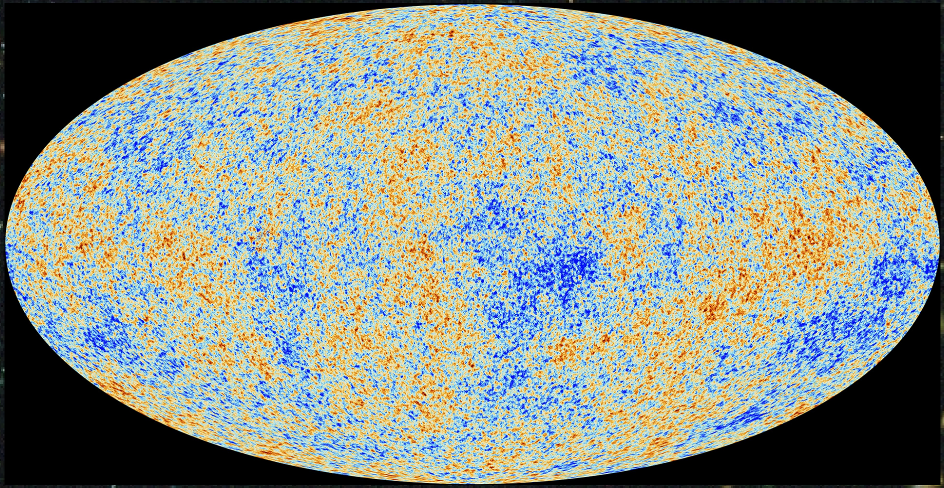
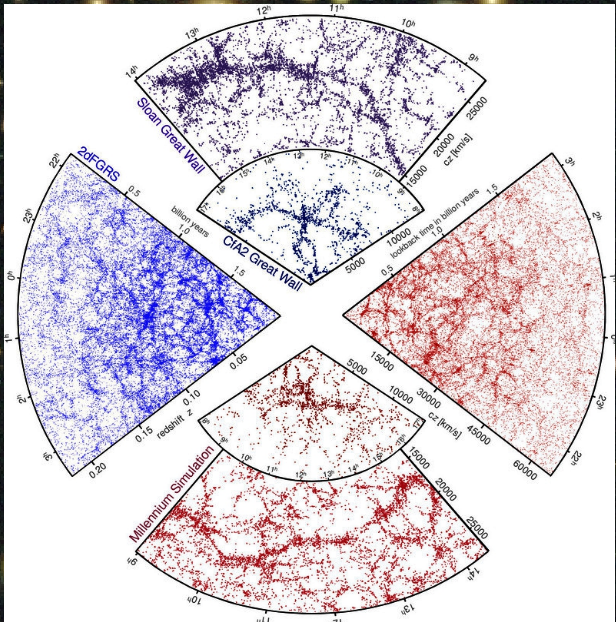


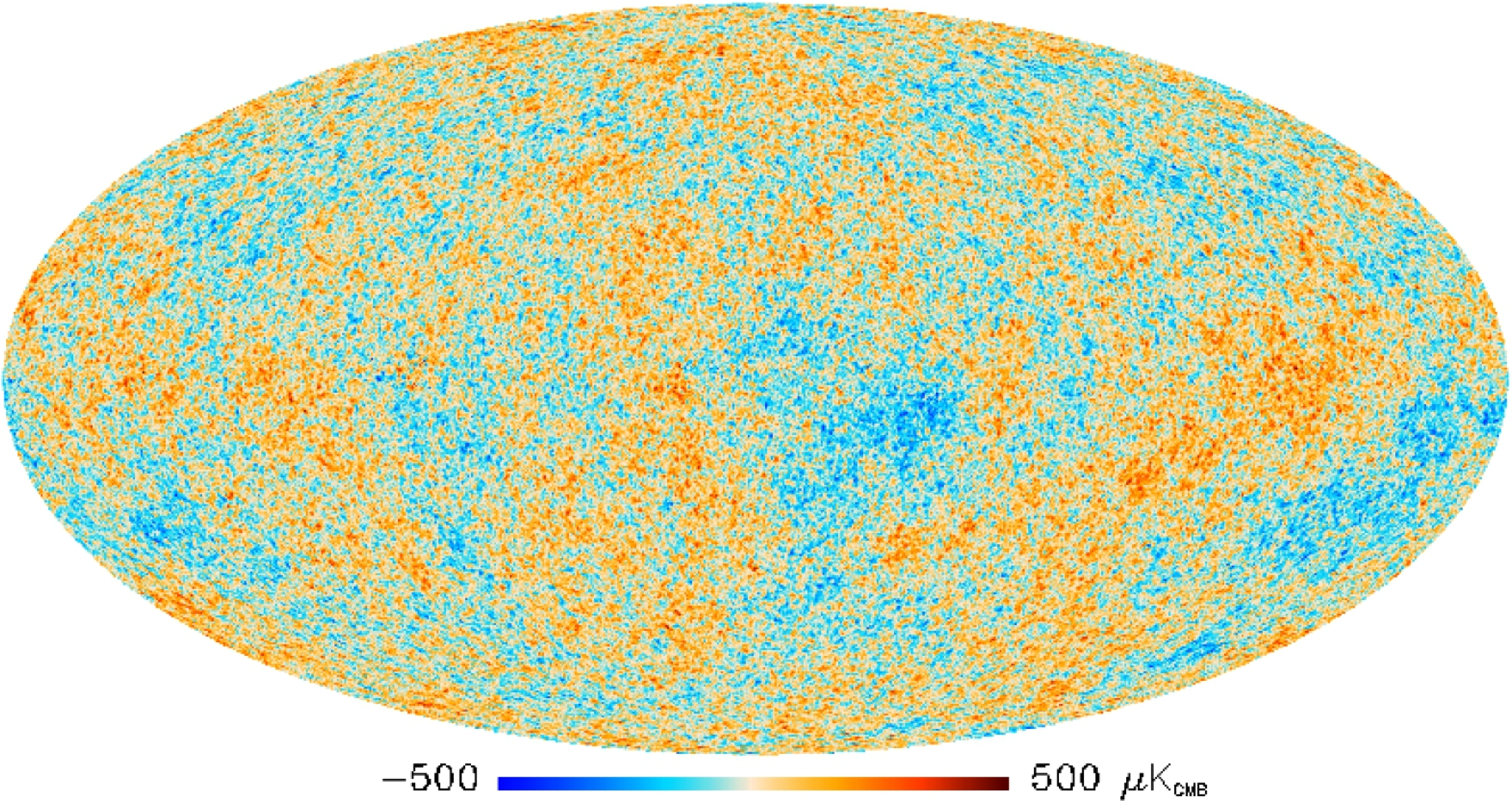
Garching, September 2013

The formation and evolution of the galaxy population

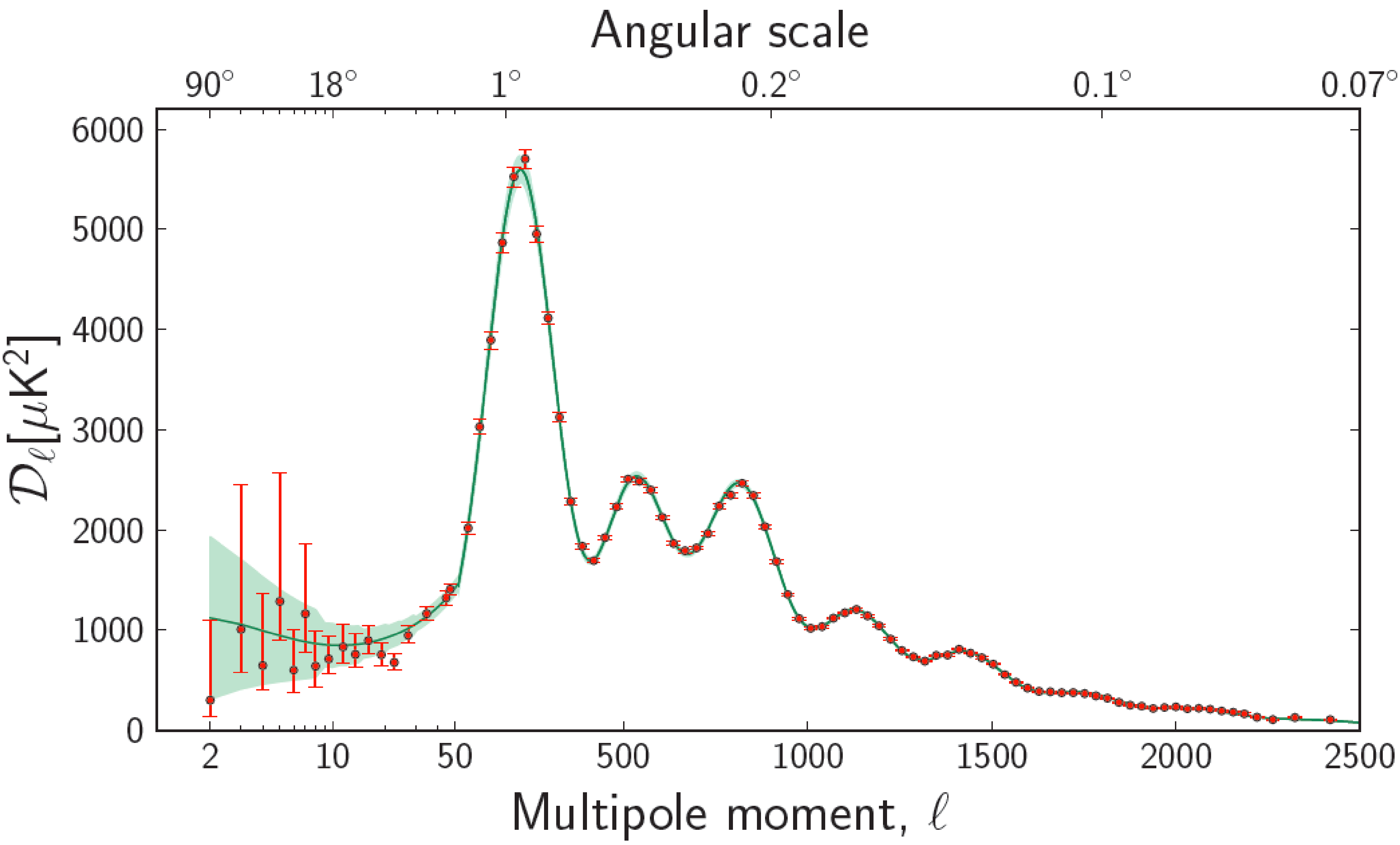


Simon White
Max Planck Institute for Astrophysics

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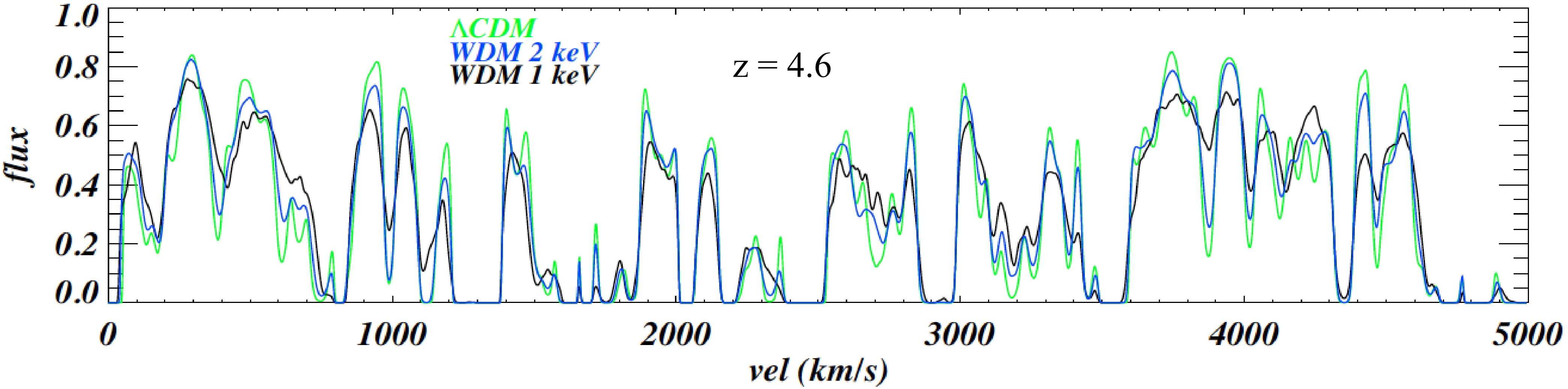
A 40σ detection of nonbaryonic DM using ***only*** z ~1000 data!

Ly α forest spectra and small-scale initial structure

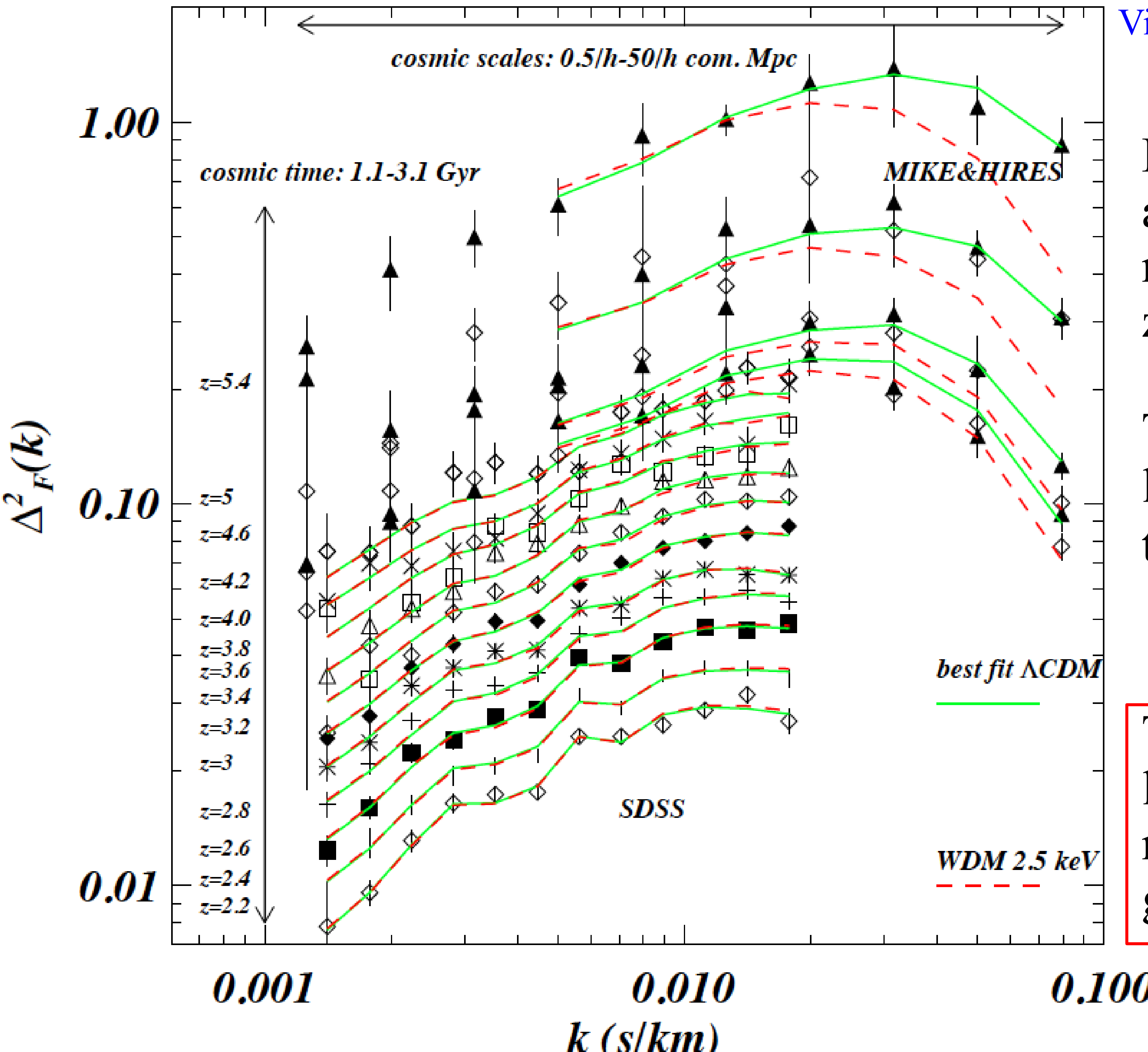
Viel, Becker, Bolton & Haehnelt 2013



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



Viel, Becker, Bolton & Haehnelt 2013

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

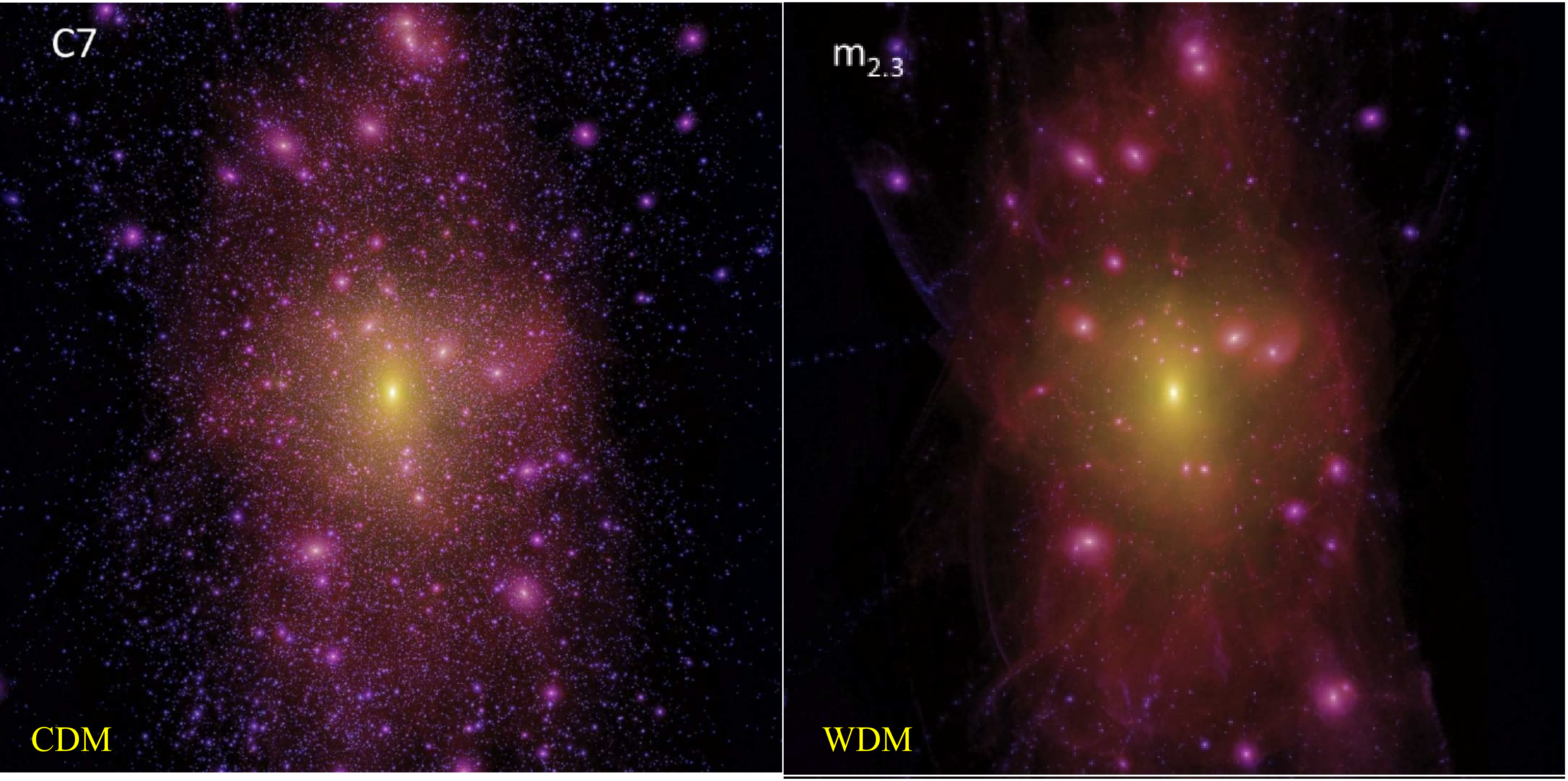
This places a 2σ lower limit on the mass of a thermal relic

$m_{WDM} > 3.3$ keV

This lower limit is too large for WDM to have much effect on dwarf galaxy structure

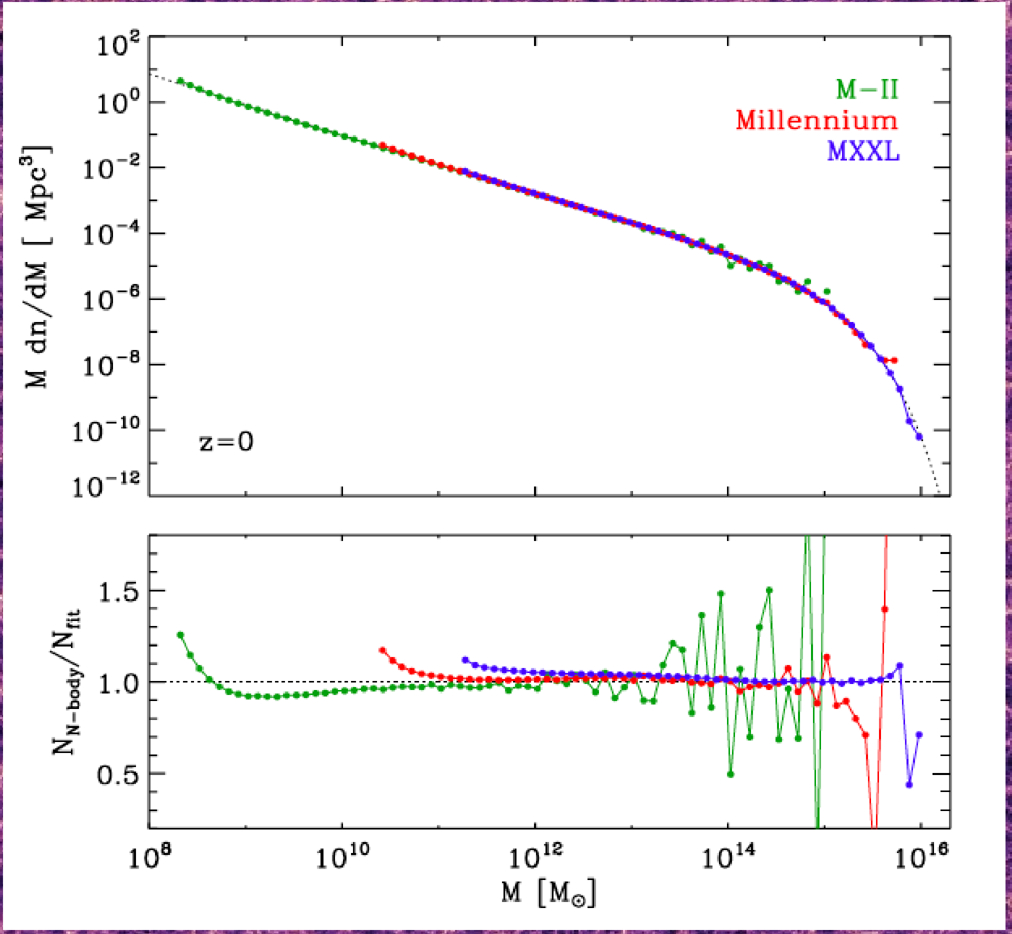
Dark matter effects on galaxy formation?

Lovell et al 2013.



“Milky Way” halos in CDM and WDM. Note, the Ly α forest 2σ lower limit gives a limiting halo mass 3 times *smaller* than assumed here. The IC's are ~ΛCDM on essentially all scales relevant to galaxies

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



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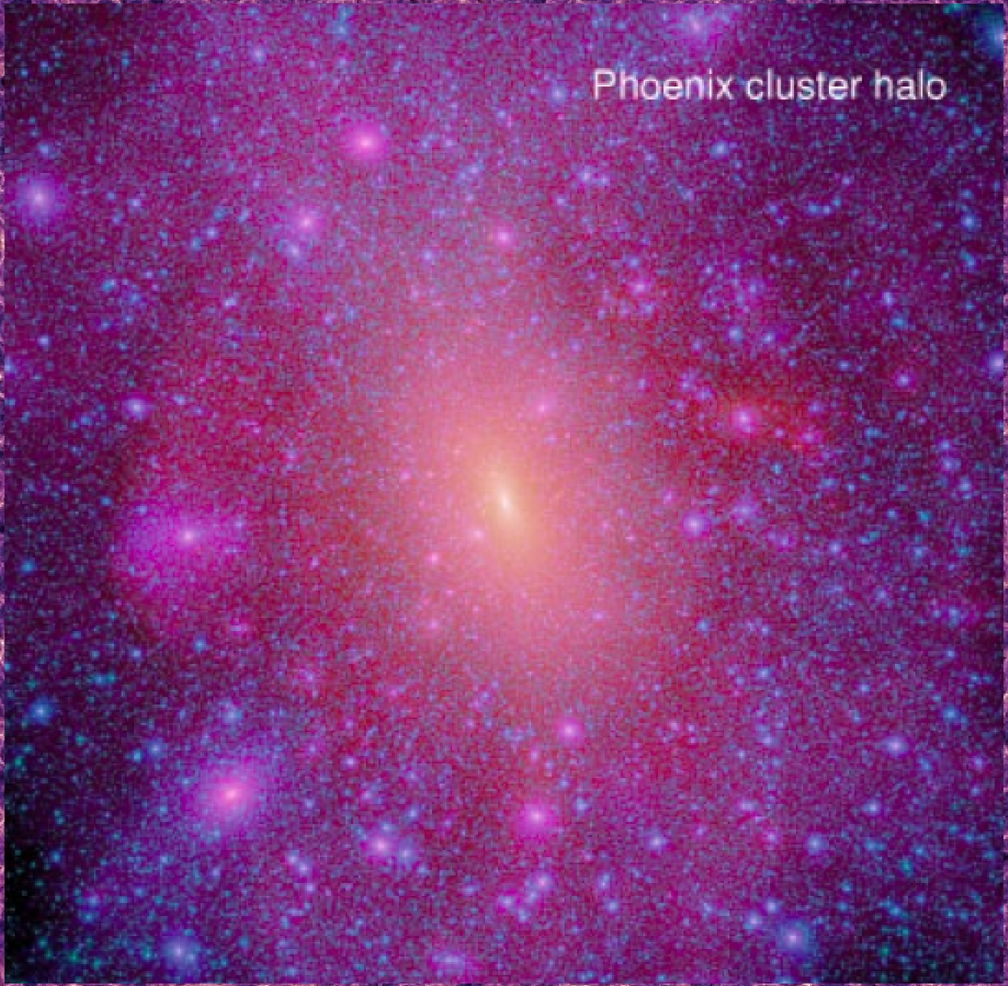
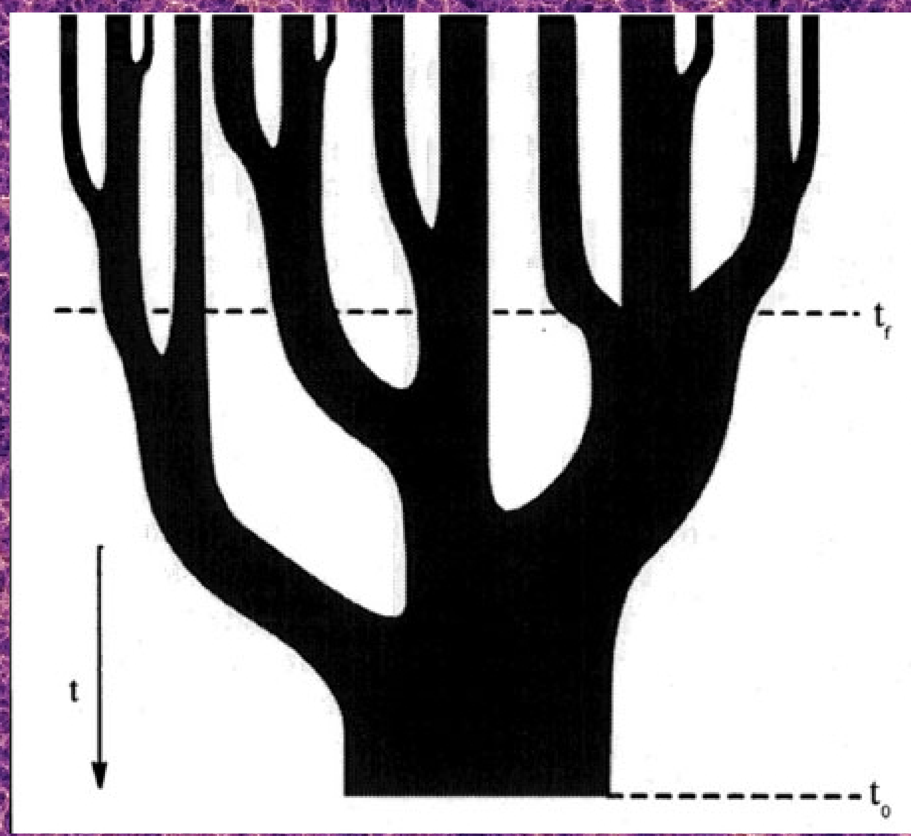
Galaxies correspond to self-bound *subhalos* within halos, rather than to the halos themselves



