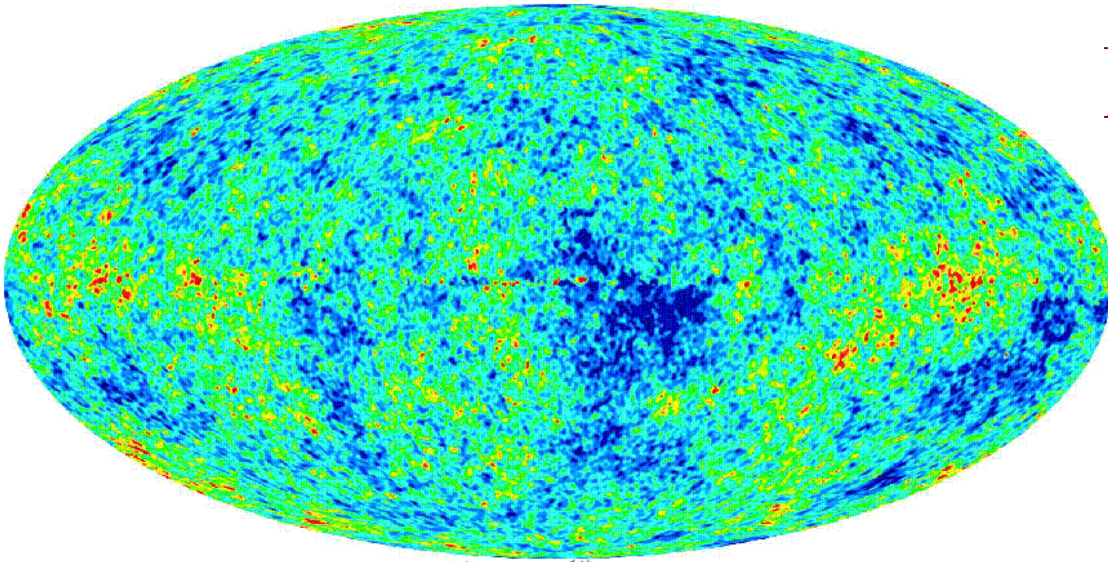
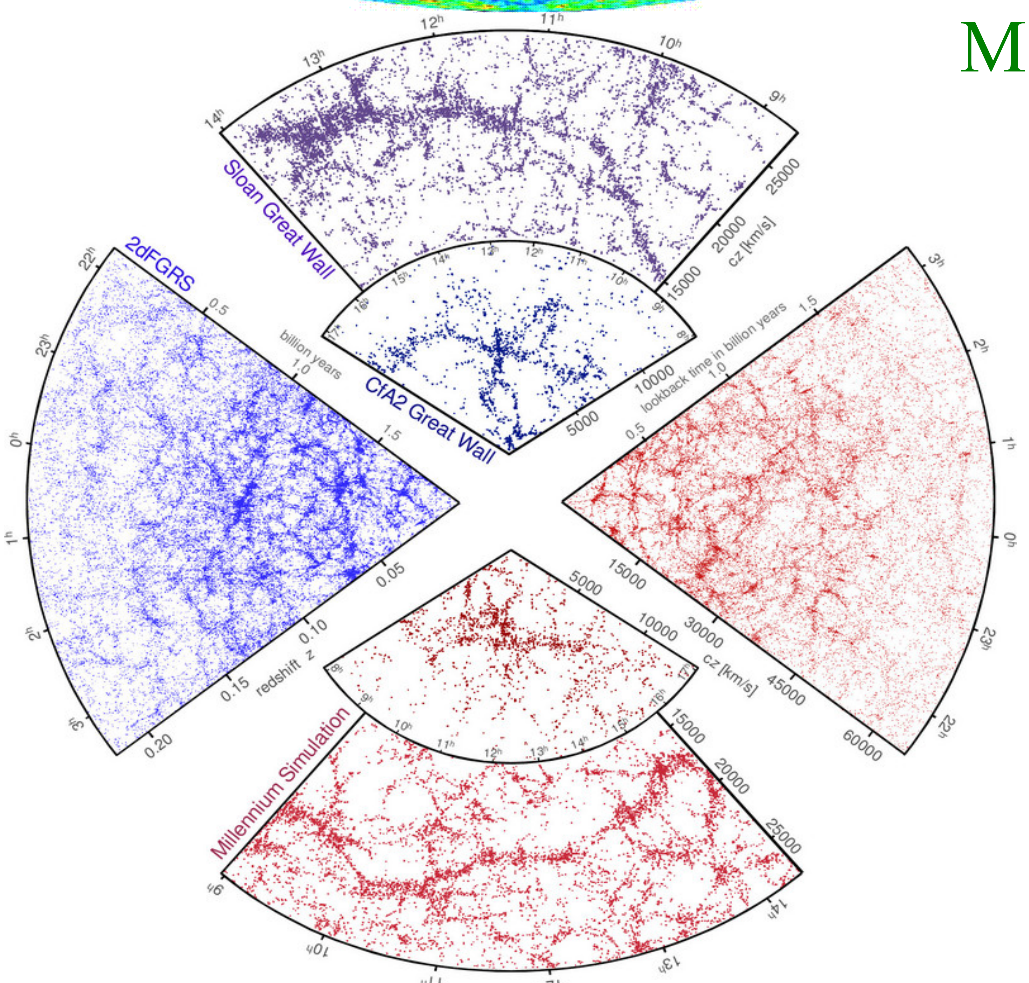
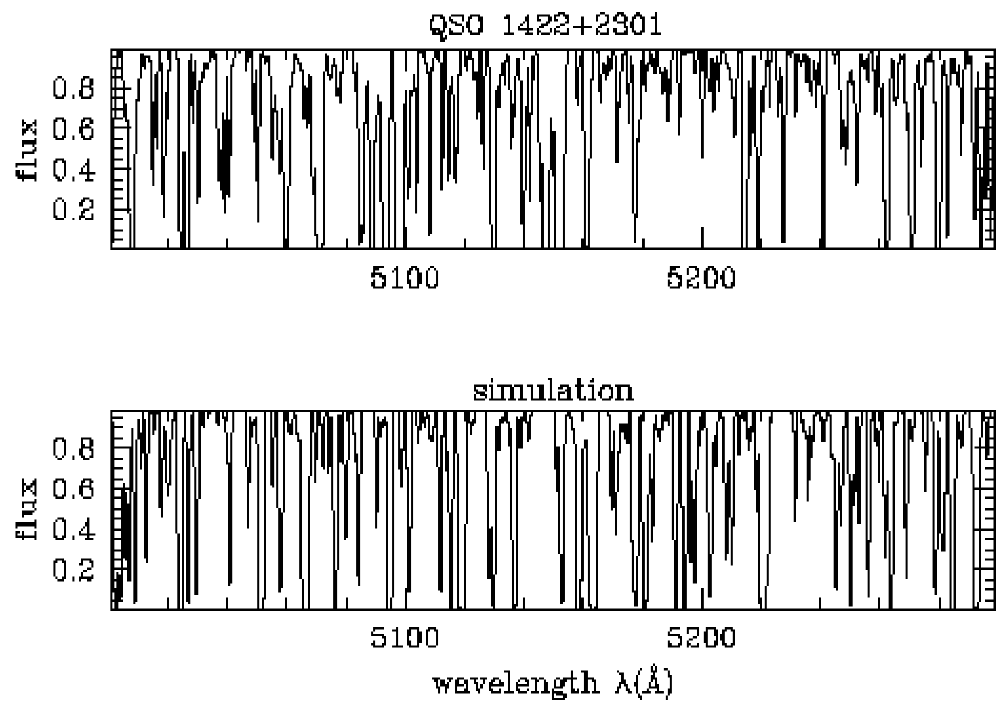
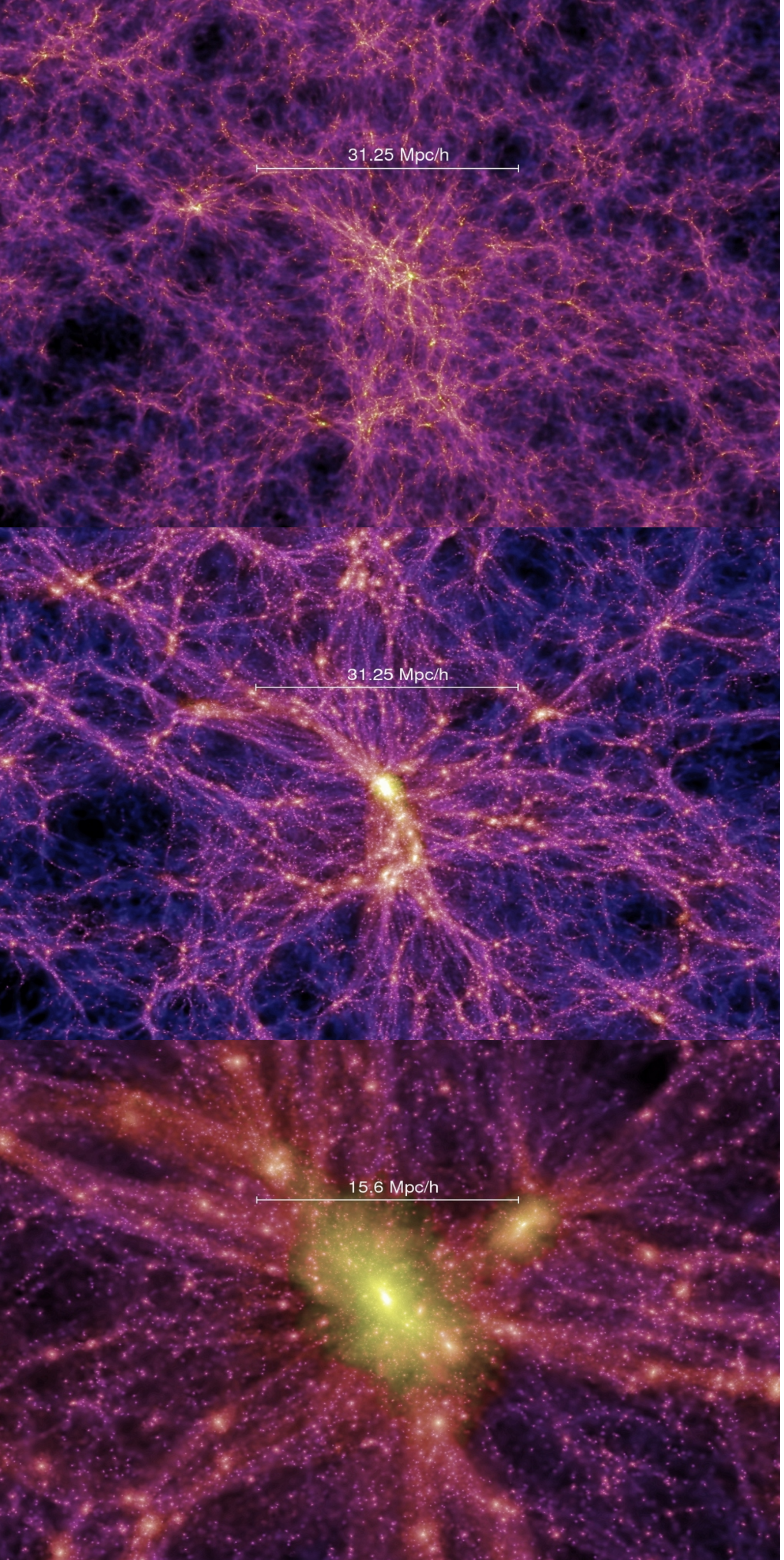


Modelling the galaxy population

Simon White
Max Planck Institut für Astrophysik





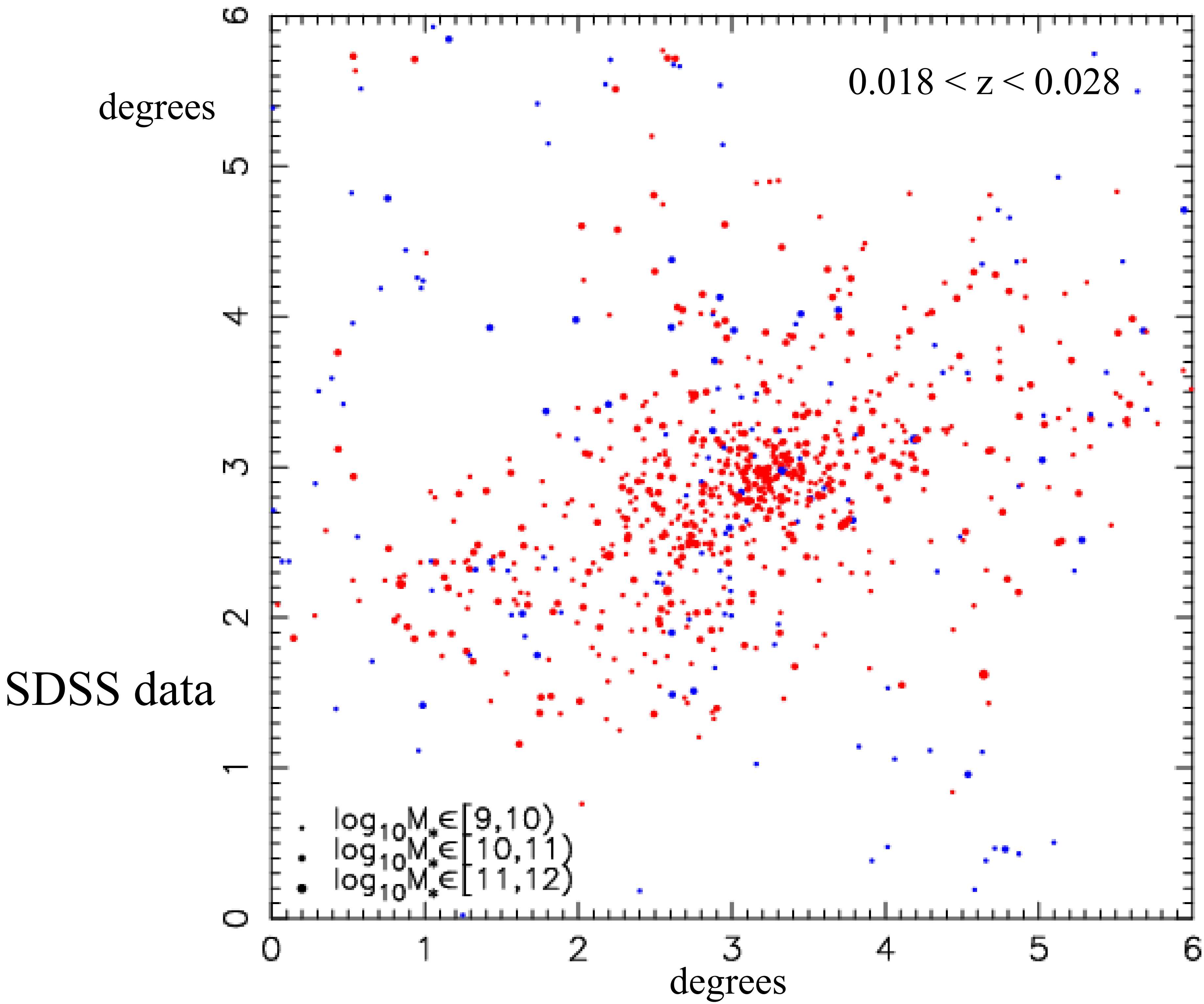


- The standard model reproduces
  - -- the linear initial conditions
  - -- IGM structure during galaxy formation
  - -- large-scale structure today
- Simulation of the standard model gives *precise* predictions for the
  - -- abundance
  - -- internal structure
  - -- assembly history
  - -- spatial/peculiar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

