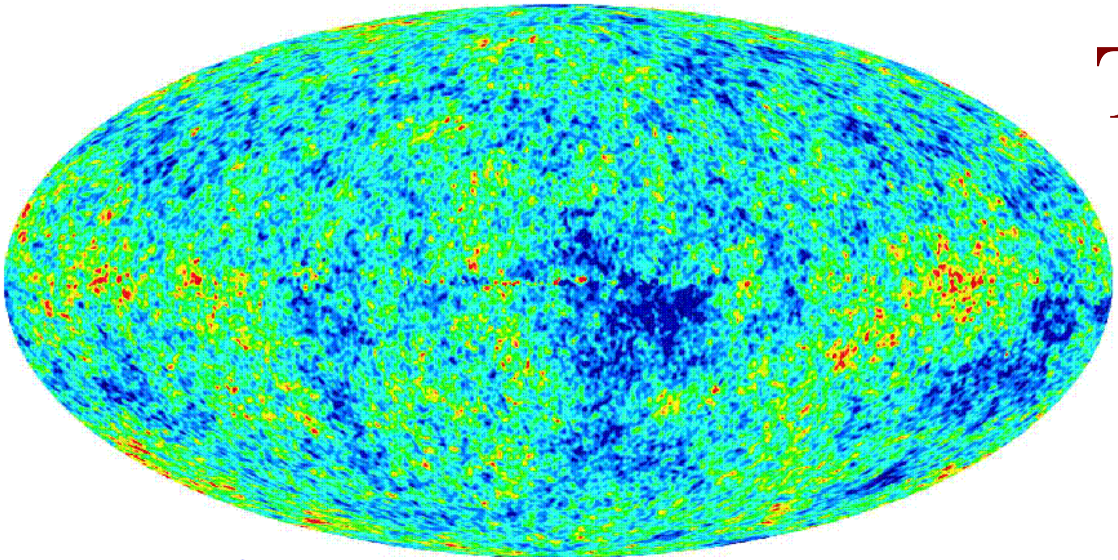
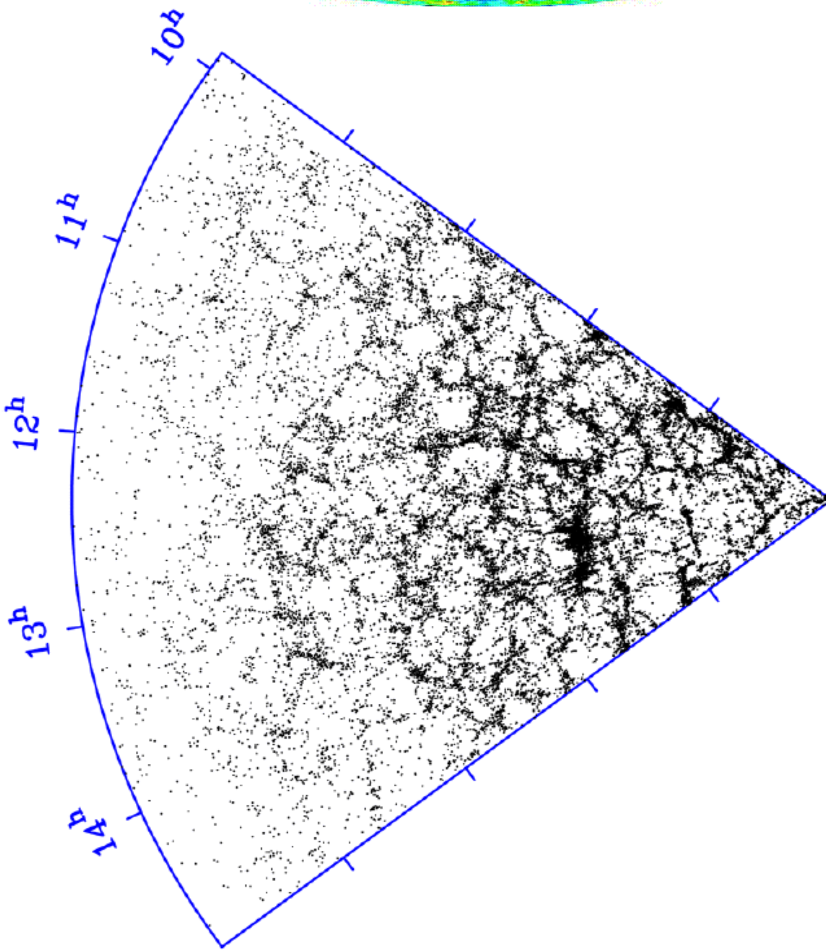
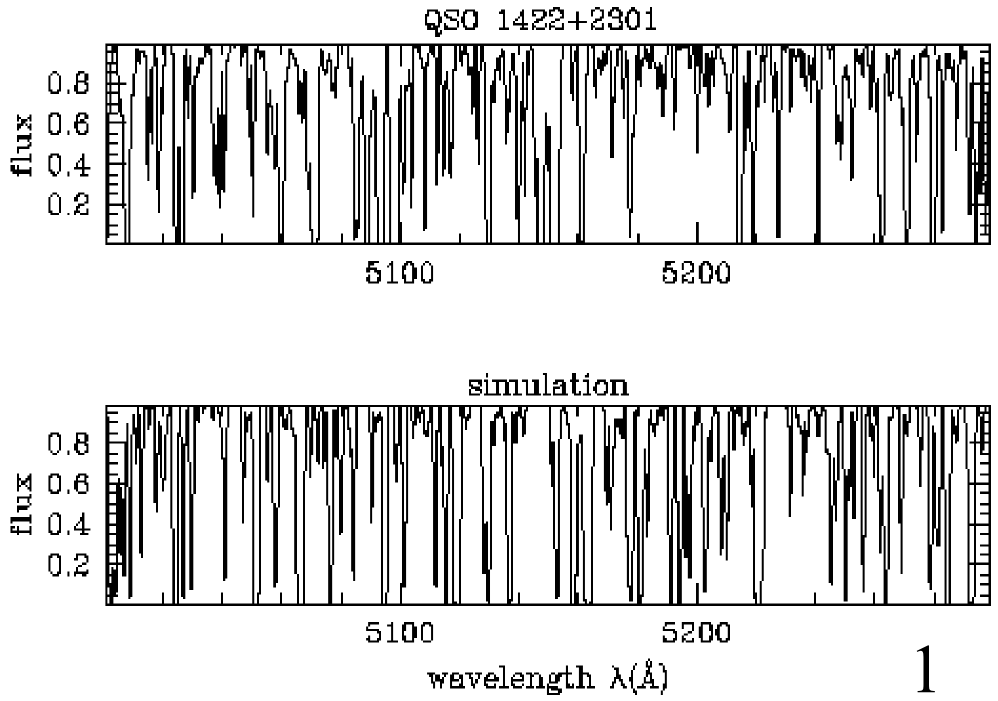


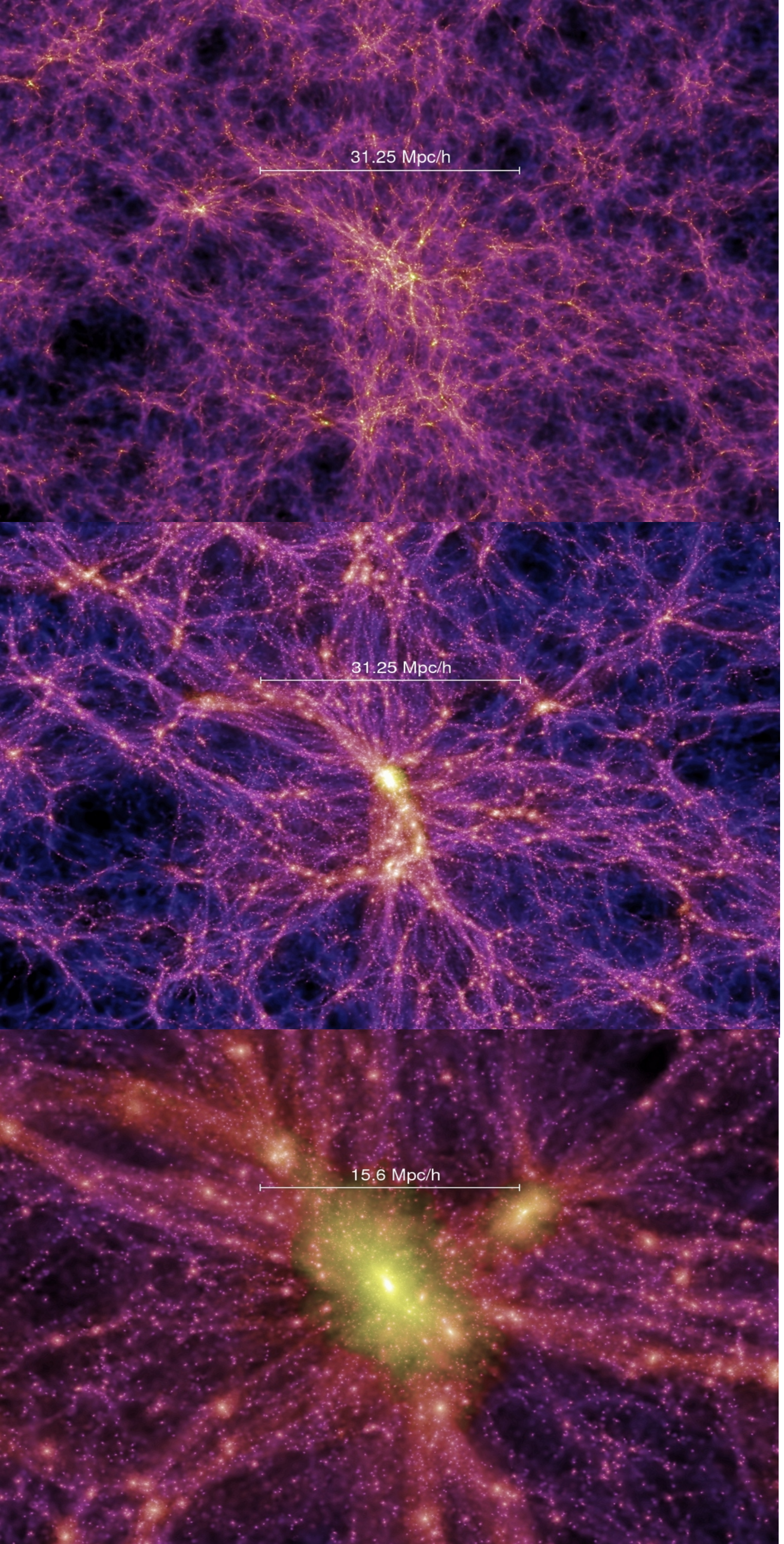
The baryon budget of galaxies

Kloster Seeon 2011

Simon White
Max Planck Institut für Astrophysik





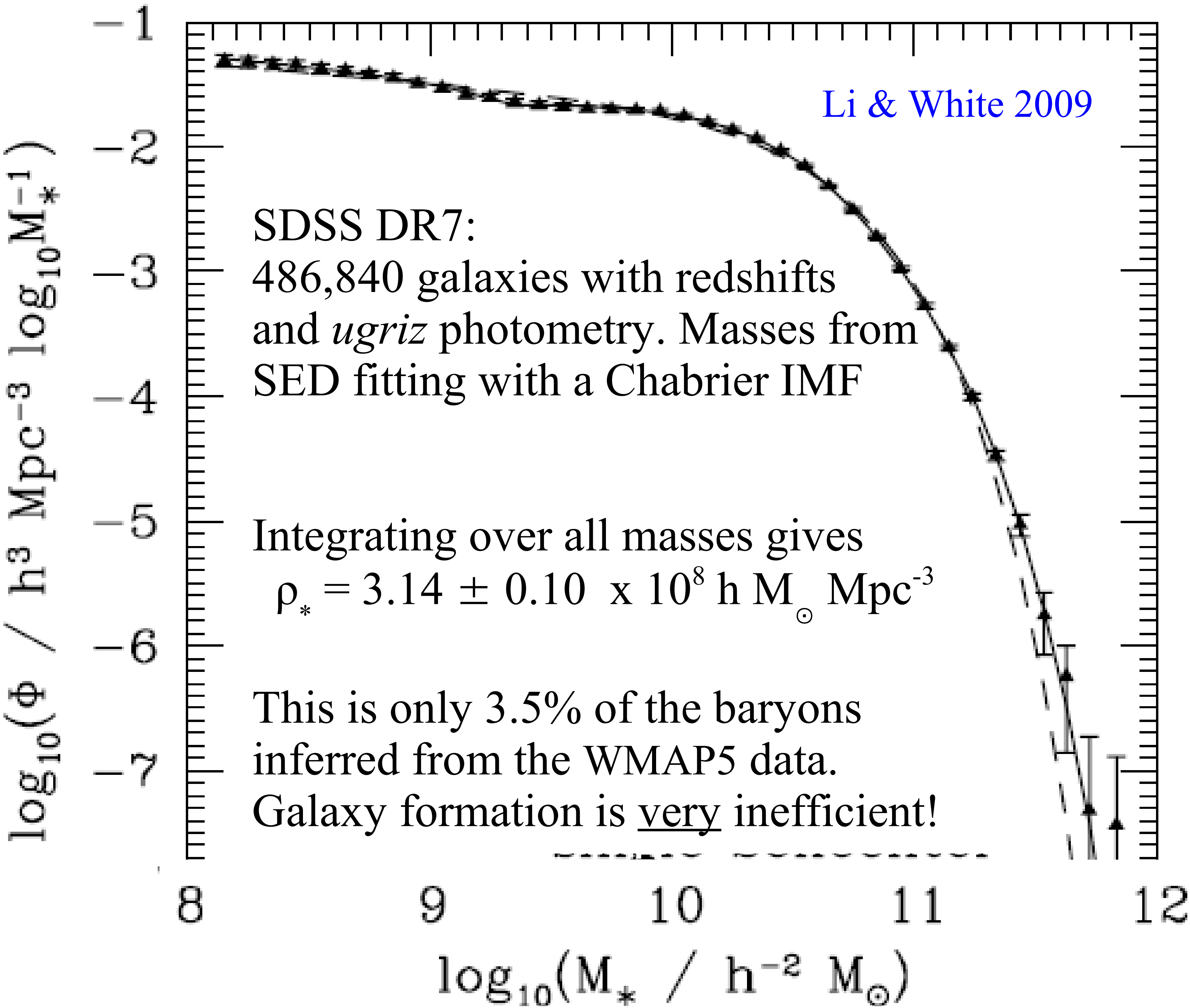


- The standard model reproduces
  - -- the linear initial conditions
  - -- IGM structure during galaxy formation
  - -- large-scale structure today
- Simulation of the standard model gives *precise* predictions for the
  - -- abundance
  - -- internal structure
  - -- assembly history
  - -- spatial/peculiar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

  of dark matter halos at all redshifts

How do galaxies form and evolve within this frame?

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

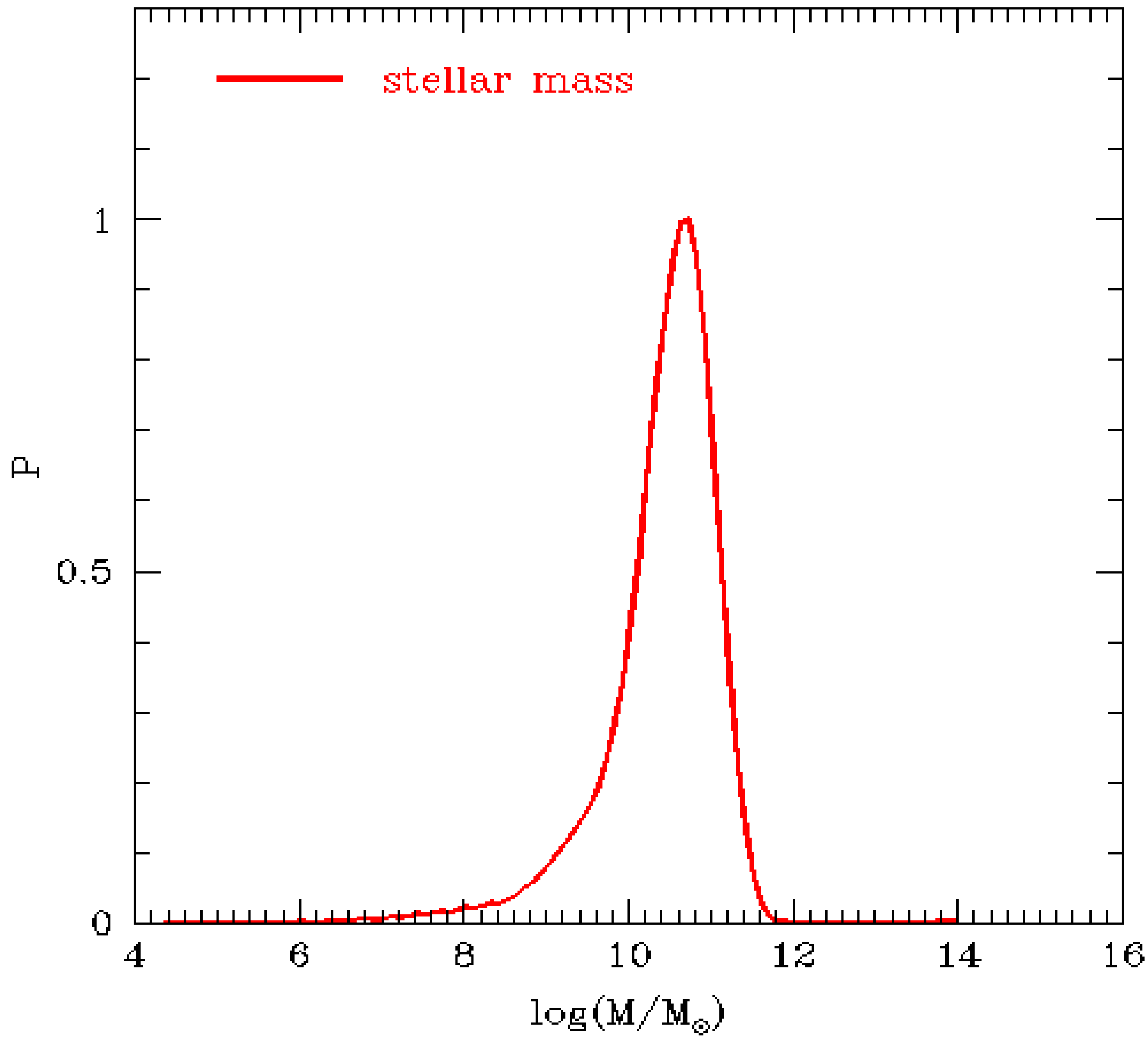


SDSS DR7:
486,840 galaxies with redshifts and *ugriz* photometry. Masses from SED fitting with a Chabrier IMF

