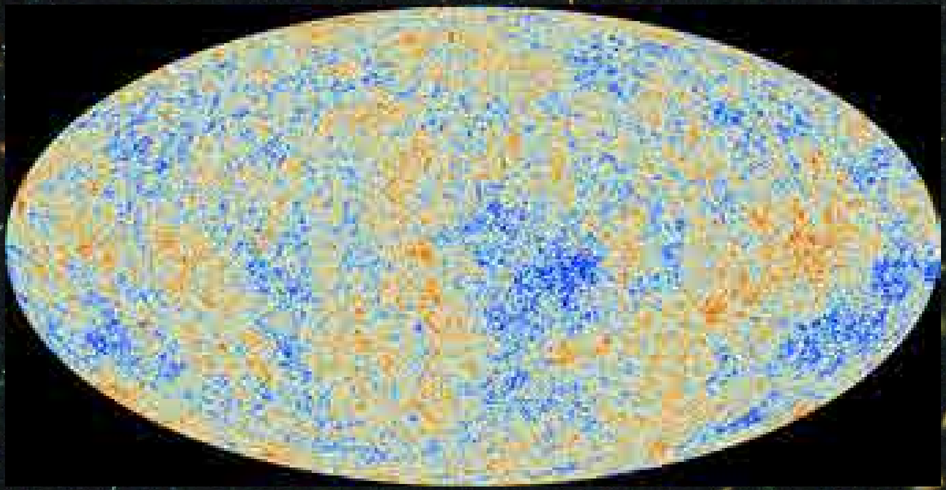
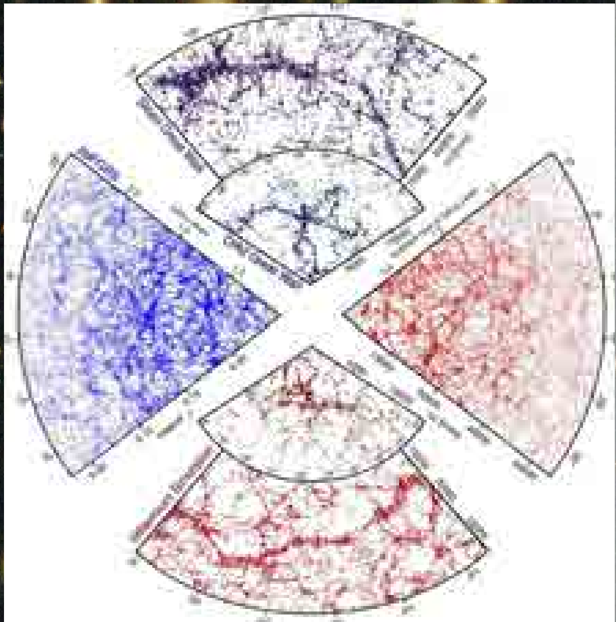
IPMU, November 2015



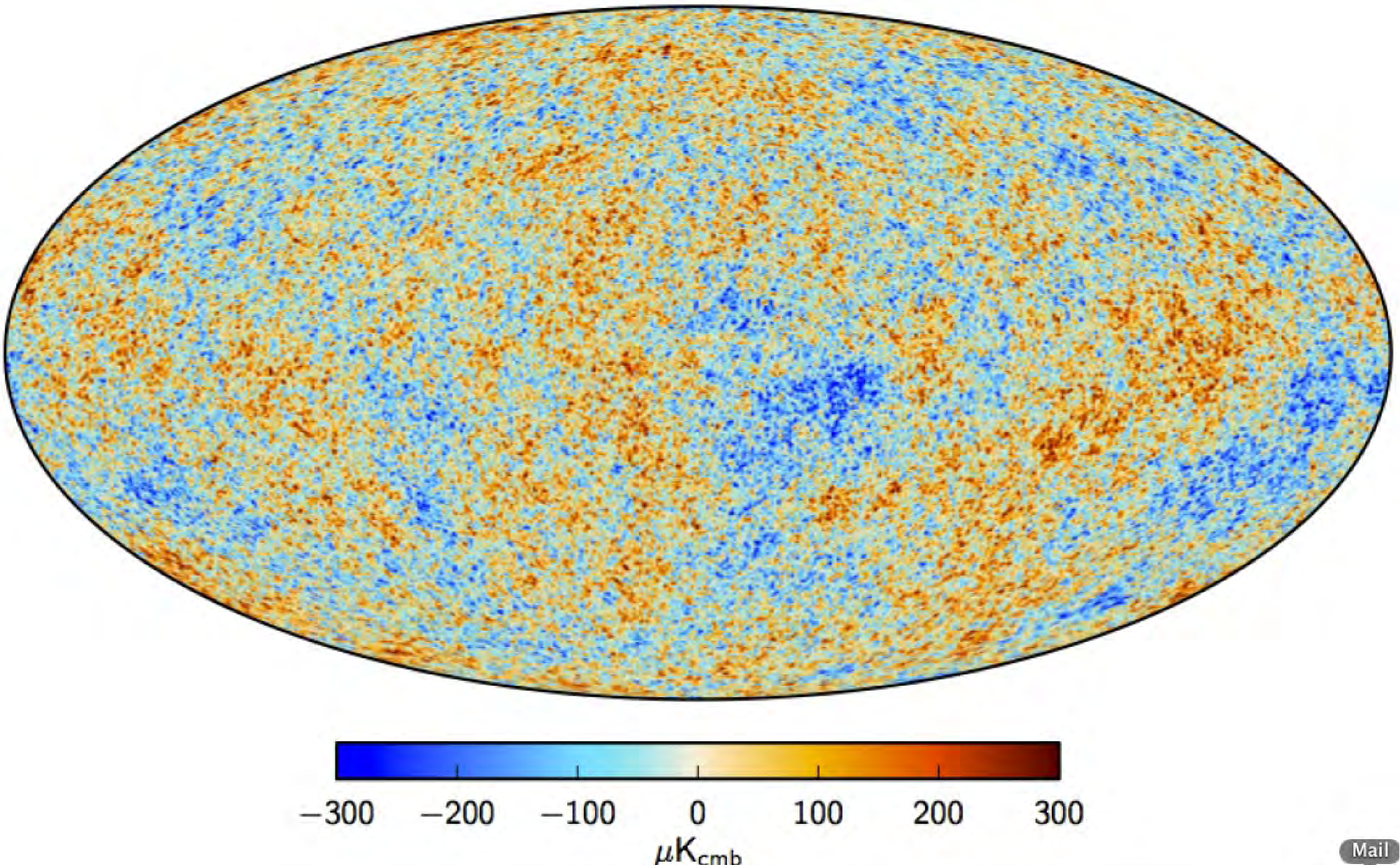
The formation and evolution of the galaxy population



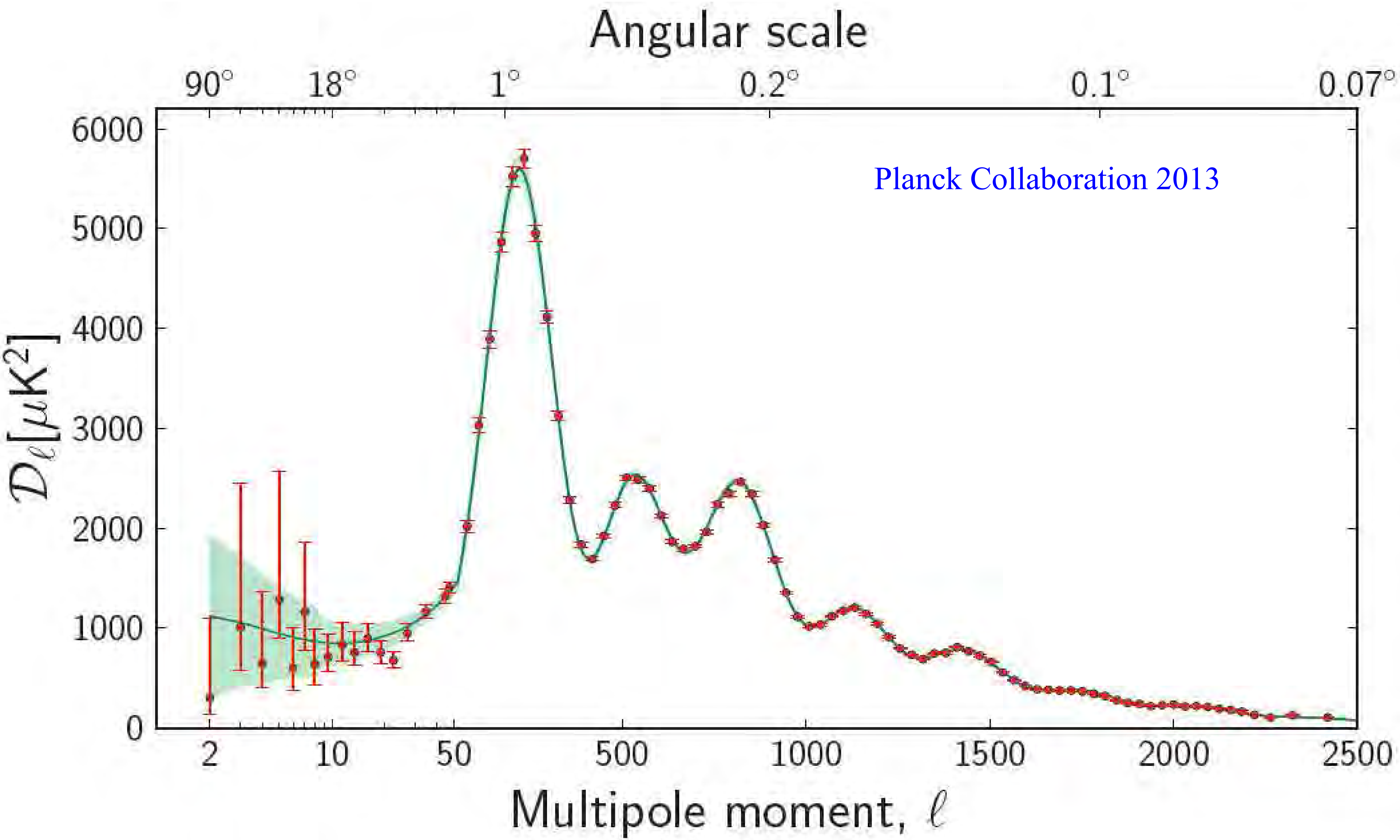
Simon White

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 Collaboration 2013

	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!

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86σ in 2015 using *Planck* data alone!!

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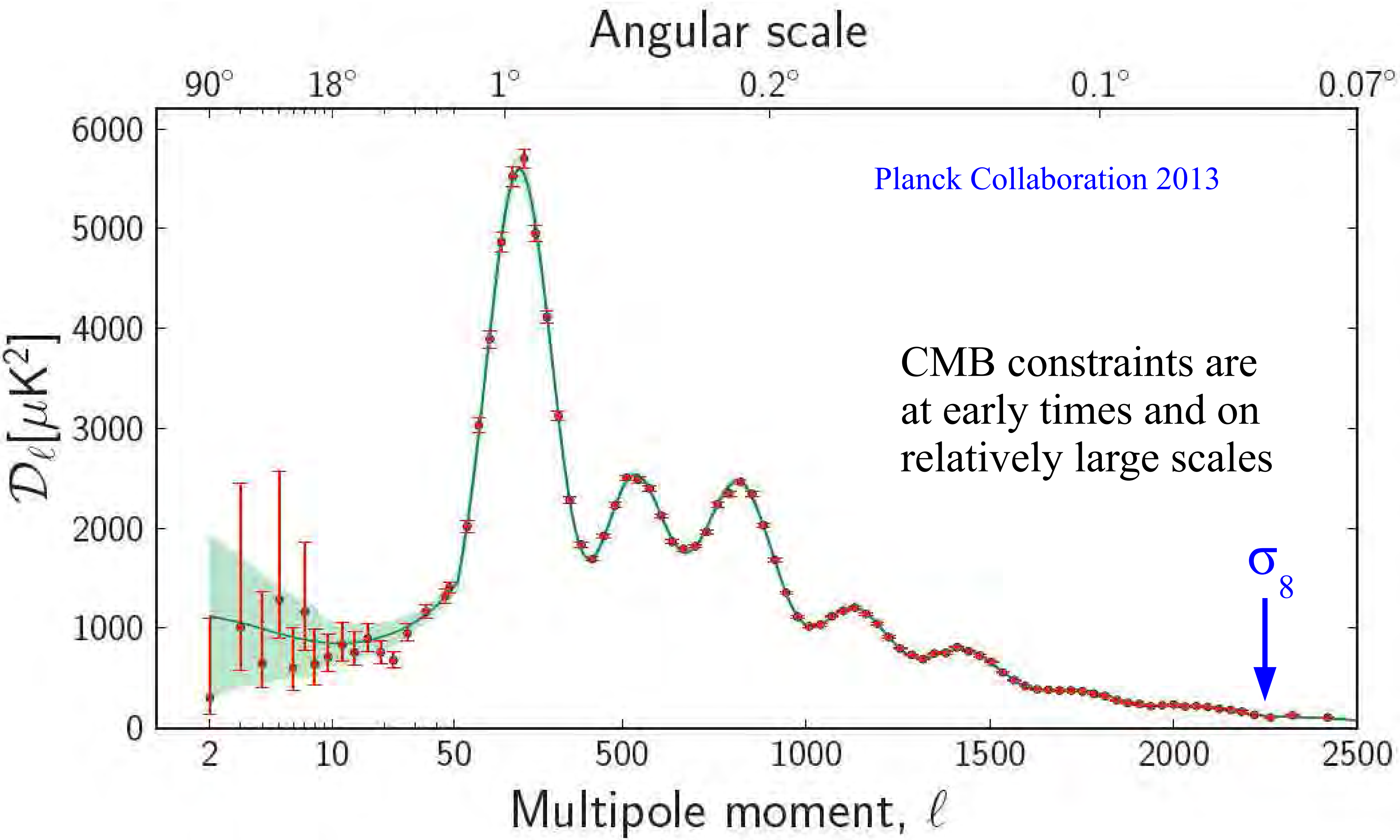
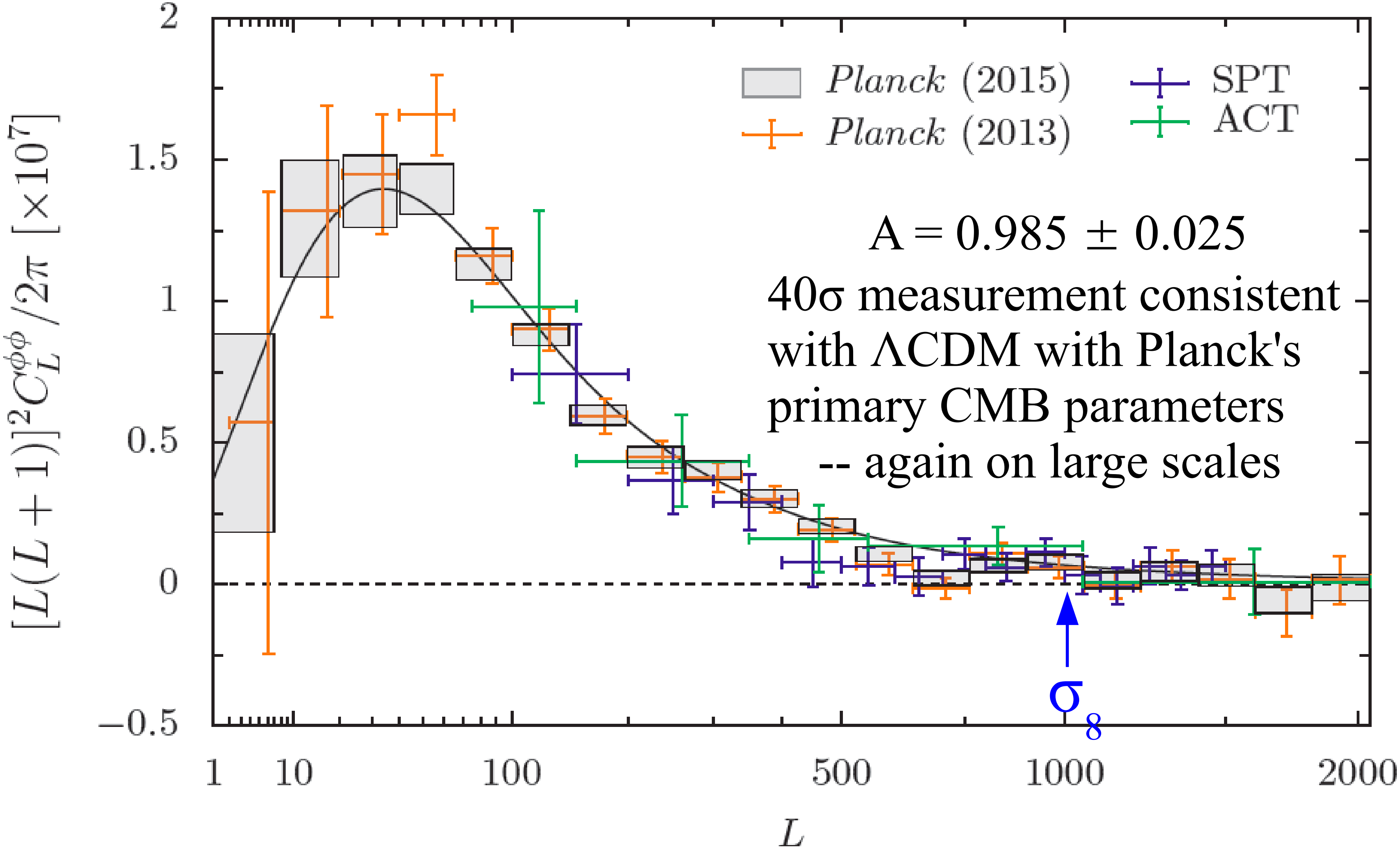
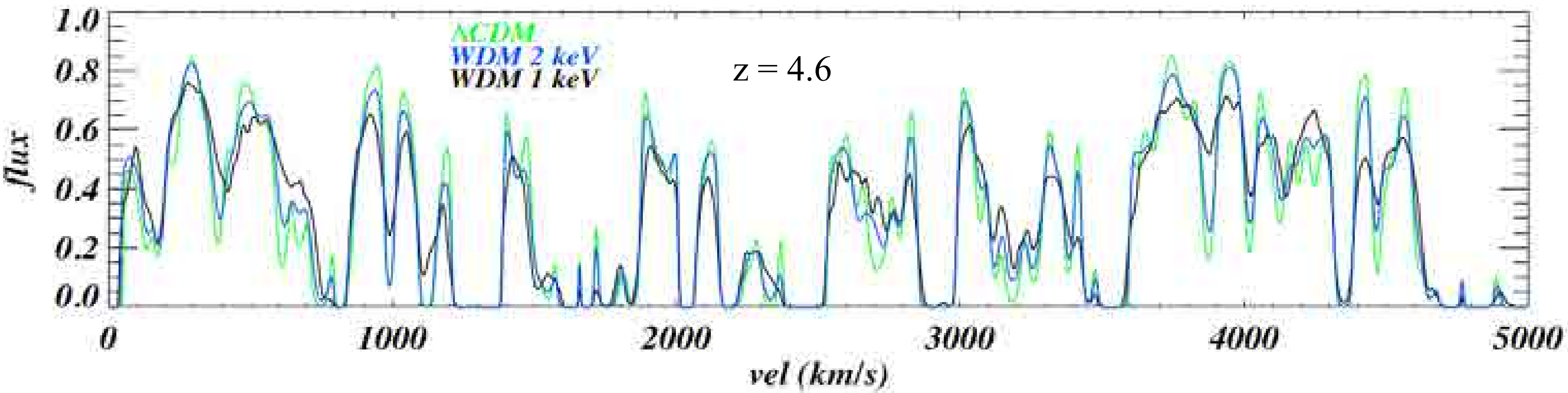


Late-time mass fluctuations from CMB lensing



Ly α forest spectra and small-scale initial structure

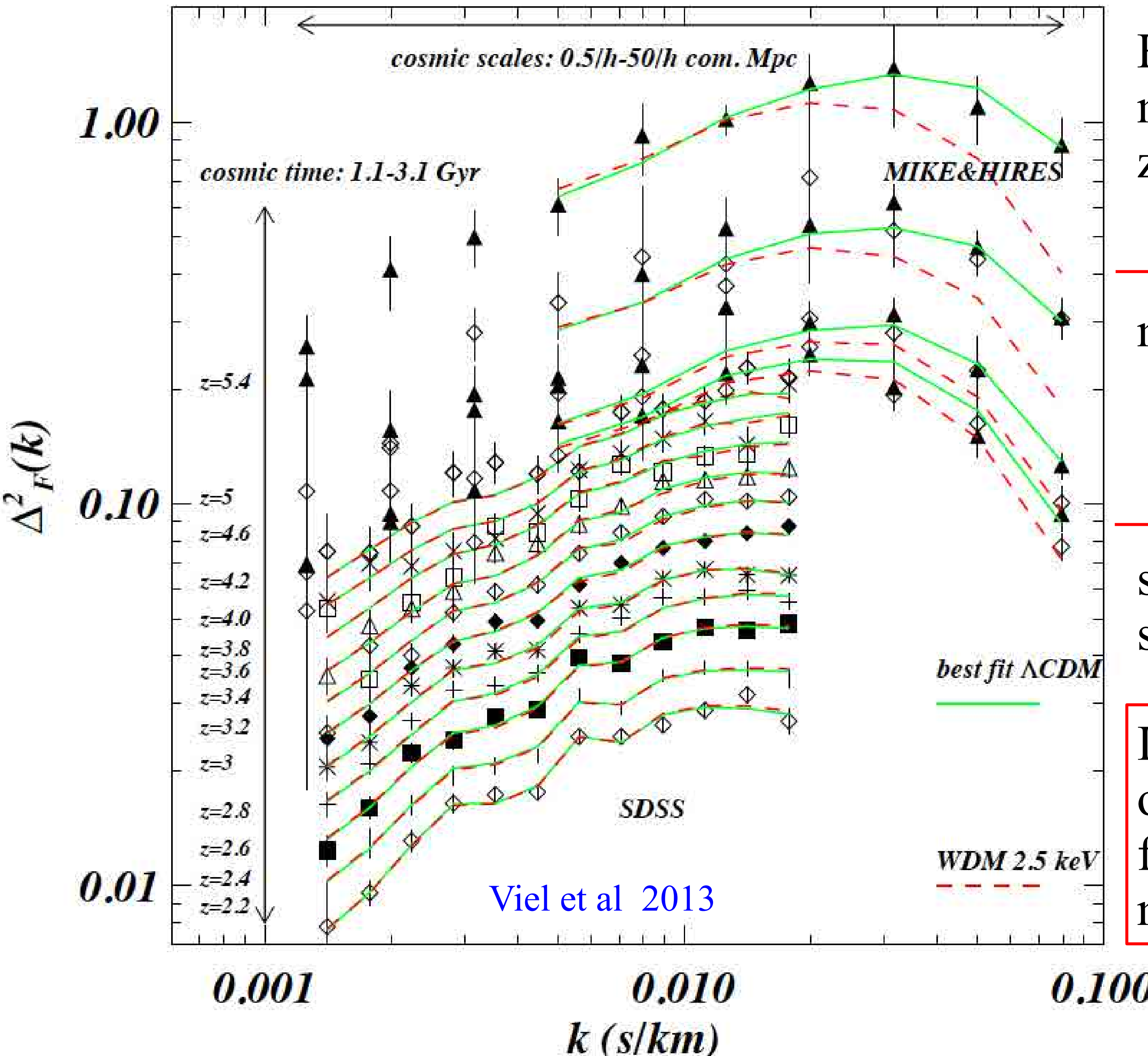
Viel, Becker, Bolton & Haehnelt 2013



Transmitted quasar flux in hydrodynamic simulations of the intergalactic medium in ΛCDM and WDM models.

