Max-Planck-Institut für Astrophysik

MAX-PLANCK-GESELLSCHAFT

The formation and evolution of massive galaxies: A major theoretical challenge

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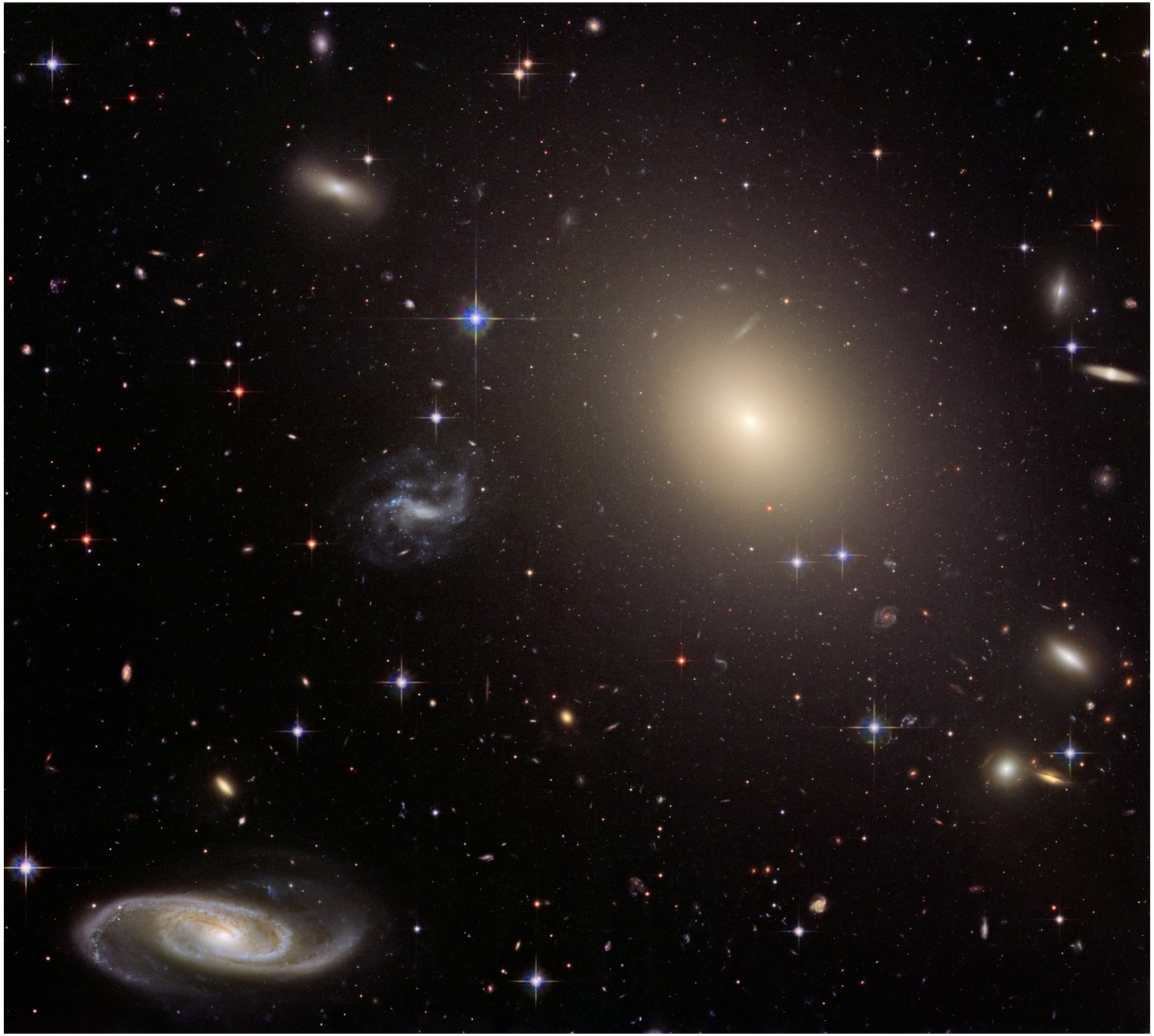
Tähtitieteilijäpäivät
Haikko, June 5sth



Size, mass (distribution), age, metallicity and velocity dispersion.....

The formation of early-type galaxies

- Elliptical galaxies are the largest, oldest and most massive galaxies in the present day universe

- All ellipticals/bulges have old metal-rich homogenous stellar populations with z_{form}> 2 making up ½ - ¾ of all stars at z=0 (Ellis et al., Bell et al., Thomas et al., Gadotti, Kormendy, Bender, Faber, Franx etc. etc.)

