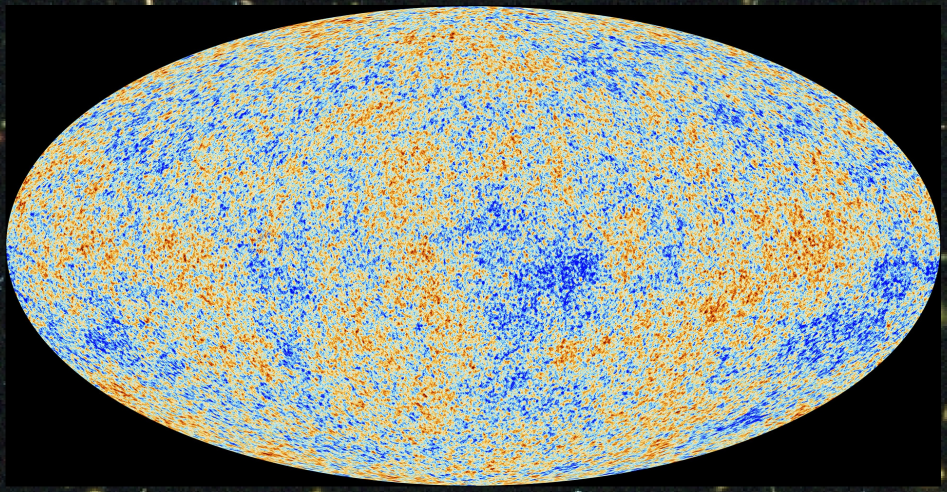
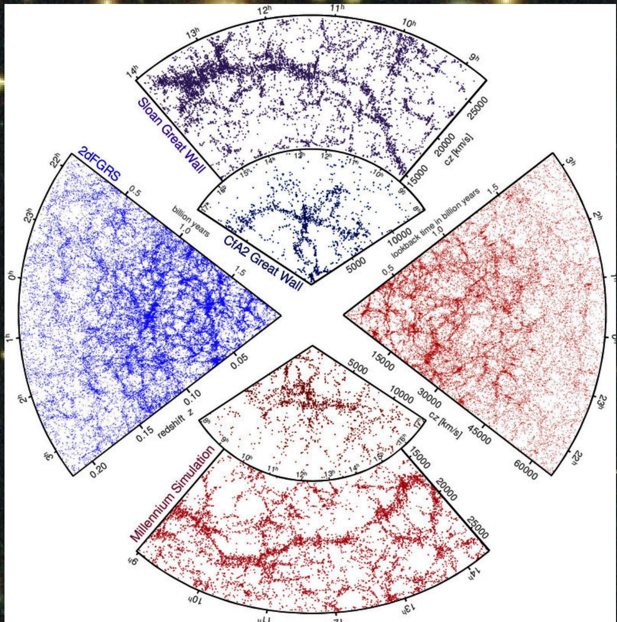


Olympian Symposium 2015

Simulating the large-scale galaxy population

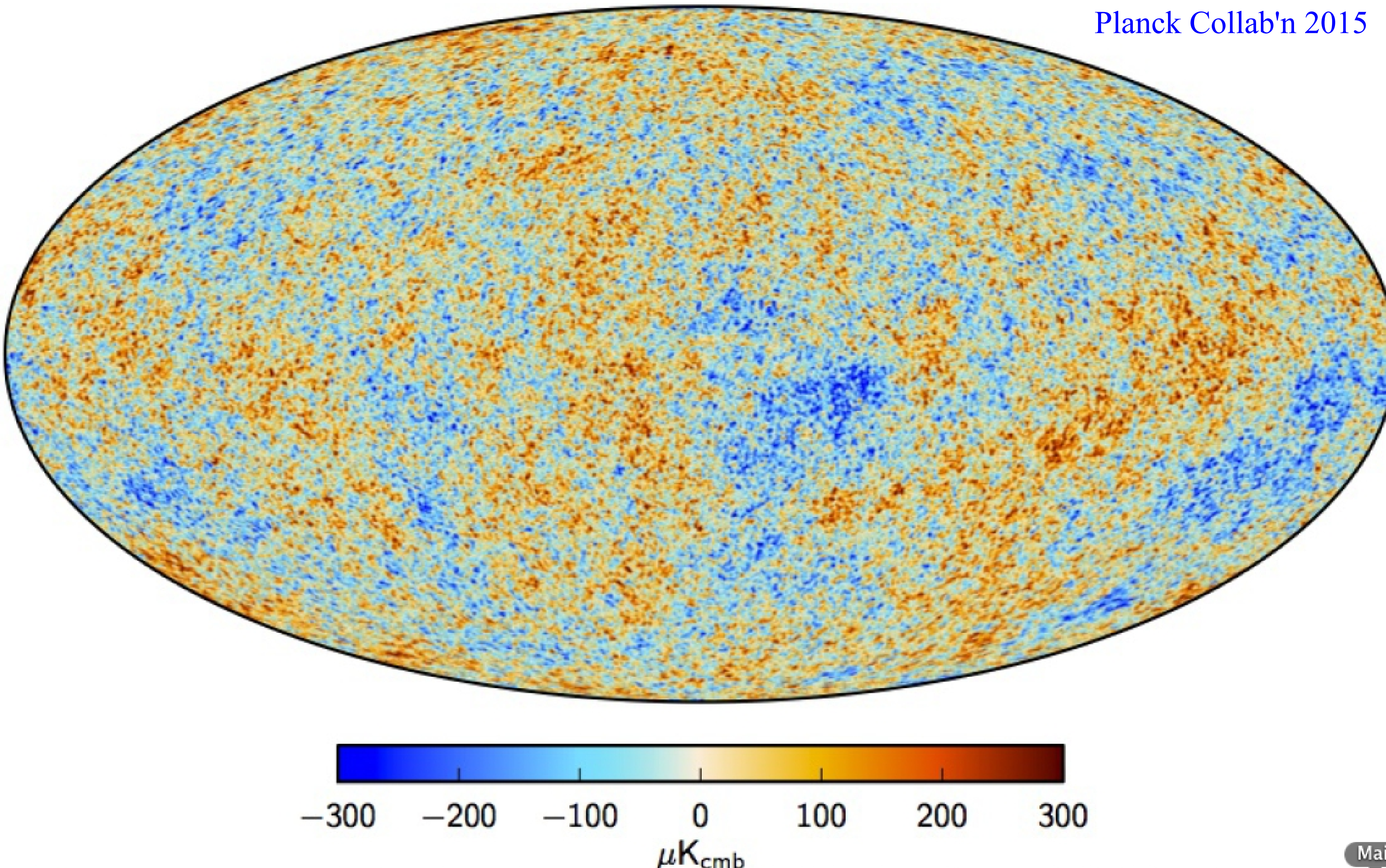
Simon White

Max Planck Institute for Astrophysics



CMB map from the full *Planck* mission

Planck Collab'n 2015

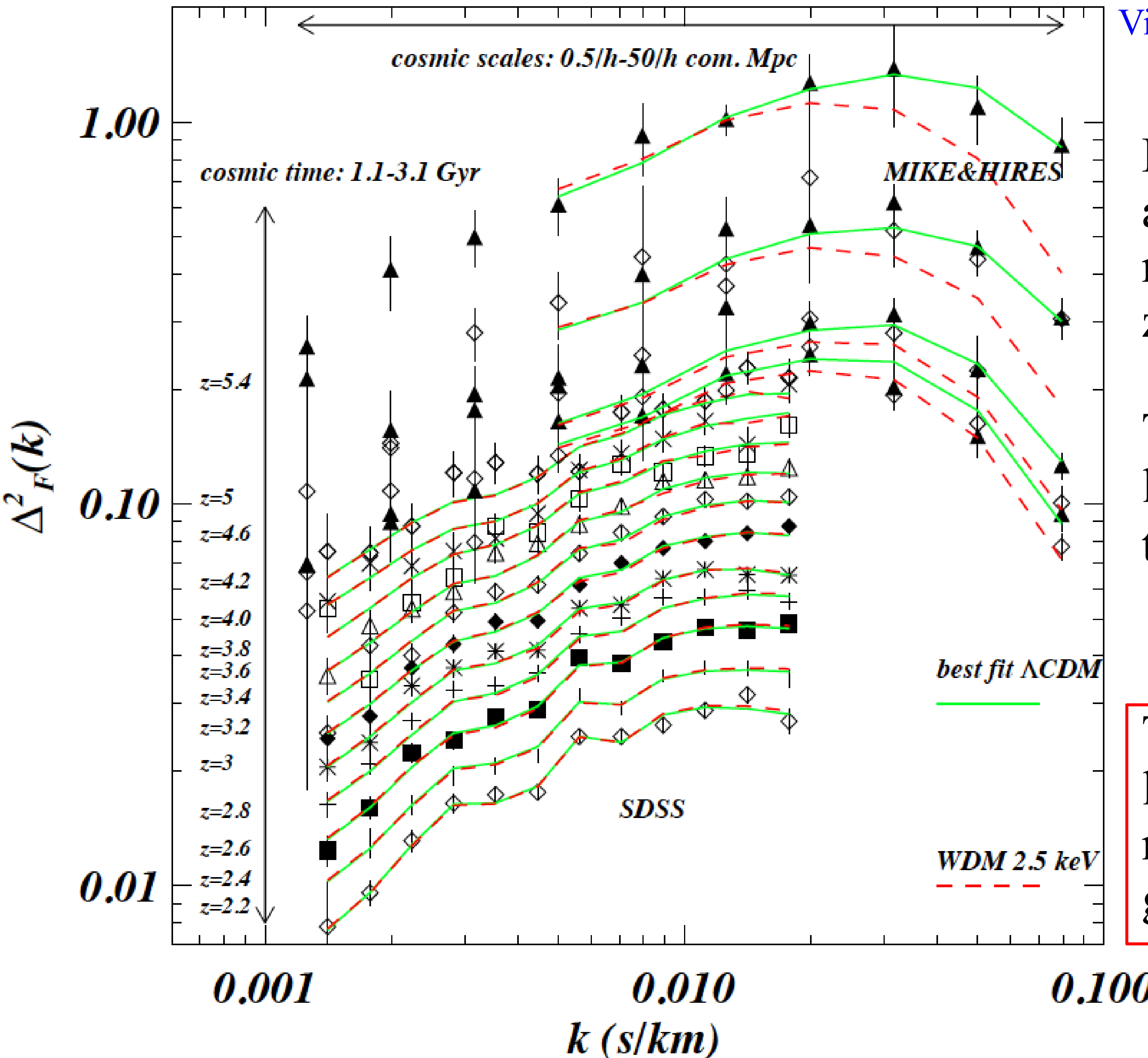


The six parameters of the base ΛCDM model

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

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- Initial non-gaussianities and $\Sigma\, m_\nu$ are both small
- Late-time expansion history – BAO signal in galaxies – w(z)
- Late-time growth factor – redshift-space distortions – mod.grav.
- Dwarf galaxy core structure / Ly α forest – WDM / SIDM
- Signatures of DE interactions with DM? with ν's? with baryons?

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- Signatures of DE interactions with DM? with ν's? with baryons?

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

Making predictions for galaxies (accurately?)

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

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

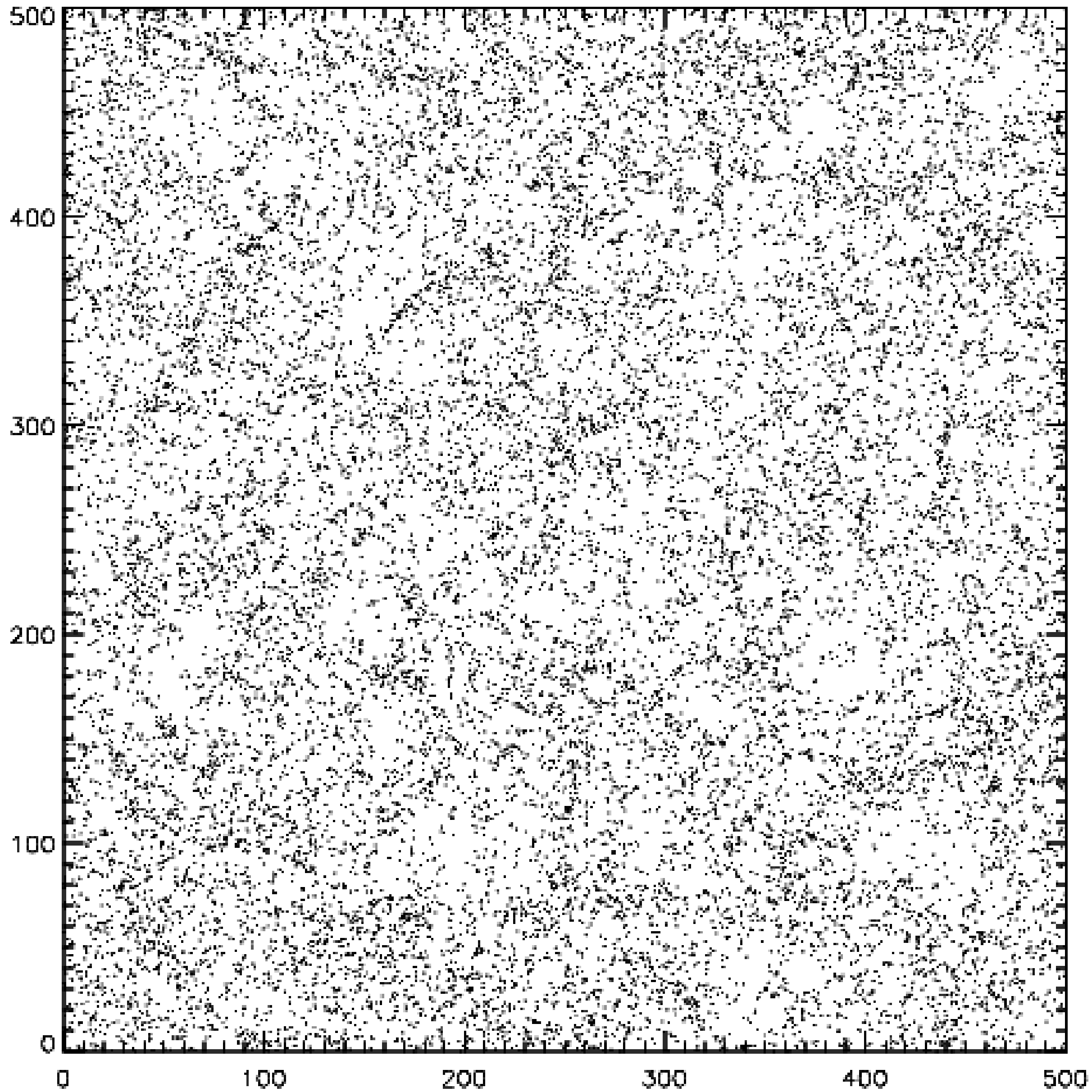
- Are the initial conditions well enough represented?
- Is the volume large enough to control cosmic variance?
- Can the code follow growth sufficiently well?
- Is galaxy formation represented at a sufficient level by:

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

Does halo clustering depend on formation history?

