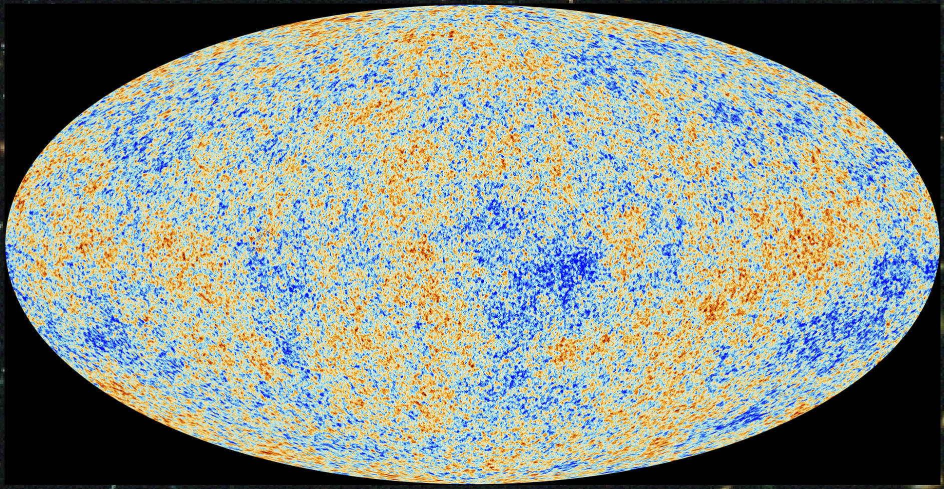
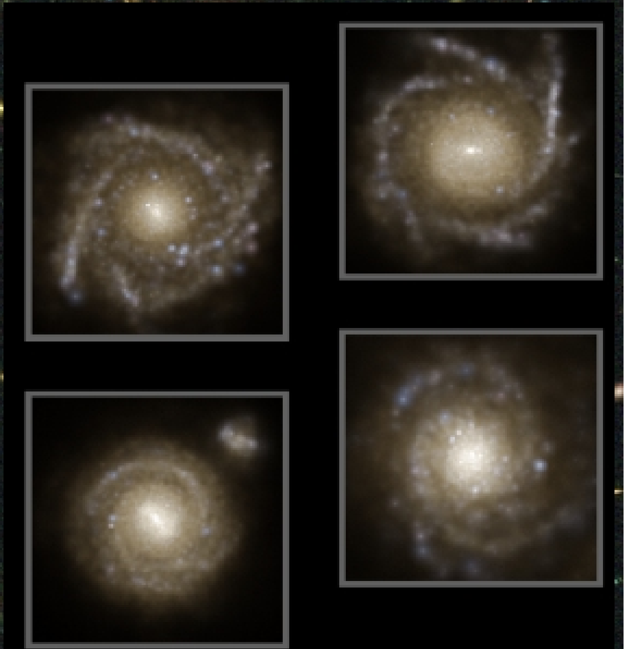


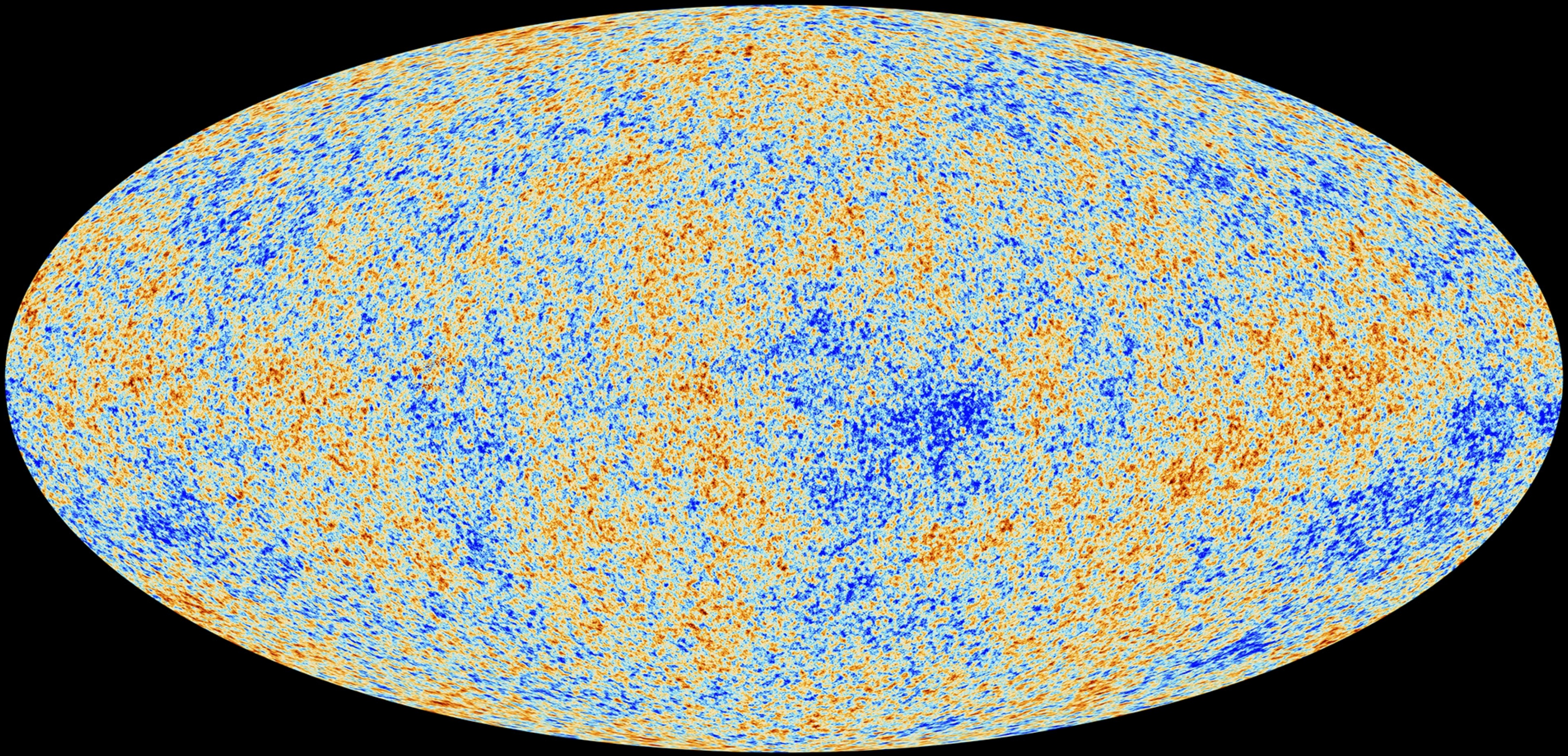
Oxford, July 2014

Galaxy masses – galaxy formation



Simon White
Max Planck Institute for Astrophysics

Planck CMB map: the IC's for structure formation



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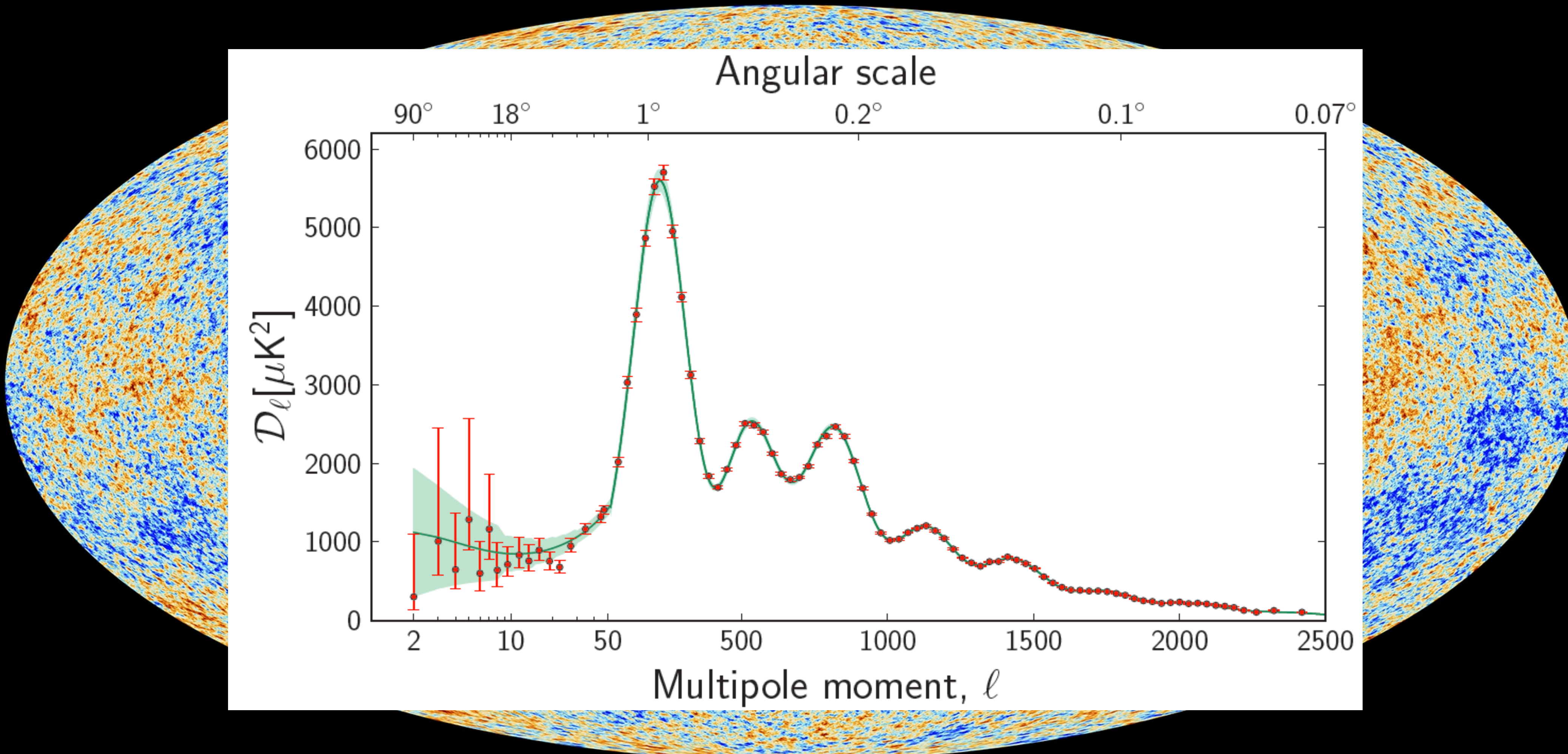

The six parameters of the minimal ΛCDM model

Parameter	*Planck*+WP Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

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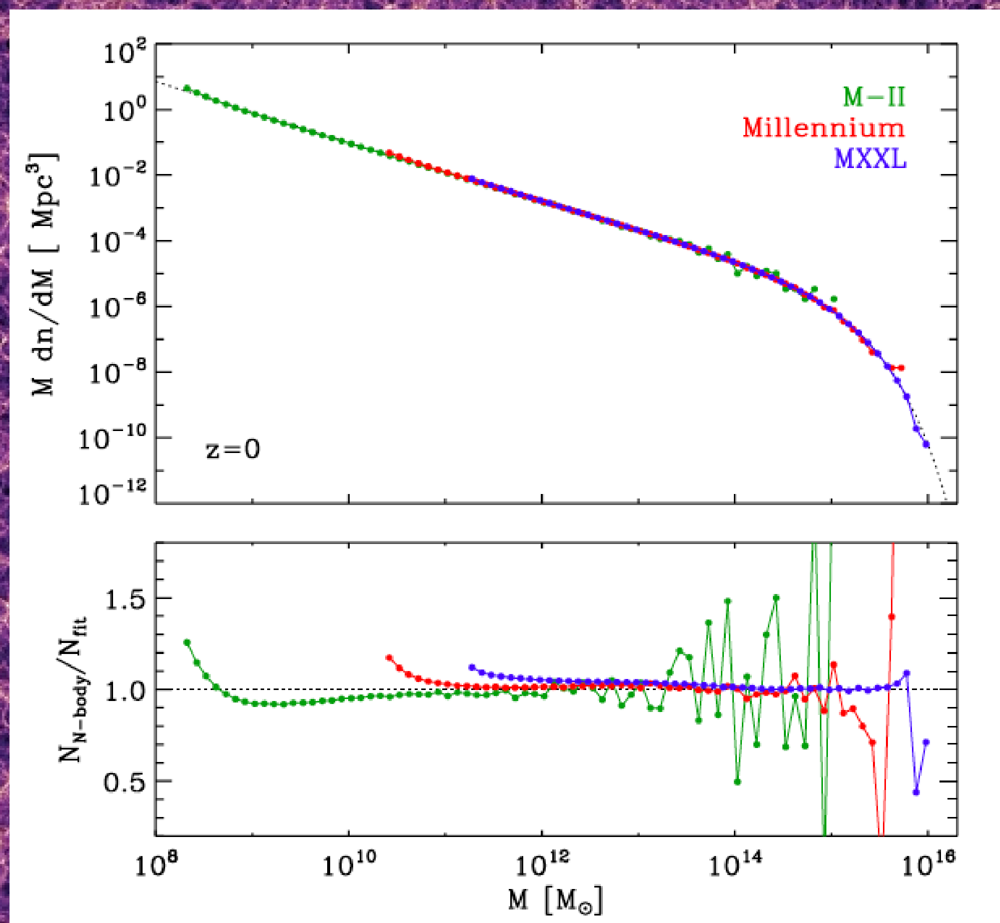
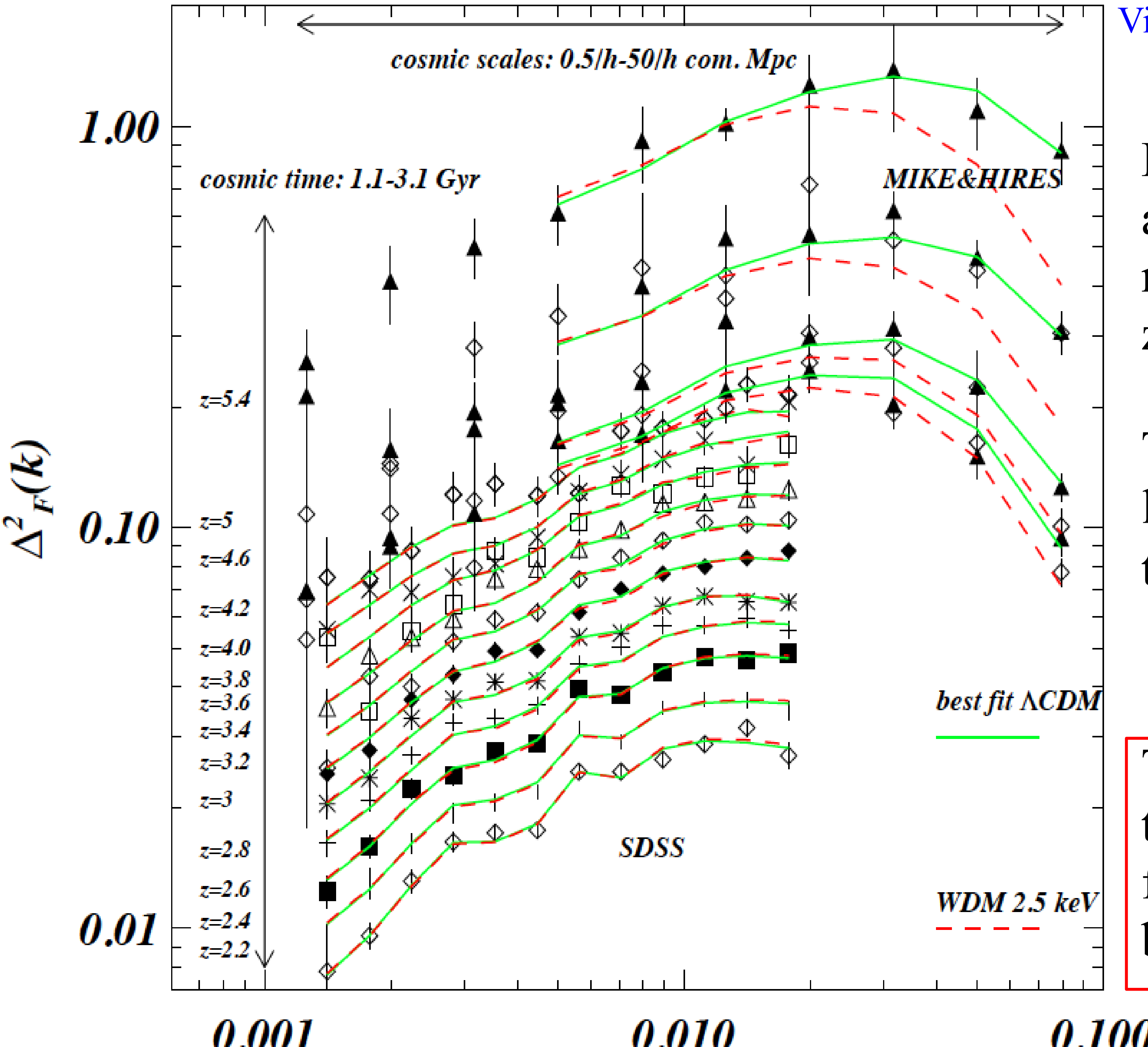
A 40σ detection of nonbaryonic DM using ***only*** z ~1000 data!

