*Obergurgl. April 2014*

# Formation and growth of galaxies in the young Universe: progress & challenges

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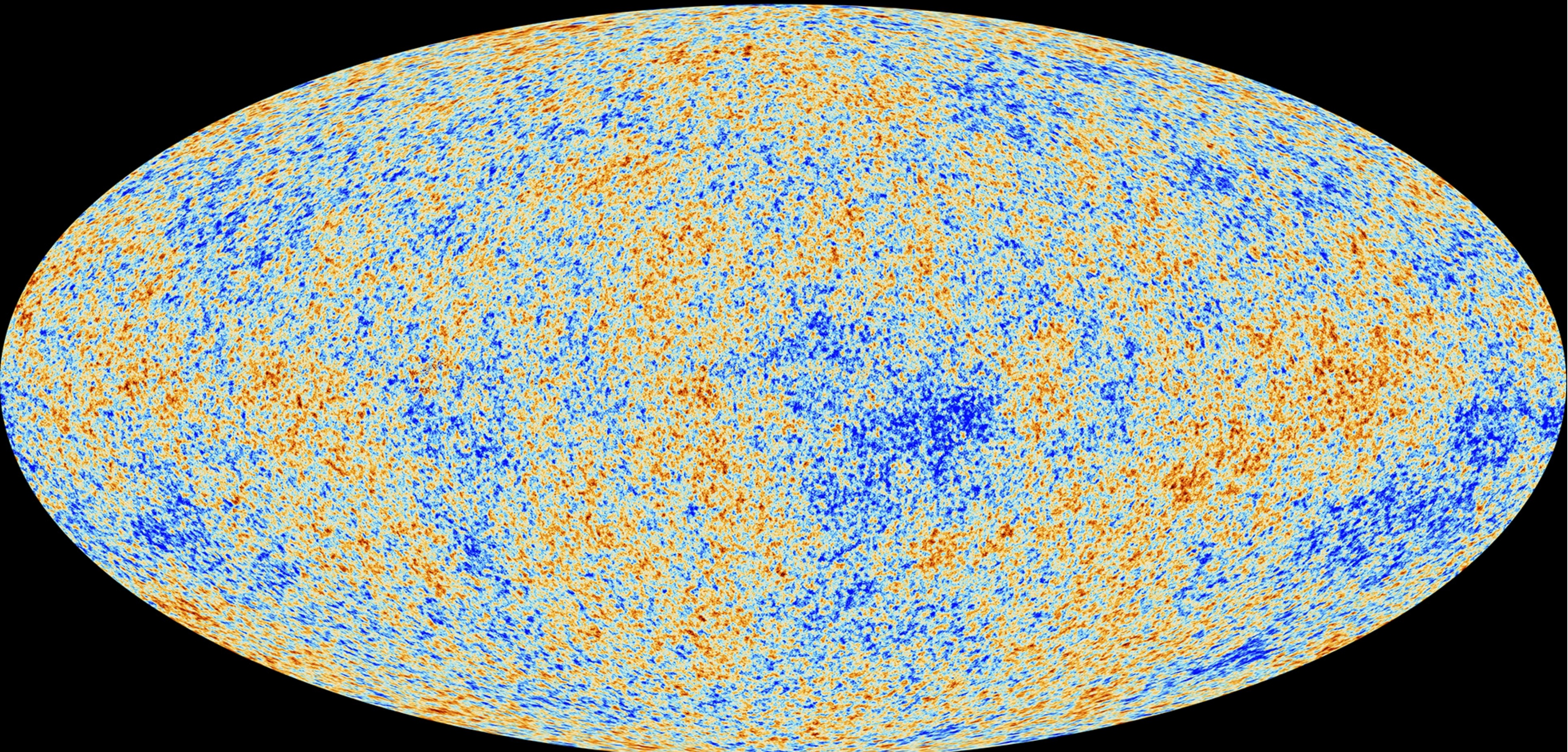
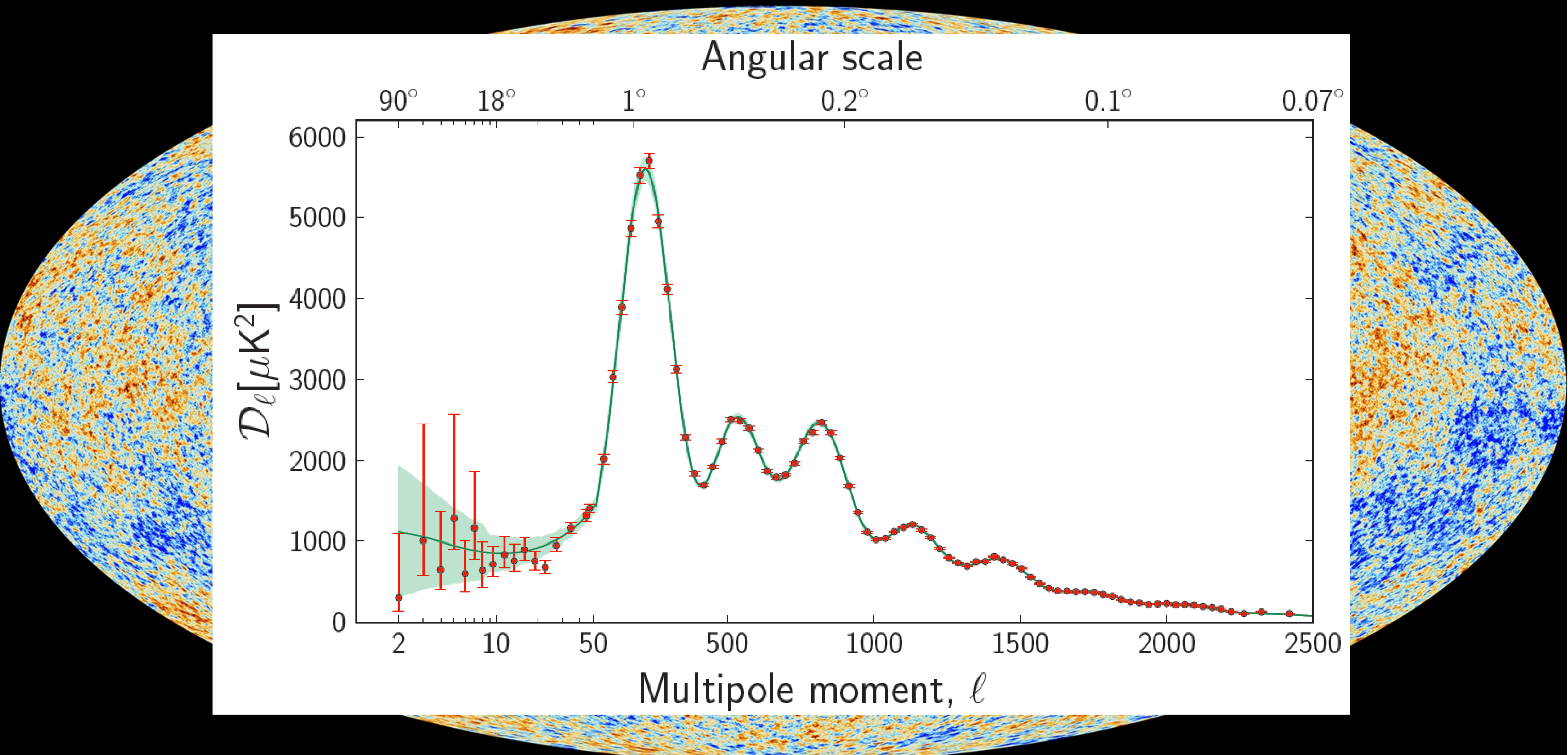
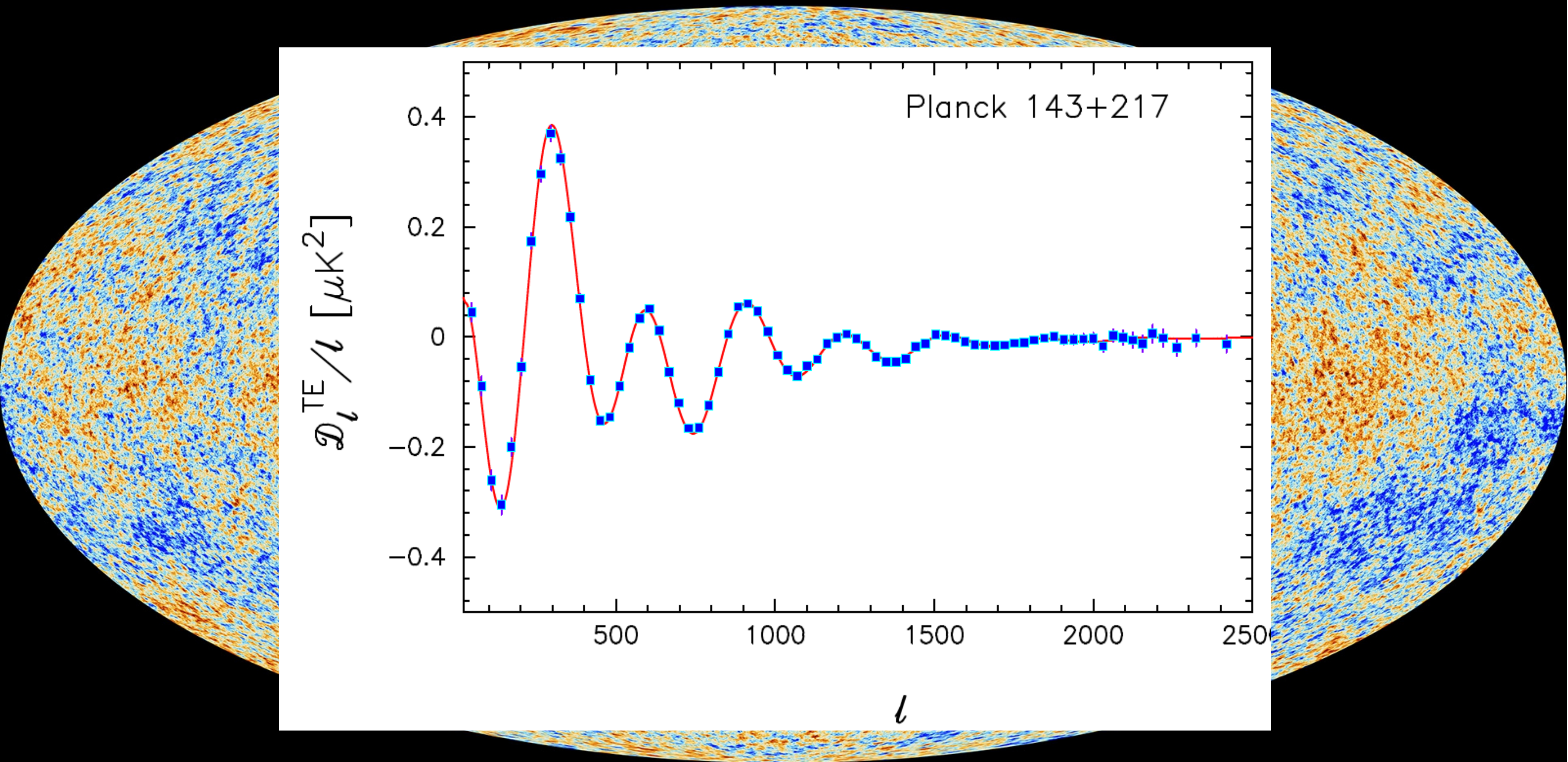
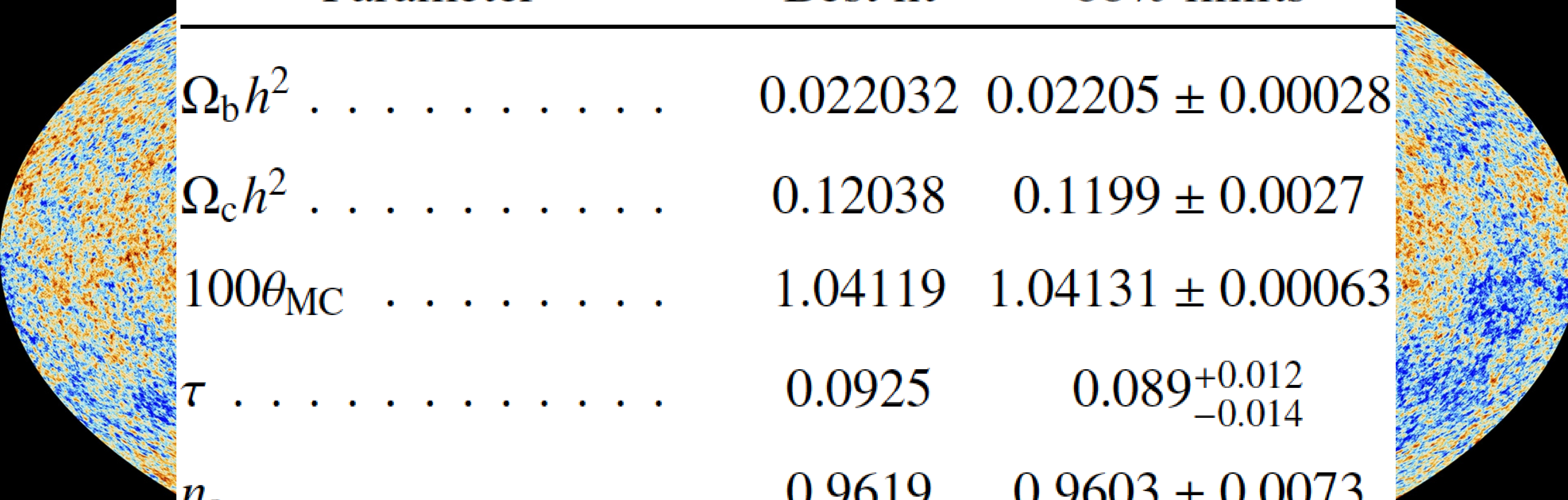
*Max Planck Institute for Astrophysics*




Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, $\ell$

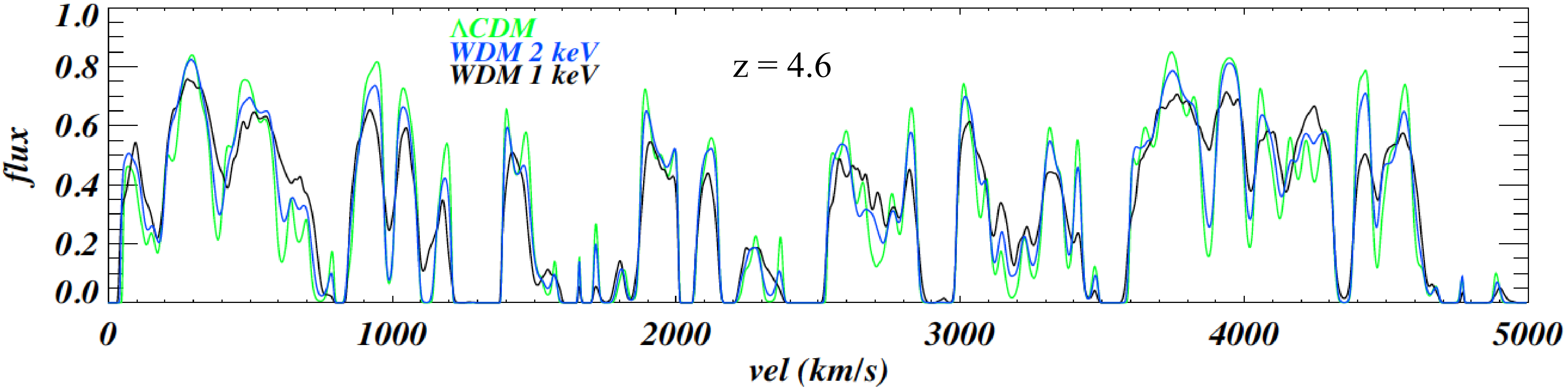

Planck 143+217
0.4
0.2
0
−0.2
−0.4
500
1000
1500
2000
250
$\mathcal{D}_\ell^{TE}/\ell\ [\mu K^2]$
$\ell$



| Parameter | *Planck*+WP Best fit | *Planck*+WP 68% limits |
|---|---|---|
| $\Omega_{\mathrm{b}} h^2$ . . . . . . . . . . | 0.022032 | $0.02205 \pm 0.00028$ |
| $\Omega_{\mathrm{c}} h^2$ . . . . . . . . . . | 0.12038 | $0.1199 \pm 0.0027$ |
| $100\theta_{\mathrm{MC}}$ . . . . . . . . | 1.04119 | $1.04131 \pm 0.00063$ |
| $\tau$ . . . . . . . . . . . . | 0.0925 | $0.089^{+0.012}_{-0.014}$ |
| $n_{\mathrm{s}}$ . . . . . . . . . . . | 0.9619 | $0.9603 \pm 0.0073$ |
| $\ln(10^{10} A_{\mathrm{s}})$ . . . . . . . | 3.0980 | $3.089^{+0.024}_{-0.027}$ |

