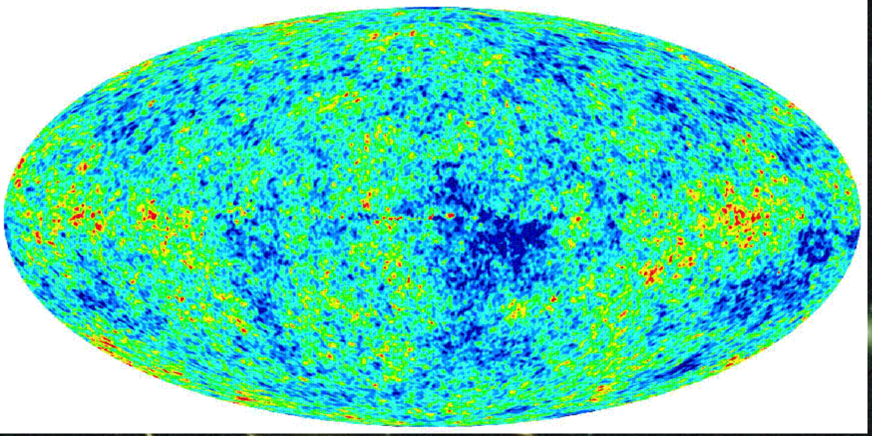
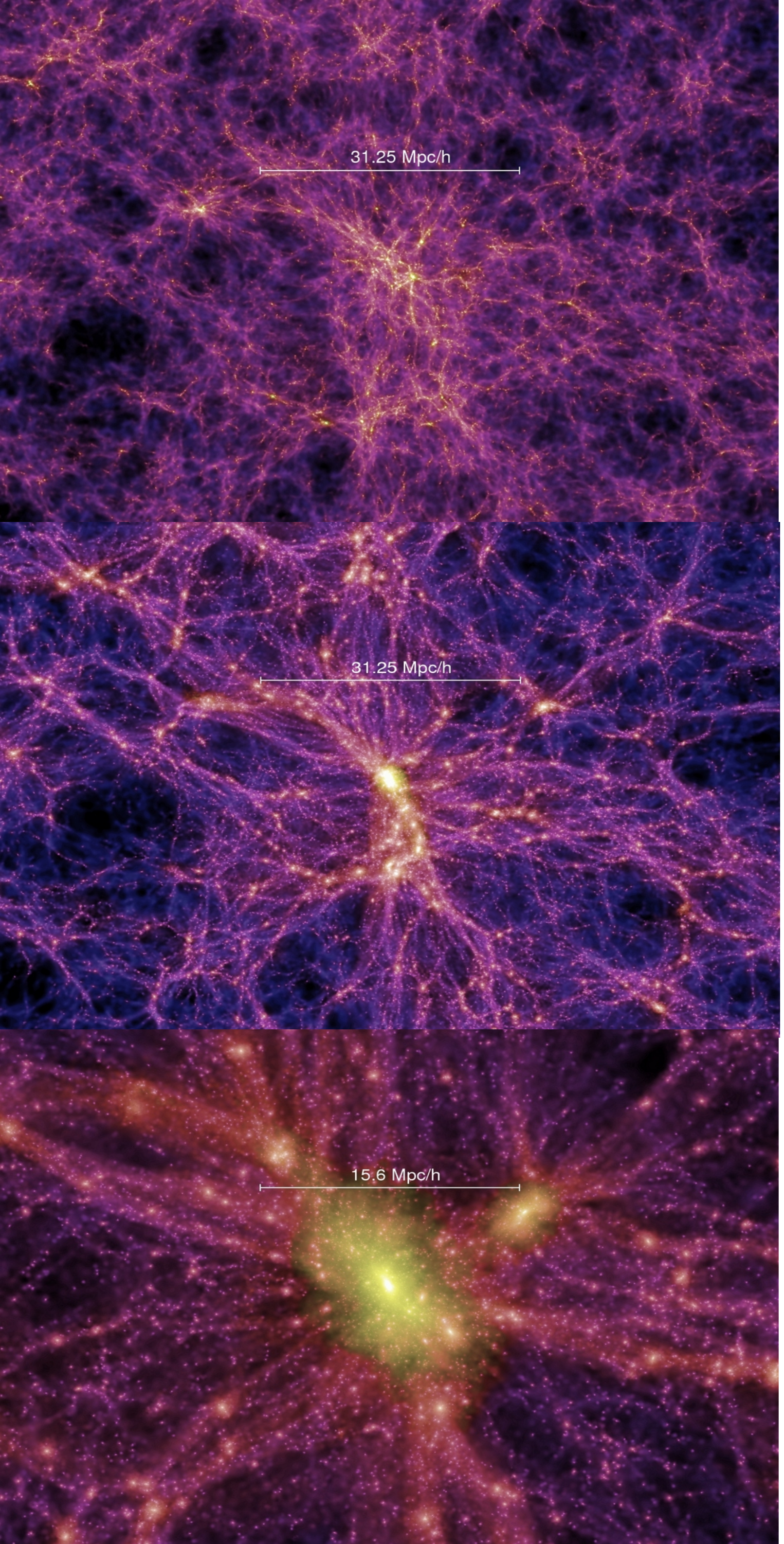


Garmisch, October 2011

Regularity or diversity? The expected properties of the cluster population

Simon White
Max Planck Institute for Astrophysics



- 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/clusters form and evolve within this frame?

Can this be understood well enough to test the frame/measure its parameters?

The semi-analytic programme

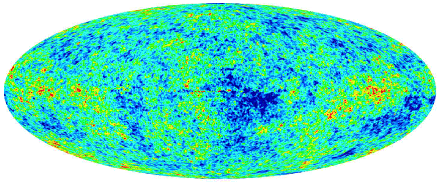
- Follow the DM distribution with high-resolution simulations

  identify dark halos/subhalos at all times, building merger trees to describe their growth, internal structure and spatial distribution

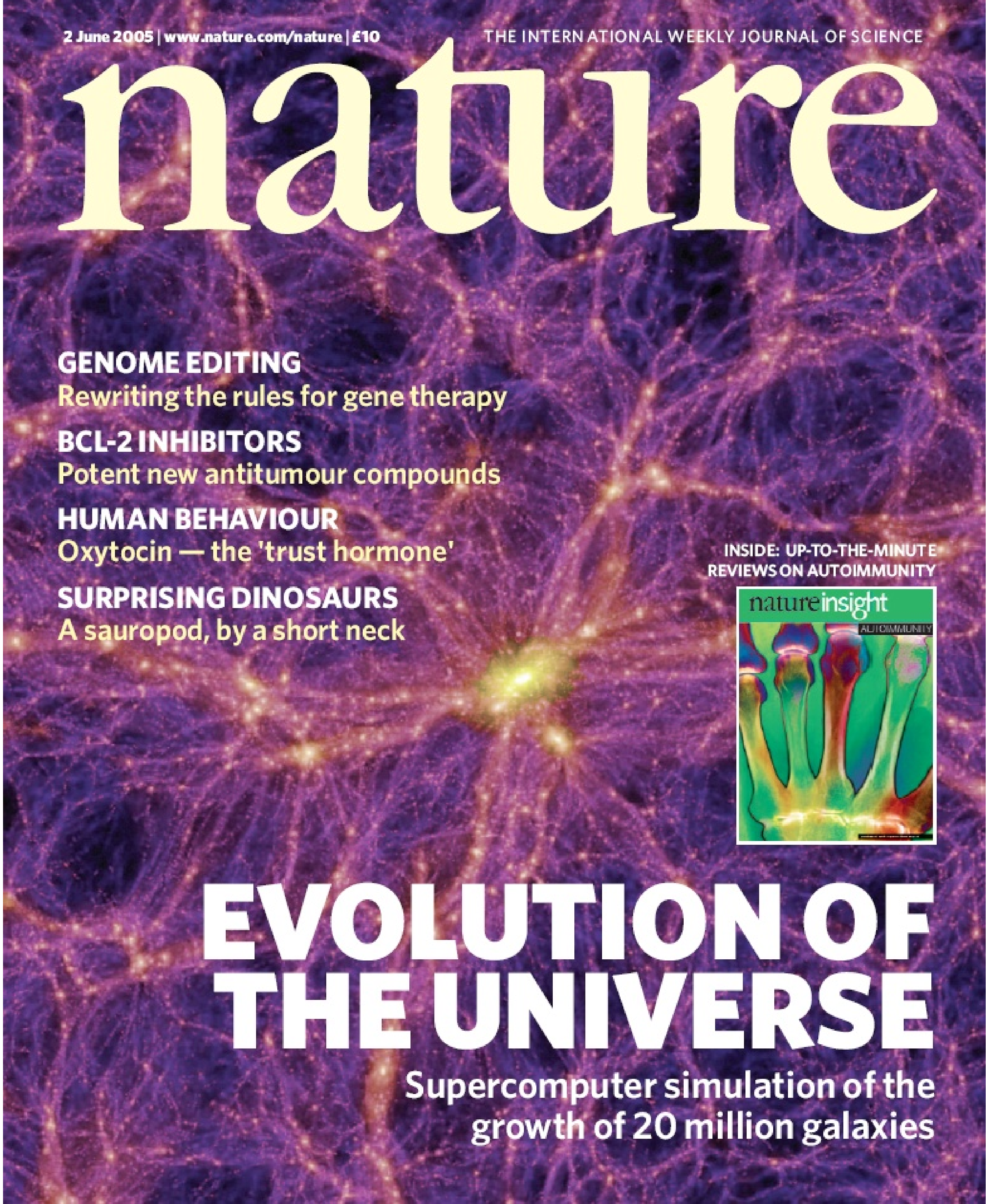
- Treat baryonic physics within the evolving population of DM objects using simplified physical models for processes such as

  gas cooling onto central galaxies
  star formation within these central galaxies
  central black hole growth
  generation of winds through stellar and AGN feedback
  production, expulsion and mixing of nucleosynthesis products

- Measure the <u>efficiencies</u> of these processes as functions of redshift and galaxy properties by comparing model output directly with observational data

