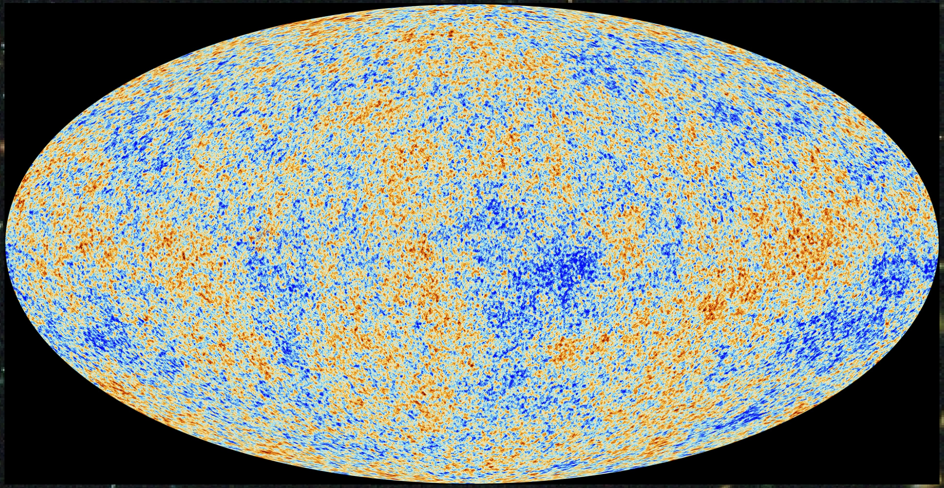
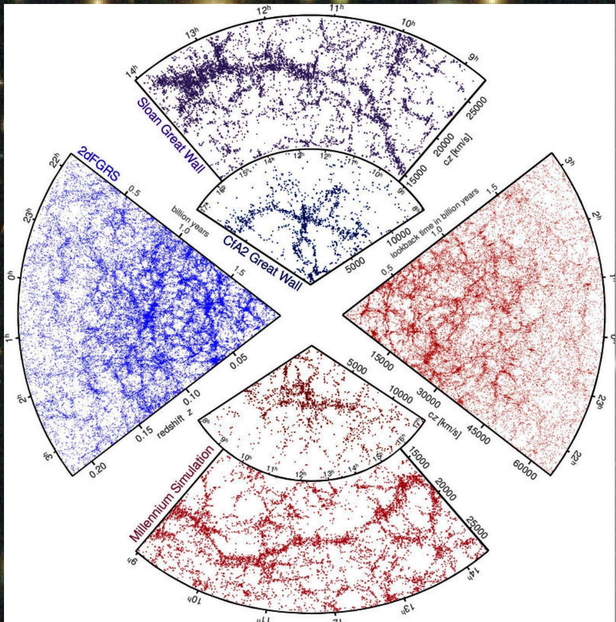


L-Galaxies workshop
MPA, February 2016

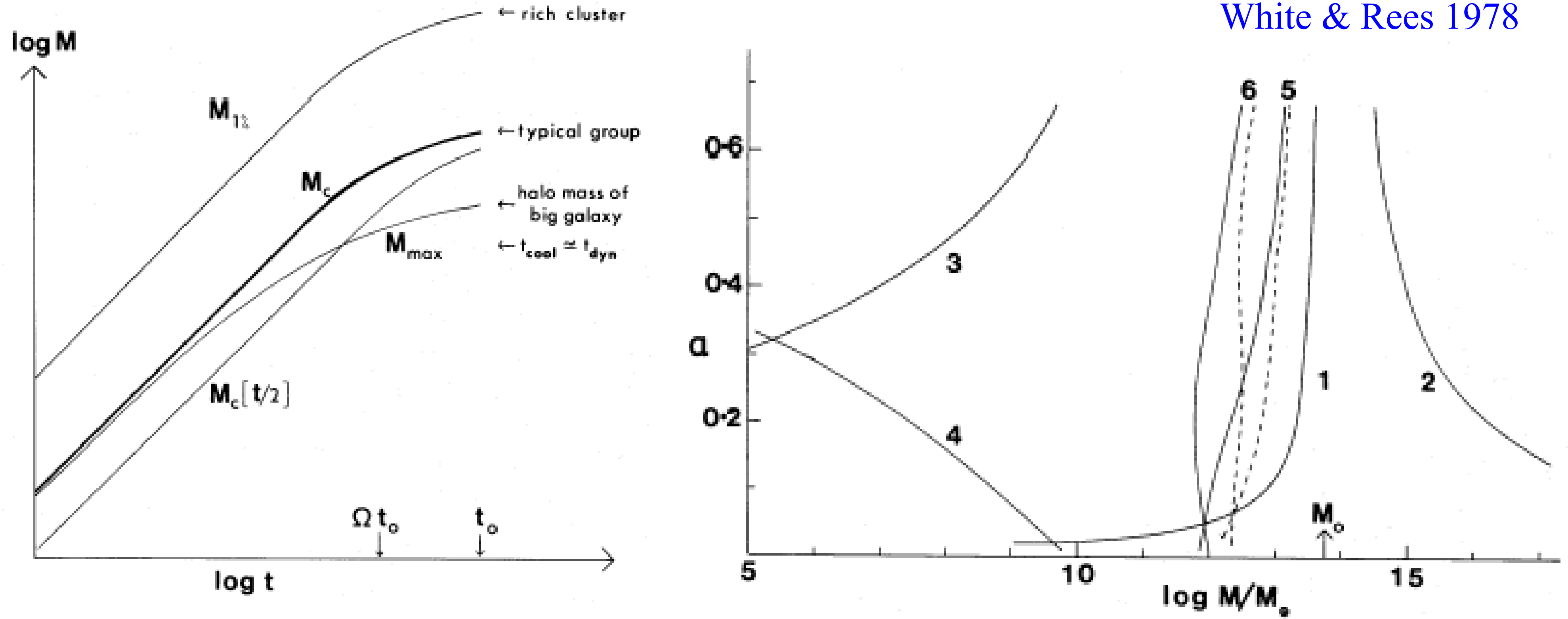
The Munich galaxy formation model: origins and raison d'être

Simon White
Max Planck Institute for Astrophysics



The beginnings

White & Rees 1978



"Galaxies form by the cooling and condensation of gas at the centres of a hierarchically aggregating population of dark matter halos"

This extended previous work by form by adding :

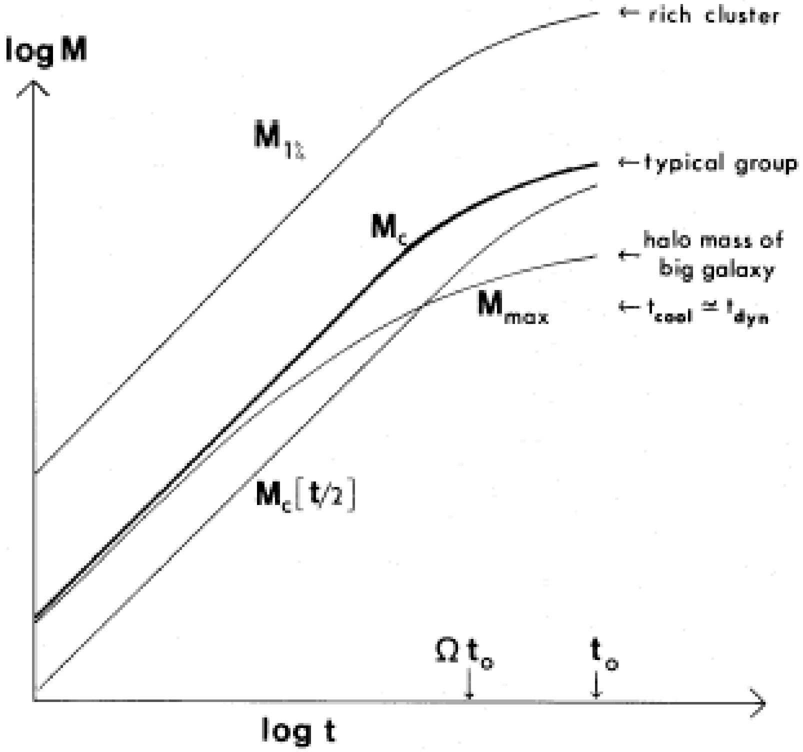
(i) dynamically dominant pre-existing dark matter,

