XIV SOCHIAS Meeting
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ΛCDM and galaxy formation: is the problem solved?

Simon White
Max Planck Institute for Astrophysics

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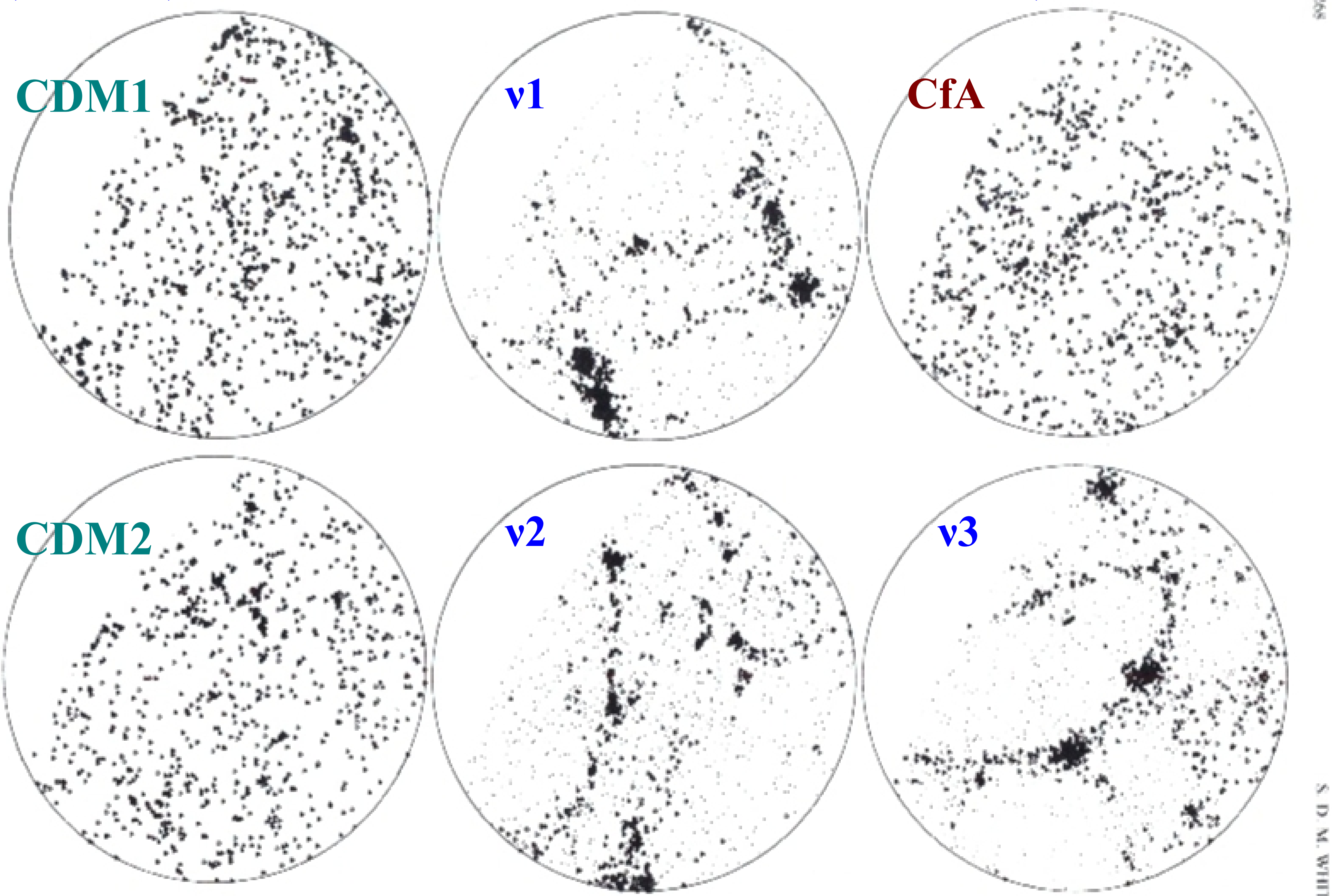
All critical elements of the ΛCDM model were in place before *any* of the last three was experimentally confirmed

The first simulation of ΛCDM structure formation dates from 1985

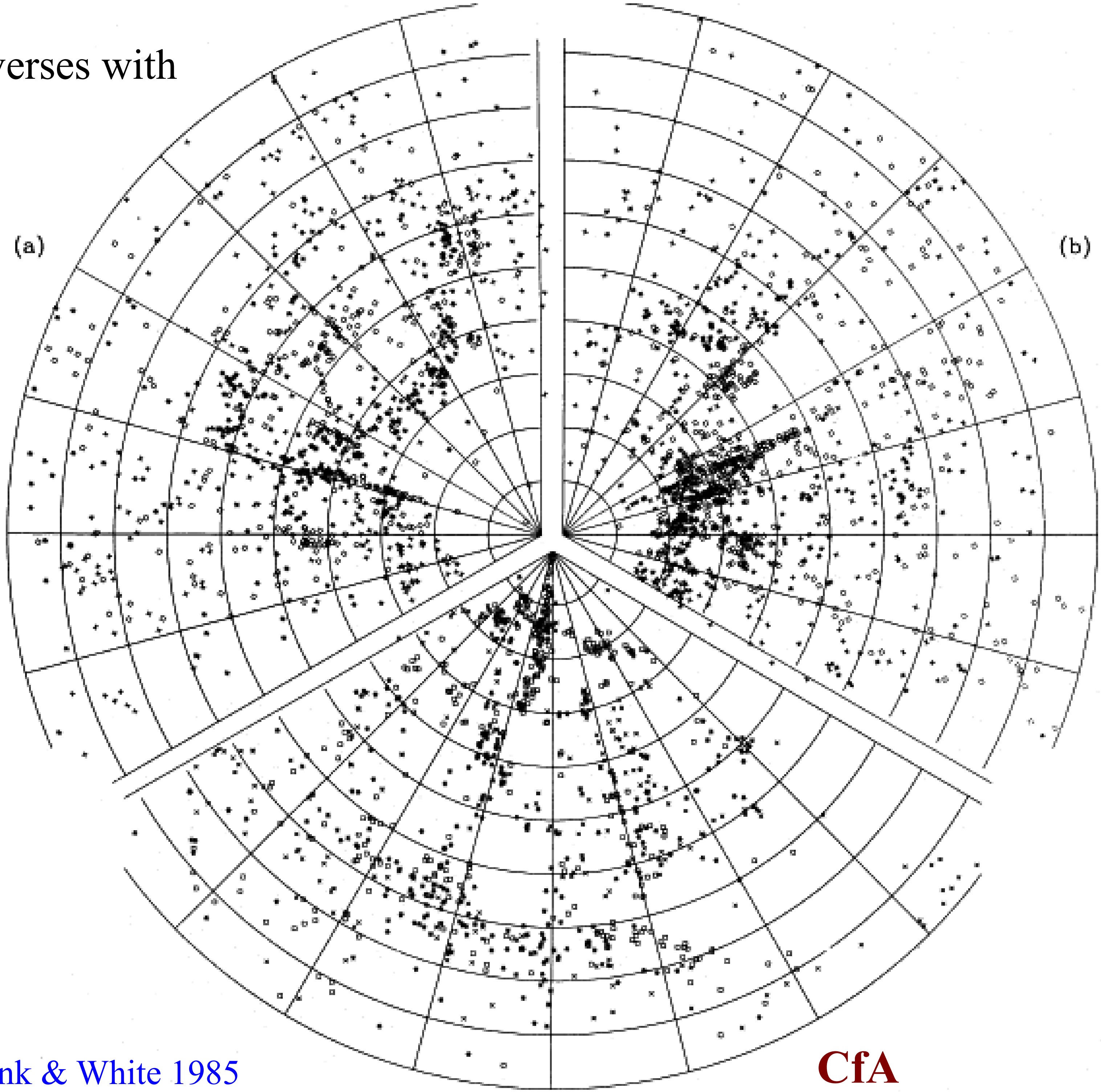
Neutrinos fail, but Cold Dark Matter, **is** possible

