Cluster and group formation in ΛCDM

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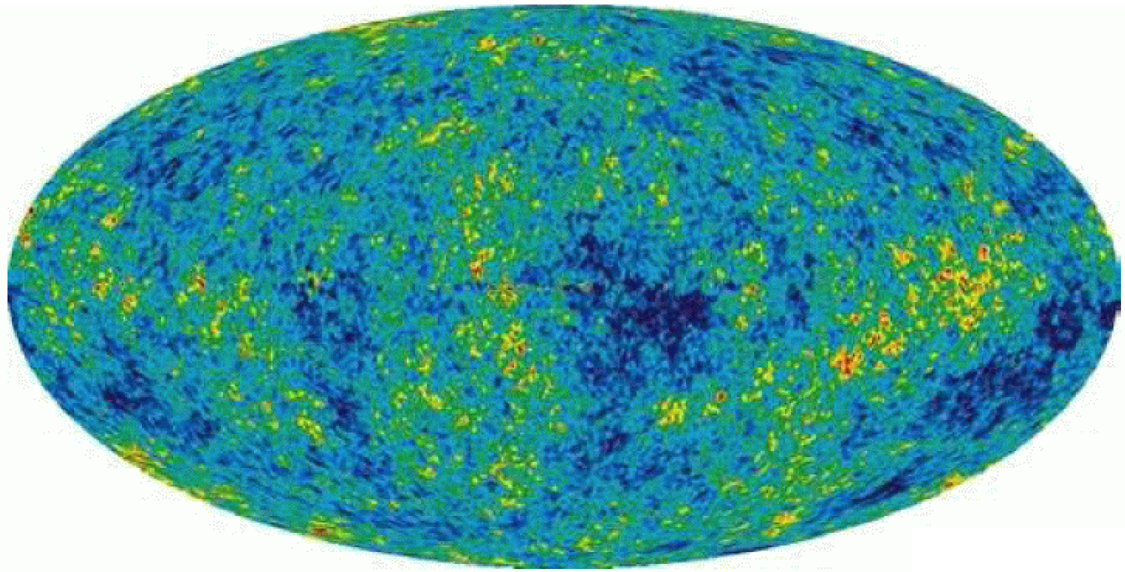


Cluster formation from ΛCDM initial conditions

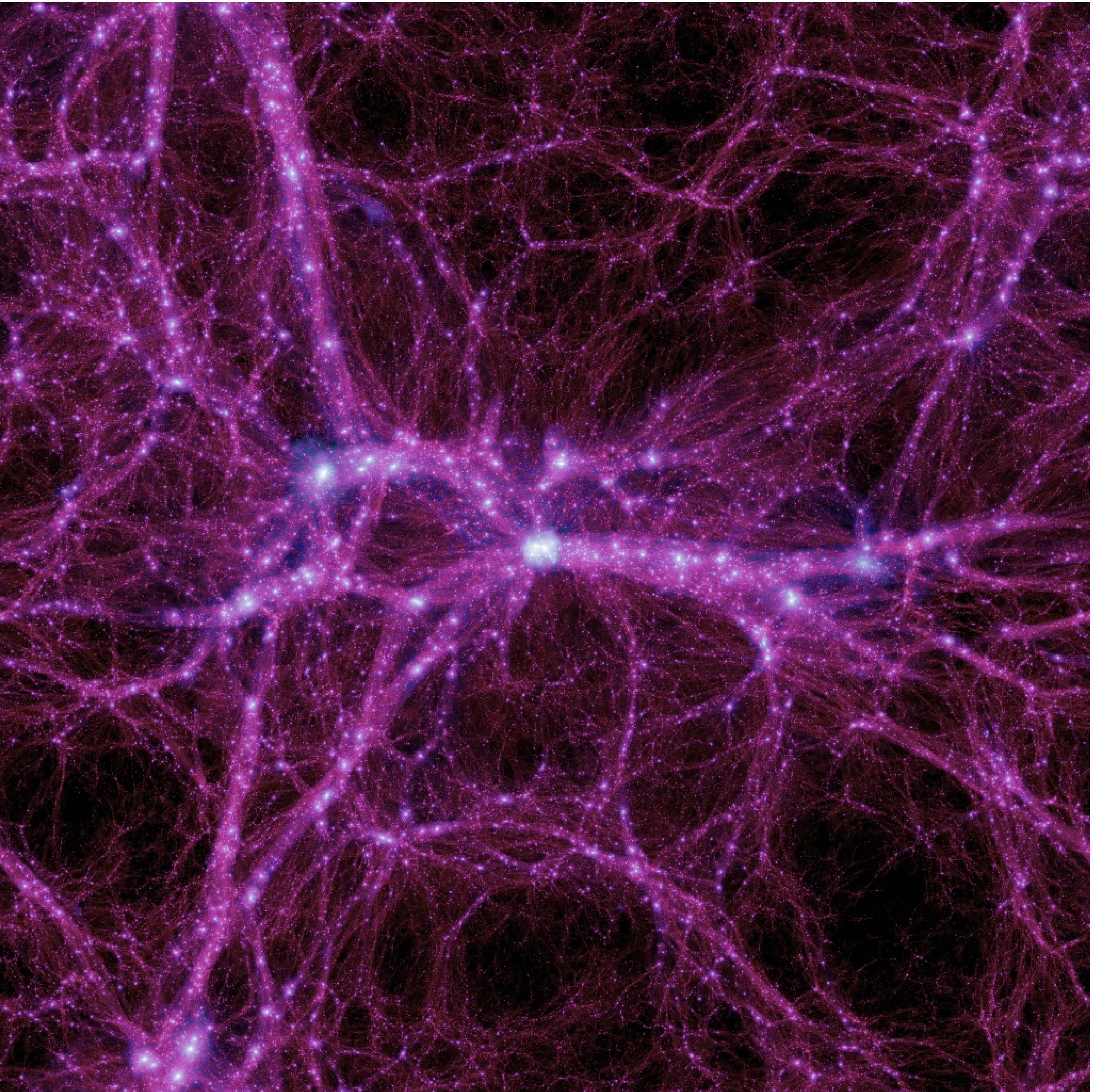
Cluster environment in a ΛCDM universe

The Millennium Simulations

	N_{part}	m_{part} $h^{-1}\ M_\odot$	L h^{-1} Mpc	ε h^{-1} kpc	$F_{halo}(z=0)$
Millennium	2160^3	8.6×10^8	500	5	0.50
Millennium-II	2160^3	6.9×10^6	100	1	0.60

$$\Omega_{tot} = 1.0, \quad \Omega_m = 0.25, \quad \Omega_{bar} = 0.045, \quad h = 0.73, \quad \sigma_8 = 0.9, \quad n = 1$$

