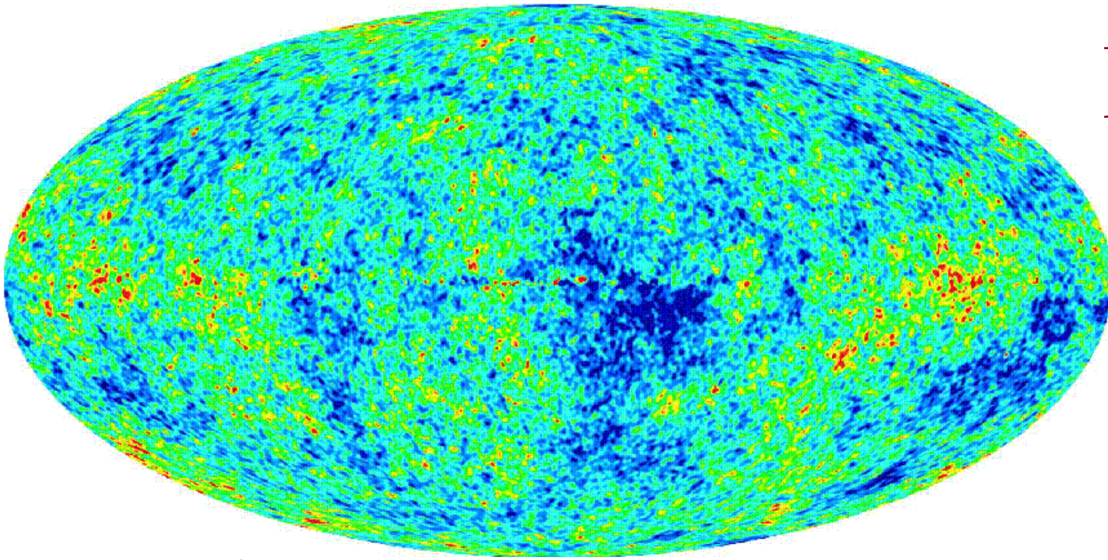
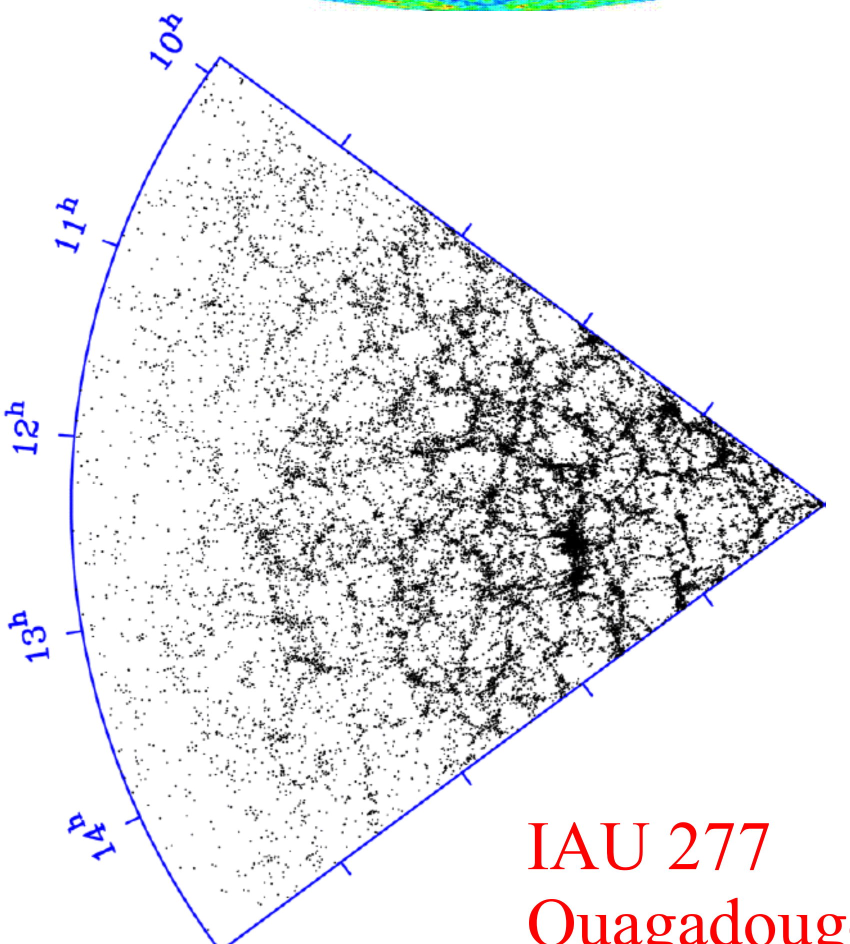
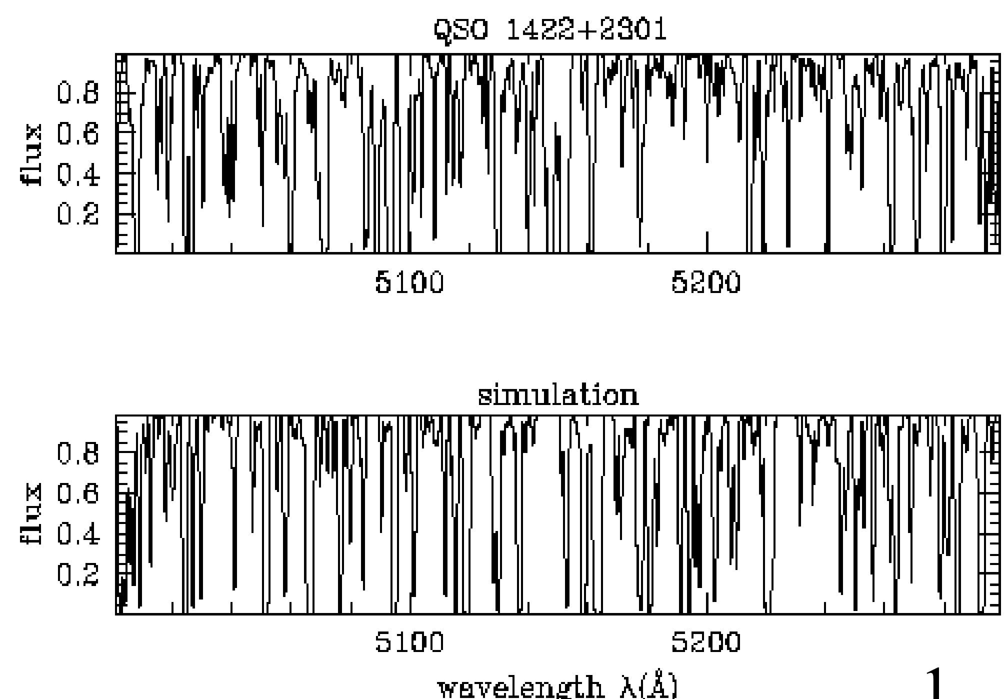
Modelling the galaxy population

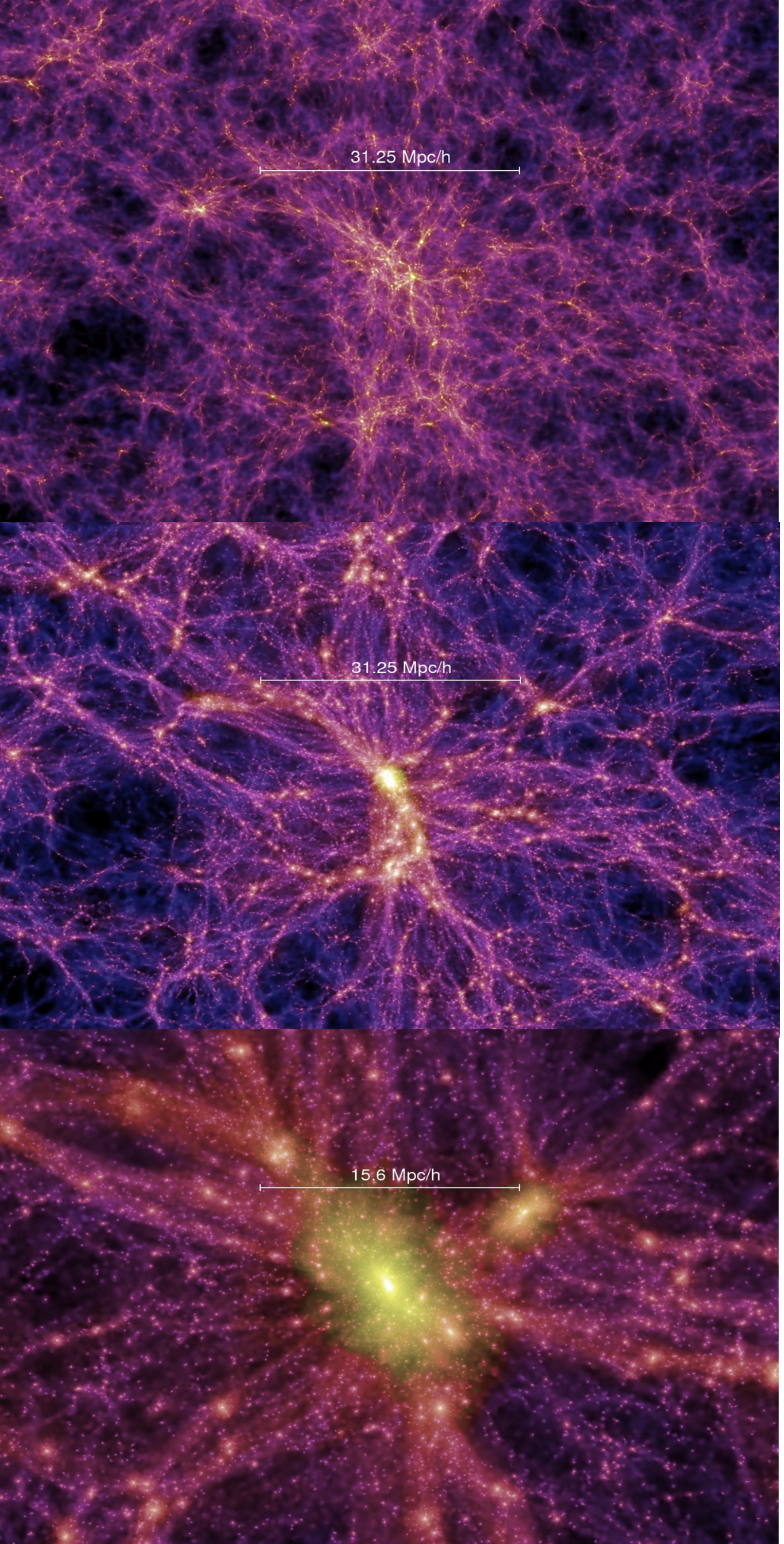


Simon White
Max Planck Institut für Astrophysik



IAU 277
Ouagadougou



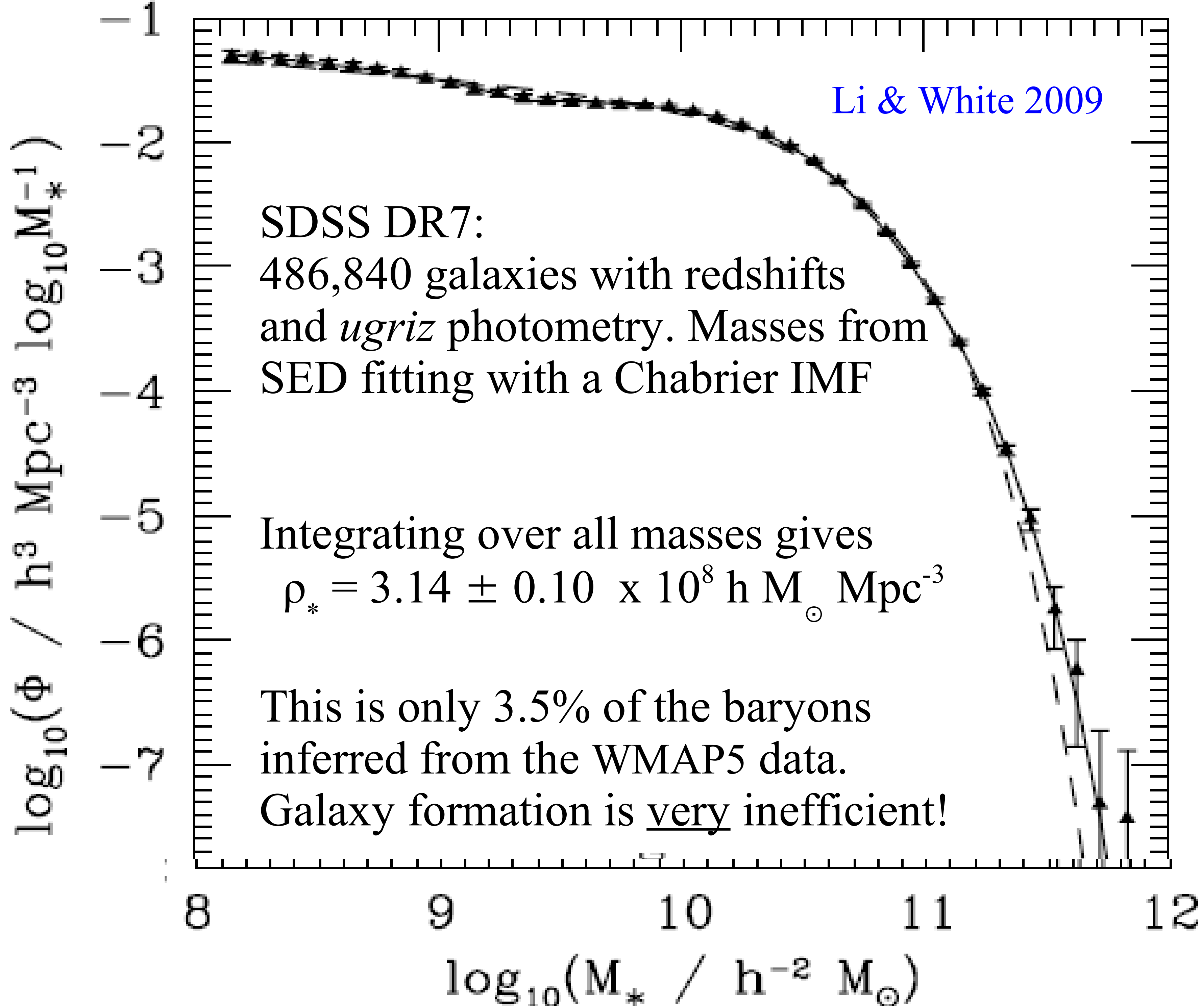


- The standard model reproduces
  - -- the linear initial conditions
  - -- IGM structure during galaxy formation
  - -- large-scale structure today
- Simulation of the standard model gives *precise* predictions for the
  - -- abundance
  - -- internal structure
  - -- assembly history
  - -- spatial/peculiar velocity distributions
  - -- merger rates

  of DM halos at all redshifts

How do galaxies form and evolve within this frame?

Can their formation and evolution be used to test the frame?

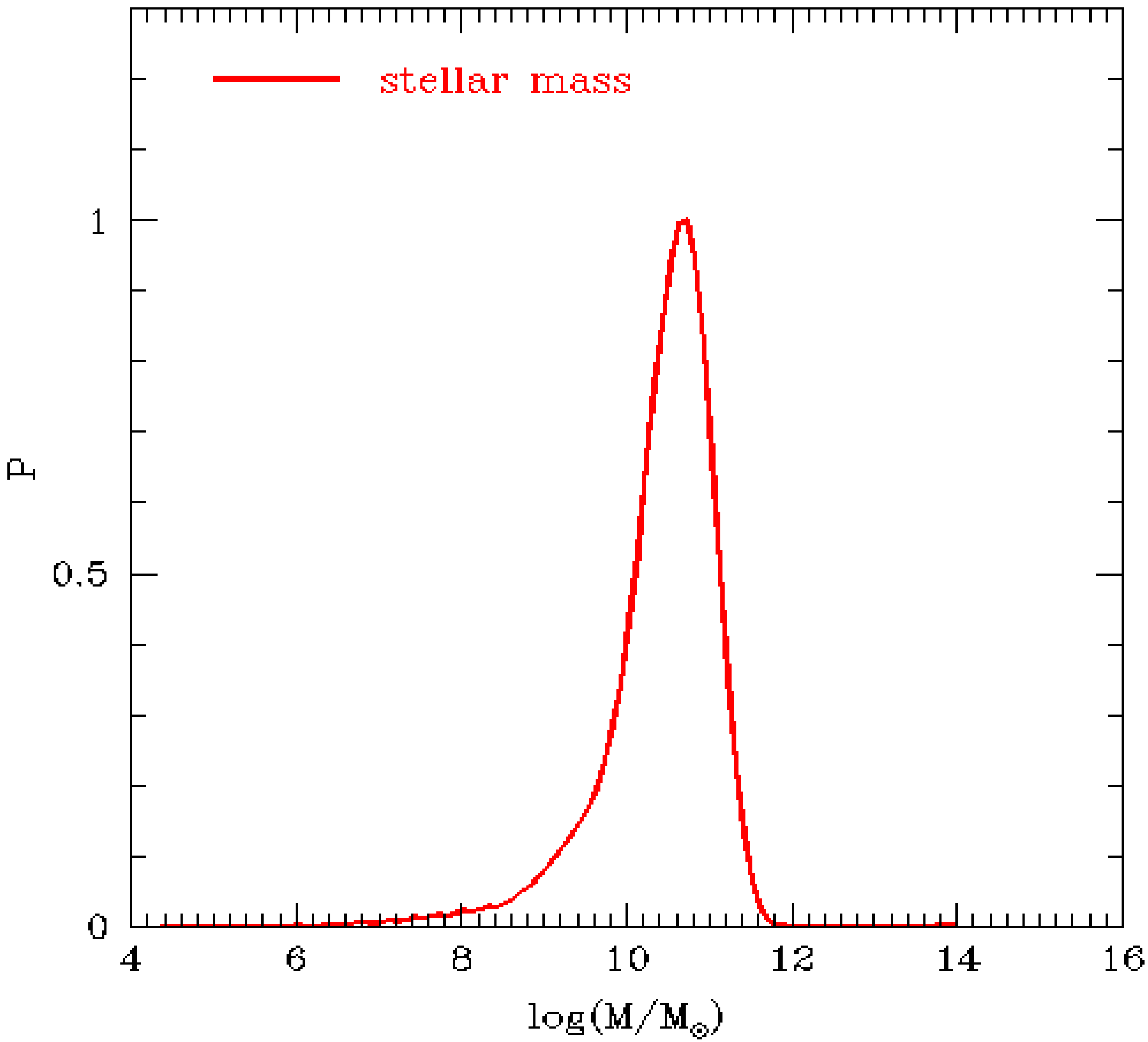


SDSS DR7:
486,840 galaxies with redshifts and *ugriz* photometry. Masses from SED fitting with a Chabrier IMF

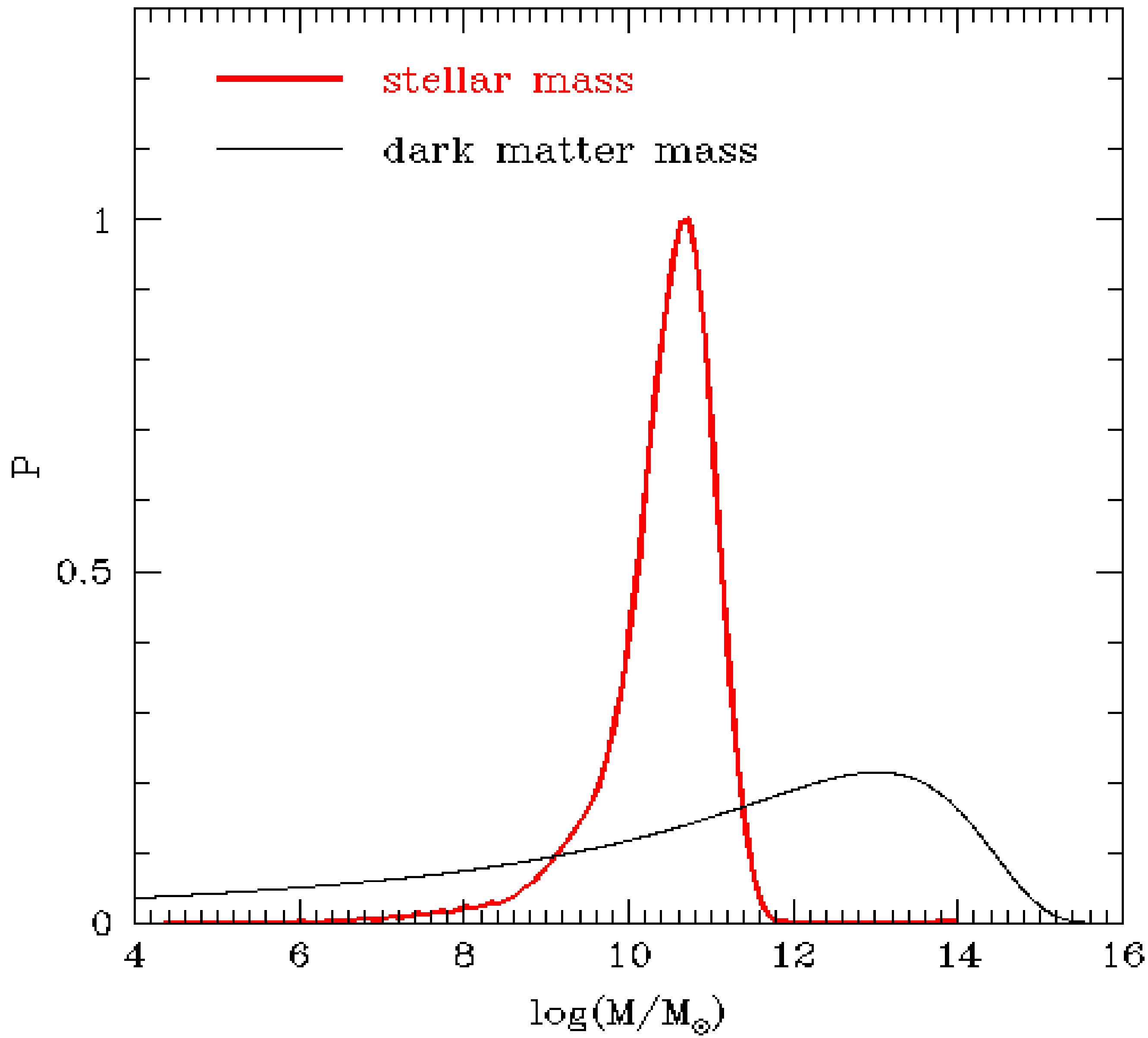
Integrating over all masses gives
$\rho_* = 3.14 \pm 0.10 \times 10^8 \, h \, M_\odot \, \mathrm{Mpc}^{-3}$

This is only 3.5% of the baryons inferred from the WMAP5 data.
Galaxy formation is <u>very</u> inefficient!