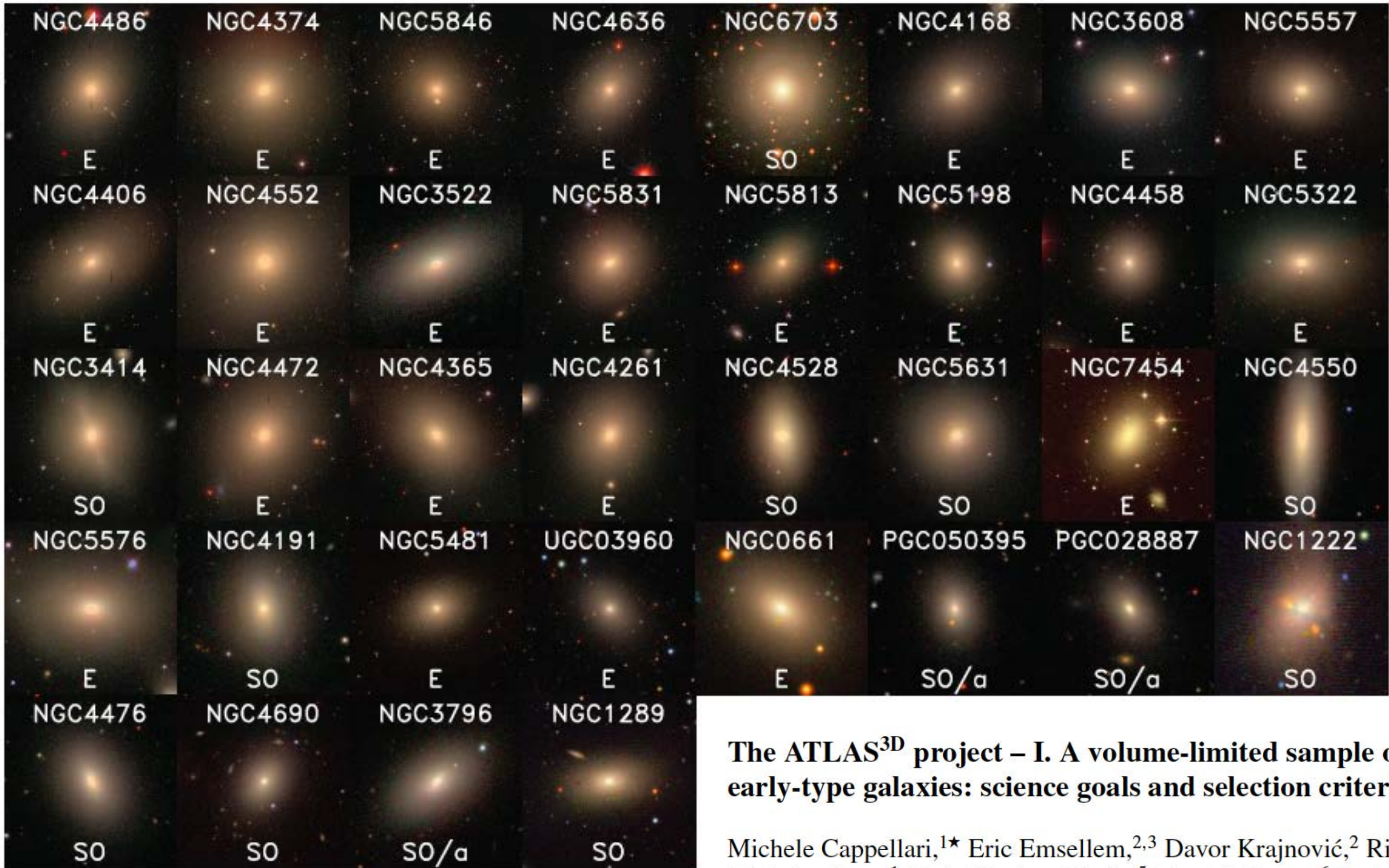
- How to understand the assembly history of massive elliptical galaxies?

- The 'archaeology' approach: investigate present day elliptical galaxies in detail and draw conclusions on their formation histories

- The 'evolution' approach: modern direct observations shed light into cosmic history of massive galaxy assembly, opening a window to our universe when it was only a few Gyrs old… !SIZE MATTERS!

