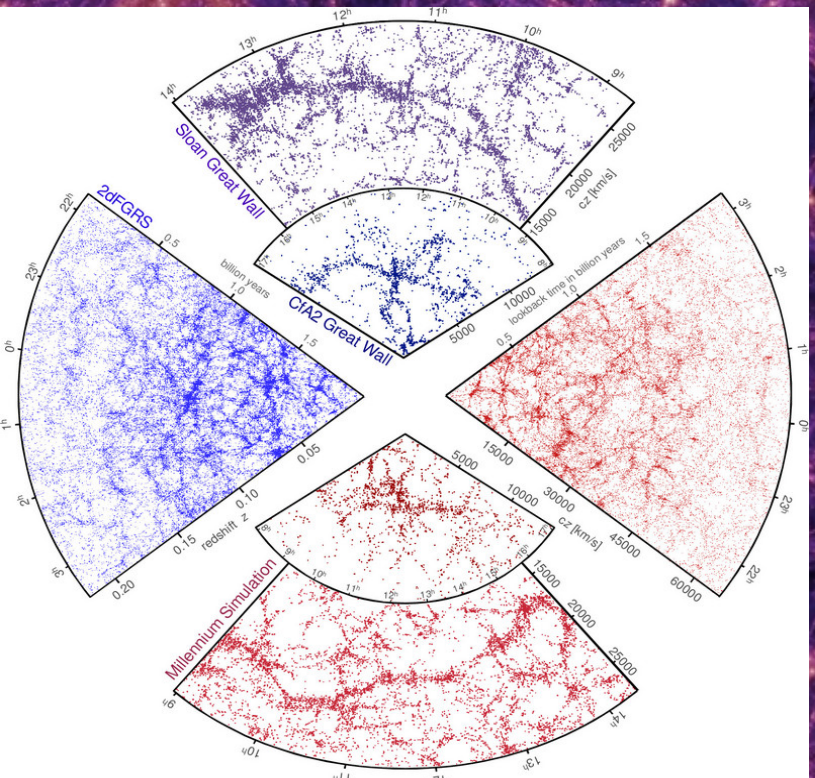
The cosmology dependence of galaxy formation



Simon White
Max Planck Institute for Astrophysics

Millennium (2005) $L = 685$ Mpc, $N = 10^{10}$, $m \sim 10^9 M_\odot$

Millennium-II (2008) $L = 137$ Mpc, $N = 10^{10}$, $m \sim 10^7 M_\odot$

Millennium-XXL (2010) $L = 4.3$ Gpc, $N = 3.10^{11}$, $m \sim 6.10^9 M_\odot$

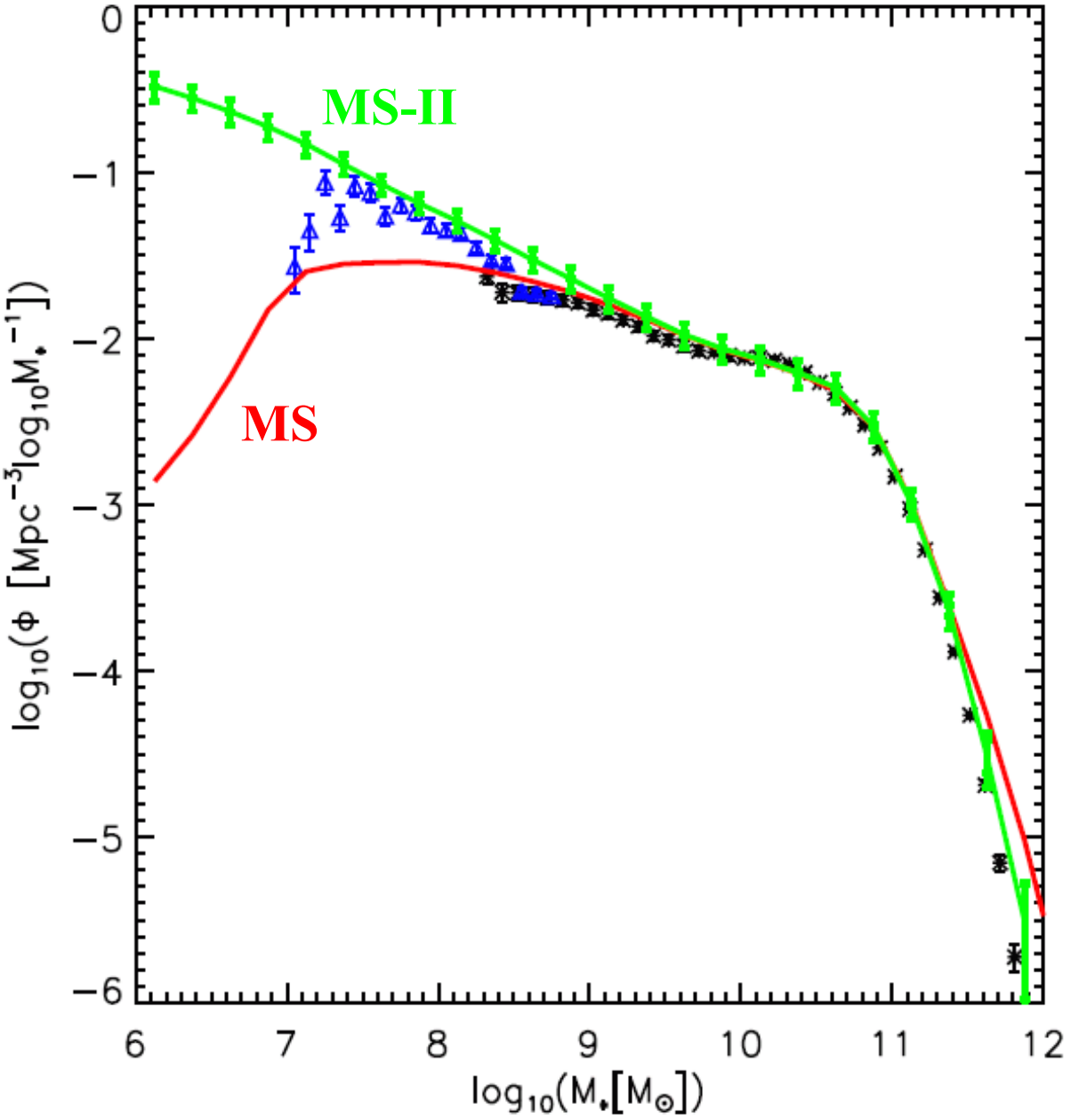
All three simulations use the same (wrong) WMAP1 cosmology and store structural data at the same set of ~60 redshifts

They can be used together with semianalysic methods to simulate the formation and evolution of the galaxy population over volumes comparable to those of next generation surveys

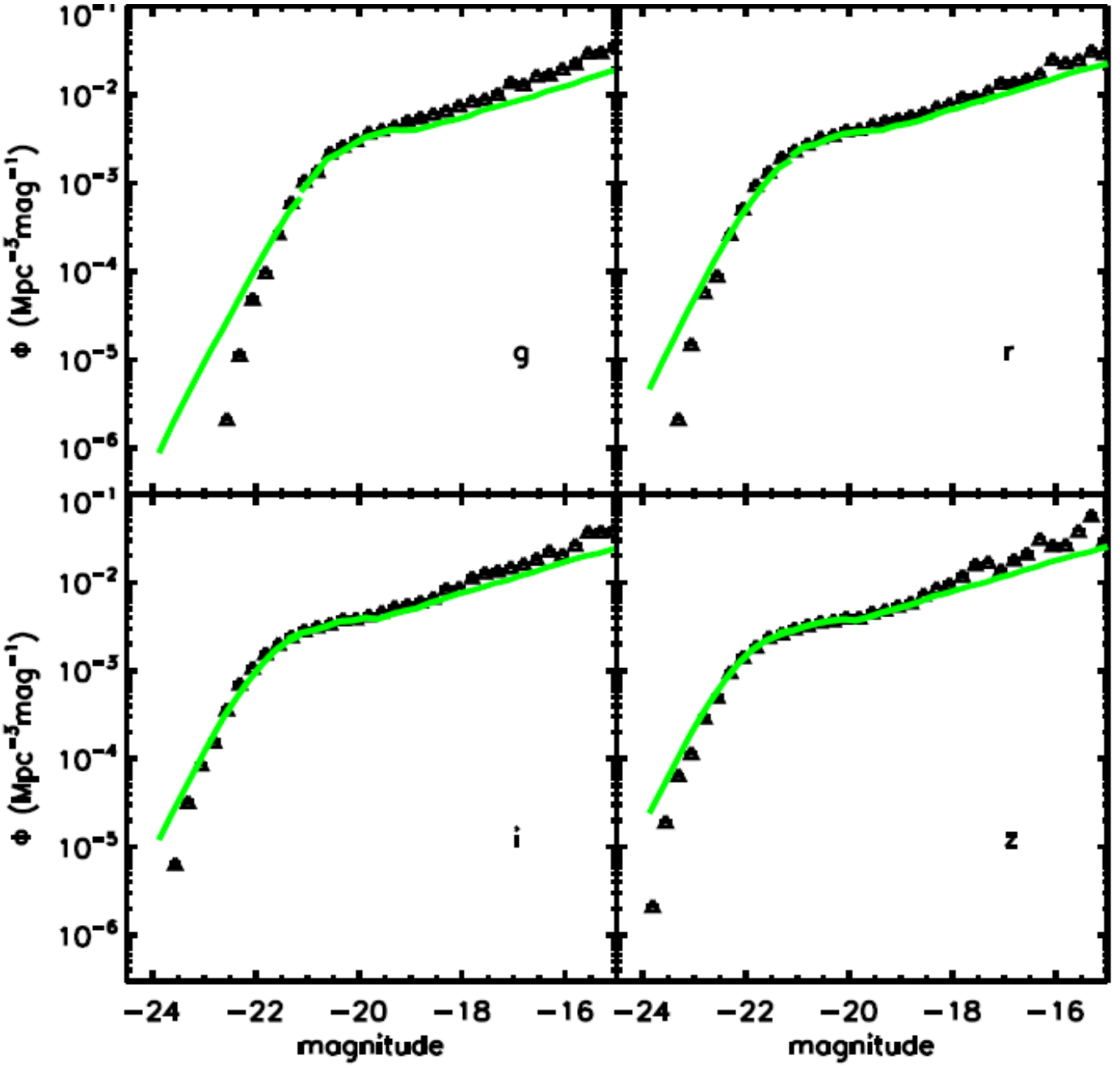
The most recent model, using MS and MS-II was published in Guo et al (2011) and is publicly available at http://www.mpa-garching.mpg.de/millennium

