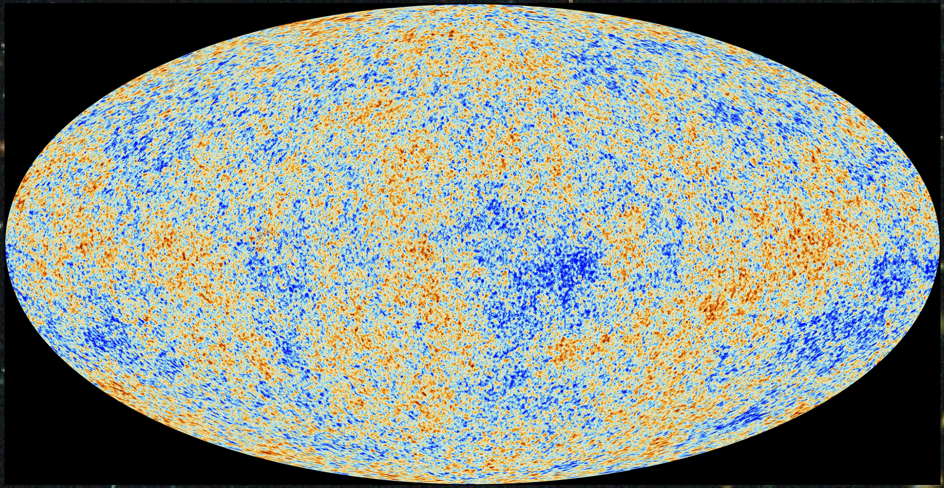
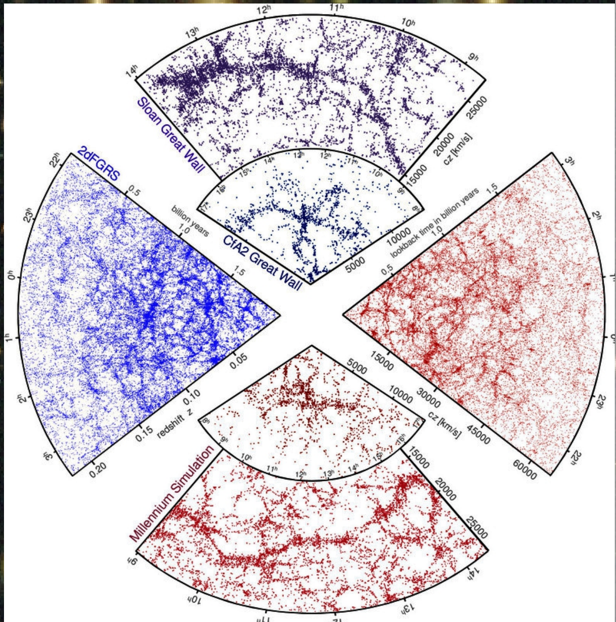


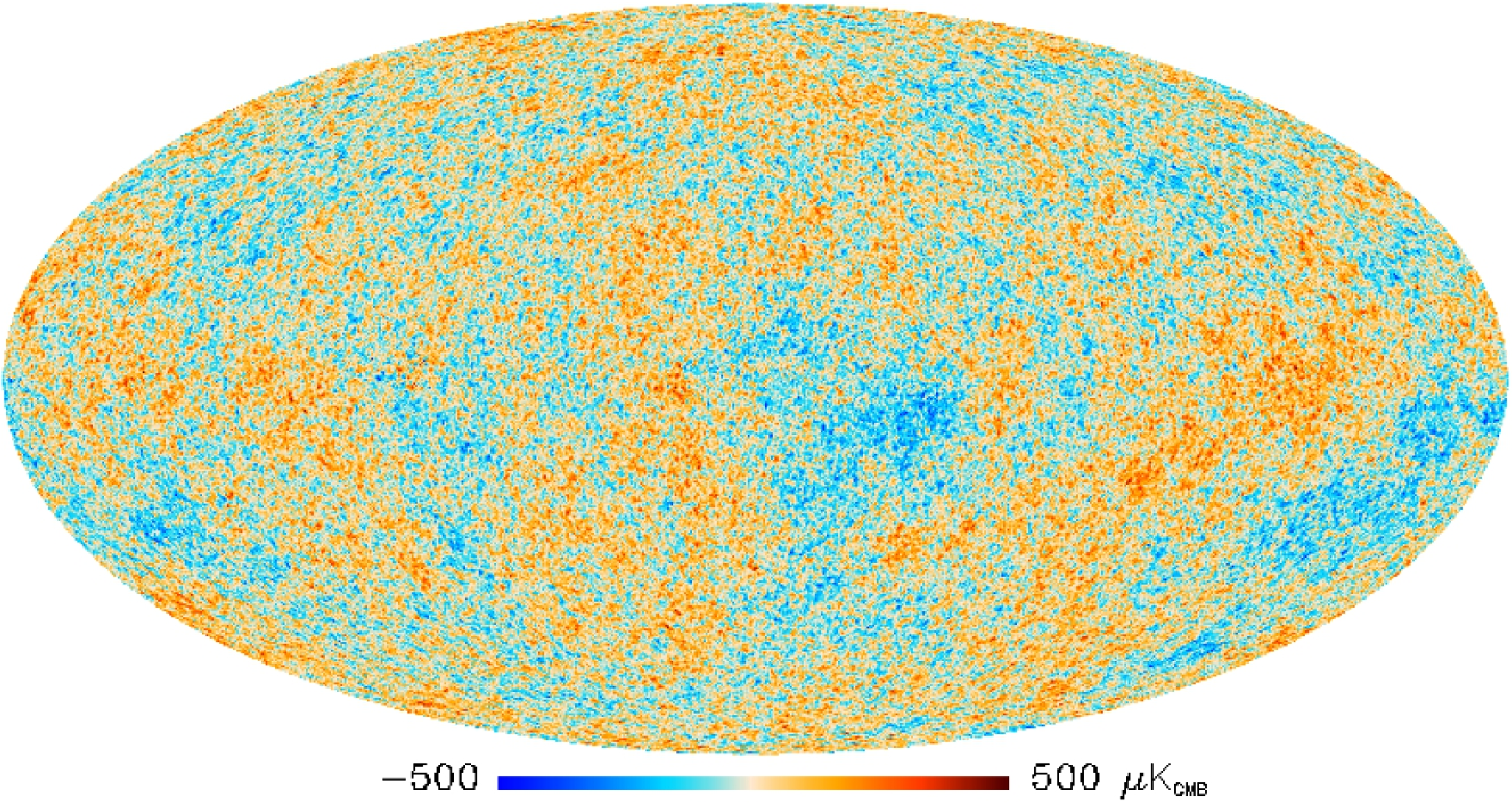
Garching, October 2013

Galaxy formation

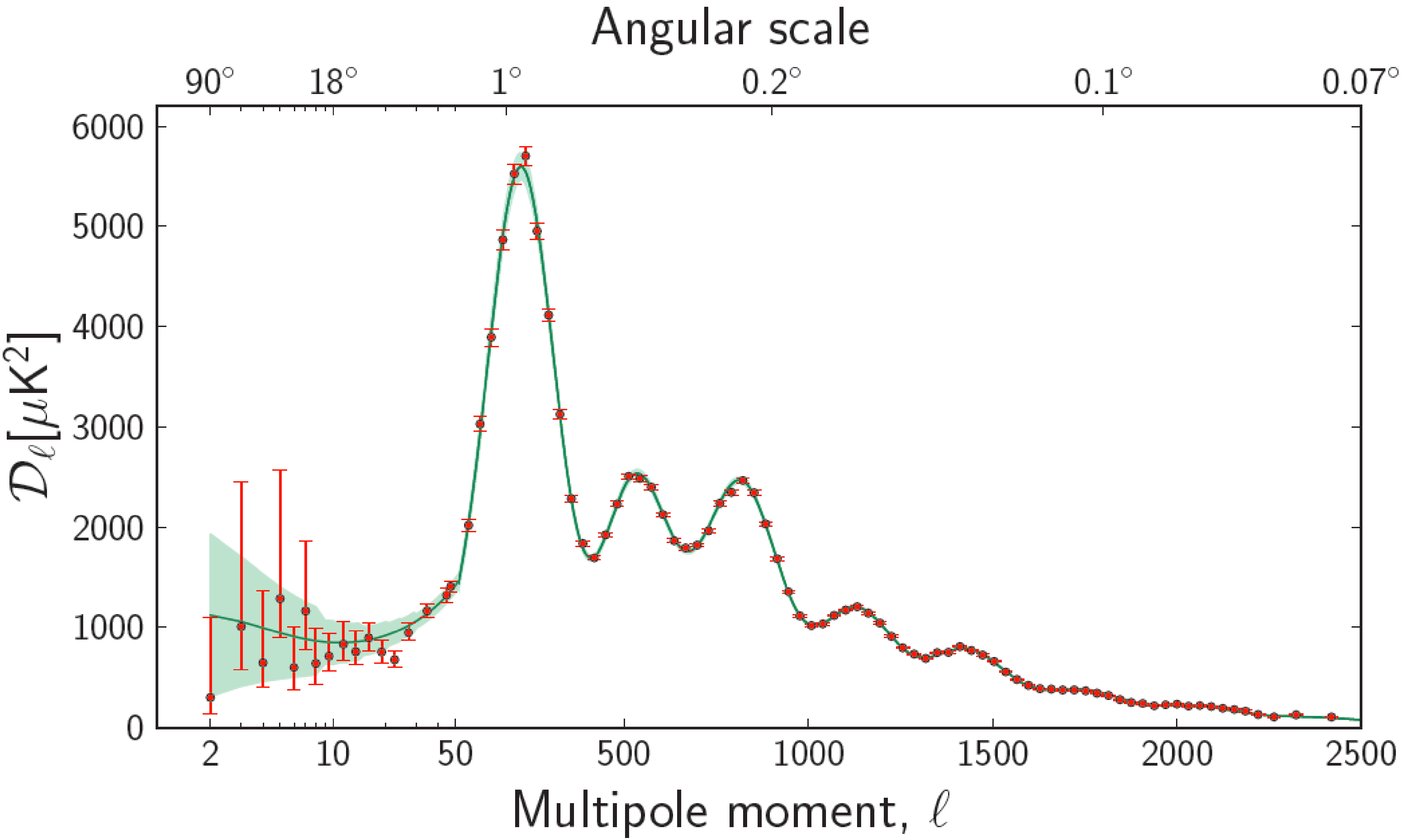


Simon White
Max Planck Institute for Astrophysics

Planck CMB map: the IC's for structure formation



Information content of the *Planck* CMB map



The six parameters of the minimal ΛCDM model

	Planck+WP	
Parameter	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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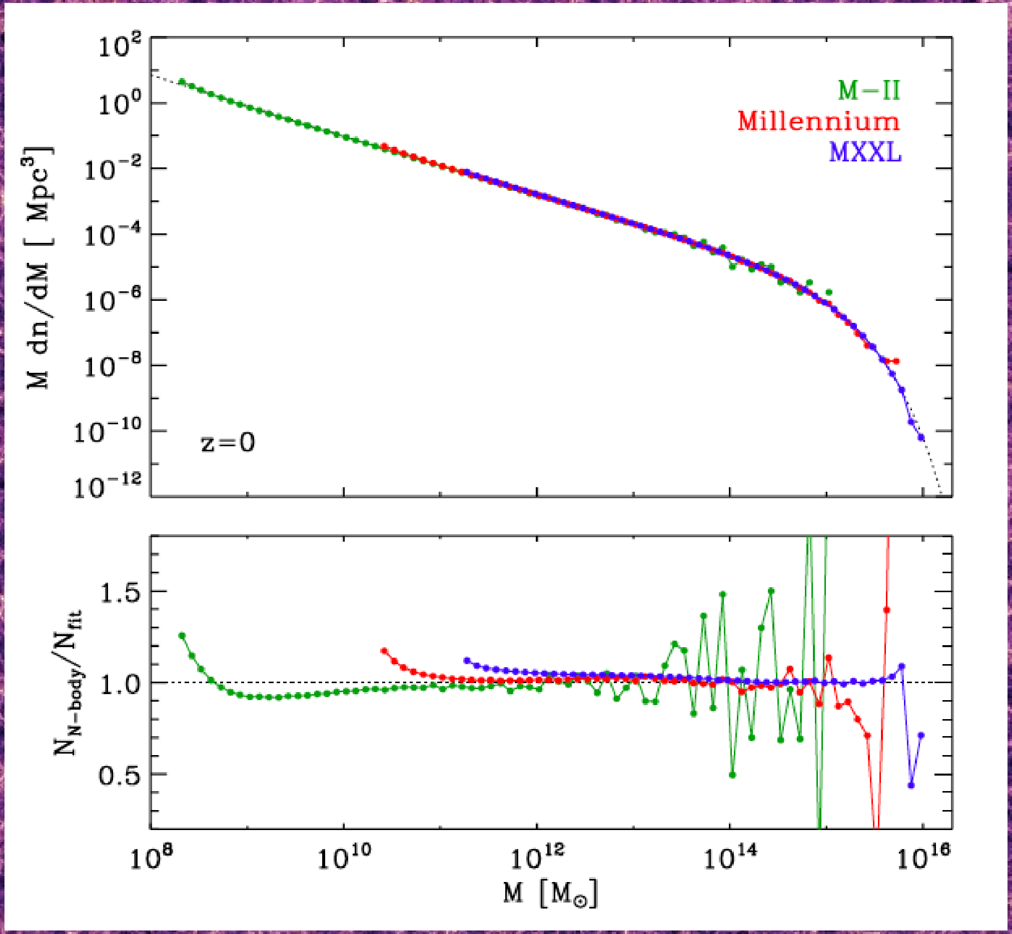
A 40σ detection of nonbaryonic DM using *only* z ~1000 data!

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



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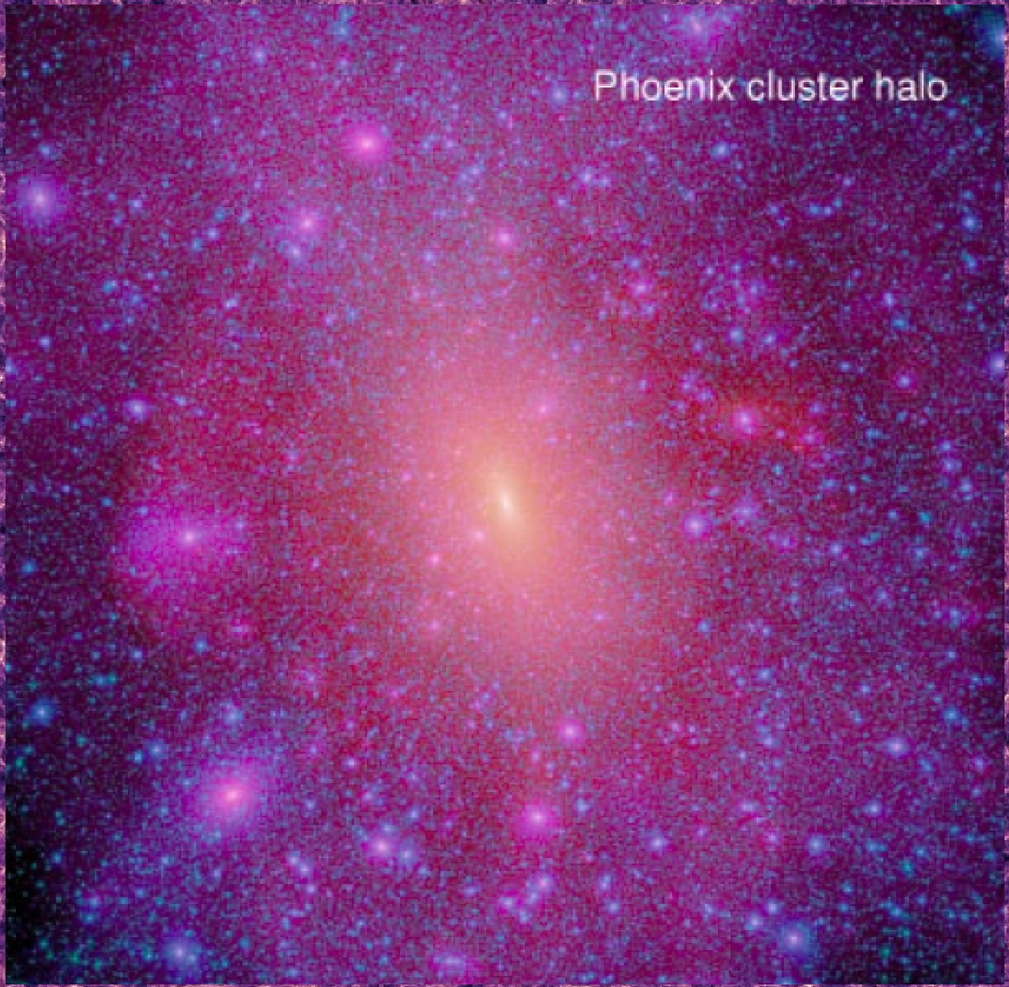
Galaxies correspond to self-bound *subhalos* within halos, rather than to the halos themselves



