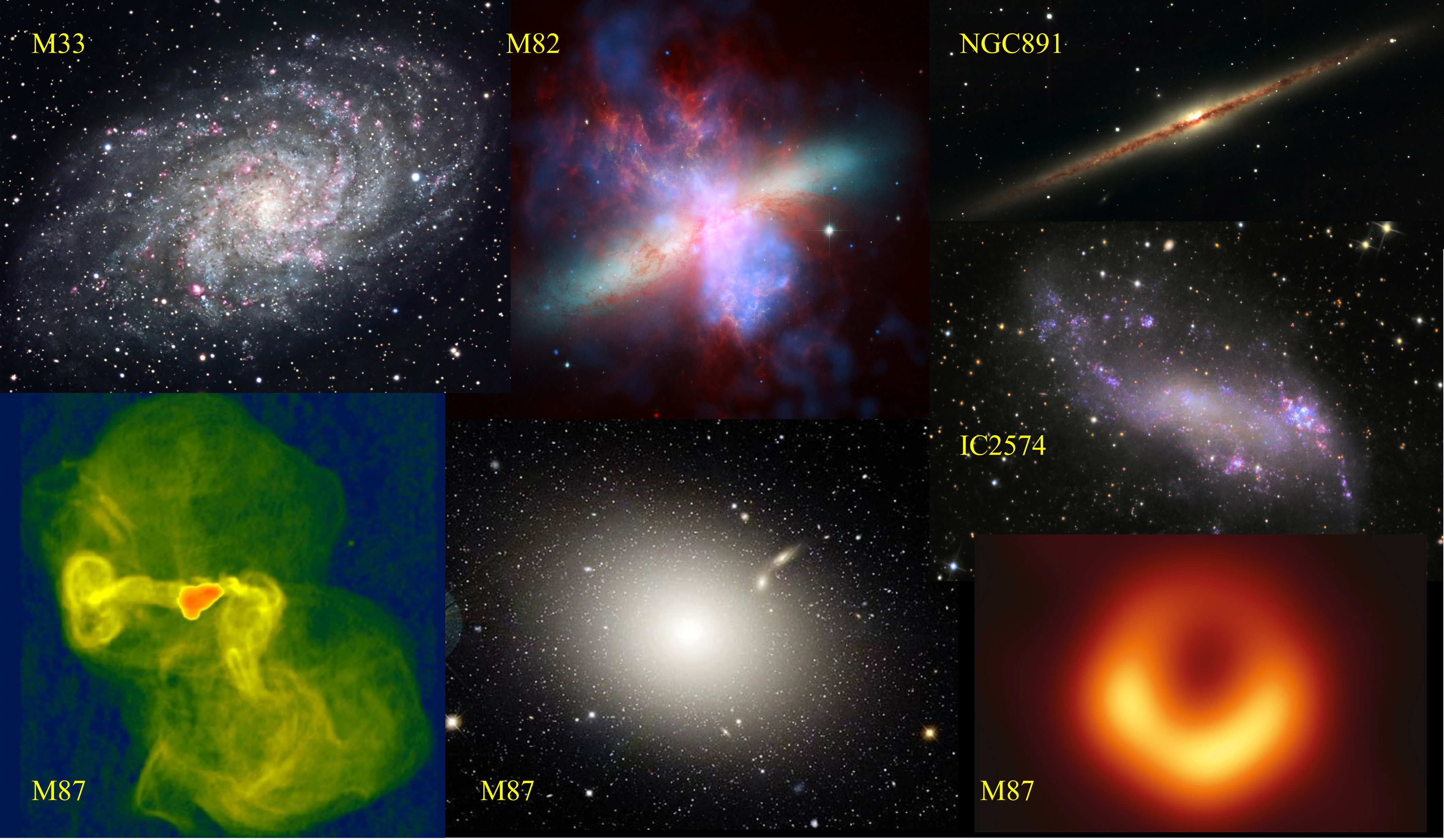
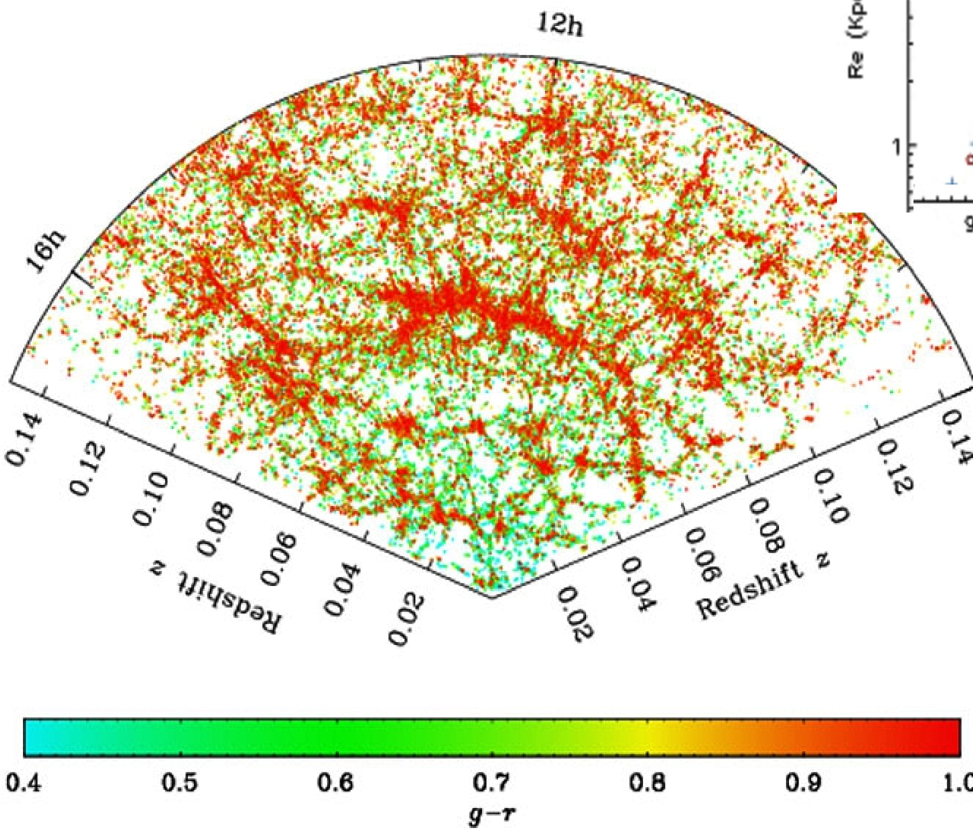
KICC 10th Anniversary Symposium
Cambridge, September 2019

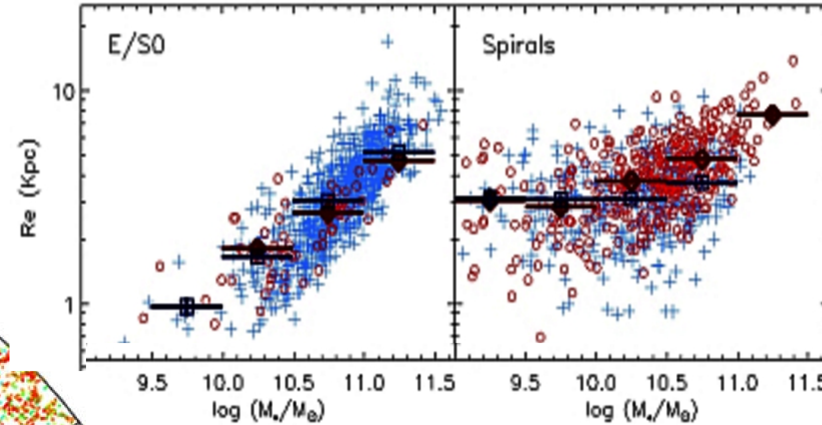
Outstanding problems in galaxy formation

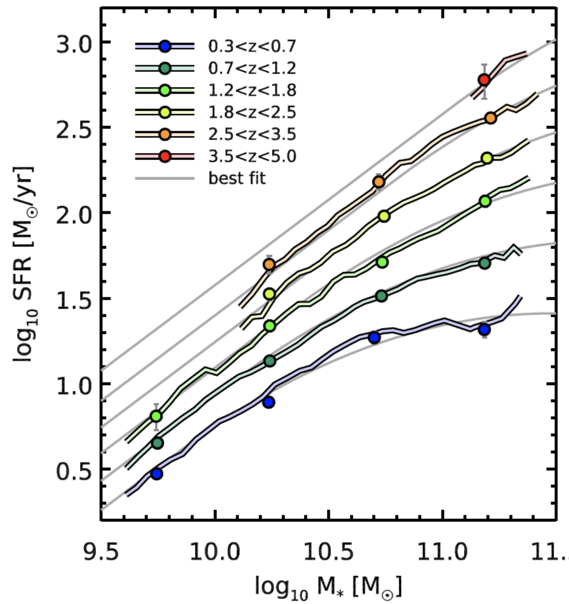
Simon White, Max Planck Institute for Astrophysics

