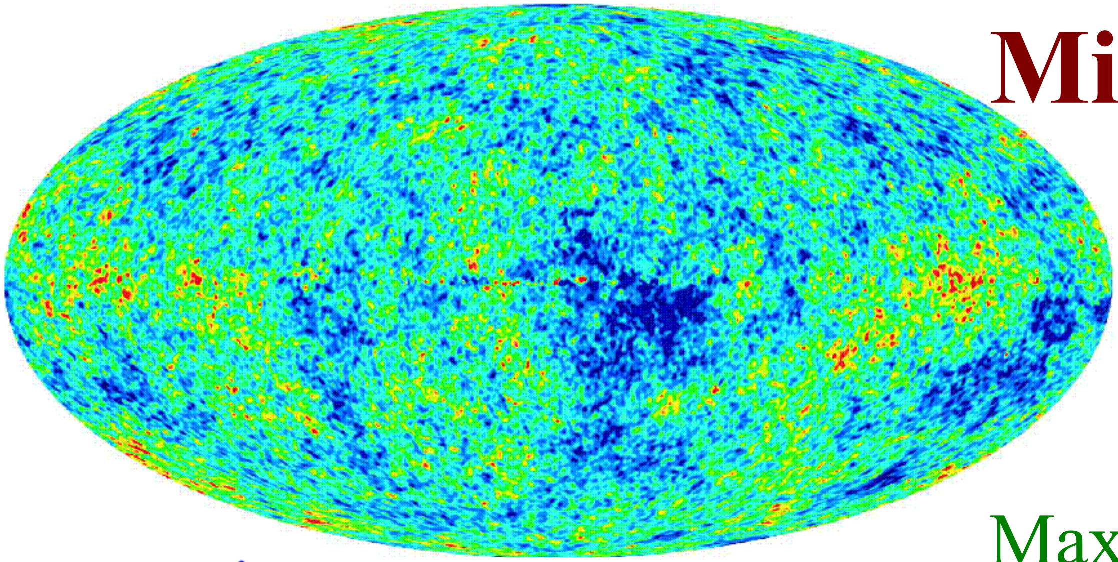
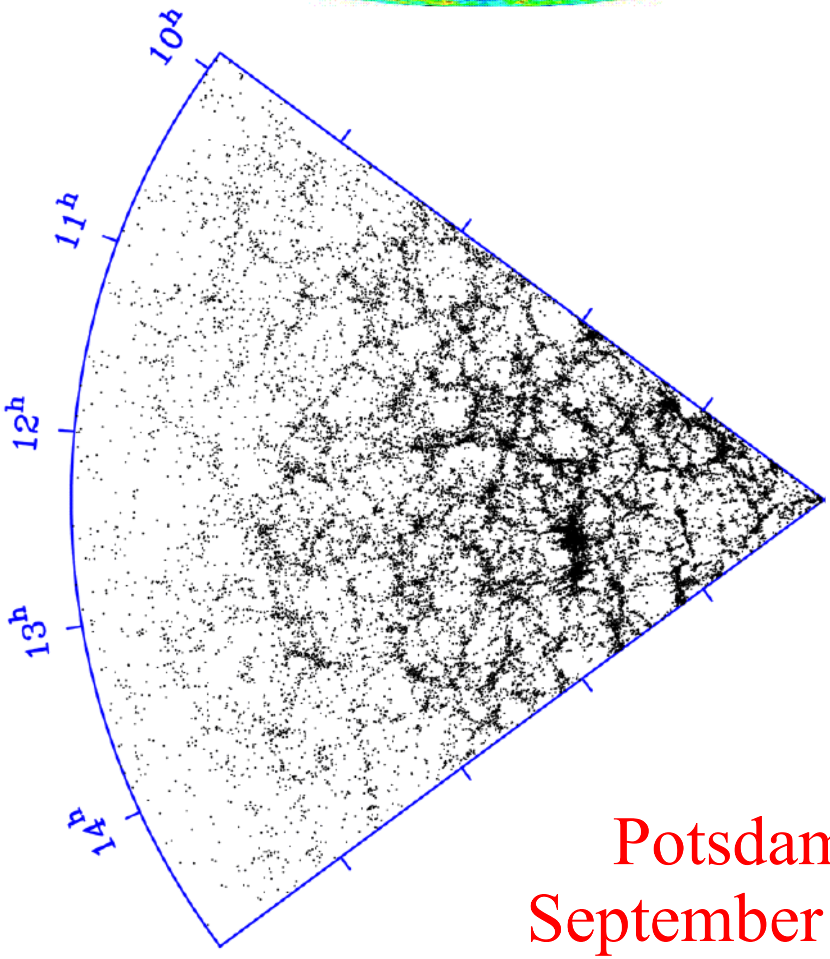
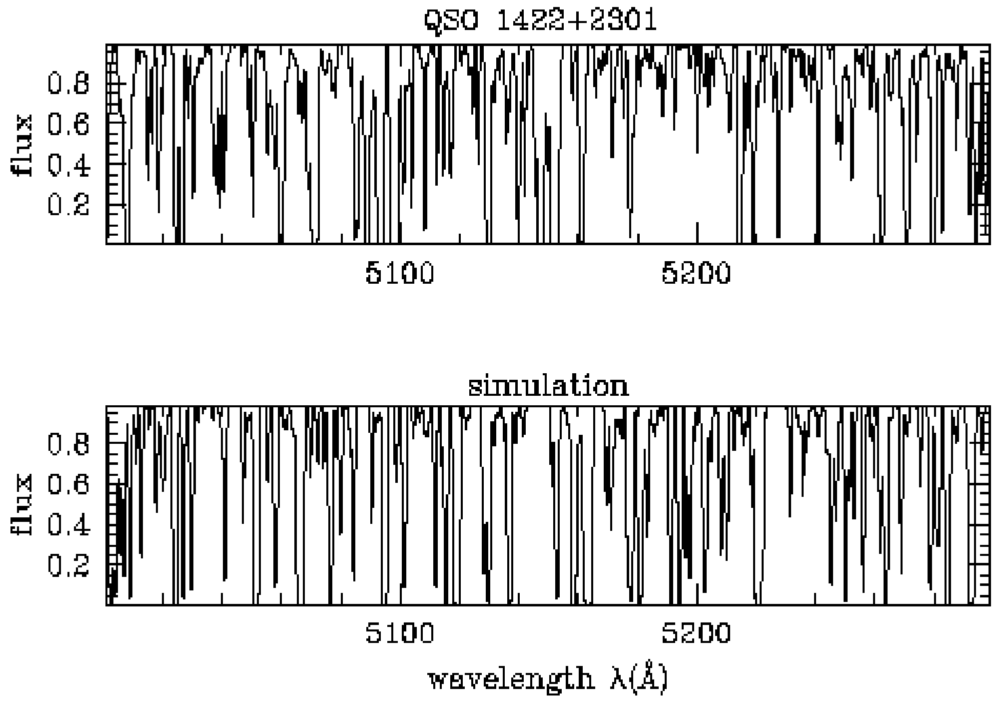
Millennium Simulations and beyond



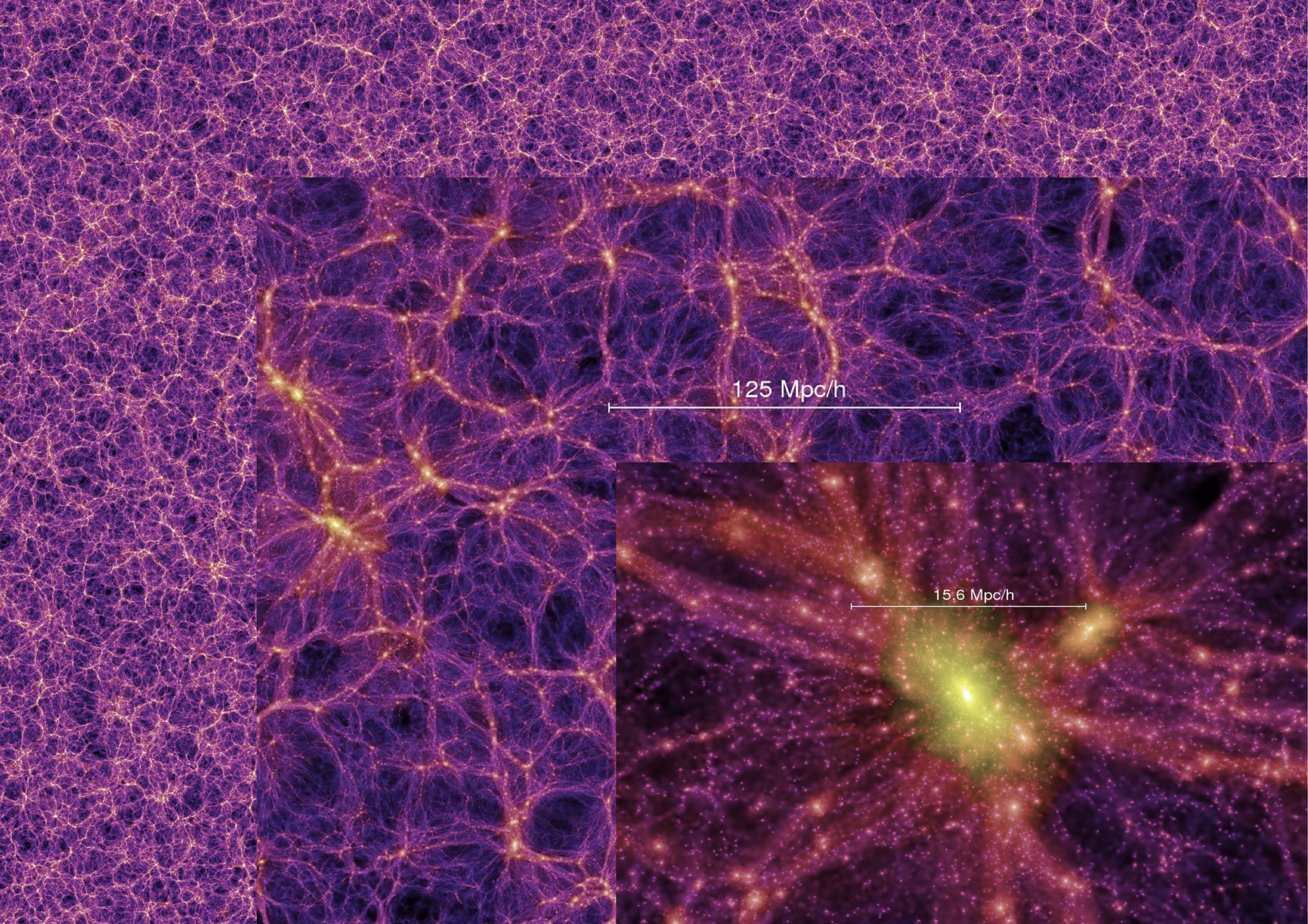
Simon White
Max Planck Institut für Astrophysik

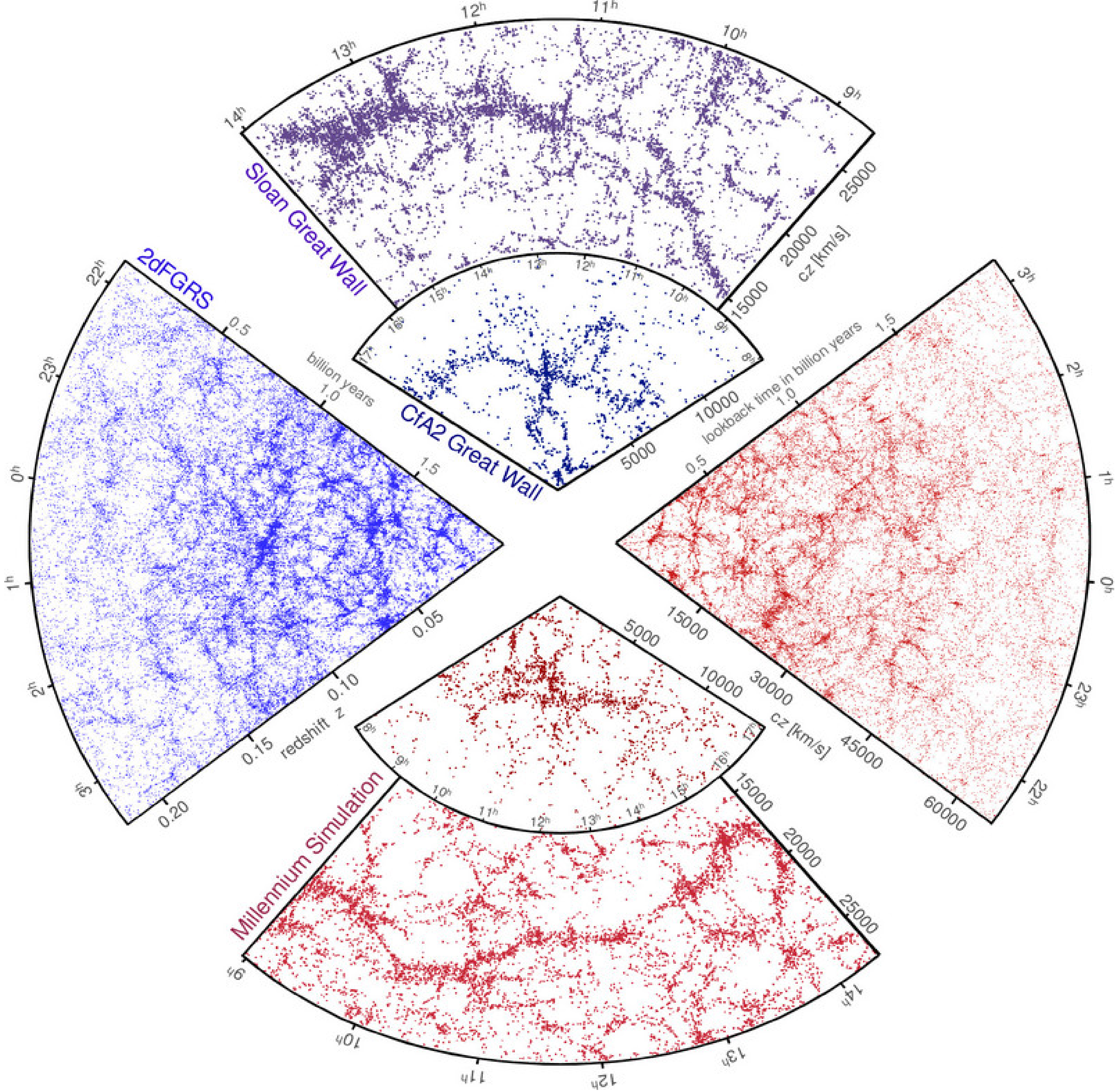


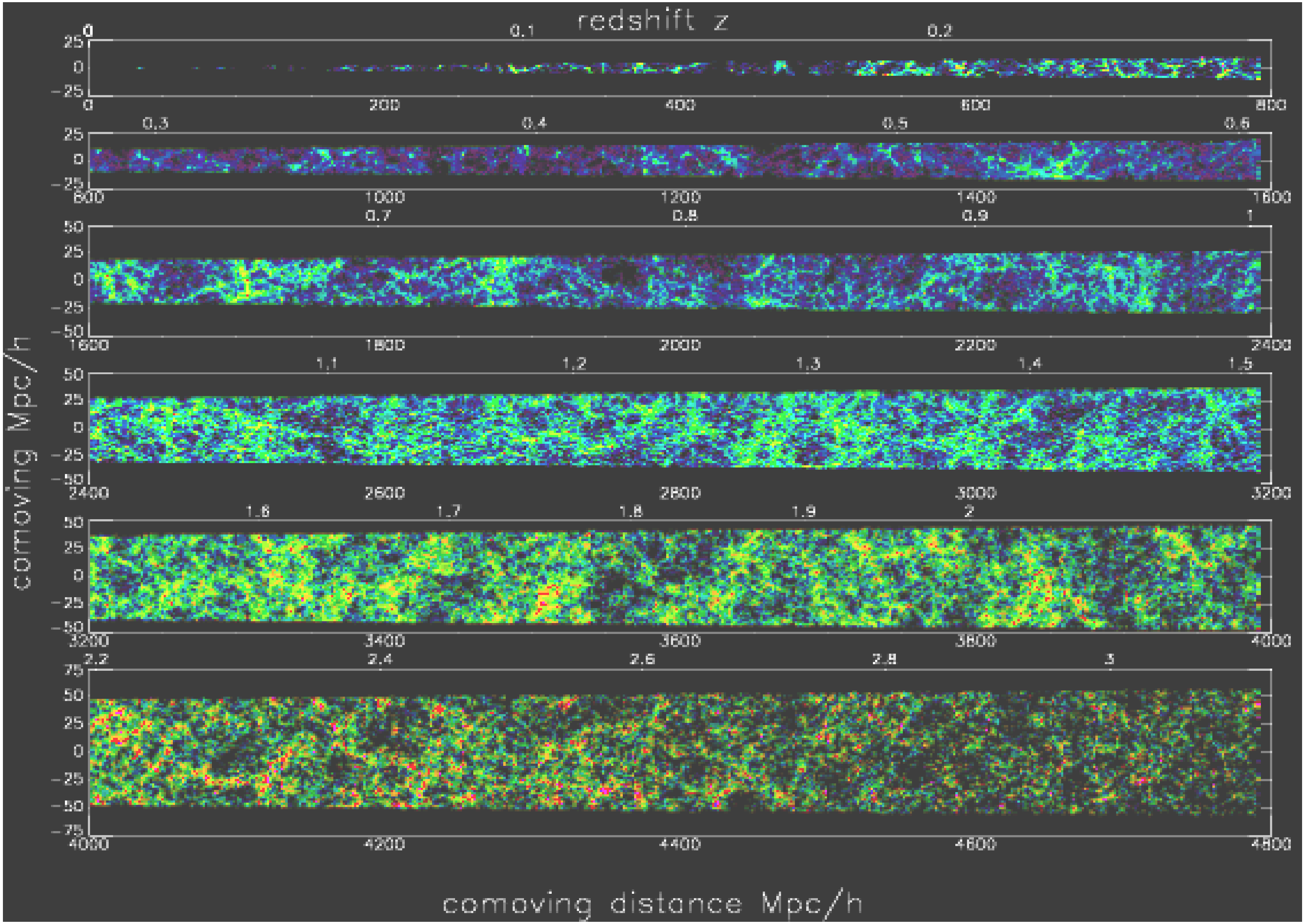


Potsdam
September 2010

The Millennium Simulation (2005)




Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
cz [km/s]
lookback time in billion years
billion years
redshift z
0.05
0.10
0.15
0.20
0.5
1.0
1.5
5000
10000
15000
20000
25000
30000
45000
60000

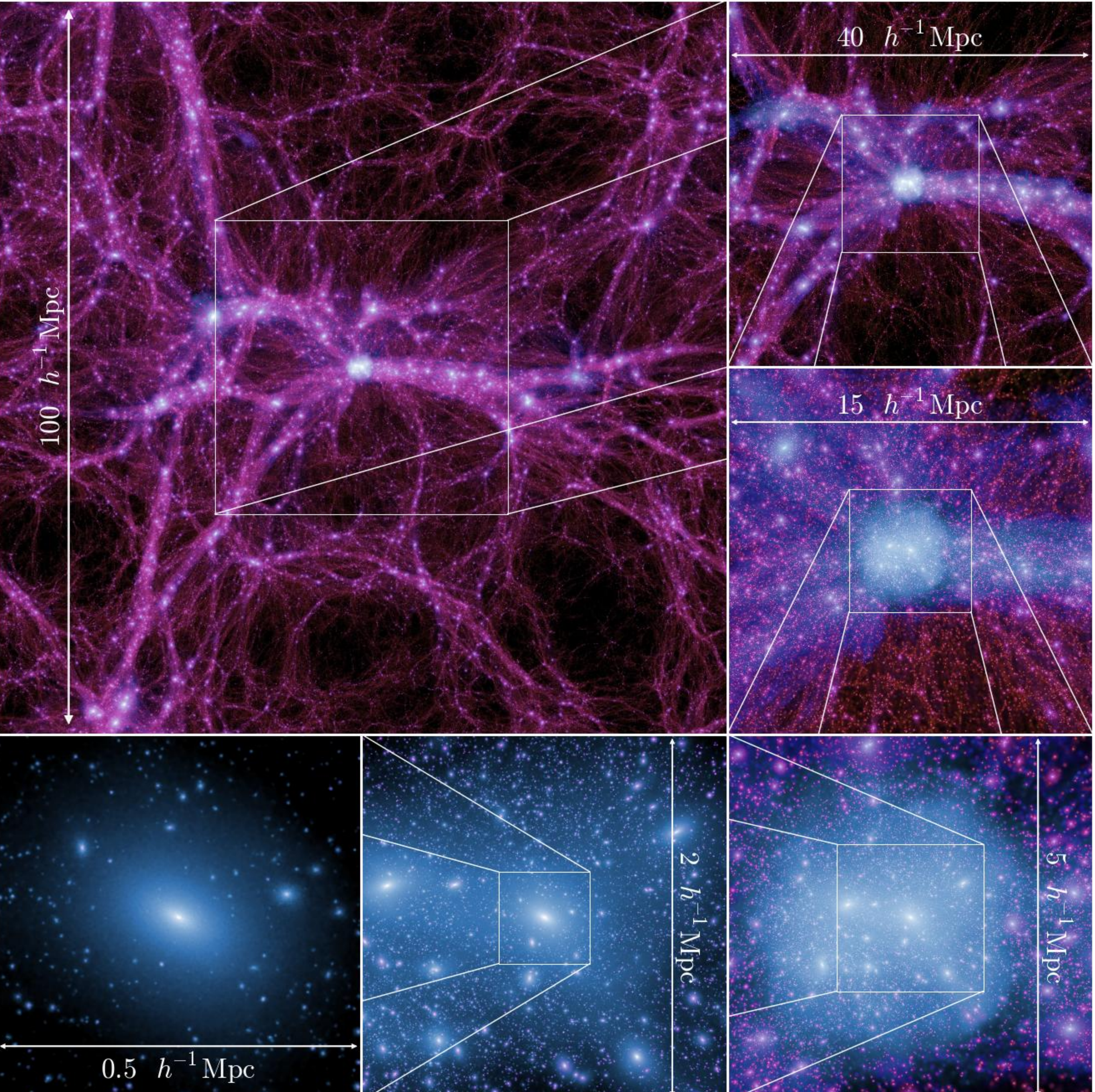


333 papers making direct use of data from the MS (18-09-2010)
Most by authors unassociated with the consortium
Most based on the galaxy catalogues, particularly mock surveys

Limitations of the Millennium Simulation

- Limited volume – too small for BAO work, precision cosmology
- Limited resolution – too poor to model formation of dwarfs
- No convergence tests – are galaxy results numerically converged?
- Only one (“wrong”) cosmology
- Users unable to test dependences on parameters/assumptions

Millennium-II (2008)



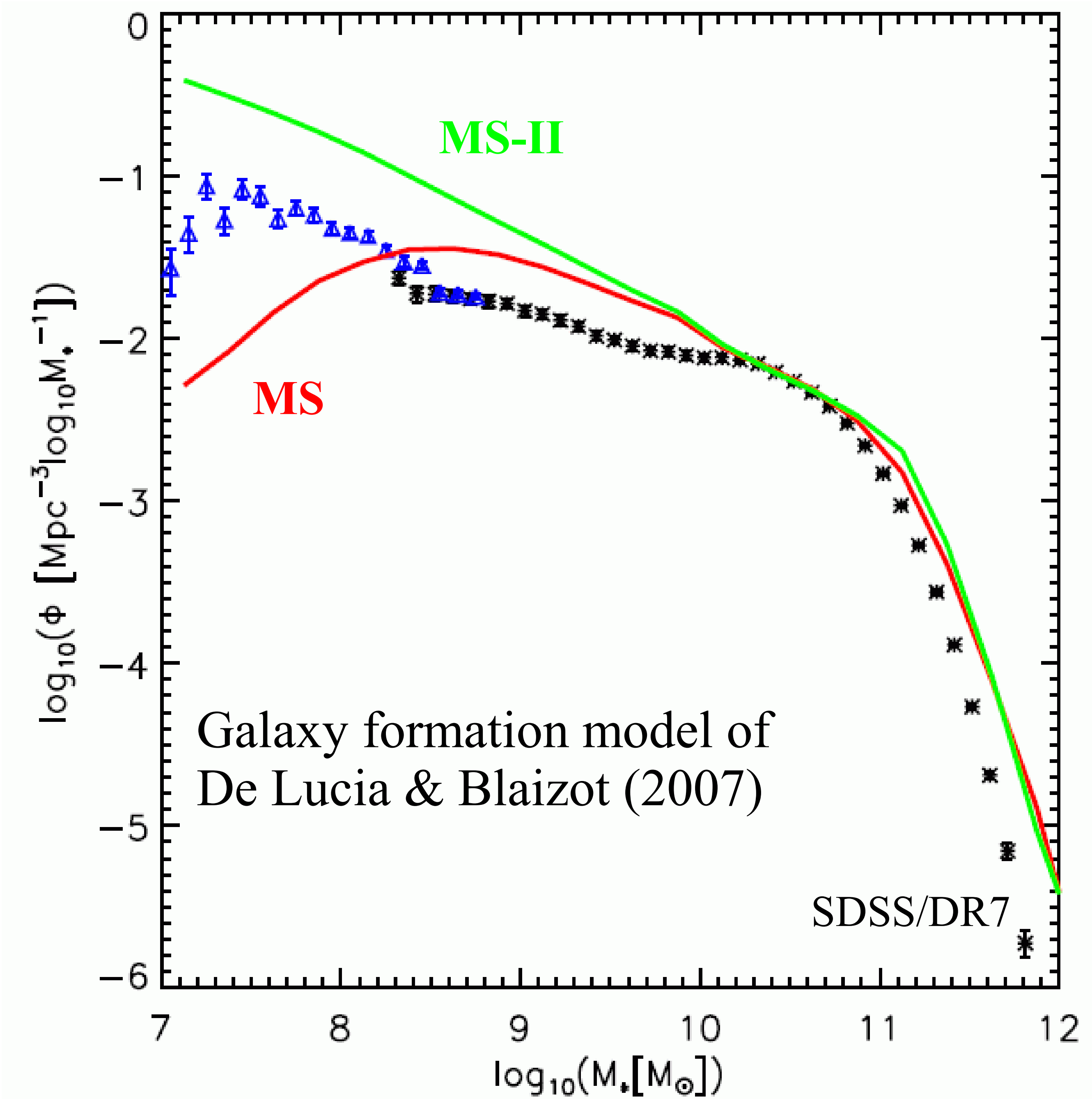
Same cosmology

Same N

1/5 linear size

Same outputs/
post-processing

Resolution tests of MS results and extension to smaller scales



Galaxy formation modelling on the MS is affected by resolution for log $M_* < 9.5$

The current standard models do not fit recent "precision" data

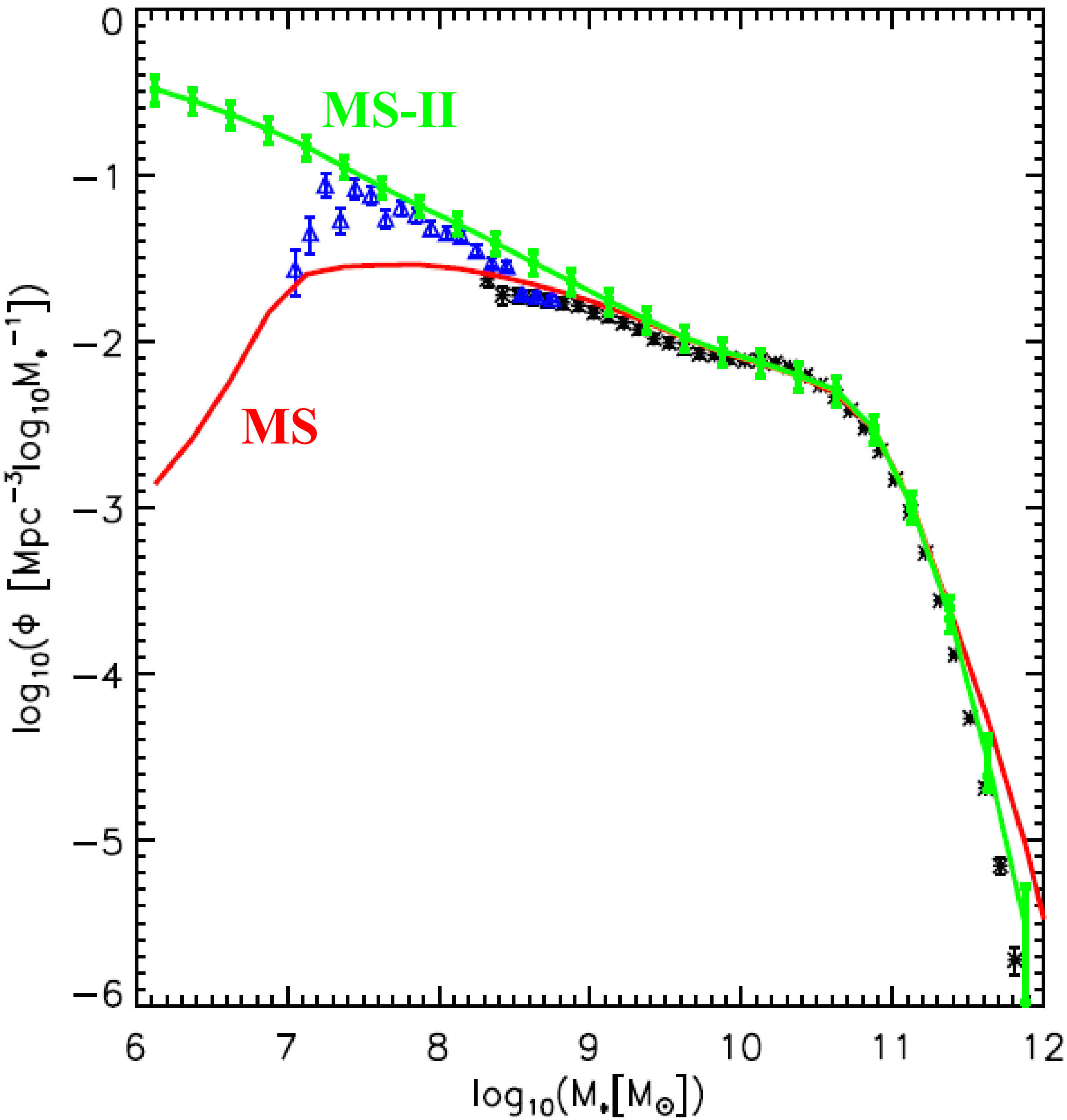
New galaxy formation models based on MS+MS-II

Qi Guo et al 2010

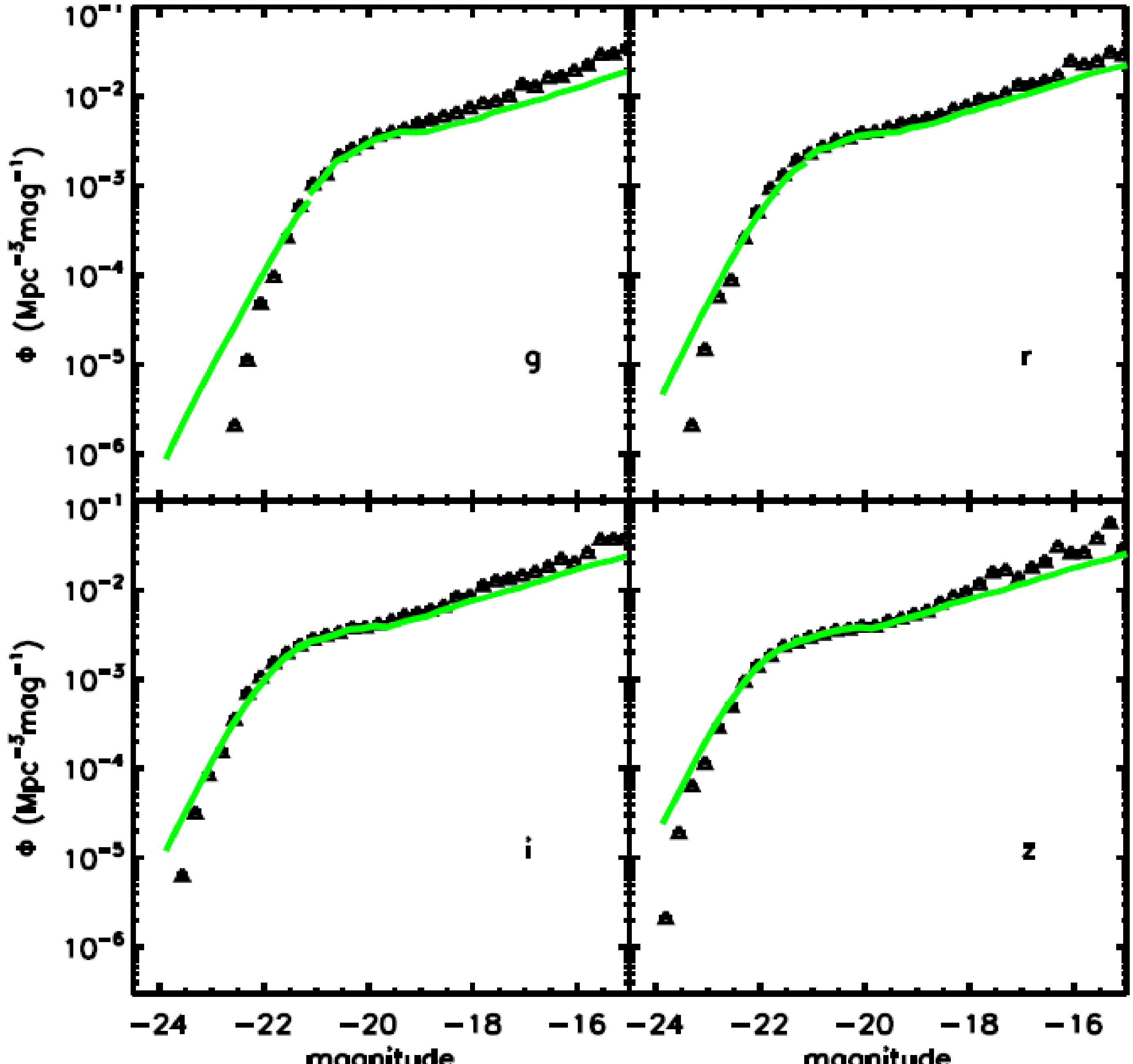
- Implement modelling simultaneously on MS and MS-II
- Test convergence of galaxy properties near resolution limit of MS
- Extend to properties of dwarf galaxies
- Improve/extend treatments of "troublesome" astrophysics
- Adjust parameters to fit new, more precise data
- Test against clustering and redshift evolution

