Forming Early-type galaxies in ΛCDM simulations

Peter Johansson
University Observatory
Munich

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With Thorsten Naab, Jeremiah Ostriker, Ludwig Oser, Andreas Burkert, George Efstathiou

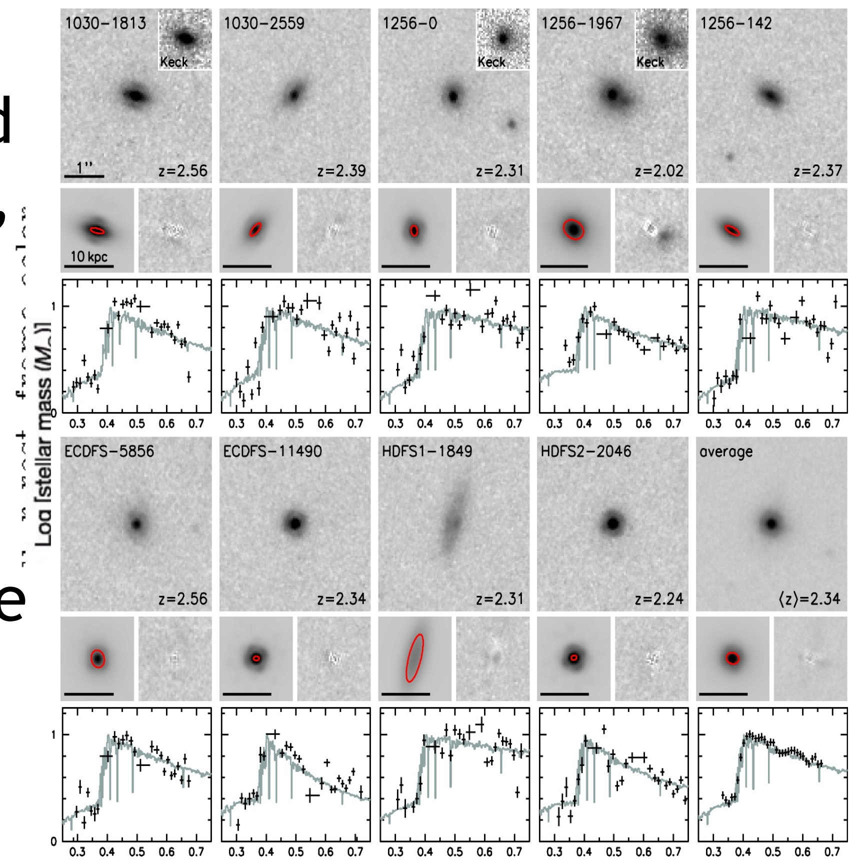
Naab, Johansson, Ostriker, Efstathiou, 2007, ApJ, 658, 710
Johansson, Naab, Ostriker, 2009, ApJL, 697, 38
Naab, Johansson, Ostriker, 2009, ApJL, 699, 178
Oser, Ostriker, Naab, Johansson, Burkert, 2010, ApJ, submitted
Johansson, Naab, Ostriker, 2010, ApJ, to be submitted

Why study Early-type galaxies?

- All ellipticals have old metal-rich stellar populations with zform>2 making up 1/2 - 3/4 of all stars (Ellis, Bell, Thomas etc.).
- Direct observations of massive galaxies at high redshift (e.g. Kriek et al. 2006, van Dokkum et al. 2008).
- Follow tight scaling relations (Colour-Magnitude relation, the Fundamental plane (σ0, Sbeff, reff).
- All early-type galaxies have BHs (e.g. Magorrian et al. 1998, Gebhardt et al. 2000, Merritt et al. 2000, Tremaine et al. 2002).
- Most massive ellipticals formed earlier and on shorter timescales (e.g. Heavens et al. 2004, Thomas et al. 2005).
- Total stellar mass in elliptical galaxies grows since z=1 which is only not caused by star formation or fading of bright blue galaxies -> dry mergers (Bell et al., 2004, Drory et al. 2004, Conselice et al. 2005, Faber et al. 2006, Brown et al. 2007).

Observational results

1. Galaxy bimodality: Mcrit,*~3x1010 Msun, above red spheroidal systems, below blue, star-forming disk galaxies (e.g. Baldry et al. 2004).
2. Downsizing: massive galaxies already at place at z~2-3, implying rapid growth of massive ellipticals at high-z (e.g. Glazebrook et al. 2004).
3. Compact sizes at z~2: Very compact (re~1 kpc) massive (M>1011 Msun) galaxies, smaller by a factor of 3-5 compared to their local