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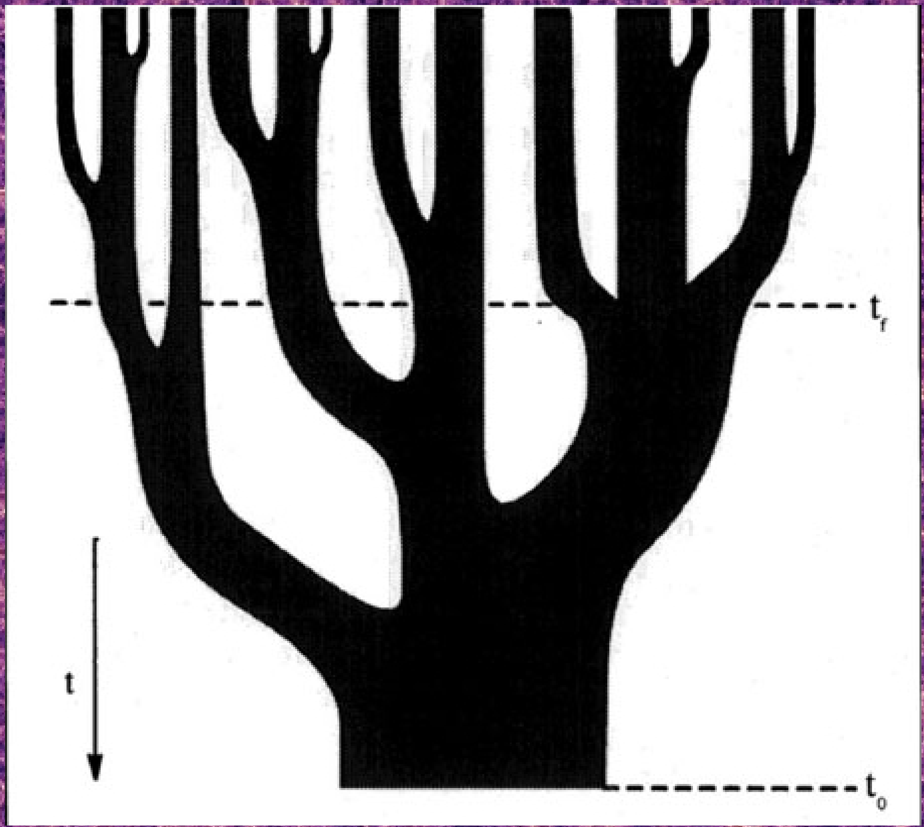
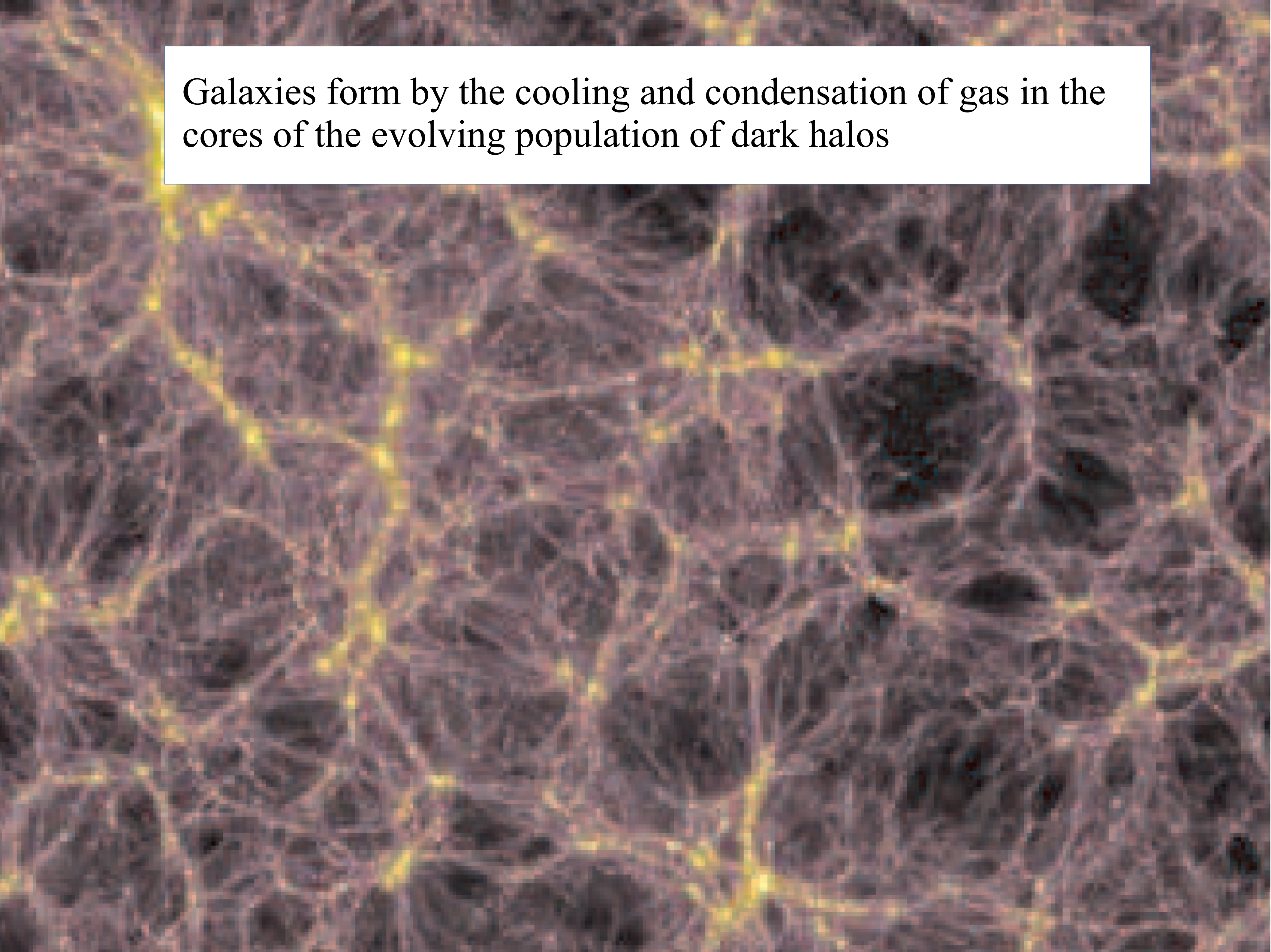
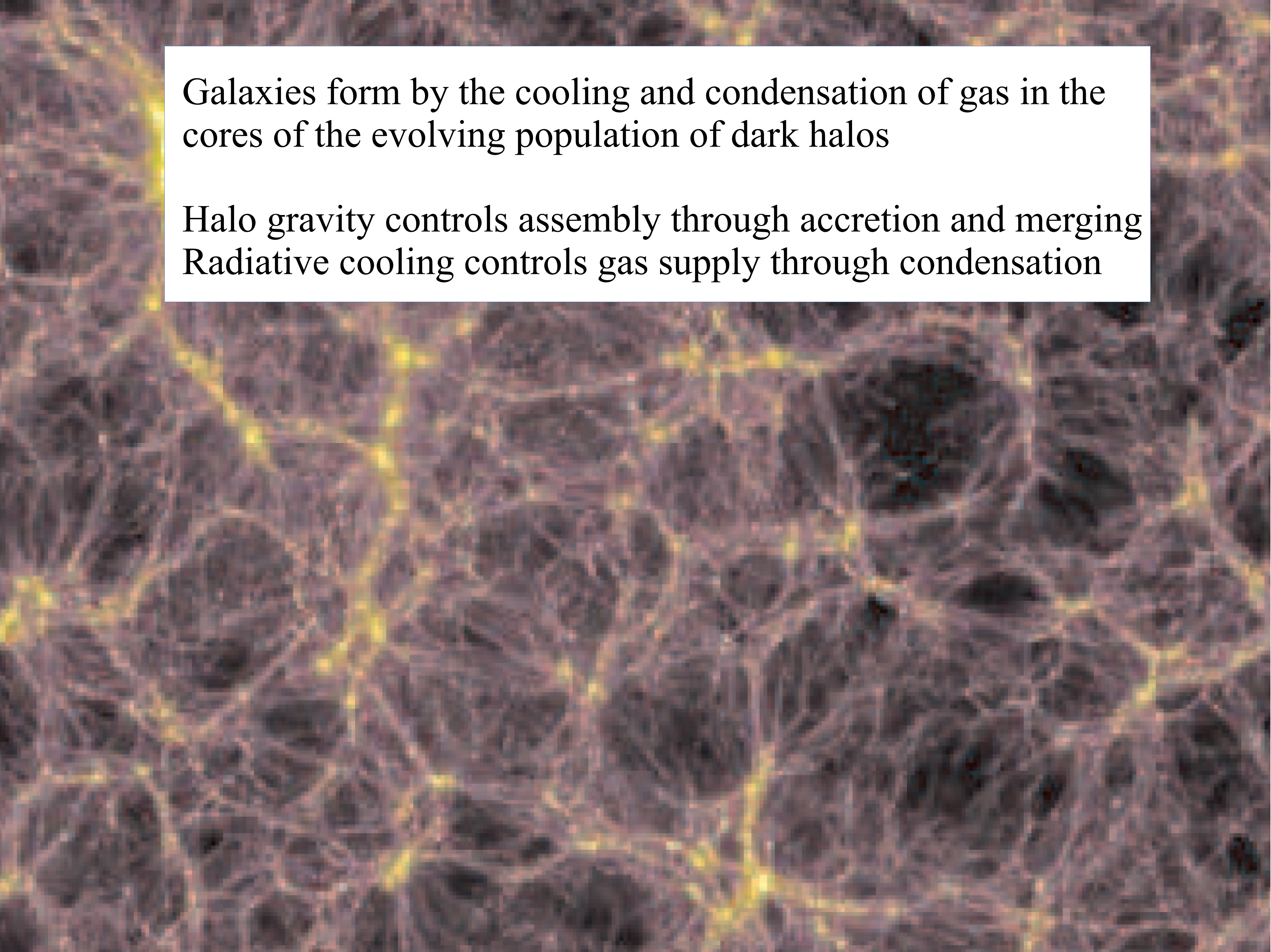
The information relevant to galaxy formation is encoded in *sub*halo merger trees





Galaxies form by the cooling and condensation of gas in the cores of the evolving population of dark halos



Galaxies form by the cooling and condensation of gas in the cores of the evolving population of dark halos

Halo gravity controls assembly through accretion and merging
Radiative cooling controls gas supply through condensation

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Halo gravity controls assembly through accretion and merging
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White & Frenk 1991

We distinguish two different cases. When $r_{\rm cool}$ is larger than the virialized region of a halo, cooling is so rapid that infalling gas never comes to hydrostatic equilibrium. The supply of cold gas for star formation is then limited by the infall rate rather than by cooling. When $r_{\rm cool}$ lies deep within the halo, the accretion shock radiates only weakly, a quasi-static atmosphere forms, and the supply of cold gas for star formation is regulated by radiative losses near $r_{\rm cool}$.

Thus, when $r_{\rm cool} \gg r_{\rm vir}$,

$$\dot{M}_{\rm inf}(V_c, z) = 0.15 f_g \Omega_b V_c^{-3} G^{-1} \, .$$

rapid infall
"cold flows"

In the opposite limit, $r_{\rm cool} \ll r_{\rm vir}$,

$$\dot{M}_{\rm cool}(V_c, z) = 4\pi \rho_g(r_{\rm cool}) r_{\rm cool}^2 \frac{dr_{\rm cool}}{dt}$$

radiative settling
"cooling flows"

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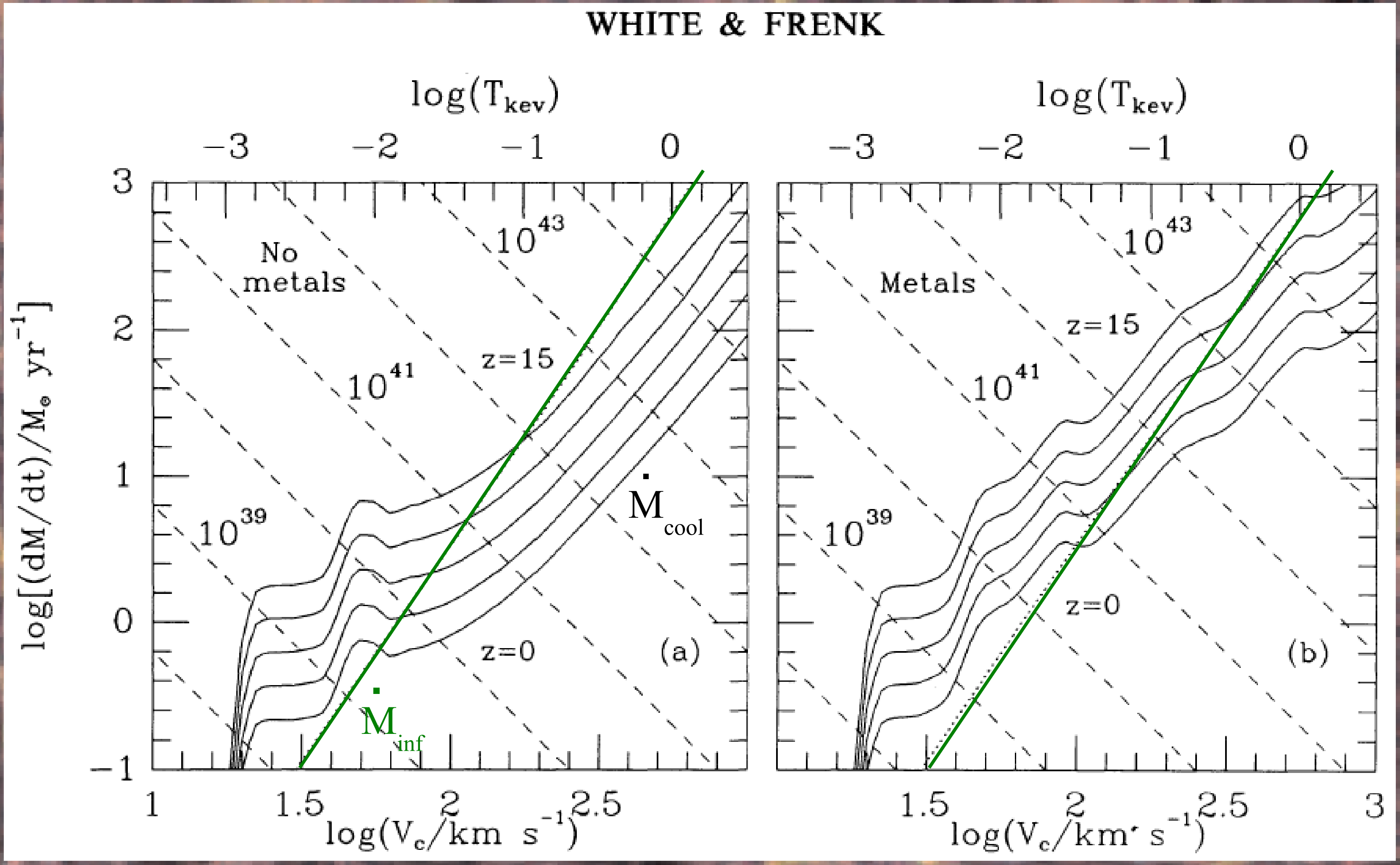

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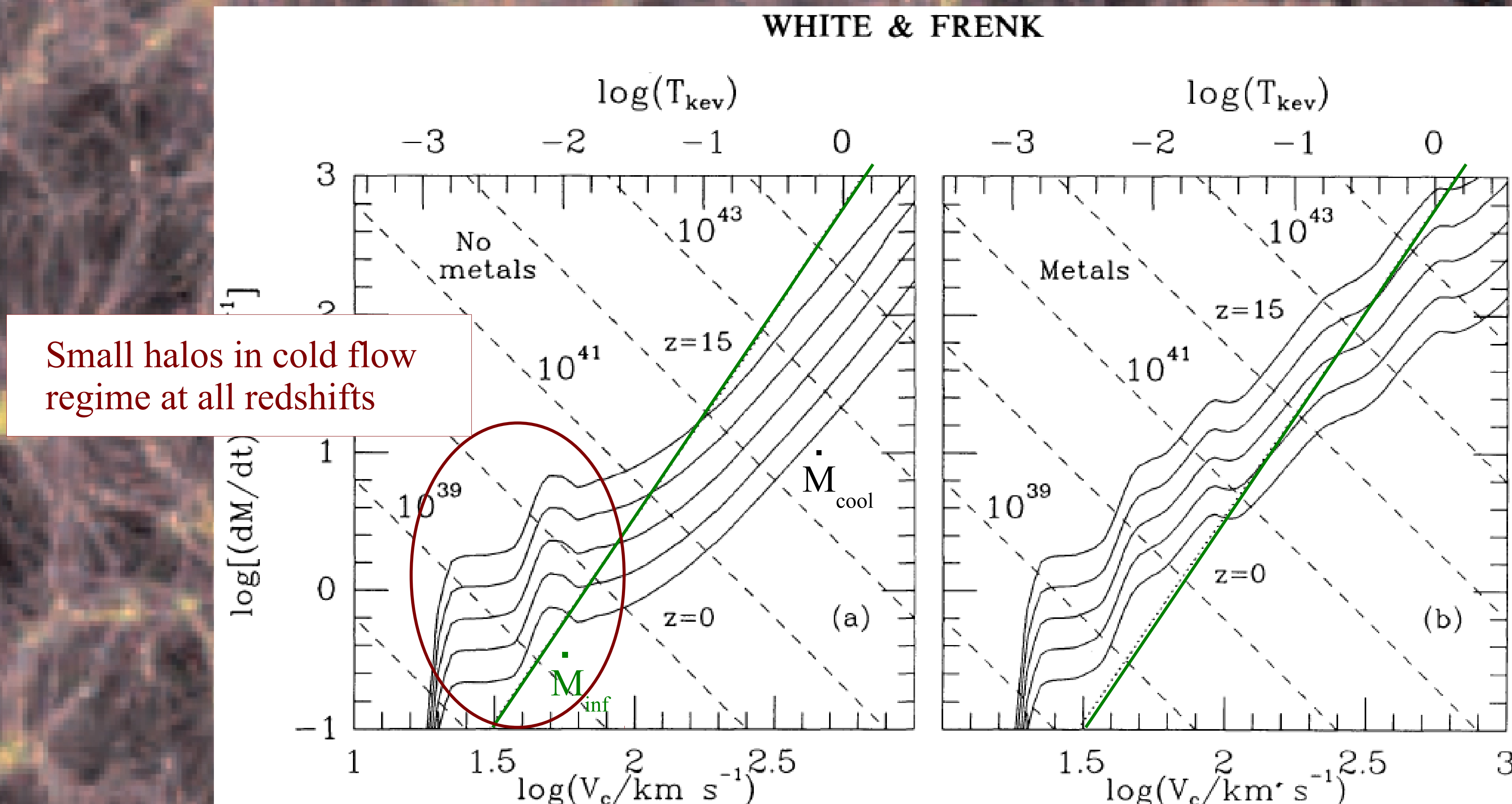