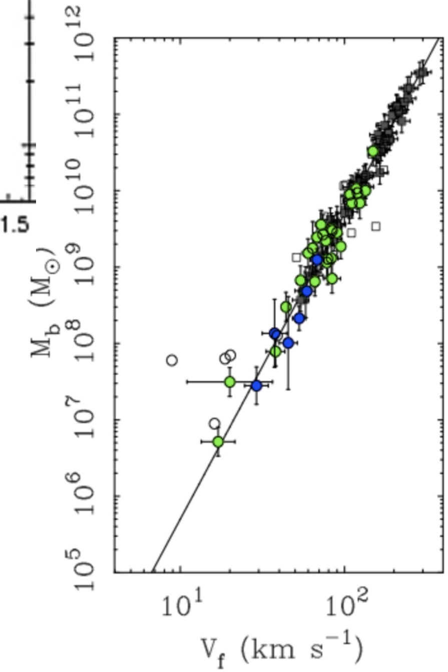


Galaxies are diverse, complex, multi-scale and evolving systems









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

Their population shows regularities with varying scatter/evolution

Galaxy formation is an insoluble problem

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or

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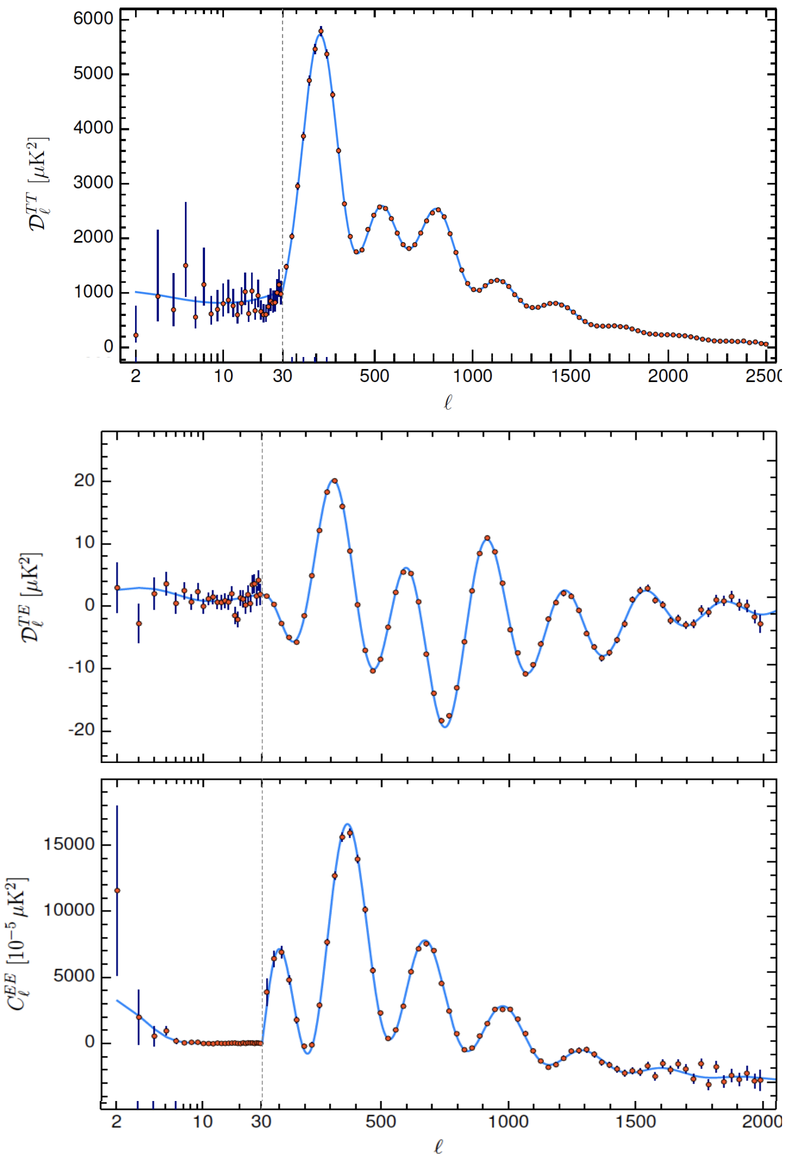
The astrophysical evidence for pre-existing dark matter



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

- Results from a single instrument (Planck/HFI)
- No local/low-redshift data are used
- Linear perturbation of a homogeneous medium
- No exotic/HE physics needed to set pattern
- Outside modified gravity regime
- Precise results applying to the whole visible Universe rather than some subregion

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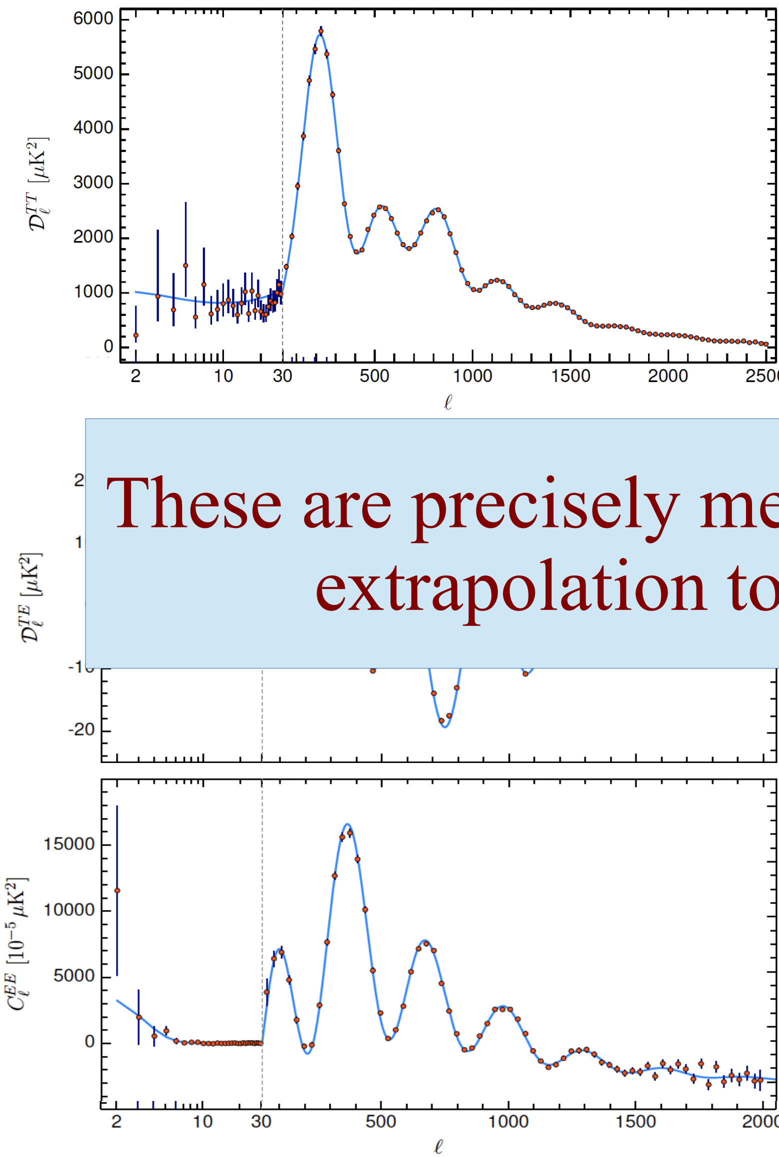

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These are precisely measured initial conditions, but they need extrapolation to the scales which form galaxies

