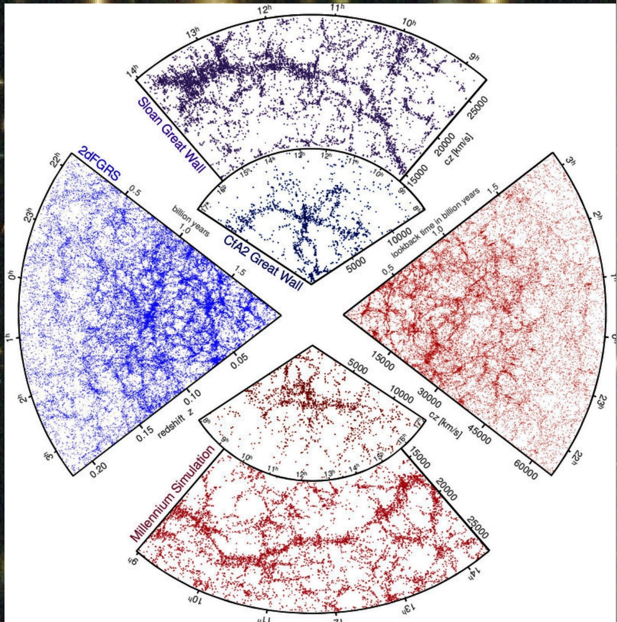
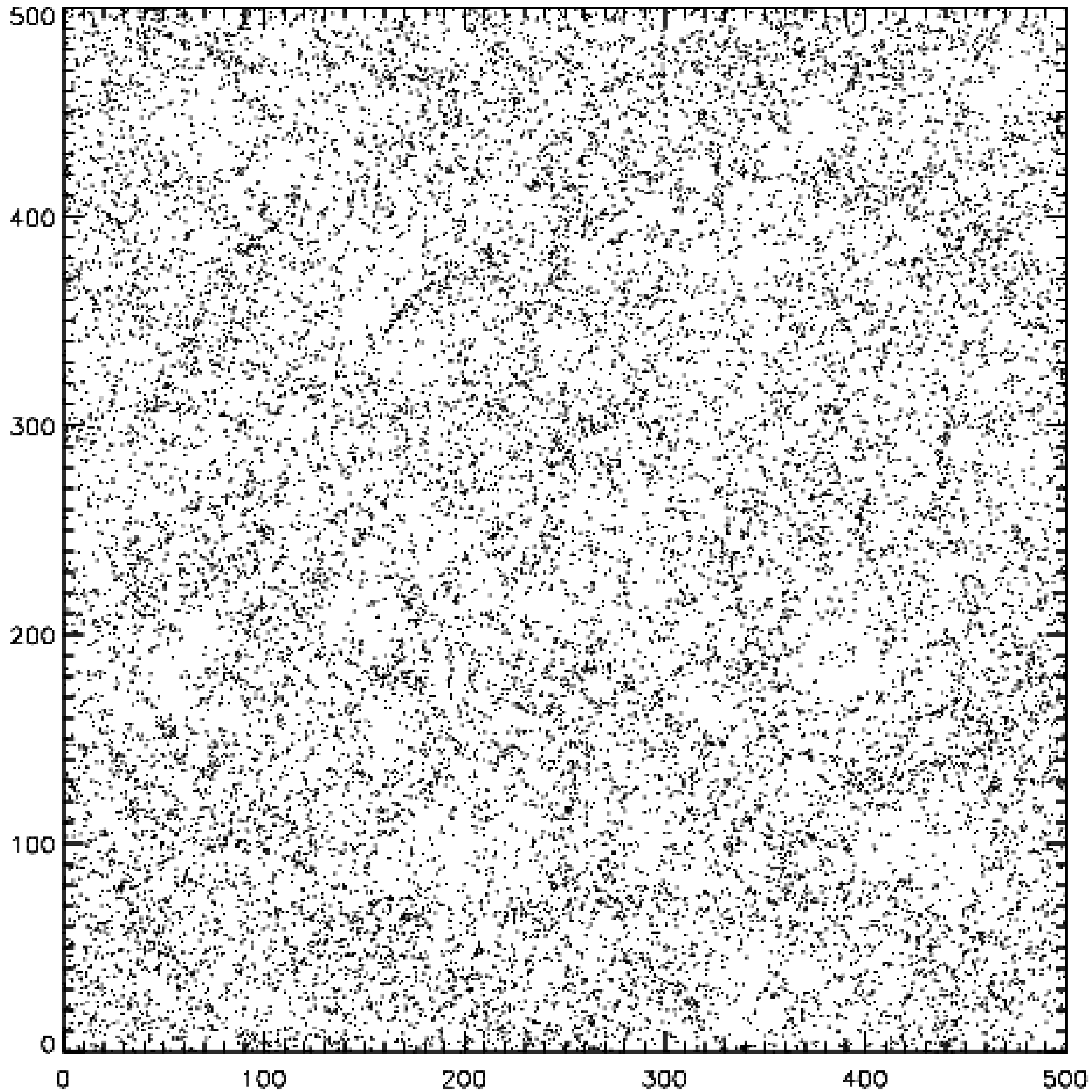
The halo-galaxy connection
KITP, May 2017`