High-frequency power is missing in the WDM case

Lyman α forest spectra for WDM relative to CDM



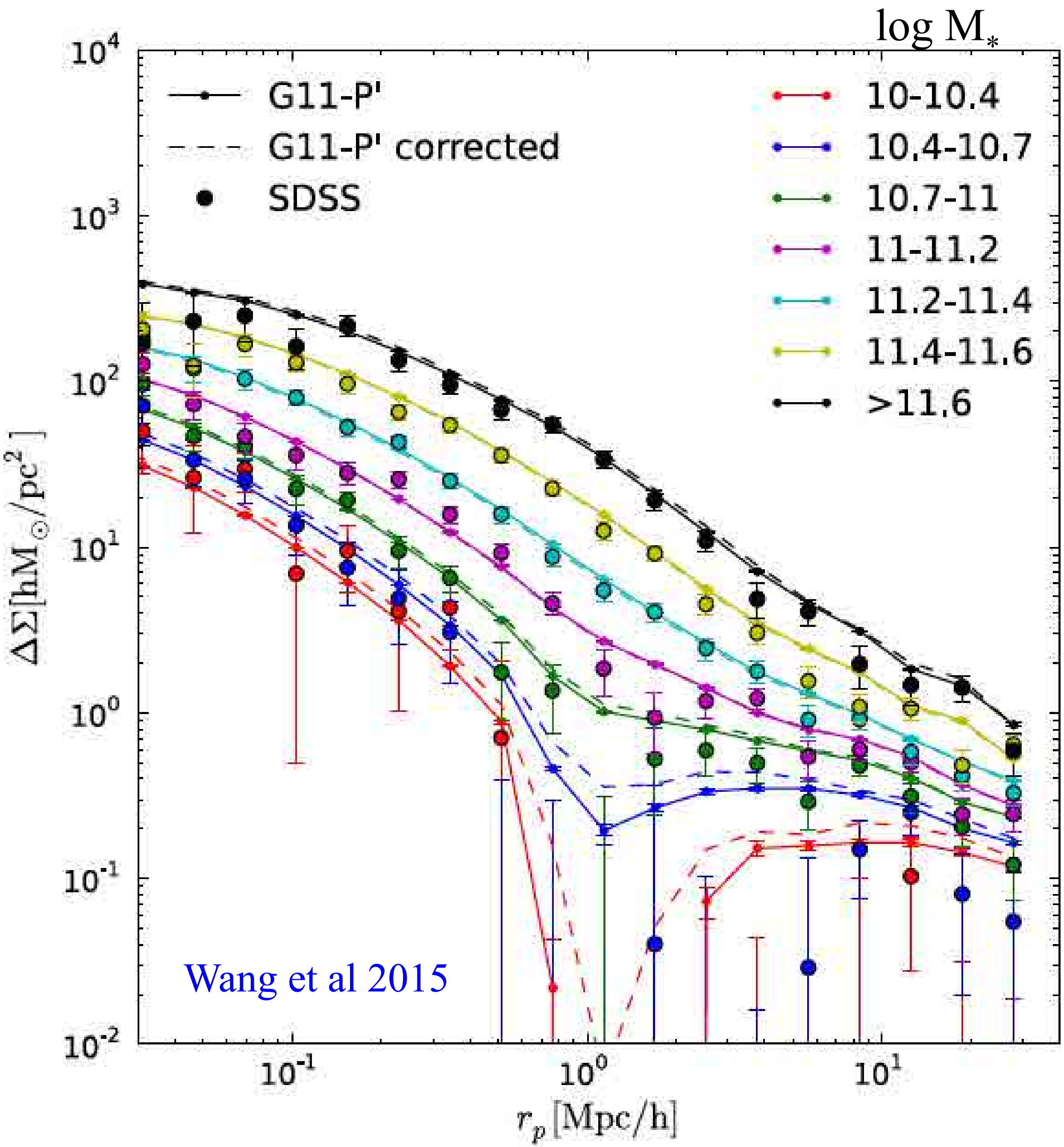
High-resolution spectra match ΛCDM up to z = 5.4

→ 2σ lower limit on the mass of a thermal relic $m_{WDM} > 3.3$ keV

→ WDM can affect the structure only of the smallest galaxies

IC's are well measured on all scales relevant for the formation of the main galaxy population

Mean mass profiles around low-redshift galaxies

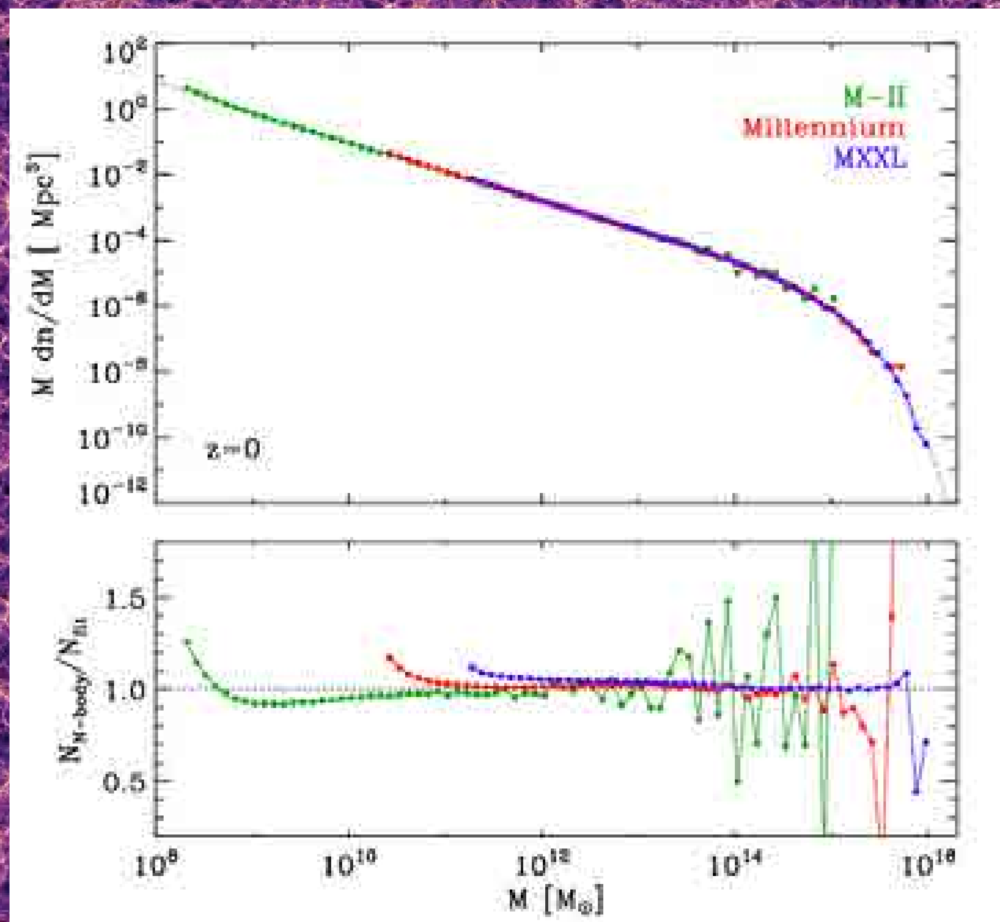


Points are mean weak lensing profiles around SDSS “central” galaxies as a function of their stellar mass.

Lines are from a <u>simulation</u> of the formation of the galaxy population within ΛCDM, assuming Planck parameters.

No simulation parameters were adjusted in this comparison, but the agreement <u>does</u> depend on the astrophysical modelling.

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



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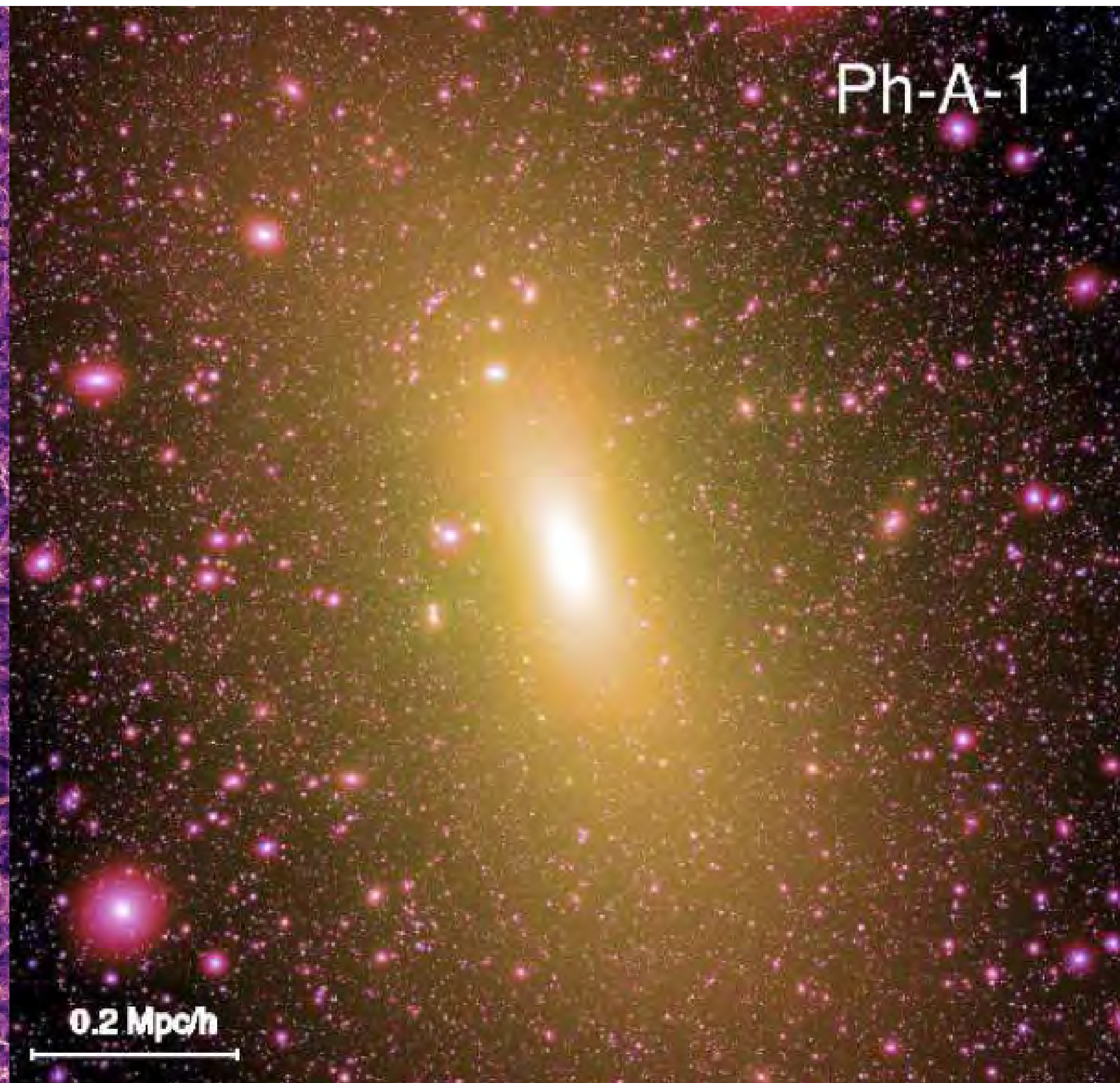
Galaxies correspond to self-bound *subhalos* within halos, rather than to the halos themselves



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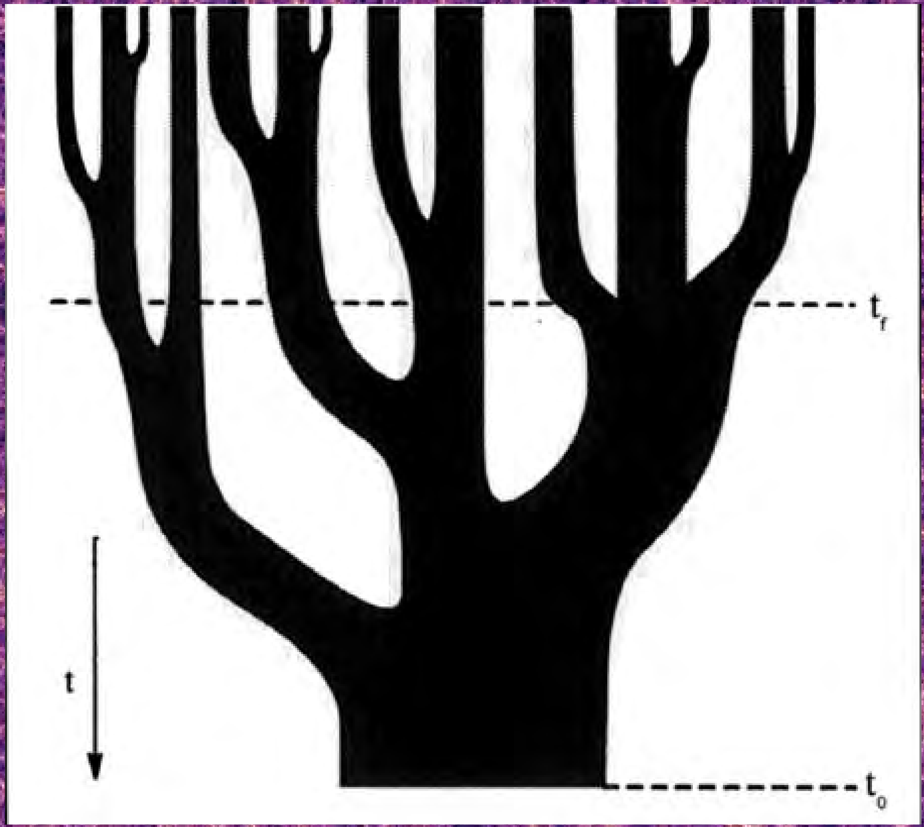
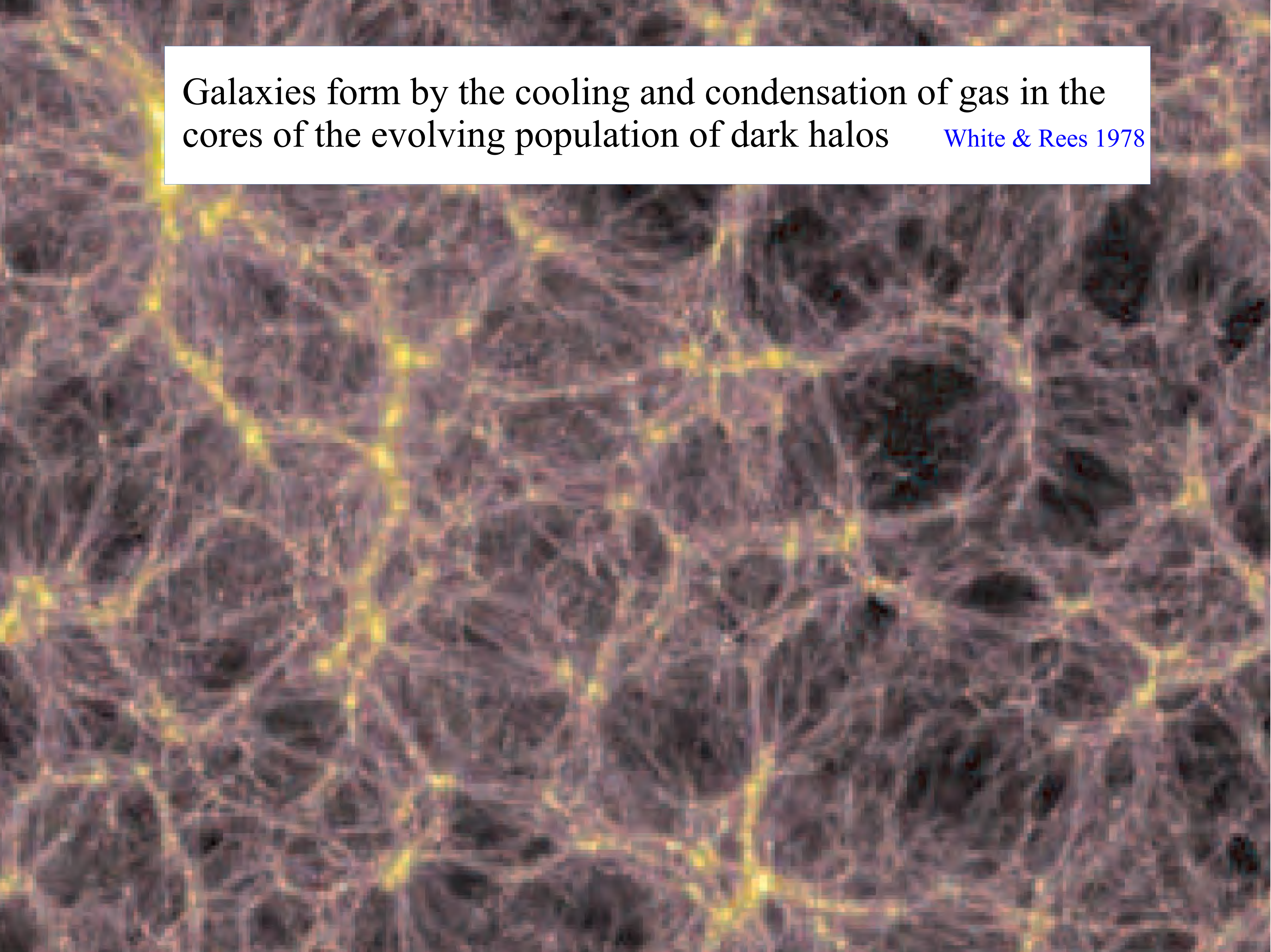
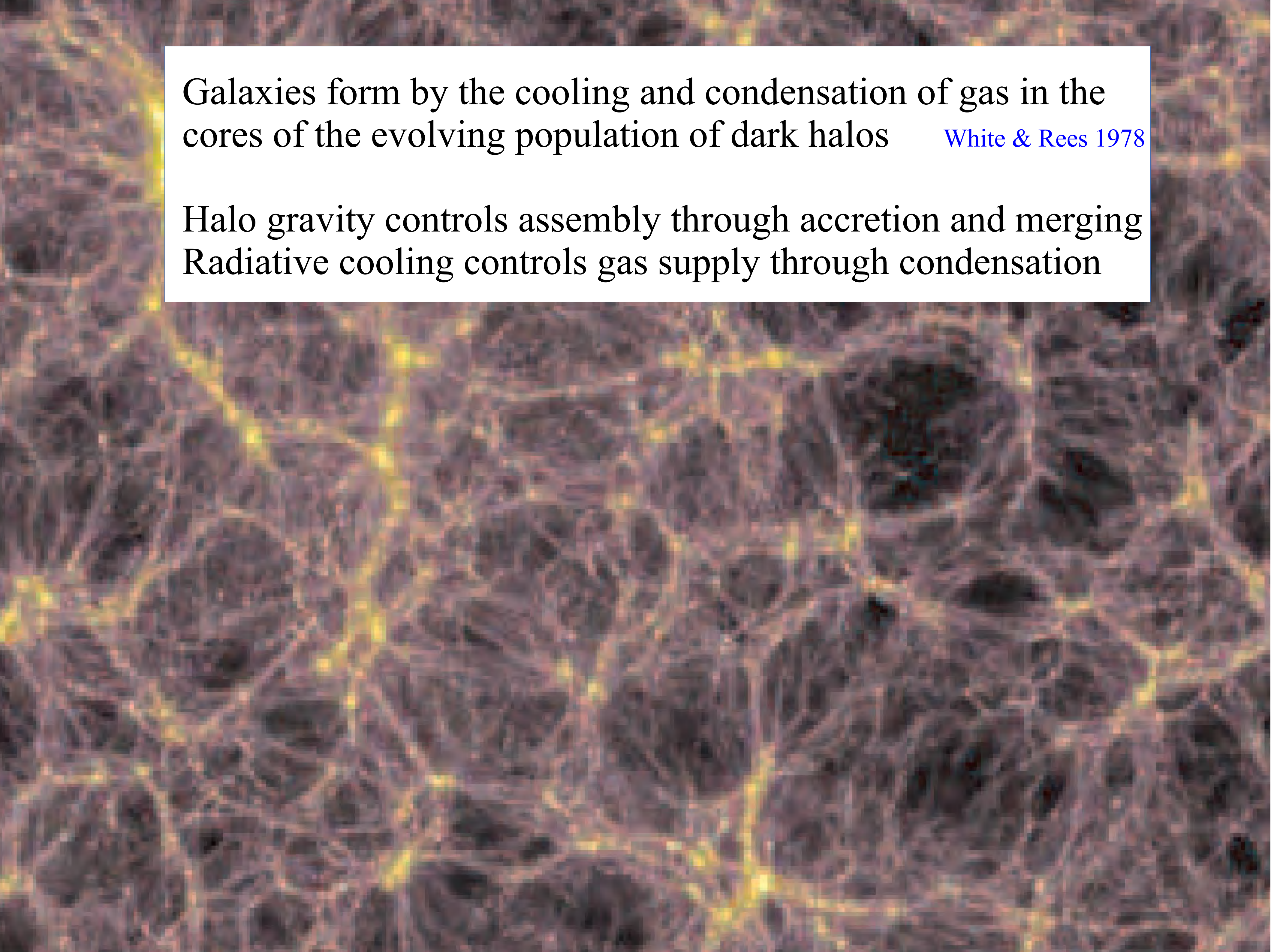
The information relevant to galaxy formation is encoded in *sub*halo merger trees



Galaxies form by the cooling and condensation of gas in the cores of the evolving population of dark halos White & Rees 1978





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

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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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low mass, hi z $$\dot{M}_{\rm inf}(V_c, z) = 0.15 f_g \Omega_b V_c^{-3} G^{-1}.$$ rapid infall "cold flows"

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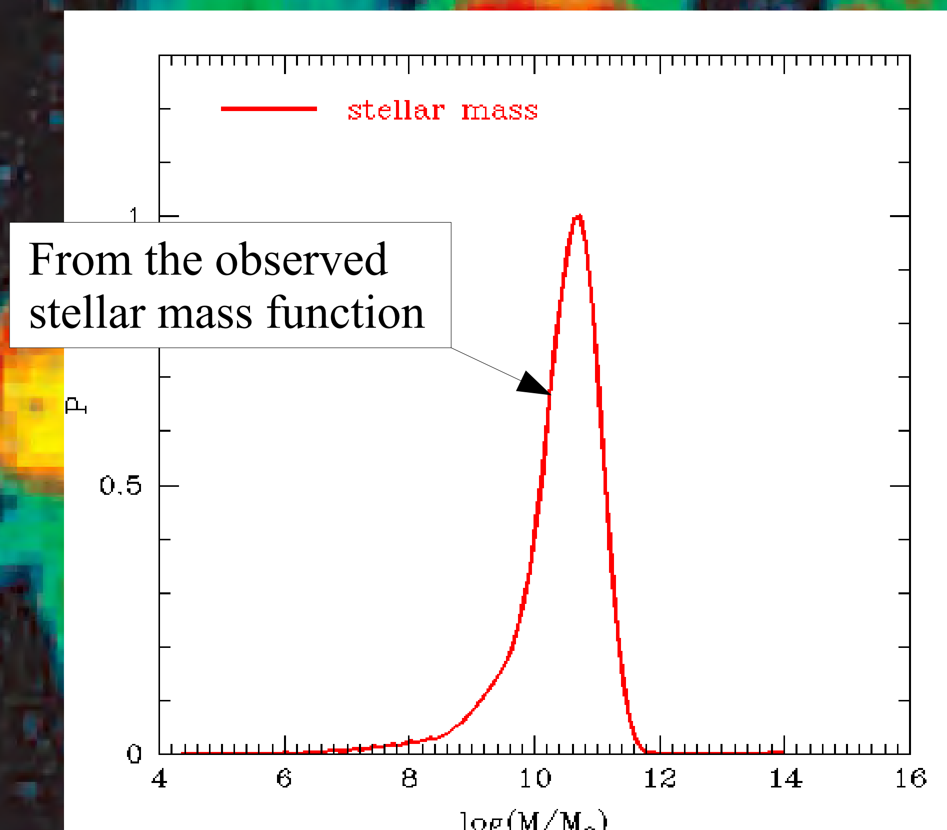
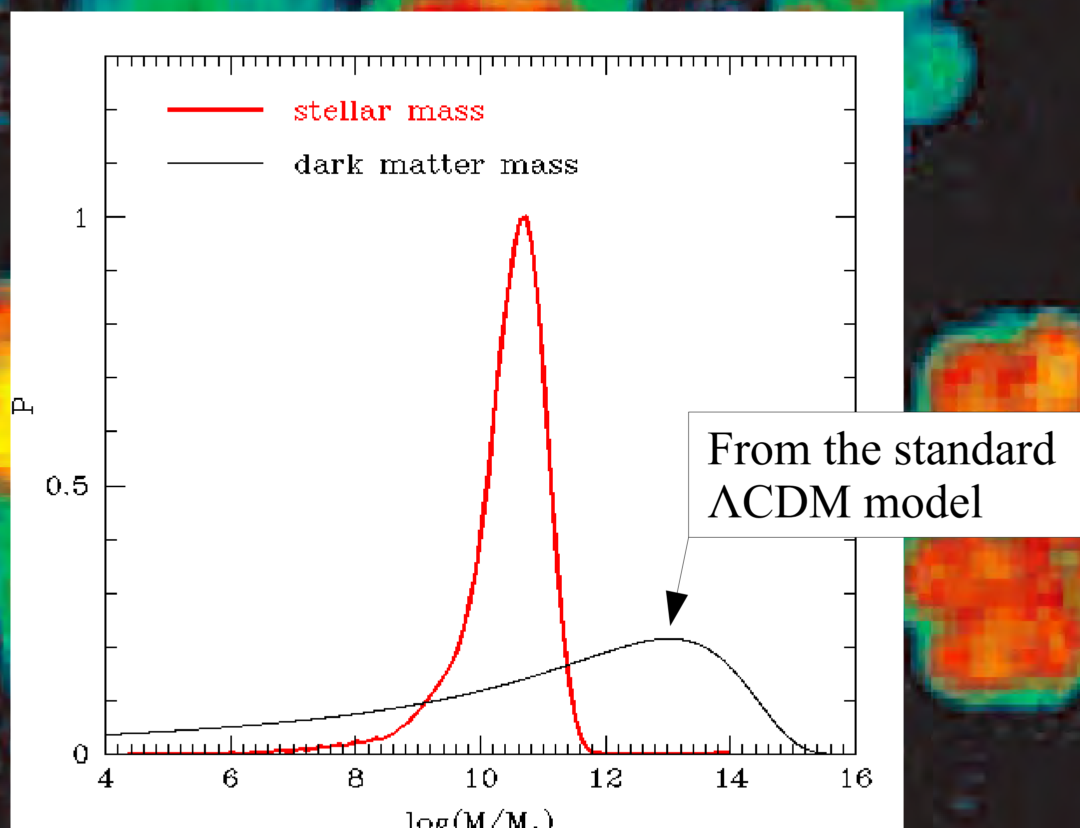
Most stars are in galaxies similar in mass to the Milky Way



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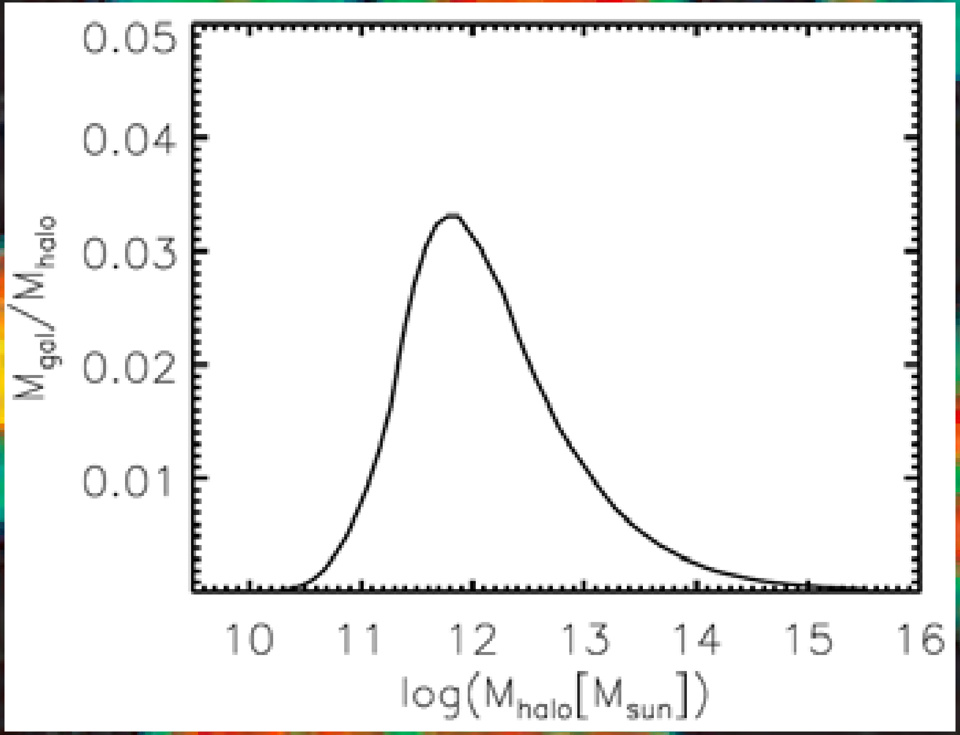
→ Galaxy to halo mass ratio varies *strongly* with mass