Davis, Efstathiou, Frenk & White 1985

White, Frenk & Davis 1983



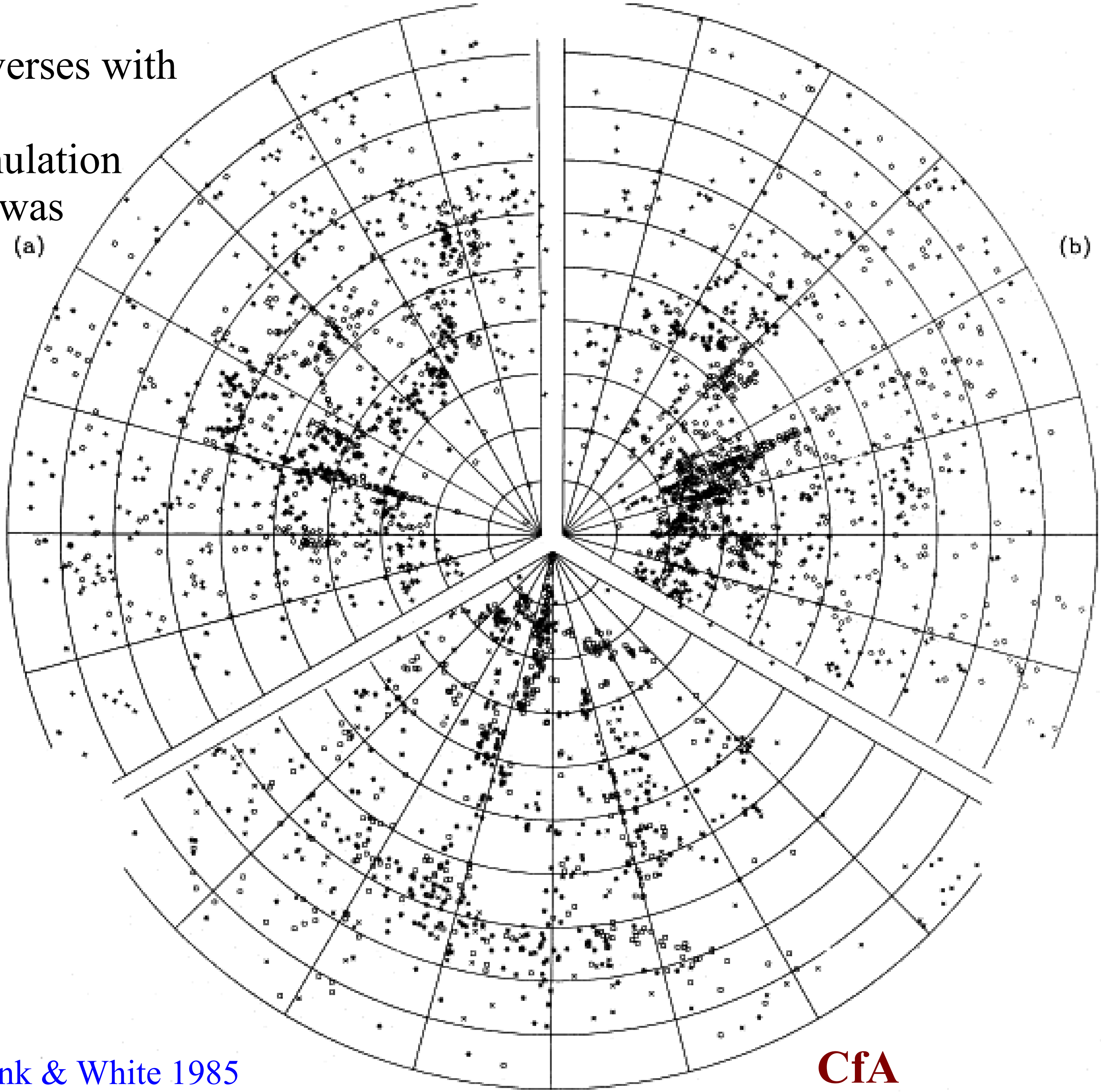
Open CDM universes with
$\Omega = 0.2$



Davis, Efstathiou, Frenk & White 1985

CfA

Open CDM universes with
$\Omega = 0.2$
but a ΛCDM simulation
with the same Ω was
indistinguishable



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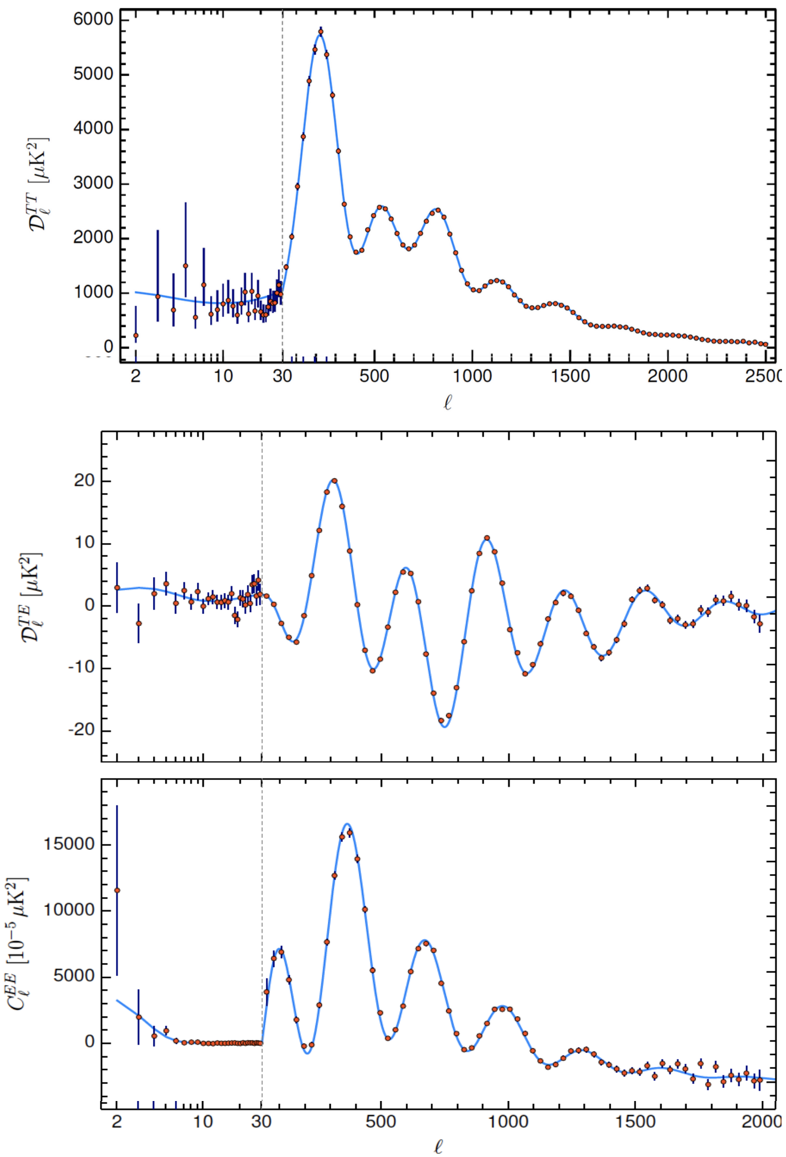
The current CMB evidence for ΛCDM



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

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

→ <u>**Measurements**</u> of all 6 ΛCDM parameters
Cosmic properties, **not** fitting parameters

- Low-z data needed to specify <u>nature</u> of the DM

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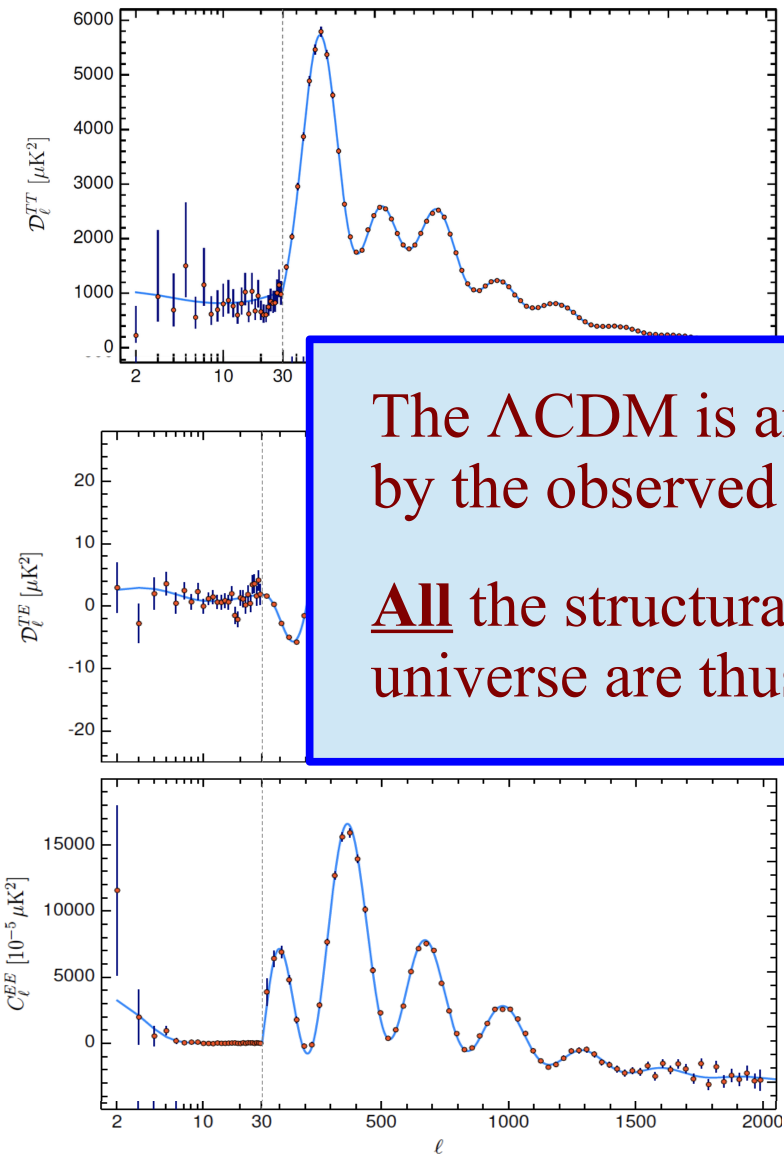

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The ΛCDM is an *a priori* model which is <u>fully</u> specified by the observed CMB temperature and fluctuations

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

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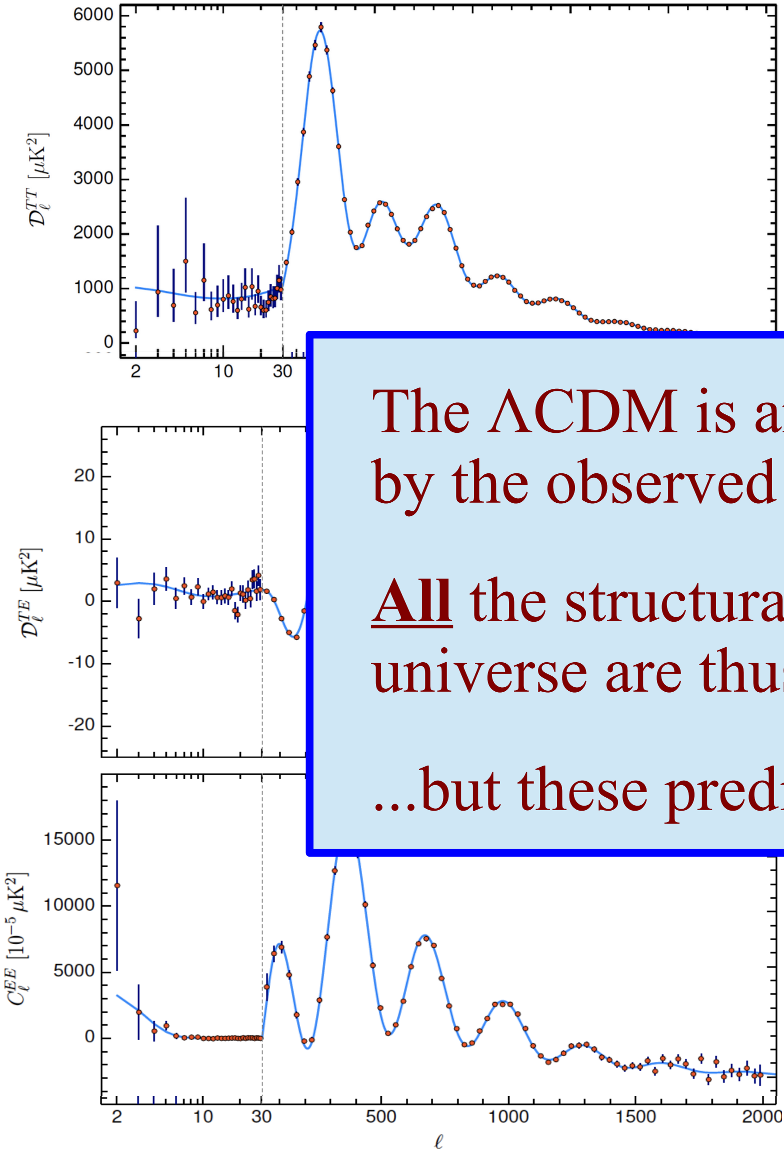

