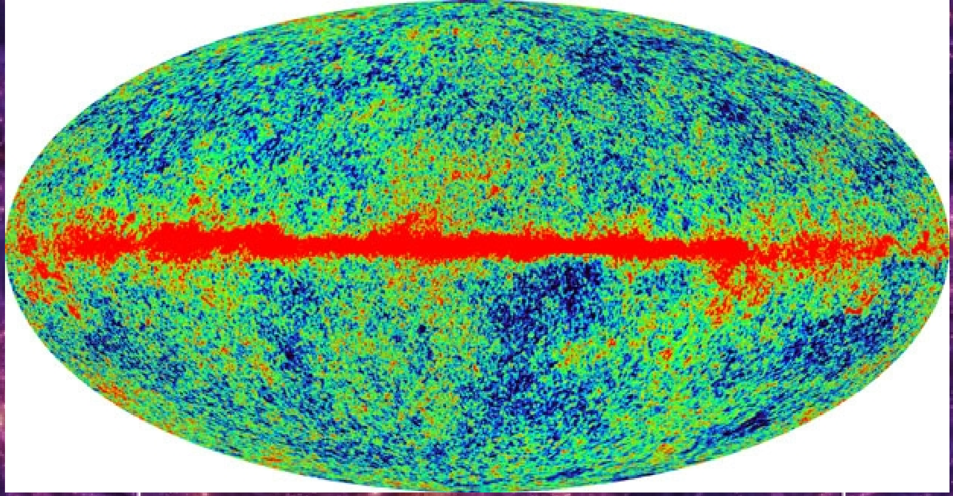


Paris
February 2007

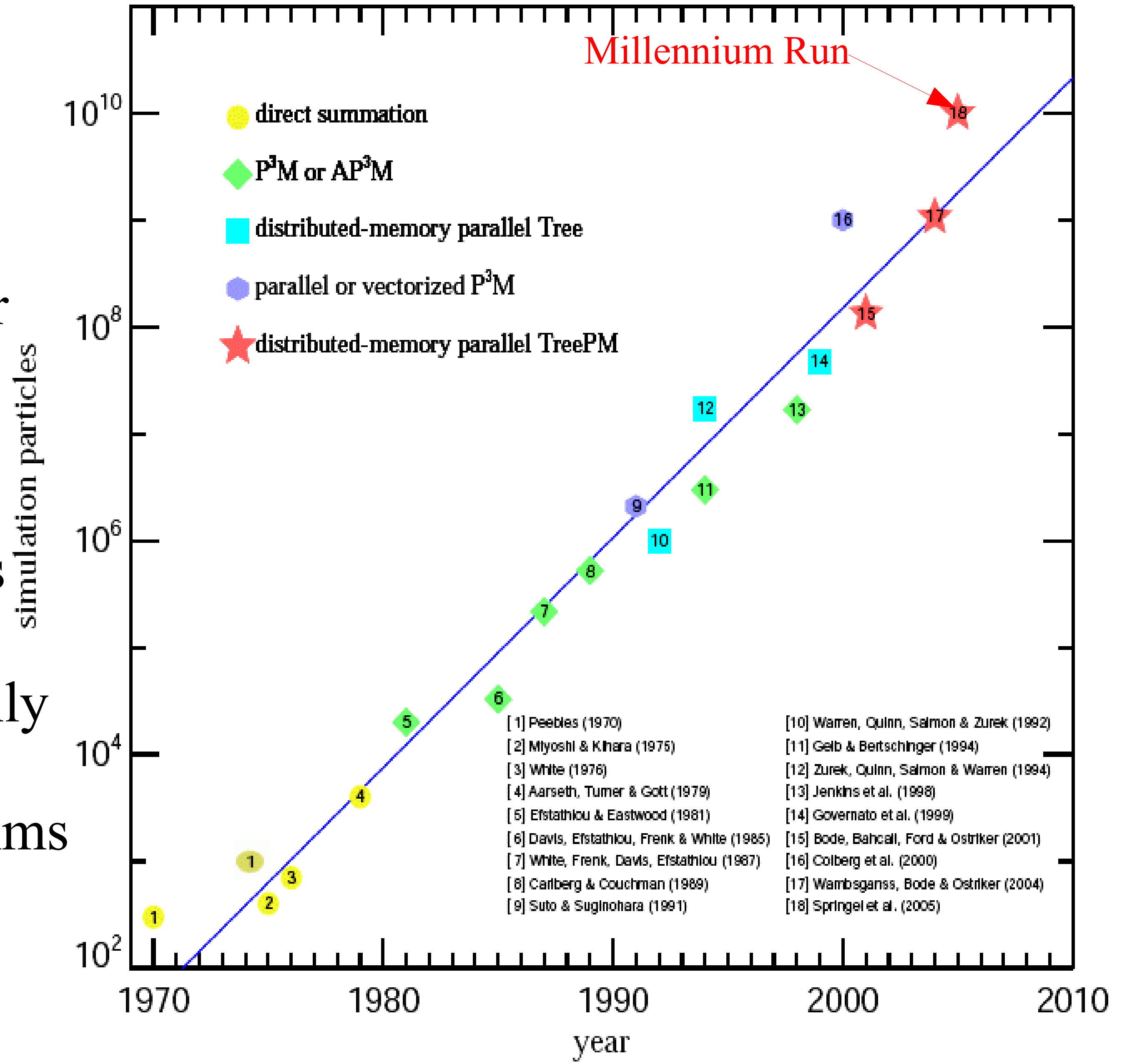
Serving the new Millennium

Simon White
Max Planck Institute for Astrophysics

Moore's Law for Cosmological N-body Simulations

- Computers double their speed every 18 months
- Simulations double their size every 16.5 months
- A naive N-body force calculation needs N^2 op's
- Progress has been roughly equally due to hardware and to improved algorithms

Springel et al 2005

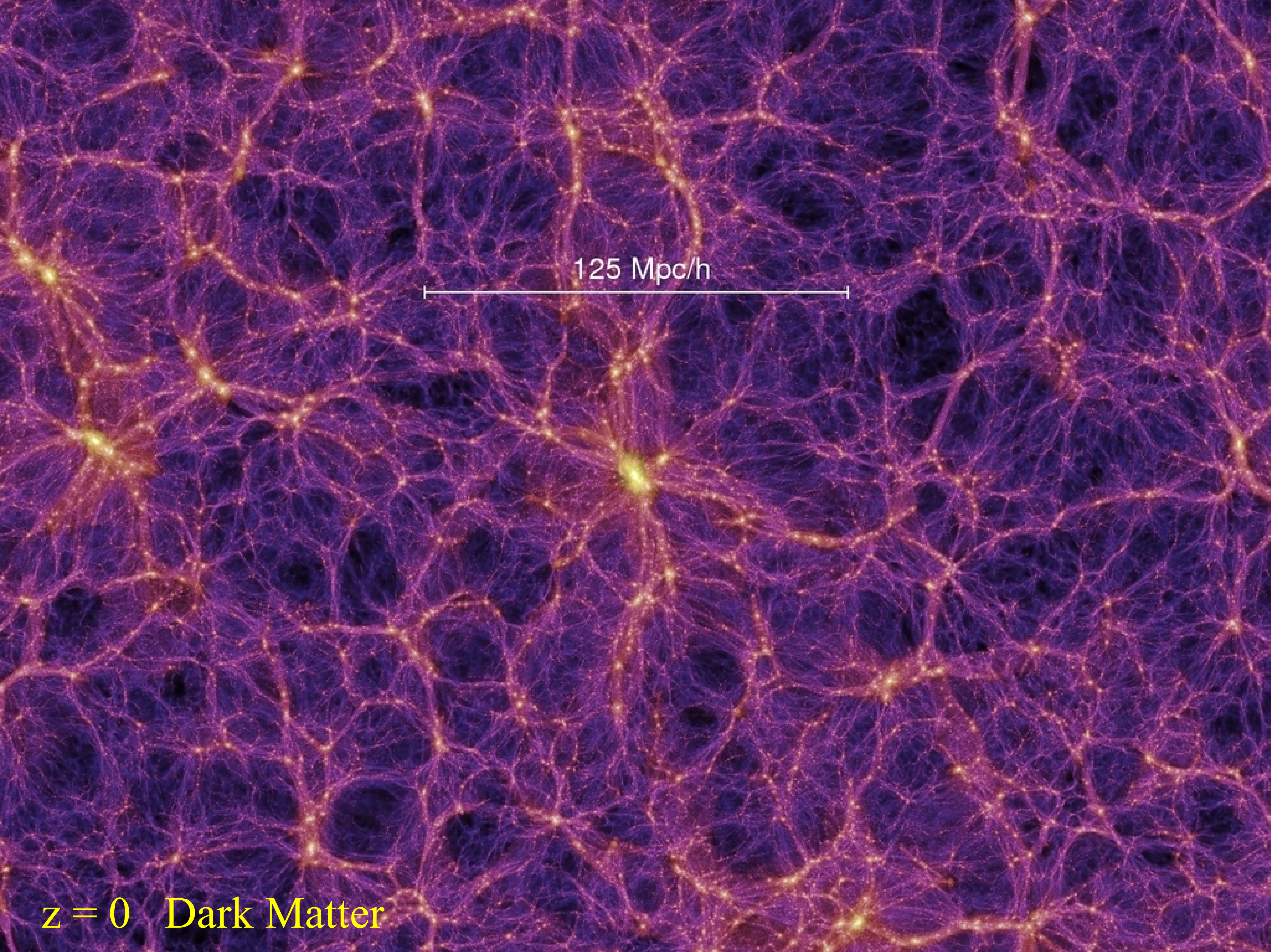


Millennium Run Statistics

Springel et al 2005: The Virgo Consortium

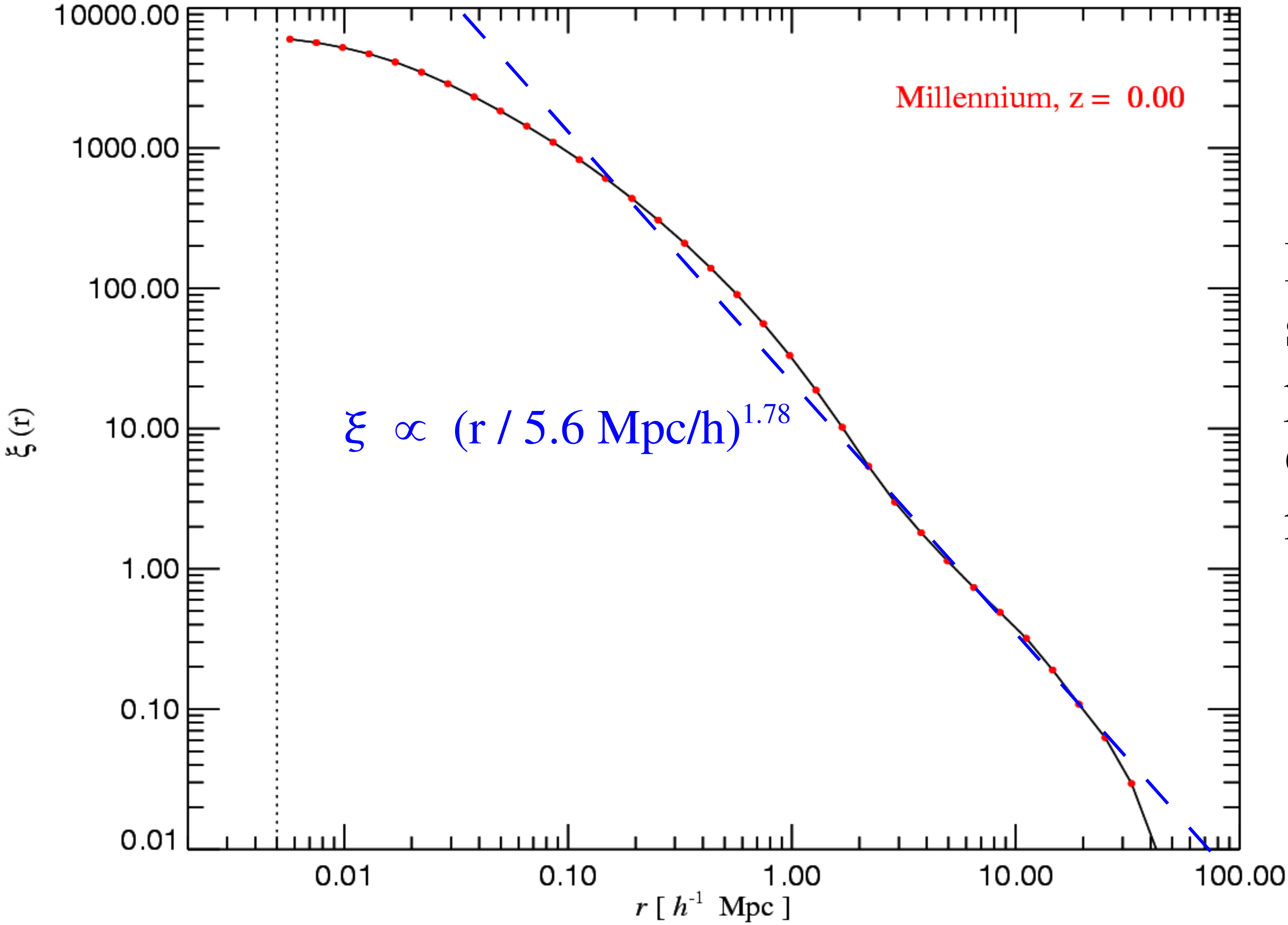
- DM particle number: $N = 2160^3 = 10{,}077{,}696{,}000 \approx 10^{10}$
- Box size: L = 500 Mpc/h, Softening: $\epsilon = 5$ kpc/h ⟶ $L/\epsilon = 10^5$
- Initial redshift: $z_{init} = 127$
- Cosmology: $\Omega_{tot}=1$, $\Omega_m=0.25$, $\Omega_b=0.045$, $h=0.73$, $n=1$, $\sigma_8=0.9$
- 343,000 processor-hours on 512 nodes of an IBM Regatta
  (28 machine days @ 0.2 Tflops using 1 Tbyte RAM)
- Full raw and reduced data stored at 64 redshifts
  ⟶ 27 Tbytes of stored data