Assembly bias



Simon White
Max Planck Institute for Astrophysics

Halo clustering depends on formation history

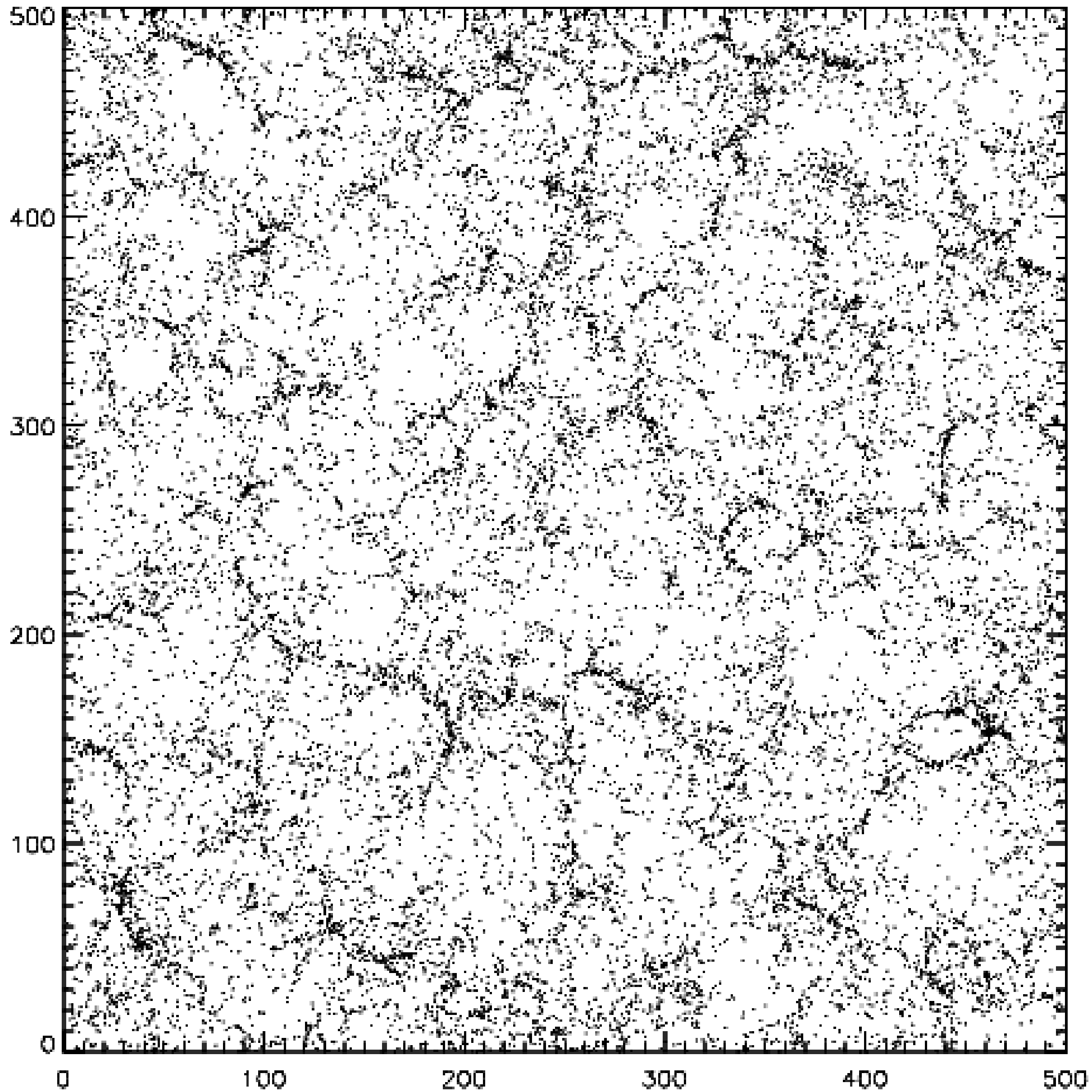


Gao, Springel & White 2005

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

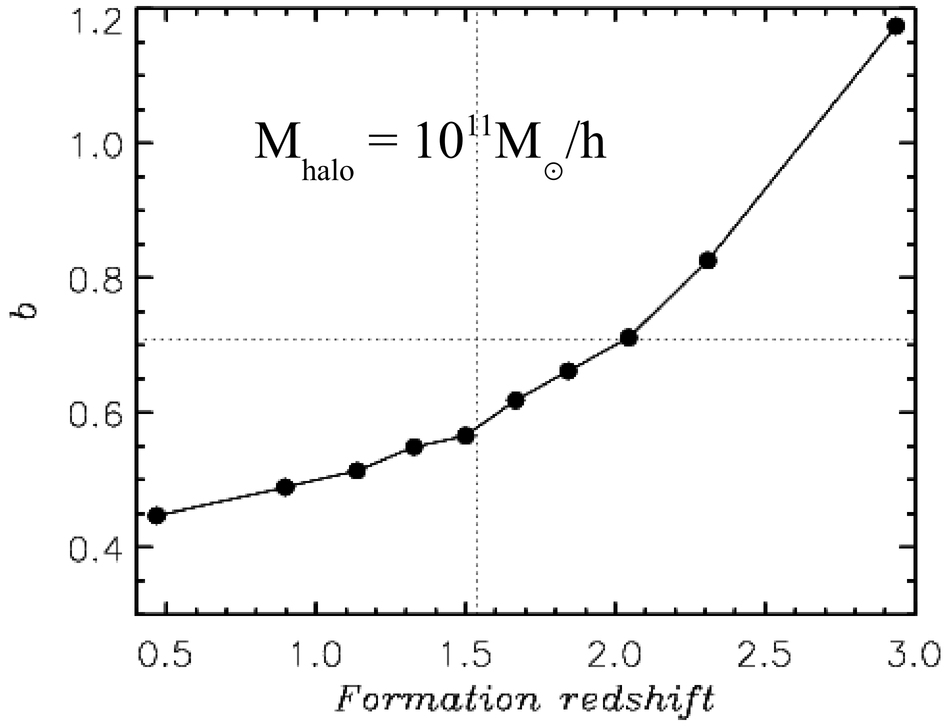


Gao, Springel & White 2005

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

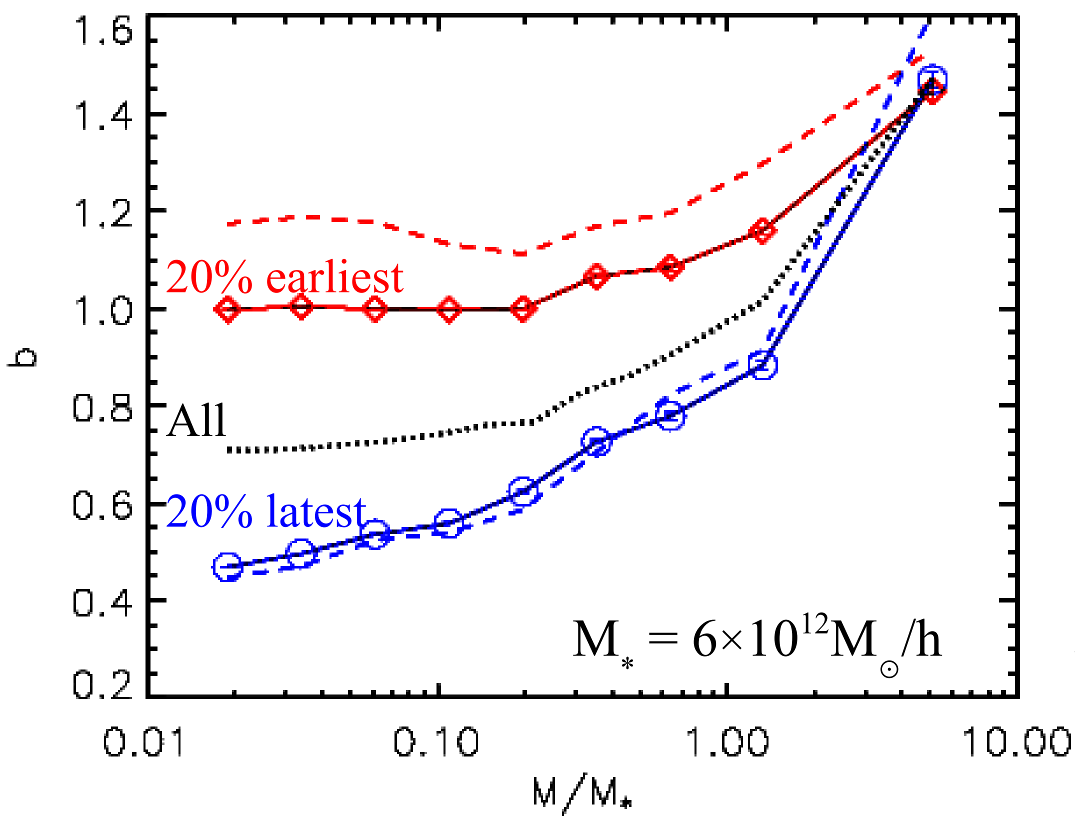
$$M_{halo} \sim 10^{11} M_{\odot}$$

Halo bias as a function of mass and formation time



Gao, Springel & White 2005

On large scales halo bias increases smoothly with formation redshift

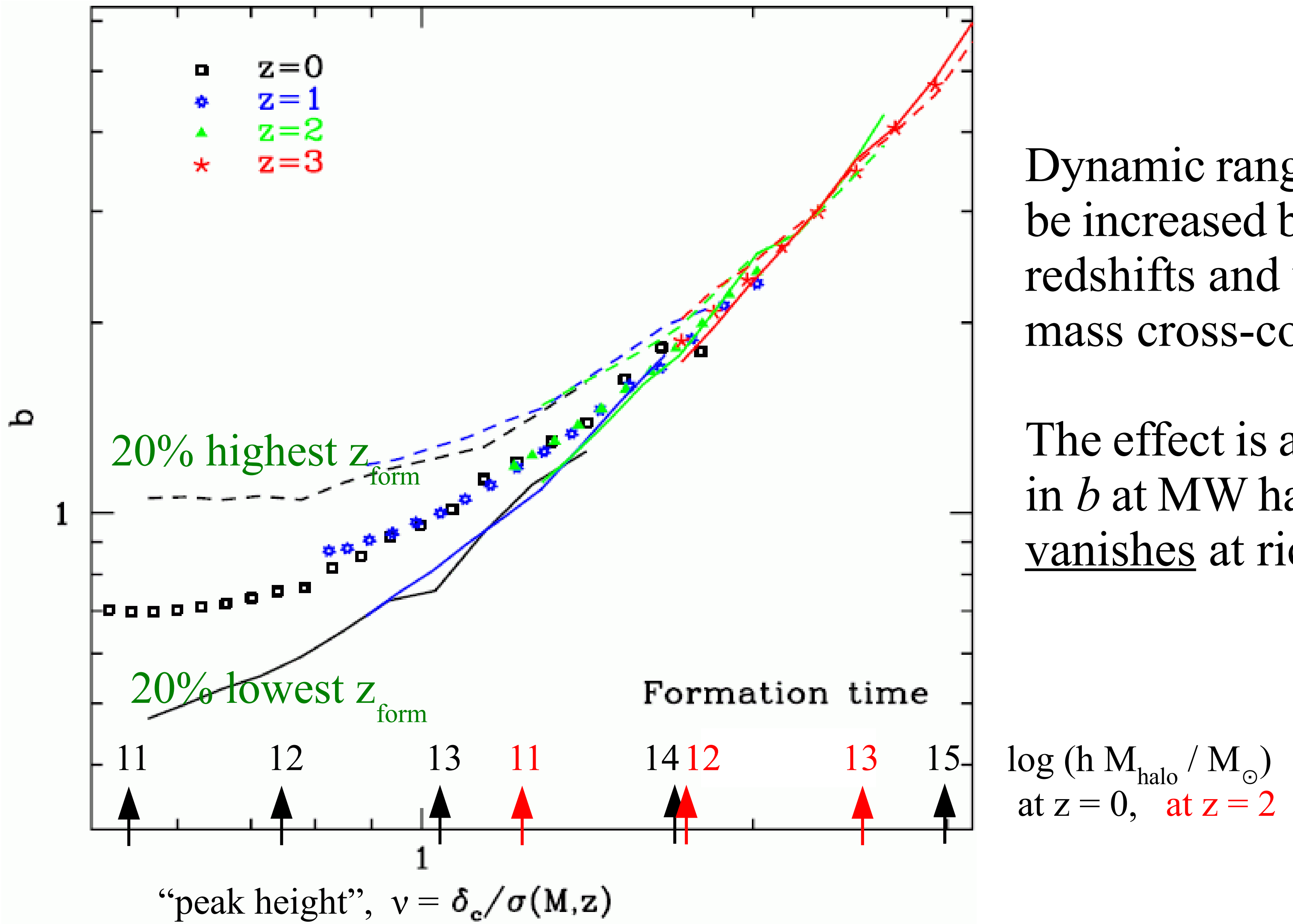


The dependence of bias on formation redshift is strongest at low mass

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

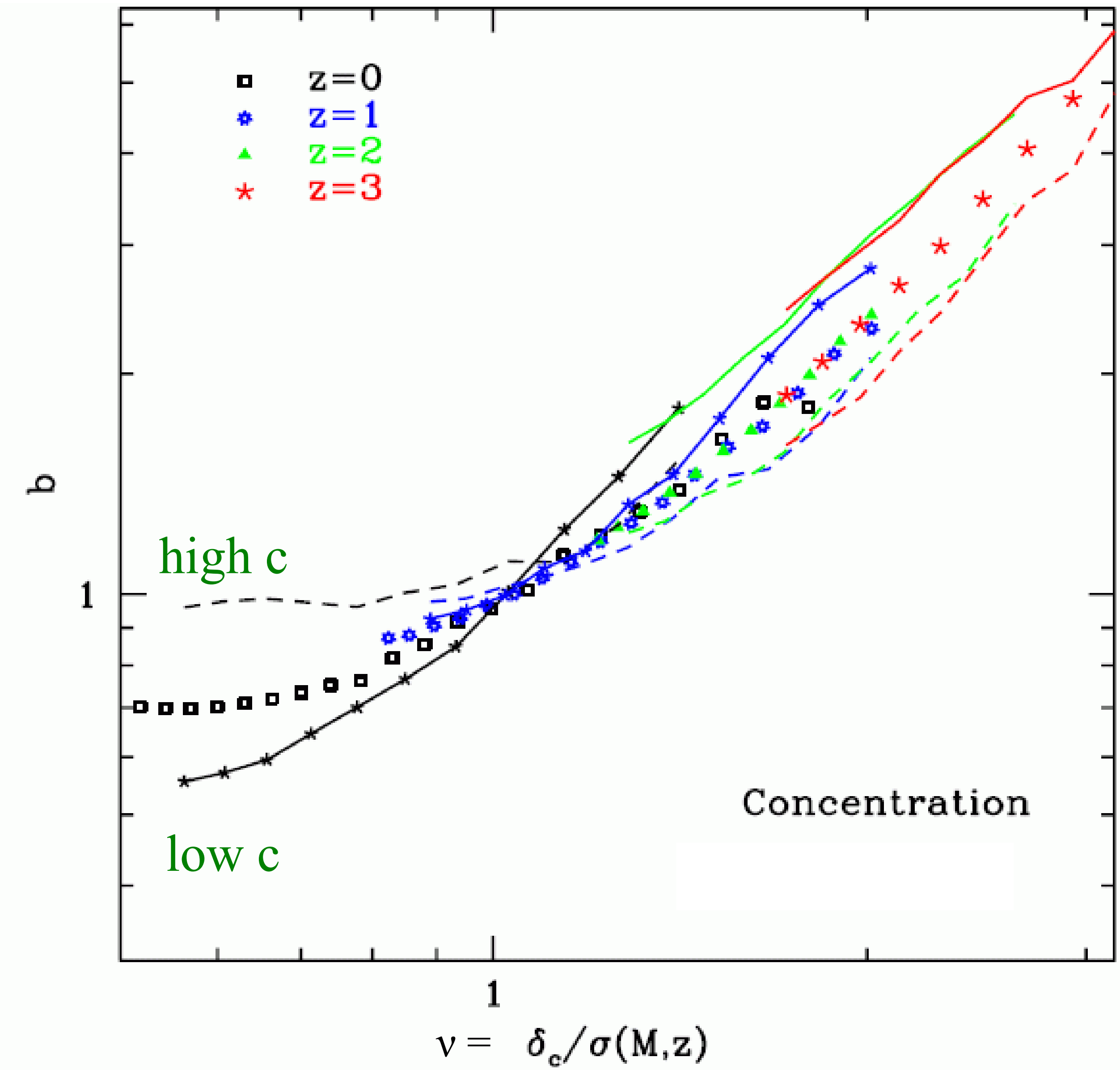


Dynamic range and S/N can be increased by superposing redshifts and using halo-mass cross-correlations

The effect is a factor of two in *b* at MW halo mass but it <u>vanishes</u> 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,
$b_{hi} / b_{lo} \sim 0.7$

