Modelling galaxy cluster evolution

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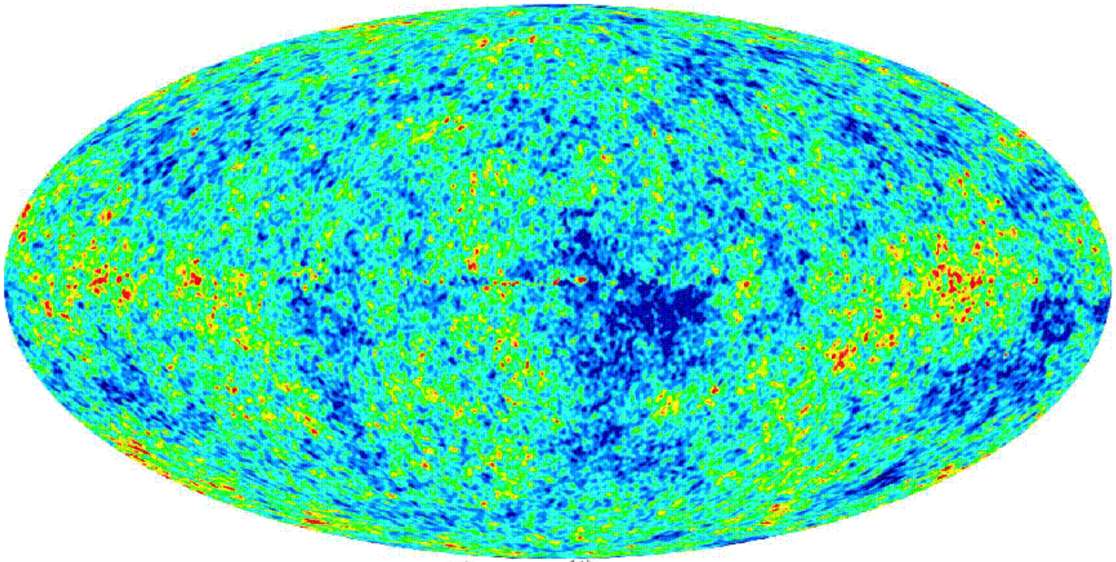
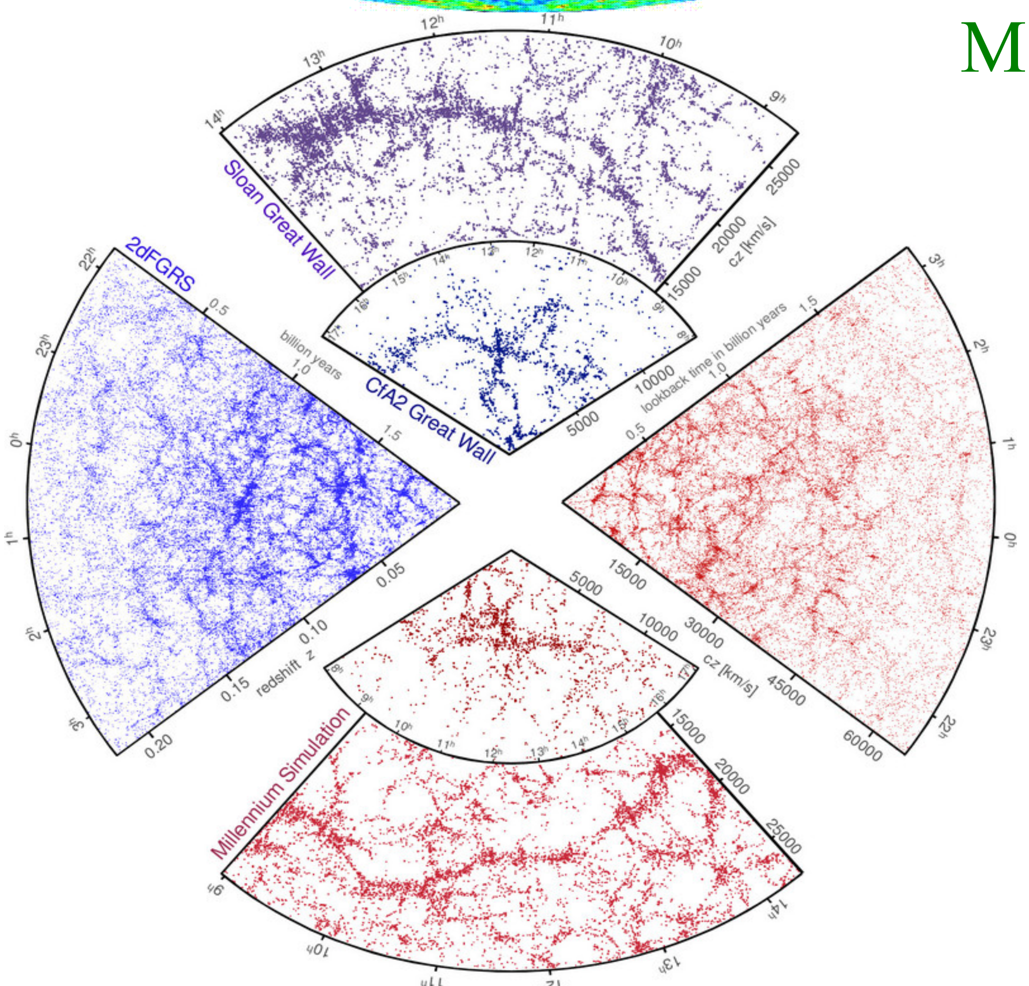
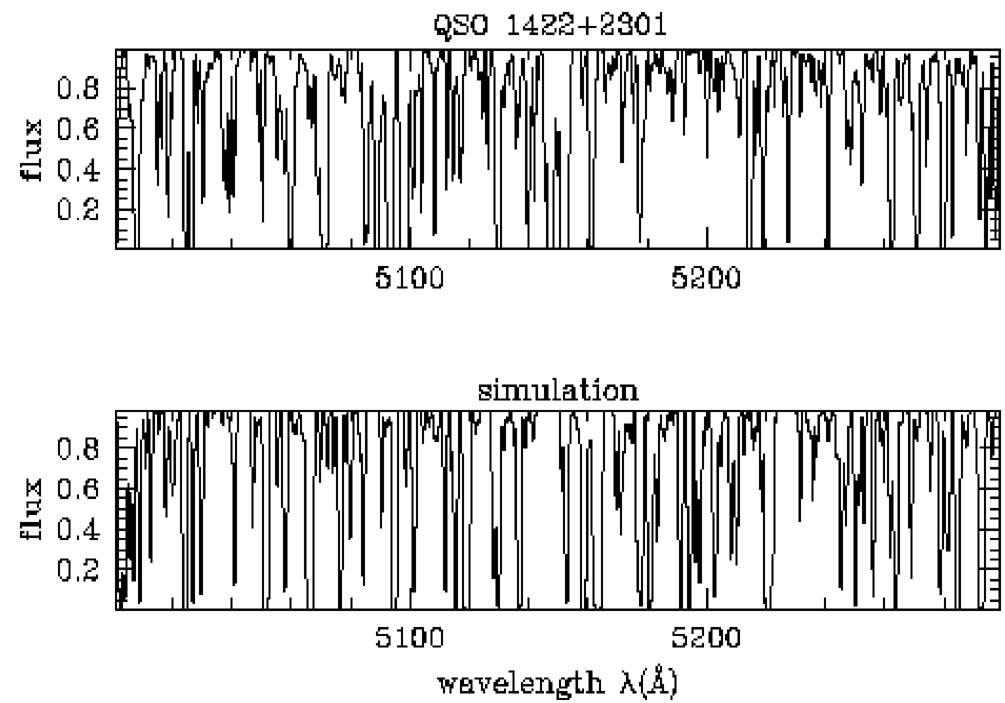
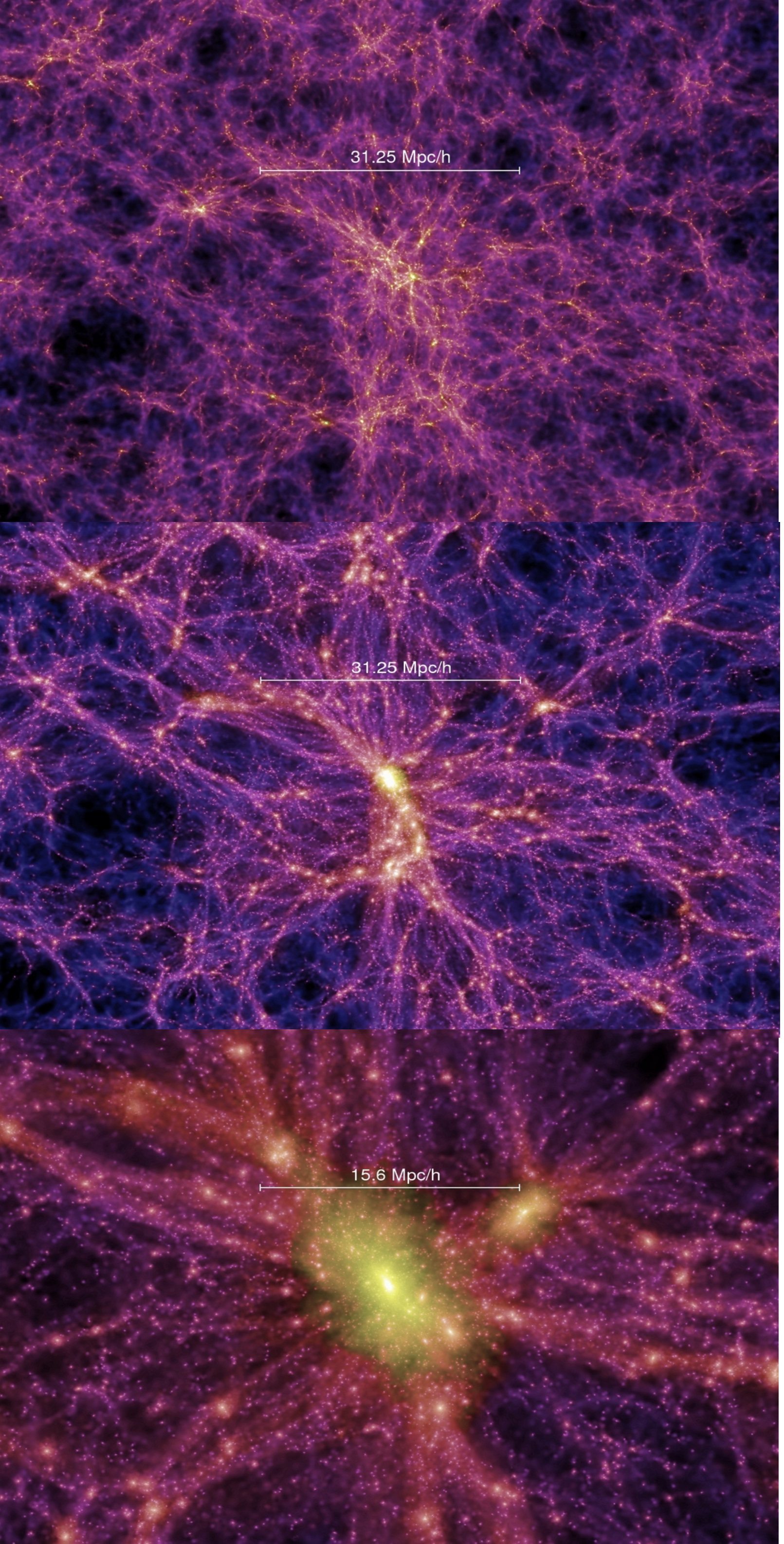








- The standard model reproduces
  - -- the linear initial conditions
  - -- IGM structure during galaxy formation
  - -- large-scale structure today
- Simulation of the standard model gives *precise* predictions for the
  - -- abundance
  - -- internal structure
  - -- assembly history
  - -- spatial/peculiar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

  of DM halos at all redshifts

How do galaxies form and evolve within this frame?

How do cluster environments affect galaxy formation and evolution?

Direct simulation of cluster/galaxy formation

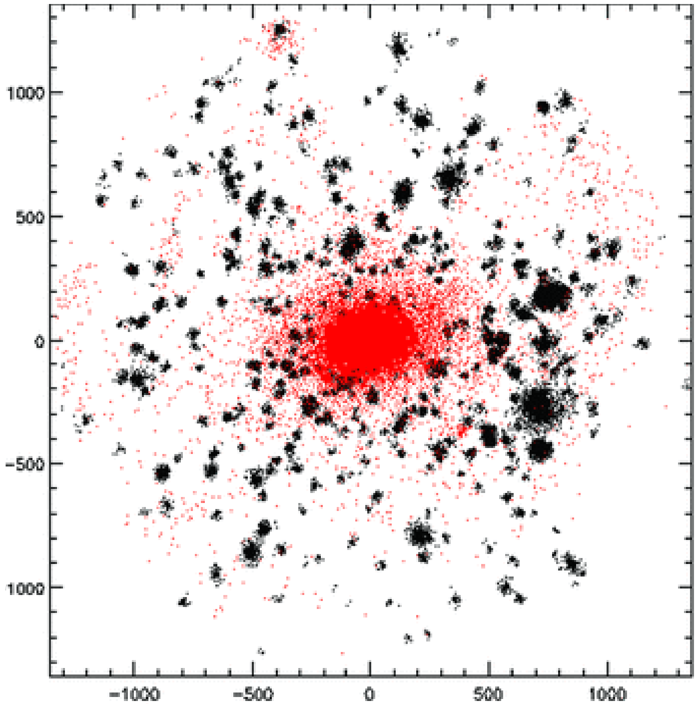
- $M_{tot}(\text{Coma}) \sim 10^3 M_{tot}(\text{Milky Way})$

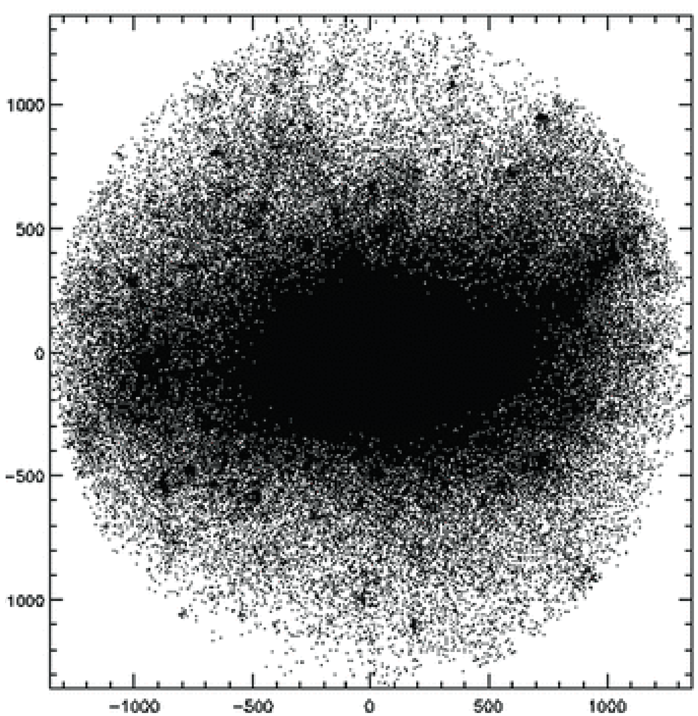
  Simulating formation of Coma's galaxy population is ~1000 times harder than simulating the formation of the Milky Way

- The problem is made even harder by the strong effects of

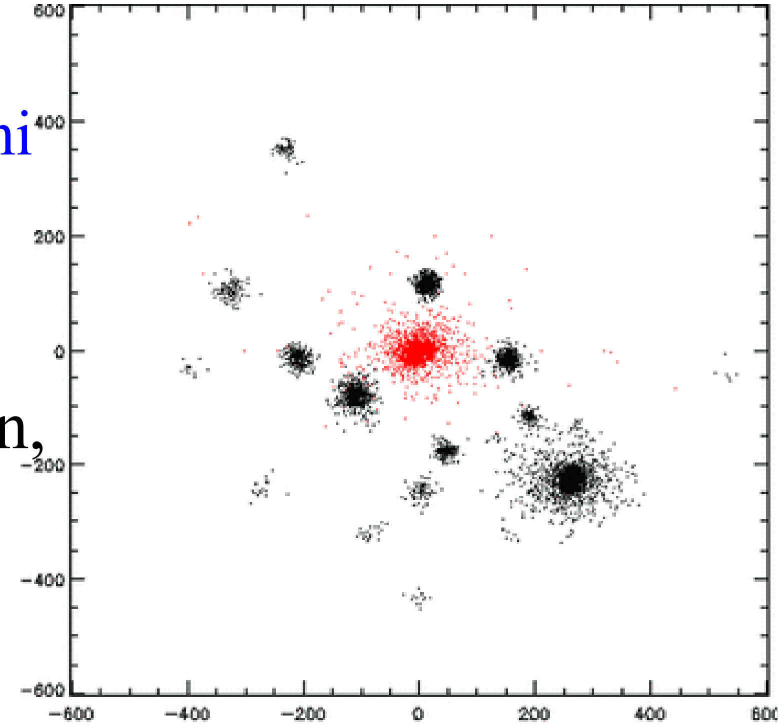
  -- the intergalactic medium
  -- tidal stripping
  -- galaxy collisions and mergers
  -- AGN feedback

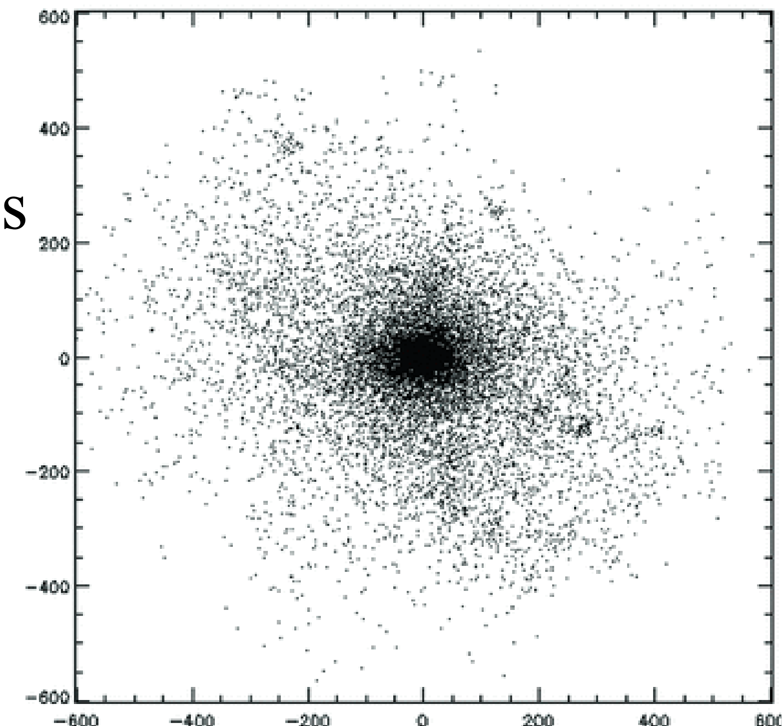
“Coma” log(M) = 15.2





“Virgo” log(M) = 14.3



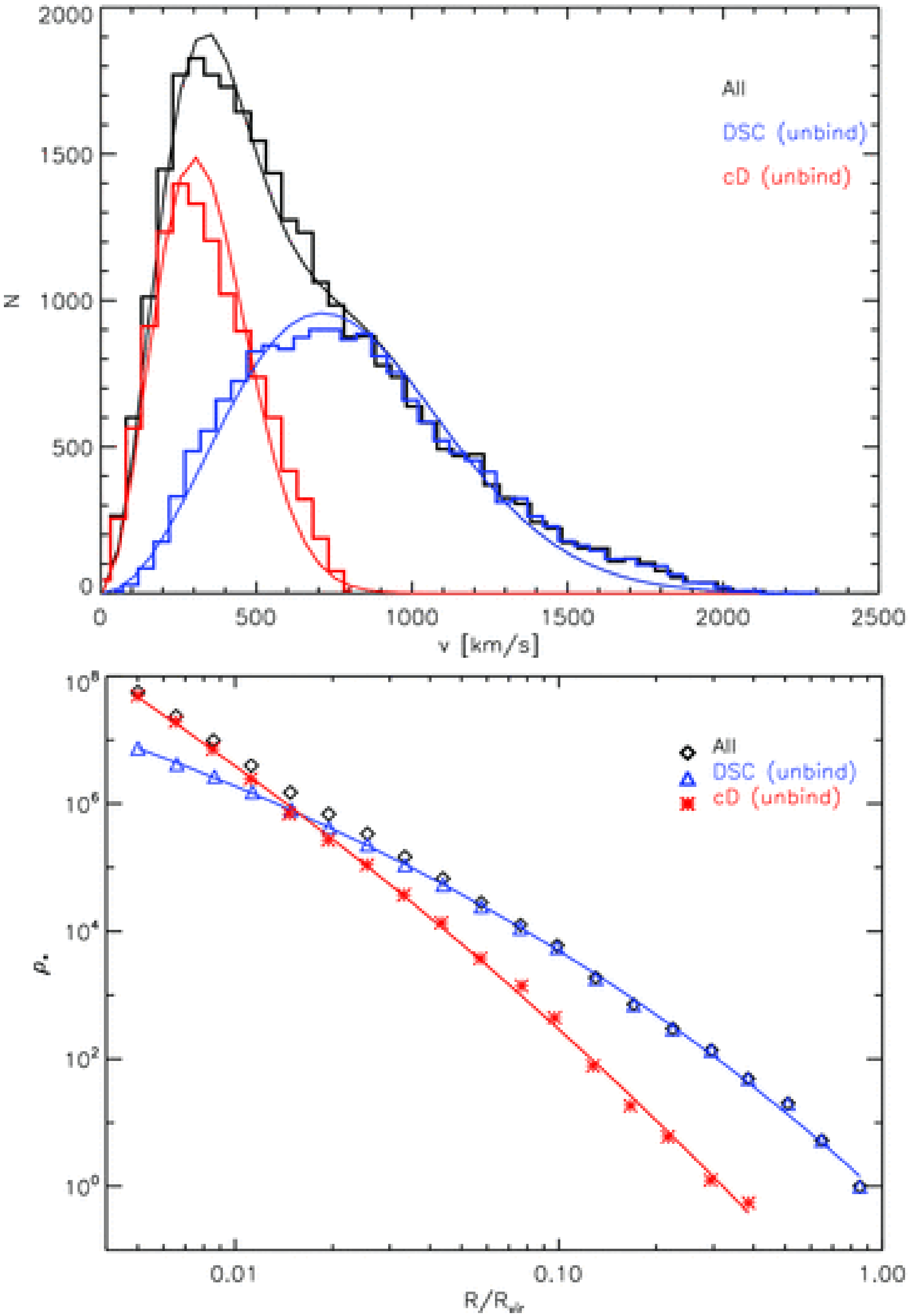


Dolag, Murante, Borgani (2010)