A testbed for simulating the formation of $\sim 10^7$ galaxies


125 Mpc/h
z = 0 Dark Matter

Mass autocorrelation function

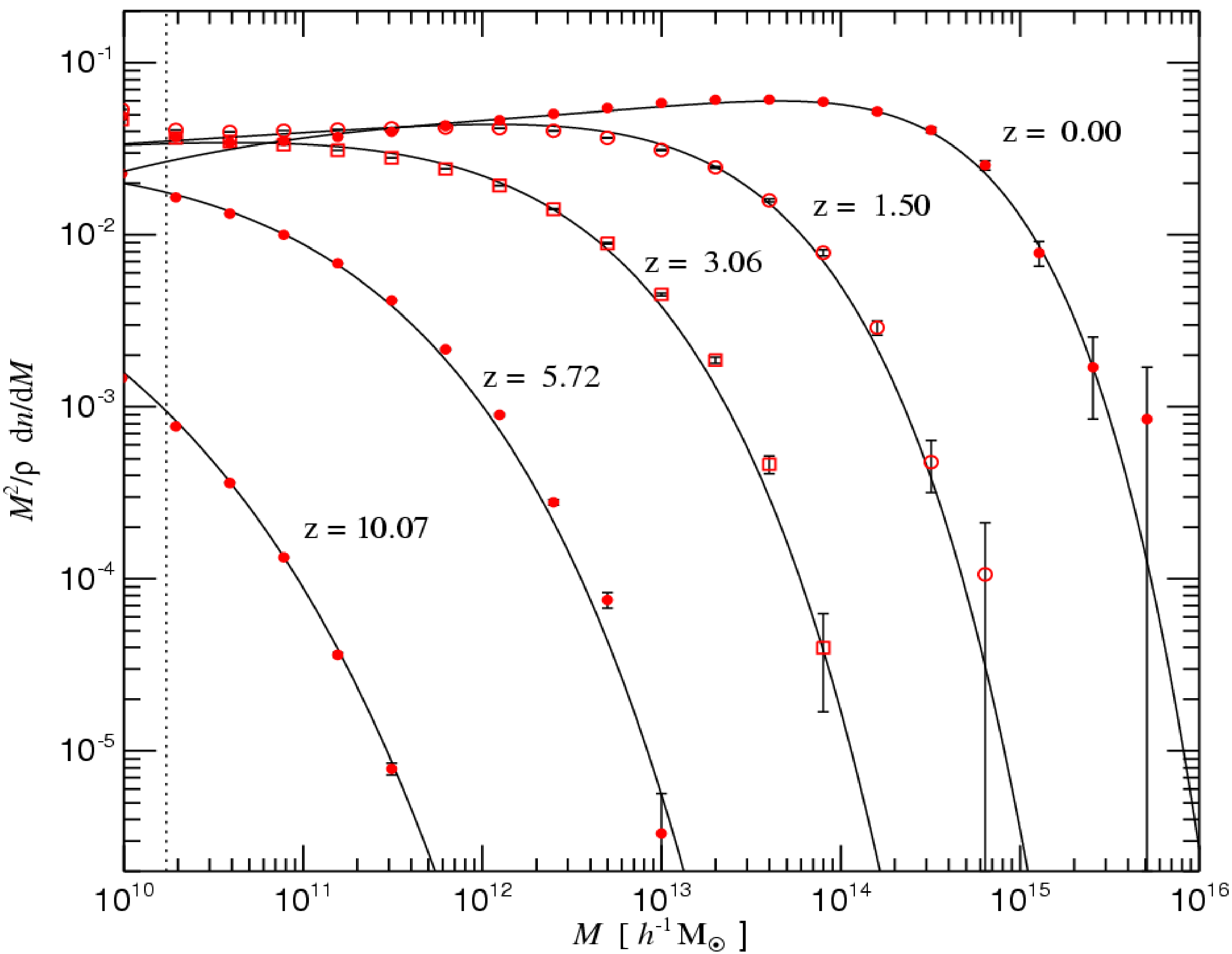
Springel et al 2005



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

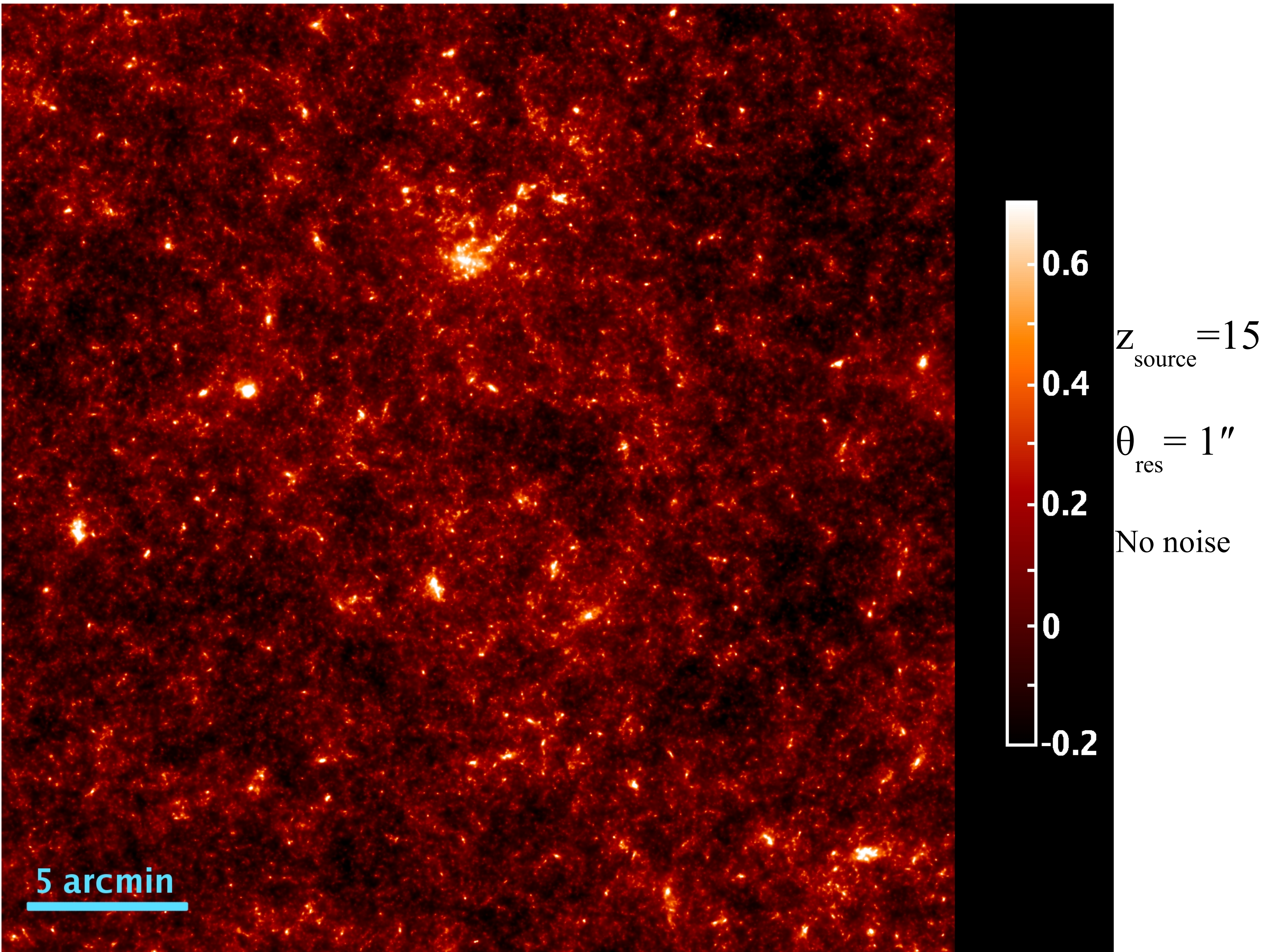
Halo Mass Functions in the MS

Springel et al 2005

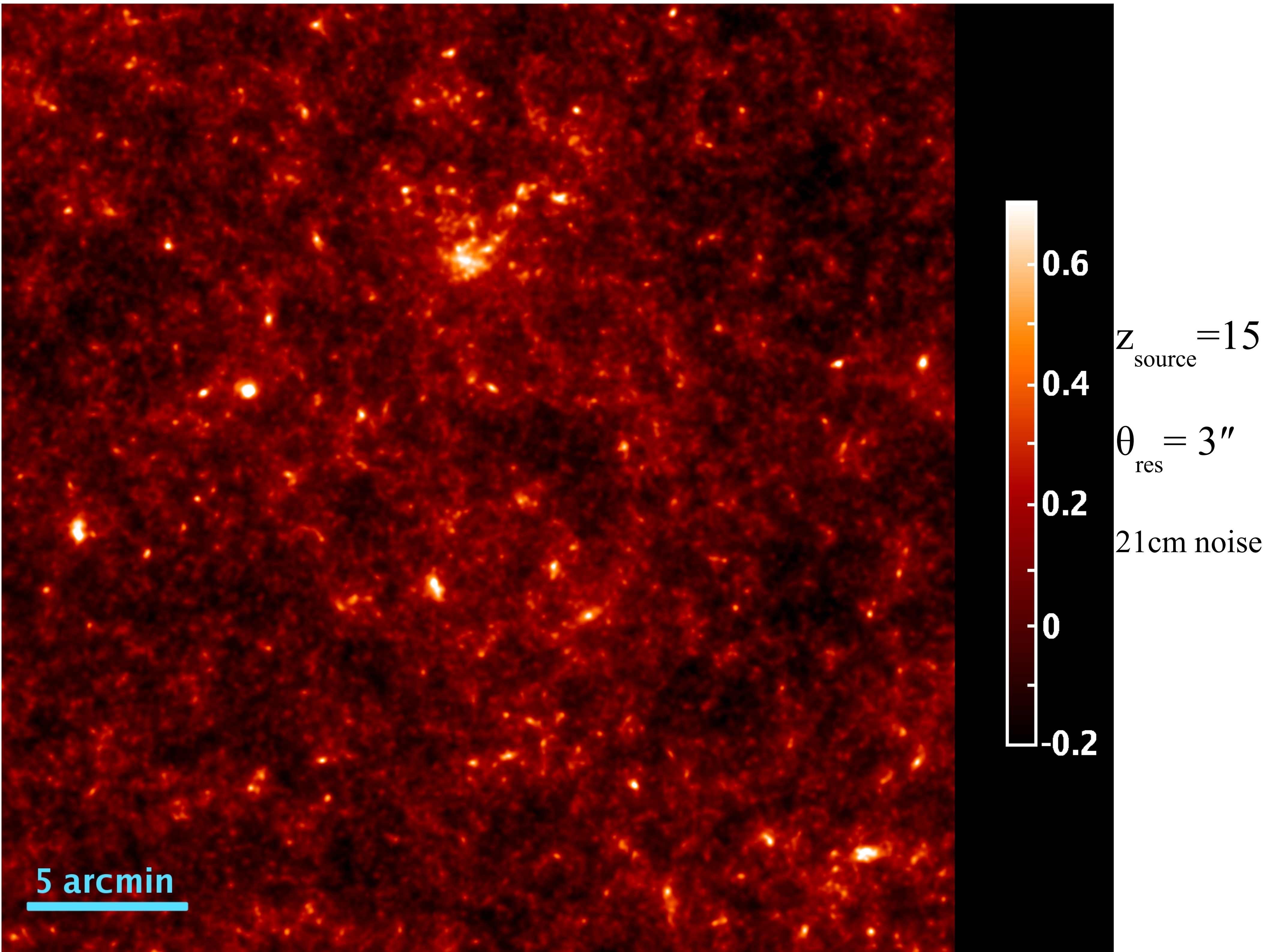


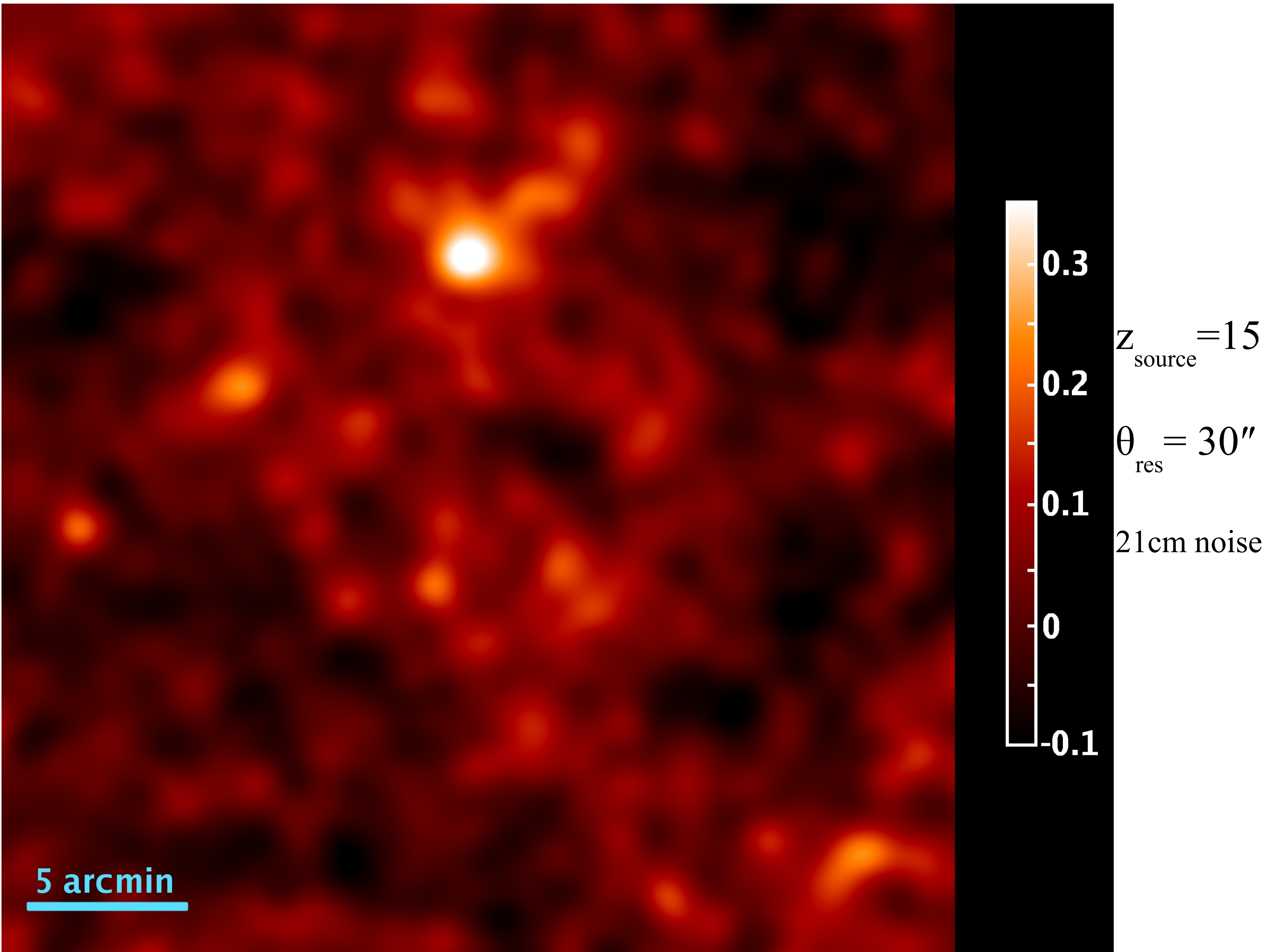
Solid curves are the empirical fitting formula from Jenkins et al 2001 with no parameters adjusted

At z = 0 half of all mass is in lumps of $M > 2 \times 10^{10} M_\odot$

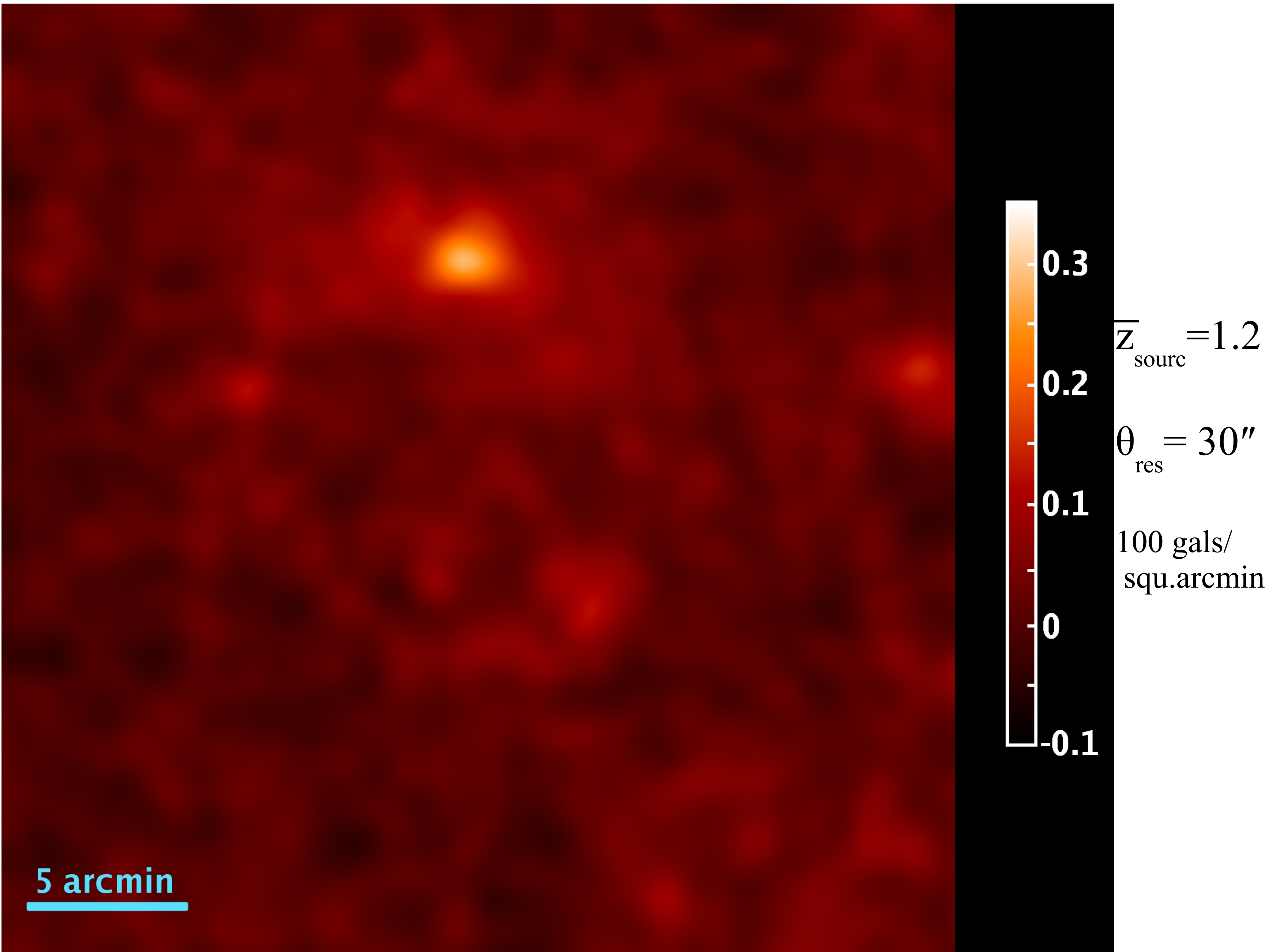


5 arcmin
0.6
0.4
0.2
0
-0.2
z_{source}=15
$\theta_{res} = 1''$
No noise


5 arcmin
0.6
0.4
0.2
0
-0.2
z_{source}=15
$\theta_{res} = 3''$
21cm noise



5 arcmin
0.3
0.2
0.1
0
-0.1
$z_{source}=15$
$\theta_{res} = 30''$
21cm noise



0.3
0.2
0.1
0
-0.1
5 arcmin
$\overline{z}_{sourc}$ =1.2
$\theta_{res} = 30''$
100 gals/
squ.arcmin

Goals for simulations of galaxy/AGN evolution

- Explore the physics of galaxy formation
- Understand the links between galaxy and SMBH formation
- Clarify why galaxy properties are related to clustering
- Determine how environment stimulates galaxy activity
- Interpret new multi-wavelength surveys of galaxies
- Check if such surveys can provide precision tests of and parameter estimates for the standard ΛCDM paradigm

Simulating galaxies /AGN in the Millennium Run

Springel et al 2005; Croton et al 2006, De Lucia et al 2006

- Build and store merger trees which encode the detailed assembly history of every z=0 halo *and* of the substructure within it

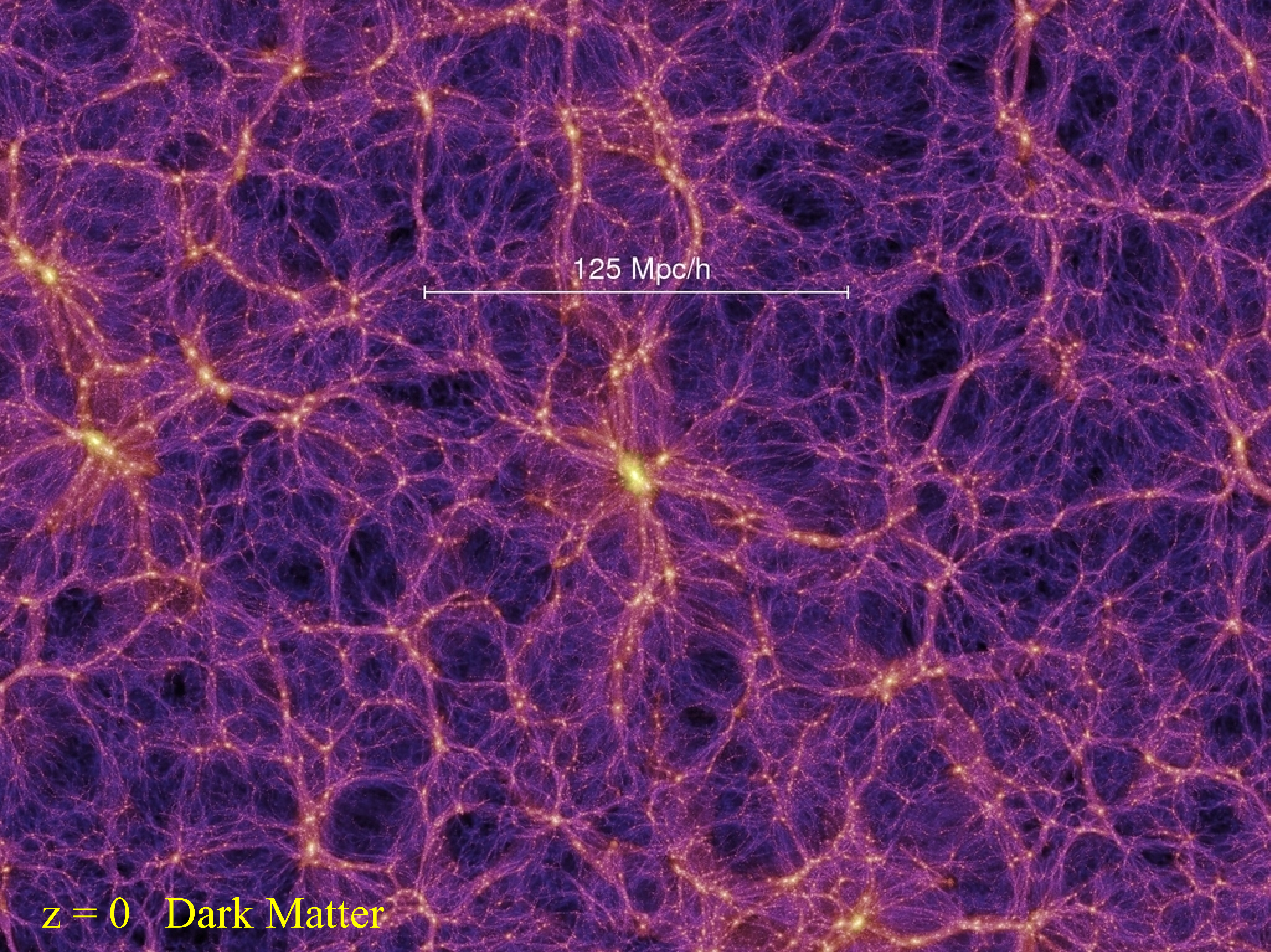
- Implement models for the formation/evolution of galaxies to follow
  - -- accretion, shock-heating and cooling of diffuse gas into disks
  - -- star formation from the ISM in disks
  - -- stellar evolution
  - -- SN feedback and stellar winds
  - -- chemical enrichment/dust formation
  - -- galaxy merging/morphological transformation

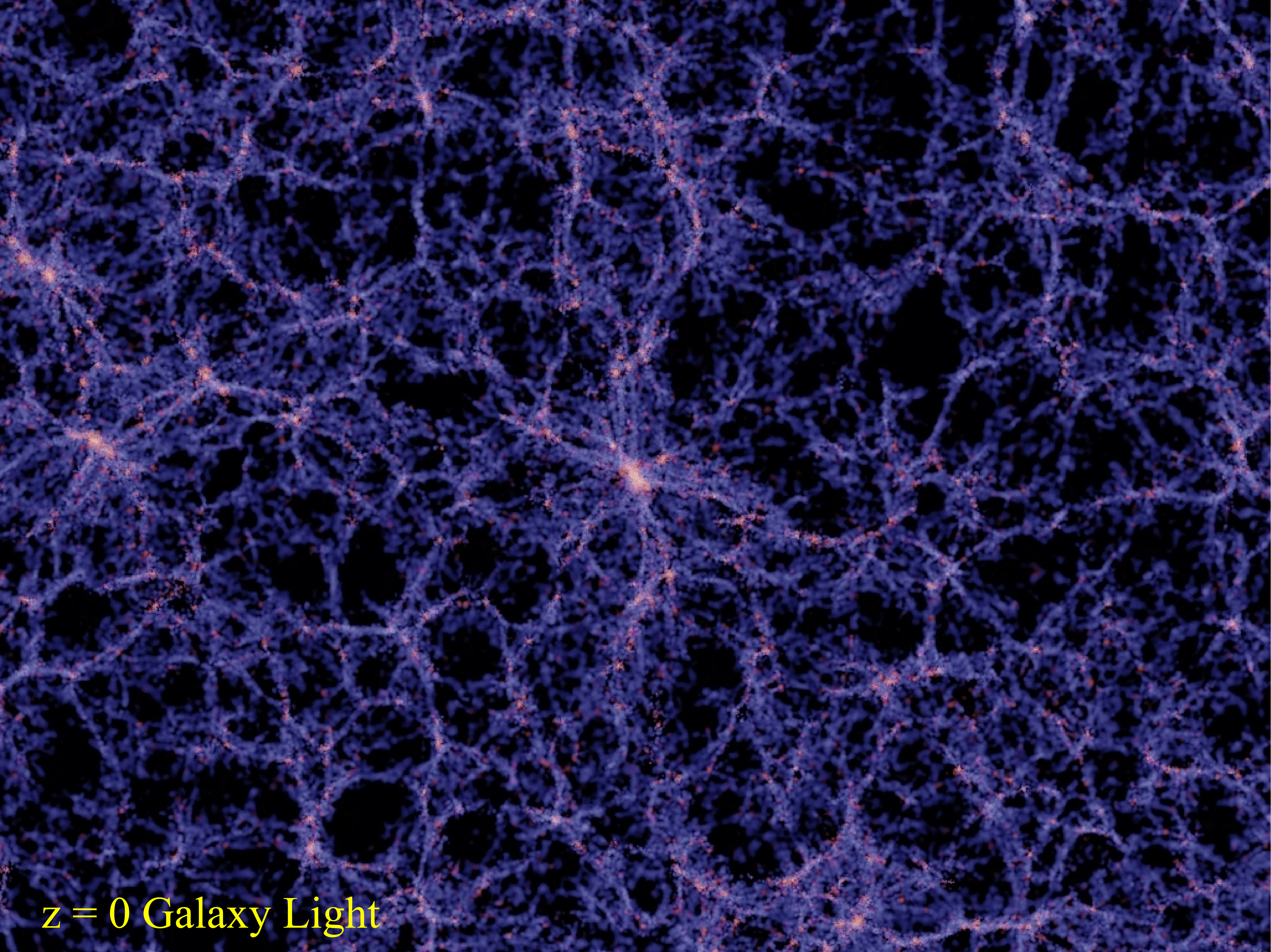
  [After Springel et al (2001) and De Lucia et al (2004)]

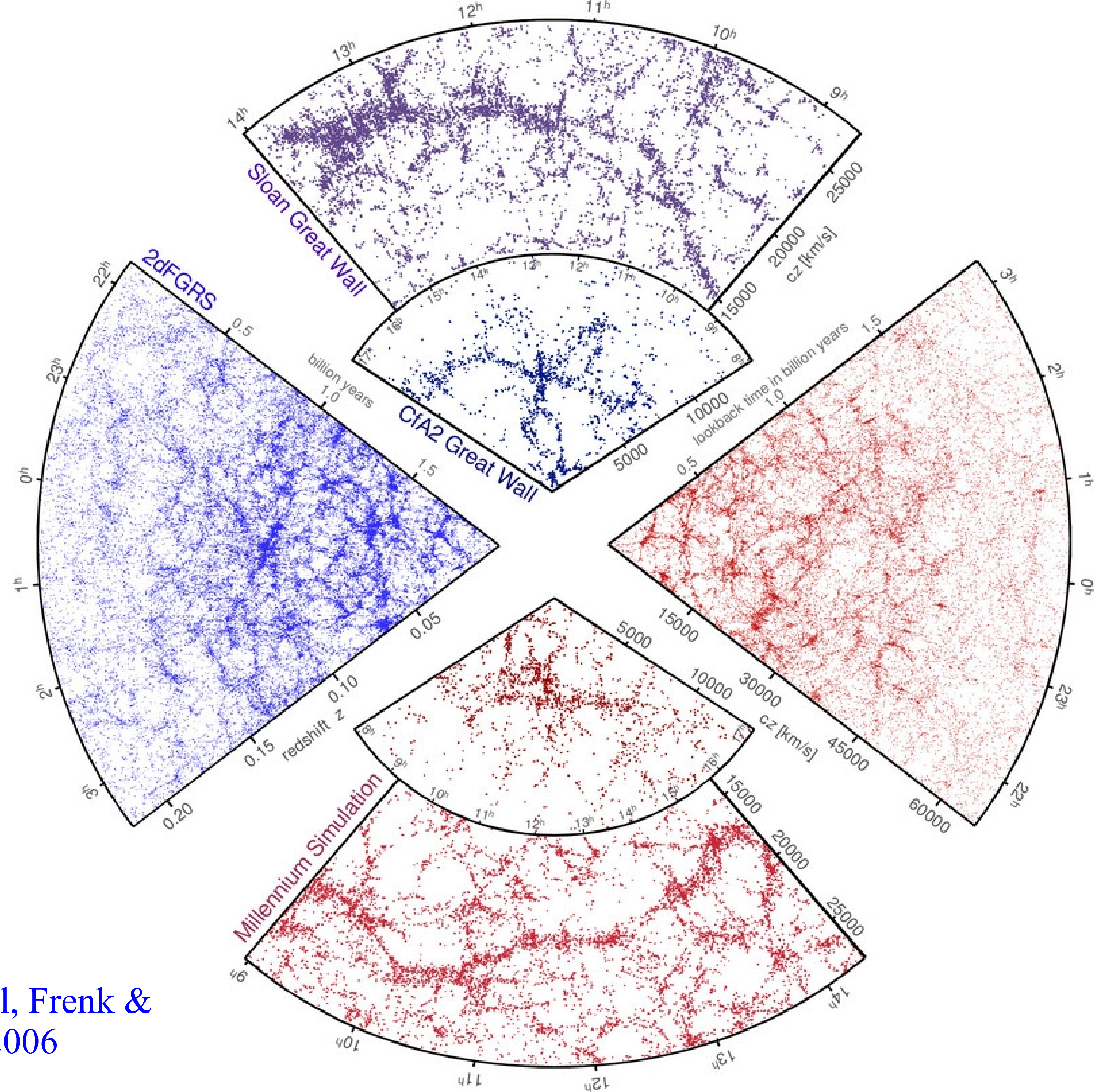
- Implement models for the growth of central black holes to follow
  - -- formation and growth from ISM gas during mergers
  - -- black hole mergers following galaxy mergers

  [After Kauffmann & Haehnelt (2000)]

- Include "radio mode" feedback from BH at cooling flow centres
  - -- energy feedback from BH in the central dominant galaxy depends on BH mass, gas temperature and gas mass fraction $\propto f_{gas} m_{BH} T^{1.5}$


