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Assembly histories and observational properties of Early-type galaxies

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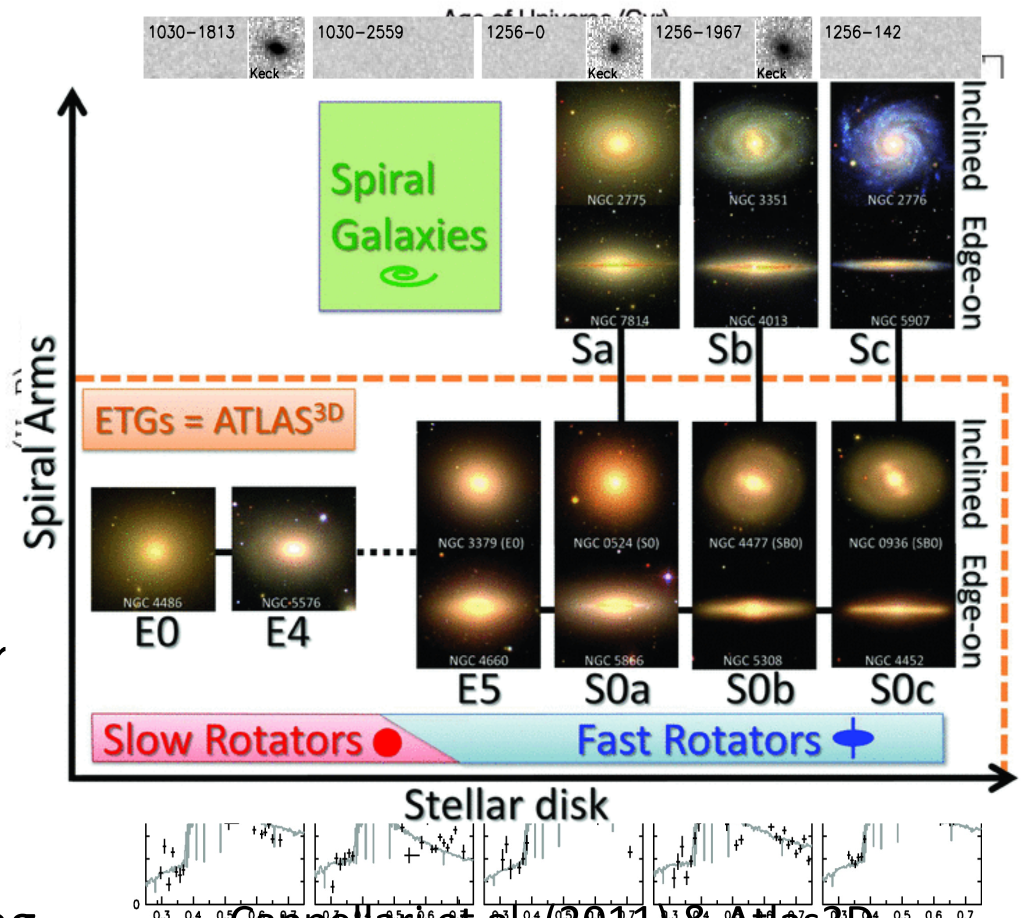
Johansson, Naab, Ostriker, 2012a, ApJ in press, ArXiv: 1202.3441
Johansson, Naab, Ostriker, 2012b, ApJ to be submitted

Observational results

1. Galaxy bimodality: $M_{crit,*} \sim 3 \times 10^{10}$ M_{sun}, above red spheroidal systems, below blue, star-forming disk galaxies.
2. Downsizing: massive galaxies already at place at z~2-3, implying rapid growth of massive ellipticals at high-z.
3. Compact sizes at z~2: Very compact (r_e~1 kpc) massive ($M > 10^{11}$ M_{sun}) galaxies, smaller by a factor of 3-5 compared to their local analogues at z=0.
4. Rotational properties: 85% (v/σ)≈1 of local Es are fast-rotating and 15% slow-rotating (v/σ)<0.1 (disks (v/σ)≈10-20).



Cappellari et al. (2011) & Atlas3D
Glazebrook et al. (2004)
van Dokkum et al. (2008)

