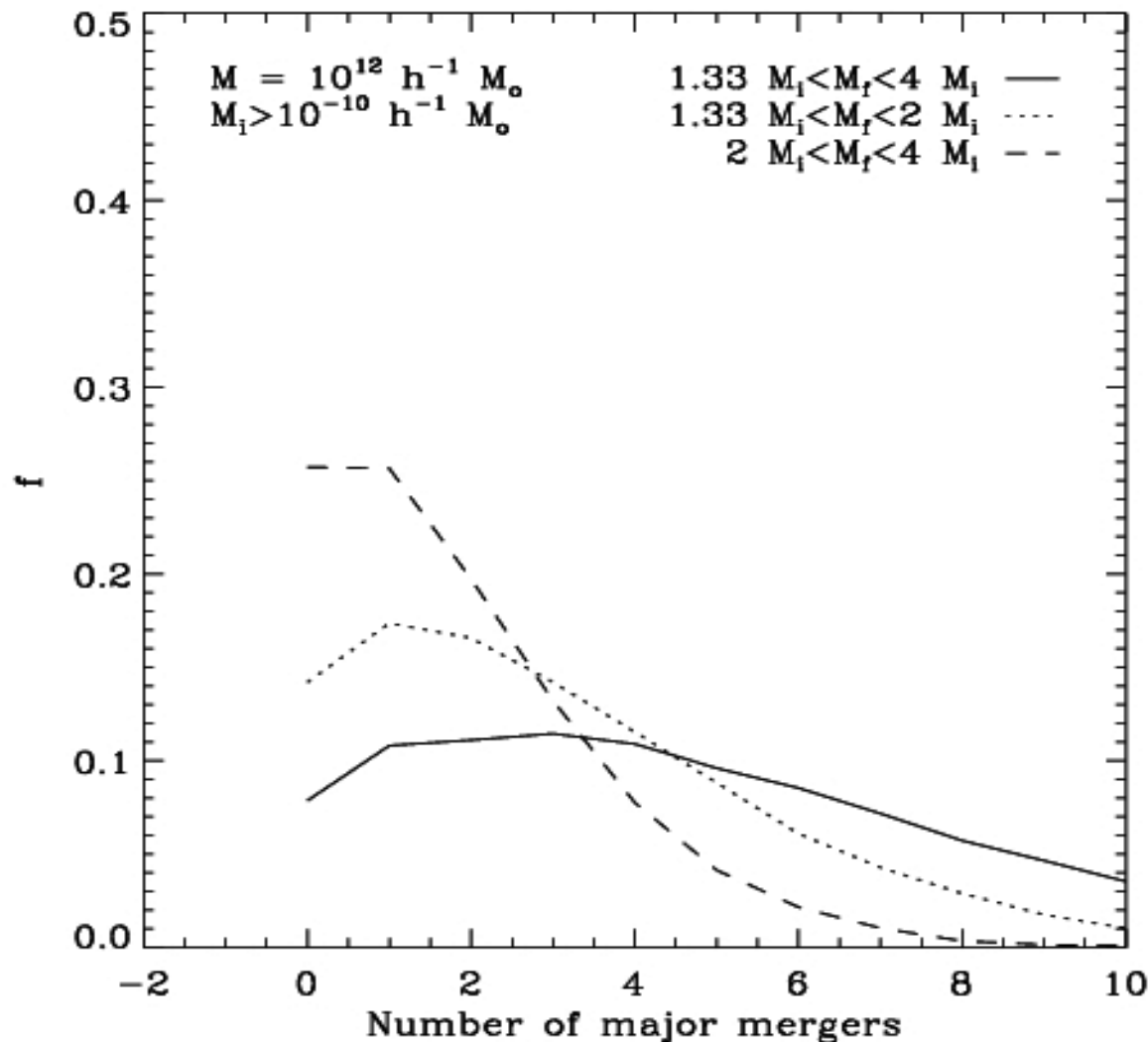
The typical mass element in a “Milky Way” halo goes through ~ 5 “infall events” where its halo falls into a halo bigger than itself.

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

EPS statistics for the standard Λ CDM cosmology

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

Angulo et al 2009



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 $z \sim 13$

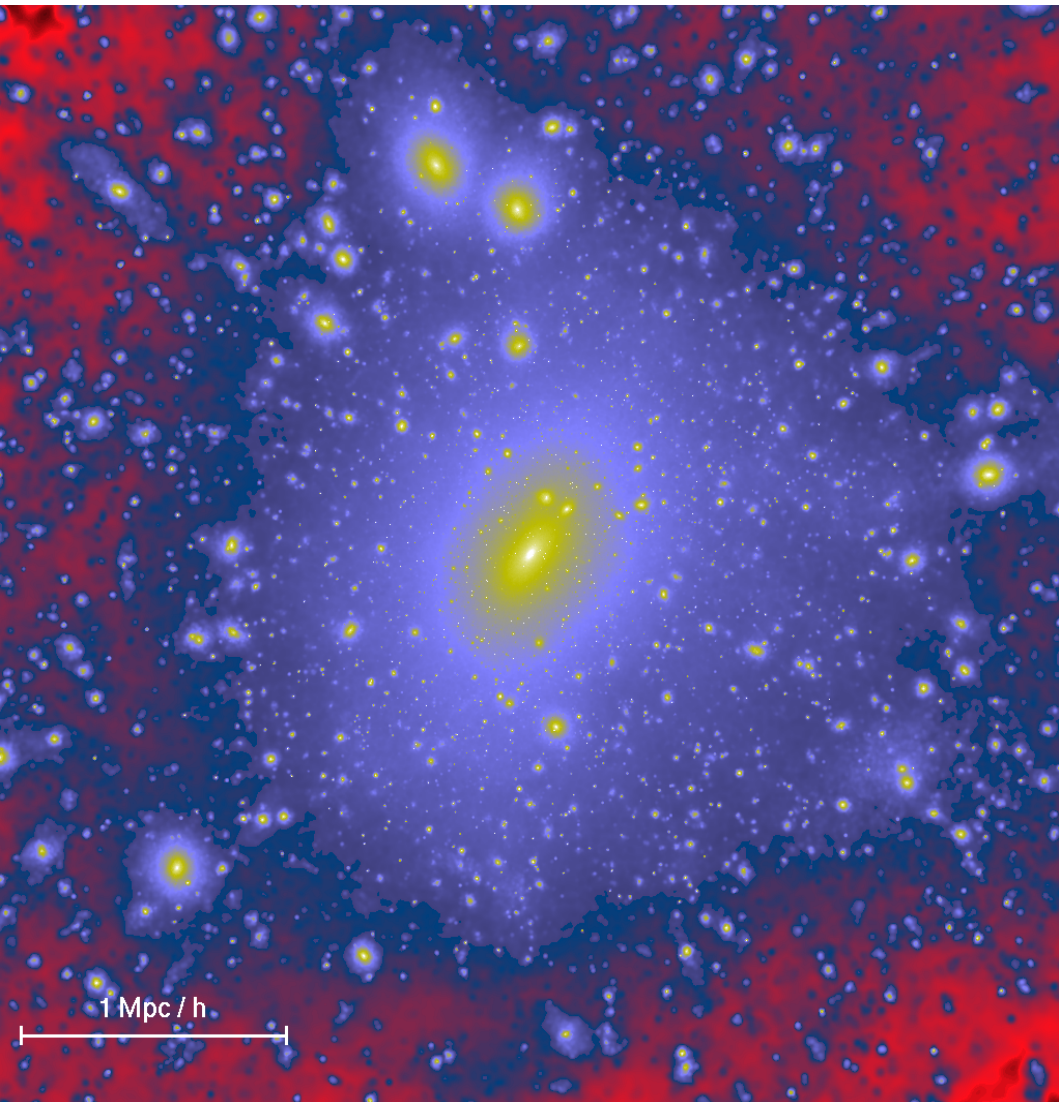
Halo growth occurs mainly by accretion of much smaller halos

There are rather few “generations” of accretion/merger events

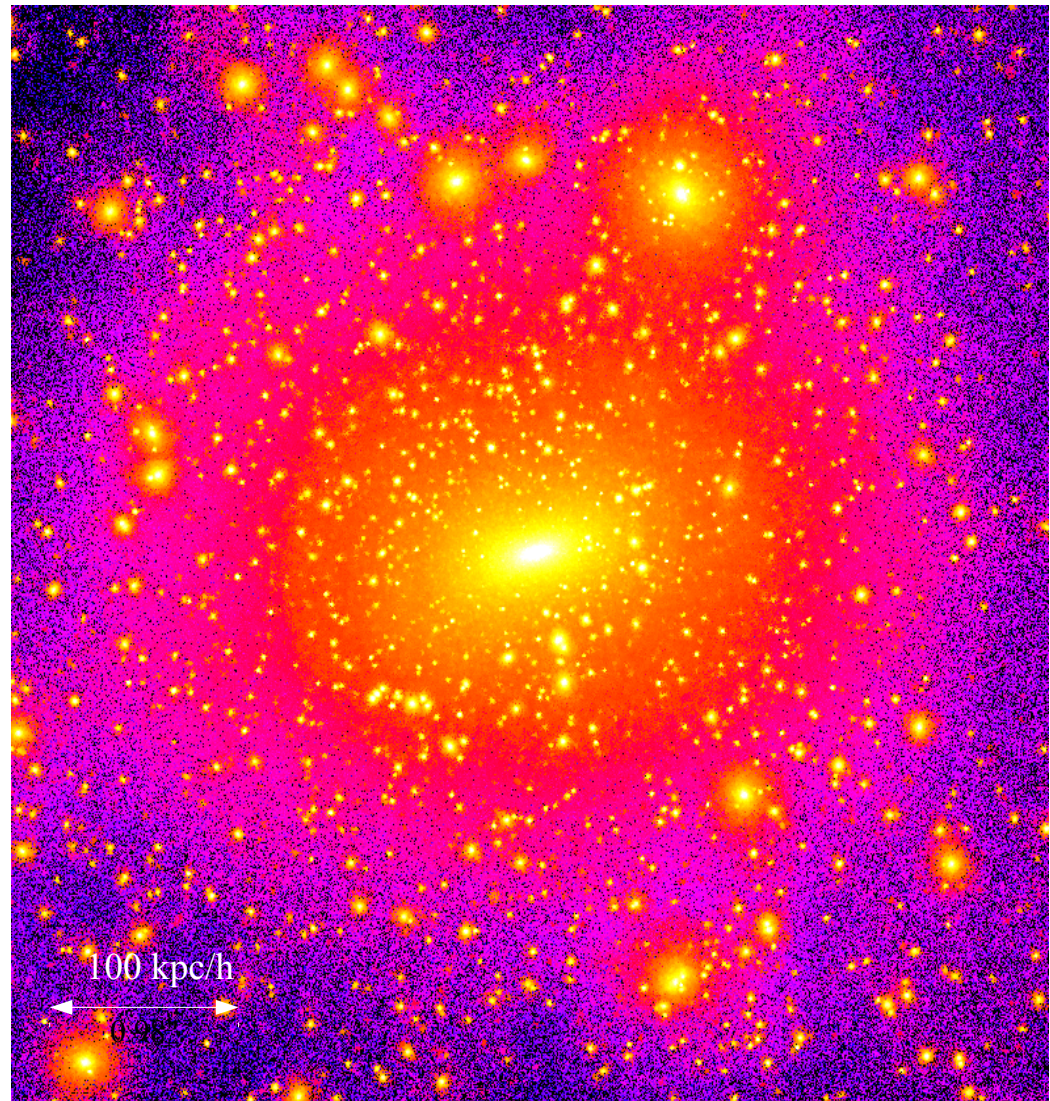
Major mergers are not a major part of the growth of most halos

The dark matter structure of Λ CDM halos

A rich galaxy cluster halo
Springel et al 2001



A 'Milky Way' halo
Power et al 2002



Λ CDM 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

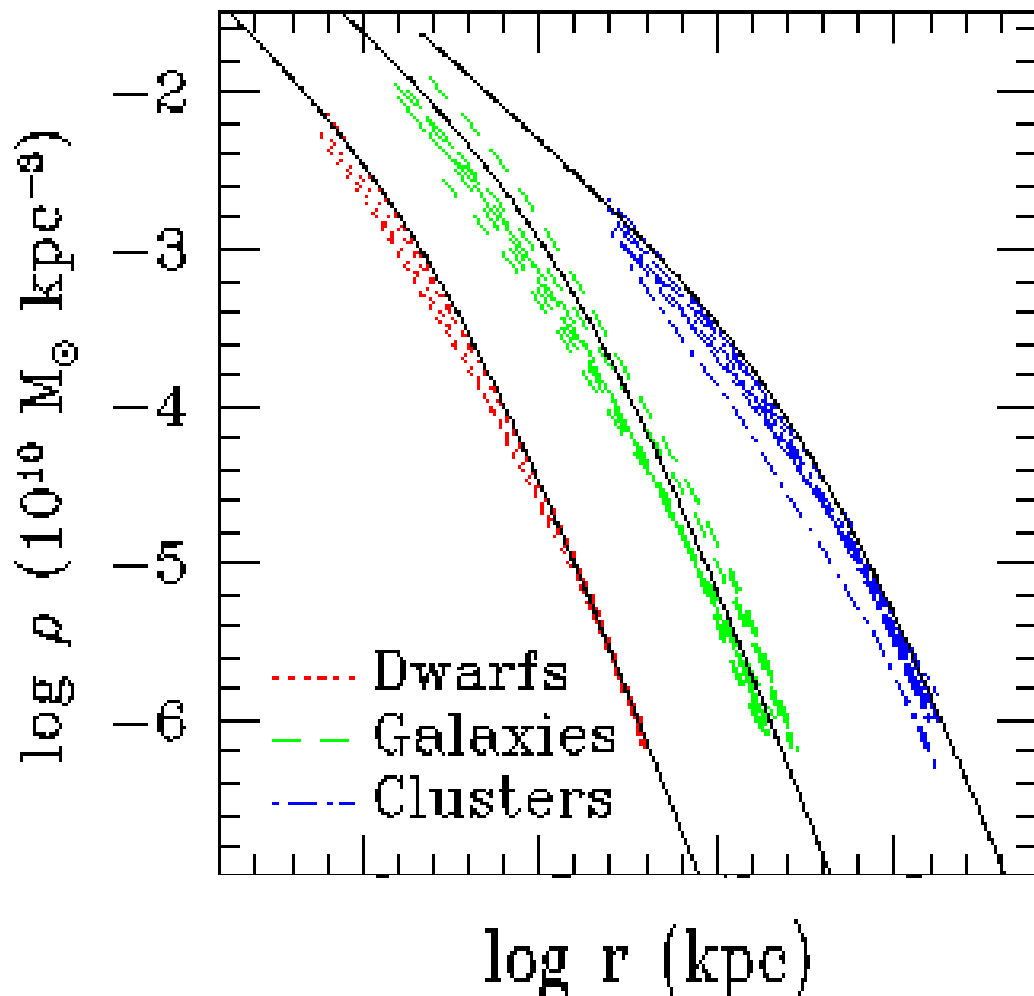
- $d \ln \rho / d \ln r = \gamma$ with $\gamma < -2.5$ at large r
 $\gamma > -1.2$ at small r

Substantial numbers of self-bound subhalos contain $\sim 10\%$ 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 --

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

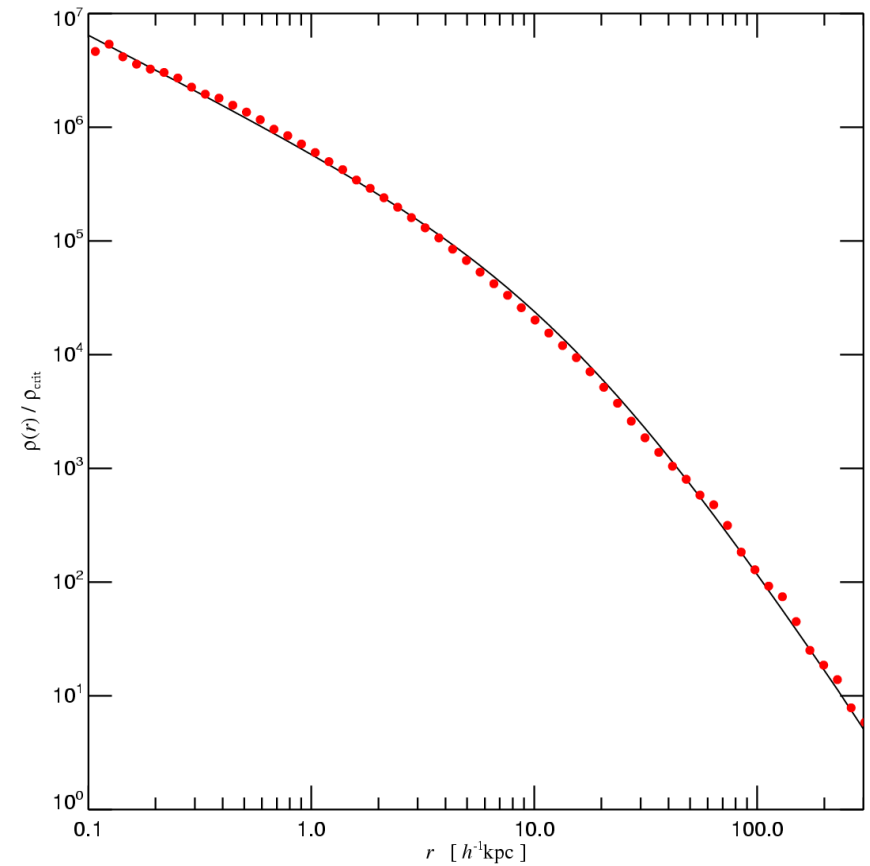
Less massive halos and halos that form earlier have higher densities (bigger δ)

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



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

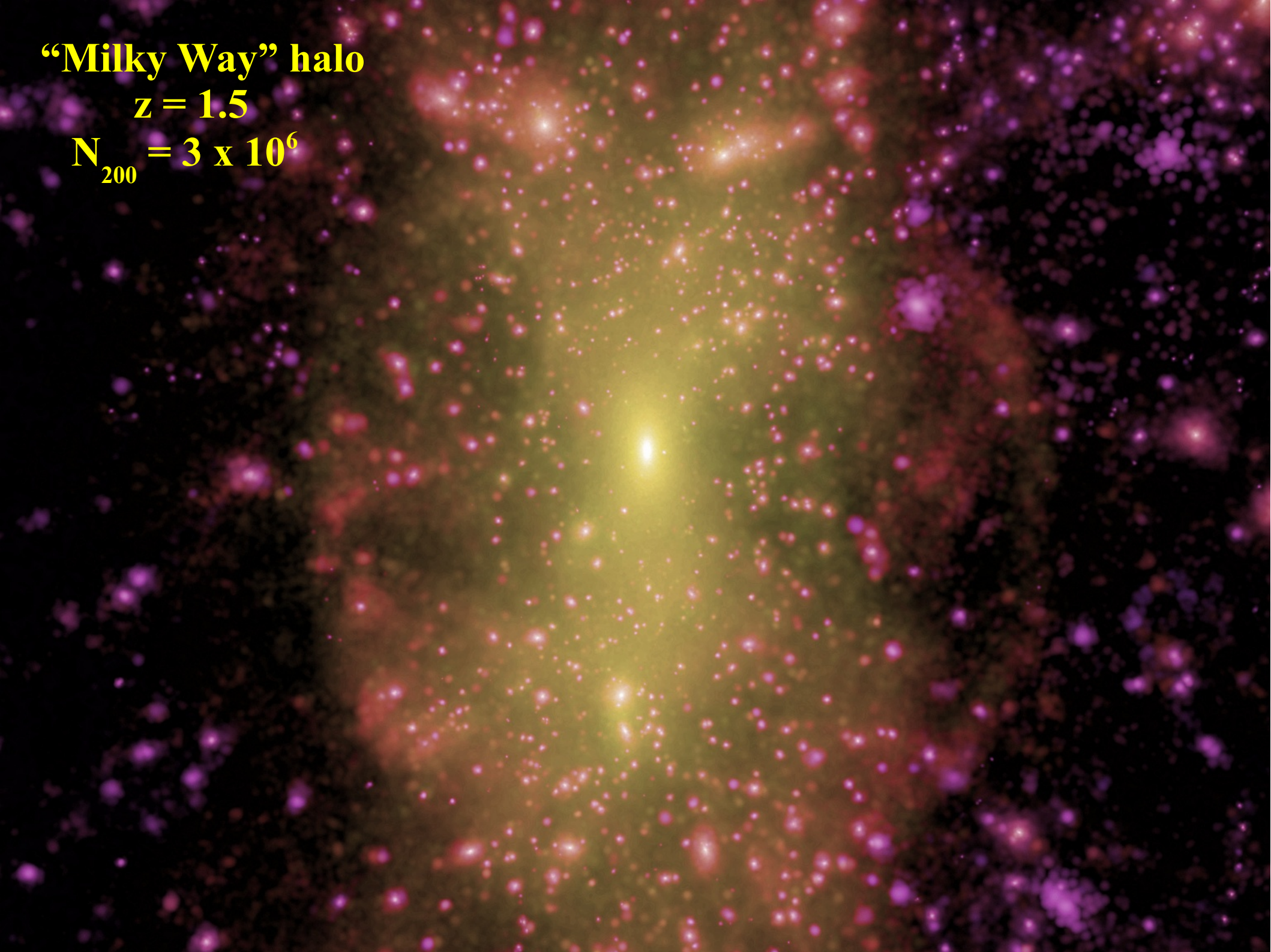
Navarro et al 2006

600 kpc

“Milky Way” halo

$z = 1.5$

$N_{200} = 3 \times 10^6$



“Milky Way” halo

$z = 1.5$

$N_{200} = 94 \times 10^6$



“Milky Way” halo

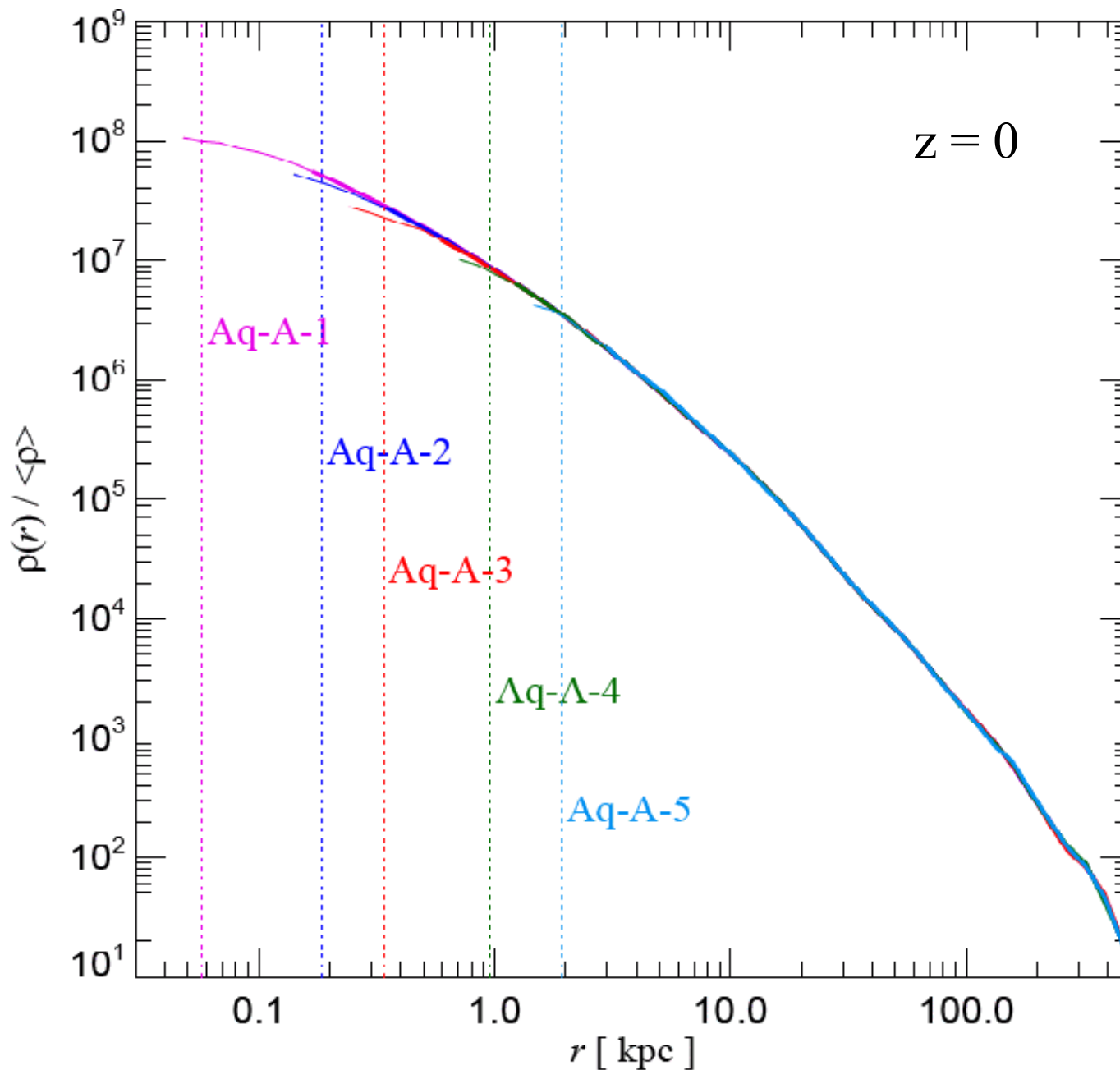
$z = 1.5$

$N_{200} = 750 \times 10^6$



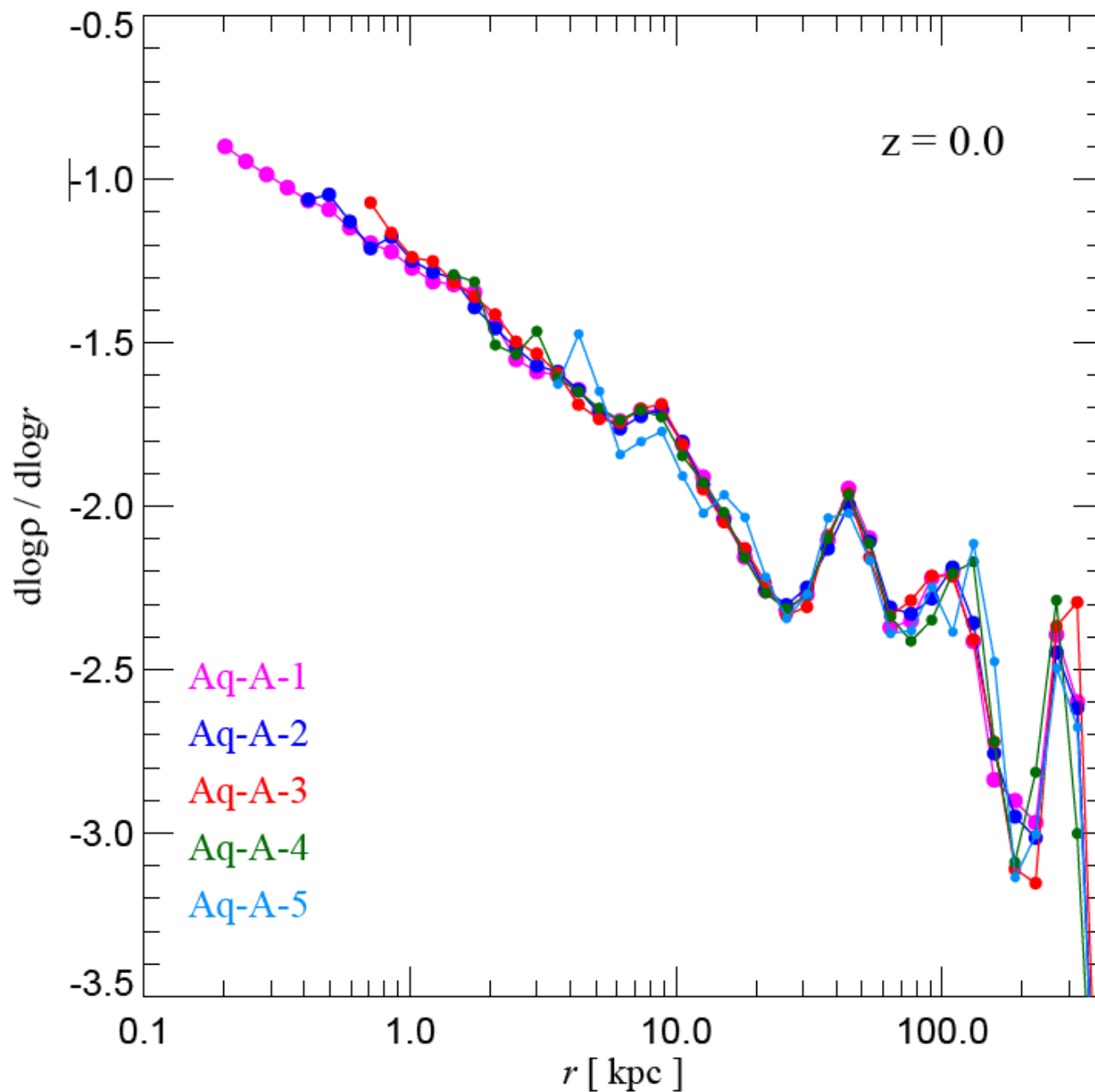
How well do density profiles converge?

Aquarius Project: Springel et al 2008



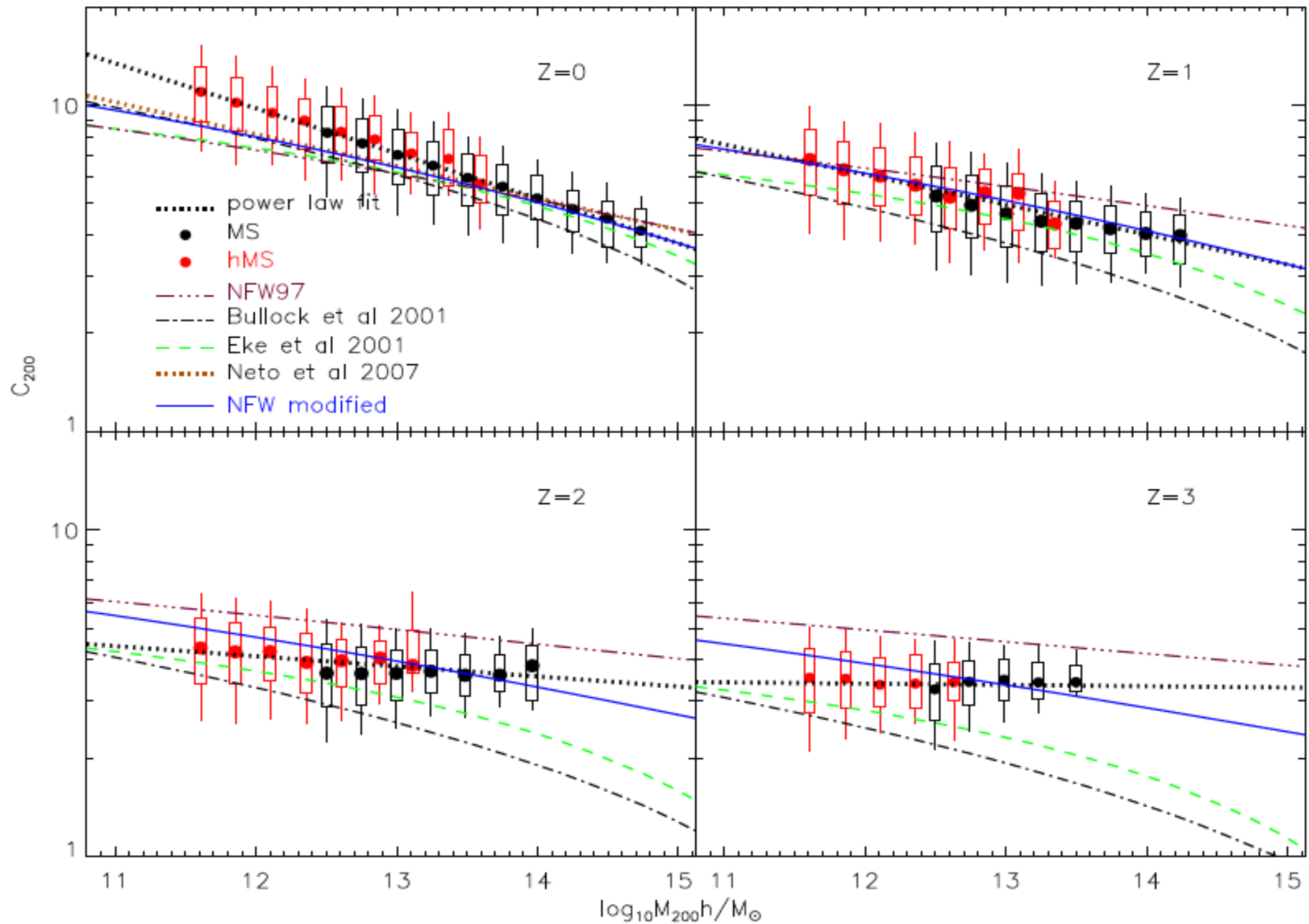
How well do density profiles converge?