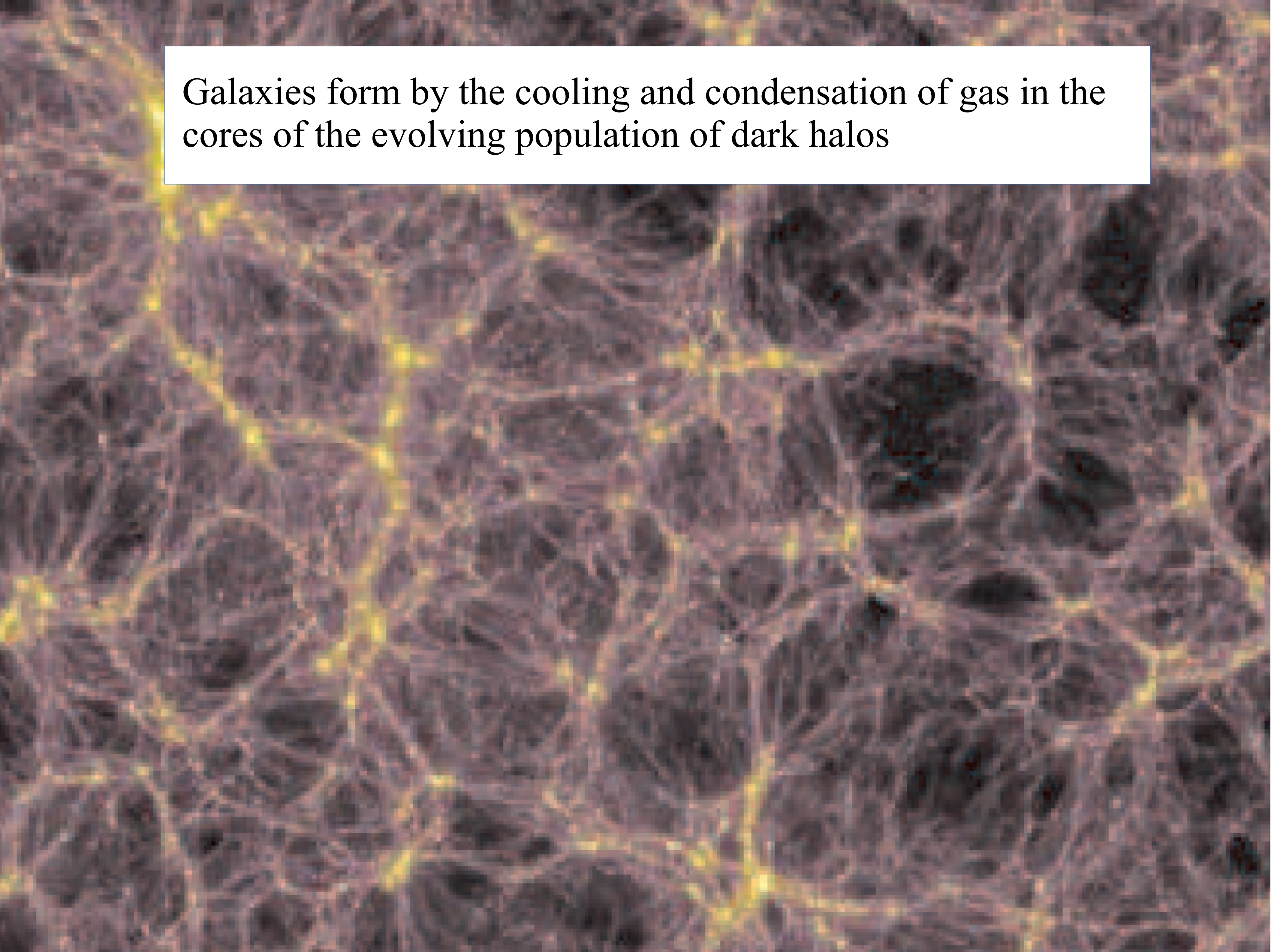
N-body codes can simulate the evolution of the abundance, internal structure and clustering of dark halos at high precision

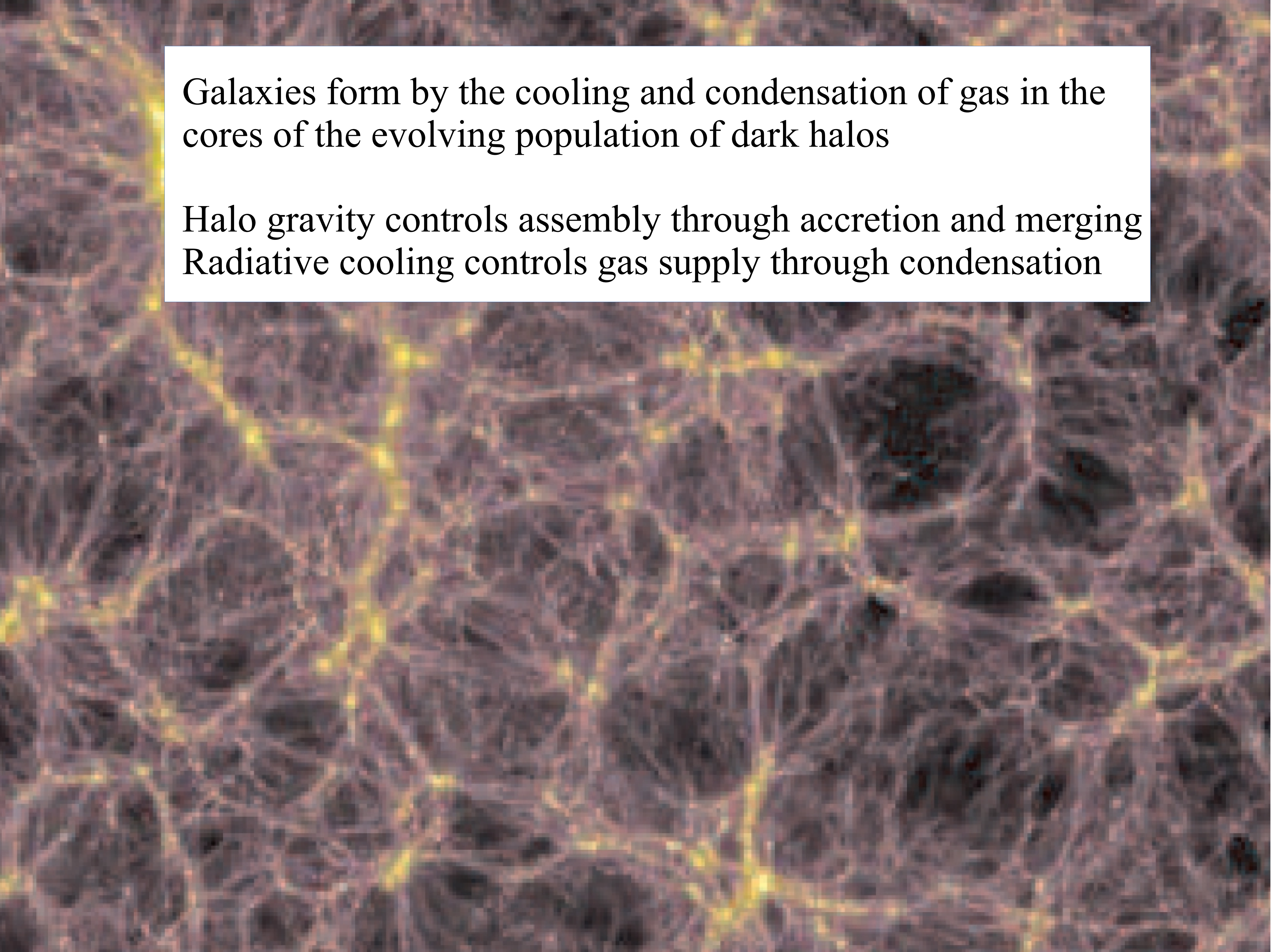
Galaxies correspond to self-bound *subhalos* within halos, rather than to the halos themselves

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
Radiative cooling controls gas supply through condensation

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"

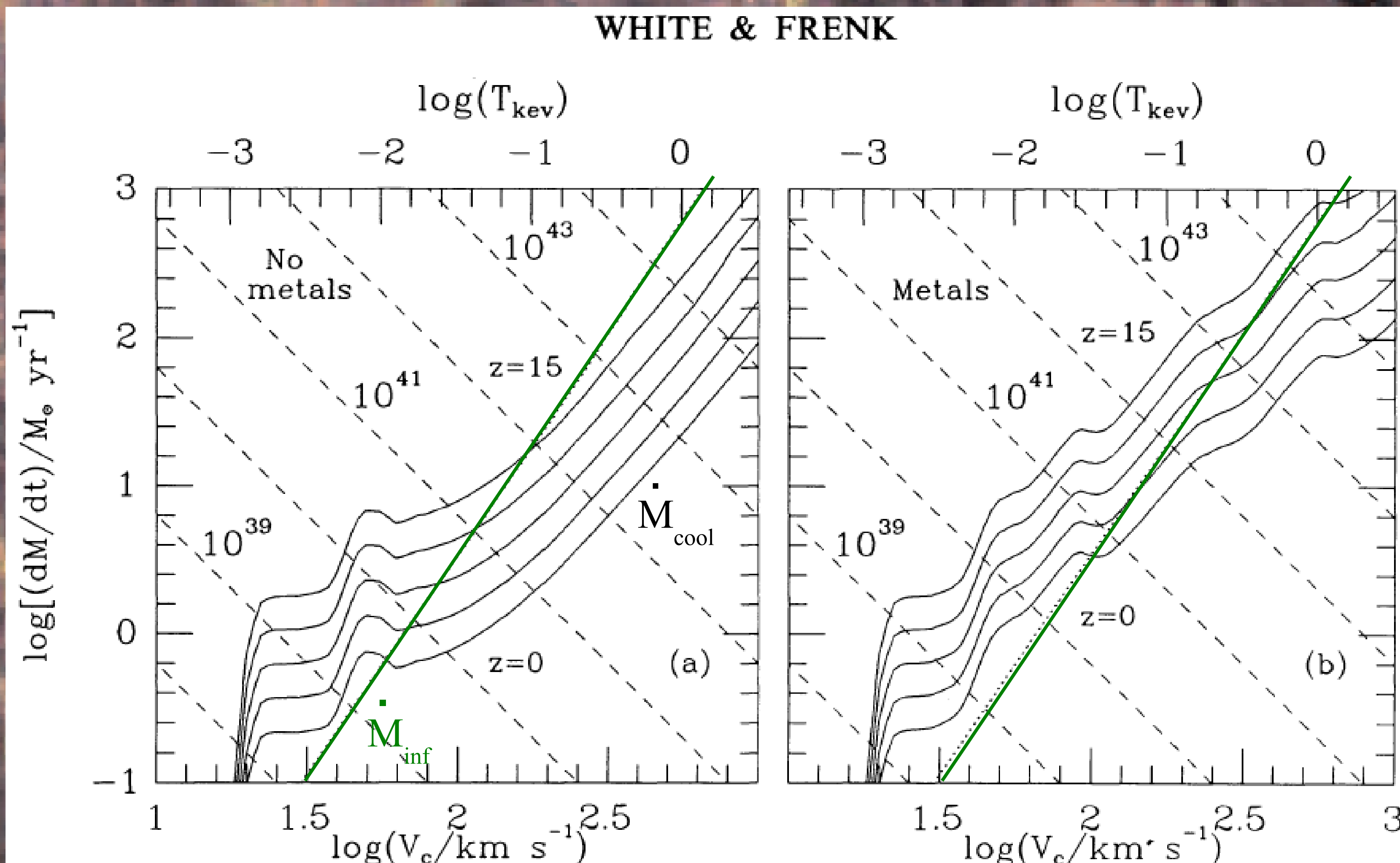
In the opposite limit, $r_{\rm cool} \ll r_{\rm vir}$,

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

radiative settling
"cooling flows"

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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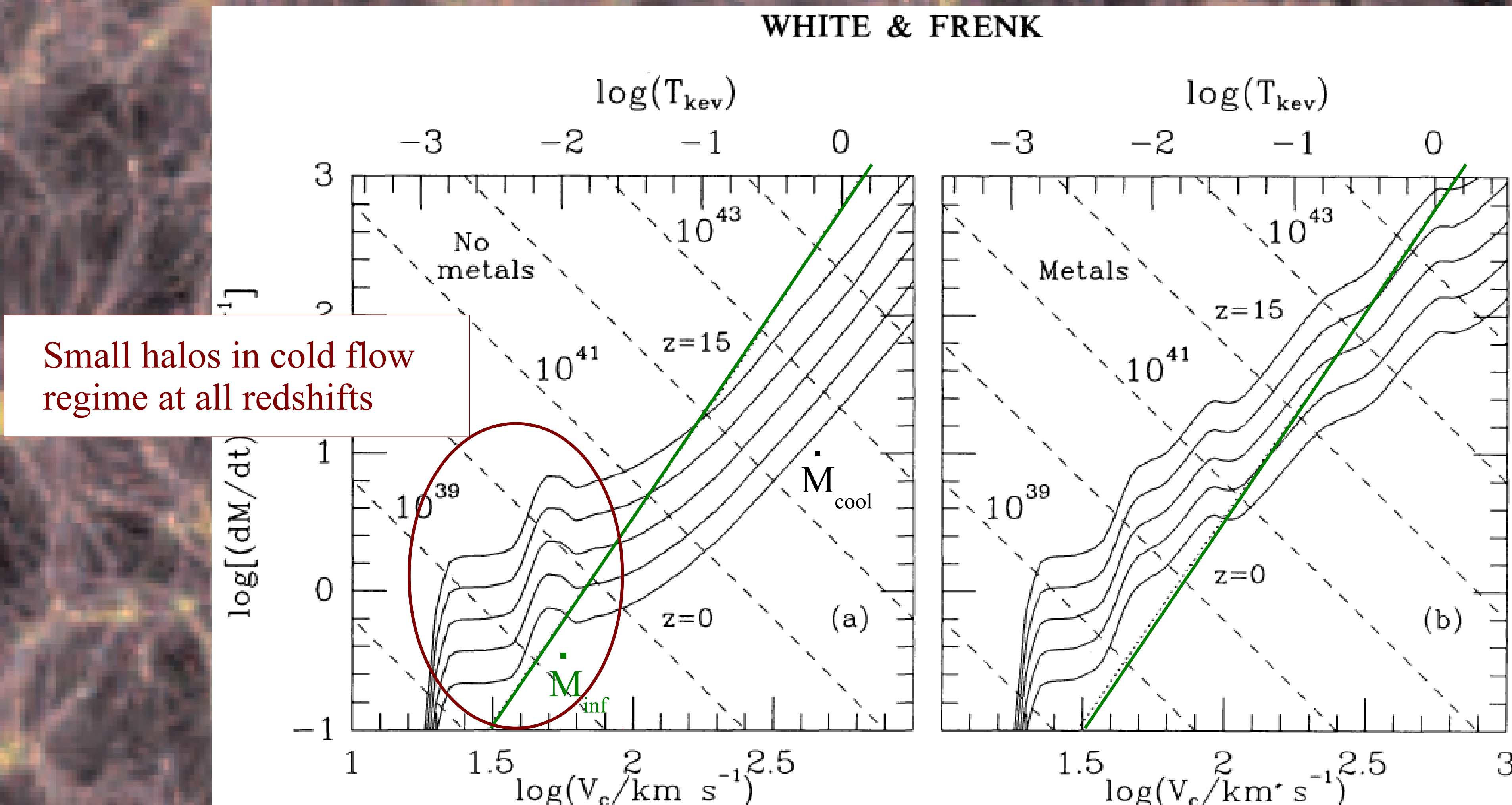

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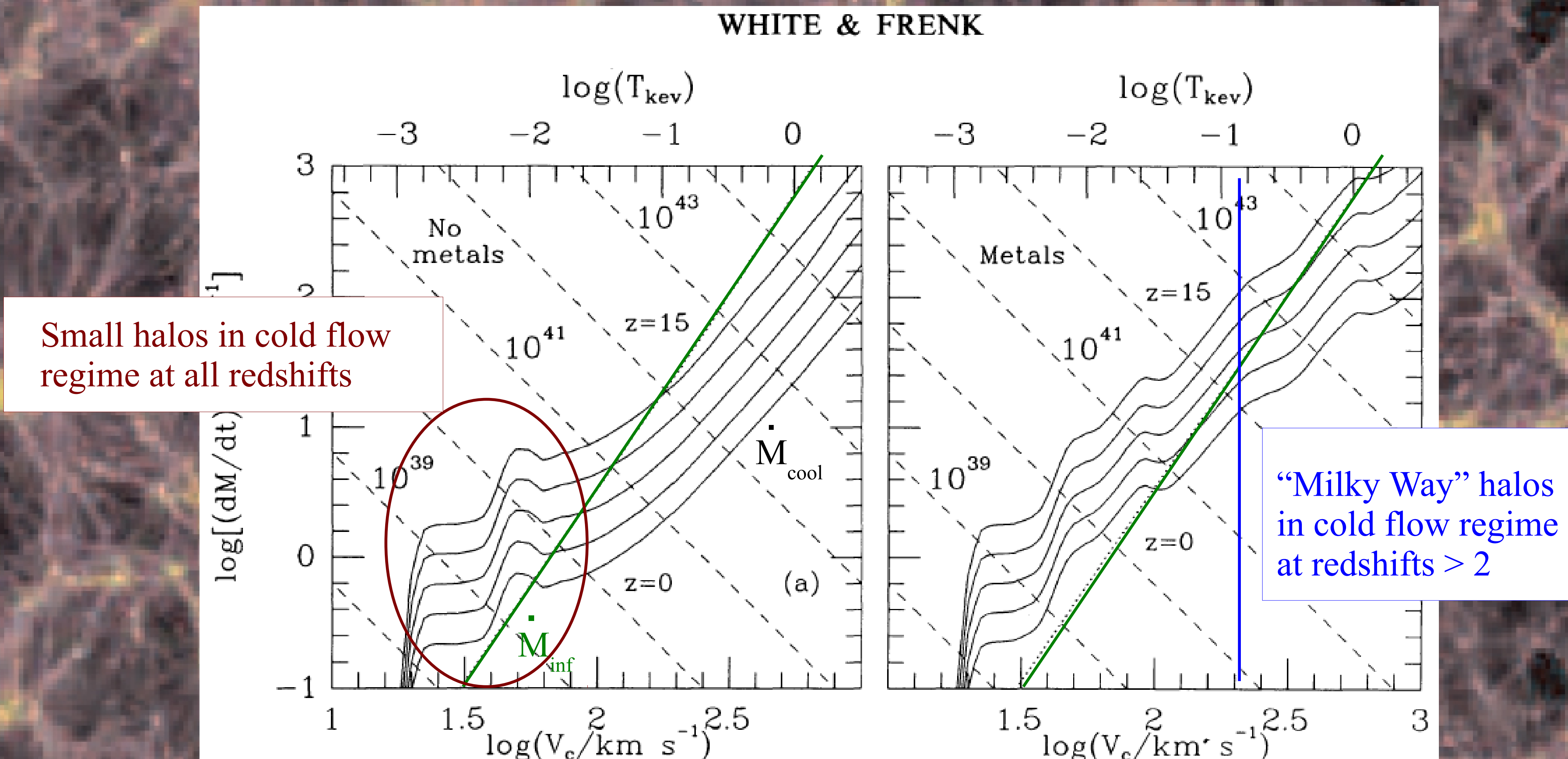
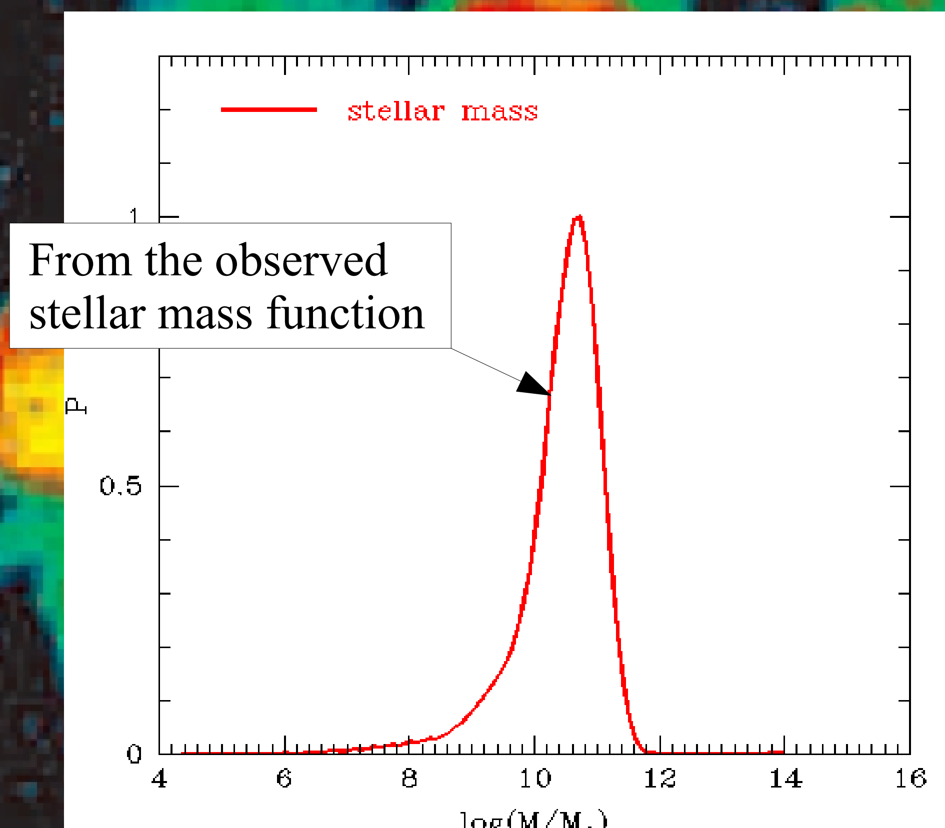
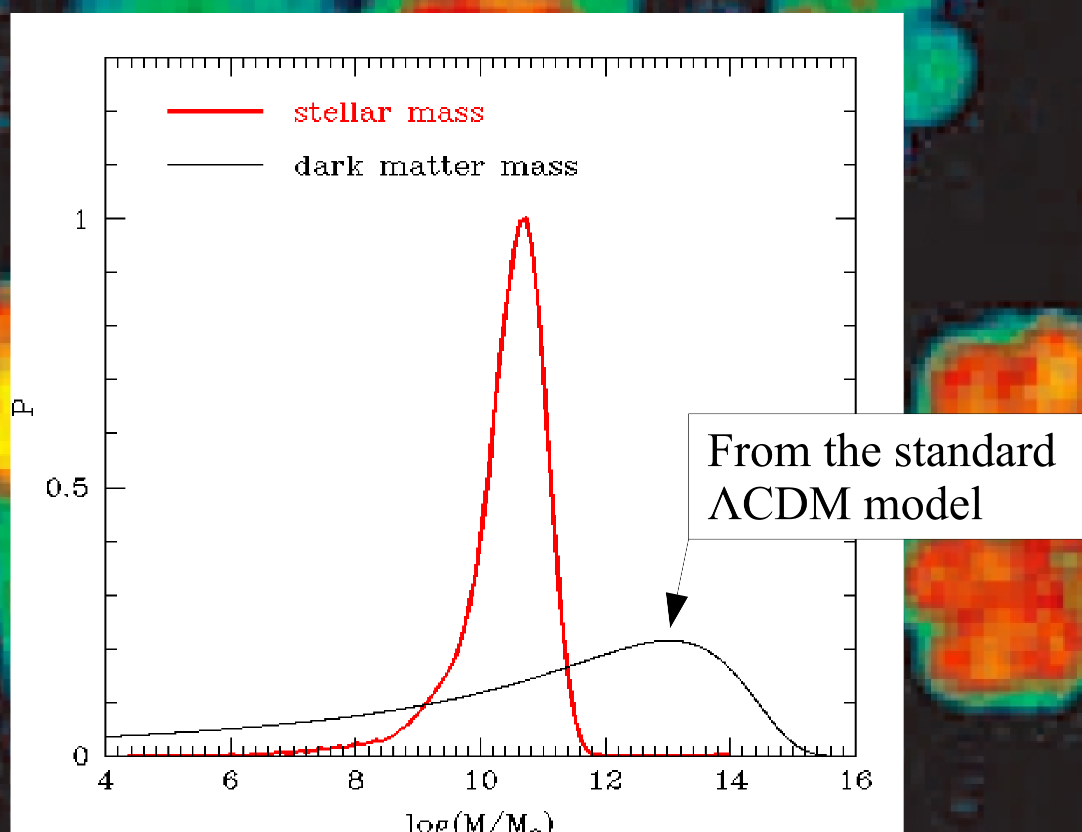


Most stars are in galaxies similar in mass to the Milky Way



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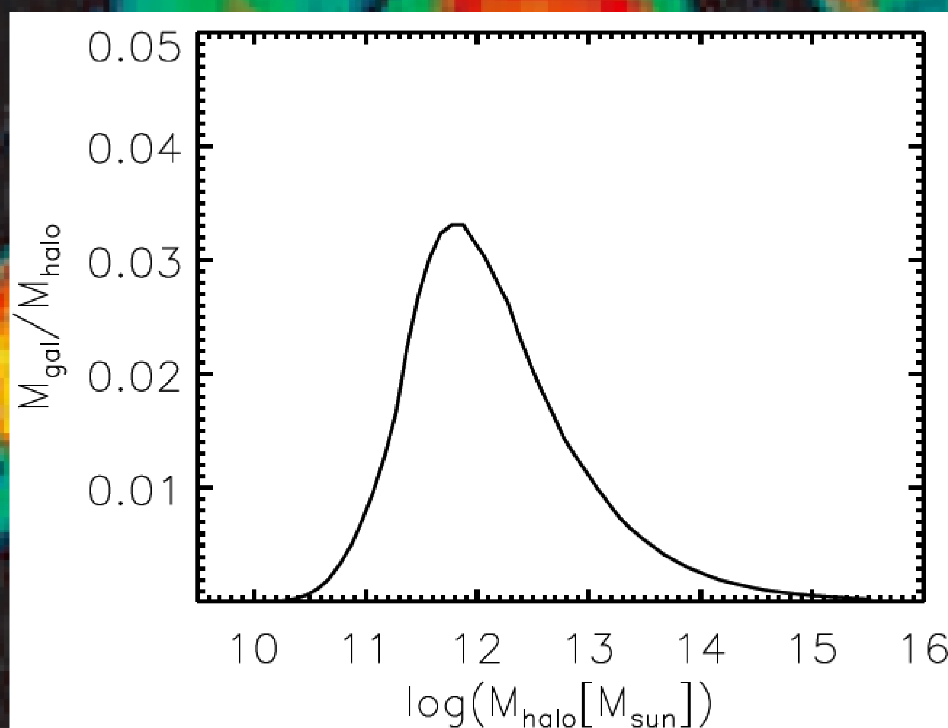
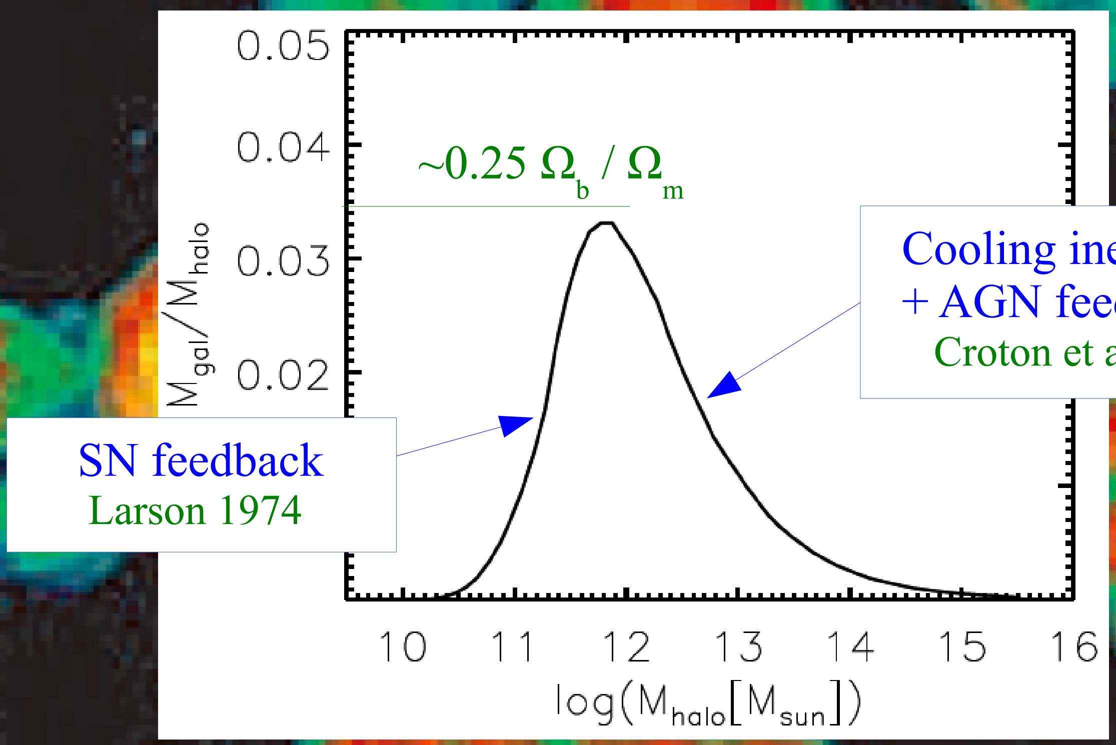
→ Galaxy to halo mass ratio varies *strongly* with mass