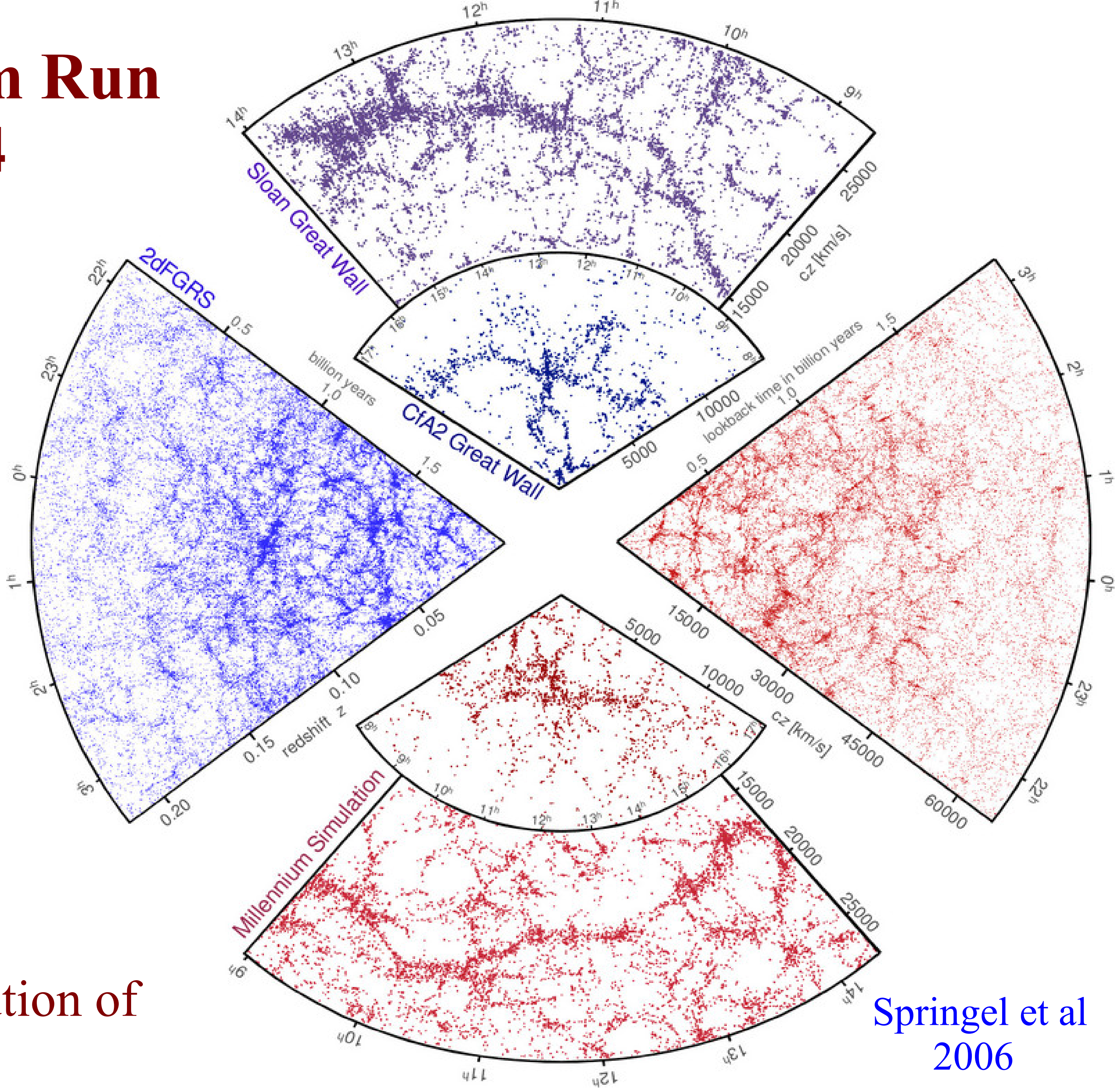
cf  → Ω

Millennium Run 2004



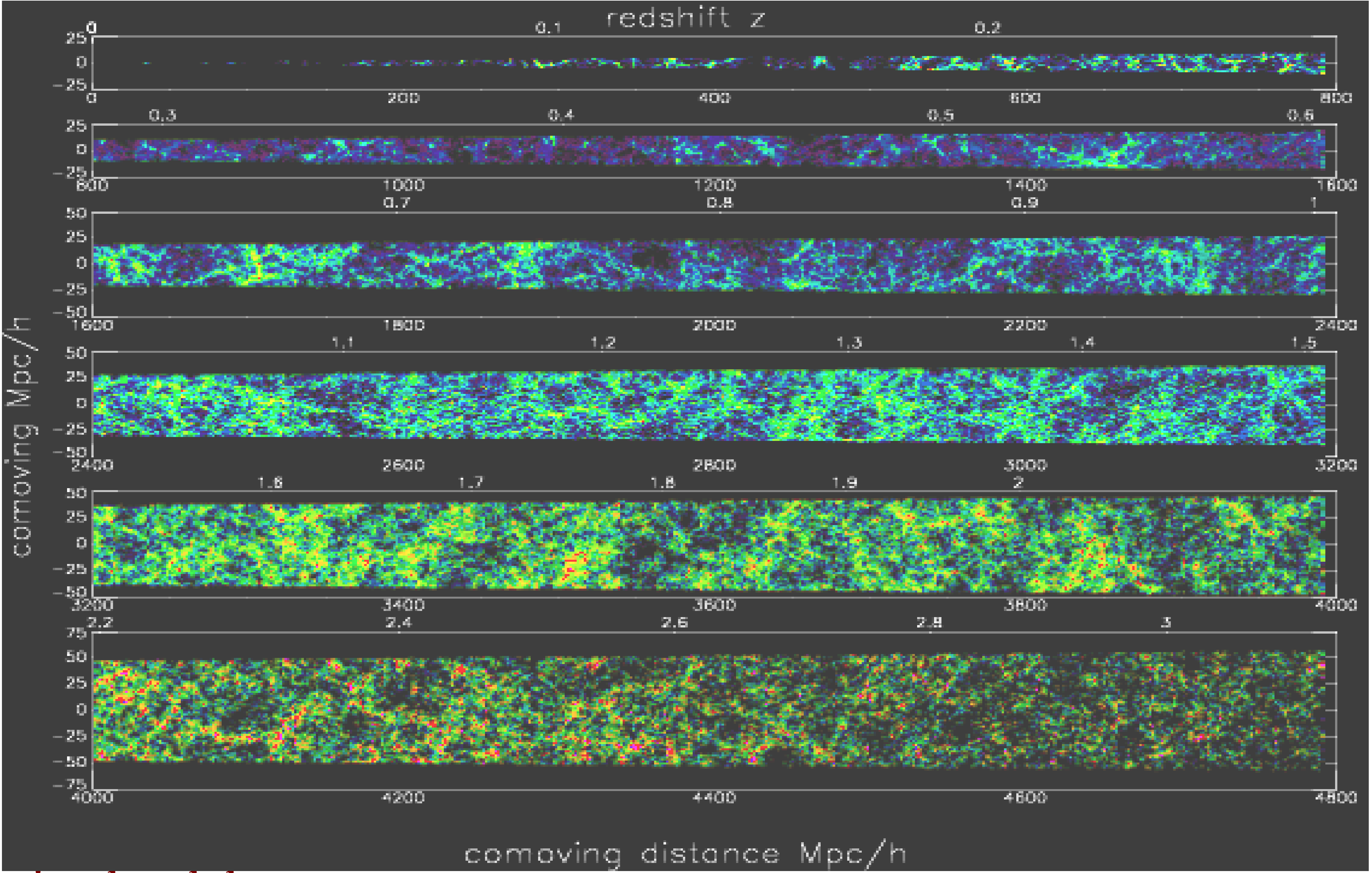
Springel et al 2005

Millennium Run 2004



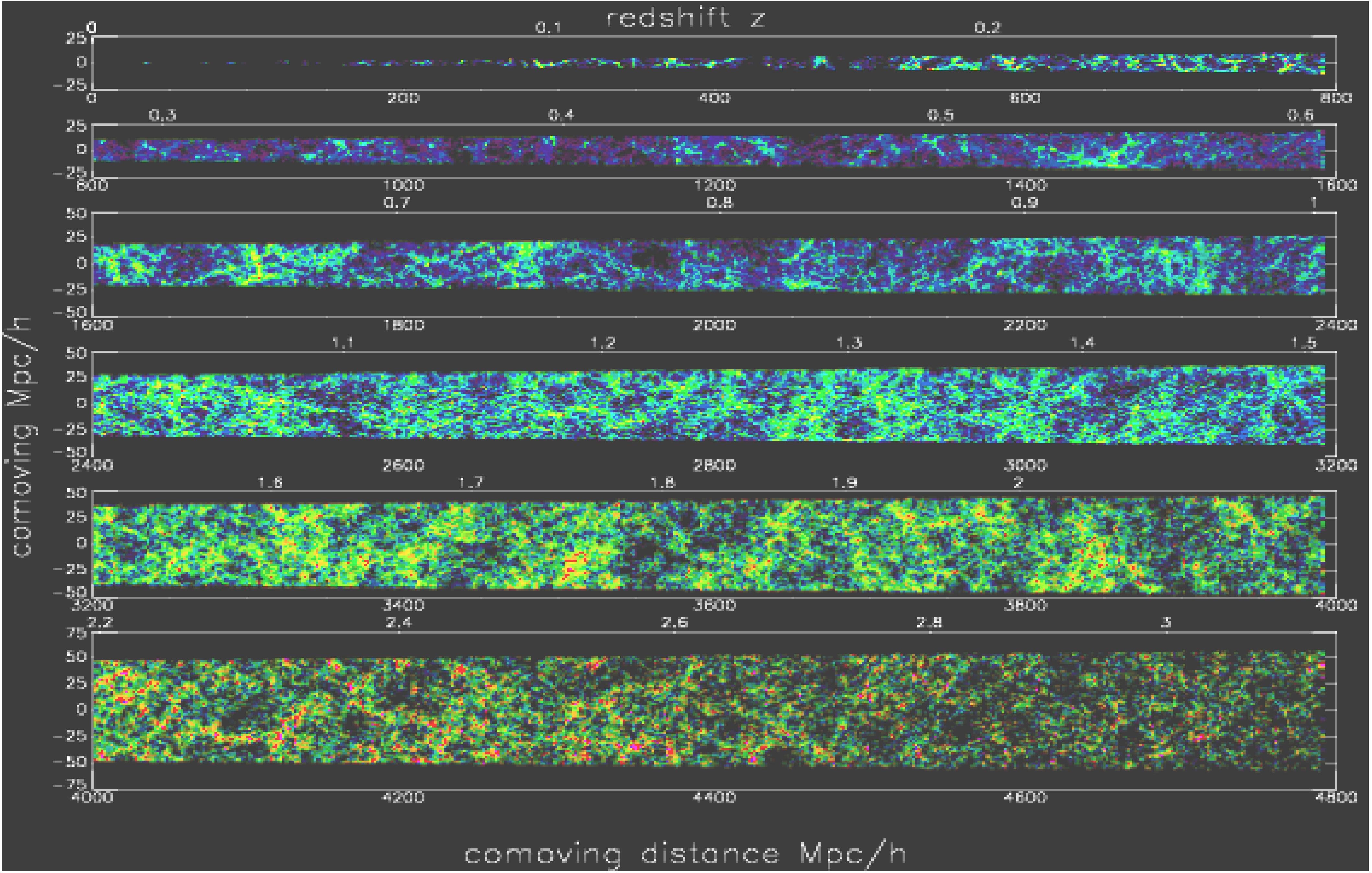
simulated the formation/evolution of 2×10^7 galaxies

Springel et al 2006



simulated the formation/evolution of $2x10^7$ galaxies from z=10 to z=0

Kitzbichler & White
2007

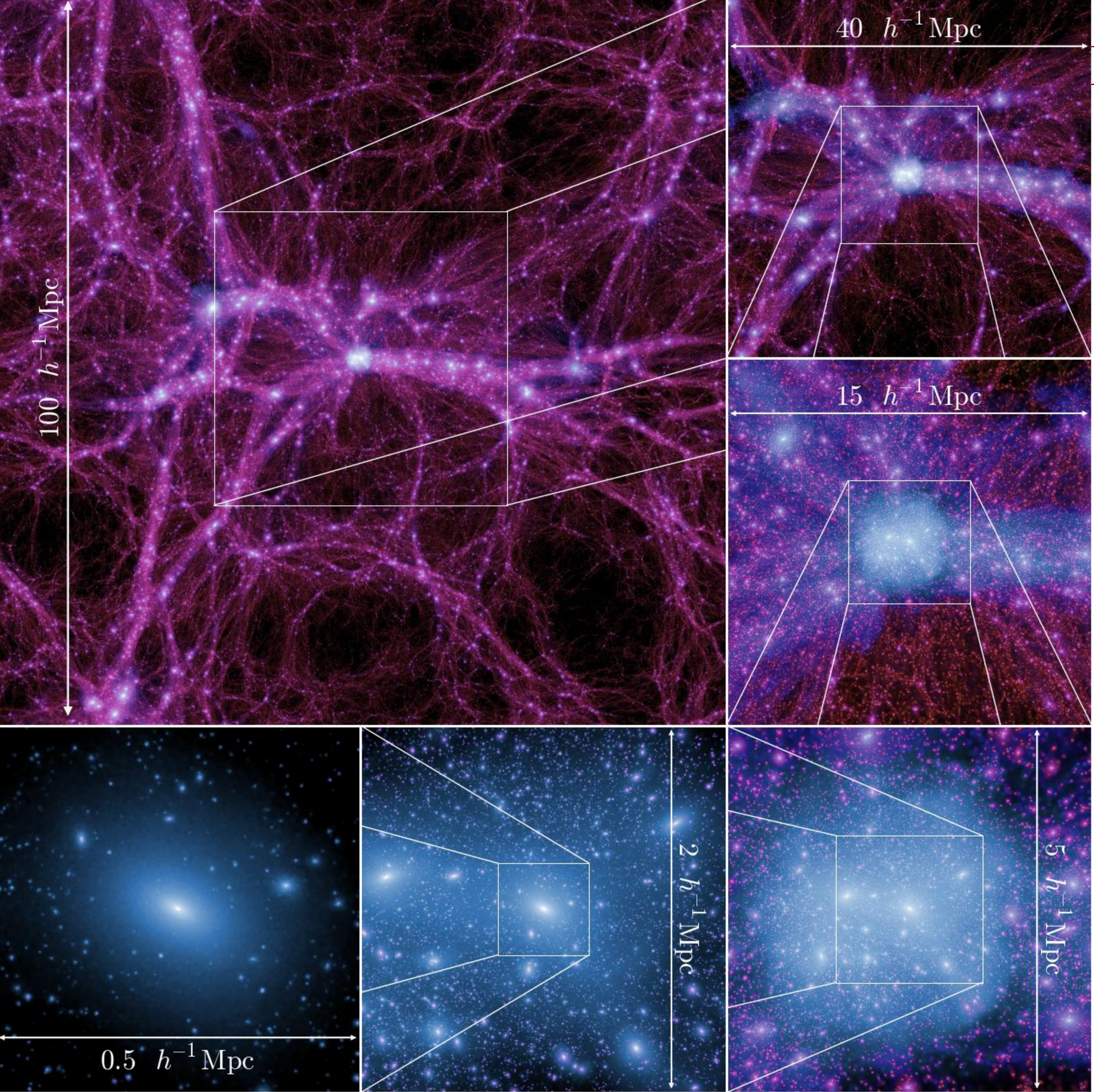


417 papers making direct use of data from the MS (18-10-2011)
Most by authors unassociated with the consortium
Most based on the galaxy catalogues, particularly mock surveys

Limitations of the Millennium Simulation

- Limited modeling of *structure* of galaxies, gas components..
- 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

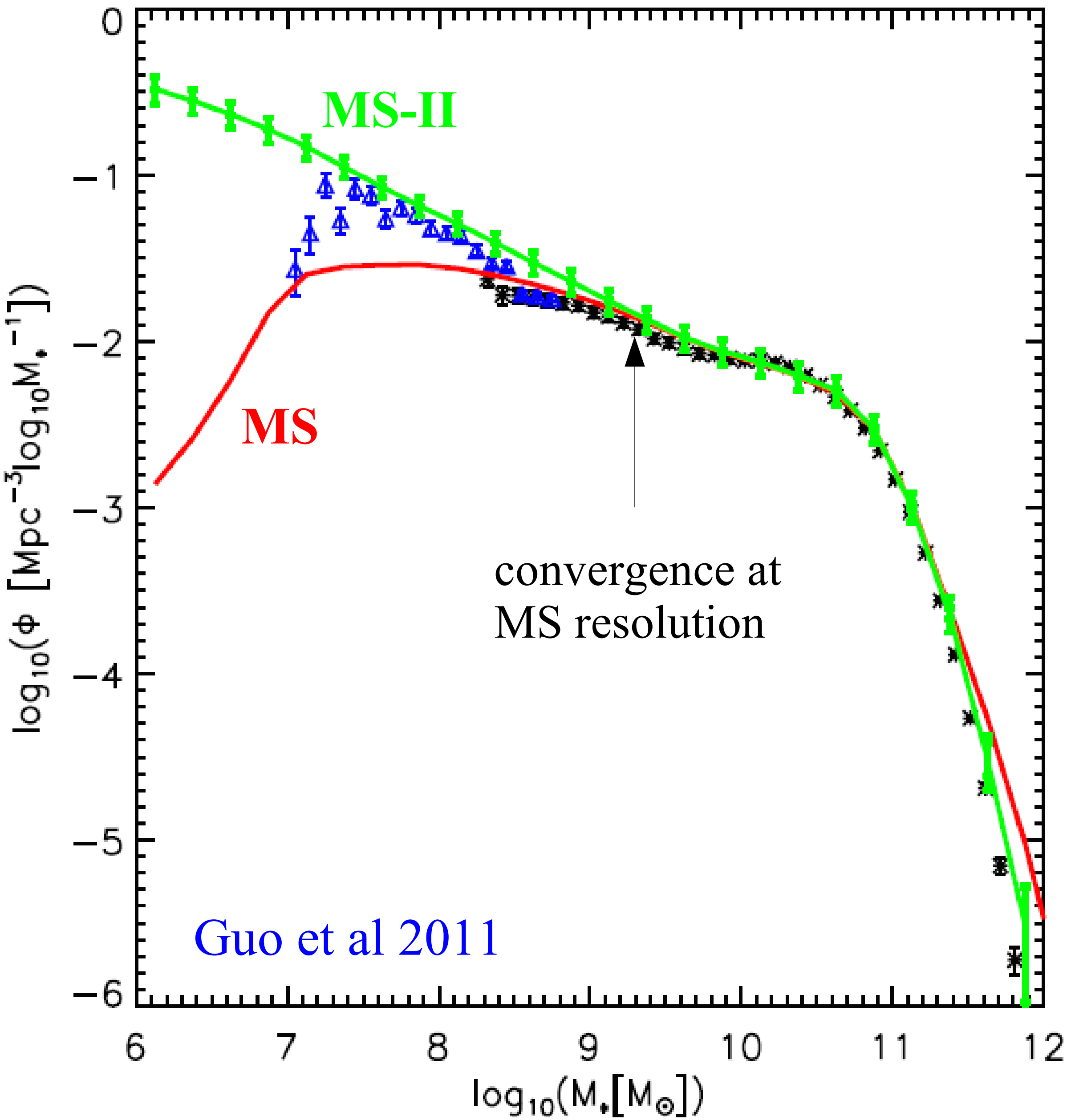
Resolution tests of MS results and extension to smaller scales