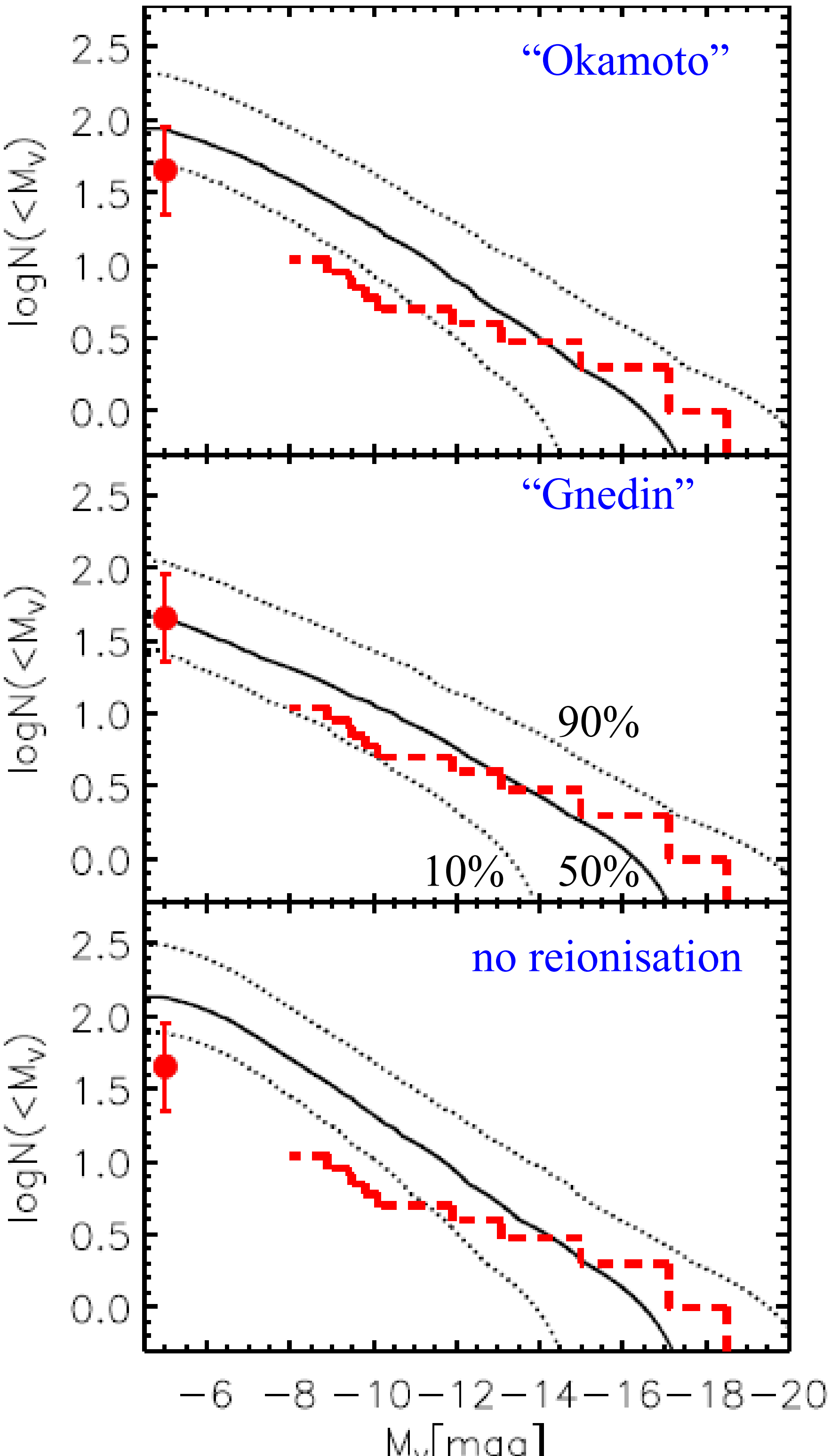
Things that work well

The stellar mass function of galaxies



Luminosity functions of galaxies

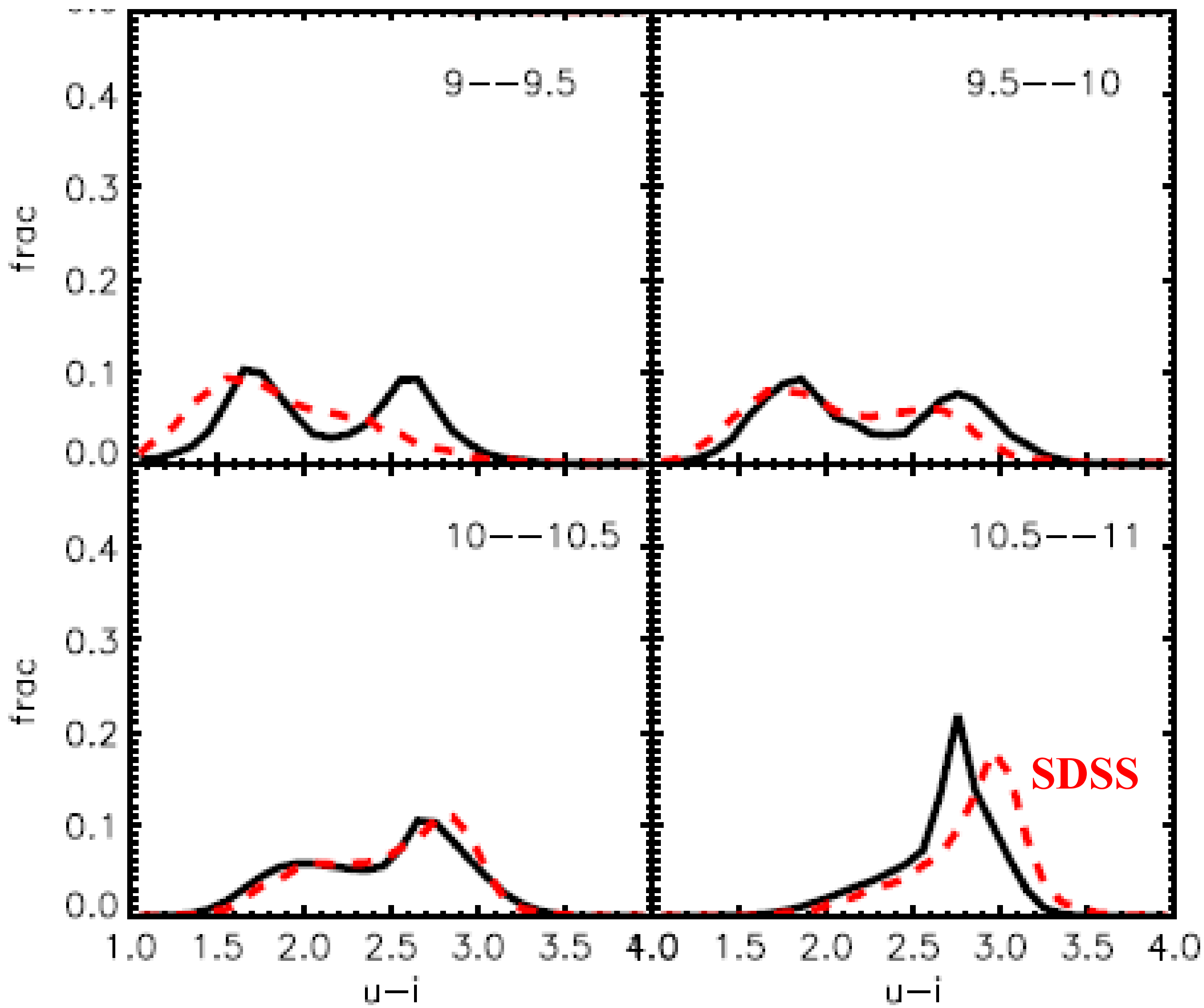




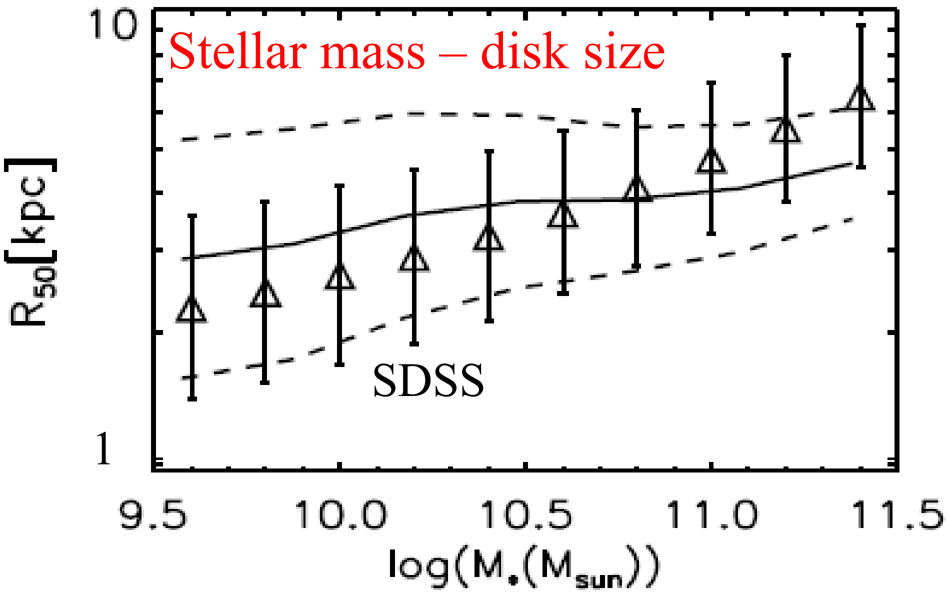
Luminosity function of Milky Way satellites

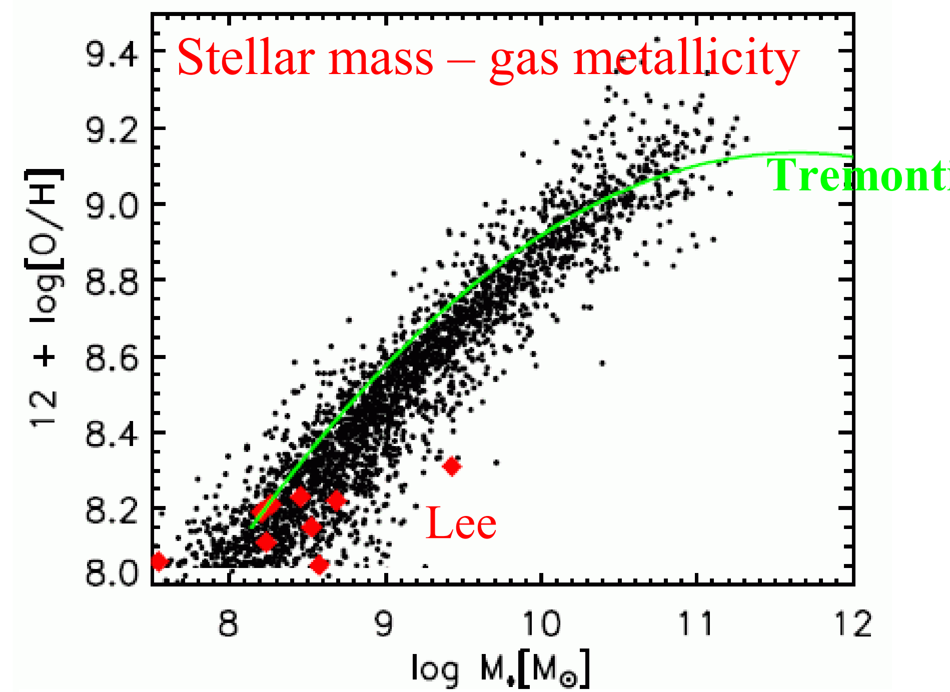
Luminosity functions of satellites around 1500 "Milky Ways" i.e. isolated disk galaxies with log $M_* = 10.8$