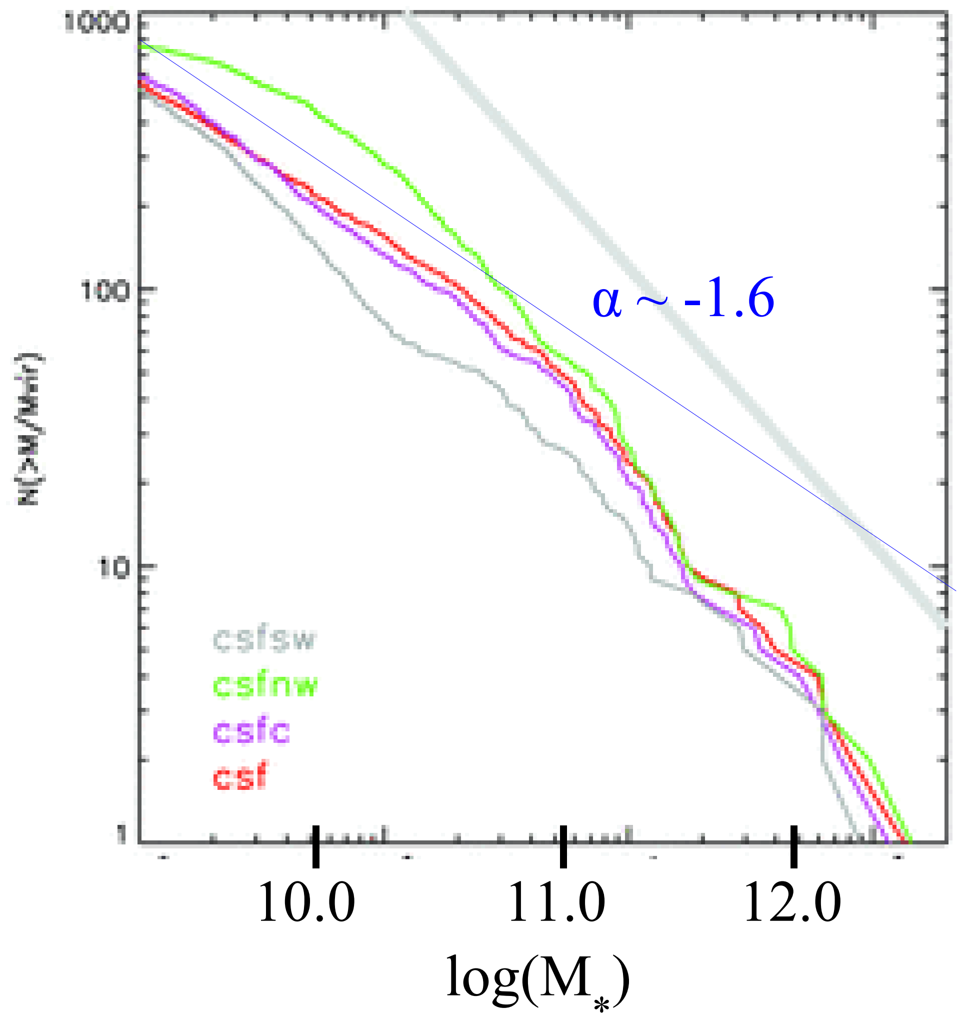
Simulations include cooling, star-formation, strong galactic winds, but no AGN effects

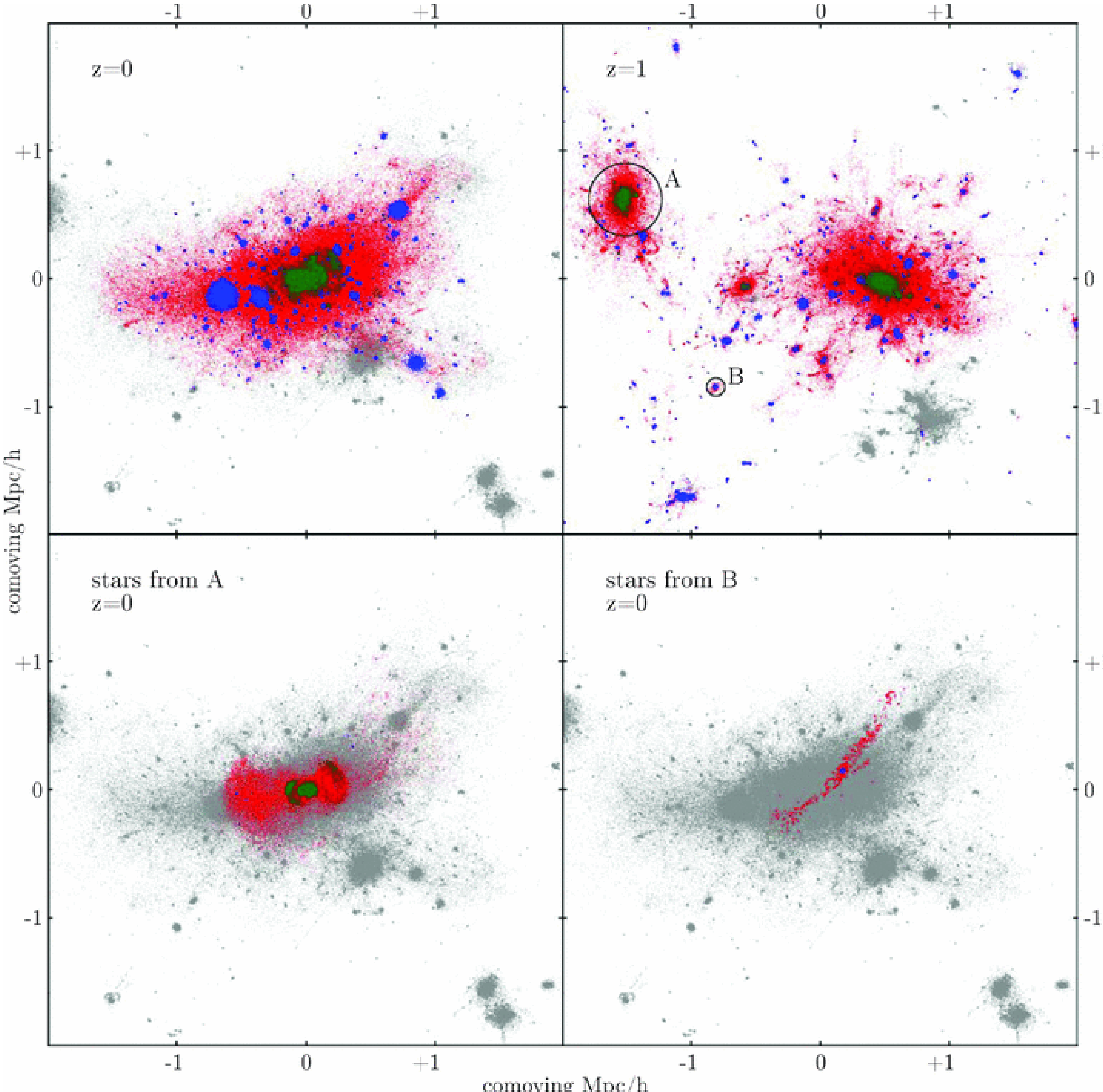
Of the “Coma” stars
42% are ICL
23% are the cD
35% are other galaxies

Dolag, Murante, Borgani (2010)



Dolag et al.(2009)





Puchwein et al. (2010)

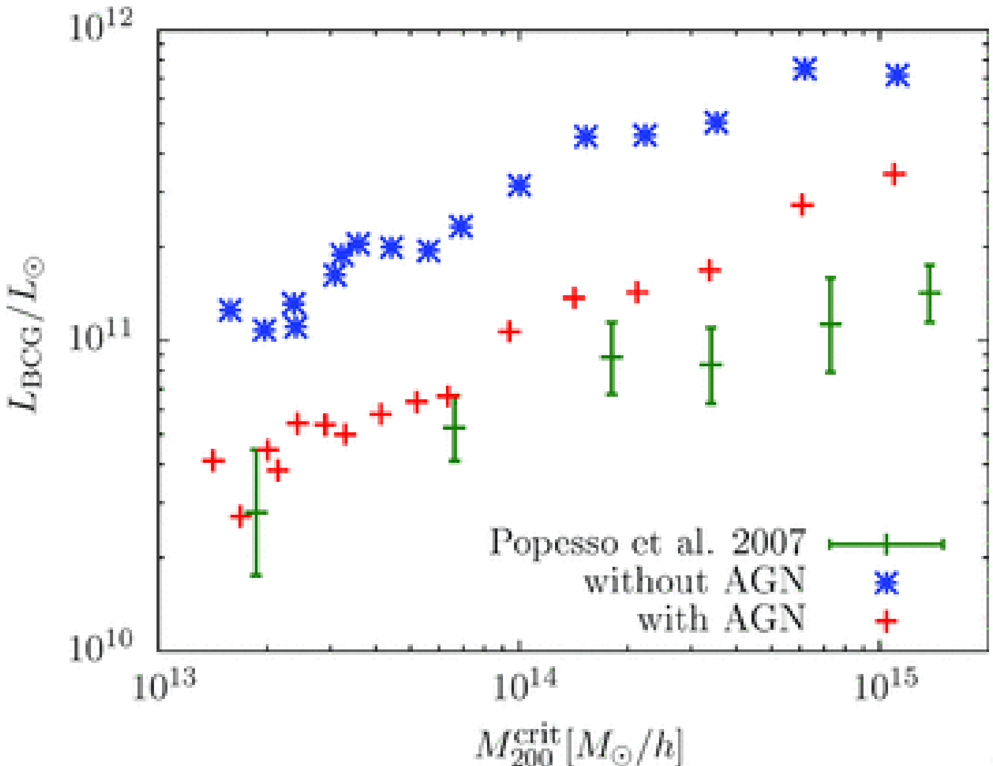
“Virgo” model including AGN feedback.

Baryon content 70% of cosmic mean

60% of baryons in stars

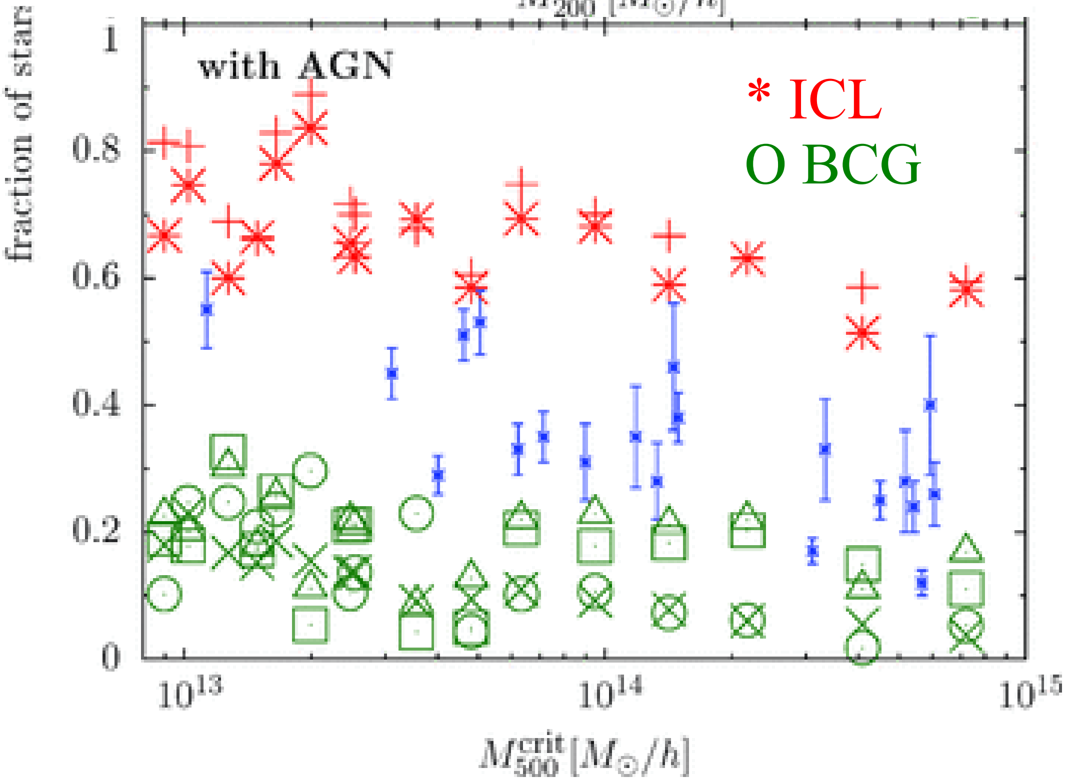
65% of stars in the ICL

50% of galaxy stars in the cD



Puchwein et al. (2010)

AGN feedback reduces cD luminosities to almost the observed values



The stellar fractions in the ICL exceed even the largest quoted observational values

The semi-analytic programme

- Follow the DM distribution with high-resolution simulations

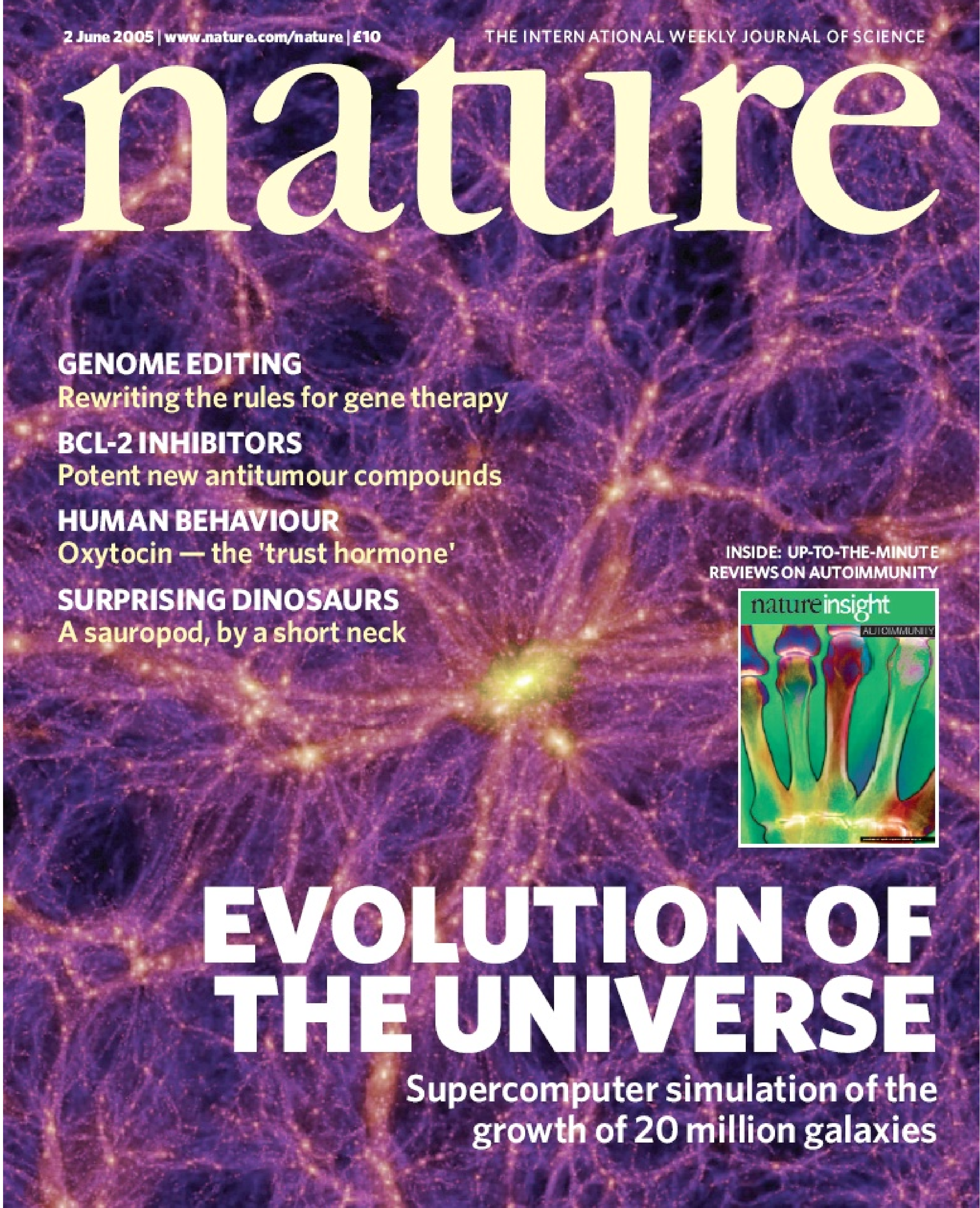
  identify dark halos and subhalos at all times and build merger trees to describe their growth and internal structure

- Treat baryonic physics within each DM object using simple physical models for processes such as

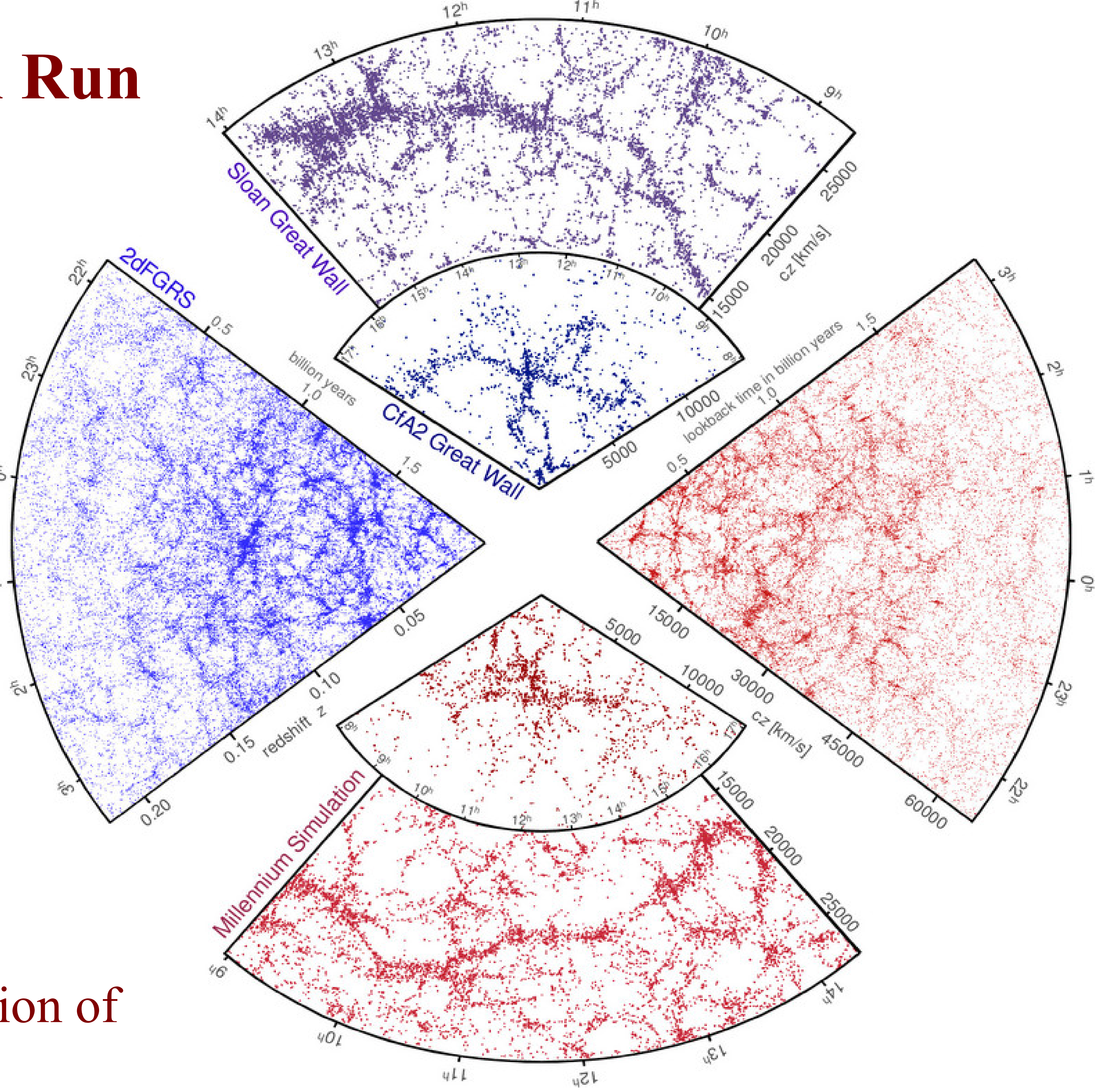
  gas cooling onto central galaxies
  star formation within these central galaxies
  central black hole growth
  generation of winds through stellar and AGN feedback
  production, expulsion and mixing of nucleosynthesis products

- Determine the efficiencies of these processes observationally by comparison of model output with appropriate data