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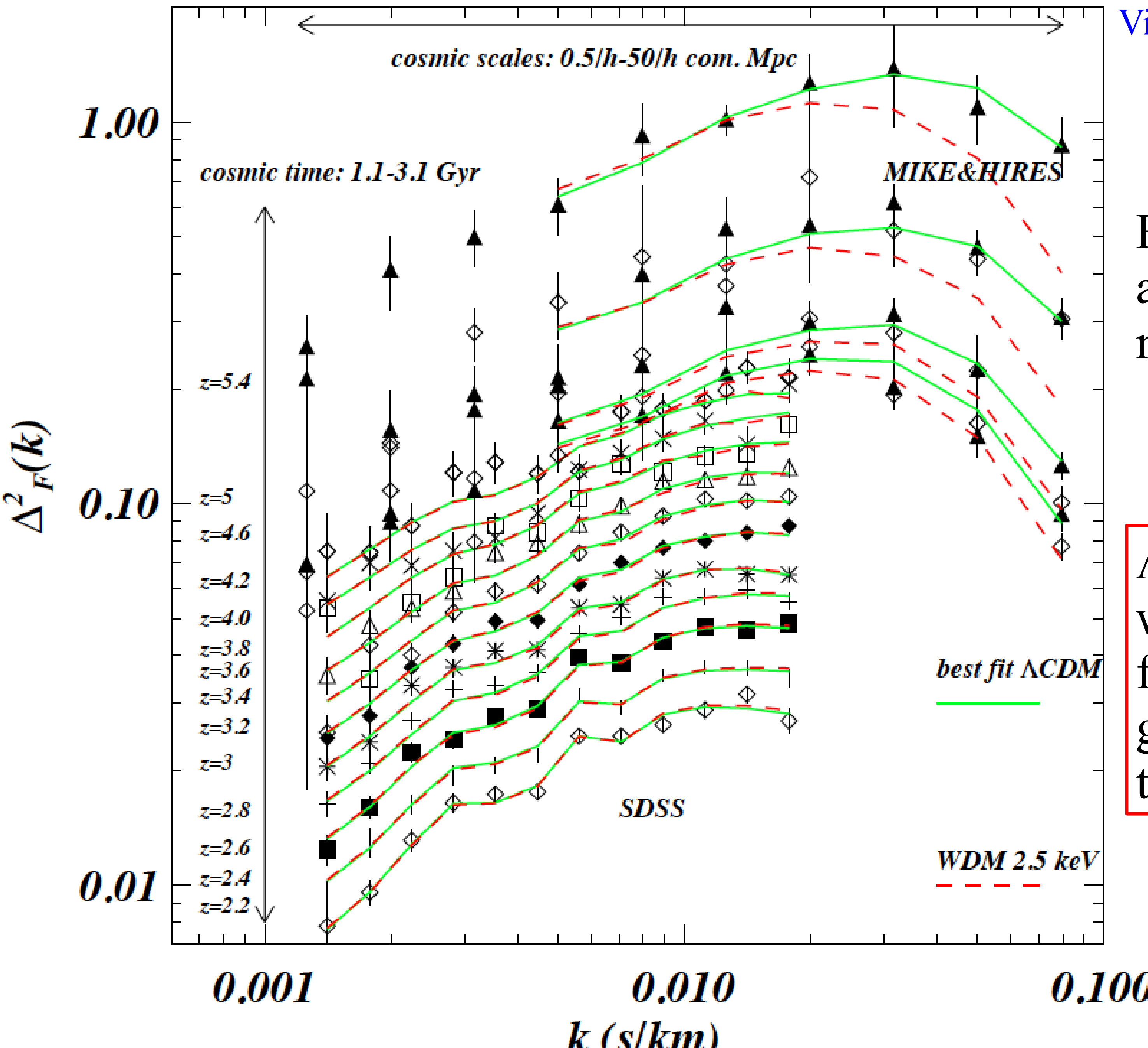
Lyman α forest spectra compared to ΛCDM predictions



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

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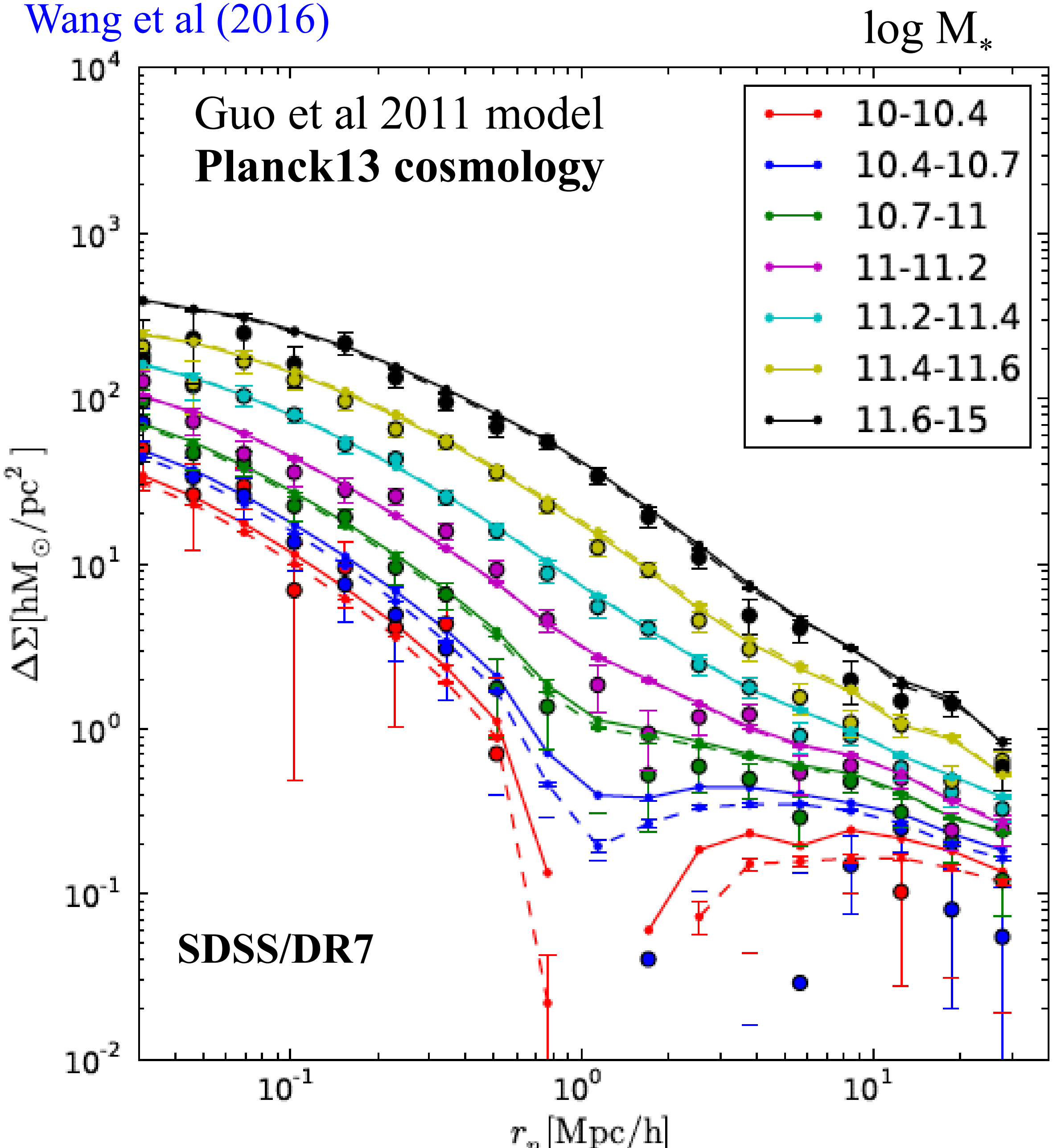
Average mass profiles around bright galaxies