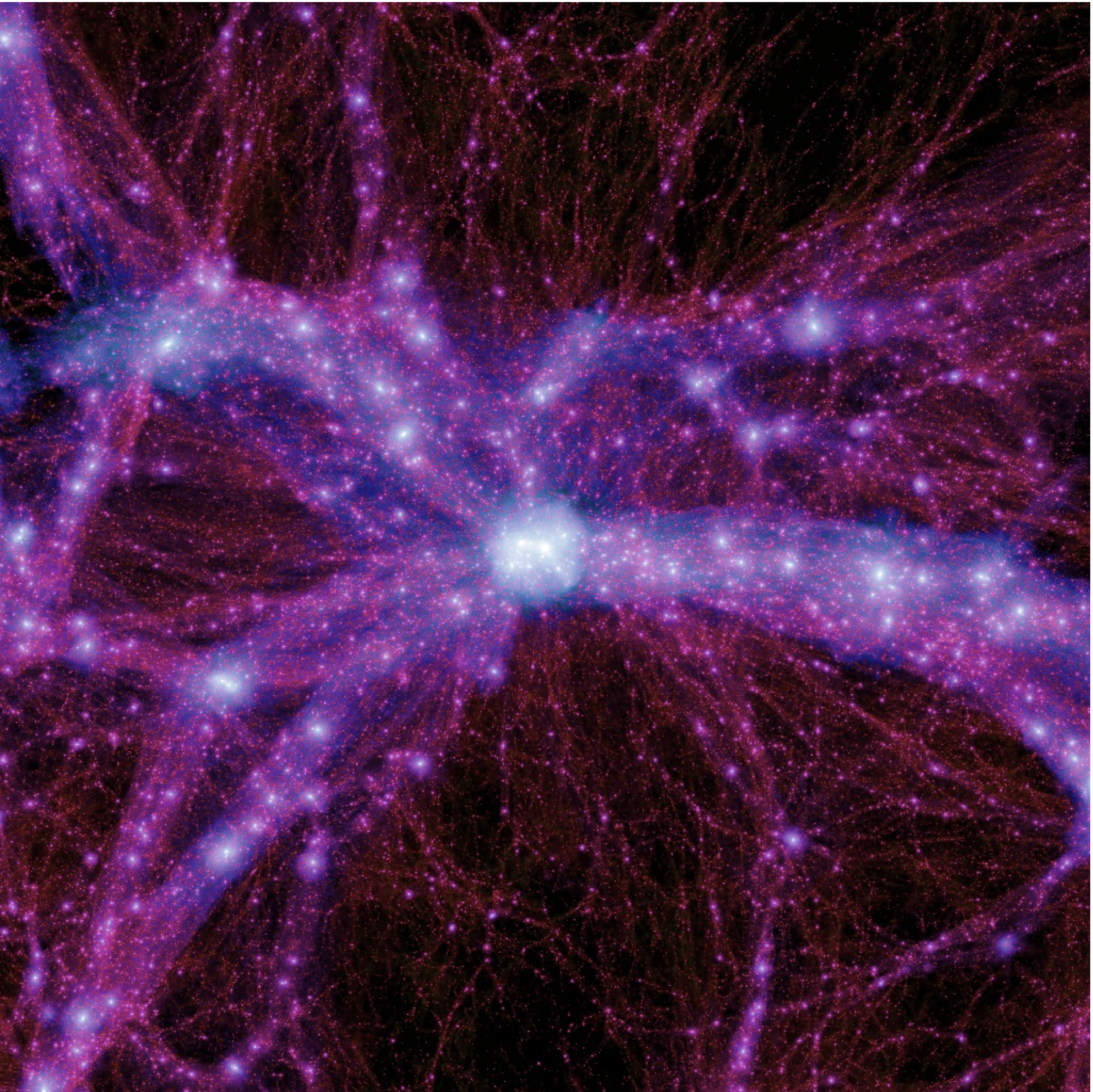
Halo/subhalo trees and galaxy catalogues for several galaxy formation models are publicly available for download for >60 redshifts and also on light-cones at: http://www.mpa-garching.mpg.de/millennium