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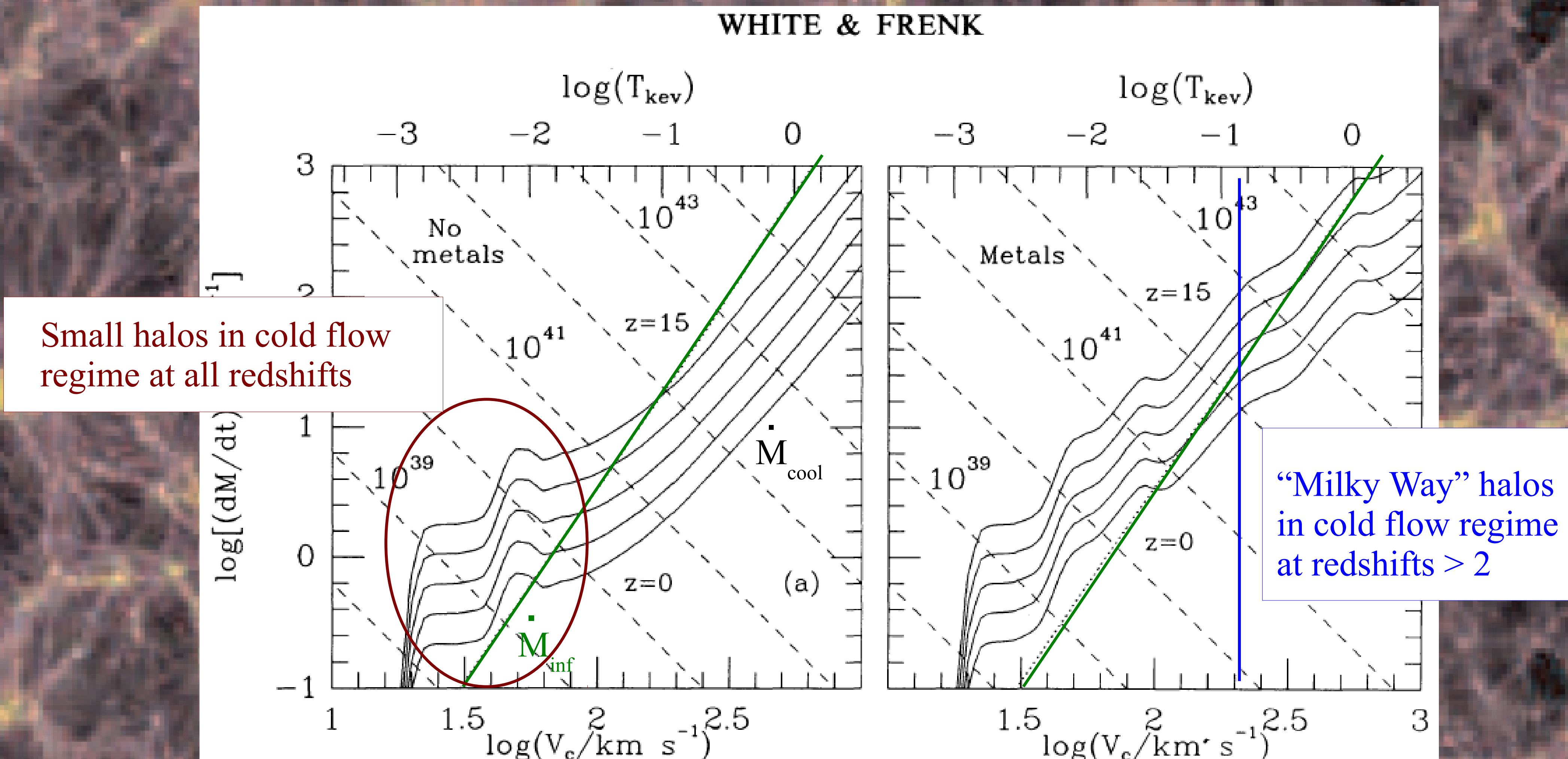
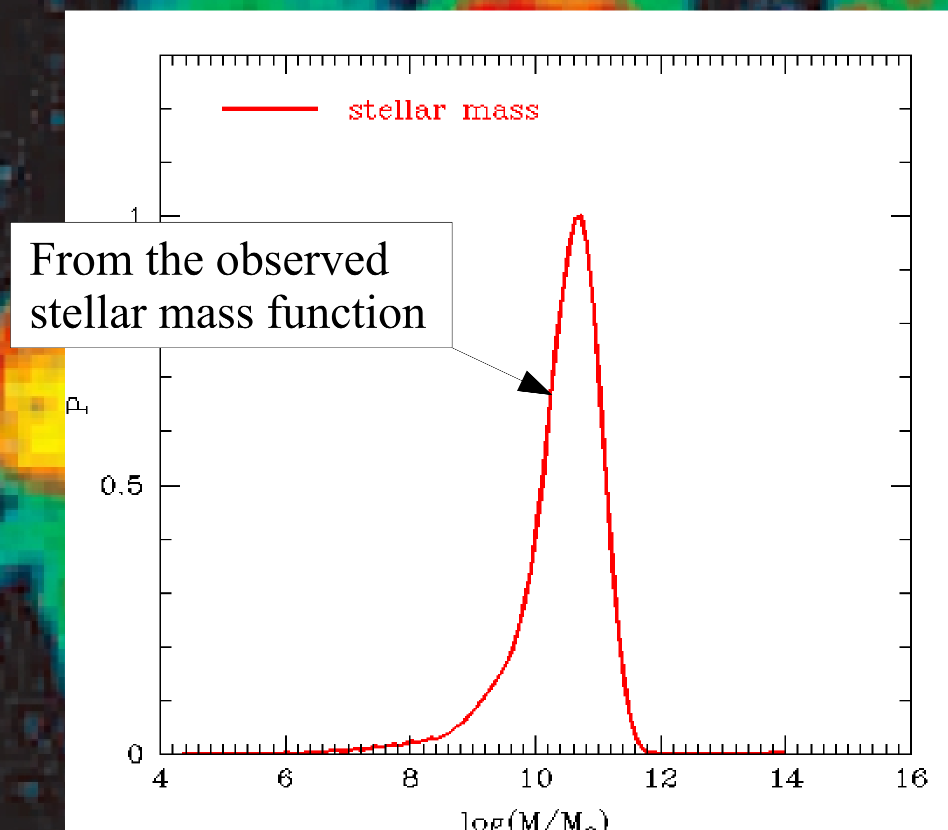
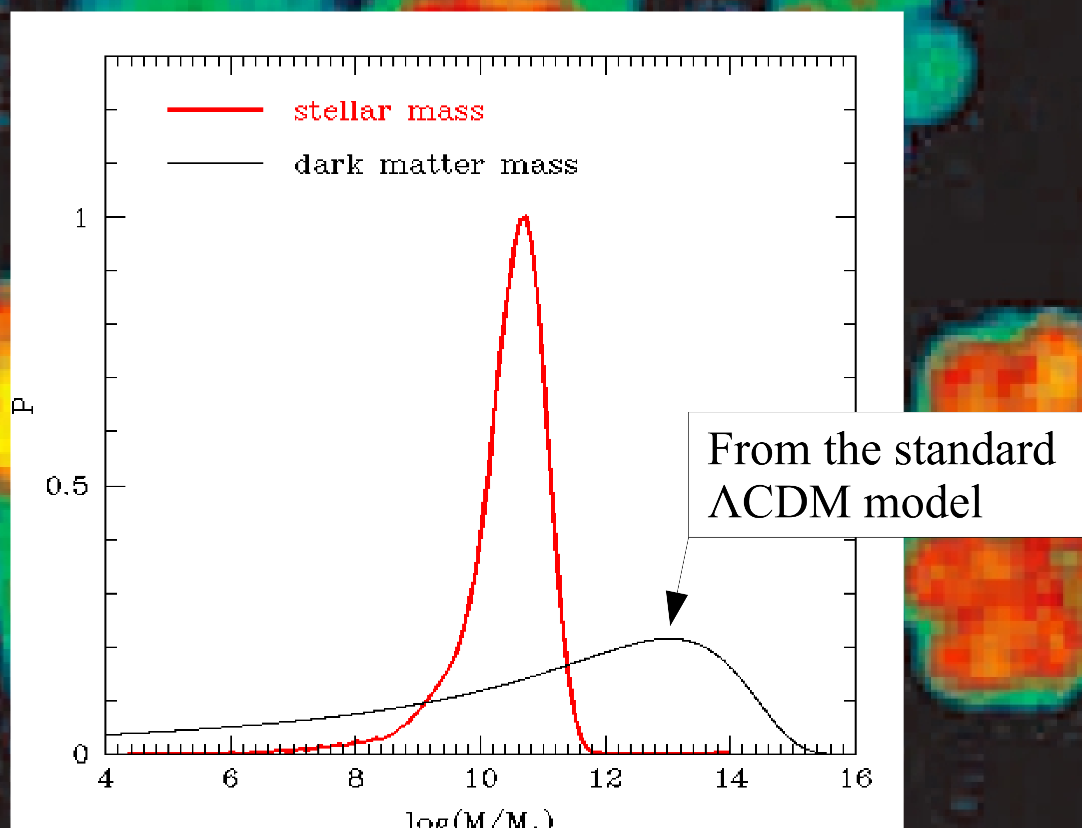


Most stars are in galaxies similar in mass to the Milky Way



Guo et al 2011b

Most stars are in galaxies similar in mass to the Milky Way
Dark matter is *much* more broadly distributed across halos



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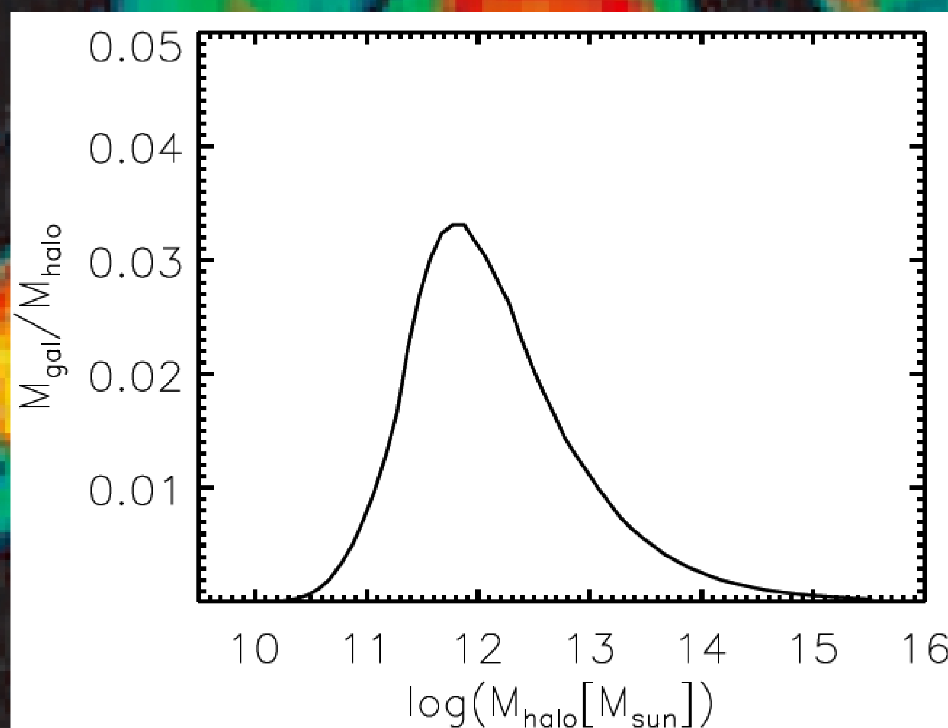
→ Galaxy to halo mass ratio varies *strongly* with mass



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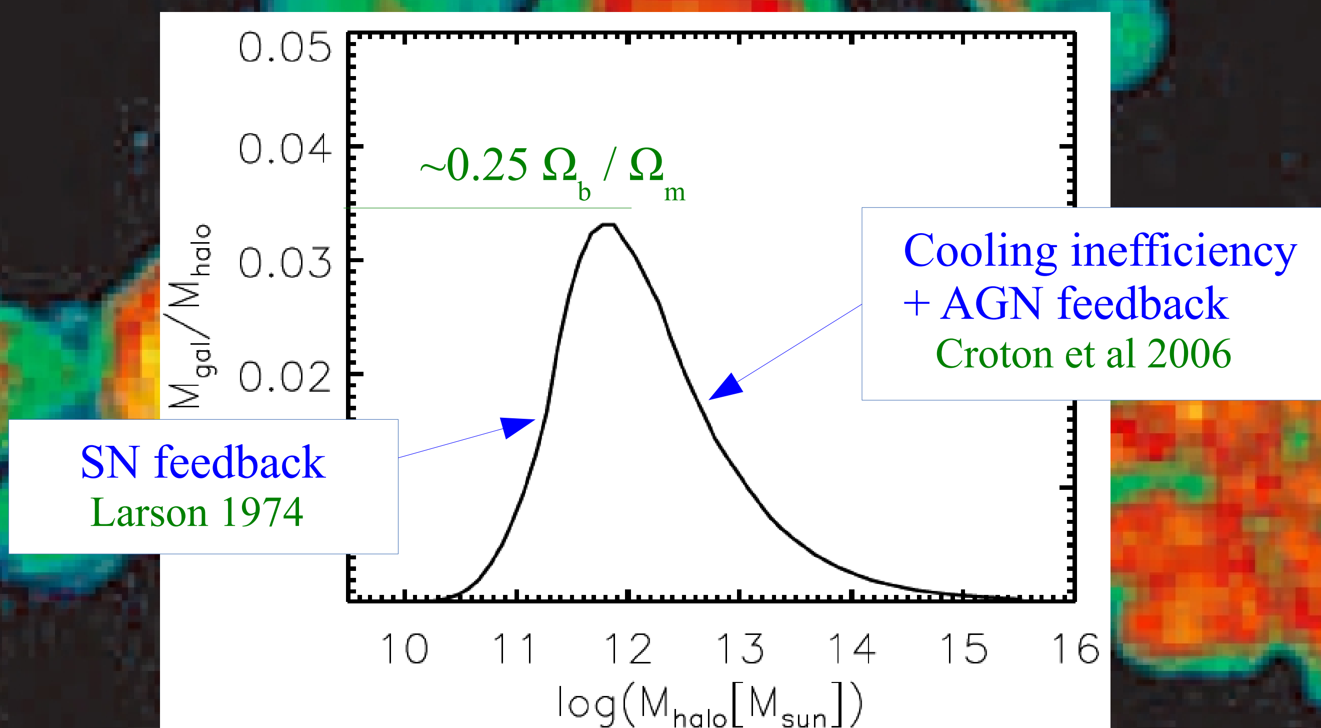
→ Halo to galaxy mass ratio varies *strongly* with mass

Star formation efficiency is reduced at both low *and* high halo mass



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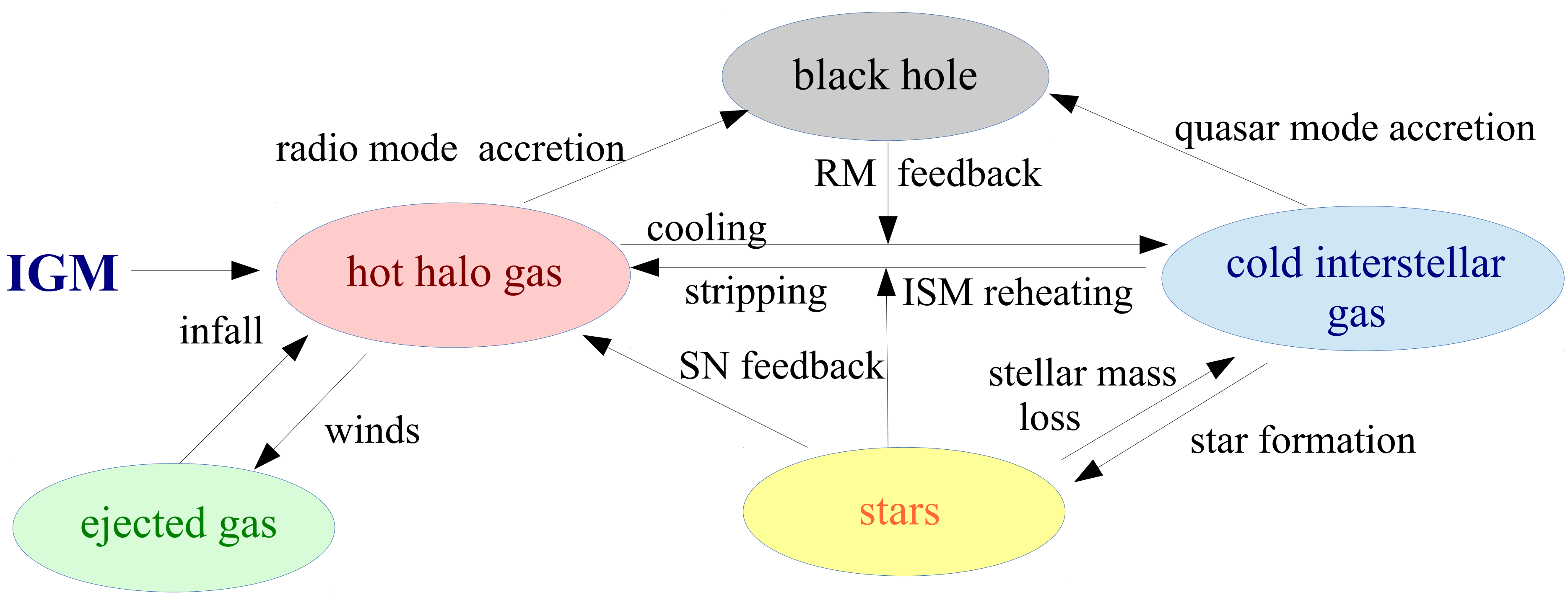
$$(\Omega_b / \Omega_m)\, M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$



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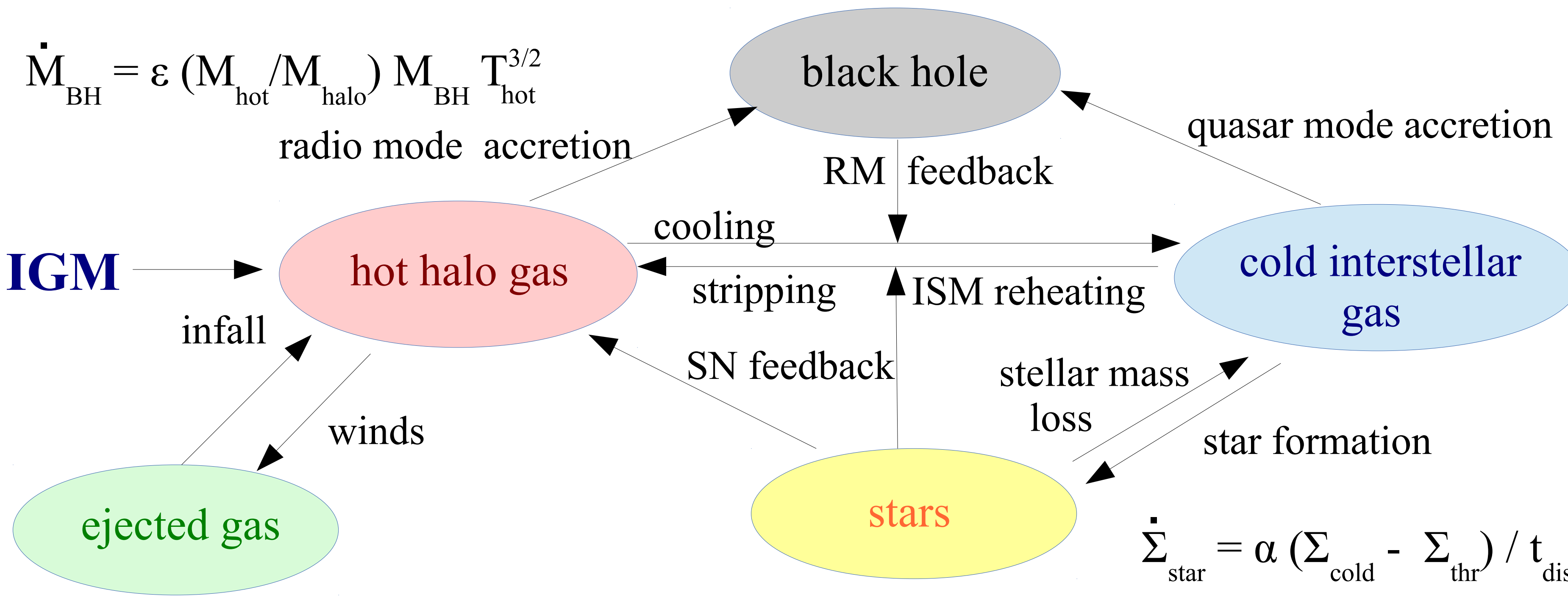
$$\dot{M}_{BH} = \varepsilon\, (M_{hot}/M_{halo})\, M_{BH}\, T_{hot}^{3/2}$$



$$\dot{\Sigma}_{star} = \alpha\, (\Sigma_{cold} - \Sigma_{thr}) / t_{disk}$$

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

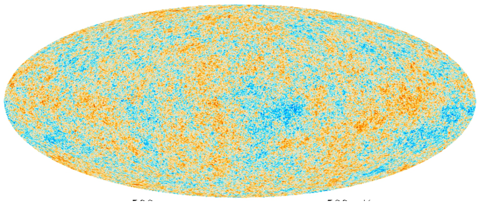
star formation within these central galaxies