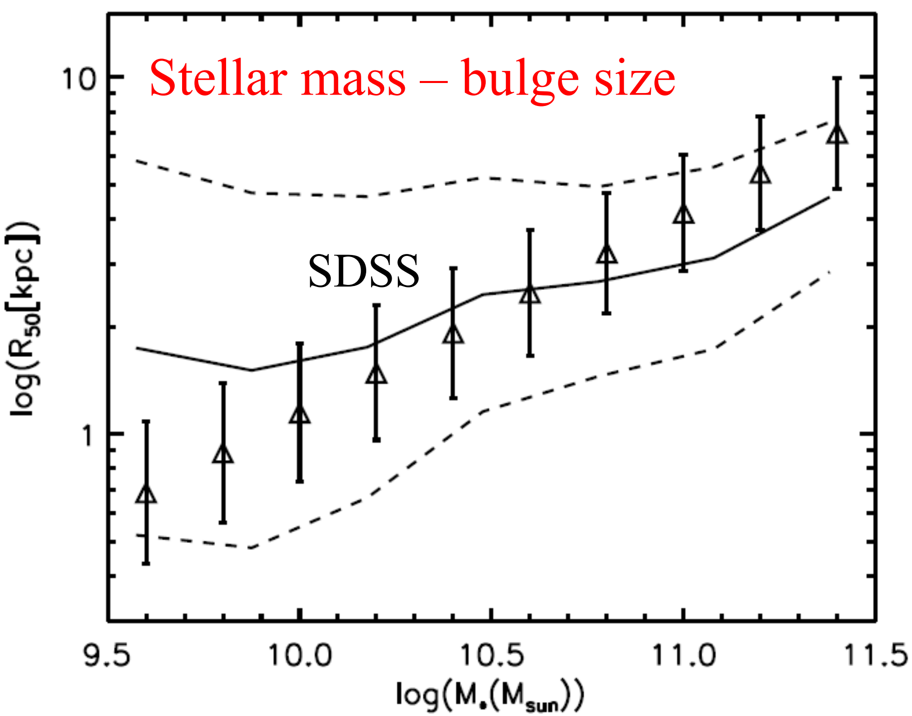
Galaxy colour distributions

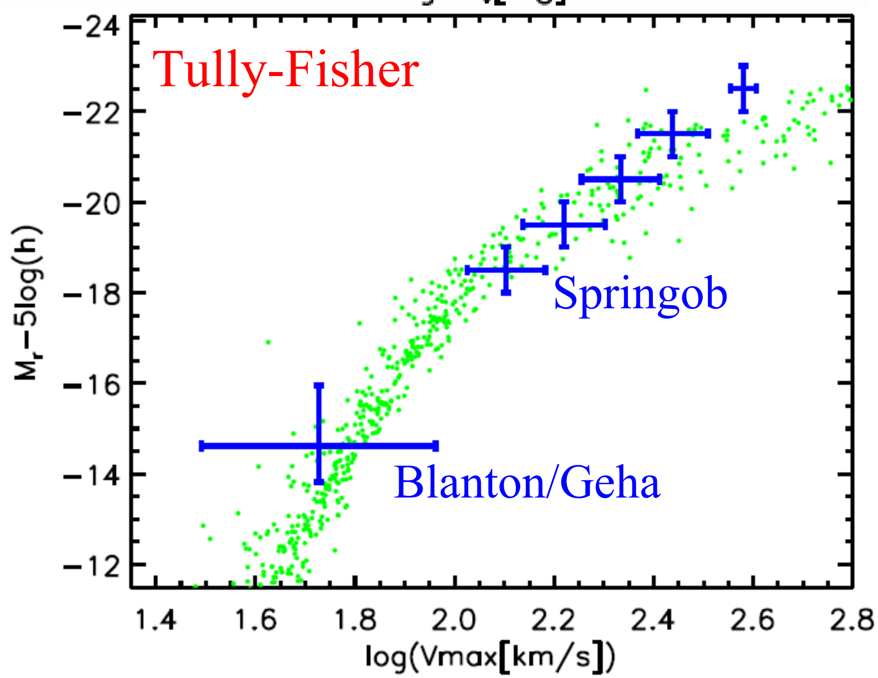


Scaling relations

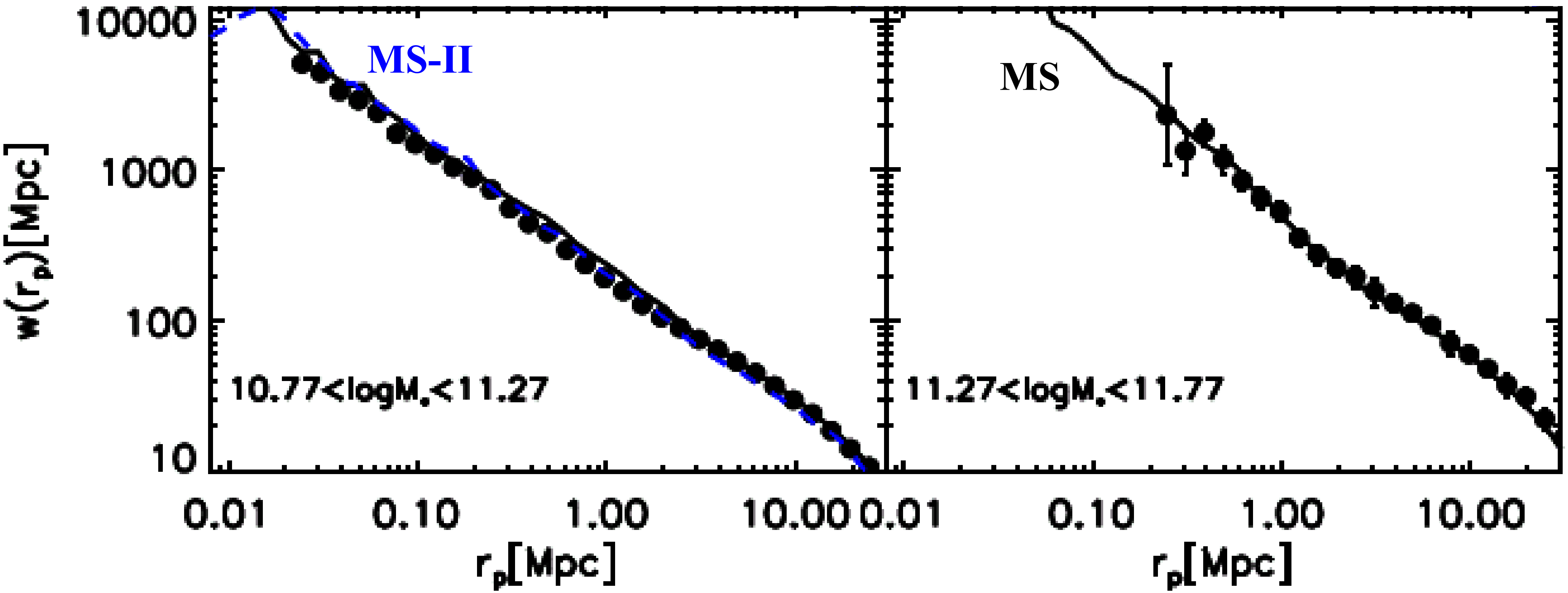






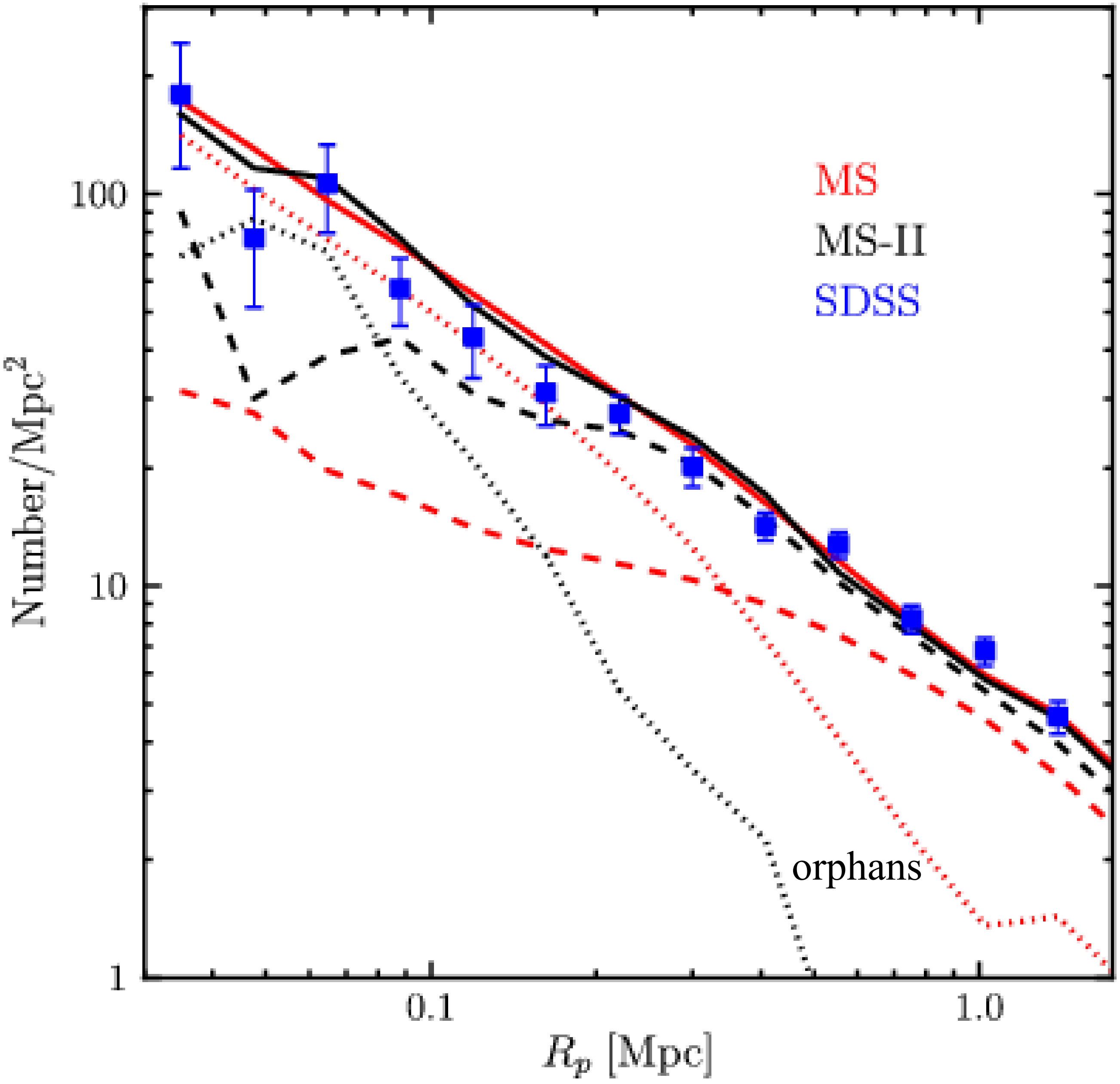


Clustering of massive galaxies



Data from SDSS/DR7

Projected galaxy number density profiles of clusters

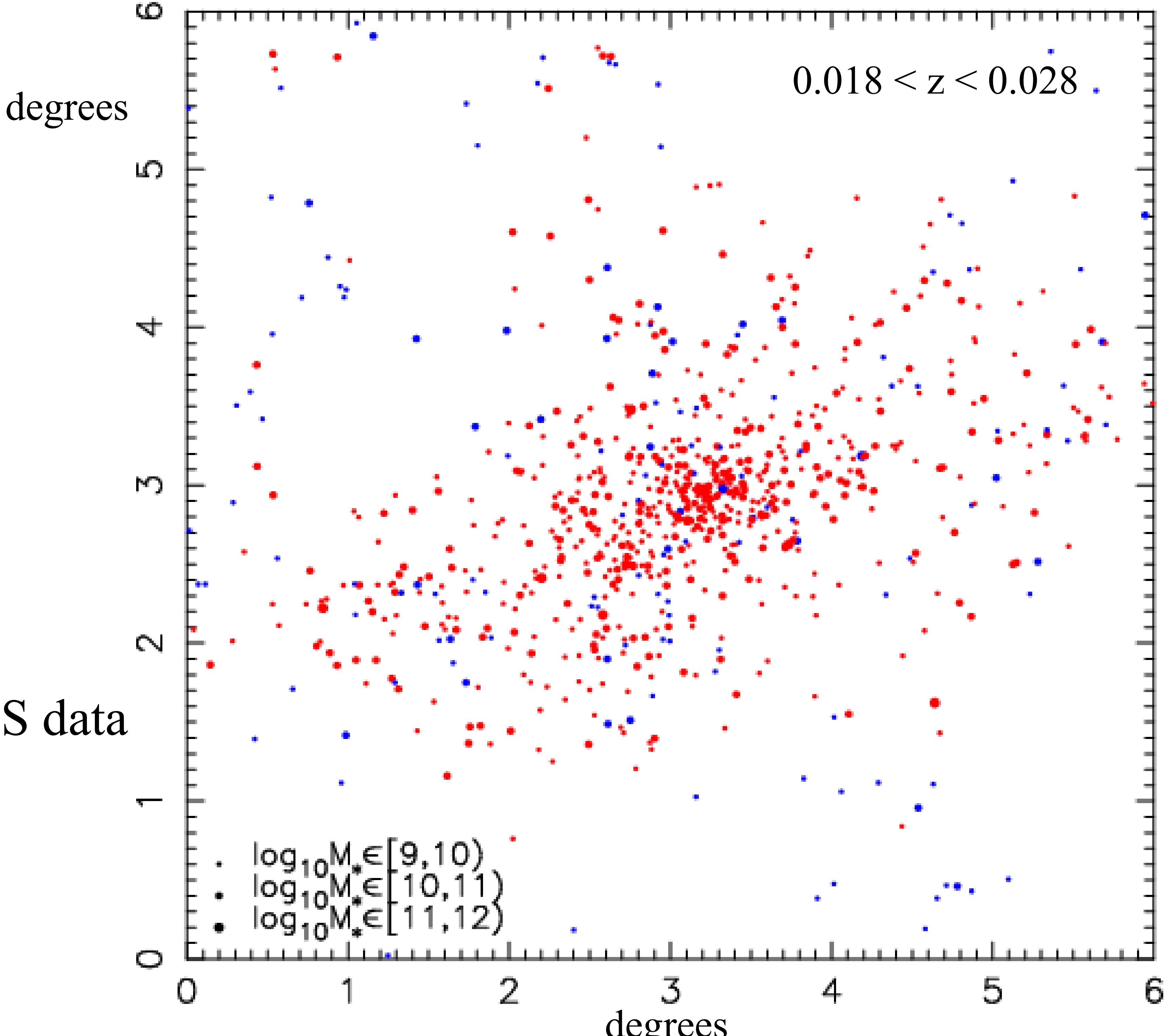


log M_{gal} > 10.0

14.0 < log M_{clus} < 14.3

Note: good agreement of MS with MS-II is *only* when orphans are included

Orphan treatment is physically consistent and needed to fit SDSS

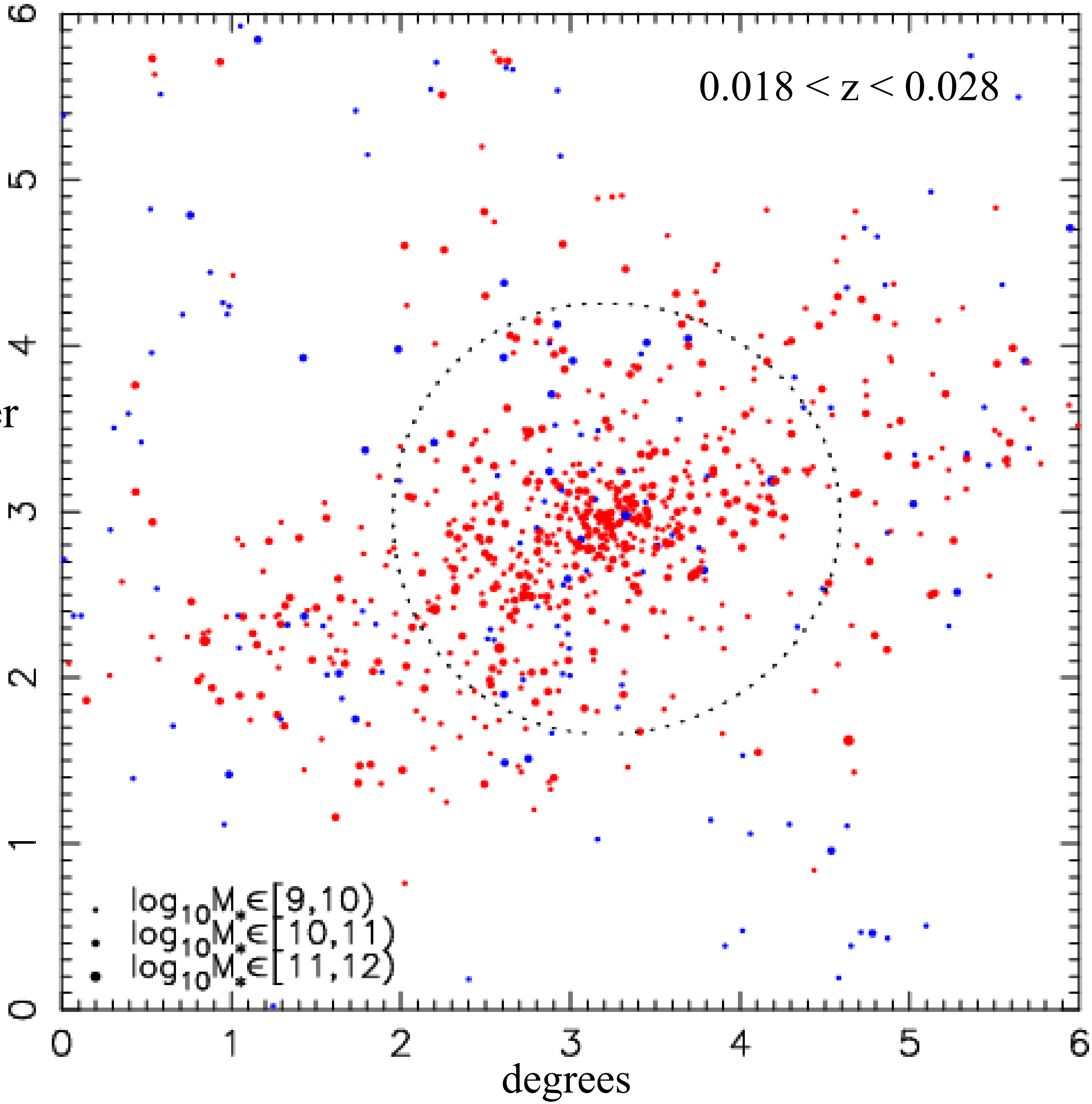

0.018 < z < 0.028
degrees
degrees
0
1
2
3
4
5
6
$\log_{10}M_* \in [9,10)$
$\log_{10}M_* \in [10,11)$
$\log_{10}M_* \in [11,12)$