- The 'forward' theoretical approach: direct or semi-empirical modelling of the full cosmological assembly of of massive galaxies – putting it all together…

Nearby massive elliptical galaxies



The ATLAS^{3D} project – I. A volume-limited sample of 260 nearby early-type galaxies: science goals and selection criteria

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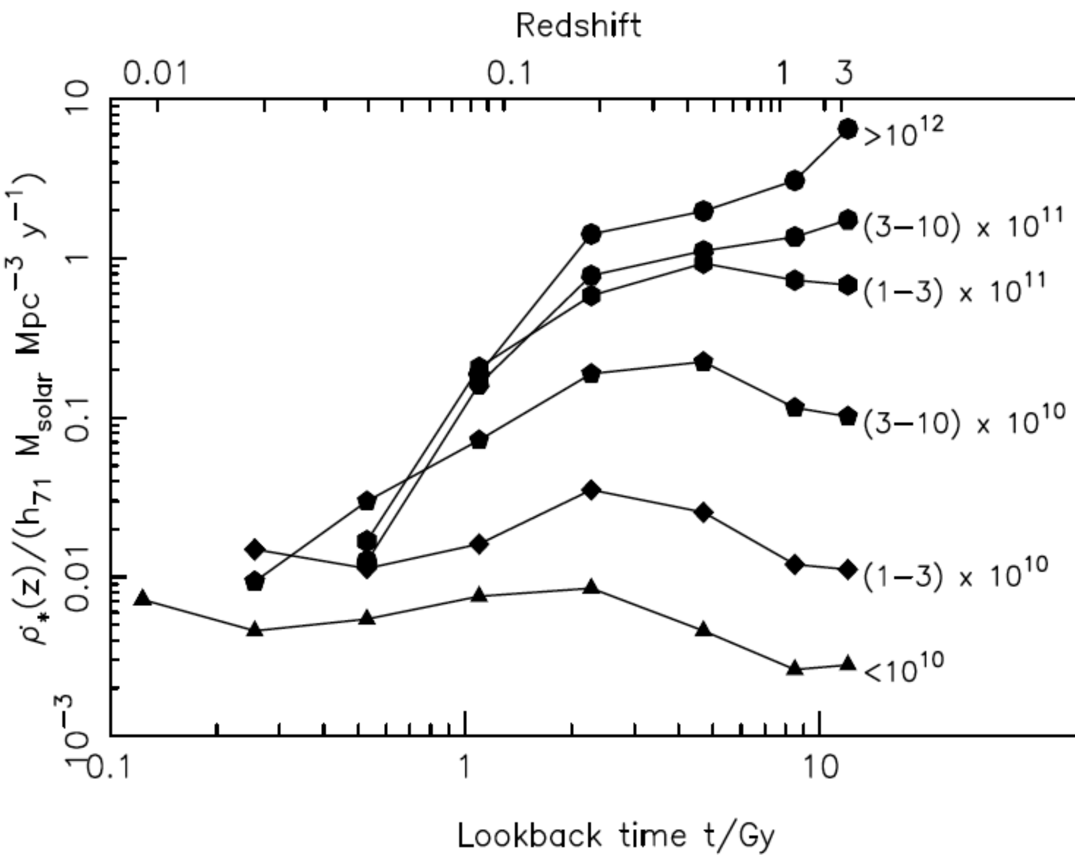
Nearby massive elliptical galaxies: the fossil record