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All the structural properties of the nonlinear low-z universe are thus zero-parameter predictions

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

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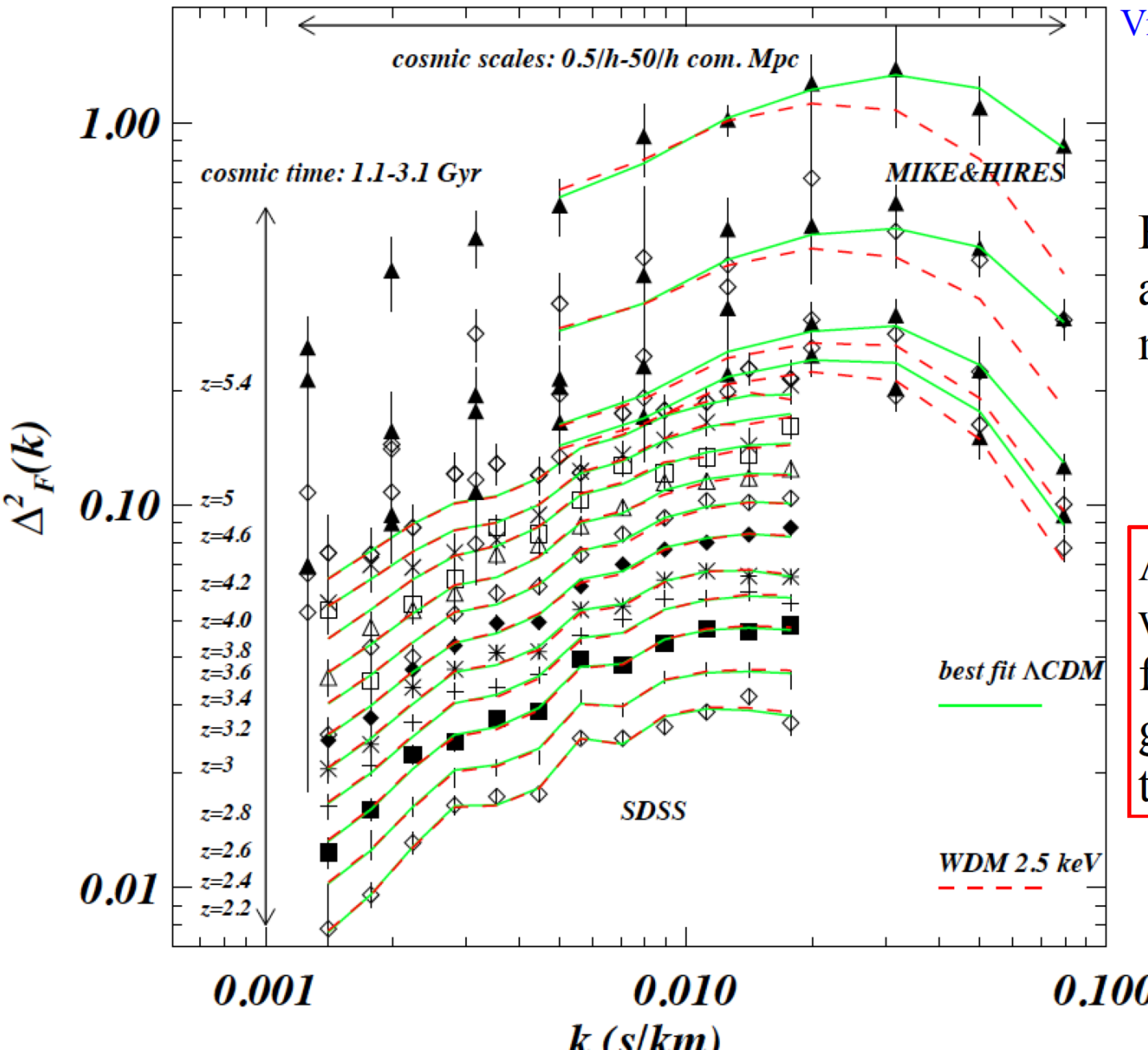
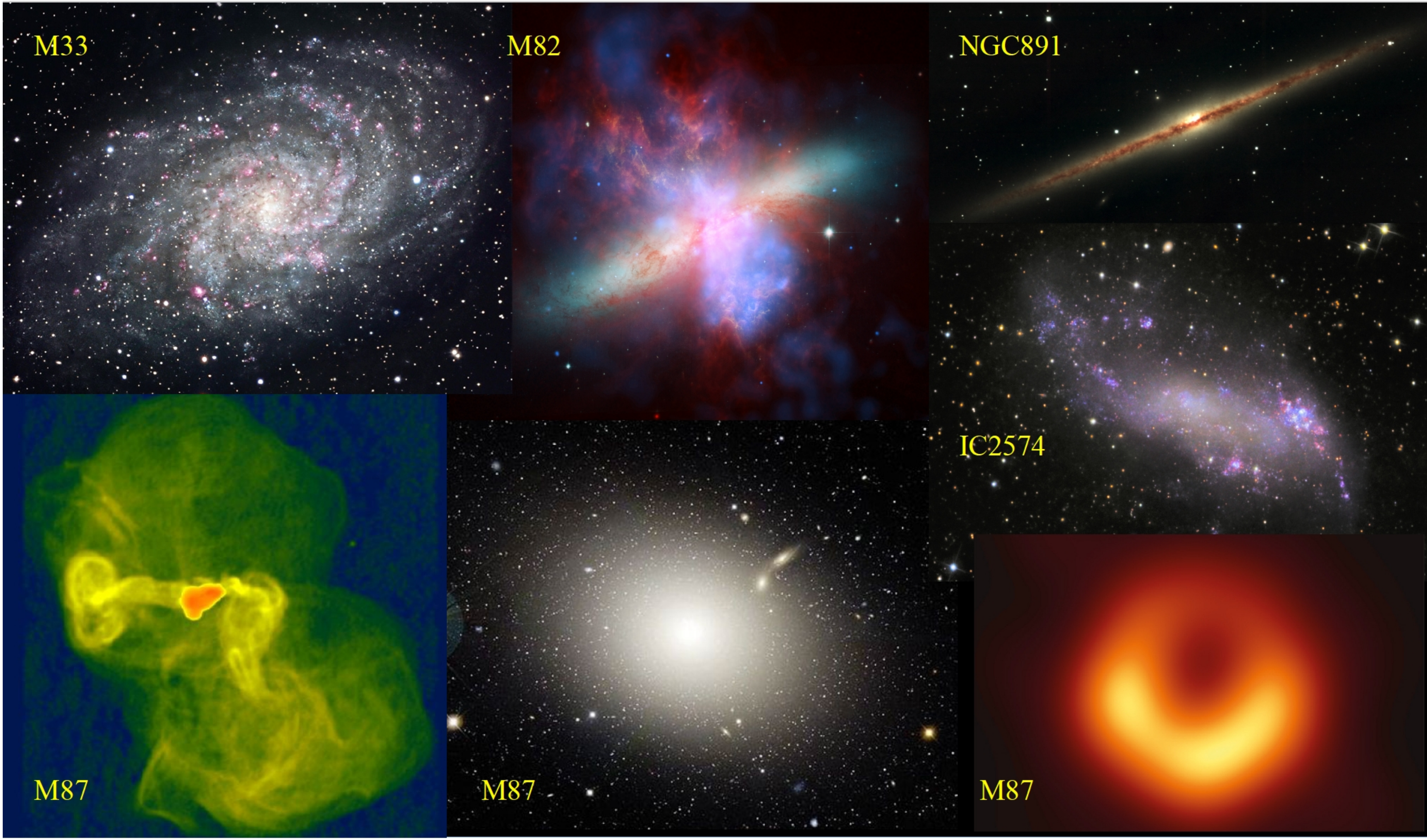
Lyman α forest spectra compared to ΛCDM predictions