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

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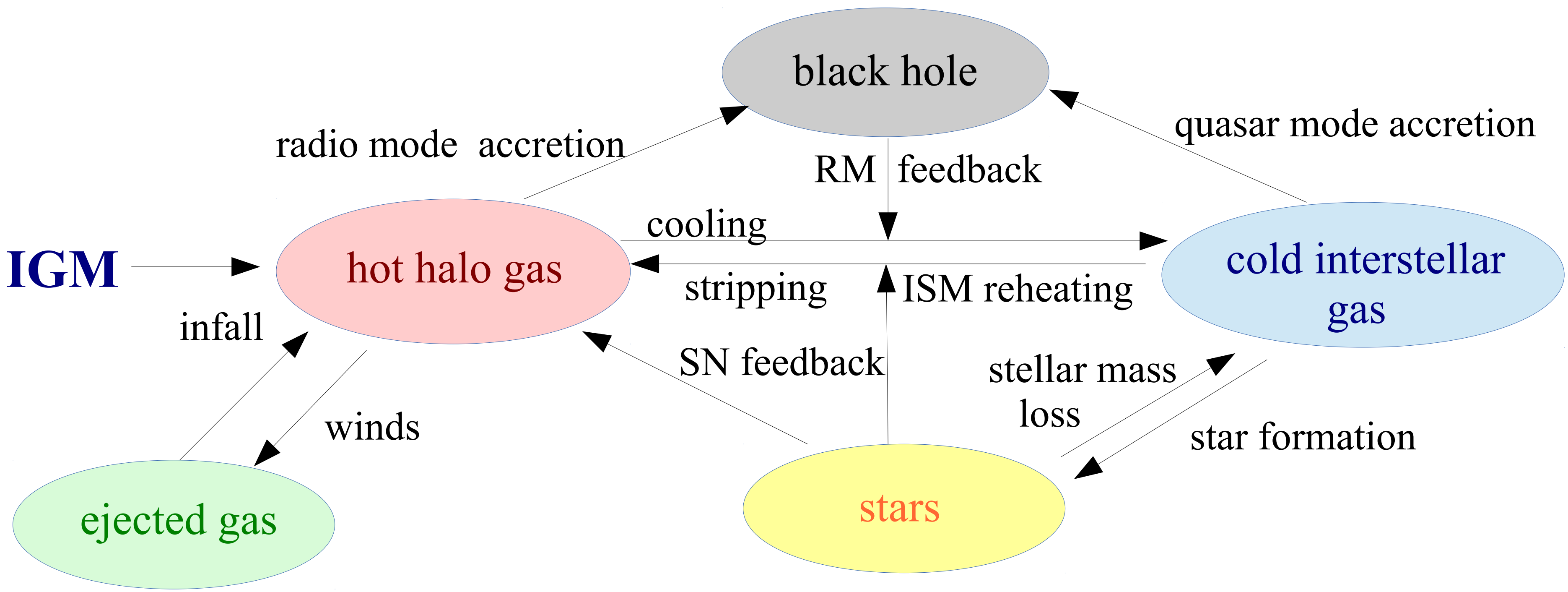
$$(\Omega_b / \Omega_m)\, M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$



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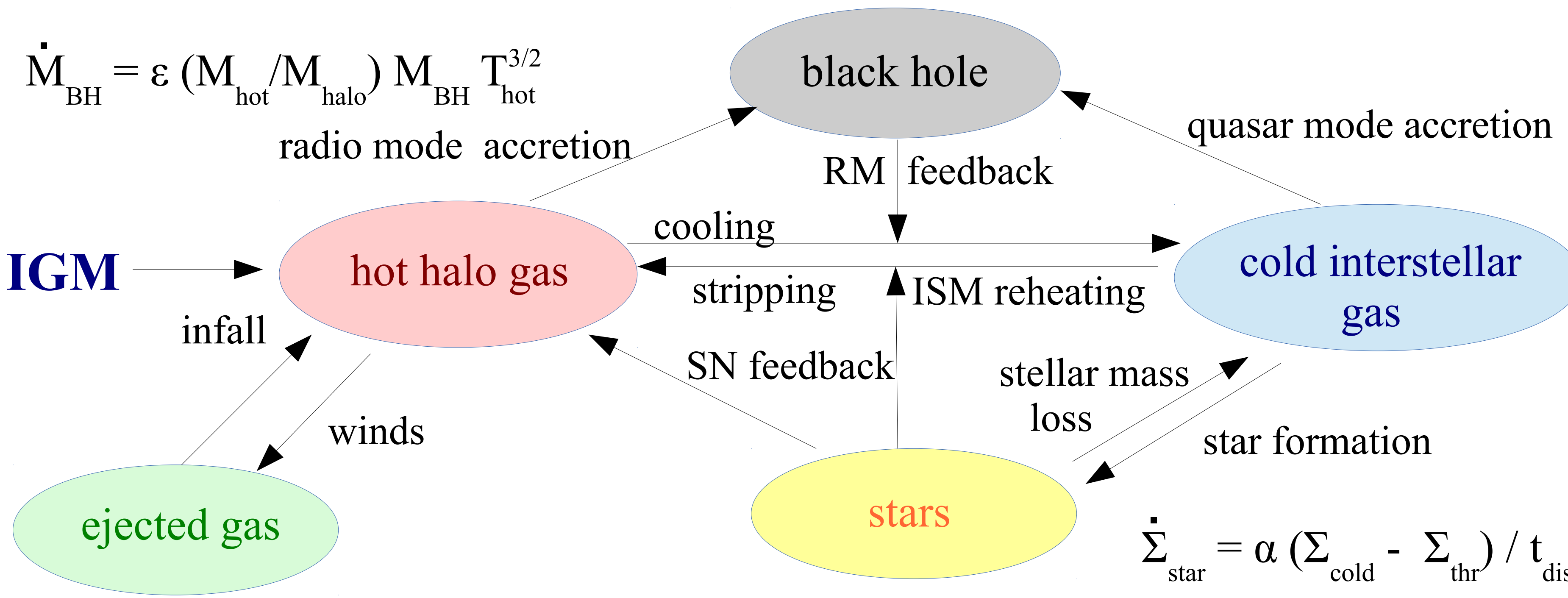
$$\dot{M}_{BH} = \varepsilon\, (M_{hot}/M_{halo})\, M_{BH}\, T_{hot}^{3/2}$$



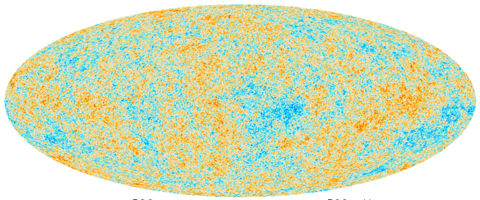
$$\dot{\Sigma}_{star} = \alpha\, (\Sigma_{cold} - \Sigma_{thr}) / t_{disk}$$

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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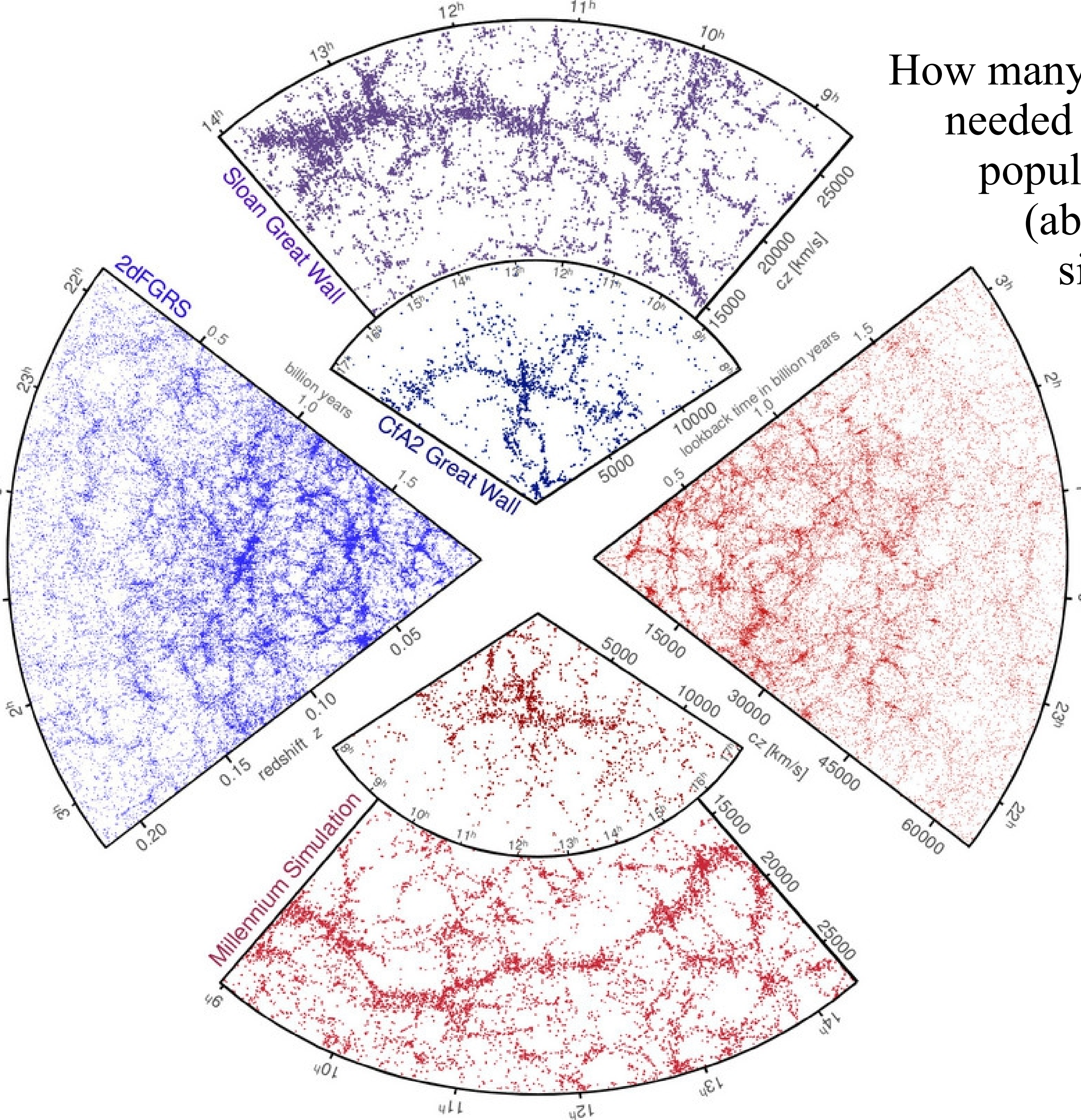
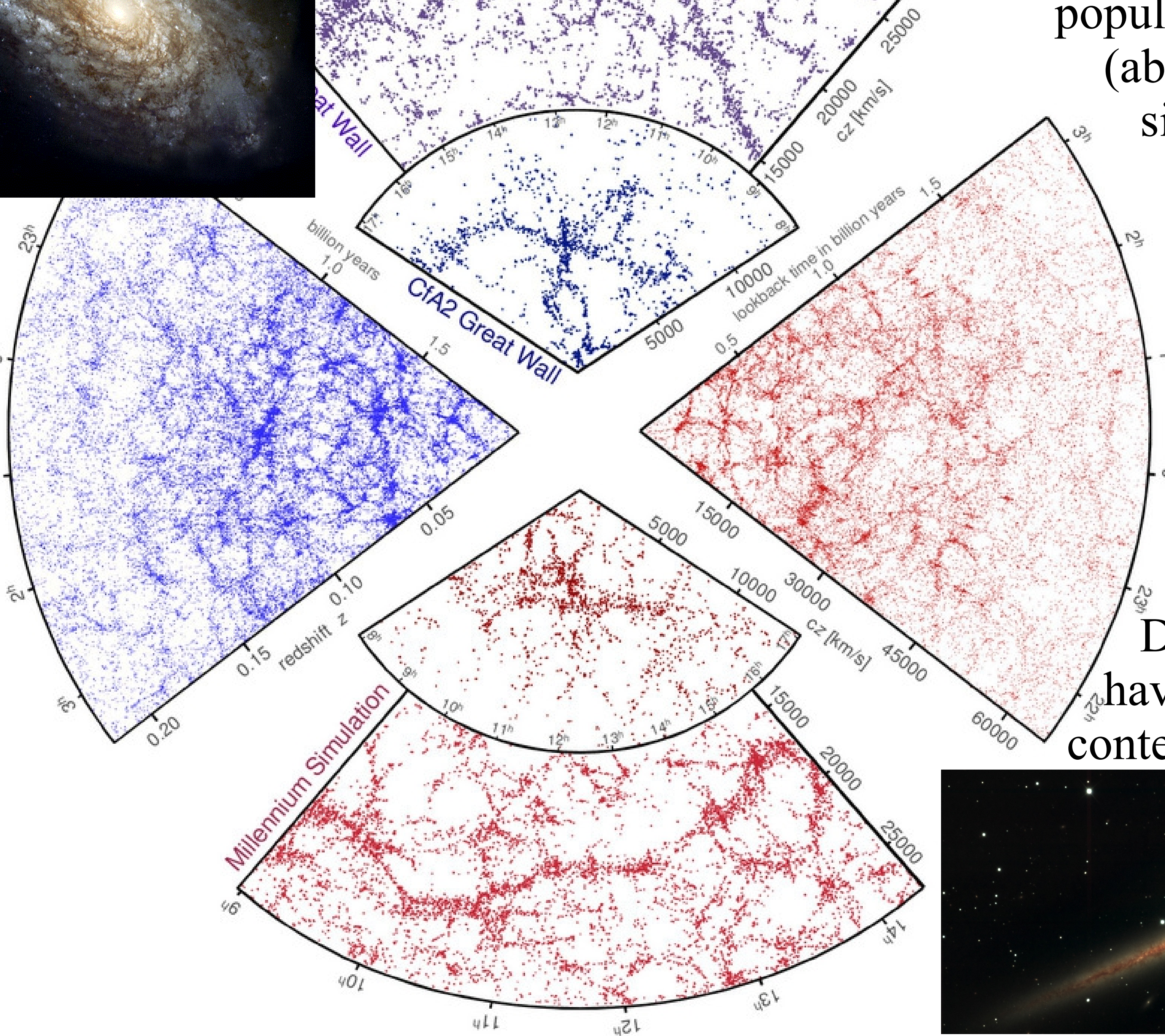


How many parameters are needed to fit the galaxy population?

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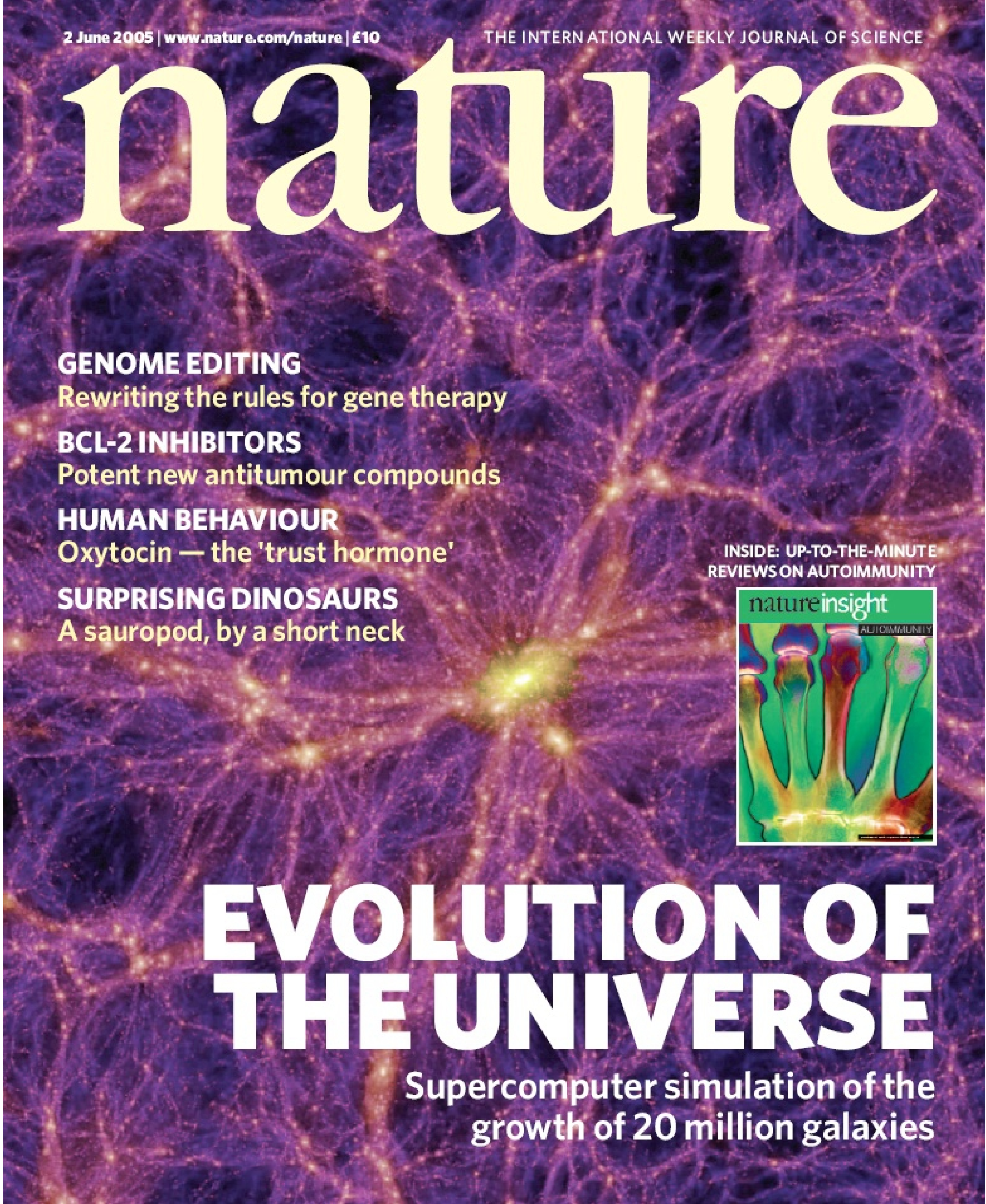
NOT to make a definitive *a priori* physical model for the formation of everything from linear ΛCDM initial conditions

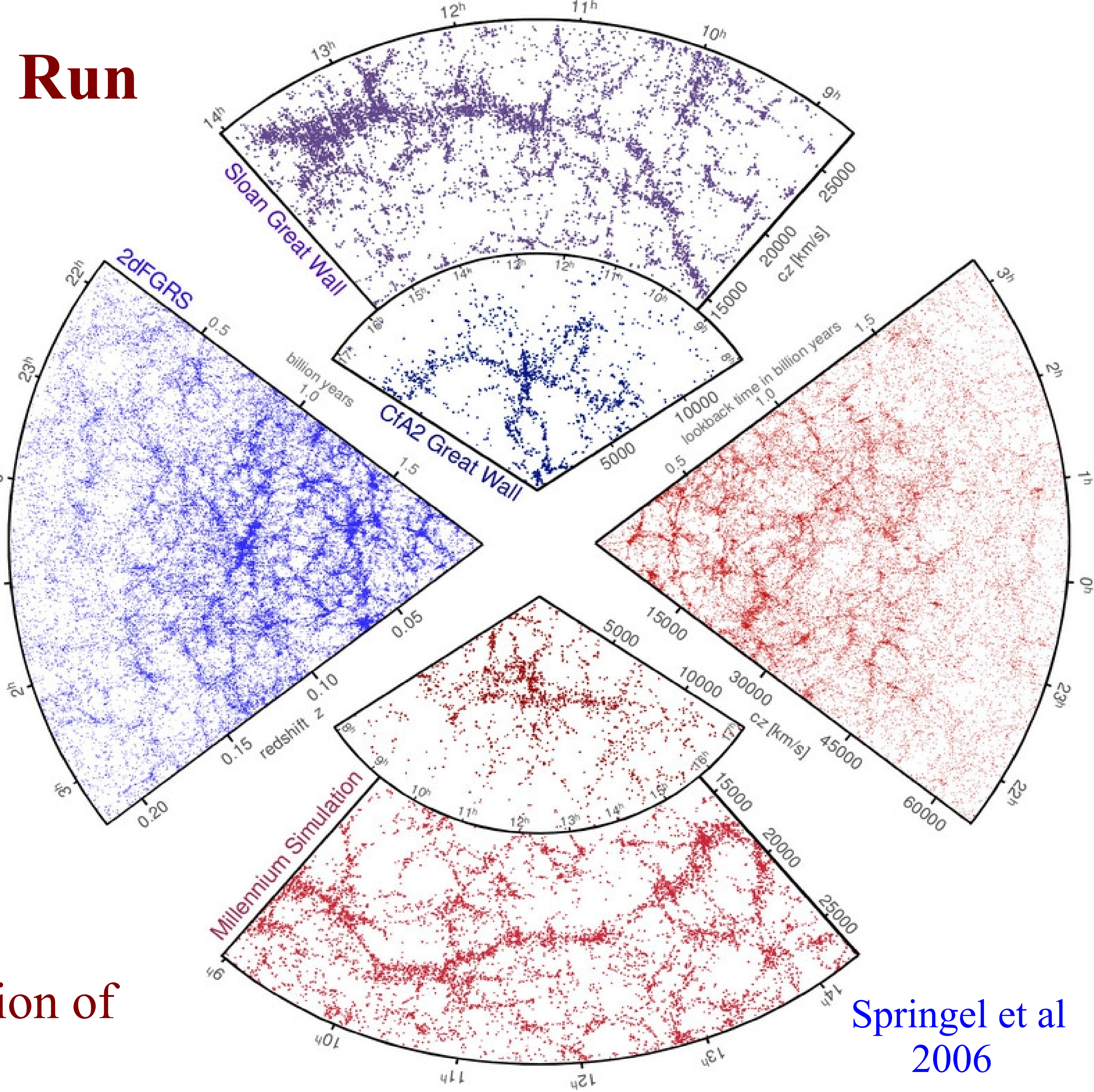
NOR to represent the internal structure of individual galaxies at anything but the most schematic level

Millennium Run 2004



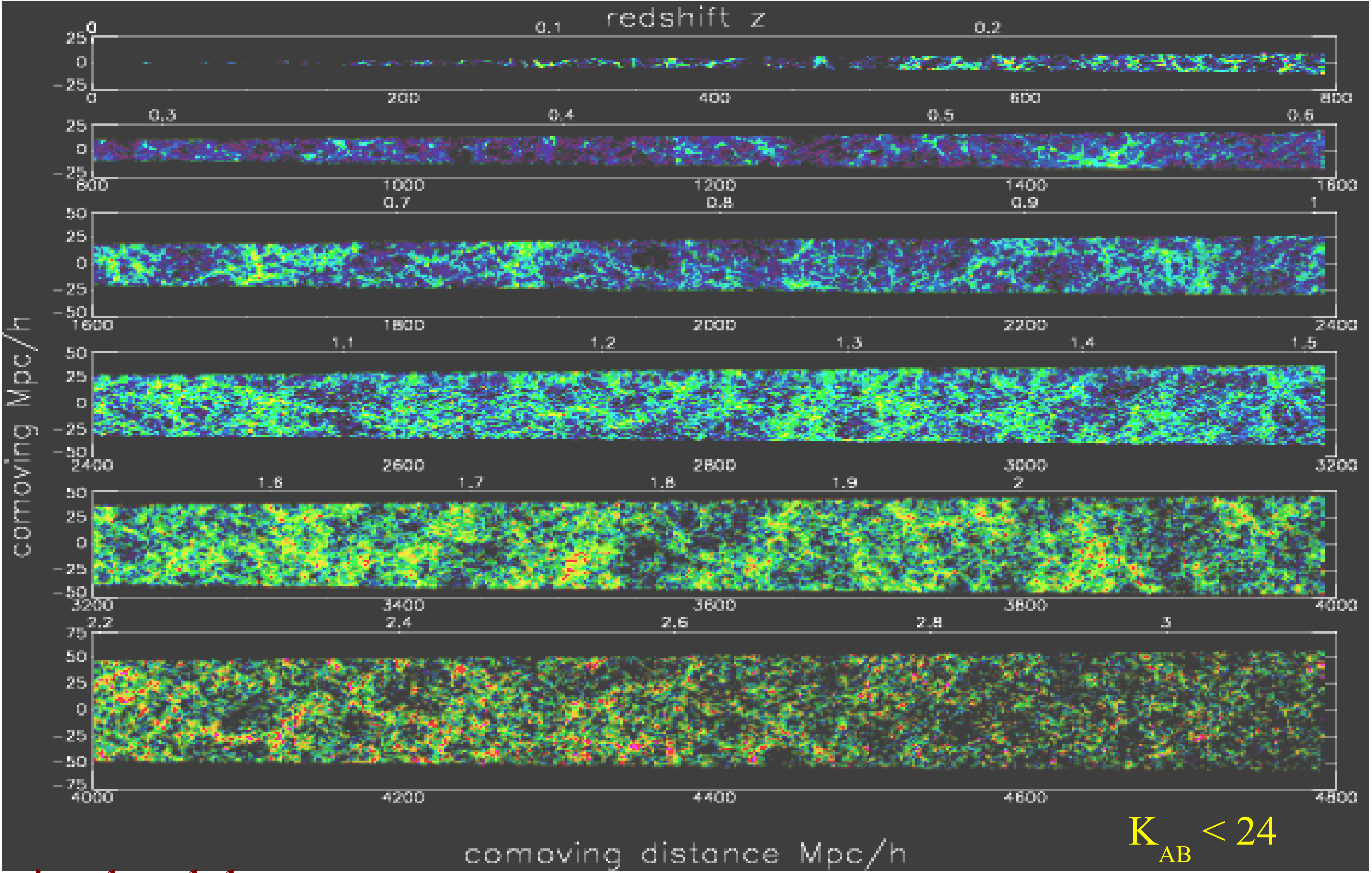
Springel et al 2005

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

Virgo - Millennium Database

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Public Databases

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

Private (MyDB) Databases

- sampling_db (r)
- swhite_db (rw) (context)

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.
Holding the mouse over the button will give a short explanation of the goal of the statement.

ShowTables | Show Views | Show Columns | Show Indexes | MyDB Size | MyDB Table Size

Create View | Drop Table | Create Index

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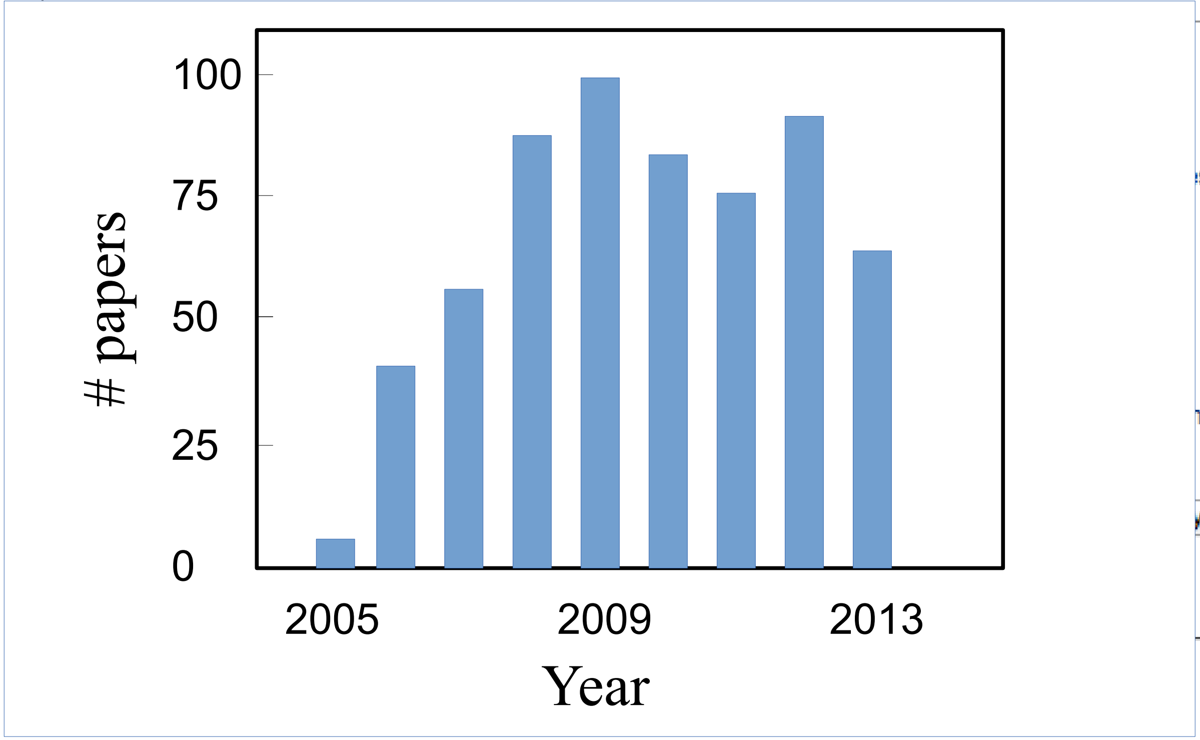

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VIRGO

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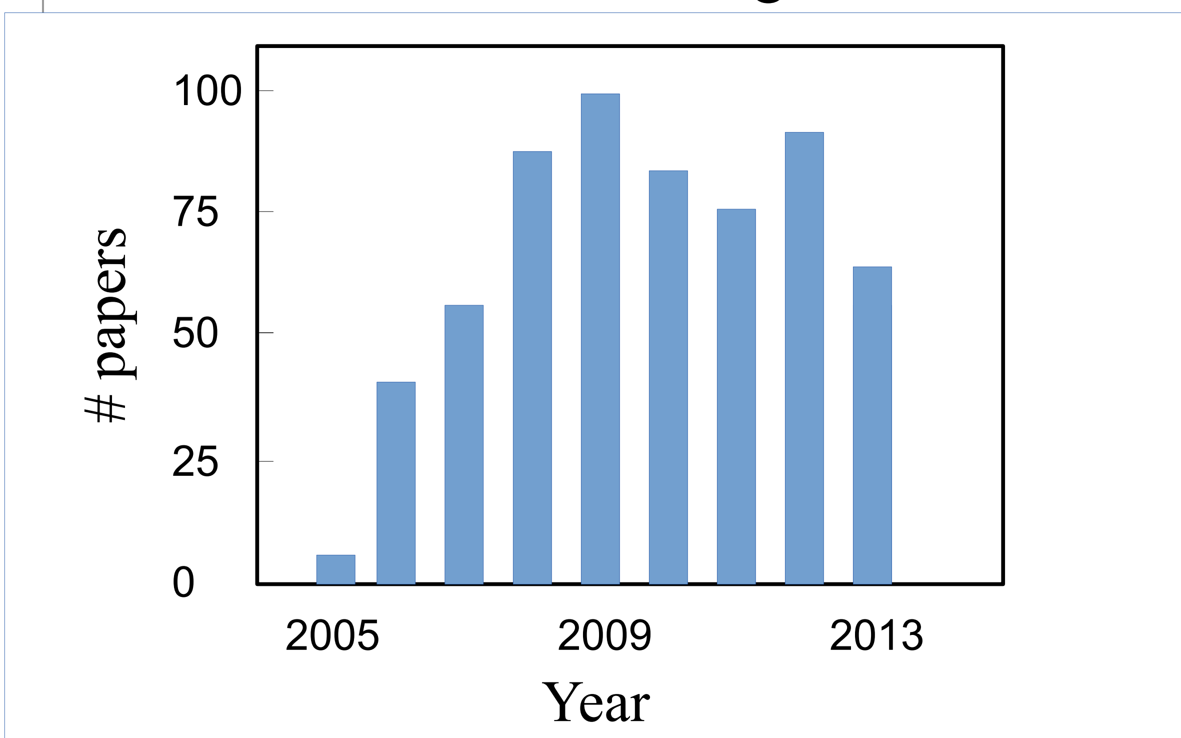
- Most use the galaxies and are by authors unassociated with the Virgo Consortium