Given the known cosmology and initial conditions, N-body codes can simulate the evolution of the abundance, internal structure and clustering of dark halos at high precision



Lyman α forest power spectra support ΛCDM ICs



Viel, Becker, Bolton & Haehnelt 2013

High-resolution Keck and Magellan spectra match ΛCDM up to z = 5.4

This places a 2σ lower limit on the mass of a thermal relic

$m_{WDM} > 3.3$ keV

This shows the DM to to be effectively cold for the formation of all but the faintest galaxies

The six parameters of the minimal ΛCDM model

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The six parameters of the minimal ΛCDM model

A 80σ measurement of the cosmic baryon density in g/cc!

$$f_{bar} = \Omega_b / \Omega_m = 0.155 \pm 0.004$$

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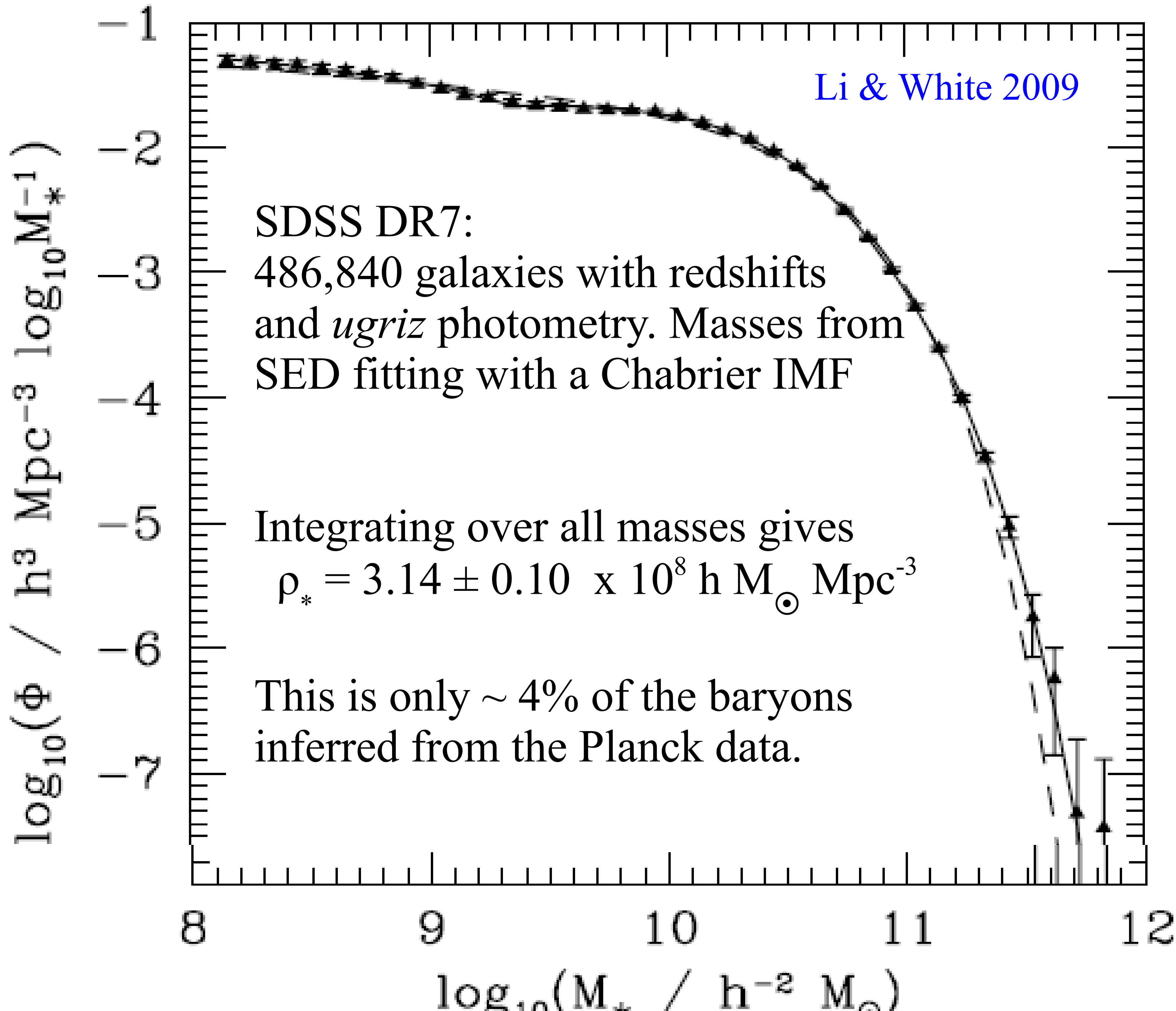
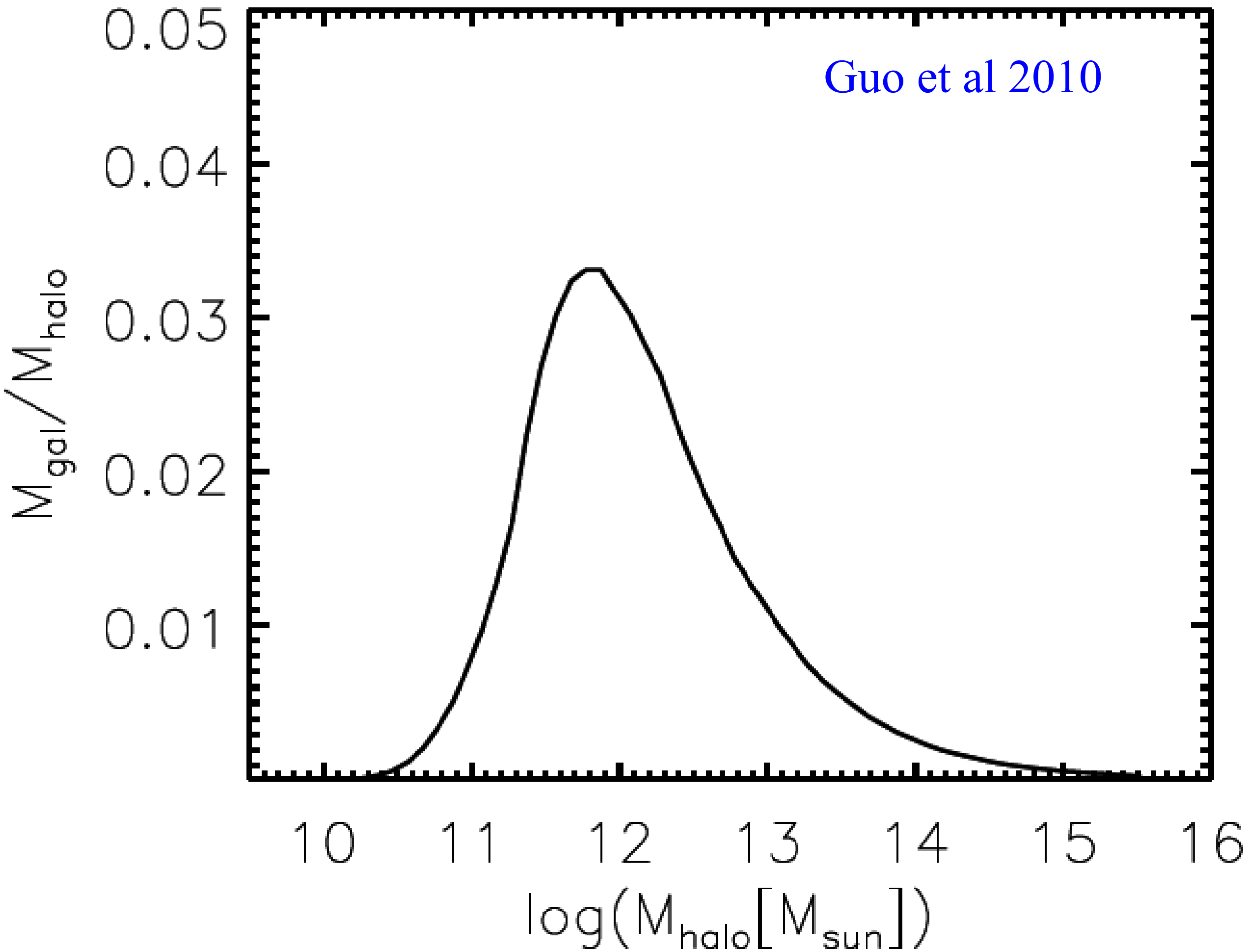

Li & White 2009
SDSS DR7:
486,840 galaxies with redshifts
and *ugriz* photometry. Masses from
SED fitting with a Chabrier IMF
Integrating over all masses gives
$\rho_* = 3.14 \pm 0.10 \times 10^8 \; h \; M_\odot \; Mpc^{-3}$
This is only ~ 4% of the baryons
inferred from the Planck data.
$\log_{10}(\Phi \; / \; h^3 \; Mpc^{-3} \; \log_{10} M_*^{-1})$
$\log_{10}(M_* \; / \; h^{-2} \; M_\odot)$
−1
−2
−3
−4
−5
−6
−7
8
9
10
11
12

From abundance matching (assuming no scatter)...