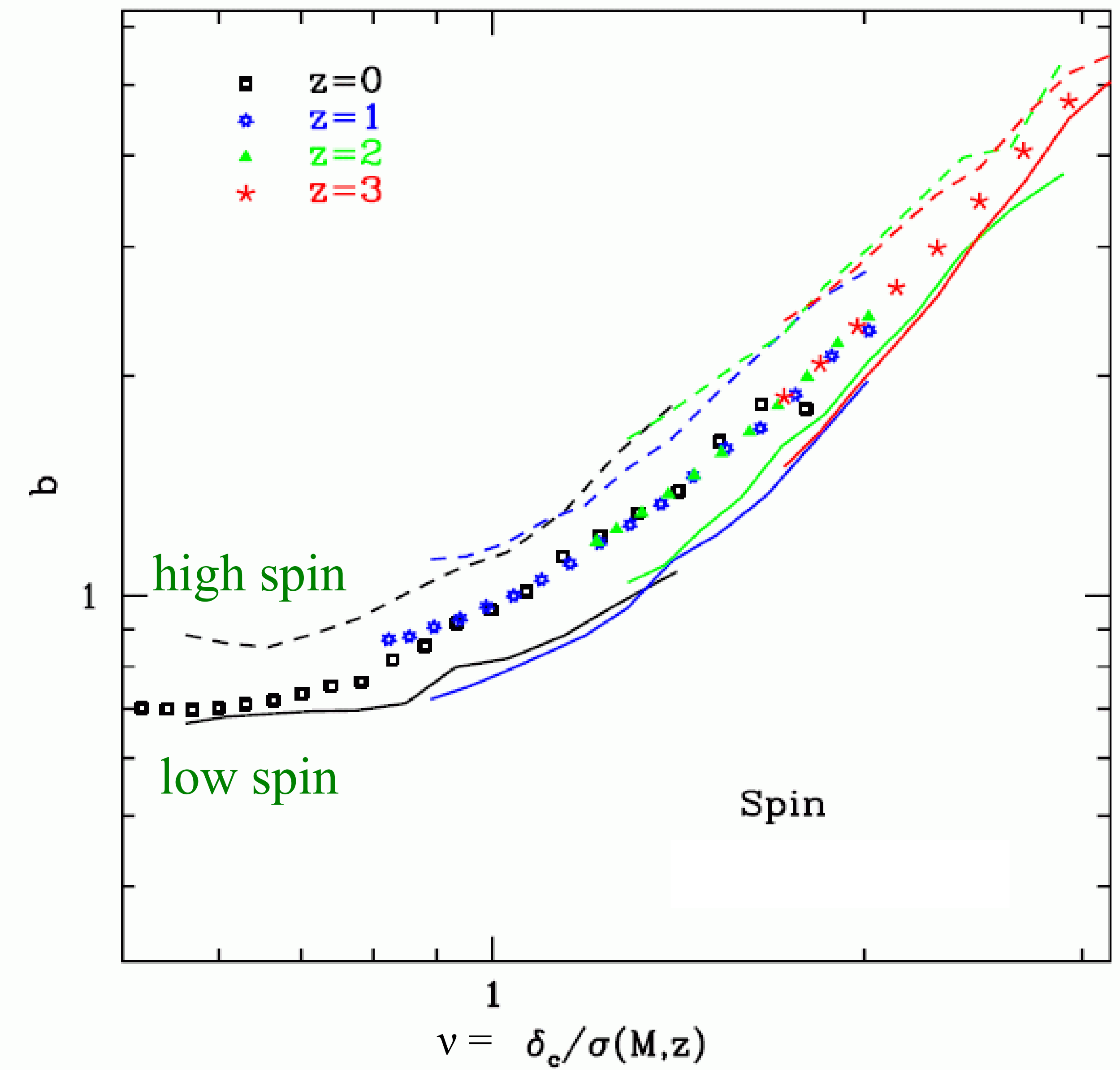
The effect <u>vanishes</u> for
$M_{halo} \sim M_*$

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



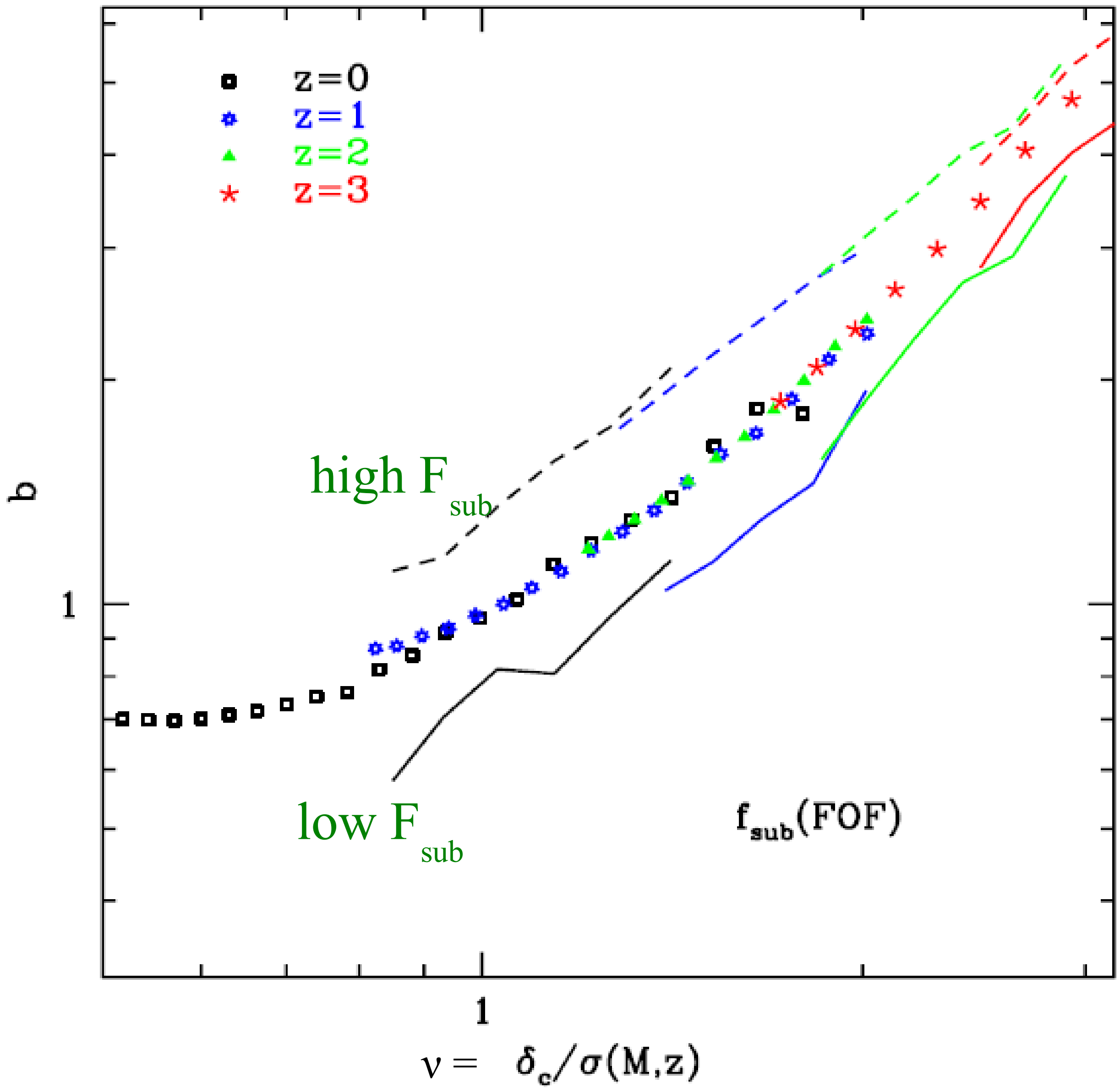
For halo spin, defined as λ' for the mass within the virial radius, the bias ratio is roughly independent of mass