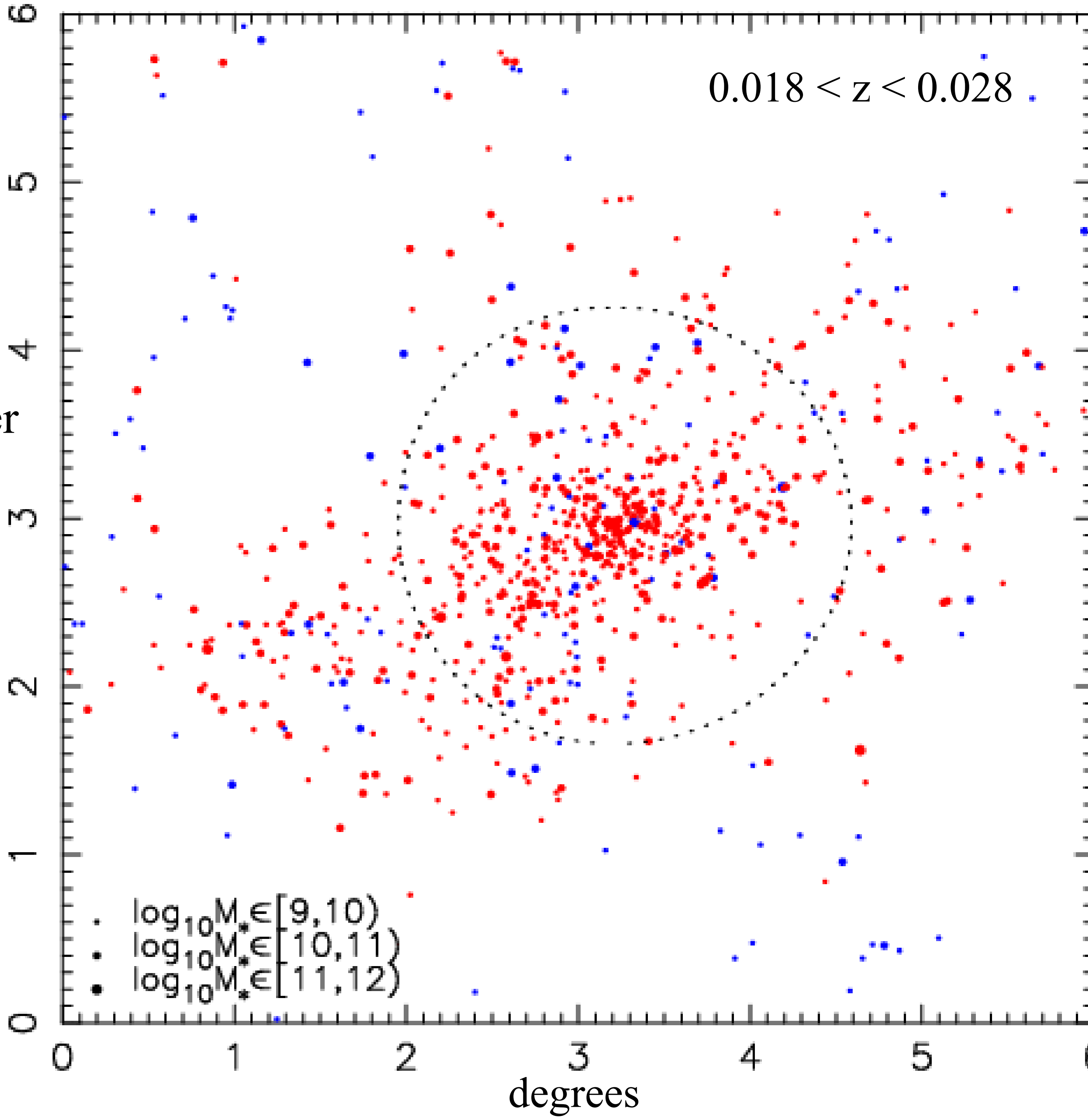


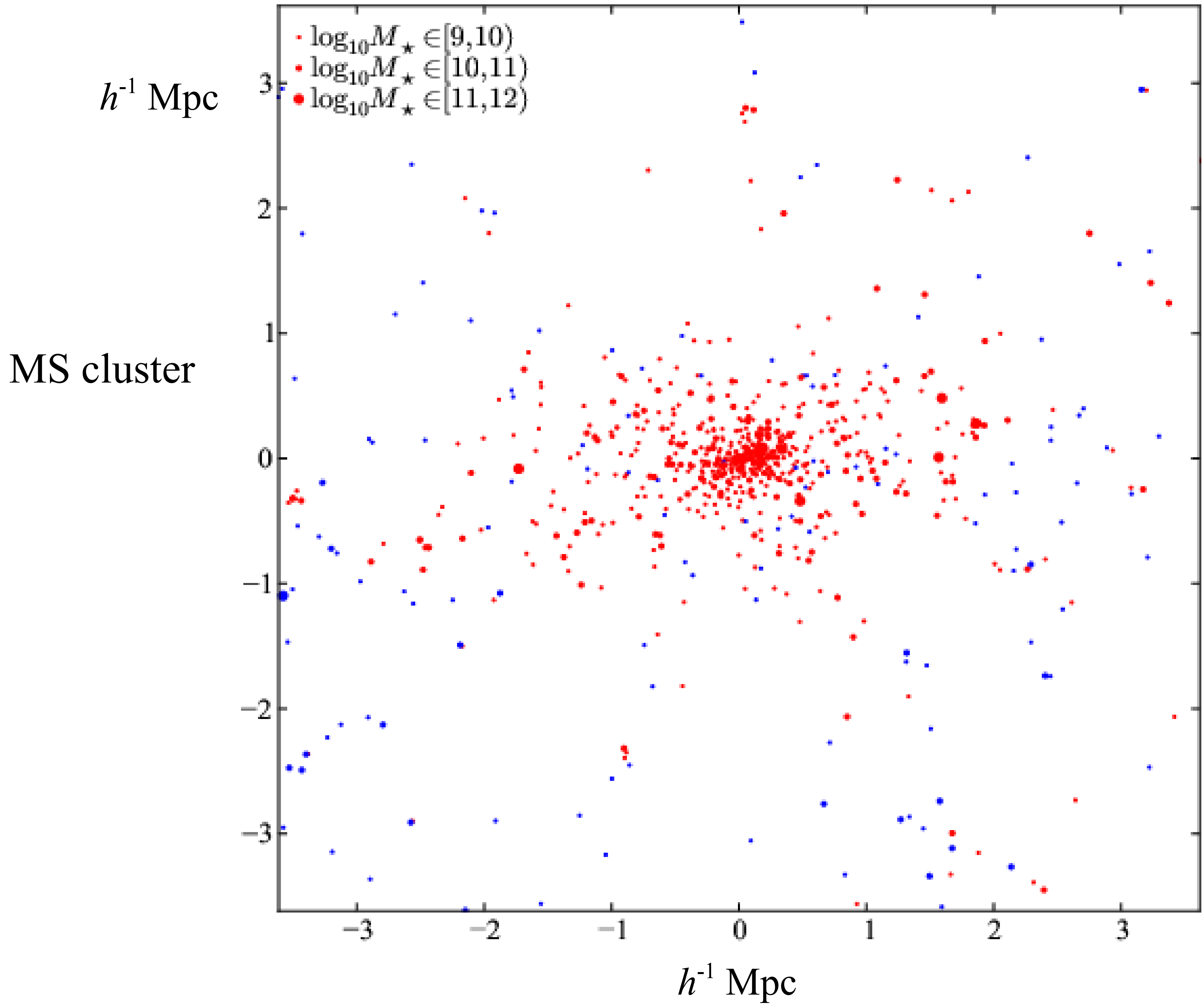
SDSS data
degrees
0.018 < z < 0.028
log10M*∈[9,10)
log10M*∈[10,11)
log10M*∈[11,12)
0
1
2
3
4
5
6
degrees

degrees

Coma cluster with R_{200}

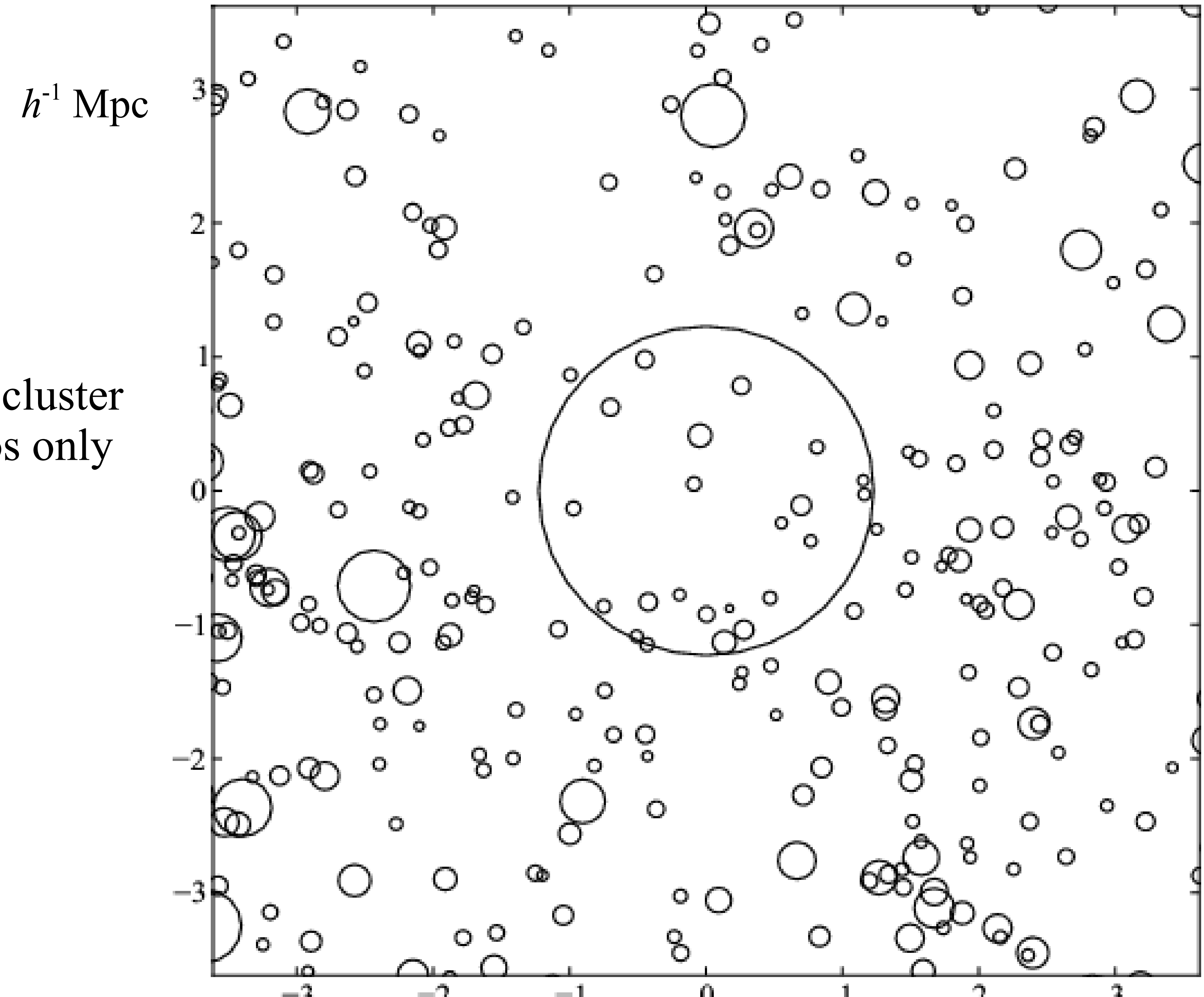
SDSS data

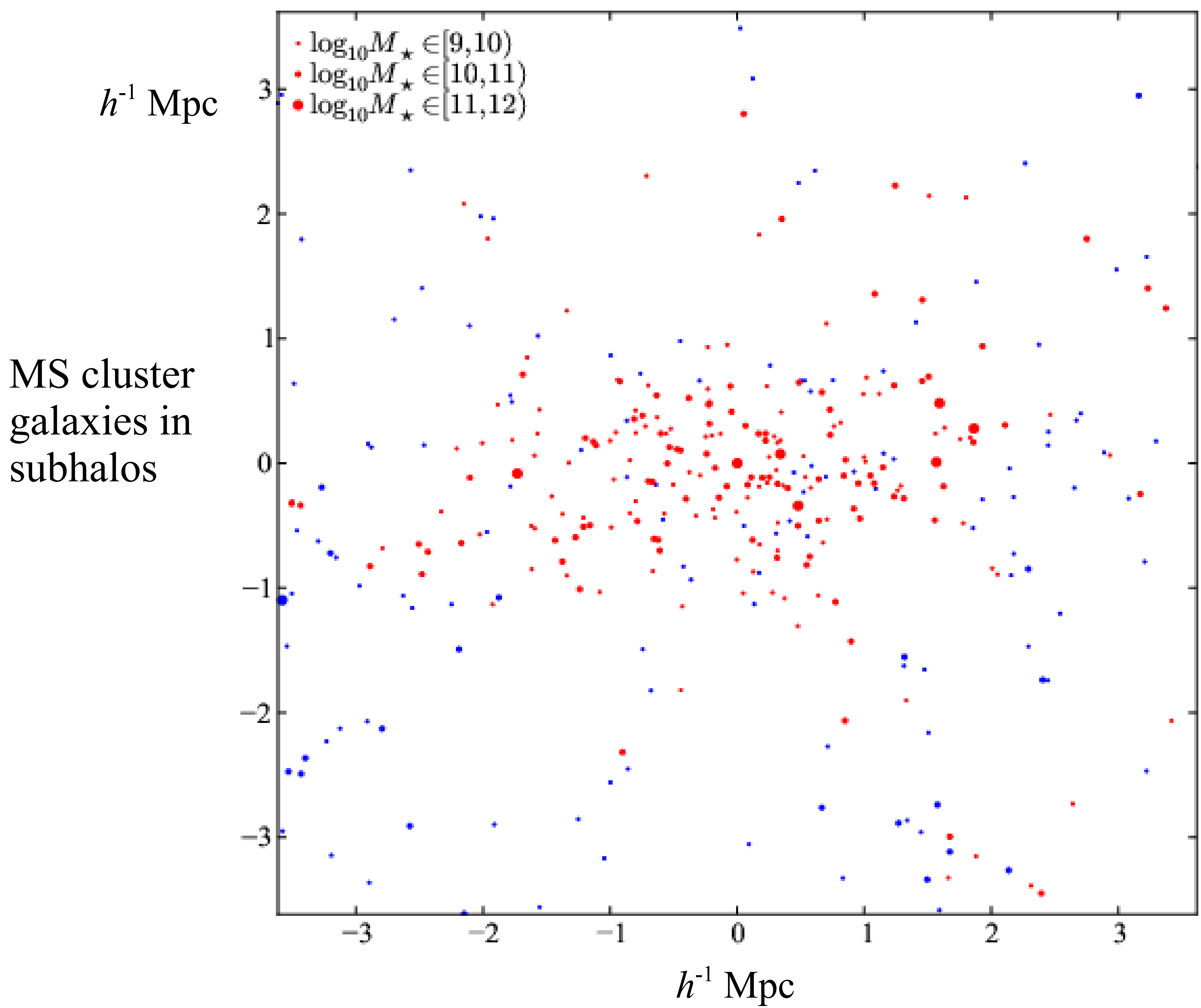




$\log_{10}M_\star \in [9,10)$
$\log_{10}M_\star \in [10,11)$
$\log_{10}M_\star \in [11,12)$
h^{-1} Mpc
MS cluster
h^{-1} Mpc

