The role of cold and hot gas flows in feeding early-type galaxy formation

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With Thorsten Naab, Jeremiah Ostriker, Ludwig Oser and
in Helsinki: Antti Rantala, John Regan, Natalia Lahén

Two-phased formation of ellipticals?

1. Ellipticals have old metal-rich stellar populations with $z_{form}>2$ making up 1/2 - 3/4 of all stars in them.
2. Direct observations of massive galaxies at high redshift show that the most massive ellipticals formed earlier and on shorter timescales than less massive ellipticals (downsizing).
3. Observations of very compact (r_e~1 kpc) and massive ($M>10^{11}$ $M_\odot$) ellipticals at z~2, which are smaller by a factor of 3-5 compared to their local analogues at z=0.

- Could these observations be explained by a two-phased formation mechanism in which the stellar mass of the galaxies is formed in two distinct components: In-situ within the galaxy ($r<r_{gal}=r_{vir}/10$) and ex-situ outside ($r>r_{gal}$).
- In-situ: Dominant at $2<z<6$, driven by cold gas flows and have high (solar) metallicity.
- Ex-situ: Dominant at $0<z<3$ driven by minor & major mergers and have sub-solar metallicity.

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Our simulation samples

- A large ensemble of zoomed simulations run of individual elliptical galaxies run using the multiparallel TreeSPH code Gadget including primordial gas cooling and star formation matched to reproduce the local Schmidt-Kennicutt relation.
- Sample 1: 3 galaxies at high (0.25 kpc) + 1 galaxy at very high (0.125 kpc) resolution without SNII feedback (Naab et al. 2007, Johansson et al. 2009).
- Sample 2: 6 galaxies at high (0.25 kpc) + 3 galaxies at very high (0.125 kpc) resolution with simple SNII feedback (Johansson et al. 2012).
- Sample 3: 40 galaxies at medium (0.4 kpc) with SNII feedback (Oser, Ostriker, Naab, Johansson, Burkert, 2010; Oser, Naab, Ostriker, Johansson, 2012).
- Sample 4: In prep, run sample of galaxies with metal-line cooling, chemical enrichment, improved SN Ia+SN II feedback + AGB winds, metallicity evolution and BH feedback.
- In this talk we mainly compare results from samples 1 and 2.

