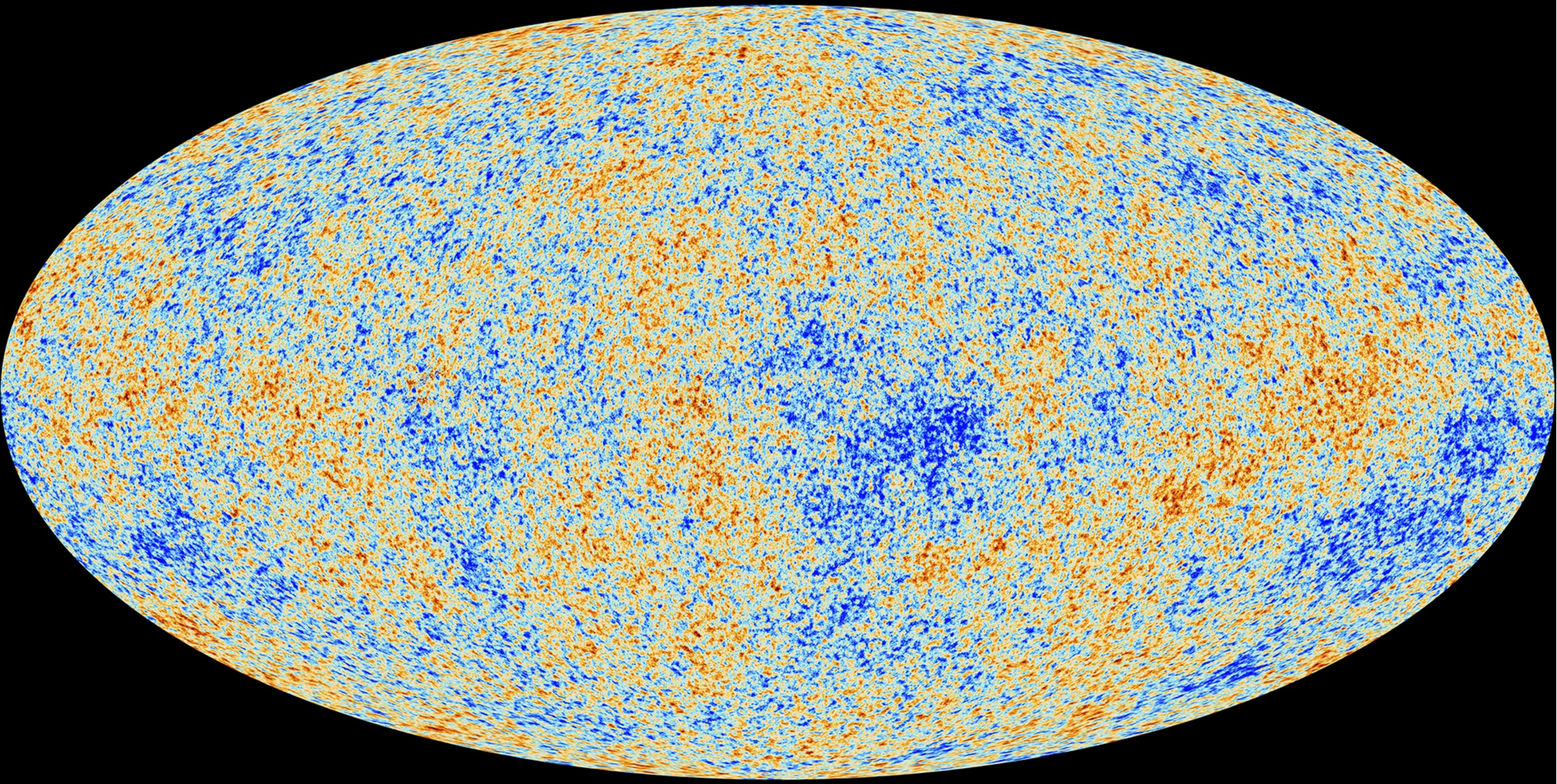
The Galaxy Ecosystem
ESO/Exzellenzcluster workshop
July 2017

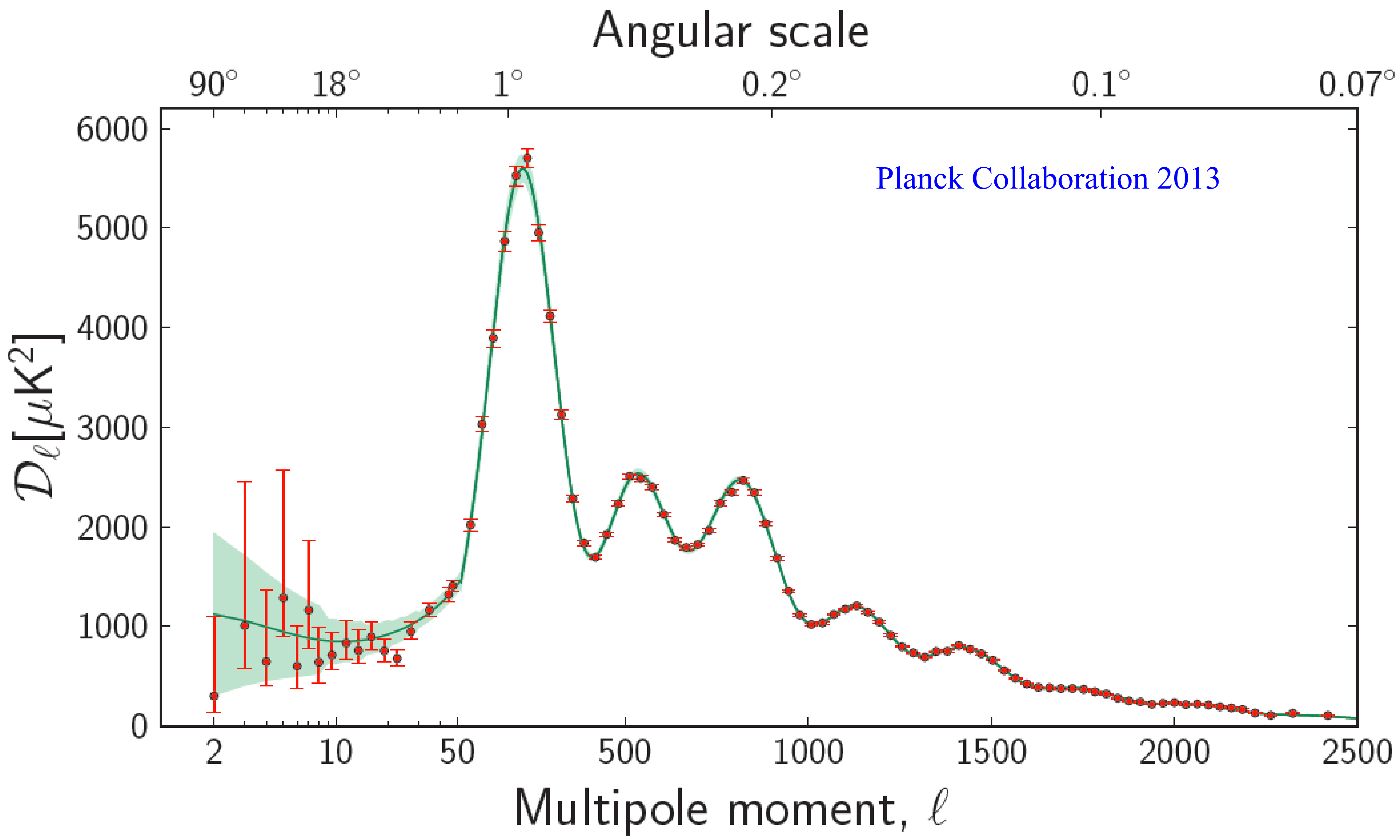
The baryon cycle: open questions

Simon White: Max Planck Institute for Astrophysics



The pregalactic Universe

Information content of the *Planck* CMB map



The six parameters of the minimal ΛCDM model

Planck Collaboration 2013

Parameter	*Planck*+WP Best fit	*Planck*+WP 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 1.5% measurement of the cosmic baryon density

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

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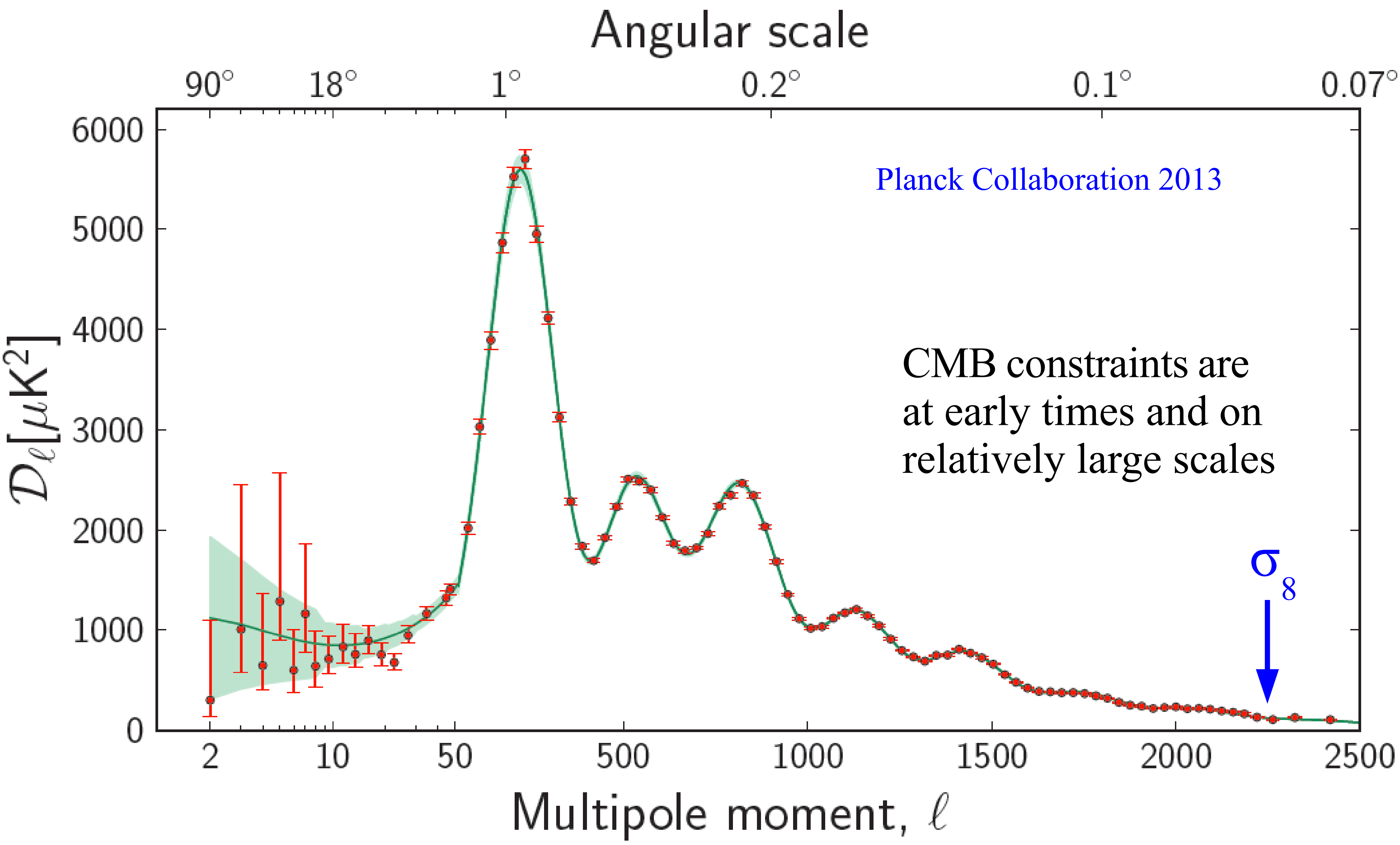
A 40σ detection of nonbaryonic DM using <u>*only*</u> z ~1000 data!