Aquarius Project: Springel et al 2008



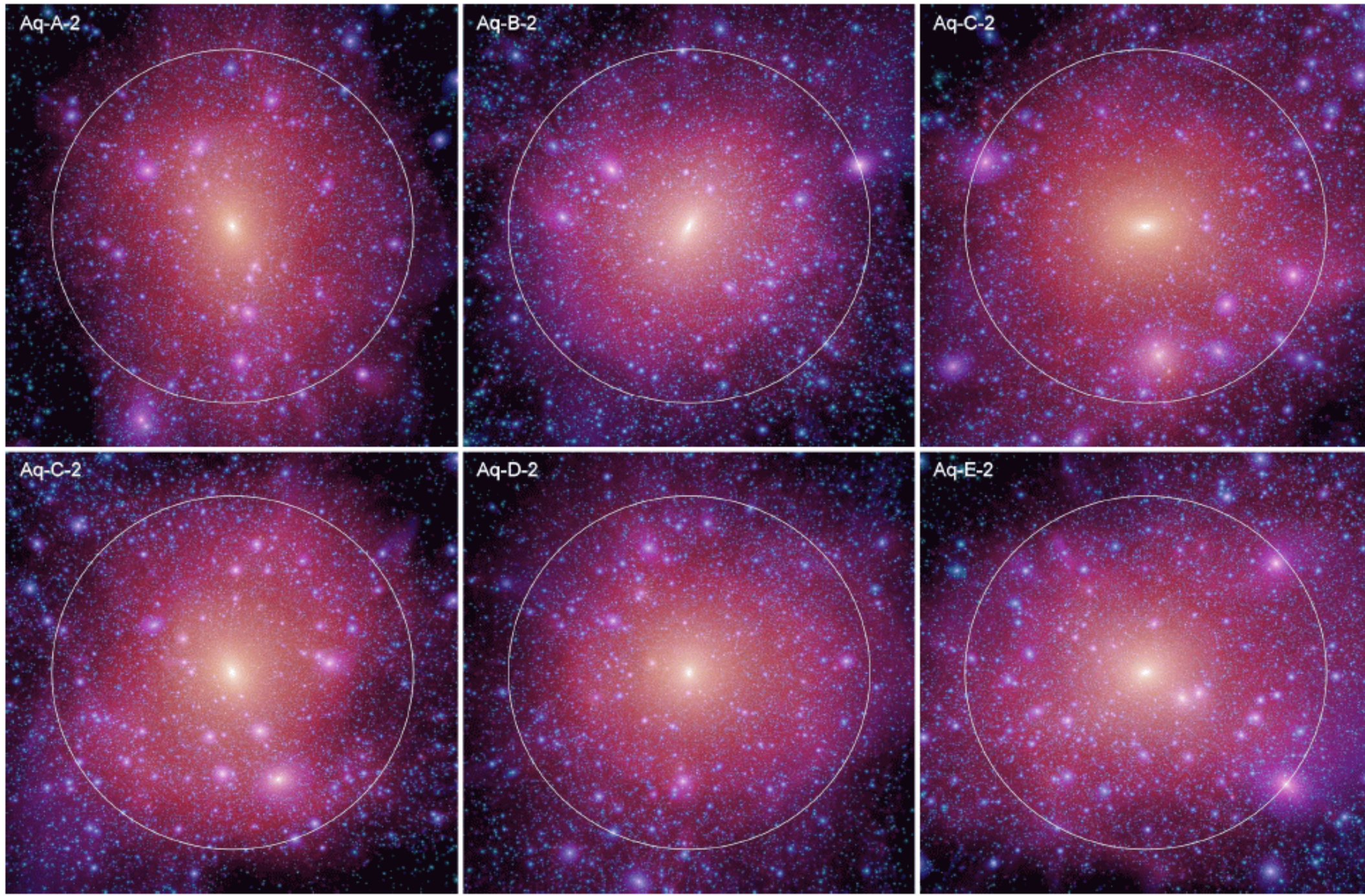
Concentration scatter and trend with M and z

Gao et al 2008



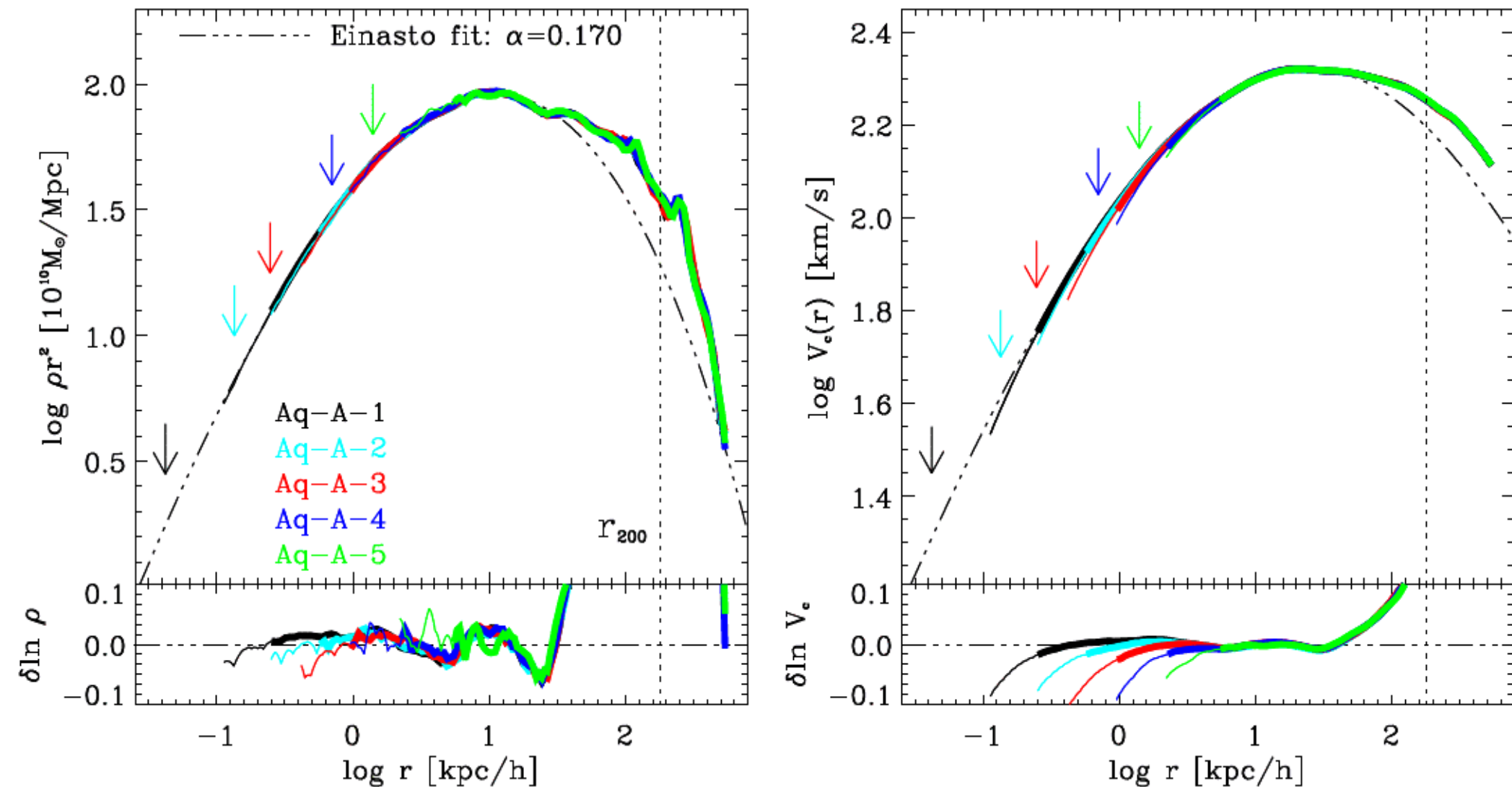
The Aquarius halos

Springel et al 2008



The Einasto profile fits the inner cusps

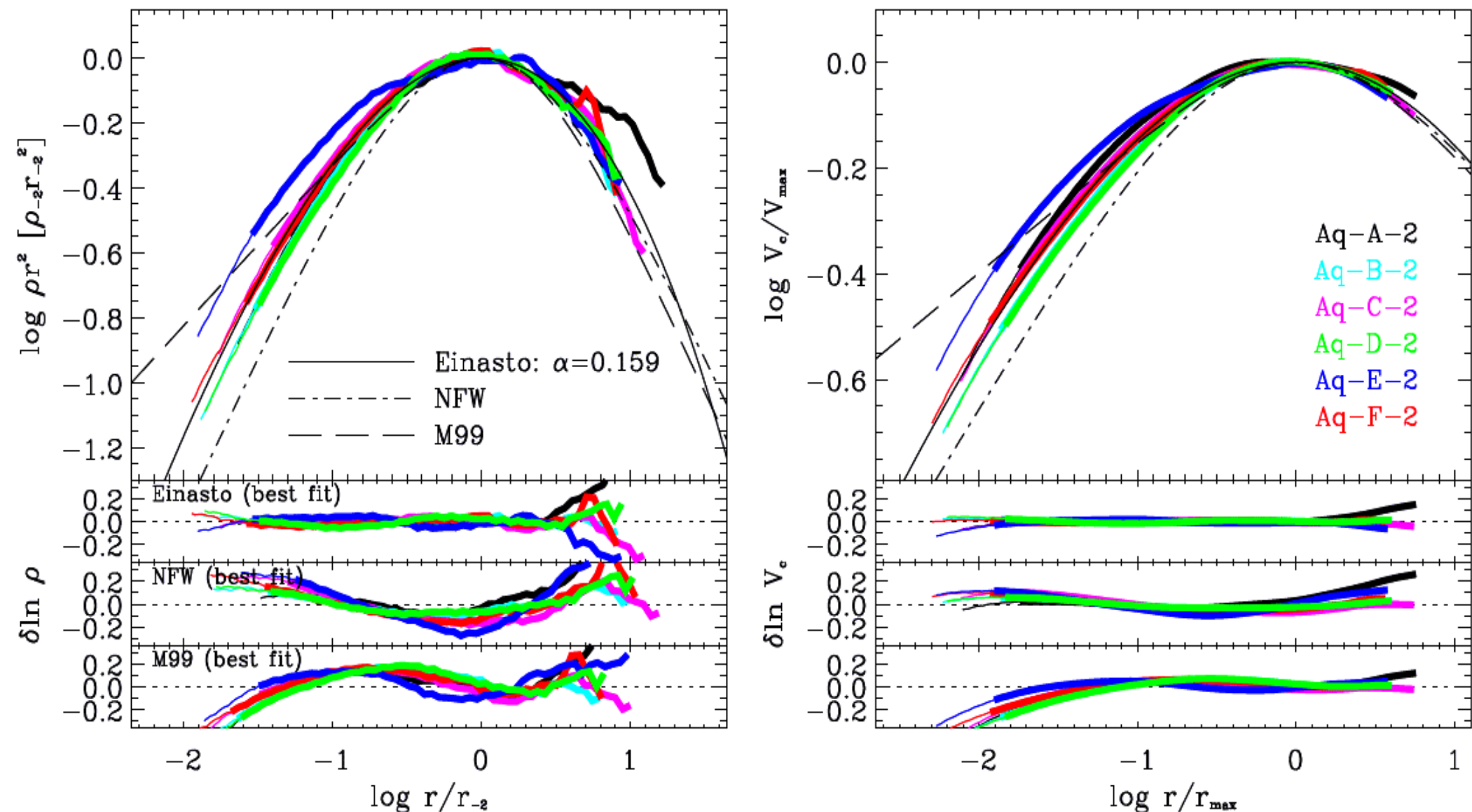
Navarro et al 2009



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

The Einasto profile fits the inner cusps

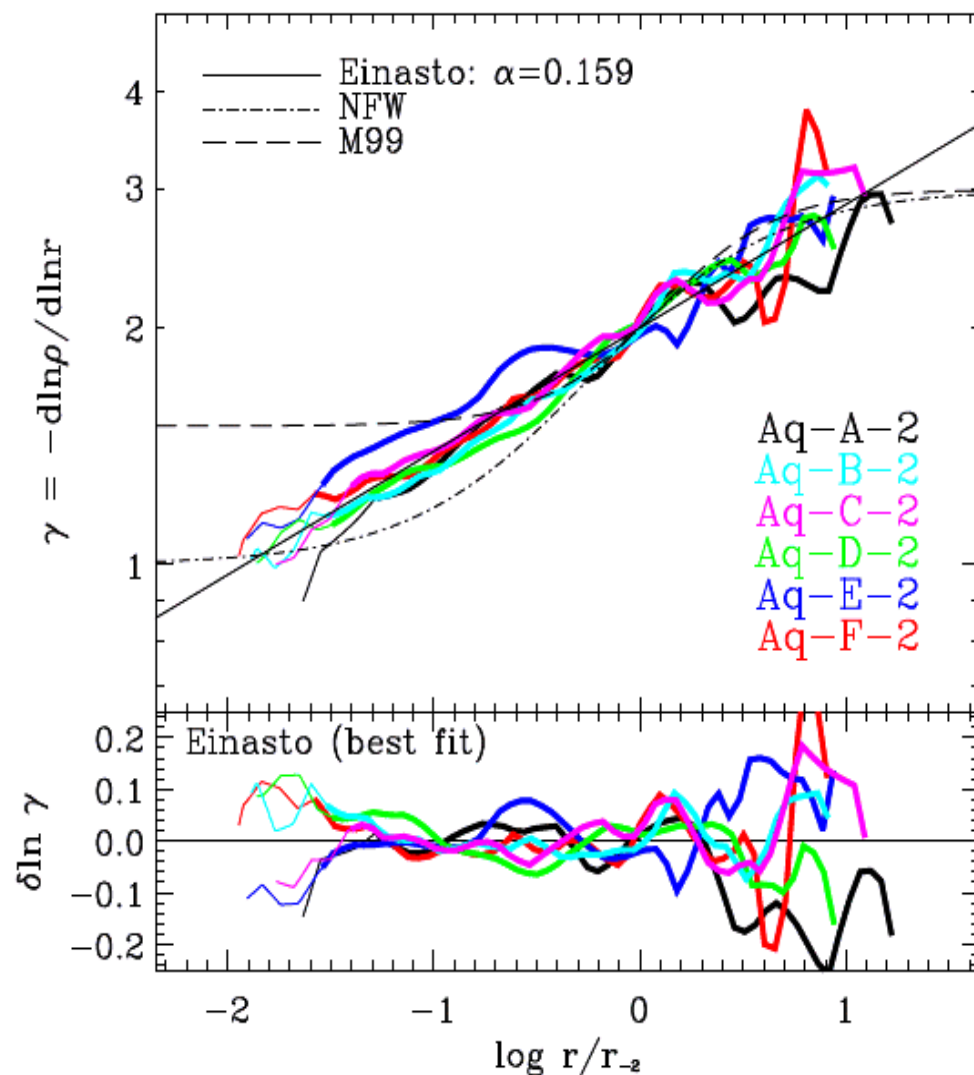
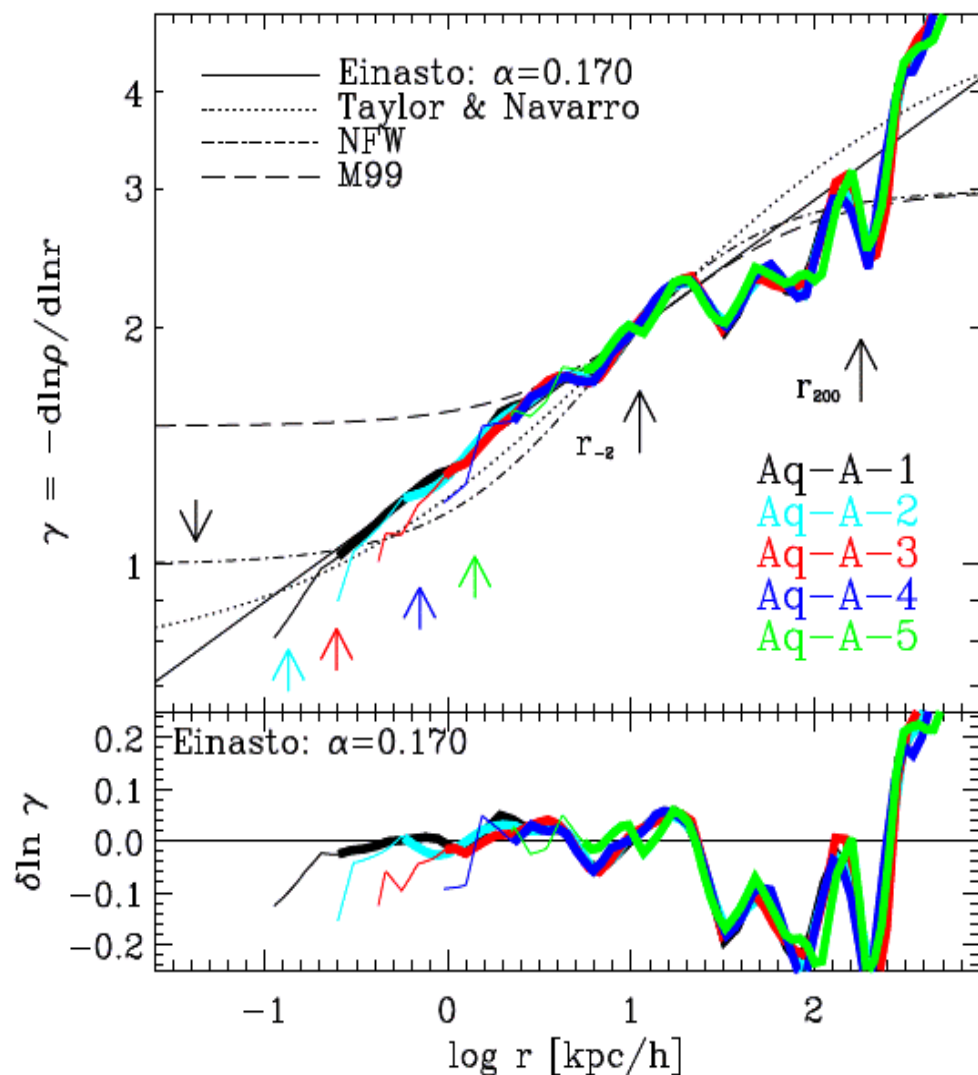
Navarro et al 2009



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The Einasto profile fits the inner cusps

Navarro et al 2009

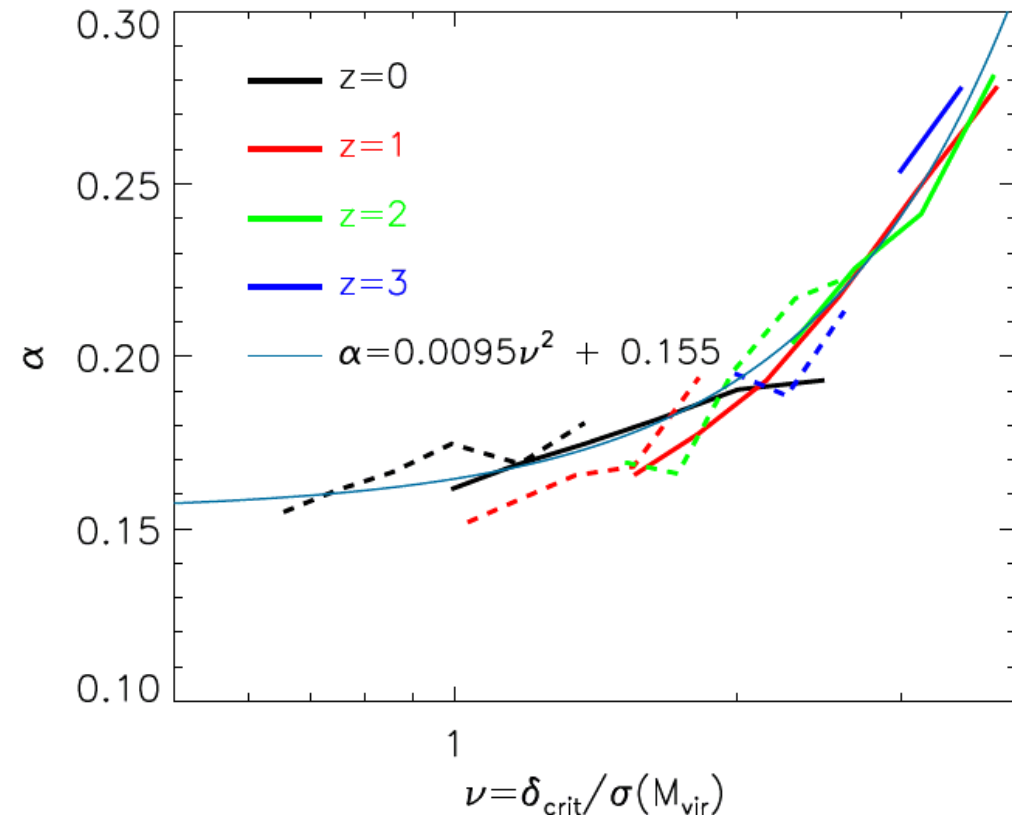
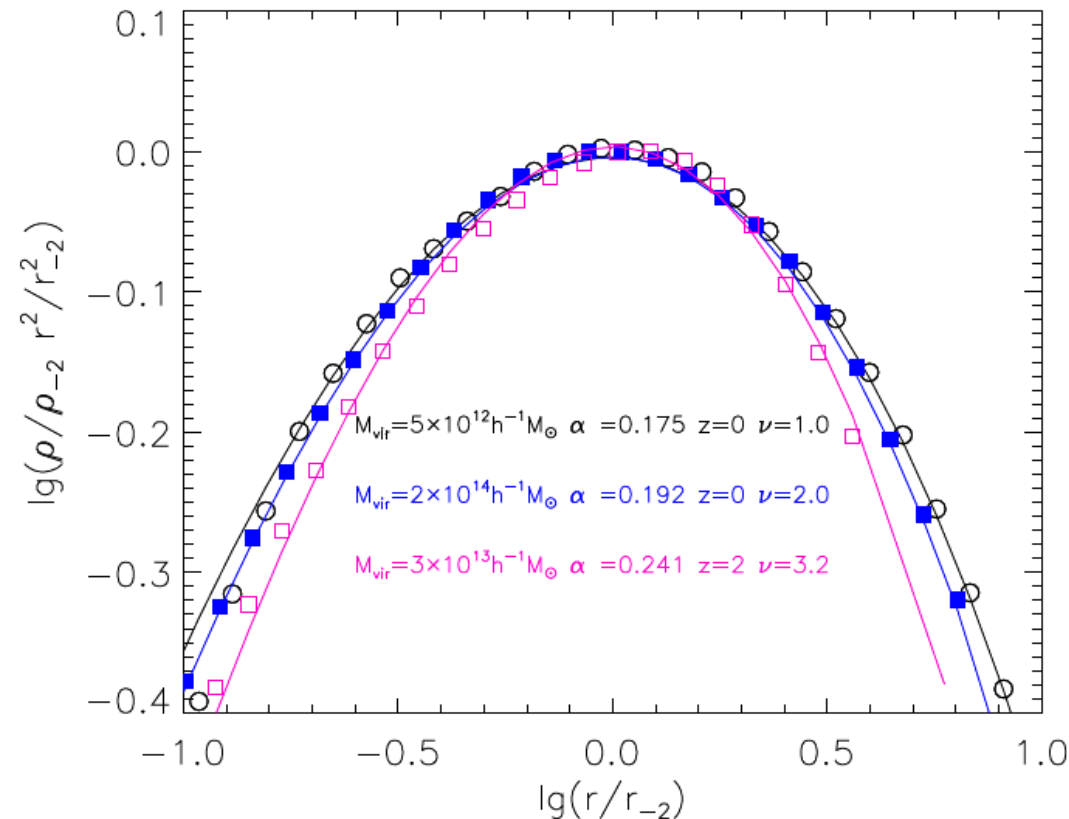


Einasto's (1965) profile: $\ln \rho(r) / \rho_{-2} = -2 / \alpha [(r / r_{-2})^\alpha - 1]$

The Einasto α varies with mass

Gao et al 2008

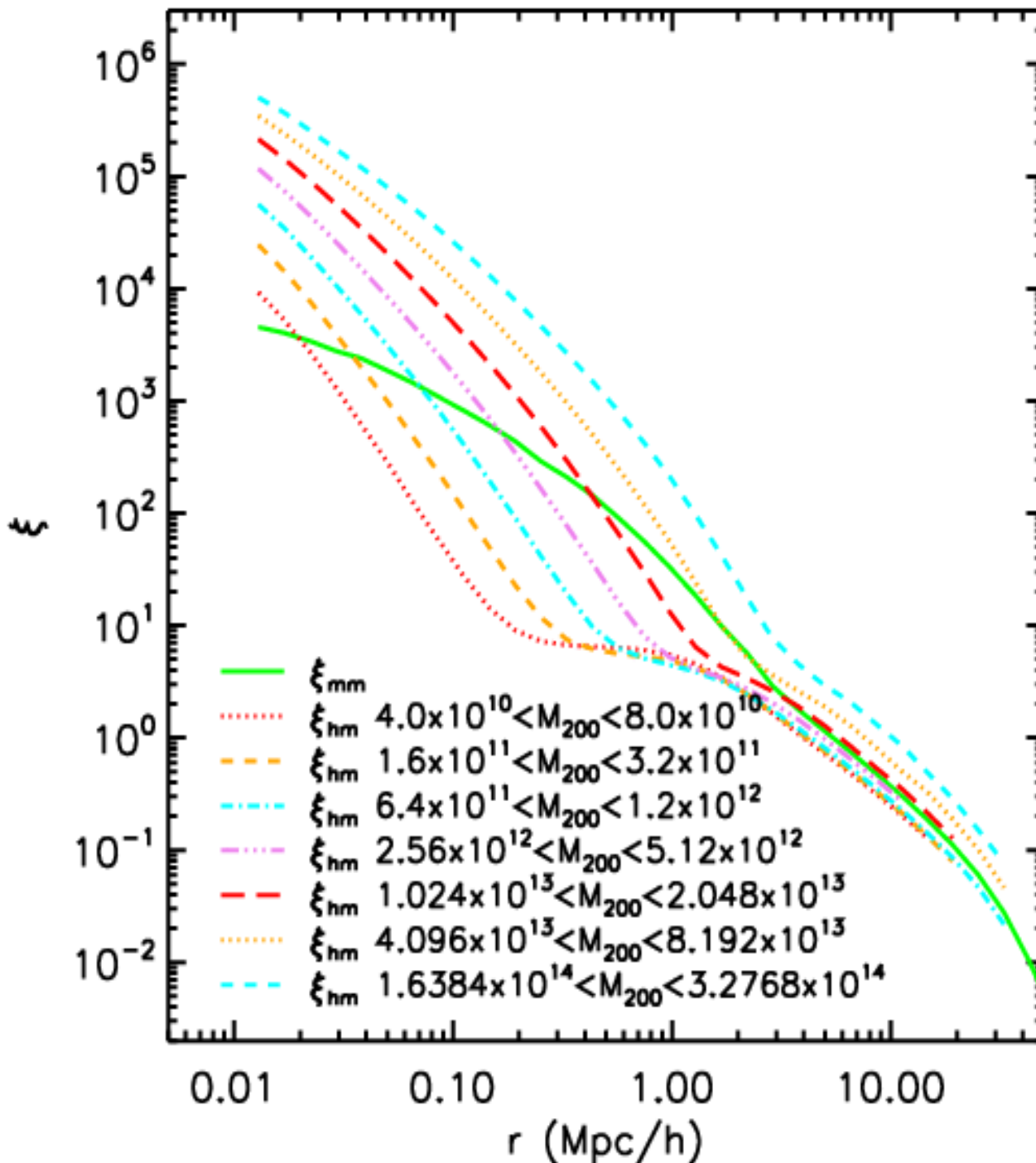
Results for stacked halos in the Millennium run



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

Mean profiles to much larger radii

Hayashi & White 2008



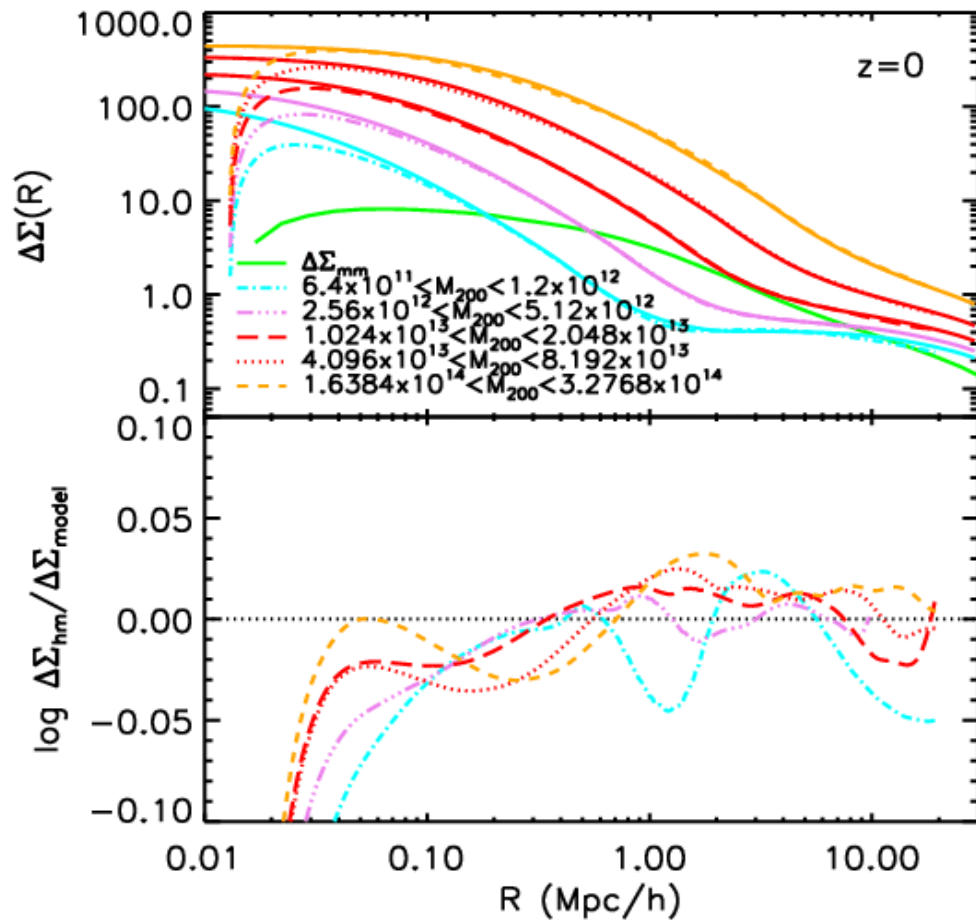
At large radii, the mean density profile $\bar{\rho}(r) \propto \xi_{lin}(r)$, the *linear* mass correlation function

To a good approximation

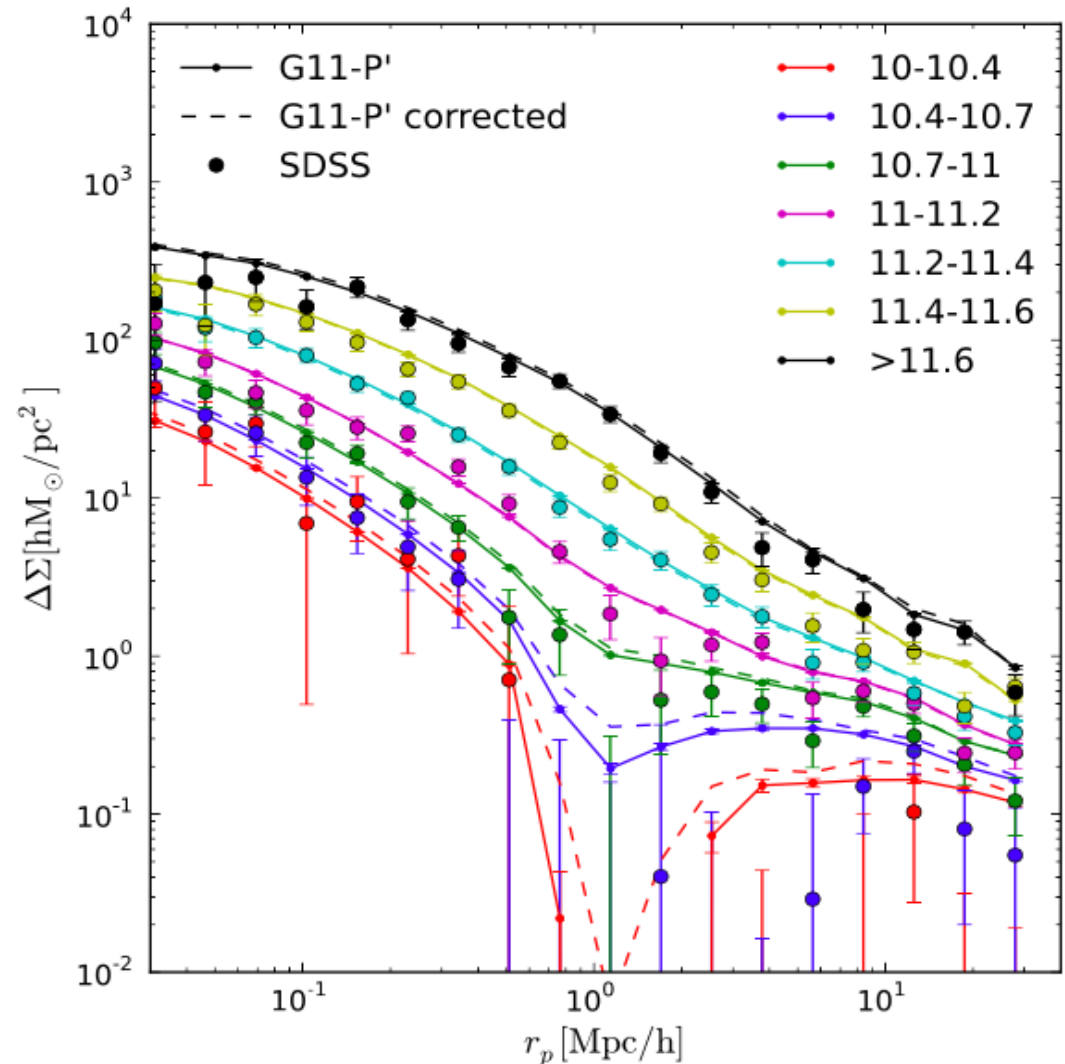
$$\bar{\rho}(r) = \max[\rho_{Ein}(r), b \xi_{lin}(r)]$$

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”

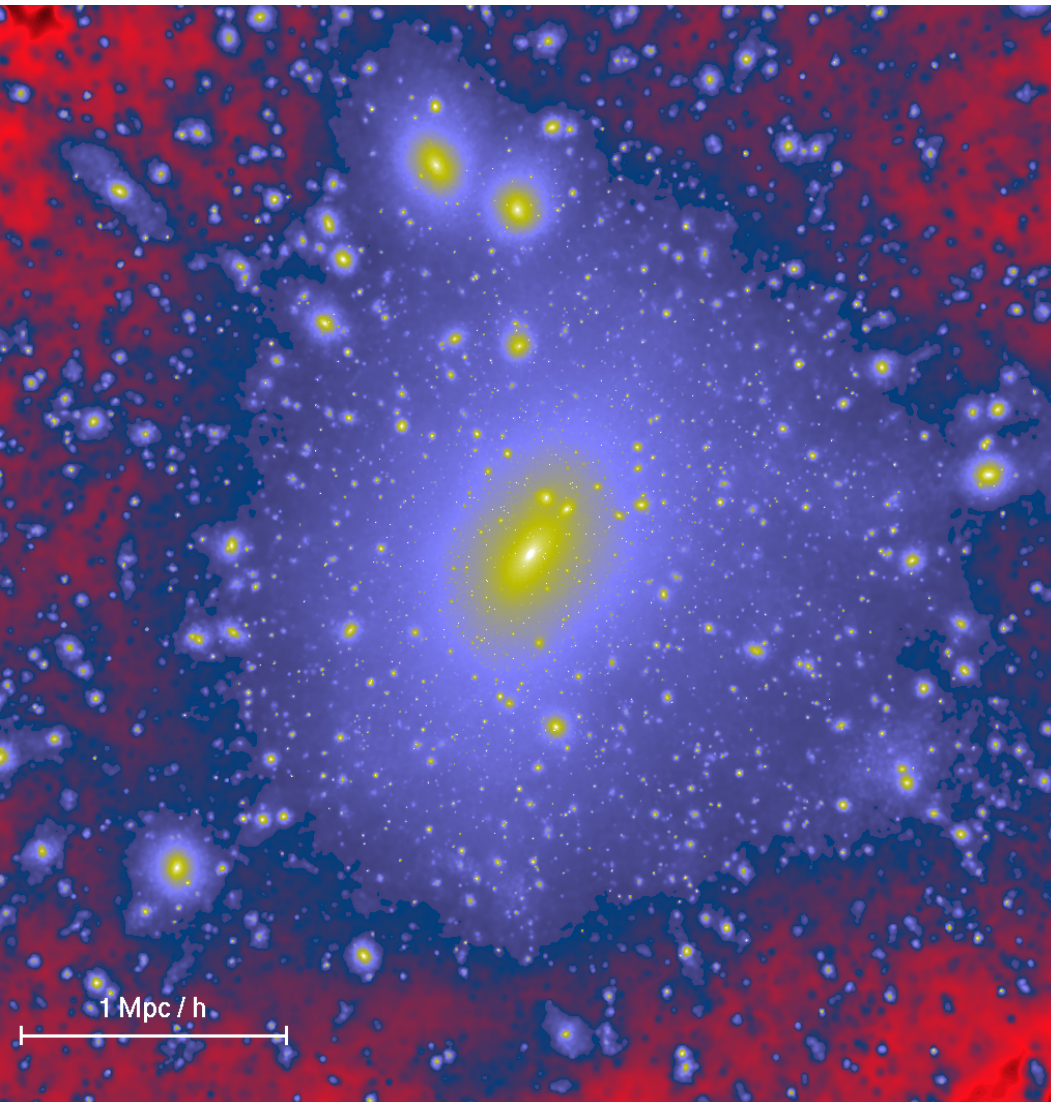
The scatter among halos is larger than the Einasto-NFW difference

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

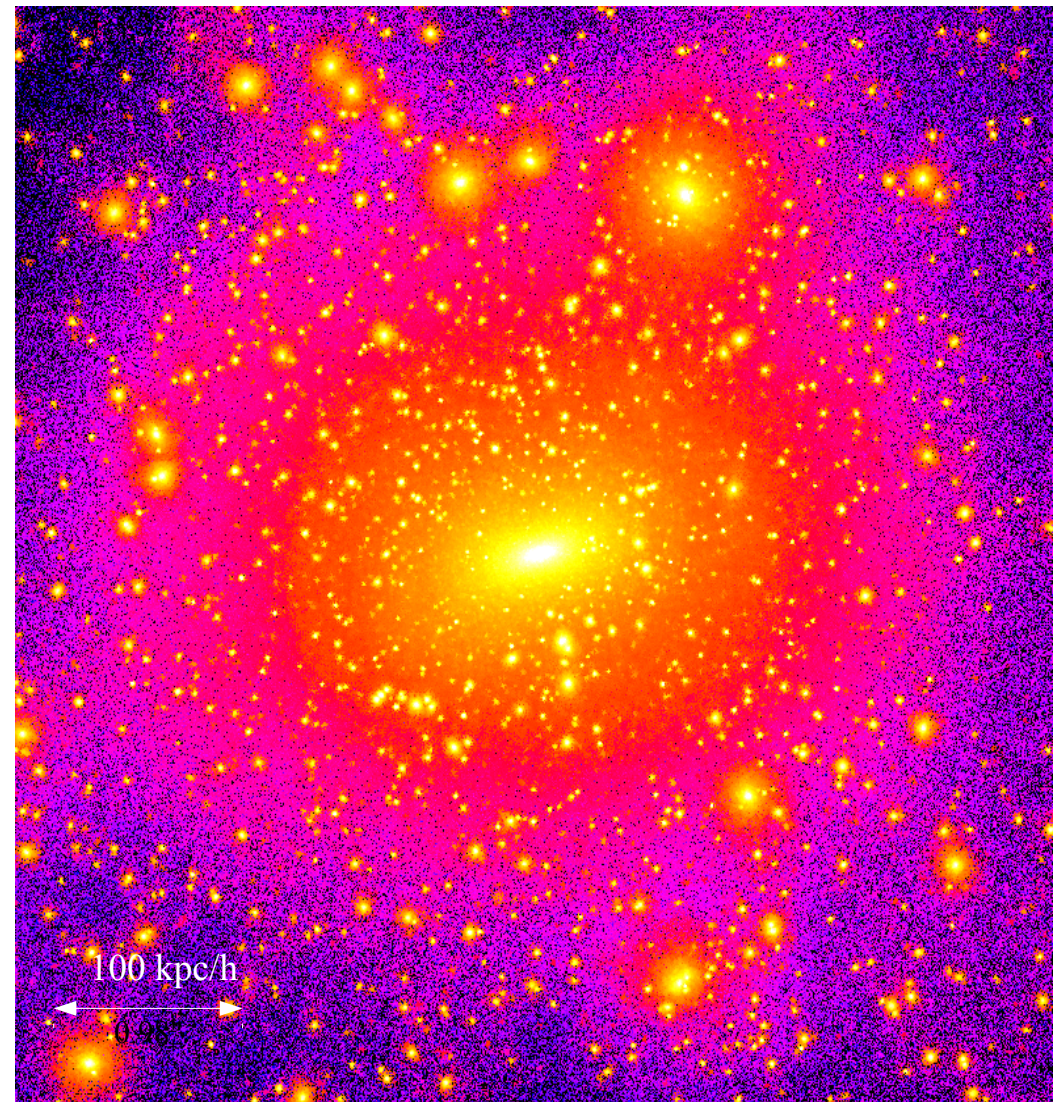
This shape change is observed directly through weak gravitational lensing, confirming Λ CDM predictions at large halo radius

The dark matter structure of Λ CDM halos

A rich galaxy cluster halo
Springel et al 2001

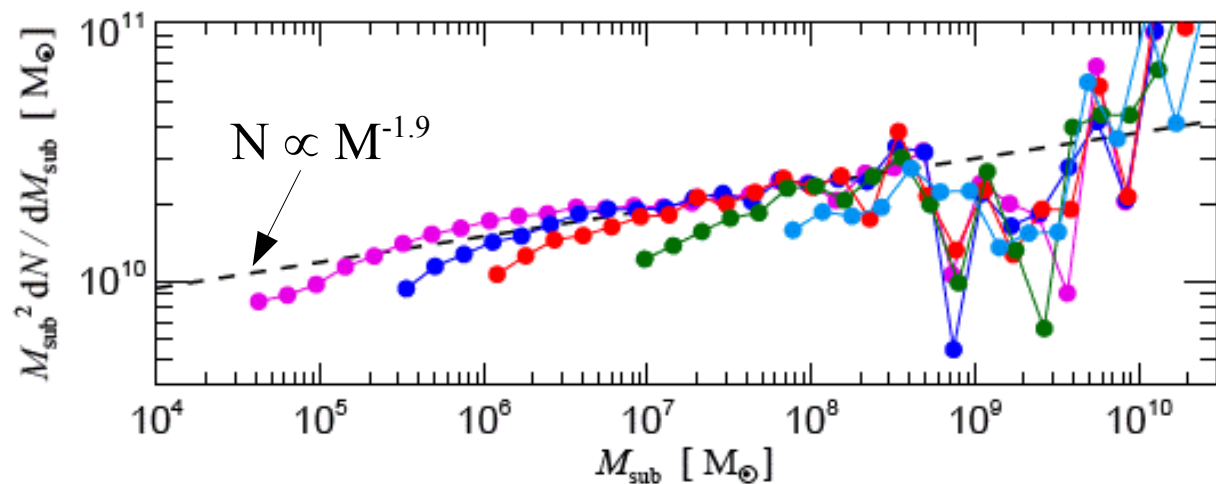
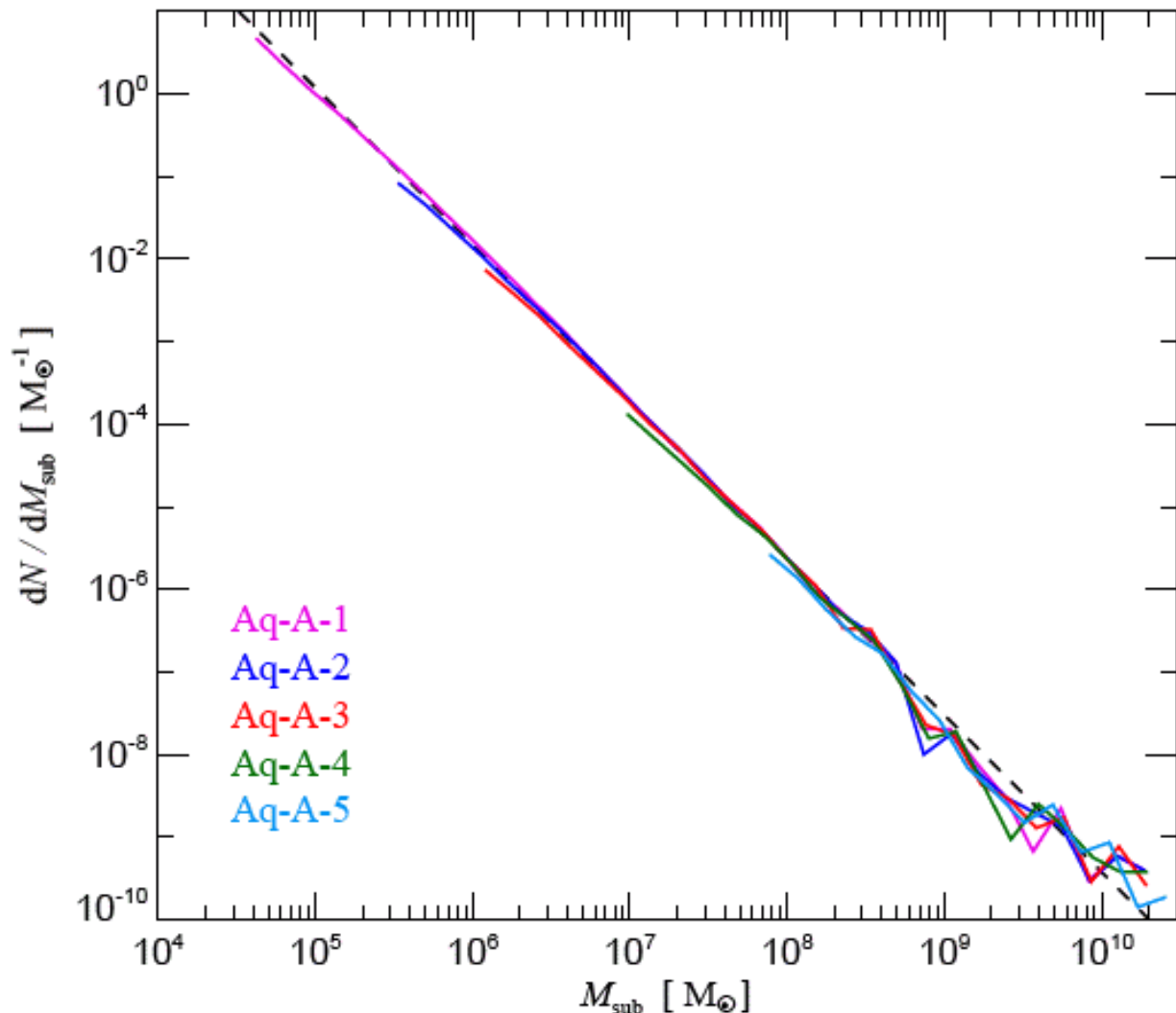


A 'Milky Way' halo
Power et al 2002



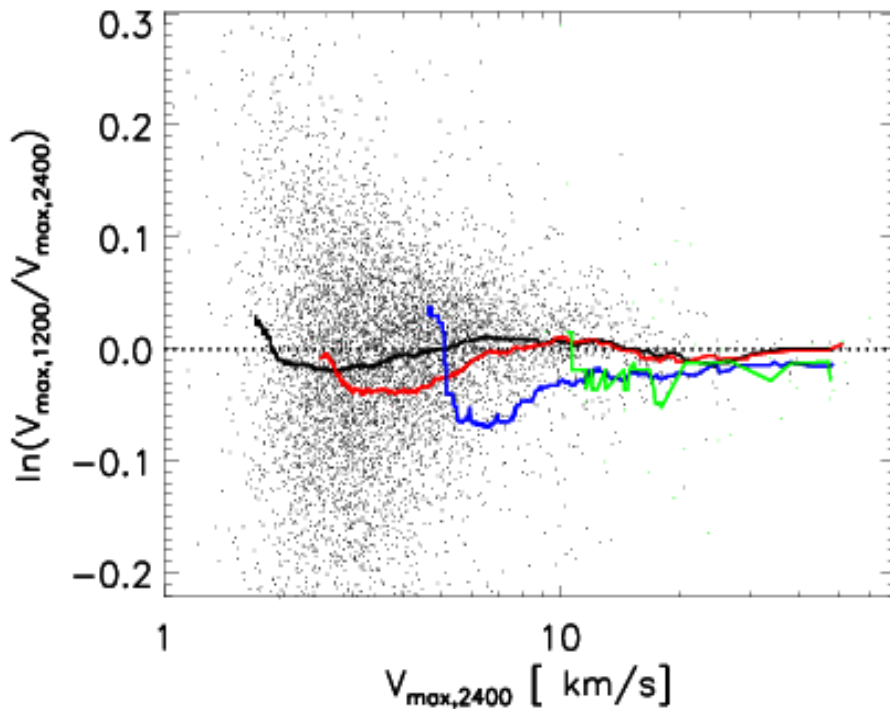
How well does substructure converge?

