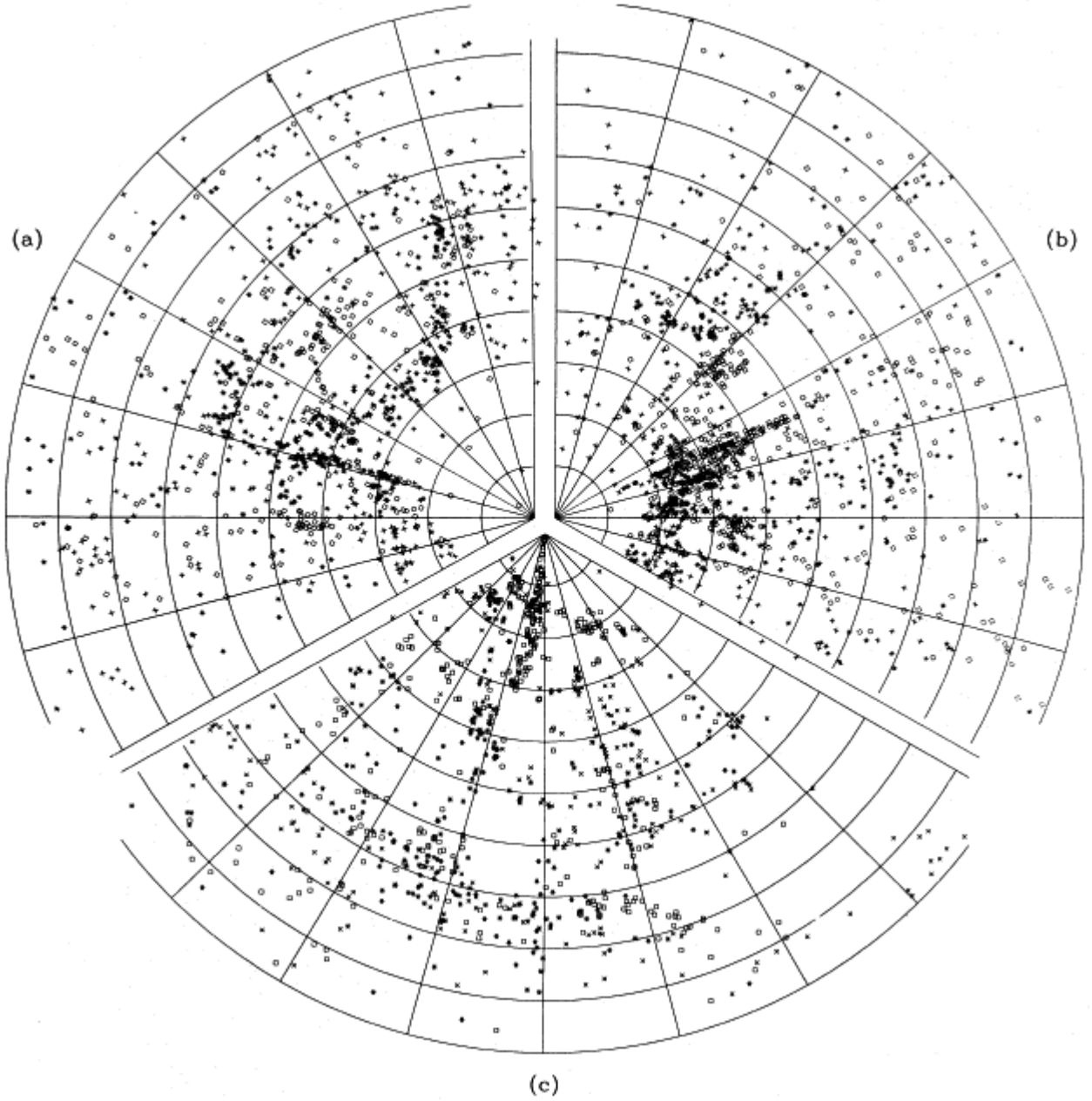
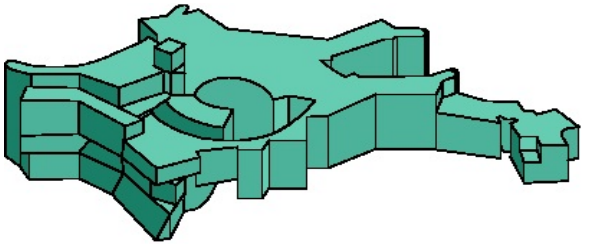
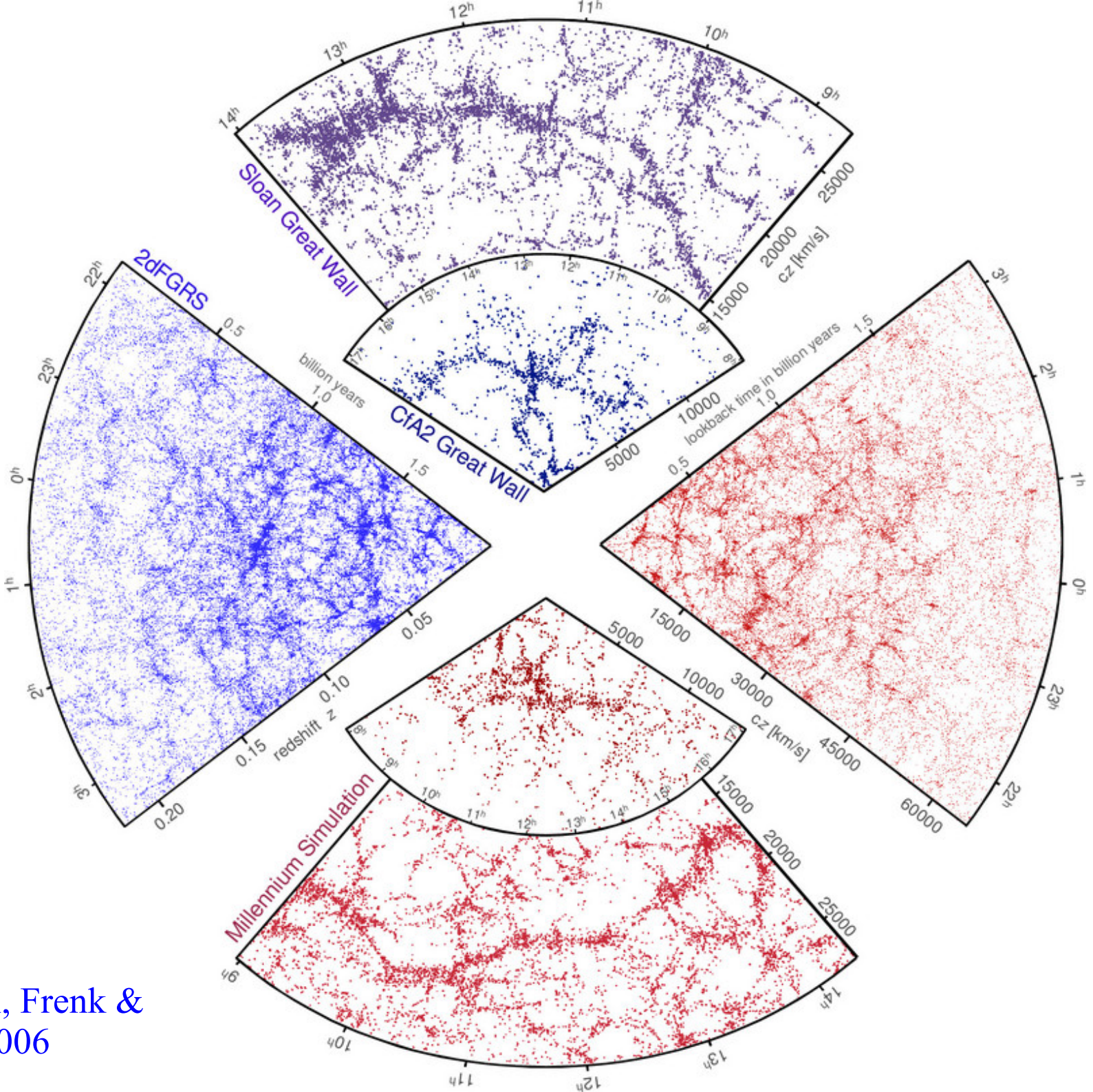
The Millennium Simulation and its use for interpreting LSS



Simon White
MPI for Astrophysics



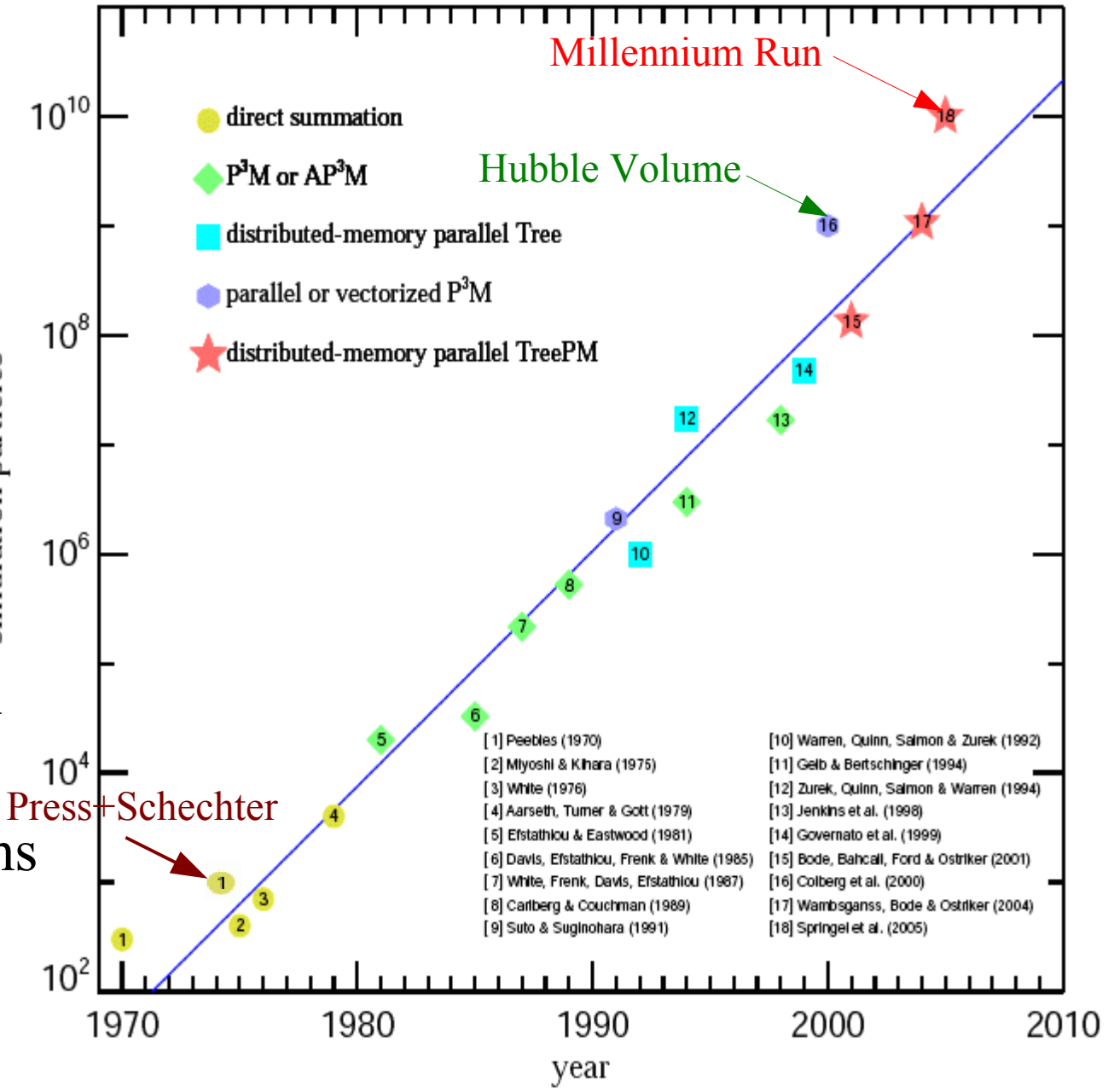


Springel, Frenk &
White 2006

Moore's Law for Cosmological N-body Simulations

Springel et al 2005

- 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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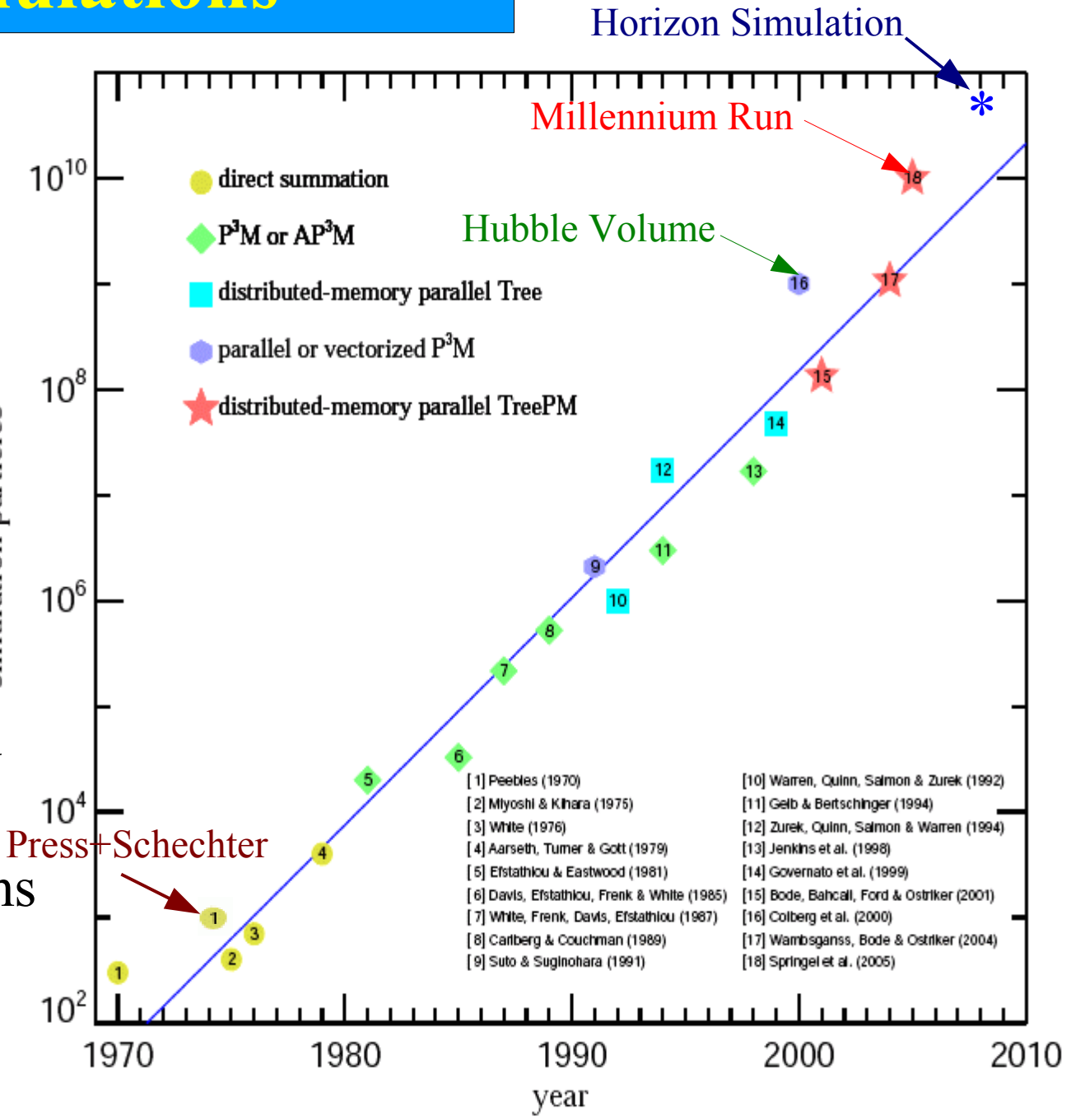
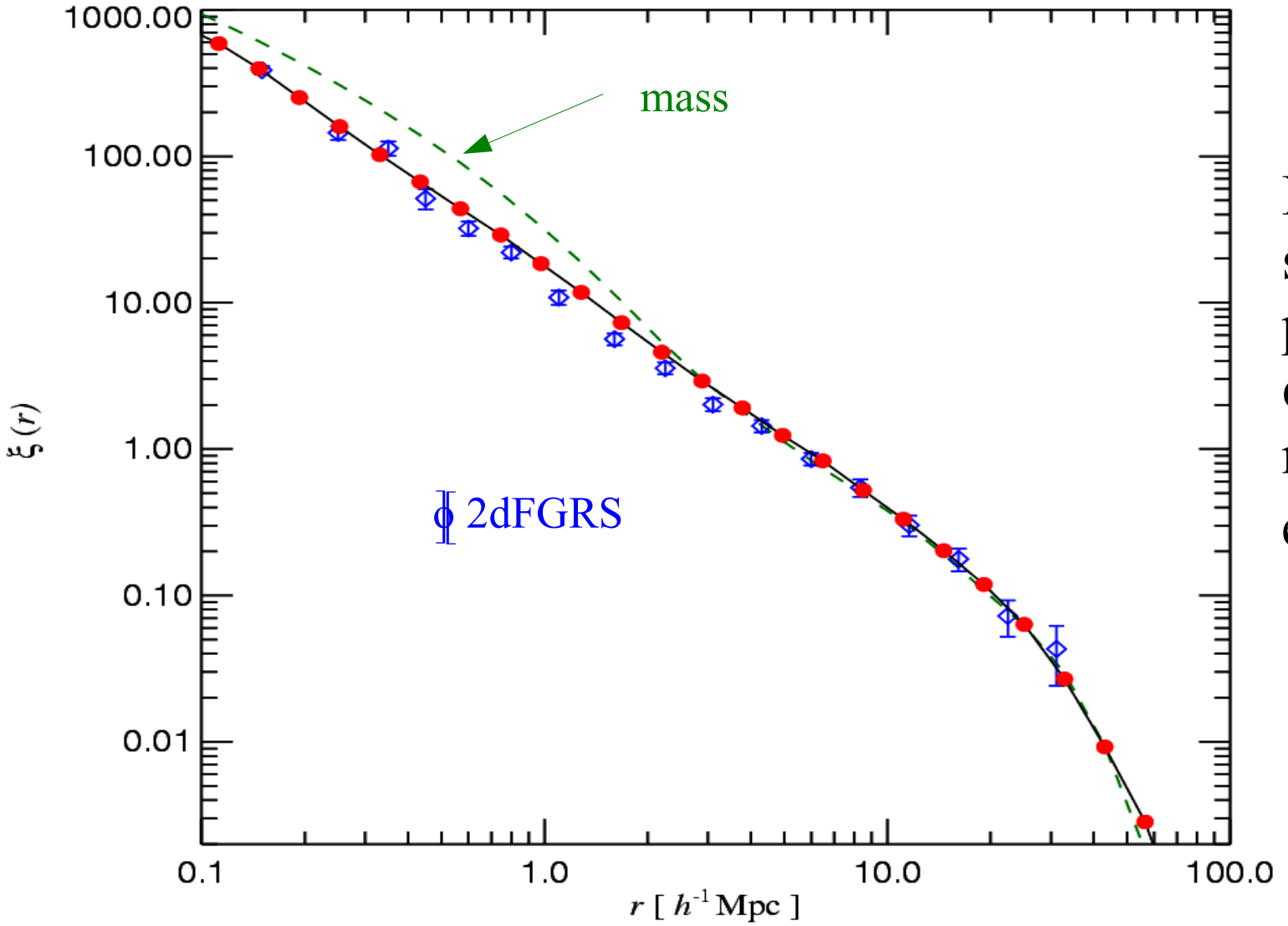
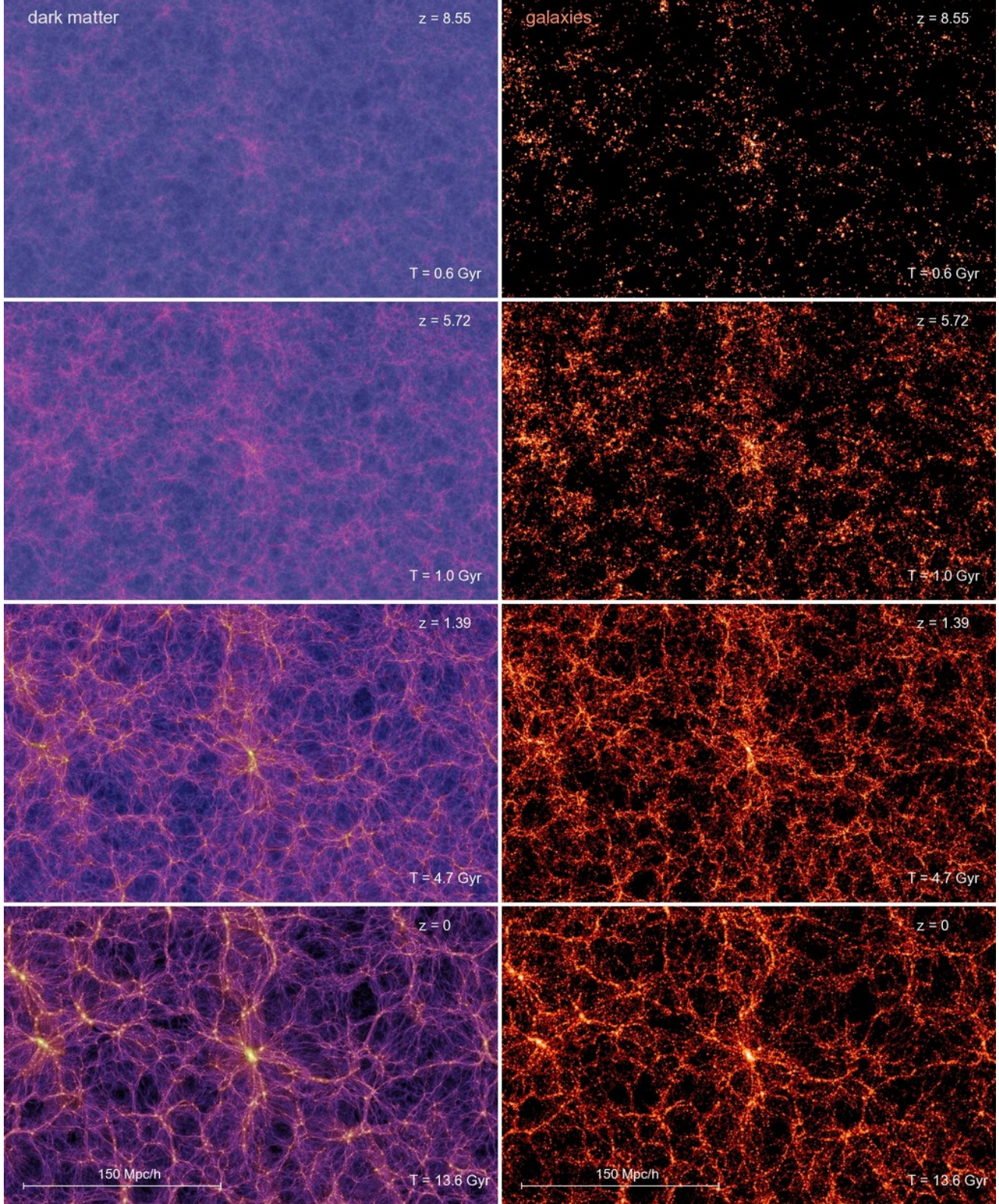