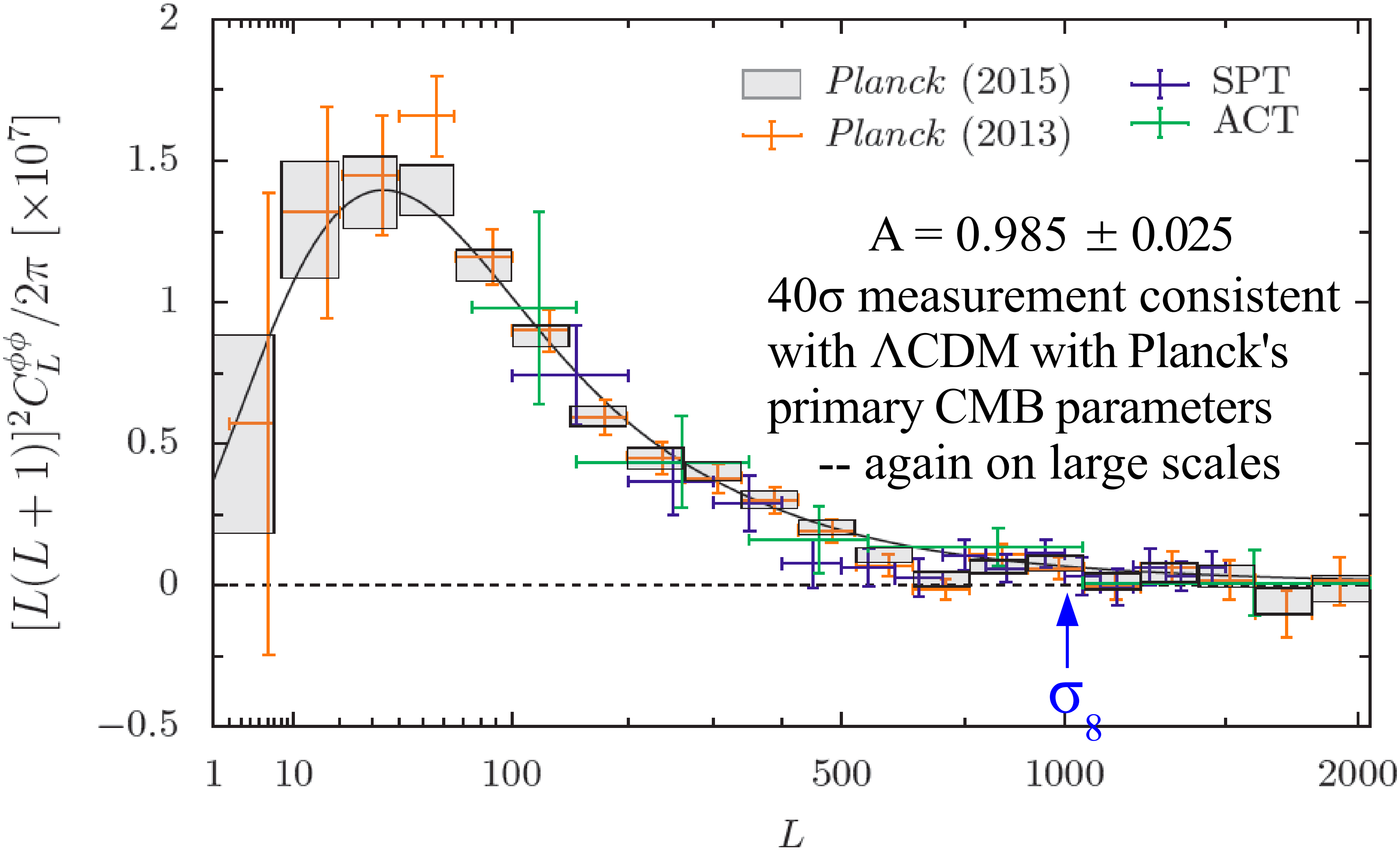
86σ in 2015 using *Planck* data alone!!