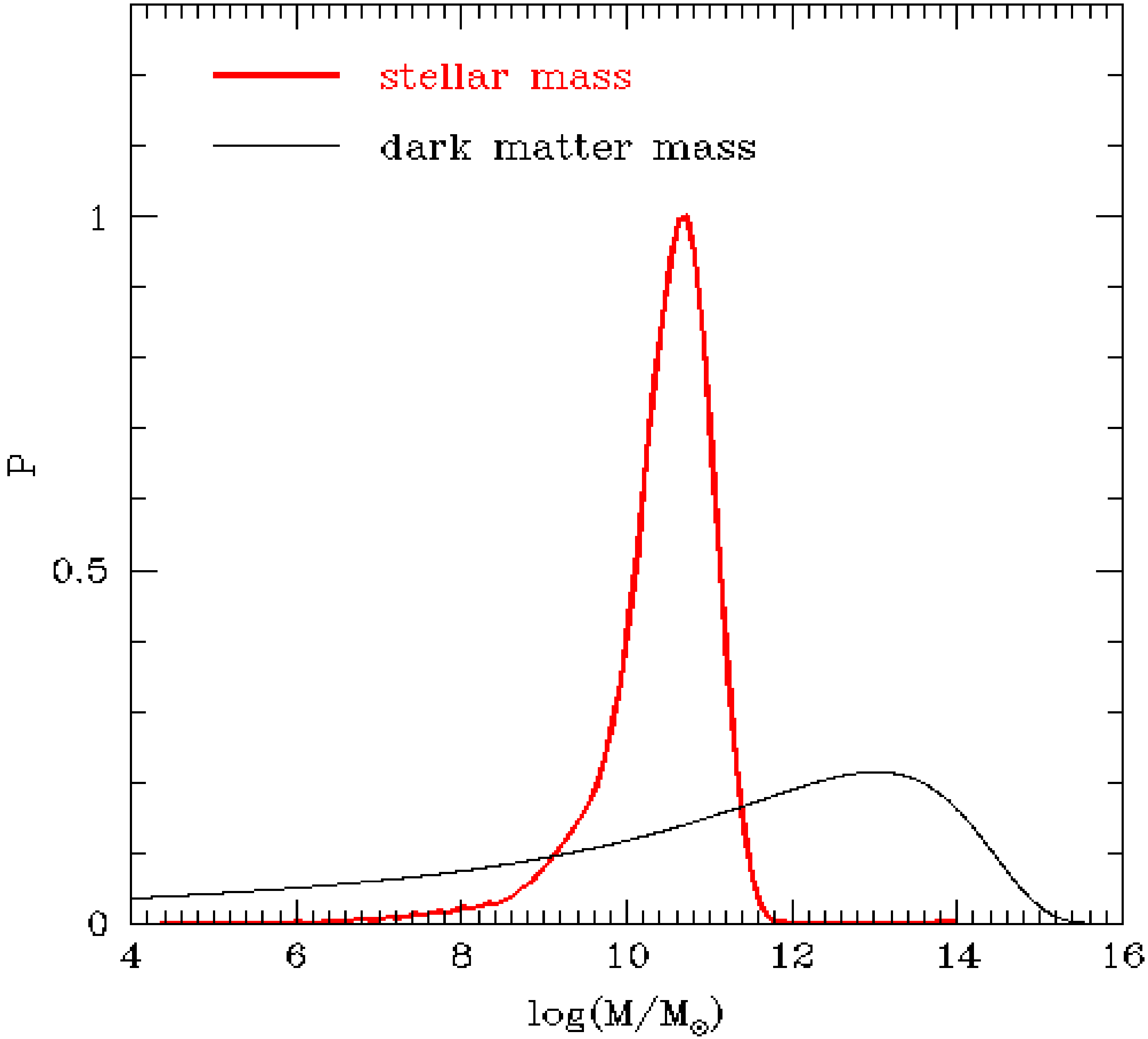
Integrating over all masses gives
$\rho_* = 3.14 \pm 0.10 \times 10^8 \, h \, M_\odot \, \mathrm{Mpc}^{-3}$

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

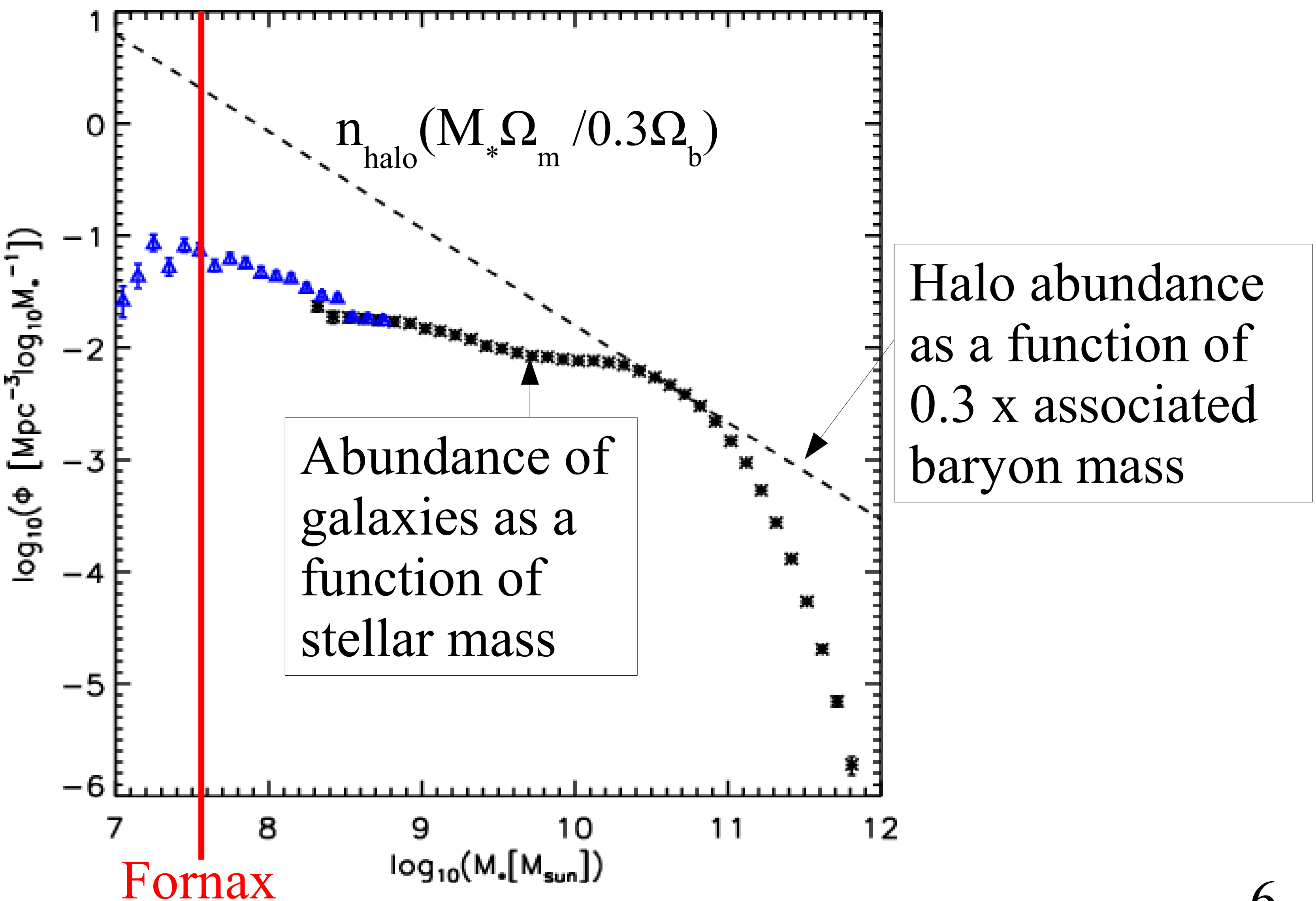


Most stars are in galaxies with similar stellar mass to the Milky Way
Dark matter (and baryons) are *much* more broadly distributed across halo mass in the WMAP7 cosmology



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

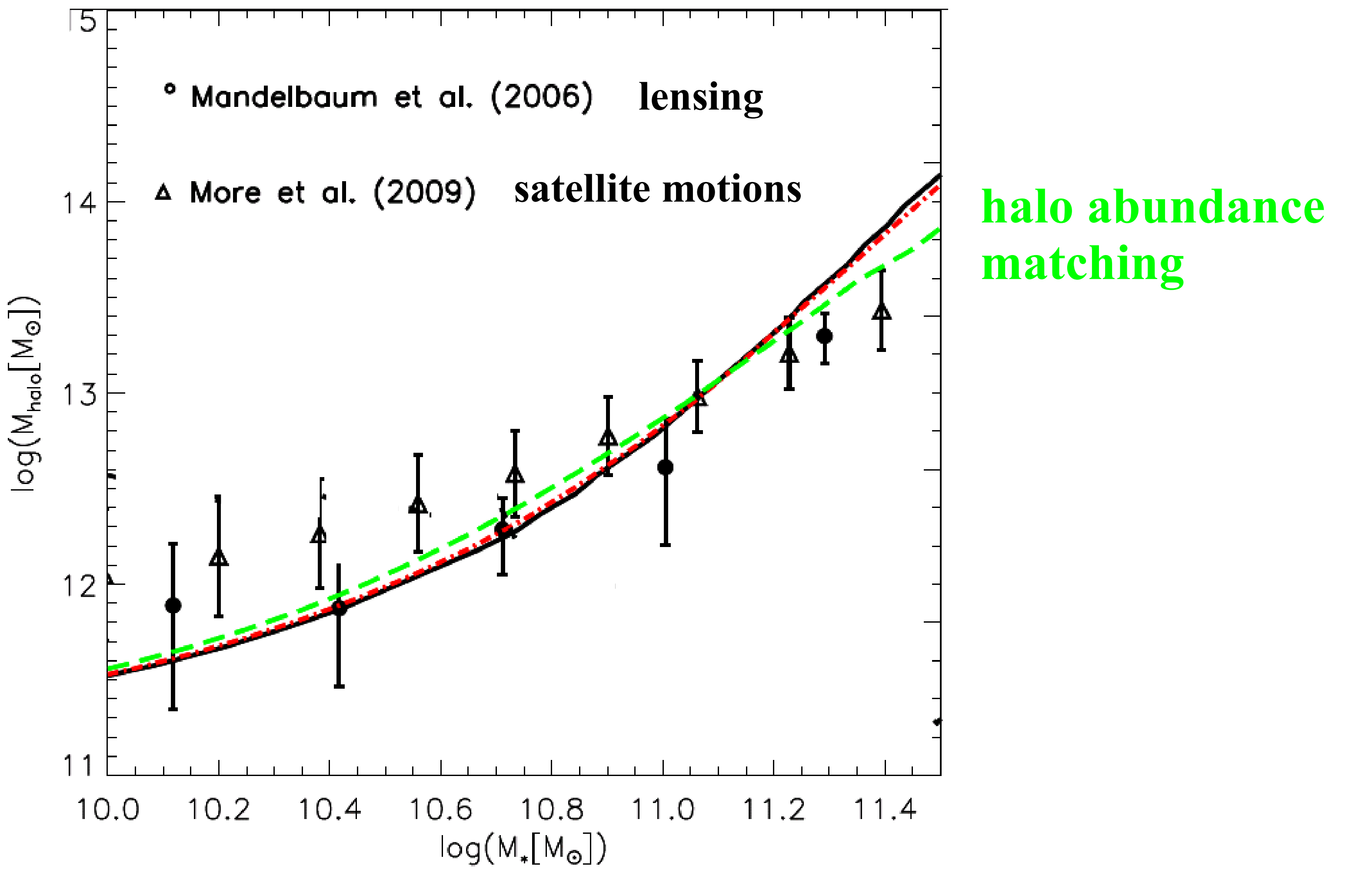
The simulations then give the halo/subhalo abundance, $n(>M_{h,max})$

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

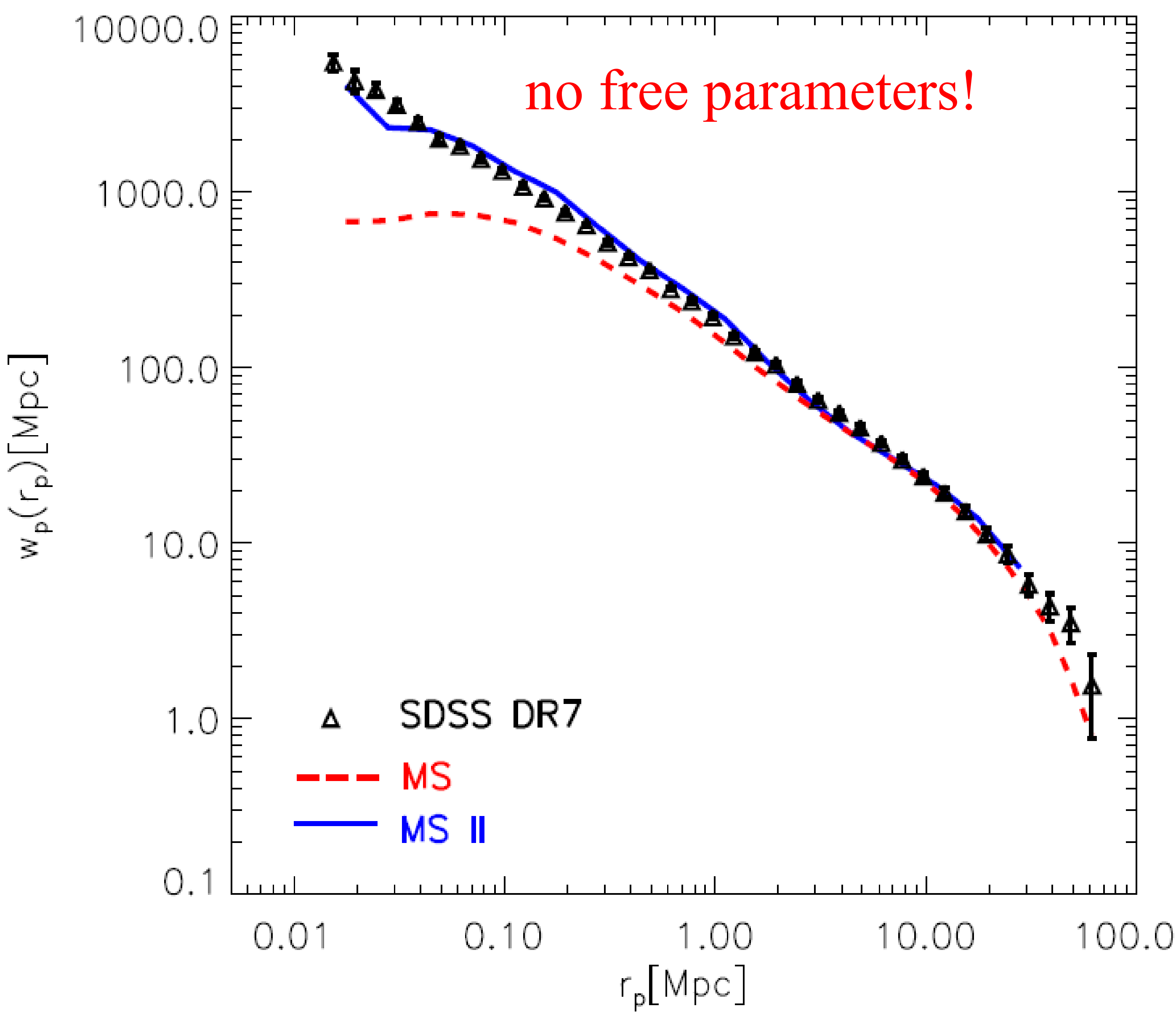
(ii) from gravitational lensing

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

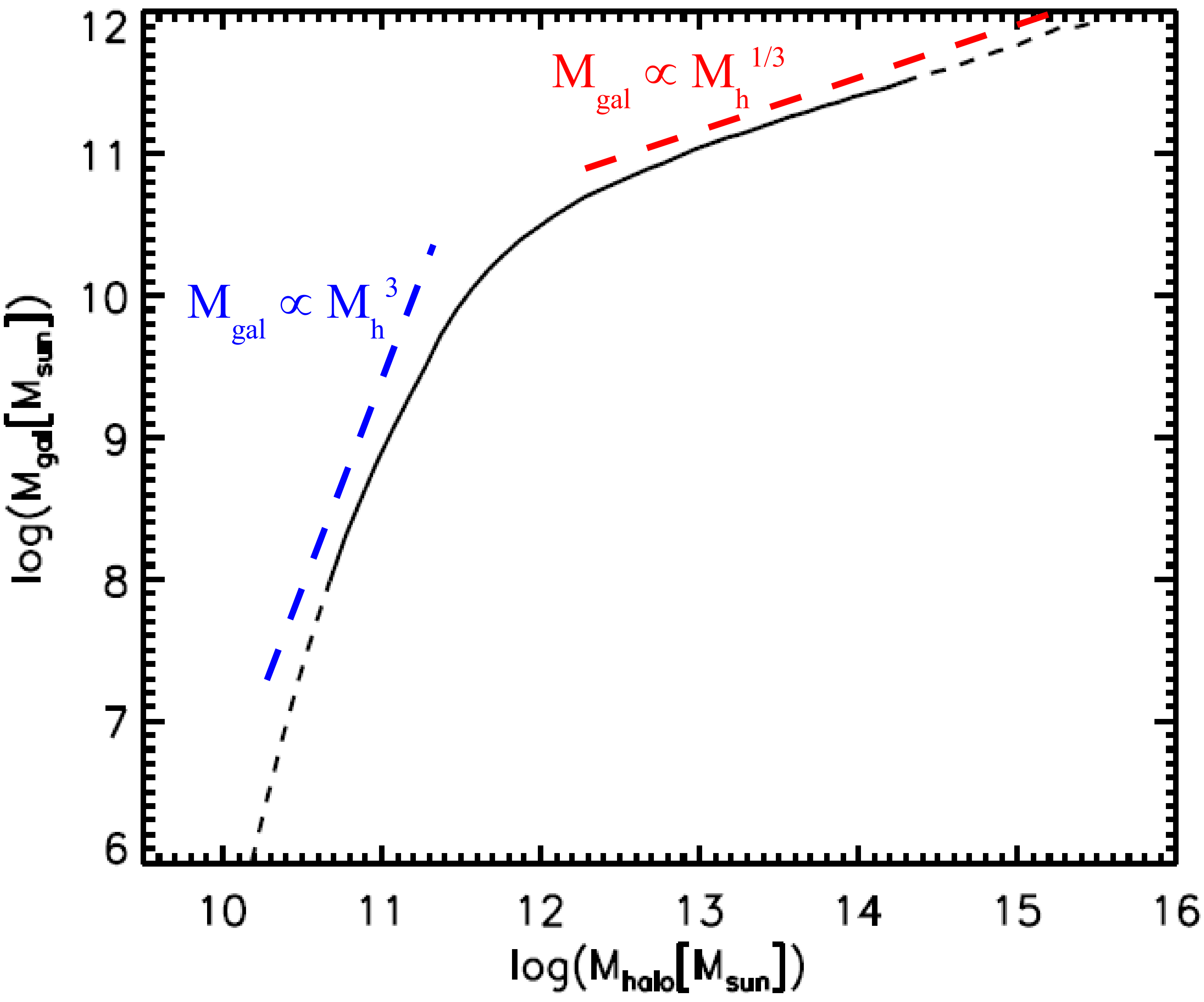
all agree, directly confirming <u>nonlinear</u> predictions of ΛCDM

