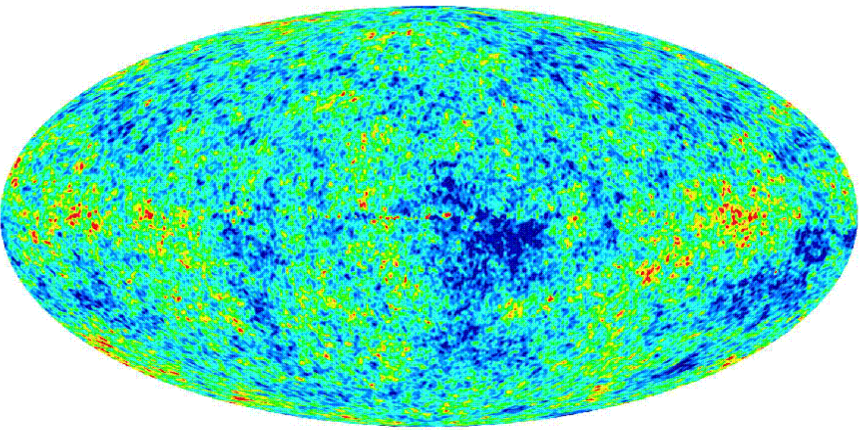


Durham, July 2011

Simulating the galaxy population

Simon White
Max Planck Institute for Astrophysics

Population simulations provide a tool...

- To explore the statistics and interactions of the many processes affecting stars and gas within growing ΛCDM structures

- To understand how the effects of these processes are reflected in the various observed <u>population</u> properties of galaxies and their evolution -- abundances, scaling relations, clustering

- To allow interpretation of large observational surveys in terms of the rates, efficiencies and significance of these processes

- NOT to make a definitive *a priori* physical model for the formation of everything from linear ΛCDM initial conditions

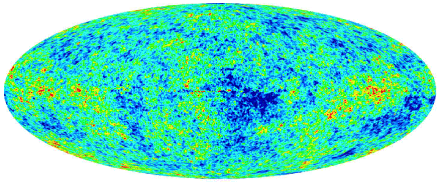
- NOR to represent the internal structure of individual galaxies at anything but the most schematic level

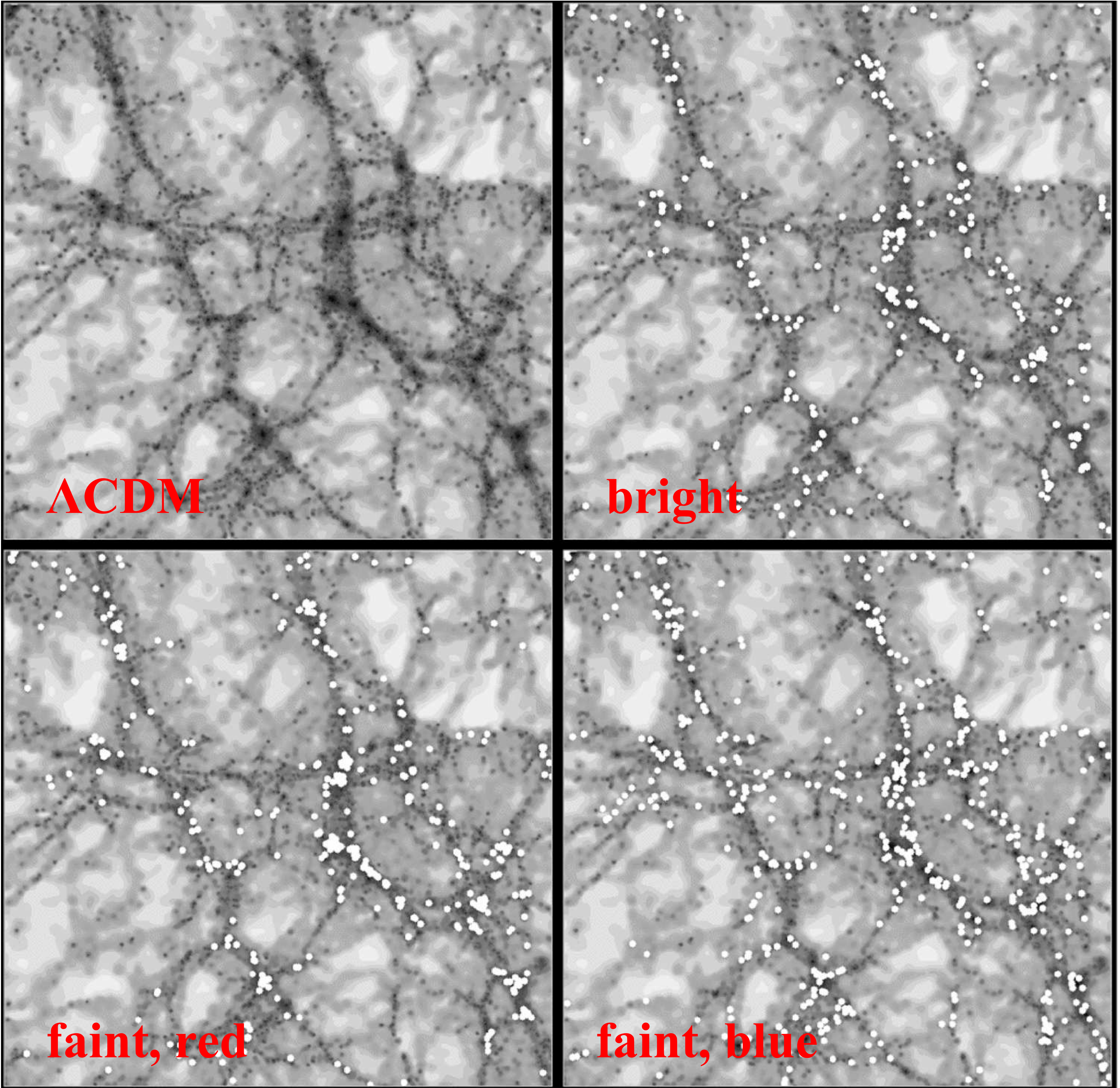
The semi-analytic programme

- 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

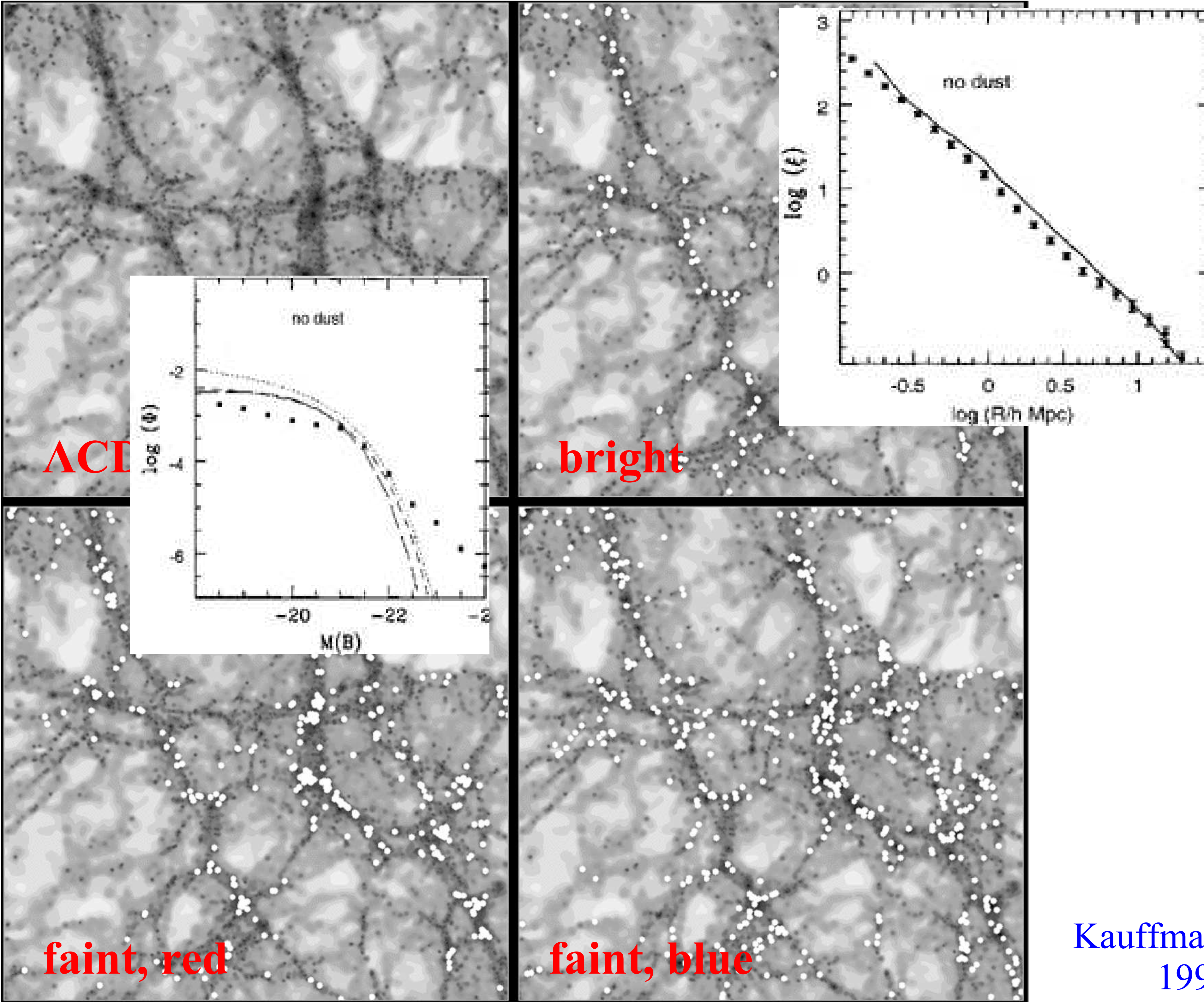
- Treat baryonic physics within the evolving population of DM objects using simplified physical models for processes such as
  gas cooling onto central galaxies
  star formation within these central galaxies
  central black hole growth
  generation of winds through stellar and AGN feedback
  production, 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