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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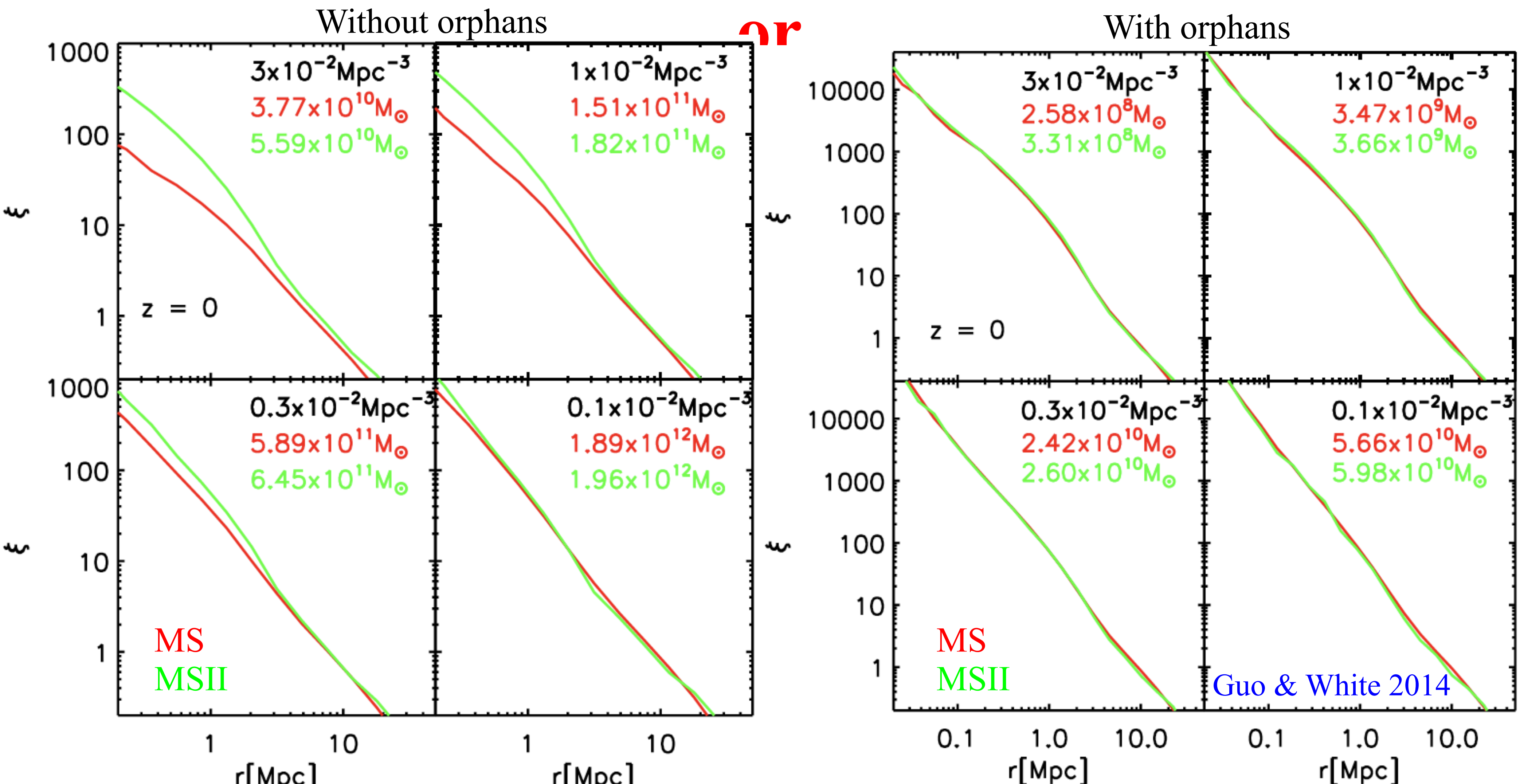

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II. The number of properties of subhalo histories needed to predict their galaxy content to the required precision – the "assembly bias" problem

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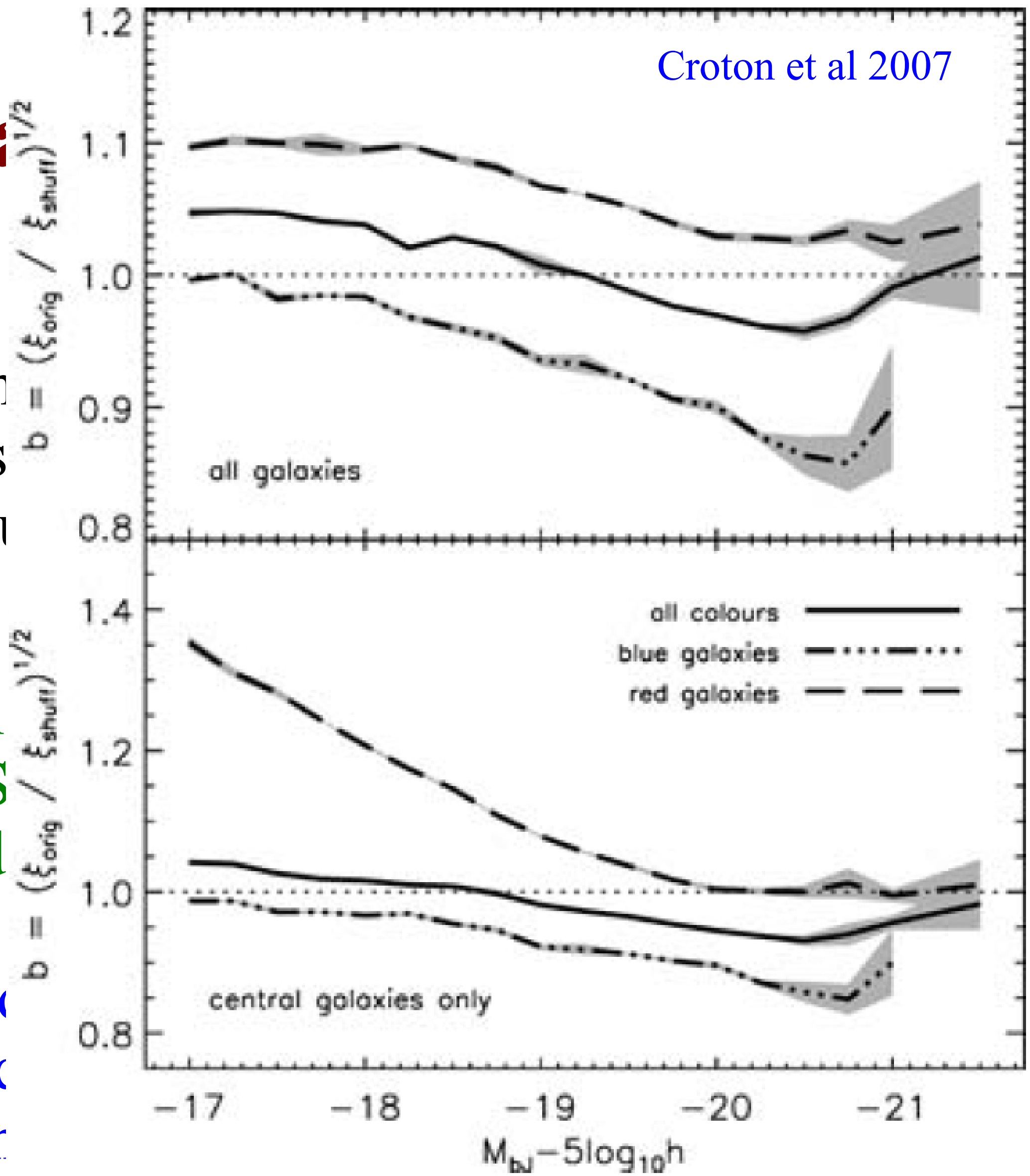