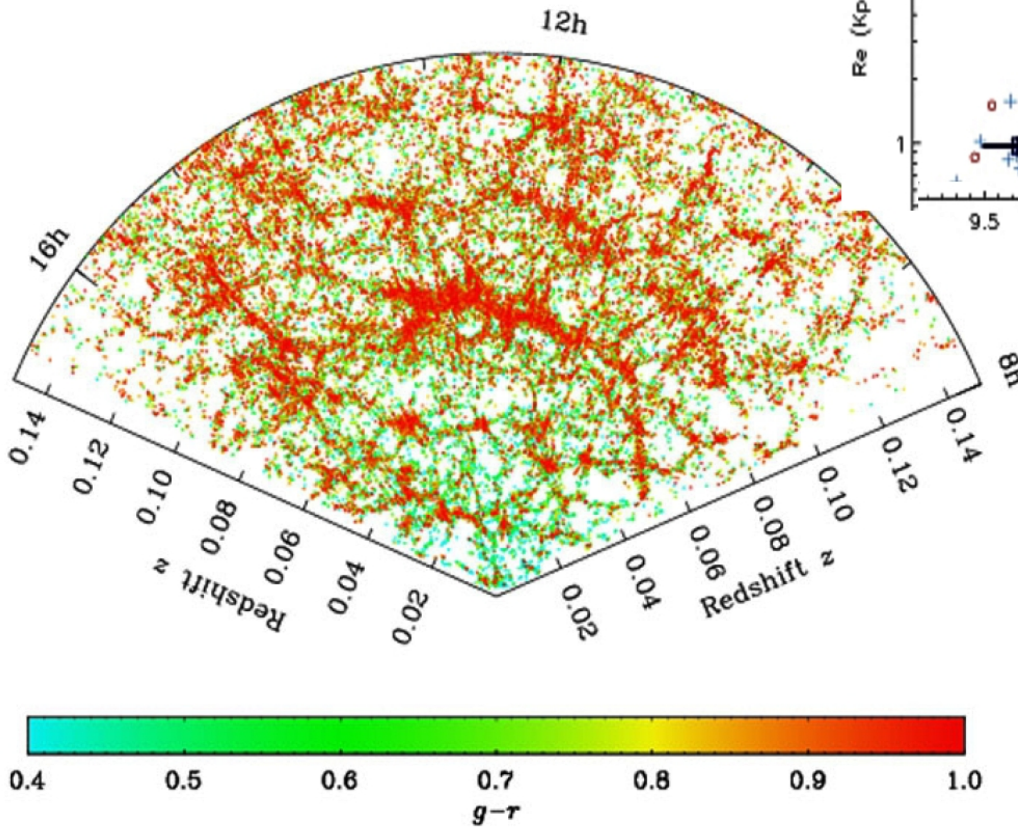
Viel, Becker, Bolton & Haehnelt 2013

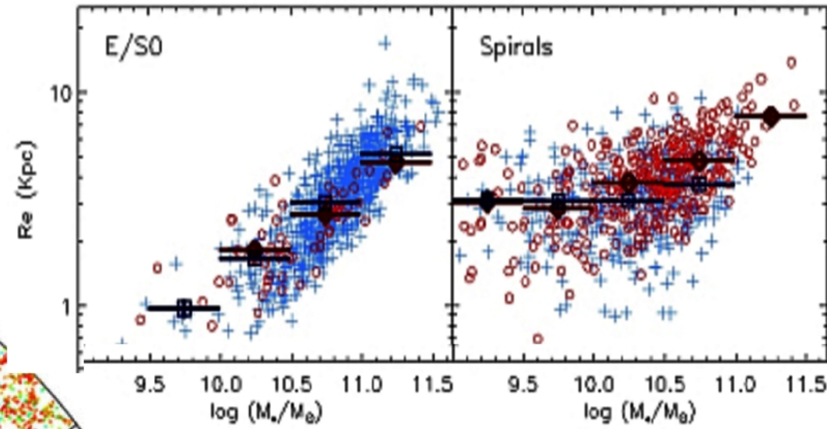
High-resolution Keck and Magellan spectra match ΛCDM up to z = 5.4

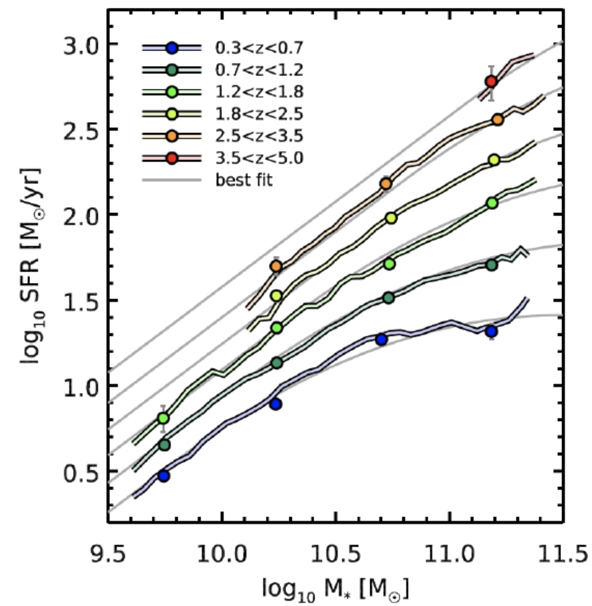
ΛCDM initial conditions with CMB parameters fit structure in the pre-galactic medium down to dwarf galaxy scales

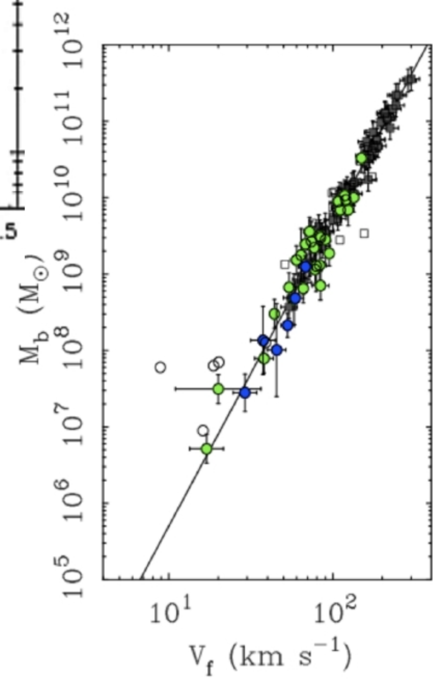


Galaxies are diverse, complex, multi-scale and evolving systems









Galaxies are diverse, complex, multi-scale and evolving systems

Their population shows regularities with varying scatter/evolution

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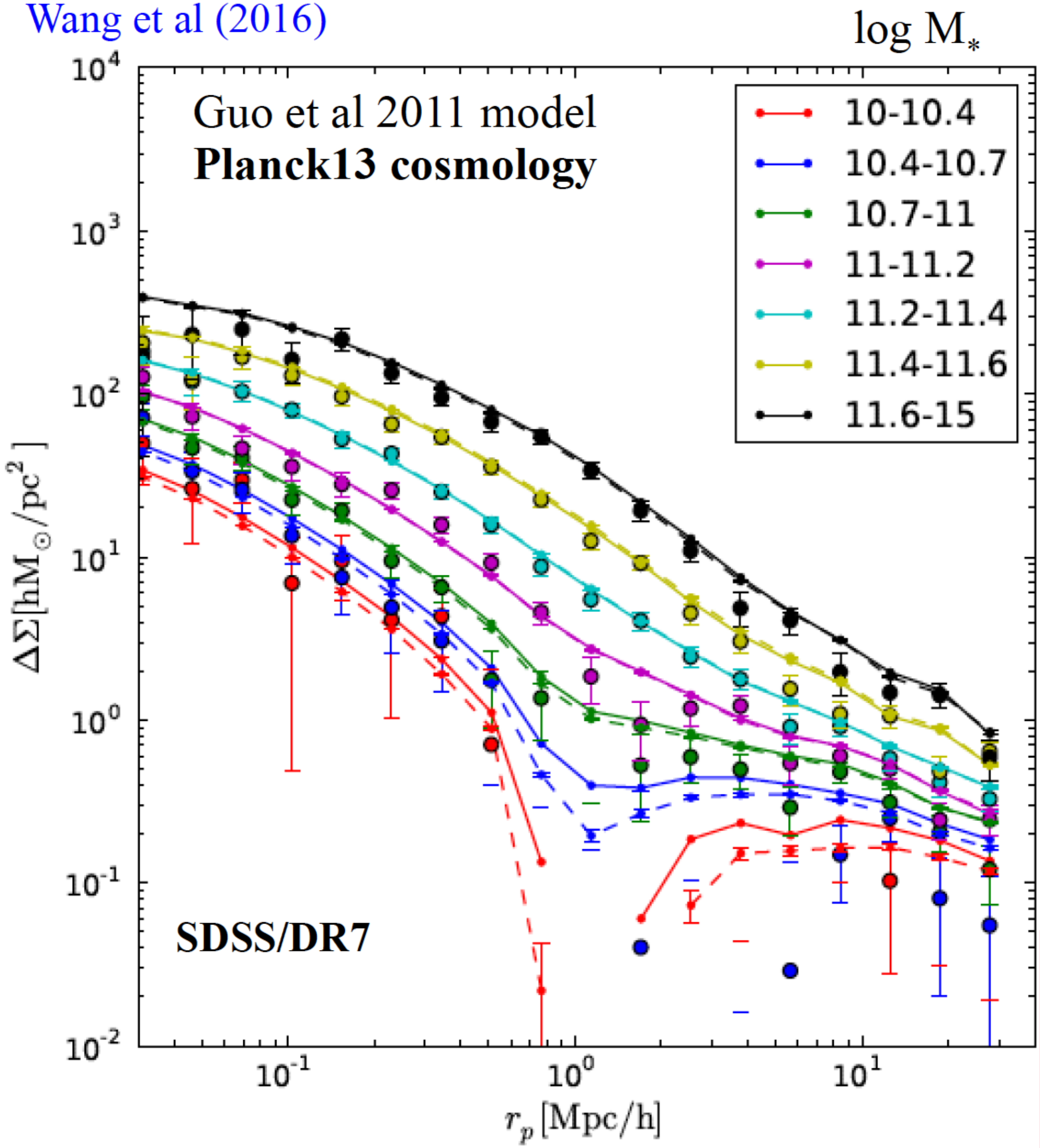
Semi-analytic and Subhalo Abundance Matching models assume this and tune a physically based (SAM) or purely statistical (SHAM) relation between galaxy properties and subhalo history to fit observation.

Average mass profiles around bright galaxies

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!