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

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

Bias as a function of ν and substructure mass fraction

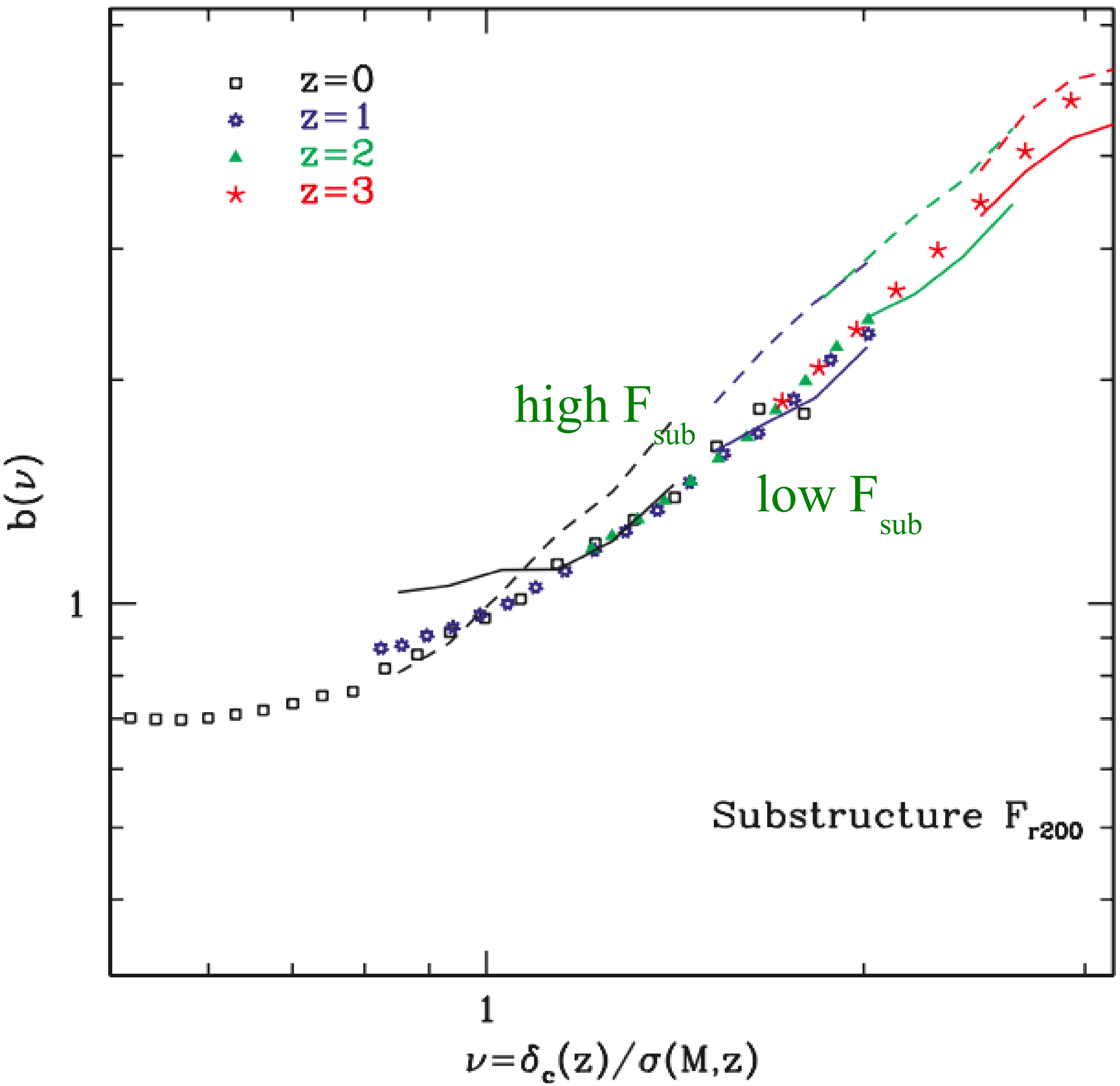
Gao & White 2007



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



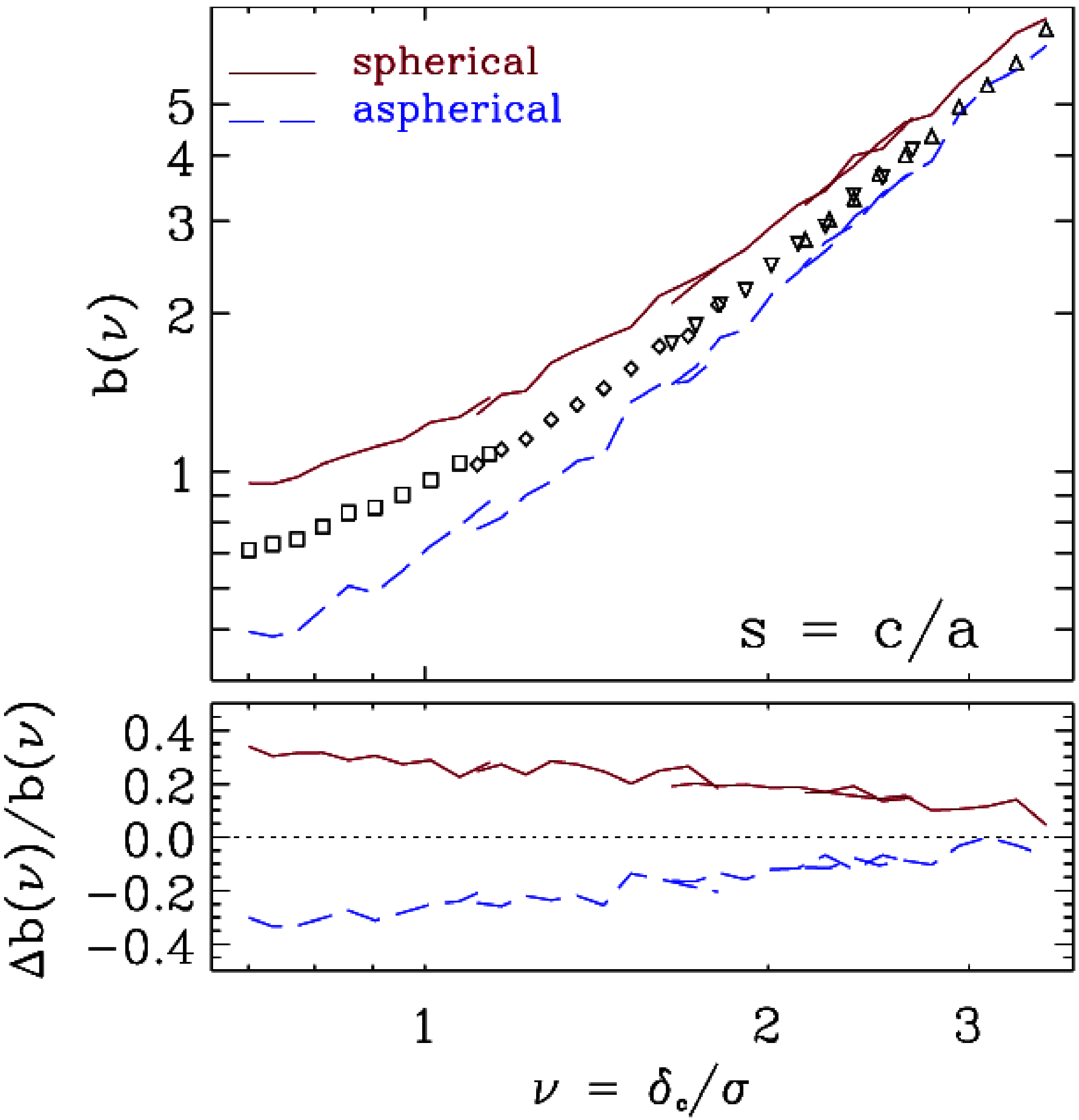
Defining substructure mass fraction so that F_{sub} is the fraction of mass in subhalos within the virial radius, the effect is much smaller, going through unity at M_*.

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

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.

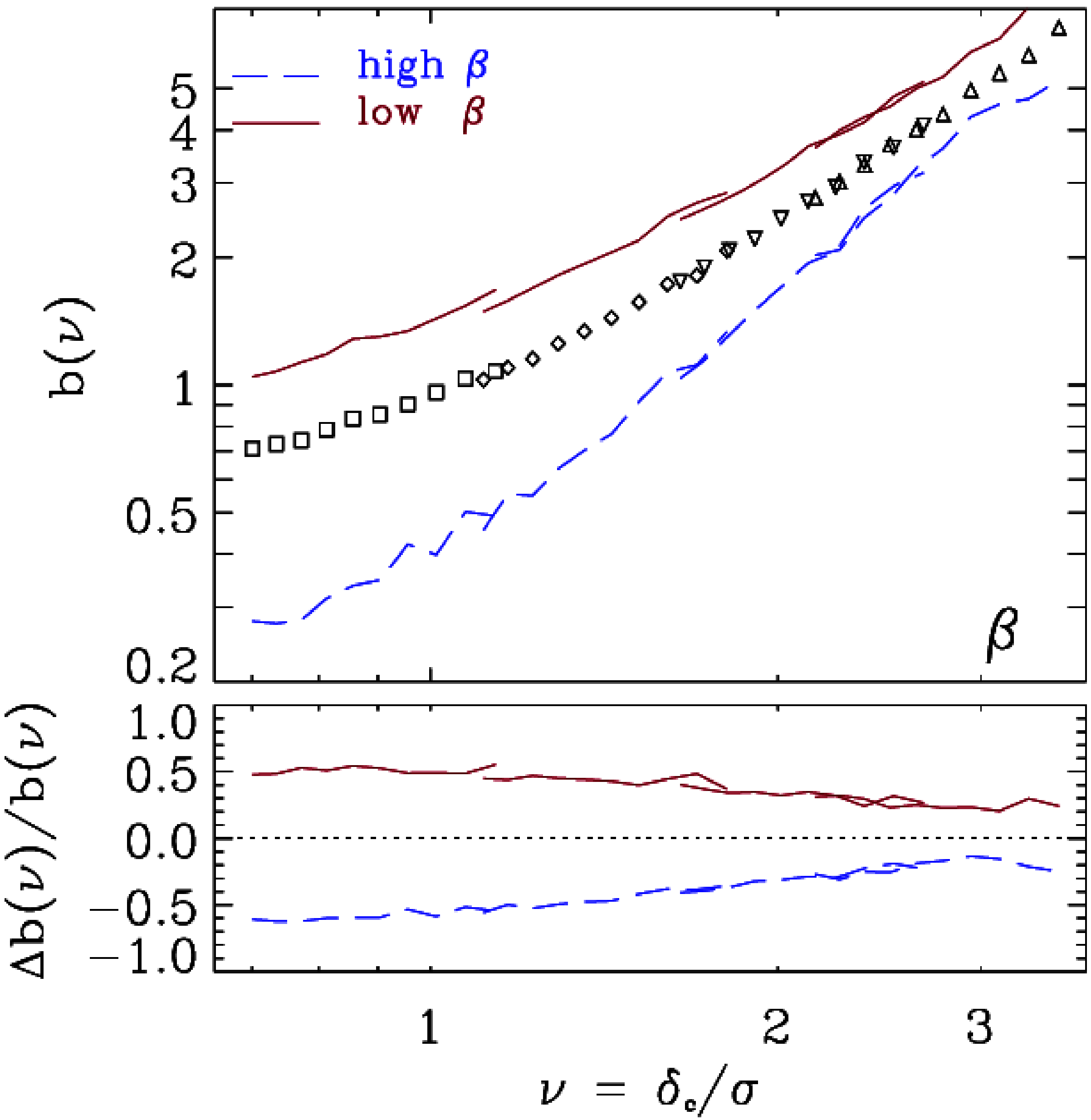
For MW-mass halos,
$b_{hi} / b_{lo} \sim 2$

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

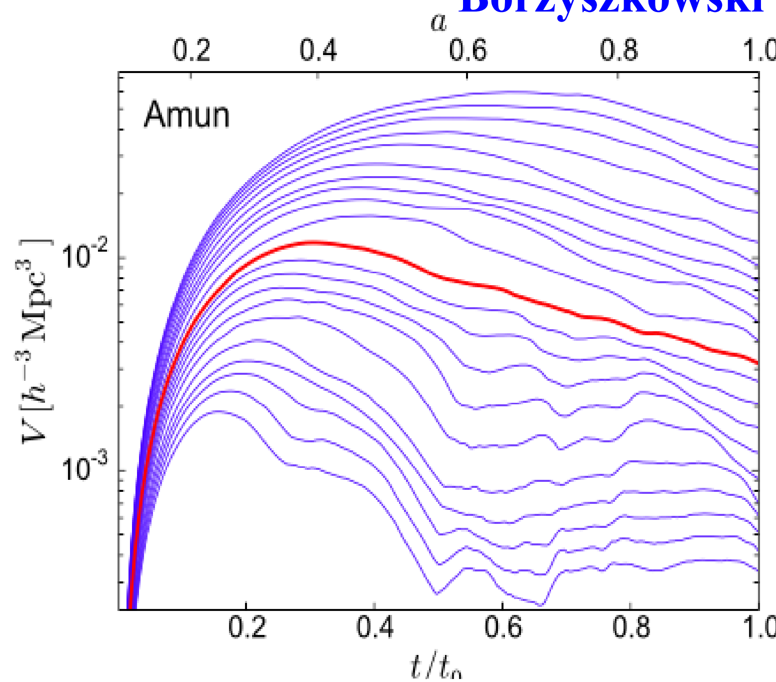
For cluster mass halos,
$b_{hi} / b_{lo} \sim 0.6$

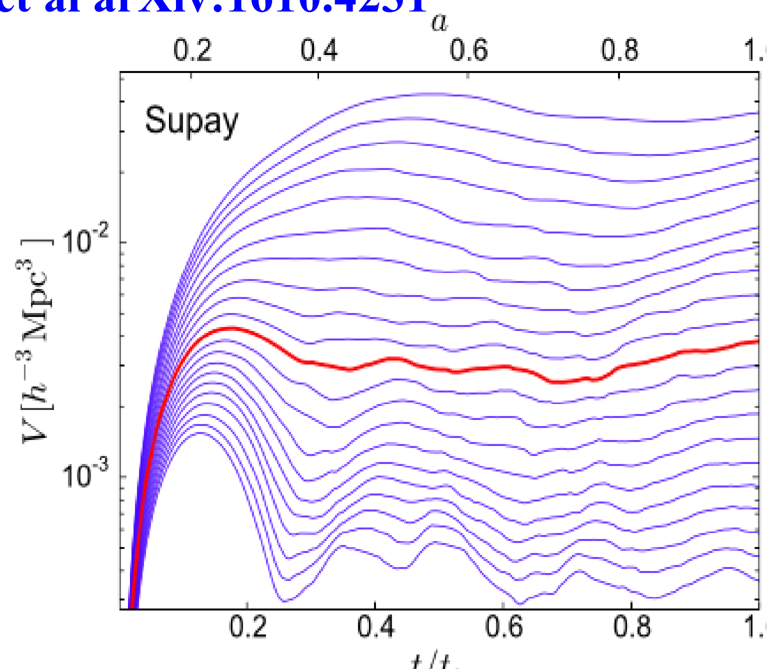
This is the strongest of all the effects considered so far