Millennium-II

$z = 0$

$100 \times 100 \times 15$
$(h^{-1}\ \mathrm{Mpc})^3$



Millennium-II

$z = 0$

$40 \times 40 \times 10$
$(h^{-1}\ \mathrm{Mpc})^3$

Millennium-II

$z = 0$

$15 \times 15 \times 6$
$(h^{-1}\ \mathrm{Mpc})^3$

Millennium-II

$z = 0$

$5 \times 5 \times 5$
$(h^{-1}\ \mathrm{Mpc})^3$

Millennium-II

z = 0

2 x 2 x 2
(h^{-1} Mpc $)^3$

Millennium-II

z = 0

0.5 x 0.5 x 0.5
(h^{-1} Mpc)^3

Millennium-II

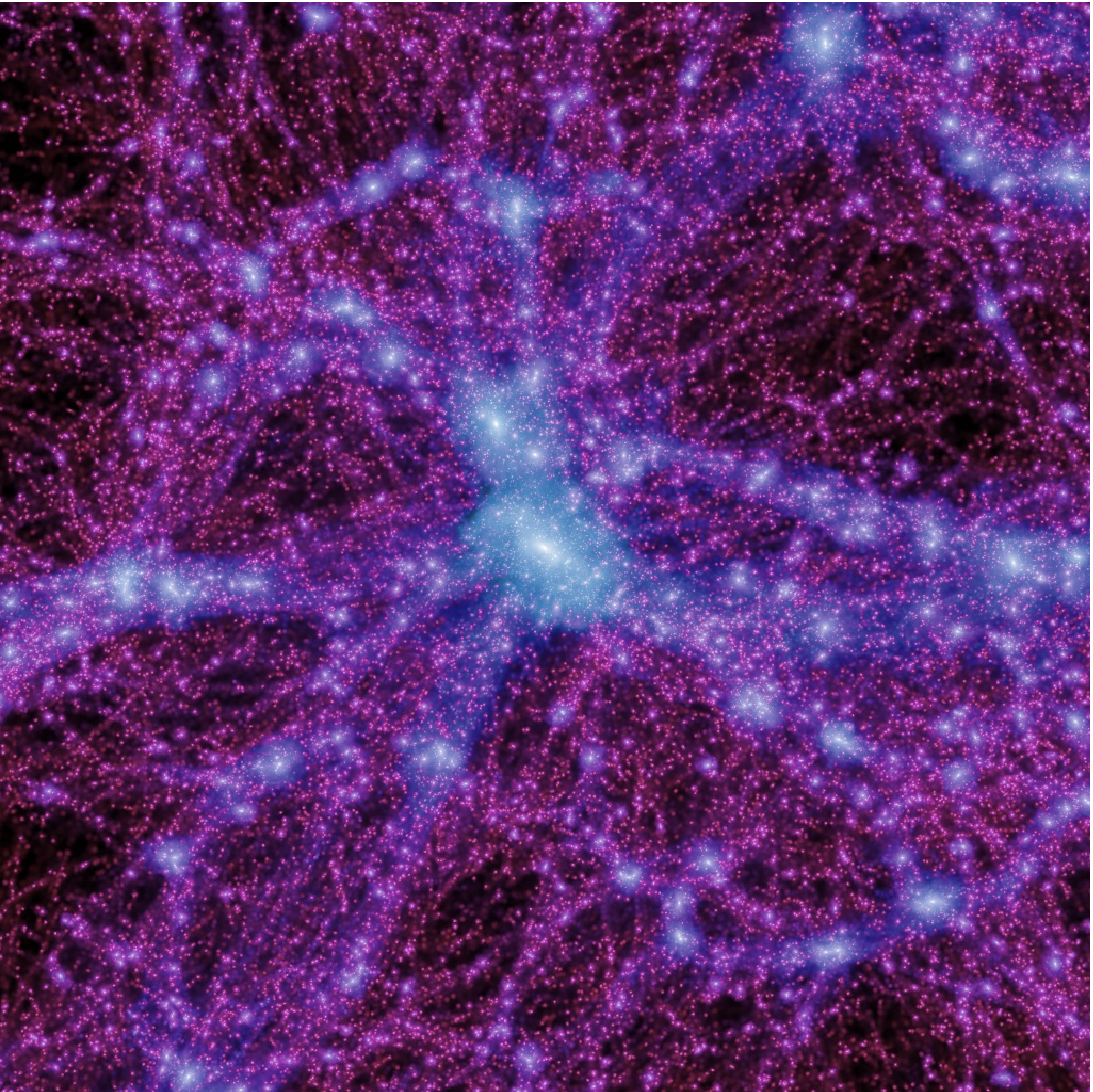
$z = 0$

$15 \times 15 \times 6$
$(h^{-1}\ \mathrm{Mpc})^3$

Millennium-II

z = 1.0

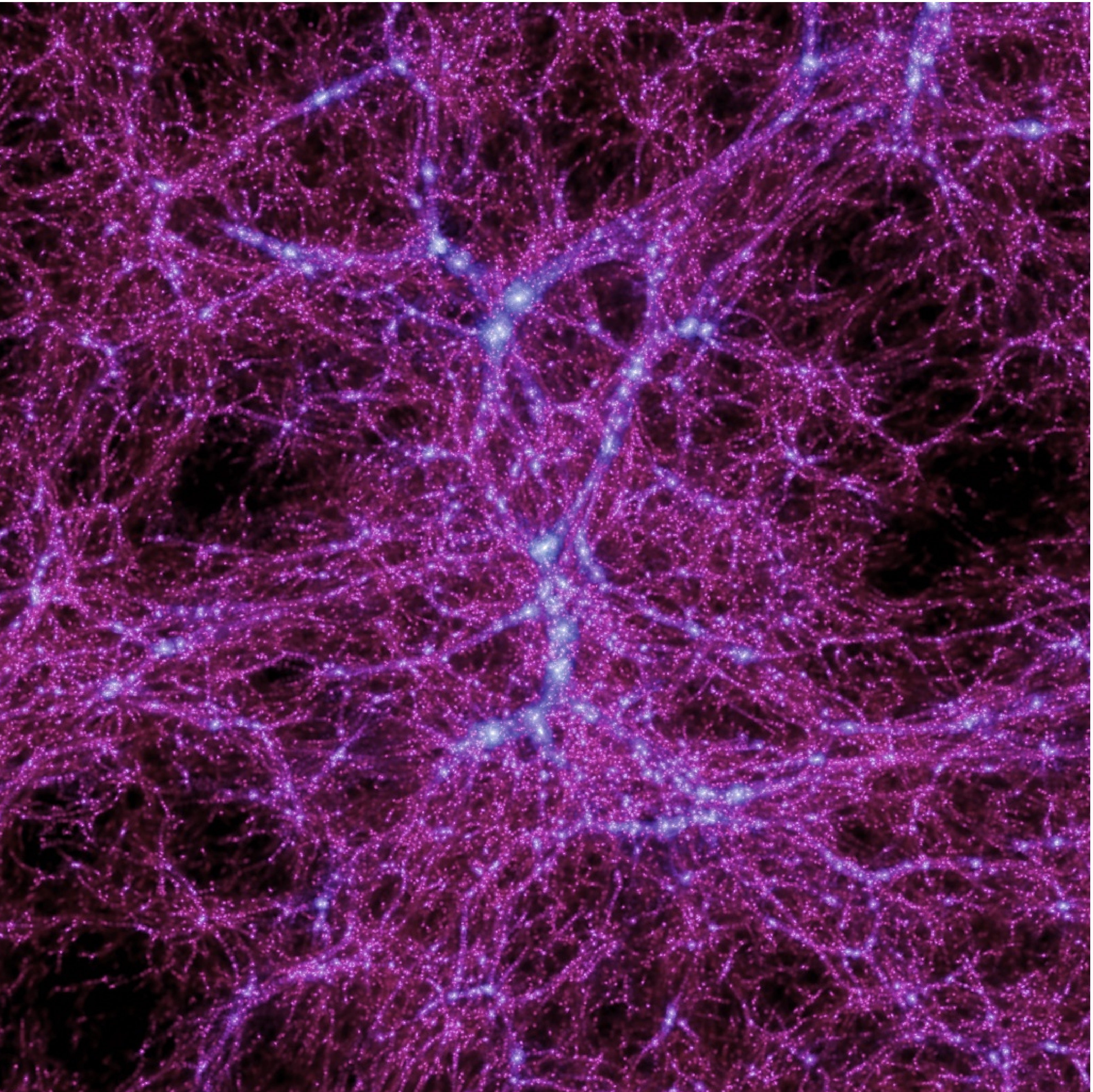
15 x 15 x 6
(h^{-1} Mpc)^3



Millennium-II

$z = 2.1$

$15 \times 15 \times 6$
$(h^{-1}\ \mathrm{Mpc})^3$



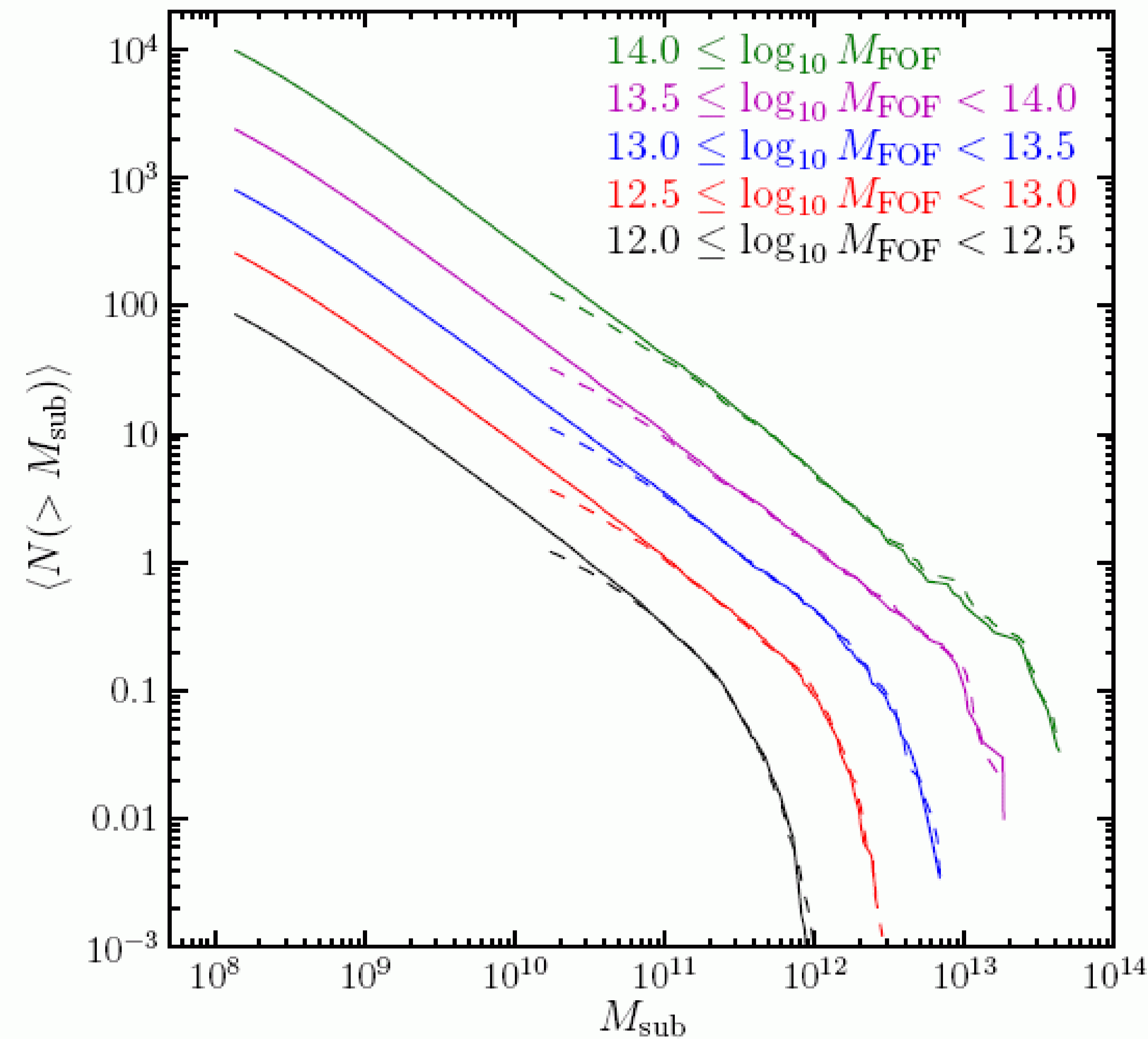
Millennium-II

$z = 6.2$

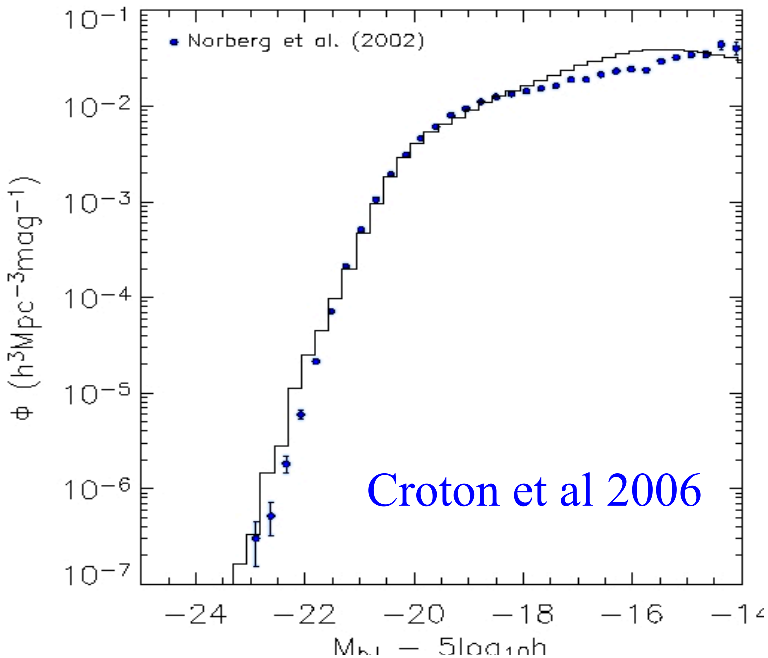
$15 \times 15 \times 6$
$(h^{-1}\ \mathrm{Mpc})^3$

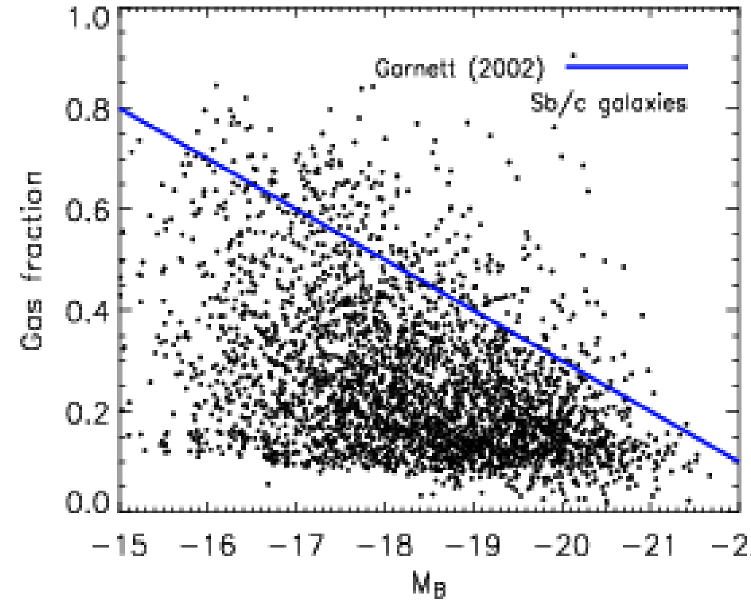
Resolving subhalos in the Millennium Simulations