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Main outstanding issues are:

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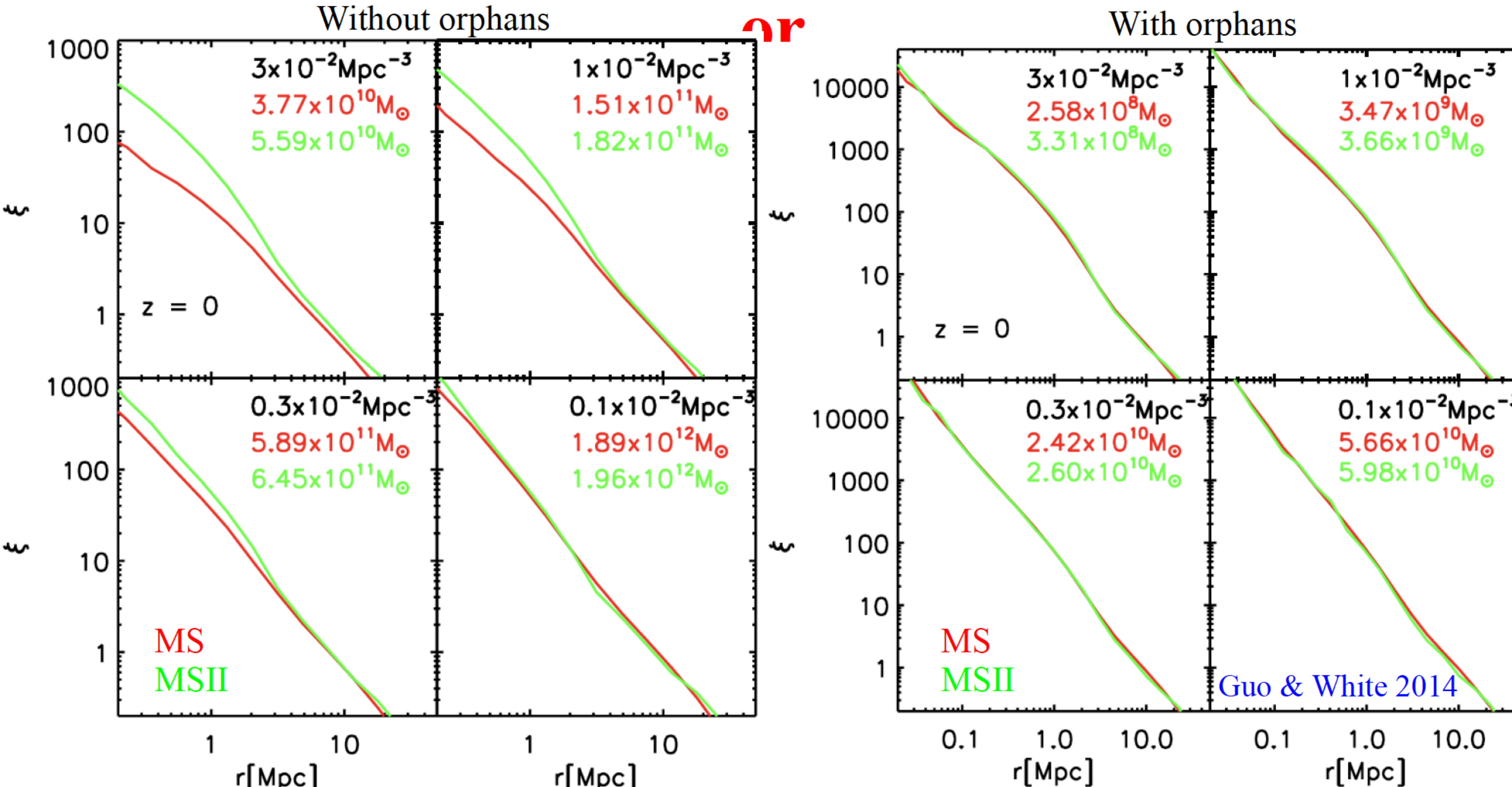

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Subhalo Abundance Matching and Semi-analytic models assume this and tune a more (SAM) or less (SHAM) complicated relation between galaxy properties and subhalo history to fit observation.

Main outstanding issues are:

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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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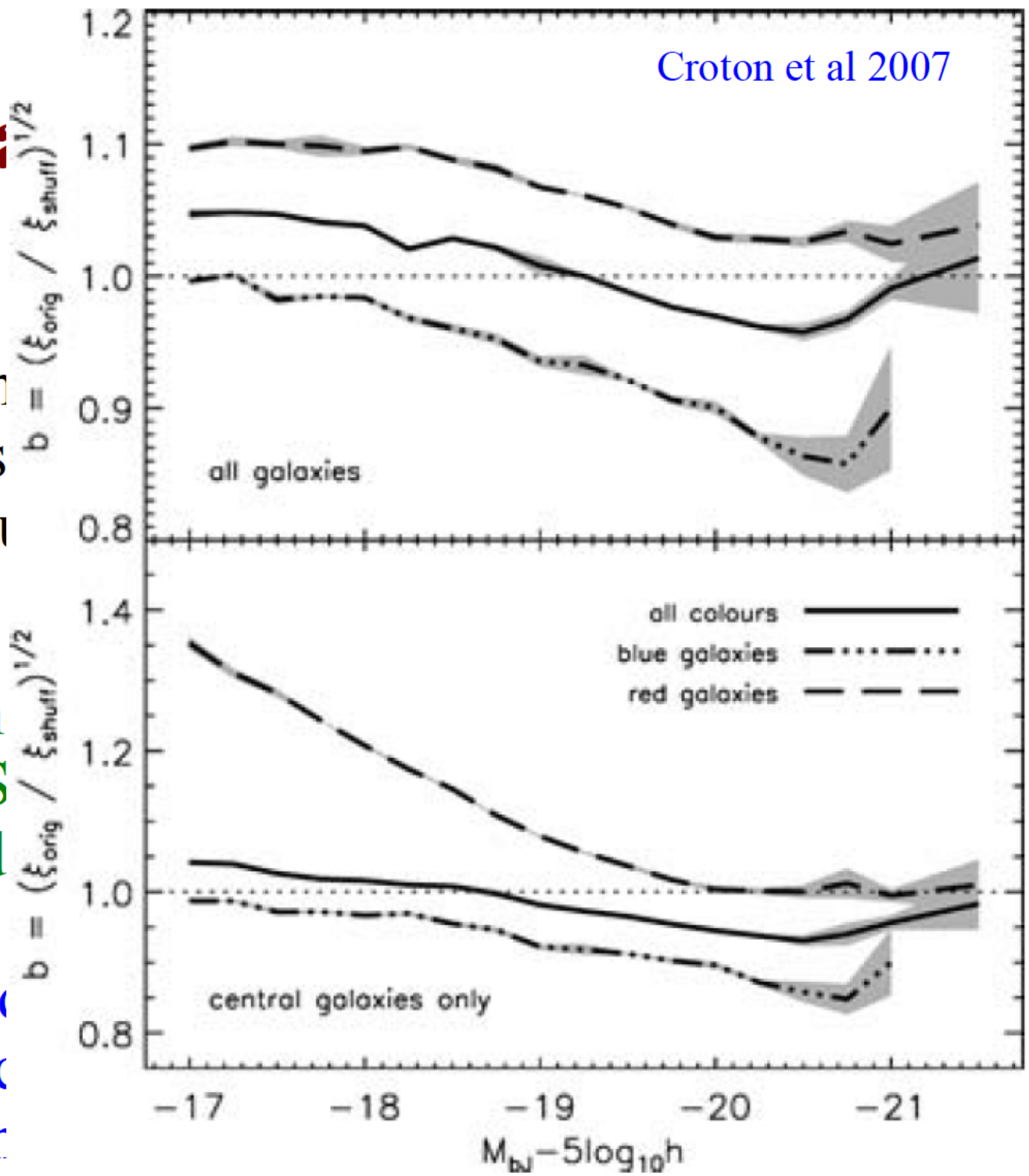

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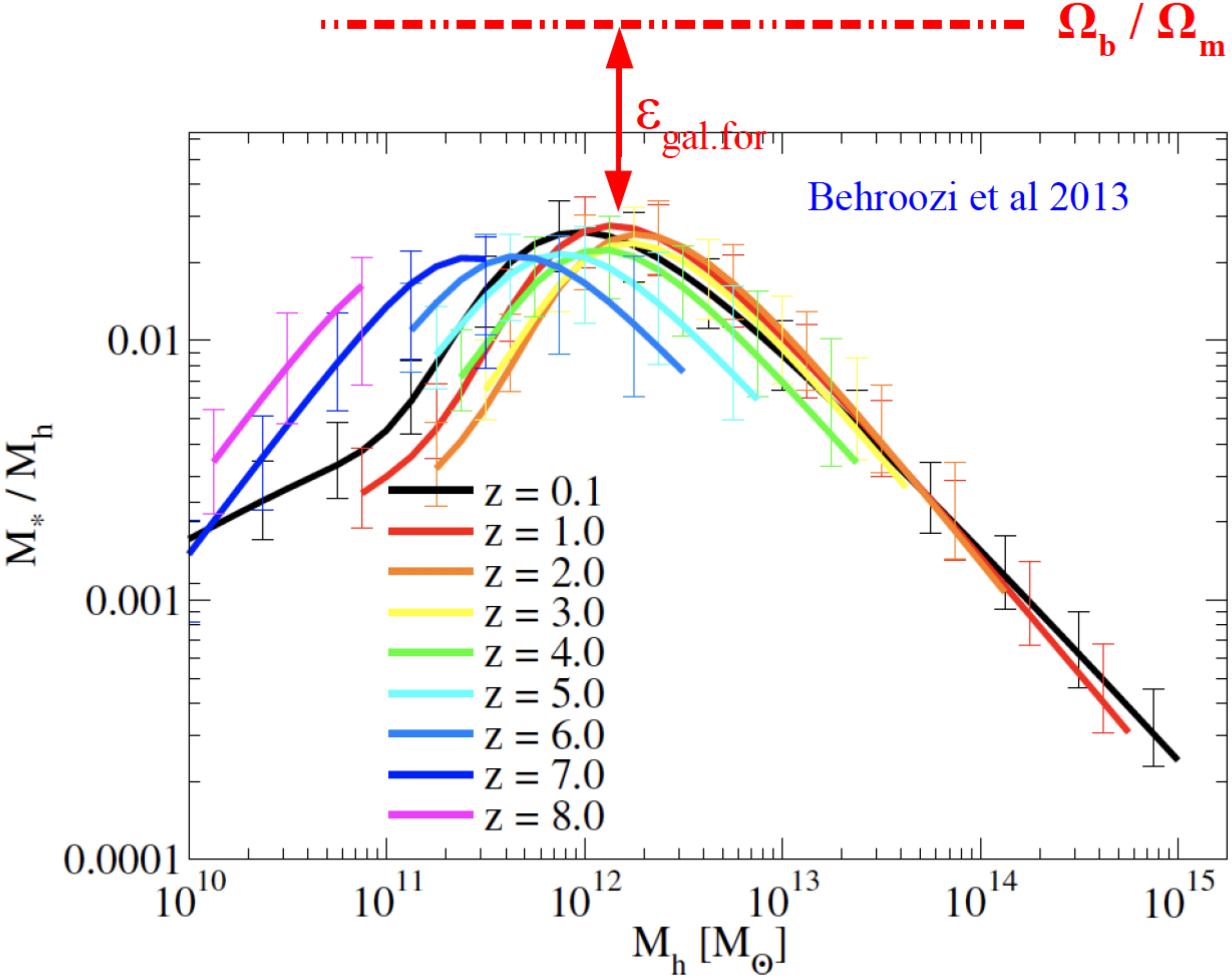

