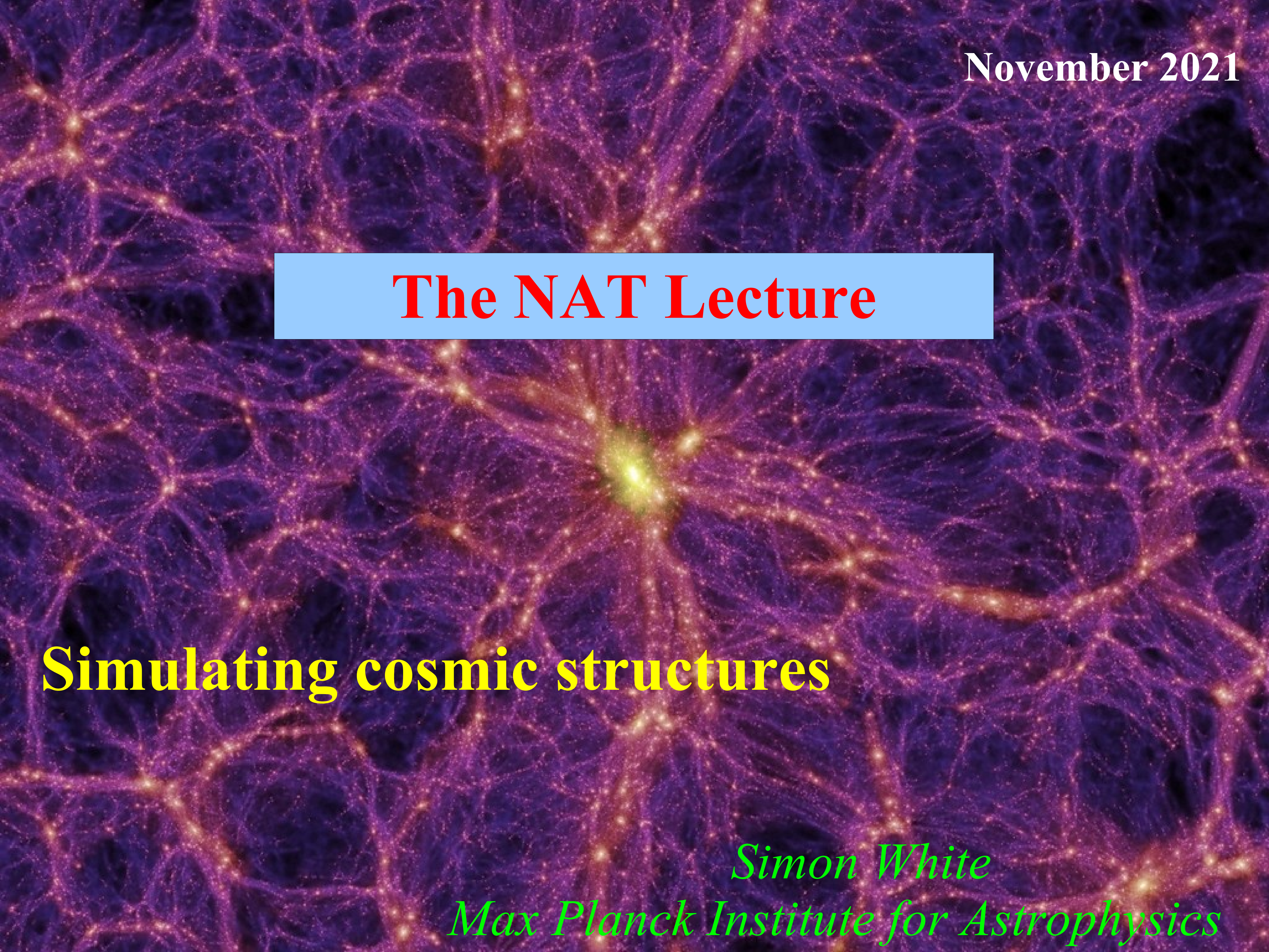


November 2021

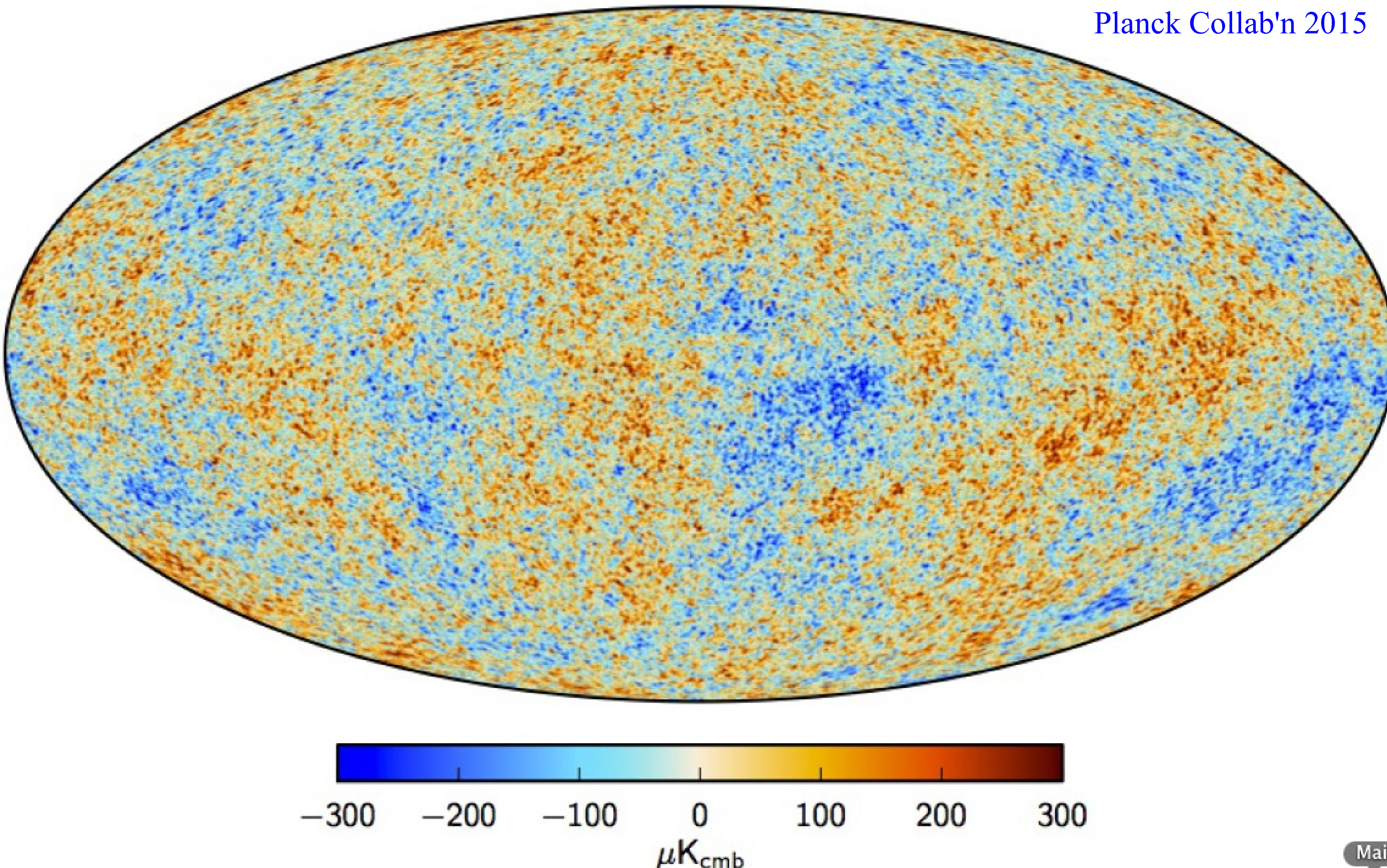
The NAT Lecture

Simulating cosmic structures

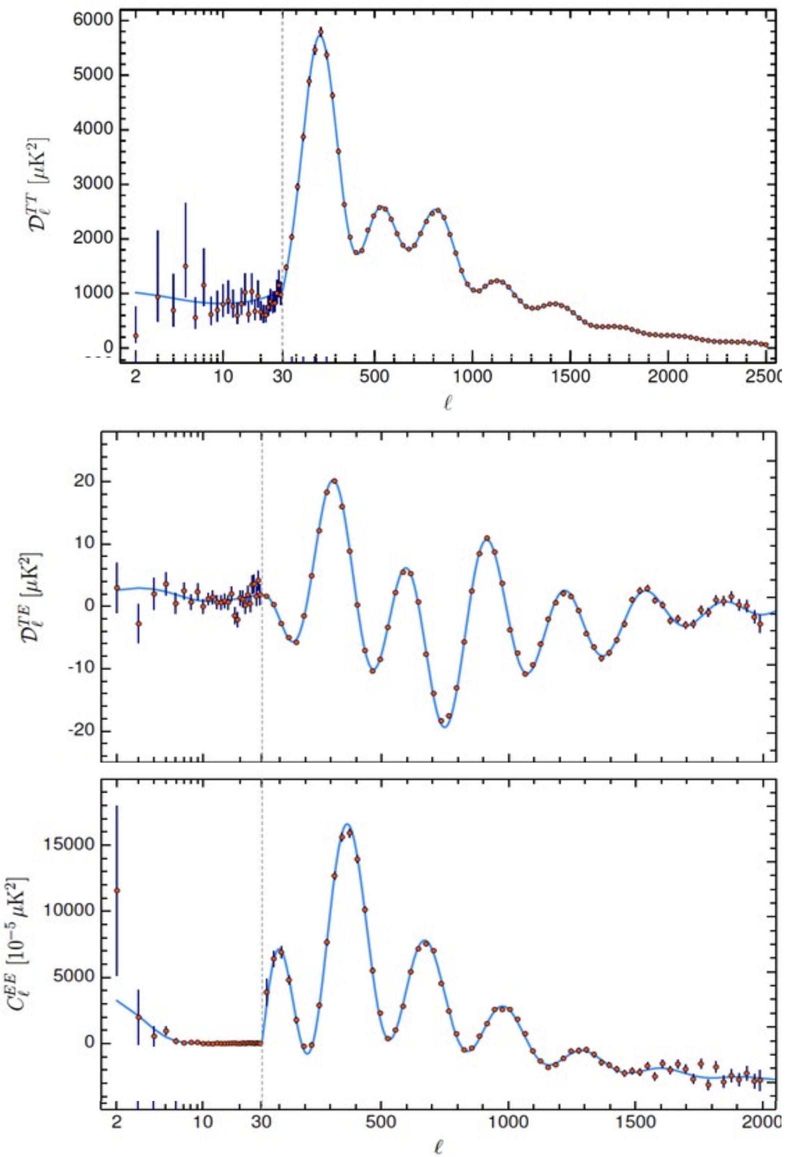
Simon White
Max Planck Institute for Astrophysics

CMB map from the full *Planck* mission

Planck Collab'n 2015



The current CMB evidence for ΛCDM



Planck Collaboration 2018

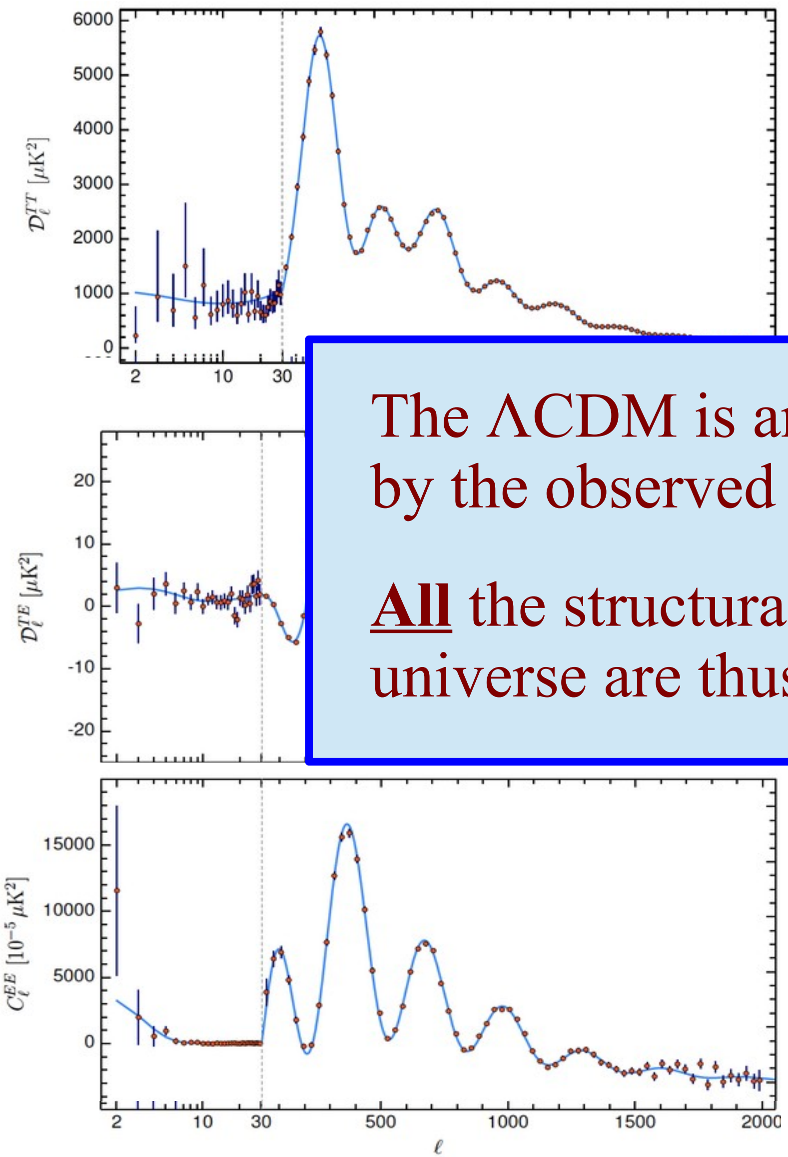
Parameter	Combined
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012
$100\theta_{MC}$	1.04089 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.043 ± 0.014
n_s	0.9652 ± 0.0042
$\Omega_m h^2$	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.37 ± 0.54
Ω_m	0.3147 ± 0.0074
Age [Gyr]	13.801 ± 0.024
σ_8	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.830 ± 0.013
z_{re}	7.64 ± 0.74
$100\theta_*$	1.04108 ± 0.00031
r_{drag} [Mpc]	147.18 ± 0.29

- **No** local/low-redshift data are used

→ **Measurements** of all 6 ΛCDM parameters
Cosmic properties, **not** fitting parameters

- Low-z data needed to specify nature of the DM

The current CMB evidence for ΛCDM



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T = 2.7255 ± 0.0005

The ΛCDM is an *a priori* model which is <u>fully</u> specified by the observed CMB temperature and fluctuations

<u>**All**</u> the structural properties of the nonlinear low-z universe are thus zero-parameter predictions

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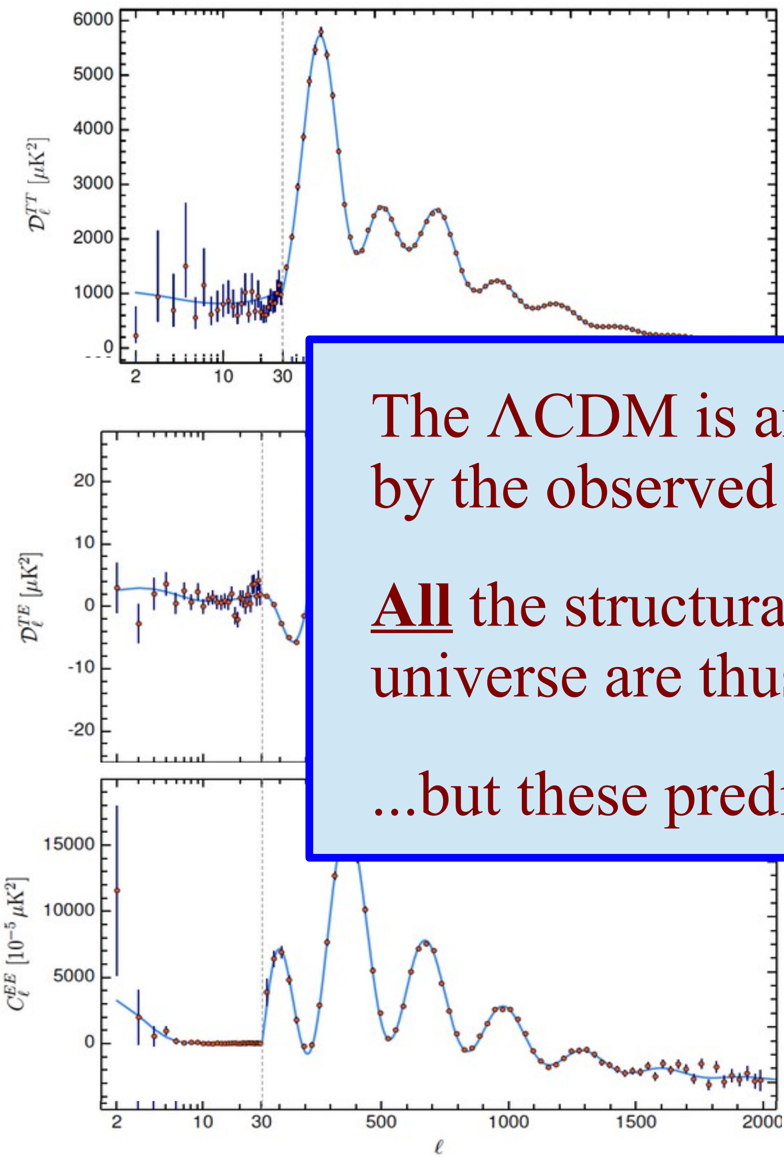

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<u>All</u> the structural properties of the nonlinear low-z universe are thus zero-parameter predictions

...but these predictions can be very hard to calculate!