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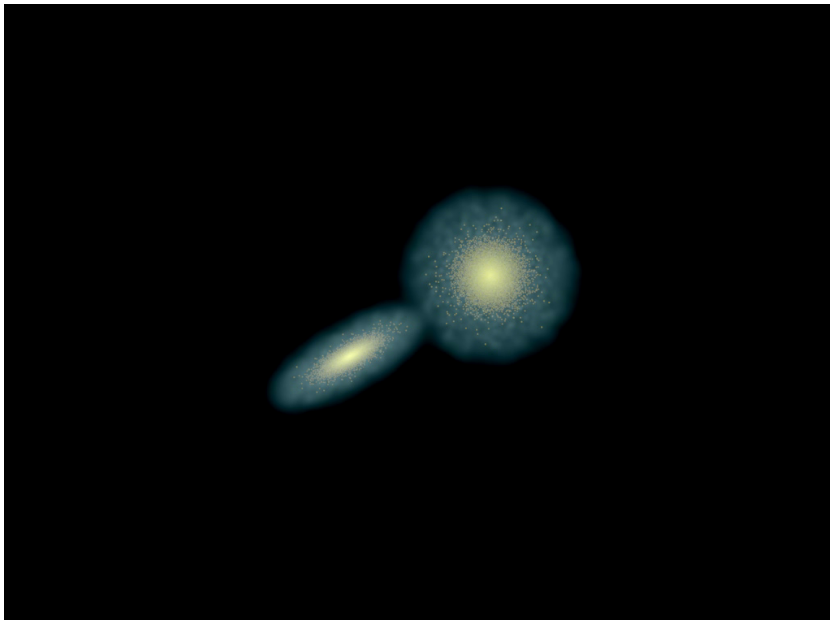
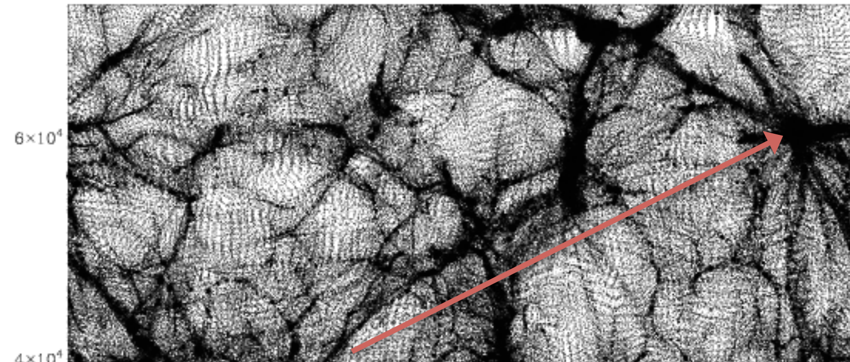
Numerical simulations of galaxy formation

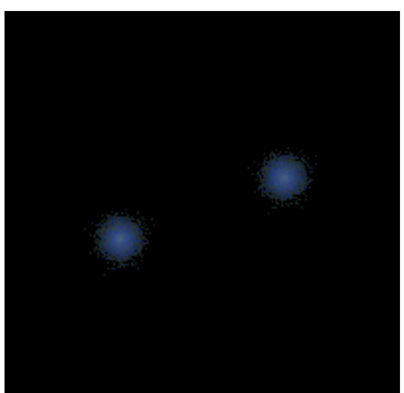
Merger simulations: Disky intermediate mass E-types?



Cosmological simulations: Boxy massive E-types?

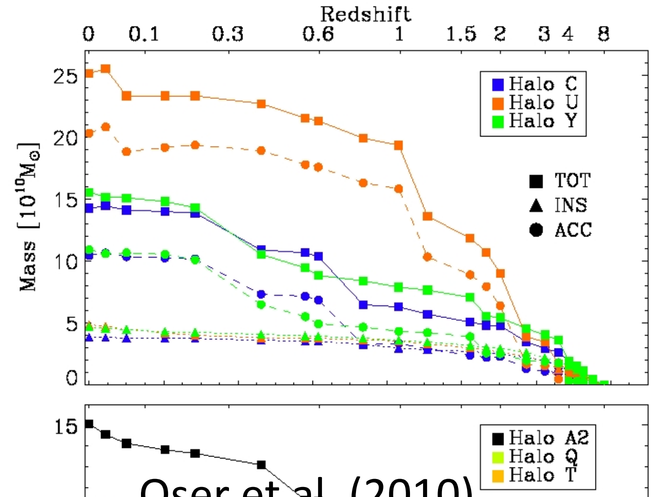


Compare with obser-vations:

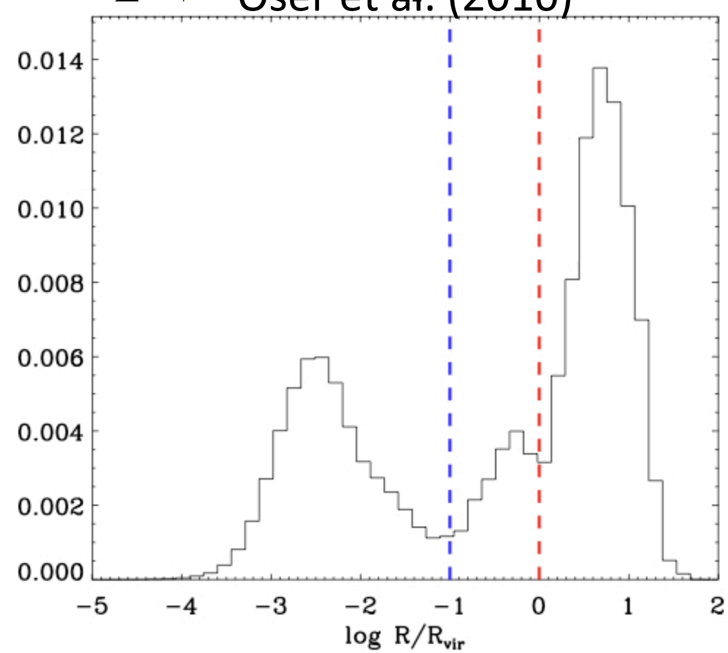


Two-phased formation history of galaxies

- The stellar mass of the simulated galaxies is formed in two distinct components: In-situ within the galaxy ($r<r_{gal}=r_{vir}/10$) and ex-situ outside ($r>r_{gal}$).
- In-situ: Dominant at 2<z<6, driven by cold gas flows, super-solar metallicity, energetically dissipative.
- Ex-situ: Dominant at 0<z<3 dri by minor & major mergers, sul solar metallicity, energetically conservative.



Oser et al. (2010)



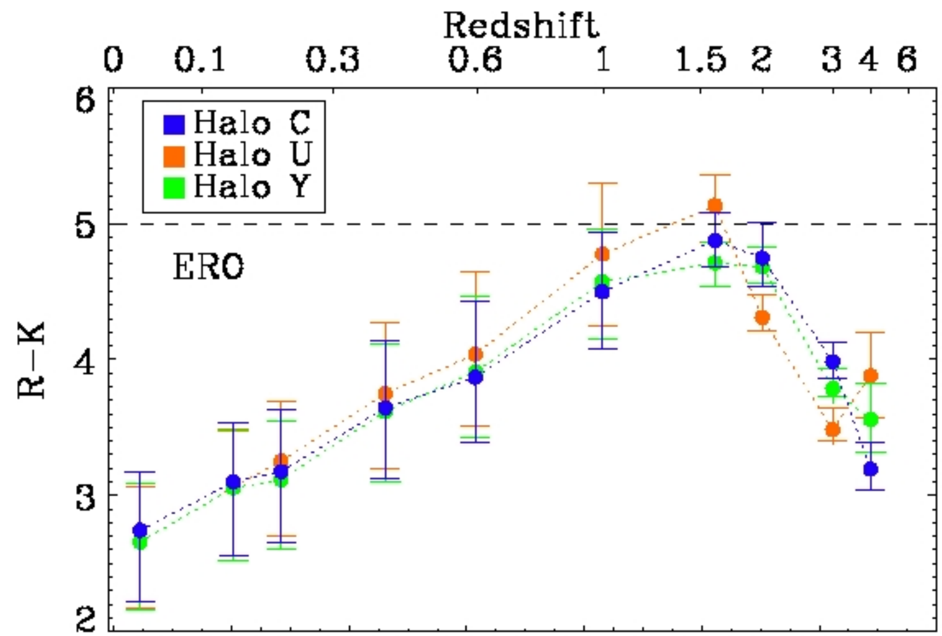
Significant ex-situ.

~Equal ex-situ & in-situ.

Significant in-situ.

Theory I: Red & dead ellipticals

- The simulations produce dead ellipticals with red colours, some with colours redder thar 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.
- Correct for dust using the simple Charlot&Fall (2000) model which obscures light from young $\tau<10^7$ yr stars.



Resulting in red galaxies by z~1. The error bar gives the range due to metallicity 0.2-2.5xsolar.

$$\hat{\tau}_\lambda(t') = \begin{cases} \hat{\tau}_V \left(\lambda/5500\,\text{Å}\right)^{-0.7}, & \text{for } t' \leq 10^7\text{yr}, \\ \mu\hat{\tau}_V \left(\lambda/5500\,\text{Å}\right)^{-0.7}, & \text{for } t' > 10^7\text{yr}, \end{cases}$$