Formation time ≠ Assembly time

Heavens et al. 2004

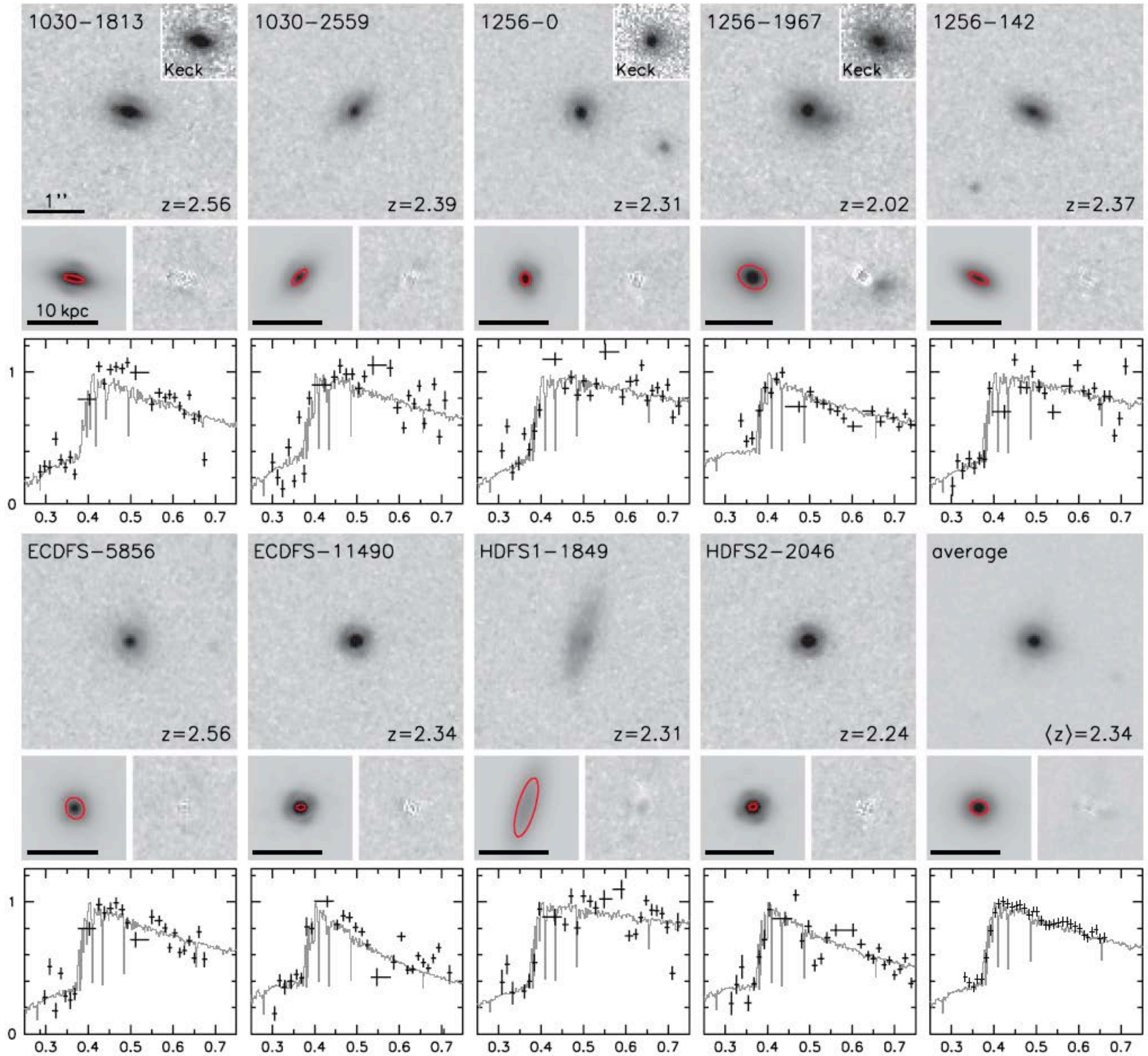
Compact massive ellipticals at $z \geq 2$

- Observations show the existence of evolved, massive ($>10^{11} M_{\odot}$), compact ($r_{1/2} \approx 1$kpc) galaxies with low star formation rates at $z \geq 2$ (Daddi et al. 2005, Trujillo et al. 2006, Toft et al. 2007, Longhetti et al. 2007, Zirm et al. 2007, van Dokkum et al. 2008, van der Wel et al. 2008, Cimatti et al. 2008, Franx et al. 2008, Buitrago et al. 2008, Damjanov et al. 2008, Kriek et al. 2008, Bezanson et al. 2009, Muzzin et al. 2009, Saracco et al. 2009, Kriek et al. 2009, van Dokkum et al. 2010, Williams et al. 2010, Cassata et al. 2011, Mancini et al. 2011, Trujillo et al. 2011, Cimatti et al. 2012, Szomoru et al. 2012, Ryan et al. 2012)

- Systems are a factor 3 to 5 smaller than present day ellipticals, two orders of magnitude denser within r_e, and 2-3 times denser within 1kpc than z=0 galaxies of similar mass

- Galaxies are really compact down to low surface brightness limits ($H \approx 28$ mag arcsec^{-2}) with no indications for a faint extended component (Szomoru et al. 2010, van Dokkum et al. 2011, Szomoru et al. 2012, see however Mancini et al. 2011, Auger et al. 2011)