Query (stream)

Query (browser)

Help



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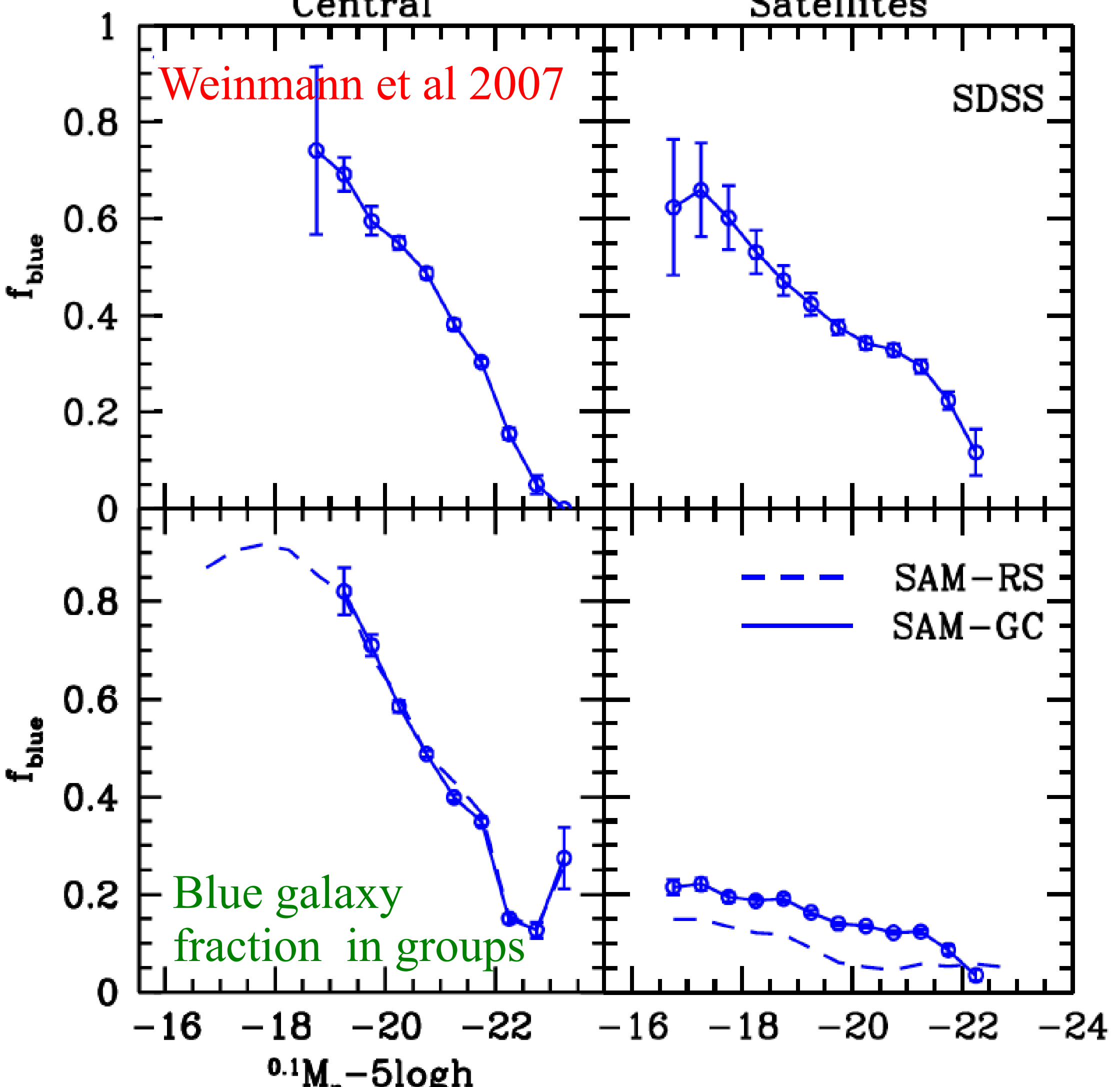
Central
Satellites
Weinmann et al 2007
SDSS
SAM−RS
SAM−GC
Blue galaxy
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f_{blue}
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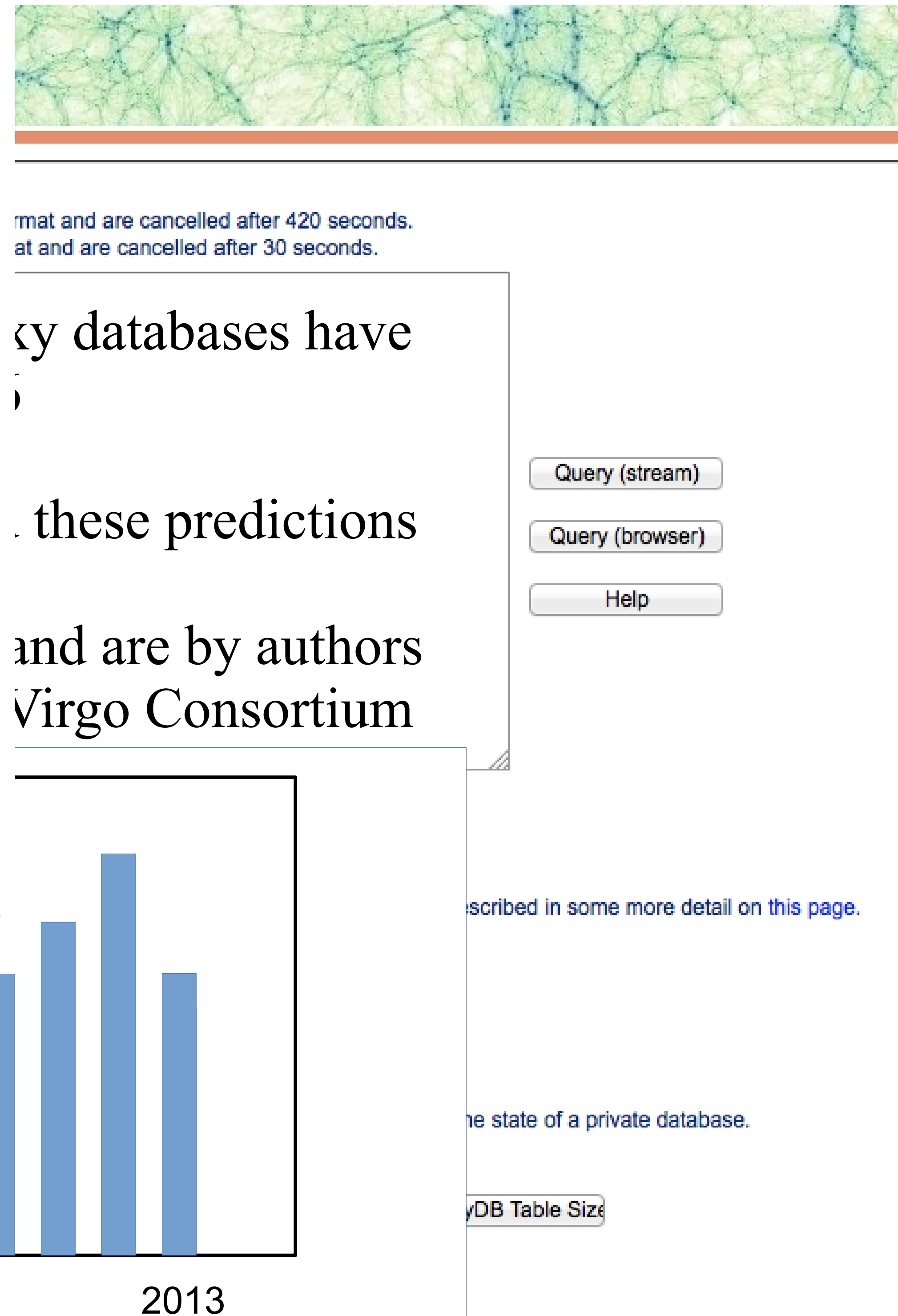
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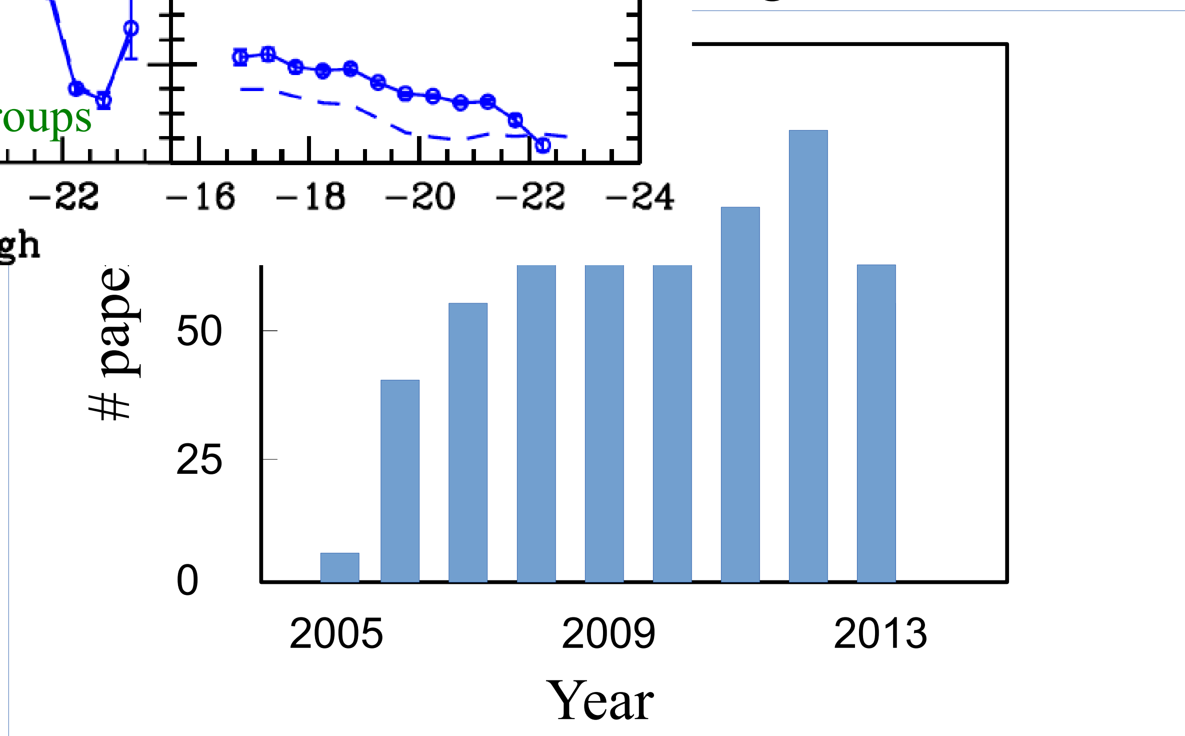
VIRGO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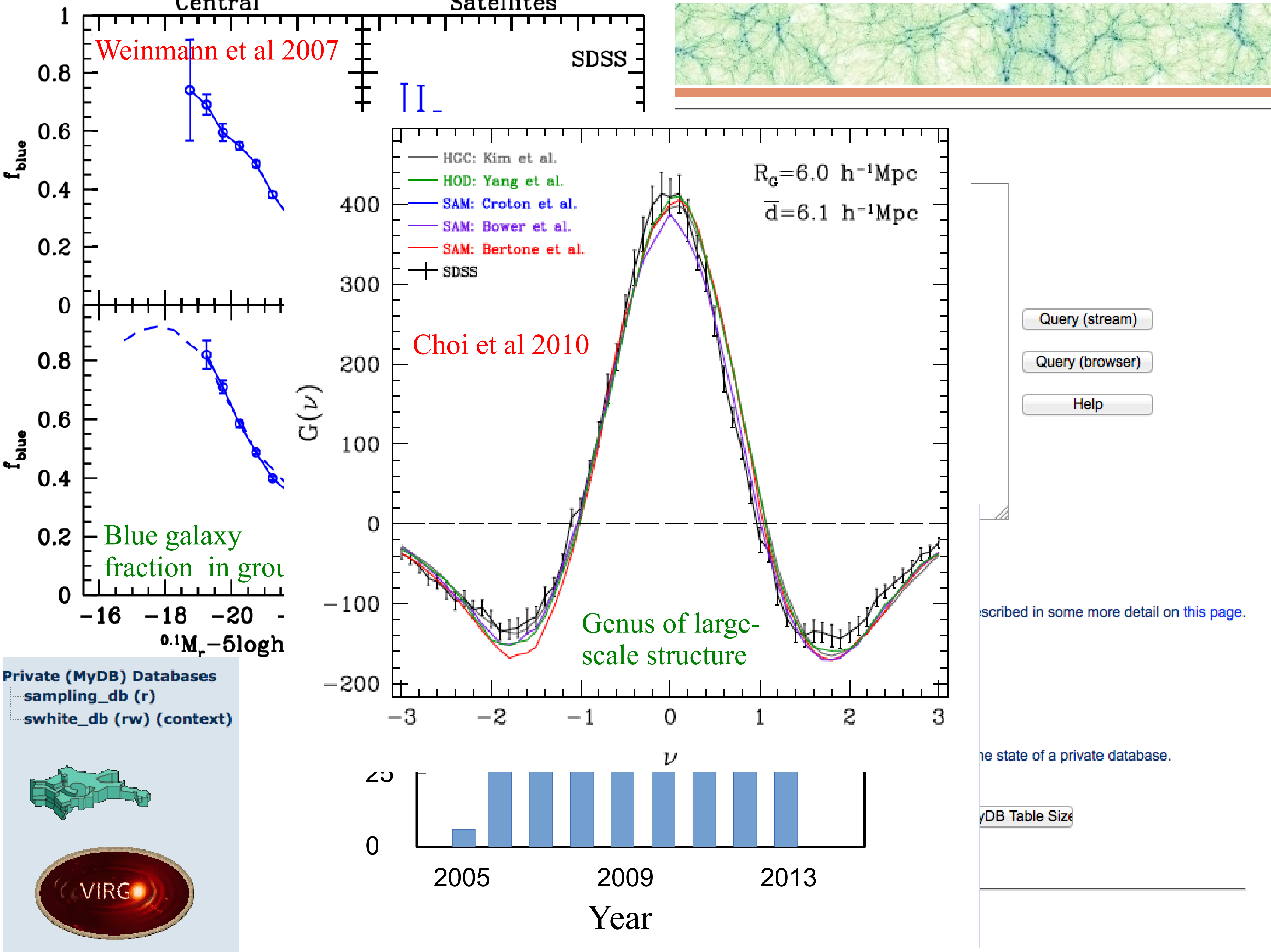

Central
Satellites
Weinmann et al 2007
SDSS
f_{blue}
1
0.8
0.6
0.4
0.2
0
Blue galaxy
fraction in grou
−16
−18
−20
$^{0.1}M_r - 5\log h$
HGC: Kim et al.
HOD: Yang et al.
SAM: Croton et al.
SAM: Bower et al.
SAM: Bertone et al.
SDSS
R_G=6.0 h^{-1}Mpc
$\bar{d}$=6.1 h^{-1}Mpc
Choi et al 2010
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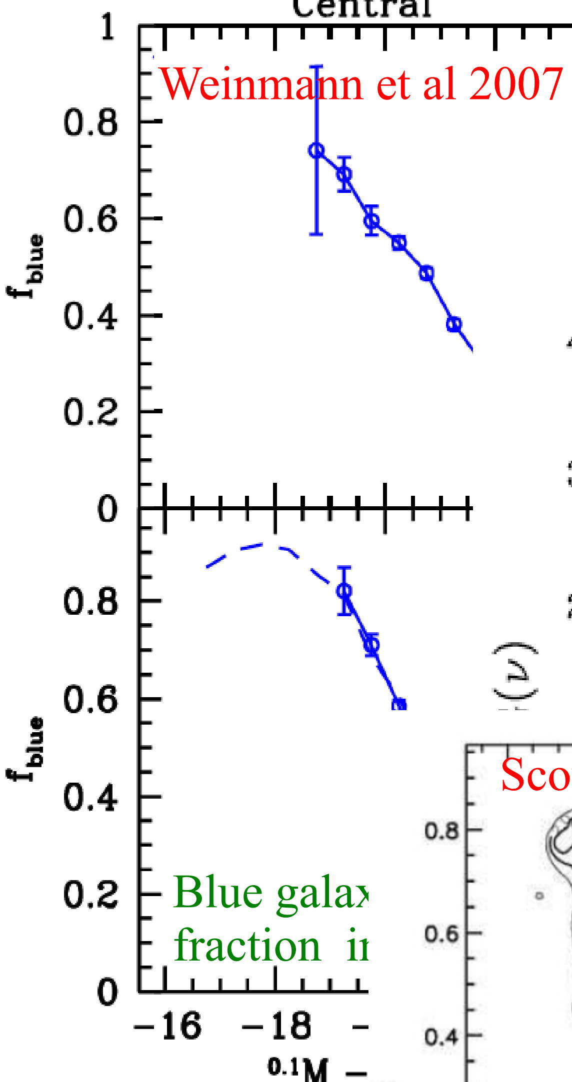
Central
Satellites
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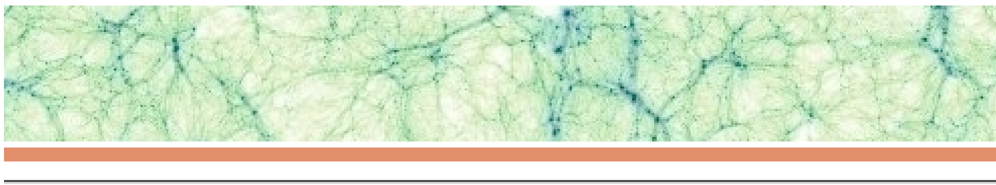

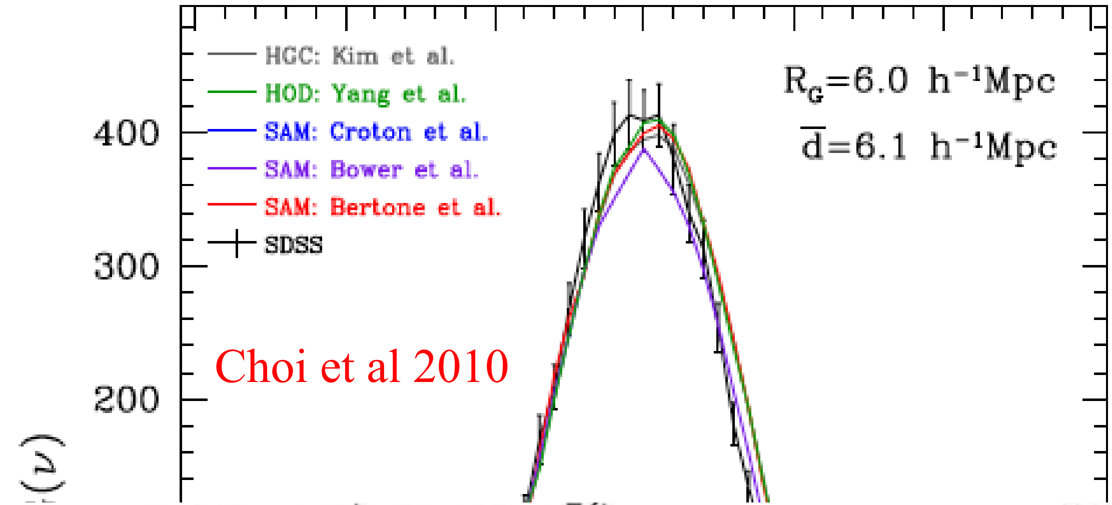
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Choi et al 2010
400
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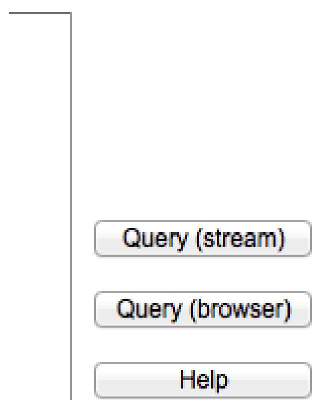
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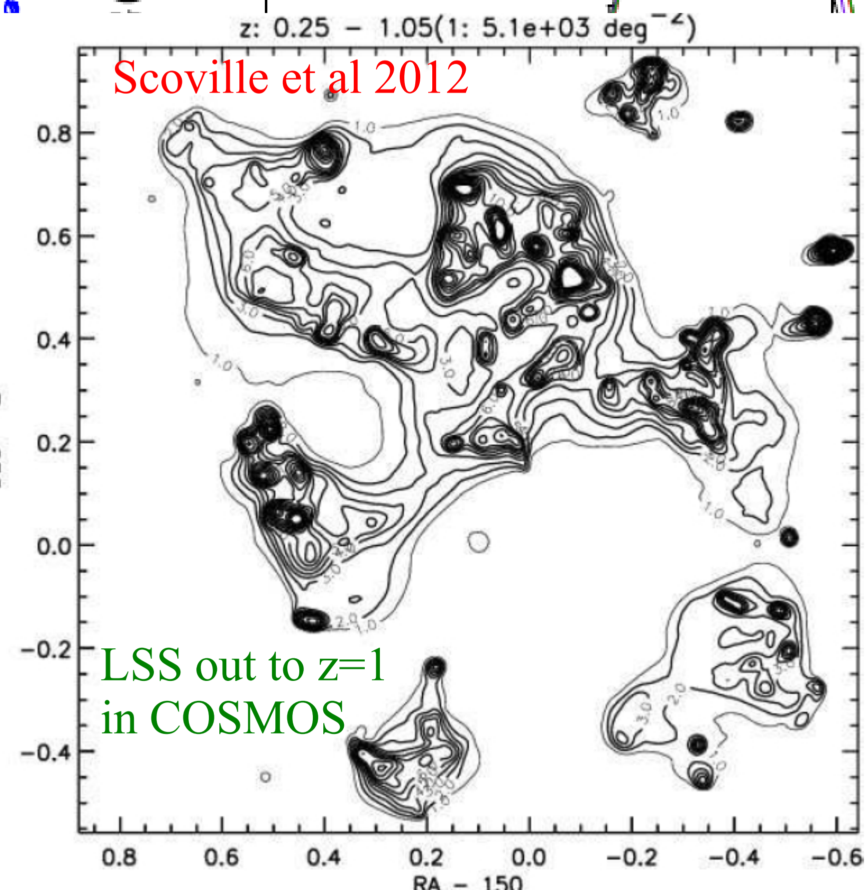
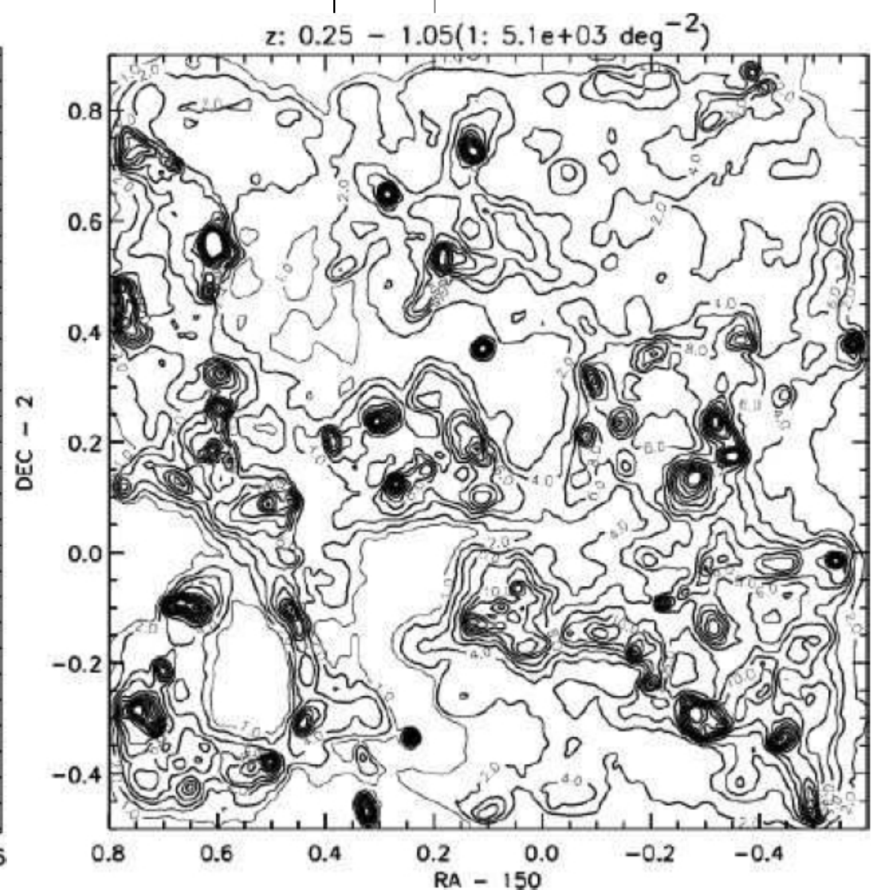
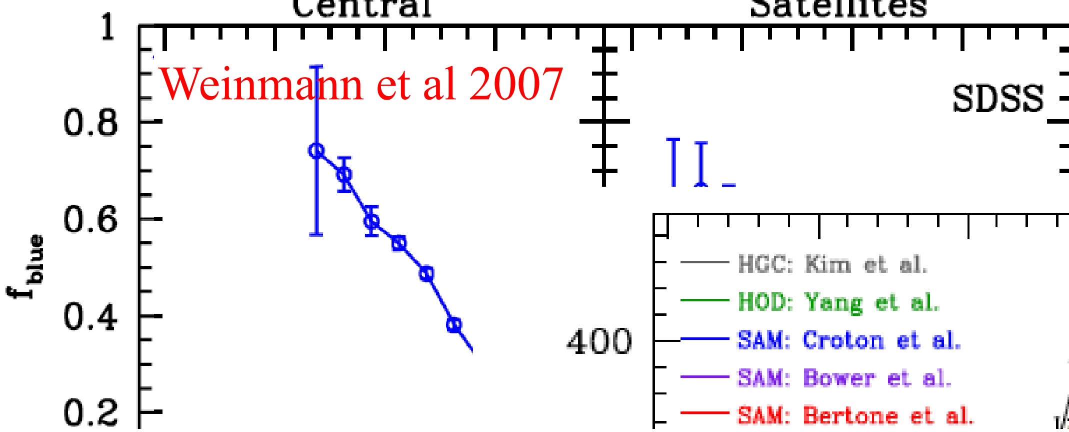
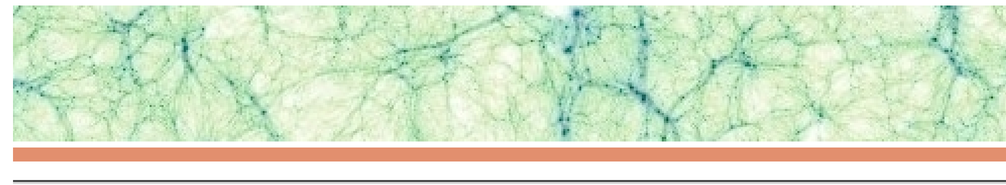
swhite_db (rw) (context
VIRGO

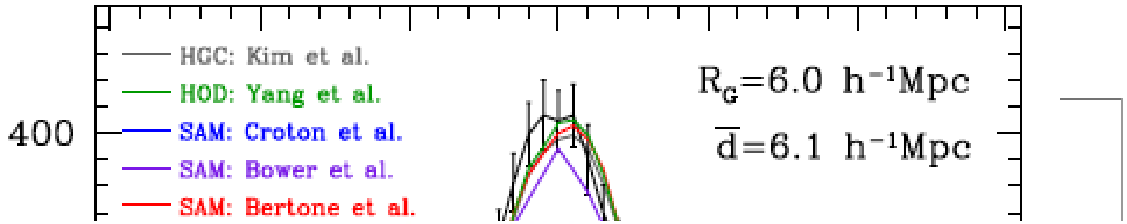

z: 0.25 − 1.05(1: 5.1e+03 deg^{-2})
Scoville et al 2012
LSS out to z=1
in COSMOS
DEC − 2
RA − 150

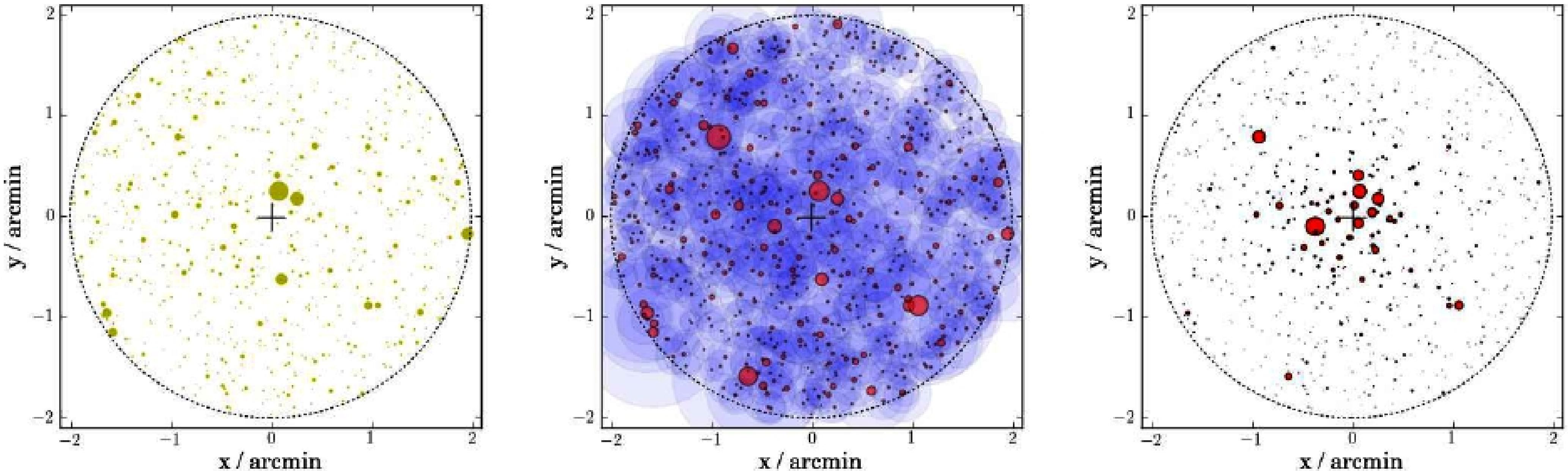

z: 0.25 − 1.05(1: 5.1e+03 deg^{-2})
DEC − 2
RA − 150



Weinmann et al 2007

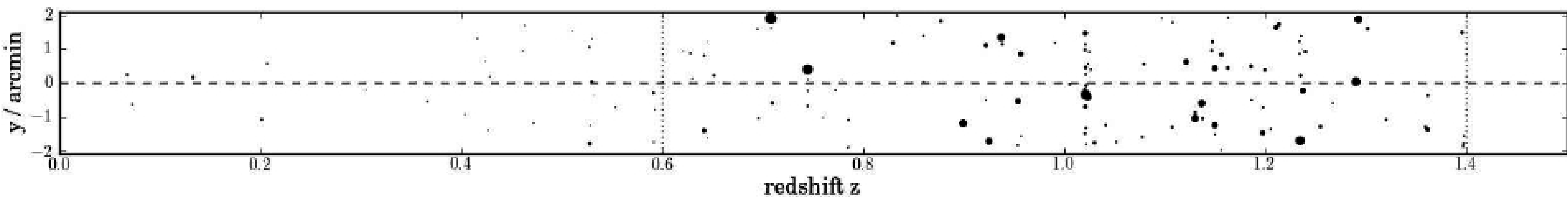


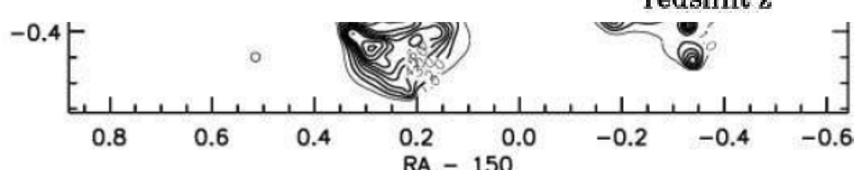


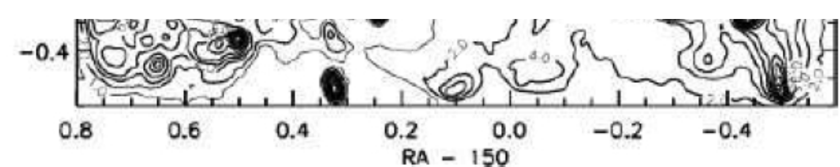


Reconstructing the cosmic lensing mass distribution

Collett et al 2013







Virgo - Millennium Database

- Documentation
- CREDITS/Acknowledgments
- Registration
- News
- FAQ

Public Databases

- DGalaxies
- 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 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

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.
Holding the mouse over the button will give a short explanation of the goal of the statement.