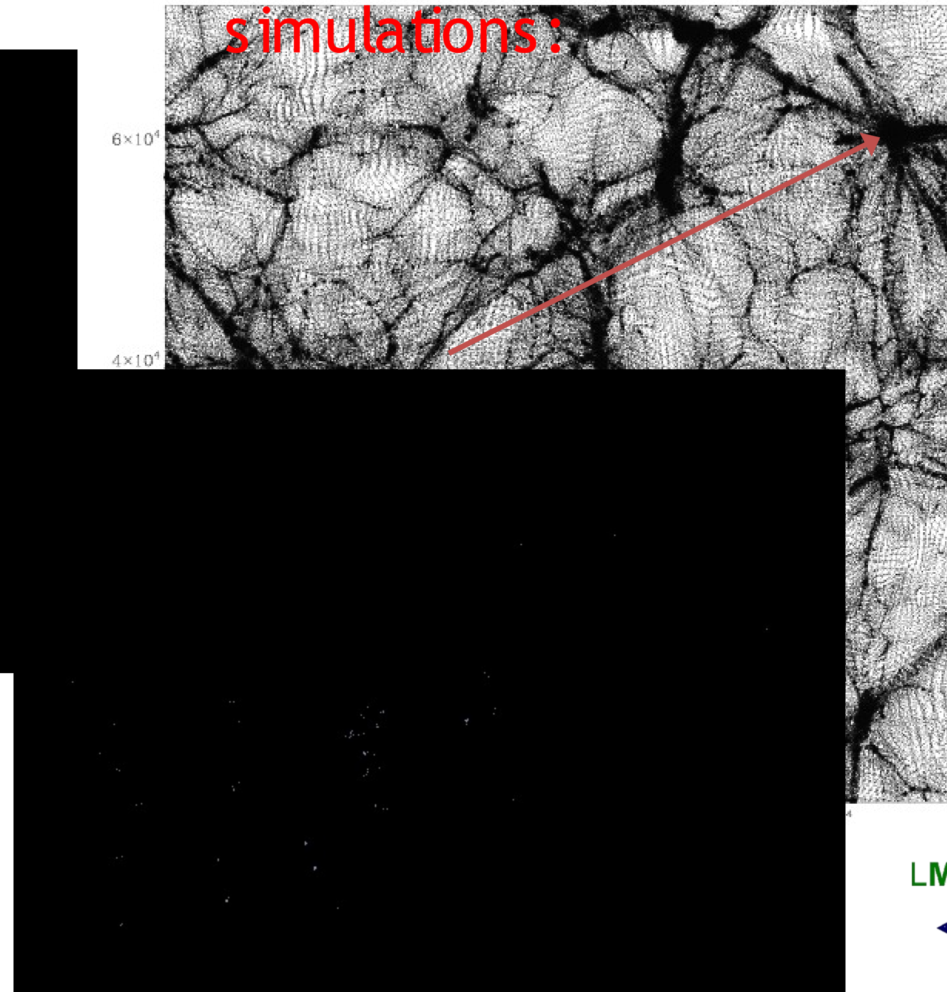
Numerical simulations of galaxy formation

Disky fast-rotating Es
Merger simulations:

Naab et al. (2006)

Naab, Johansson et al. (2007)

Boxy slowly-rotating Es
Cosmological simulations:

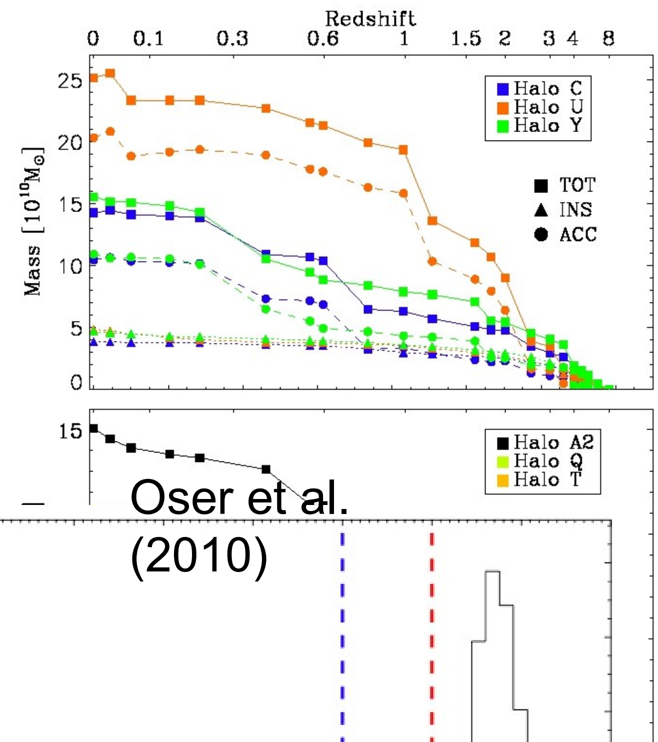


Our simulation samples

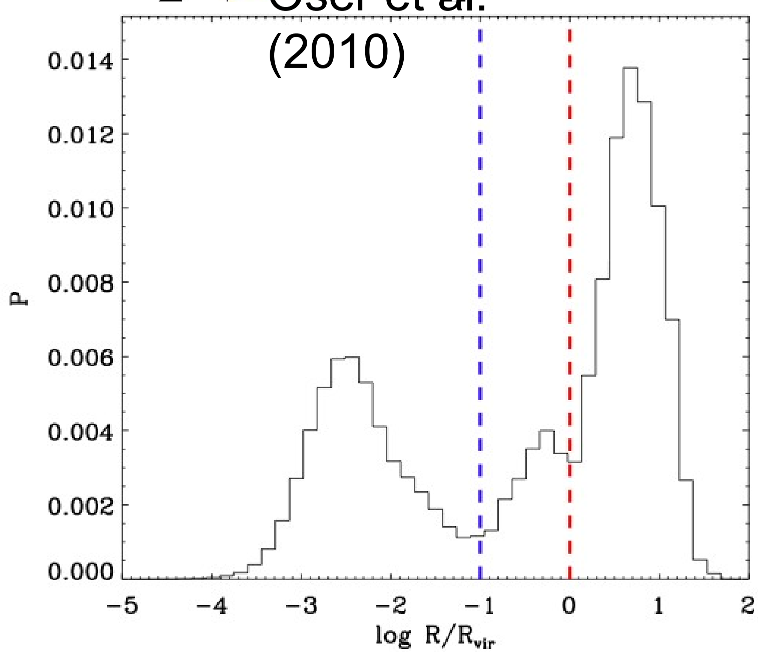
- A large ensemble of zoomed simulations run of individual elliptical galaxies using the multiparallel TreeSPH code Gadget-2.
- Code includes primordial gas cooling and star formation matched to reproduce the local Schmidt-Kennicutt relation.
- Sample 1: 3 galaxies at high (0.25 kpc) + 1 galaxy at ultra-high (0.125 kpc) resolution without SNII feedback (Naab et al. 2007, Johansson et al. 2009).
- Sample 2: 7 galaxies at high (0.25 kpc) + 2 galaxies at ultra-high (0.125 kpc) resolution with SNII feedback (Johansson et al. 2010).
- Sample 3: 40 galaxies at medium (0.4 kpc) with SNII feedback (Oser, Ostriker, Naab, Johansson, Burkert, 2010).
- The instantaneous SNII feedback is modelled using a subgrid multiphase model (Springel&Hernquist 2003), which adds pressure to starforming gas particles. No additional SN wind

Two-phased formation history of galaxies

- The stellar mass of the simulated galaxies is formed in two distinct components: In-situ within the galaxy (r<rgal=rvir/10) and ex-situ outside (r>rgal).
- In-situ: Dominant at 2<z<6, driven by cold gas flows, su solar metallicity, energeticall dissipative.
- Ex-situ: Dominant at 0<z<3 driven by minor & major mergers, sub-solar metallici energetically conservative.



Oser et al. (2010)



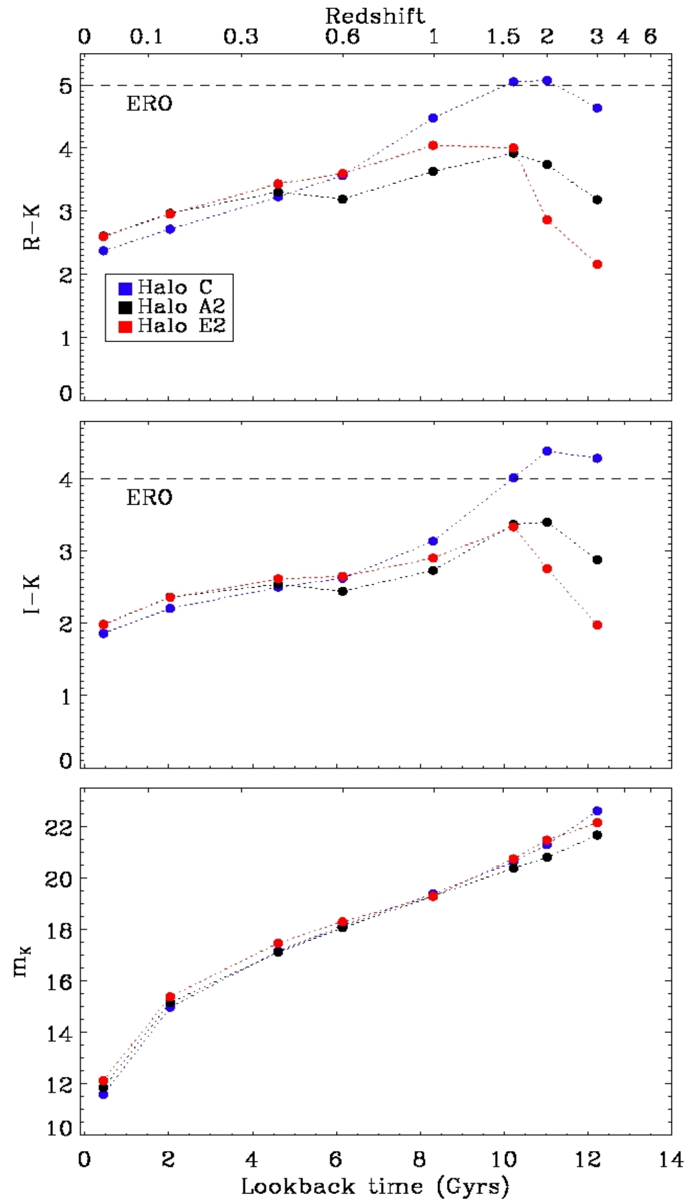
Significant ex-situ.