Assembly bias and the cosmic web

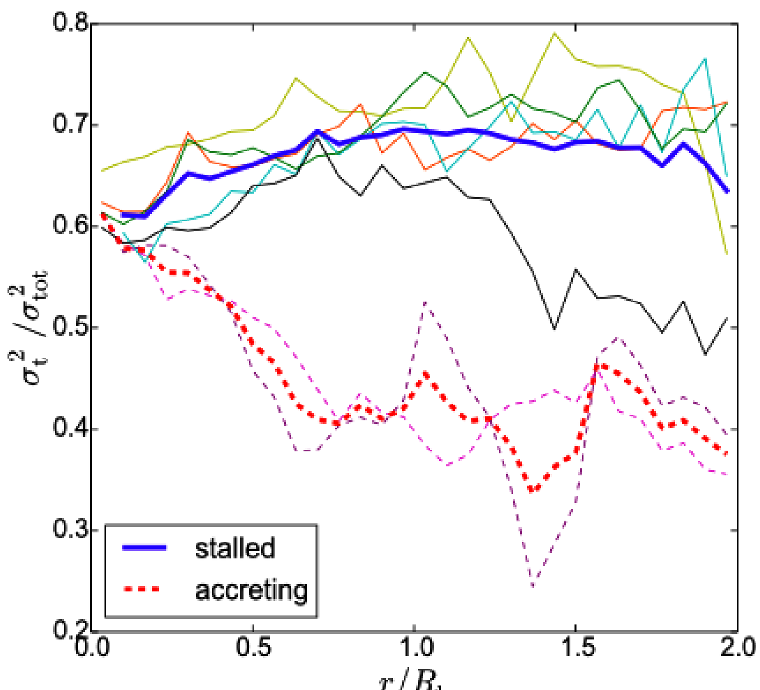
Borzyszkowski et al arXiv:1610.4231

“accreting”
~20%

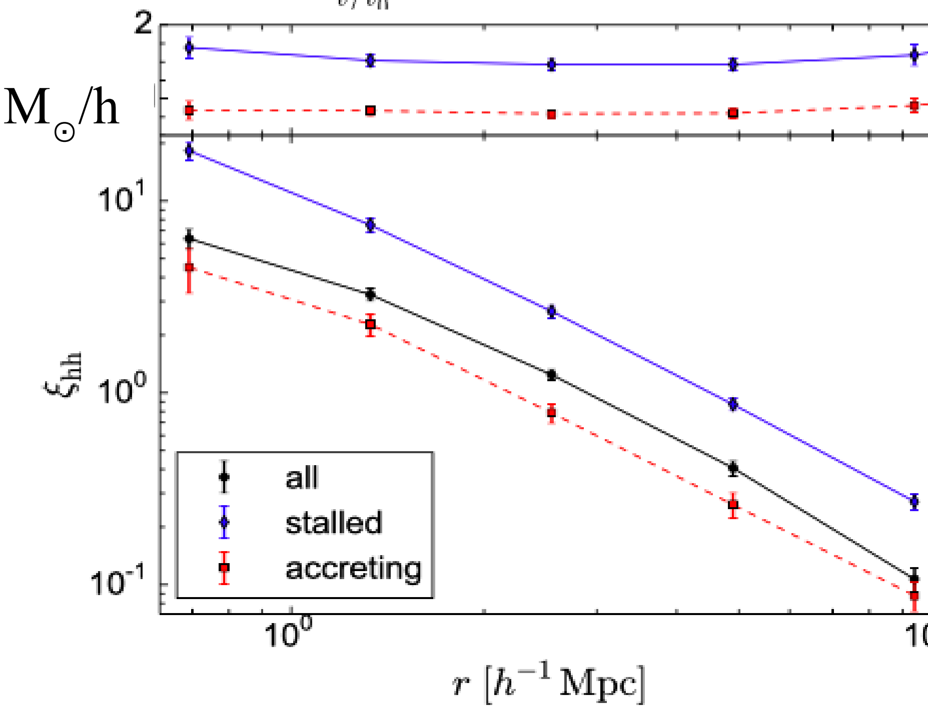




“stalled”
~70%



$M_h \sim 4 \times 10^{11} M_\odot/h$



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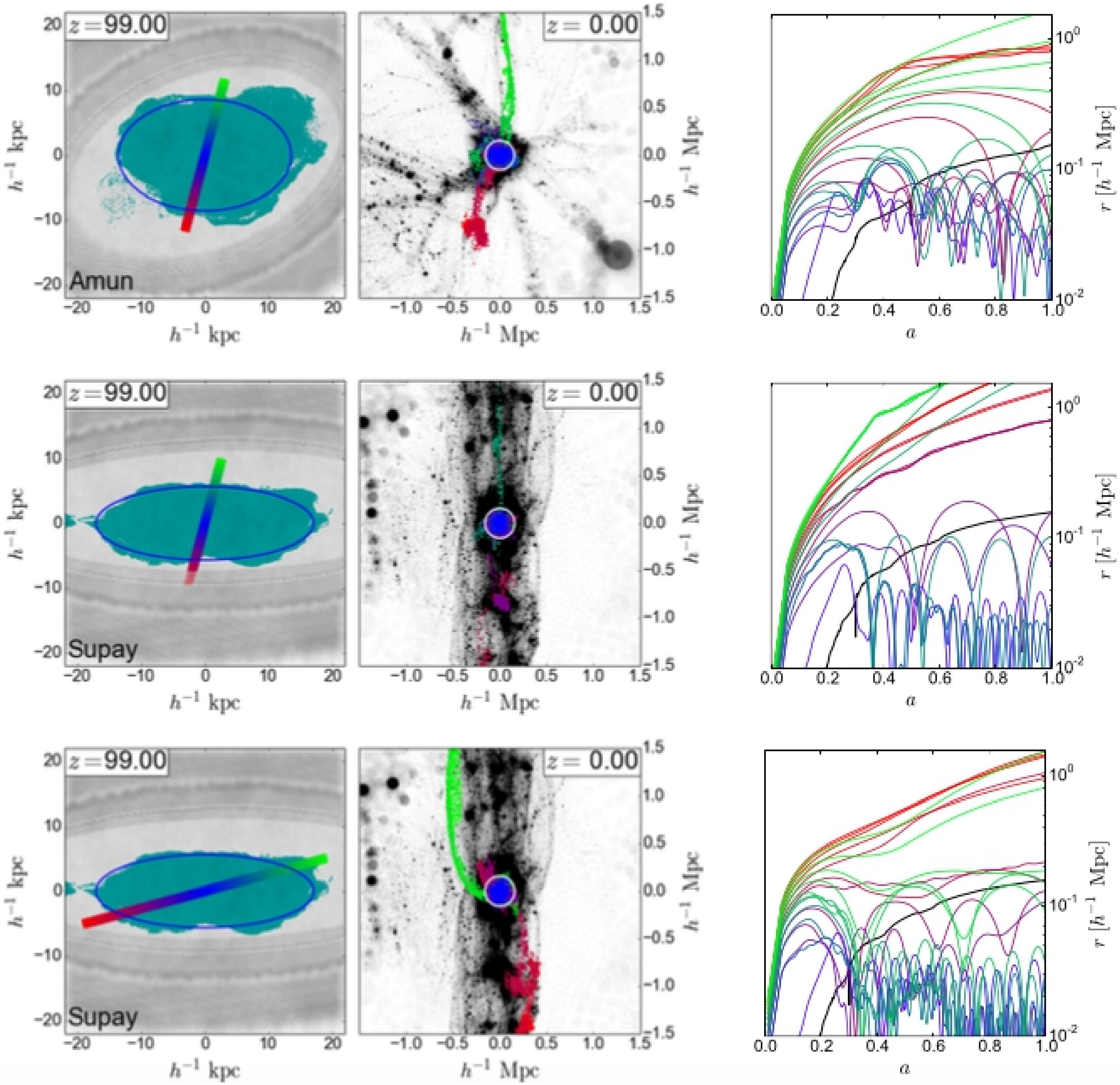


Stalled halos form from much more elongated Lagrangian regions than accreting halos

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

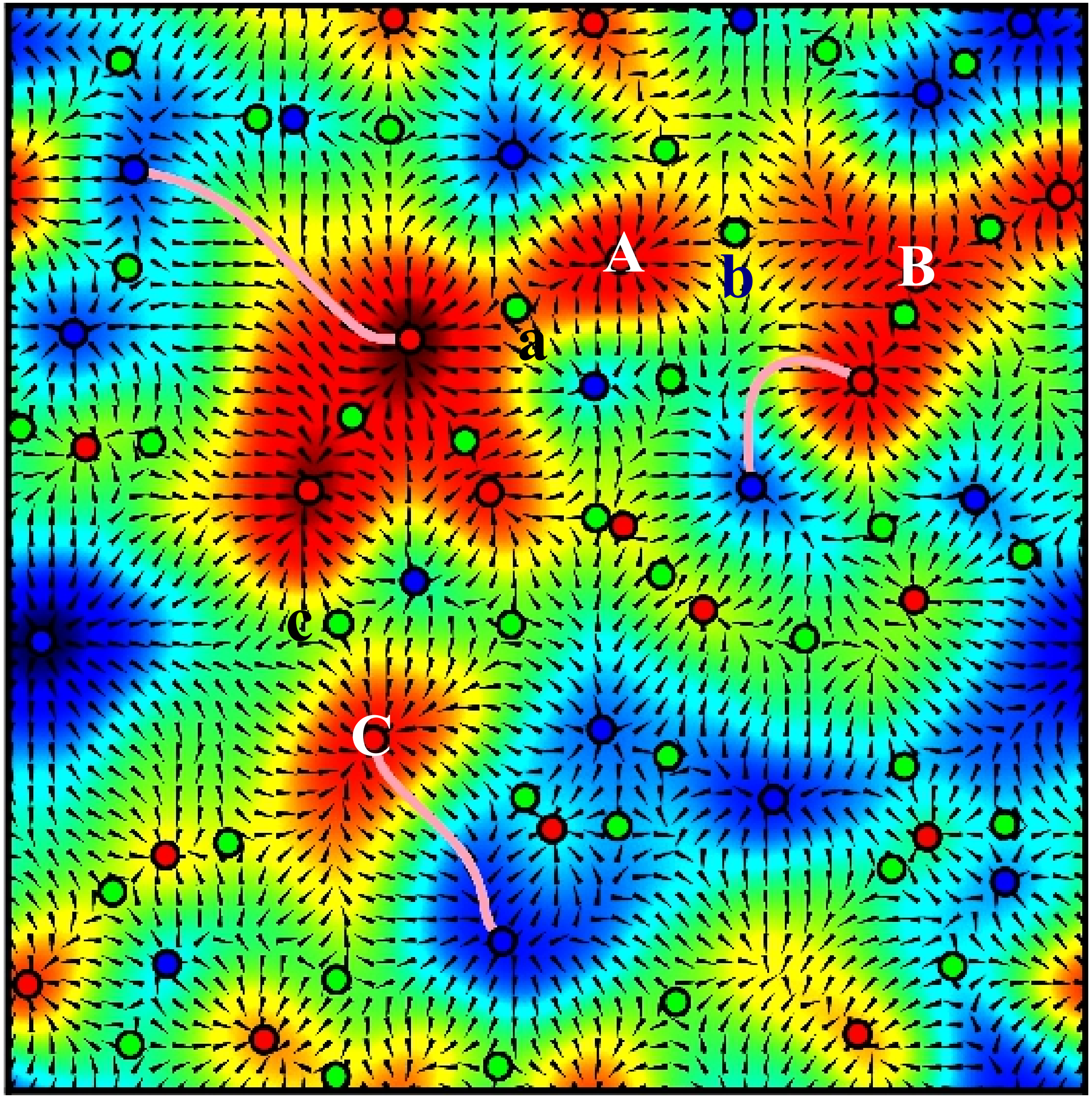


Image from T. Sousbie (2011)