125 Mpc/h
z = 0 Dark Matter

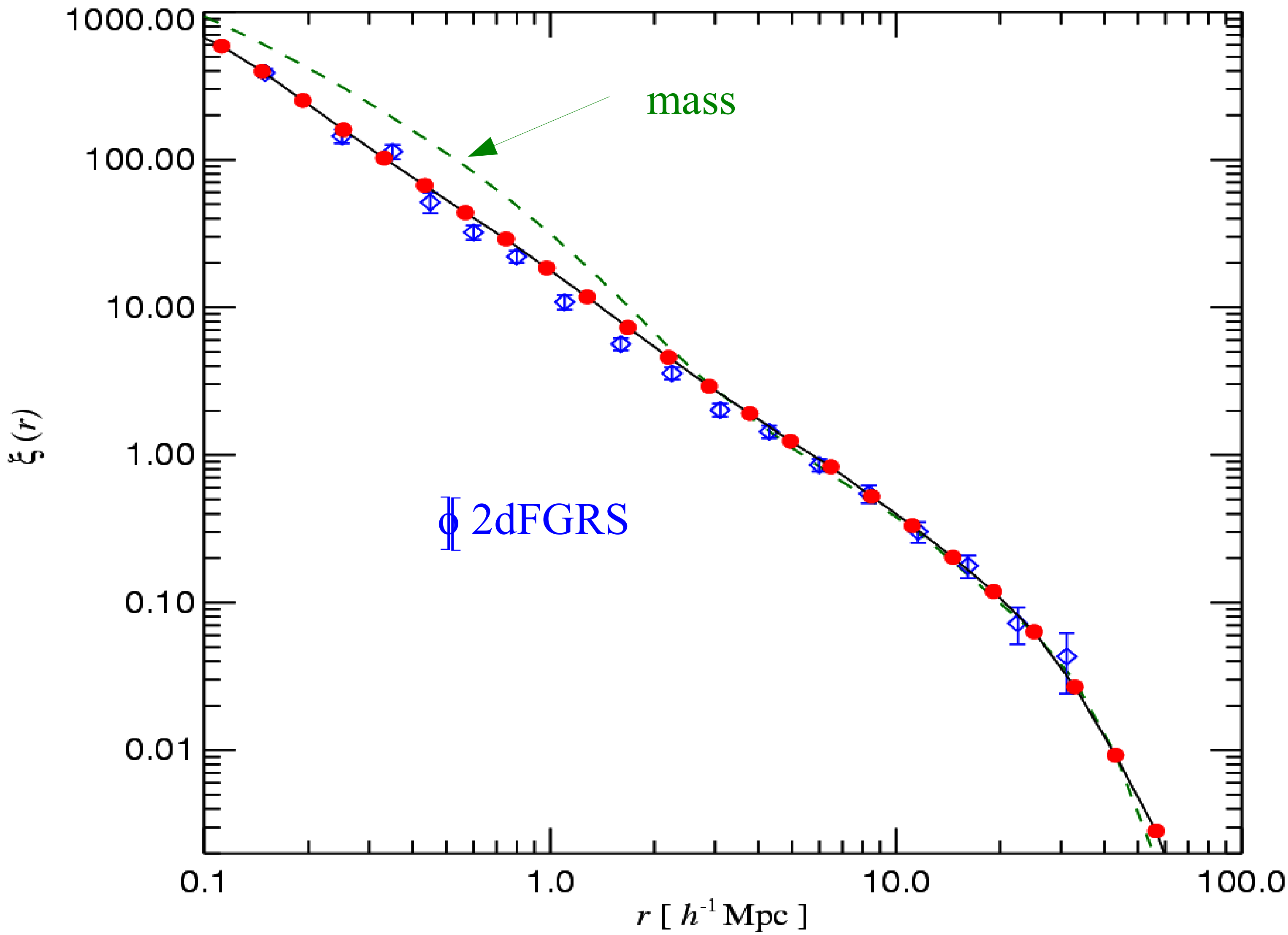

z = 0 Galaxy Light



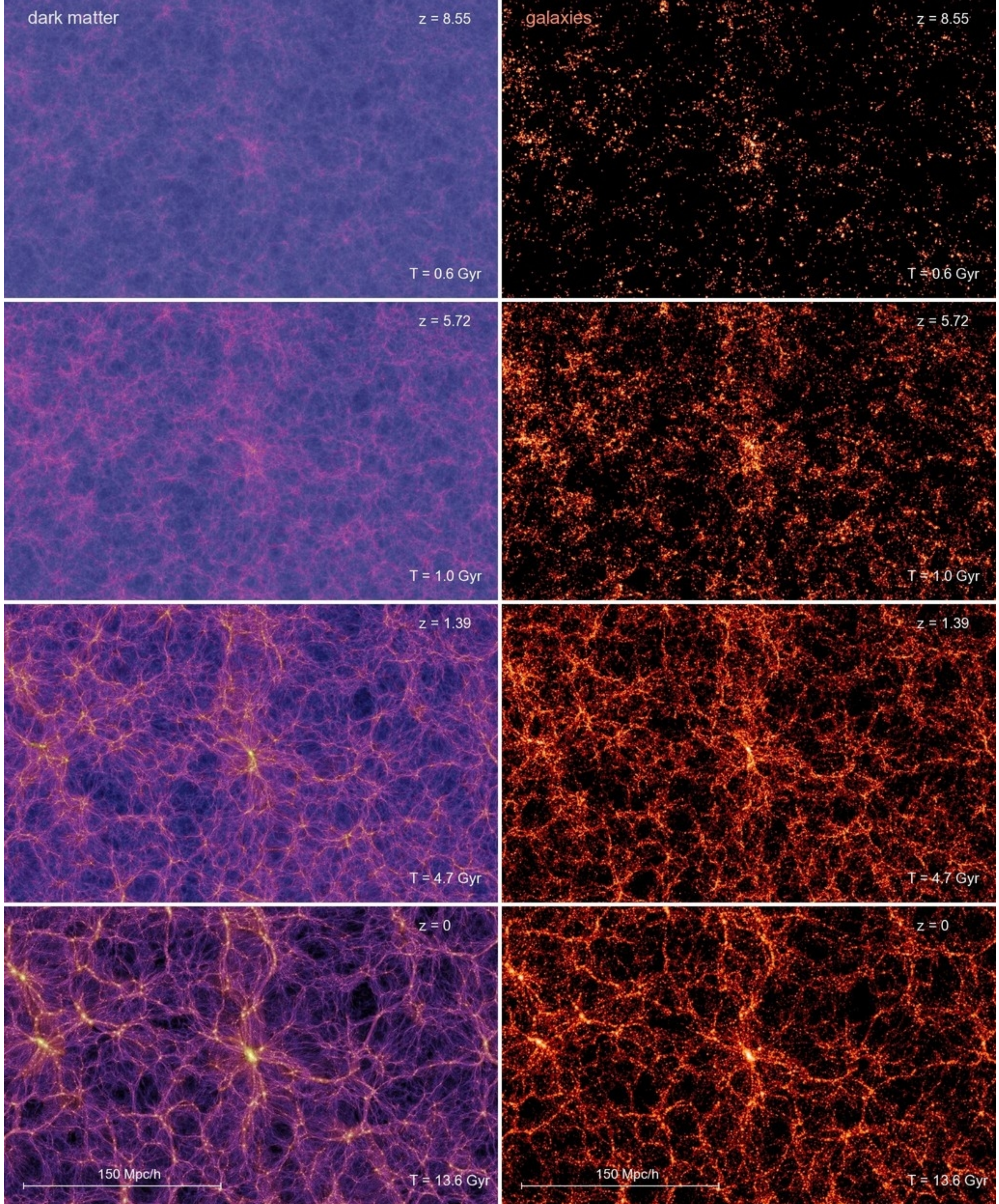
Springel, Frenk &
White 2006

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

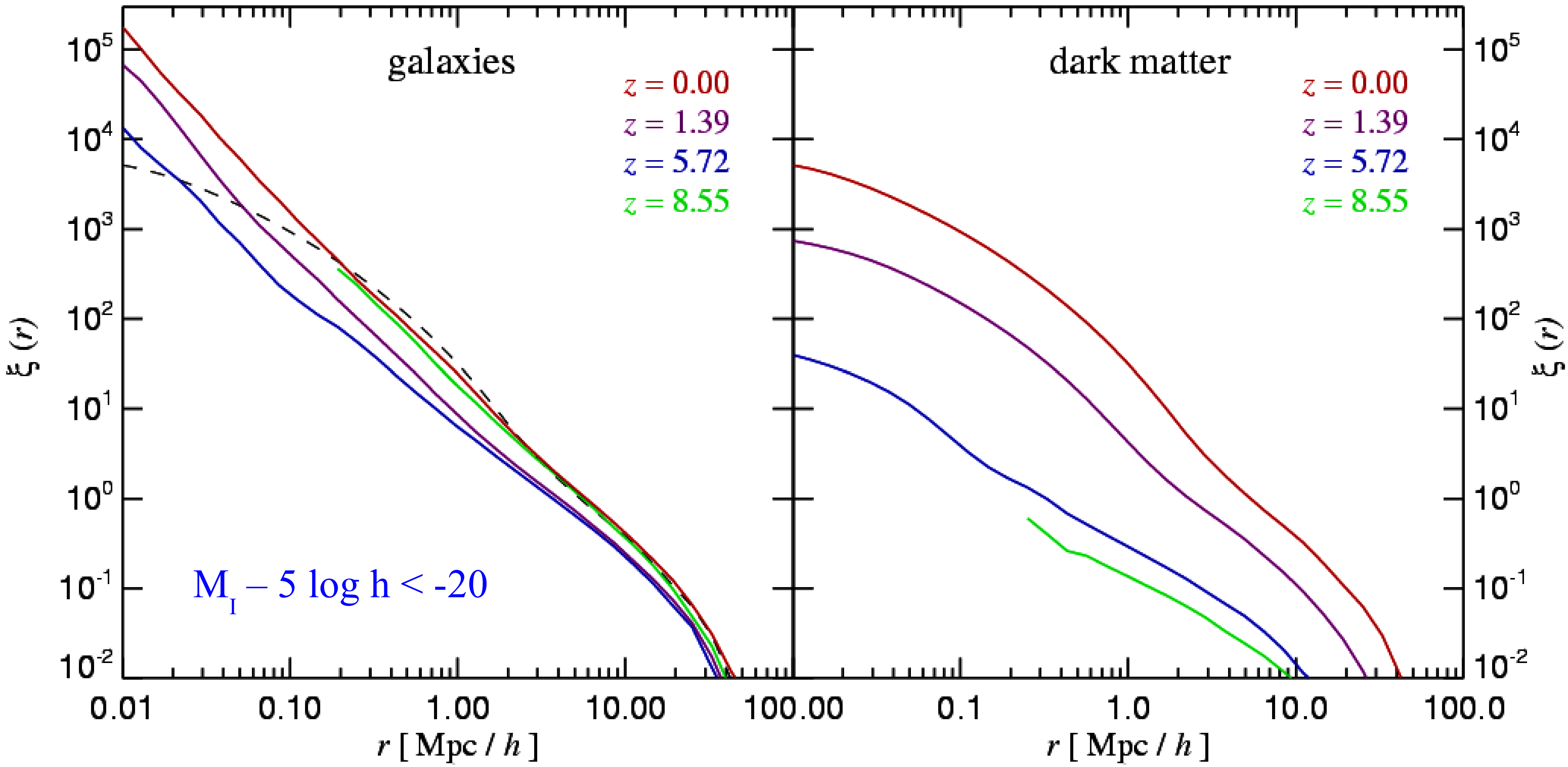
Springel, Frenk & White 2006

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

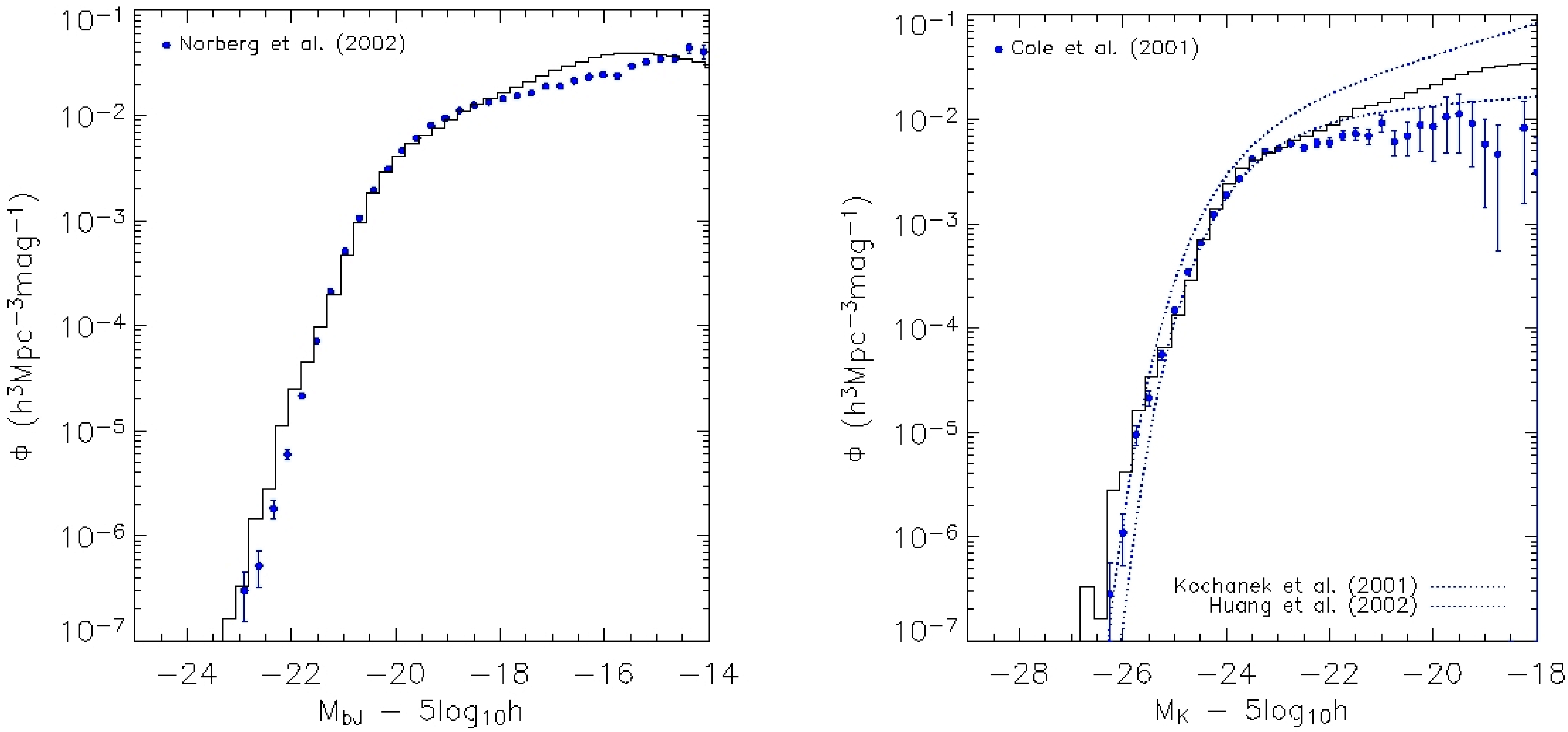
It is as strong at z=8.5 as at z=0

Evolution of mass and galaxy correlations

Springel, Frenk & White 2006

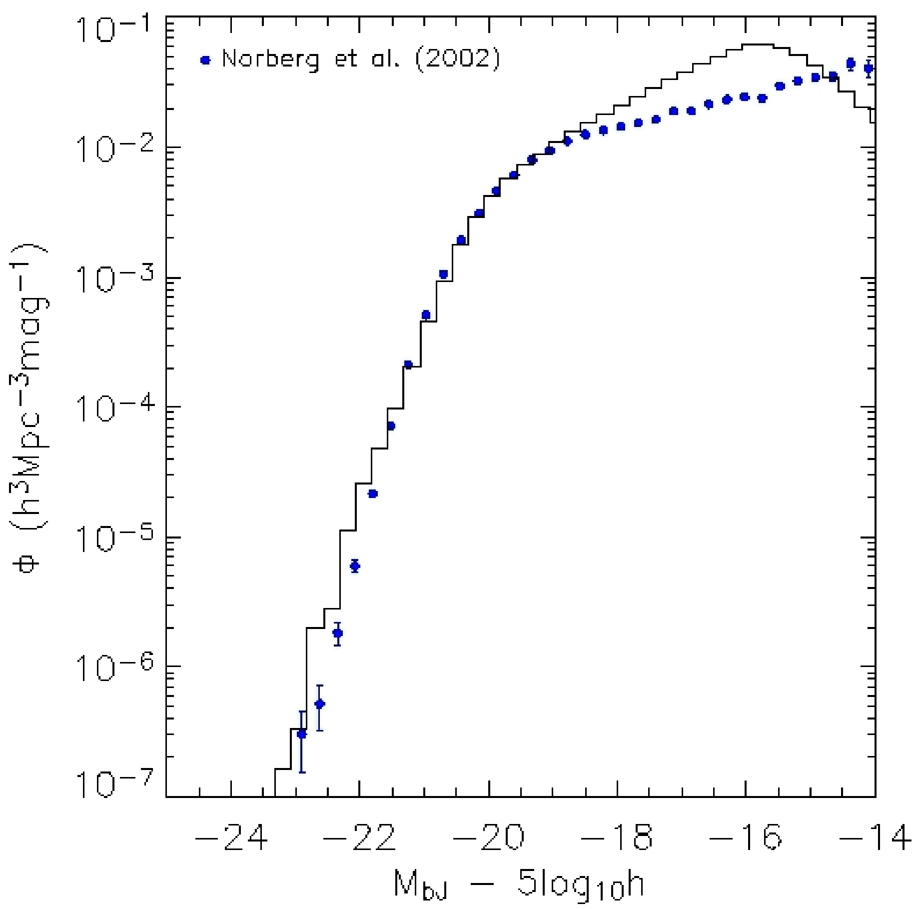


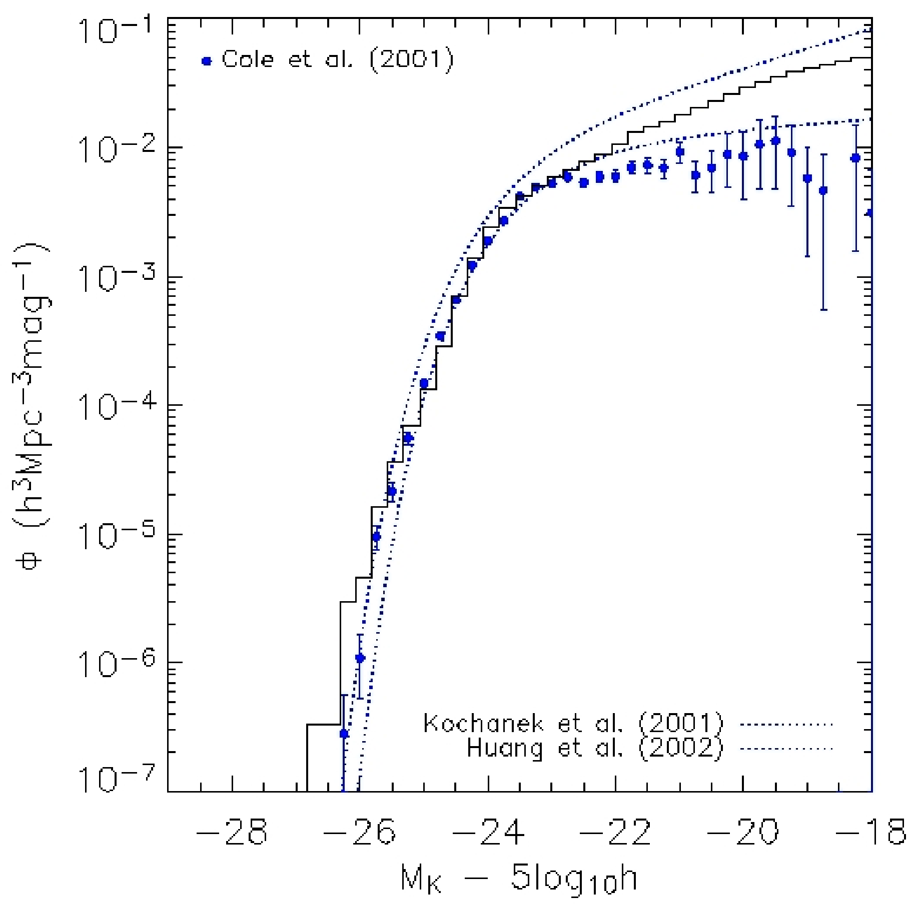
Effect of feedback on the Luminosity Function