SDSS data

degrees

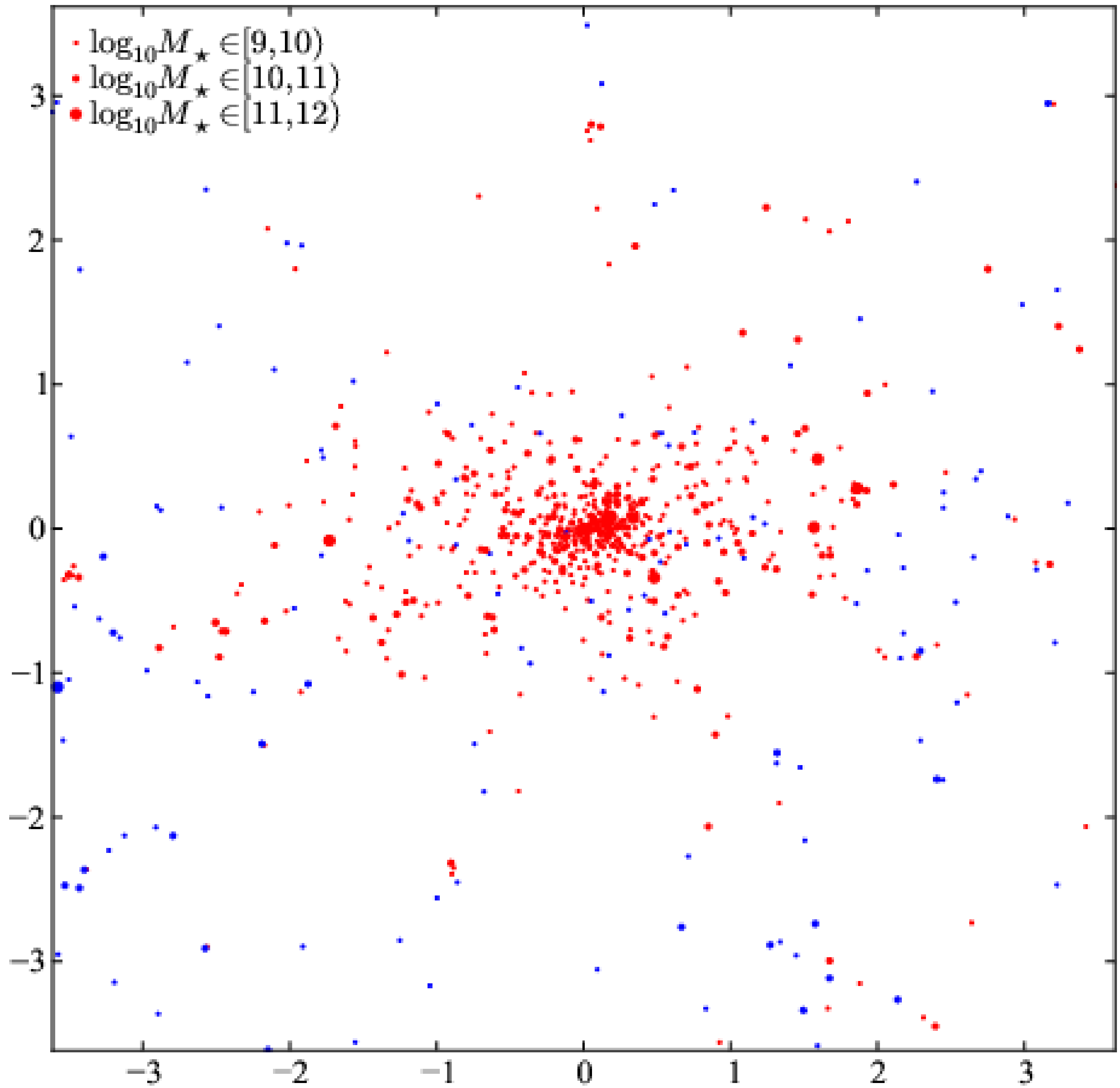
Coma cluster with R_{200}

SDSS data



h^{-1} Mpc

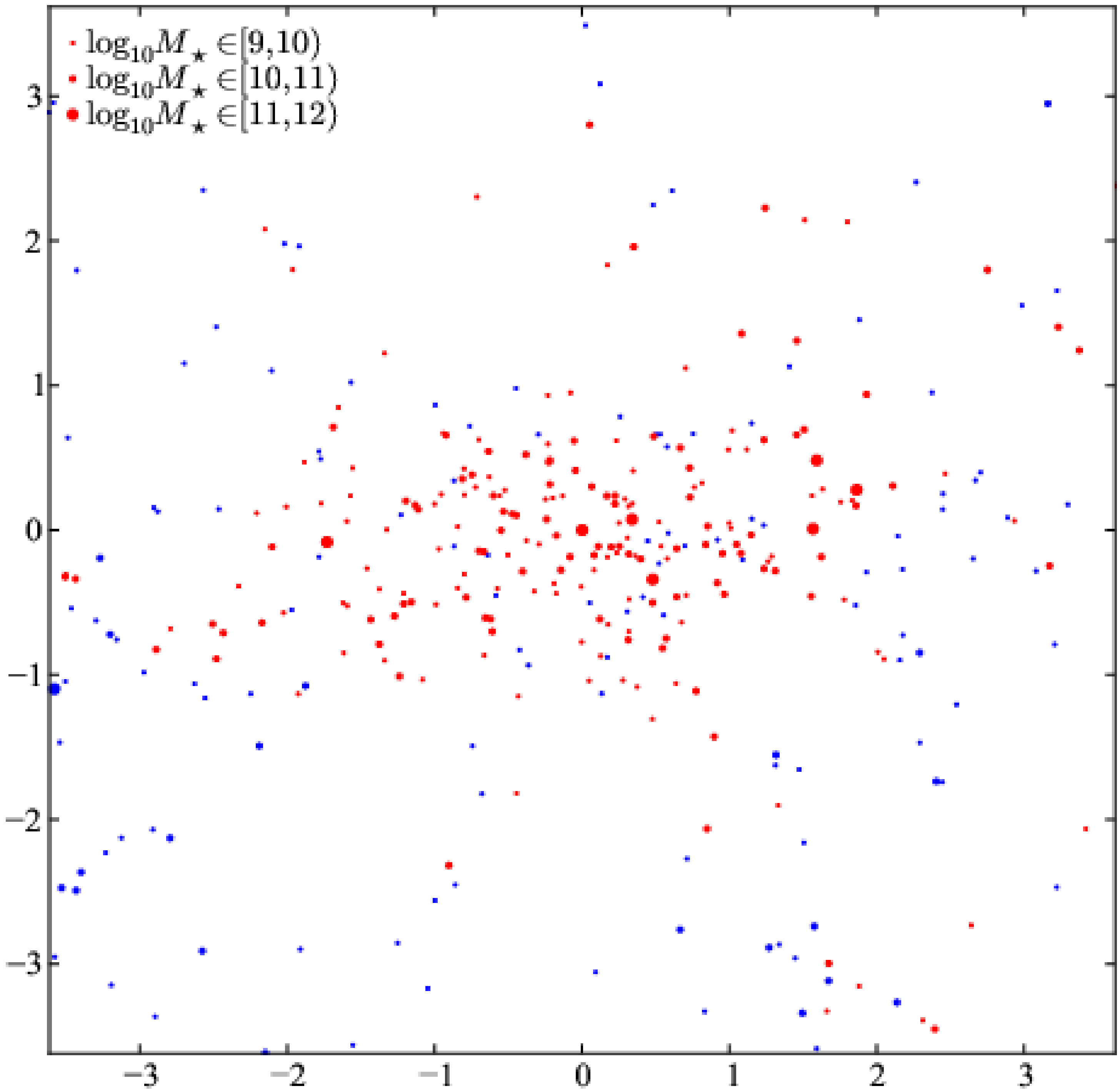
MS cluster



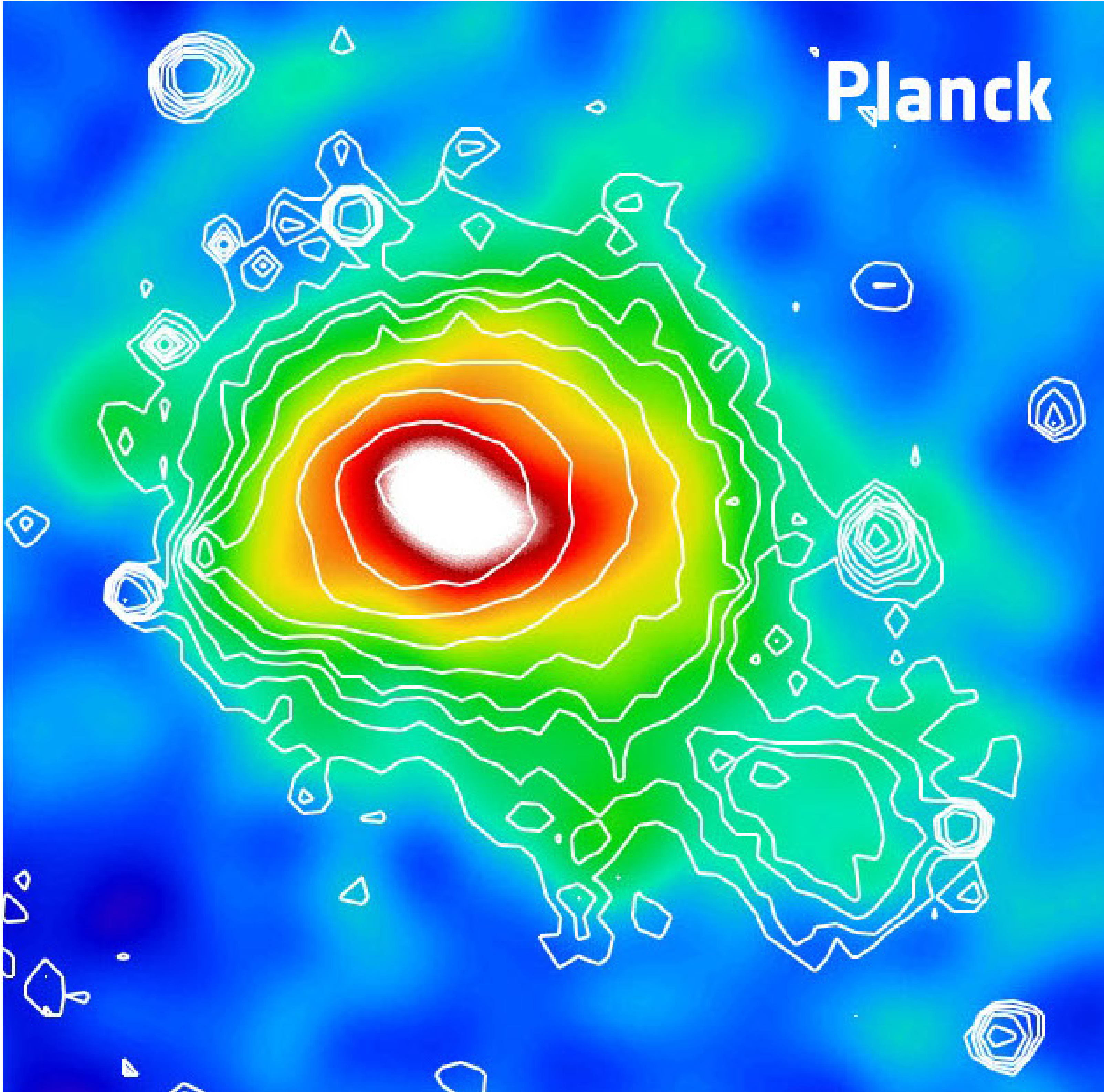
h^{-1} Mpc

h^{-1} Mpc

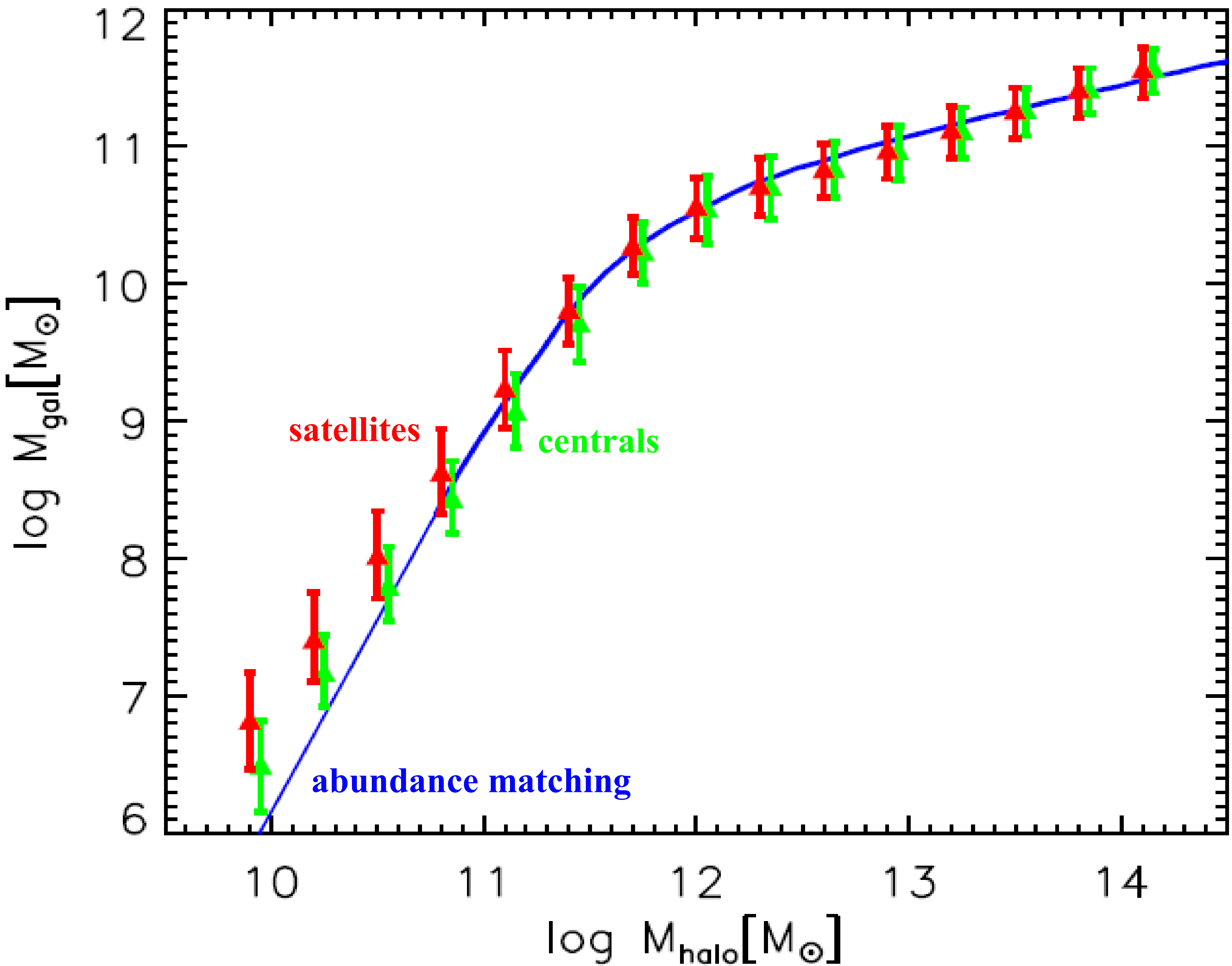
MS cluster galaxies in subhalos



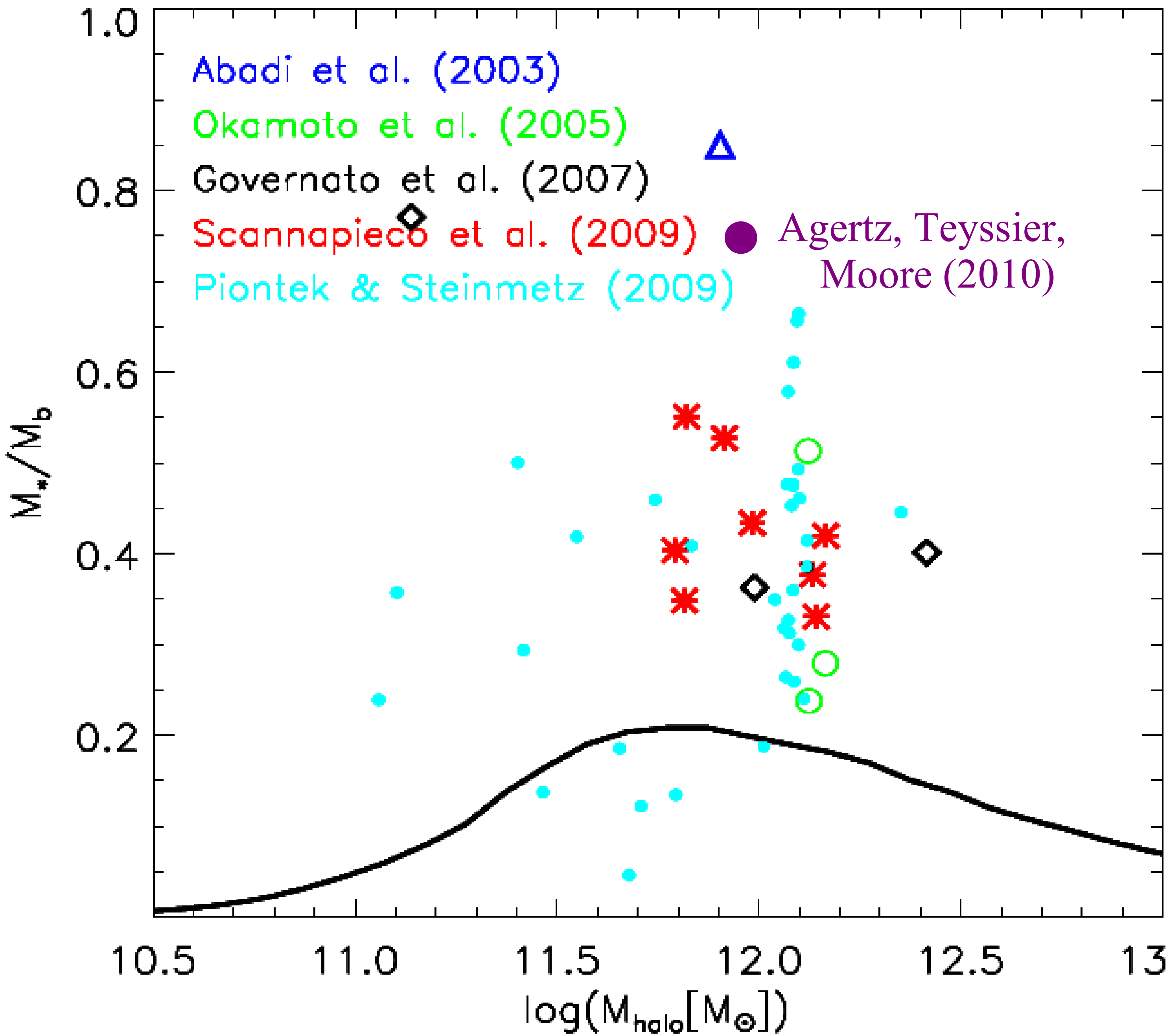
h^{-1} Mpc


Planck

Galaxy stellar mass versus maximum past halo mass



“Successful” simulations fail to match this



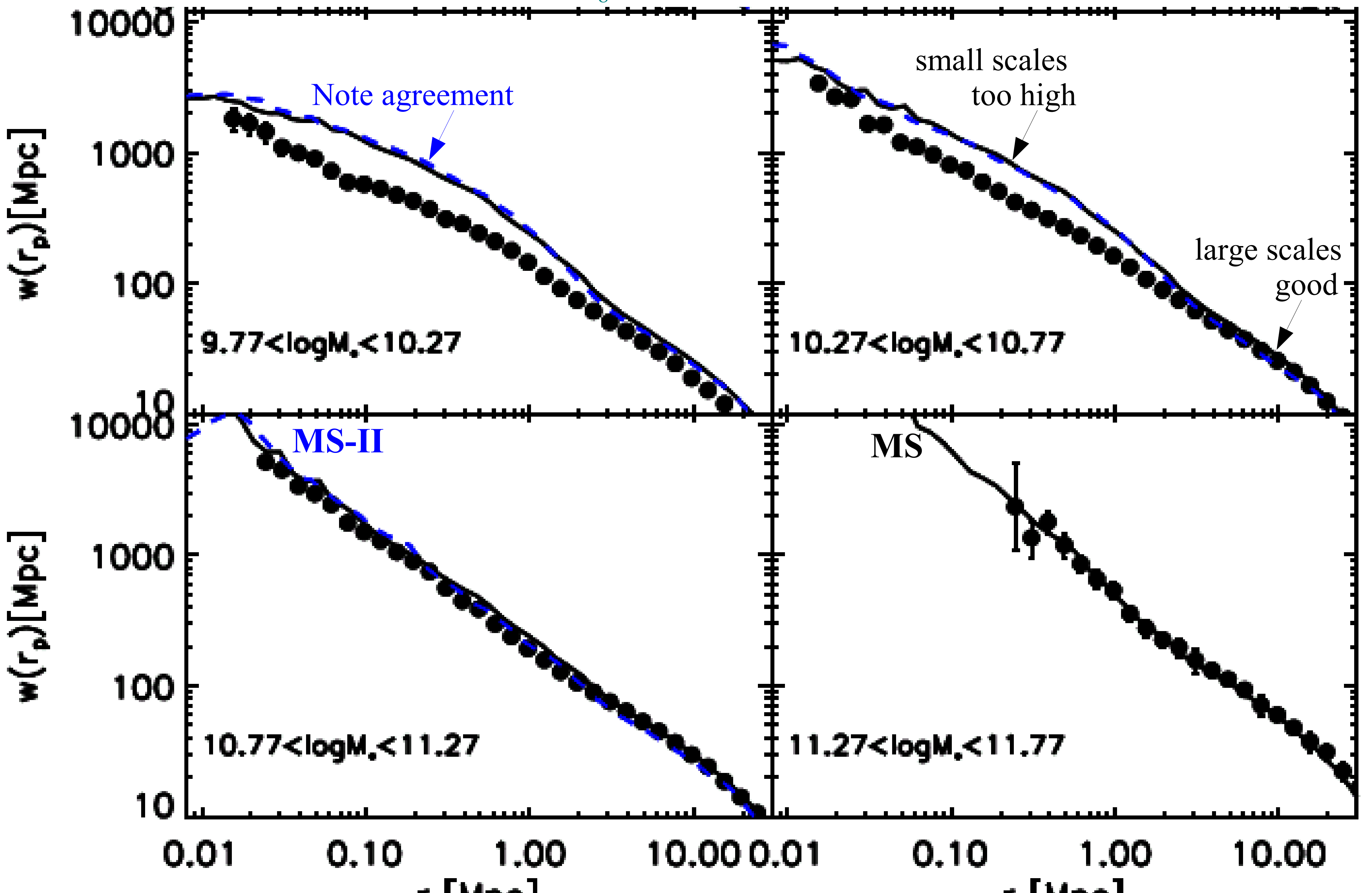
Guo et al 2010

Agertz et al 2010

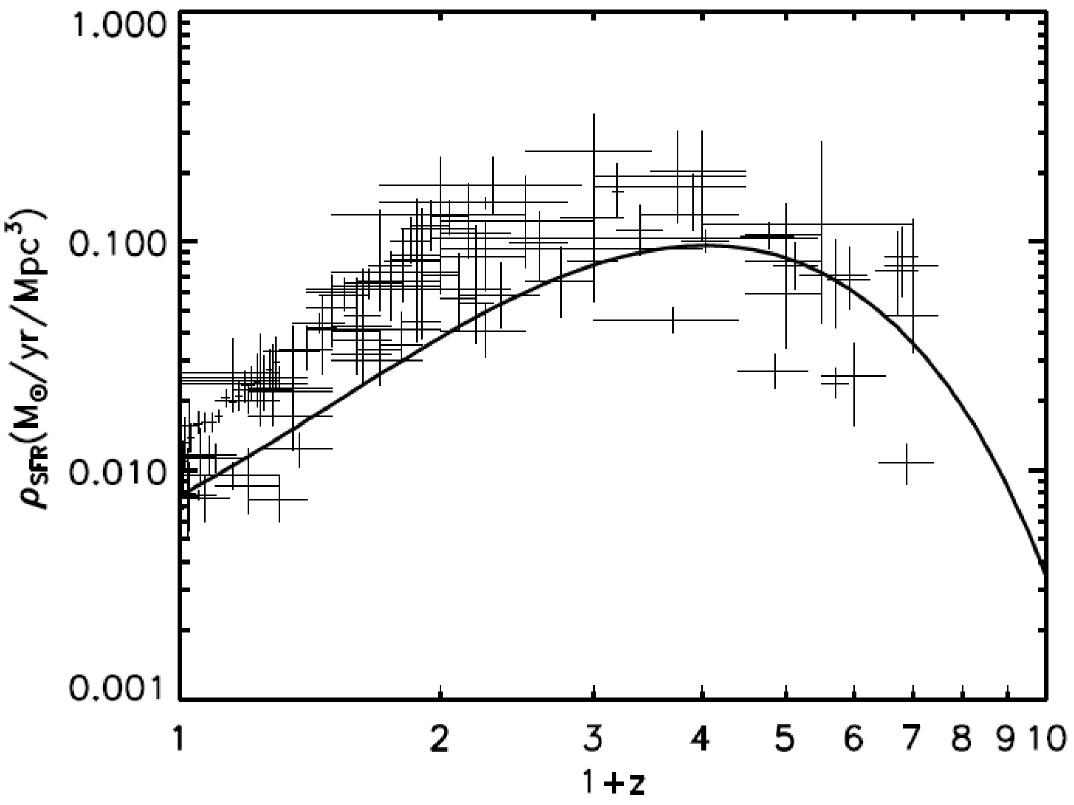
Things that work less well

Clustering of less massive galaxies

--- $\sigma_8 = 0.9$ is too high ---



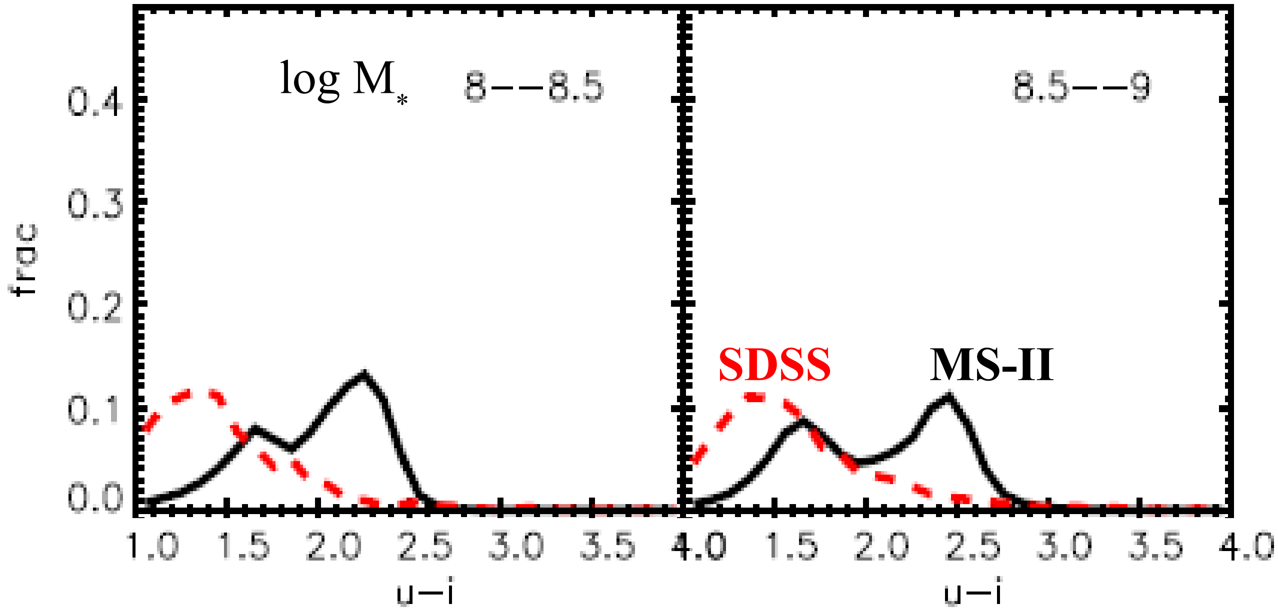
The cosmic star formation density history



--- <u>observed</u> SFR are inconsistent with <u>observed</u> stellar masses ---

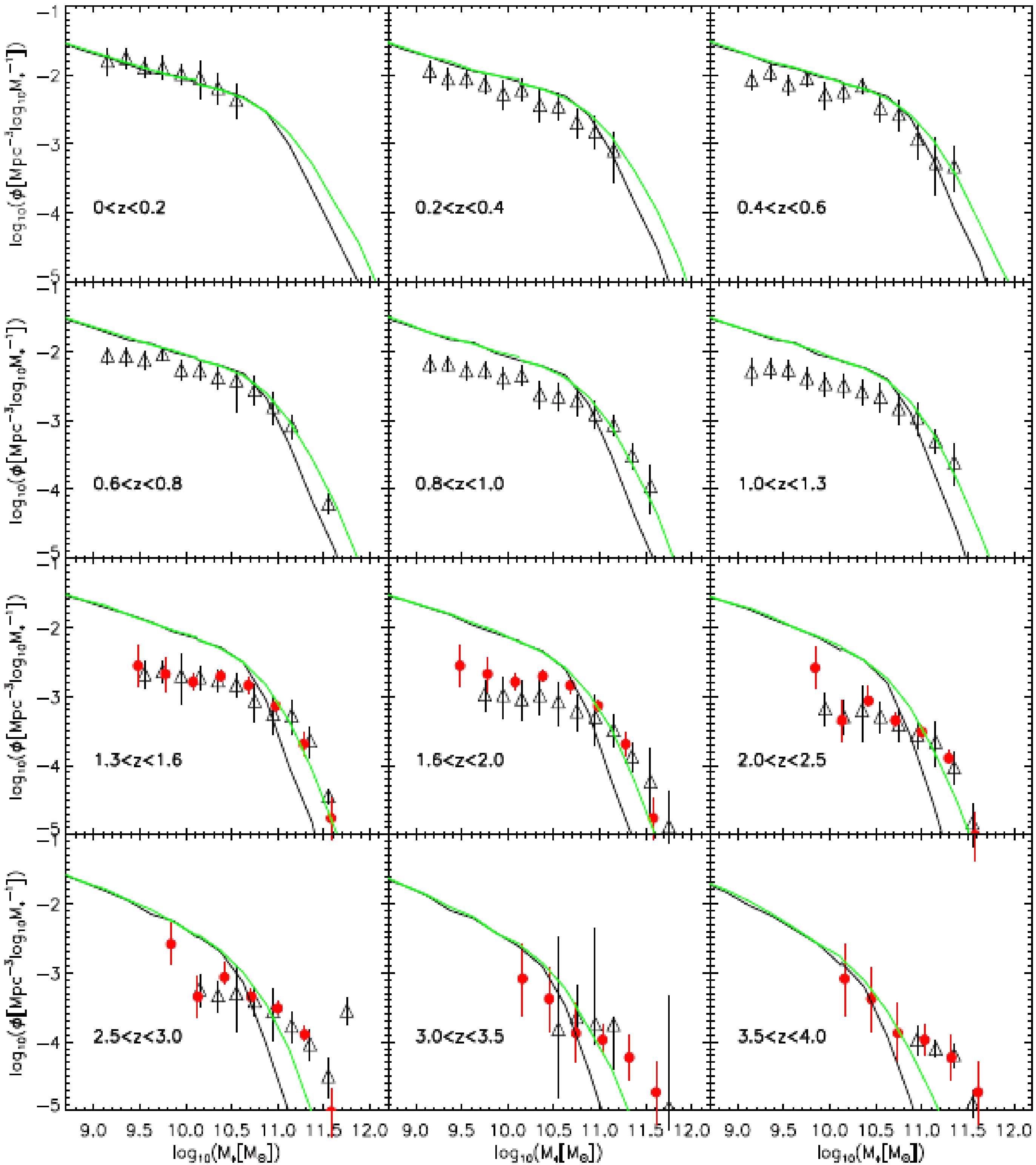
--- star formation peaks <u>too early</u> in the model ---