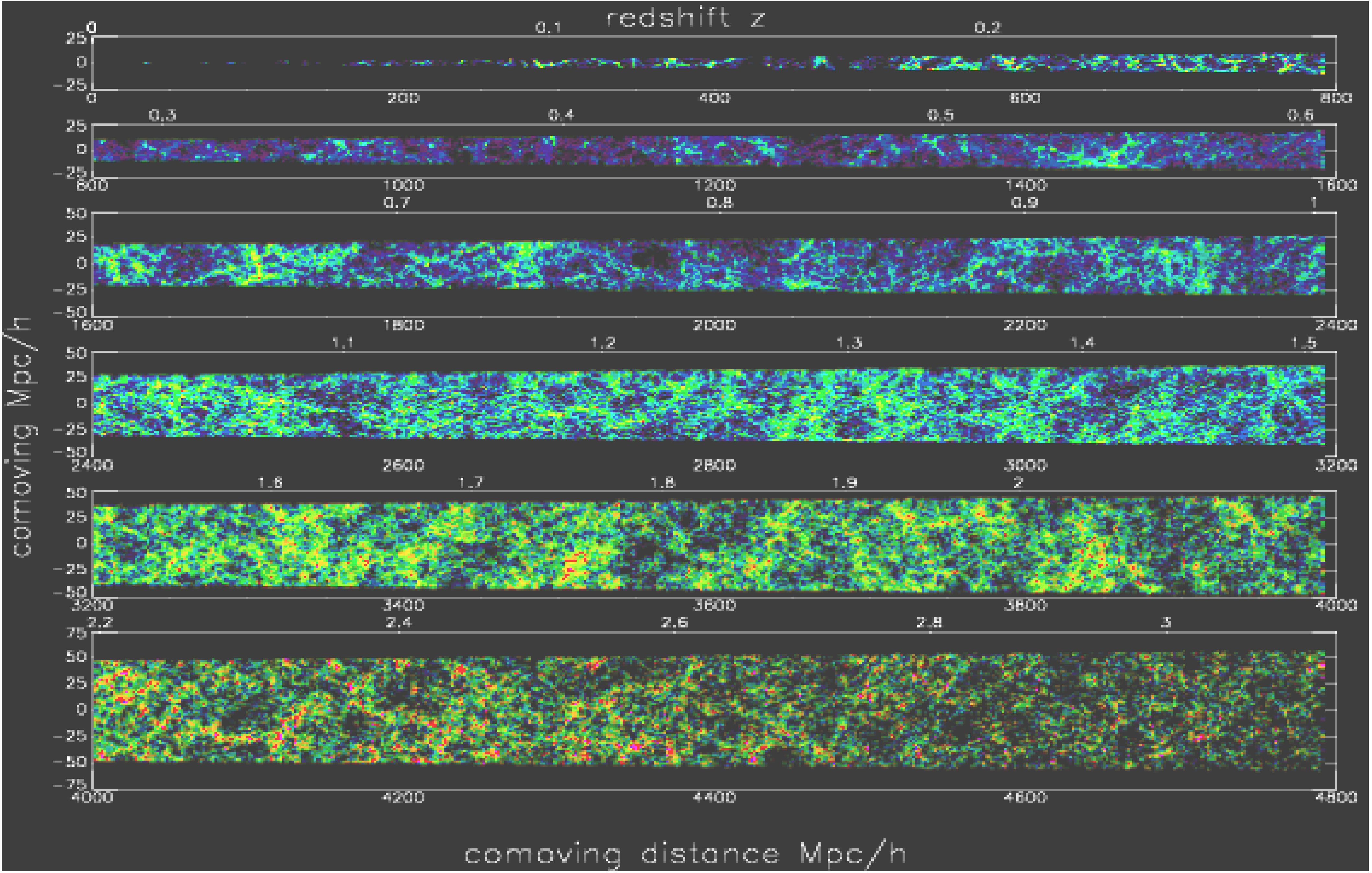
Millennium Run
2005



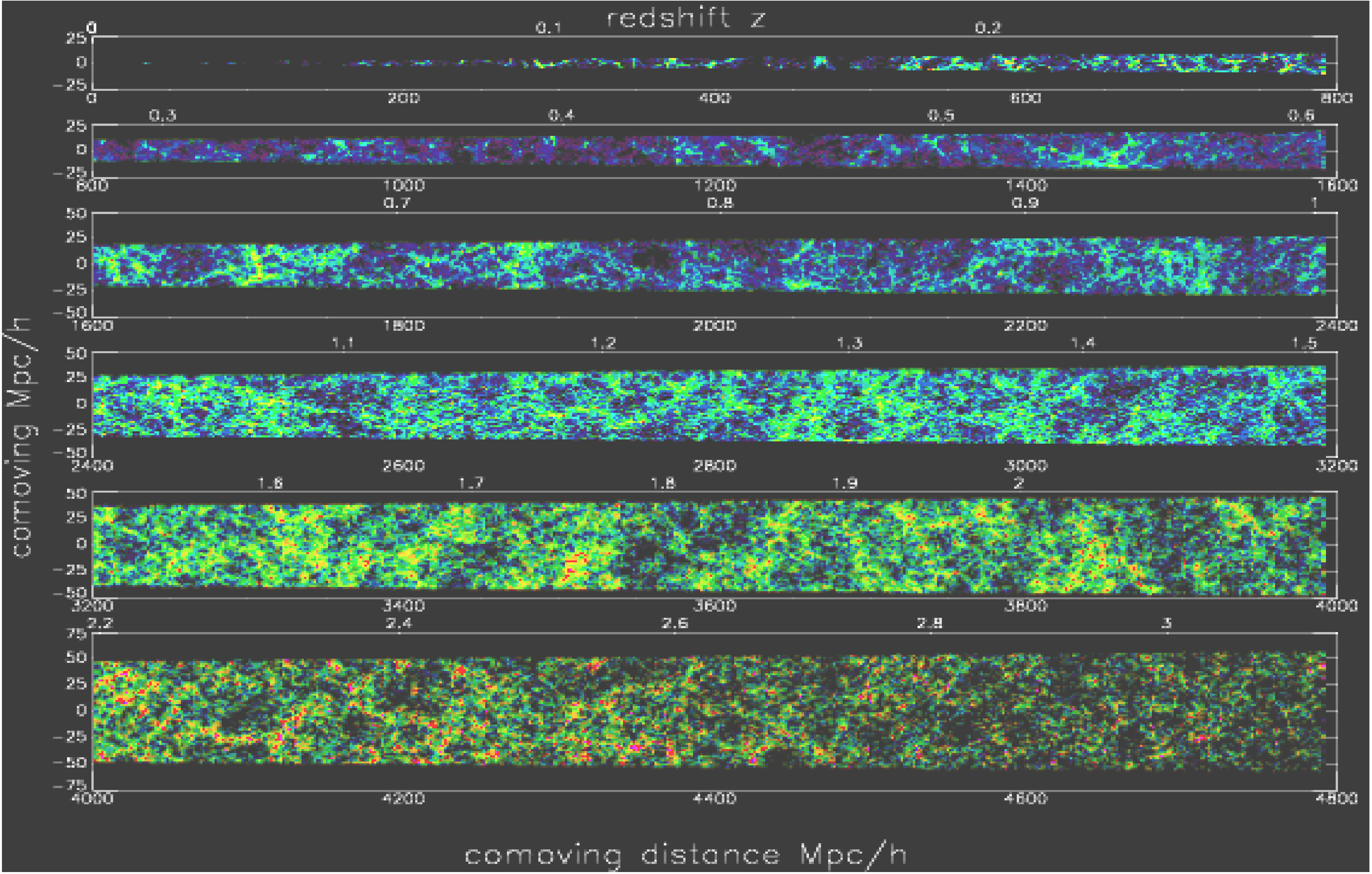
Millennium Run 2005



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



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

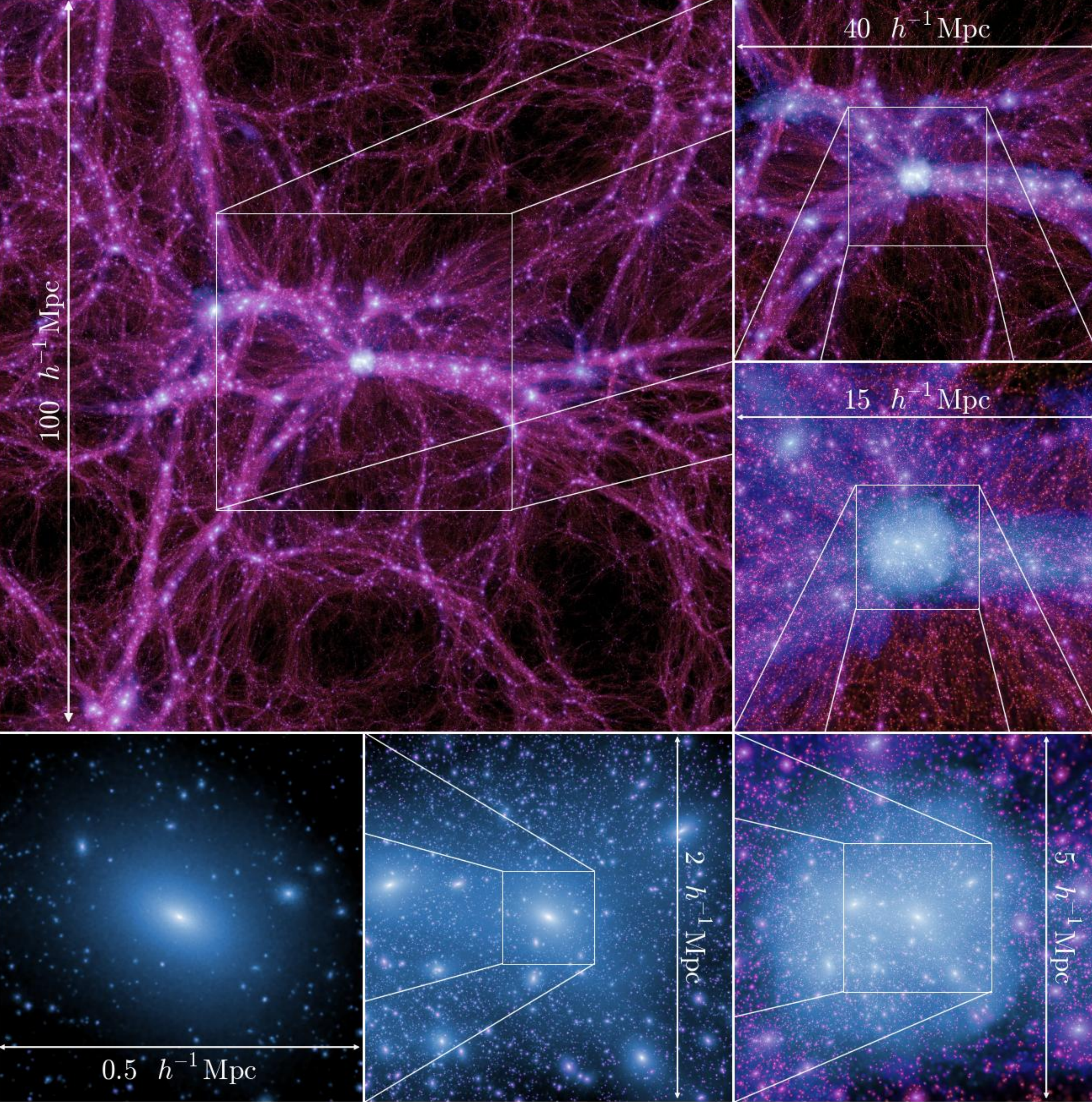


393 papers making direct use of data from the MS (27-6-2011)
Most by authors unassociated with the consortium
Most based on the galaxy catalogues, particularly mock surveys

Limitations of the Millennium Simulation

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

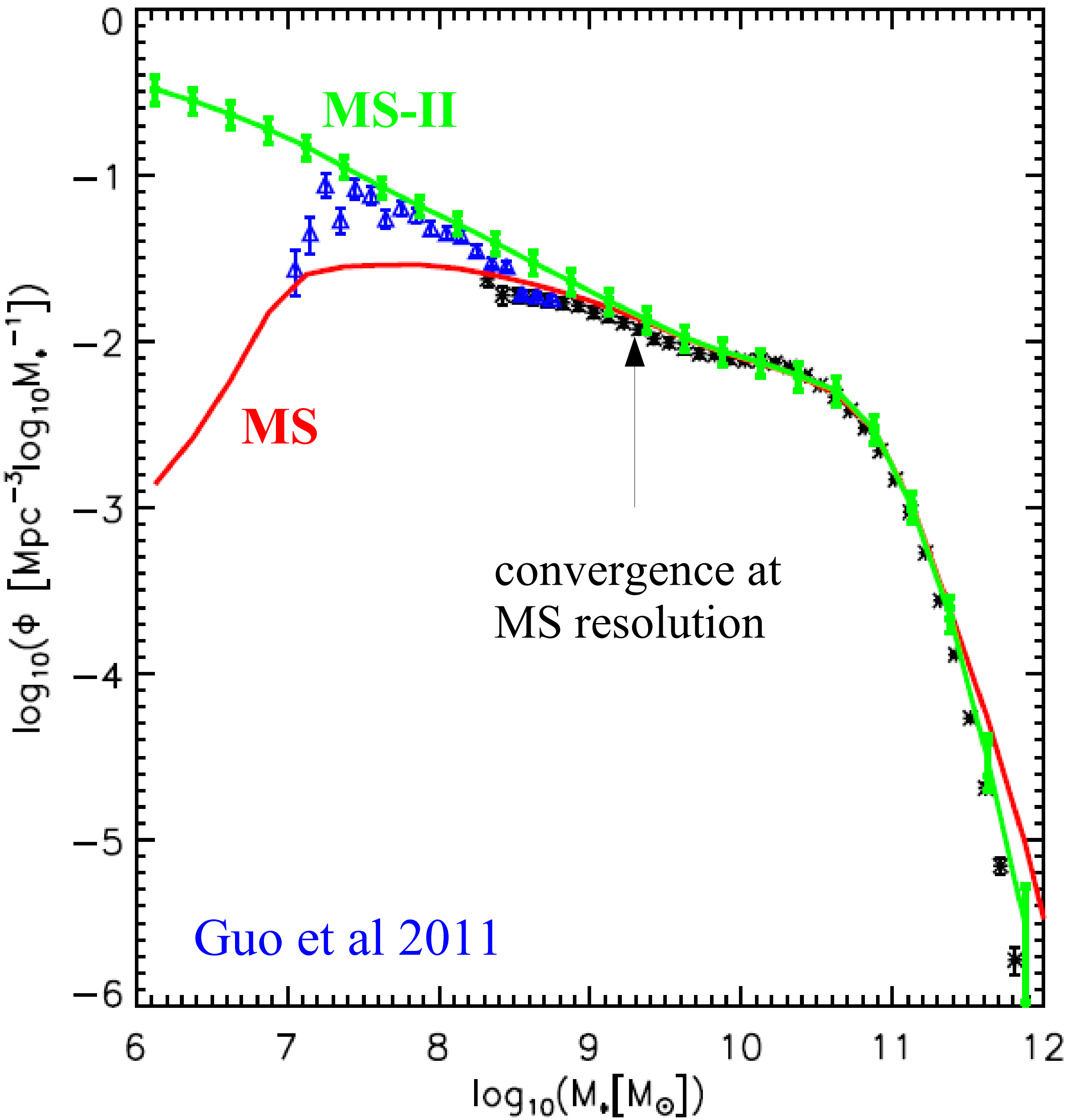
Resolution tests of MS results and extension to smaller scales

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

Qi Guo et al 2011

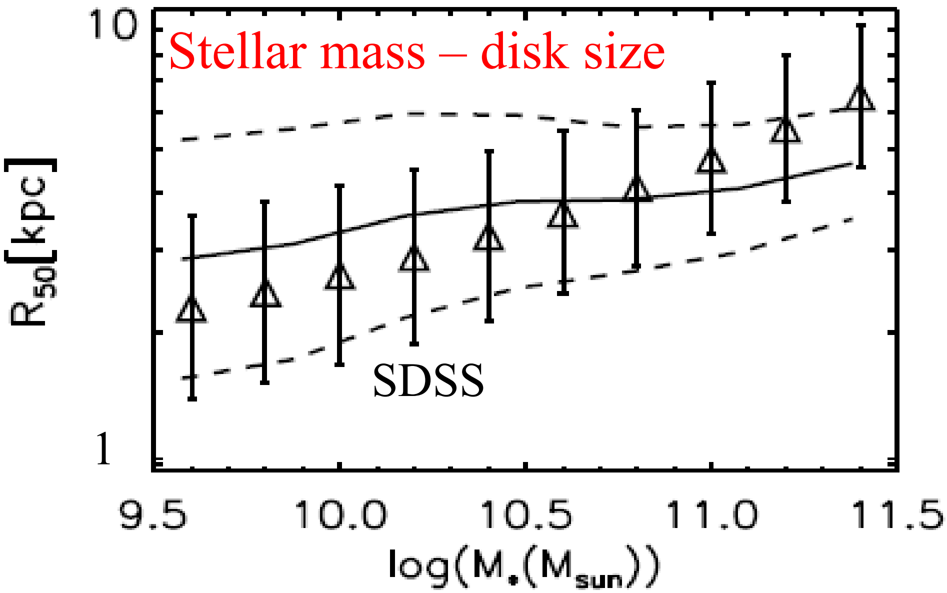
- Implement modelling simultaneously on MS and MS-II
- Test convergence of galaxy properties near resolution limit of MS
- Extend to properties of dwarf galaxies
- Improve/extend treatments of "troublesome" astrophysics
- Adjust parameters to fit new, more precise data
- Test against clustering and redshift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

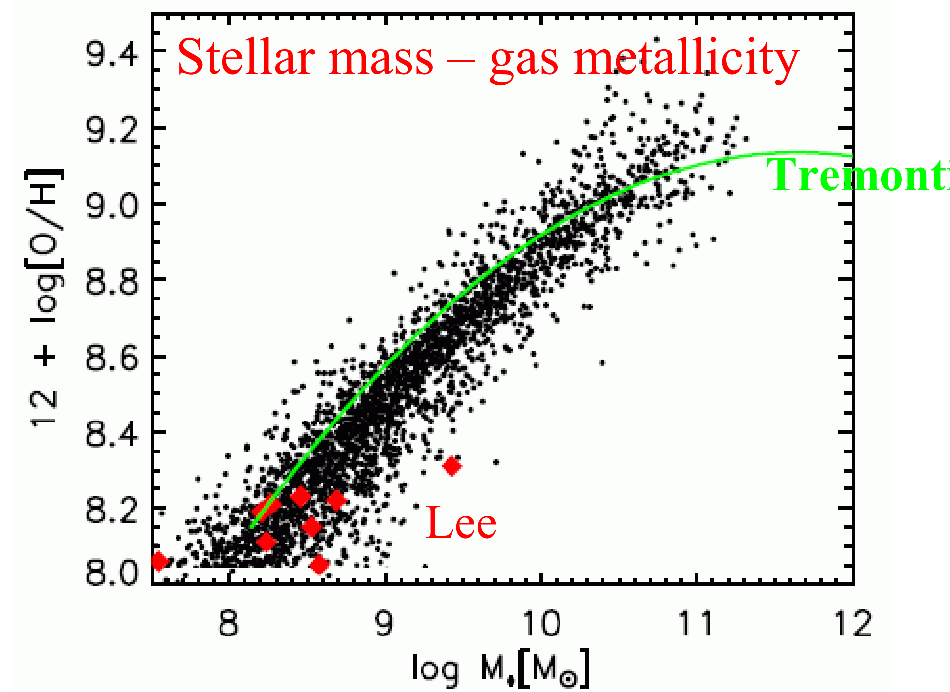
The stellar mass function of galaxies

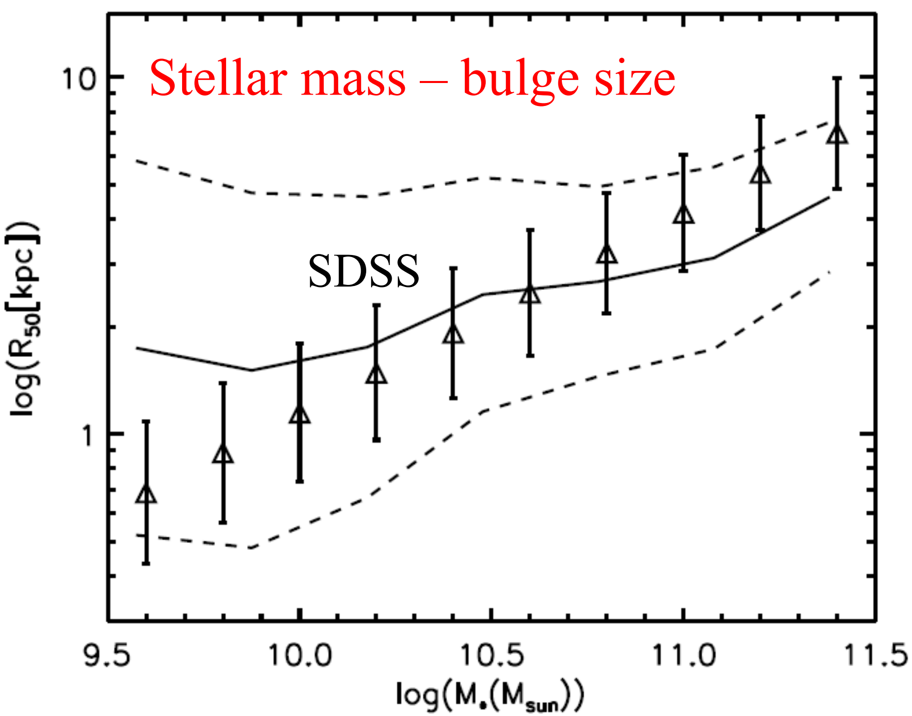


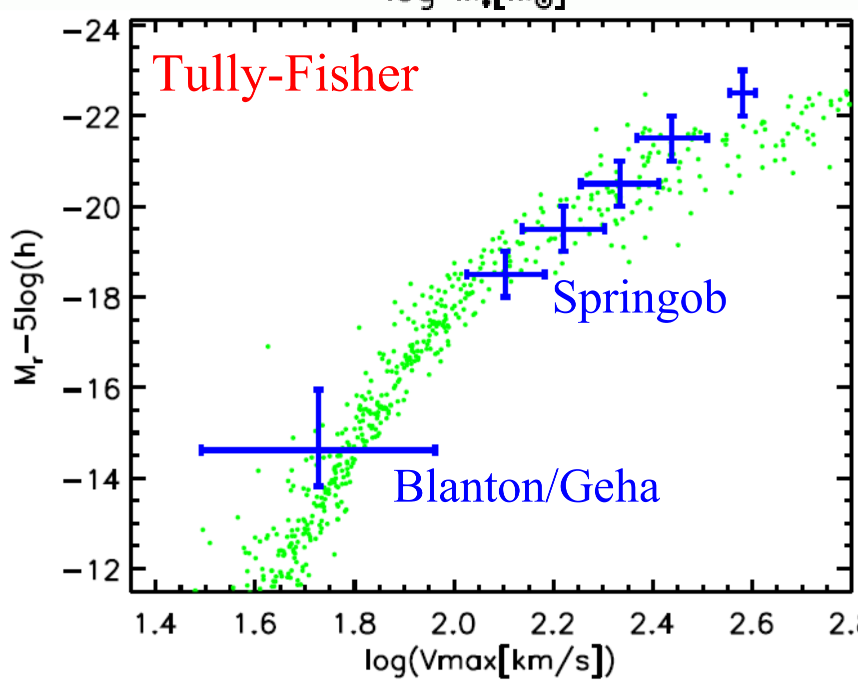
Note that the simulated mass function fits the data over 5 dex!