Most stars are in galaxies with similar stellar mass to the Milky Way

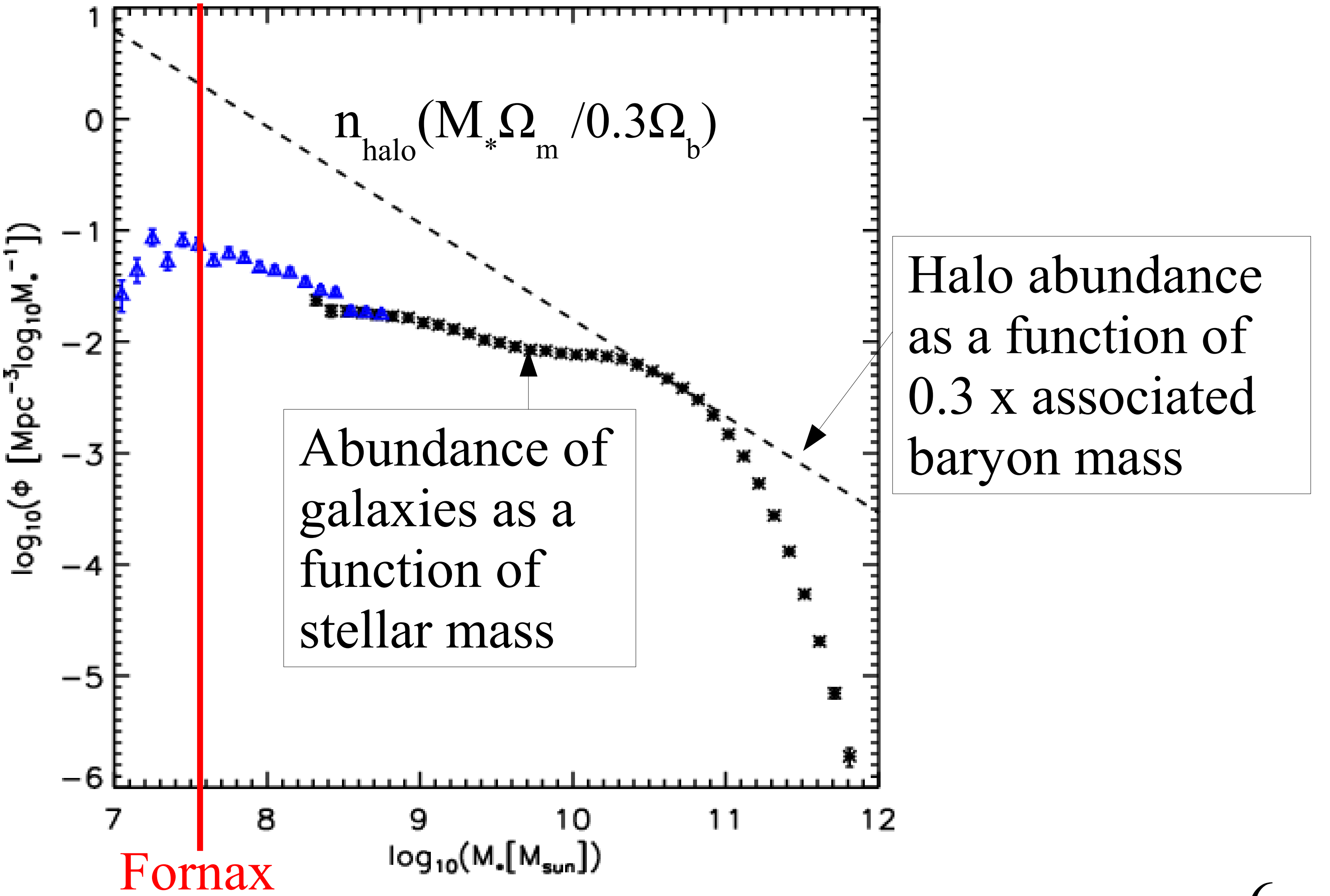


Most stars are in galaxies with similar stellar mass to the Milky Way
Dark matter (and baryons) are *much* more broadly distributed across halo mass in the WMAP7 cosmology



The problem with matching dwarfs in ΛCDM

A formation efficiency which matches abundance of “Milky Ways” overproduces the number of “Fornax's” by a factor of 30!



A counting argument to relate halo and galaxy masses

The SDSS/DR7 data give a precise measurement of the abundance of galaxies as a function of stellar mass threshold, $n(> M_*)$

High-resolution simulations allow all halos/subhalos massive enough to host z=0 galaxies to be identified

Define $M_{h,max}$ as the maximum mass *ever* attained by a halo/subhalo

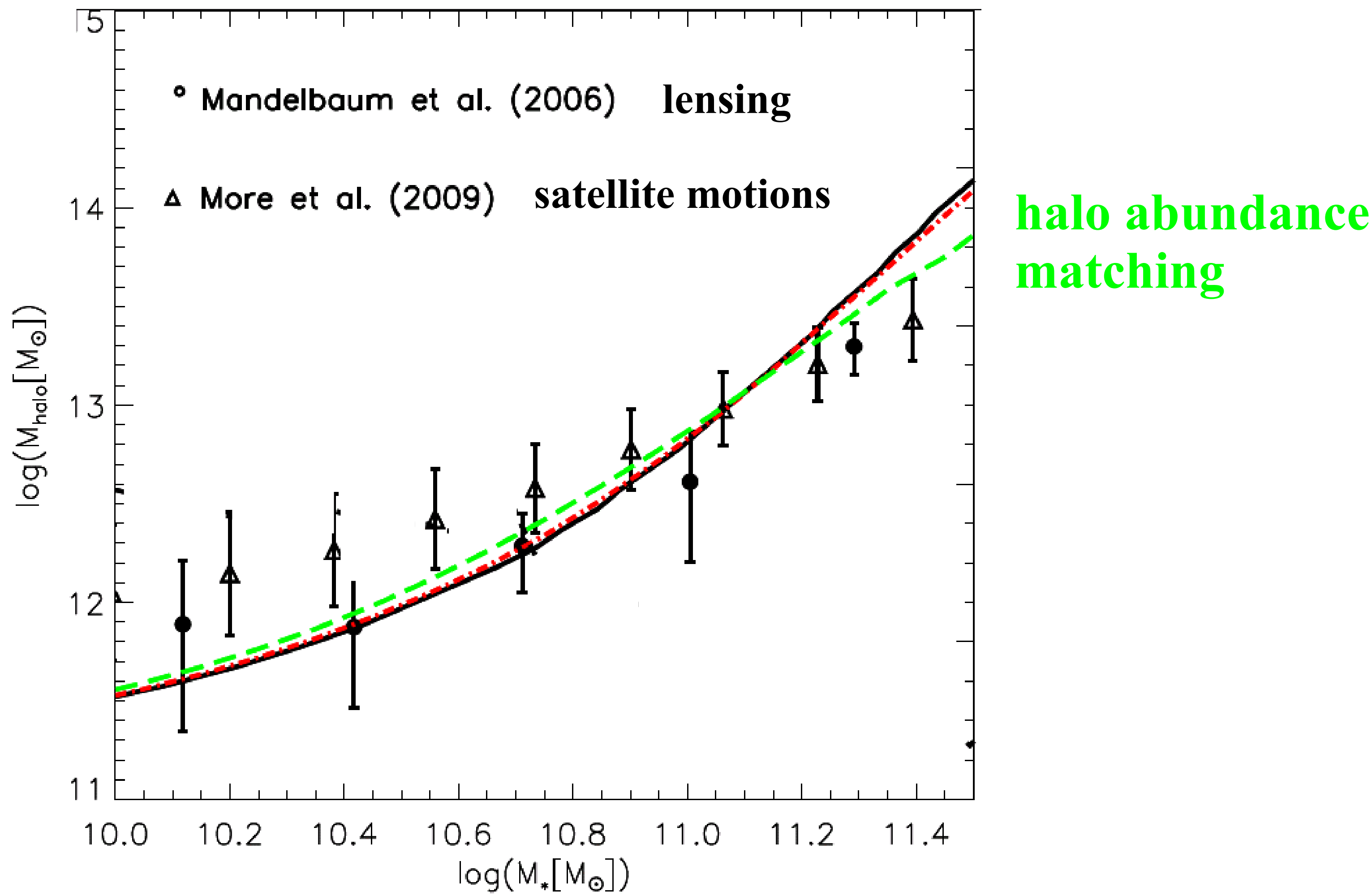
The simulations then give the halo/subhalo abundance, $n(> M_{h,max})$

Ansatz: Assume the stellar mass of a galaxy to be a monotonically increasing function of the maximum mass ever attained by its halo

We can then derive $M_*(M_{h,max})$ by setting $n(> M_*) = n(> M_{h,max})$

Consistency of ΛCDM for galaxy halos

Guo et al 2010



Relations between dark halo mass and galaxy stellar mass inferred

(i) from the motions of satellite galaxies

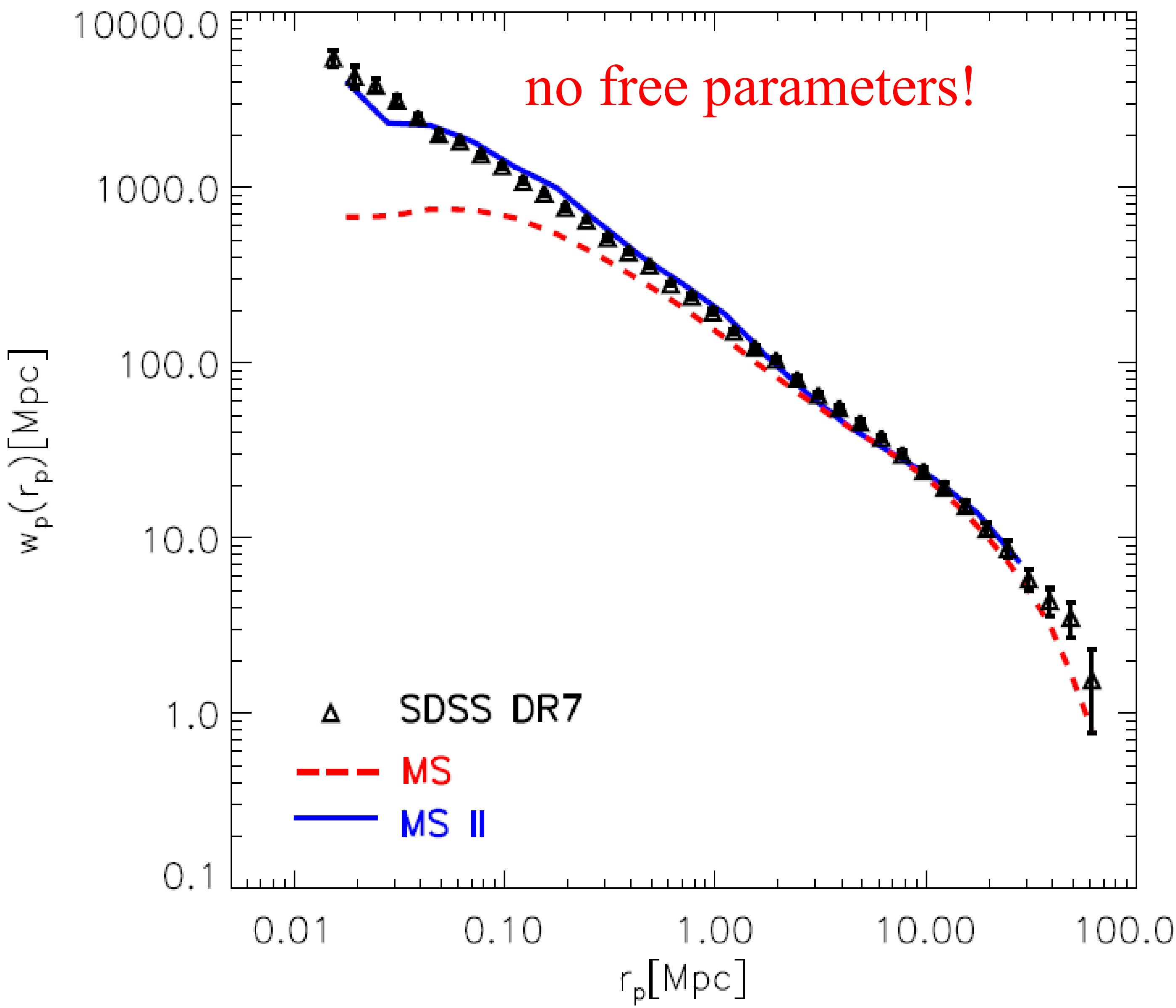
(ii) from gravitational lensing

(iii) from matching predicted halo count to observed galaxy count

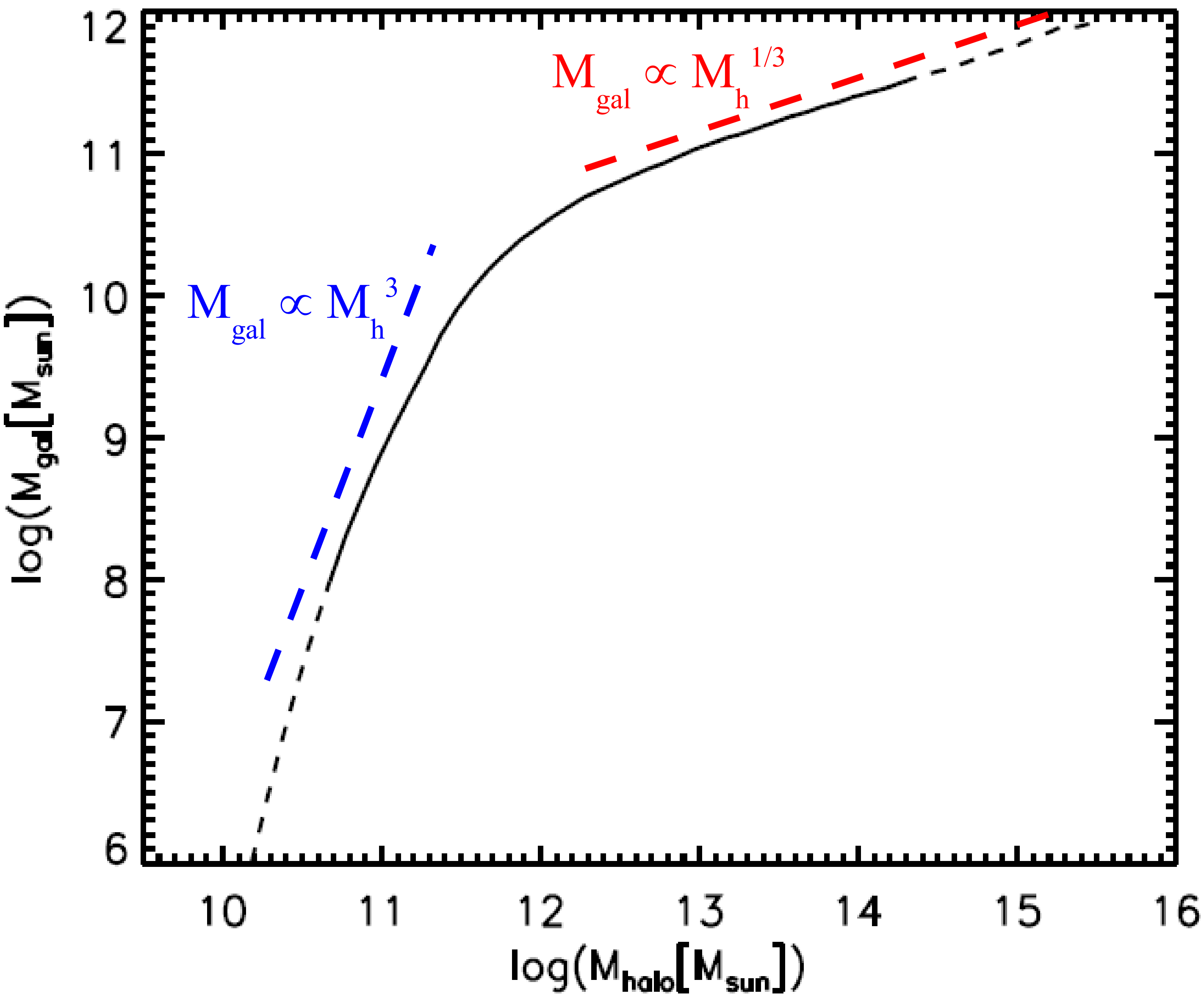
all agree!

Consistency of ΛCDM for galaxy clustering

Guo et al 2010

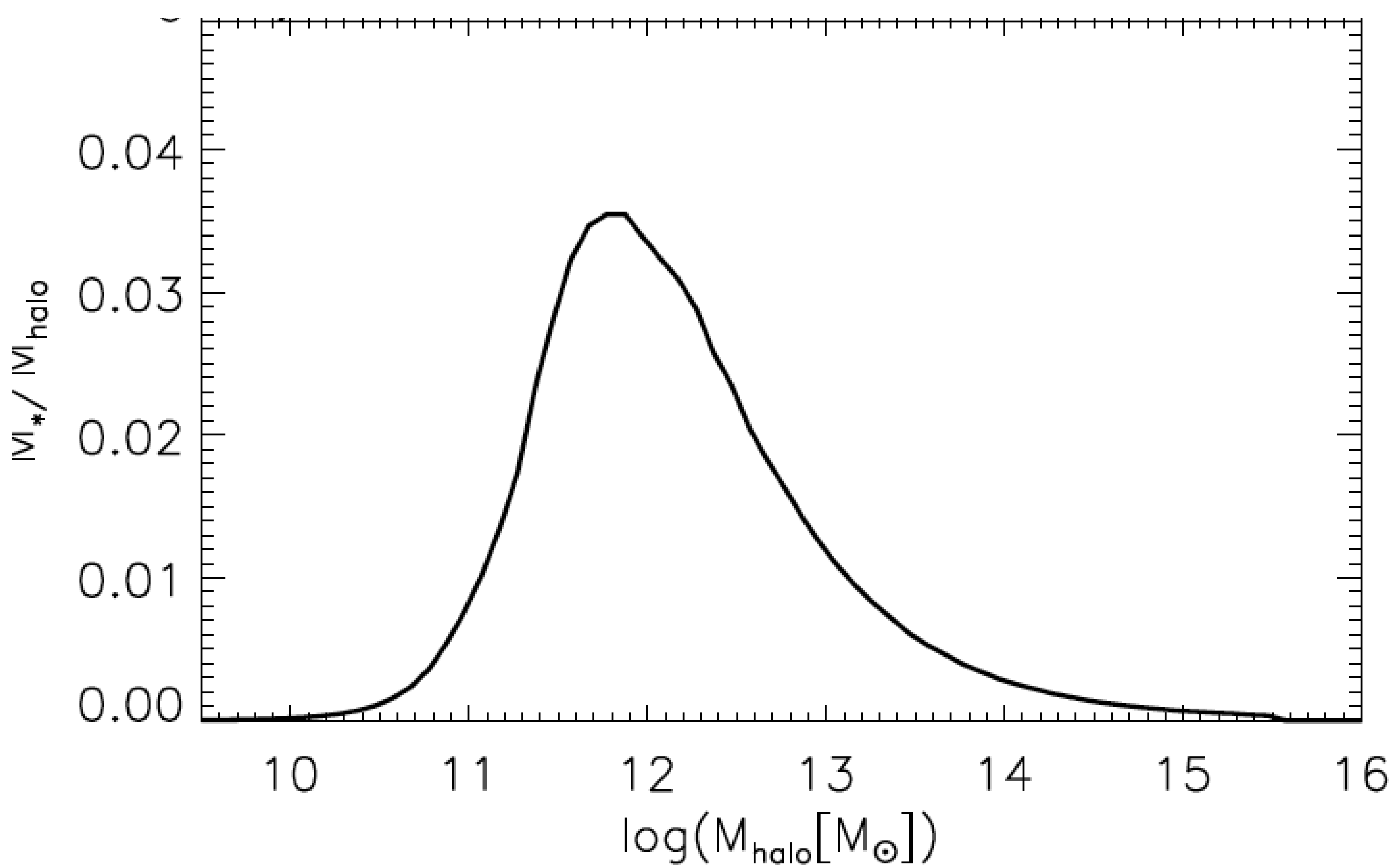


Populating halos/sub-halos by assigning galaxies as inferred by abundance matching to the stellar mass function gives an excellent fit to the observed clustering of stellar mass



- The stellar mass of the central galaxy increases rapidly with halo mass at small halo mass, but slowly at large halo mass
- The characteristic halo mass at the bend is $5 \times 10^{11}\ M_{\odot}$

The efficiency of galaxy formation is low!