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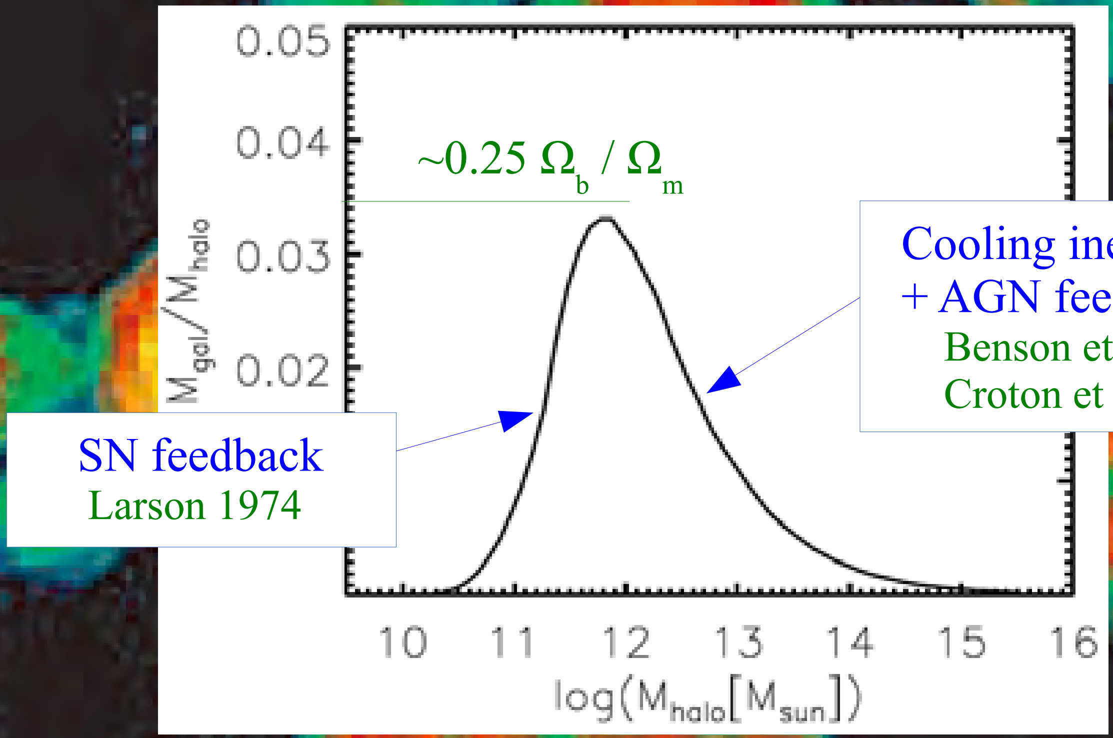
→ Halo to galaxy mass ratio varies *strongly* with mass

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



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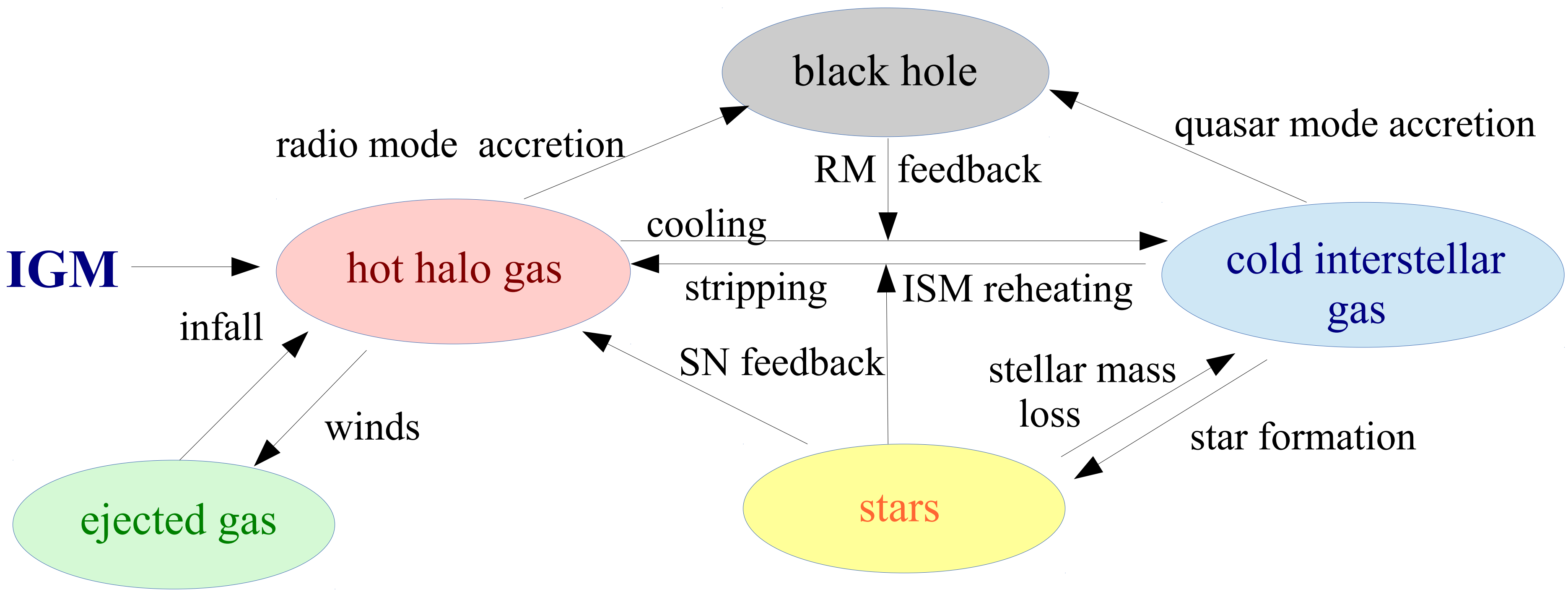

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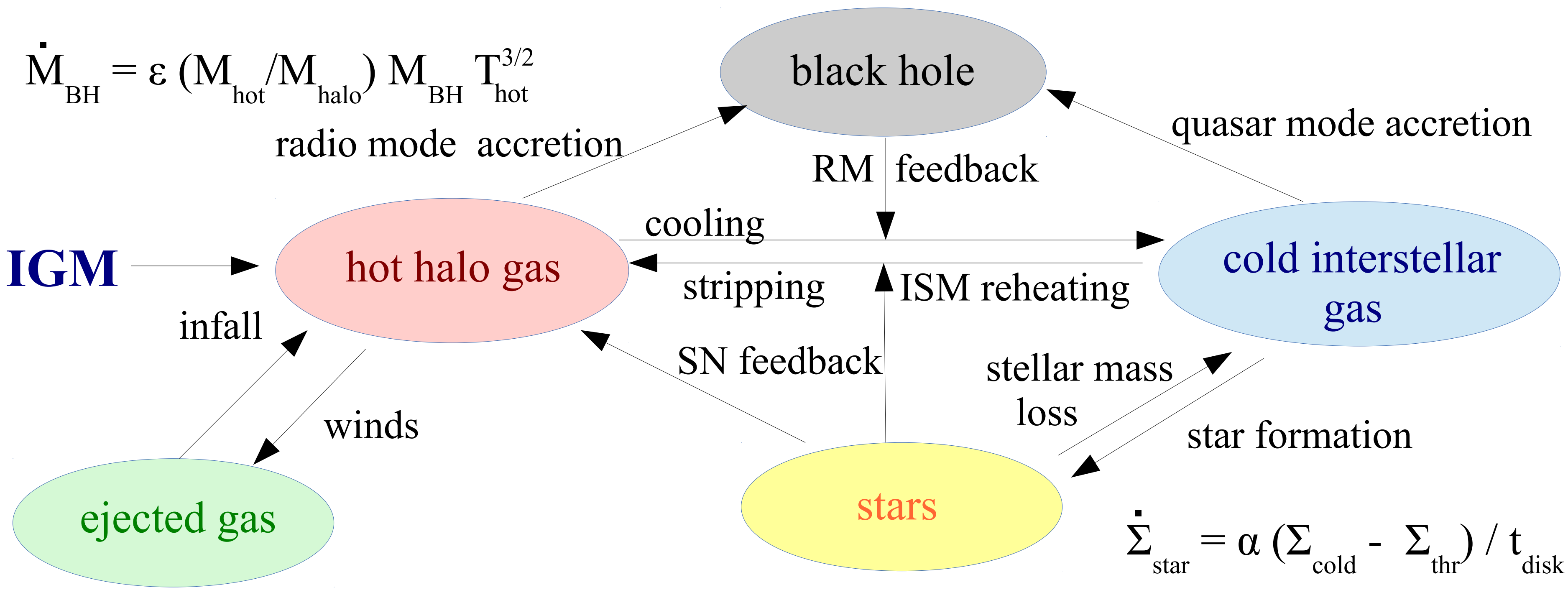


The semi-analytic programme

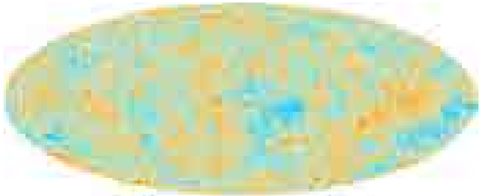
Follow the DM distribution with high-resolution simulations

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 efficiencies 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

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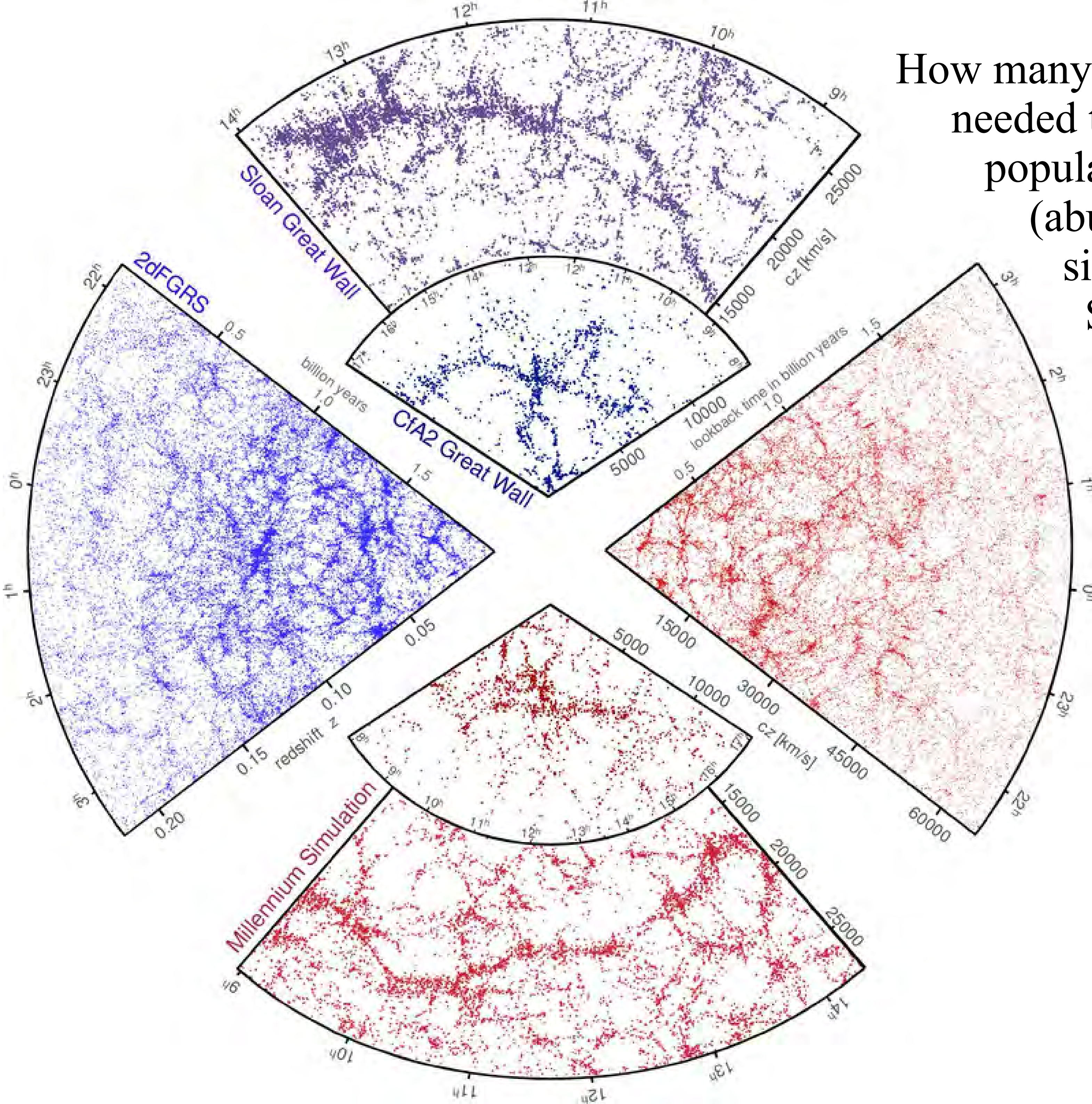
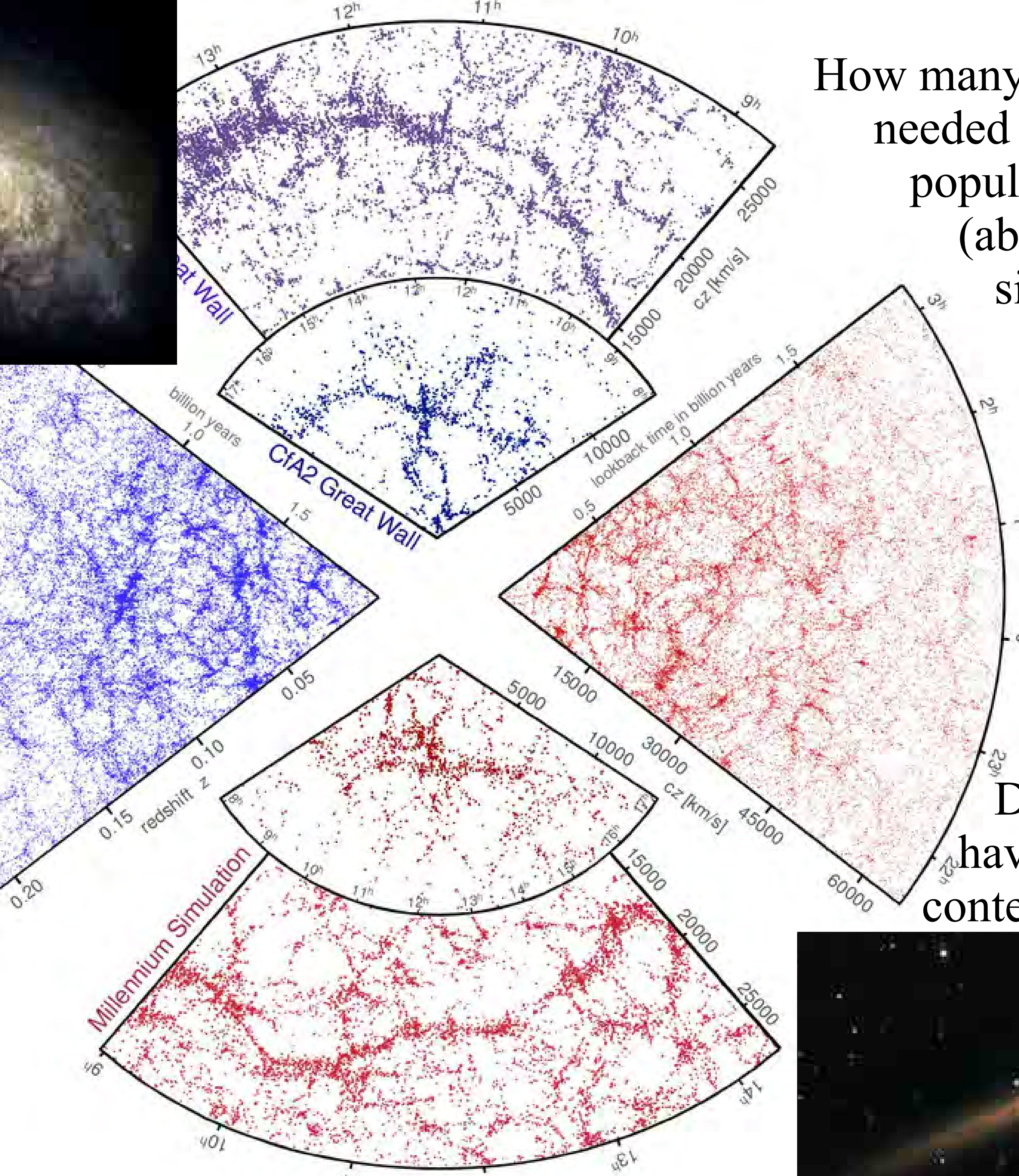
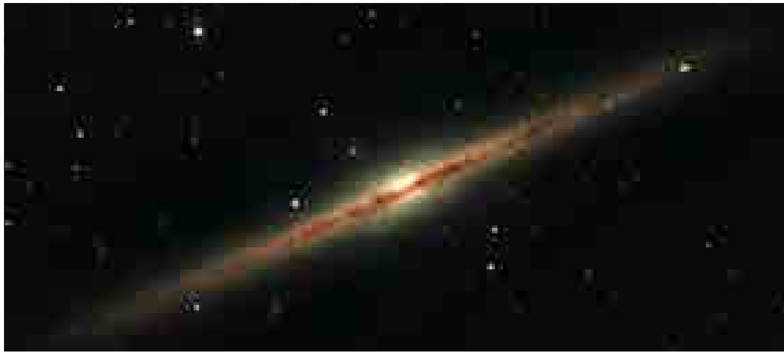


How many parameters are needed to fit the galaxy population?
(abundance by mass, size, gas content, SFR, B/T, AGN; scaling relations; clustering...)



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 <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

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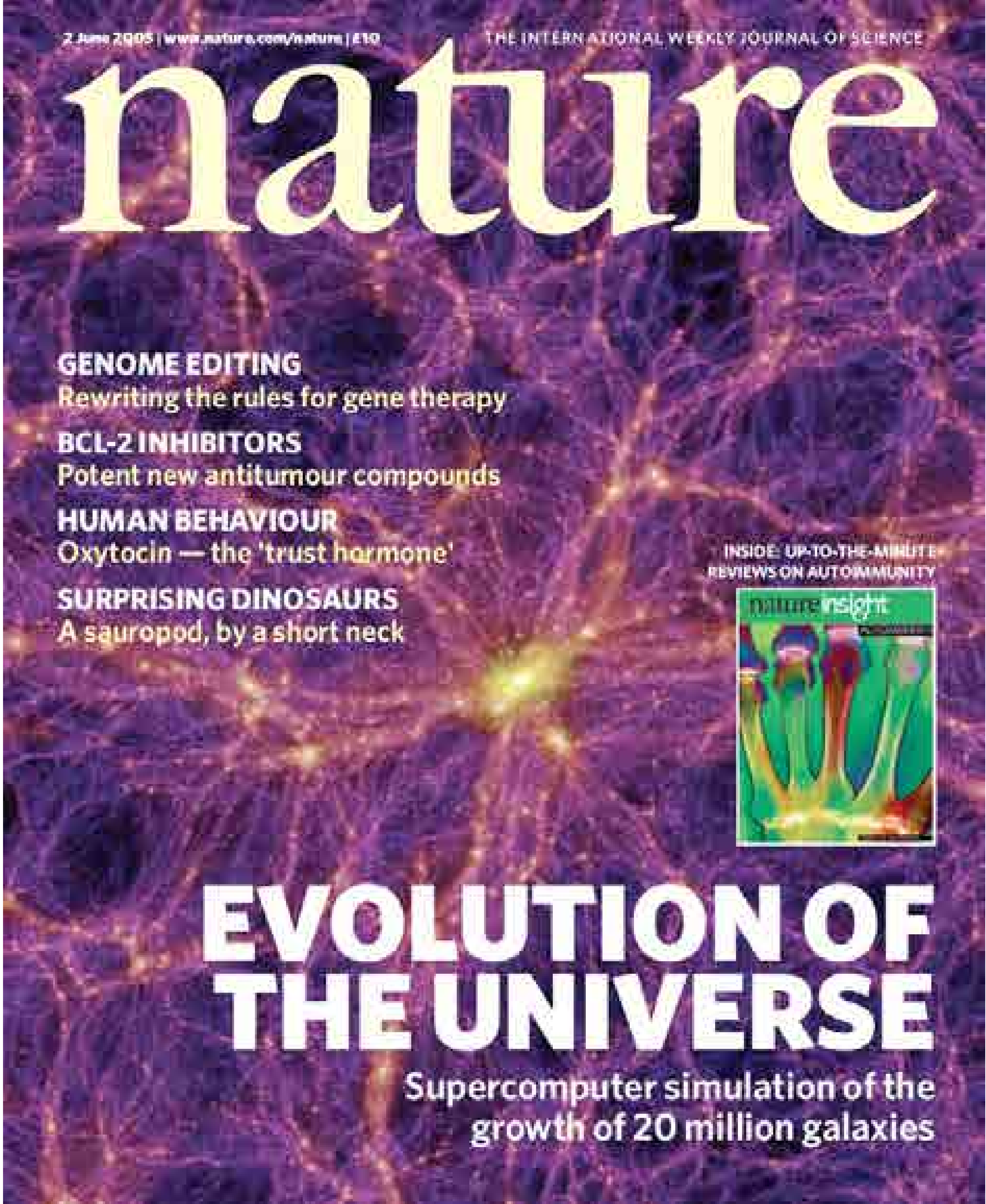
NOT to make a definitive *a priori* physical model for the formation of everything from linear ΛCDM initial conditions

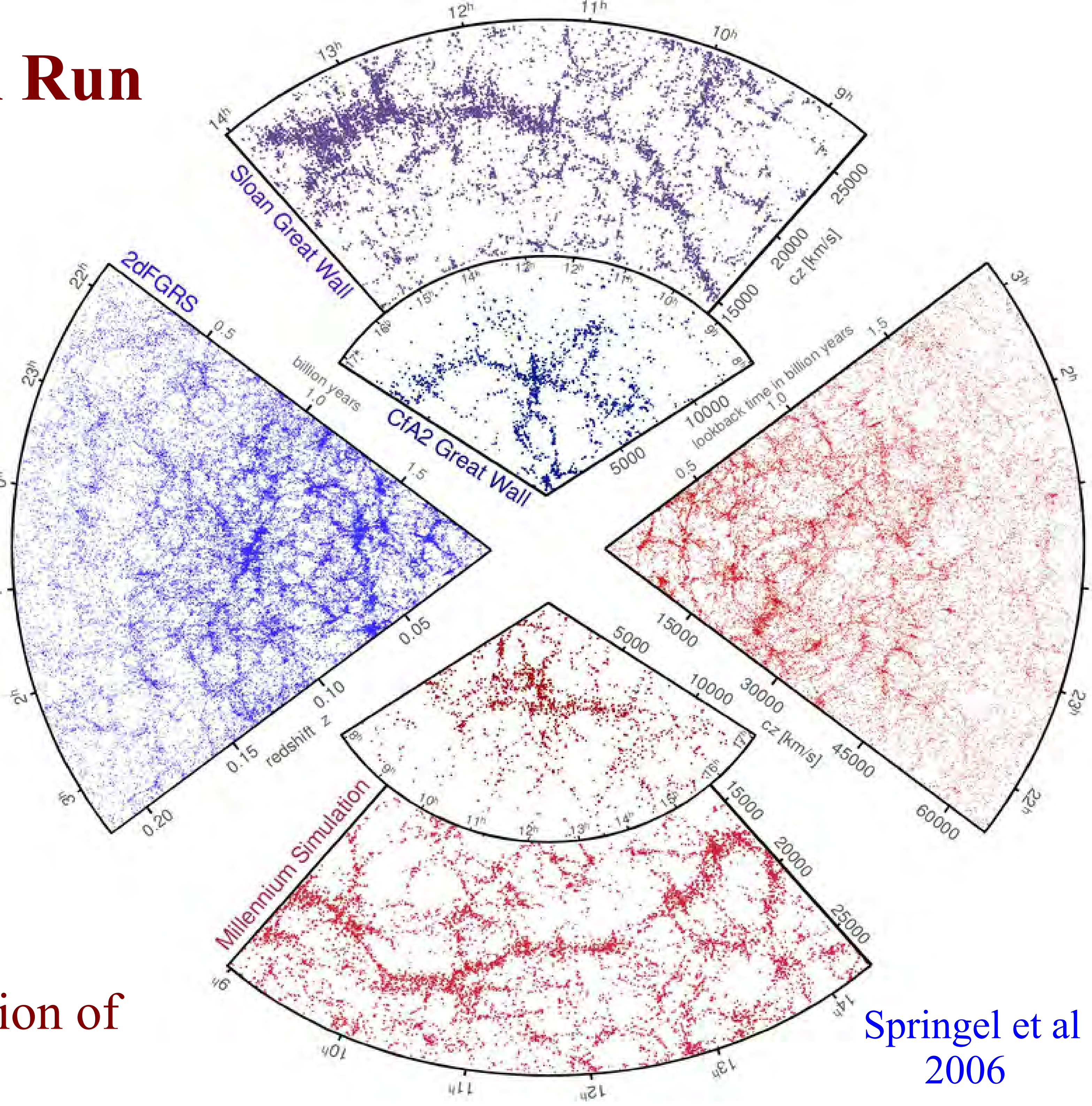
NOR to represent the internal structure of individual galaxies at anything but the most schematic level