Boylan-Kolchin et al 2009

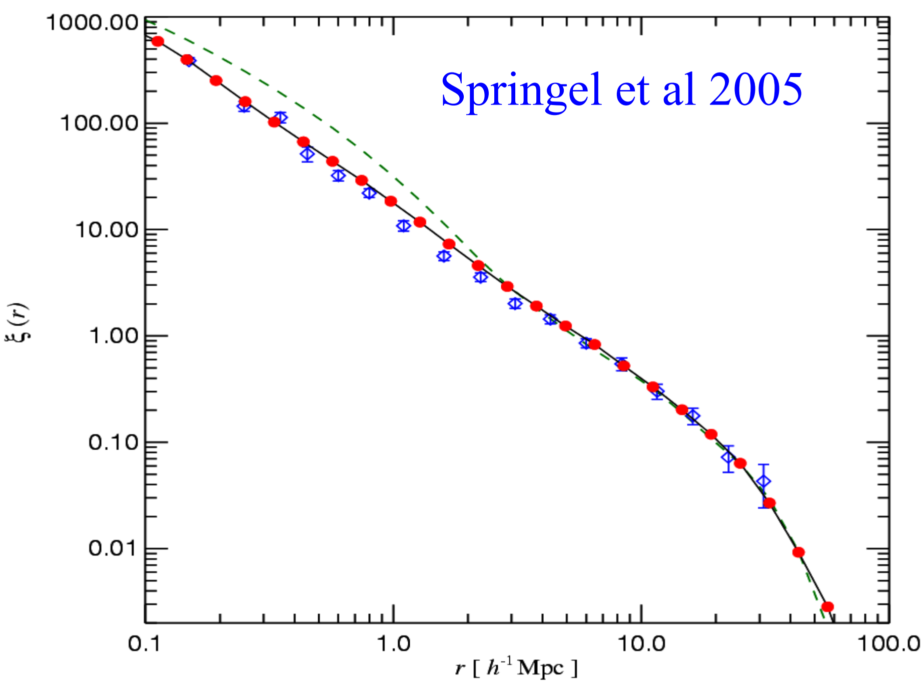


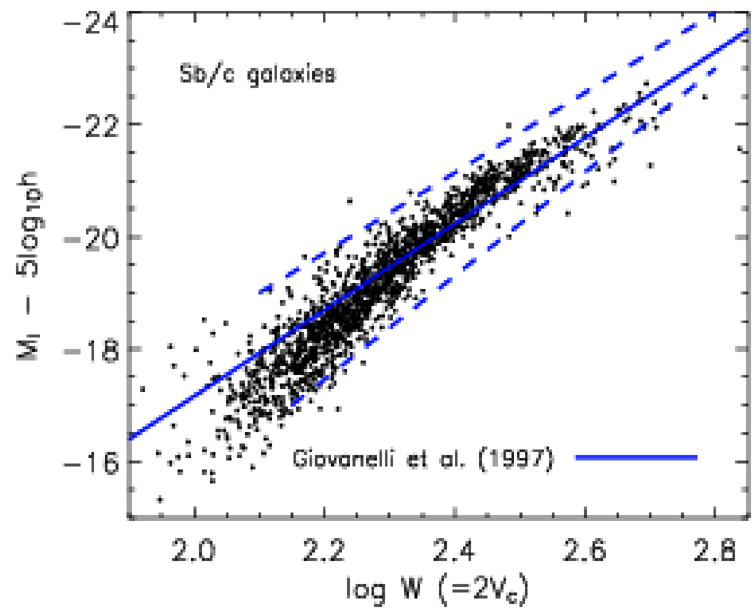
Galaxy formation simulations fitted to the z=0 population