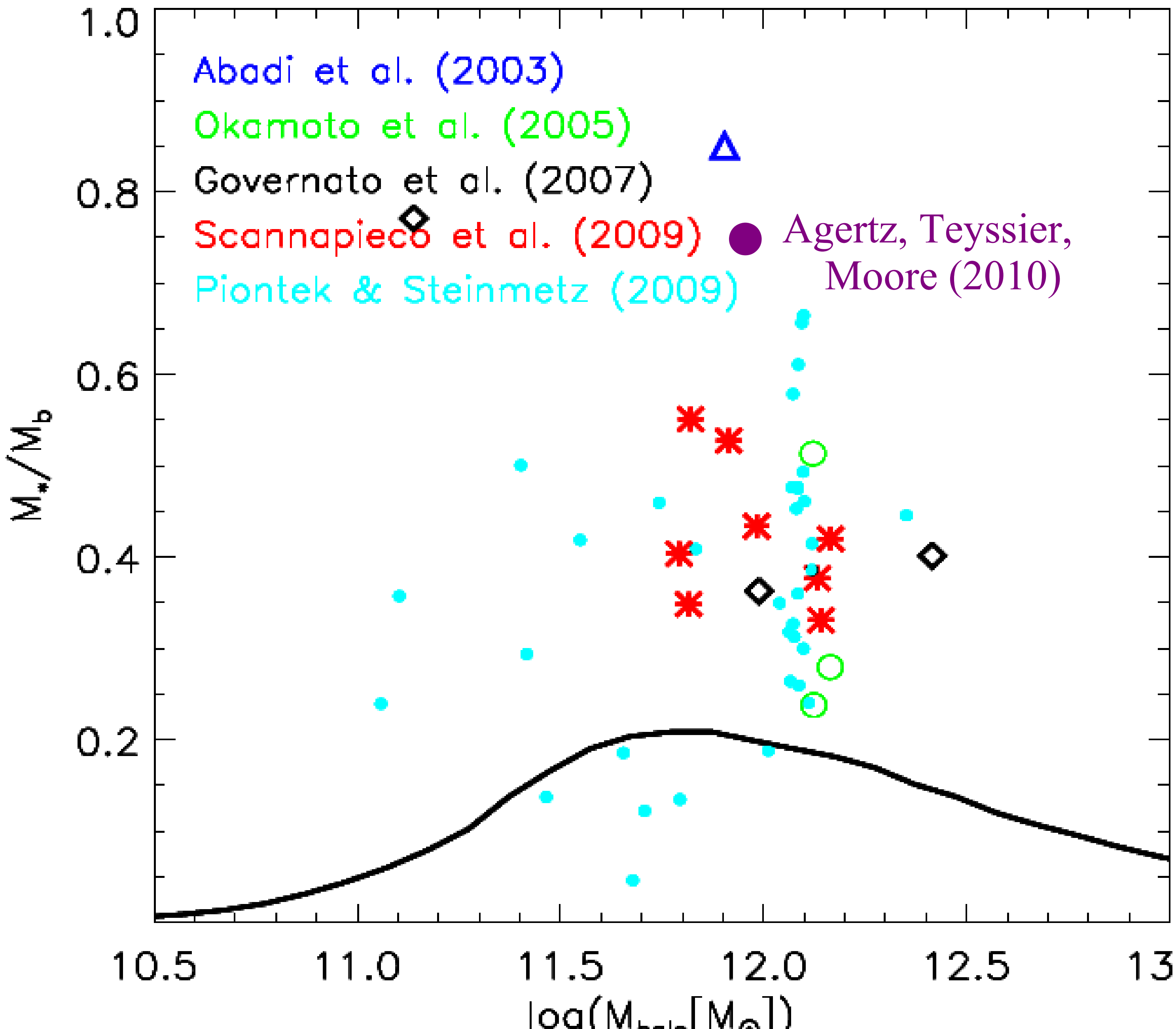


The ratio of central galaxy stellar mass to maximum past halo mass *maximises* at just 3.5% at halo masses of $\sim 10^{12} M_\odot$

This is *much* less than the global baryon fraction ~ 17%

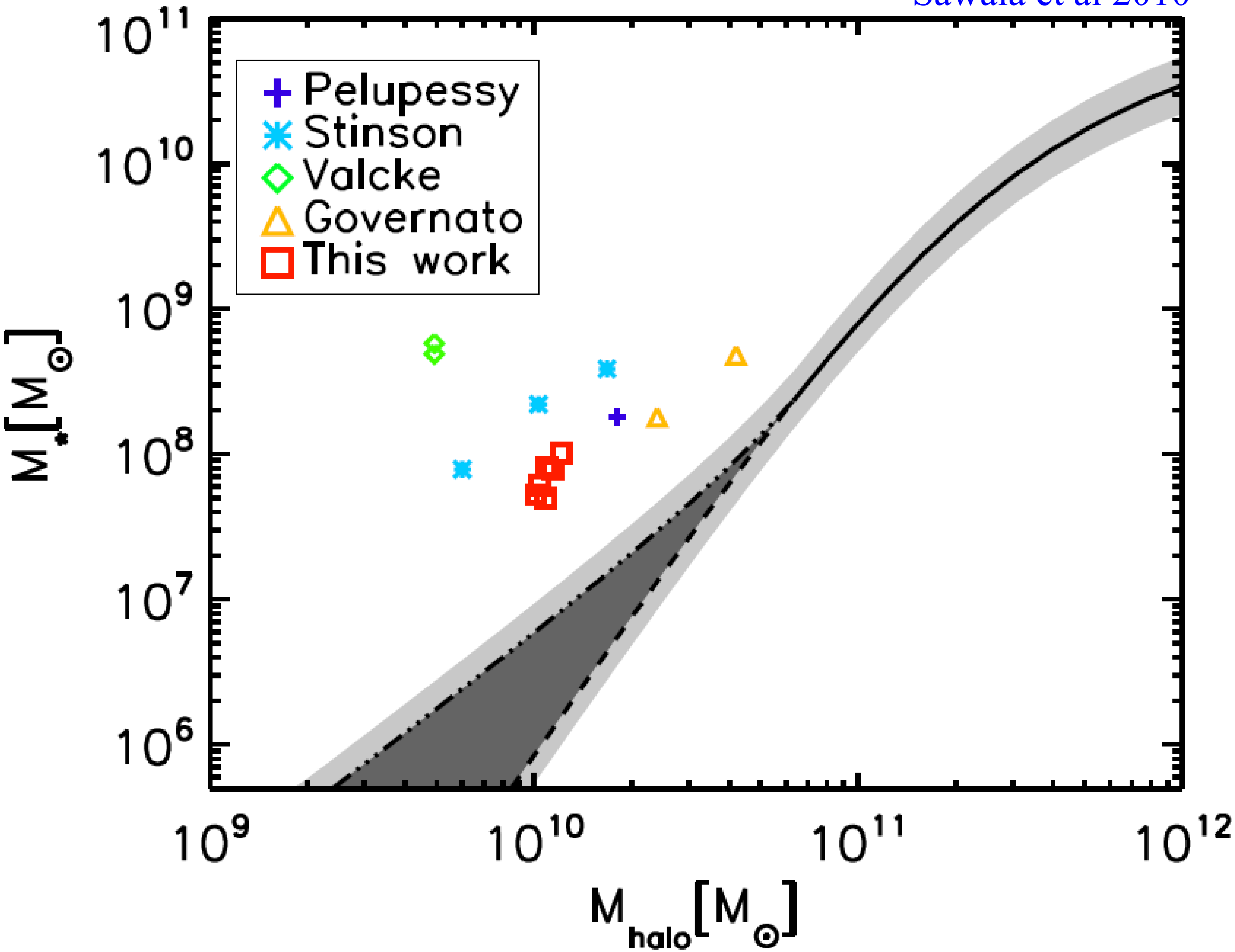
“Successful” simulations fail to match this...

Guo et al 2010



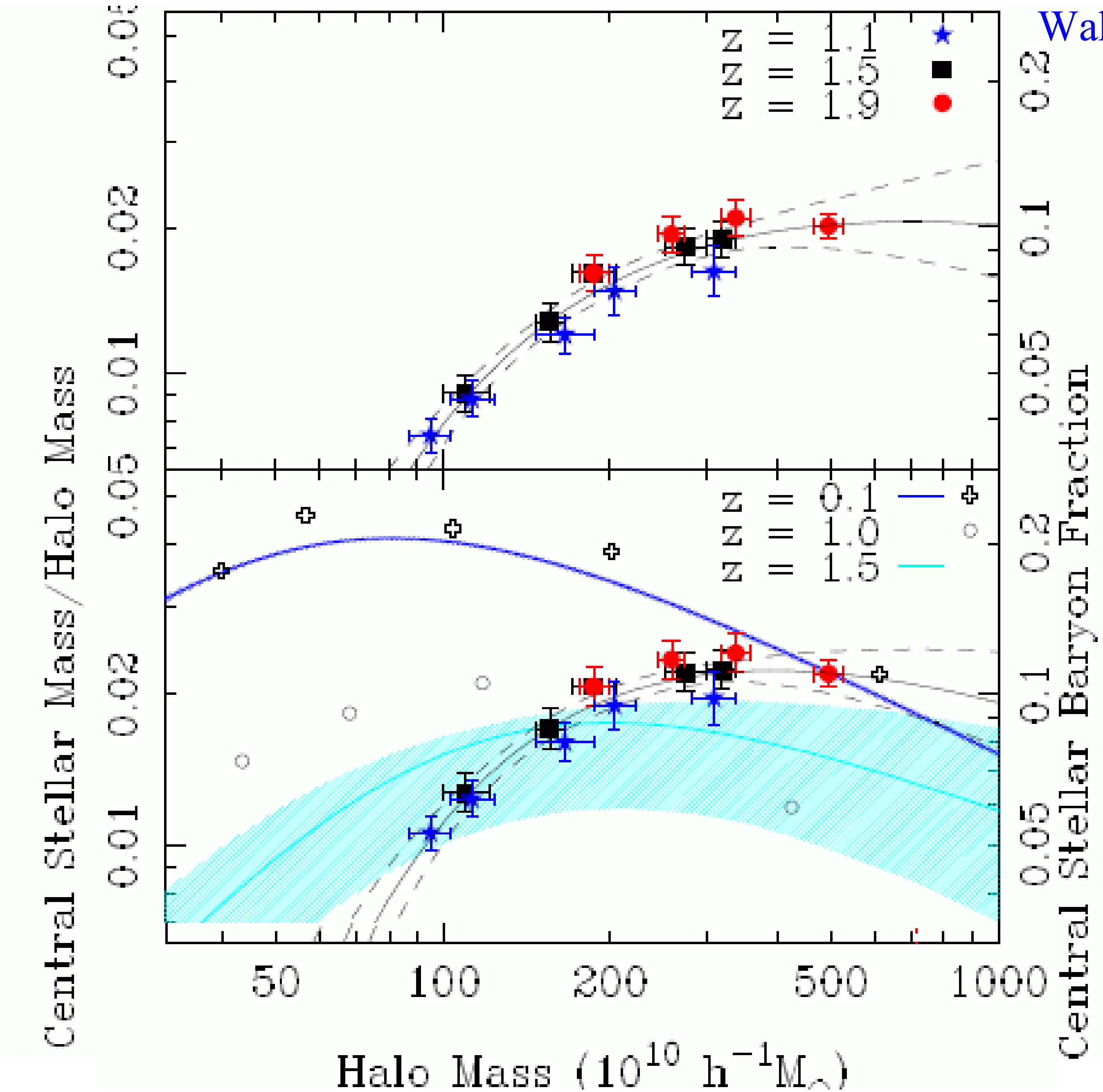
...and do worse for dwarfs than for giants

Sawala et al 2010



Formation efficiencies are lower at high z!

Wake et al 2010



How to proceed with model-building
--the semianalytic program--

- Begin with counts!
  -- luminosity/mass functions, central/satellite abundances

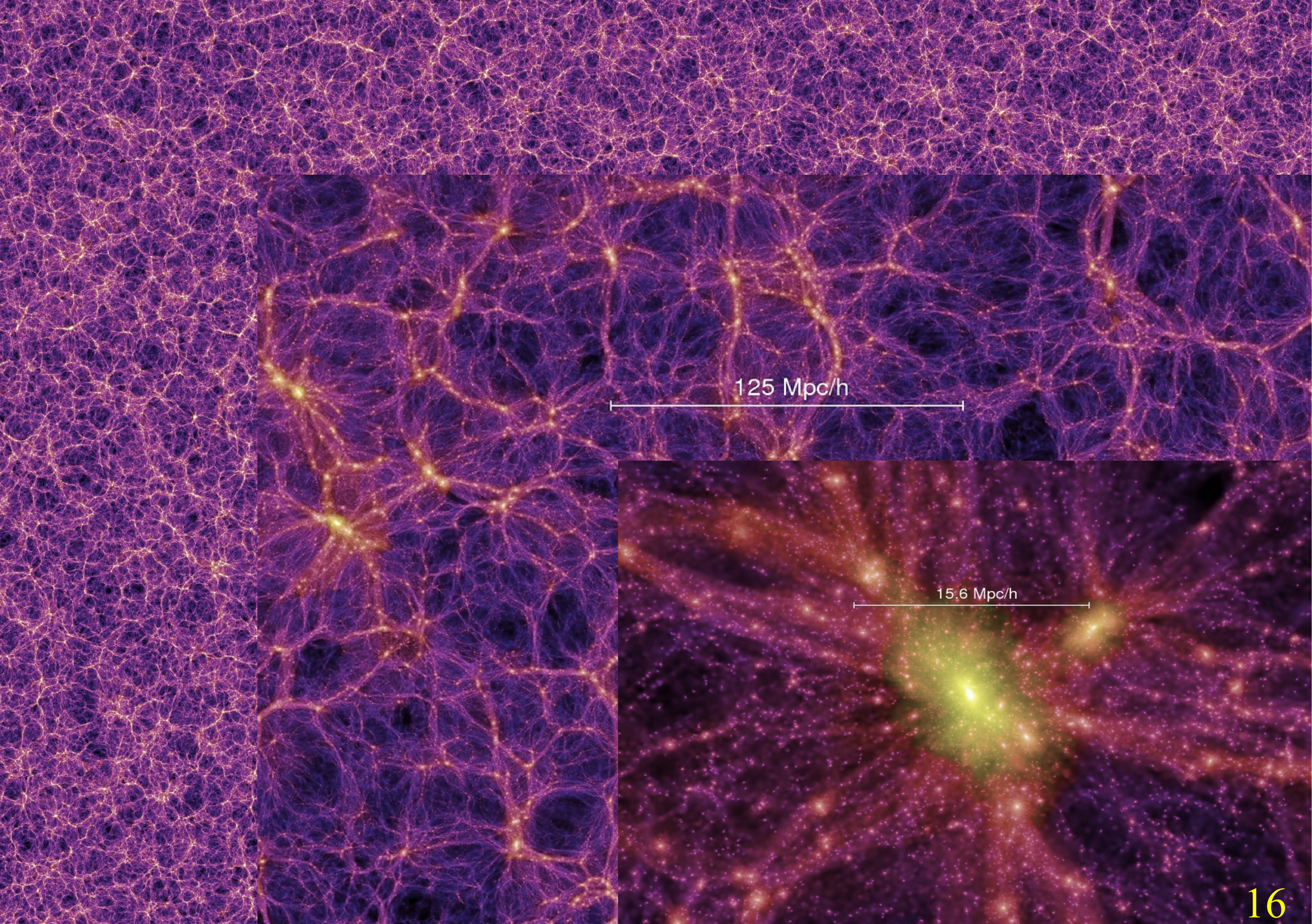
- Use clustering measurements!
  -- correlations as a function of stellar mass and colour

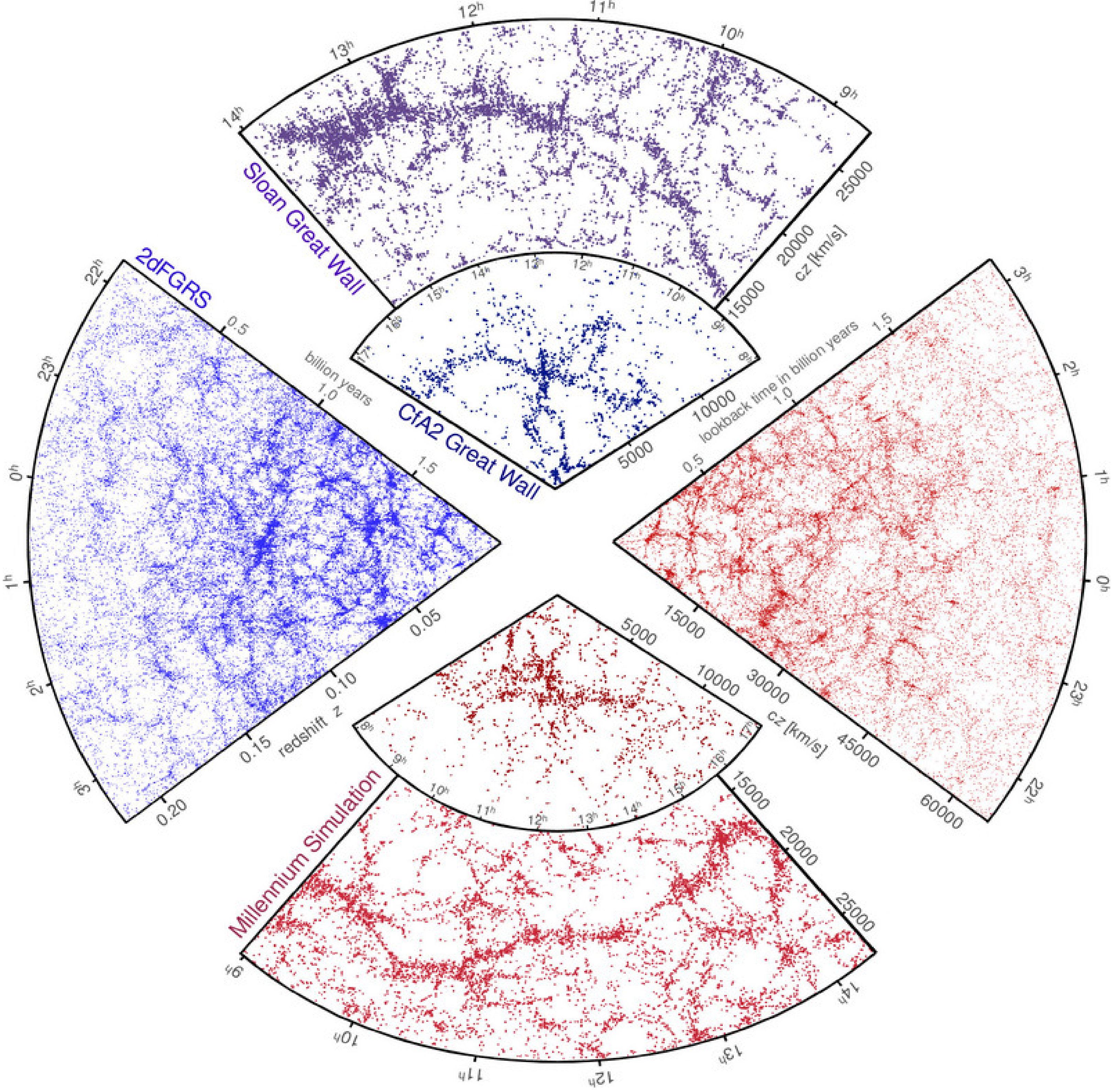
- Use assembly history information from simulations!
  -- base on high-resolution DM simulations
  -- use simulated assembly history/substructure data directly

- Use physically plausible recipes for relevant processes
  -- tie recipes to detailed simulations when possible
  -- otherwise use observational phenomenology

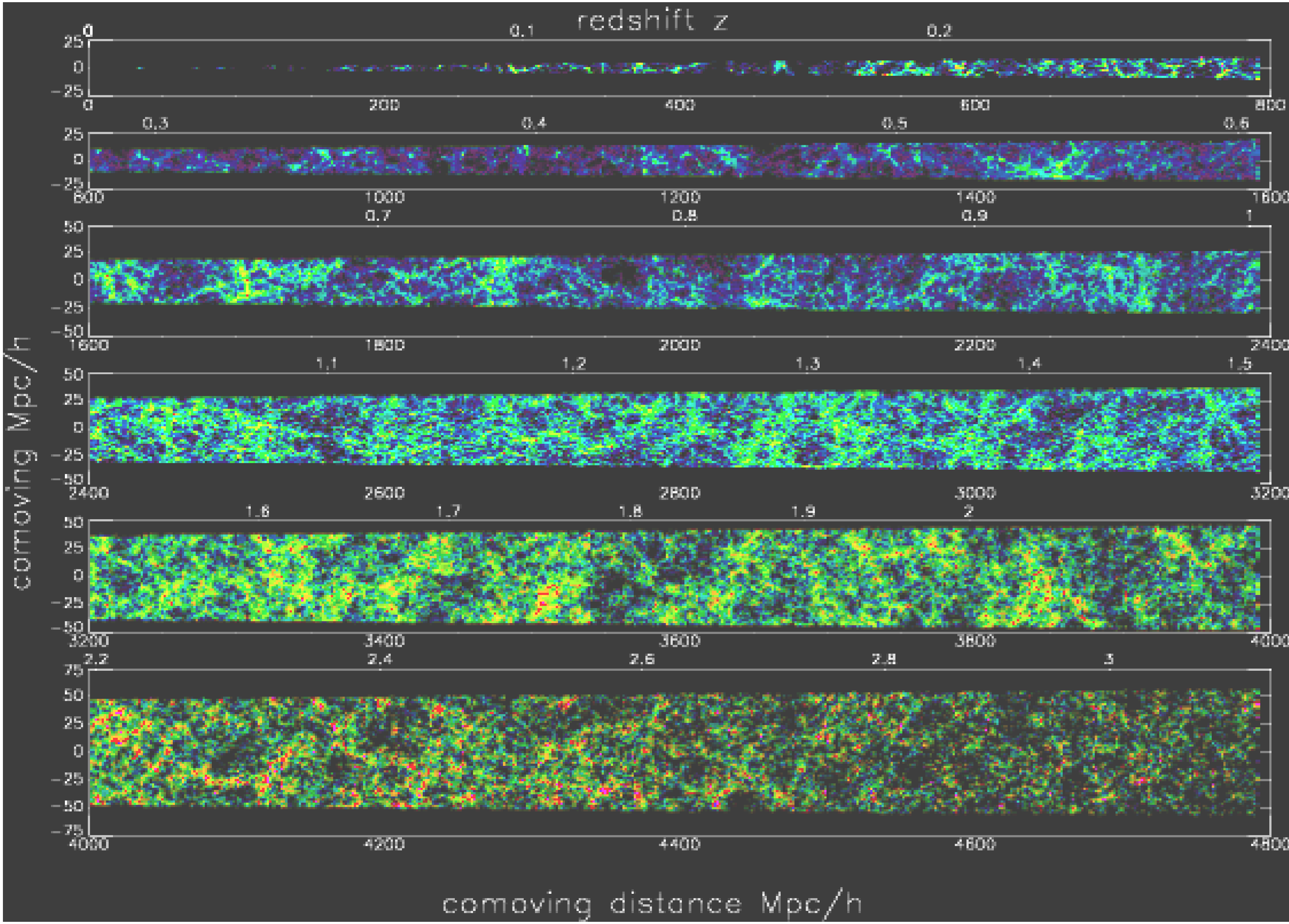
- Separate measurement from hypothesis when model-testing