MS cluster
halos only

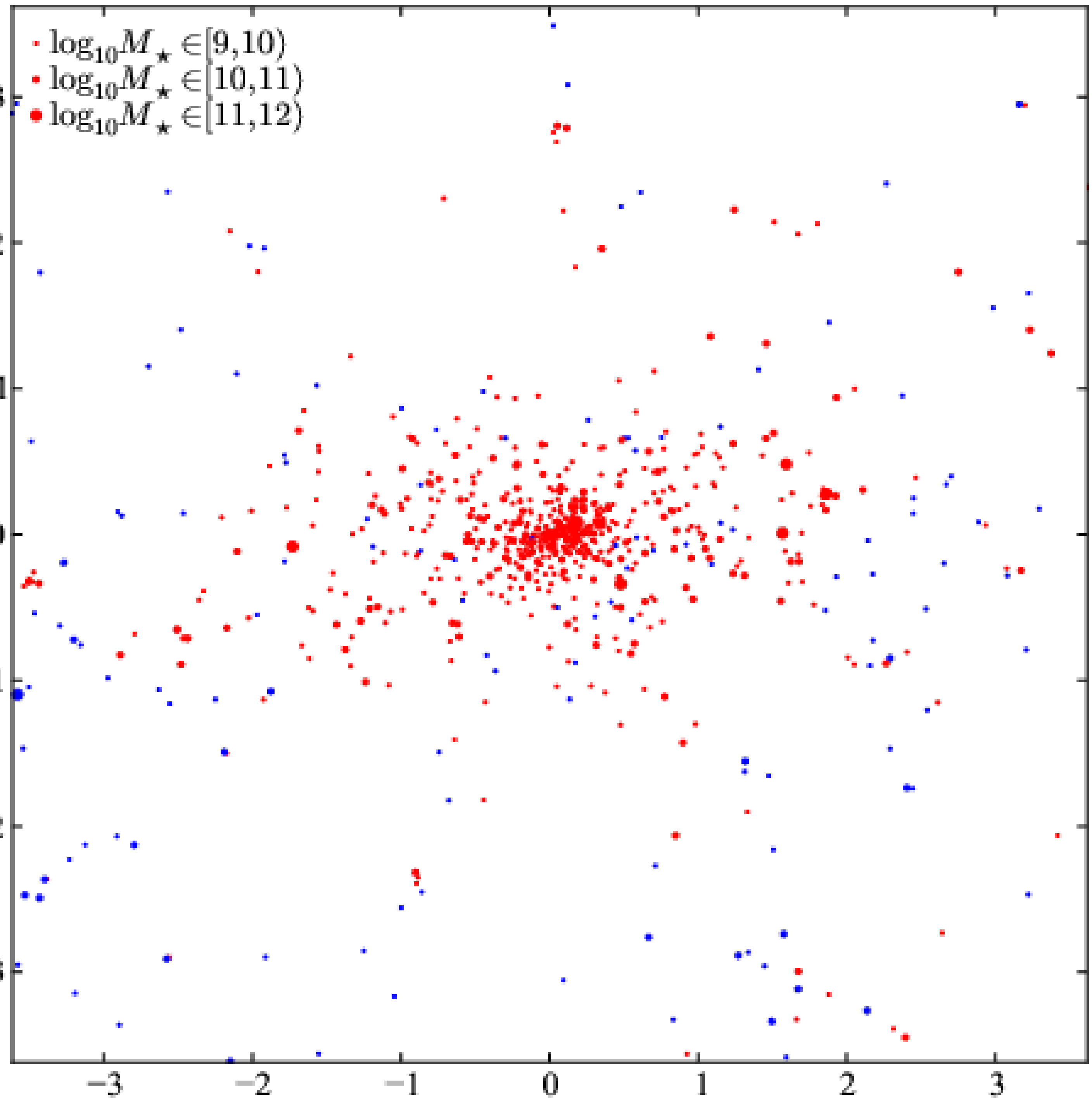




$\log_{10}M_\star \in [9,10)$
$\log_{10}M_\star \in [10,11)$
$\log_{10}M_\star \in [11,12)$
h^{-1} Mpc
MS cluster galaxies in subhalos
h^{-1} Mpc

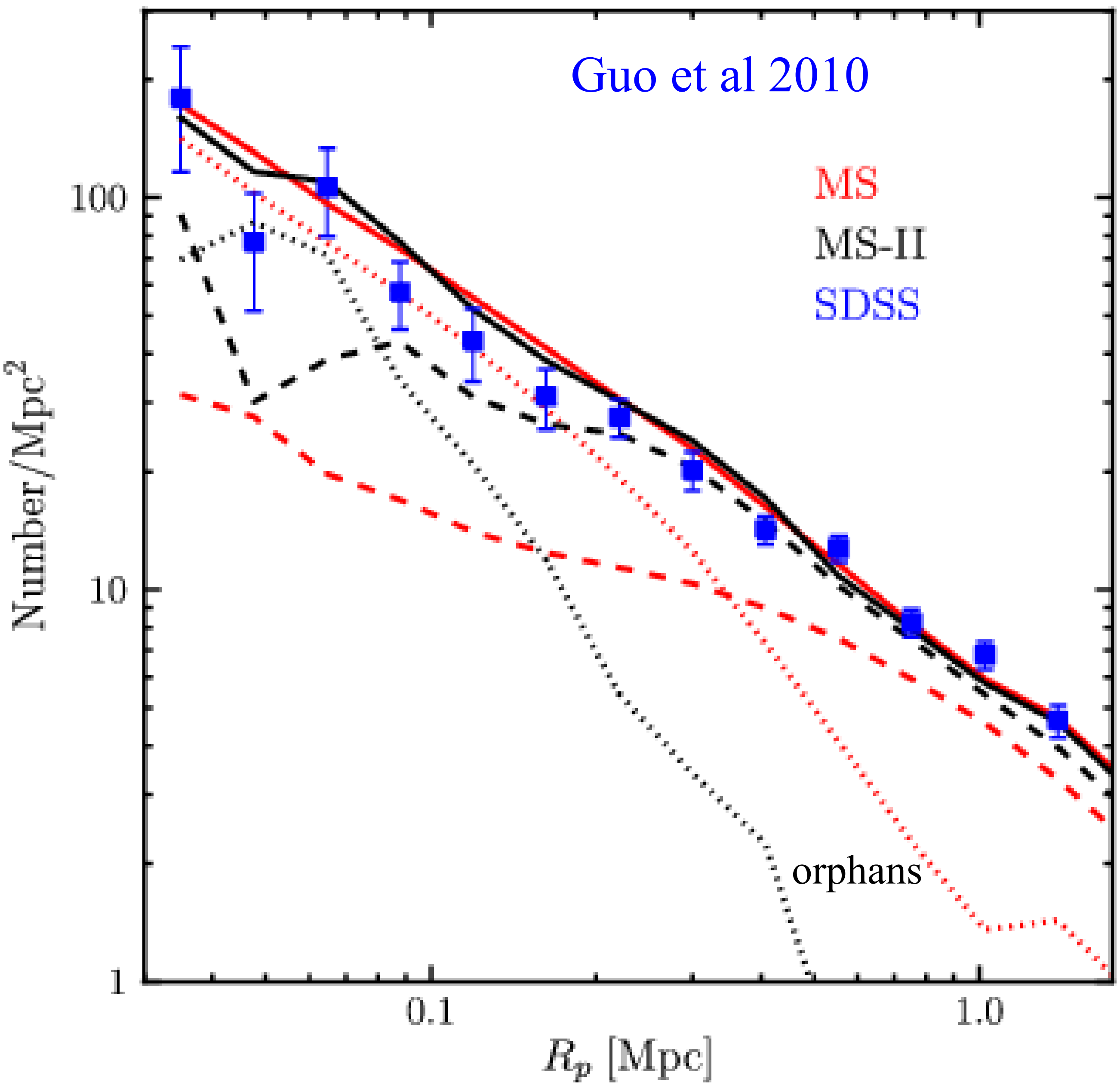
h^{-1} Mpc

MS cluster



h^{-1} Mpc

Projected galaxy number density profiles of clusters



log M_{gal} > 10.0

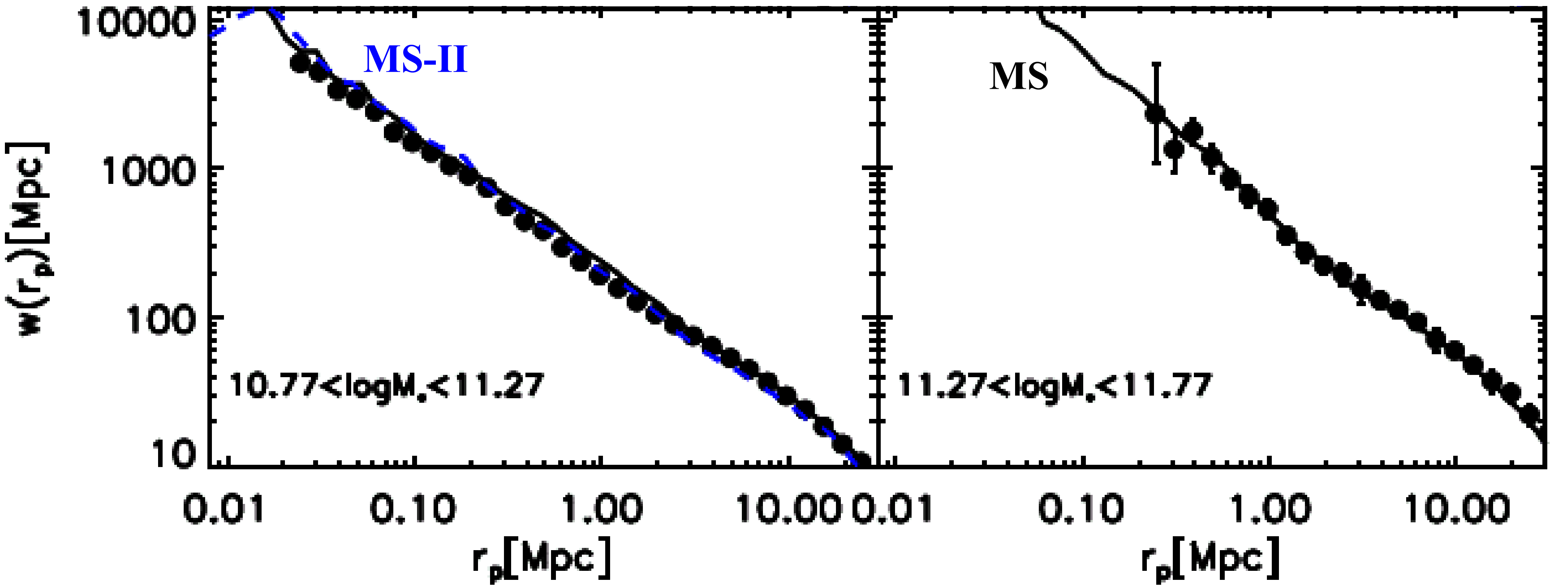
14.0 < log M_{clus} < 14.3

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

Orphan treatment is physically consistent and needed to fit SDSS

Clustering of massive galaxies

Guo et al 2010

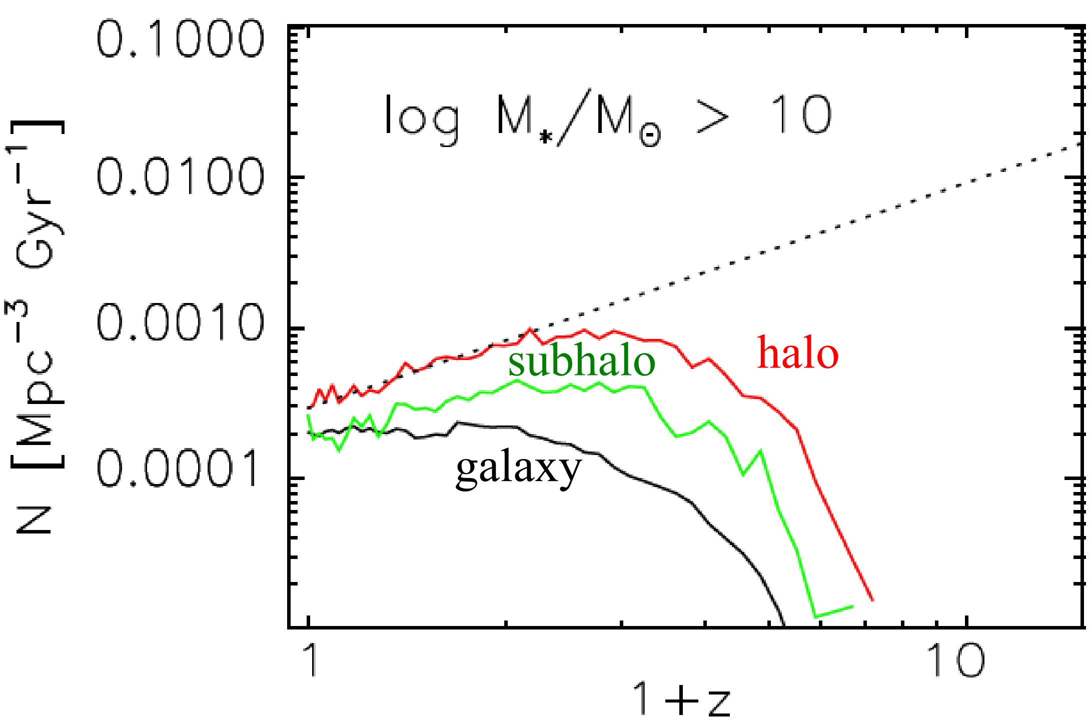


Data from SDSS/DR7

- Halos in simulations do not correspond to galaxies
  - -- many galaxies are satellites within big halos

- Subhalos also do not correspond perfectly to galaxies
  - -- the subhalos of many galaxies are prematurely destroyed
  - -- this has both numerical *and* physical origins

- DM simulations alone, even at high resolution, cannot faithfully predict the galaxy distribution



Kitzbichler & White 2008

How to proceed with model-building?

- Begin with counts!
  - -- luminosity/mass functions, halo/subhalo abundance
- Use clustering measurements!
  - -- correlations, bias estimates, HOD models
- Use assembly history information!
  - -- combine high-z with local (e.g. SDSS) information
  - -- use theoretical assembly history distributions
- Make sure theoretical input precisely reflects the theory
  - -- use appropriate (DM) simulations
- Separate measurement from hypothesis in model-testing

Example: merger rates

- There are **NO** observational measurements of galaxy merger rates at <u>any</u> redshift, even $z = 0$: There are
  - -- measurements of close pair abundances : $n(m_1, m_2, r_p, t)$
  - -- measurements of the abundance of visibly interacting pairs
- The merger rate at $t + \Delta t$ can be written as