Next generation galaxy formation models based on the MS and the MS-II jointly

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

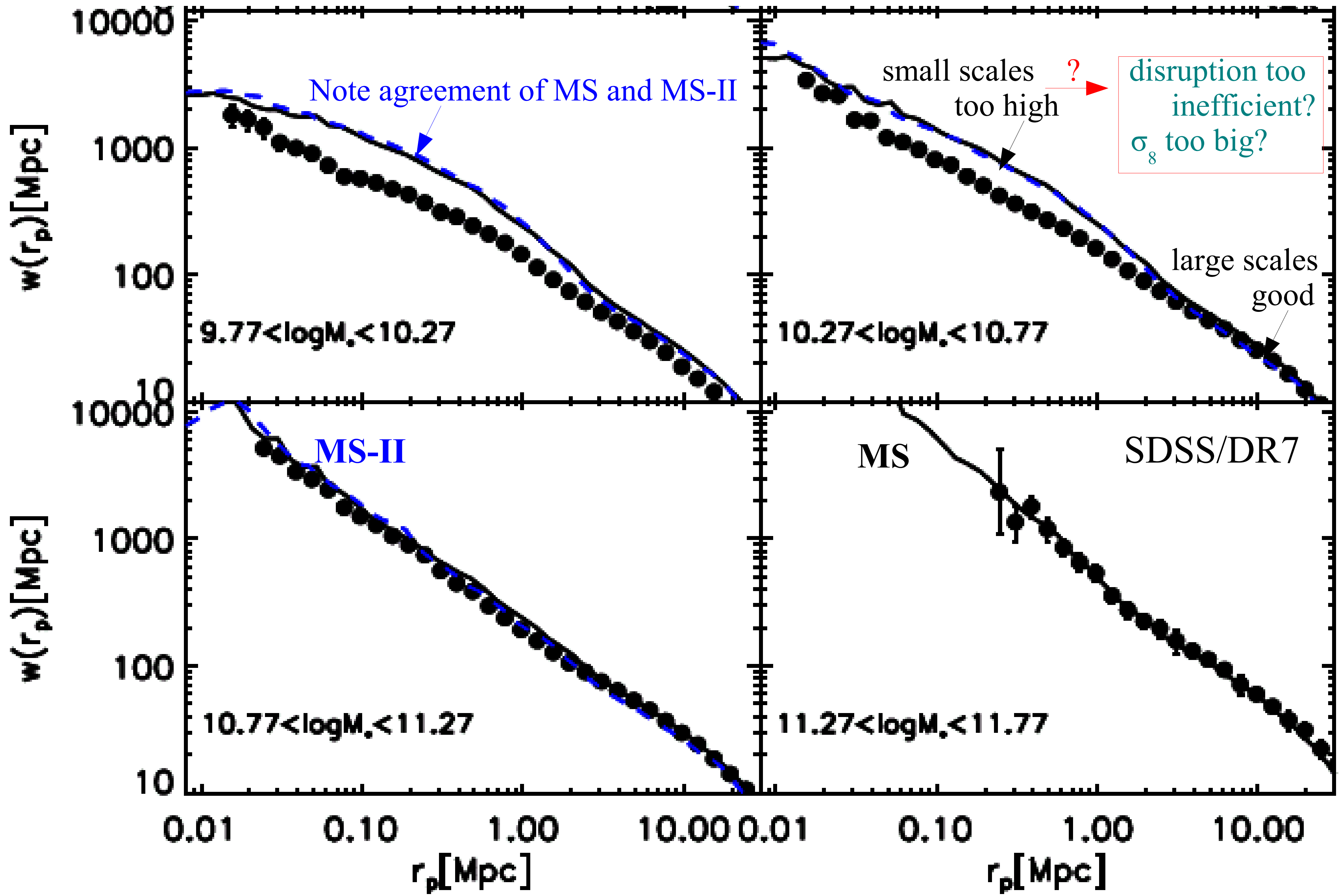
The stellar mass function of galaxies

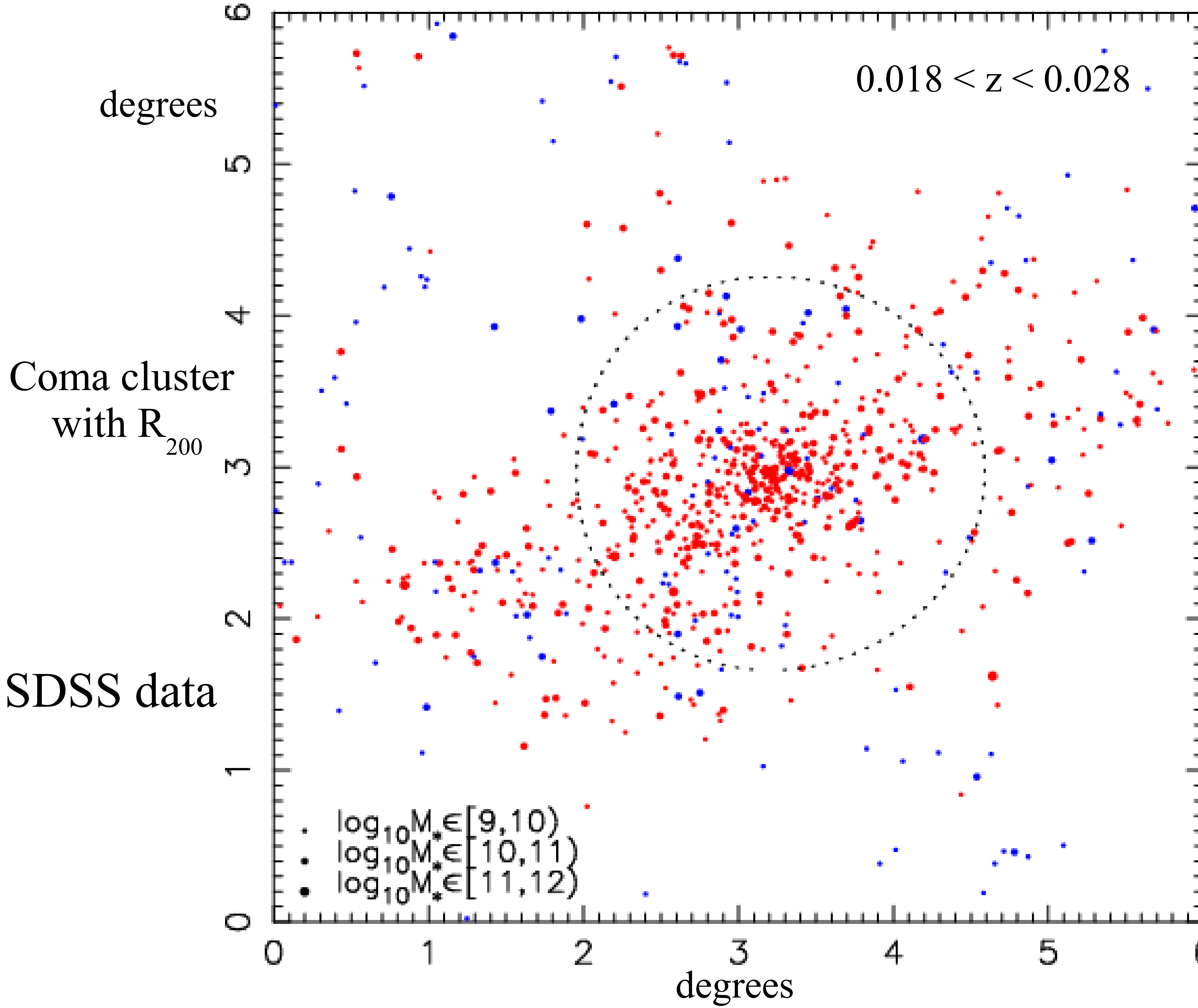


Note that the simulated mass function fits the data over 5 dex!

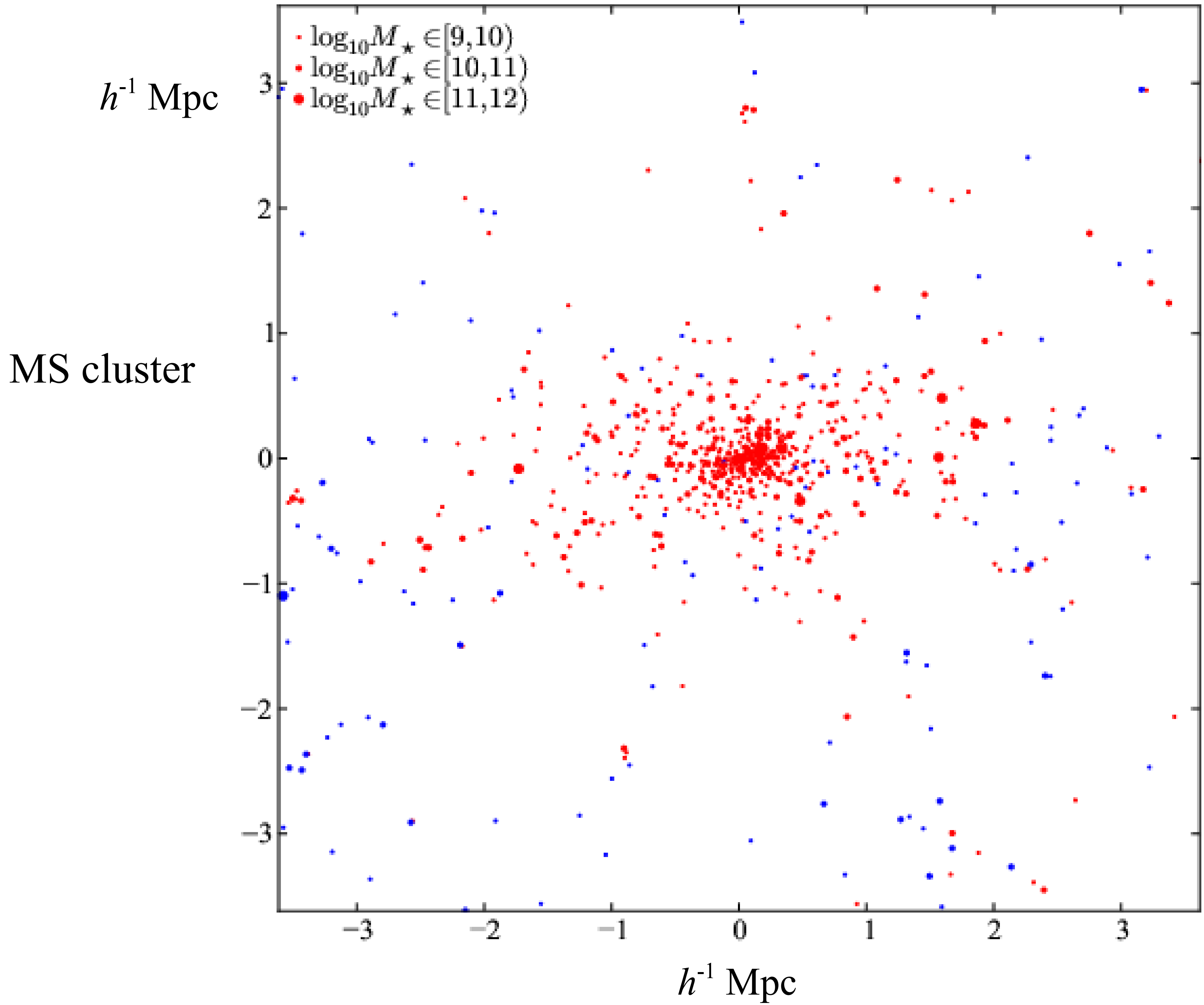
Mass-dependent galaxy clustering

Guo et al 2011

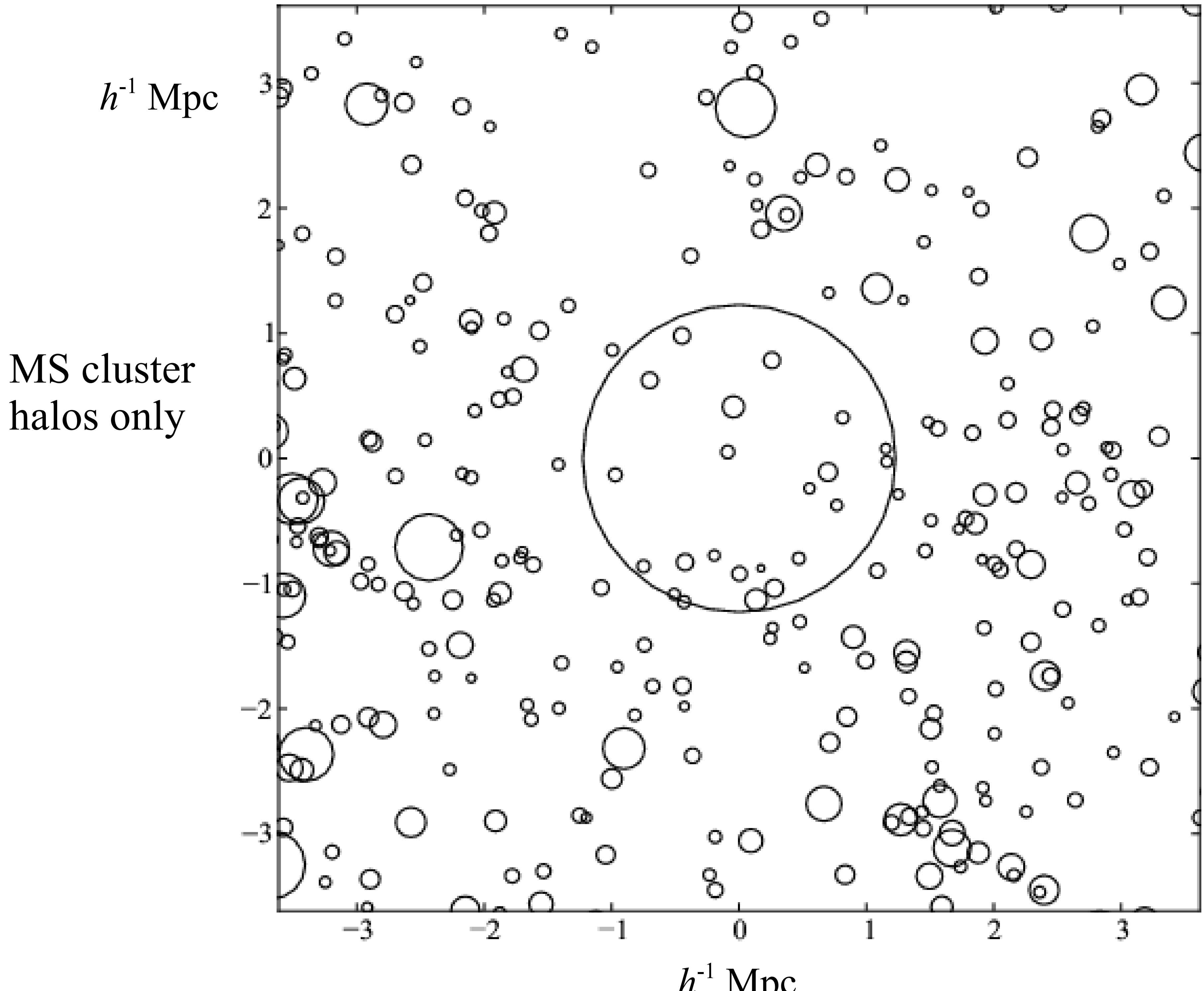




0.018 < z < 0.028
degrees
Coma cluster with R_{200}
SDSS data
$\log_{10}M_* \in [9,10)$
$\log_{10}M_* \in [10,11)$
$\log_{10}M_* \in [11,12)$
degrees
0
1
2
3
4
5
6



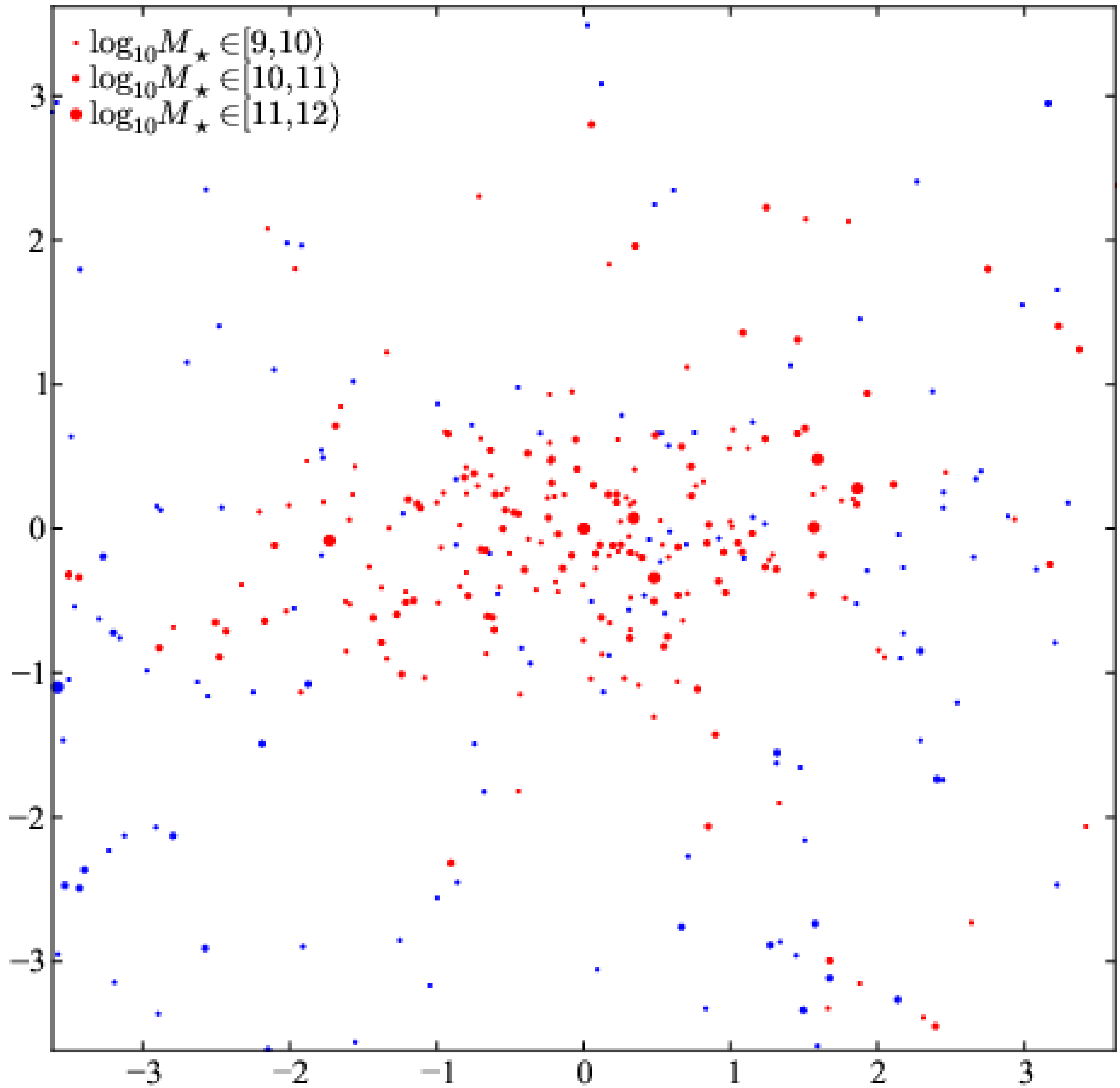
h⁻¹ Mpc
MS cluster
log10M⋆ ∈[9,10)
log10M⋆ ∈[10,11)
log10M⋆ ∈[11,12)
3
2
1
0
−1
−2
−3
h⁻¹ Mpc