Scaling relations



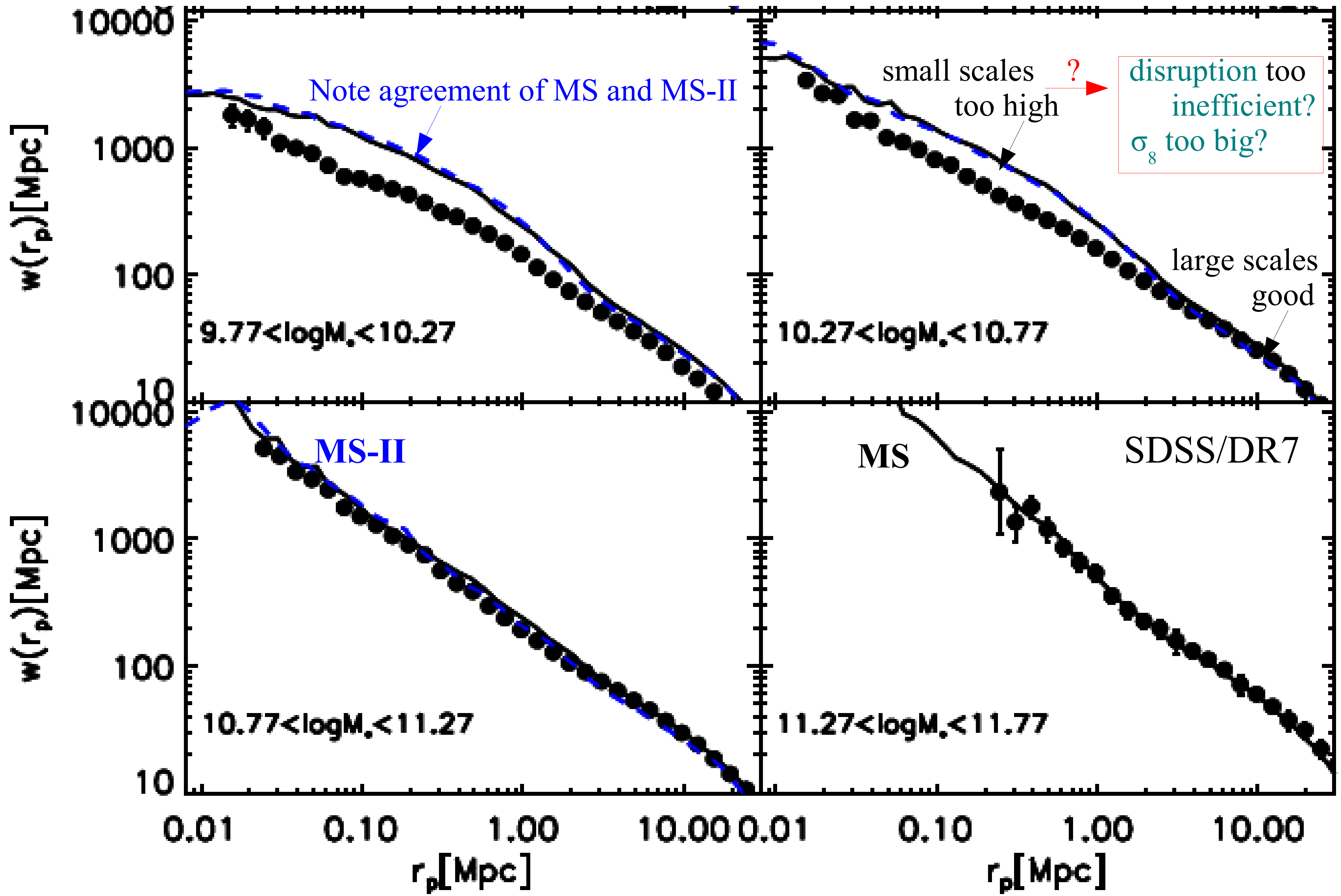


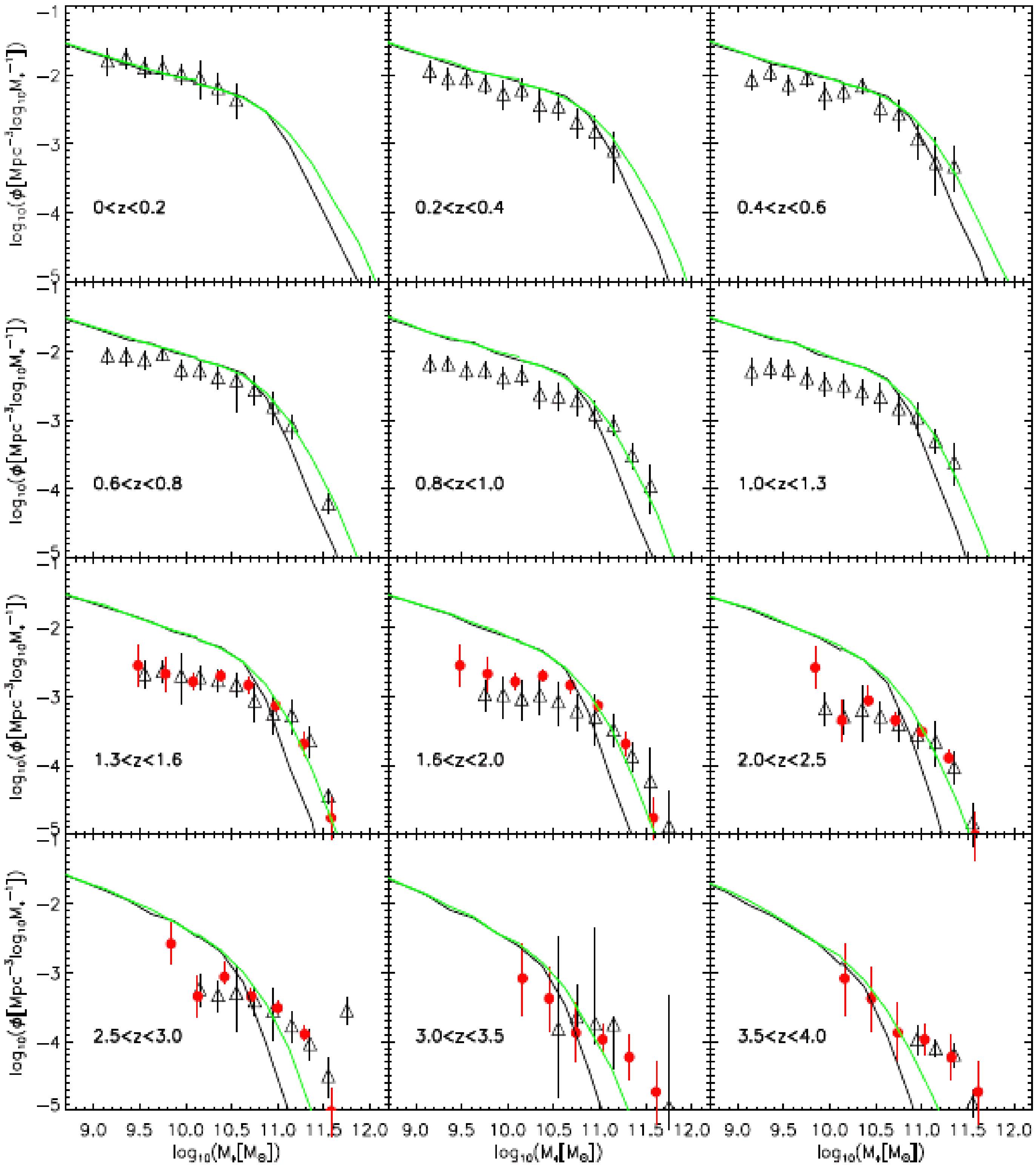




Mass-dependent galaxy clustering

Guo et al 2011



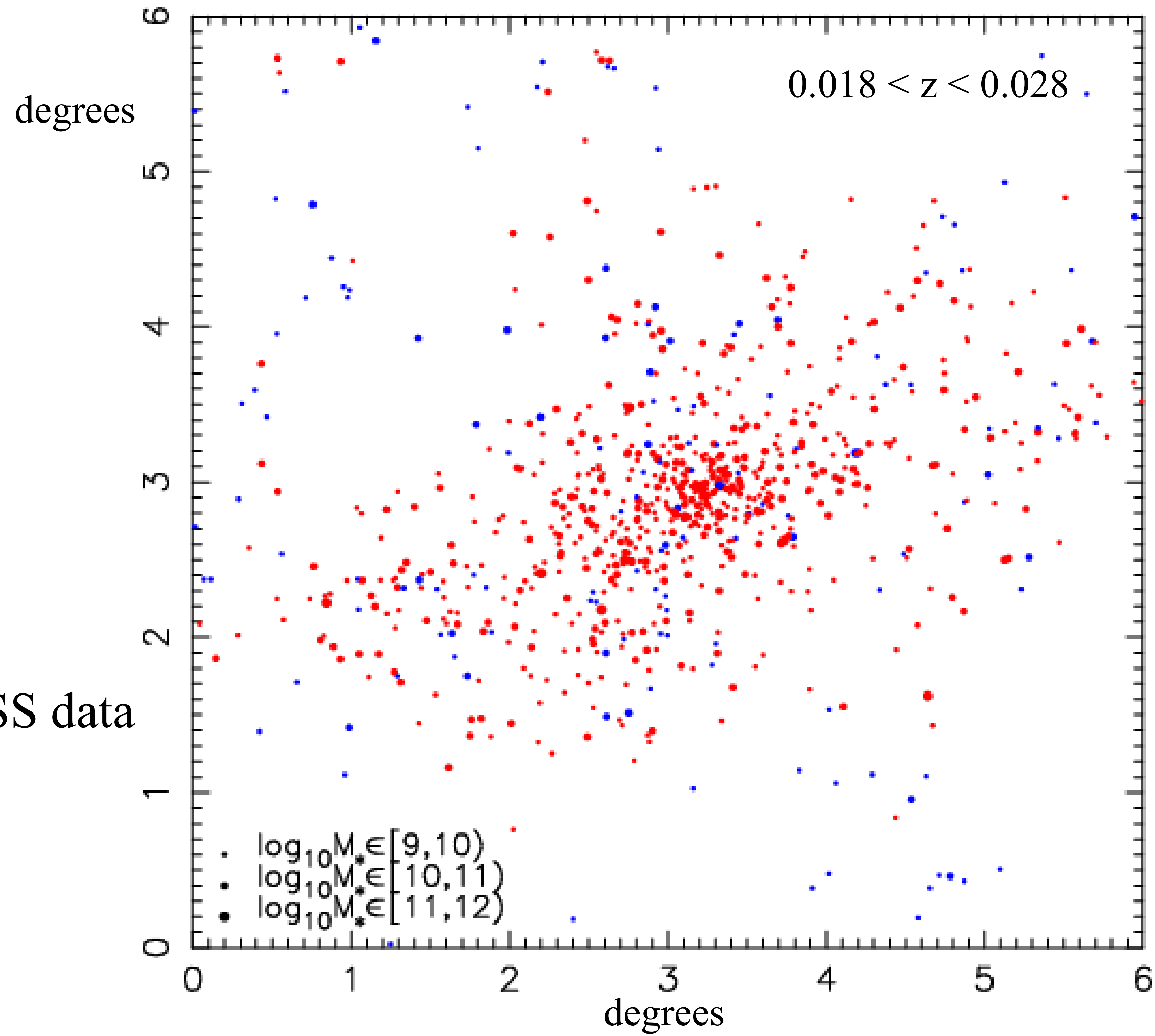


Evolution of stellar mass function

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

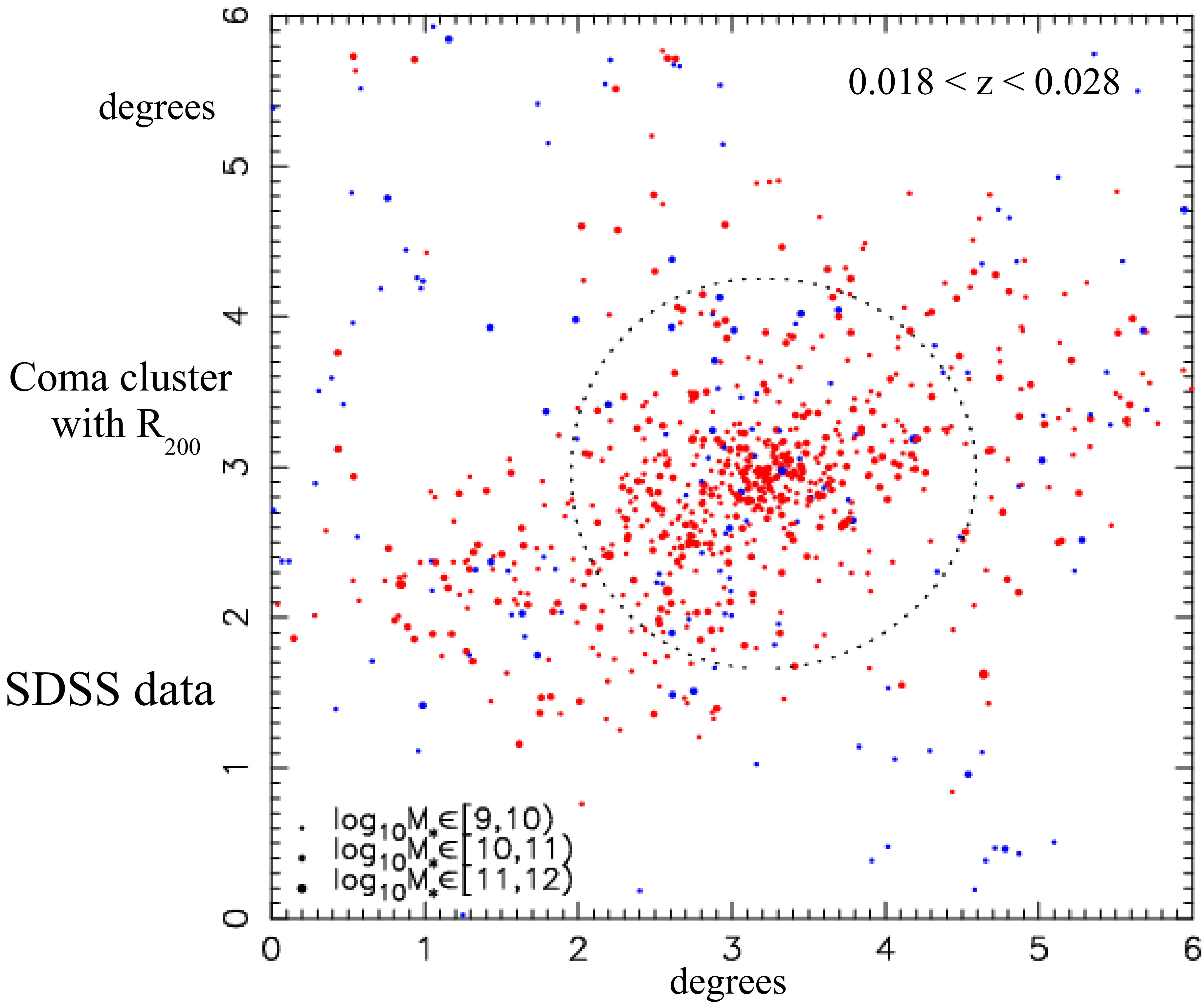
Efficiency of star-formation is too high in lower mass objects at high z?

Guo et al 2011

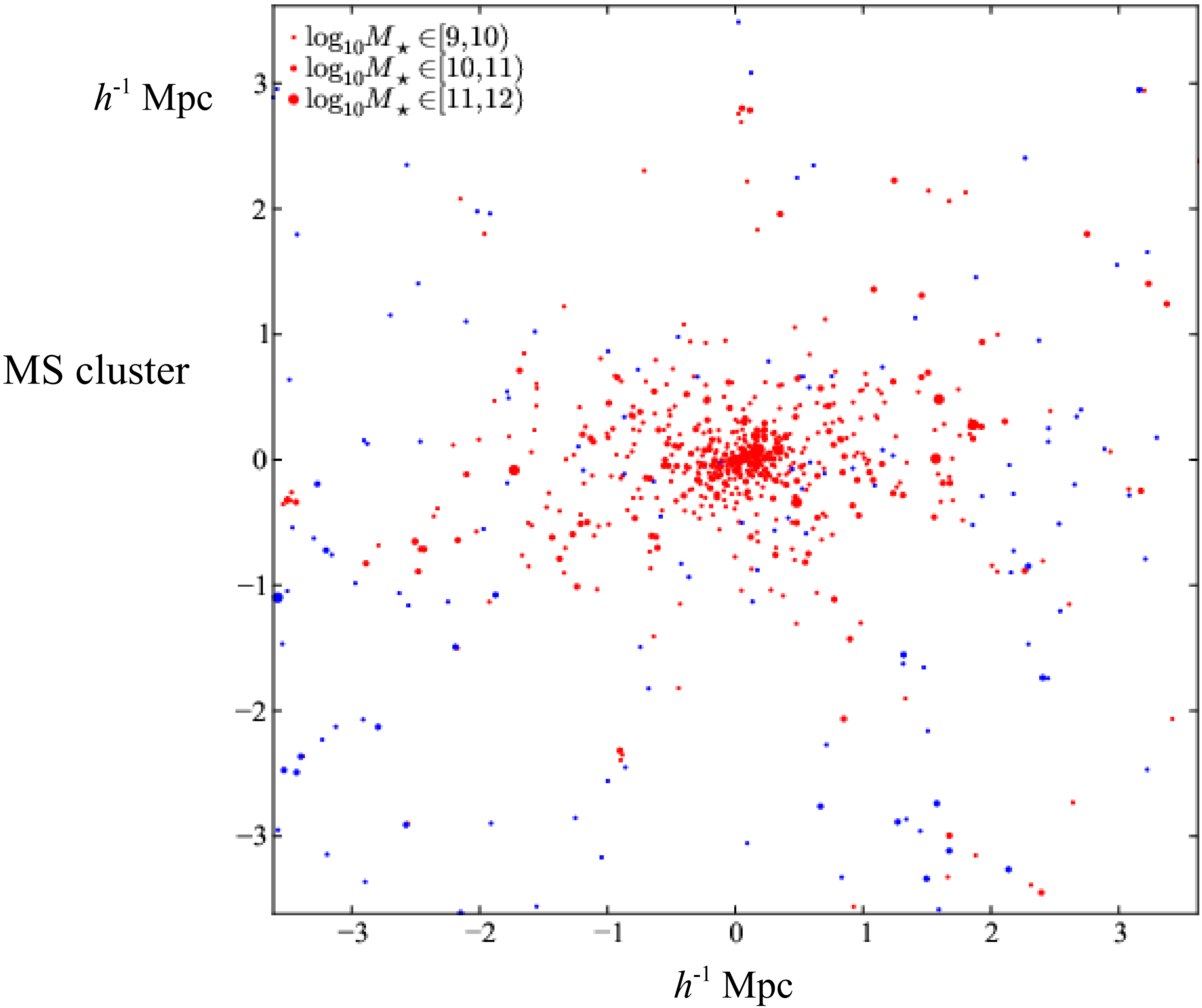


0.018 < z < 0.028
degrees
degrees
0
1
2
3
4
5
6
$\log_{10}M_* \in [9,10)$
$\log_{10}M_* \in [10,11)$
$\log_{10}M_* \in [11,12)$

SDSS data



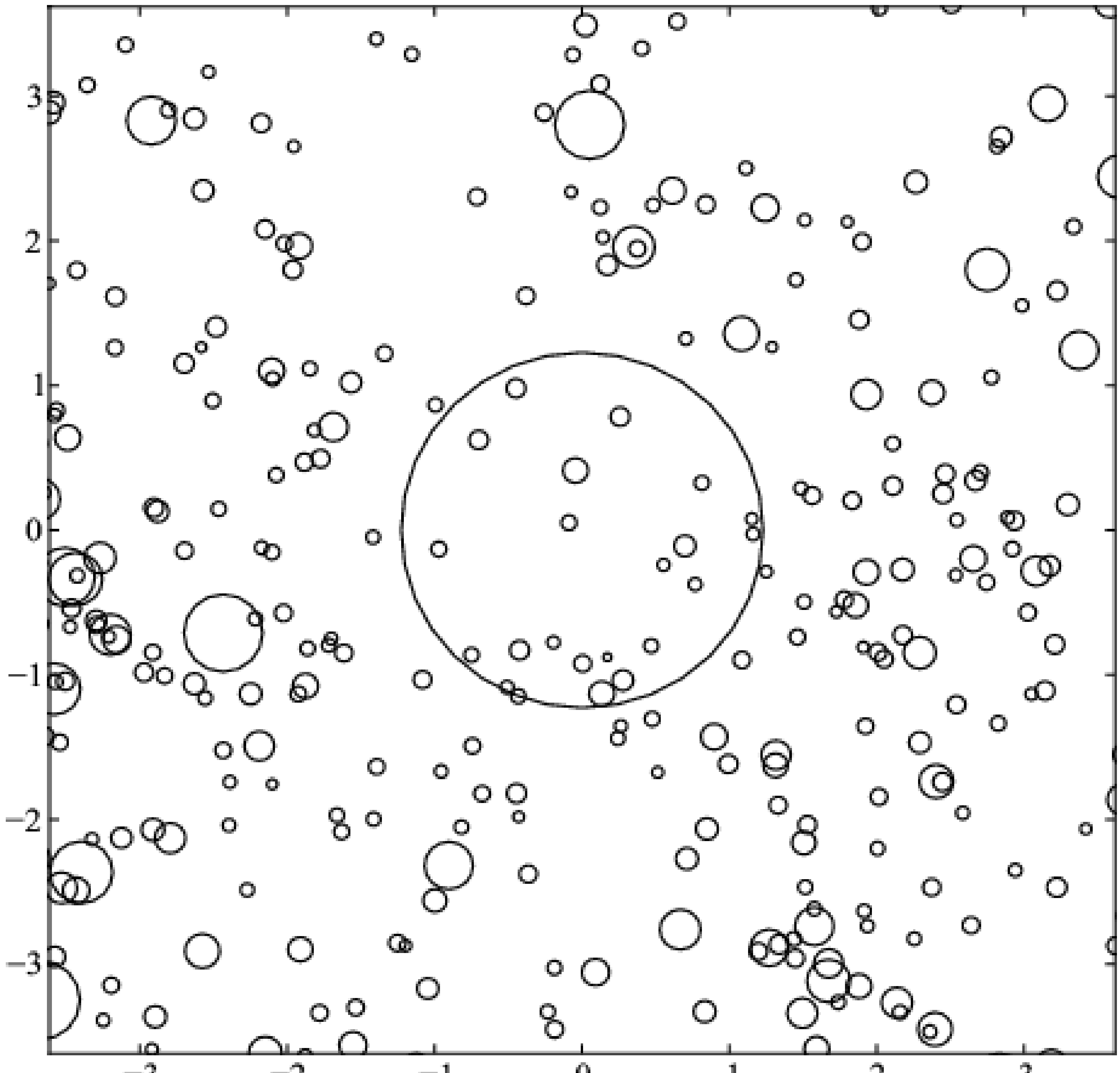
0.018 < z < 0.028
degrees
Coma cluster
with R_{200}
SDSS data
$\log_{10}M_* \in [9,10)$
$\log_{10}M_* \in [10,11)$
$\log_{10}M_* \in [11,12)$
0
1
2
3
4
5
6
degrees