The Millennium Simulation (2005)





Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
billion years
lookback time in billion years
redshift z
cz [km/s]

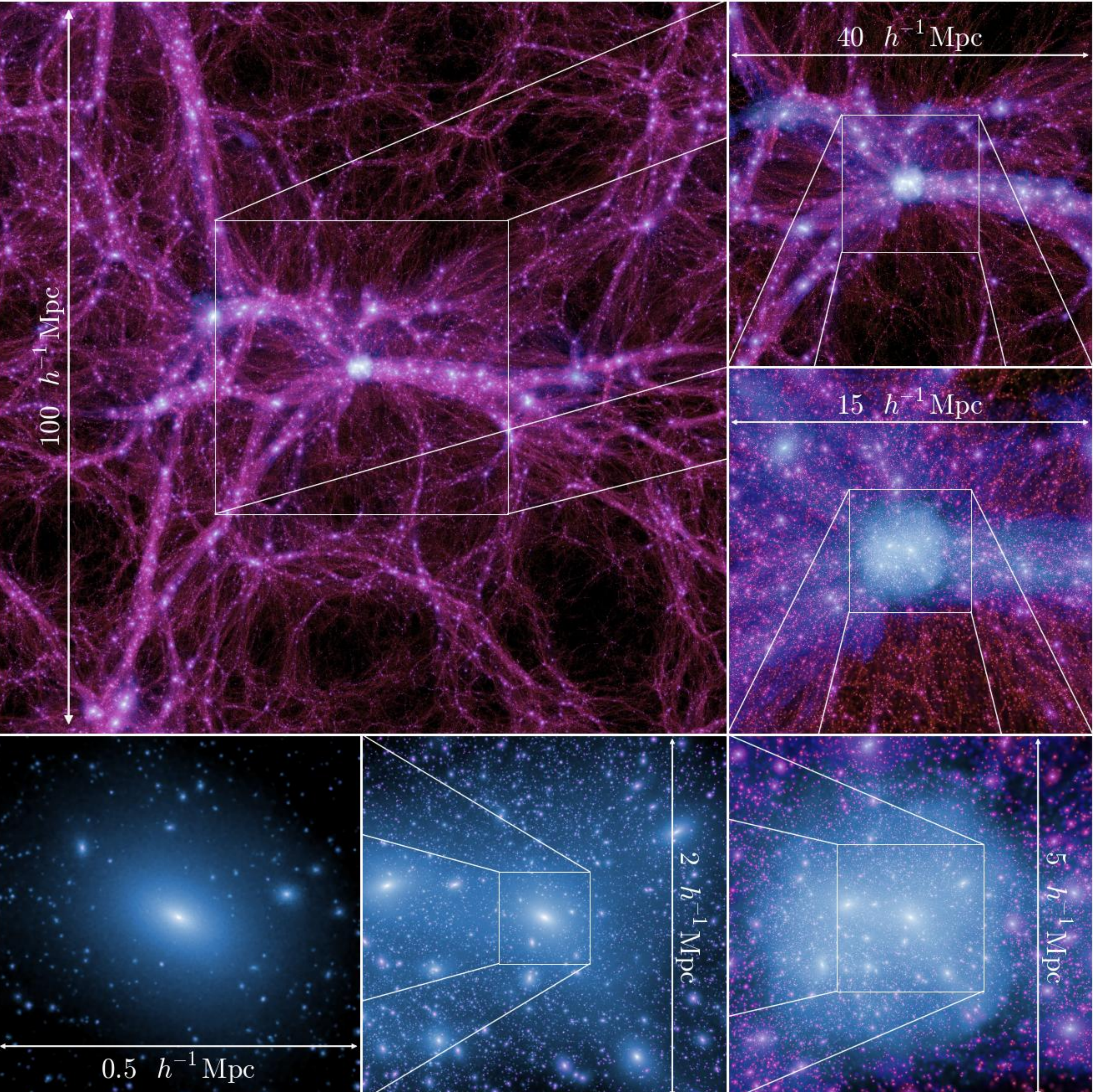


350 papers making direct use of data from the MS (8-12-2010)
Most by authors unassociated with the consortium
Most based on the galaxy catalogues, particularly mock surveys

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)



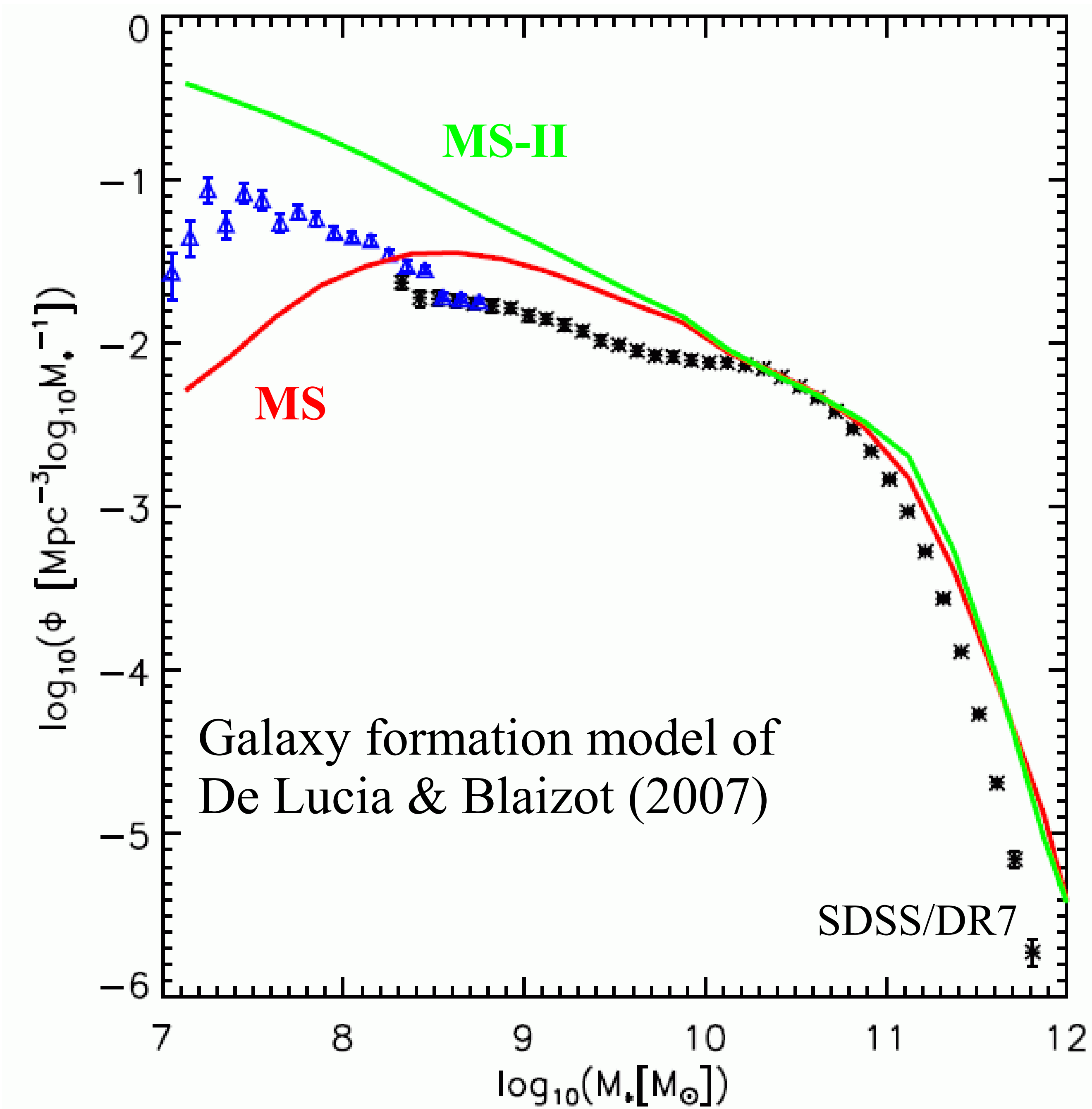
Same cosmology

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

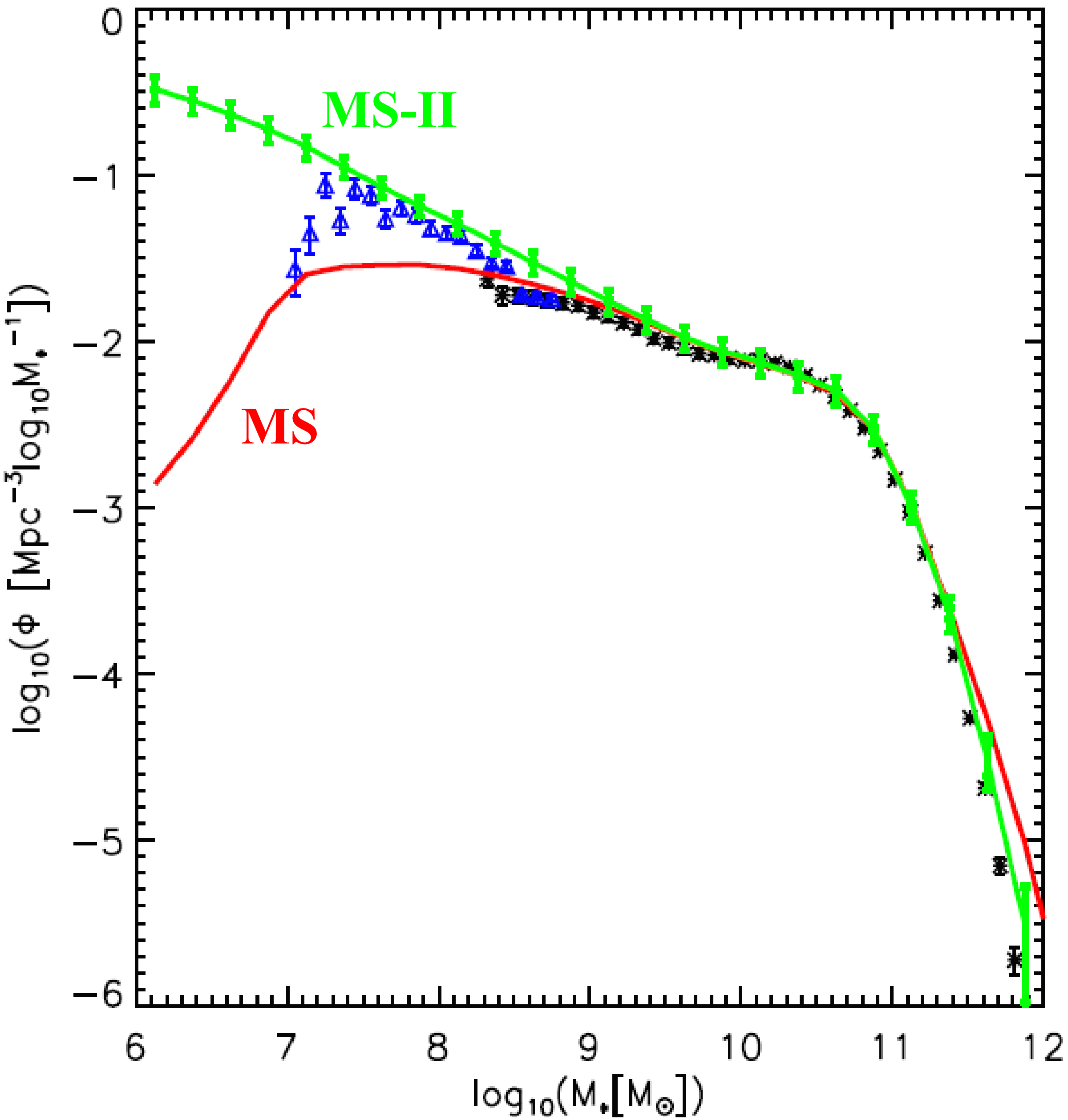
New galaxy formation models based on MS+MS-II

Qi Guo et al 2010b

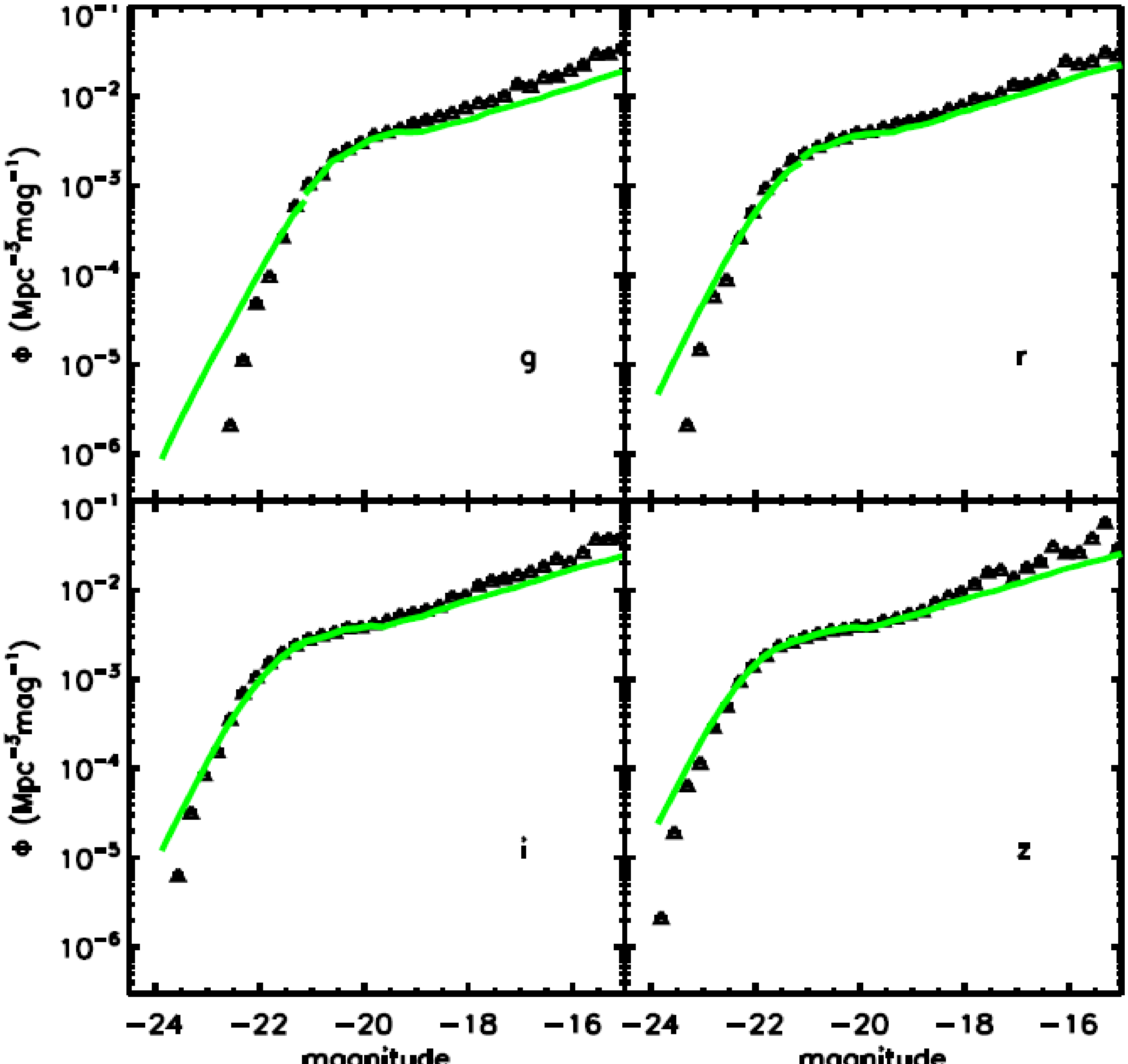
- Implement modelling simultaneously on MS and MS-II
- Test convergence of galaxy properties near resolution limit of MS
- Extend to properties of dwarf galaxies
- Improve/extend treatments of “troublesome” astrophysics
- Adjust parameters to fit new, more precise data
- Test against clustering and redshift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