ShowTables | Show Views | Show Columns | Show Indexes | MyDB Size | MyDB Table Size

Create View | Drop Table | Create Index

Limitations of the Millennium Simulation

Limited modeling of *structure* of galaxies, gas components

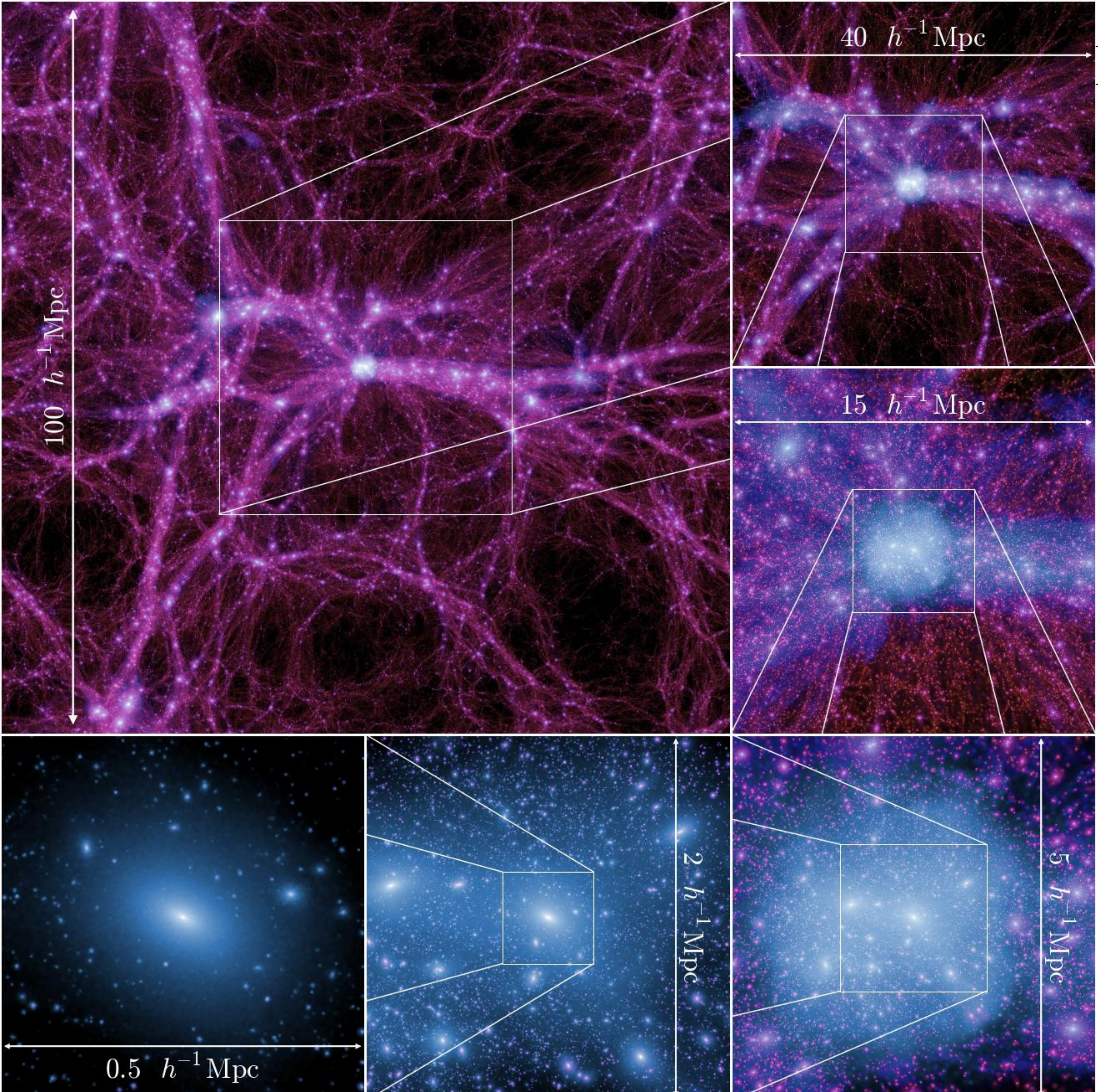
Limited resolution – too poor to model formation of dwarfs

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

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

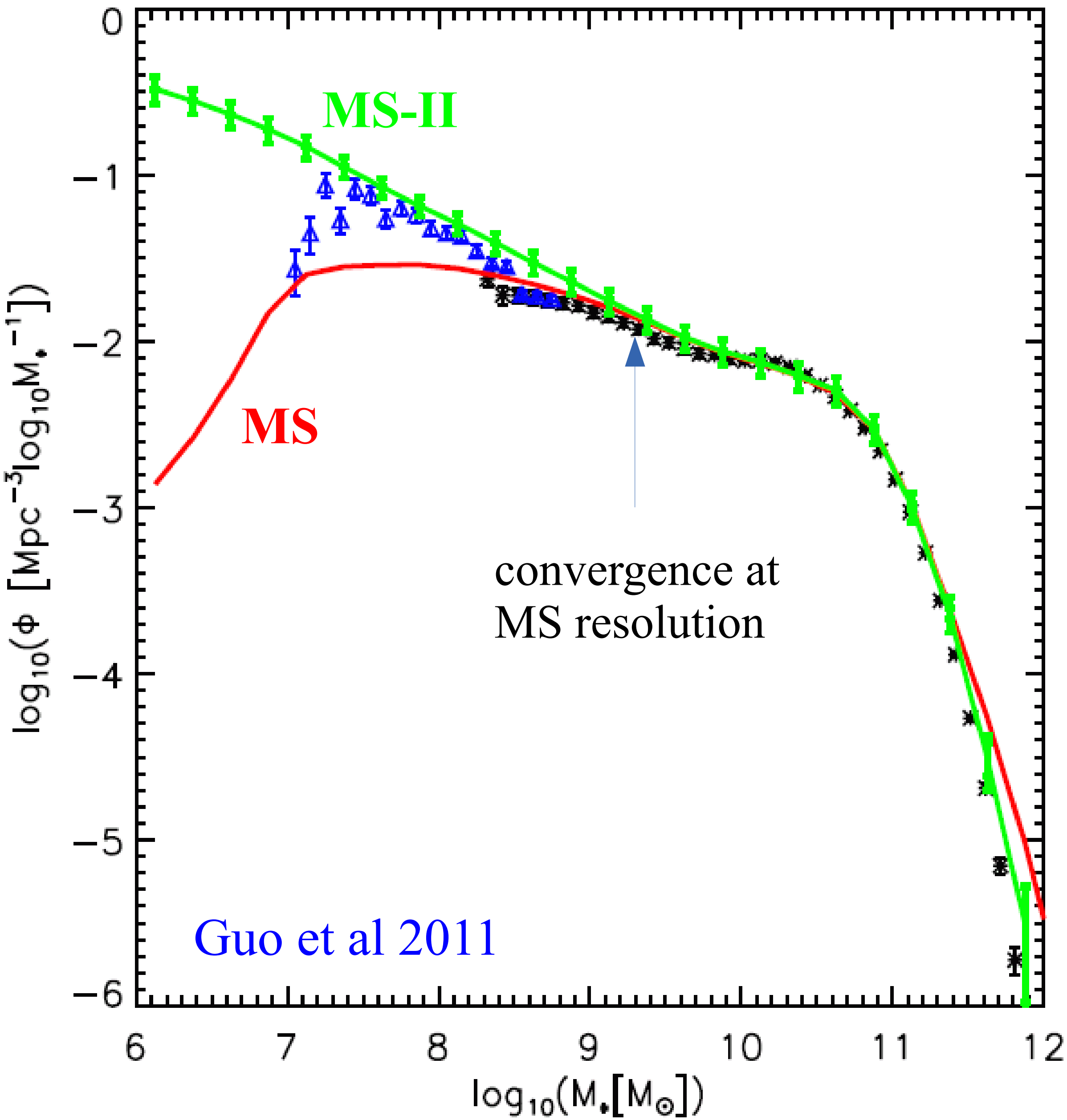
Extend to properties of dwarf galaxies

Improve/extend treatments of "troublesome" astrophysics

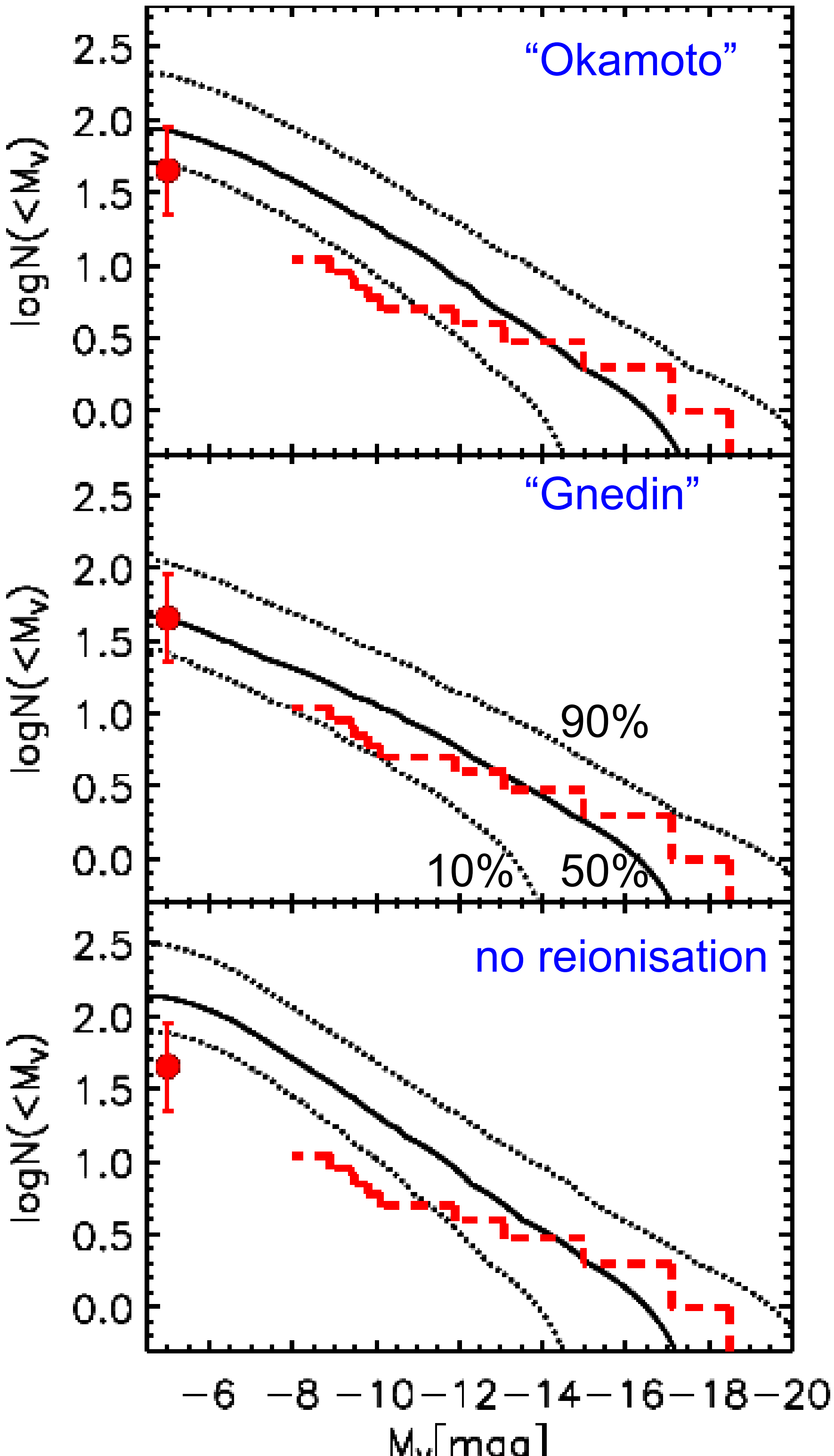
Adjust parameters to fit new, more precise data

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!



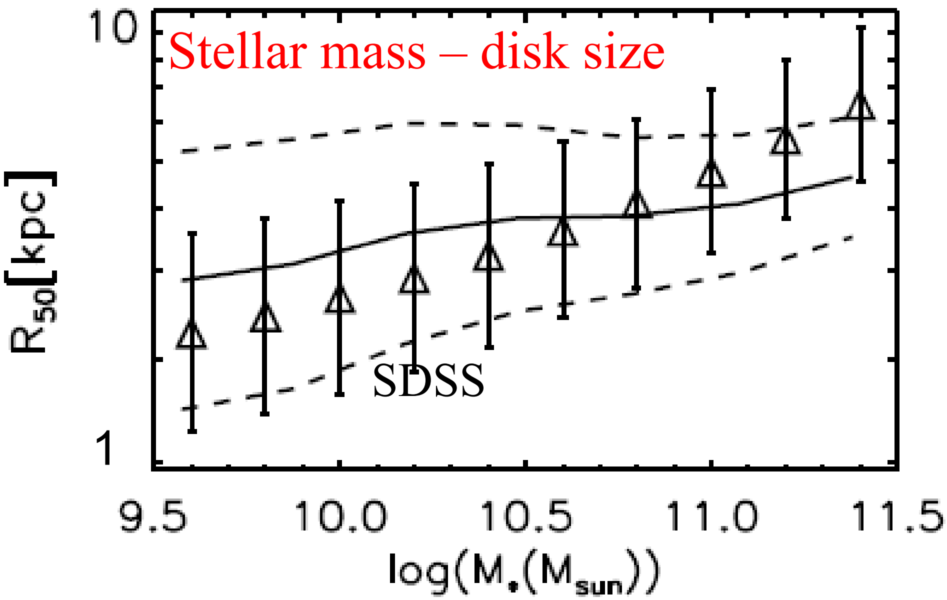
Luminosity function of Milky Way satellites

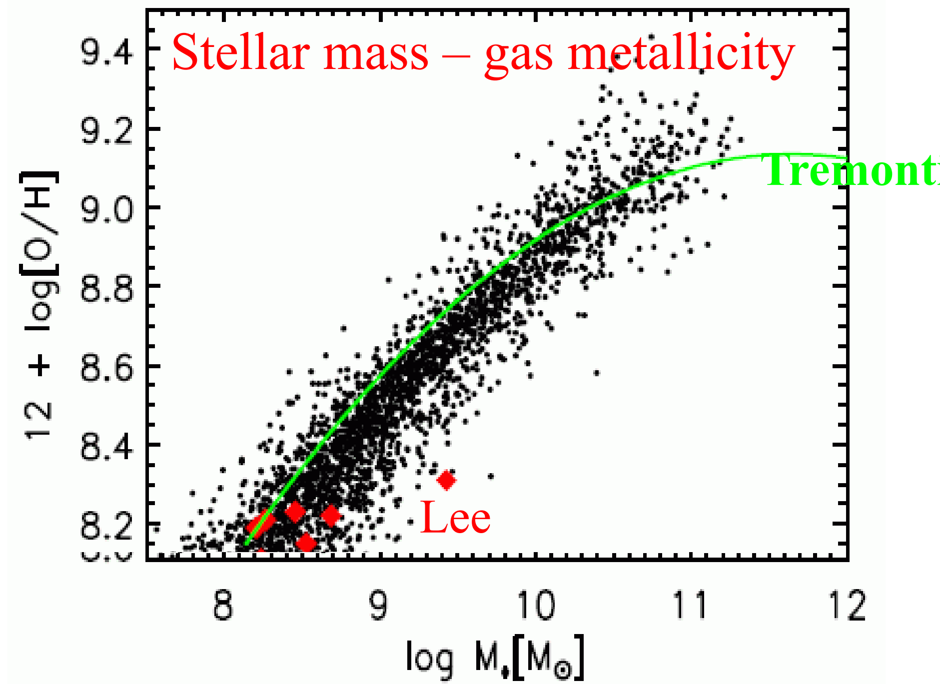
Luminosity functions of satellites around 1500 "Milky Ways" i.e. isolated disk galaxies with log $M_* = 10.8$

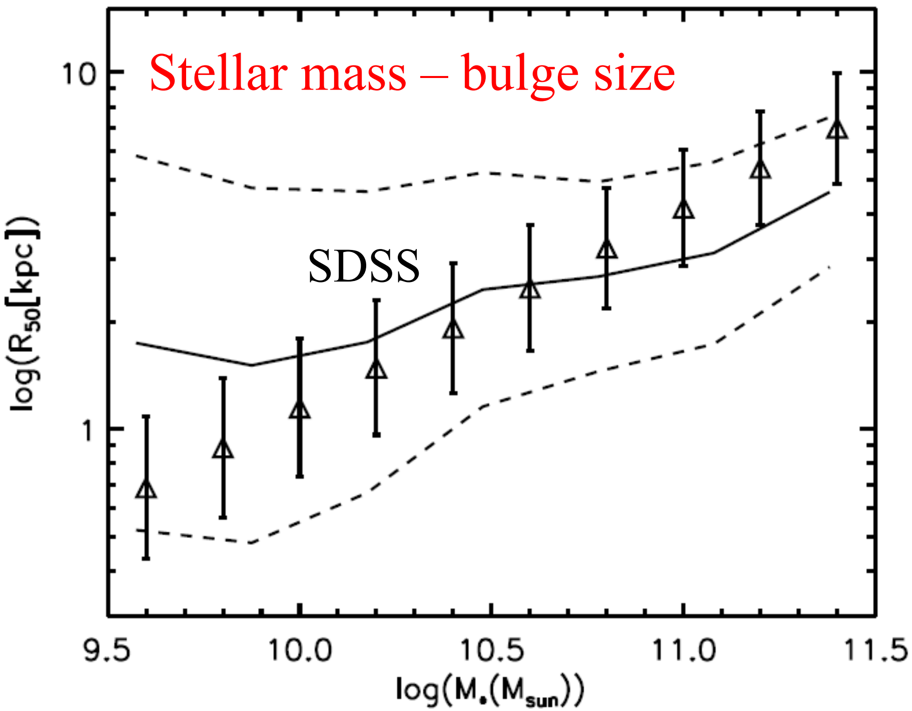
Guo et al 2011

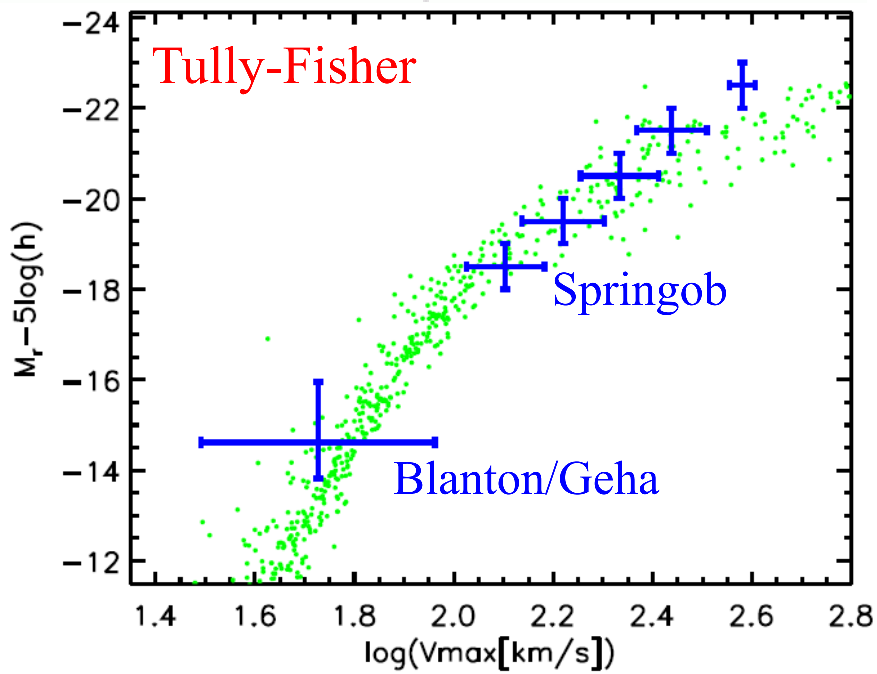
Scaling relations

Guo et al 2011



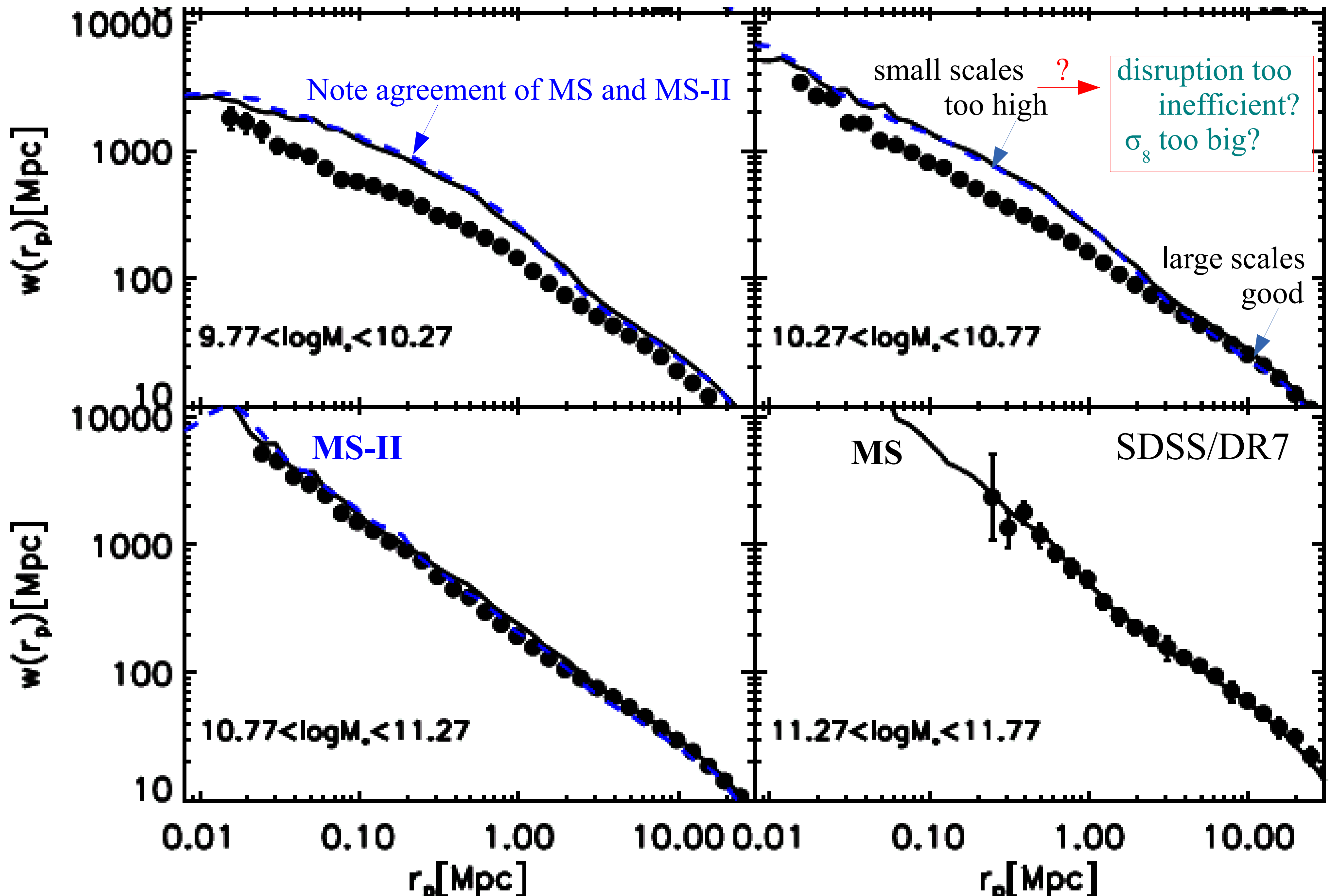




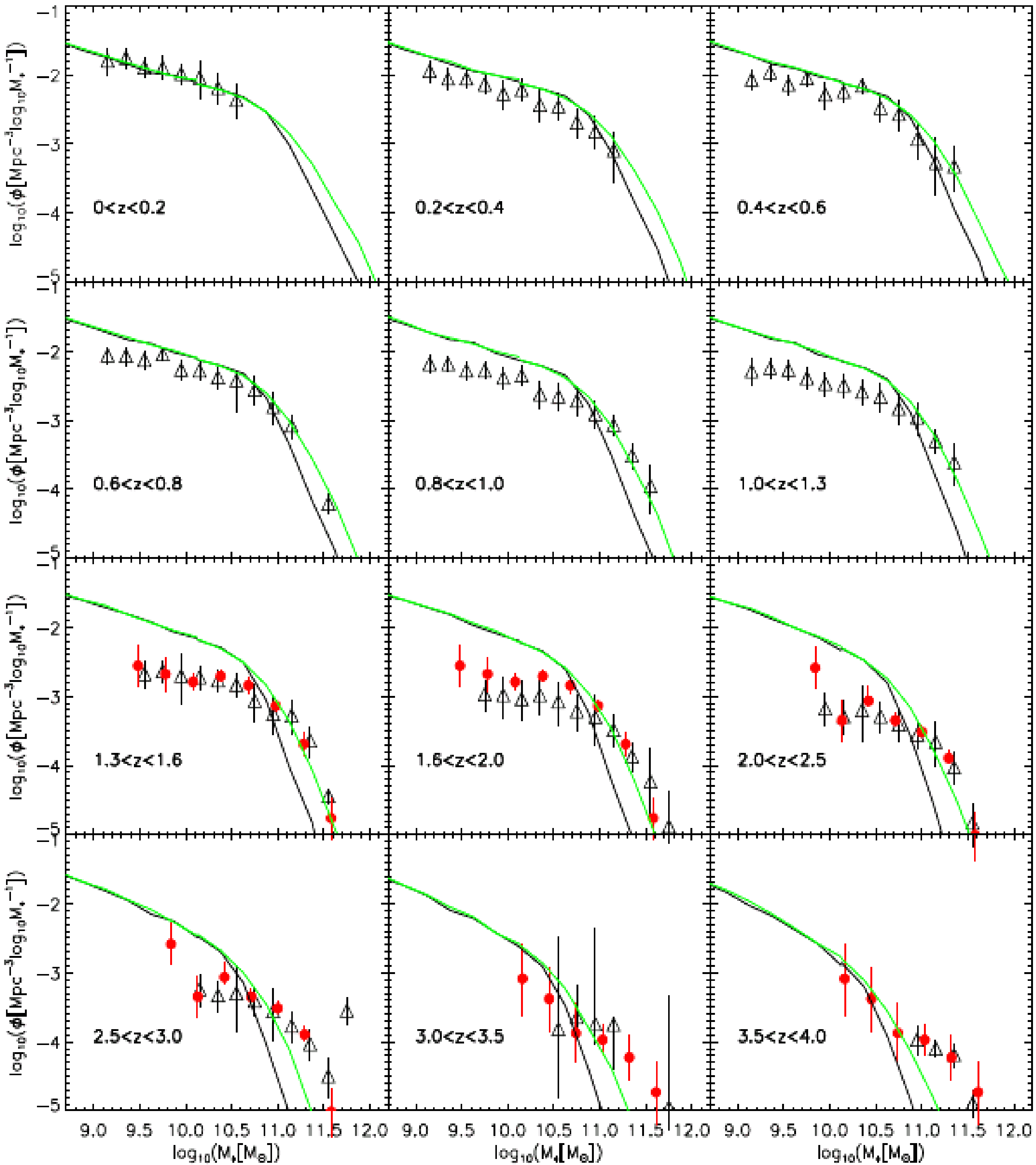


Mass-dependent galaxy clustering

Guo et al 2011



Evolution of stellar mass function



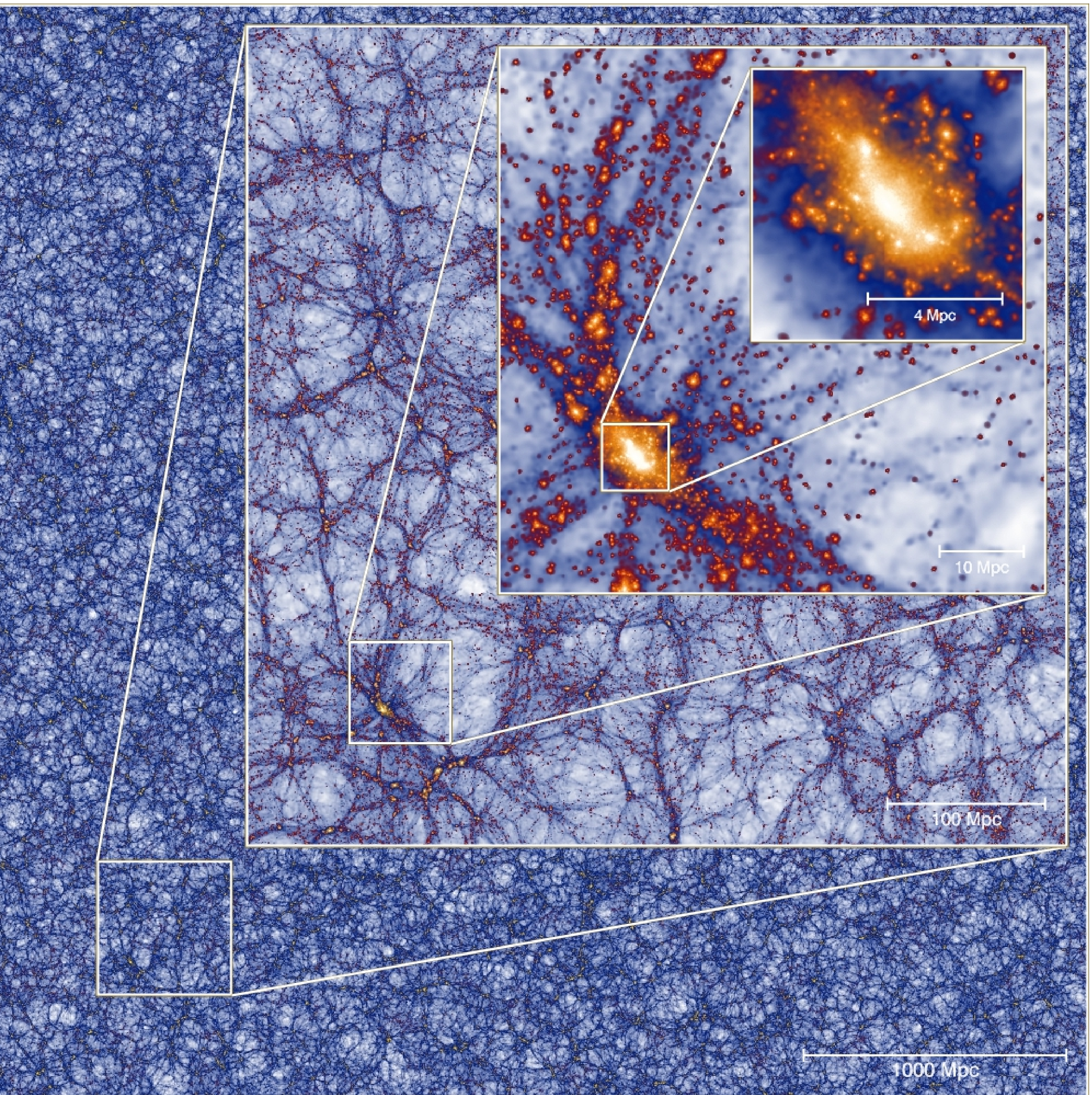
△ Perez-Gonzalez et al 2008

● 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



The MXXL

(2010)