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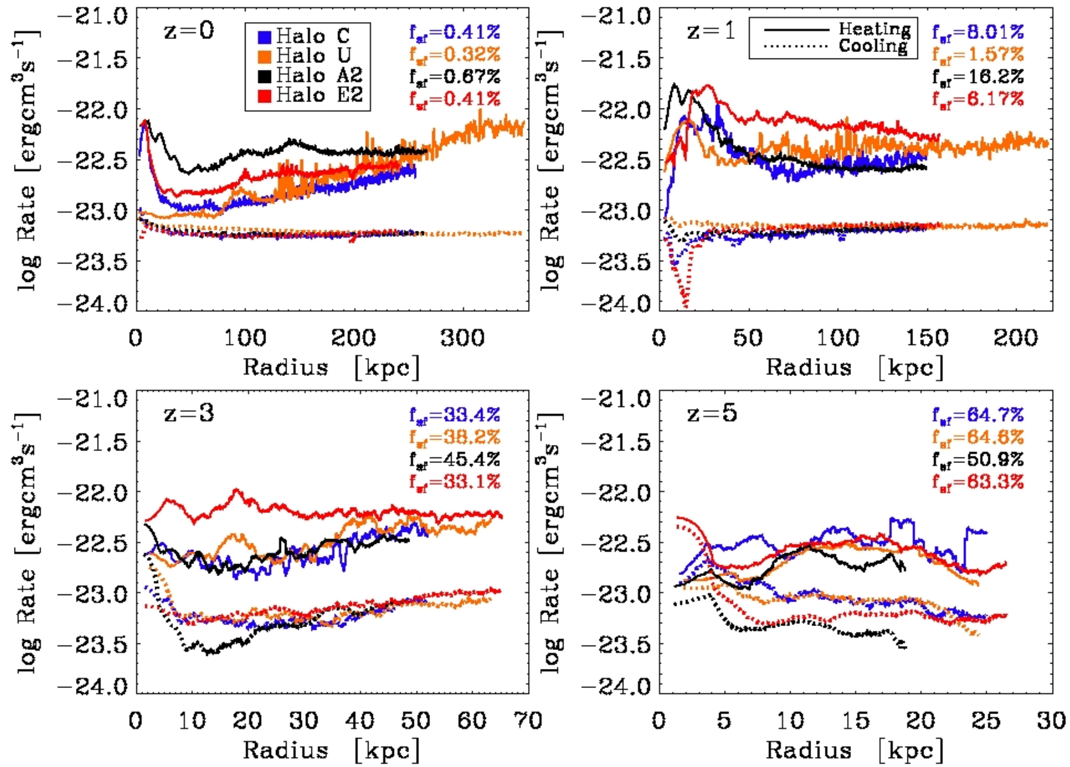
Gravitational or black hole feedback?

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

SN Feedback included, no black holes.



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

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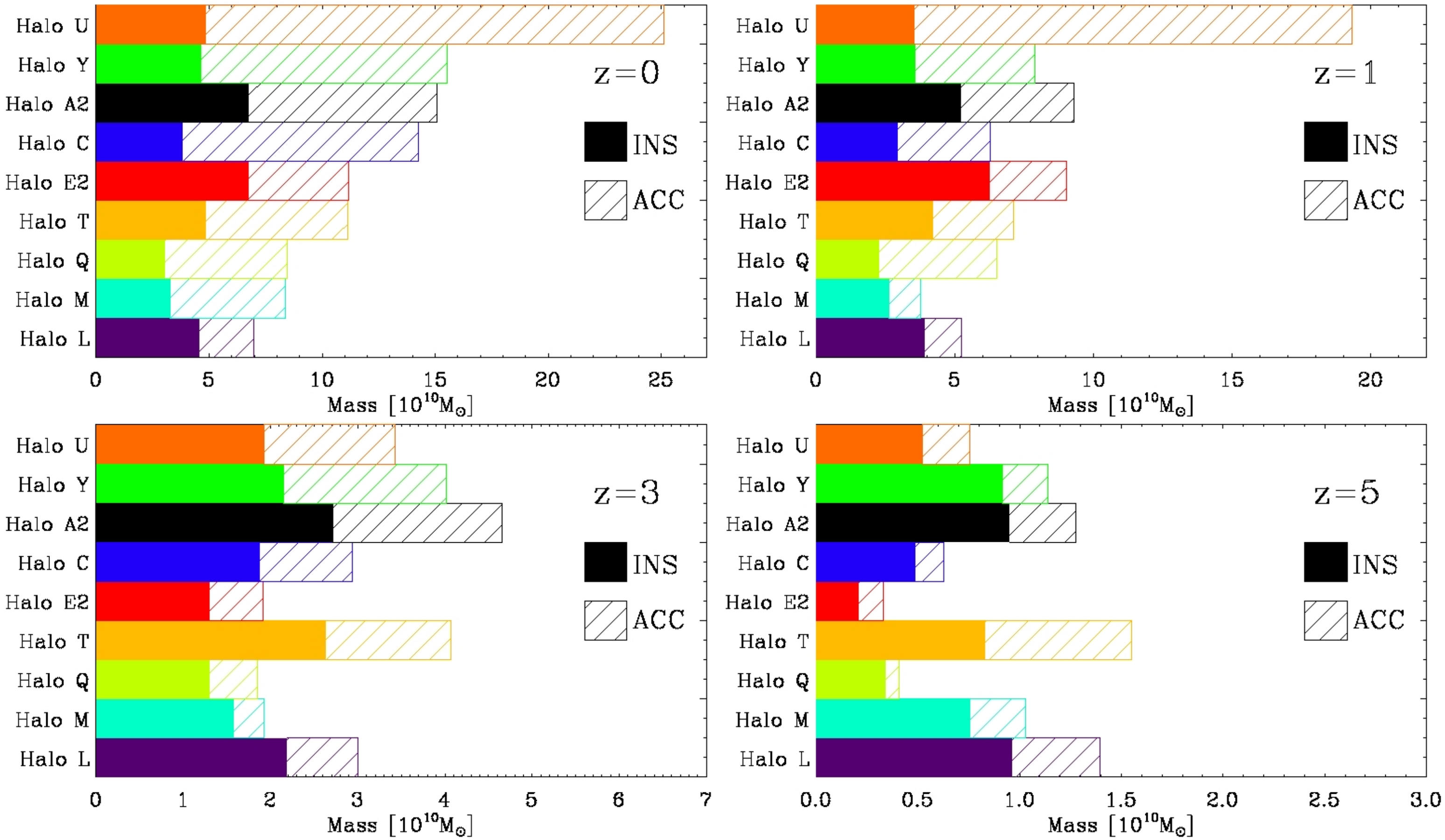
Theory II: Downsizing



