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Assembly histories and observational properties of simulated Early-Type Galaxies

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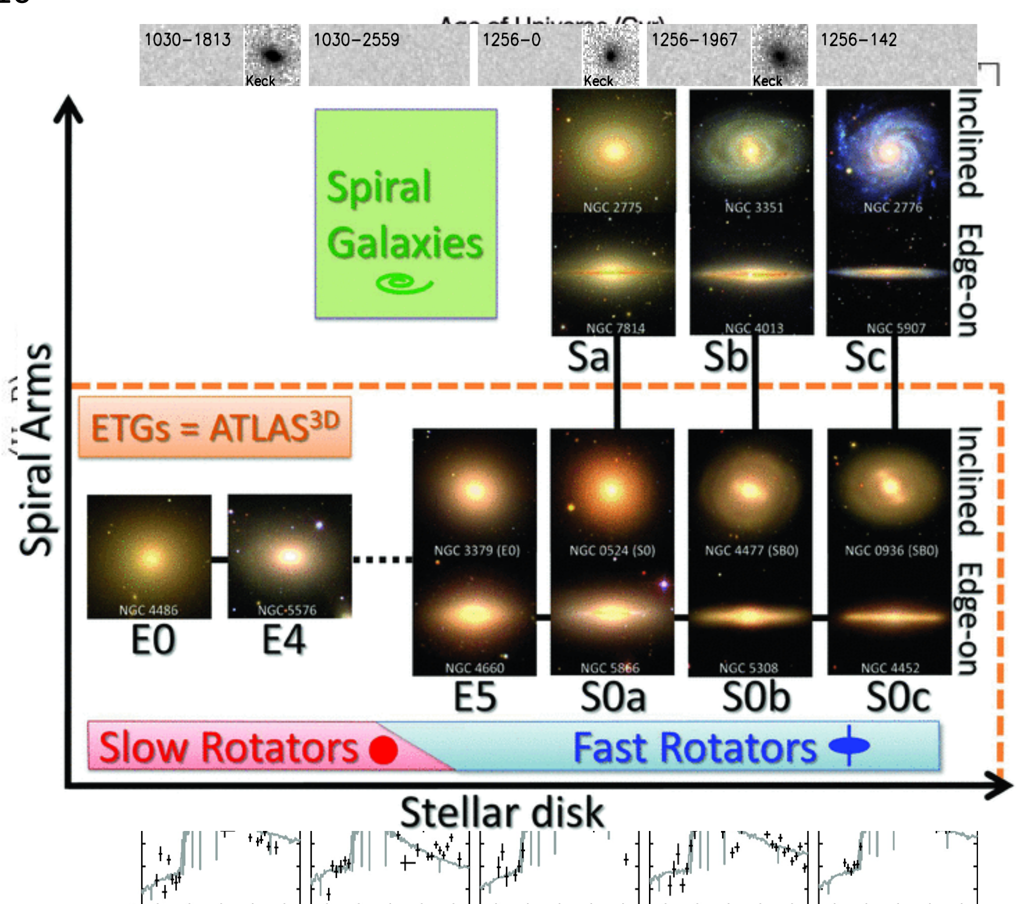
with Thorsten Naab, Ludwig Oser, Jeremiah Ostriker

Observational results

1. Galaxy bimodality: $M_{crit,*}$~$3x10^{10}$ $M_{\odot}$, 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 ($M>10^{11}$ $M_{\odot}$) galaxies, smaller by a factor of 3-5 compared to their local analogues at z=0.
4. Rotational properties: 85% $(v/\sigma)\approx1$ of local ETGs are fast-rotating and 15% slow-rotating $(v/\sigma)<0.1$.



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

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What are the implications for massive galaxy evolution?

- No 'monolithic collapse' at high redshift followed by passive evolution – galaxies would be too small and too red today
- No formation of massive present day elliptical galaxies by just 'binary mergers of disk galaxies' – small/large sizes cannot be explained
- Dissipative early formation – high phase space densities
- Size growth and mass growth is not dominated by star formation, unlike for disk galaxies – average stellar populations are old and leave little room for new stars born late
- Evolution by a common process in hierarchical cosmologies: 'minor' mergers – major mergers of massive galaxies are 'rare' and stochastic
- Additional processes? – rapid/slow mass-loss (stars;AGN;M/L…)

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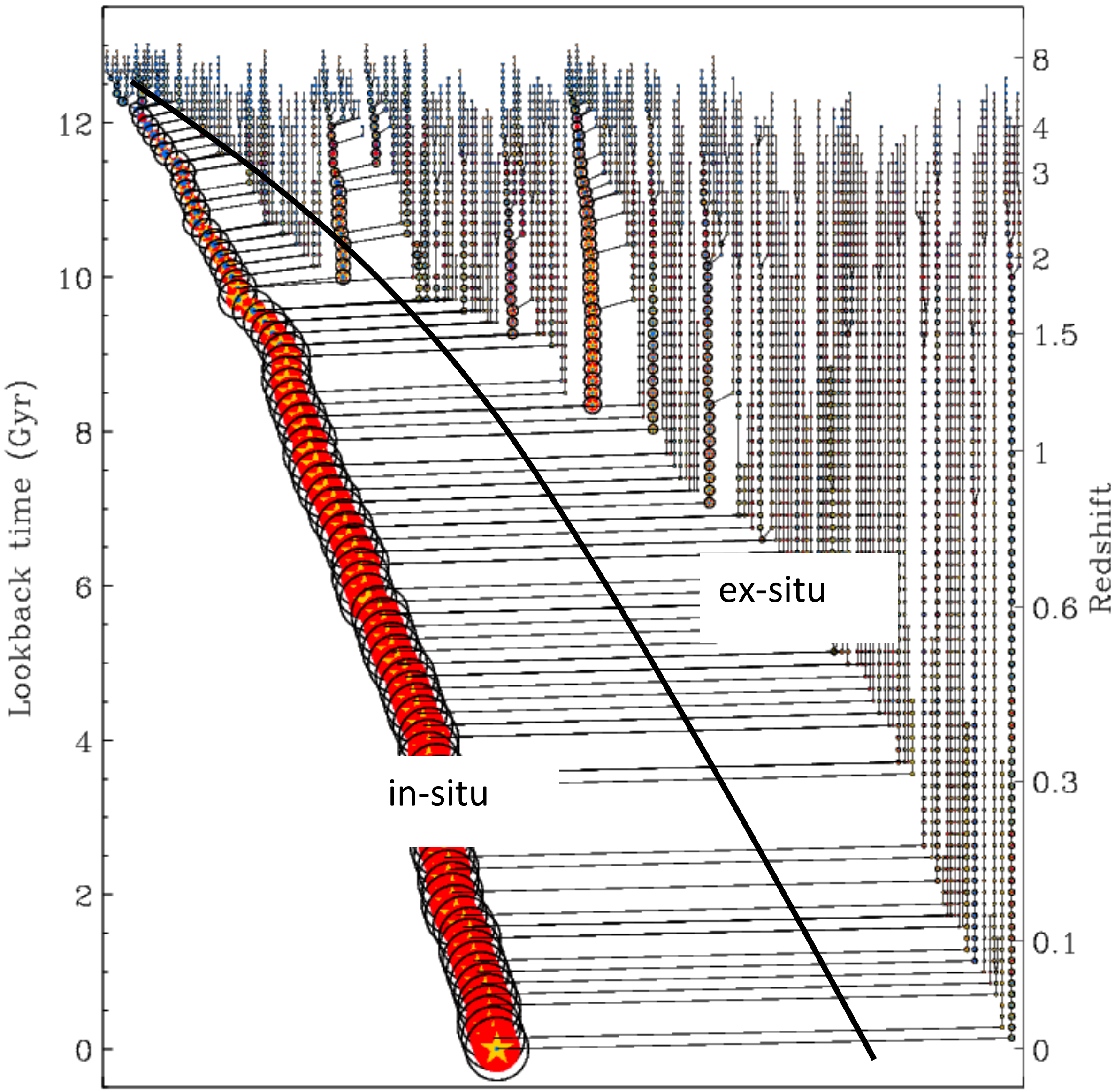
The complex cosmological assembly histories



- Cosmological simulations are the ultimate way to understand this process.
- Compact high-redshift galaxies form naturally (e.g. Joung et al. 2009, Naab et al. 2009, Sommer-Larsen et al. 2010).
- Typical contribution of mergers (> 1:4) in massive galaxies since z=2 is 30% - 40%.