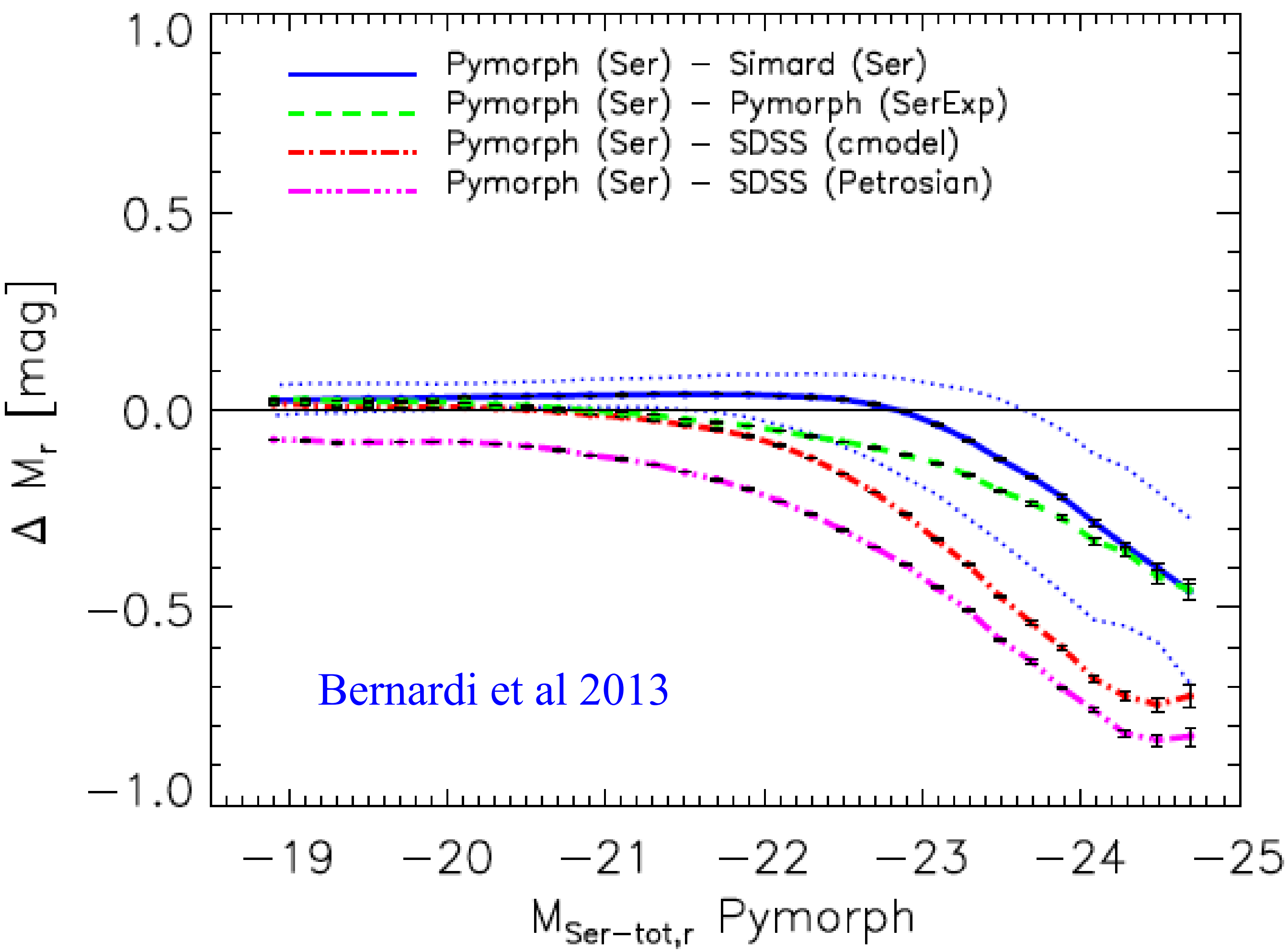


The maximum fraction of halo mass in central galaxy stars is 3.5%

This is attained for halos similar in mass to the Milky Way's halo

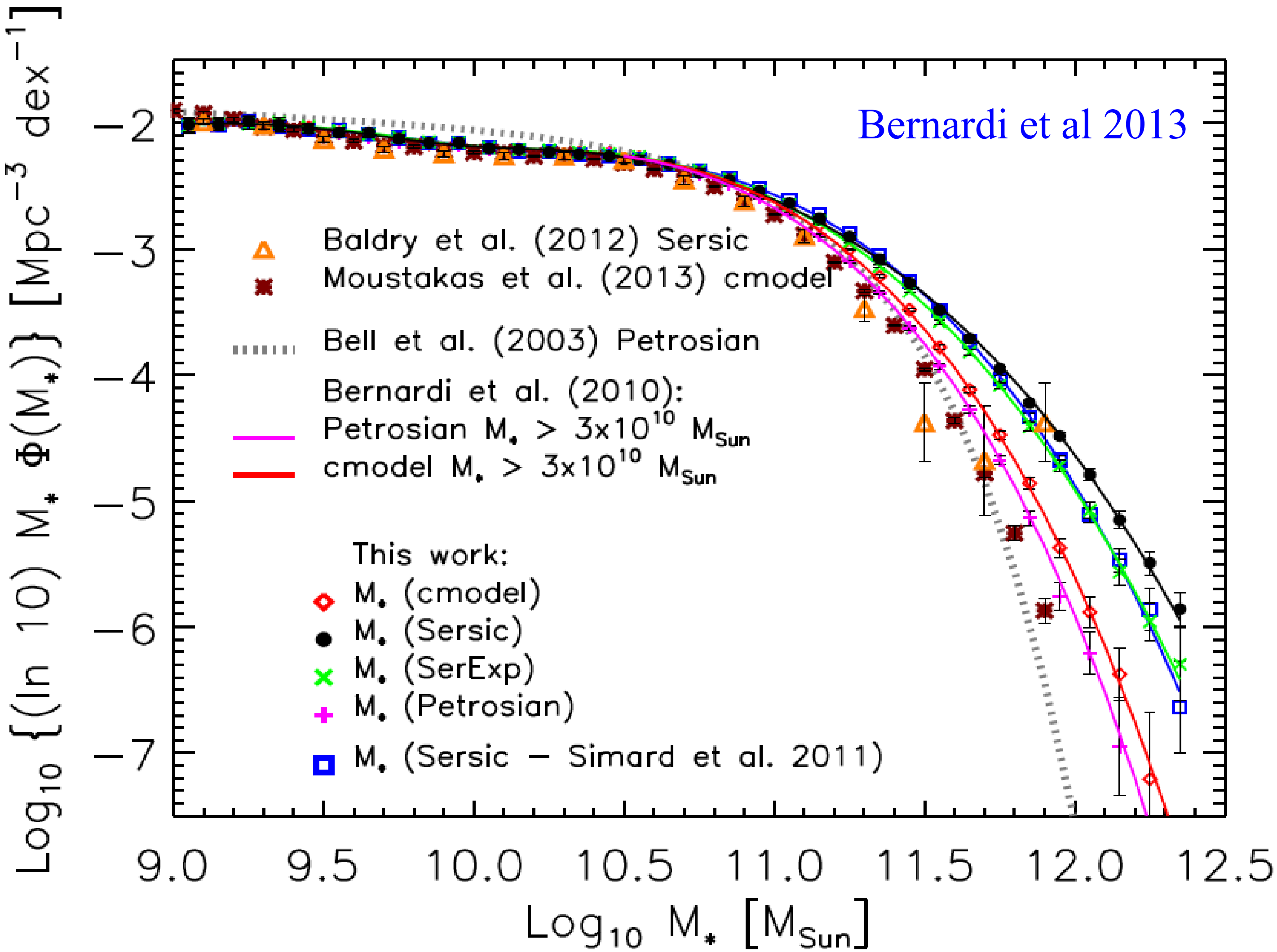
The fraction drops very rapidly to higher and lower masses

Uncertainties in the total light in galaxies



Different fitting algorithms <u>extrapolate</u> to different total luminosities

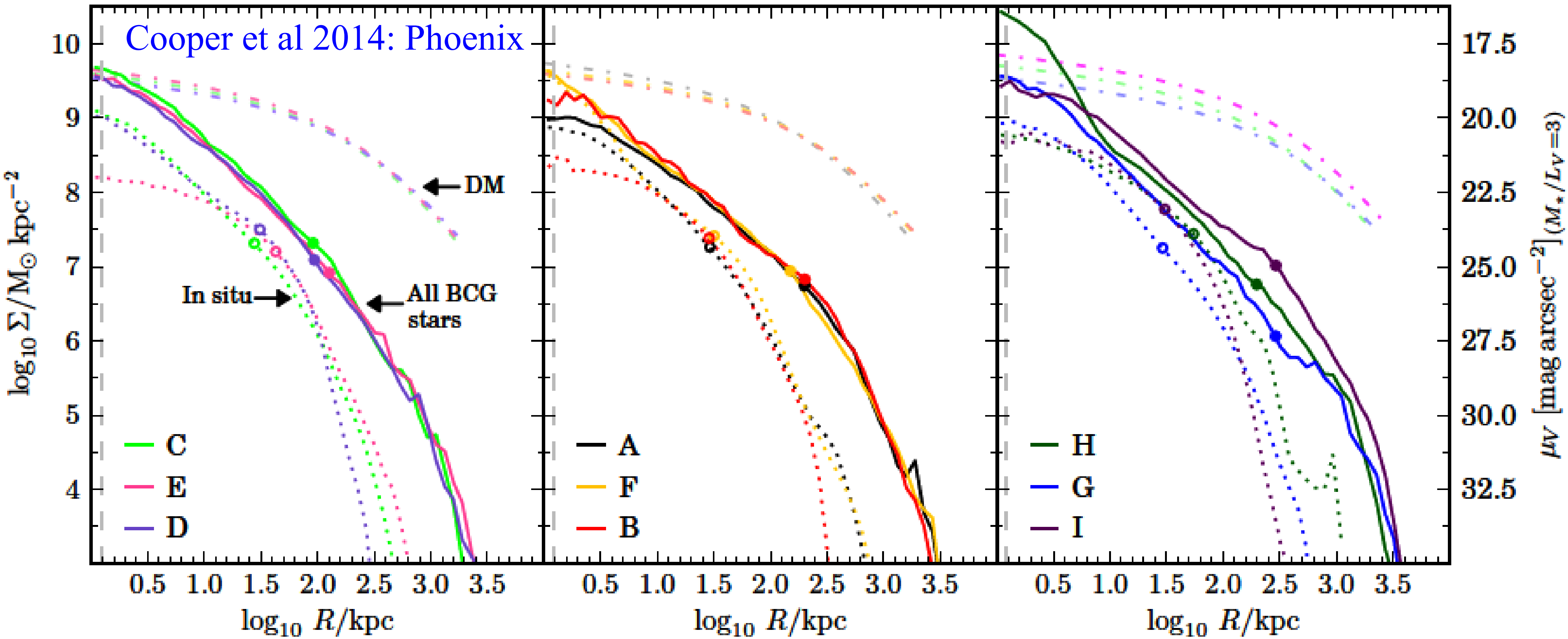
Uncertainties due to the total light in galaxies



Different fitting algorithms <u>extrapolate</u> to different total luminosities

This changes the SMF at high mass, increasing ρ_* by 20 to 50%

Simulating mass growth in massive galaxies

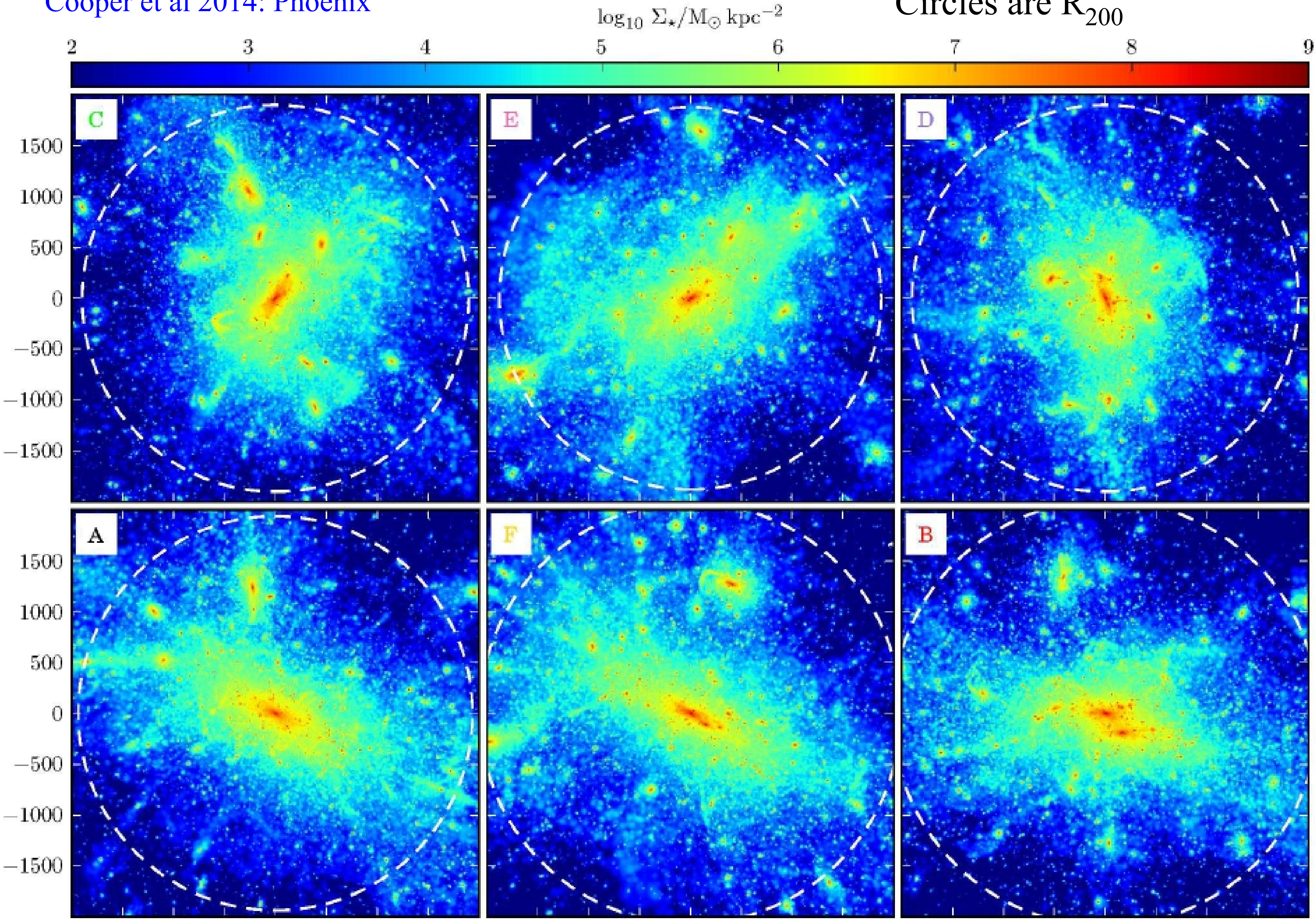


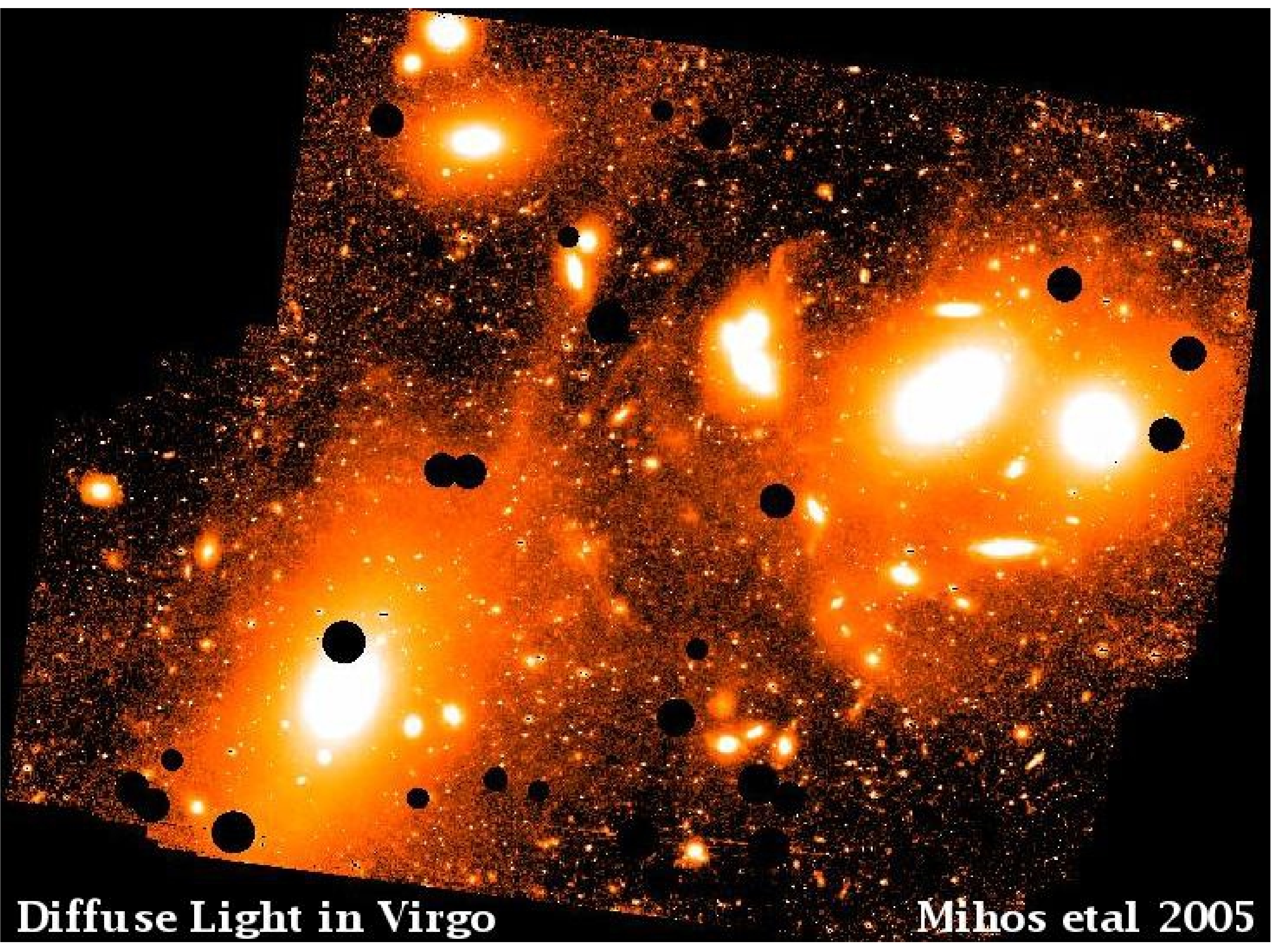
Simulations of BCG assembly → most stars accreted rather than *in situ*