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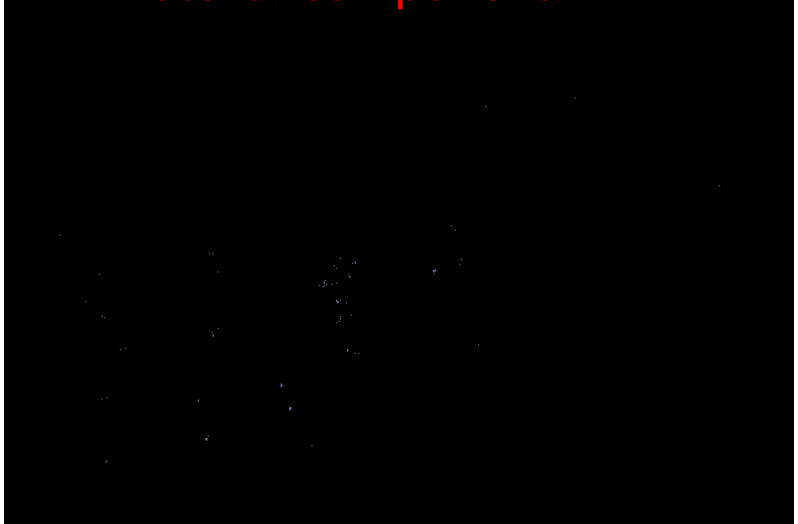
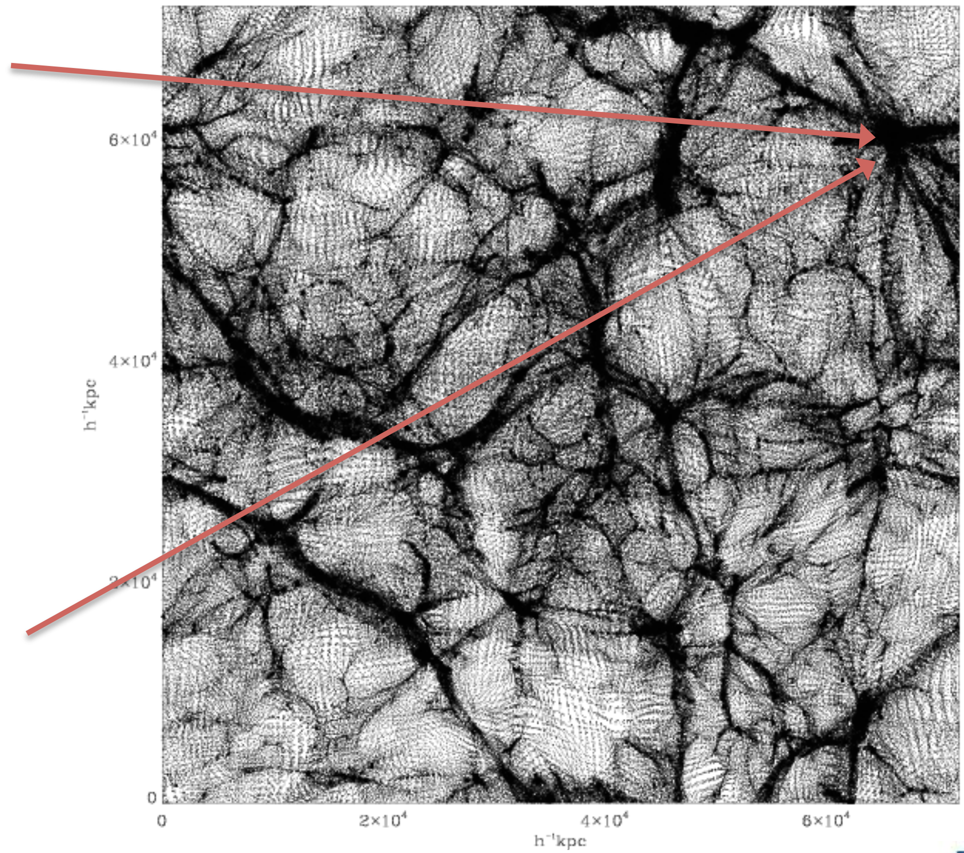
Zoom-in simulations of elliptical galaxies

Gas component:

Stellar component:

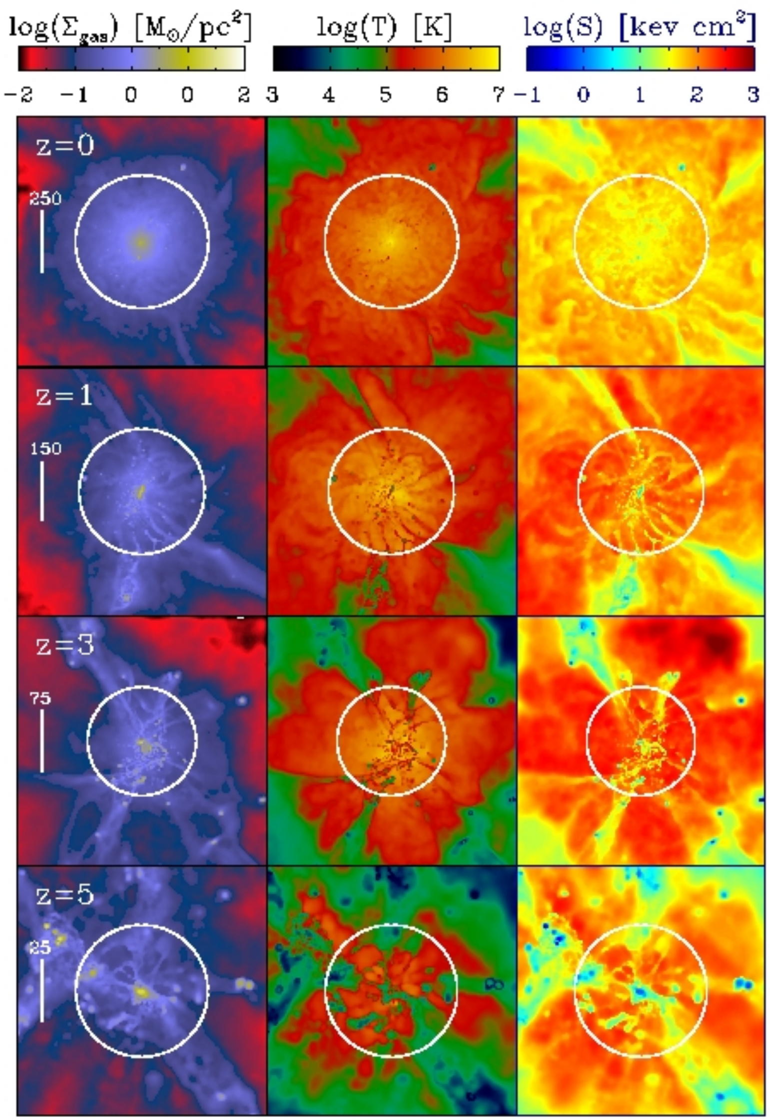


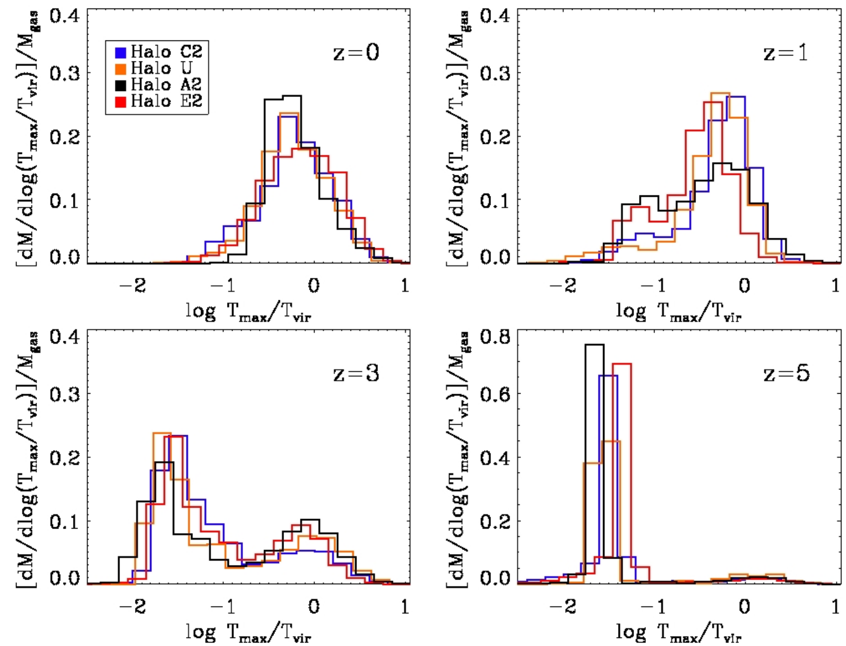
Cosmological DM-only simulation:



Naab, Johansson et al. (2007)