- **<u>No</u>** local/low-redshift data are used

→ **<u>Measurements</u>** of all 6 ΛCDM parameters
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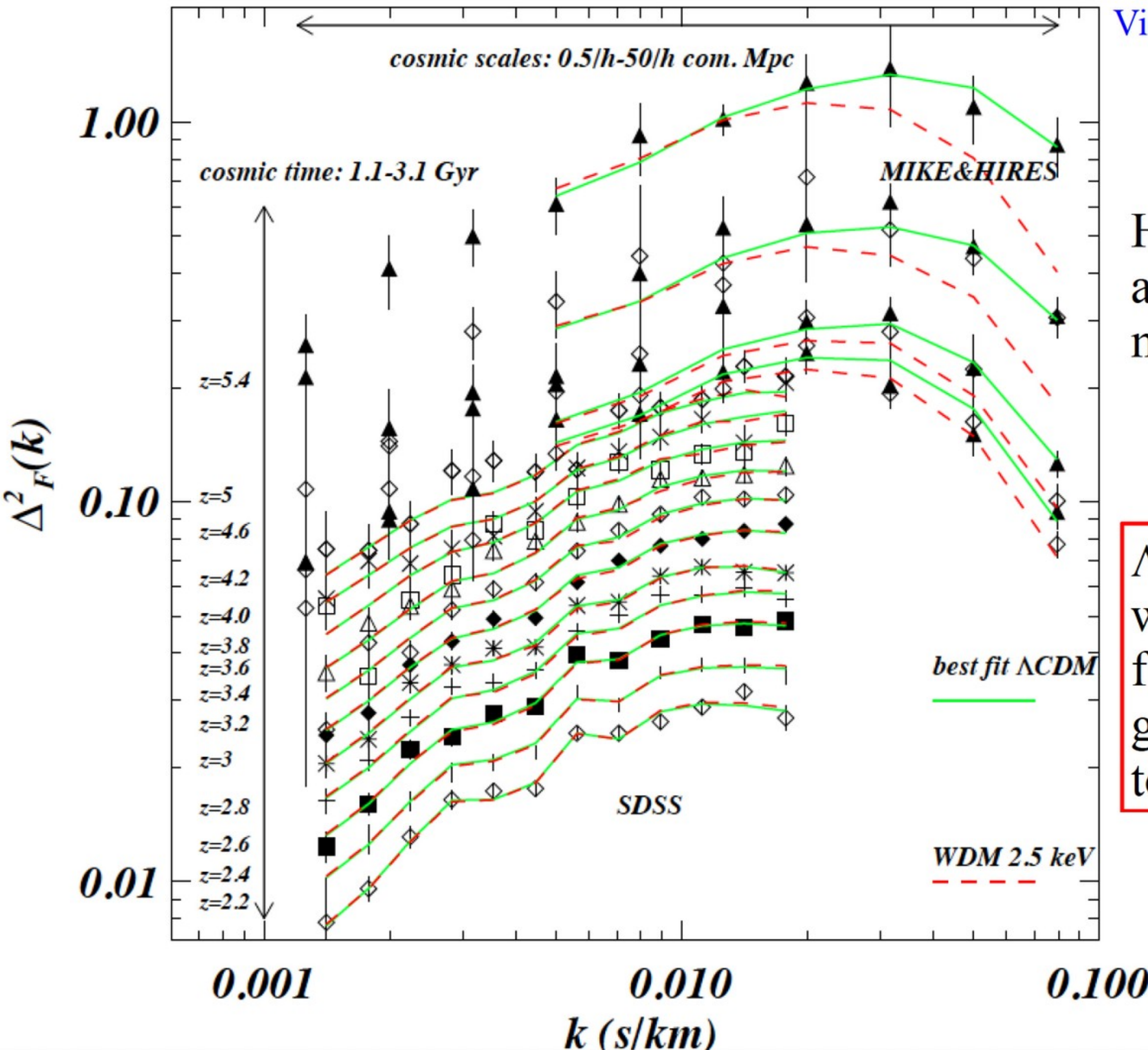
Lyman α forest spectra compared to ΛCDM predictions



Viel, Becker, Bolton & Haehnelt 2013

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

ΛCDM initial conditions with CMB parameters fit structure in the pre-galactic medium down to dwarf galaxy scales

Cosmology and galaxy formation

- The geometry is flat to better than 0.5%
- Baryon and CDM densities, H_0 and σ_8 are known to ~1%
- Initial P(k) is ΛCDM with n ~ 0.97 down to subgalactic scales
- Initial non-gaussianities and $\Sigma\, m_\nu$ are both small

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- Late-time growth factor – z-space distortions – mod.grav., ν masses
- Dwarf galaxy core structure / Ly α forest – WDM / SIDM / fuzzy DM
- Signatures of DE interactions with DM? with ν's? with baryons?

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Does galaxy formation distort or mask these signals at the 1% level?

Making predictions for galaxies (accurately?)

Simulations are ***required*** to show that nonlinear effects are under control and to represent realistic observational surveys

Making predictions for galaxies (accurately?)

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- Are the initial conditions well enough represented?
- Is the volume large enough to control cosmic variance?
- Can the code follow growth sufficiently well?
- Is galaxy formation represented at a sufficient level by:

Making predictions for galaxies (accurately?)

Simulations are ***required*** to show that nonlinear effects are under control and to represent realistic observational surveys

- Are the initial conditions well enough represented?
- Is the volume large enough to control cosmic variance?
- Can the code follow growth sufficiently well?
- Is galaxy formation represented at a sufficient level by:
    - Halo occupation distribution (HOD) models
    - Subhalo abundance matching (SHAM) models
    - Semianalytic population simulations (SAM)
    - Cosmological hydrodynamical simulations

Modelling galaxies for large-scale structure

Halo Occupation Distributions (HOD)

Input: N-body simulation with halos
Fit data: Galaxy abundances and clustering at a given redshift
Output: Parameters $\boldsymbol{\alpha}$ in $P_{\boldsymbol{\alpha}}\{L_{cen}\ldots \mid M_{halo}\ldots\}$, $n_{\boldsymbol{\alpha}}(L_{sat}, r \mid M_{halo}\ldots)$

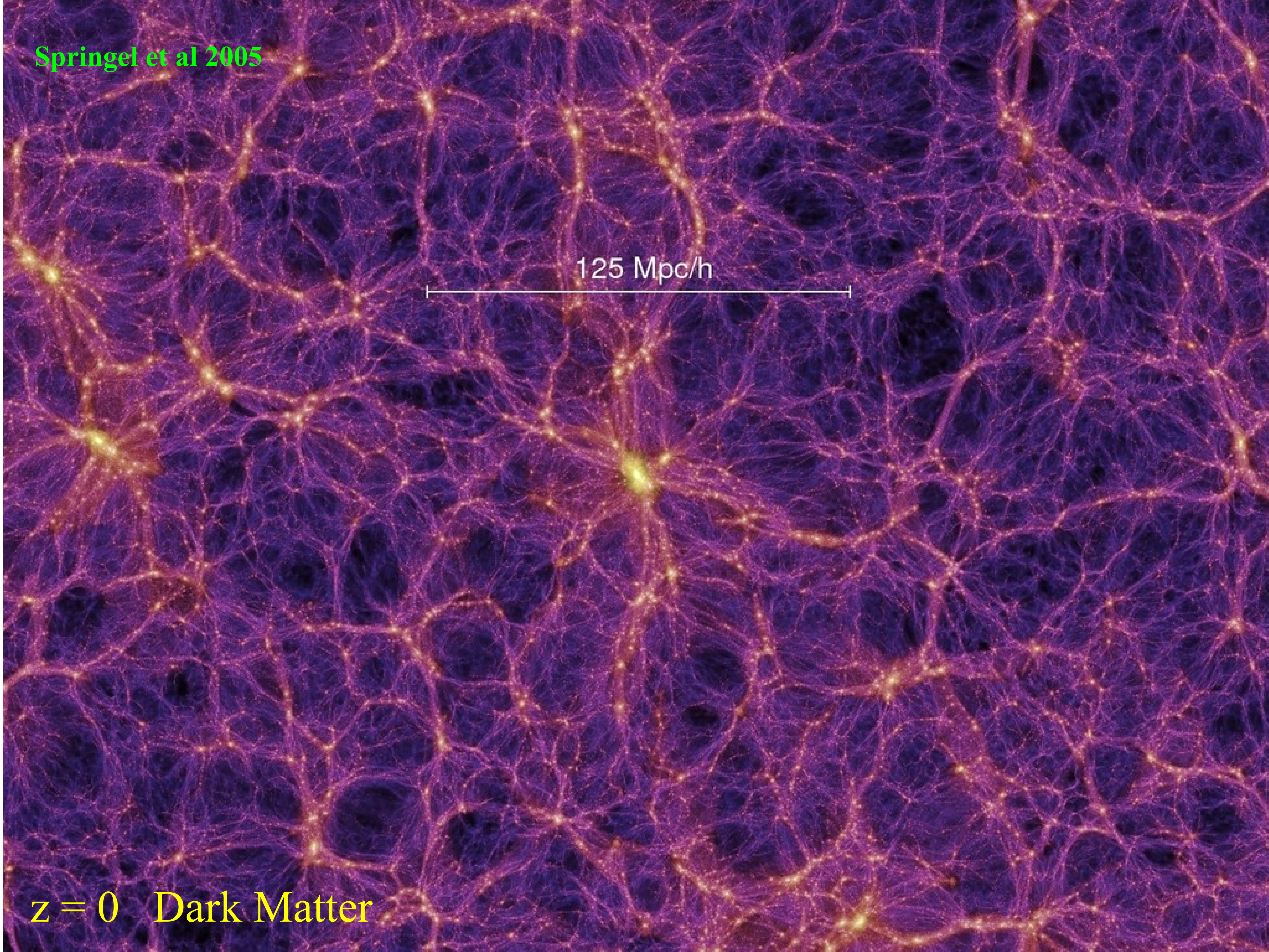
Subhalo Abundance Matching (SHAM)

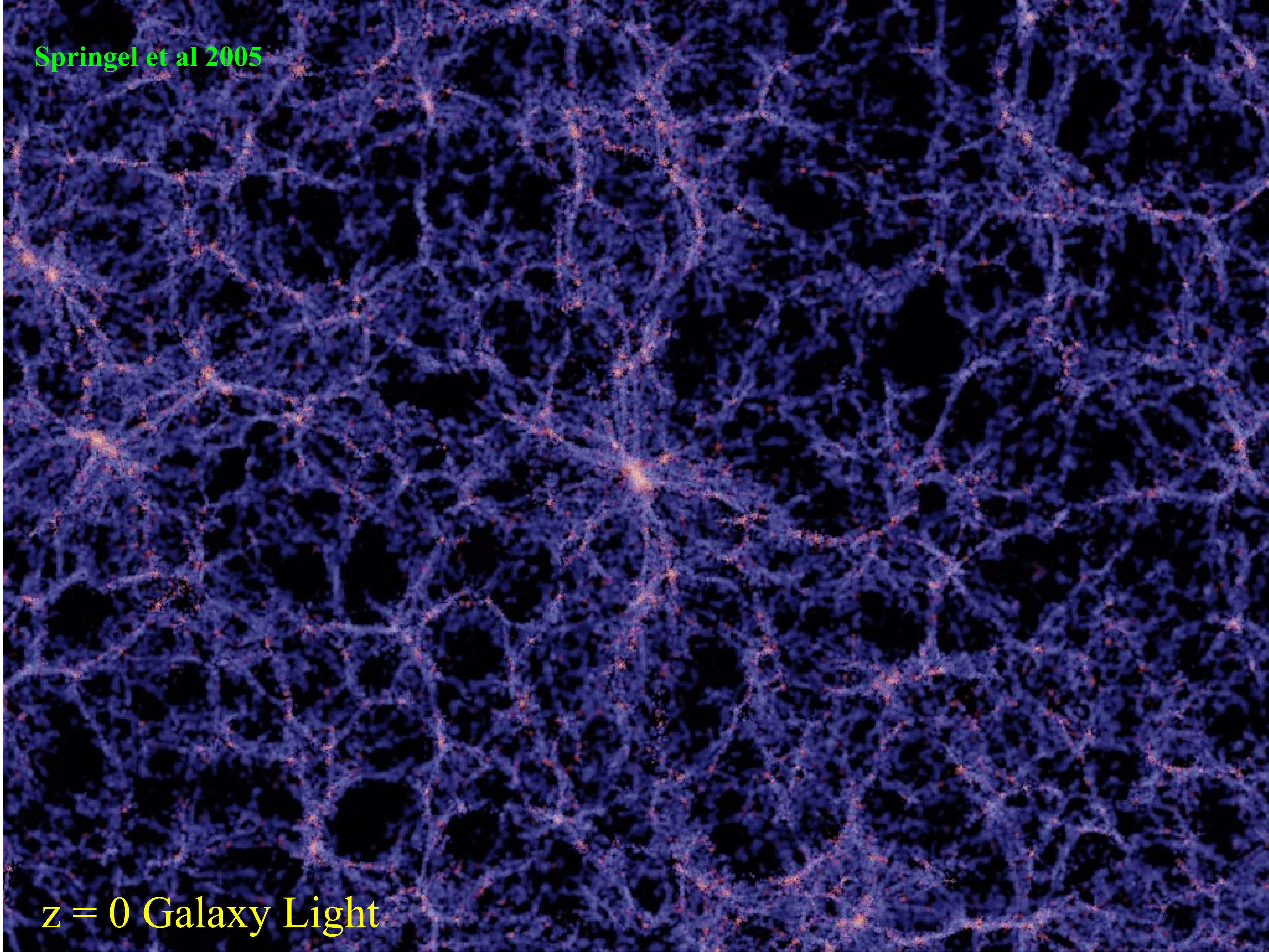
Input: N-body simulation with halos+subhalos, observed $\Phi(L)$
Fit data: Galaxy clustering at a given redshift
Output: Scatter in $L - M_{halo}$ relation, "best" estimator for M_{halo}

Semianalytic/Empirical Models (SAM)

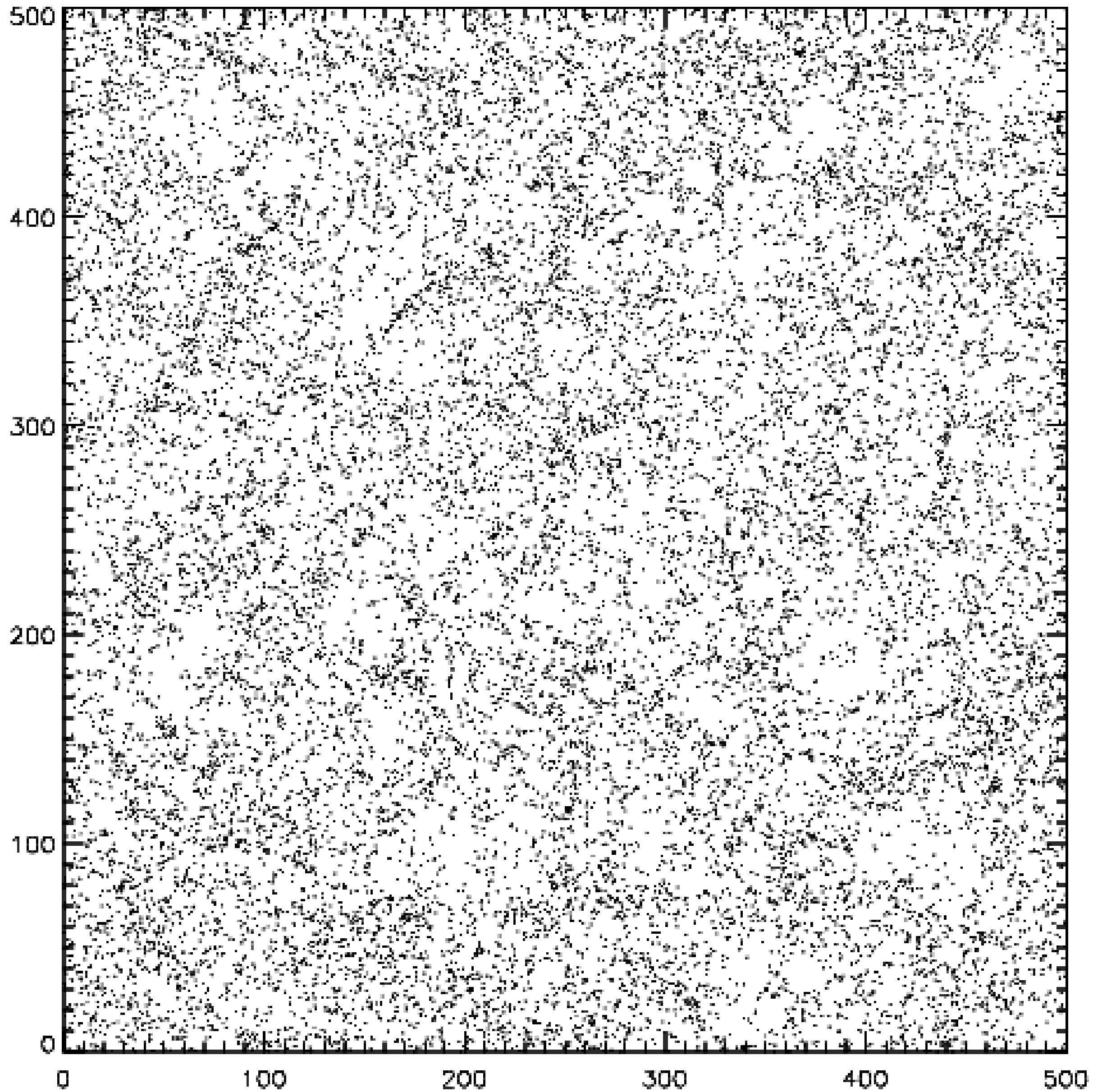
Input: N-body simulation with halos+subhalos+merger tree
Fit data: Galaxy abundances (and clustering) at multiple redshifts
Output: Parameters of physical/empirical galaxy formation model