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

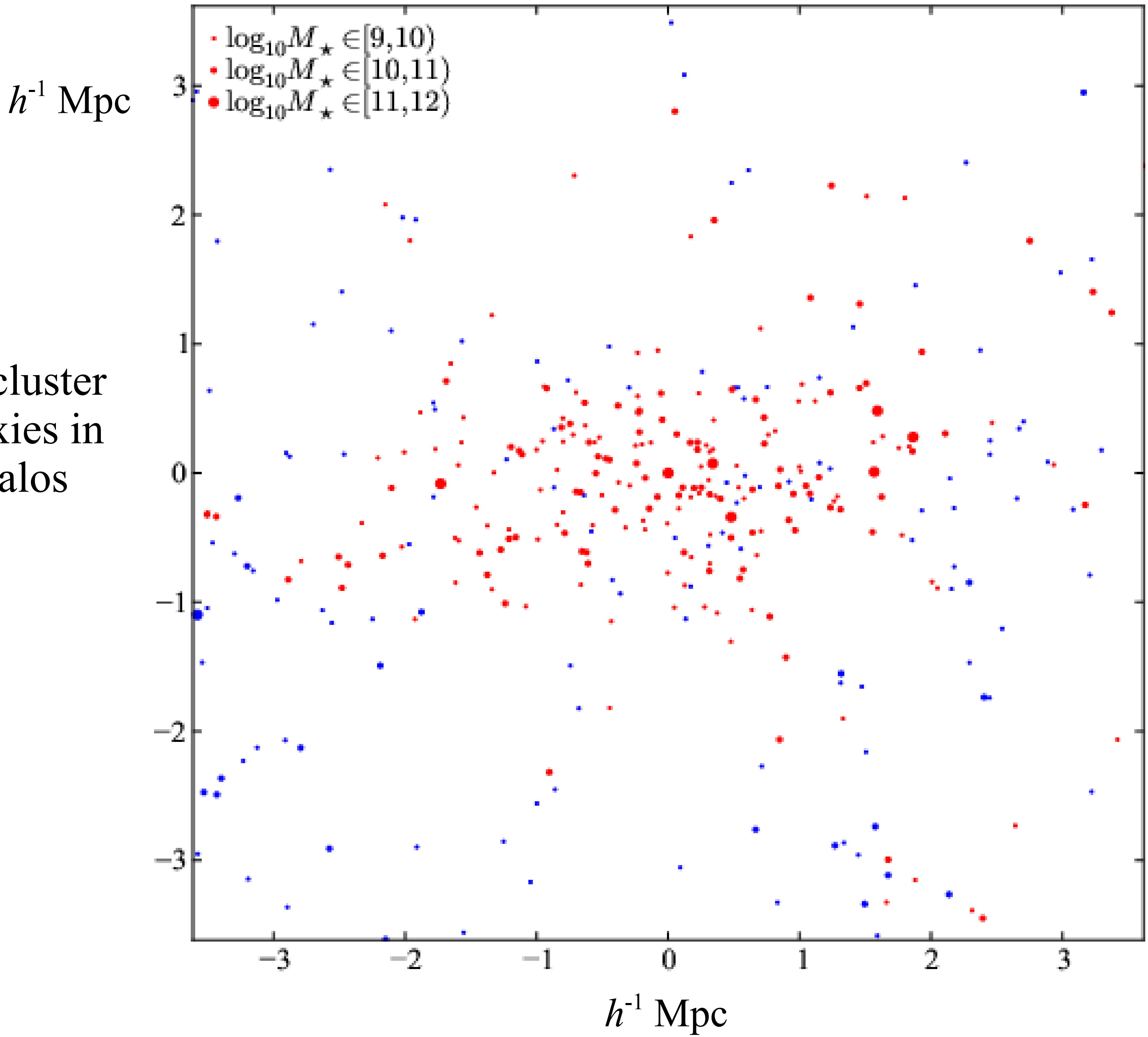
h^{-1} Mpc

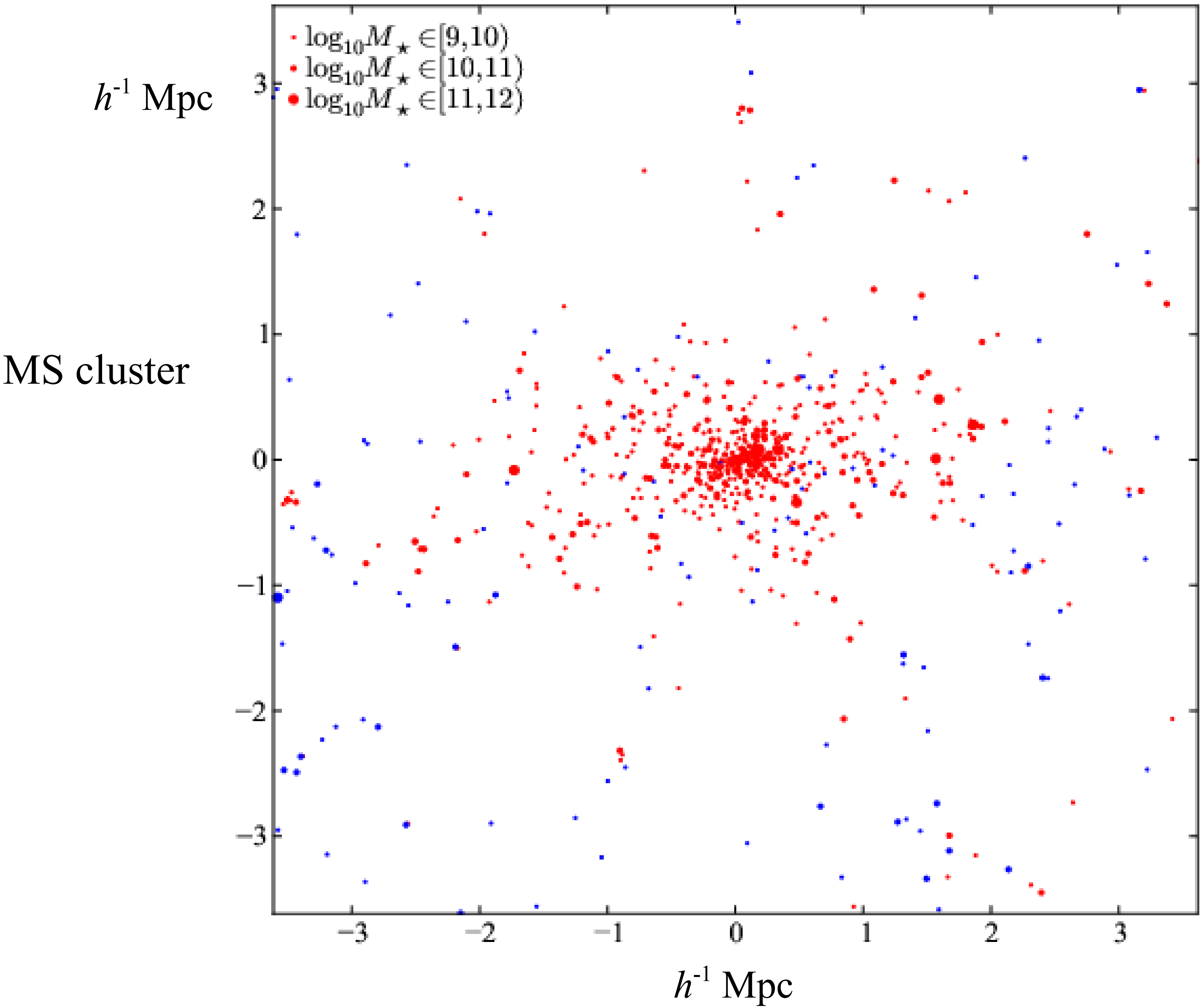
MS cluster
halos only



h^{-1} Mpc

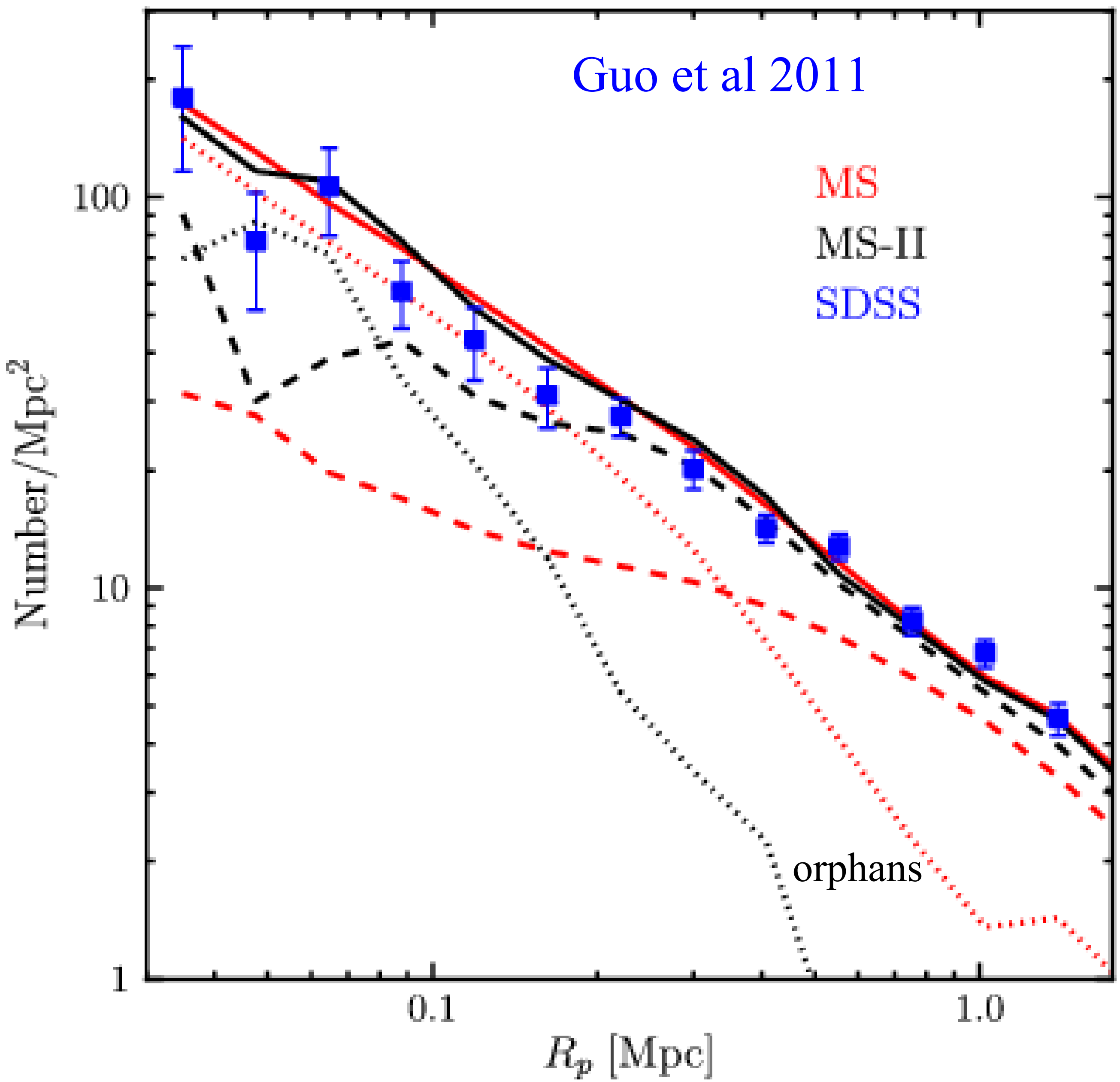
MS cluster galaxies in subhalos





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

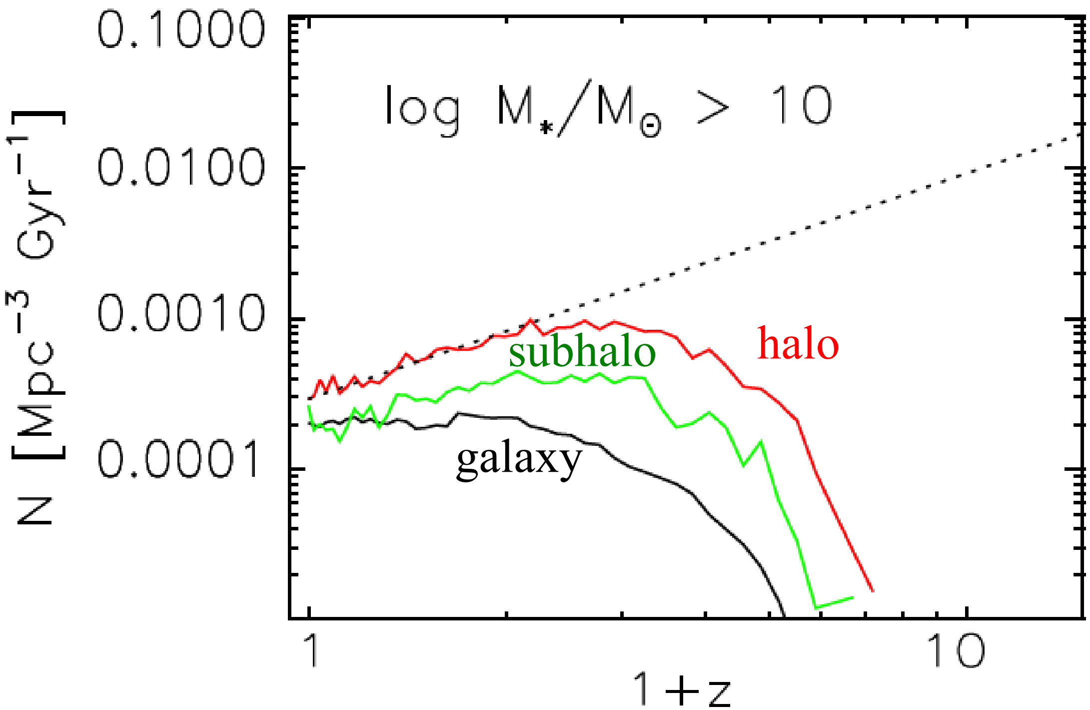
Orphan treatment is physically consistent and needed to fit SDSS

Disruption efficiency too low near centre?

- Halos in simulations do not correspond to galaxies
  - -- many galaxies are satellites within big halos

- Subhalos also do not correspond perfectly to galaxies
  - -- the subhalos of many galaxies are prematurely destroyed
  - -- this has both numerical *and* physical origins

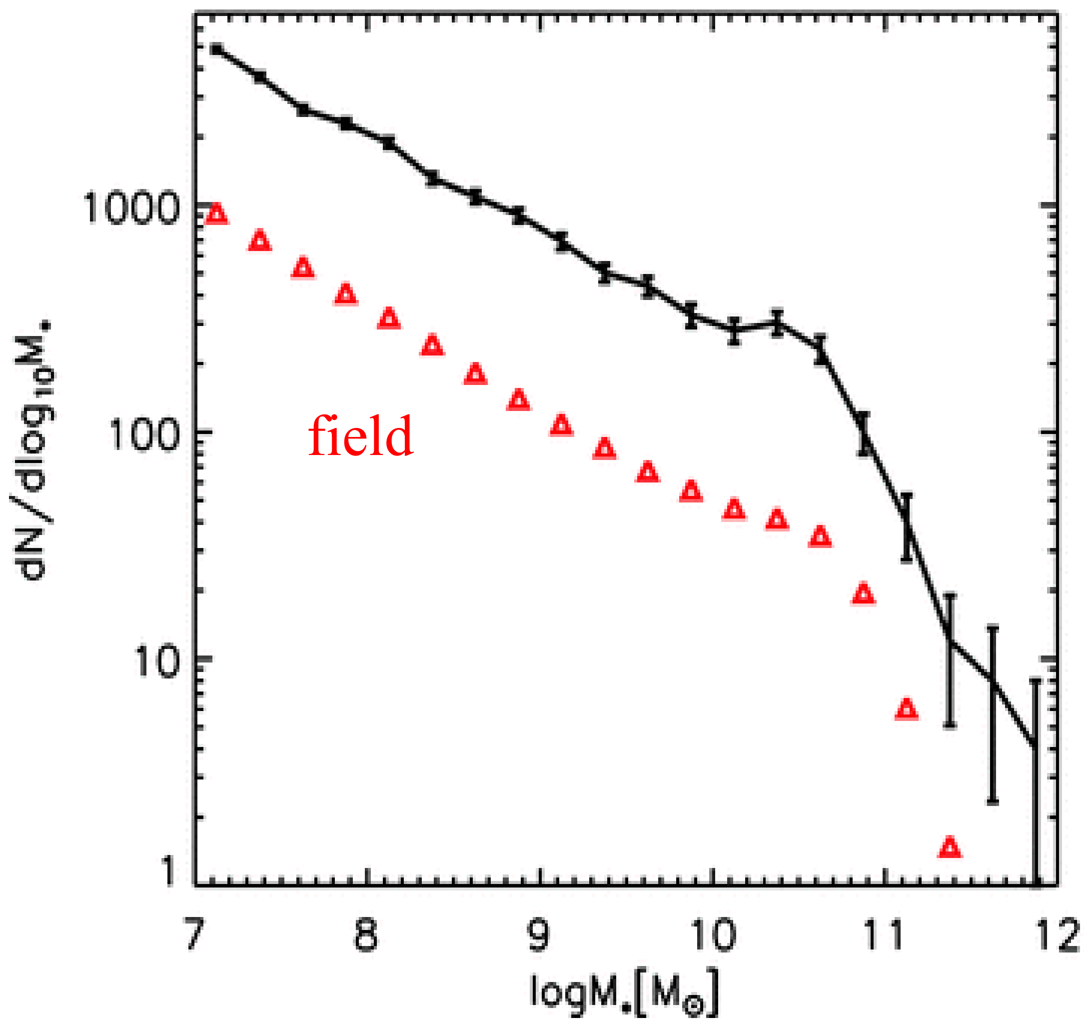
- DM simulations alone, even at high resolution, cannot faithfully predict the galaxy distribution