Consistency of ΛCDM for galaxy clustering

Guo et al 2010

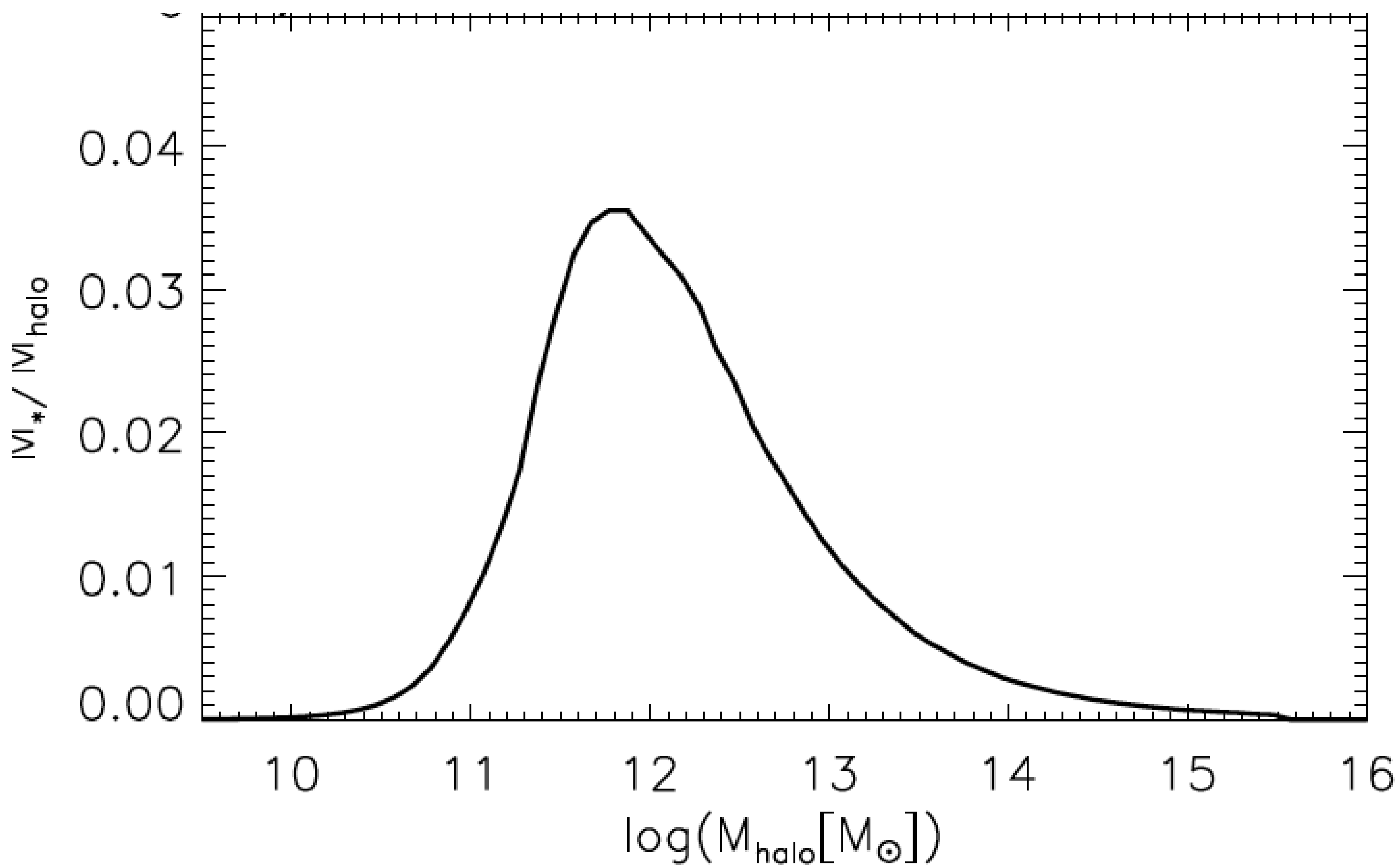


Populating halos/sub-halos by assigning galaxies as inferred by abundance matching to the stellar mass function gives an excellent fit to the observed clustering of stellar mass



- 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 $5 \times 10^{11}\ M_\odot$

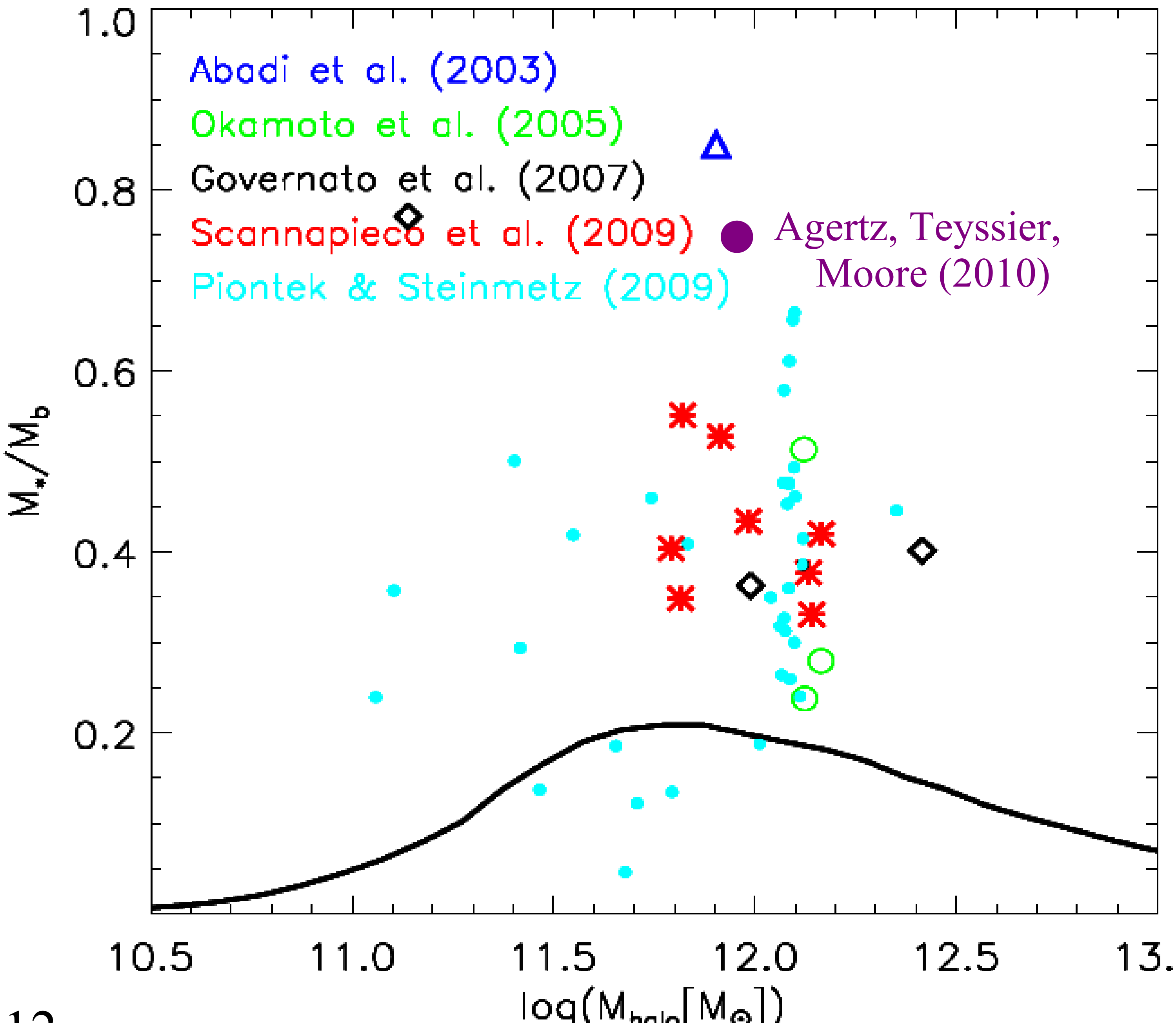
The efficiency of galaxy formation is low!



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%

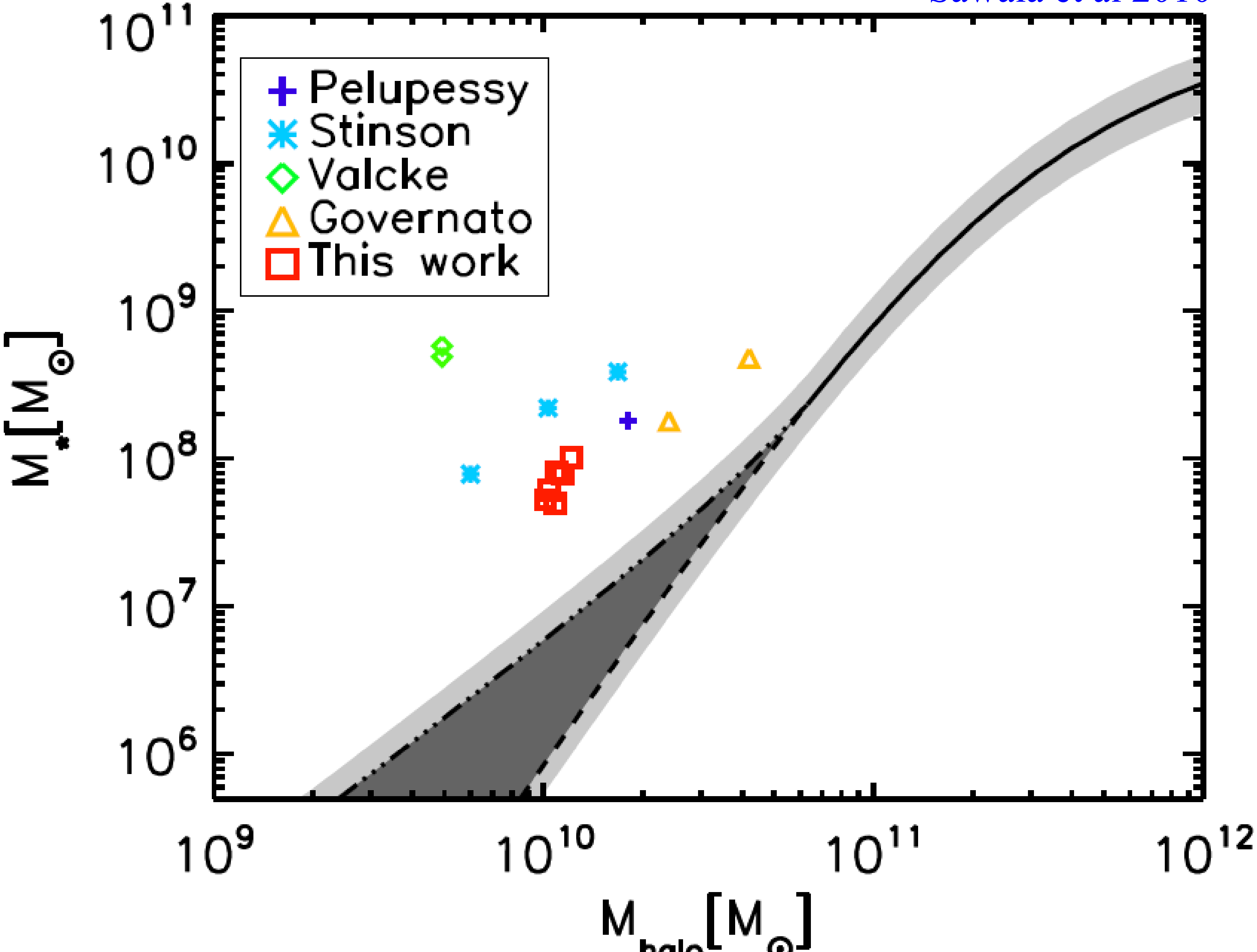
"Successful" simulations fail to match this...



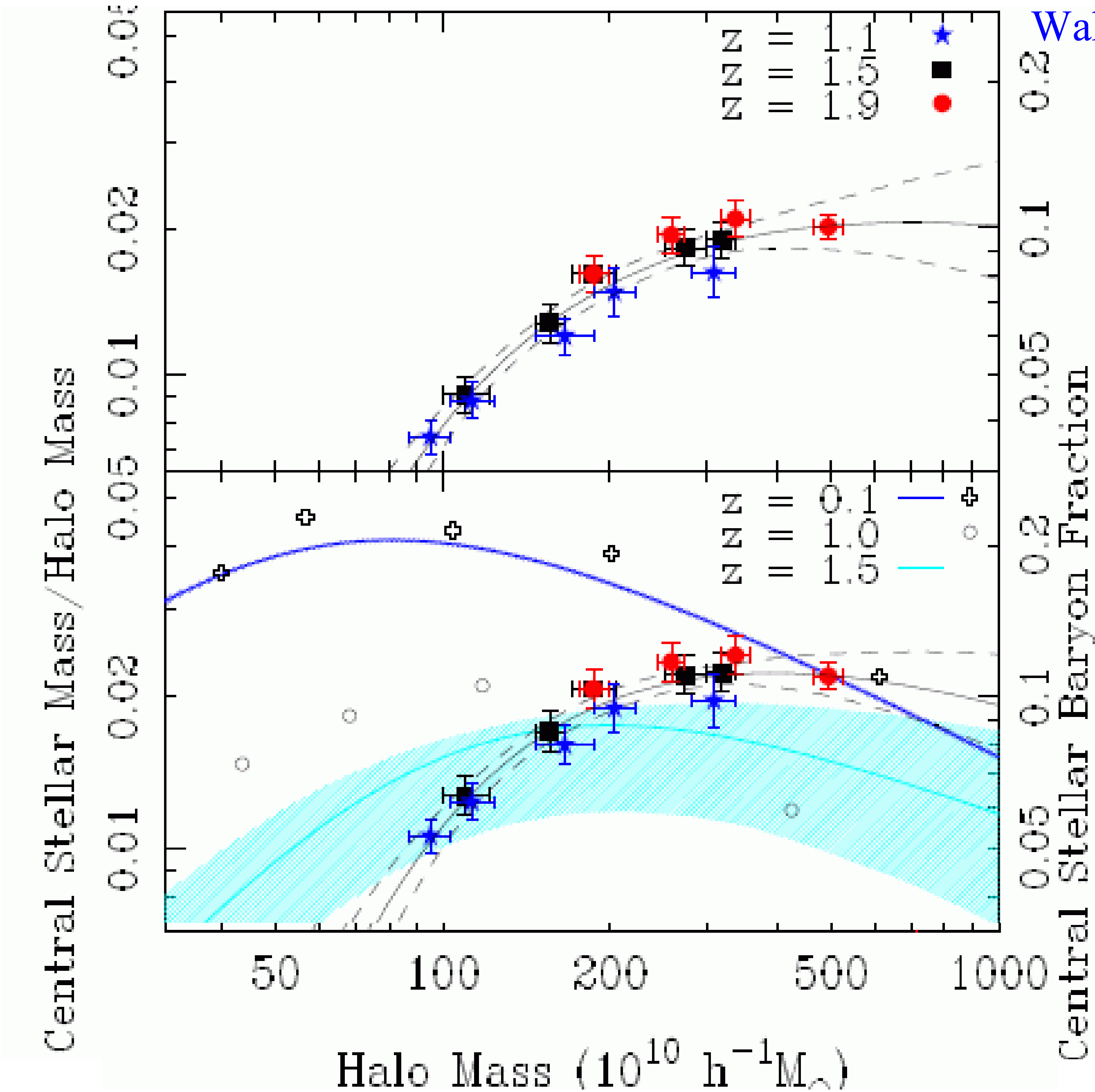
Guo et al 2010

...and do worse for dwarfs than for giants

Sawala et al 2010



Formation efficiencies are <u>lower</u> at high z!