Colours of dwarf galaxies



Too many passive low mass galaxies in the MS-II

--- formation is too fast/too early ---



Evolution of stellar mass function

Lower mass galaxies
$\log M_* < 10.5$
form too early

Conclusions from MS/MS II comparison

"Precision" modelling of the formation and evolution of the galaxy population is now possible

Viable models should address abundances *and* scaling relations *and* clustering *and* evolution

The Millennium Simulation amplitude $\sigma_8 = 0.9$ is too high

In current models star formation occurs *too early* in low-mass systems

→ Need a better understanding of star formation and a lower fluctuation amplitude

Limitations of the Millennium Simulation

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- Limited resolution – too poor to model formation of dwarfs
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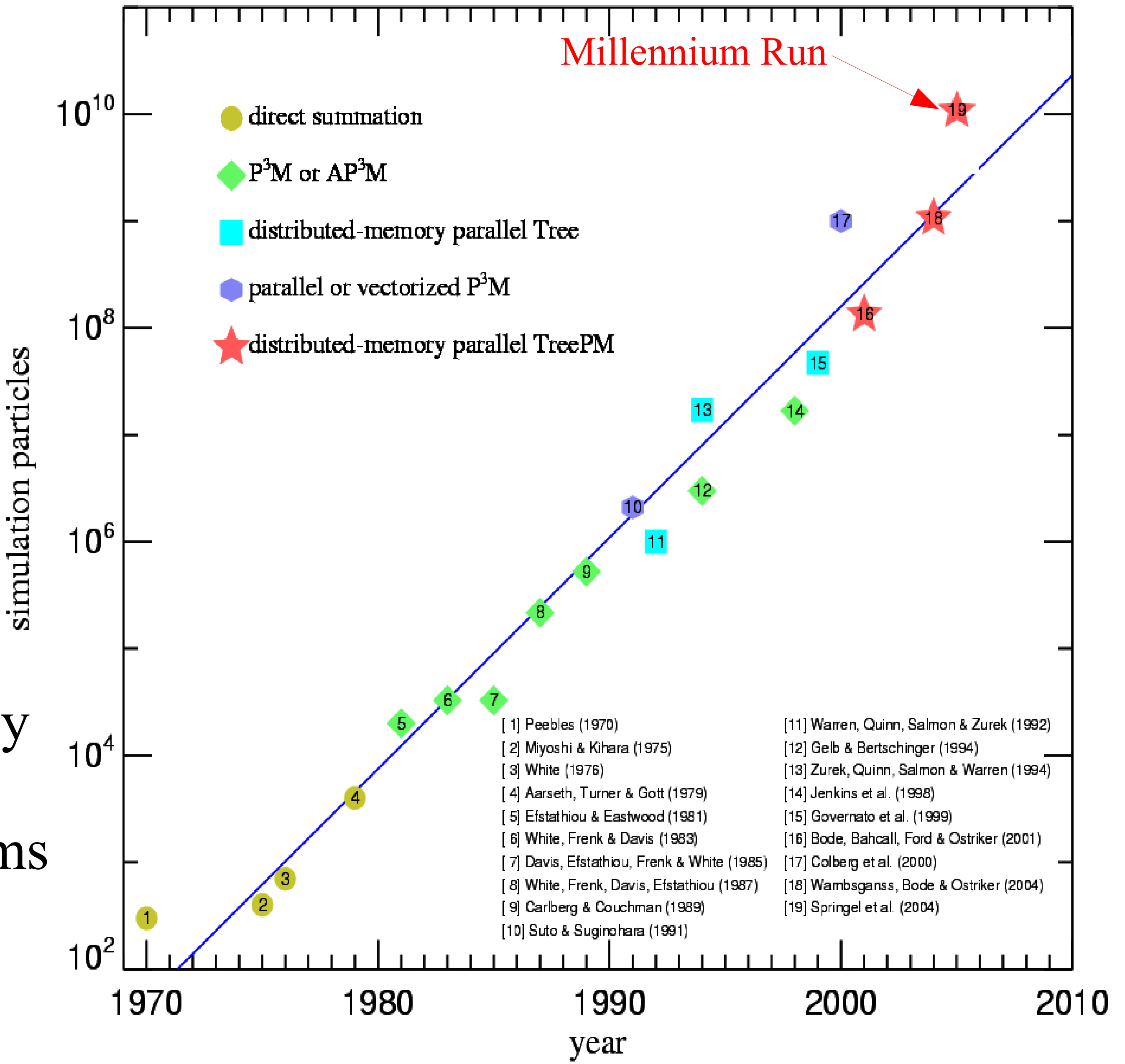
Moore's Law for Cosmological N-body Simulations