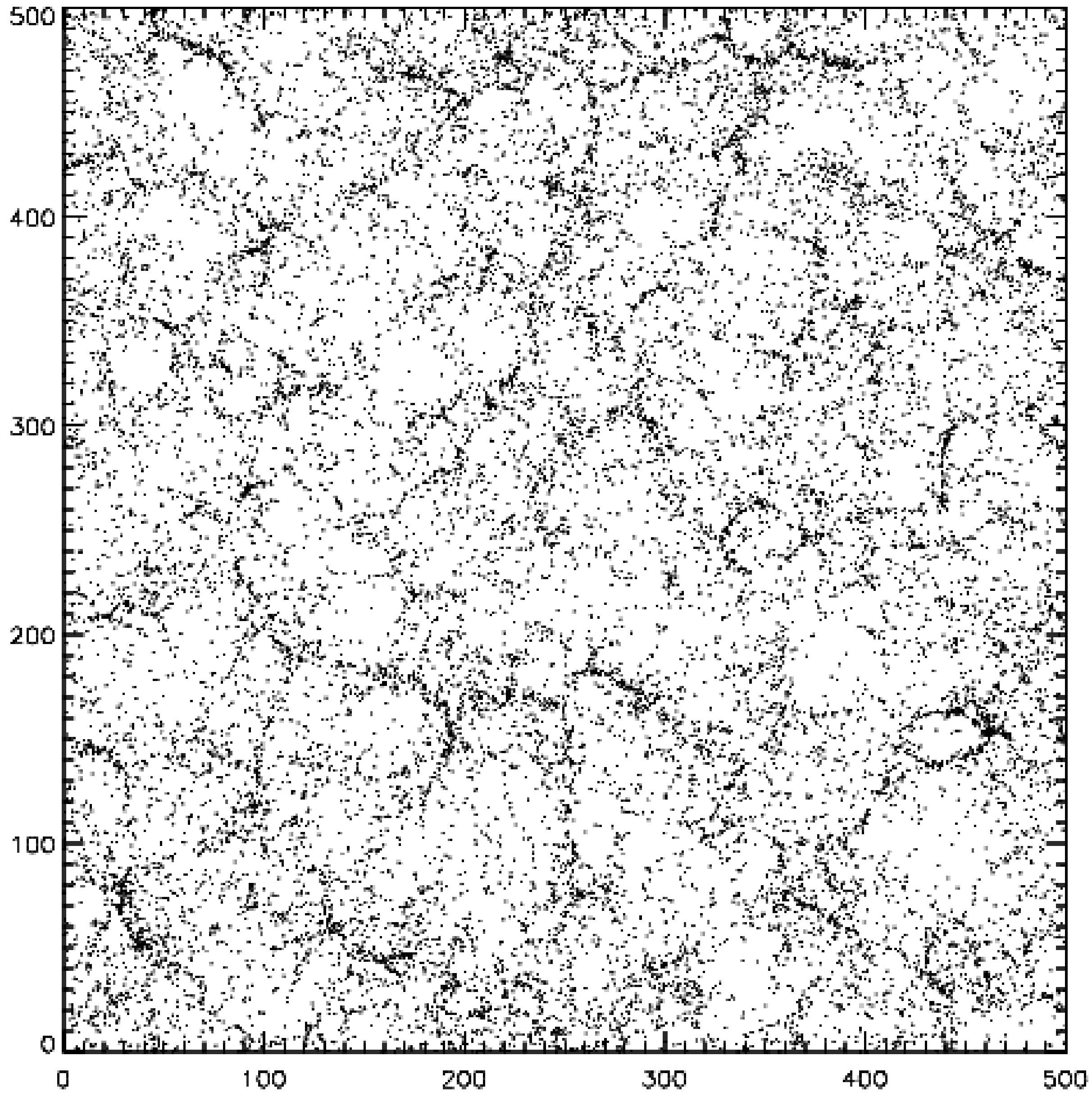


Gao, Springel & White 2005

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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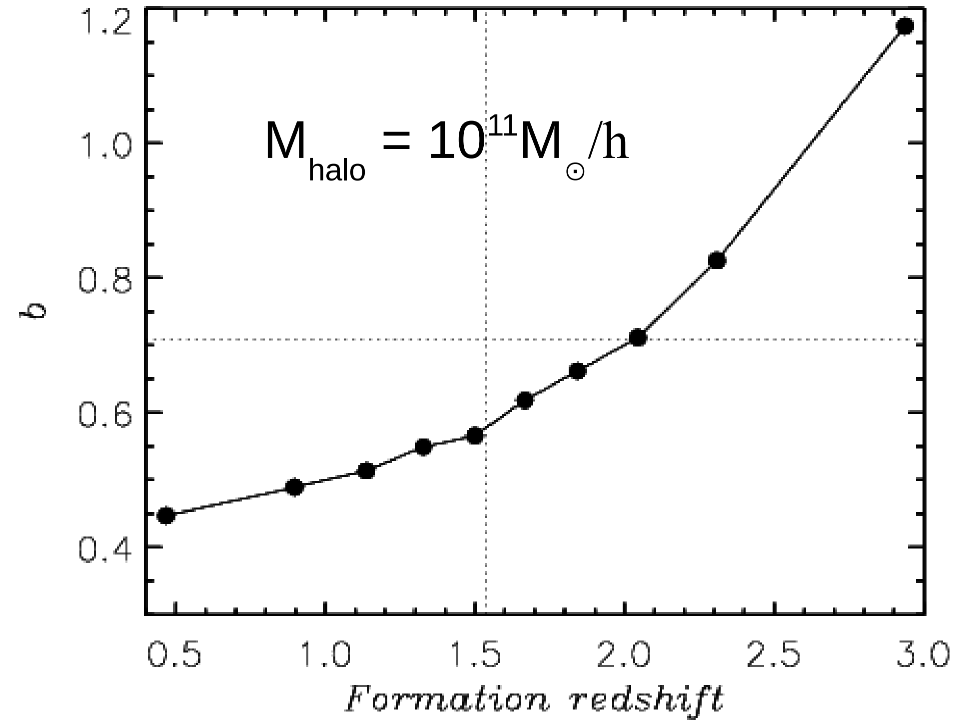
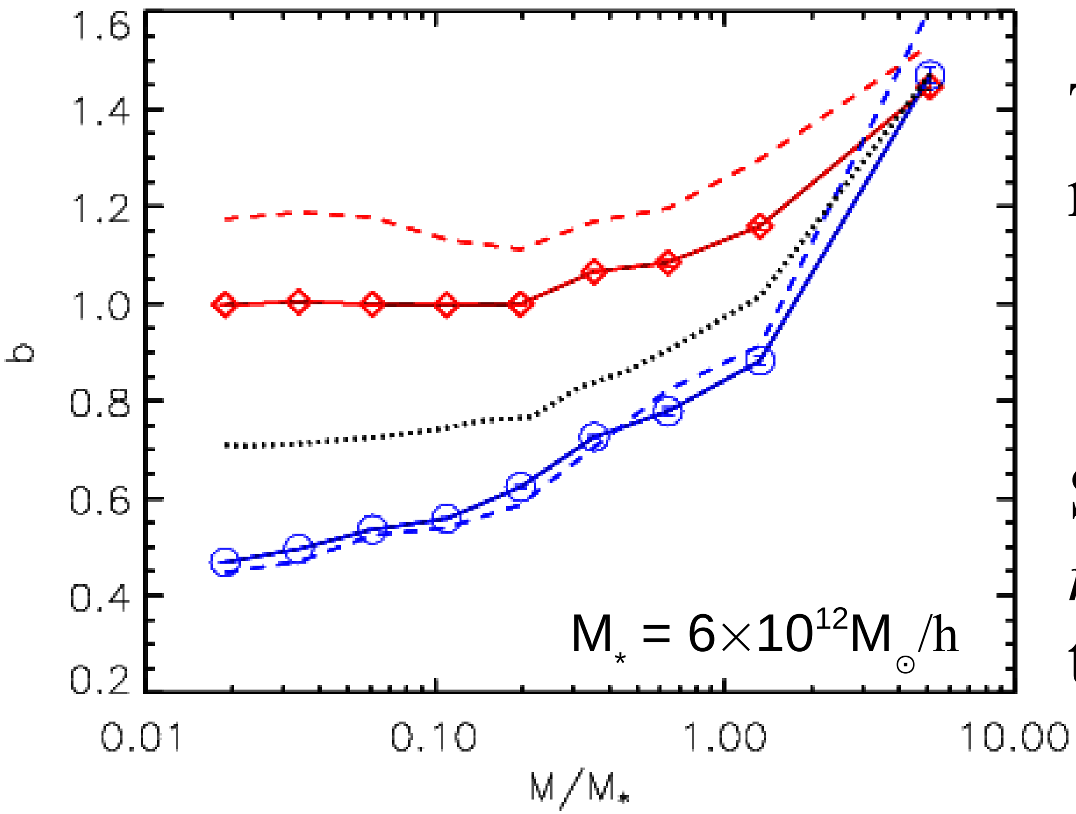
Halo bias as a function of mass and formation time

Gao, Springel & White 2005



Bias increases smoothly with formation redshift

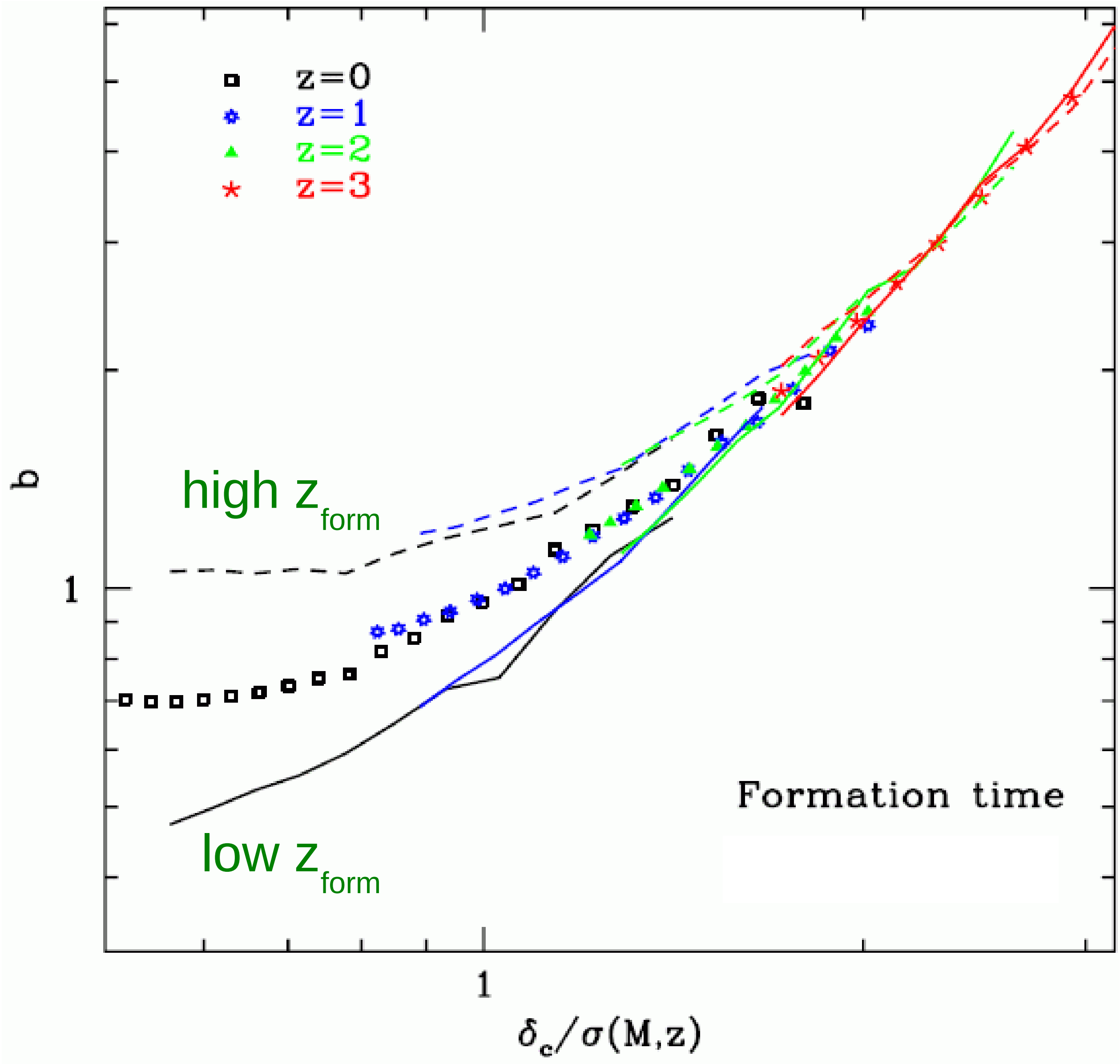


The dependence on formation redshift is strongest at low mass

Such **assembly bias** is consistent *neither* with excursion set theory *nor* with HOD models

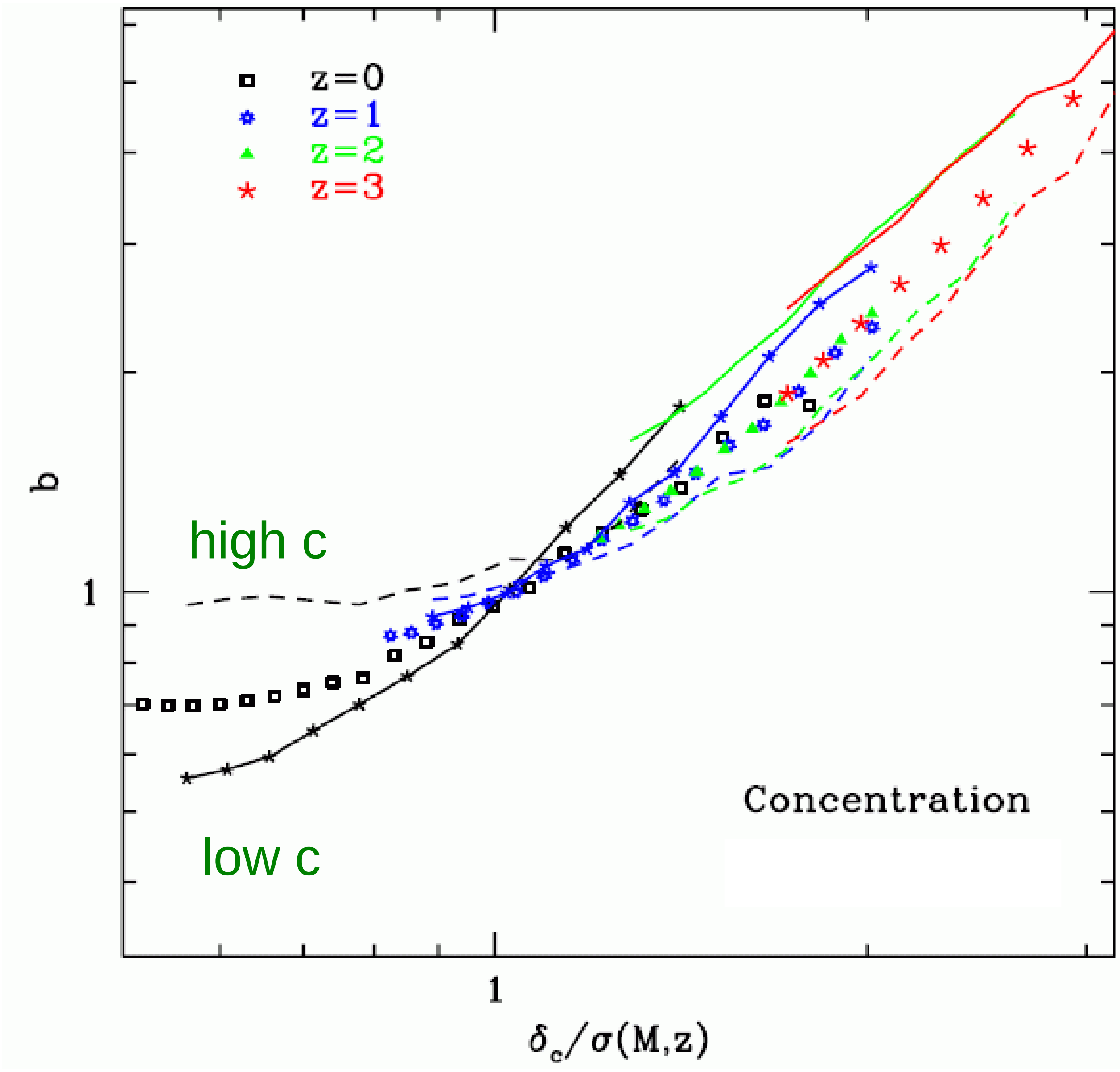
Bias as a function of ν and formation time

Gao & White 2007



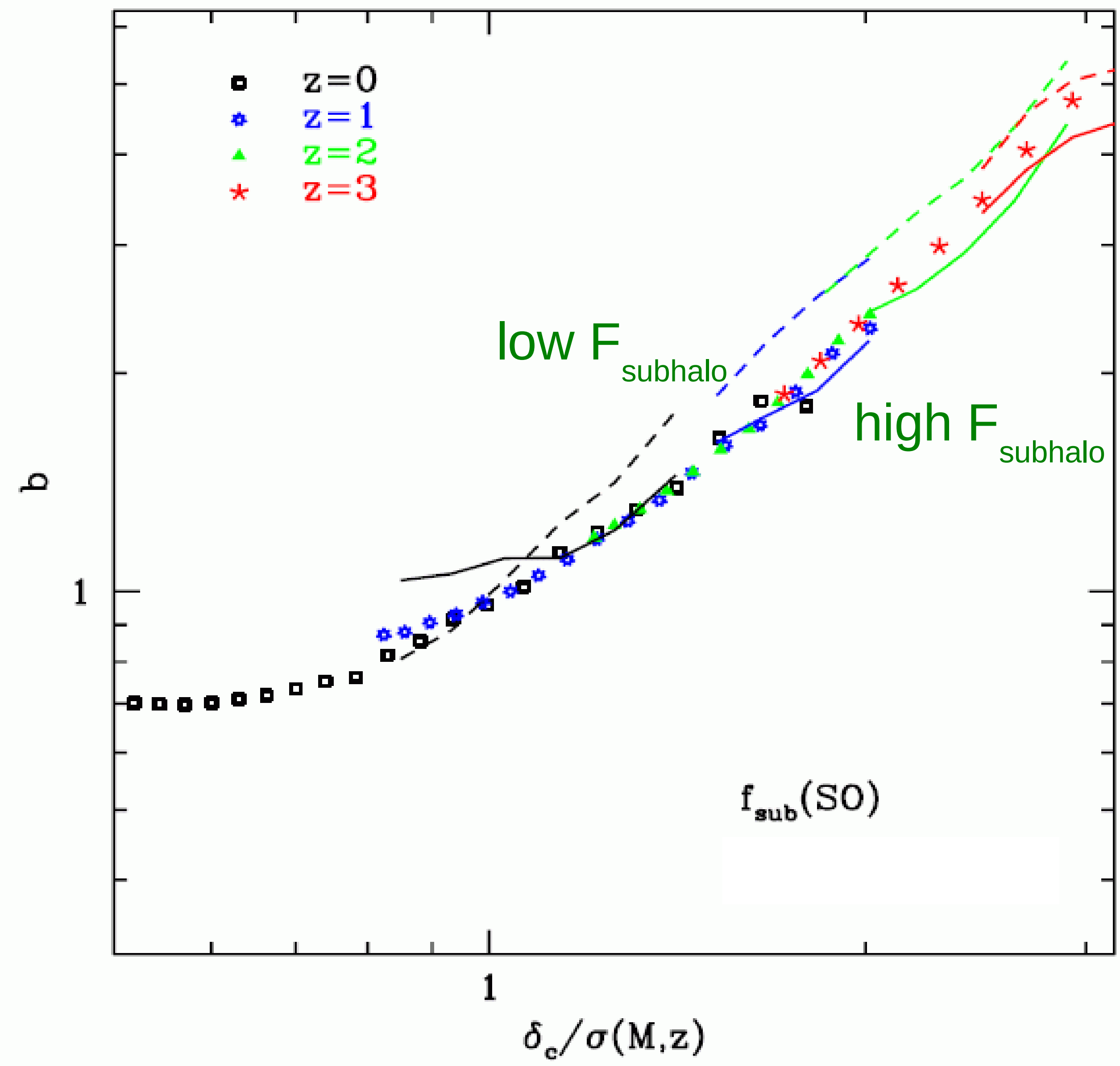
Bias as a function of ν and concentration