Hirschmann et al. 2012, Oser et al. 2012

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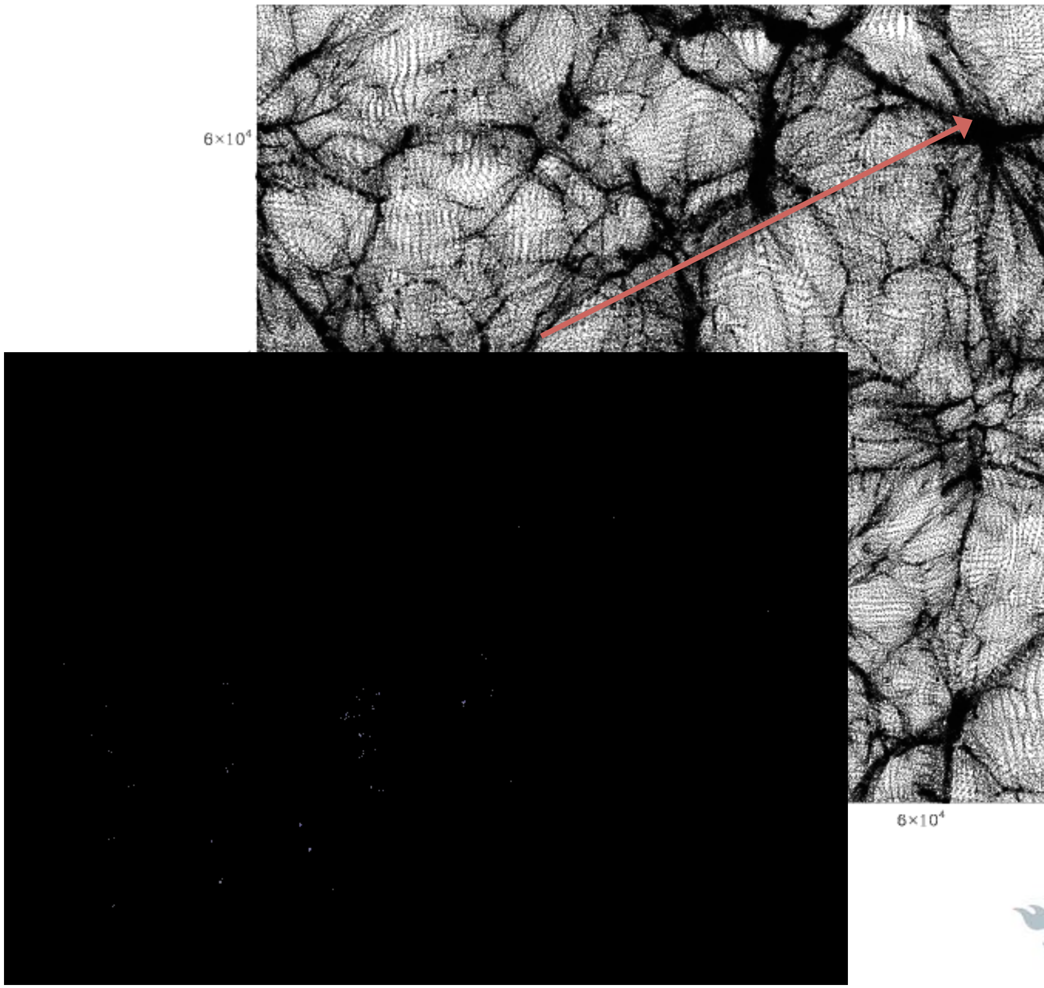
Cosmological simulations of galaxy formation

- A simulated sample of 6 galaxies at high (0.25 kpc) + 3 galaxies at ultrahigh (0.125 kpc) resolution run using the Gadget-2 code.

- Physics included: gas cooling, star formation, instantaneous SNII feedback. No additional SN wind or AGN feedback included.

Johansson et al. 2012



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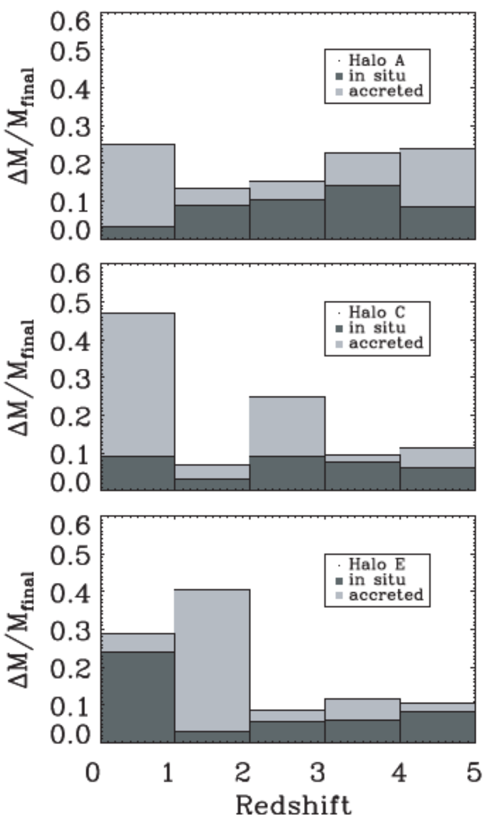
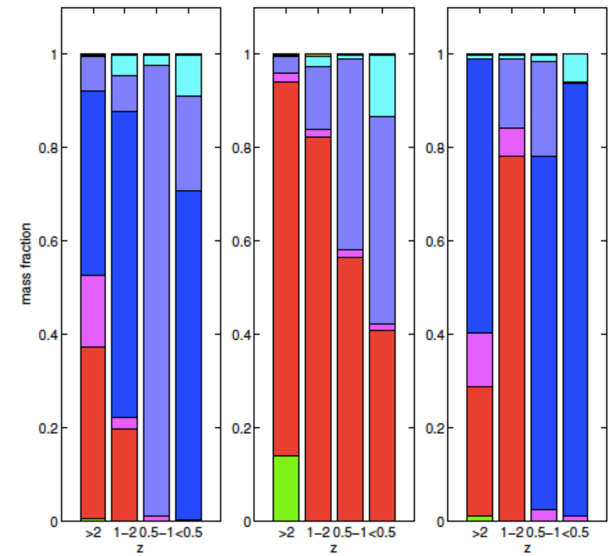
The origin of stars in massive galaxies

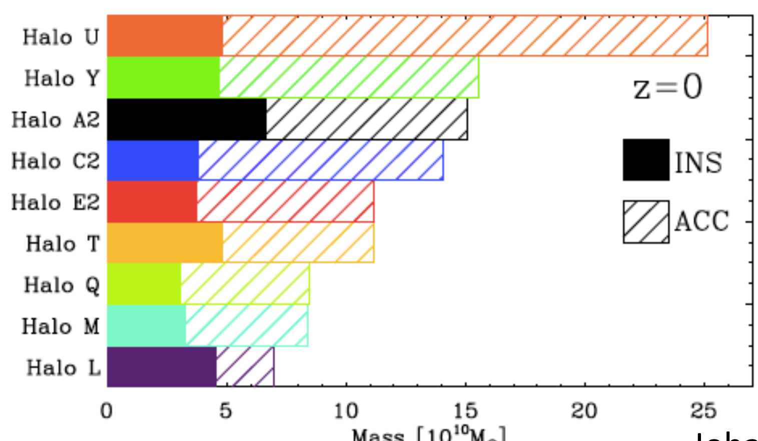
A significant fraction of stars in massive galaxies is accreted
(e.g. White & Rees 1978, Cole et al. 2000, Abadi et al. 2006, de Lucia et al. 2006, Cooper et al. 2010, Guo et al. 2011, Laporte et al. 2012 and more…)