Information content of the *Planck* CMB map

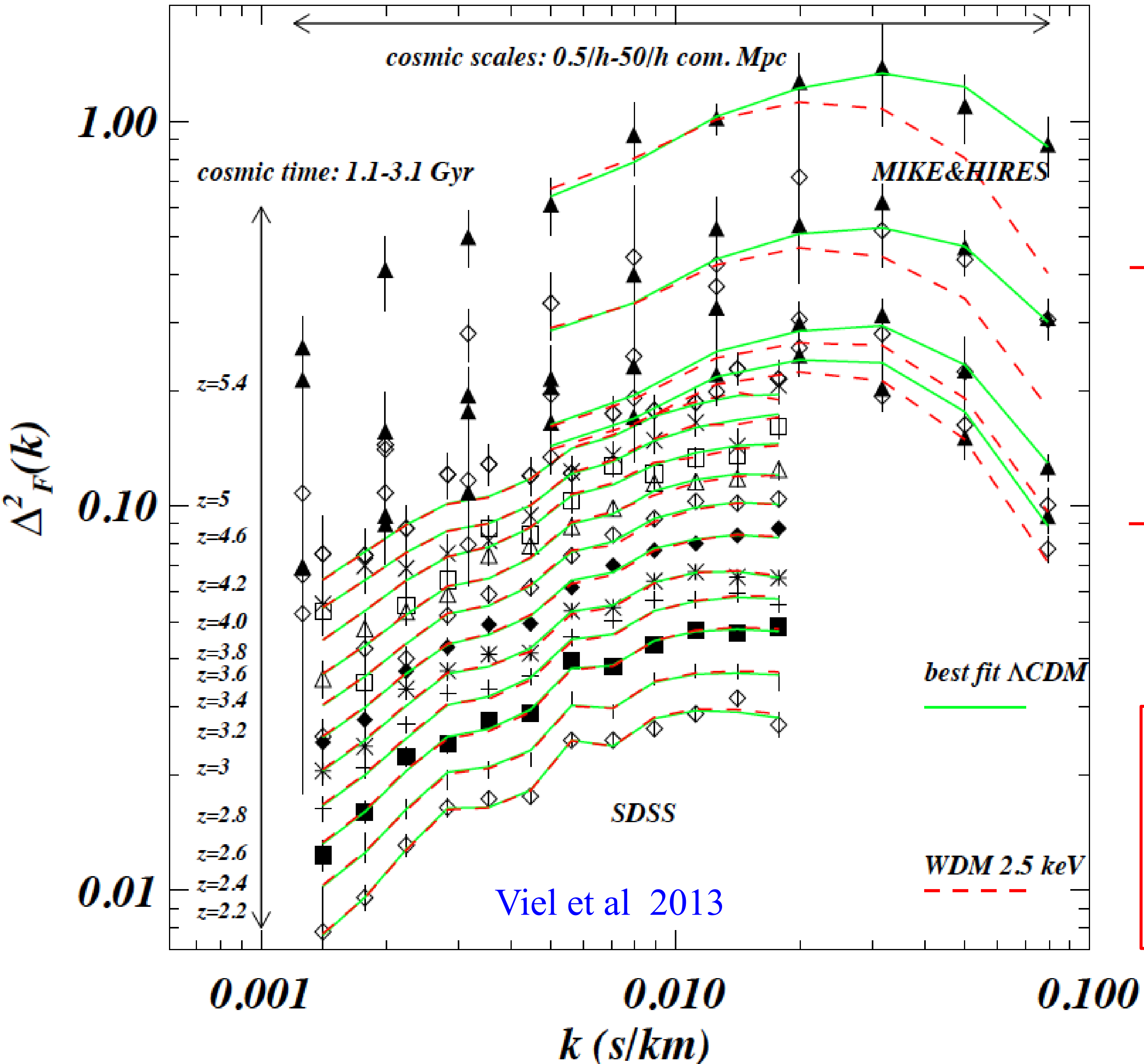


CMB constraints are at early times and on relatively large scales

Late-time mass fluctuations from CMB lensing



Lyman α forest spectra for WDM relative to CDM



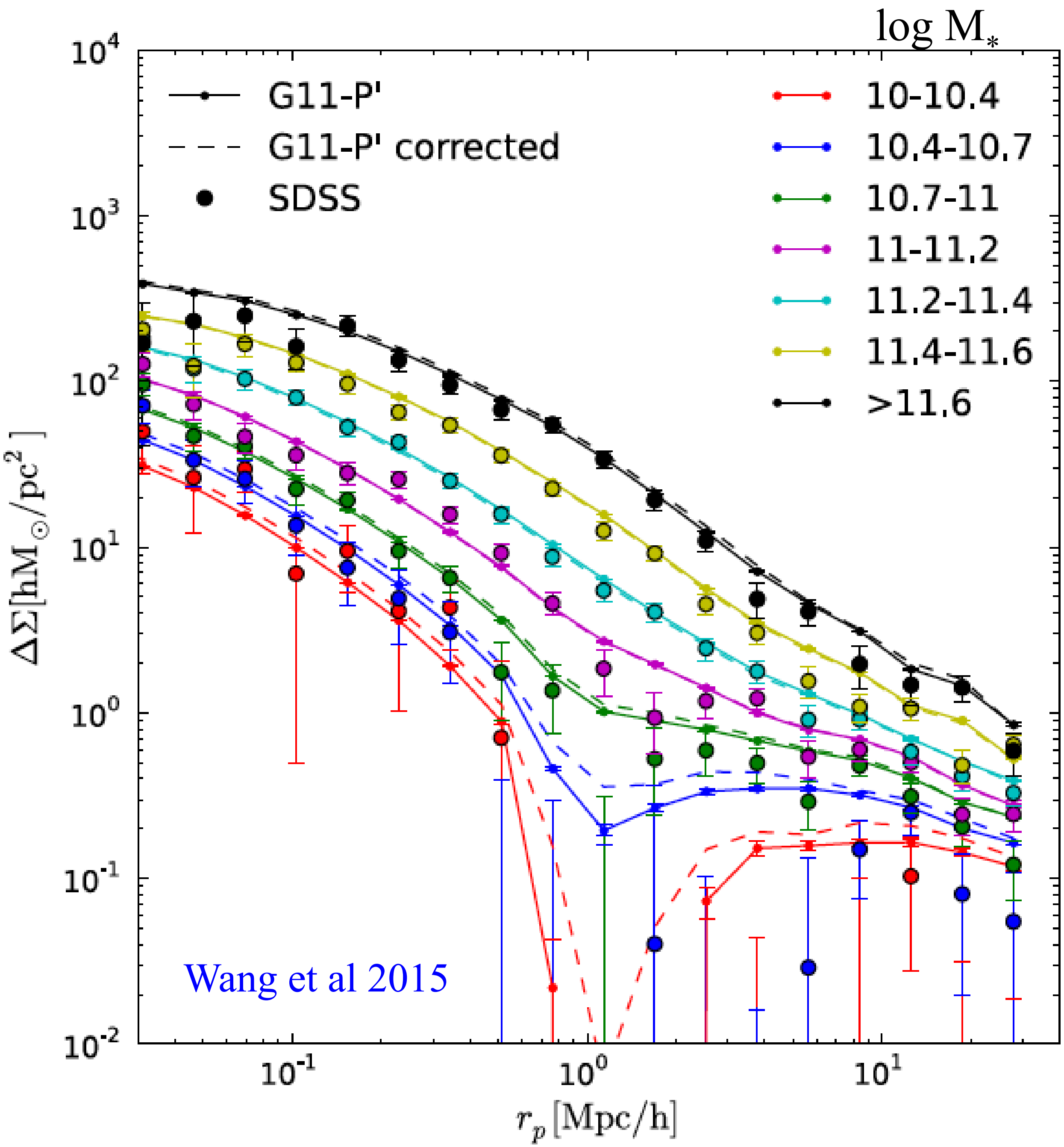
High-resolution spectra match ΛCDM up to z = 5.4

→ 2σ lower limit on the mass of a thermal relic $m_{WDM} > 3.3$ keV

→ WDM can affect the structure only of the smallest galaxies

IC's are well measured on all scales relevant for the formation of the main galaxy population

Mean mass profiles around low-redshift galaxies



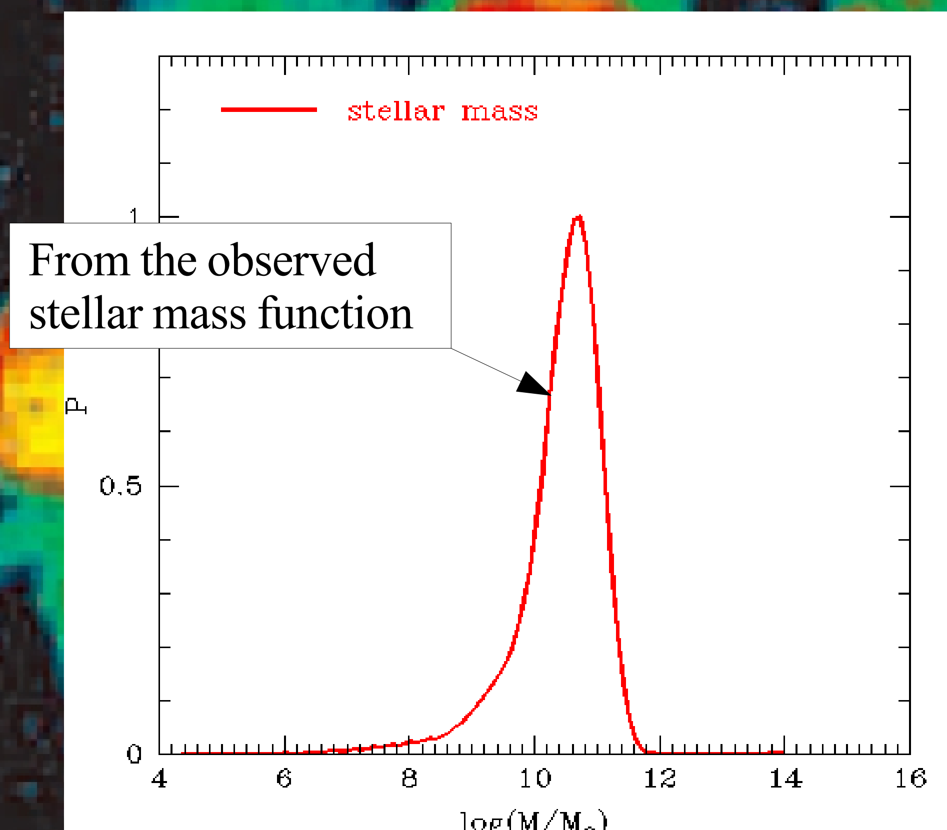
Points are mean weak lensing profiles around SDSS "central" galaxies as a function of their stellar mass.

Lines are from a <u>simulation</u> of the formation of the galaxy population within ΛCDM, assuming Planck parameters.

No simulation parameters were adjusted in this comparison, but the agreement <u>does</u> depend on the astrophysical modelling.

Here parameters were tuned to reproduce the abundance and colours of galaxies

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



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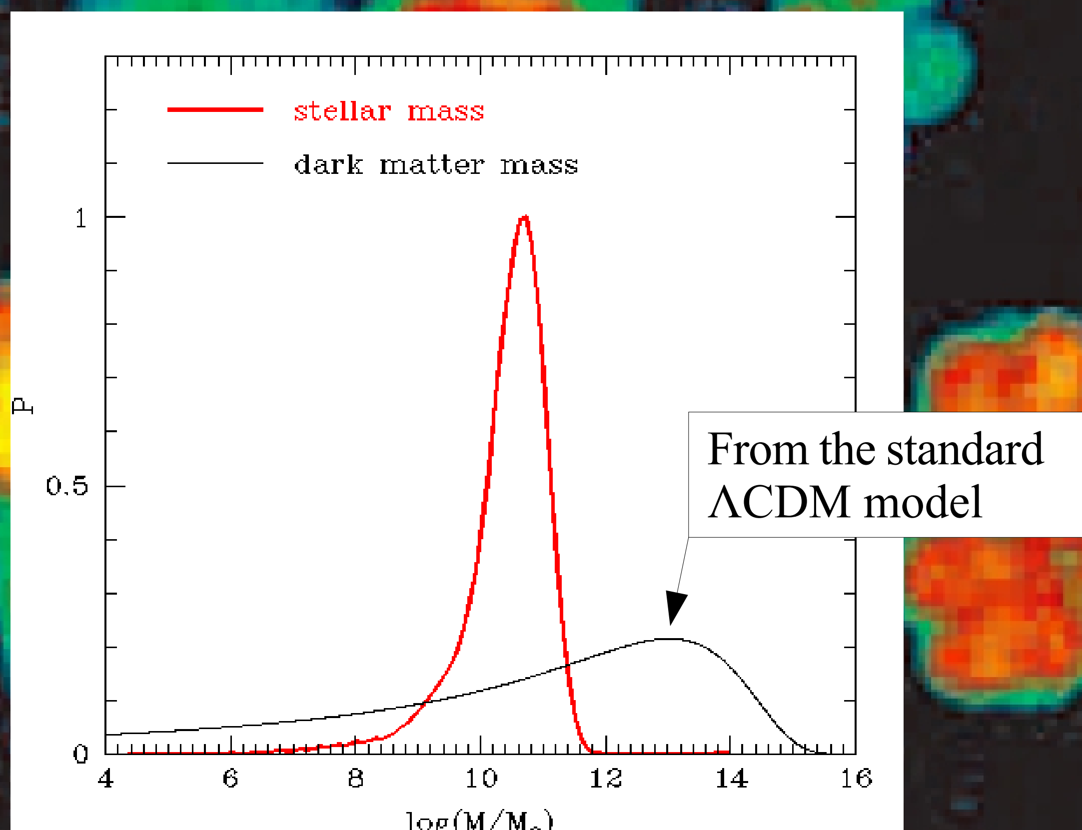
Dark matter is *much* more broadly distributed across halos