Gao & White 2007



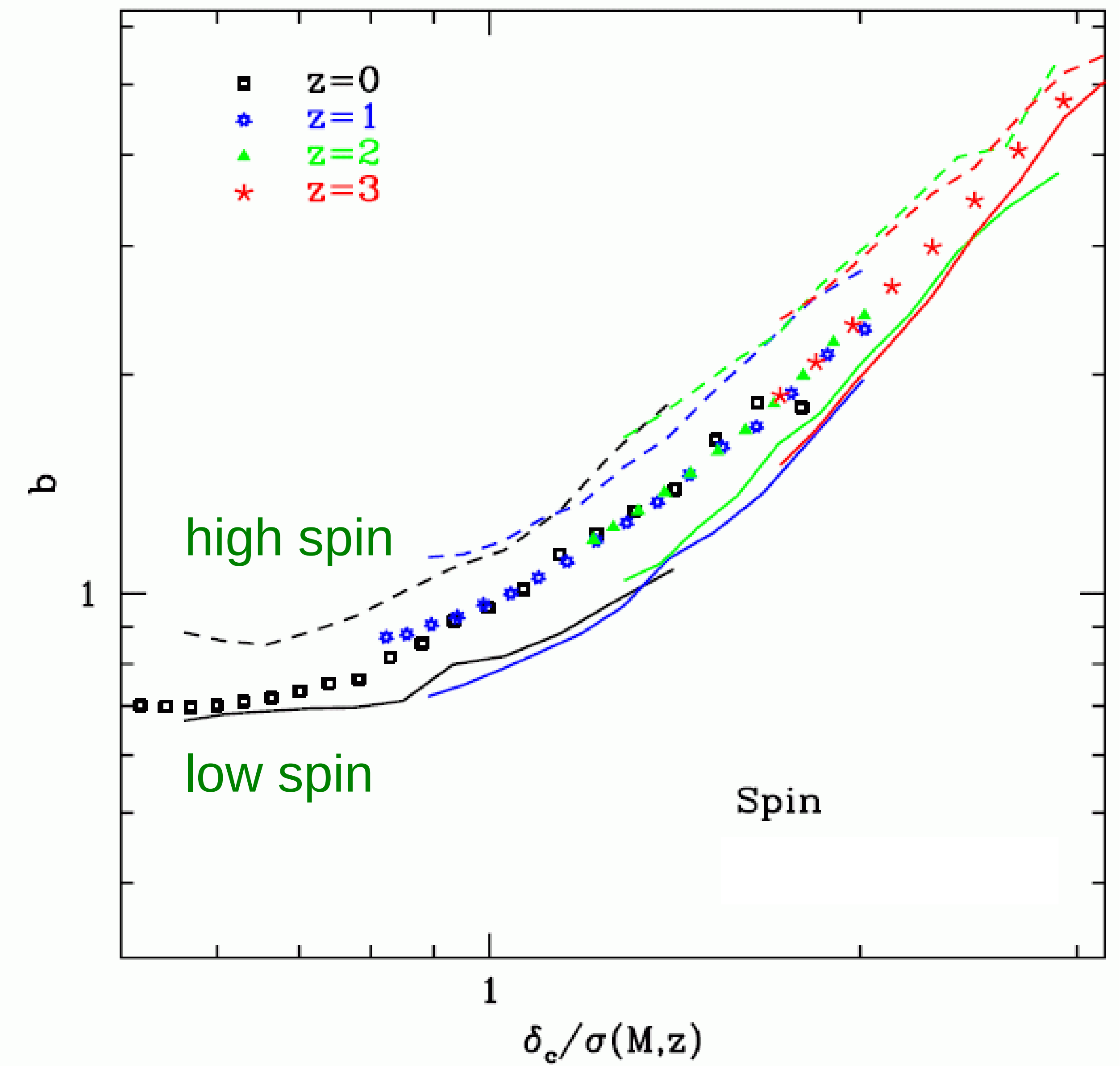
Bias as a function of ν and subhalo mass fraction

Gao & White 2007



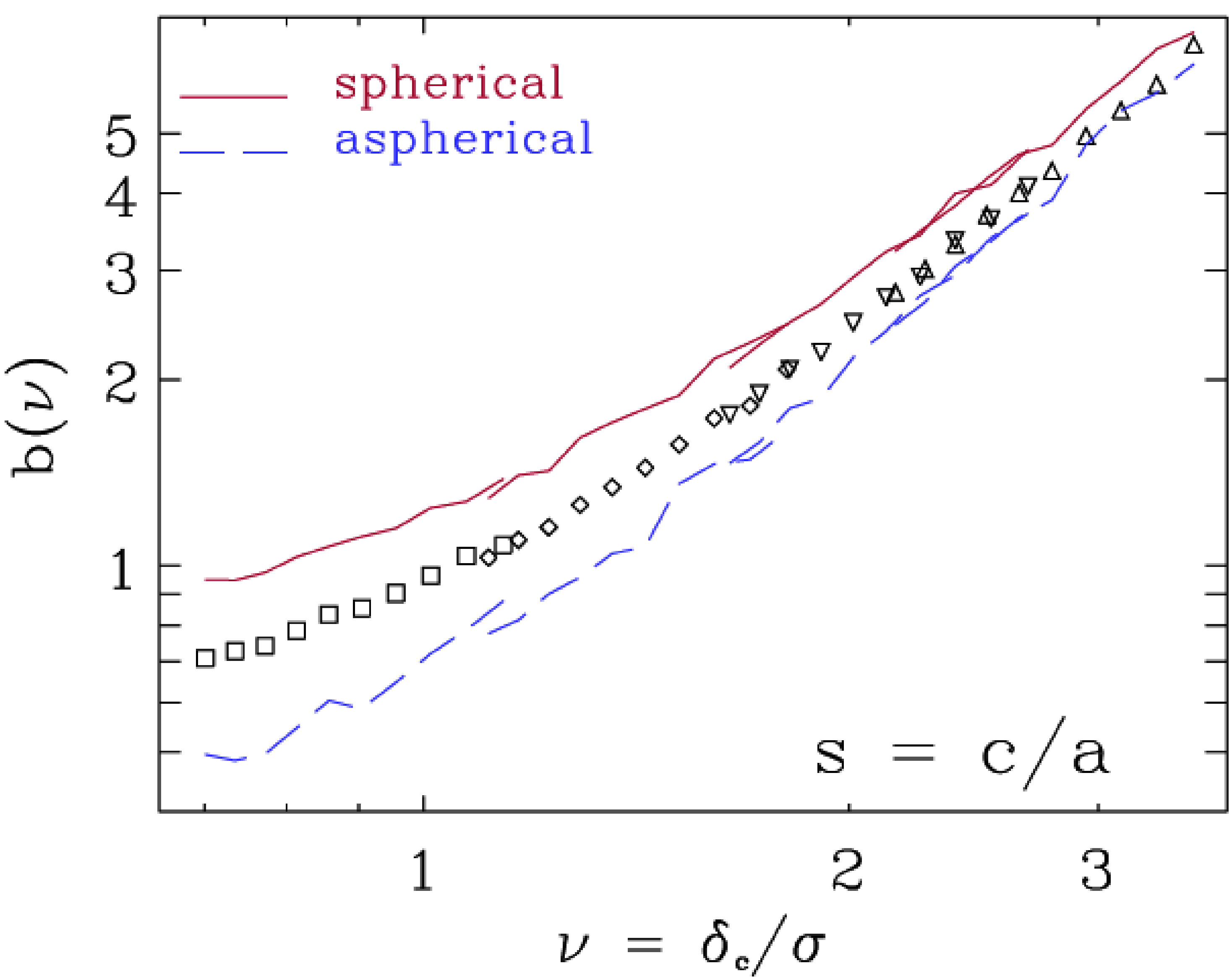
Bias as a function of ν and spin

Gao & White 2007



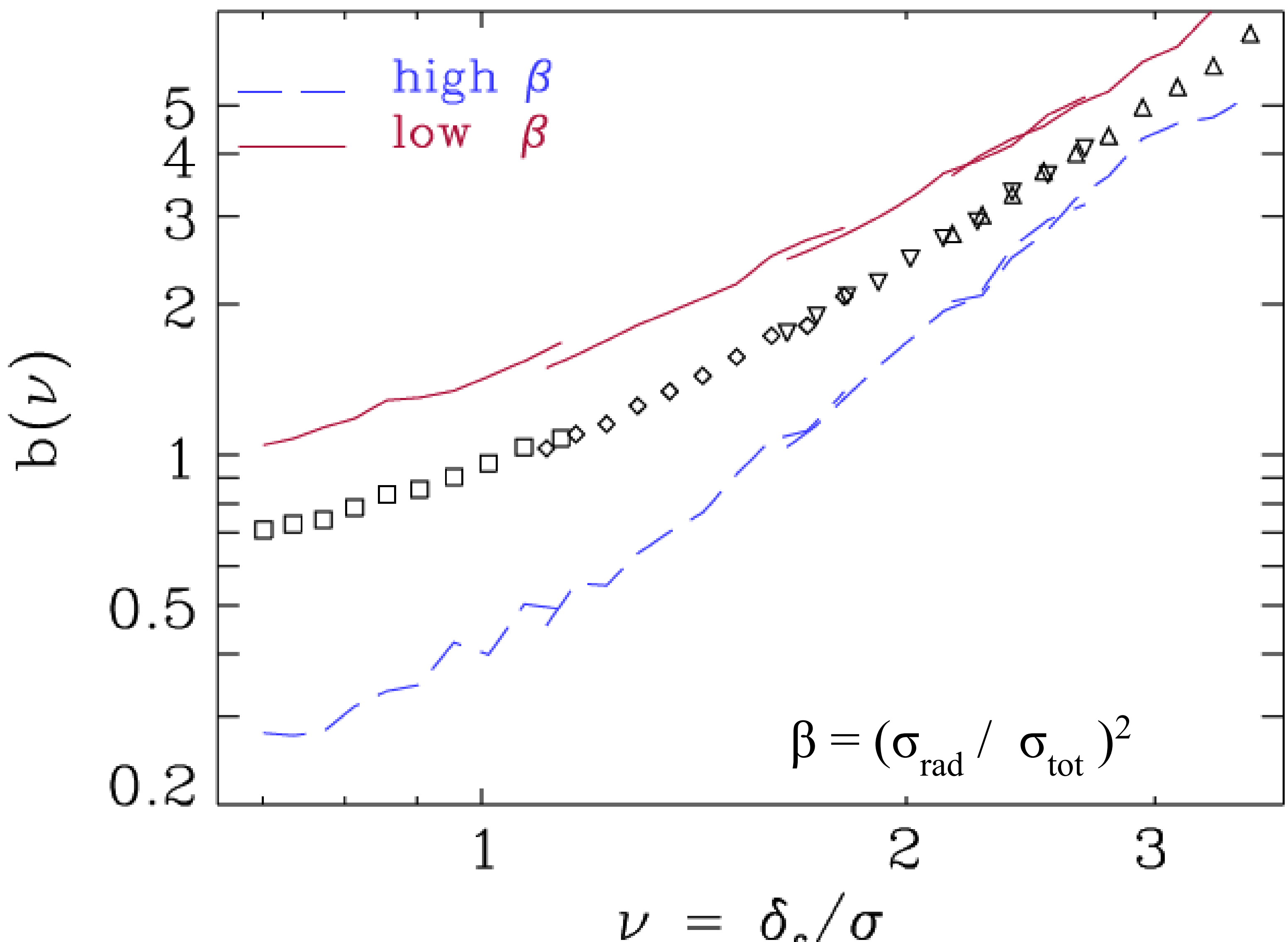
Bias as a function of ν and shape

Faltenbacher & White 2010



Bias as a function of ν and internal kinematics

Faltenbacher & White 2010



Halo assembly bias: conclusions

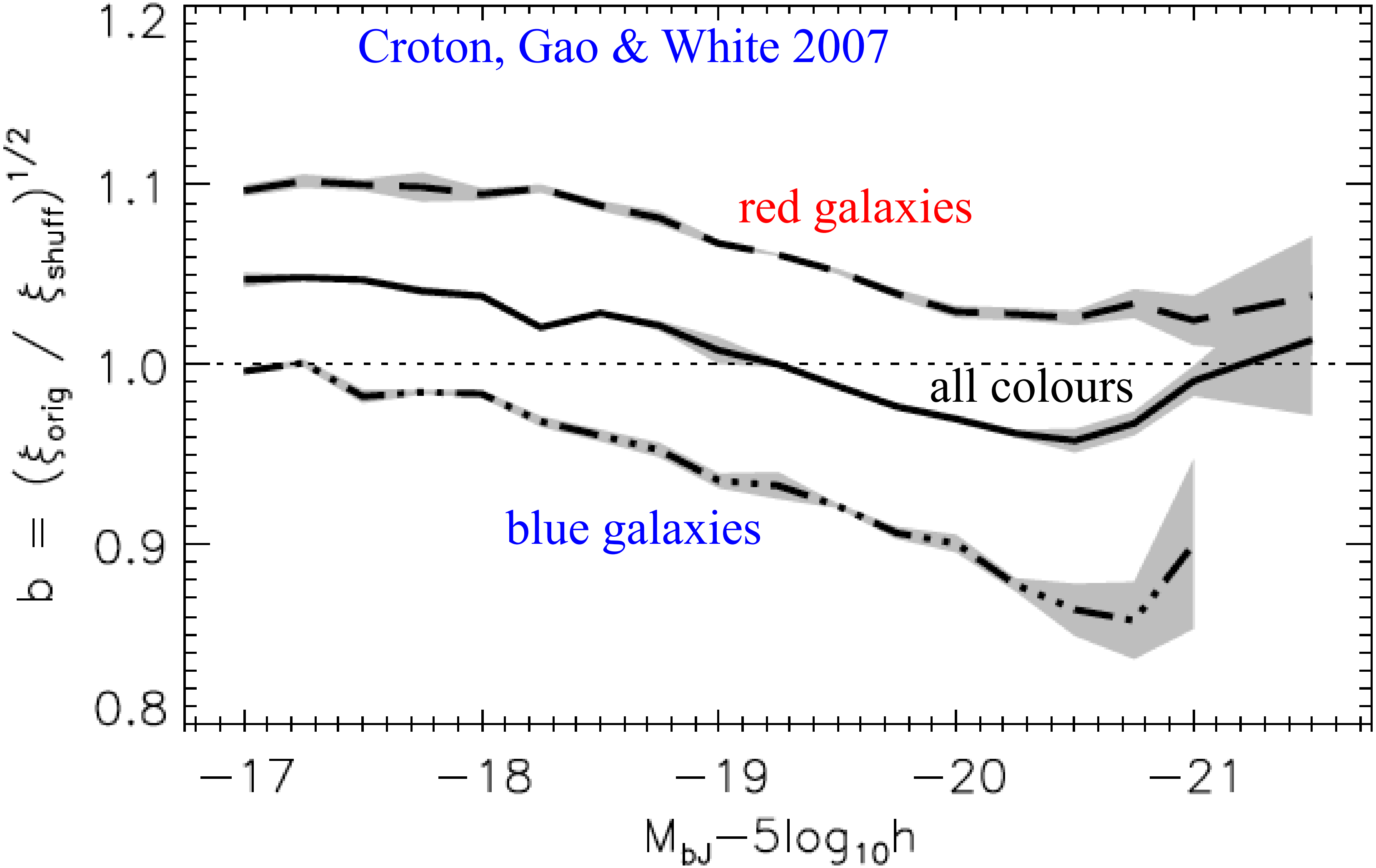
The large-scale bias of halo clustering relative to the dark matter depends on halo mass through $\nu = \delta_c / D(z)\, \sigma_o(M)$ and also on

- formation time
- concentration
- substructure content
- spin
- shape
- internal kinematic structure...

The dependences on these variables differ 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 equally clustered at all masses.