Compact massive ellipticals at z≈2



van Dokkum et al. 2008, Kriek et al. 2006

Compact massive ellipticals at $z \geq 2$

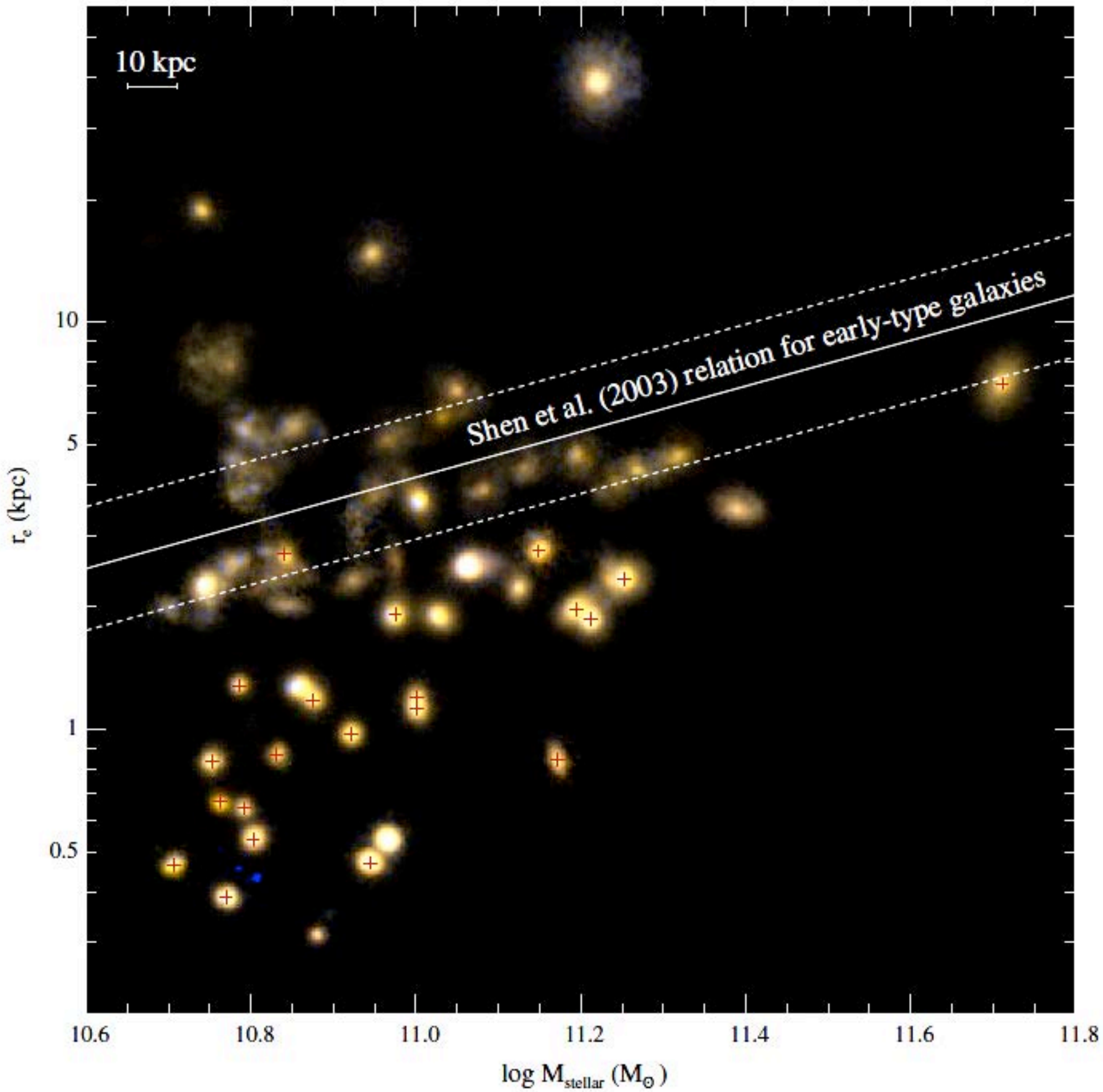
- Quiescent massive high-redshift galaxies have higher dispersion – a direct dynamical confirmation for them being more compact (van der Wel et al. 2005, di Serego Alighieri et al. 2005, Cenarro & Trujillo 2009, van Dokkum et al. 2009, Cappellari et al. 2009, Onodera et al. 2010, Martinez-Manzo et al. 2011, van de Sande et al. 2011, Toft et al. 2012)

- Massive compact ellipticals are rare (0.03%, at $10^{11} M_{\odot}$) in the local Universe (Trujillo et al. 2009, Taylor et al. 2010, Valentinuzzi et al. 2010, Ferre-Mateu et al. 2012, Trujillo et al. 2012)

- But they make up about half of the general high redshift population (van Dokkum et al. 2006, Kriek et al. 2006, Wiliams et al. 2008, Szomorou et al. 2012)