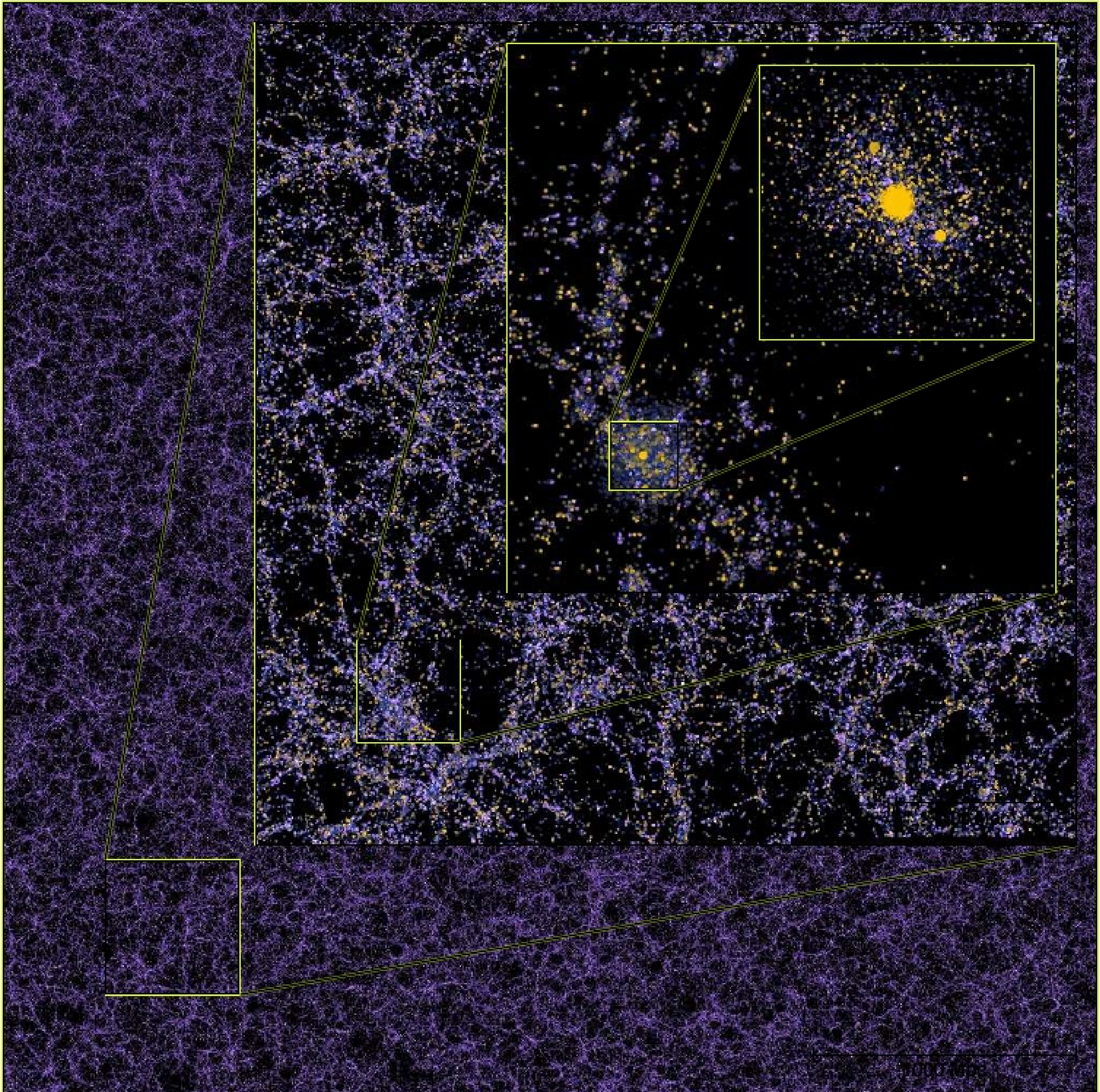
Angulo et al 2011

Bigger than the Millennium Run by factors of

30 in $N_{particle}$

200 in Volume

6 in $m_{particle}$



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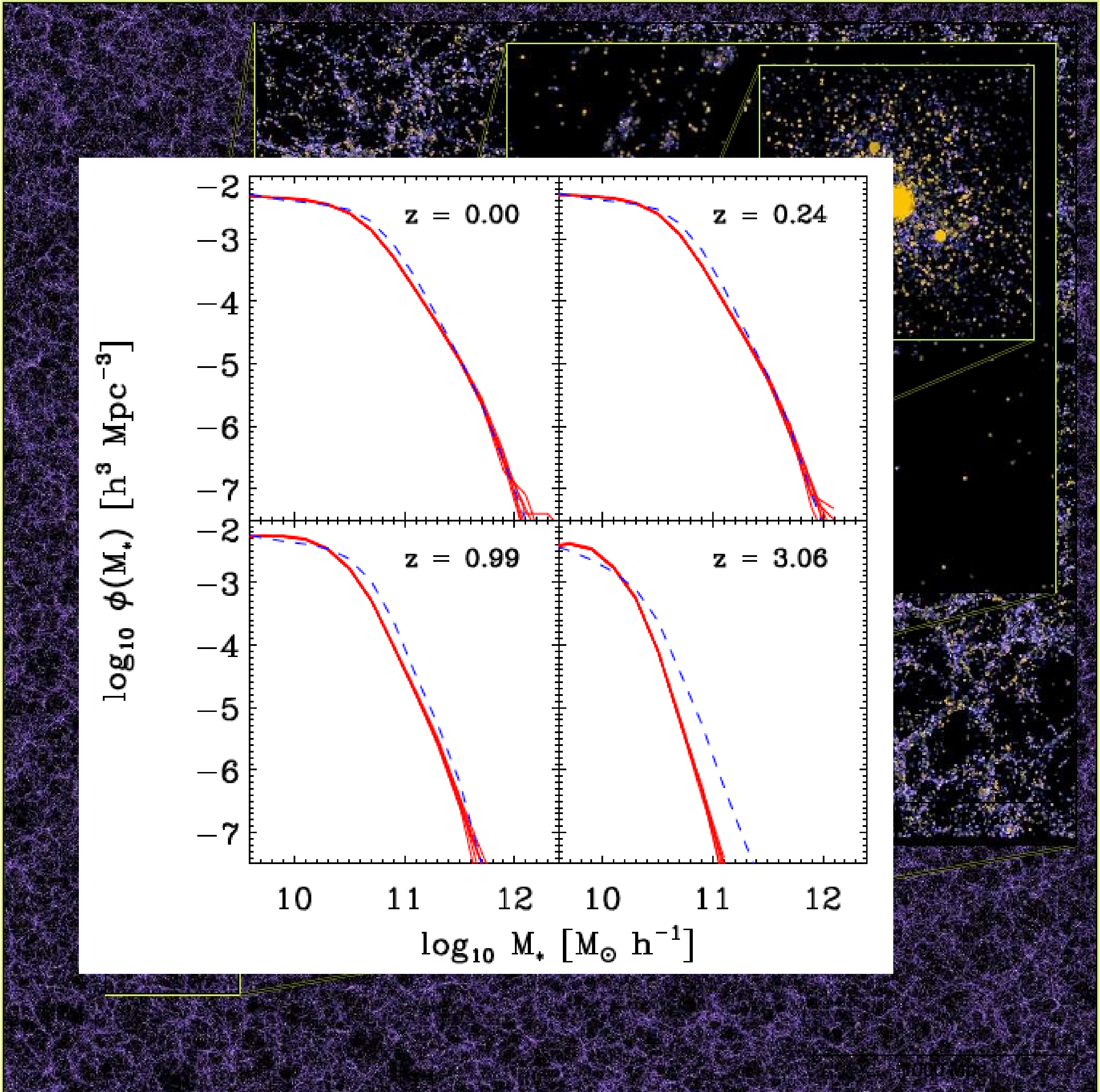
3.3×10^8 galaxies at $z = 0$ with $\log M_*/M_\odot > 10$



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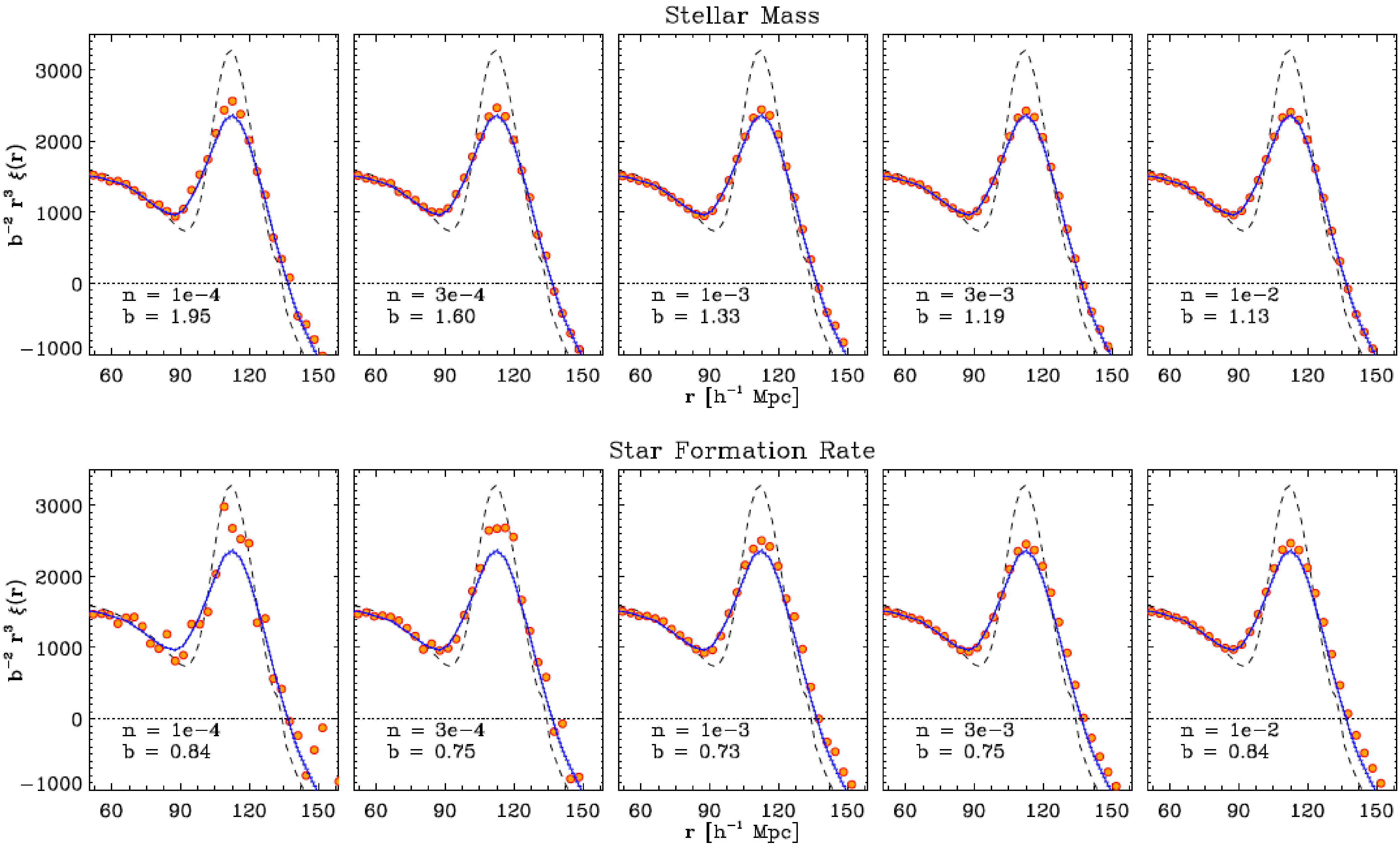
Distortions of BAO feature in the galaxy population



Angulo et al 2013

Small but measurable shifts for different selection methods

Scaling simulations to neighboring cosmologies

Angulo & White 2010

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

-- 685 Mpc 620 Mpc

2) Reassign redshifts to match linear amplitudes on these scales

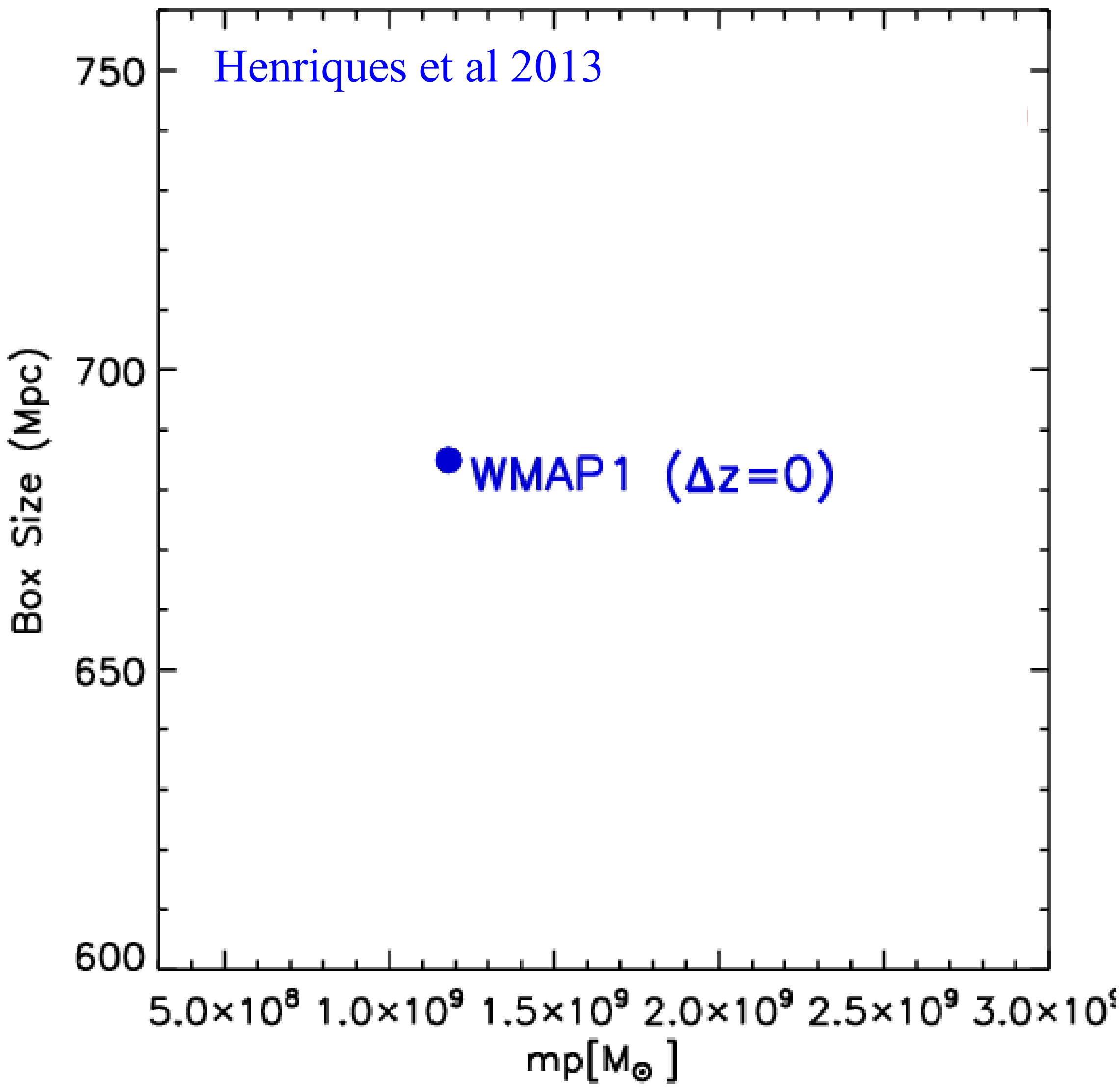
-- $z = 0.69, 1.75, 3.02$ $z = 0, 1, 2$

3) Scale particle masses and velocities to match Ω_m and new size

-- $1.1 \times 10^9\ M_\odot$ $7.1 \times 10^8\ M_\odot$

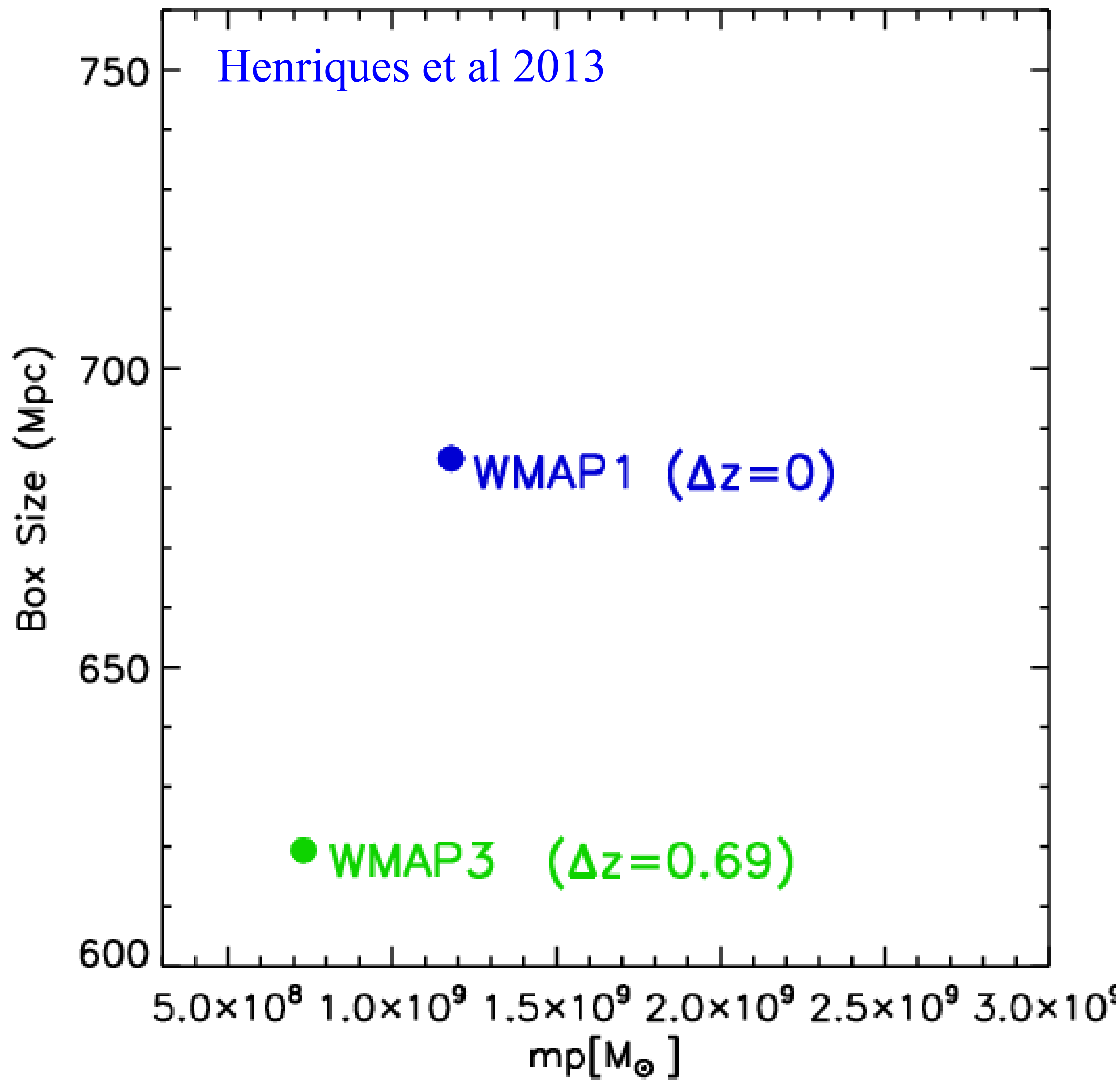
4) Adjust for the difference between amplitudes of original and target power spectra on large scales using linear theory.

Effect of changing cosmology on structure growth



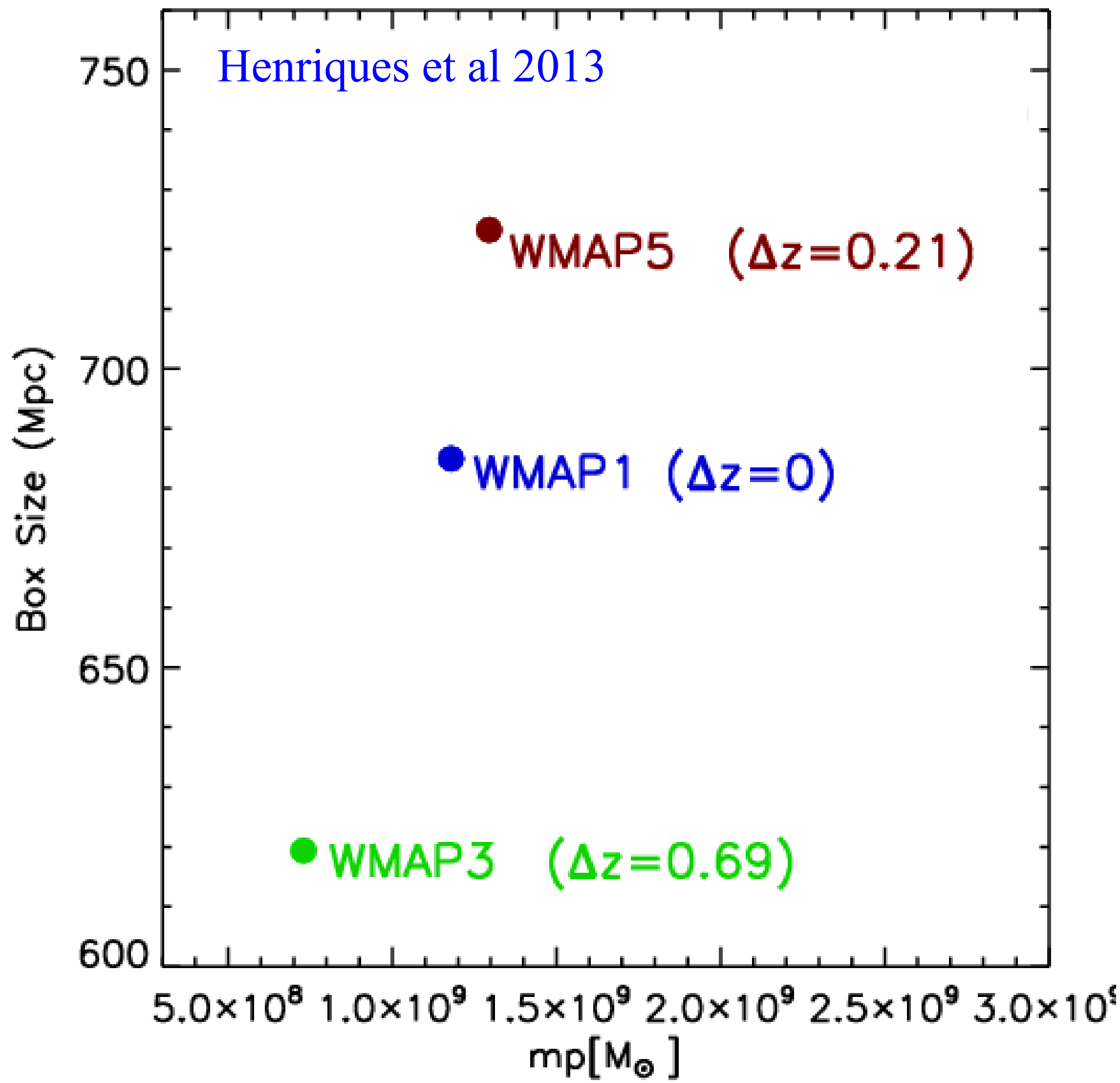
Scalings needed to adapt the MS to changing CMB cosmologies

Effect of changing cosmology on structure growth



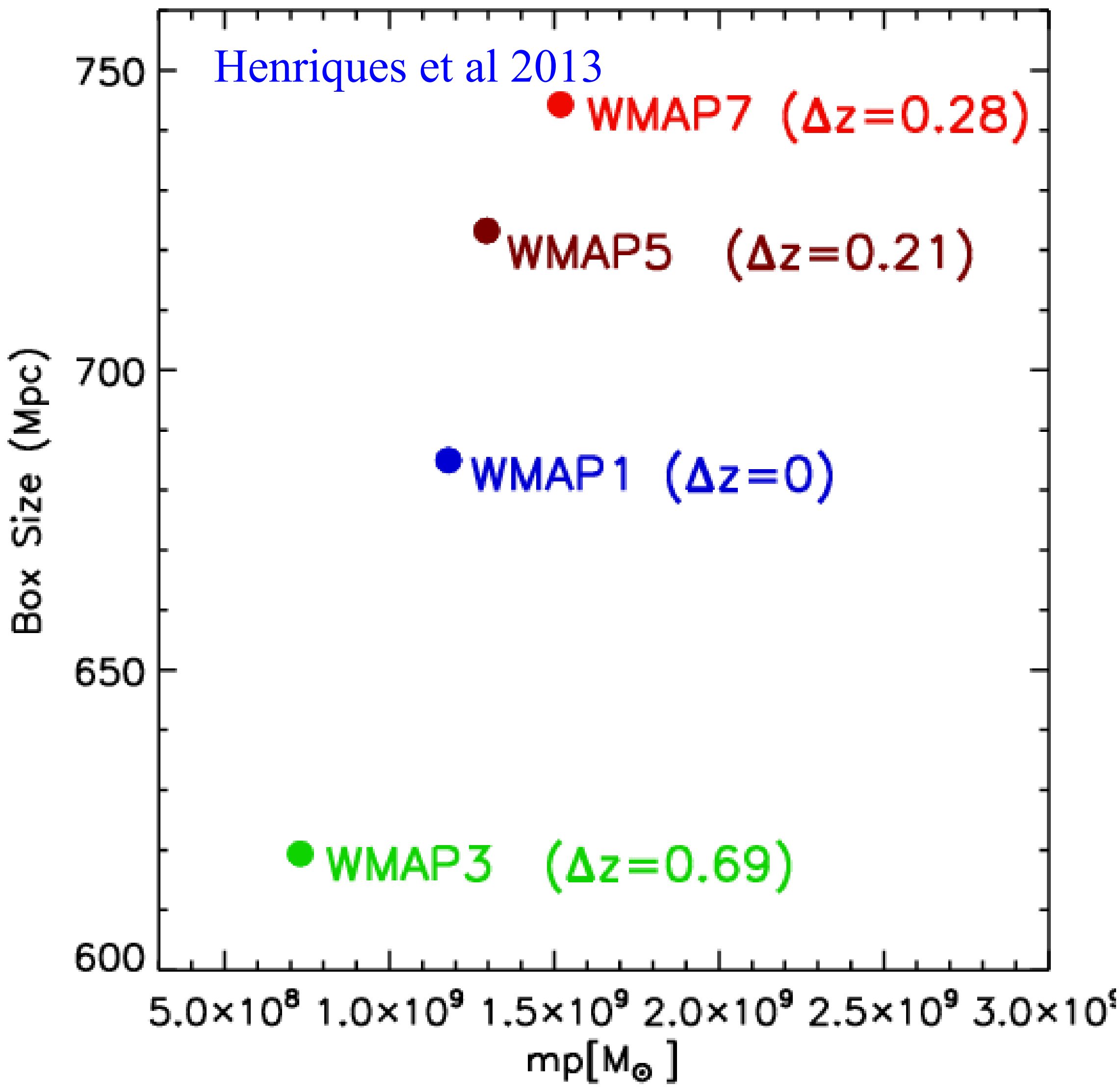
Scalings needed to adapt the MS to changing CMB cosmologies