Wake et al 2011

The galaxy baryon budget in a ΛCDM universe

- The total amounts of baryons associated with the halos of galaxies are >5 times the observed stars+gas at all redshifts
- These baryons should have accreted onto all but the smallest of galaxy/halo systems as their halos grew
- At higher z and in smaller objects, shocks were inefficient at heating this gas, so it should have reached the galaxies
- Infall <u>and</u> outflow rates from galaxies should <u>on average</u> be >5 times their star formation rates
- In present-day galaxies <u>most</u> of the baryons associated with galaxy halos must be in the WHIM

Model-building --the semianalytic program

- Begin with abundances
  -- by L, M_*, B−V, R_e, V_{rot}, SFR, morphology, central/satellite

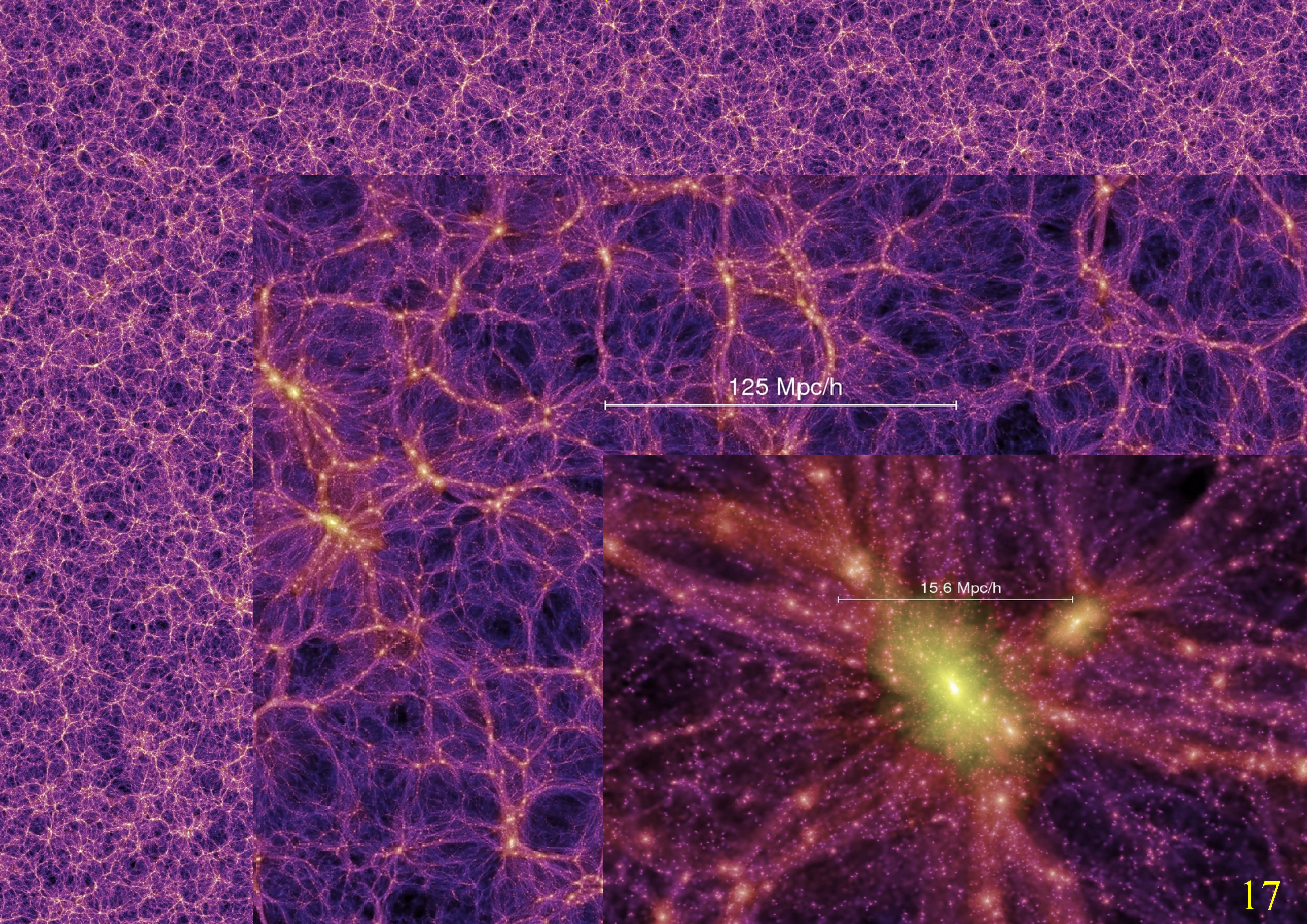
- Use clustering measurements
  -- correlations as a function of stellar mass and colour

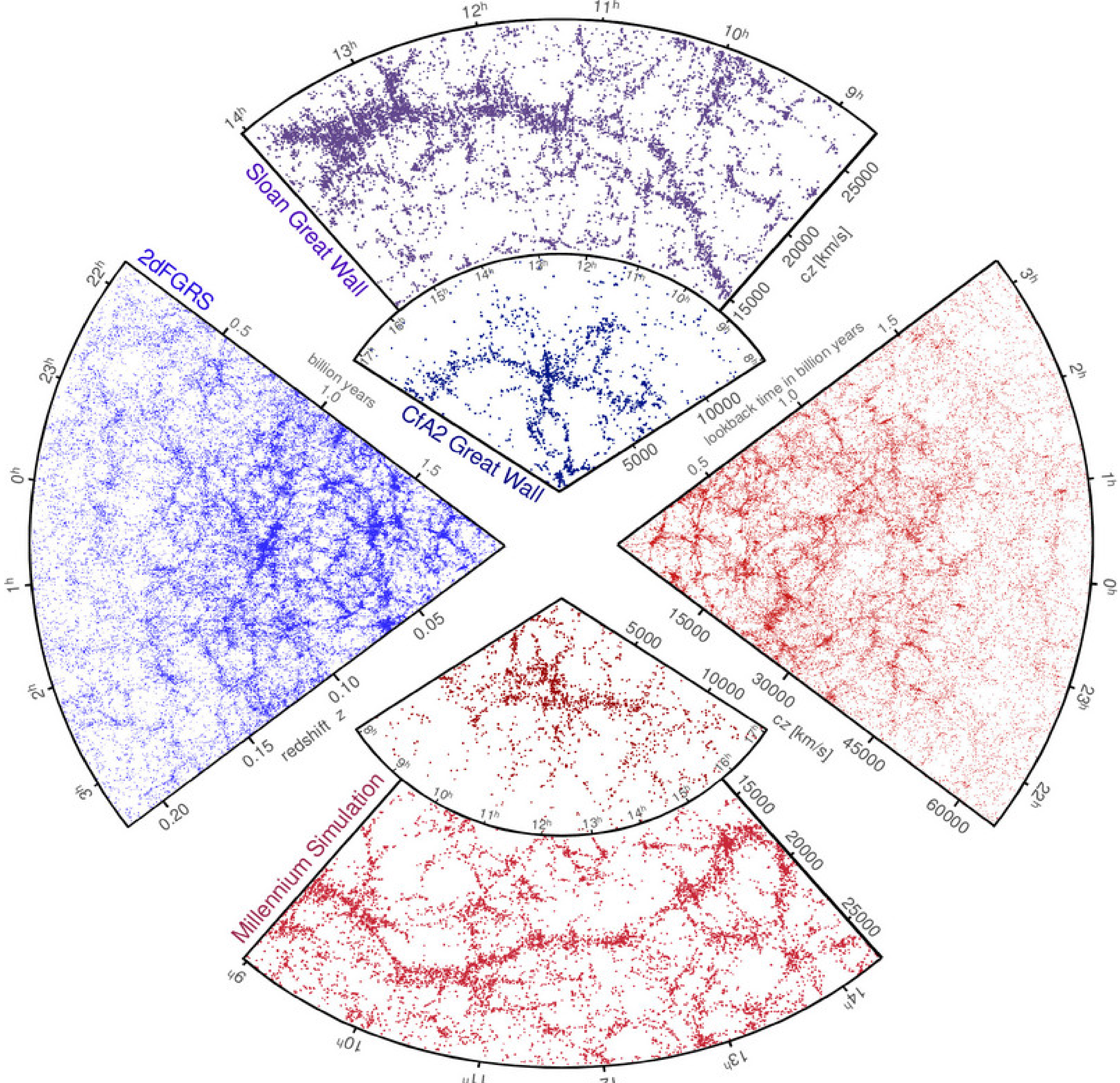
- Use assembly history information from simulations
  -- base on high-resolution DM simulations
  -- use simulated assembly history/substructure data directly

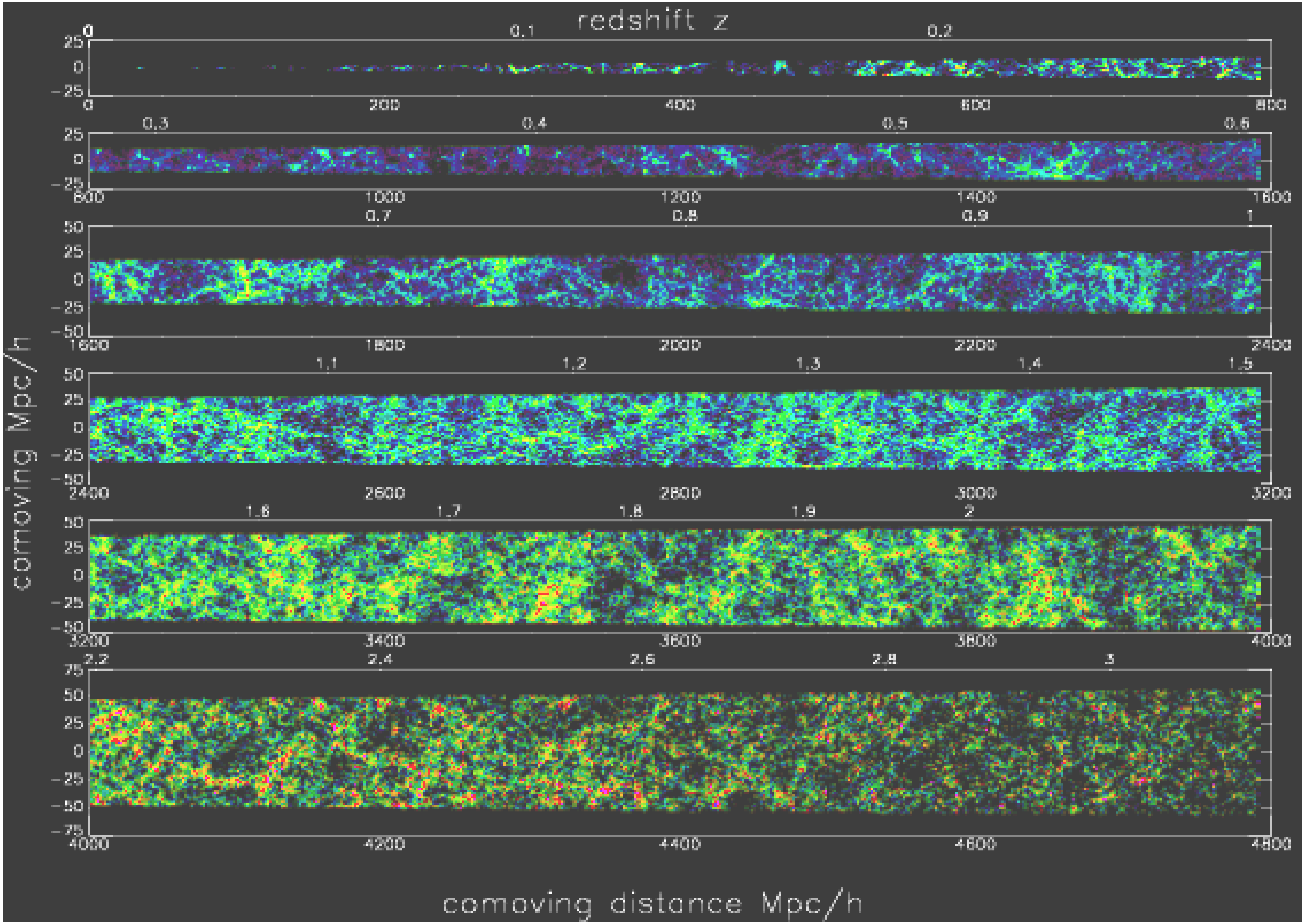
- Use physically plausible recipes for relevant processes
  -- tie recipes to detailed simulations when possible
  -- otherwise use observational phenomenology

- Separate measurement from hypothesis when model-testing

The Millennium Simulation (2005)



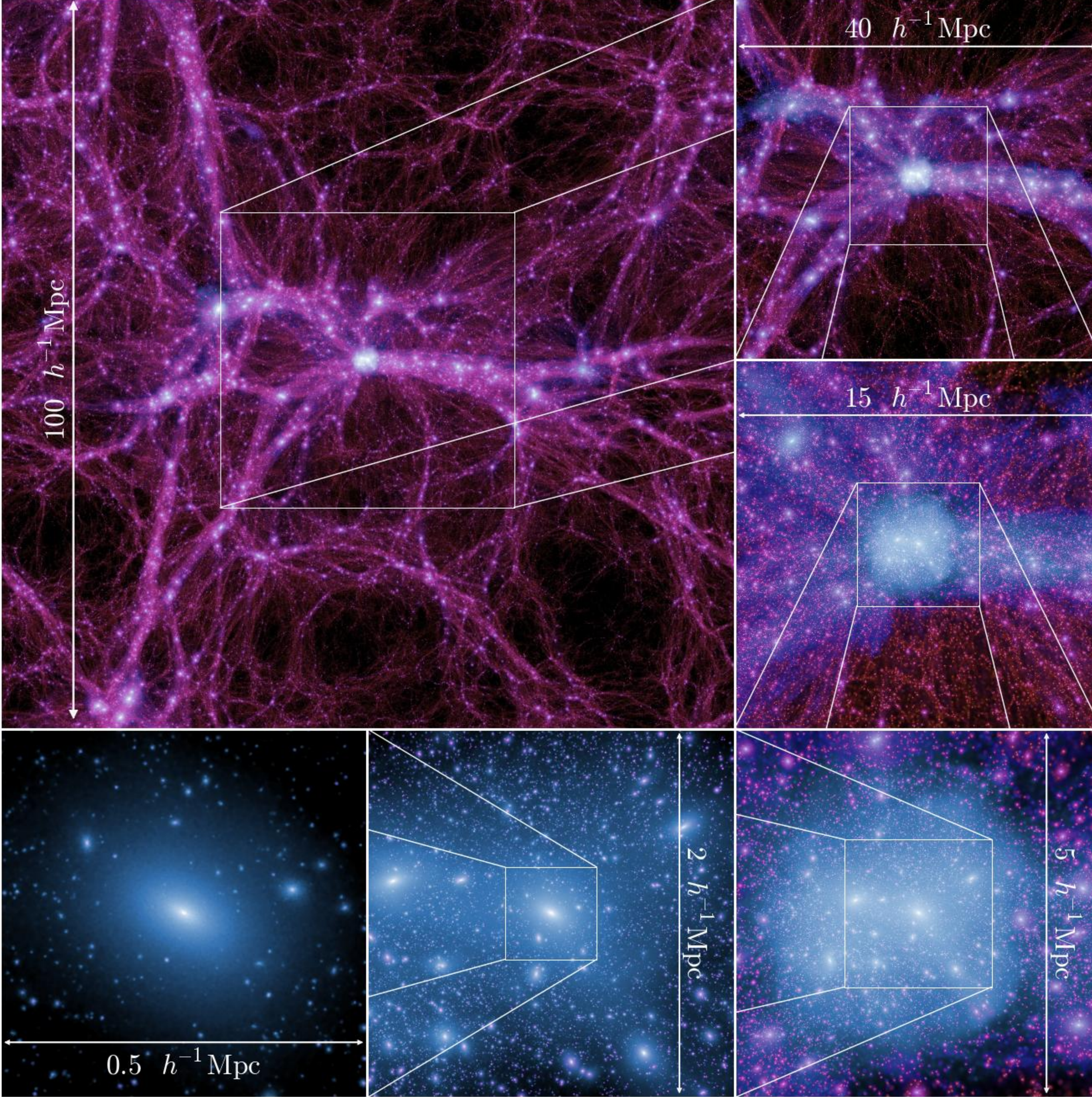

Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
cz [km/s]
lookback time in billion years
billion years
redshift z
cz [km/s]



392 papers making direct use of data from the MS (15-6-2011)
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

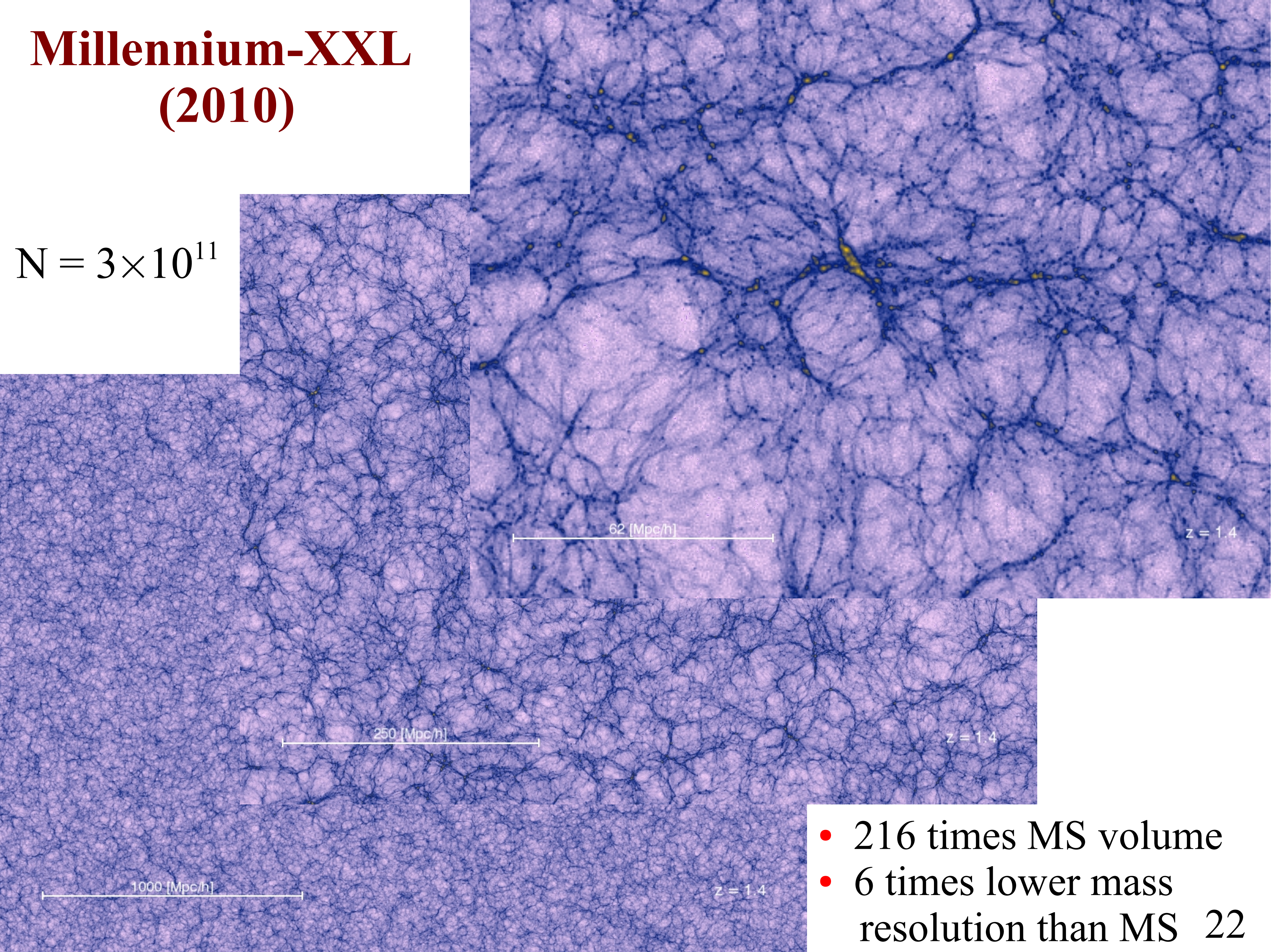
Same outputs/ post-processing

↓

Resolution tests of MS results and extension to smaller scales

Millennium-XXL (2010)