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

Assembly bias in the galaxy distribution

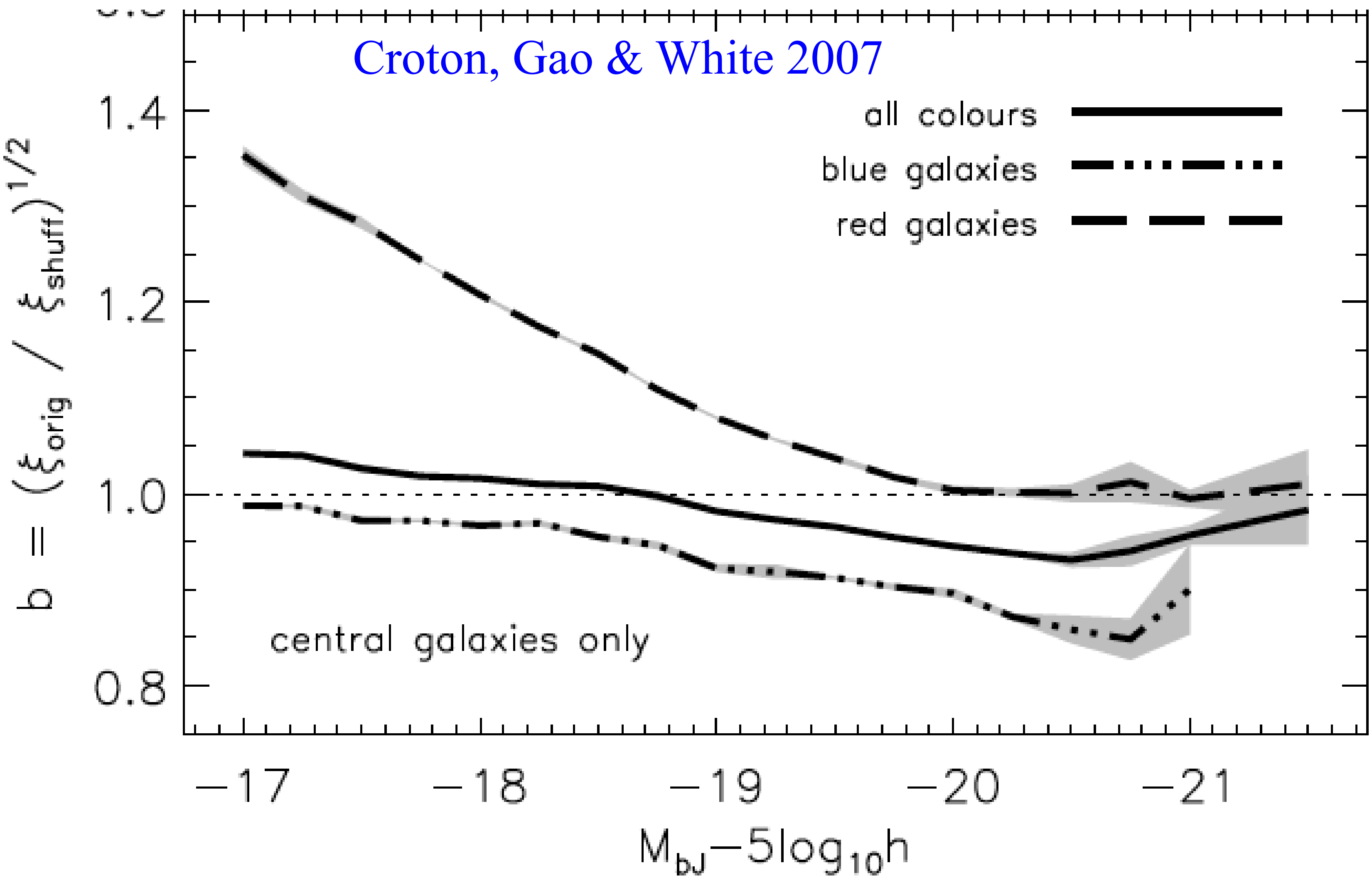


Simulated galaxy populations are <u>shuffled</u> among halos of similar mass

→ clustering differences due purely to assembly history differences

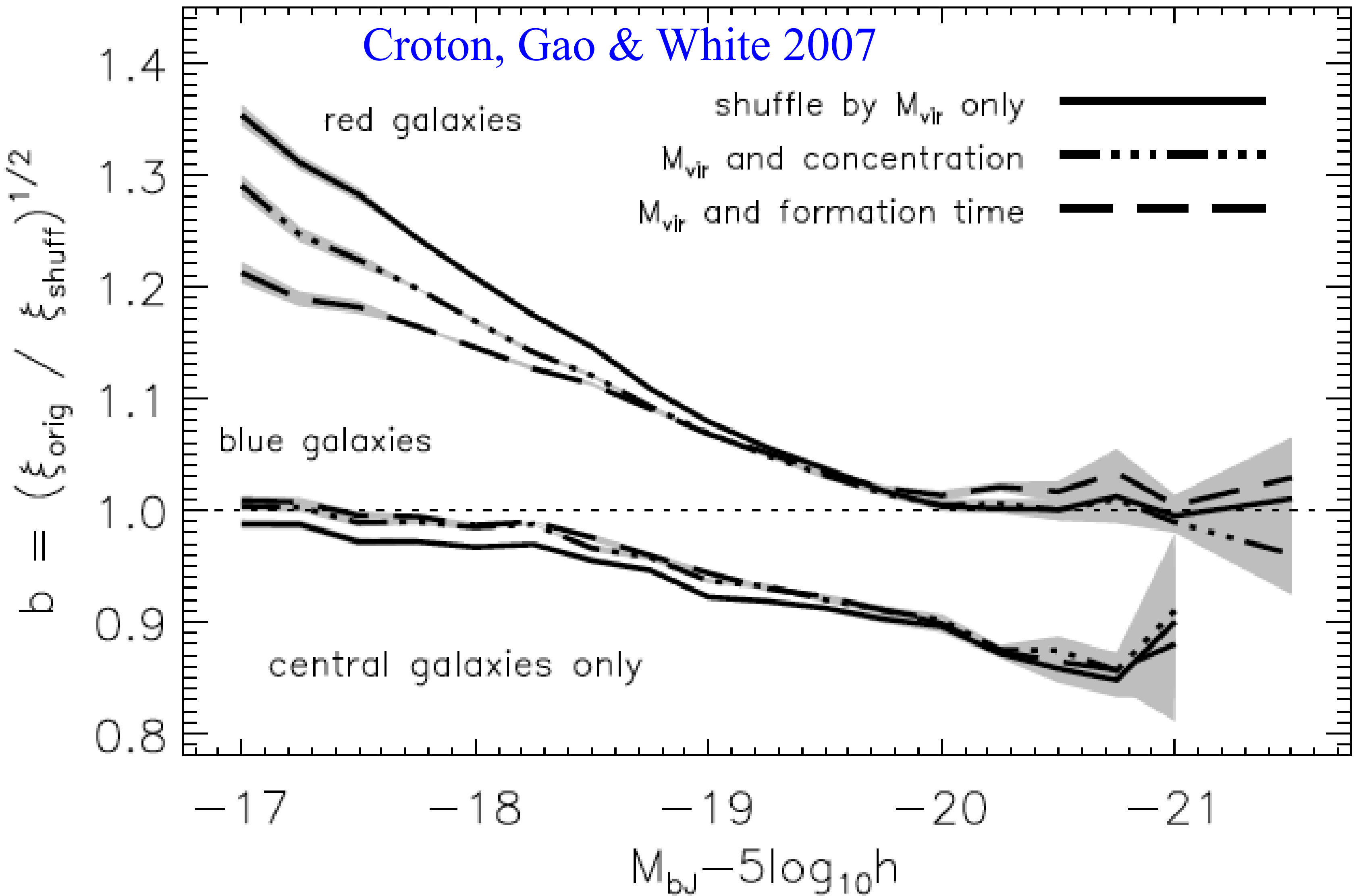
Luminosity- and colour-dependent effects at the ~10% level

Assembly bias in the galaxy distribution



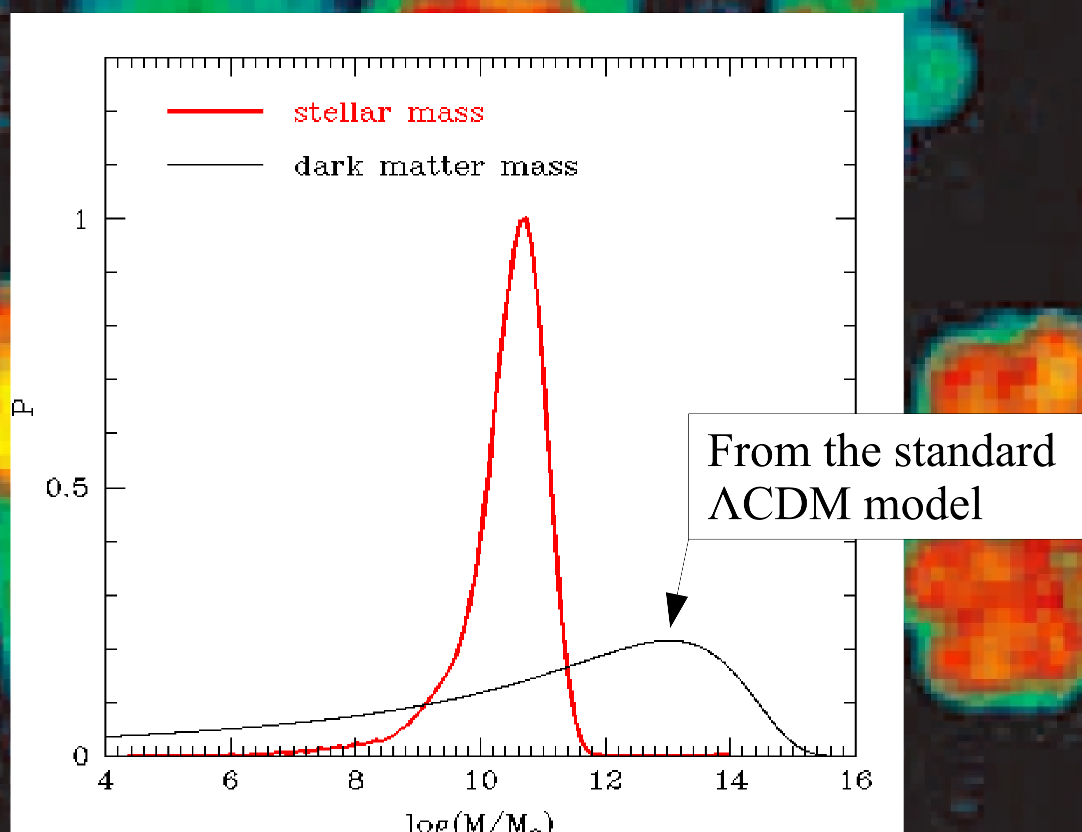
Effects are present in both central and satellite galaxy populations but differ between them

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

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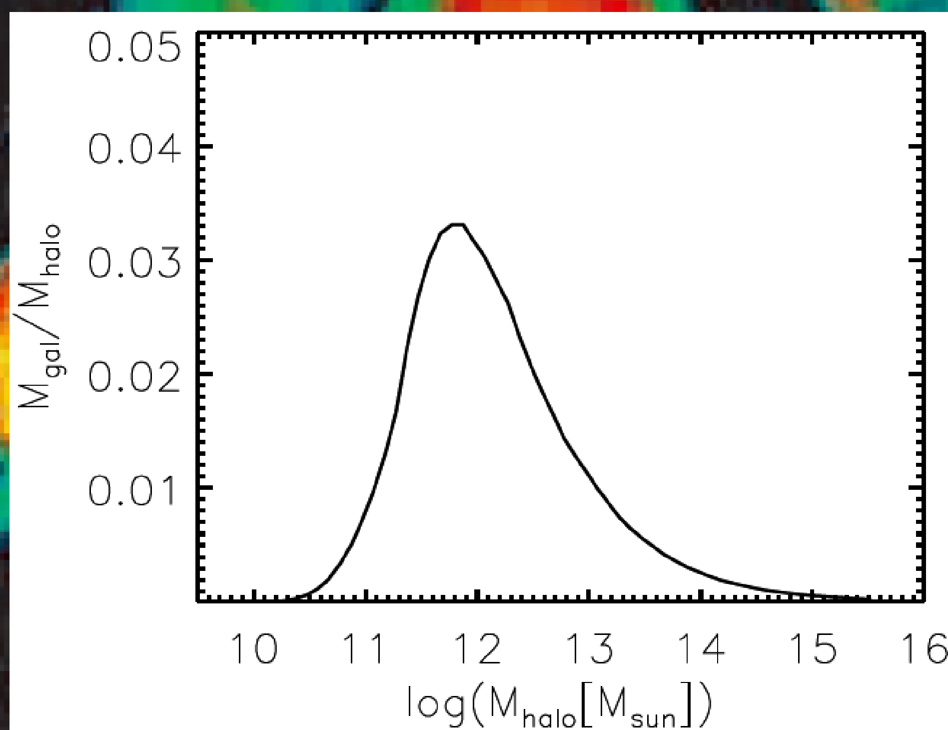
→ Galaxy to halo mass ratio varies *strongly* with mass



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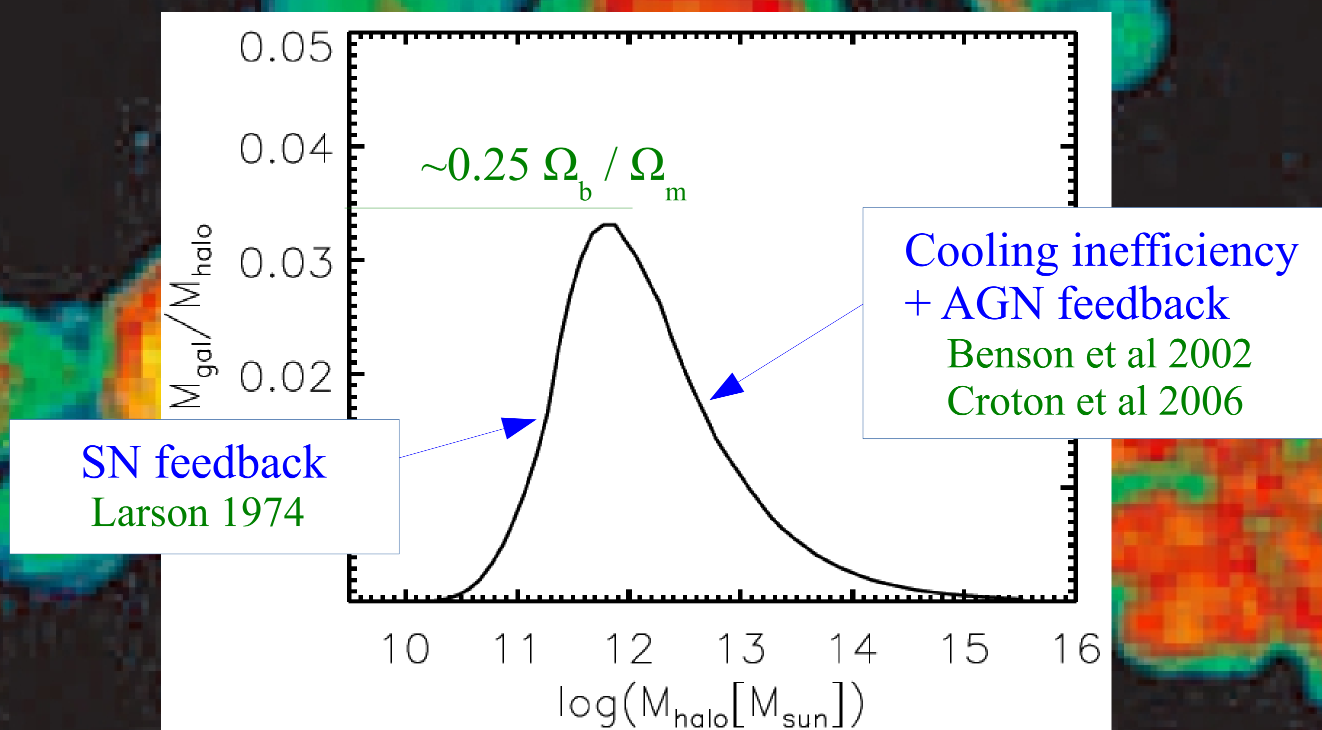
Star formation efficiency is reduced at both low *and* high halo mass



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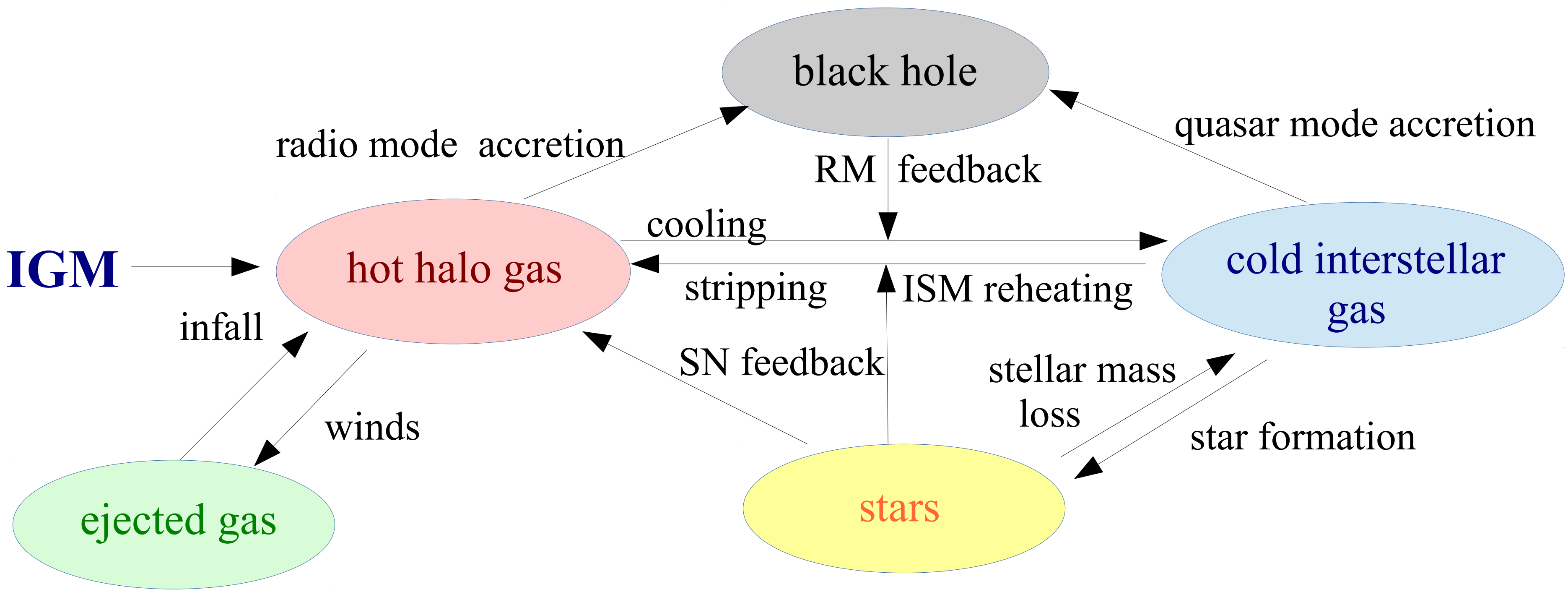
$$(\Omega_b / \Omega_m)\, M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$



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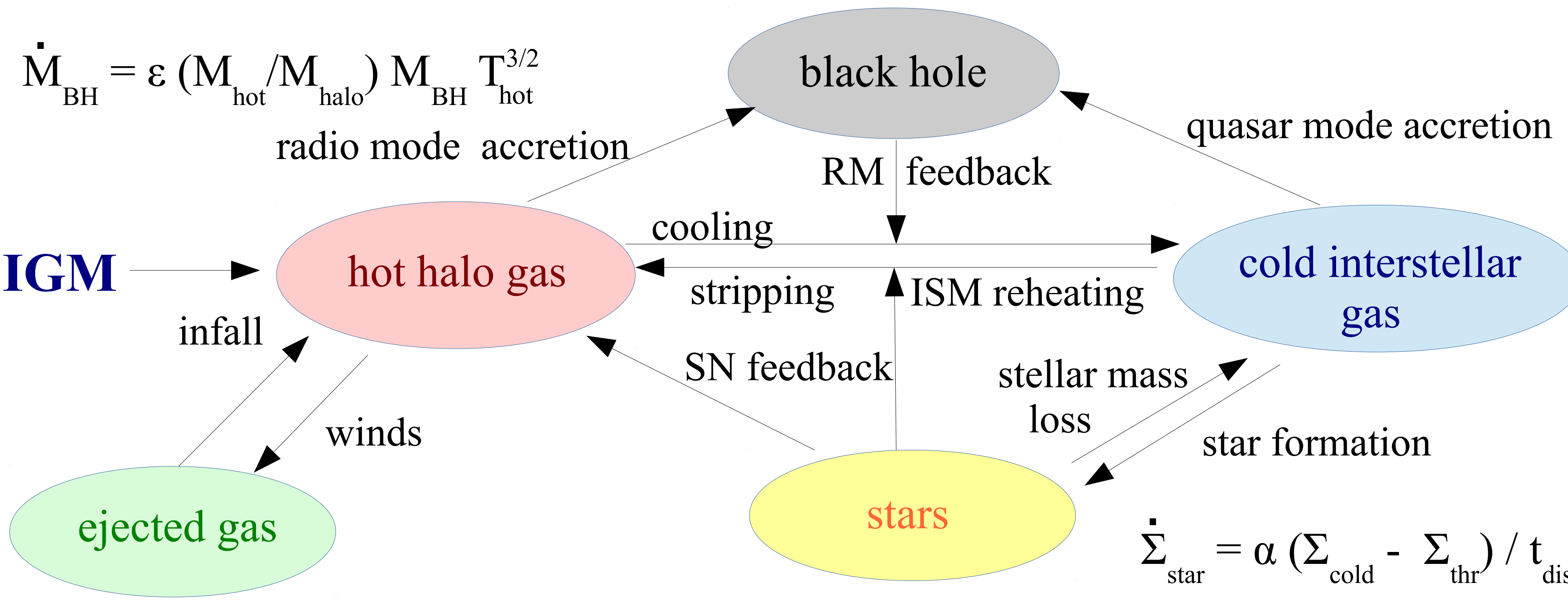
$$\dot{M}_{BH} = \varepsilon\, (M_{hot}/M_{halo})\, M_{BH}\, T_{hot}^{3/2}$$