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

Six parameters fine-tuned to fit a single curve

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
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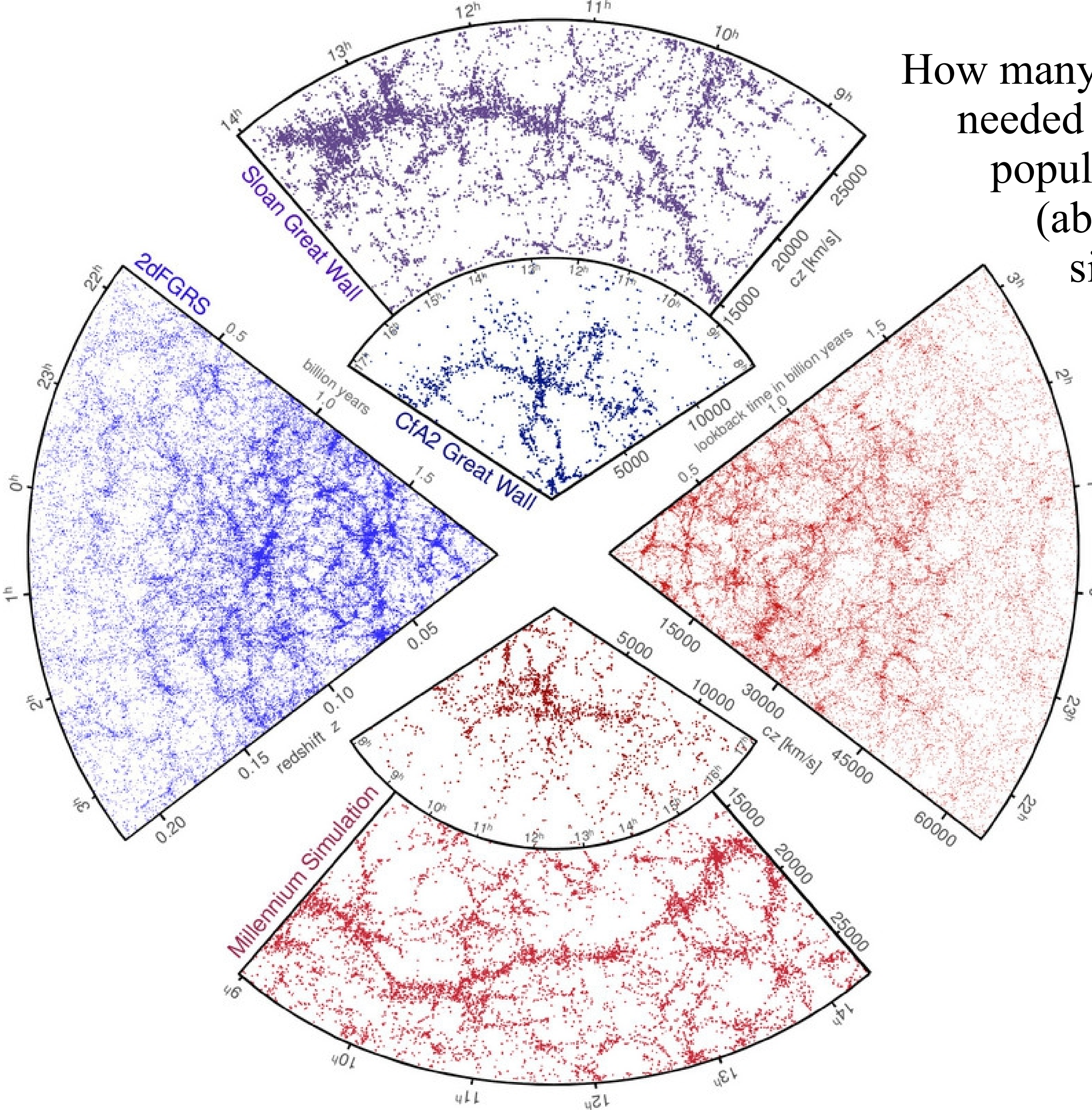
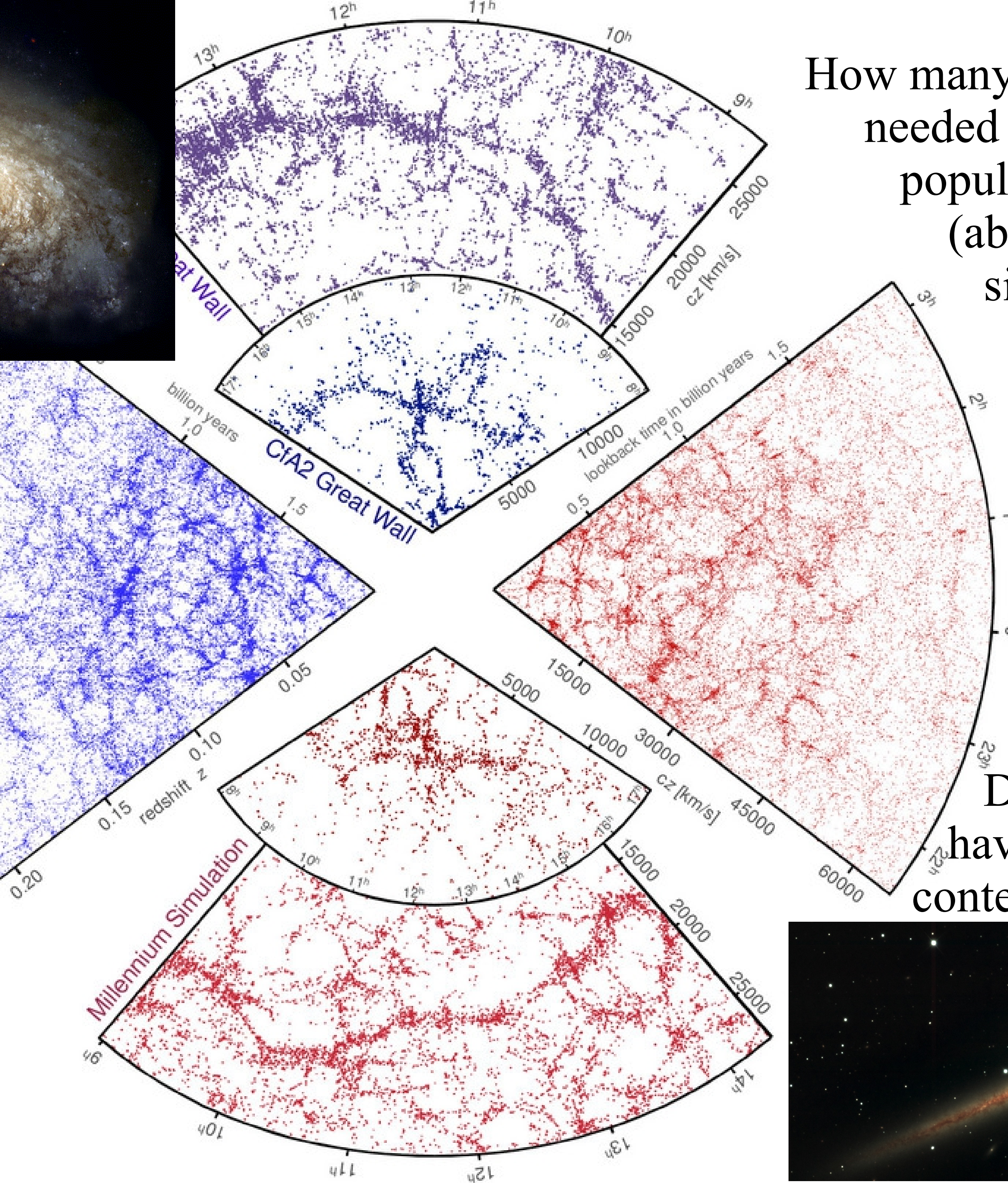


How many parameters are needed to fit the galaxy population?
(abundance by mass, size, gas content, SFR, B/T, AGN; scaling relations; clustering...)



How many parameters are needed to fit the galaxy population?
(abundance by mass, size, gas content, SFR, B/T, AGN; scaling relations; clustering...)

Do the parameters have useful *physical* content?

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 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

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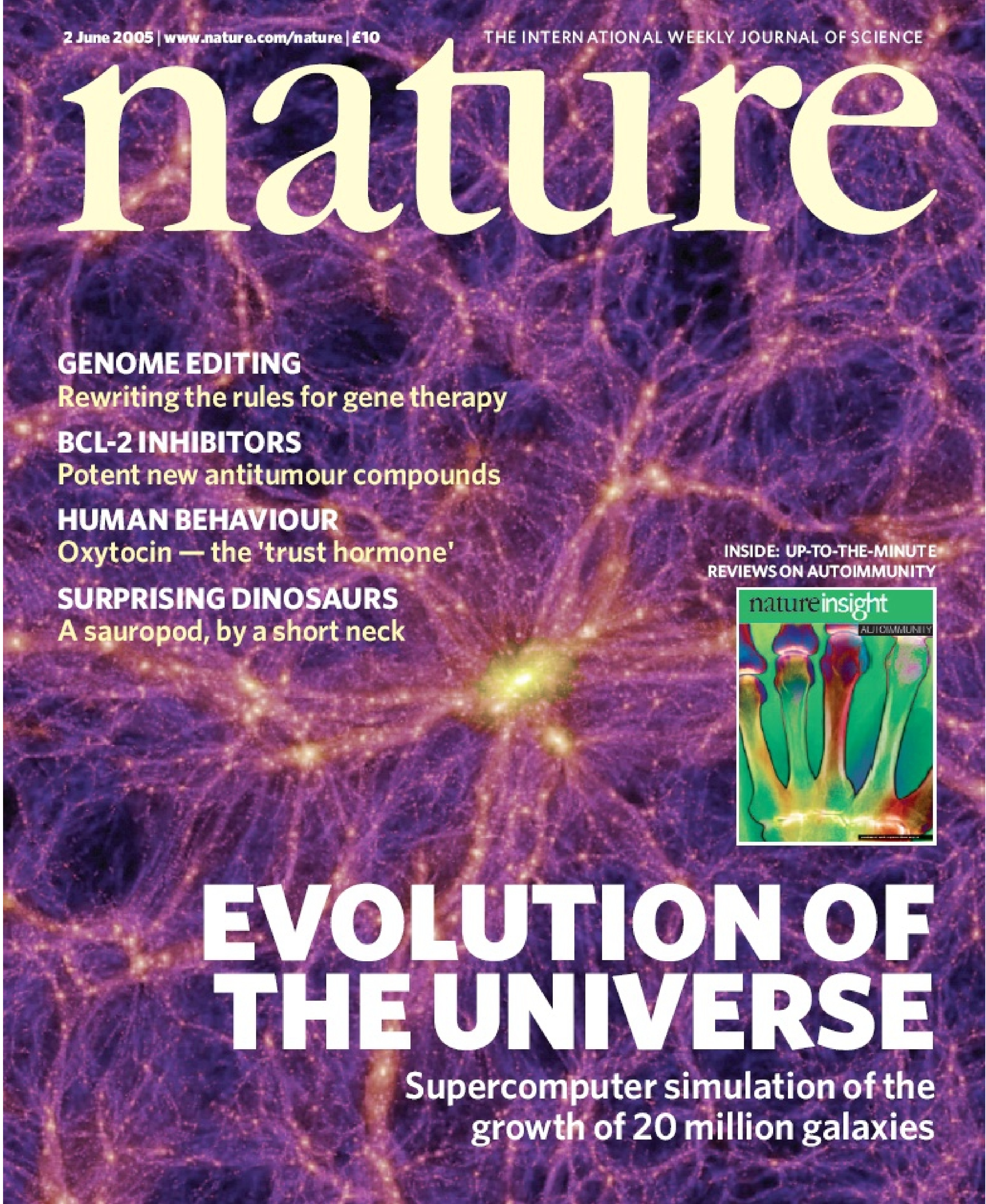
NOT to make a definitive *a priori* physical model for the formation of everything from linear ΛCDM initial conditions

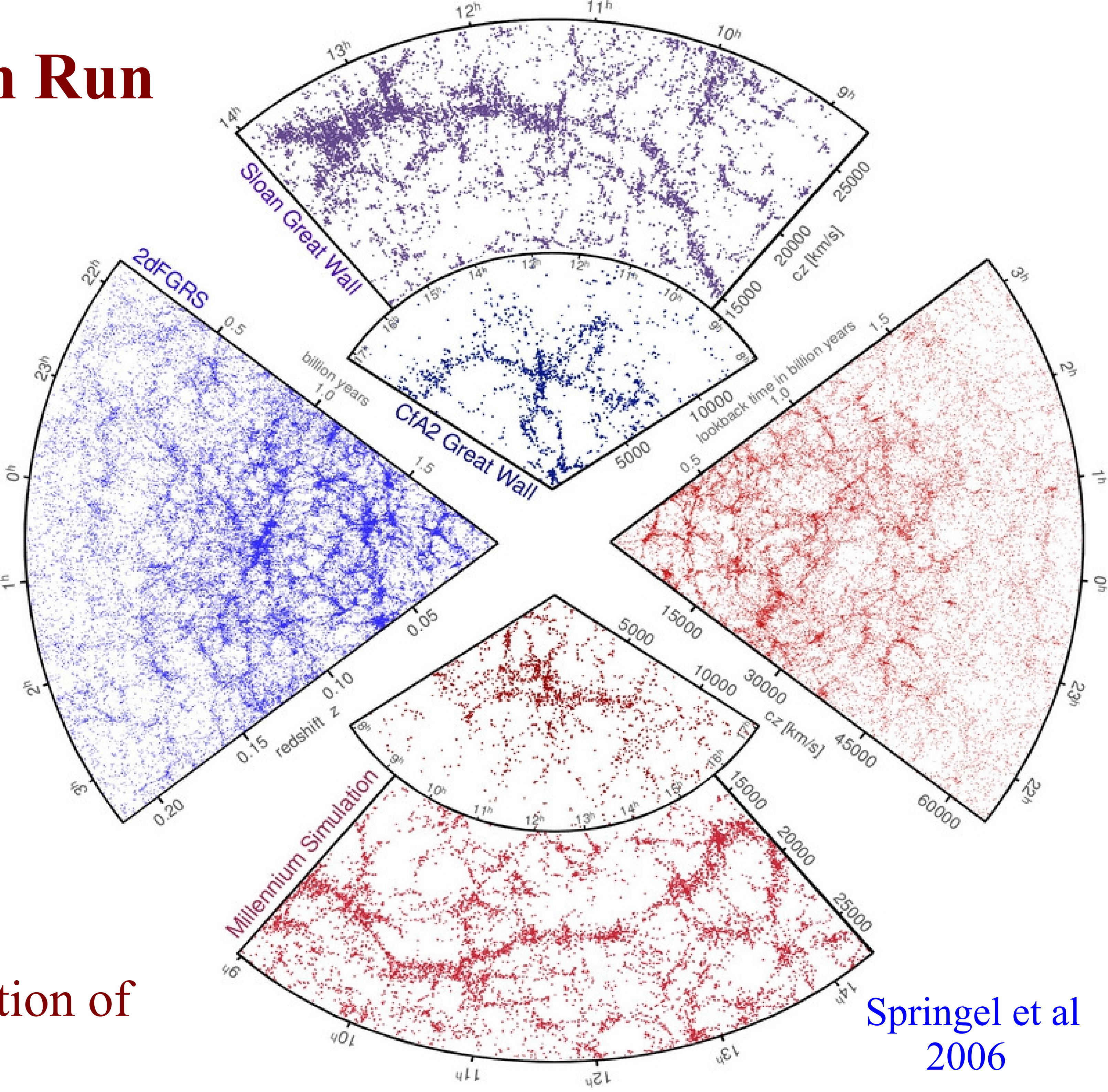
NOR to represent the internal structure of individual galaxies at anything but the most schematic level