Galaxy autocorrelation function

Springel et al 2005



For such a large simulation the purely statistical error bars are negligible on ξ even for galaxies



Large-scale structure at high redshift

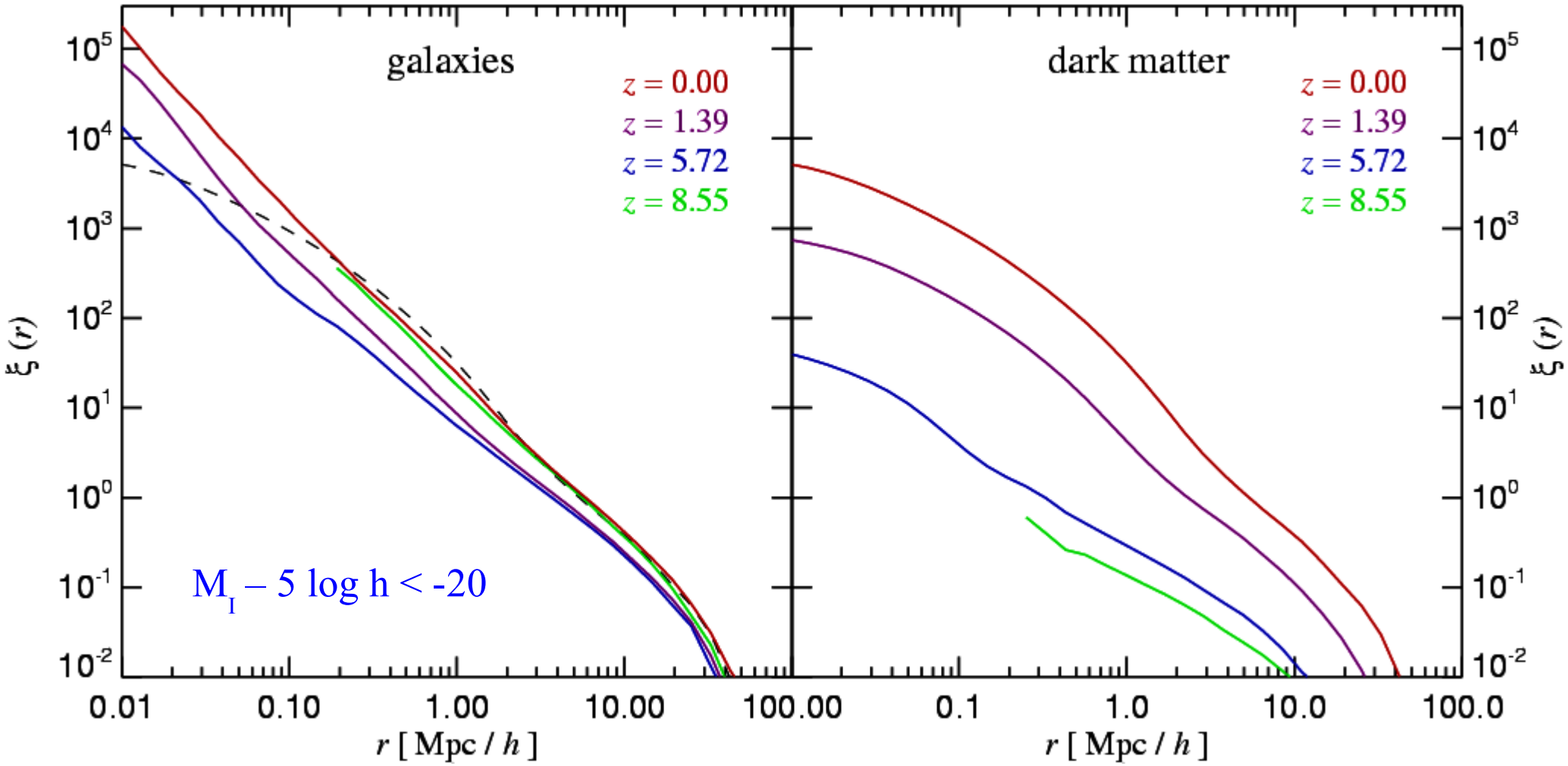
Springel, Frenk & White 2006

Large-scale structure in the galaxy distribution evolves very little with redshift

It is as strong at z=8.5 as at z=0

Evolution of mass and galaxy correlations

Springel, Frenk & White 2006



Questions for the Millennium

How well do the models fit high-z structure?

Does WMAP1 → 3 change observed LSS?

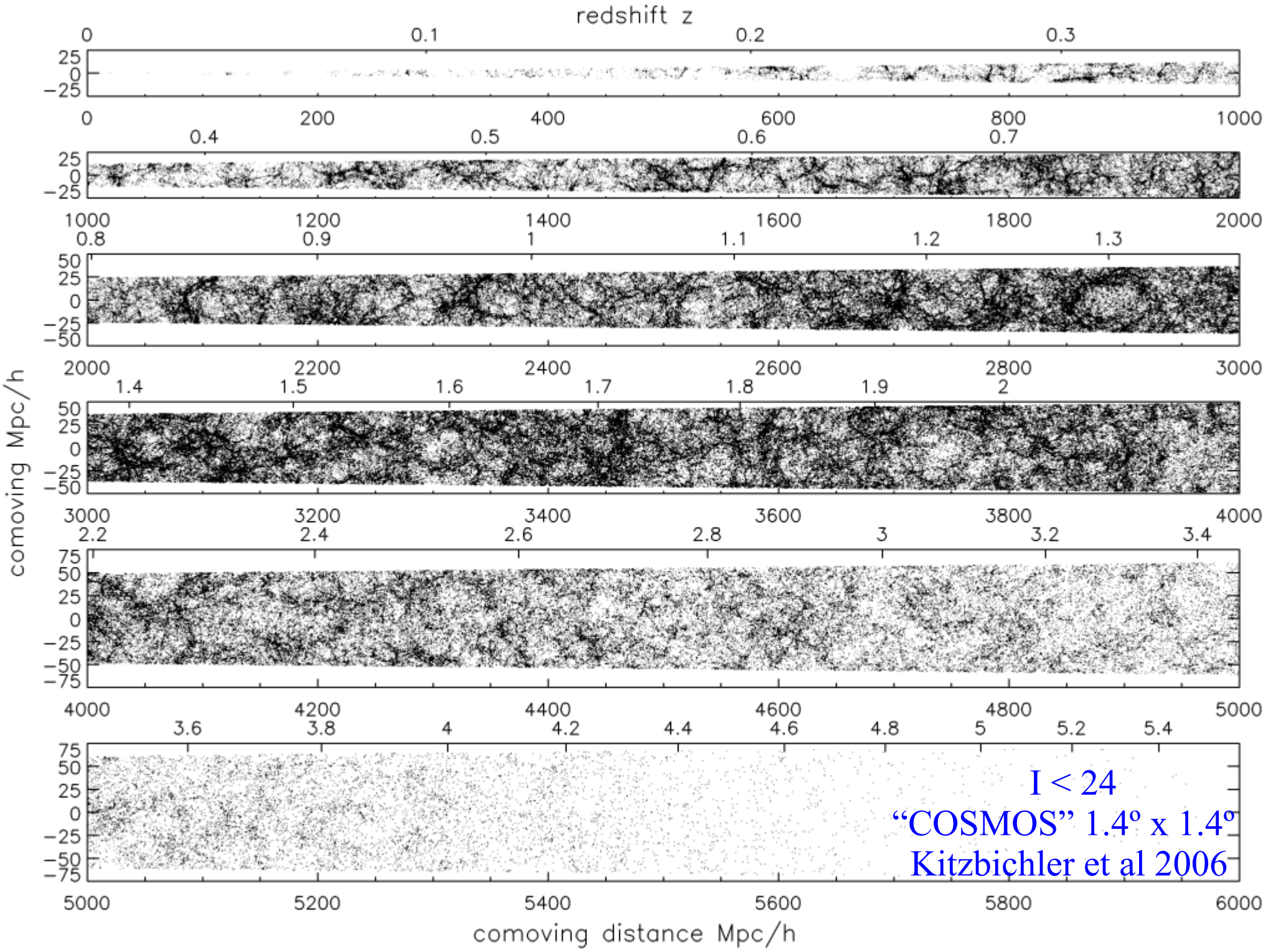
Which galaxies hold the baryons at high-z?

What do observed high-z galaxies become?

How do galaxies grow?

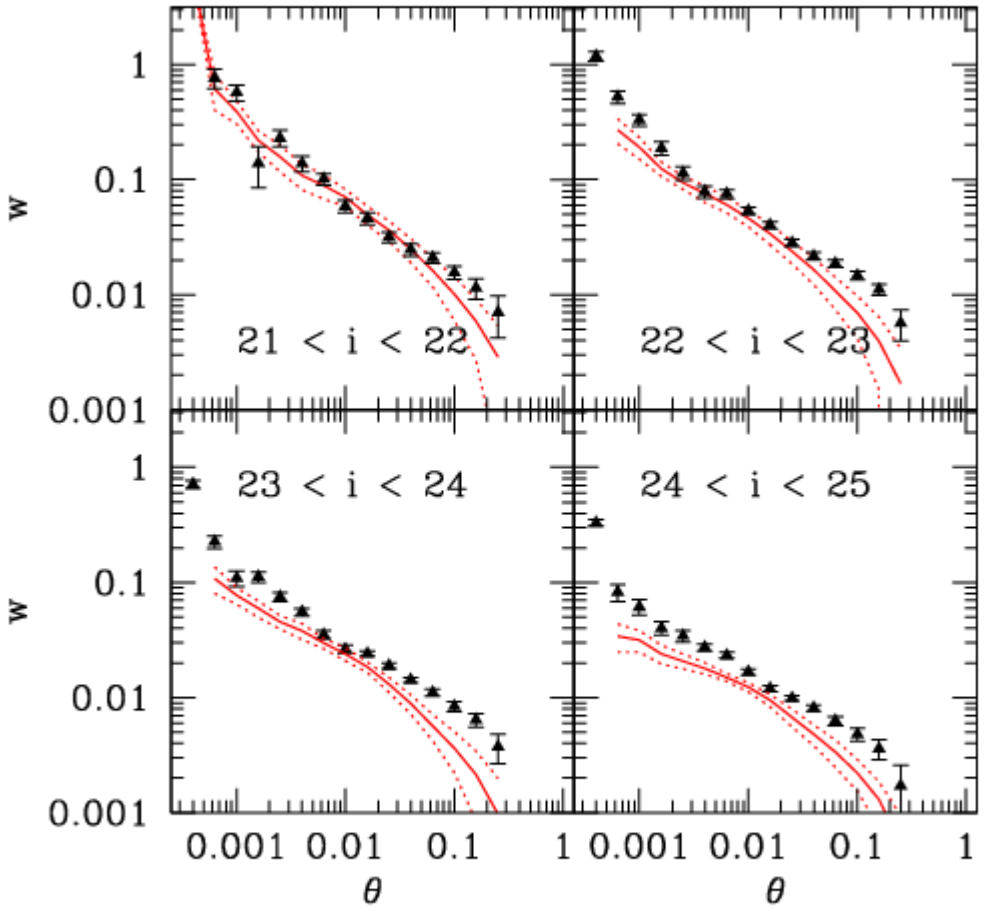
Can we measure merging rates?

How well do the models fit high-z structure?


redshift z
0
0.1
0.2
0.3
25
0
−25
0
200
400
600
800
1000
0.4
0.5
0.6
0.7
1000
1200
1400
1600
1800
2000
0.8
0.9
1
1.1
1.2
1.3
50
25
0
−25
−50
2000
2200
2400
2600
2800
3000
1.4
1.5
1.6
1.7
1.8
1.9
2
3000
3200
3400
3600
3800
4000
2.2
2.4
2.6
2.8
3
3.2
3.4
75
50
25
0
−25
−50
−75
4000
4200
4400
4600
4800
5000
3.6
3.8
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5000
5200
5400
5600
5800
6000
comoving Mpc/h
comoving distance Mpc/h
I < 24
“COSMOS” 1.4º x 1.4º
Kitzbichler et al 2006

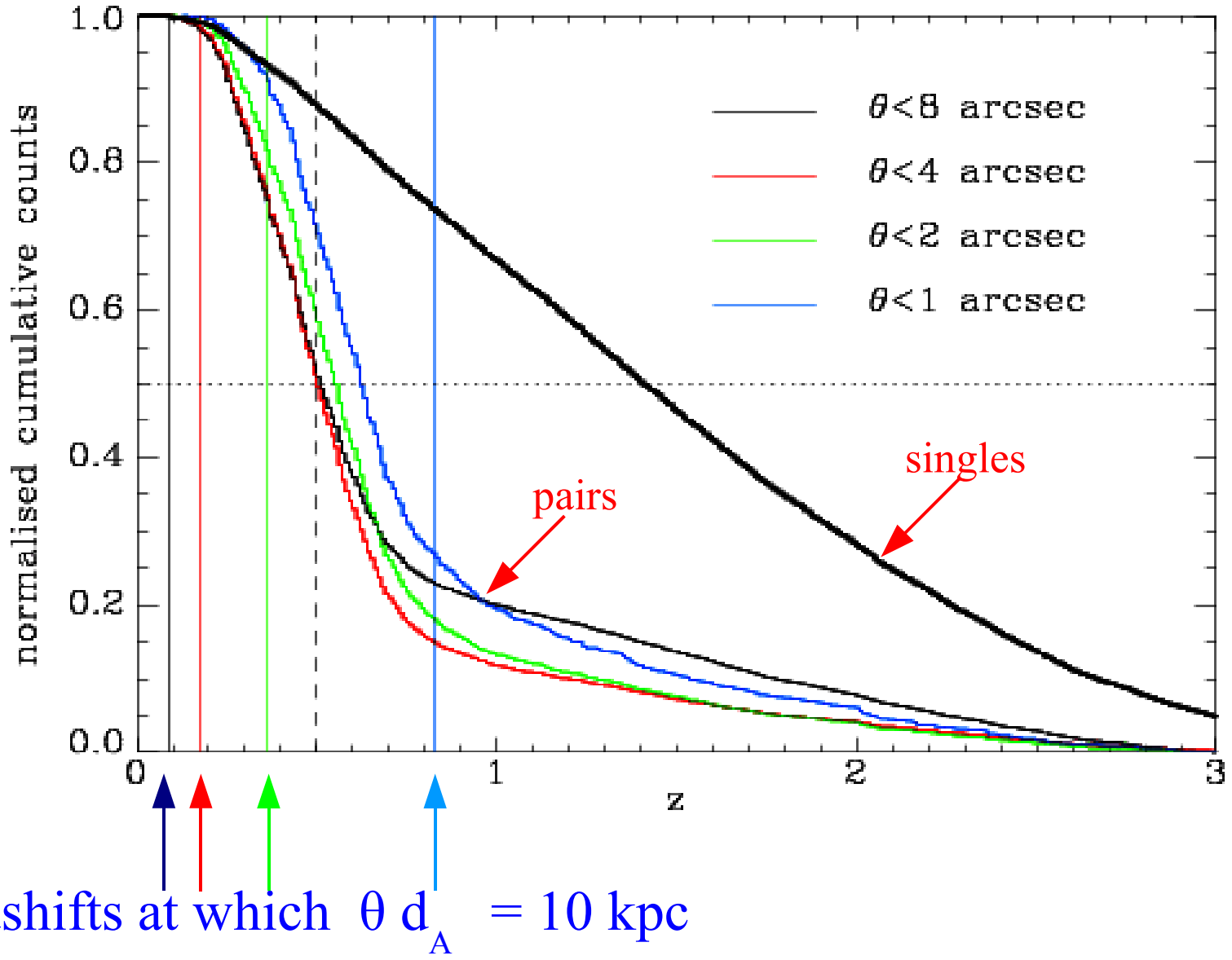
Comparison with COSMOS survey w(θ)

McCracken et al 2007



Redshift distributions for single galaxies and pairs to $B_{AB} = 26$

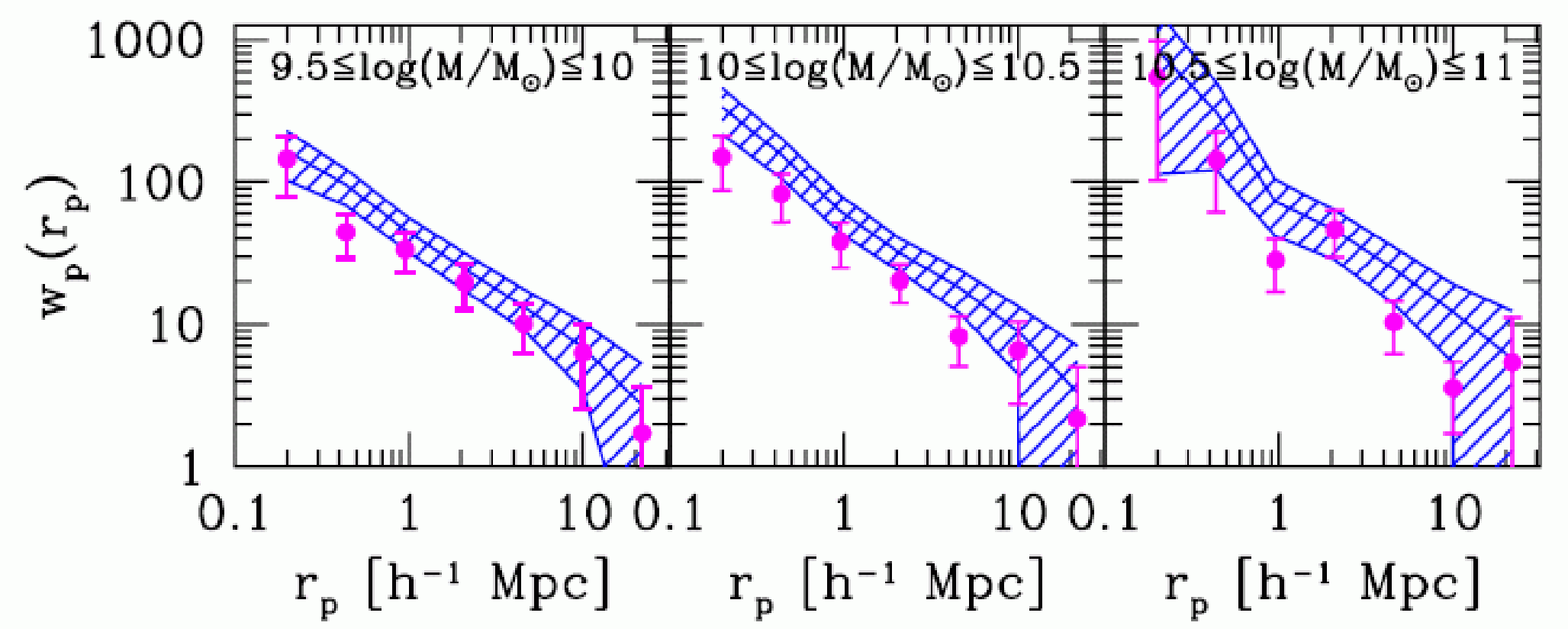
pairs with 3D physical separation $r < \theta\, d_A$