~Equal ex-situ & in- situ.

Significant in-situ.

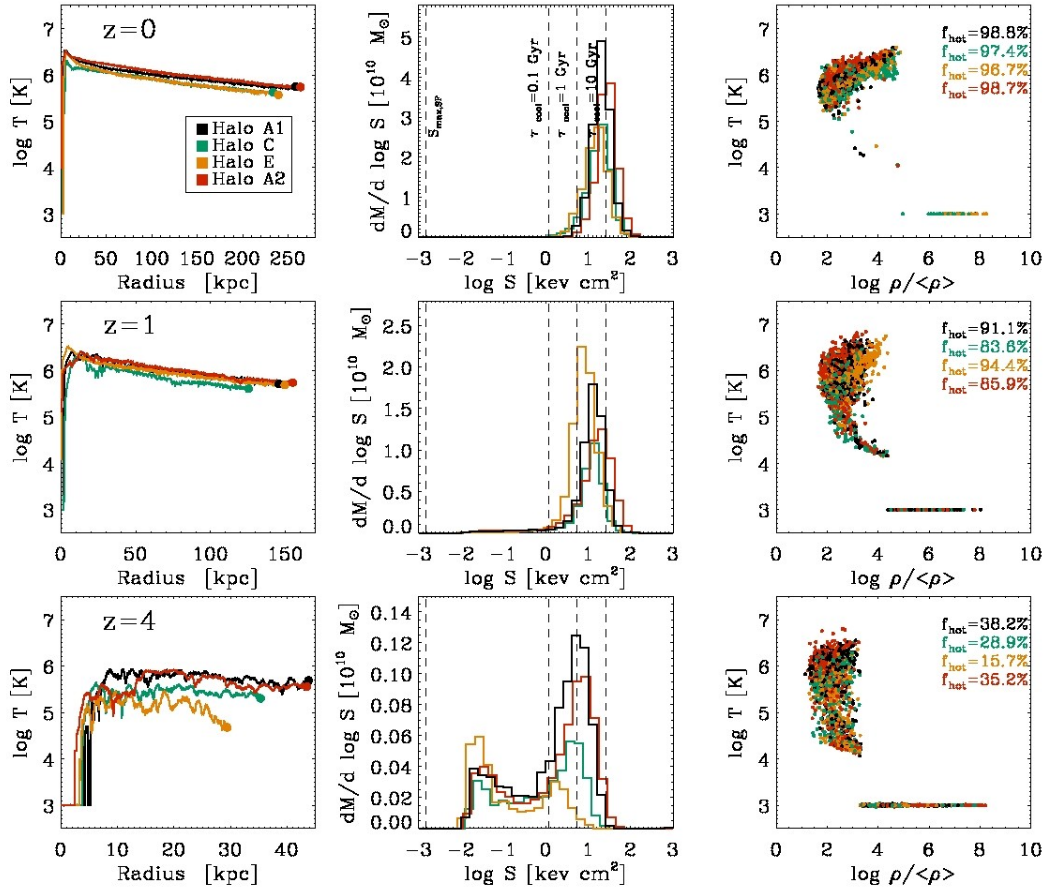
Theory I: Red & dead ellipticals

- The simulations produce red & dead ellipticals with red colours, some with colours redder than the ERO limit of R-K>5.0 & I-K>4.0.
- Magnitudes calculated using Bruzual&Charlot (2003) SSP using a Salpeter IMF and solar metallicity.
- No correction for obscuration yet, a simple Charlot&Fall (2000) model will obscure some light from τ<107 yr stars making the galaxies even redder.



Terminating SF by gravitational feedback

- Temperature of the diffuse gas is increasing in all simulations with decreasin redshift.
- Transition from cold to hot accretion at z~2-3 at M~3-5x1011 Msun.
- The cooling time is shorter than Hubble time, still T is increasing.
- At low redshifts only high entropy gas remains, hot gas fraction is >97% .
- In these simulations no SN feedback! What is heating the gas?



No SN feedback!