Springel et al 2008

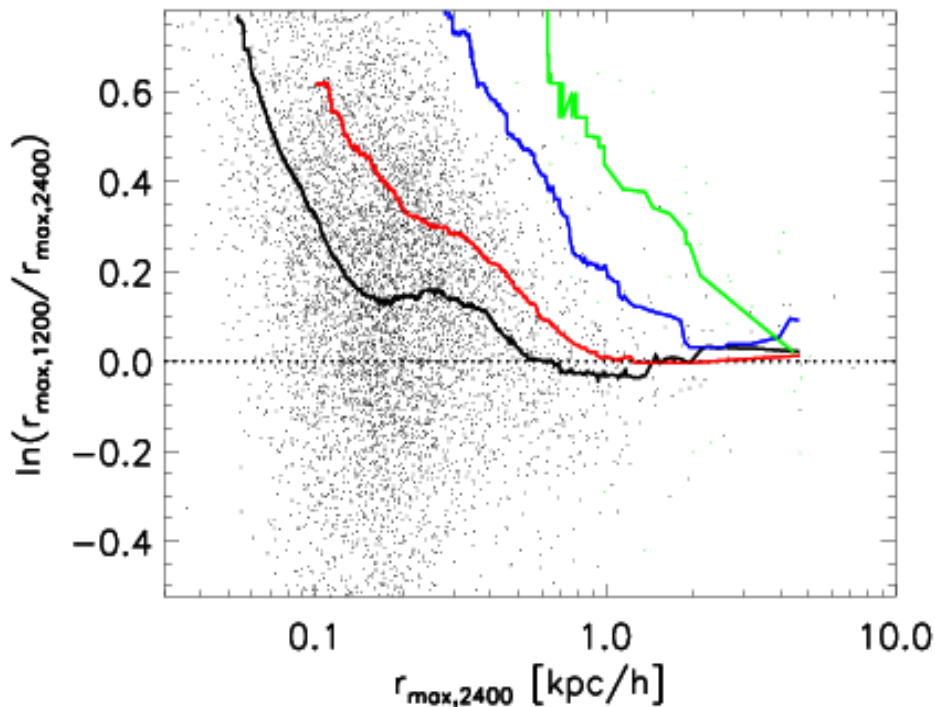


How well does substructure converge?

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

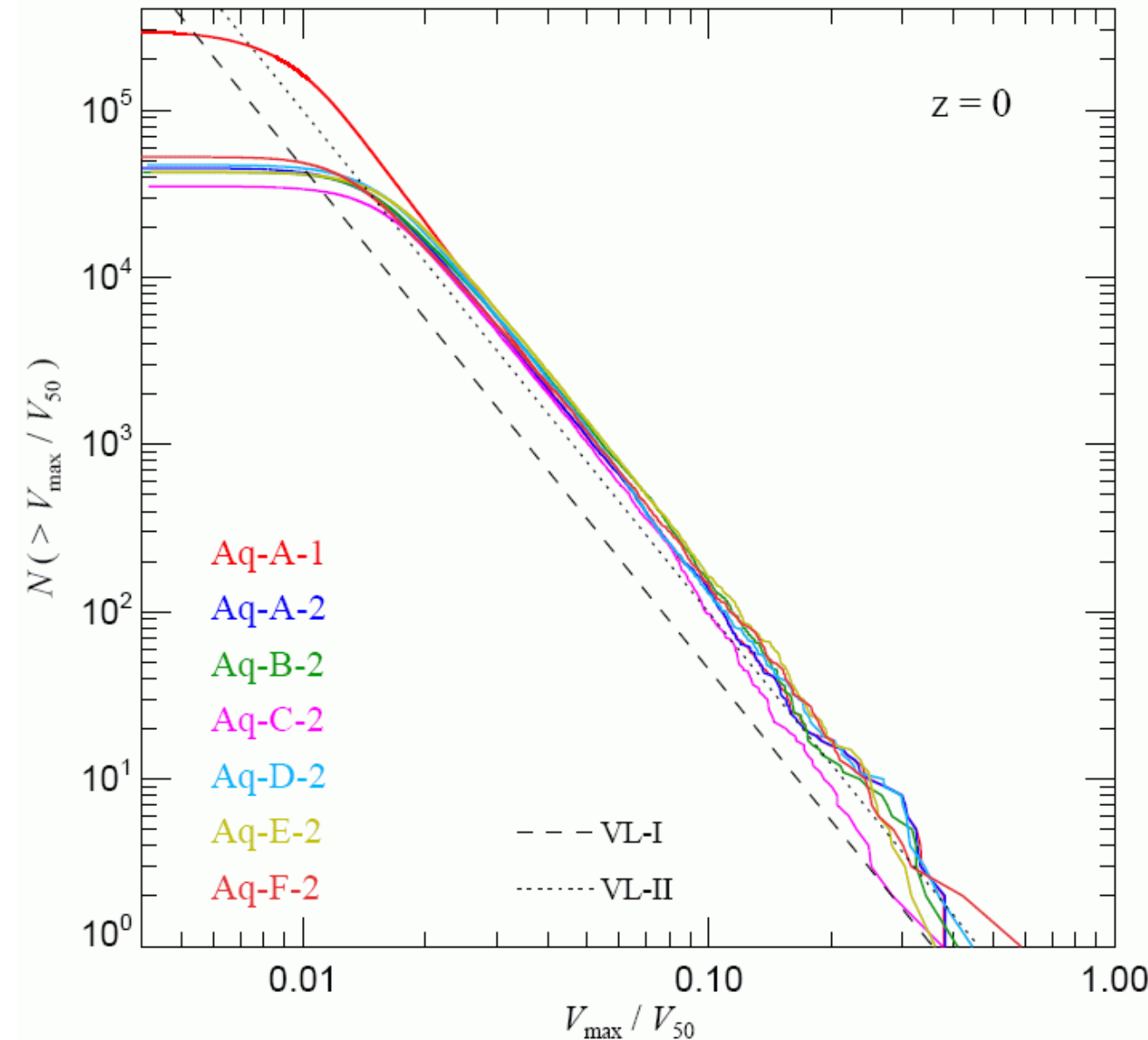
$$V_{\max} > 1.5 \text{ km/s}$$

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

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

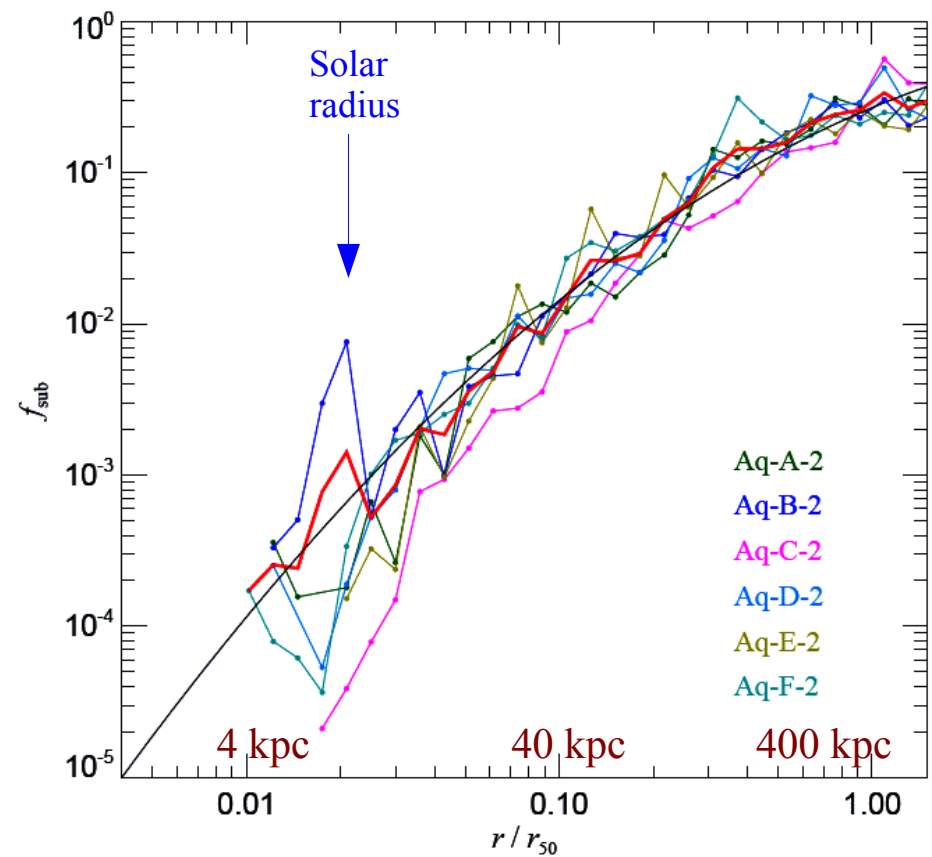
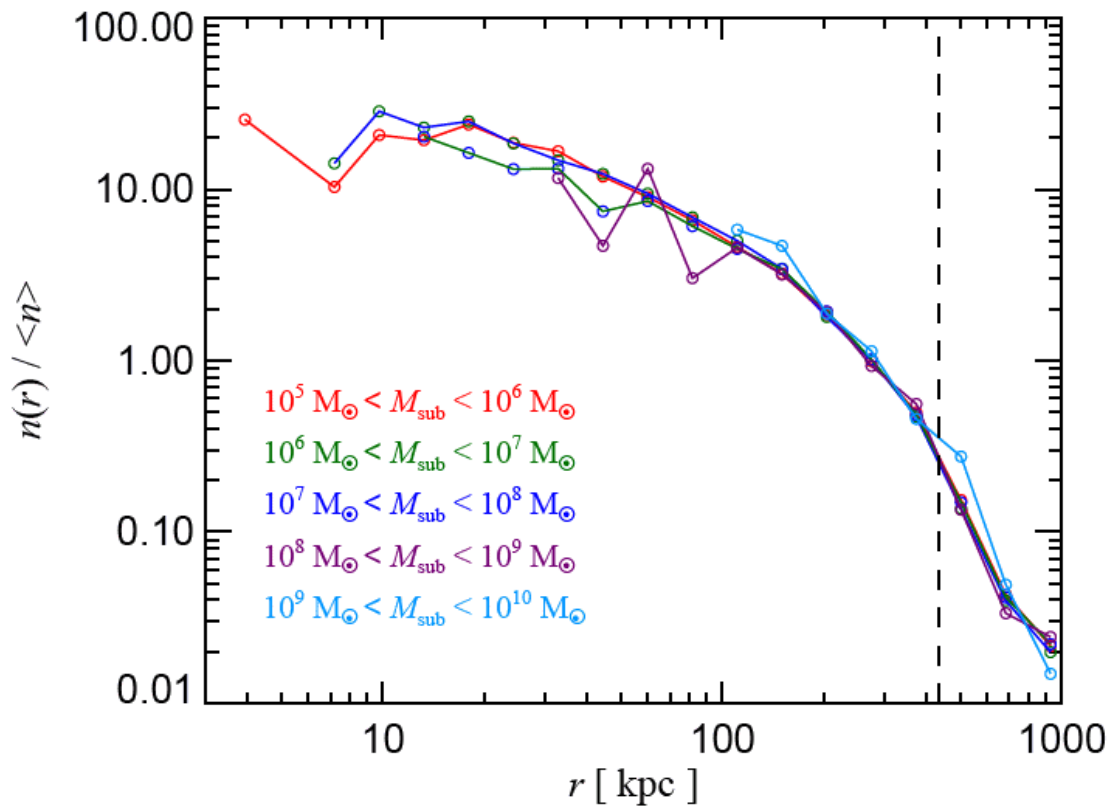
How uniform are subhalo populations?

Springel et al 2008

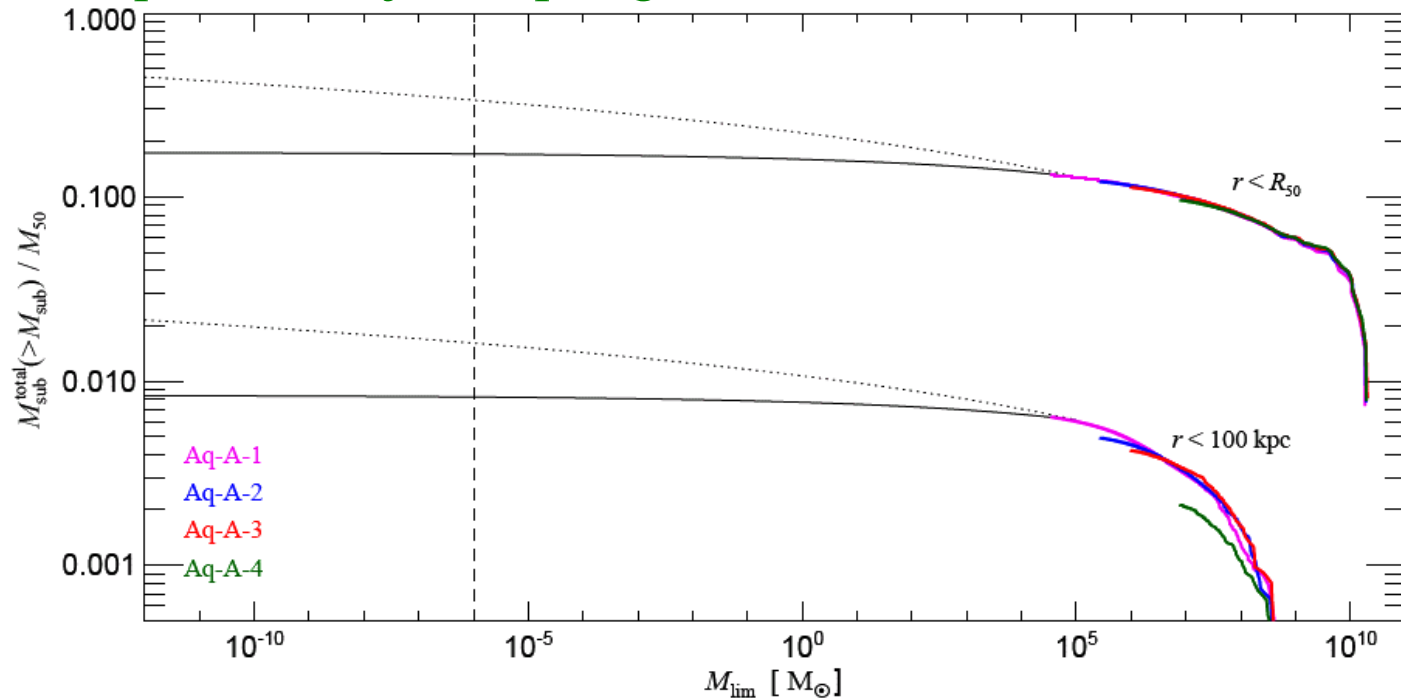


For the six Aquarius halos, the scatter in subhalo abundance is Poisson at high mass and $\sim 20\%$ at low mass

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

$\ll 1\%$ 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

Small-scale structure of the CDM distribution

Direct detection involves bolometers/cavities of meter scale which are sensitive to particle momentum

- what is the density structure between m and kpc scales?
- how many streams intersect the detector at any time?

Intensity of annihilation radiation depends on

$$\int \rho^2(\mathbf{x}) \langle \sigma v \rangle dV$$

- what is the density distribution around individual CDM particles on the annihilation interaction scale?

Predictions for detection experiments depend on the CDM distribution on scales far below those accessible to simulation

→ We require a good theoretical understanding of mixing and small-scale structure

Detectability issues for the CDM distribution

Laboratory experiments

What is the expected CDM distribution in space and in velocity on the scale of the apparatus?

Small-scale clumping

How much γ -emission comes from small clumps?

Which structures should be most easily detected?

Unbound phase-space structure

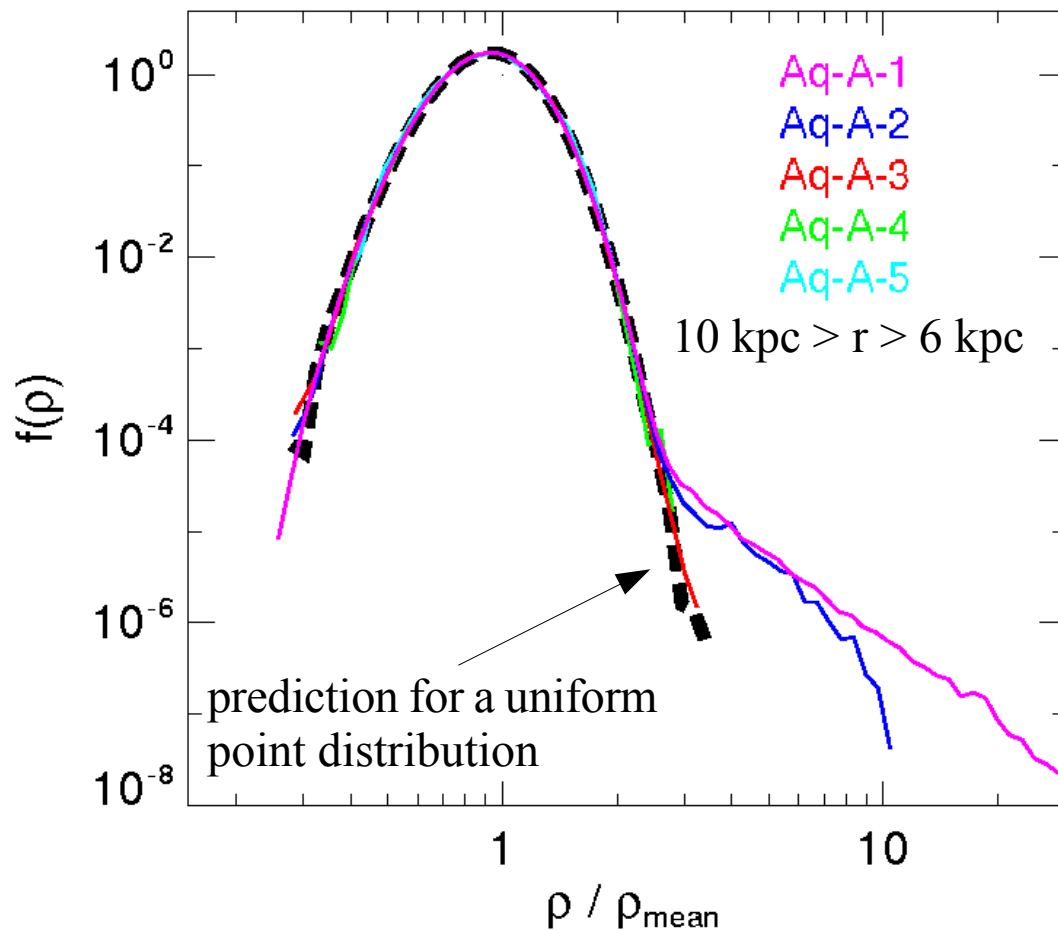
How much γ -emission comes from caustics?

Galactic Centre

How much γ -emission comes from the black hole's cusp?

Density relative to a smooth ellipsoidal model

Vogelsberger et al 2008



Estimate a density ρ at each point by adaptively smoothing using the 64 nearest particles

Fit to a smooth density profile stratified on similar ellipsoids

The chance of a random point lying in a substructure is $< 10^{-4}$

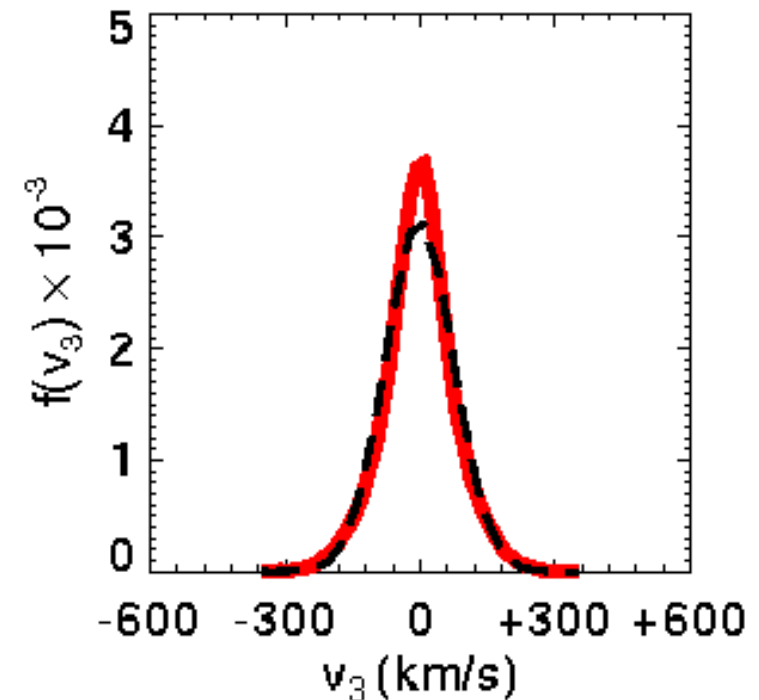
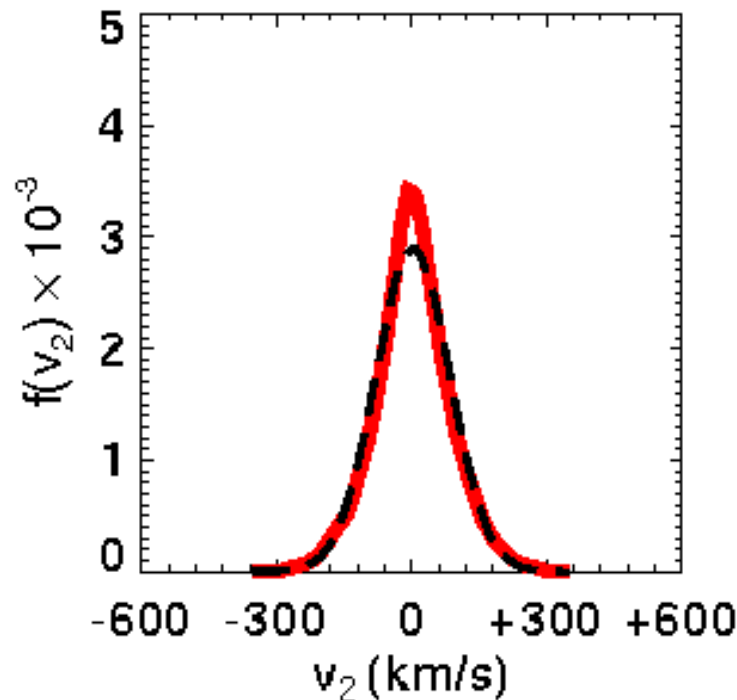
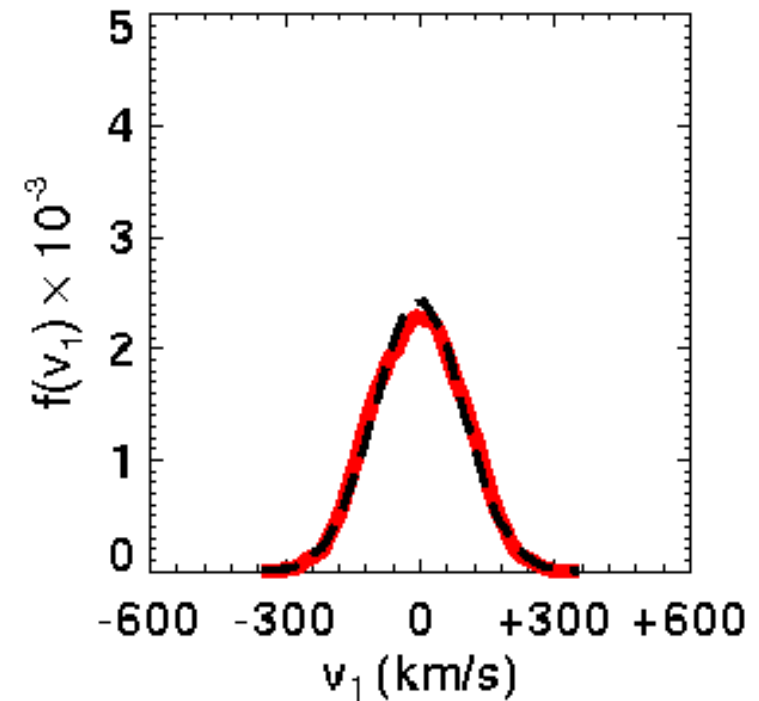
The *rms* scatter about the smooth model for the remaining points is only about 4%

Local velocity distribution

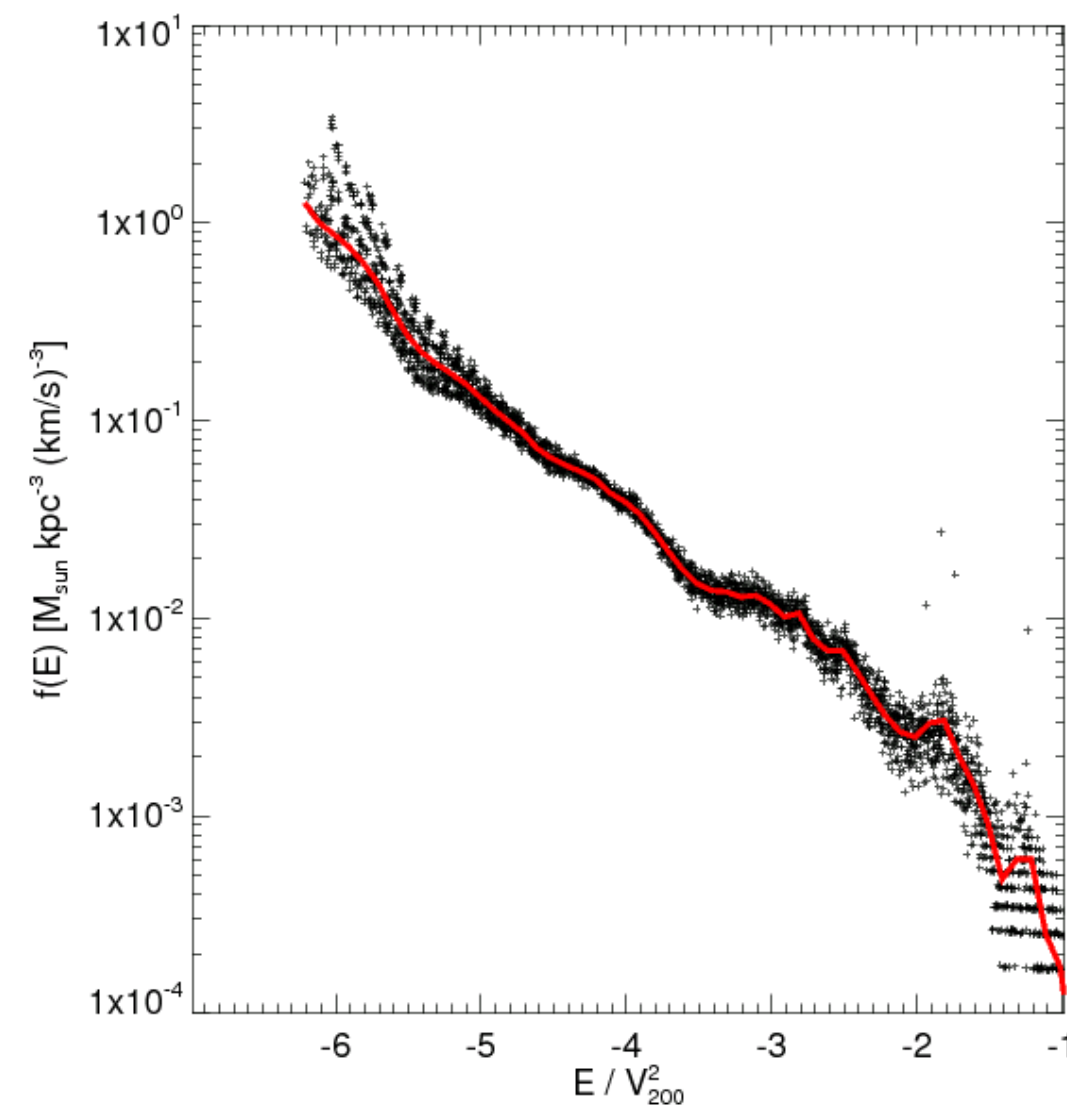
Velocity histograms for particles in a typical $(2\text{kpc})^3$ box at $R = 8\text{ kpc}$

Distributions are smooth, near-Gaussian and different in different directions

No individual streams are visible



Energy space features – fossils of formation



The energy distribution within $(2 \text{ kpc})^3$ boxes shows bumps which

- repeat from box to box
- are stable over Gyr timescales
- repeat in simulations of the same object at varying resolution
- are different in simulations of different objects

These are potentially observable fossils of the formation process

Conclusions for direct detection experiments

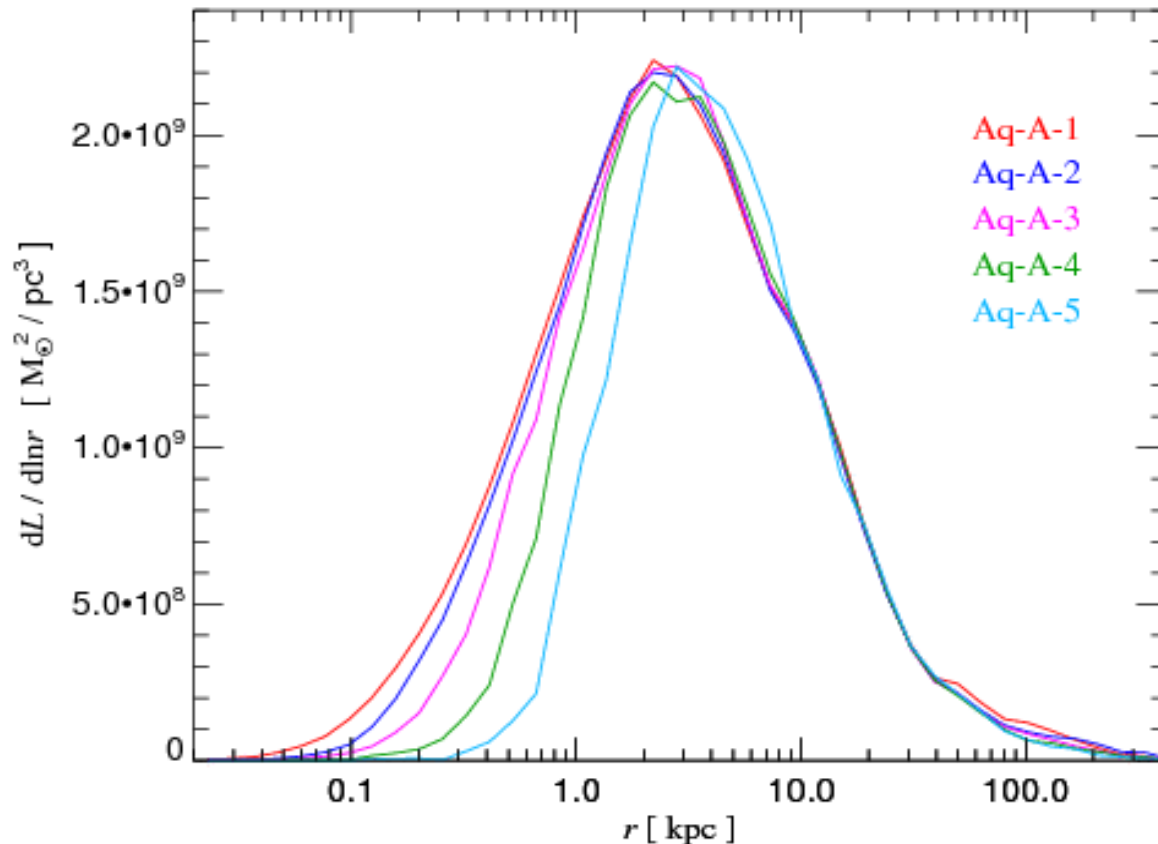
With more than 99.9% confidence the Sun lies in a region where the DM density differs from the smooth mean value by $< 20\%$

The local velocity distribution of DM particles is similar to a trivariate Gaussian with no measurable “lumpiness” due to individual DM streams

The energy distribution of DM particles should contain broad features with $\sim 20\%$ amplitude which are the fossils of the detailed assembly history of the Milky Way's dark halo