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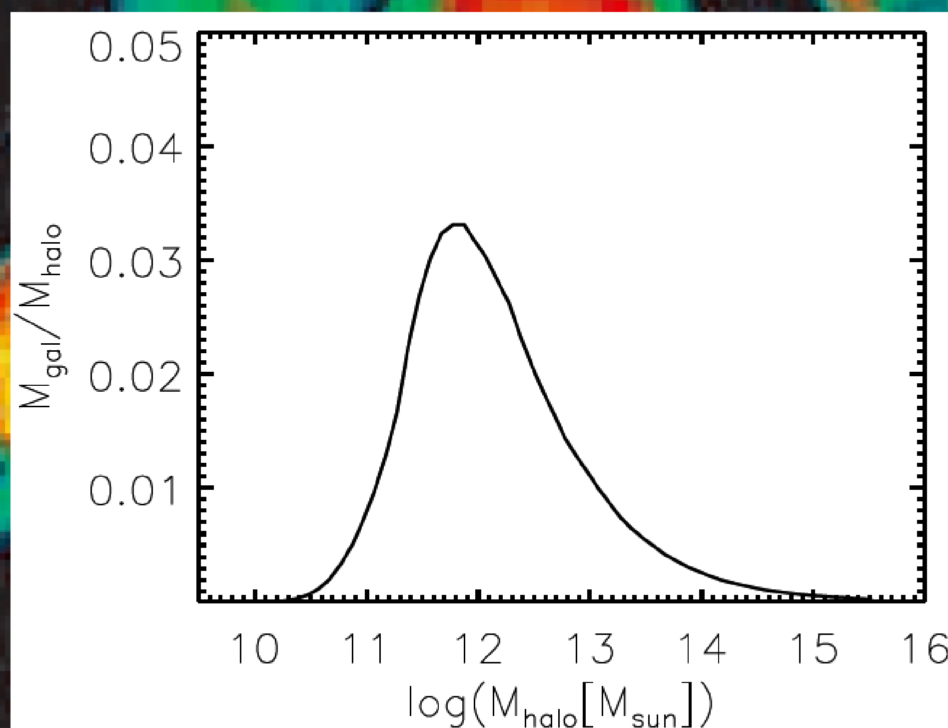

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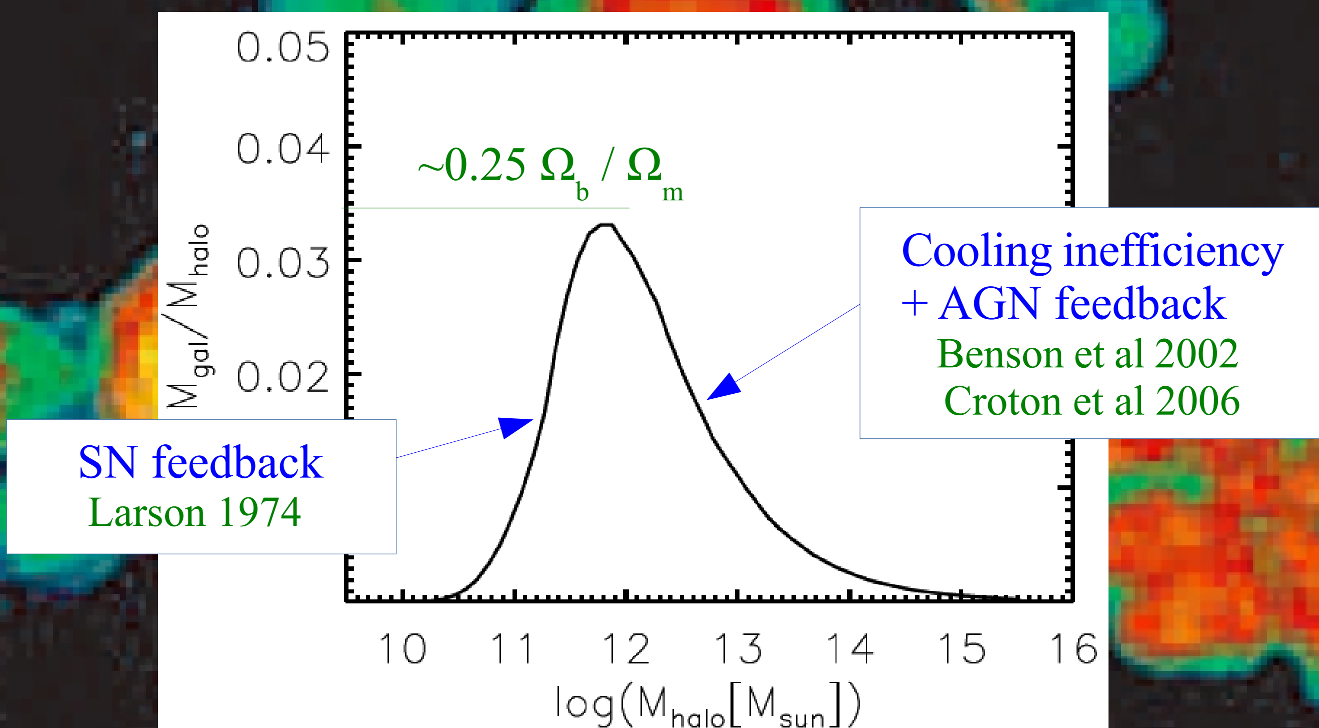
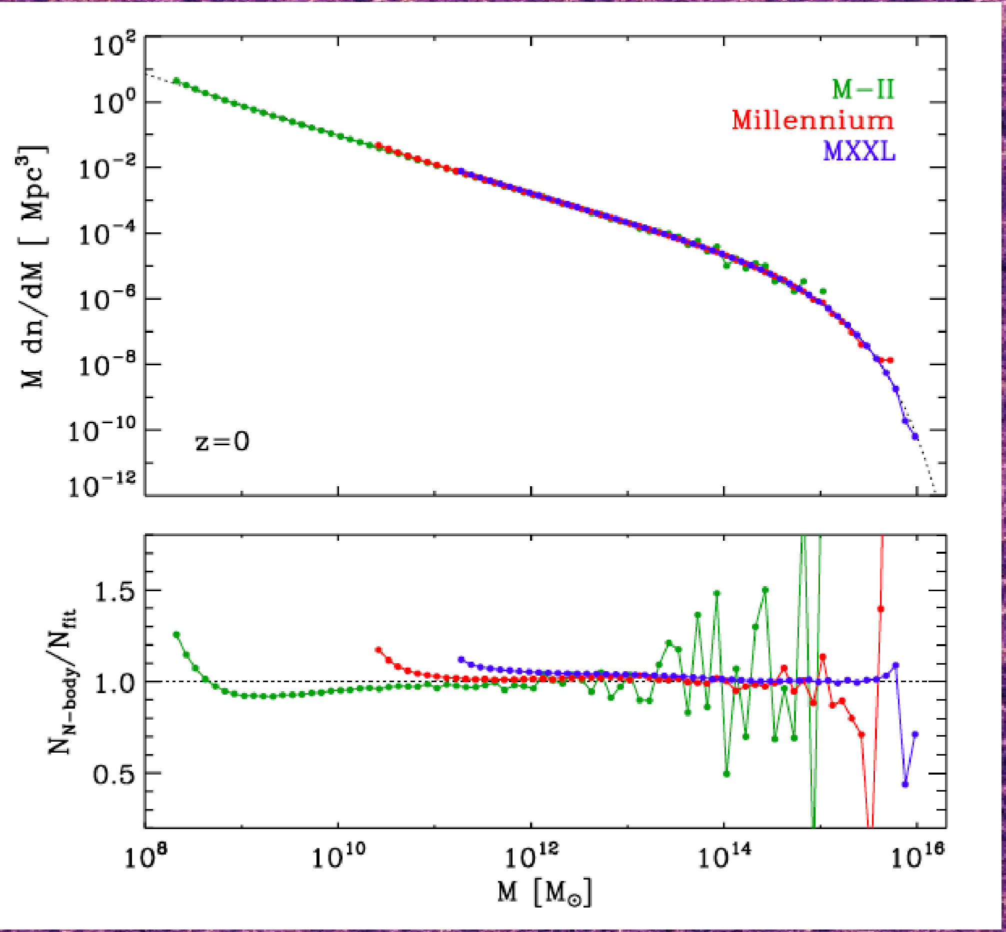
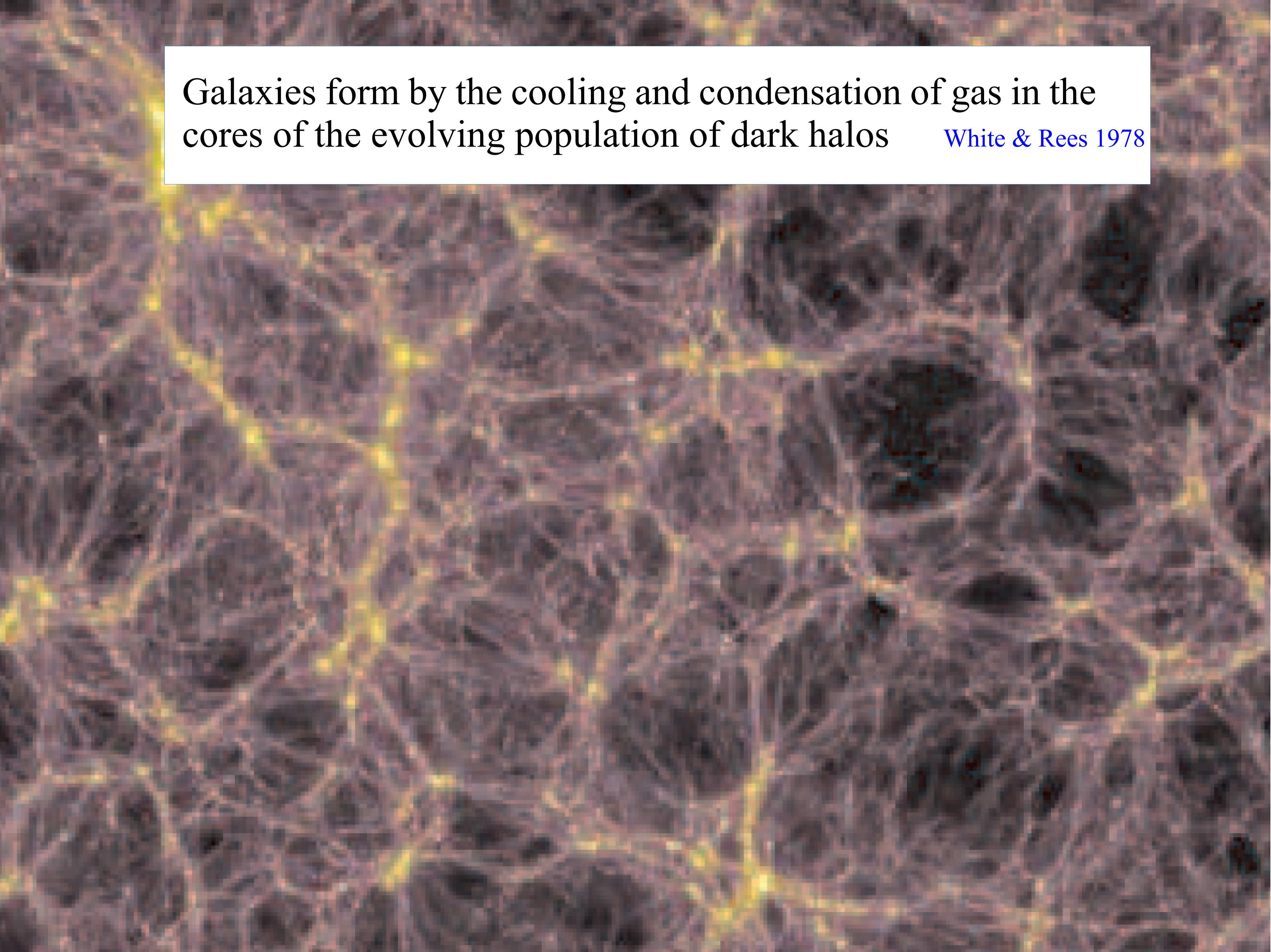
Star formation efficiency is reduced at both low *and* high halo mass, and <u>maximises</u> at about 25% near the mass of the MW's halo