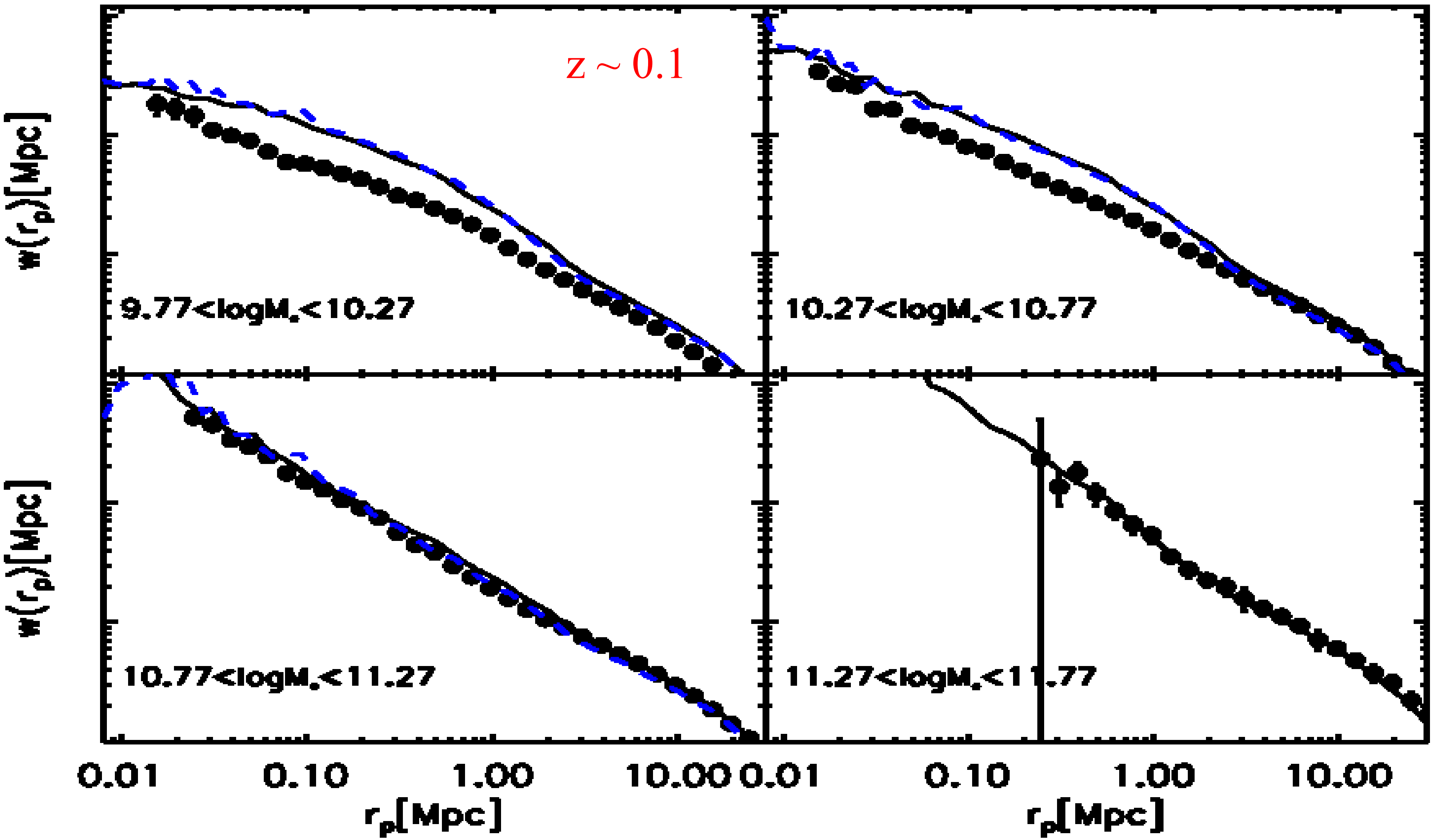
$$n_{mer}(m_1, m_2, t + \Delta t) = \int dr_p \; n(m_1, m_2, r_p, t) \; R(\Delta t \,;\, m_1, m_2, r_p, t)$$

  where R is the (per pair) rate of (m_1, m_2, r_p, t) mergers after Δt

- R is a *theoretical* construct, depending strongly on (m_1, m_2, r_p, t)
- One should compare model predictions of $n(m_1, m_2, r_p, t)$ with the observations, **NOT** predictions of $n_{mer}(m_1, m_2, t)$

Projected correlations in SDSS/DR7 and the MS runs

Guo et al 2010

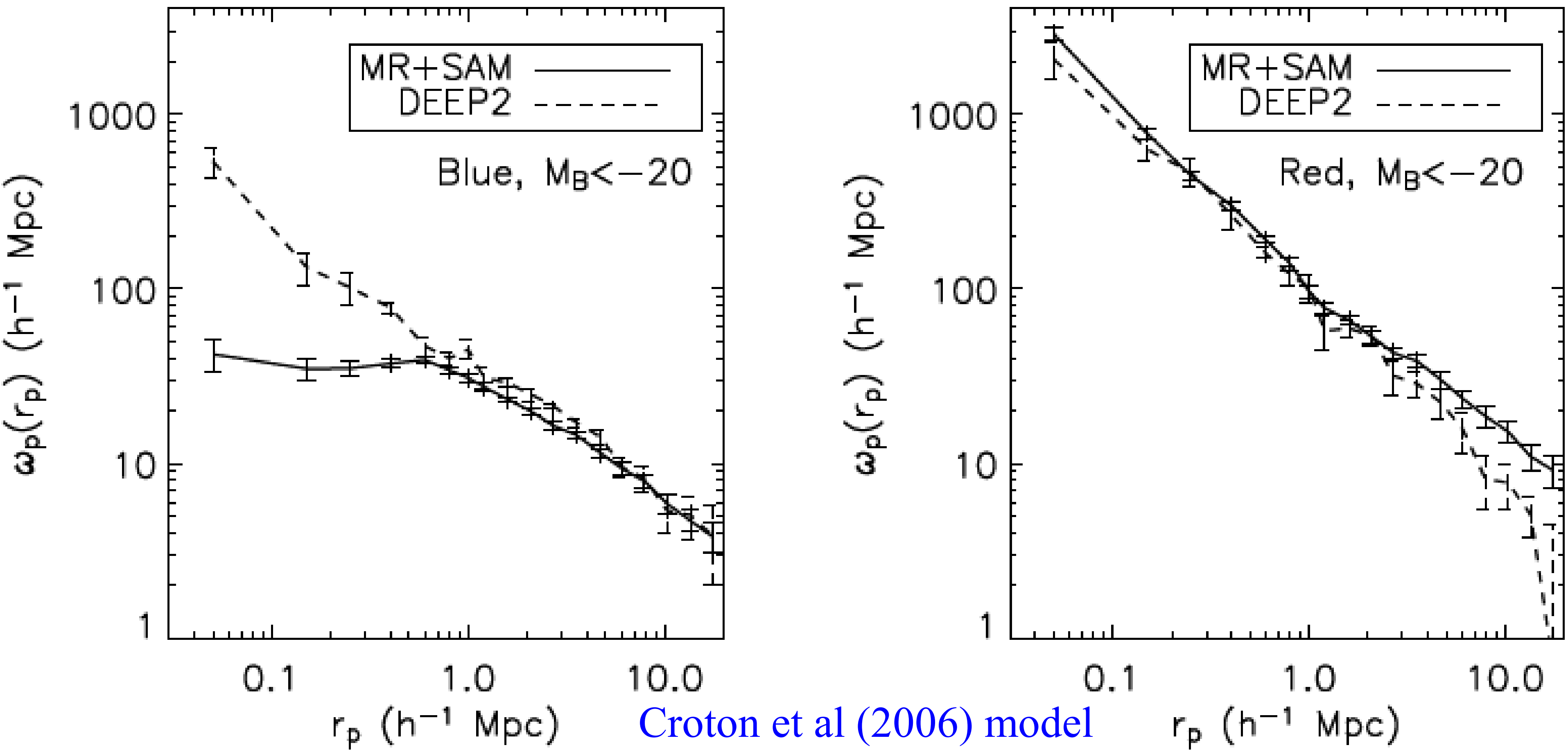


The Millennium simulation galaxy formation models predict the correct number, or somewhat *too many* close pairs – major merger progenitors

Projected correlations in DEEP2 and the MS runs

Coil et al 2008

z ~ 0.7

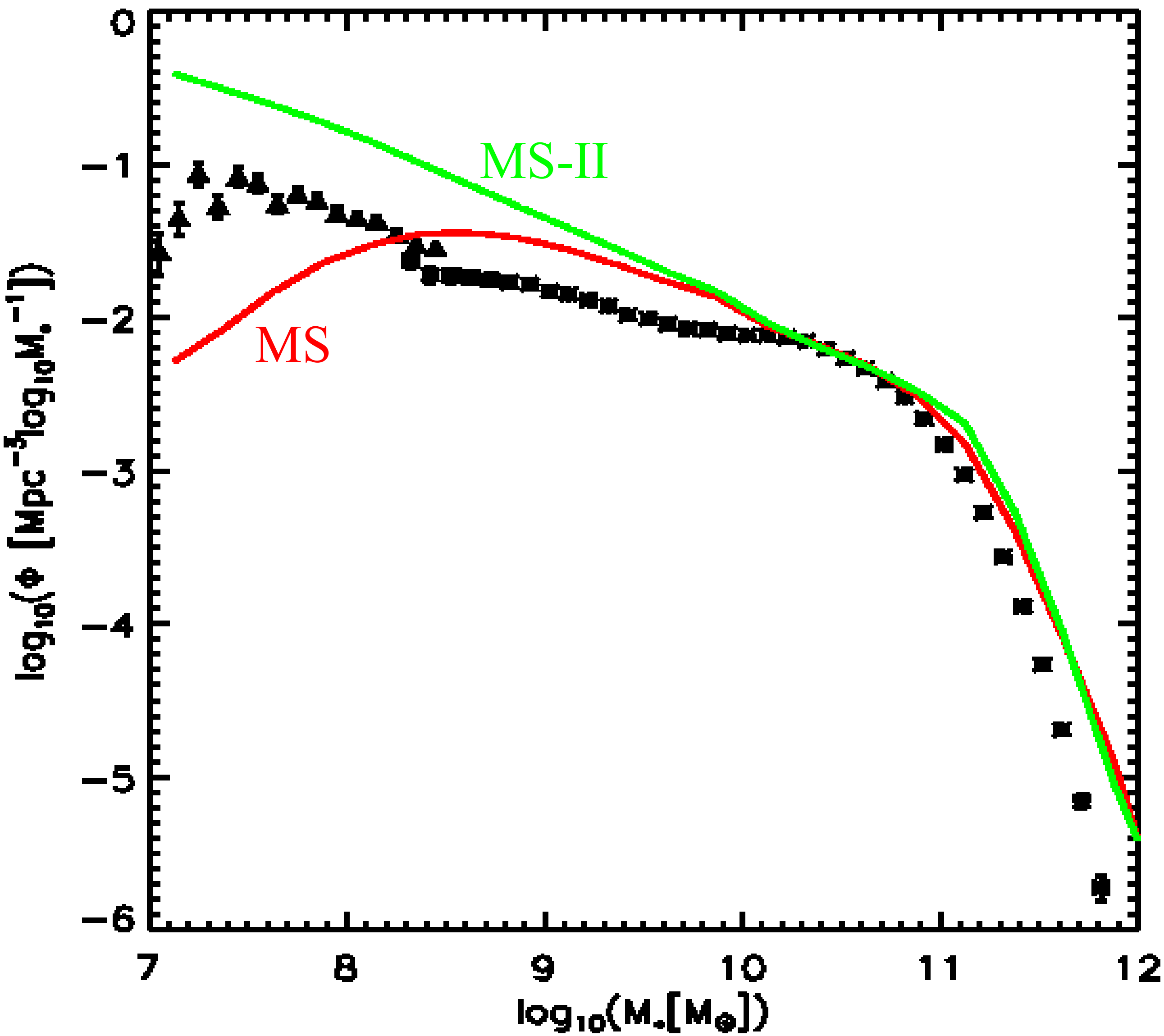


Croton et al (2006) model

The Millennium simulation galaxy formation models predict the correct number, or somewhat *too many* close pairs – major merger progenitors

Counting galaxies at low redshift

Guo et al 2010

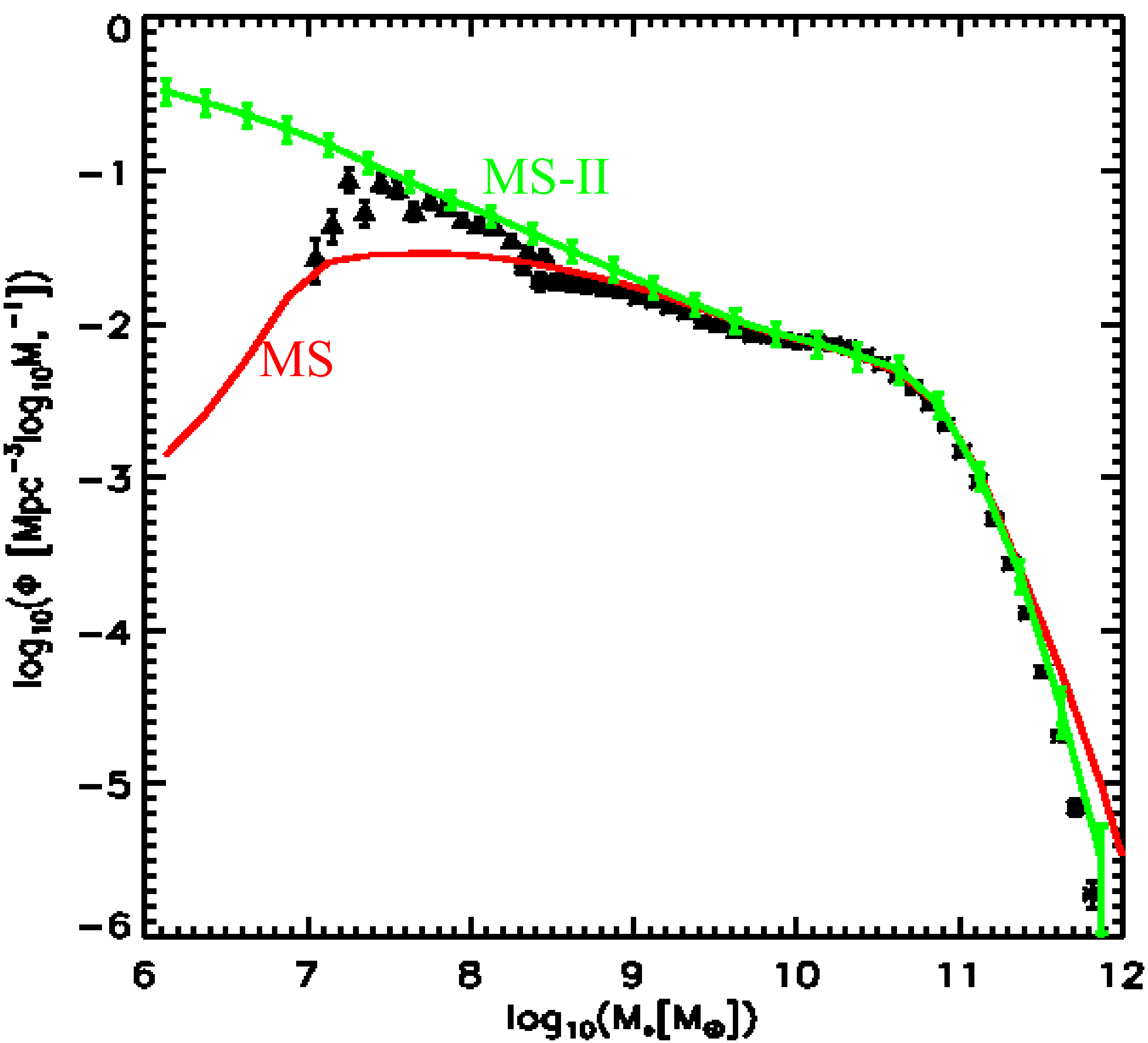


SDSS/DR7 mass functions cover 5 dex in M_* with very small error bars above $10^8\,M_\odot$