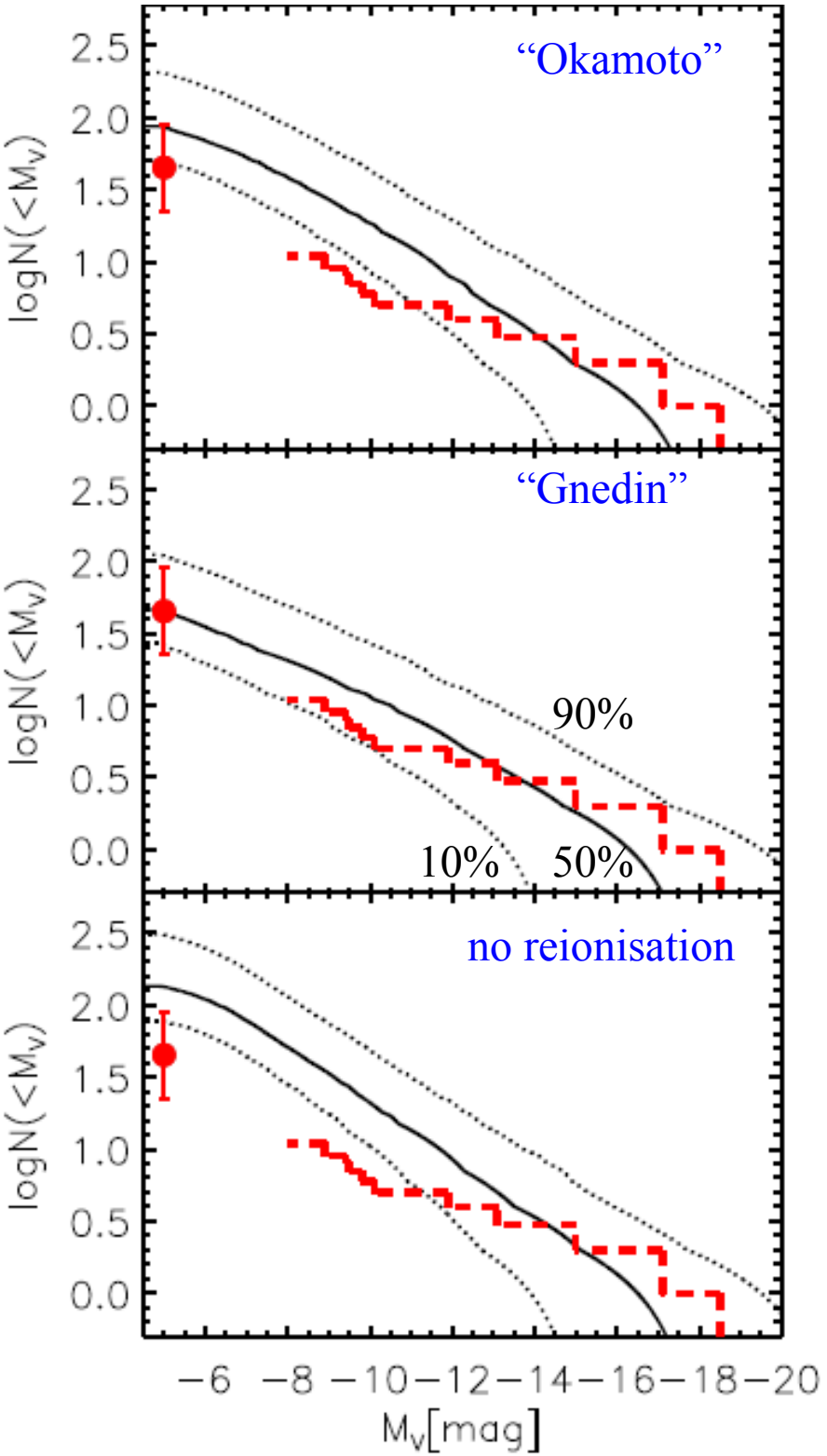
Things that work well

The stellar mass function of galaxies



Luminosity functions of galaxies

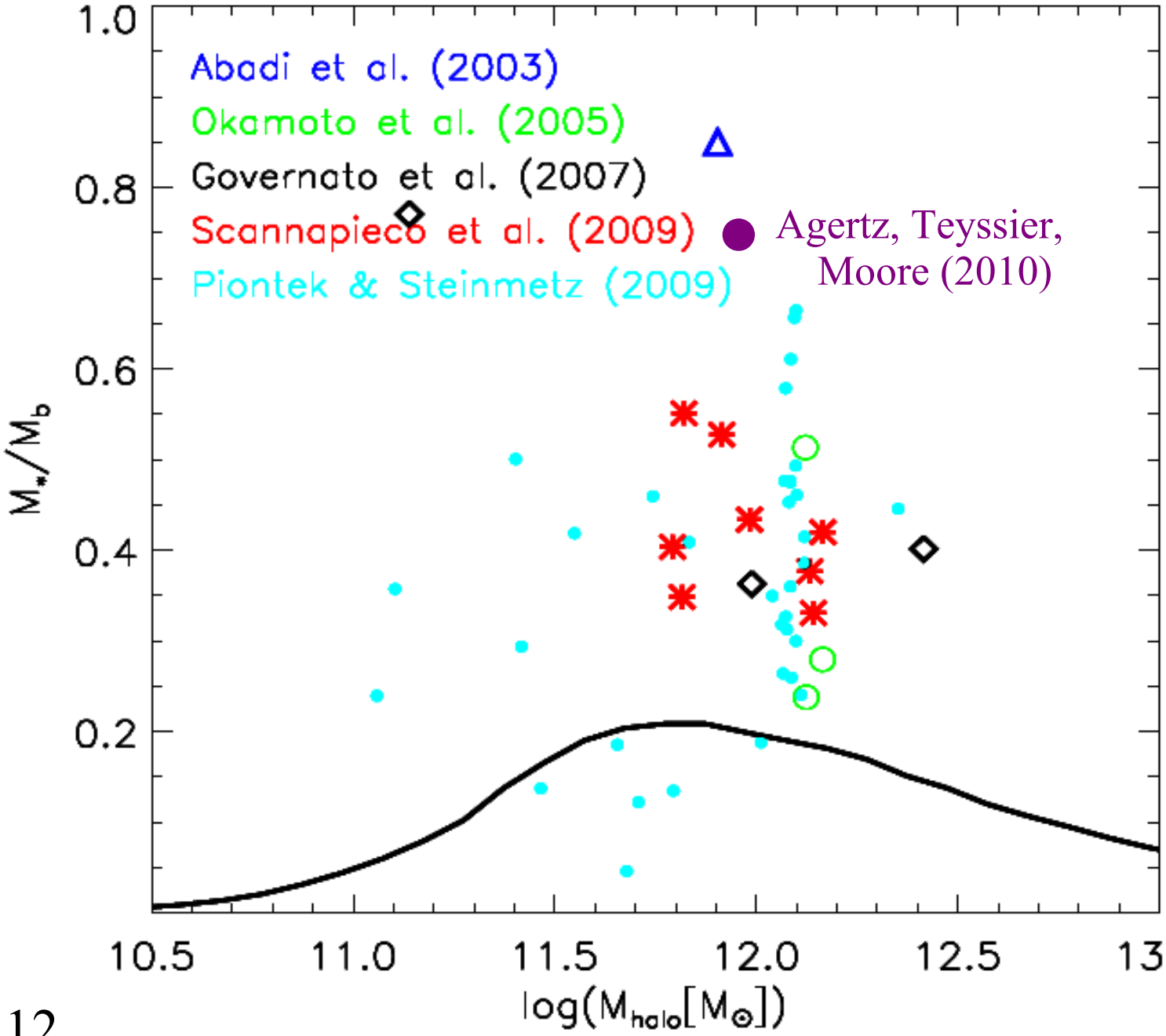




Luminosity function of Milky Way satellites

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

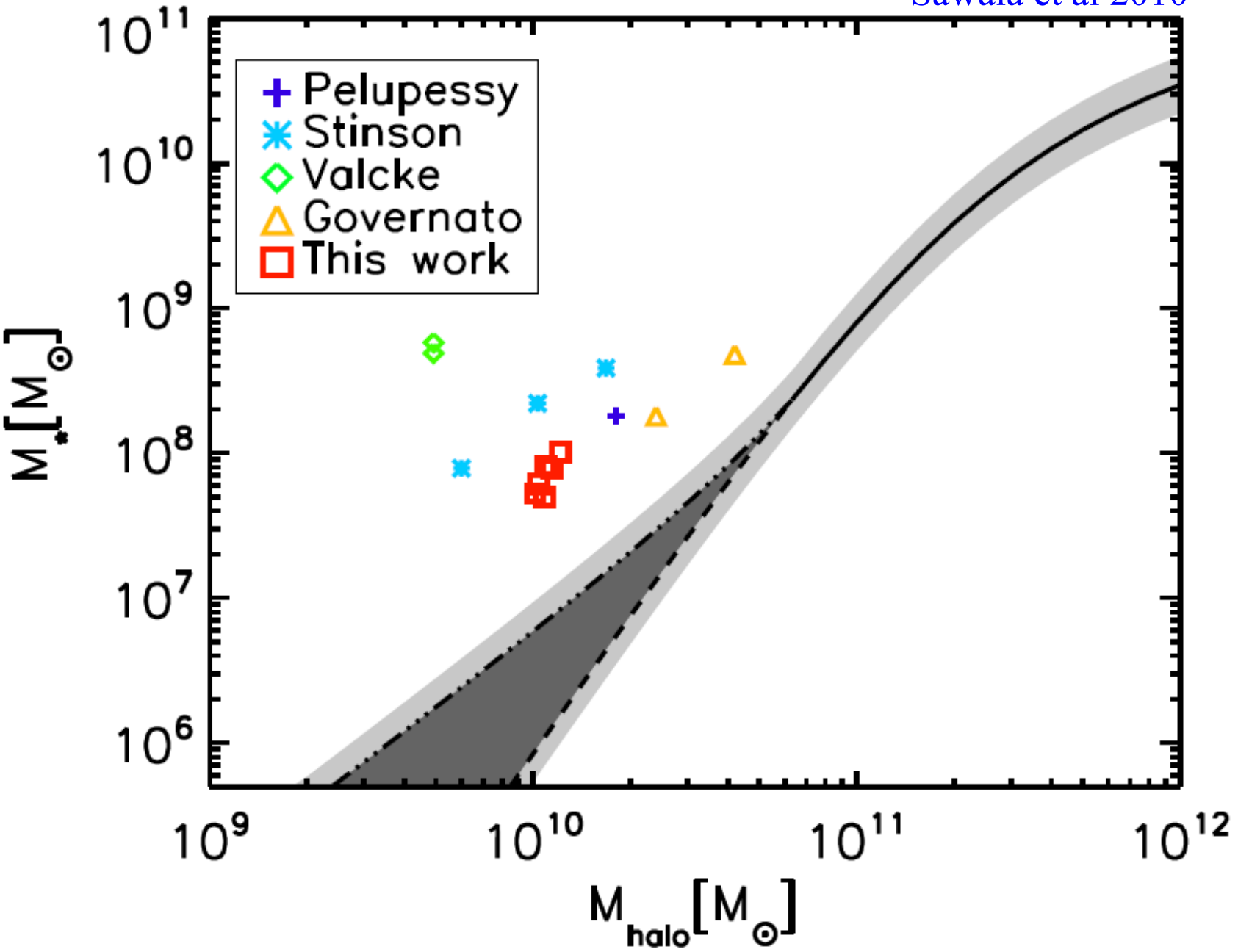
"Successful" simulations do not match the low efficiencies needed to fit galaxy abundances