# Ly α forest spectra and small-scale initial structure

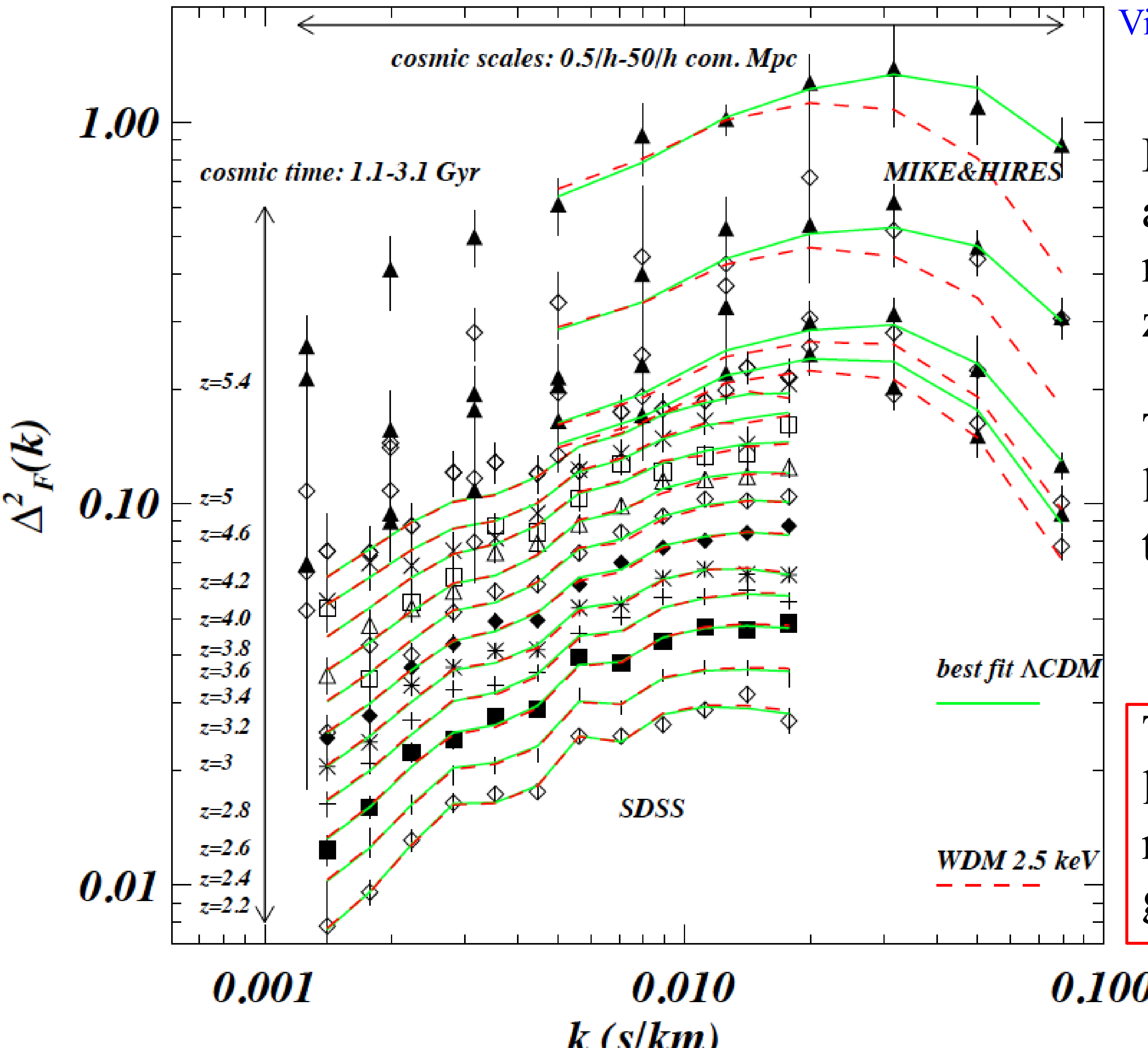
Viel, Becker, Bolton & Haehnelt 2013




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

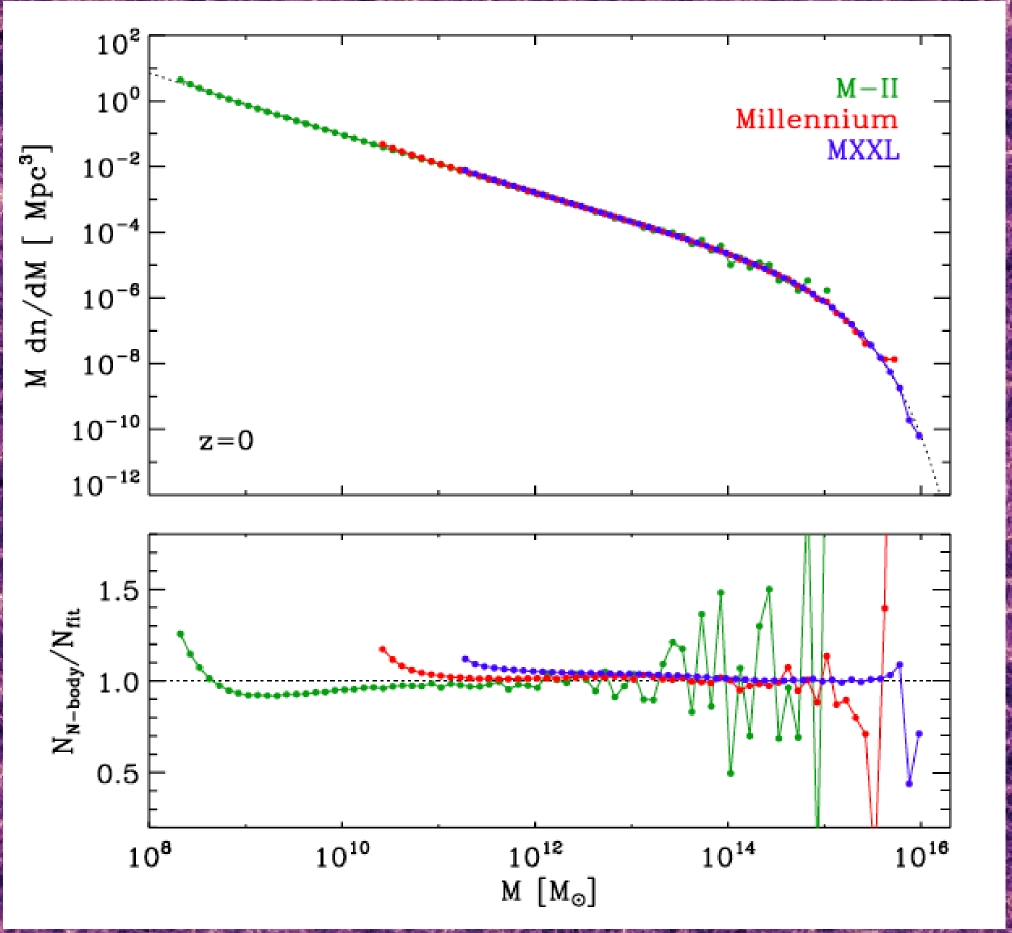
High-resolution Keck and Magellan spectra match ΛCDM up to z = 5.4

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

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



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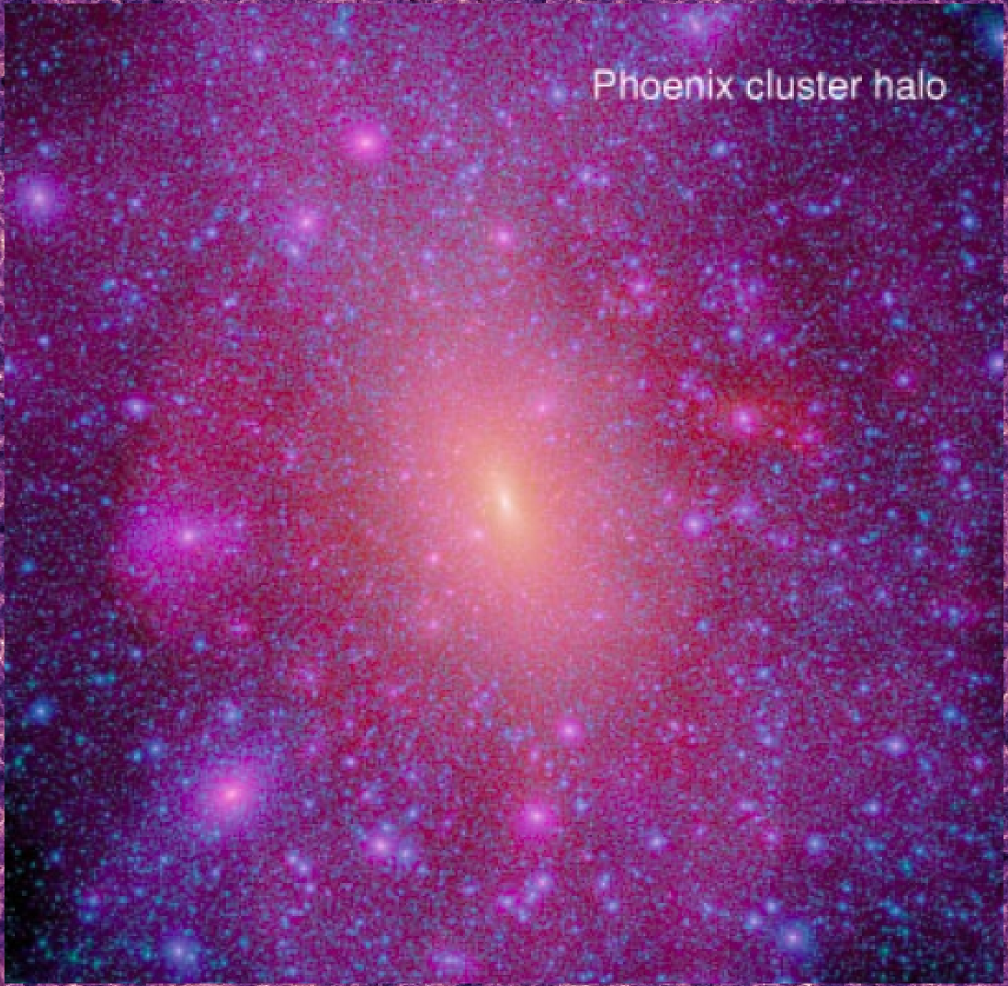
Galaxies correspond to self-bound *subhalos* within halos, rather than to the halos themselves



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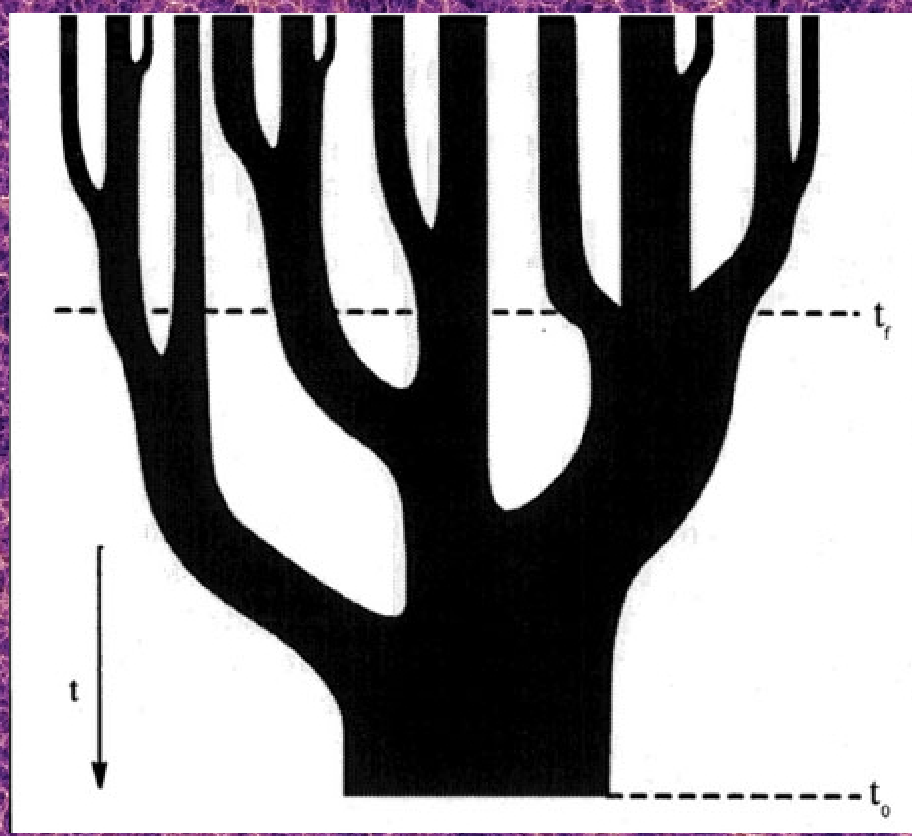
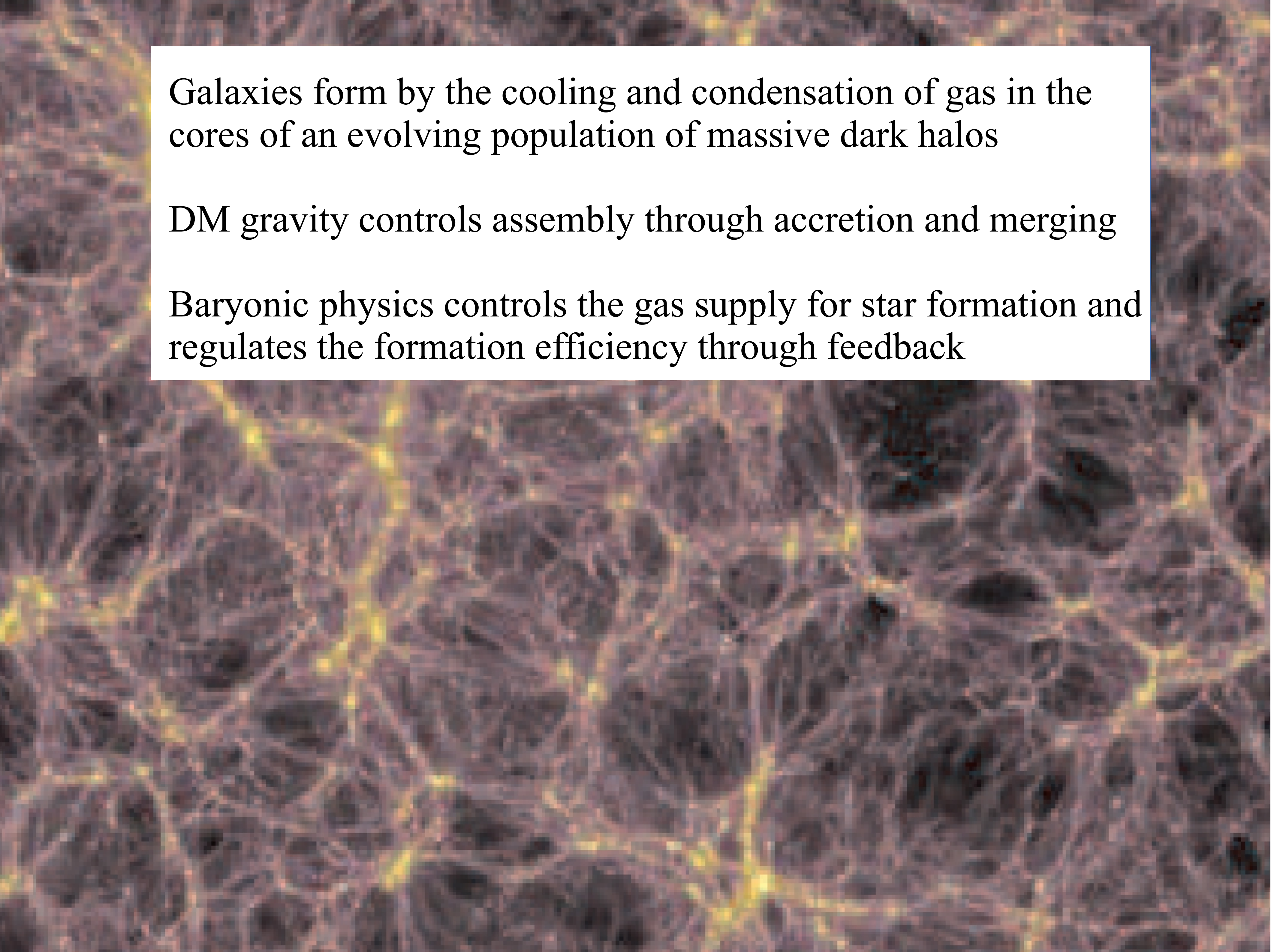
The information relevant to galaxy formation is encoded in *sub*halo merger trees