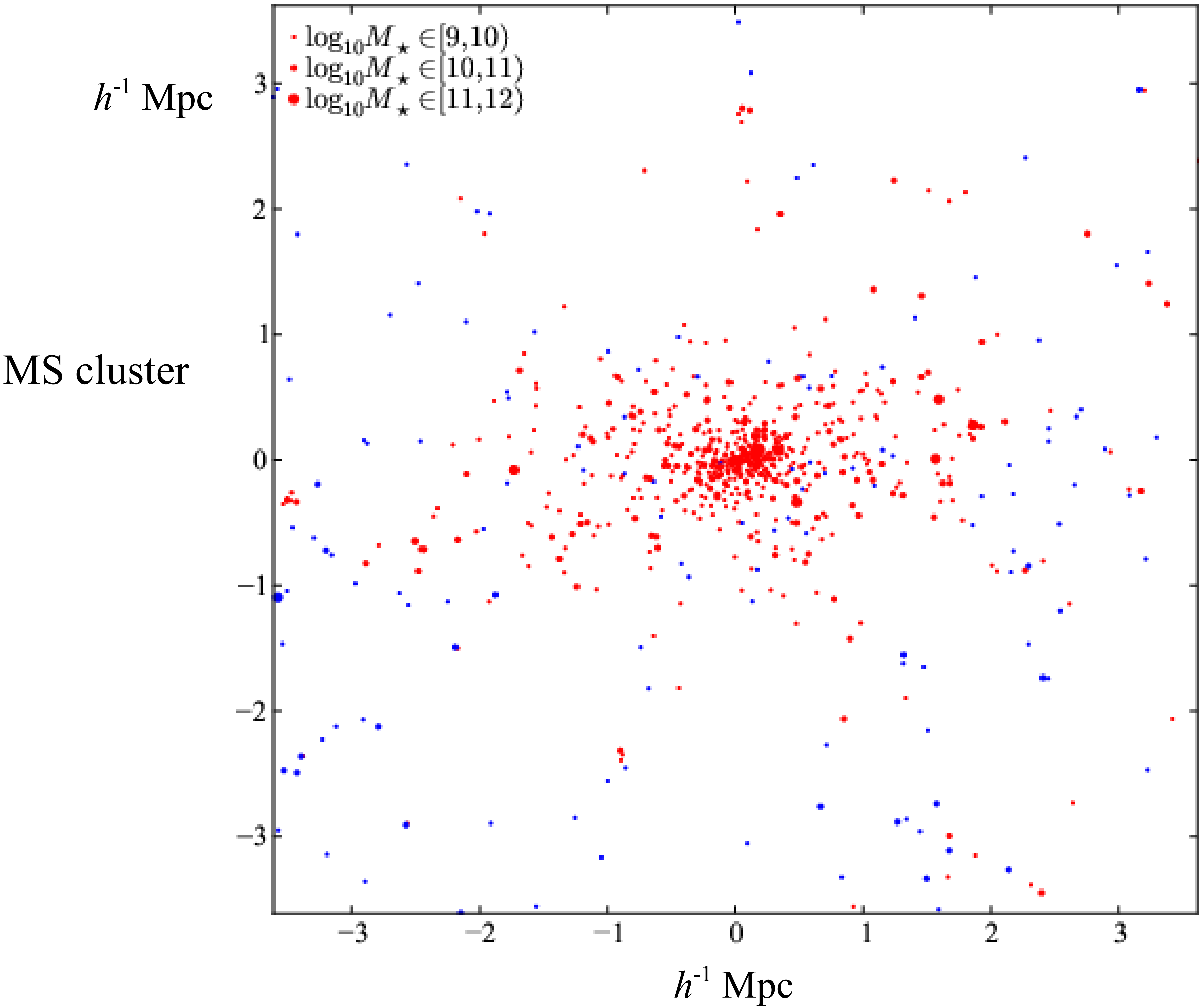
h^{-1} Mpc
MS cluster halos only
3
2
1
0
−1
−2
−3
−3
−2
−1
0
1
2
3
h^{-1} Mpc

h^{-1} Mpc

MS cluster galaxies in subhalos

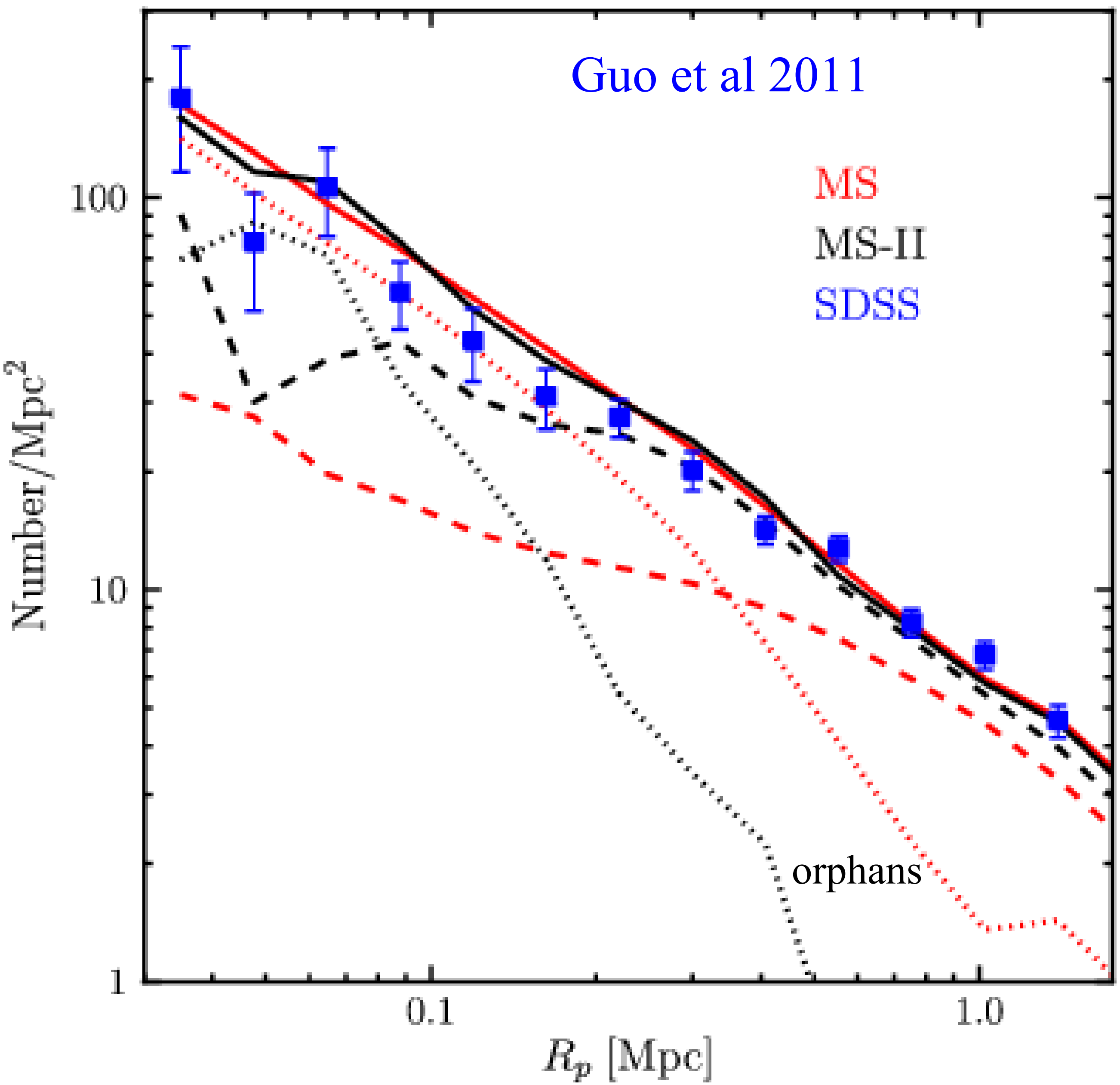


h^{-1} Mpc



$\log_{10} M_\star \in [9,10)$
$\log_{10} M_\star \in [10,11)$
$\log_{10} M_\star \in [11,12)$
h^{-1} Mpc
MS cluster
3
2
1
0
−1
−2
−3
−3
−2
−1
0
1
2
3
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

Disruption efficiency too low near centre?

Millennium-XXL was successfully executed on JUROPA in 2010

PARAMETERS OF FINAL RUN

6720^3 ~ 303 billion particles

3000 Mpc/h box, Millennium cosmology

12288 cores: 3072 MPI-task / 4 threads (70% of Juropa)

9216^3 FFT mesh

86 trillion force calculations

Cost: 2.7 million CPU hours (~300 years), corresponding to 9.3 days wallclock time (including FOF+SUBFIND)

Peak memory usage: 29 TB
(105 bytes/particle)

700 million halos at z=0 (44% of particles)

About 25 billion (sub)halos in merger trees

Largest cluster has $9 \times 10^{15}\ M_{\odot}$

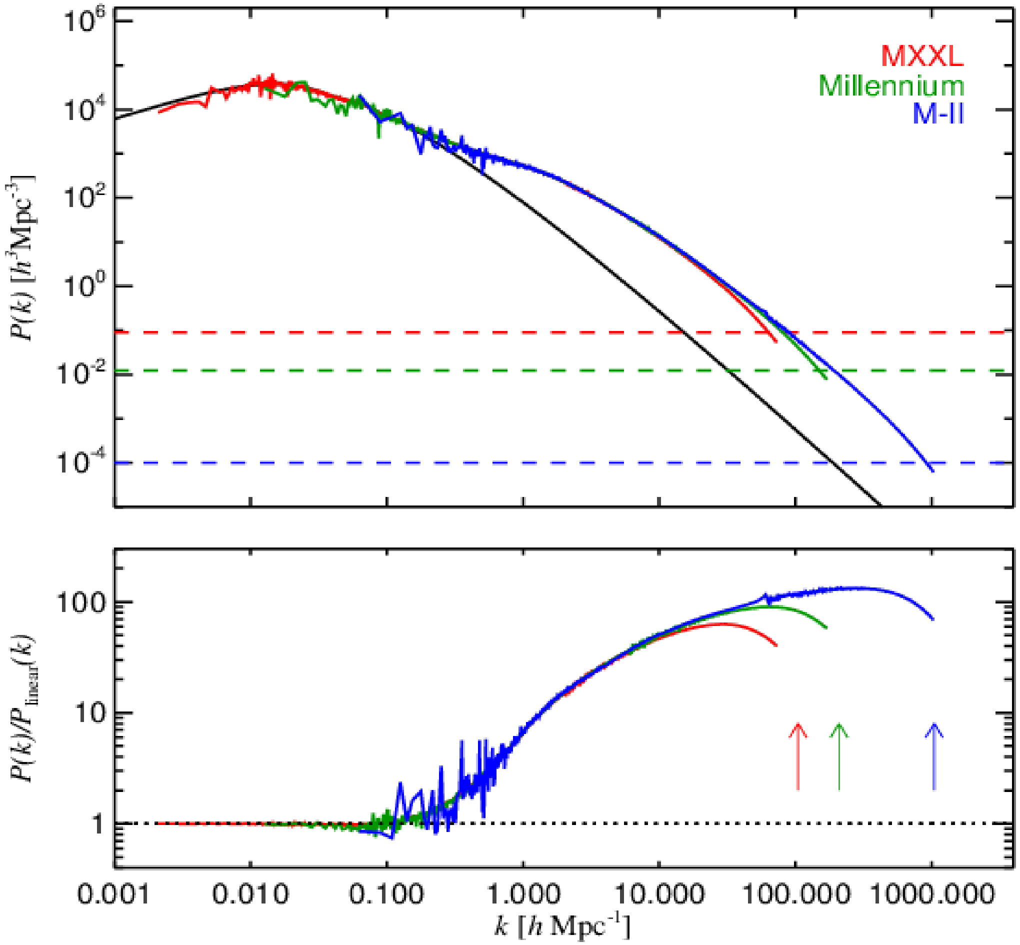
Size of a full snapshot: ~10 TB

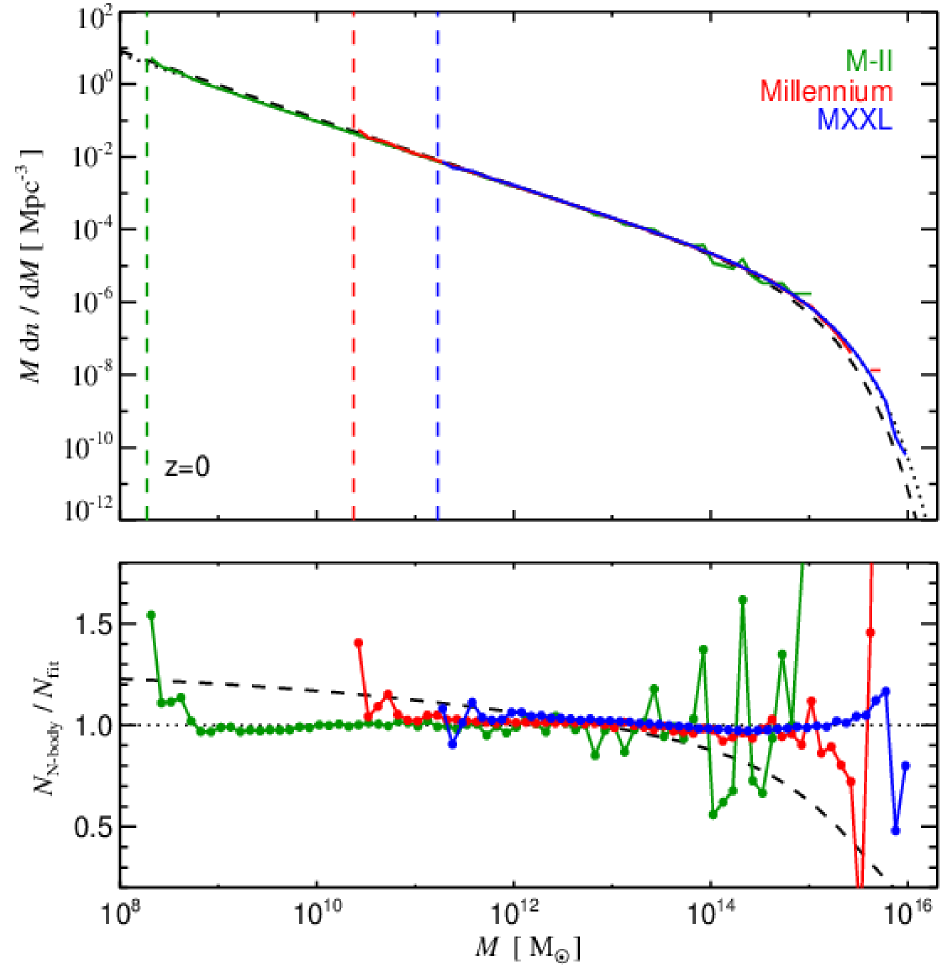
More than 120 TB stored for science

JUROPA
Jülich
Forschungszentrum

Carried out by Raul Angulo and Volker Springel within the Virgo Consortium

Comparison with previous MS

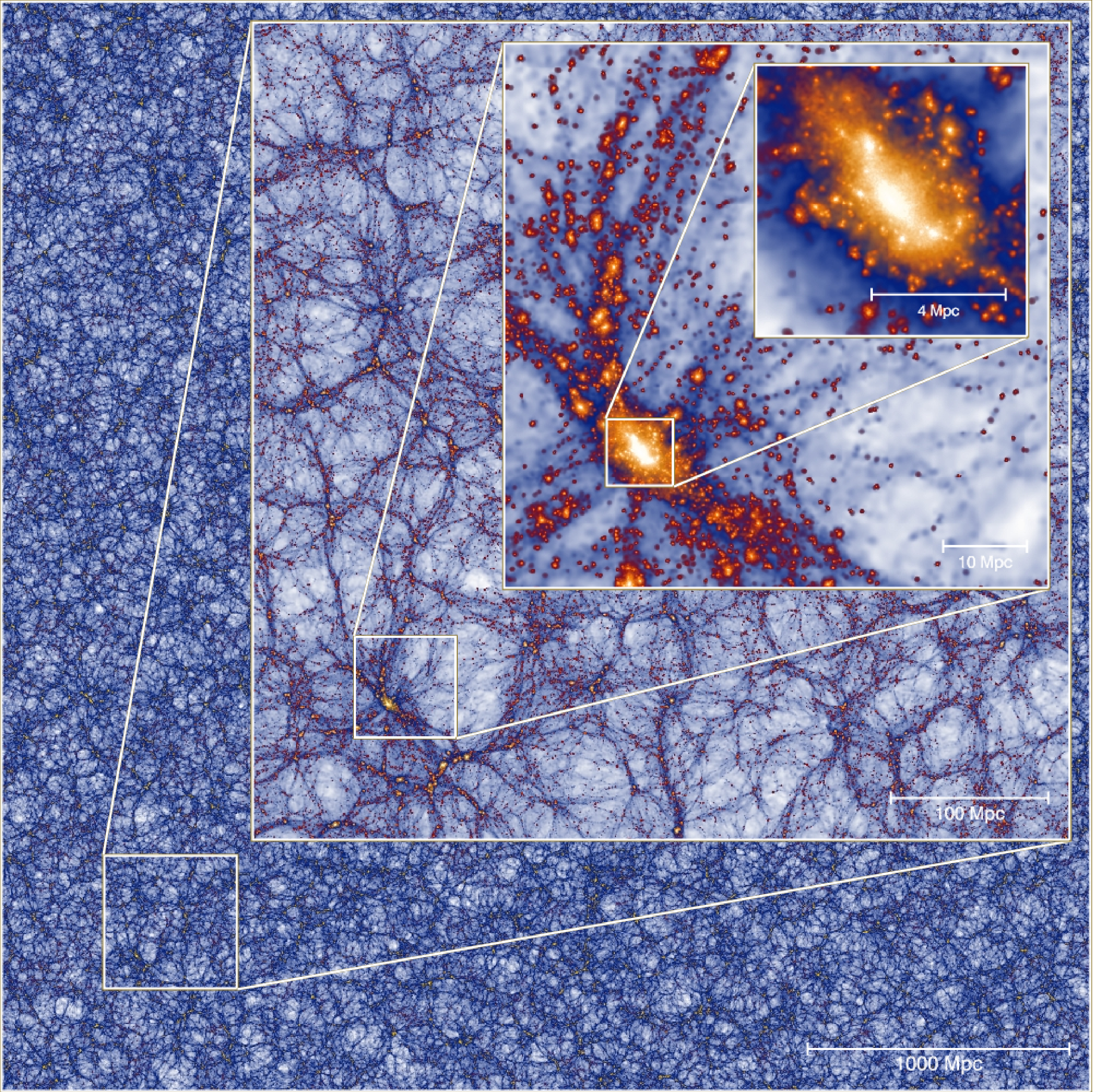




Combining these simulations we have predictions for the LCDM paradigm;

… from a 7 kpc up to 4 Gpc.