Transition from cold to hot accretion mode

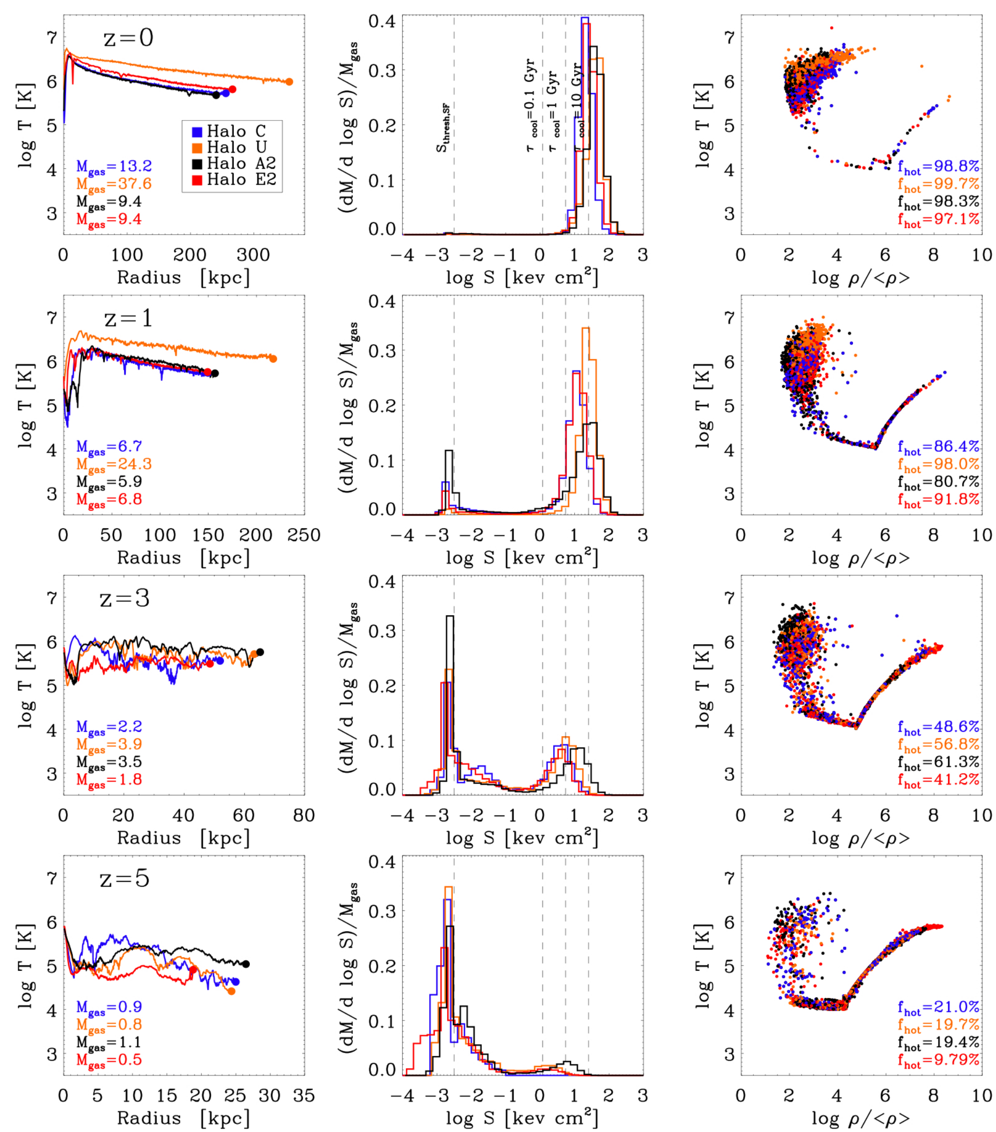




- At high redshifts the gas flows in mostly cold, at z~3 the distribution is more bimodal and at lower redshifts most of the accreted gas is hot.
- Transition from cold to hot accretion at z~2-3 at $M \sim 5 \times 10^{11}$-10^{12} $M_{\odot}$. This transition is also mass-dependent, with an earlier transition for more massive haloes.