$N = 3\times10^{11}$



- 216 times MS volume
- 6 times lower mass resolution than MS

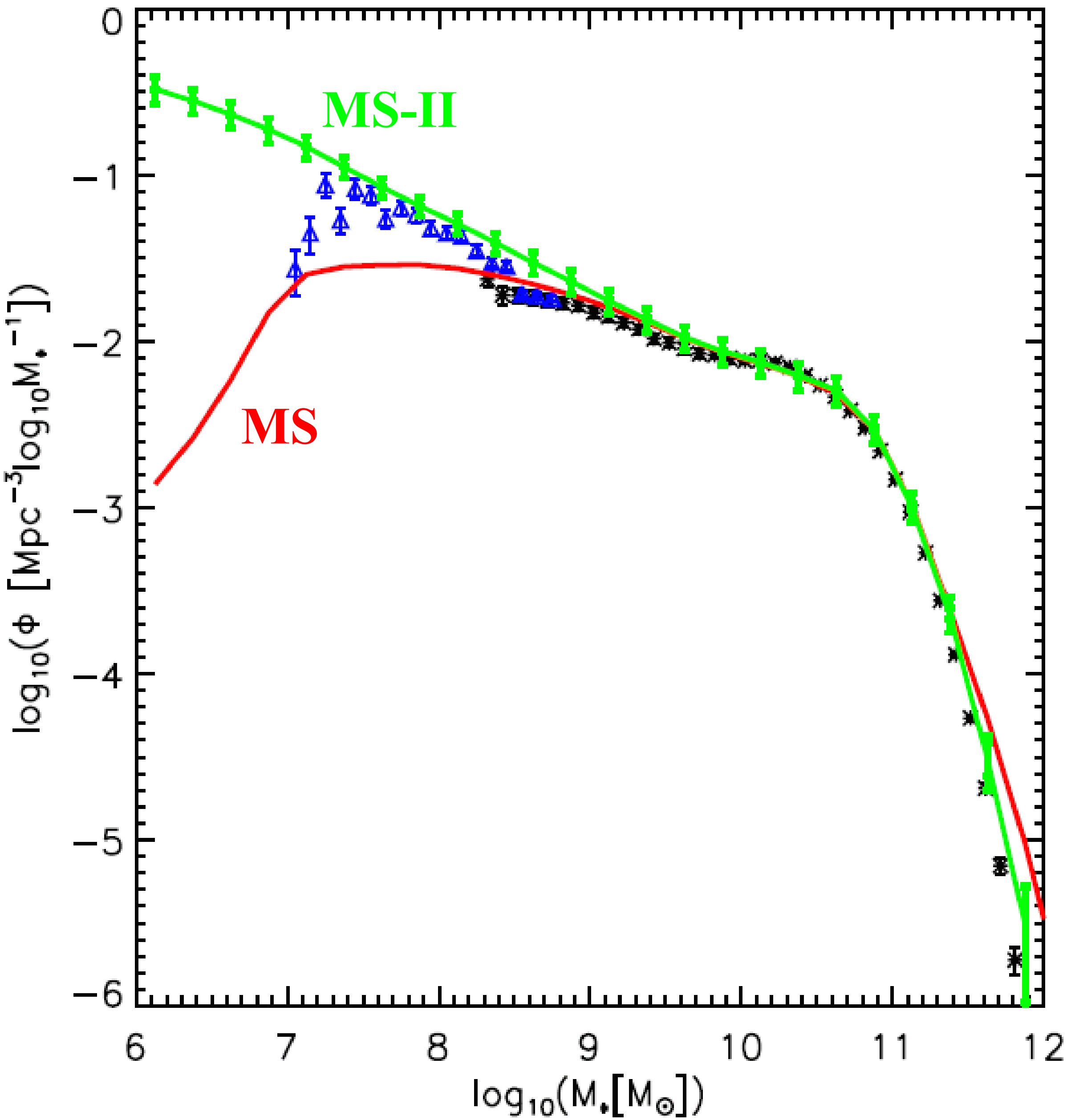
New galaxy formation models based on MS+MS-II

Qi Guo et al 2011

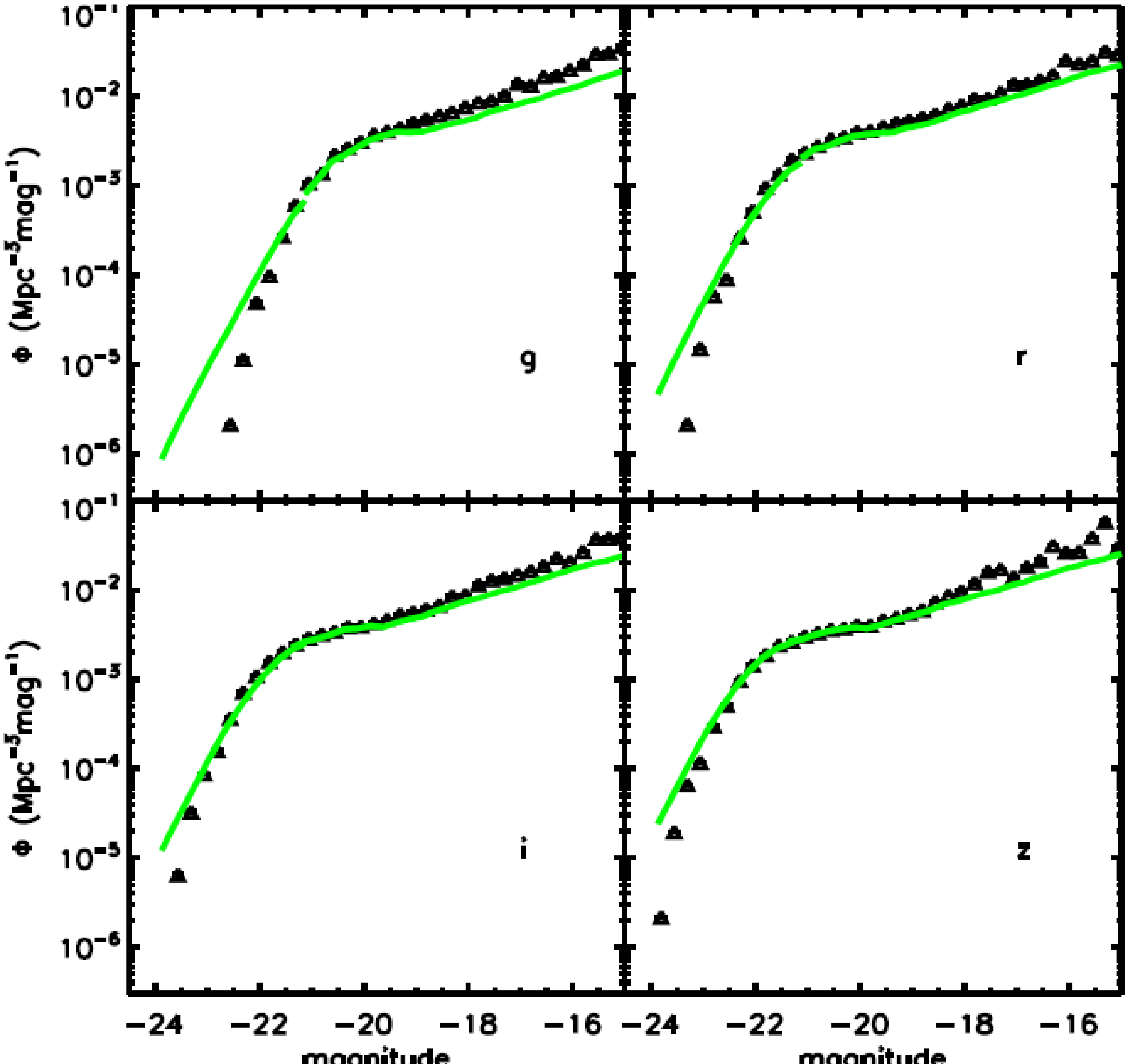
- Implement modelling simultaneously on MS and MS-II
- Test convergence of galaxy properties near resolution limit of MS
- Extend to properties of dwarf galaxies
- Improve/extend treatments of "troublesome" astrophysics
- Adjust parameters to fit new, more precise data
- Test against clustering and redshift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