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

The semi-analytic programme

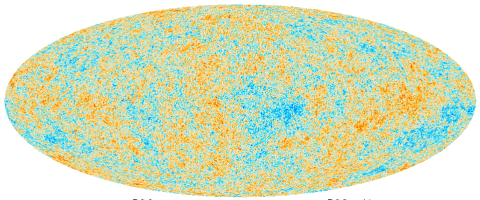
Follow the DM distribution with high-resolution simulations

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

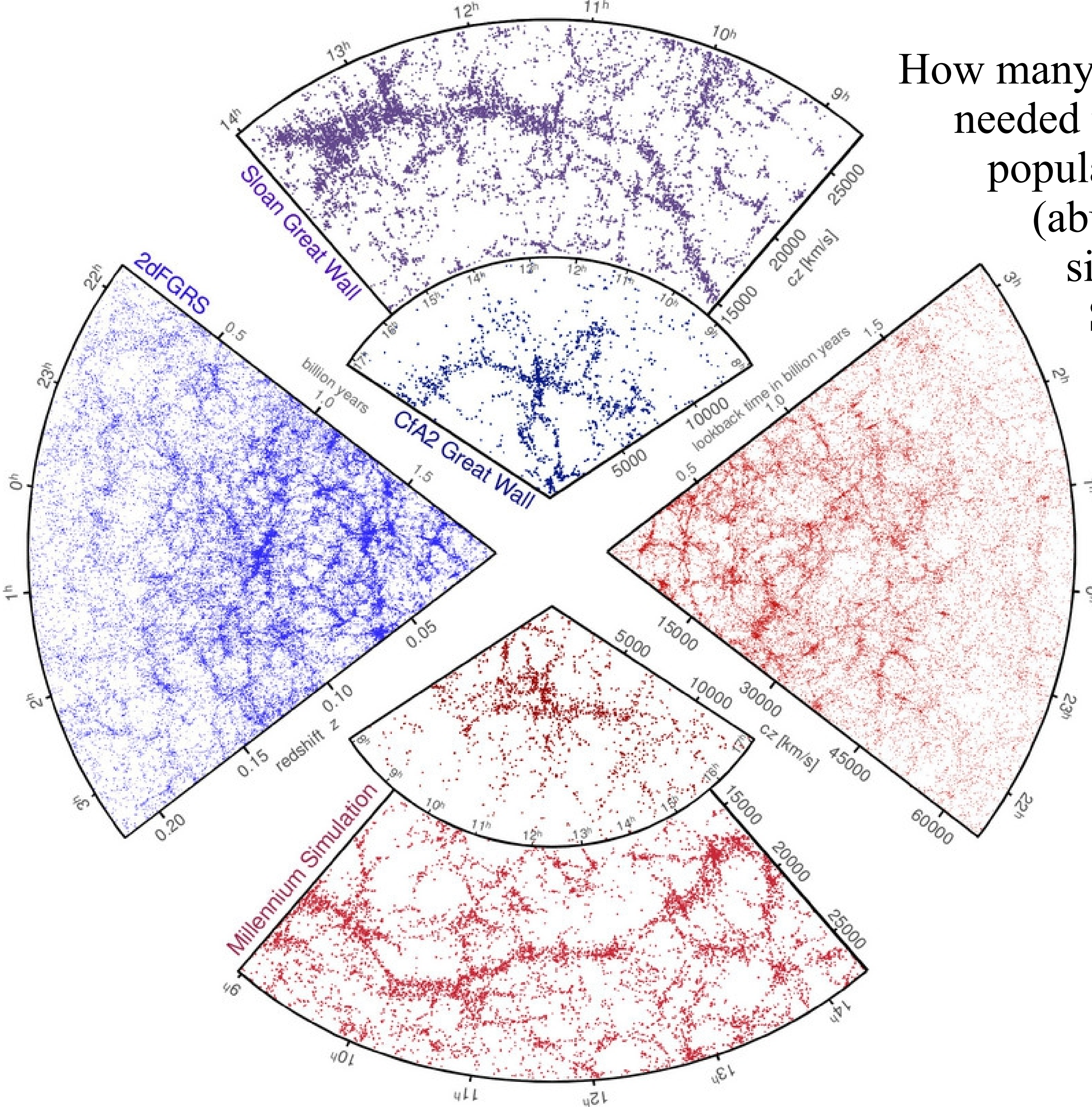
gas cooling onto central galaxies
star formation within these central galaxies
central black hole growth
generation of winds through stellar and AGN feedback
production, expulsion and mixing of nucleosynthesis products

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

e.g.  → Ω

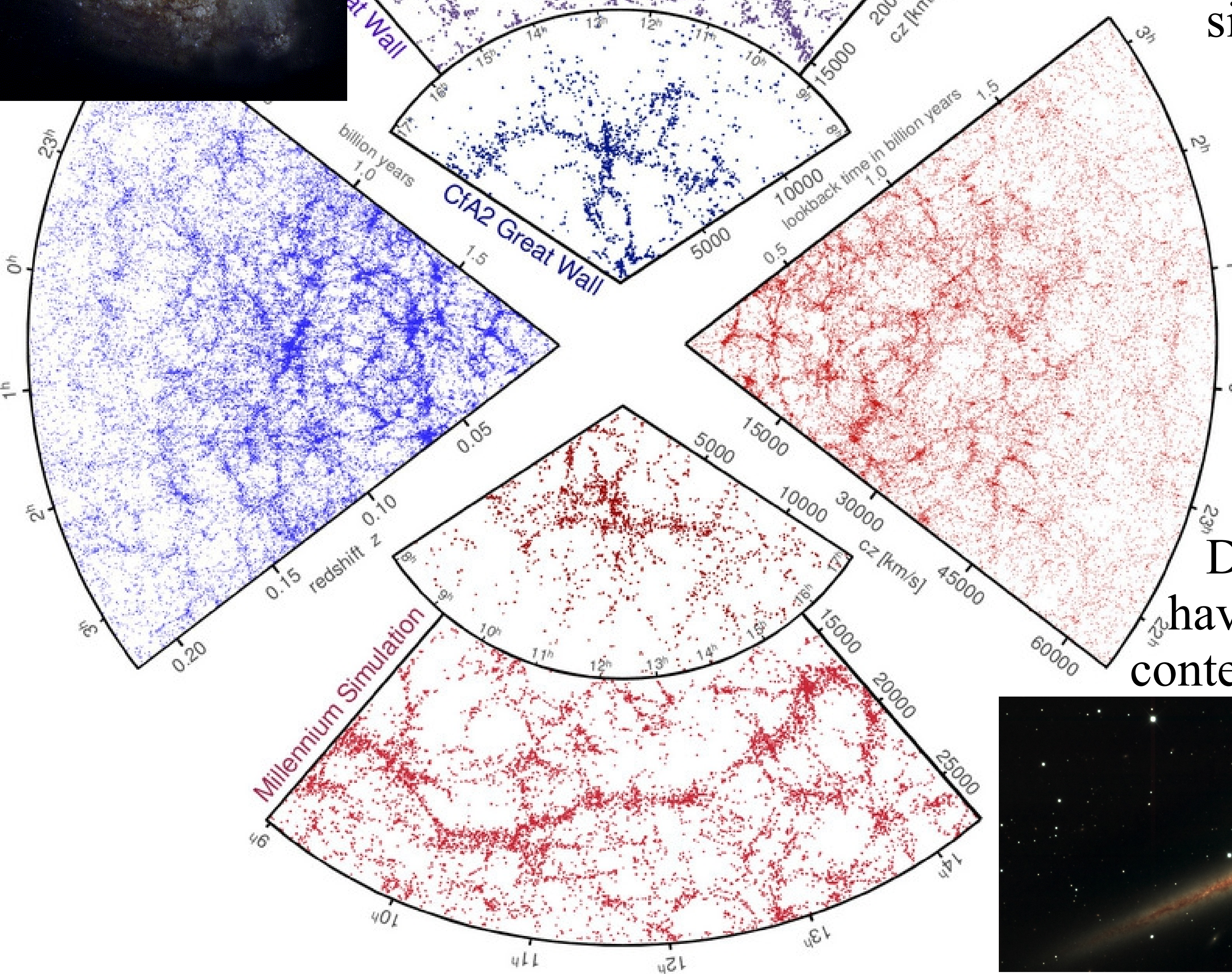
Six parameters fine-tuned to fit a single curve

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



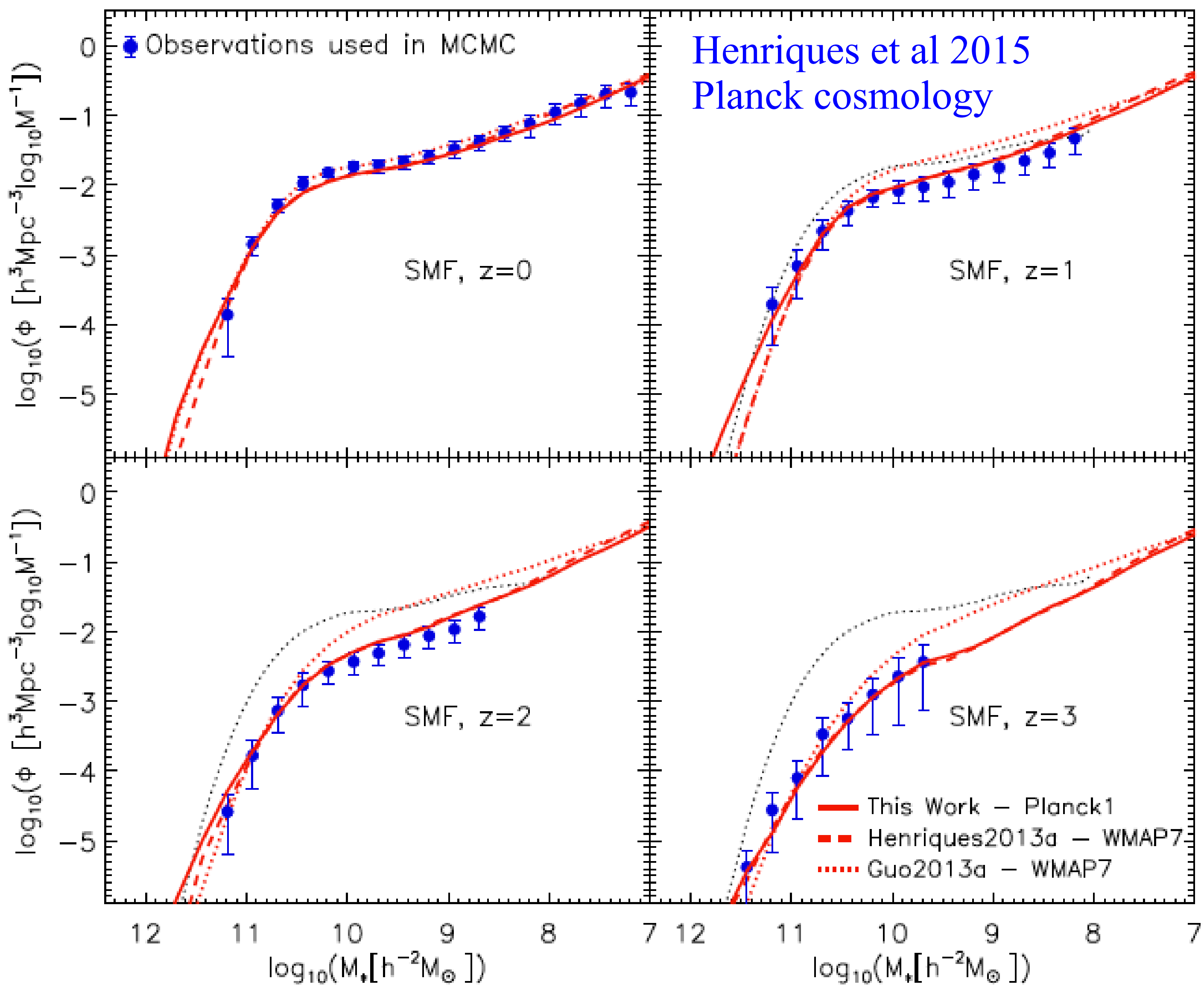
How many parameters are needed to fit the galaxy population?

(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?