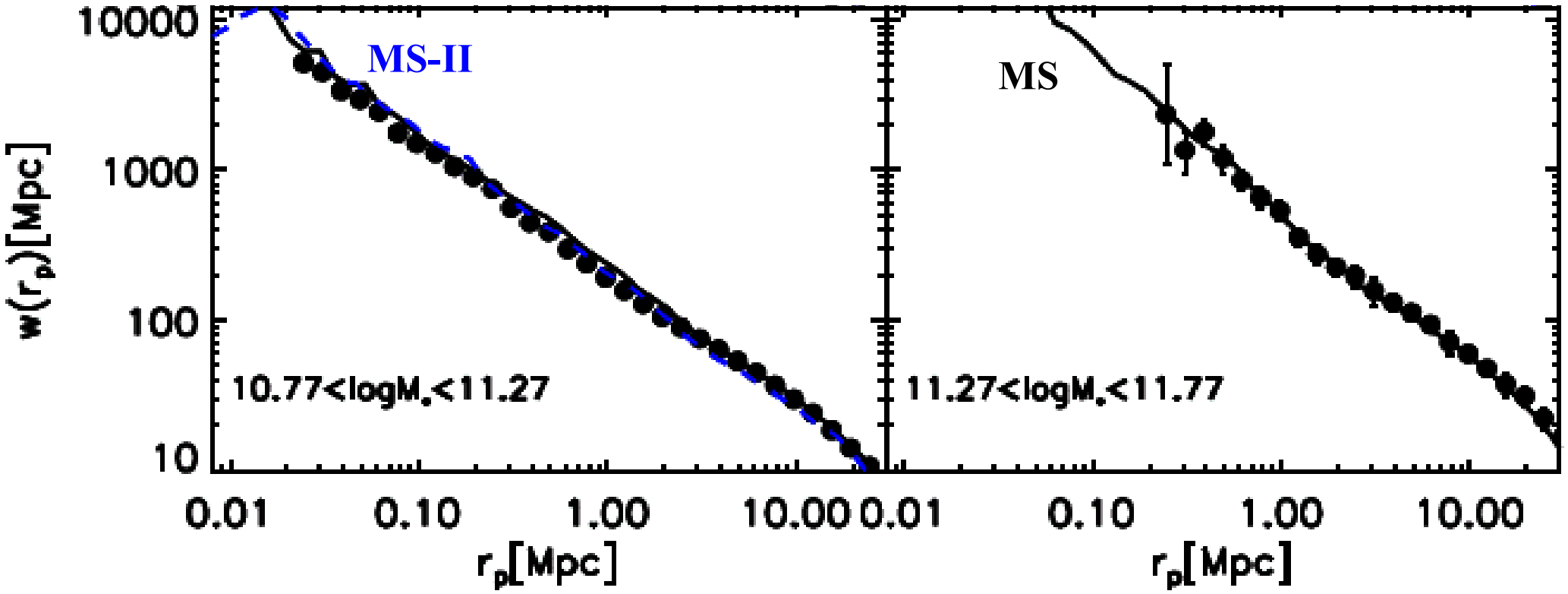
Guo et al 2010

...and do worse for dwarfs than for giants

Sawala et al 2010

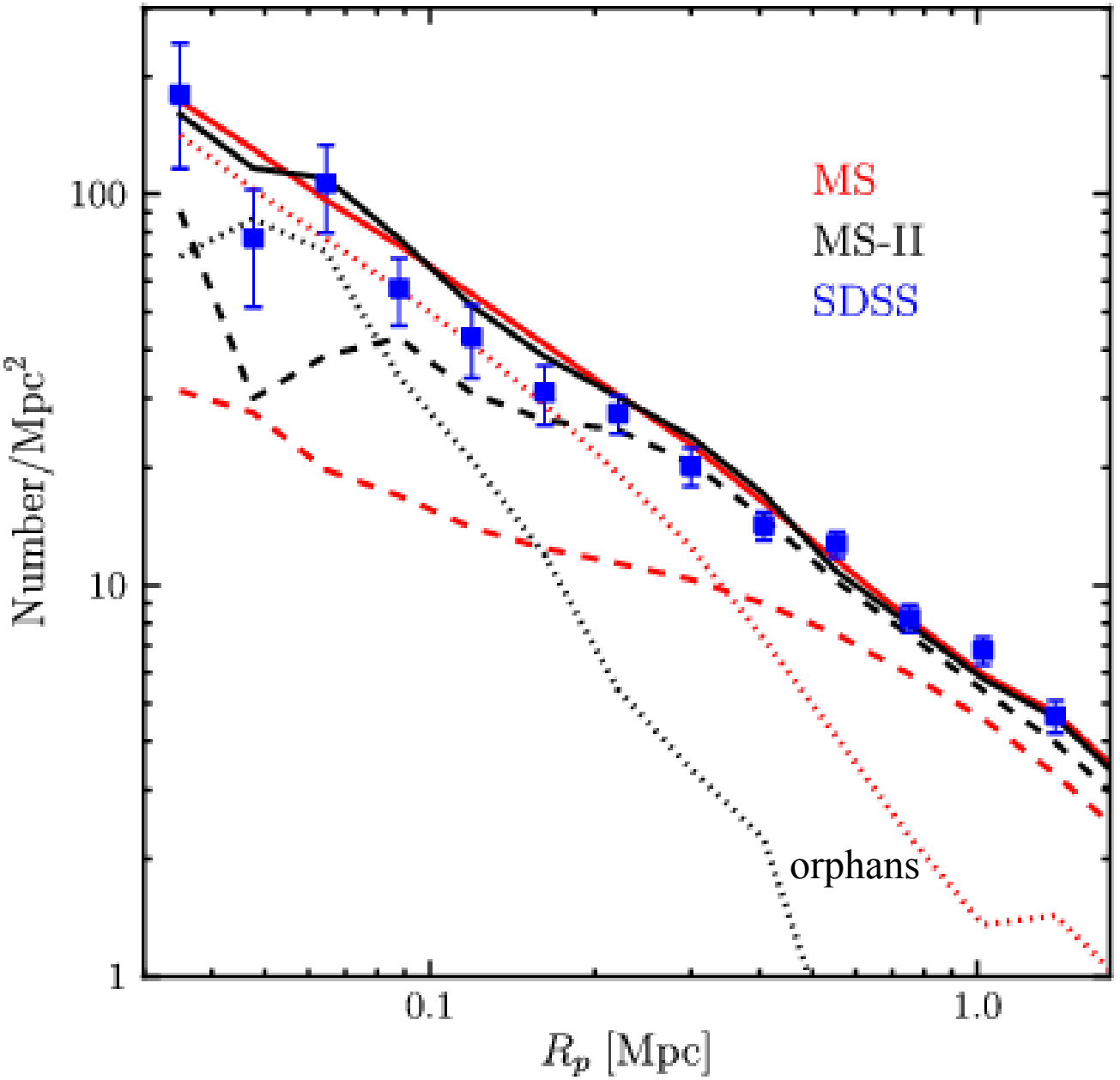


Clustering of massive galaxies



Data from SDSS/DR7

Projected galaxy number density profiles of clusters



$\log M_{gal} > 10.0$

$14.0 < \log M_{clus} < 14.3$

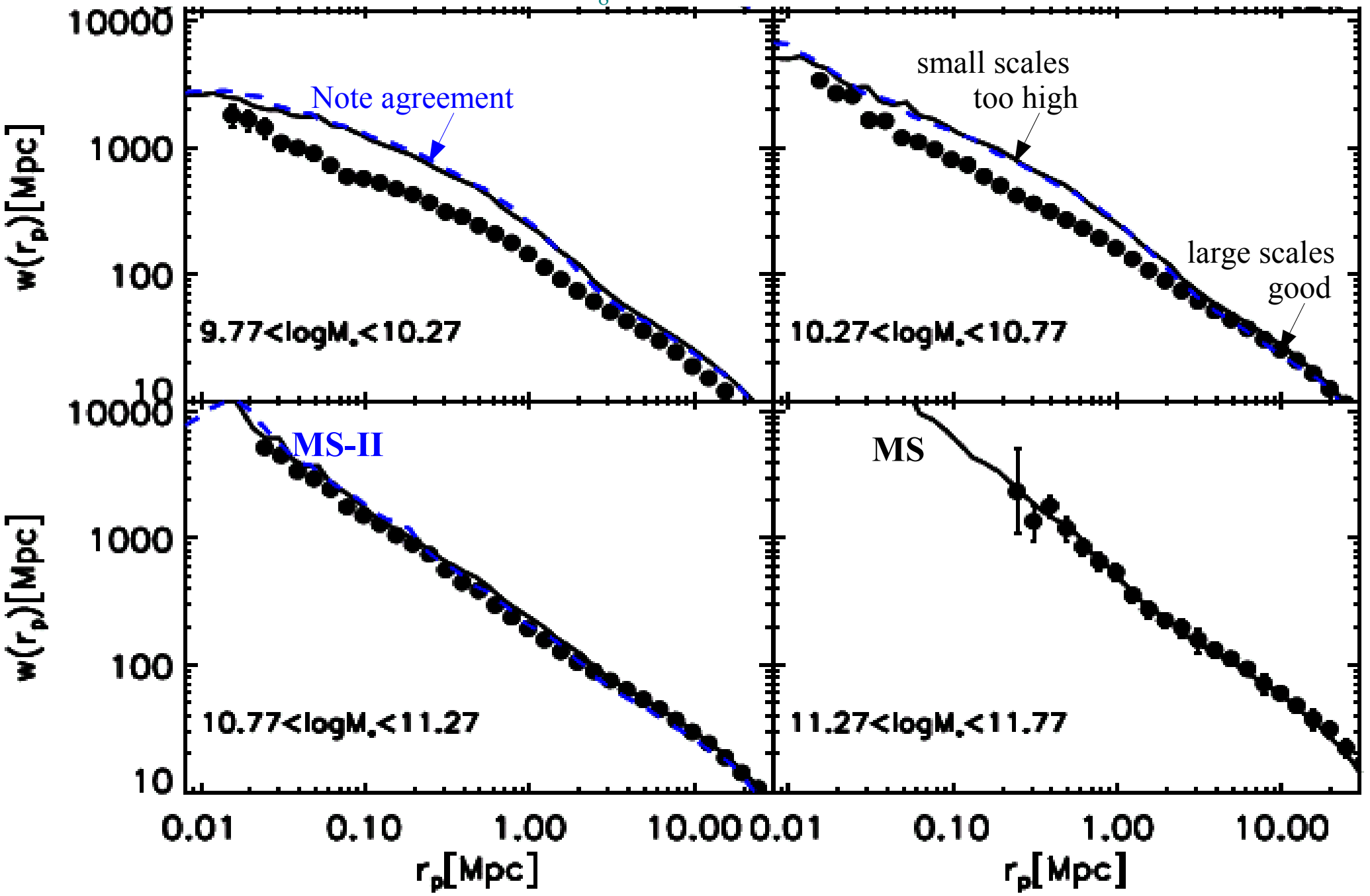
Note: good agreement of MS with MS-II is *only* when orphans are included