Millennium Run 2004



Springel et al 2005

Millennium Run 2004



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

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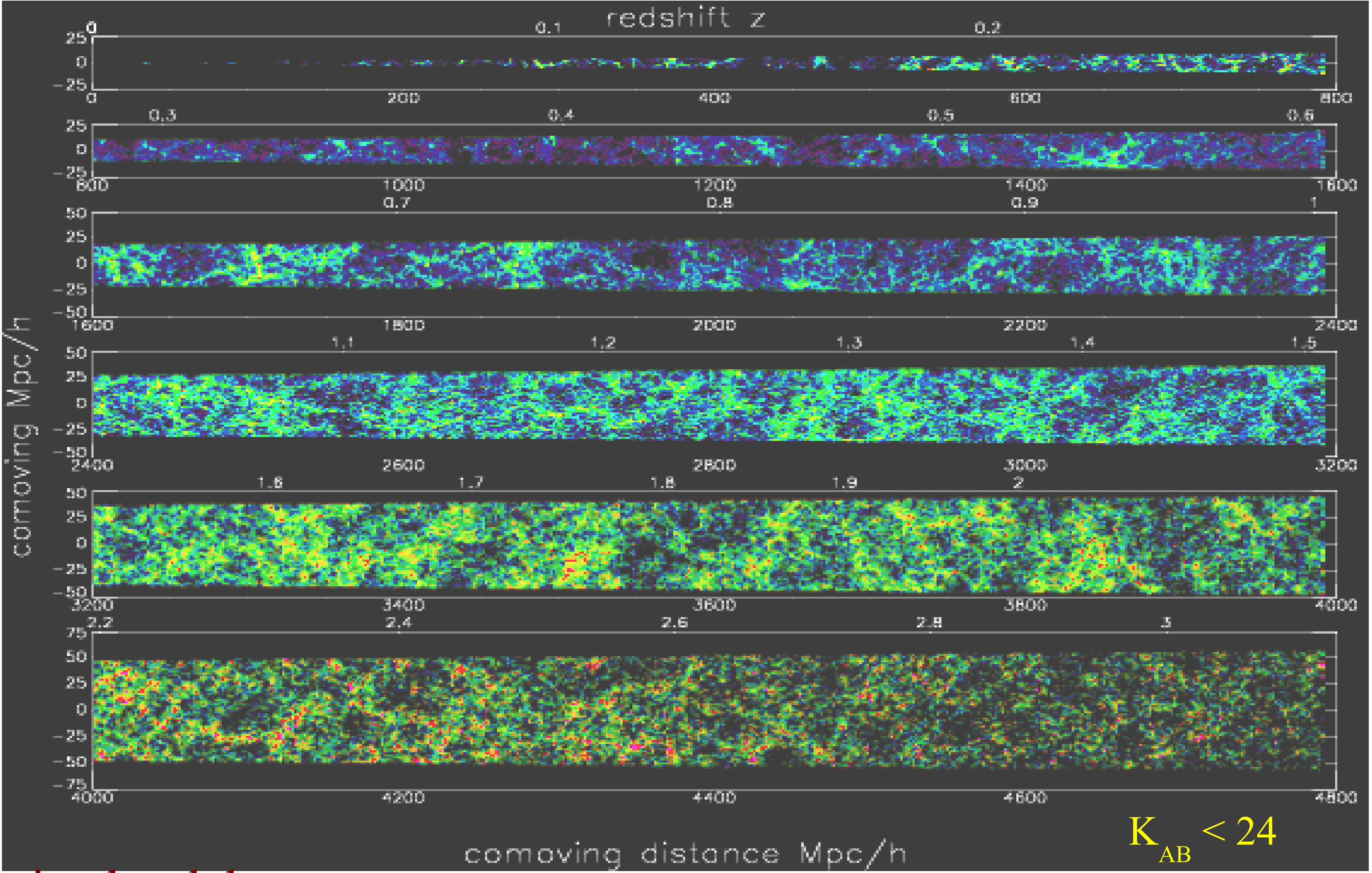

simulated the formation/evolution of $2x10^7$ galaxies from z = 10 to z = 0

Kitzbichler & White 2007

Virgo - Millennium Database

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Public Databases
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- DHaloTrees
- Guo2010a
- Guo2013a
- Henriques2012a
- MField
- MillenniumII
- millimil
- miniMilII
- MMSnapshots
- MPAGalaxies
- MPAHaloTrees
- MPAMocks
- Snapshots

Private (MyDB) Databases
- sampling_db (r)
- swhite_db (rw) (context)

VIRGO

Welcome Simon White.
Streaming queries return unlimited number of rows in CSV format and are cancelled after 420 seconds.
Browser queries return maximum of 1000 rows in HTML format and are cancelled after 30 seconds.

- The MS halo and galaxy databases have been public since 2006

Query (stream) | Query (browser) | Help

Maximum number of rows to return to the query form: 10

Demo queries: click a button and the query will show in the query window.
Holding the mouse over the button will give a short explanation of the goal of the query. These queries are described in some more detail on this page.

Mainly Halos: H 1 | H 2 | H 3 | H 4 | H 5 | HF 1 | HF 2 | HF 3

Mainly Galaxies: G 1 | G 2 | G 3 | G 4 | G 5 | G 6 | HG 1 | HG 2 | GF 2

Metadata queries: The SQL statements under these buttons provide examples for querying and managing the state of a private database.
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ShowTables | Show Views | Show Columns | Show Indexes | MyDB Size | MyDB Table Size

Create View | Drop Table | Create Index

Virgo - Millennium Database

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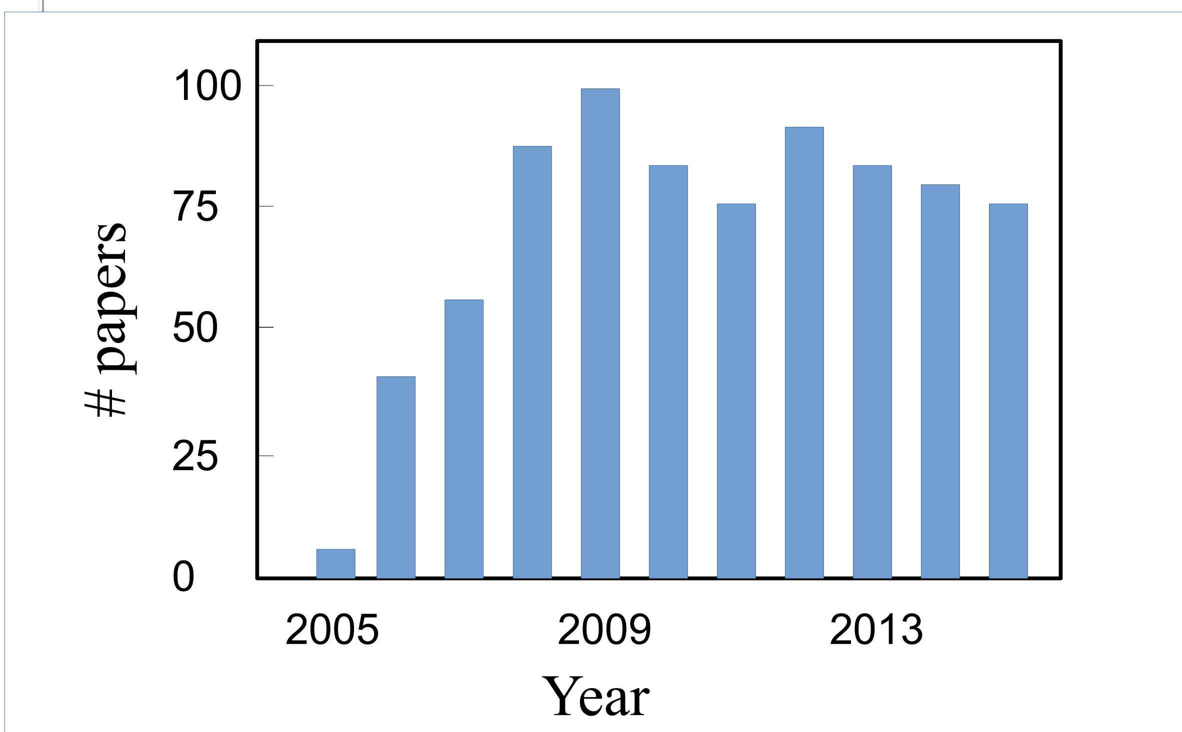

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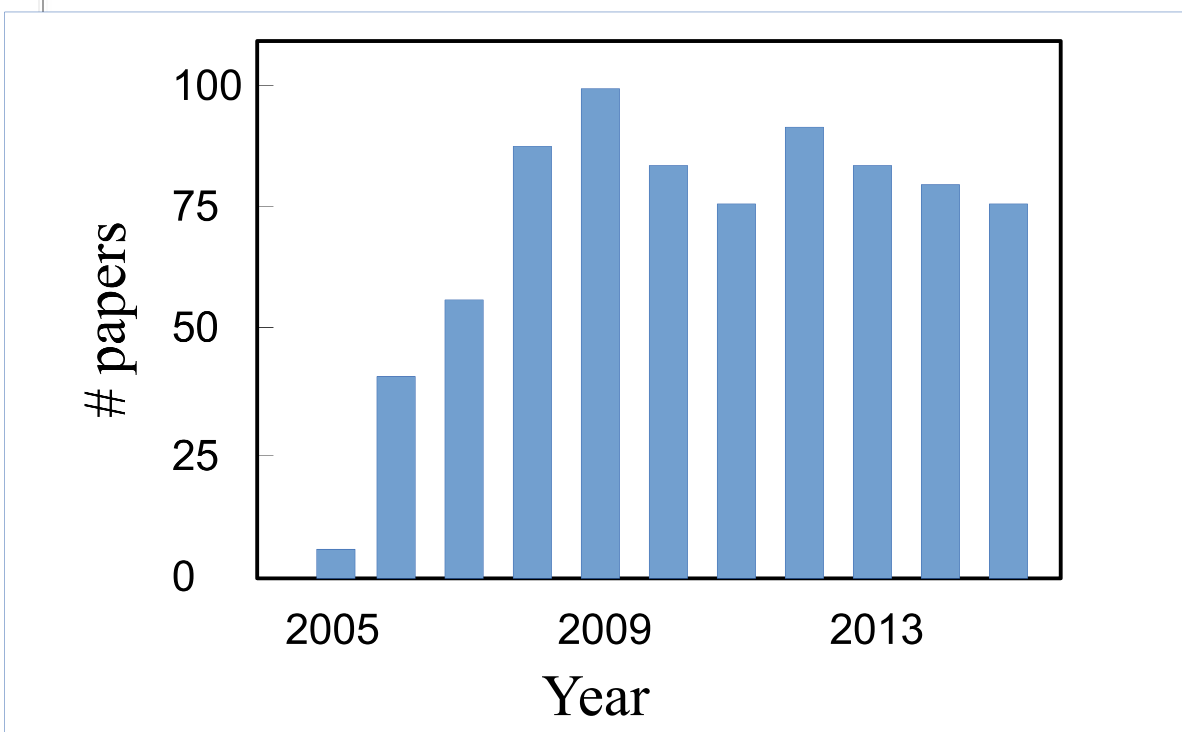
- The MS halo and galaxy databases have been public since 2006
- >750 papers have used these predictions
- Most use the galaxies and are by authors unassociated with the Virgo Consortium

Query (stream)

Query (browser)

Help



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- The MS halo and galaxy databases have been heavily used because
  - (i) they are publicly available
  - (ii) they are easy to use
  - (iii) they provide data in the form needed to calibrate and interpret observations
  - (iv) they give results for <u>physical</u> models

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Create View | Drop Table | Create Index

Limitations of the original Millennium Simulation

Limited modeling of *structure* of galaxies, gas components

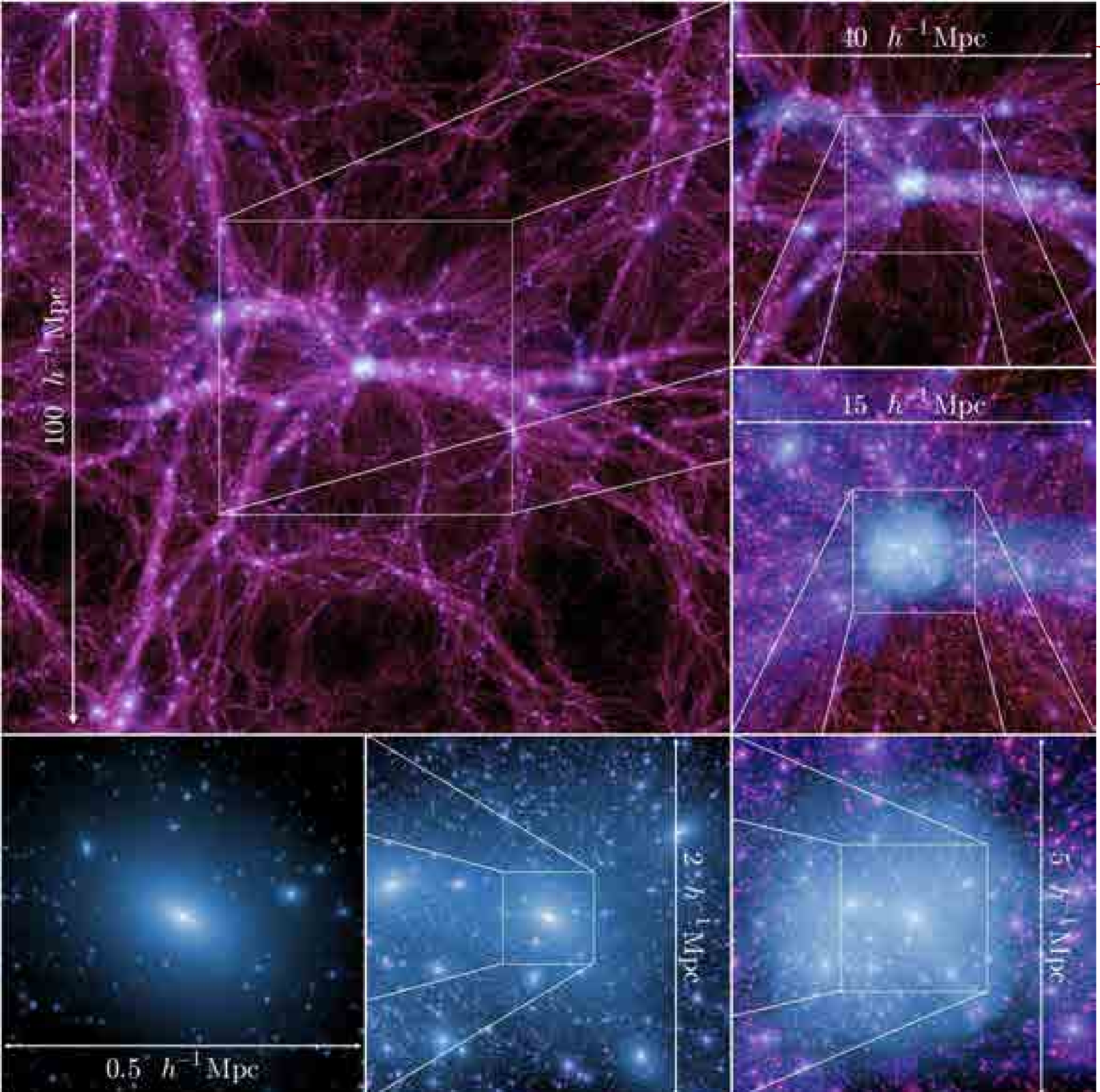
Limited resolution – too poor to model formation of dwarfs

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

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

Guo et al 2011

Implement modelling <u>simultaneously</u> on MS and MS-II

Test <u>convergence</u> of galaxy properties near resolution limit of MS

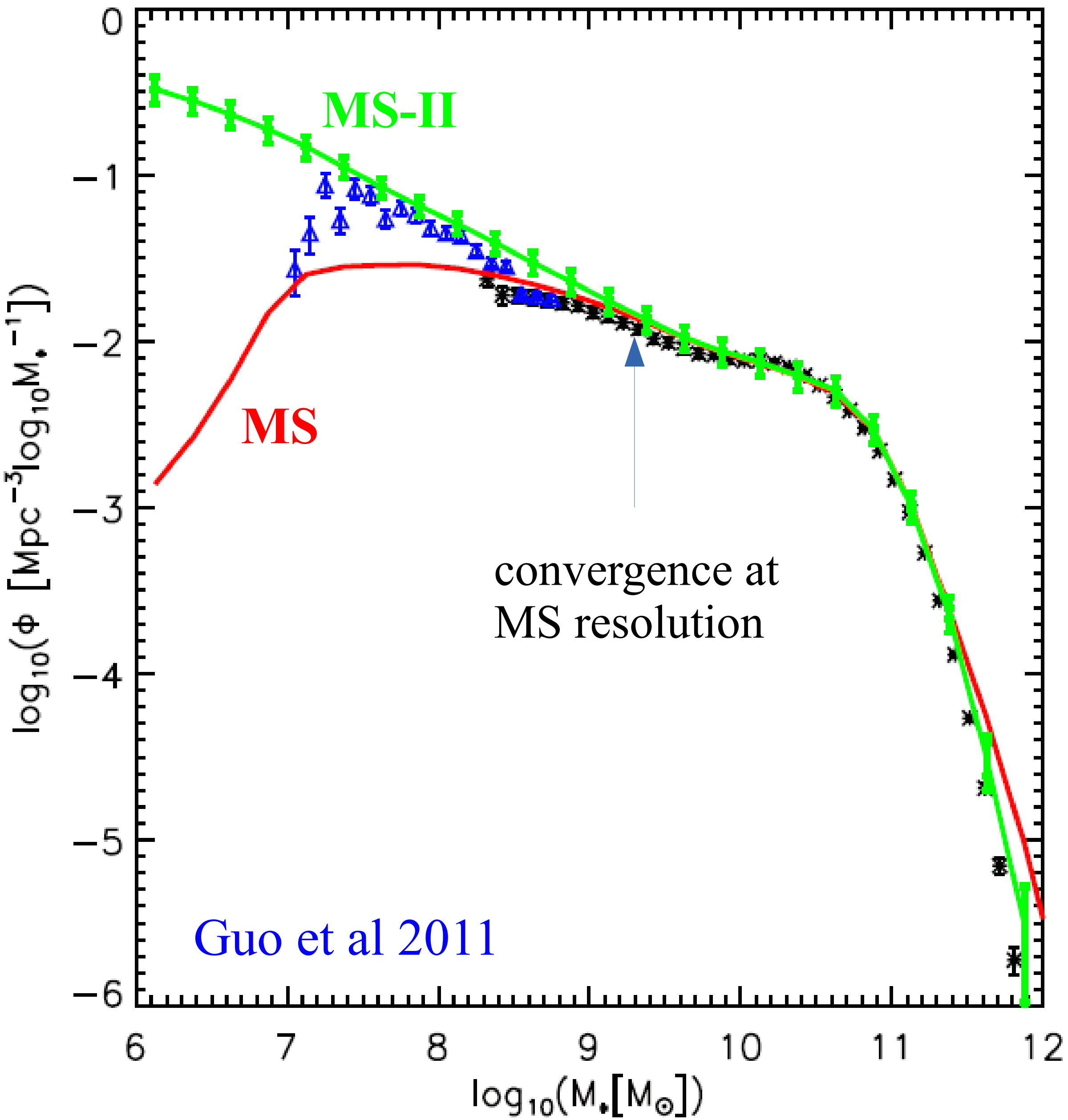
Extend to properties of <u>dwarf</u> galaxies

Improve/extend treatments of "troublesome" astrophysics

Adjust parameters to fit new, more precise data

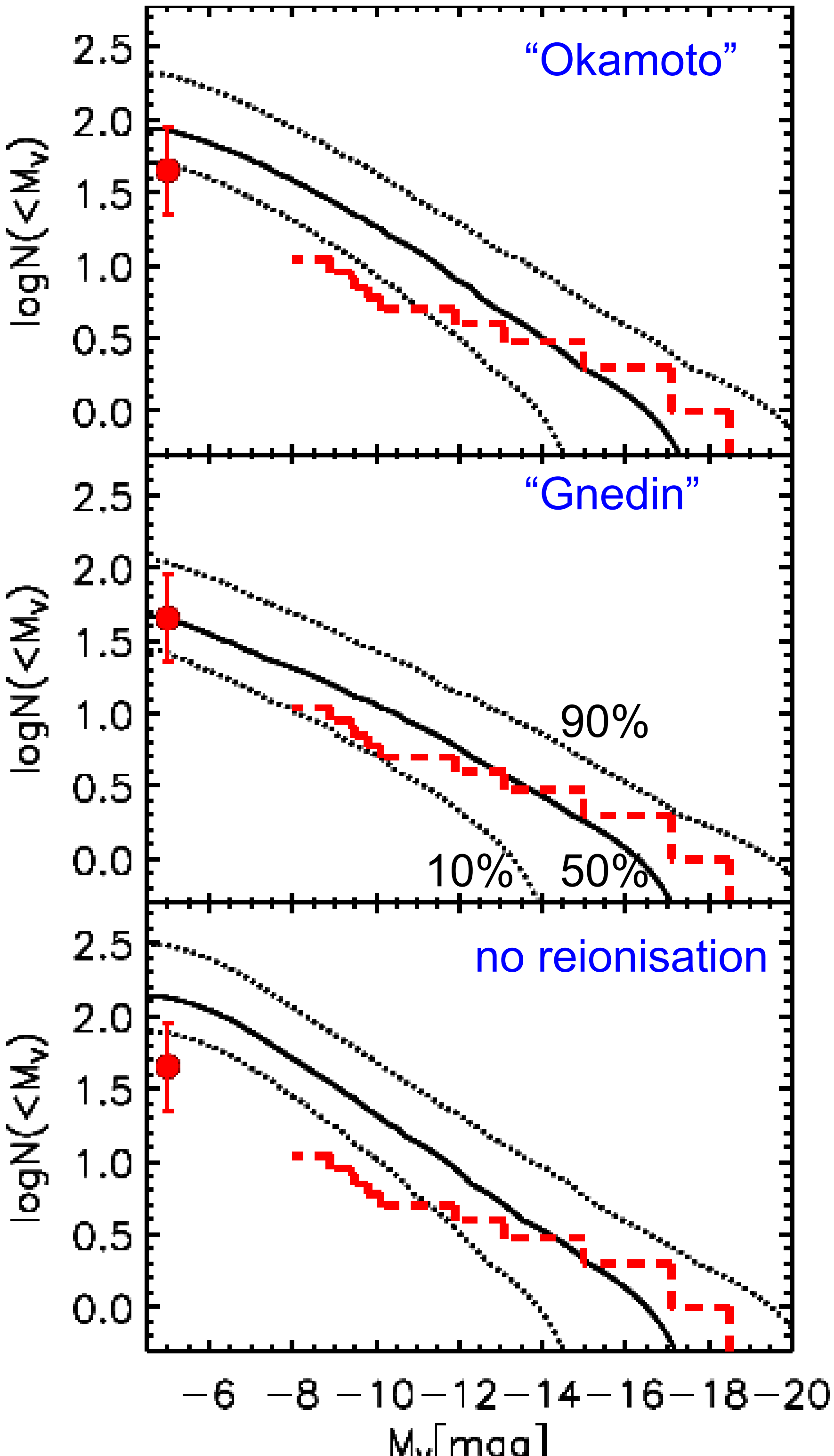
Test against clustering and redshift evolution

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

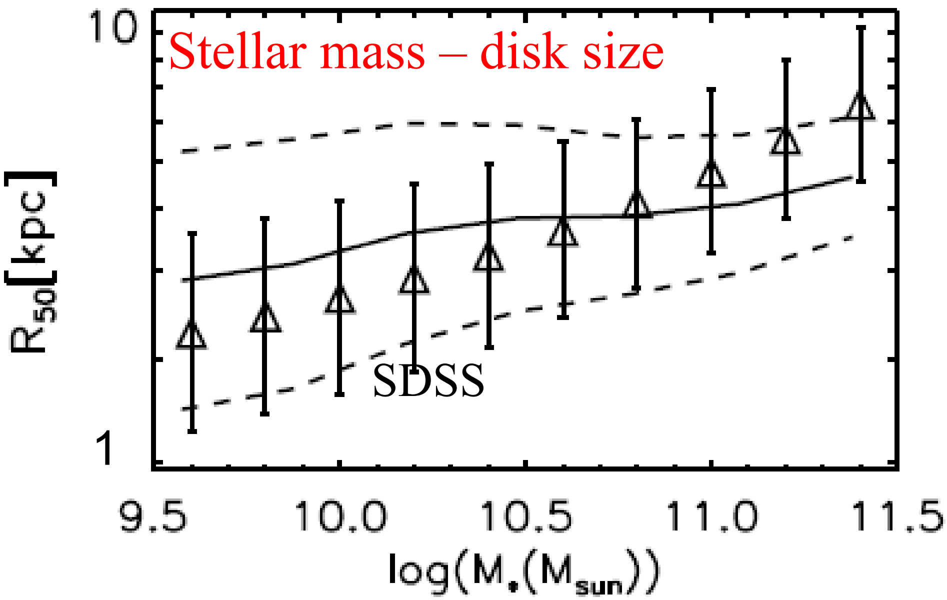


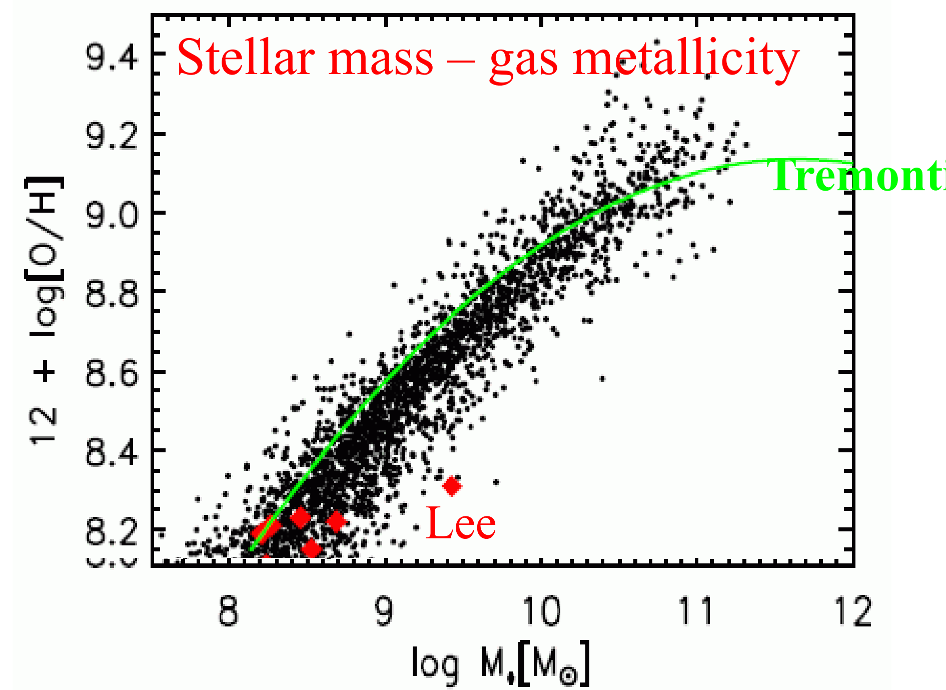
Luminosity functions of satellites around 1500 "Milky Ways" i.e. isolated disk galaxies with log $M_* = 10.8$