… from 10^8 up to 10^{16} $M_\odot$ haloes.



The MXXL

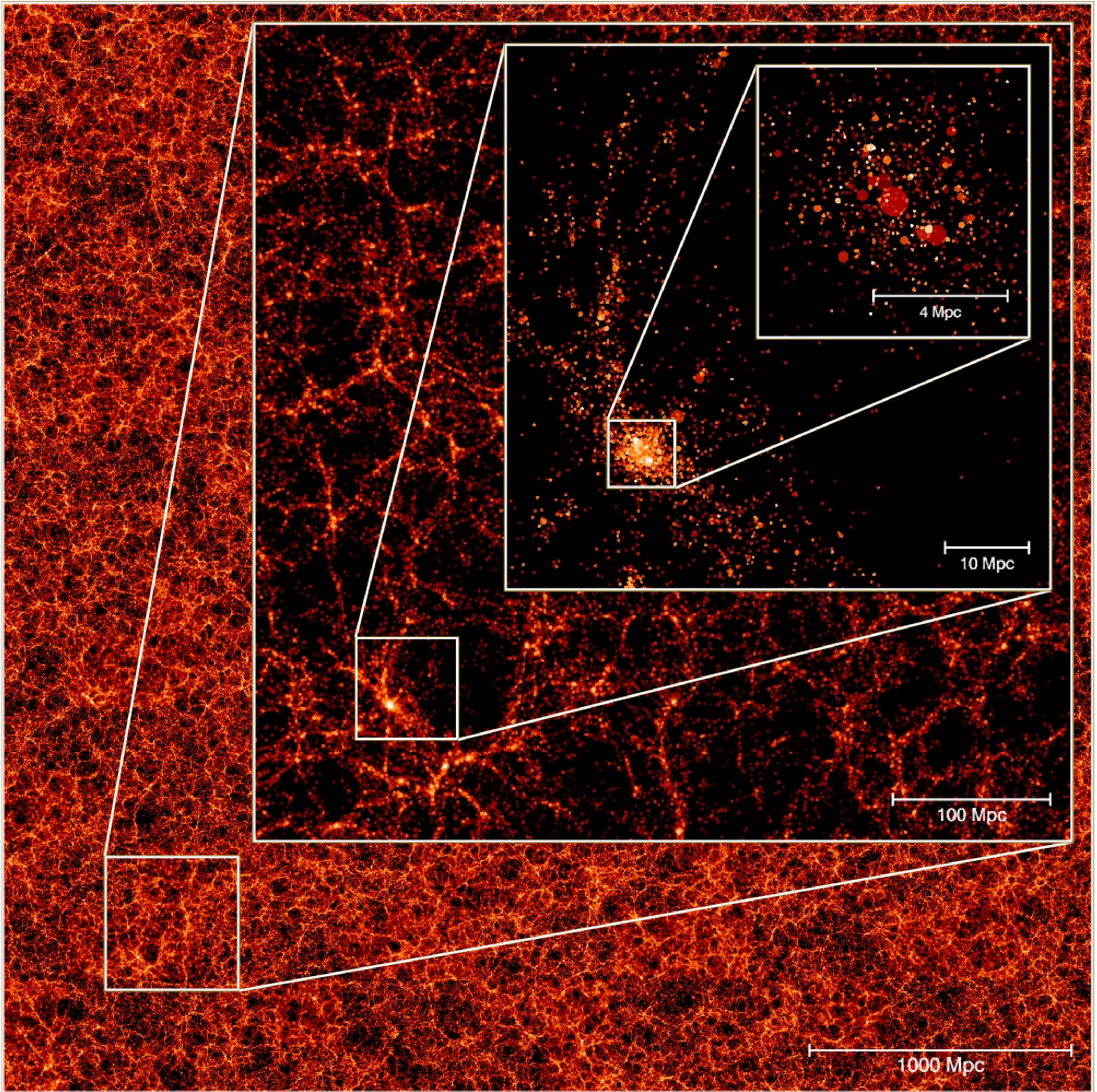
Angulo, Springel et al 2011

Bigger than the Millennium Run by factors of

30 in $N_{particle}$

200 in Volume

6 in $m_{particle}$



The MXXL

Angulo, Springel et al 2011

Bigger than the Millennium Run by factors of

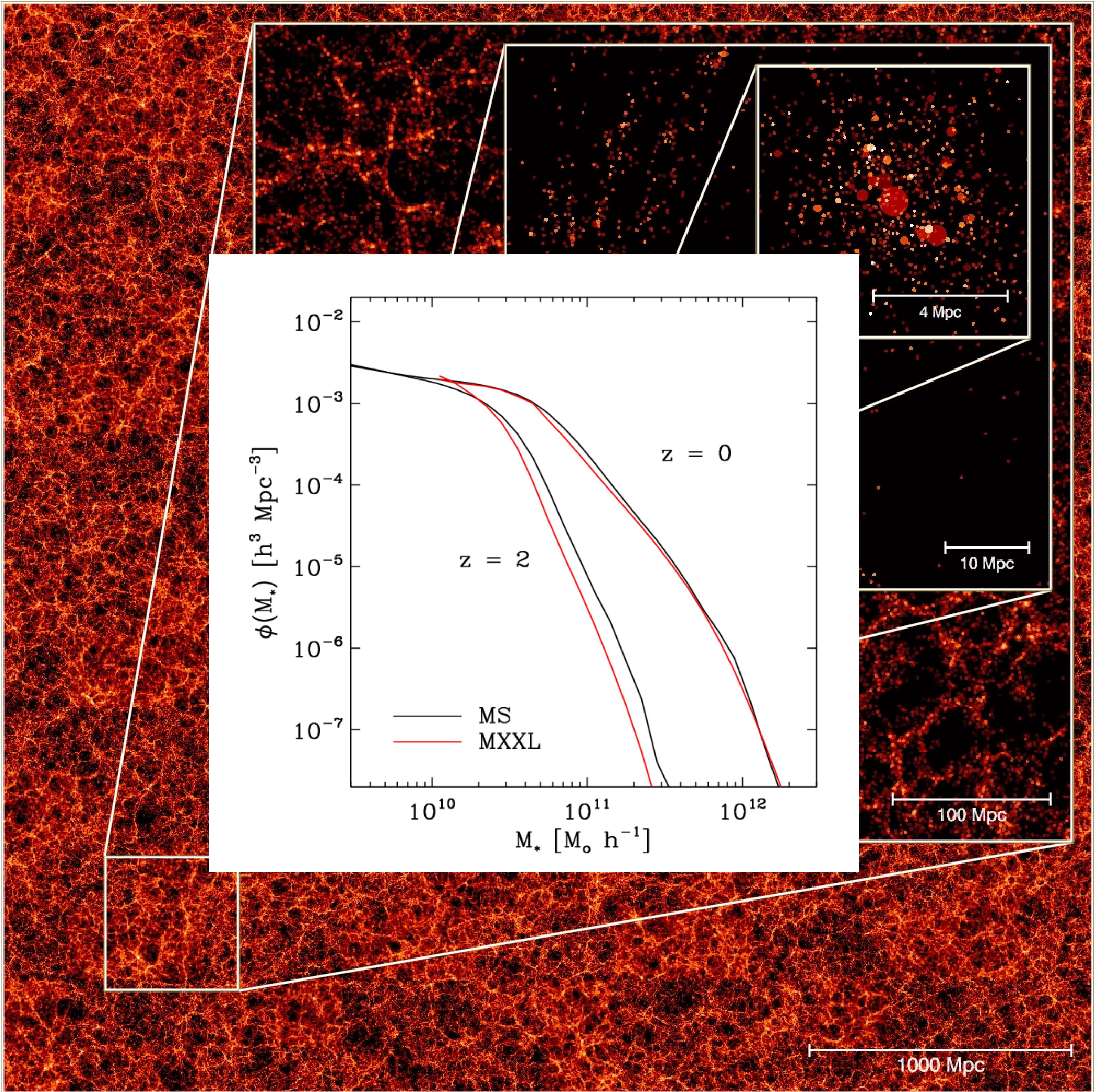
30 in $N_{particle}$

200 in Volume

6 in $m_{particle}$

3×10^8 galaxies $\log M_*/M_\odot > 10$

3×10^5 clusters $\log M_*/M_\odot > 14$



The MXXL

Angulo, Springel et al 2011

Bigger than the Millennium Run by factors of

30 in $N_{particle}$

200 in Volume

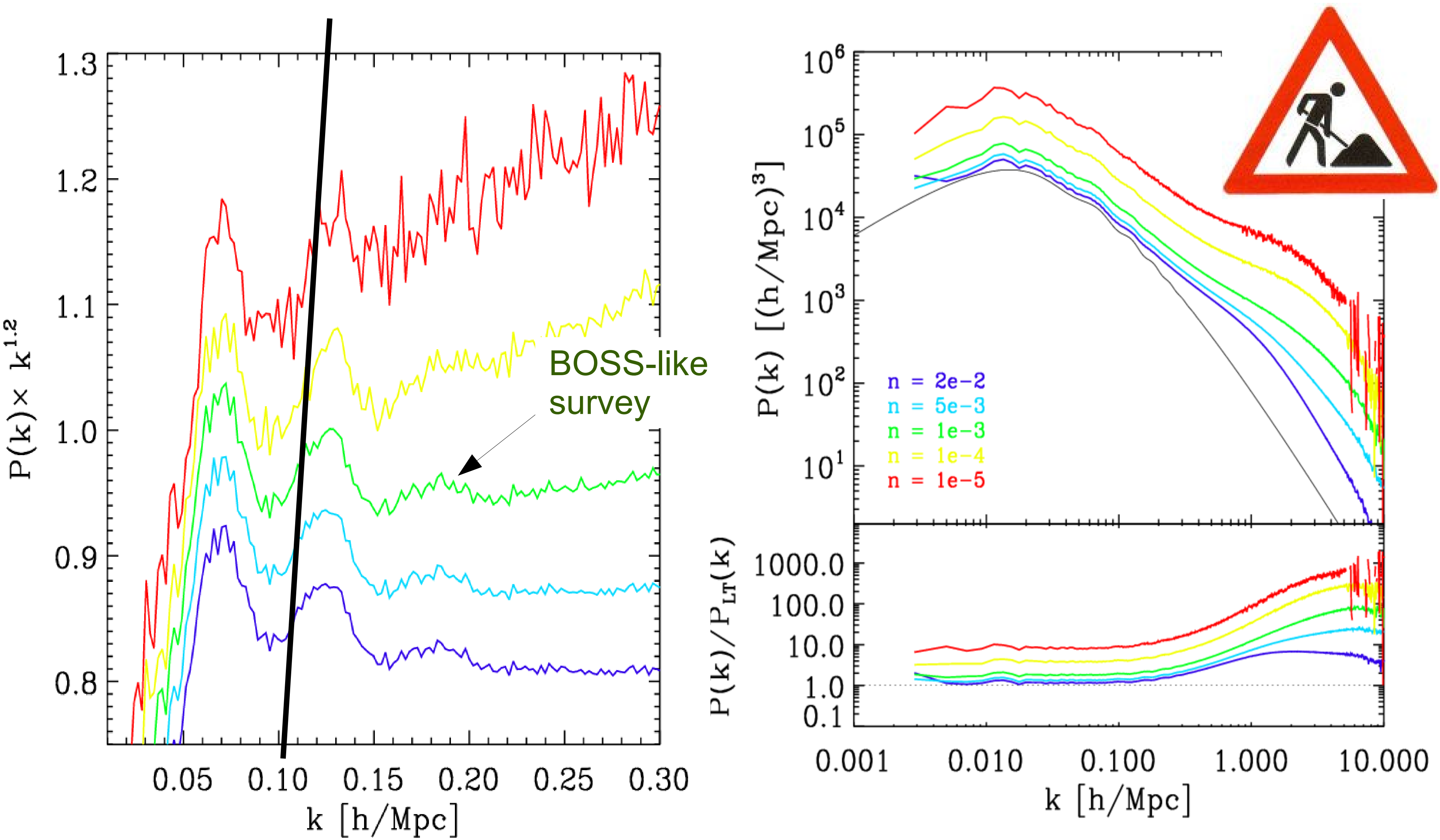
6 in $m_{particle}$

3×10^8 galaxies $\log M_*/M_\odot > 10$

3×10^5 clusters $\log M_*/M_\odot > 14$

Different galaxy catalogues in the MXXL simulation trace the BAO features with a scale-dependent bias