Millennium Run 2004



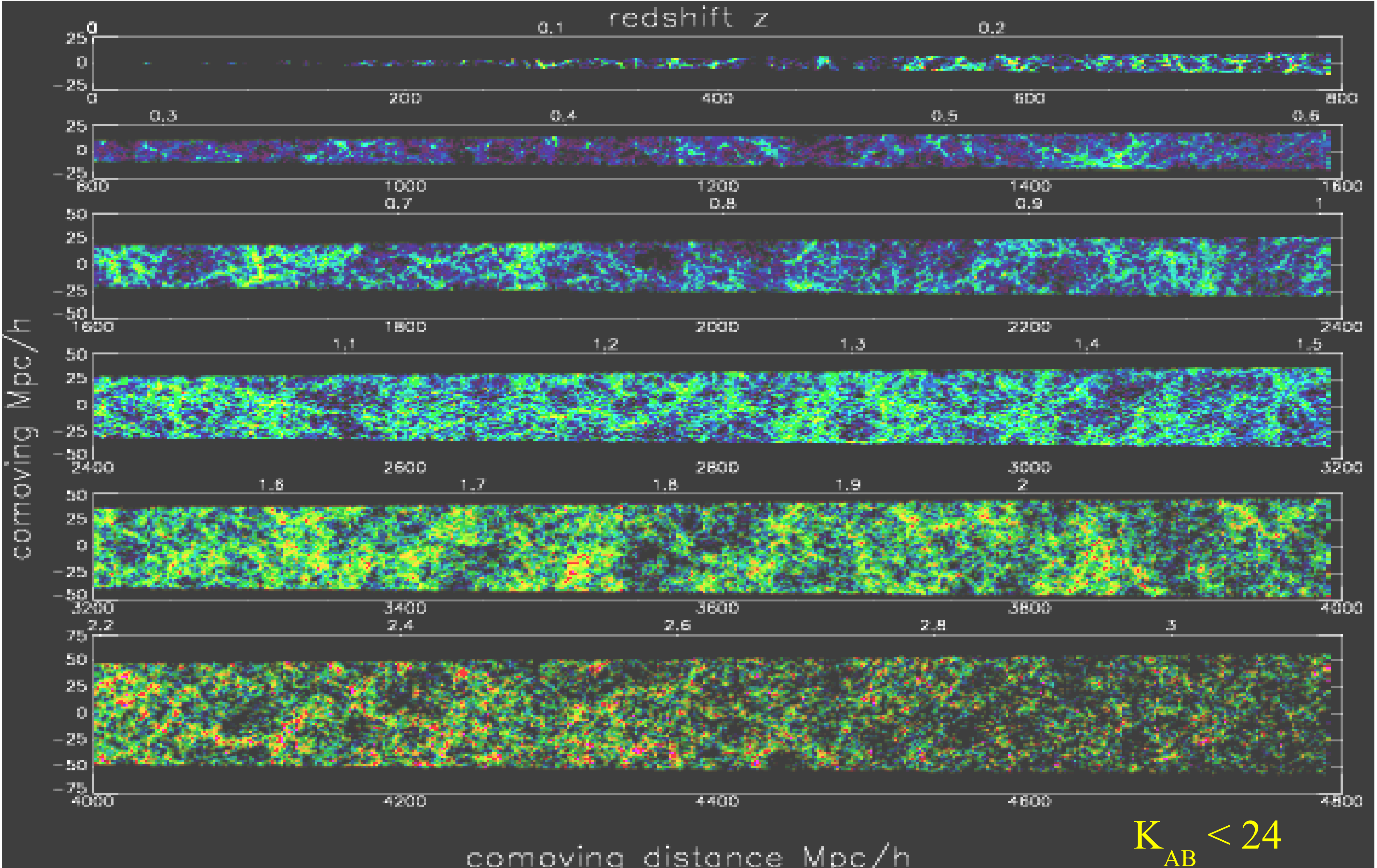
Springel et al 2005

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

Limitations of the Millennium Simulation

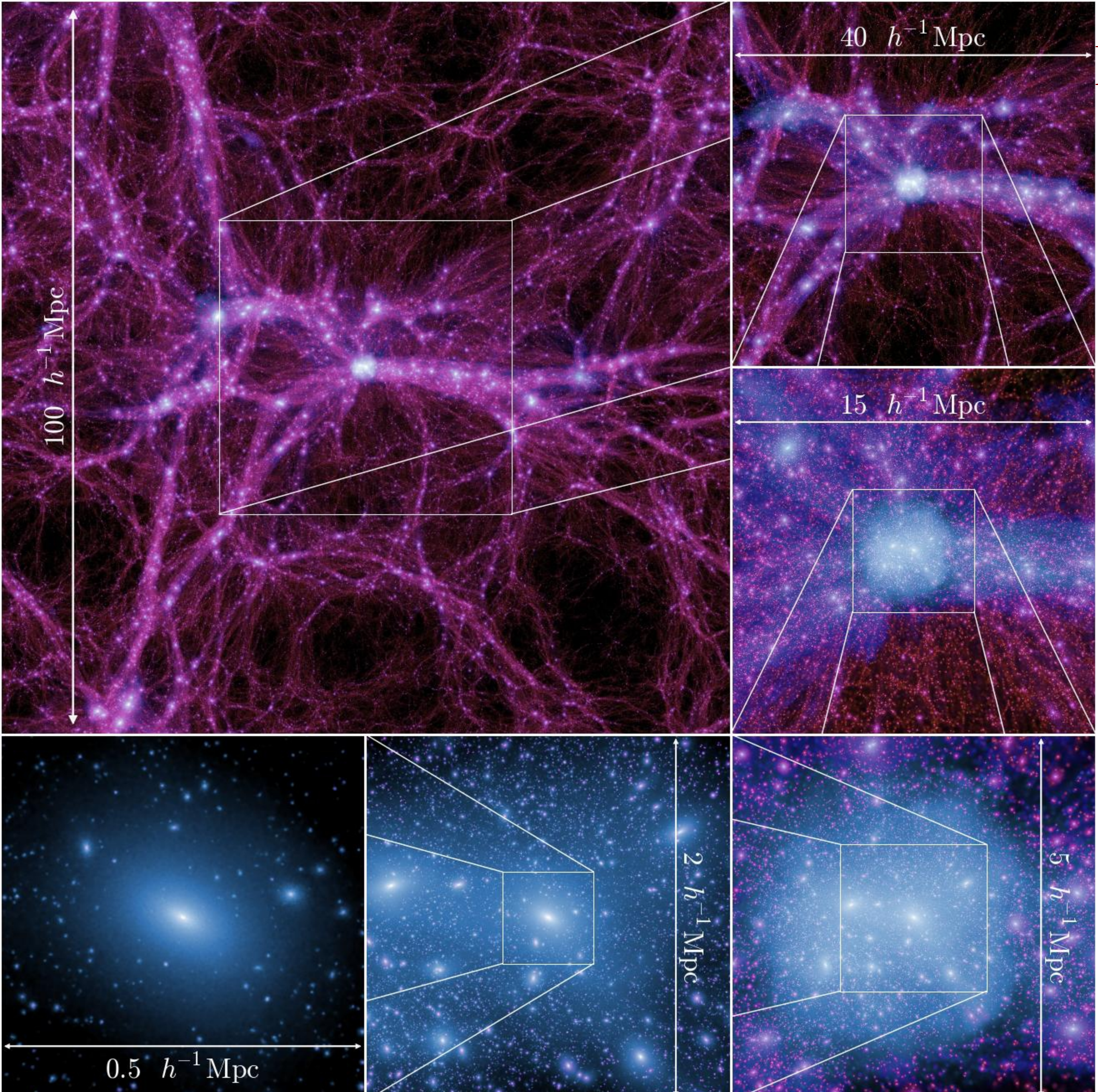
Limited modeling of *structure* of galaxies, gas components

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



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

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

Guo et al 2011

Implement modelling simultaneously on MS and MS-II

Test convergence of galaxy properties near resolution limit of MS

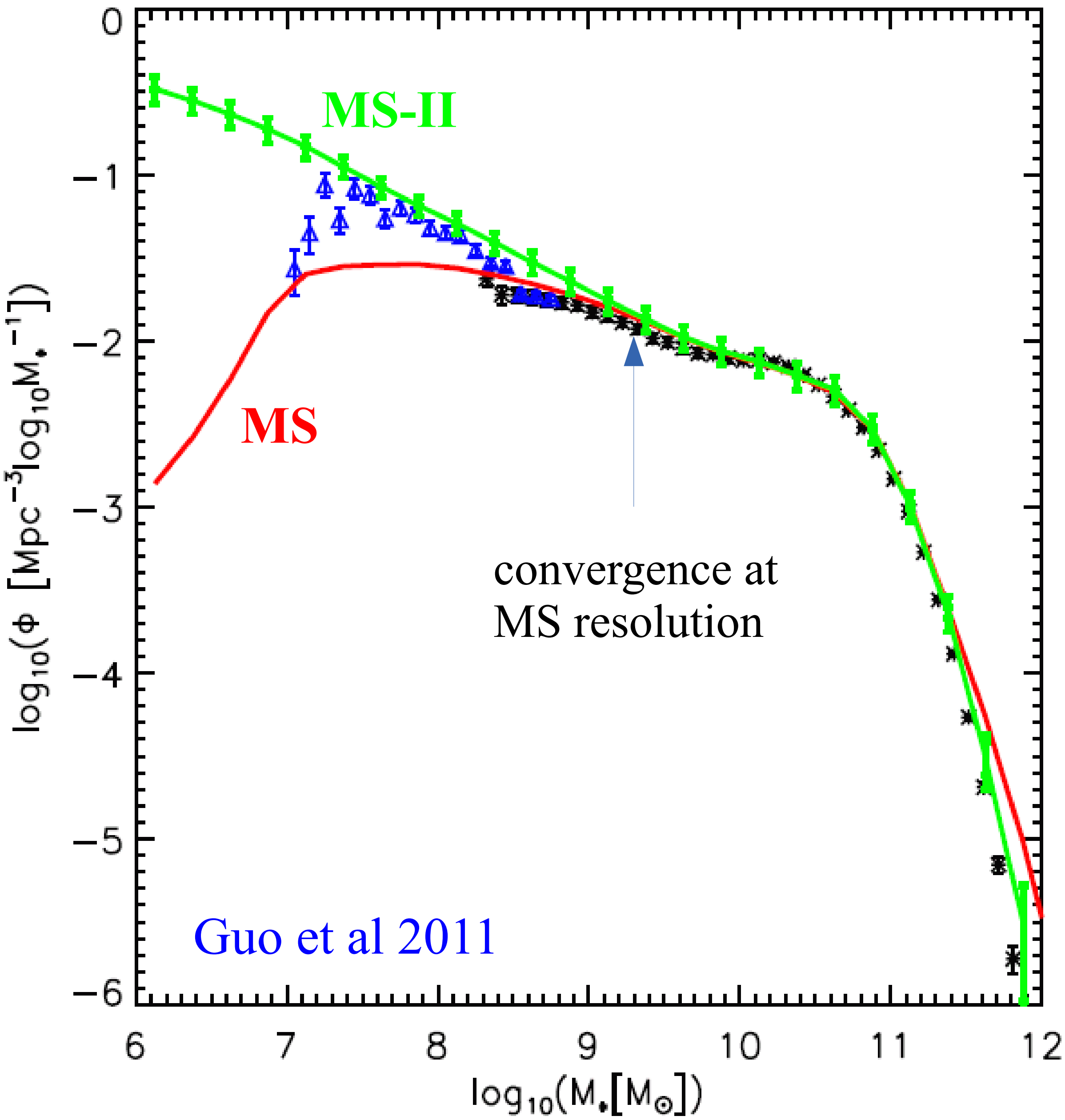
Extend to properties of dwarf galaxies

Improve/extend treatments of "troublesome" astrophysics

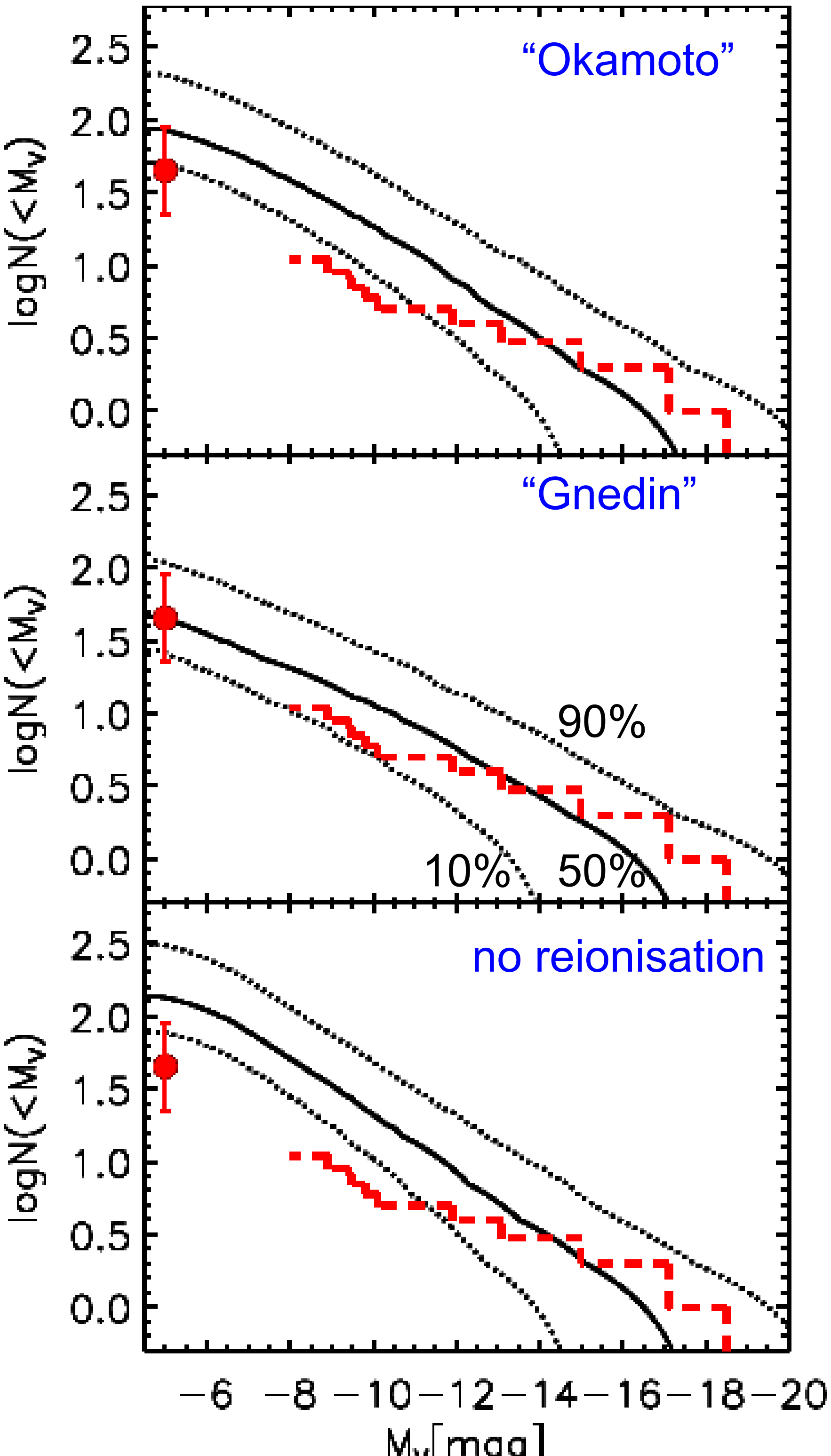
Adjust parameters to fit new, more precise data

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!



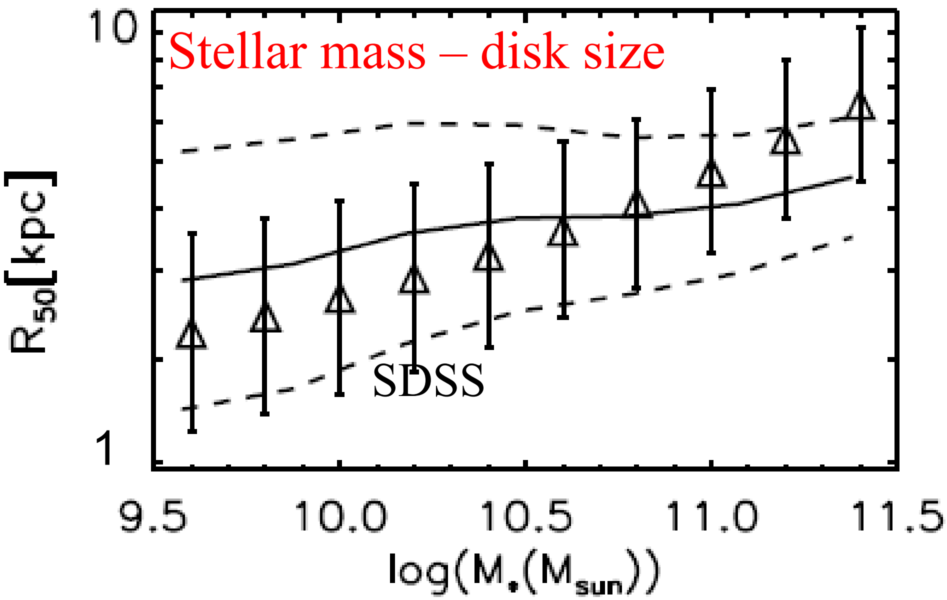
Luminosity function of Milky Way satellites

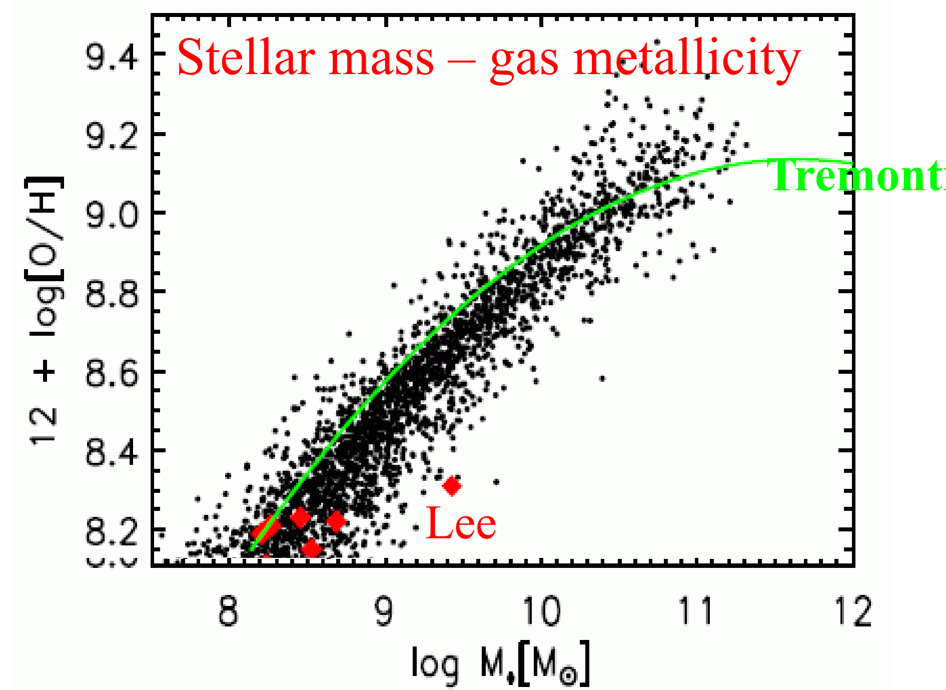
Luminosity functions of satellites around 1500 "Milky Ways" i.e. isolated disk galaxies with log $M_* = 10.8$