The old MS models do not fit well when applied to MS-II

Counting galaxies at low redshift

Guo et al 2010



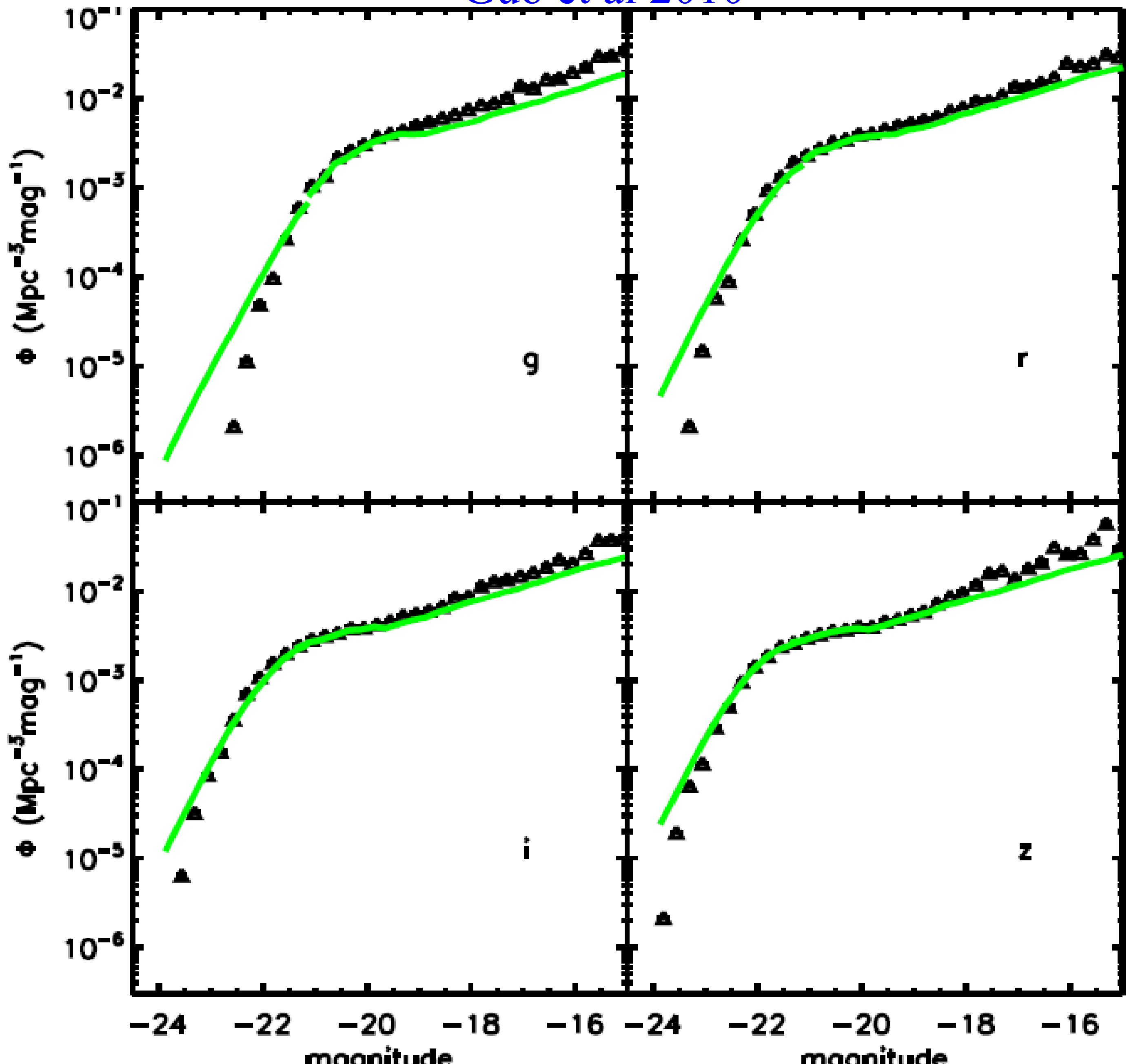
SDSS/DR7 mass functions cover 5 dex in M_* with very small error bars above $10^8\,M_\odot$

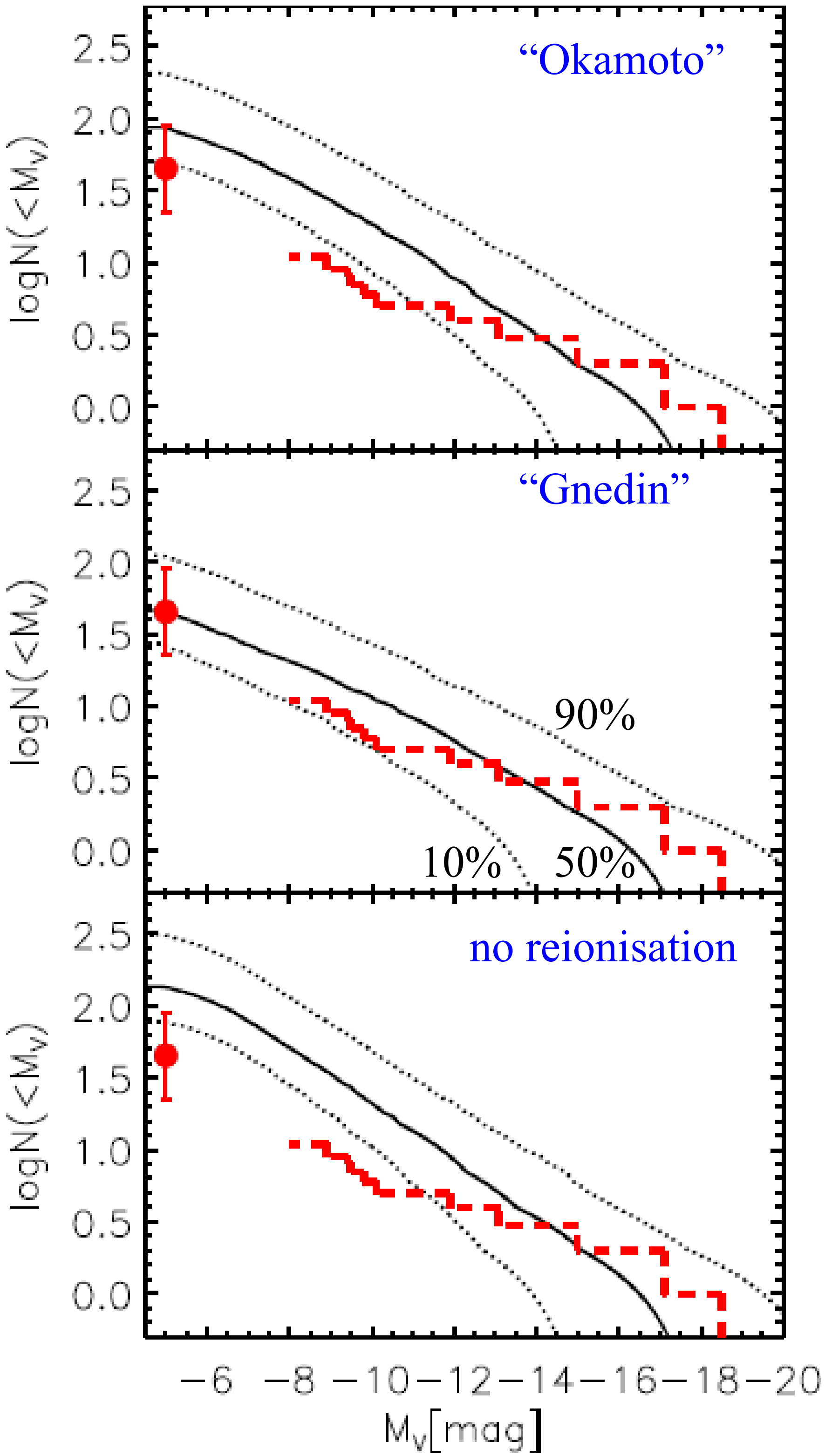
The old MS models do not fit well when applied to MS-II

The new models fit much better

Luminosity functions of galaxies

Guo et al 2010





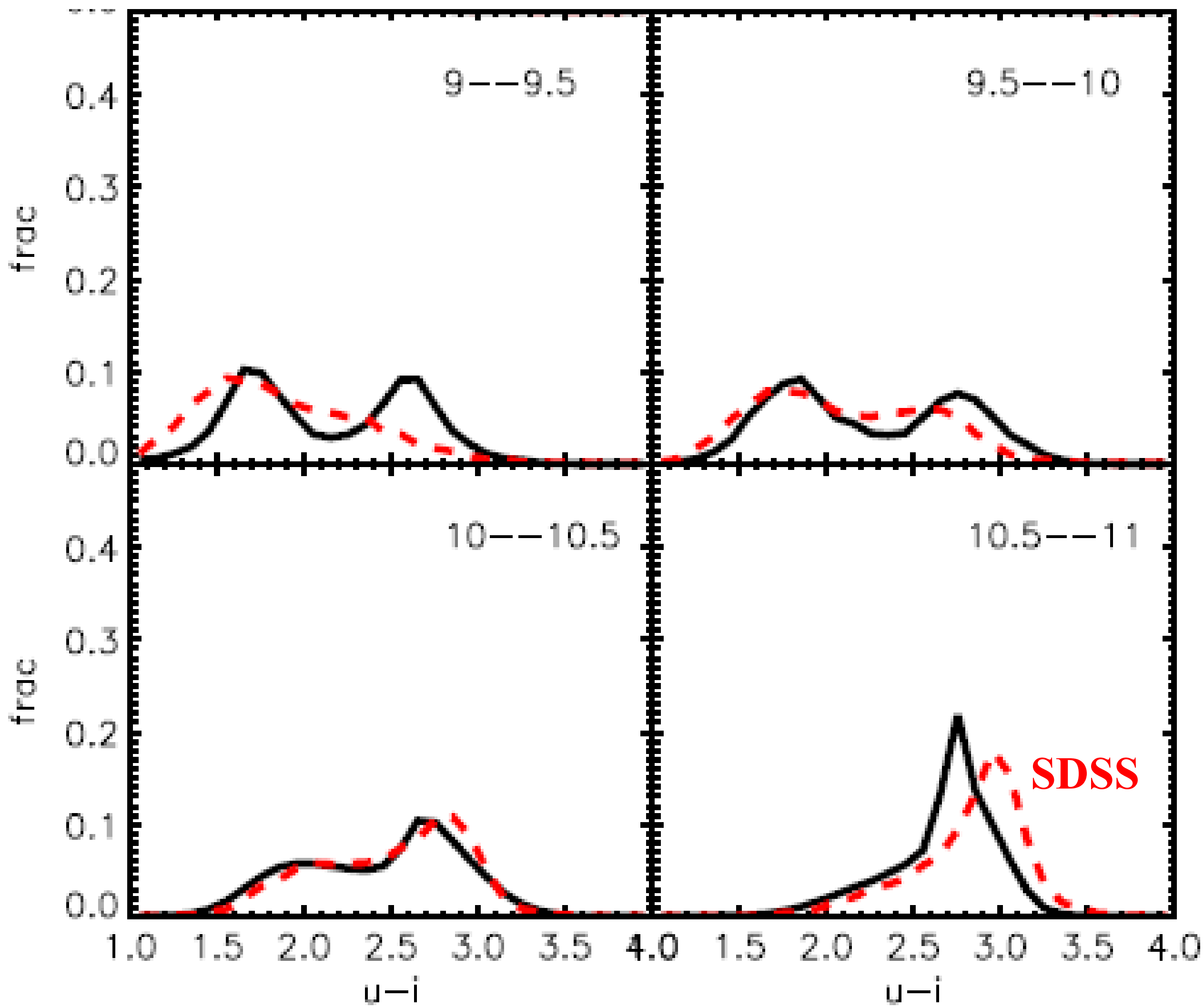
Luminosity function of Milky Way satellites

Guo et al 2010

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

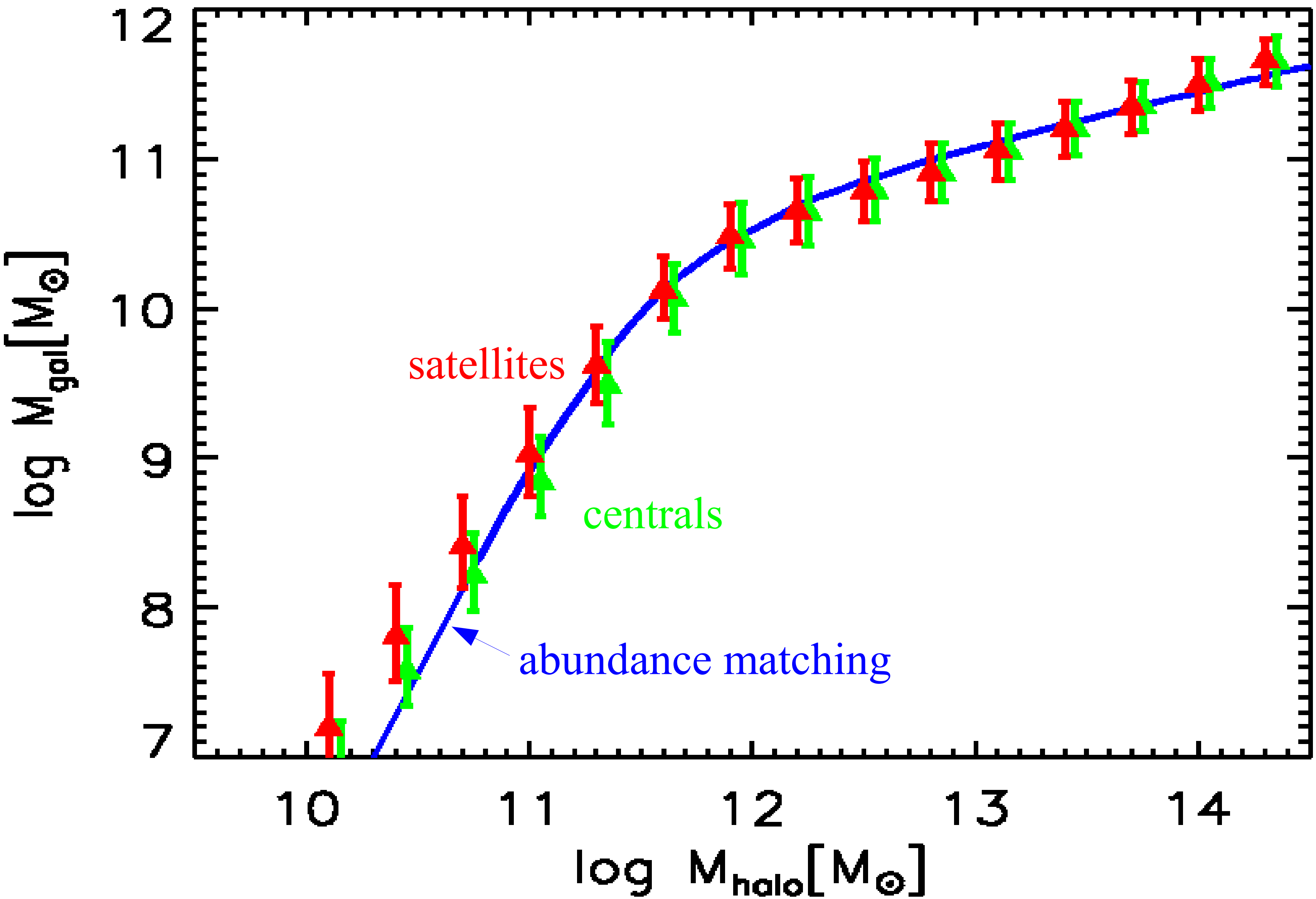
Galaxy colour distributions

Guo et al 2010



Stellar mass versus maximum past halo mass

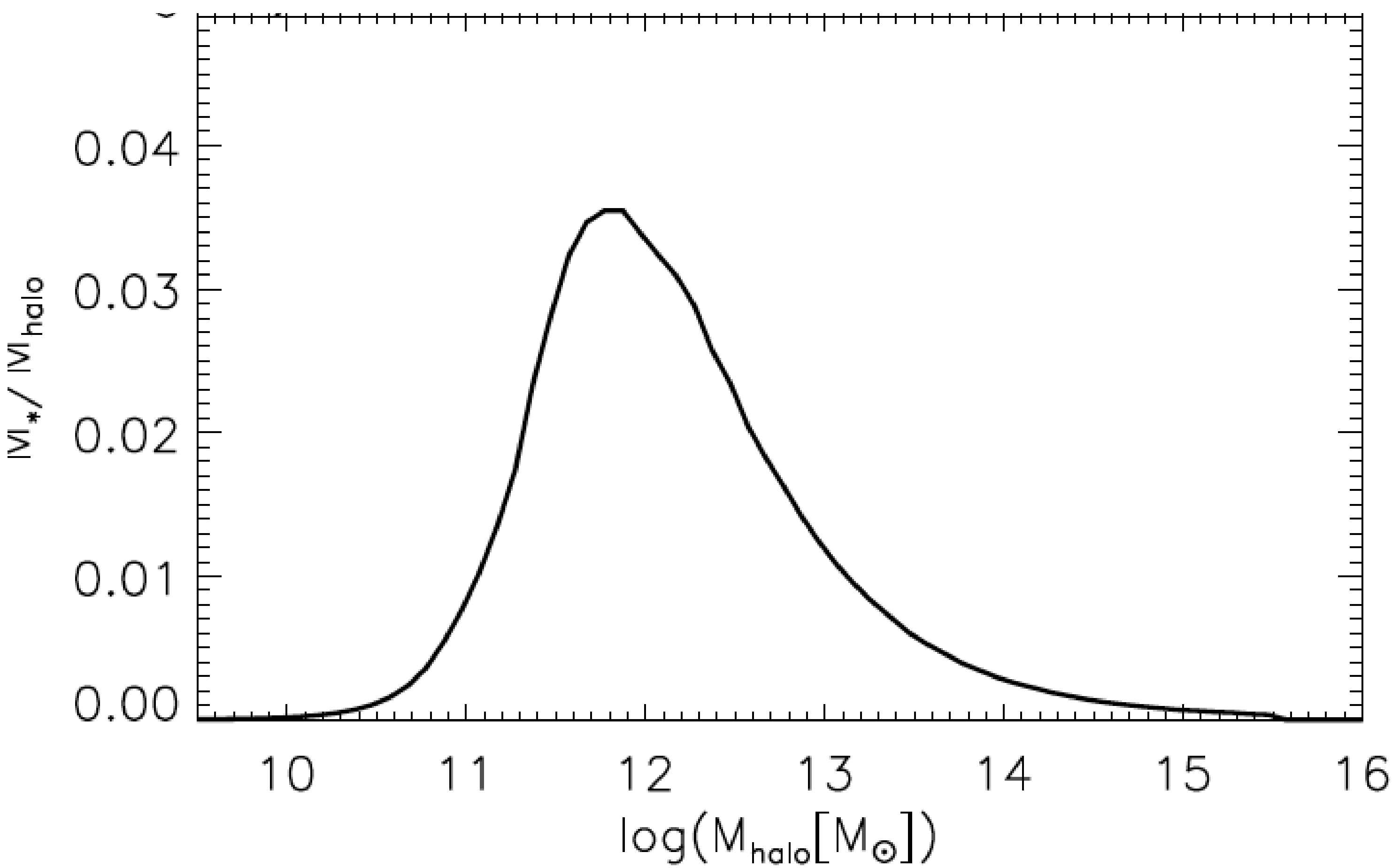
Guo et al 2010



Detailed simulation fits abundance matching result with small scatter

The efficiency of galaxy formation is low!