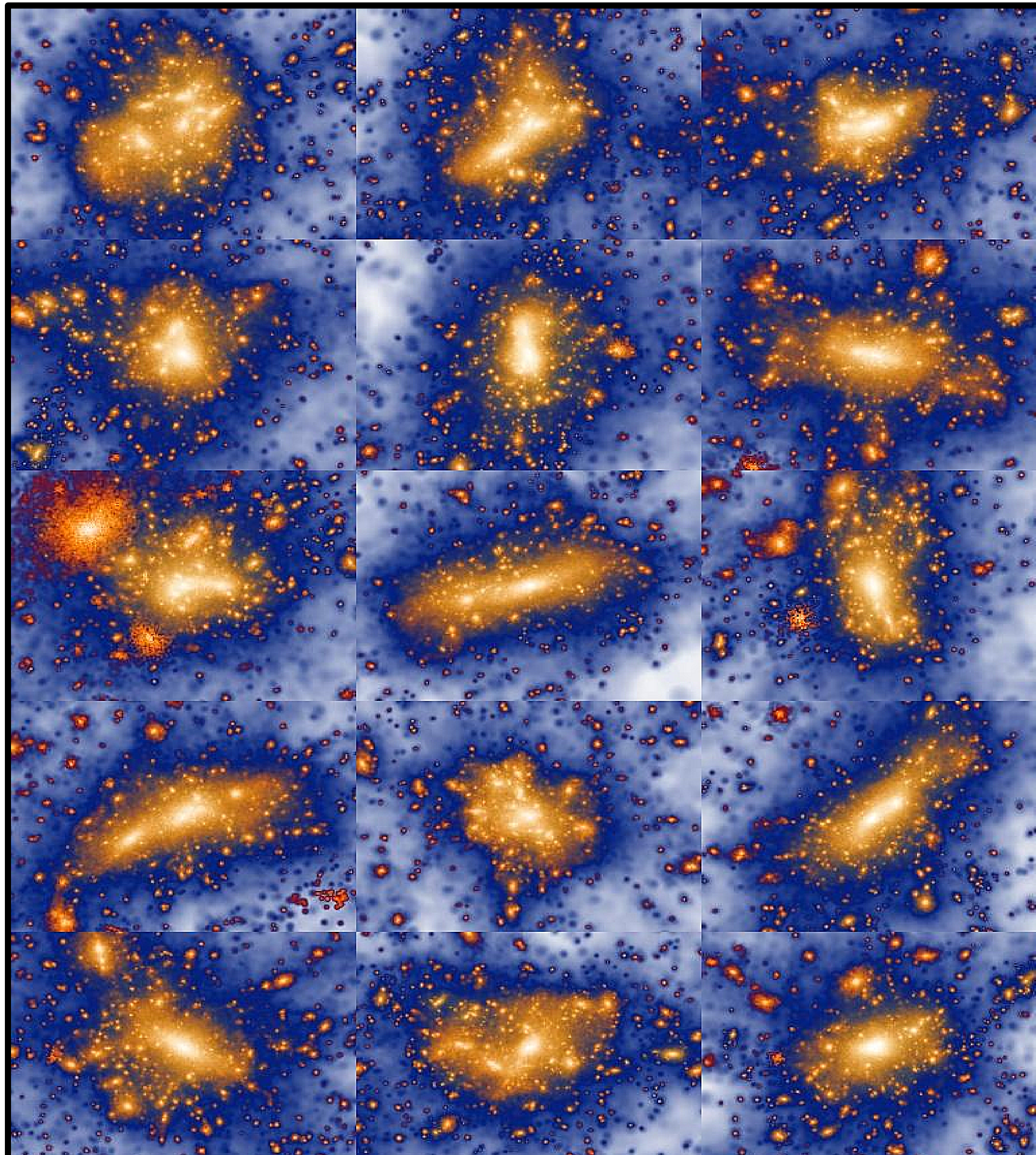
POWER SPECTRA OF THE GALAXY DISTRIBUTION AT Z=0 FOR DIFFERENT SPACE DENSITIES

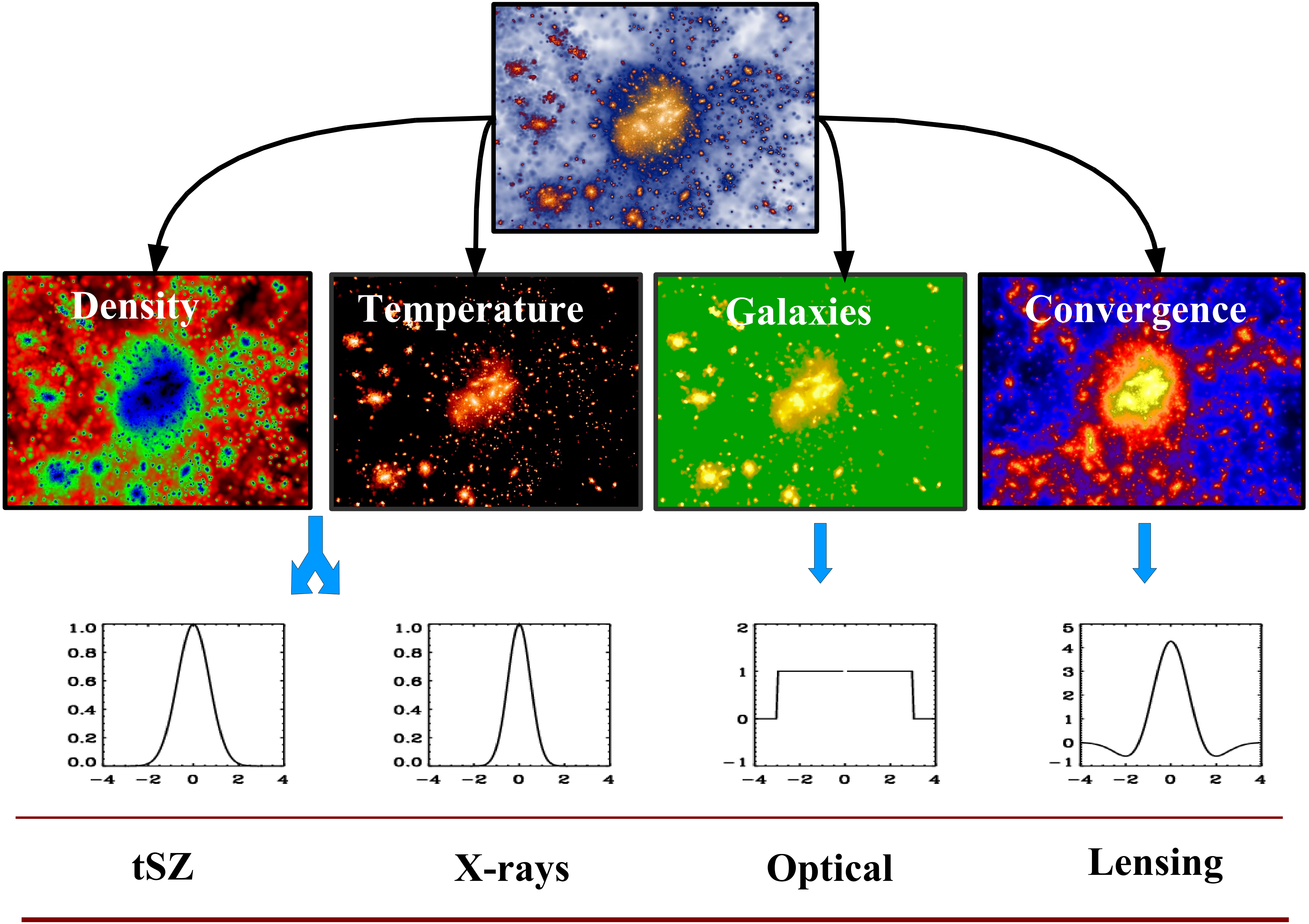


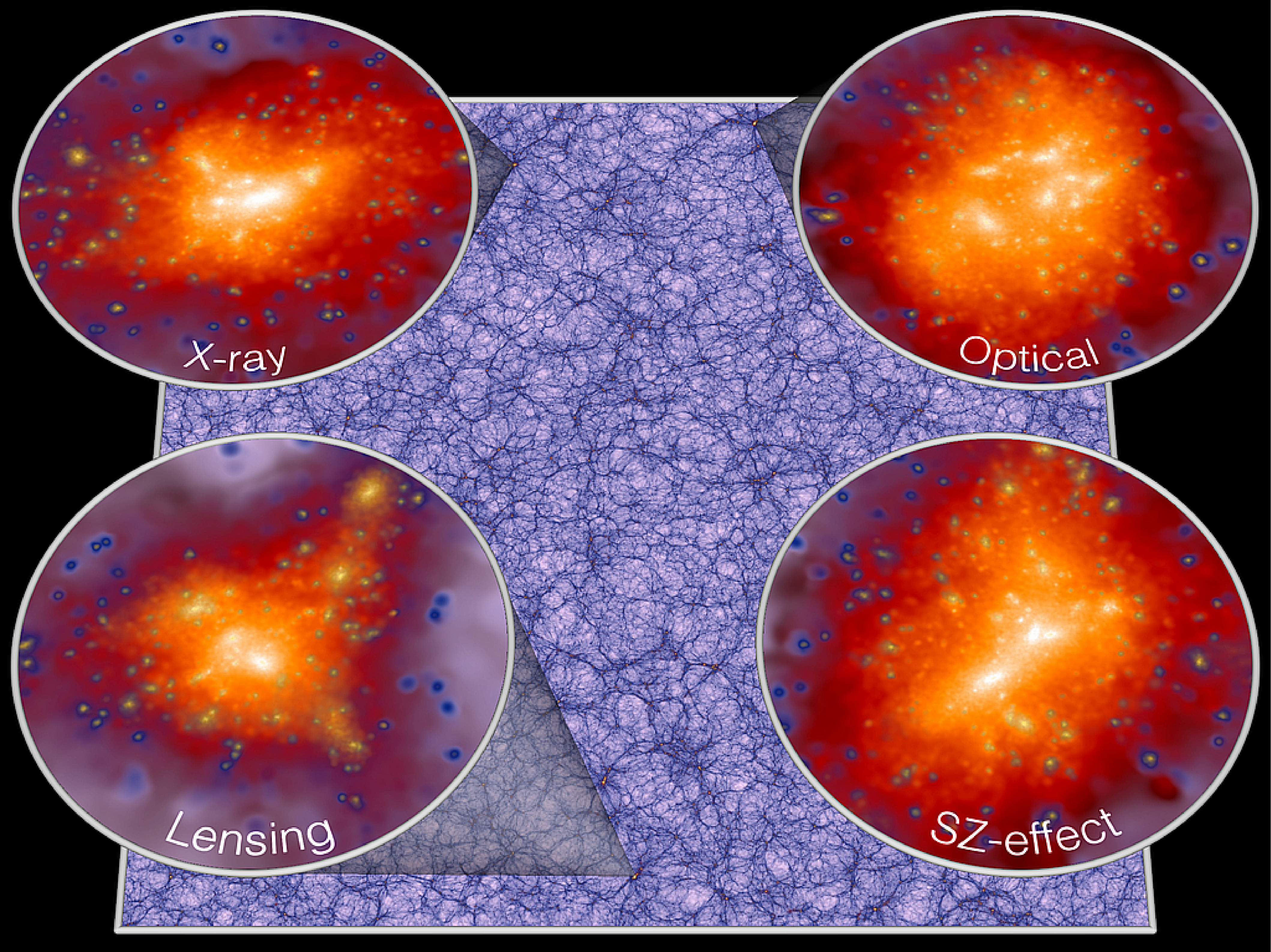
Angulo et al. (2011)

Massive clusters aren't a homogenous population and are often irregular

Snapshot z=0.32
15 most massive clusters according to M_{200}
$M = [2.5 – 4] \times 10^{15} M_\odot/h$




Density
Temperature
Galaxies
Convergence
tSZ
X-rays
Optical
Lensing



X-ray
Optical
Lensing
SZ-effect

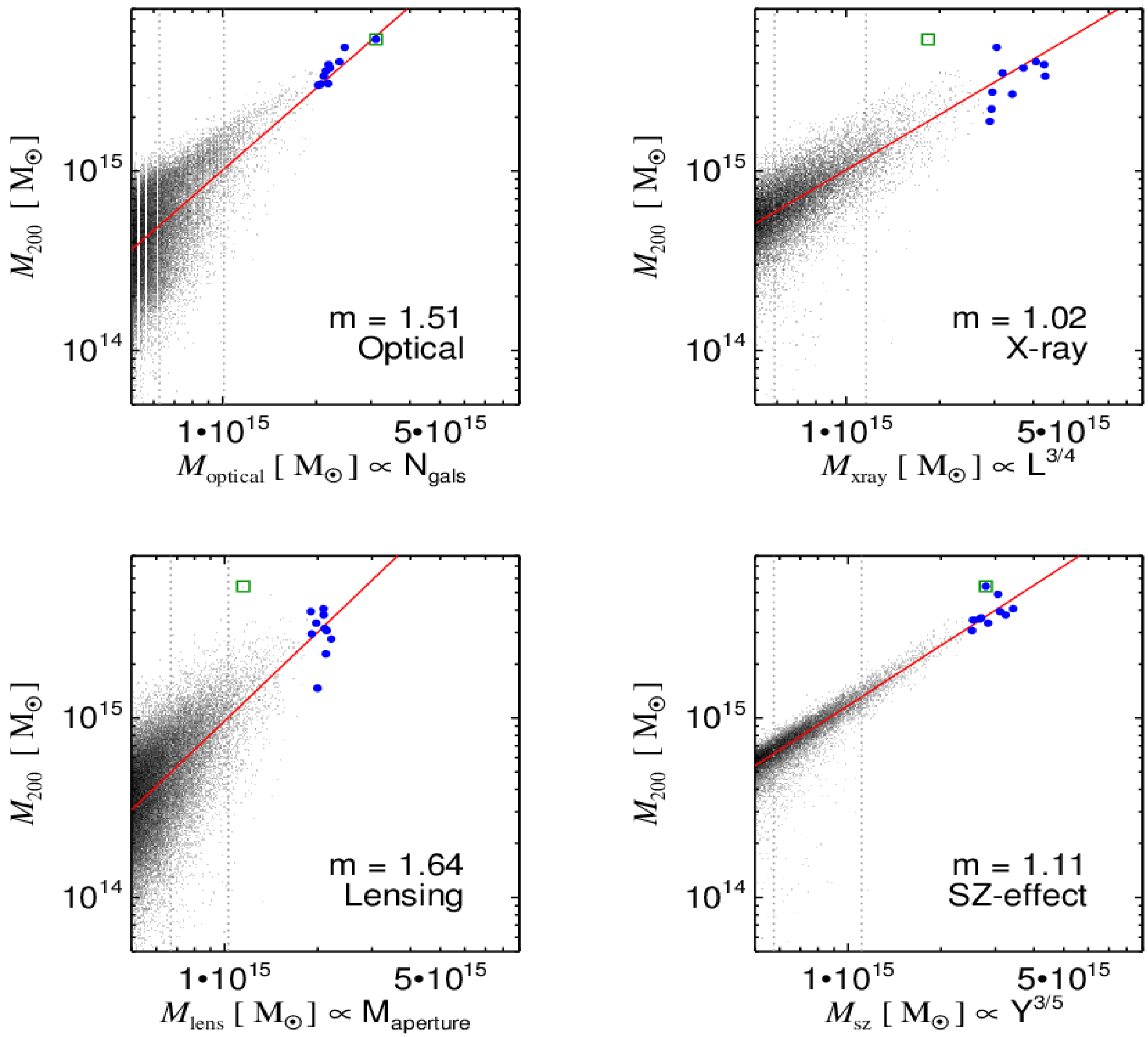
Observational techniques induce structural diversity among massive clusters

Largest observable signals on the sky are not due to the most massive objects

Different methods select objects with systematically different properties.

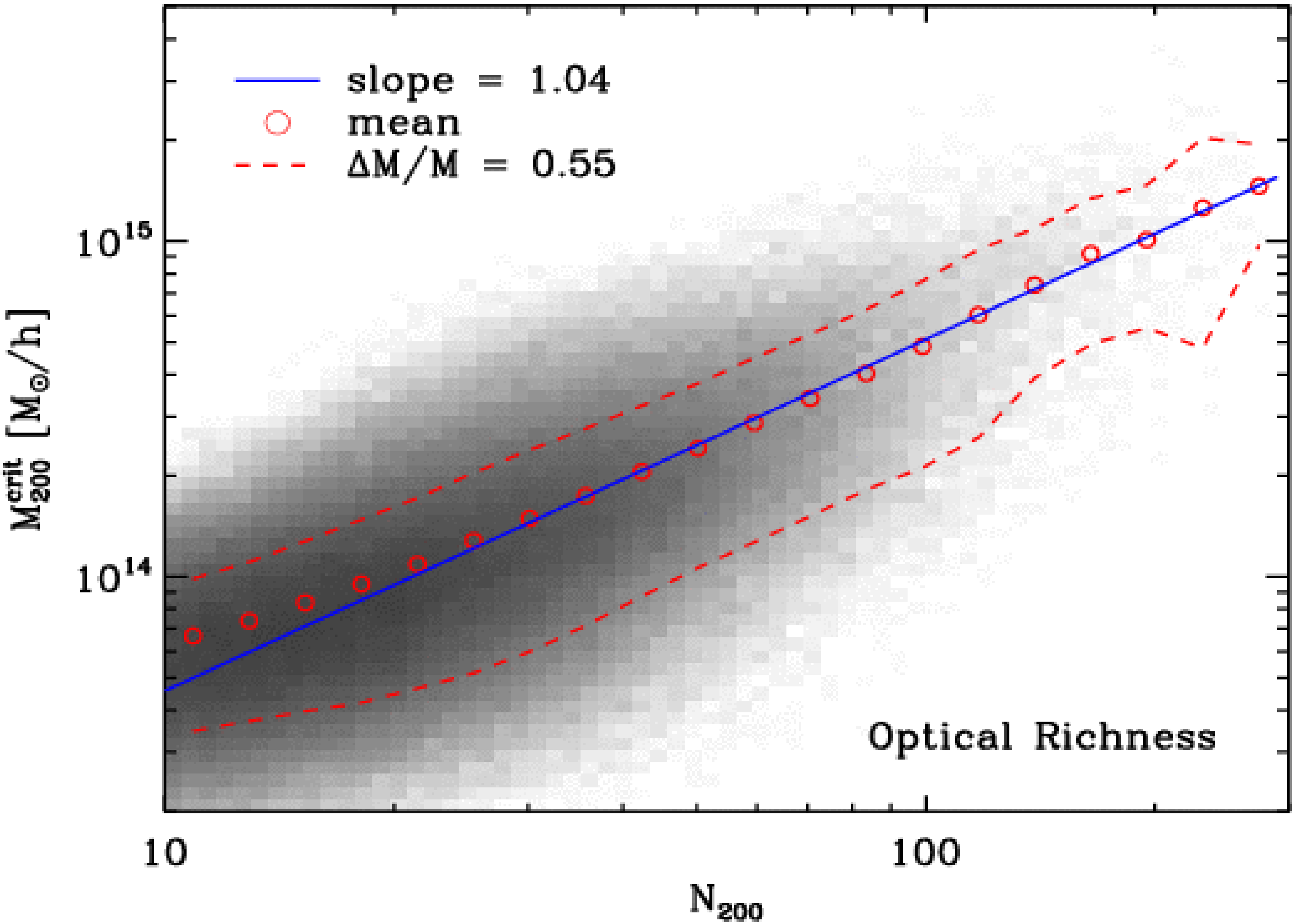
Two haloes of very different mass can have the same observable signal.