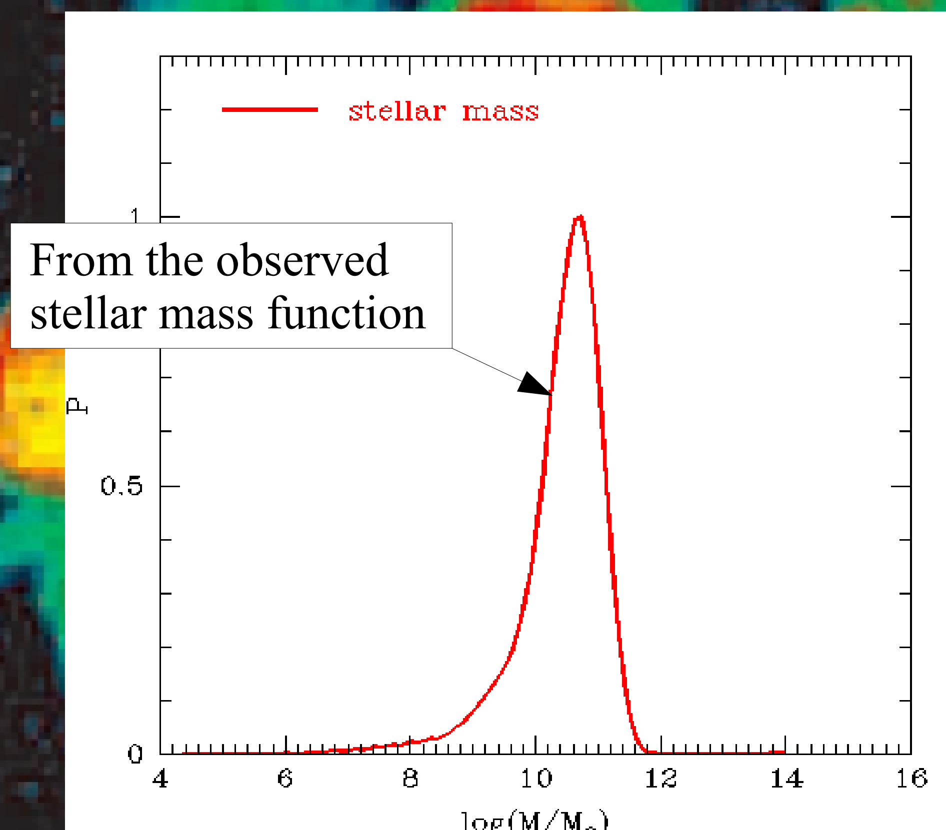


Galaxies form by the cooling and condensation of gas in the cores of an evolving population of massive dark halos

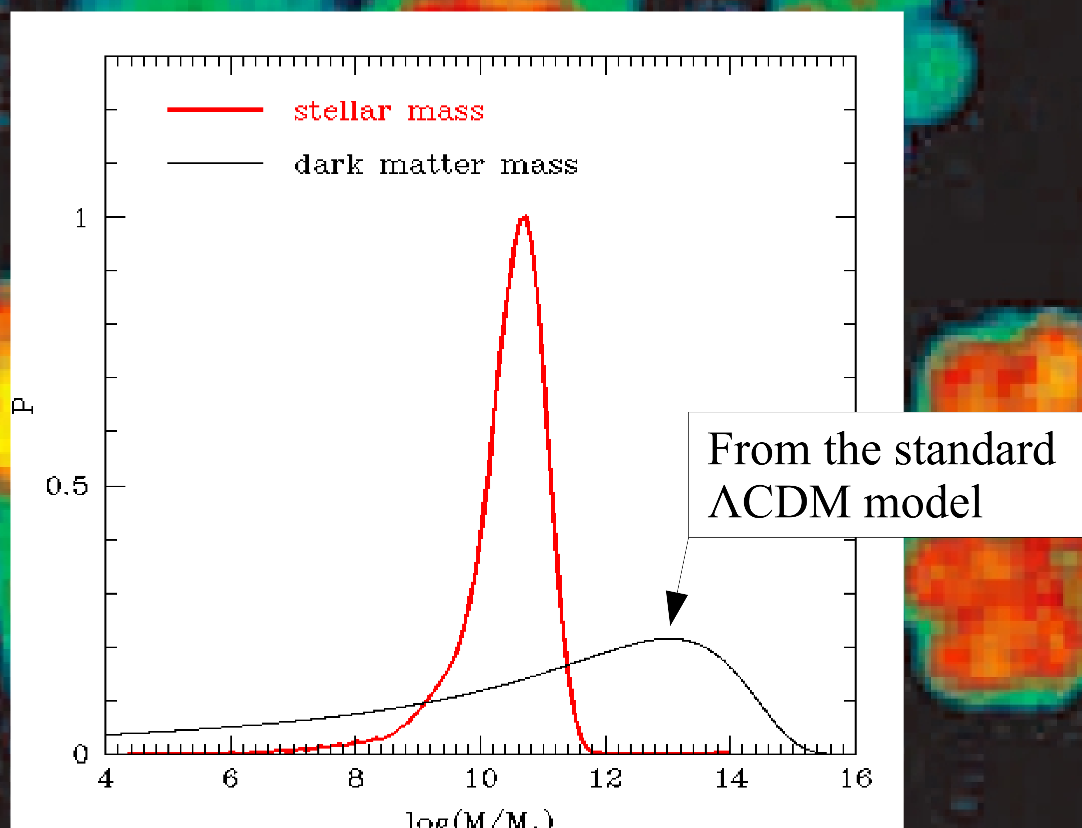
DM gravity controls assembly through accretion and merging

Baryonic physics controls the gas supply for star formation and regulates the formation efficiency through feedback

# 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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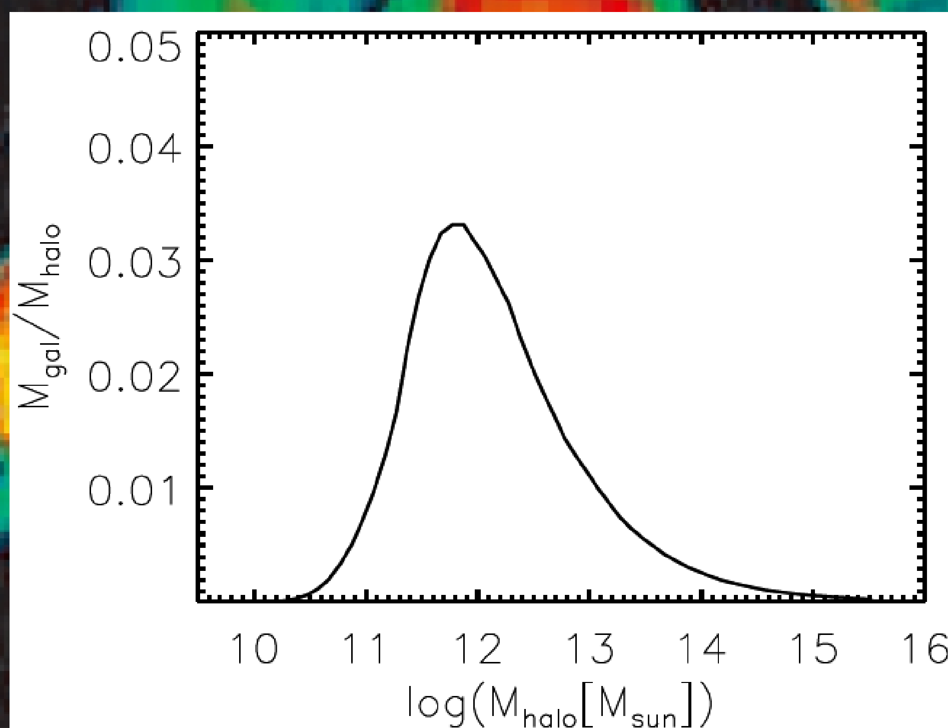