Comparison with VVDS survey $w_p(r_p)$

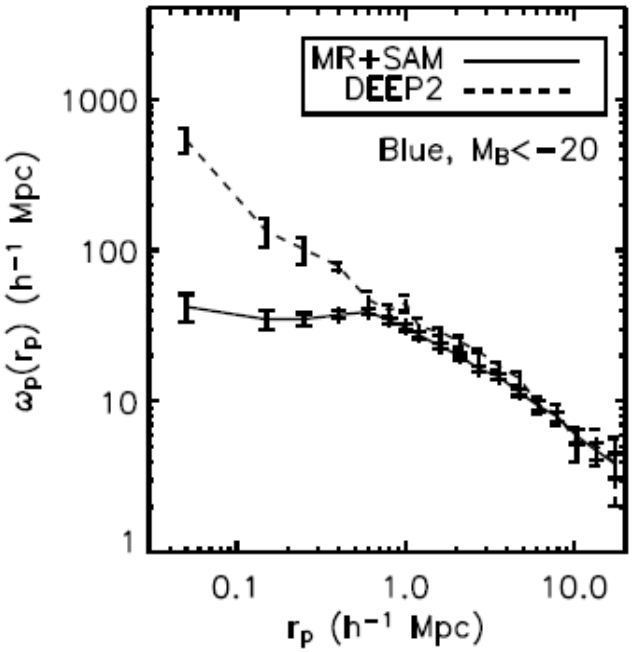
Meneux et al 2007

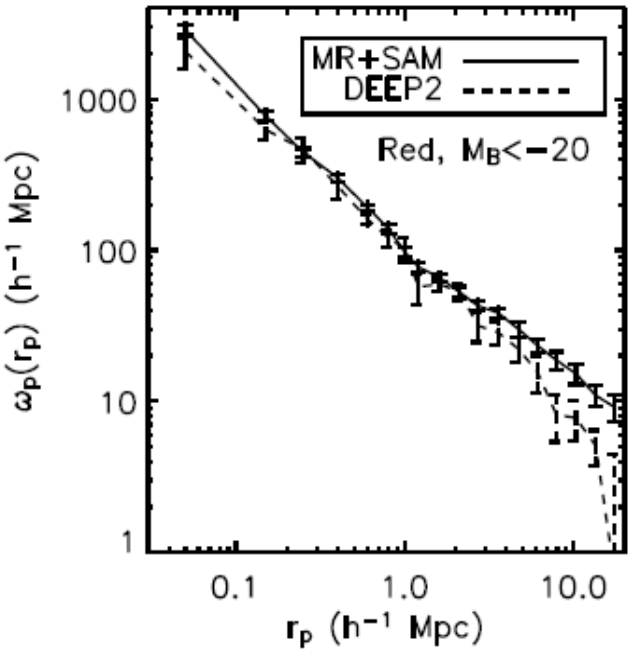
$\langle z \rangle \sim 0.6$

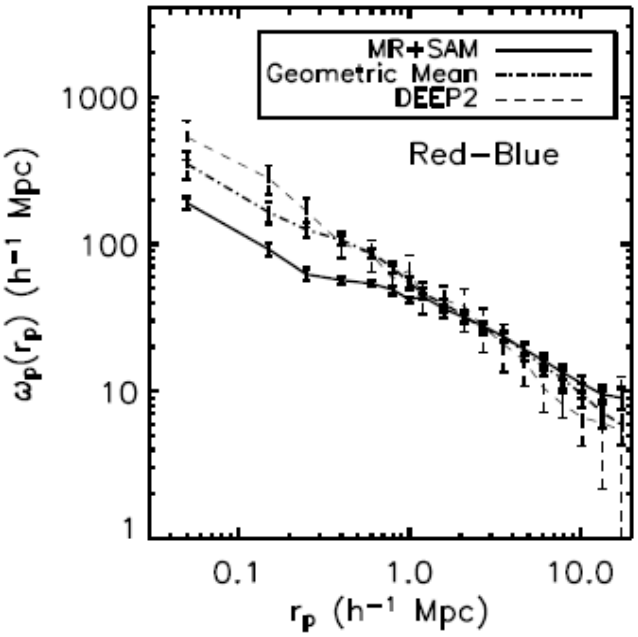


Comparison with DEEP2 survey $w_p(r_p)$

Coil et al 2007



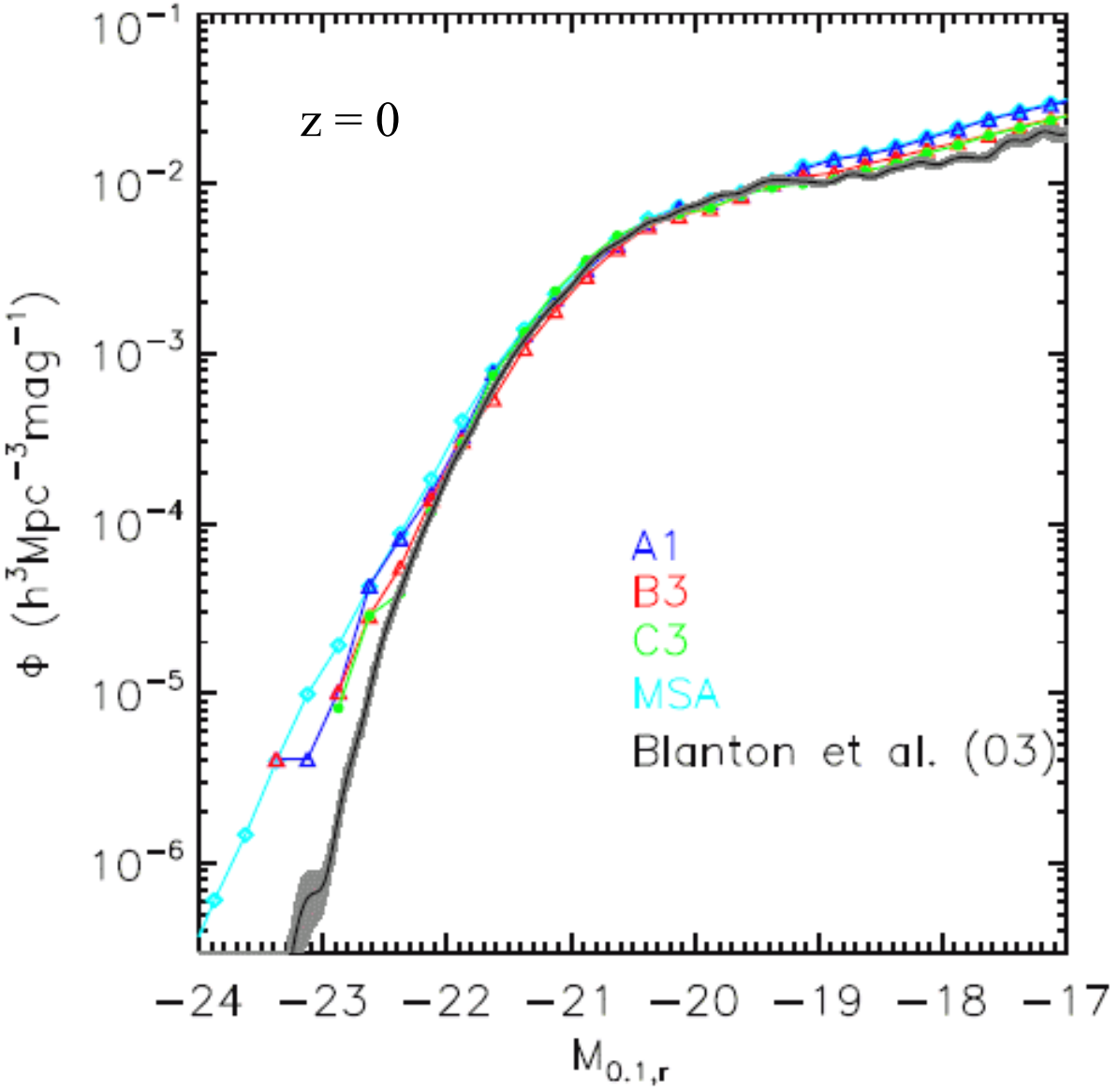


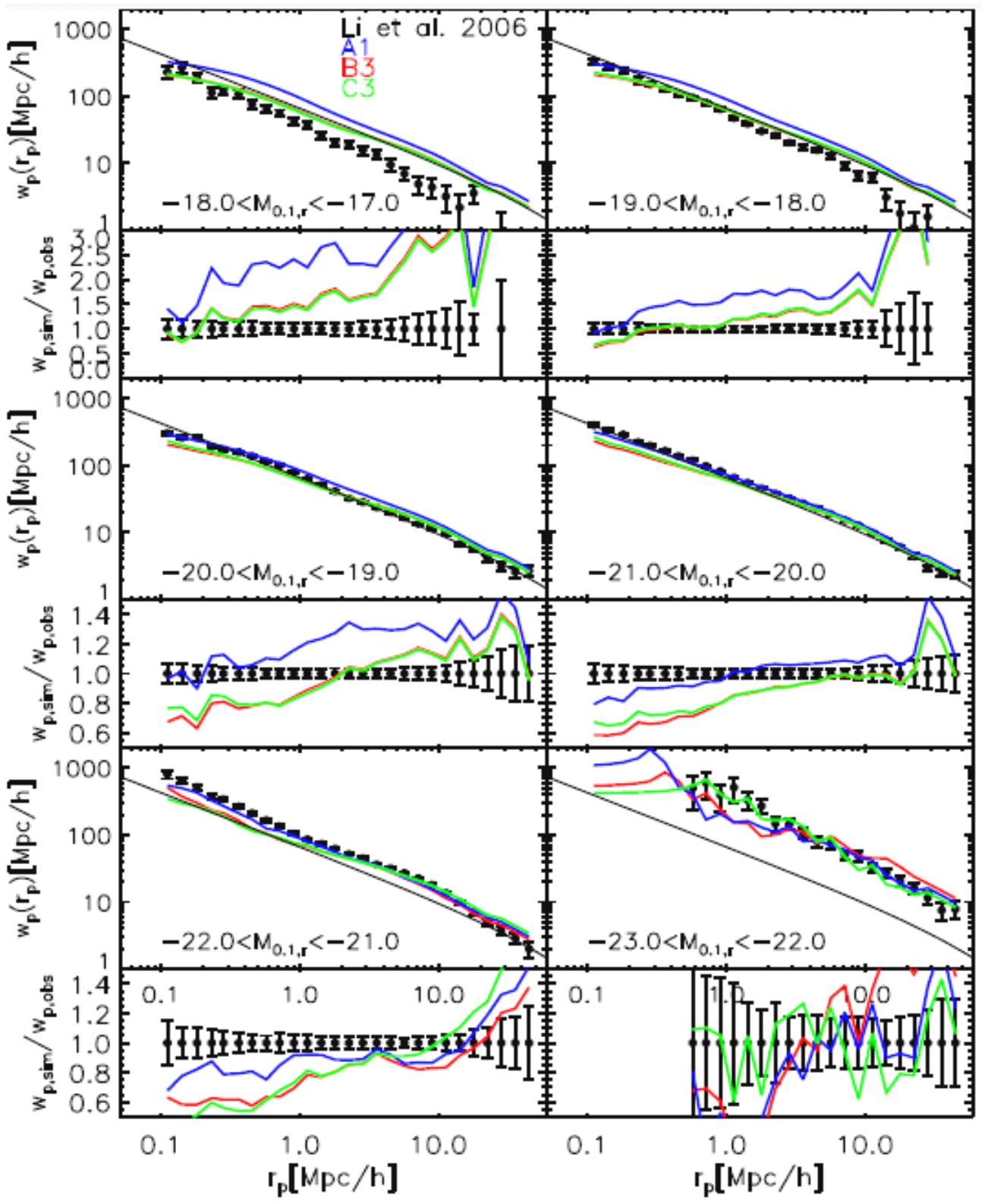


Does WMAP1 → 3 change observed LSS?