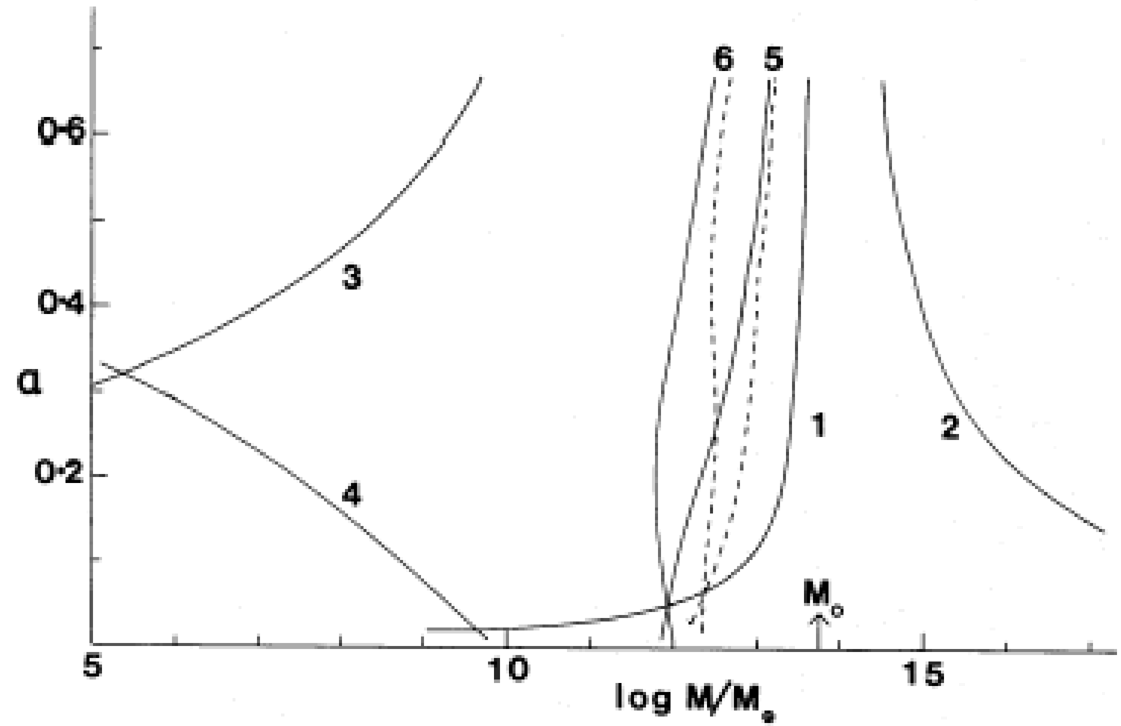
(ii) hierarchical growth of clustering,

(iii) supernova feedback to limit star formation

The beginnings

White & Rees 1978

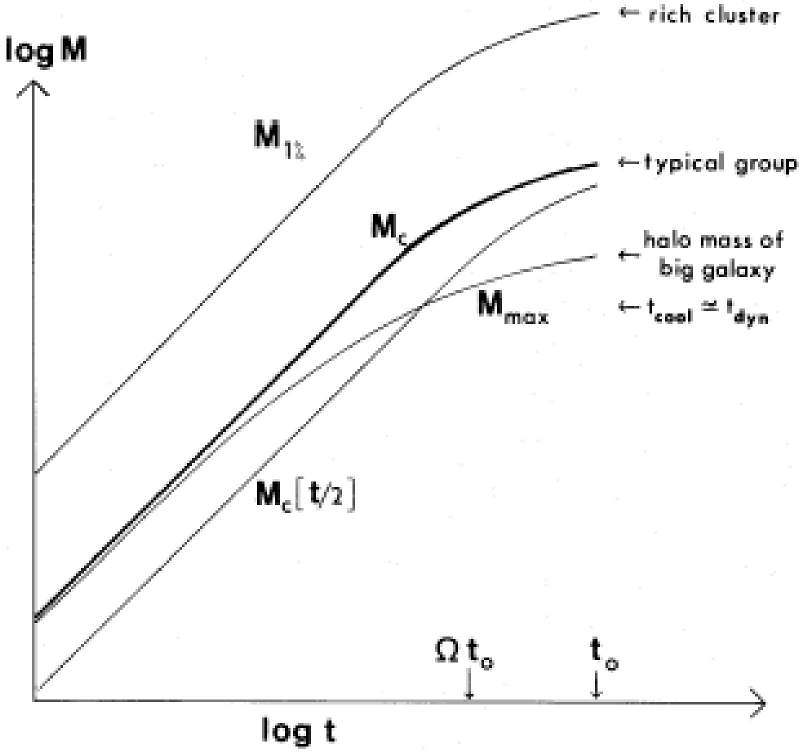




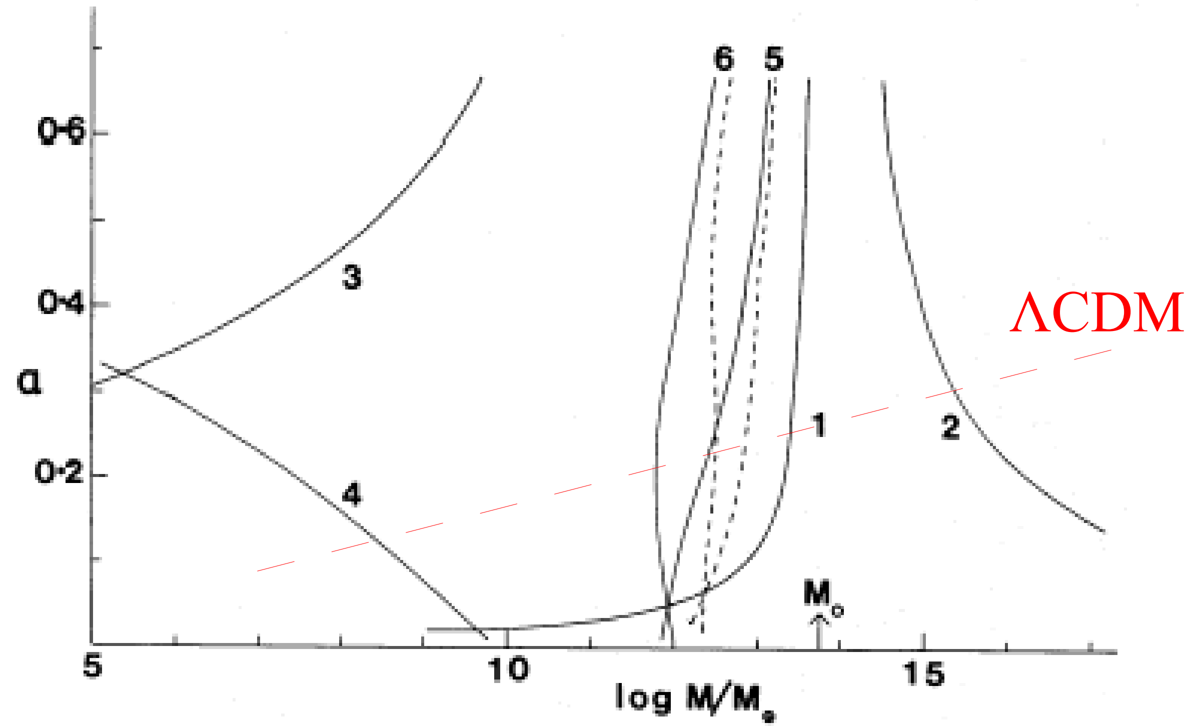
– random-phase initial conditions with a scale-free power spectrum
– evolving halo mass distribution: $\Phi_{PS}(M_h , z)$
– uniform spherical halos at the virial density ~200 $\rho_{crit}(z)$
– star formation occurs when the baryonic cooling time $t_{cool} < t_{hubble}(z)$
– star formation efficiency regulated by SN feedback
– no galaxy merging, no tracking of assembly histories

A good model had: $\Omega_m = 0.20$, $\Omega_{gas} / \Omega_{DM} = 0.20$, $\alpha = 1/3$ $(n = -1)$

The beginnings



White & Rees 1978



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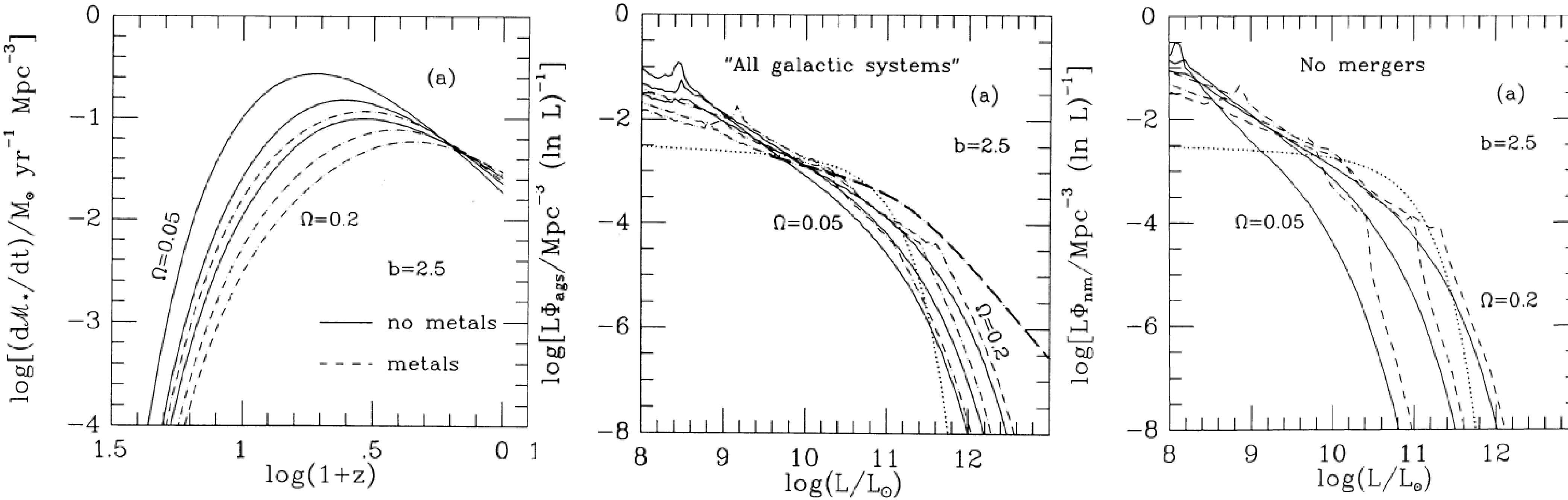
First CDM models

White & Frenk 1991

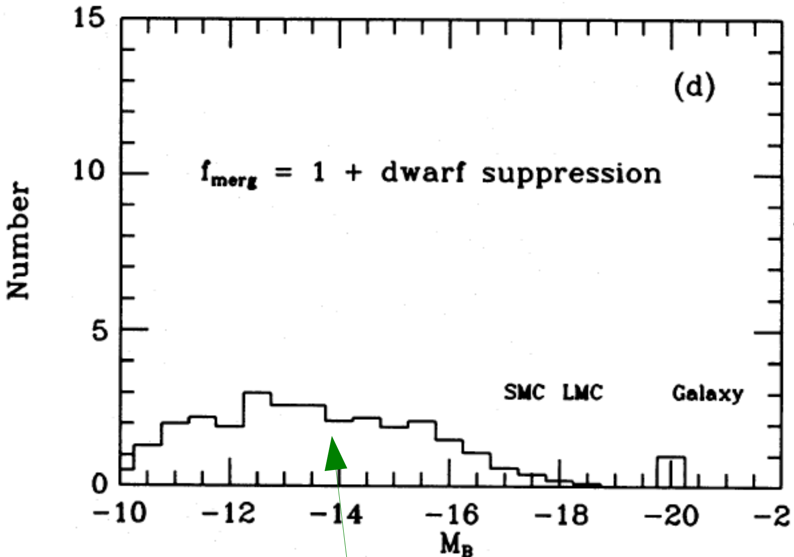


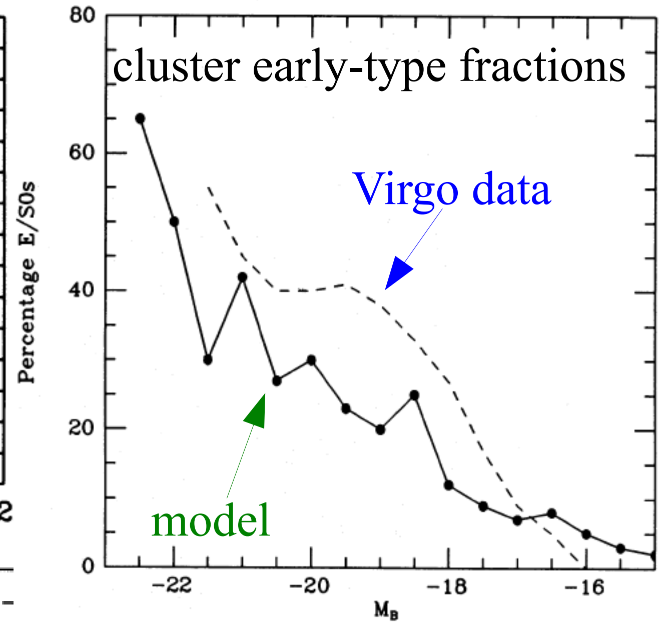
Updates to WR78 include:

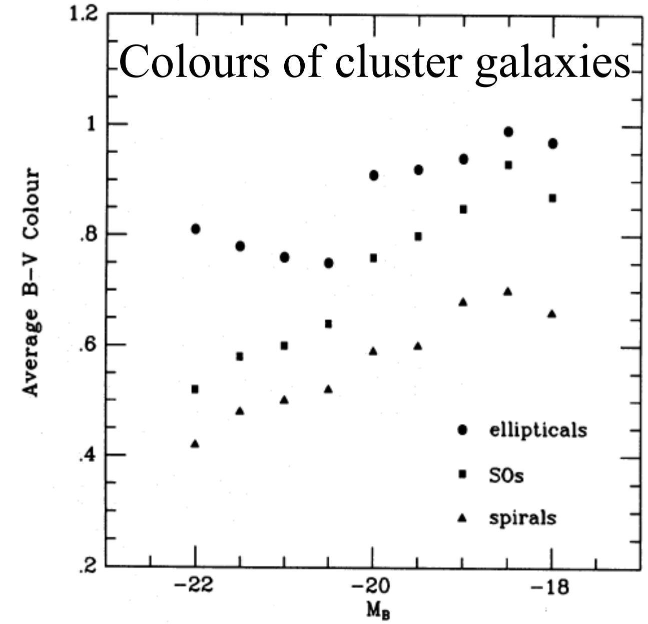
– CDM initial power spectrum, EdS cosmology
– conditional MF, $\Phi_{PS}(M_{h,0}, z_0 \mid M_{h,1}, z_1)$ used to track stars statistically
– infall and cooling flow models with a SIS halo
– self-regulating star formation (now called the “bathtub model”)
– chemical evolution modelling

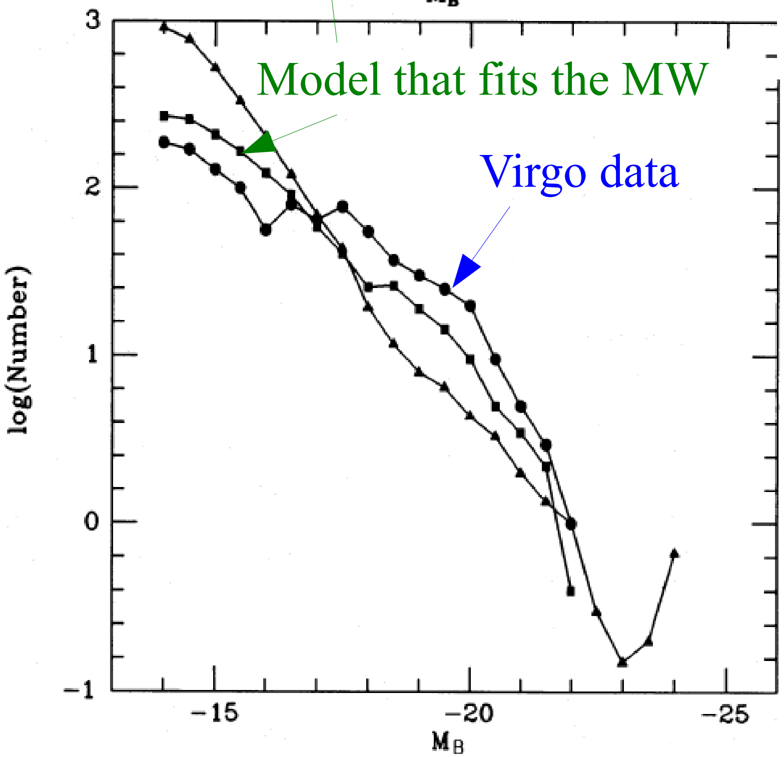
First use of merger trees

Kauffmann, White & Guiderdoni 1993









– PS-based algorithm for realistic merger trees
→ individual galaxy assembly histories