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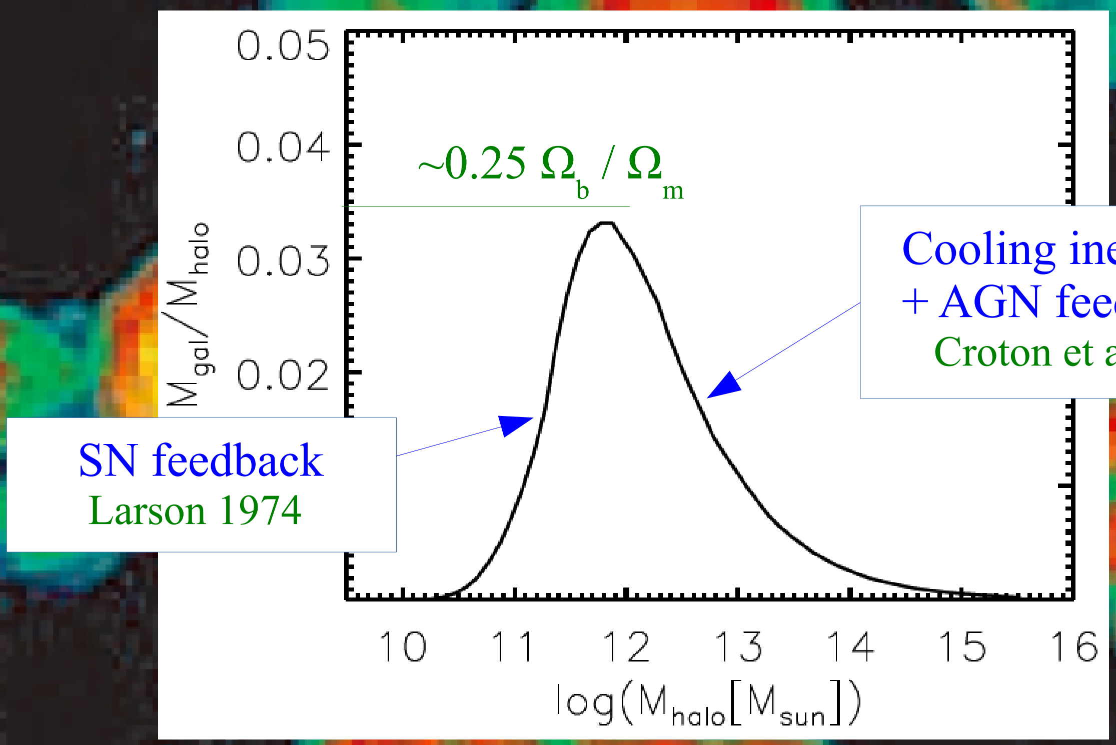
→ Halo to galaxy mass ratio varies *strongly* with mass

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



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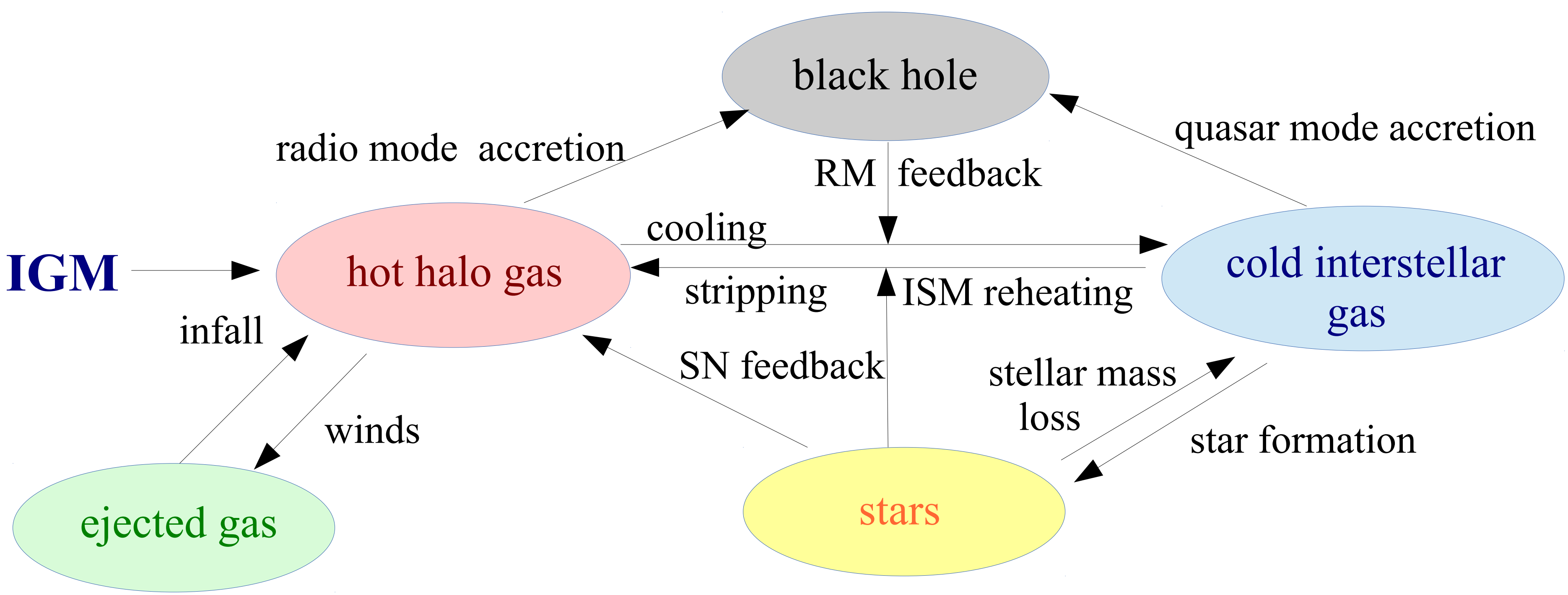
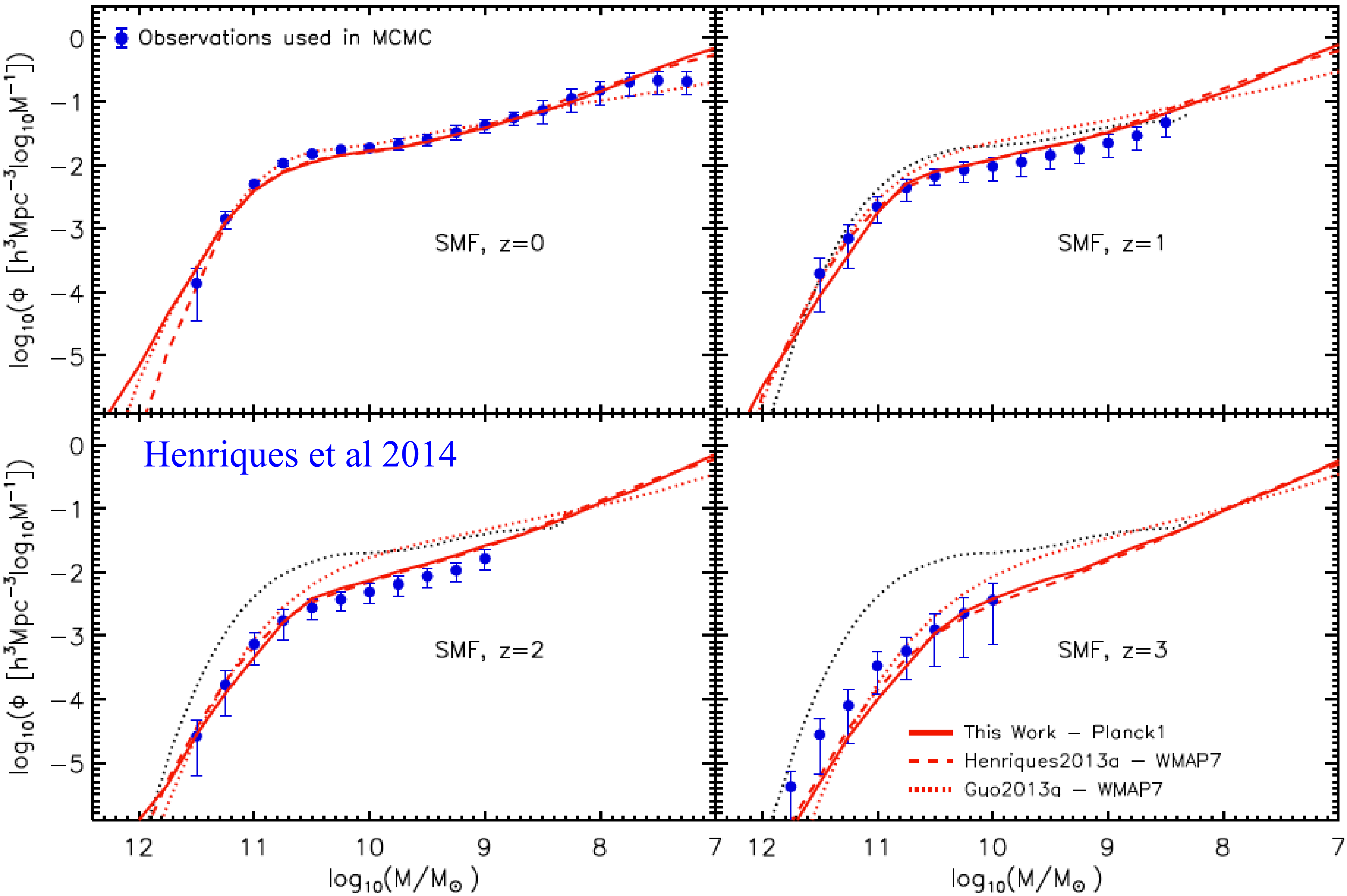
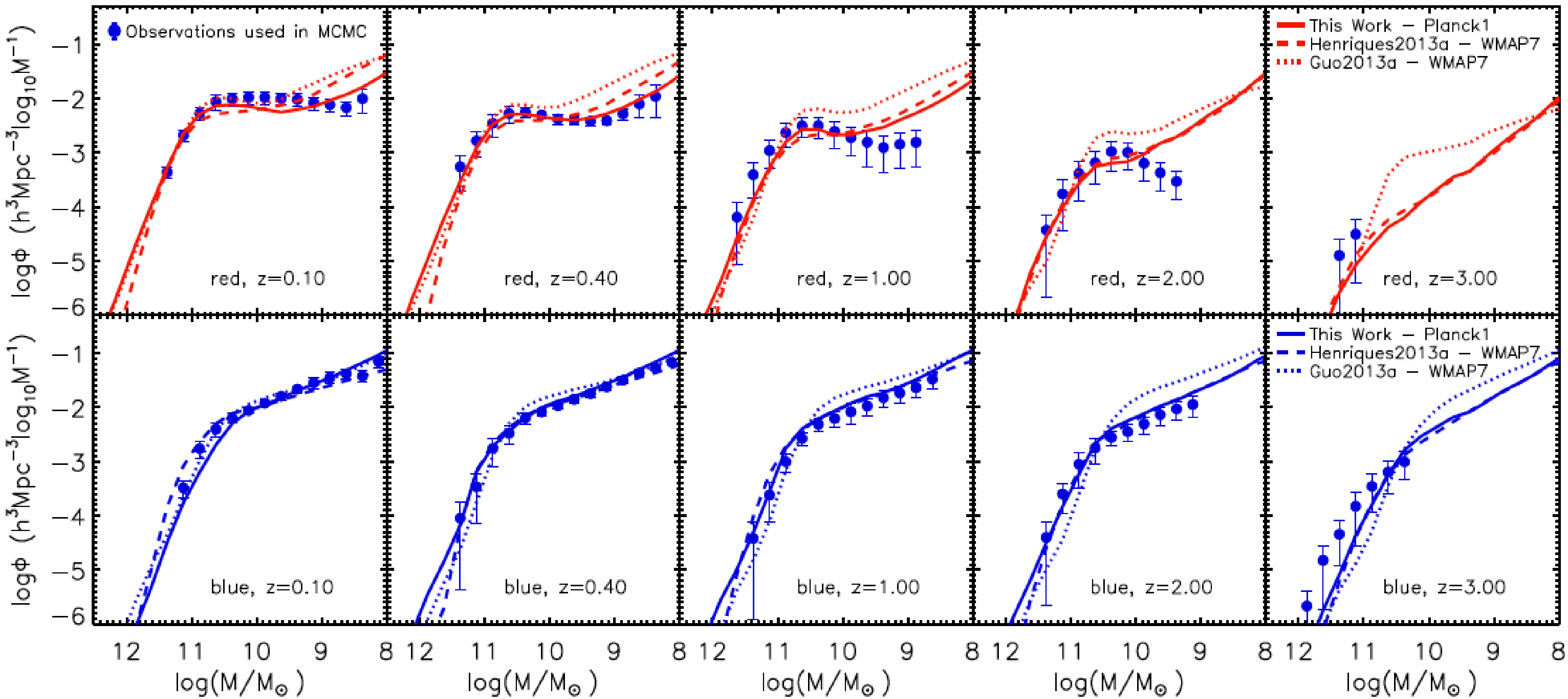
$$(\Omega_b / \Omega_m)\, M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$$