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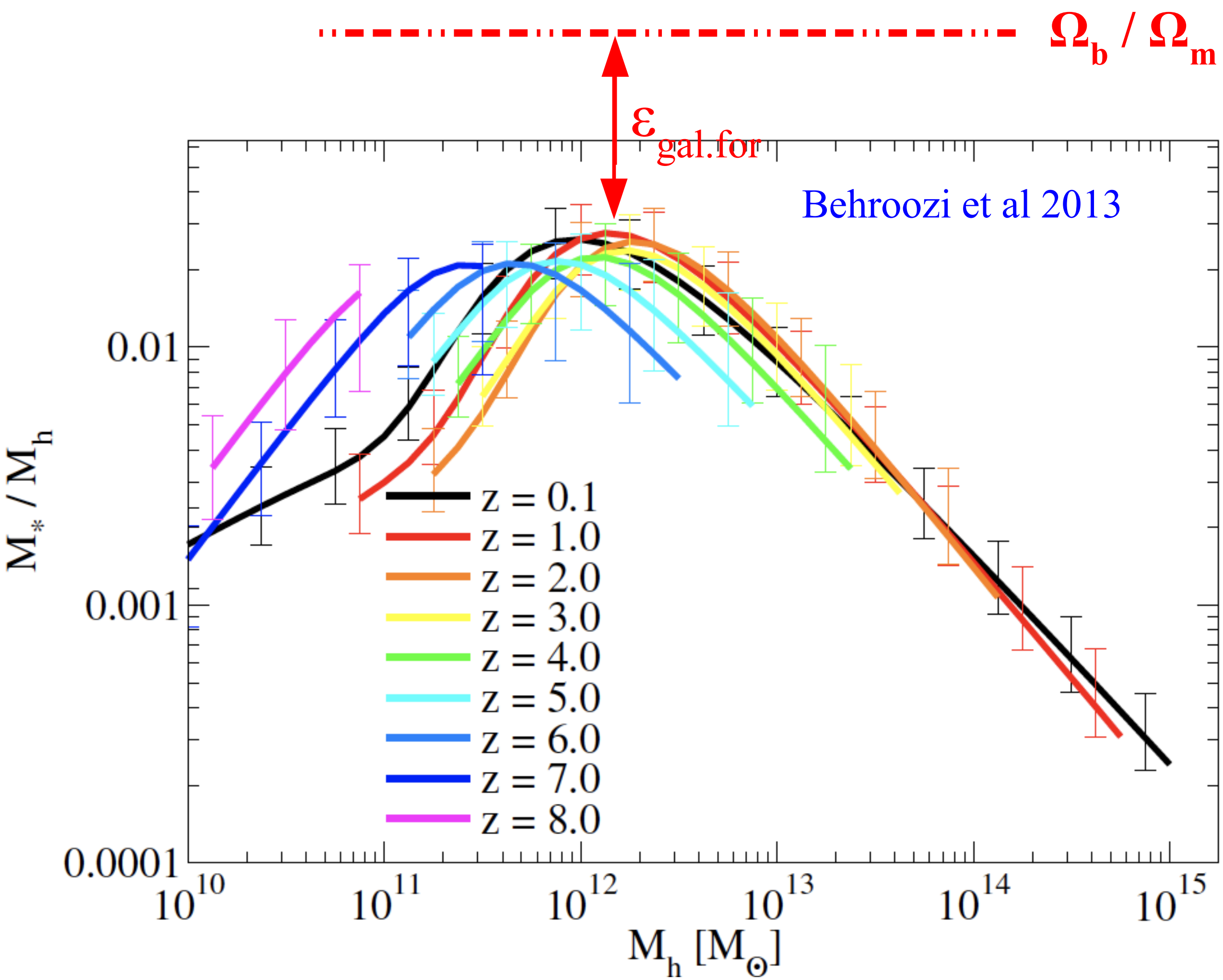

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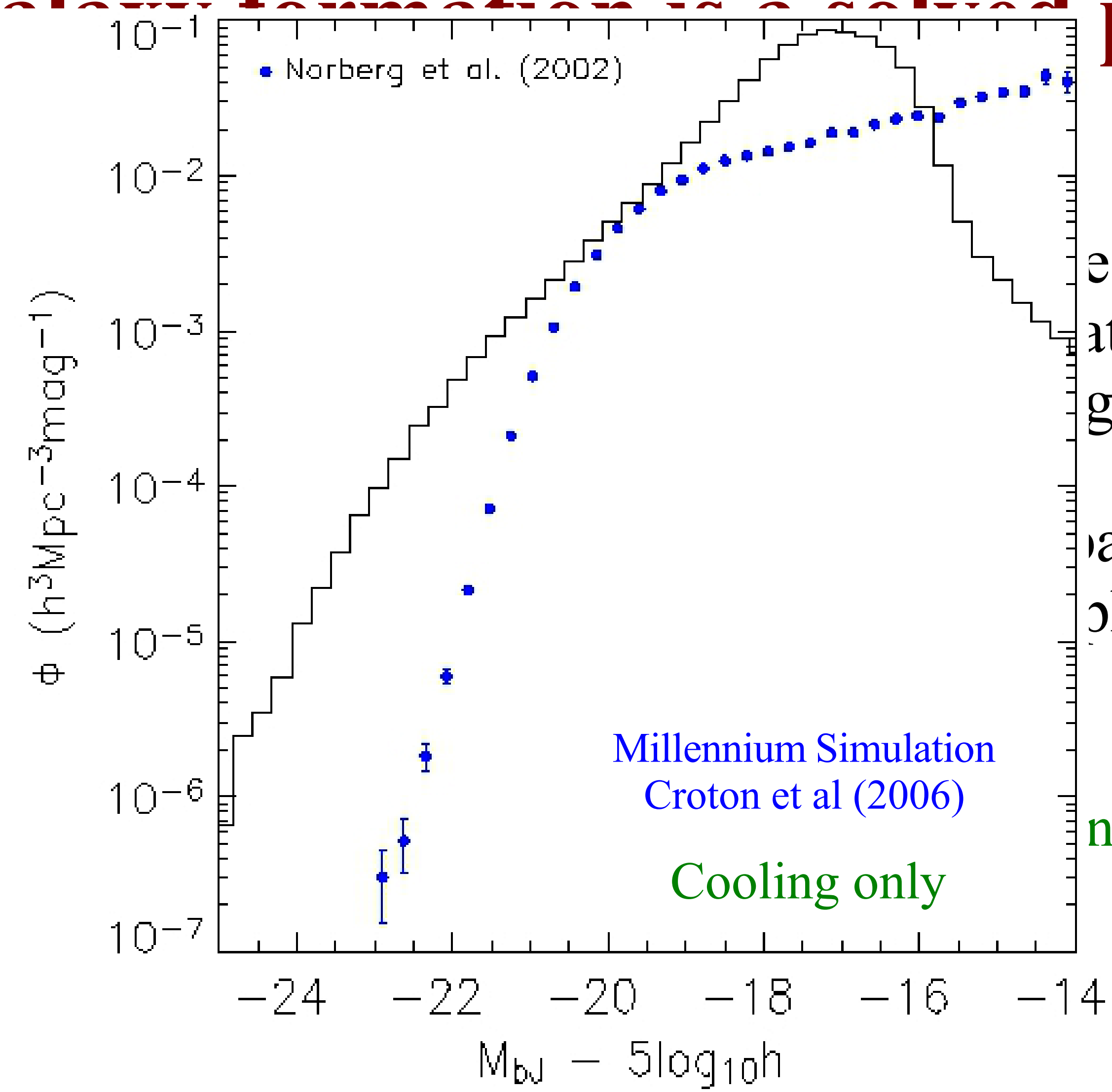

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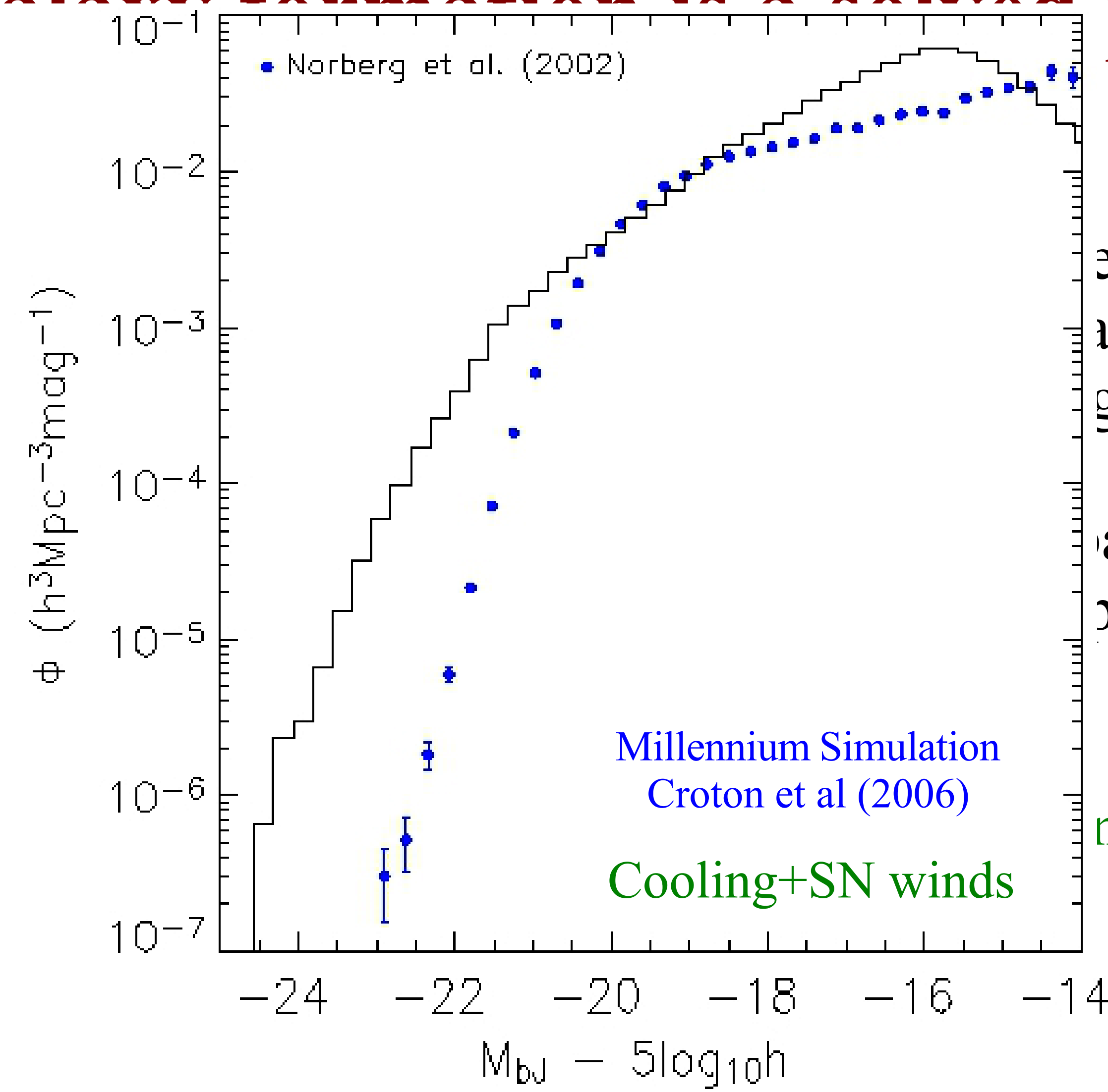