Convergence of annihilation luminosity of main halo

Springel et al 2008



Distribution has converged at the percent level for the main halo

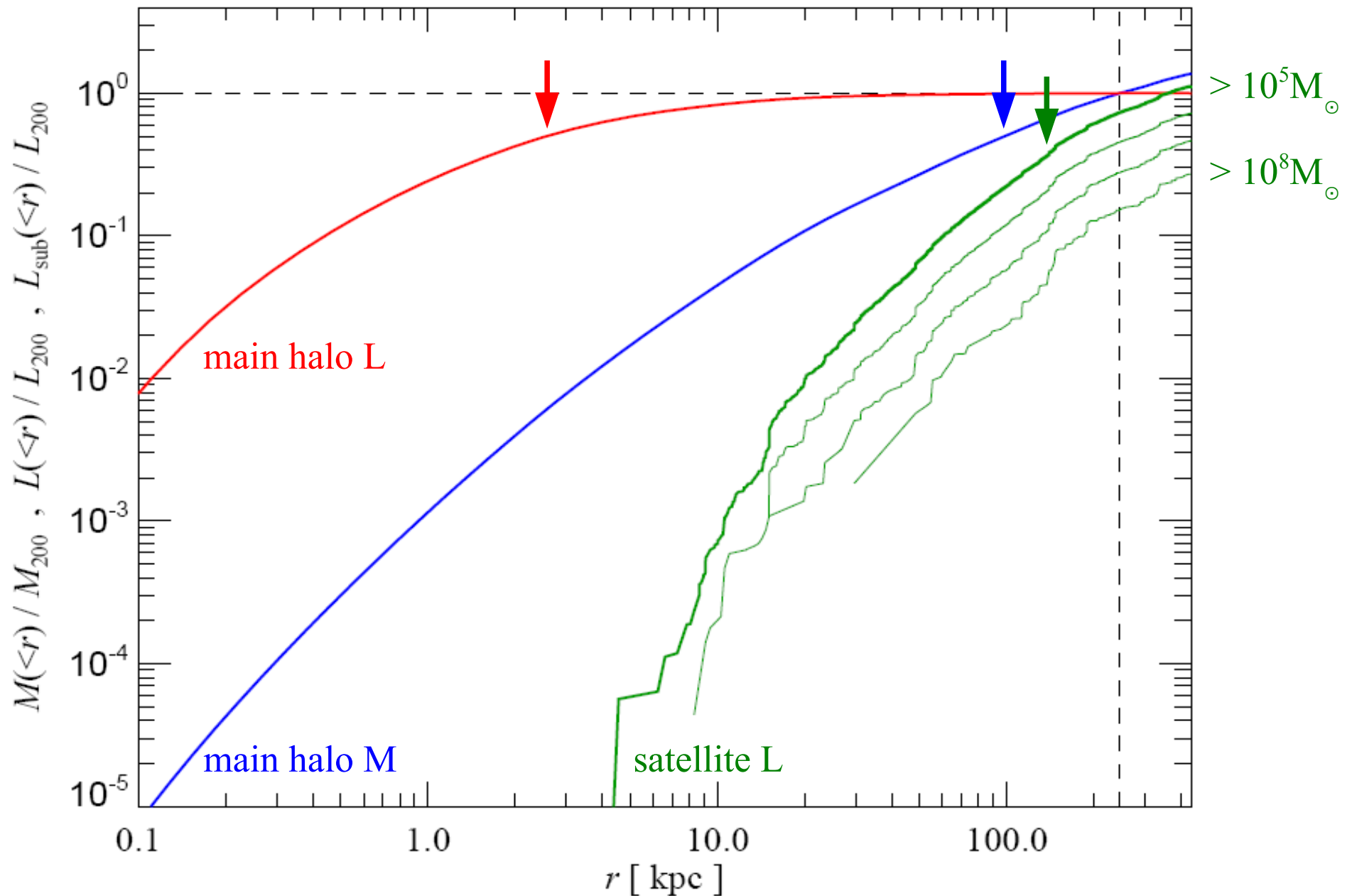
Most emission comes from $0.5 \text{ kpc} < r < 20 \text{ kpc}$

Emission is not converged for most subhalos but should scale as $V_{\text{max}}^4 / r_{\text{max}}$

This estimate is converged for $V_{\text{max}} > 1.5 \text{ km/s}$
 $r_{\text{max}} > 165 \text{ pc}$

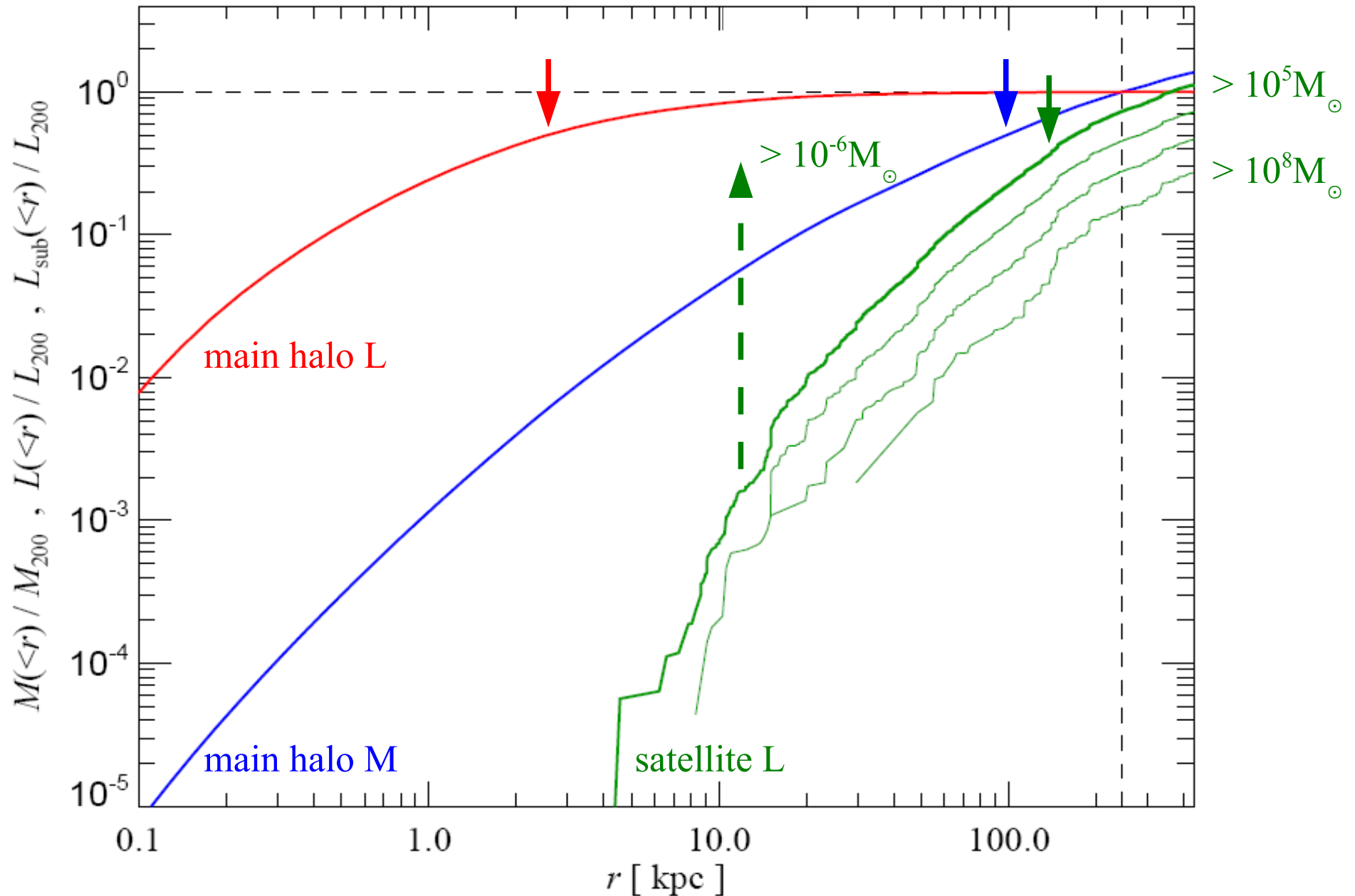
Mass and annihilation radiation profiles of a MW halo

Springel et al 2008



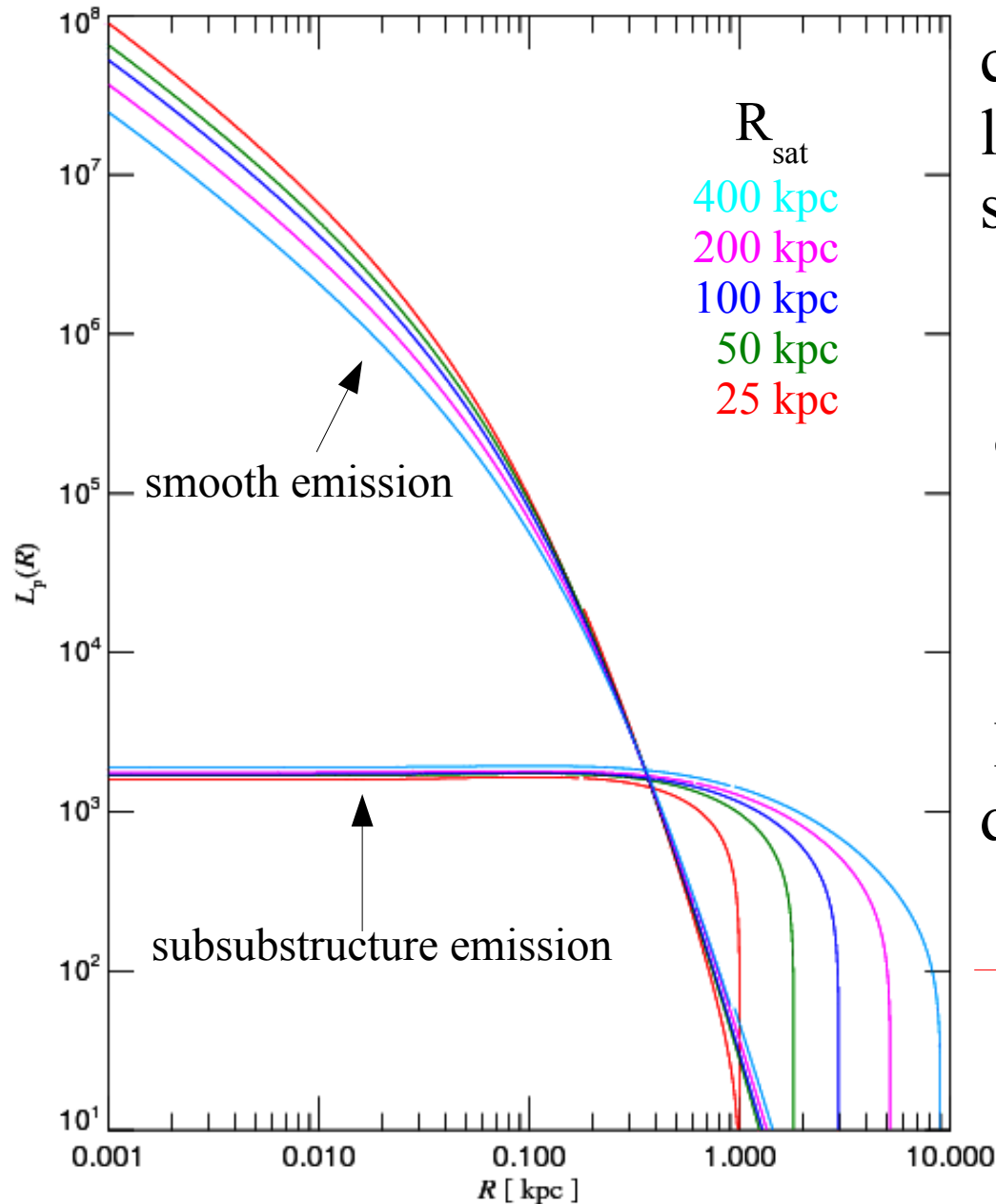
Mass and annihilation radiation profiles of a MW halo

Springel et al 2008



Subhalo annihilation luminosity profiles: $V_{\text{max}} = 10 \text{ km/s}$

Springel et al 2008



MW subhalos above Earth mass contribute 230 times as much luminosity within 250 kpc as the smooth halo mass distribution

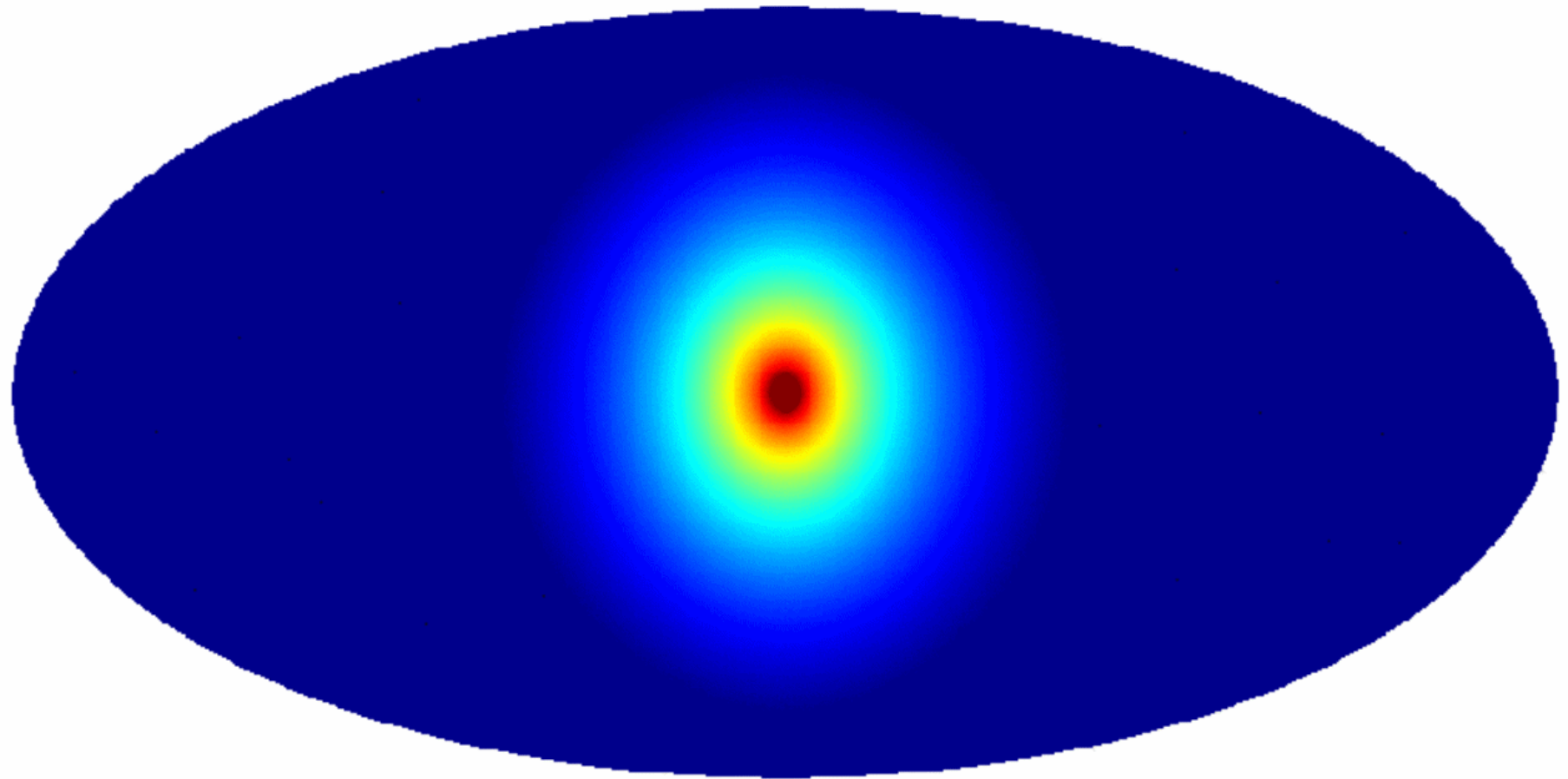
The projected surface brightness of the subhalo population is almost uniform

When a small object falls into the MW, tides remove its subhalos but don't affect its smooth emission

→ substructure does not much boost subhalo luminosities in the inner Galaxy ($r < 30 \text{ kpc}$)

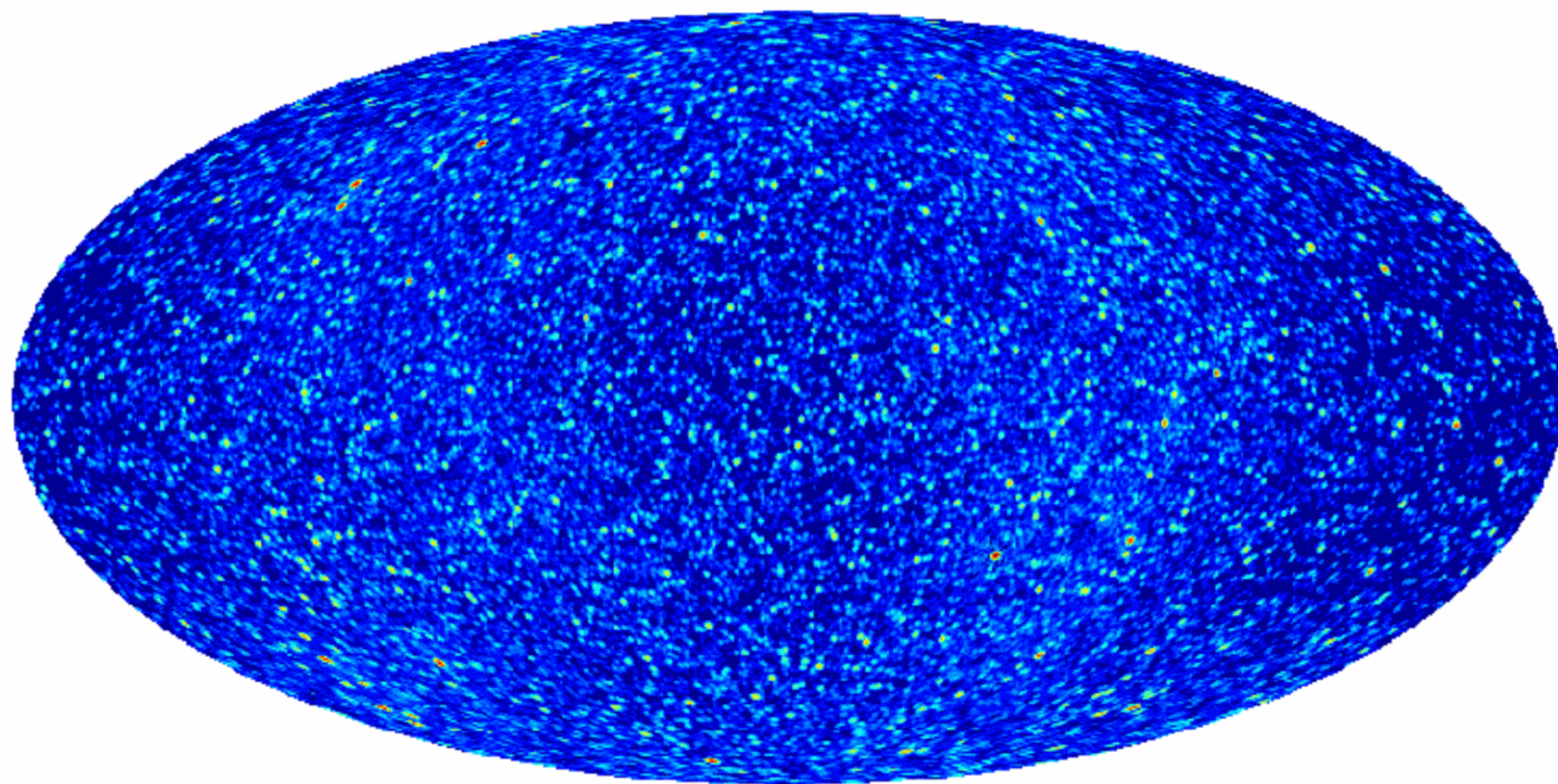
Milky Way halo seen in DM annihilation radiation

smooth main halo emission (MainSm)



Milky Way halo seen in DM annihilation radiation

emission from resolved subhalos (SubSm+SubSub)



-3.0  2.0 Log(Intensity)

Milky Way halo seen in DM annihilation radiation

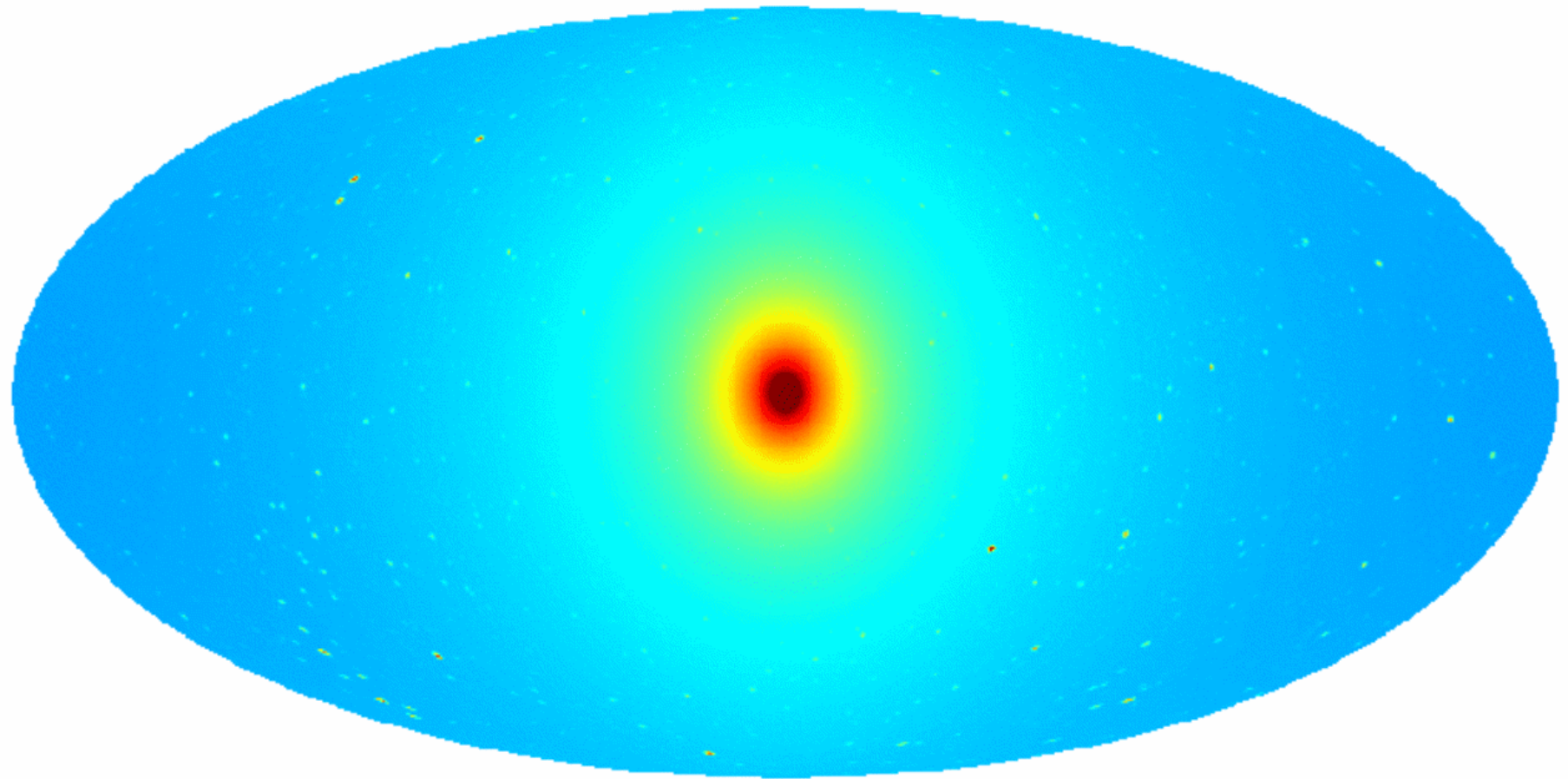
unresolved subhalo emission (MainUn)



-0.50  2.0 Log(Intensity)

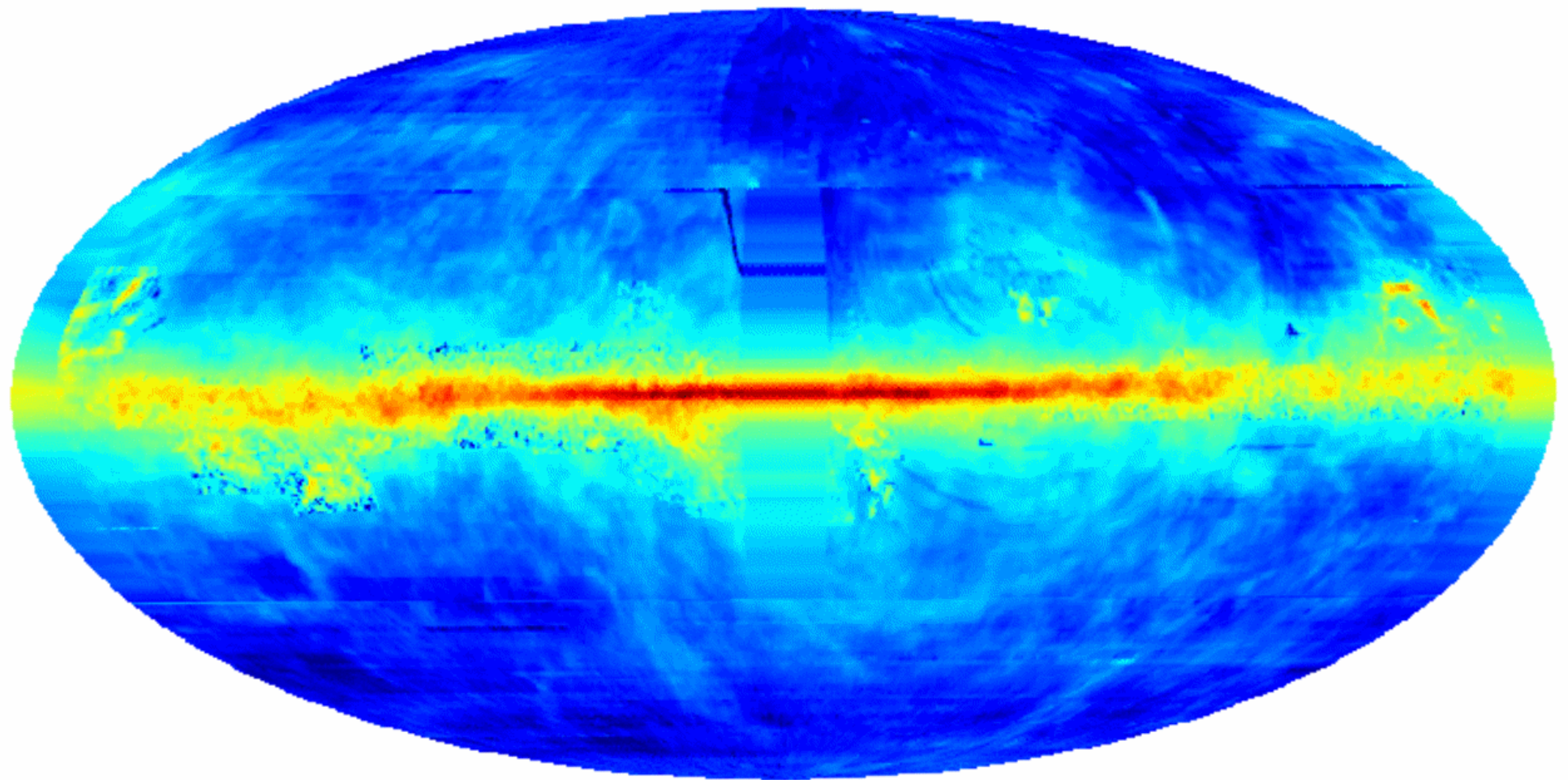
Milky Way halo seen in DM annihilation radiation

total emission



-0.50  2.0 Log(Intensity)

GALPROP, optimized



-1.0  2.0 Log(Intensity)

Conclusions about clumping and annihilation

Subhalos increase the MW's total flux within 250 kpc by a factor of 230 as seen by a distant observer, but its flux on the sky by a factor of only 2.9 as seen from the Sun

The luminosity from subhalos is dominated by small objects and is nearly uniform across the sky (contrast is a factor of ~ 1.5)

Individual subhalos have lower S/N for detection than the main halo

The highest S/N *known* subhalo should be the LMC, but smaller subhalos without stars are likely to have higher S/N

Myths about small-scale structure and DM detection

Halo DM is mostly in small (e.g. Earth mass?) clumps

—→ direct detectors typically live in low density regions

DM streams —→ non-Maxwellian, “clumpy” $f(\mathbf{v})$

—→ direct detectors will see an irregular energy distribution

Small (Earth-mass?) clumps dominate observable annihilation signal

Dwarf Spheroidals/subhalos are best targets for detecting annihilation
(and are boosted by sub-substructure)

Smooth halo annihilation emission is dominated by caustics

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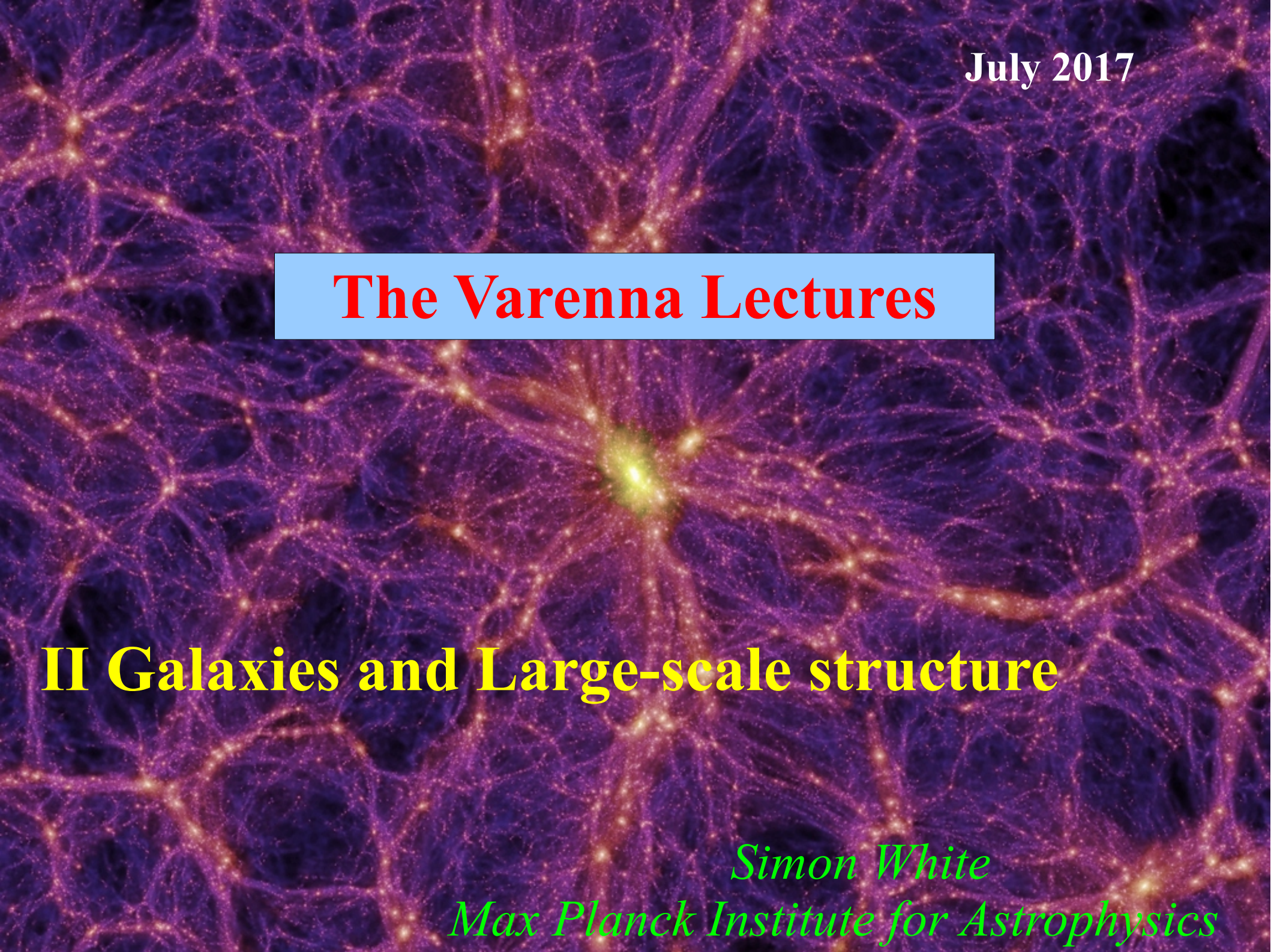
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The background of the slide is a detailed visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are depicted as thin, branching structures in shades of purple and blue, while the clusters are represented by denser regions of yellow and orange. A prominent, bright yellow cluster is visible near the center of the image.

July 2017

The Varenna Lectures

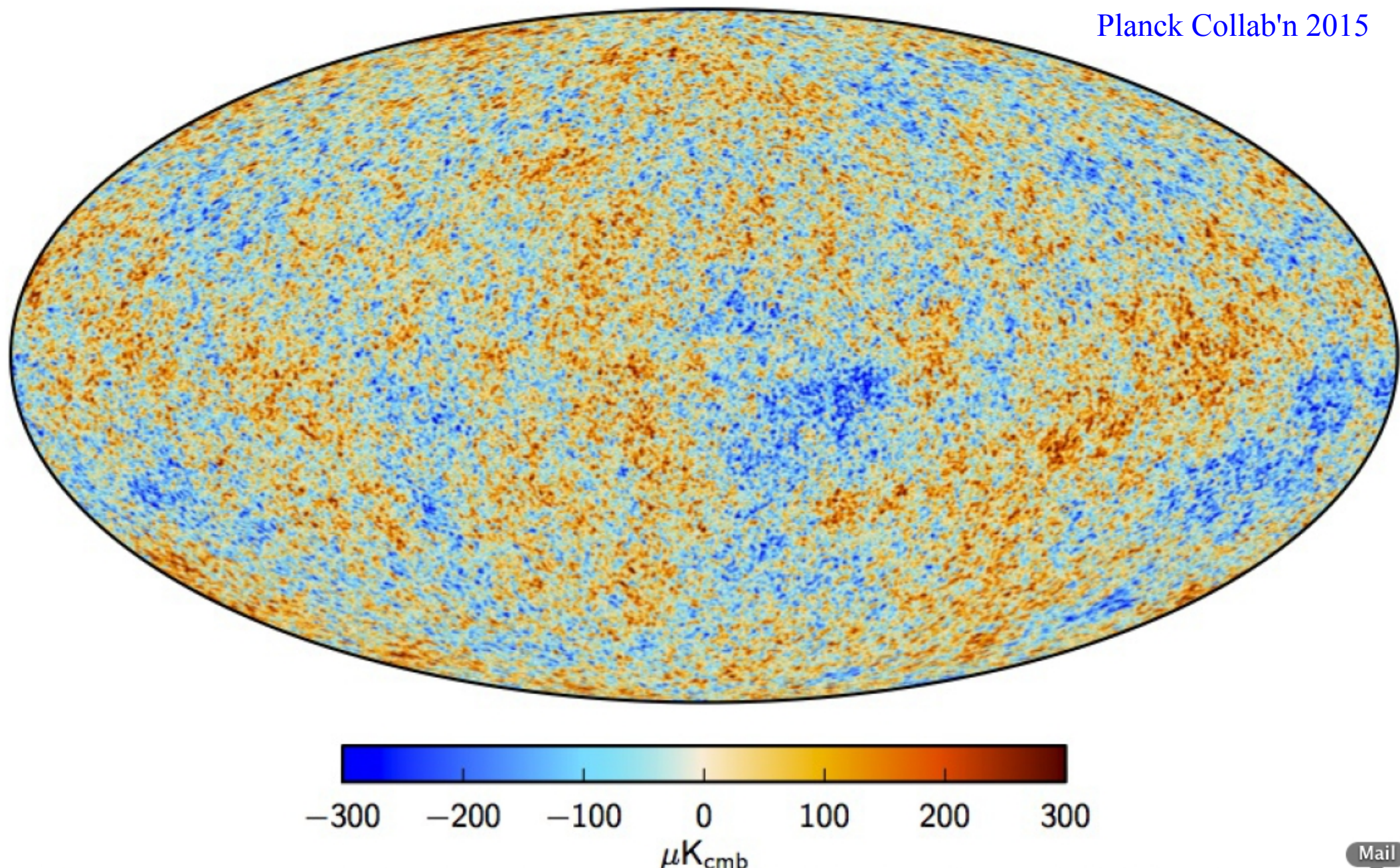
II Galaxies and Large-scale structure

Simon White

Max Planck Institute for Astrophysics

CMB map from the full *Planck* mission

Planck Collab'n 2015

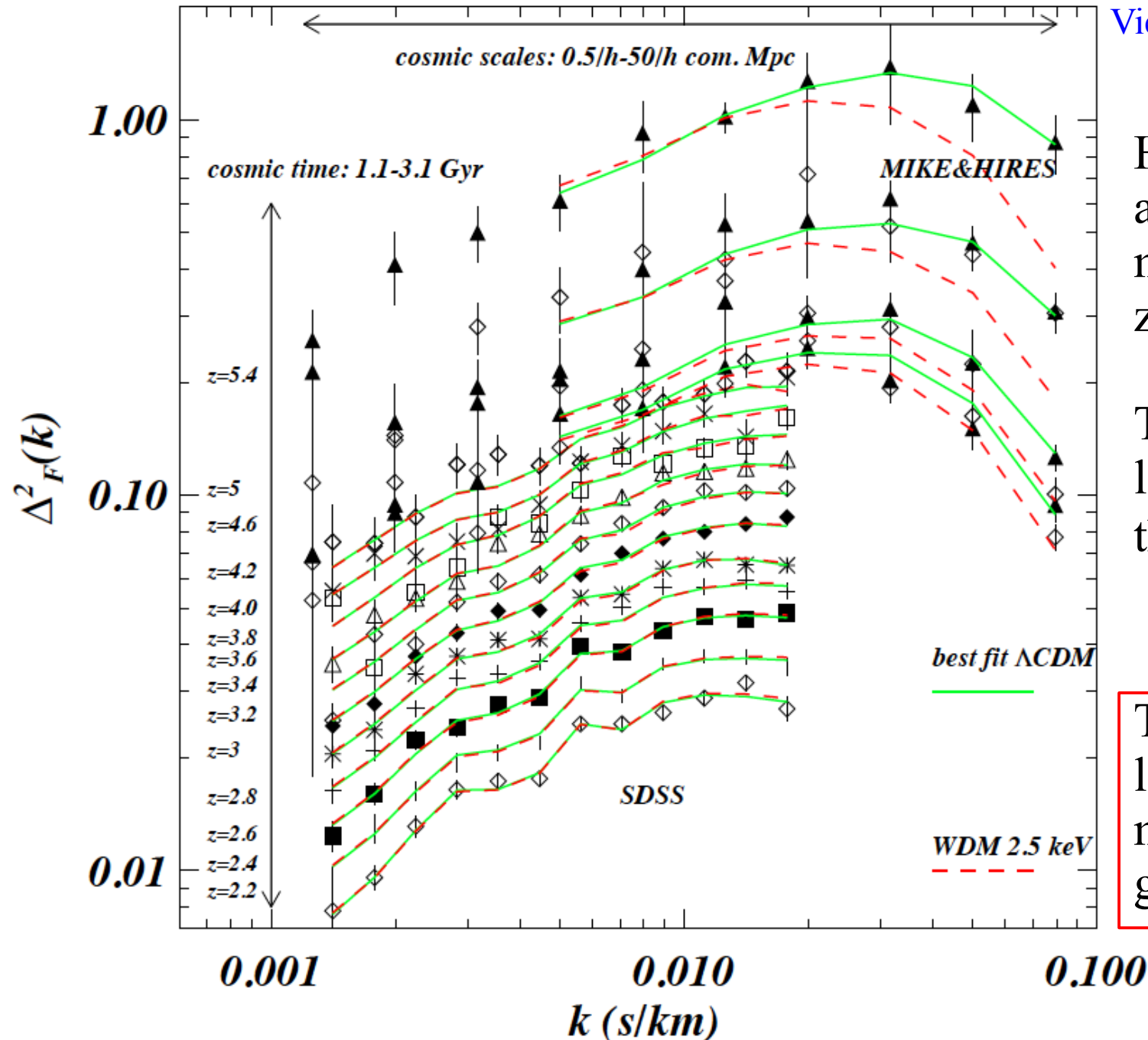


The six parameters of the base Λ CDM model

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 Λ CDM up to
 $z = 5.4$

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

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

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 Λ CDM with $n \sim 0.97$ down to subgalactic scales
- Initial non-gaussianities and Σm_ν are both small

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- 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?)