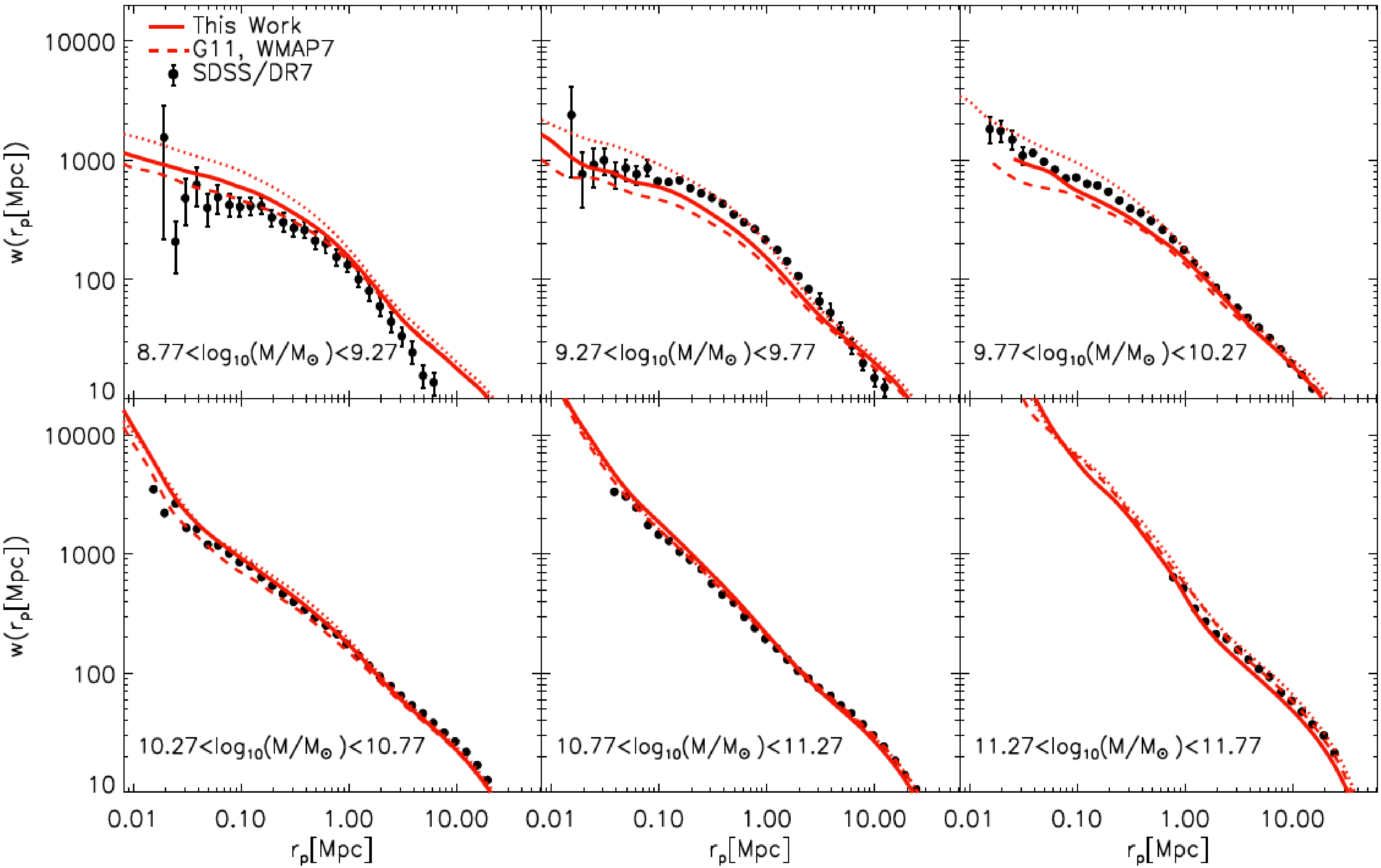

Plausible models for the efficiency of cooling/condensation, star formation, stellar and AGN feedback reproduce galaxy abundances for $0 < z < 3$

Henriques et al 2014




Plausible models for the efficiency of cooling/condensation, star formation, stellar and AGN feedback reproduce galaxy abundances for $0 < z < 3$ for both passive and actively star-forming galaxies