- 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.

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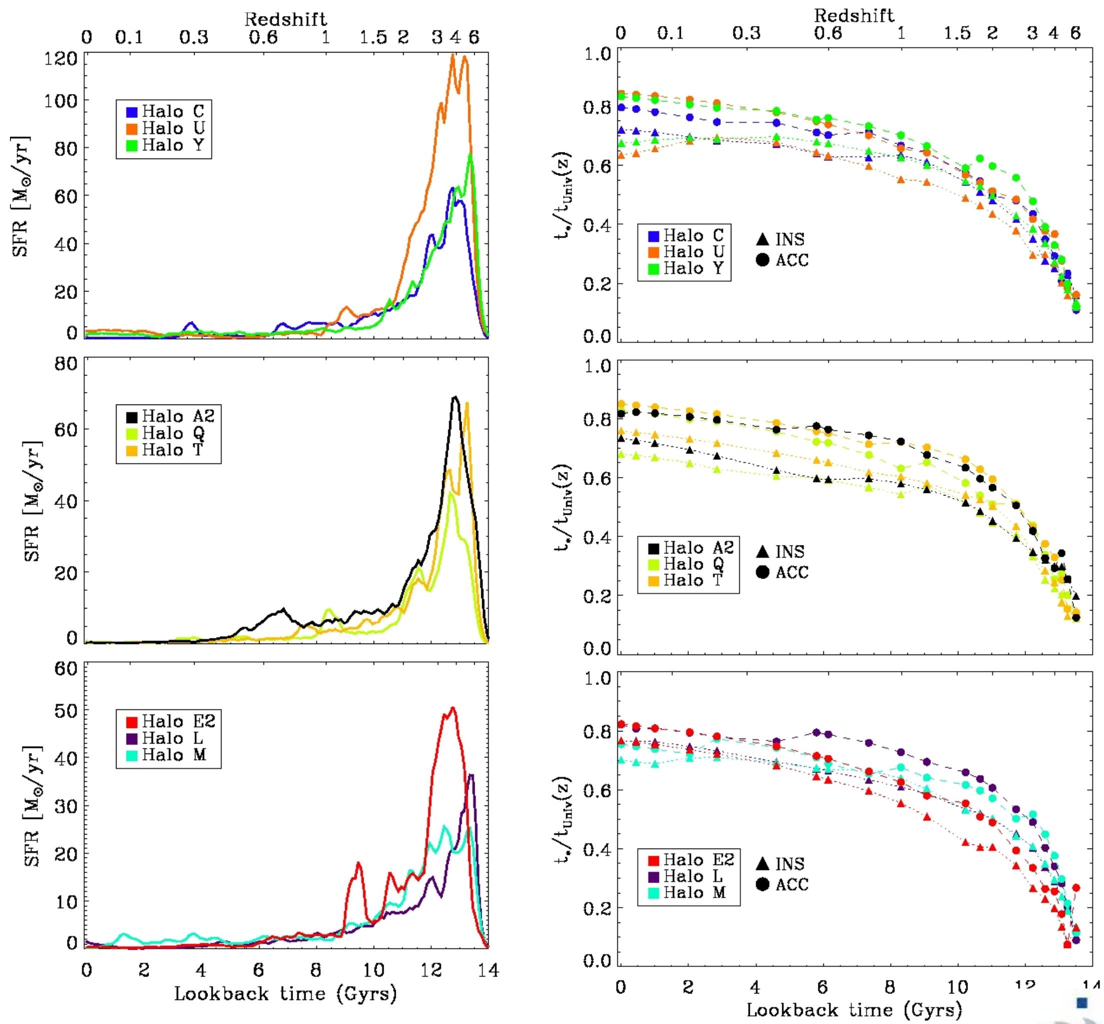
Star formation rates & Ages of galaxies

- 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 the highest fraction of accreted stars-> oldest ages as observed.