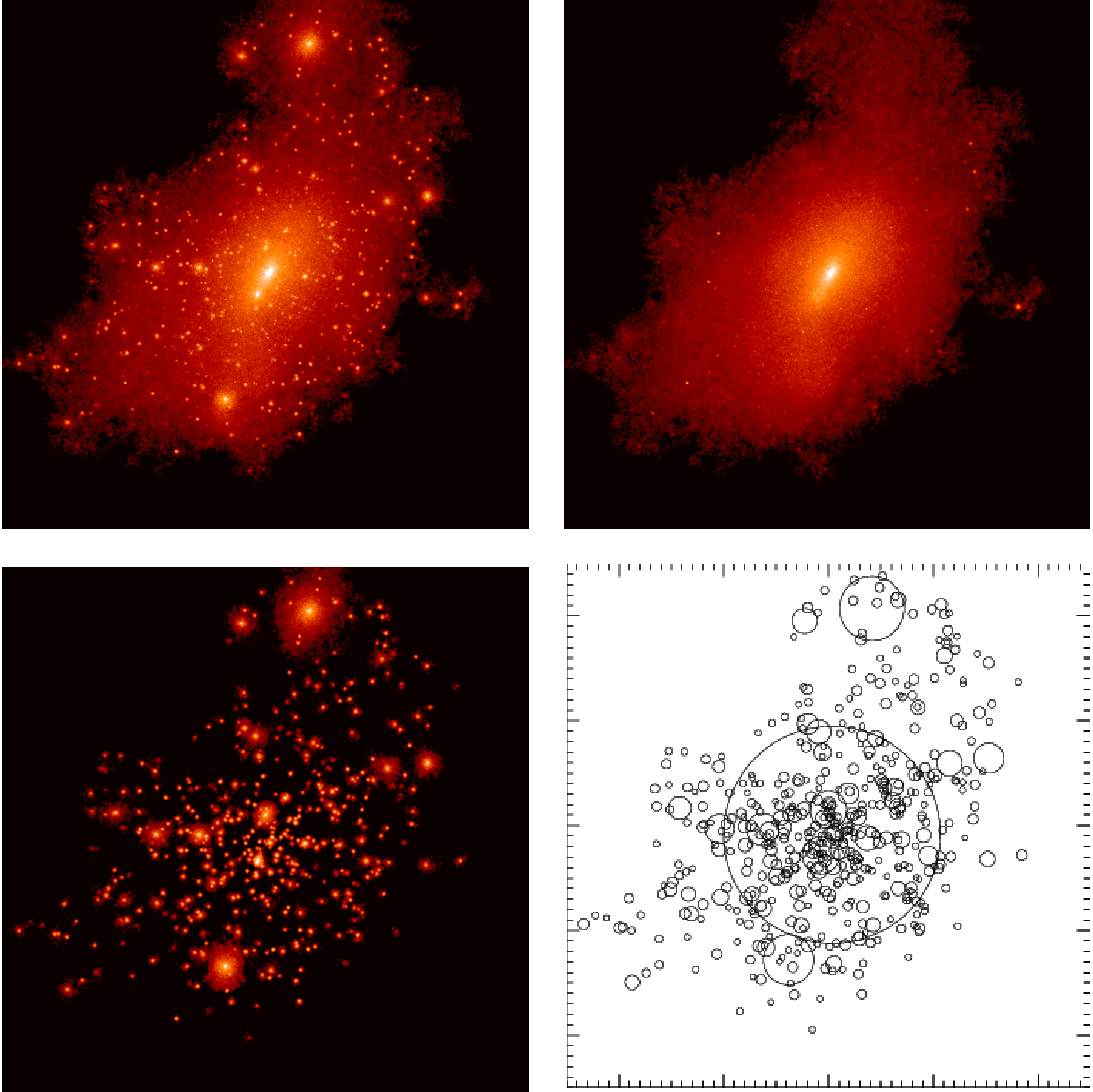
e.g.  → Ω



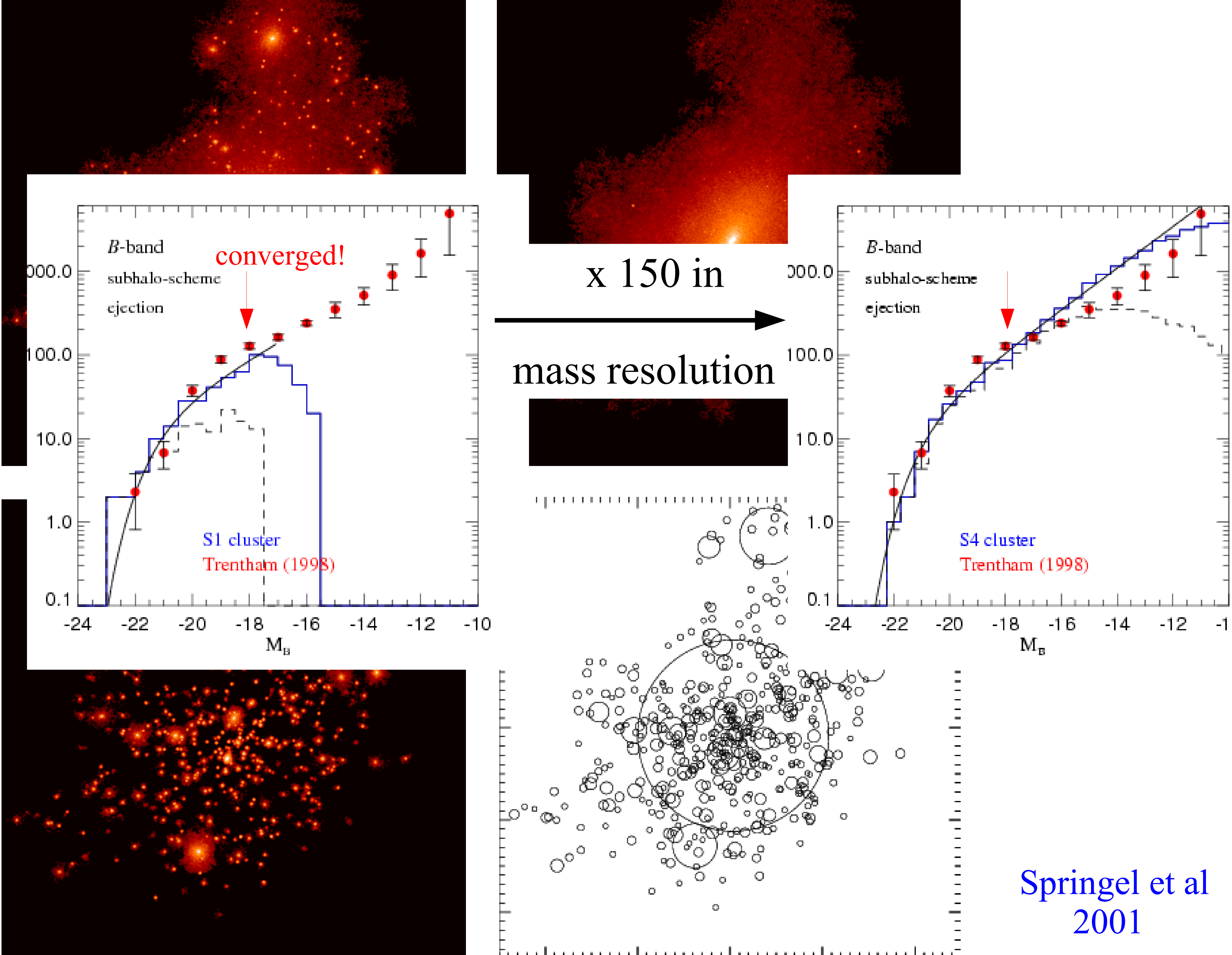
Kauffmann et al
1999



Kauffmann et al 1999

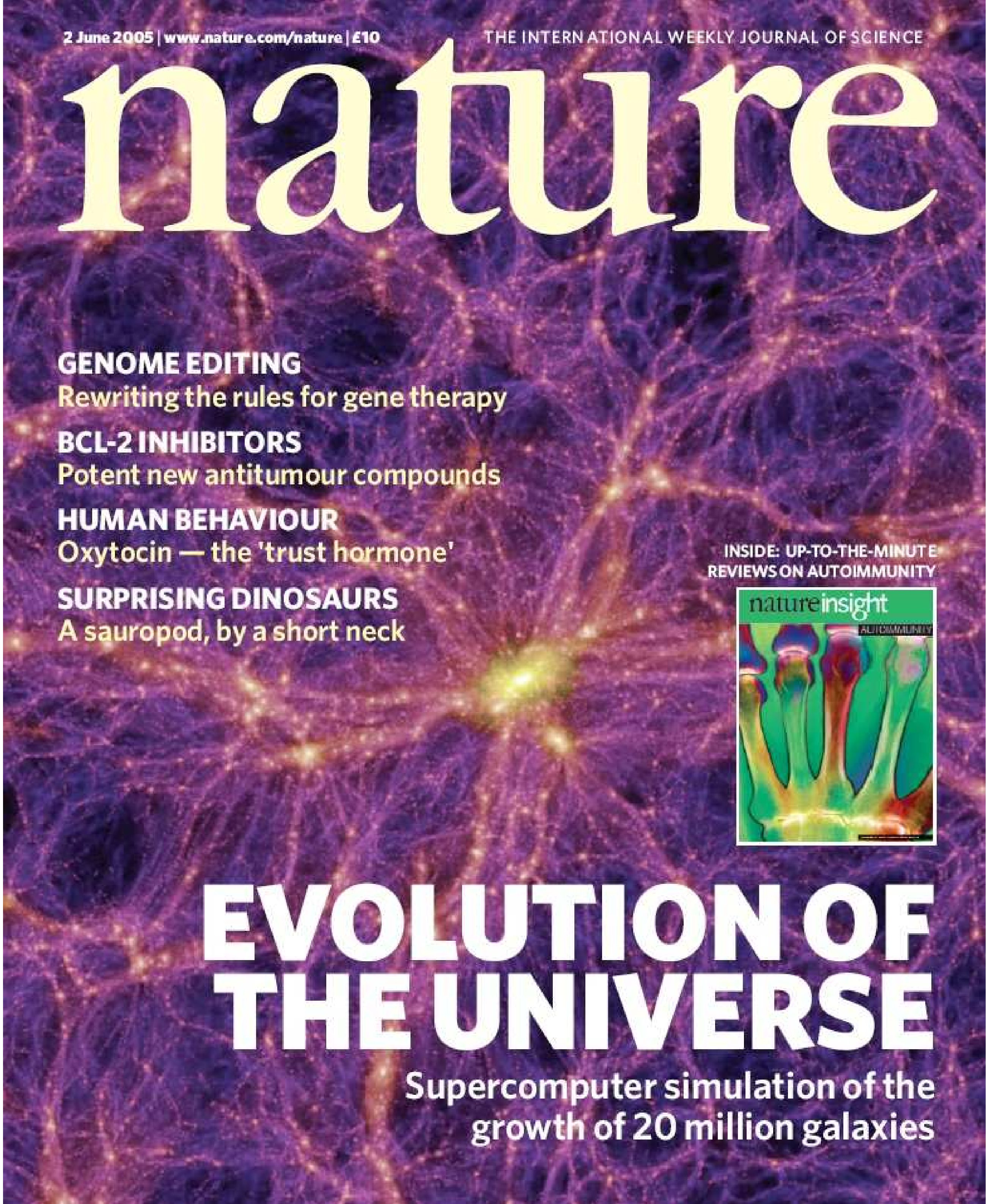


Springel et al
2001



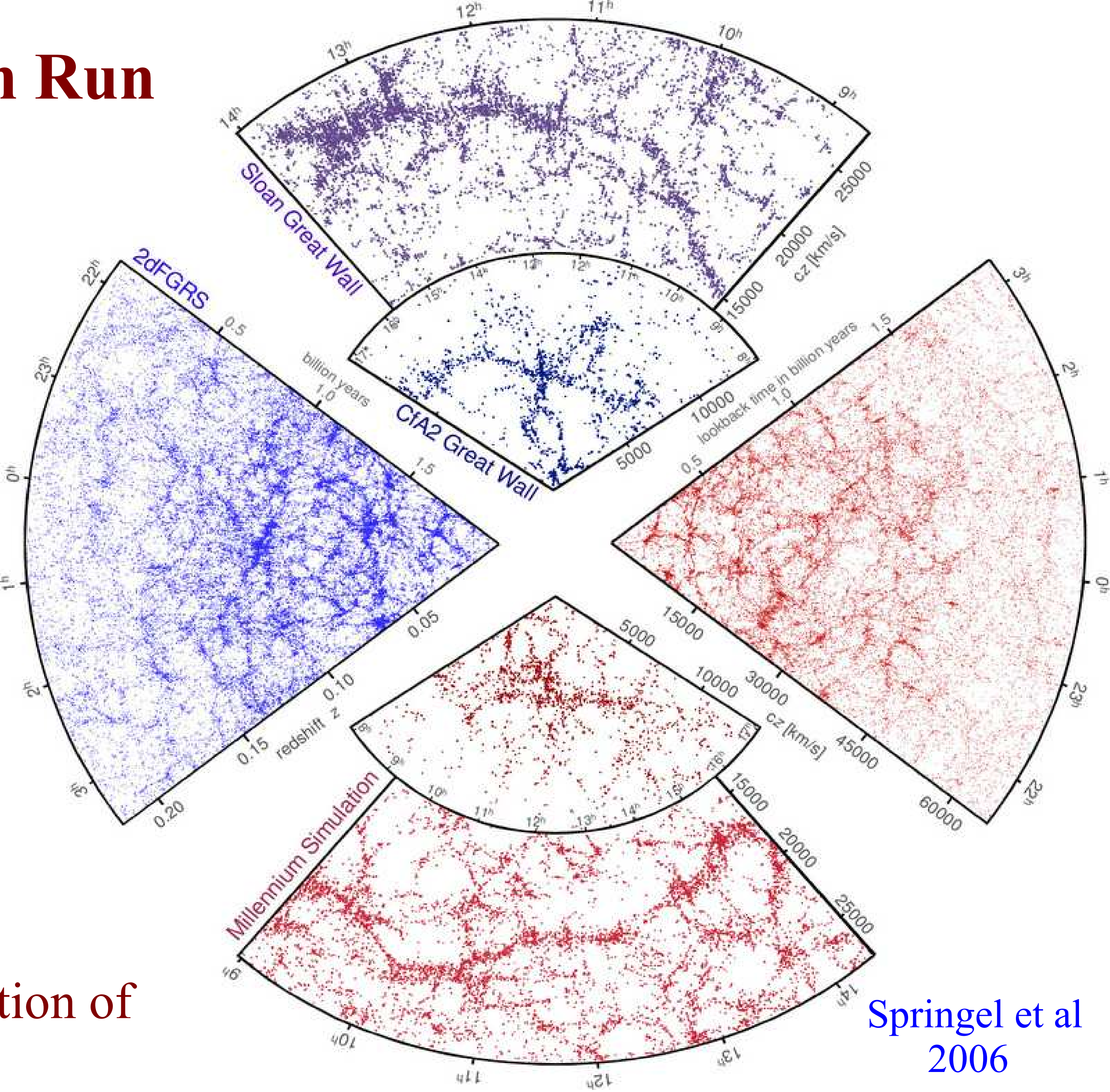
Springel et al 2001

Millennium Run
2004



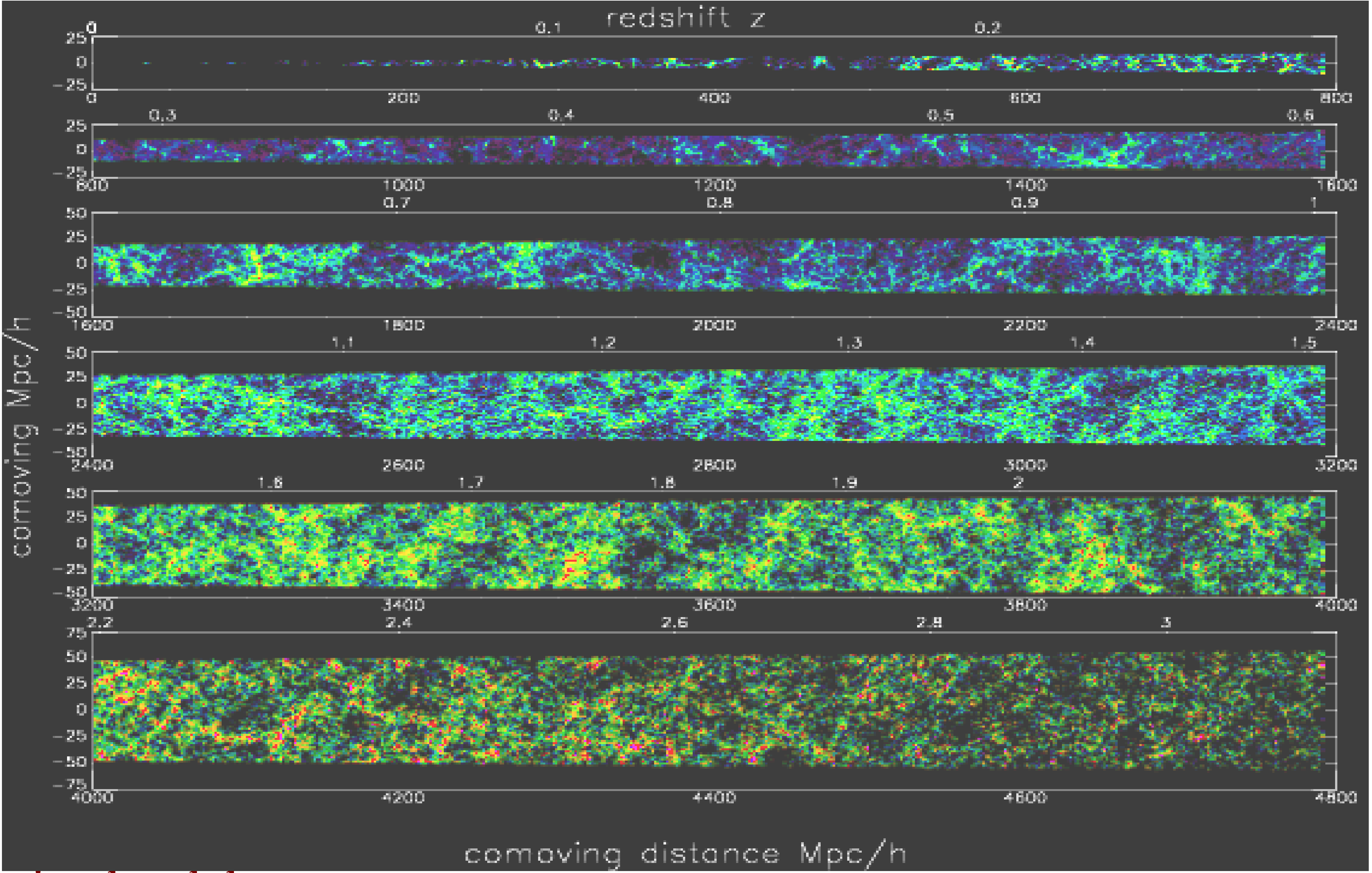
Springel et al
2005

Millennium Run
2004



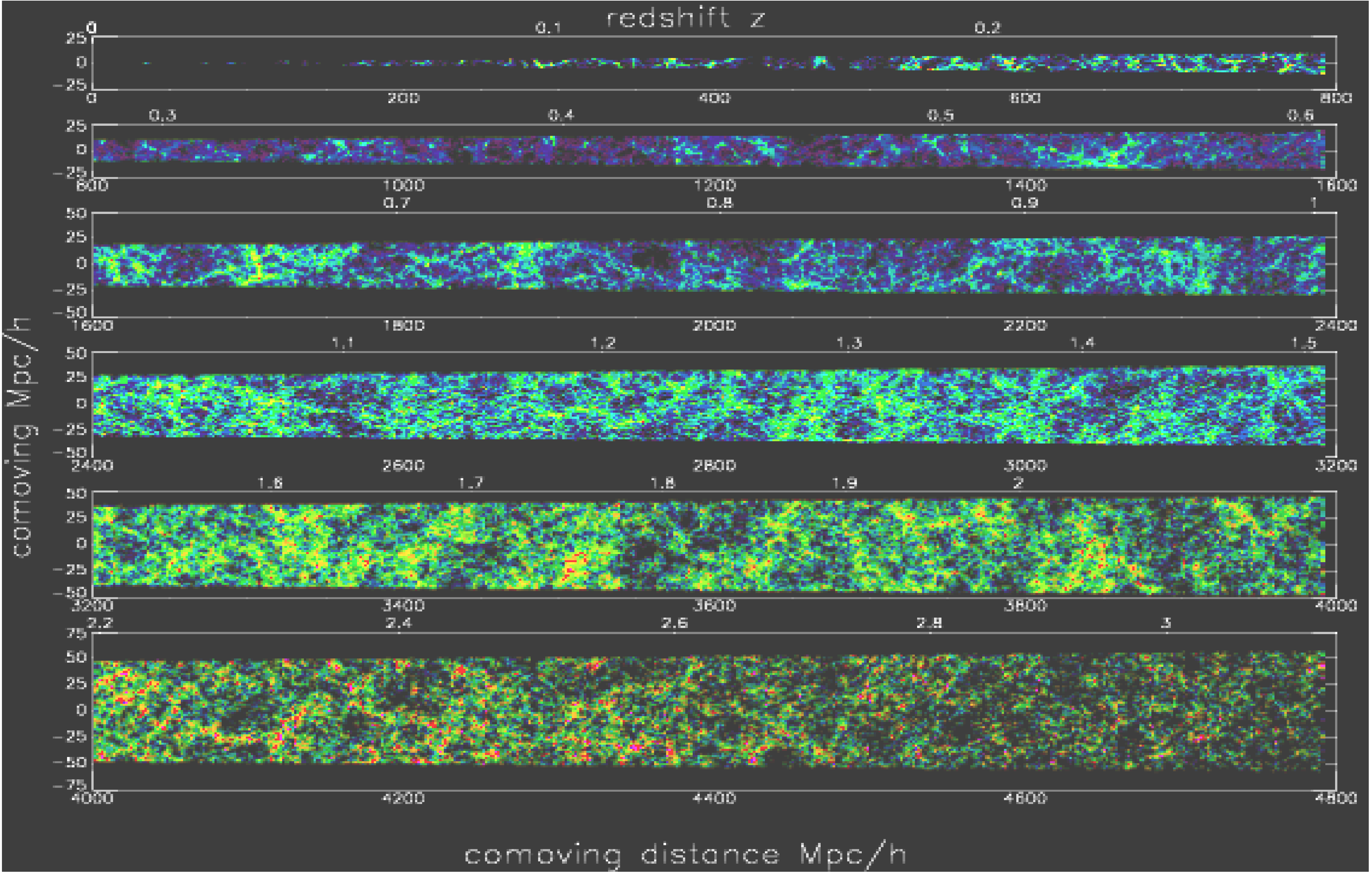
simulated the formation/evolution of $2x10^7$ galaxies

Springel et al
2006



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

Kitzbichler & White
2007

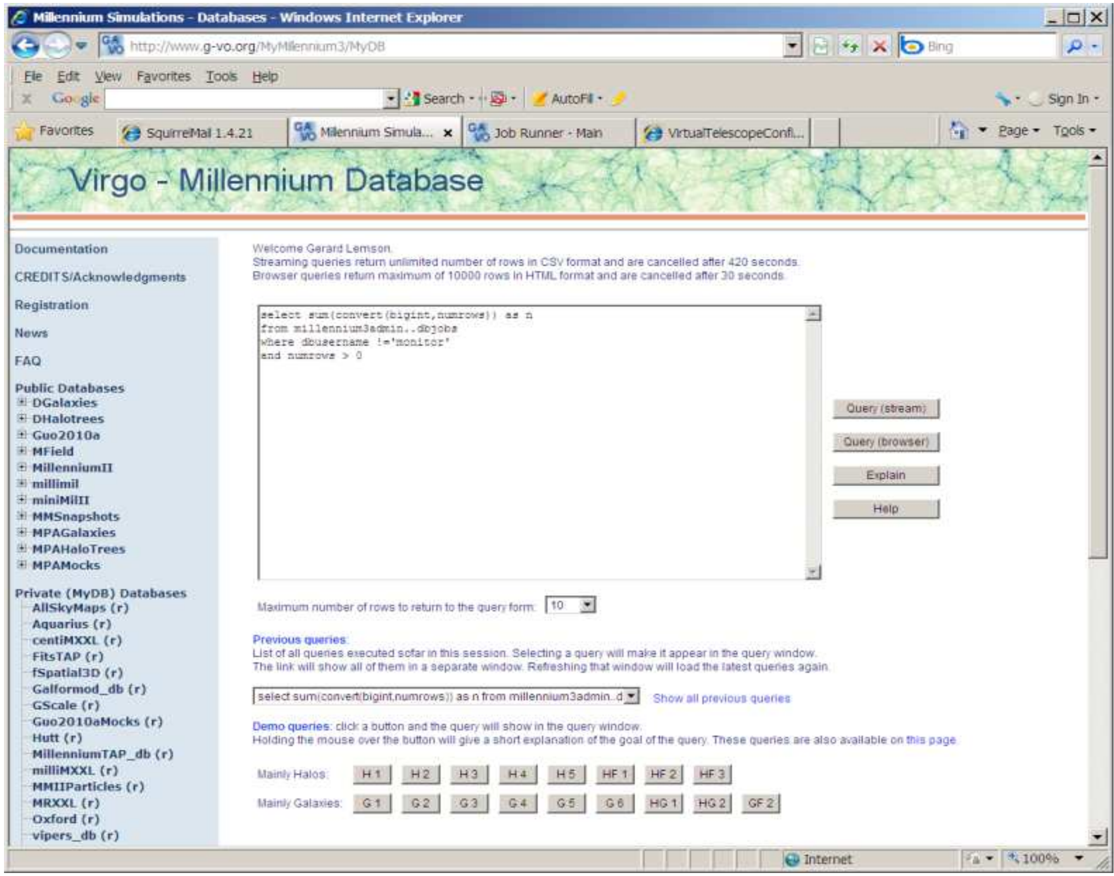


398 papers making direct use of data from the MS (14-7-2011)
Most by authors unassociated with the consortium
Most based on the galaxy catalogues, particularly mock surveys

Virgo-Millennium Database

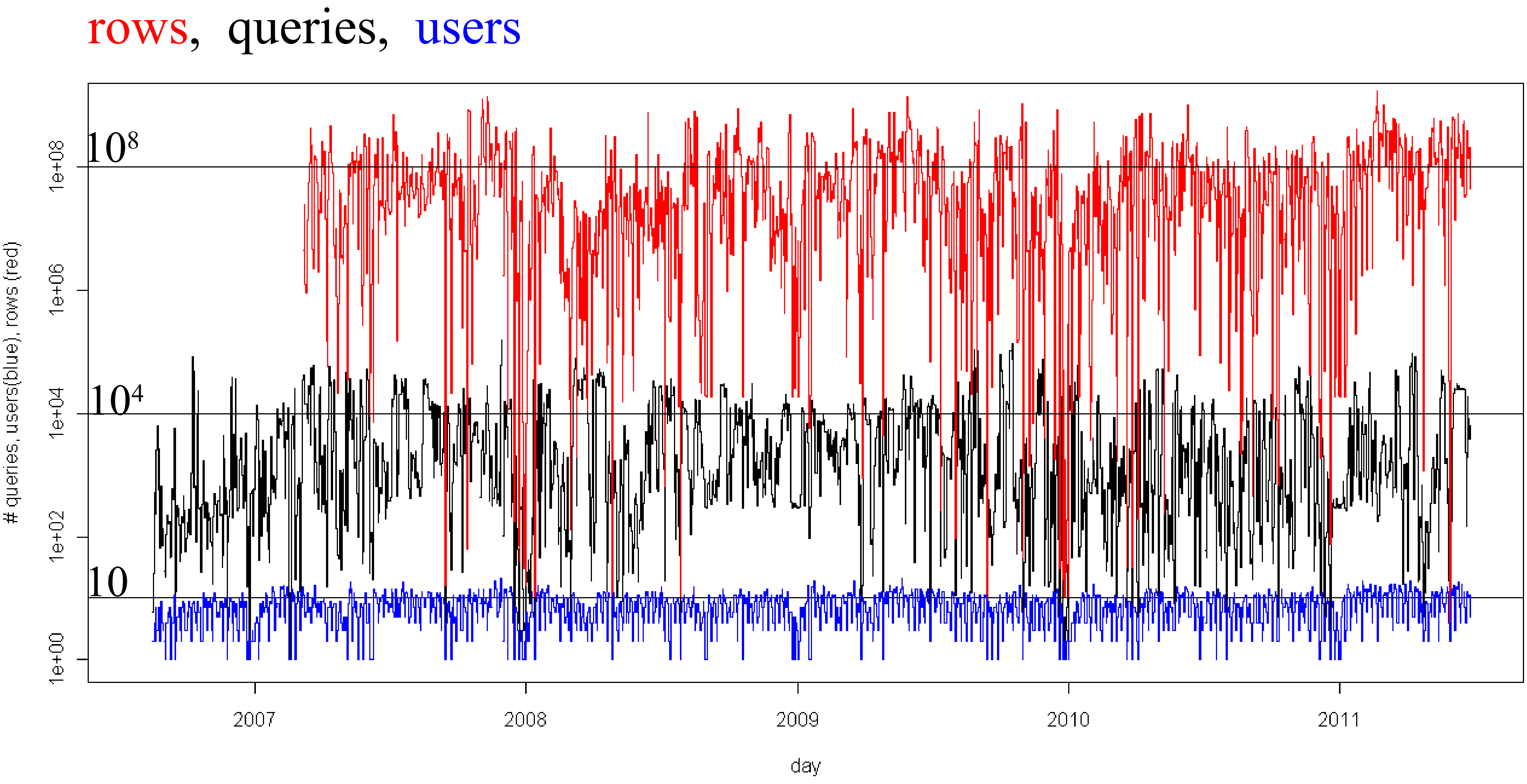
Since 2006

- > 450 registered users
- > 13 million queries
- ~ 170 billion rows
- mirror@Durham
- copy@AIP: multidark.org (incl Bolshoi, Multidark sim's)



Lemson et al 2006

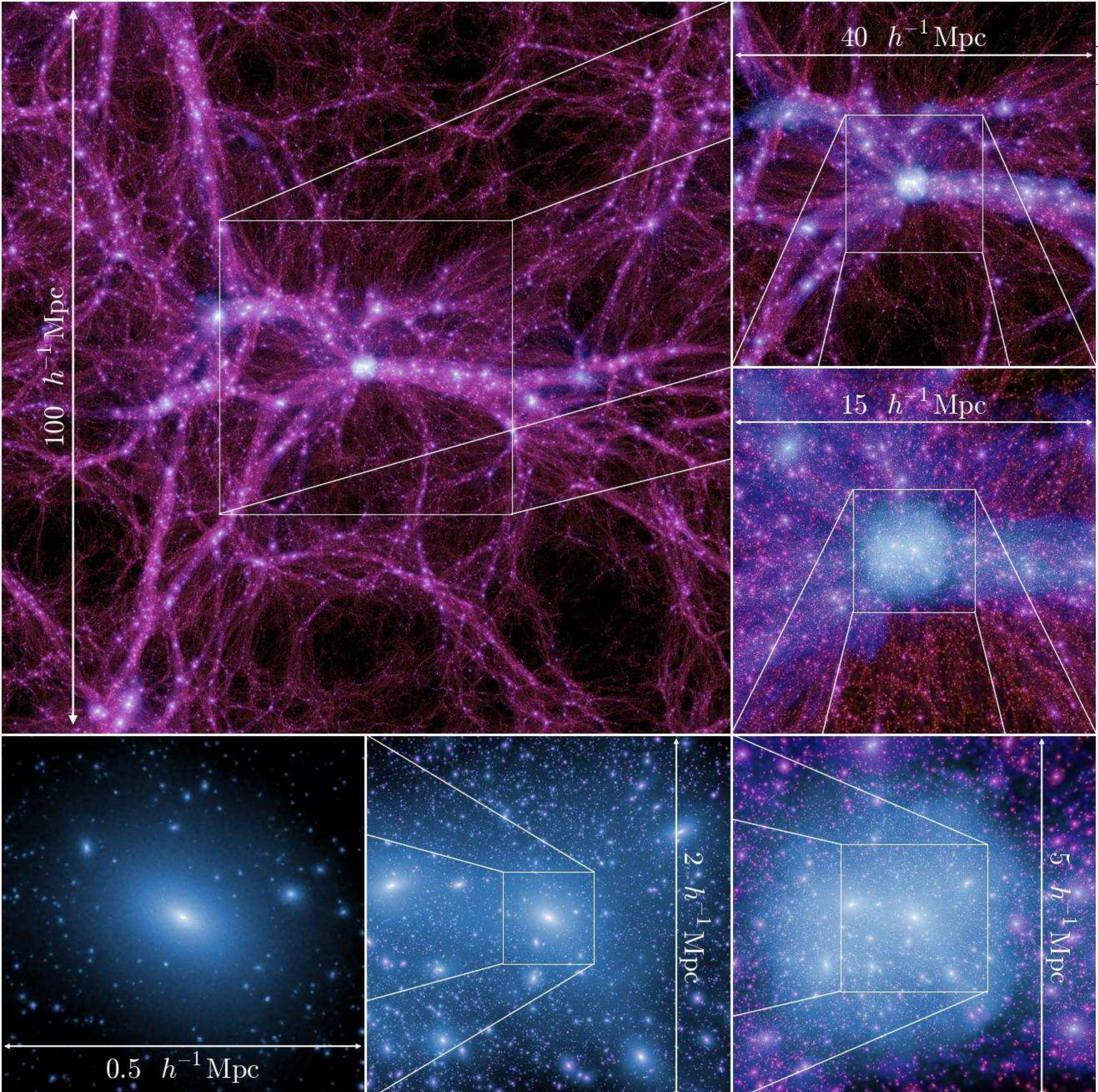
Daily usage



rows, queries, users
10^8
10^4
10
1e+08
1e+06
1e+04
1e+02
1e+00
queries, users(blue), rows (red)
2007
2008
2009
2010
2011
day

Limitations of the Millennium Simulation

- Limited modeling of *structure* of galaxies, gas components
- Limited resolution – too poor to model formation of dwarfs
- No convergence tests – are galaxy results numerically converged?
- Limited volume – too small for BAO work, precision cosmology
- 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