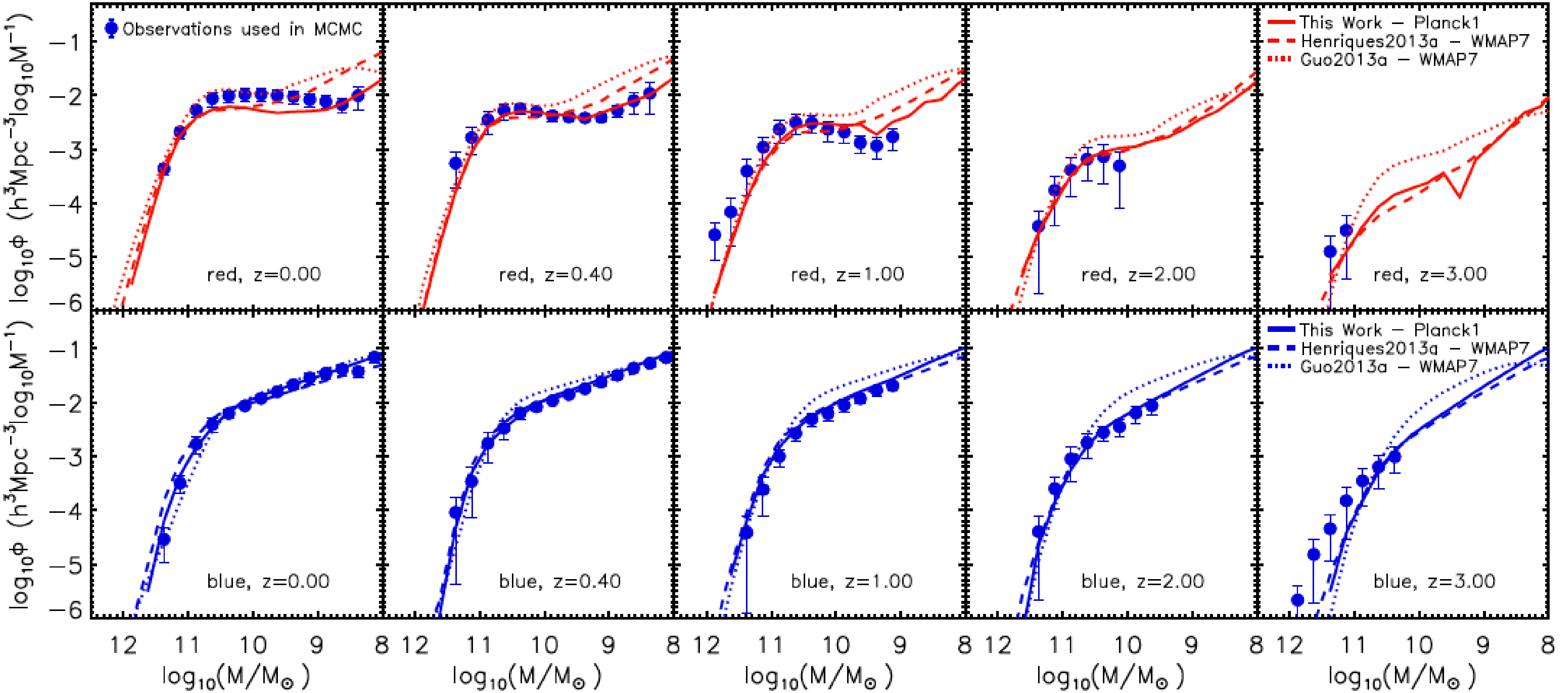


Changing the assumed timescale for reincorporation of wind ejecta

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

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

Henriques et al 2015, Planck cosmology



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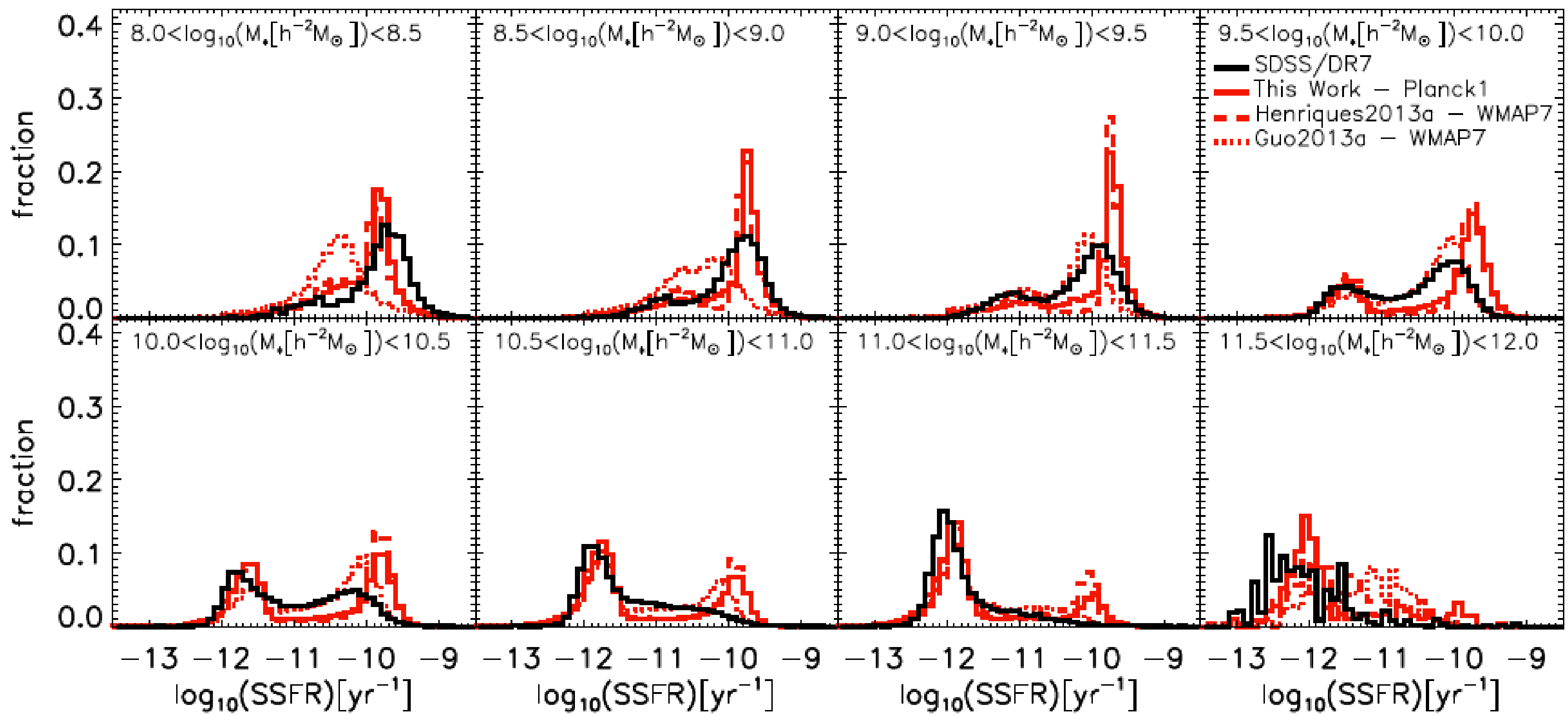
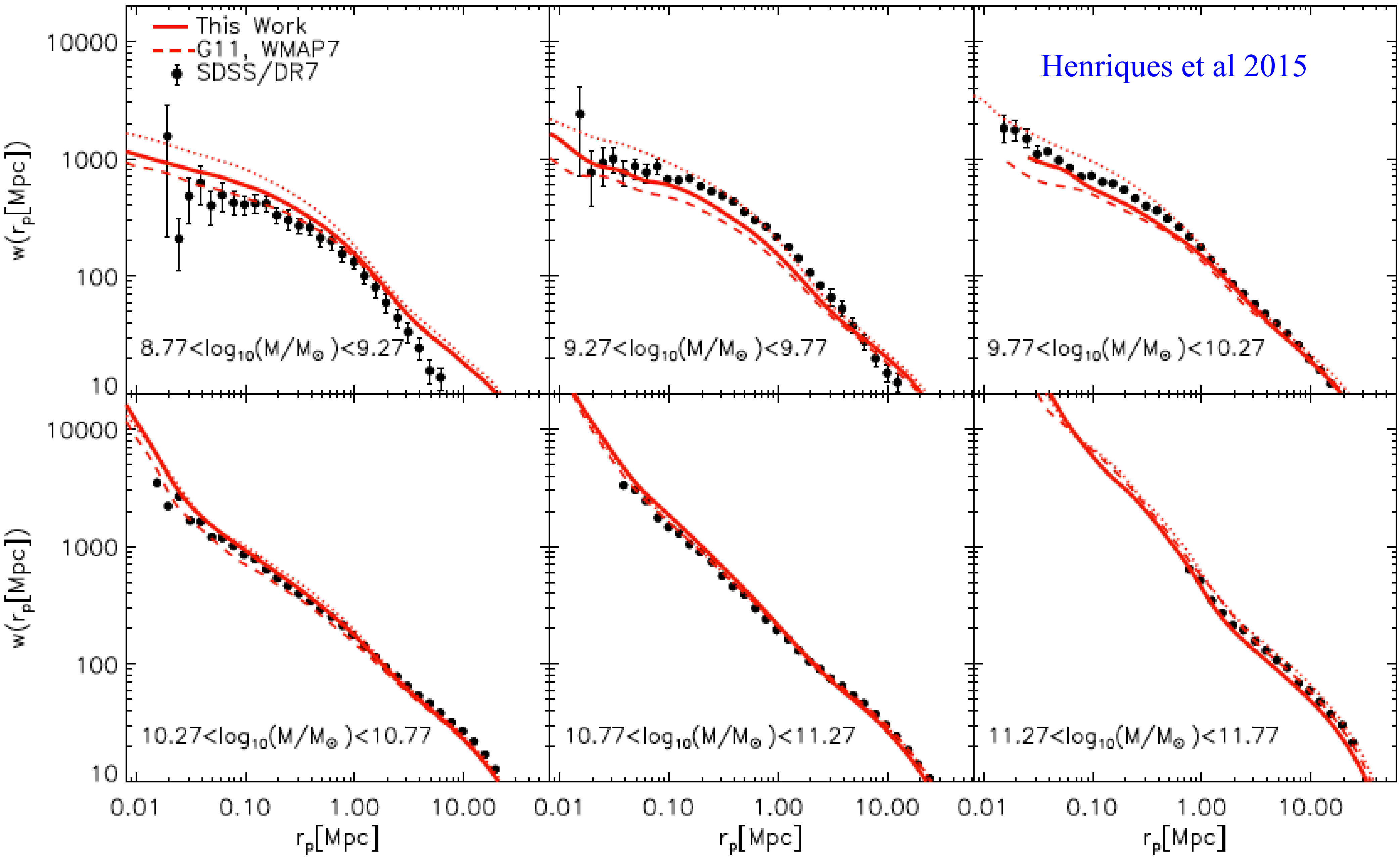
Further recent updates to astrophysical modelling

- Adjust efficiency and z-dependence of AGN feedback/mass quenching
- Eliminate ram-pressure stripping in low-mass halos (log M < 14)
- Reduce gas surface density threshold for star formation
- Switch to Planck (2013) cosmology

Henriques et al 2015



Clustering predictions of the new simulations



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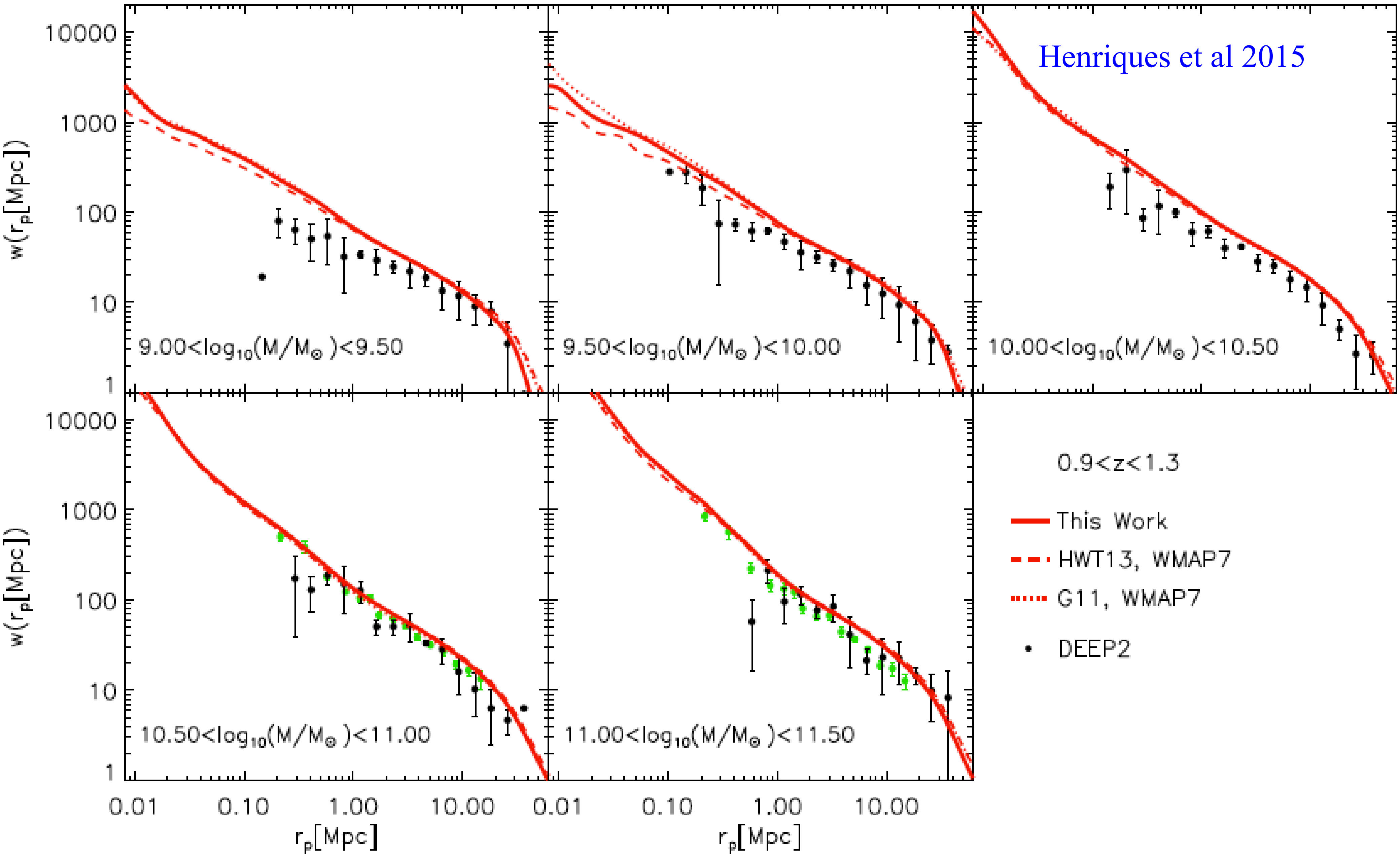
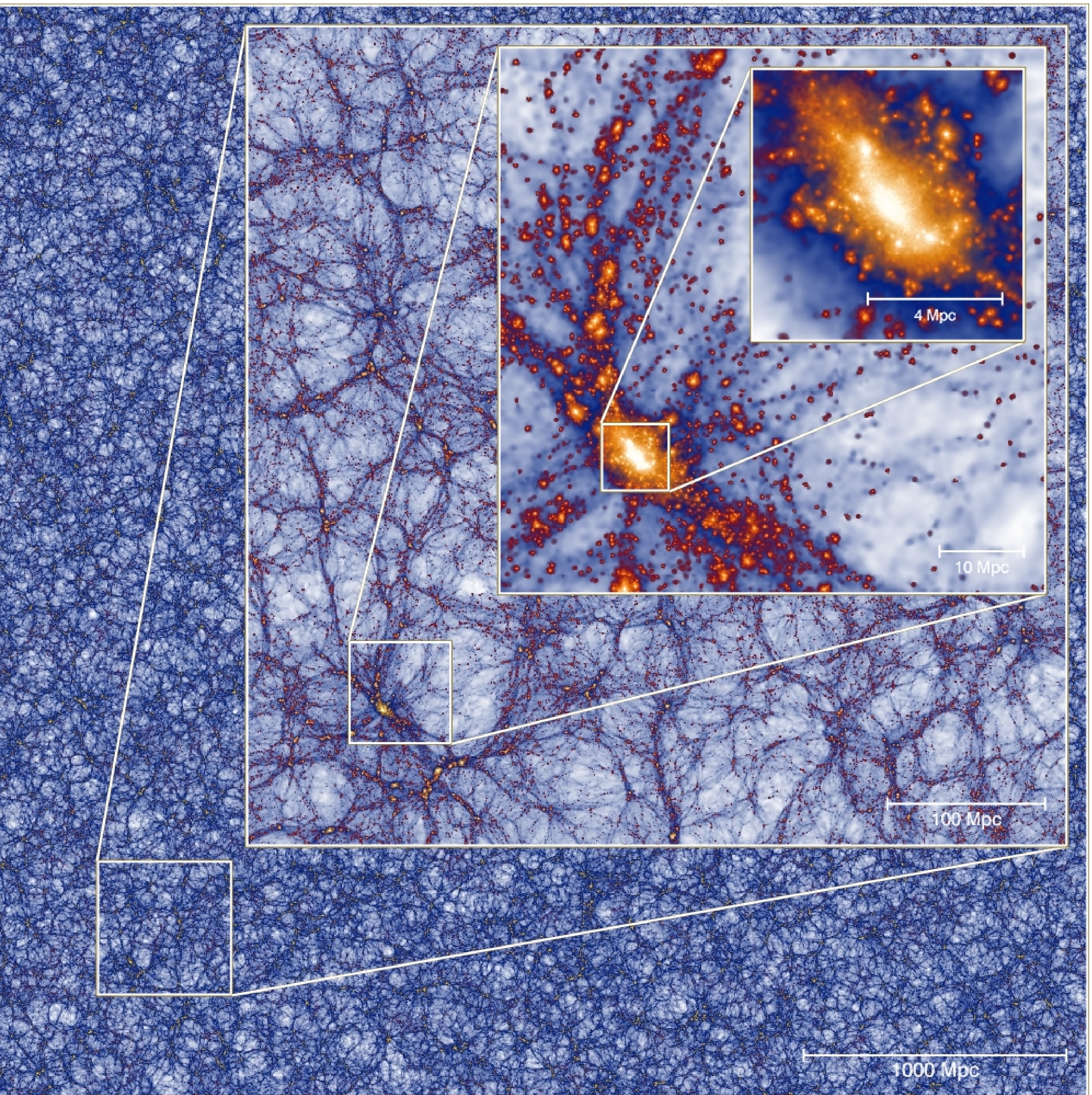




The MXXL

(2010)

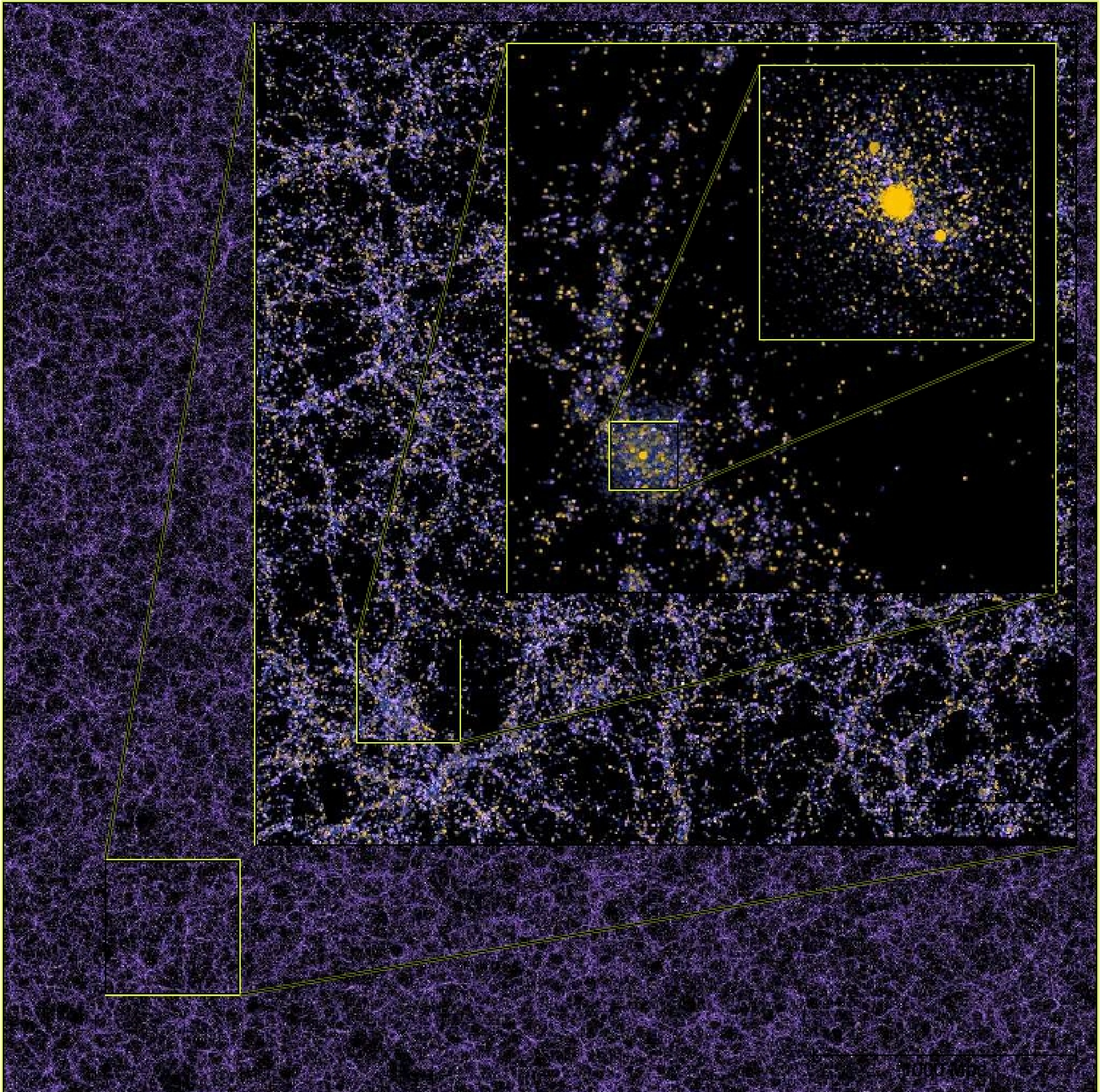
Angulo et al 2012

Bigger than the Millennium Run by factors of

30 in $N_{particle}$

200 in Volume

6 in $m_{particle}$



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3.3×10^8 galaxies at $z = 0$ with $\log M_*/M_\odot > 10$