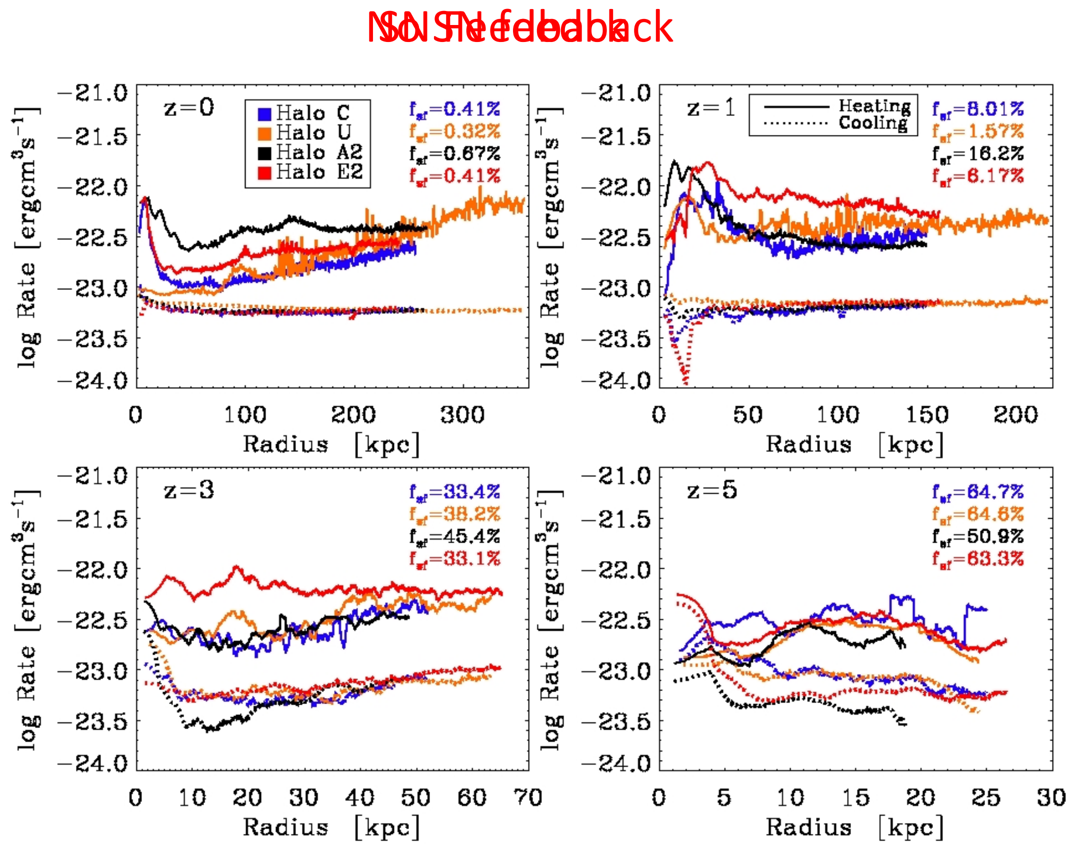
Gravitational feedback

- Temperature of the diffuse non-starforming gas inside the halo is increasing in all simulations with decreasing redshift.
- At high redshifts the the entropy distribution is bimodal with cold high-density gas and hot shock-heated gas.
- We have either no SN feedback or only weak self-regulated SN feedback!
- Gravitational heating from infalling clumps is responsible for heating the diffuse gas.



Heating of the gas component

- $E_{grav} \sim m_* v_c^2$ unlike E_{SN} and E_{AGN} which are both proportional to the stellar mass, m_*. E_{grav} might be important for massive galaxies with high v_c.
- Shock-heating of the diffuse gas dominates at all redshifts over the primordial cooling rates, shock-heating is especially important at low redshifts (z<3).



$$(\Delta E)_{\rm grav} = \Delta m_\star v_c^2 \log(100) \sim 4.5 \times 10^{-6} v_{300}^2 m_\star c^2, \qquad (4)$$

Heating rates in the SN feedback runs are somewhat lower than in the no SN feedbacks simulations, as expected.