Orphan treatment is physically consistent and needed to fit SDSS

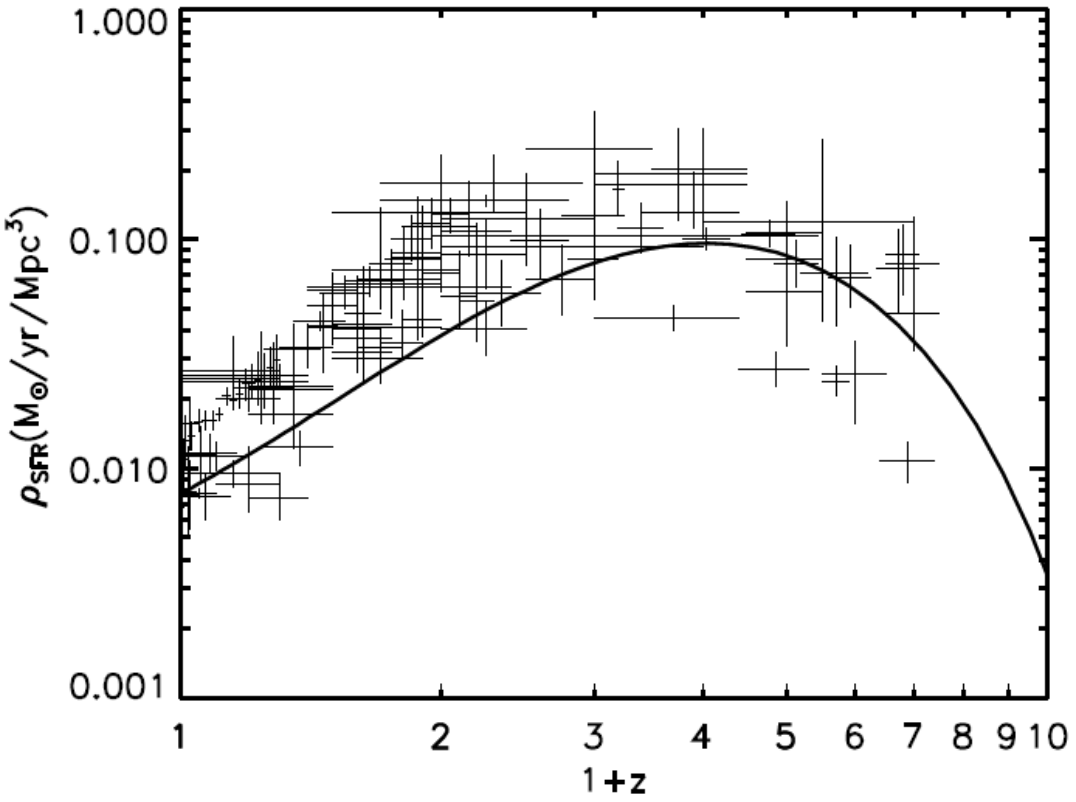
Things that work less well

Clustering of less massive galaxies

--- σ_8 = 0.9 is too high ---

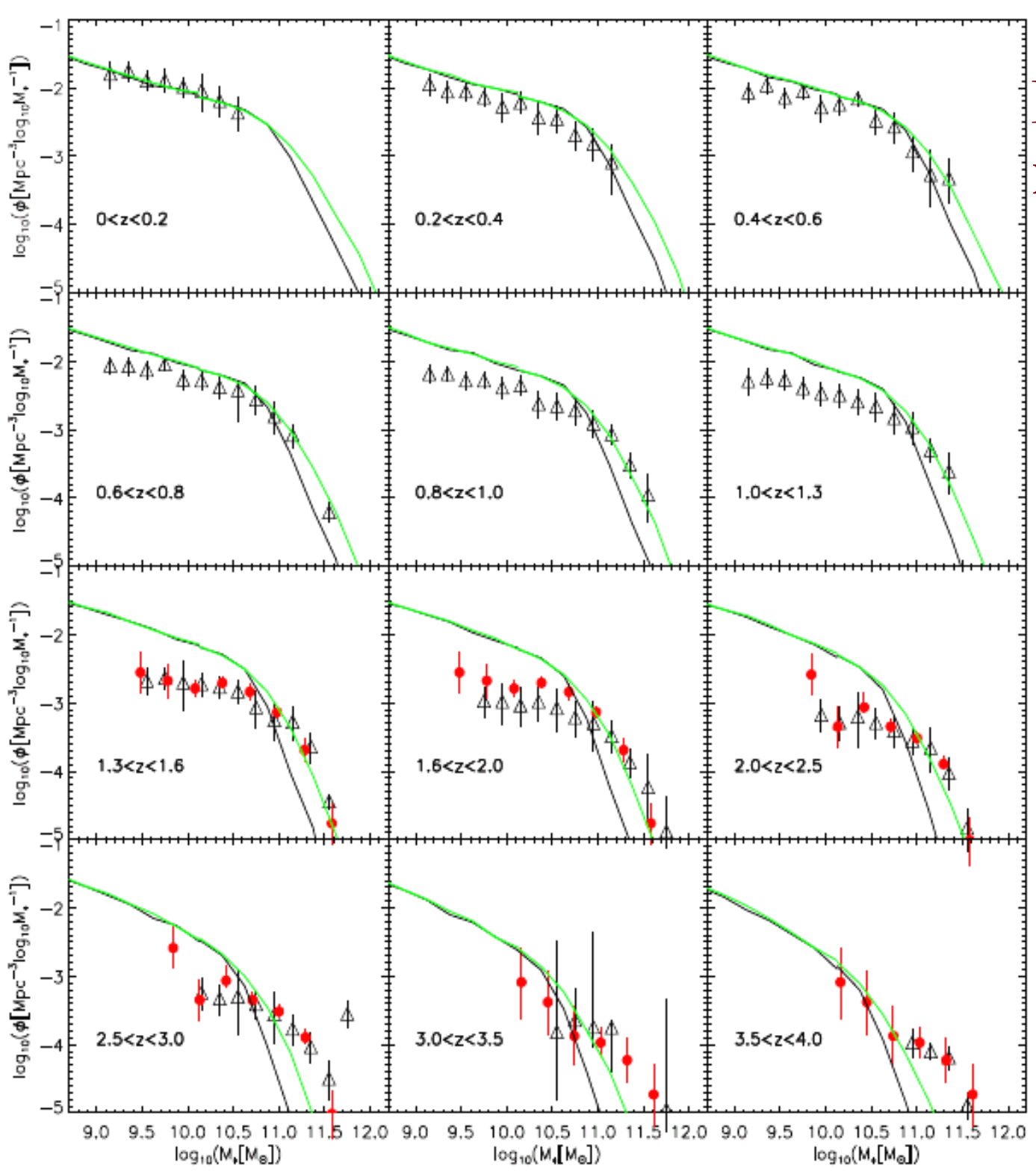


The cosmic star formation density history



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

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



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

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

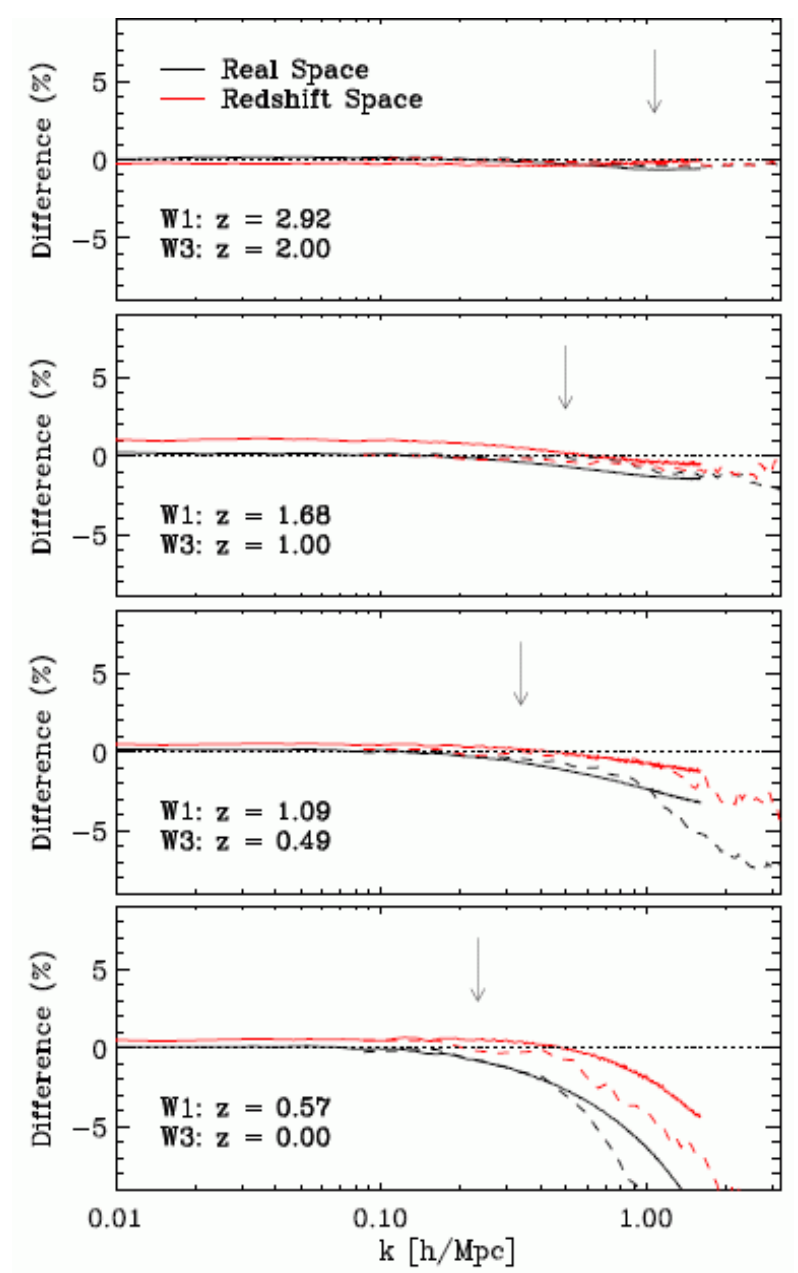
2) Reassign redshifts to match linear amplitudes on these scales