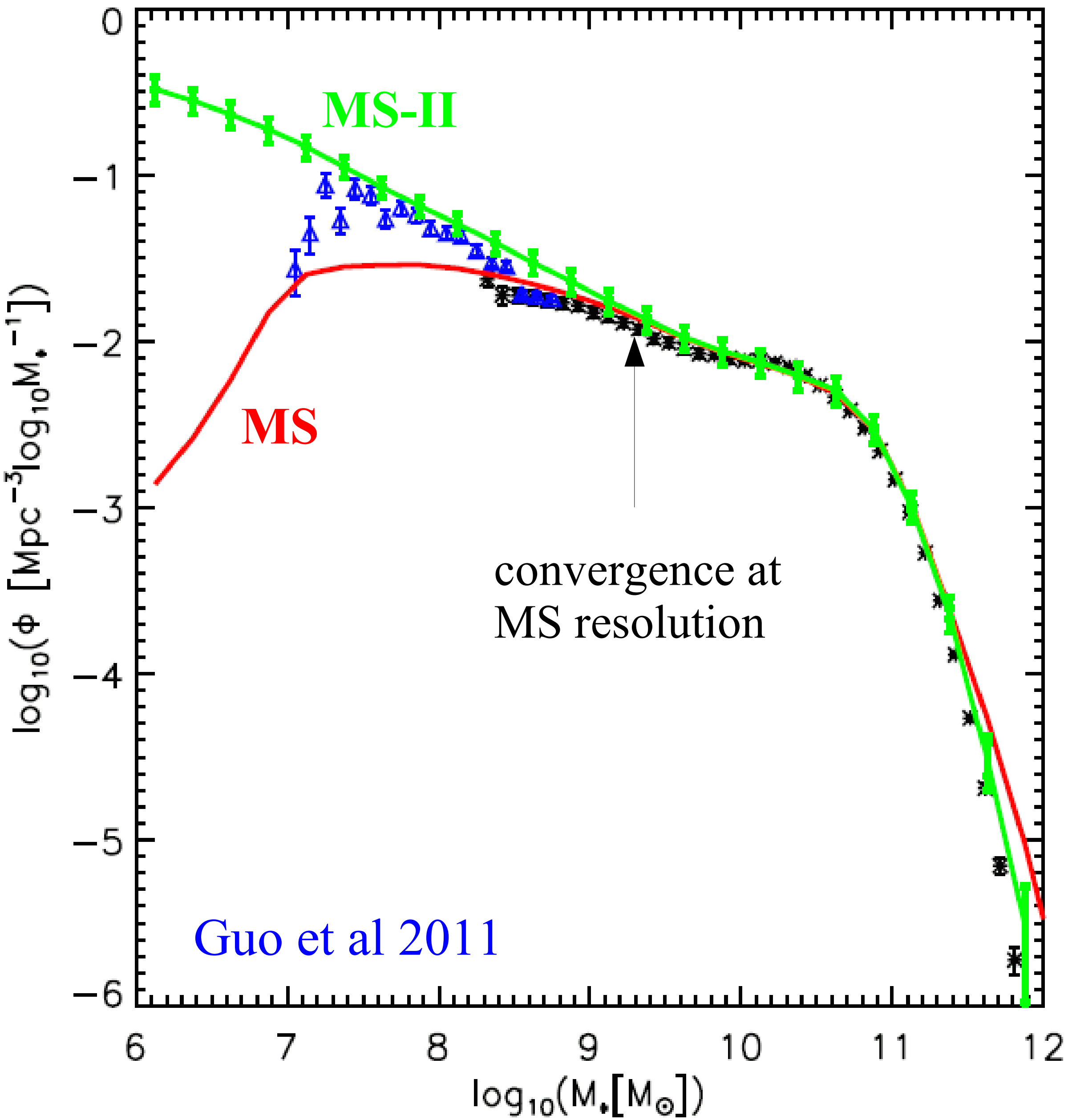
Boylan-Kolchin et al 2009

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

Qi Guo et al 2011

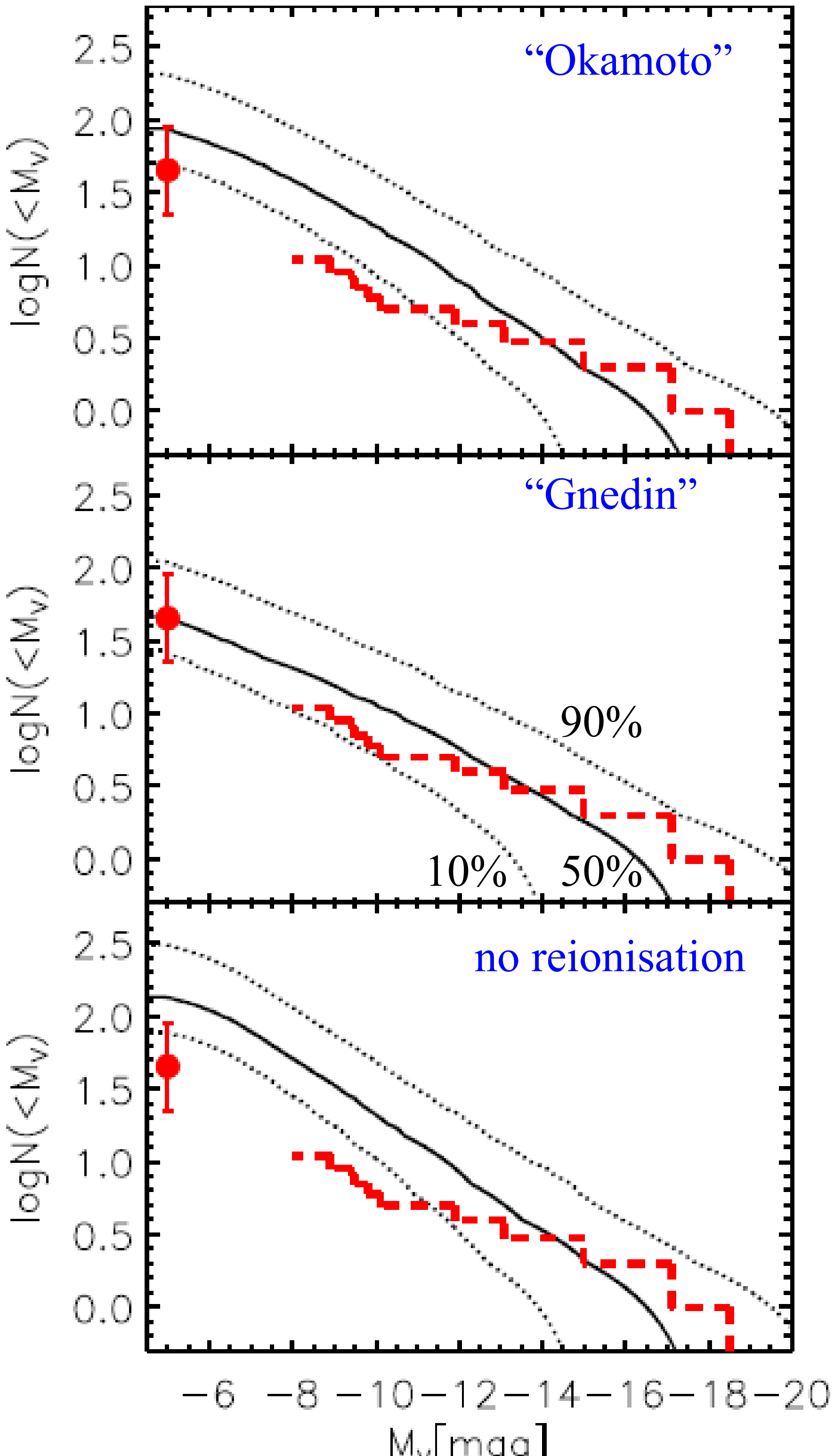
- Implement modelling simultaneously on MS and MS-II
- Test convergence of galaxy properties near resolution limit of MS
- Extend to properties of dwarf galaxies
- Improve/extend treatments of "troublesome" astrophysics
- Adjust parameters to fit new, more precise data
- Test against clustering and redshift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

The stellar mass function of galaxies



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

Luminosity function of Milky Way satellites

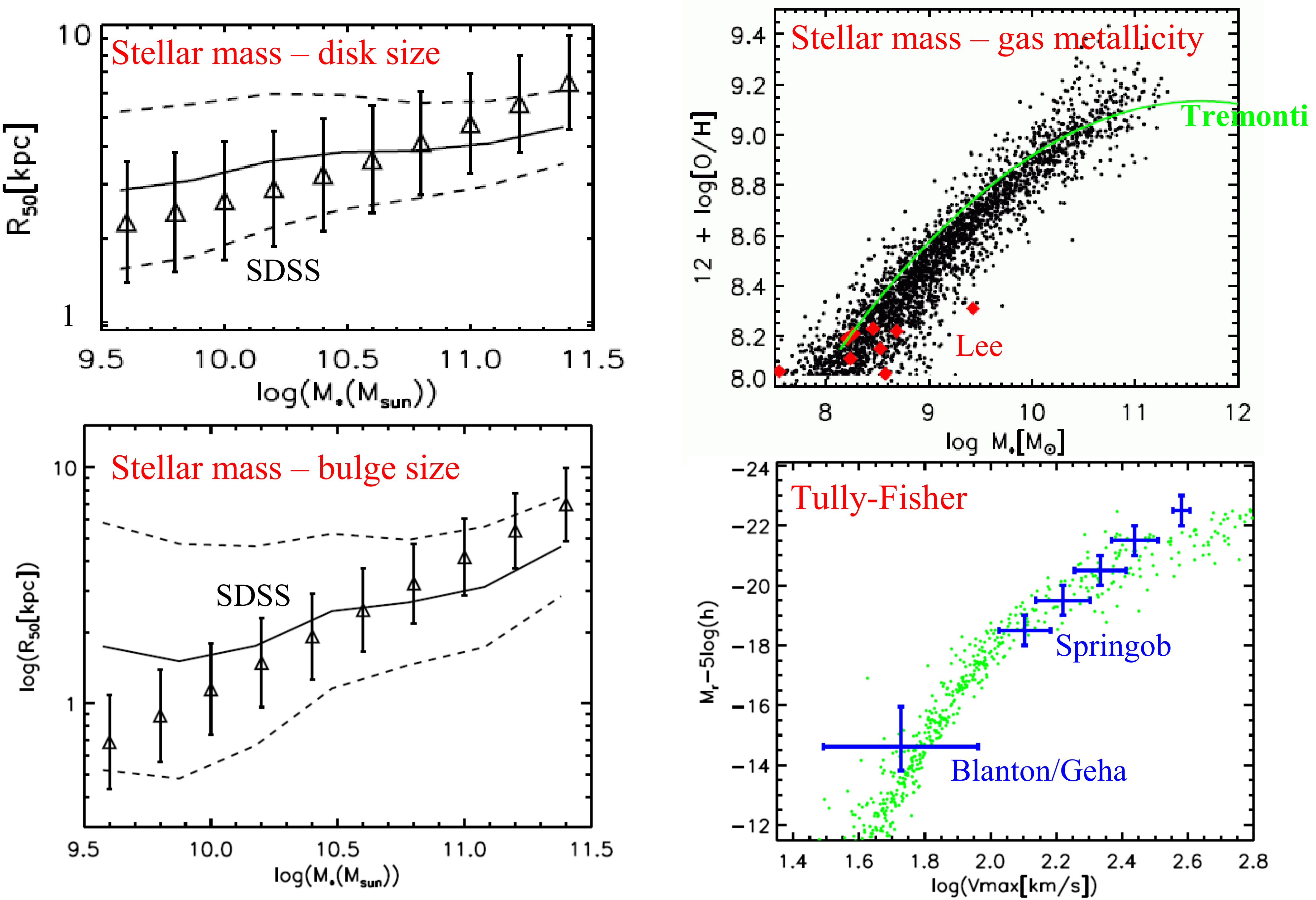


Luminosity functions of satellites around 1500 "Milky Ways" i.e. isolated disk galaxies with log $M_* = 10.8$

Guo et al 2011

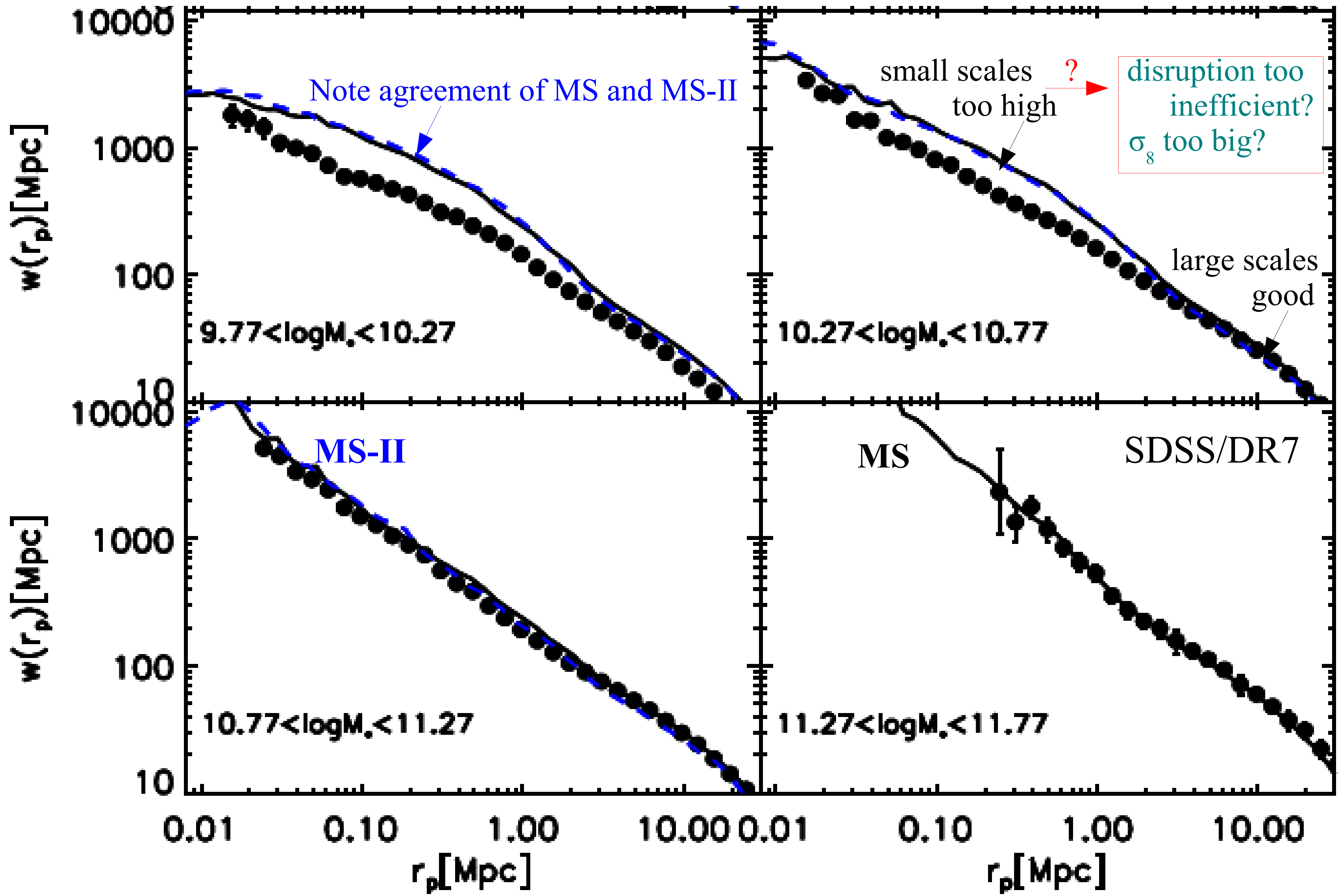
Scaling relations

Guo et al 2011



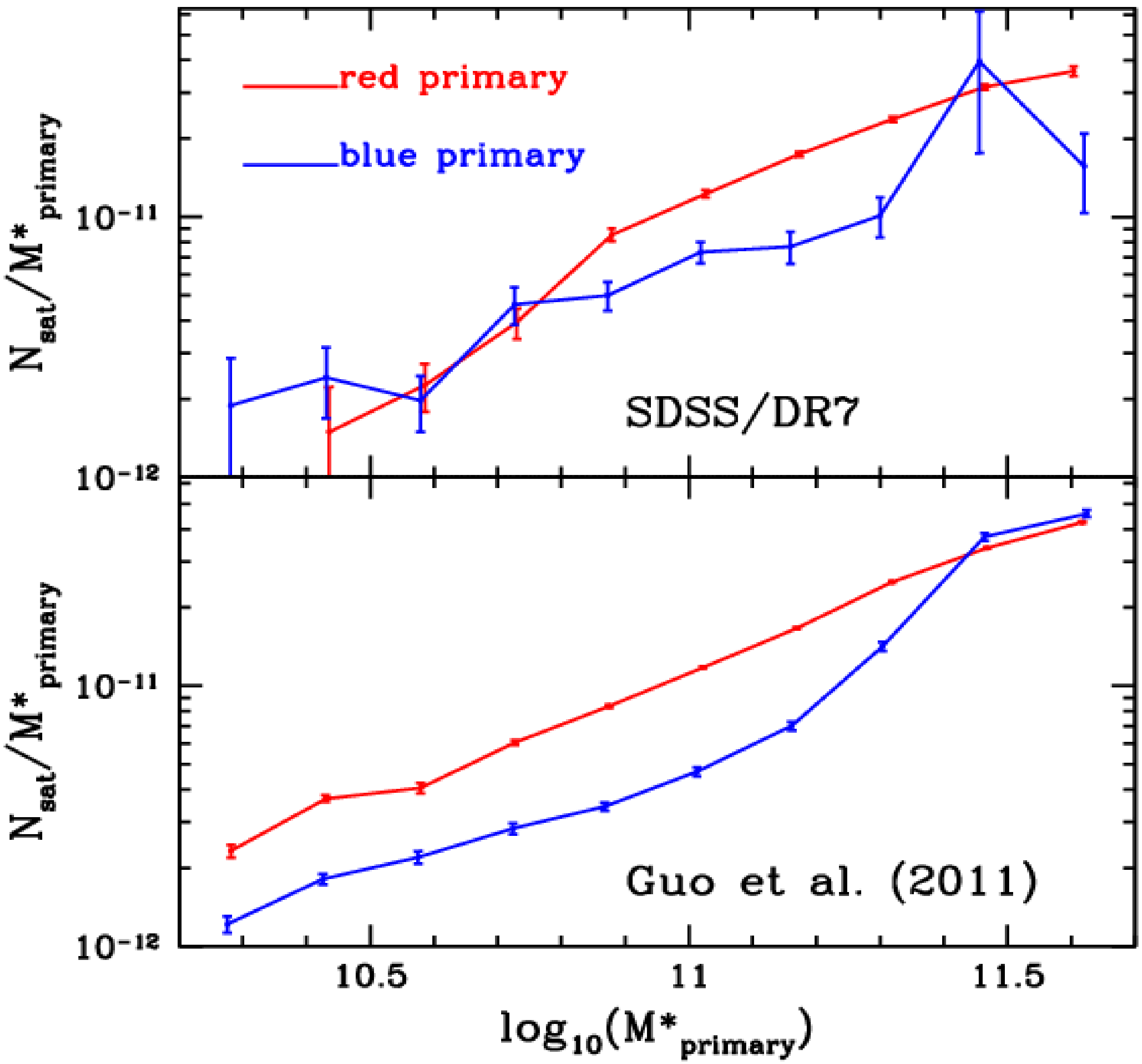
Mass-dependent galaxy clustering

Guo et al 2011



Satellite abundances around isolated bright galaxies

Wang & White 2011



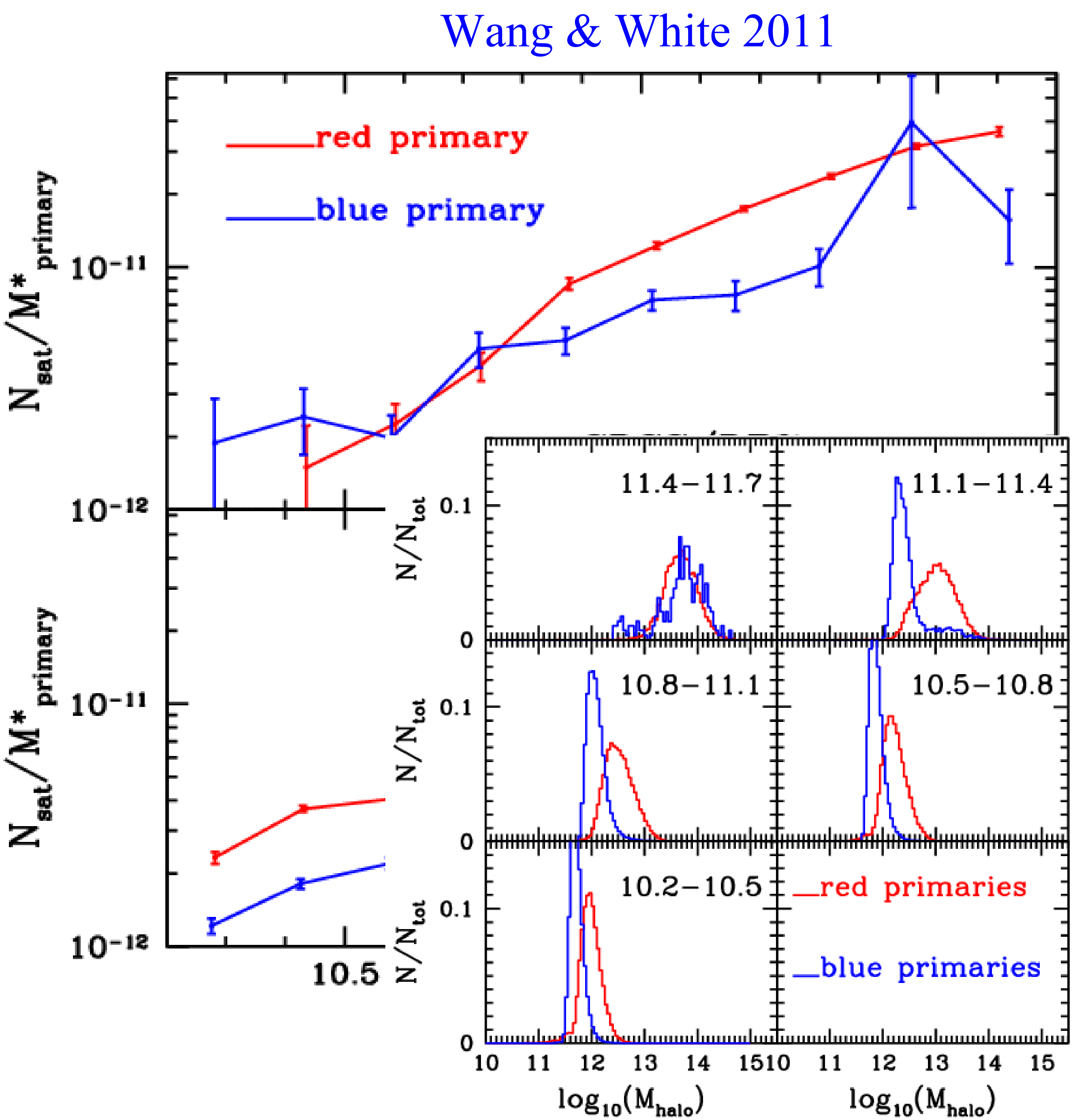
N_{sat} is satellite number with $\log M_*/M_\odot > 9.5$ in $50\ \mathrm{kpc} < r_p < 300\ \mathrm{kpc}$