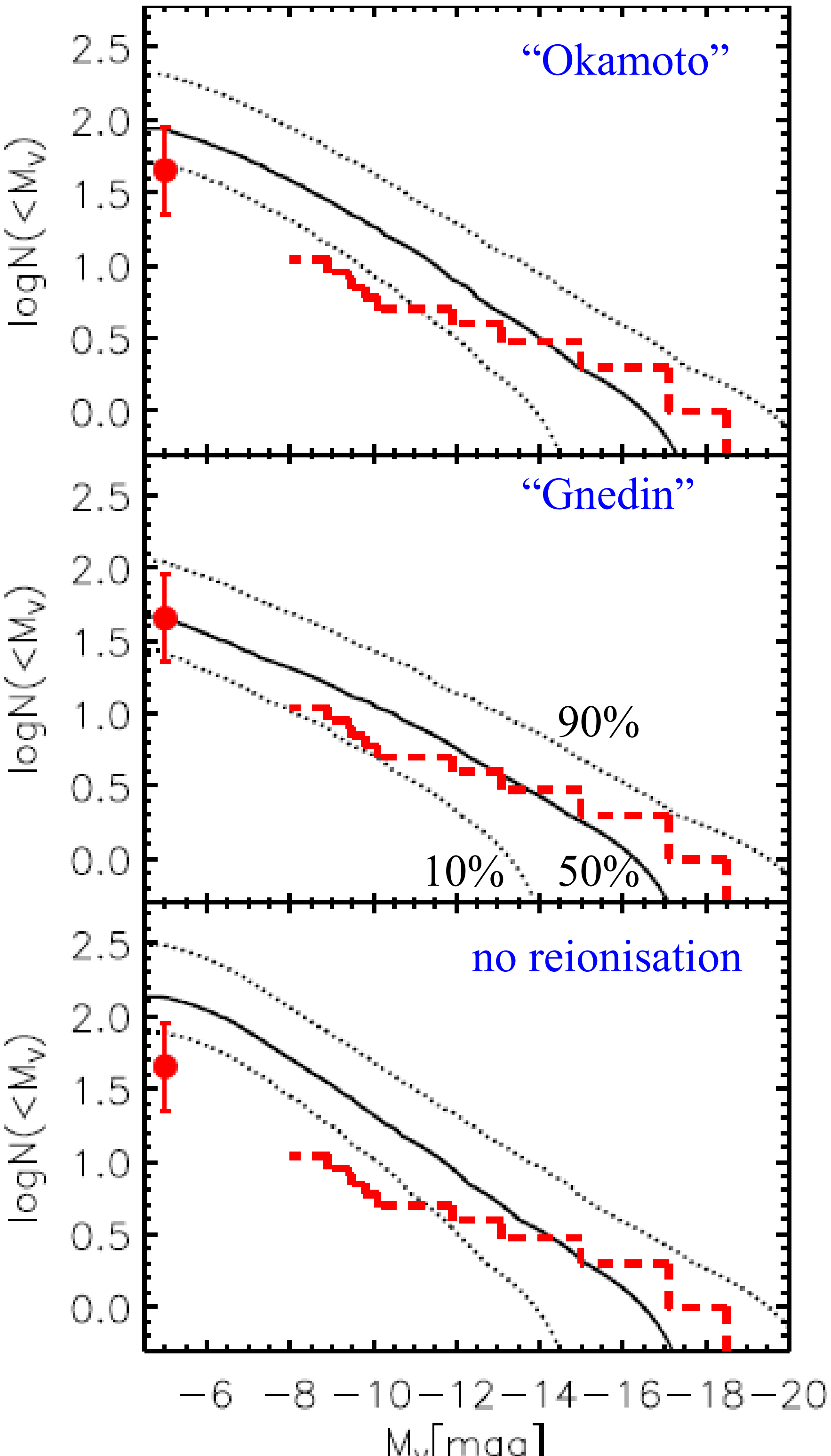
Things that work well

The stellar mass function of galaxies



Luminosity functions of galaxies

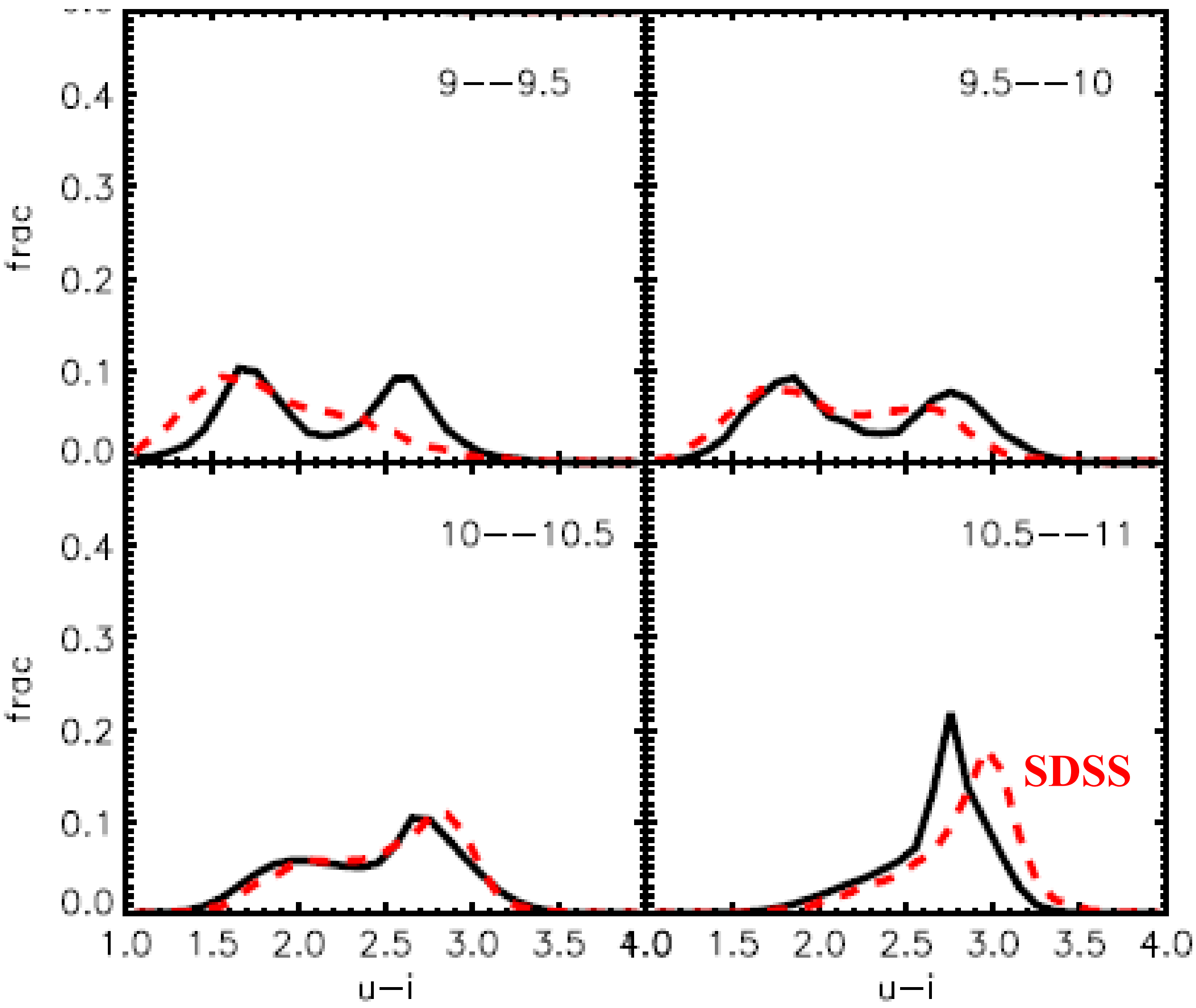




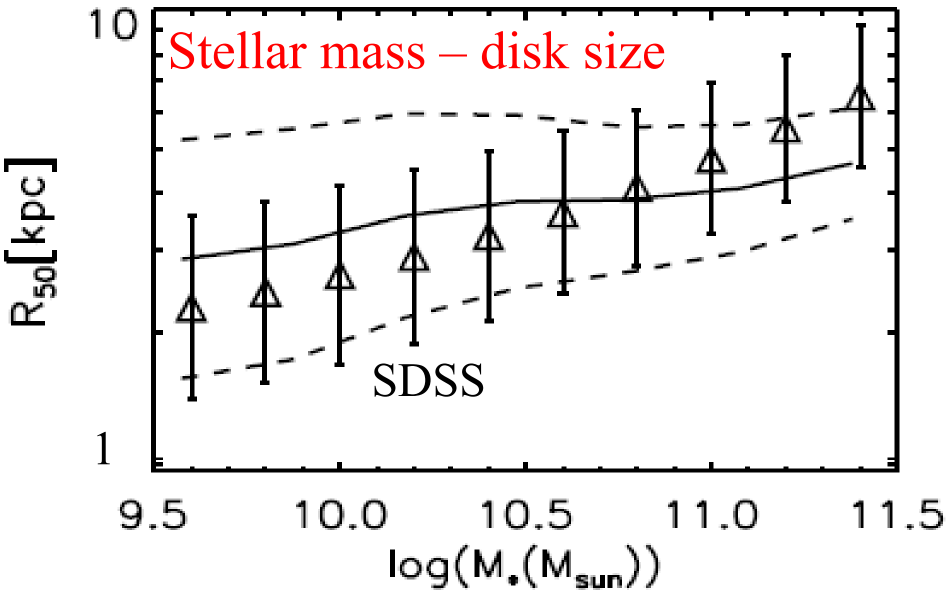
Luminosity function of Milky Way satellites

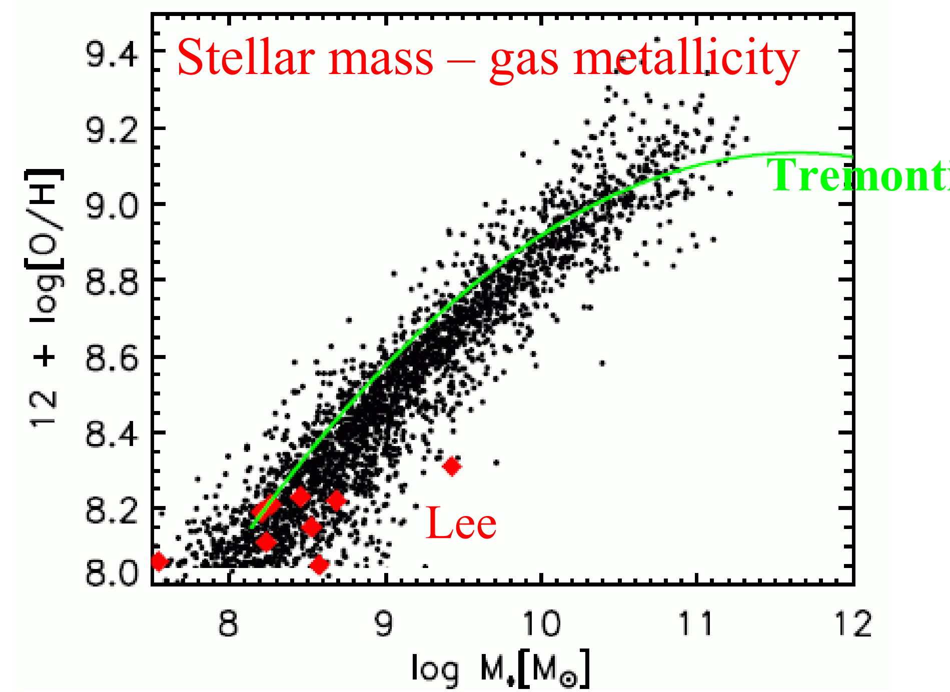
Luminosity functions of satellites around 1500 "Milky Ways" i.e. isolated disk galaxies with log $M_* = 10.8$