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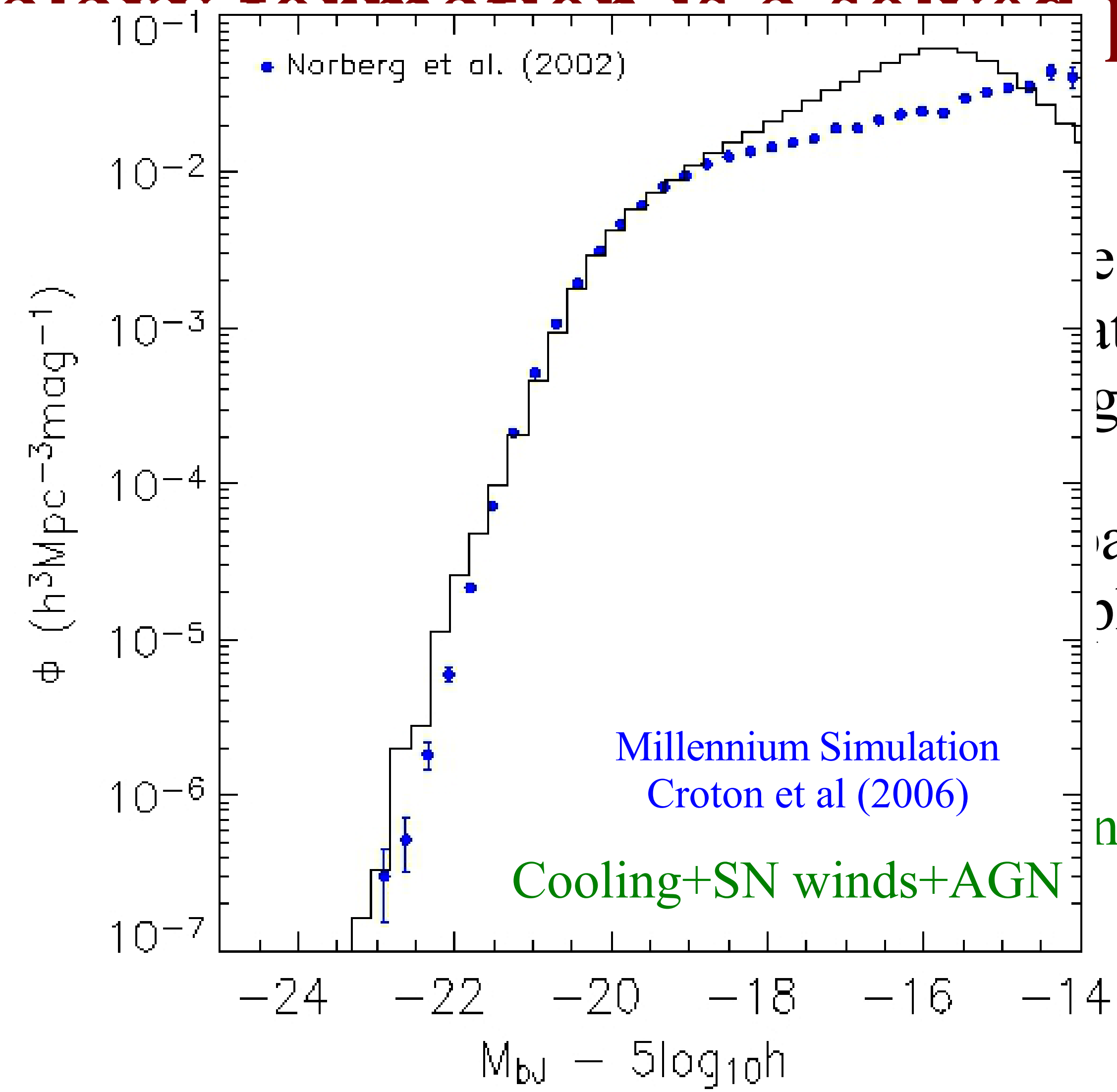

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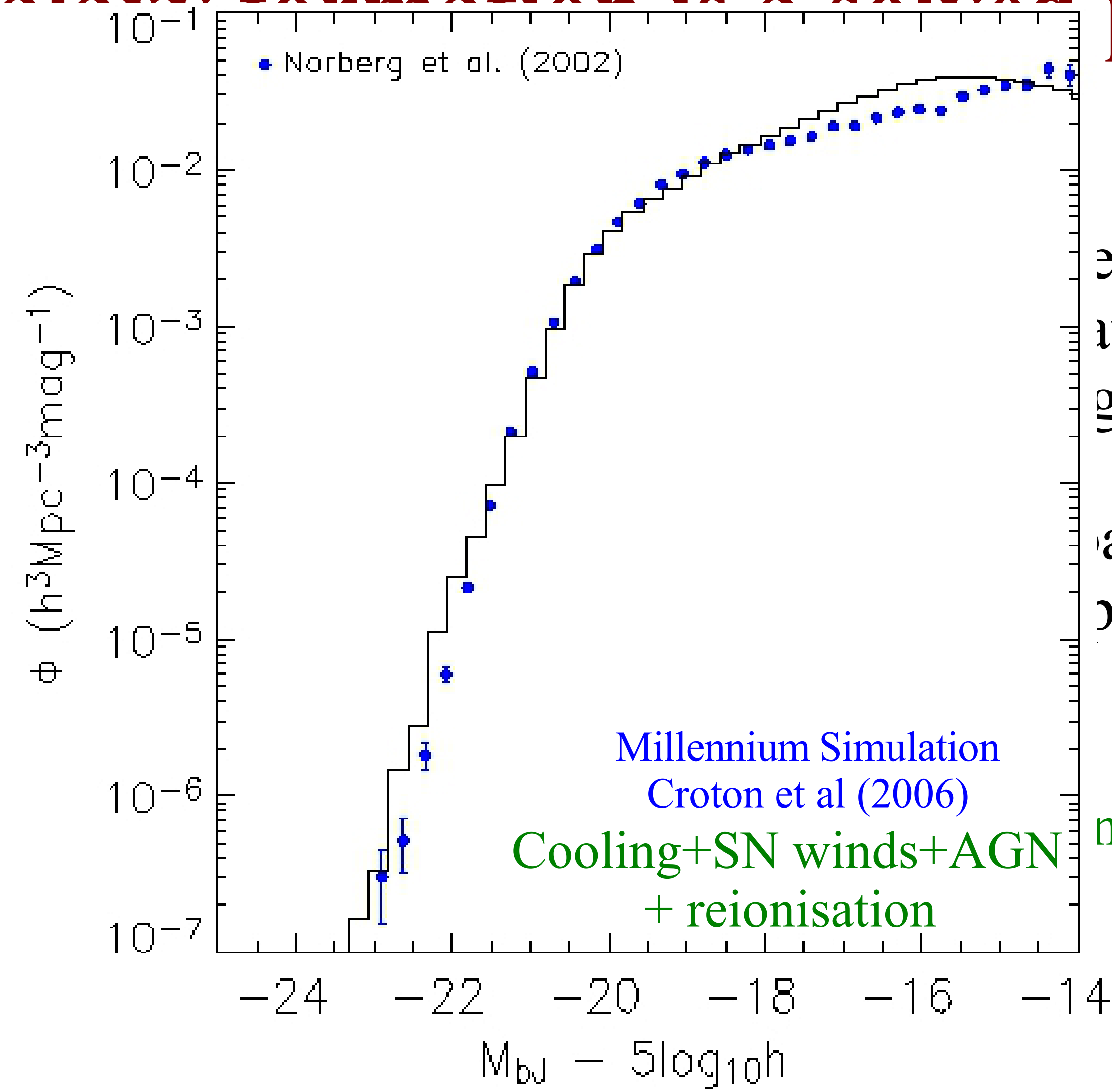

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Main outstanding issues:
I. Mechanical/radiative feedback, B-fields/cosmic rays, ejection/recycling
II. Can "subgrid" processes be sufficiently well/uniquely characterised?