Guo et al 2010

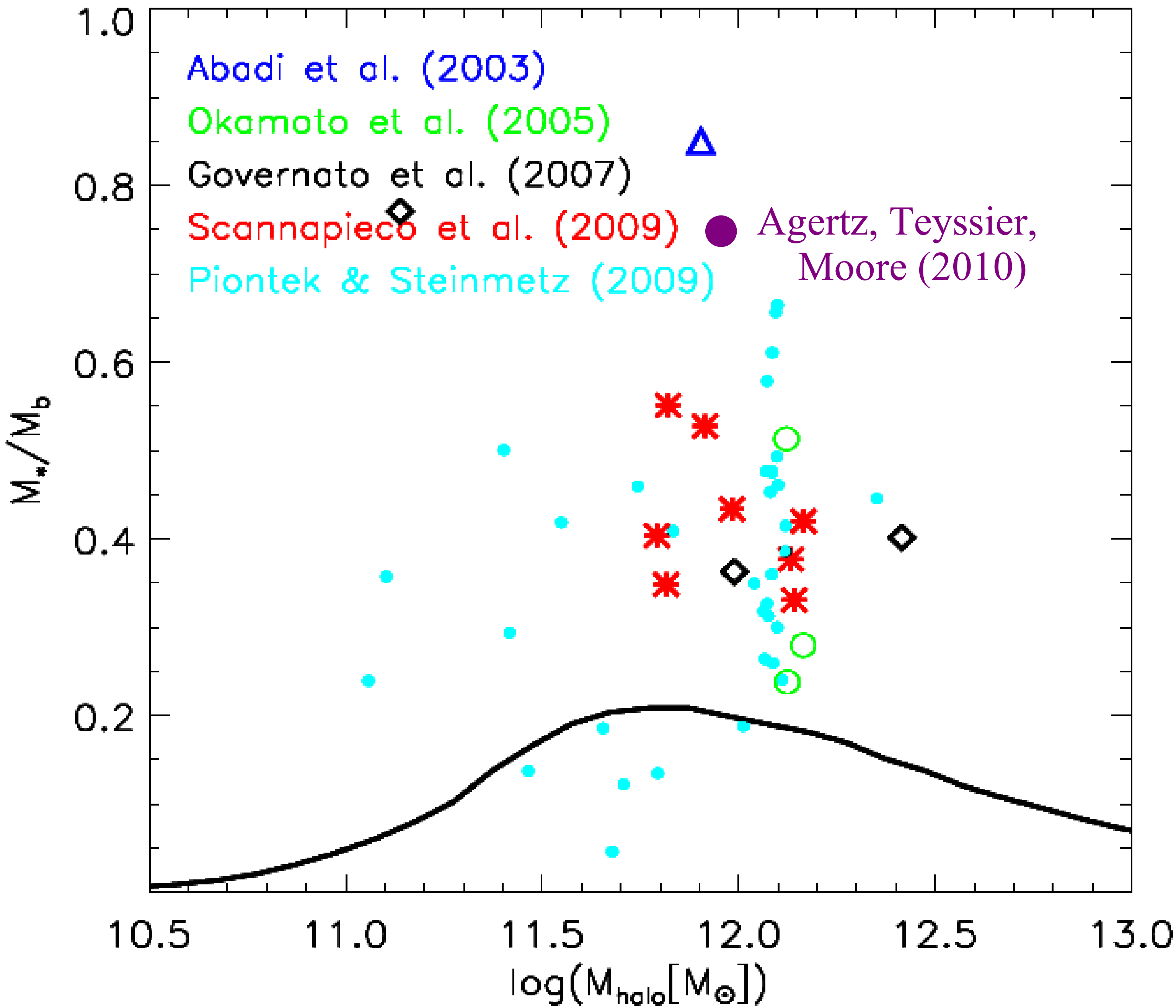


The ratio of central galaxy stellar mass to maximum past halo mass *maximises* at just 3.5% at halo masses of $\sim 10^{12} M_\odot$

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

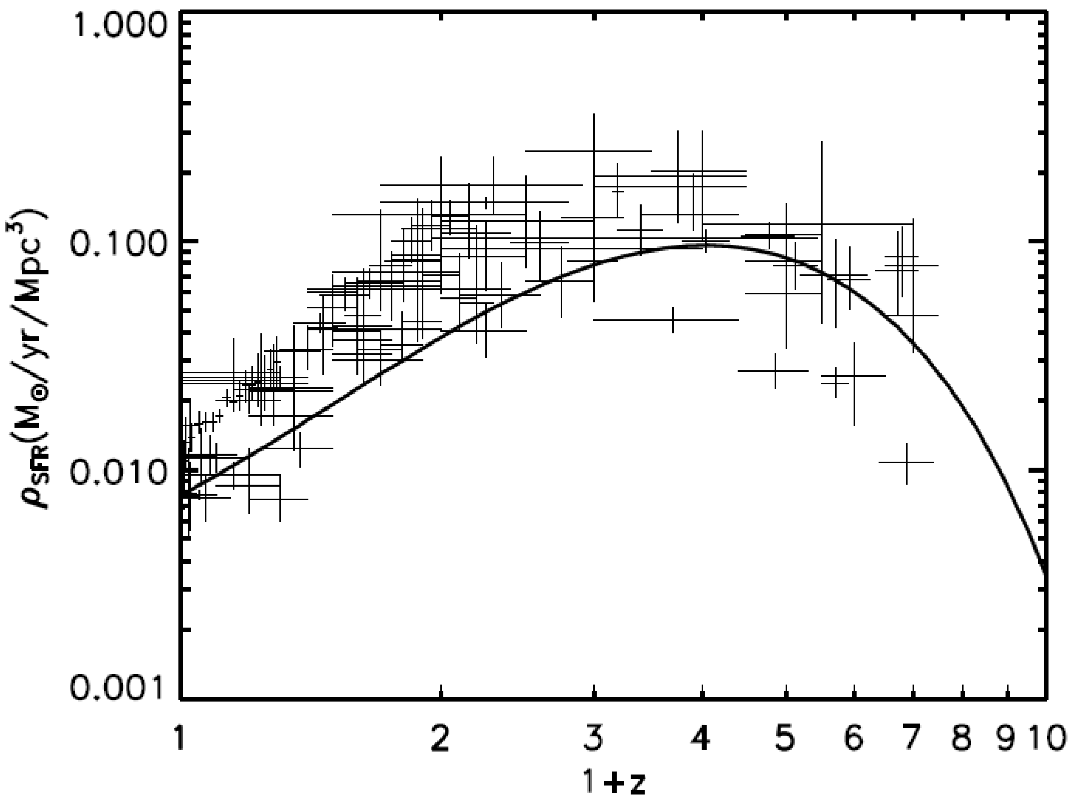
"Successful" simulations fail to match this

Guo et al 2010



The cosmic star formation density history

Guo et al 2010

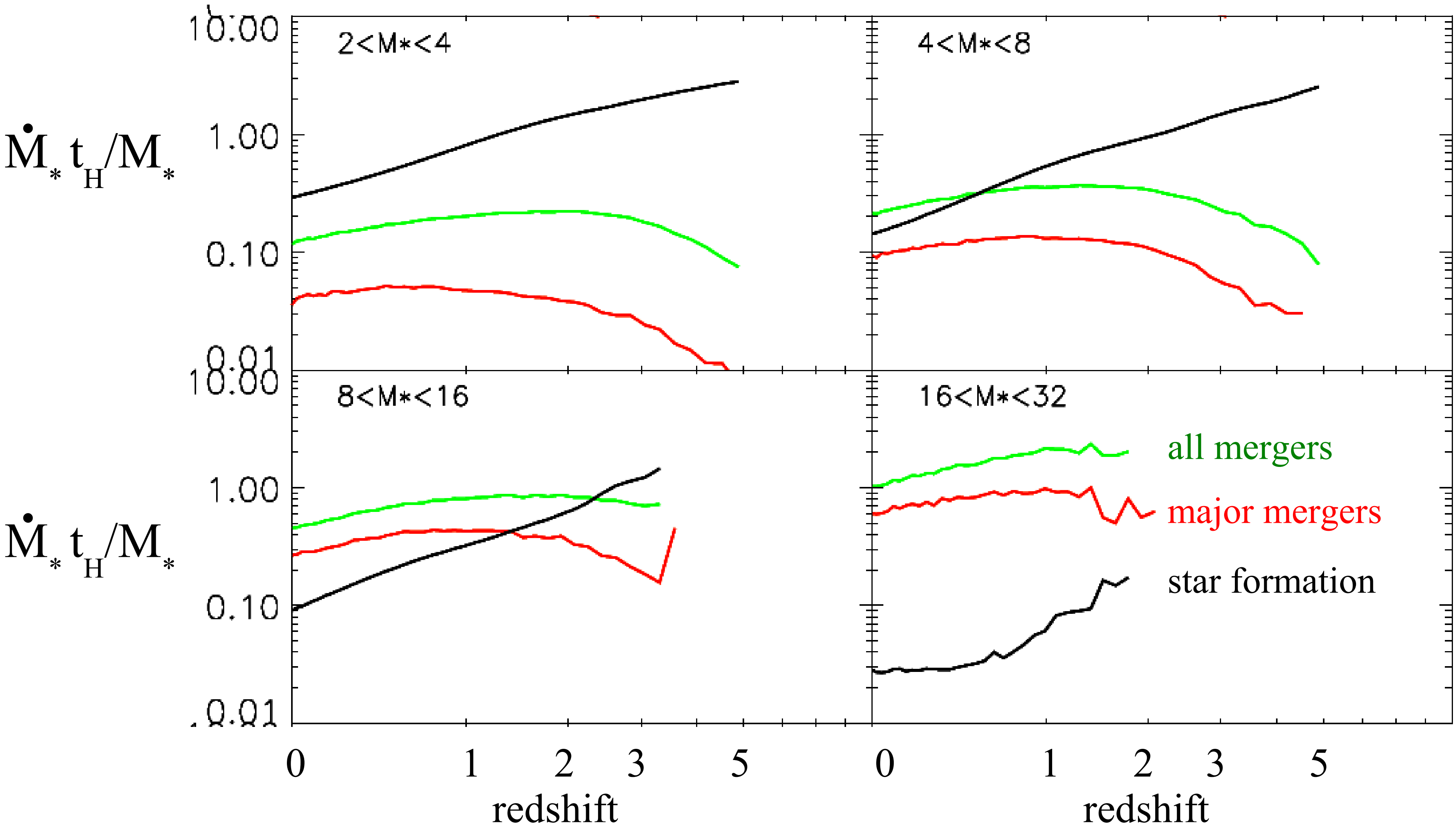


--- observed SFR are inconsistent with observed stellar masses ---

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

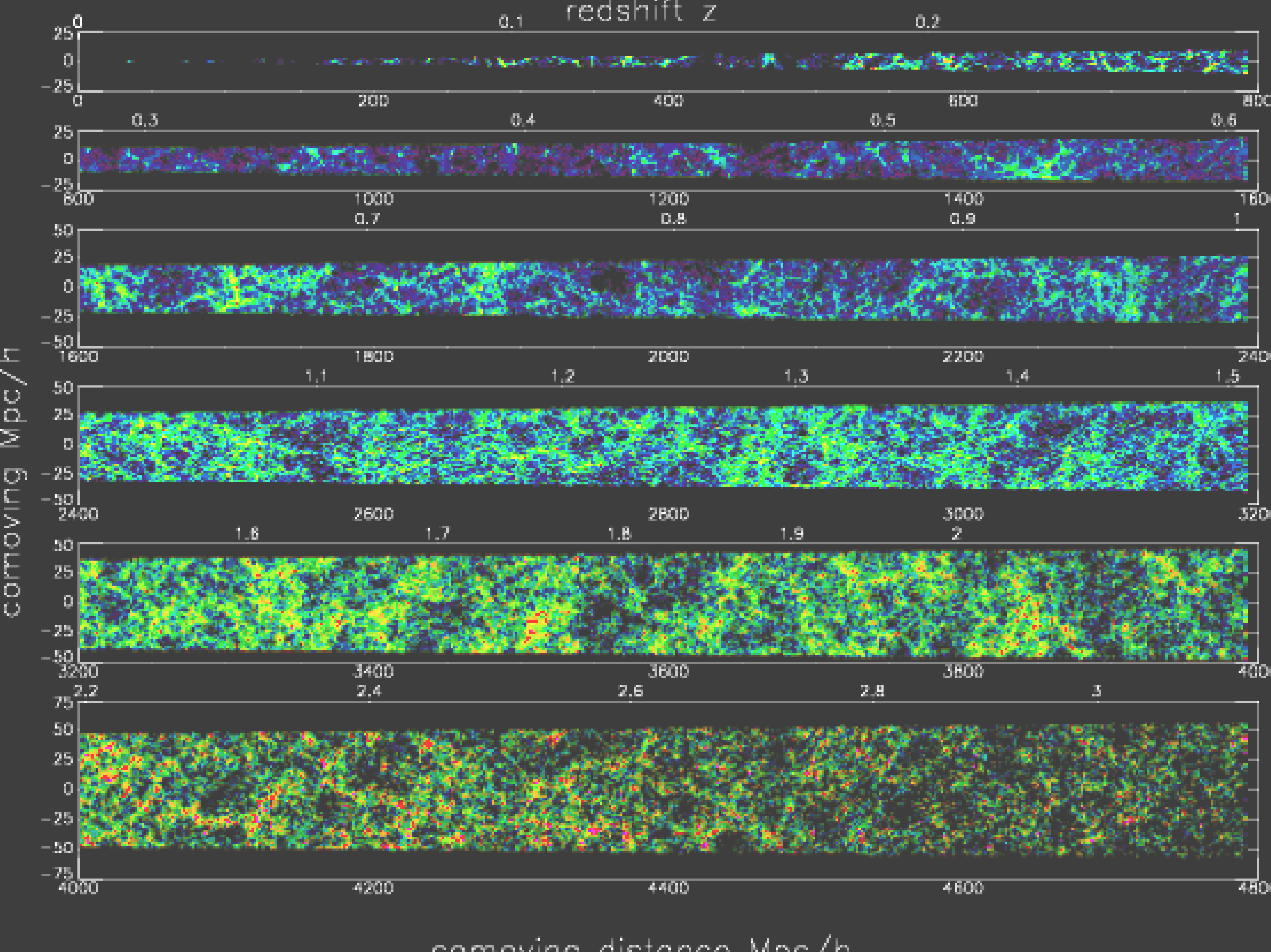
Galaxy growth through mergers and star formation