Full model with reionisation, AGN and SN feedback Croton et al 2006

Effect of feedback on the Luminosity Function





Full model with ~~reionisation~~, AGN and SN feedback   Croton et al 2006

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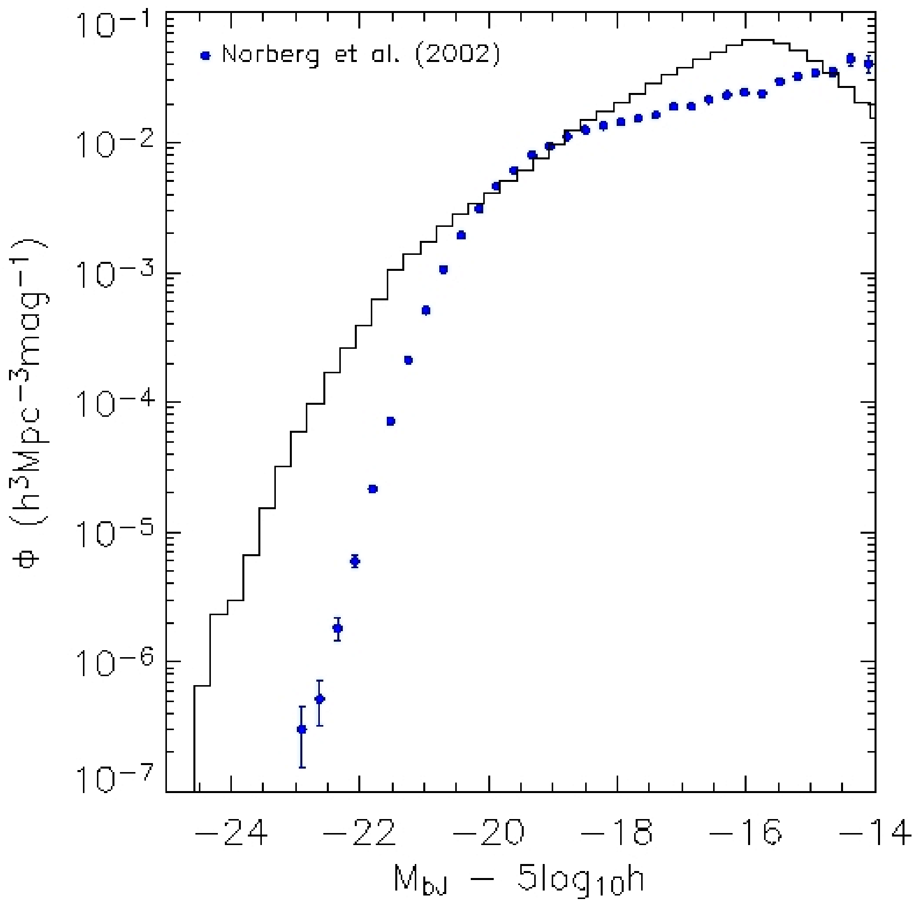
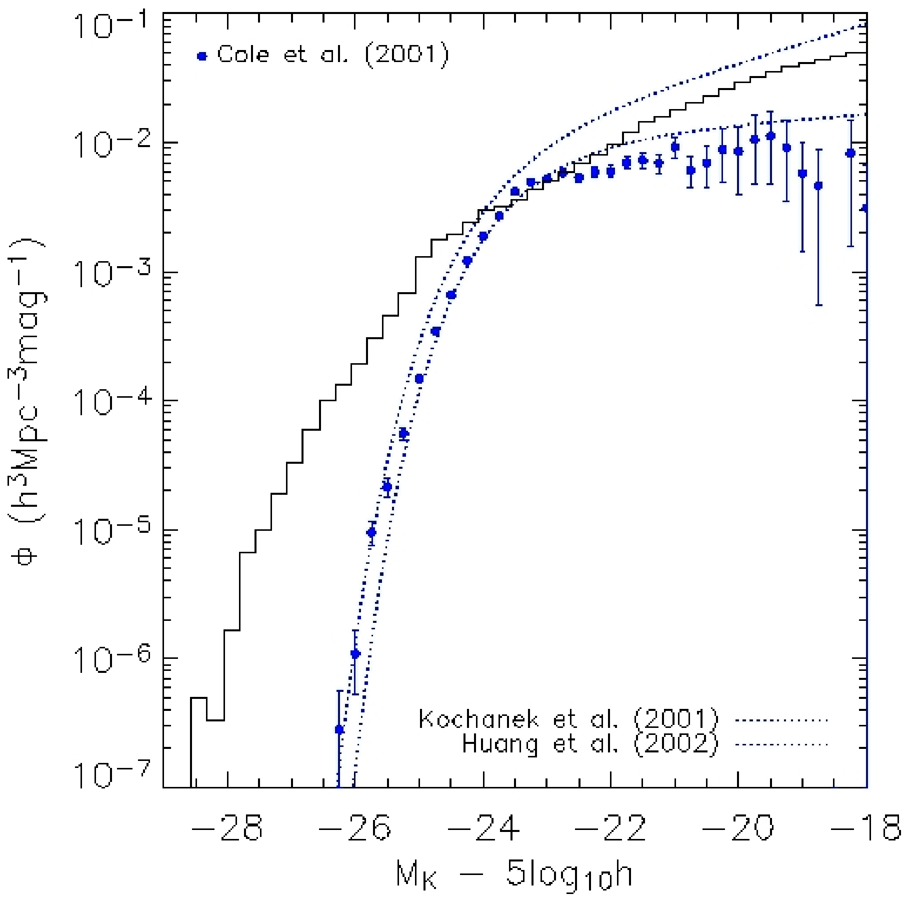
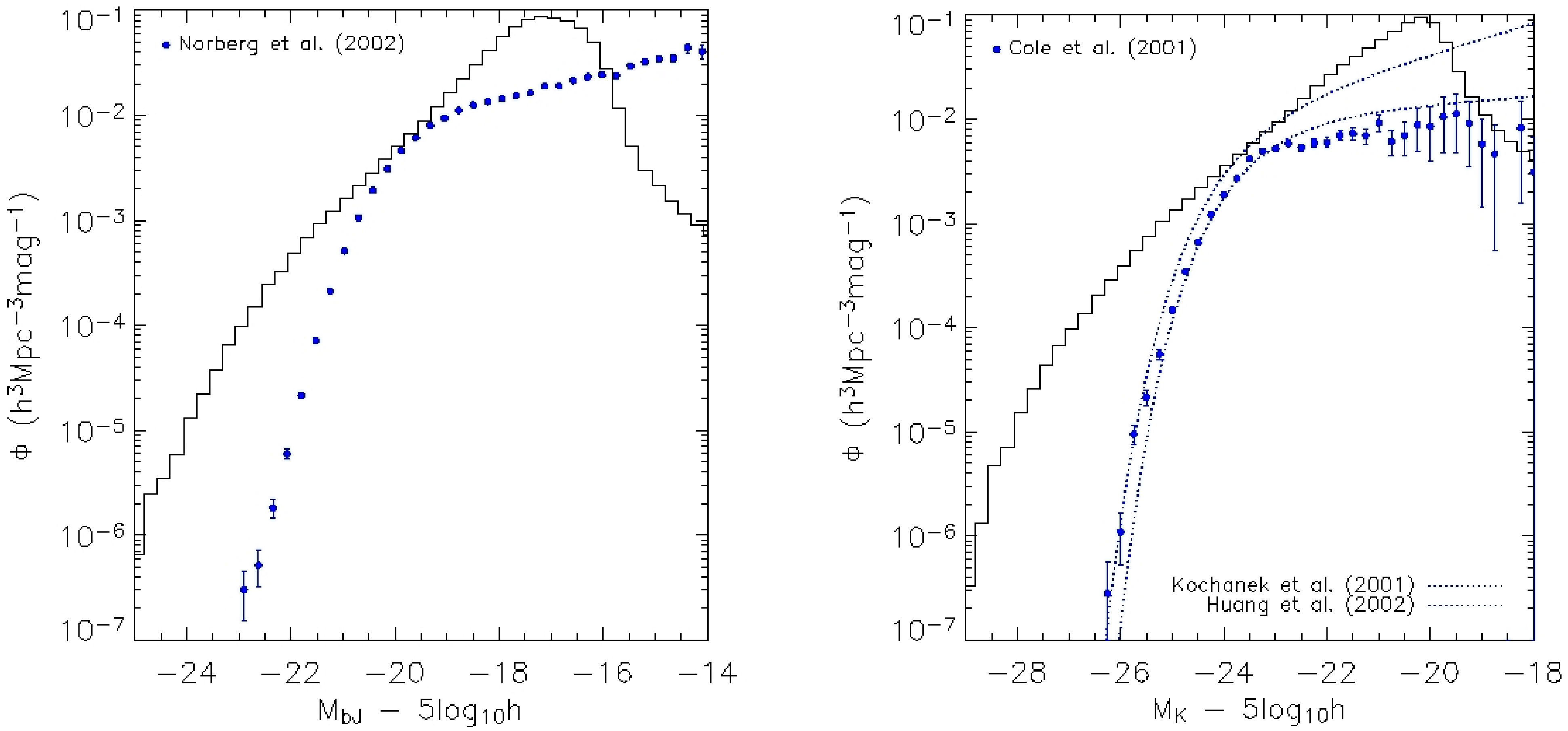




Full model with ~~reionisation~~, ~~AGN~~ and SN feedback   Croton et al 2006

Effect of feedback on the Luminosity Function



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Croton et al 2006

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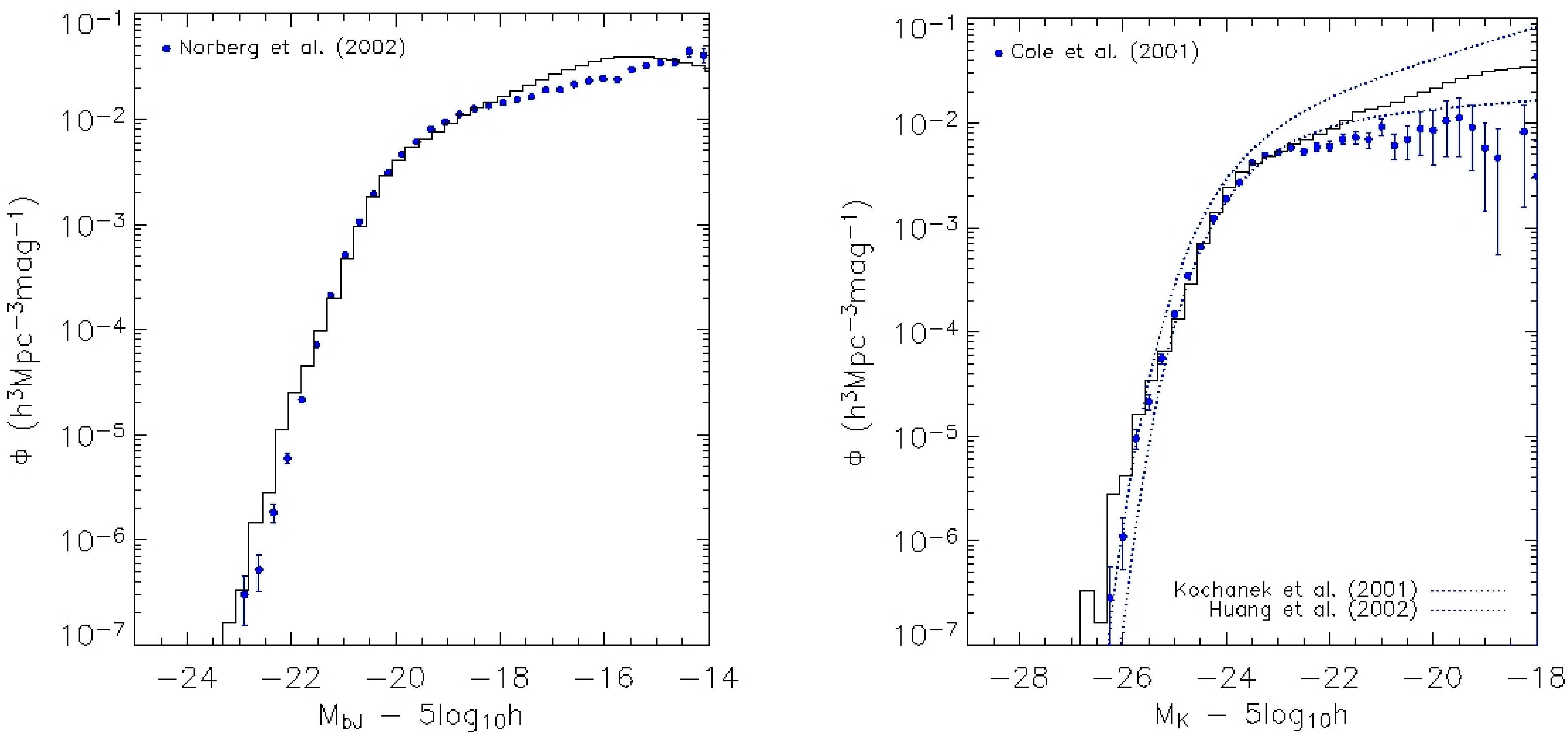

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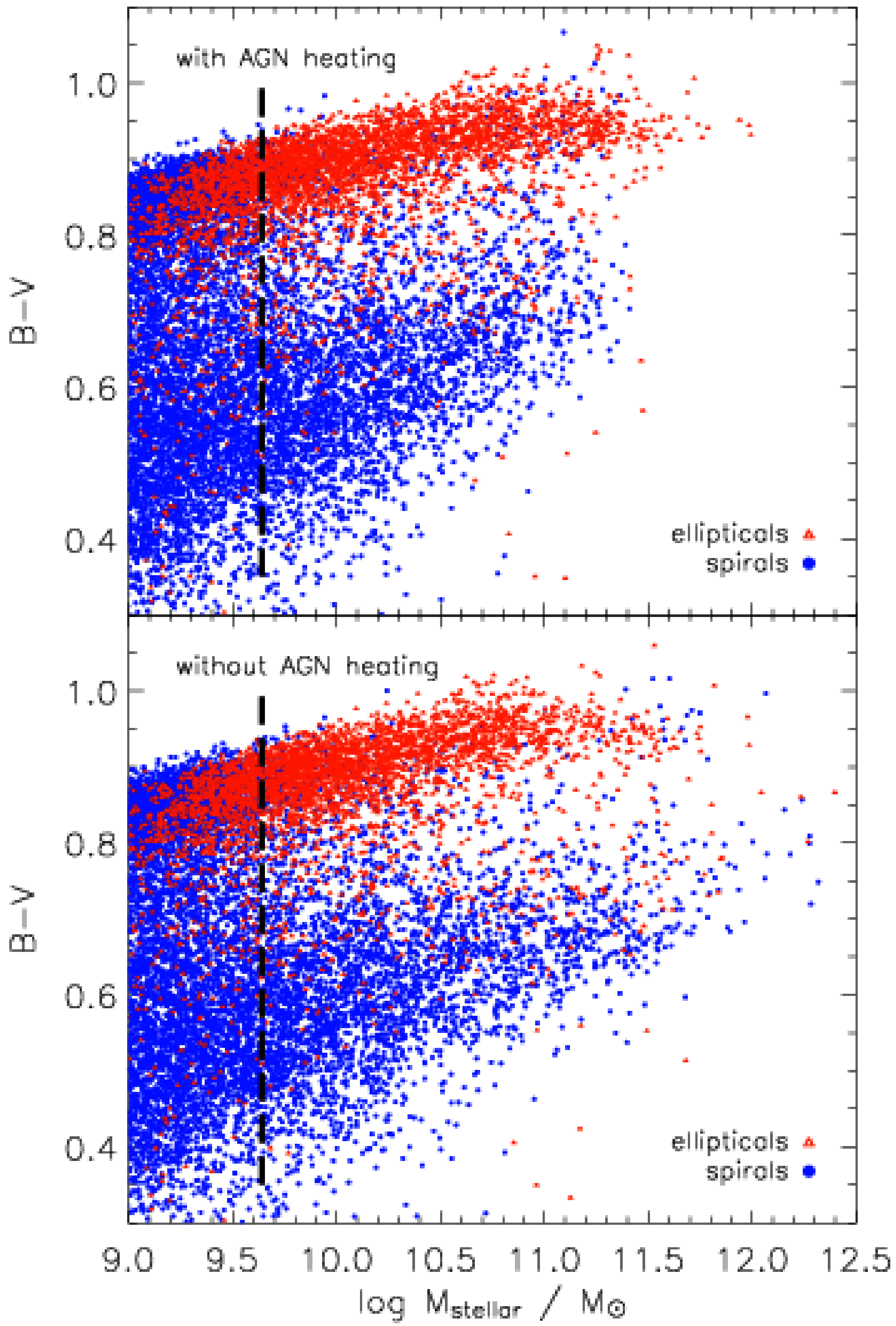


The effects of "radio mode" feedback on z=0 galaxies

Croton et al 2006

- In the absence of a "cure" for the cooling flow problem, the most massive galaxies are:
  - too bright
  - too blue
  - disk-dominated
- With cooling flows suppressed by "radio AGN" these galaxies are
  - less massive
  - red
  - elliptical

Issues for public release of Millennium data

- Data Volume
  - Raw data ---- 64 snapshots ---- 20 Tbytes
  - Halo data ---- 7.5 10^8 halos/subhalos ---- 300 Gbyte database
  - Galaxy data ---- 10^9 galaxies ---- 1 Tbyte database *per model*
- Complexity of data relations
  - Spatial relations ---- real space, redshift space....
  - Temporal relations ---- many to one forwards in time
  - Variety of attributes ---- M_*, age, L, B-V, B/T, V_{rot}
  - Linking data of different type -- (sub)halos — galaxies
    - halos/galaxies — mass
    - galaxies — shear field
    - lightcone — snapshot
- Ease of use for non-specialists
  - Good documentation
  - Widely known, 'simple' and powerful search engine

GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

Exploring the milli-Millennium simulation with a relational database

Documentation


```
select D.I_HALO,
       D.SNAPNUM,
       D.N_P as D_NP,
       P1.N_P as P1_NP,
       P2.N_P as P2_NP
  from HALO P1,
       HALO P2,
       HALO D
 where P1.SNAPNUM=P2.SNAPNUM
   and P1.I_HALO < P2.I_HALO
   and P1.I_DESCENDANT = D.I_HALO
   and P2.I_DESCENDANT = D.I_HALO
   and P1.N_P >= .2*D.N_P
   and P2.N_P >= .2*D.N_P
   and D.N_P > 1000
```

Execute Query | Clear all | Help

Maximum number of rows to return to the query form: 10

Previous queries :

Halo 1 | Galaxy 1 — Find halos/galaxies at a given redshift (SNAPNUM) within a certain part of the simulation volume (X,Y,Z).

Halo 2 — Find the whole progenitor tree, in depth-first order, of a halo identified by its id (I_HALO)

Halo 3 — Find the progenitors at a given redshift (SNAPNUM) of all halos of mass (N_P) greater than 4000 at a later redshift (SNAPNUM). The progenitors are limited to have mass >= 100.

Halo 4 — Find all the halos of mass (N_P) >= 1000 that have just had a major merger, defined by having at least two progenitors of mass >= 0.2*descendant mass.

Halo 5 | Galaxy 5 — Find the mass/luminosity function of halos/galaxies at z=0 using logarithmic intervals.

Galaxy 6 — Find the Tully-Fisher relation, Mag_b/v/i/k vs V_vir for galaxies with bulge/total mass ratio < 0.1. Subsample by about 1% (RANDOM between 20000 and 30000).

Reformat | CSV

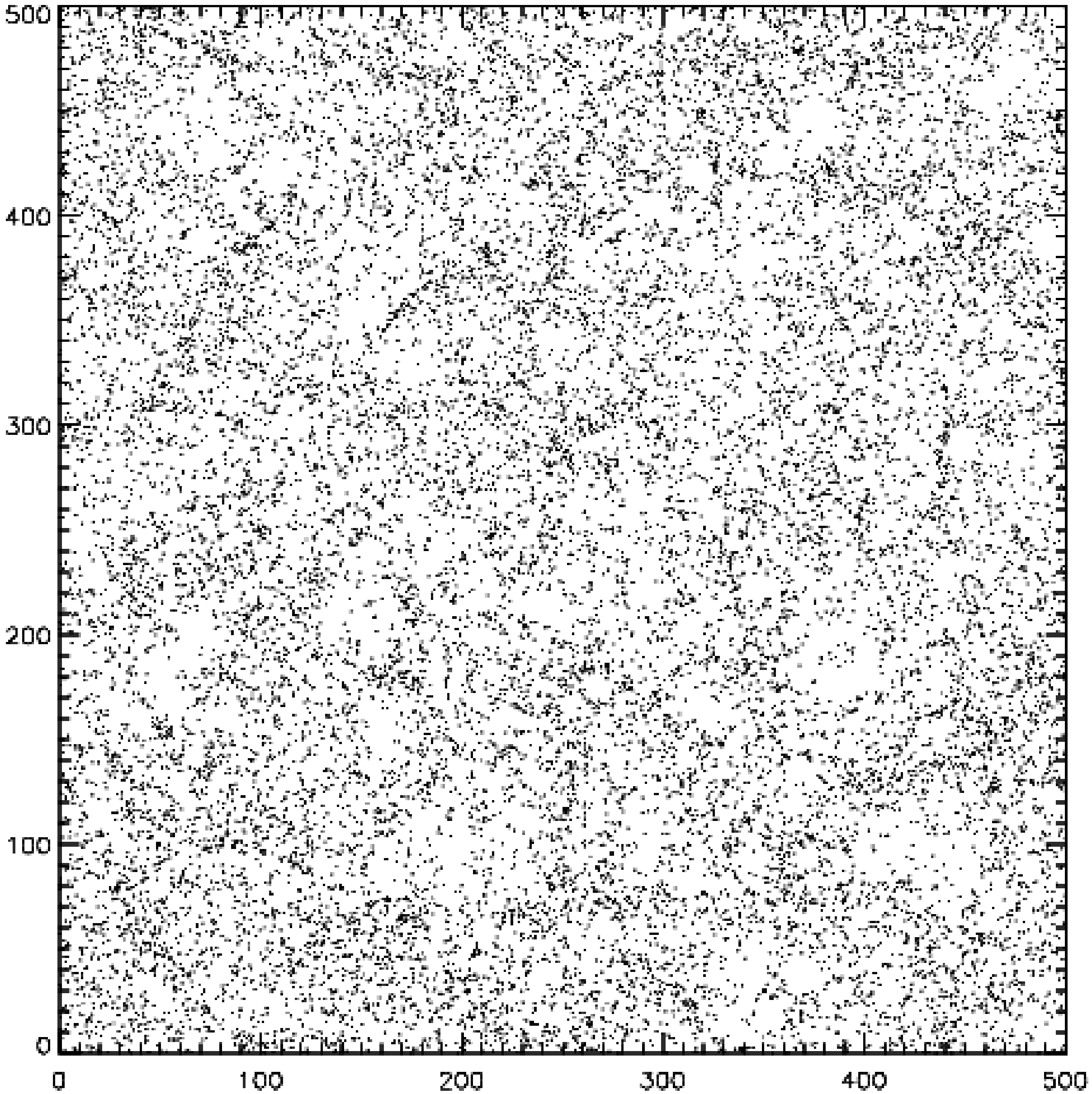
Plot (VOPlot) — This button wil attempt to start up VOPlot within an applet, so that the current result can be explored graphically. This clearly requires that the browser has been configured for viewing applets.
DISCLAIMER This functionality has been partially tested only. Any problems are our responsibility, not VOPlot's.
It seems that the applet does not work properly with Konqueror.

Query time (in millisec) = 15623
Number of rows retrieved from database = 12 (Maximum # = 10000)

i_halo	snapnum	d_np	p1_np	p2_np
2576	60	1079	924	222

http://www.mpa-garching.mpg.de/Millennium

Does halo clustering depend on formation history?



Gao, Springel & White 2005

The 20% of halos with the *lowest* formation redshifts in a 30 Mpc/h thick slice

$$M_{halo} \sim 10^{11} M_\odot$$

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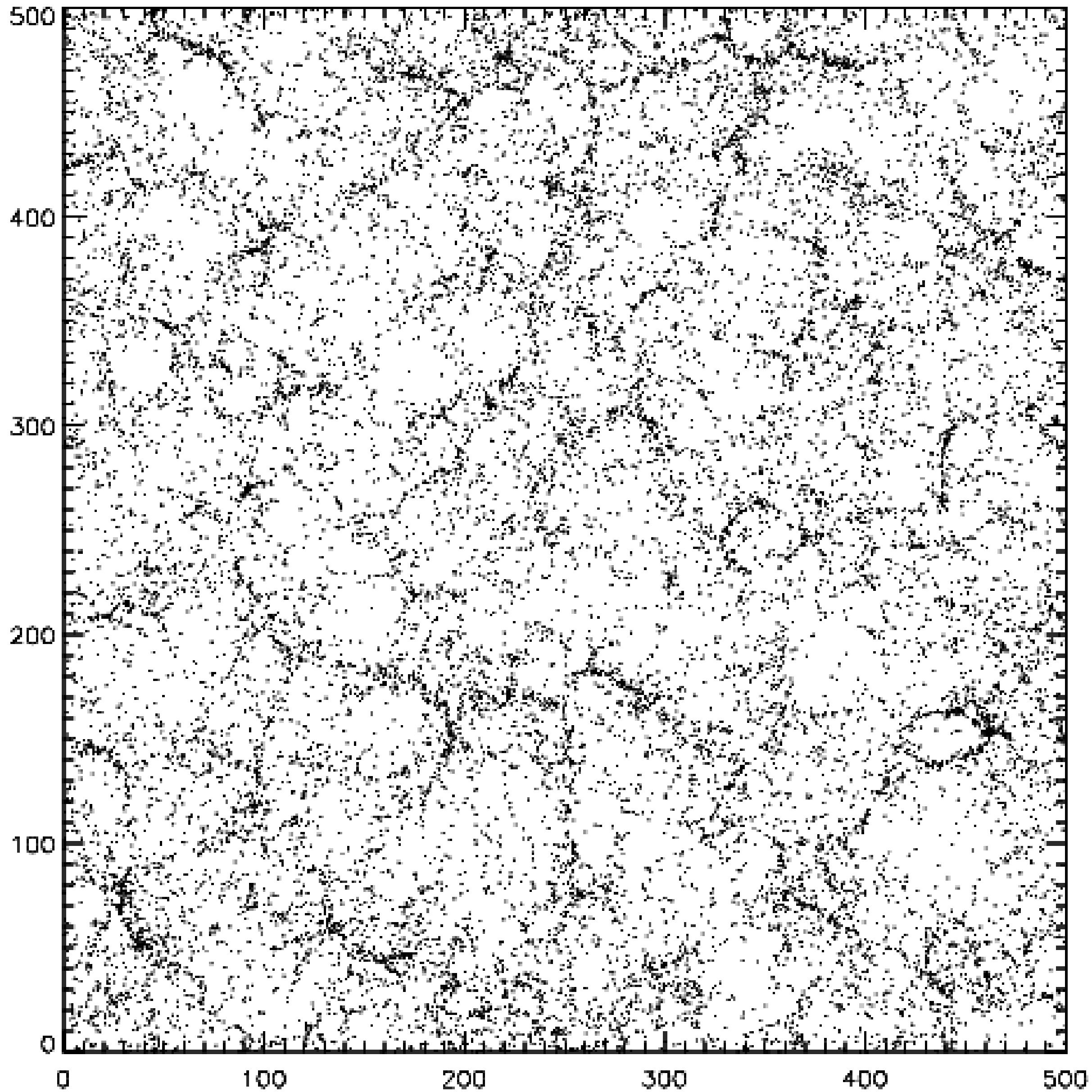