Naab et al. 2007

Feldmann et al. 2010





Johansson et al. 2012

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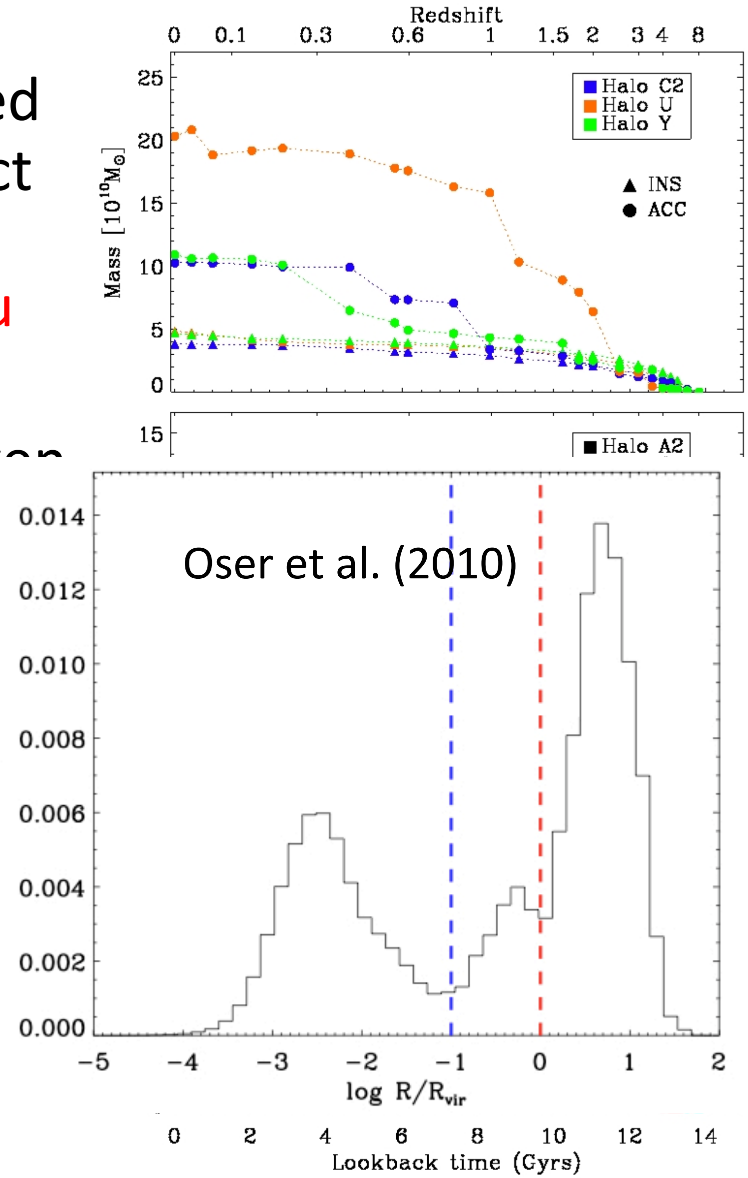
Two-phased formation history of galaxies

- 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, dri[...] by cold gas flows and have sup[...] solar metallicity.
- Ex-situ: Dominant at 0<z<3 dri[...] by minor & major mergers and have sub-solar metallicity.



Significant ex-situ.

~Equal ex-situ & in-situ.

Significant in-situ.

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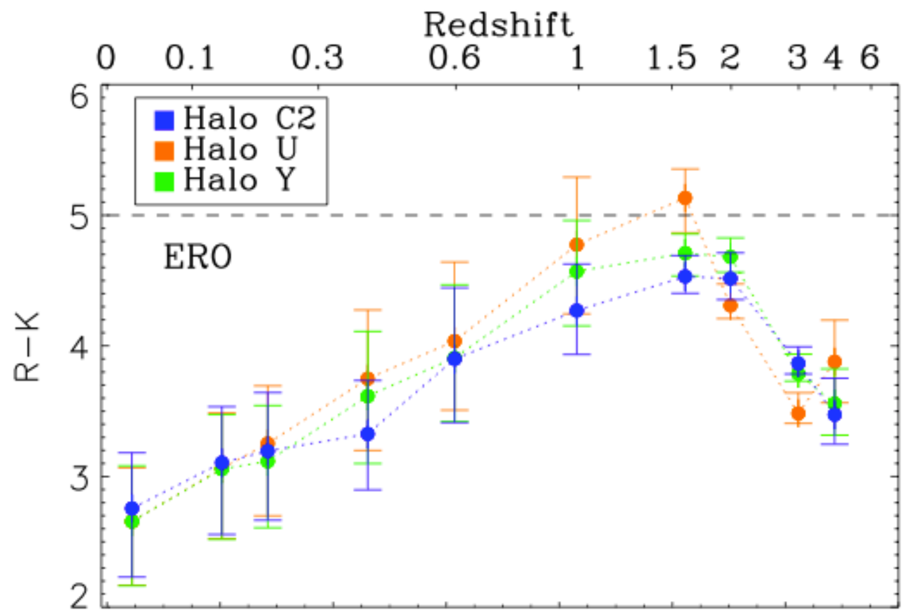
I: Red & dead ellipticals

- The simulations produce 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.
- 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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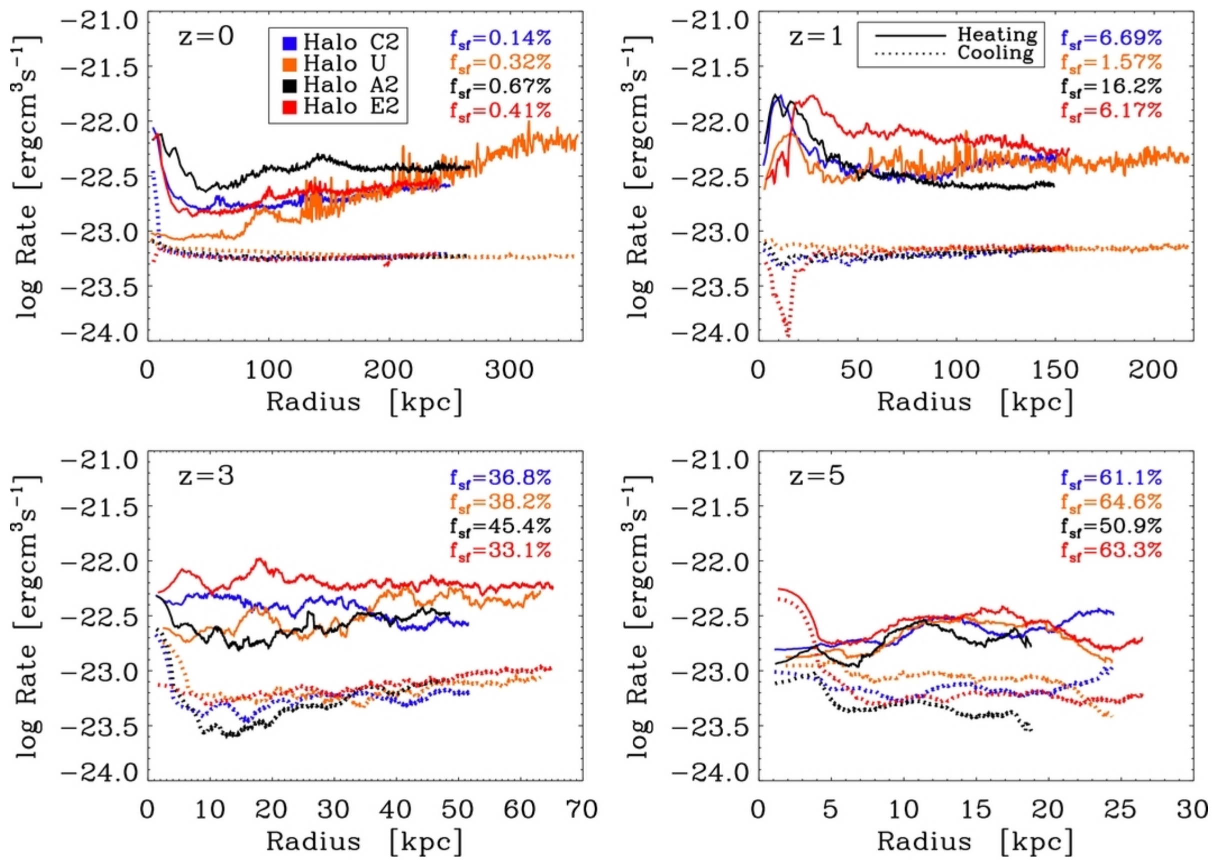
Gravitational or AGN feedback?