Cosmological Hydrodynamical Simulations


Springel et al 2005
125 Mpc/h
z = 0   Dark Matter


Springel et al 2005
z = 0 Galaxy Light

Halo clustering depends on formation history



Gao, Springel & White 2005

The 20% of halos with the <u>*latest*</u> half-mass assembly redshifts in a 30 Mpc/h thick slice

$$M_{halo} \sim 10^{11} M_{\odot}$$

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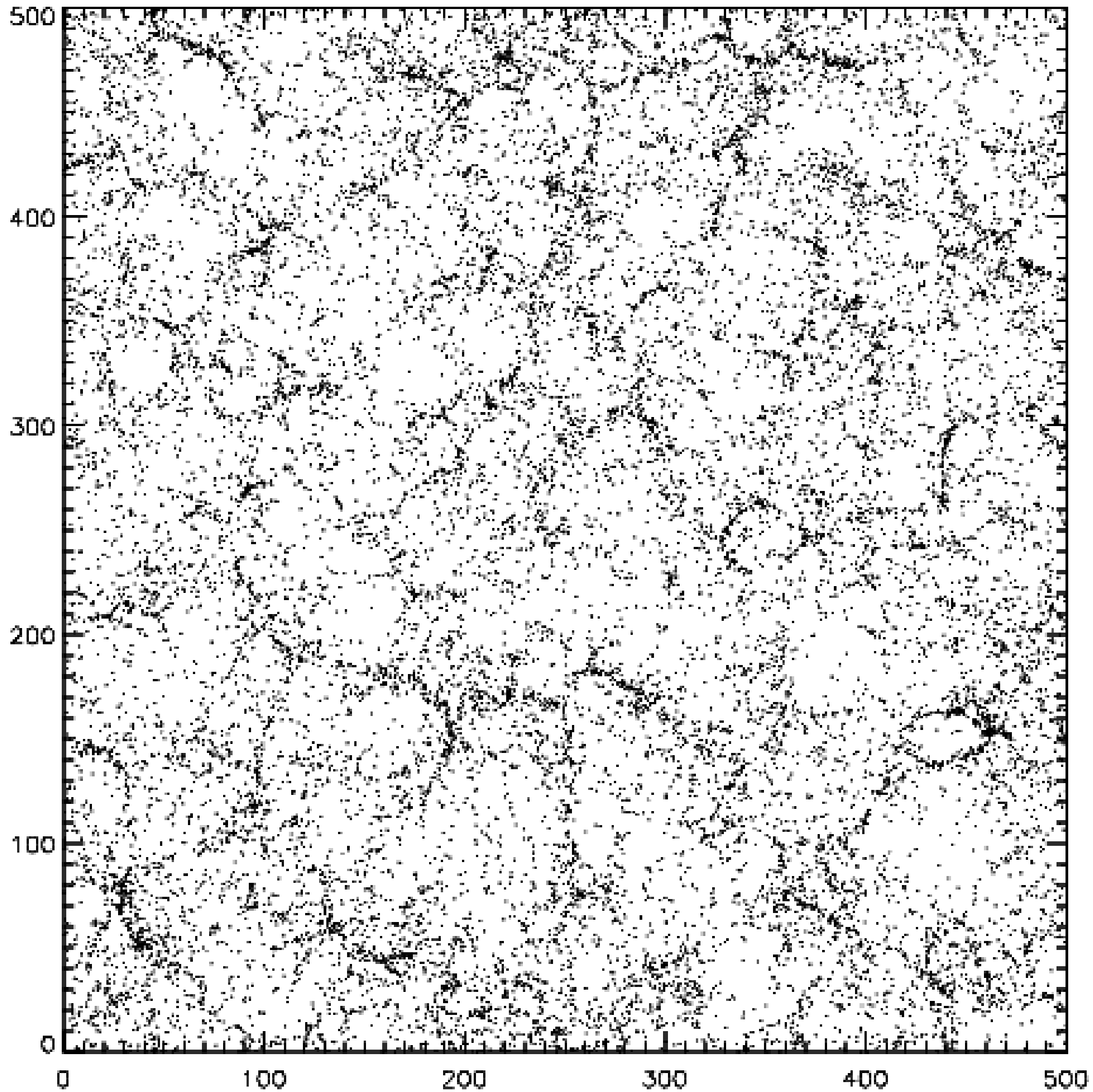
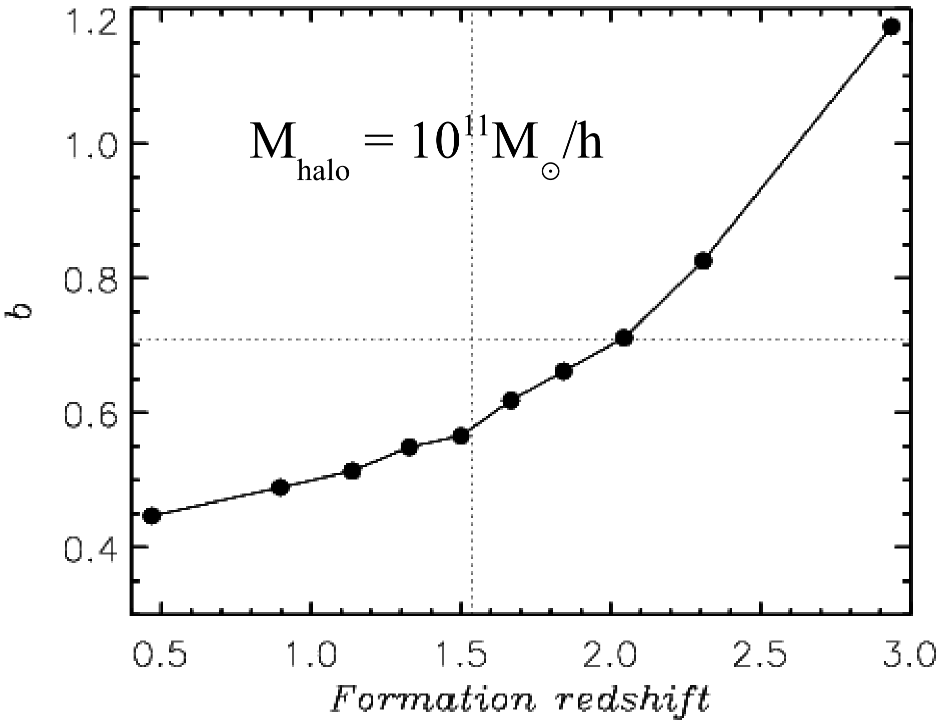


Gao, Springel & White 2005

The 20% of halos with the *earliest* half-mass assembly redshifts in a 30 Mpc/h thick slice

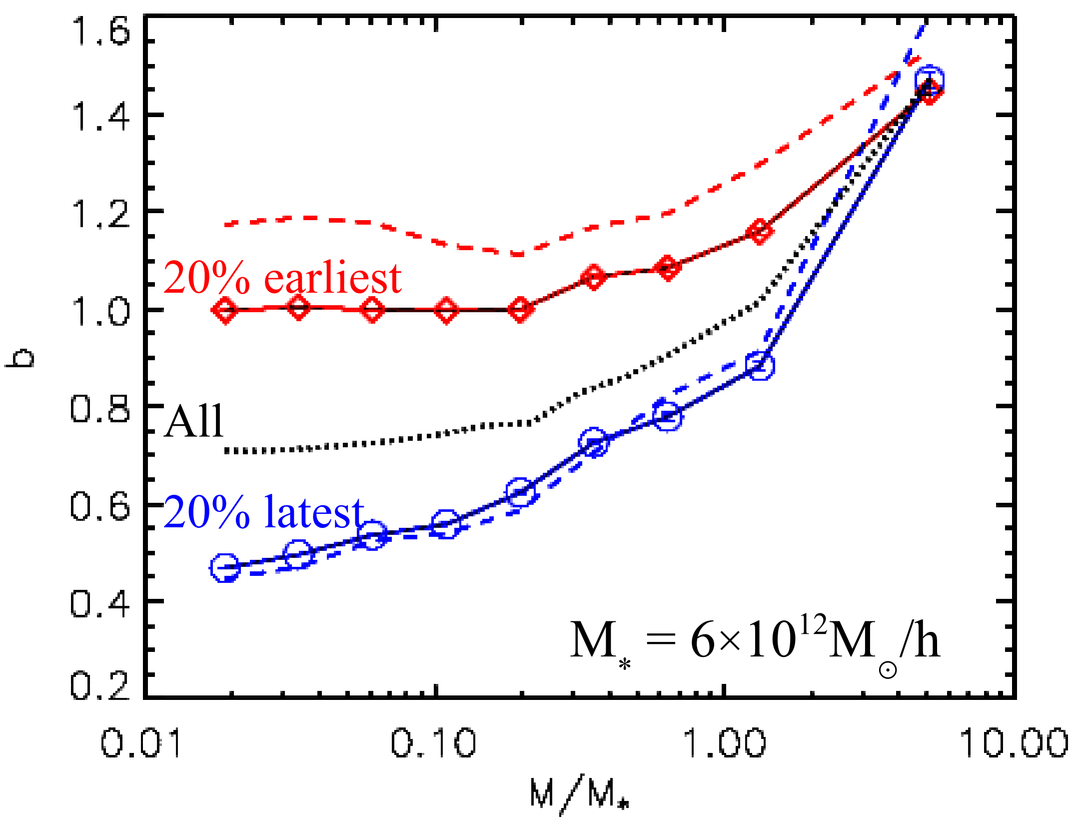
$$M_{halo} \sim 10^{11} M_{\odot}$$

Halo bias as a function of mass and formation time



Gao, Springel & White 2005

On large scales halo bias increases smoothly with formation redshift



The dependence of bias on formation redshift is strongest at low mass

This behaviour is inconsistent with simple versions of excursion set theory, and of HOD and halo abundance matching models

Halo assembly bias: conclusions

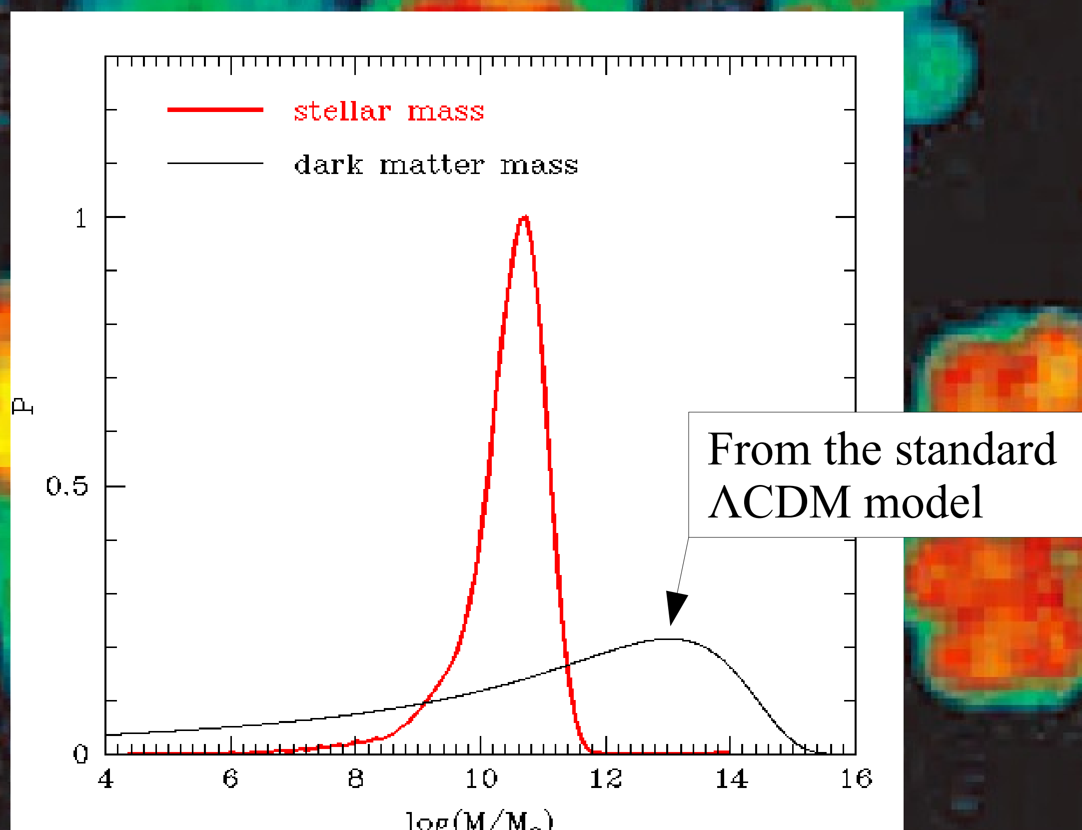
The large-scale bias of halo clustering depends not only on halo mass through $\nu = \delta_c / D(z)\, \sigma_o(M)$, but <u>also</u> on

- formation time
- concentration
- substructure content
- spin
- shape
- velocity anisotropy

The dependences on different assembly variables are different and <u>cannot</u> be derived from each other: $b = b(\mathrm{M}, \underline{\mathbf{A}})$ with $\underline{\mathbf{A}}$ multi-dimensional.

These dependences are likely to be reflected in <u>galaxy</u> bias

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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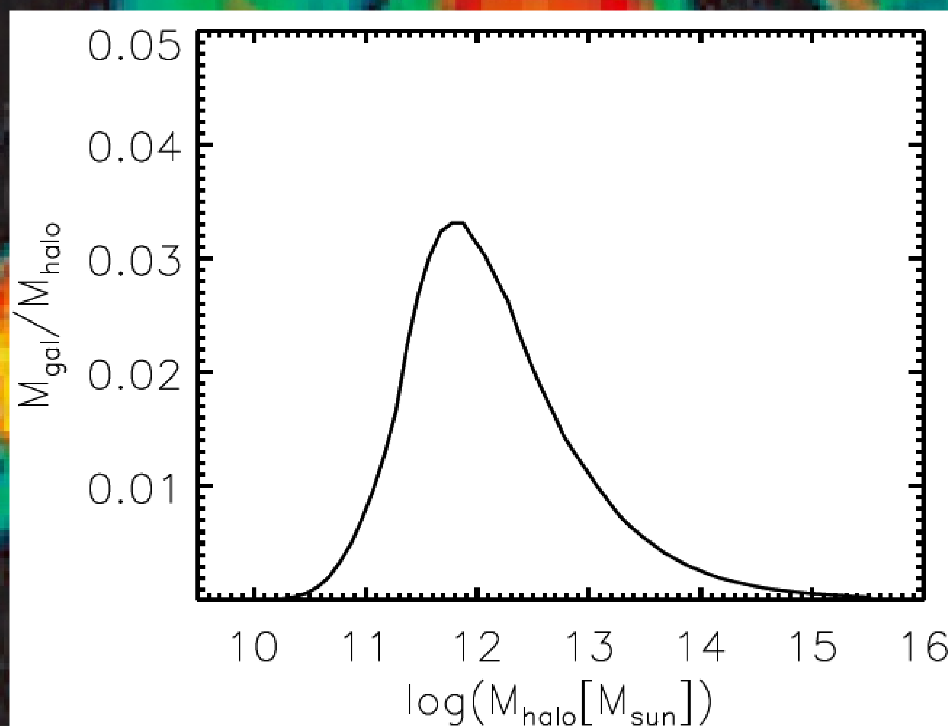

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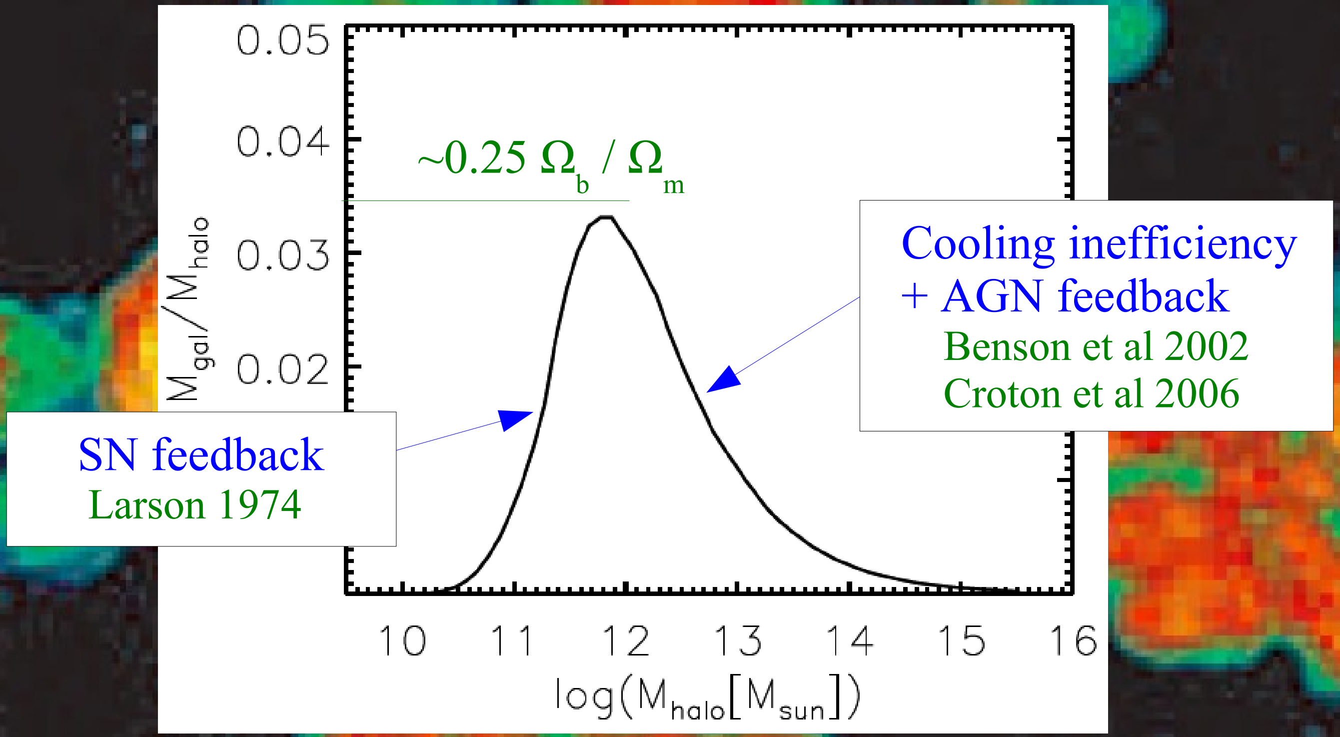
Star formation efficiency is reduced at both low *and* high halo mass