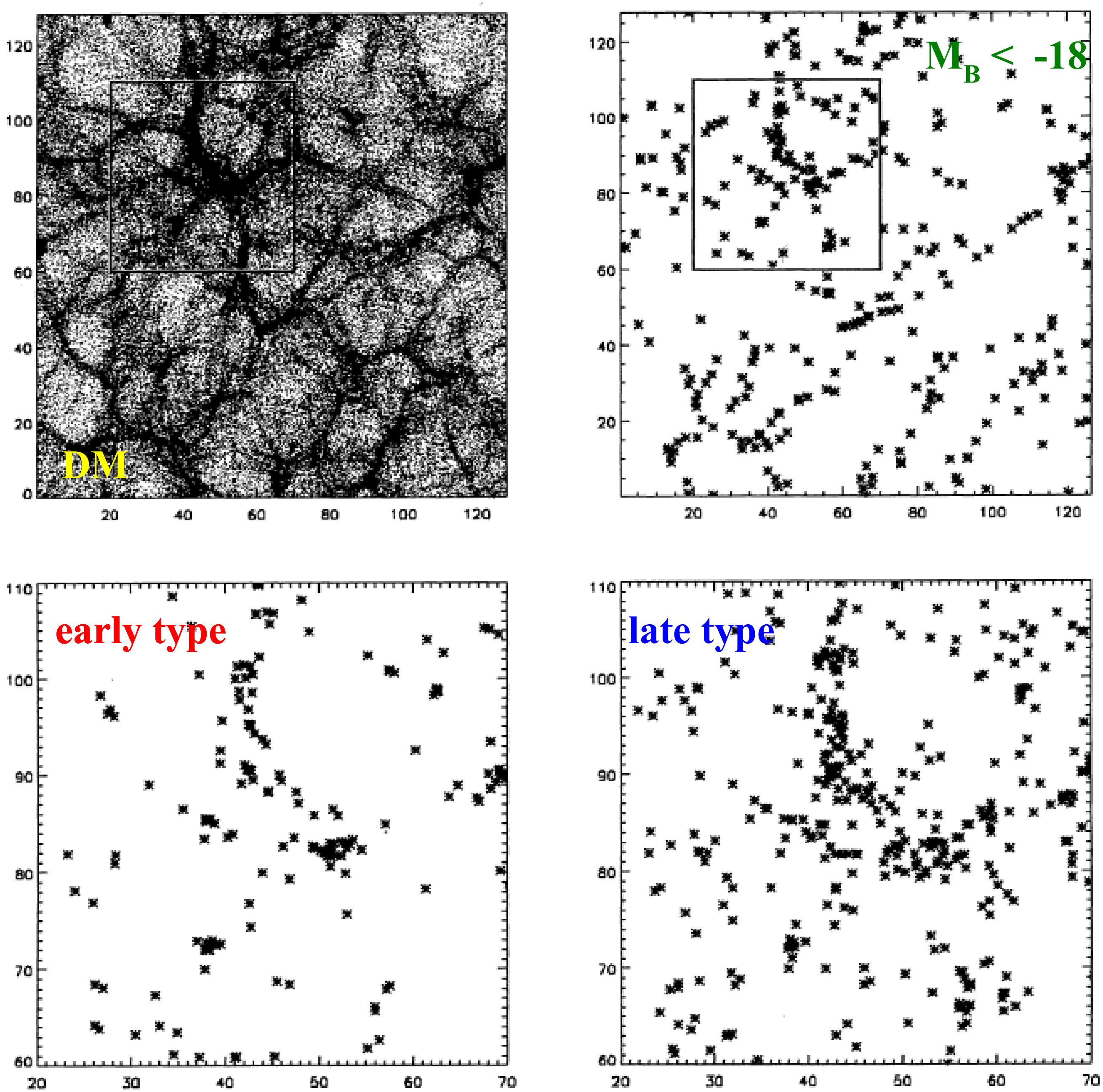
– galaxy populations within individual halos

– merger and star formation histories
→ colours and morphologies of galaxies

The first “modern” **semi-analytic** model

SA models in N-body halos

Kauffmann, Nusser & Steinmetz 1996



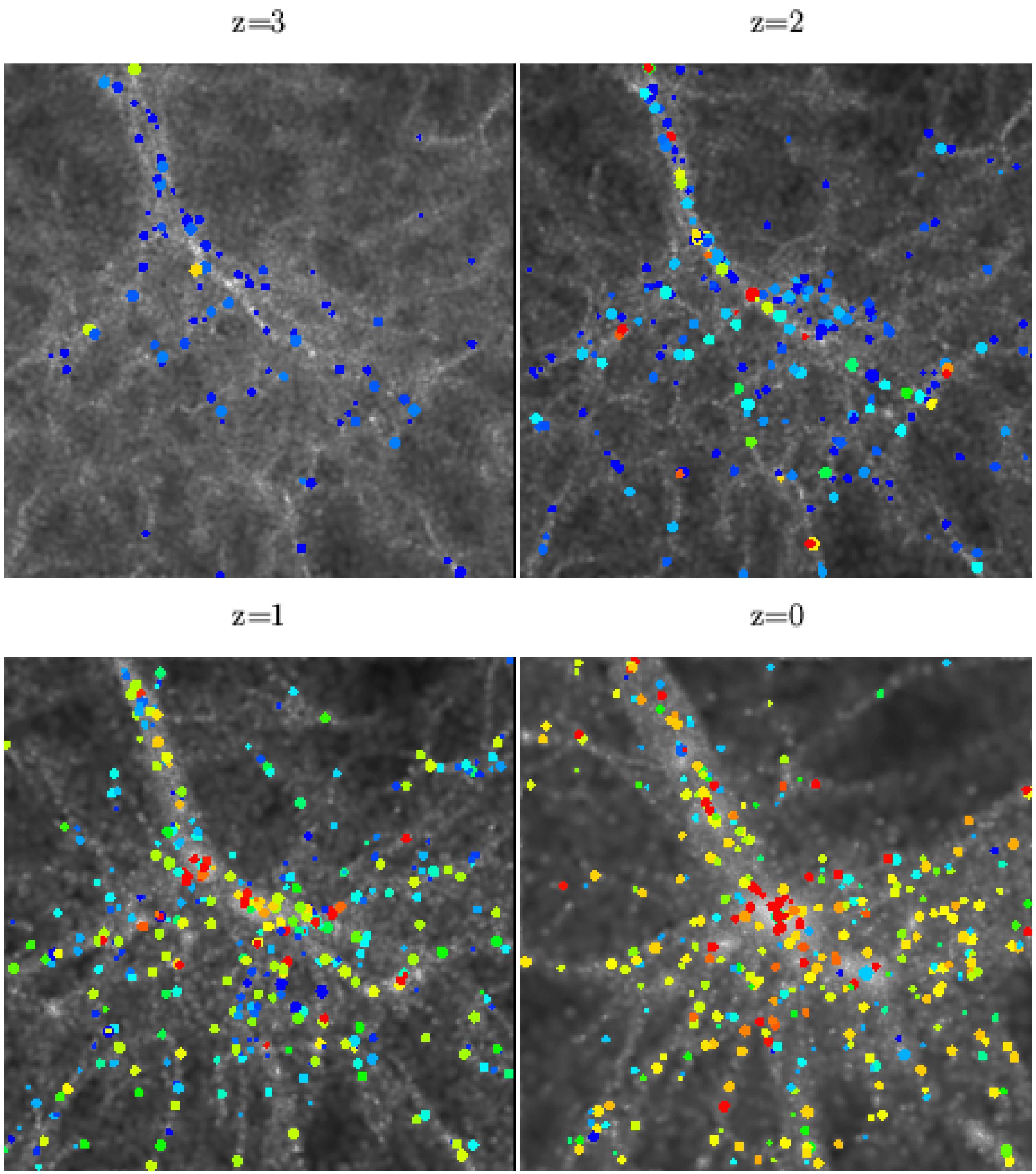
– assign each simulated halo the galaxies from a PS tree
    - correlation functions
    - morphology vs density
    - void probabilities

– First use of an HOD to model galaxies in an N-body simulation

– Later HOD modelling took out the galaxy formation physics to gain simplicity and flexibility

Semi-analytic simulations

Kauffmann, Colberg, Diaferio & White 1999



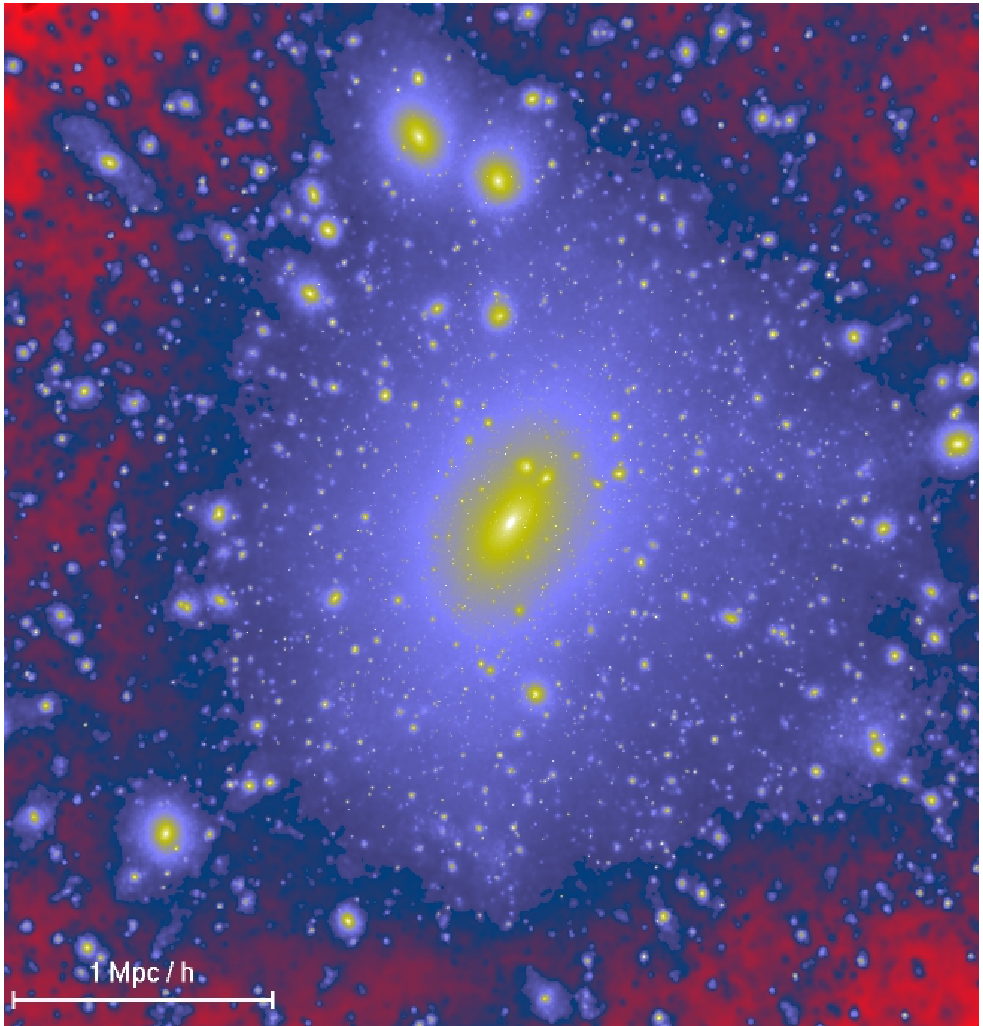
- Replace PS trees by *halo* merger trees built directly from an N-body simulation
- central halo particles represent central galaxies and trace satellite galaxies after halo nergers
  - the formation of the galaxy population is tracked directly
  - large-scale progenitors structure can be studied, e.g .protoclusters
  - “assembly bias” effects auto-matically included