Formation age is not equal to the assembly age!



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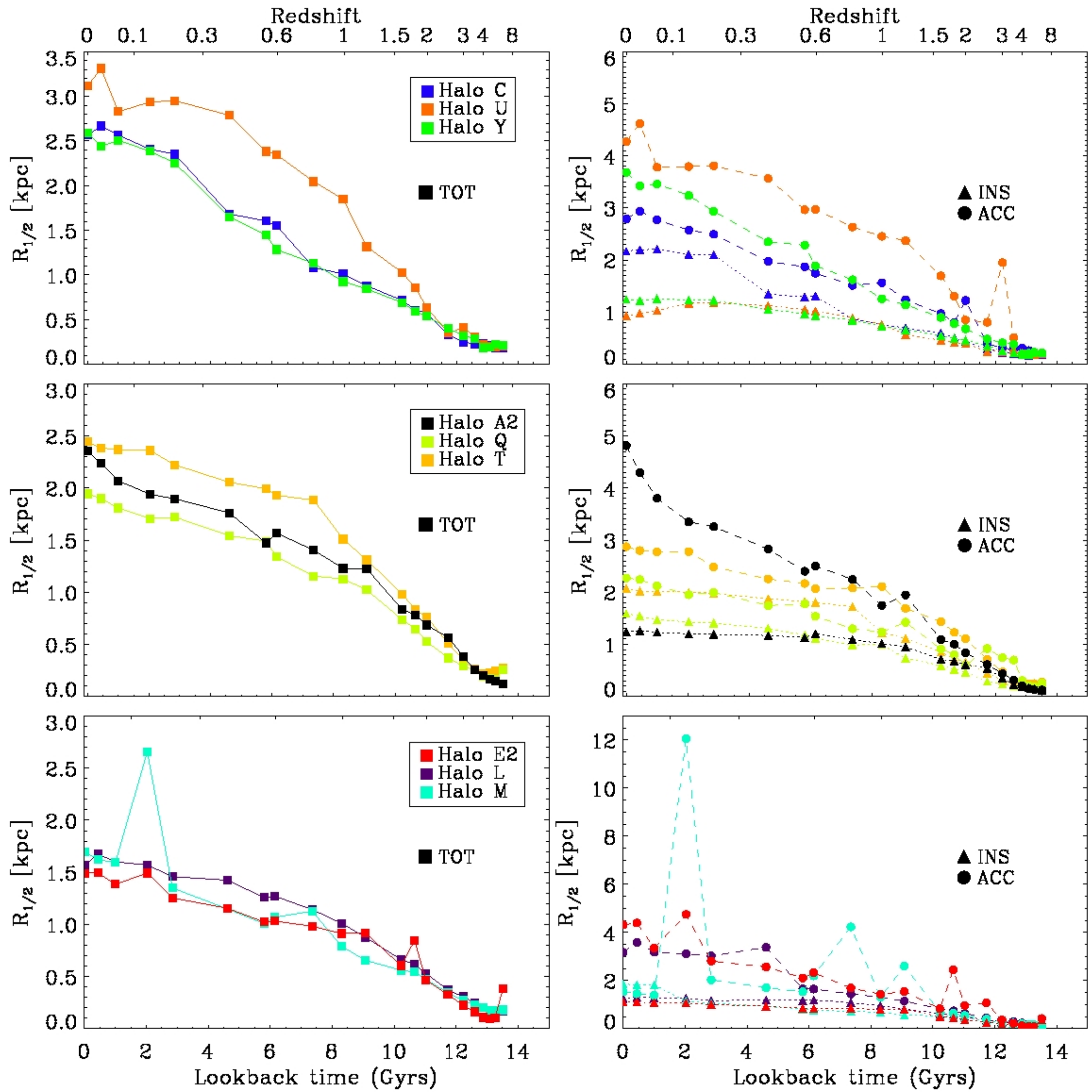
Theory III: Size growth through minor dry merging

- 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.