Guo & White 2008

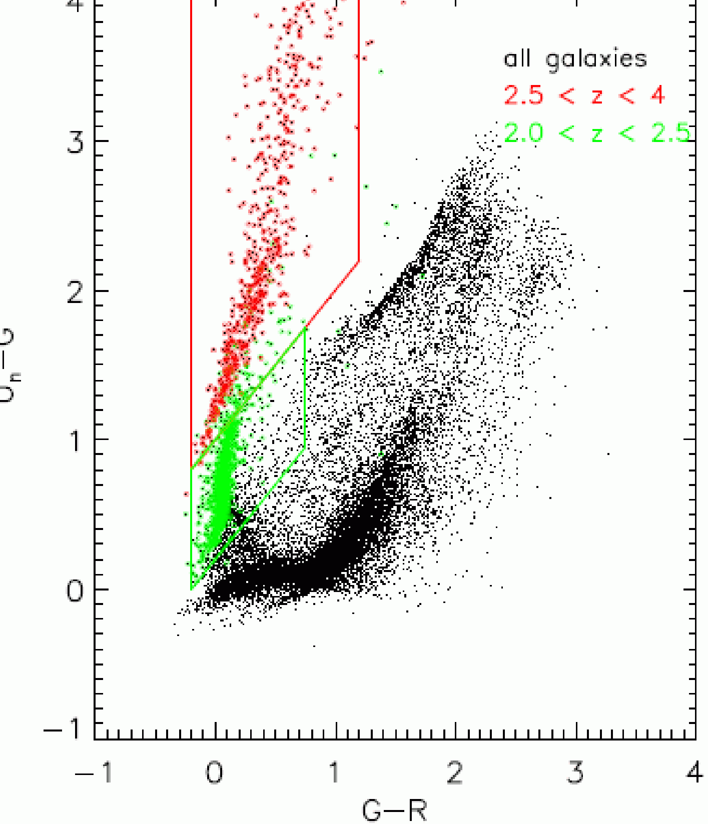


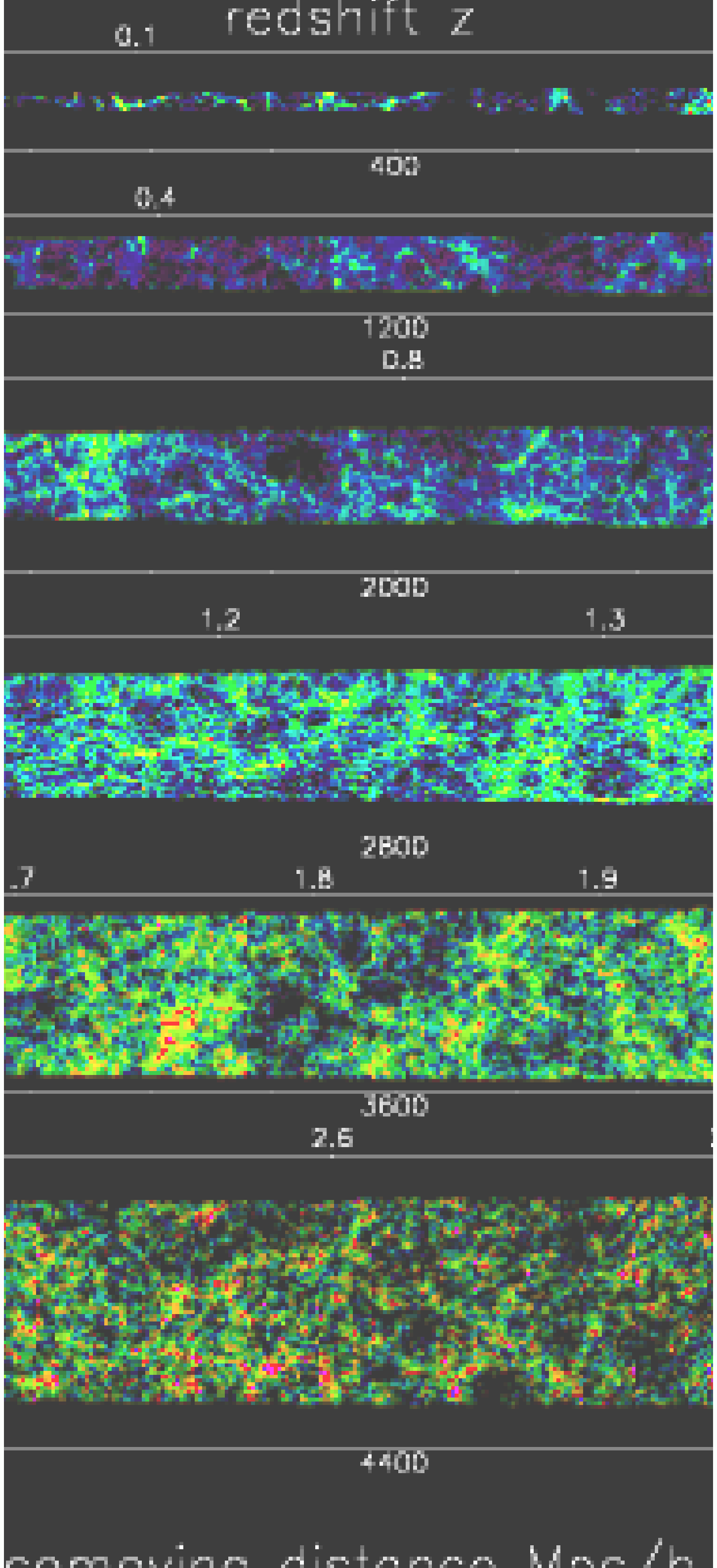
More massive galaxies have lower SSFR at *all* redshifts

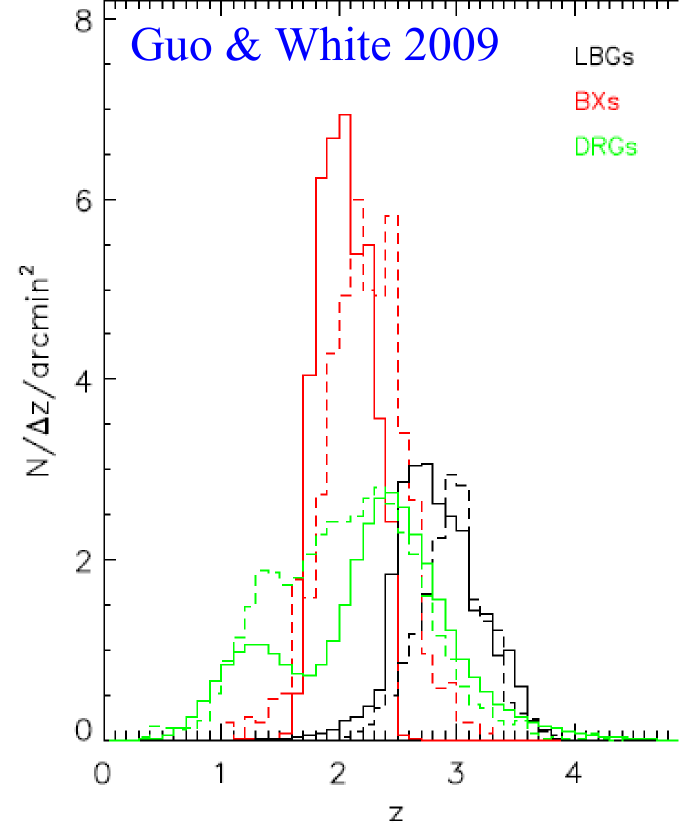
Mergers dominate SF growth at low z and low stellar mass

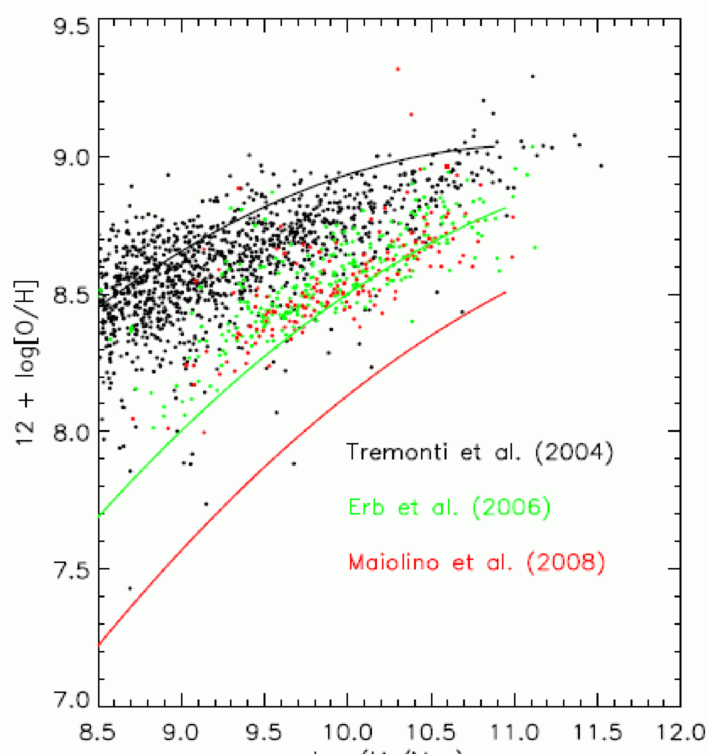


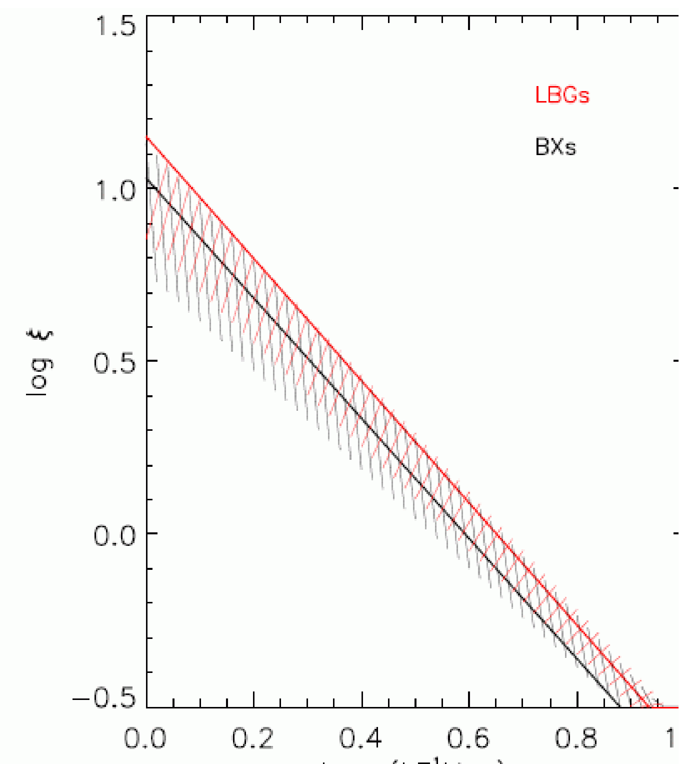
redshift z
0 0.1 0.2
25 0 −25
0 200 400 600 800
0.3 0.4 0.5 0.6
25 0 −25
800 1000 1200 1400 1600
0.7 0.8 0.9 1
50 25 0 −25 −50
1600 1800 2000 2200 2400
1.1 1.2 1.3 1.4 1.5
50 25 0 −25 −50
2400 2600 2800 3000 3200
1.6 1.7 1.8 1.9 2
50 25 0 −25 −50
3200 3400 3600 3800 4000
2.2 2.4 2.6 2.8 3
75 50 25 0 −25 −50 −75
4000 4200 4400 4600 4800
comoving Mpc/h
comoving distance Mpc/h