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**

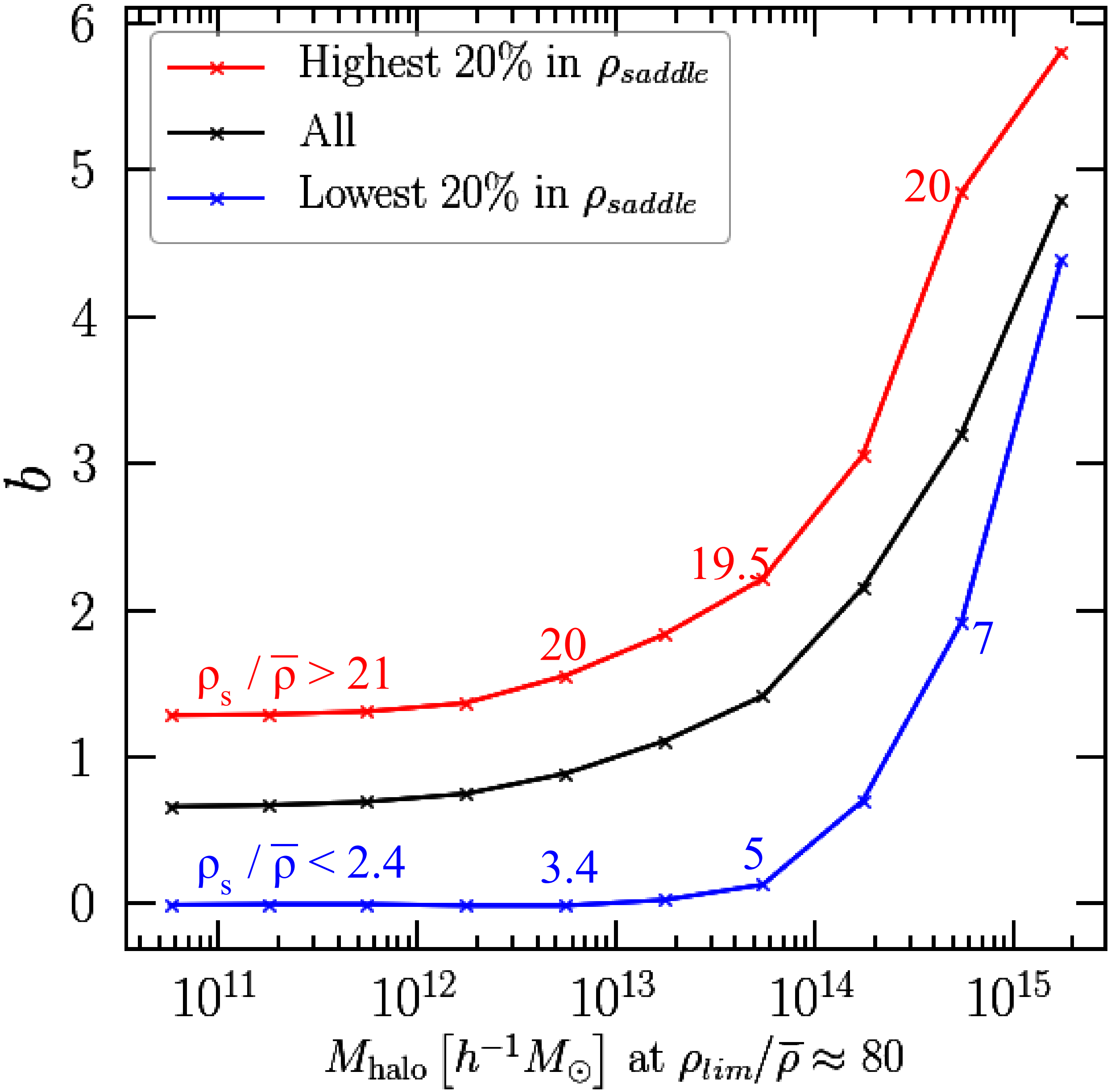
Halo **C** links at saddle point **c**

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

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

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 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 $\nu = \delta_c / D(z)\, \sigma_o(M)$, 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: $b = b(\mathrm{M}, \underline{\mathbf{A}})$ with $\underline{\mathbf{A}}$ multi-dimensional.

These dependences are likely to be reflected in galaxy bias

Assembly bias: from halos to galaxies

How should one put galaxies into simulated DM halos in order to account for all aspects of assembly bias as well as possible?

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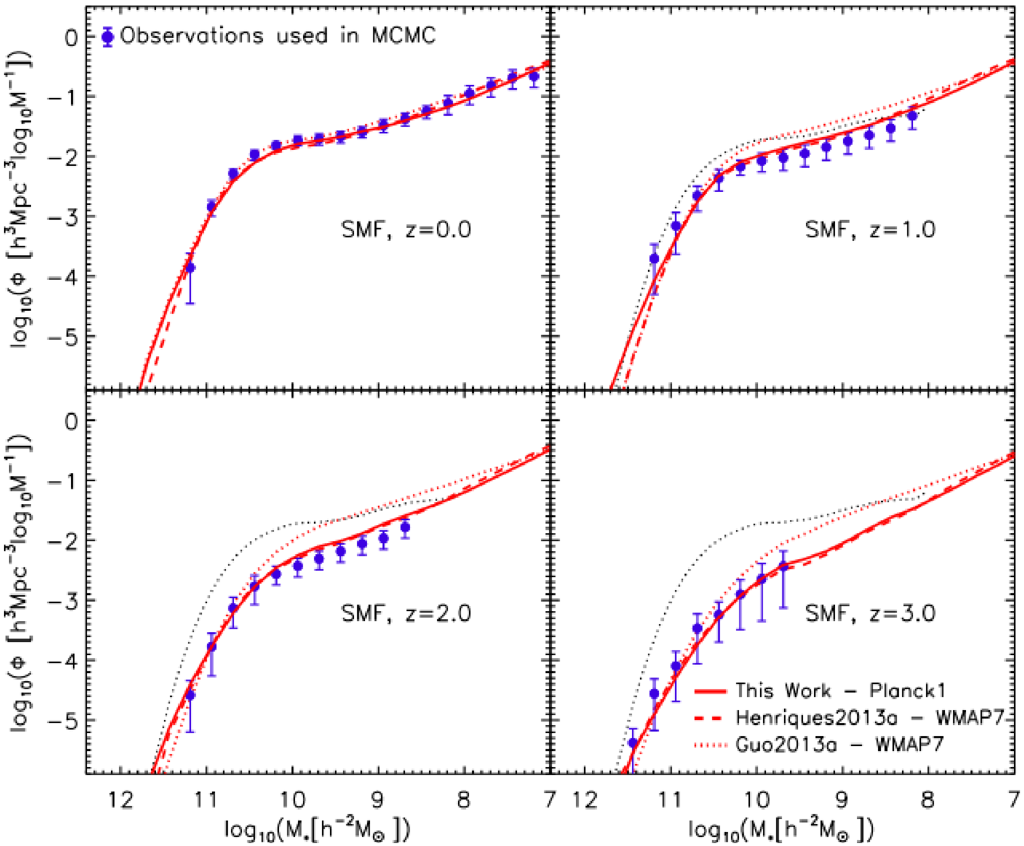
A semi-analytic model applied to the simulation?

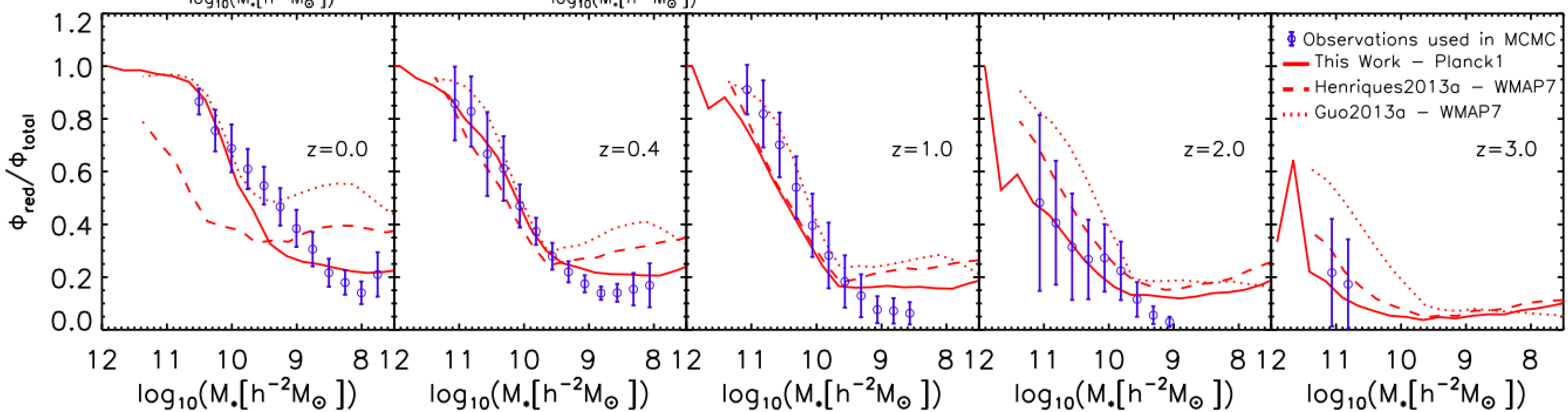
Calibrating models for (sub)halo occupation