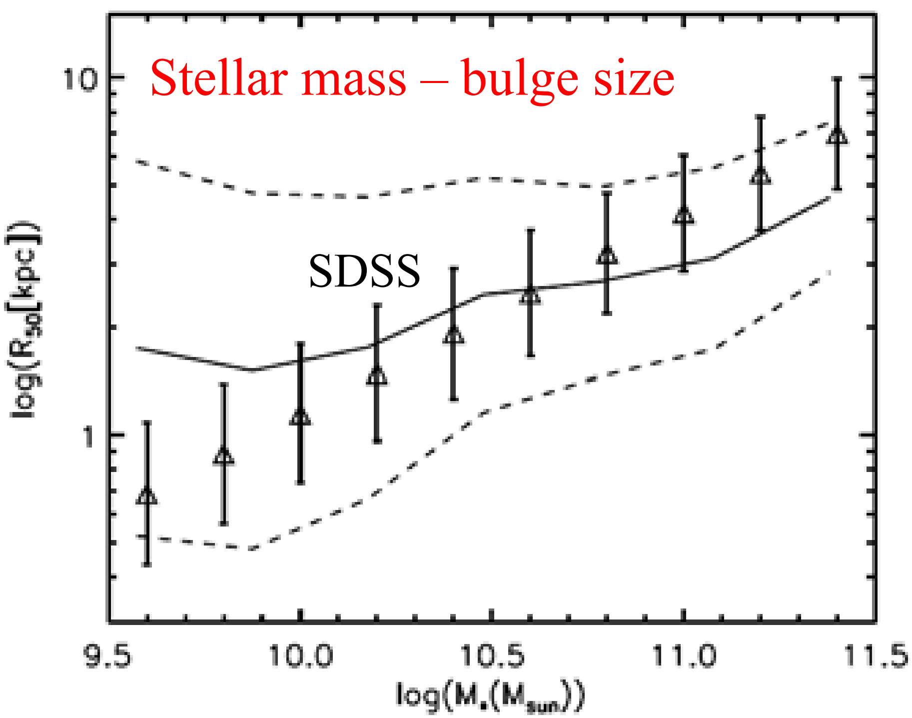
Guo et al 2011

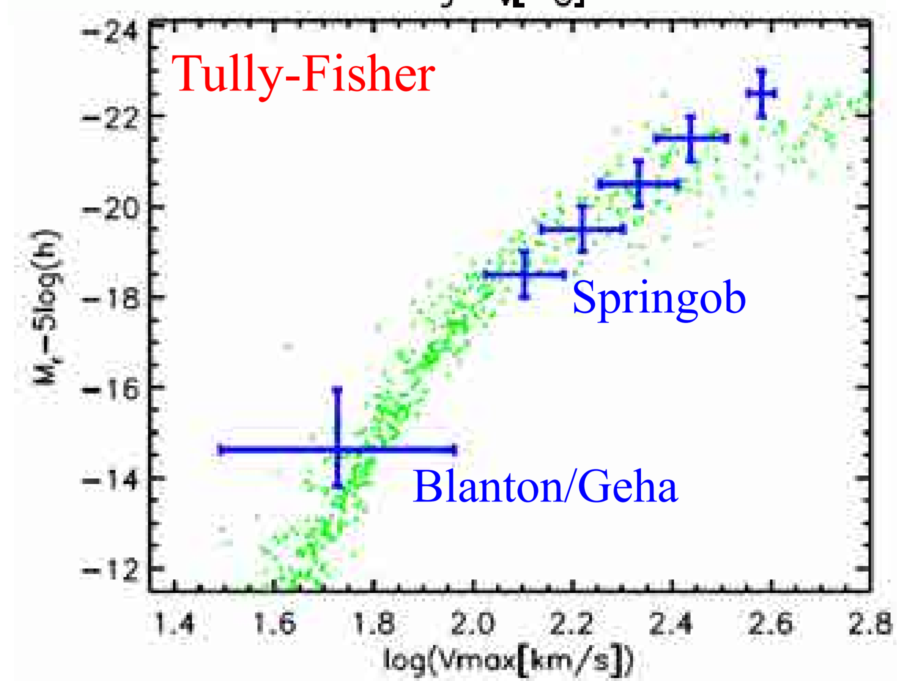
Scaling relations

Guo et al 2011



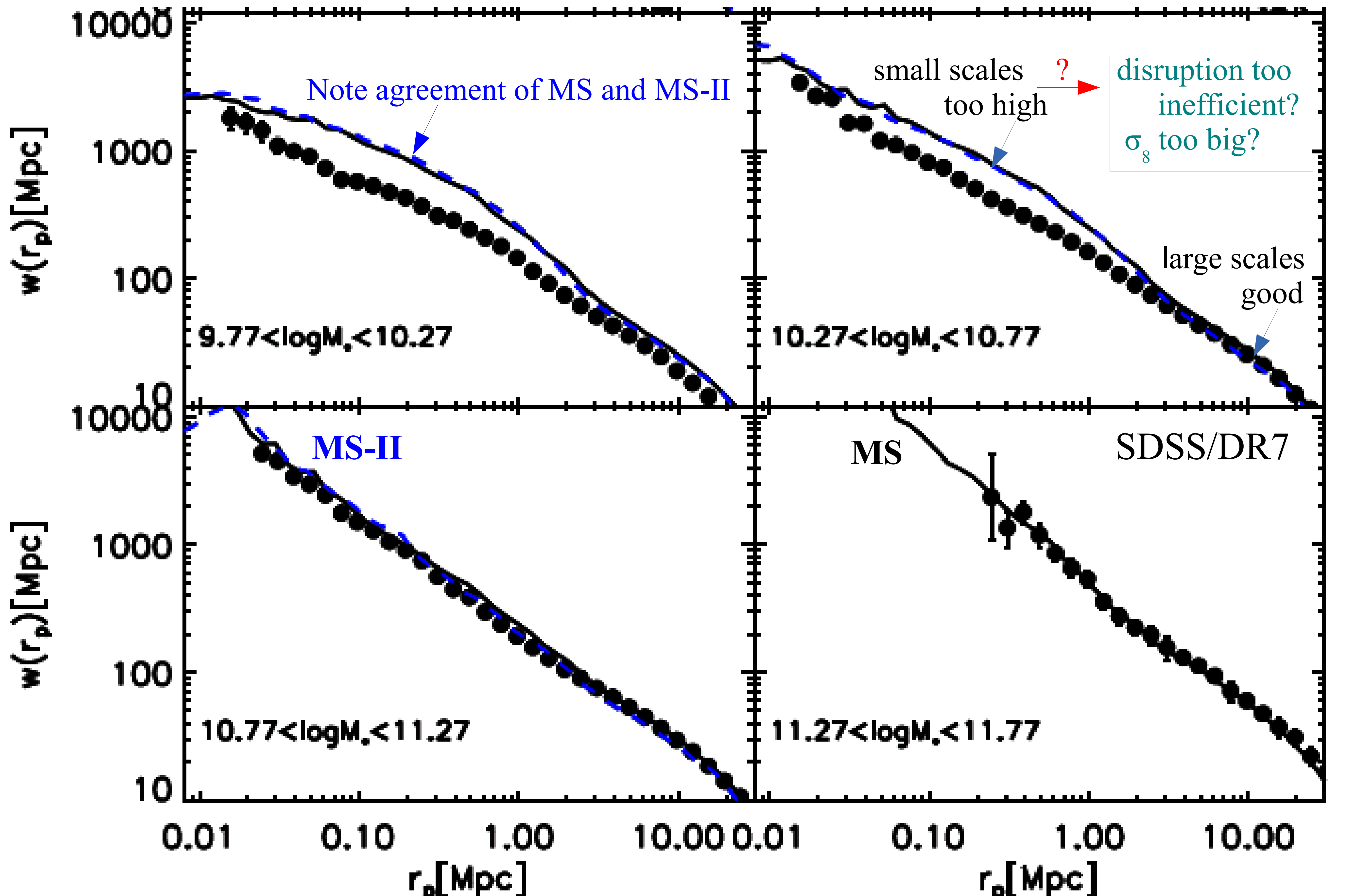




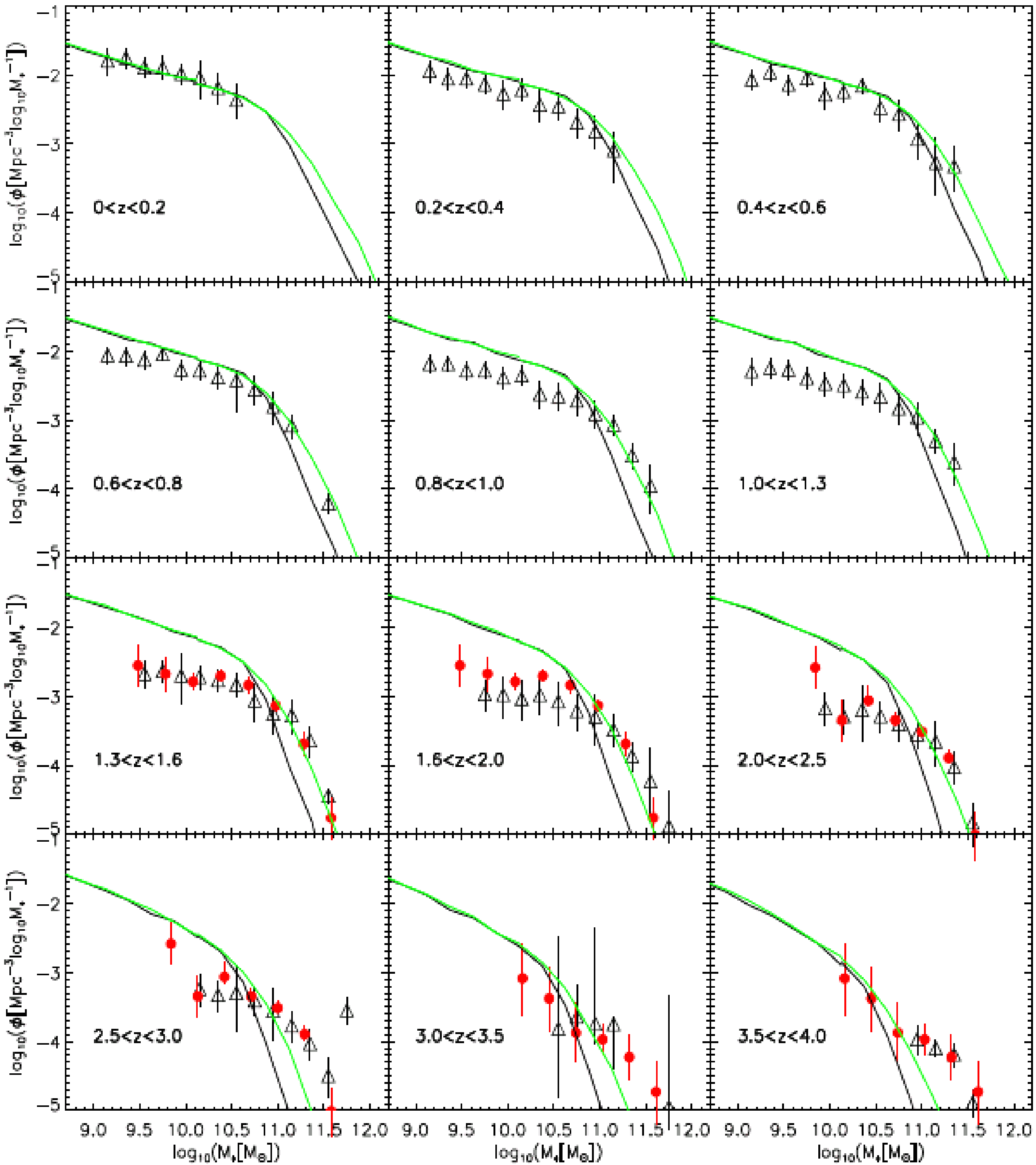


Mass-dependent galaxy clustering

Guo et al 2011



Evolution of stellar mass function



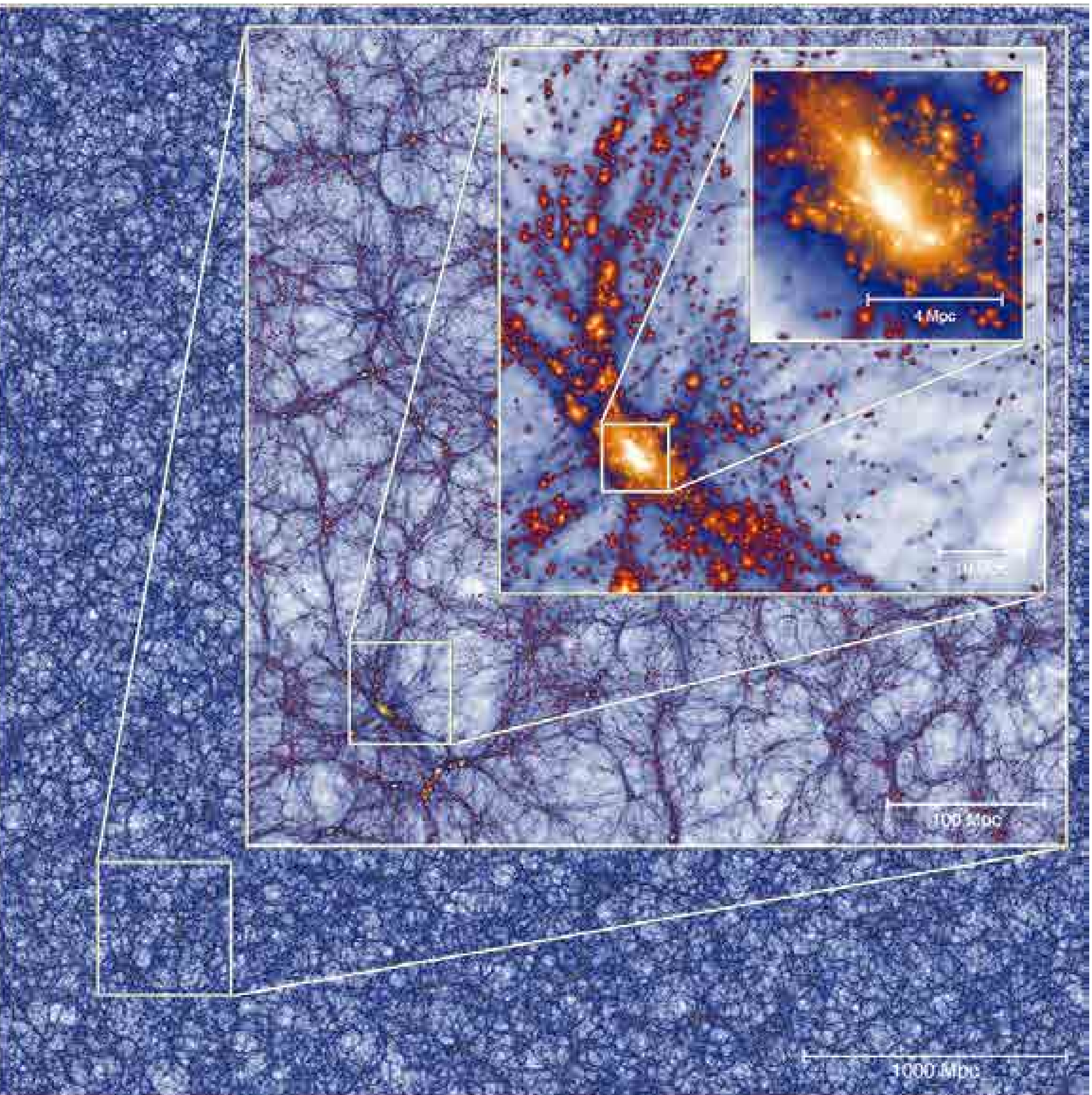
△ Perez-Gonzalez et al 2008

● Marchesini et al 2009

Lower mass galaxies
log M_* < 10.5
form too early

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

Guo et al 2011



The MXXL

(2010)

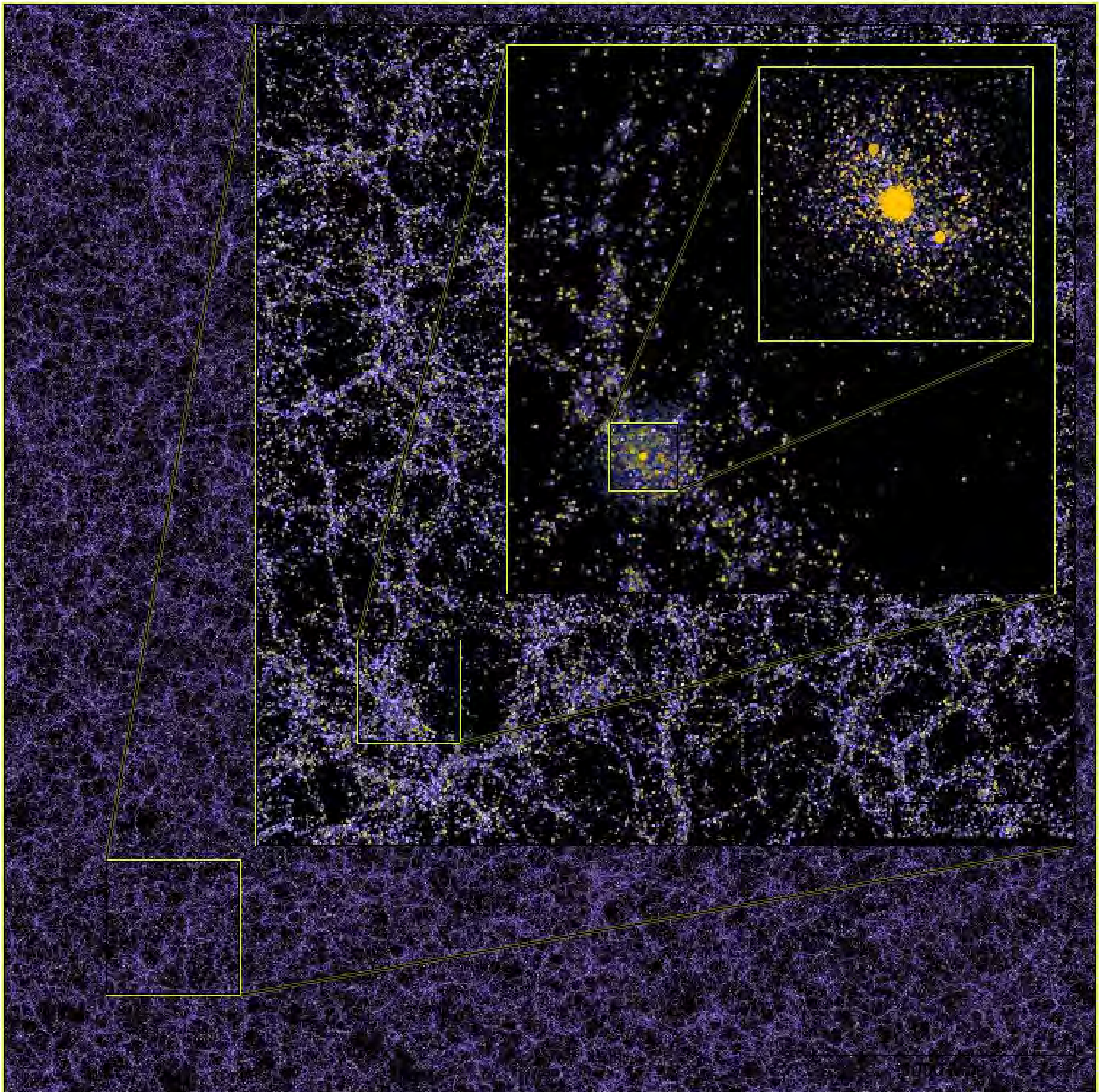
Angulo et al 2011

Bigger than the Millennium Run by factors of

30 in $N_{particle}$

200 in Volume

6 in $m_{particle}$



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30 in $N_{particle}$

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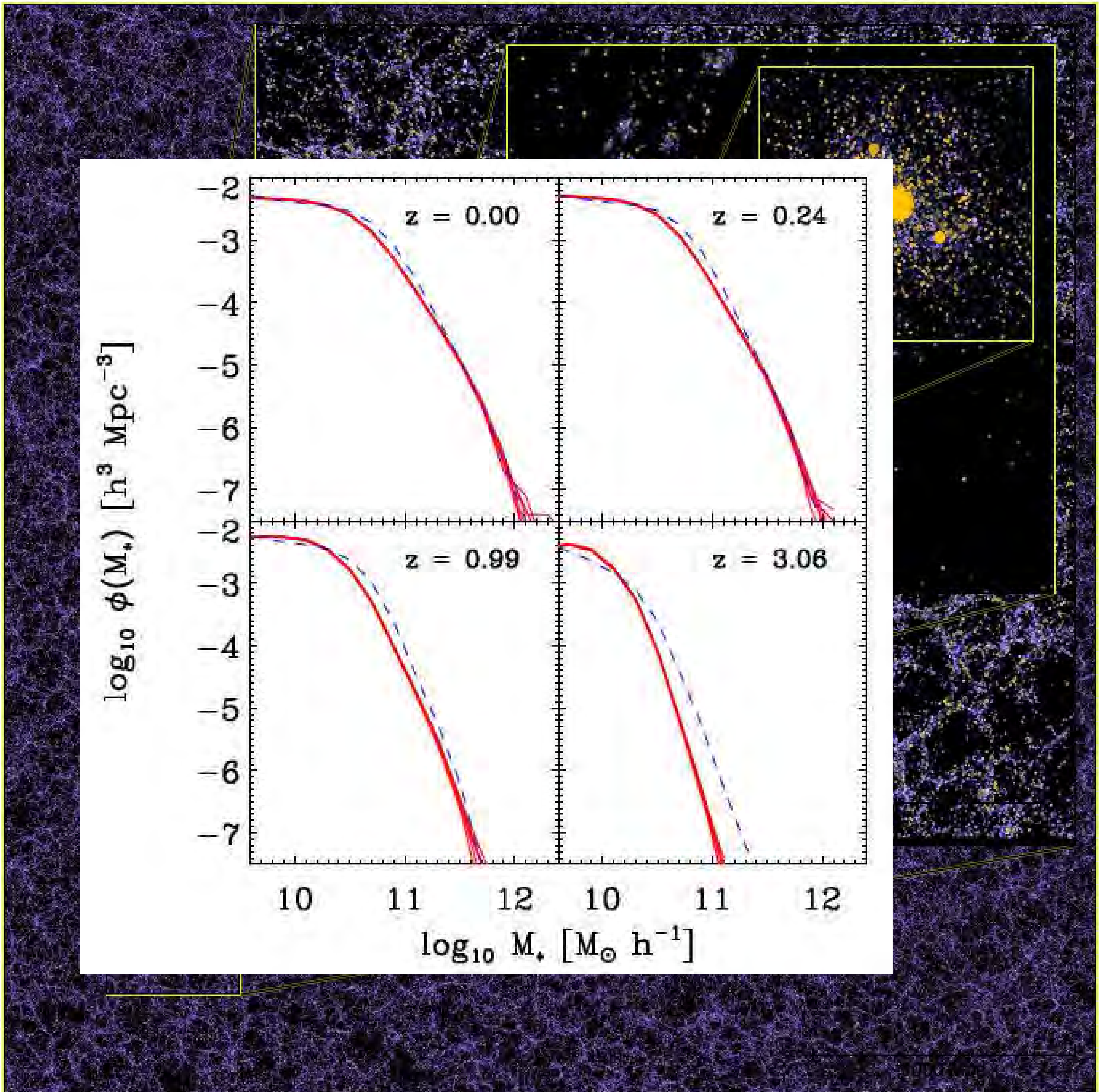
3.3×10^8 galaxies at $z = 0$ with $\log M_*/M_\odot > 10$



The MXXL

(2010)

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Bigger than the Millennium Run by factors of