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- Are the initial conditions well enough represented?
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- 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 α in $P_{\alpha}\{L_{\text{cen}}\dots \mid M_{\text{halo}}\dots\}$, $n_{\alpha}(L_{\text{sat}}, r \mid M_{\text{halo}}\dots)$

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 $L - M_{\text{halo}}$ relation, “best” estimator for M_{halo}

Semianalytic/Empirical Models (SAM)

Input: N-body simulation with halos+subhalos+merger tree

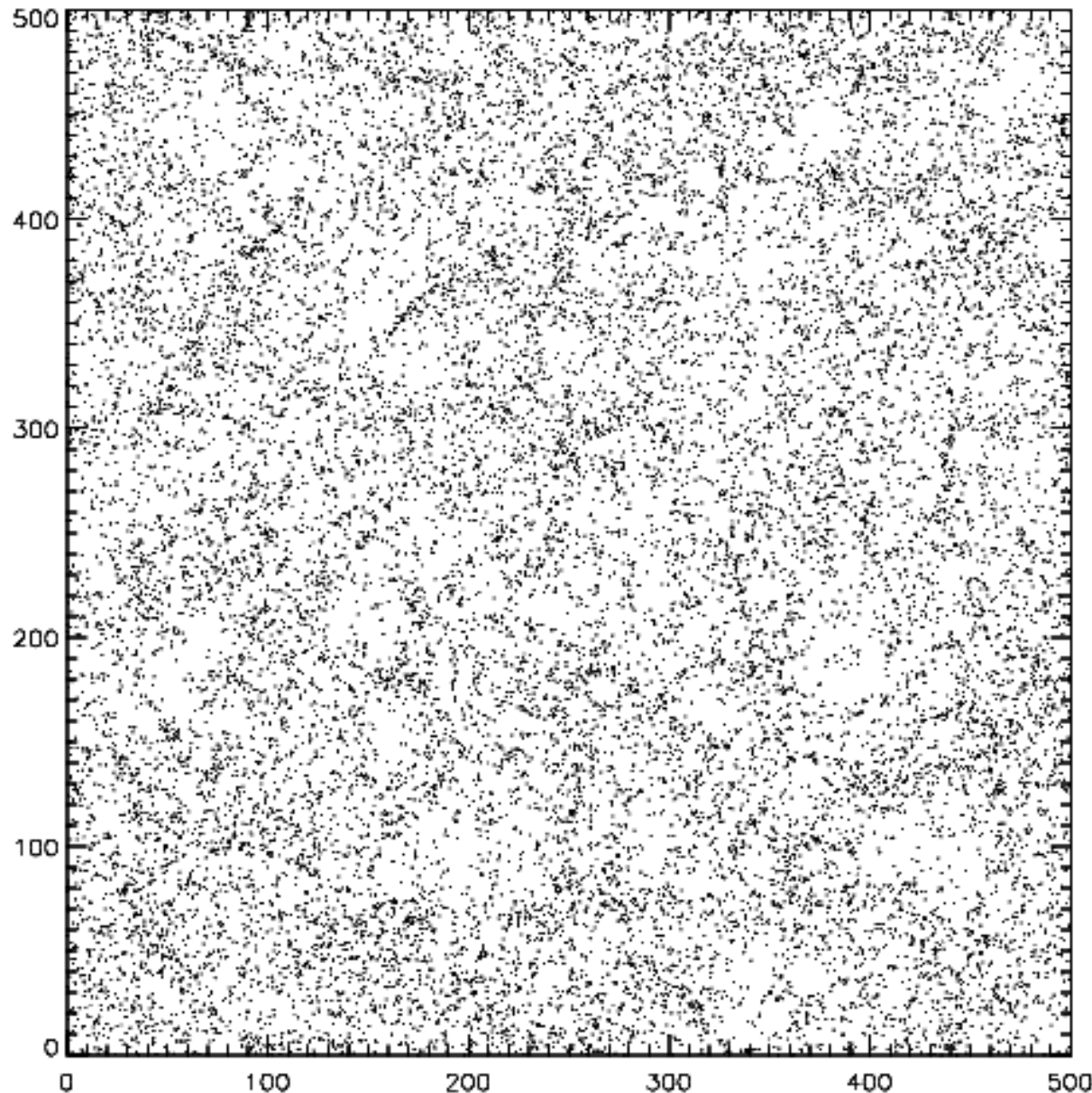
Fit data: Galaxy abundances and clustering at multiple redshifts

Output: Parameters of physical/empirical galaxy formation model

Cosmological Hydrodynamical Simulations

Halo clustering depends on formation history

Gao, Springel & White 2005

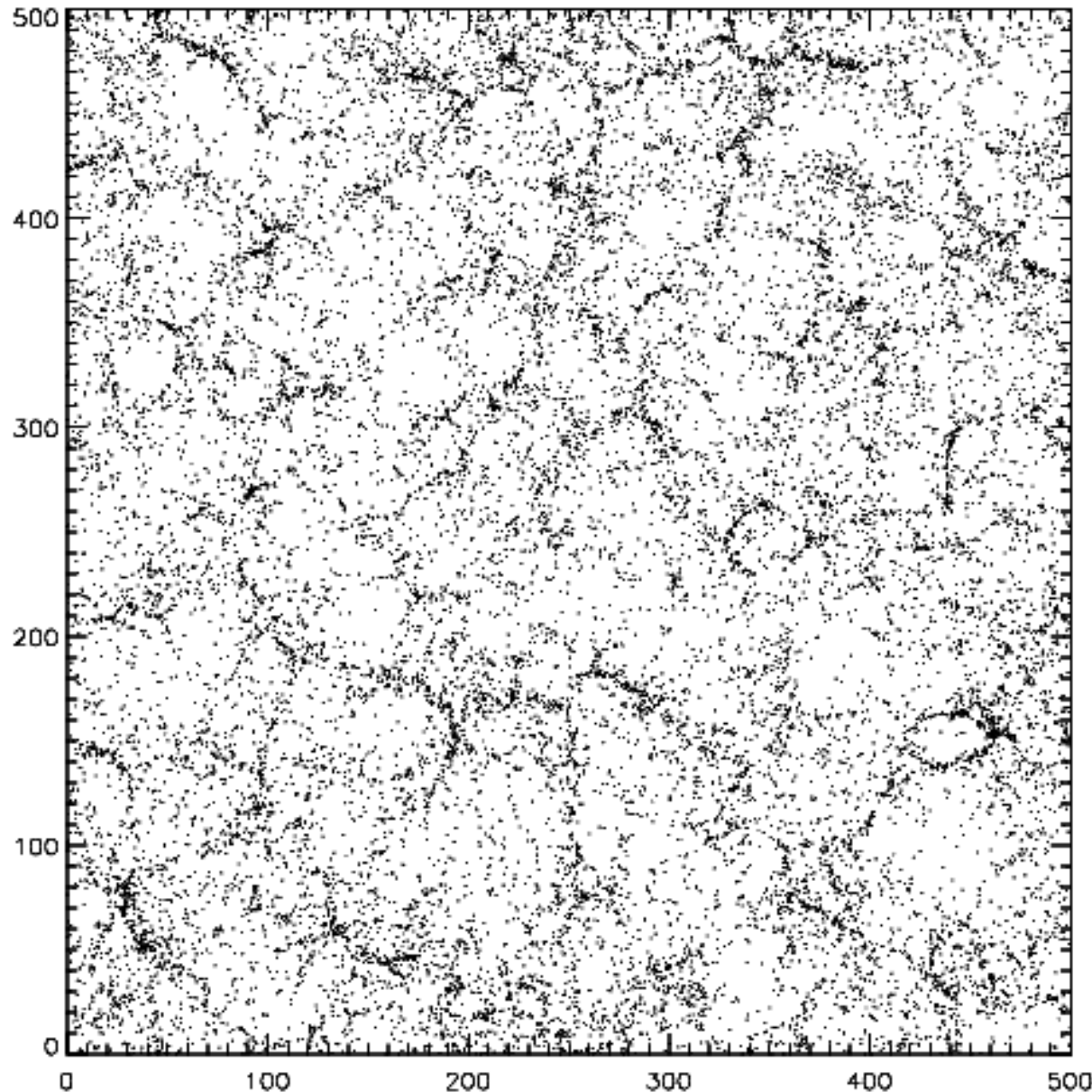


The 20% of halos with the *latest* half-mass assembly redshifts in a 30 Mpc/h thick slice

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

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Gao, Springel & White 2005



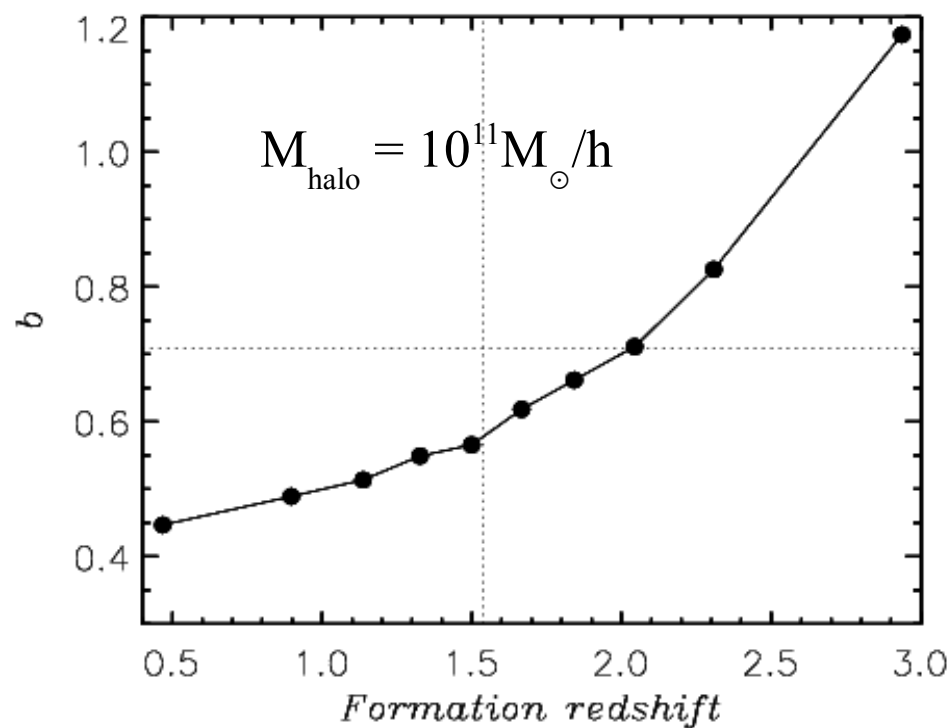
The 20% of halos with the *earliest* half-mass assembly redshifts in a 30 Mpc/h thick slice

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

Halo bias as a function of mass and formation time

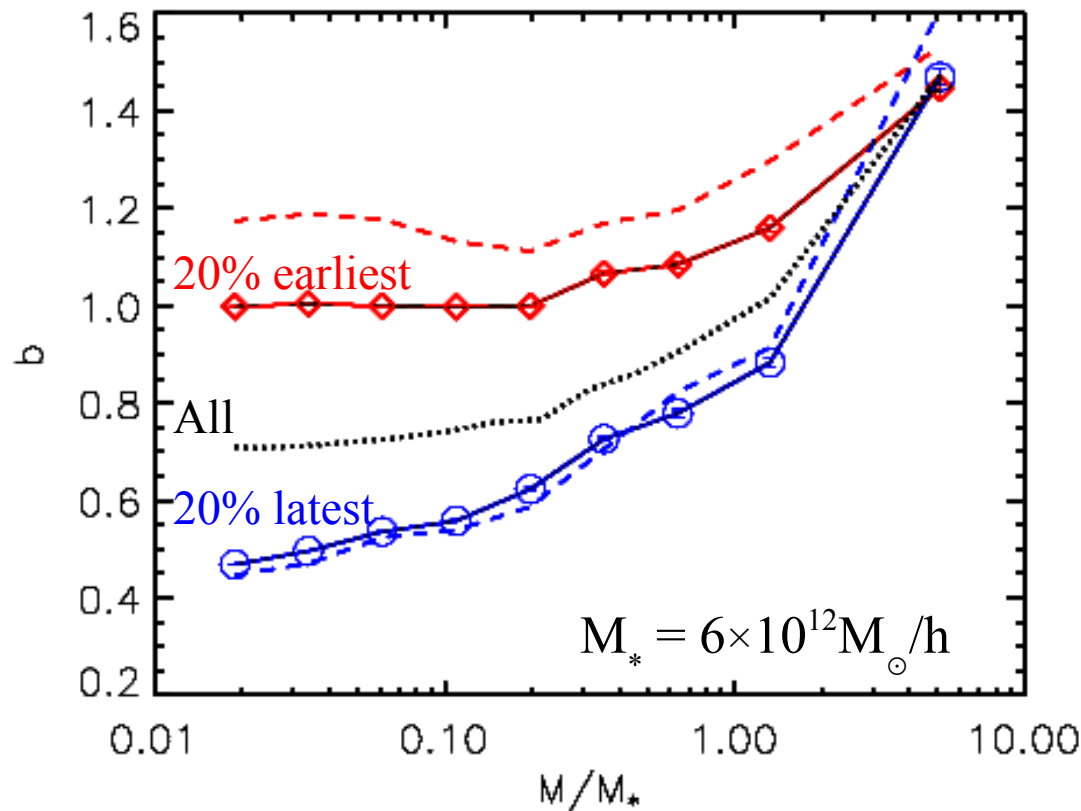
Gao, Springel & White 2005

On large scales halo bias increases smoothly with formation redshift



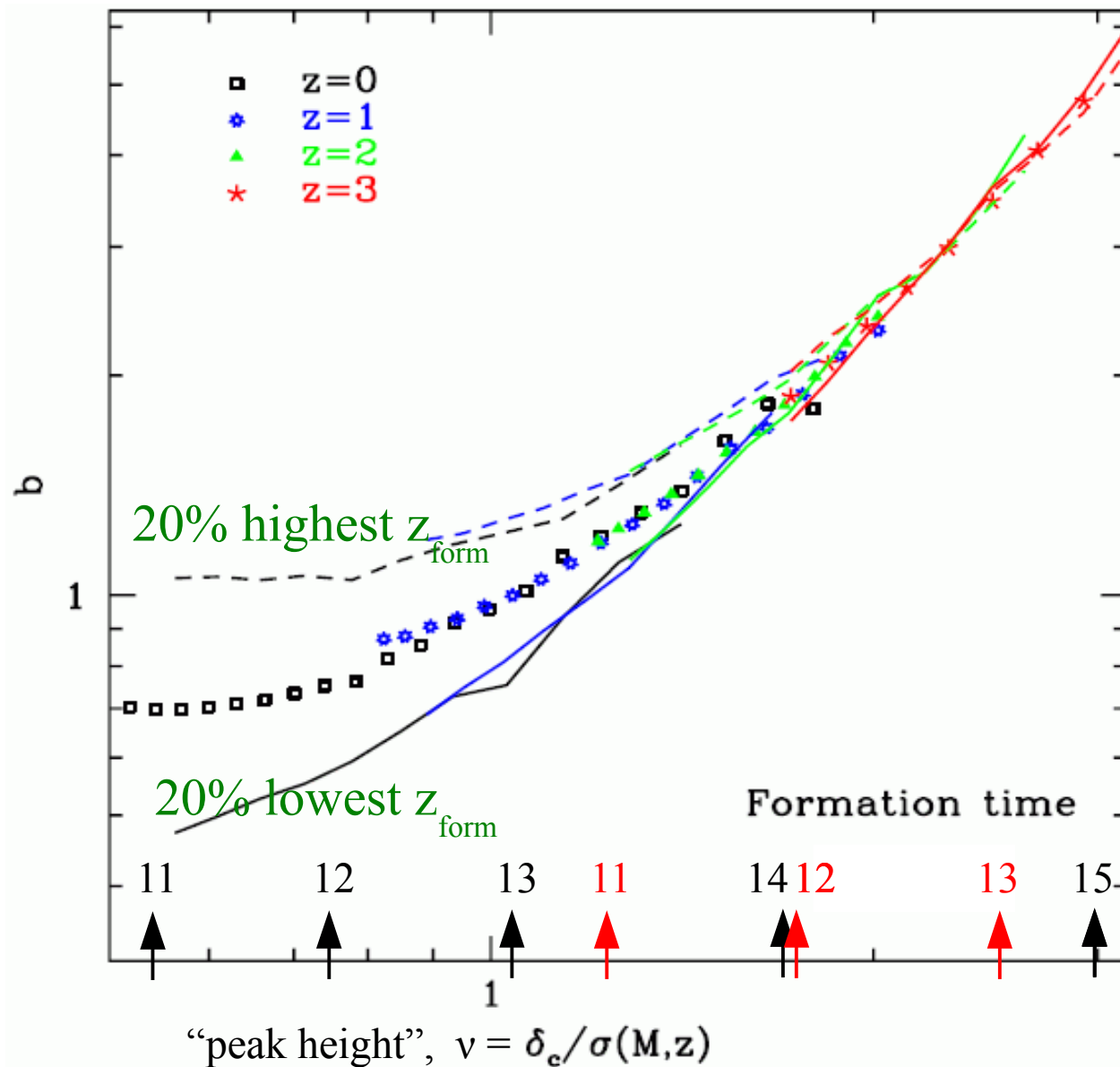
The dependence of bias on formation redshift is strongest at low mass

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



Bias as a function of v and formation time

Gao & White 2007



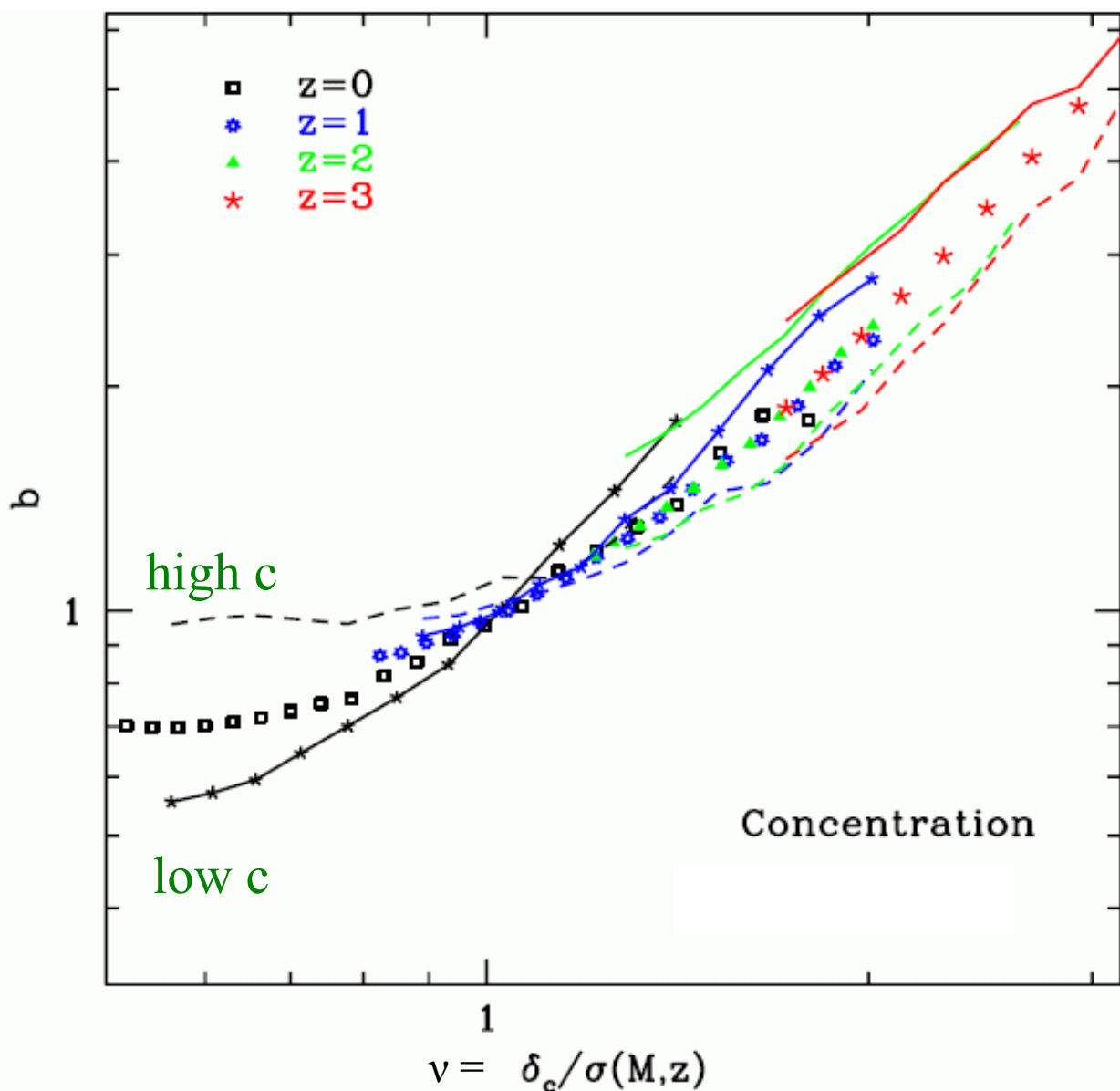
Dynamic range and S/N can be increased by superposing redshifts and using halo-mass cross-correlations

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

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

Bias as a function of v and concentration

Gao & White 2007



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

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

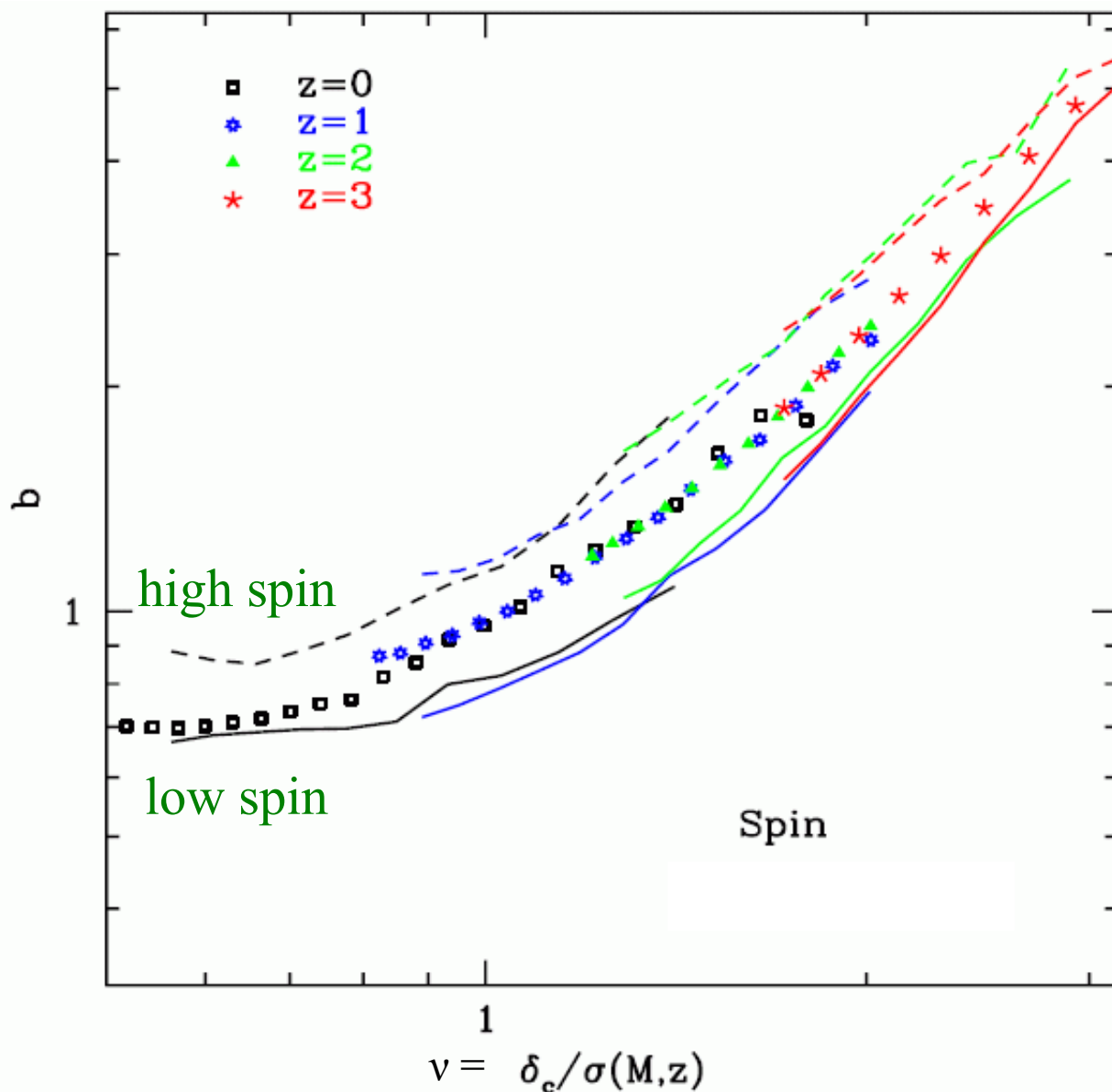
The effect vanishes for
 $M_{\text{halo}} \sim M_*$

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

c.f. Wechsler et al 2006

Bias as a function of v and spin

Gao & White 2007



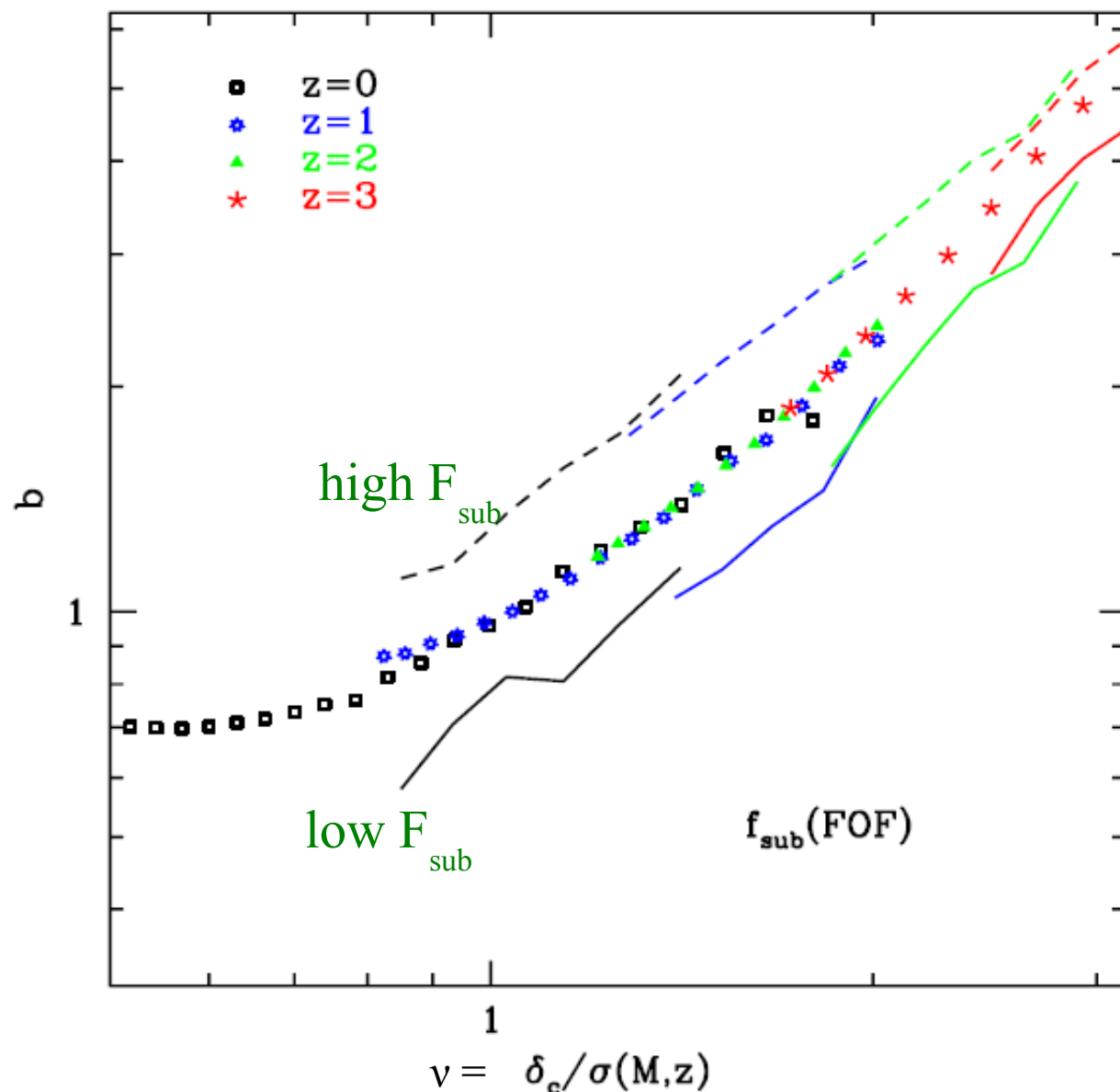
For halo spin, defined as λ' for the mass within the virial radius, the bias ratio is roughly independent of mass

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

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

Bias as a function of v and substructure mass fraction

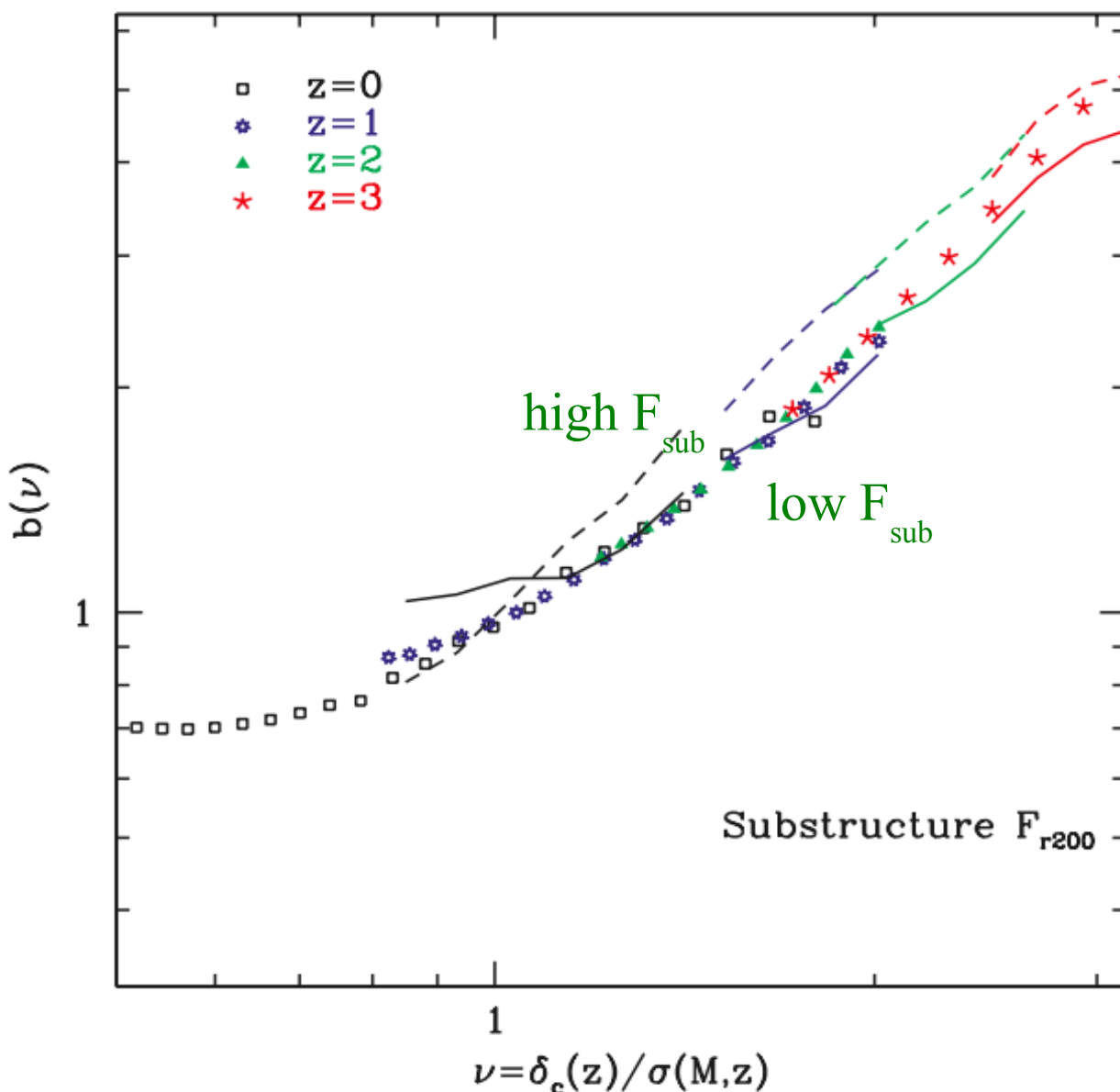
Gao & White 2007



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

Bias as a function of ν and substructure mass fraction

Gao & White 2007



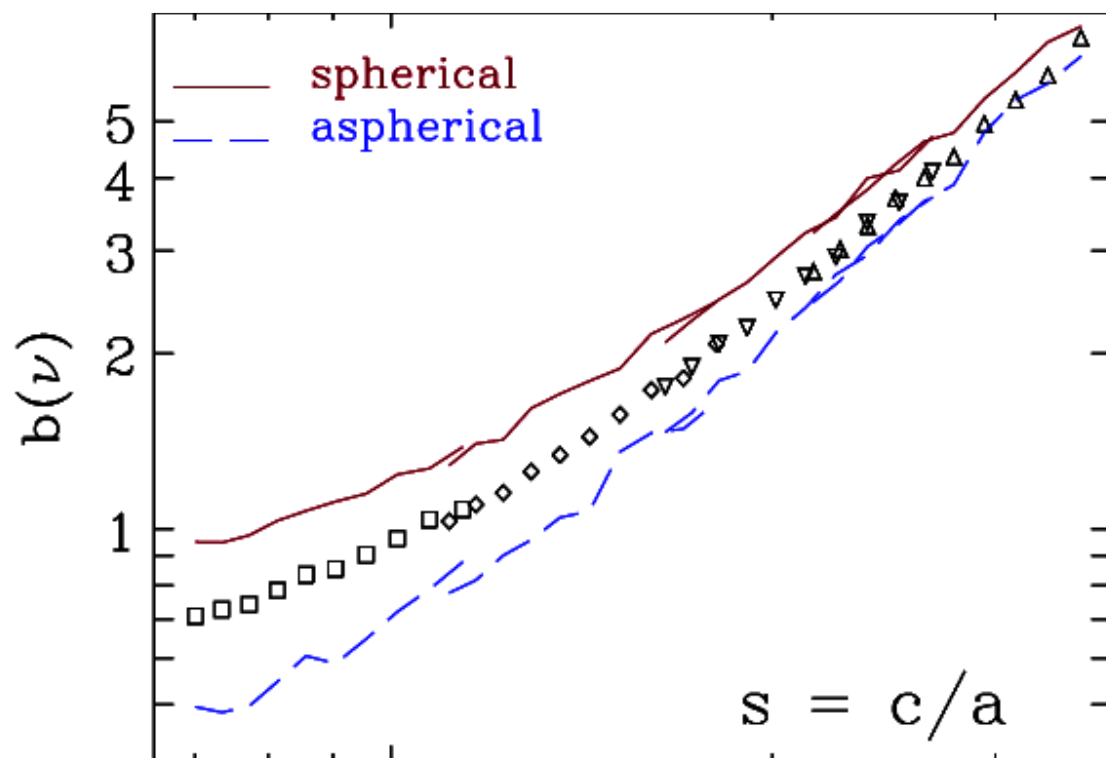
Defining substructure mass fraction so that F_{sub} is the fraction of mass in subhalos within the virial radius, the effect is much smaller, going through unity at M_* .

At high mass $b_{\text{hi}} / b_{\text{lo}} \sim 1.2$

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



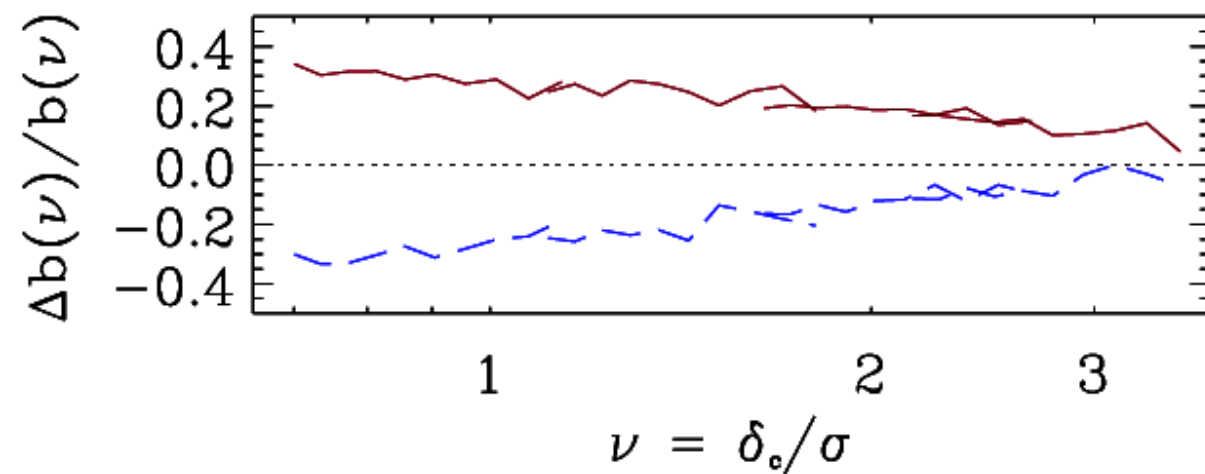
Main subhalos which are rounder are more strongly clustered at all masses.