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



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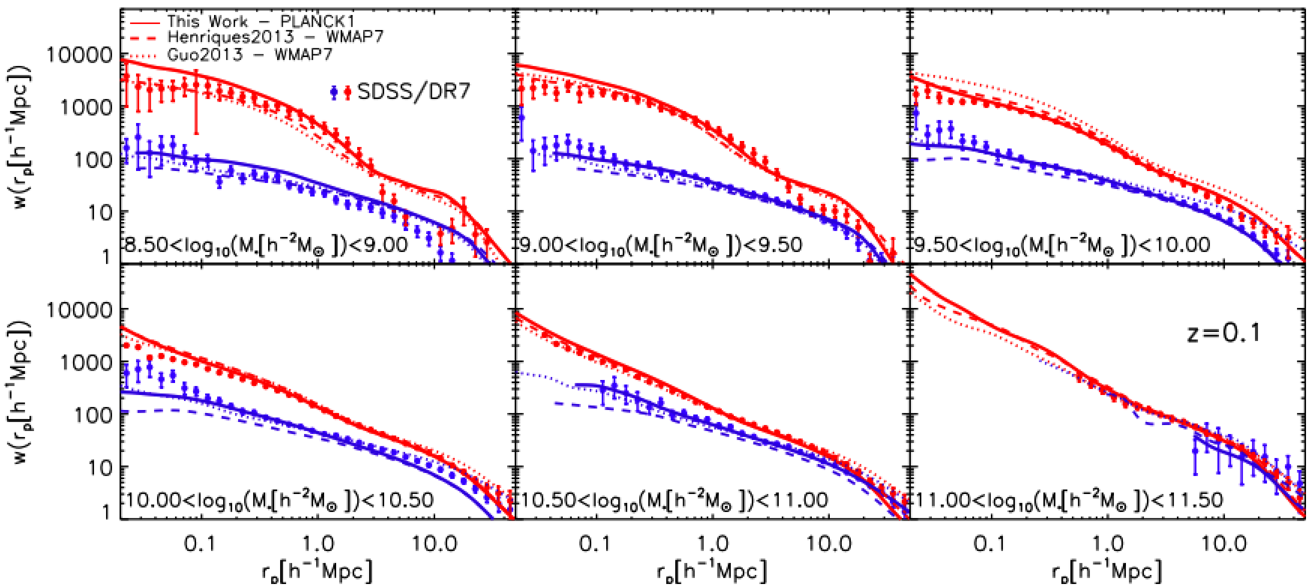
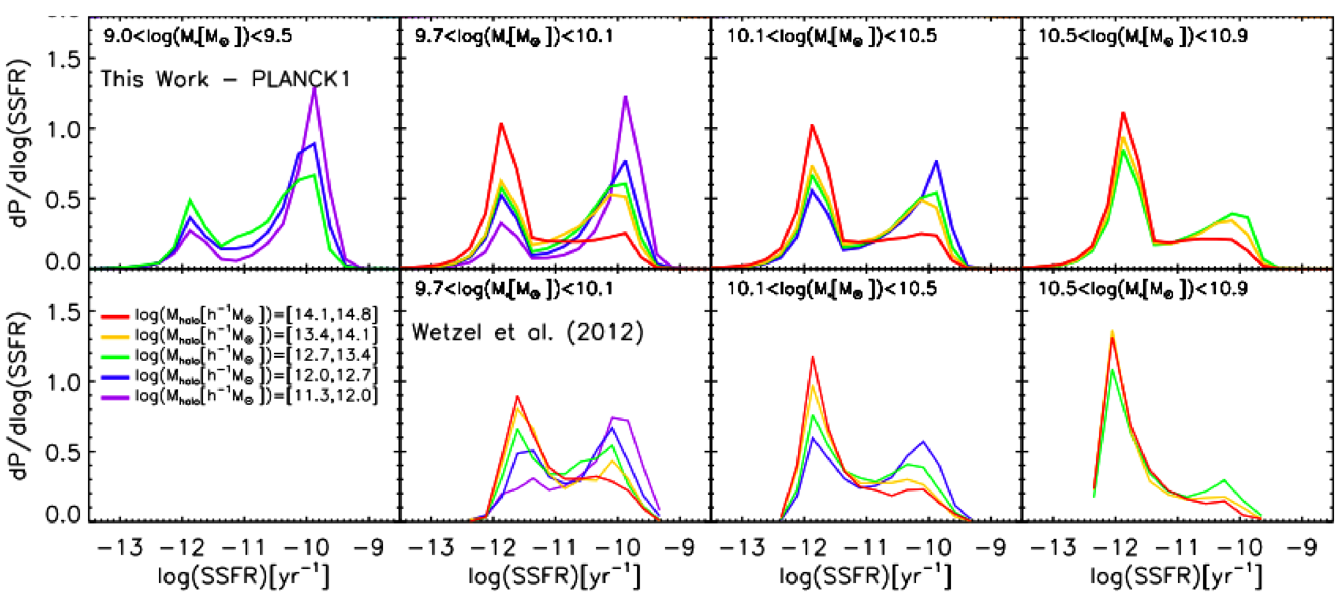
Henriques et al 2017



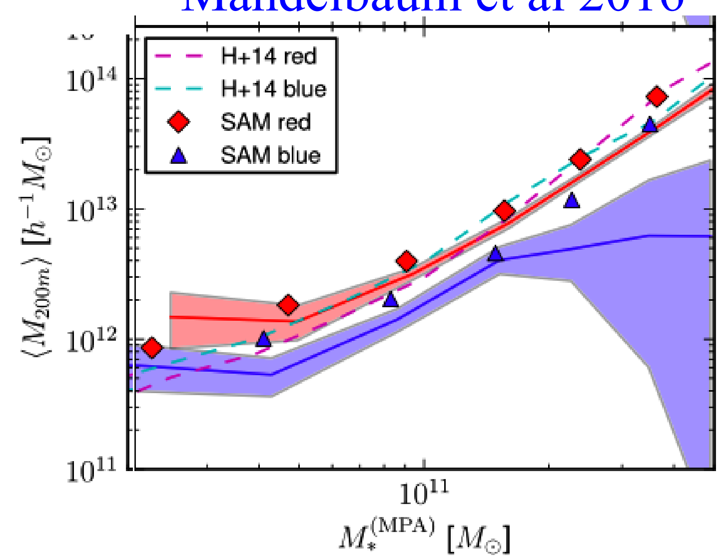
Model reproduces: w(r_p) for active/passive galaxies at r_p > 20 h^{-1} kpc and over 3 orders of magnitude in stellar mass

Variation of passive fraction with halo and stellar mass

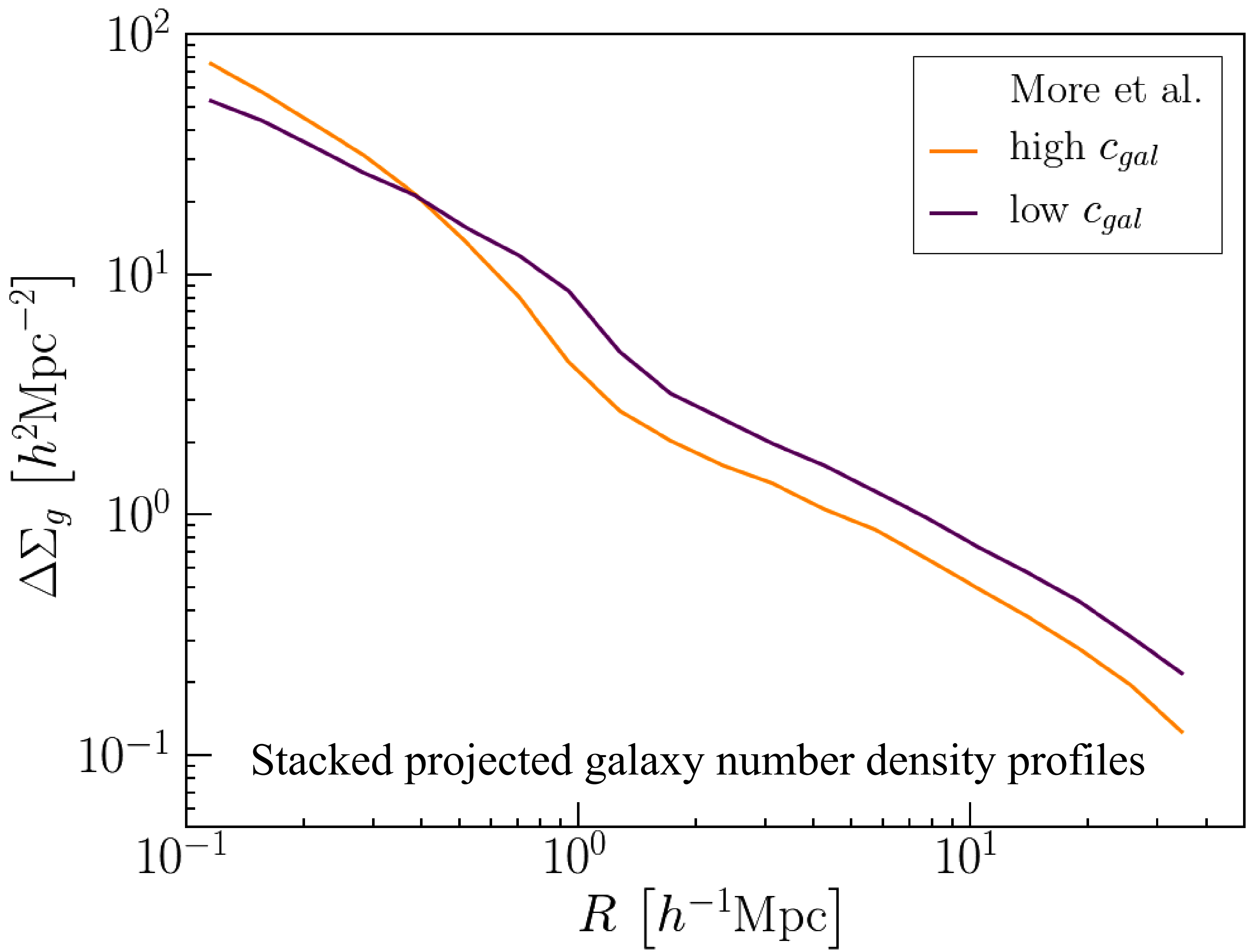


Variation of halo mass with central galaxy colour

Mandelbaum et al 2016



Detection of assembly bias in redMaPPer clusters



More et al 2016

$b_{\mathrm{lo}}/b_{\mathrm{hi}} \sim 1.5$

RedMaPPer clusters with $0.1 < z_{\mathrm{phot}} < 0.33$ and $20 < \lambda < 100$ are split into two samples with <u>identical</u> redshift and richness distributions but <u>disjoint</u> distributions of $\langle R_{\mathrm{mem}}\rangle$, the mean projected radius of RS members