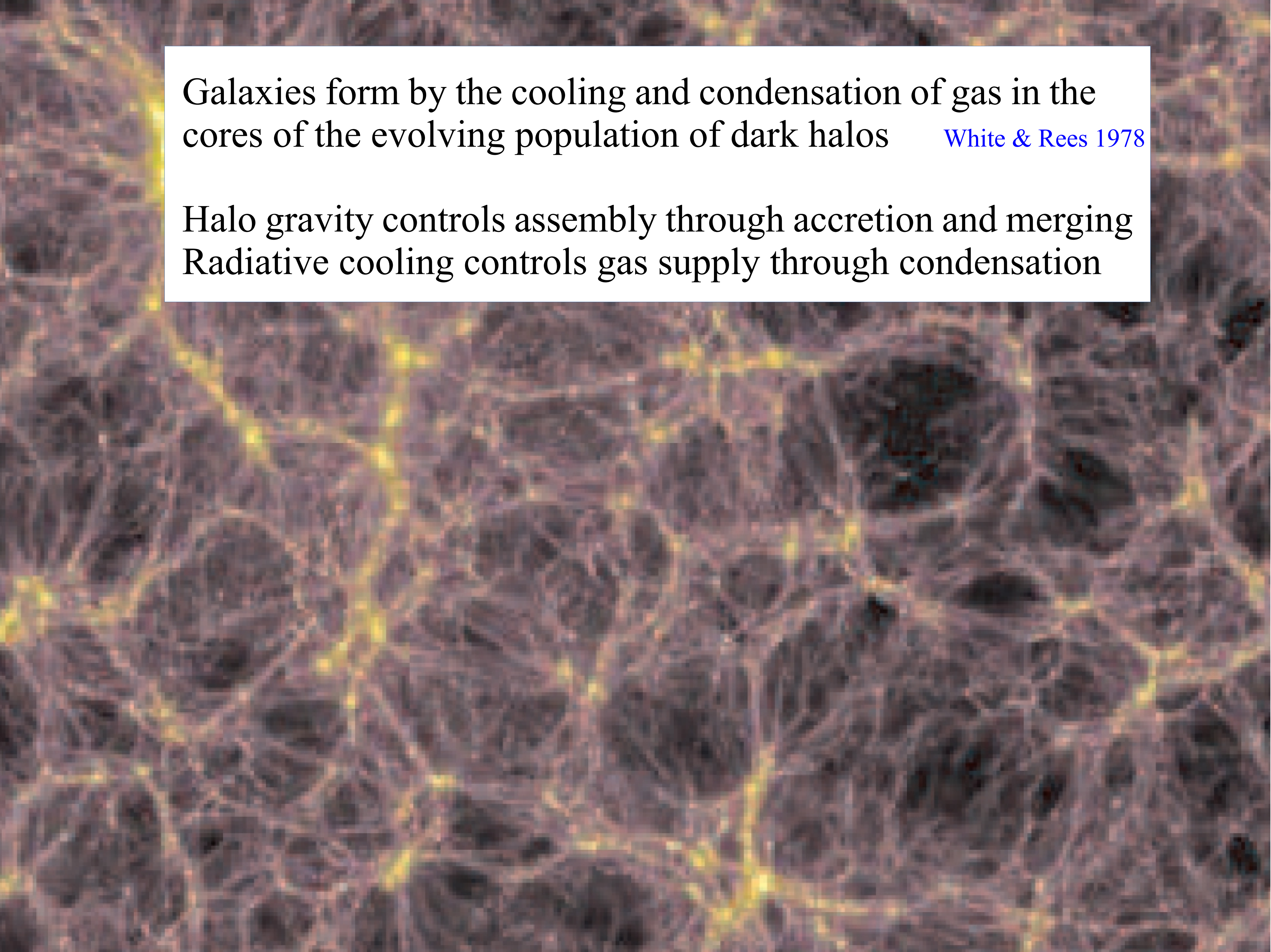


N-body codes can simulate the evolution of the abundance, internal structure and clustering of dark halos at high precision





Galaxies form by the cooling and condensation of gas in the cores of the evolving population of dark halos White & Rees 1978



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Radiative cooling controls gas supply through condensation

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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
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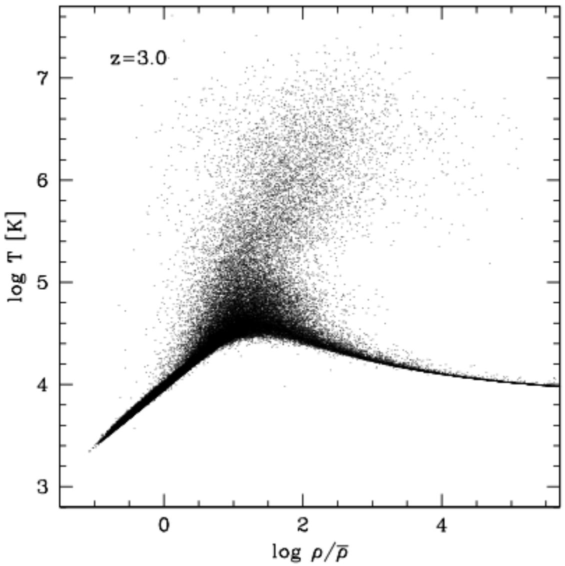
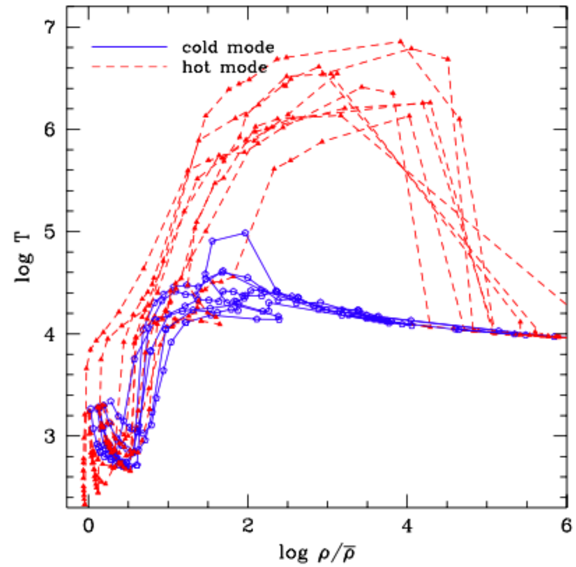
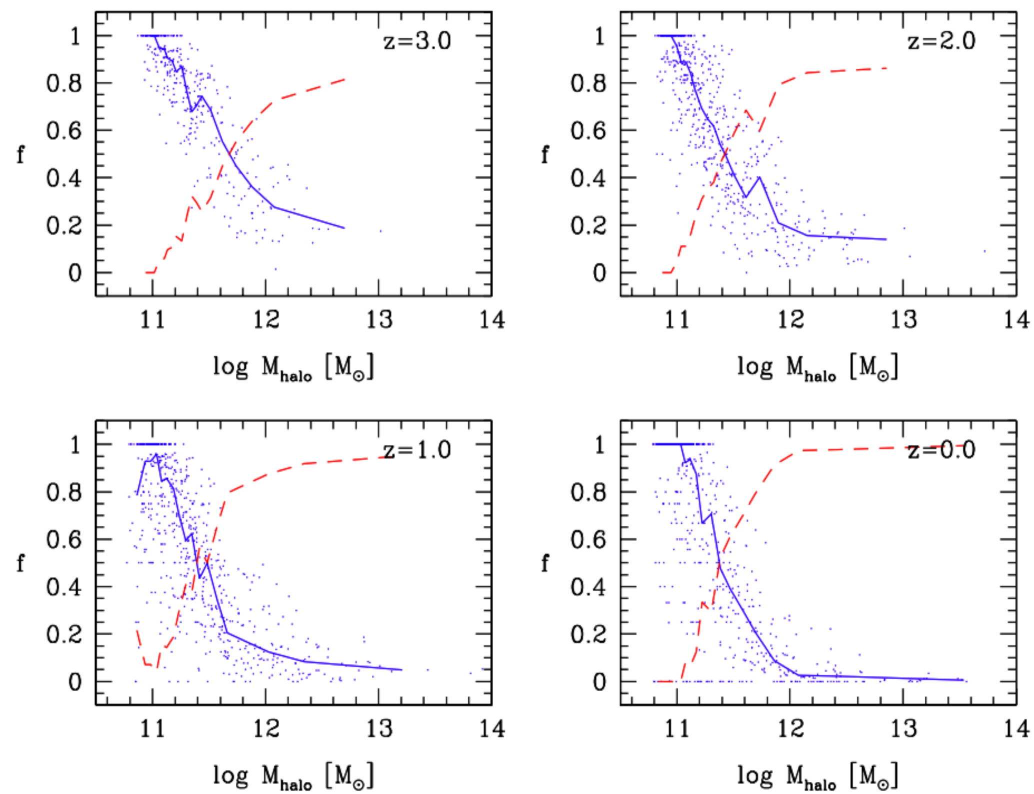
Hot and cold accretion onto galaxies





In MW mass halos, gas accretes onto the central galaxy in <u>both</u> hot and cold modes, even without significant winds.