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At high mass: Inefficient cooling; AGN feedback

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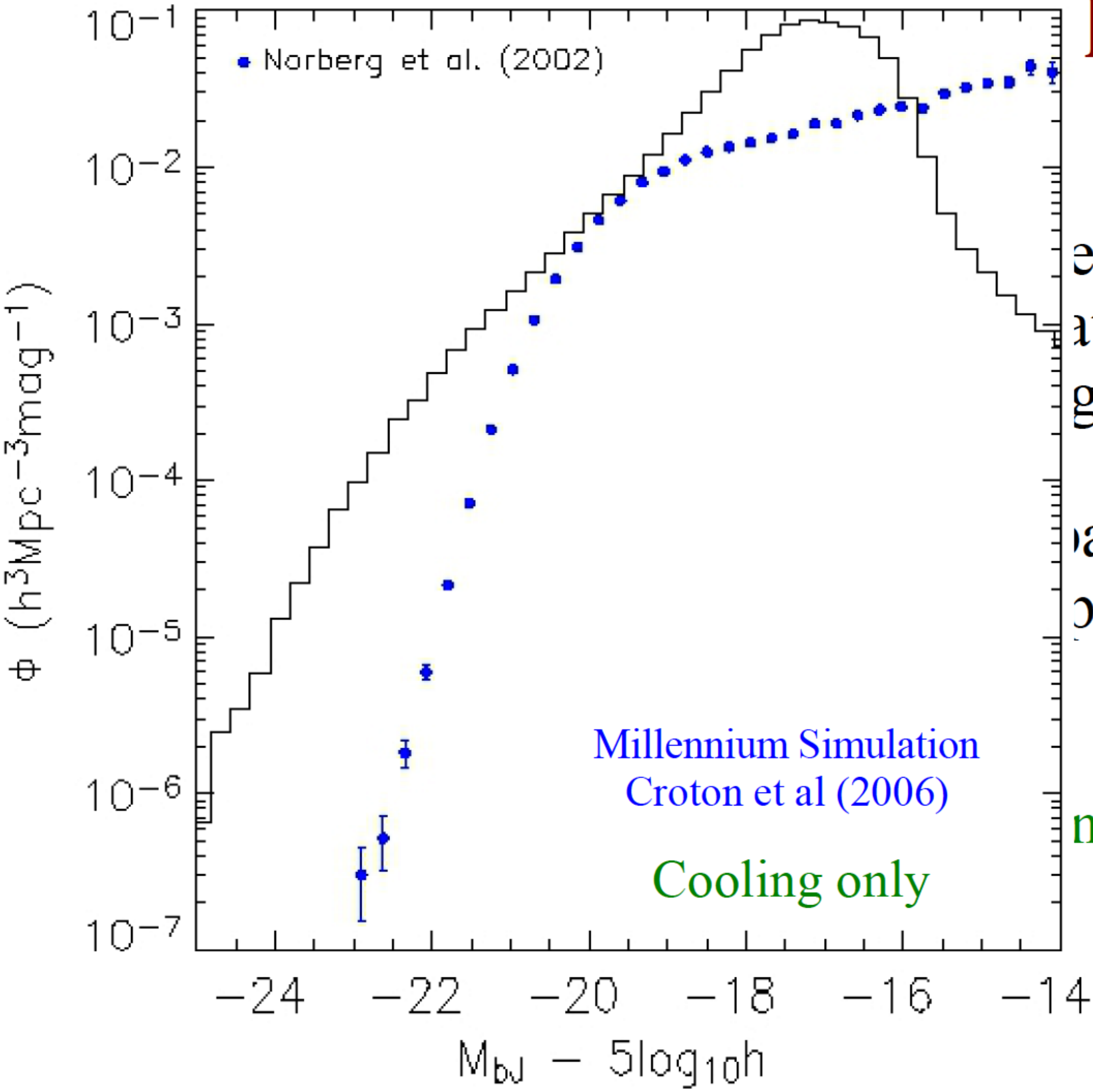

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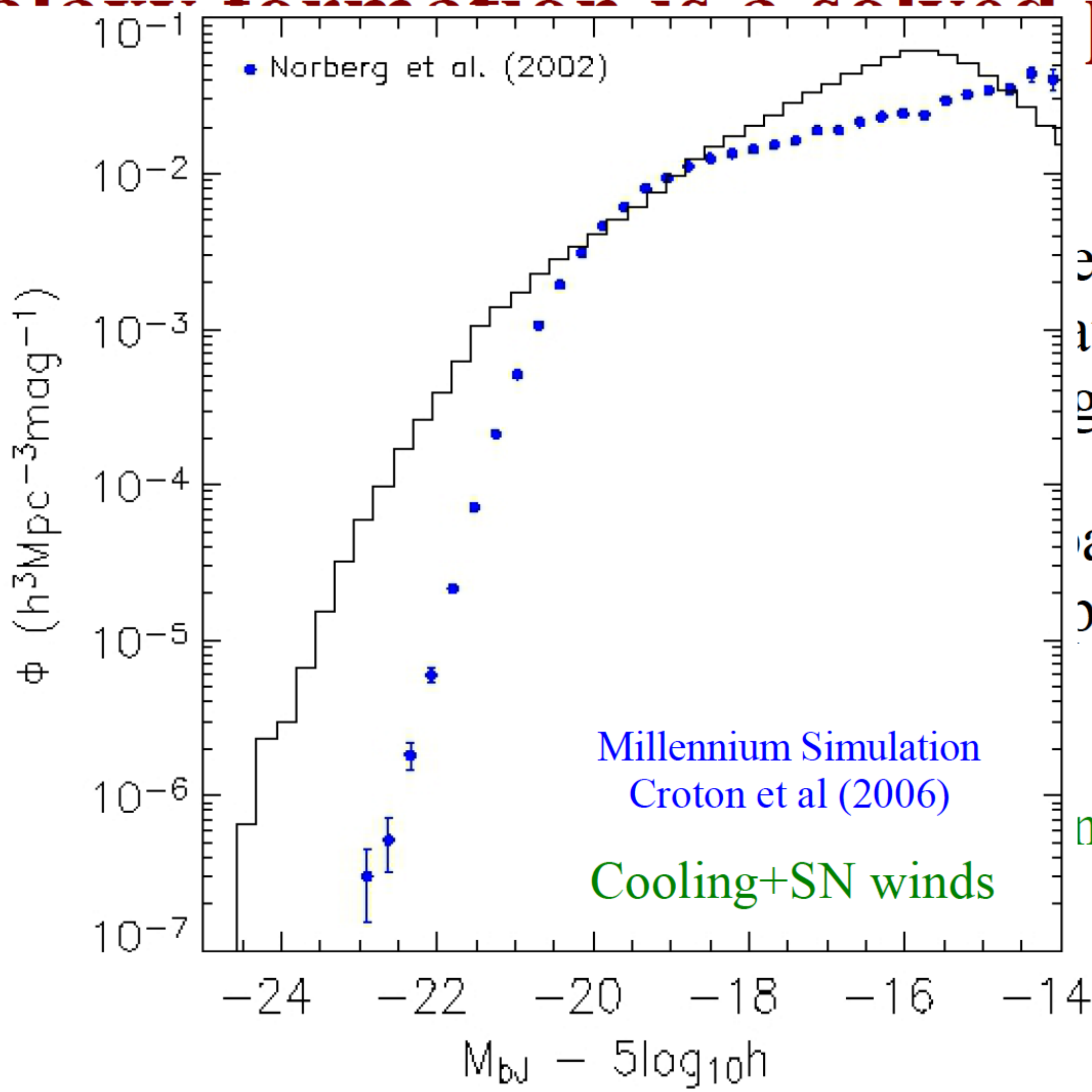