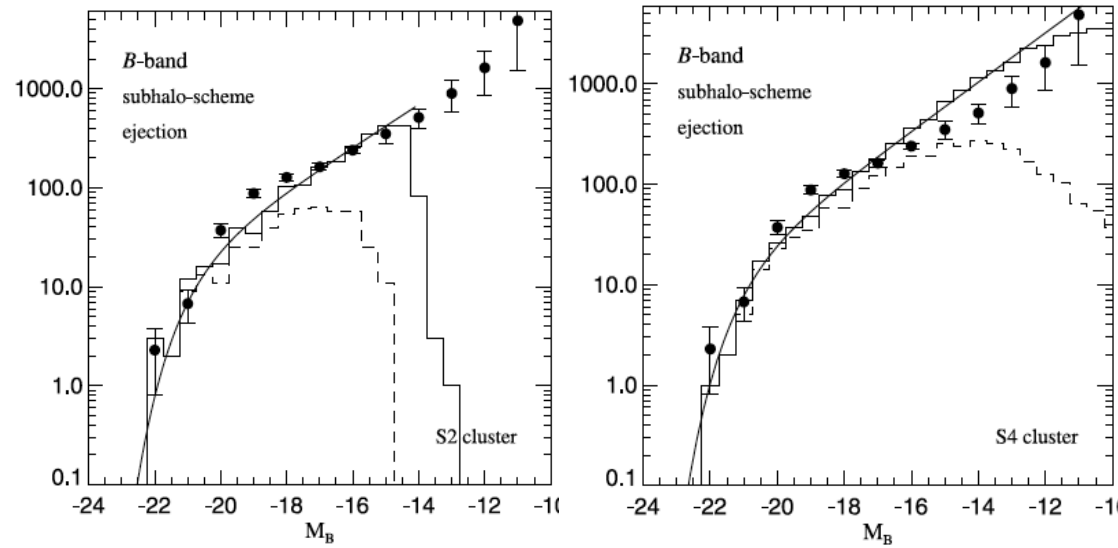
A **simulation** of galaxy formation

High-resolution SA simulations

Springel, White, Tormen & Kauffmann 2001

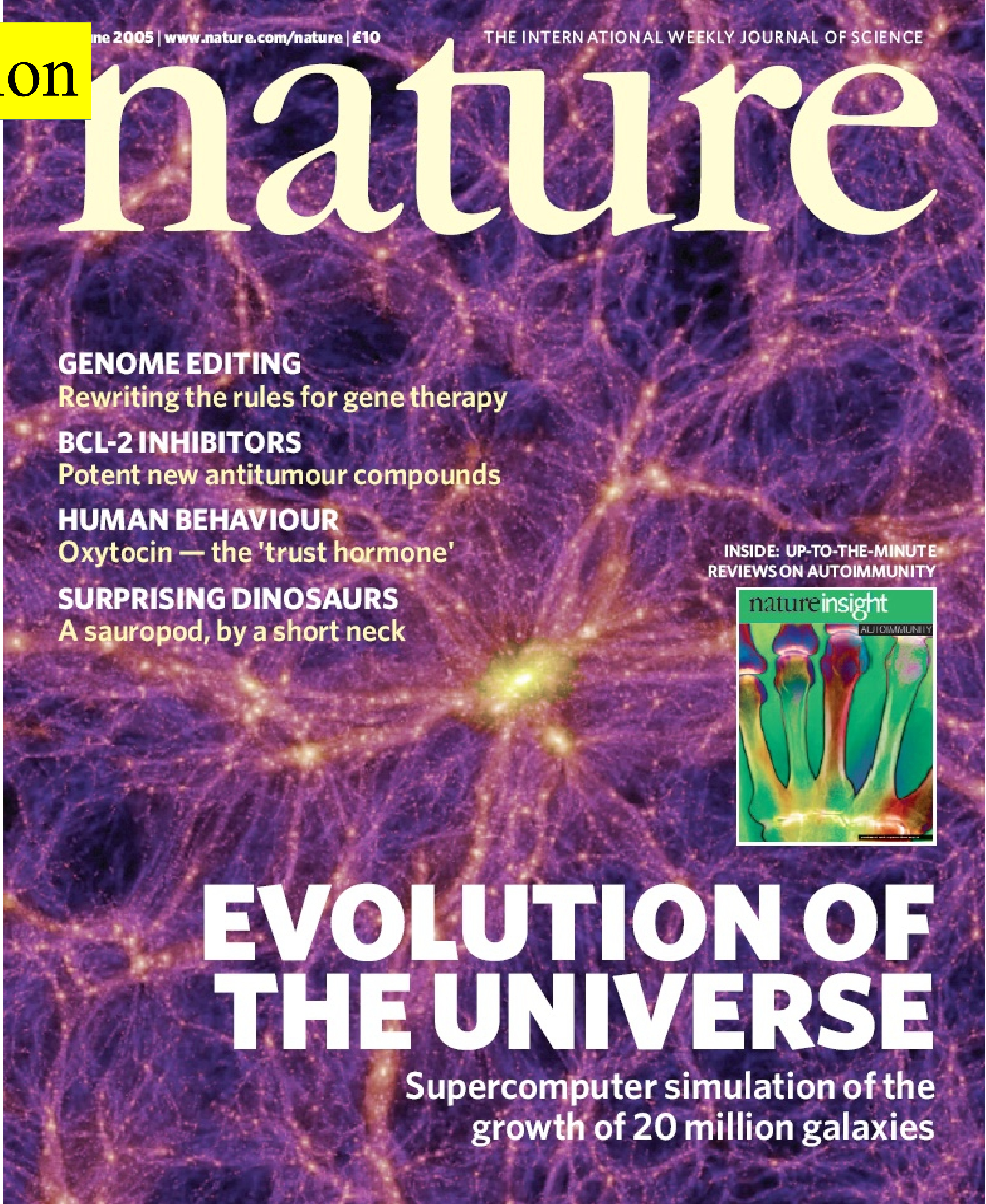
First version of L-Galaxies!





- high-resolution simulations + subhalo identifier → *subhalo* merger trees
  - halos of *some* satellite galaxies can be followed explicitly
  - tidal stripping and dynamical friction are simulated consistently
- resolution tests needed to check consistency of "orphans" and subhalo satellites

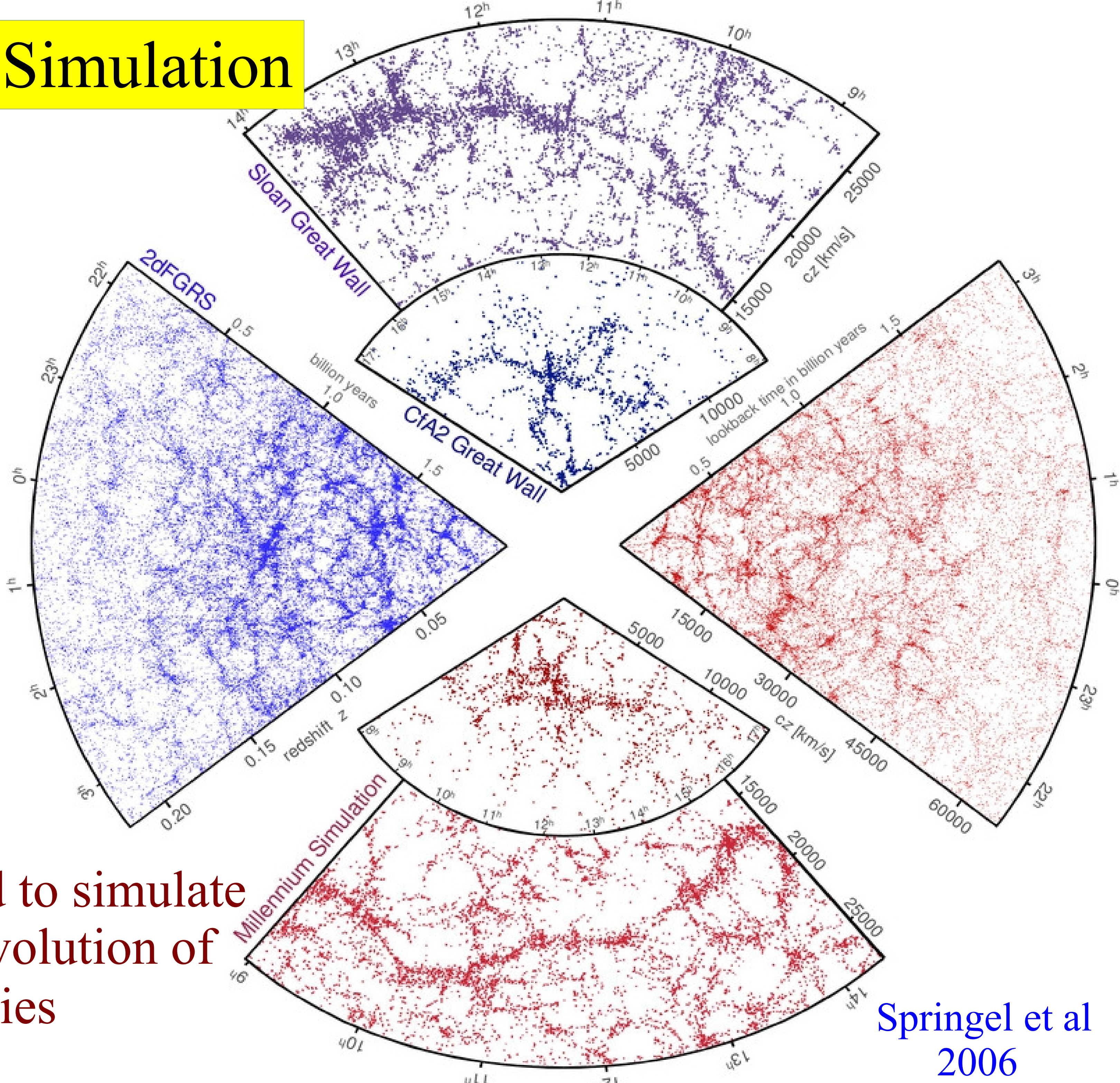
Millennium Simulation



The most highly cited astrophysics article ever published in Nature

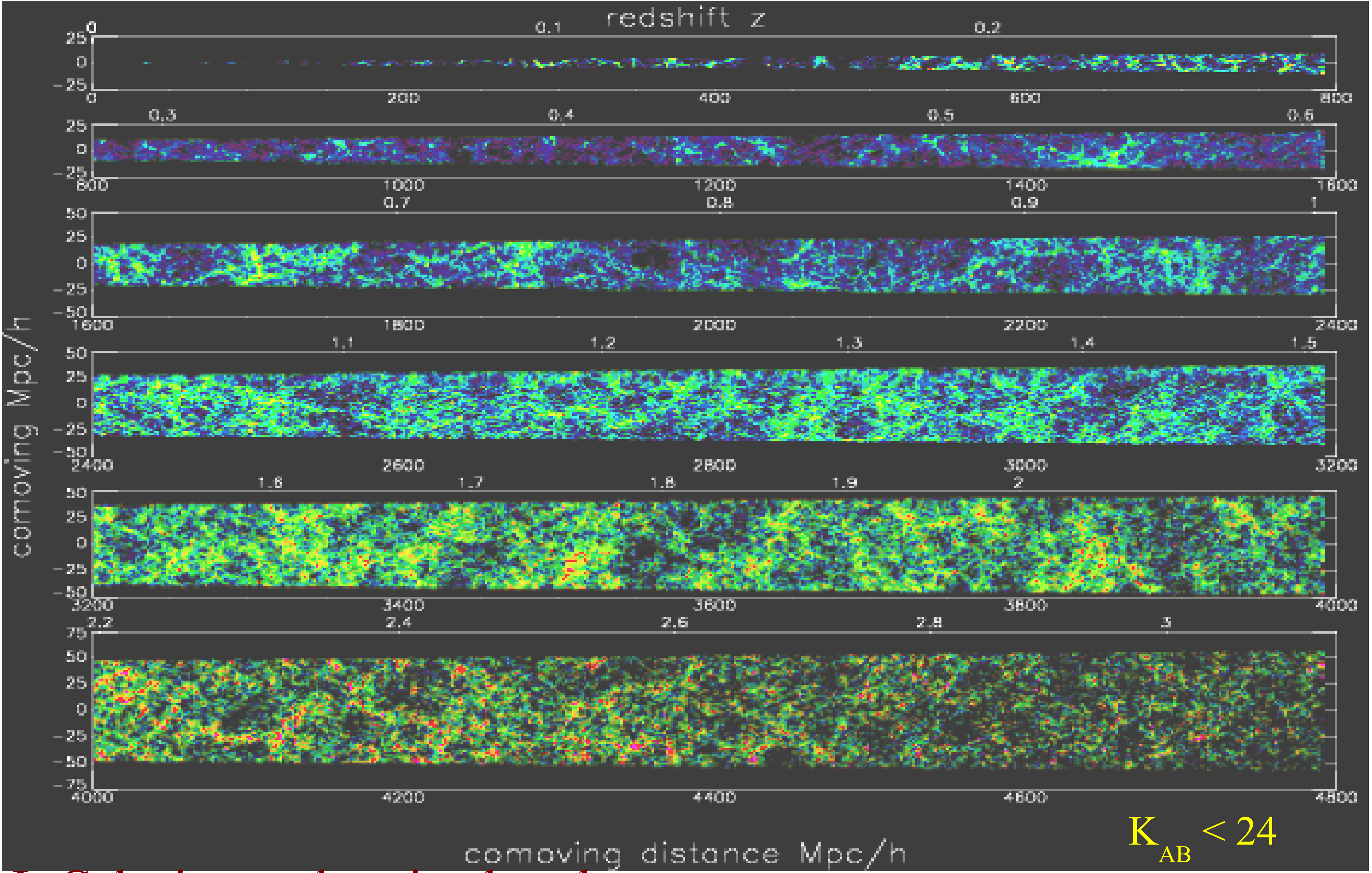
Springel et al
2005

Millennium Simulation



L-Galaxies used to simulate the formation/evolution of $\sim 2\times 10^{7}$ galaxies

Springel et al 2006

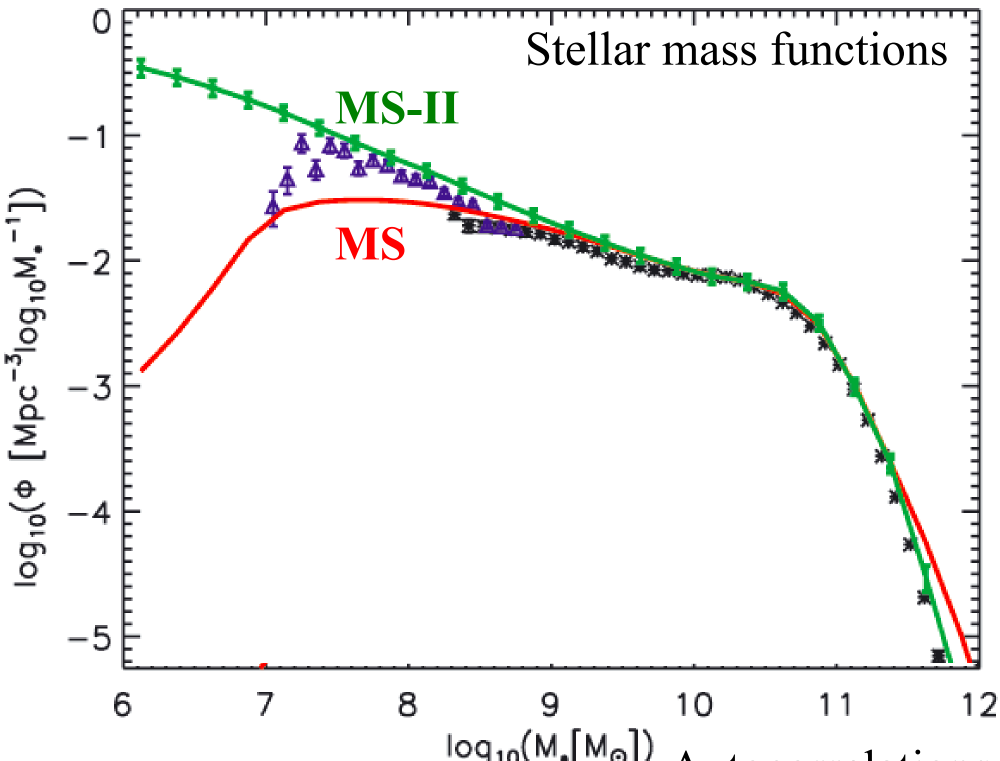


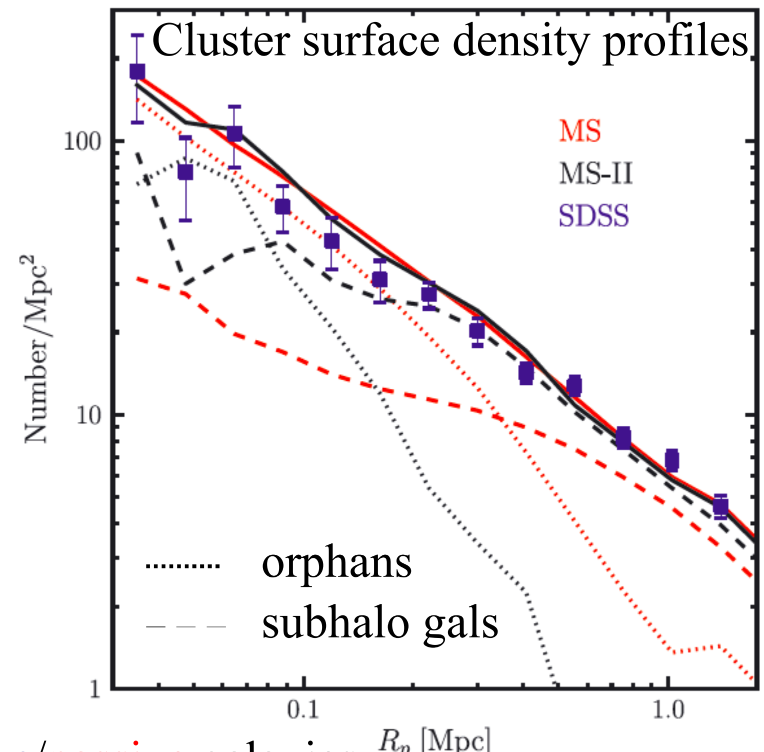
L-Galaxies used to simulate the formation/evolution of ~2x10[7] galaxies from z = 10 to z = 0