See also Birnboim, Dekel 2008

LMU USM

Heating of the gas component

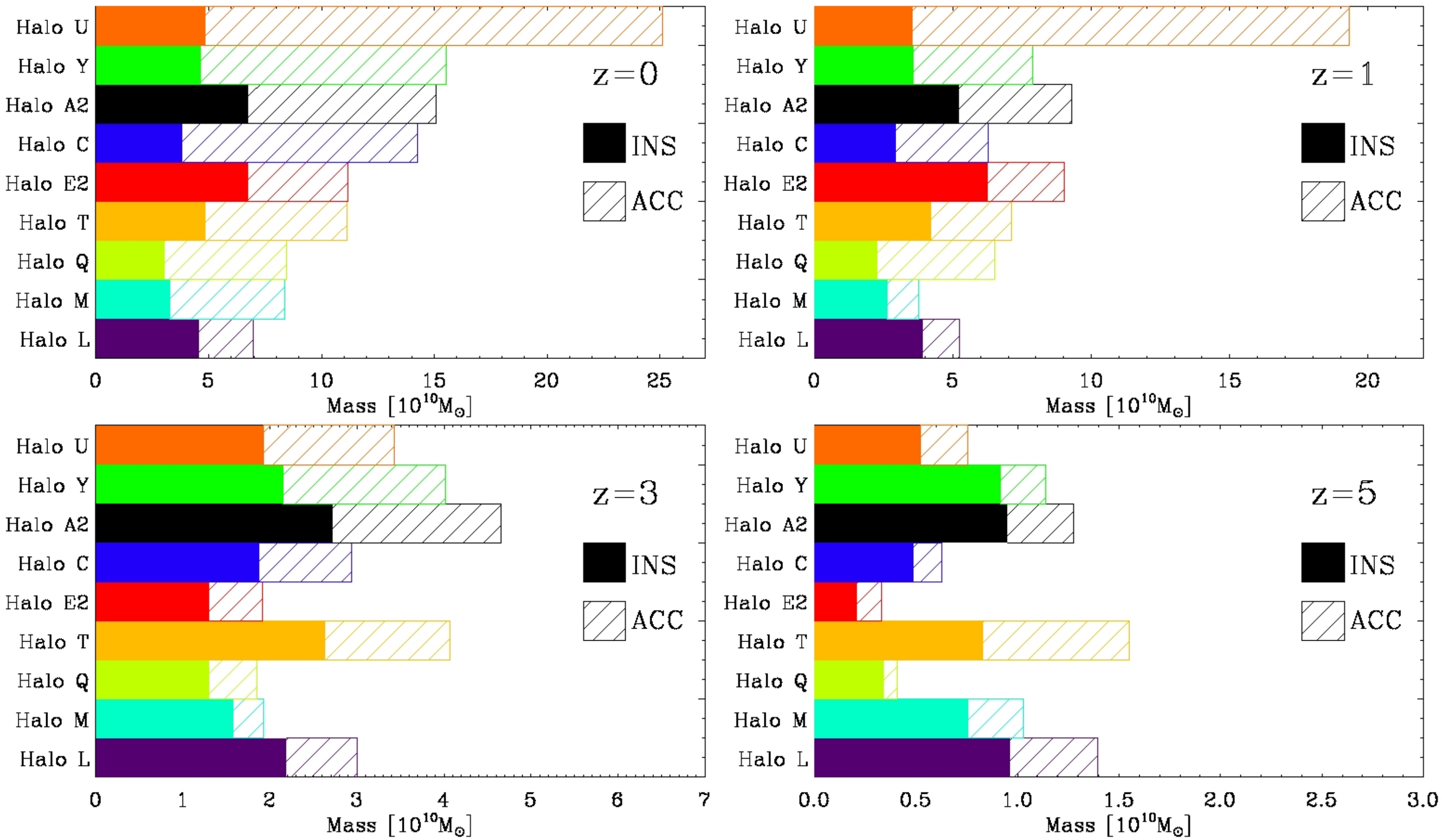
- $E_{grav} \sim m^* v_c^2$ unlike E_{SN} and E_{AGN} which are both proportional to m*. Egrav dominates for massive galaxies with high vc.
- Shock-heating of the diffuse gas dominates at all redshifts, but especially at z<3, when the galaxies are massive enough to support stable

Heating of the DM component

- The DM is initially adiabatically contracted at z~3, after which the central DM mass is decreasing for haloes A and C (dissipationless formation).
- Halo E has constant DM mass as a function of z (dissipational formaion).

Results need to be confirmed in simulations
including SN feedback.