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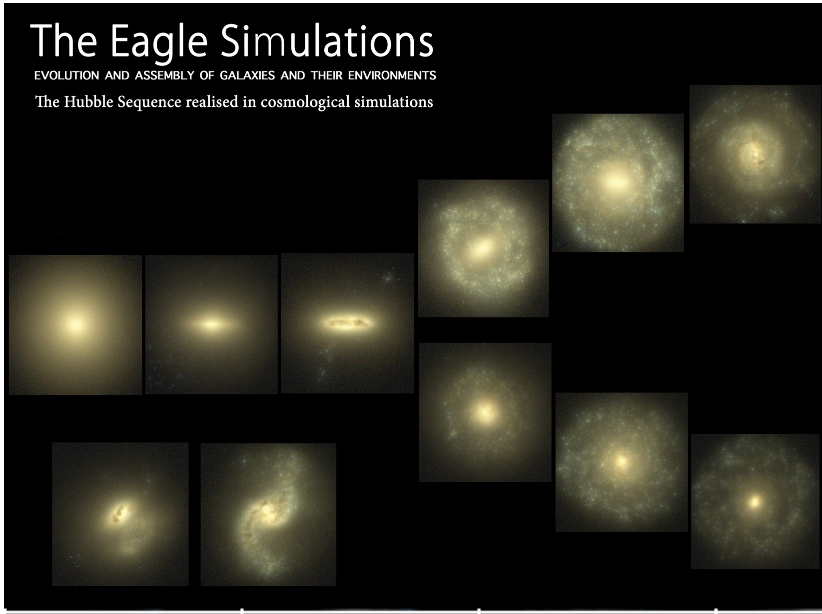
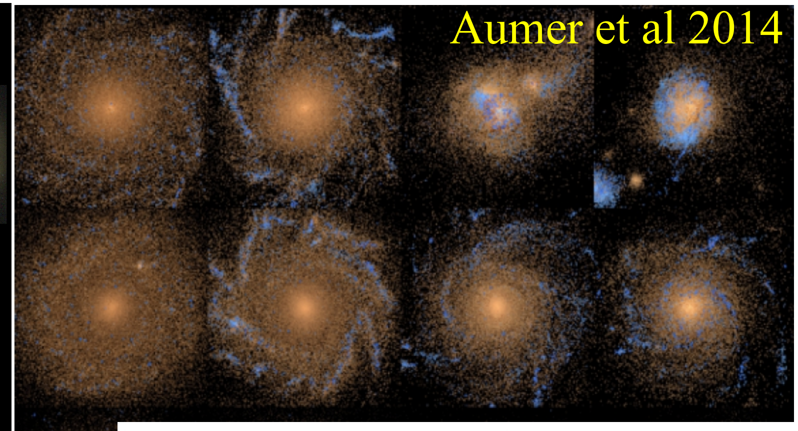
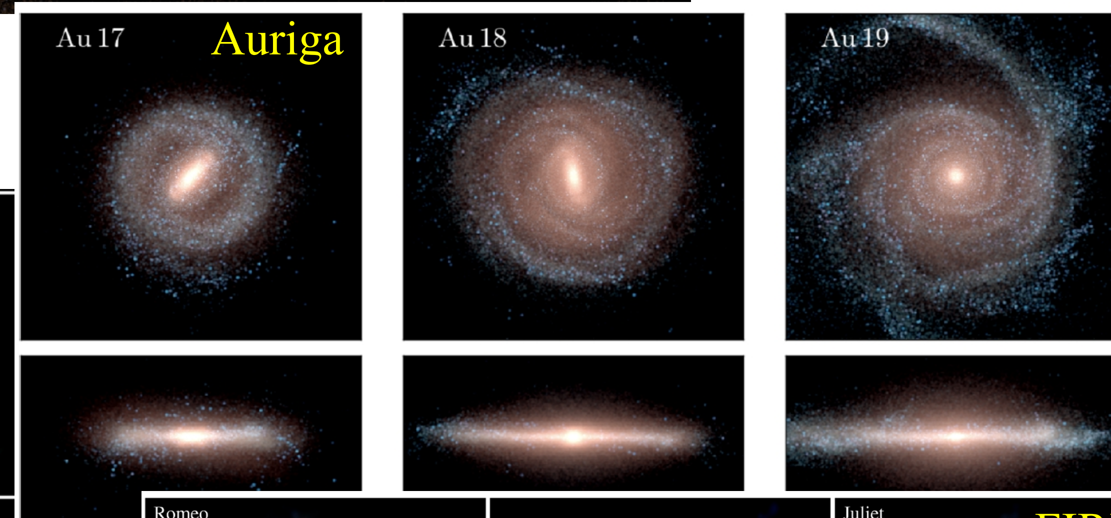
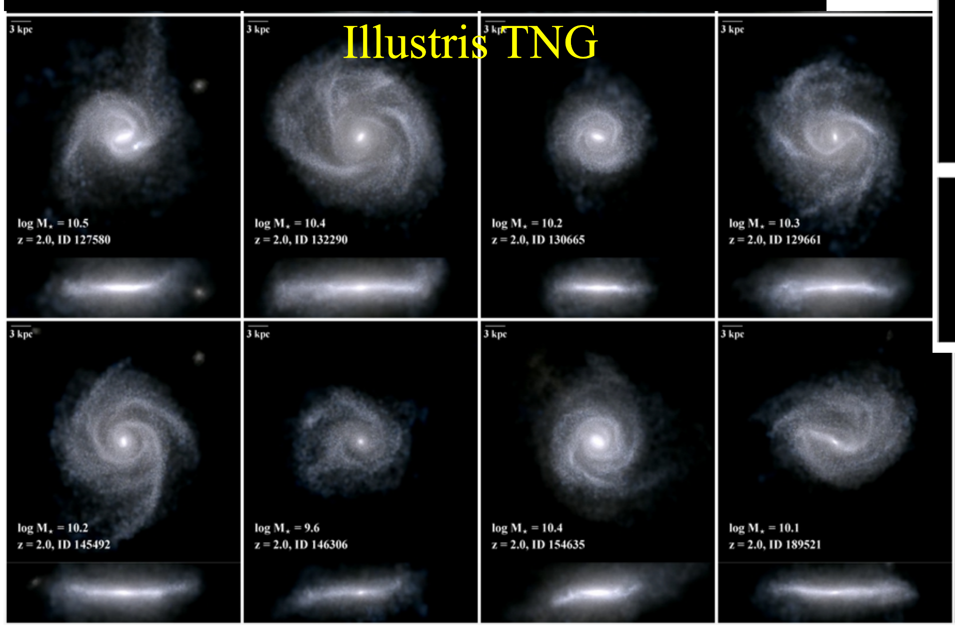
  Tidal torques on protogalaxies.
  Disk formation and instability
  (Lack of) loss in winds, transfer in galactic fountains
  Randomisation in mergers, feeding of AGN