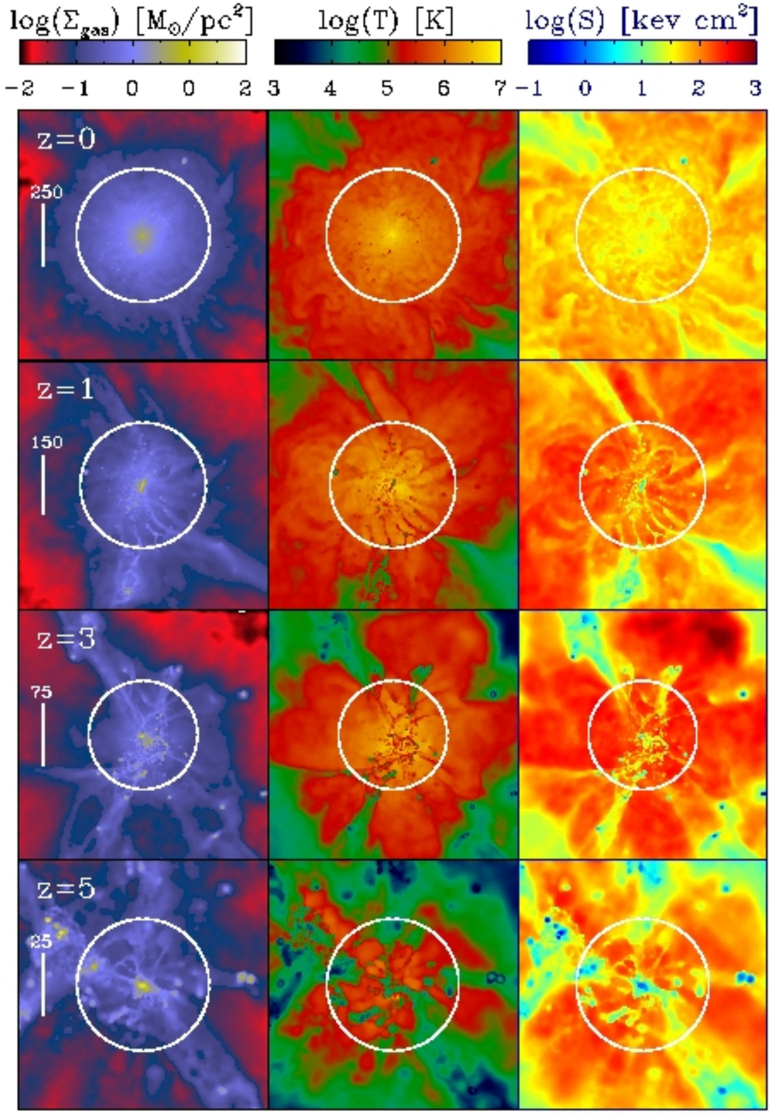
- $E_{grav} \sim m_* v_c^2$ unlike E_{SN} and E_{AGN} which are both proportional to m_*. E_{grav} might be important for massive galaxies with high v_c.
- Shock-heating of the diffuse gas dominates at all redshifts, but especially at z<3, when the galaxies are massive enough to support stable shocks.

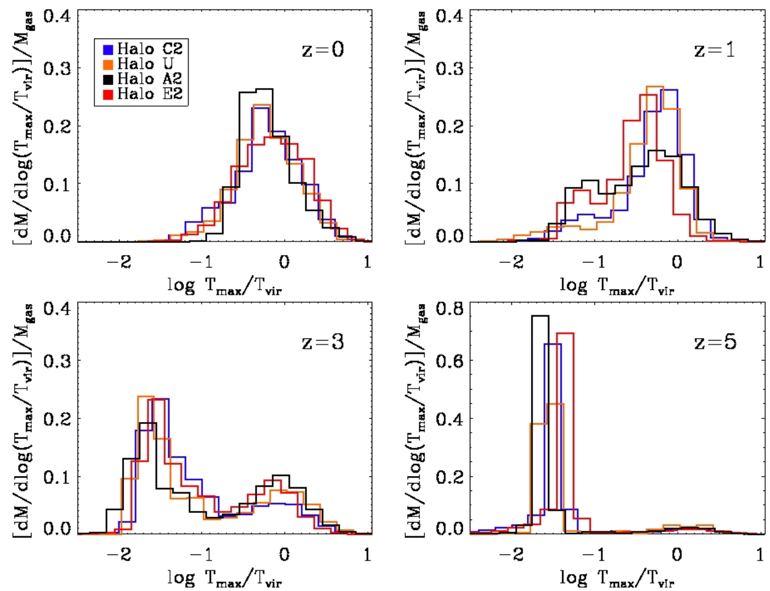
SN Feedback included, no black holes.



$$(\Delta E)_{\rm grav} = \Delta m_\star v_c^2 \log(r_{\rm vir}/r_{\rm eff}) \sim 4.5 \times 10^{-6} v_{300}^2 m_\star c^2$$

Cold/hot accretion mode – Need for AGN feedback





- Transition from cold to hot accretion at z~2-3 at M~3-5x10^{11} M$_{sun}$ (see Dekel et al. 2006).
- The late central star formation in these numerical simulations could potentially be terminated by AGN feedback.

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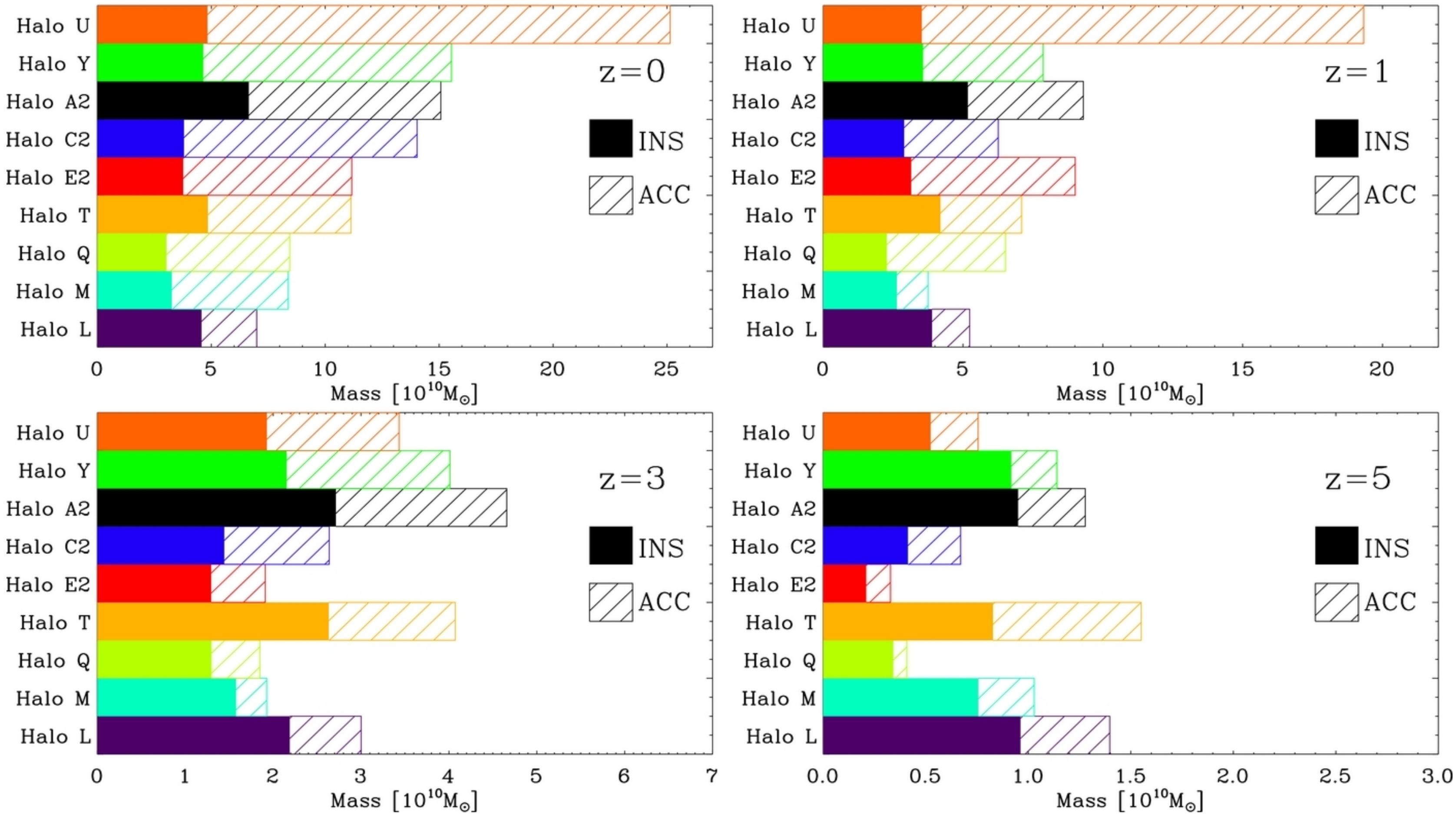
II: Downsizing