The majority come from a few big galaxies, some of which may survive

Cooper et al 2014: Phoenix

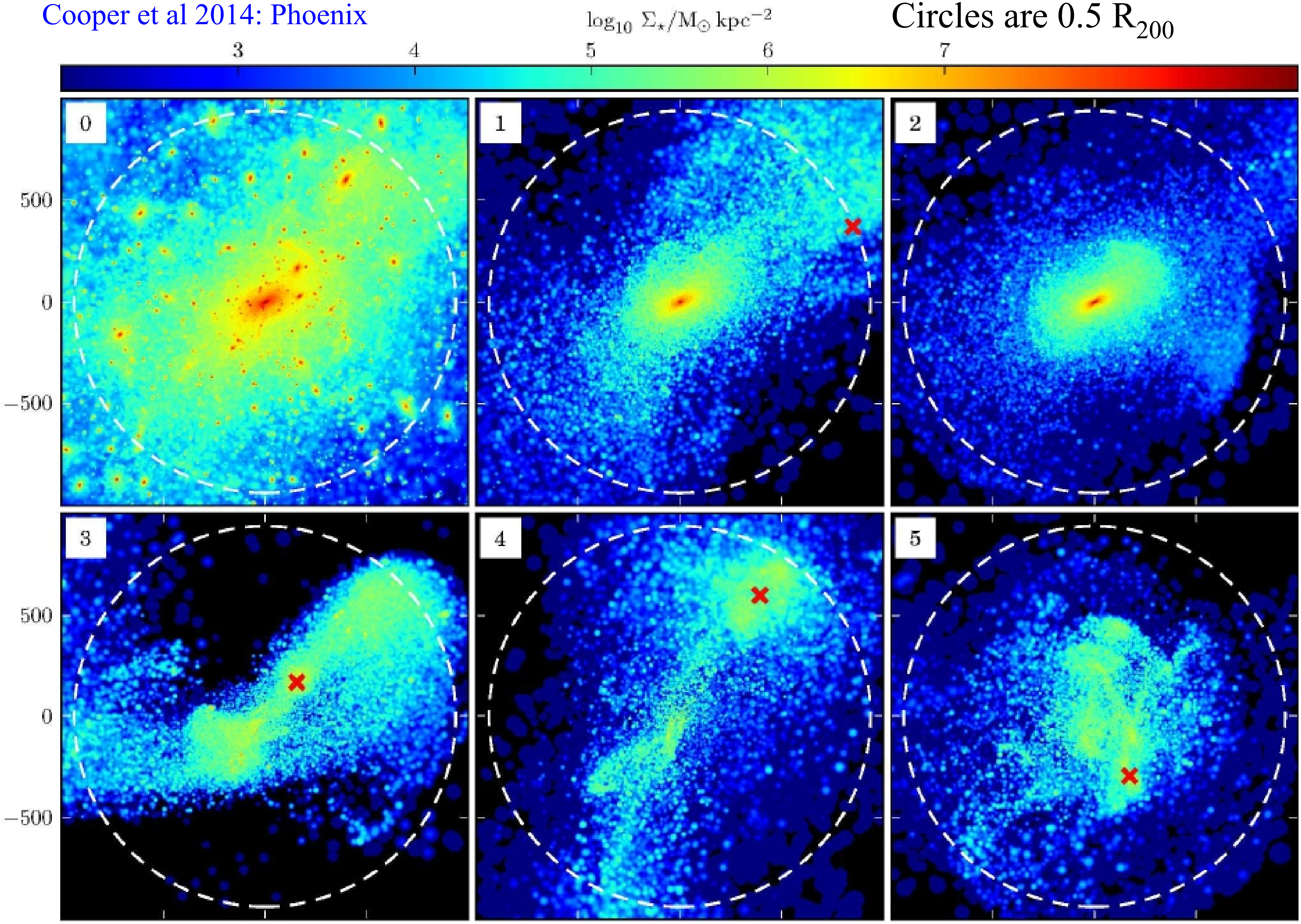
Circles are R_{200}




Diffuse Light in Virgo
Mihos etal 2005

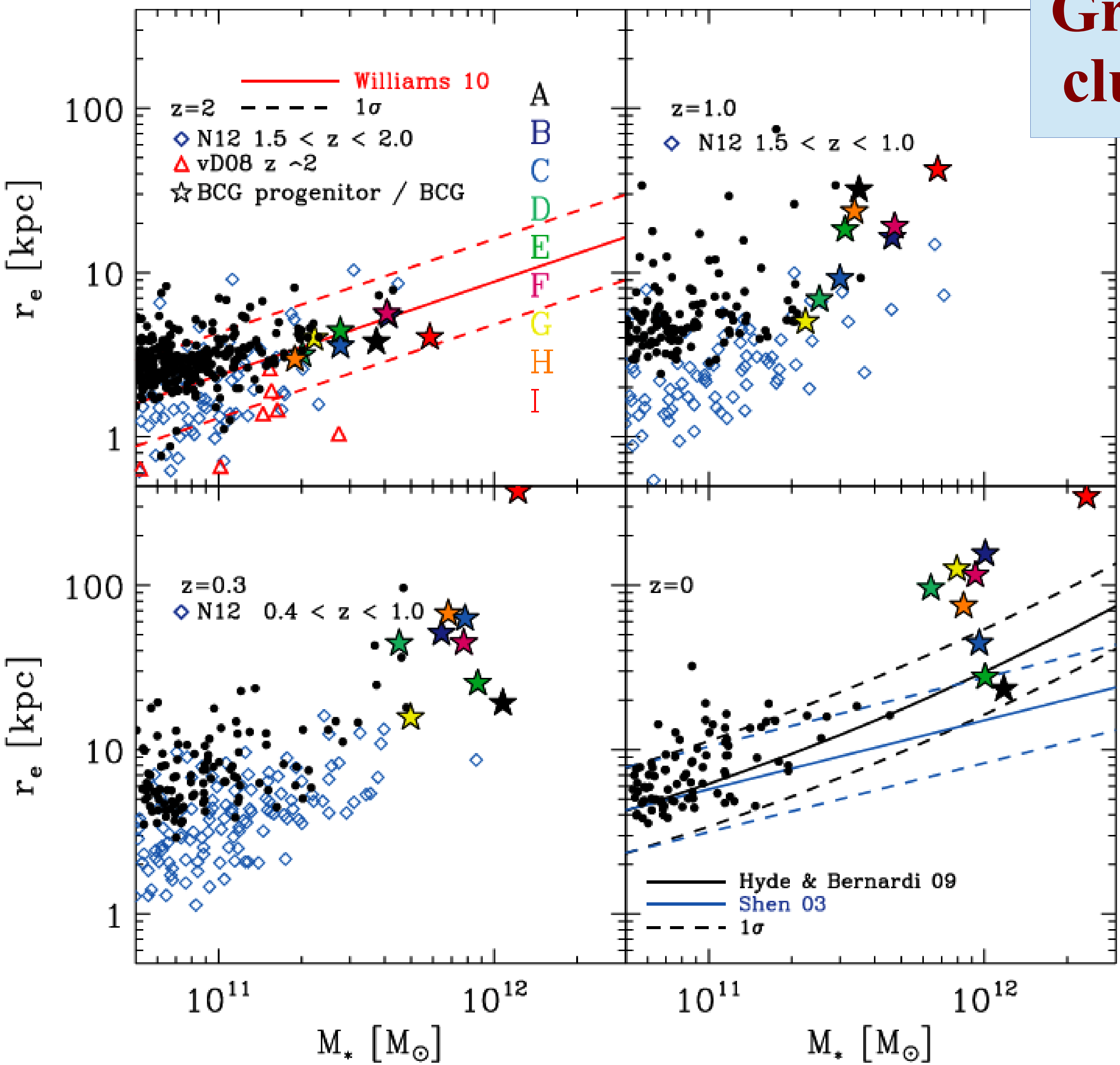
Cooper et al 2014: Phoenix

Circles are 0.5 R_{200}



Laporte et al 2013: Phoenix

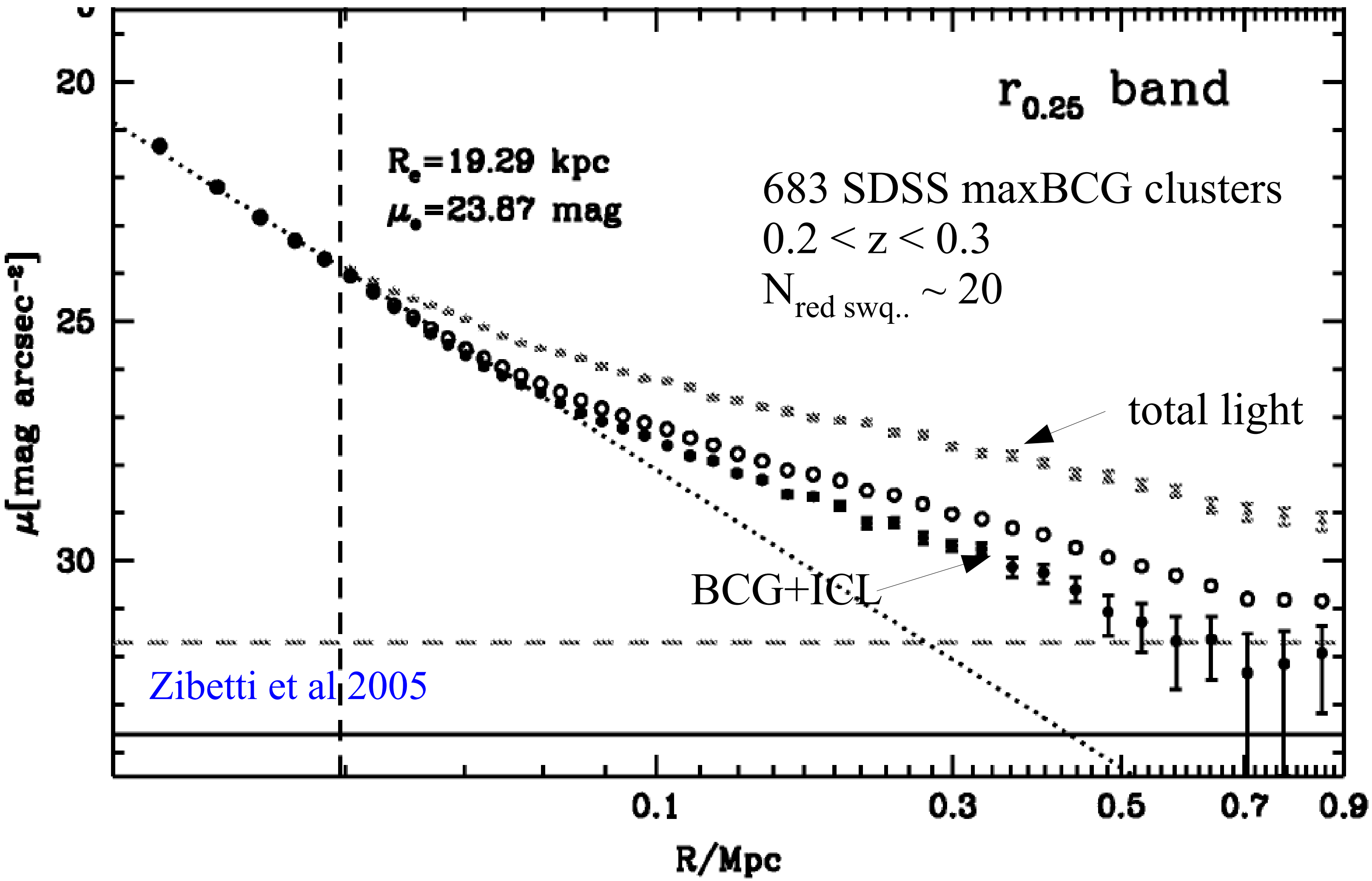
Growth in size of cluster ellipticals



Merging of smaller galaxies onto big ellipticals increases their size from z=2 to z=0 as observed

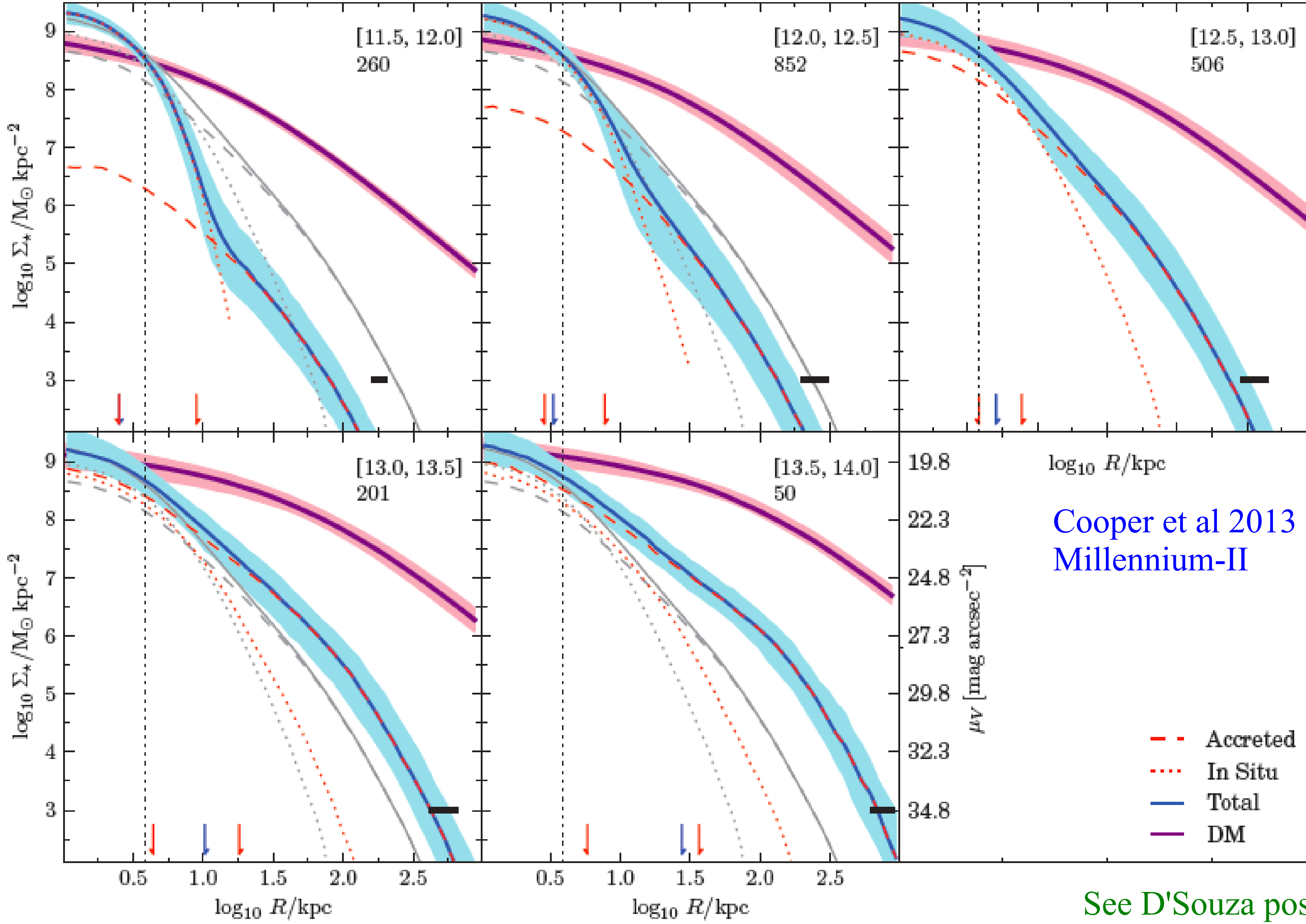
Effects are much larger for BCGs than for other Es