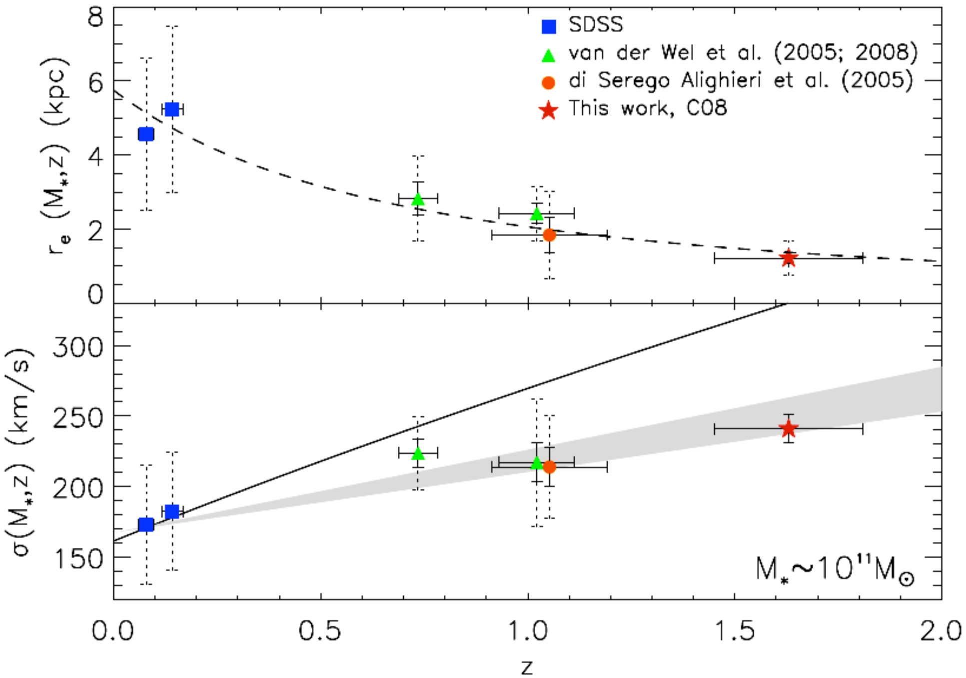
- Inside-out size growth without star formation – compact massive quiescent high-redshift galaxies are the 'cores' of present day giant elliptical galaxies (van Dokkum et al. 2010, Szomorou et al. 2012)