Kitzbichler & White
2007

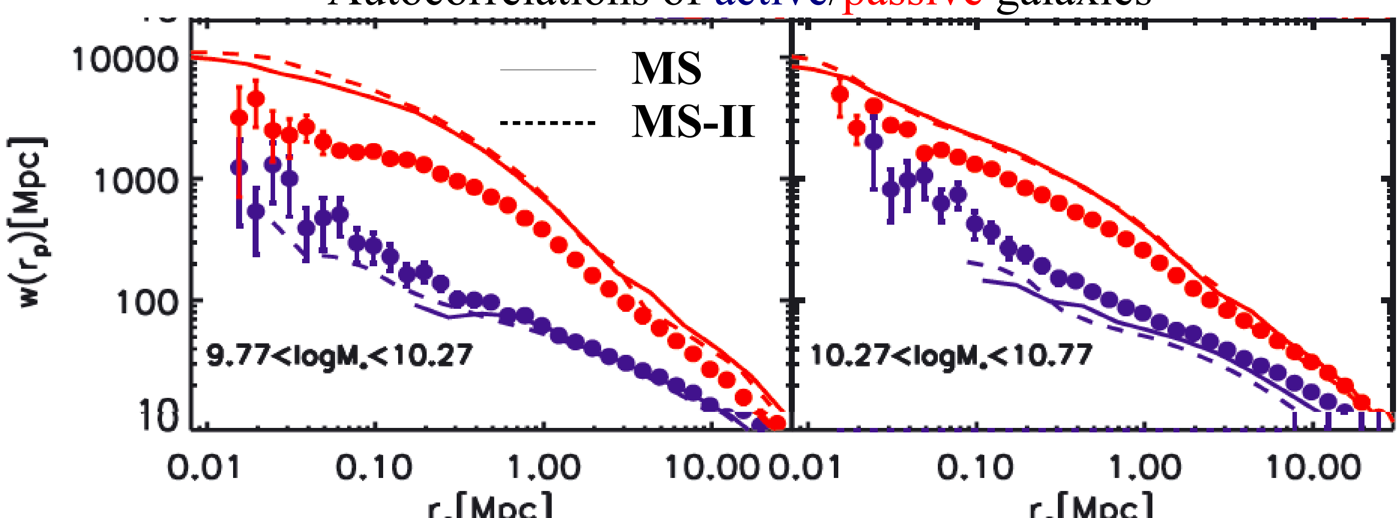
The Millennium-II: providing convergence tests

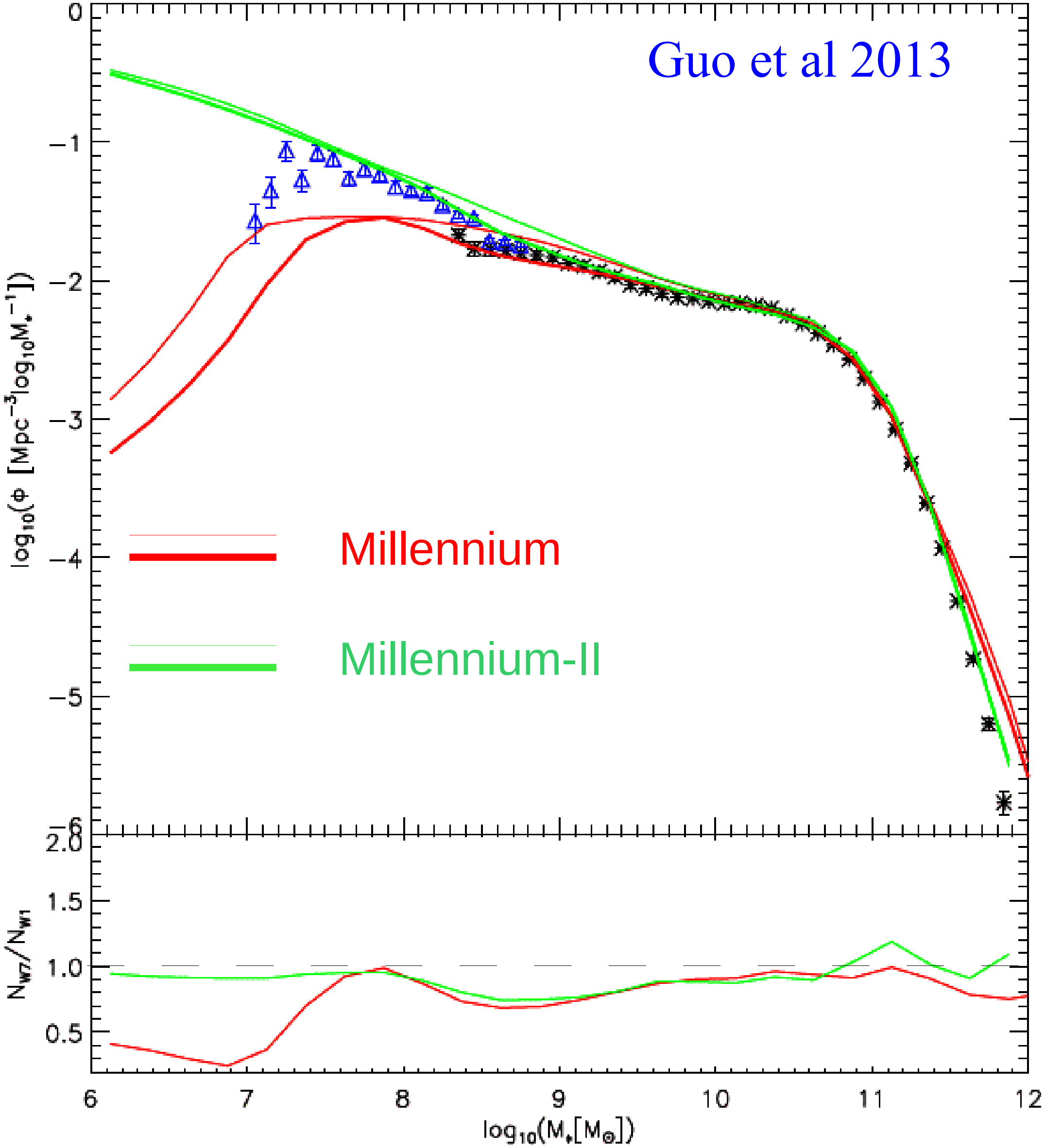
Guo et al 2011





Autocorrelations of active/passive galaxies





Switching from WMAP1 to WMAP7

Suitable scaling of L, M and t allows the cosmology of the MS and MS-II to be reinterpreted

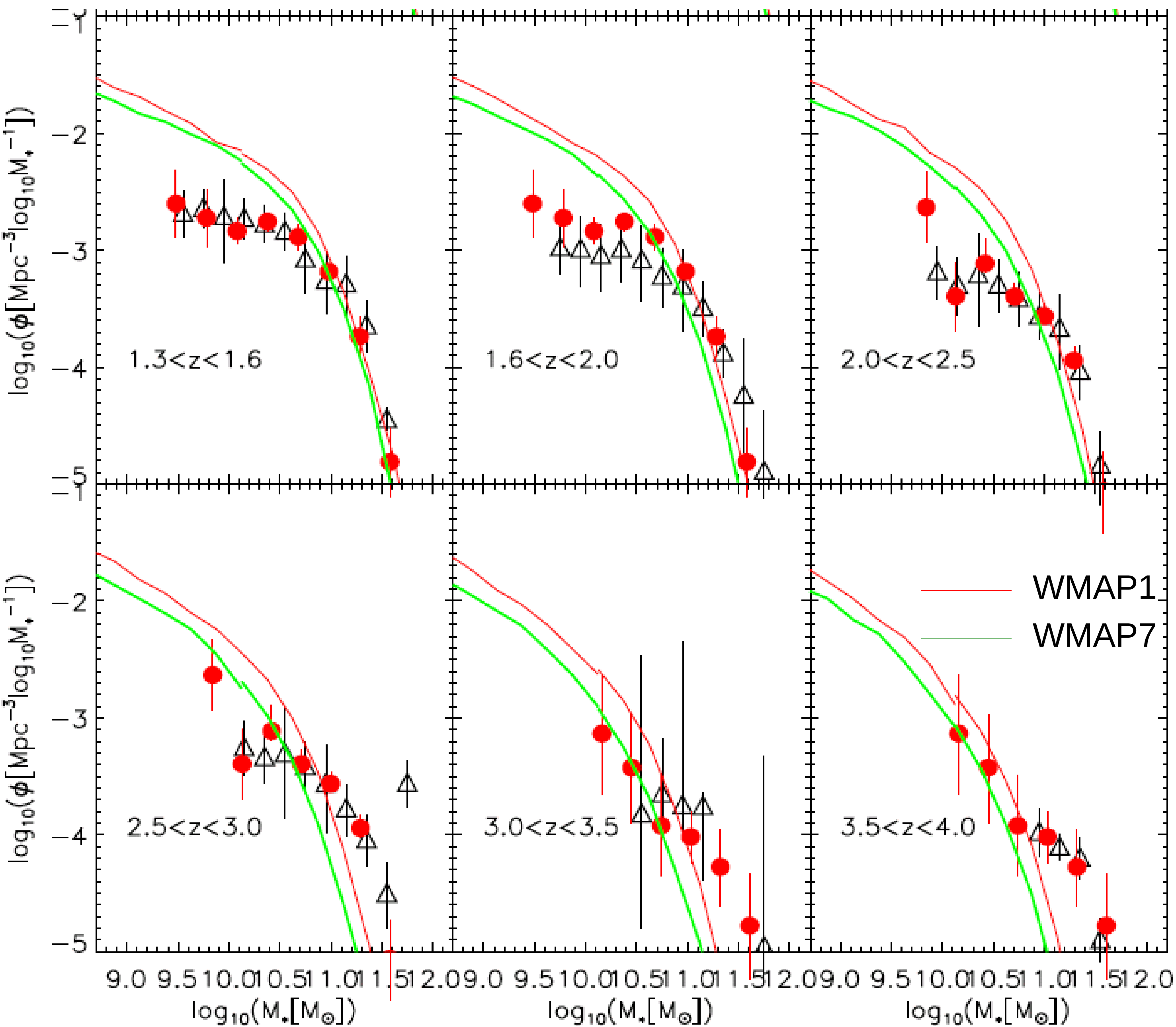
Small shifts in the parameters of the galaxy formation model allow the galactic stellar mass function to be fit equally well in the two different cosmologies despite