Stacking allows the ICL to be seen to large radius



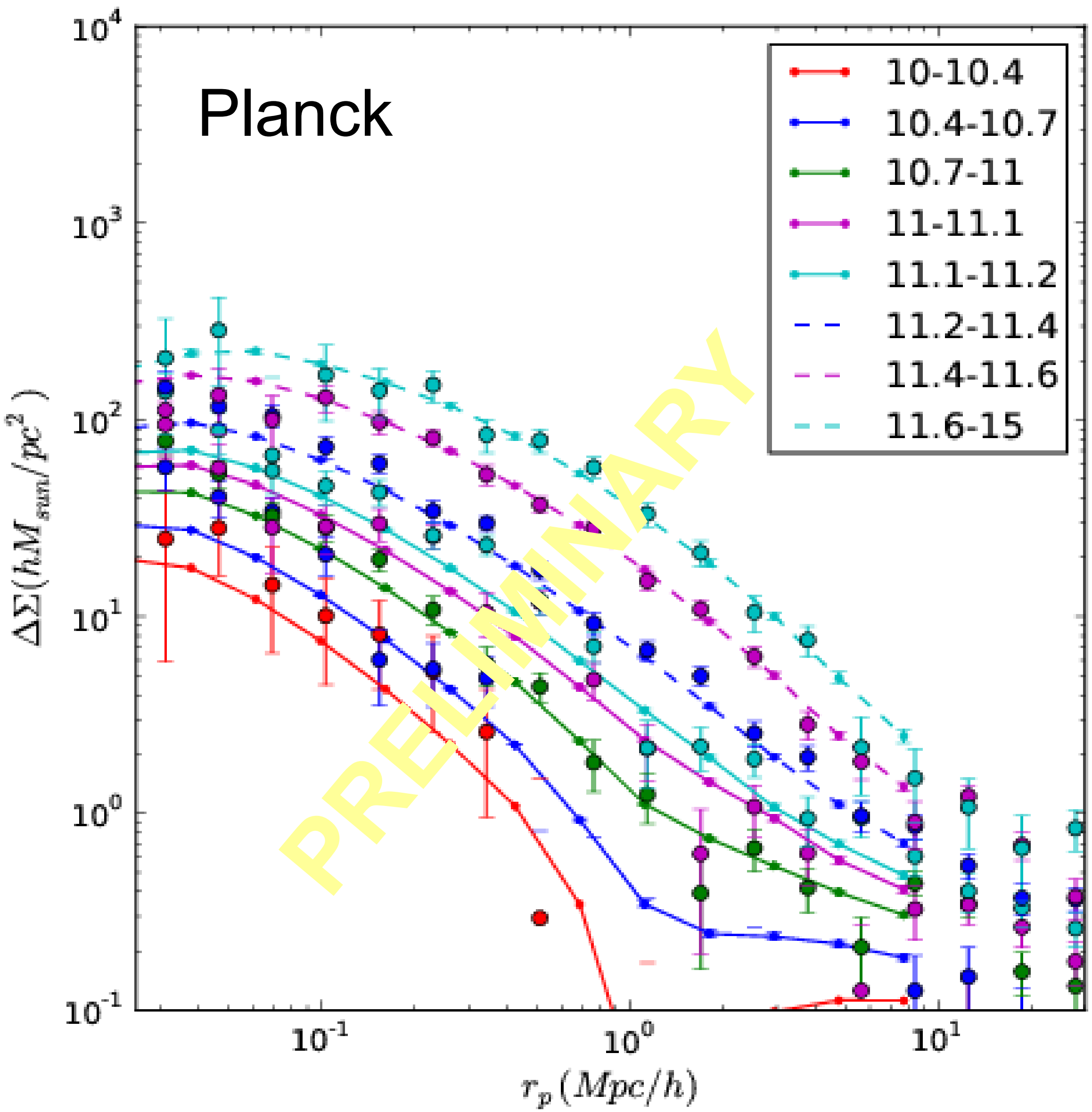
Stacking results in smooth (average) distributions, and pushes the limiting surface brightness down to 10^{-4} of the sky

Lower mass galaxies have fewer accreted stars?



See D'Souza poster

Dark matter halos – as predicted by simulatios?



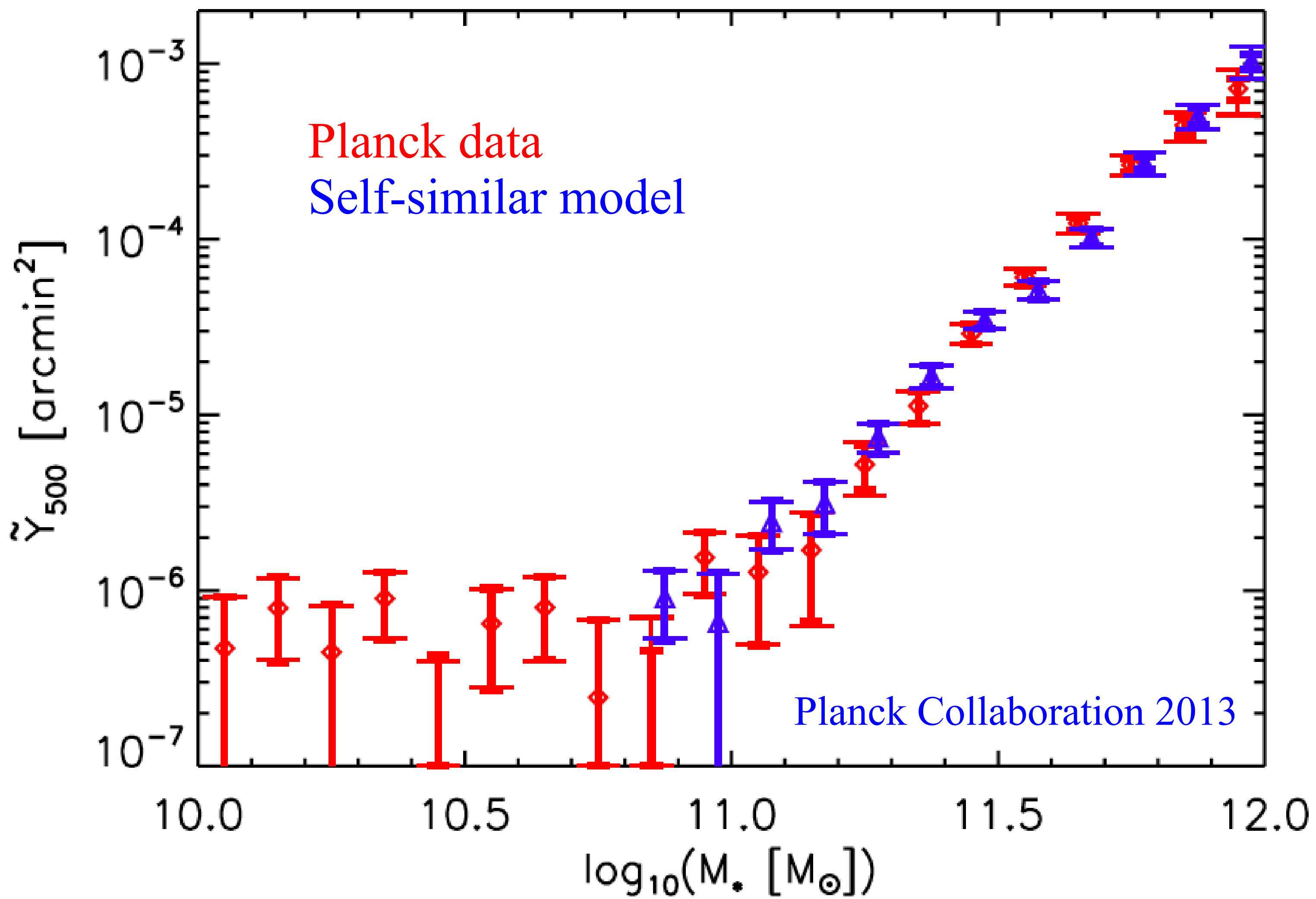
Wang, Mandelbaum et al, in prep.

Stacked weak lensing signal around Locally Brightest Galaxies in the SDSS/DR7 in bins of LBG stellar mass.

Dashed lines are similarly selected samples from the Guo et al (2013) galaxy formation model applied to the *Planck* cosmology

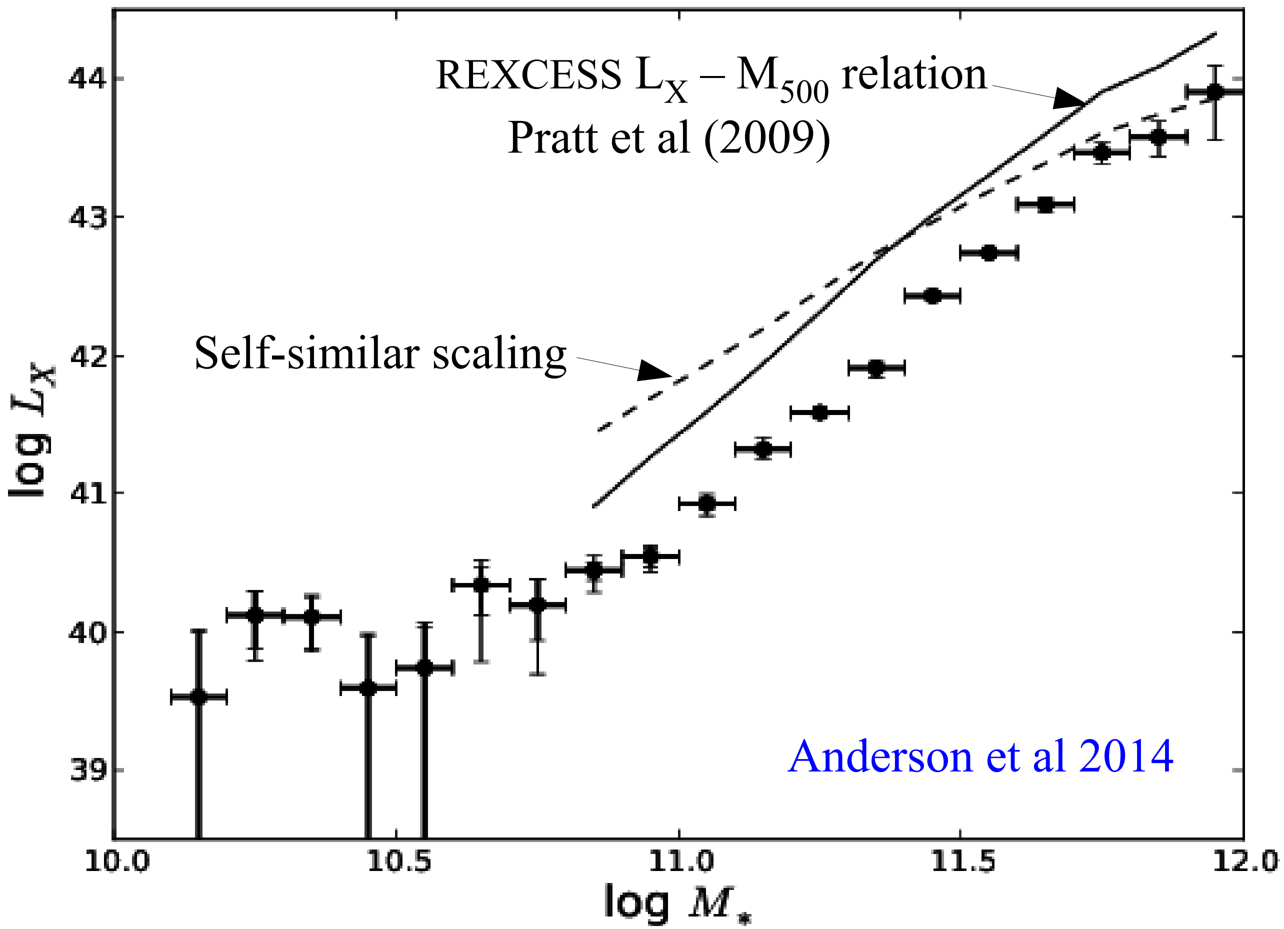
This prediction has **<u>no</u>** free parameters!

Gaseous halos – the missing baryons?



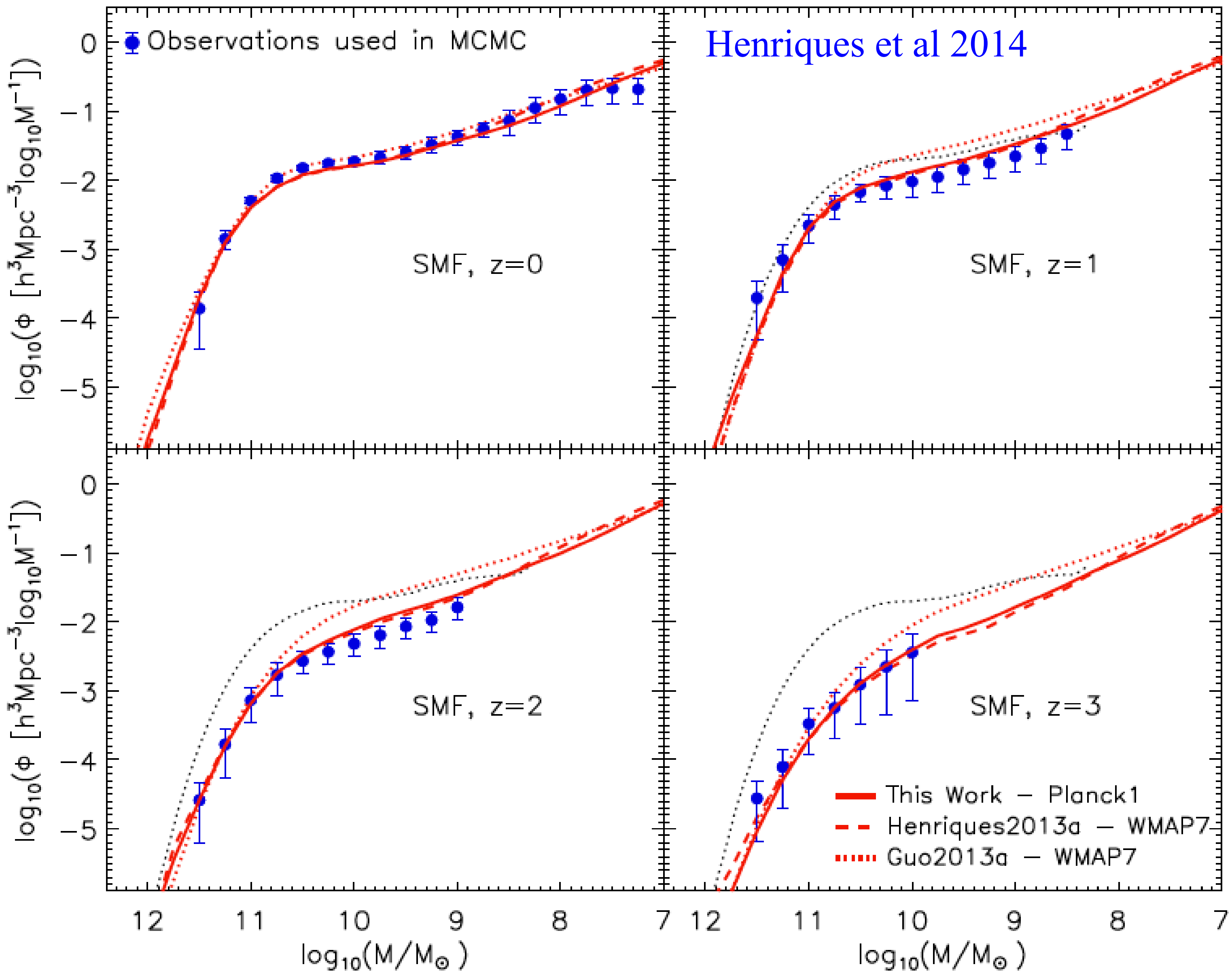
Stacked Planck SZ signal around Locally Brightest Galaxies in SDSS
Signal detected down to isolated galaxies with stellar mass of M31
Scaling is as predicted by a gas-follows-mass model with $f_{bar} \sim 0.15$!

Gaseous halos – the missing baryons?