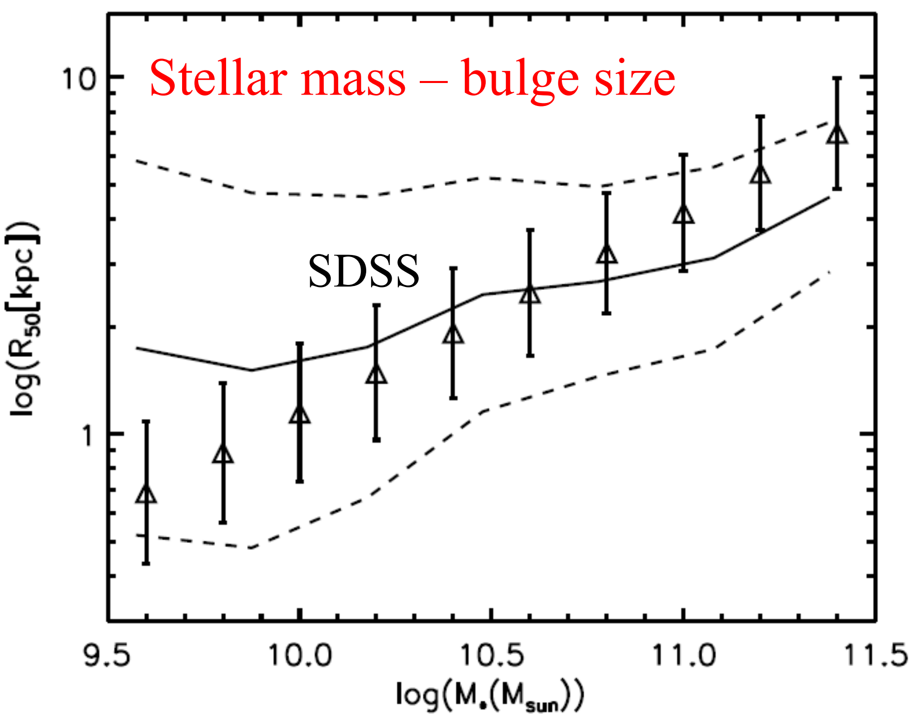
Galaxy colour distributions

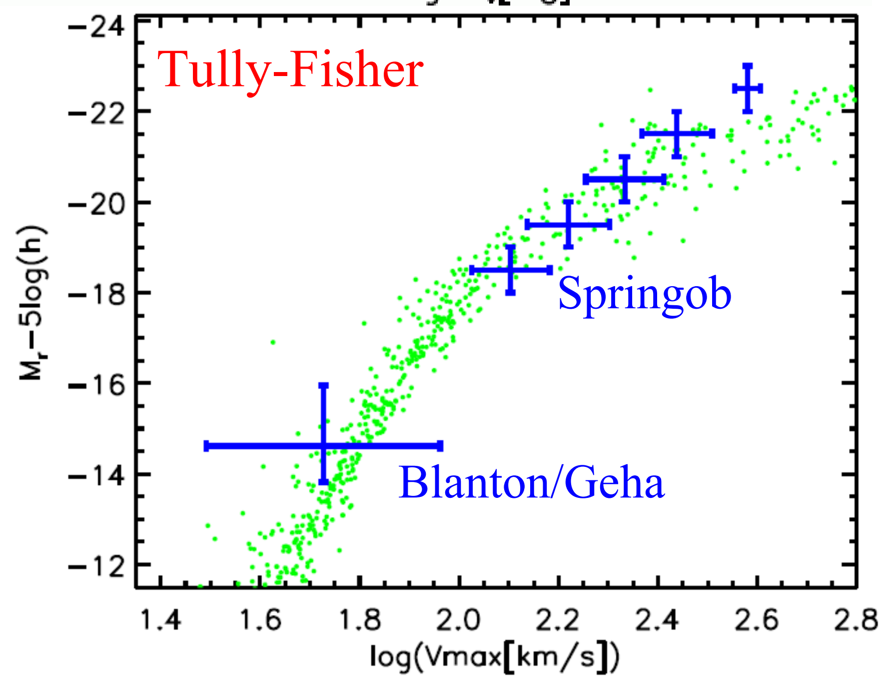


Scaling relations

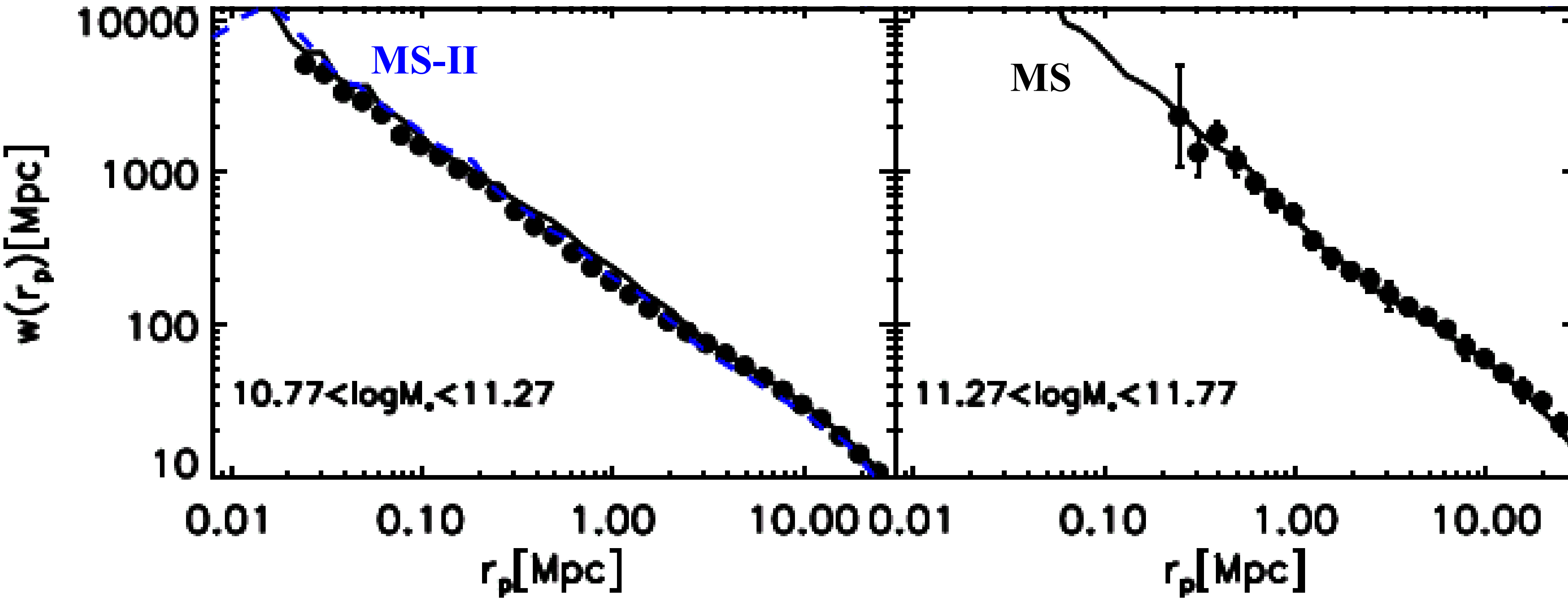




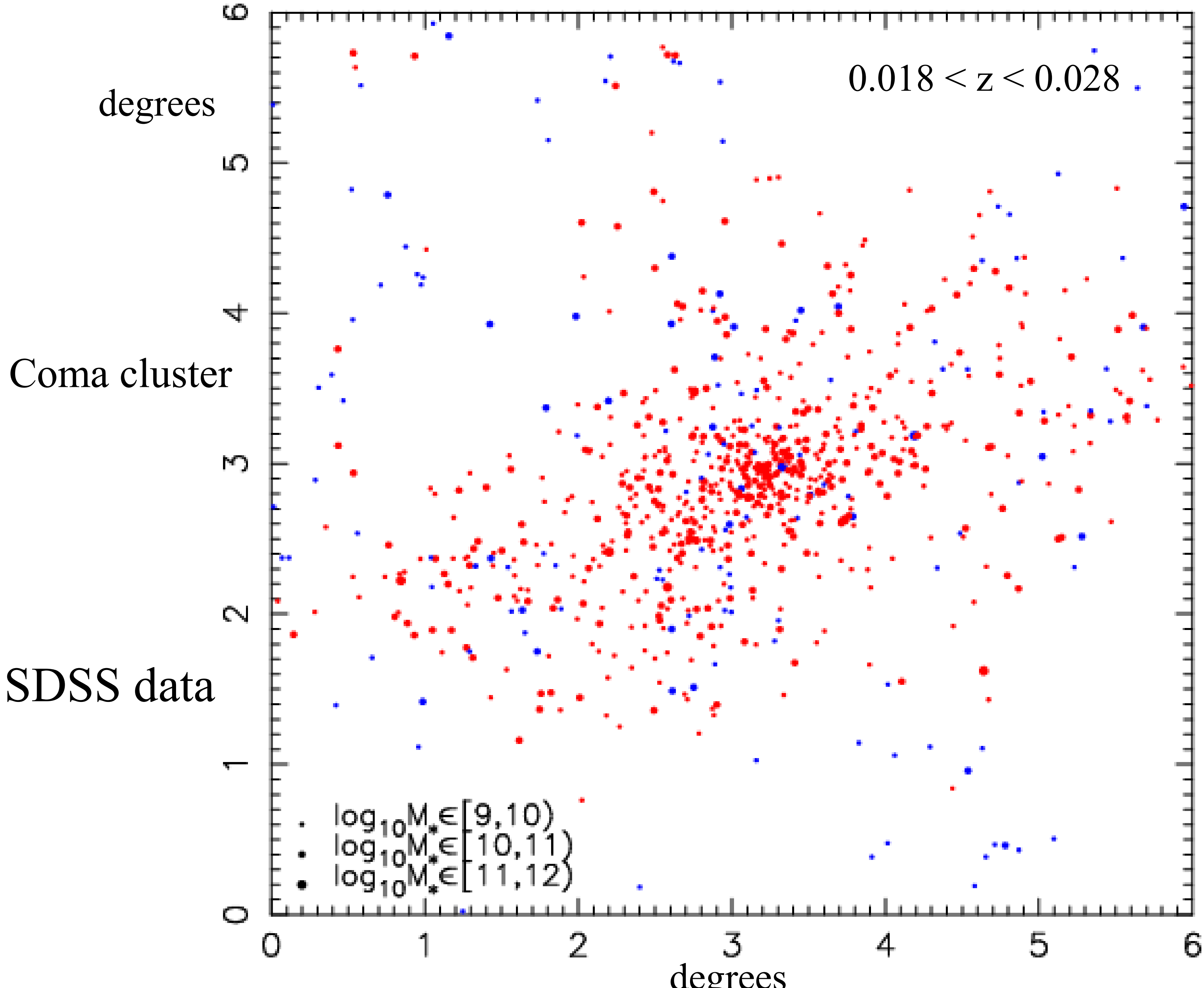




Clustering of massive galaxies



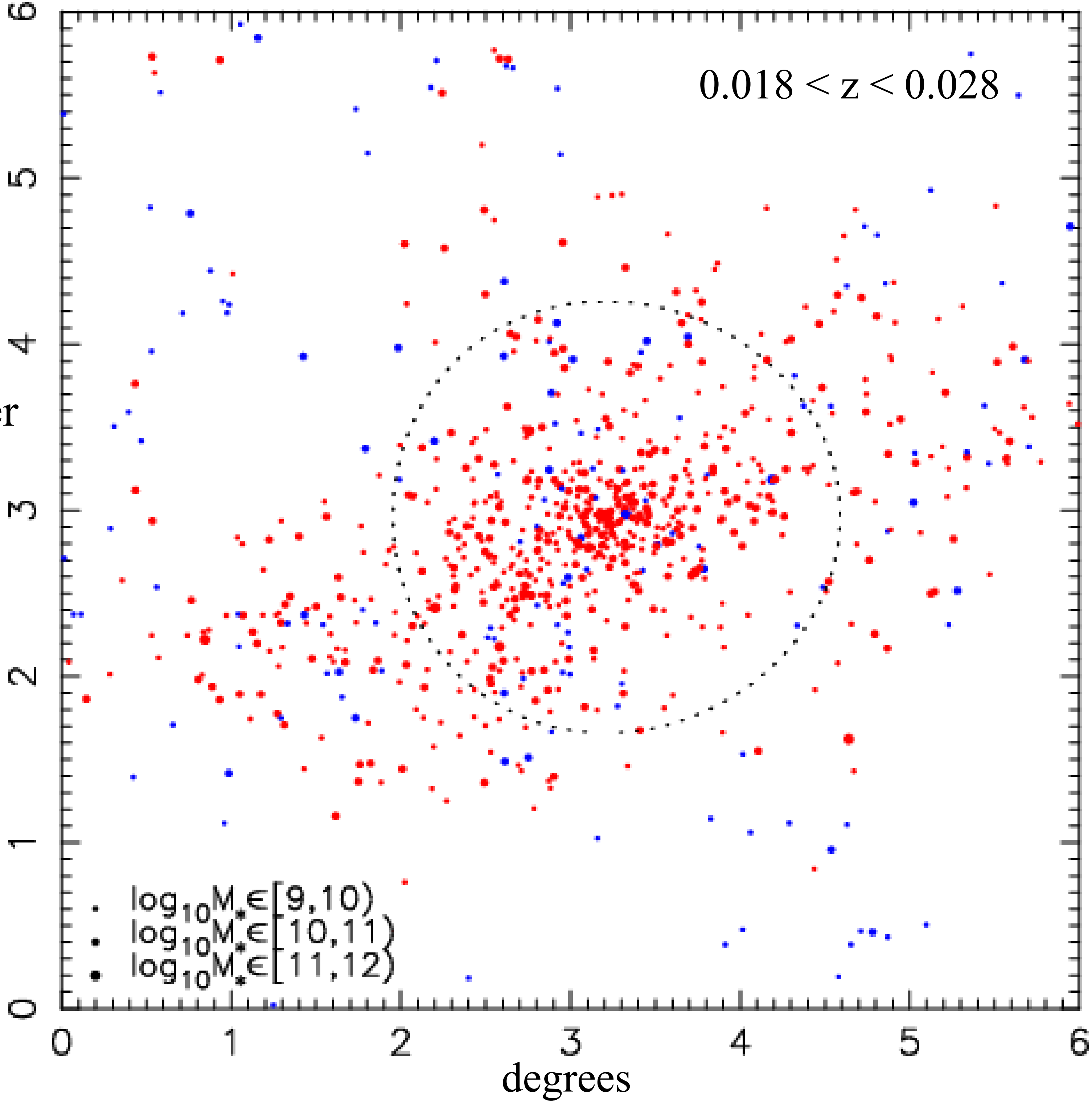
Data from SDSS/DR7


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

degrees

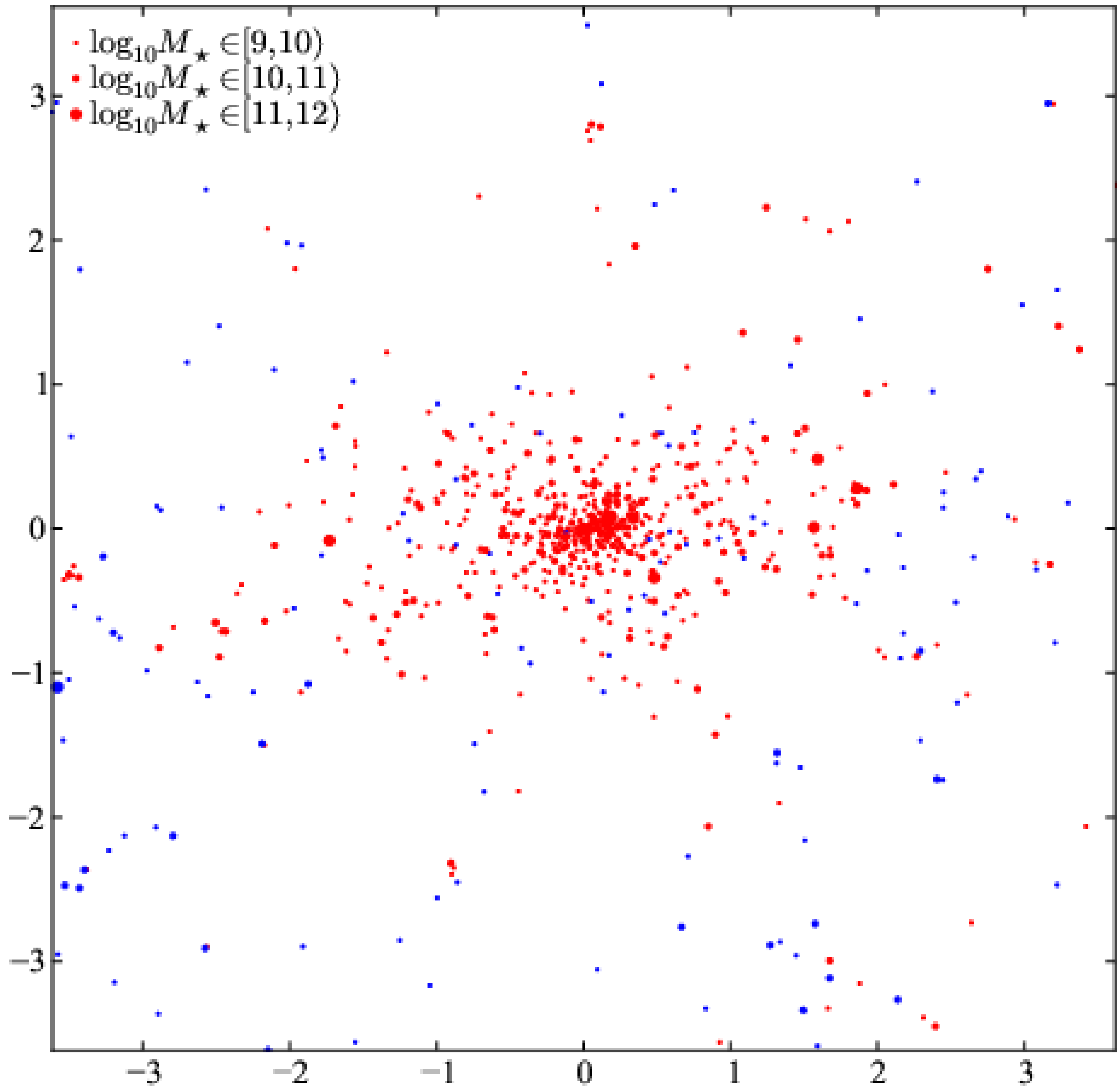
Coma cluster with R_{200}

SDSS data



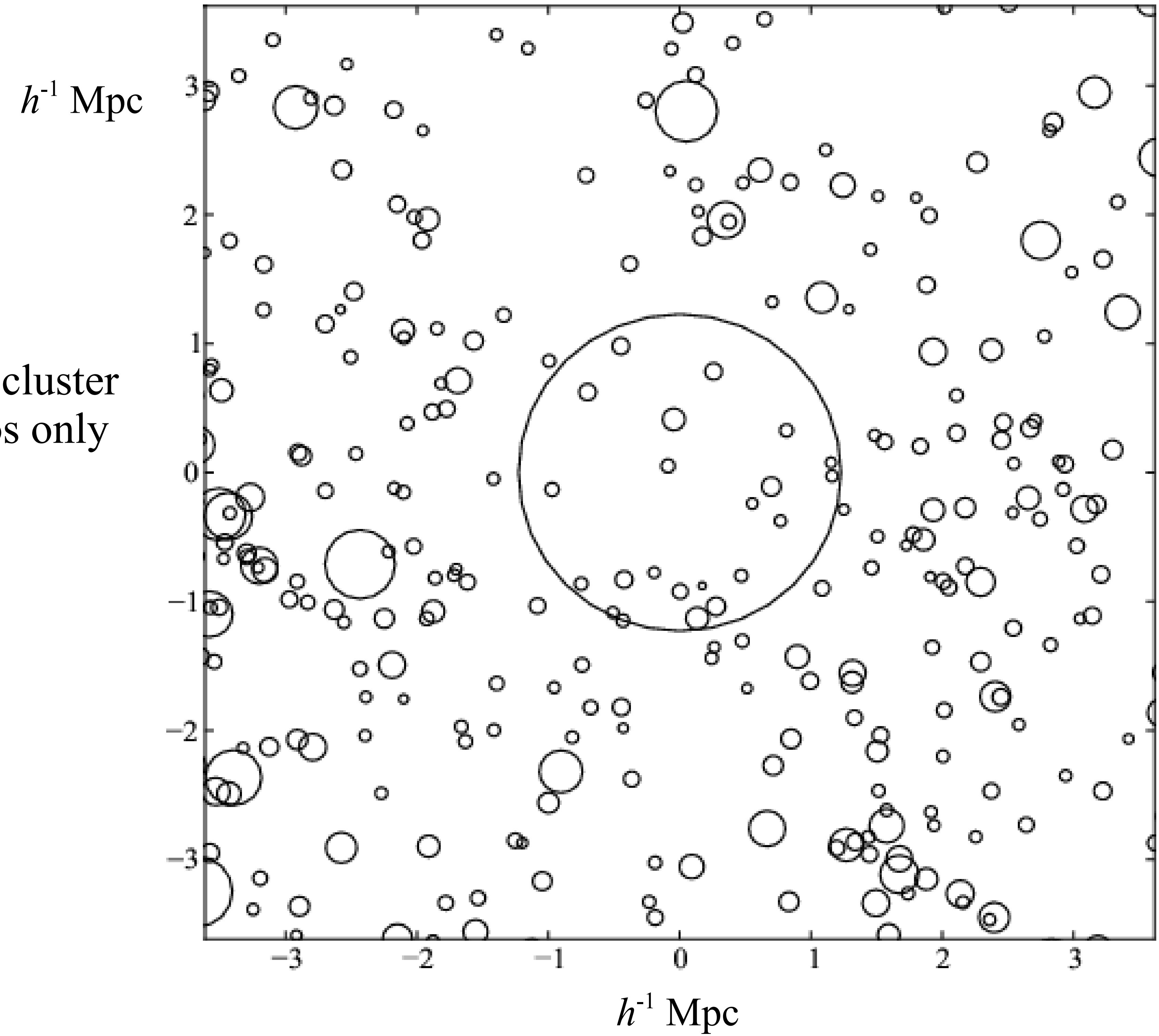
h^{-1} Mpc

MS cluster



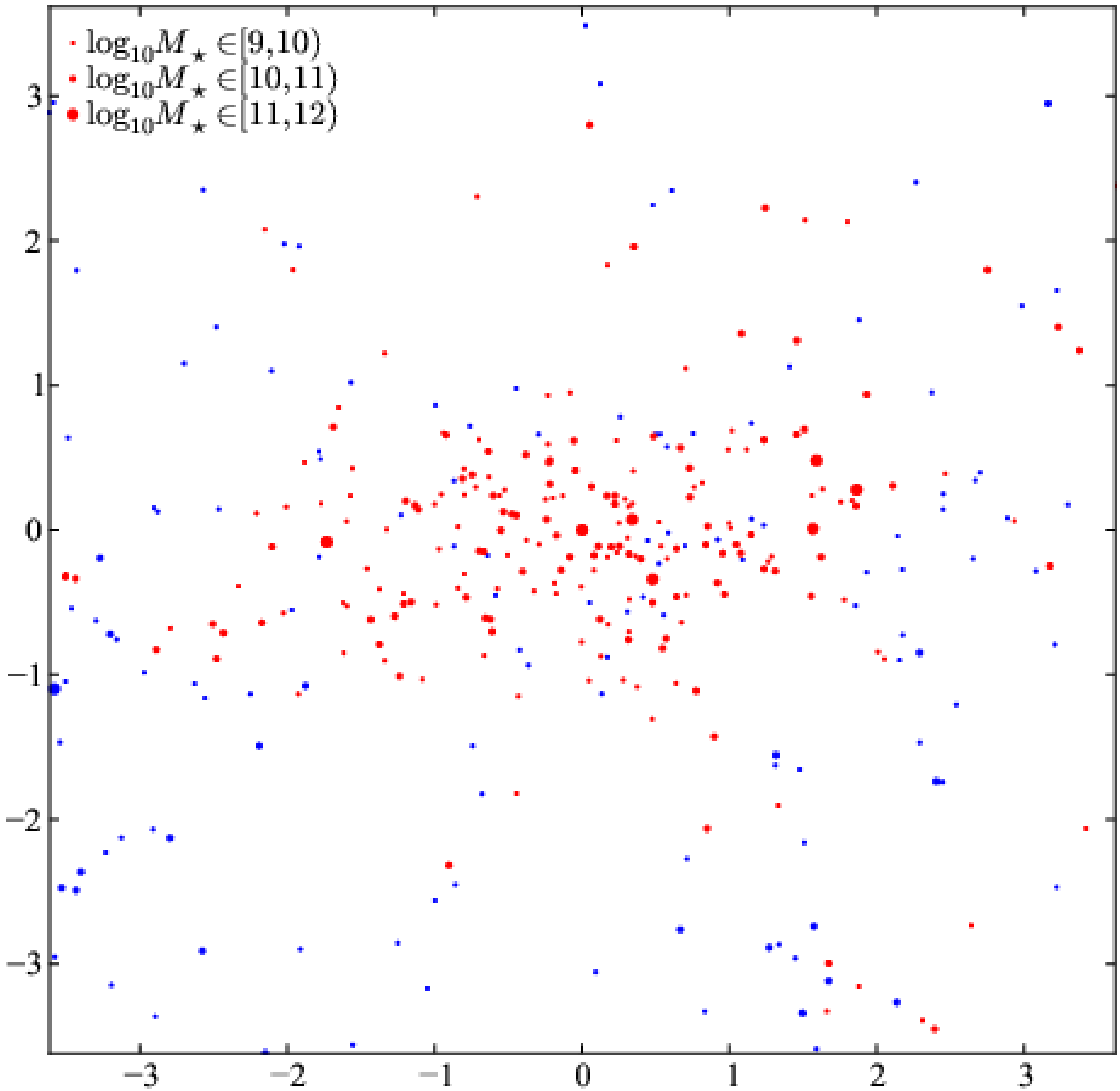
h^{-1} Mpc

MS cluster
halos only



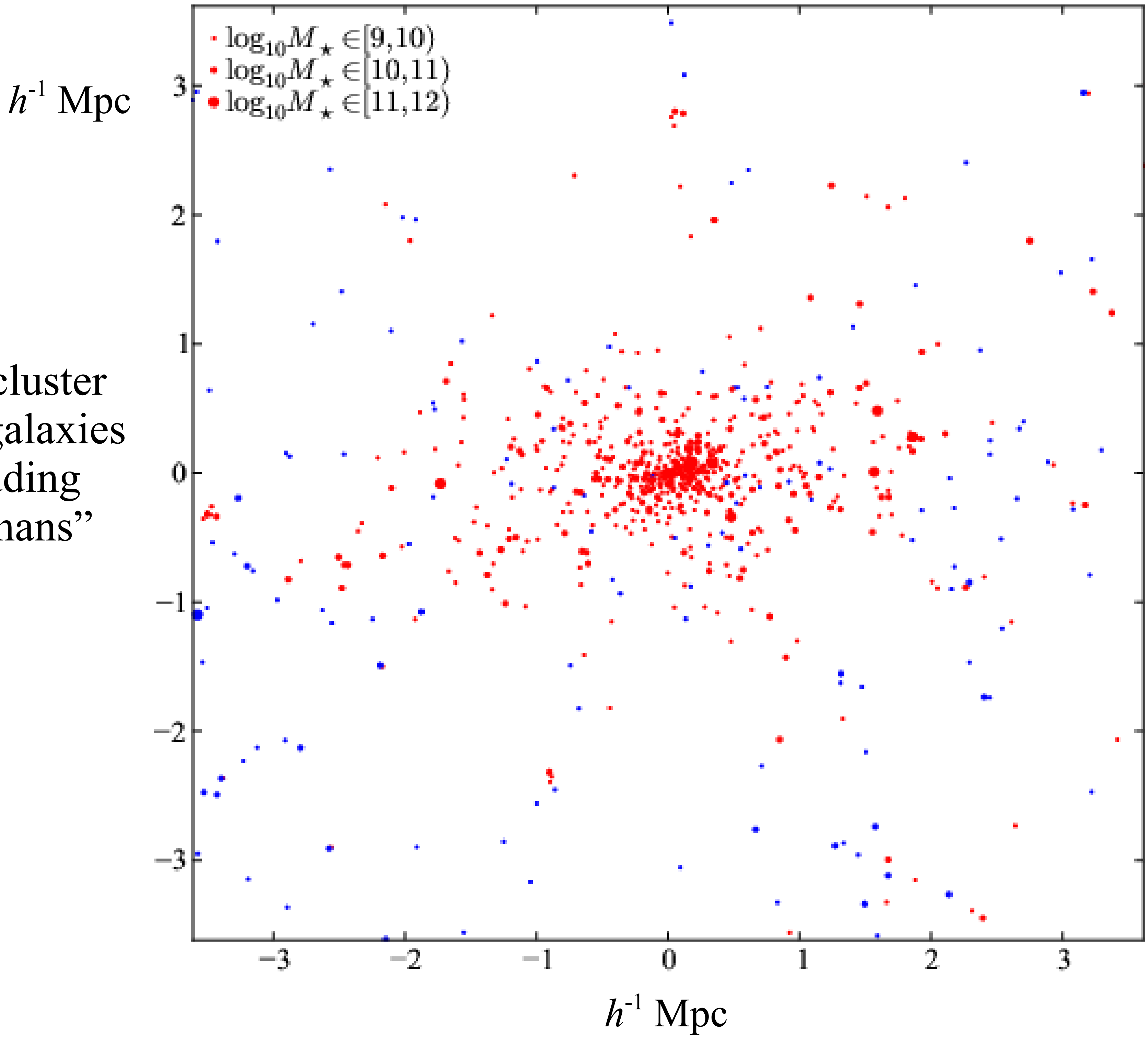
h^{-1} Mpc

MS cluster galaxies in subhalos



h^{-1} Mpc

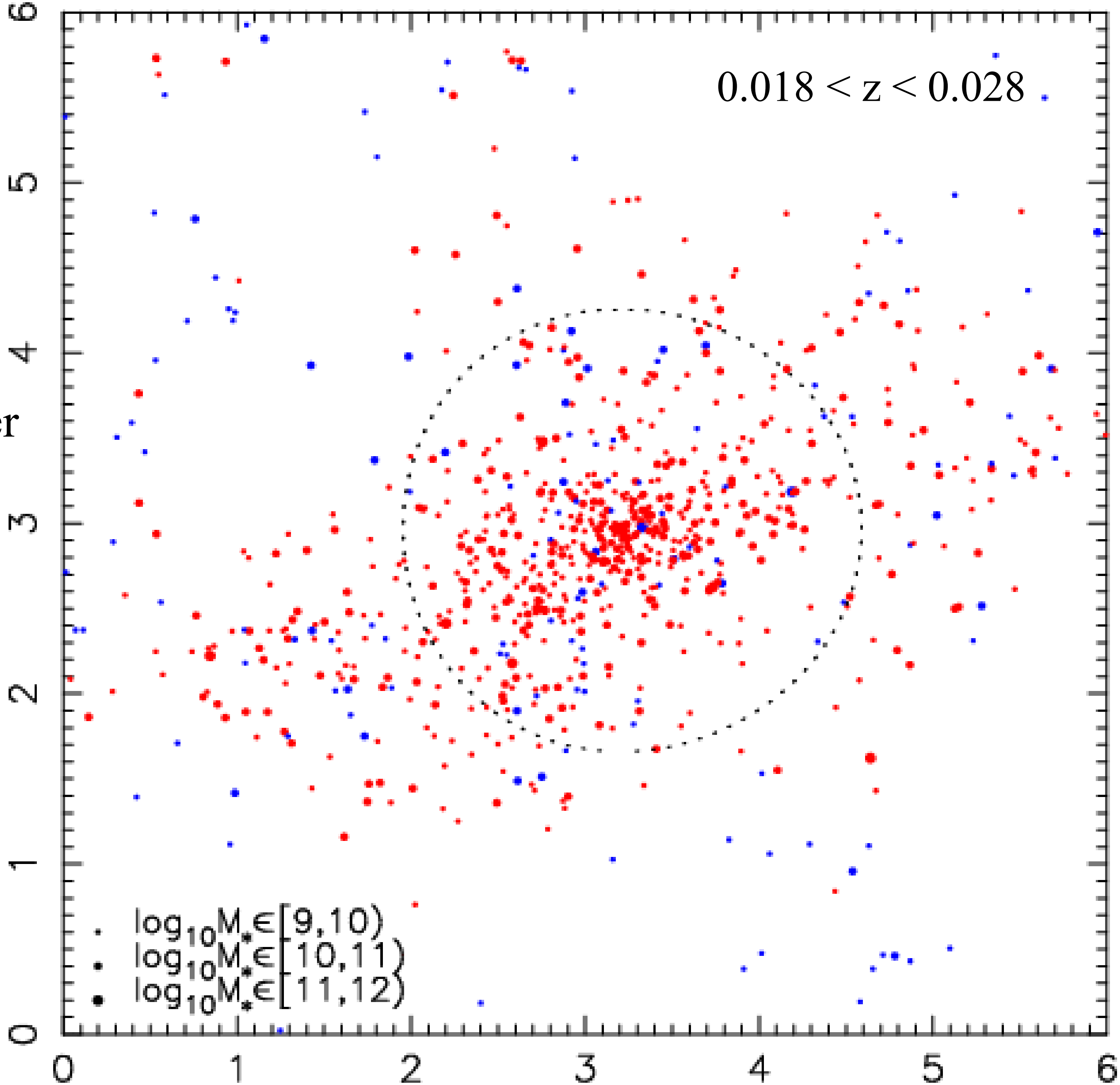
MS cluster
All galaxies
including
“orphans”