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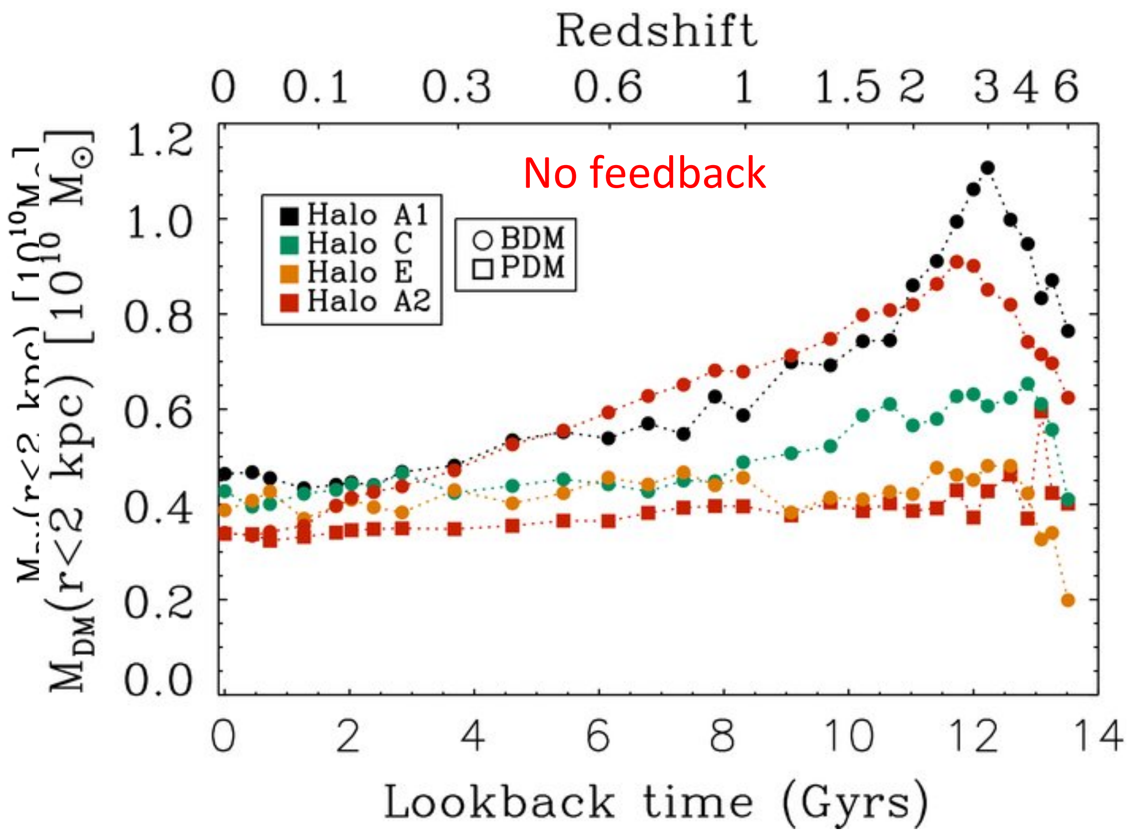
Heating of the DM component

- The DM is initially adiabatically contracted at z~3, after which the central DM mass is decreasing.
- Halo U (most massive halo) has a late (z<0.5) increase in the central DM mass due to gas inflows and associated star formation.
- The most massive galaxies need an additional central heating source (AGN).



Overall the relative expansion of the central DM is lower in the SN feedback case by factors of 2-3 compared to the no feedback case.