$\sigma_8 = 0.90 \longrightarrow \sigma_8 = 0.81$

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

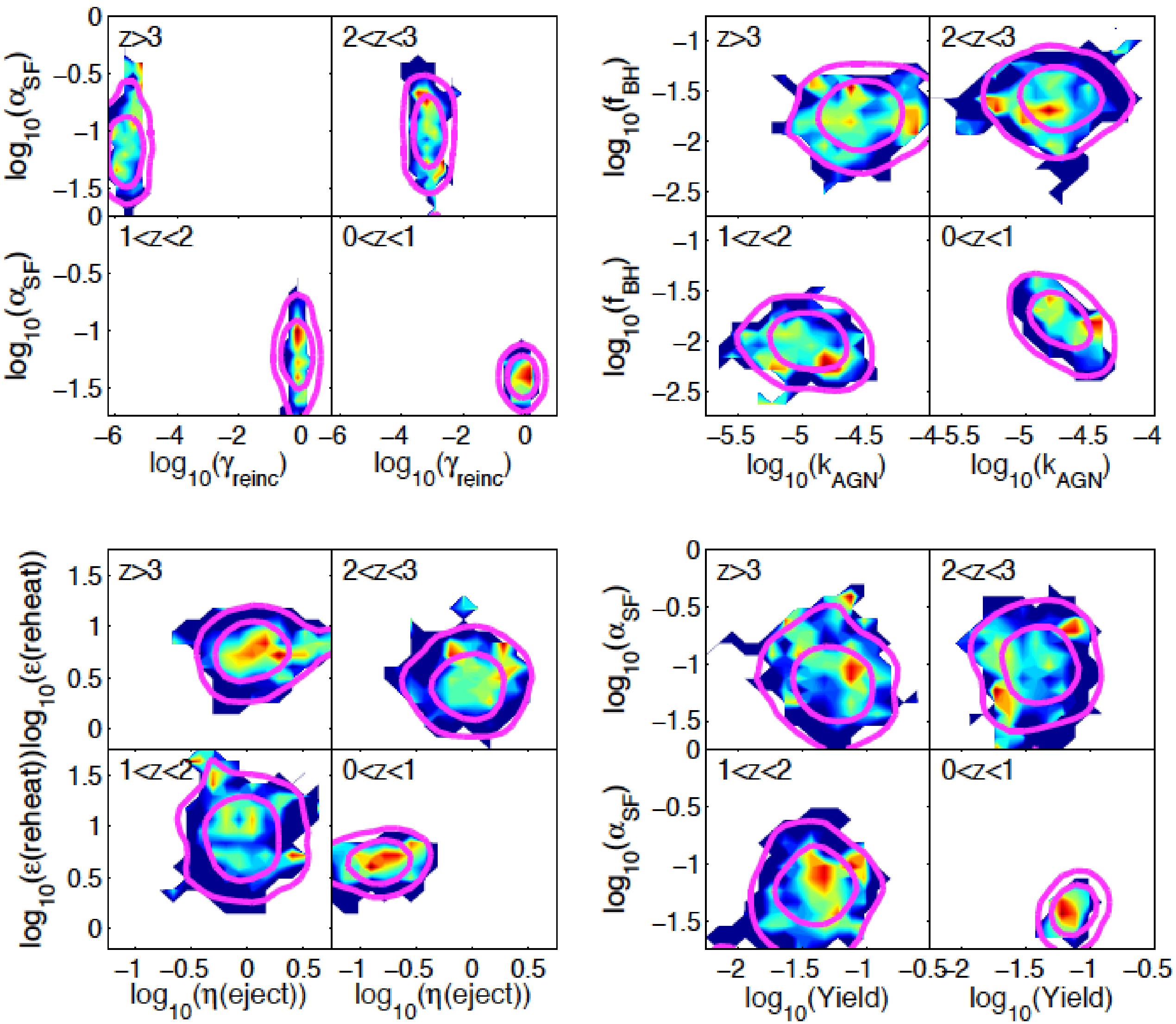
Guo et al 2013



New cosmology does not fix the problem that low-mass galaxies form too early in the Guo11 model

This must be an astrophysical modelling problem

MCMC allows systematic exploration of parameter space



Henriques et al 2013

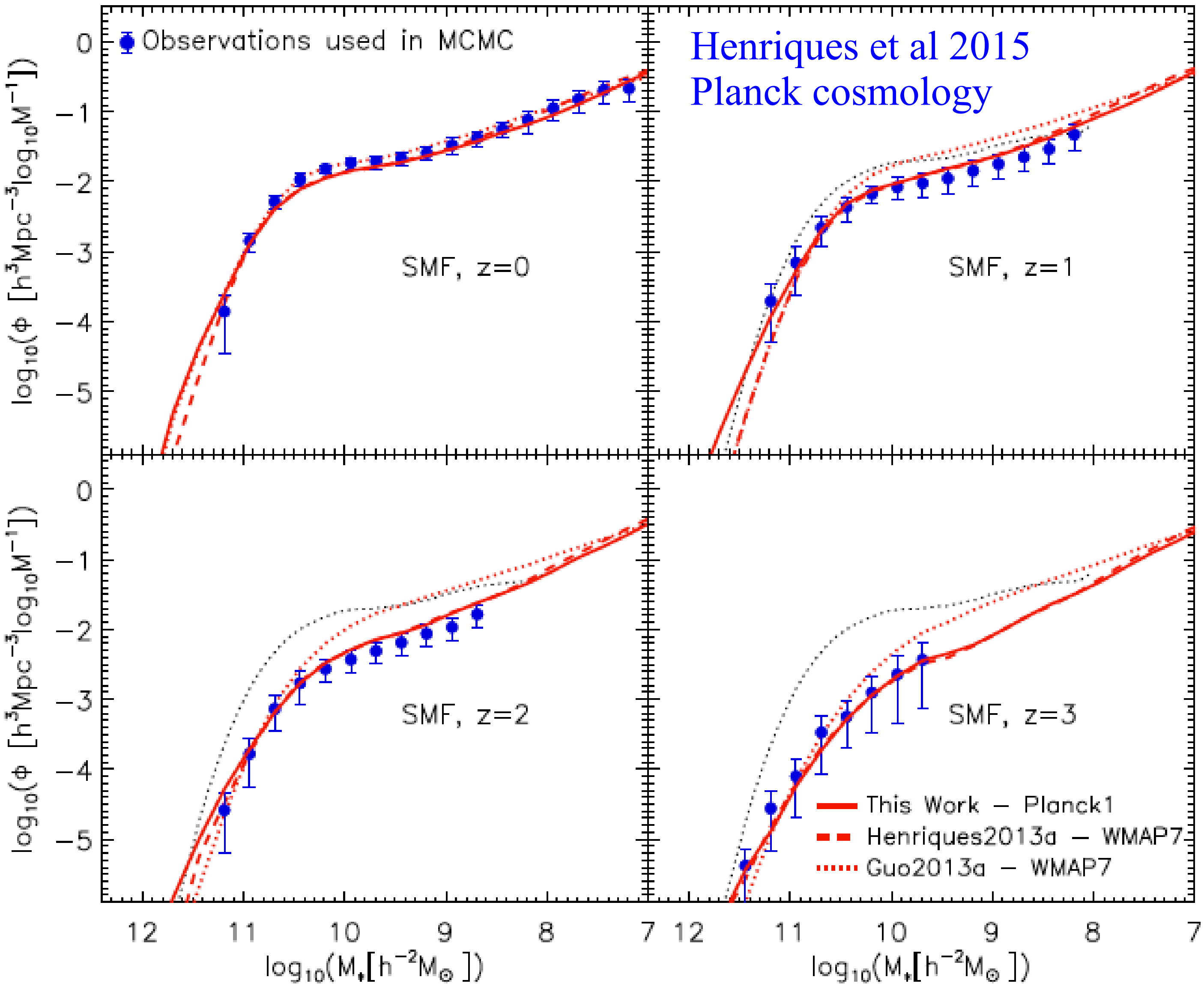
SA model of Guo et al (2011) constrained by observed stellar mass and luminosity functions at z = 0, 1, 2 and 3

Parameters are determined by data at each individual redshift

No parameter set is consistent with data at all redshifts

(At least) one parameter is required to vary with redshift

The underlying **model** must change, not just its parameters



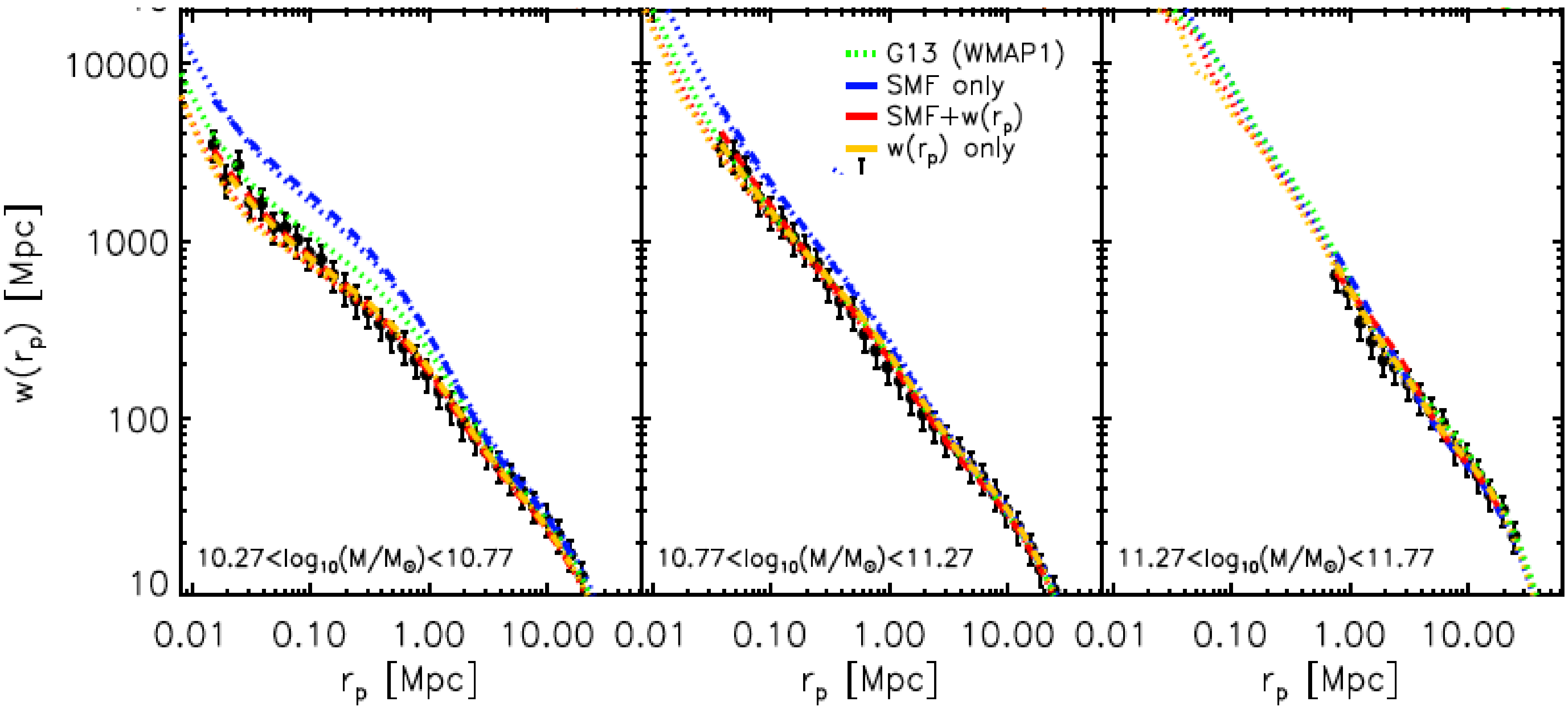
Changing the assumed timescale for reincorporation of wind ejecta

$$t_{return} = \text{const.} / H(z)\, V_{halo} \longrightarrow t_{return} = \text{const.} / M_{halo}$$

allows a good fit to data at all redshifts for the same # of parameters

MCMC can also be used to explore clustering constraints

van Daalen et al 2016



– Special techniques needed to evaluate clustering fast and accurately enough for implementation in an MCMC procedure

– Clustering fits can be improved for only a small penalty in the SMF

– **Only** technique currently able to explore constraints from abundances clustering and evolution simultaneously and systematically

Cl0024

Harsono & De Propris
2007

$z = 0.40$

3.4' x 3.4'

HST/ACS

"Cl0024"

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

$z = 0.41$

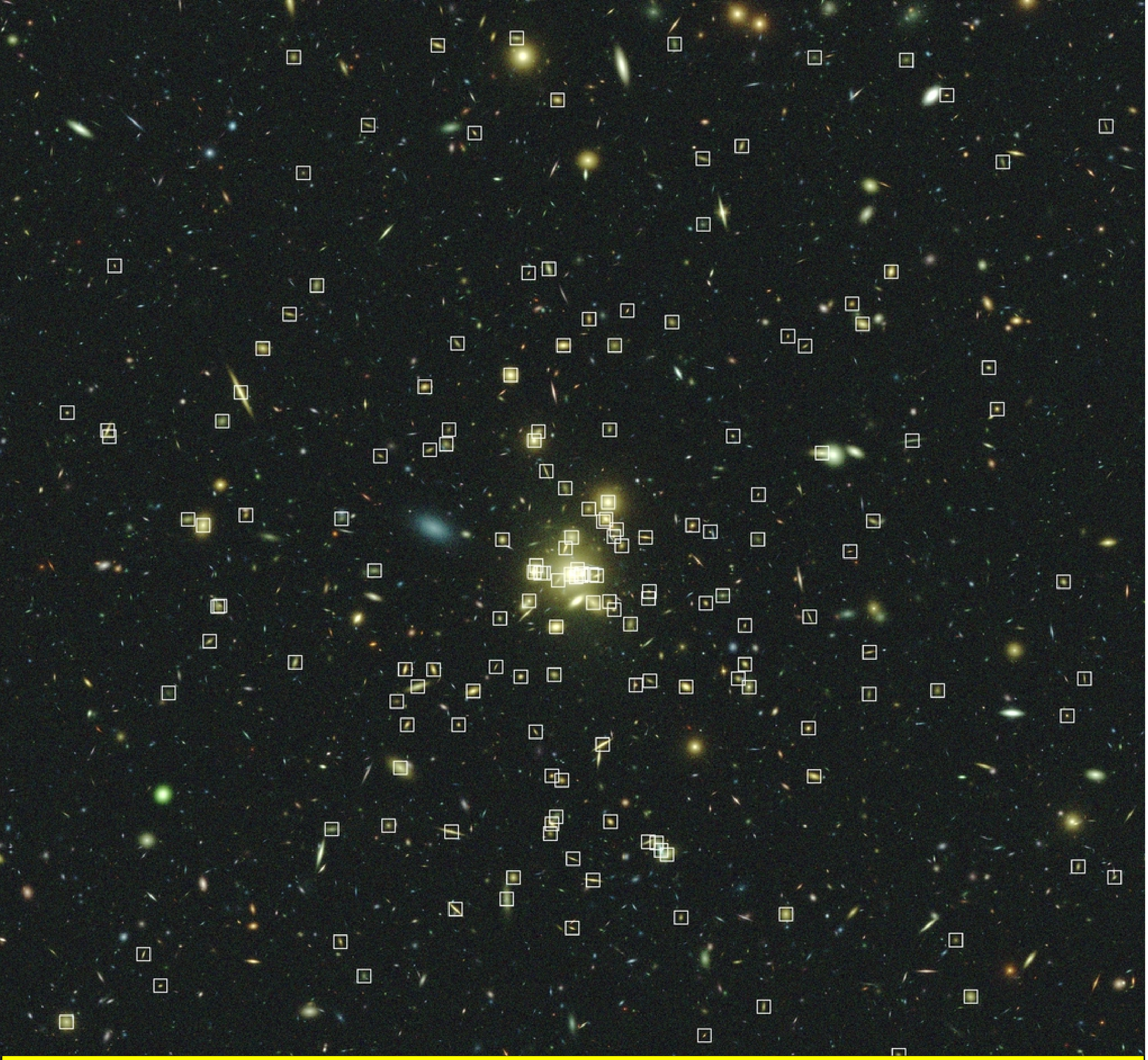
3.4' x 3.4'