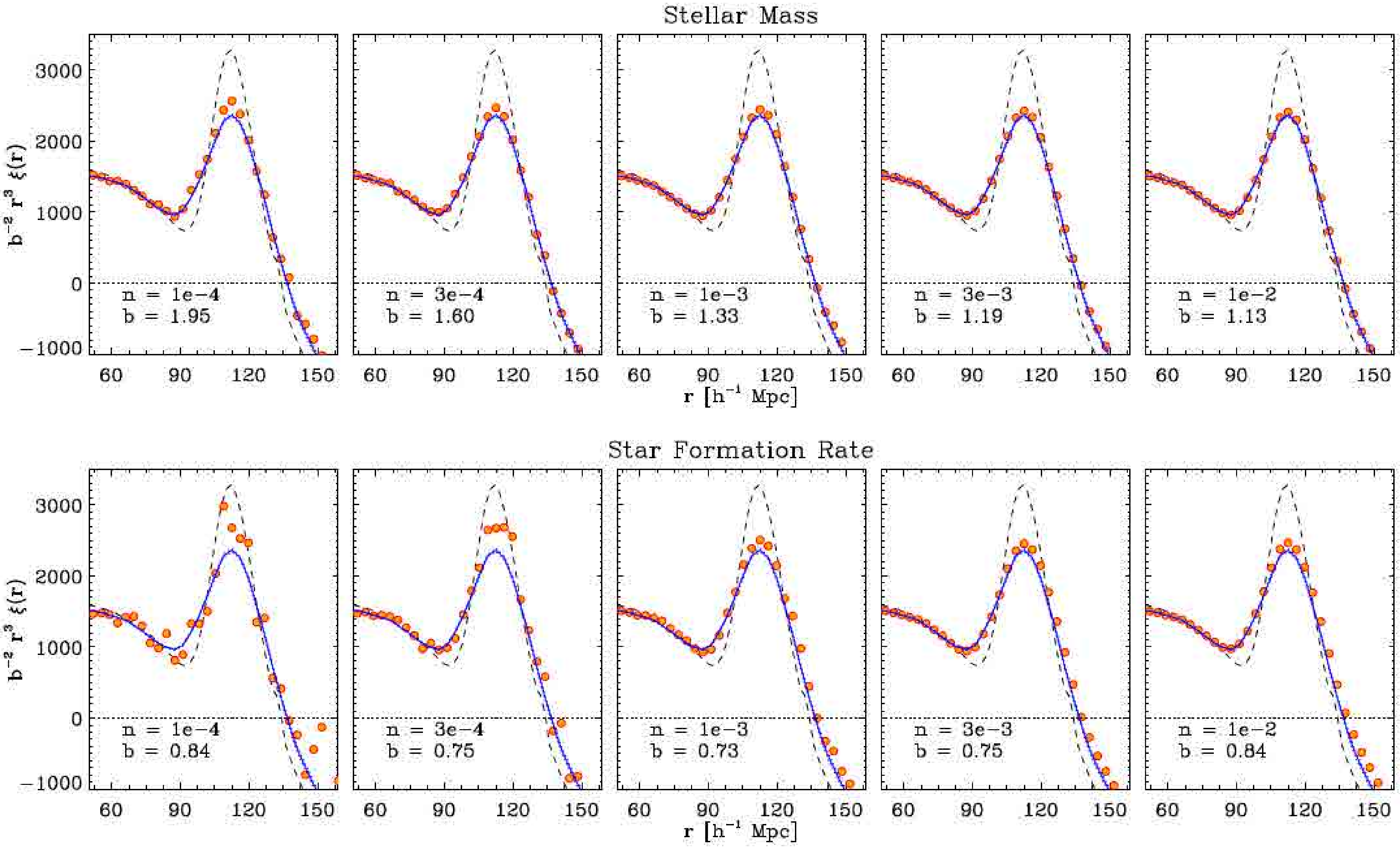
30 in $N_{particle}$

200 in Volume

6 in $m_{particle}$

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

Distortions of BAO feature in the galaxy population



Angulo et al 2013

Small but measurable shifts for different selection methods

Scaling simulations to neighboring cosmologies

Angulo & White 2010
Angulo & Hilbert 2014

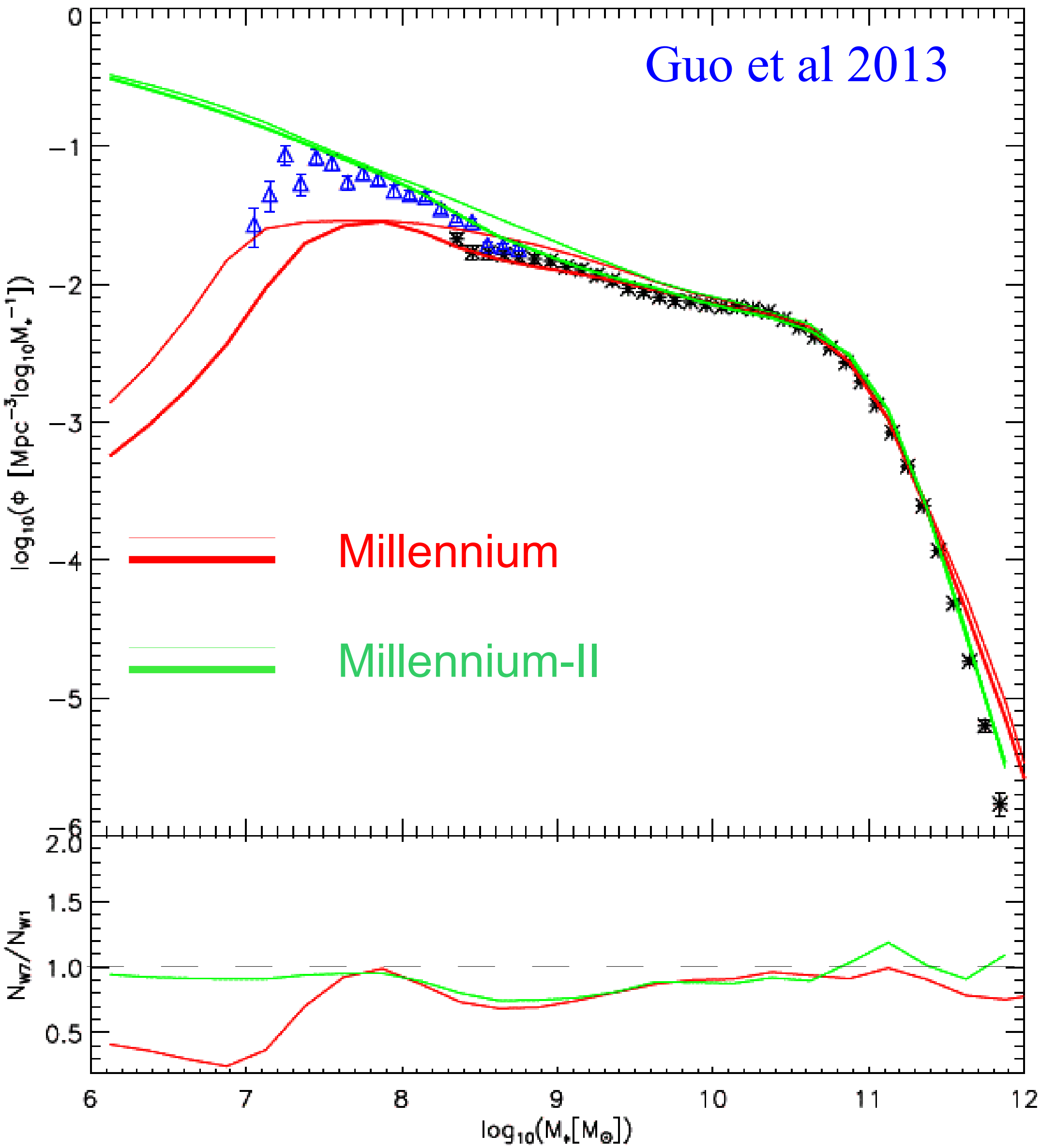
For example: `WMAP1' – $\Omega_m = 0.25$, $n = 1$, $\sigma_8 = 0.9$
to `Planck1' – $\Omega_m = 0.315$, $n = 0.96$, $\sigma_8 = 0.829$

1) Scale simulation size to match power spectrum slopes of original and target cosmologies on the scales of the target z=0 halos
-- 685 Mpc 713 Mpc

2) Reassign redshifts to match linear amplitudes on these scales
-- $z = 0.12, 1.22, 2.34$ $z = 0, 1, 2$

3) Scale particle masses and velocities to match Ω_m and new size
-- $1.19 \times 10^9 M_\odot$ $1.44 \times 10^8 M_\odot$

4) Adjust for the difference between amplitudes of original and target power spectra on large scales using linear theory.



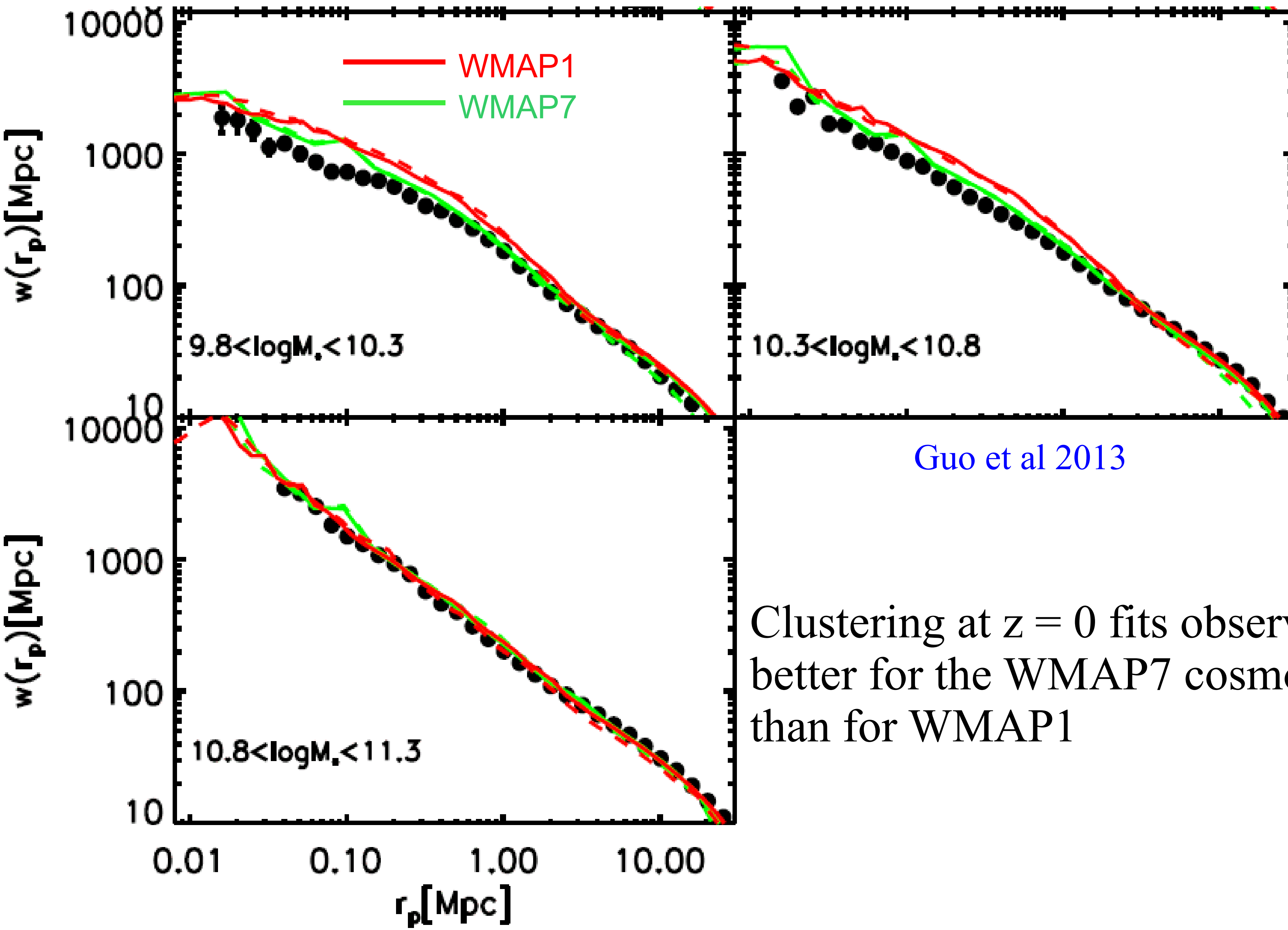
Switching from **WMAP1** to **WMAP7**

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

$\sigma_8 = 0.90$ → $\sigma_8 = 0.81$

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}

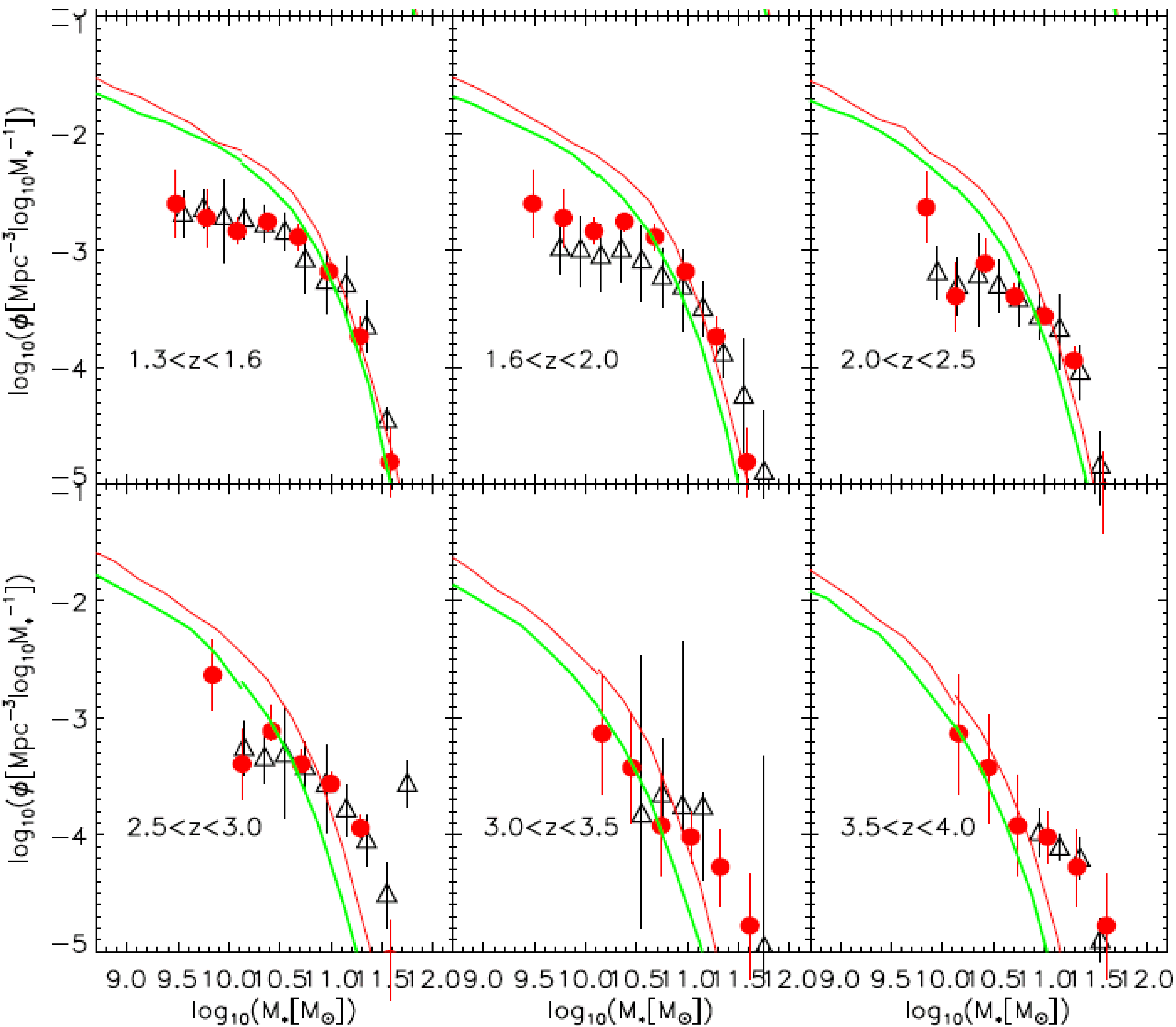
Switching from WMAP1 to WMAP7



Guo et al 2013

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

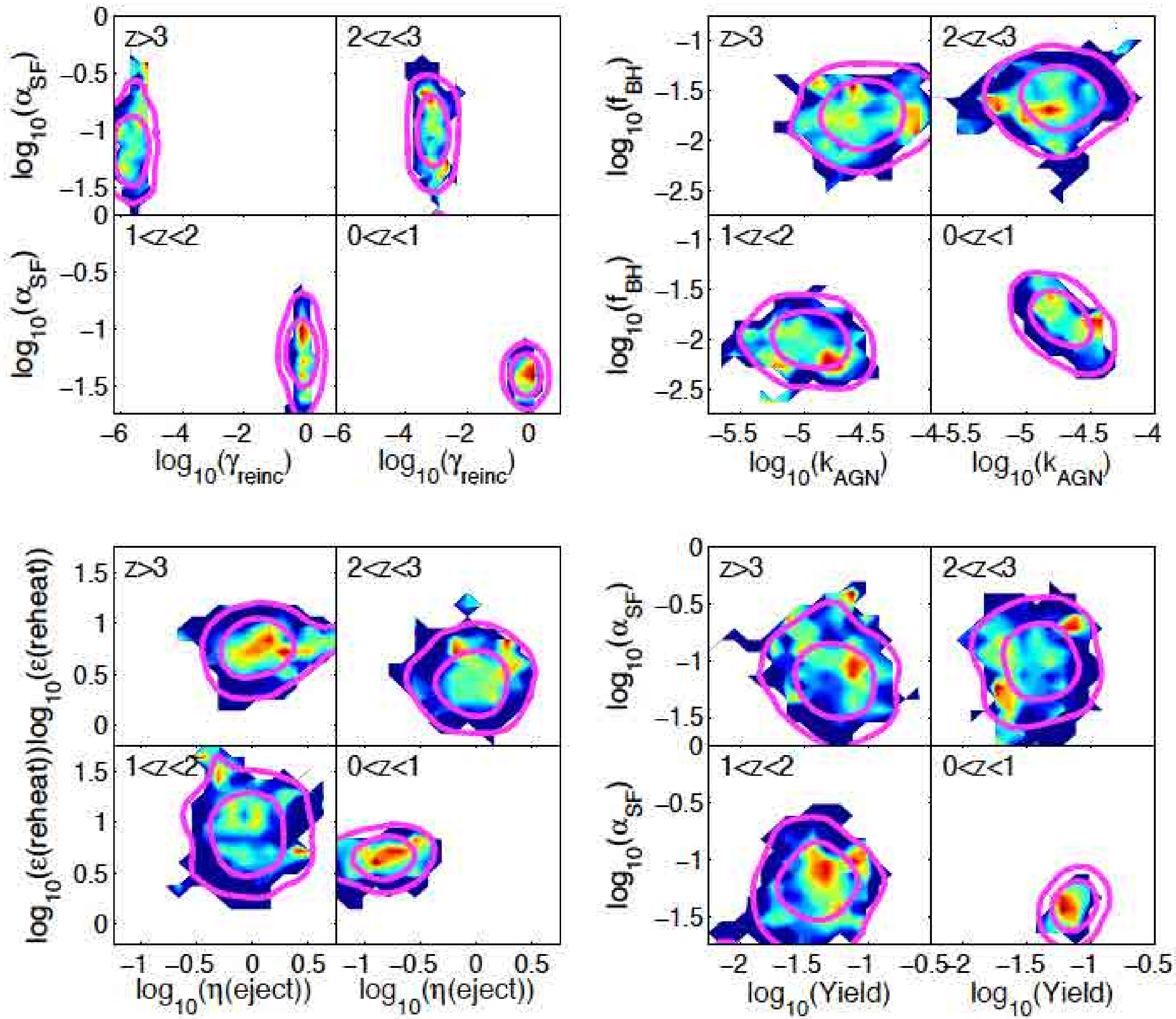
Switching from WMAP1 to WMAP7



Guo et al 2013

..but the galaxy formation sequence is still incorrect

MCMC allows exploration of parameter space



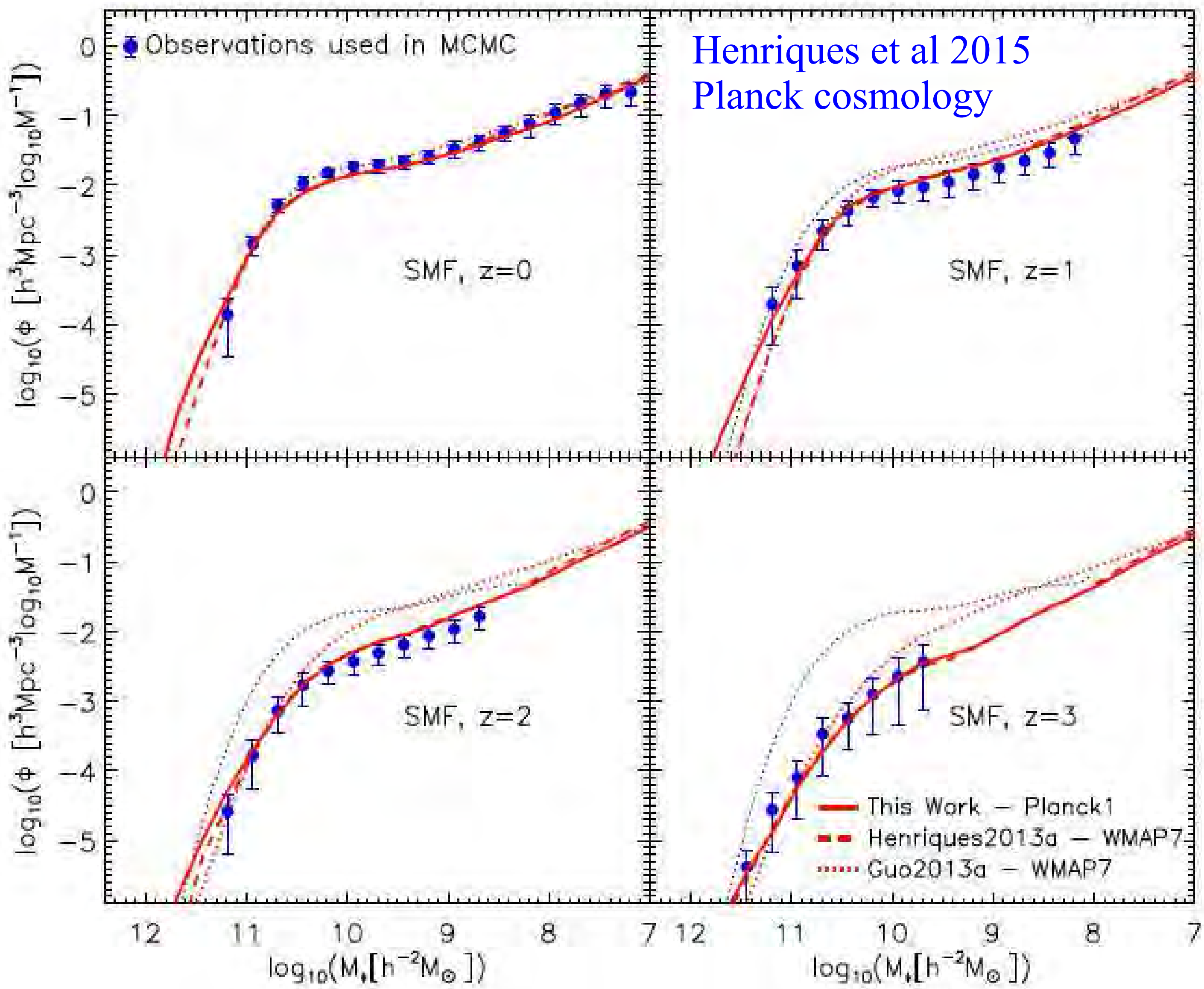
SA model of Guo et al (2011) constrained by observed stellar mass and luminosity functions at z = 0, 1, 2 and 3