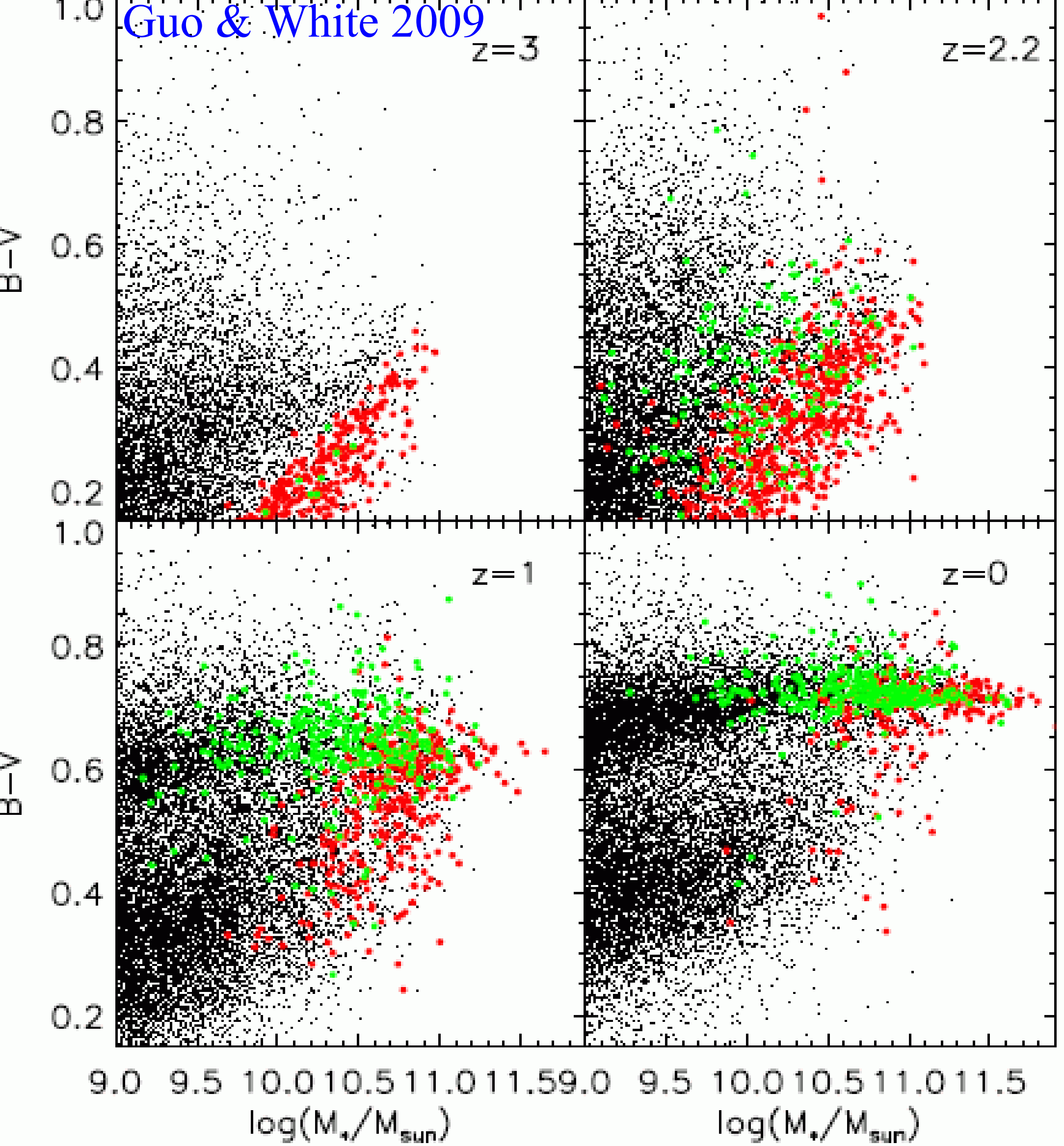

all galaxies
2.5 < z < 4
2.0 < z < 2.5
G−R

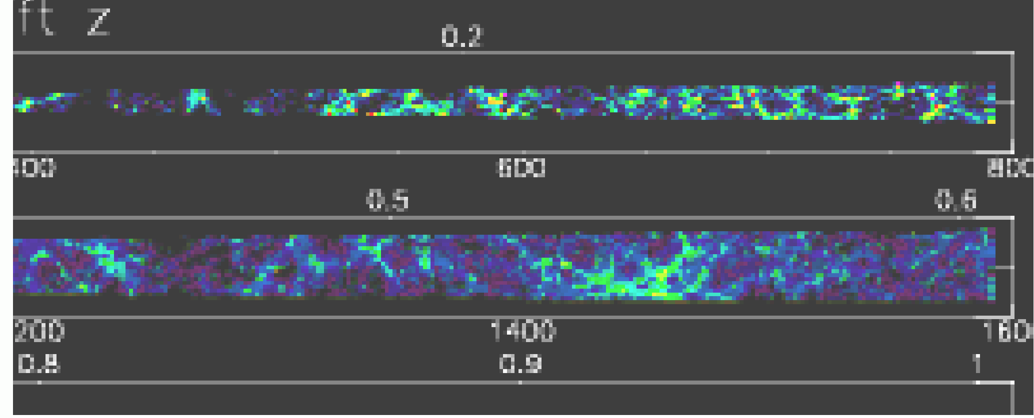

redshift z
0.1
400
0.4
1200
0.8
2000
1.2
1.3
2800
1.8
1.9
3600
2.6
4400

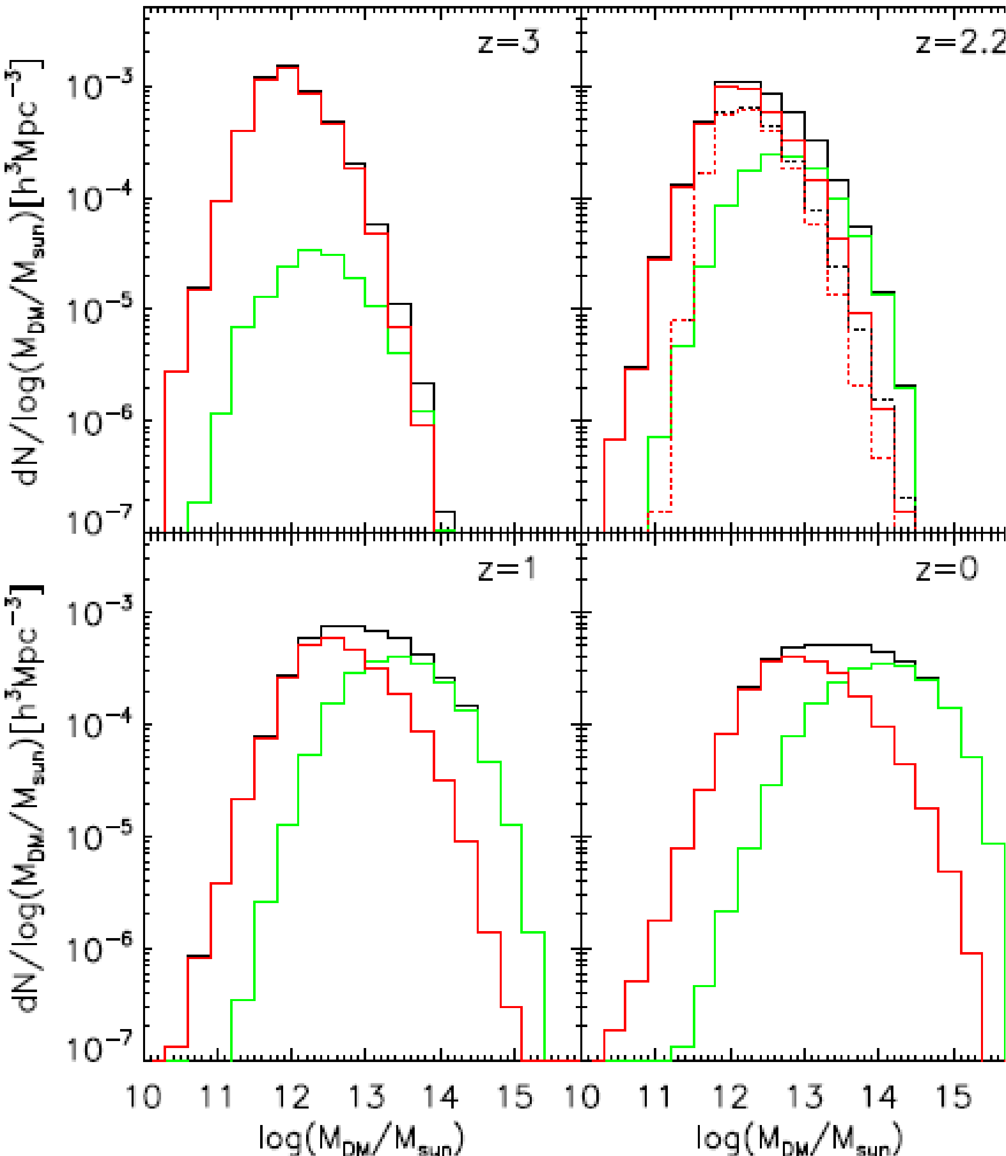

Guo & White 2009
LBGs
BXs
DRGs
N/Δz/arcmin²
z

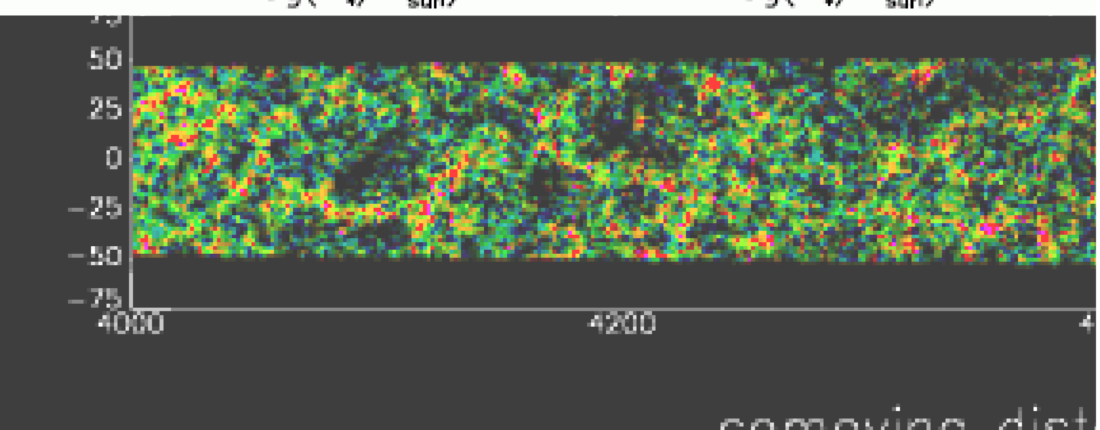

12 + log[O/H]
Tremonti et al. (2004)
Erb et al. (2006)
Maiolino et al. (2008)

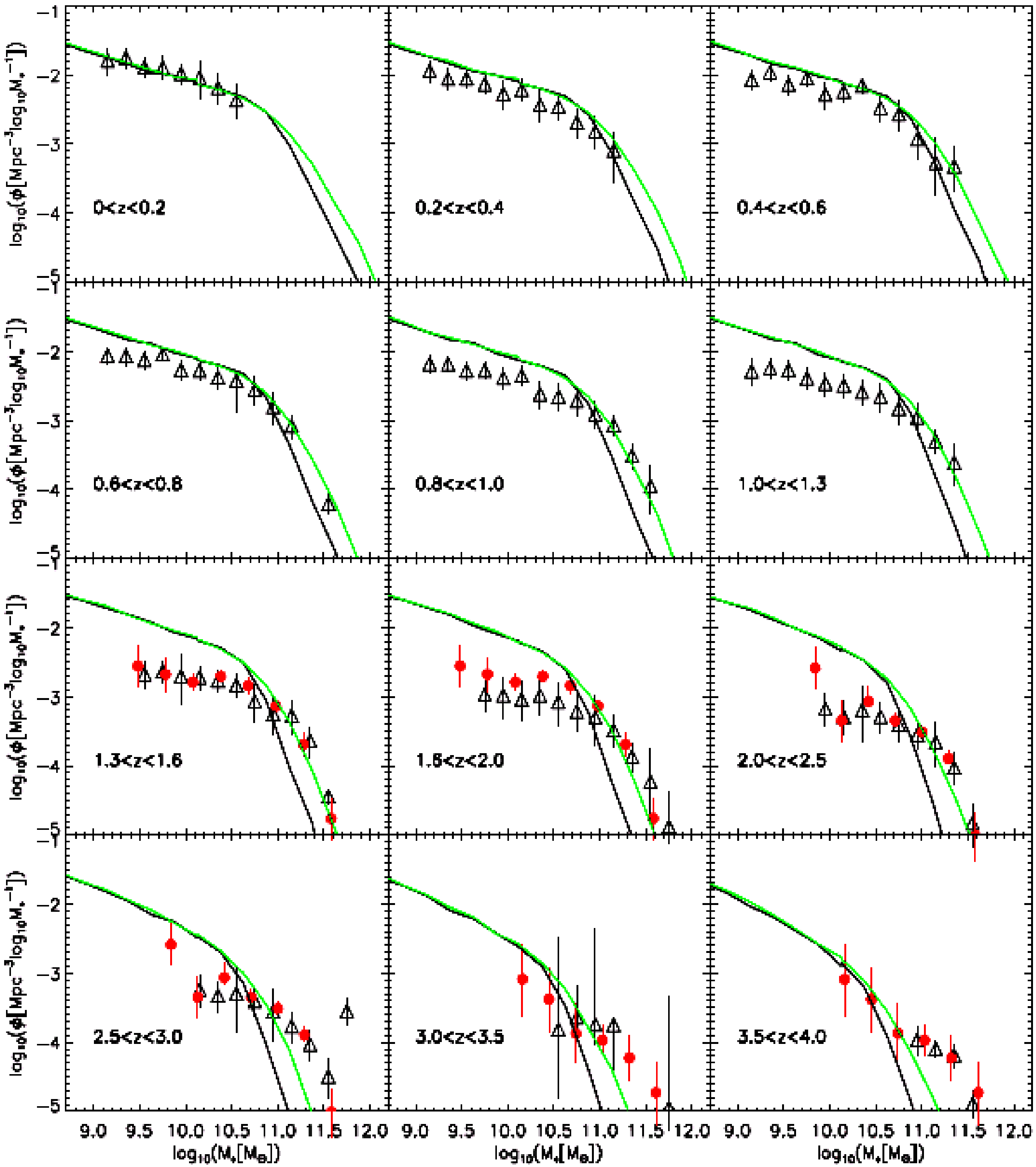

LBGs
BXs
log ξ


Guo & White 2009
z=3
z=2.2
z=1
z=0
B−V
1.0
0.8
0.6
0.4
0.2
9.0 9.5 10.0 10.5 11.0 11.5
log(M*/Msun)


0.2
0.5
0.6
0.8
0.9
1
600
1400


z=3
z=2.2
z=1
z=0
dN/log(MDM/Msun)[h3Mpc−3]
10−3
10−4
10−5
10−6
10−7
10 11 12 13 14 15
log(MDM/Msun)


50
25
0
−25
−50
−75
4000
4200



Evolution of stellar mass function

Guo et al 2010

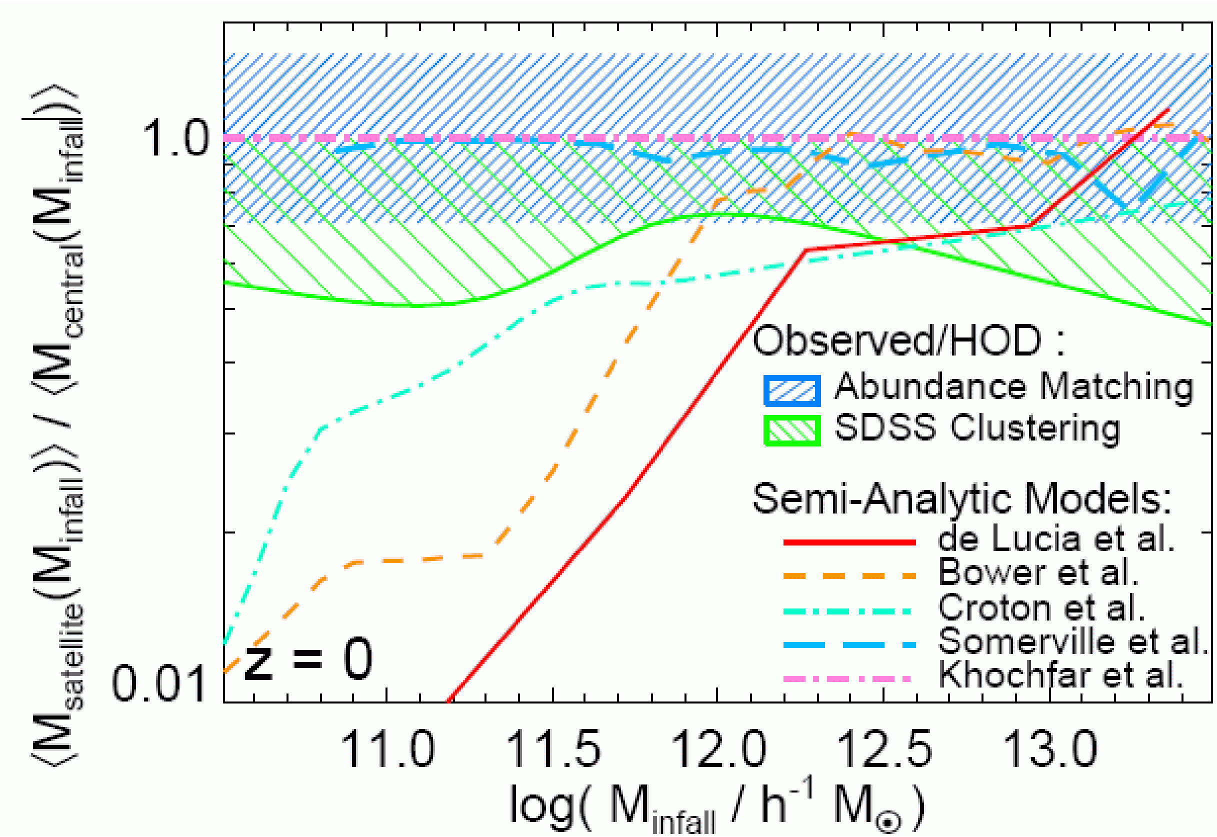
Lower mass galaxies
log $M_* < 10.5$
form too early

Data from
Gonzalez-Perez et al 2008
Marchesini et al 2009

Summary

- Distinguish observational measurement from model hypothesis
- Use models which match ΛCDM expectations precisely
- Distinguish clarification of astrophysics from tests of ΛCDM
- Galaxy formation efficiency is <u>low</u>, $< 20\%$ in each DM halo. Simulations which do not match this are not viable
- Models which populate resolved DM subhalos with galaxies cannot match observed small-scale clustering accurately
- Current models can match abundances, colours, morphologies and clustering of low z galaxies, but produce galaxies of MW mass too early --- better star formation modelling needed

Hopkins et al 2010



Wang et al 2006