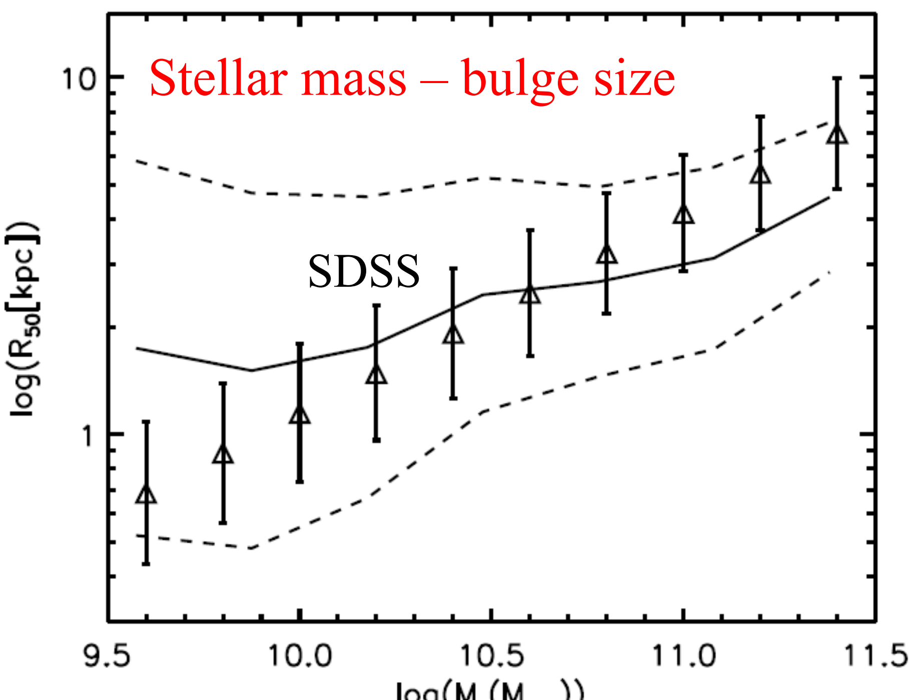
Guo et al 2011

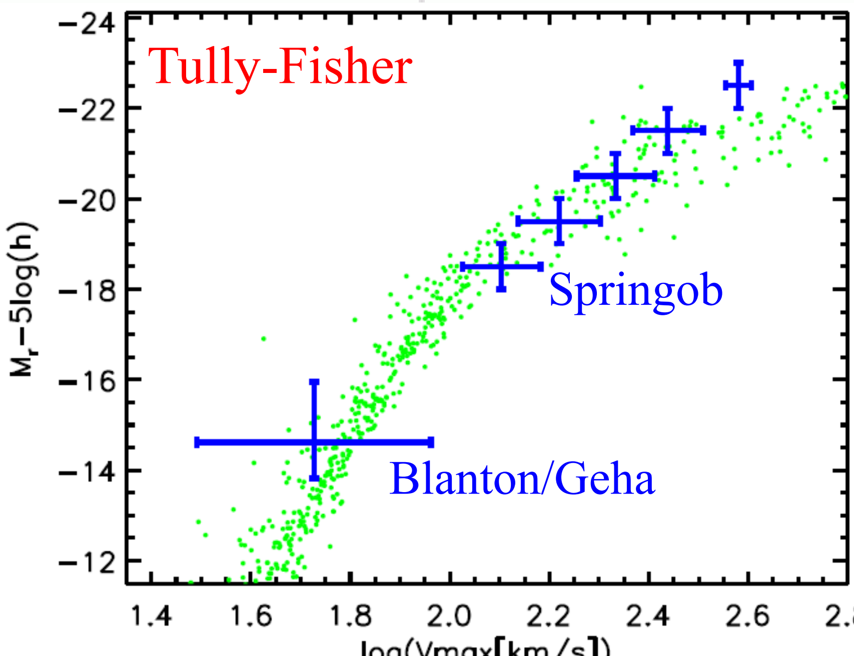
Scaling relations

Guo et al 2011



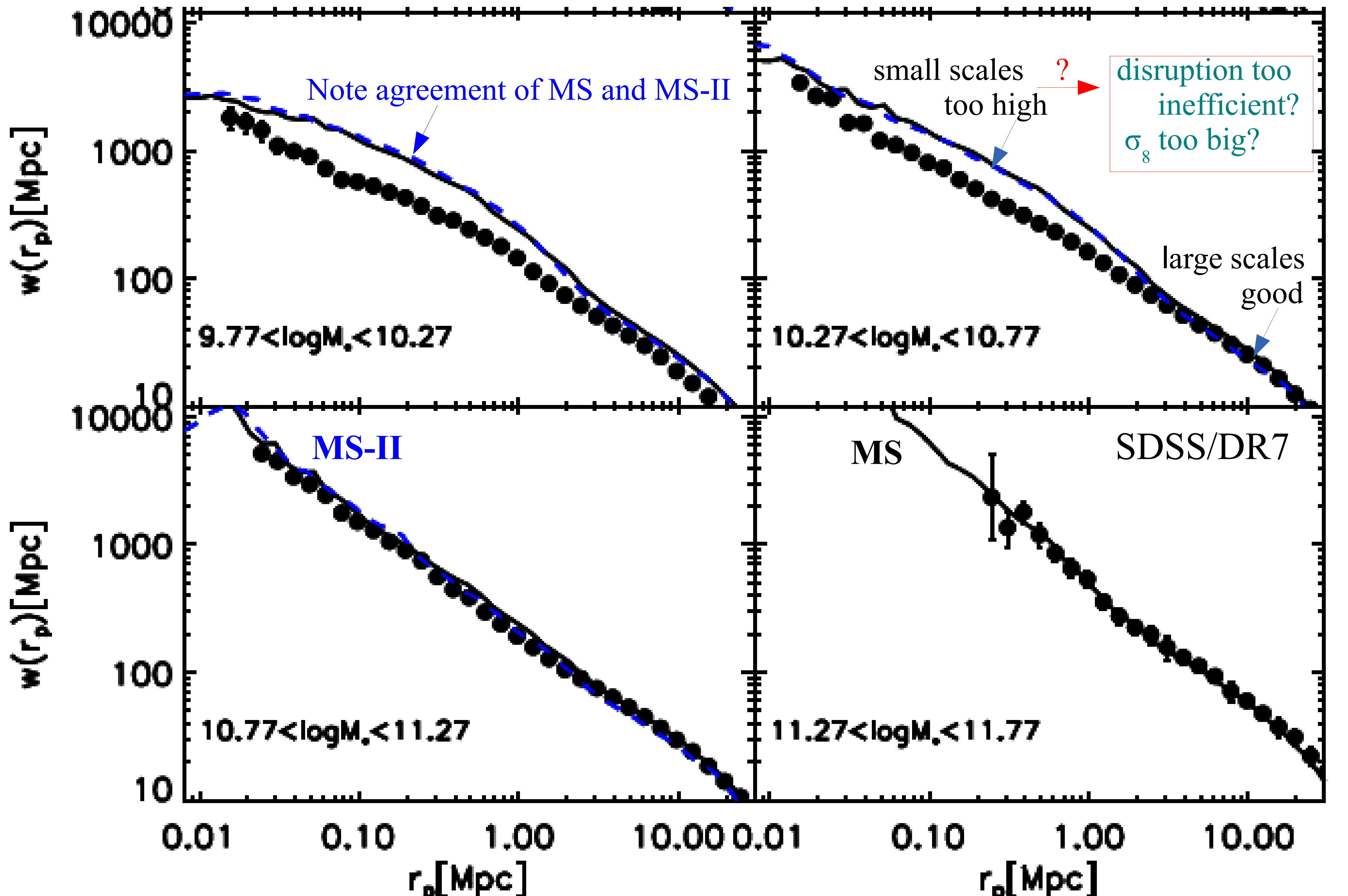




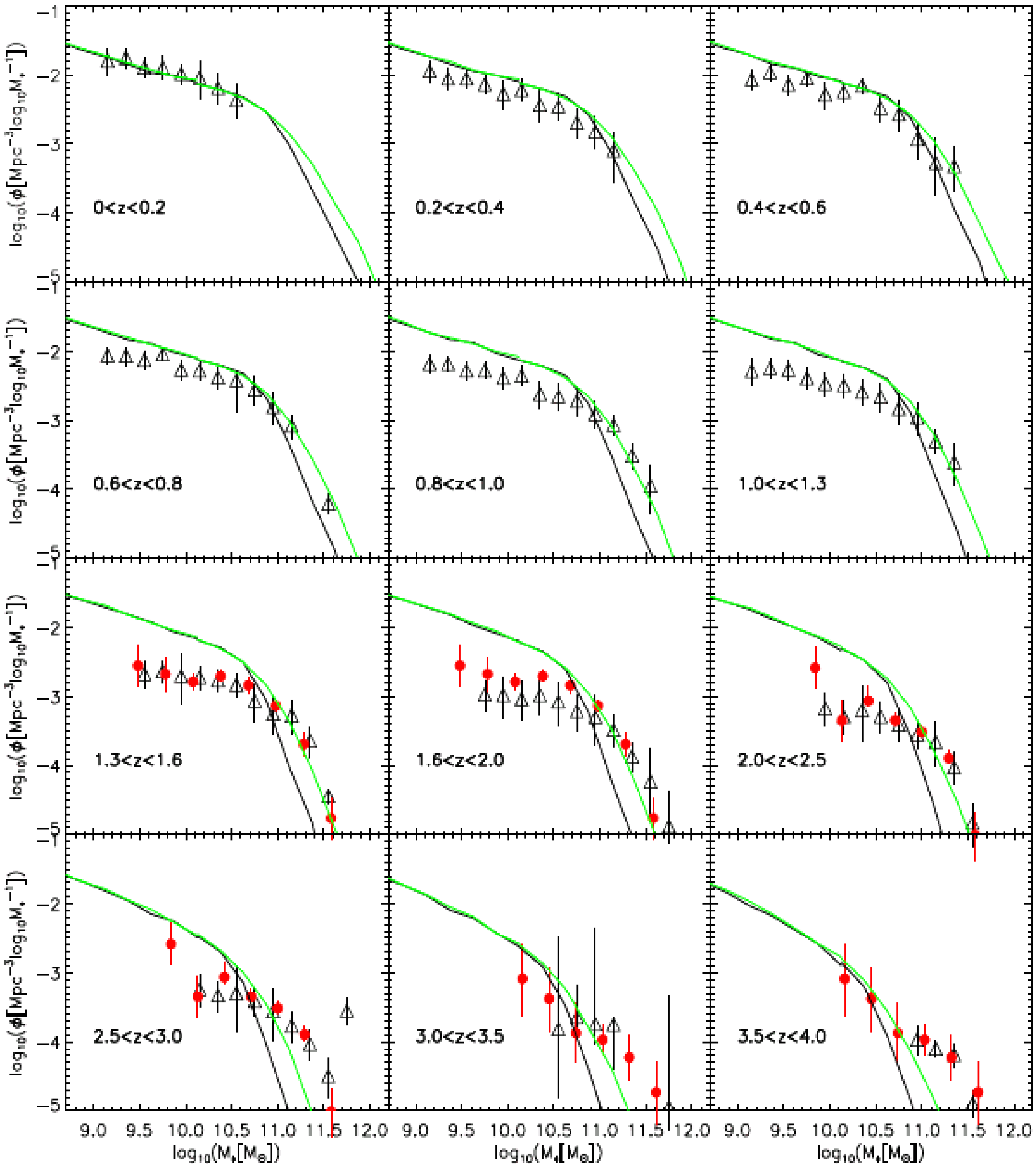


Mass-dependent galaxy clustering

Guo et al 2011



Evolution of stellar mass function



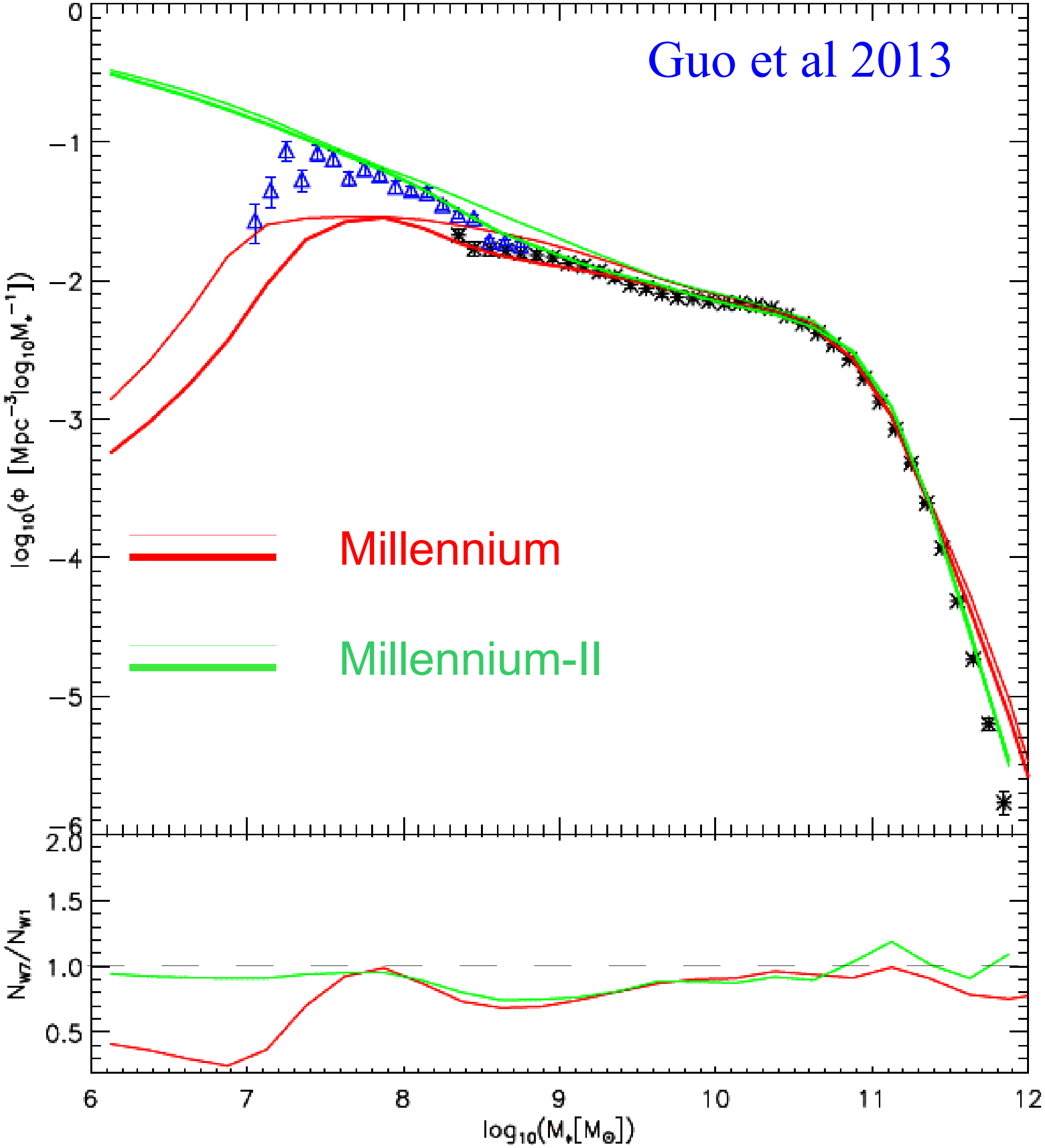
△ Perez-Gonzalez et al 2008

● 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



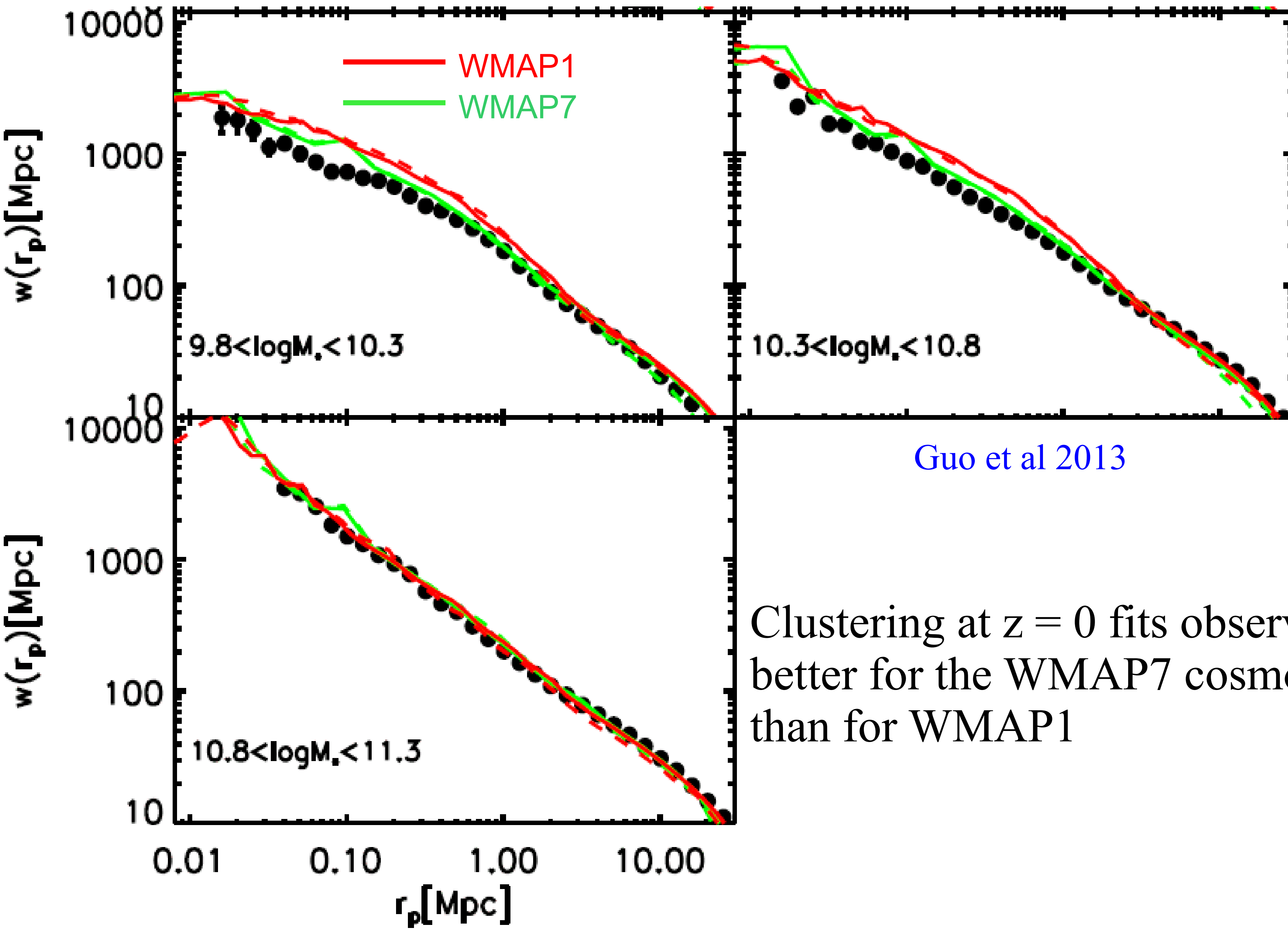
Switching from WMAP1 to WMAP7

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

$\sigma_8 = 0.90$ → $\sigma_8 = 0.81$

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

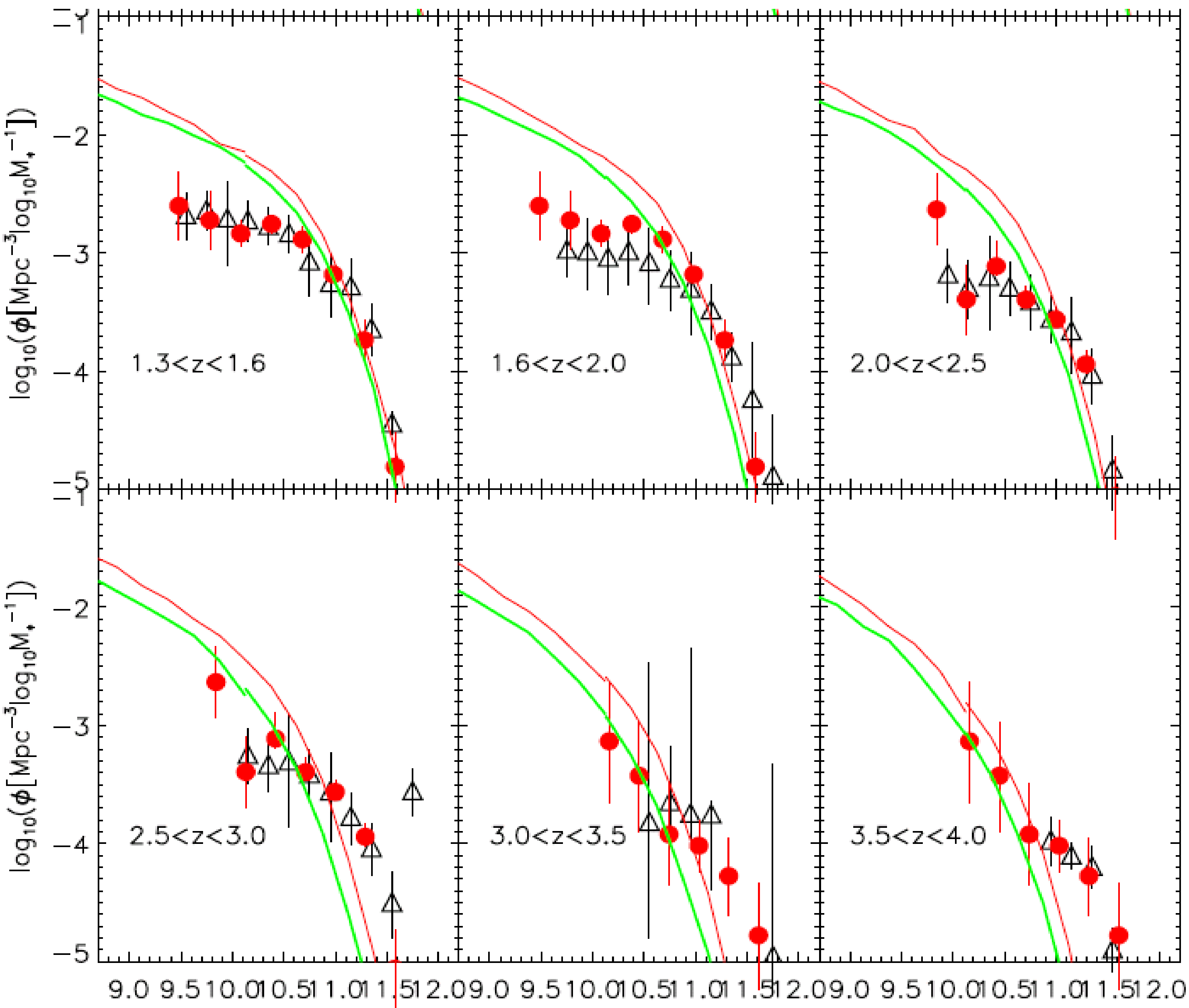


Guo et al 2013

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

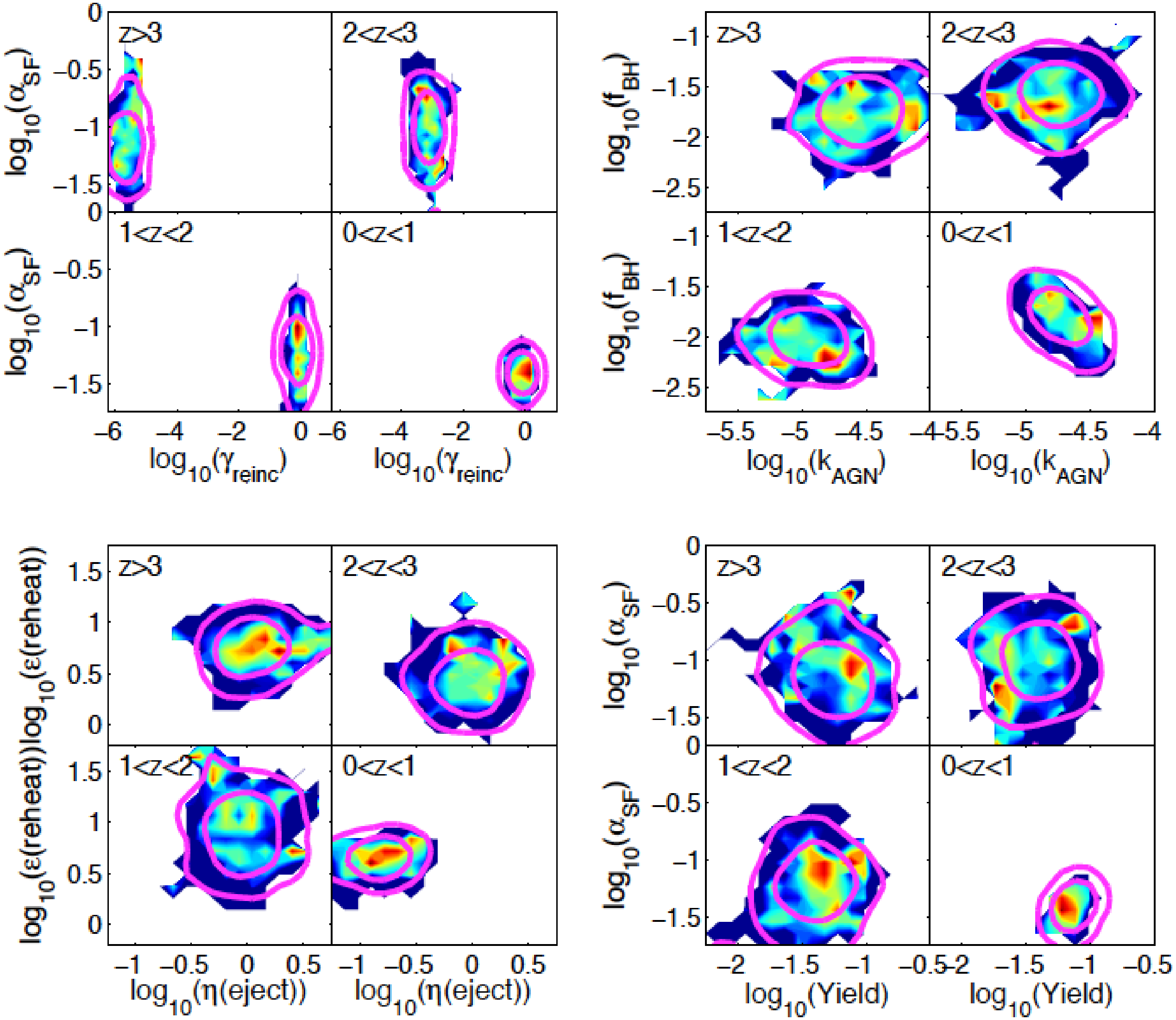
Switching from WMAP1 to WMAP7

Guo et al 2013



..but the galaxy formation sequence is still incorrect

MCMC allows exploration of parameter space



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