degrees

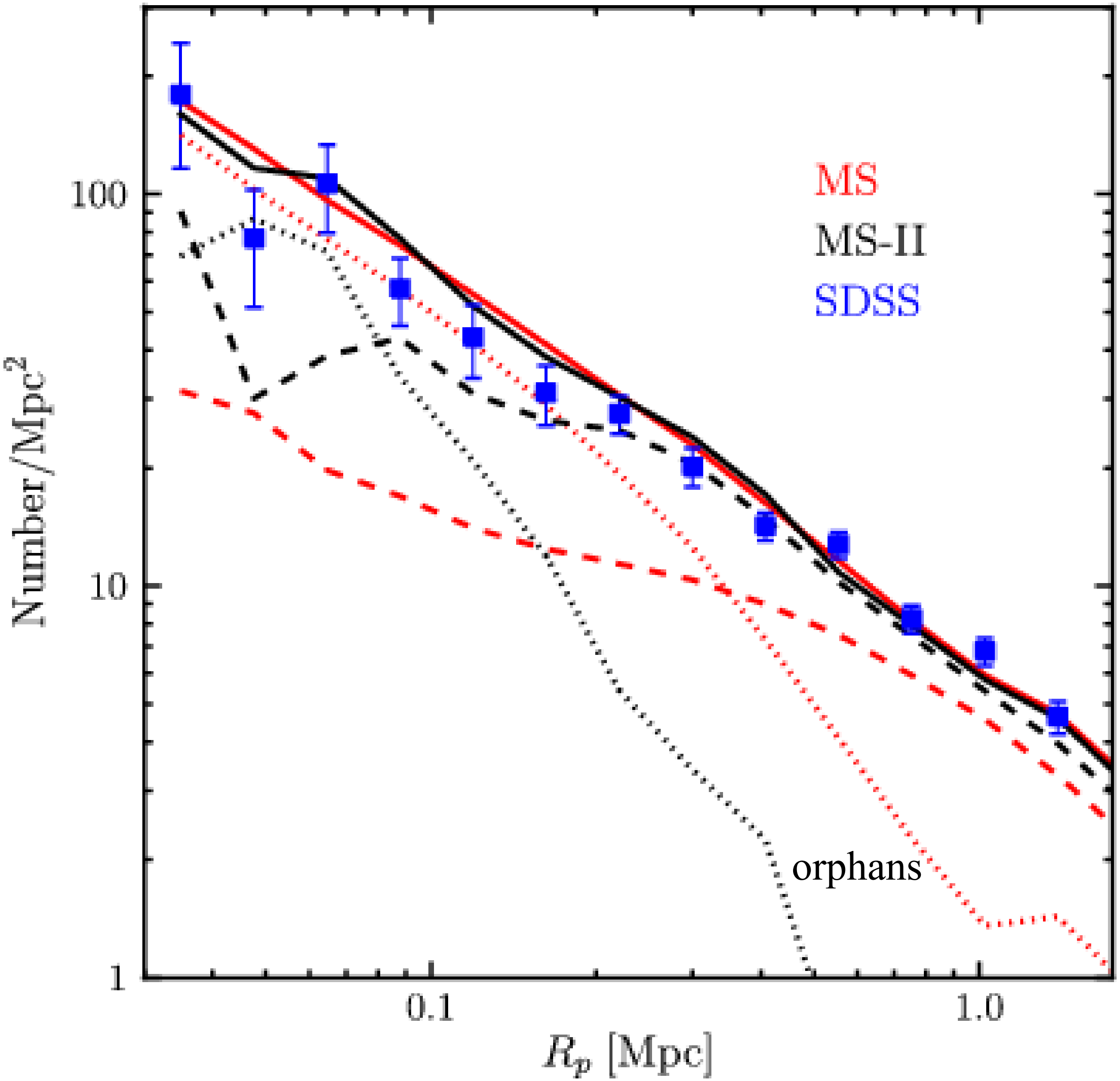
Coma cluster with R_{200}

SDSS data



degrees

Projected galaxy number density profiles of clusters



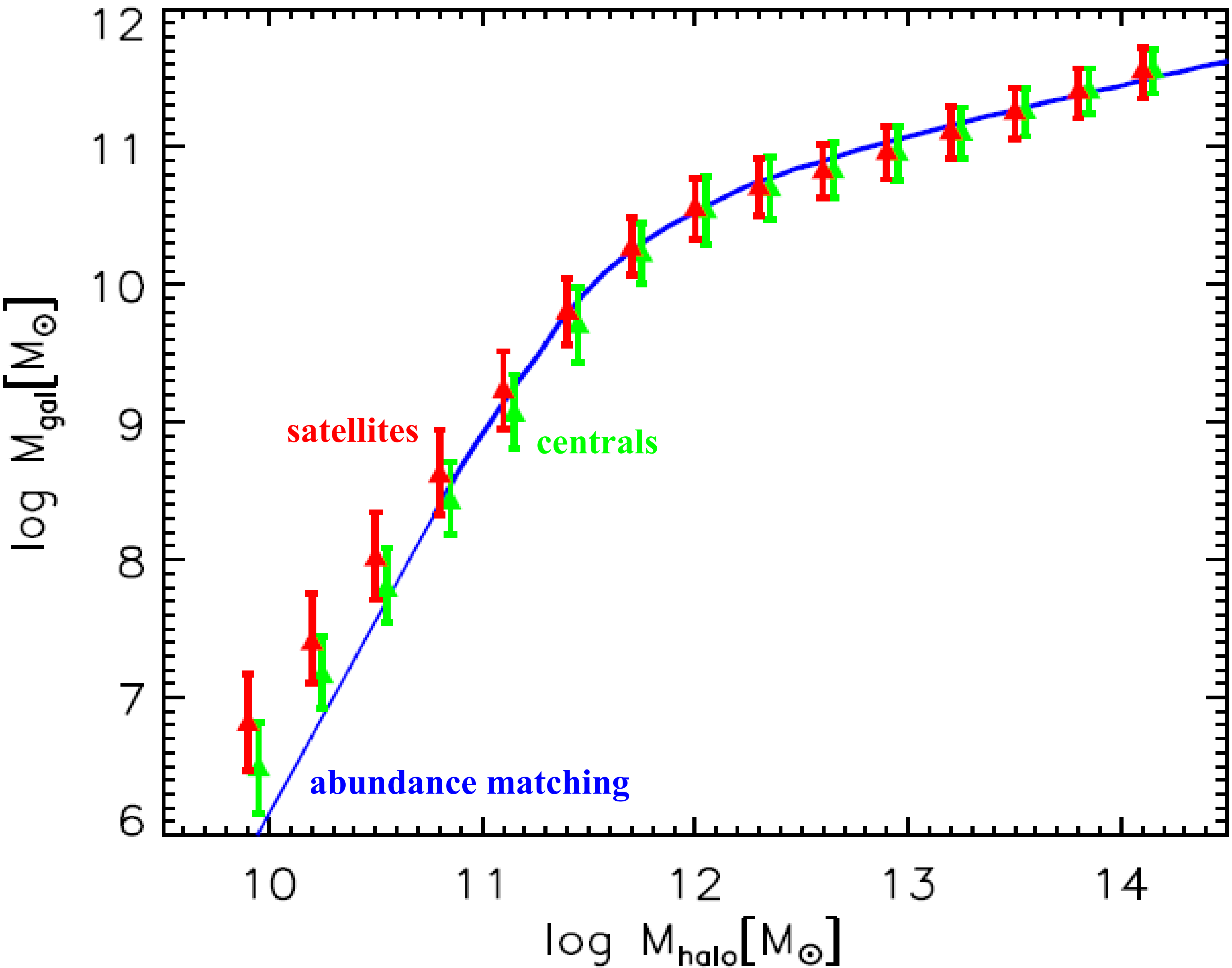
log M_{gal} > 10.0

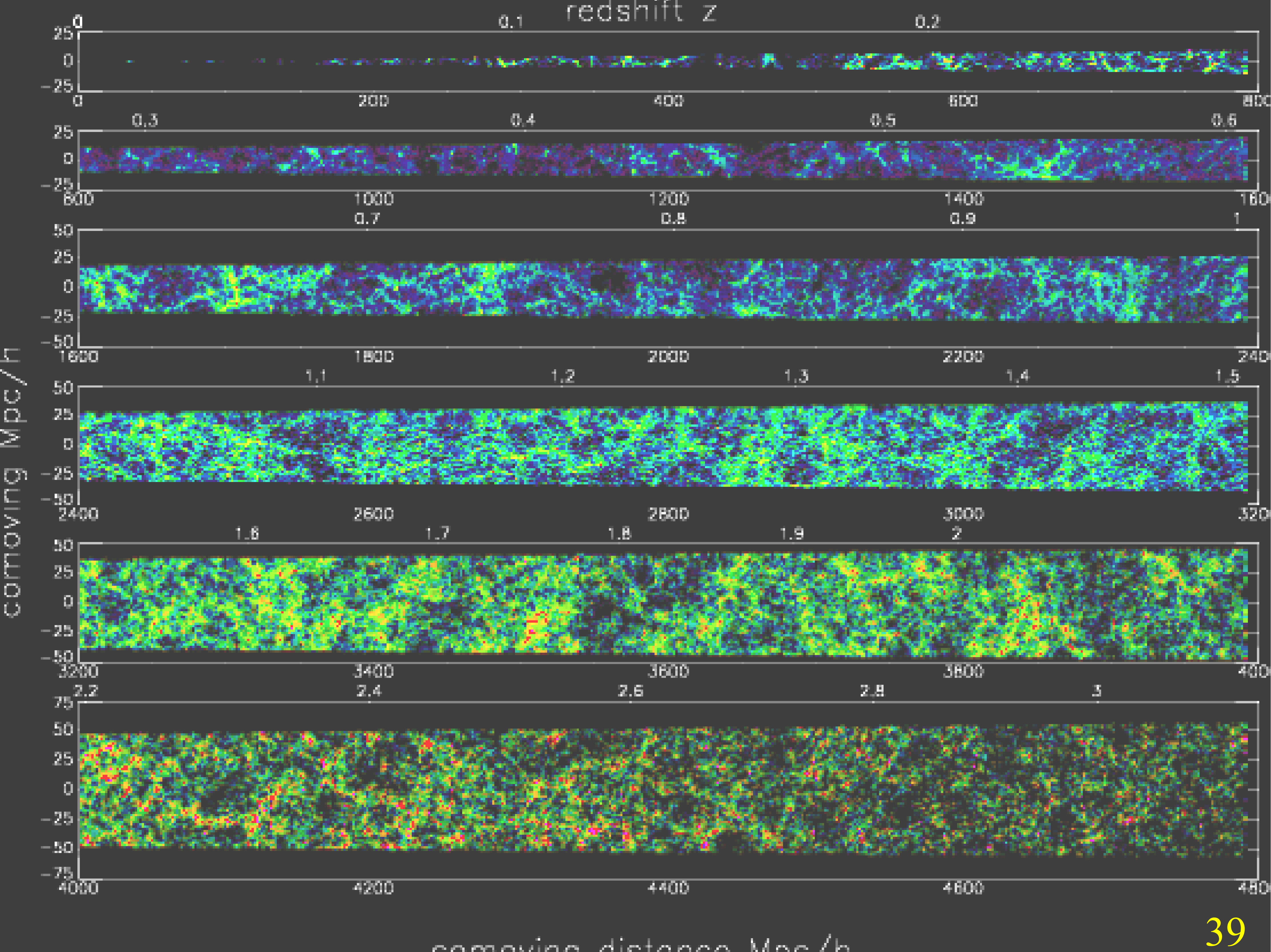
14.0 < log M_{clus} < 14.3

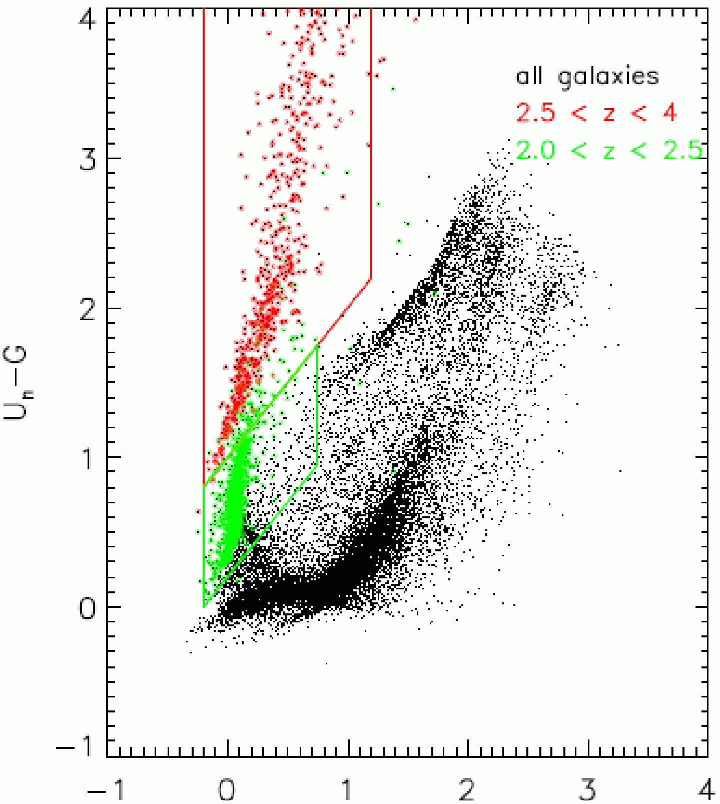
Note: good agreement of MS with MS-II is *only* when orphans are included

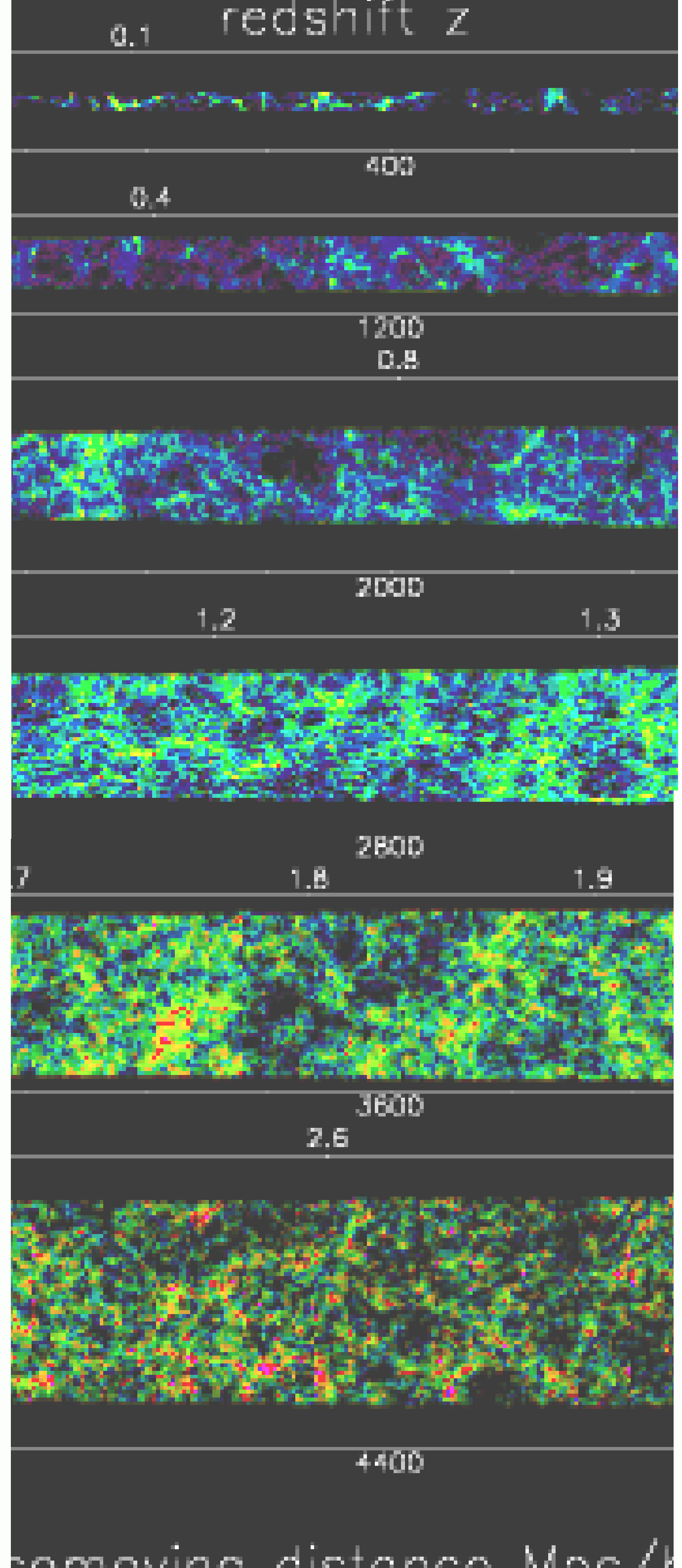
Orphan treatment is physically consistent and needed to fit SDSS

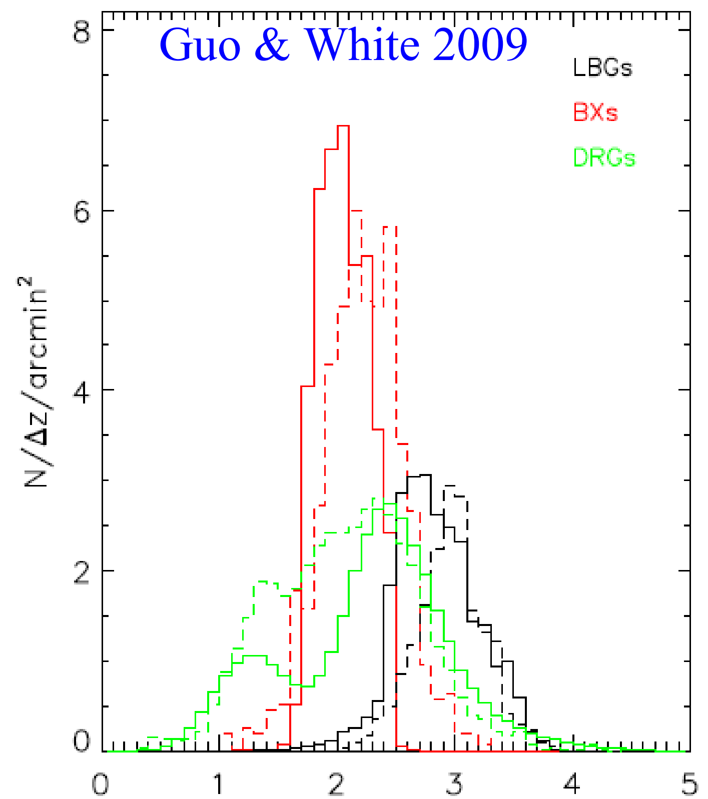
Galaxy stellar mass versus maximum past halo mass