Keres et al 2005

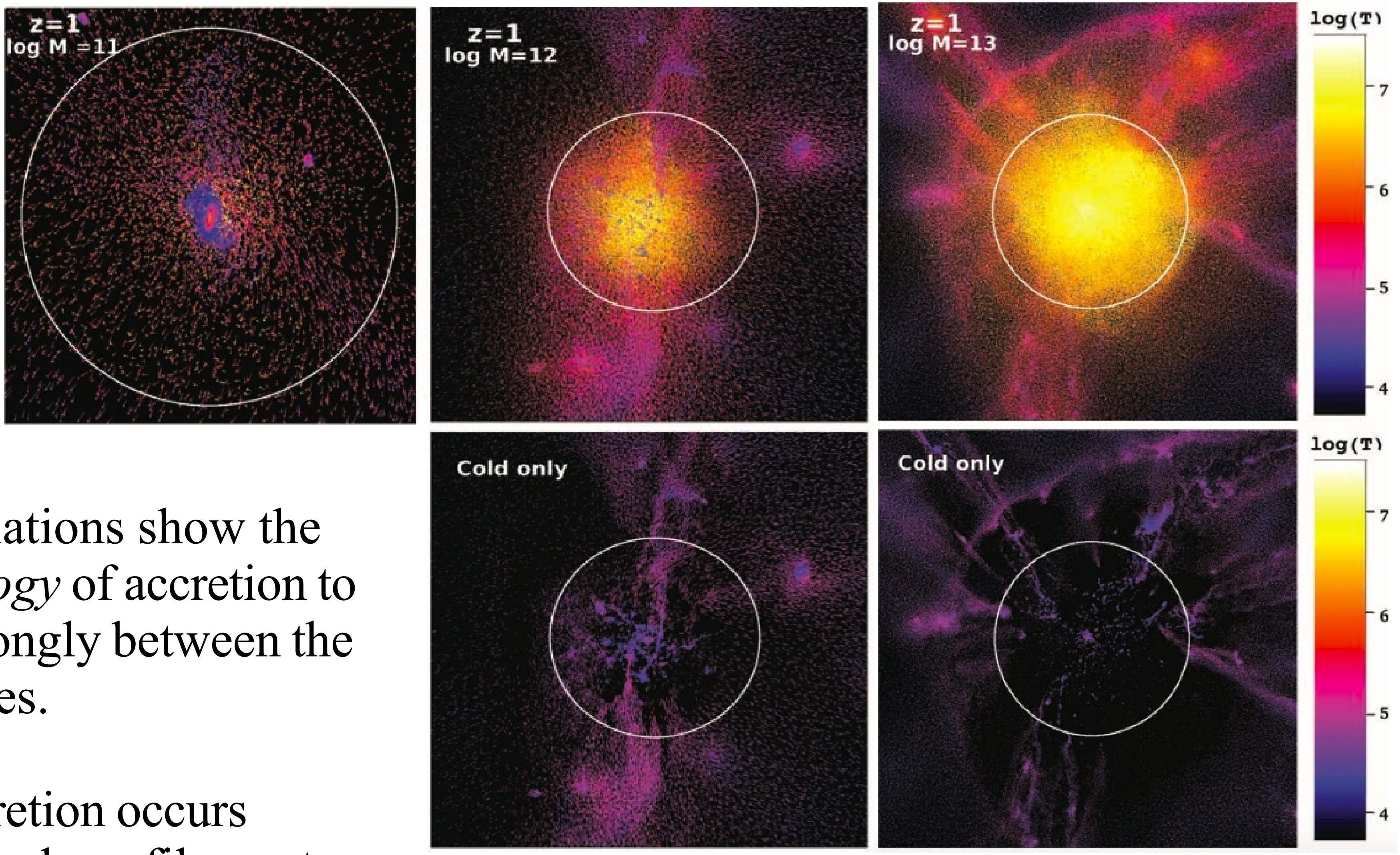


The cold to hot mode transition occurs over a decade in halo mass centred on the WF91 characteristic mass.

Below this mass <u>most</u> halo baryons cool onto the central galaxy.

The transition has little z-dependence.

Hot and cold accretion onto galaxies



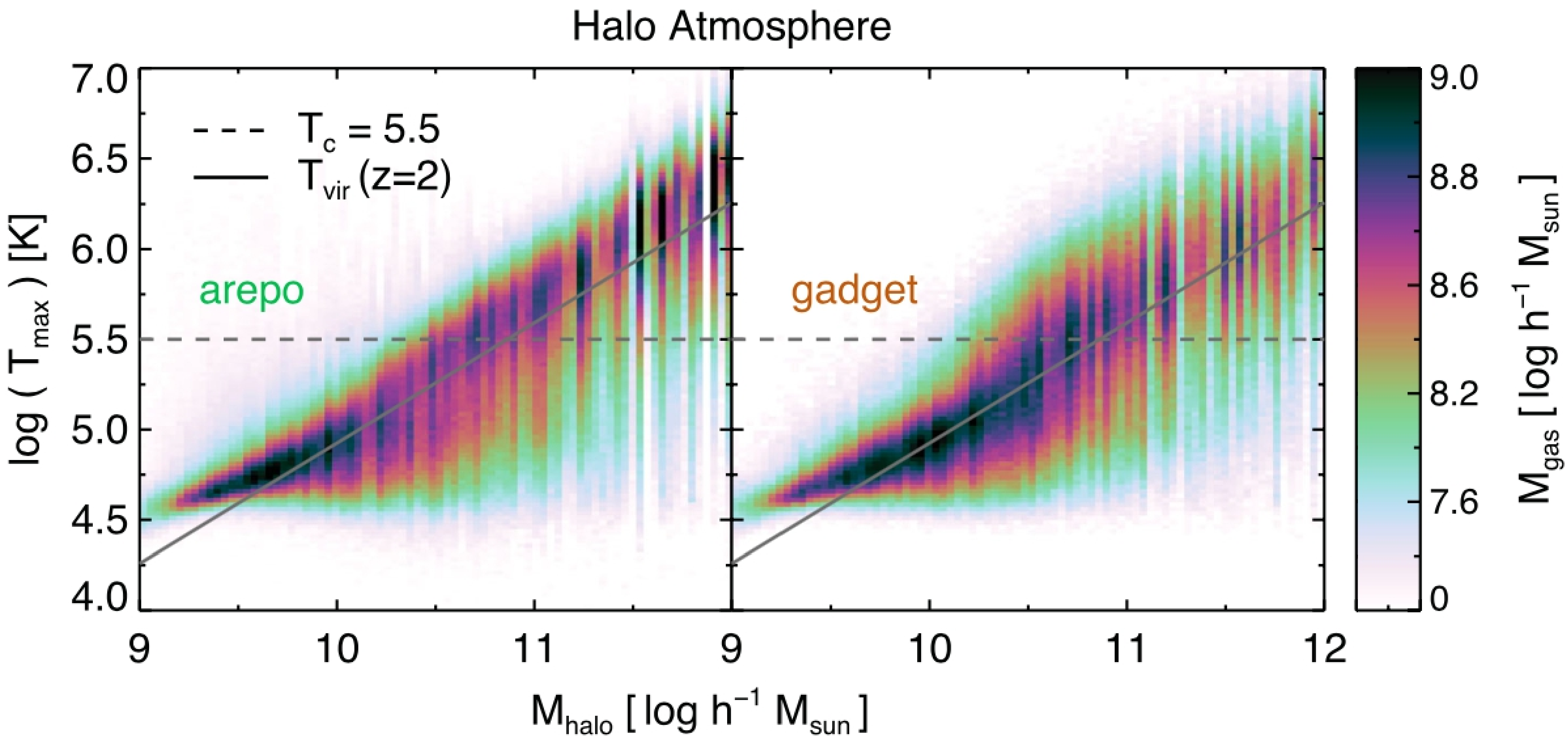
Keres et al 2009

3D simulations show the *morphology* of accretion to differ strongly between the two modes.

Cold accretion occurs primarily along filaments

Hot and cold accretion onto galaxies

Nelson et al 2013



Simulations with different hydro codes (same resolution and initial conditions) find similar thermodynamic histories for gas accreted onto galaxy halos.