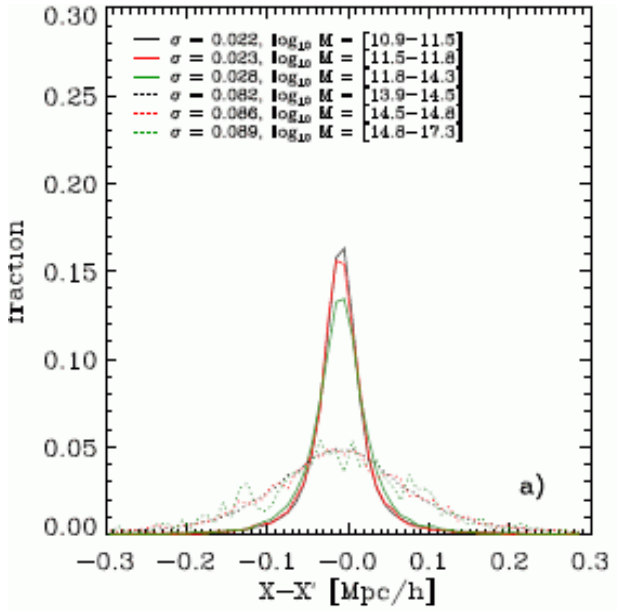
-- z = 0.57, 1.68, 2.92 z = 0, 1, 2

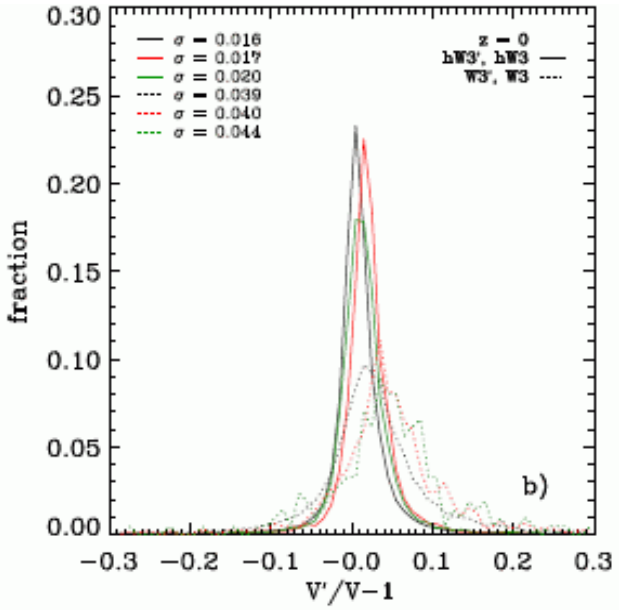
3) Scale particle masses and velocities to match Ω_m and new size

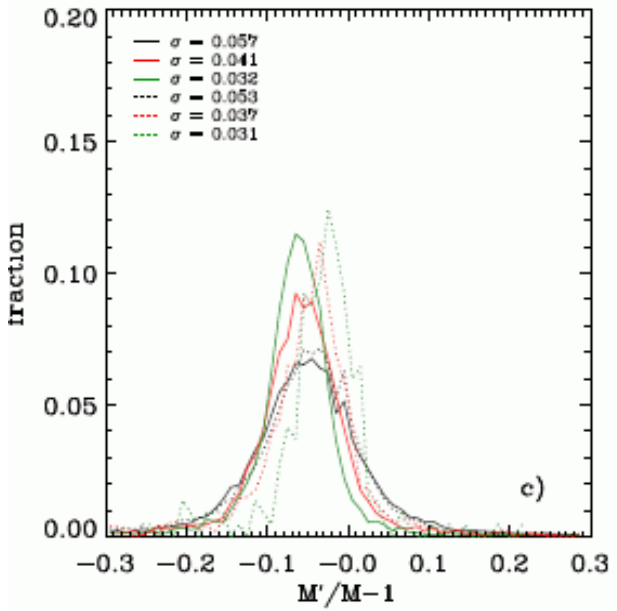
-- $9 \times 10^8\ M_\odot/h$ $5.6 \times 10^8\ M_\odot/h$

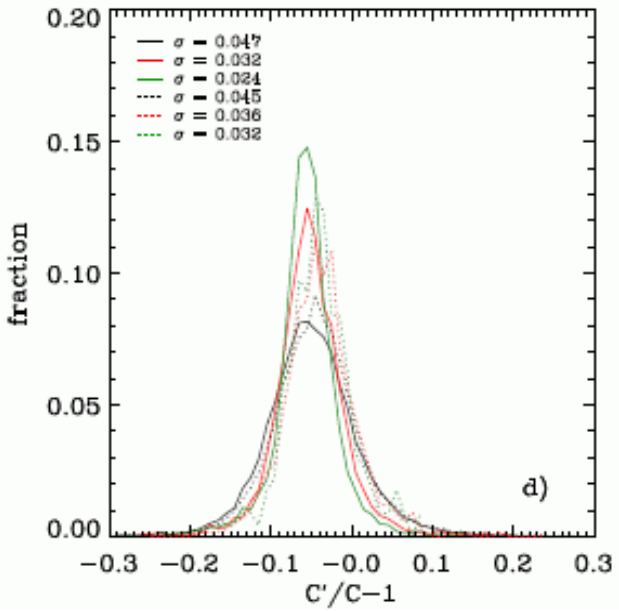
4) Adjust for the difference between amplitudes of original and target power spectra on large scales using linear theory.