Stacked ROSAT signal around Locally Brightest Galaxies in SDSS
Signal detected down to isolated galaxies of Milky Way stellar mass
Cluster relation extends to low mass, but offset due to optical selection?
Failure of self-similar scaling → gas distribution varies with halo mass

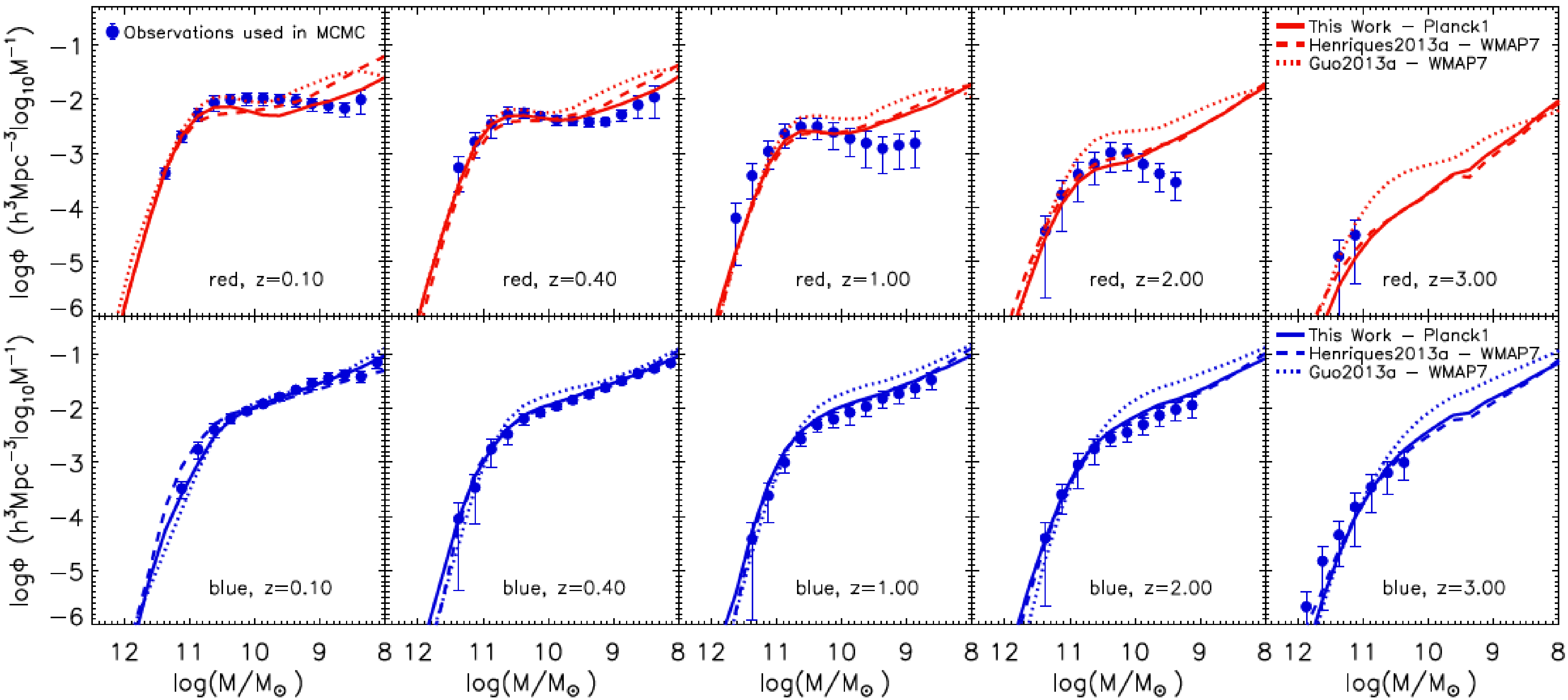
Simulating the galaxy population in the Planck cosmology



Plausible models for the efficiency of cooling/condensation, star formation, stellar and AGN feedback reproduce galaxy abundances for 0 < z < 3

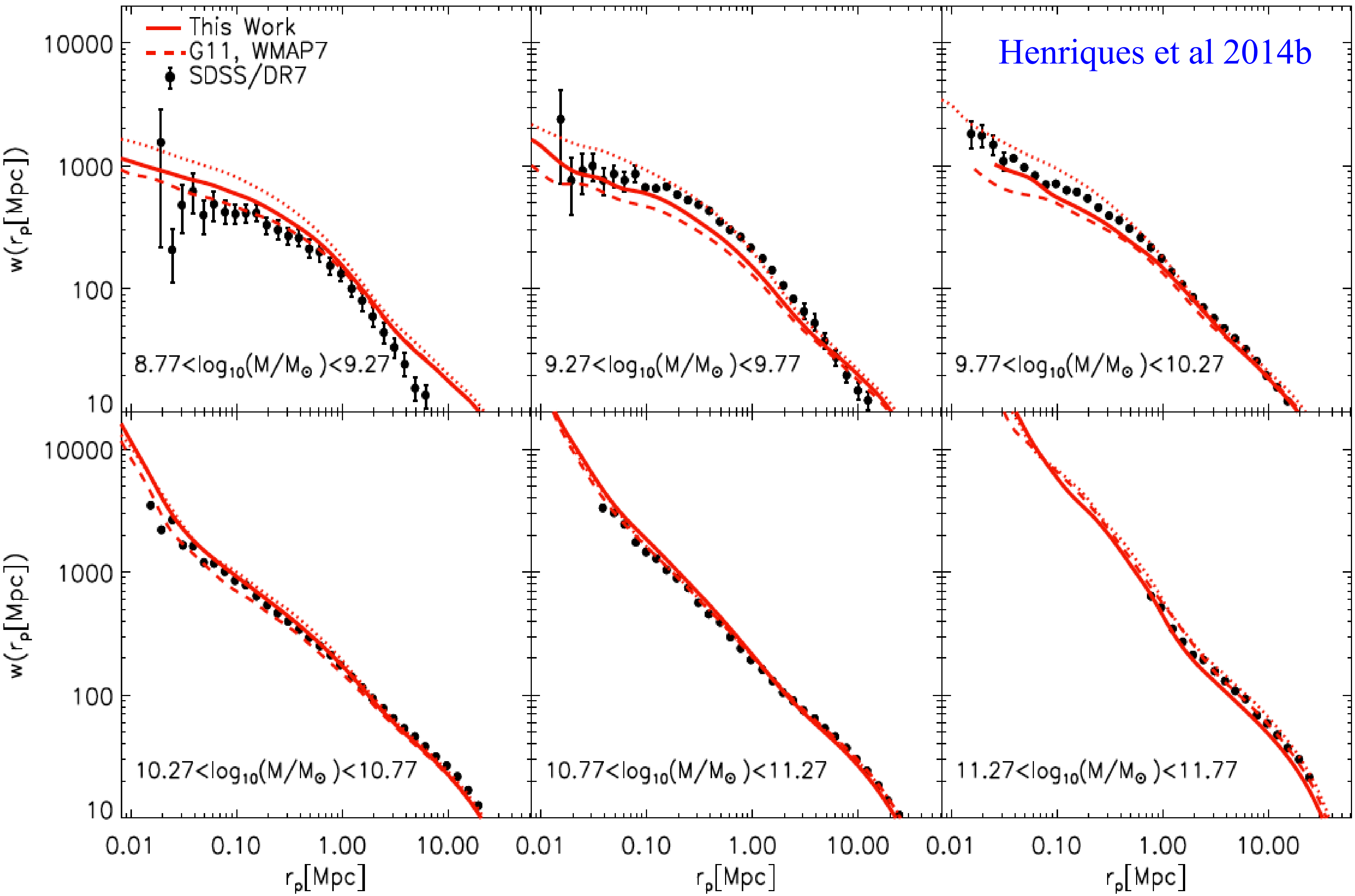
Simulating the galaxy population in the Planck cosmology

Henriques et al 2014



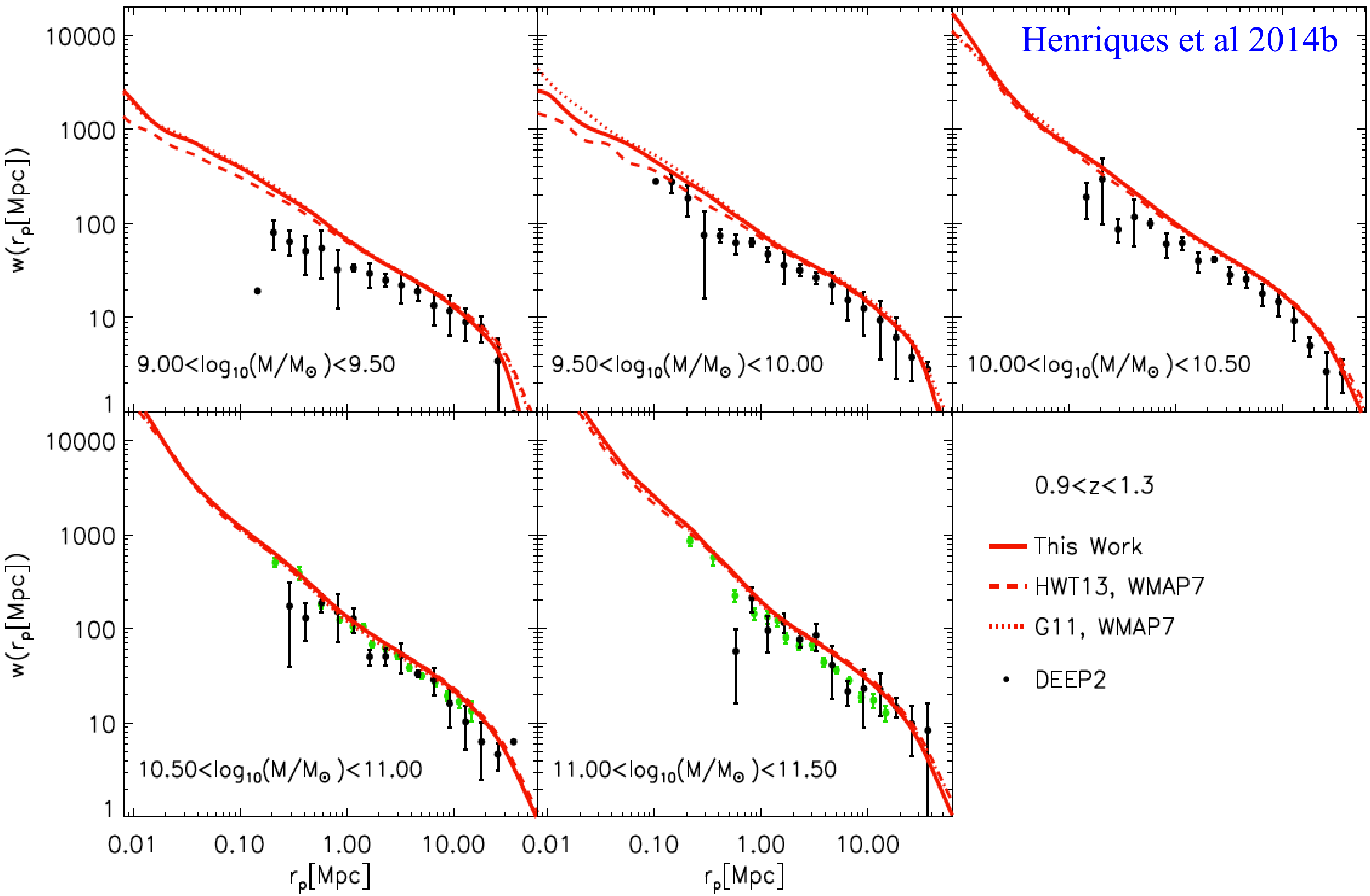
Plausible models for the efficiency of cooling/condensation, star formation, stellar and AGN feedback reproduce galaxy abundances for $0 < z < 3$ for both passive and actively star-forming galaxies

Simulating the galaxy population in the Planck cosmology



....and can be tested against measures of clustering both at $z = 0$

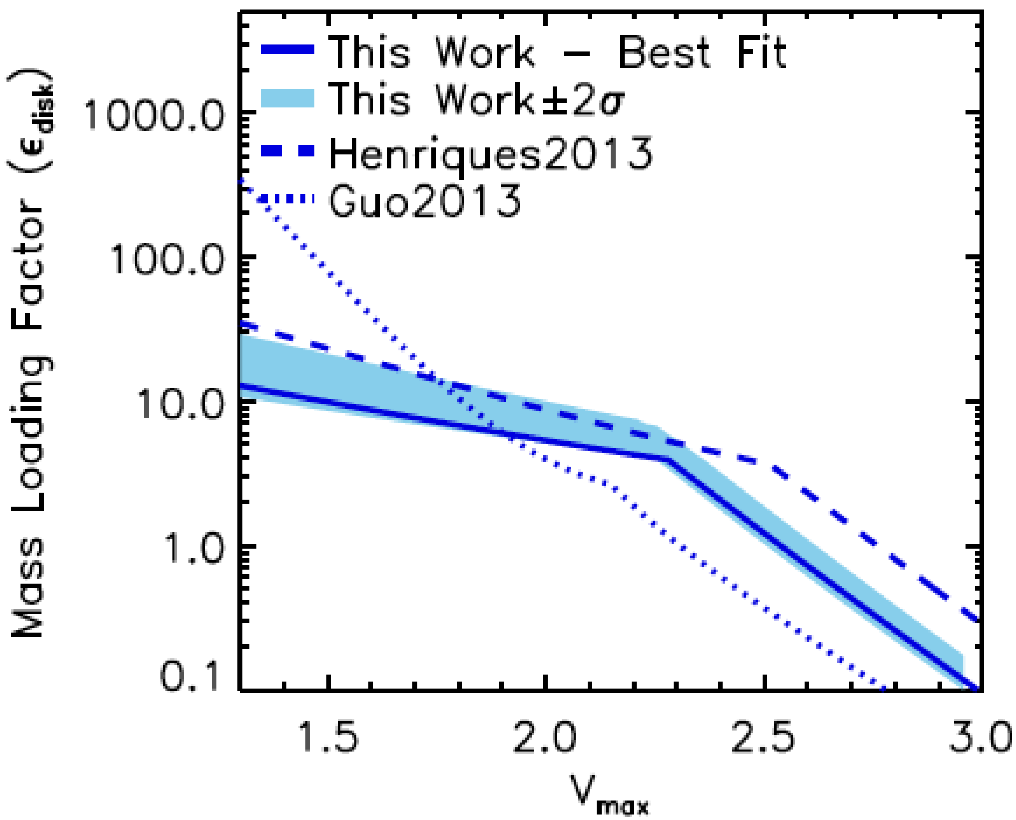
Simulating the galaxy population in the Planck cosmology