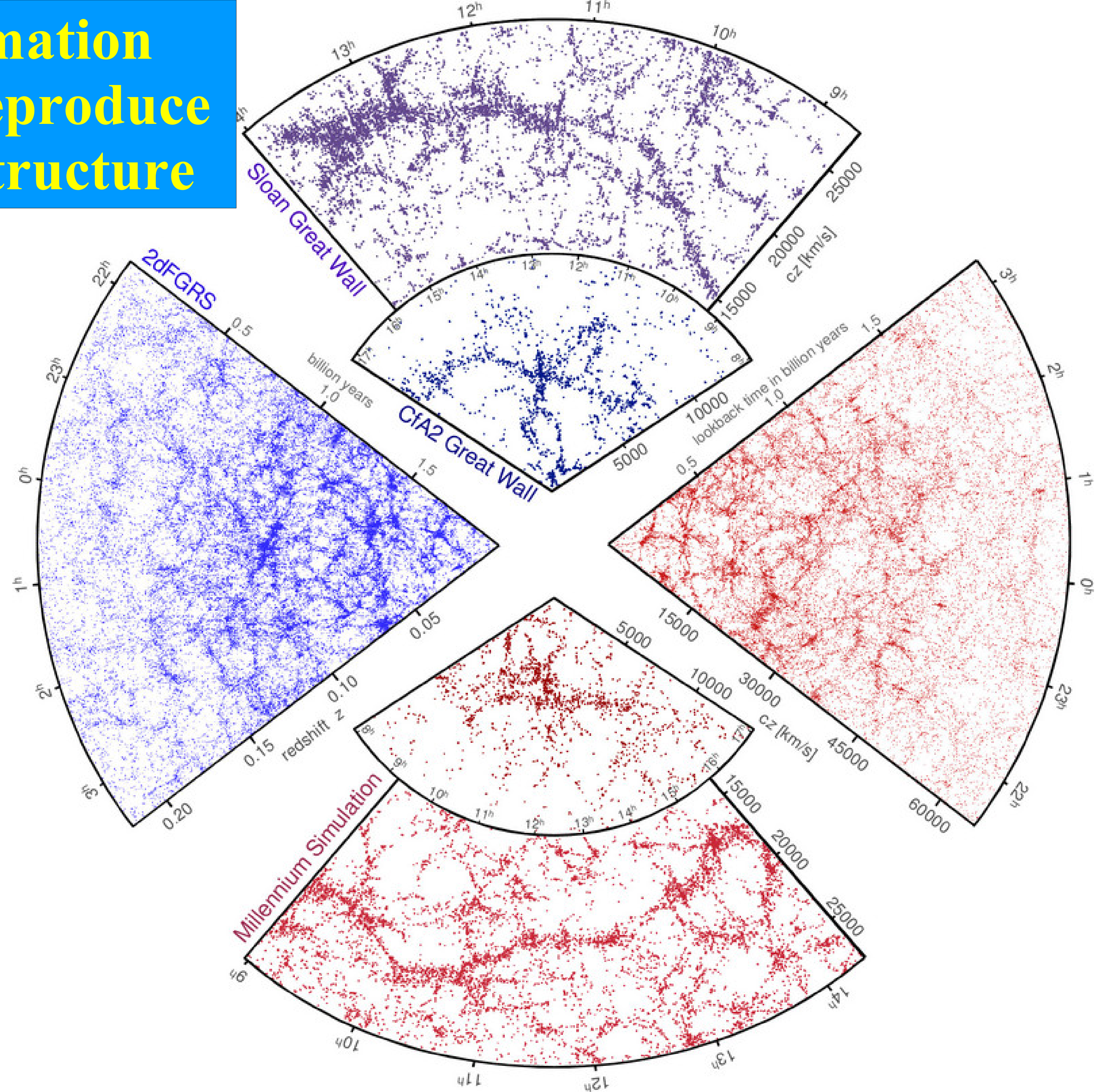


Croton et al 2006





Galaxy formation simulations reproduce large-scale structure



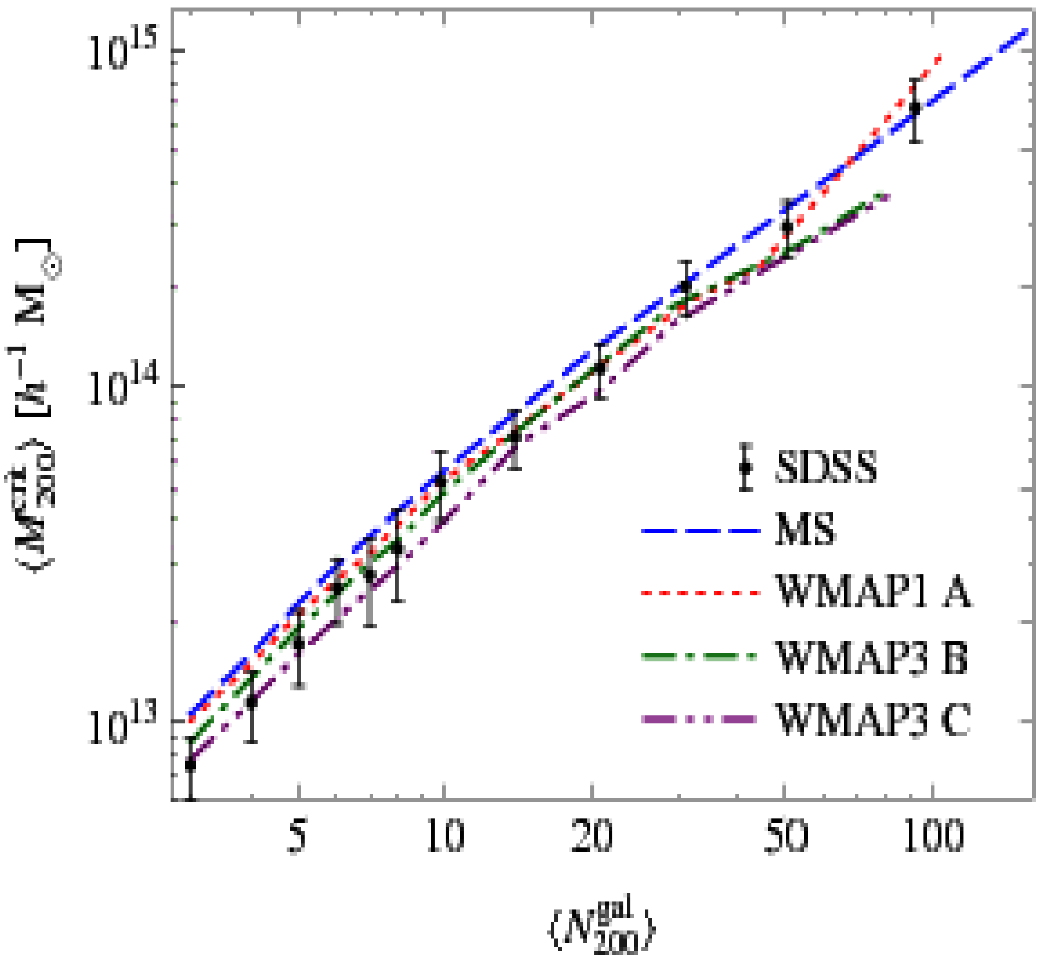
Springel, Frenk & White 2006

Galaxy formation simulations fit low-z groups and clusters

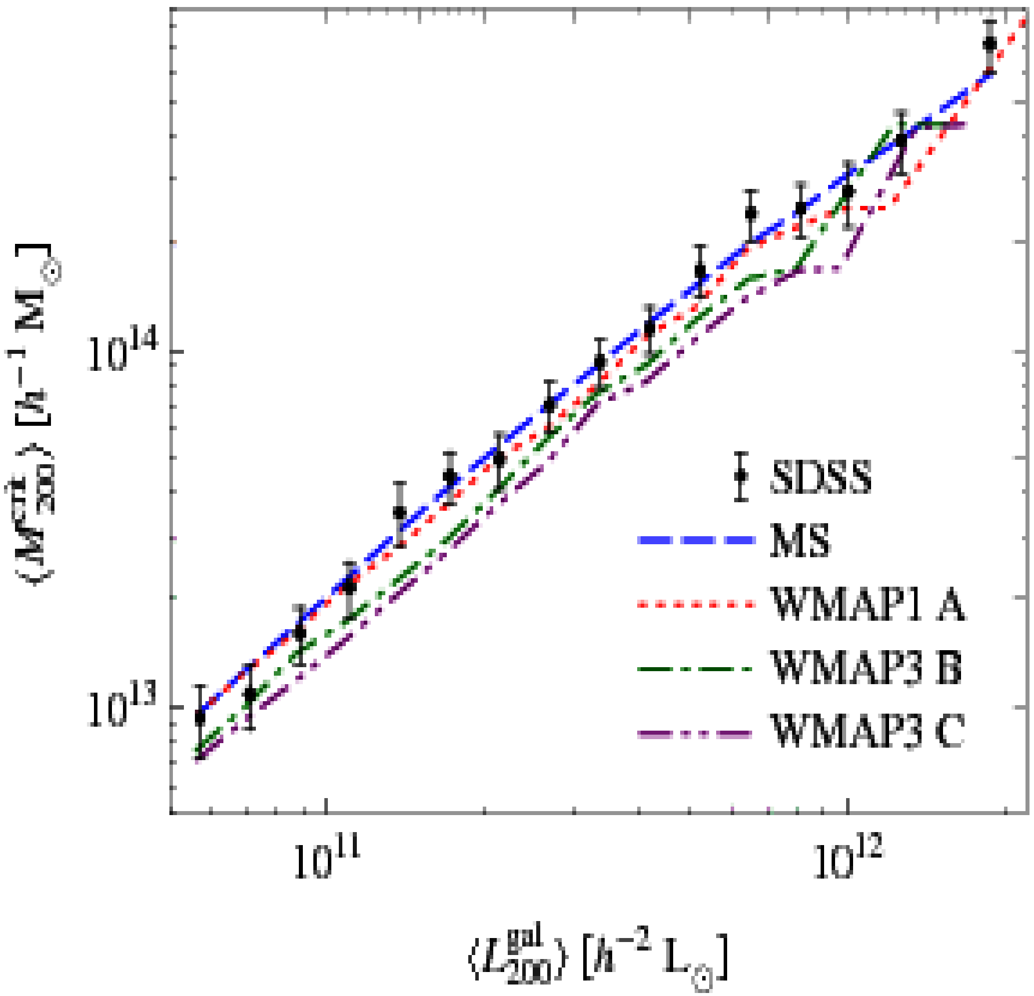
Hilbert & White (2009)

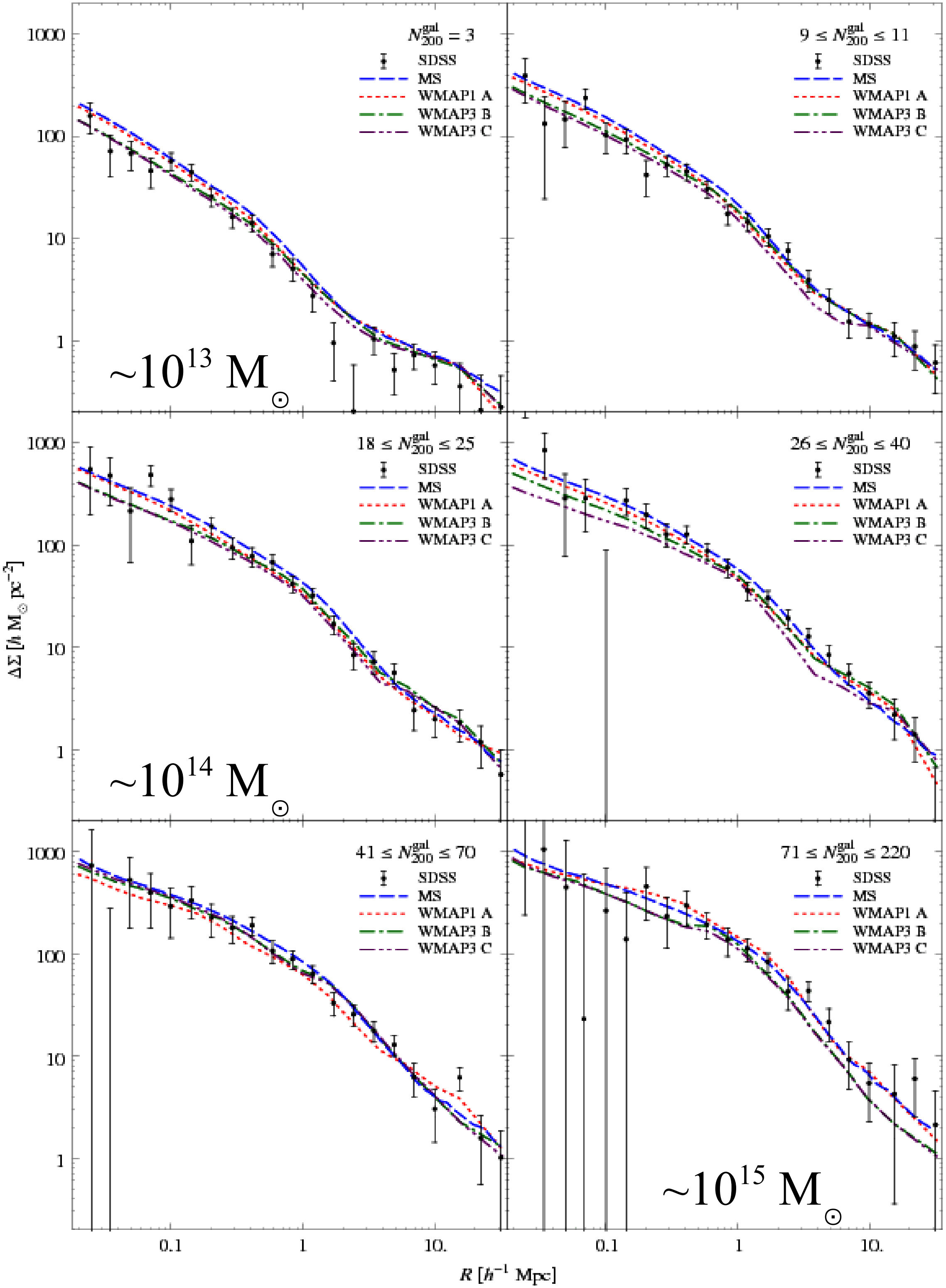
Observational data from the SDSS/maxBCG catalogue (Johnson et al 2007)