Merger rates from Kitzbichler & White 2008

Stellar mass function of the most massive MS-II cluster

Guo et al 2011



$M_{tot} = 6 \times 10^{14} M_\odot$

shape is very similar to the field stellar mass f'n

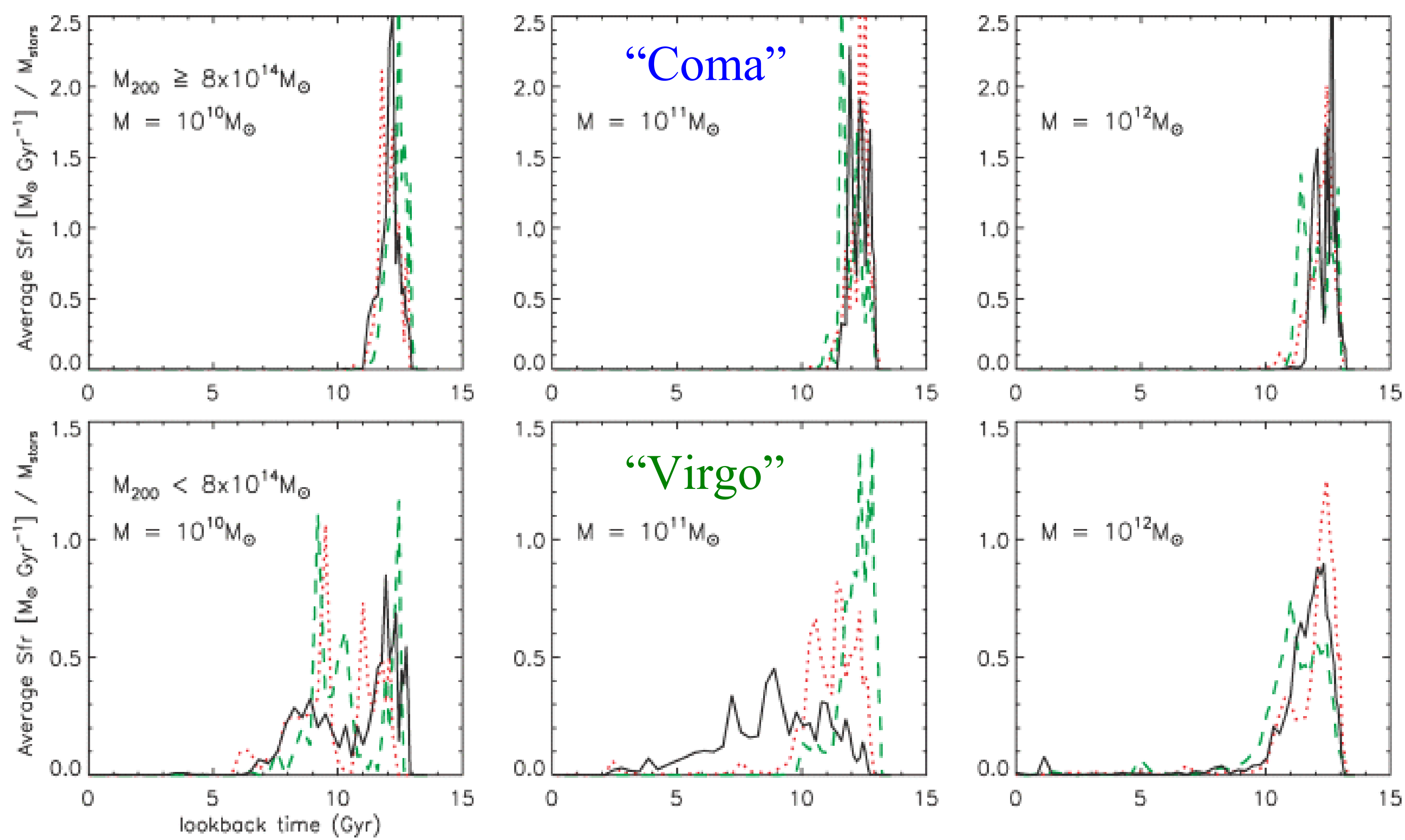
low mass slope is

$\alpha \sim 1.35$

see T. Lisker's talk

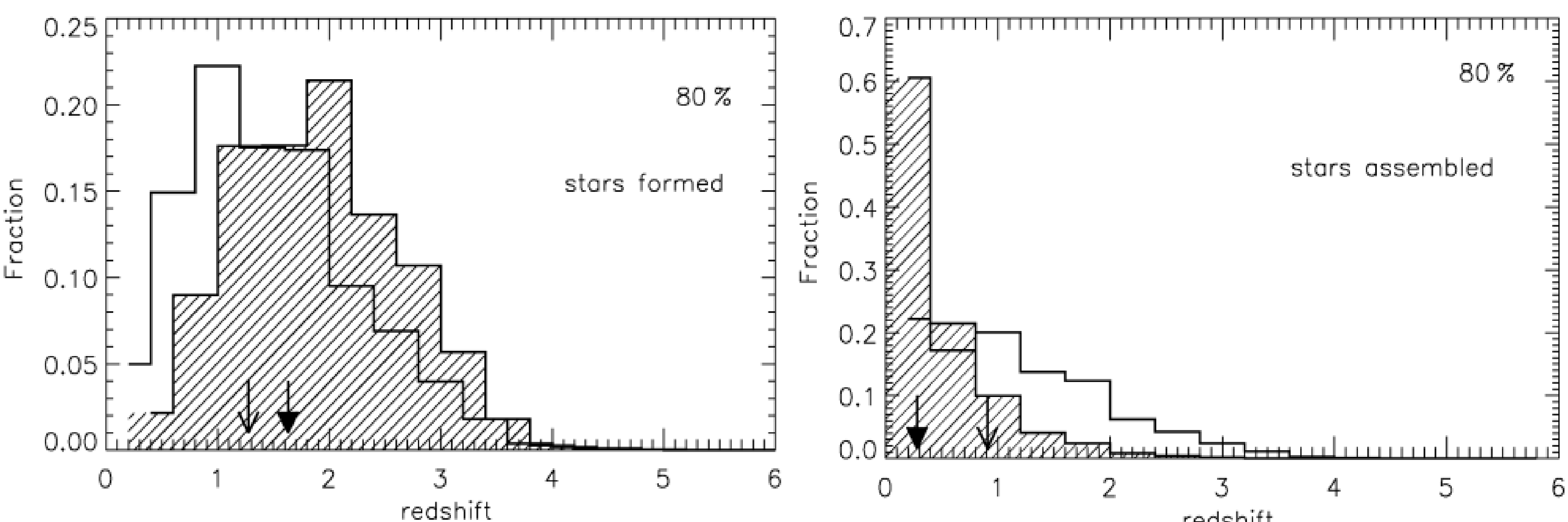
Elliptical formation

De Lucia et al 2006



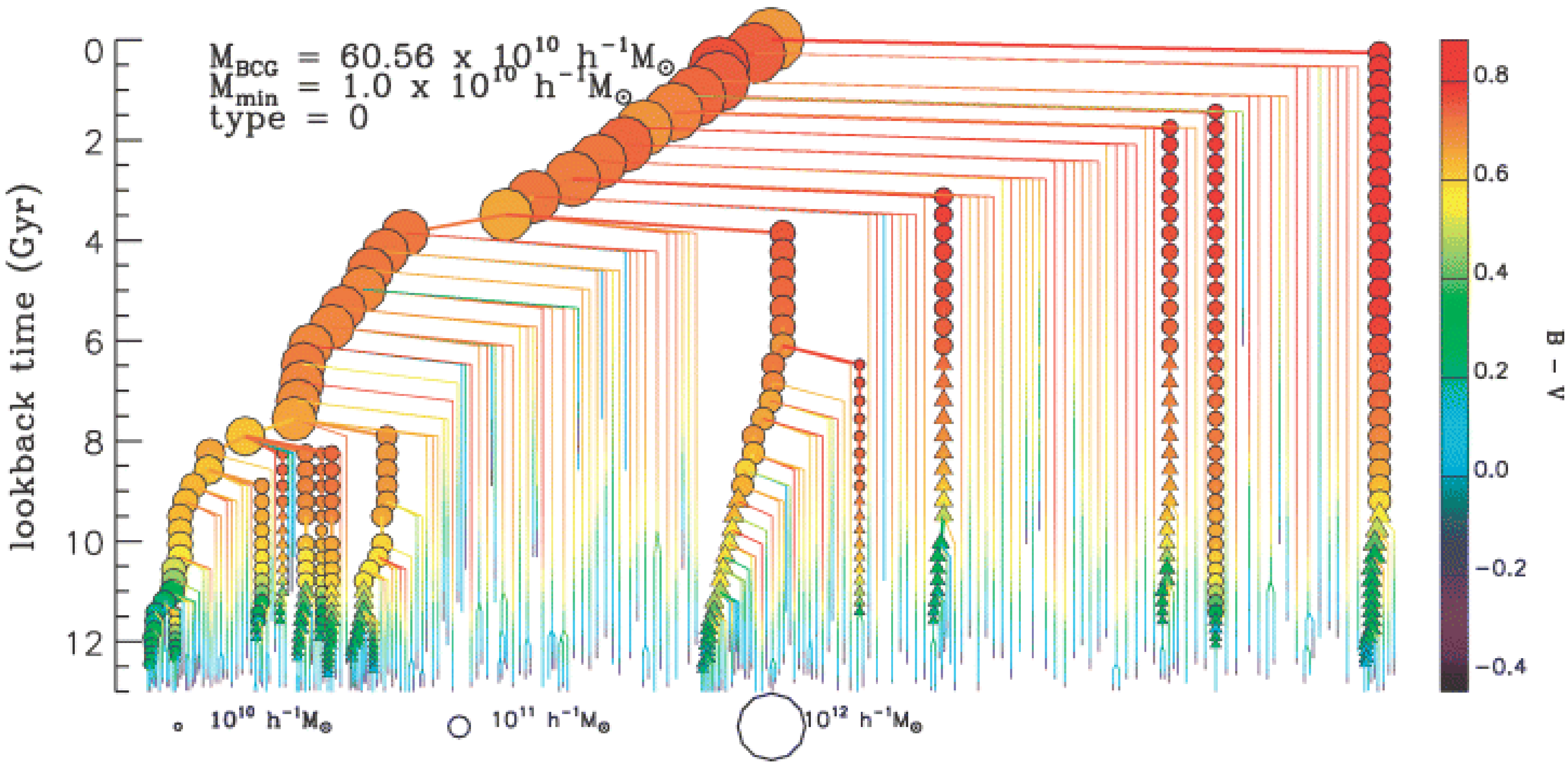
Massive E's form stars early but assemble late

Assembly is later in lower mass clusters



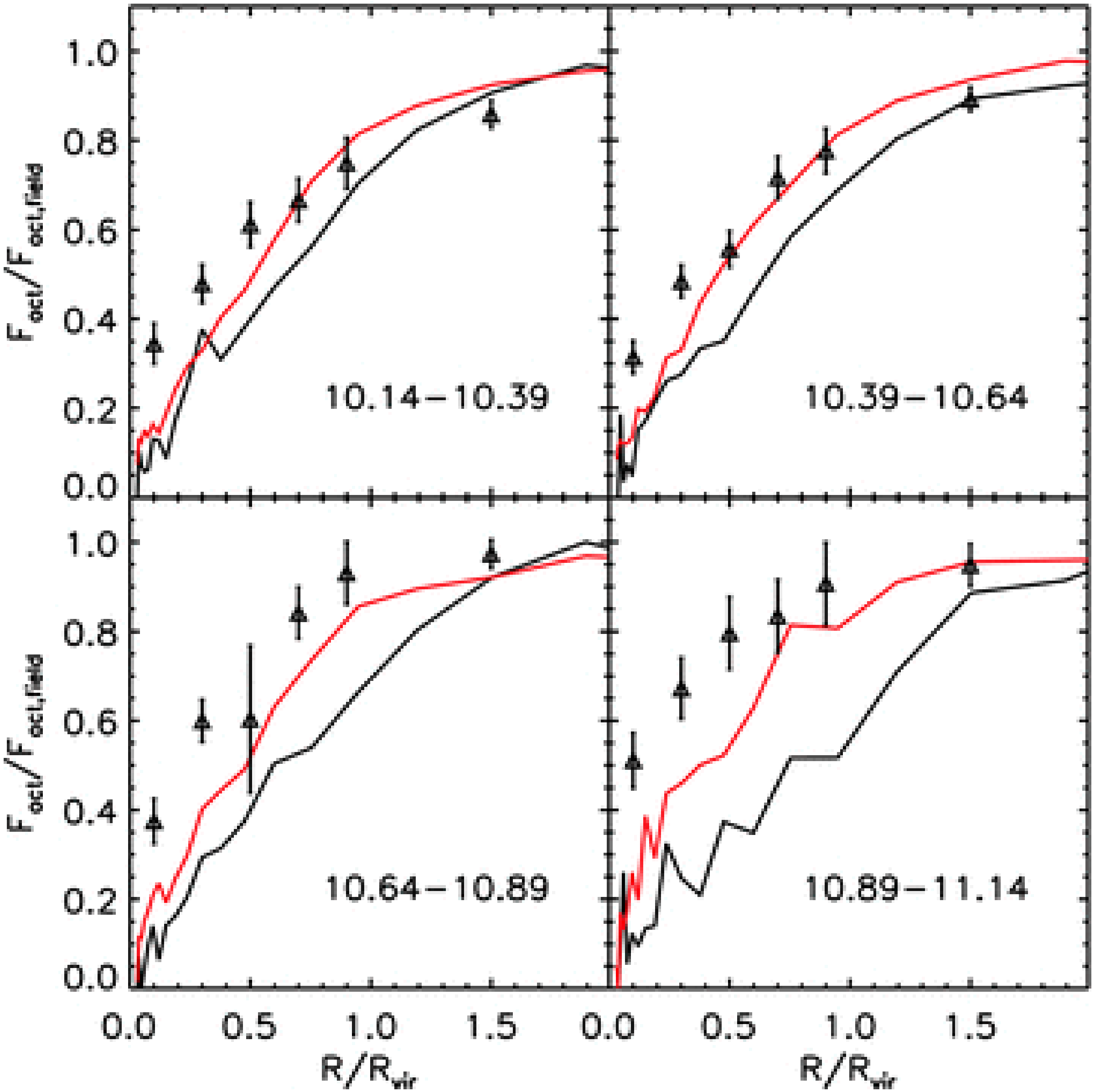
Formation of a brightest cluster galaxy

De Lucia & Blaizot 2007



Suppression of star formation within rich clusters

Guo et al 2011



Fraction of actively star-forming galaxies (i.e. $M_* > M_* / 10^{11}$ yr) relative to the value "in the field"

SDSS data taken from Weinmann et al (2008)

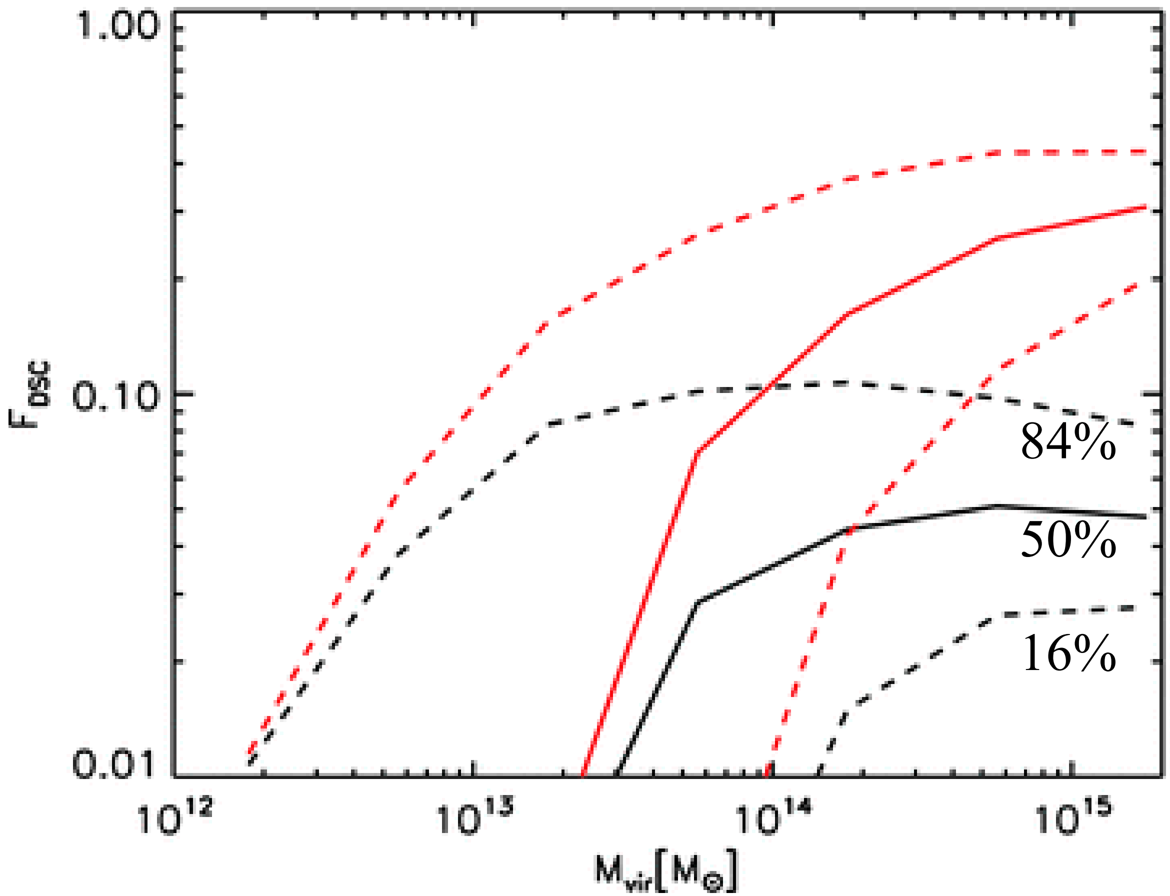
Model data for 1000 clusters in the MS with $M_{tot} > 2 \times 10^{14} M_\odot$

black line DLB07
red line Guo et al (2011)

Suppression of star-formation still too efficient?

Diffuse intracluster light in groups and clusters

Guo et al 2011



Fraction of cD+ICL stars in the ICL

Fraction of all stars within R_{200} in the ICL

Disruption producing ICL too inefficiently?

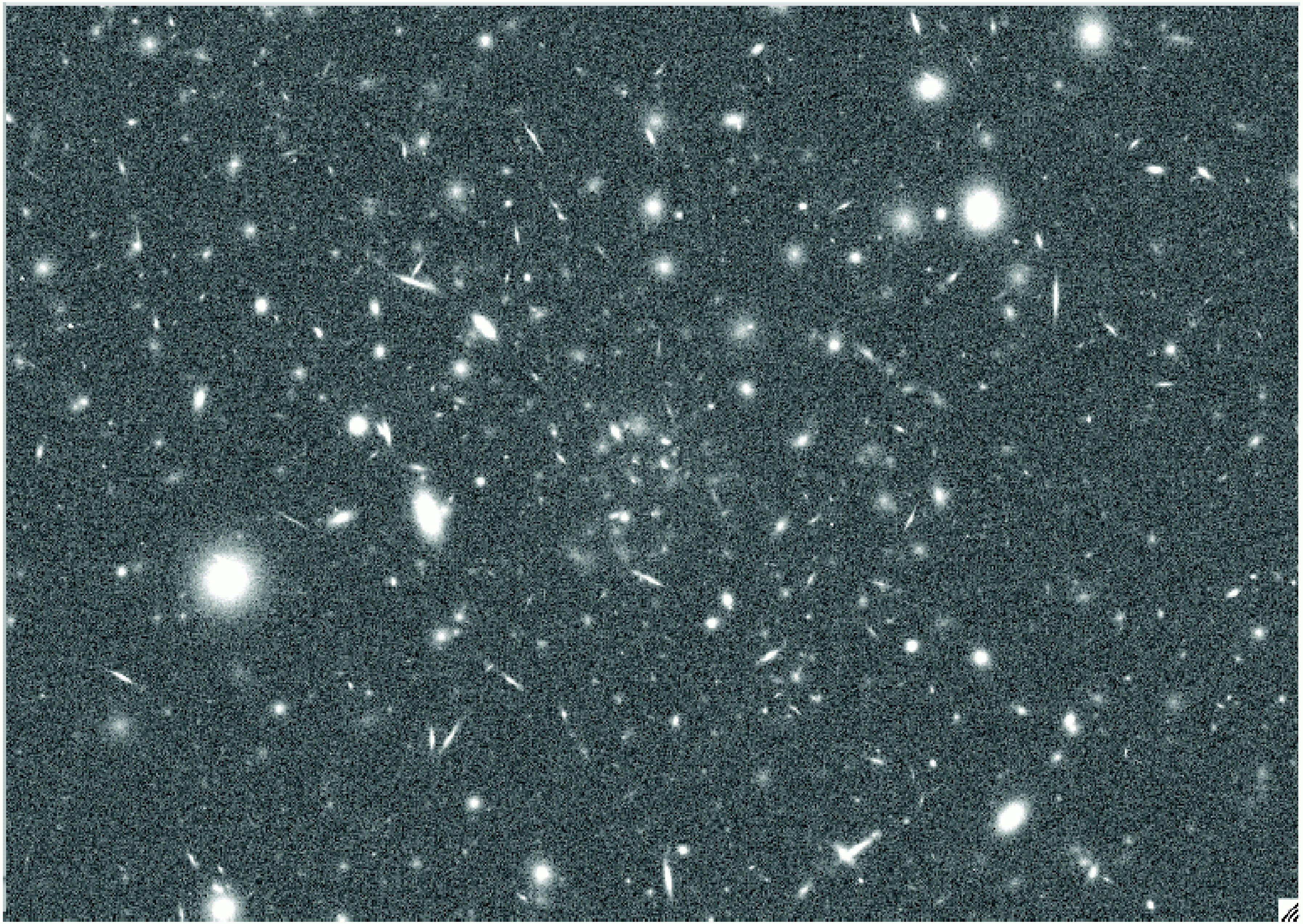
see talks by G. De Lucia and M.Arnaboldi

The Millennium Run Observatory

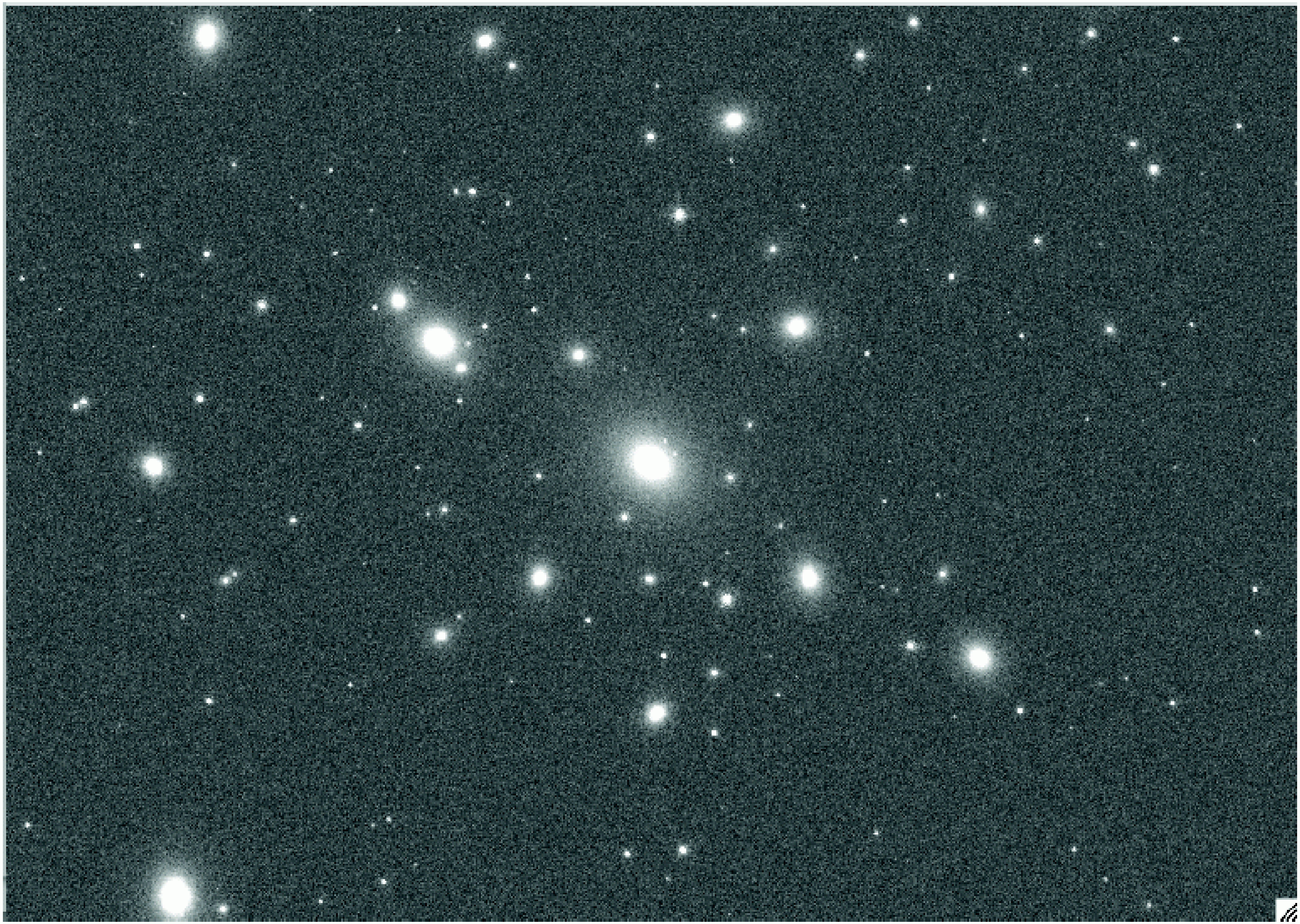
(Overzier, Lemson, et al. in prep.)