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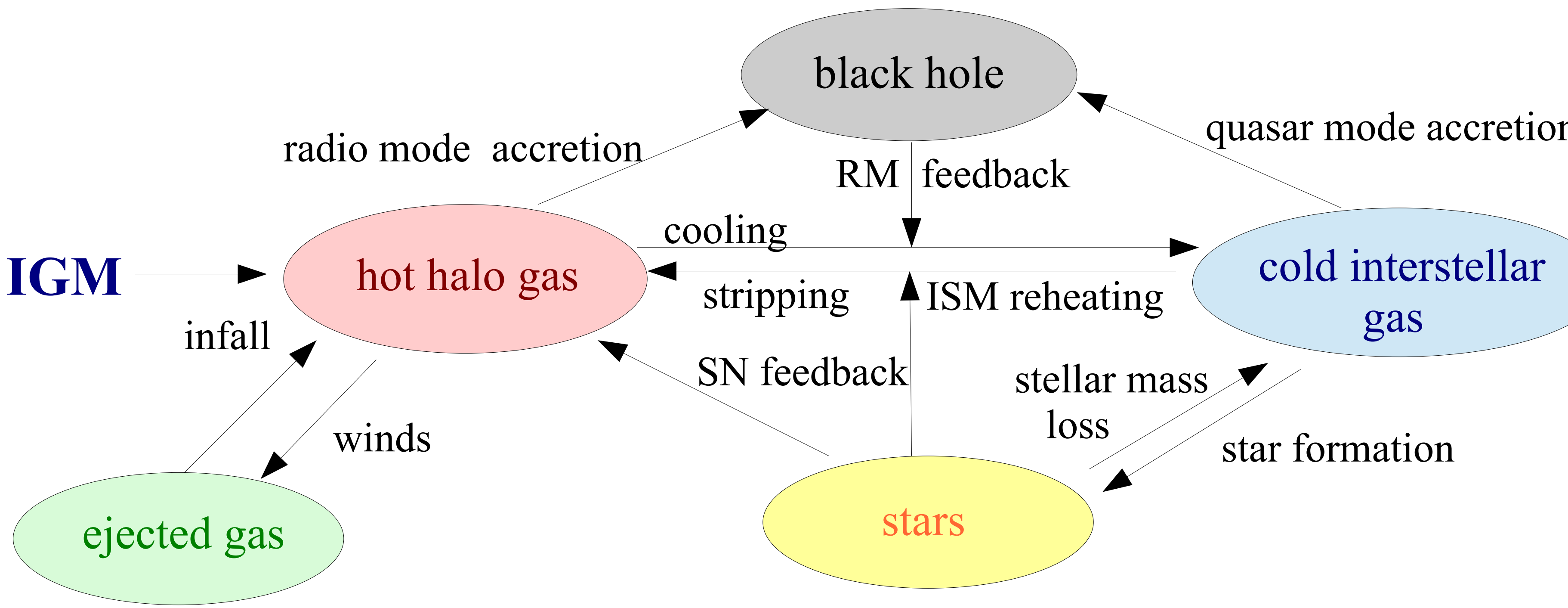
$$(\Omega_b / \Omega_m) M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$



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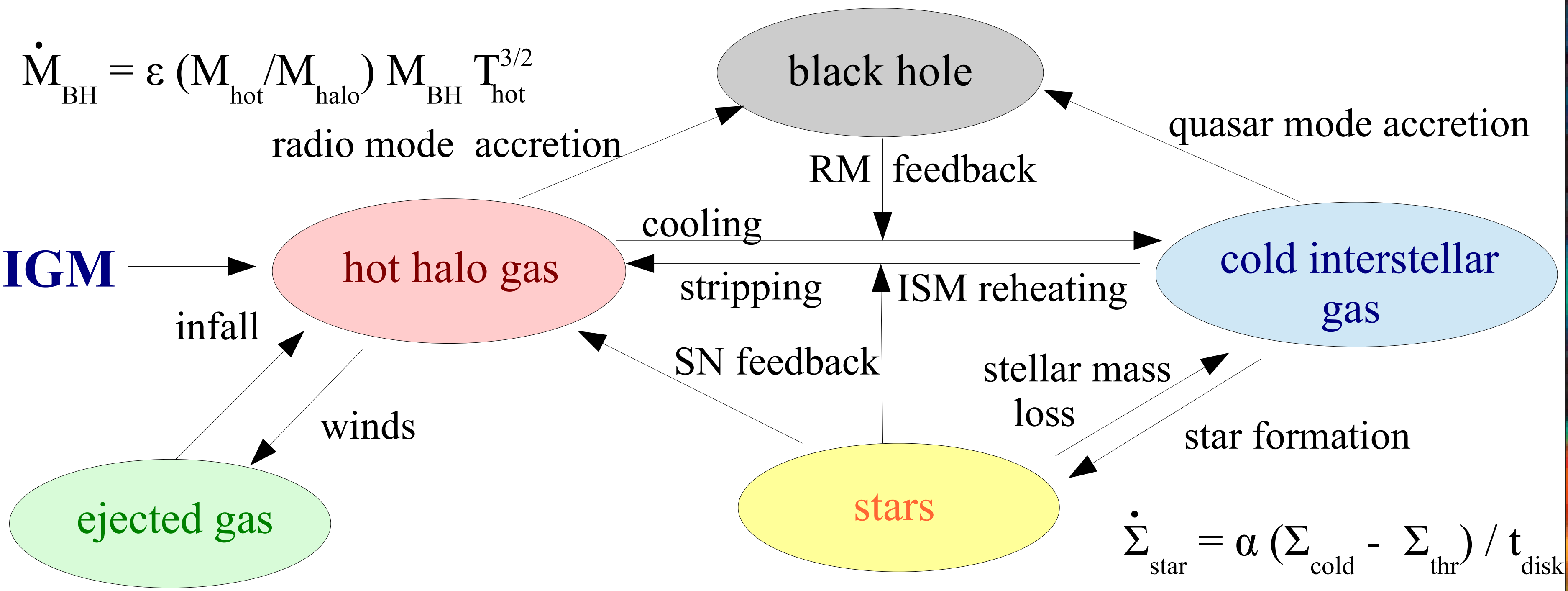
$$(\Omega_b / \Omega_m)\, M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$

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



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

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

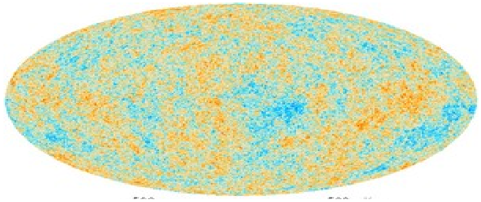
Star formation within these central galaxies

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

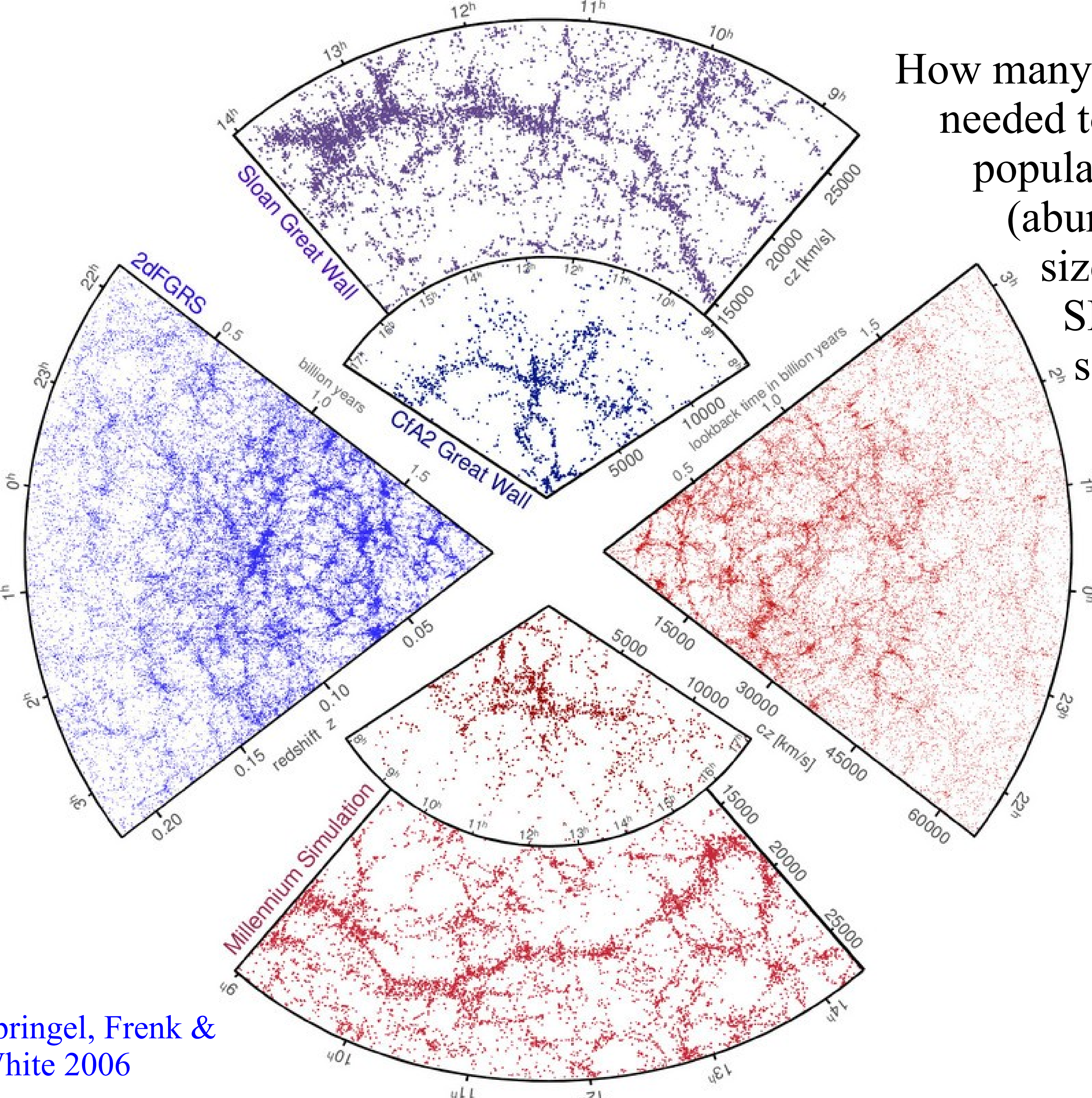
e.g.  → Ω

Six parameters fine-tuned to fit three curves

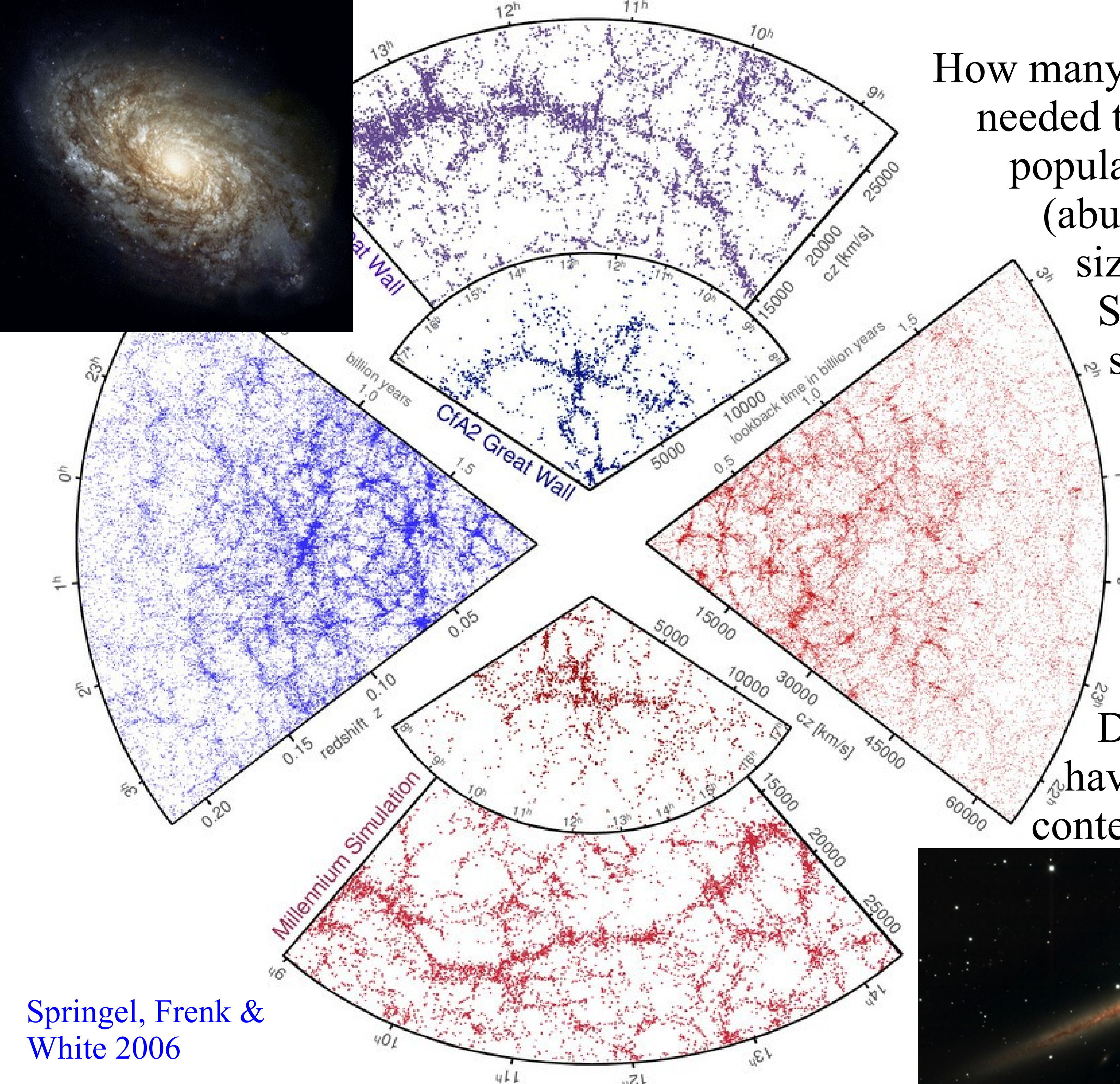
	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

How many parameters are needed to fit the galaxy population?

(abundance by mass, size, gas content, SFR, B/T, AGN; scaling relations; clustering; evolution...)



Springel, Frenk & White 2006



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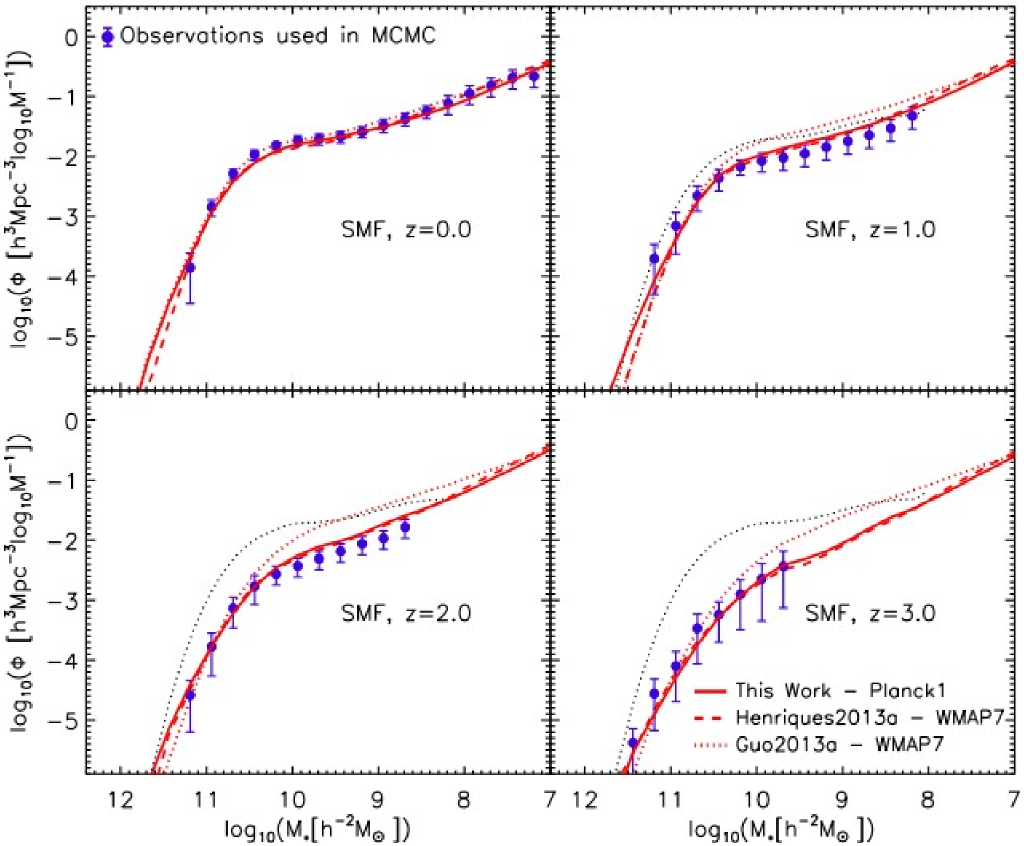
(abundance by mass, size, gas content, SFR, B/T, AGN; scaling relations; clustering; evolution...)

Do the parameters have useful *physical* content?