HST/ACS
F475W, F625W,
F850LP

10,000sec/filter

Overzier et al 2014

The Millennium Run Observatory



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3.4' x 3.4'

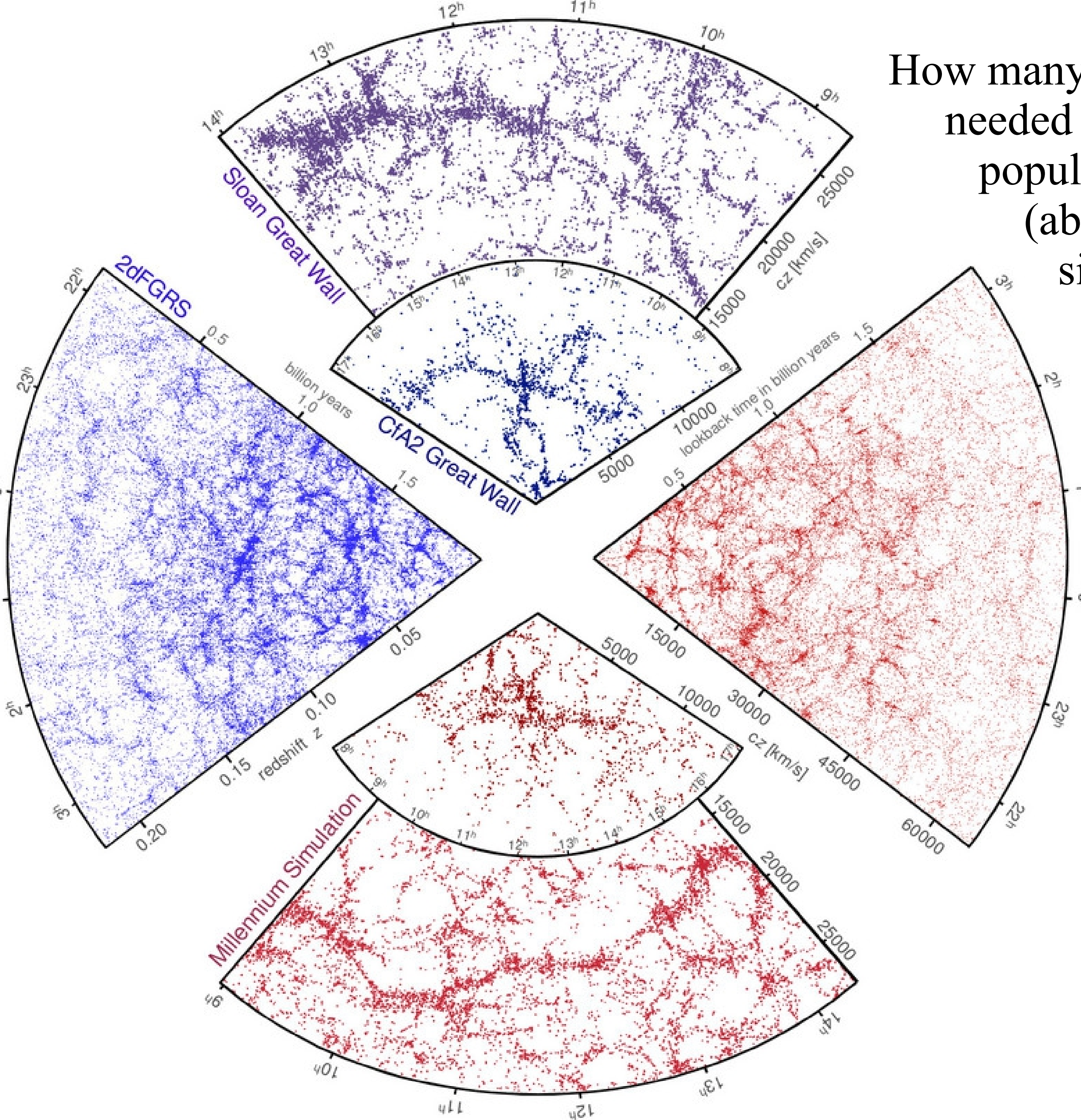
HST/ACS
F475W, F625W, F850LP

10,000sec/filter

Overzier et al 2014

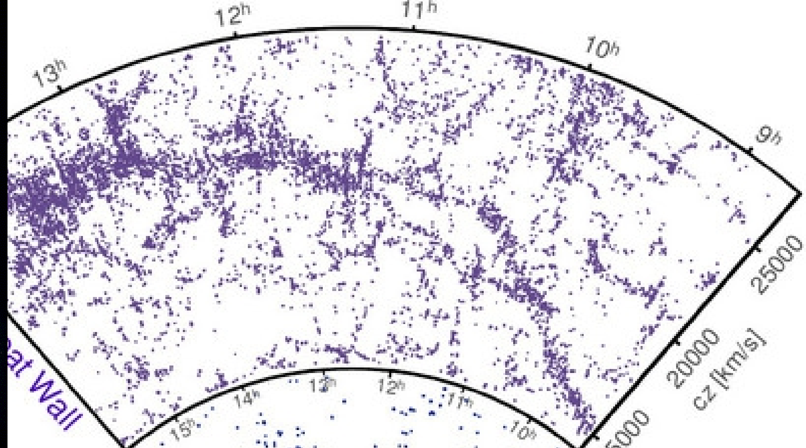
Six parameters fine-tuned to fit a single curve

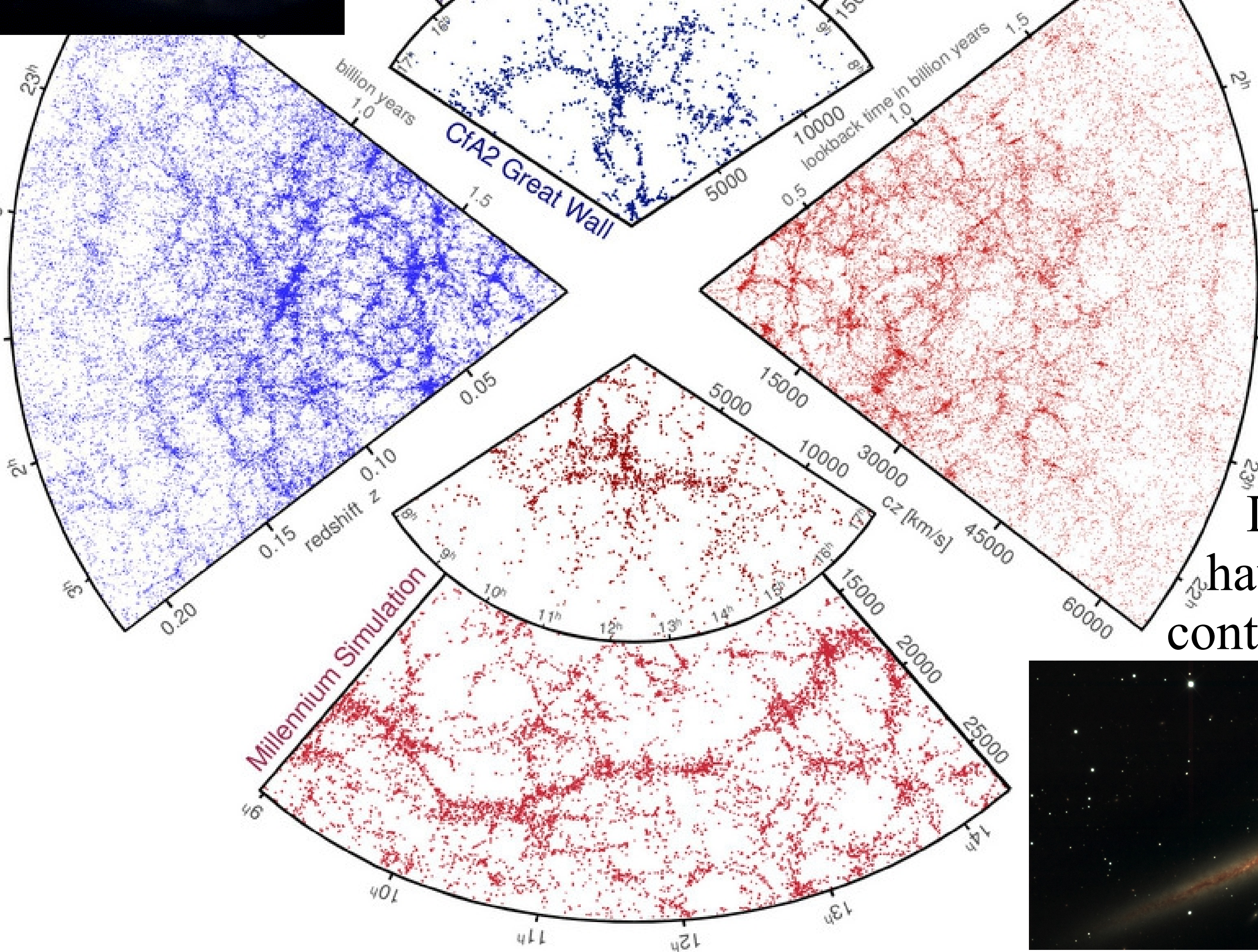
Parameter	*Planck*+WP	
	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$



How many parameters are needed to fit the galaxy population?

(abundance by mass, size, gas content, SFR, B/T, [Fe/H], M_{BH} , V_{rot}; scaling relations; clustering; and their evolution)





How many parameters are needed to fit the galaxy population?

(abundance by mass, size, gas content, SFR, B/T, [Fe/H], M_{BH}, V_{rot}; scaling relations; clustering; and their evolution)

Do the parameters have useful *physical* content?

Population simulations provide a tool...

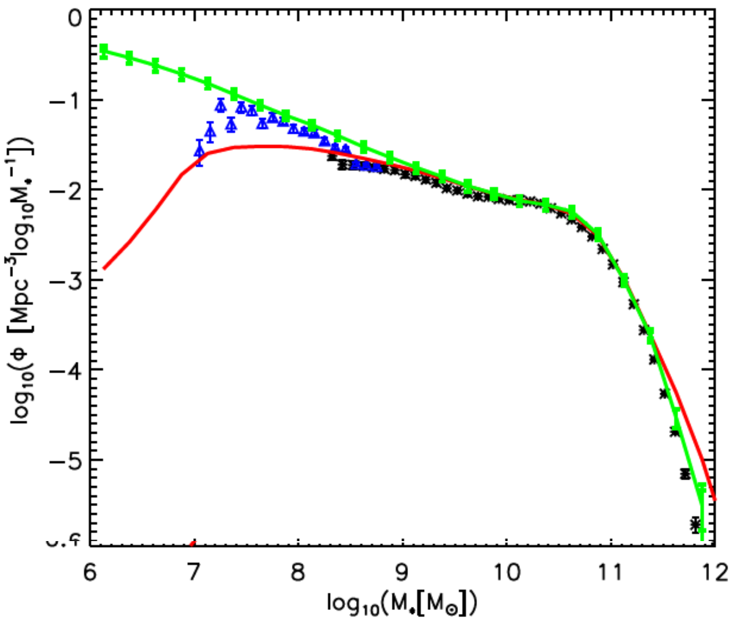
To explore the relative importance and the physical scaling of the many processes that affect stars, gas and central black holes within growing ΛCDM structures

To understand how the these processes interact to produce the various observed population properties of galaxies and their evolution – abundances, scaling relations, clustering