- *Lightcones can now be pointed at* ***arbitrary objects at any z*** *(e.g.* ***CLUSTERS)***
- sky-projected ***angular size, inclination & PA*** *(from z, radius, ang. mom., and l.o.s.)*
- IGM absorption: ***corrected observed-frame magnitudes*** *(important for high-z)*
- Telescope Simulator: ***Realistic simulated images*** *(with proper PSF, rms, pix scale, ...)*
  (modified version of Skymaker (Bertin 2007) plus custom code)
- Choice of spectral synthesis models (e.g., BC03 vs. M05)
- Scalable cosmology (e.g., WMAP 1 vs. WMAP 7)
- **Open-access database implementation (expected late 2011)**

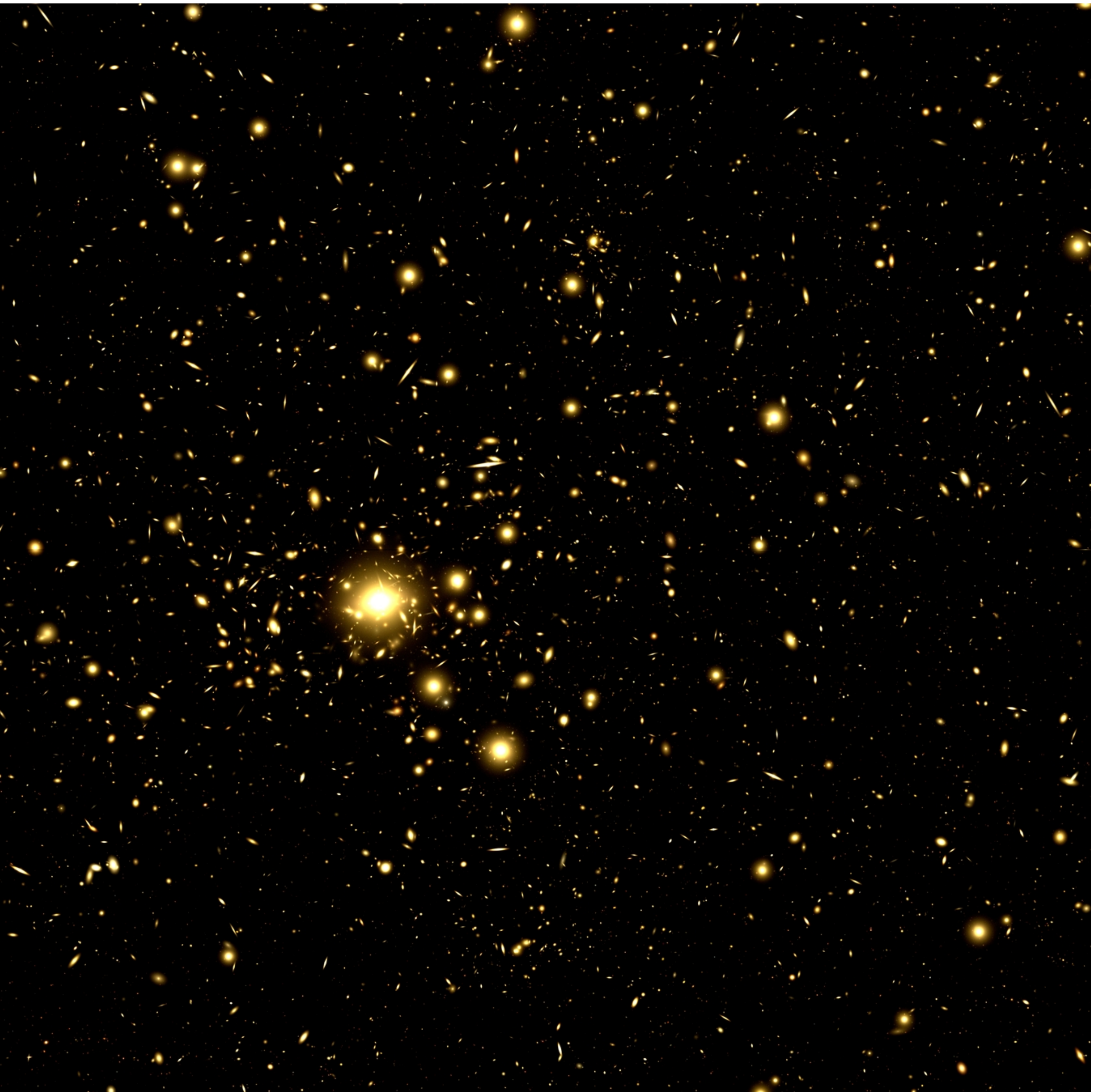
Inserting the Disks...



Inserting the Bulges...



Putting it all together...



“Coma”

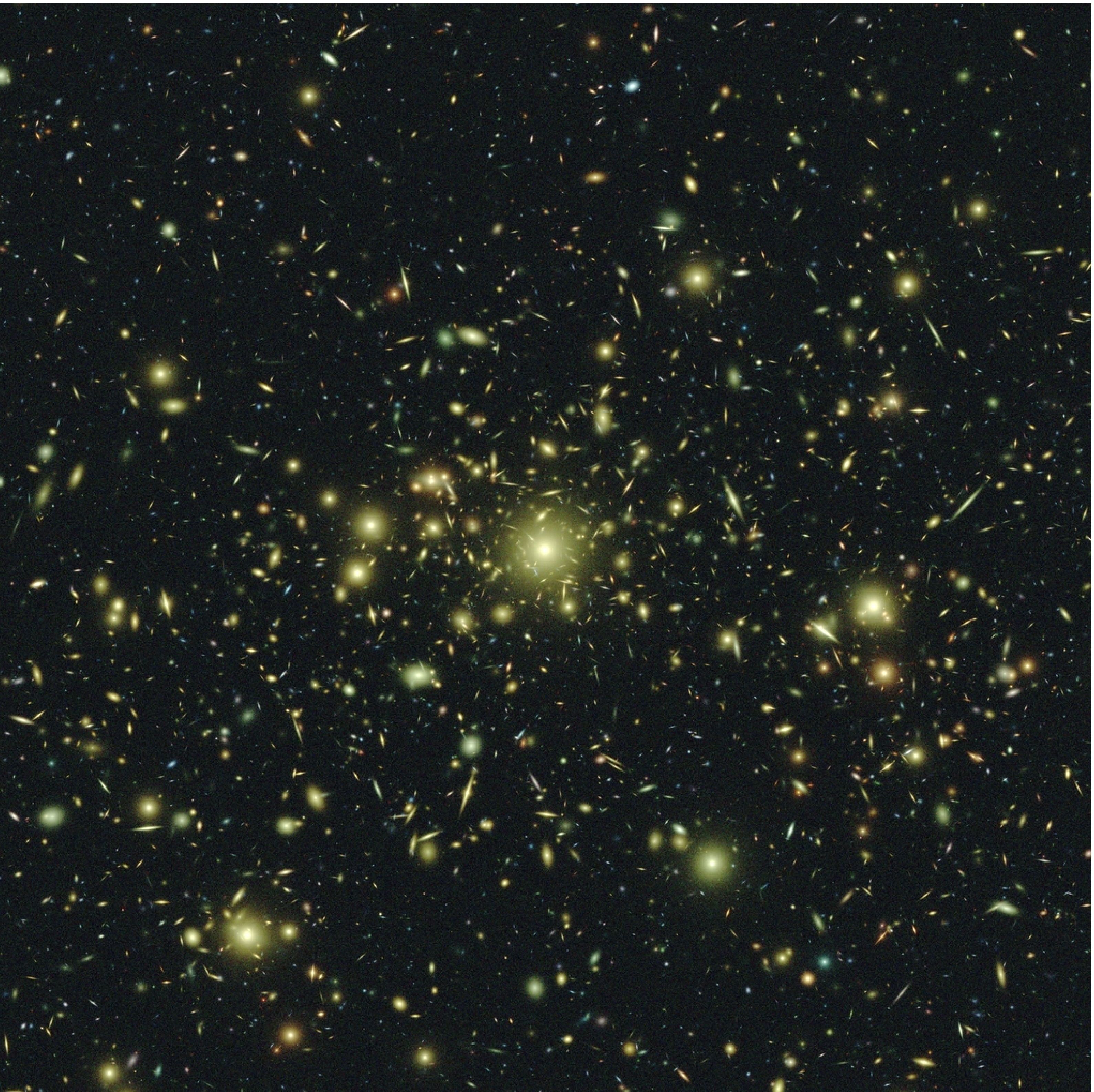
$M_{200} = 4 x 10^{15} M_{\odot}$

$z = 0.02$

1° x 1°

SDSS g, r, I

54 sec/filter



"Coma"

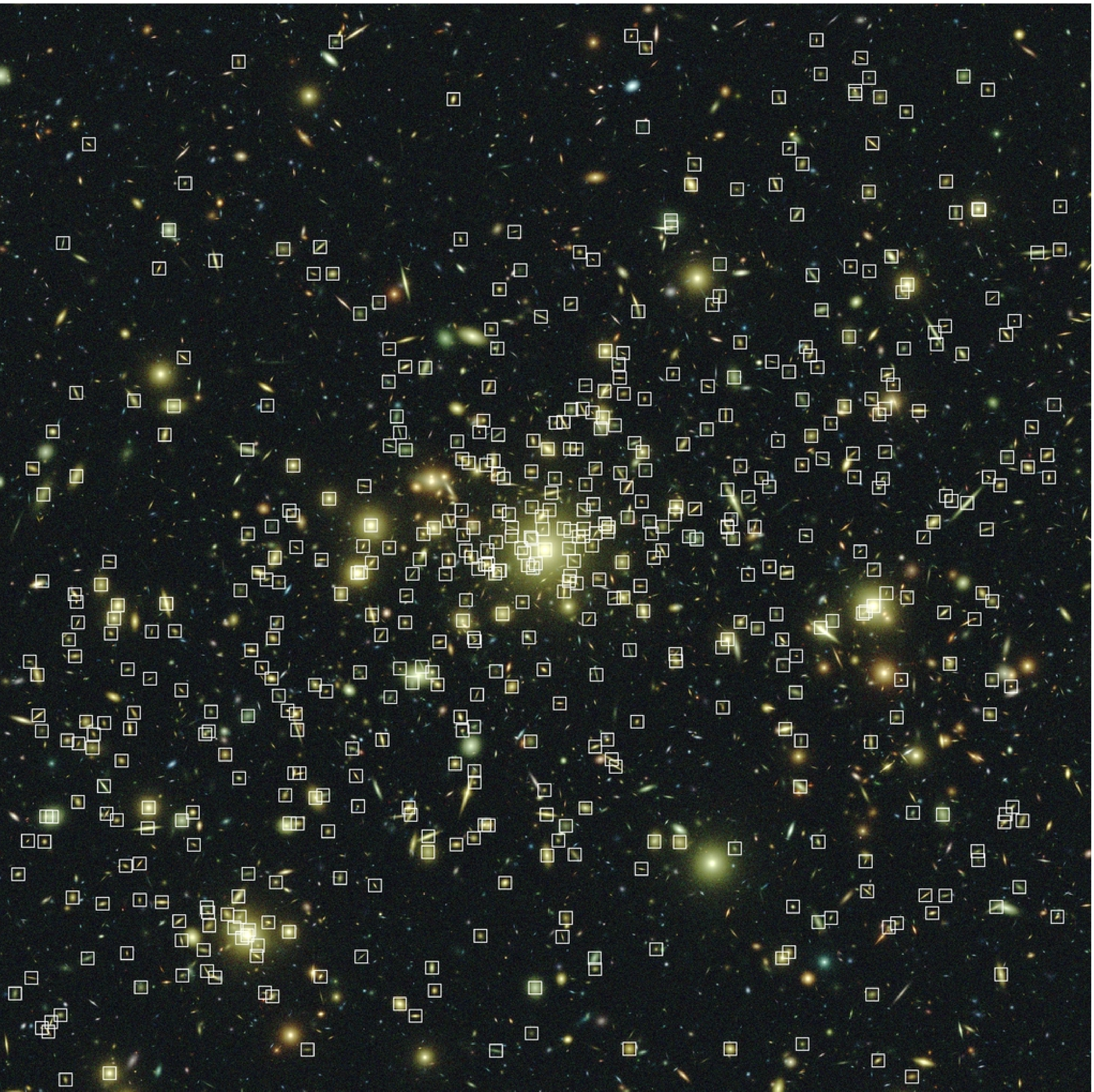
$M_{200} = 4x10^{15}M_\odot$

$z = 0.41$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000sec/filter



"Coma"

$M_{200} = 4x10^{15}M_\odot$

z = 0.41

3.4' x 3.4'

HST/ACS
F475W, F625W,
F850LP

10,000sec/filter

Cl0024

Harsono & De Propris
2007

z = 0.40

3.4' x 3.4'

HST/ACS

"Coma"

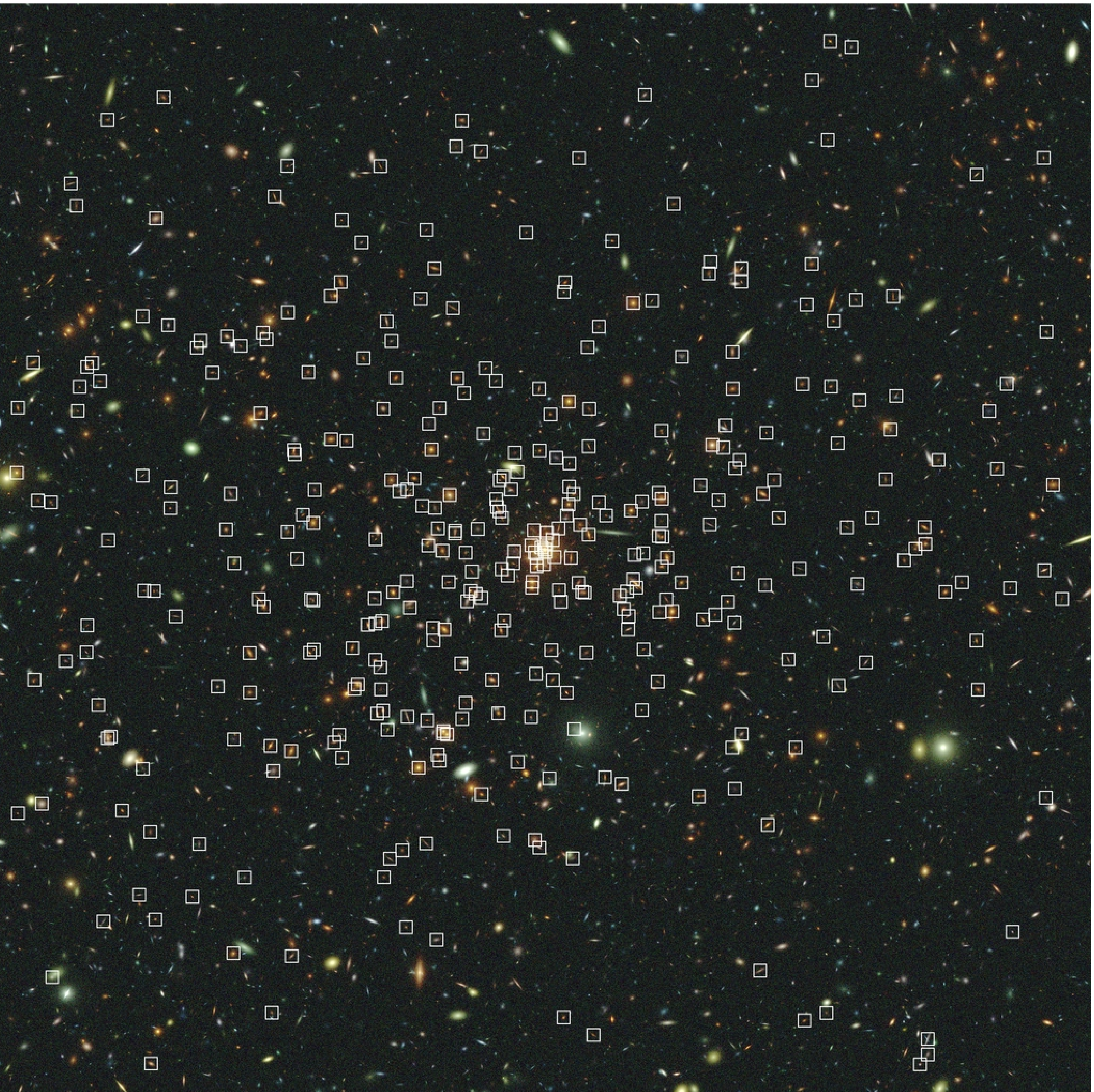
$M_{200} = 4 \times 10^{15} M_{\odot}$

$z = 0.83$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000sec/filter



"Coma"

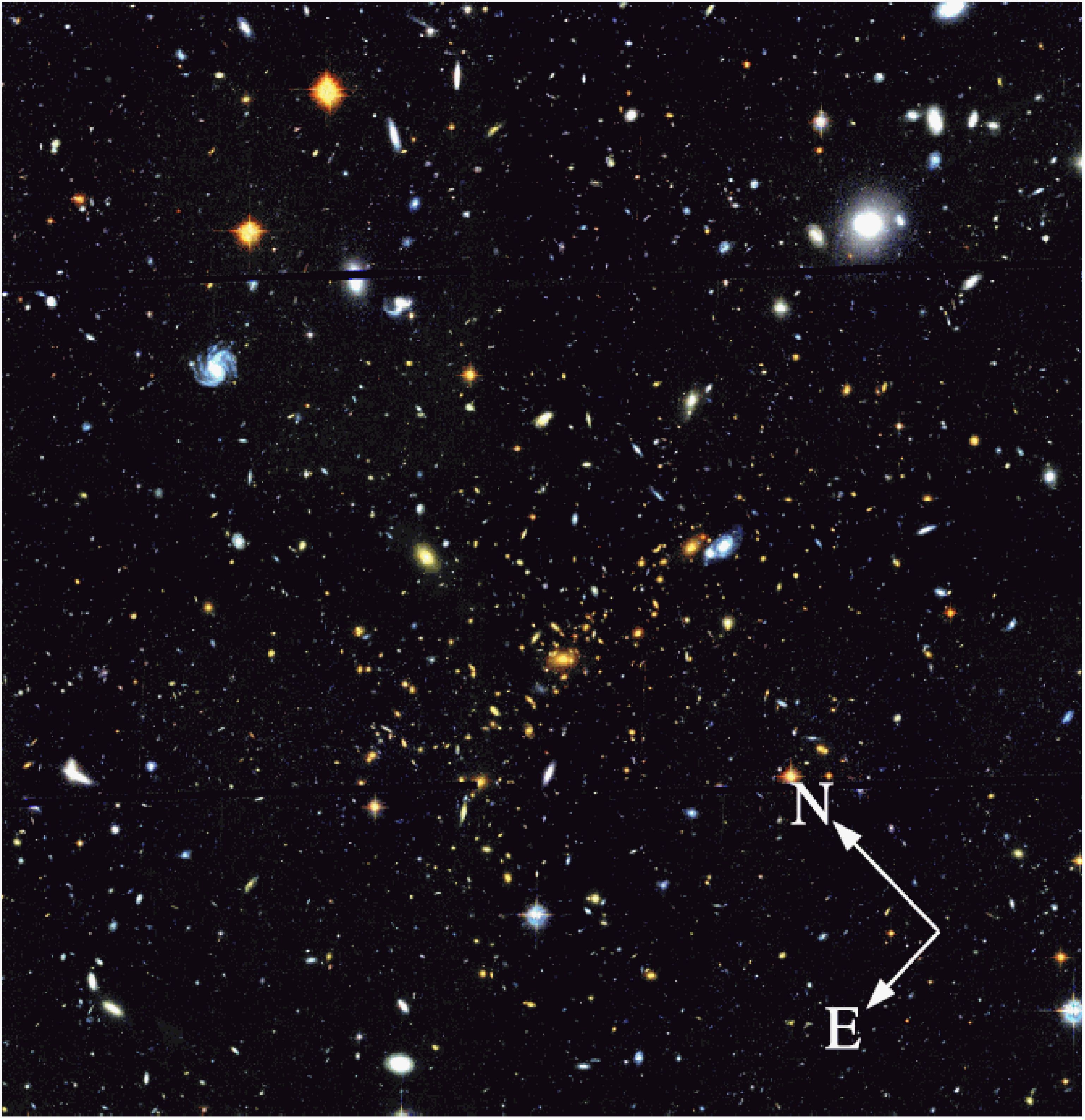
$M_{200} = 4x10^{15}M_{\odot}$

$z = 0.83$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000sec/filter



MS1054

Blakeslee et al 2006

z = 0.83

3.4' x 3.4'

HST/ACS

“Coma”

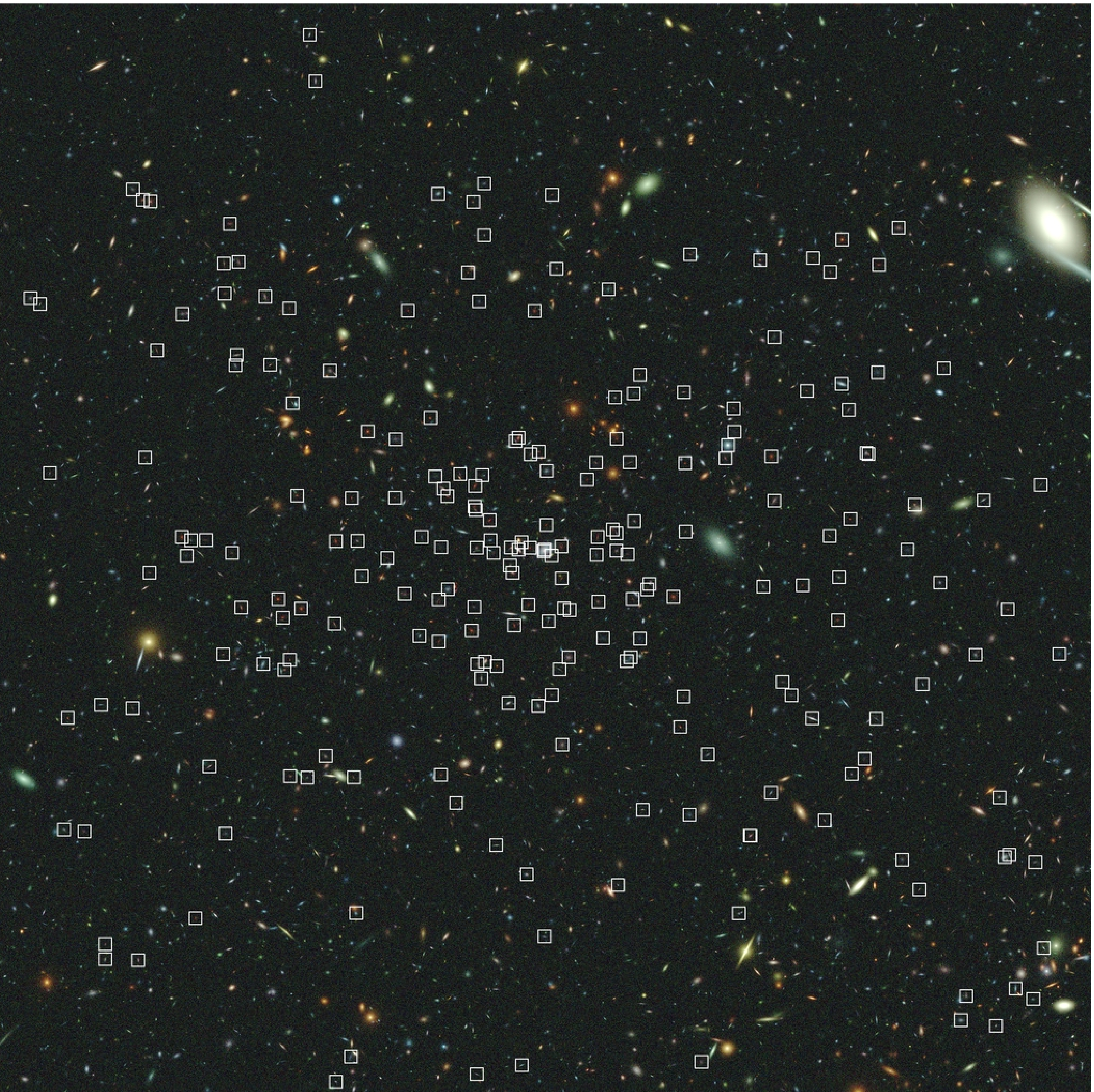
$M_{200} = 4x10^{15} M_{\odot}$

z = 1.50

3.4' x 3.4'