Springel, Frenk & White 2006

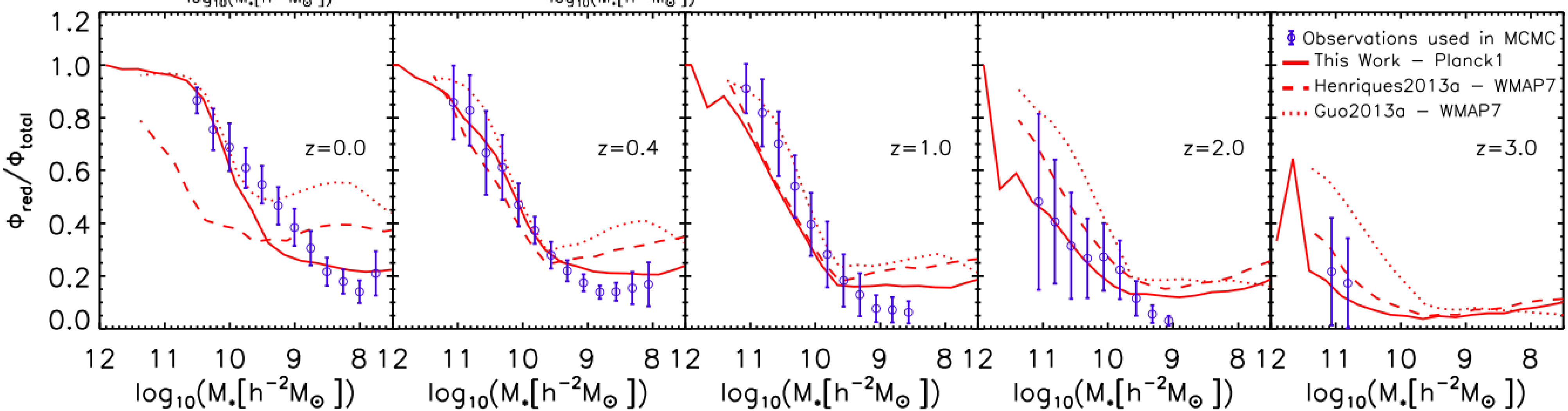
Calibrating models for (sub)halo occupation



Henriques et al (2015)

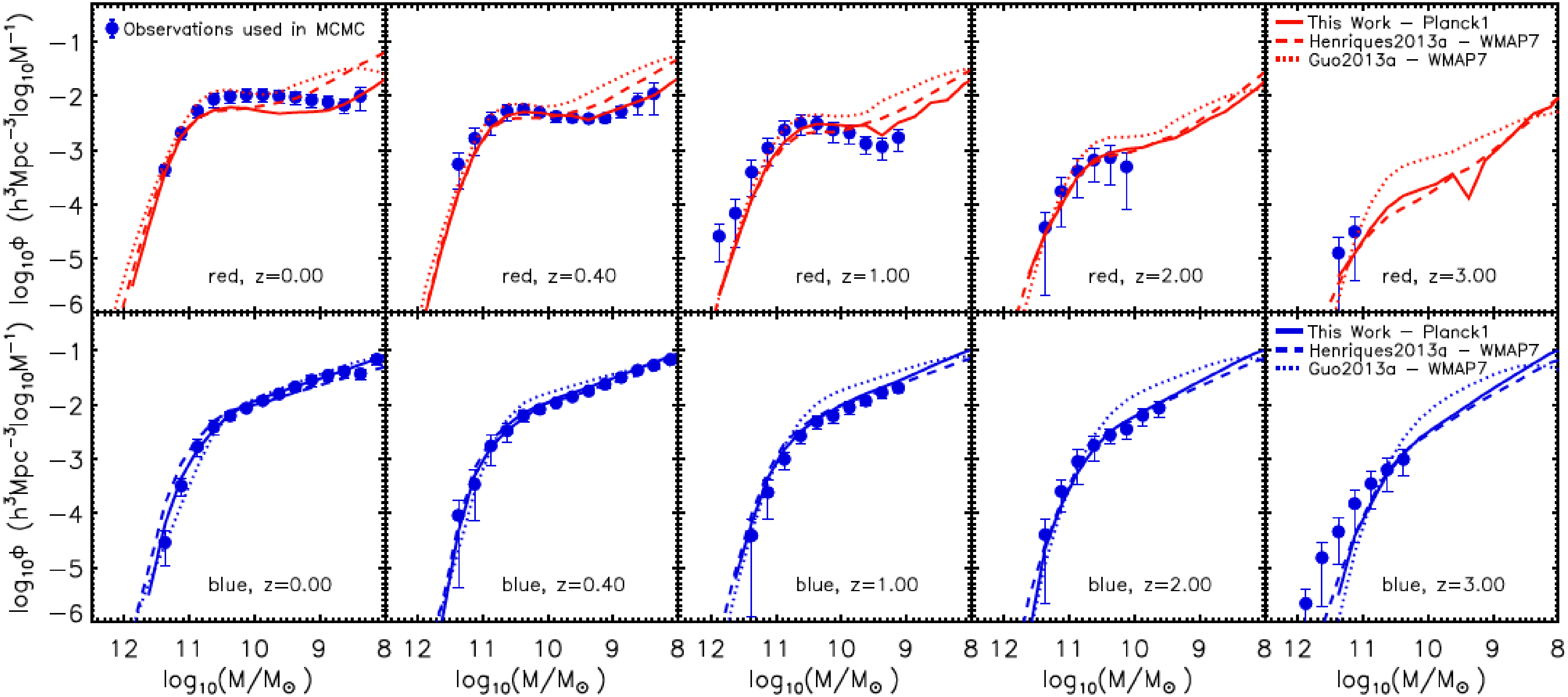
The 17 parameters of the SA subhalo occupation model constrained by MF and passive fraction observations over $0 \leq z \leq 3$ and three orders of magnitude in stellar mass

The MCMC chains show all parameters to be determined to moderate accuracy with no major degeneracies



Testing semianalytic simulations

Henriques et al 2015, Planck cosmology



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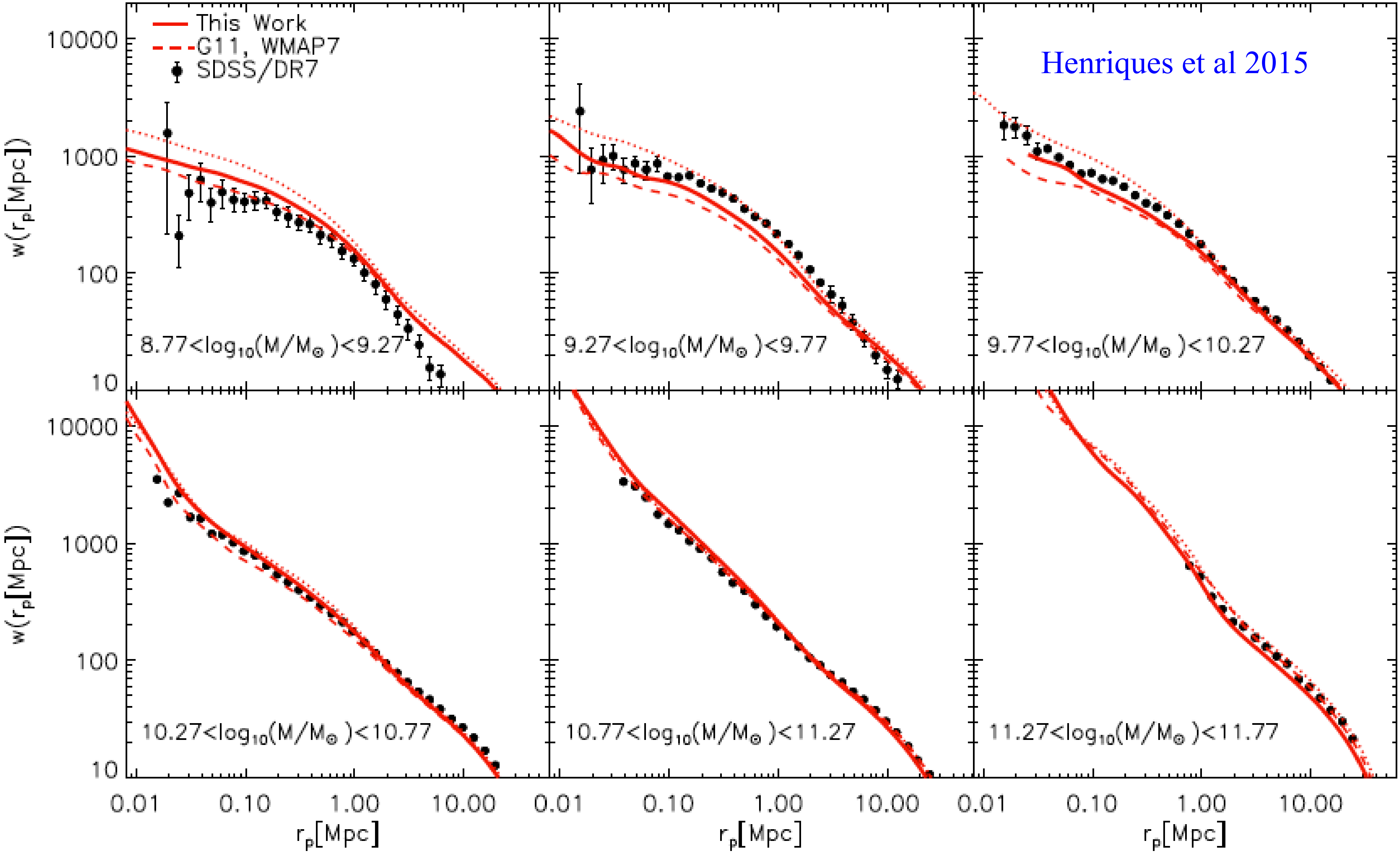

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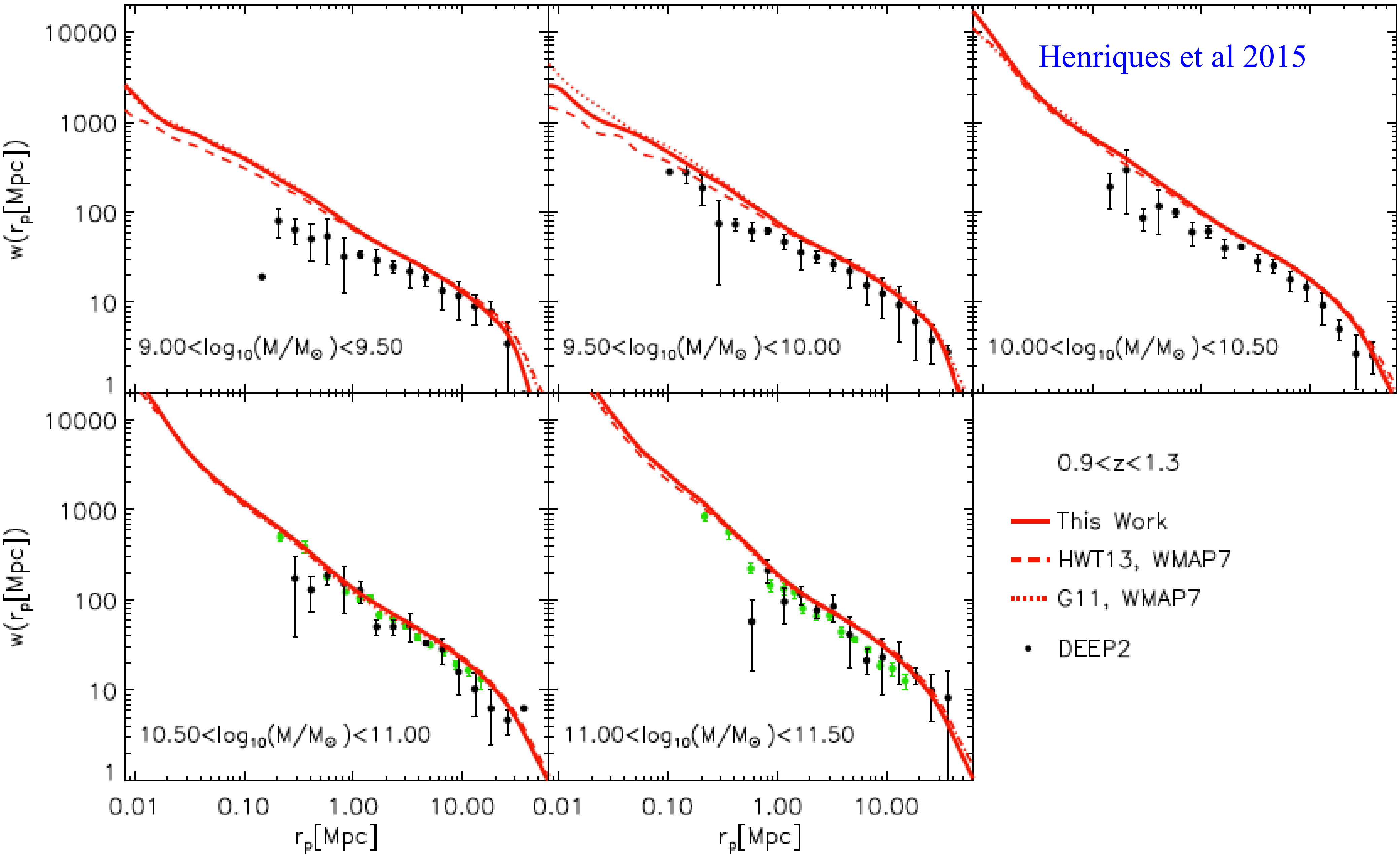
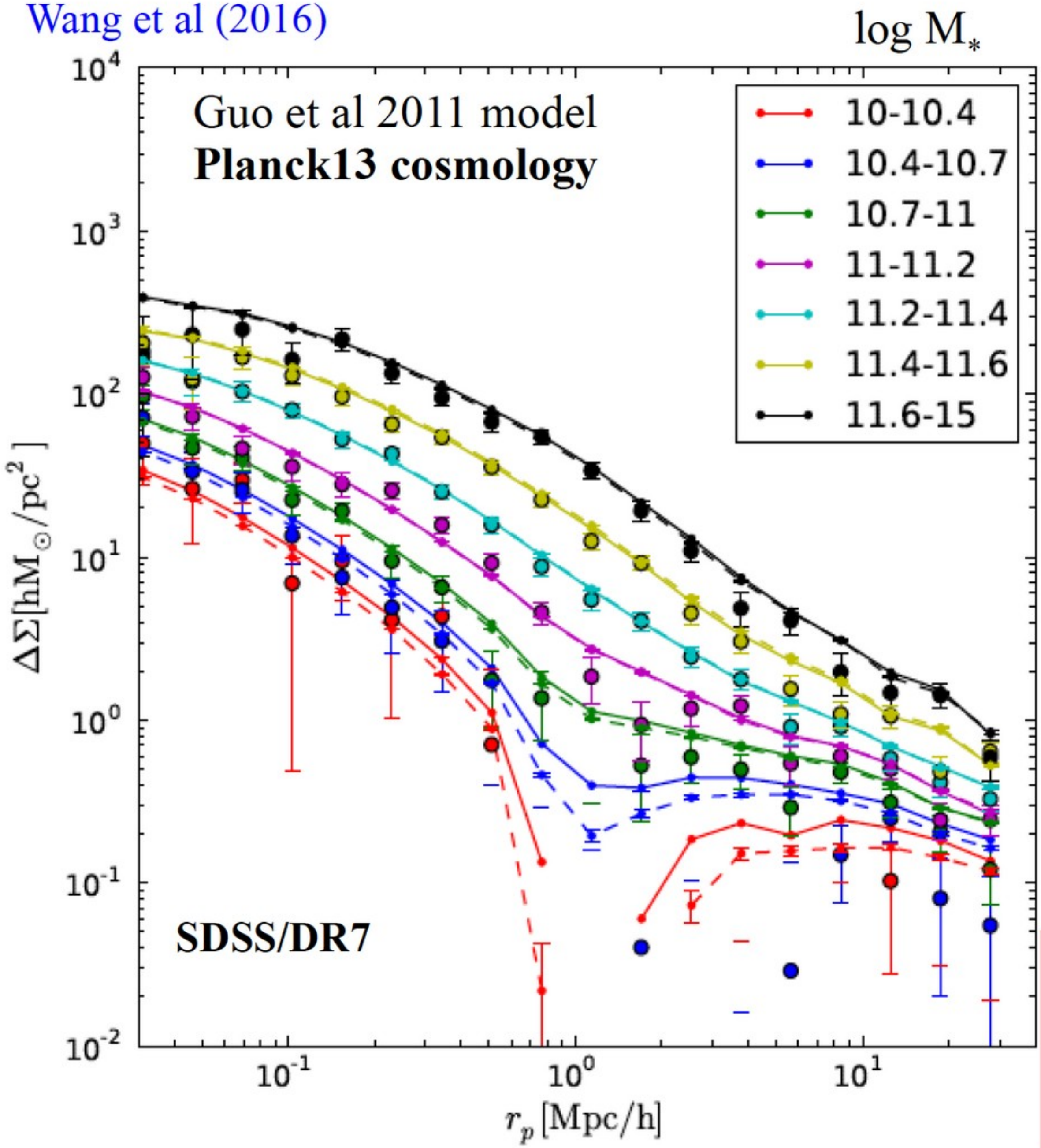


Testing semianalytic simulations

Wang et al (2016)



The points are measured mass profiles around the central galaxies of galaxy groups