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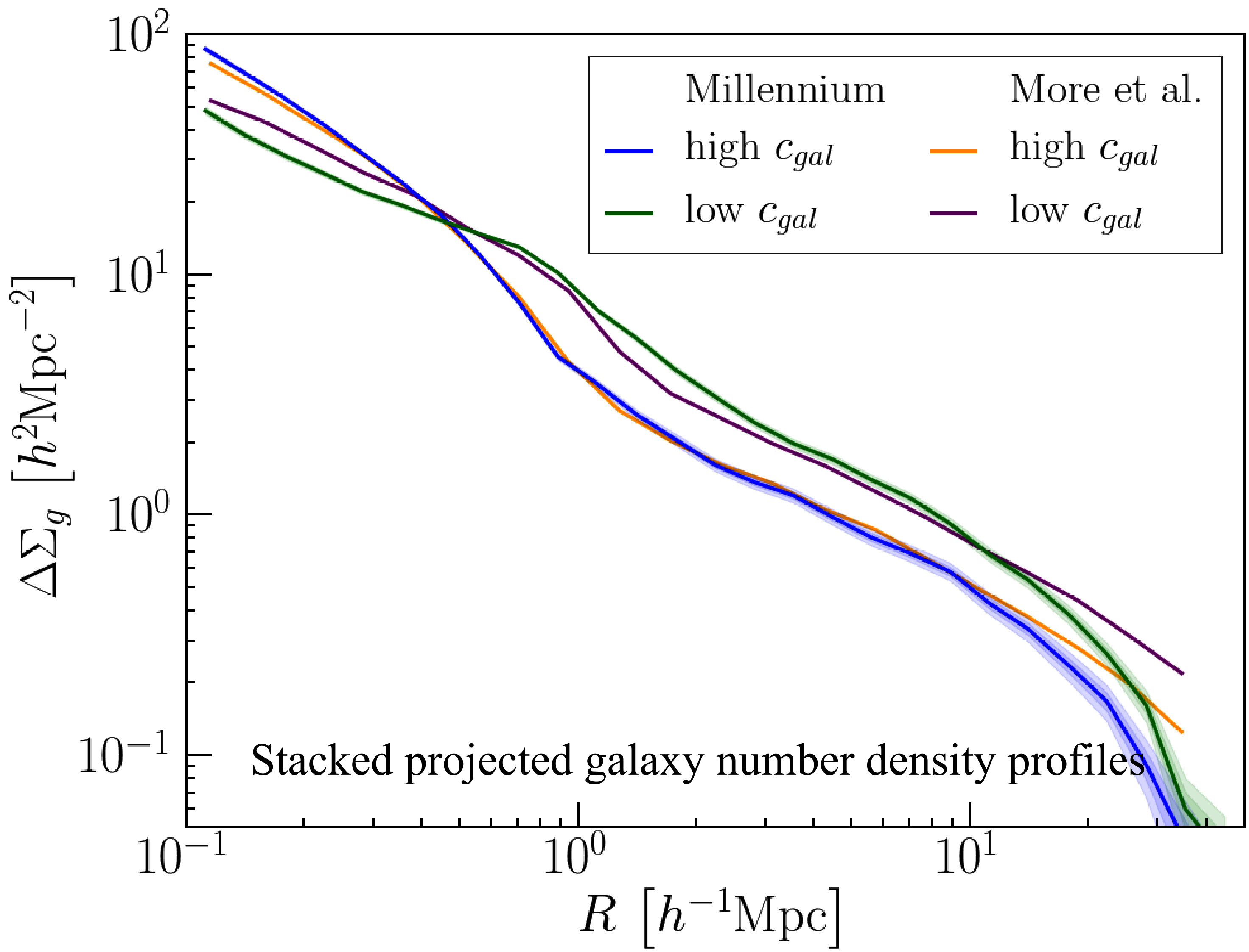
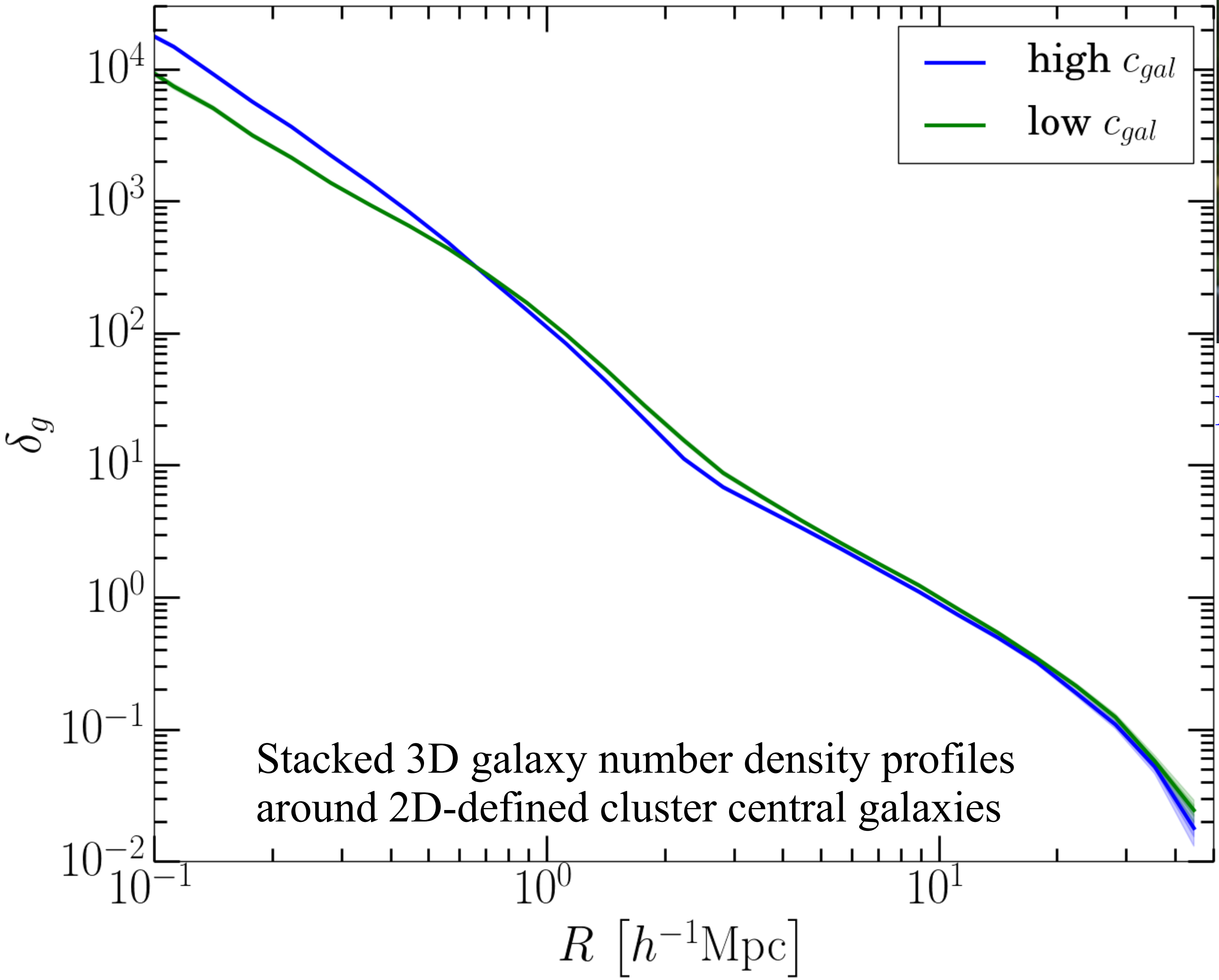


Busch & White 2017

Millennium drop-off at large R due to finite box size, otherwise good agreement

Detection of assembly bias in redMaPPer clusters

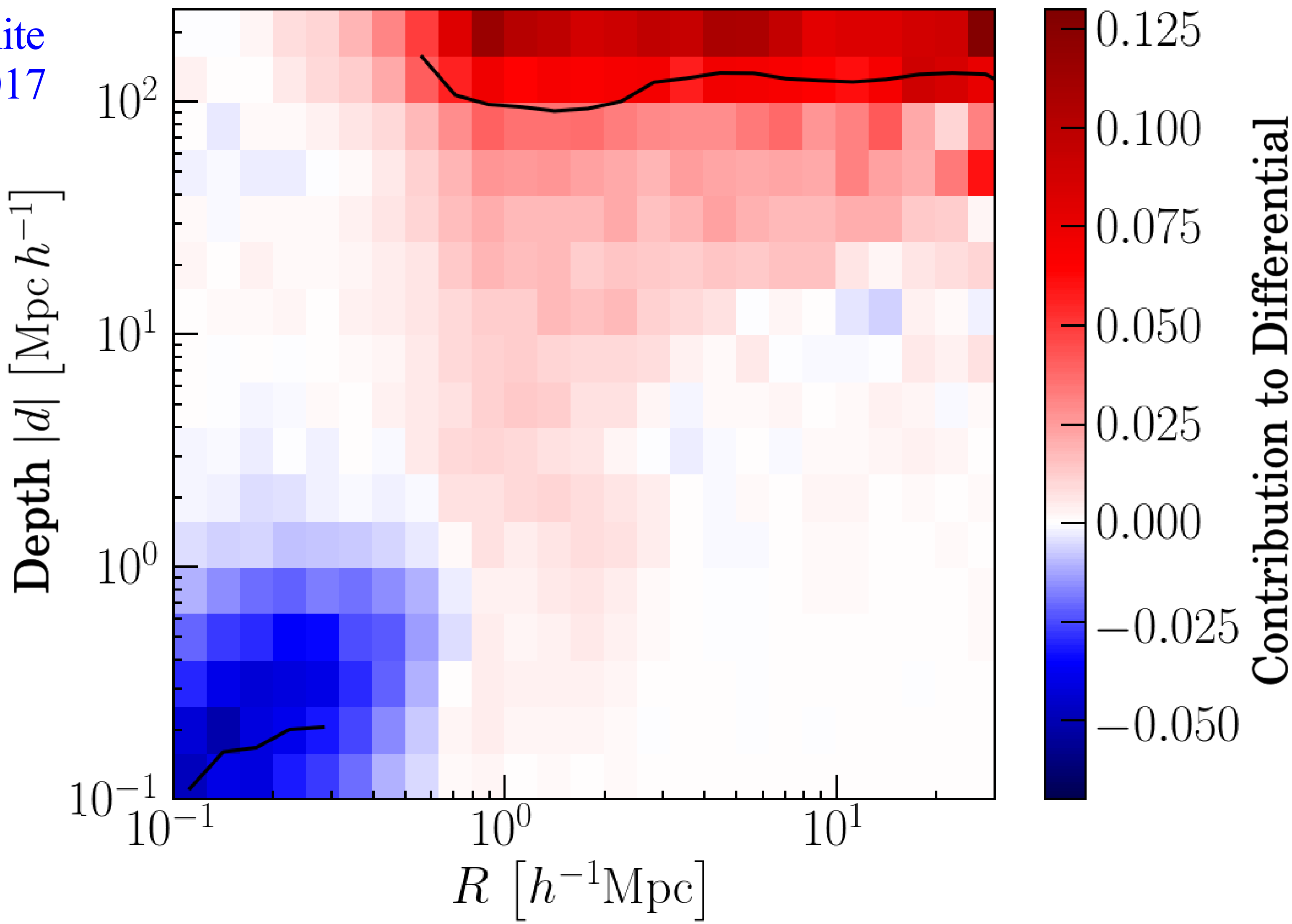


Busch & White 2017

In 3D the low concentration clusters are less rich and there is smaller assembly bias

Detection of assembly bias in redMaPPer clusters

Busch & White 2017



The galaxies which produce the excess projected surface densities are typically at differential depths of 10's to 100's of Mpc at R > 1.0 h^{-1} Mpc (→ the assembly bias signal) and of a few 100's of kpc at R < 300 h^{-1} kpc (→ 2D cluster concentration)

Conclusions?

- Assembly bias depends independently and in complex ways on many aspects of how halos are assembled: $\xi_{12}(r) = \xi(\underline{\mathbf{r}} \mid M_1, M_2, \underline{\mathbf{A}}_1, \underline{\mathbf{A}}_2)$
- Halo assembly histories will also affect many properties of the galaxy population within halos (e.g. central galaxy mass, spin, orientation, activity...; satellite abundance, radial profiles, passive fraction...)
- Accounting for the interplay of these factors will require tracking the detailed assembly history of individual halos
- Simple physical principles (continuity, positivity, causality...) and basic astrophysics (stellar evolution...) constrain possible models
- Such constraints are most easily implemented by direct forward modelling with a physically based model