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

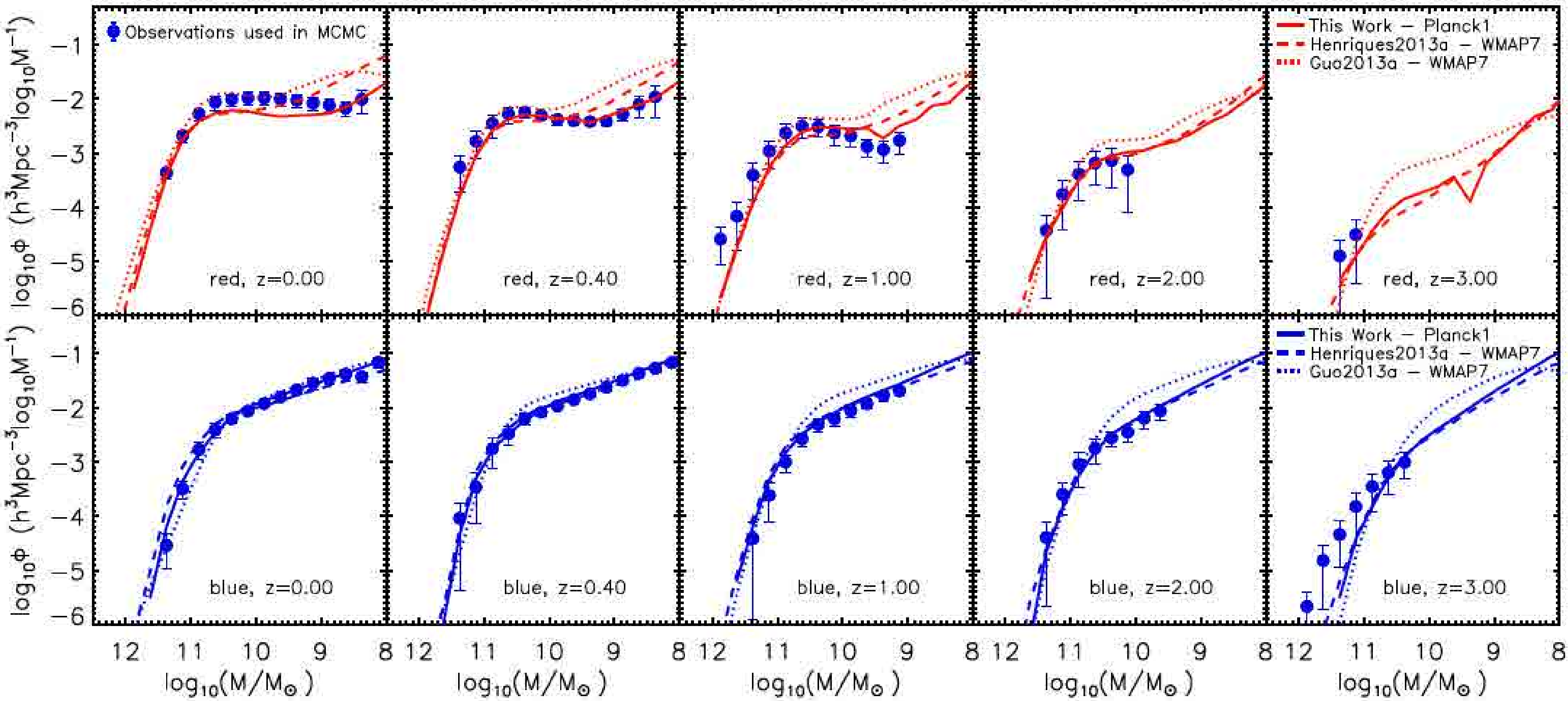


Changing the assumed timescale for reincorporation of wind ejecta

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

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

Henriques et al 2015, Planck cosmology



Changing the assumed timescale for reincorporation of wind ejecta

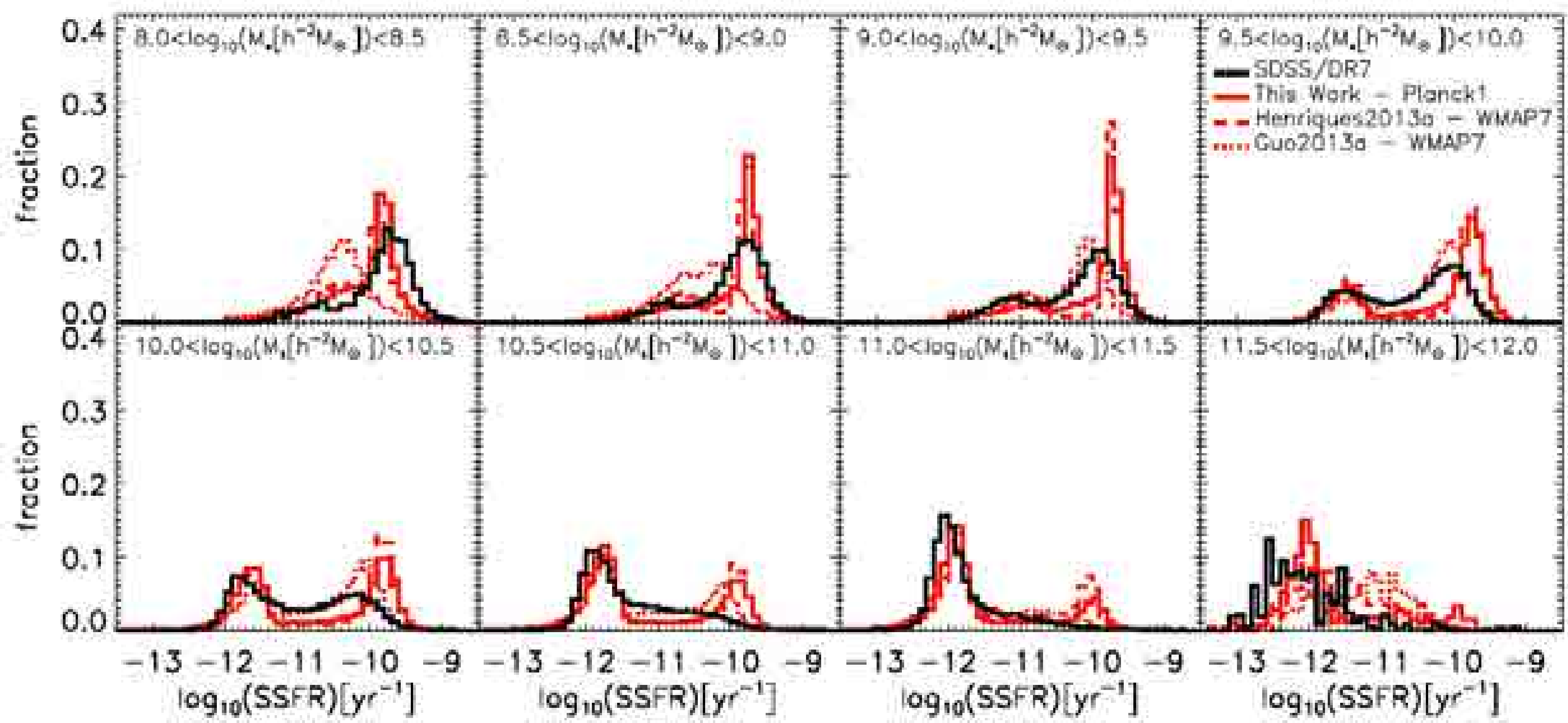
t_{return} = const. / H(z) V_{halo} → t_{return} = const. / M_{halo}

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

Updates to astrophysical modelling in 3rd generation models

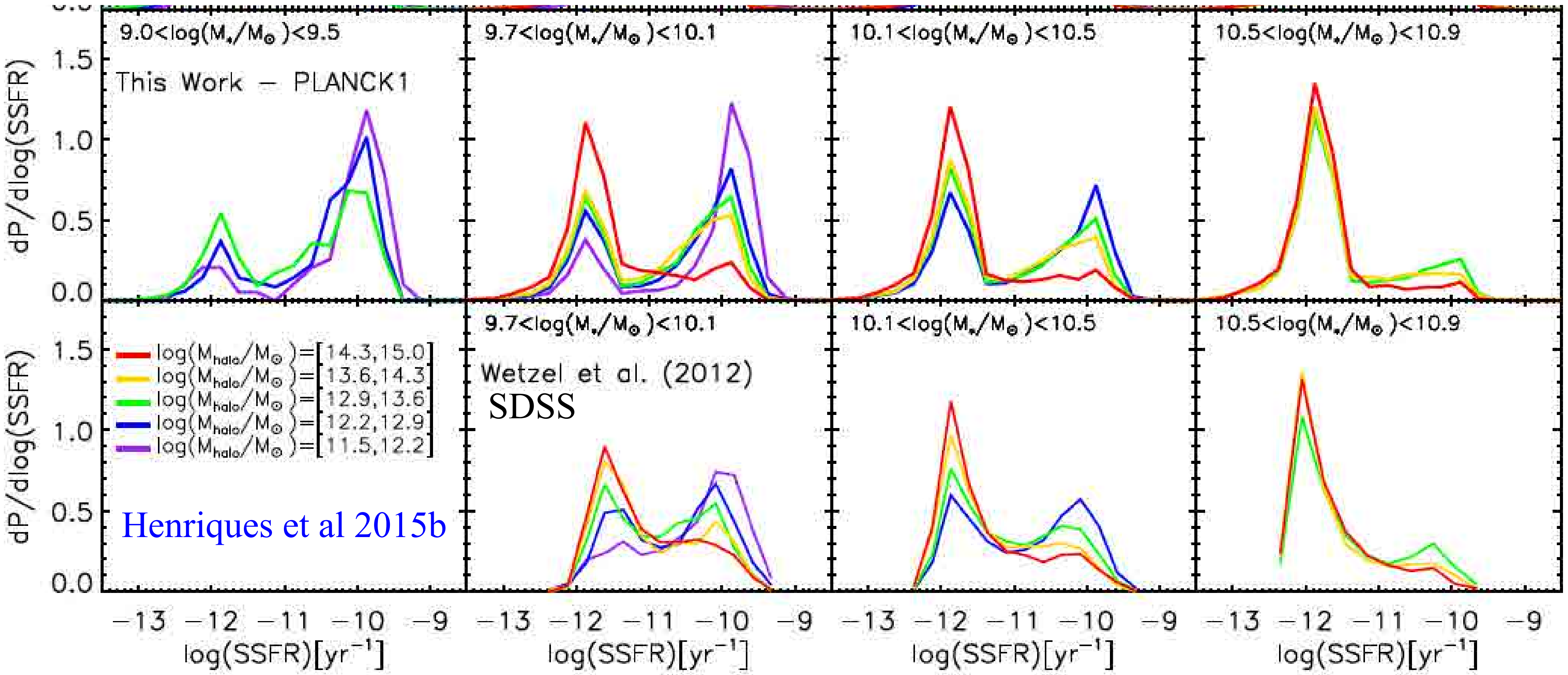
- Improved ejection/reincorporation models
- Elimination of ram-pressure stripping in low-mass halos (log M < 14)
- MCMC exploration of full parameter space.
- Switch to Planck (2013) cosmology

Henriques et al 2015

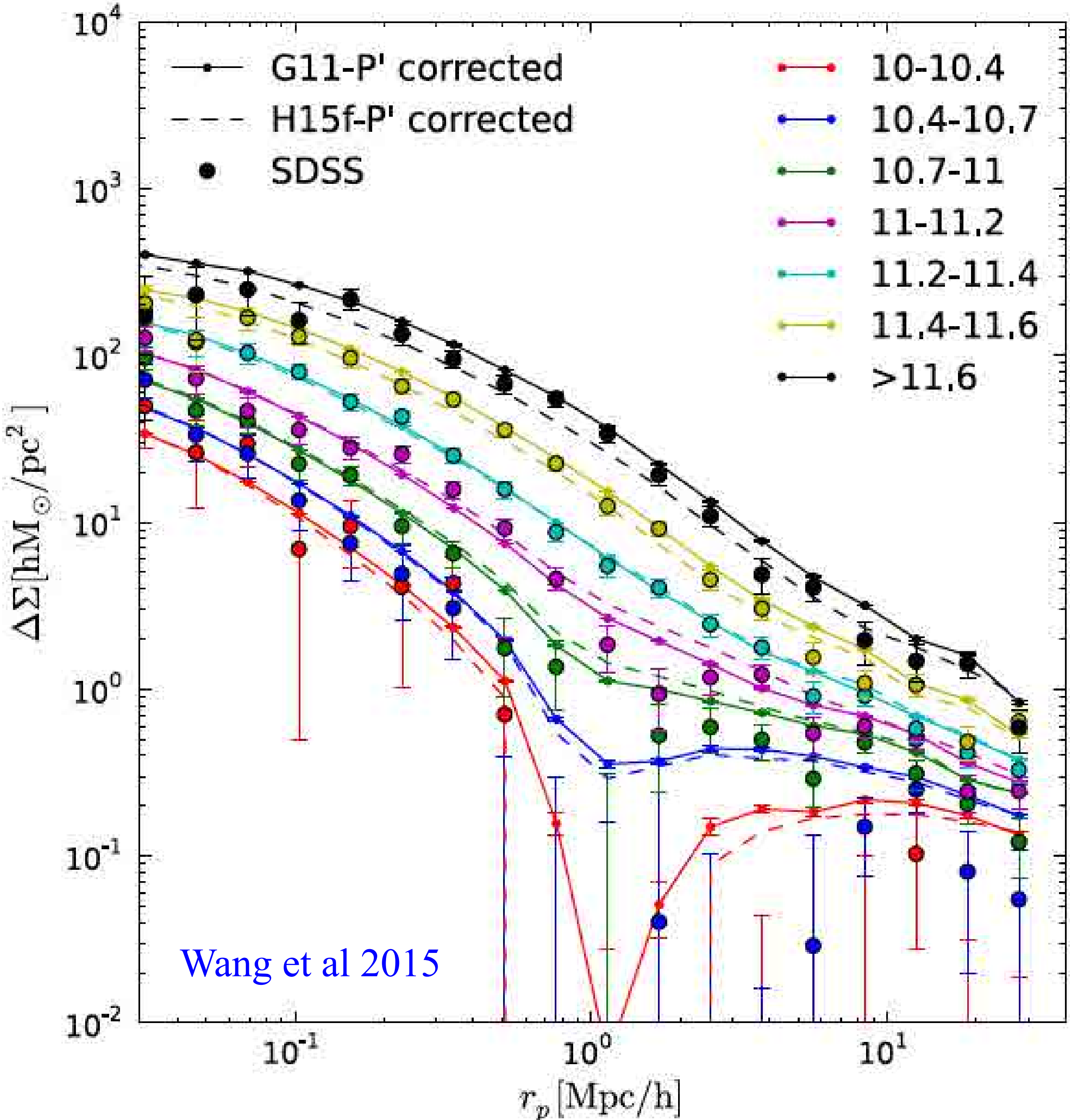


Updates to astrophysical modelling in 3rd generation models

Specific star formation rates of satellite galaxies as a function of halo mass



Influence of astrophysical modelling on halo predictions

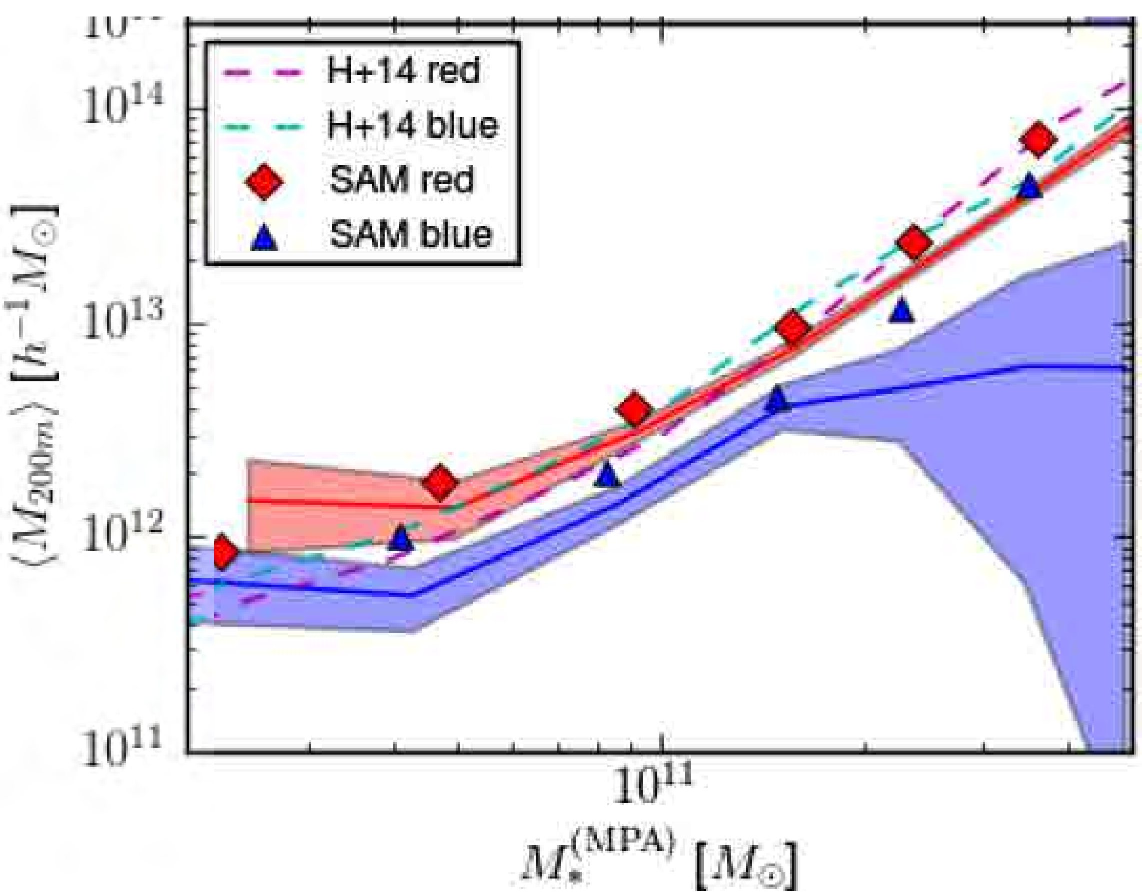


Two simulations of galaxy formation implemented on the same simulation of DM evolution and producing identical galaxy stellar mass functions give significantly different lensing predictions.

→ It matters exactly how the galaxies are assigned to dark matter (sub)halos

HOD models are not enough. Astrophysics is important!

Relative halo masses of red and blue galaxies



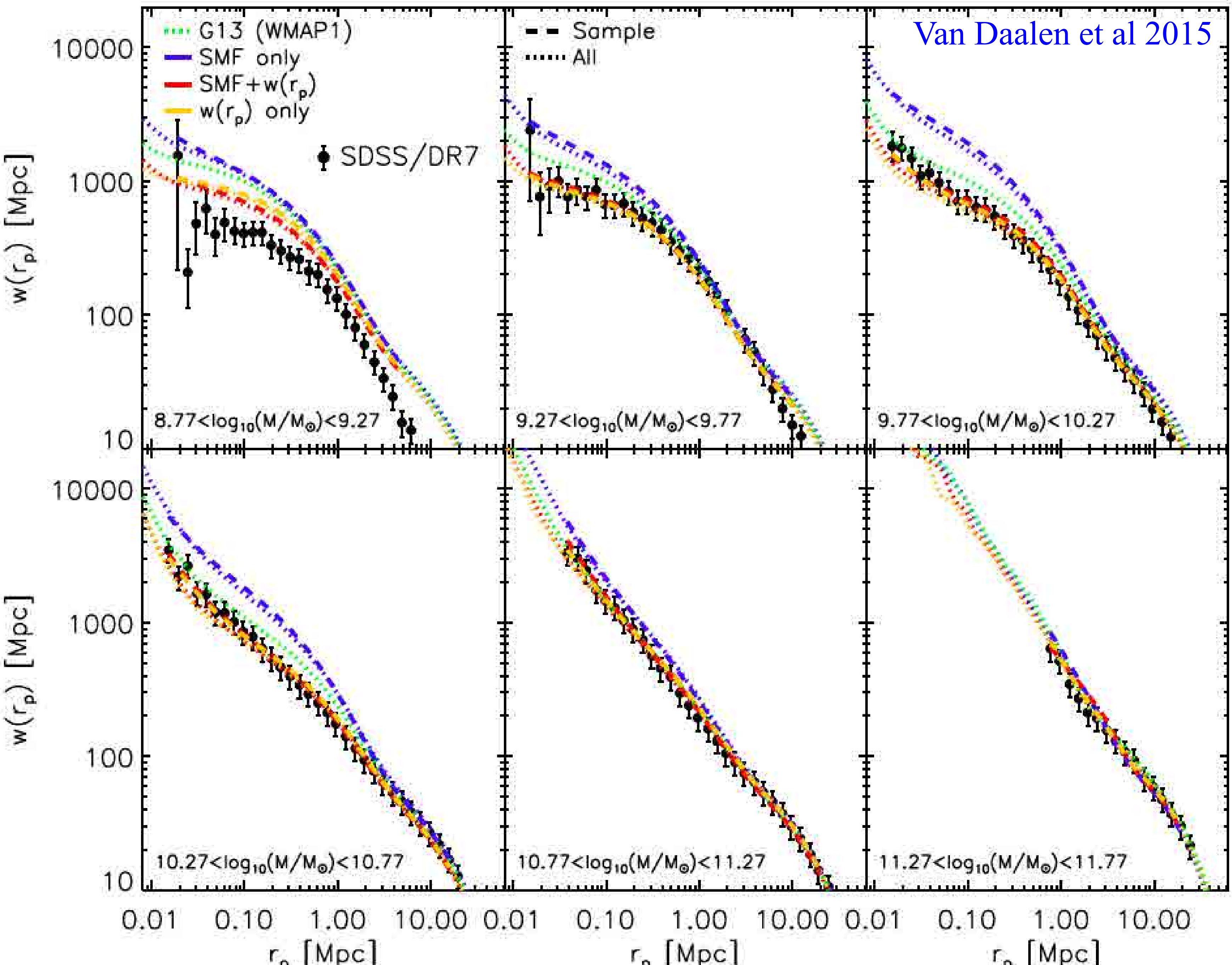
Mandelbaum et al 2015

The halo masses of "central" galaxies in SDSS estimated separately for star-forming and passive systems.

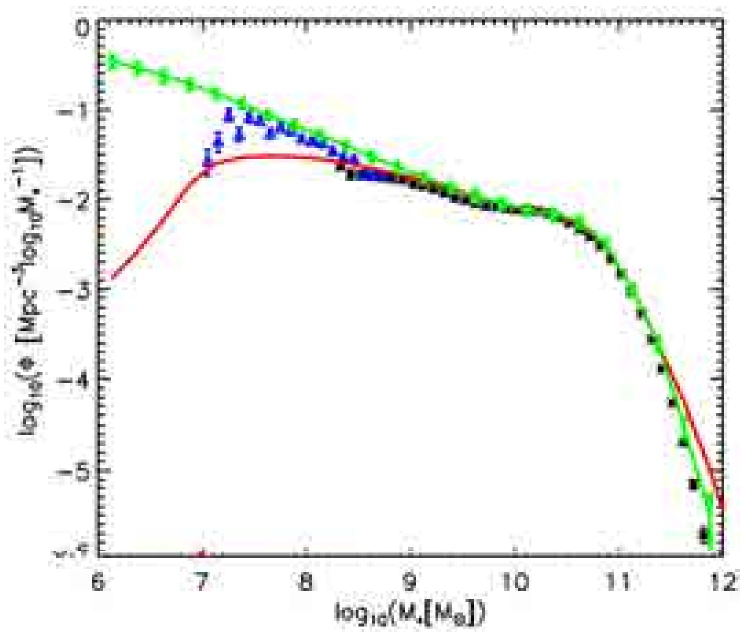
At given stellar mass red galaxies have more massive halos than blue ones.

This is reproduced by the galaxy formation simulations, but "age-matching" models (Hearin et al 2014) predict the opposite.

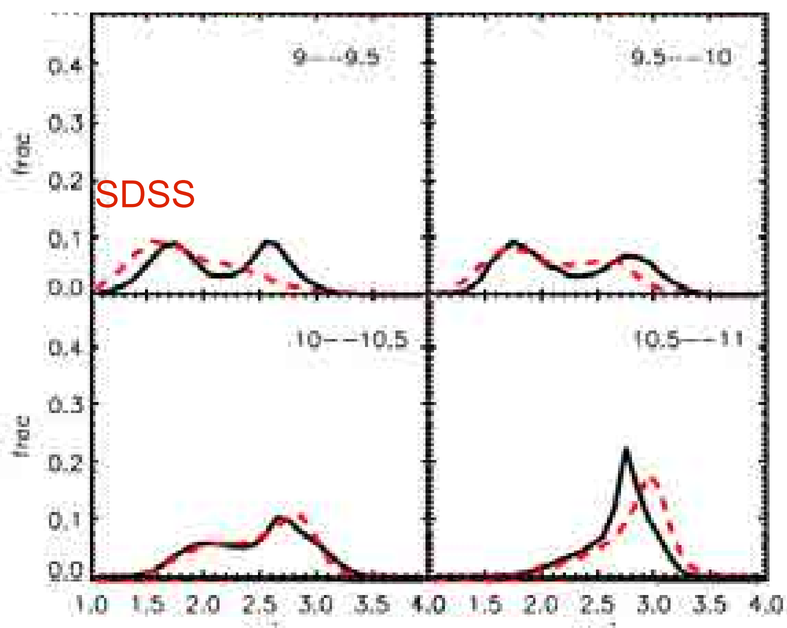
Simultaneous MCMC fits to abundances *and* clustering



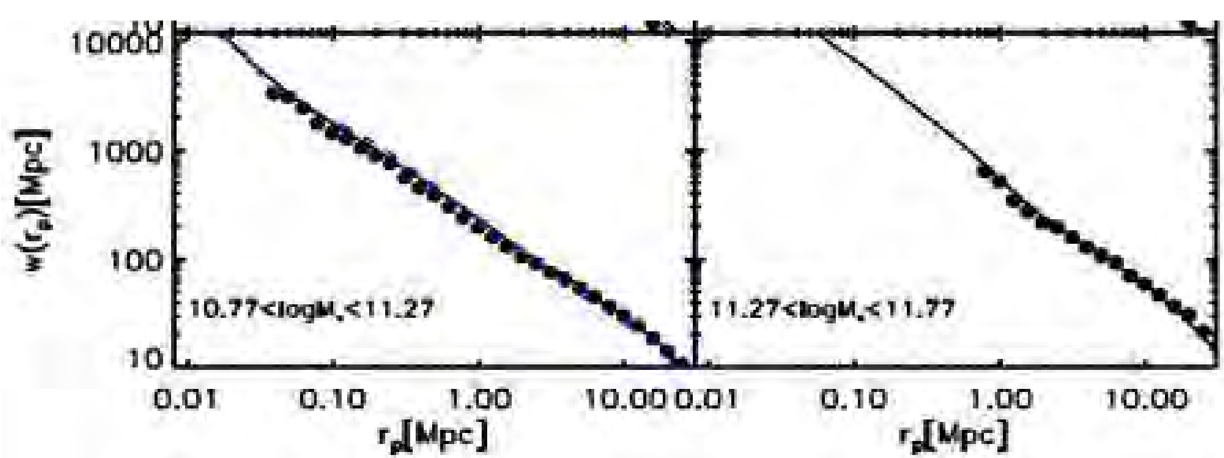
How do we learn from population simulations?