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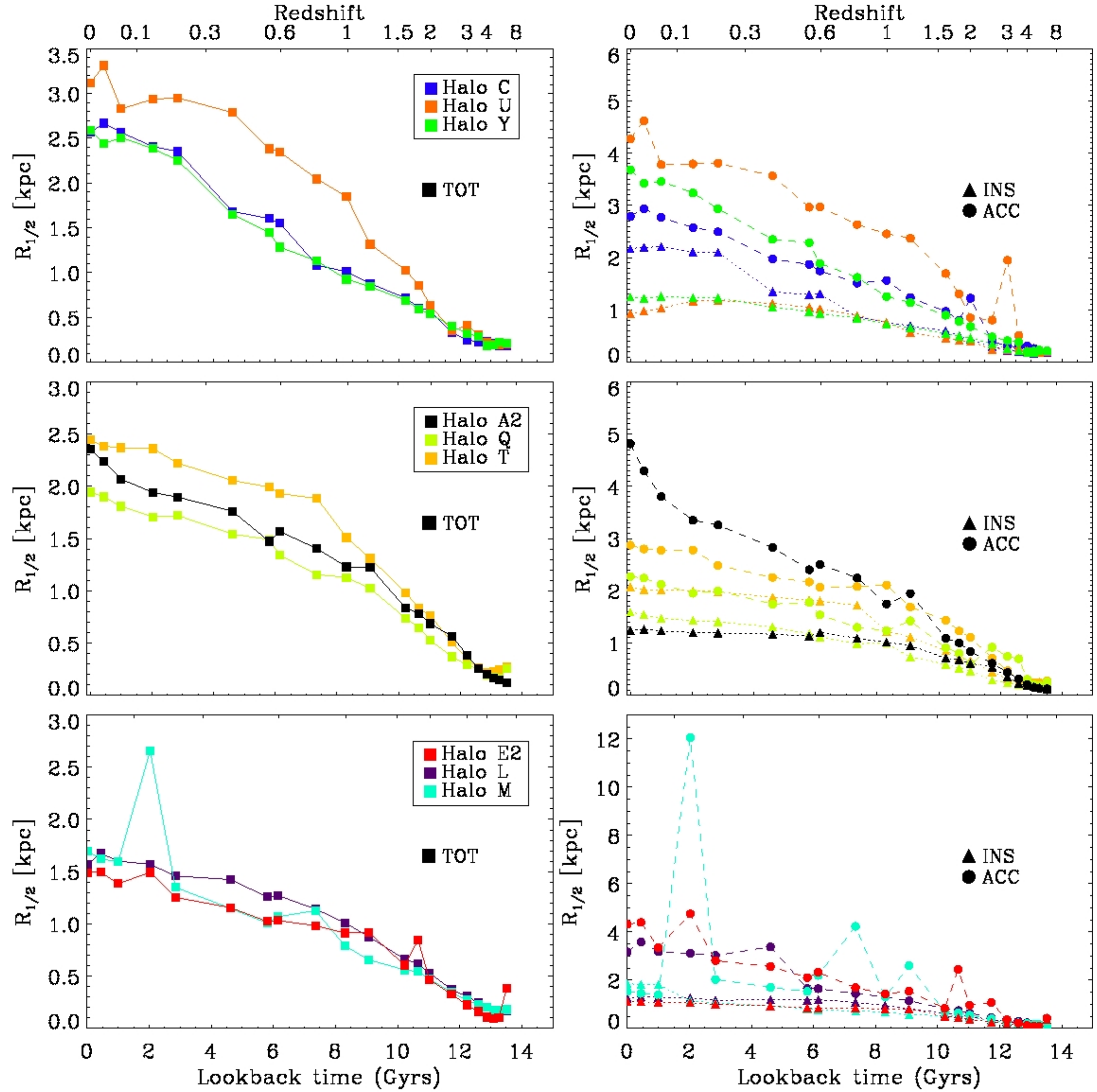
Size growth in the two-phased model

- In-situ stars form a compact high density stellar system, with $r_{1/2}$=1-2 kpc.
- Accreted stars are building up a more extended lower mass system, $r_{1/2}$=3-5 kpc.
- The predicted size growth is in good agreement with the observations.