WMAP1 vs WMAP3 luminosity functions

Wang et al 2007





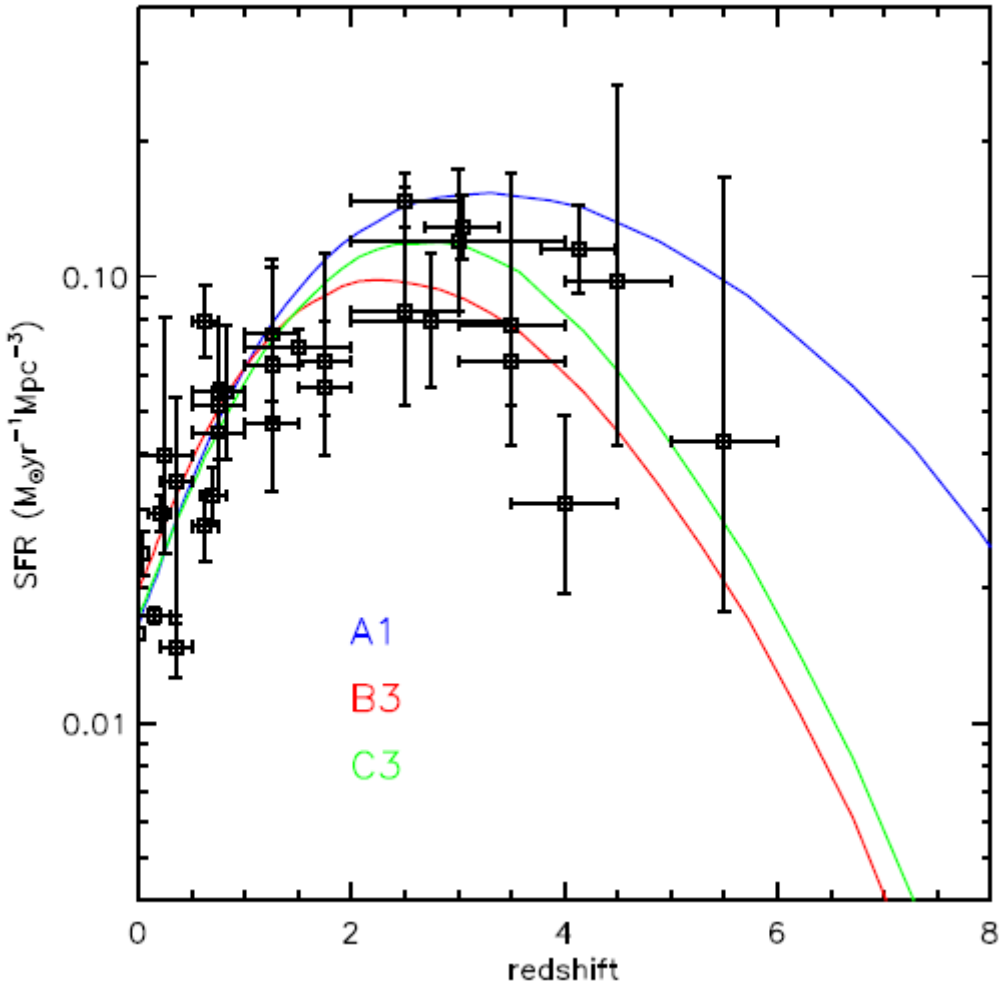
WMAP1 vs WMAP3 galaxy correlations

Wang et al 2007

$z = 0$

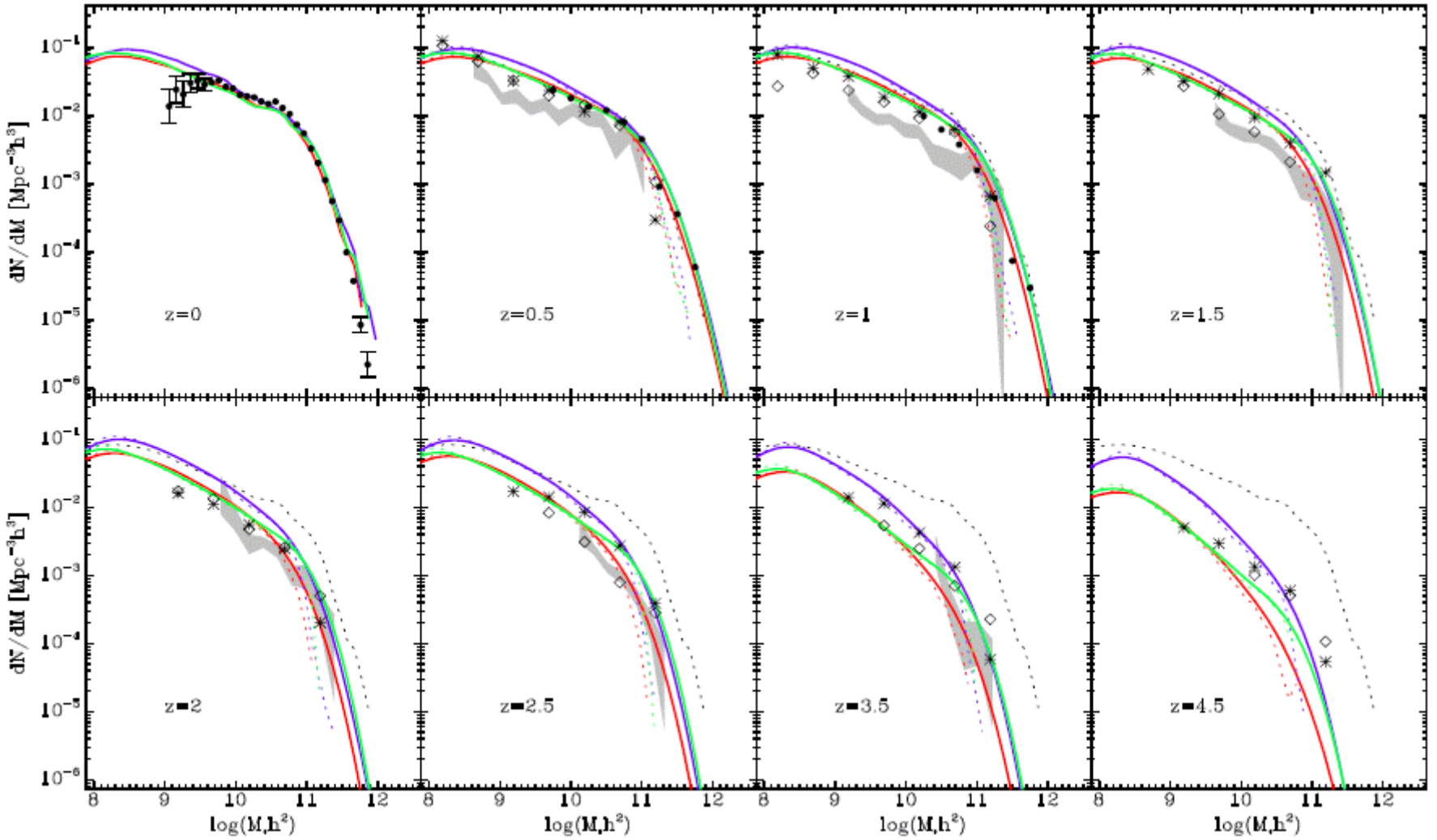
WMAP1 vs WMAP3 cosmic SFH

Wang et al 2007



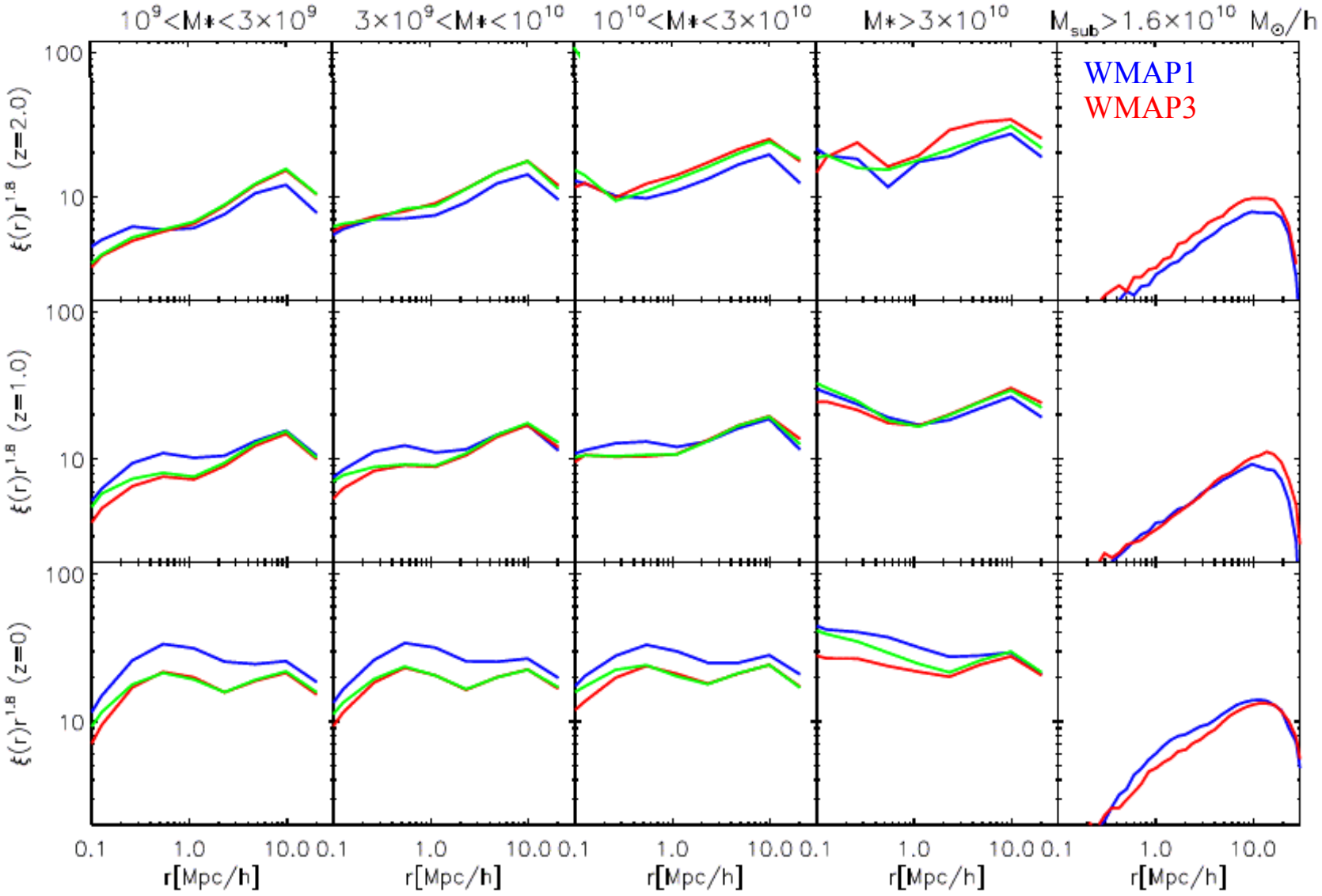
WMAP1 vs WMAP3 galaxy mass functions

Wang et al 2007



WMAP1 vs WMAP3 high-z galaxy correlations

Wang et al 2007



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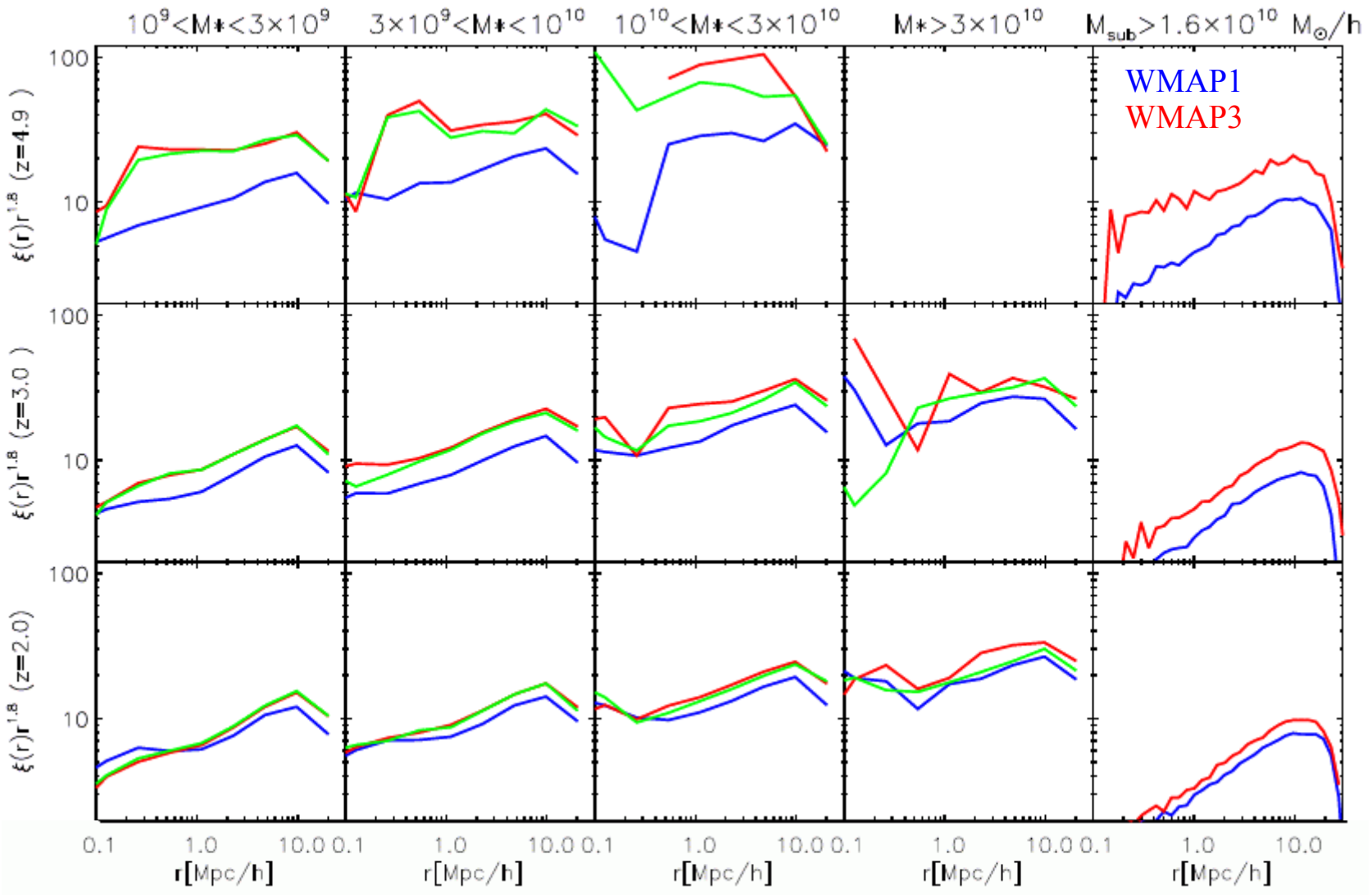
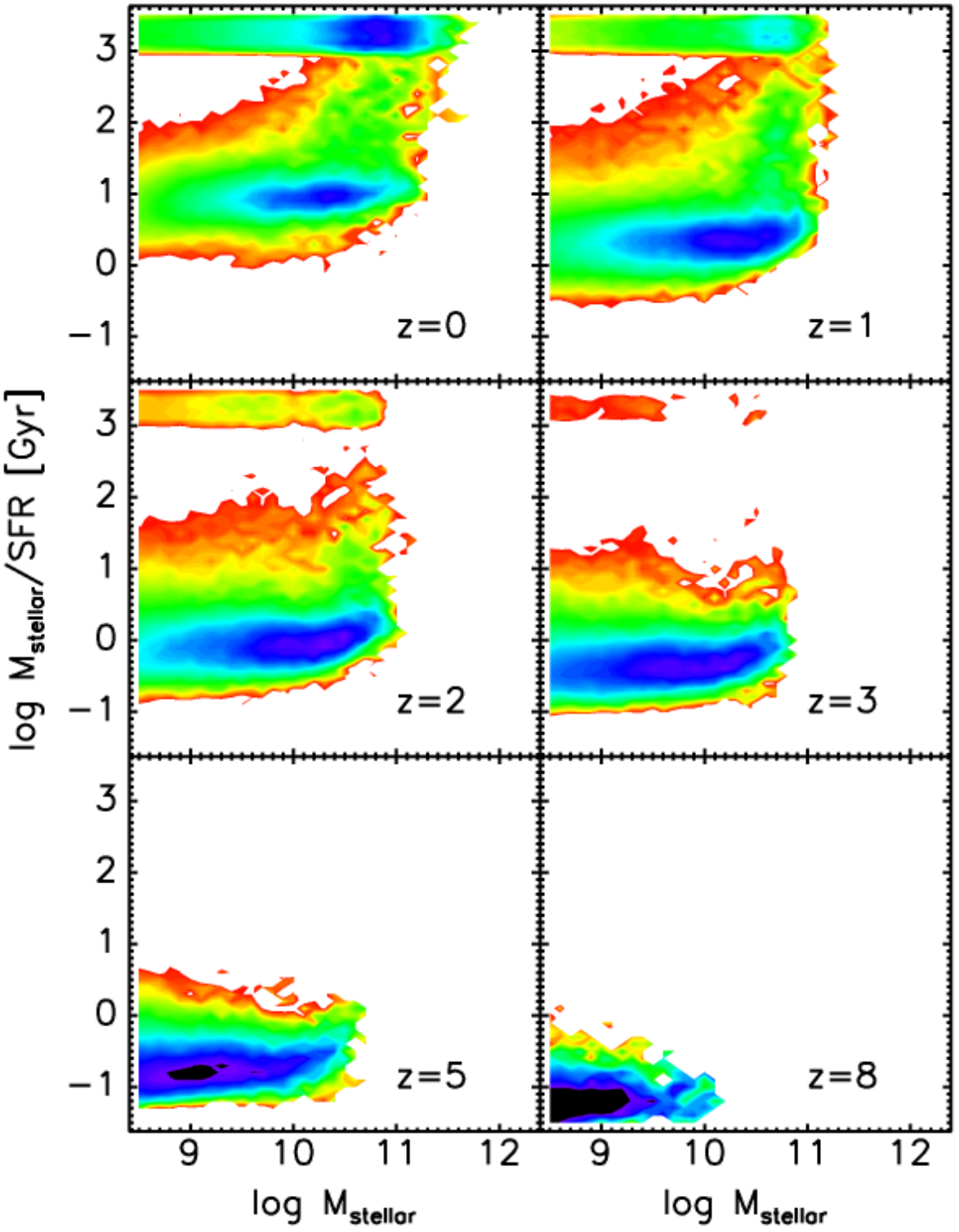
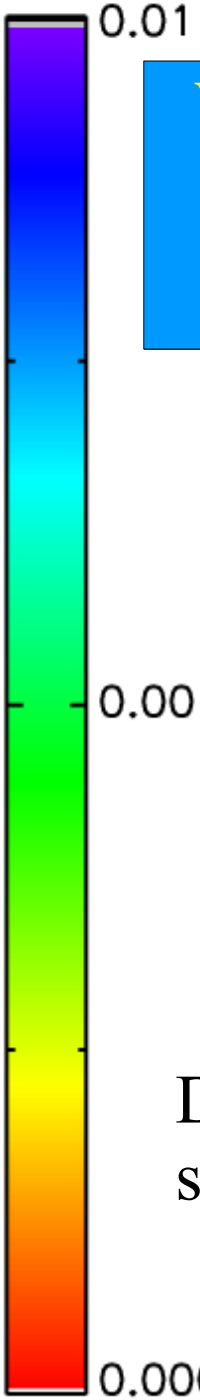


Which galaxies hold the baryons at high-z?

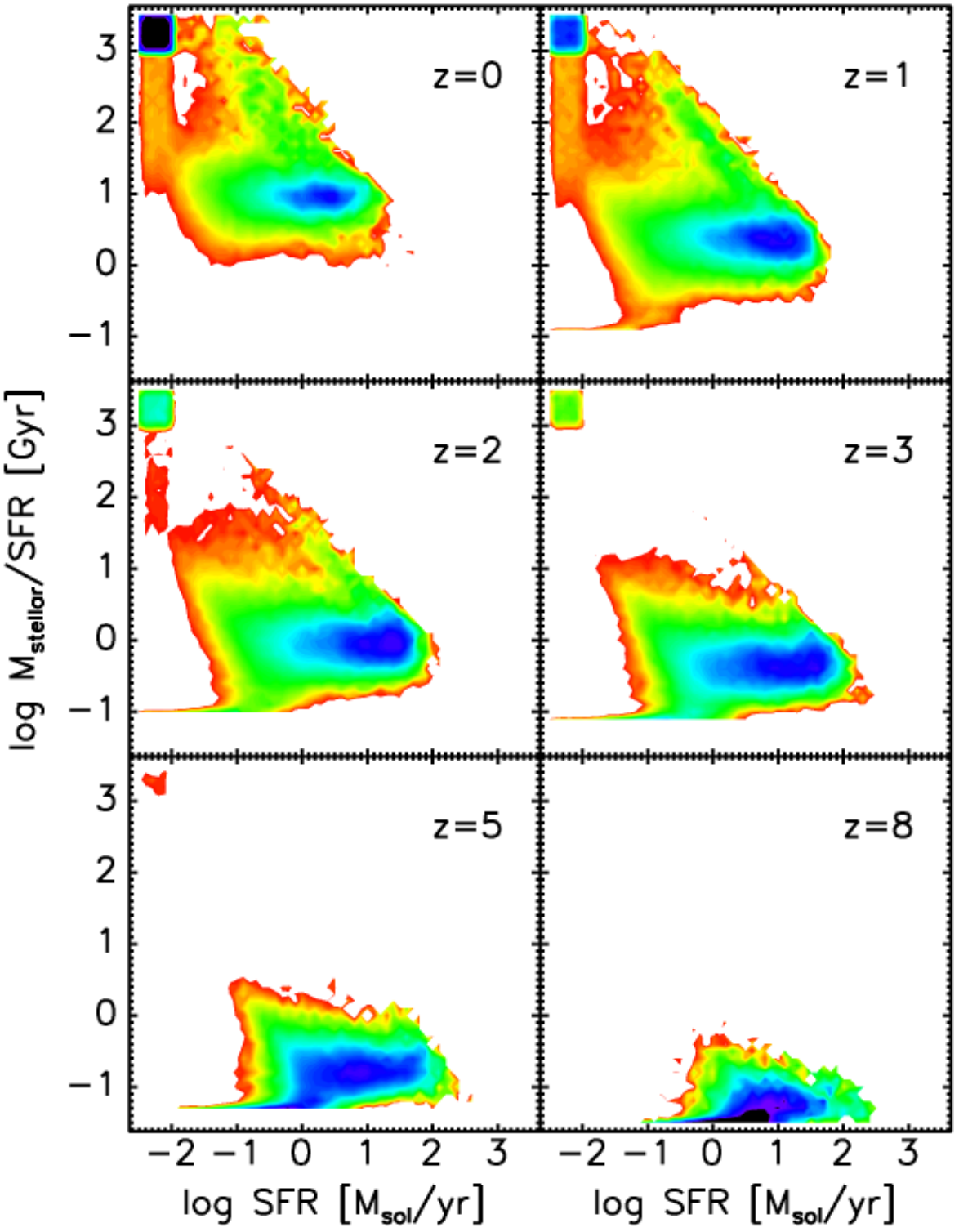


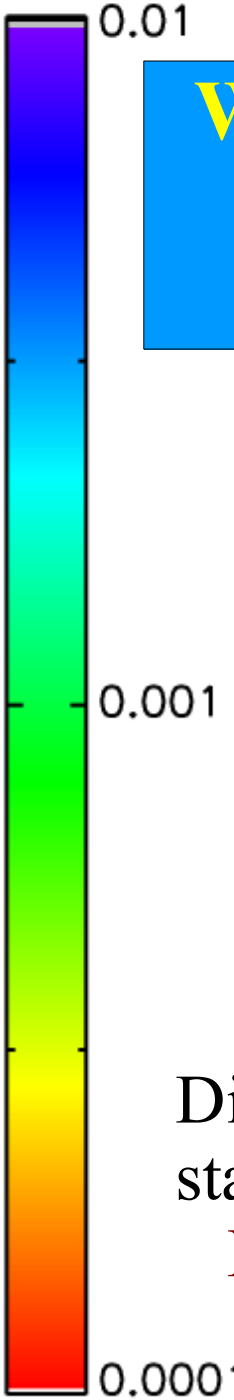


Which galaxies host the baryons?