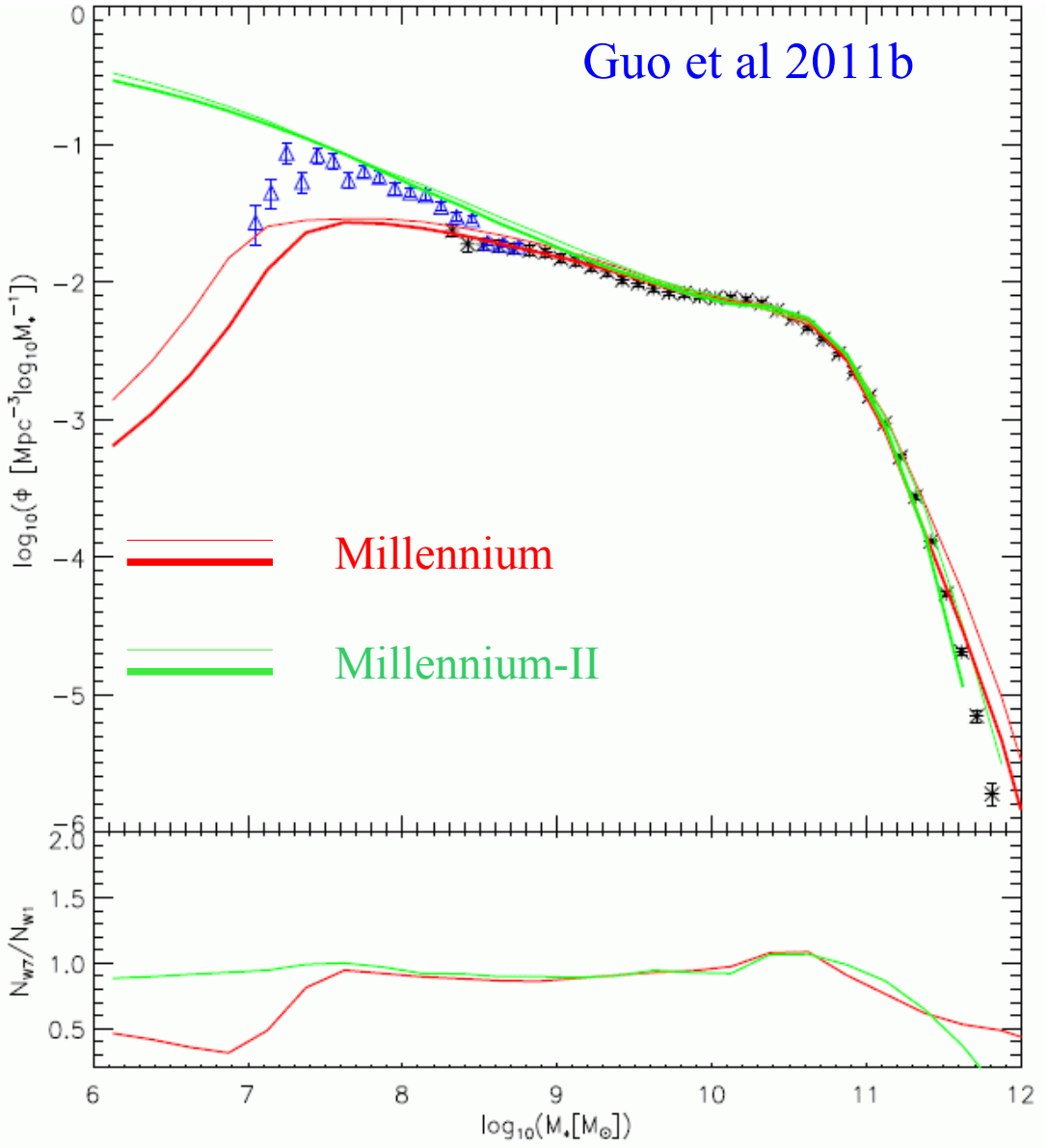






Power spectra agree to better than 1% for k < 0.3

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



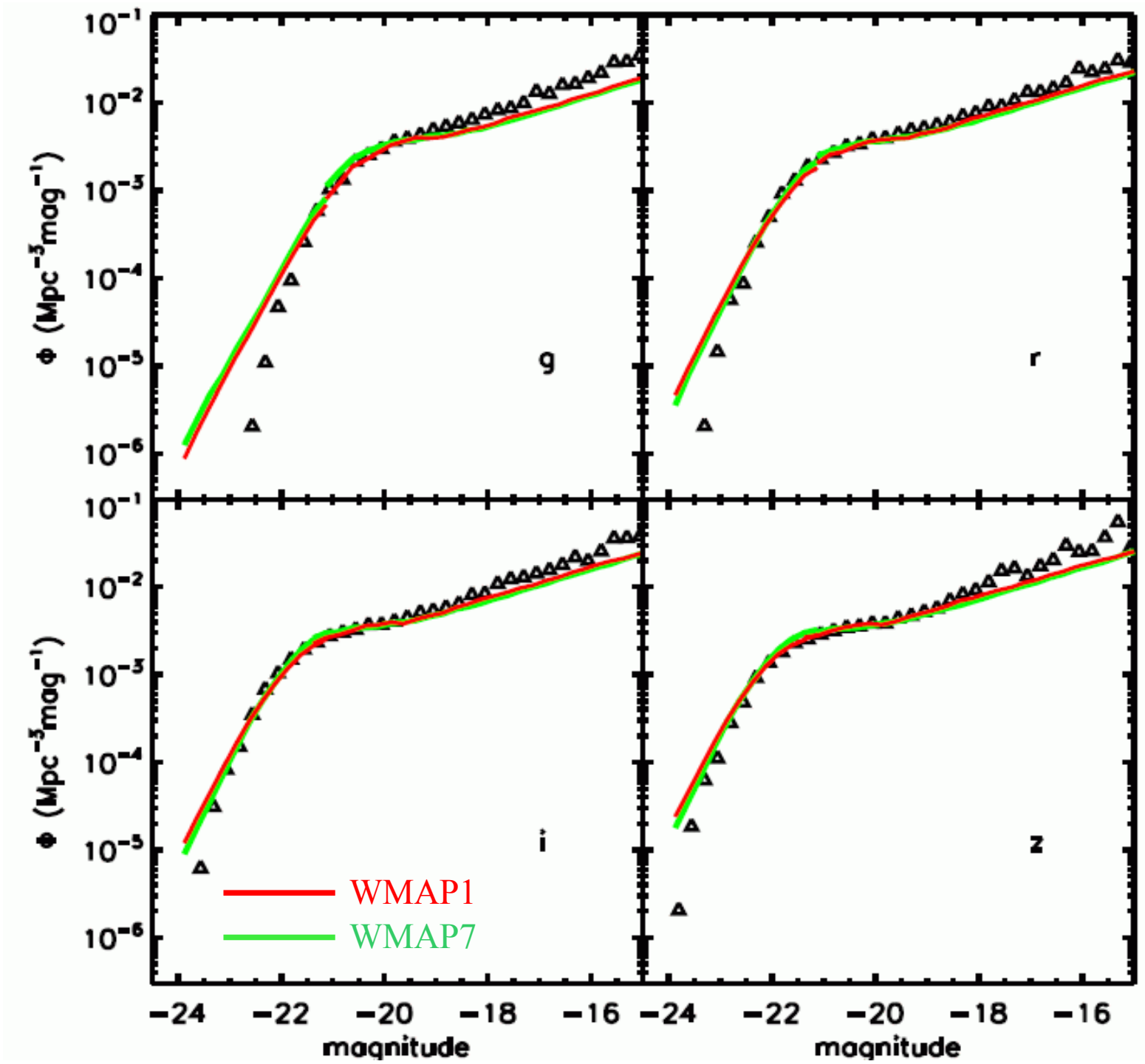
Switching from WMAP1 to WMAP7

Small shifts in the parameters of the galaxy formation model allow the galactic stellar mass function to be fit equally well in the two different cosmologies despite