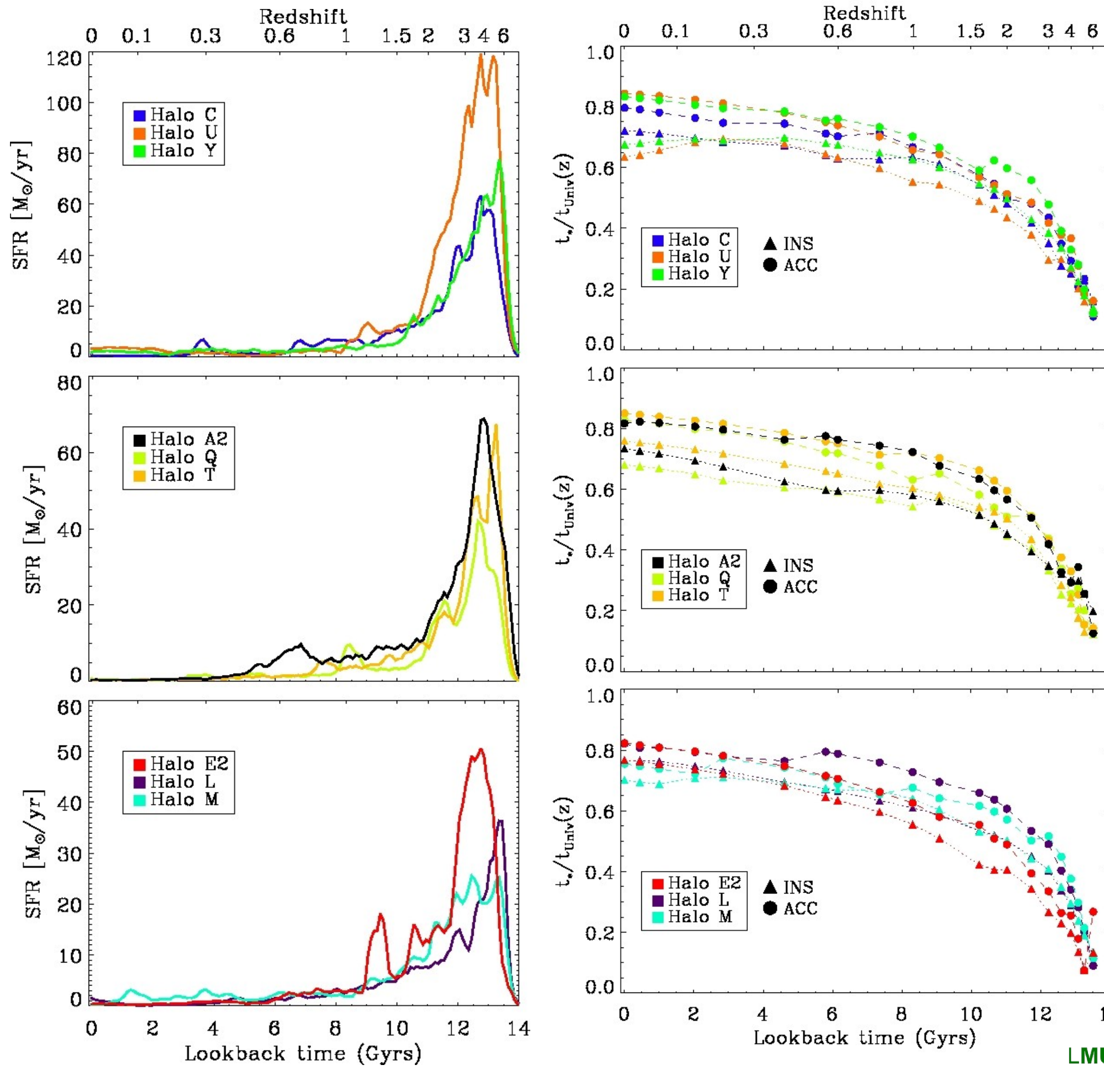
Theory II: Downsizing



- Galaxies assemble rapidly at high-z through in-situ star formation, later stellar assembly dominated by accreted ex-situ stars, with accretion being more dominant for more massive systems