Hot and cold accretion onto galaxies

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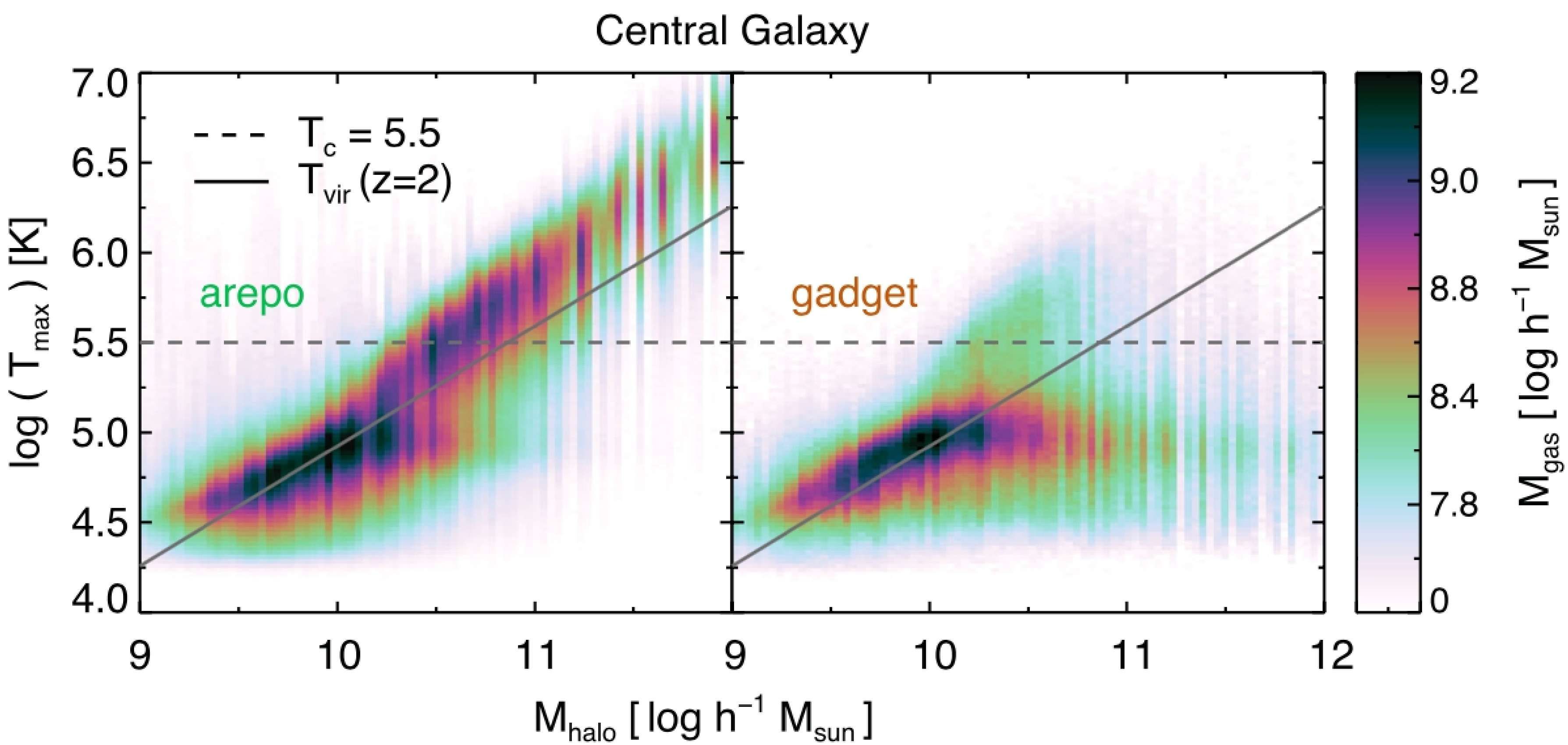
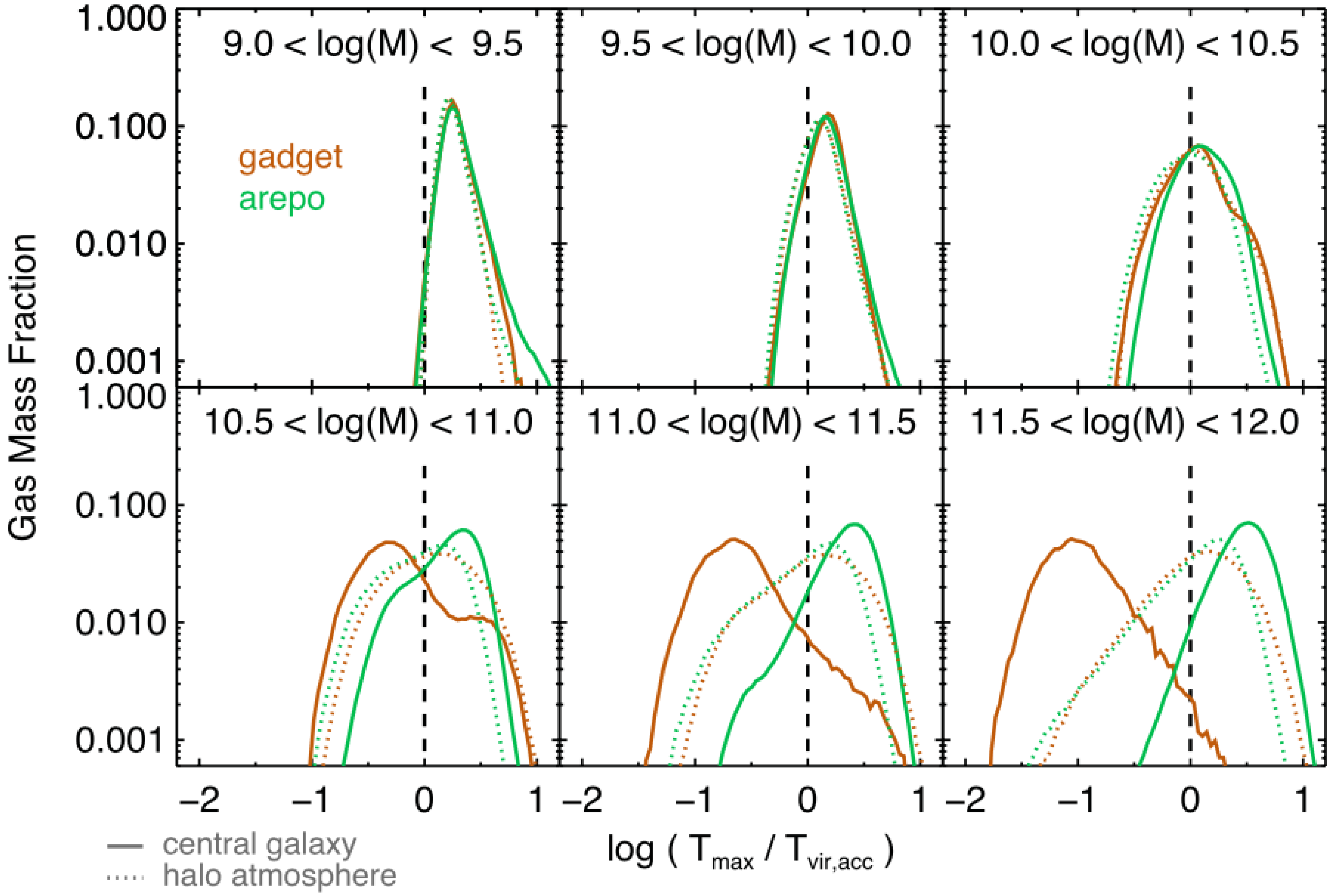


Simulations with different hydro codes (same resolution and initial conditions) find similar thermodynamic histories for gas accreted onto galaxy halos, but NOT for gas accreted onto galaxies.

Hot and cold accretion onto galaxies

Nelson et al 2013



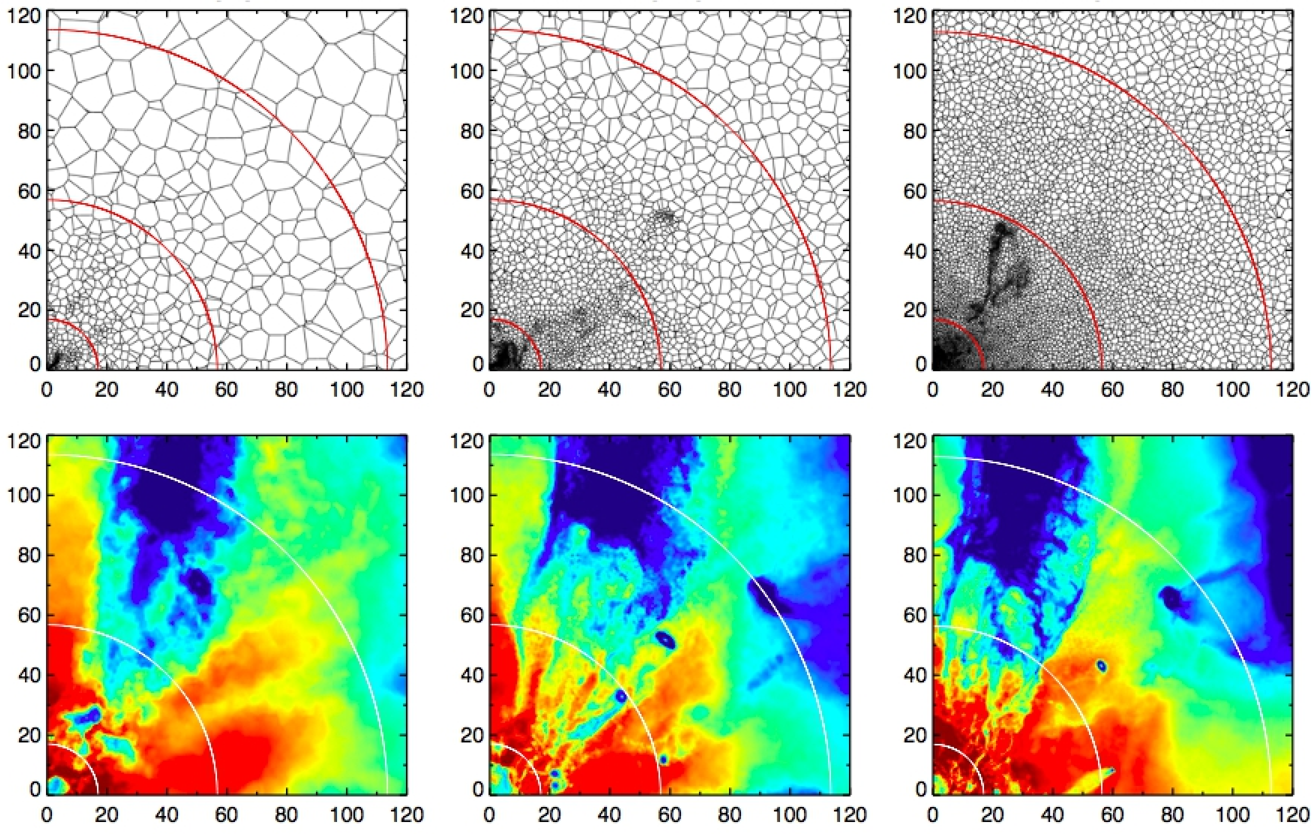
The codes agree on the T-distribution (and amount) of gas accreted onto halos

They disagree on the T-distribution of gas cooling onto galaxies

With the moving mesh, galaxies accrete half as much in cold mode as in SPH while in hot mode they accrete ten times as much.