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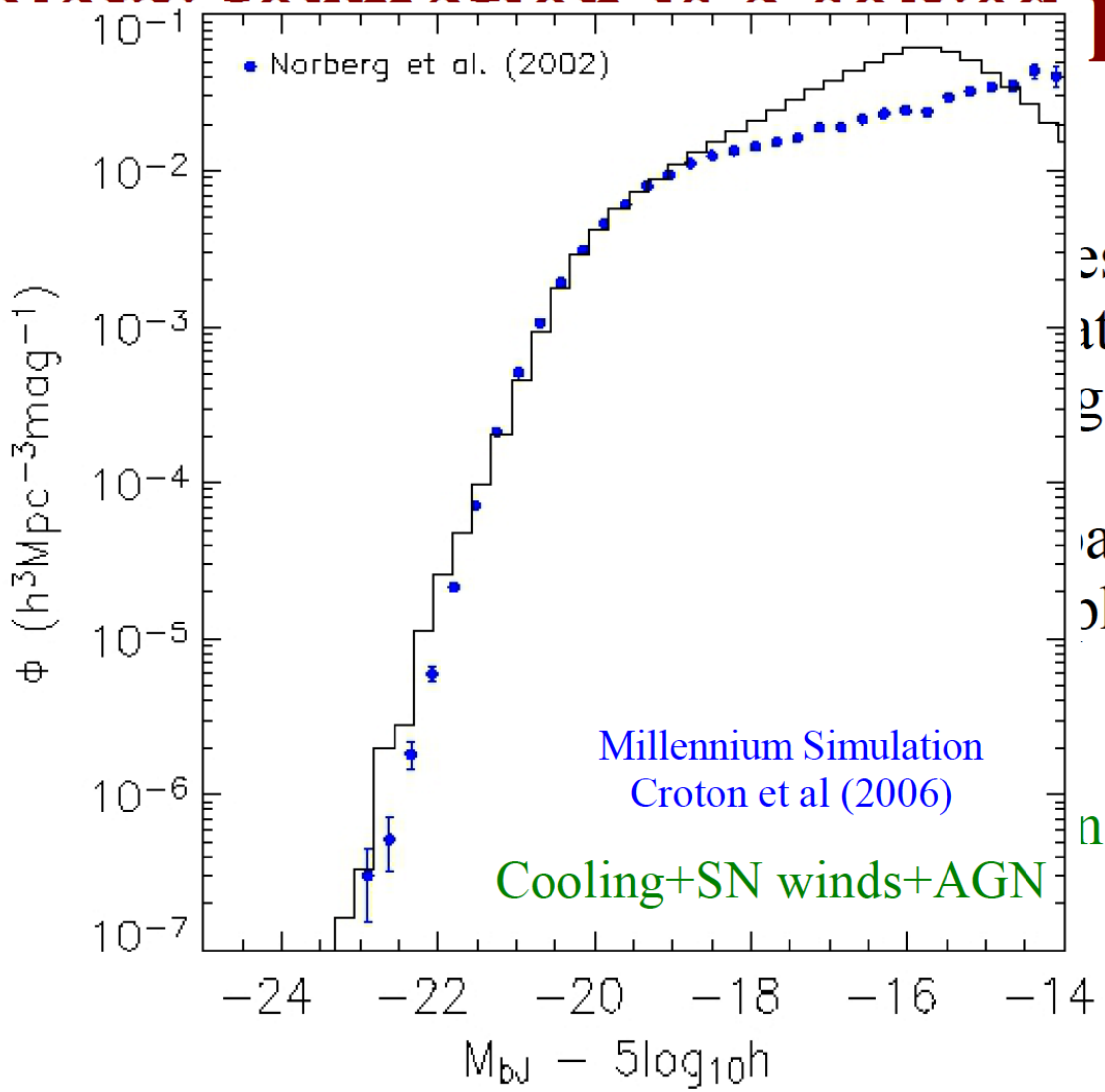

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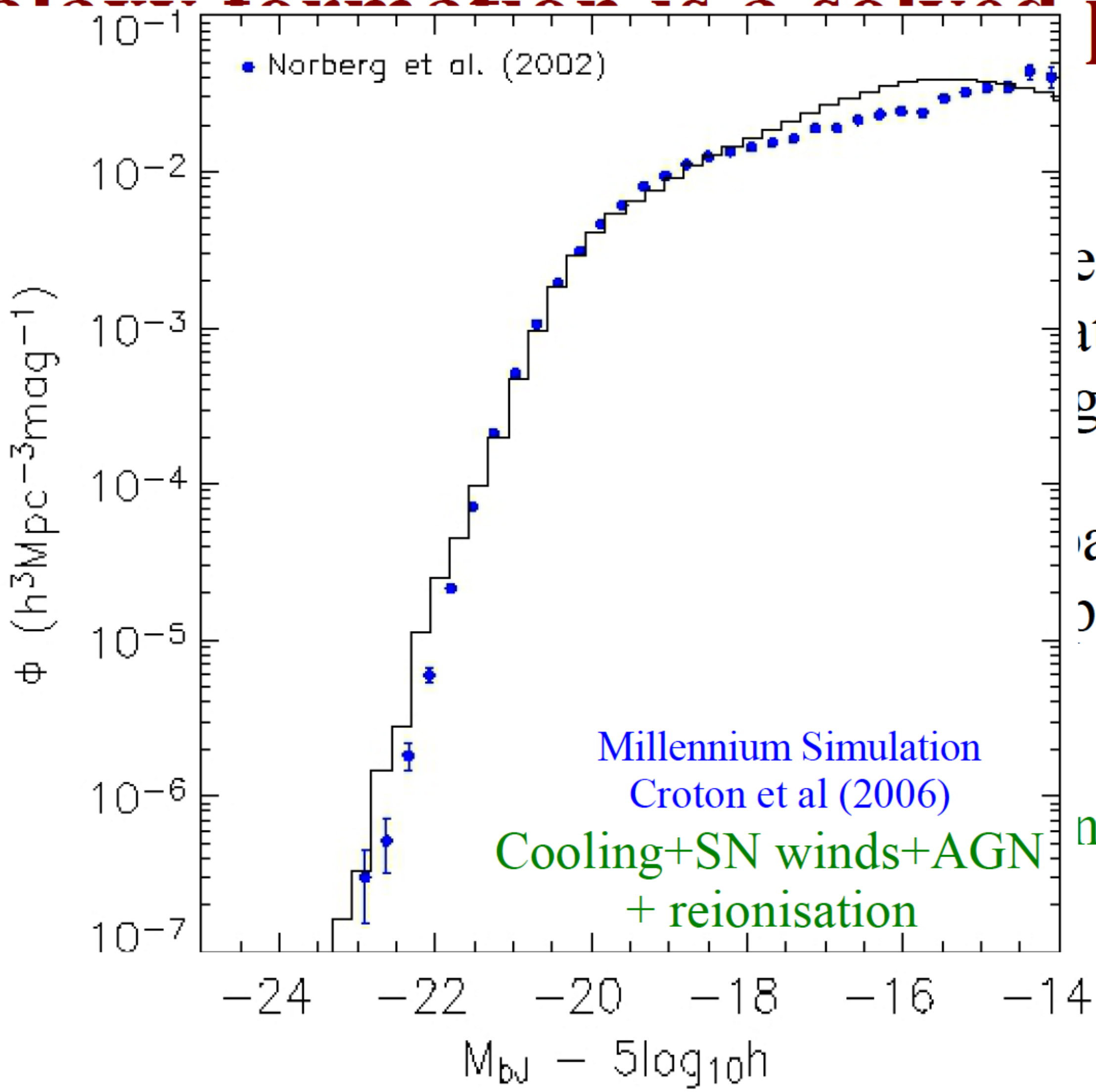

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Main outstanding issues:
I. Mechanical/radiative feedback, B-fields/cosmic rays, ejection/recycling
II. Can "subgrid" processes be sufficiently well/uniquely characterised?

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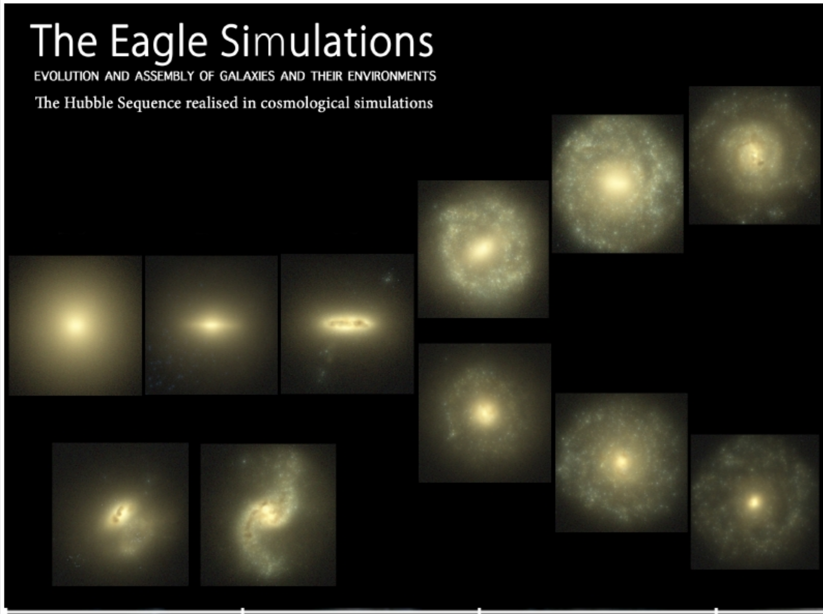
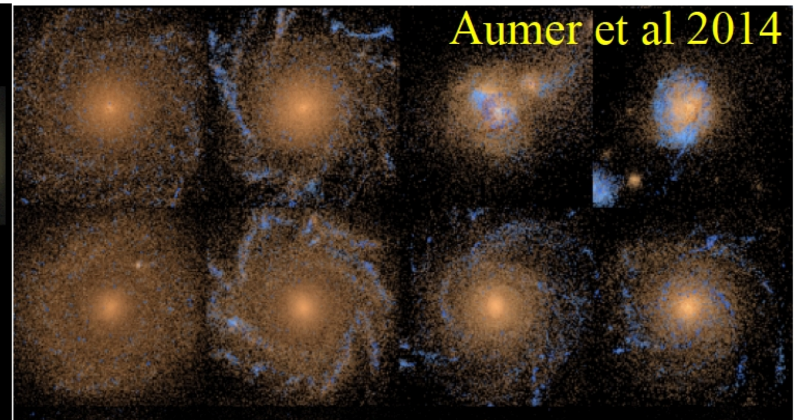
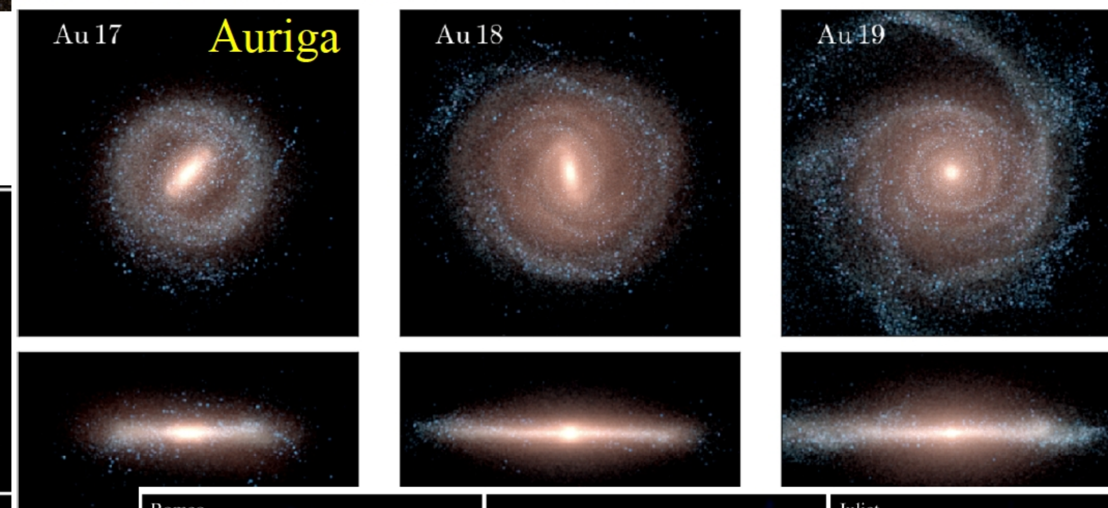
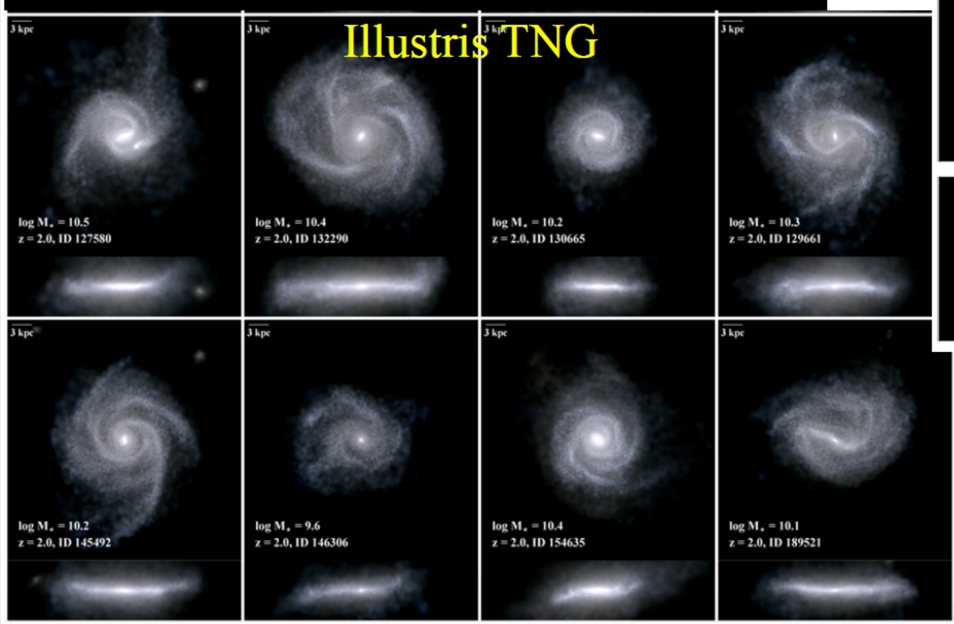
  Tidal torques on protogalaxies.
  Disk formation and instability
  (Lack of) loss in winds, transfer in galactic fountains
  Randomisation in mergers, feeding of AGN