For MW-mass halos,

$$b_{\text{hi}} / b_{\text{lo}} \sim 2$$

For cluster mass halos,

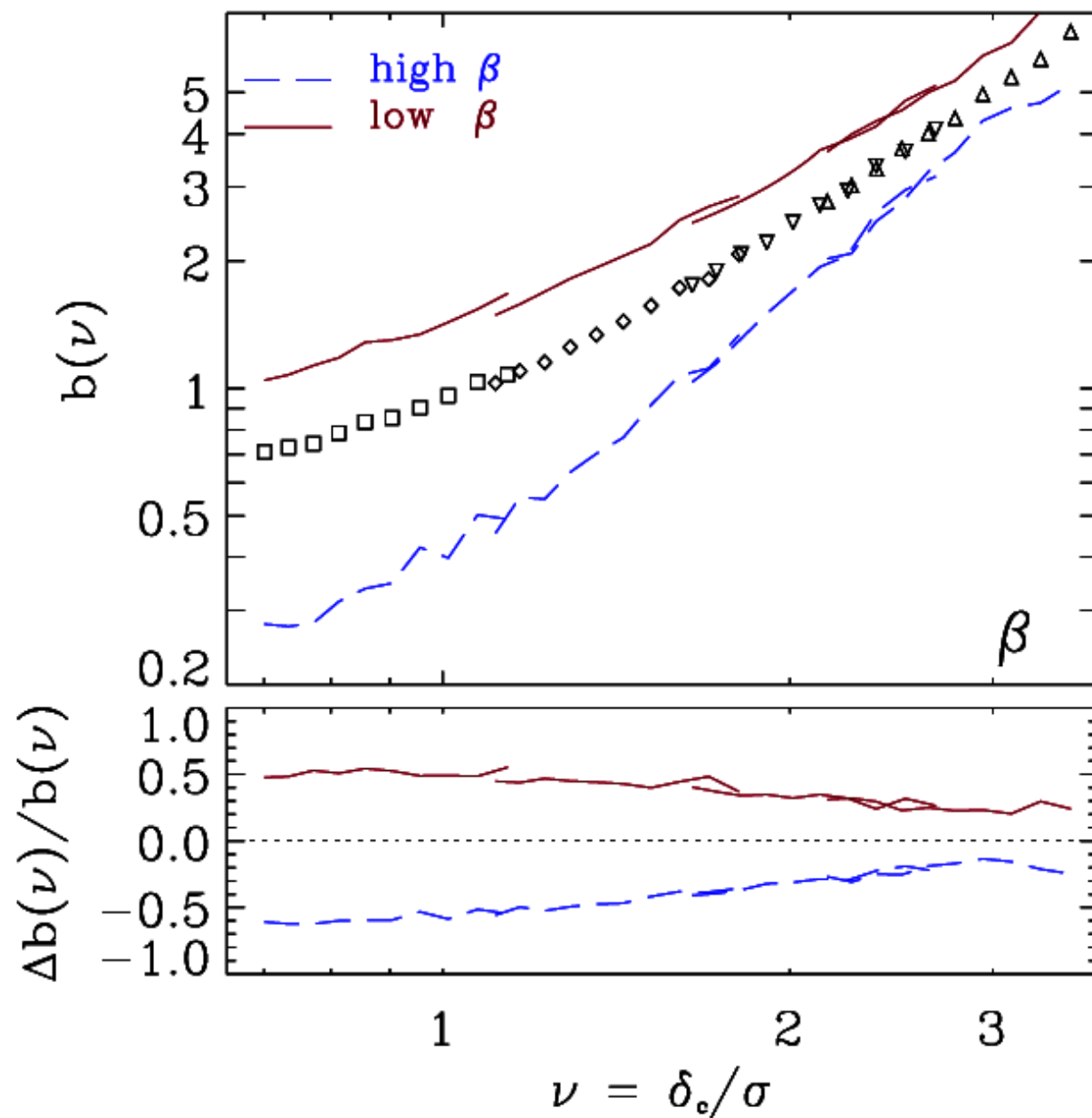
$$b_{\text{hi}} / b_{\text{lo}} \sim 1.2$$



The orientation 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,

$$b_{\text{hi}} / b_{\text{lo}} \sim 0.3$$

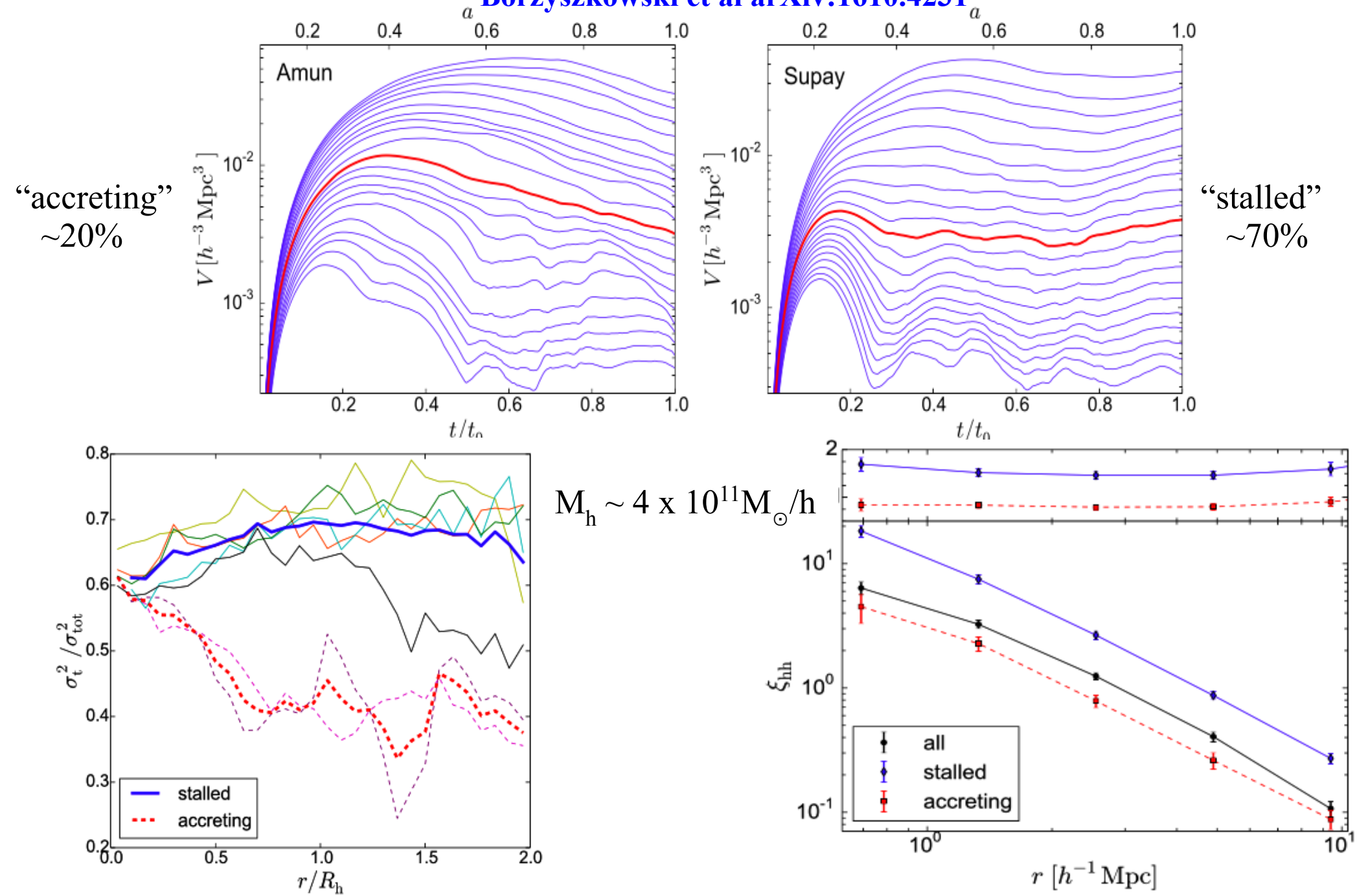
For cluster mass halos,

$$b_{\text{hi}} / b_{\text{lo}} \sim 0.6$$

This is the strongest of all the effects considered so far

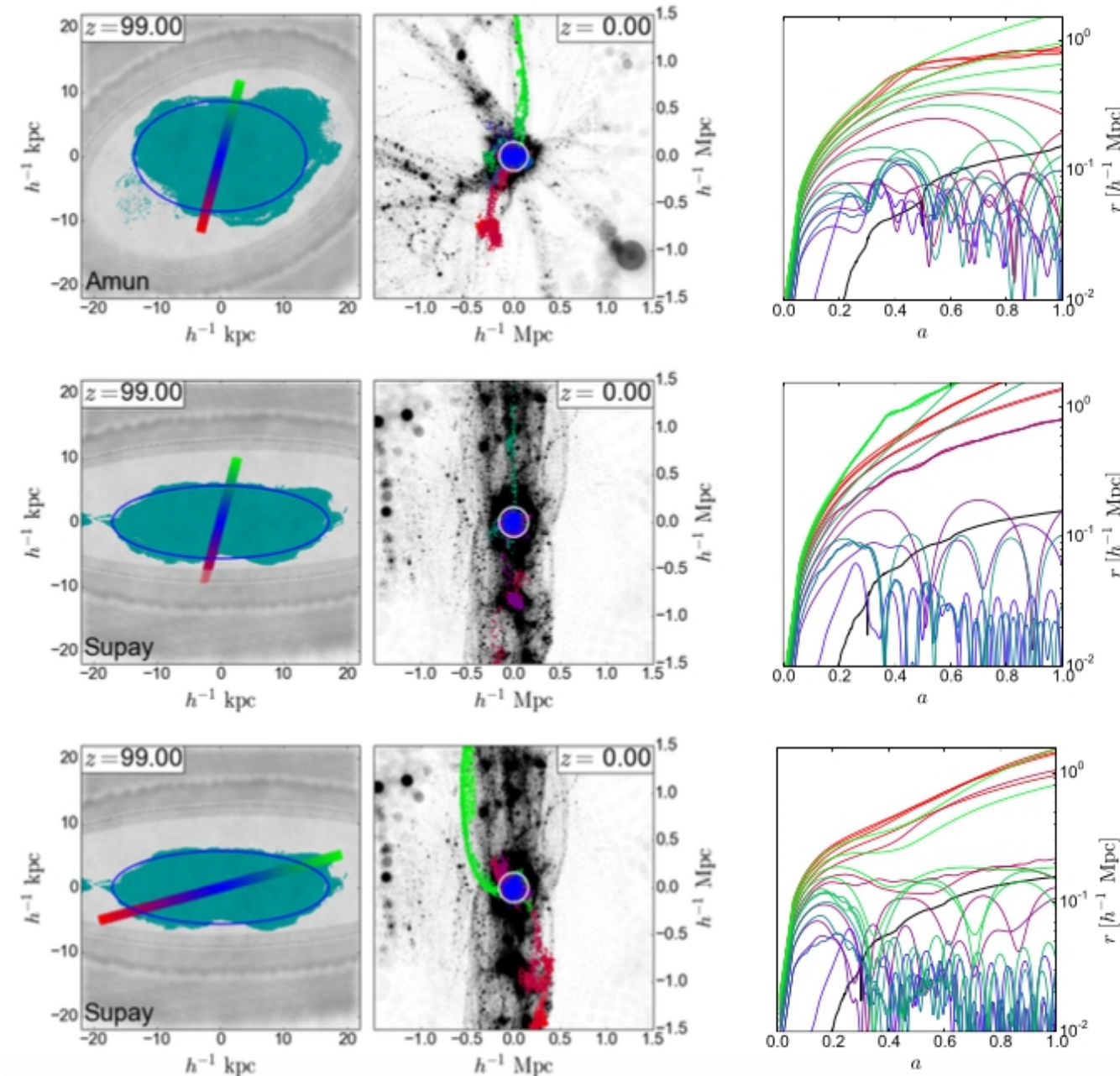
Assembly bias and the cosmic web

Borzyszkowski et al arXiv:1610.4231



Assembly bias and the cosmic web

Borzyszkowski et al arXiv:1610.4231



Stalled halos form from much more elongated Lagrangian regions than accreting halos

The elongation is usually perpendicular to a strong filament.

The filament causes very strong environment shear

This results in nett outflow around the halo and strong tangential motions within it

Assembly bias and the cosmic web

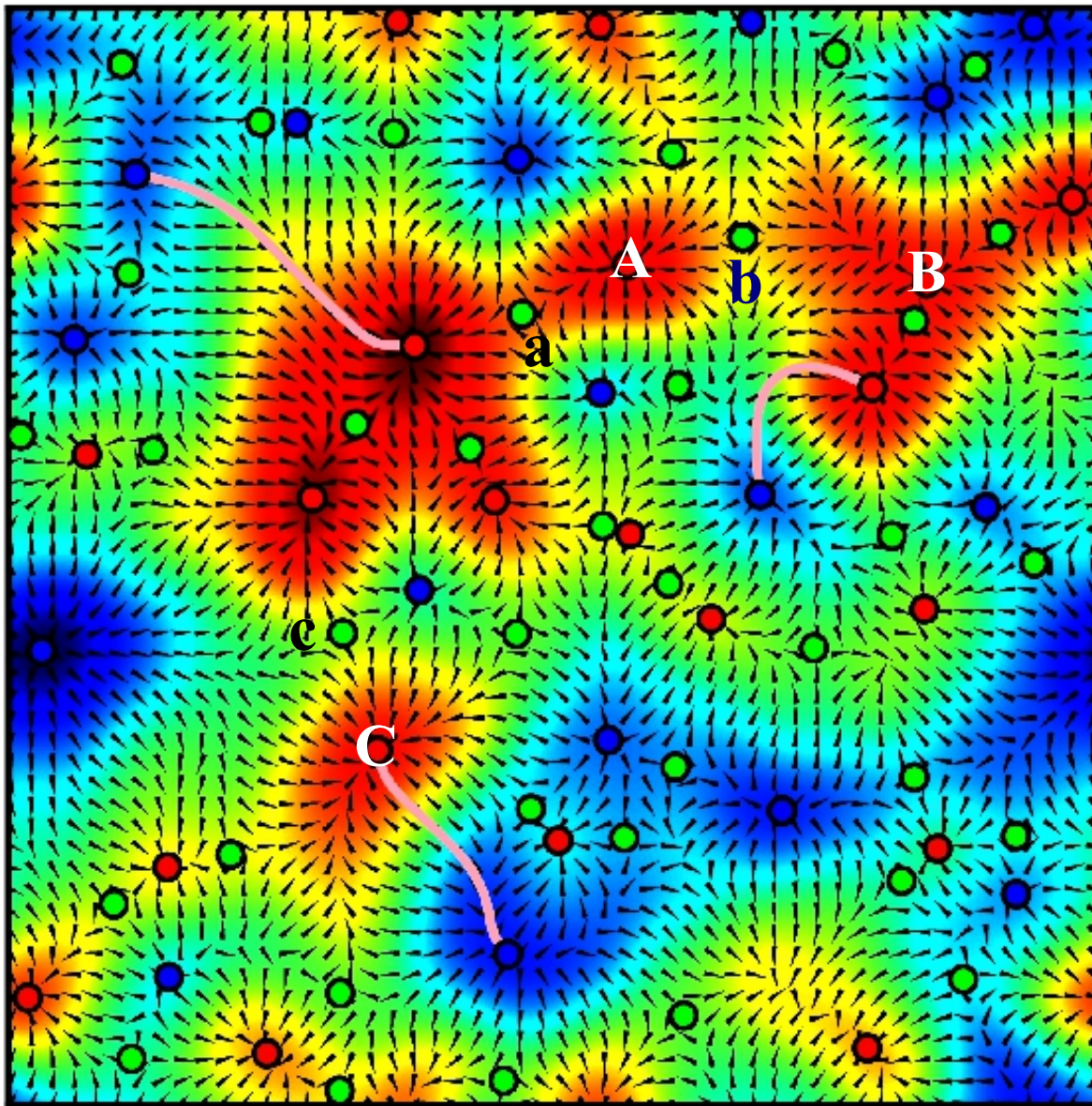


Image from T. Sousbie (2011)

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**

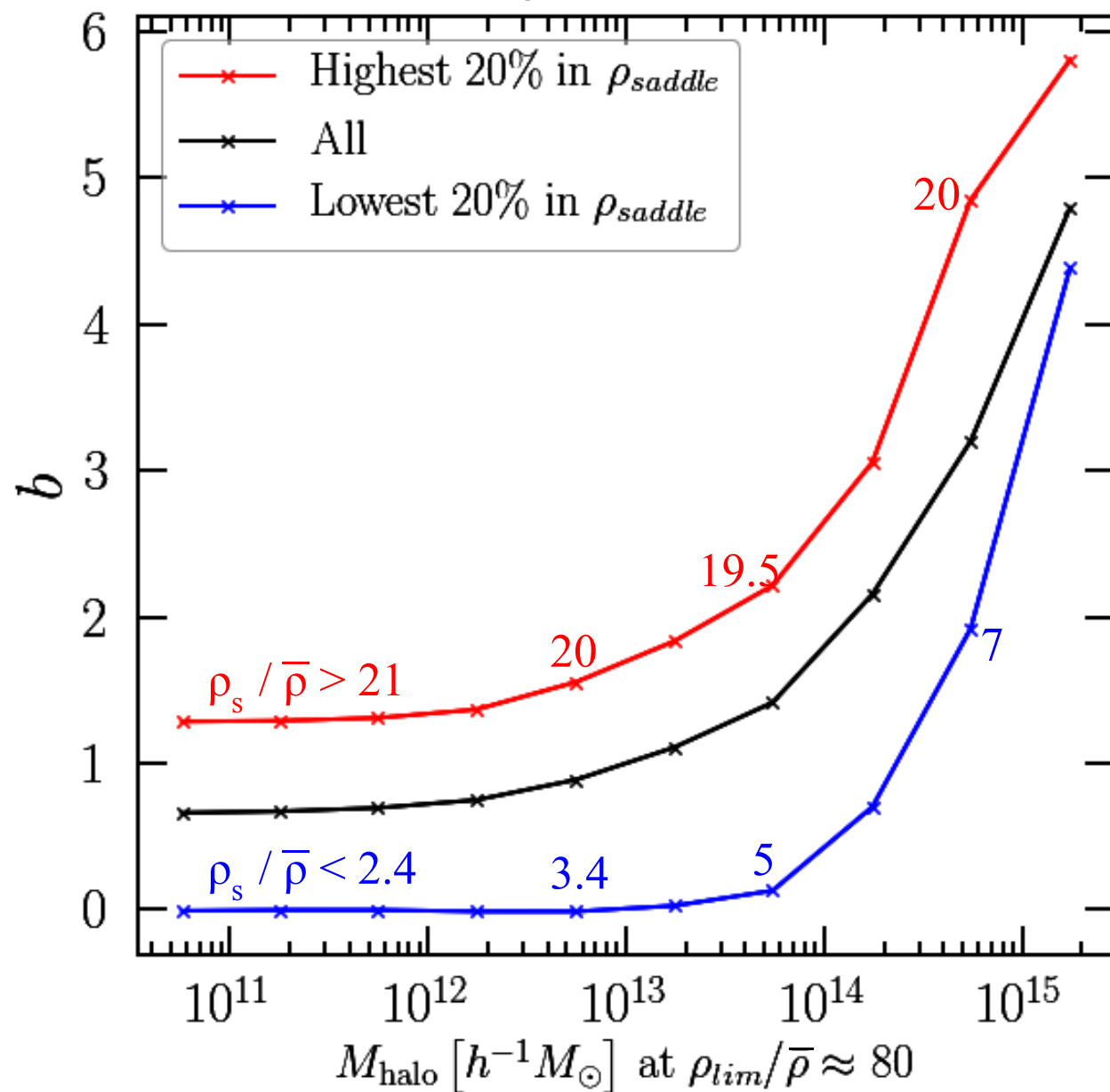
Halo **C** links at saddle point **c**

$\rho_a > \rho_b > \rho_c$ in this example

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

Bias as a function of mass and saddle point density

Millennium data: ρ from Voronoi tessellation



Busch et al,
in prep.



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

Halo assembly bias: conclusions

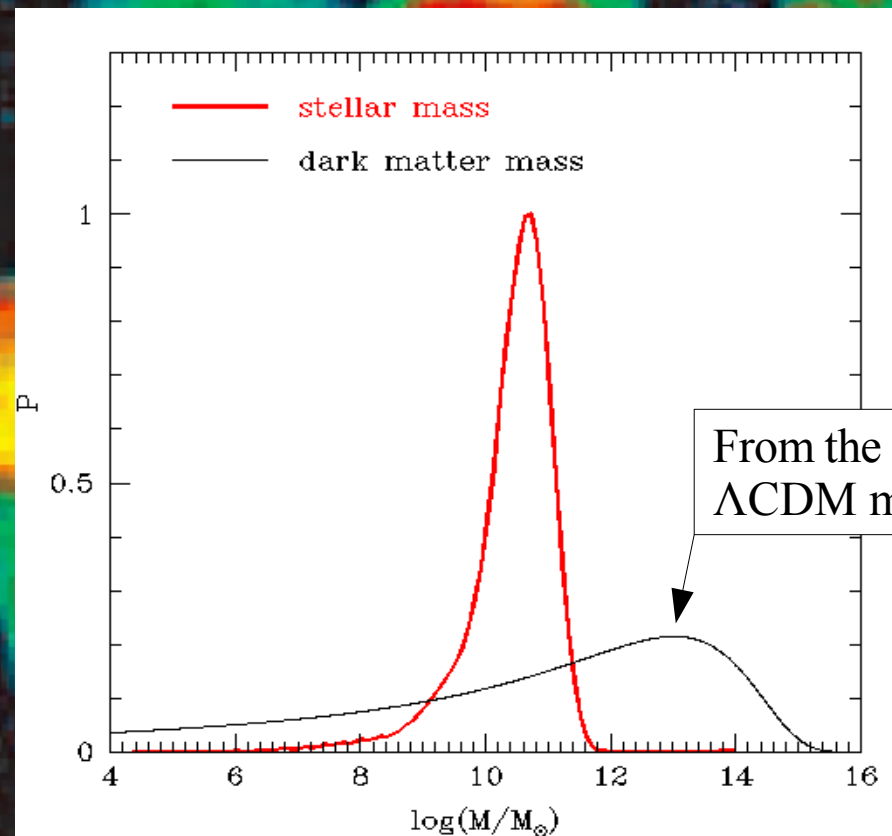
The large-scale bias of halo clustering depends not only on halo mass through $v = \delta_c / D(z) \sigma_0(M)$, but also on

- 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: $b = b(M, \underline{\mathbf{A}})$ with $\underline{\mathbf{A}}$ multi-dimensional.

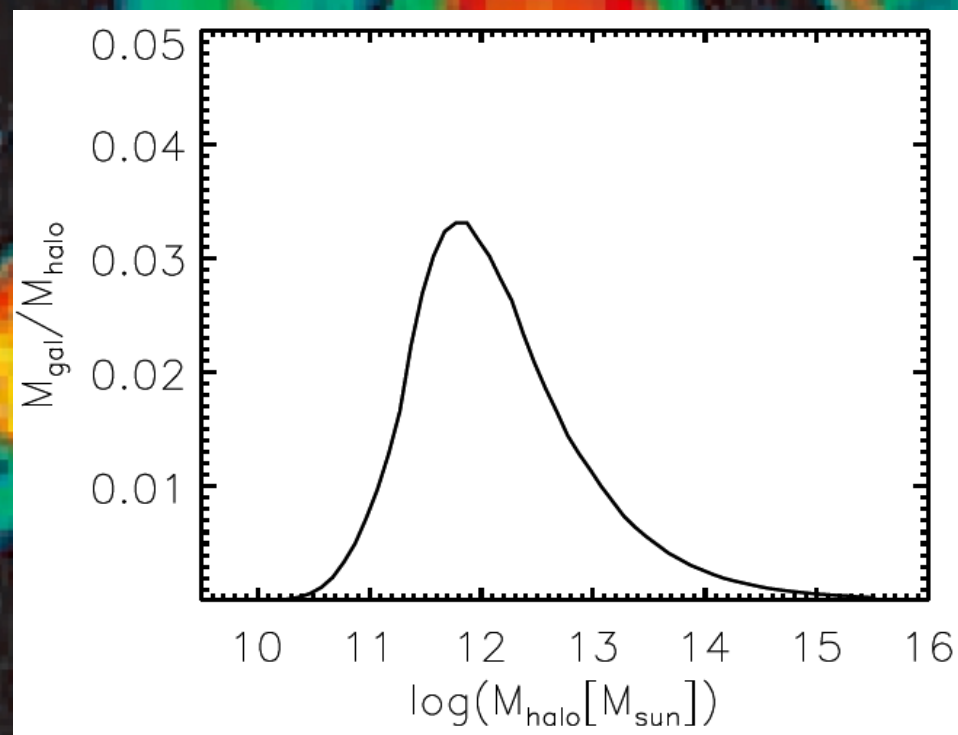
These dependences are likely to be reflected in galaxy bias

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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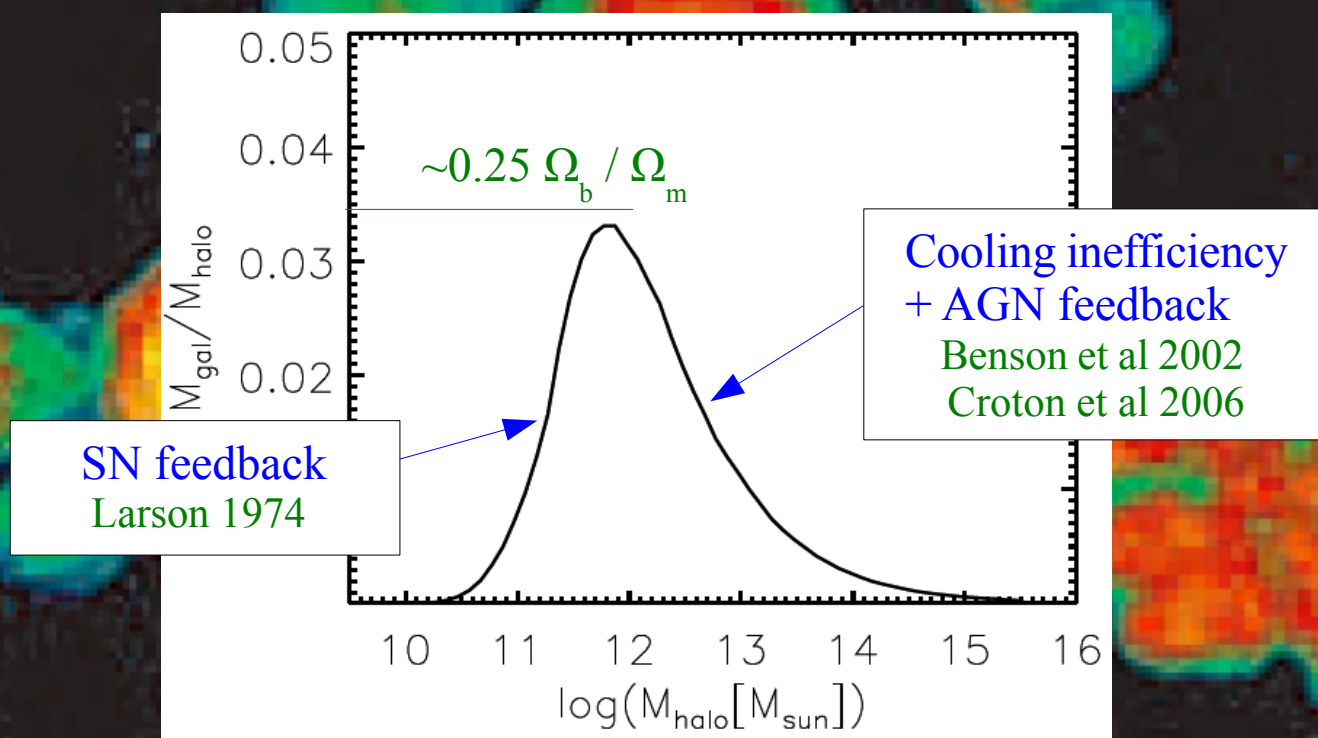
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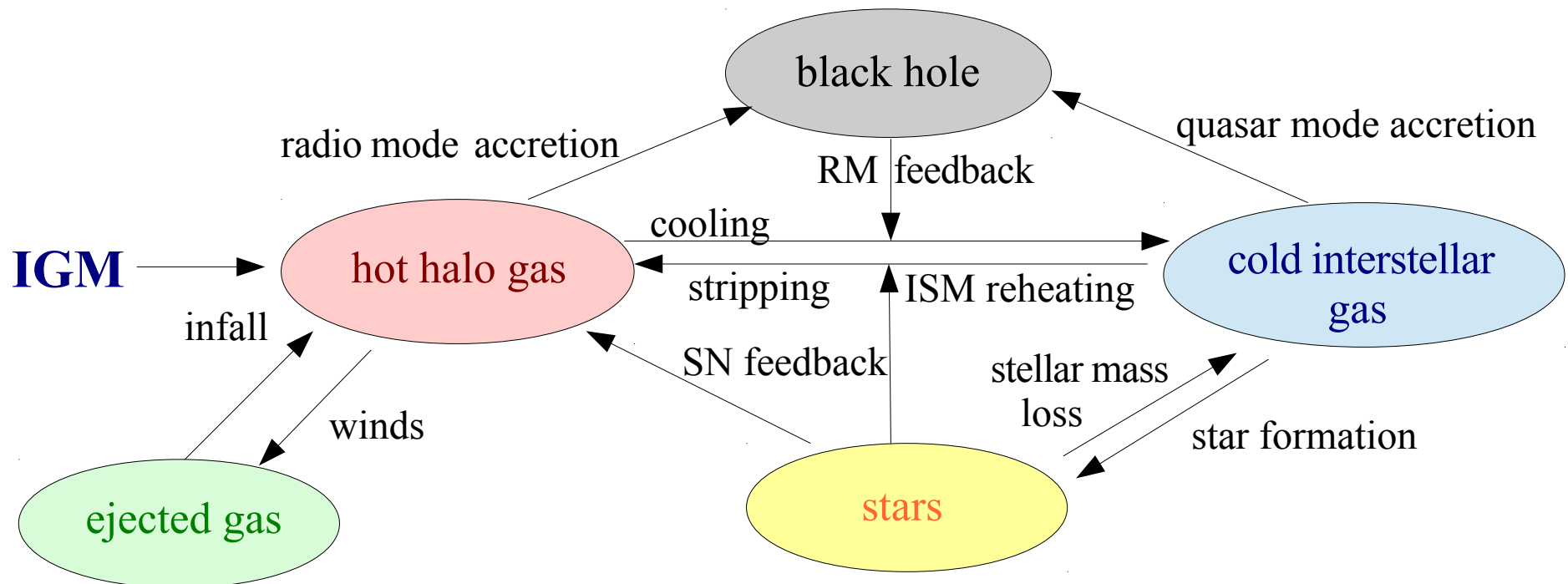


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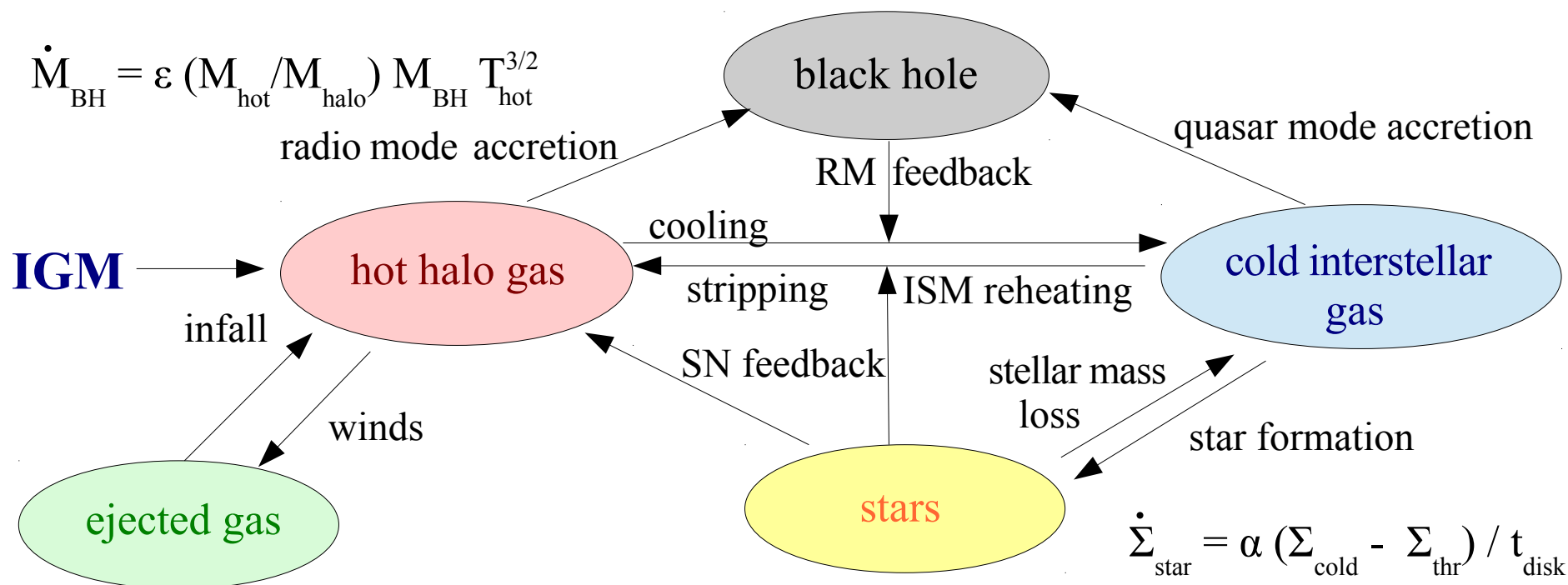


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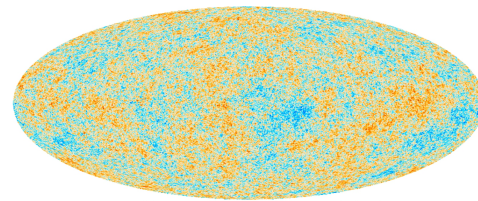
The semi-analytic programme

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.

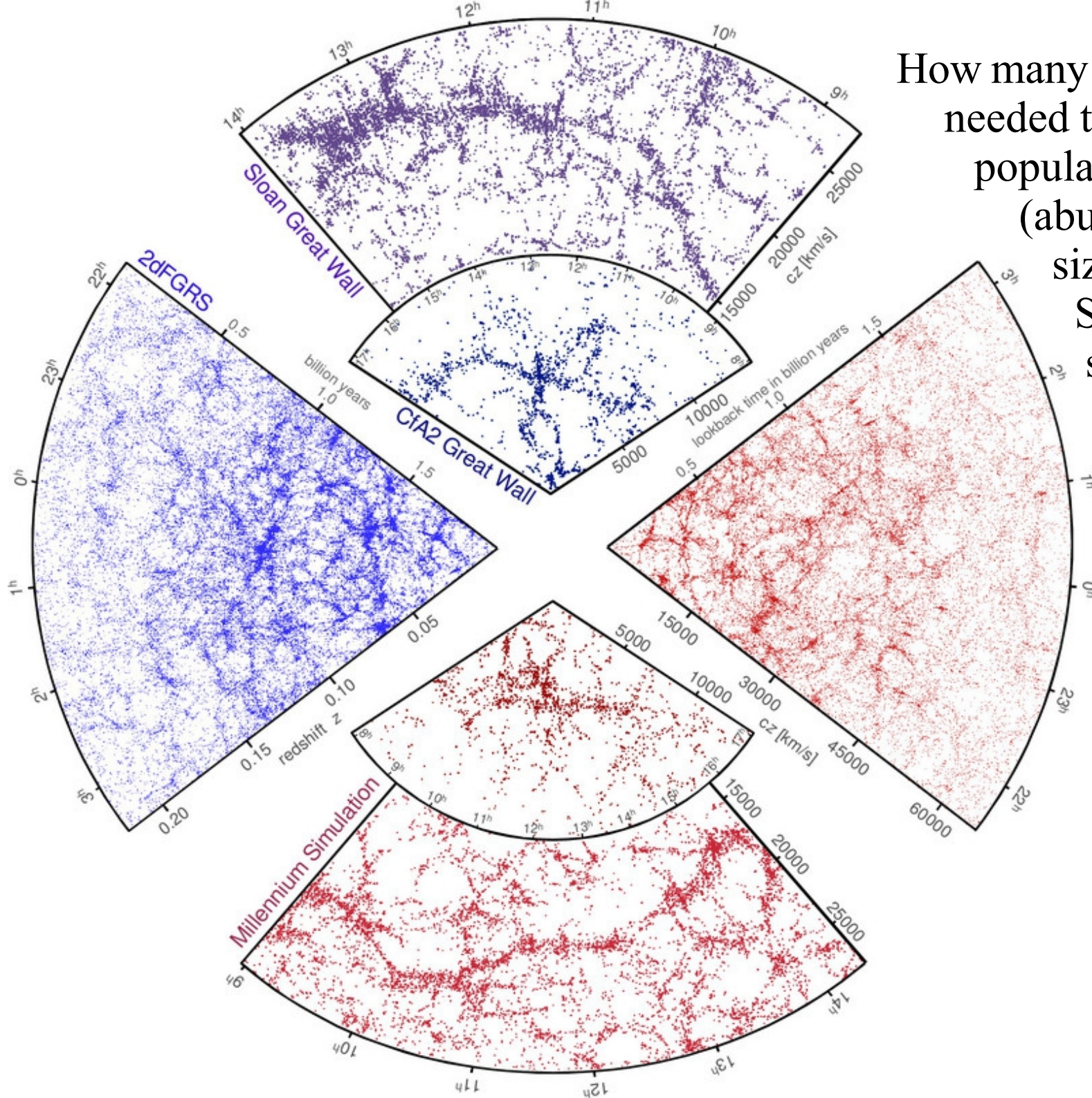


Ω

Six parameters fine-tuned to fit a single curve

Parameter	<i>Planck</i> +WP	
	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	$3.089^{+0.024}_{-0.027}$

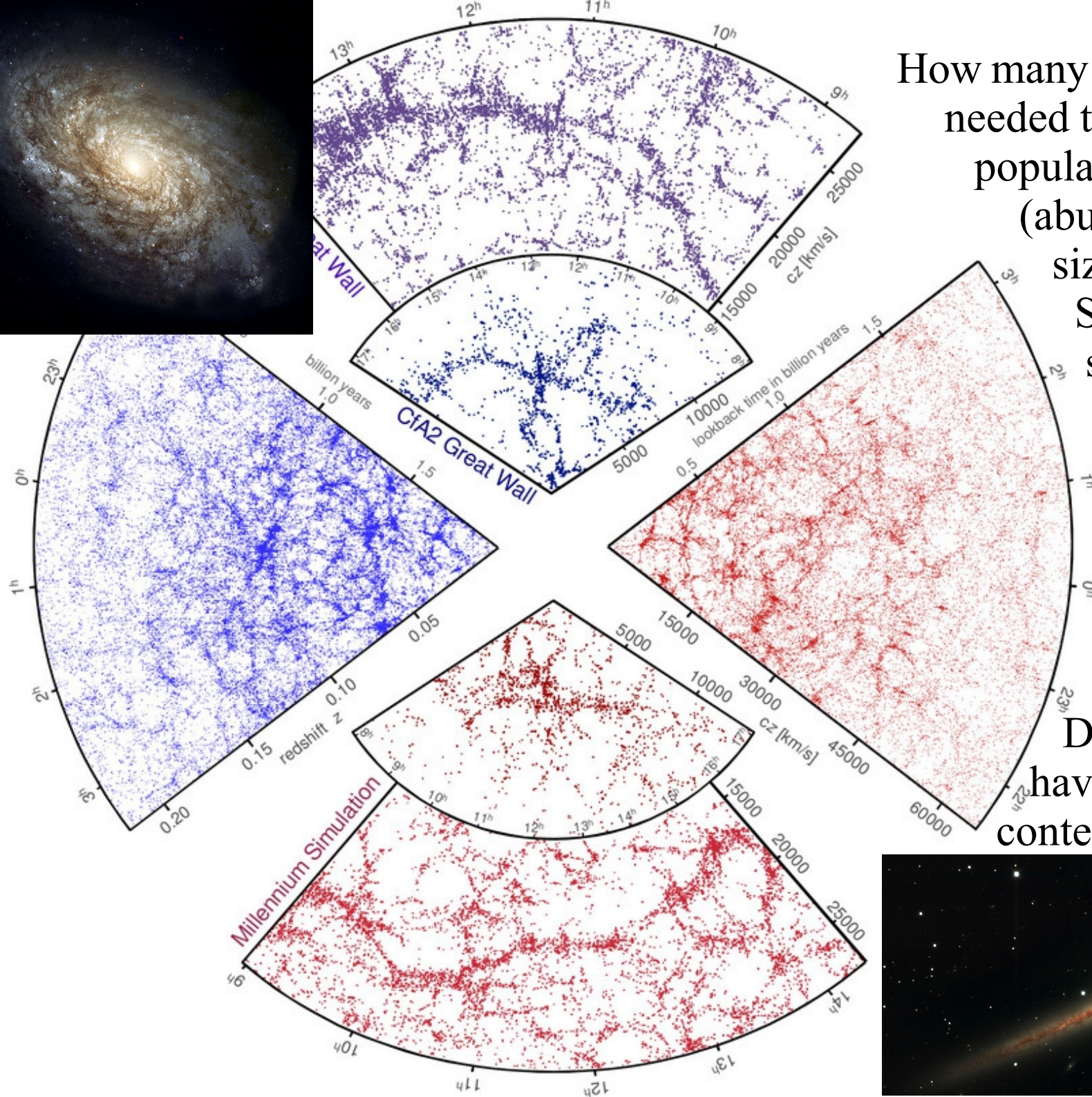
How many parameters are
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population?
(abundance by mass,
size, gas content,
SFR, B/T, AGN;
scaling relations;
clustering...)