- 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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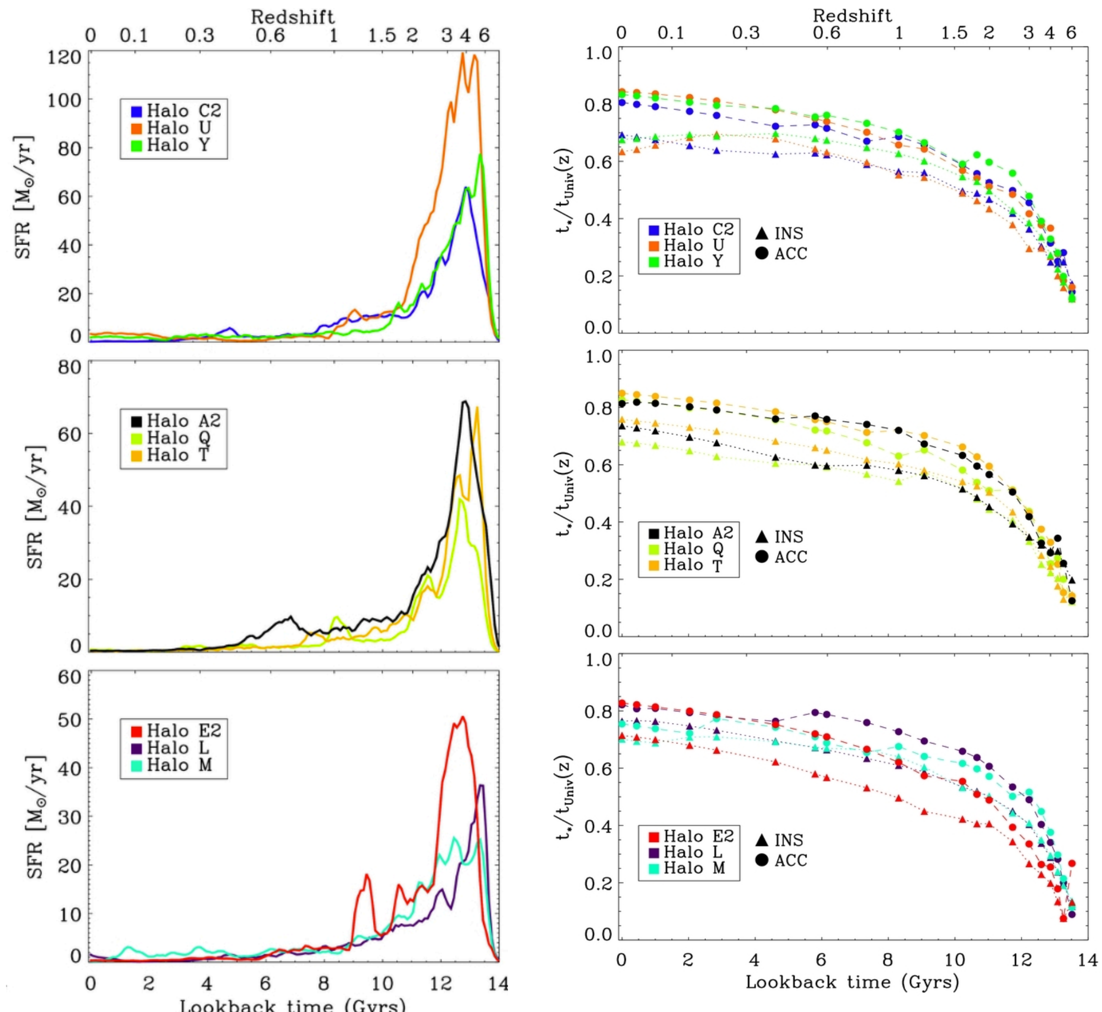
Star formation rates & Ages of galaxies

- Star formation rates high 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 in situ. Most massive galaxies have the highest fraction of accreted stars-> oldest ages as observed.

Formation age is not equal to the assembly age!



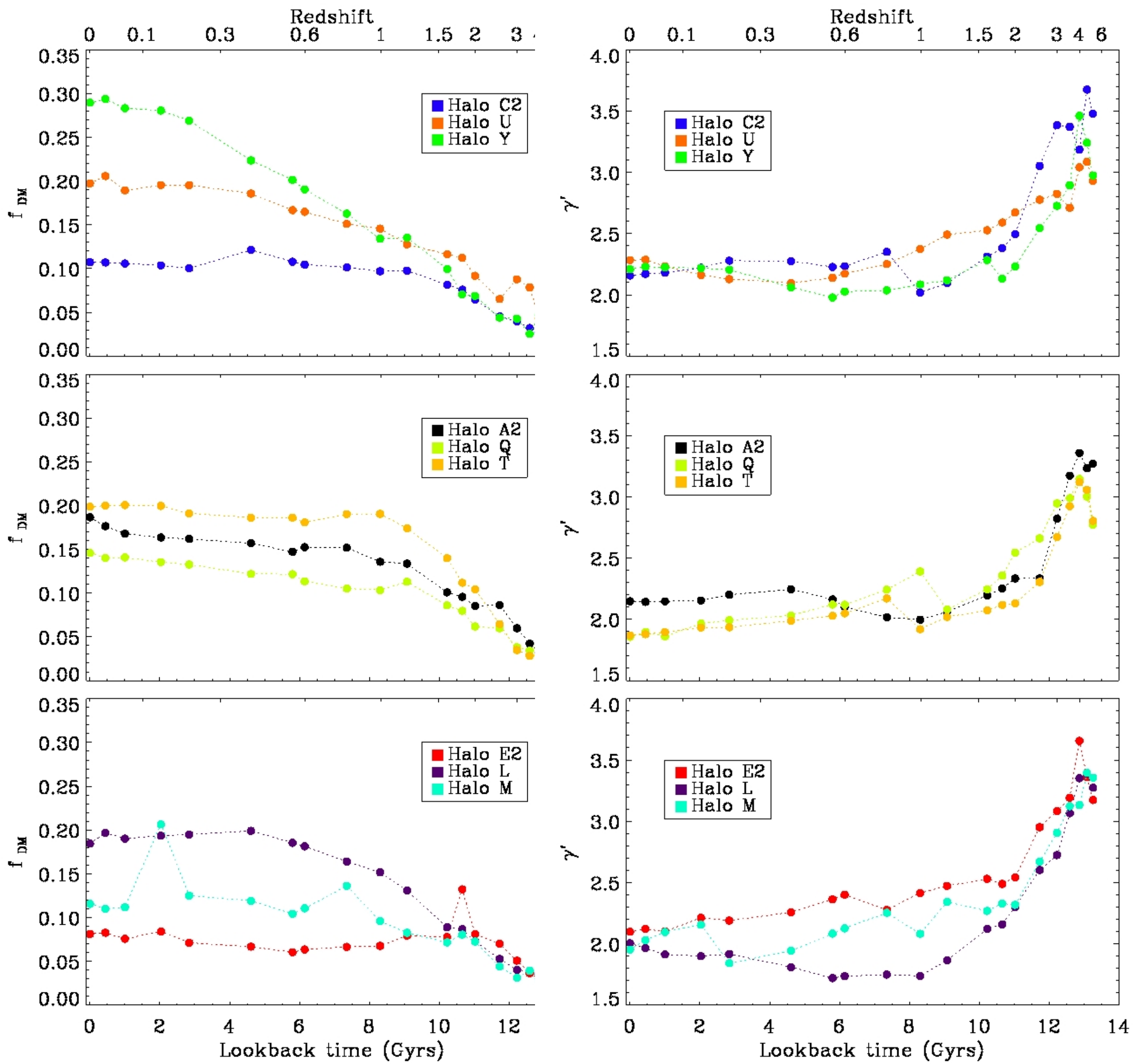
Dark matter fractions

- DM fractions are very low at high redshift $f_{DM}\approx 0.05$, but increase to $f_{DM}\approx 0.1\text{-}0.3$ by z=0.

- Also the logarithmic slope of the total density is (isothermal) at z=0, in agreement with observations.

$$\rho_{\rm tot} = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma'}$$

$$\gamma' = -d\log\rho_{\rm tot}/d\log r$$



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III. Minor mergers and the virial theorem

$M_f = (1+\eta)*M_i$ and assume $\eta=1$, e.g. mass increase by factor two, and small velocity dispersions for the accreted matter ($\langle v_a^2 \rangle \sim 0 \rightarrow \varepsilon \sim 0$).

$$\eta = M_a/M_i$$
$$\epsilon = \langle v_a^2 \rangle / \langle v_i^2 \rangle$$

$$\frac{\langle v_f^2 \rangle}{\langle v_i^2 \rangle} = \frac{(1+\eta\epsilon)}{1+\eta}$$

Dispersion can decrease by factor 2

$$\frac{r_{g,f}}{r_{g,i}} = \frac{(1+\eta)^2}{(1+\eta\epsilon)}$$

Radius can increase by factor 4

$$\frac{\rho_f}{\rho_i} = \frac{(1+\eta\epsilon)^3}{(1+\eta)^5}$$

Density can decrease by factor 32

$r \sim M^\alpha$, $\alpha = 1$ for major mergers, $\alpha = 2$ for minor mergers
see Hilz et al. 2012 for more details.