Effect of changing cosmology on structure growth



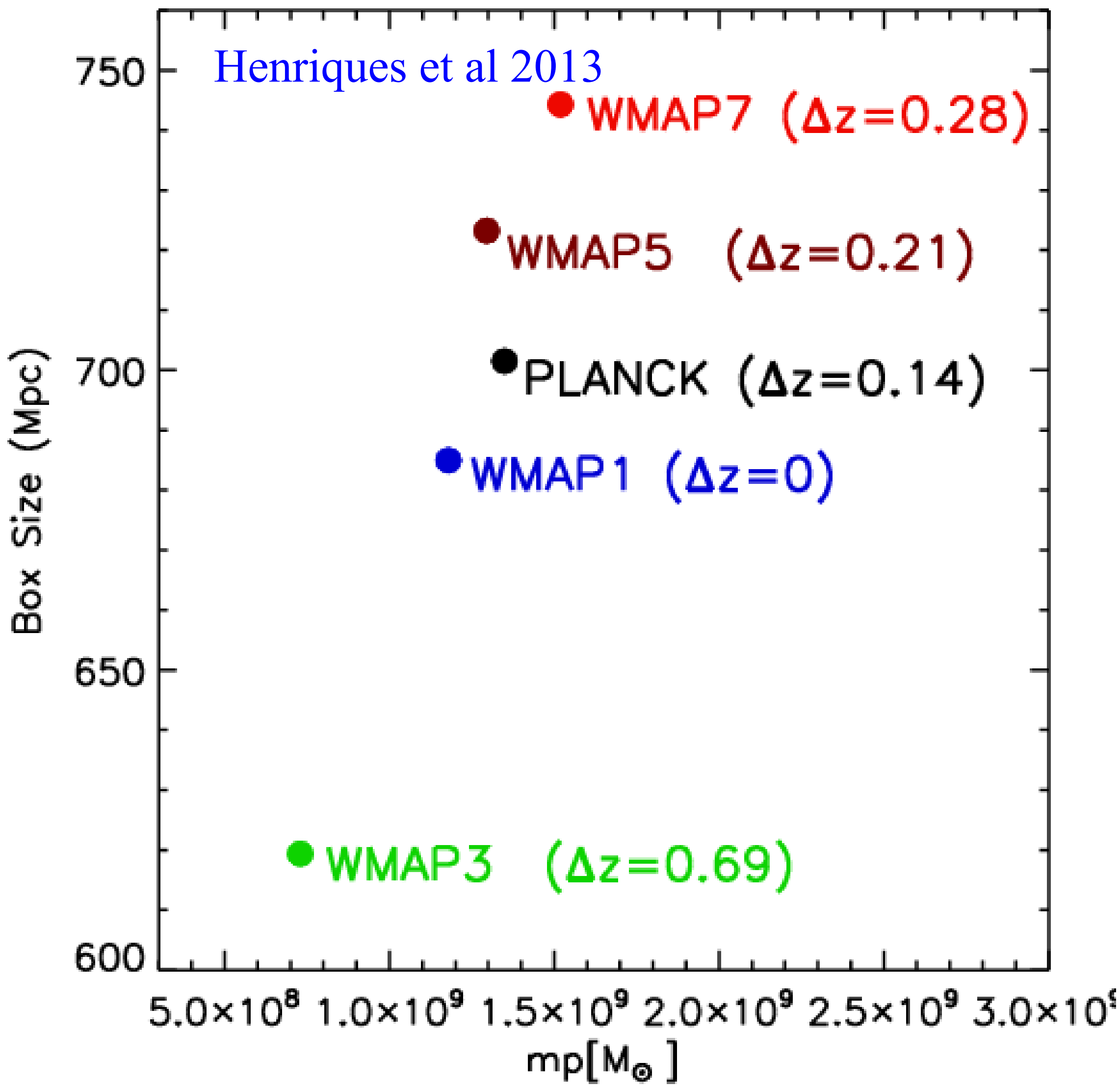
Scalings needed to adapt the MS to changing CMB cosmologies

Effect of changing cosmology on structure growth

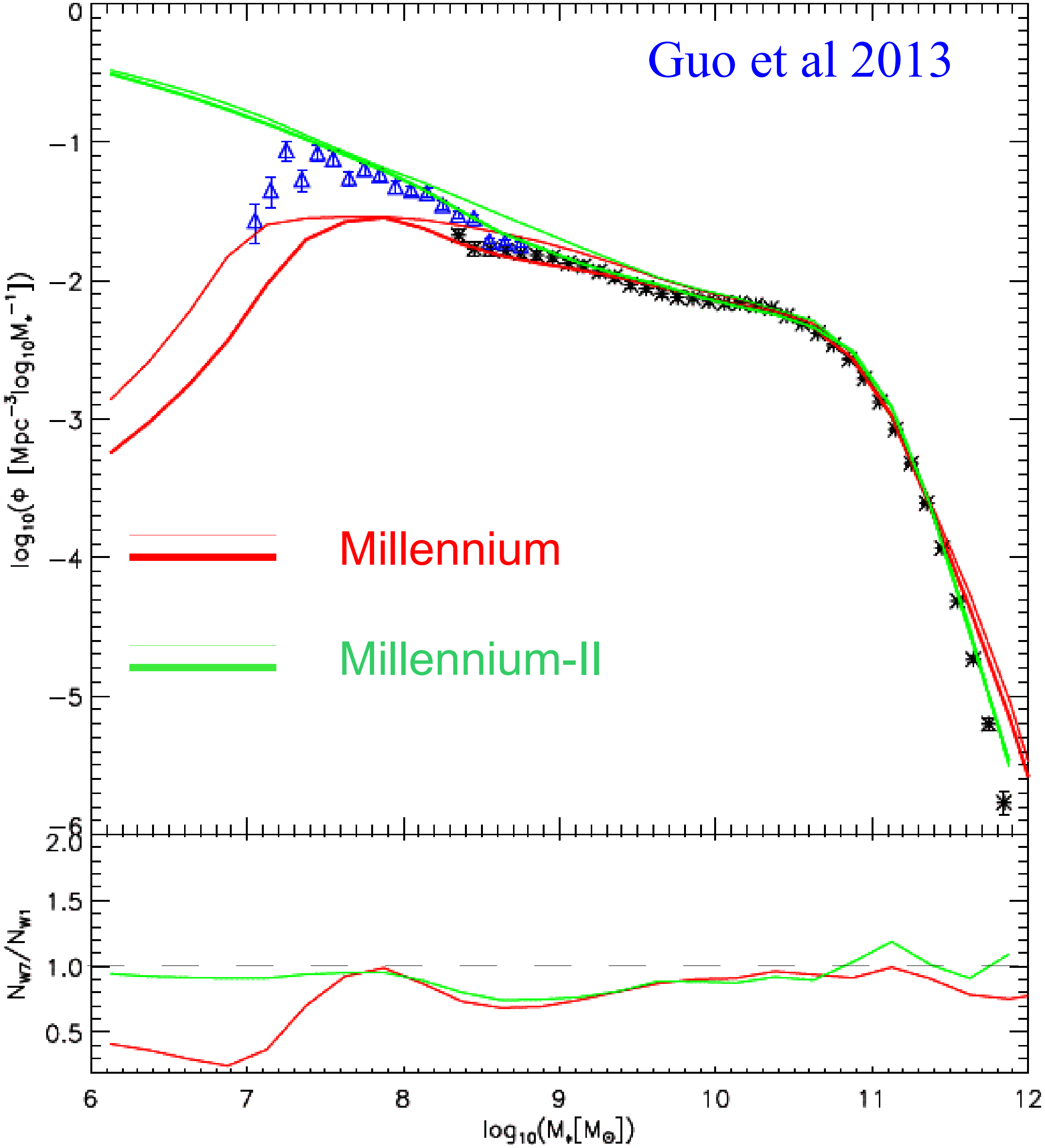


Scalings needed to adapt the MS to changing CMB cosmologies

Effect of changing cosmology on structure growth



Scalings needed to adapt the MS to changing CMB cosmologies



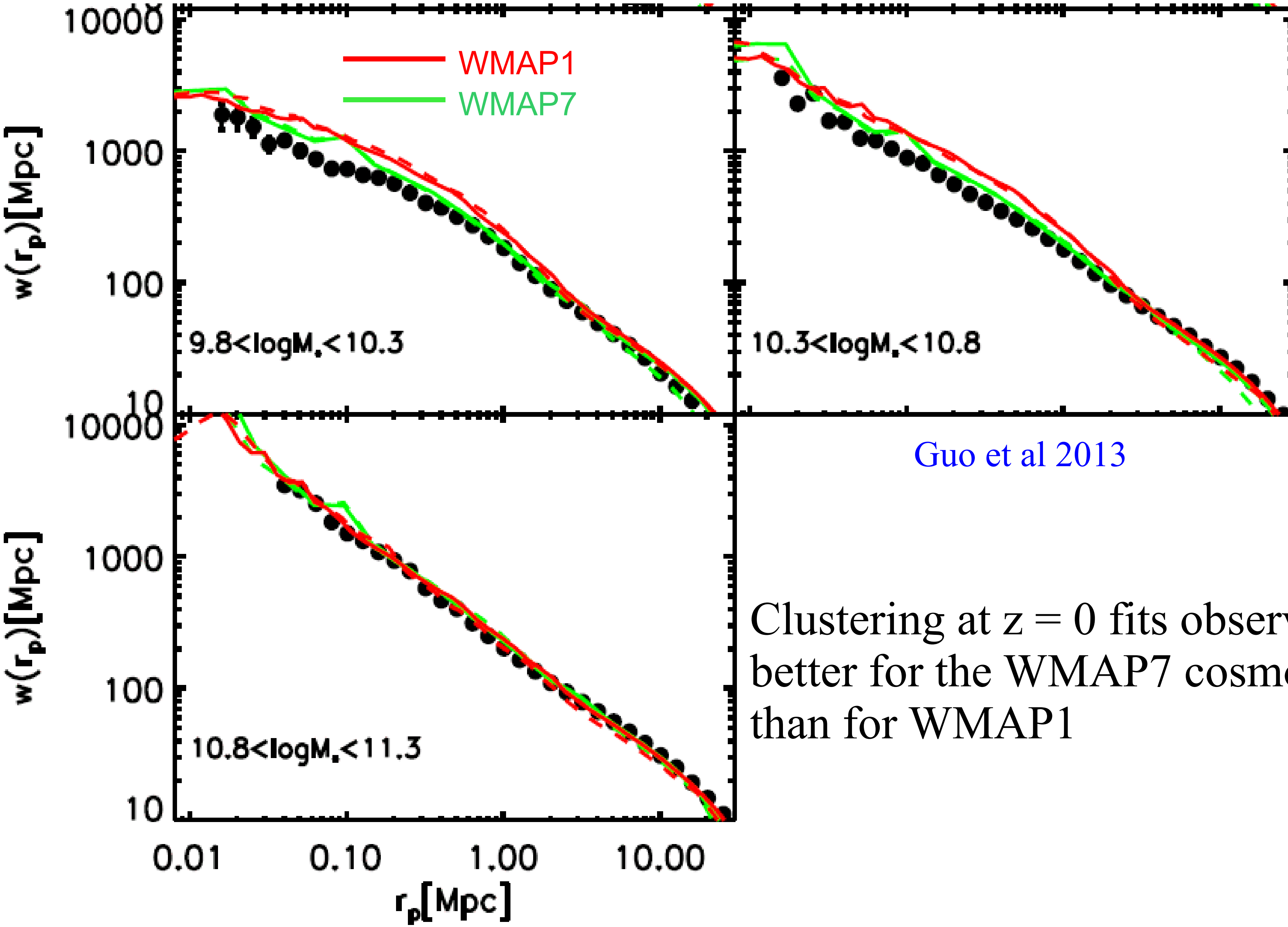
Switching from **WMAP1** to **WMAP7**

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}

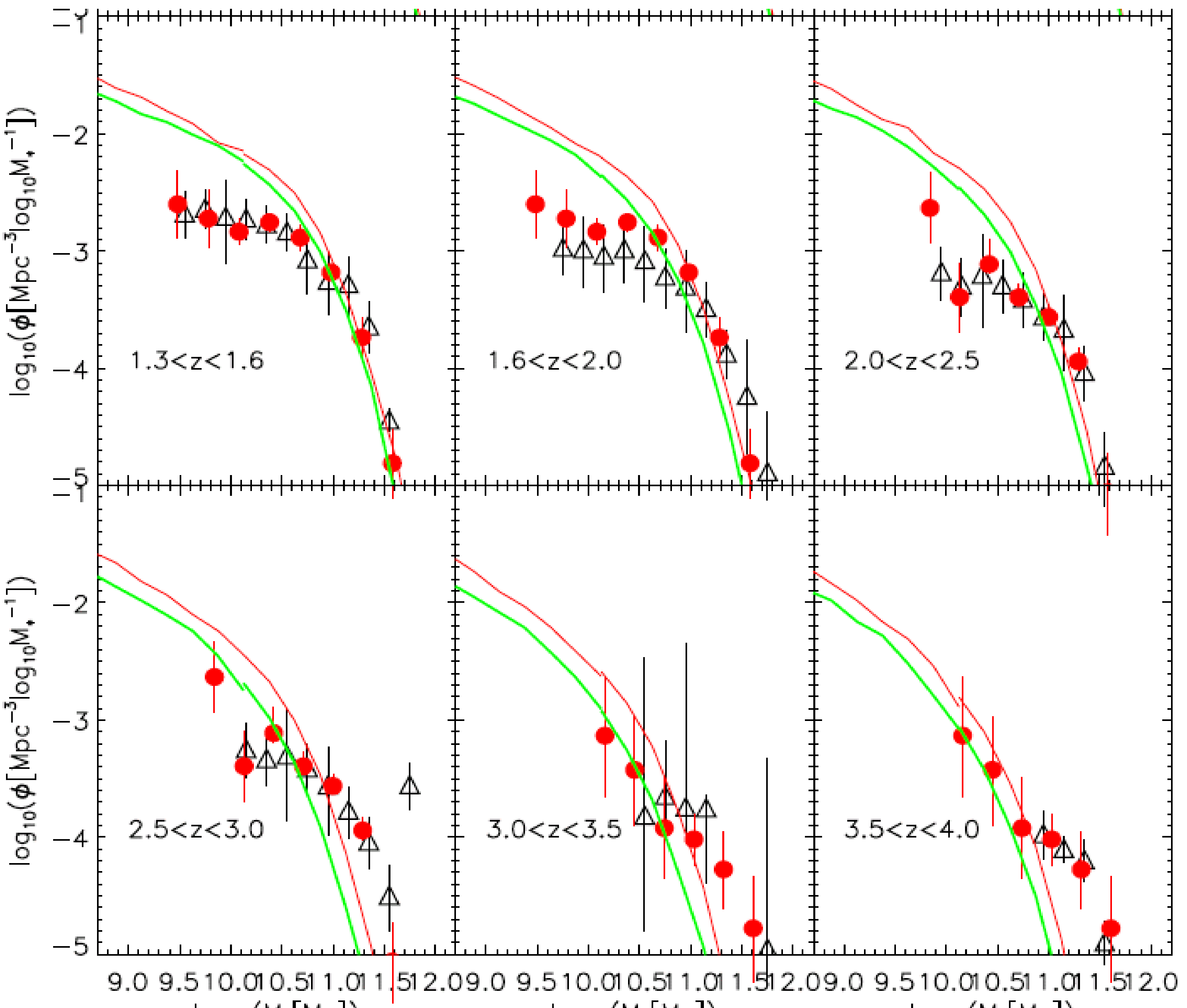
Switching from WMAP1 to WMAP7



Guo et al 2013

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

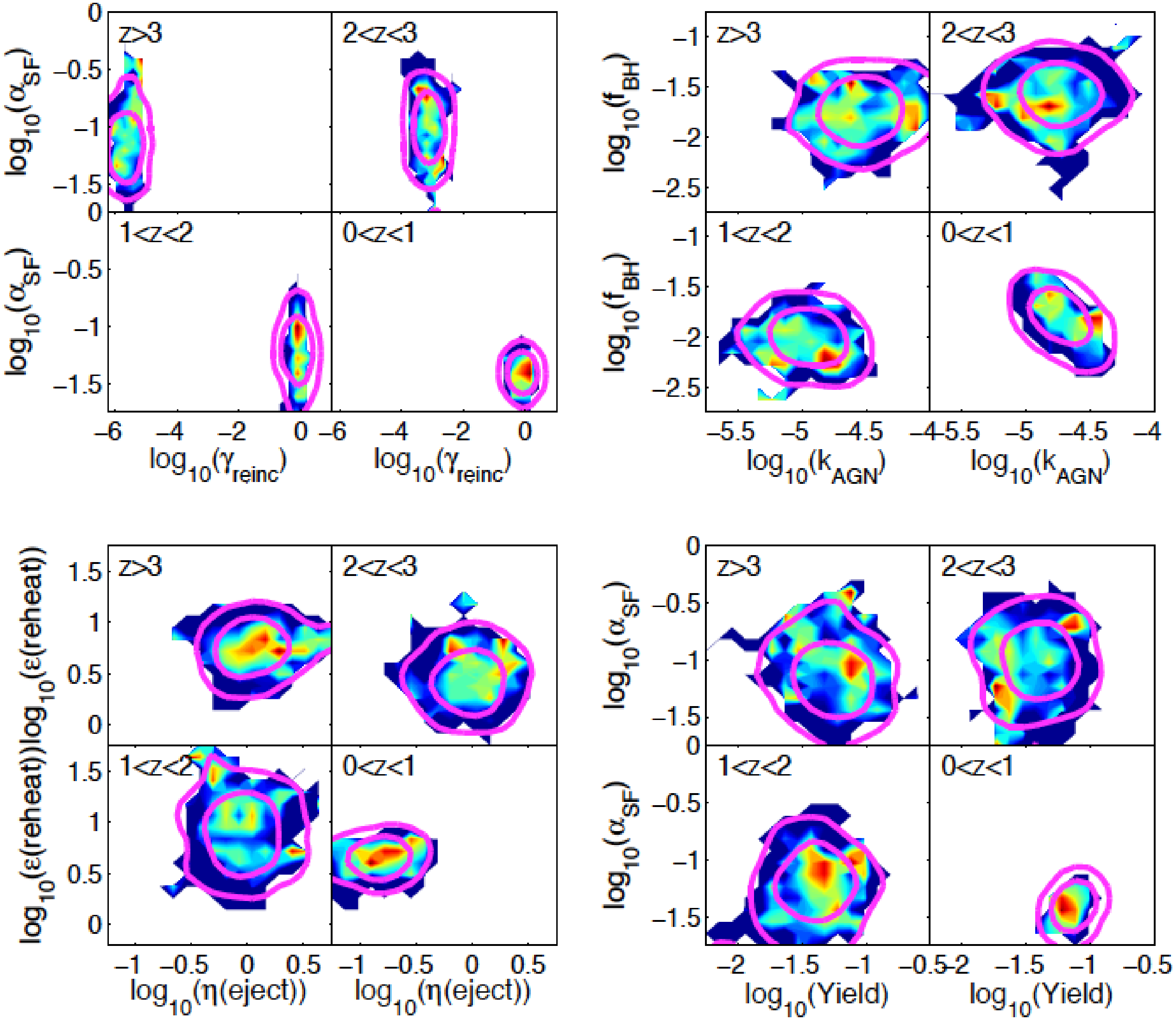
Switching from WMAP1 to WMAP7



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

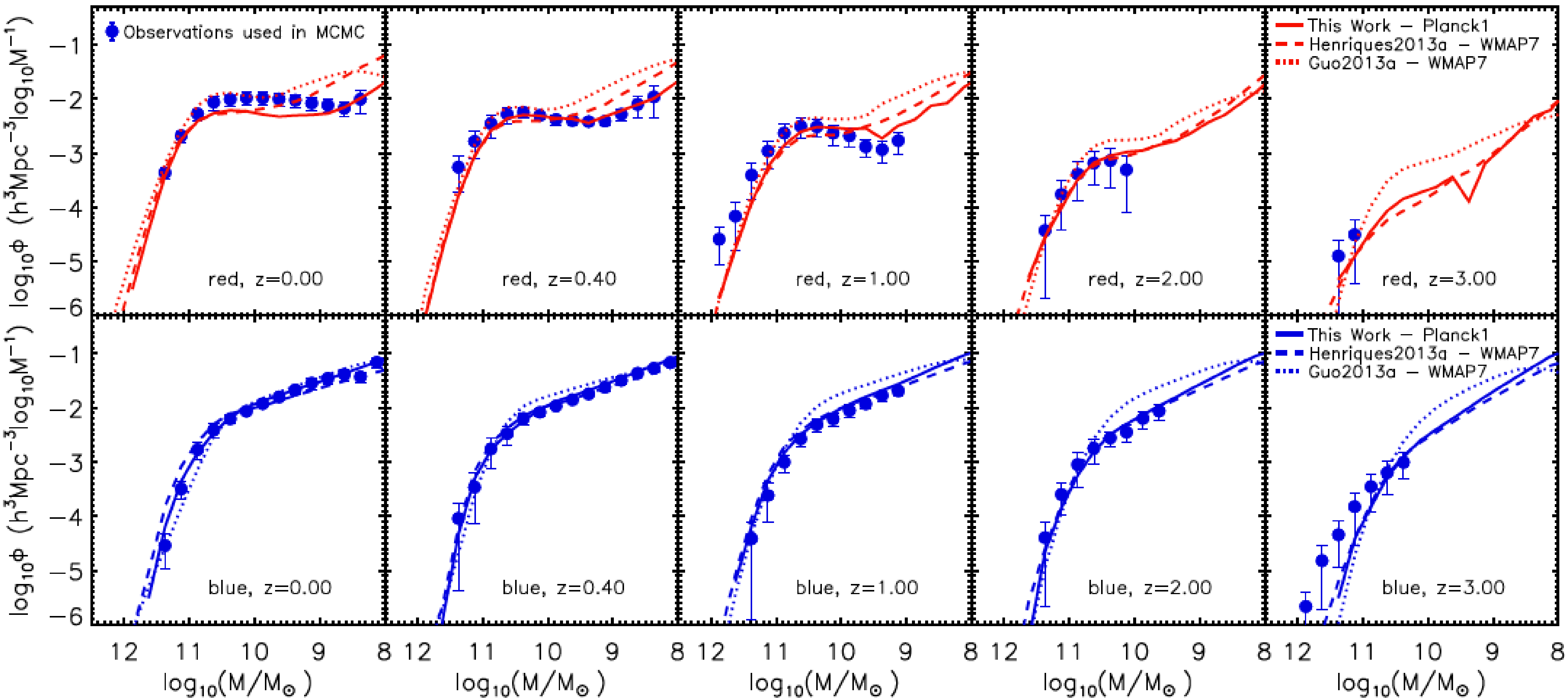
Parameters are determined by data at each individual redshift

No parameter set is consistent with data at all redshifts

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

Henriques et al 2013

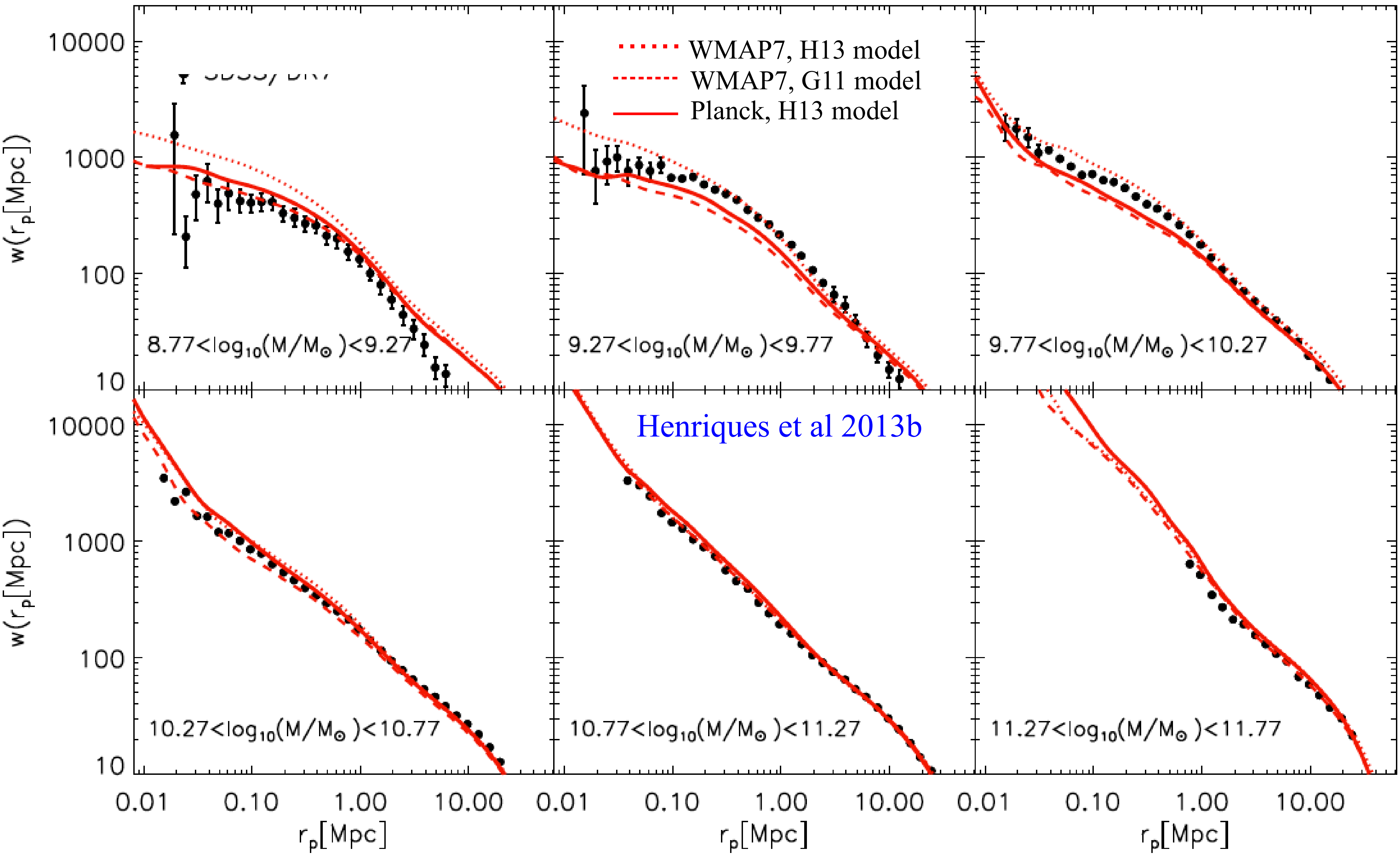
Henriques et al 2013b, Planck cosmology



Changing the assumed timescale for reincorporation of wind ejecta

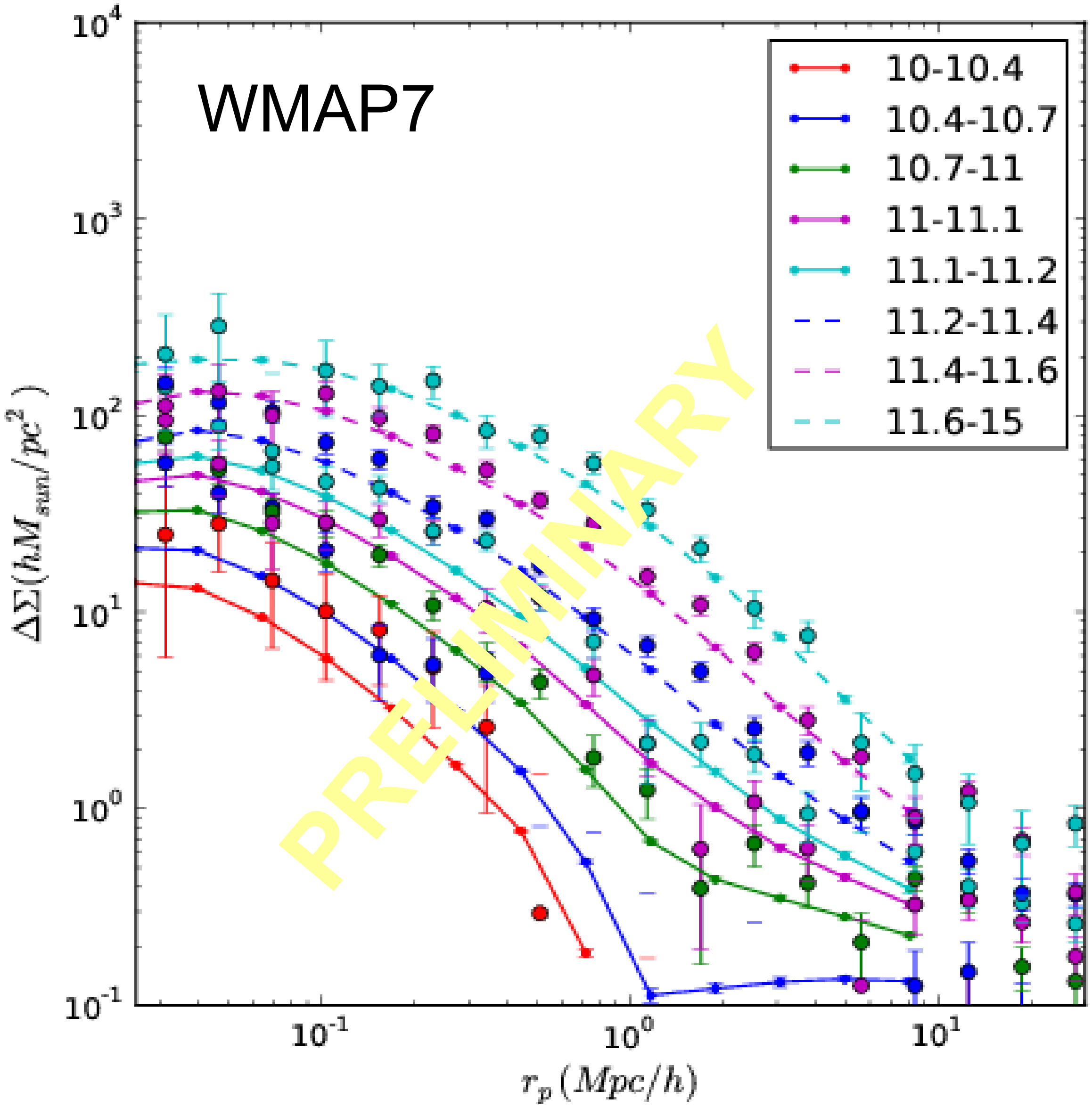
$$t_{return} = \text{const.} / H(z)\, V_{halo} \longrightarrow t_{return} = \text{const.} / M_{halo}$$

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



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

Galaxy-galaxy lensing: a cosmological test?