- Computers double their speed every 18 months
- A naive N-body force calculation needs N^2 op's
- Simulations double their size every 16.5 months
- Progress has been roughly equally due to hardware and to improved algorithms



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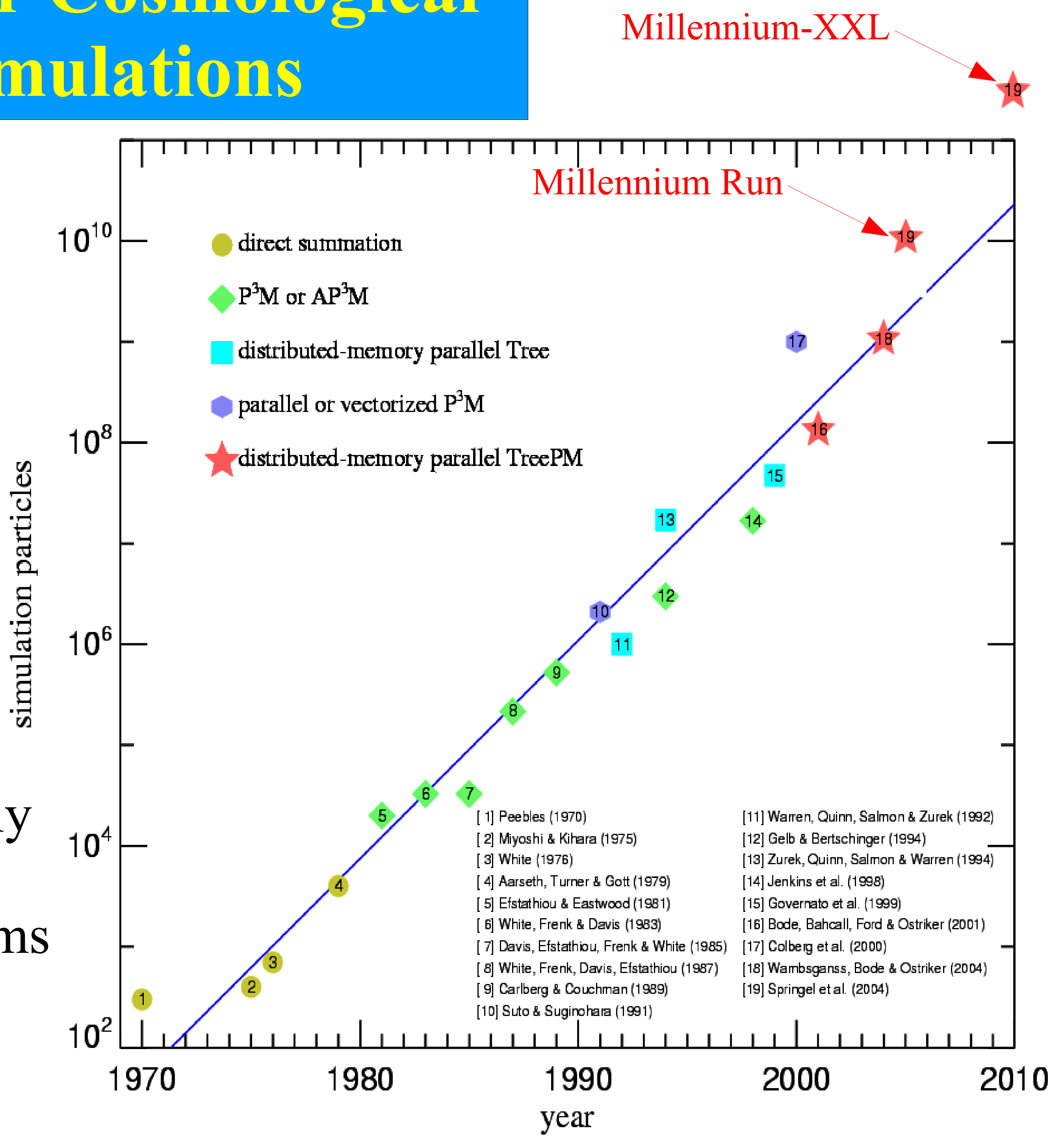
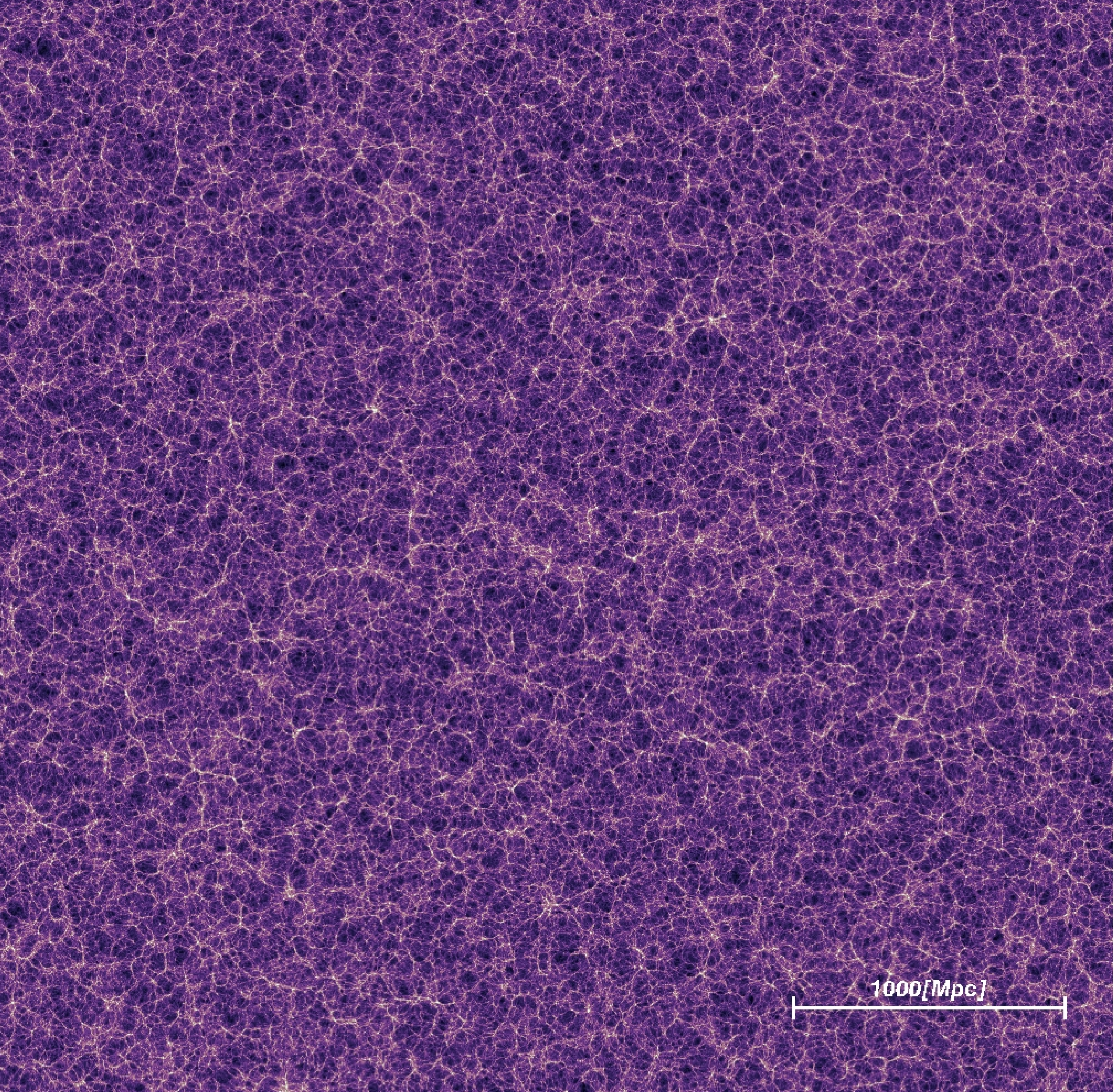




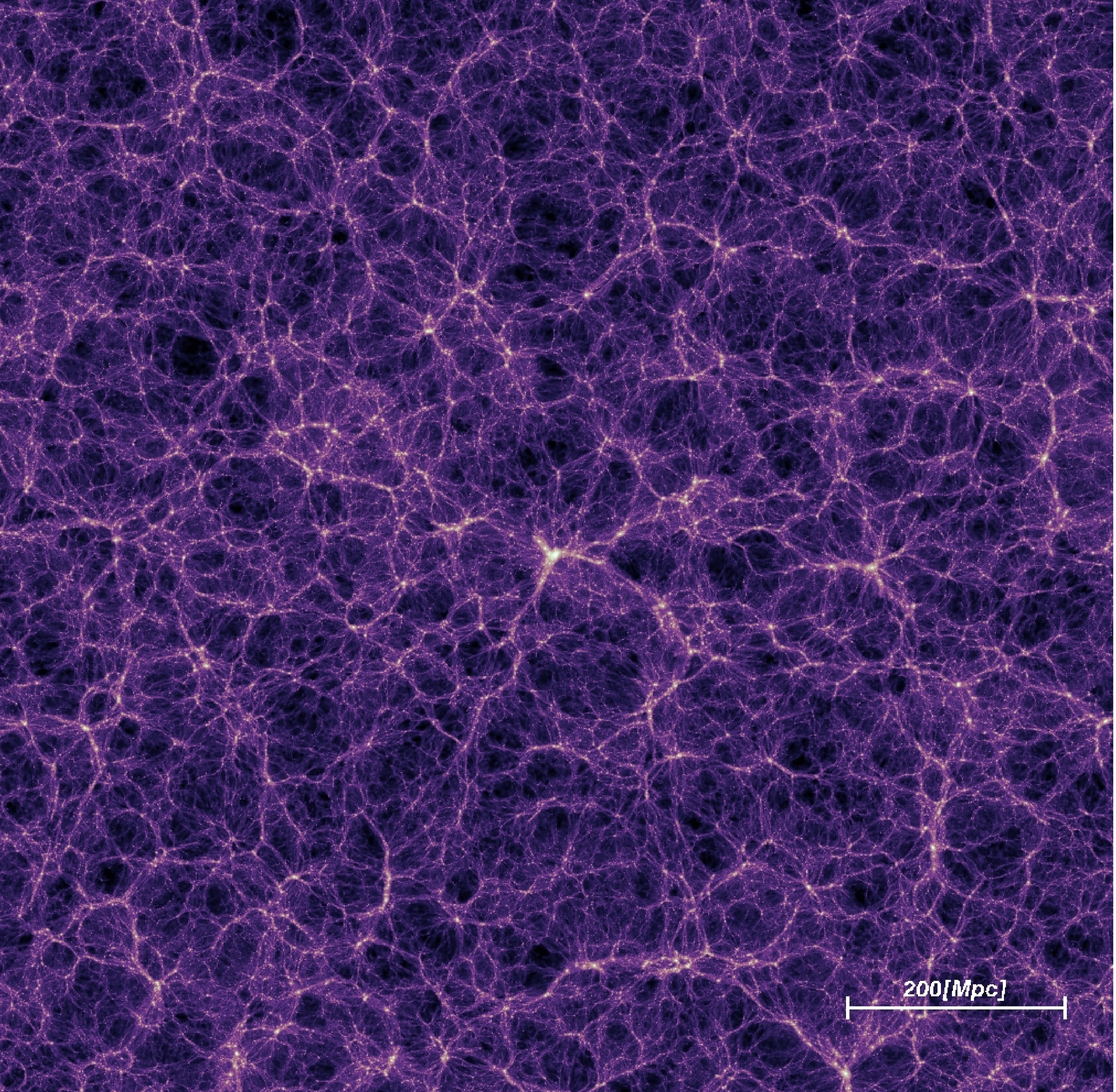
Millennium XXL

Angulo et al 2010

$N = 3 \times 10^{11}$

$m_p = 5 \times 10^9 M_\odot$

$L = 4.3$ Gpc



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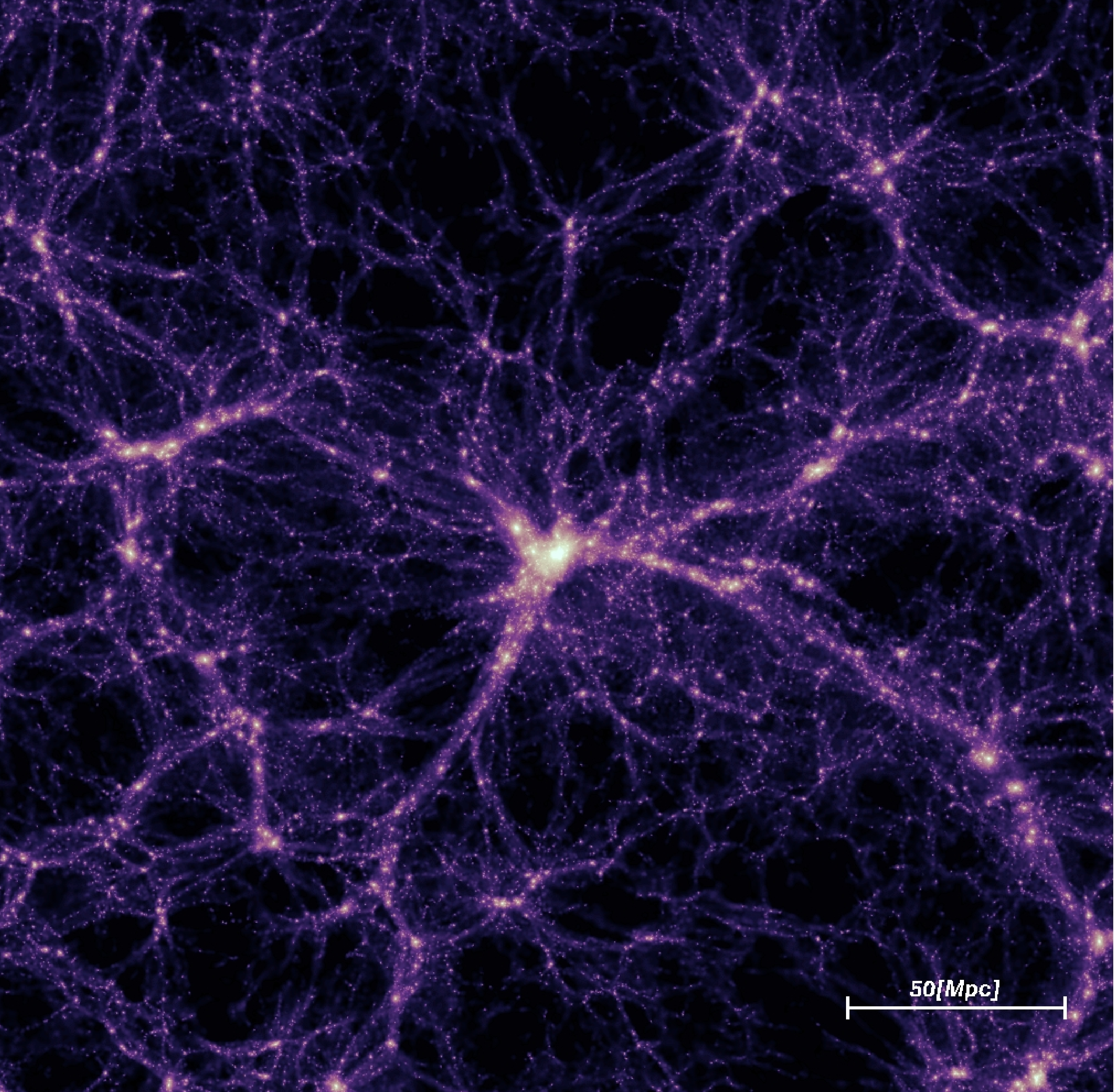