virial mass vs optical richness



virial mass vs red sequence luminosity





Galaxy formation simulations fit low-z groups and clusters

Hilbert & White (2009)

The simulated cluster population fits the detailed shape of the mean mass profile of groups and clusters as functions of N_{200} and L_{200}

This holds for masses

$$10^{13}\,M_\odot \le M_{200} \le 10^{15}\,M_\odot$$

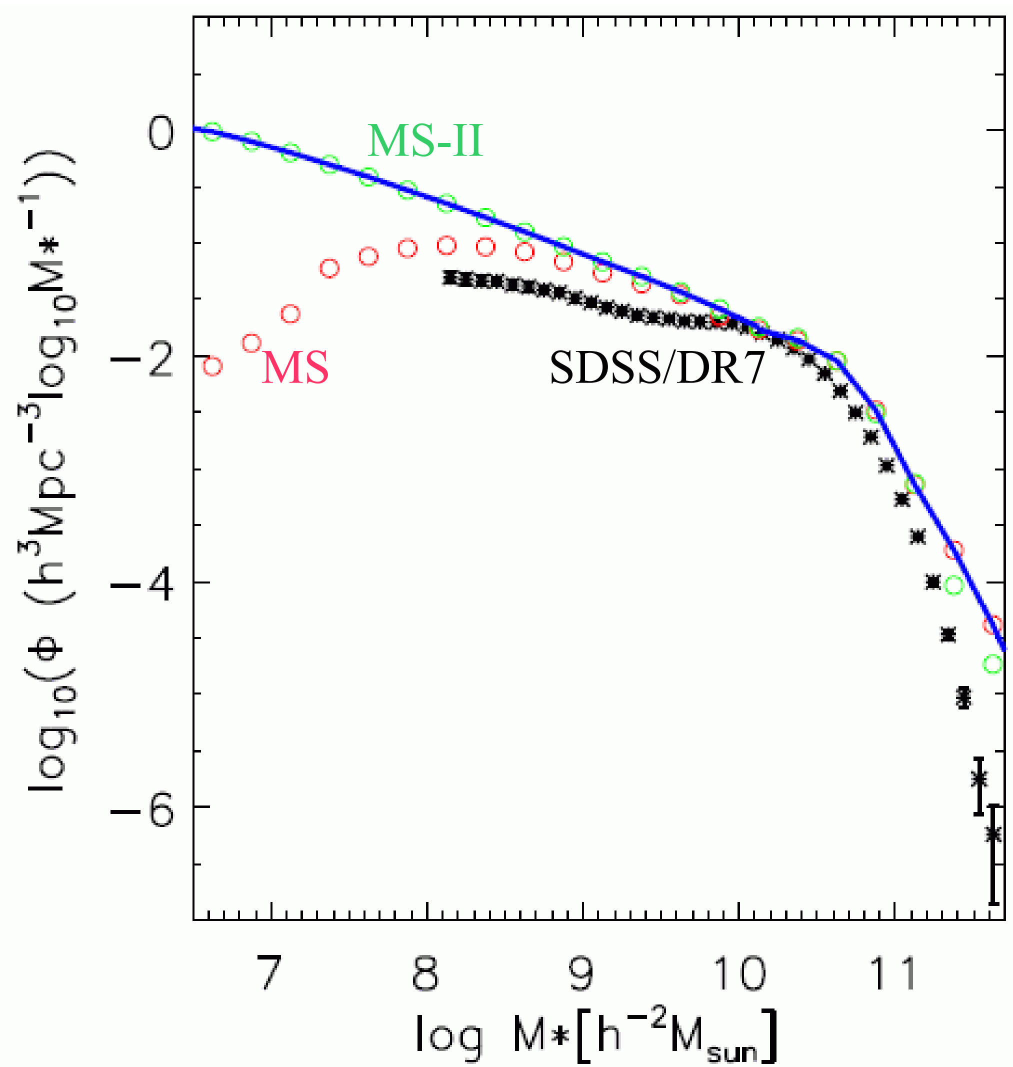
Note the strong central concentration of the observed and predicted mass profiles

Lensing data from SDSS/maxBCG (Sheldon et al 2007)

Using MS-II to extend galaxy formation simulations to low mass

Guo et al 2009

The stellar mass function of galaxies



With the De Lucia & Blaizot (2007) model, the MS and MS-II converge for $M_* > 10^9\ M_\odot$

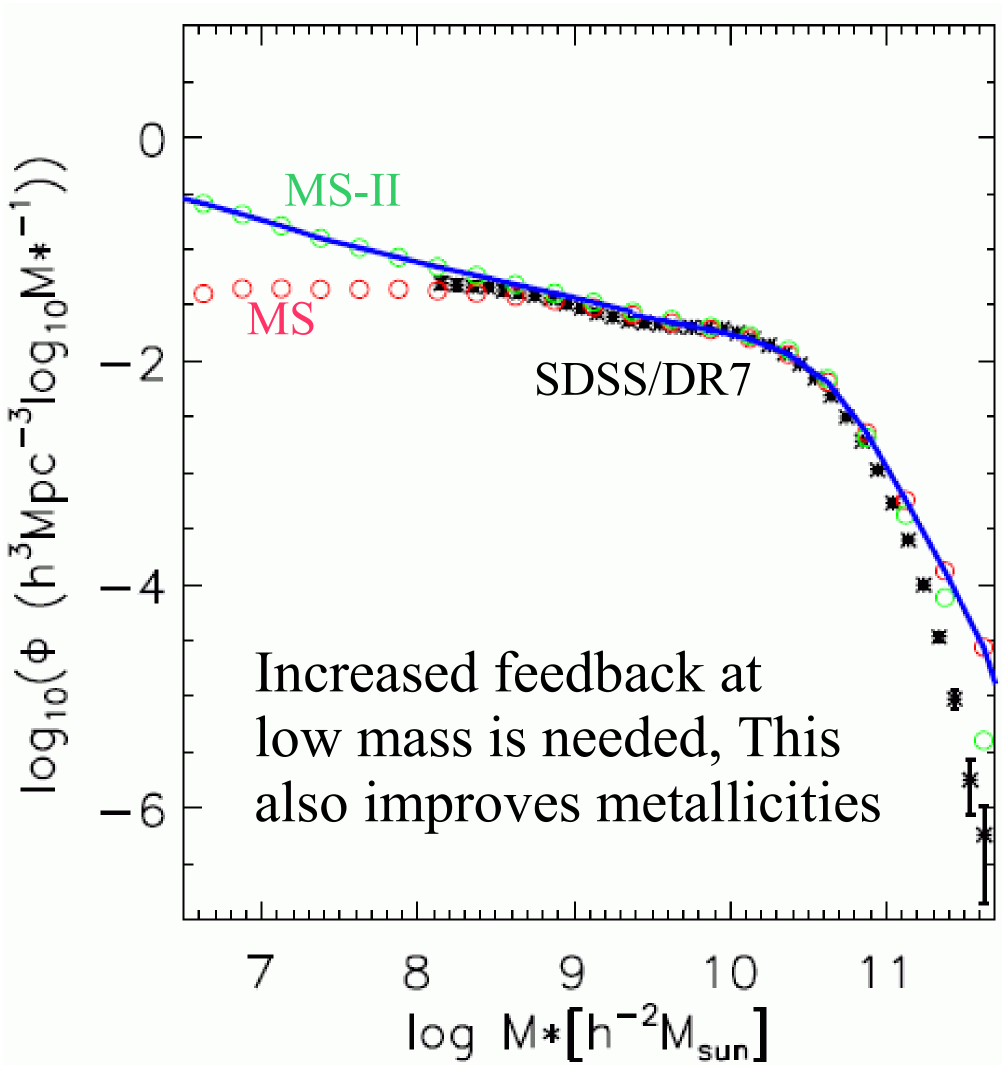
At lower masses the resolution limit of MS causes it to underpredict the stellar mass function