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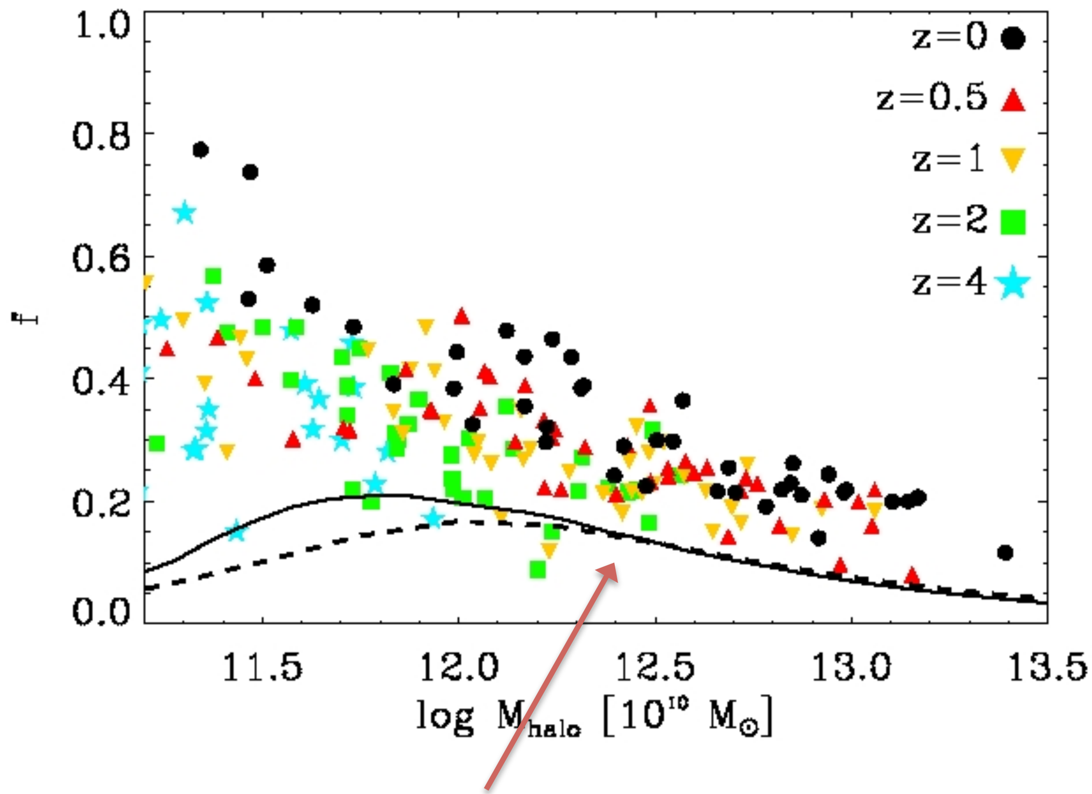
Caveat: Baryon conversion factor

- Baryon conversion factor: $f=M_*/(f_b x m_{vir,DM})$, where $f_b=\Omega_b/\Omega_m=0.2$.
- Our simulated conversion factor is too large by a factor of ~2 -> too much stars for given halo mass.
- Missing physics: Strong supernova winds and AGB winds at lower masses & AGN feedback at higher masses. -> Sample 4 simulations in prep.



Lines: Prediction from HOD models: $\phi(L)$-n(DM)

Guo et al. (2010)

Moster et al. (2010)

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Conclusions

1. We present a two phased model of massive galaxy formation with in-situ star formation dominating at high-z and accretion of ex-situ formed stars through dry minor merging at low-z.
2. The gas accretion history is bimodal with cold gas flows feeding the in-situ star formation at high redshifts. At intermediate redshifts of z~3 there is a transition to a hot gas mode, which truncates the in-situ forming stellar component.
3. The resulting accretion of ex-situ formed stars at ($z \leq 3$) results in gravitational feedback that heats both the diffuse gas in the haloes and the dark matter component in the galaxies.
4. A caveat remains in explaining the low baryon conversion factors, which probably requires strong supernova wind feedback and AGN feedback.

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