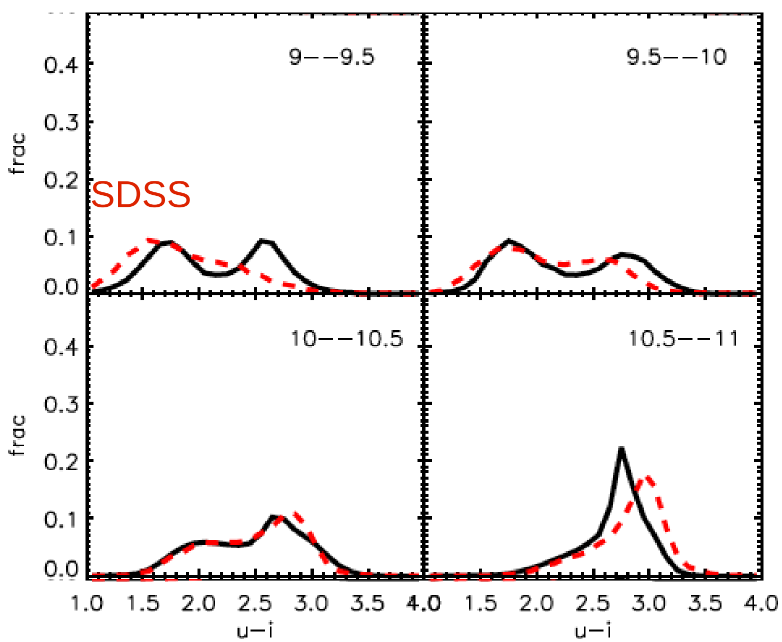
To allow interpretation of large observational surveys in terms of the rates, efficiencies and significance of these processes

To investigate whether uncertainties in the astrophysics of galaxy formation compromise the "precision cosmology" programme of such surveys

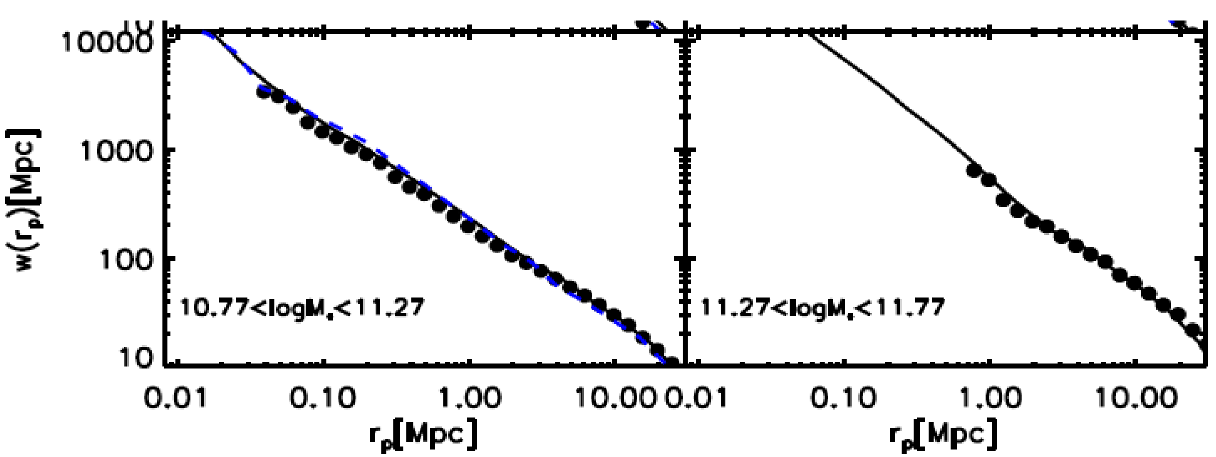
How do we learn from population simulations?



When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...



Guo et al 2011



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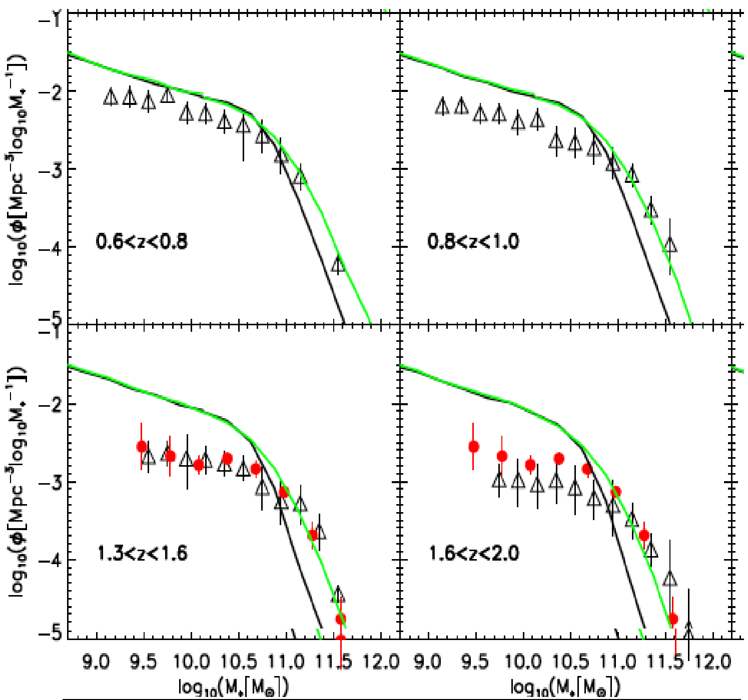
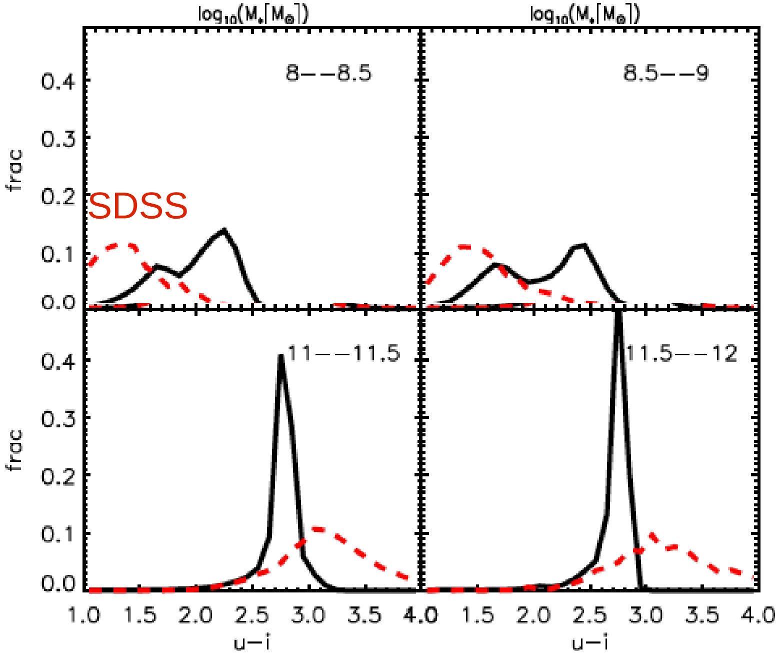


When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

...but it is the failures which show where there is missing or inadequate physics

cosmology? star formation? enrichment and feedback? environmental effects?



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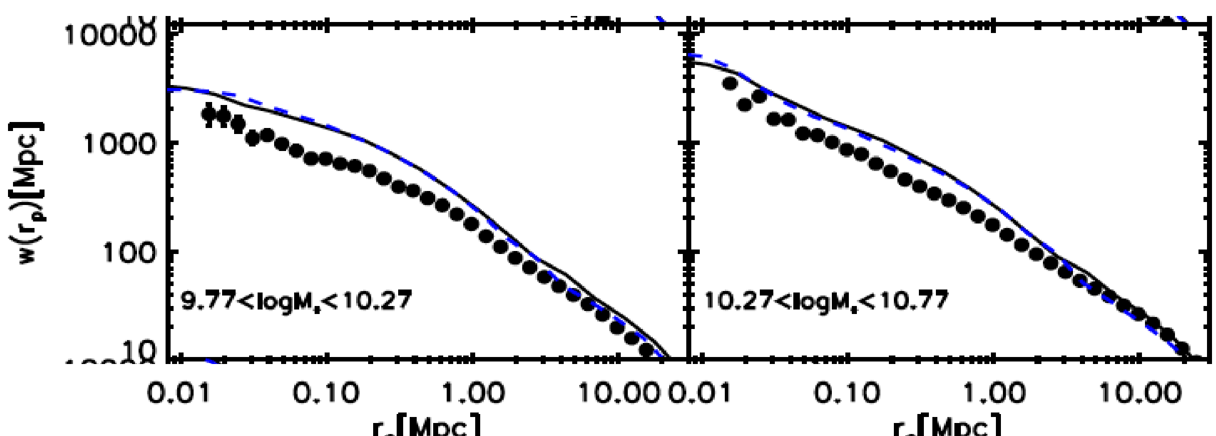

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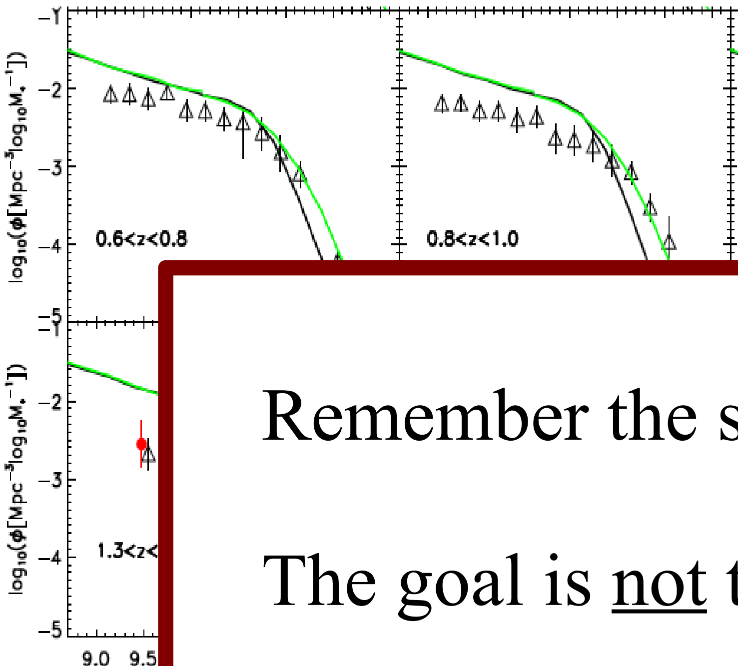

When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

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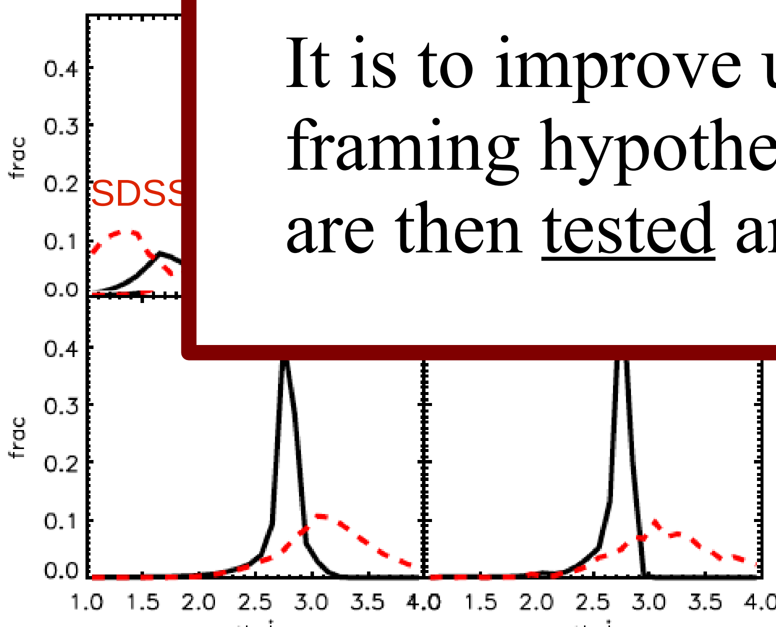

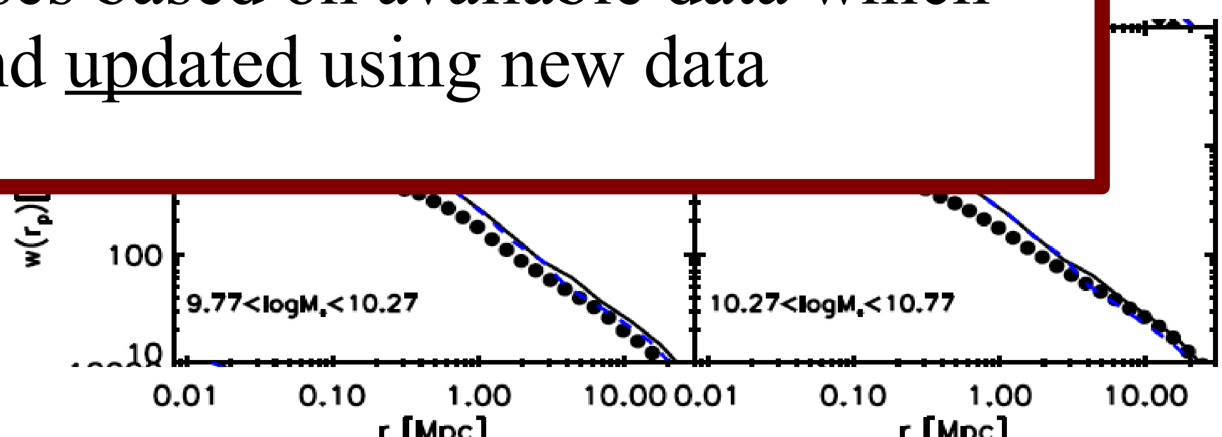

Remember the scientific method!

The goal is not to fit the observations

It is to improve understanding of the real world by framing hypotheses based on available data which are then tested and updated using new data