Henriques et al 2014b




....and can be tested against measures of clustering both at z = 0

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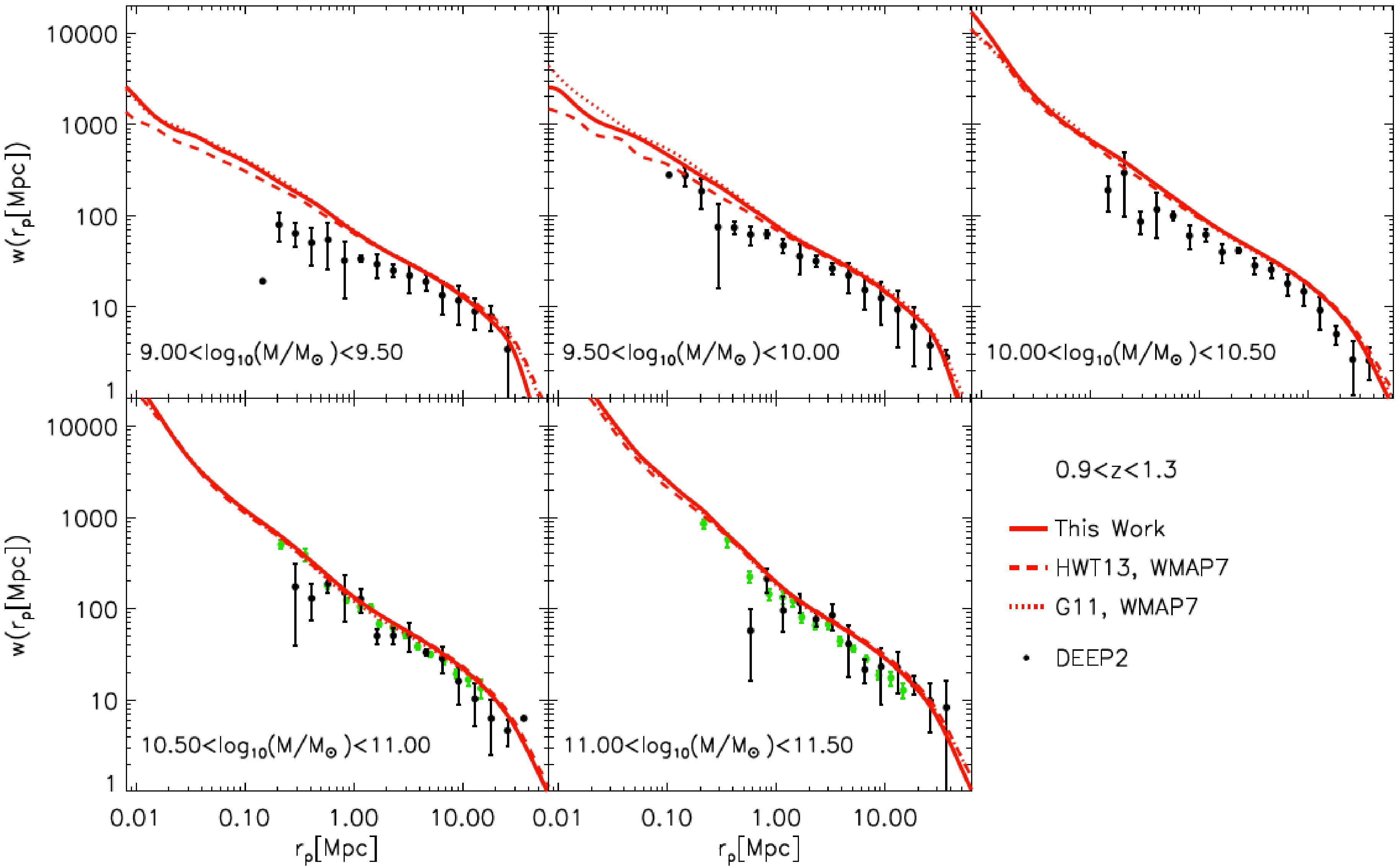
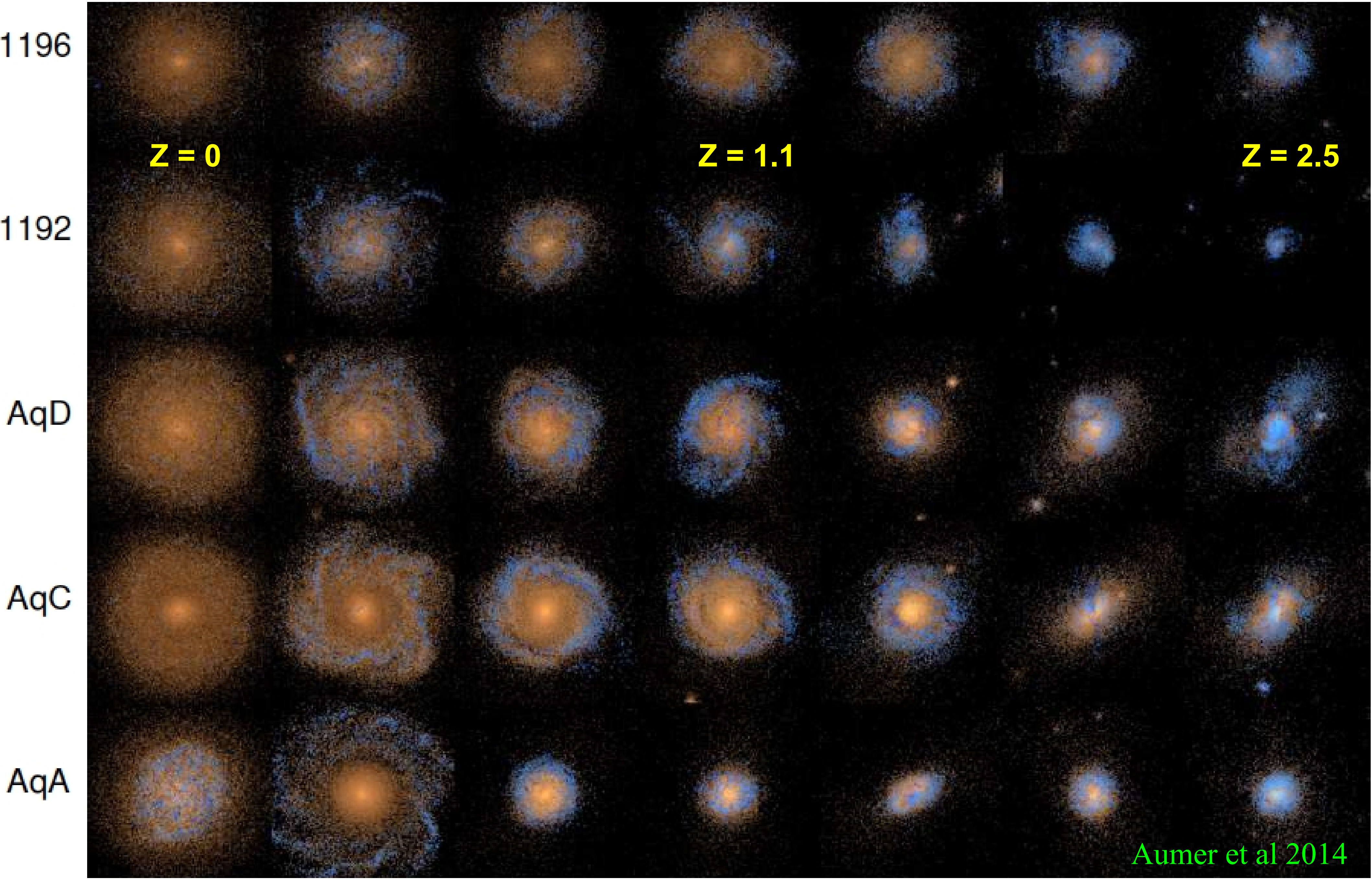
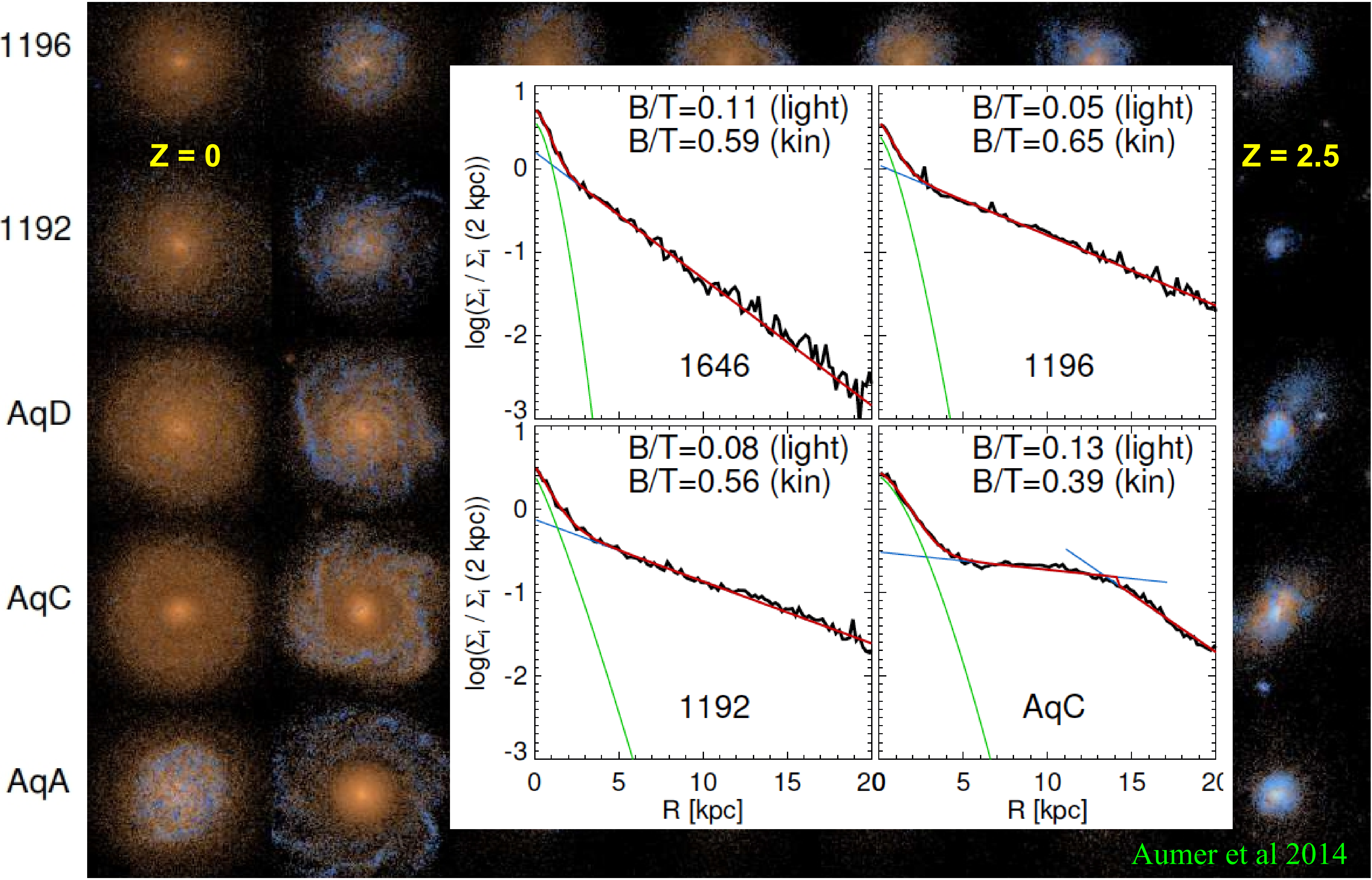



....and can be tested against measures of clustering both at z = 0 and at z = 1



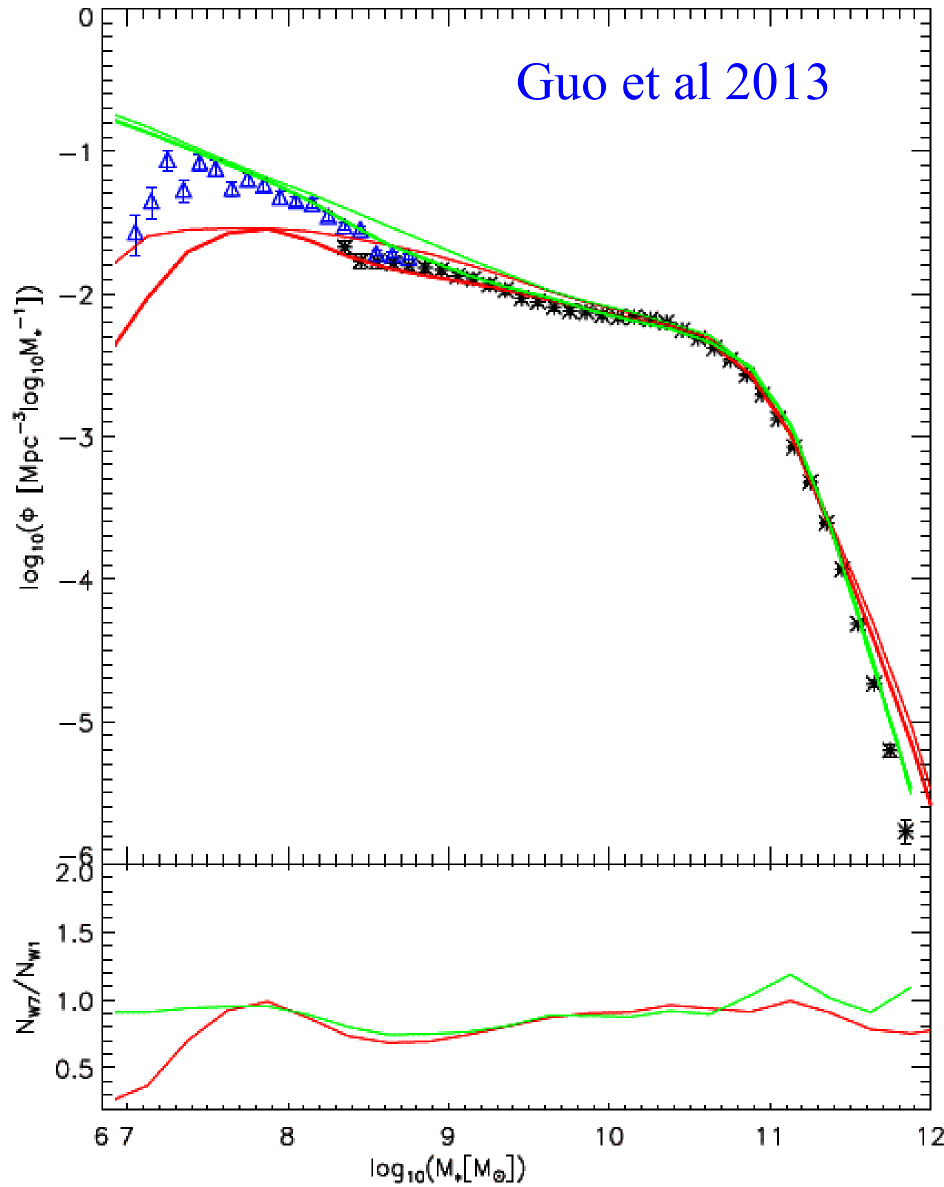

Plausible efficiencies also result in disc galaxy formation




Plausible efficiencies also result in disc galaxy formation with dominant discs and photometric profiles similar to observation