Bigger galaxies have more satellites/star mass

At $\log M_*/M_\odot \sim 11$, red galaxies have more satellites than blue ones

Simulation reproduces both effects (partly)

Satellite abundances around isolated bright galaxies



N_{sat} is satellite number with $\log M_*/M_\odot > 9.5$ in 50 kpc < r_p < 300 kpc

Bigger galaxies have more satellites/star mass

At $\log M_*/M_\odot \sim 11$, red galaxies have more satellites than blue ones

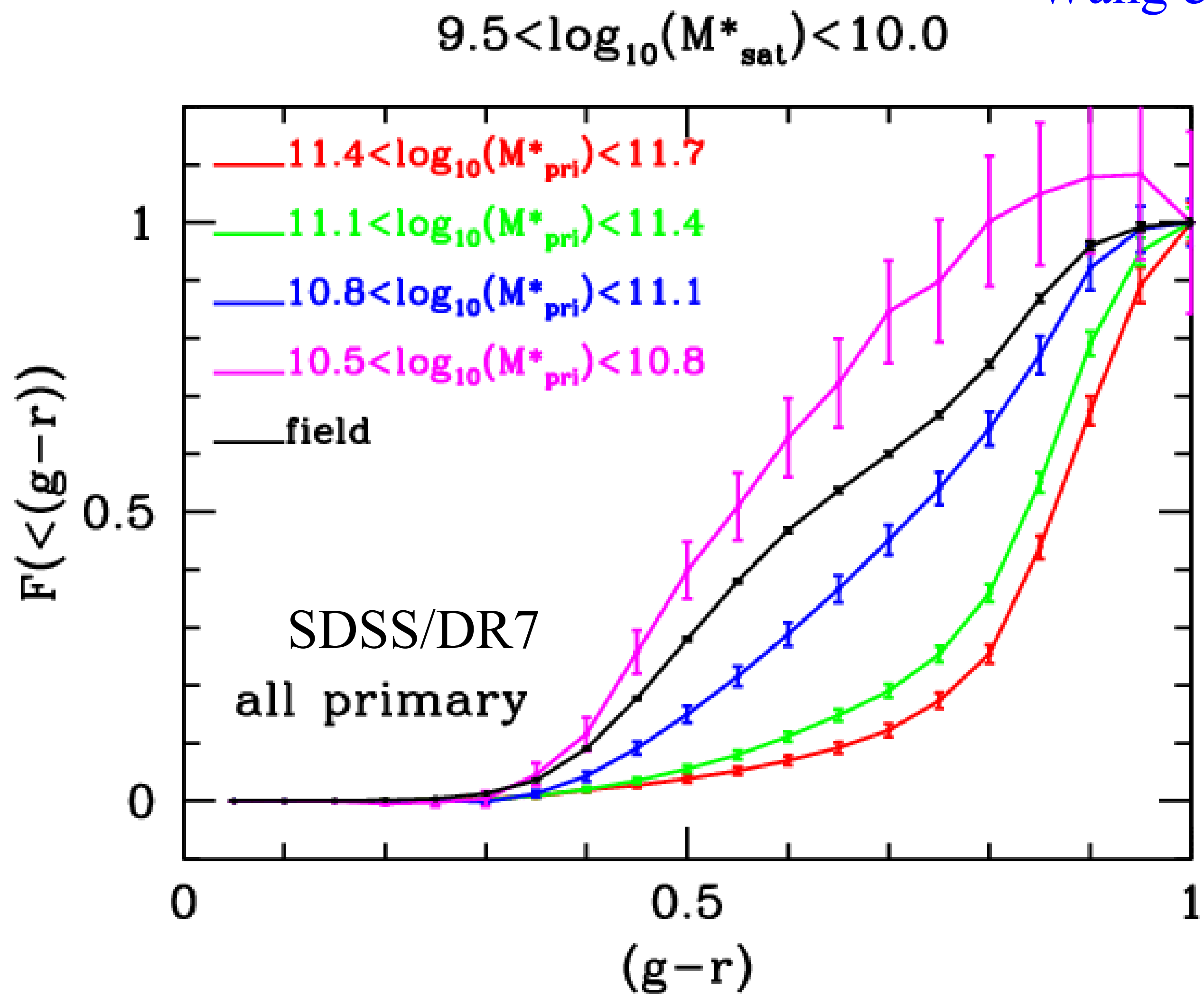
Simulation reproduces both effects (partly)

red/blue offset due to *halo* mass differences

cf Mandelbaum et al 2006

Satellite colours around isolated bright galaxies

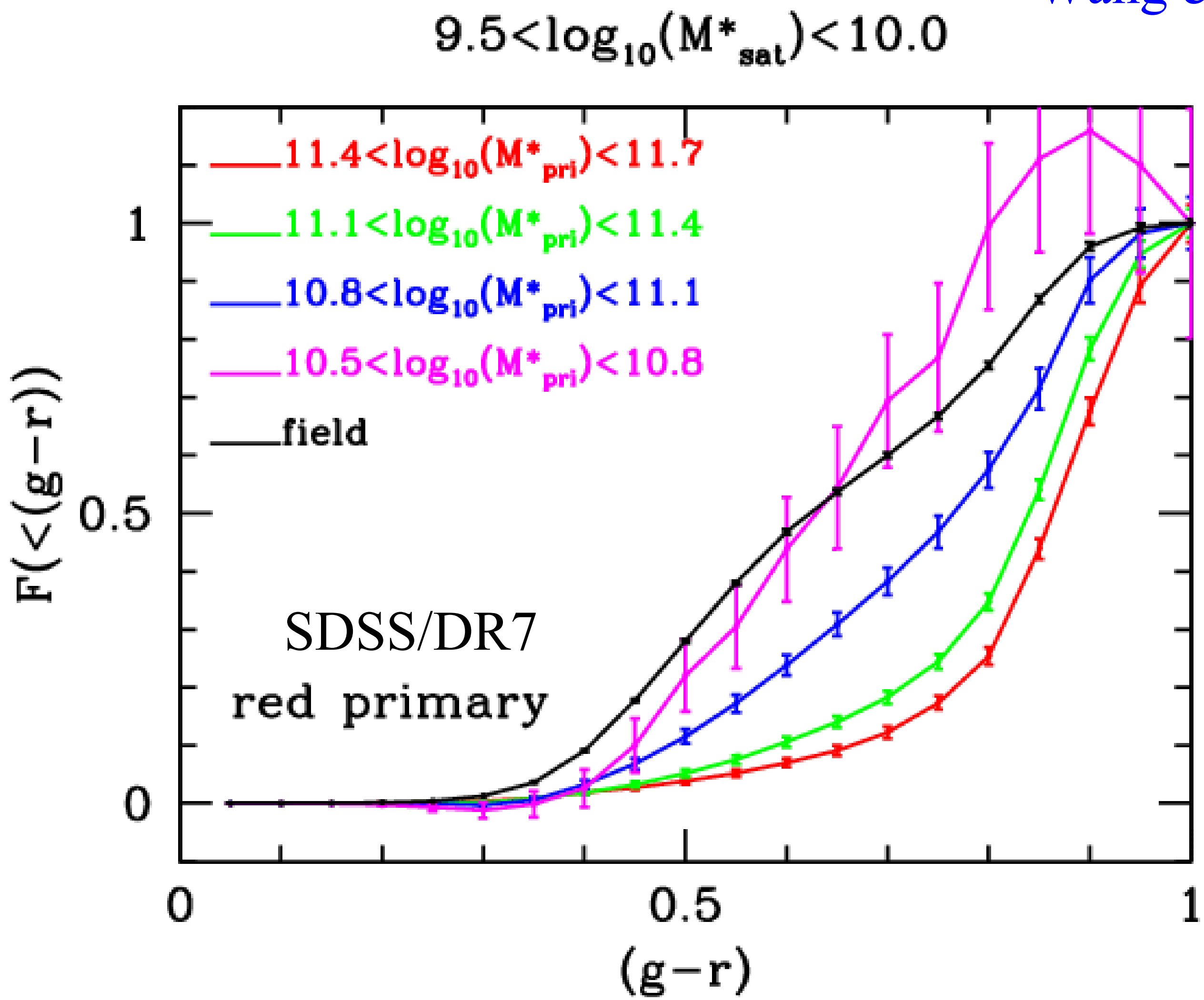
Wang & White 2011



Satellites of big galaxies are **redder** than field galaxies of the same mass
More massive central galaxies have **redder** satellites

Satellite colours around isolated bright galaxies

Wang & White 2011

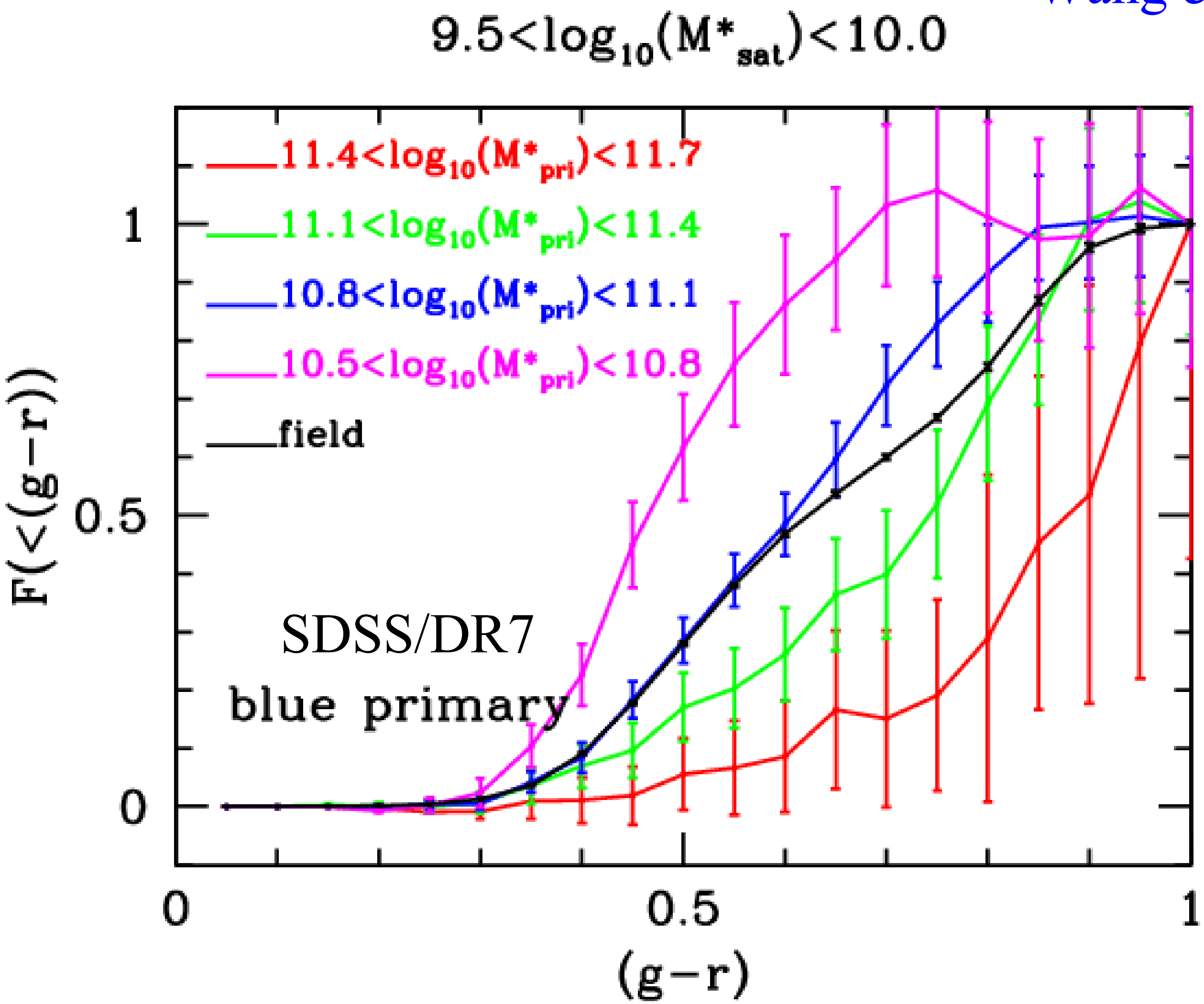


Red central galaxies have **redder** satellites

"Galactic conformity" Weinmann et al (2006)

Satellite colours around isolated bright galaxies

Wang & White 2011

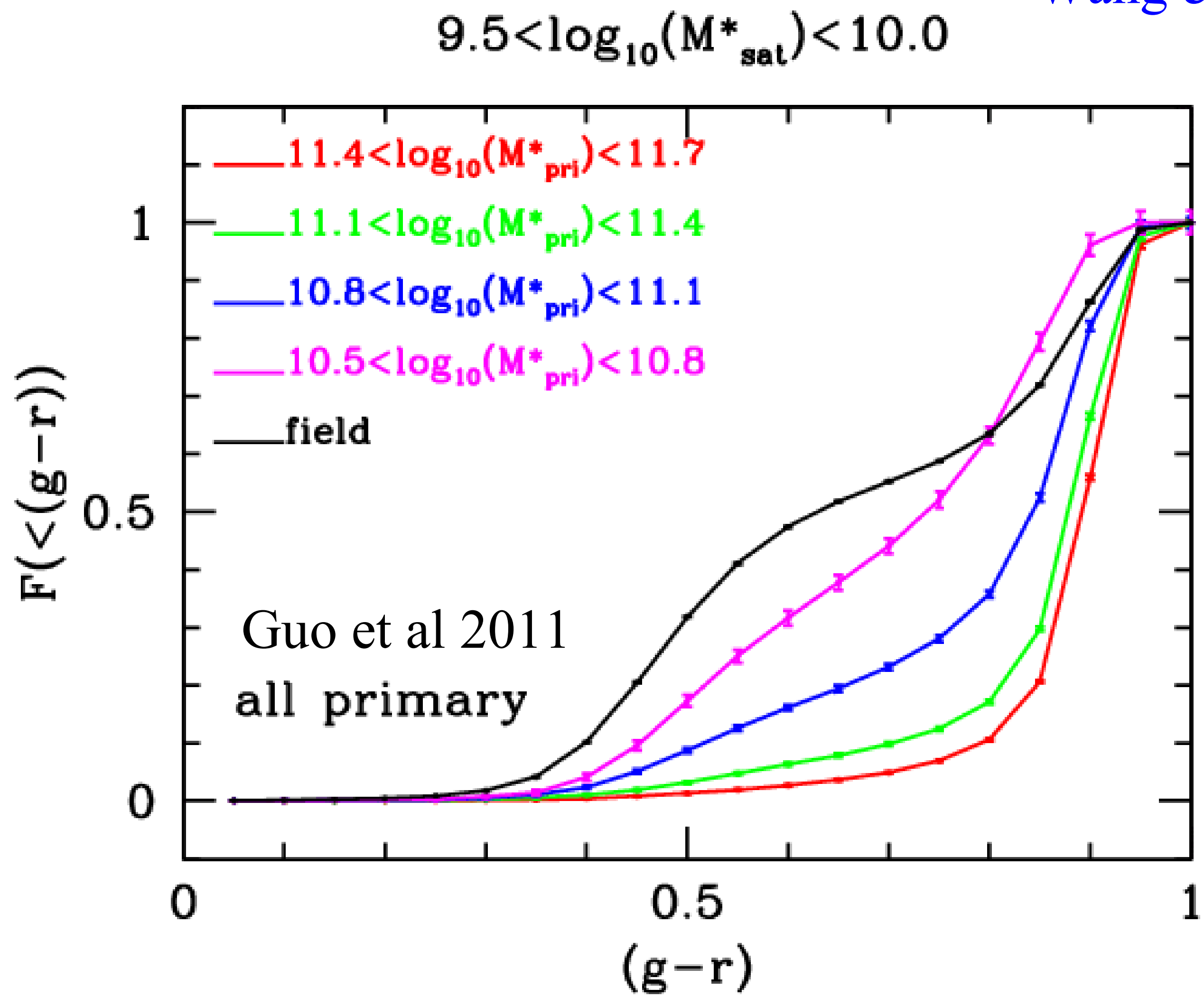


Blue central galaxies have **bluer** satellites

"Galactic conformity" Weinmann et al (2006)

Satellite colours around isolated bright galaxies

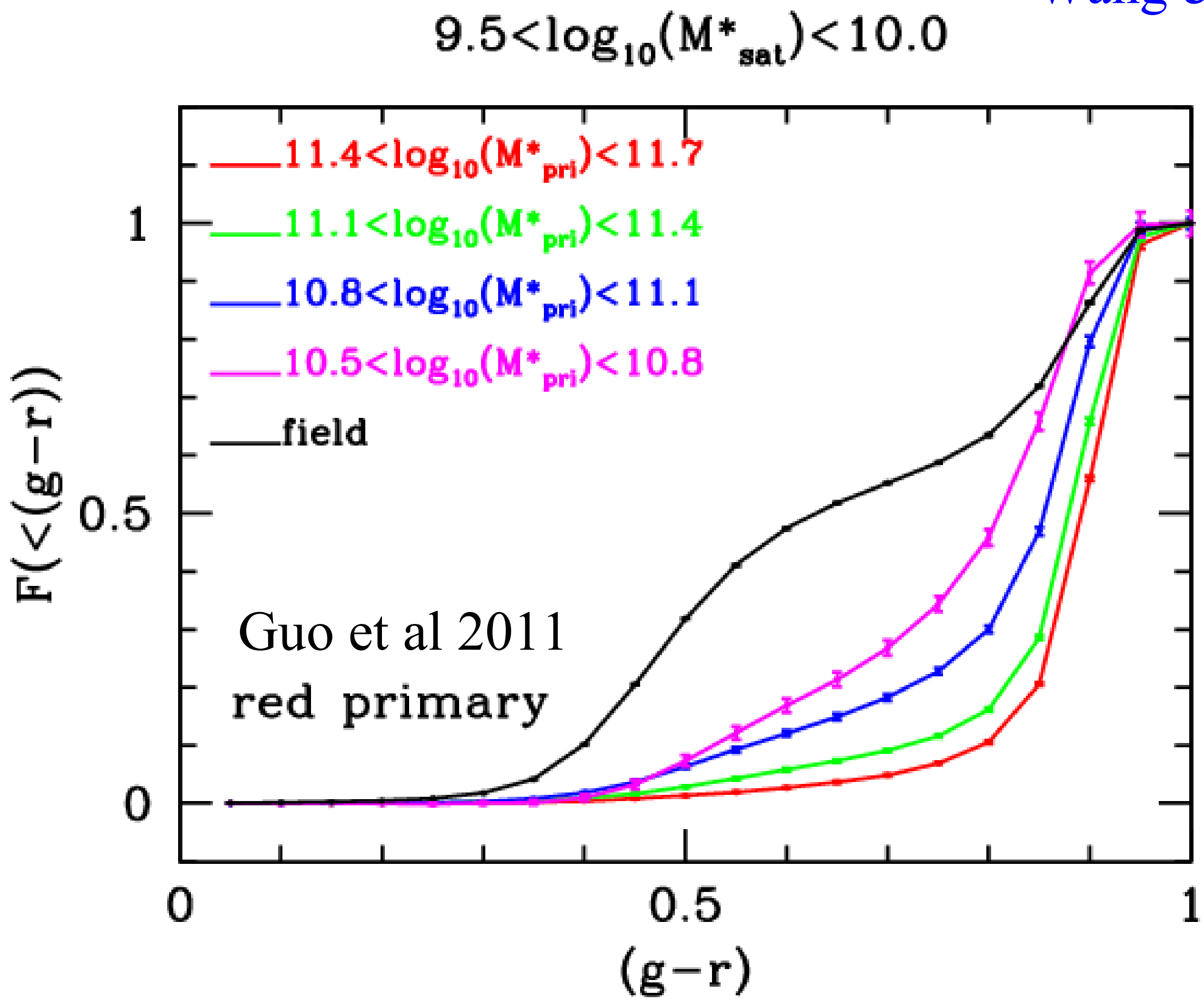
Wang & White 2011



The simulation reproduces the trends with primary mass and colour, reflecting the <u>higher mass</u> and <u>hot gas content</u> of halos of **red** galaxies