$\sigma_8 = 0.90 \longrightarrow \sigma_8 = 0.81$

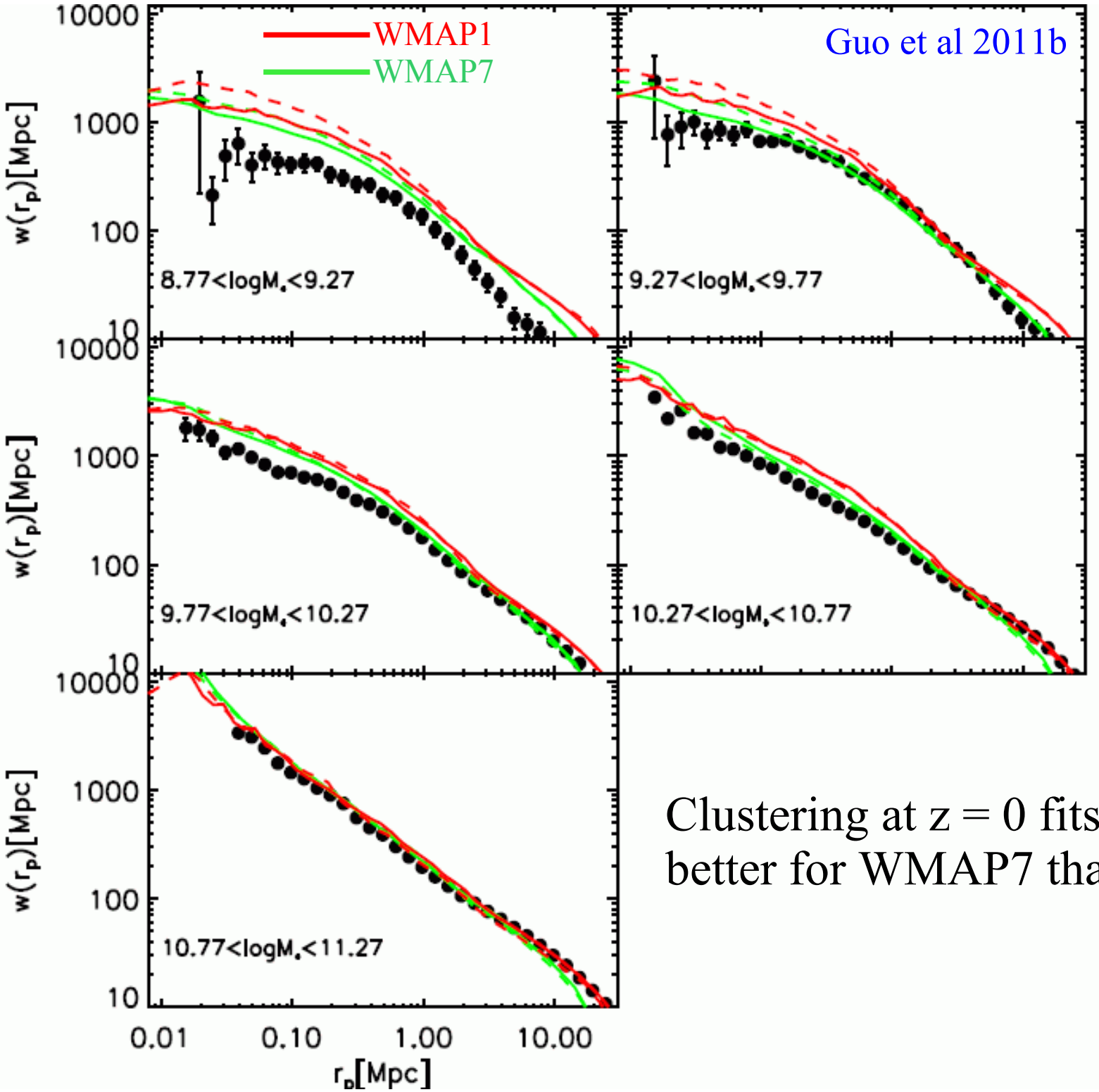
Parameter	Description	WMAP1	WMAP7
α	Star formation efficiency	0.02	0.016
ϵ	Amplitude of SN reheating efficiency	6.5	4.5
η	Amplitude of SN ejection efficiency	0.32	0.2
κ	Hot gas accretion efficiency onto black holes	1.5×10^{-5}	7.0×10^{-6}