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



Guo et al 2011



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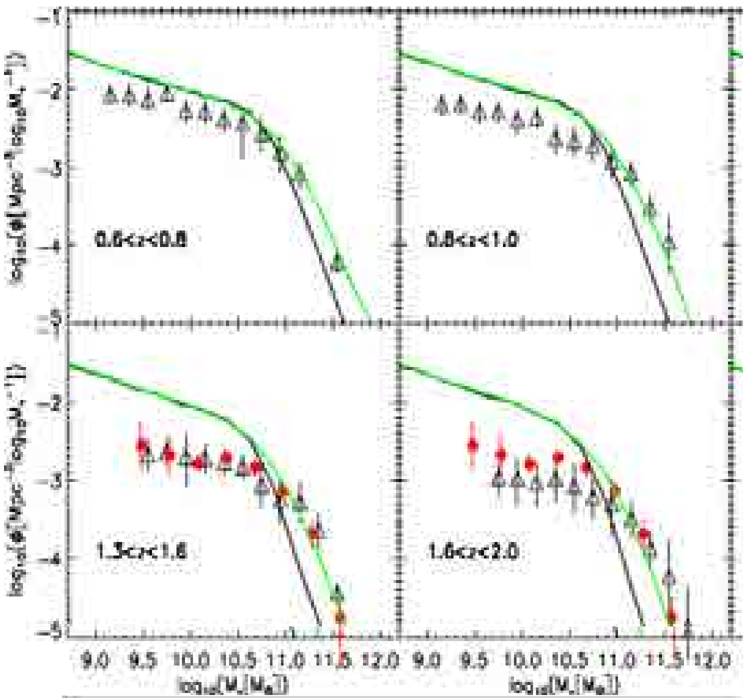
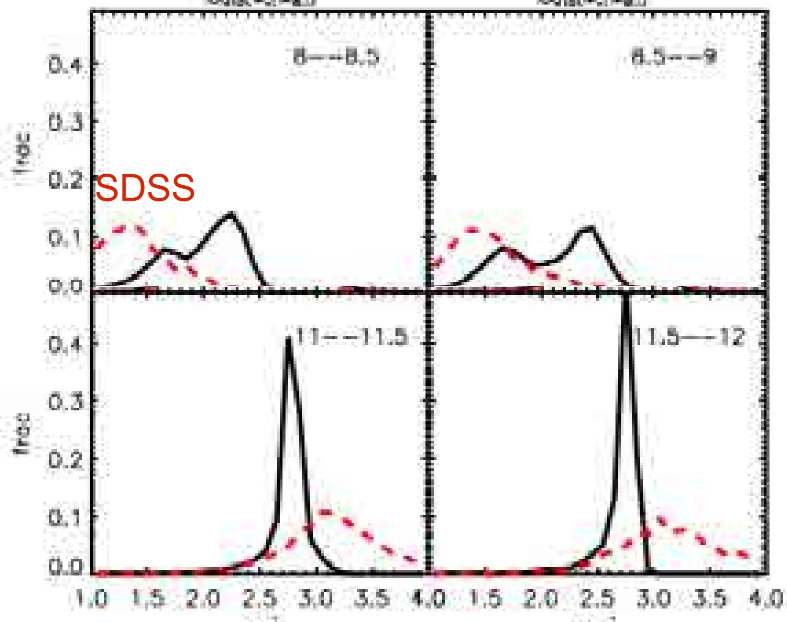


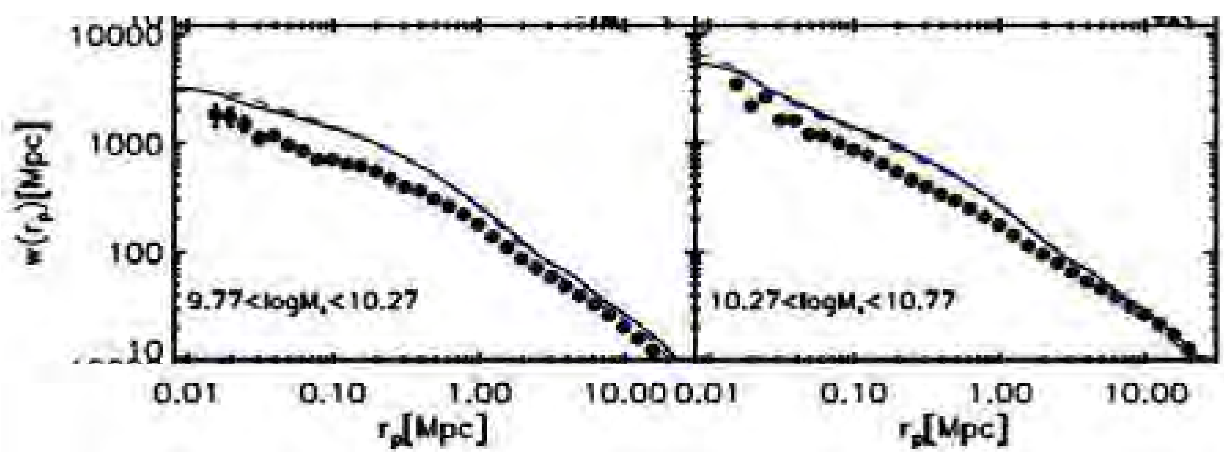


When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

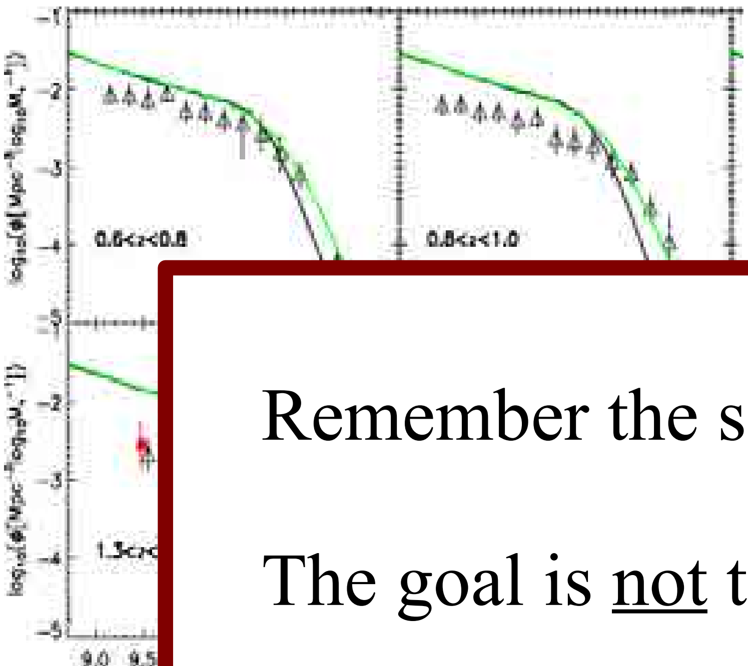
...but it is the failures which show where there is missing or inadequate physics

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

Guo et al 2011



How do we learn from population simulations?

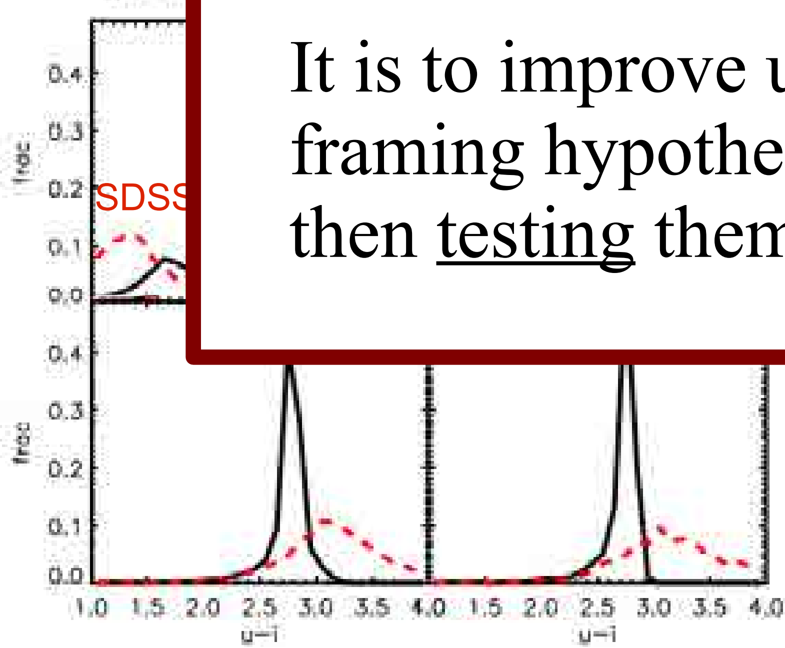


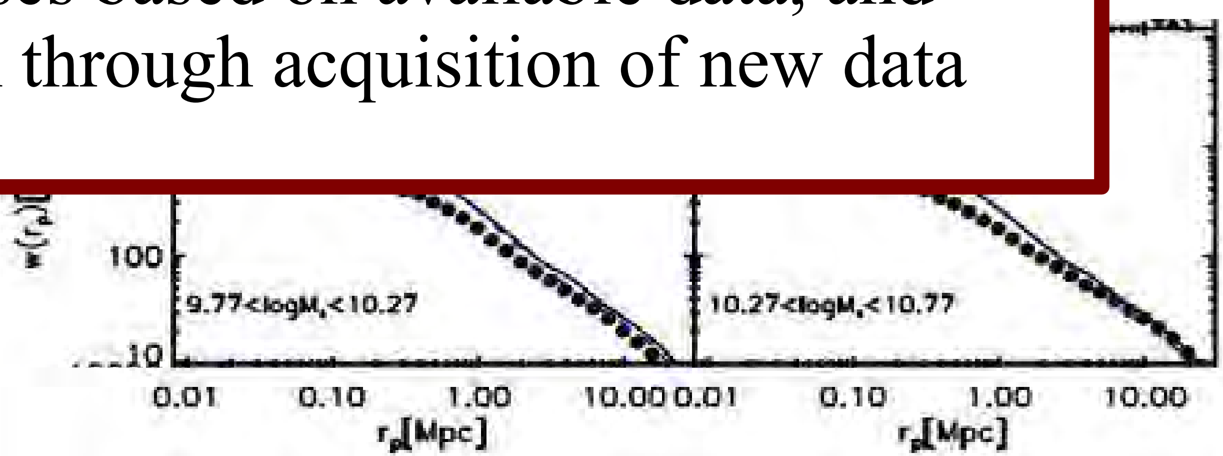
When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

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





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 histories 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, clustering and evolution found in large observational surveys
- Such comparisons indicate how galaxy formation and cosmological factors combine to influence observables, and hence allow us

→ i) to identify/characterize the primary galaxy formation processes
ii) to assess systematics when extracting cosmological information

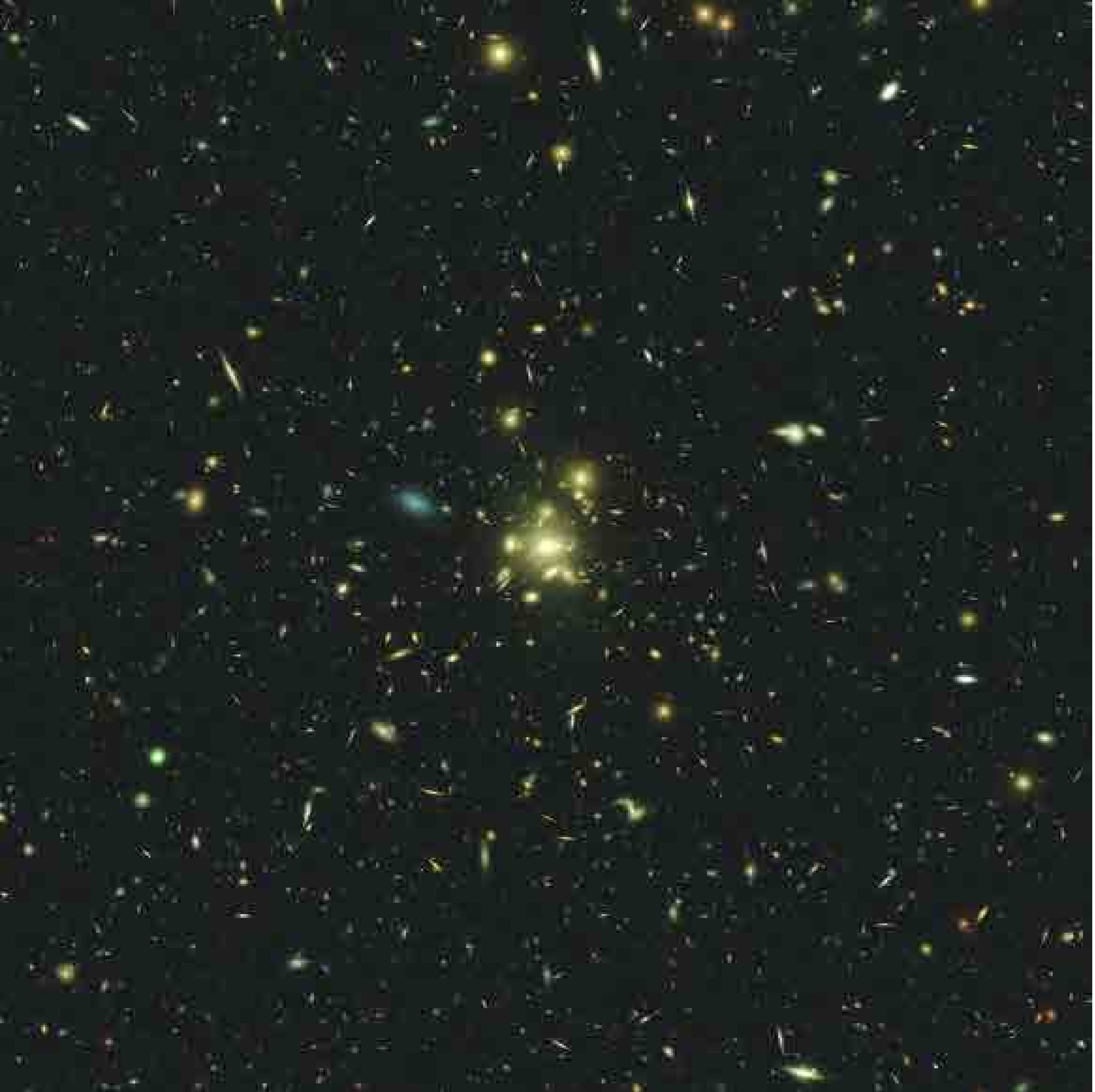
Cl0024

Harsono & De Propris
2007

z = 0.40

3.4' x 3.4'

HST/ACS



"Cl0024"

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

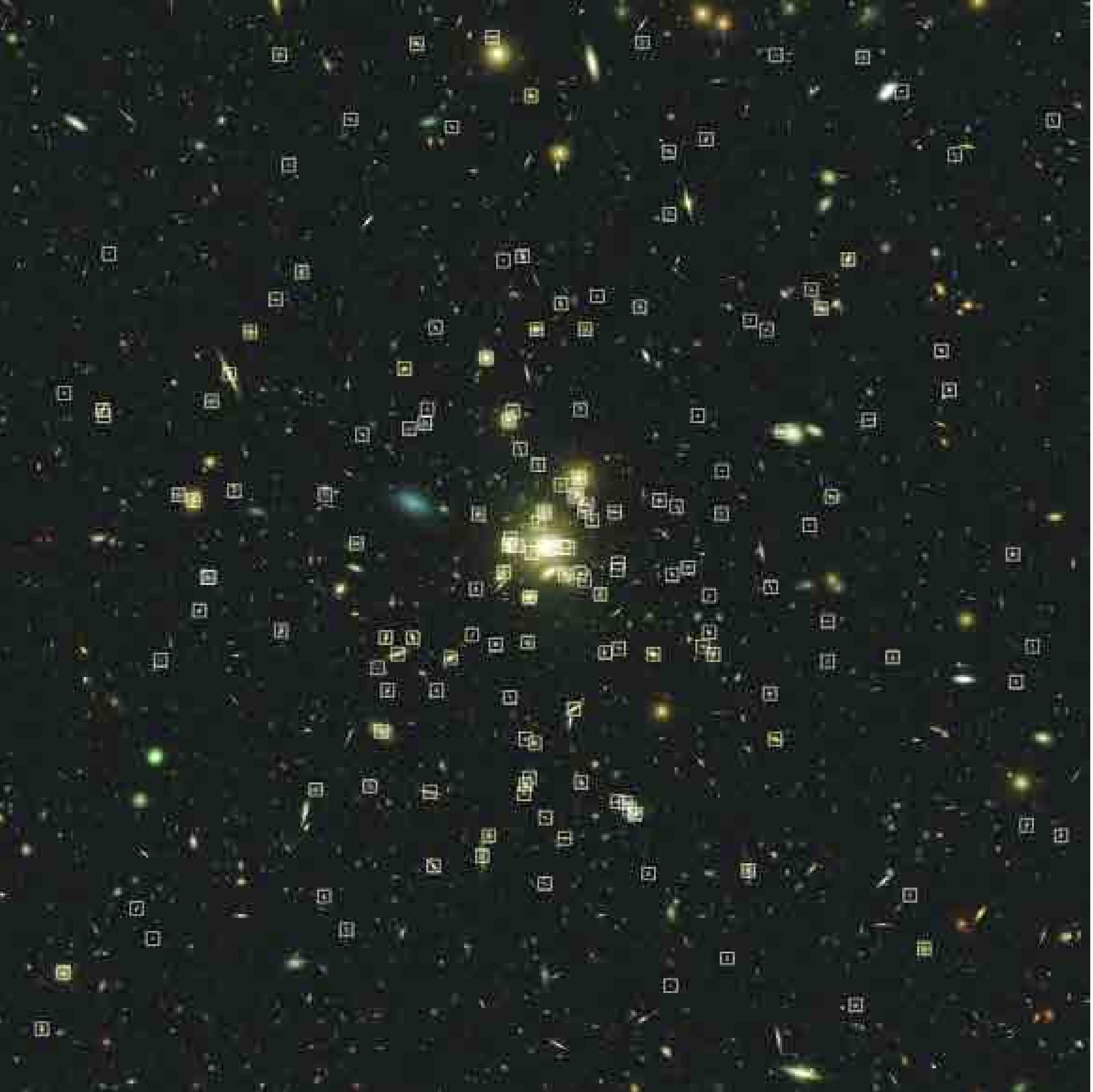
z = 0.41

3.4' x 3.4'

HST/ACS
F475W, F625W,
F850LP

10,000sec/filter

Overzier et al 2014



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HST/ACS
F475W, F625W,
F850LP

10,000sec/filter

Overzier et al 2014

Max-Planck-Institut für Astrophysik

The MROBS Project
- Imaging Portal -

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portal
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help

We have developed the Millennium Run Observatory (MRObs), a theoretical virtual observatory framework which uses virtual telescopes to `observe' semi-analytic galaxy formation simulations based on the suite of Millennium Run (MR) dark matter simulations.

Description of data products in the MRObs: Here

Explore our virtual observations in the MRObs Image Browser: Here (Interactive version of the MRObs Image Browser: Here)

Data release: Here

FAQ and How-to: Here

Visualisations and PR material: Here

Contact: Roderik Overzier, Gerard Lemson

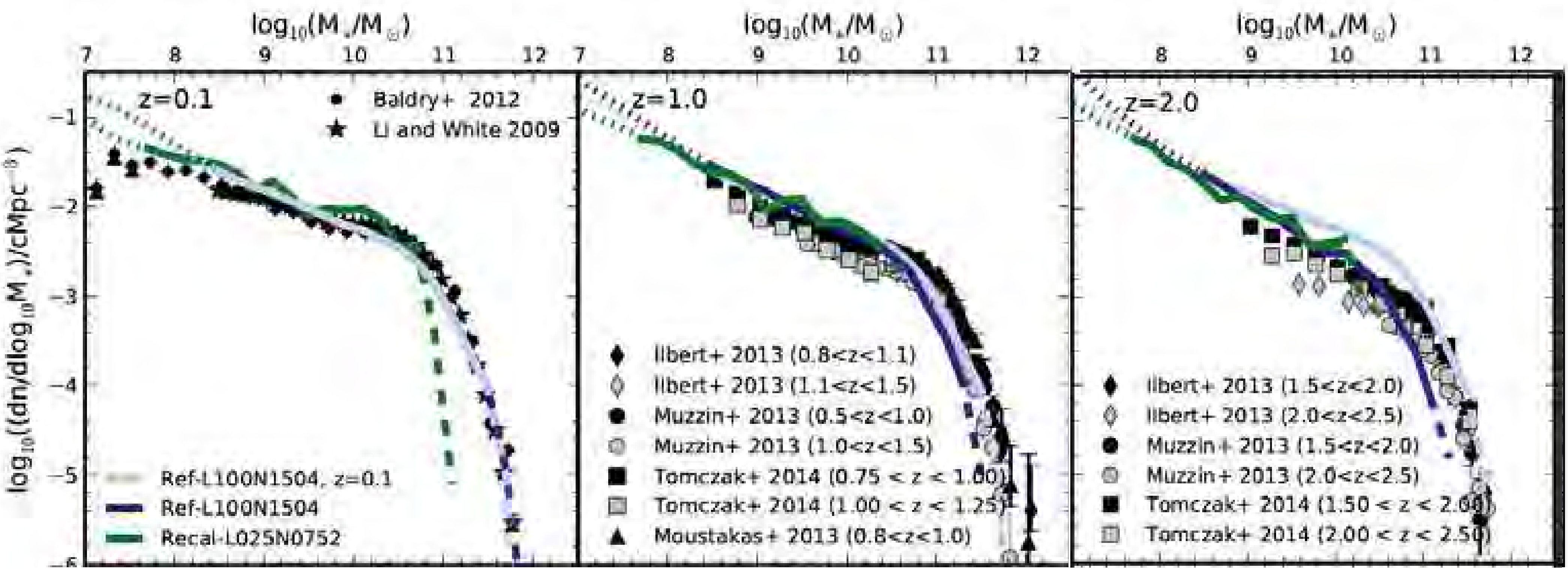
References: Overzier, Lemson, et al. 2012, MNRAS, in press (arXiv:1206.6923v2, high resolution paper here). (see 'about & credits' for further references).

Surveys Overview Table

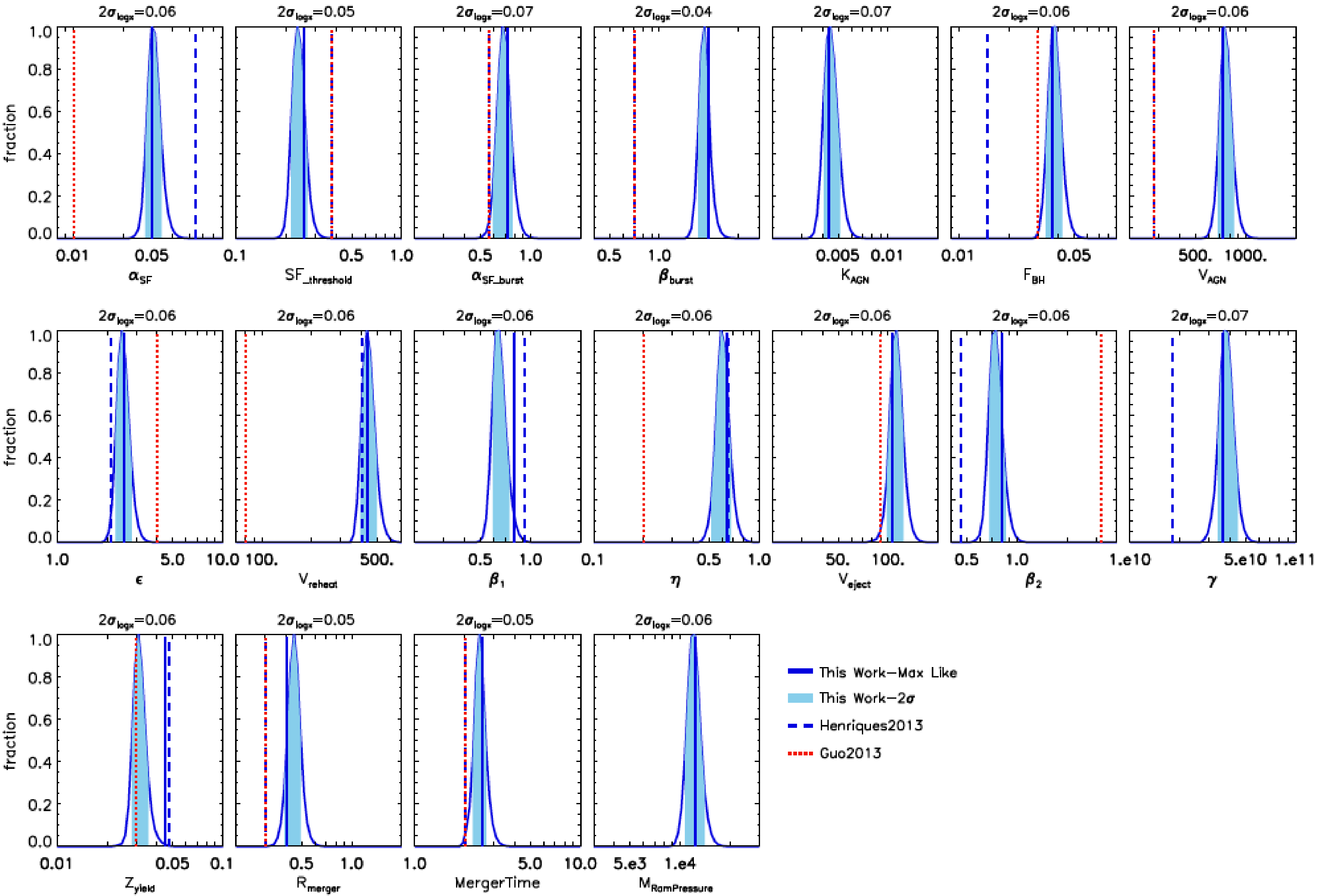
http://galformod.mpa-garching.mpg.de/mrobs/

Survey ▲	Instrument/Filter	Stellar Population	IGM Model	Cosmology	Download
CANDELS/COSMOS	HST/ACS F606W HST/ACS F814W WFC3/IR F105W WFC3/IR F125W WFC3/IR F160W	BC03 M05	MADAU MEIKSIN INOUE-IWATA	WMAP1 WMAP7*	v0.5
CANDELS/UDS	HST/ACS F606W HST/ACS F814W WFC3/IR F105W WFC3/IR F125W WFC3/IR F160W	BC03 M05	MADAU MEIKSIN INOUE-IWATA	WMAP1 WMAP7*	v0.5
CFHT-LS Deep	Megacam u Megacam g Megacam r Megacam i Megacam z	BC03 M05	MADAU MEIKSIN INOUE-IWATA	WMAP1 WMAP7*	v0.5

Stellar mass function evolution in the Eagle simulations



Furlong et al 2015



2σ_logx=0.06
2σ_logx=0.05
2σ_logx=0.07
2σ_logx=0.04
2σ_logx=0.07
2σ_logx=0.06
2σ_logx=0.06
fraction
α_SF
SF_threshold
α_SF_burst
β_burst
K_AGN
F_BH
V_AGN
ε
V_reheat
β_1
η
V_eject
β_2
γ
Z_yield
R_merger
MergerTime
M_RamPressure
This Work–Max Like
This Work–2σ
Henriques2013
Guo2013