Top to bottom goes from rich galaxy clusters to poor groups

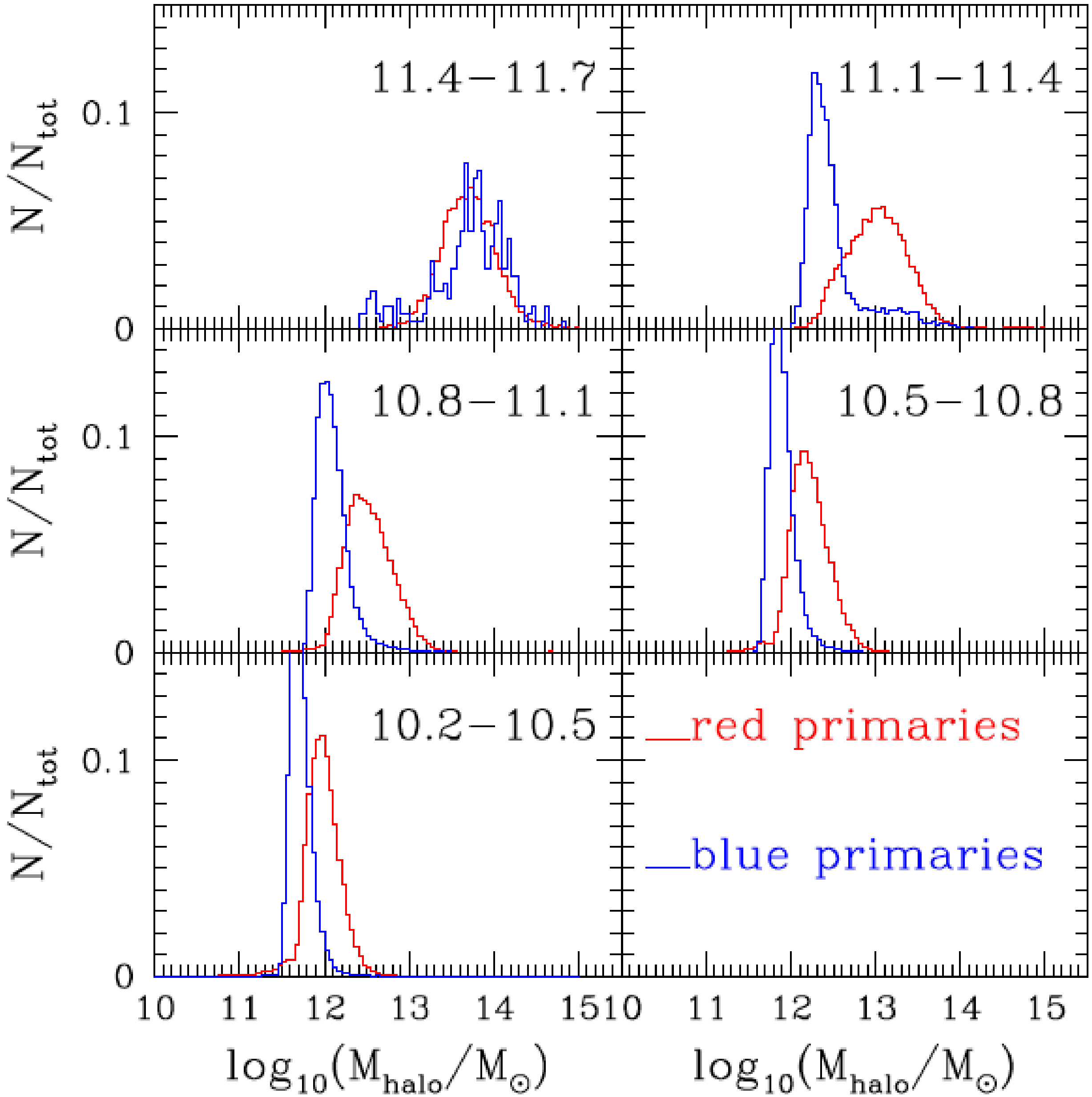
The lines are the predicted mass profiles about such groups in the Millennium Simulation

Parameters were fit using galaxy *abundances* only. **No** parameters adjusted to fit clustering

The simulation matches the mass distribution around galaxies even in regions where no light is seen!

A population simulation prediction for galaxy halos

Wang & White 2012



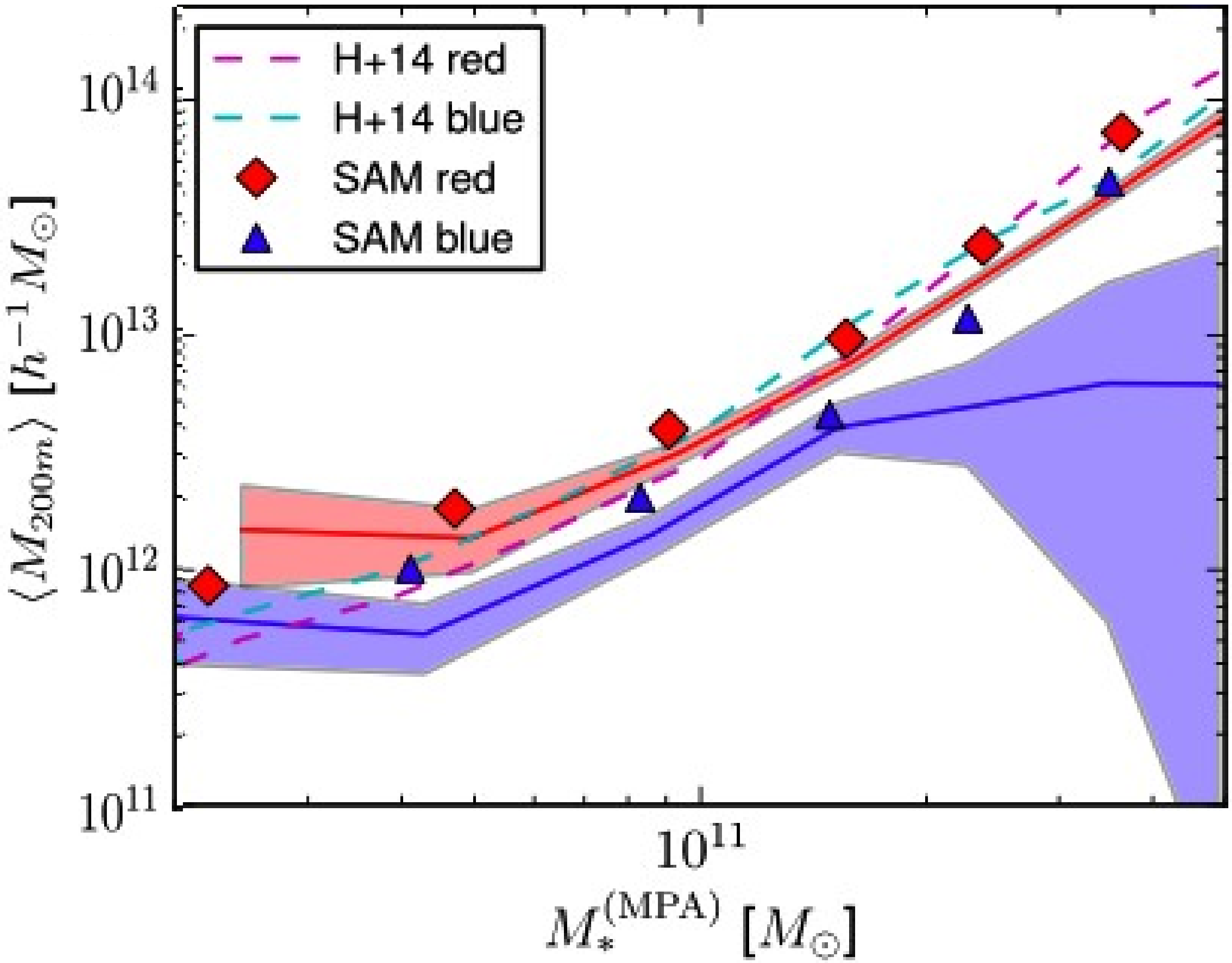
Central galaxies of a given stellar mass are predicted to have larger halo masses if they are red (passive) than if they are blue (star-forming)

This is because central galaxies stop growing after quenching but their halos do not

This effect is **not** present (by construction) in age+abundance SHAM models

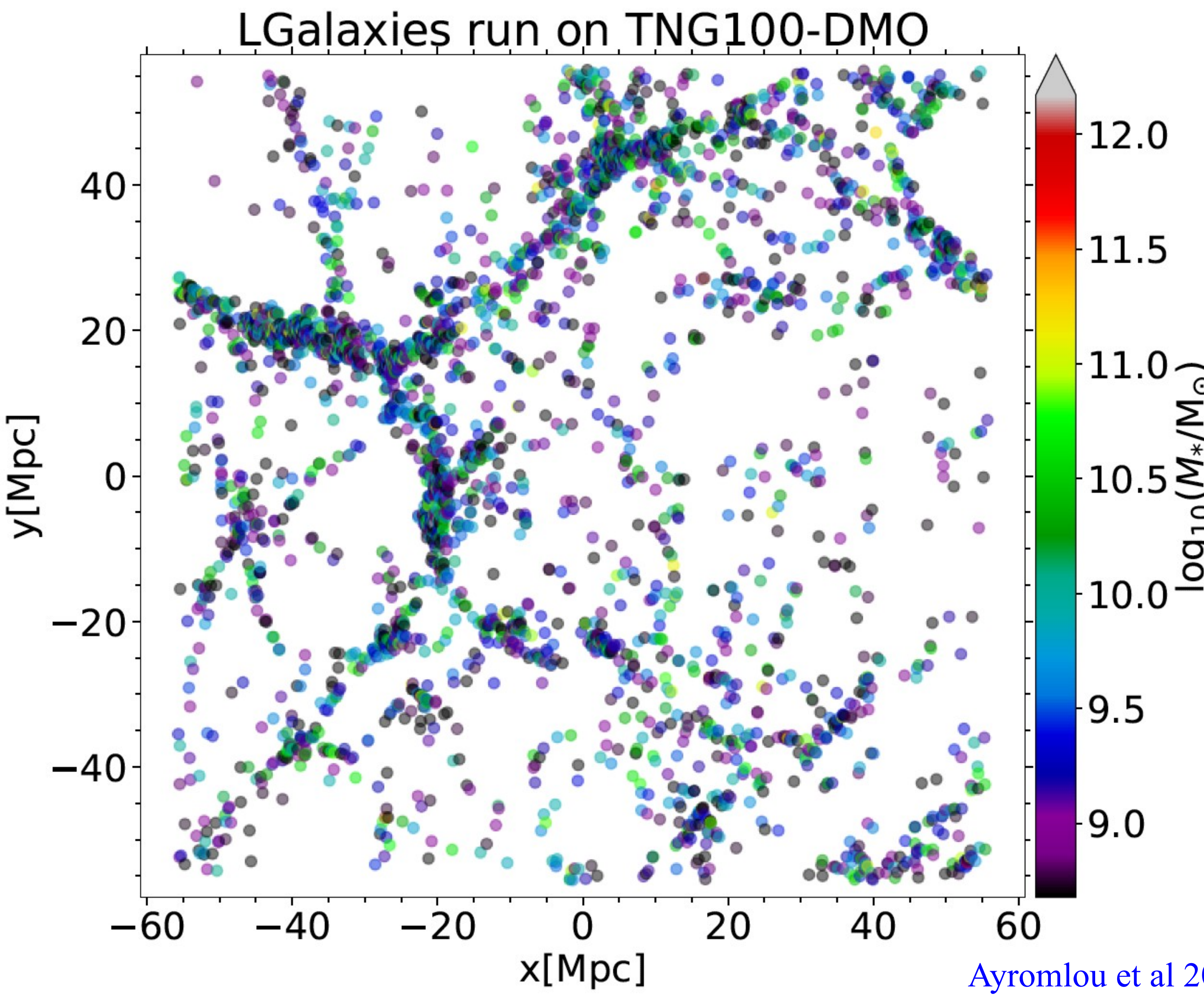
Halo mass dependence on central galaxy colour?

Mandelbaum et al 2016



Blue centrals have lower mass halos than red centrals of the same stellar mass according to estimates based on the motions of satellites and on weak gravitational lensing

Semianalytic versus full MHD simulations



Ayromlou et al 2021

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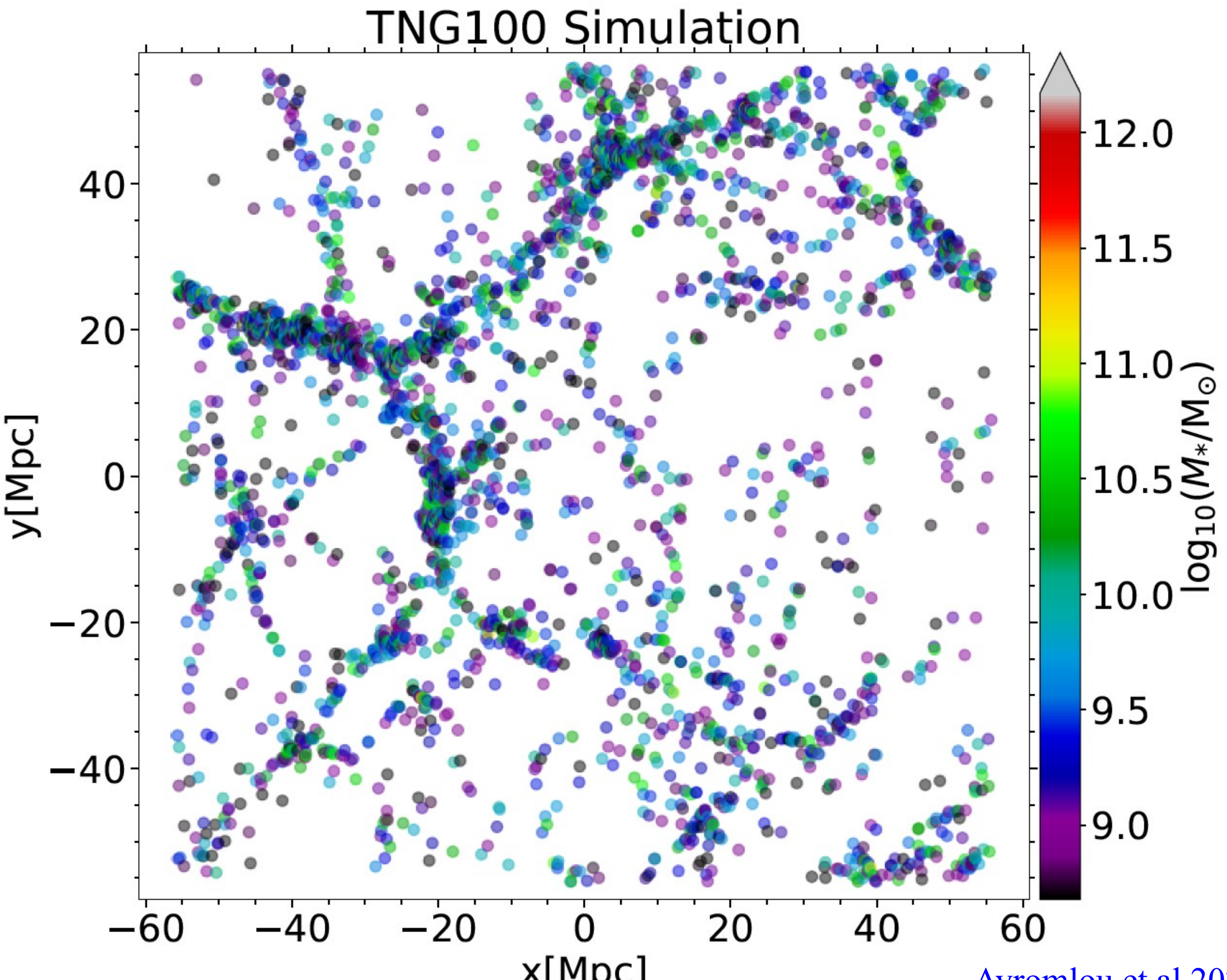
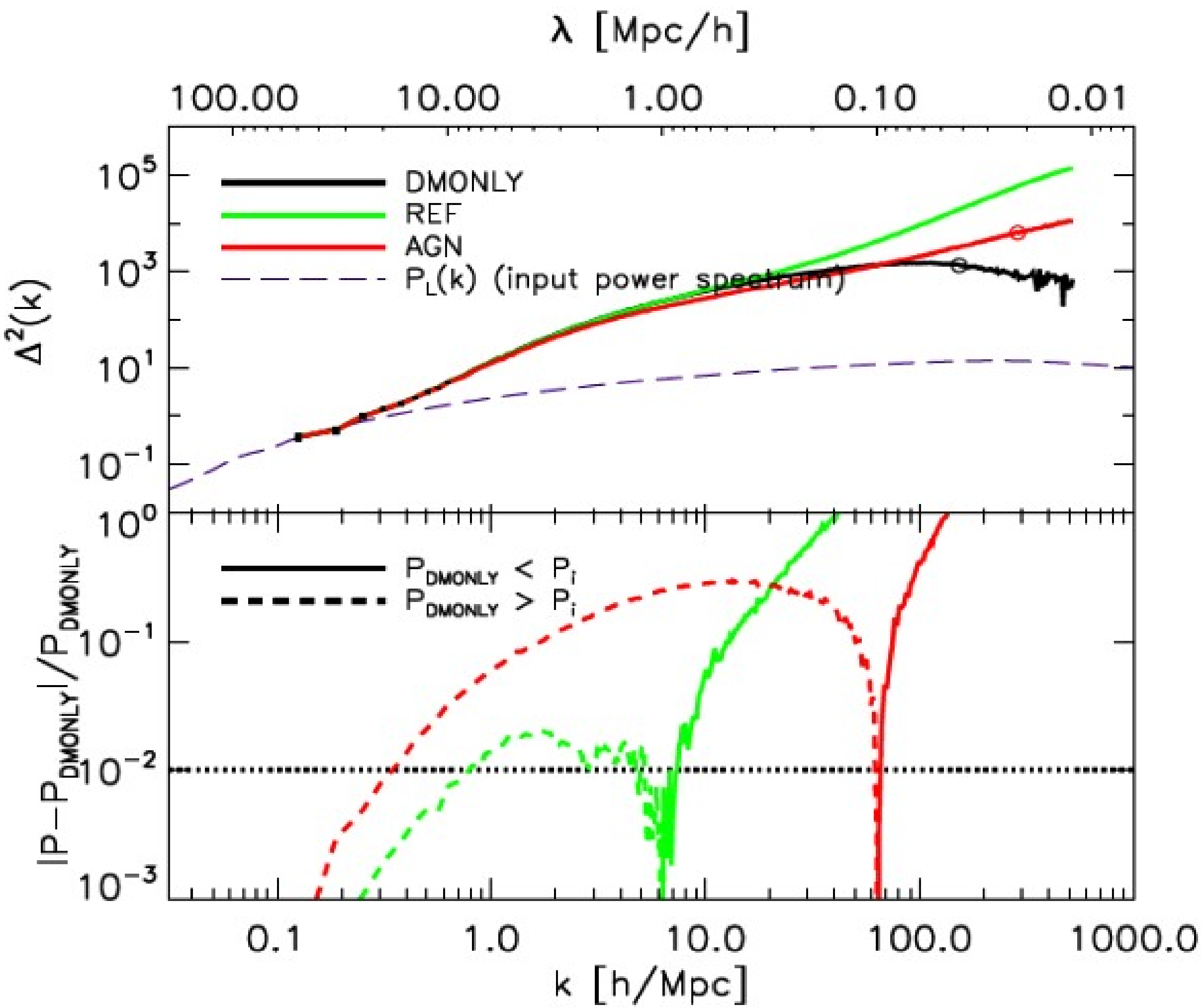


Ayromlou et al 2021

Mass distribution dependence on baryon physics



AGN feedback sufficient to match the stellar mass function of galaxies at high mass affects the power spectrum of the total mass distribution at > 1% for k > 0.3 h/Mpc

This will affect the small-scale lensing power spectrum.

van Daalen et al 2011

In summary...