Kitzbichler & White 2007

Distribution of total star + ISM mass over $M_* / \dot{M}_*$ and M_*





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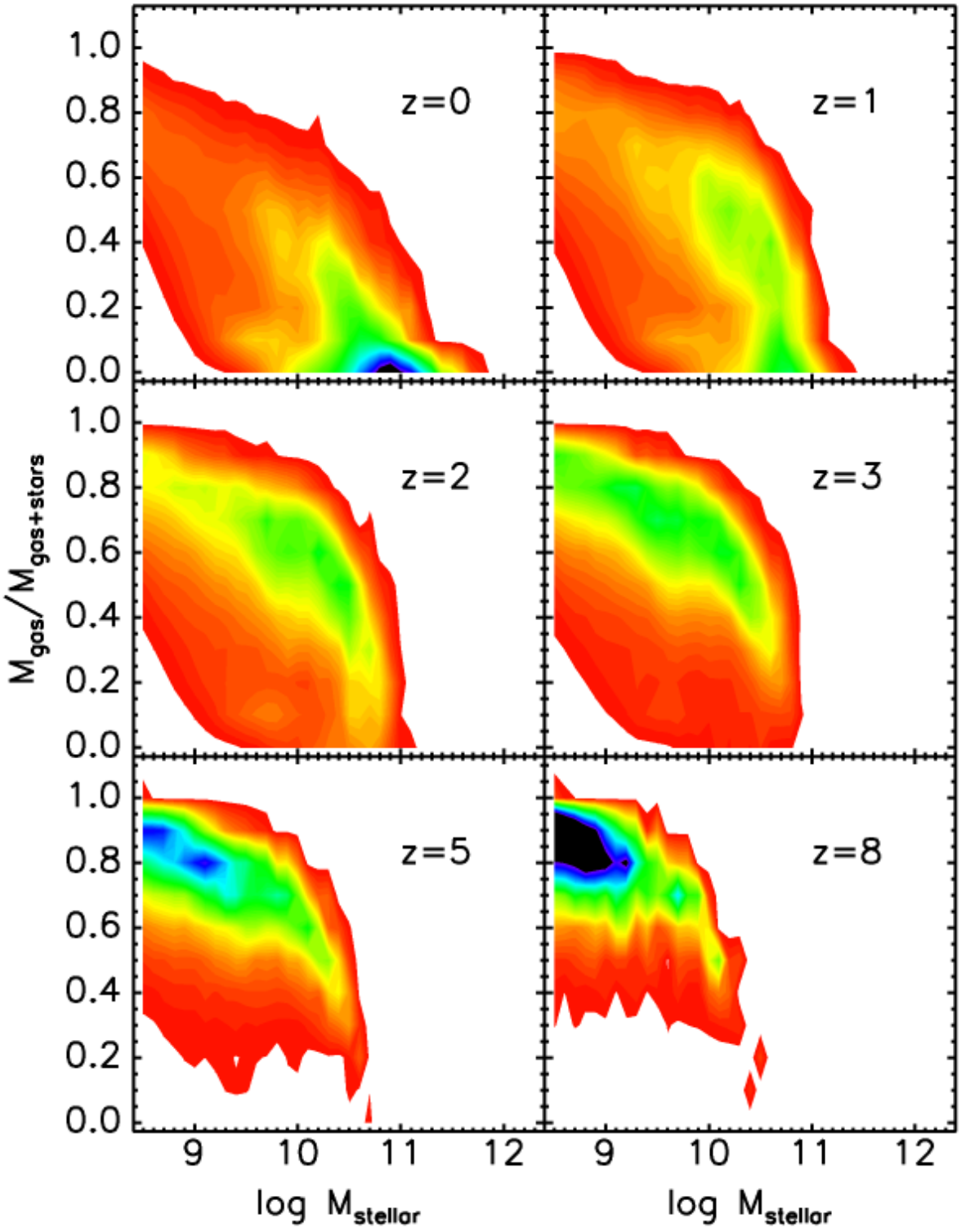
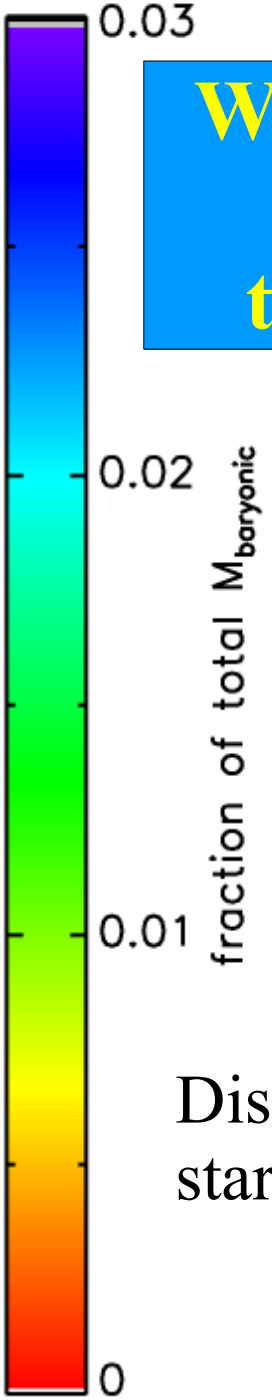
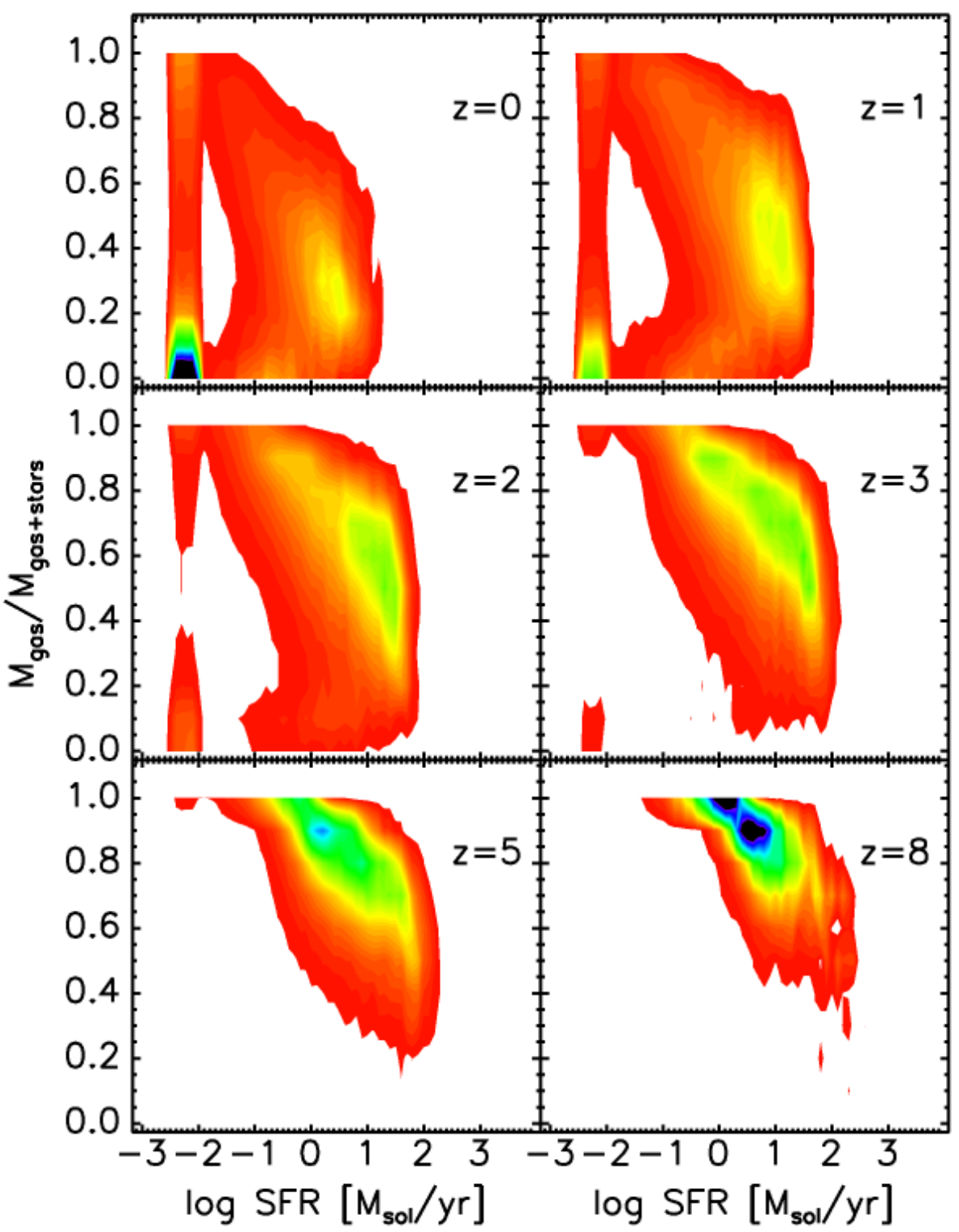


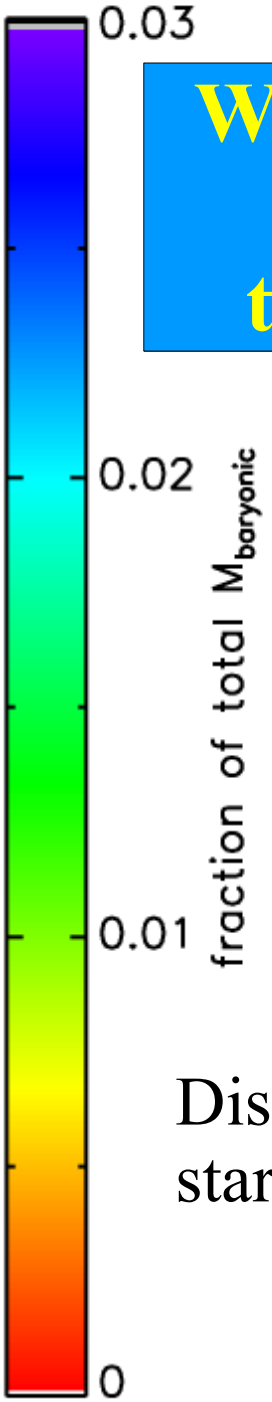


Which galaxies host the baryons?

Kitzbichler & White 2007

Distribution of total star + ISM mass over F_{gas} and M_*





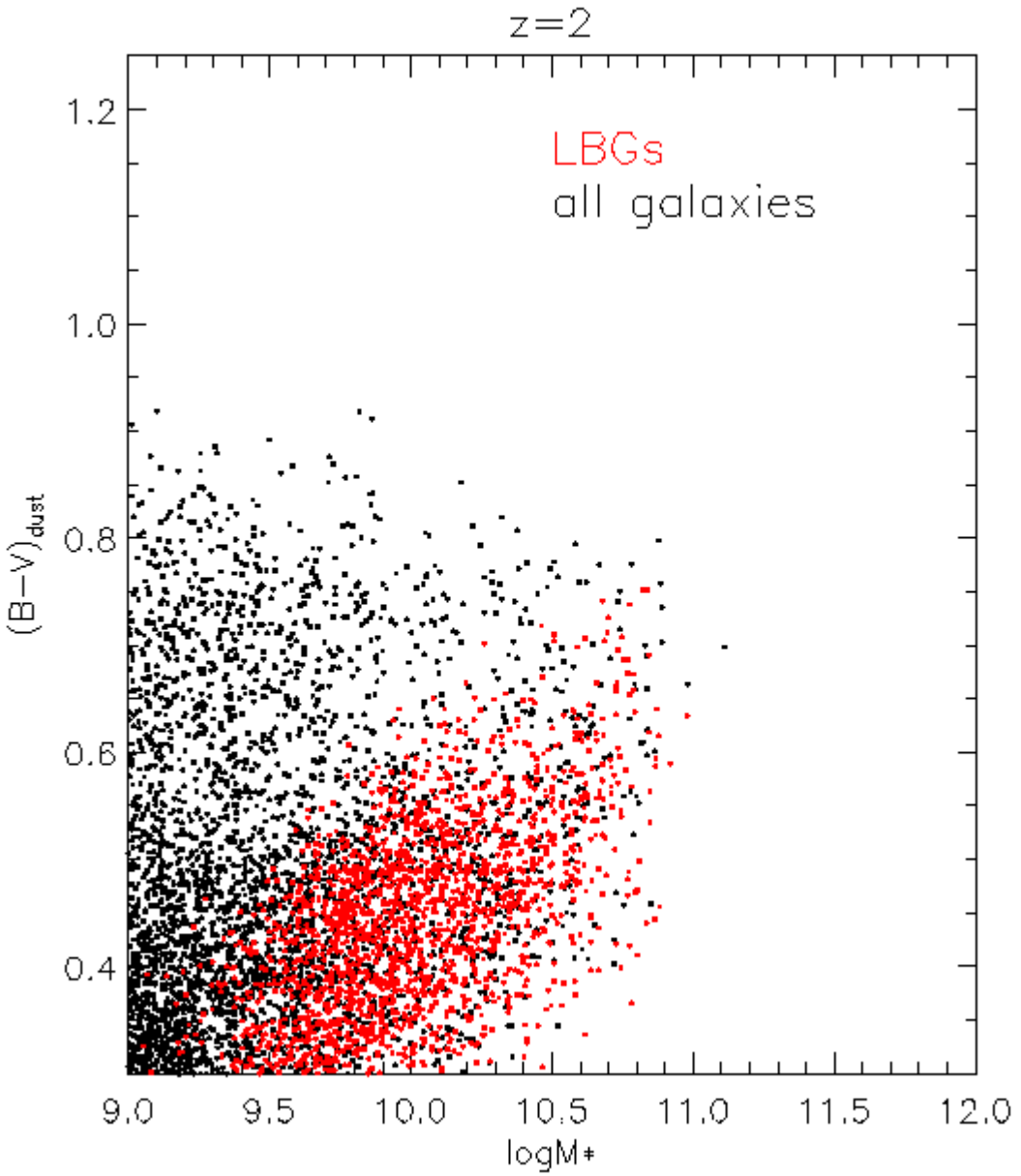
Which galaxies host the baryons?

Kitzbichler & White 2007

Distribution of total star + ISM mass over F_{gas} and $\dot{M}_{*}$

What do observed high-z galaxies become?

Colour-stellar mass plot for z=2 star-forming galaxies (SFR > 5 $M_\odot$/yr) and their descendants



Guo & White 2008

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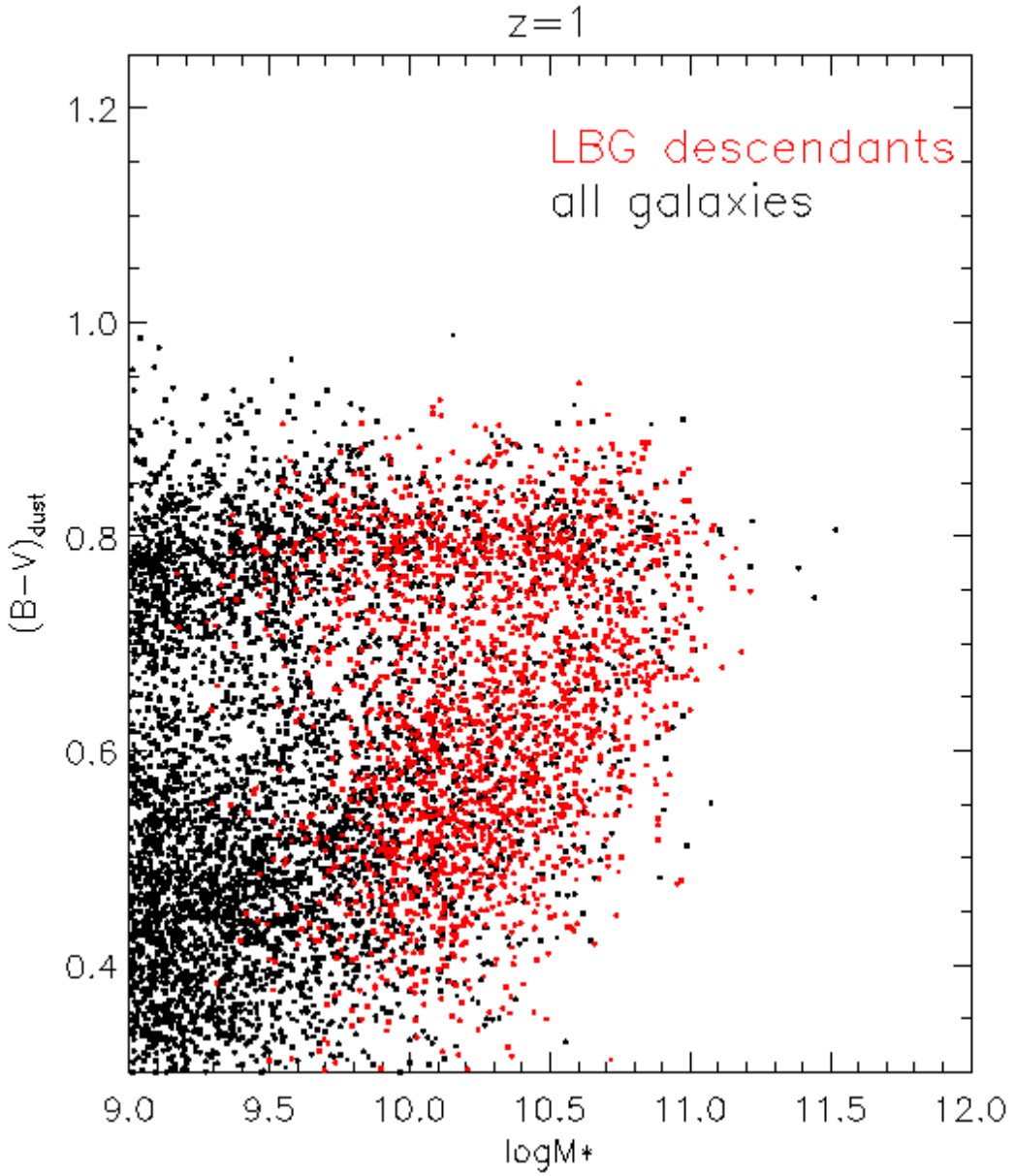

Guo & White 2008

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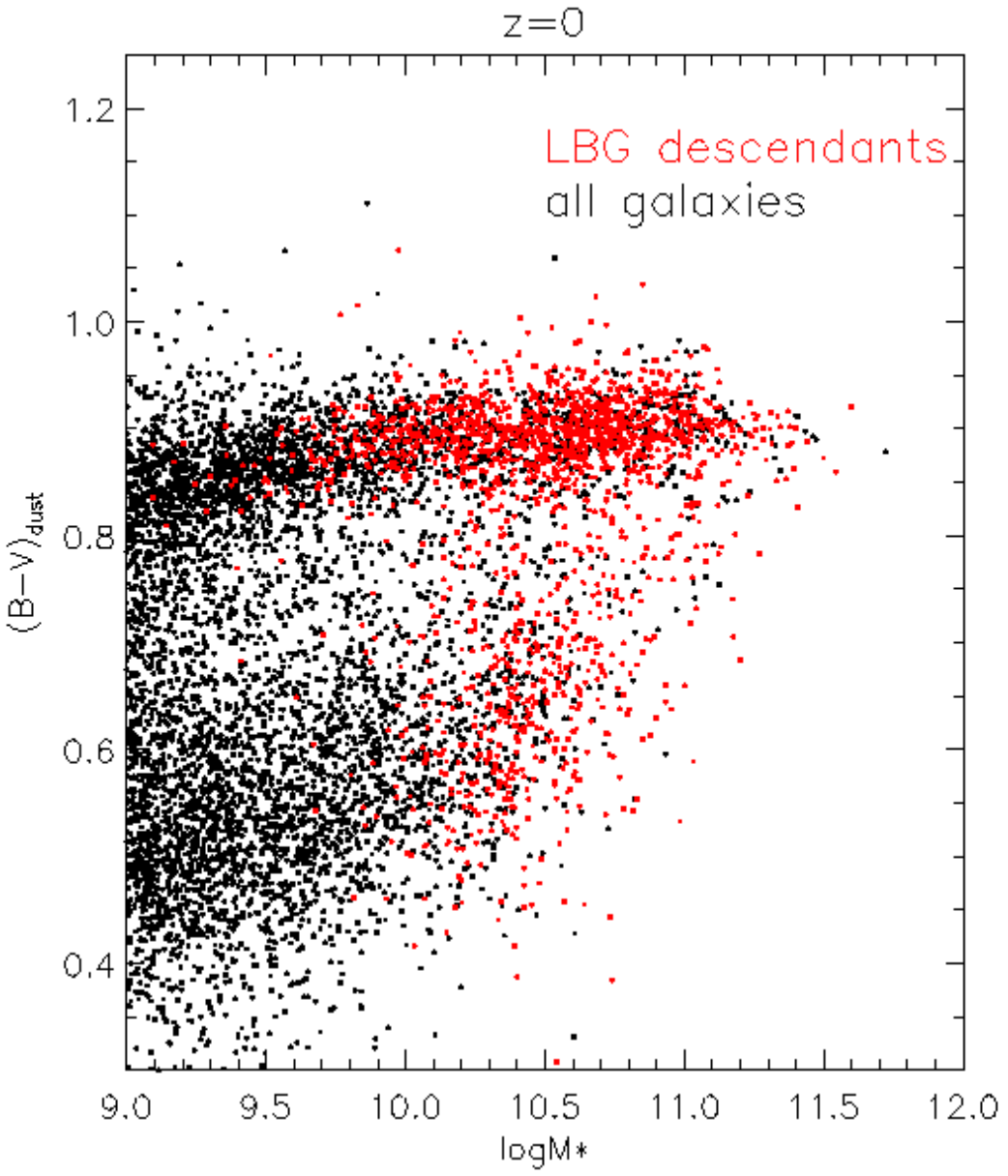
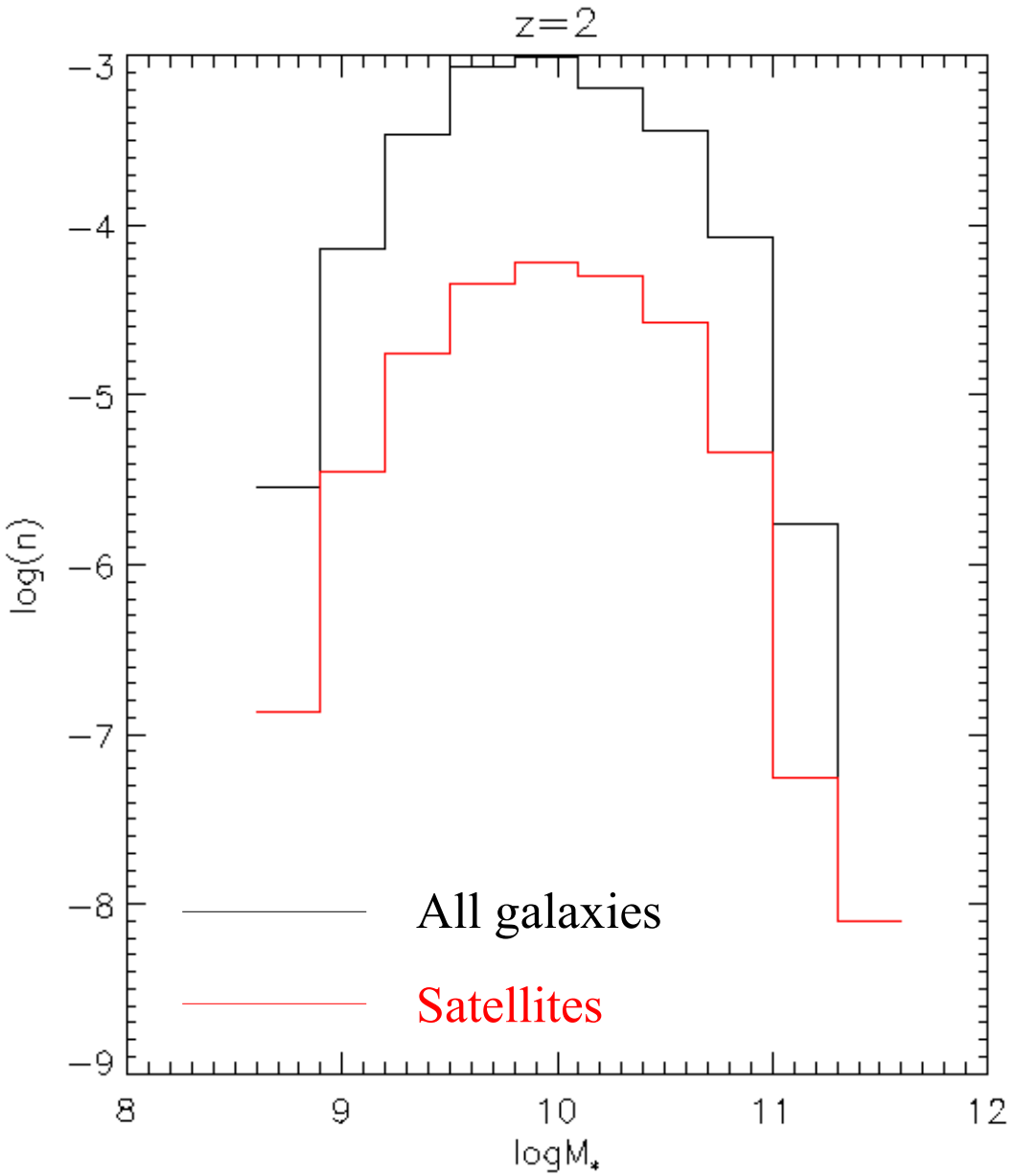