Satellite colours around isolated bright galaxies

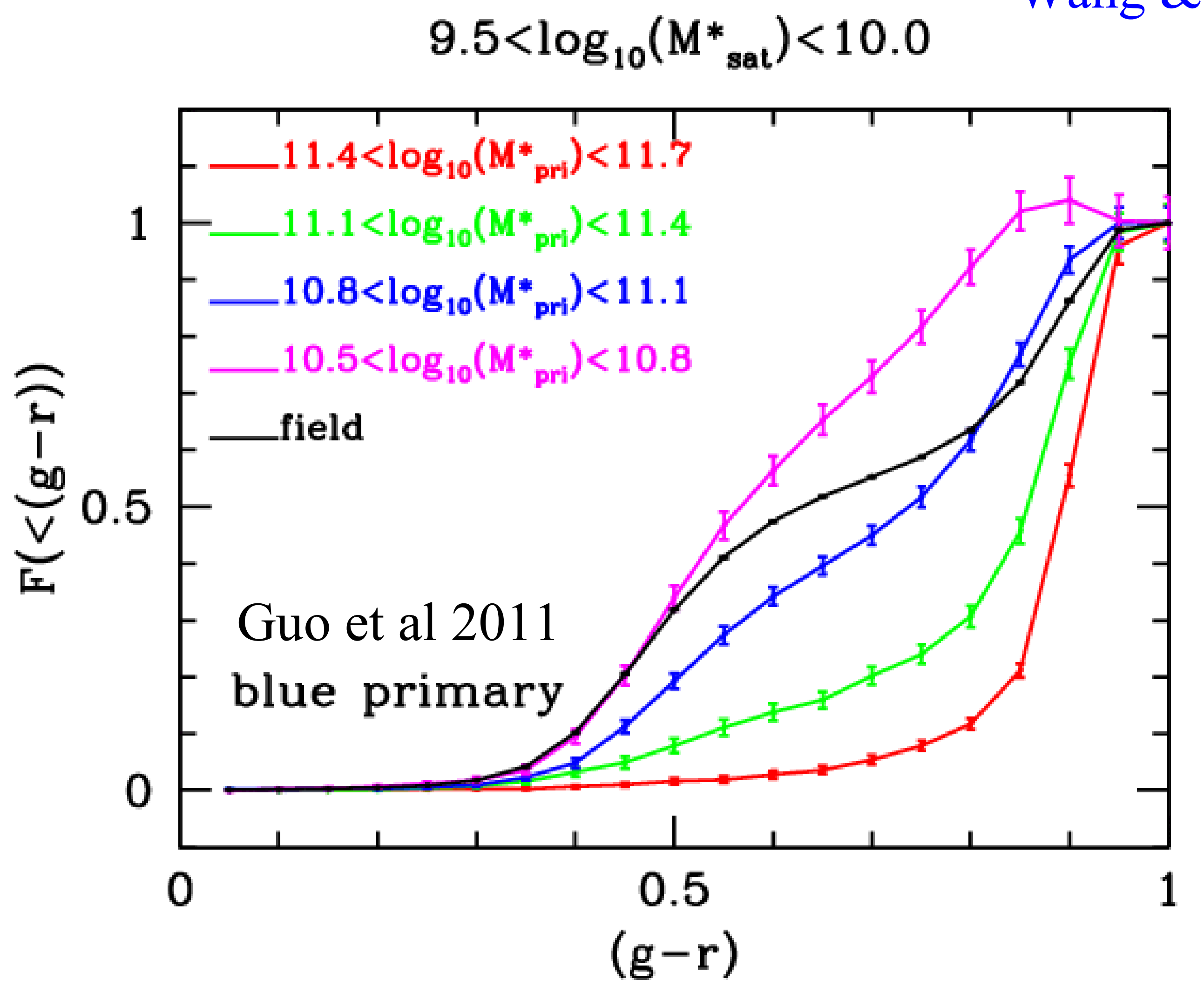
Wang & White 2011



The simulation reproduces the trends with primary mass and colour, reflecting the higher mass and hot gas content of halos of **red** galaxies

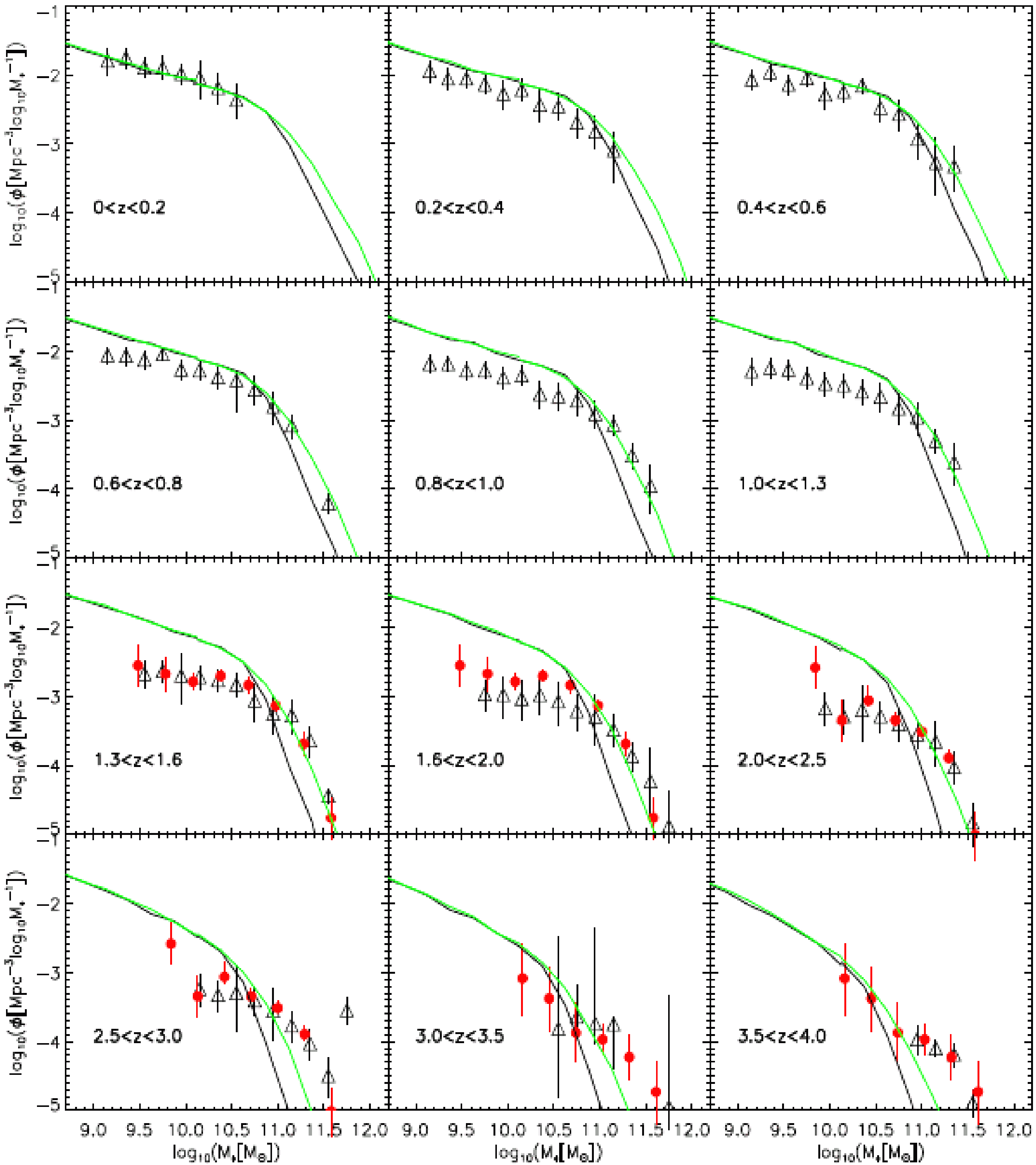
Satellite colours around isolated bright galaxies

Wang & White 2011



The simulation reproduces the trends with primary mass and colour, reflecting the higher mass and hot gas content of halos of **red** galaxies

Evolution of stellar mass function



△ Perez-Gonzalez et al 2008

● Marchesini et al 2009

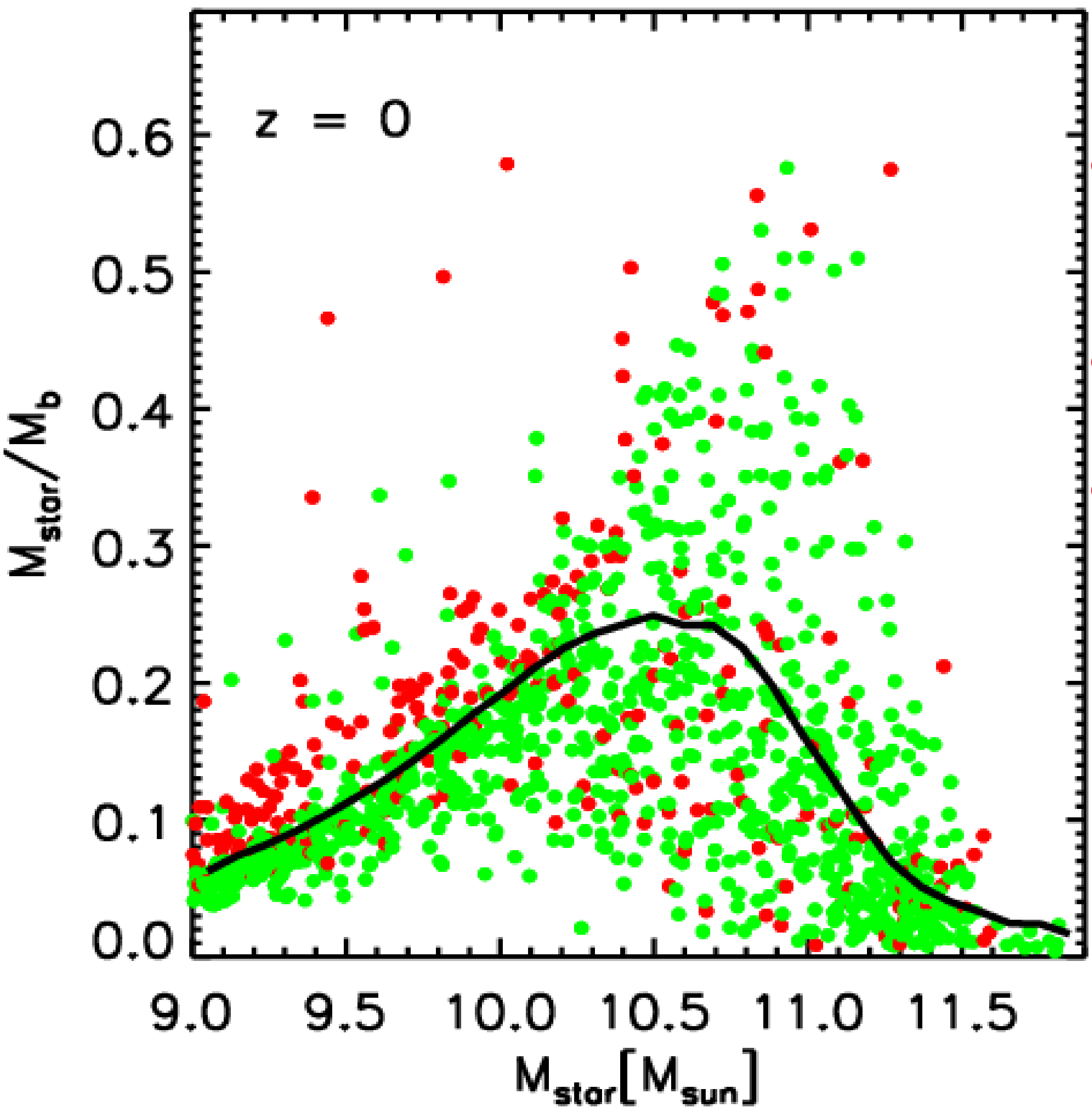
Lower mass galaxies $\log M_* < 10.5$ form <u>too early</u>

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

Guo et al 2011

Star formation efficiency vs stellar mass

Guo et al 2011

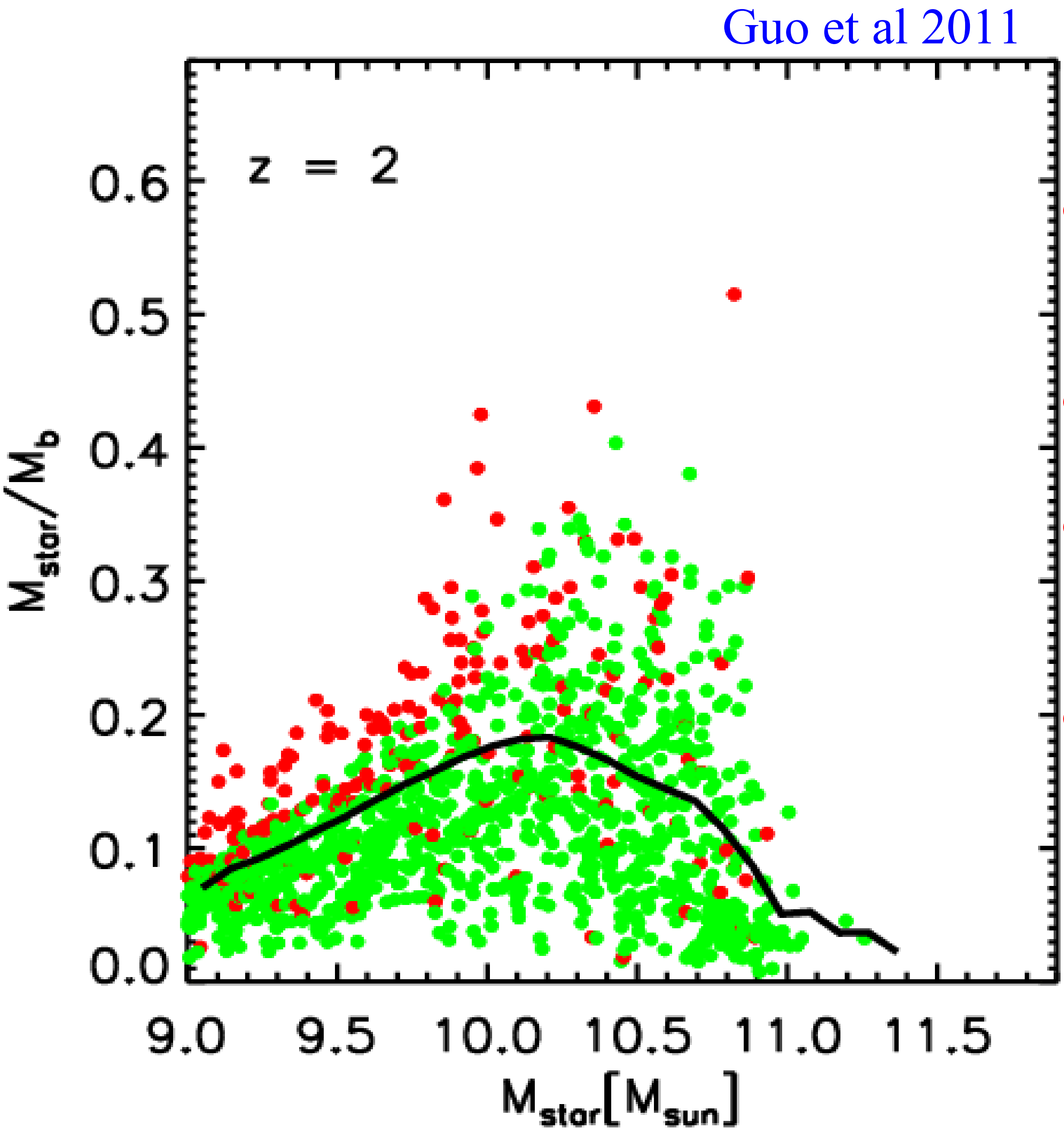


$$M_b = \Omega_b / \Omega_m \; M_{halo,max}$$

- Median efficiency is higher than at given halo mass
- Scatter is substantial
- Satellites galaxies form more efficiently than centrals

- **central galaxy**
- **satellite galaxy**

Star formation efficiency vs stellar mass



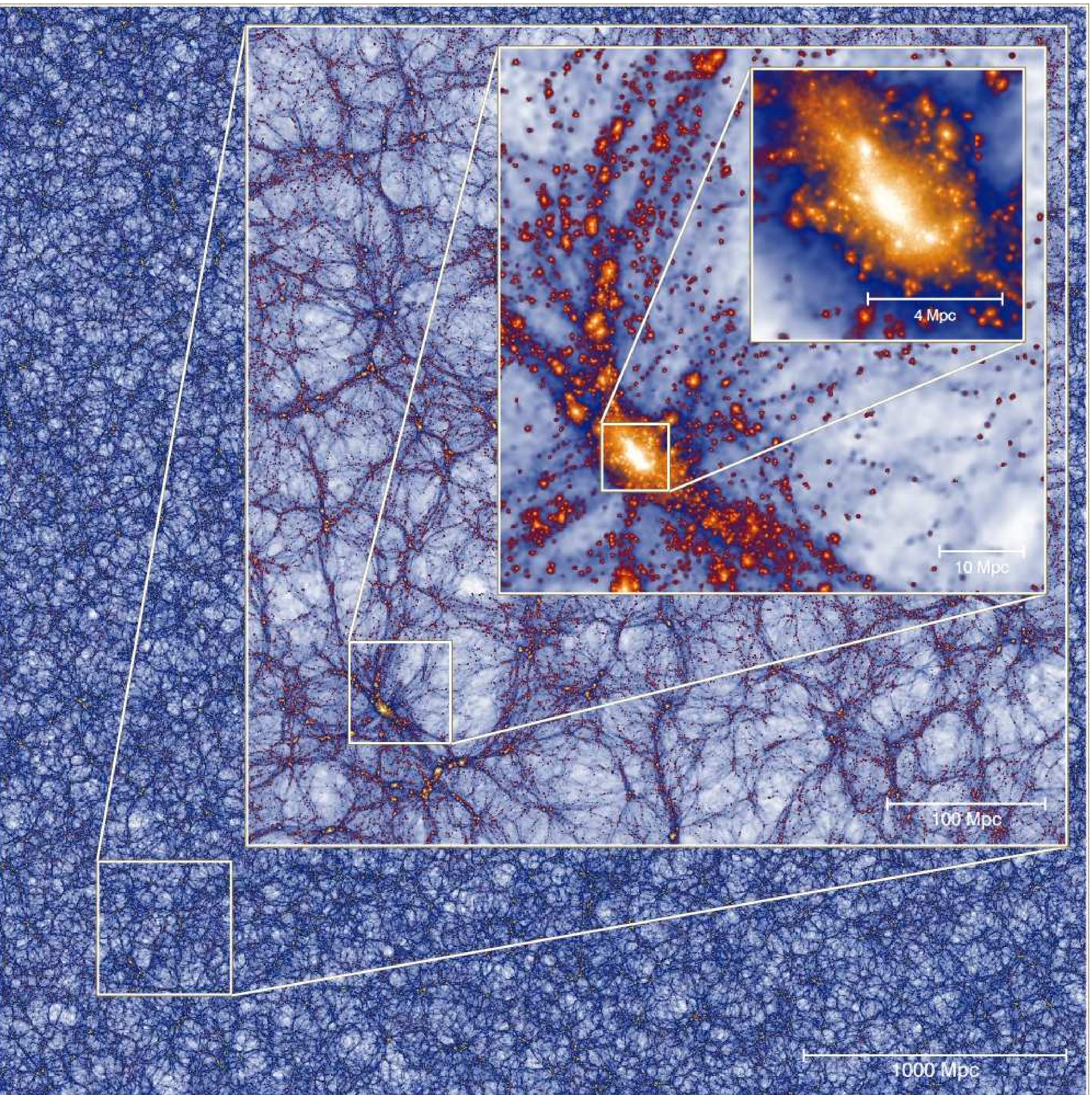
$$M_b = \Omega_b / \Omega_m \; M_{halo,max}$$

- Median efficiency is higher than at given halo mass
- Scatter is substantial
- Satellites galaxies form more efficiently than centrals
- At given stellar mass, the efficiency is <u>lower</u> at high z

- **central galaxy**
- **satellite galaxy**

Limitations of the Millennium Simulation

- Limited modeling of *structure* of galaxies, gas components..
- Limited resolution – too poor to model formation of dwarfs
- No convergence tests – are galaxy results numerically converged?
- Limited volume – too small for BAO work, precision cosmology
- Only one ("wrong") cosmology
- Users unable to test dependences on parameters/assumptions



The MXXL

(2010)

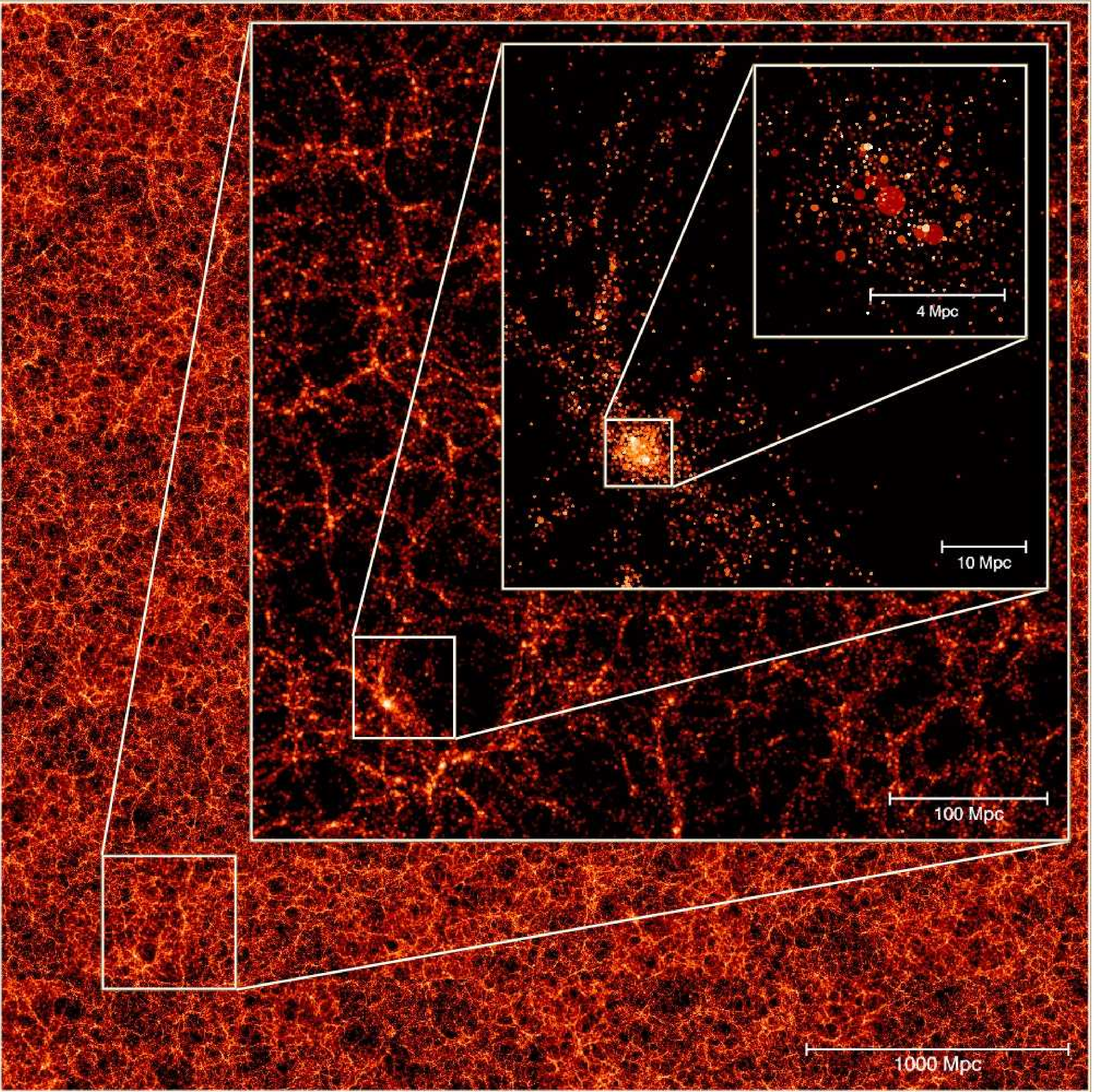
Angulo et al 2011

Bigger than the Millennium Run by factors of

30 in $N_{particle}$

200 in Volume

6 in $m_{particle}$



The MXXL

(2010)