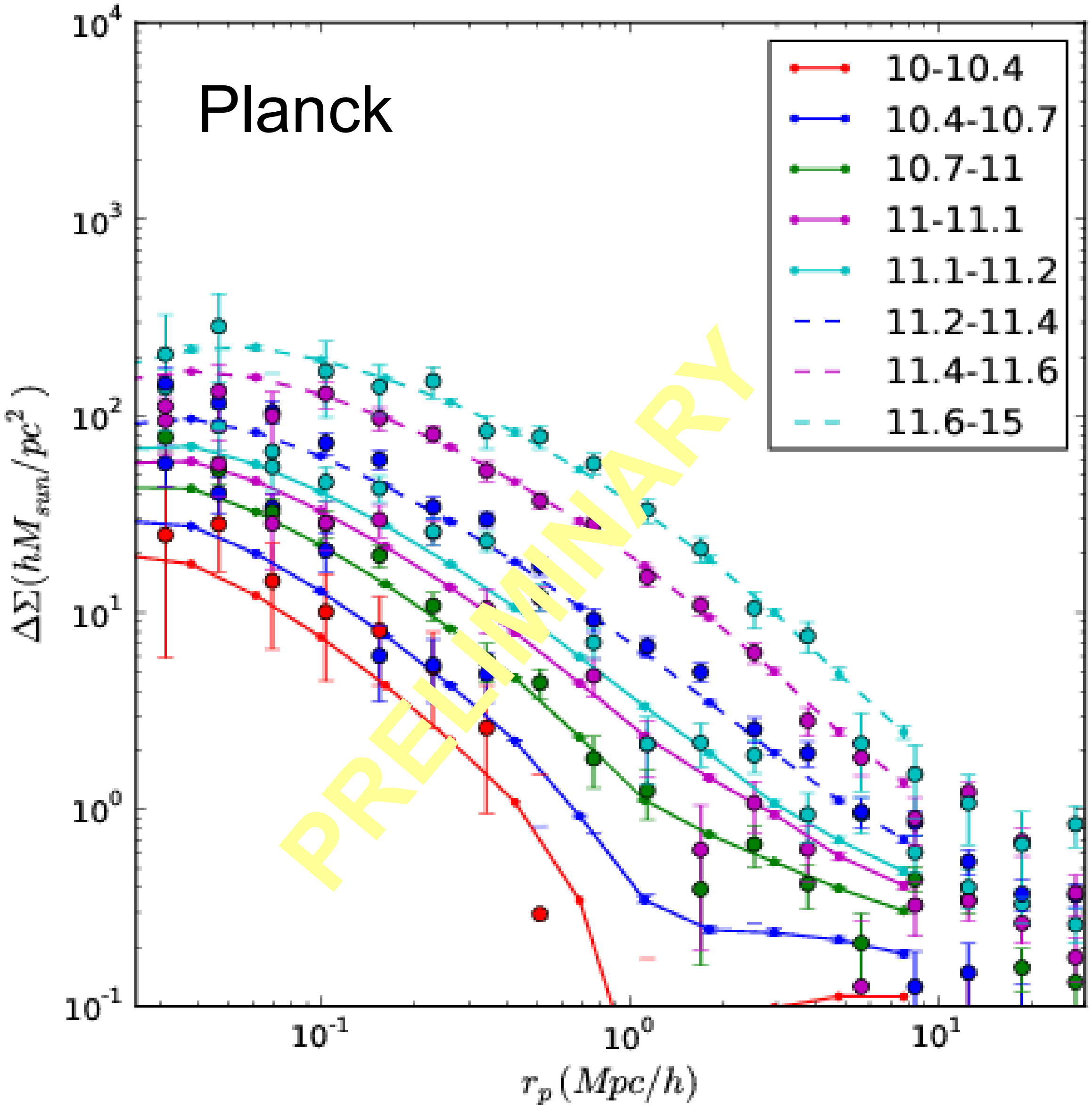


Wang, Mandelbaum et al, in prep.

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 assuming WMAP7 cosmology

Galaxy-galaxy lensing: a cosmological test?



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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 assuming *Planck* cosmology

The Millennium Run Observatory

Overzier et al 2013

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 under construction

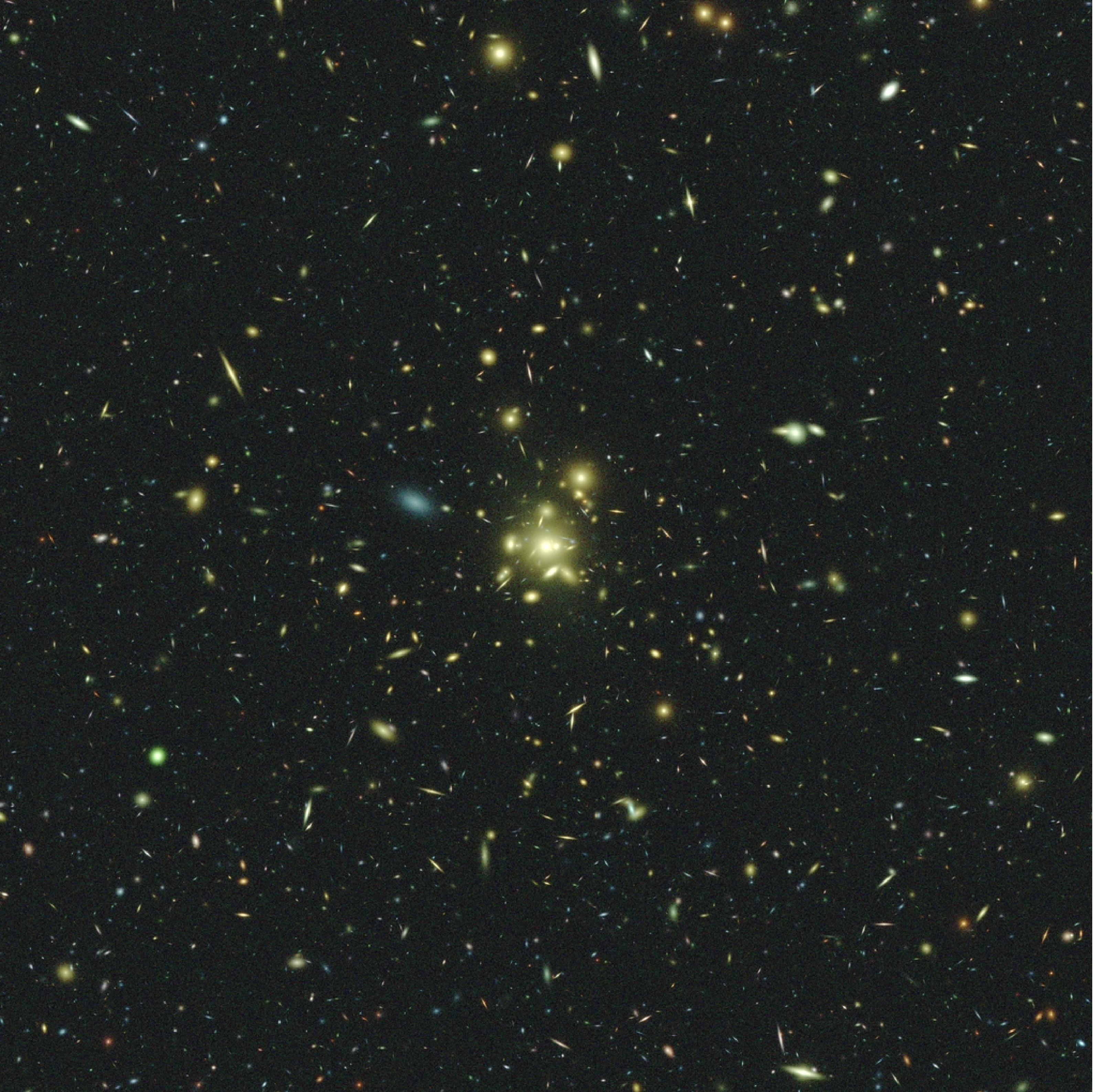
Cl0024

Harsono & De Propris
2007

$z = 0.40$

3.4' x 3.4'

HST/ACS



“Cl0024”

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

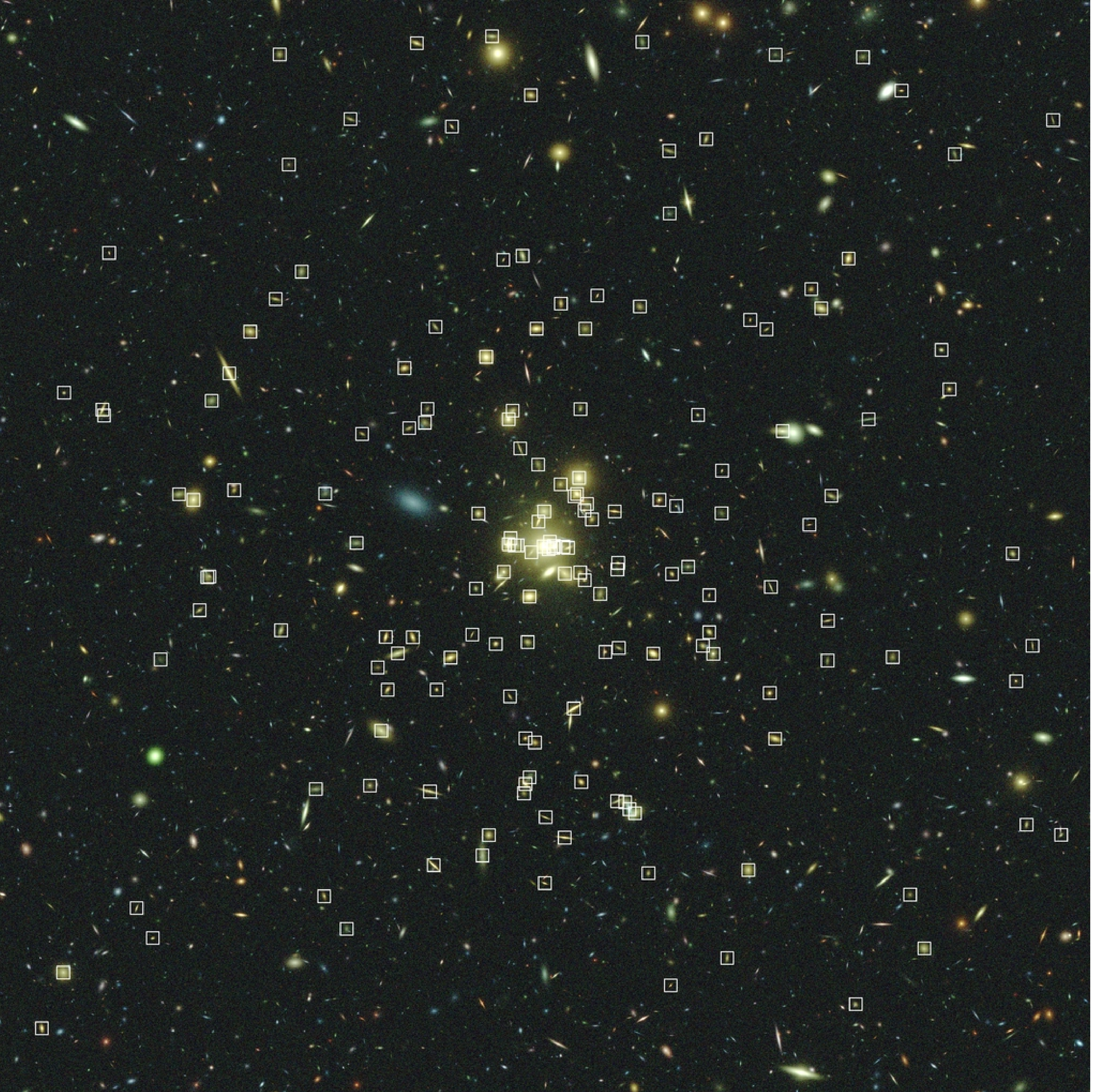
$z = 0.41$

3.4' x 3.4'

HST/ACS
F475W, F625W,
F850LP

10,000sec/filter

Overzier et al 2013



"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 2013

Max-Planck-Institut für Astrophysik

The MROBS Project
- Imaging Portal -

Hi guest | login
legal notice
portal
about & credits
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

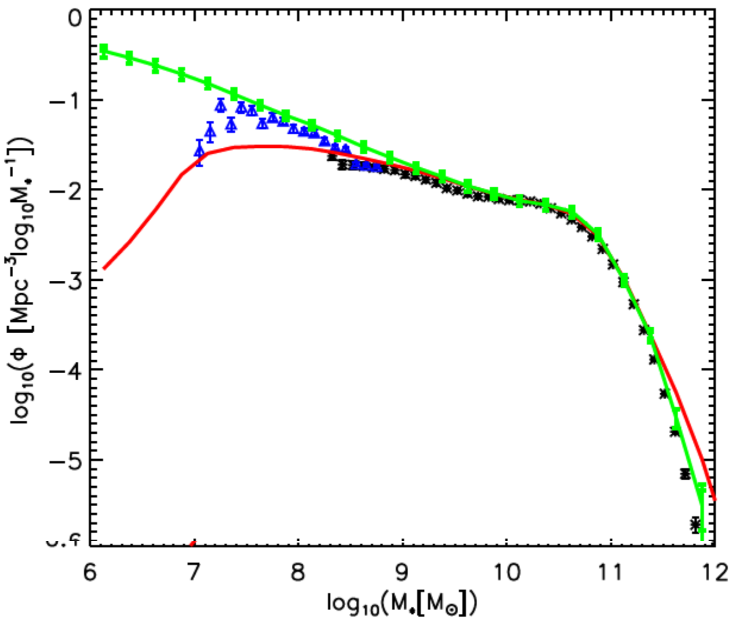
References: Overzier, Lemson, et al. 2012, MNRAS, in press (arXiv:1206.6923v2, high resolution paper here). (see 'about & credits' for further references).

Surveys Overview Table

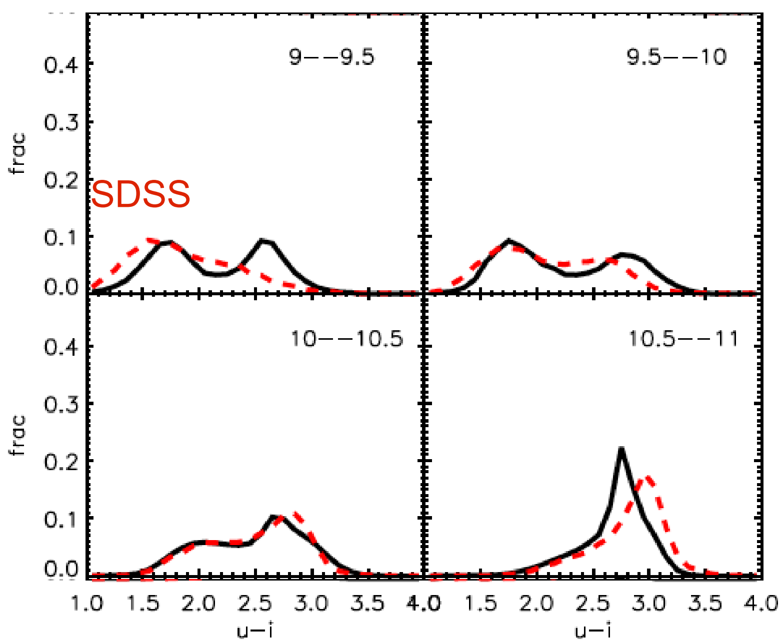
http://galformod.mpa-garching.mpg.de/mrobs/

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

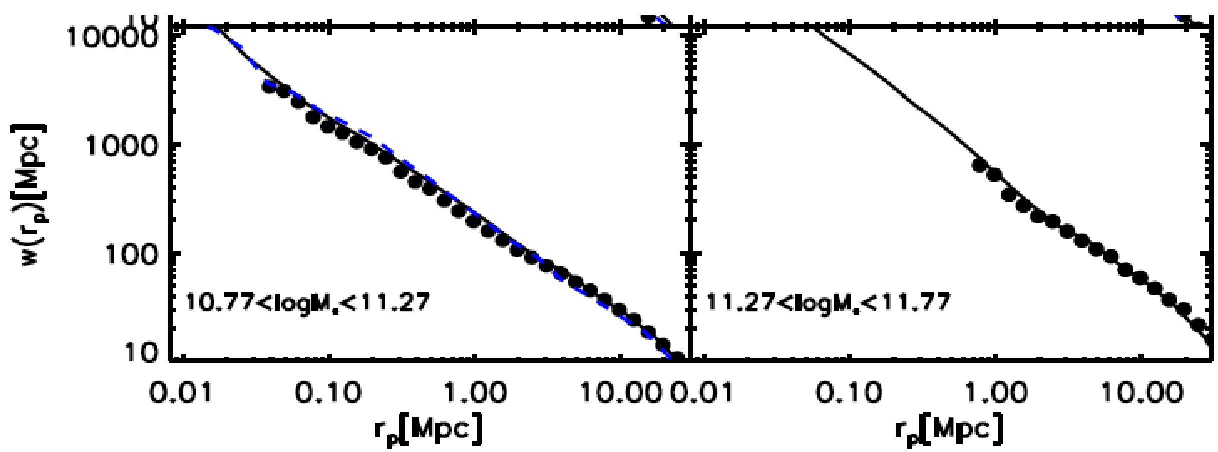
How do we learn from population simulations?



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



Guo et al 2011



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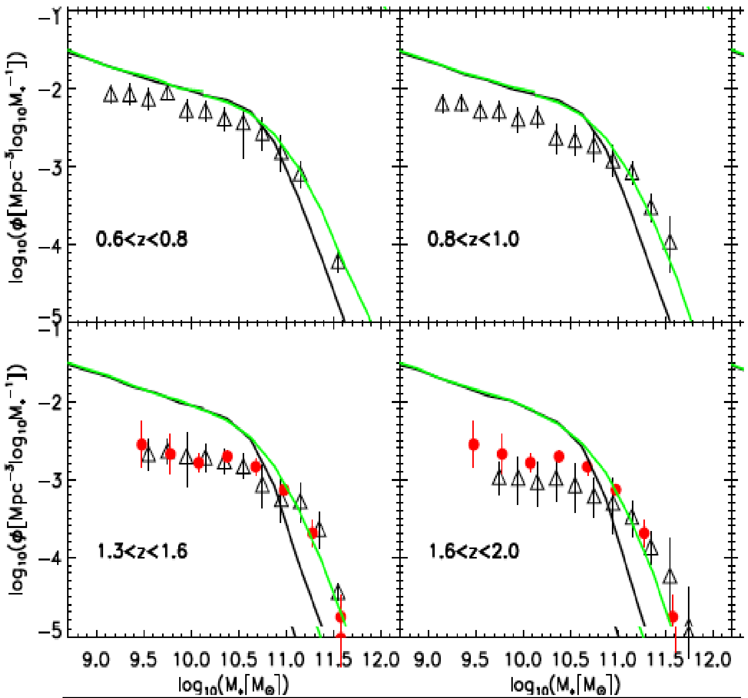
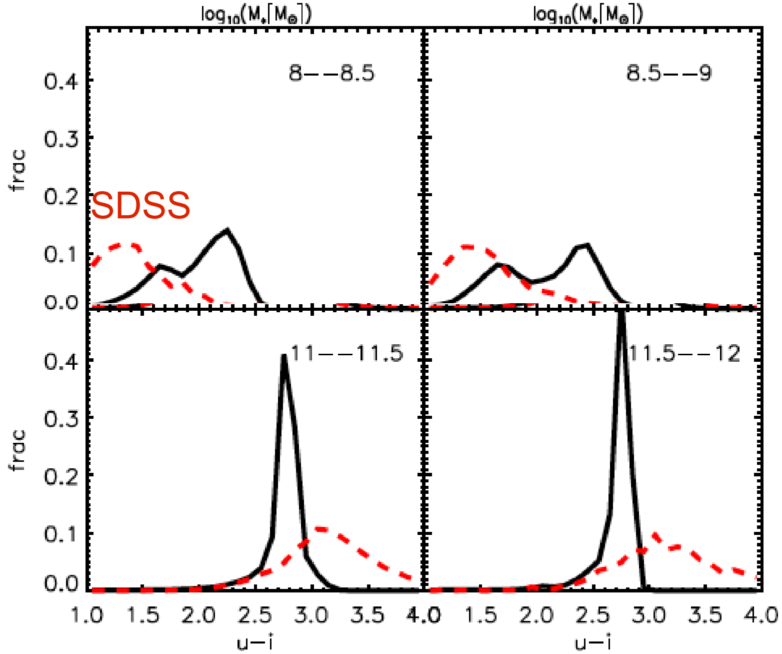


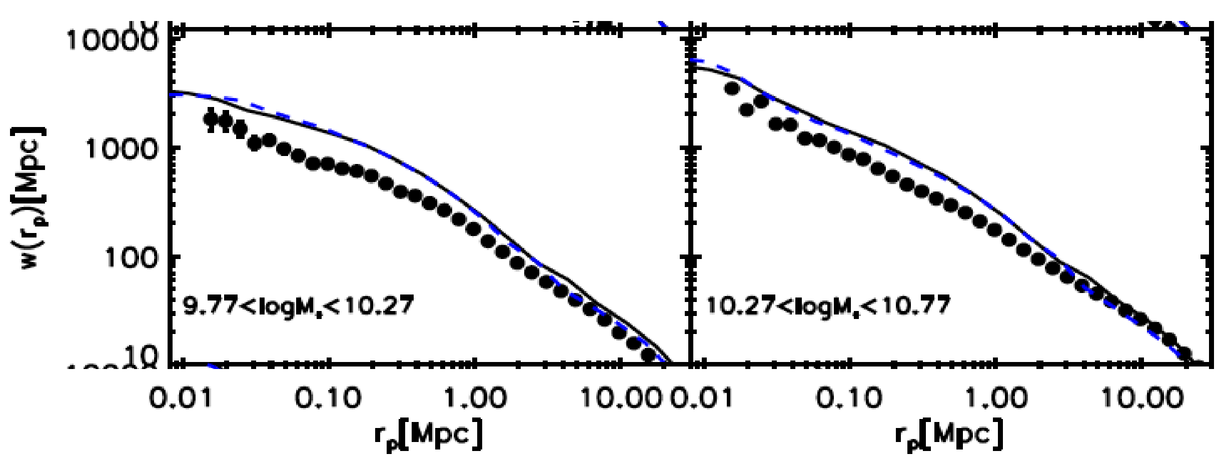


When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

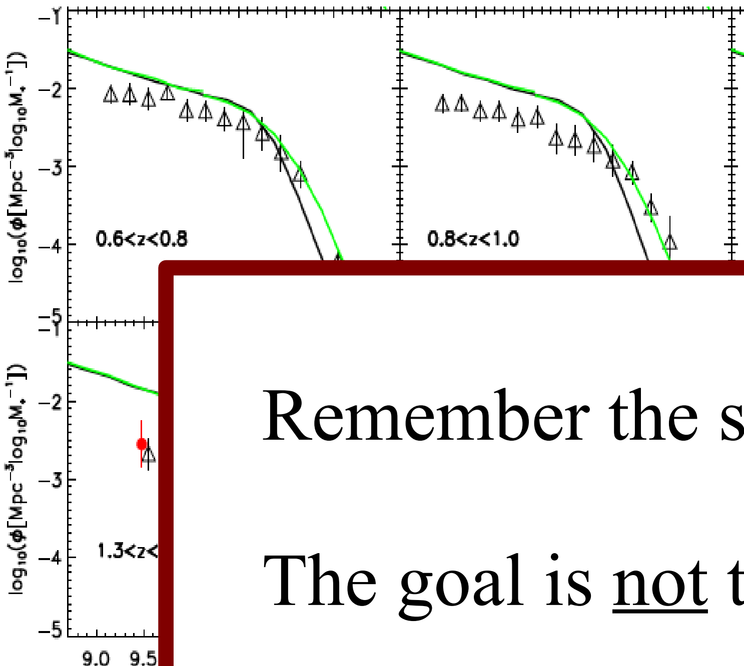
...but it is the failures which show where there is missing or inadequate physics

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

Guo et al 2011



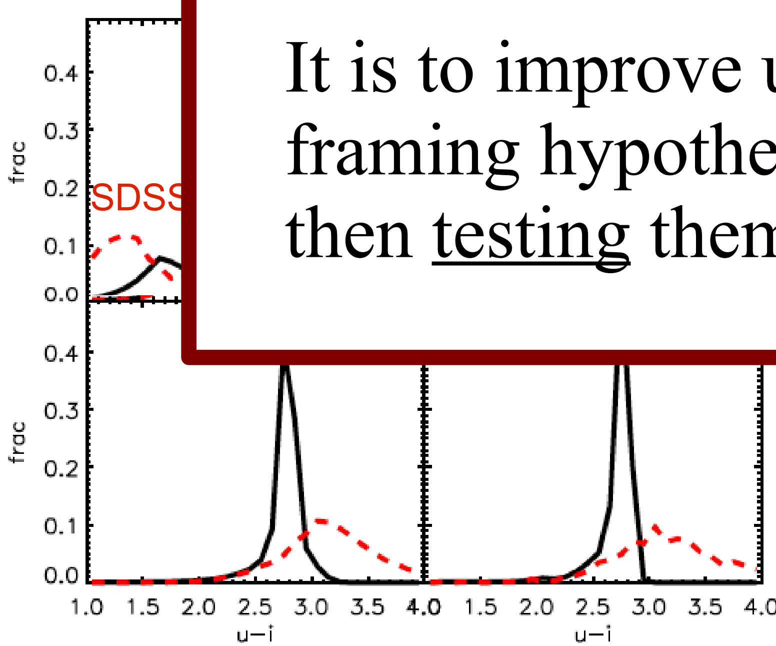
How do we learn from population simulations?

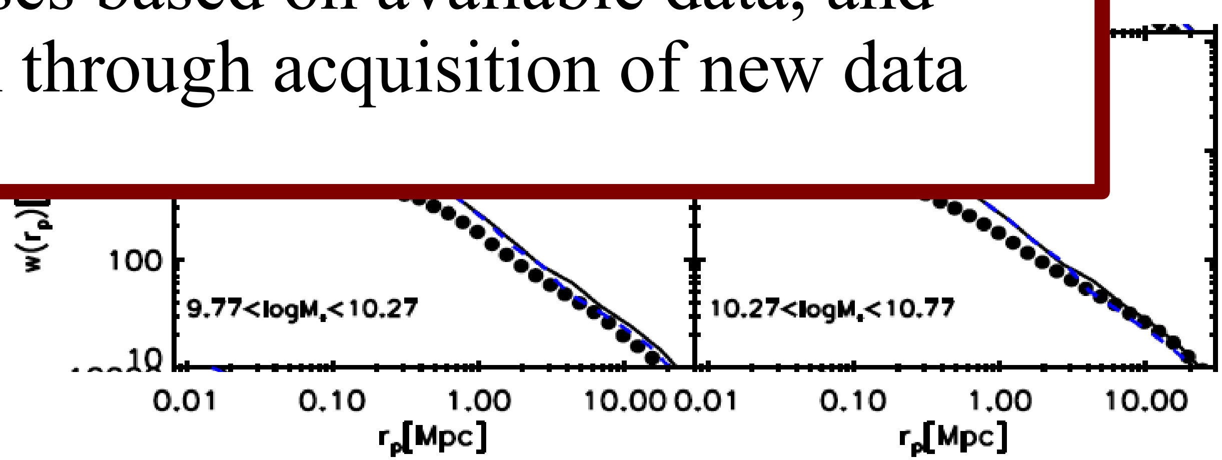


When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

re

ent





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, and then testing 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 observed galaxy abundances, scaling relations and clustering
- Such comparisons indicate how galaxy formation and cosmological factors combine to influence observables, and hence allow us

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