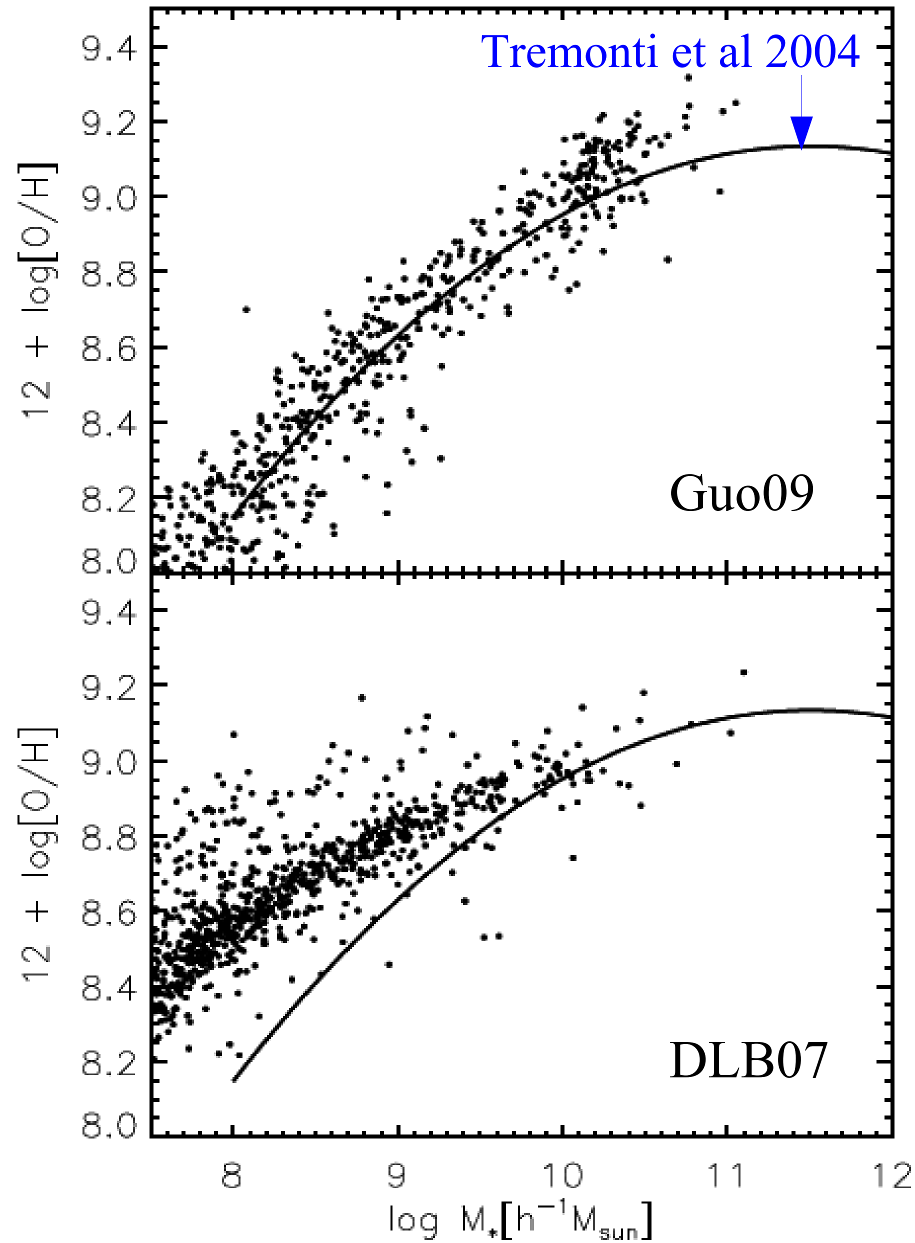
The result lies above SDSS/DR7 mass function of Li & White (2009) for $M_* < 10^{10}\ M_\odot$