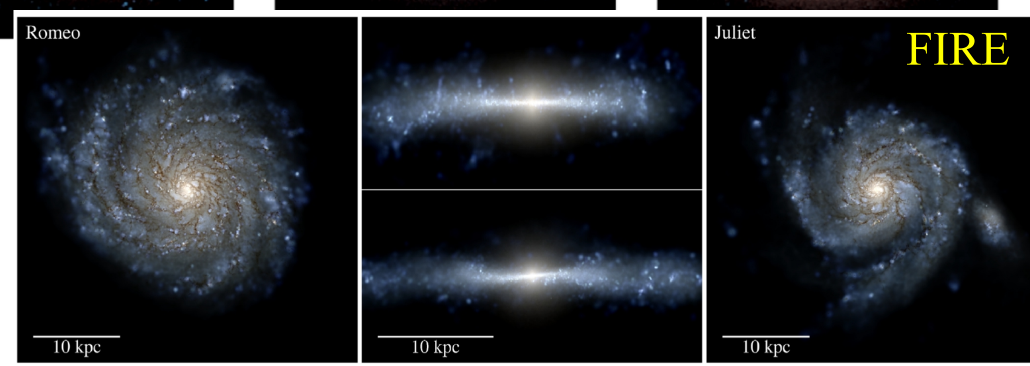
Simulating the structure of galaxies











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

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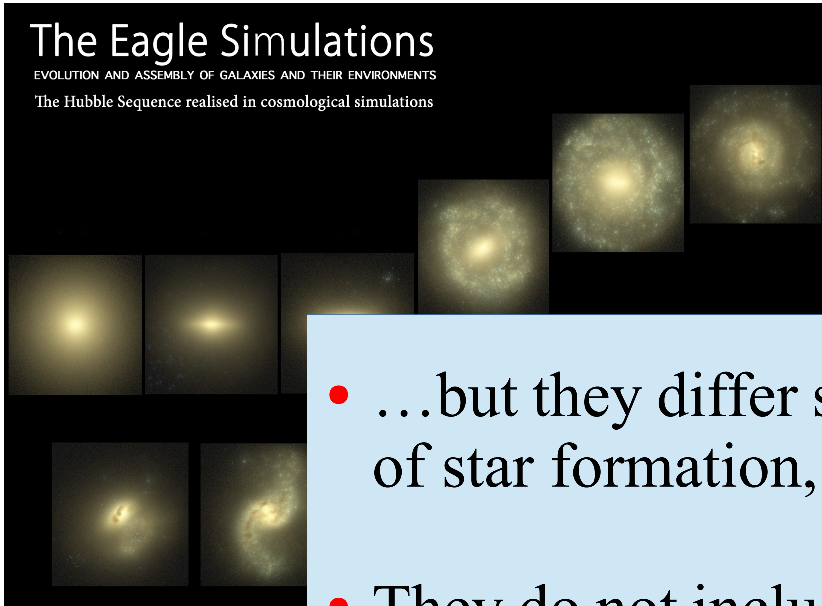

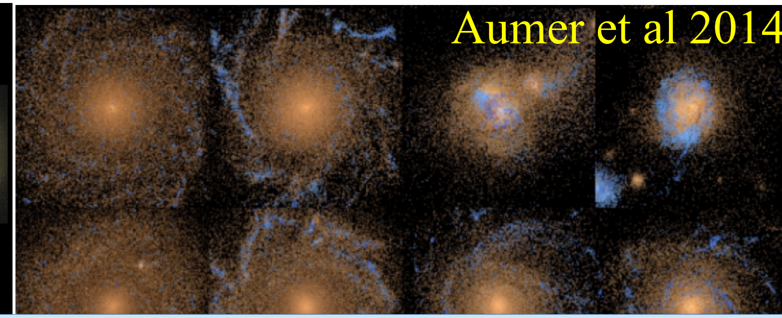

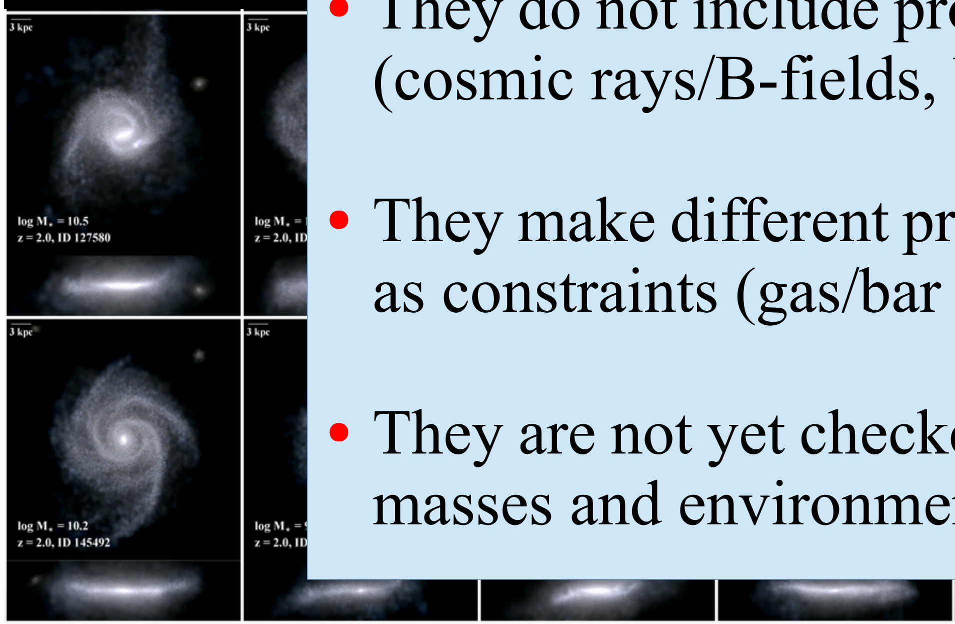

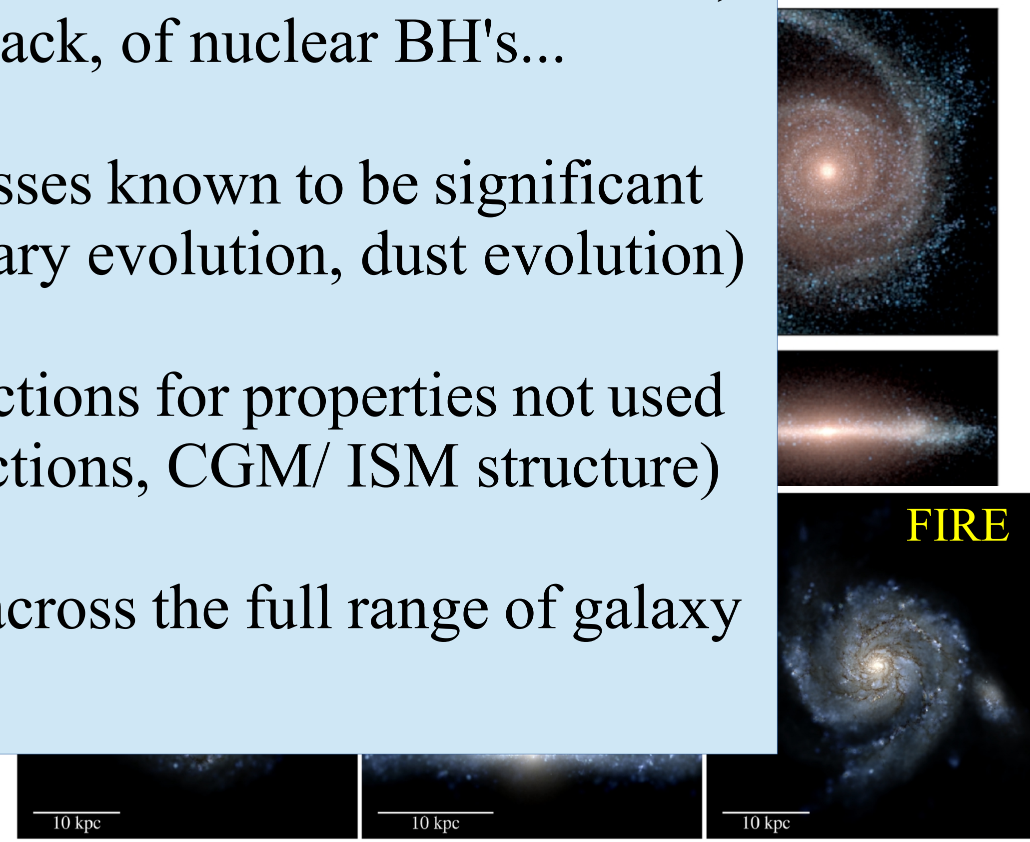

- …but they differ strongly in their treatment of the ISM, of star formation, of feedback, of nuclear BH's...
- They do not include processes known to be significant (cosmic rays/B-fields, binary evolution, dust evolution)
- They make different predictions for properties not used as constraints (gas/bar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

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

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