Hot and cold accretion onto galaxies

Nelson et al 2016



$z = 2.0$

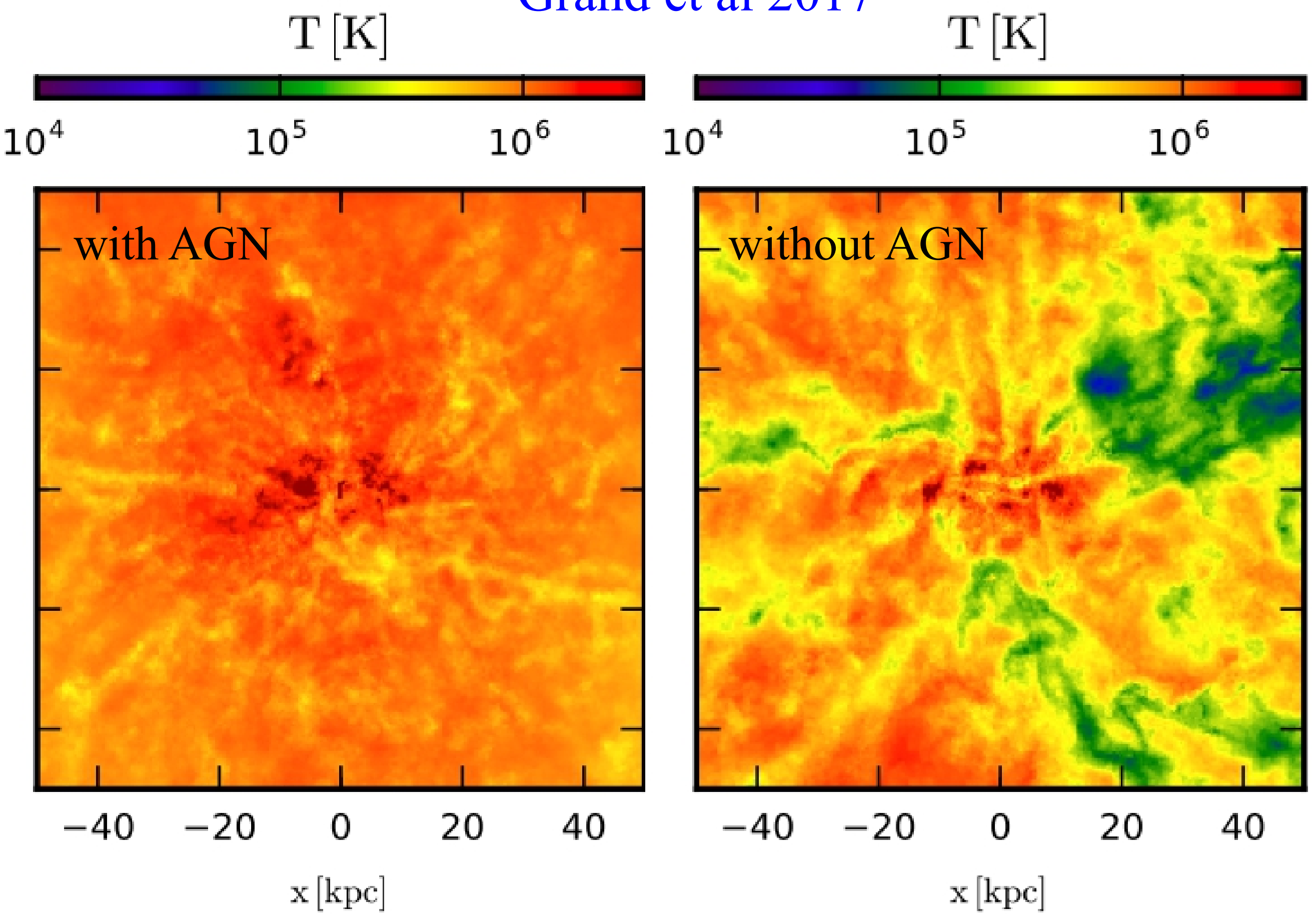
$M_{halo} \sim 10^{12}\, M_{\odot}$

No wind

Resolution is typically low in the circumgalactic medium
Increasing resolution leads to finer structure, even without winds

Hot and cold accretion onto galaxies

Grand et al 2017



$z = 0.5$

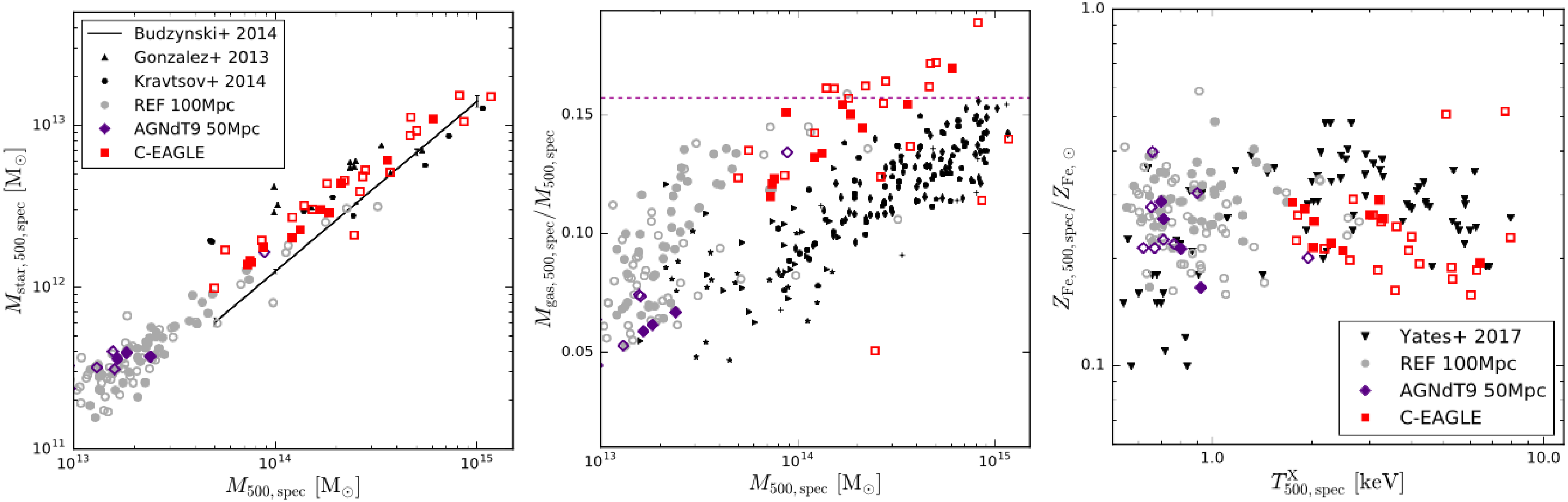
$M_{halo} \sim 10^{12}\ M_{\odot}$

Winds from SN with/ without AGN feedback

Resolution is typically low in the circumgalactic medium
Increasing resolution leads to finer structure, even without winds
Feedback and winds lead to much more complex structure.

The baryon budget in galaxy clusters

Barnes et al 2017

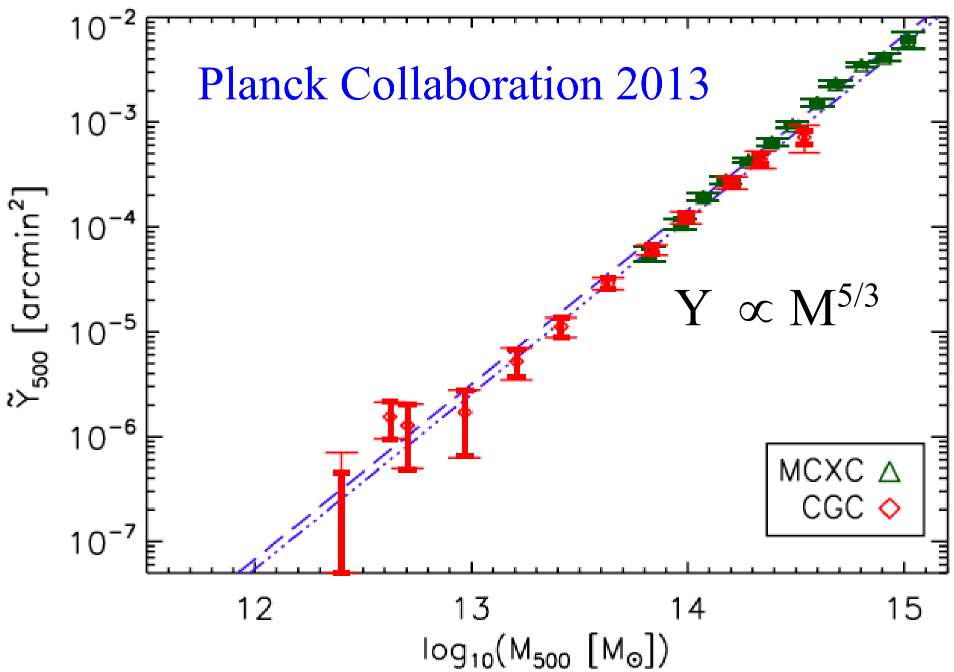


Current high-resolution simulations of rich cluster formation appear to

– slightly overpredict the total mass in stars (overefficient star-formation?)
– slightly overpredict the gas fractions (underefficient feedback?)
– underpredict [Fe/H] in the ICM (yields too low?)

but uncertainties are too large for convincing conclusions

The baryon budget in "field" galaxies



Planck has detected the stacked SZ signal around locally brightest galaxies down to objects similar to M31.

The scaling seems to imply that all the expected baryons are seen and are hot.

Their spatial distribution is unresolved

- Both observations and simulations suggest the CGM is multiphase
- Both the relative and total amounts of the different phases are unknown
- Observations show that ejecta reach to the virial radius and perhaps beyond
- The nature both of the dynamical inflow/outflow/fountain "equilibrium" and of exchanges between the phases is poorly understood

Some other open questions about the baryon cycle

- The scaling of ISM structure to higher SFR and lower Z (e.g. high z)
- The driving mechanism for galactic winds
- The effects of AGN on star-formation in their host galaxy
- Small-scale mixing in the ISM/CGM and its effects on abundances
- The role of dust in large-scale chemical evolution

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Simulations will play a critical role in building the intuition needed for better understanding of these issues and to interpret new observations, but in many ways they remain schematic. Their failures are often more informative than their successes.