Guo & White 2008

Stellar mass histograms for z=2 star-forming galaxies (SFR > 5 $M_\odot$/yr) and their descendants



Guo & White 2008

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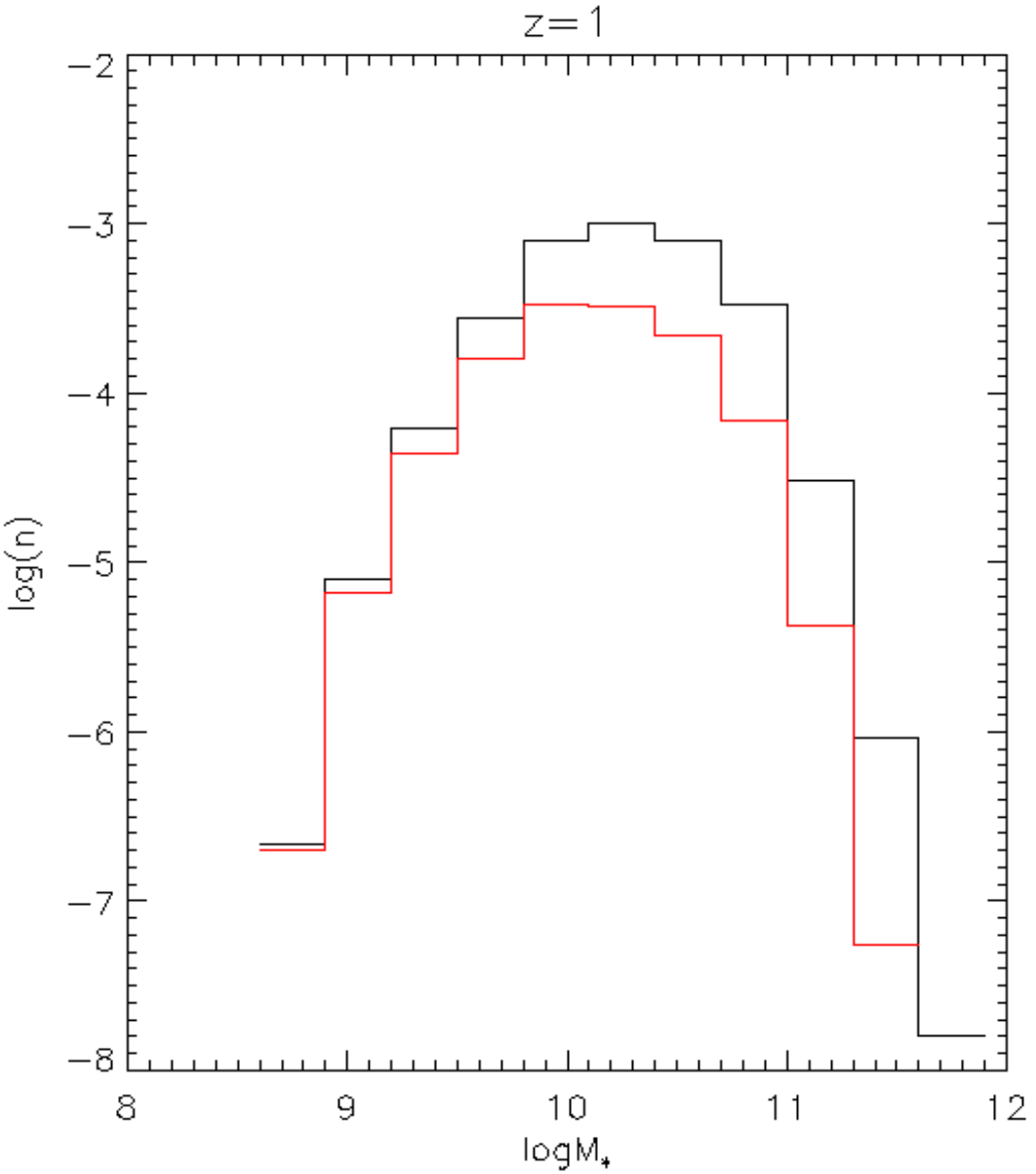

Guo & White 2008

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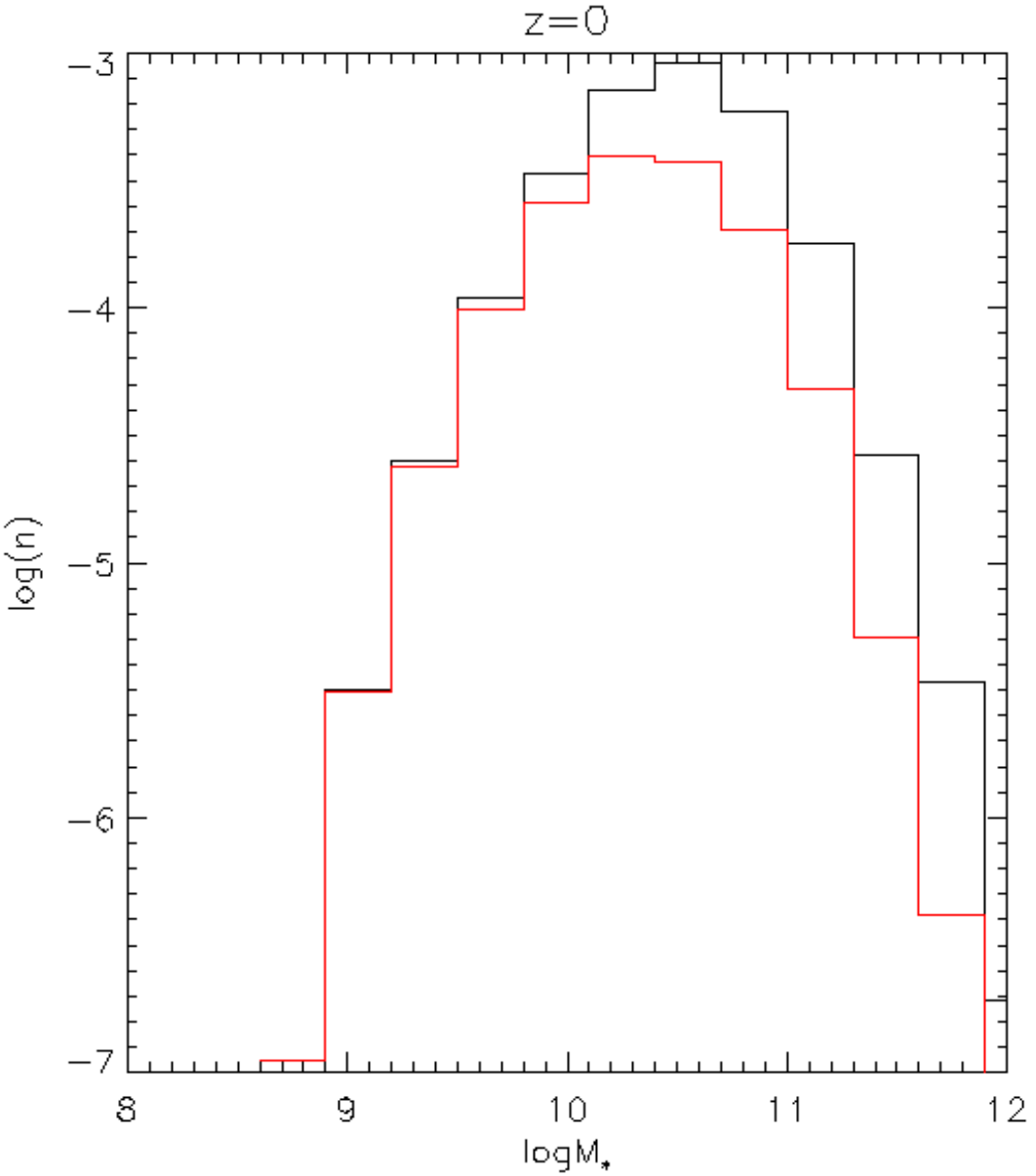
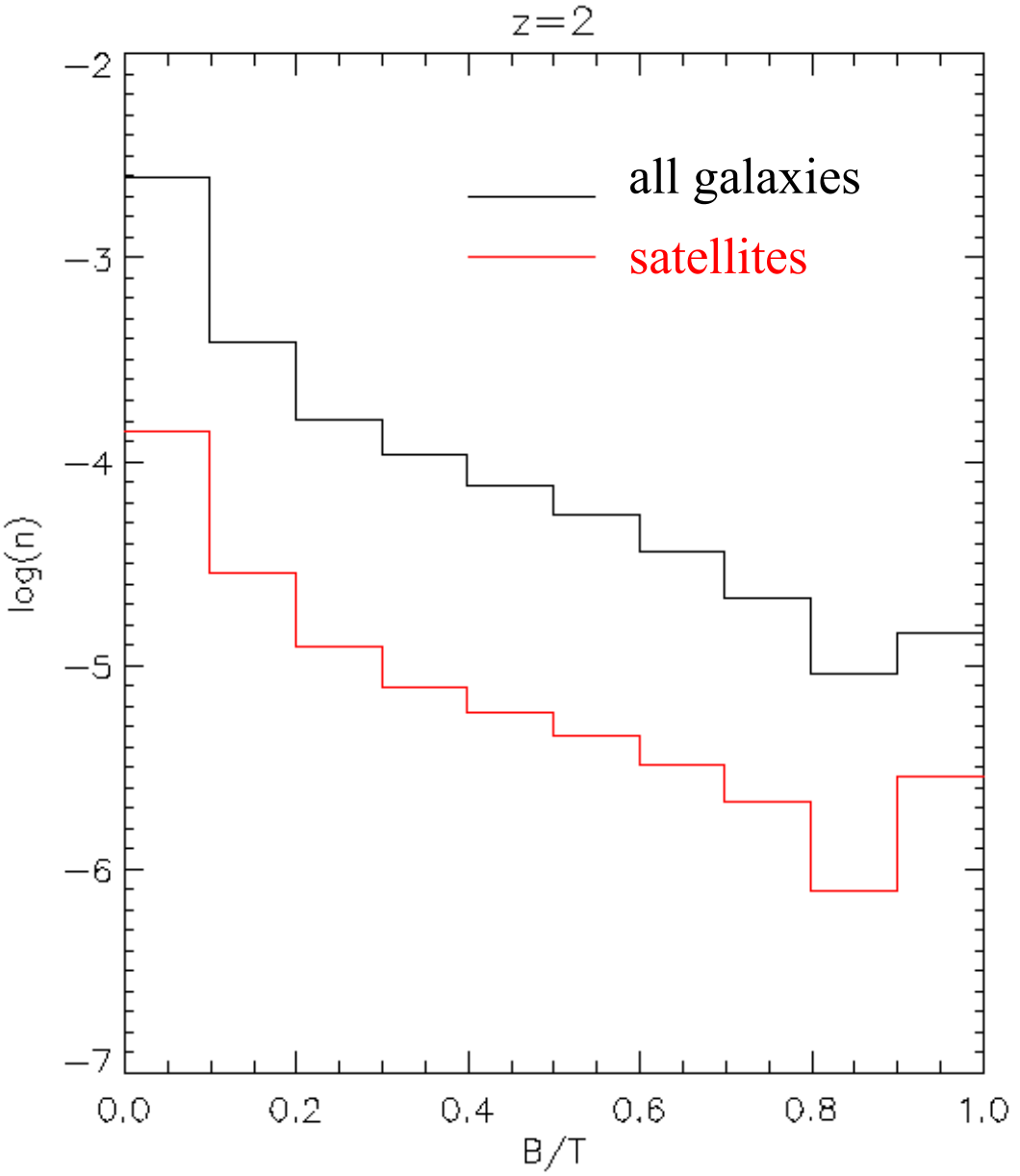


Guo & White 2008

Bulge-to-total histograms for z=2 star-forming galaxies (SFR > 5 $M_\odot$/yr) and their descendants



Guo & White 2008

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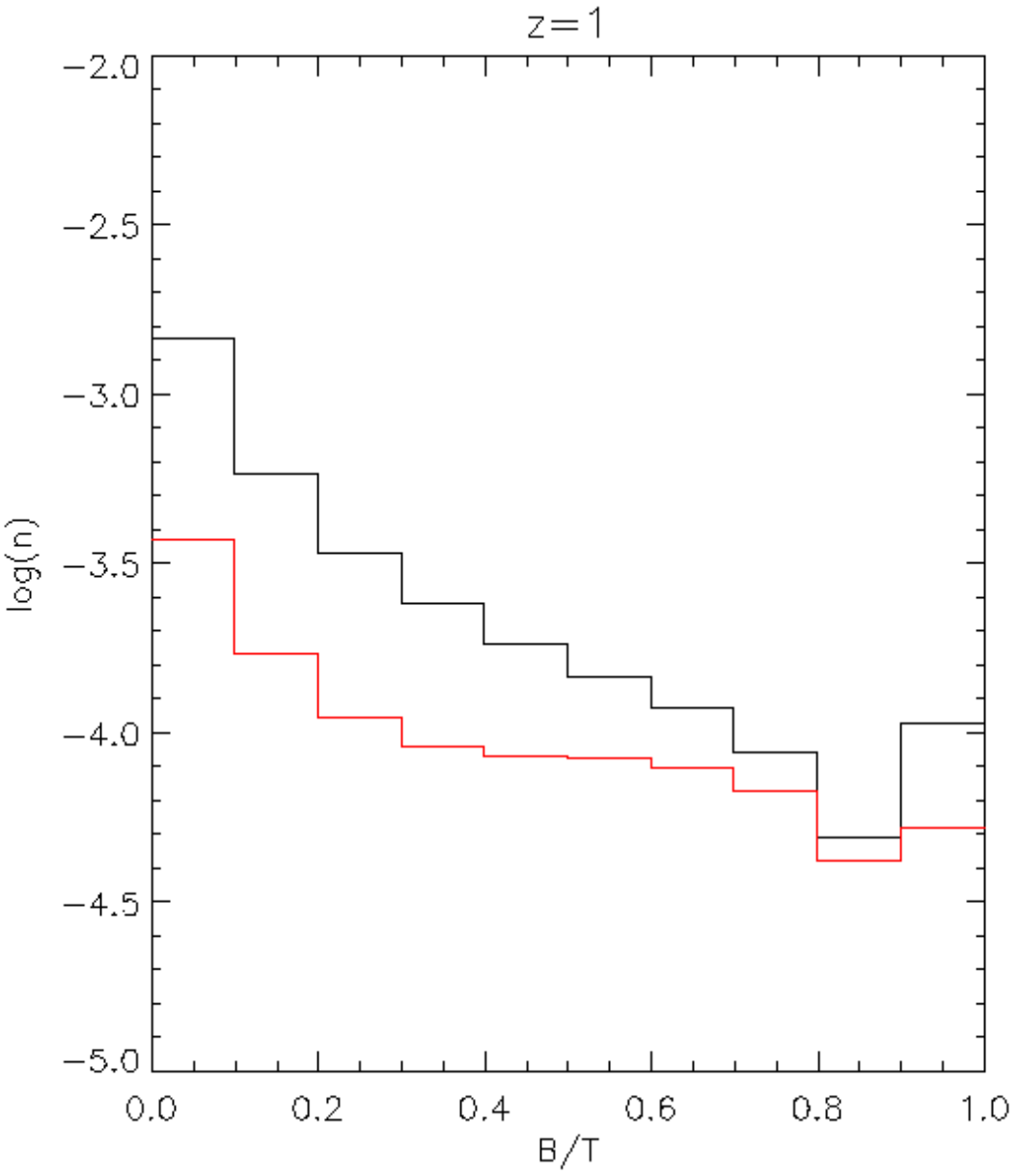

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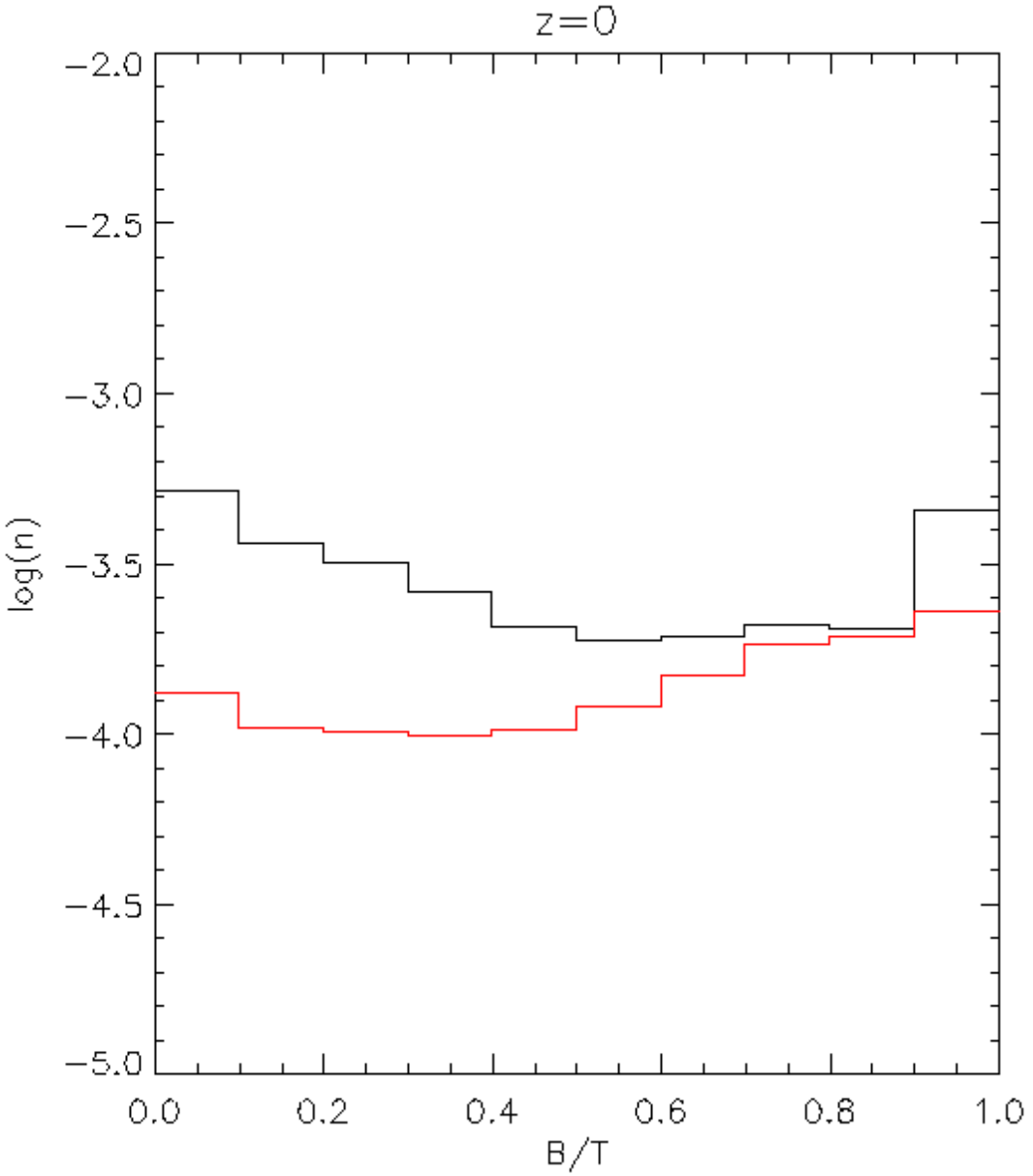
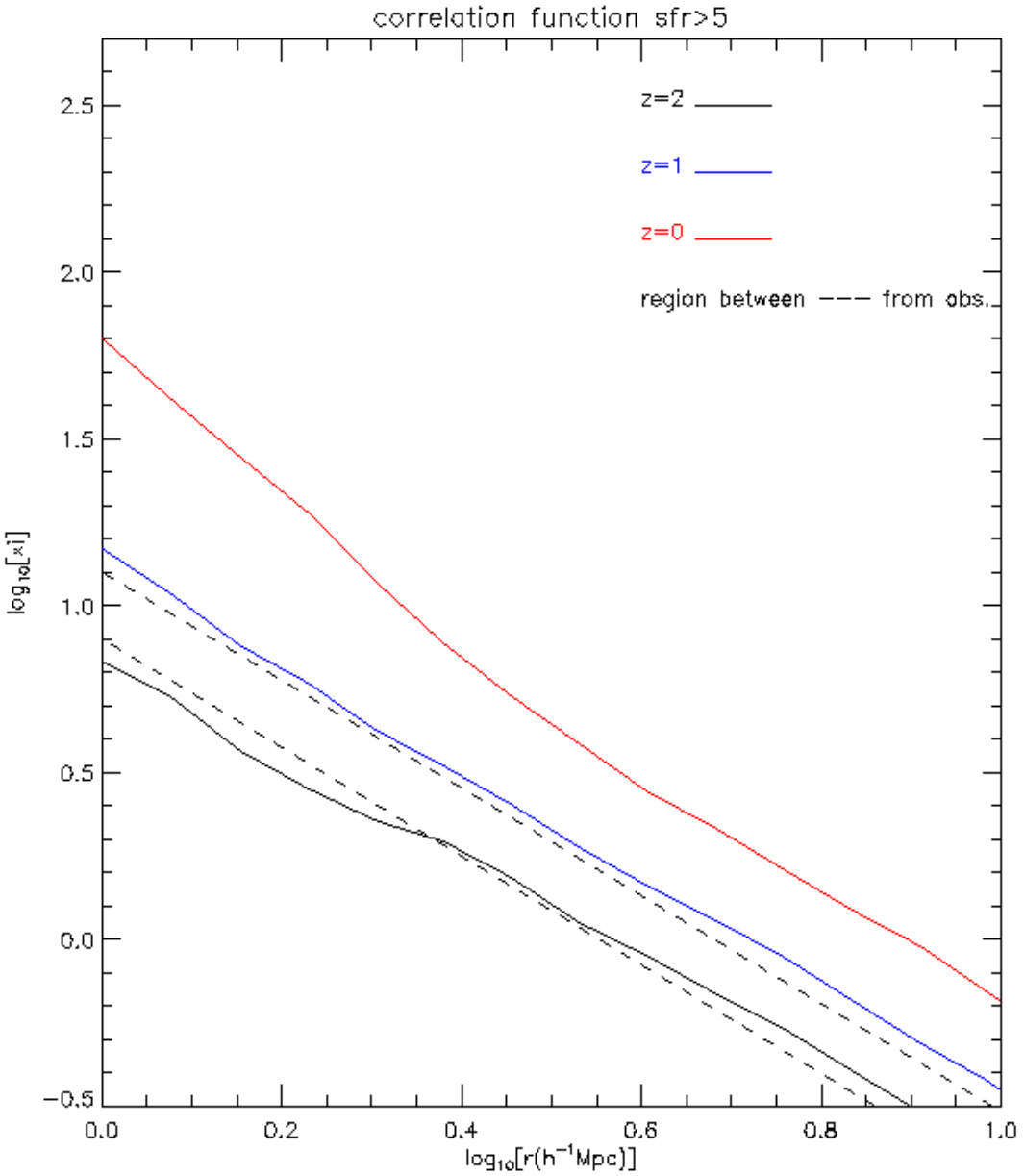