Things that work well

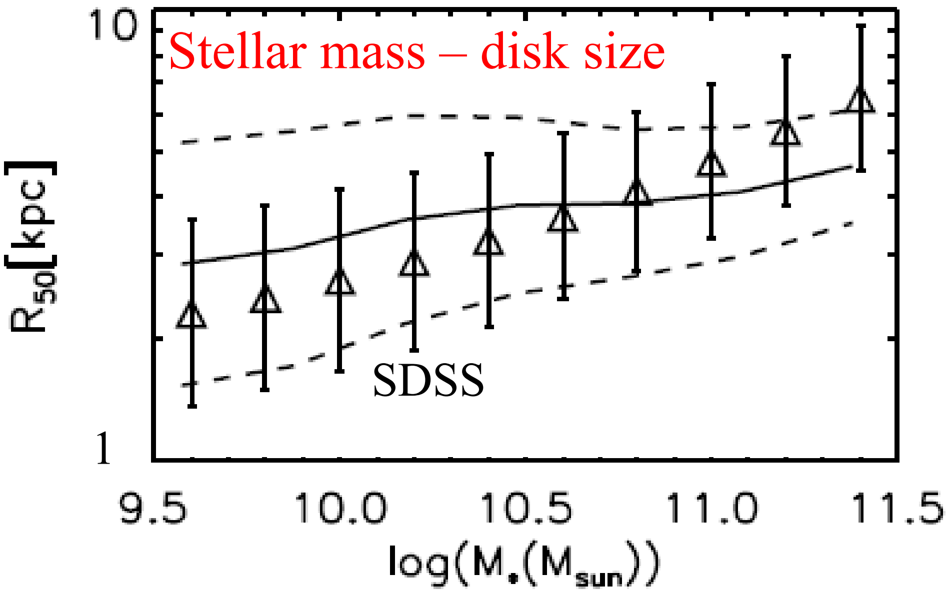
The stellar mass function of galaxies

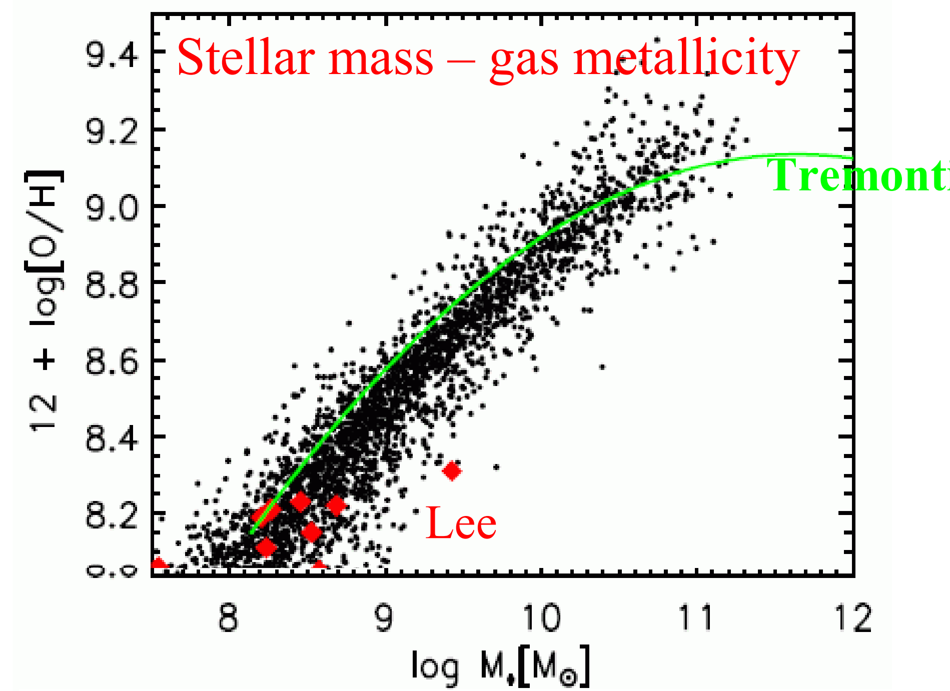


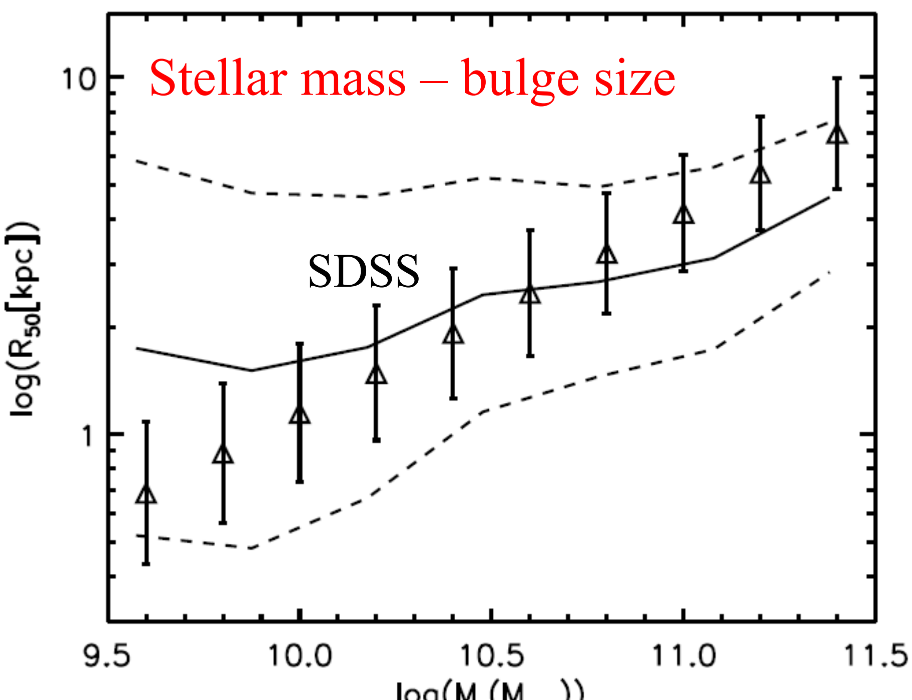
Luminosity functions of galaxies

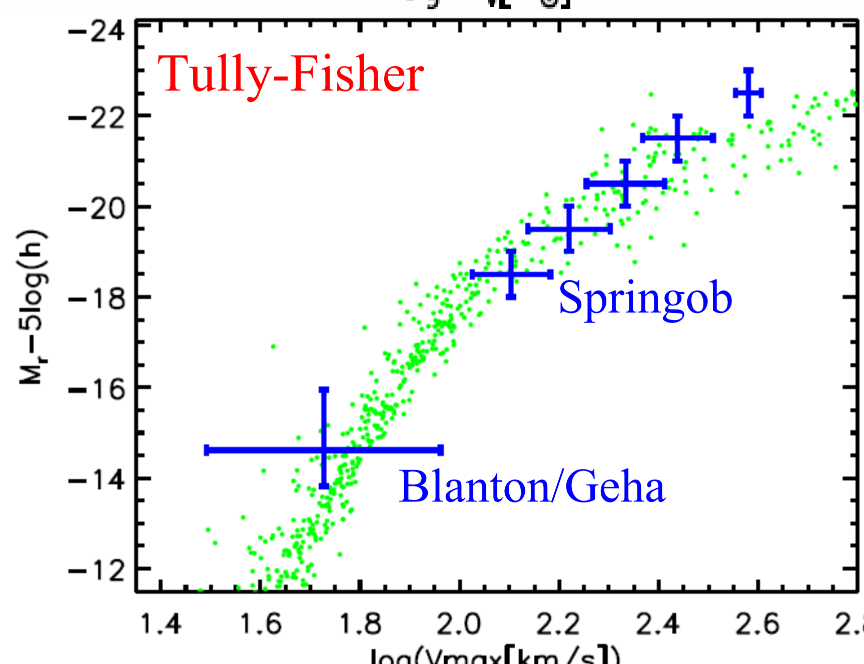


Scaling relations

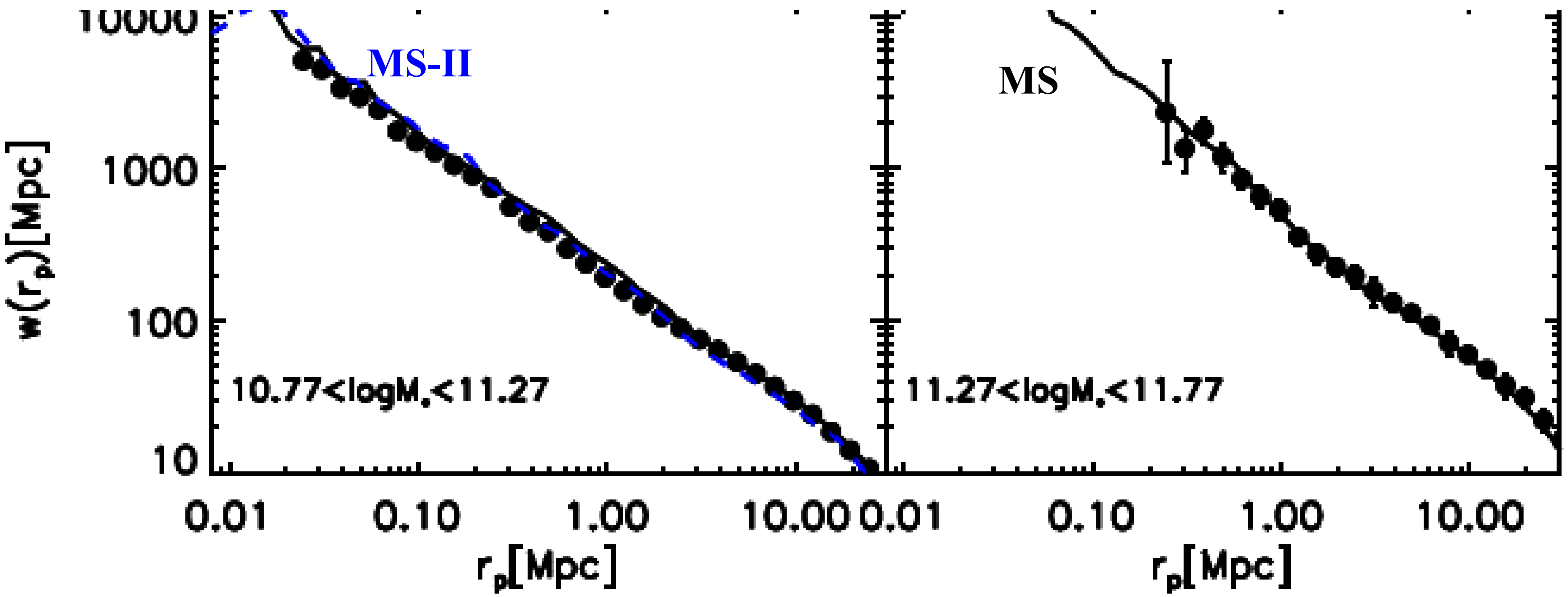








Clustering of massive galaxies

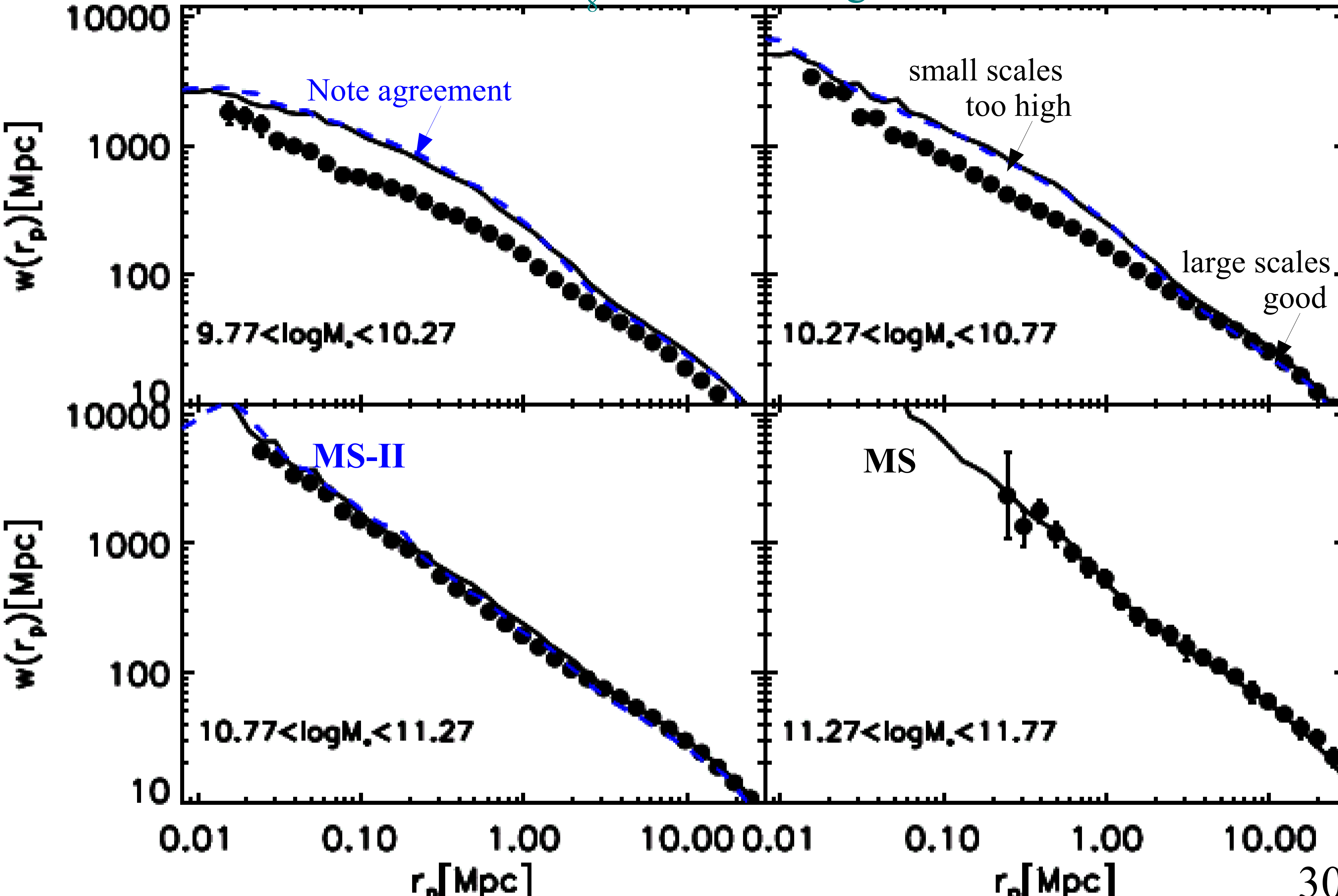


Data from SDSS/DR7

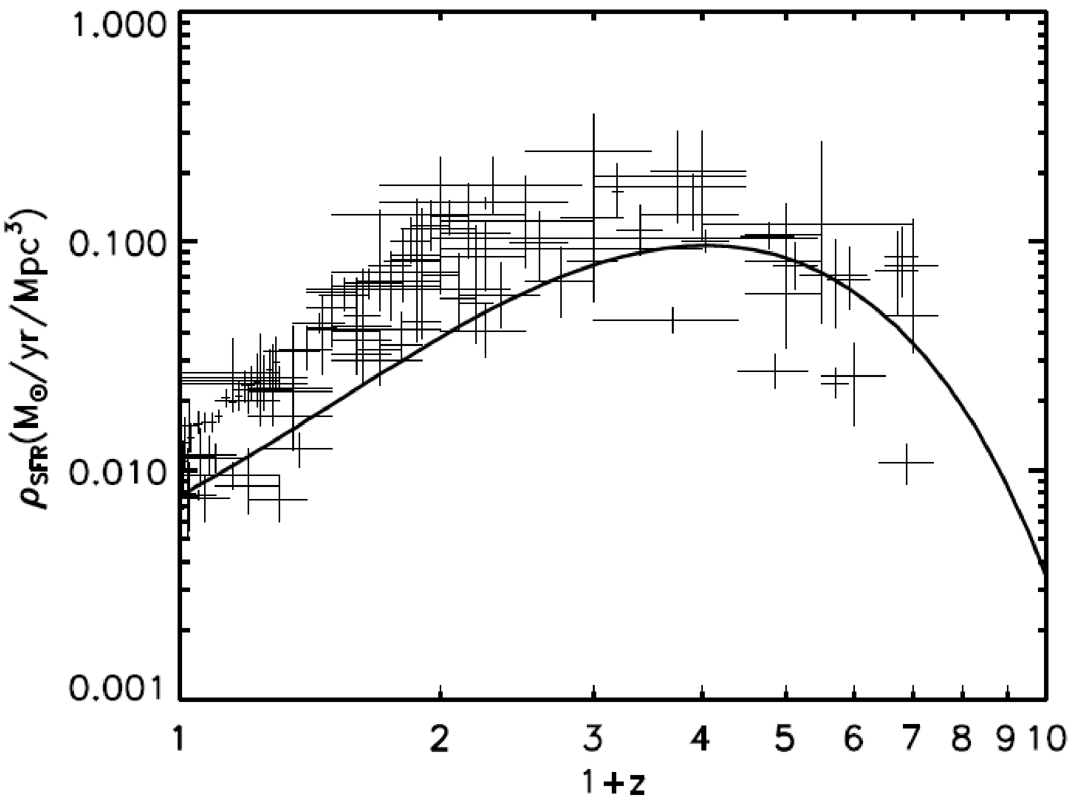
Things that work less well

Clustering of less massive galaxies

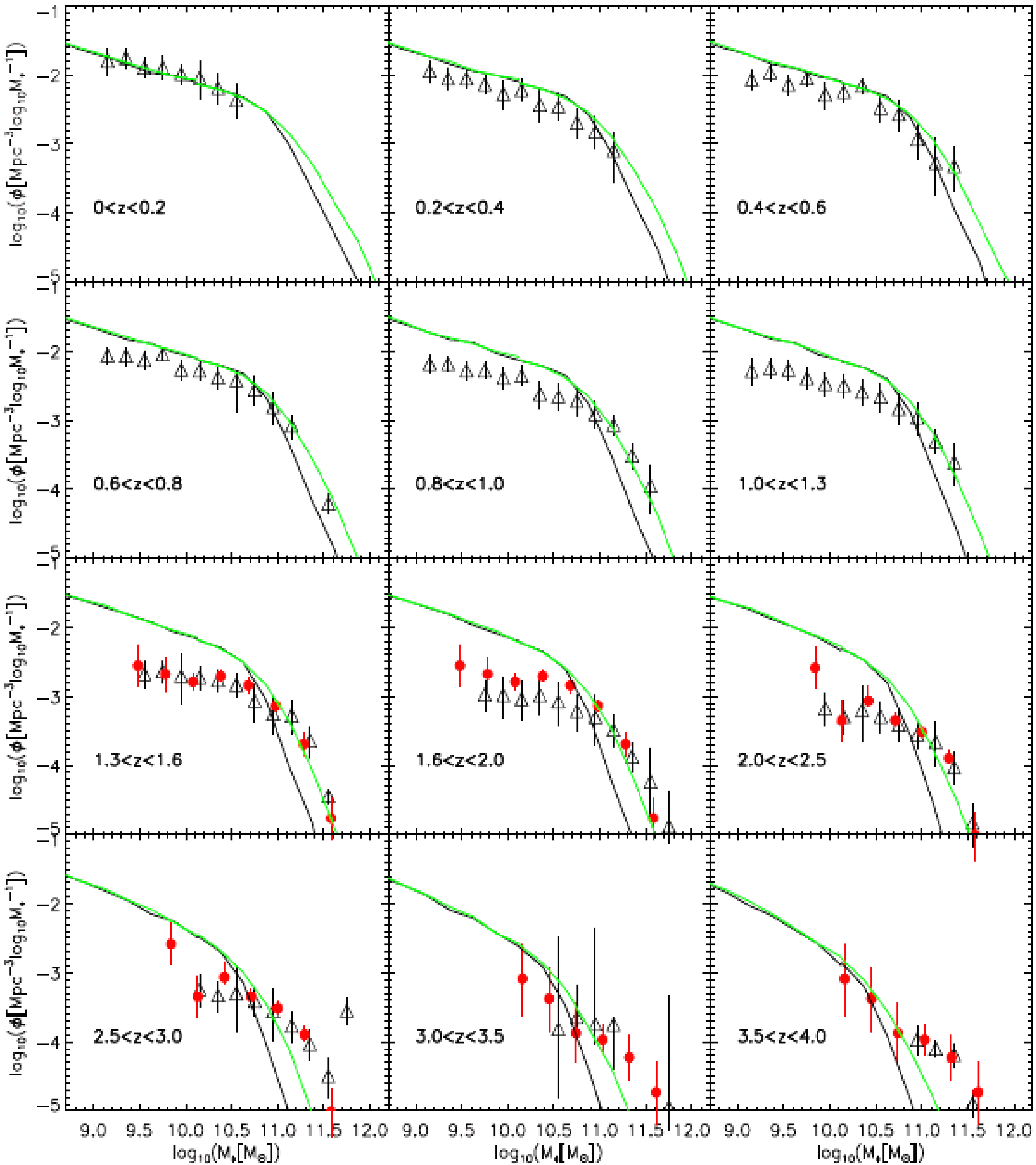
--- $\sigma_8 = 0.9$ is too high ---



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 ---

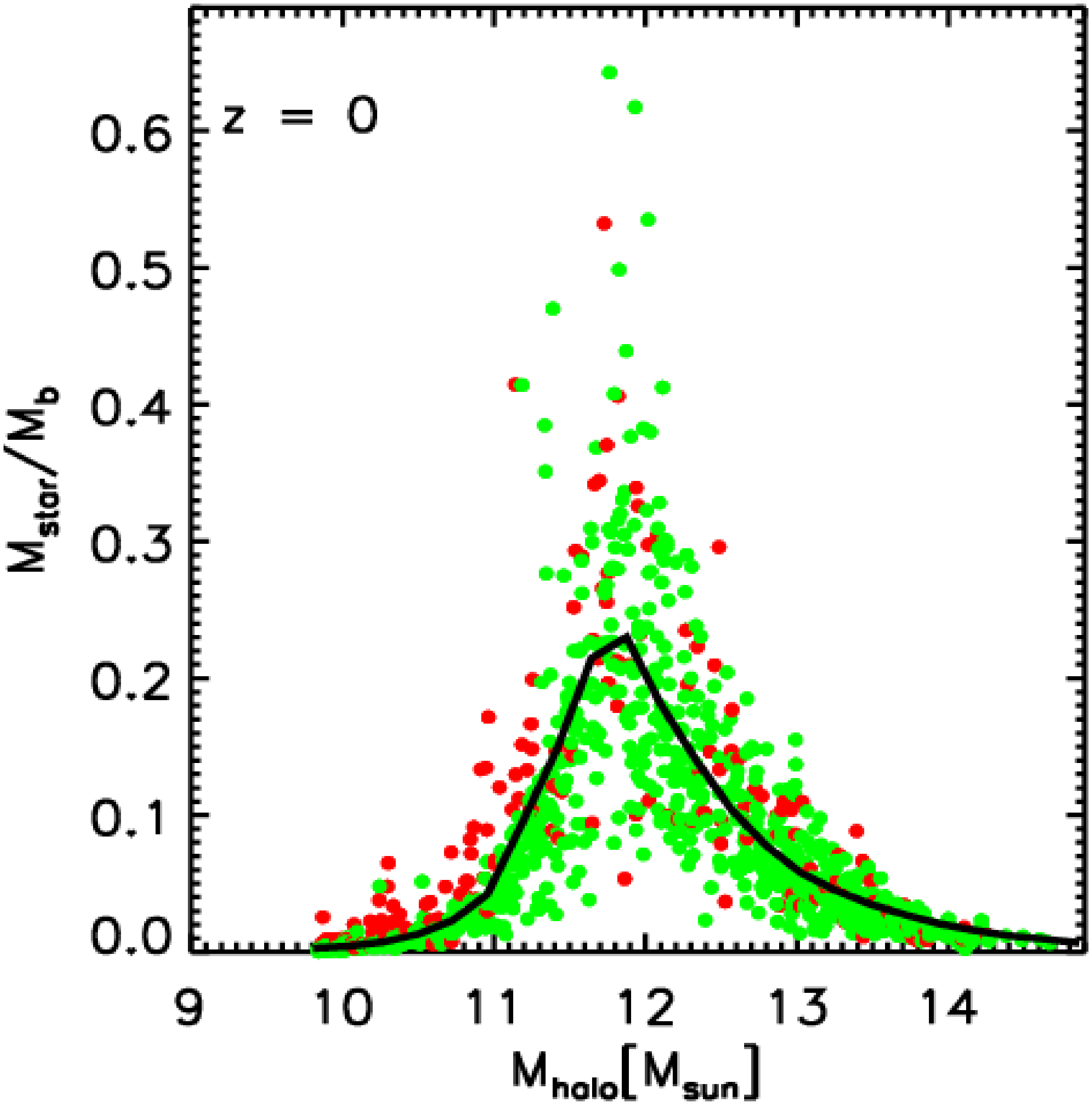


Evolution of stellar mass function

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

Star formation efficiency vs past maximum halo mass

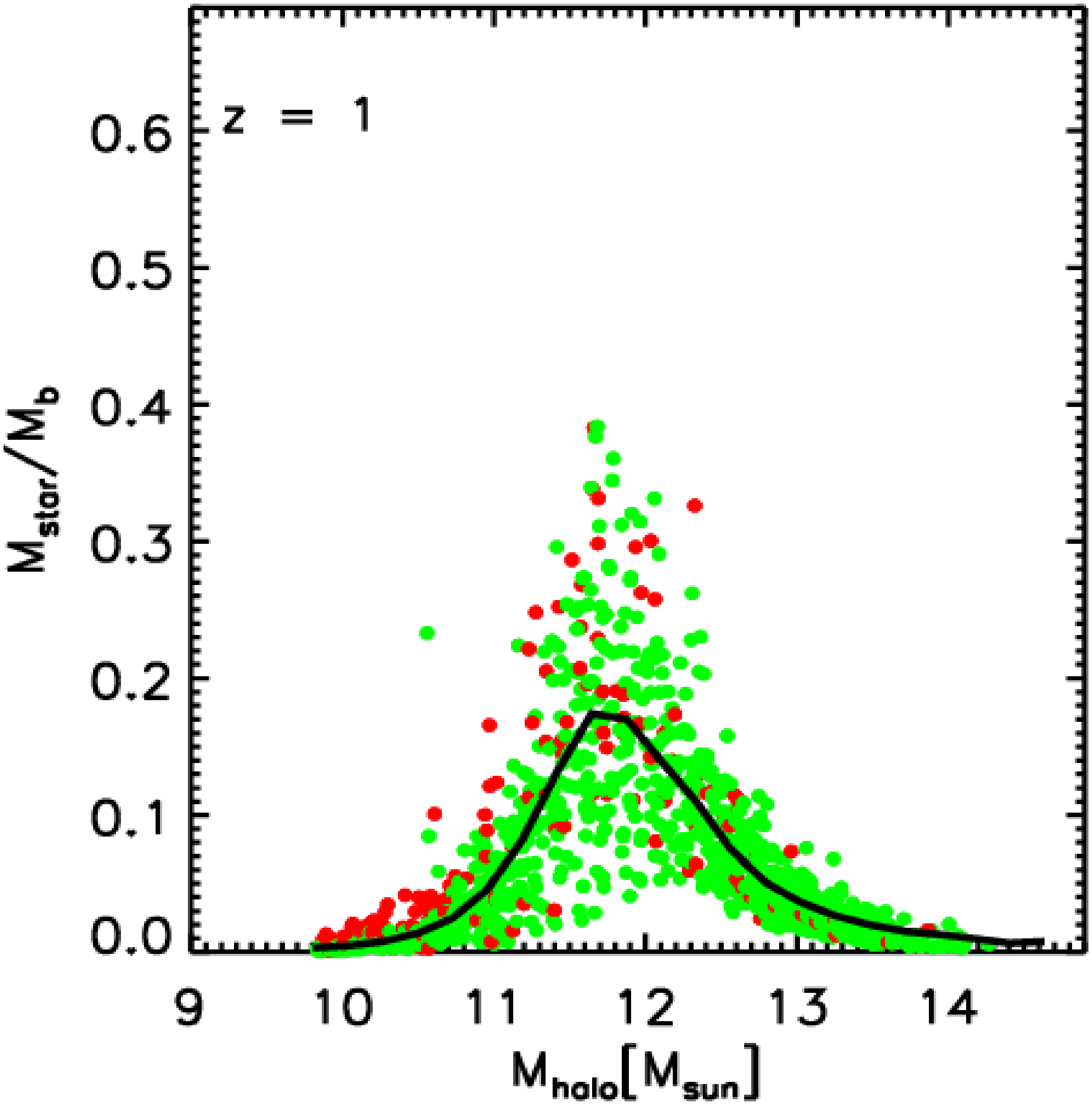
Guo et al 2011



- Median efficiency follows the relation predicted by abundance-matching
- Scatter is substantial
- Satellites form slightly more efficiently than centrals