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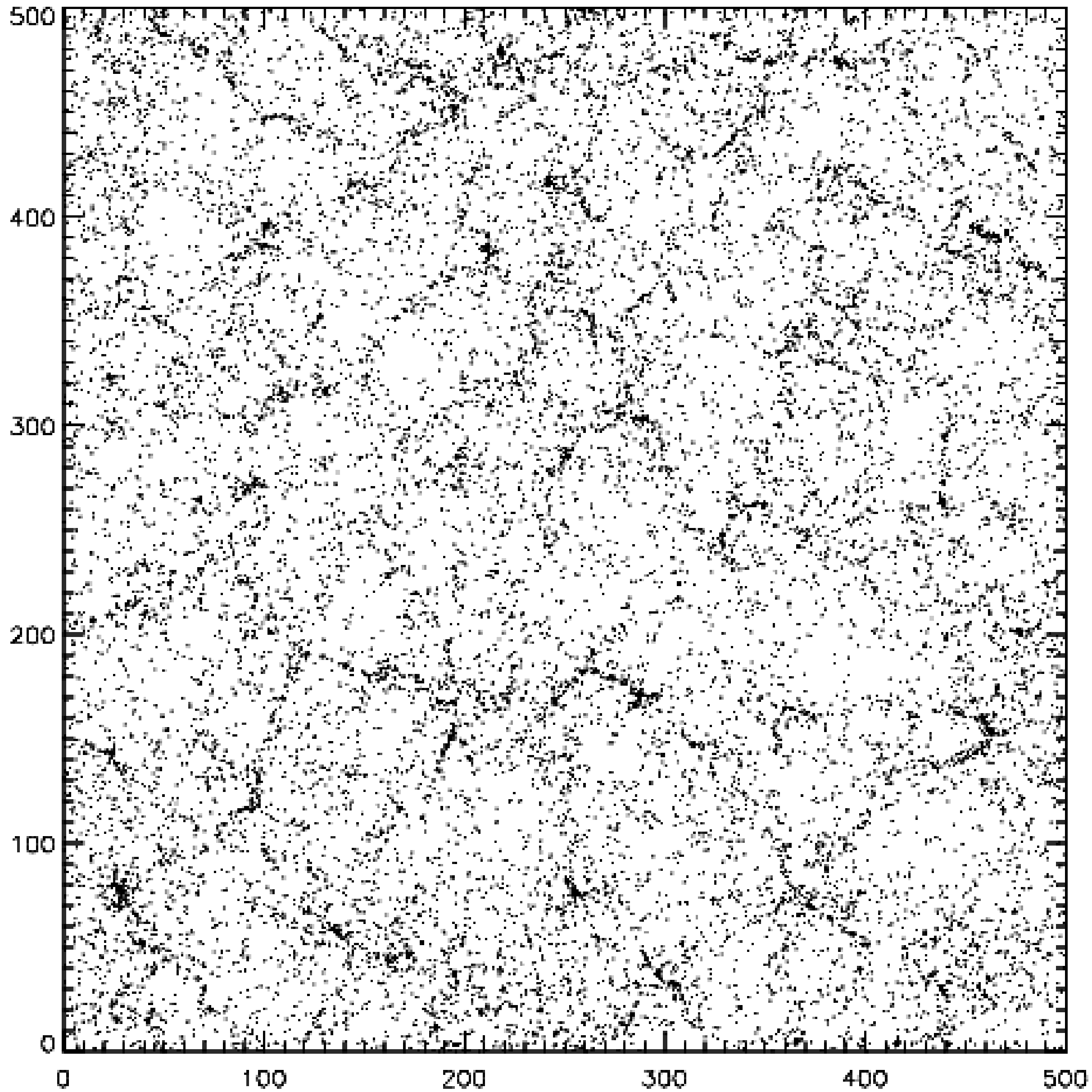
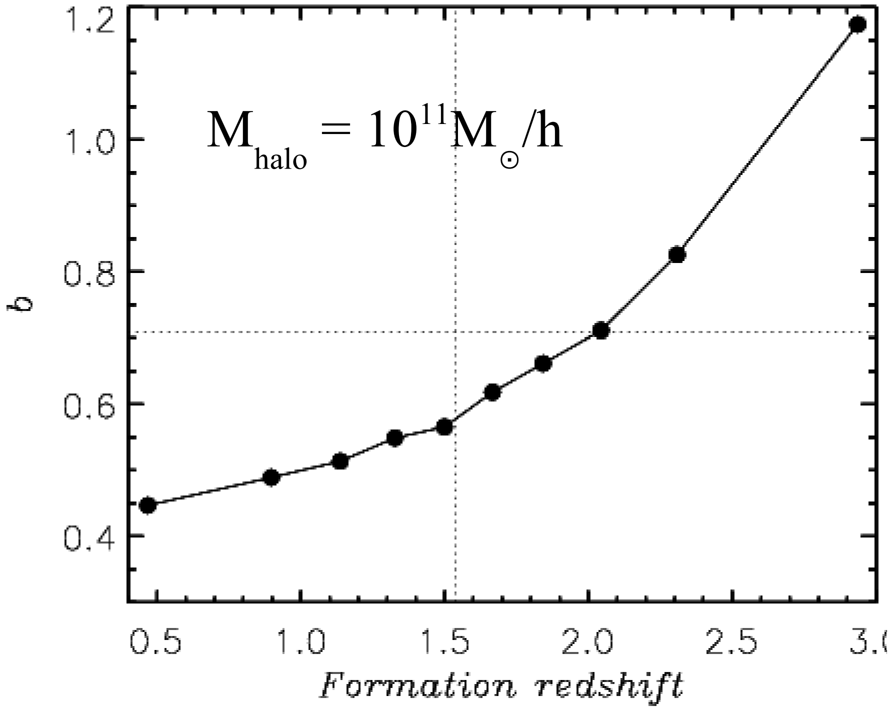


Gao, Springel & White 2005

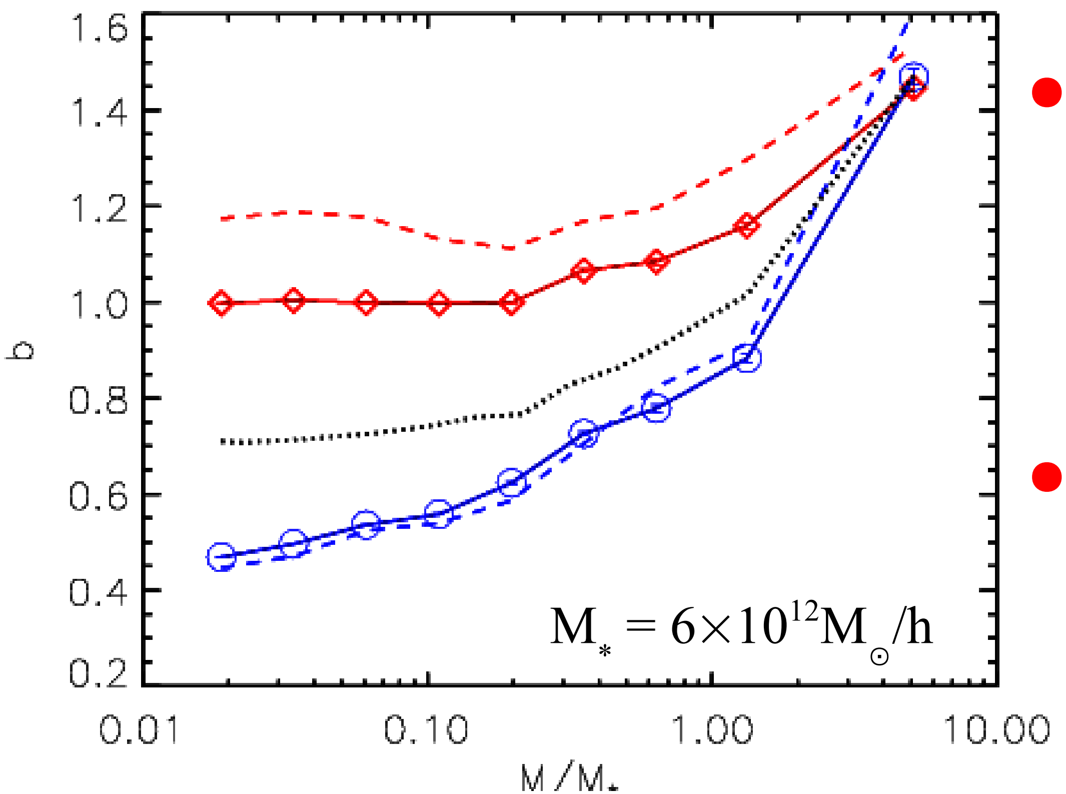
An equal number of randomly chosen DM particles

Halo bias as a function of mass and formation time

Gao, Springel & White 2005



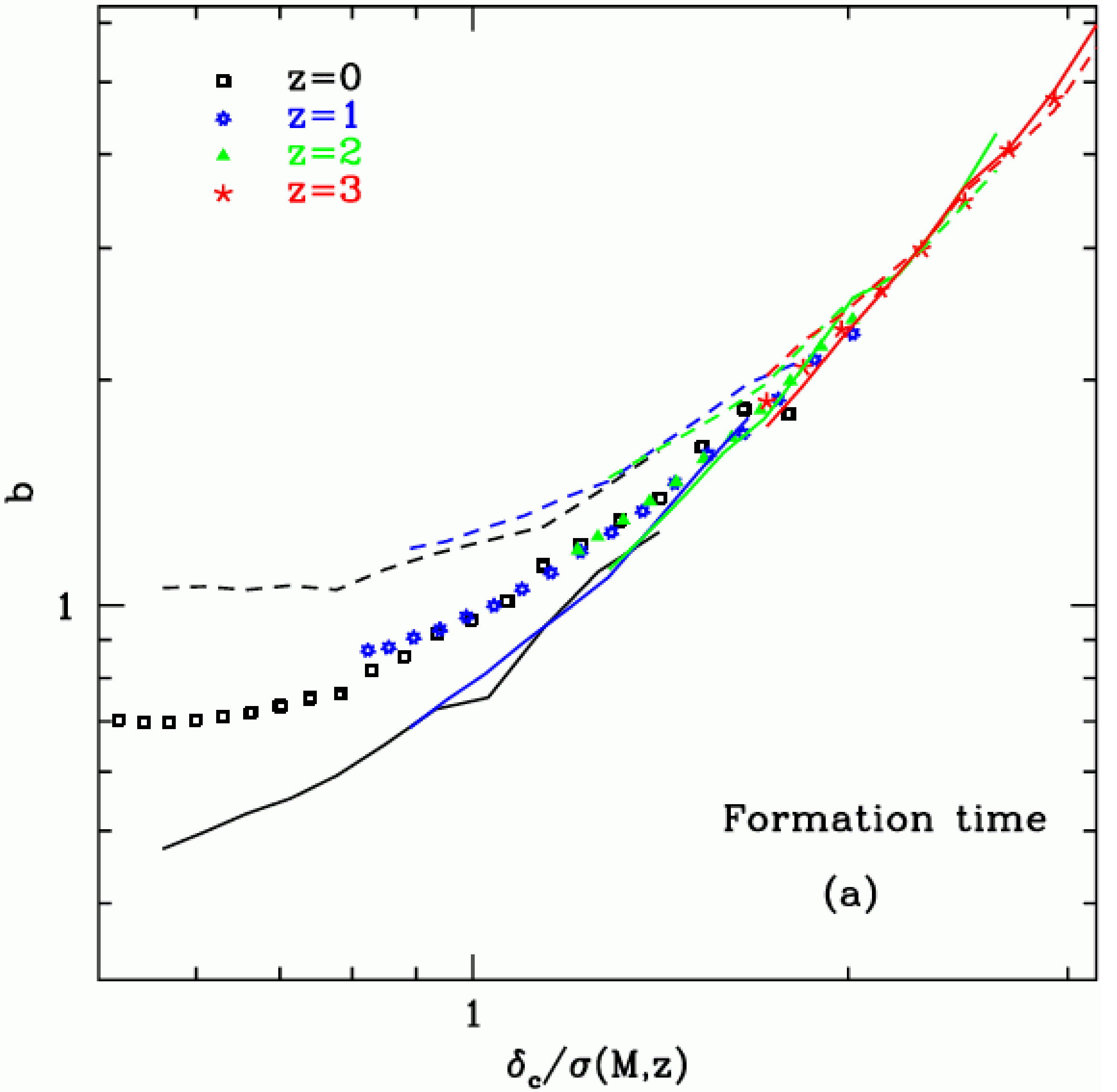
- Bias increases smoothly with formation redshift



- The dependence on formation redshift is strongest at low mass
- This dependence is consistent *neither* with excursion set theory *nor* with HOD models

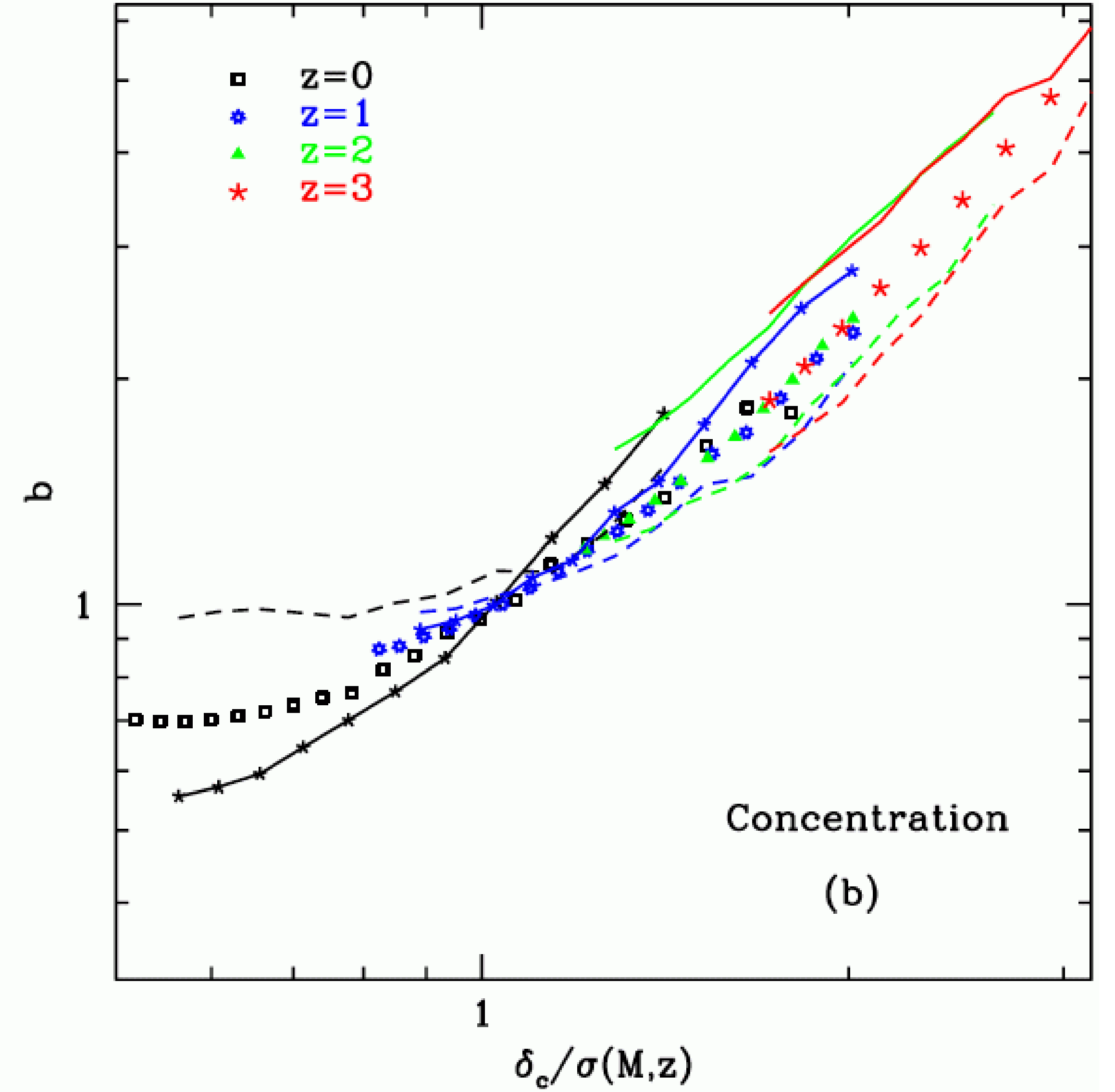
Halo bias as a function of mass and formation time

Gao & White 2006



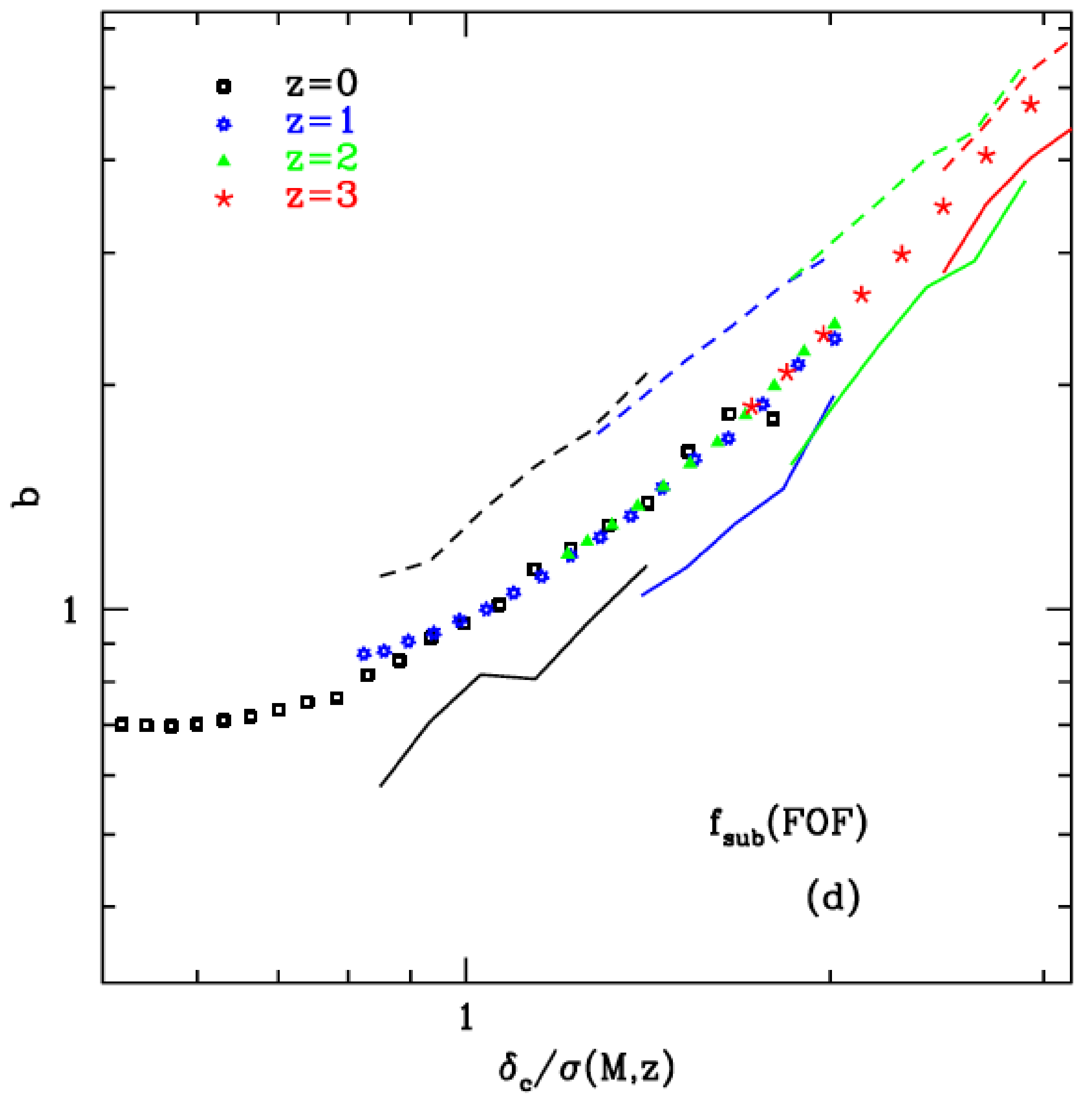
Halo bias as a function of mass and concentration

Gao & White 2006



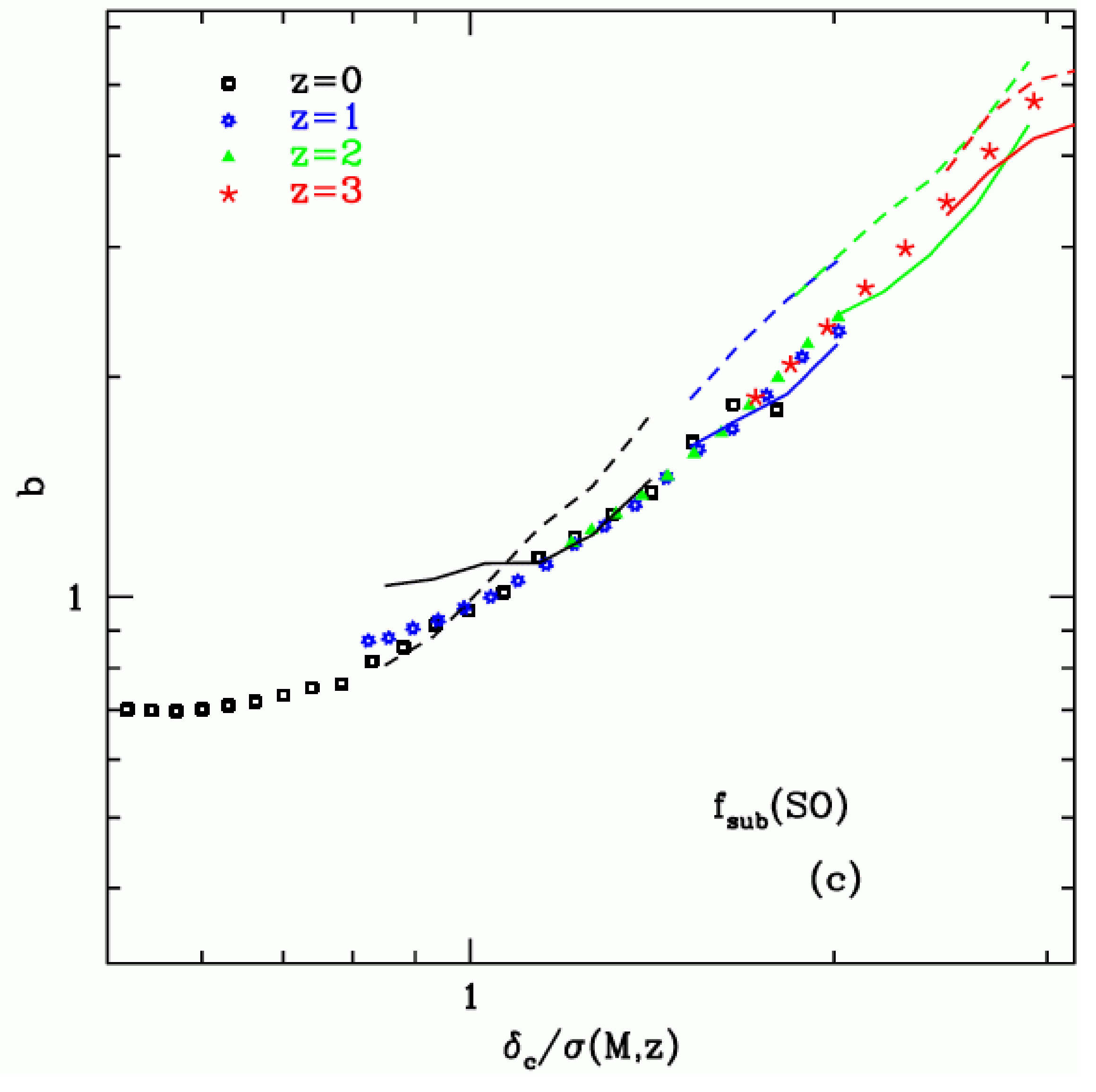
Halo bias as a function of mass and substructure