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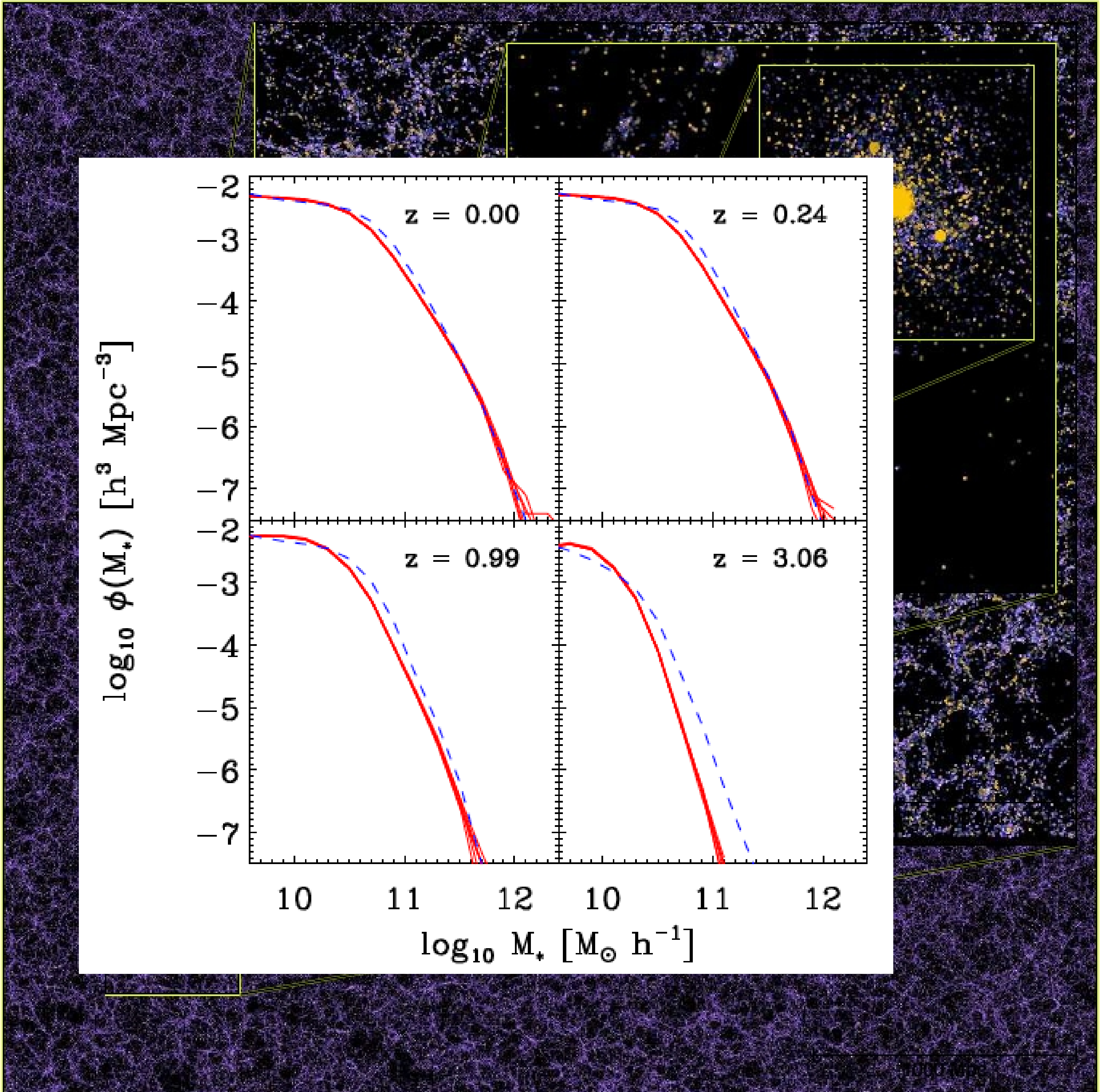

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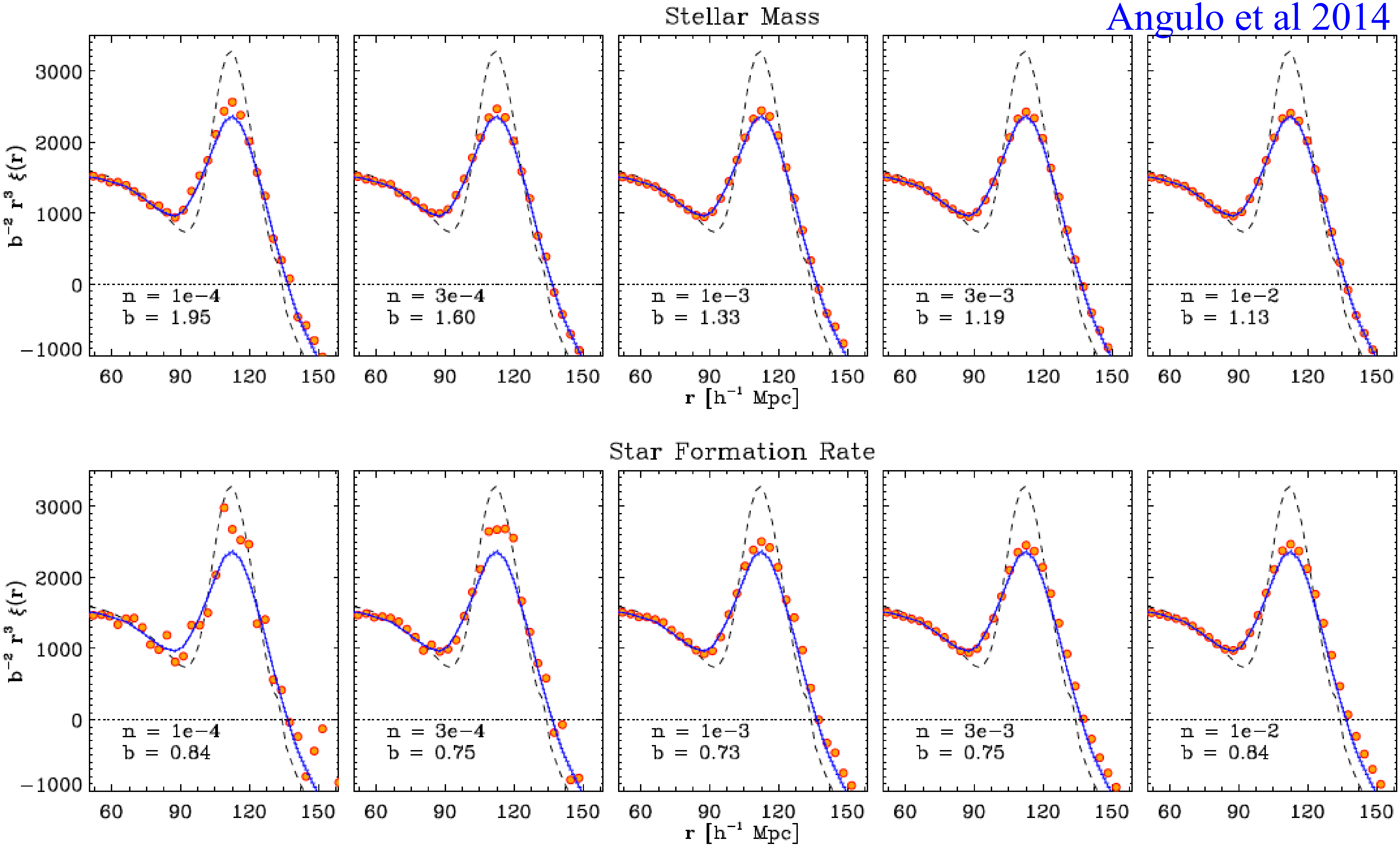
Distortions of BAO feature in the galaxy population

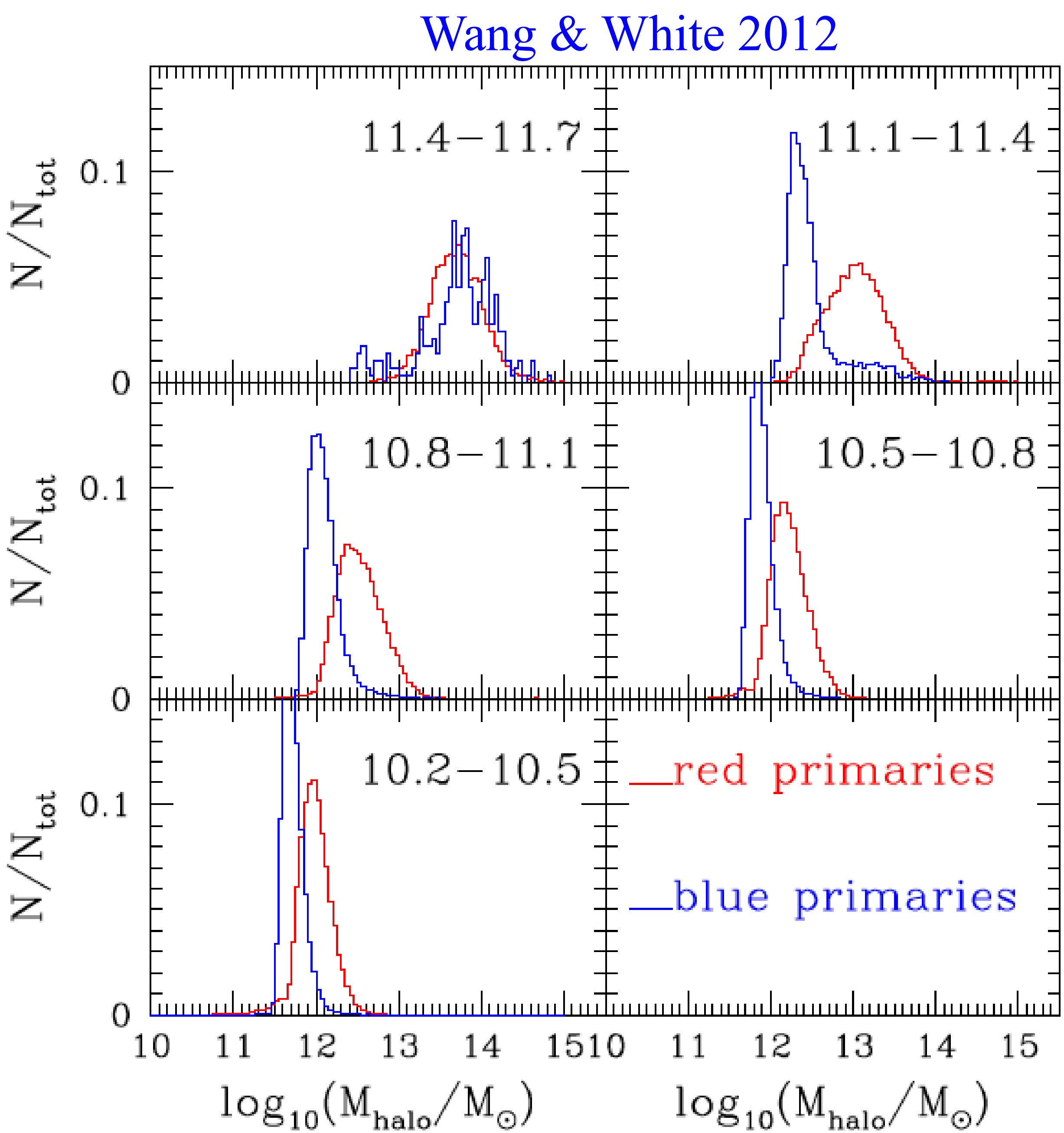
Angulo et al 2014



Angulo et al 2013

Small but measurable shifts for different selection methods

A population simulation prediction for galaxy halos



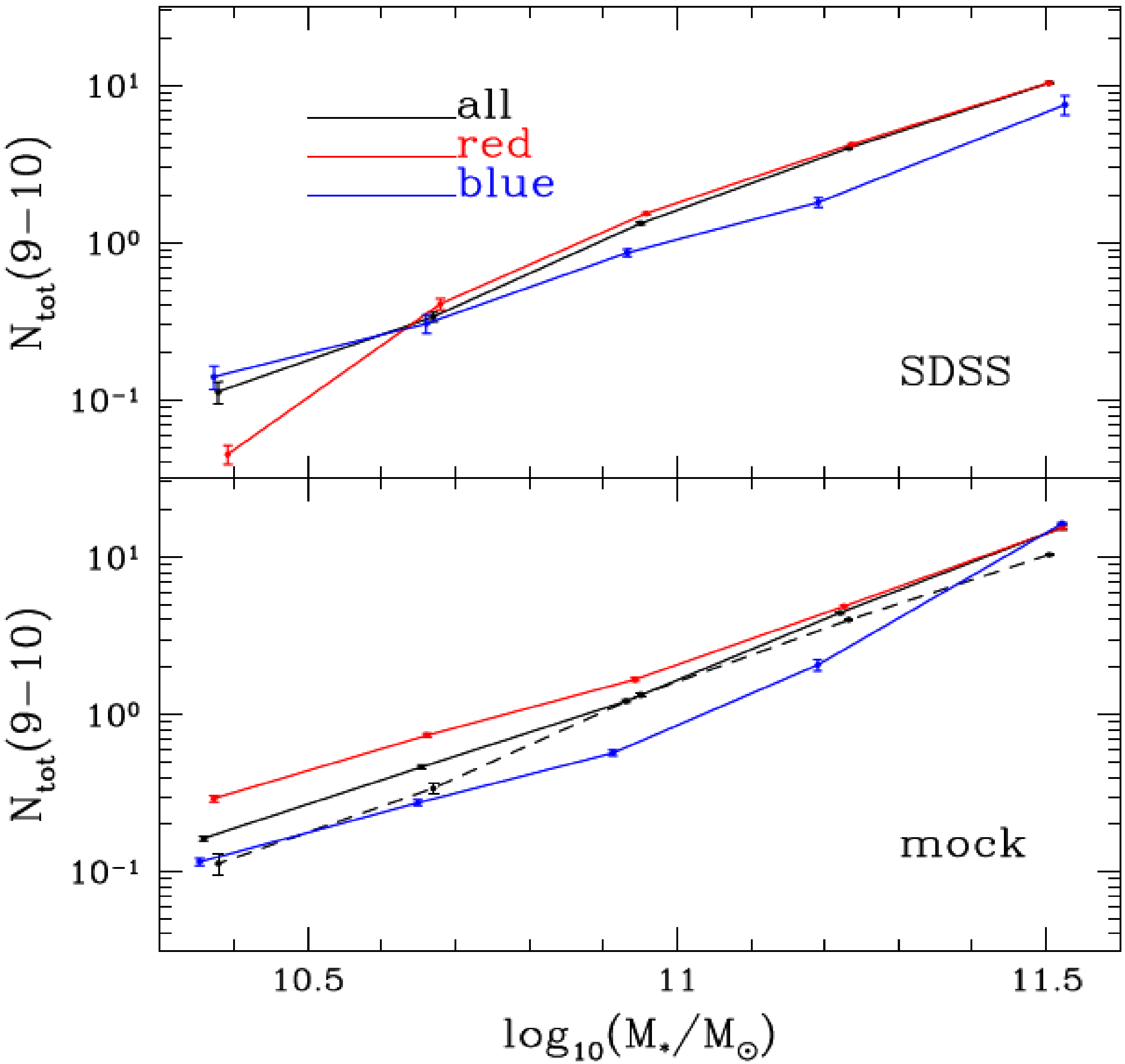
Central galaxies of a given stellar mass are predicted to have larger halo masses if they are red (passive) than if they are blue (star-forming)

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

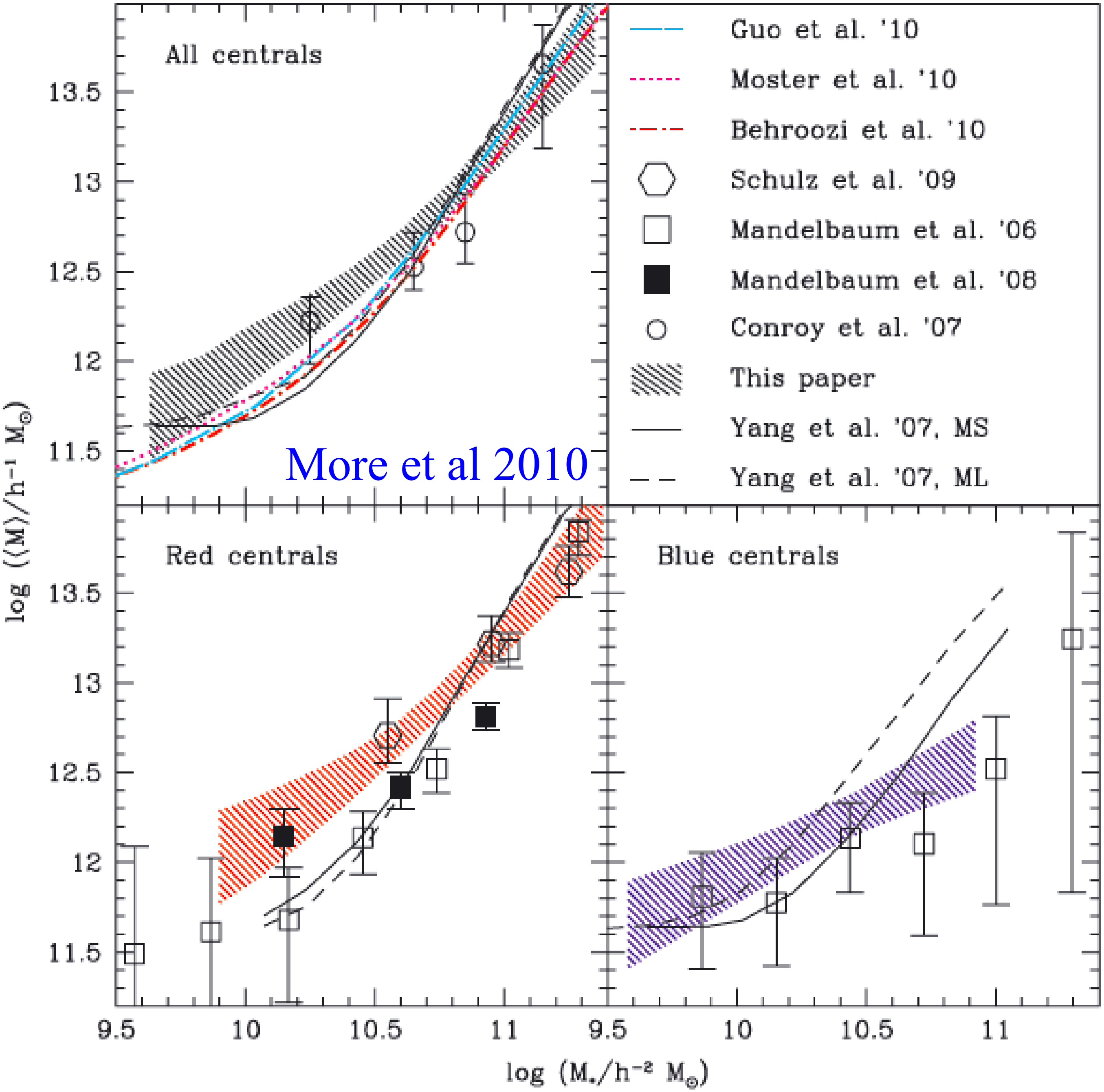


Central galaxies of a given stellar mass are predicted to have larger halo masses if they are red (passive) than if they are blue (star-forming)