Precision cosmology with galaxy surveys requires the relation between the galaxy and dark matter distributions to be known precisely

- Halo clustering depends at the 10 to 30% level on many aspects of halo structure and formation history in addition to halo mass
- This complexity carries over to the galaxy population and affects both the spatial and kinematic (peculiar velocity) properties
- Different galaxy types can have BAO features of different shape
- Halo mass depends on both colour and mass of the central galaxy
- Baryon physics can affect the lensing P(k) down to k ~ 0.3 h/Mpc

All these effects depend on the details of galaxy formation physics

None is easily included in the HOD or SHAM modelling frameworks

Galaxy formation is an insoluble problem

Galaxy formation is an insoluble problem
or
Galaxy formation is a solved problem

Galaxy formation is an insoluble problem
or
Galaxy formation is a solved problem

- Galaxies form as gas cools and condenses at the centres of a population of massive halos growing by gravitational amplification of fluctuations in an initially near-uniform distribution of pre-existing dark matter

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Semi-analytic and Subhalo Abundance Matching models assume this and tune a physically based (SAM) or purely statistical (SHAM) relation between galaxy properties and subhalo history to fit observation.

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Subhalo Abundance Matching and Semi-analytic models assume this and tune a more (SAM) or less (SHAM) complicated relation between galaxy properties and subhalo history to fit observation.

Main outstanding issues are:

I. The dependence of the survival of satellite subhalos on resolution, integration accuracy, and baryon effects – the "orphan" problem

II. The number of properties of subhalo histories needed to predict their galaxy content to the required precision – the "assembly bias" problem

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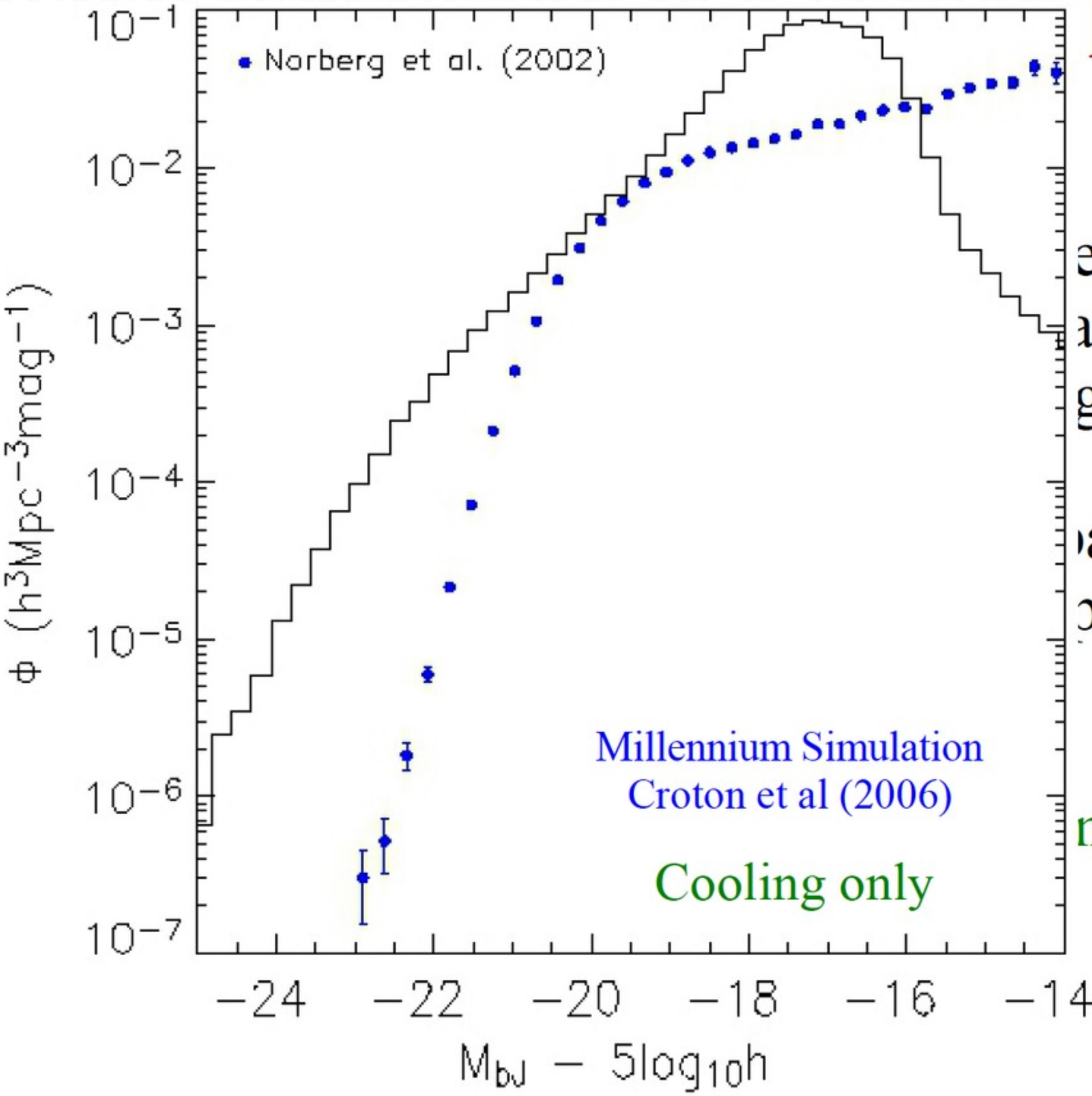
At low mass: Reionization heating; Star-formation-driven winds
At high mass: Inefficient cooling; AGN feedback

Galaxy formation is an insoluble problem
or
G… problem



- Galaxies f… es of a population of massive ha… ation of fluctuations in an initia… g dark matter

- The effici… back that is most effective a… physical processes are require…

At low ma… n winds
At high ma…

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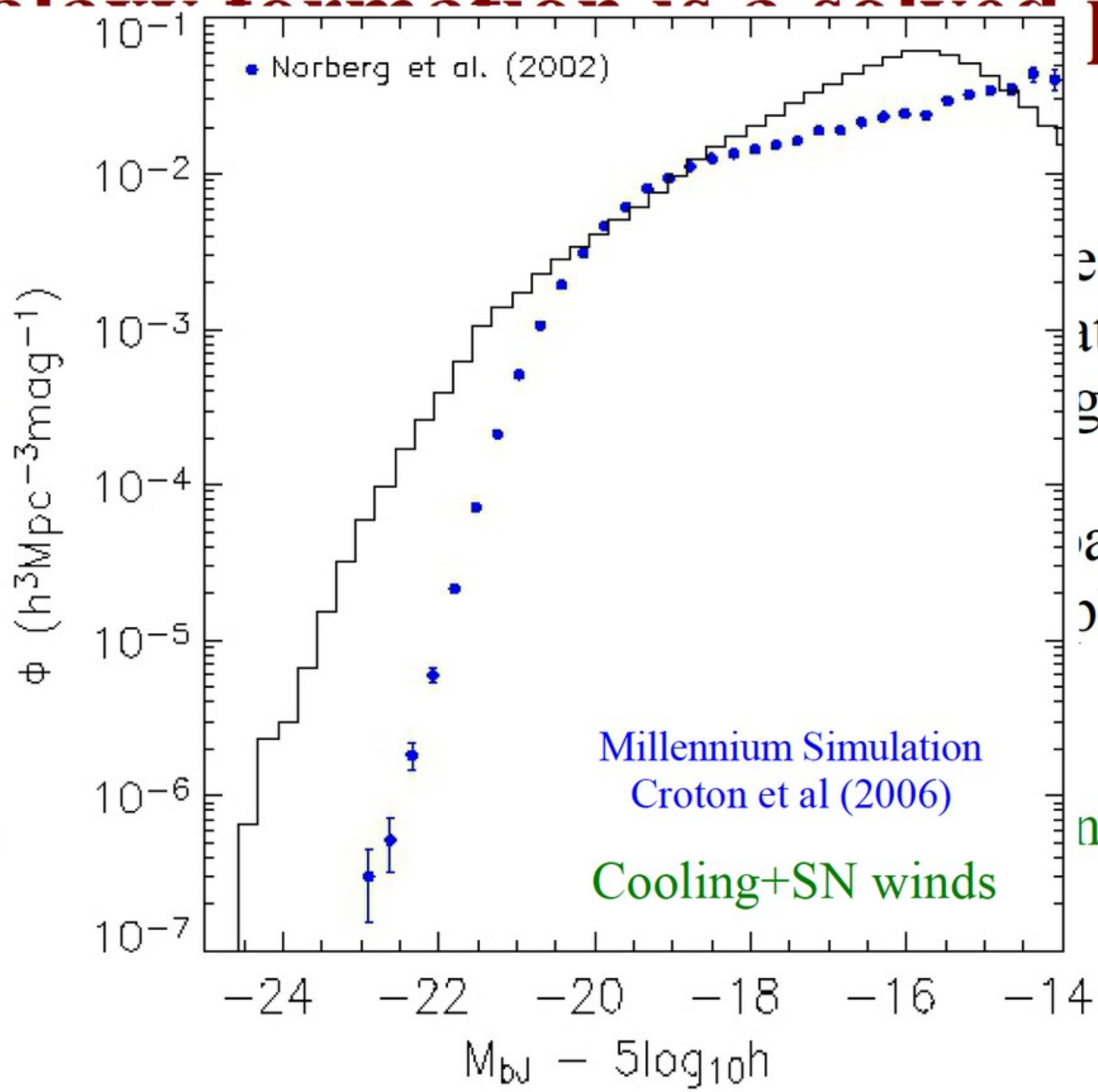

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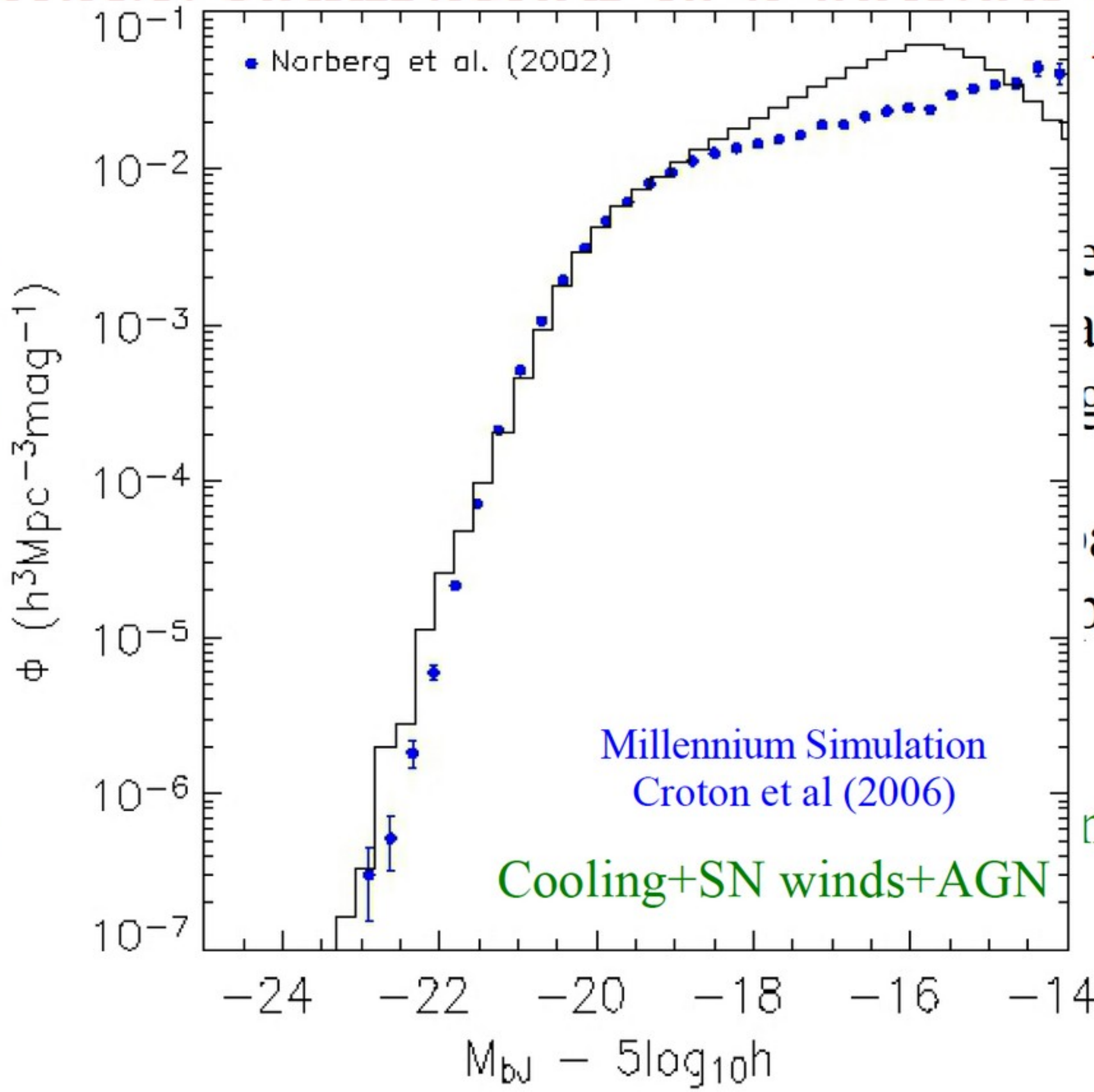
or
G… problem



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At low ma… …n winds
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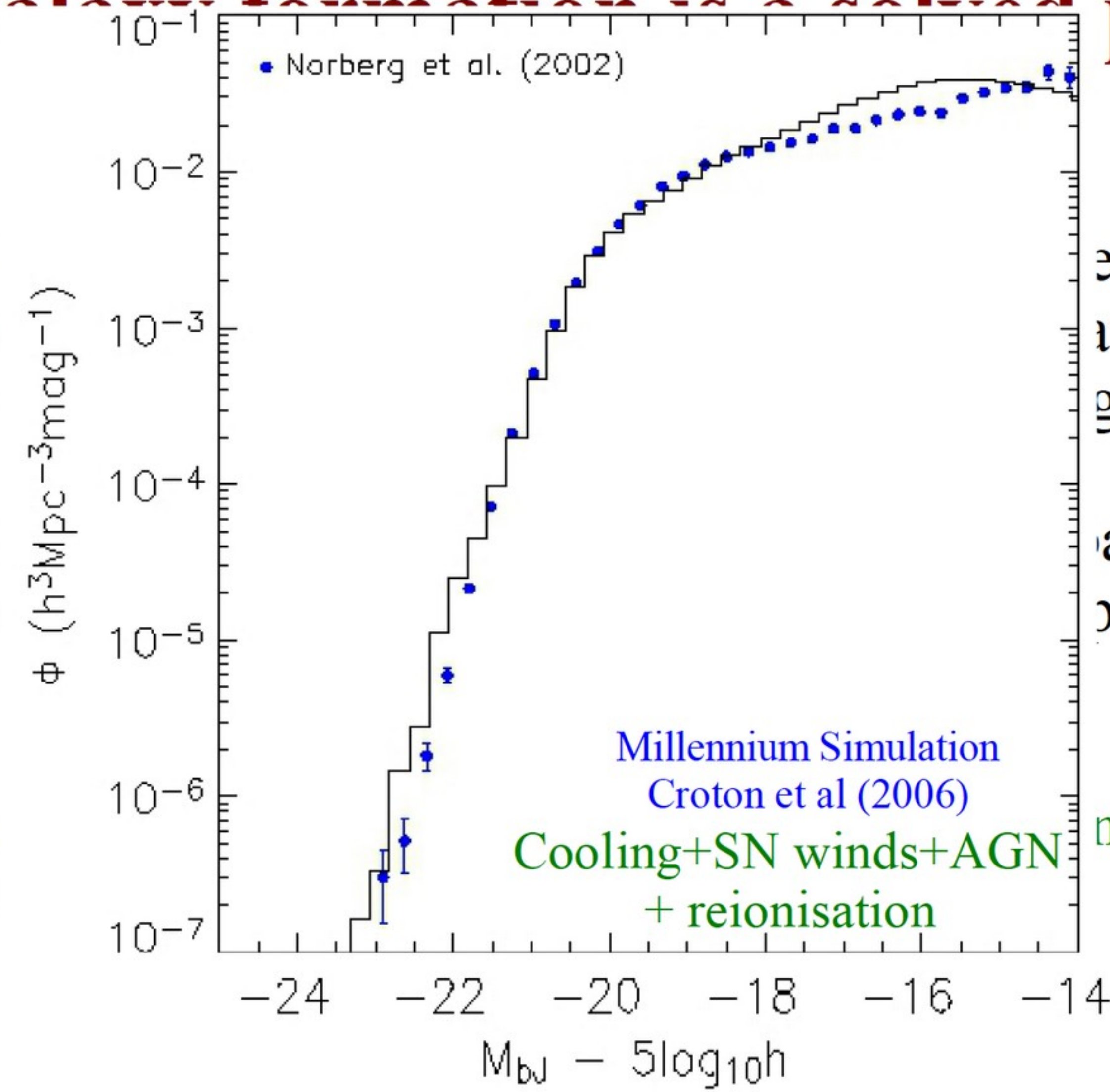