Gao & White 2006



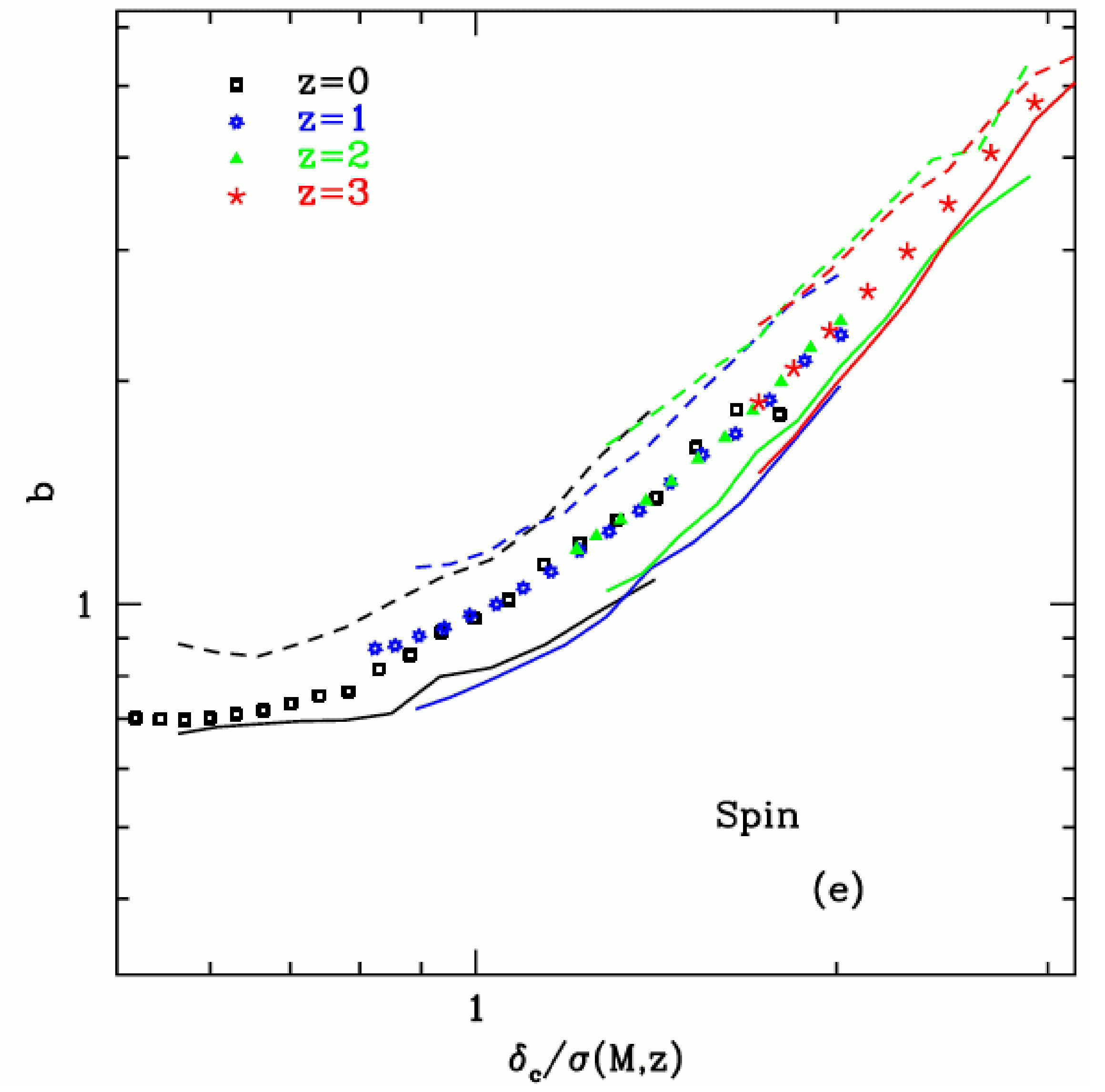
Halo bias as a function of mass and substructure

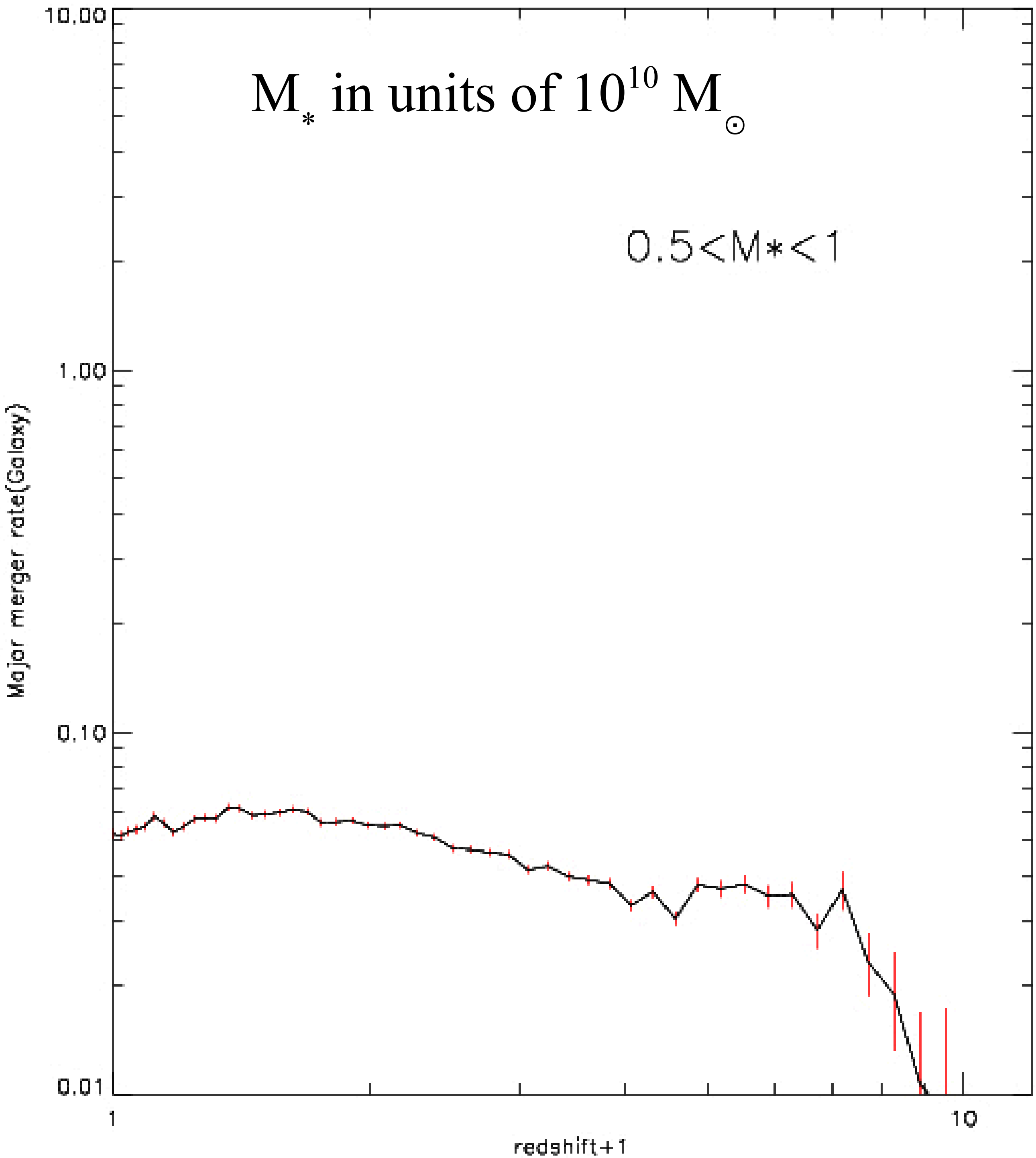
Gao & White 2006



Halo bias as a function of mass and spin

Gao & White 2006



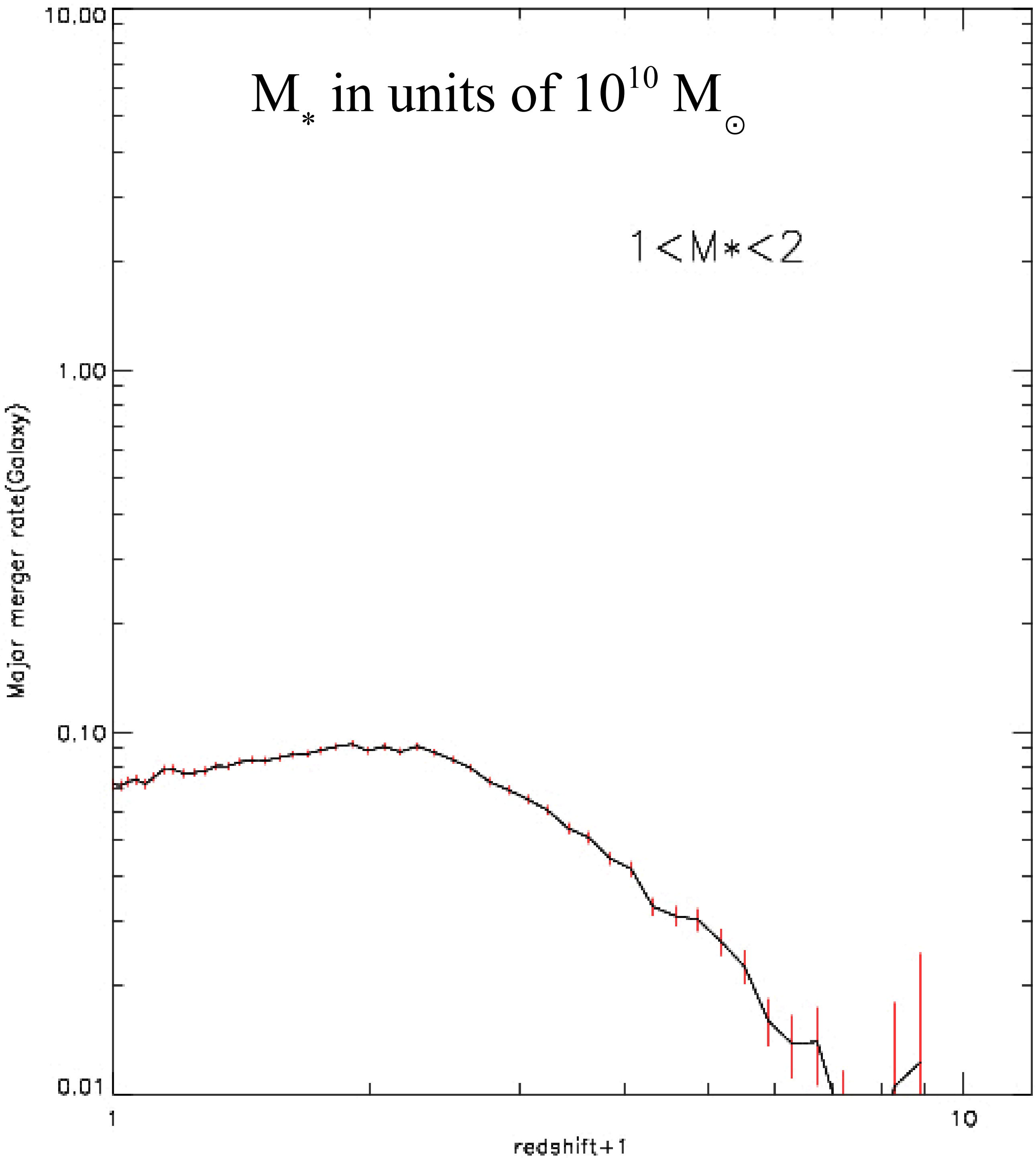


DIMENSIONLESS MAJOR MERGER RATES

Qi Guo & SW

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

where F is the fraction of galaxies that had a major merger ($M_{proj, 1} > M_{proj, 2} / 3$) in the last $\Delta t \sim 0.2$ Gyr



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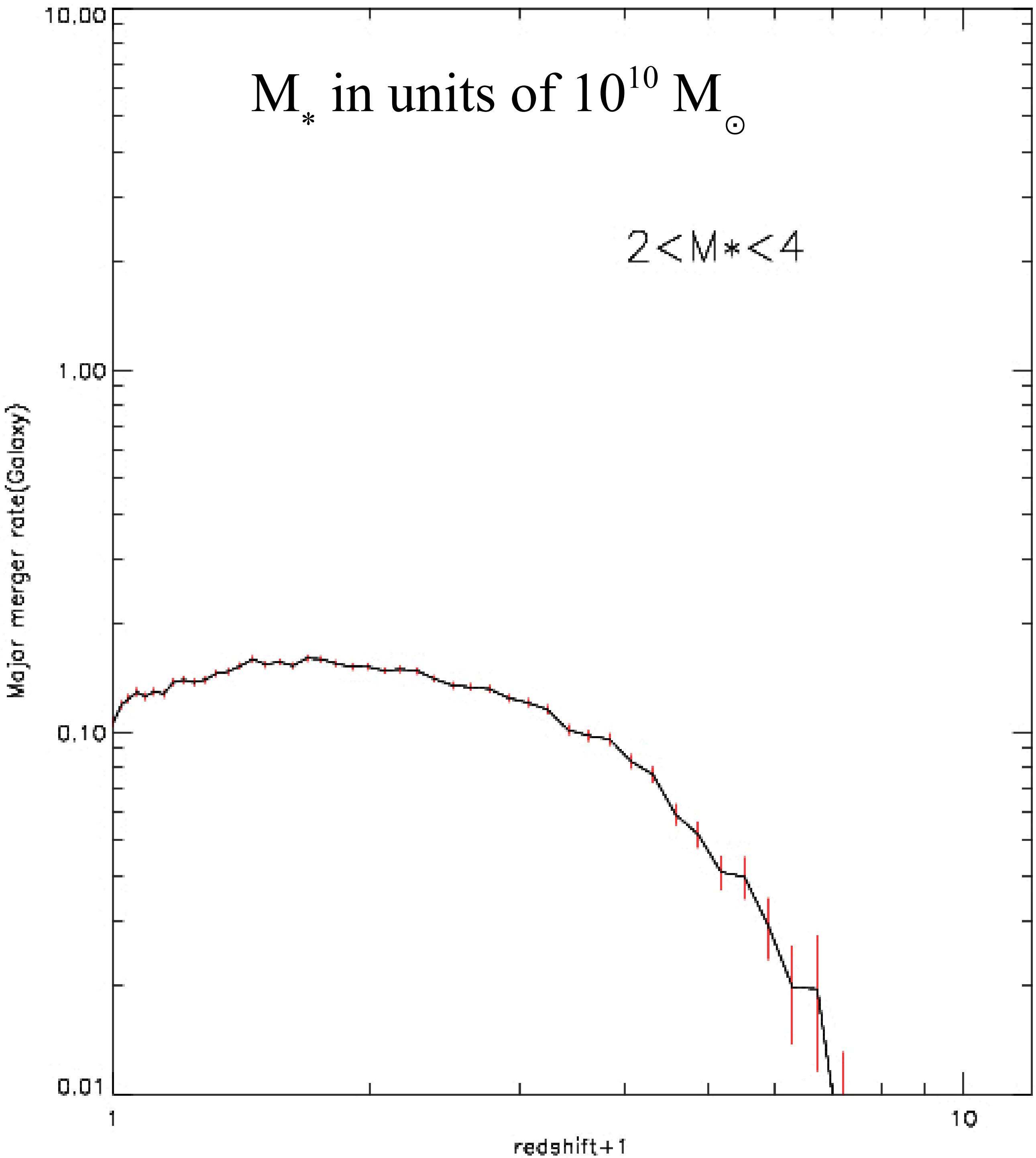

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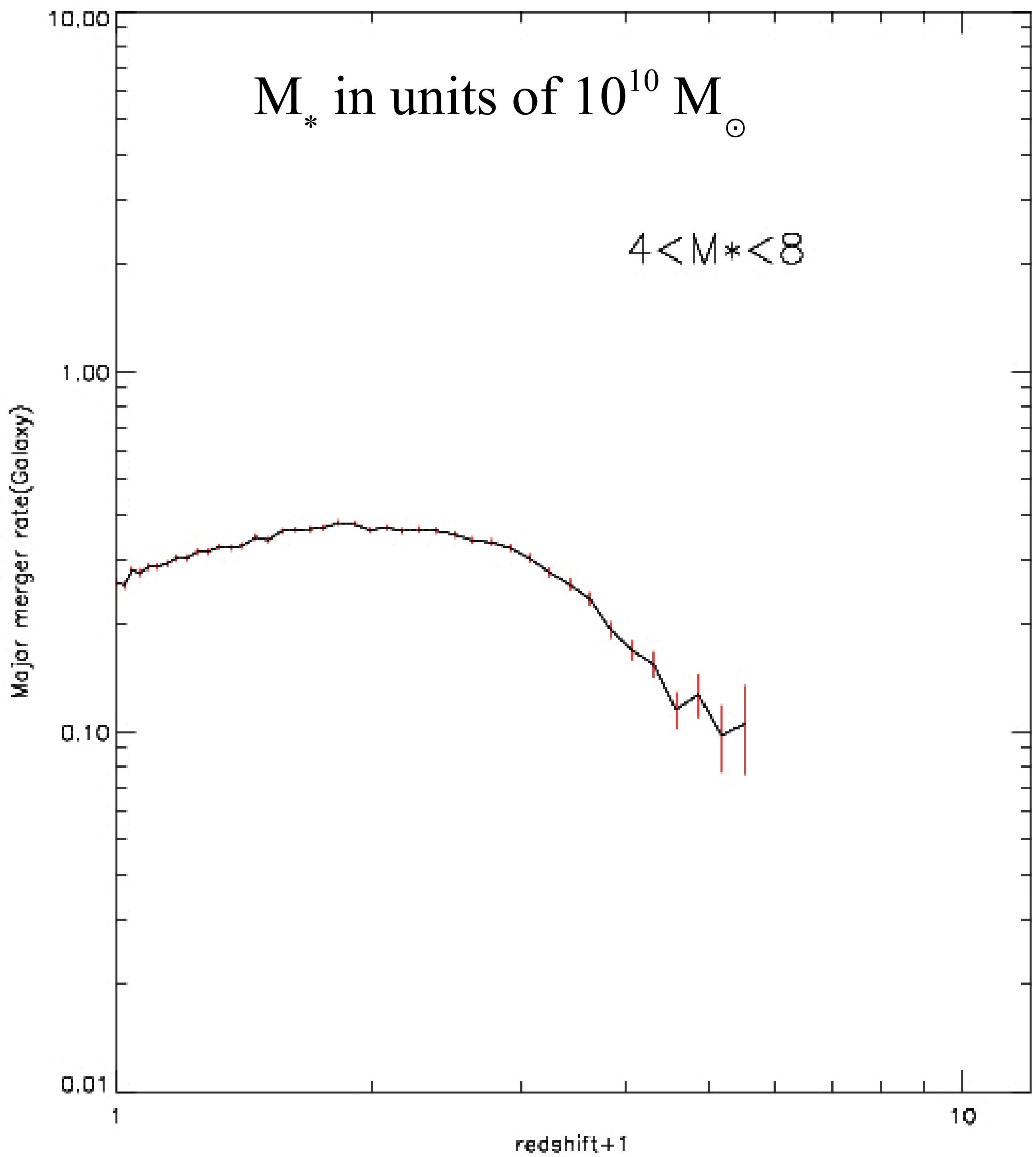

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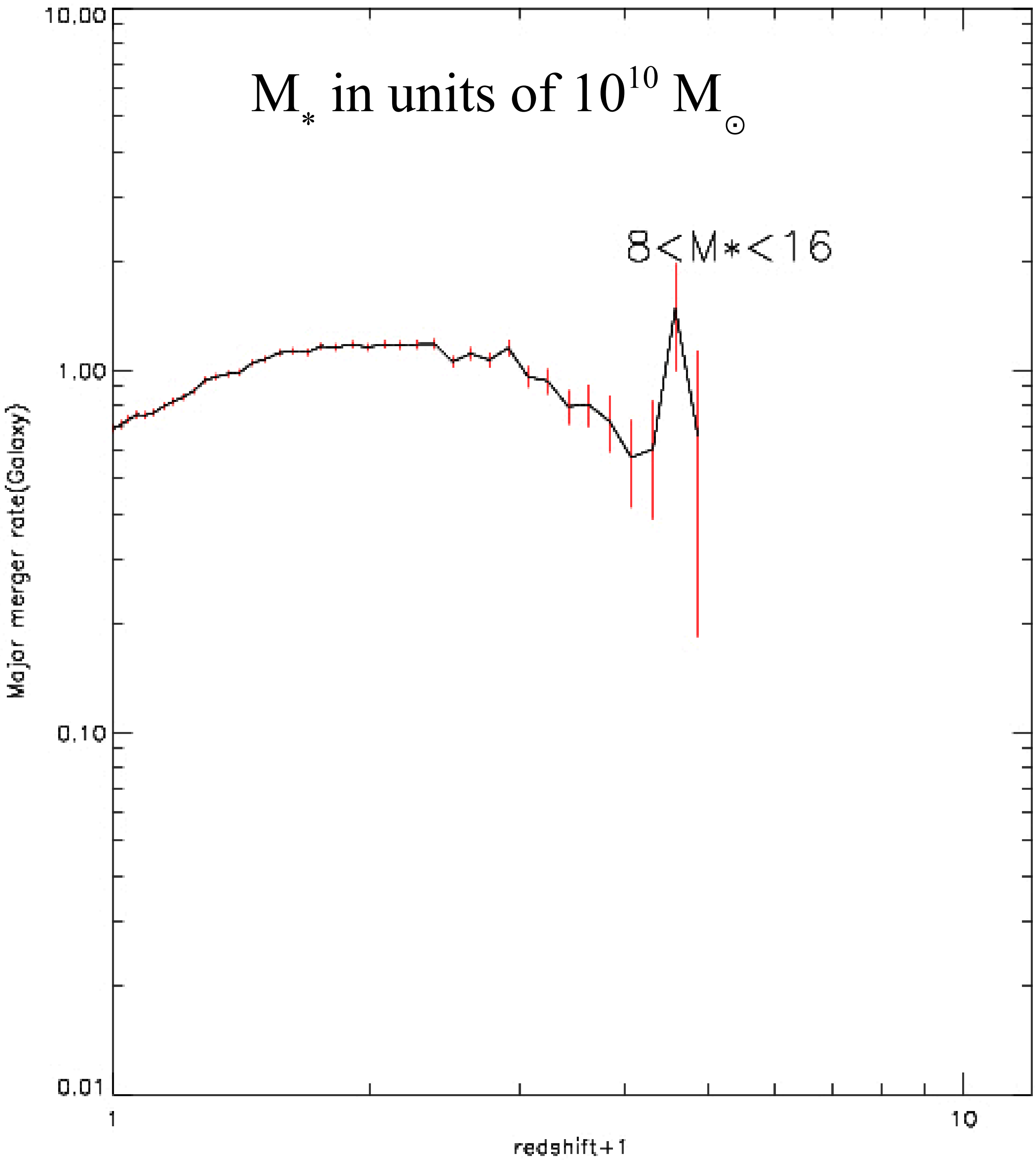