Naab, Johansson & Ostriker 2009, see also Bezanson et al. 2009, Khochfar & Silk 2006, Cole et al. 2000

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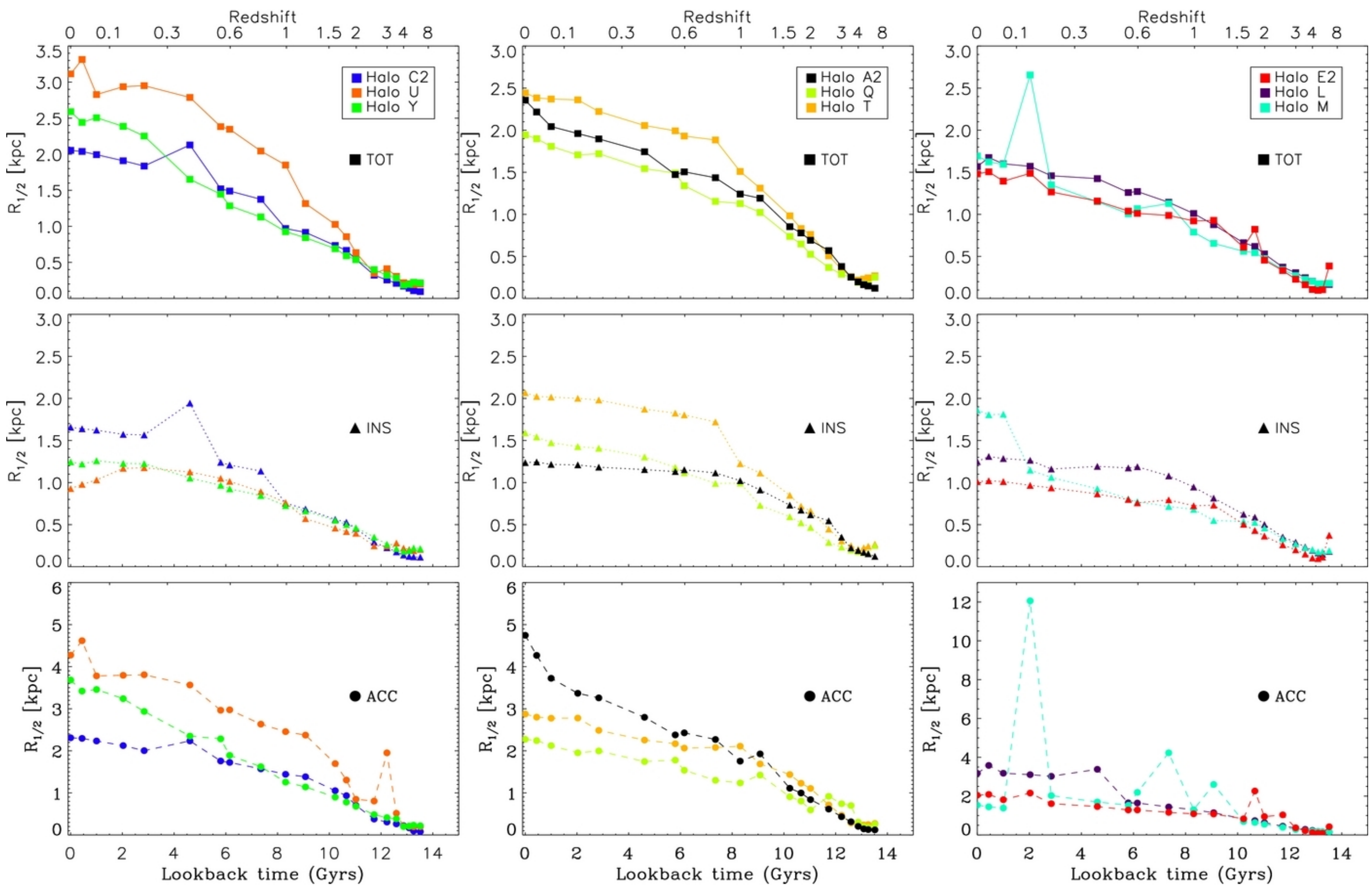
Size growth through minor dry merging

- 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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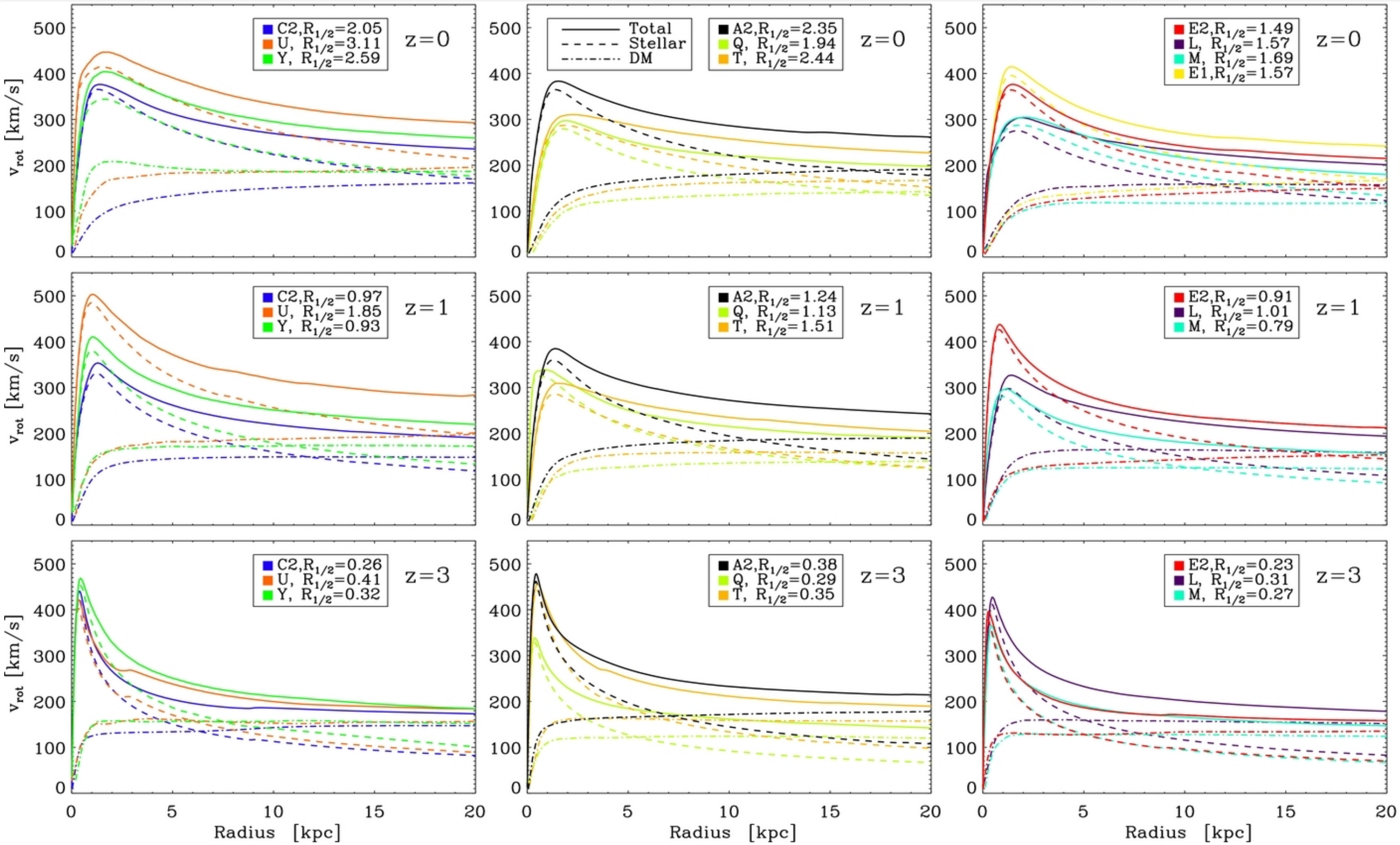
Size growth and rotation curves