Star formation rates & Ages of galaxies

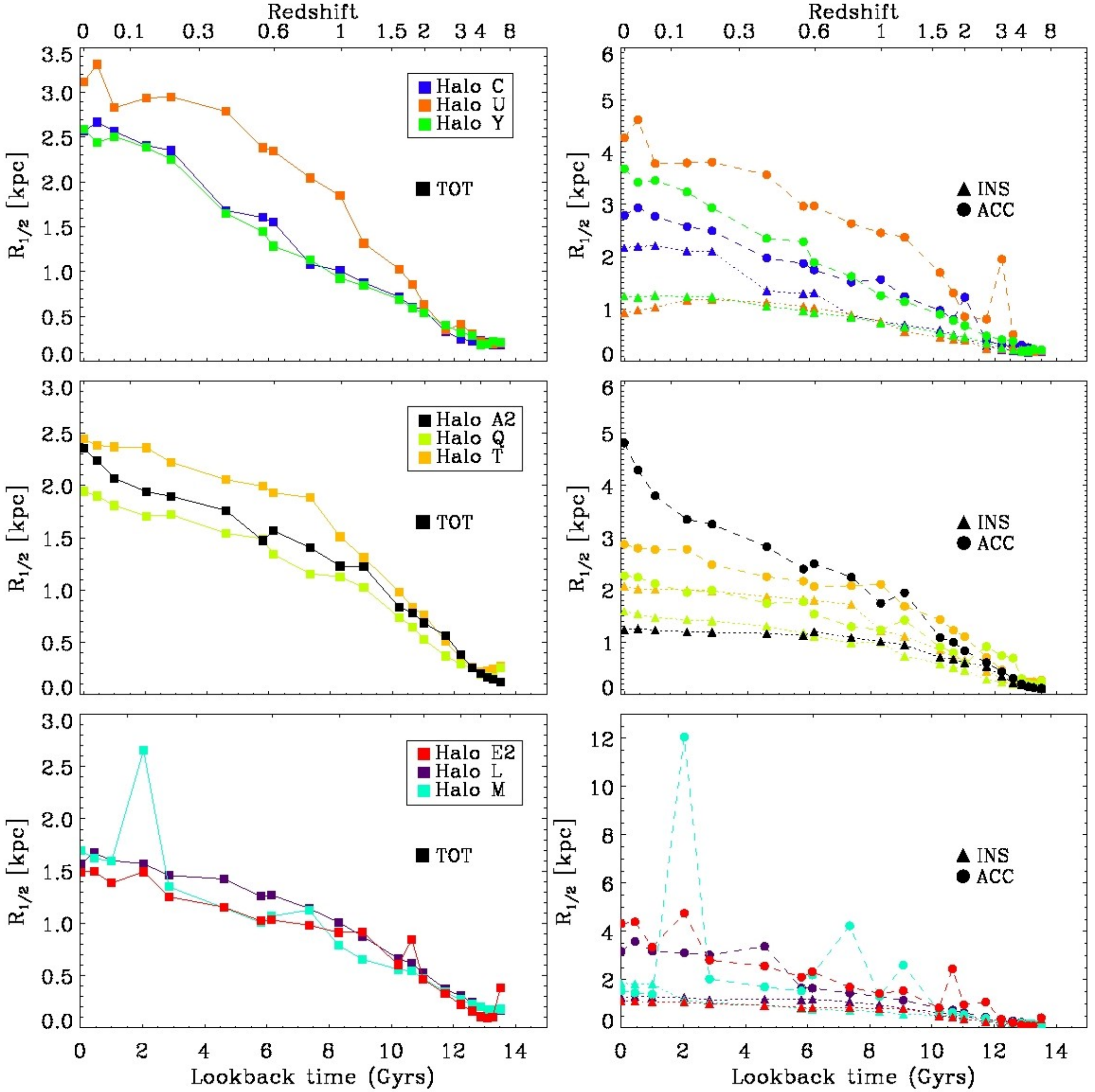
- Star formation rates large at high-redshift during in-situ formation phase. Below z<2 in general very low SFRs, growth dominated by dry merging.
- Old stars, with accreted population being older than the insitu. Most massive galaxies have highest fraction of accreted stars -> oldest ages



Theory III: Size growth through minor dry merging

·In-situ stars form a compact high density stellar system, with r1/2=1-2 kpc.

·Accreted stars are building up a more extended lower mass system, r1/2=3-5 kpc.