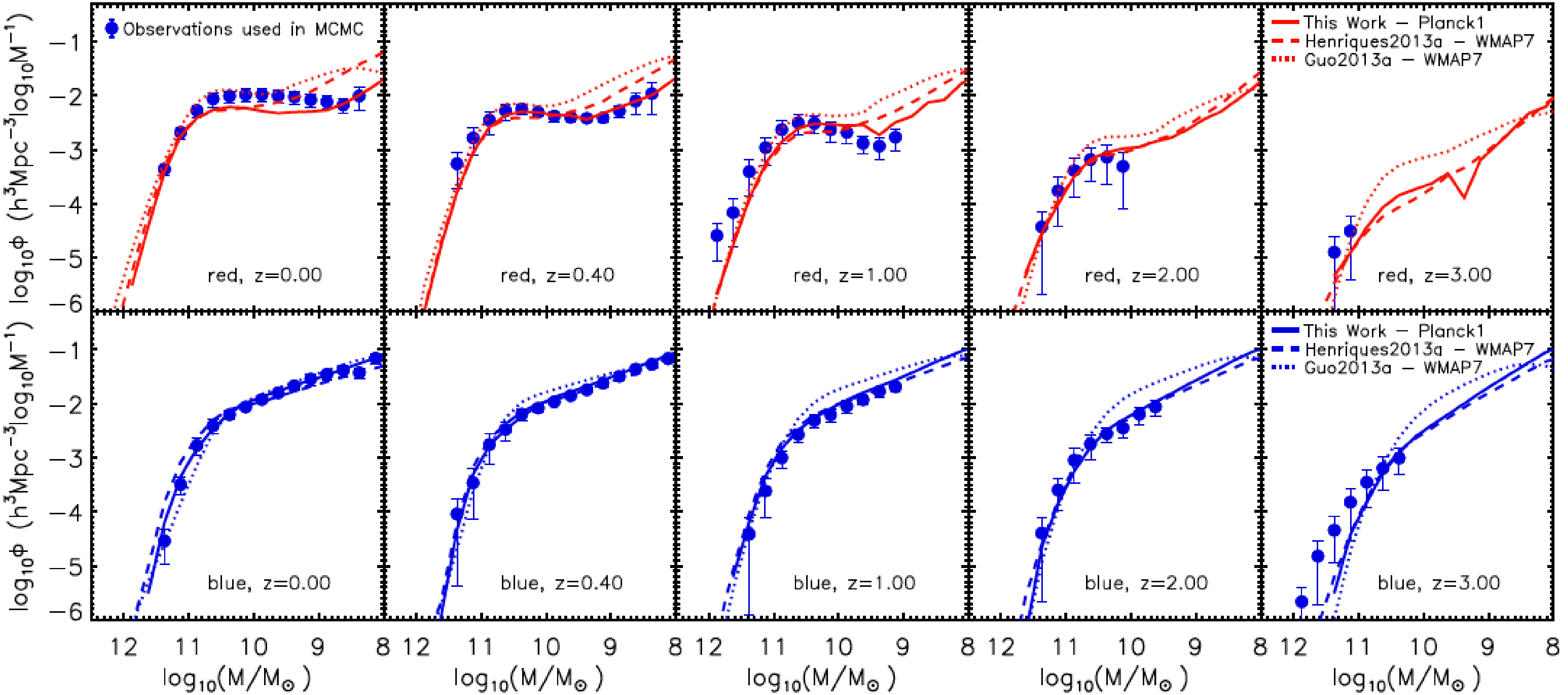
Parameters are determined by data at each individual redshift

No parameter set is consistent with data at all redshifts

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

Henriques et al 2013

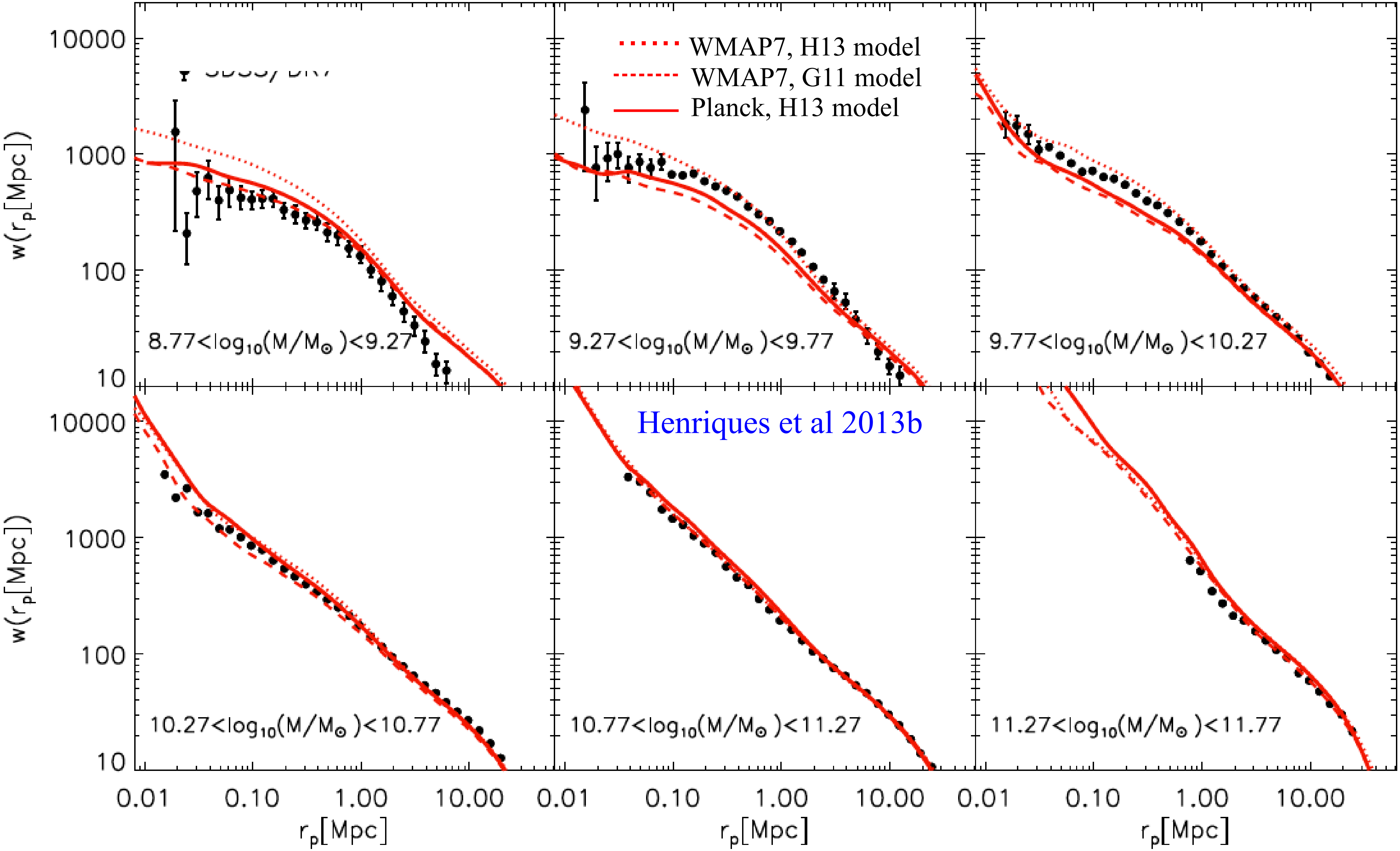
Henriques et al 2013b, Planck cosmology



Changing the assumed timescale for reincorporation of wind ejecta

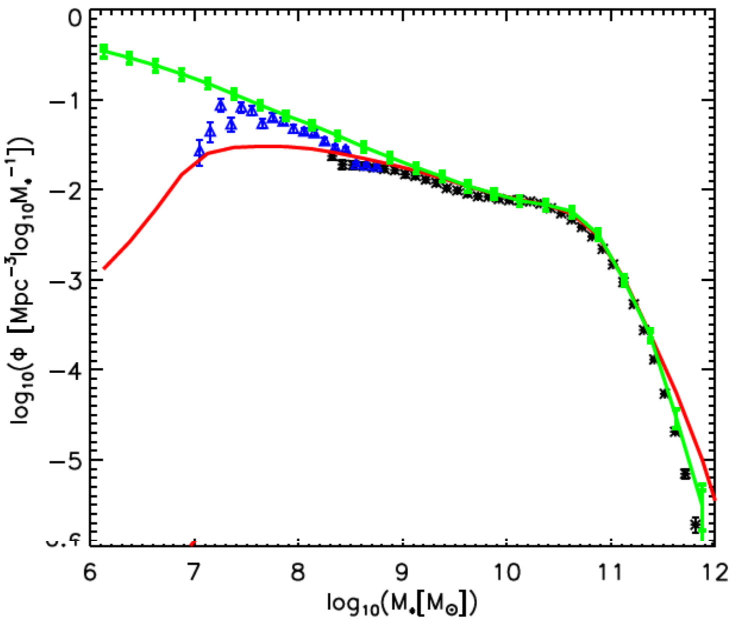
$$t_{return} = const. / H(z)\,V_{halo} \longrightarrow t_{return} = const. / M_{halo}$$

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

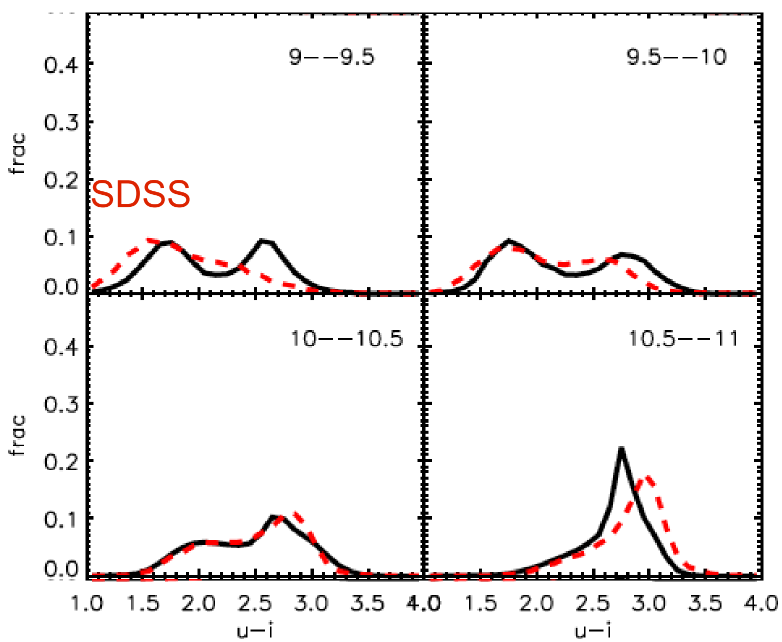


Clustering predictions depend weakly and at a similar level on cosmology and galaxy formation model

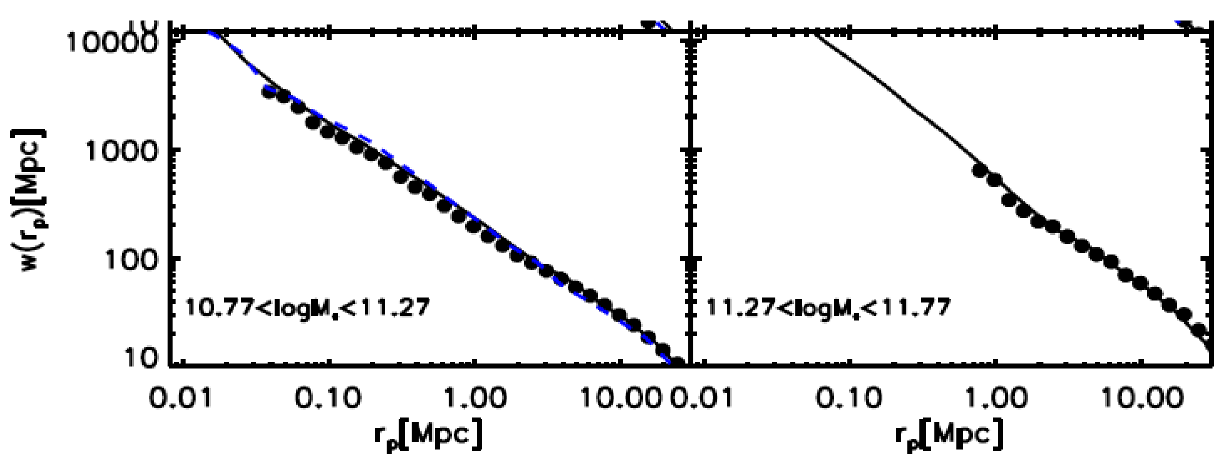
How do we learn from population simulations?



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



Guo et al 2011



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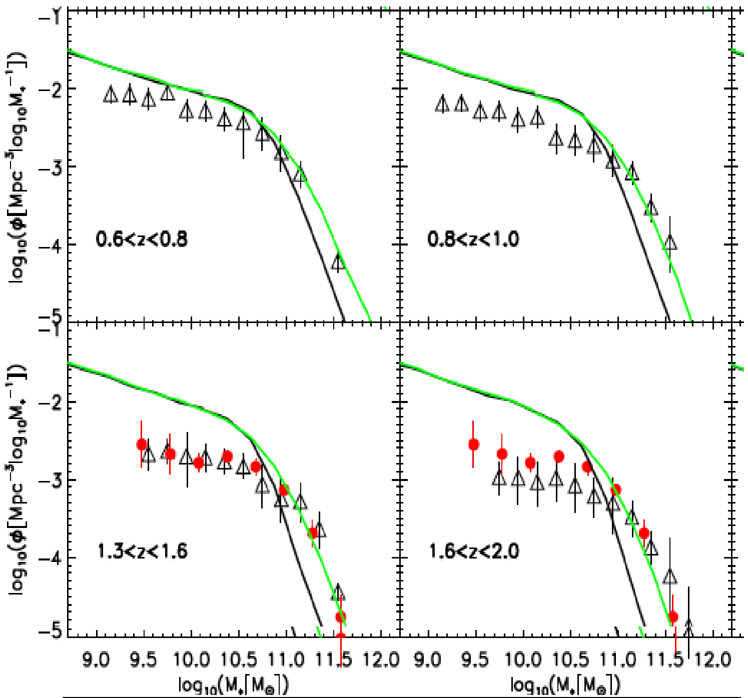
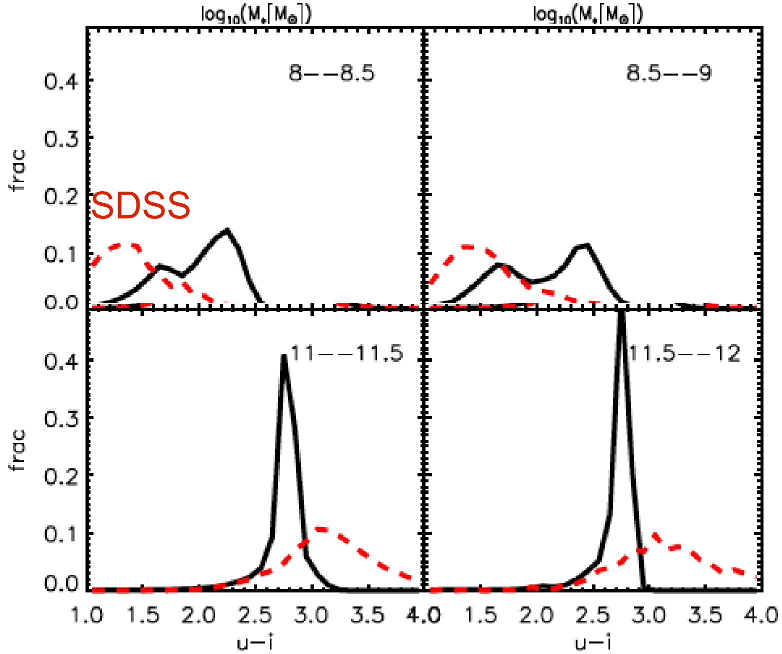