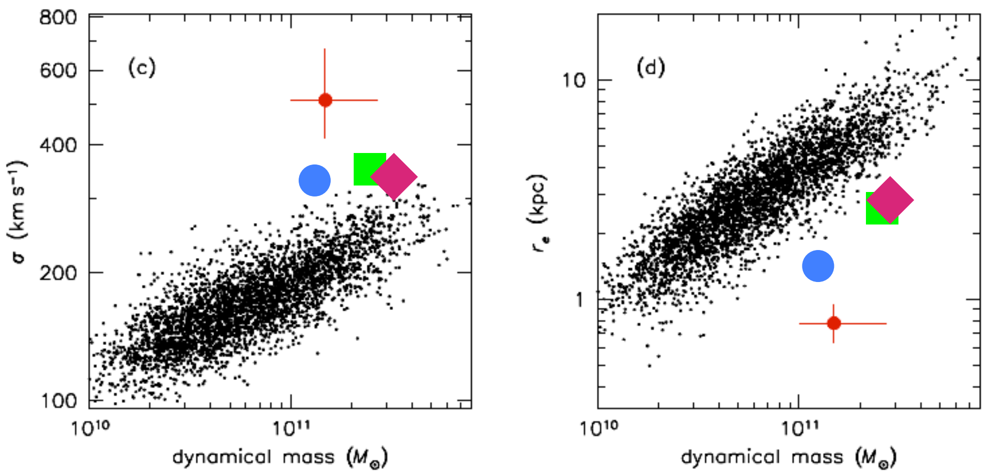
Compact massive ellipticals at z≈2



Szomoru, Franx & van Dokkum 2012

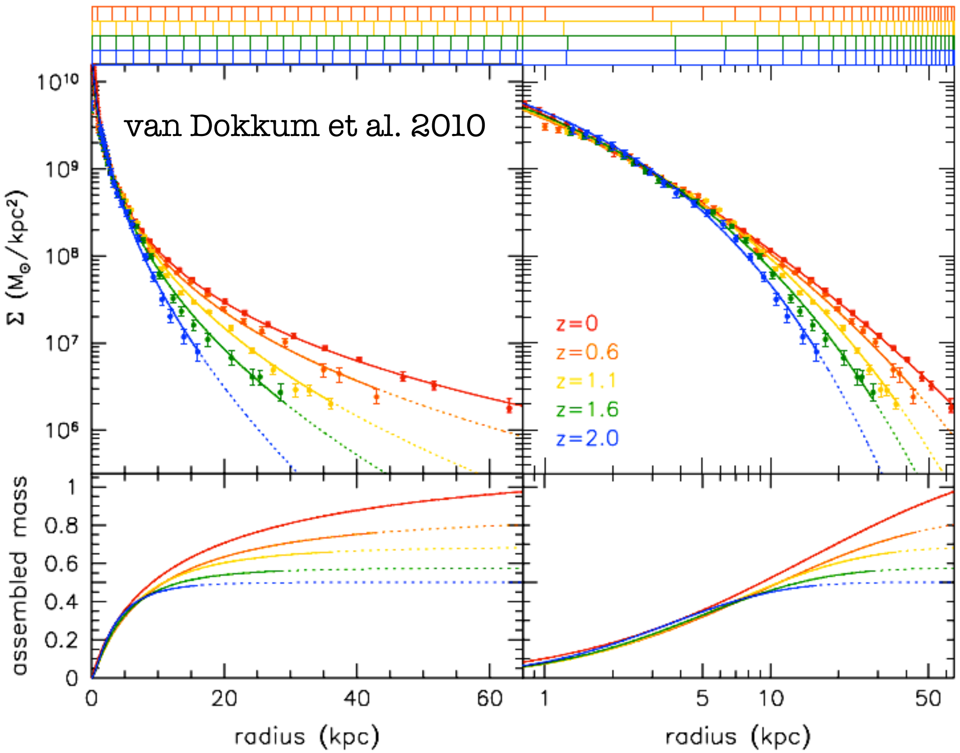
Size and dispersion evolution since z≈2

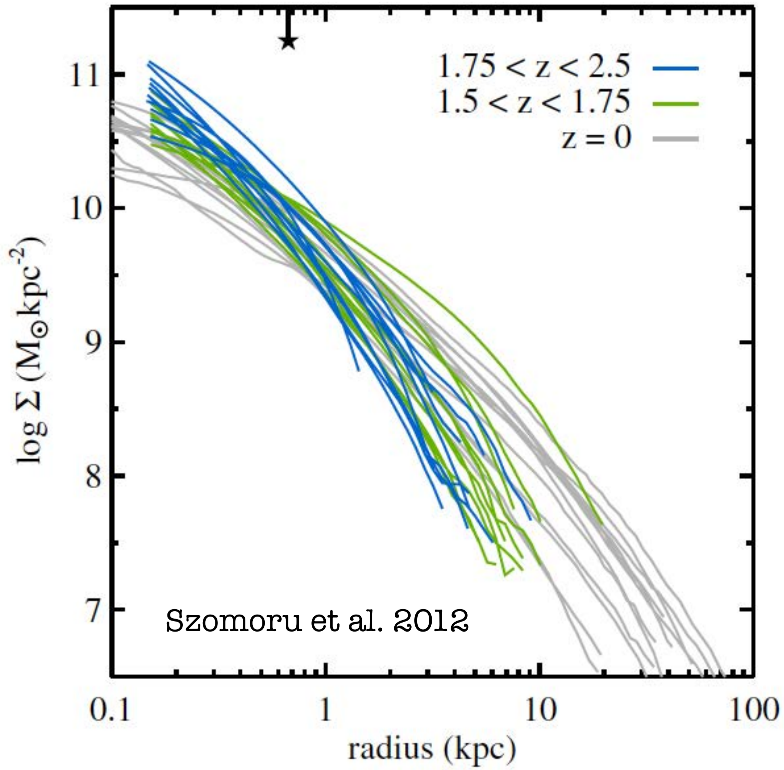




- Rapid size evolution for massive early-type galaxies proportional to $(1+z)^\alpha$, α=-1.22 (Franx et al. 2008), -1.48 (Buitrago et al. 2008), -1.17 (Williams et al. 2010, see also e.g. Ryan et al. 2012)
- Mild stellar velocity dispersion evolution of $\approx 10^{11} M_\odot$ ellipticals from 240km/s at z≈1.6 (240km/s) to 180 km/s at z=0 from stacked spectra (e.g. Cenarro & Trujillo 2009)
- Confirmed high velocity dispersions of a few z≈2 galaxies indicate high dynamical masses
- Consistent with mass estimates and ($\approx 10^{11} M_\odot$) and compactness (≈1kpc) from photometric data (van Dokkum et al. 2009, Onodera et al. 2010, van de Sande et al. 2011, Toft et al. 2012)