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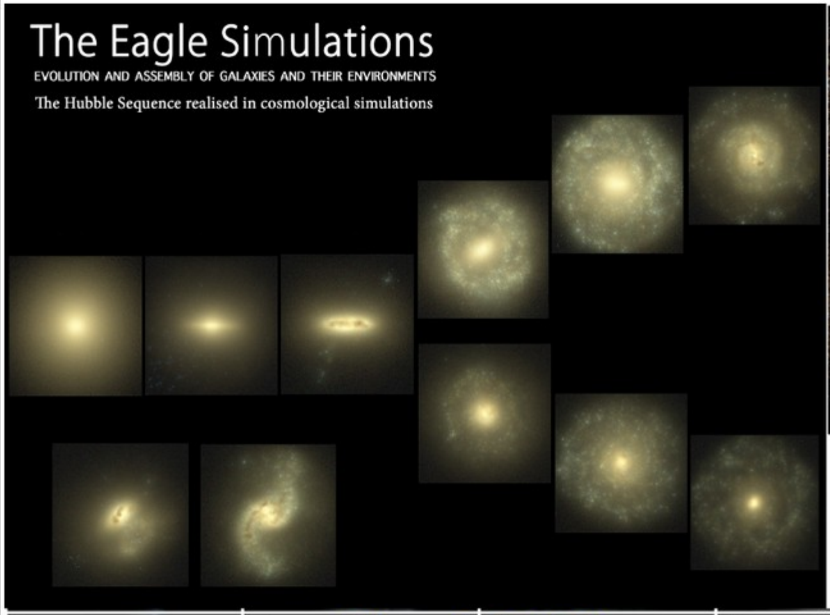
Galaxy formation is a solved problem

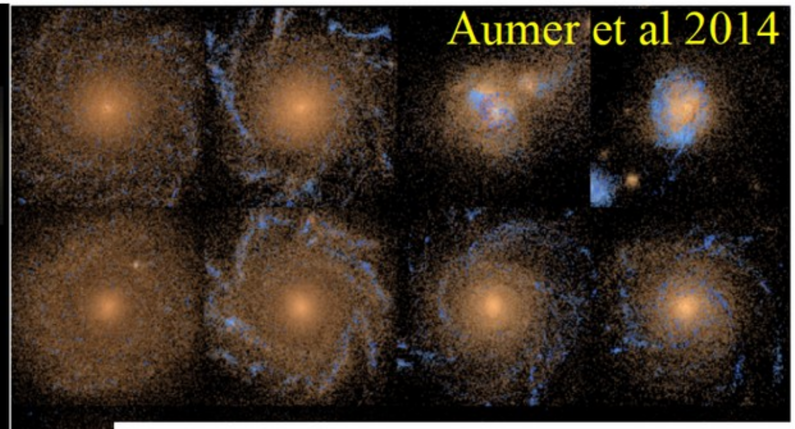
- Galaxies form as gas cools and condenses at the centres of a population of massive halos as these grow by gravitational amplification of fluctuations in an initially near-uniform distribution of pre-existing dark matter

- The efficiency of galaxy formation is limited by feedback that is most effective at low and at high halo mass. Different astrophysical processes are required in the two cases.

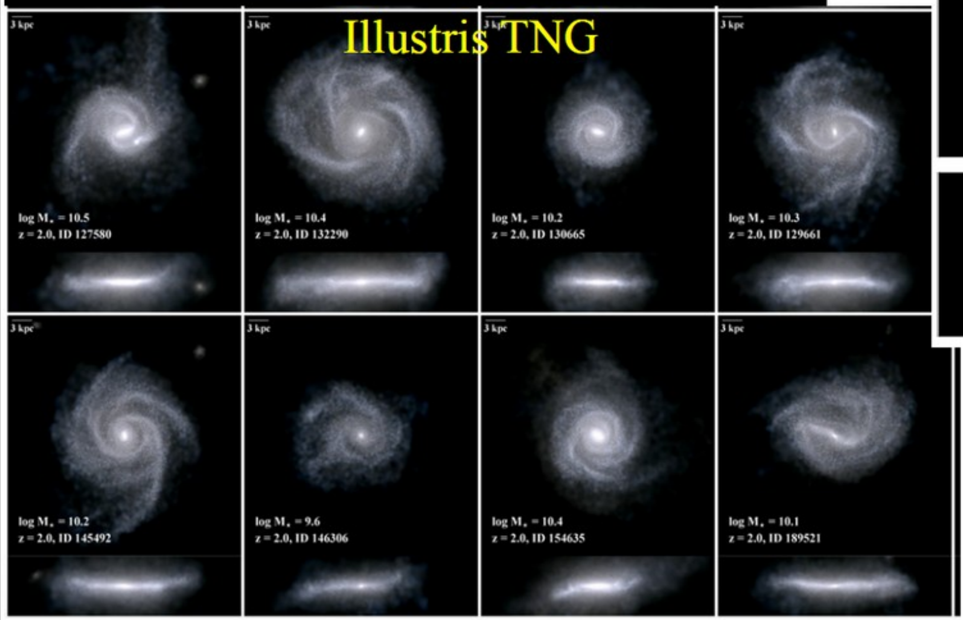
At low mass: Reionization heating; Star-formation-driven winds
At high mass: Inefficient cooling; AGN feedback

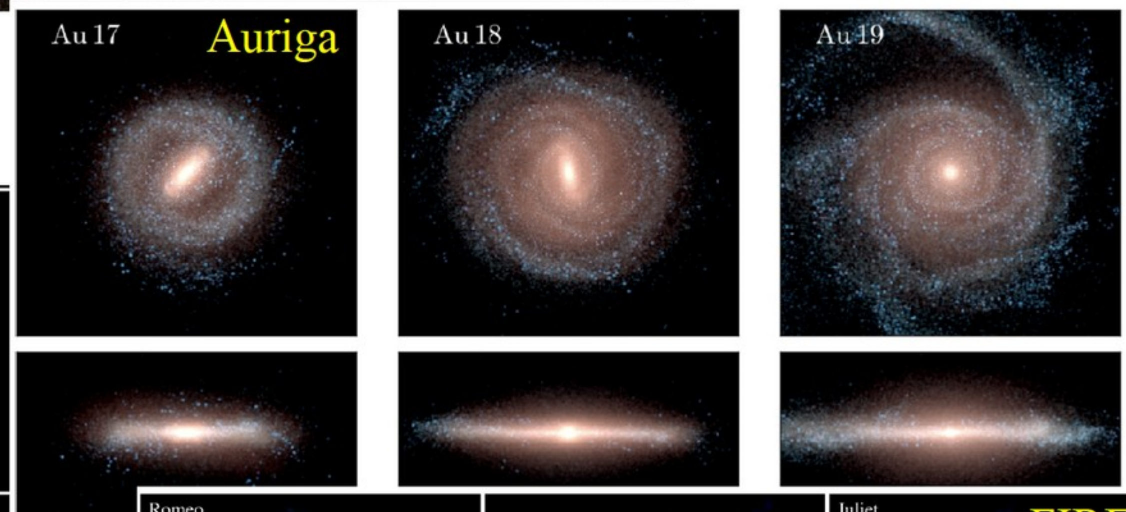
Main outstanding issues:
I. Mechanical/radiative feedback, B-fields/cosmic rays, ejection/recycling
II. Can "subgrid" processes be sufficiently well/uniquely characterised?

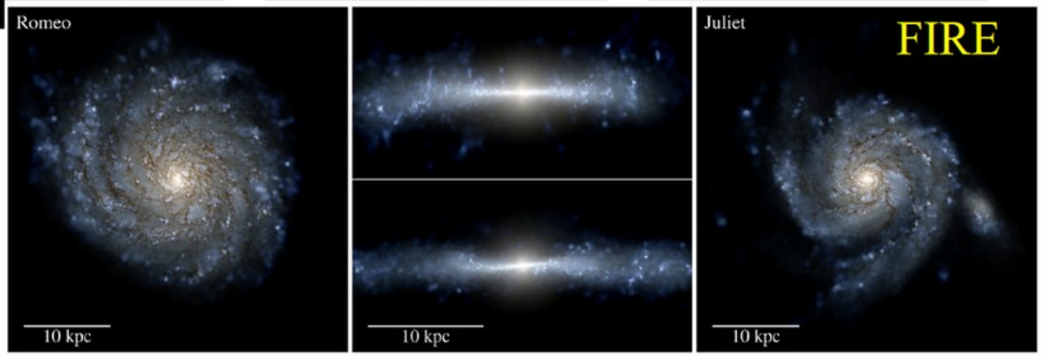




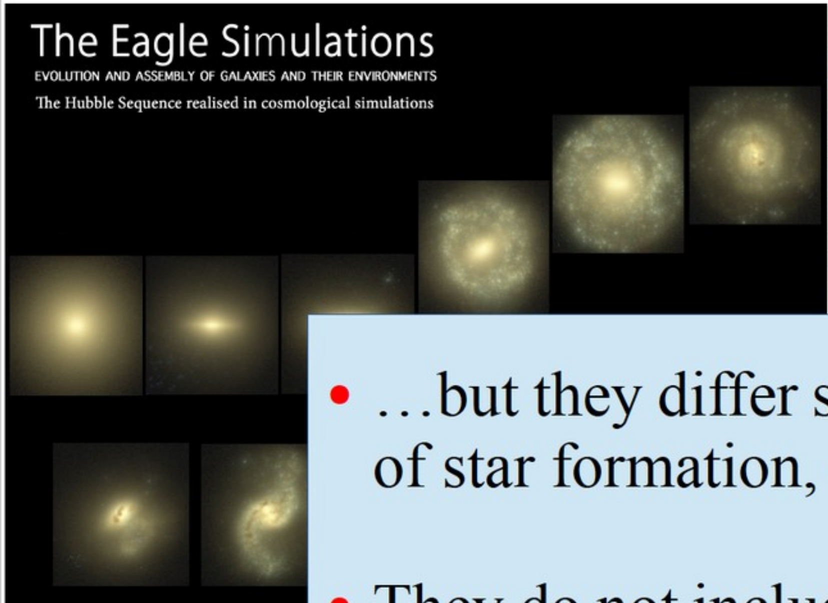
Simulating the structure of galaxies

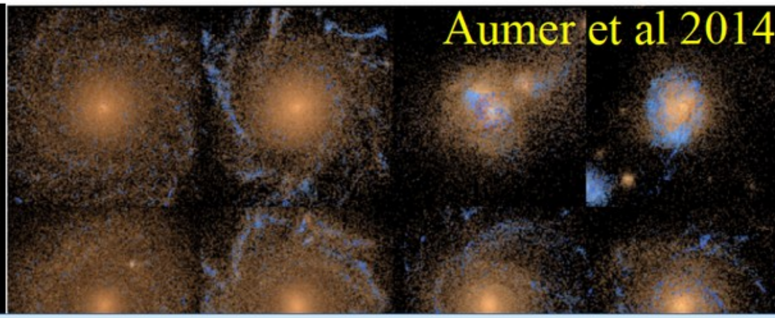






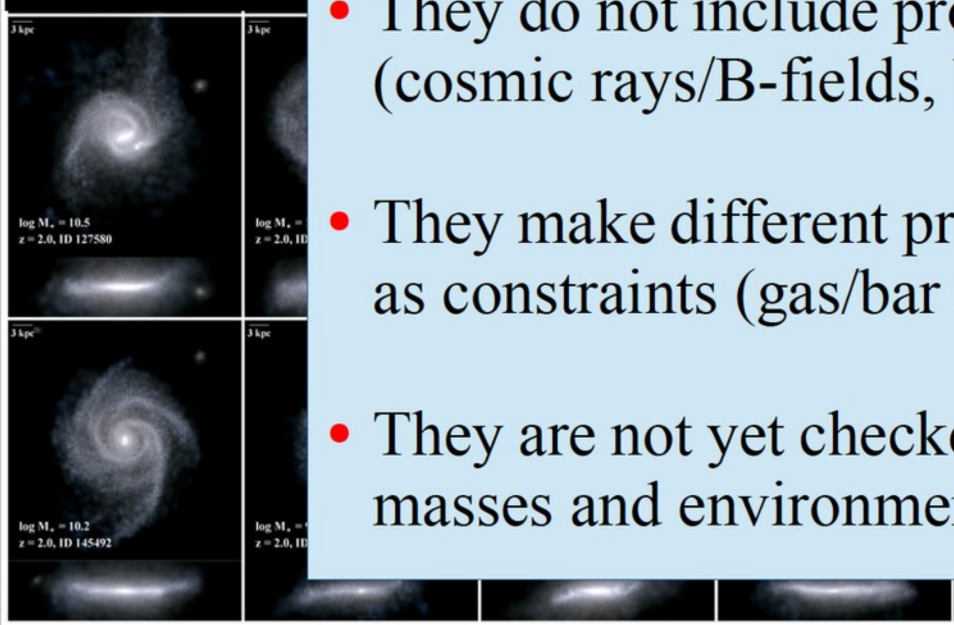
Recent cosmological (magneto)hydrodynamical simulations reproduce many aspects of the observed internal structure of galaxies....

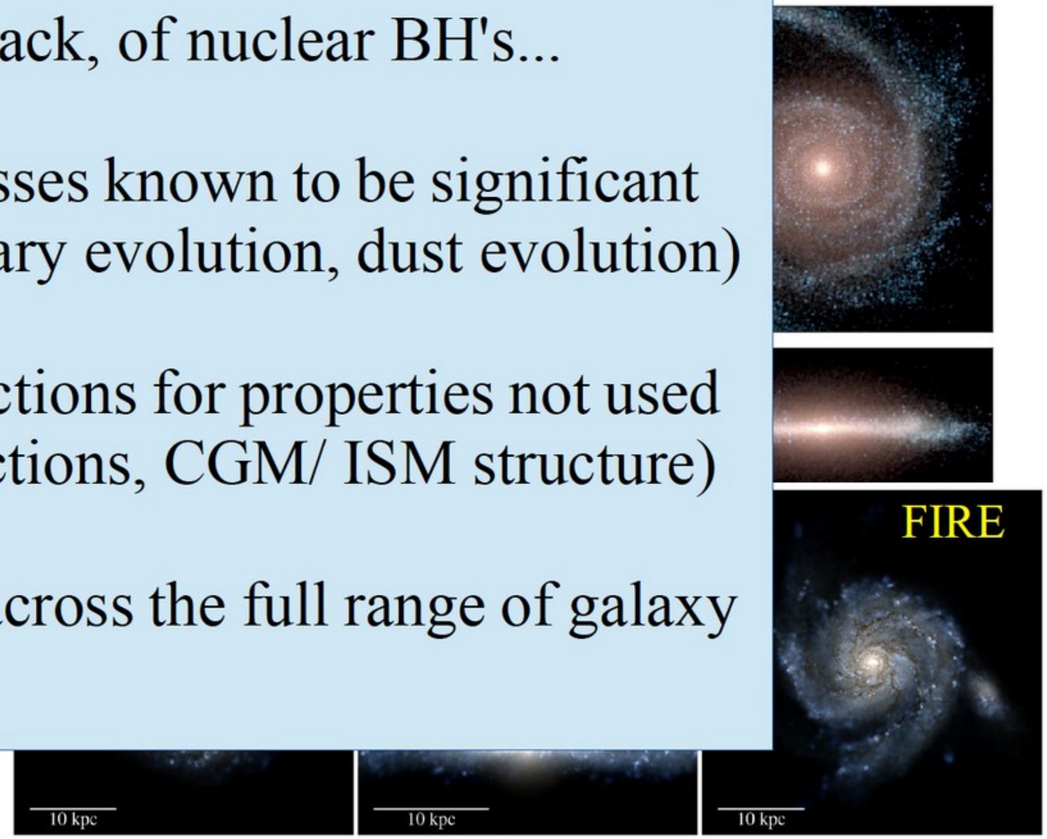




Simulating the structure of galaxies

- …but they differ strongly in their treatment of the ISM, of star formation, of feedback, of nuclear BH's...
- They do not include processes known to be significant (cosmic rays/B-fields, binary evolution, dust evolution)
- They make different predictions for properties not used as constraints (gas/bar fractions, CGM/ ISM structure)
- They are not yet checked across the full range of galaxy masses and environments.





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(Multiple) phenomenological models have been suggested for all of these
Convincing *ab initio* physical models are available for very few
Mass and detailed assembly history determine their relative importance

Epistemology for complex systems

(galaxy formation, climate change, ecology, macro-economics, brain function)

- Agreement of the galaxy population in a modern cosmological hydro-dynamical simulation with (aspects of) real populations may contribute rather little to our knowledge/understanding of galaxy formation, since
  - part of the agreement is due to calibration/tuning
  - simulations with *different* subgrid models often agree equally well
  - unexamined (but linked) aspects often disagree with observation
  - better resolution or subgrid modelling may ruin the agreement

- It is important to understand *why* simulation and observation agree. Intuition is often helped by models which isolate individual processes

- Stronger conclusions can often be drawn from showing that some aspects of the observations *cannot* be fit, implying e.g. that
  - the integration scheme is insufficiently accurate, or
  - the subgrid models incorrectly represent the astrophysics, or
  - critical processes are not yet included, or
  - ΛCDM is wrong

Summary points?

- ΛCDM is an *a priori* theoretical model with parameters fully specified by CMB measurements
- Of its basic tenets, only the cold nature of the Dark Matter *requires* data from the low-redshift Universe for justification/validation
- In principle, ΛCDM thus predicts **all** properties of the nonlinear, late-time universe (e.g. all galaxy properties) with no further freedom
- In practice, it can be very hard to calculate these predictions reliably.
- Different (uncertain) treatments of astrophysical processes can lead to very different galaxy properties within the *same* ΛCDM framework

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It seems very unlikely that the detailed structural properties of galaxies can be used reliably to infer failings of ΛCDM

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Complex simulations of limited realism/fidelity	⟺ knowledge?	Limited observations of a more complex reality