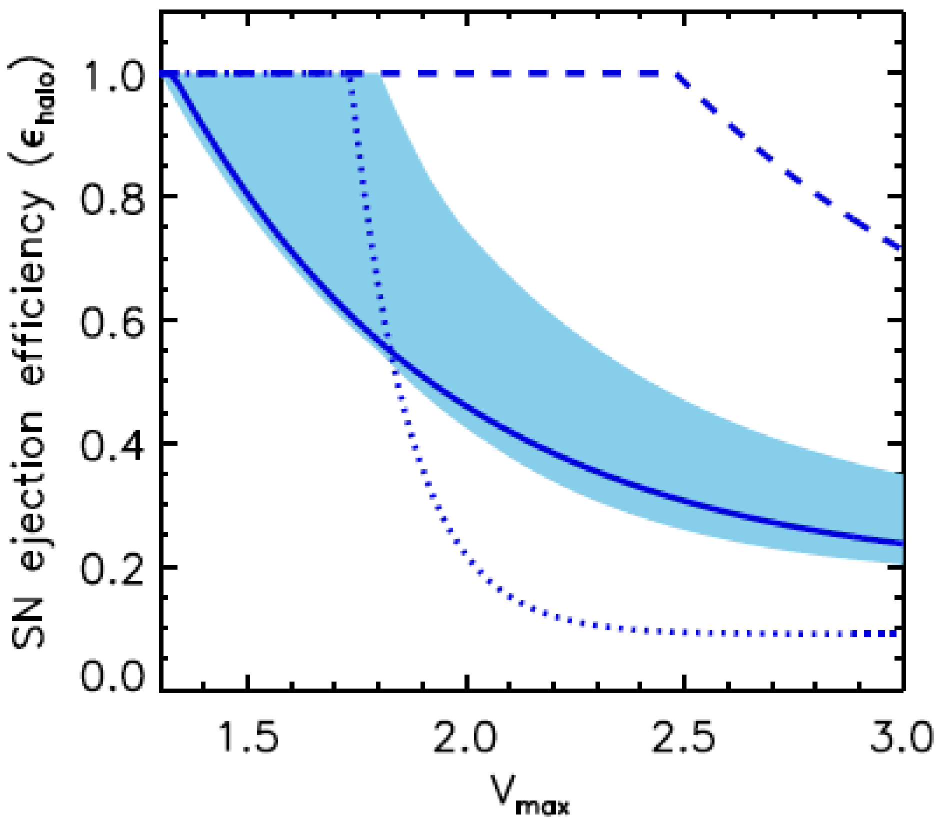


....and can be tested against measures of clustering both at z = 0 and at z = 1

Simulating the galaxy population in the Planck cosmology

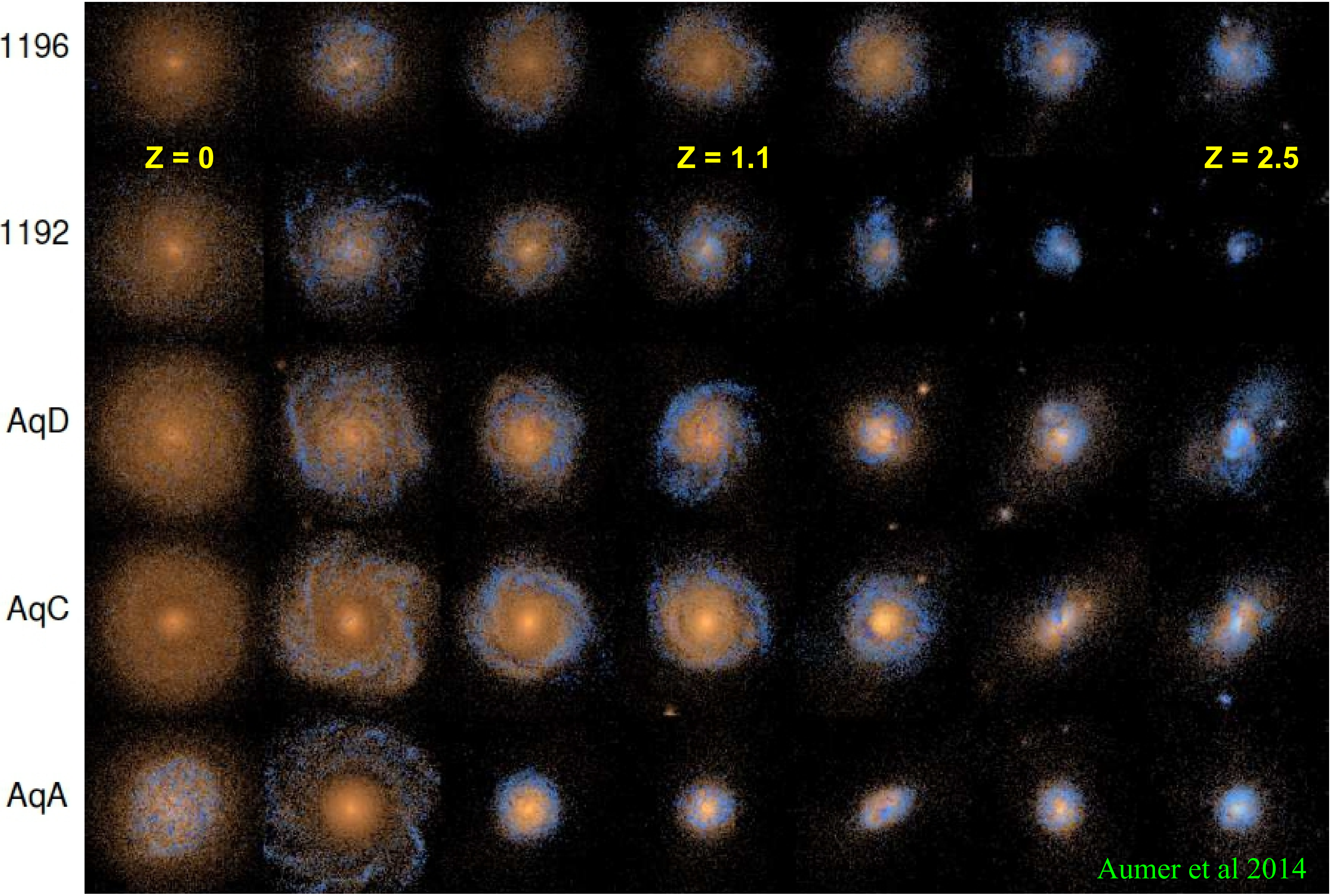
Henriques et al 2014b



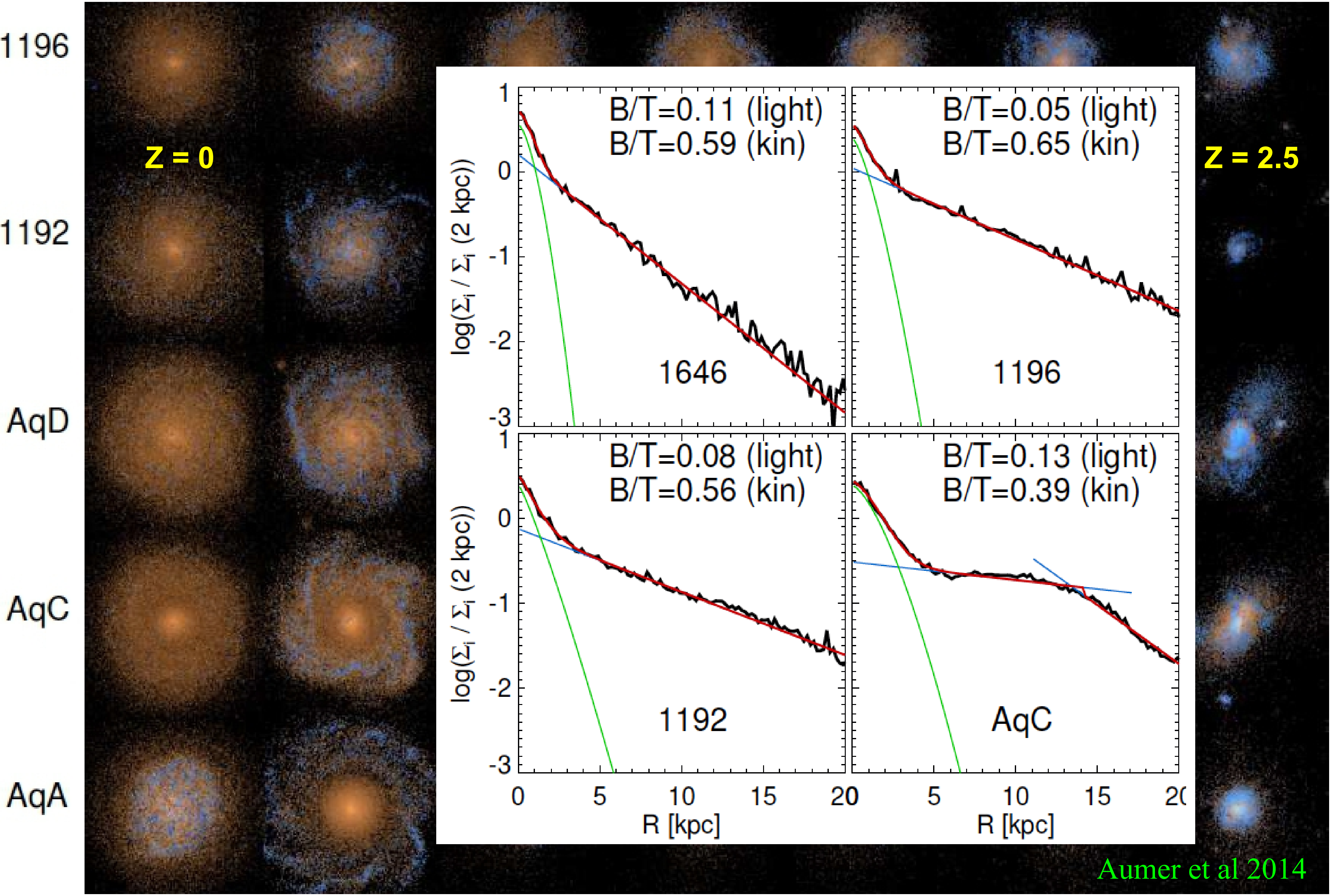


Fitting the observational data using phenomenological models for the physical processes shaping galaxy formation provides estimates of the efficiencies of those processes and their dependence on galaxy properties

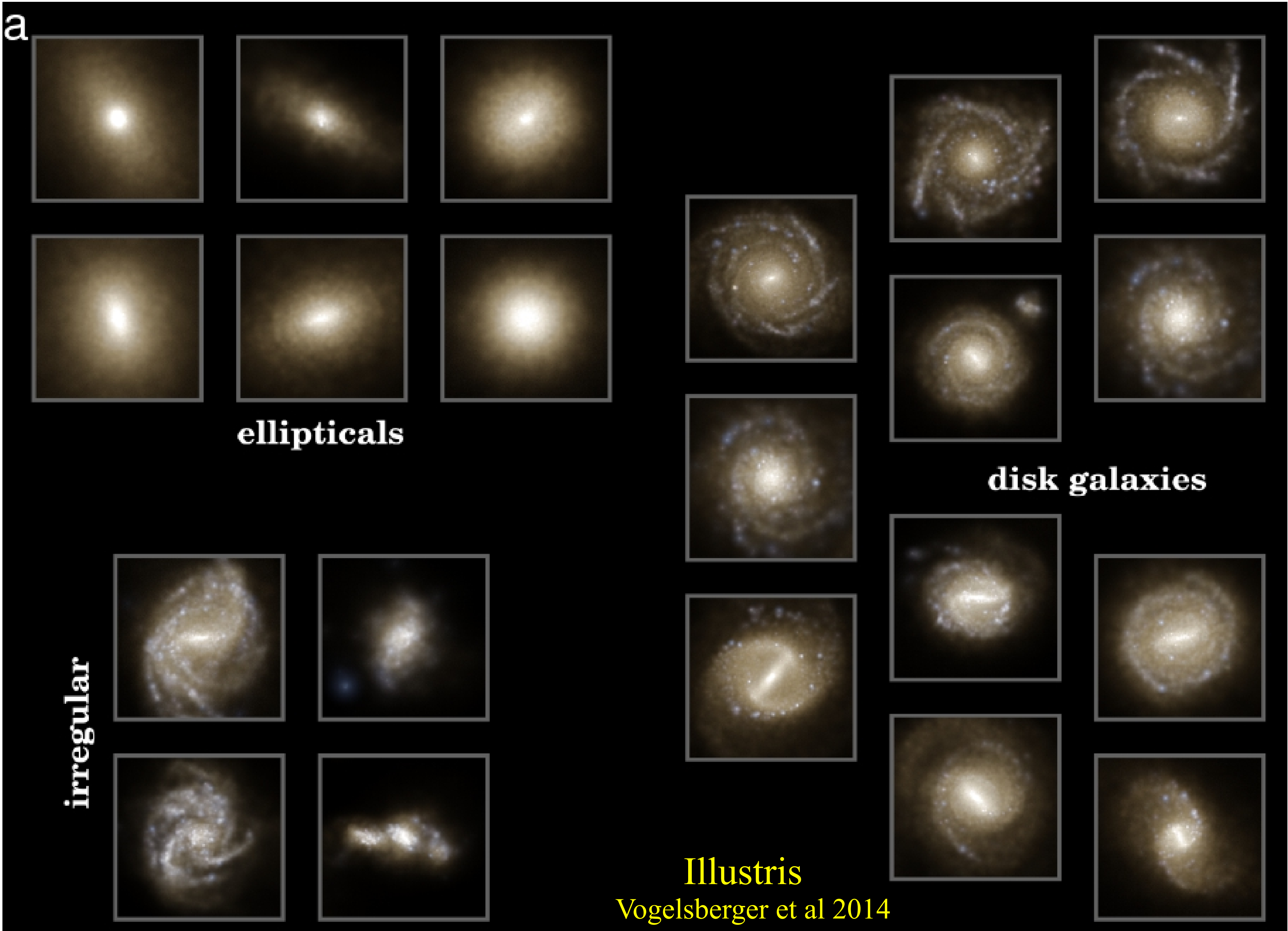
Efficient, mass-loaded winds, late re-incorporation of ejecta, and weak environmental effects in lower mass halos are <u>required</u> by the data