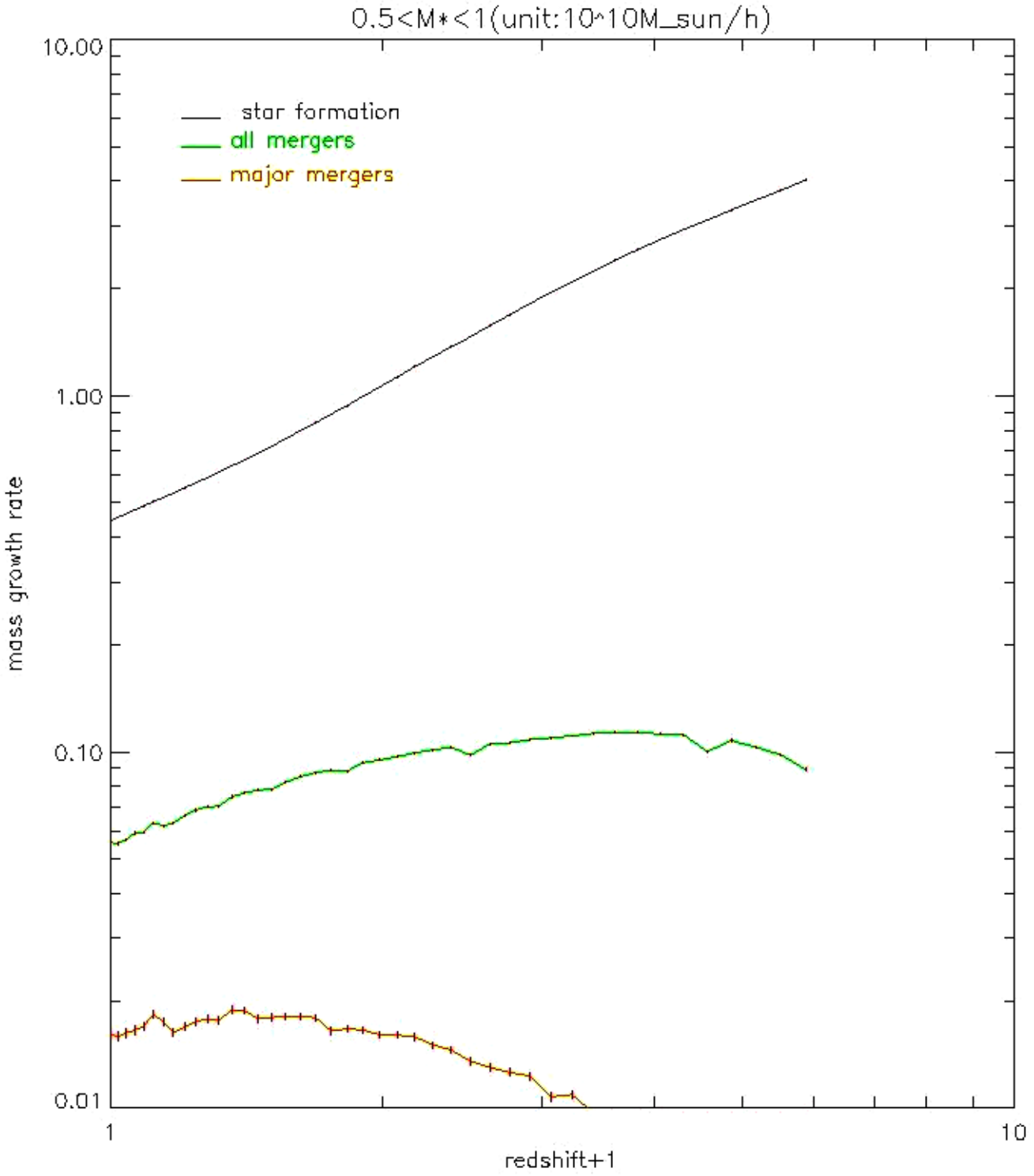
Guo & White 2008

Autocorrelation functions for z=2 star-forming galaxies (SFR > 5 $M_\odot$/yr) and their descendants



Guo & White 2008

How do galaxies grow?



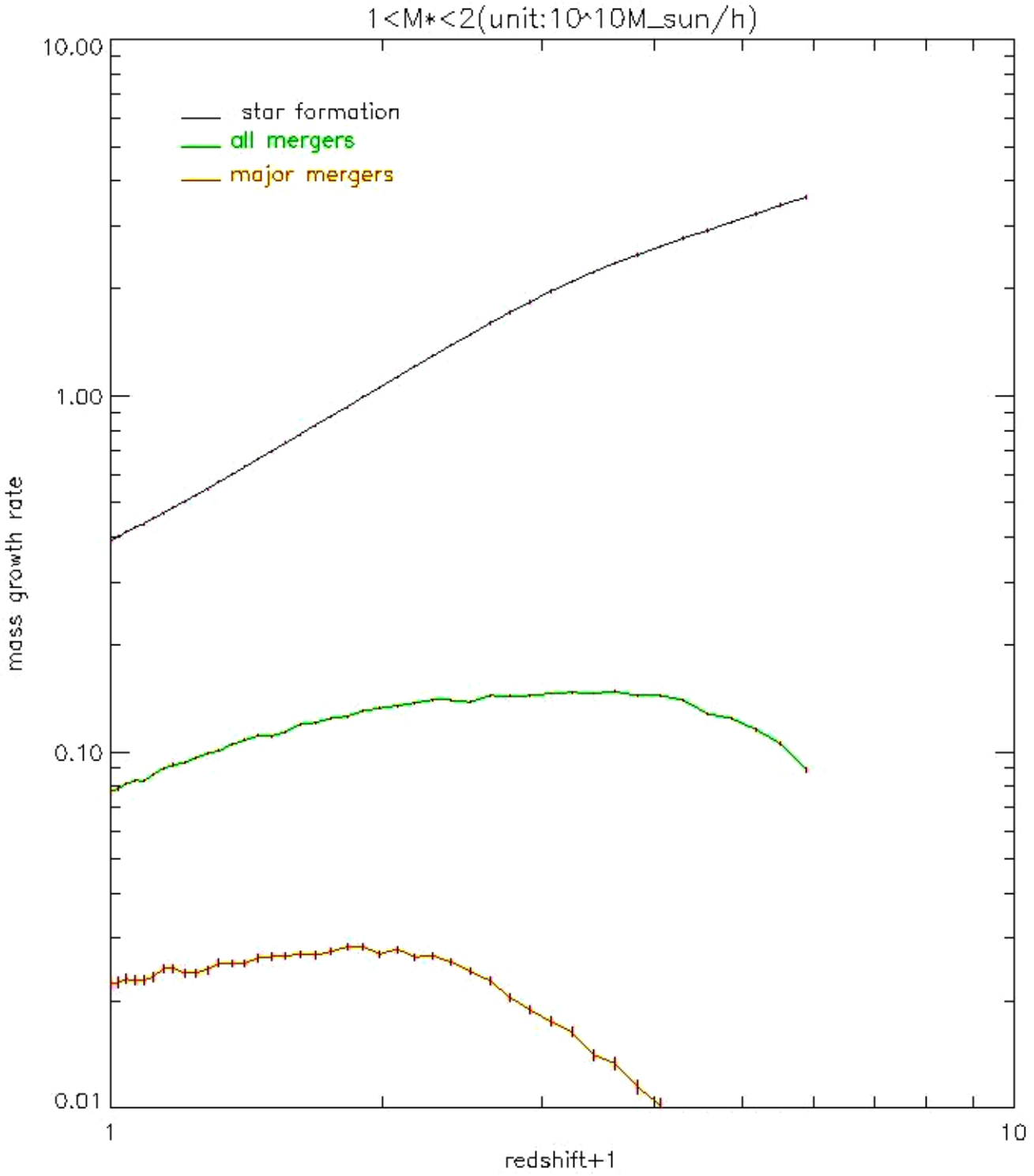
DIMENSIONLESS GROWTH RATES IN STELLAR MASS

Guo & White 2007

$$R = \langle t_{Hubb} \Delta M / M \Delta t \rangle$$

where $\Delta M/M$ is the stellar mass fraction added over the last ~0.2Gyr through

- Major Mergers
- All Mergers
- Star Formation



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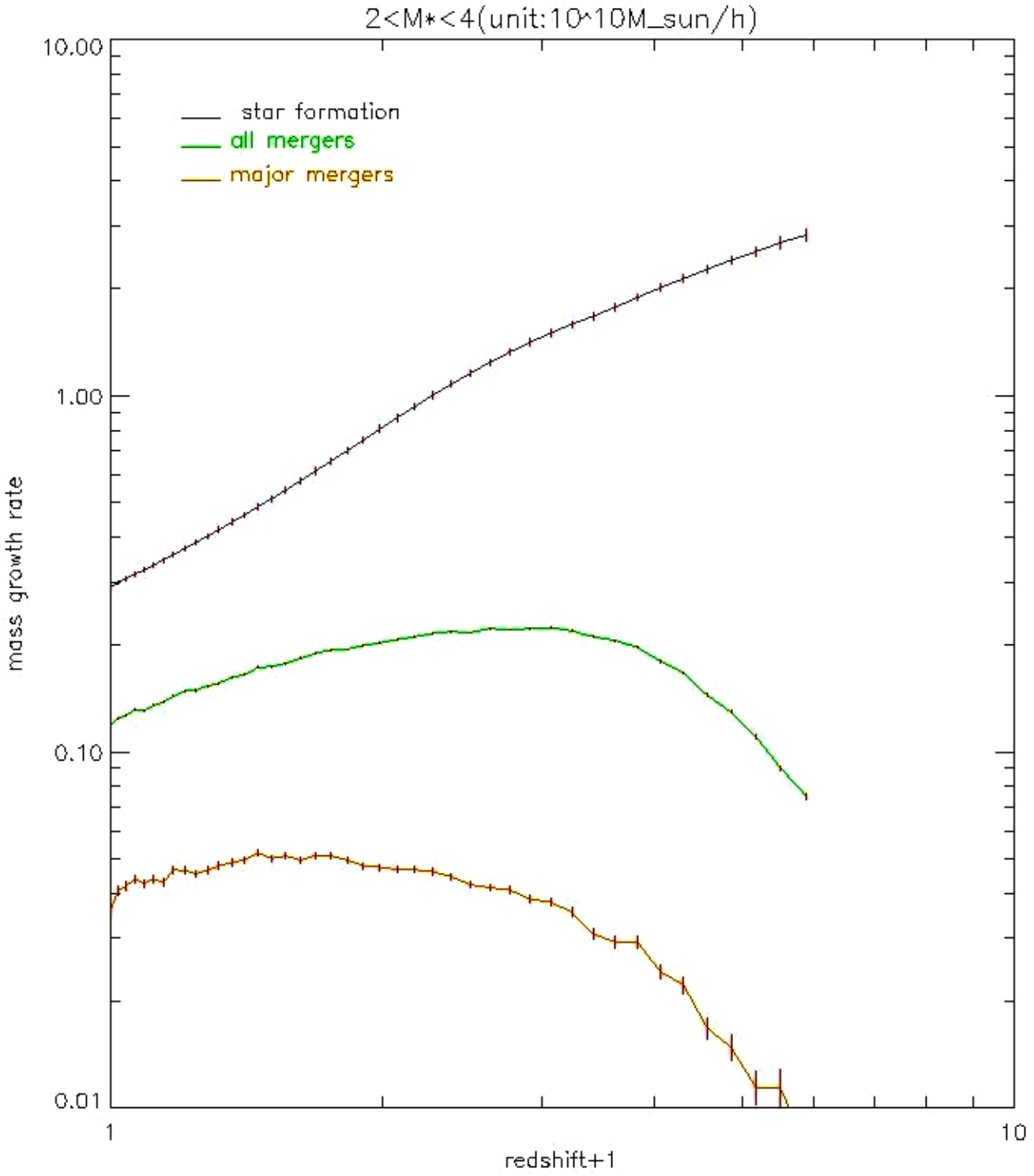

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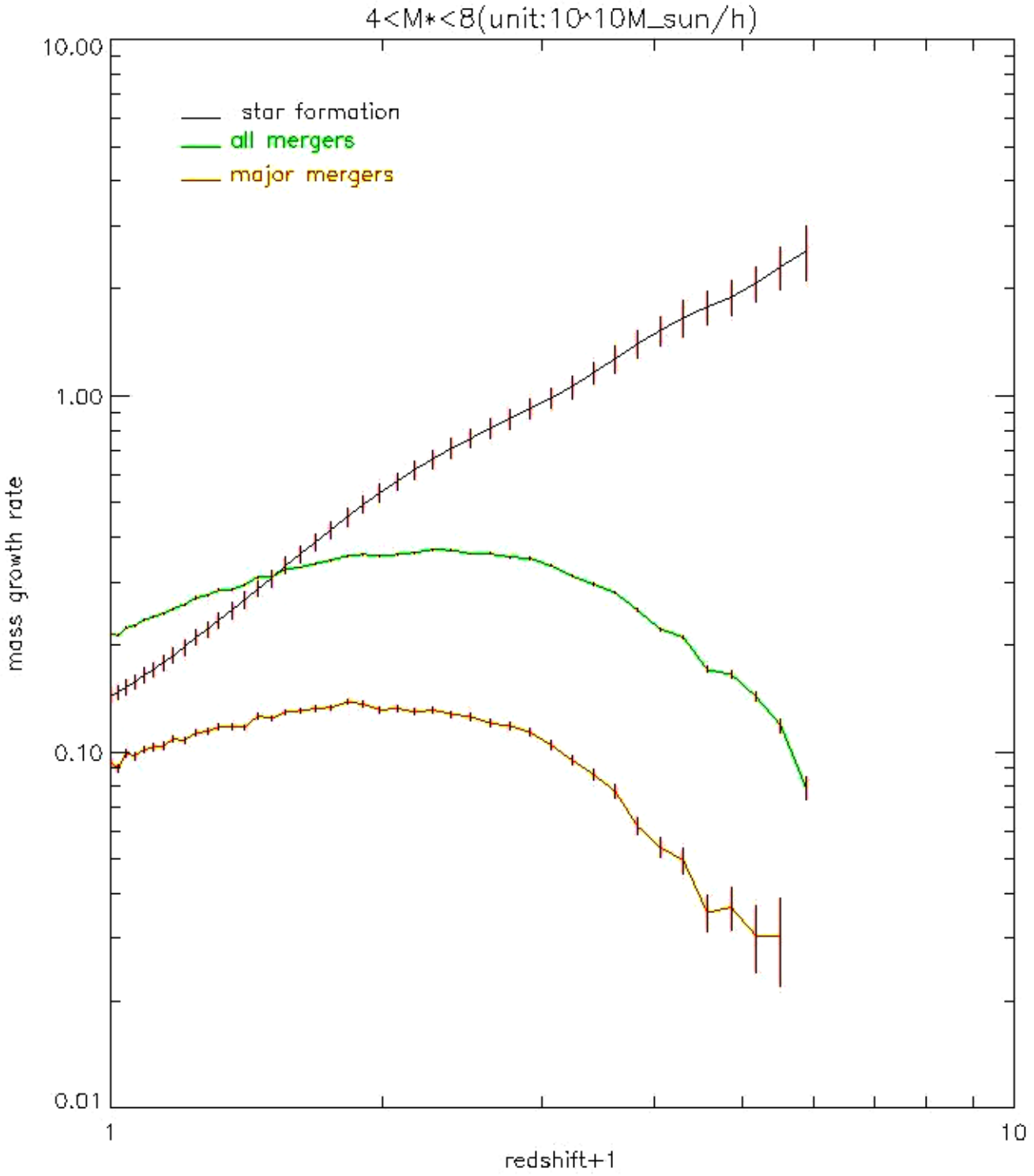

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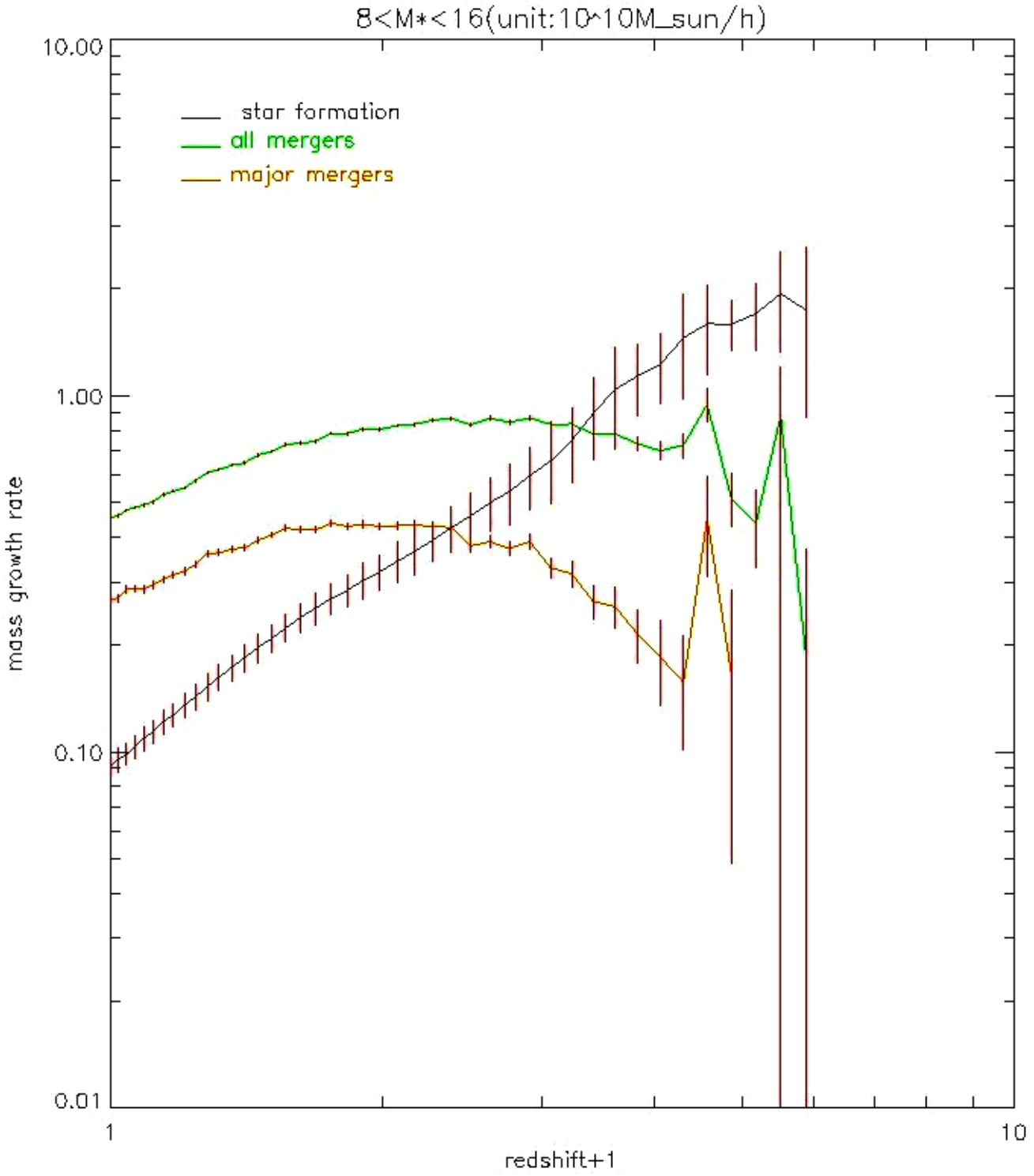