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30 in $N_{particle}$

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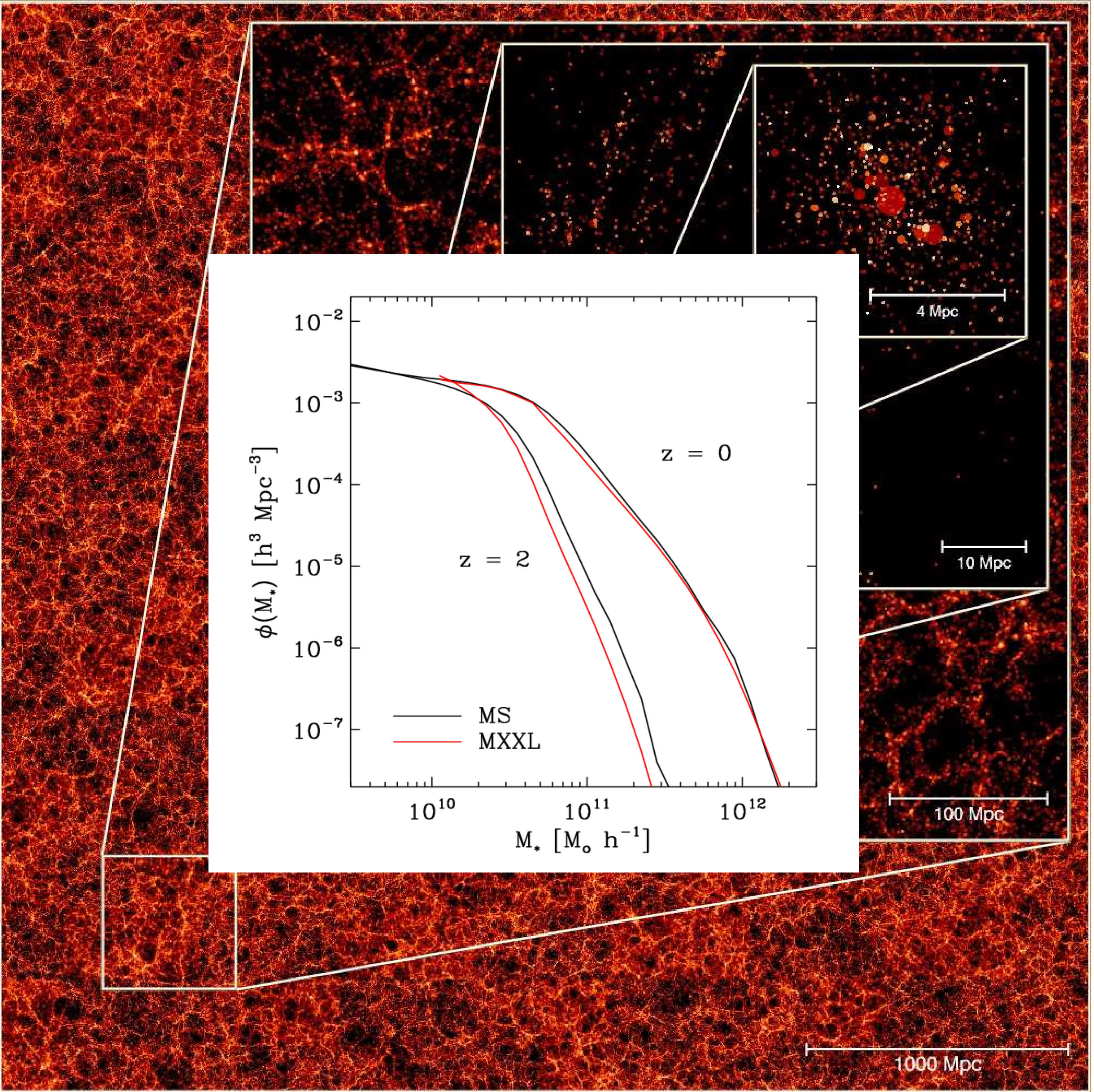
3.3×10^8 galaxies at $z = 0$ with $\log M_*/M_\odot > 10$

The MXXL

(2010)

Angulo et al 2011



Bigger than the Millennium Run by factors of

30 in $N_{particle}$

200 in Volume

6 in $m_{particle}$

3.3×10^8 galaxies at z = 0 with $\log M_*/M_\odot > 10$

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 target z=0 halos

-- 500 Mpc/h 433 Mpc/h

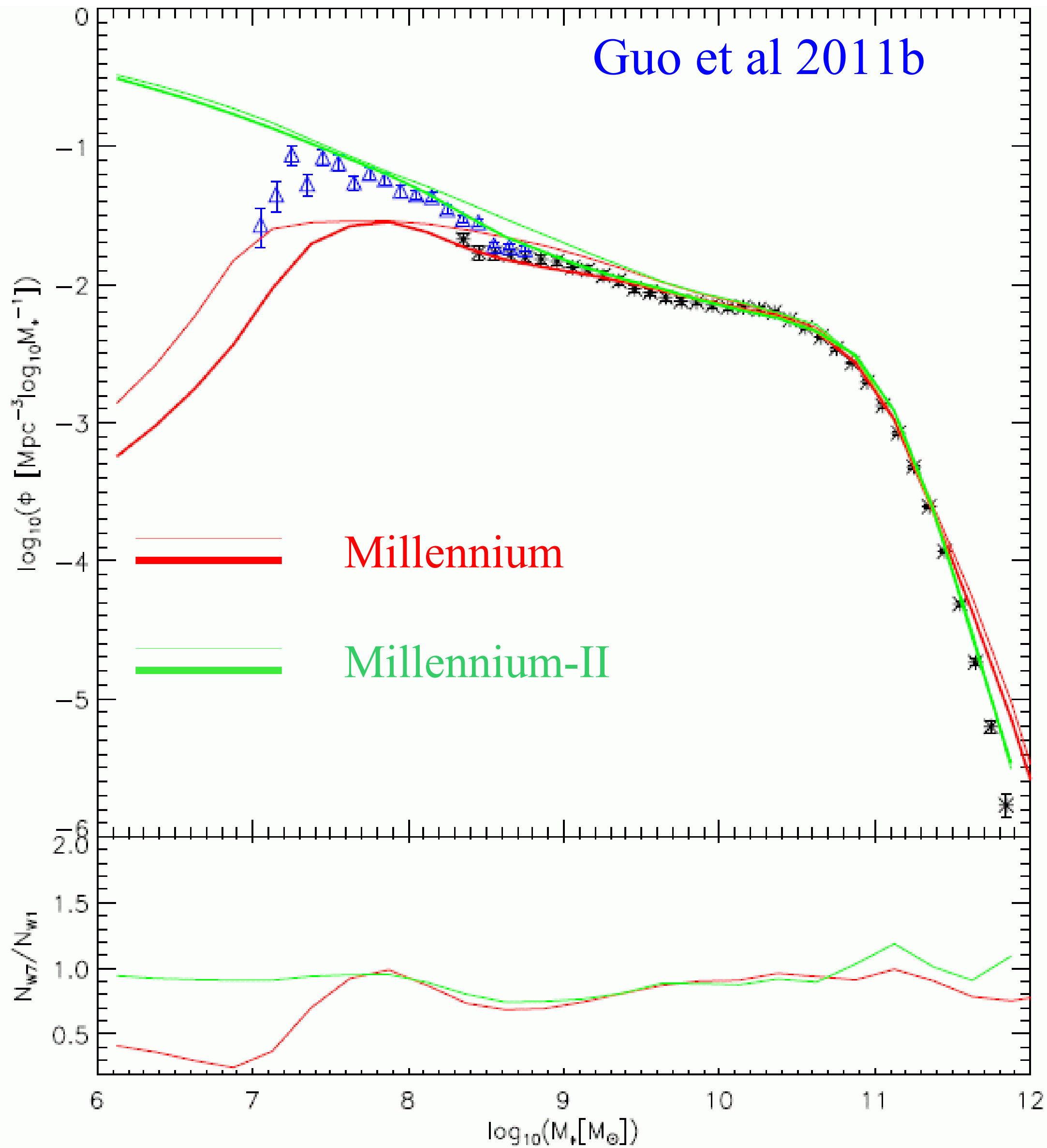
2) Reassign redshifts to match linear amplitudes on these scales

-- 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.



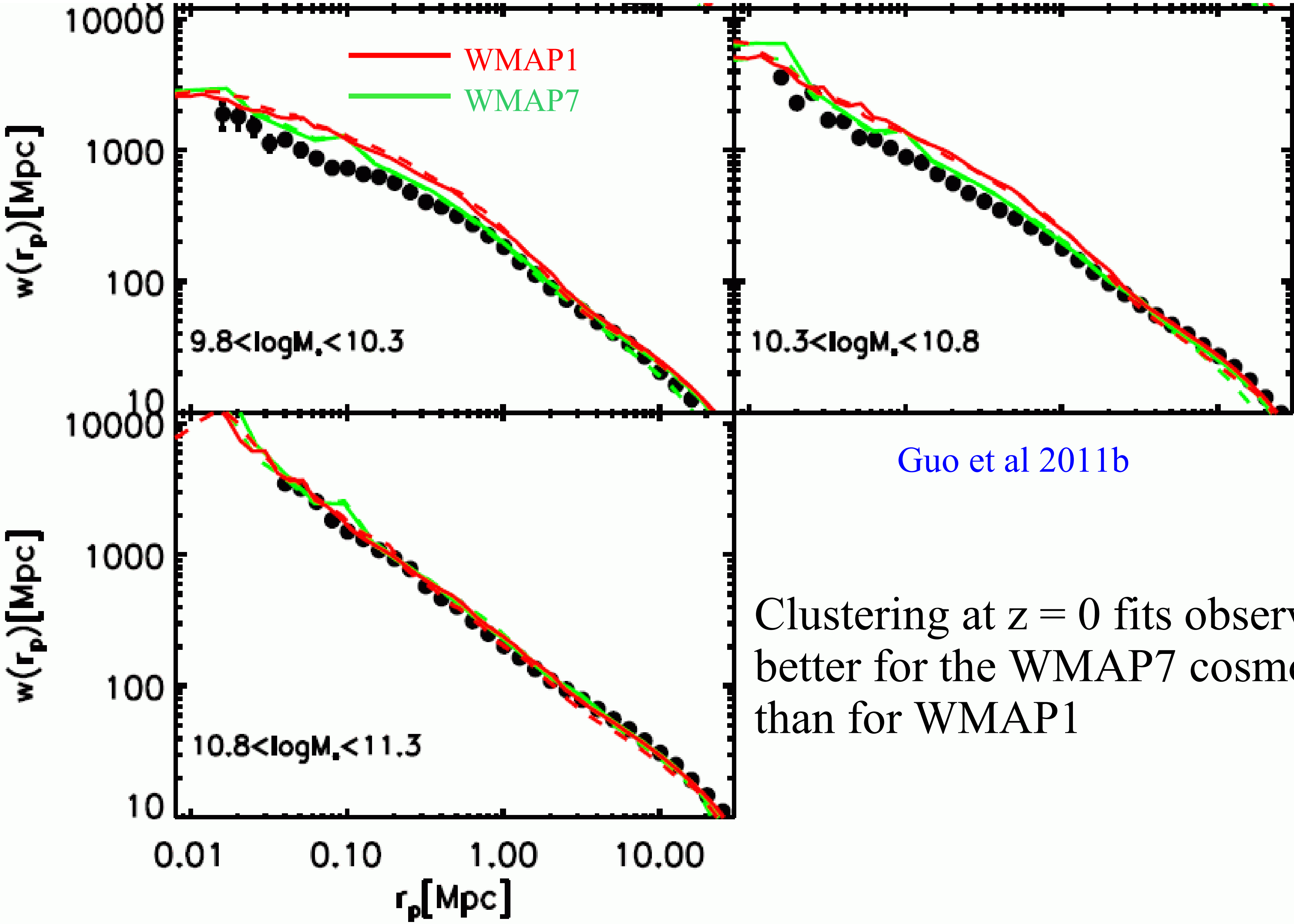
Switching from WMAP1 to WMAP7

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	0.015
ϵ	Amplitude of SN reheating efficiency	6.5	4.5
β_1	Slope of SN reheating efficiency	3.5	4
V_{reheat}	normarlization of SN reheating efficiency dependence on Vmax	70	80
η	Amplitude of SN ejection efficiency	0.32	0.33
β_2	Slope of SN ejection efficiency	3.5	6.5
V_{eject}	normarlization of SN ejection efficiency dependence on Vmax	70	80
κ	Hot gas accretion efficiency onto black holes	1.5×10^{-5}	6.0×10^{-6}

Switching from WMAP1 to WMAP7

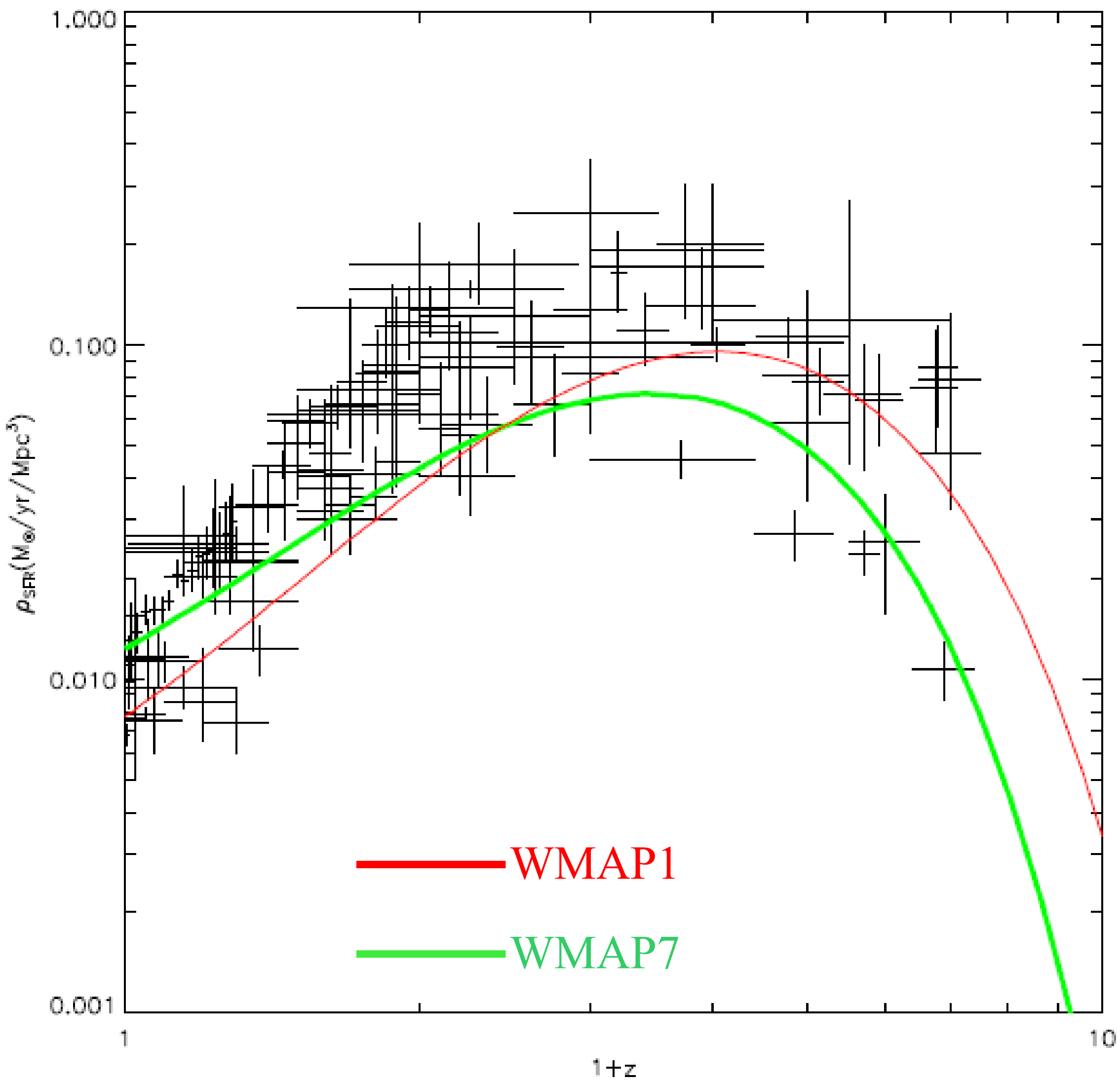


Guo et al 2011b

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

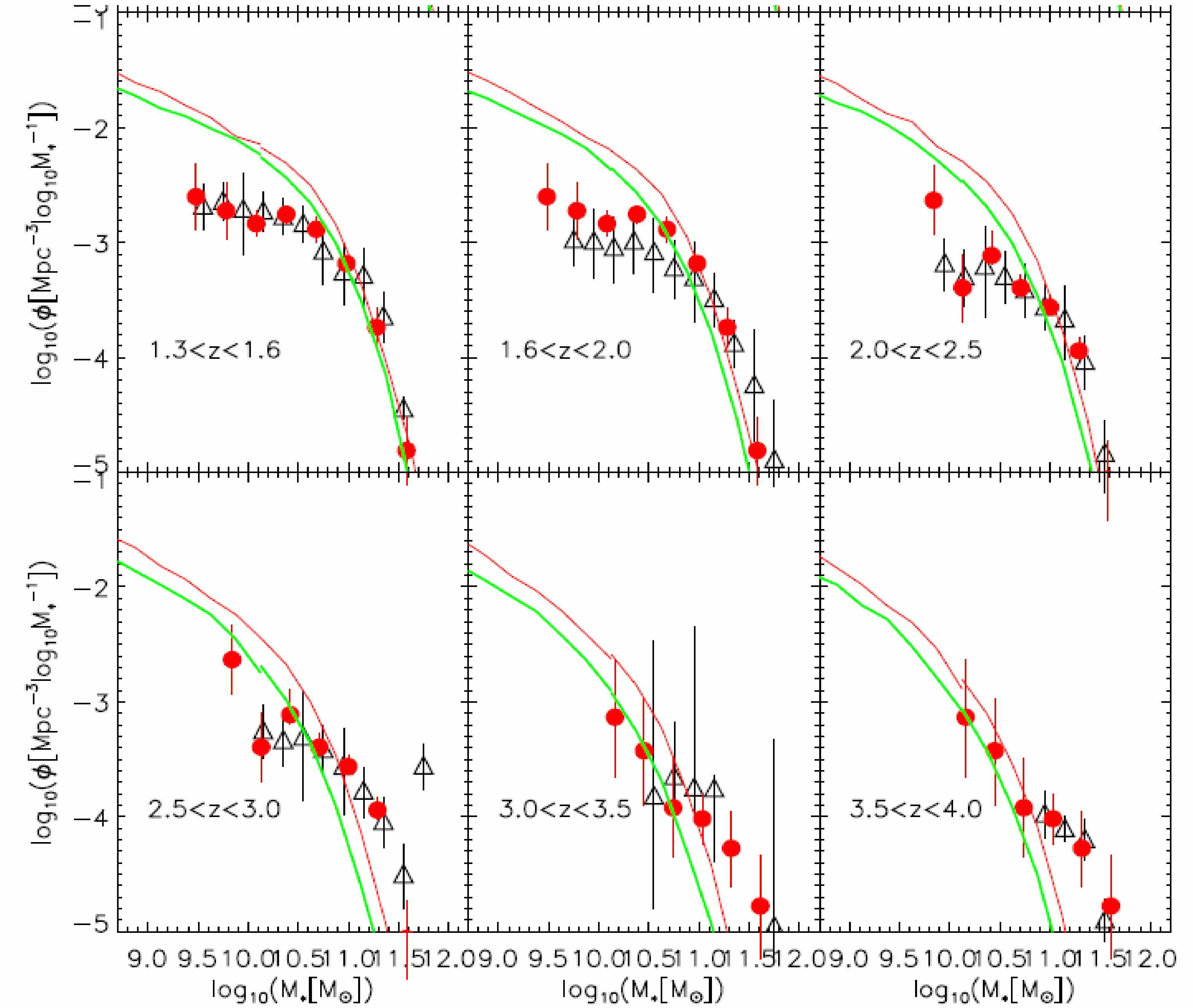
Switching from WMAP1 to WMAP7

Guo et al 2011b



Galaxies form later in the WMAP7 cosmology than in WMAP 1

Switching from WMAP1 to WMAP7



Guo et al 2011b

..but the galaxy formation sequence is still incorrect

The Millennium Run Observatory

Overzier, Lemson et al 2011

- Construct deep light cones to z~10 in arbitrary directions including any desired object (e.g. a cluster) at any desired redshift for a choice of cosmologies (e.g. WMAP1, WMAP7...)
- Project each galaxy onto the sky using size, mass, stellar population and orientation (**J**) as input to standard profiles for disk and bulge
- Choose a population synthesis codes to simulate photometry
- Create observer frame photometry including IGM absorption
- Use a telescope simulator to create realistic images (e.g. pixel scale, PSF, counting noise, etc.)
- Open-access database implementation in preparation (late 2011?)