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?

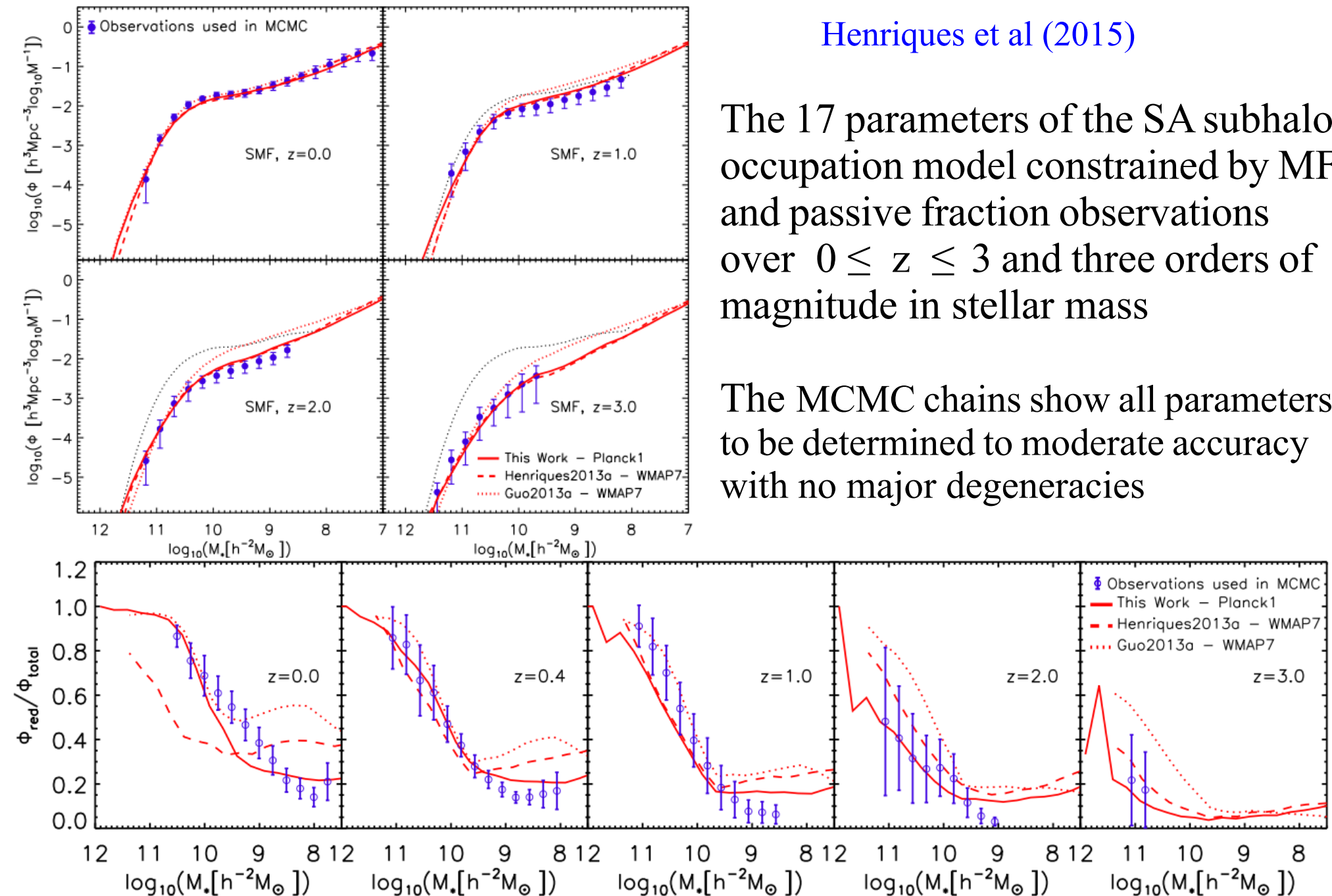


Calibrating models for (sub)halo occupation

Henriques et al (2015)

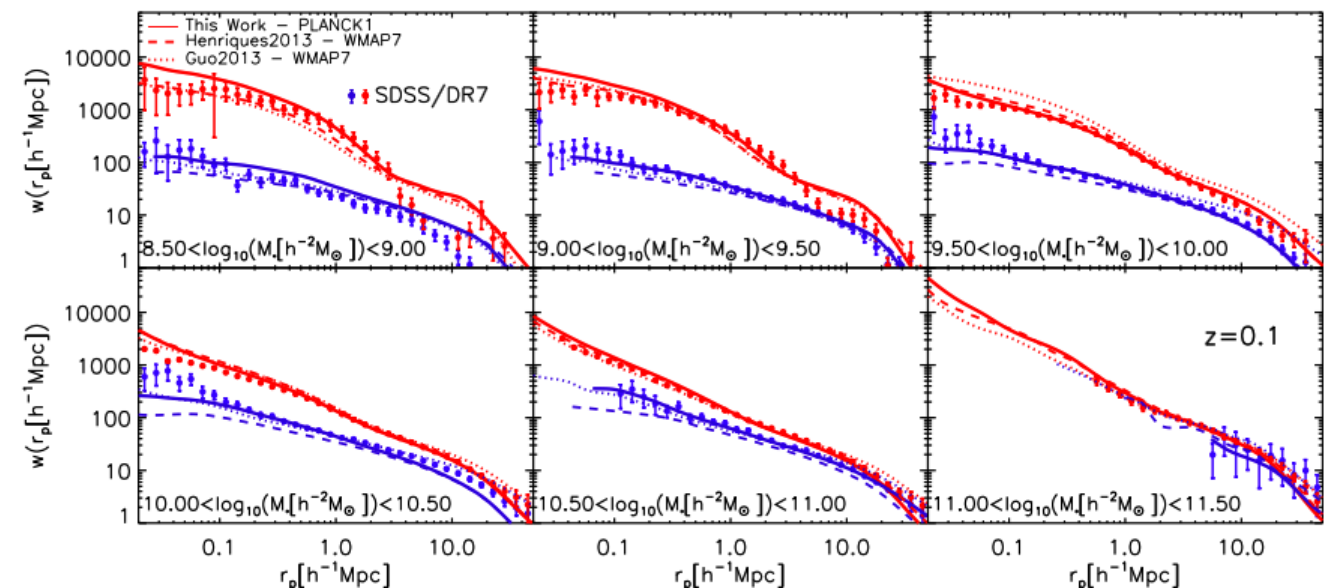
The 17 parameters of the SA subhalo occupation model constrained by MF and passive fraction observations over $0 \leq z \leq 3$ and three orders of magnitude in stellar mass

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

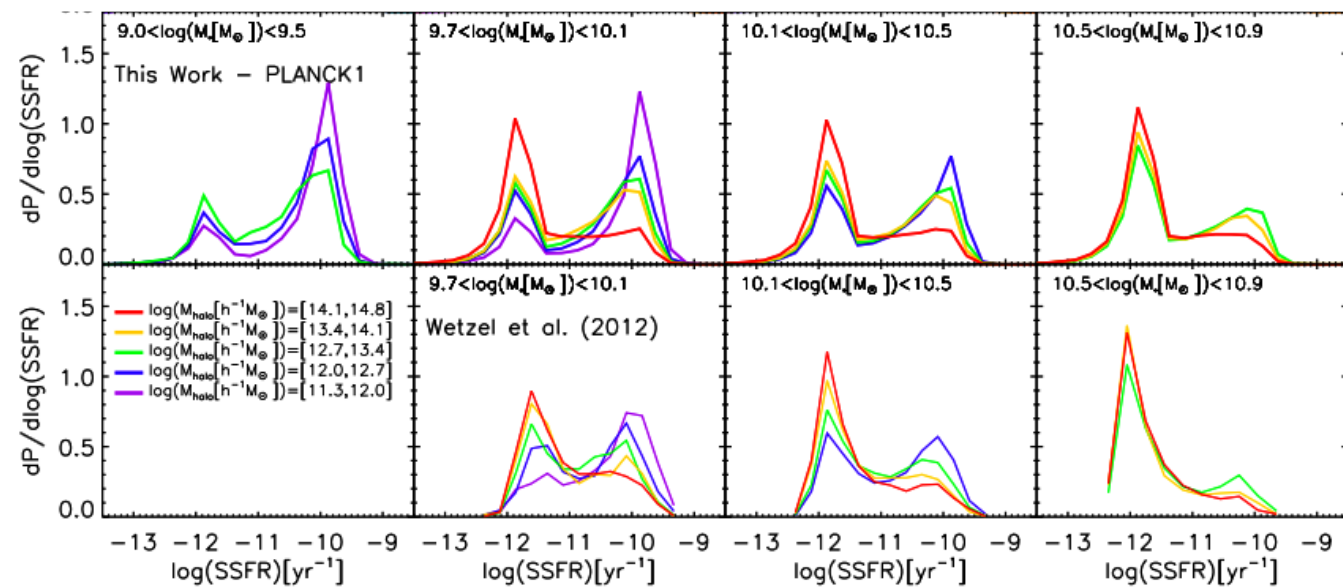


Testing semianalytic simulations

Henriques et al 2017

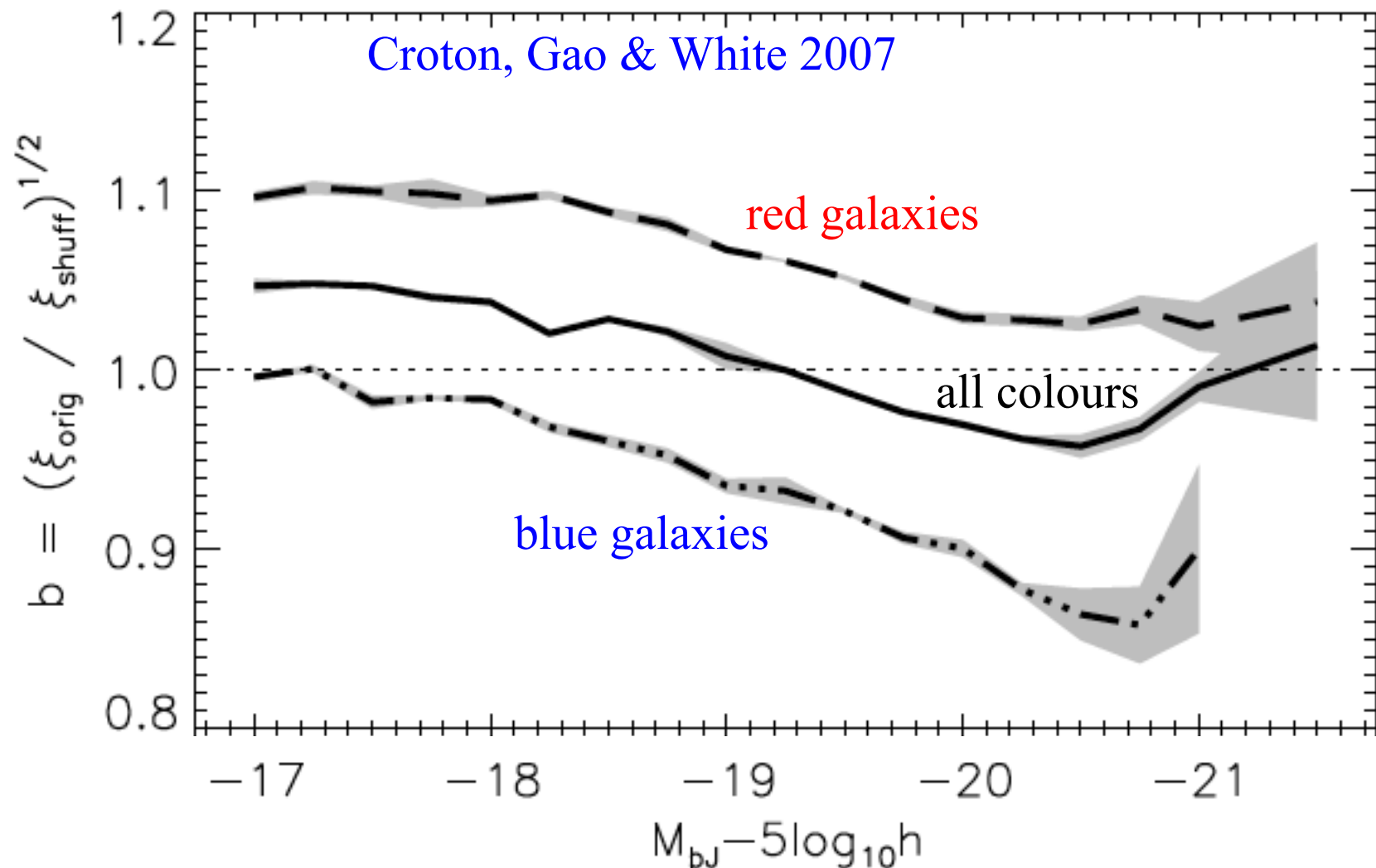


Model reproduces: $w(r_p)$ for active/passive galaxies at $r_p > 20 h^{-1}$ kpc and over 3 orders of magnitude in stellar mass



Variation of passive fraction with halo and stellar mass

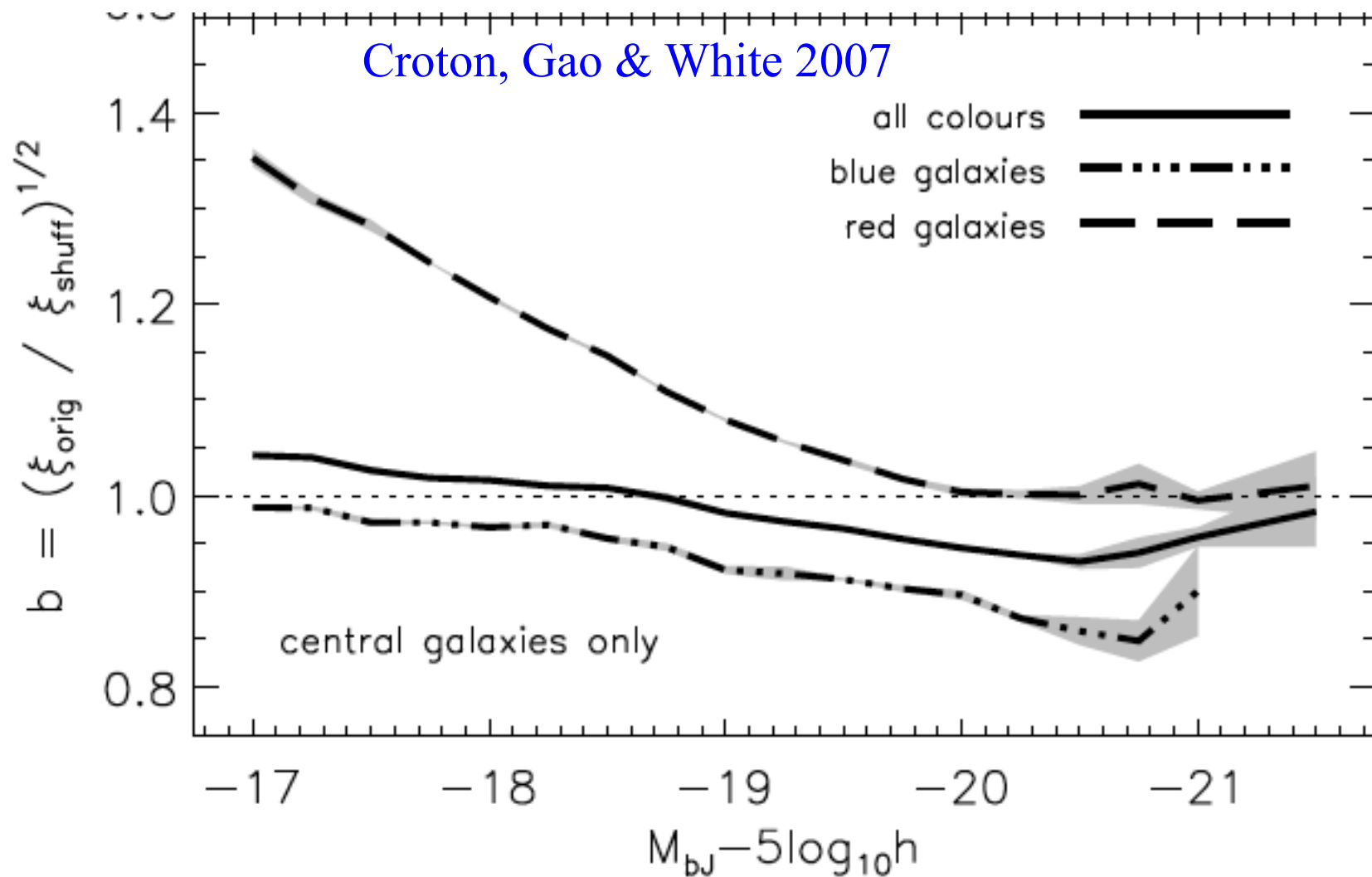
Assembly bias in the galaxy distribution



Simulated galaxy populations are shuffled among halos of similar mass
→ clustering differences due purely to assembly history differences

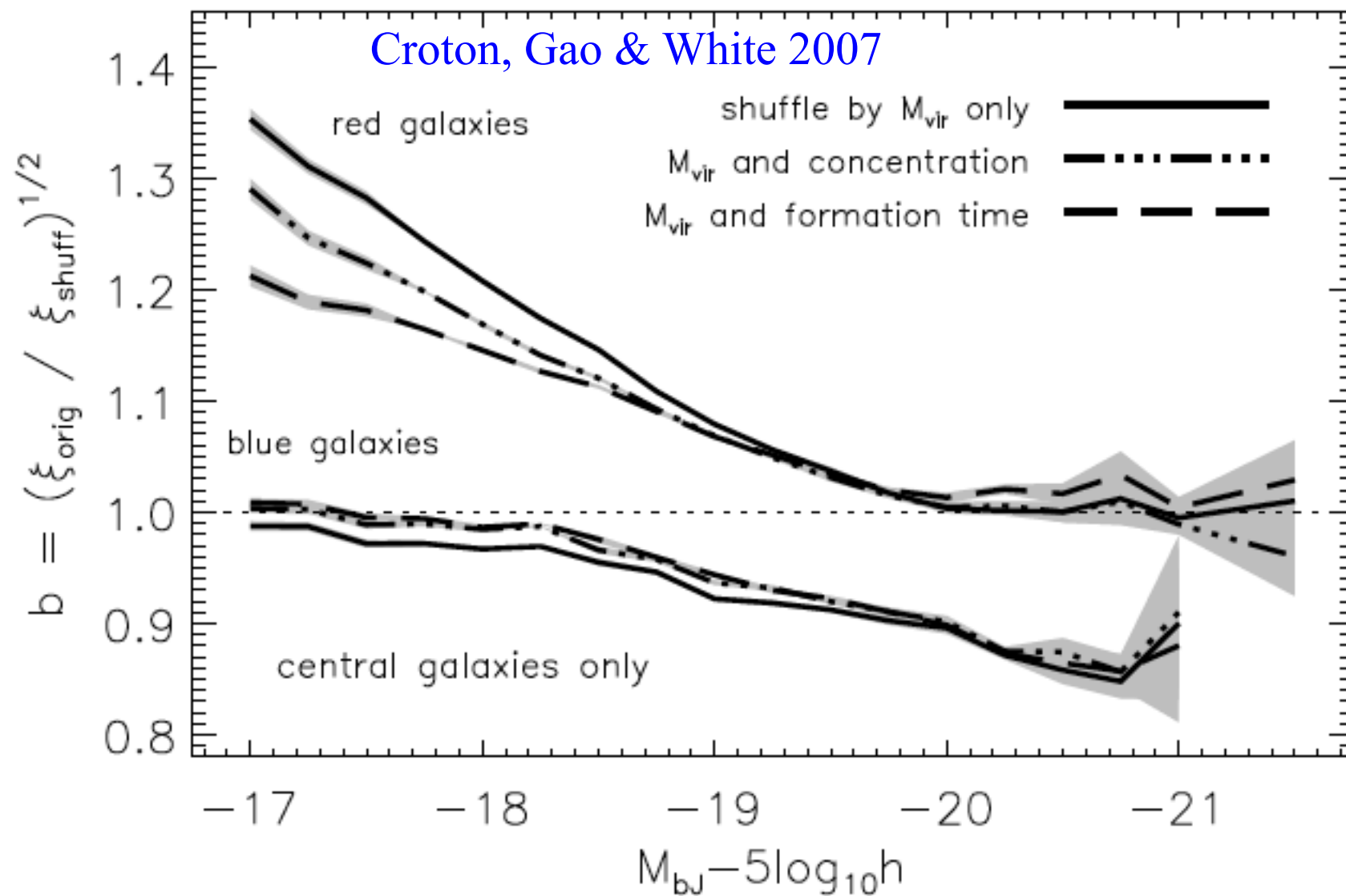
Luminosity- and colour-dependent effects at the ~10% level

Assembly bias in the galaxy distribution

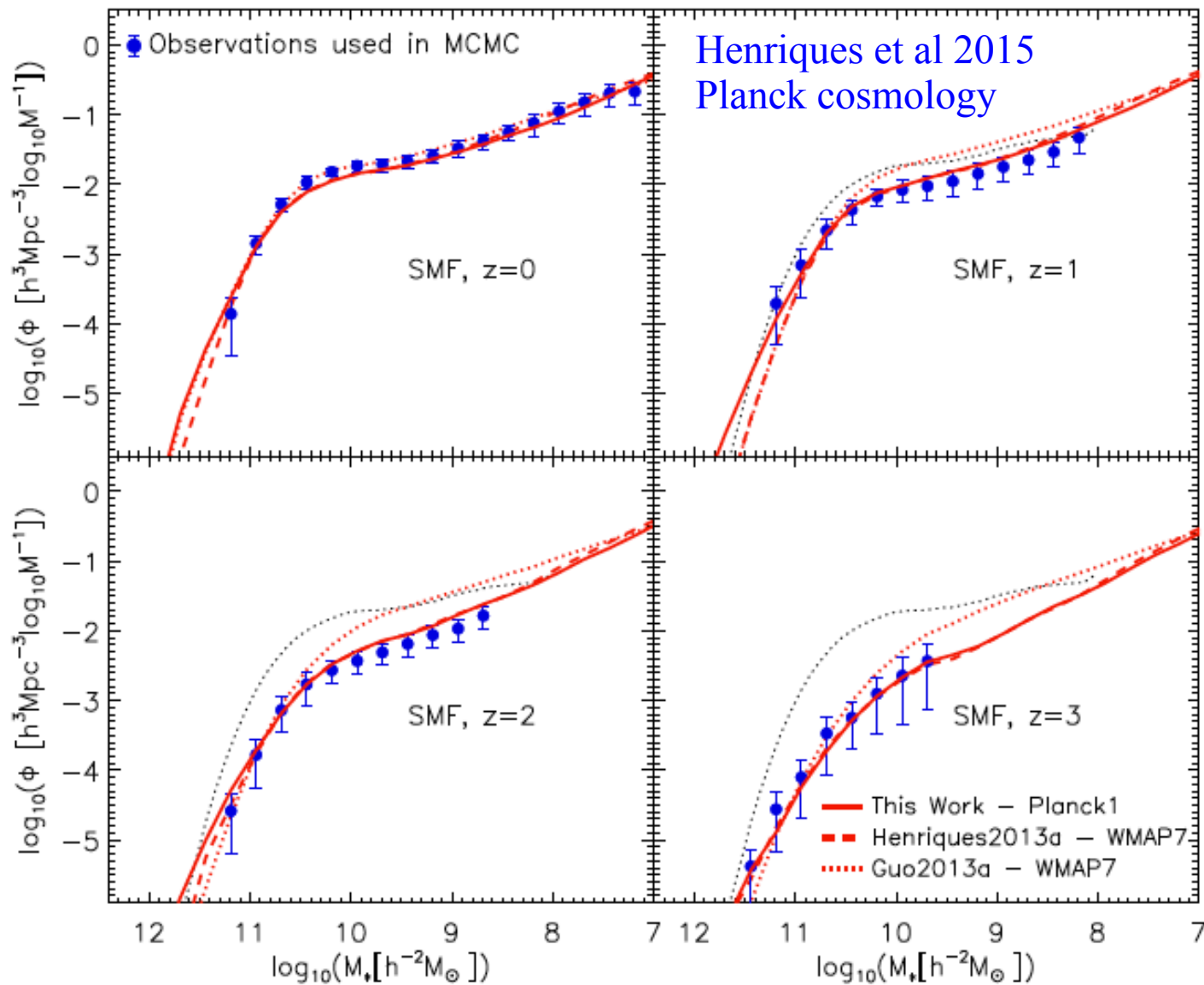


Effects are present in both central and satellite galaxy populations but differ between them

Assembly bias in the galaxy distribution



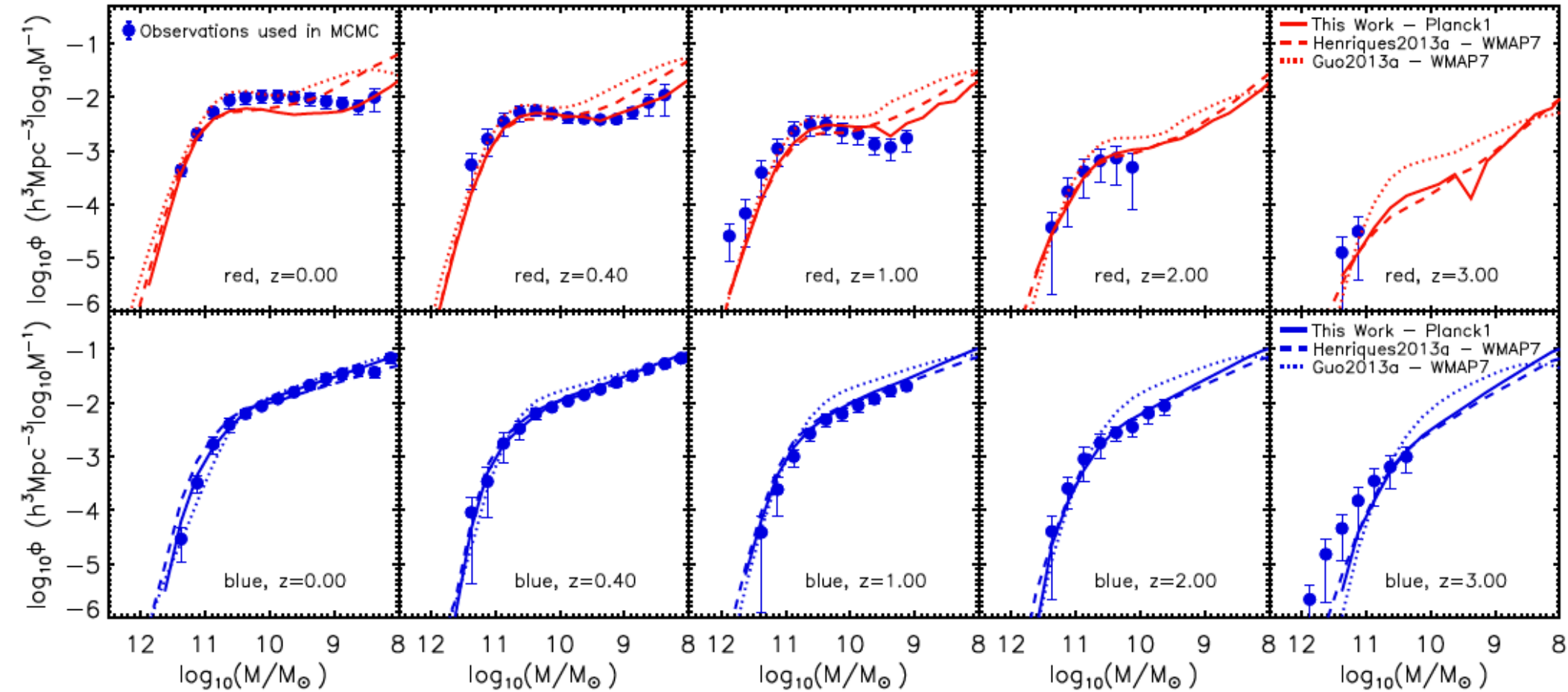
Constraining the HOD by additional halo properties (formation time, concentration) does little to reduce assembly bias effects on the galaxies



Changing the assumed timescale for reincorporation of wind ejecta

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

fits all data well for the same # of parameters as in previous models

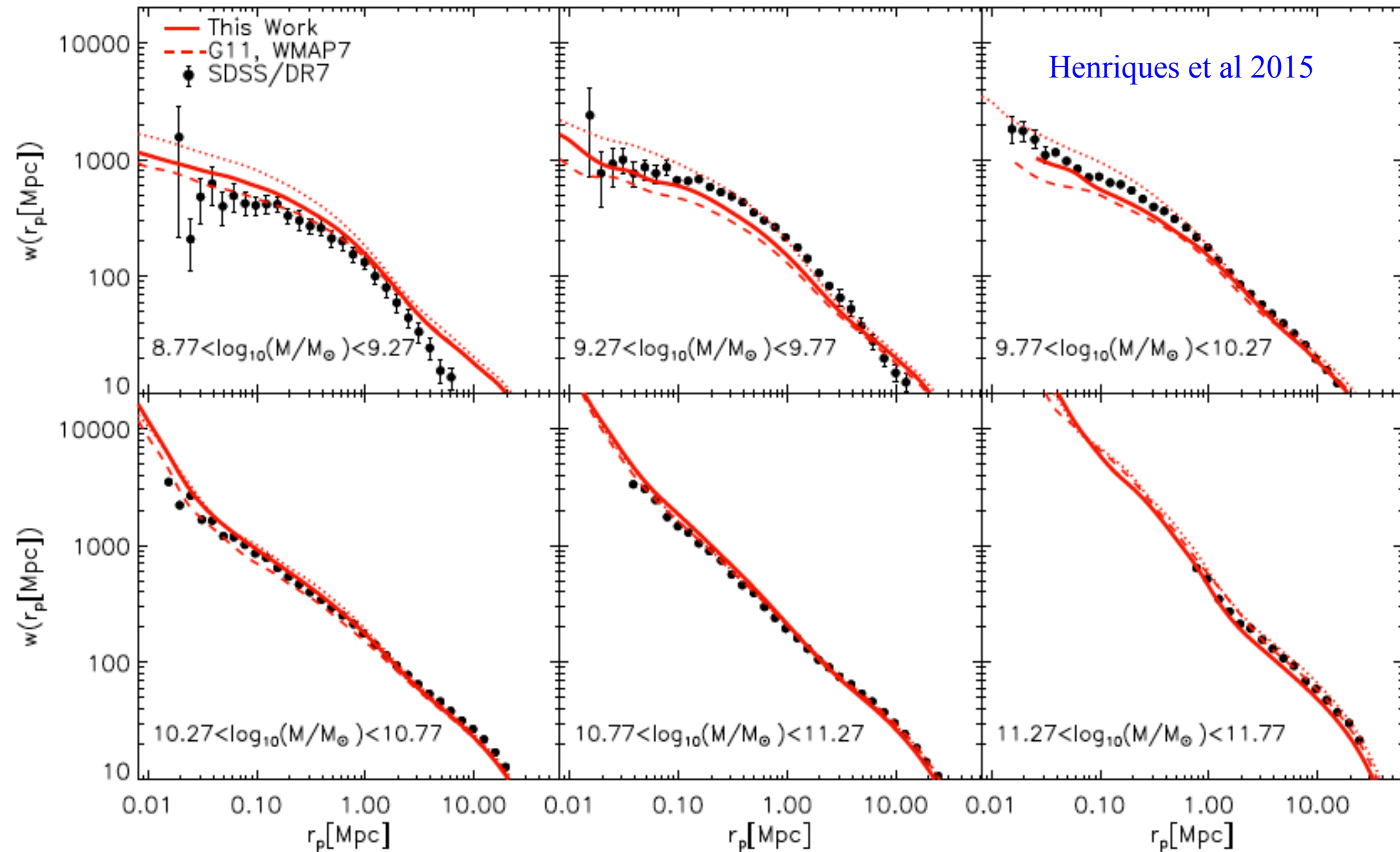


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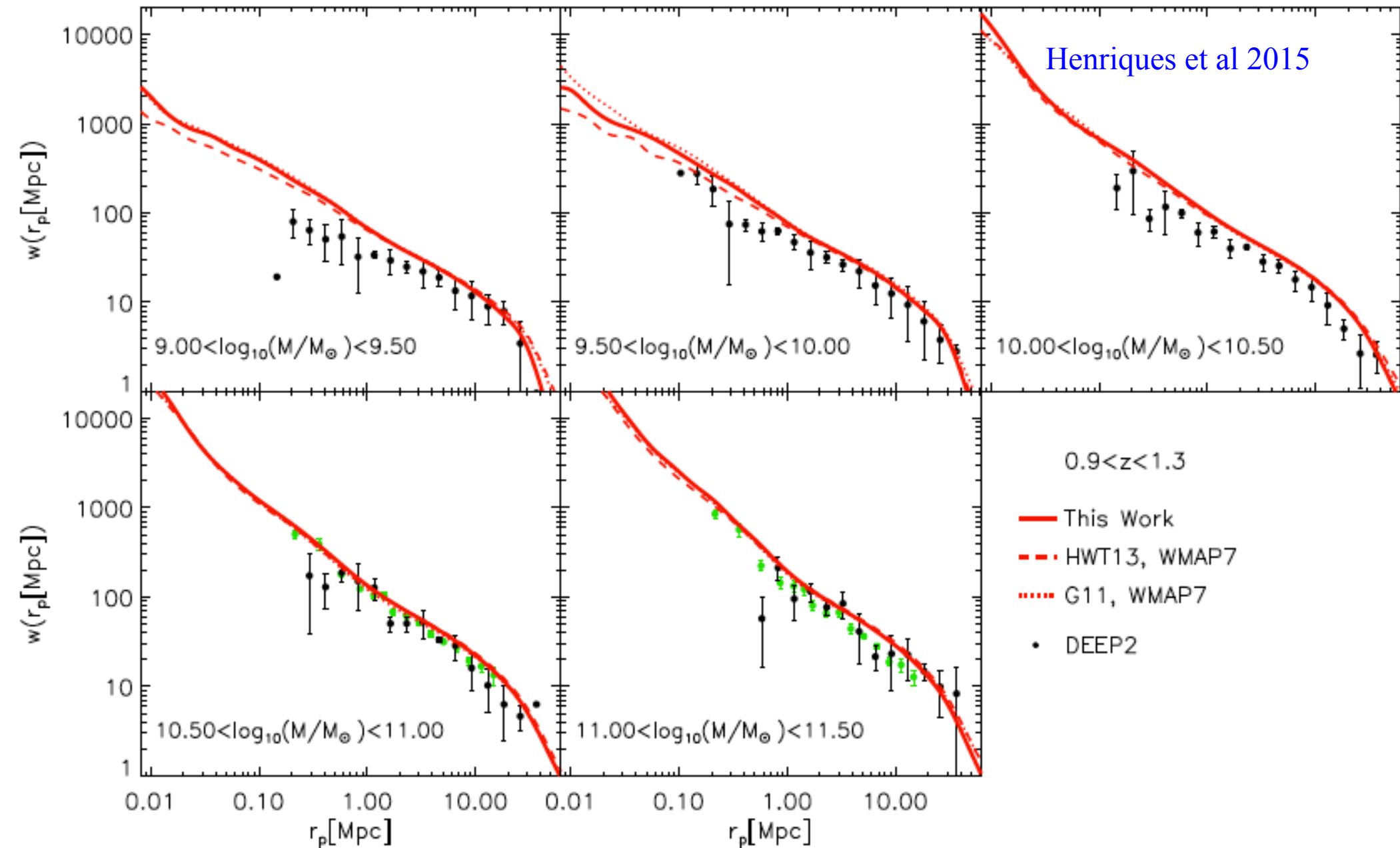
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Clustering predictions of the new simulations



High redshift clustering predictions



The MXXL (2010)