Star formation efficiency vs past maximum halo mass

Guo et al 2011



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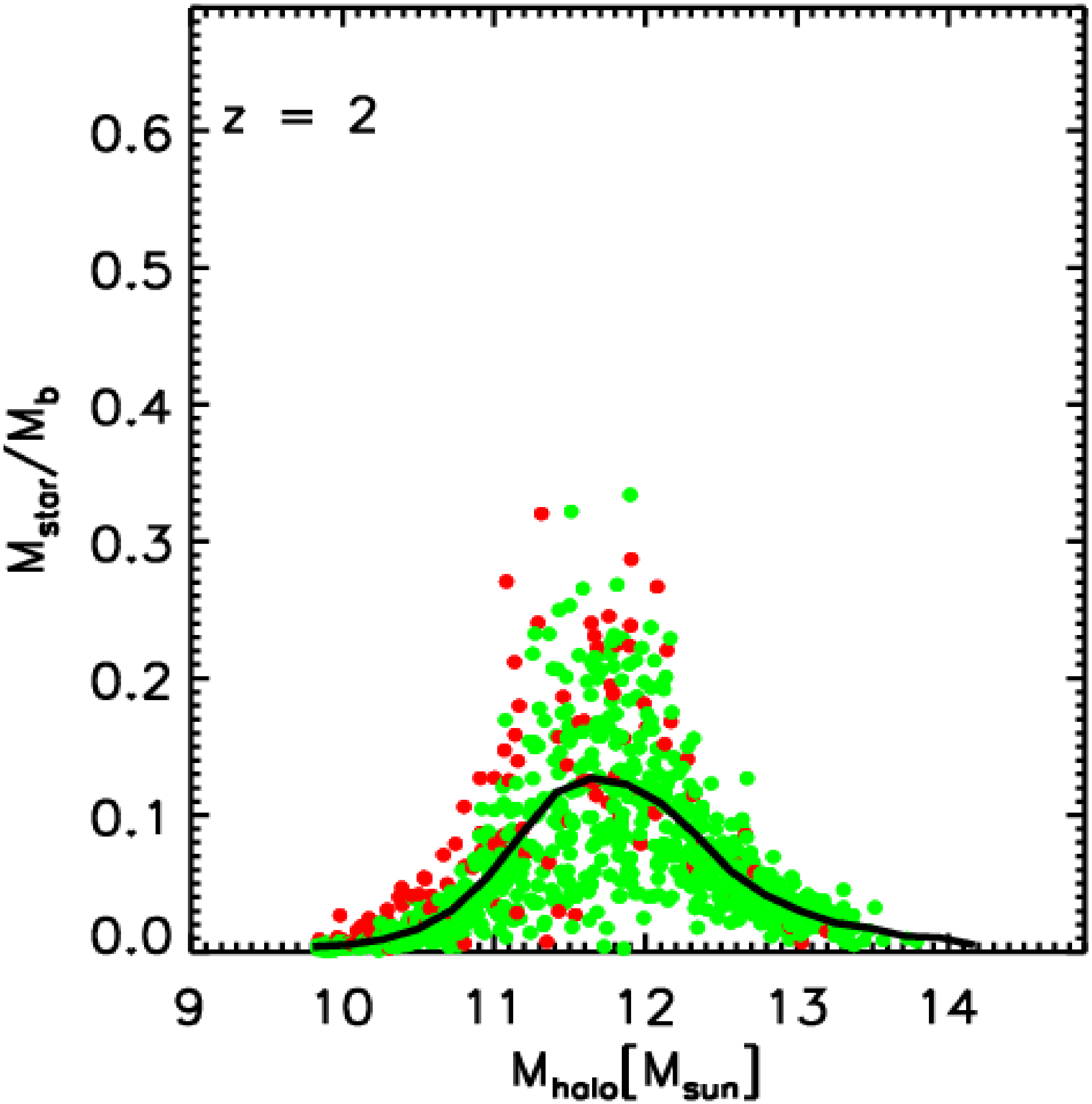
Star formation efficiency vs past maximum halo mass

Guo et al 2011



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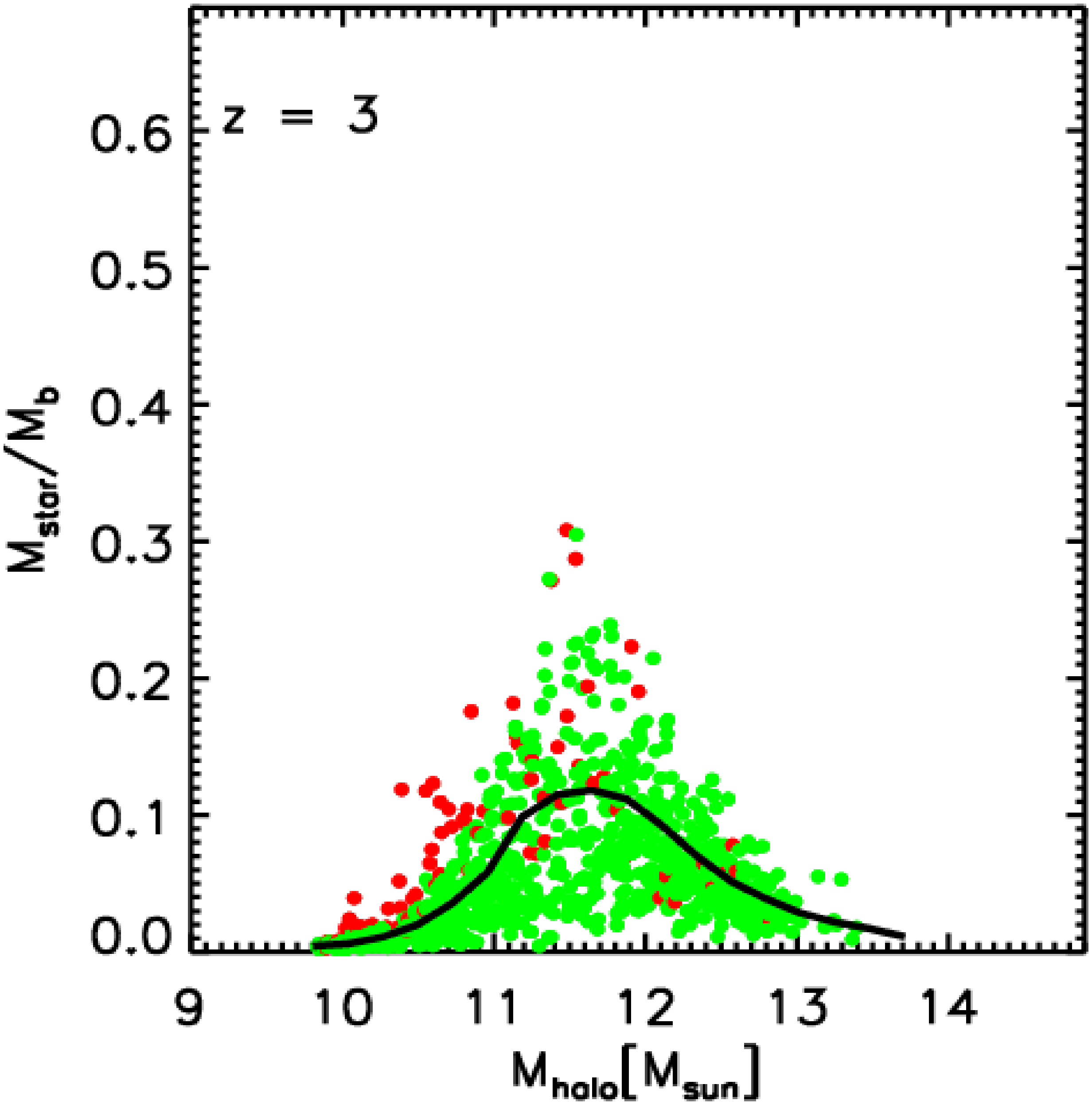

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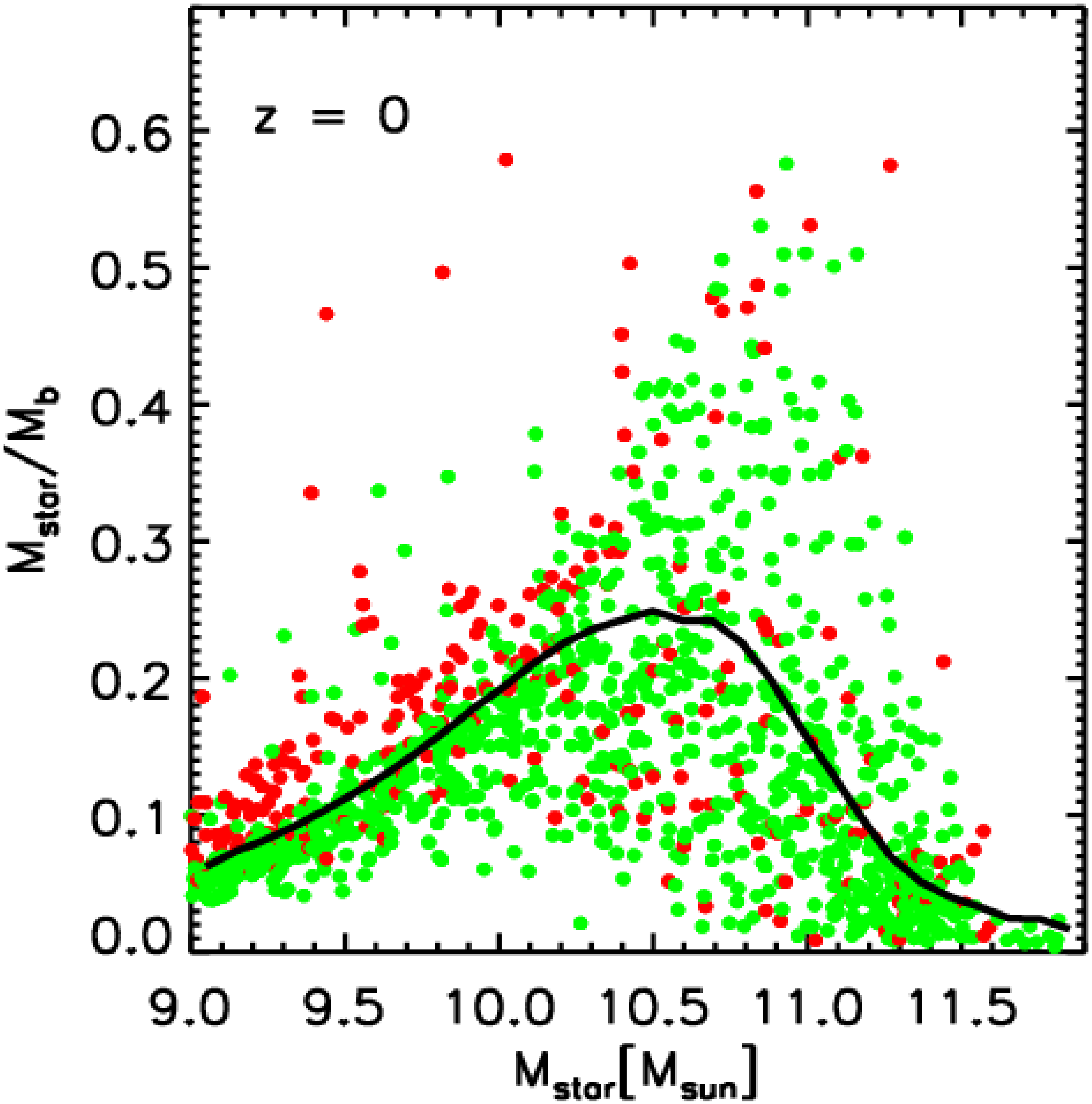
Star formation efficiency vs stellar mass

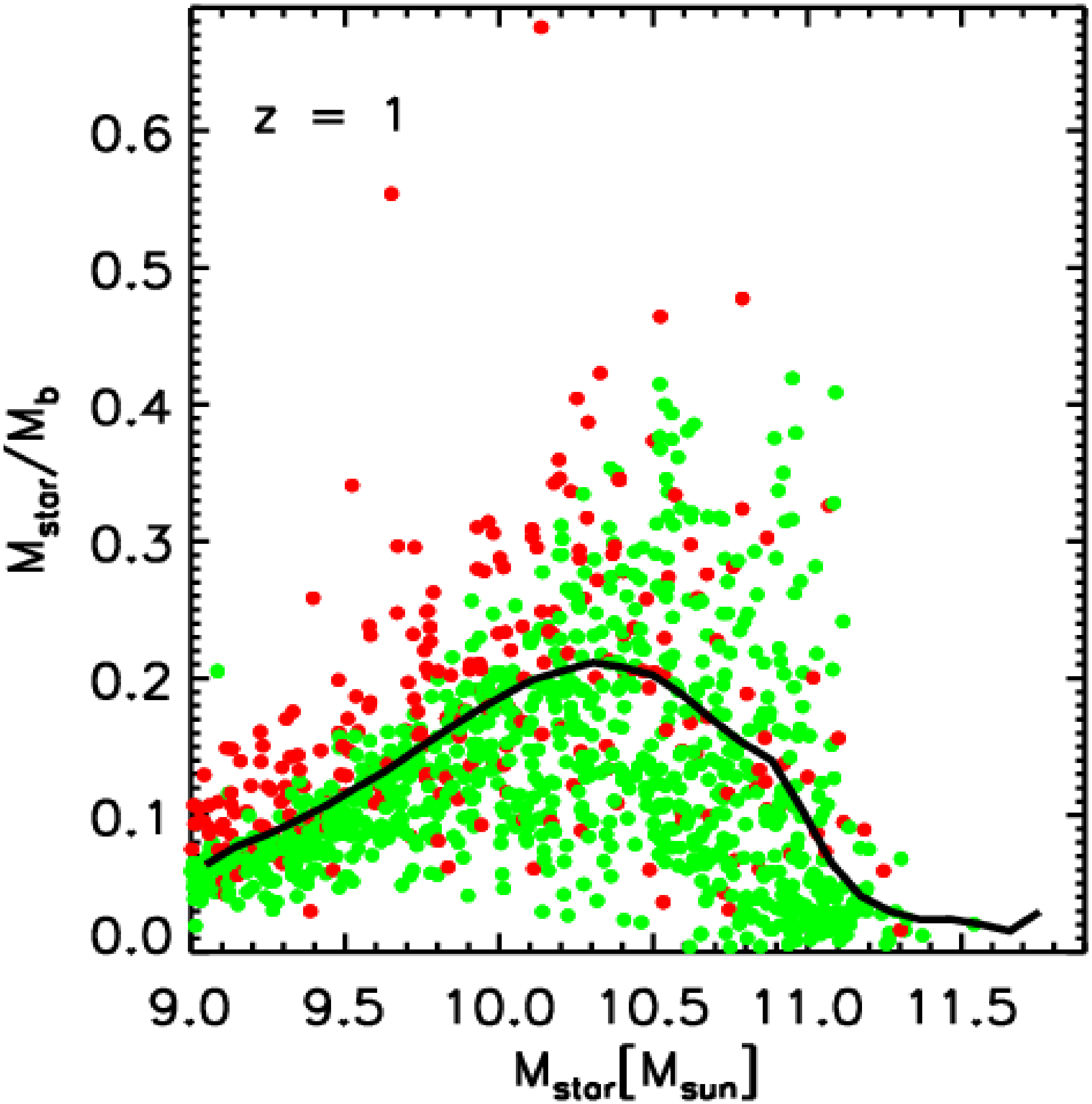
Guo et al 2011



- Median efficiency is higher than at given maximum halo mass
- Scatter is again substantial
- Satellites again form more efficiently than centrals

Star formation efficiency vs stellar mass

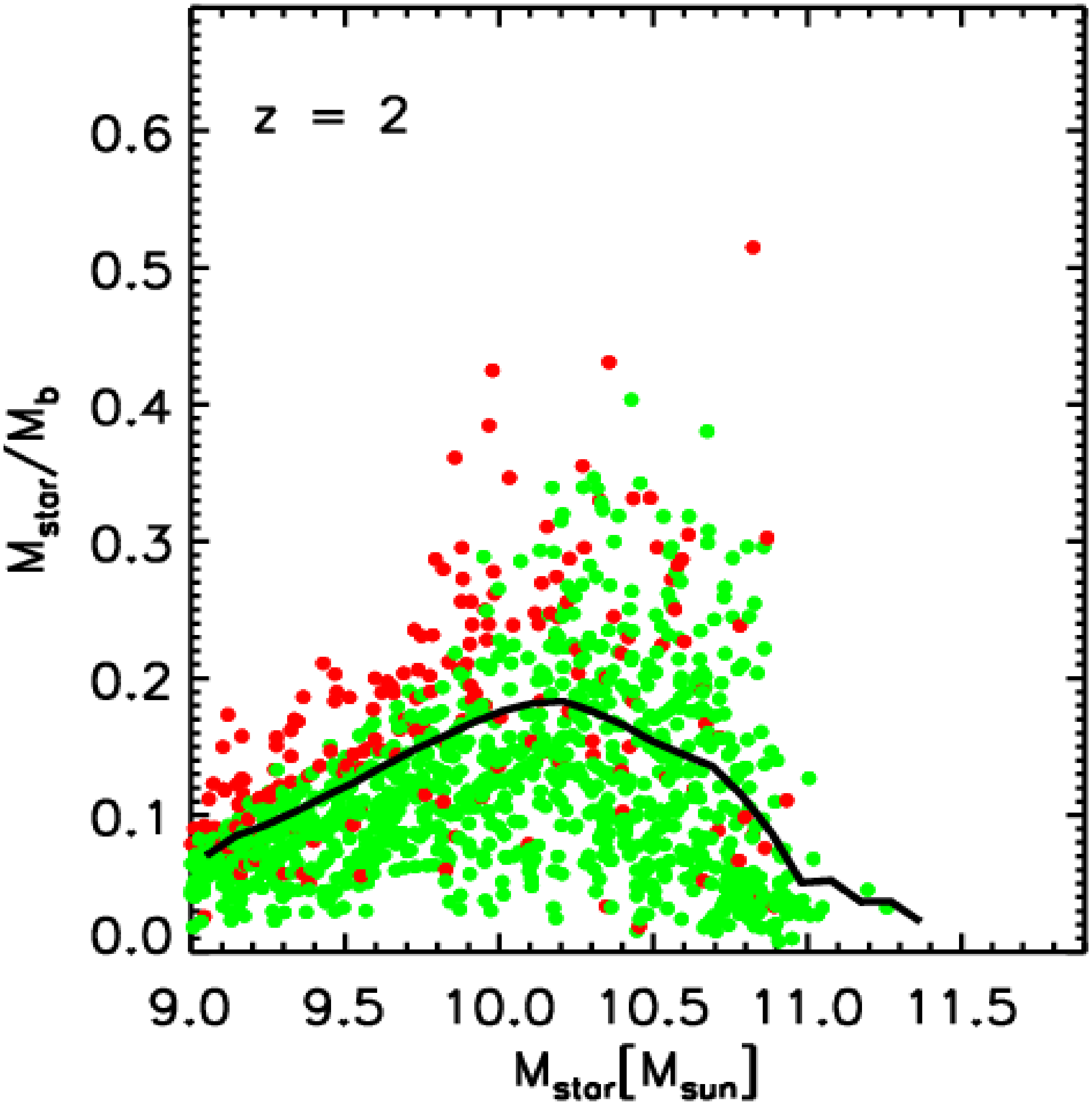
Guo et al 2011



- Median efficiency is higher than at given maximum halo mass
- Scatter is again substantial
- Satellites again form more efficiently than centrals
- At given stellar mass, the efficiency is lower at high z