Using MS-II to extend galaxy formation simulations to low mass

Guo et al 2009

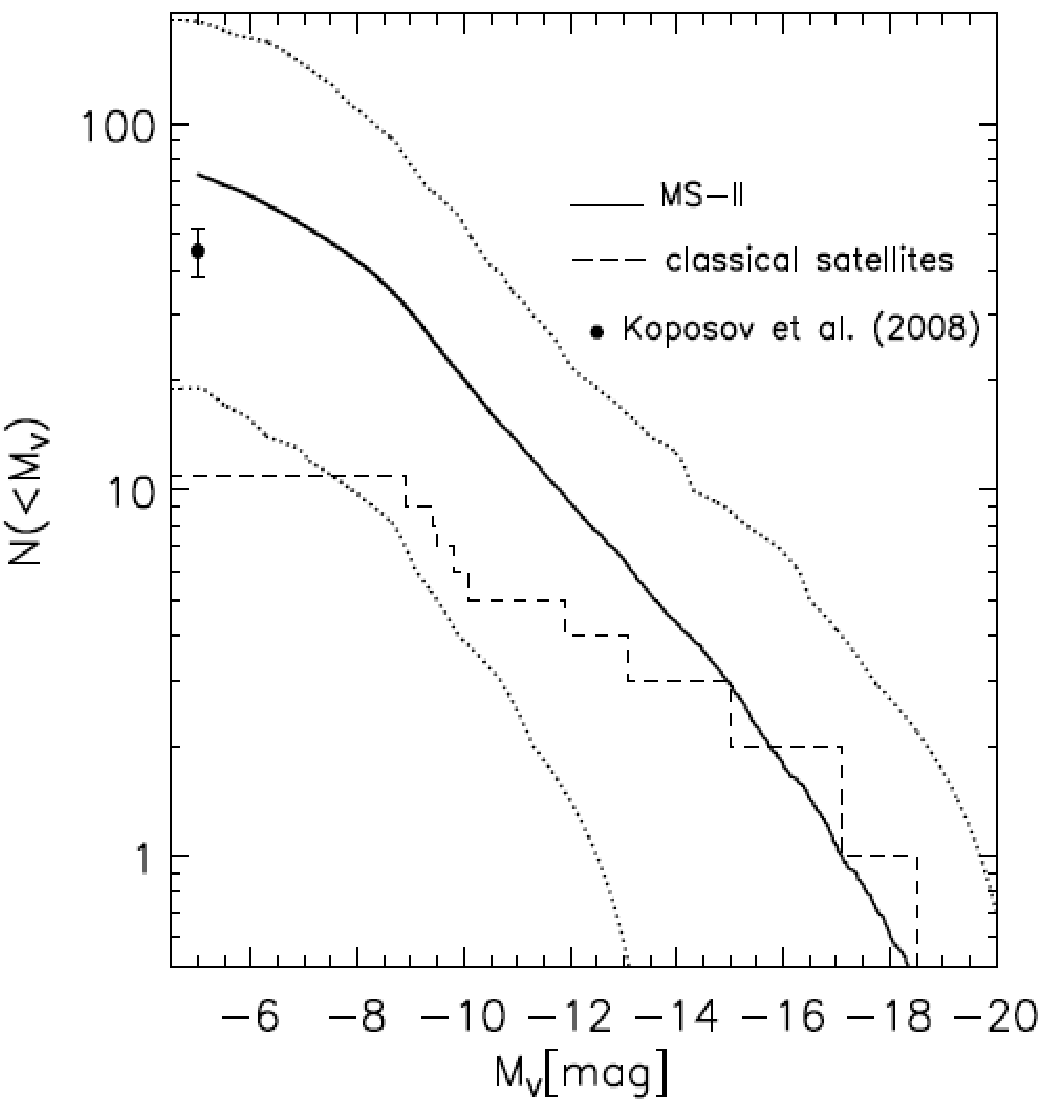
The stellar mass function of galaxies





Using MS-II to extend galaxy formation simulations to low mass

Guo et al 2009

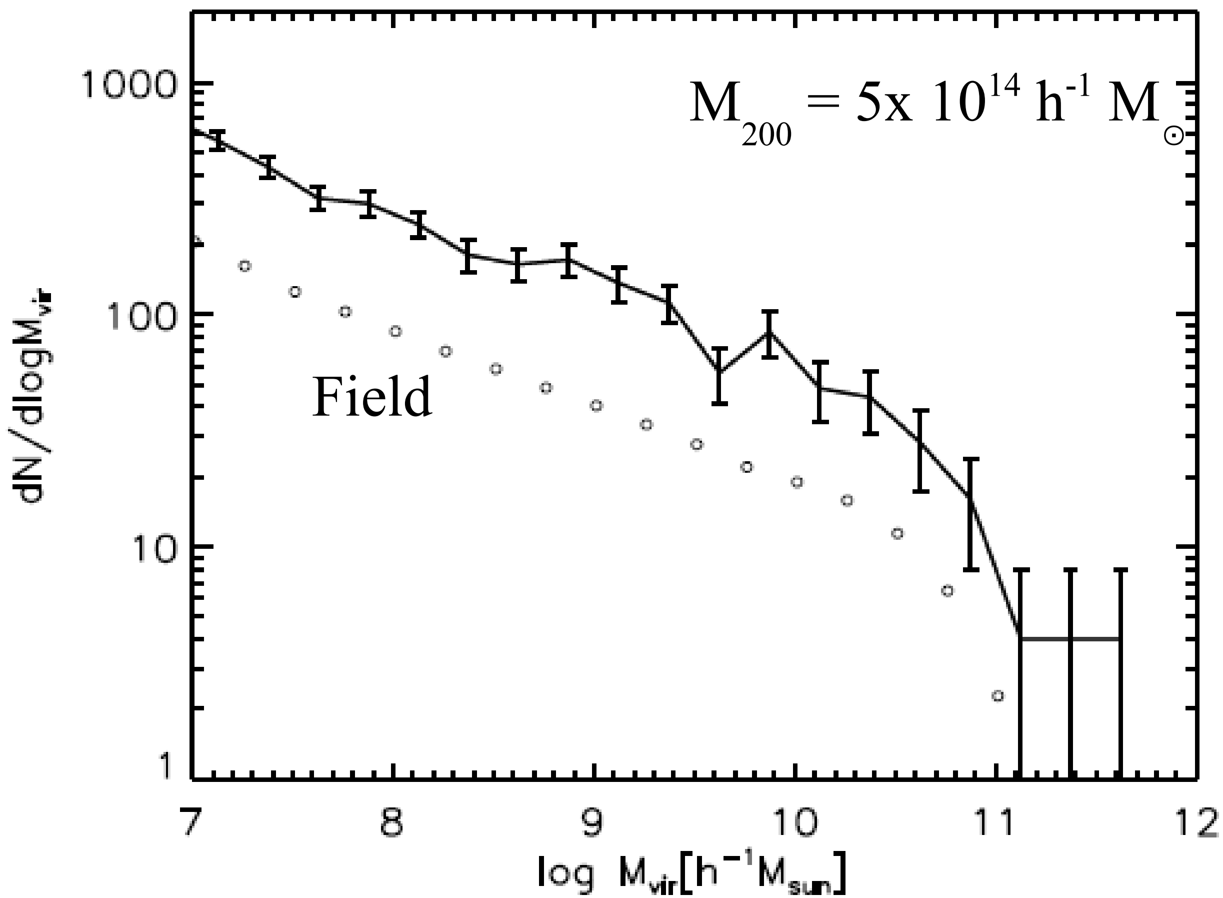


The *same* model then fits the LF of Milky Way satellites. Reionisation is significant in suppressing the faintest systems

Considerable scatter is predicted between different halos of similar mass

Model rich cluster stellar mass function versus the field

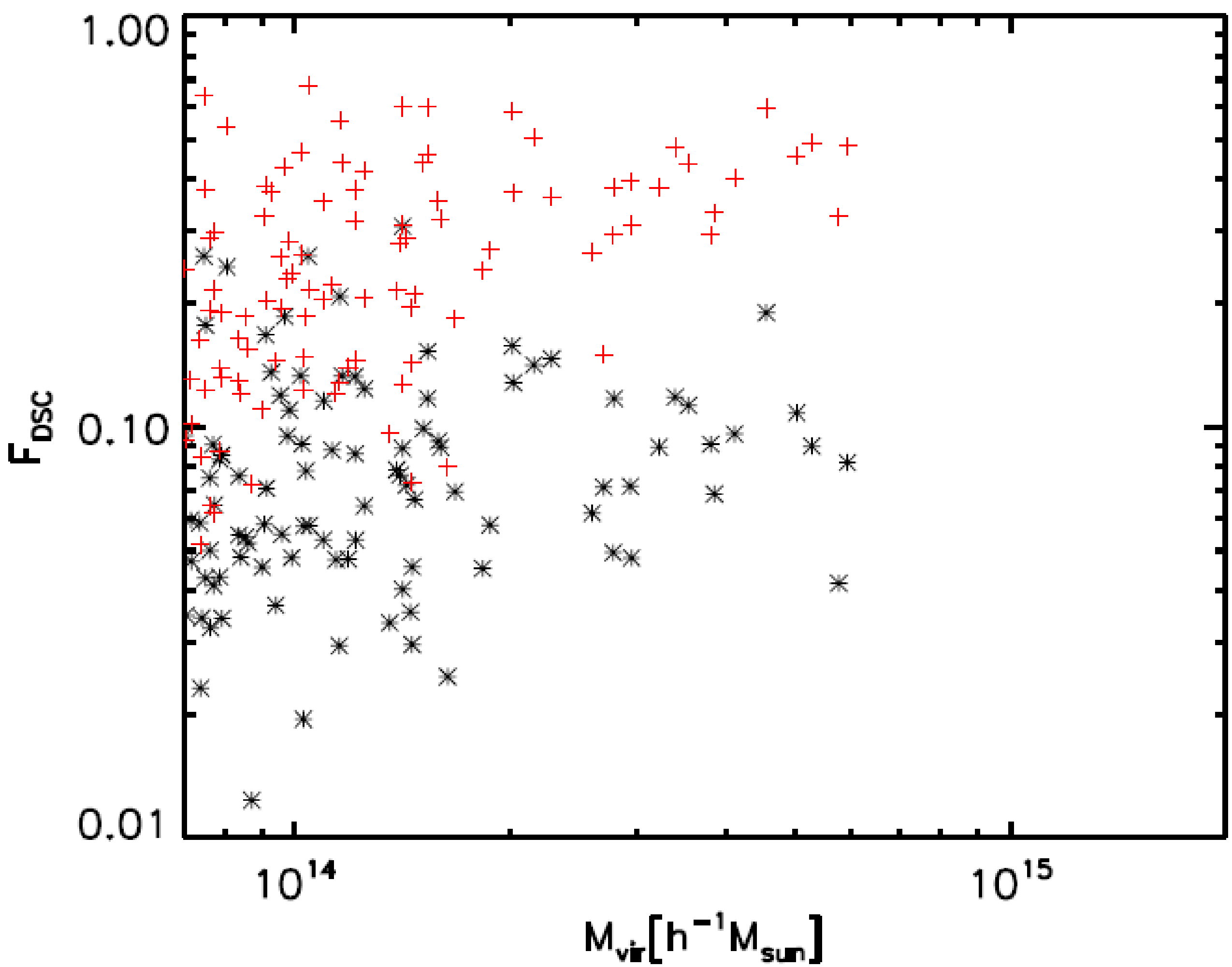
Guo et al 2009



Stellar mass functions in massive clusters and the field are predicted to have very similar shape except for the BCGs

The ICL in model groups and clusters

Guo et al 2009



+ $L_{ICL} / (L_{ICL} + L_{BCG})$

* L_{ICL} / L_{clust}

ICL is assumed due to tidally disrupted galaxies, based on galaxy orbits and sizes and stripping of DM halo

Considerable scatter in the ICL fraction relative to BCG and to the total cluster light is predicted due to variations in assembly/stripping history

Conclusions

- Galaxy formation simulations now reproduce most properties of the *population* of groups/clusters in a ΛCDM universe over the mass range $10^{12}\,M_\odot \leq M_{halo} \leq 10^{15}\,M_\odot$

- The galaxy populations of groups/clusters can be studied over the full stellar mass range $10^{7}\,M_\odot \leq M_{*} \leq 10^{12}\,M_\odot$

- The simulations provide a means to study the physical origin of environment - morphology relation including realistic scatter

- The stellar mass function of cluster galaxies is predicted to have the same faint end slope as the field stellar mass function

- The ICL fractions are predicted to have large scatter depending on the assembly history of individual systems