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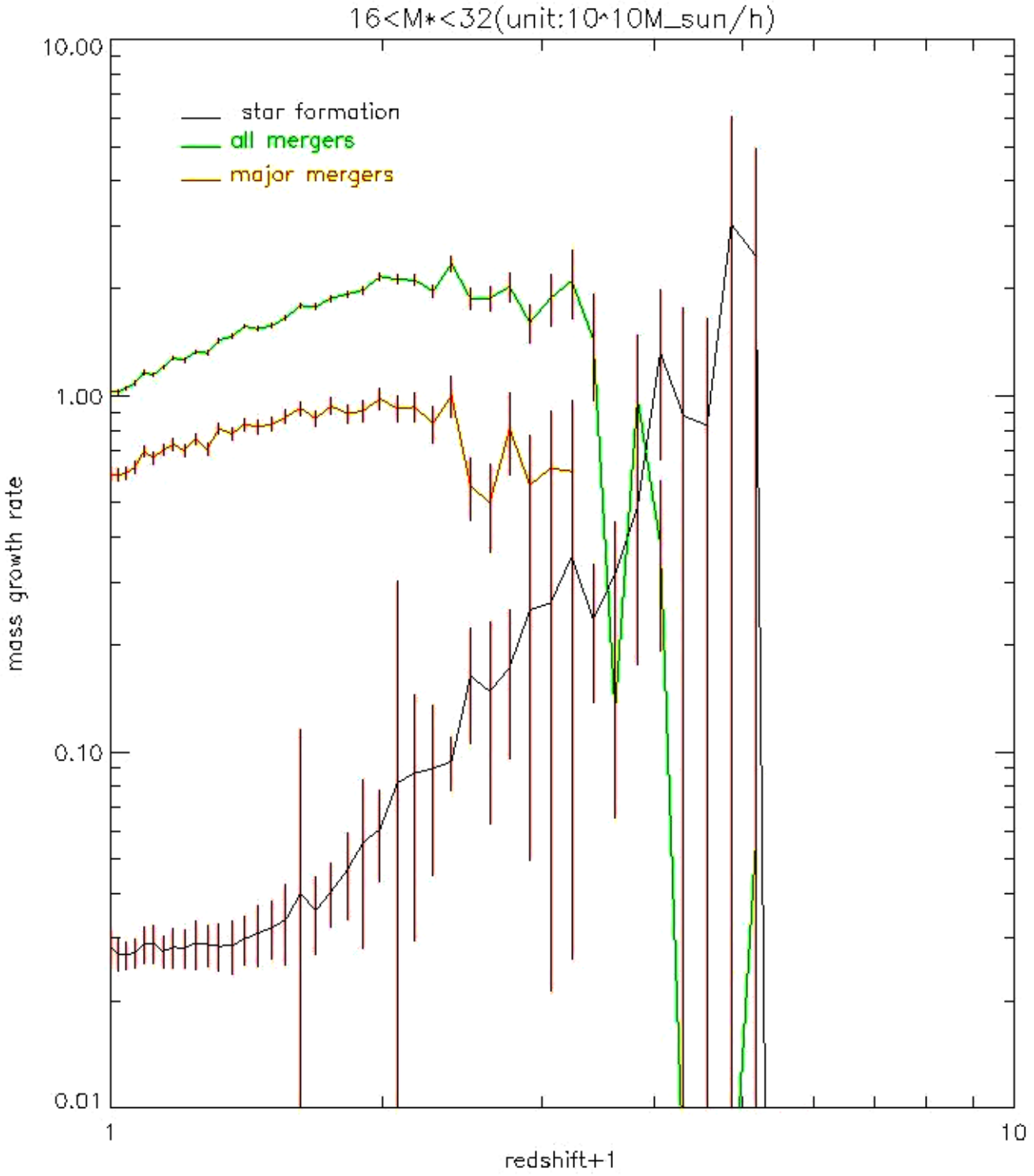

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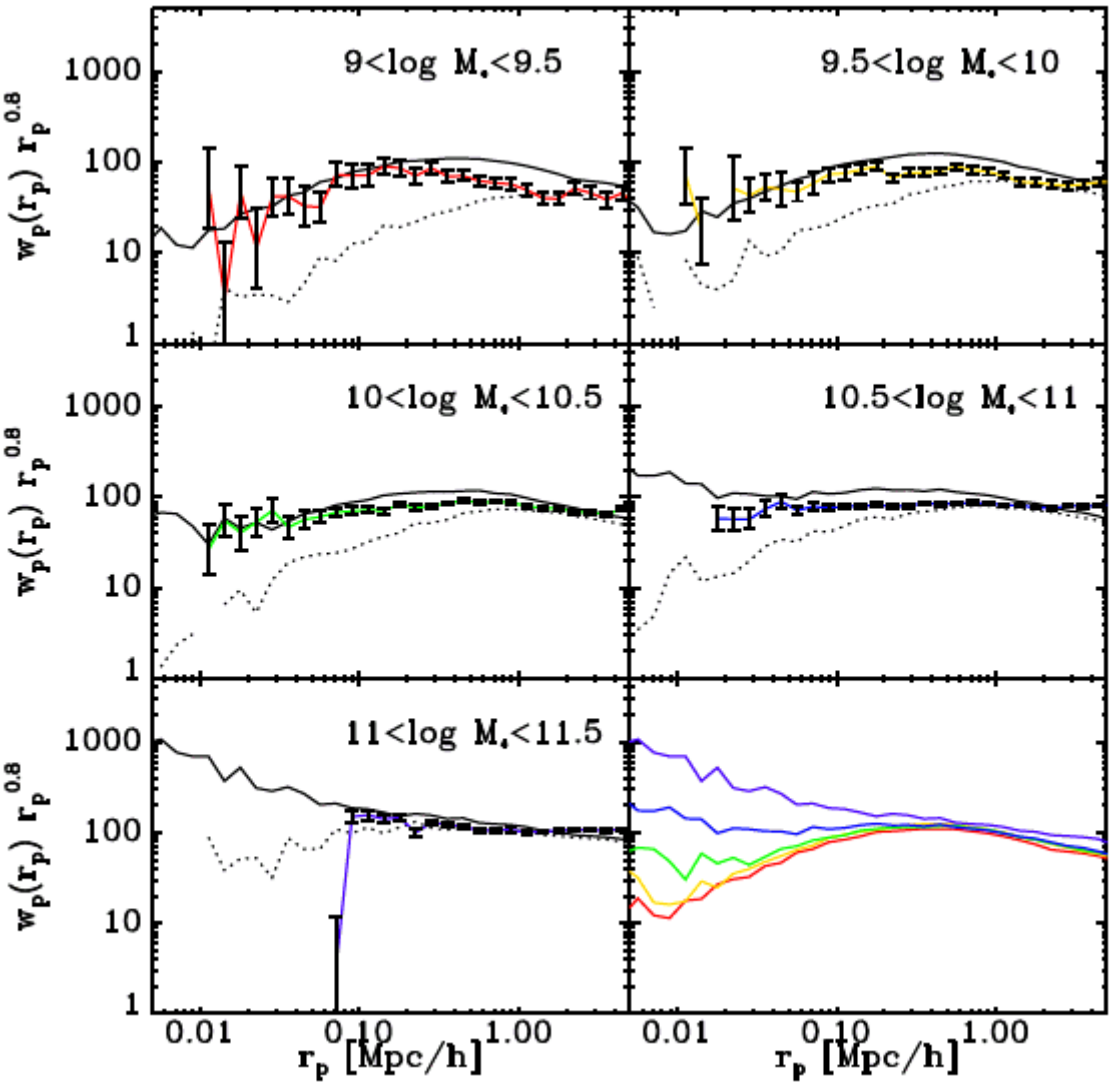
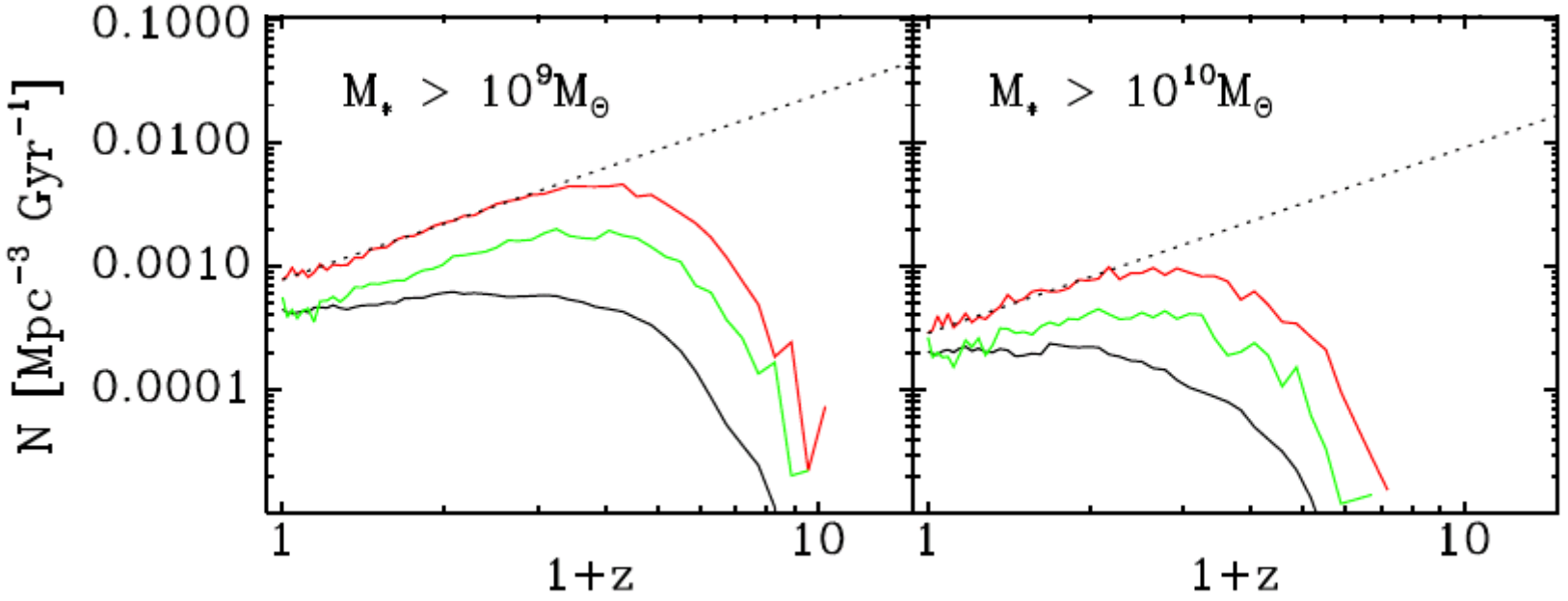
Can we measure merging rates?

Small-scale correlations in the MS versus SDSS



Kitzbichler & White 2008

Major merger rate in the Millennium Simulation



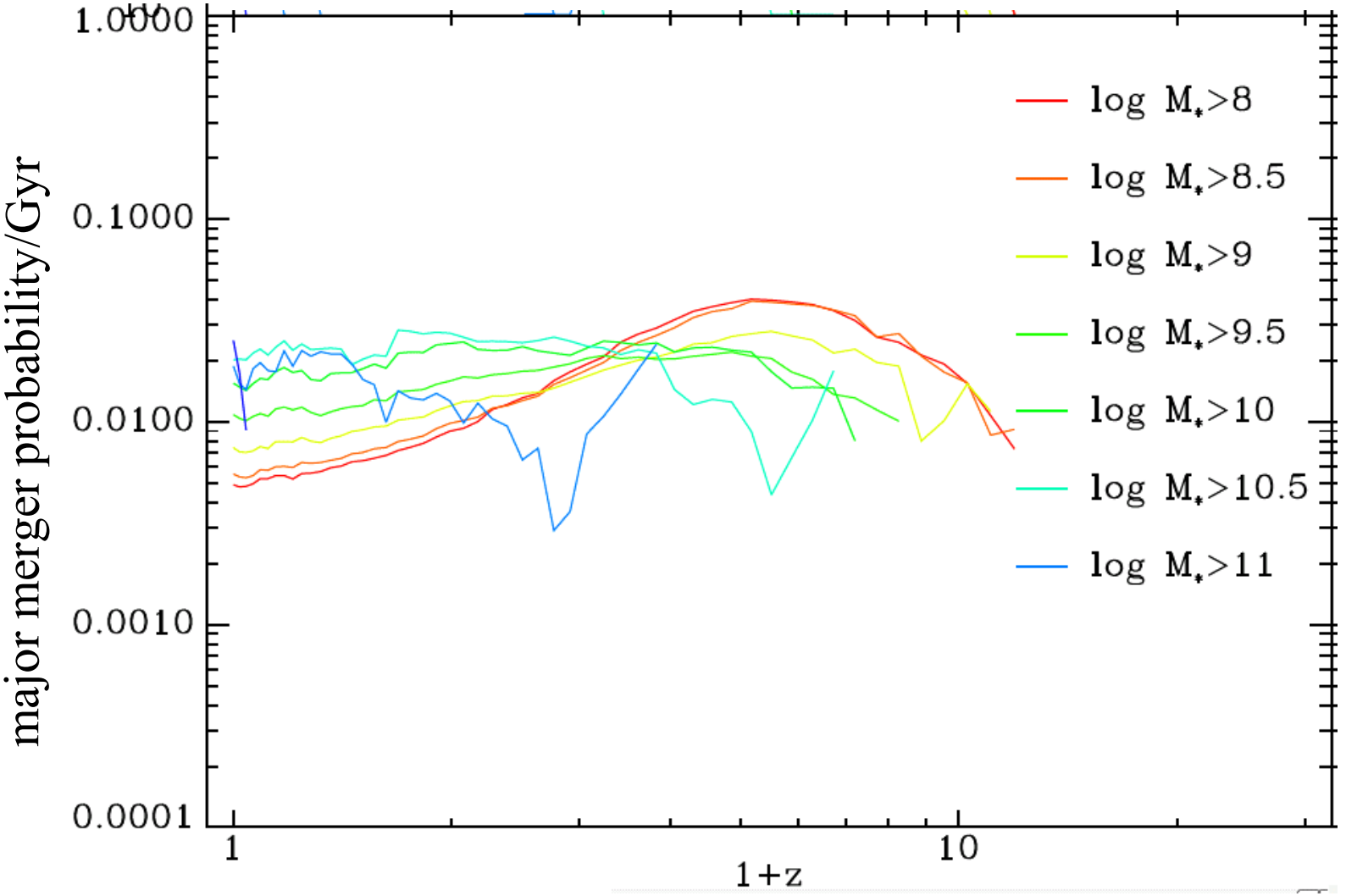
galaxy merger rate

halo merger rate

halo accretion rate

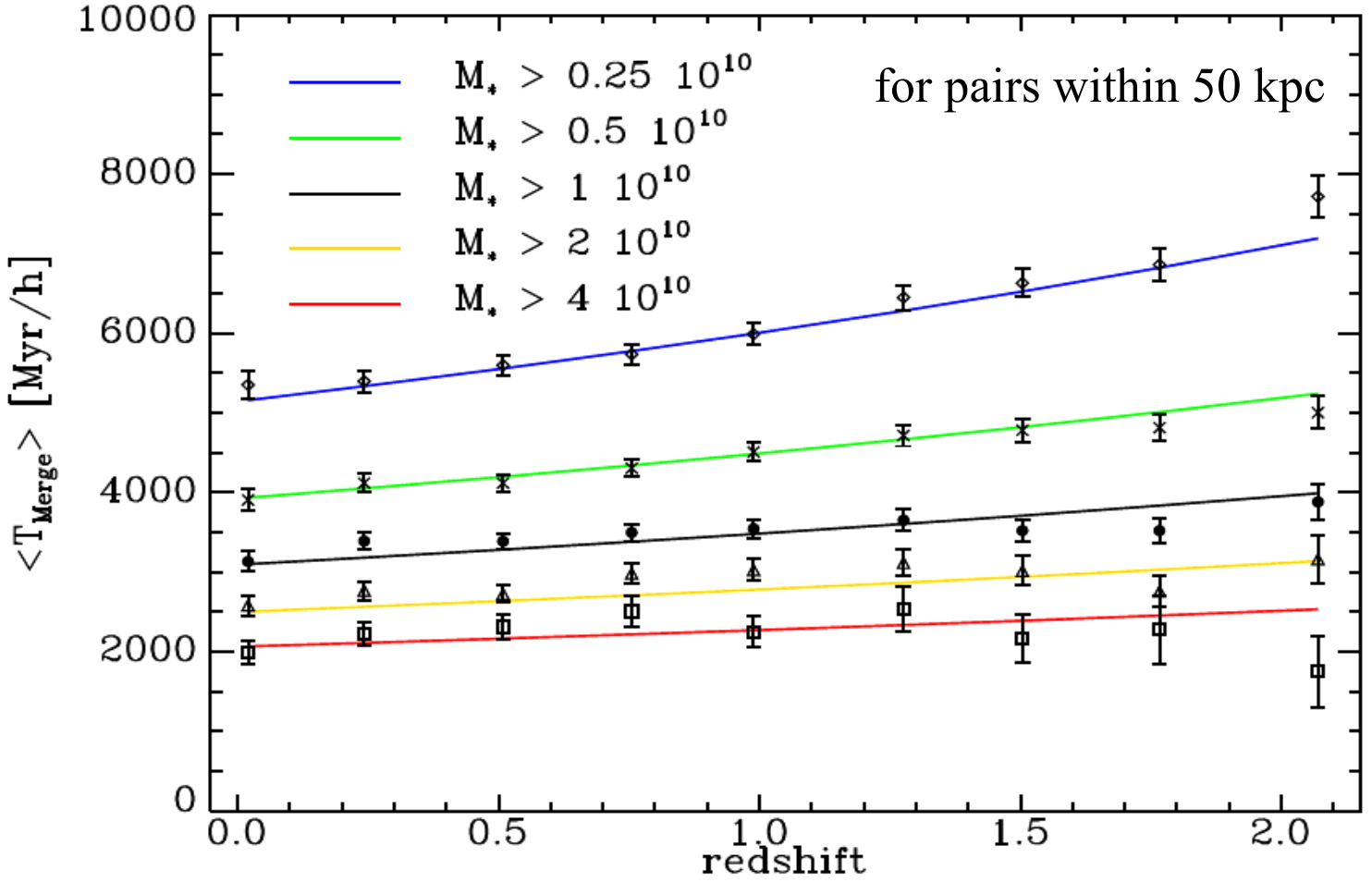
Kitzbichler & White 2008

Major merger probability as function of mass and redshift



Kitzbichler & White 2008

Timescale for converting close pair counts into merger rates



T_{merge} = (Abundance of projected close pairs) / (Merger rate of such pairs)

$\propto r_p M^{-0.3} (8 + z)$

Kitzbichler & White 2008

How to estimate merger rates from pair counts

1 Count close pairs (r_p < 50 *or* 30 kpc) with well defined criteria on magnitude difference, stellar mass, etc.

2 Make completeness and background corrections to estimate abundance of pairs of chosen type at known z

3 Divide close pair abundance by the merger timescale to get merger rate (per unit volume) of the chosen pair type

e.g. for pairs of $\sim 10^{10}\ M_\odot$ galaxies at $z \sim 1$ with

$$r_p \leq 30 \text{ kpc/h (physical) and } \Delta v < 300 \text{ km/s}$$

$$T_{merge} = 2.0 \text{ Gyr/h}$$

Happy Birthday, Marc!