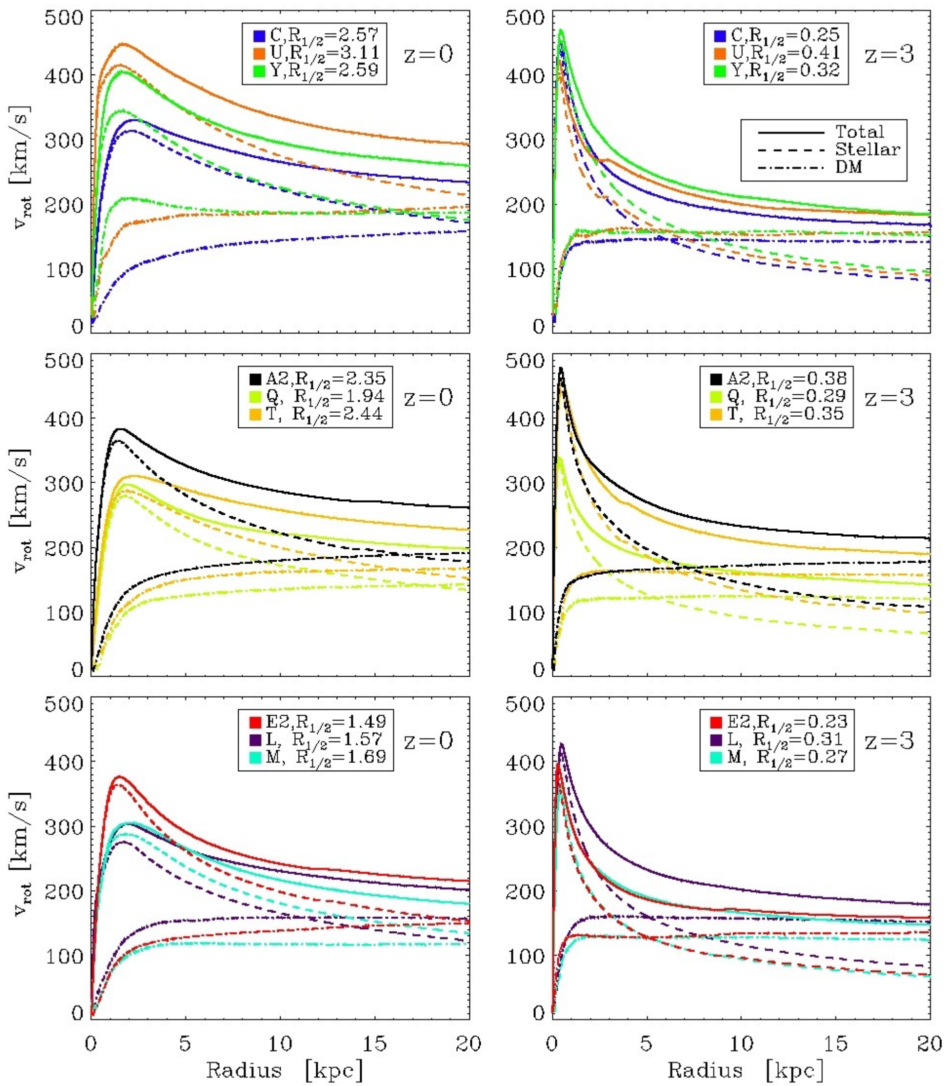


Size growth continued

· Most massive systems have, facc=75% , size growth z=3->z=0, x8.5.

·Intermediate massive systems, facc=60% , size growth z=3->z=0, x6.5.

·Galaxies in lowest mass bin, facc=45% , size growth z=3->z=0, x5.5.

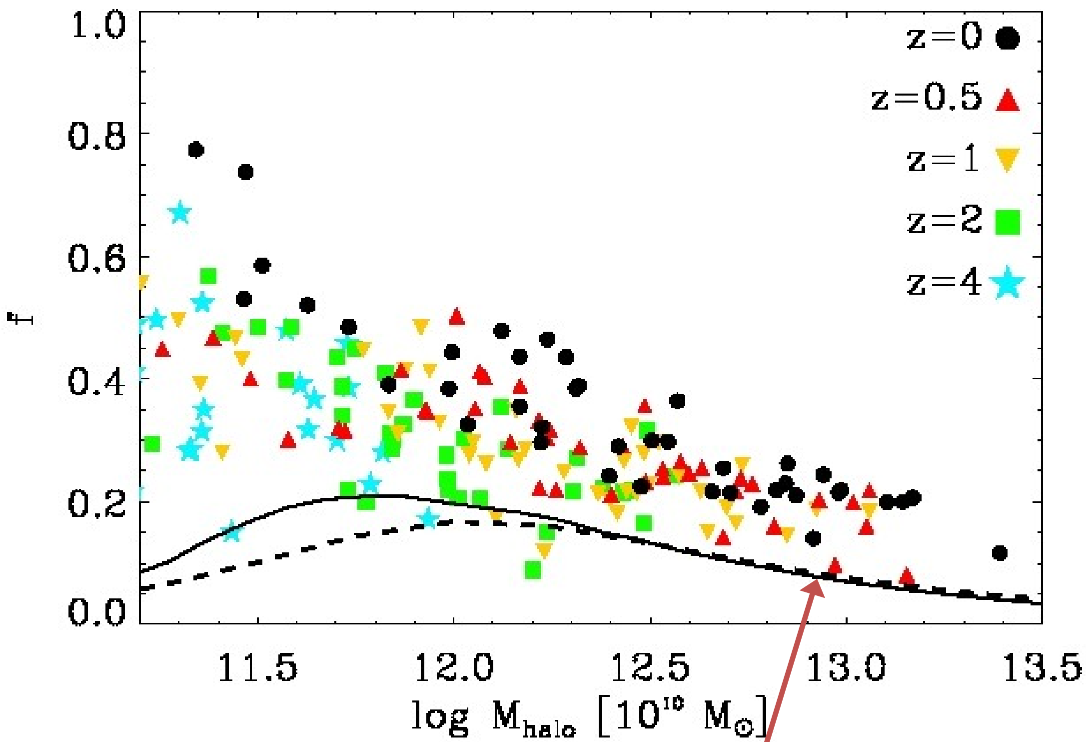


Conclusions

- 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.
- 1) Bi-modality: Energy release from gravitational feedback is an important component naturally included in numerical simulations and could help make massive galaxies red and dead.
- 2) Downsizing: Massive galaxies form stars in-situ rapidly at high redshifts, and later accrete substantial amounts of ex-situ stars that were formed in smaller subunits.
- 3) Size evolution: Minor dry mergers can potentially explain the strong size evolution of Elliptical galaxies

Caveat: Baryon conversion factor

- Baryon conversion factor: f=M*/(fb*mvir,DM), where fb=Ω b/Ω m=0.2.
- Our simulated conversion factor is too large by a factor of two -> too much stars for given halo mass.
- Missing physics: Supernova winds at lower masses & AGN feedback at higher masses.
- Slope at high masses



Lines: φ(L)-n(DM)
Guo et al.
Moster et al.