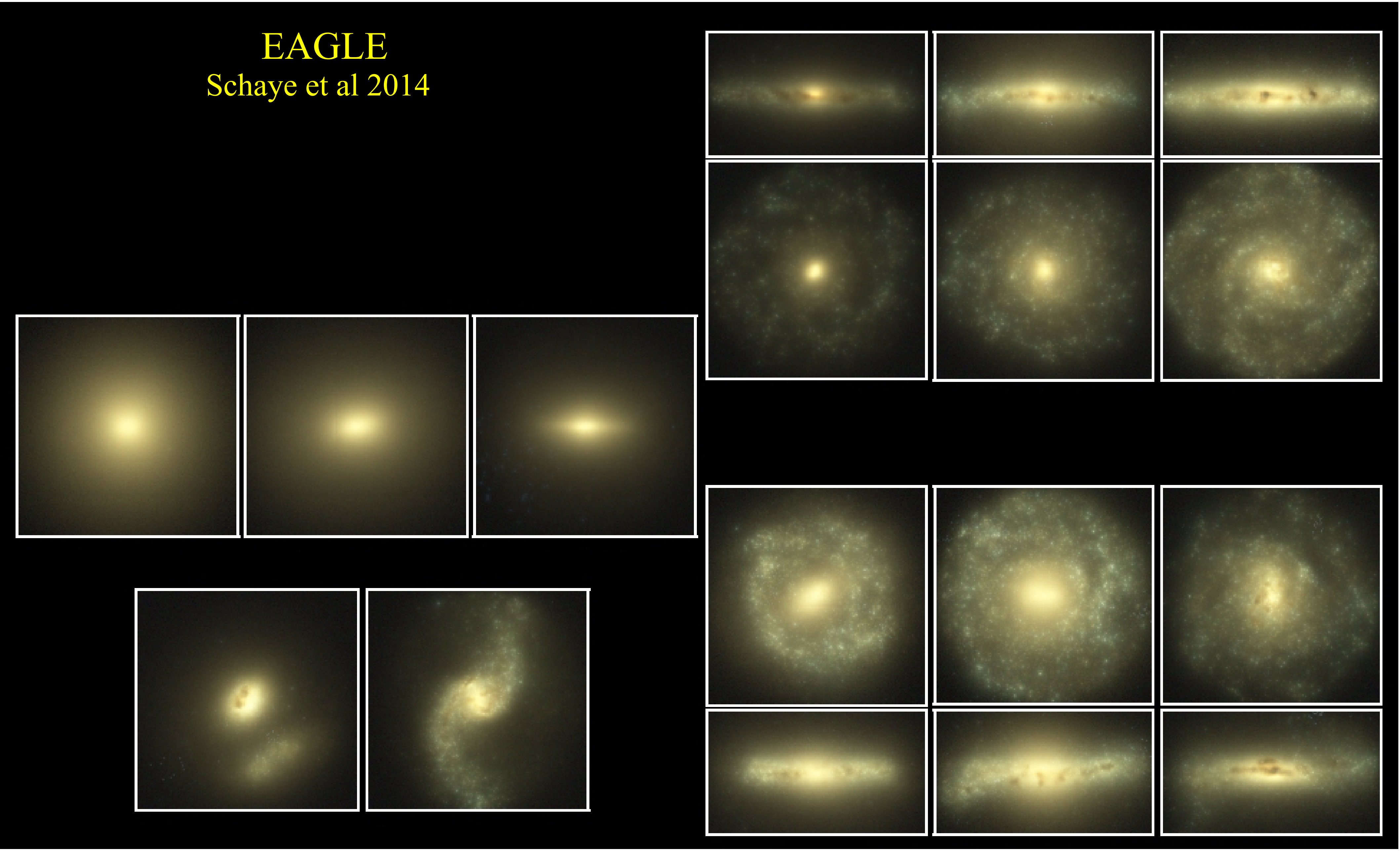


Plausible (but high) feedback efficiencies also result in disc galaxy formation

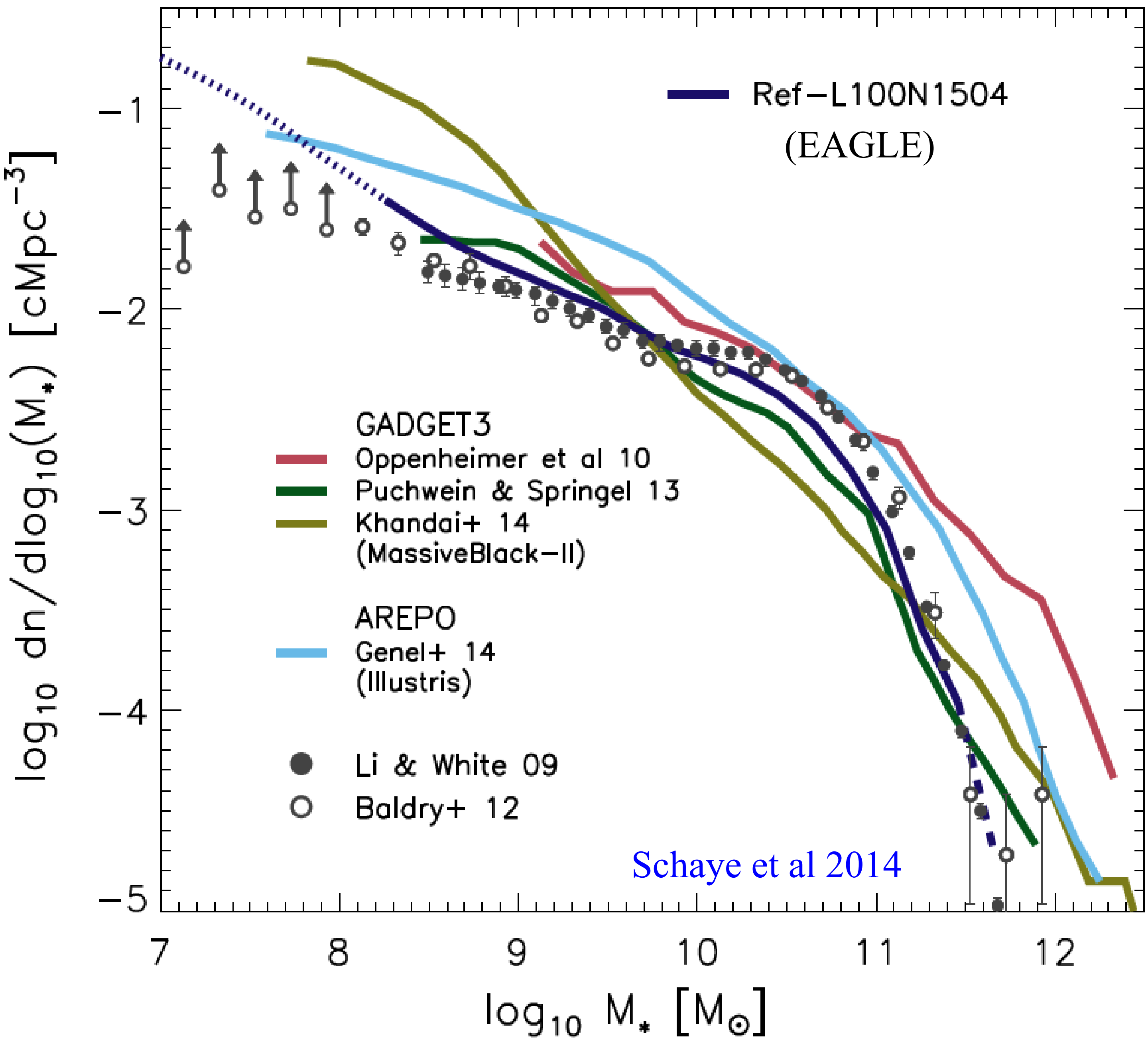


Plausible efficiencies also result in disc galaxy formation with dominant discs and photometric profiles similar to observation


a
ellipticals
disk galaxies
irregular
Illustris
Vogelsberger et al 2014



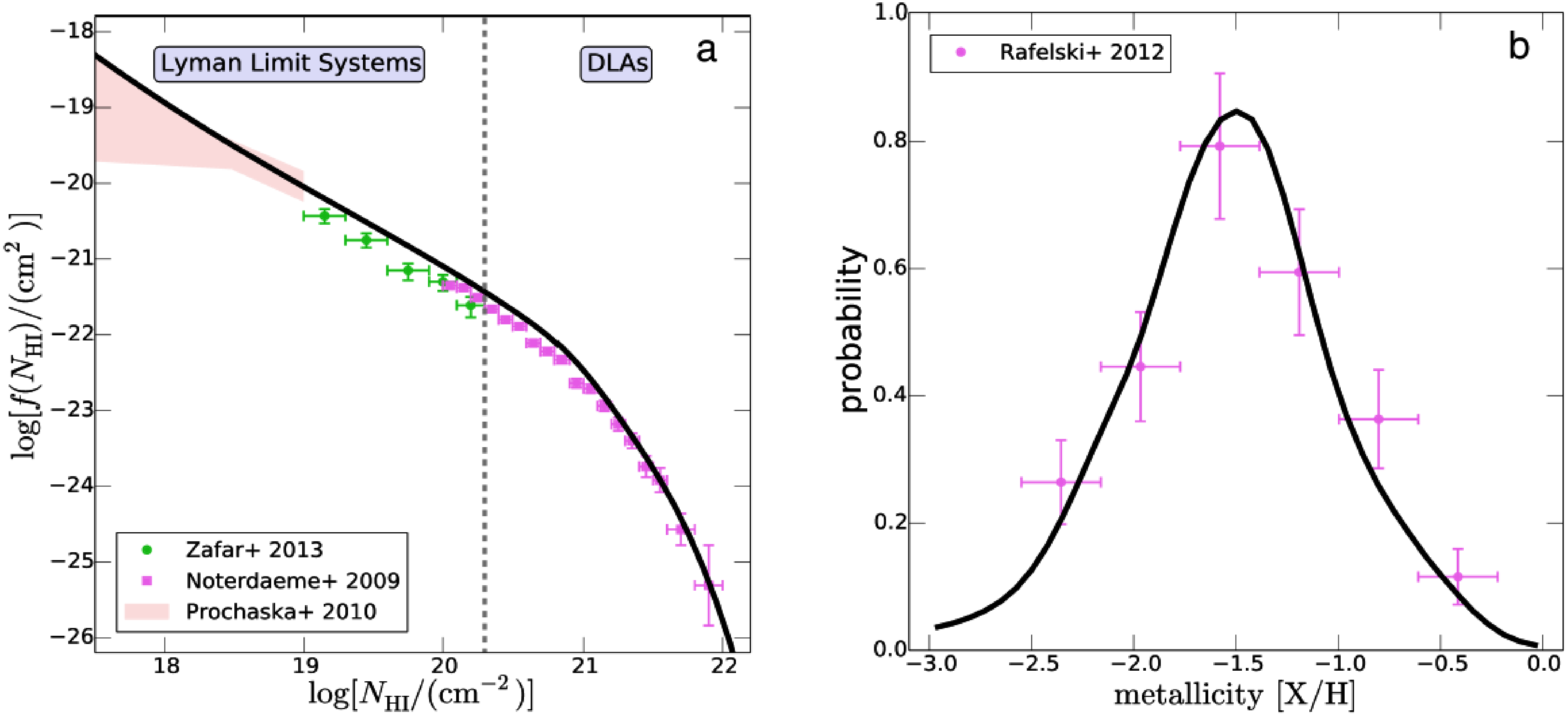
Individual galaxies in the largest of the EAGLE simulations



Stellar mass functions from recent large cosmological hydrodynamics simulations. (Note – in most cases feedback is <u>tuned</u> to fit observation)

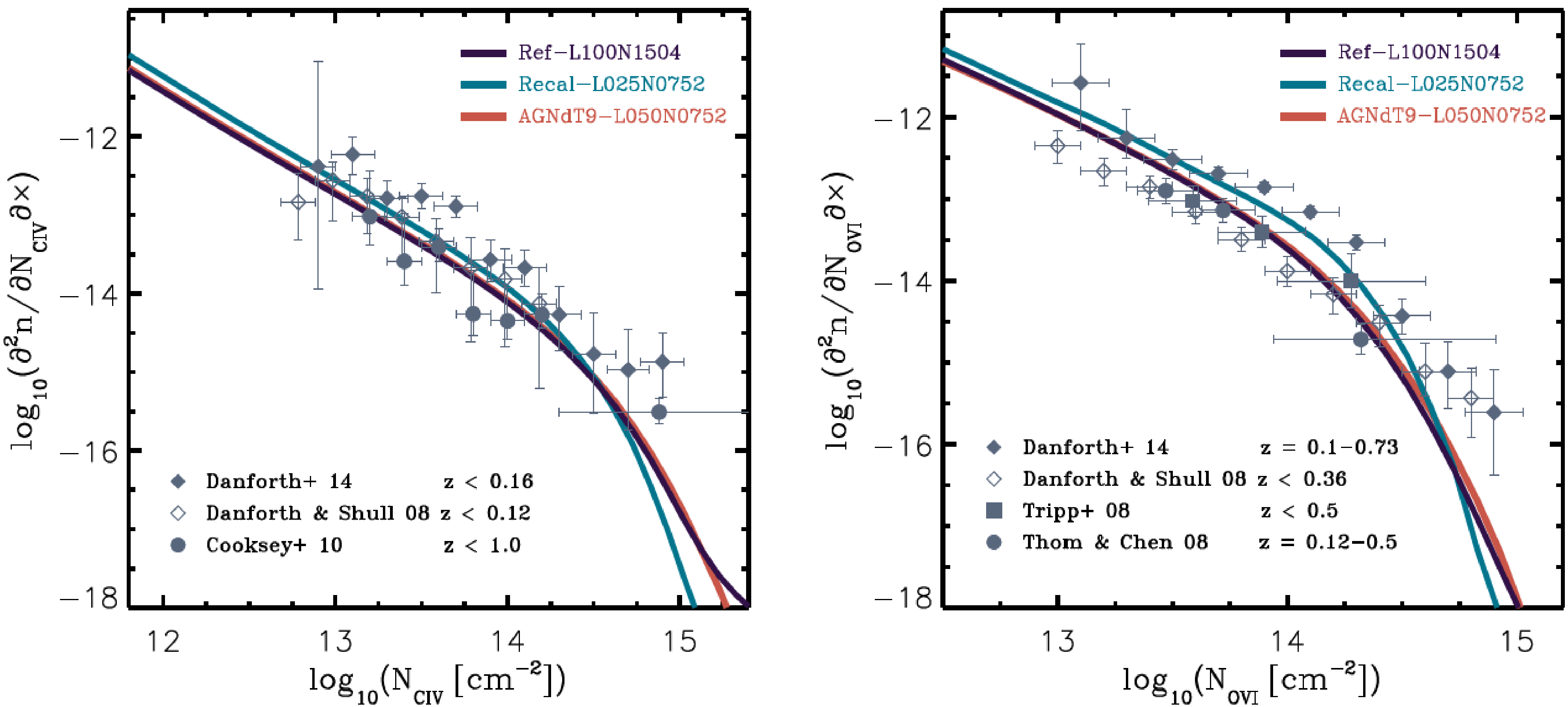
Abundance and metallicity of Lyα absorbers

Illustris: Vogelsberger et al 2014



Abundance of CGM metal lines

EAGLE: Schaye et al 2014



What about our Milky Way?

In the Milky Way: $M_* = 6 \pm 1 \times 10^{10} M_\odot$, $M_b = 9 \pm 1 \times 10^{9} M_\odot$ Licquia & Newman 2014

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Many estimates of the MW's halo mass give much lower values:

-- Escape velocity estimate from local HV stars: $16 \pm 4 \times 10^{11} M_\odot$ Piffl+ 2014

-- Distant stellar tracers: 5 to $10 \times 10^{11} M_\odot$ Deason+ 2014

-- Distant satellite dynamics (incl. Leo I): 12 to $17 \times 10^{11} M_\odot$ Watkins+ 2014

-- Sagittarius stream: : $\sim 6 \times 10^{11} M_\odot$ Gibbons+ 2014

-- "Too big to fail" : ~ 10 or $\sim 8 \times 10^{11} M_\odot$ Wang+ 2012, Vera-Ciro+ 2013

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Simulated central galaxies with the MW's M_*, M_b and SFR ~ $1.0\ M_\odot$/yr have median $M_{halo} = 14 \times 10^{11} M_\odot$, 90% range 8 to $26 \times 10^{11} M_\odot$ Guo+ 2011

Issues from mass ratios

DM vs stars in the galaxy cores

IMF variations with metallicity, velocity dispersion,...?

Cores vs cusps – the nature of DM or star formation dynamics?

Origin of the *diversity* in inner structure?

Gas vs stars

Gas fractions in high redshift galaxies

Molecular to atomic gas ratios (CO $\rightarrow$ H_2, H_2 in Ly α absorbers)

The fate of ejecta

Ratio of Fe, Si.. in galaxies and in the ICM in clusters

Amount of O, N etc in the CGM and the ISM

Detection of dust to large distances around galaxies

Influence of wind cavities on Ly α statistics

Galaxy formation modelling

The concordance cosmological model establishes the gravitational context for galaxy formation in considerable detail

→ The main issue is how does astrophysics structure galaxies

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Stellar and AGN feedback are strong and have major effects, but must be treated using subgrid “recipes” both in SA and hydro simulations

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Further progress cannot come from toy or partial models

Understanding galaxy formation will require simultaneous and improved astrophysical modelling of all relevant processes

Promising areas for improvement

3D modelling of stellar evolution/atmospheres

new asteroseismology/astrometry data (Gaia, Corot, Kepler)

→ new population synthesis models, IMF/SFH diagnostics

More sophisticated kinematic/dynamic modelling of galaxy cores

Detailed modelling of the launching of winds

ISM on the scale of HII regions superbubbles, SN remnants

quasar and radio AGN environments

Measuring the content and structure of gas in high-redshift galaxies

Following the evolution and structuring of the CGM

Interactions between inflowing and outflowing material

Measuring and characterising environmental effects

Are extrahalo effects important?