Star formation efficiency vs stellar mass

Guo et al 2011



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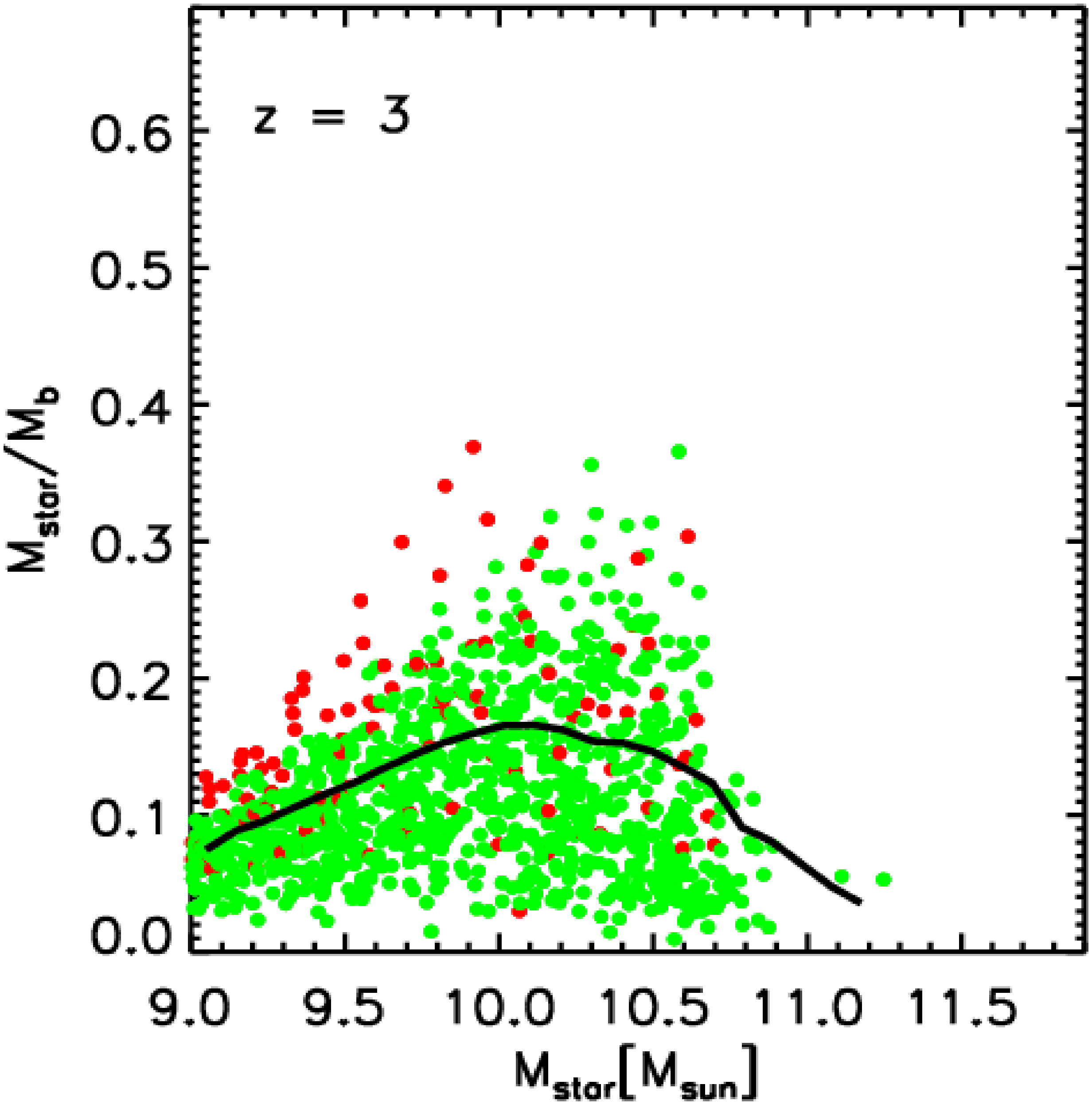
Star formation efficiency vs stellar mass

Guo et al 2011



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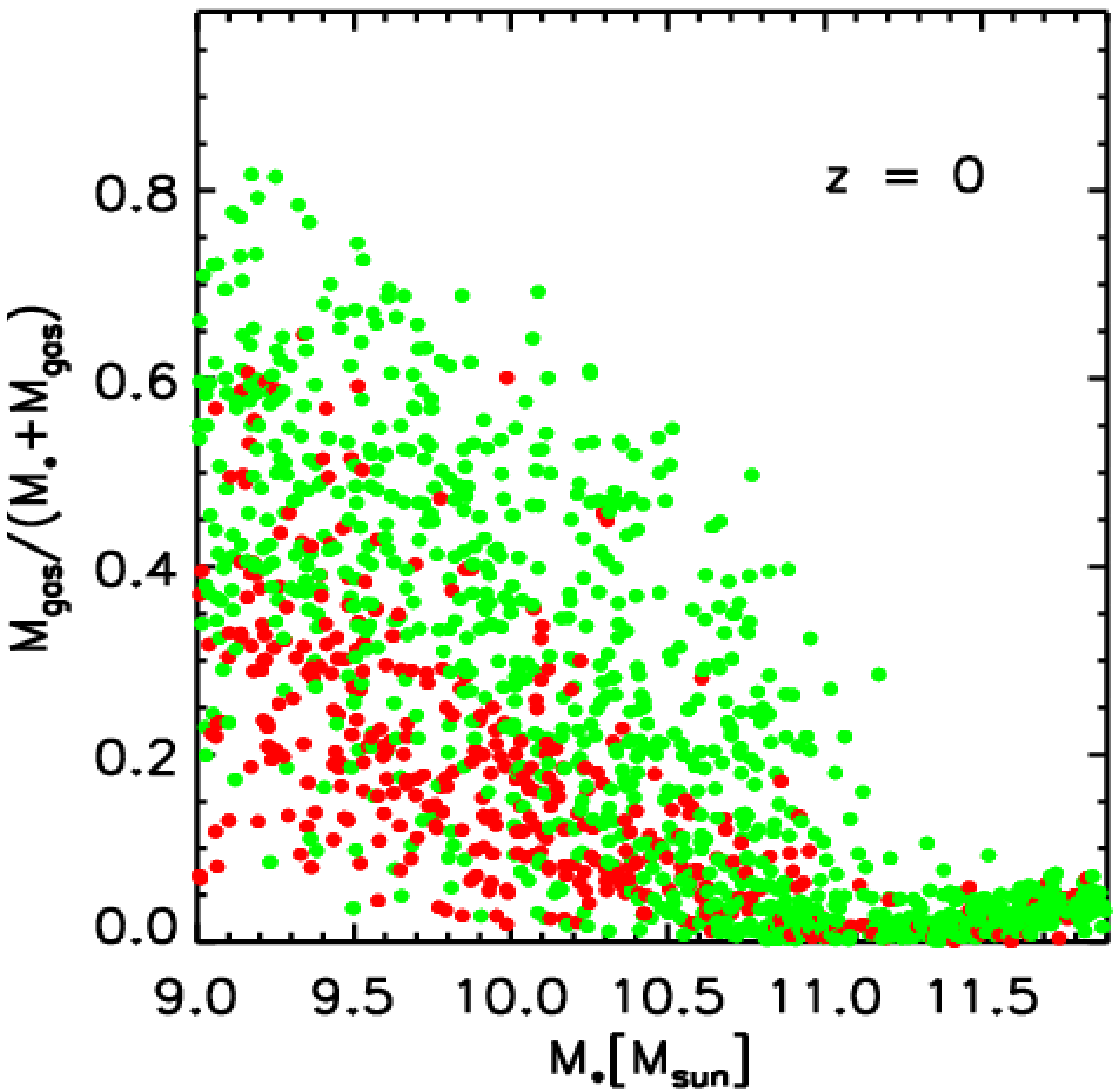
Predicted cold gas fractions vs stellar mass

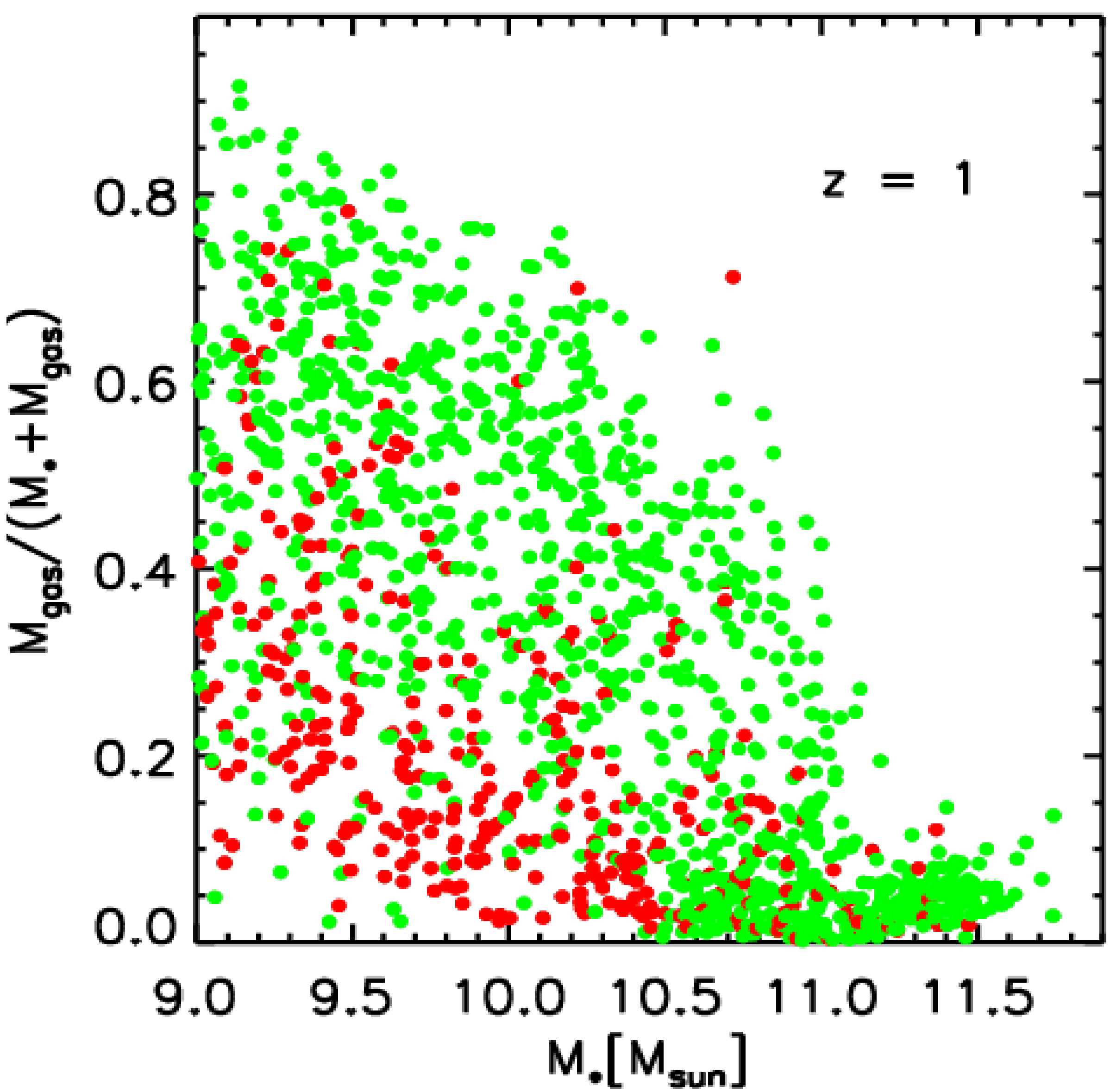
Guo et al 2011



- No high mass galaxies contain more than a few percent of cold gas
- Large scatter at lower mass
- Cold gas fraction increases with decreasing mass
- Satellites contain less cold gas than centrals

Predicted cold gas fractions vs stellar mass

Guo et al 2011



- No high mass galaxies contain more than a few percent of cold gas
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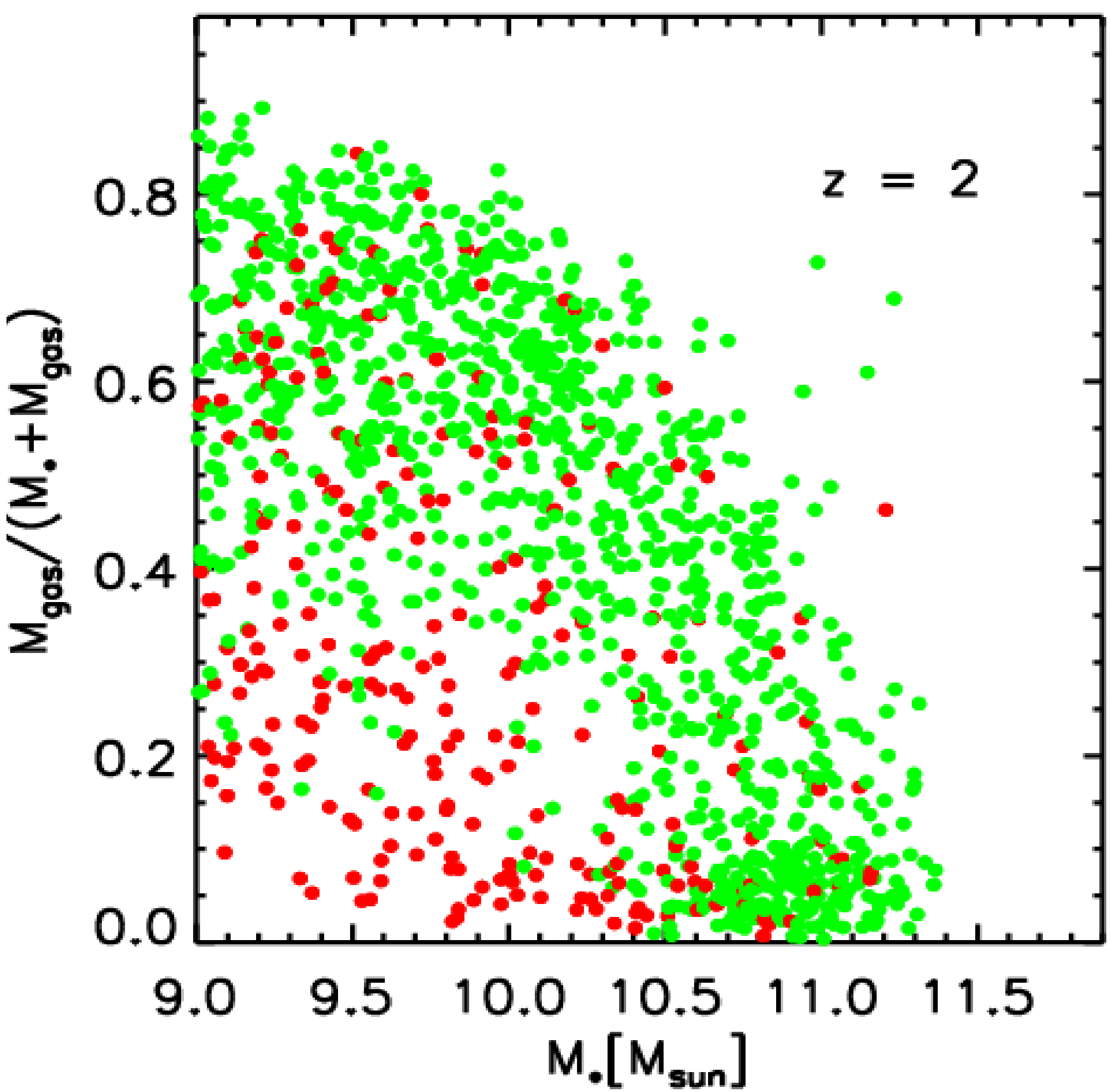
- Gas fractions increase with redshift

Predicted cold gas fractions vs stellar mass

Guo et al 2011



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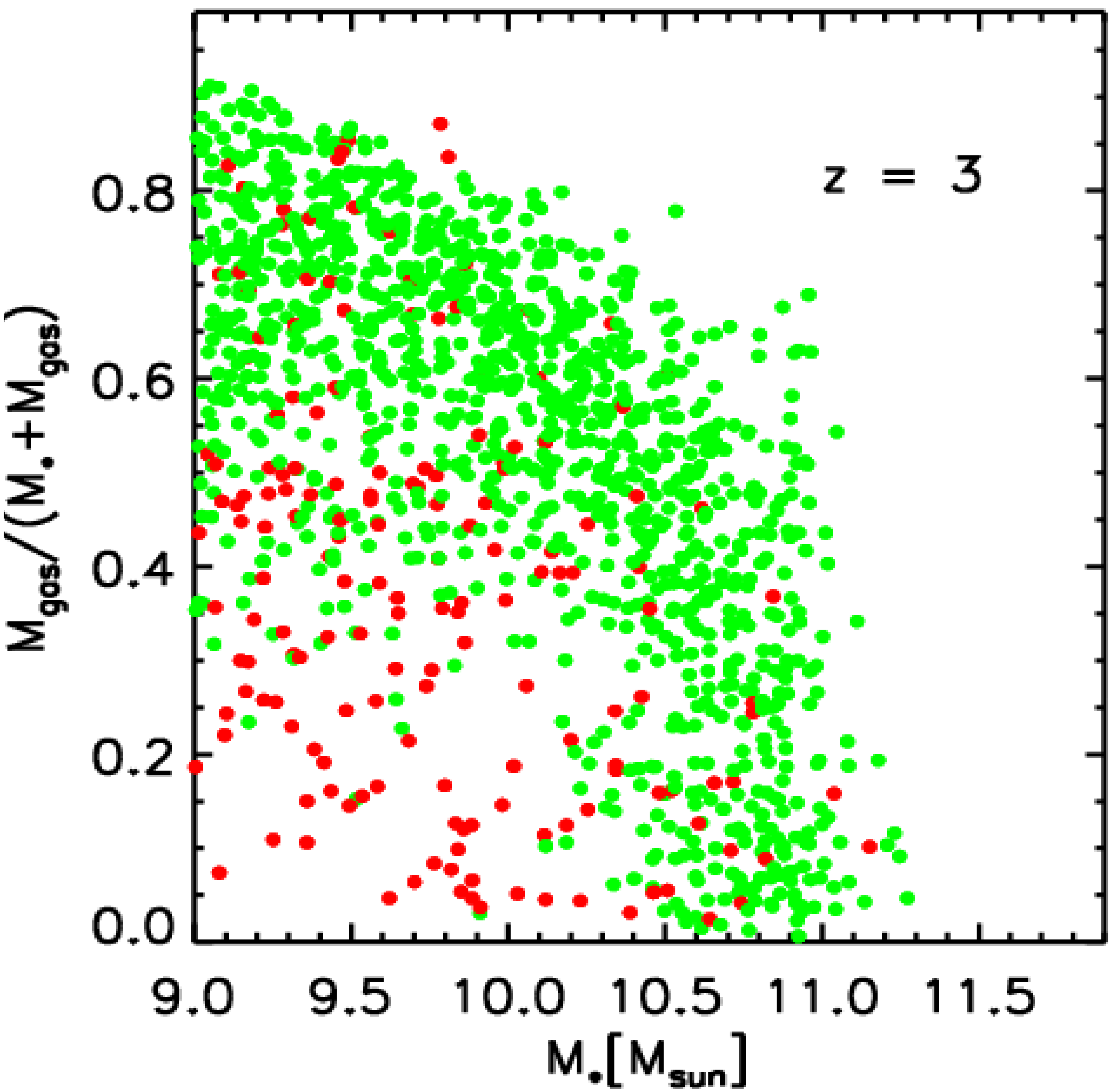
- Gas fractions increase with redshift
- Massive gas-free galaxies vanish at high redshift

Predicted cold gas fractions vs stellar mass

Guo et al 2011



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Conclusions

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

Models must simultaneously 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

Mean inflow and outflow rates from typical galaxies are <u>large</u> compared to mean star-formation rates

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

→ A better understanding of the baryon cycle
inflow -- star/AGN formation -- outflow is needed