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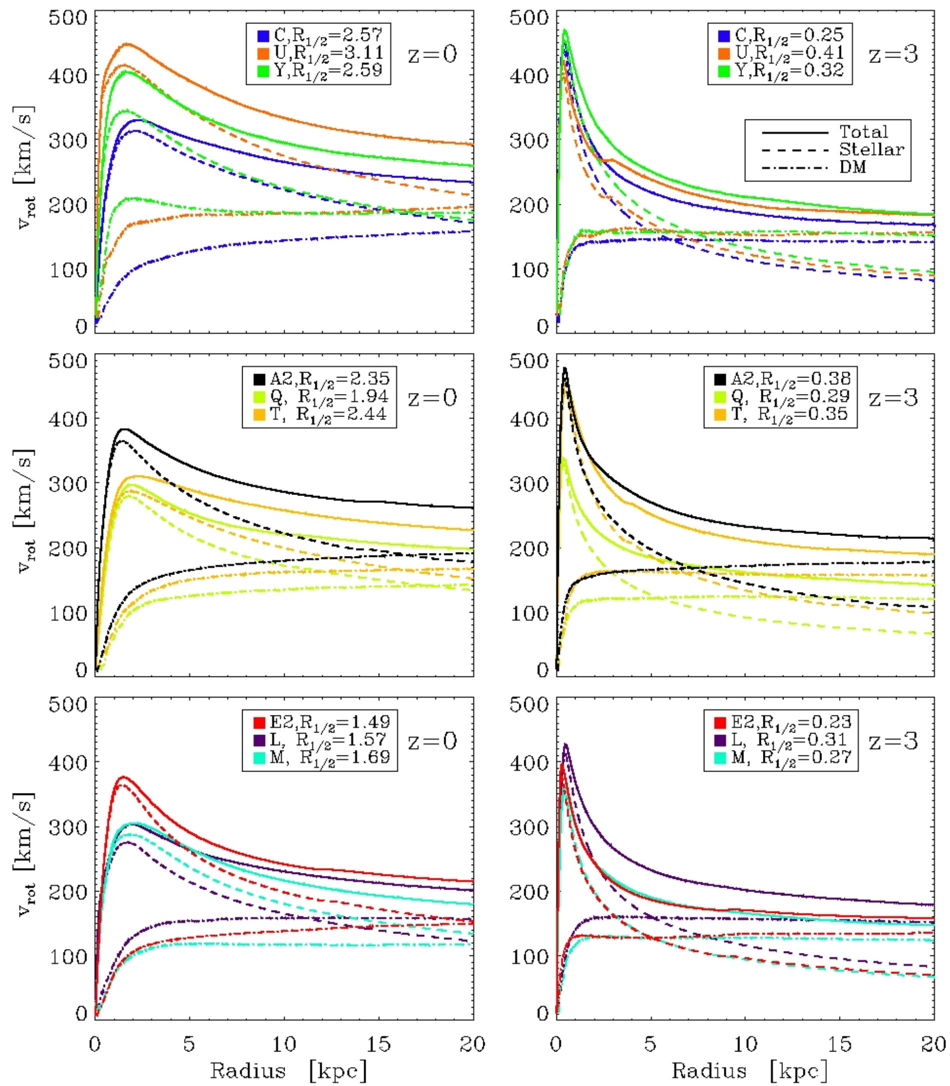
Size growth and rotation curves

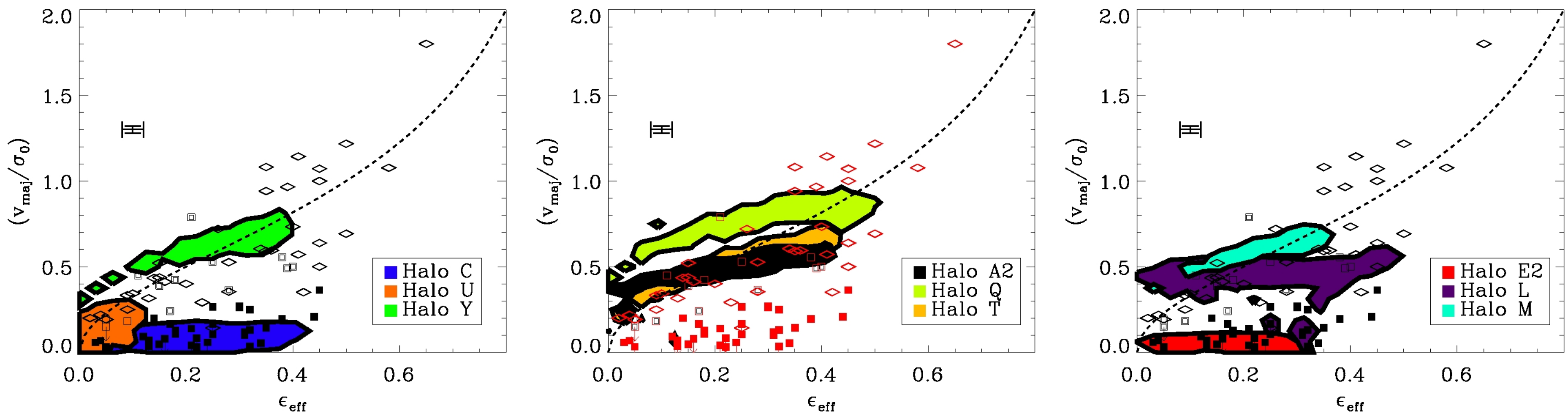
- Most massive systems have, f_{acc}=75%, size growth z=3->z=0, x8.5.

- Intermediate massive systems, f_{acc}=60%, size growth z=3->z=0, x6.5.

- Galaxies in lowest mass bin, f_{acc}=45%, size growth z=3->z=0, x5.5.