Guo et al 2011b



Switching from WMAP1 to WMAP7

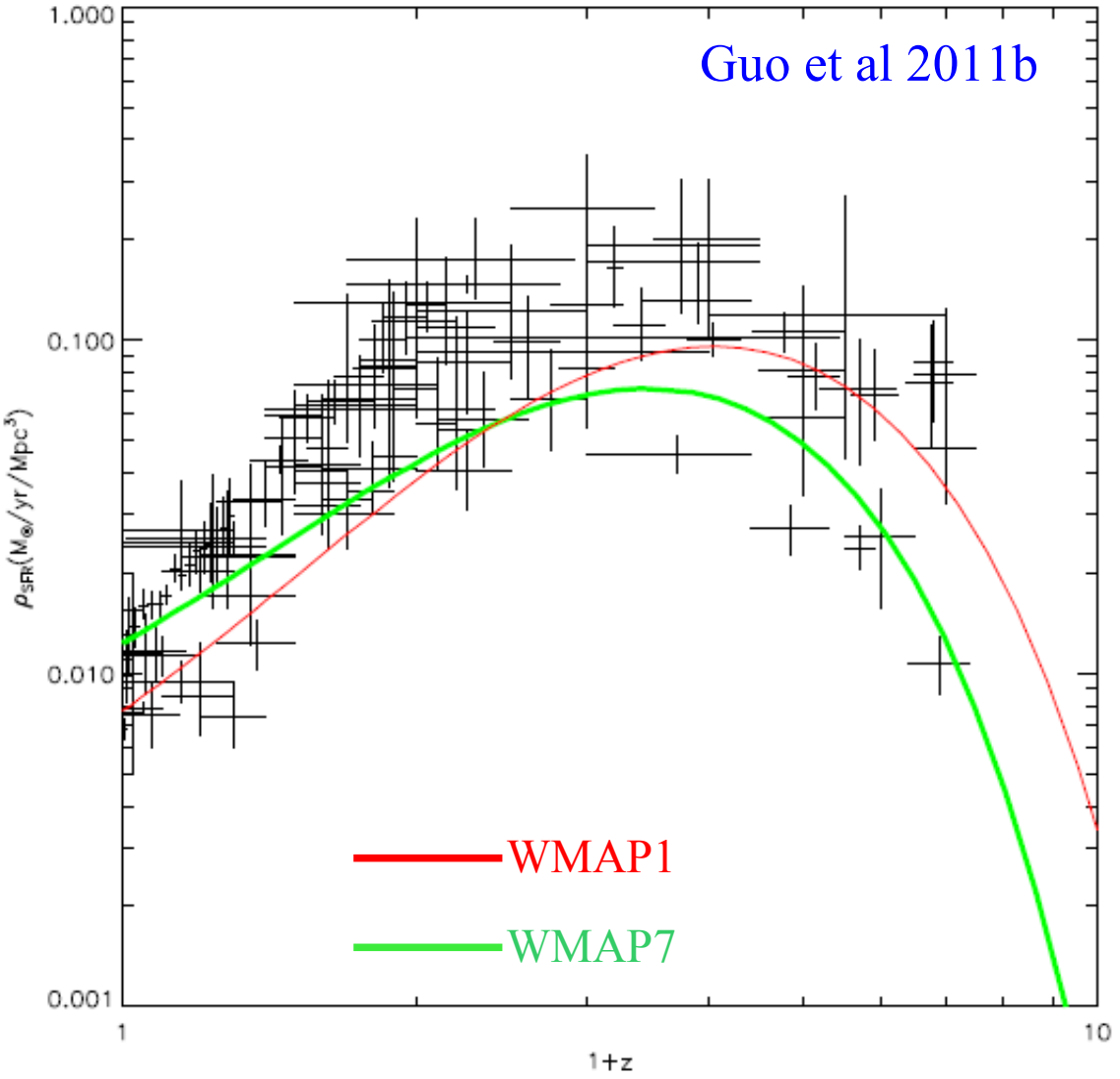
Luminosity functions fit equally well in the two cosmologies



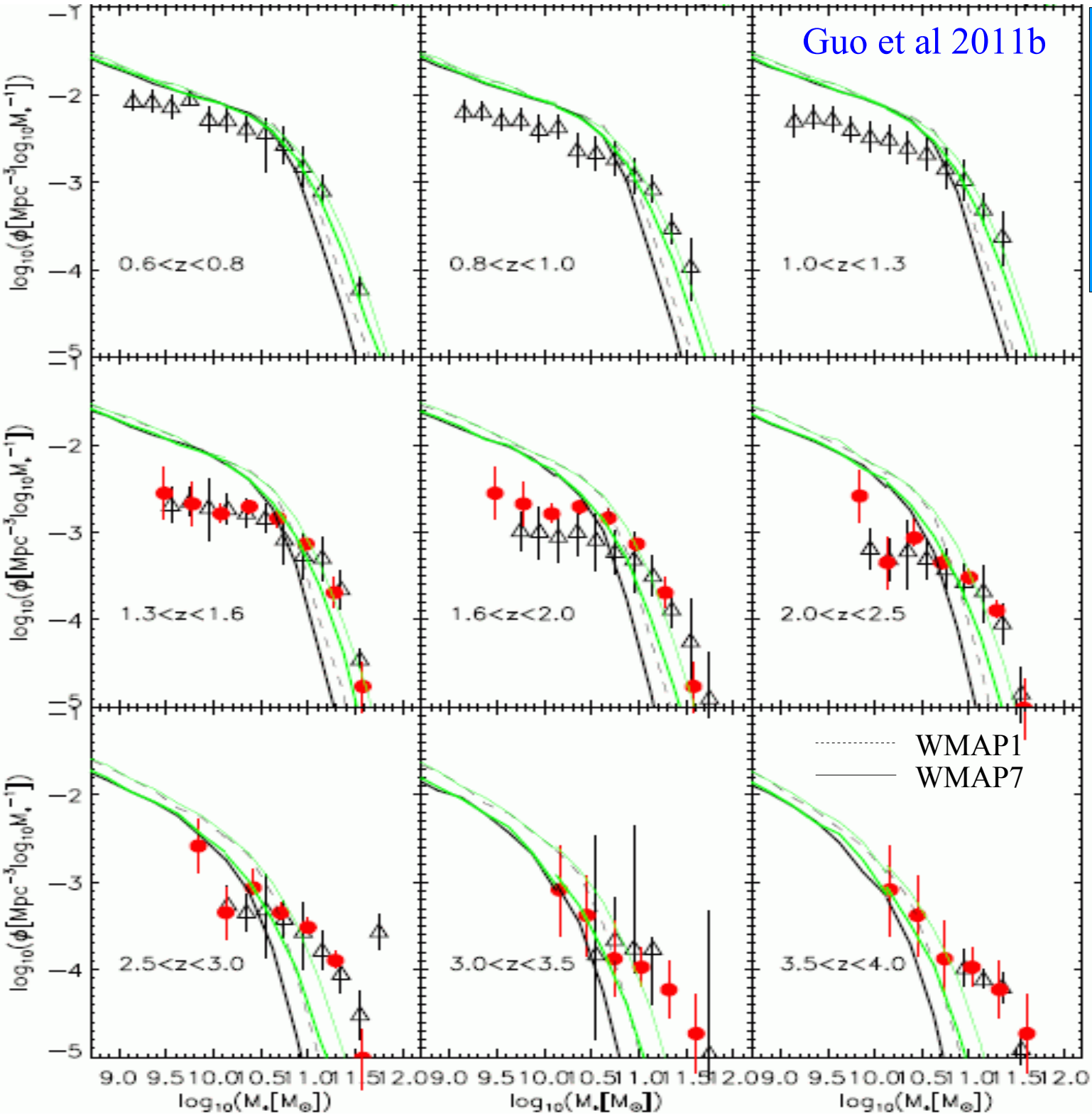
Switching from WMAP1 to WMAP7

Clustering at z = 0 fits observation better for WMAP7 than for WMAP1

Switching from WMAP1 to WMAP7



Galaxies form <u>later</u> in the WMAP7 cosmology than in WMAP 1



Switching from WMAP1 to WMAP7

..but the galaxy formation sequence is still incorrect

Conclusions

- Only small adjustments to the efficiencies of star formation and feedback are needed to match the observed abundances and scaling properties of galaxies in *any* currently viable LCDM cosmology

- The present-day clustering of galaxies is more easily matched by current simulations in a WMAP7 than in a WMAP1 cosmology

- Current simulations do not match the observed sequence of galaxy formation – observed downsizing is stronger than predicted
  → modelling of star formation needs improving

- Uncertainties due to poor modelling of formation and evolution processes dwarf those due to uncertain cosmological parameters

- Hydrodynamic simulations currently overestimate galaxy formation efficiencies in an LCDM cosmology by *large* factors