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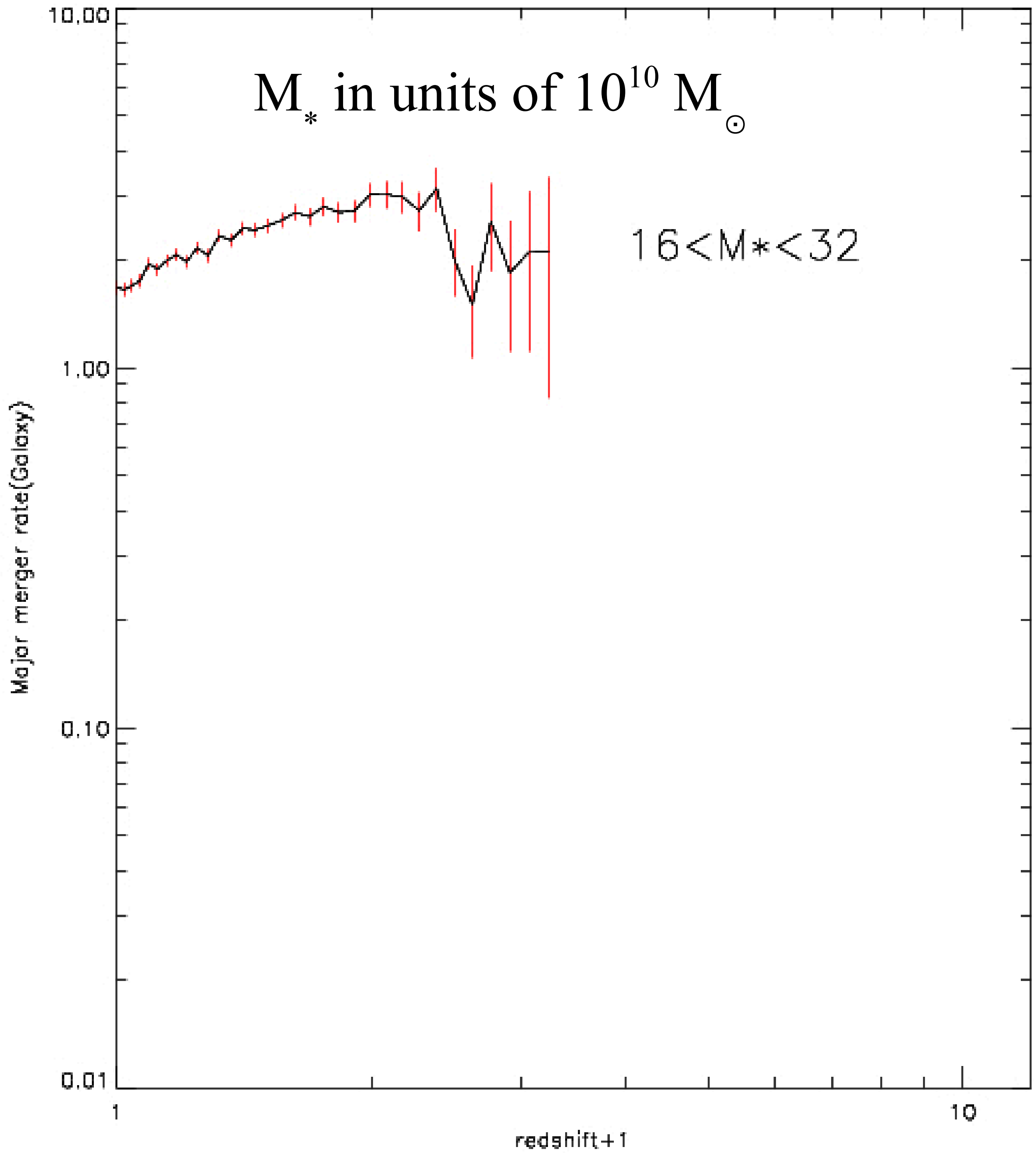

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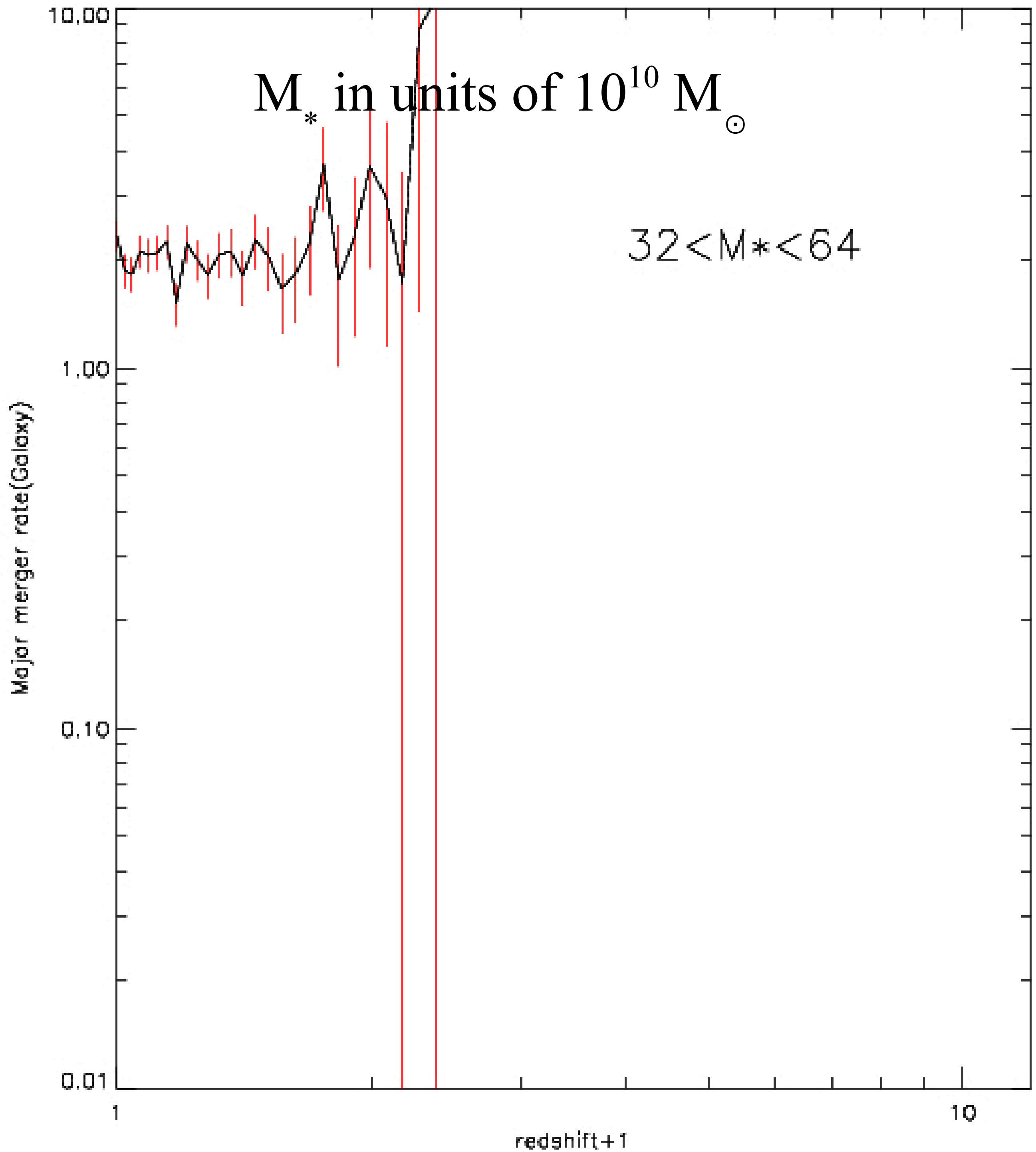

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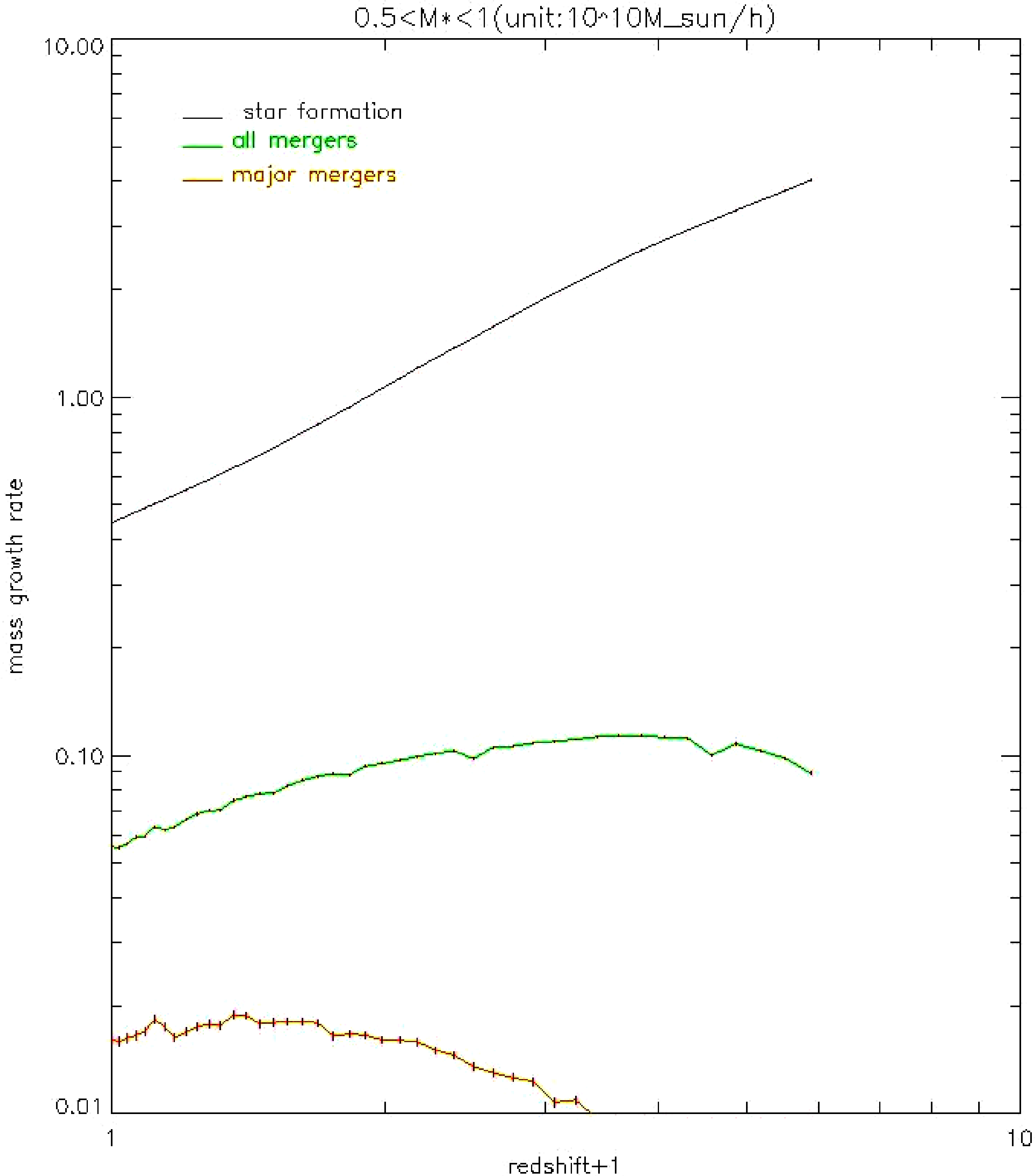


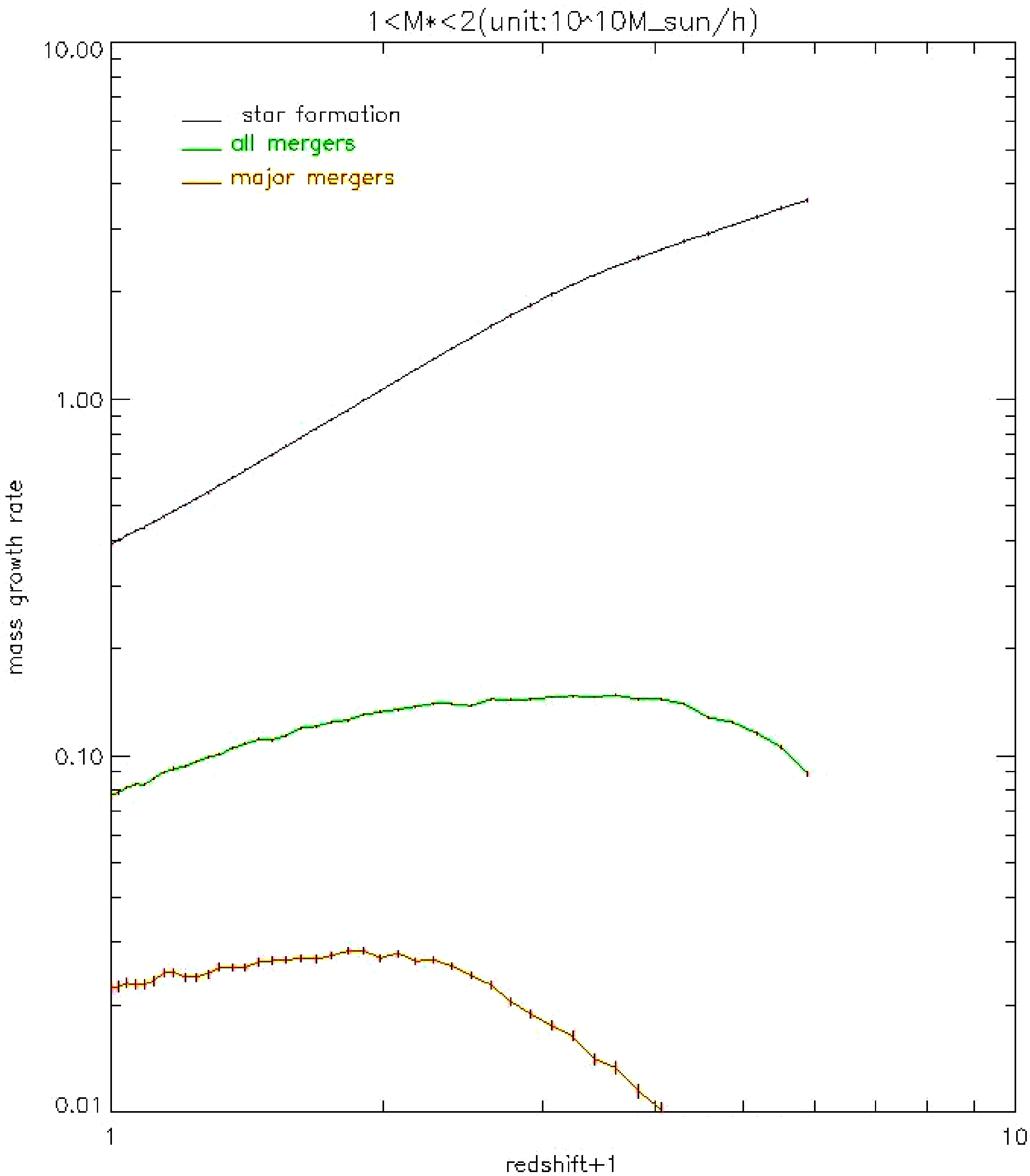
DIMENSIONLESS GROWTH RATES IN STELLAR MASS

Qi Guo & SW

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

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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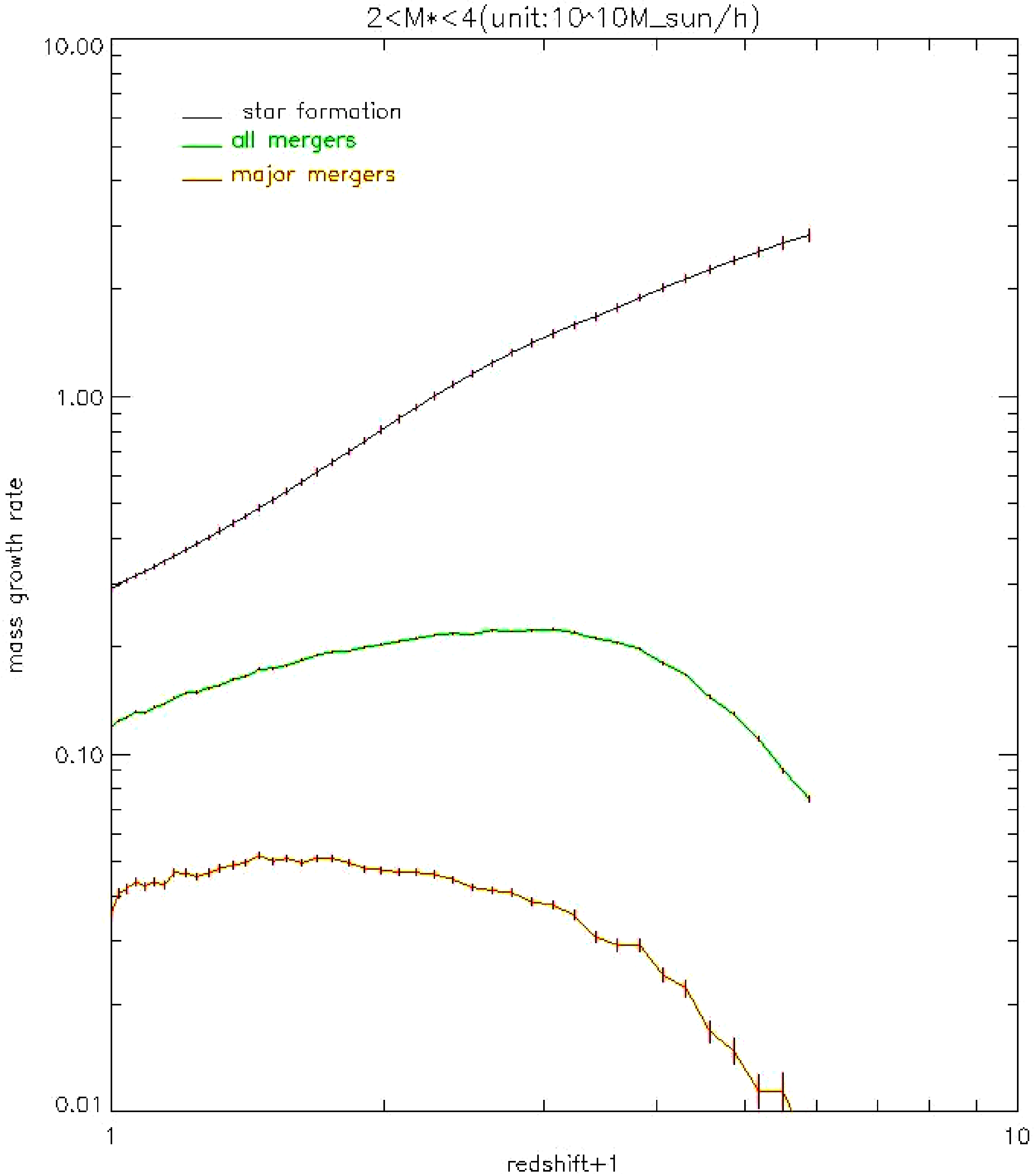

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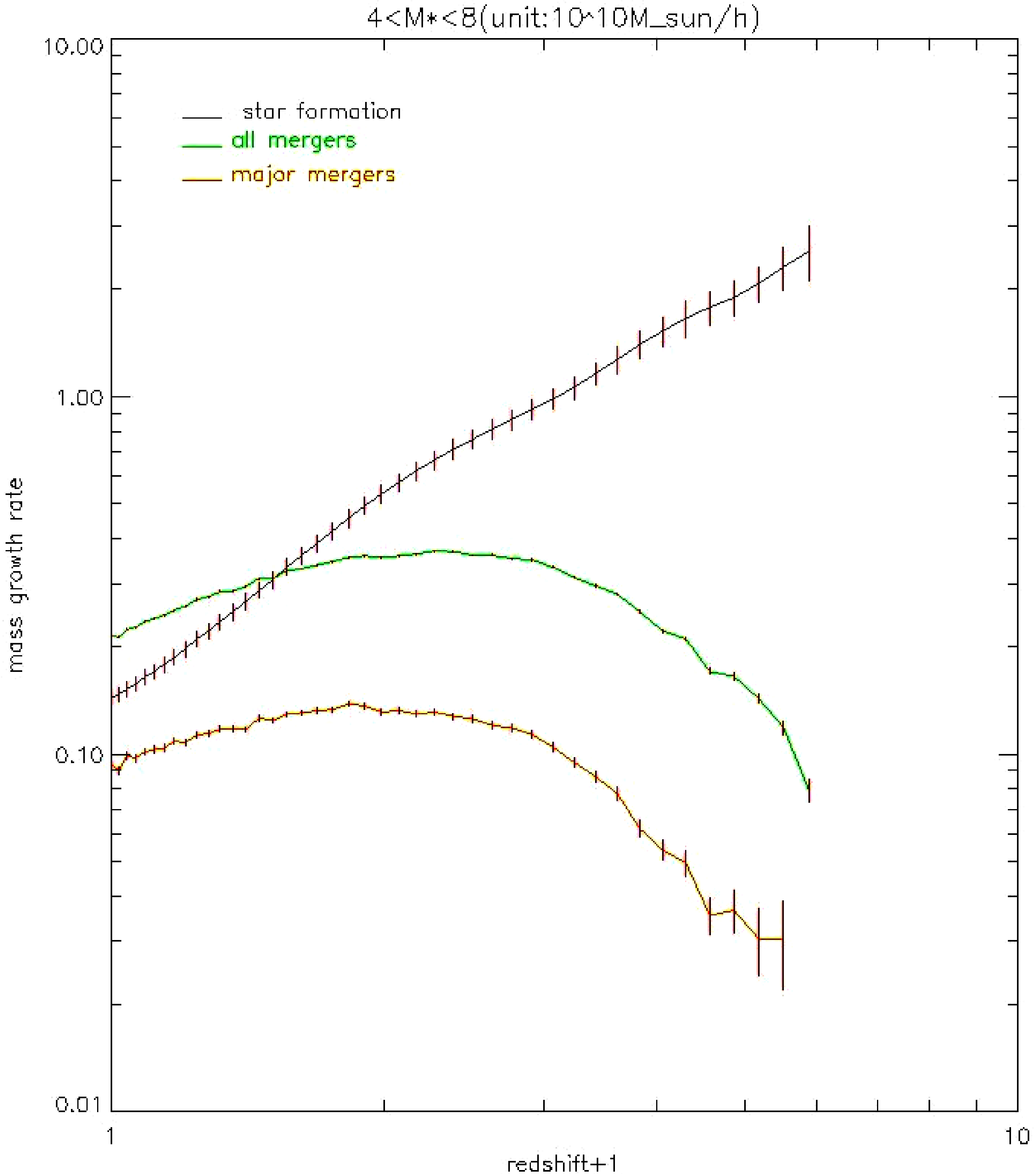


DIMENSIONLESS GROWTH RATES IN STELLAR MASS

Qi Guo & SW

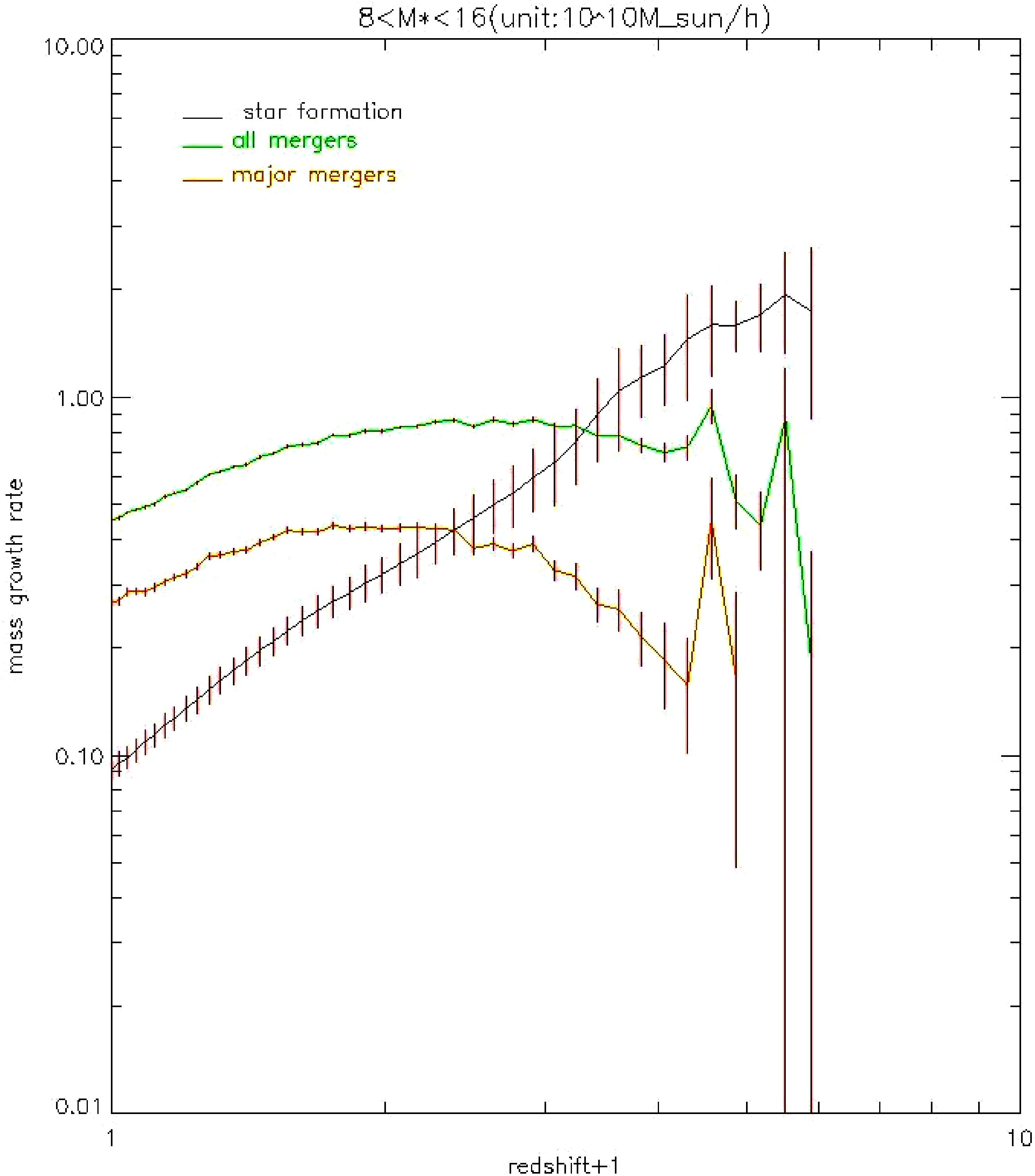
$$R = \langle\, t_{Hubb}\, \Delta M \,/\, M\, \Delta t \,\rangle$$