Scatter of 20% produces modifications in the observed halo mass function at the same level as primordial non-Gaussianity with $f_{nl} = 100$



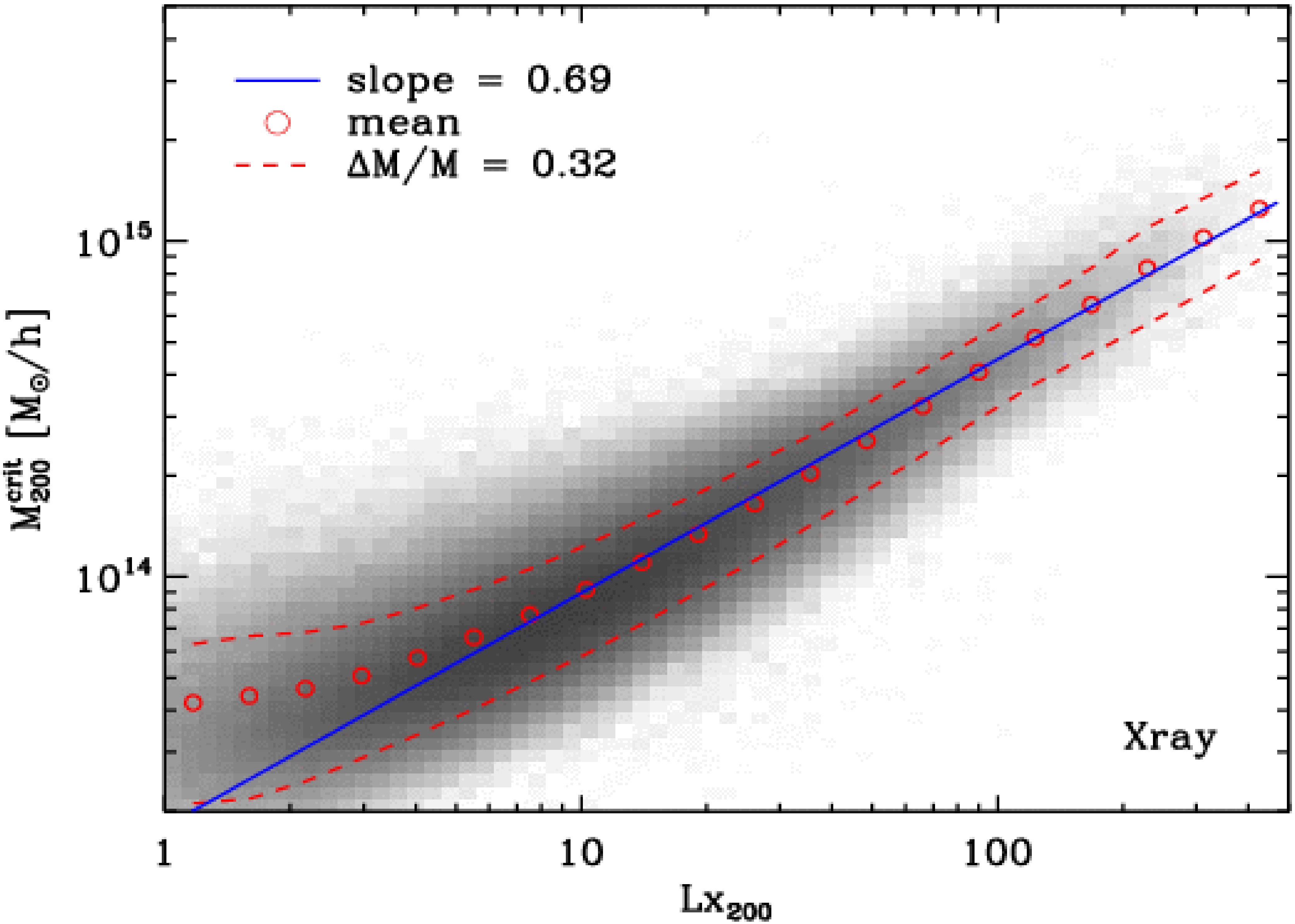
True virial mass as a function of maxBCG richness

Angulo et al 2011



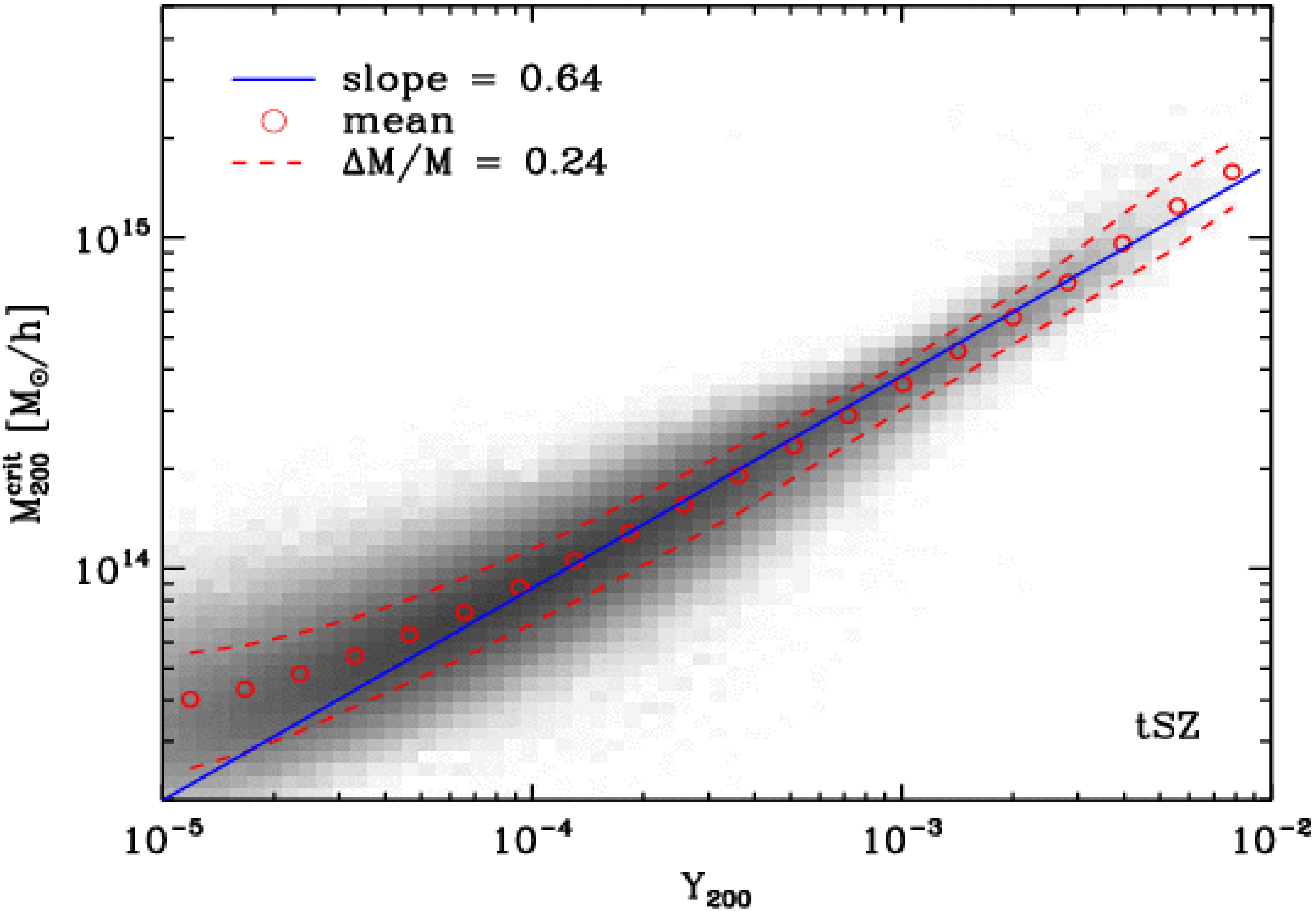
True virial mass as a function of maxBCG L_X

Angulo et al 2011



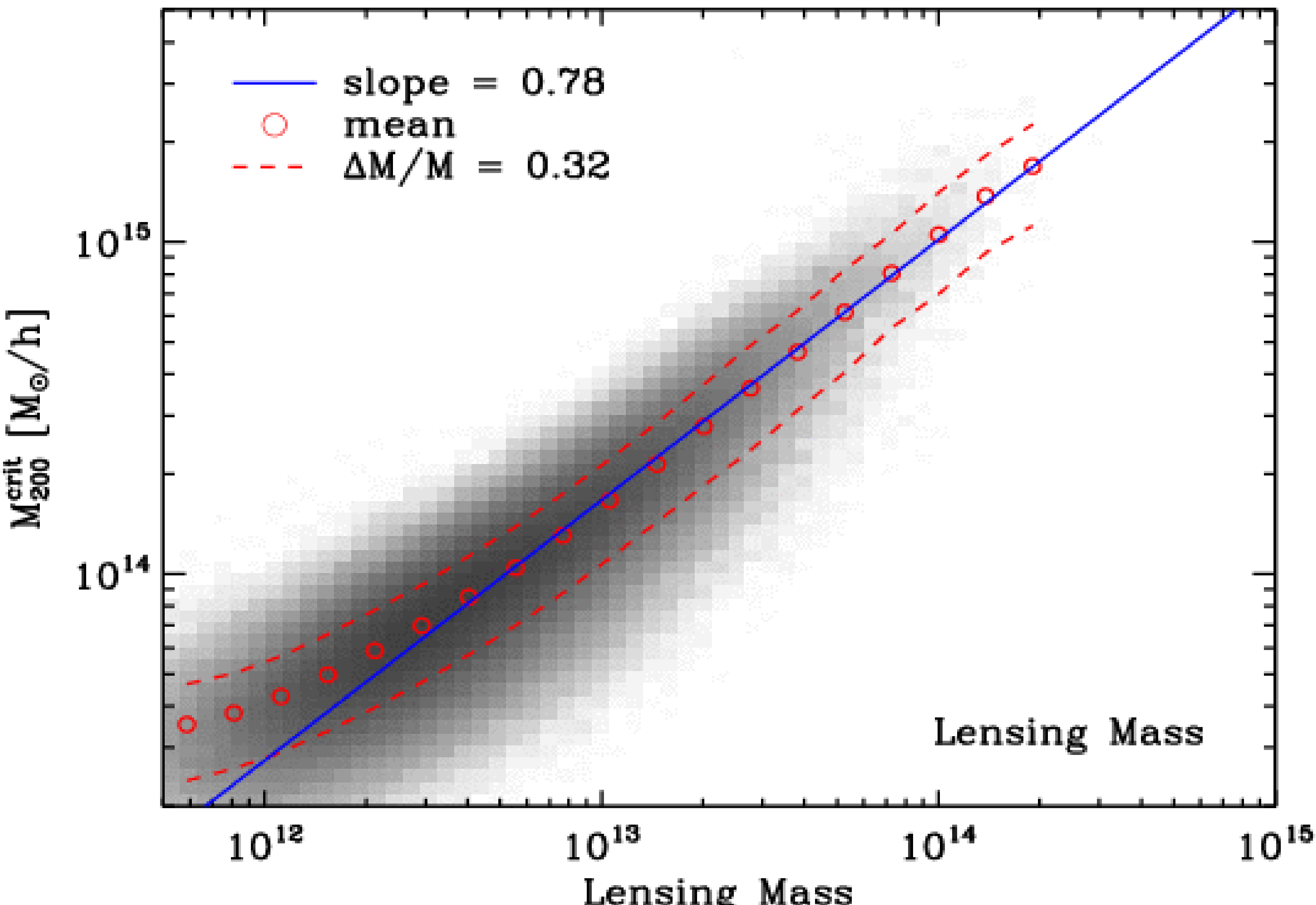
True virial mass as a function of maxBCG Y_{SZ}