HST/ACS
F475W, F625W,
F850LP

10,000sec/filter



"Coma"

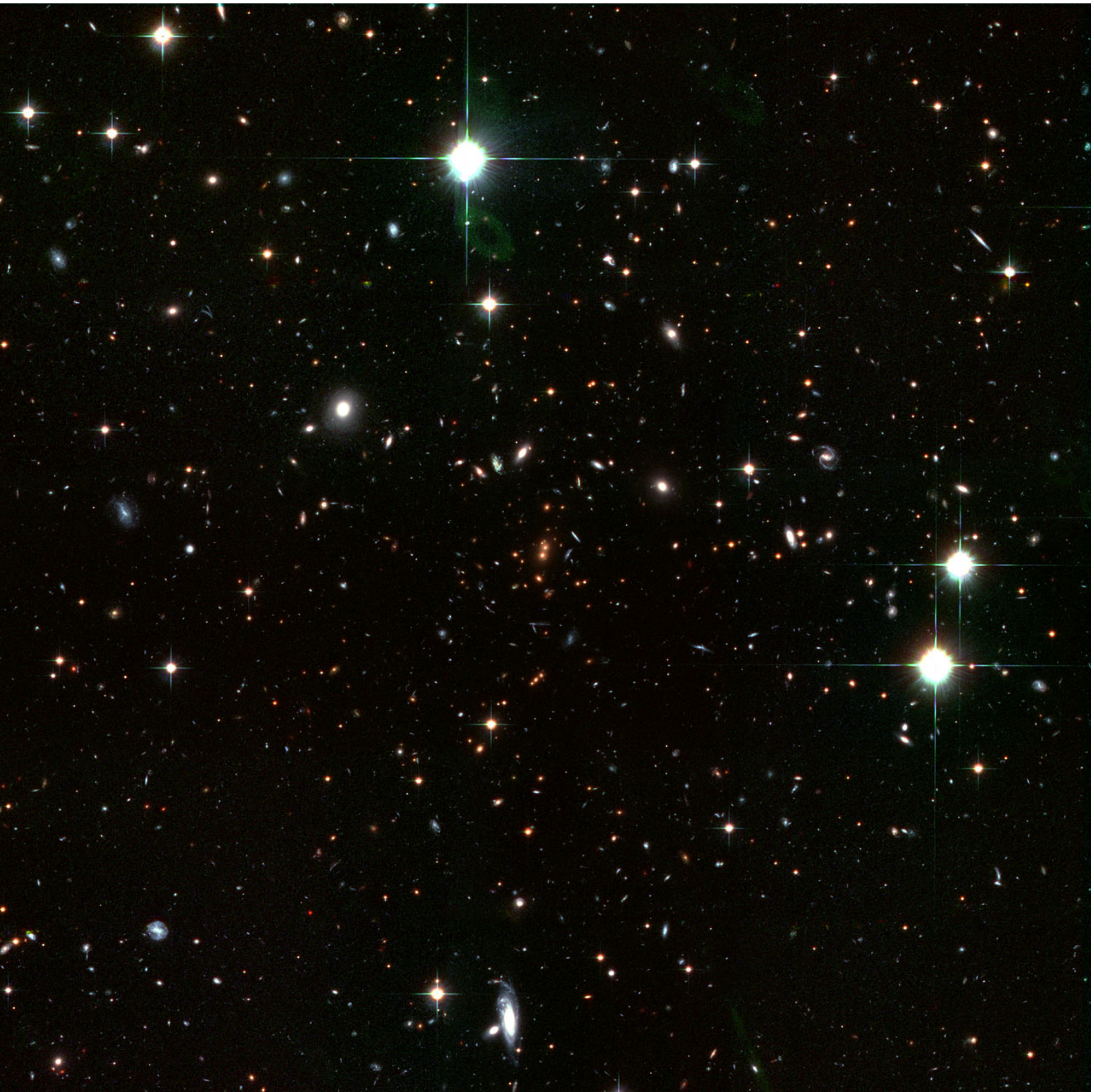
$M_{200} = 4x10^{15}M_{\odot}$

$z = 1.50$

3.4' x 3.4'

HST/ACS F475W, F625W, F850LP

10,000sec/filter



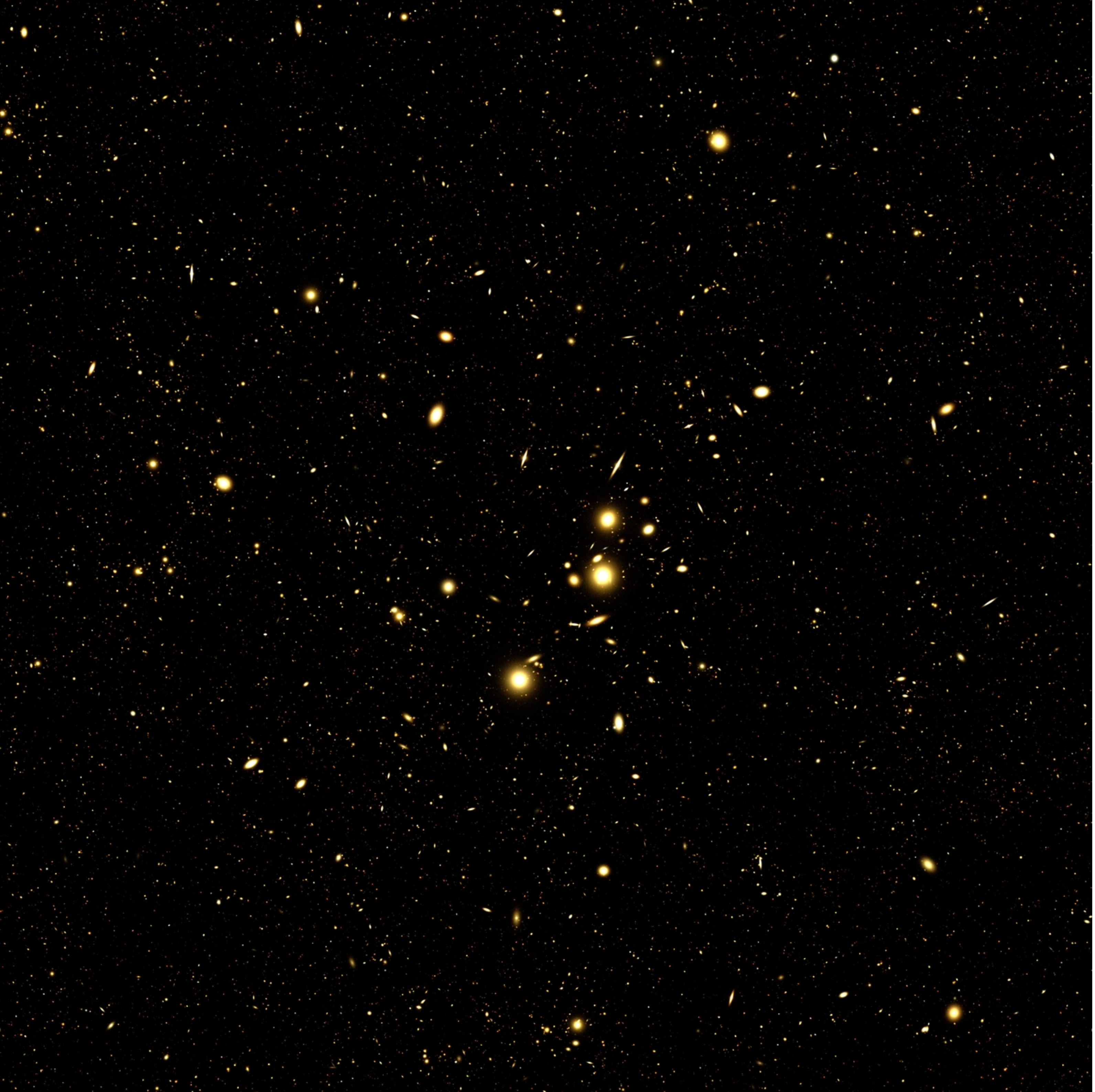
RCDS1252

Demarco et al 2007

z = 1.24

3.4' x 3.4'

HST/ACS



“Virgo”

$M_{200} = 2x10^{14}M_{\odot}$

z = 0.005

4° x 4°

SDSS g, r, I

54 sec/filter

“Virgo”

$M_{200} = 2x10^{14}M_{\odot}$

$z = 0.41$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000sec/filter

“Virgo”

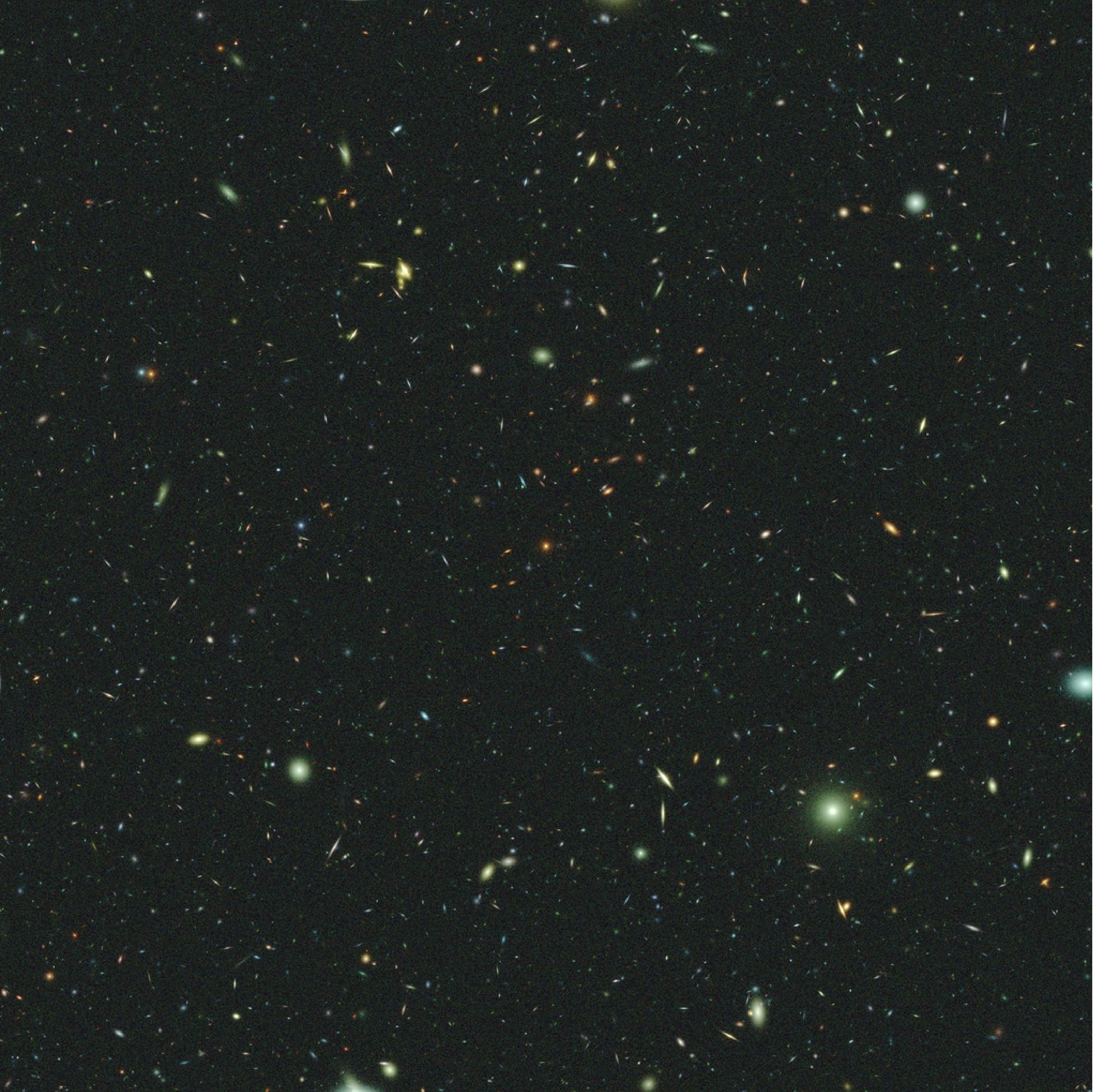
$M_{200} = 2x10^{14} M_{\odot}$

$z = 0.41$

3.4' x 3.4'

HST/ACS
F475W, F625W,
F850LP

10,000sec/filter



“Virgo”

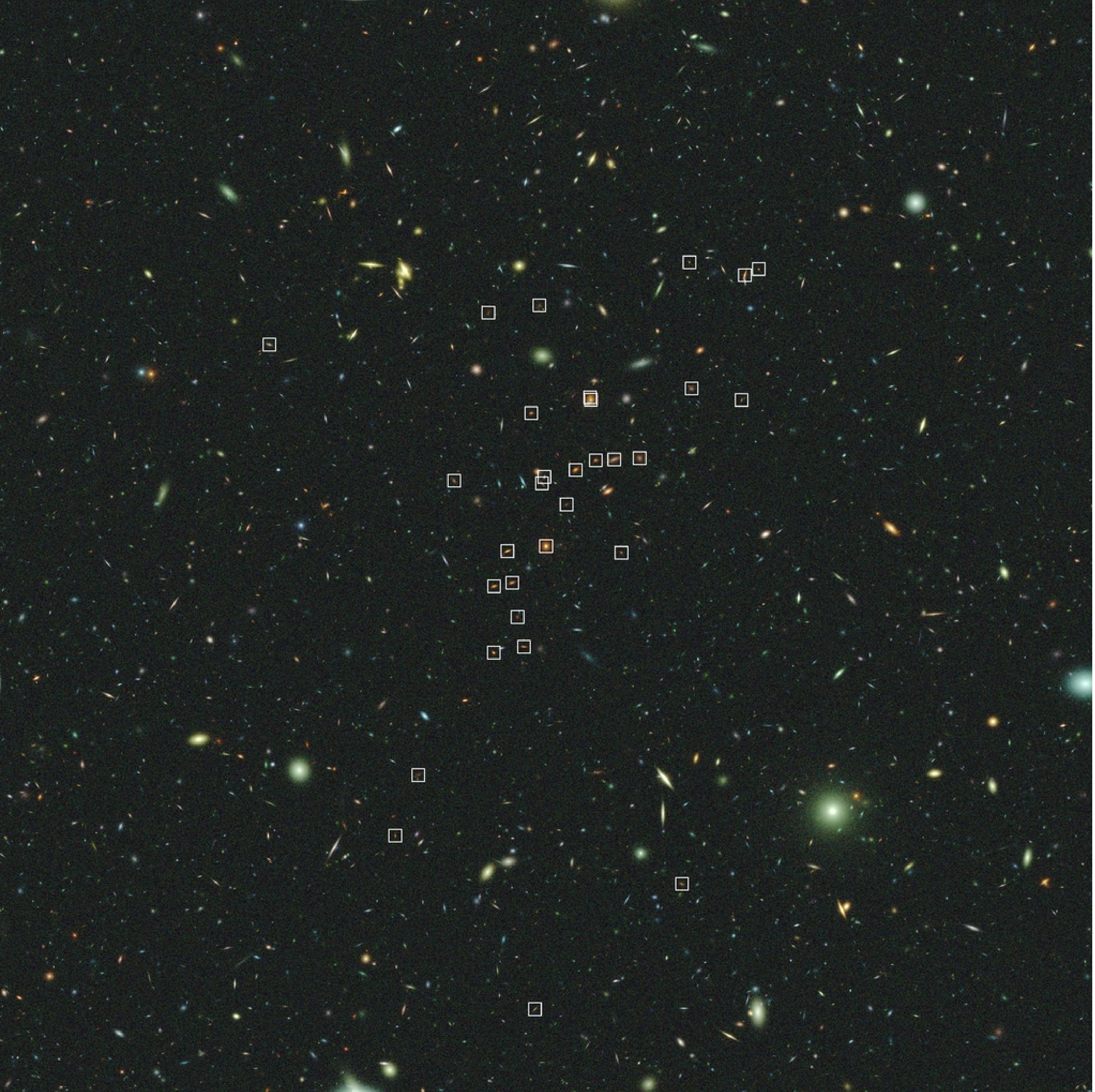
$M_{200} = 2x10^{14}M_\odot$

$z = 0.83$

3.4' x 3.4'

HST/ACS
F475W, F625W,
F850LP

10,000sec/filter



“Virgo”

$M_{200} = 2 \times 10^{14} M_{\odot}$

$z = 0.83$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000sec/filter

“Virgo”

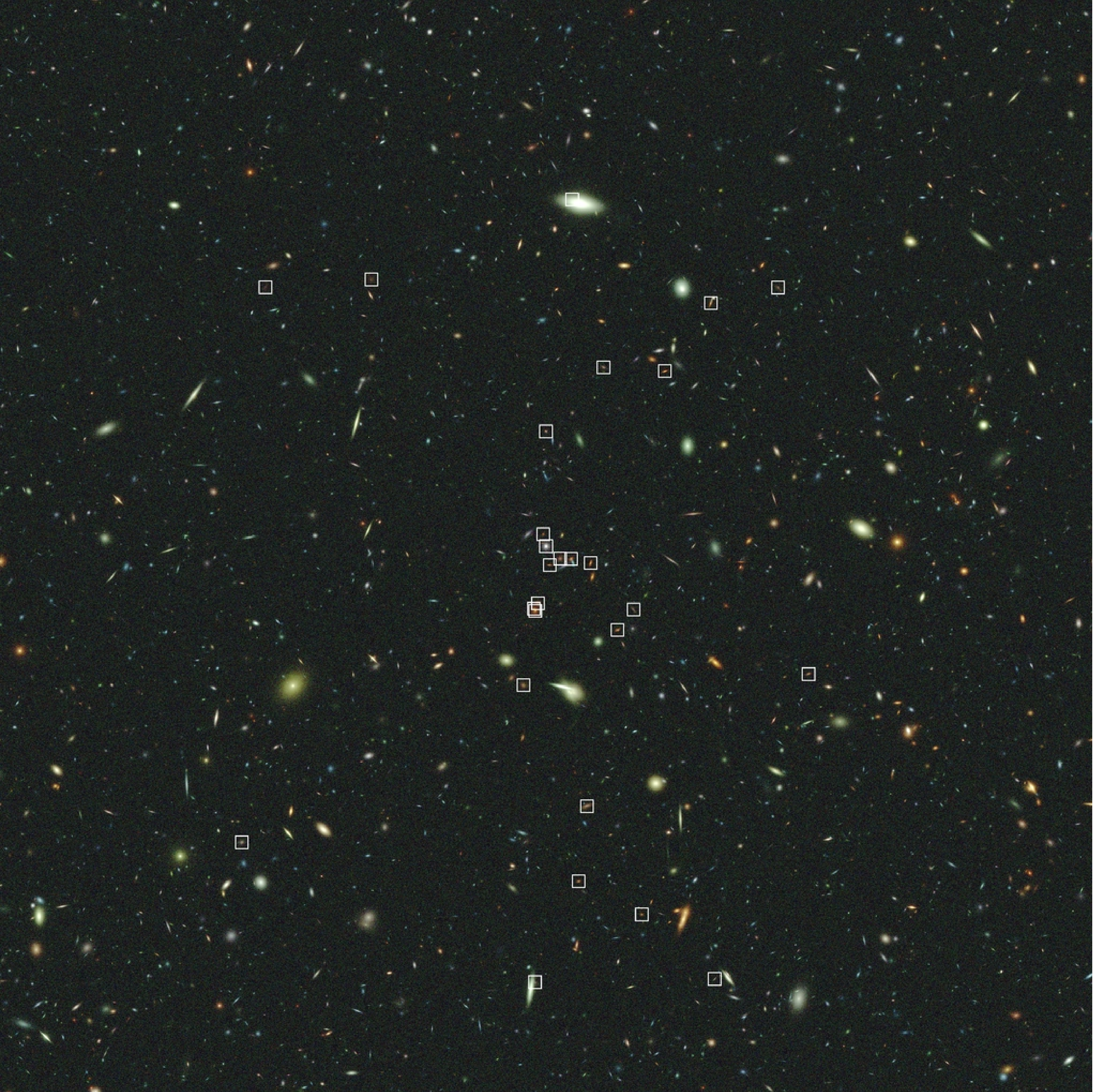
$M_{200} = 2x10^{14}M_{\odot}$

$z = 1.08$

3.4' x 3.4'

HST/ACS
F475W, F625W,
F850LP

10,000sec/filter



"Virgo"

$M_{200} = 2x10^{14}M_{\odot}$

z = 1.08

3.4' x 3.4'

HST/ACS
F475W, F625W,
F850LP

10,000sec/filter

Concluding remarks

- New techniques enable simulation of the *full galaxy population* within the current standard ΛCDM paradigm

- Comparison with observed populations produces *measurements* of the efficiency and mass/redshift/Z dependences of e.g.

    sequestration of baryons in galaxies
    driving of winds
    quiescent vs merger driven growth of galaxies/BH's
    galaxy disruption
    enrichment of the ICM/IGM

- When comparing with nearby clusters and their high-z analogues, current models appear

    too efficient at making stars at early times in lower mass halos
    too efficient at suppressing star formation after satellite infall
    too inefficient at disrupting galaxies to make the ICL