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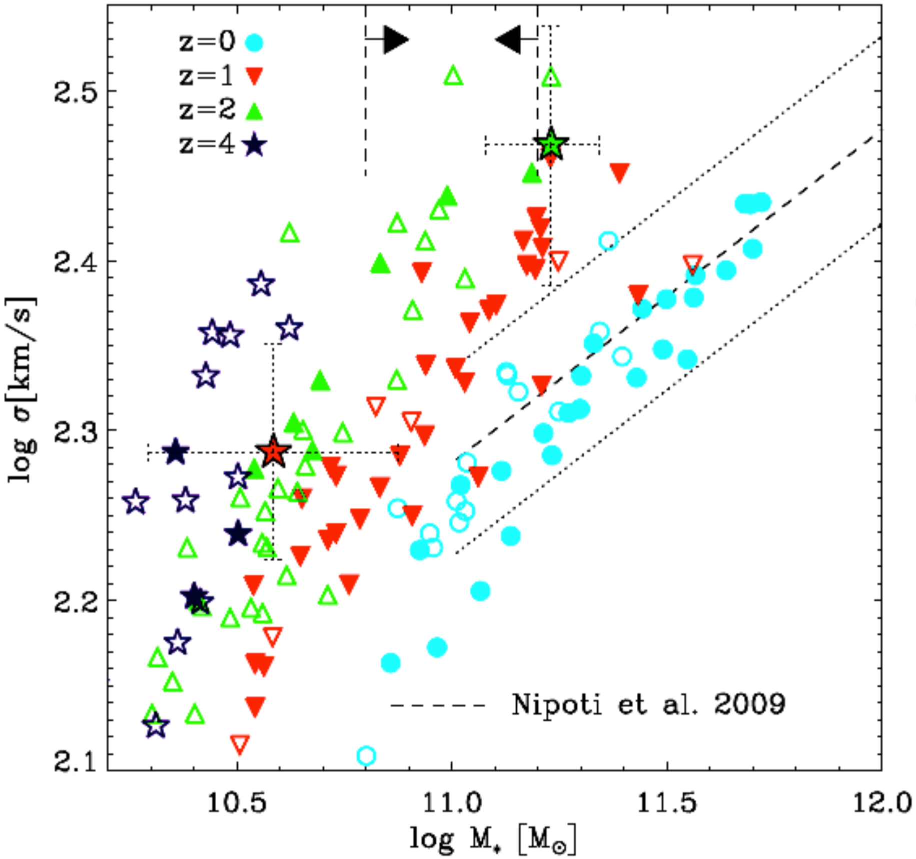
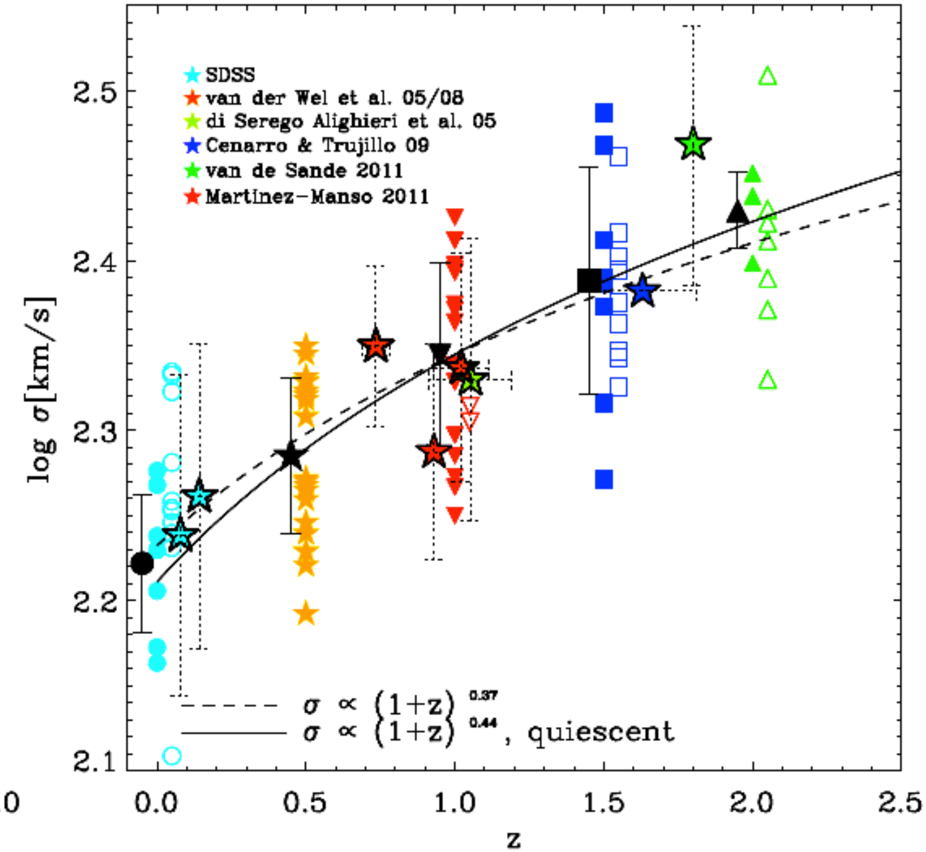
- Most massive systems have, f_{acc}=75%, size growth z=3->z=0, x7.9.
- Intermediate massive systems, f_{acc}=60%, size growth z=3->z=0, x6.6.
- Galaxies in lowest mass bin, f_{acc}=45%, size growth z=3->z=0, x5.9.

The dispersion evolution of spheroids

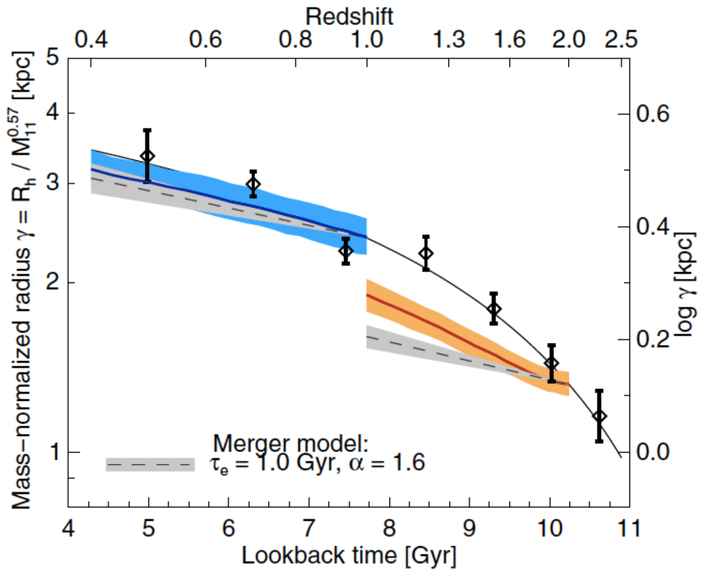




- Galaxies at higher redshift have higher velocity dispersions but move onto the local correlations.

Oser et al. 2012

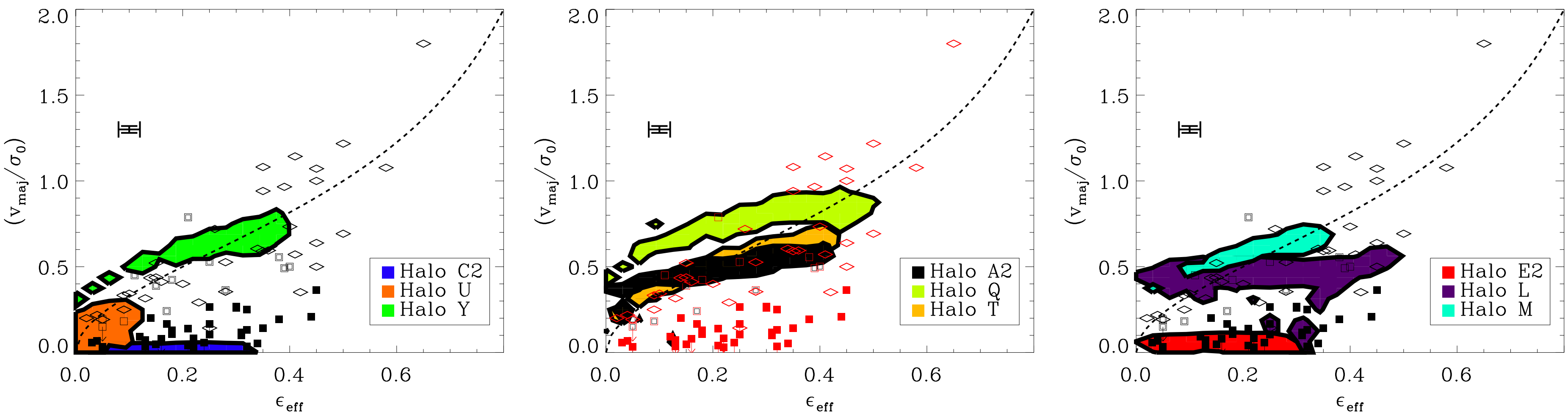
Is there a size evolution ‘problem’?