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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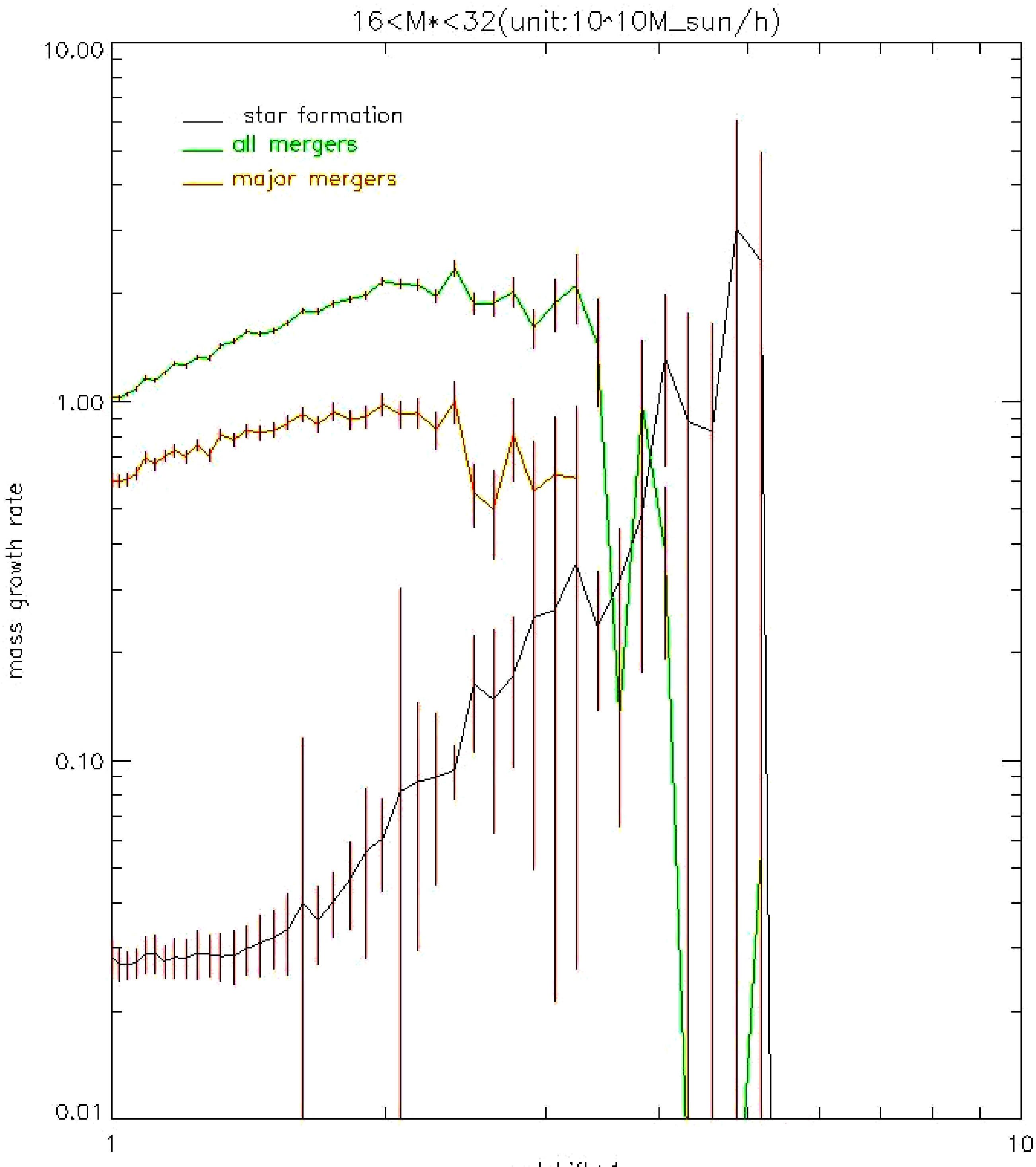

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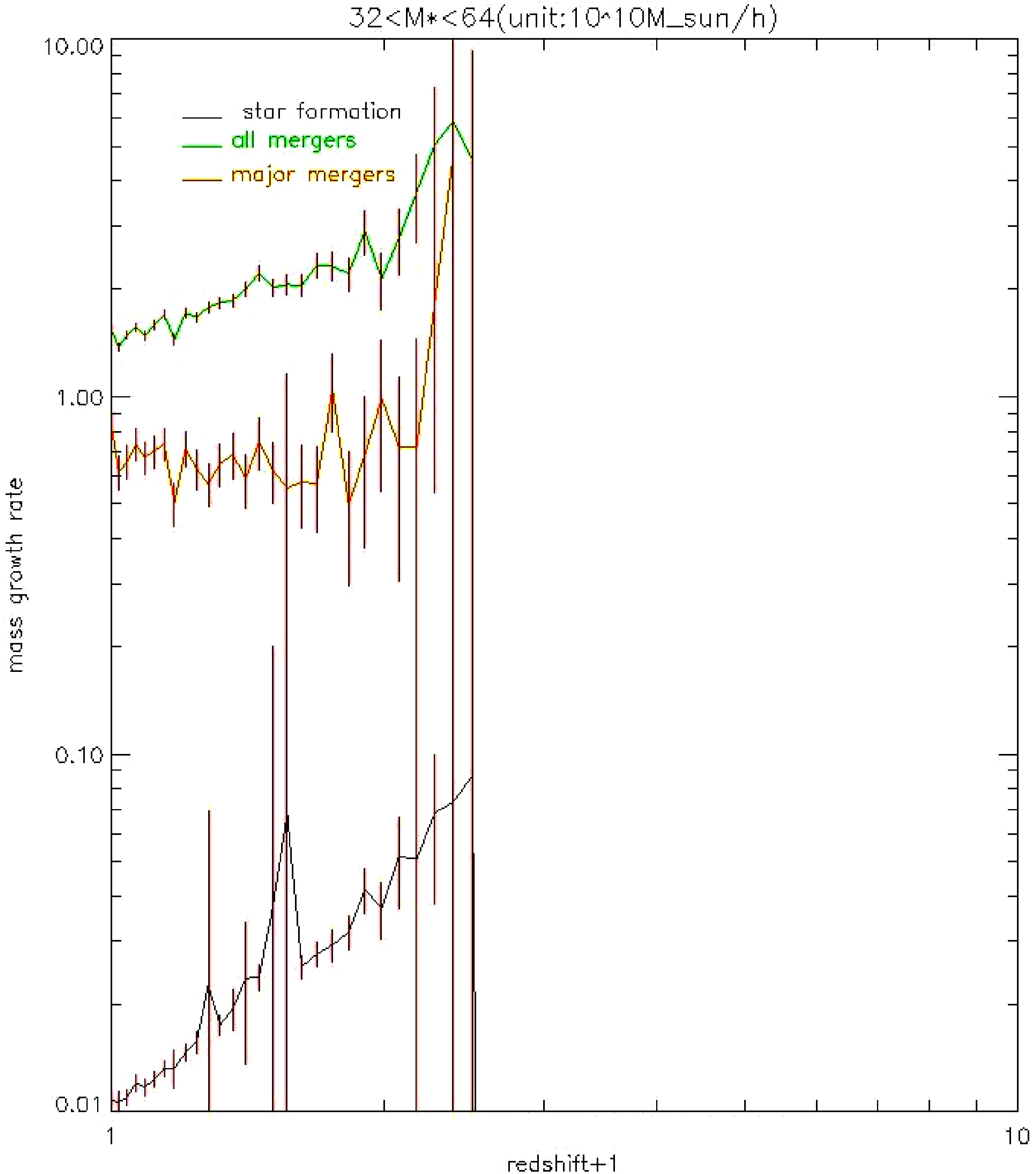

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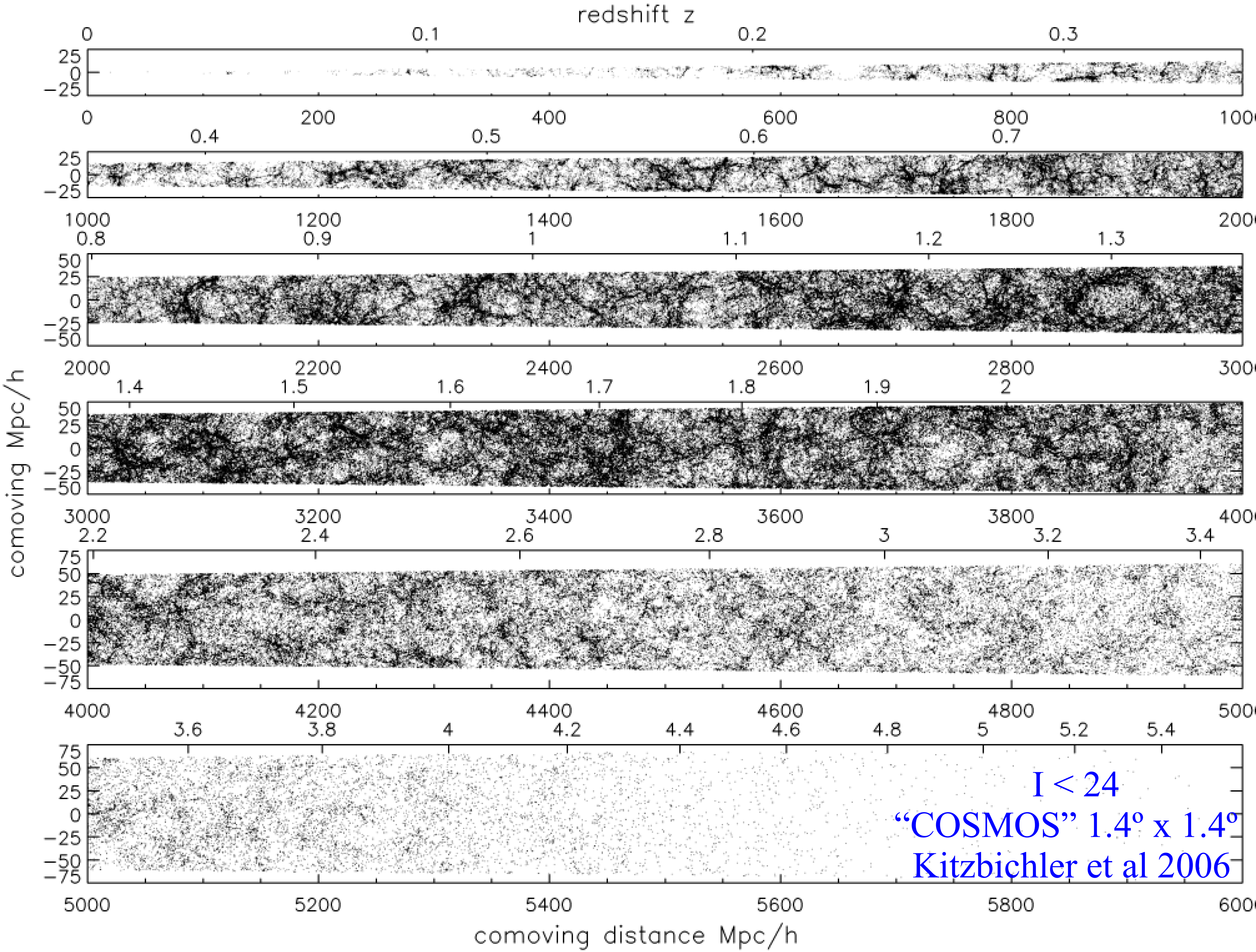
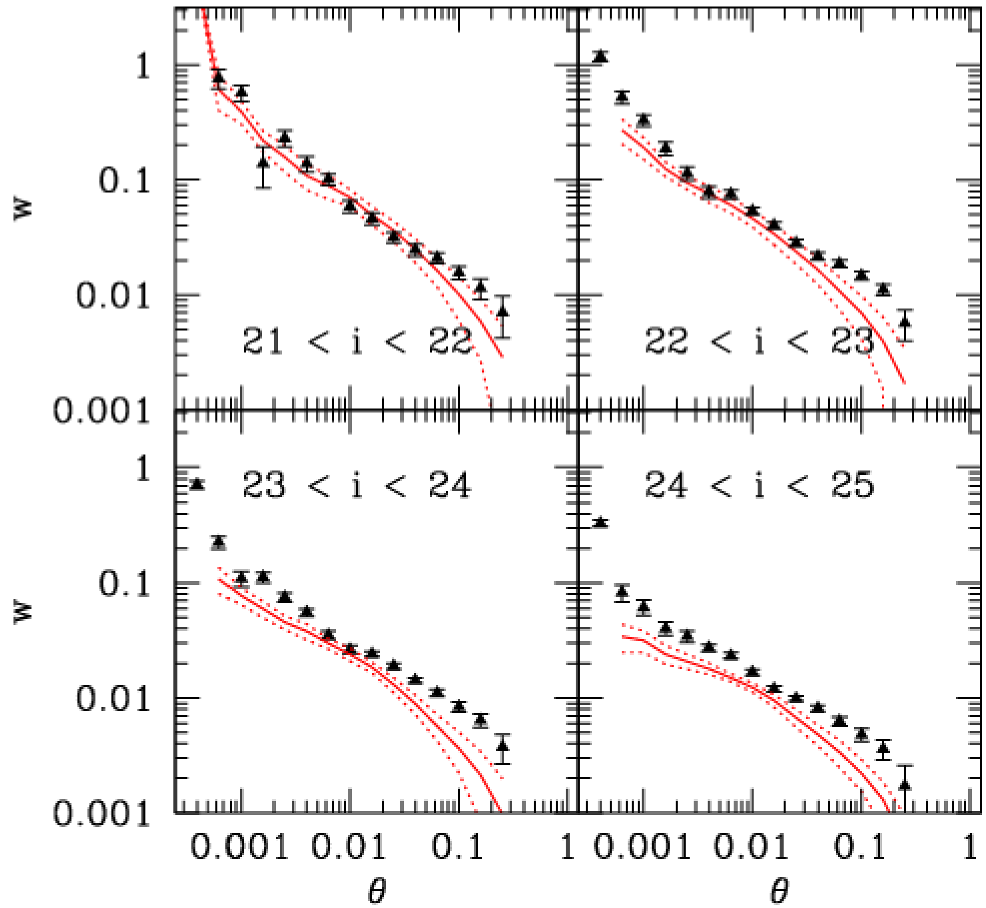


redshift z
comoving Mpc/h
comoving distance Mpc/h
I < 24
"COSMOS" 1.4º x 1.4º
Kitzbichler et al 2006

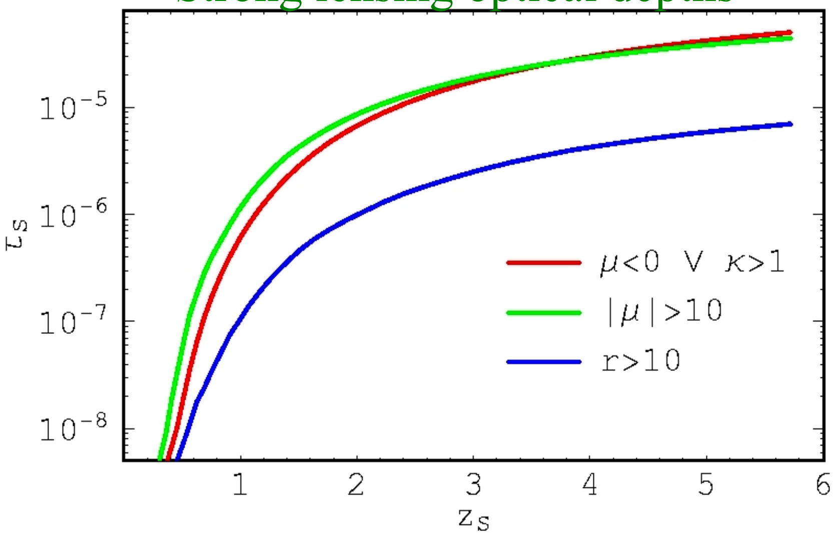
Comparison with COSMOS survey w(θ)

McCracken et al 2007

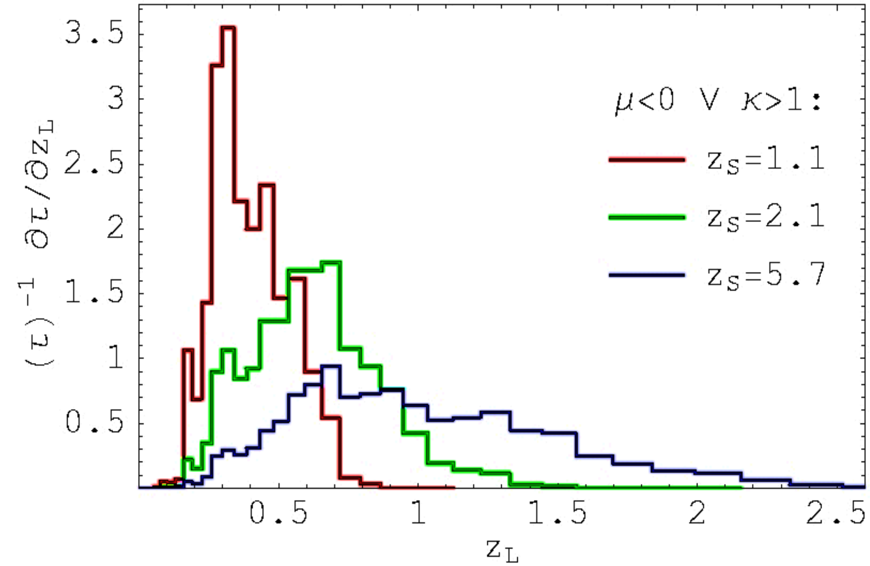


Strong lensing statistics in a DM-only universe

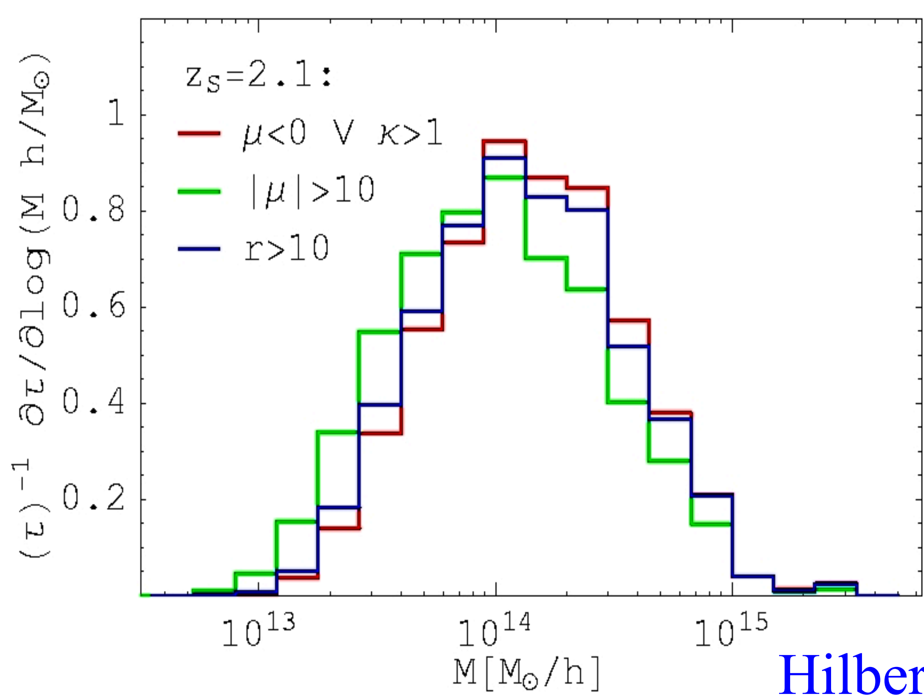
Strong lensing optical depths



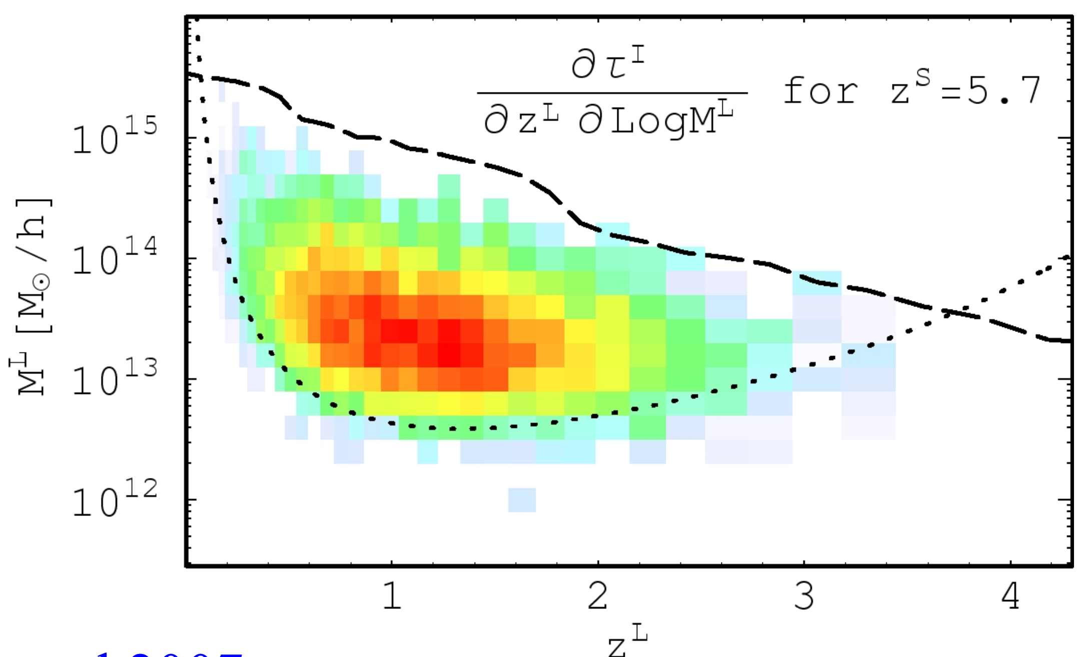
Lens redshift distributions



Lens mass distributions



Joint redshift-mass distribution



Hilbert et al 2007