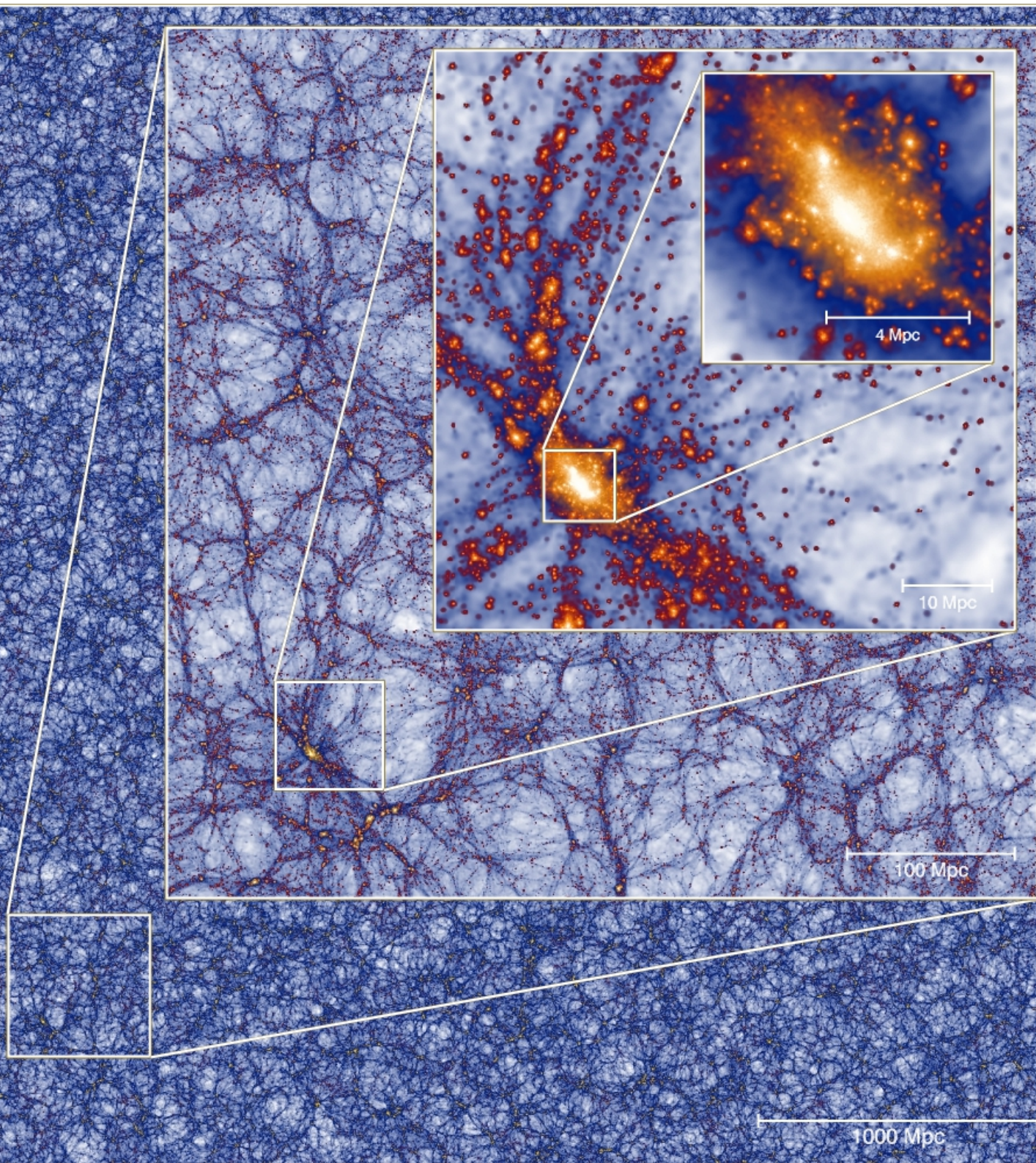
Angulo et al 2012

Bigger than the
Millennium Run
by factors of

30 in N_{particle}

200 in Volume

6 in m_{particle}



The MXXL

(2010)

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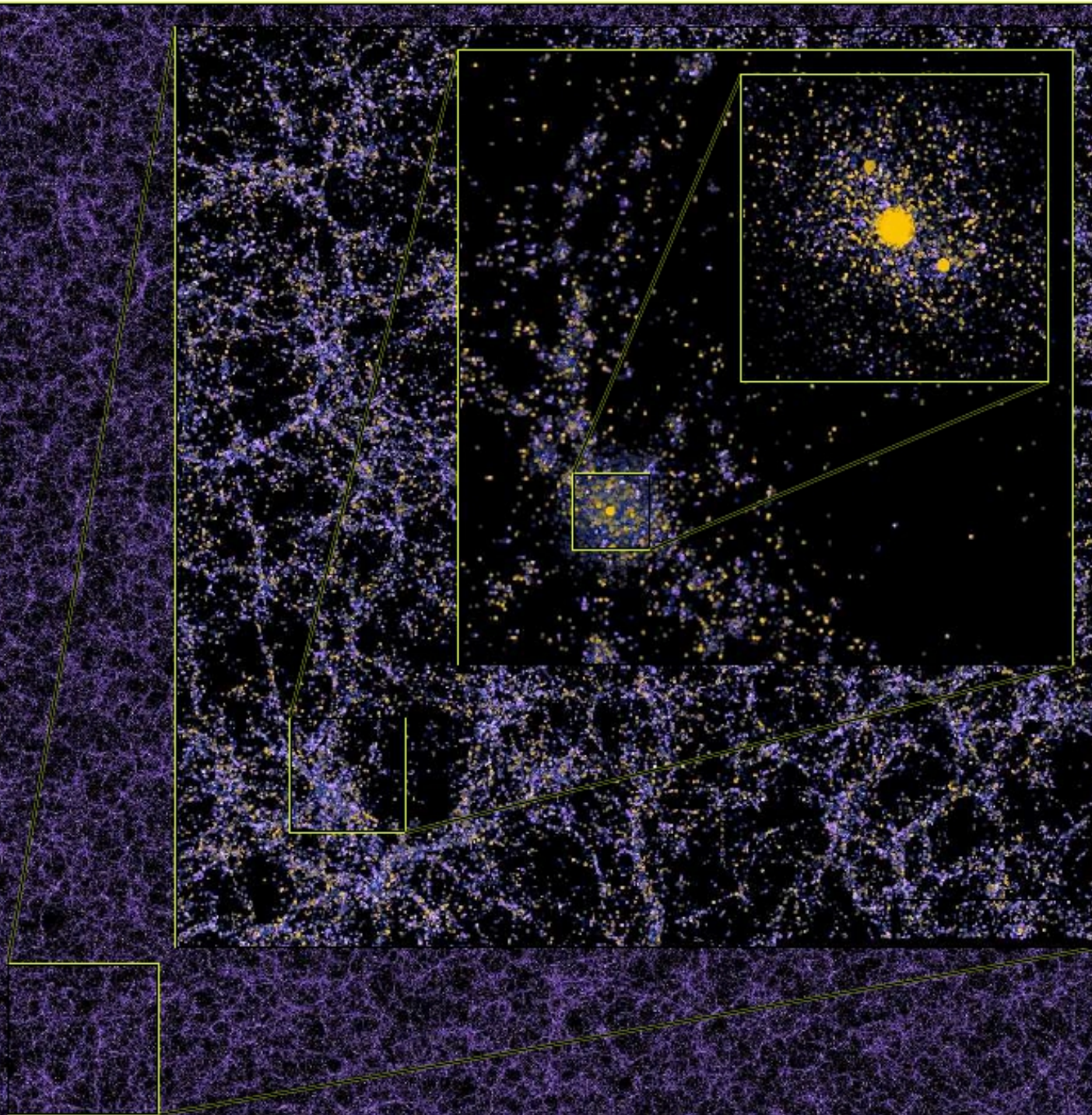
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3.3×10^8 galaxies
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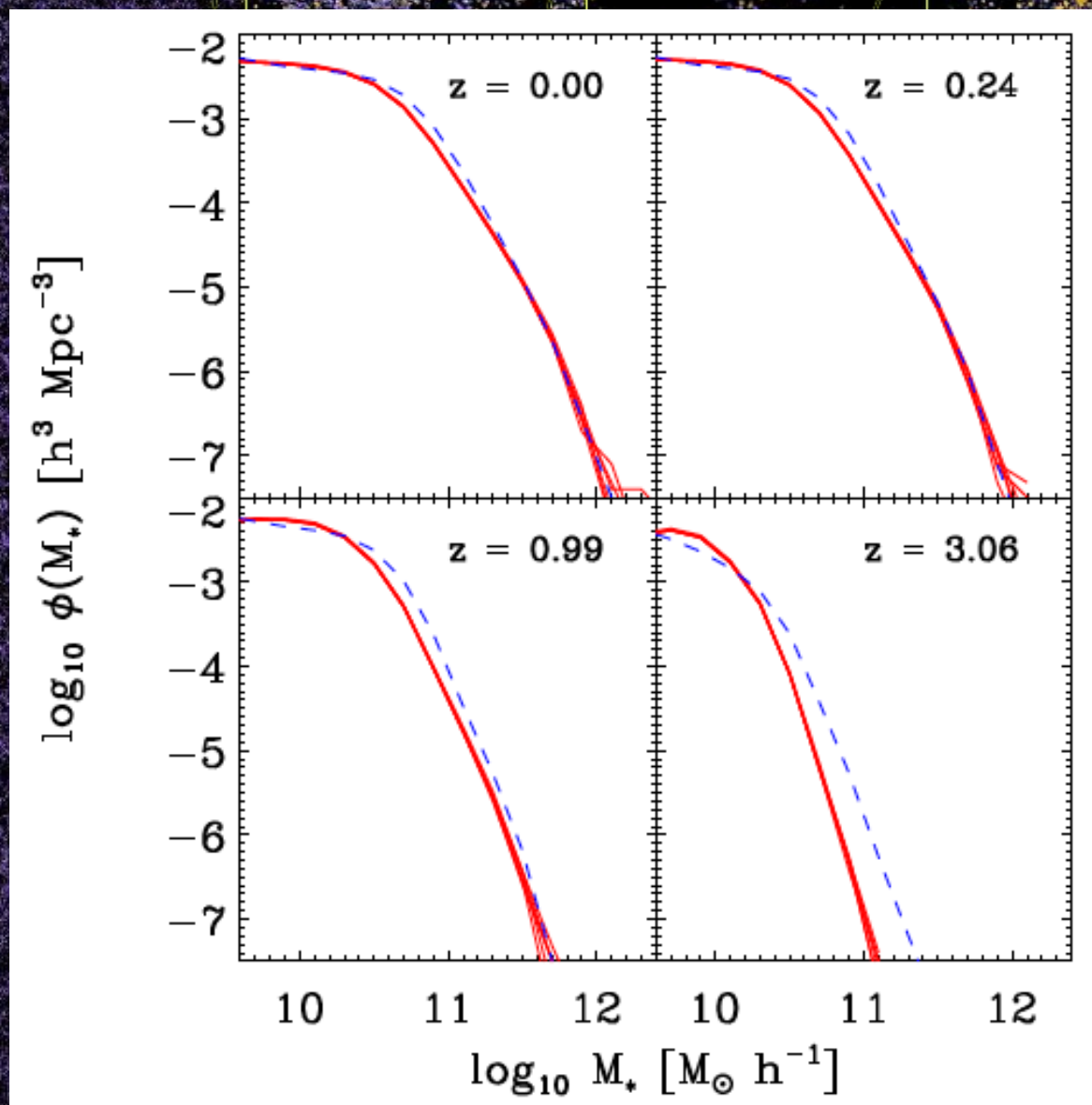
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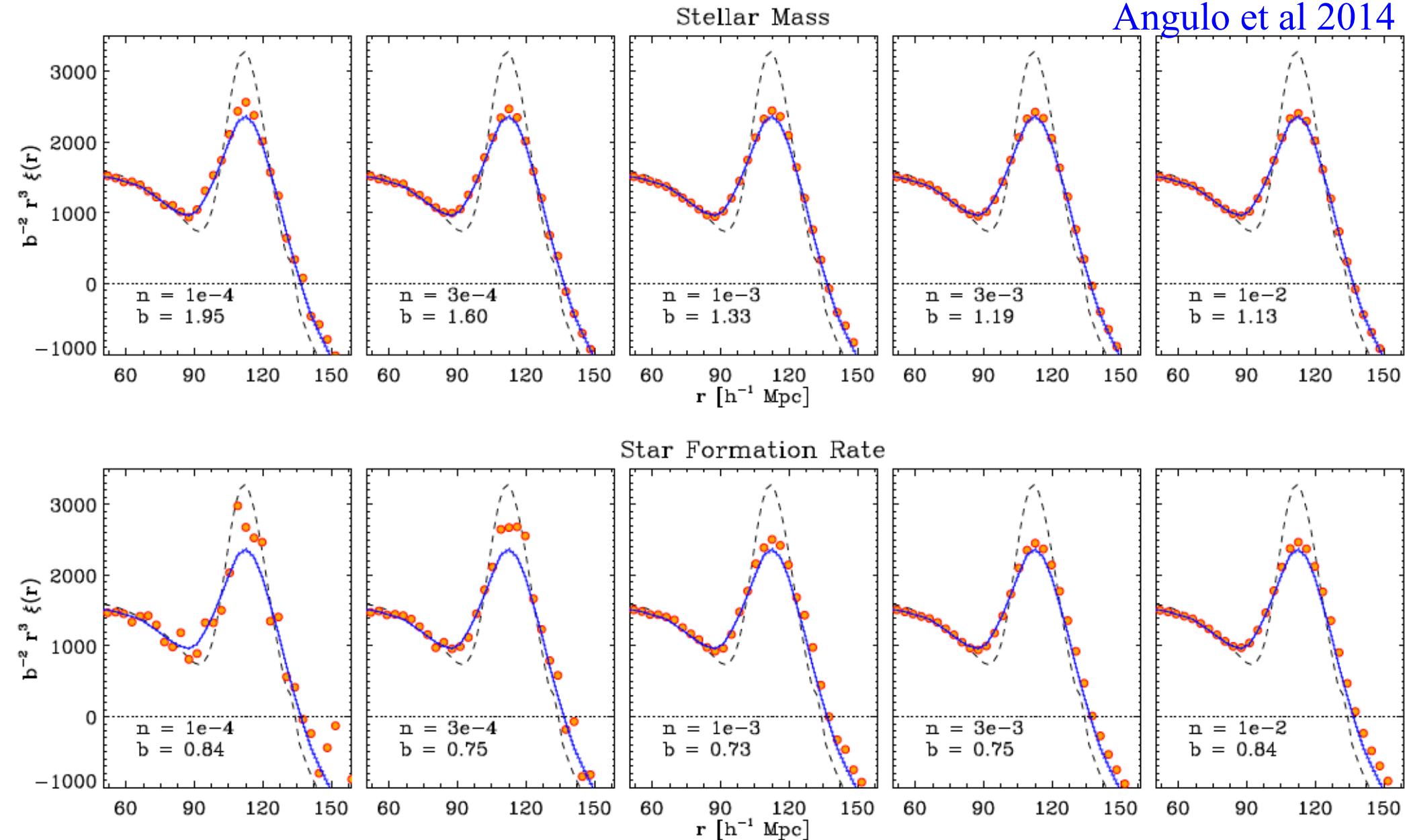
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Distortions of BAO feature in the galaxy population

Angulo et al 2014

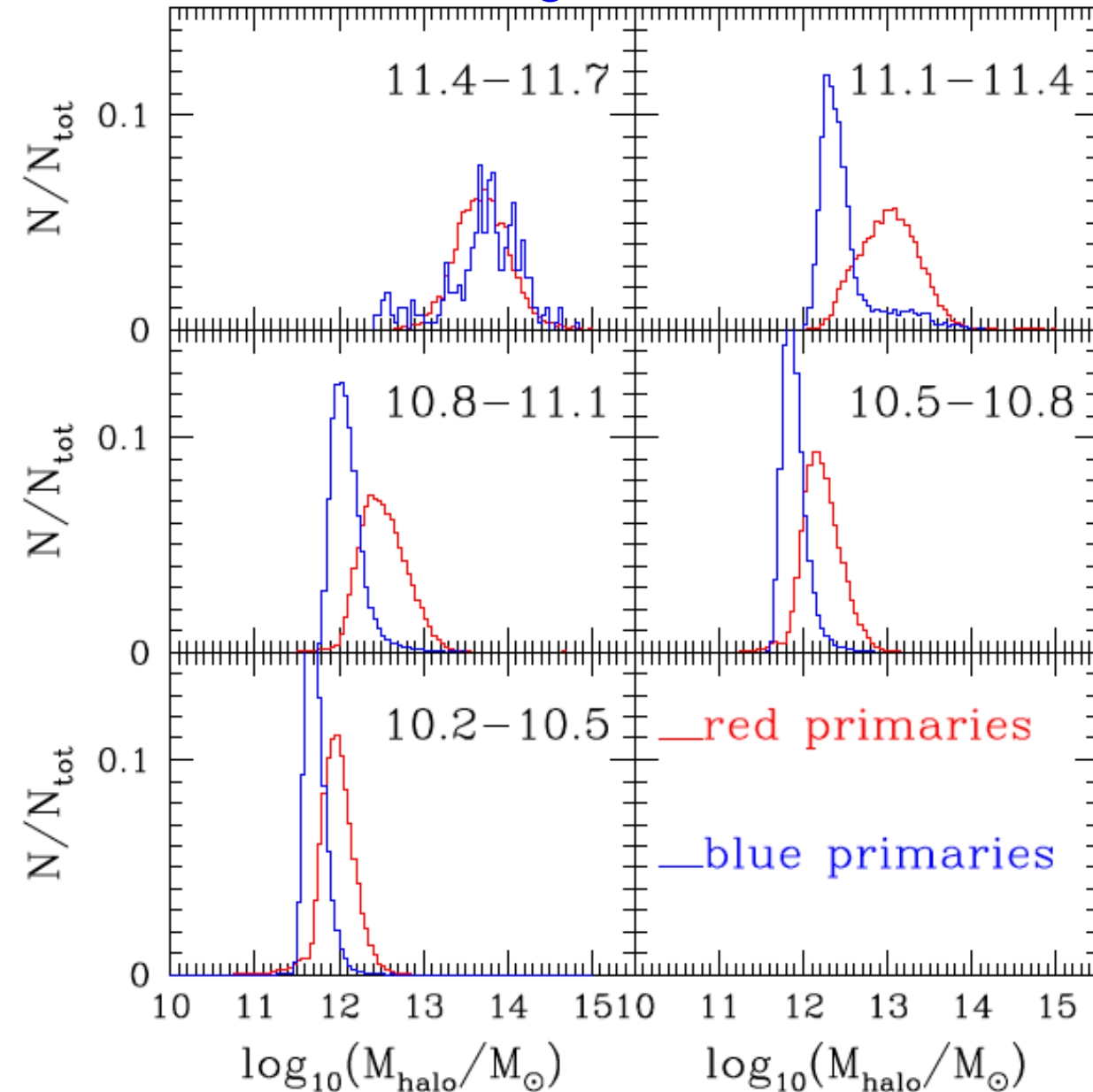


Small but measurable shifts for different selection methods

Angulo et al 2013

A population simulation prediction for galaxy halos

Wang & White 2012



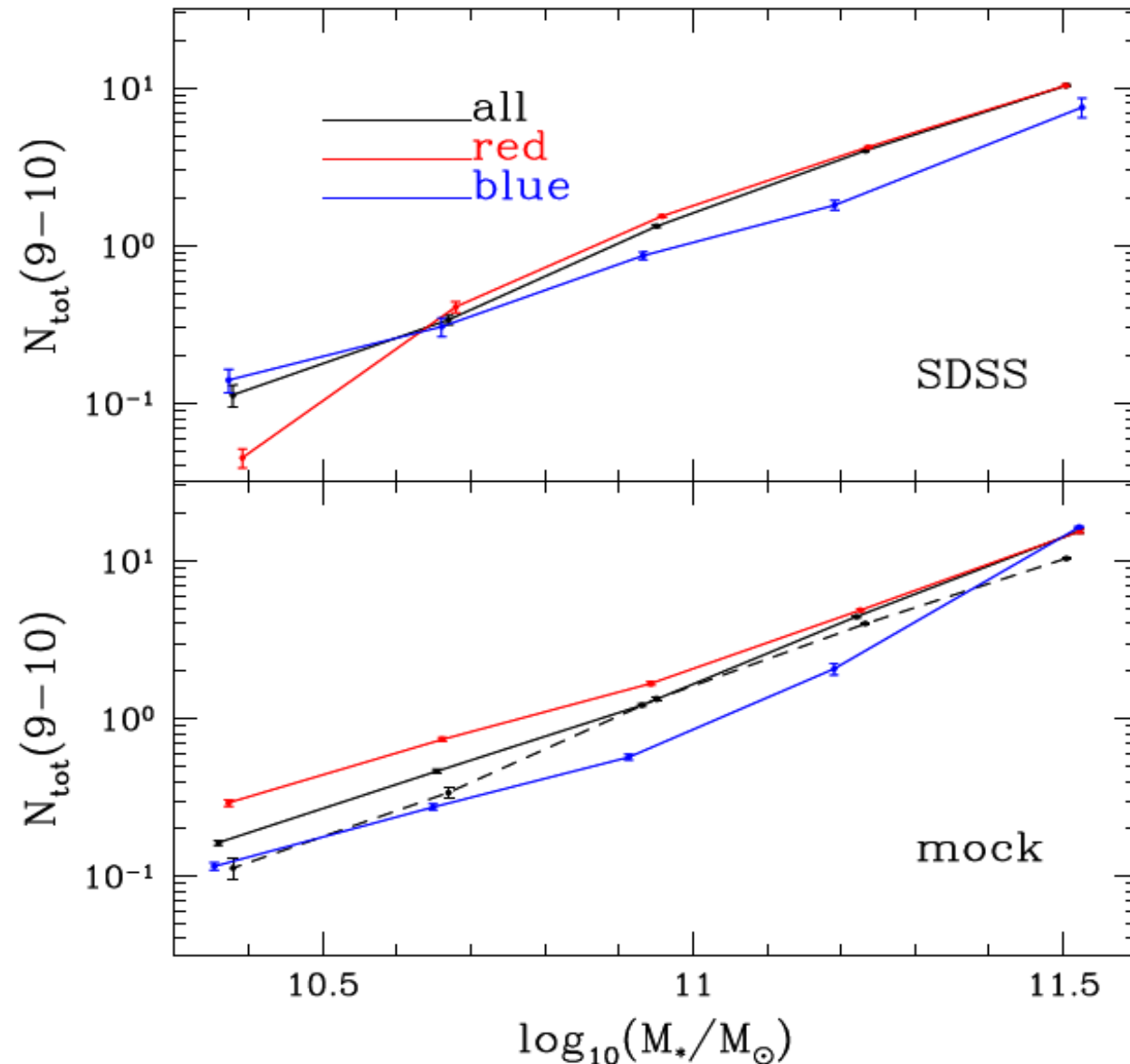
Central galaxies of a given stellar mass are predicted to have larger halo masses if they are **red** (passive) than if they are **blue** (star-forming)

This 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

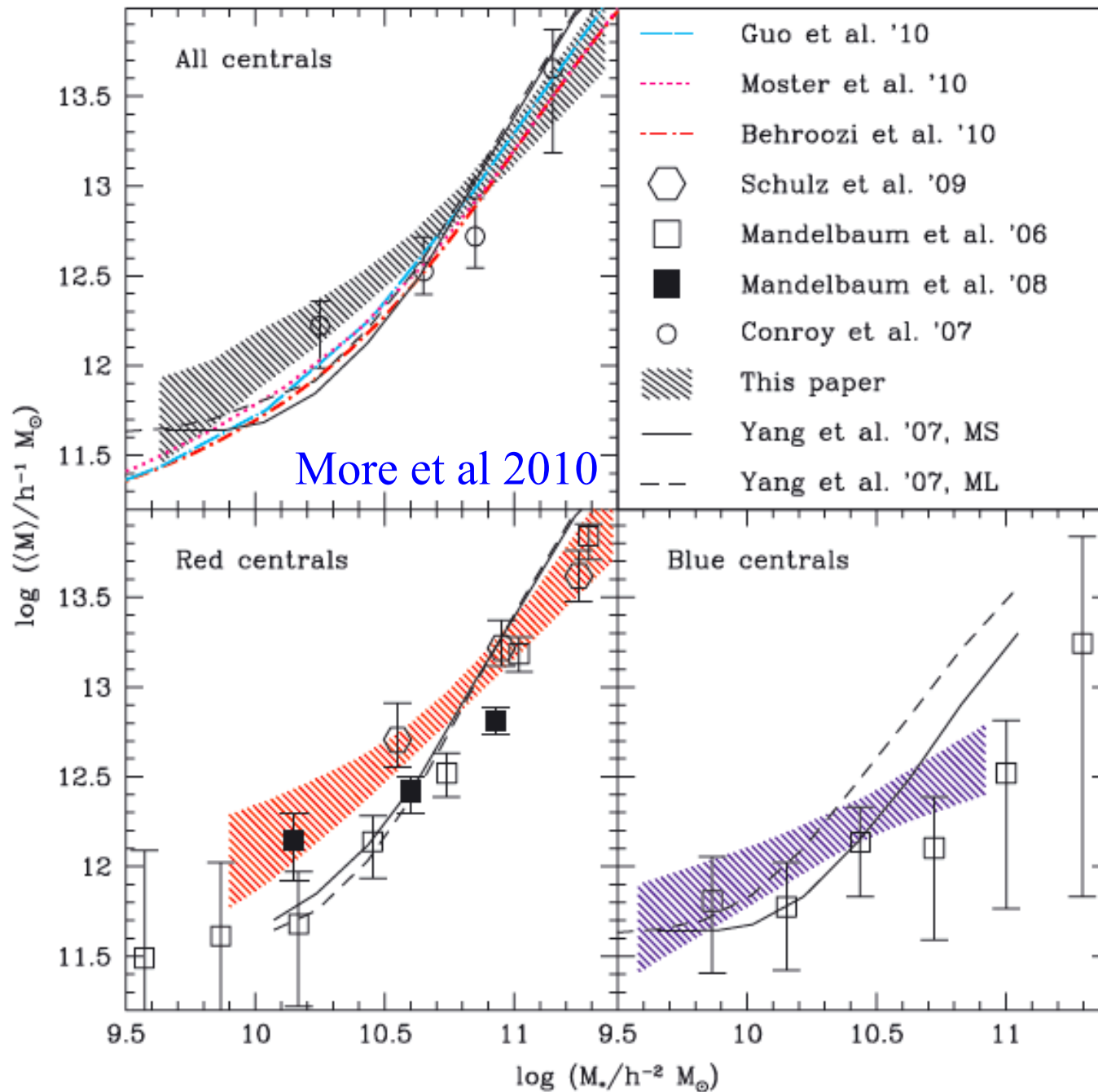


Central galaxies of a given stellar mass are predicted to have larger halo masses if they are **red** (passive) than if they are **blue** (star-forming)

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

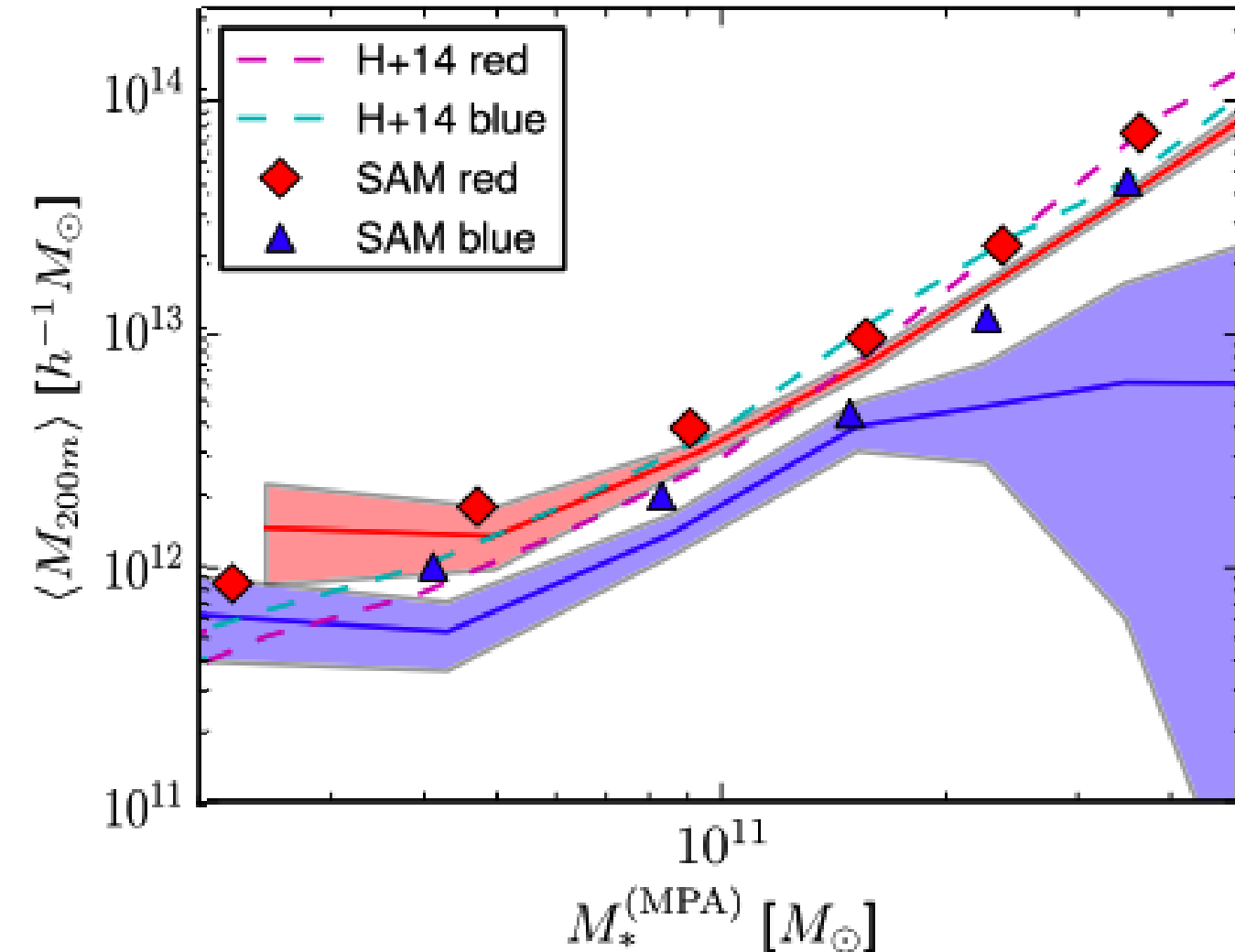
Halo mass dependence on central galaxy colour?



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

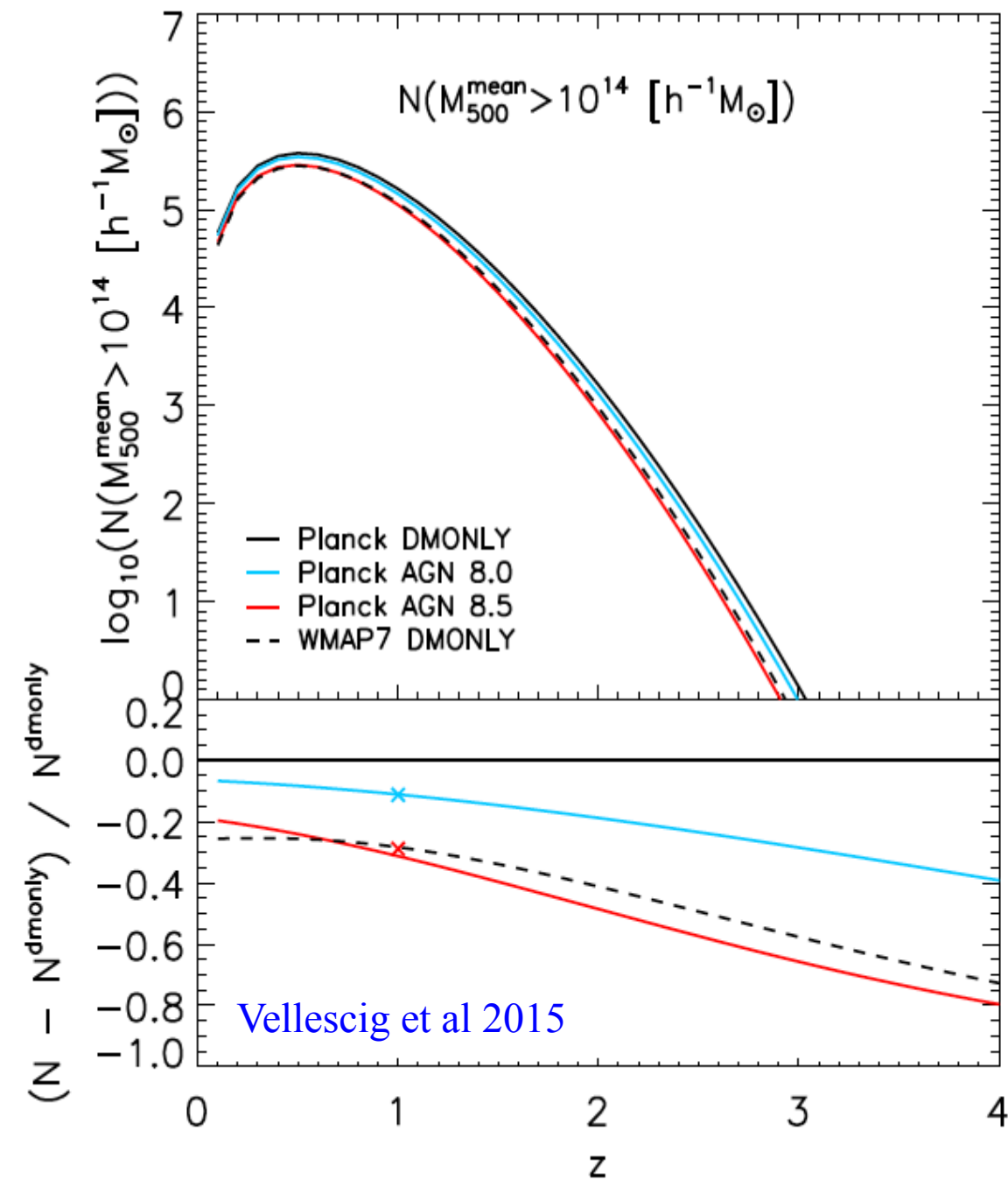
Halo mass dependence on central galaxy colour?

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

Mass distribution dependence on baryon physics

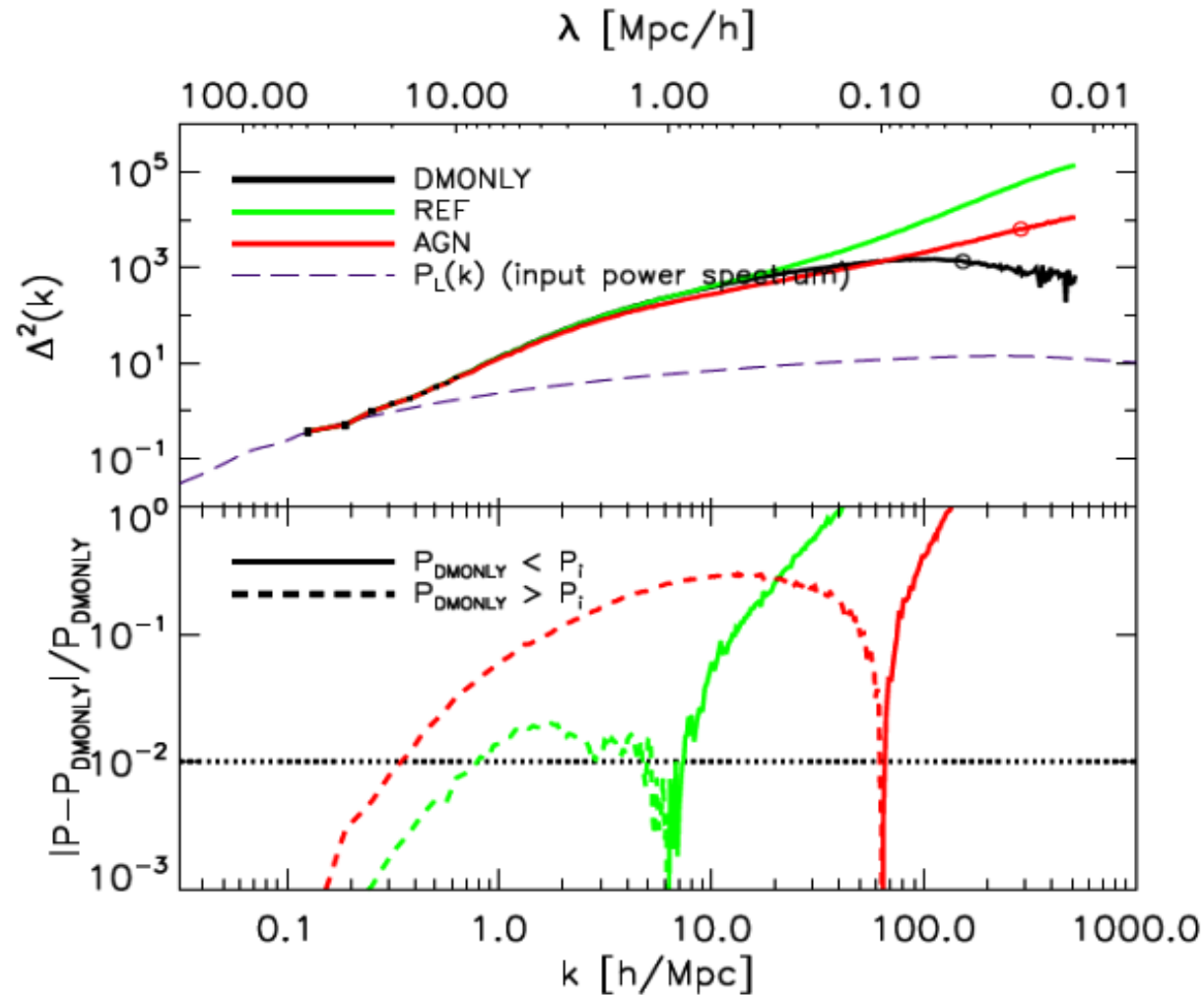


AGN feedback sufficient to suppress cooling flows in clusters can shift their mass function by an amount similar to the Planck/WMAP7 difference.

The offset increases with redshift in these models

It is smaller for higher mass thresholds

Mass distribution dependence on baryon physics



AGN feedback sufficient to match the stellar mass function of galaxies at high mass affects the power spectrum of the total mass distribution at $> 1\%$ for $k > 0.3 \text{ h/Mpc}$

This will affect the small-scale lensing power spectrum.

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 $k \sim 0.3 \text{ h/Mpc}$

All these effects depend on the details of galaxy formation physics

None is easily included in the HOD or SHAM modelling frameworks