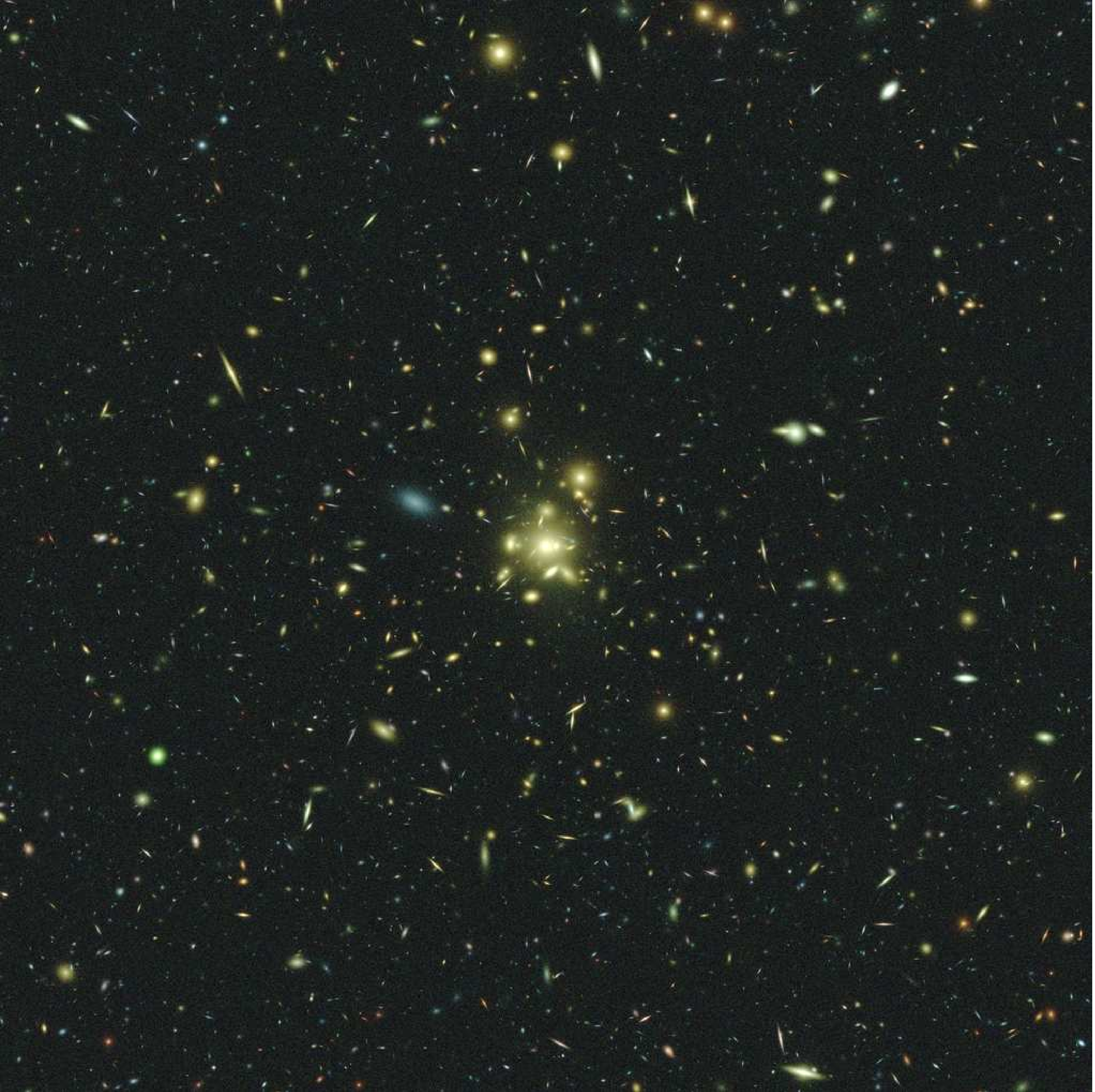
Cl0024

Harsono & De Propris
2007

z = 0.40

3.4' x 3.4'

HST/ACS



“Cl0024”

$M_{200} = 7x10^{14} M_{\odot}$

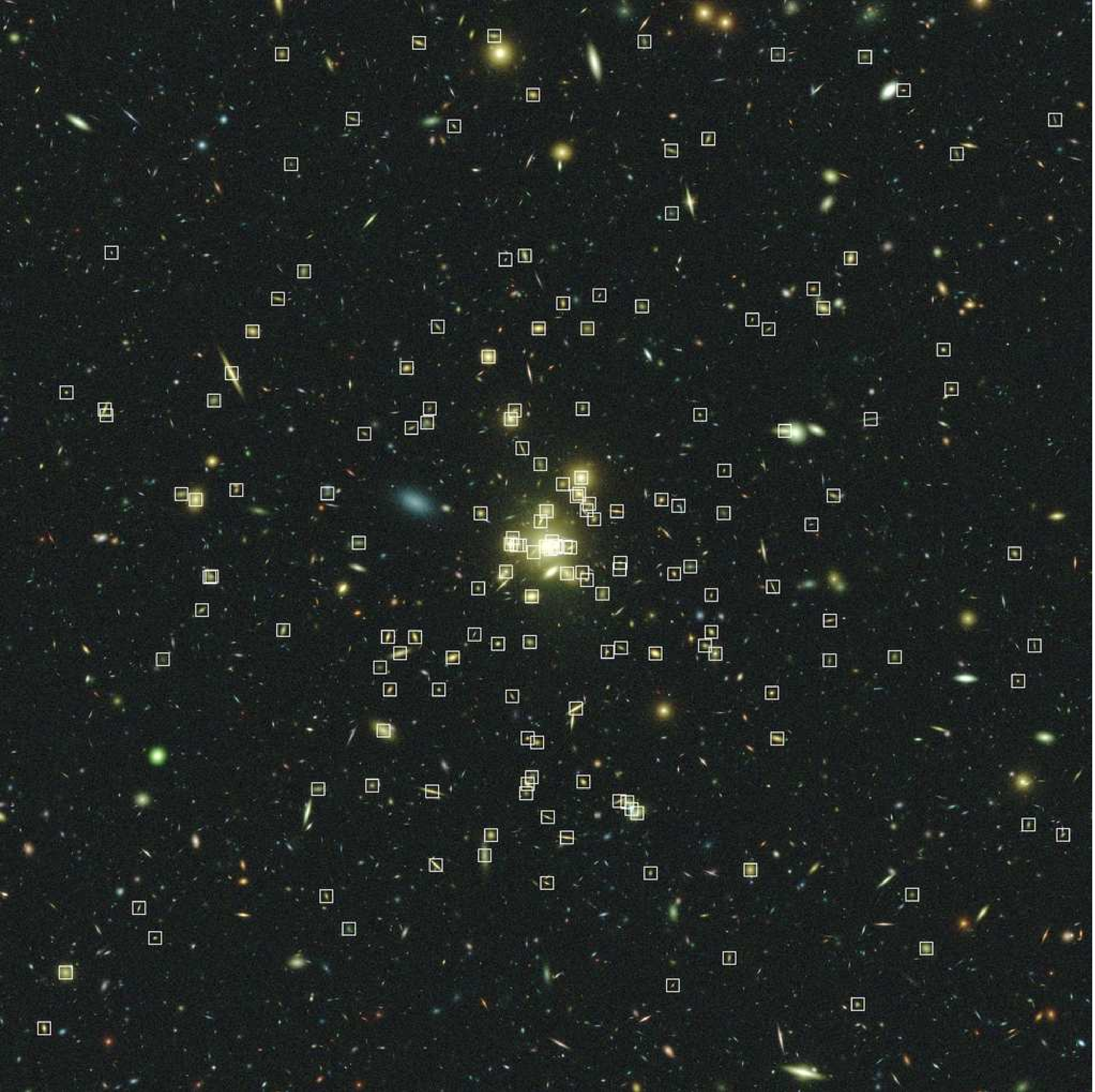
z = 0.41

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000sec/filter

Overzier & Lemson 2011



“Cl0024”

$M_{200} = 7x10^{14}M_{\odot}$

$z = 0.41$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000sec/filter

Overzier & Lemson 2011

Concluding remarks

- New techniques enable simulation of the *full galaxy population* within the ΛCDM paradigm for all viable cosmological parameters

- 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

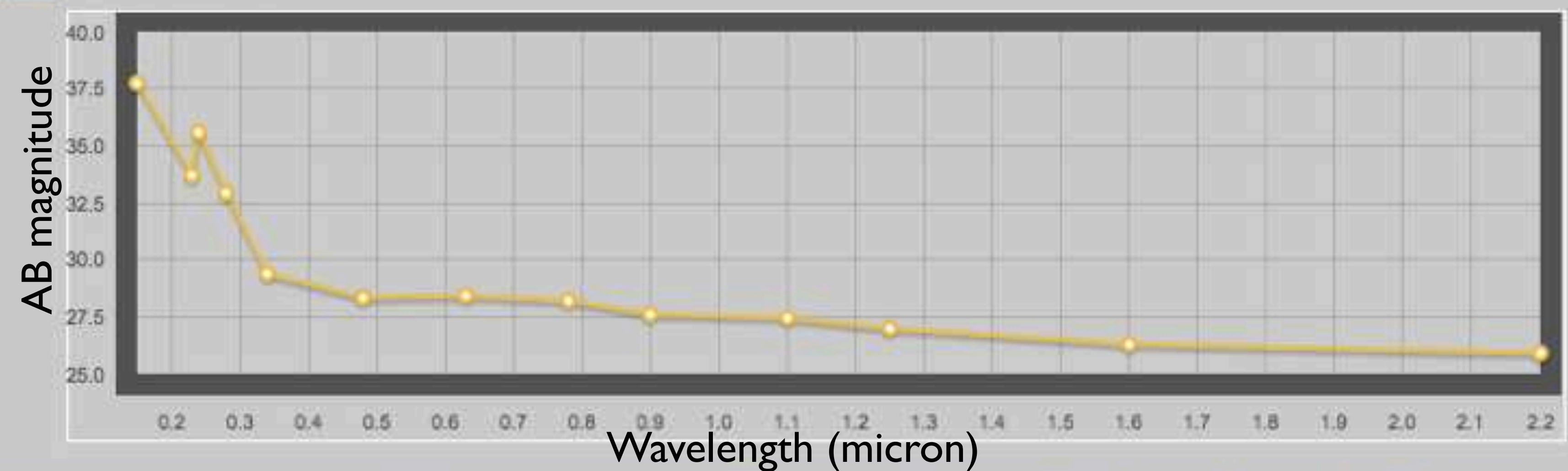
- Current treatments are

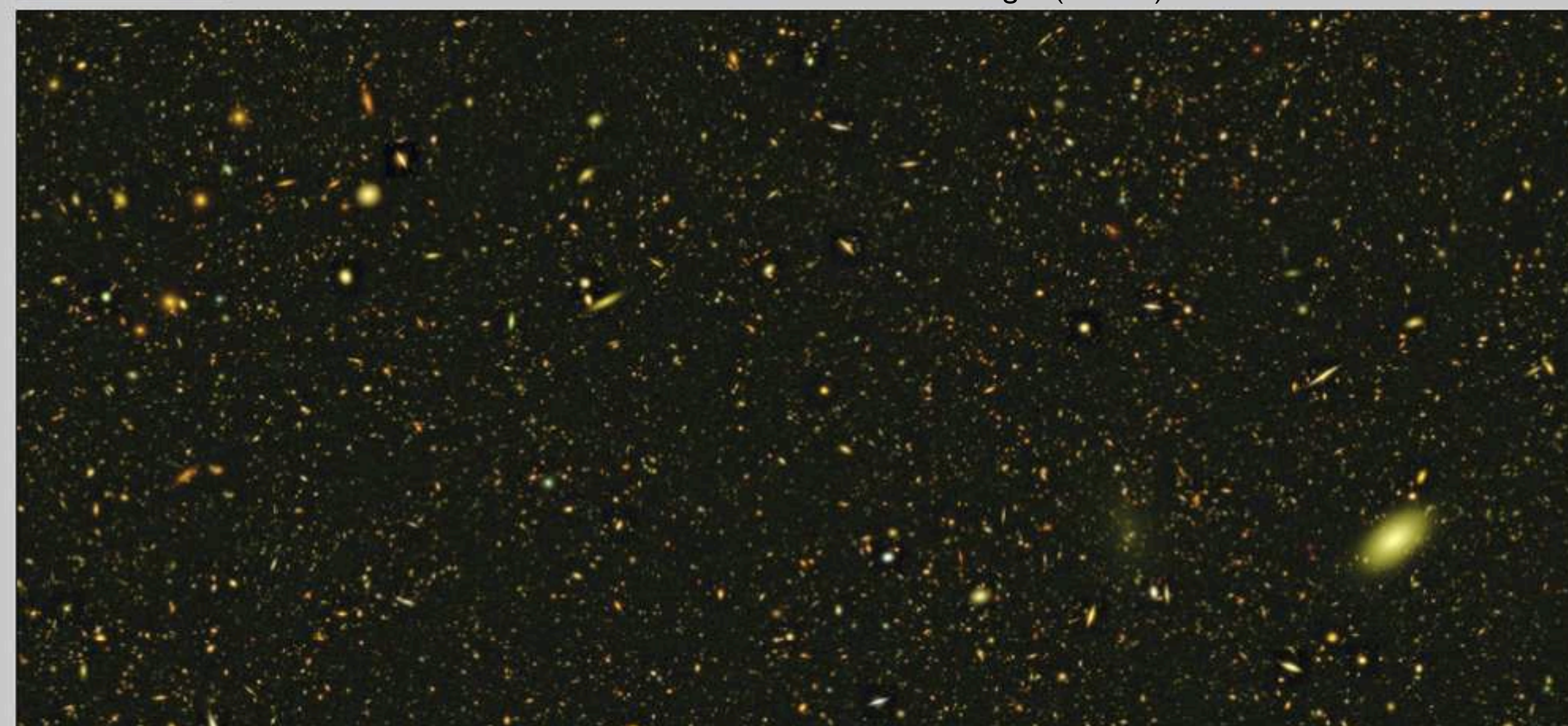
  too efficient at making stars at early times in lower mass halos
  too efficient at suppressing star formation after satellite infall
  too inefficient at disrupting galaxies to make the ICL

Millennium Run Observatory - Mock Image Browser

Show: (1) Blue Galaxy (2) Big Galaxy (3) Two Red Nuggets 0:0:2.227 -0:0:5.419

Galaxy Info	
Galaxy Id	259001486000775
RA, Dec (deg)	(-0.0604,-0.0369)
Redshift (z_app)	2.26515
Inclination | PA	75.4 | 33.3
B-V (AB mag)	0.422
r' (AB mag)	28.4251
Stellarmass (1e10 Msun)	0.1756
SFR (Msun/yr)	1.8922
Age (Gyr)	1.0004



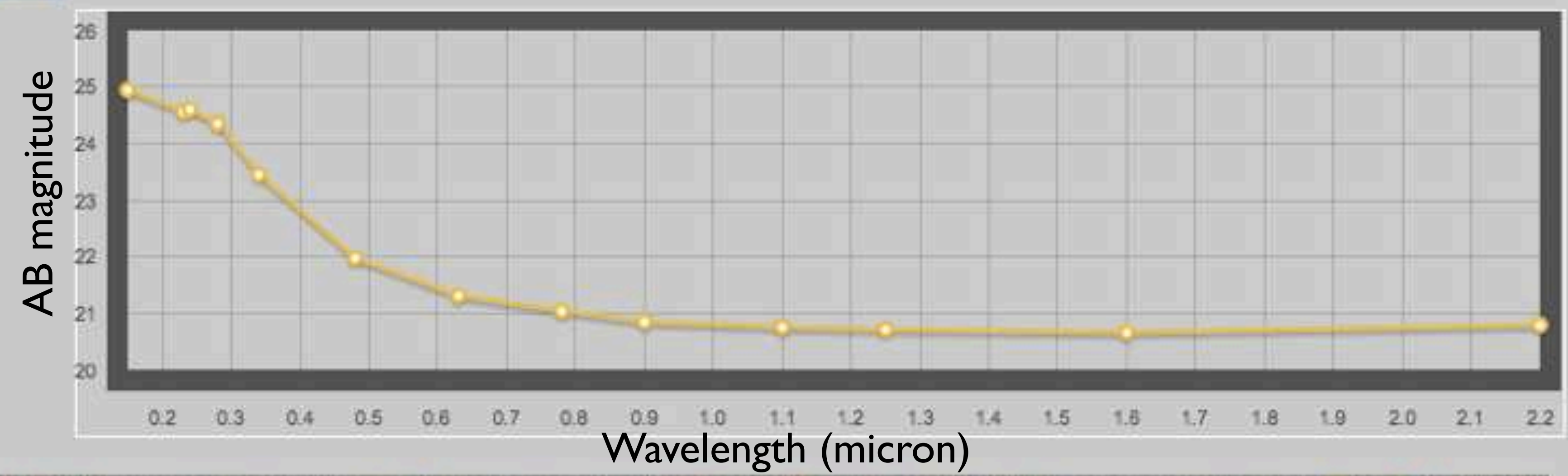


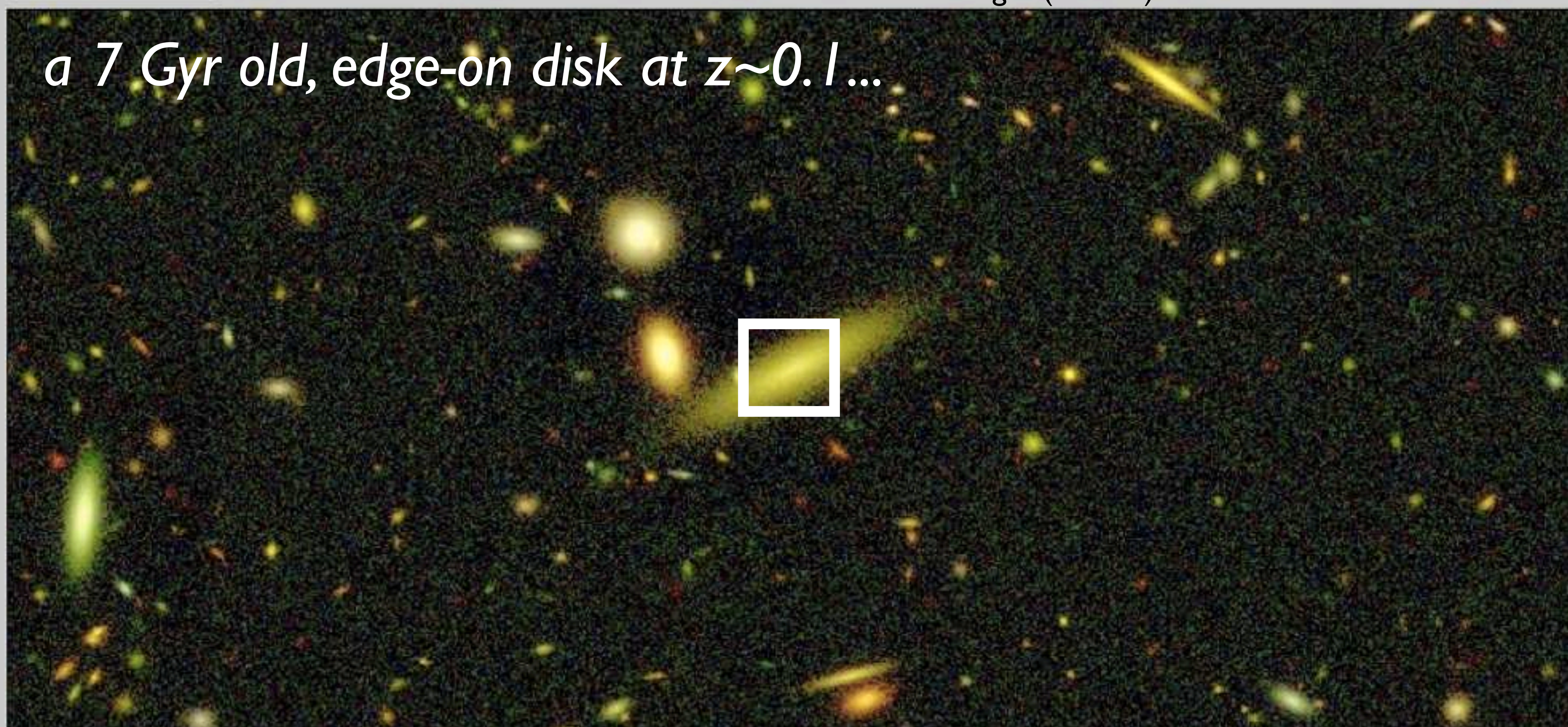
[Overzier, Lemson et al. in prep.]