Newman et al. (2012)

- Major and minor mergers might not be sufficient to explain the observed size growth - in particular at $1 < z < 2$ - and the small scatter in the scaling relations (Newman at al. 2012, Nipoti et al. 2012)
- Different conclusion by Oogi & Habe 2012, Hilz et al. 2013, Bedorf & Portegies Zwart 2013 – size growth is sufficient
- Is an additional process necessary, such as rapid outflows –’puffing up’ necessary?

IV: Slow and fast rotators



The contours indicate the 95% probablity of finding a simulated galaxy as seen from 500 random projections. Observational data from Bender et al. (1994).

- 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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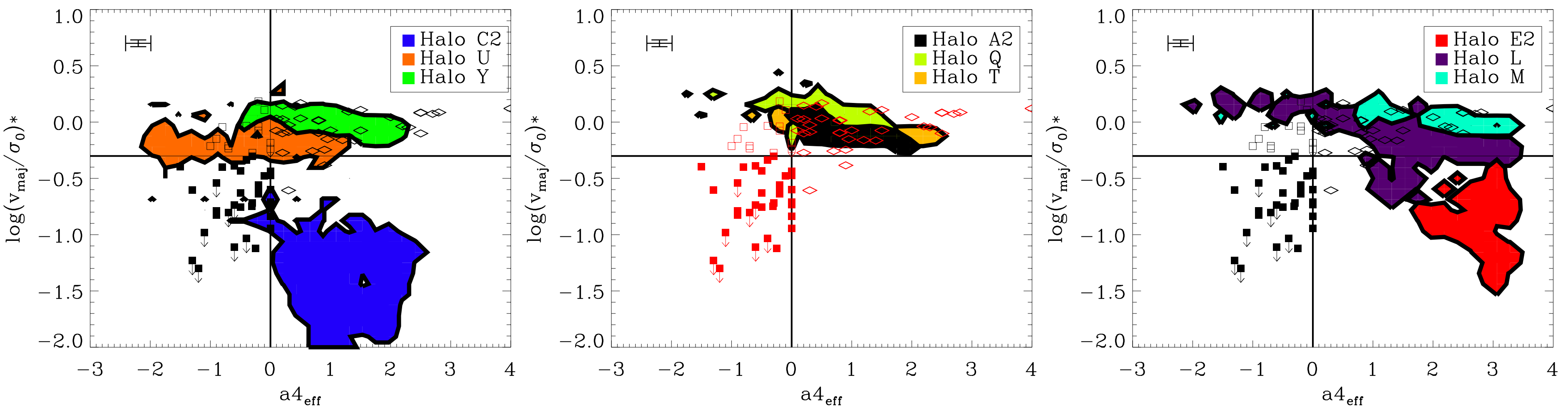
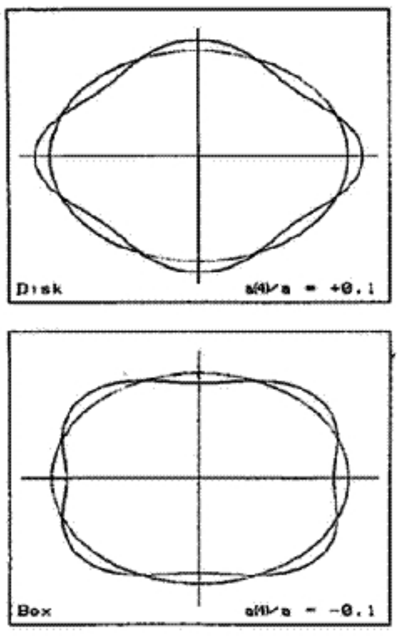
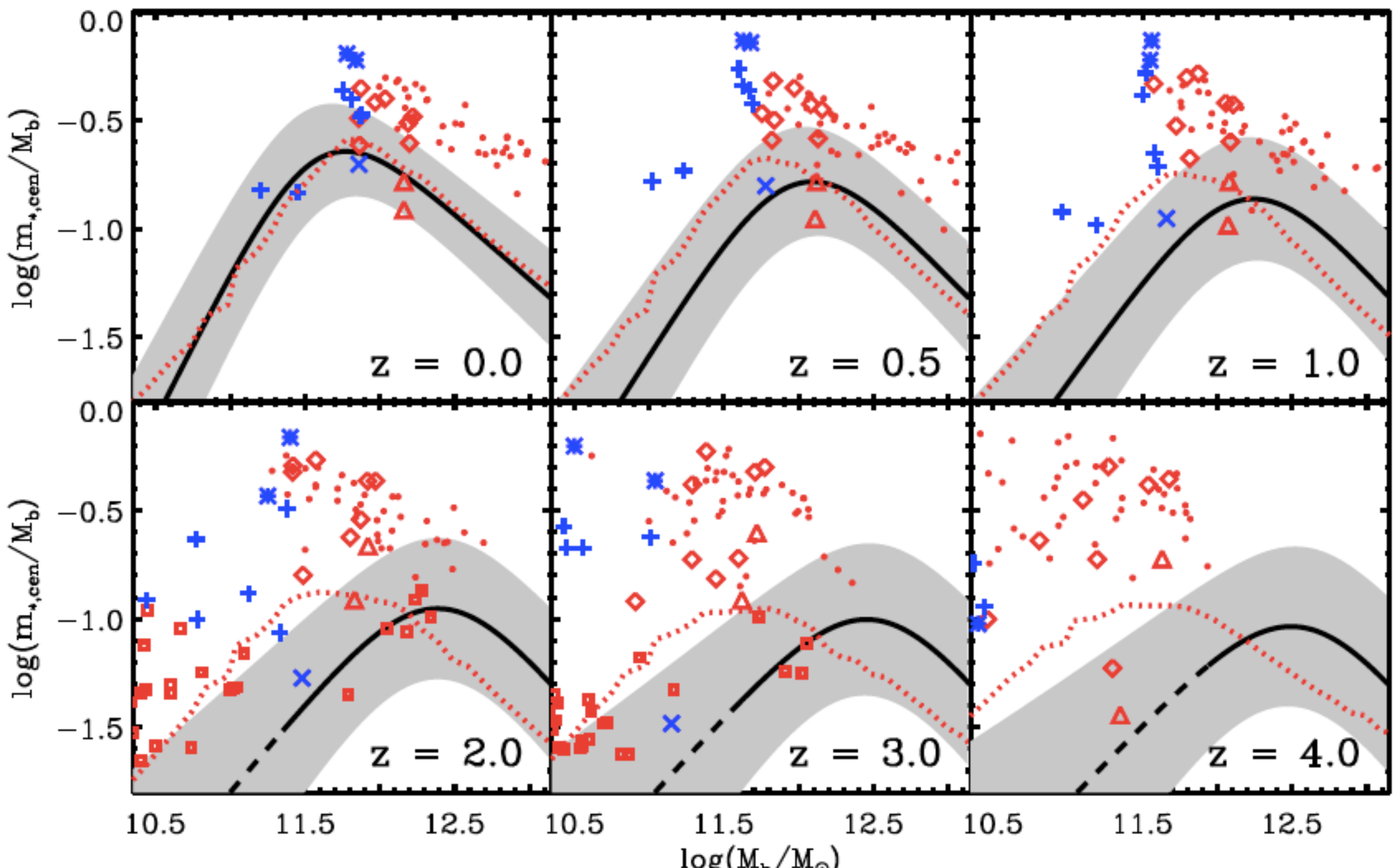
The shapes of early-type galaxies



- 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 broad agreement with the observations.



Caveats: Conversion efficiencies



- Most simulations form stars too efficiently compared to simple theoretical estimates using halo-abundance matching techniques (Guo et al. 2010, Moster et al. 2012, Oser, Genel, Brooks, Stinson, Scannapieco, Okamoto, Governato…).

Conclusions

- The formation of massive elliptical galaxies is a two phase process.

1. Bi-modality: Energy release from gravitational feedback is an important component and could help make and maintain massive galaxies as red and dead, however AGN feedback is also required, especially for terminated late star formation.
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 Early-type 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.

- A lot more work is needed on modelling the details of feedback from SN and AGN (see e.g. Puchwein & Springel 2012, Martizzi et al. 2012, Dubois et al. 2013)
- The complex formation and evolution of massive galaxies is far from being understood….

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