Theory IV: Slow and fast rotators



The contours indicate the 95% probablity of finding a simulated galaxy as seen from 500 random projections.

- The more massive galaxies that have the largest fraction of accreted stars are also typically slow rotators and also more round.
- Lower mass galaxies with larger fractions of in-situ formed stars are typically fast rotators and also exhibit on average more elongated shapes.

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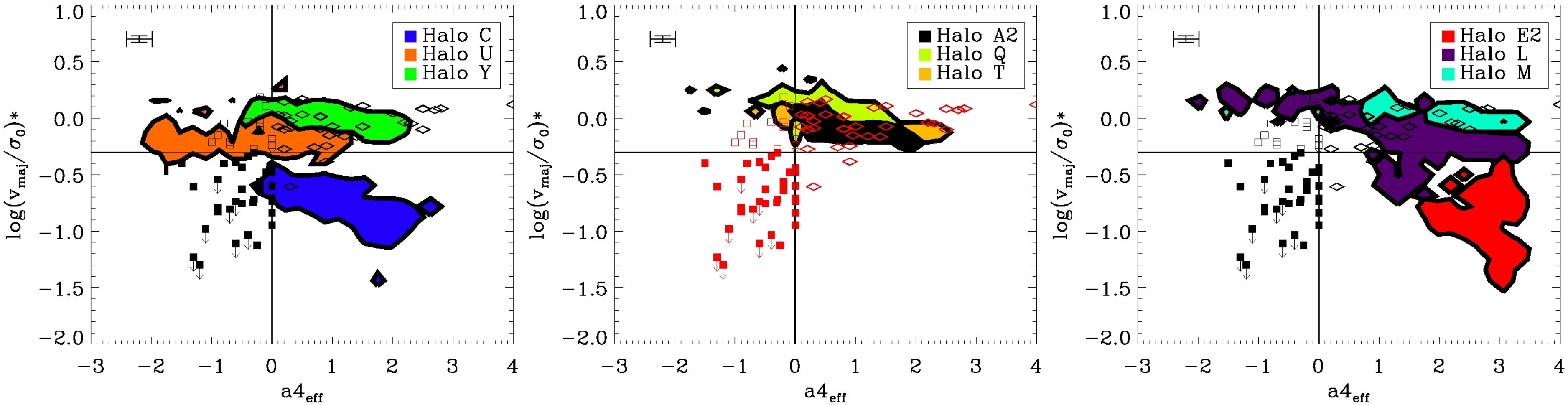
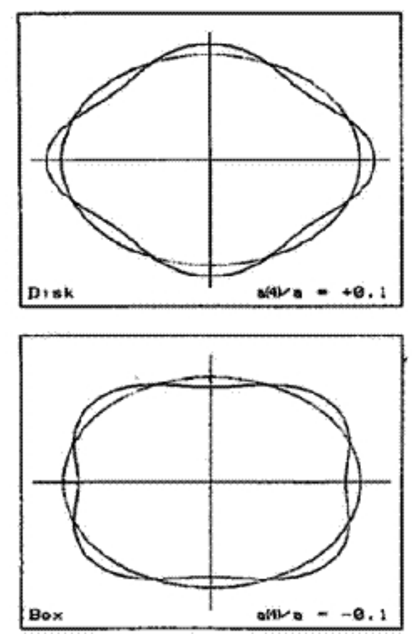
The shapes of early-type galaxies



• More massive galaxies show projections with distinctly boxy isophotes ($a_4<0$), whereas lower mass galaxies with higher in-situ stellar fractions have typically disky isophotes ($a_4>0$).

• The massive galaxies are slow-rotating and boxy, whereas the lower mass galaxies are fast-rotating and disky, in agreement with the observations.



Conclusions

1. Bi-modality: Energy release from gravitational feedback is an important component and could help make and maintain massive galaxies as red and dead, although other feedback sources (AGN) is needed for the most massive galaxies.
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 -> Downsizing.
3. Size evolution: Minor dry mergers can potentially explain the strong size evolution of Elliptical galaxies from z=2->0.
4. Rotational properties: Massive galaxies are slow-rotating, round and boxy, lower mass galaxies are fast-rotating, elongated and disky.

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Our simulation samples

- A large ensemble of zoomed simulations run of individual elliptical galaxies using the multiparallel TreeSPH code Gadget-2 and -3.
- Code includes primordial gas cooling and star formation matched to reproduce the local Schmidt-Kennicutt relation.
- 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 or AGN feed-back is included.
- Galaxy Sample: 6 galaxies at high (0.25 kpc, $M \approx 8 \times 10^5 M_\odot$) + 3 galaxies at ultra-high (0.125 kpc, $M \approx 10^5 M_\odot$) resolution.
- The code has been run on 40,000 cores (DM only), our simulations with gas physics are typically run on 64-256 cores on machines in Princeton, Munich and now CSC.

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