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

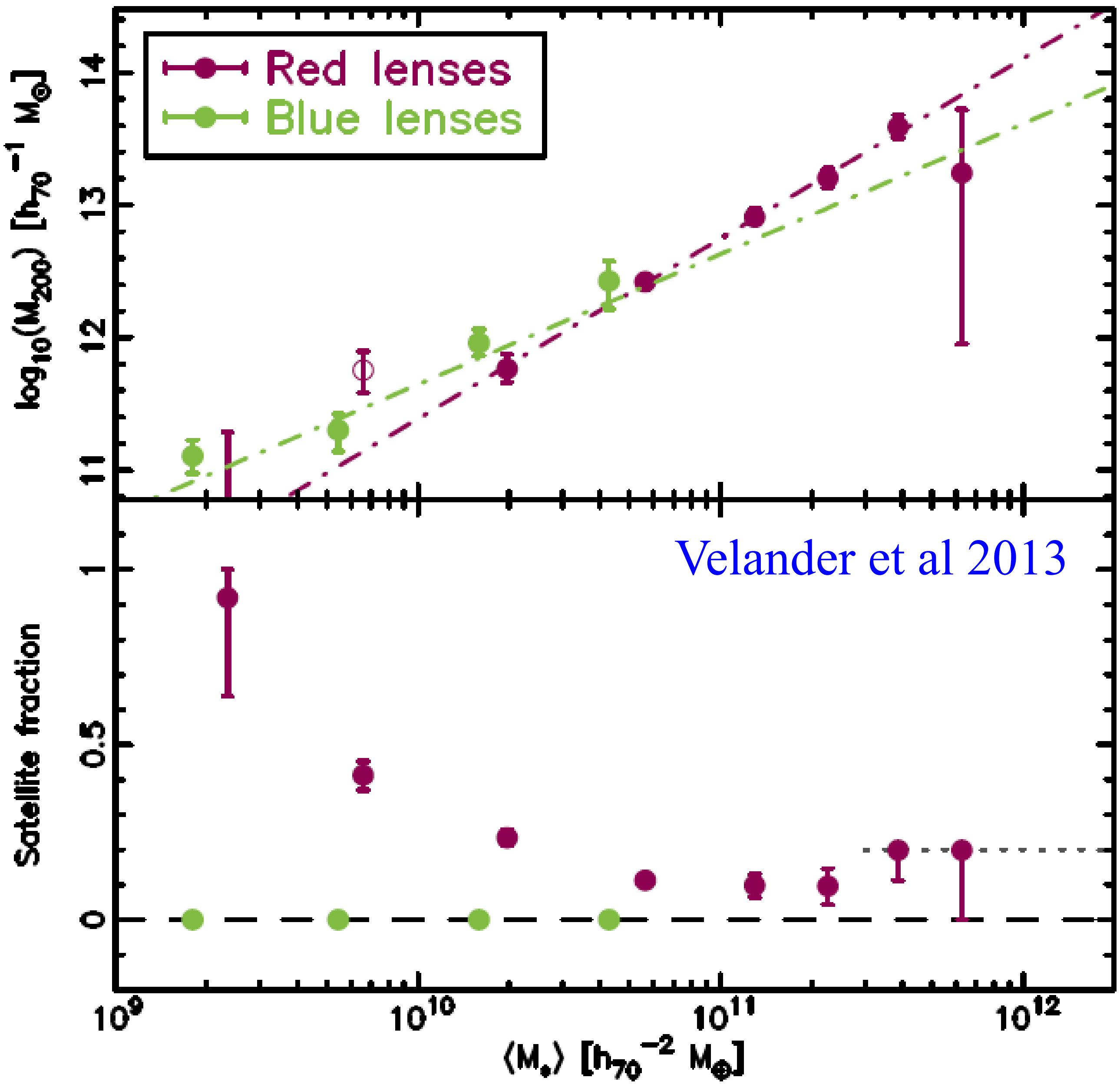
This effect **is** seen in SDSS above Milky Way stellar mass

Halo mass dependence on central galaxy colour?



Blue centrals may have lower mass halos according to estimates based on the motions of satellites (More et al 2010) and to *some* galaxy-galaxy lensing estimates (Mandelbaum et al 2006)

Halo mass dependence on central galaxy colour?



Blue centrals may have lower mass halos according to estimates based on the motions of satellites (More et al 2010) and to *some* galaxy-galaxy lensing estimates, but not all...

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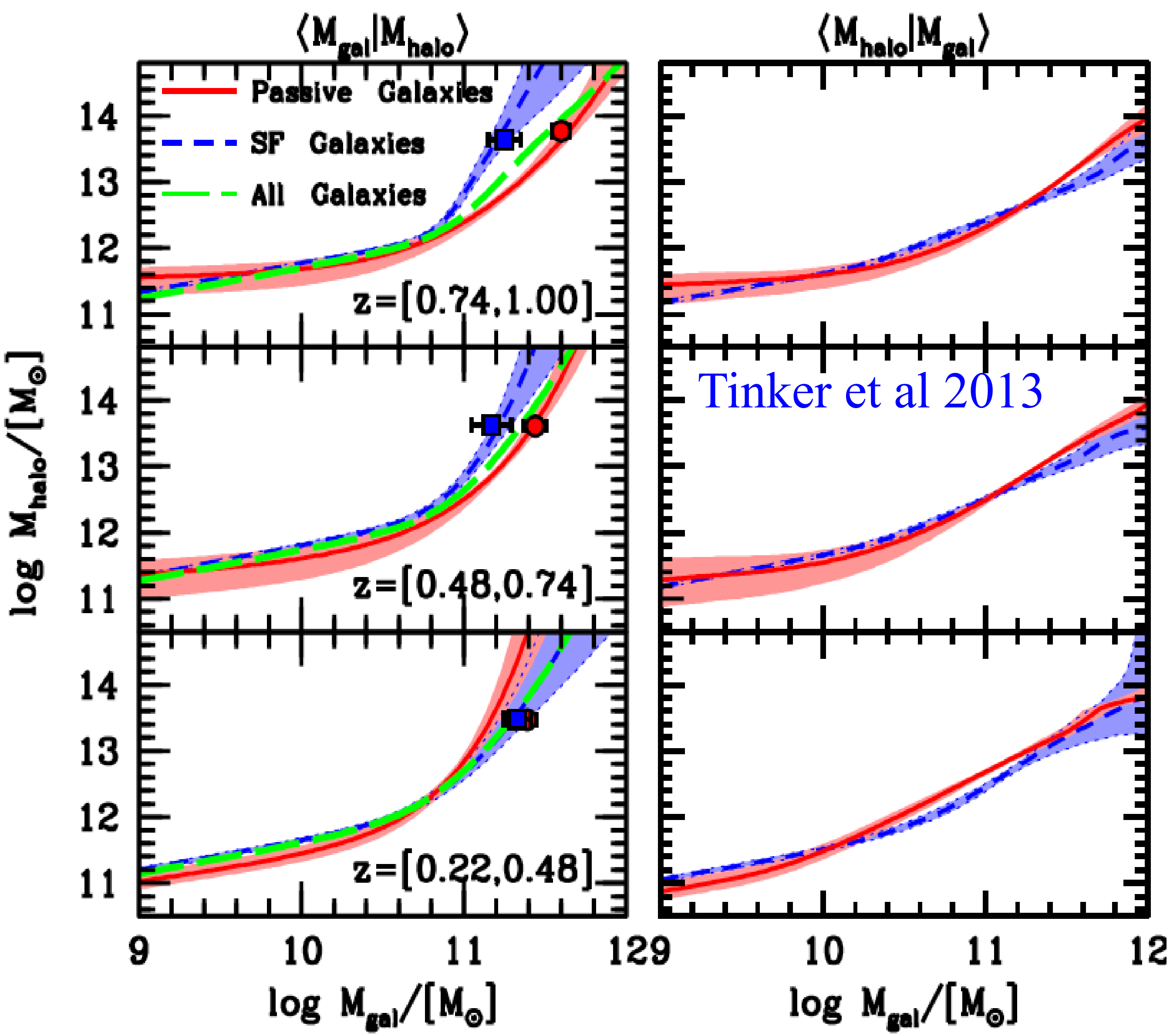
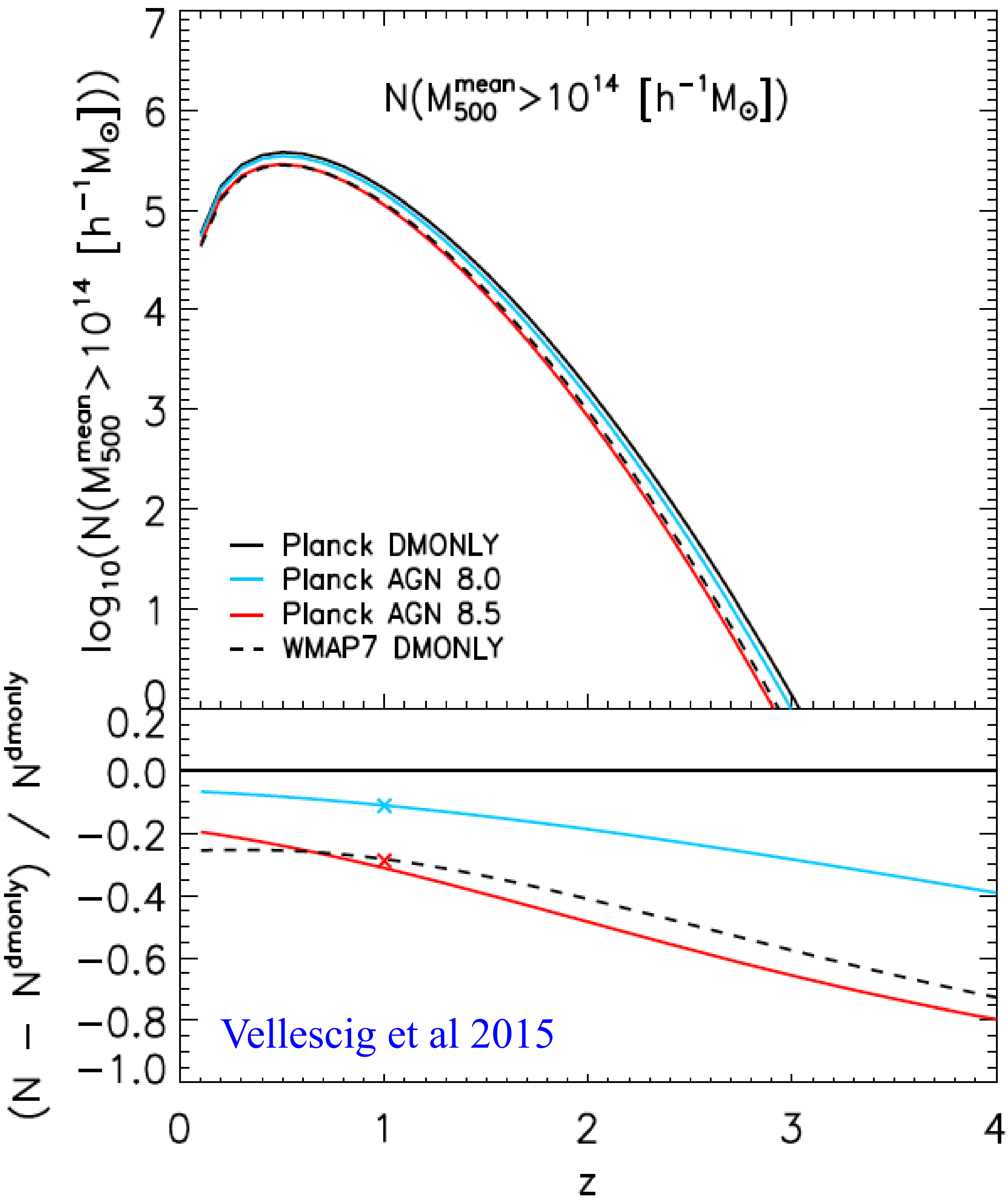


Blue centrals may have lower mass halos according to estimates based on the motions of satellites (More et al 2010) and to *some* galaxy-galaxy lensing estimates, but not all...

(These results based on fitting an 81 parameter HOD model to clustering and lensing data)

Mass distribution dependence on baryon physics

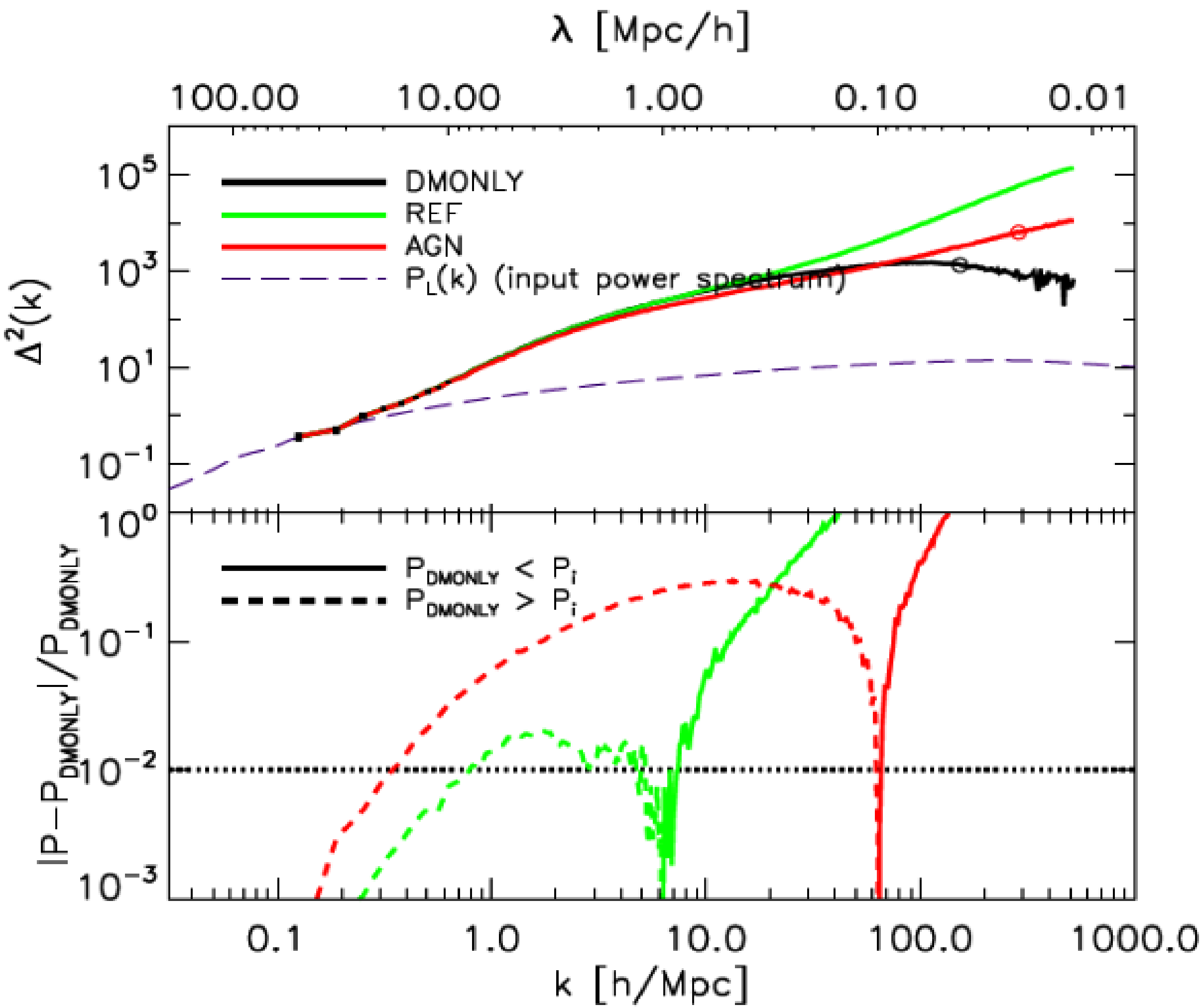


AGN feedback sufficient to suppress cooling flows in clusters can shift their mass function by an amount similar to the Planck/WMAP7 difference.

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 h/Mpc

This will affect the small-scale lensing power spectrum.

van Daalen et al 2011

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

The six parameters of the base ΛCDM model

Planck Collab'n 2015

Derived parameters

Parameter	TT+lowP 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
H_0	67.31 ± 0.96	67.27 ± 0.66	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.6844 ± 0.0091	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.3156 ± 0.0091	0.3089 ± 0.0062
σ_8	0.829 ± 0.014	0.831 ± 0.013	0.8159 ± 0.0086
z_{re}	$9.9^{+1.8}_{-1.6}$	$10.0^{+1.7}_{-1.5}$	$8.8^{+1.2}_{-1.1}$
Age/Gyr	13.813 ± 0.038	13.813 ± 0.026	13.799 ± 0.021

One parameter extensions of the base ΛCDM model

Planck Collab'n 2015

Parameter	TT, TE, EE	TT, TE, EE+lensing+ext
Ω_K	$-0.040^{+0.038}_{-0.041}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.492	< 0.194
N_{eff}	$2.99^{+0.41}_{-0.39}$	$3.04^{+0.33}_{-0.33}$
Y_{P}	$0.250^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$\mathrm{d}n_{\mathrm{s}}/\mathrm{d}\ln k$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.0987	< 0.113
w	$-1.55^{+0.58}_{-0.48}$	$-1.019^{+0.075}_{-0.080}$

Planck results bearing on models of inflation

Planck Collab'n 2015

Parameter values

Parameter	TT, TE, EE+lensing+ext
Ω_K	$0.0008^{+0.0040}_{-0.0039}$
n_s	0.9667 ± 0.0040 ← $\sim 8\sigma$!
$dn_s/d\ln k$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.113

Non-Gaussianity constraints

f_{NL}

	Independent KSW			ISW-lensing subtracted KSW		
SMICA (T+E)						
Local	6.5	±	5.0	**0.8**	±	**5.0**
Equilateral	3	±	43	**−4**	±	**43**
Orthogonal	−36	±	21	**−26**	±	**21**