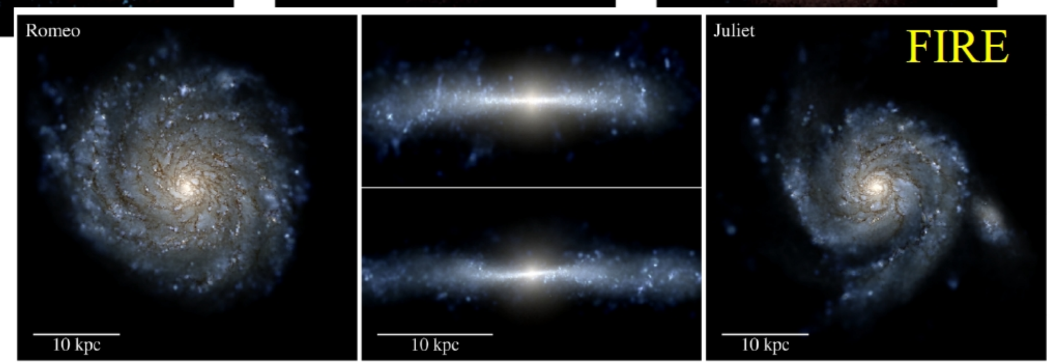
Simulating the structure of galaxies











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

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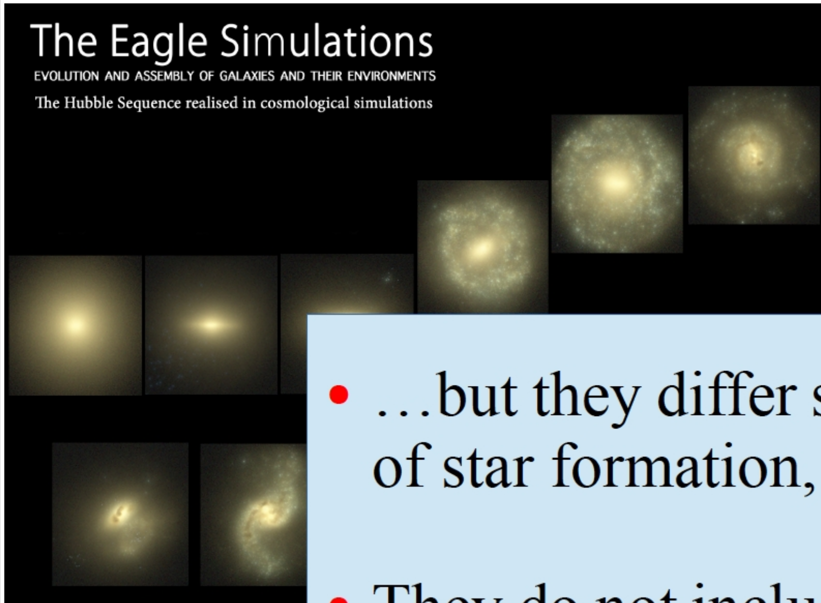

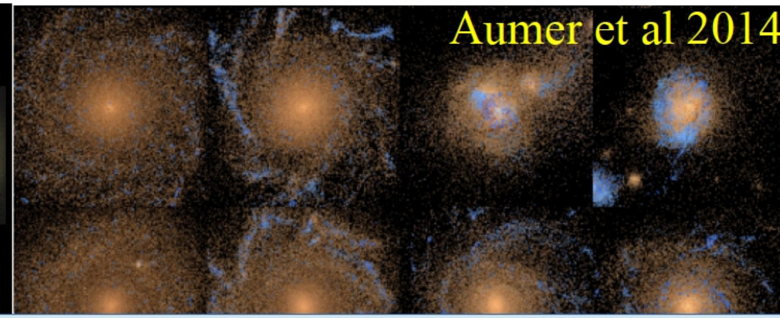

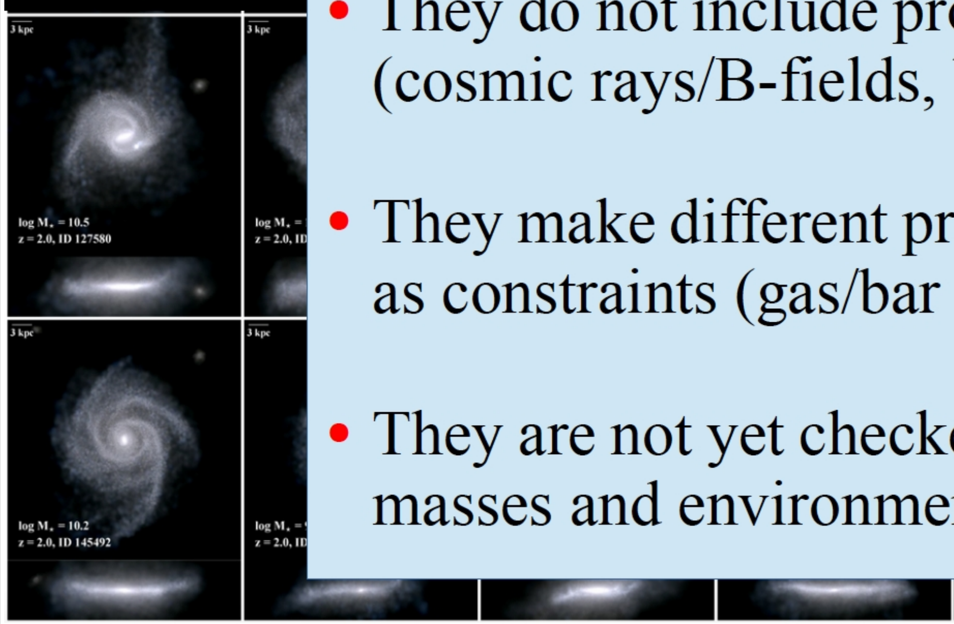

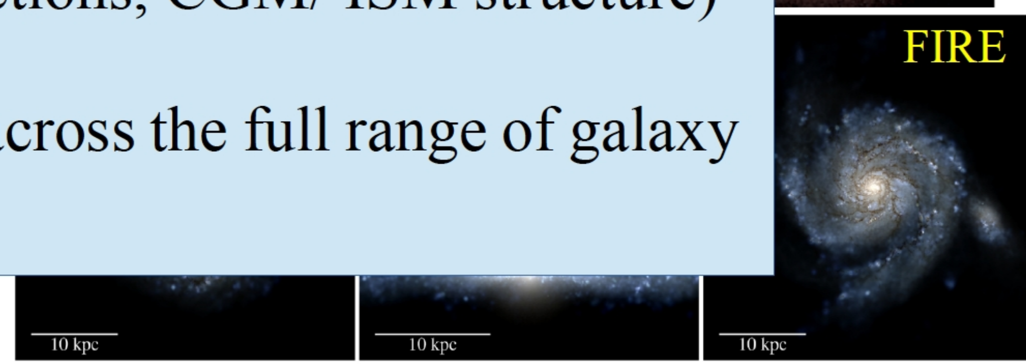

- …but they differ strongly in their treatment of the ISM, of star formation, of feedback, of nuclear BH's...
- They do not include processes known to be significant (cosmic rays/B-fields, binary evolution, dust evolution)
- They make different predictions for properties not used as constraints (gas/bar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

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A selection of outstanding issues:

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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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- 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

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

Summary points?

- ΛCDM is an *a priori* theoretical model with parameters fully specified by CMB measurements

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