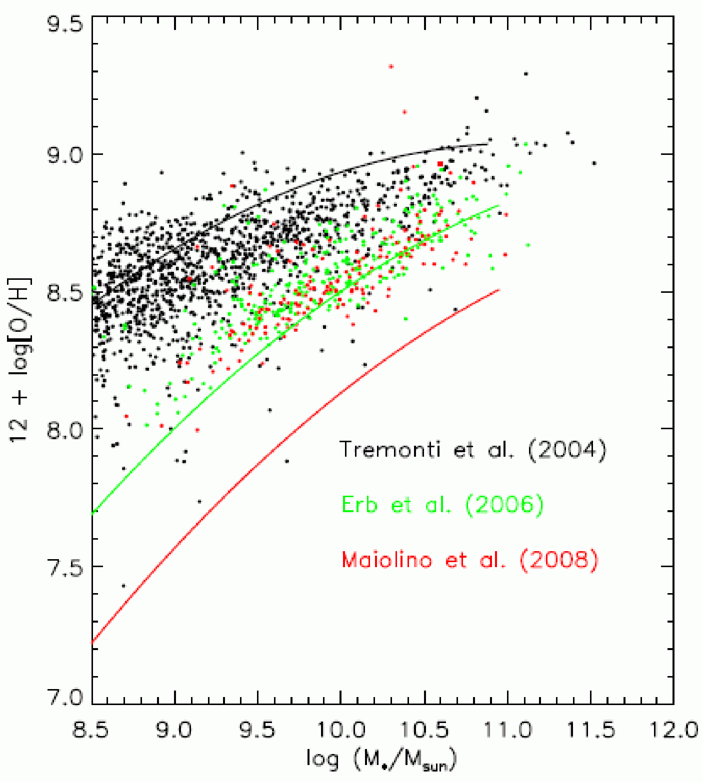


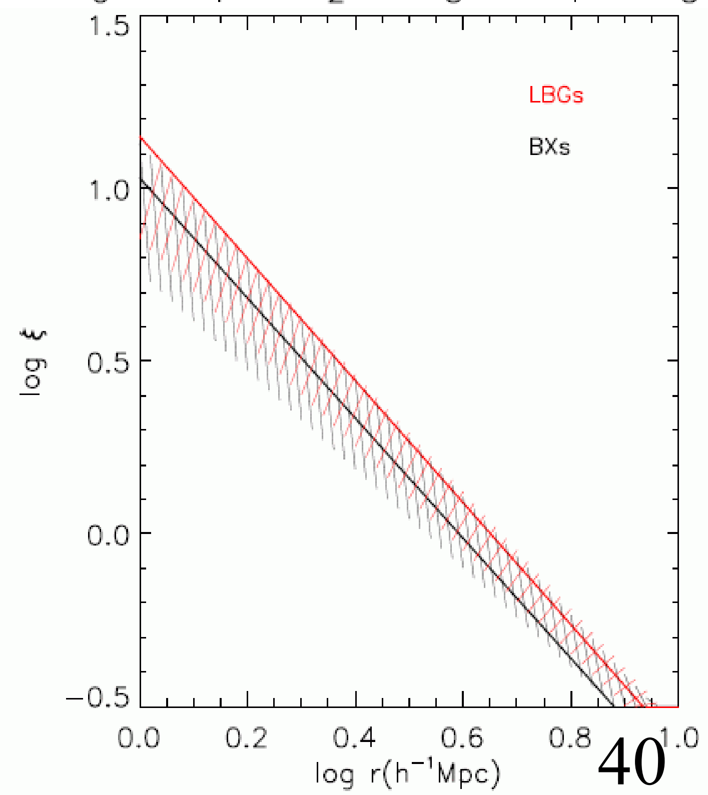

redshift z
comoving Mpc/h


all galaxies
2.5 < z < 4
2.0 < z < 2.5
$U_n - G$

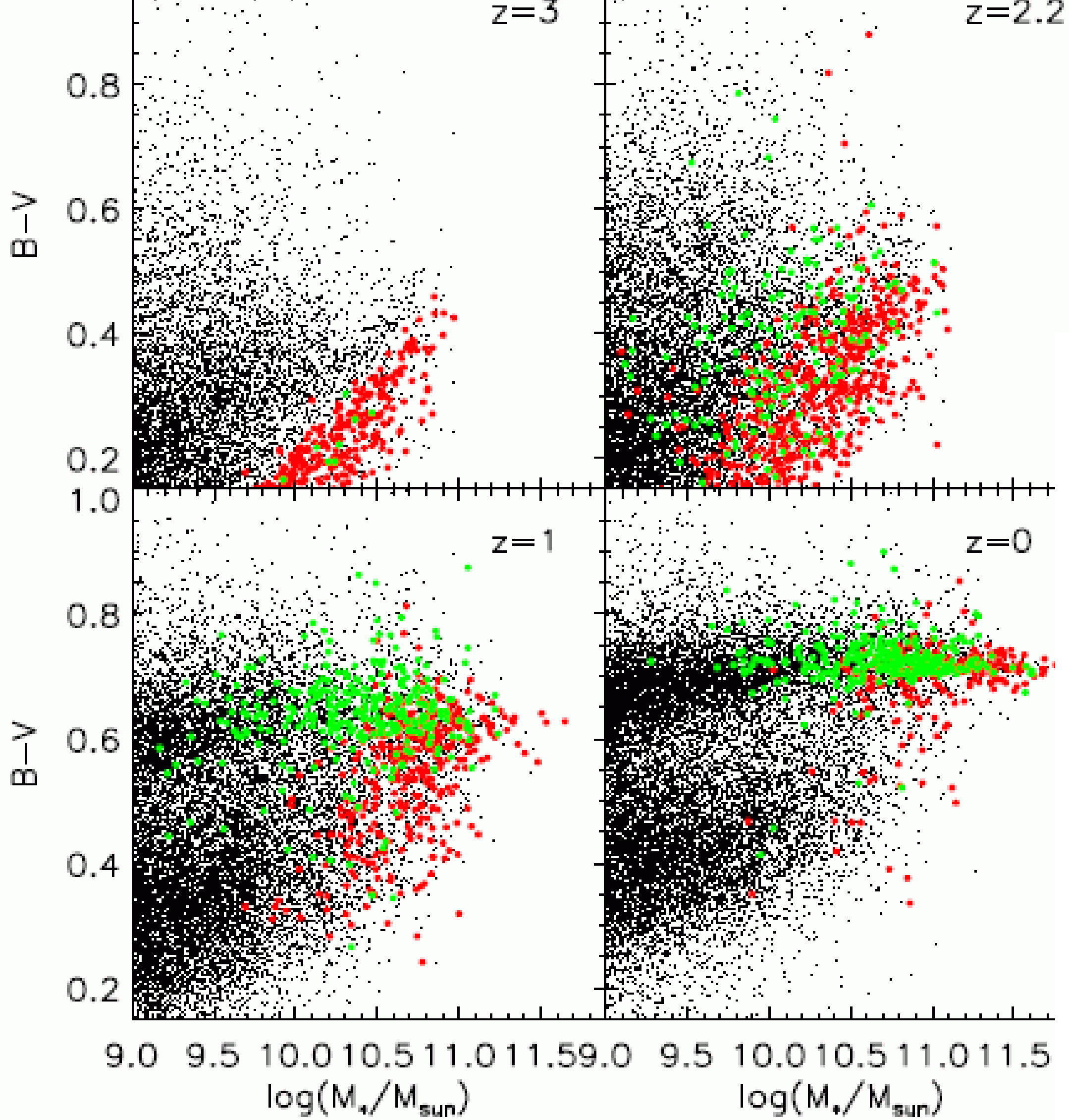

redshift z
0.1
400
0.4
1200
0.8
2000
1.2
1.3
2800
1.8
1.9
3600
2.6
4400

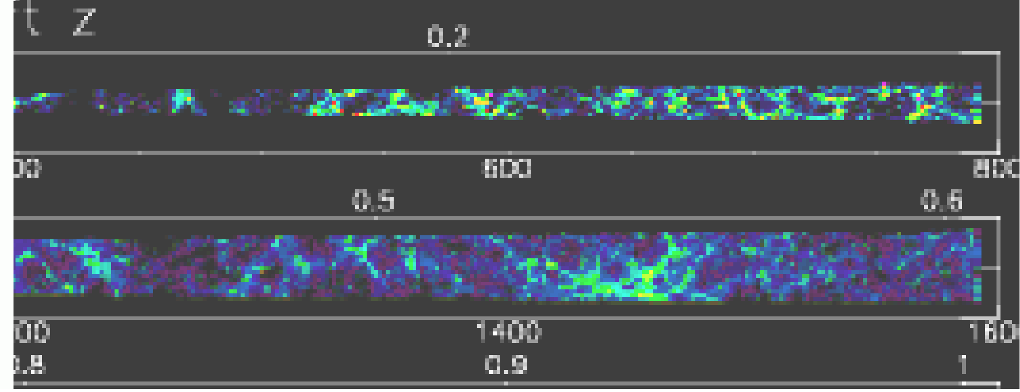

Guo & White 2009
LBGs
BXs
DRGs
$N/\Delta z/\mathrm{arcmin}^2$

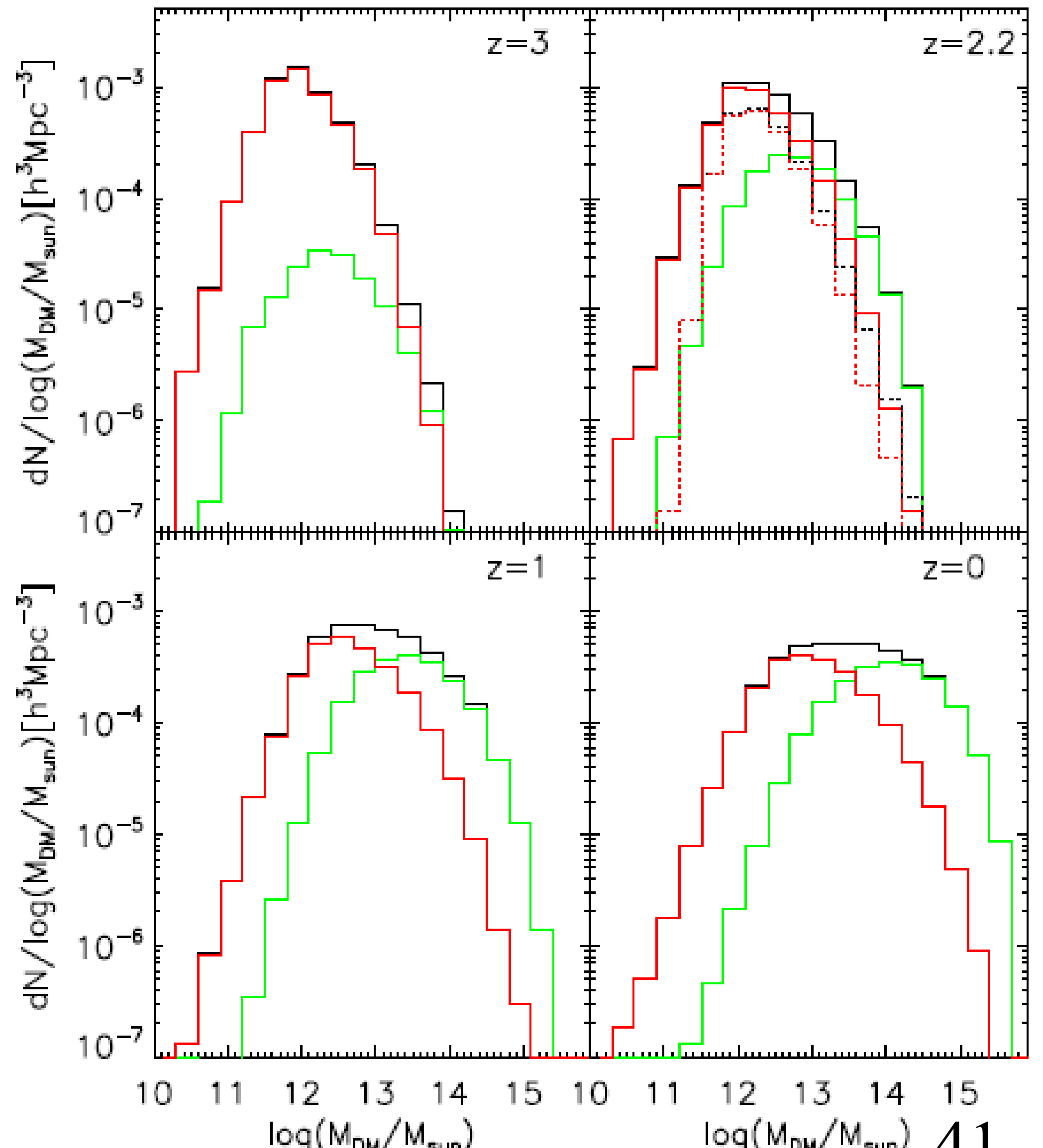

Tremonti et al. (2004)
Erb et al. (2006)
Maiolino et al. (2008)
12 + log[O/H]
log (M_*/M_{sun})

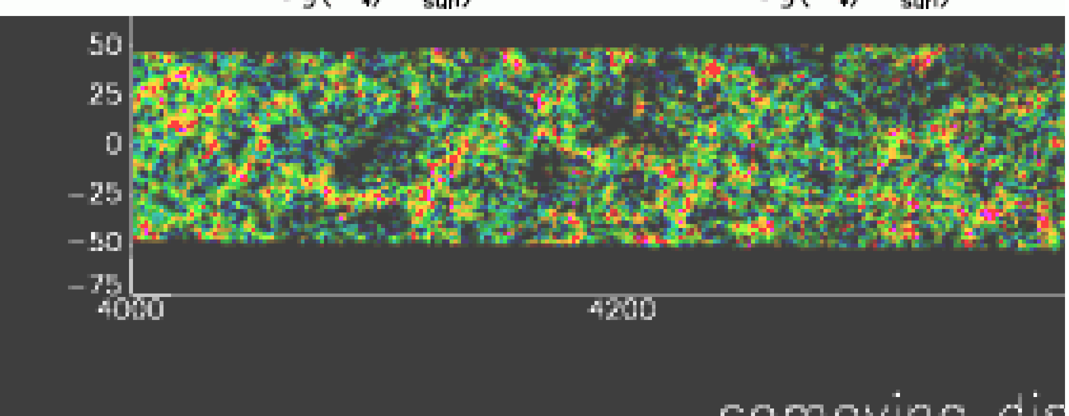

LBGs
BXs
log ξ
log $r(h^{-1}\mathrm{Mpc})$

Guo & White 2009





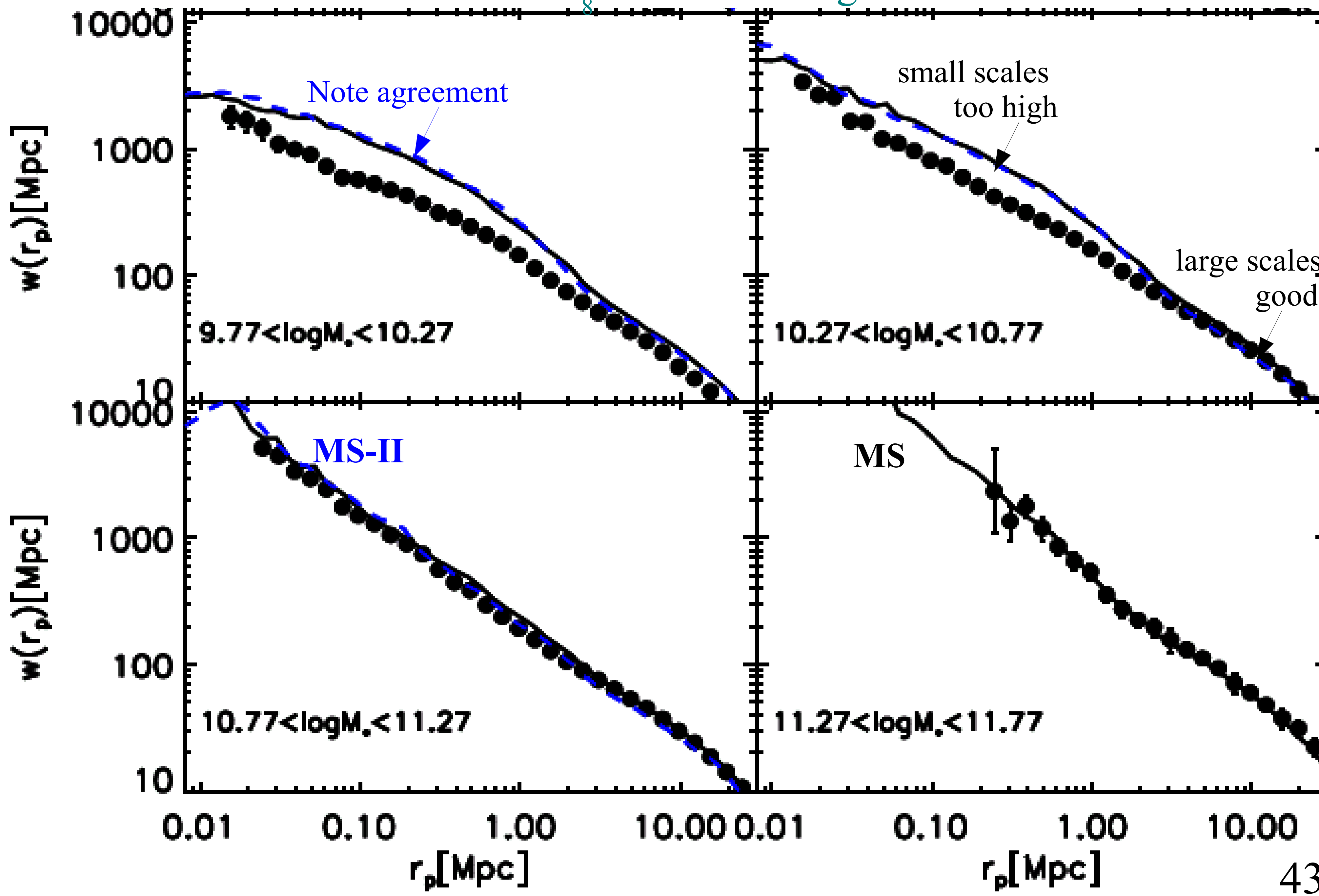




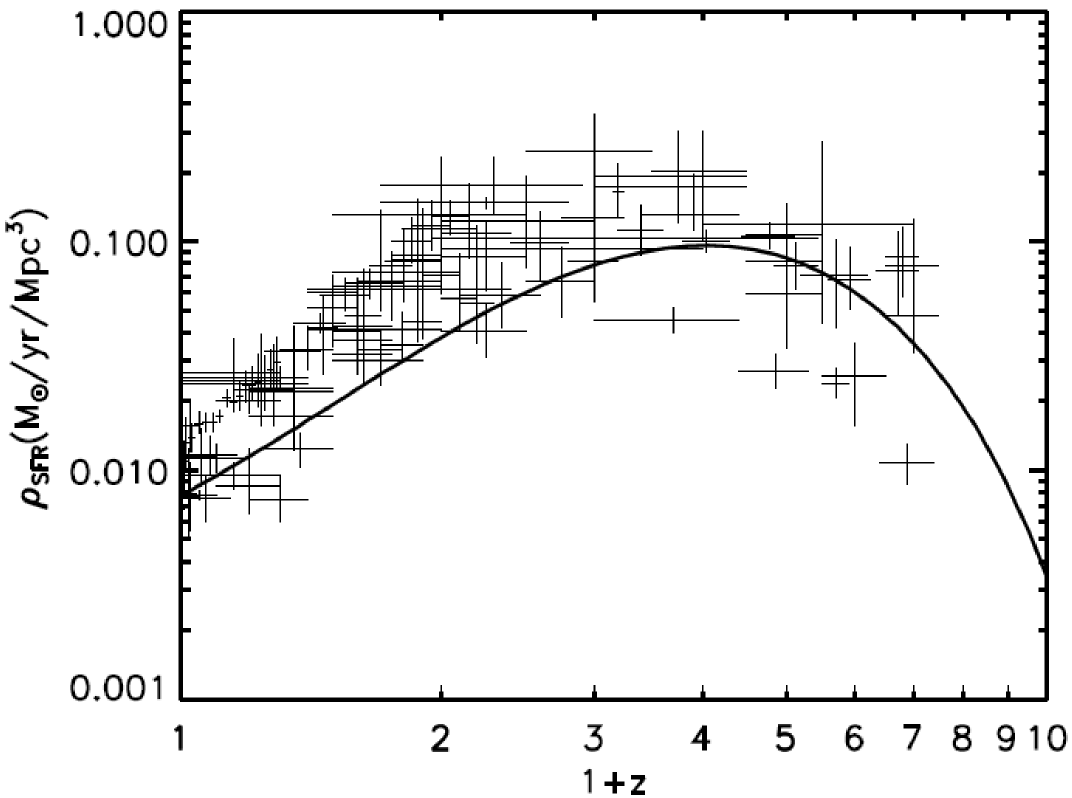
Things that work less well

Clustering of less massive galaxies

--- σ_8 = 0.9 is too high ---



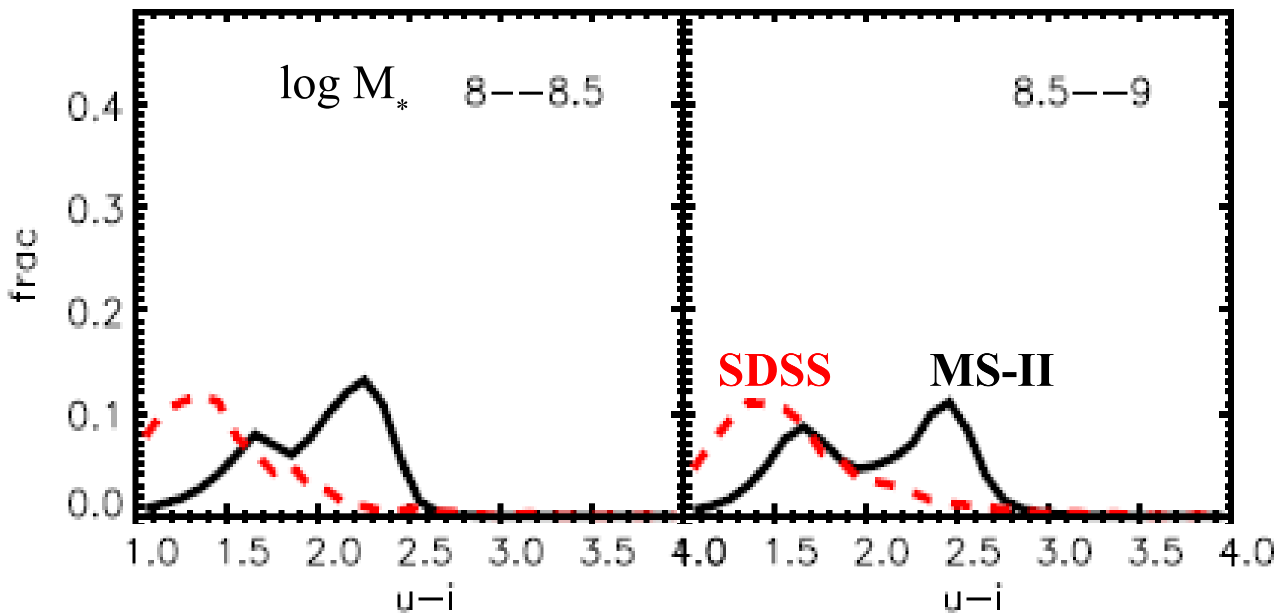
The cosmic star formation density history



--- observed SFR are inconsistent with observed stellar masses ---

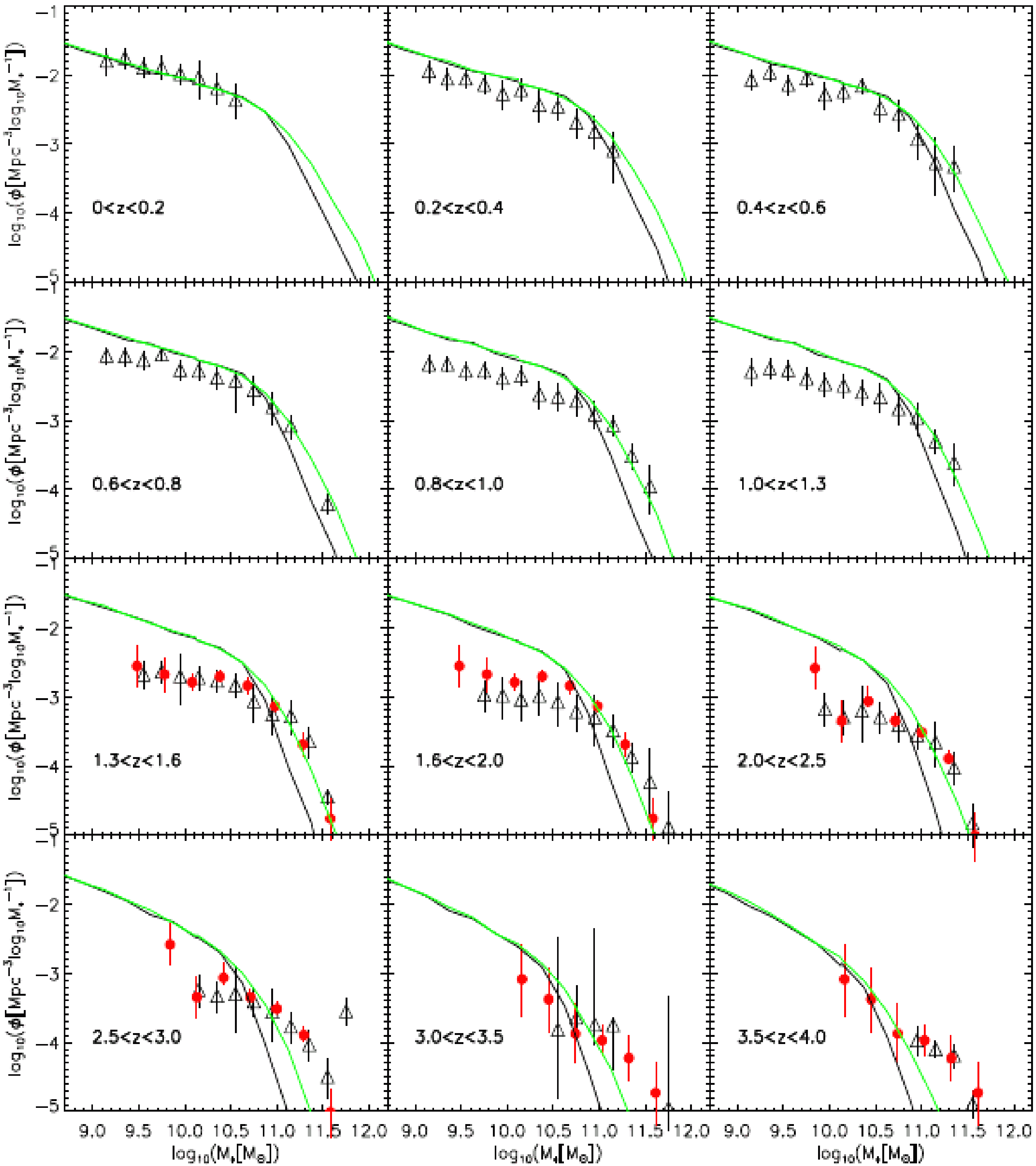
--- star formation peaks too early in the model ---

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 <u>too early</u>

Conclusions

"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

Viable models require strong SN? feedback at low masses and strong AGN? feedback at high masses to match observed LF's

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