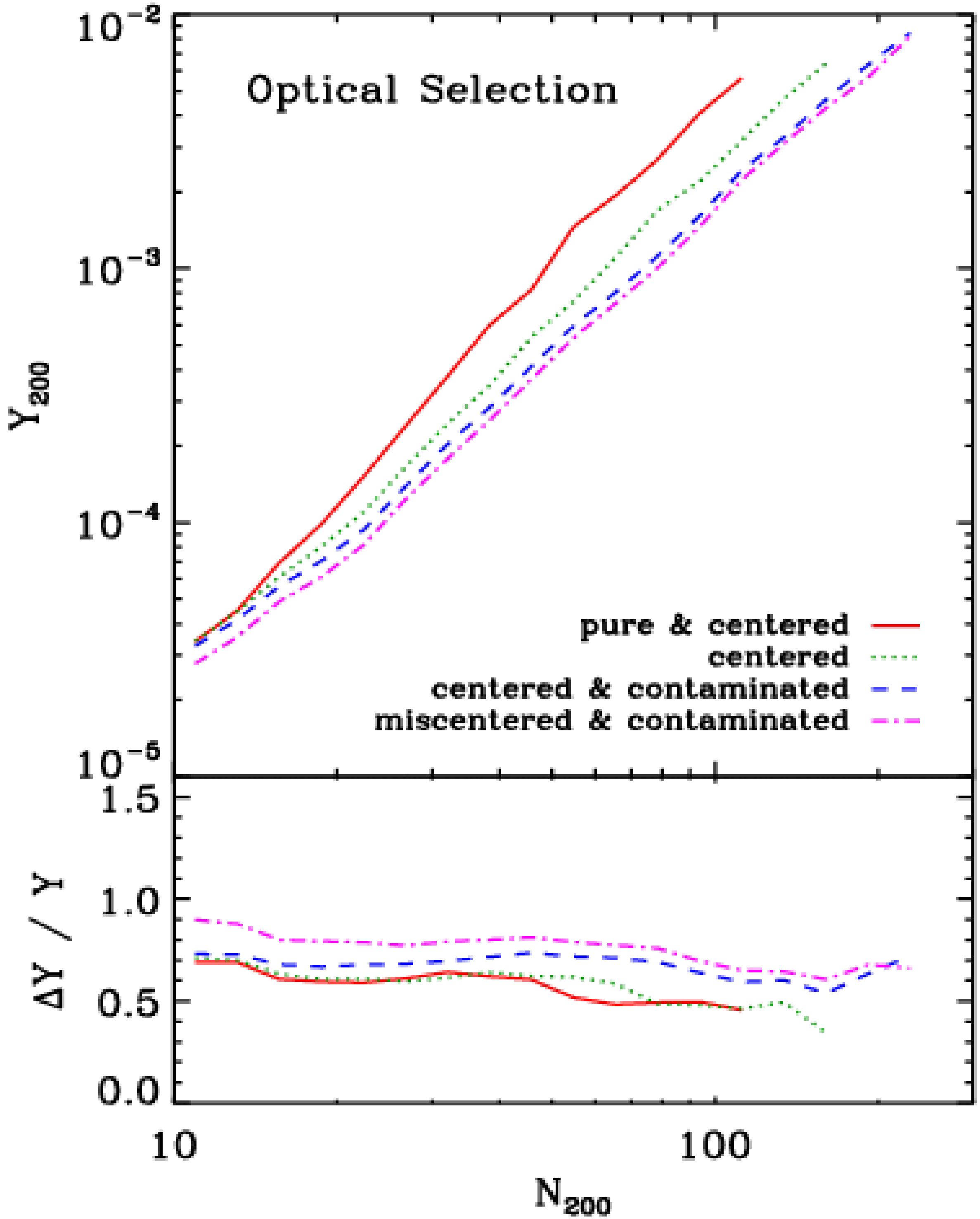
Angulo et al 2011



True virial mass as a function of maxBCG M_{lens}

Angulo et al 2011

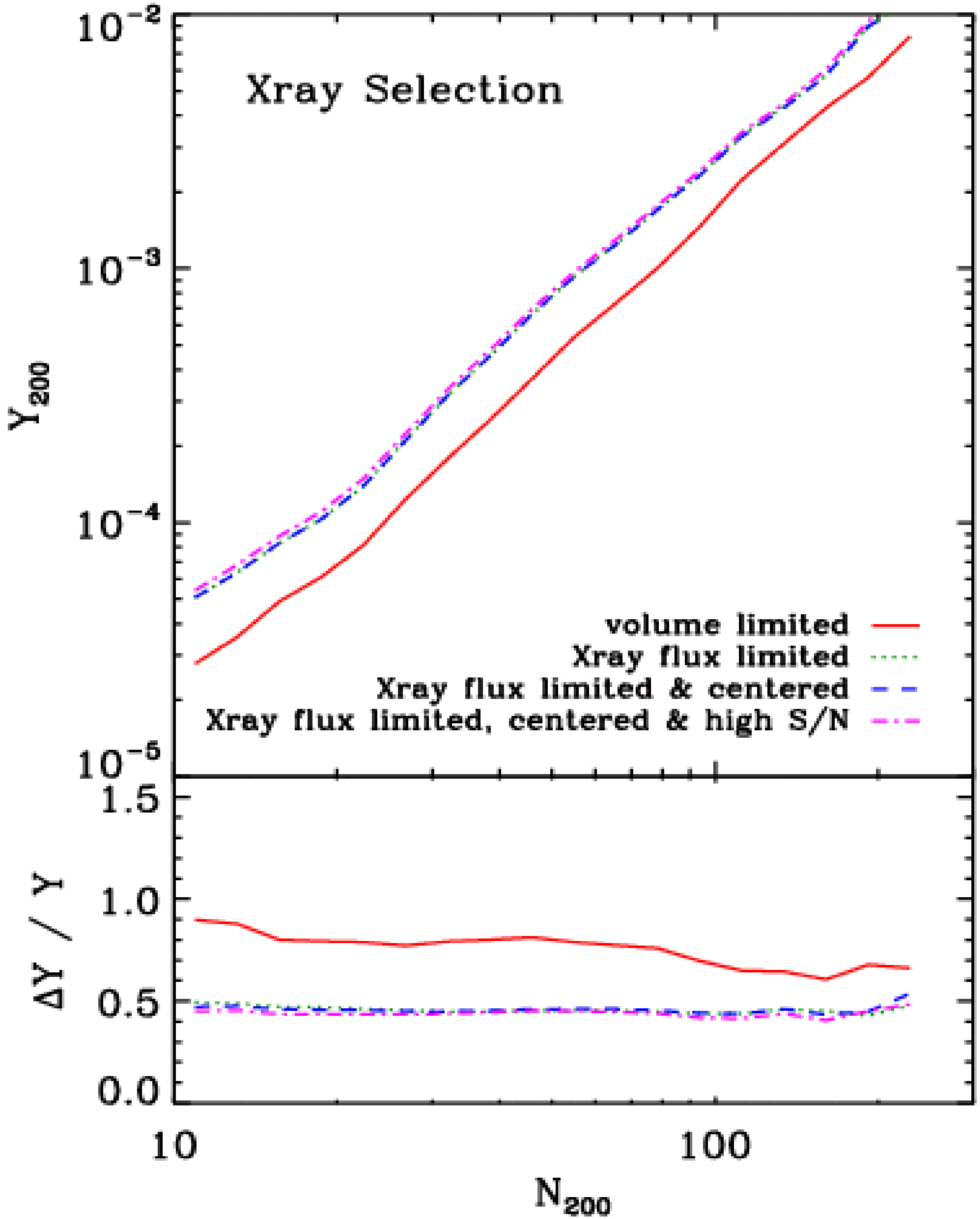




SZ–richness relations and observational selection

Angulo et al 2011

- projection effects lower the mean SZ signal and increase the scatter at given (apparent) N_{200}
- Miscentering (incorrect BCG choice) increases scatter



SZ–richness relations and observational selection

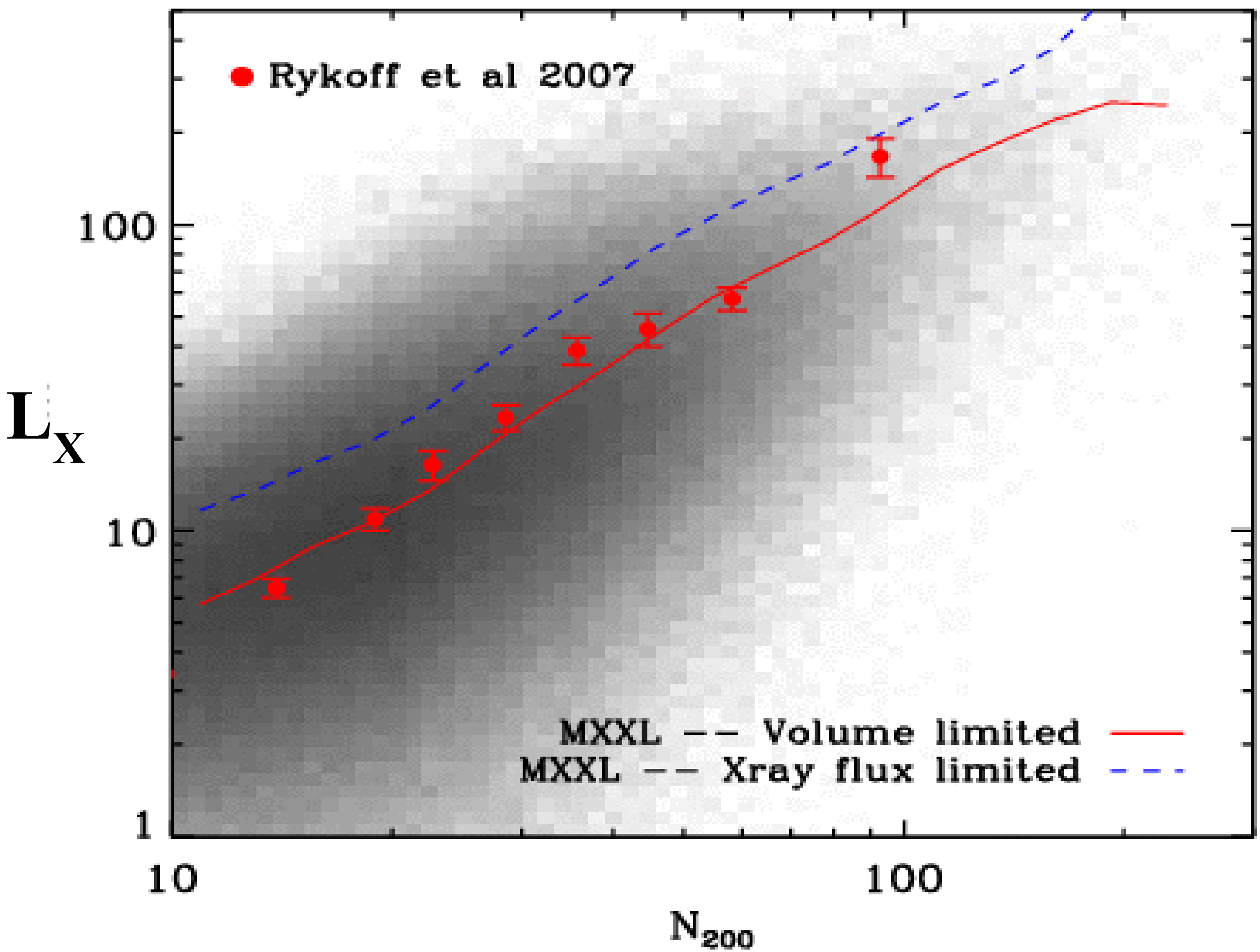
Angulo et al 2011

- cluster catalogues which are flux-limited at given richness (or mass) have higher mean SZ signal than if volume-limited

- They also have much smaller scatter in Y at given richness (or mass)

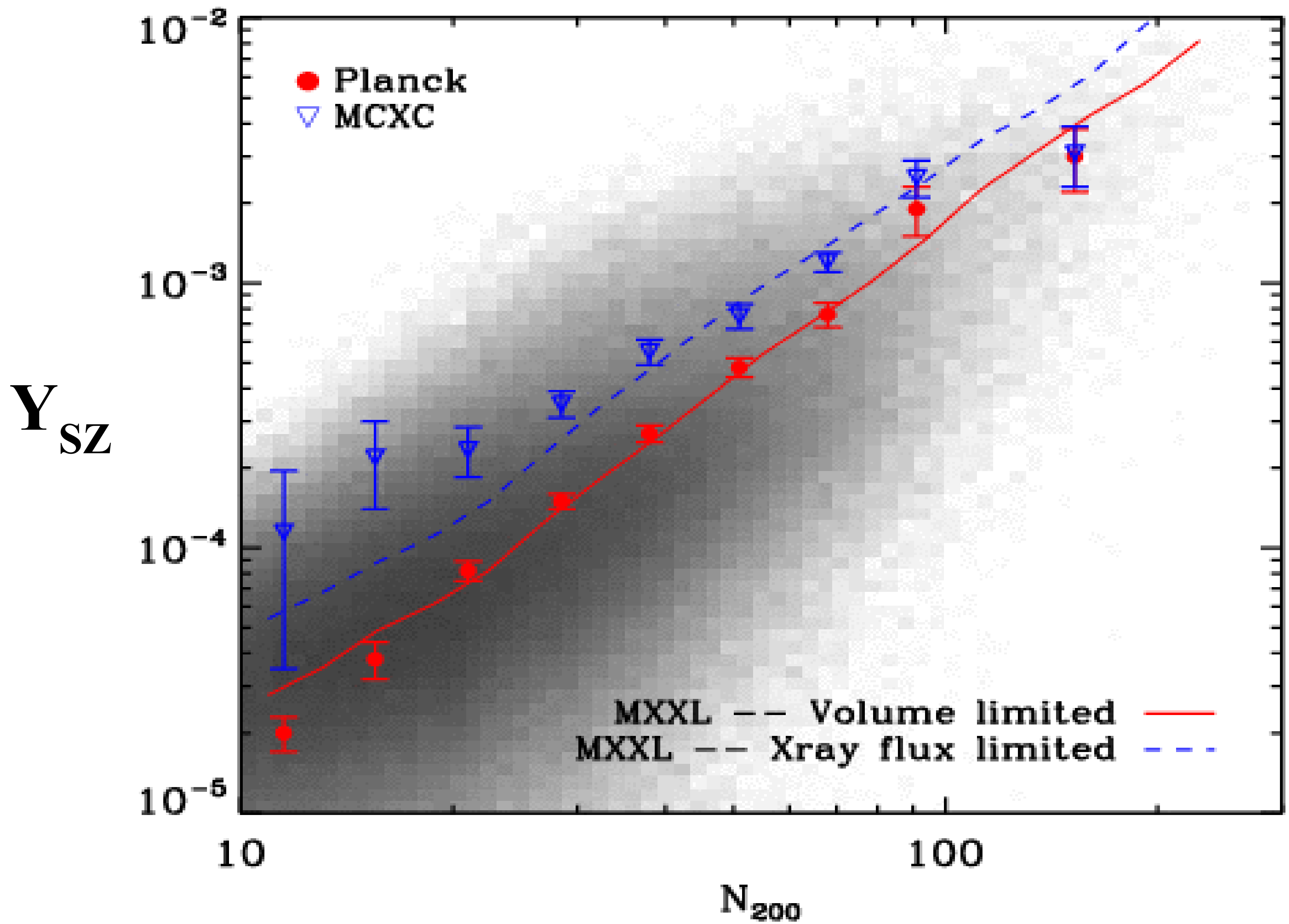
Stacked L_X as a function of maxBCG richness

Angulo et al 2011



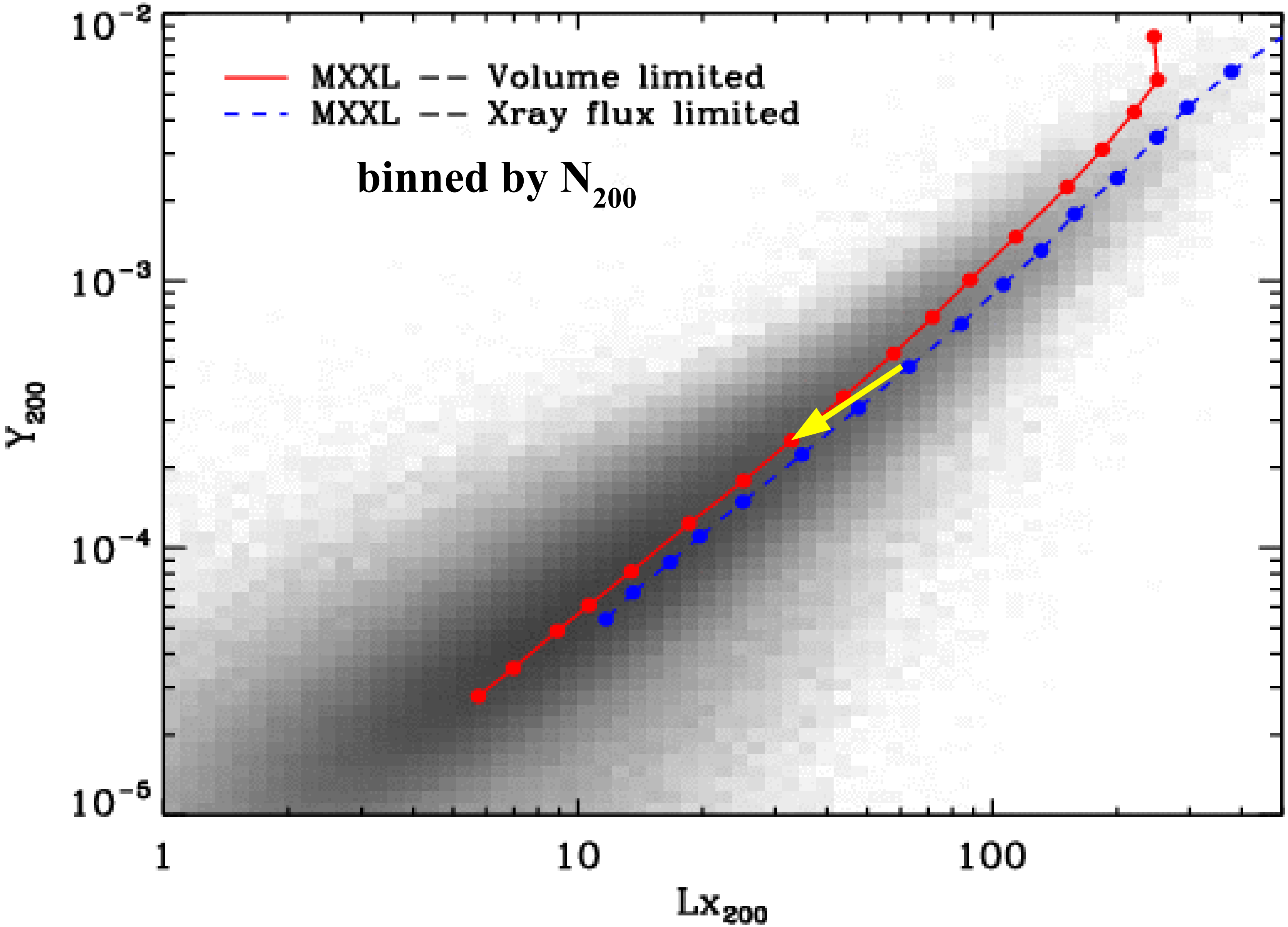
Stacked Y_{SZ} as a function of maxBCG richness

Angulo et al 2011



Y_{SZ} as a function of L_X around BCG centres

Angulo et al 2011



Conclusions

- The ΛCDM cluster population is expected to show almost self-similar scalings but with large scatter

- "Observed" scaling relations will depend substantially on survey strategy and on the definition of the observables

- Both slopes and amplitudes can be affected by such bias

- The apparent inconsistency found by Planck in SZ signals from stacked maxBCG and X-ray clusters *may* reflect such effects

- Precision cosmology with clusters will require purpose-designed surveys with calibration strategies which fully account for the scatter in all relations between observables