Millennium Run Observatory - Mock Image Browser

Show: (1) Blue Galaxy (2) Big Galaxy (3) Two Red Nuggets 0:0:5.025 -0:1:6.055

Galaxy Info	
Galaxy Id	10005360000004
RA, Dec (deg)	(0.0209,-0.0196)
Redshift (z_app)	0.09047
Inclination | PA	76.2 | 62.6
B-V (AB mag)	0.724
r' (AB mag)	21.3112
Stellarmass (1e10 Msun)	0.0301
SFR (Msun/yr)	0.0047
Age (Gyr)	6.6298



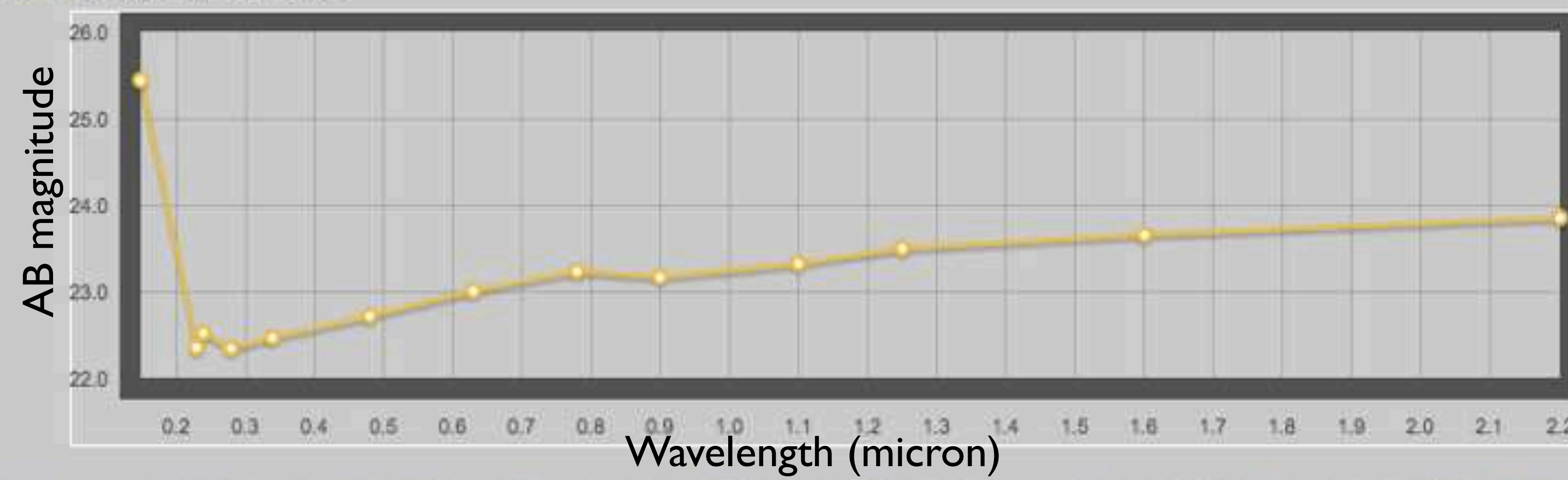


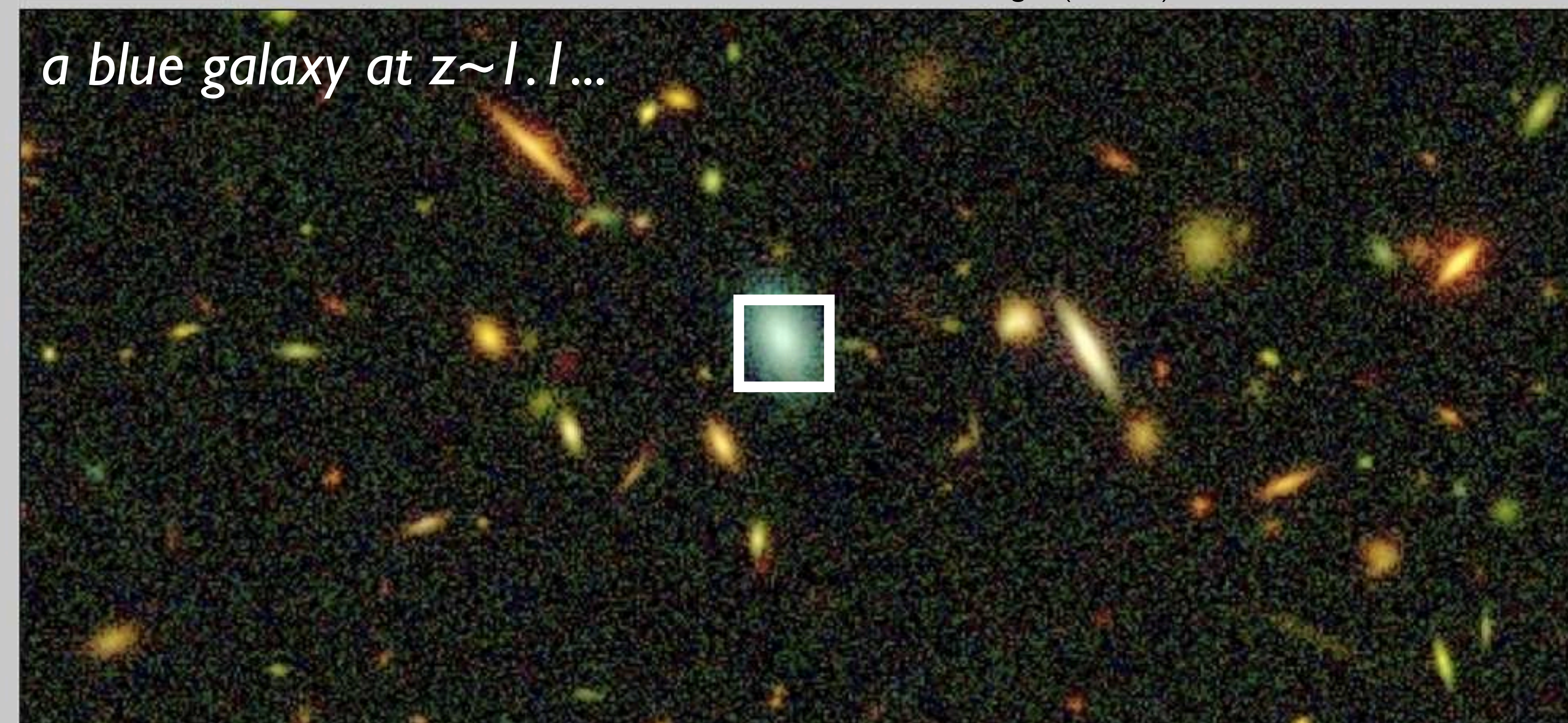
[Overzier, Lemson et al. in prep.]

Millennium Run Observatory - Mock Image Browser

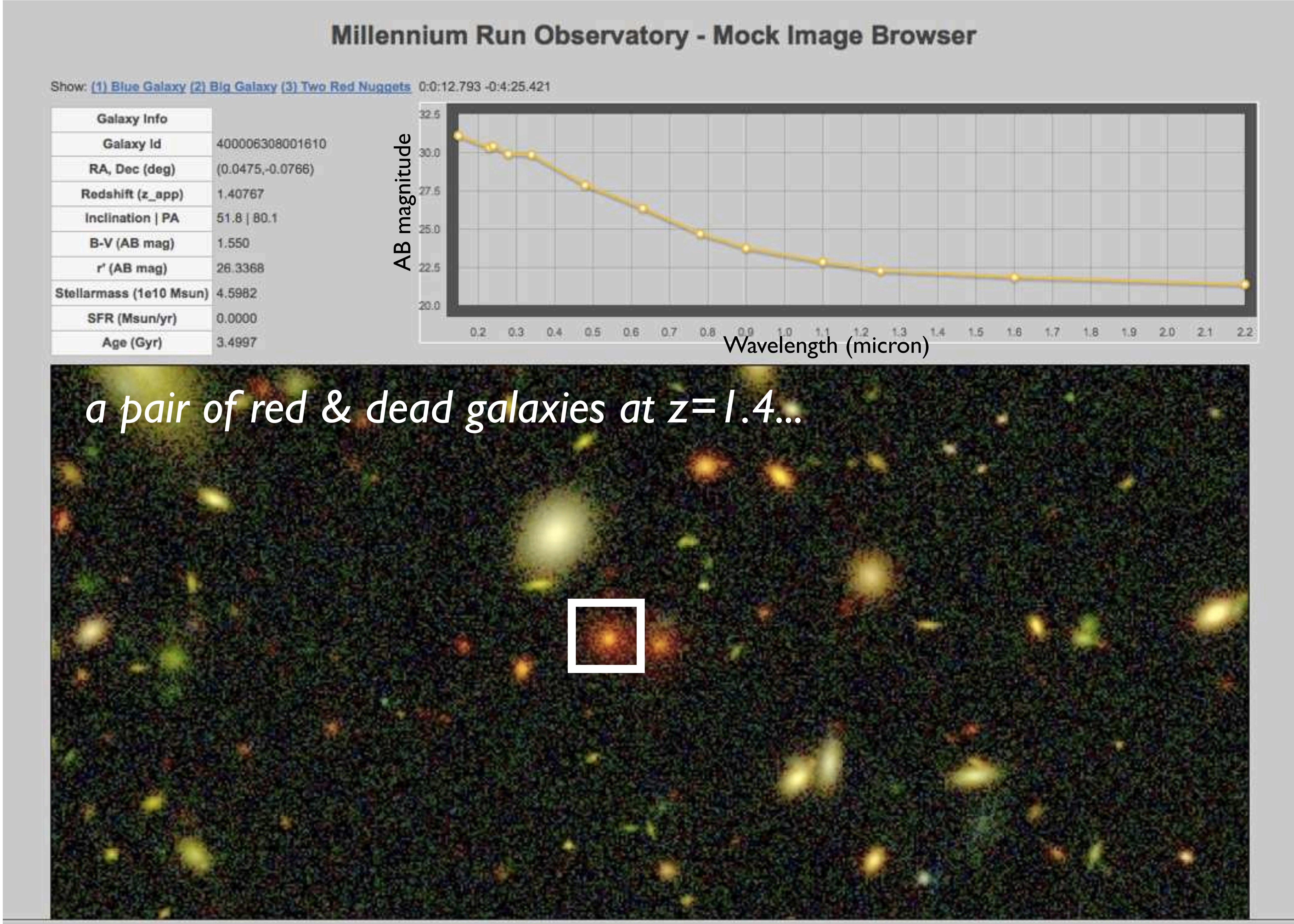
Show: (1) Blue Galaxy (2) Big Galaxy (3) Two Red Nuggets 23:59:57.325 +0:0:29.592

Galaxy Info	
Galaxy Id	445004987036456
RA, Dec (deg)	(-0.0111,0.0083)
Redshift (z_app)	1.11273
Inclination | PA	51.7 | 157.6
B-V (AB mag)	-0.212
r' (AB mag)	22.9992
Stellarmass (1e10 Msun)	0.0172
SFR (Msun/yr)	0.7946
Age (Gyr)	0.8156





[Overzier, Lemson et al. in prep.]

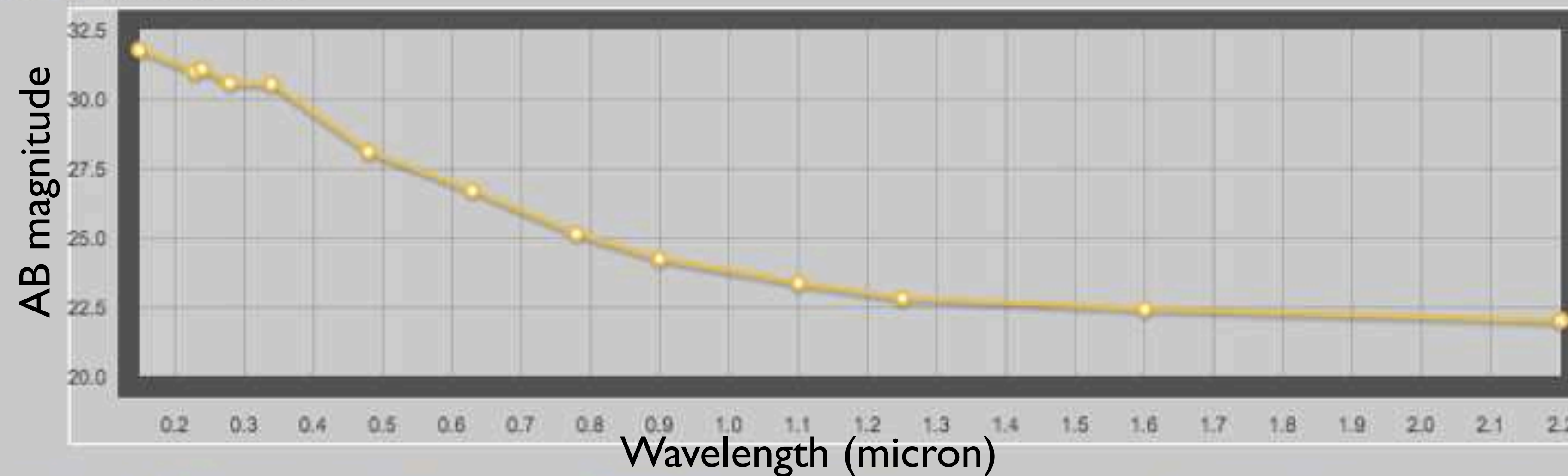


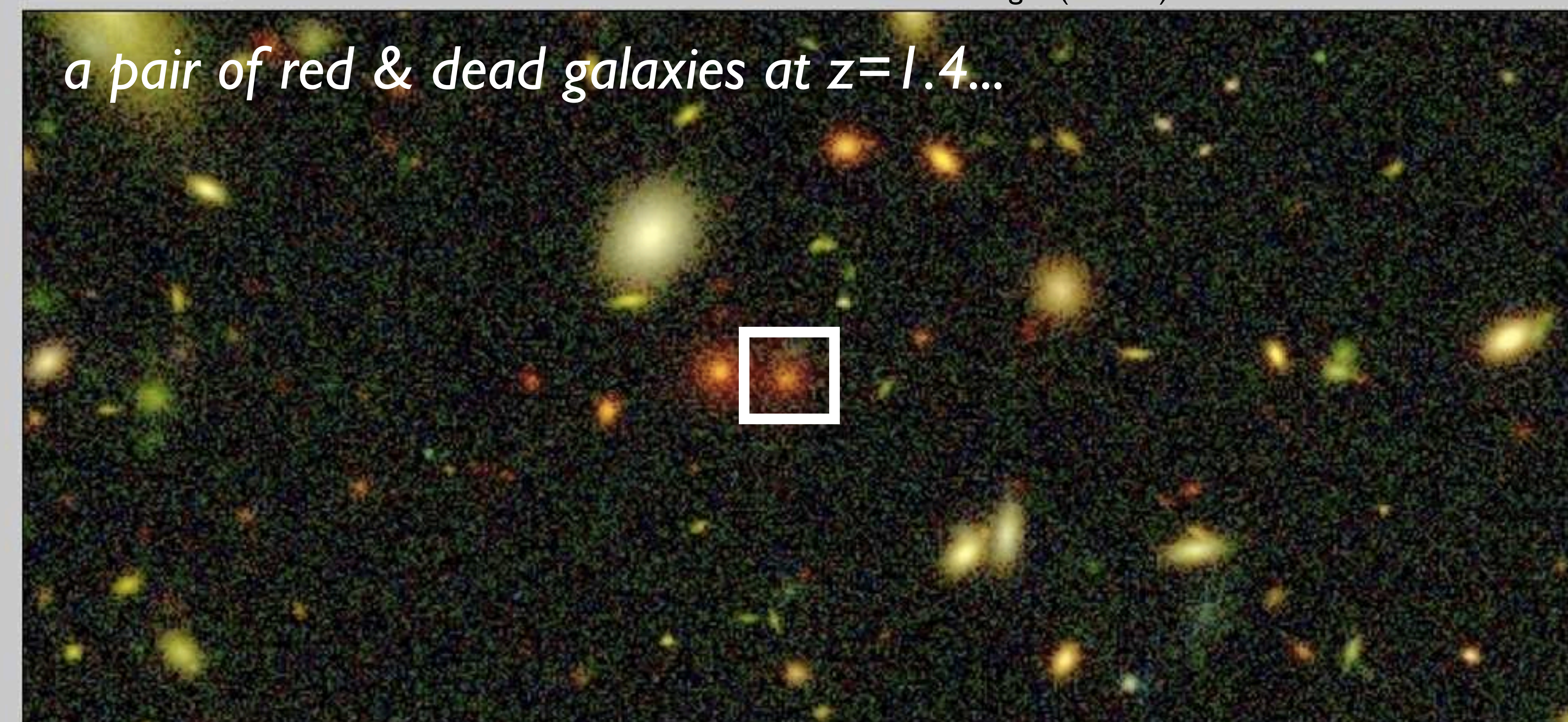
[Overzier, Lemson et al. in prep.]

Millennium Run Observatory - Mock Image Browser

Show: (1) Blue Galaxy (2) Big Galaxy (3) Two Red Nuggets 0:0:11.357 -0:4:28.272

Galaxy Info	
Galaxy Id	400006308001790
RA, Dec (deg)	(0.0469,-0.0767)
Redshift (z_app)	1.40824
Inclination | PA	48.6 | 39.3
B-V (AB mag)	1.494
r' (AB mag)	26.6995
Stellarmass (1e10 Msun)	2.0069
SFR (Msun/yr)	0.0000
Age (Gyr)	2.8619



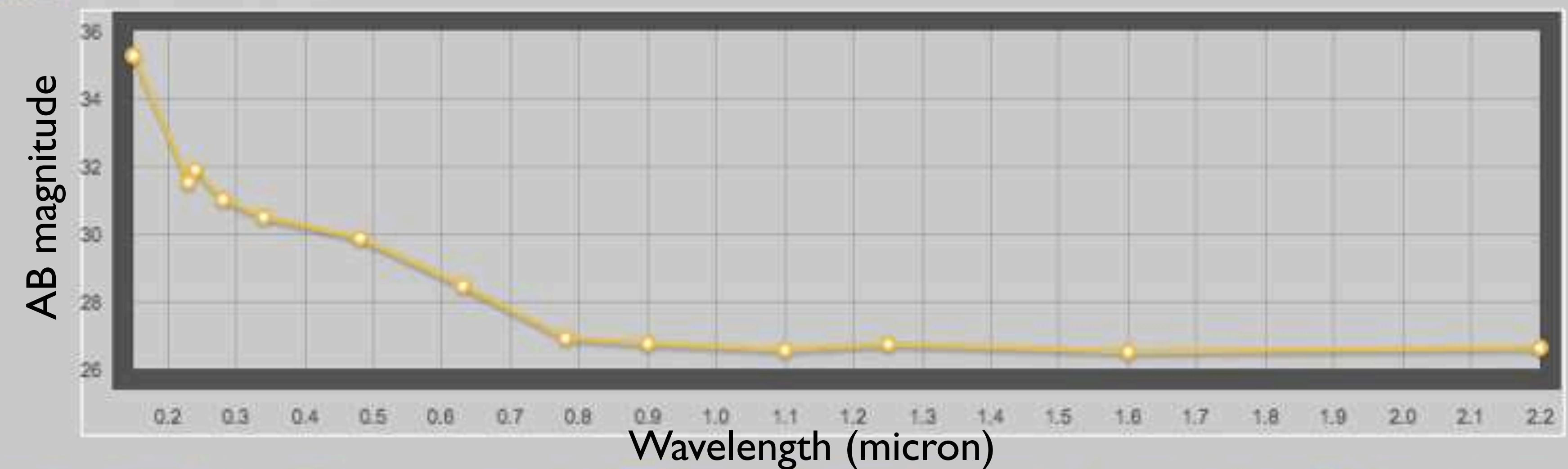


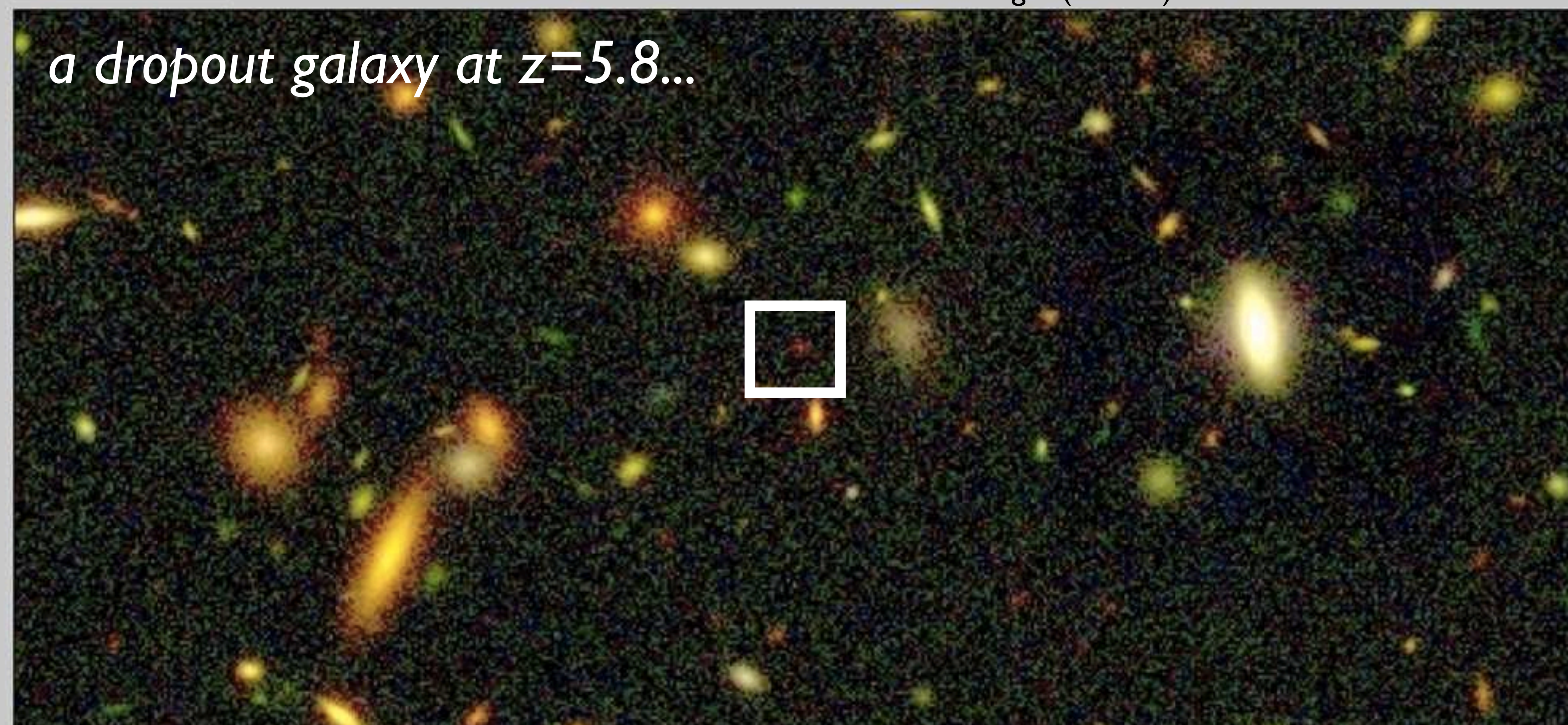
[Overzier, Lemson et al. in prep.]

Millennium Run Observatory - Mock Image Browser

Show: (1) Blue Galaxy (2) Big Galaxy (3) Two Red Nuggets 0:0:10.534 +0:1:34.702

Galaxy Info	
Galaxy Id	186014843016767
RA, Dec (deg)	(0.0420,0.0260)
Redshift (z_app)	5.77513
Inclination | PA	62.0 | 67.1
B-V (AB mag)	0.400
r' (AB mag)	28.4523
Stellarmass (1e10 Msun)	0.0270
SFR (Msun/yr)	5.8982
Age (Gyr)	0.0461





[Overzier, Lemson et al. in prep.]