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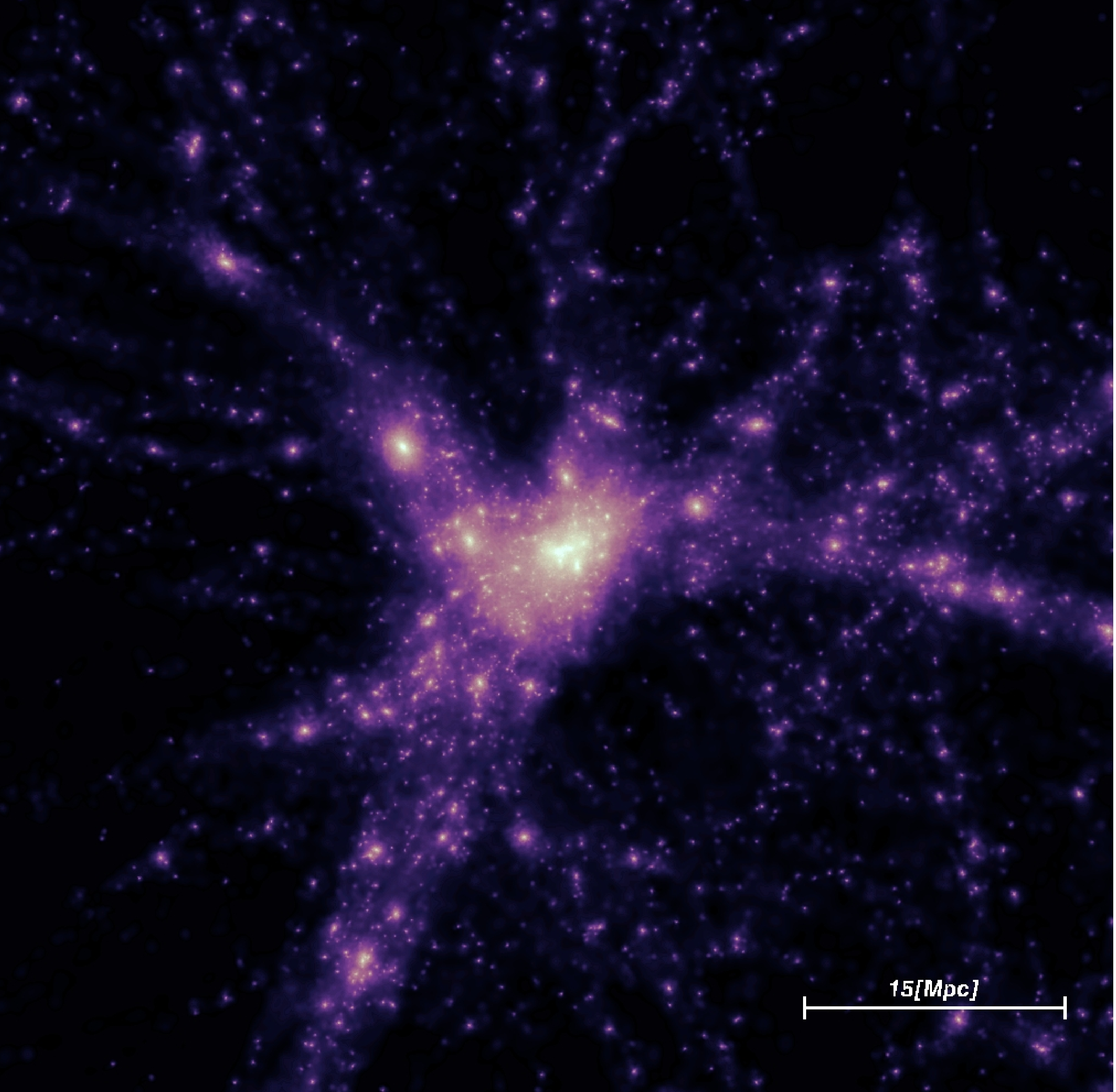

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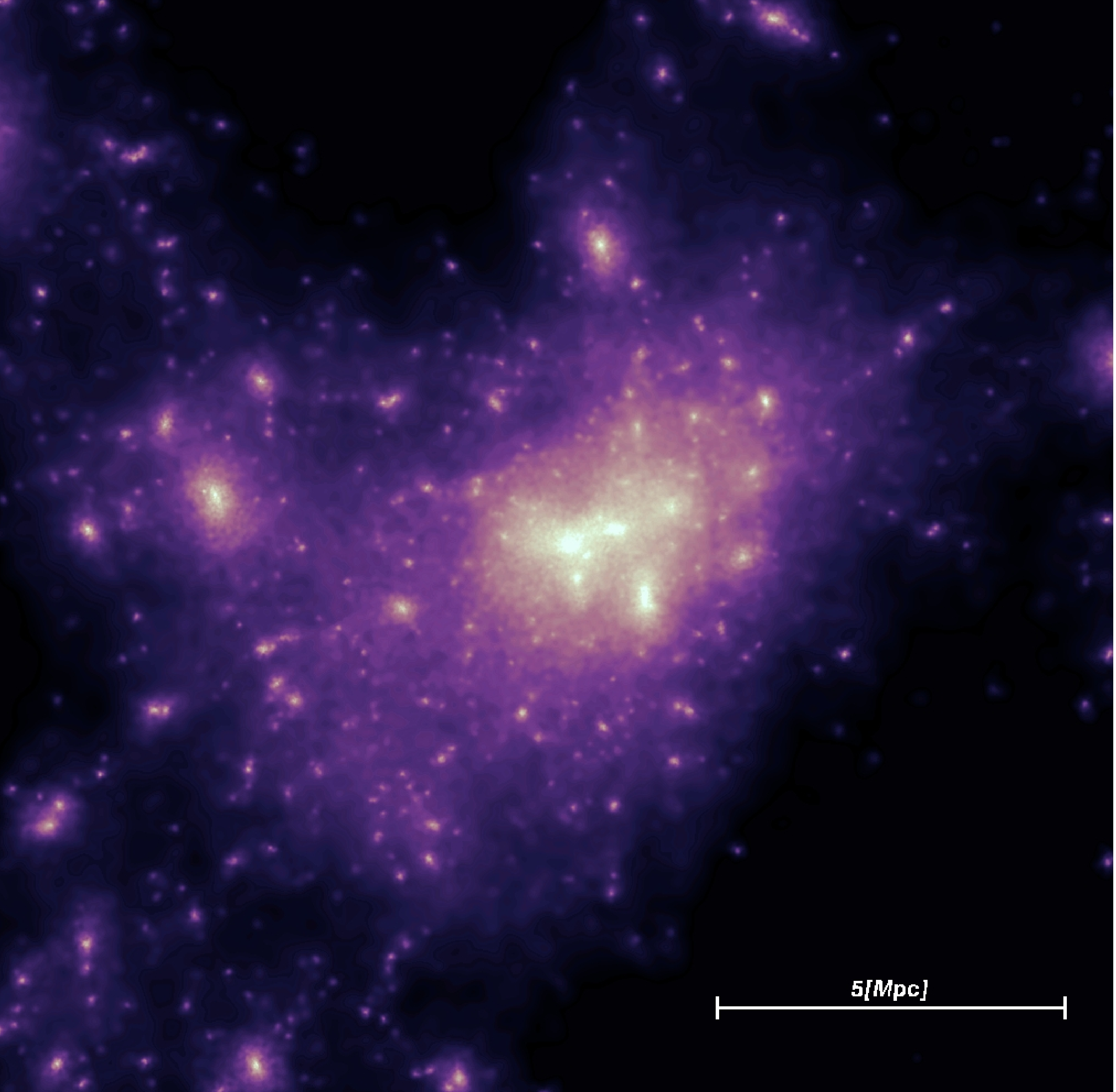

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Scaling Simulations to neighboring cosmologies

Angulo & White 2010

For example: \`WMAP1' – $\Omega_m = 0.25$, $\Omega_b = 0.045$, $\sigma_8 = 0.9$

to \`WMAP3' – $\Omega_m = 0.238$, $\Omega_b = 0.0418$, $\sigma_8 = 0.76$

1) Scale simulation size to match power spectrum slopes of original and target cosmologies on the scales of the original z=0 halos

-- 500 Mpc/h 433 Mpc/h

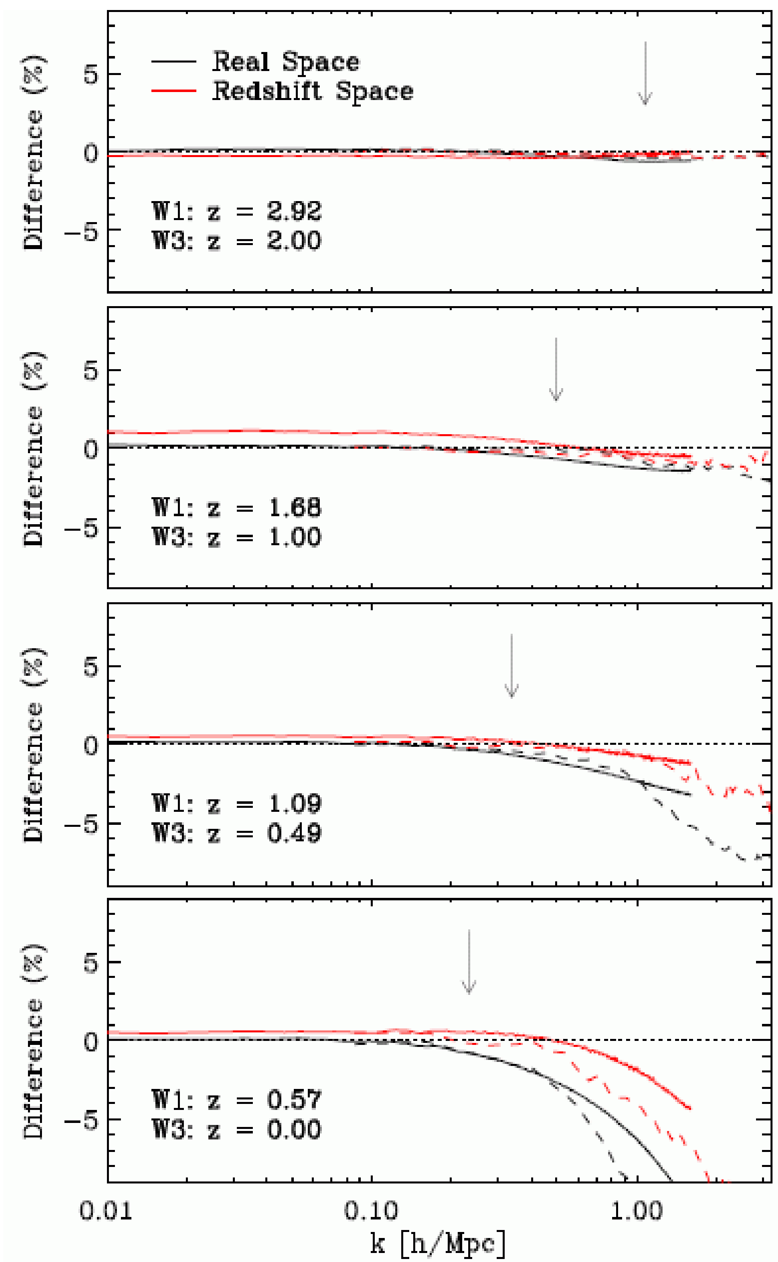
2) Reassign redshifts to match linear amplitudes on these scales

-- z = 0.57, 1.68, 2.92 z = 0, 1, 2

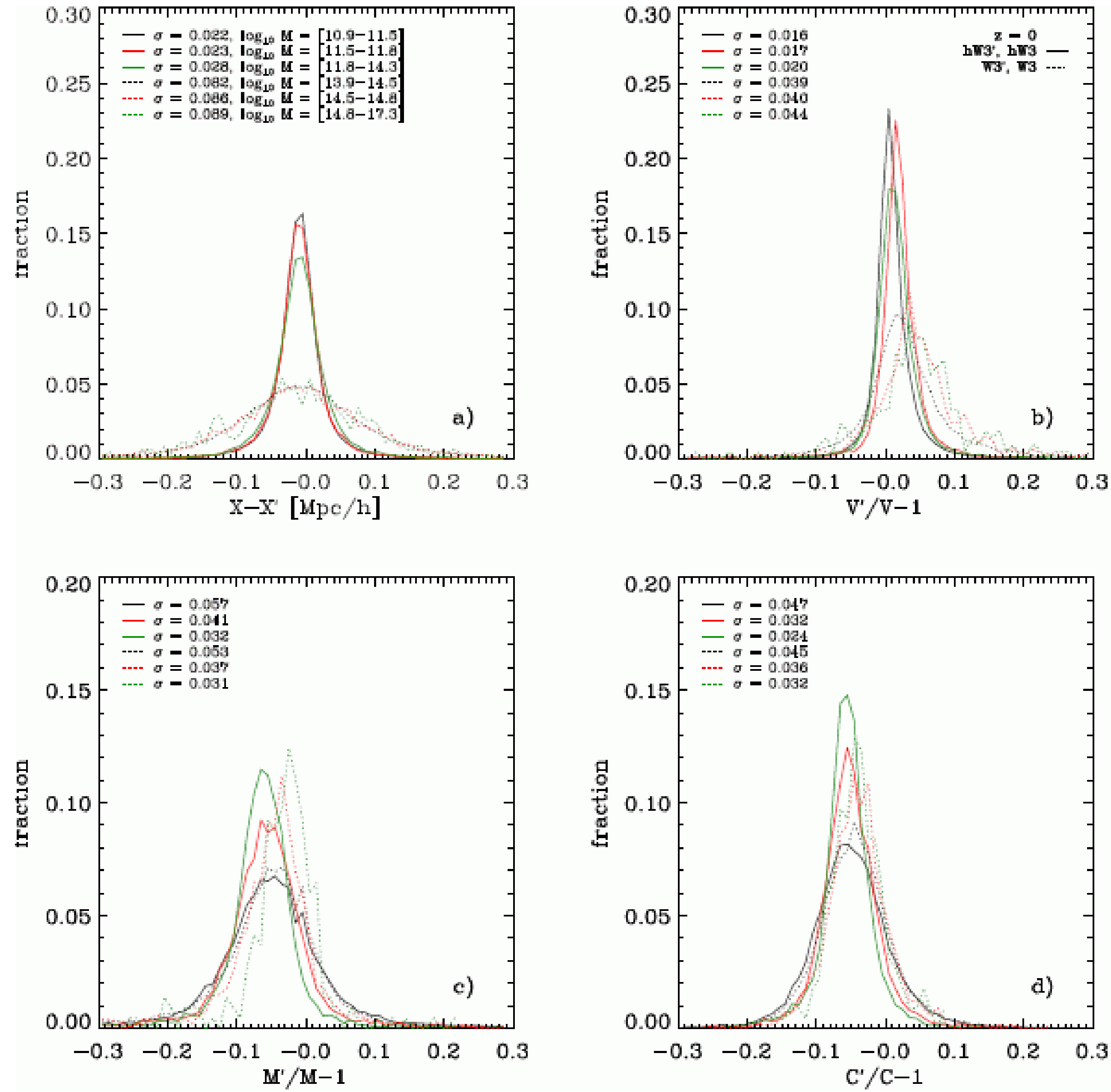
3) Scale particle masses and velocities to match Ω_m and new size

-- $9 \times 10^8\ M_\odot/h$ $5.6 \times 10^8\ M_\odot/h$

4) Adjust for the difference between amplitudes of original and target power spectra on large scales using linear theory.



Power spectra agree to better than 1% for k < 0.3



Positions agree to a few tens of kpc
Peculiar velocities, masses and concentrations to a few percent

Goals for the GALFORMOD project

- Model formation and evolution of the full galaxy population
  - -- over volumes comparable to next generation surveys
  - -- out to redshifts beyond 6
  - -- for all viable gaussian cosmologies
  - -- for a wide range of DE and galaxy formation models

- Study the interplay between galaxy formation physics and "precision" estimates of cosmological parameters

- Enable rapid exploration of the full parameter space with accelerated MCMC or similar techniques

- Make the modelling capabilities publicly available through high-speed VO-type databases and web interfaces