# Challenges?

- Cosmology sensitivity is very weak
  → data primarily constrain astrophysics



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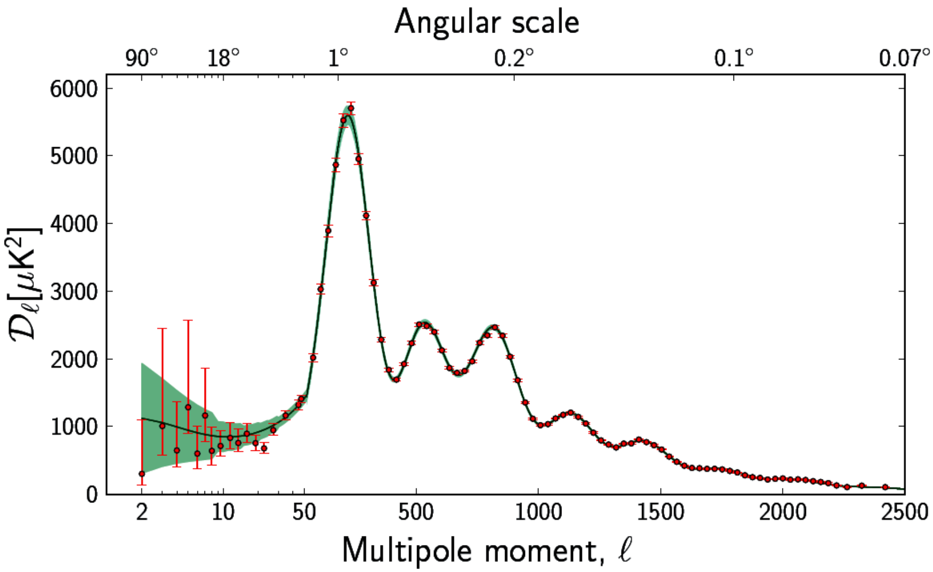

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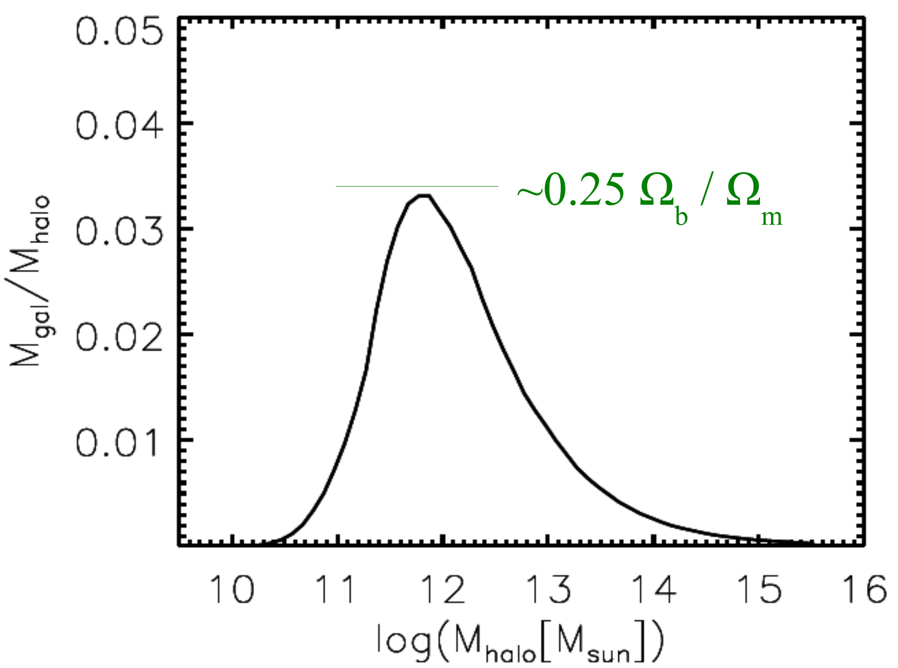
→ most ejected into the IGM by winds?



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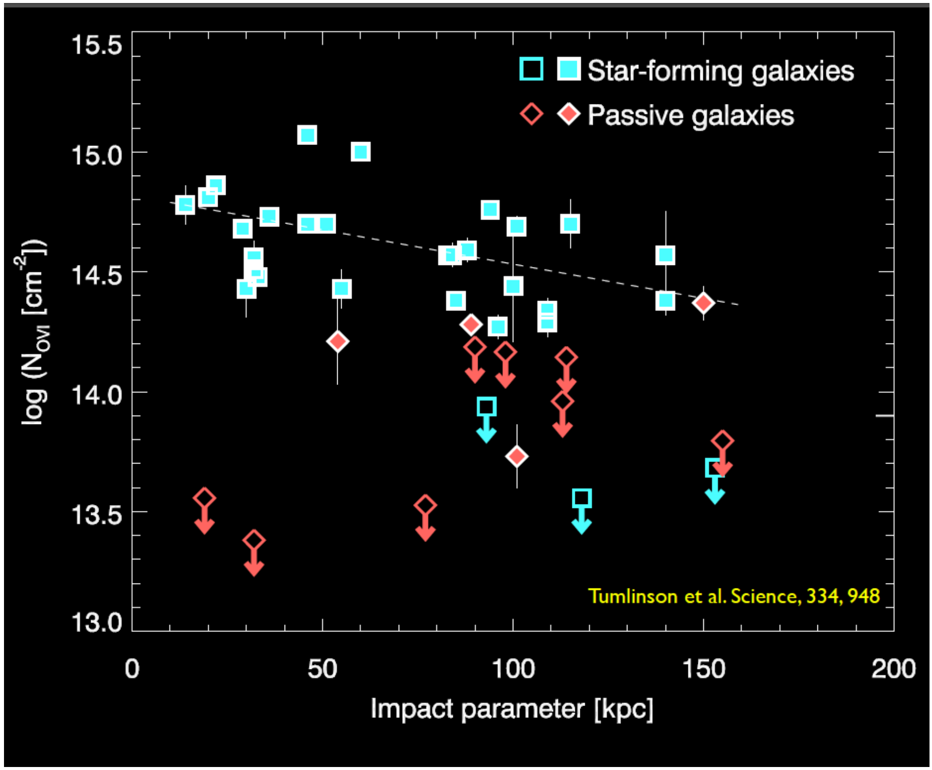
- The observed galaxies also account for only a small fraction of the metals
  → inflow/outflow are *both* big effects



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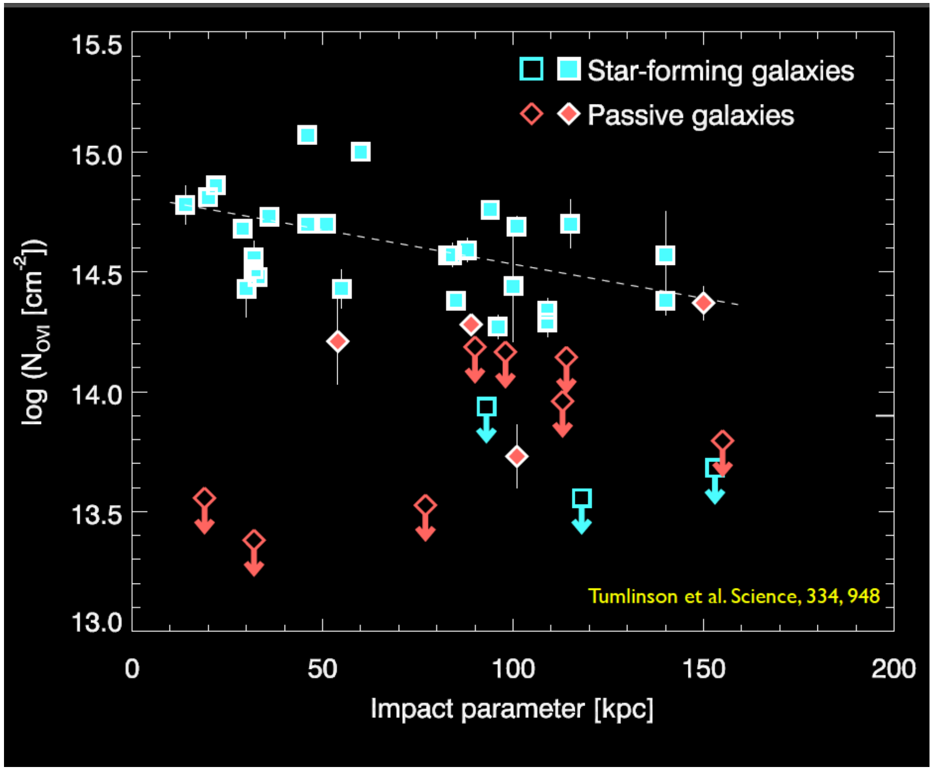


- Plausible scalings/efficiencies will likely explain N(M*, sSFR, Z, z)

- Clustering properties will constrain environmental effects

- Gas and IGM properties are critical and are currently poorly constrained

# Promising frontiers?

- The high redshift universe
  - What did the first objects look like? (galaxies? SN? BH?)
  - Where did they form?
  - How did they drive/structure/interact with reionisation?
- The intergalactic/circumgalactic medium
  - What is the large-scale morphology/filling factor of wind cavities?
  - Is their growth driven by thermal or nonthermal pressure?
  - What is the phase and metallicity structure of the gas within them?
  - How does this influence later galaxy growth?
  - Can they bias cosmological inferences from the Ly α forest?
- The cold gas content of high redshift galaxies
  - Molecular line emission (ALMA)
  - Dust emission (Planck, Herschel....)
- The internal structure of high redshift galaxies
  - Differentiation and growth of disks, bulges, bars, stellar halos..