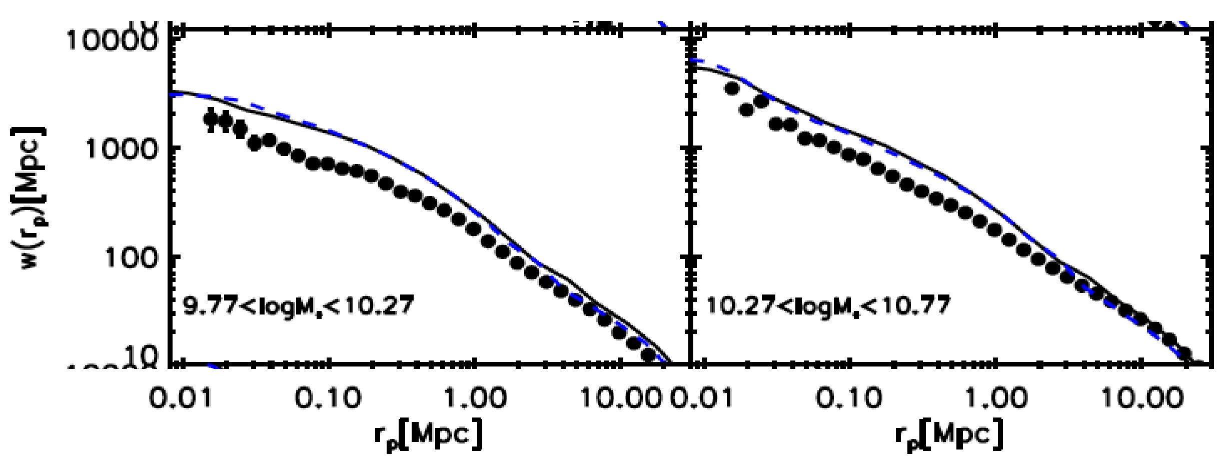
When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

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

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



Guo et al 2011



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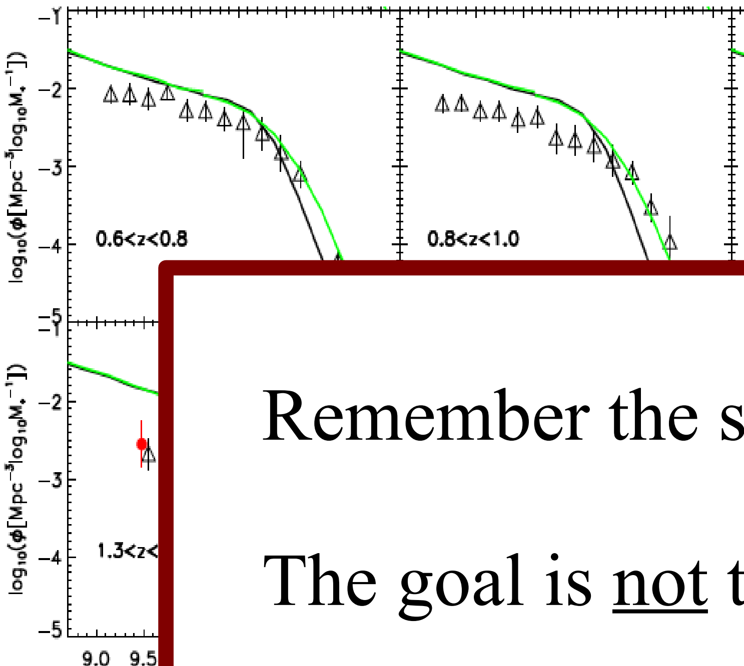


When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

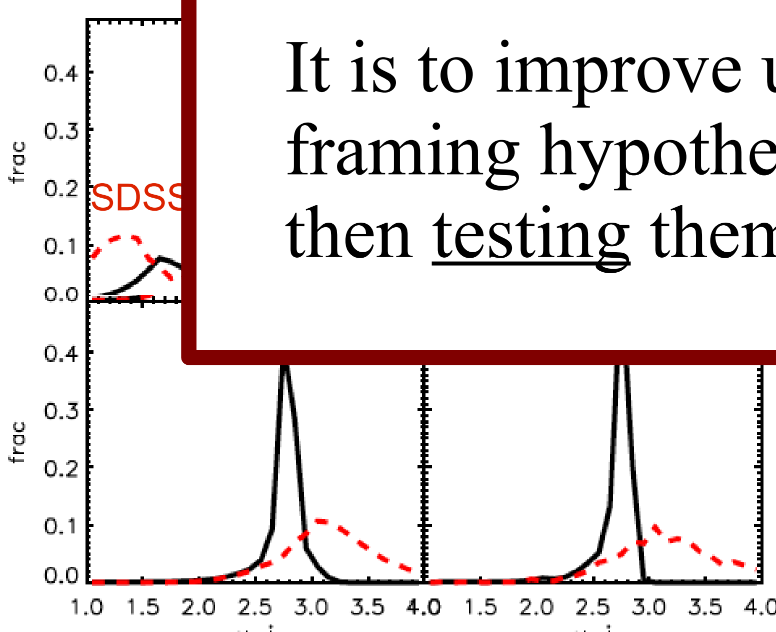
re

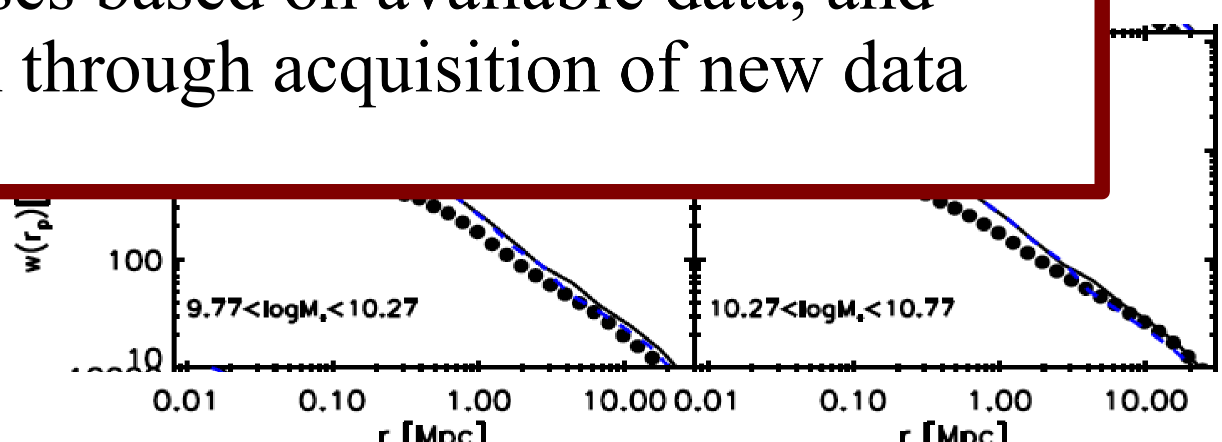
ent

Remember the scientific method!

The goal is <u>not</u> to fit the observations

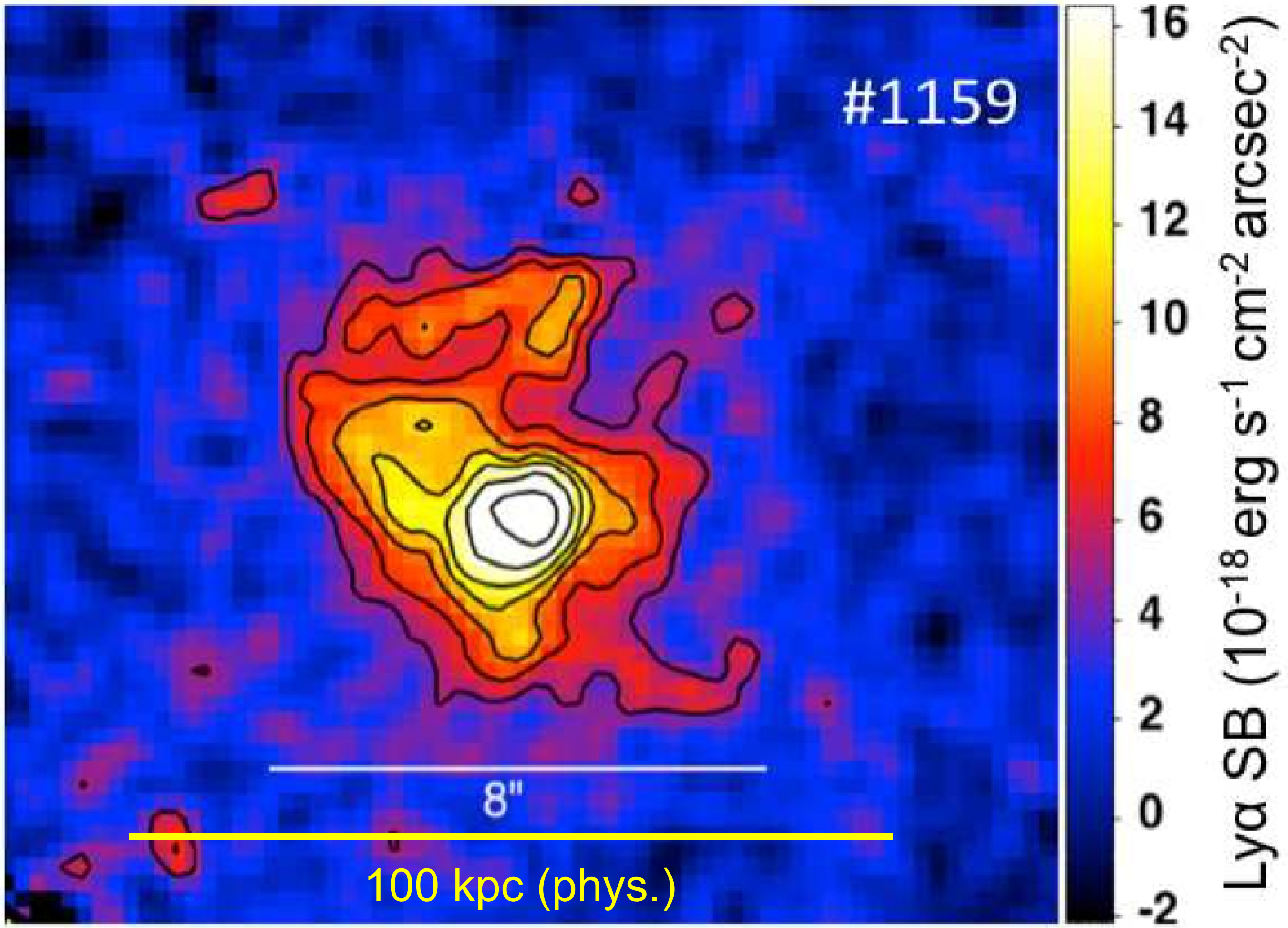
It is to improve understanding of the real world by framing hypotheses based on available data, and then <u>testing</u> them through acquisition of new data



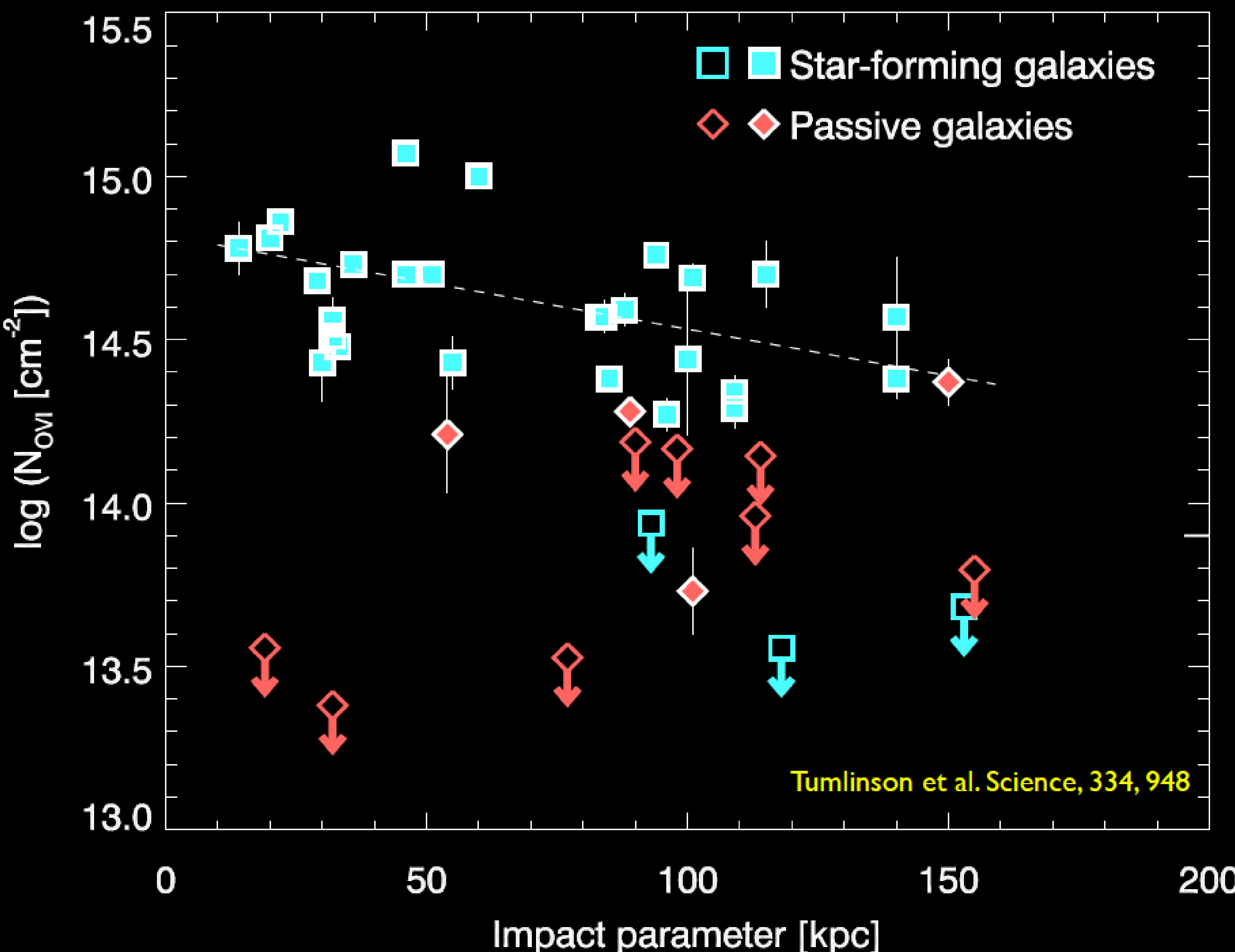


UV input to galaxy formation

Cantalupo, Lilly & Haehnelt 2013

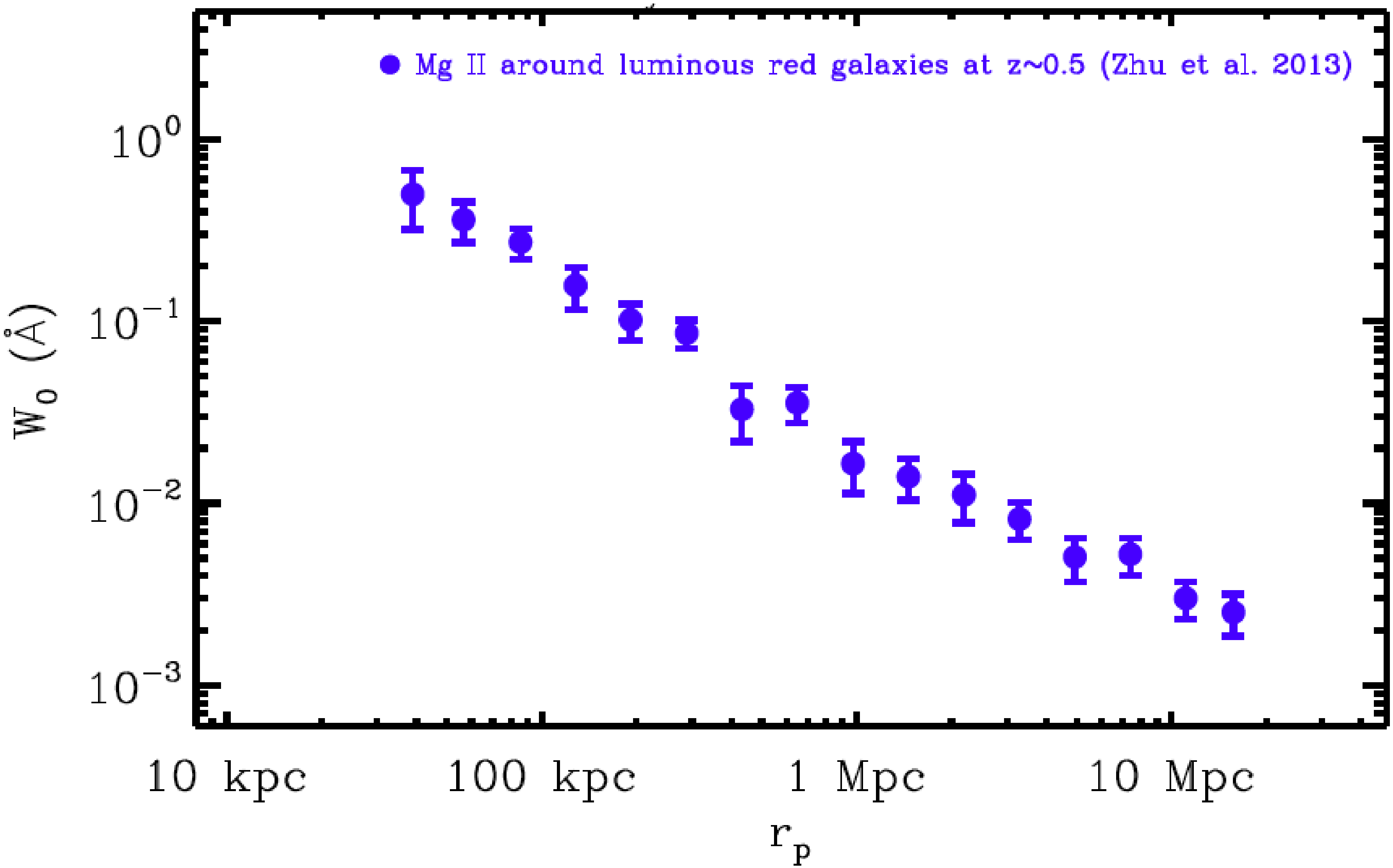


Ly α flourescent emission from cold filaments around a z=2..4 quasar
Gas flow into galaxies



At least as much oxygen is estimated in the CGM as in the ISM of galaxies
Outflows from galaxies!

The galaxy-gas correlation function



MgII is distributed around passive galaxies similarly to the dark matter (from Guangtun Zhu & Brice Ménard) Outflows to large distances?

in conclusion...

- The initial conditions for galaxy formation are now precisely known in terms of both baryon/DM/radiation content and structure
- Simulations of nonlinear structure growth give precise and detailed statistics for the assembly history of halos of all relevant masses
- Implementation of simplified treatments of baryonic processes (inflow, condensation, star and BH formation, enrichment, feedback, mergers...) gives *numerically converged* predictions for the full galaxy population
- These can be compared directly with the galaxy abundances, scaling relations and clustering found in large observational surveys, giving insight into galaxy formation processes
- Recent UV input to galaxy formation has been through absorption and emission line studies of the circum- and intergalactic media