Inside-out growth since z = 2





- Stacks of 70-80 galaxies at different redshifts (van Dokkum et al. 2010) and direct comparison to Virgo ellipticals (Szomoru et al. 2012) indicate inside-out growth of ellipticals since z=2
- Mass increase by a factor of ~ 2 , Size increase by a factor of ~ 4
- $r \sim M^{\alpha}$, $\alpha \geq 2$, no significant star formation

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

- 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 no room for new stars

- Evolution by a common process in hierarchical cosmologies: ‘minor’ mergers – major mergers of massive galaxies are ‘rare’ and stochastic

Minor mergers and the virial theorem

Initial stellar system formed by e.g. dissipative collapse then add stellar material under energy conservation (‘dry merging’)...

$$E_i = K_i + W_i = -K_i = \frac{1}{2} W_i$$
$$= -\frac{1}{2} M_i \langle v_i^2 \rangle = -\frac{1}{2} \frac{G M_i^2}{r_{g,i}}.$$

&

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

$$E_f = E_i + E_a = -\frac{1}{2} M_i \langle v_i^2 \rangle - \frac{1}{2} M_a \langle v_a^2 \rangle$$
$$= -\frac{1}{2} M_i \langle v_i^2 \rangle - \frac{1}{2} \eta M_i \epsilon \langle v_i^2 \rangle$$
$$= -\frac{1}{2} M_i \langle v_i^2 \rangle (1 + \epsilon \eta)$$
$$= -\frac{1}{2} M_f \langle v_f^2 \rangle.$$

Minor mergers and the virial theorem

$M_f = (1+\eta) * M_i$ and assume $\eta=1$, e.g. mass increase by factor two, and varying dispersions...

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

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

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

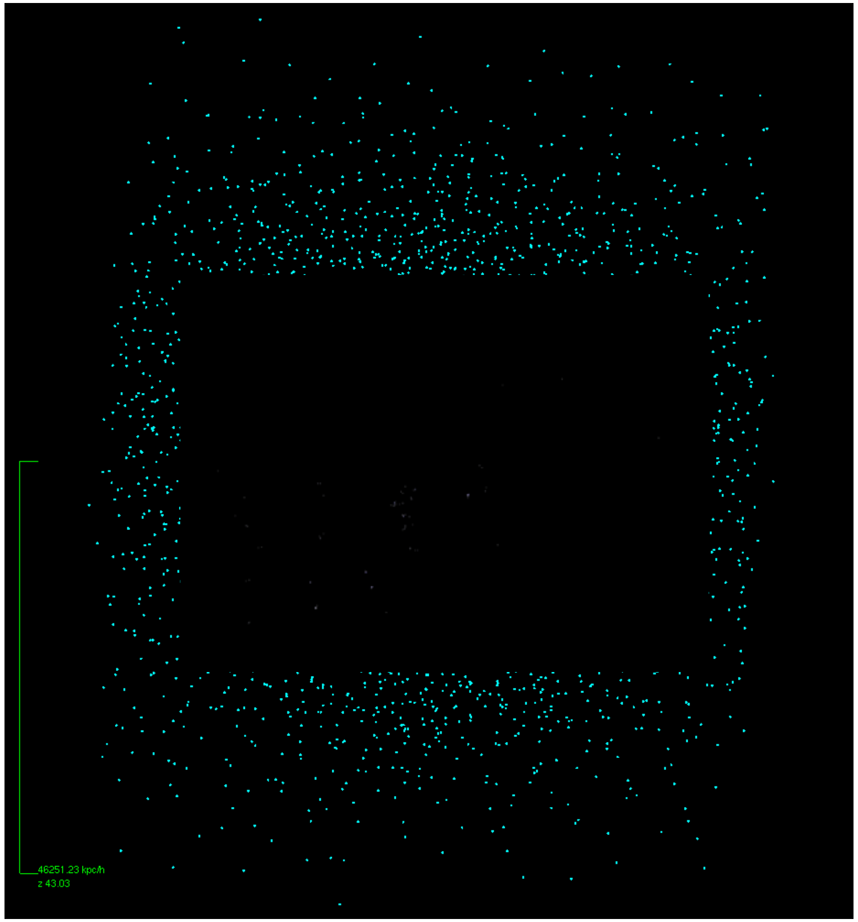
$$\frac{\rho_f}{\rho_i} = \frac{(1+\eta\epsilon)^3}{(1+\eta)^5}$$

Density can decrease by factor 32

$r \sim M^{\alpha}$, $\alpha = 1$ for major mergers , $\alpha = 2$ for minor mergers
more complex: gas, dark matter, dynamics

Naab, Johansson & Ostriker 2009

The tool: re-simulations



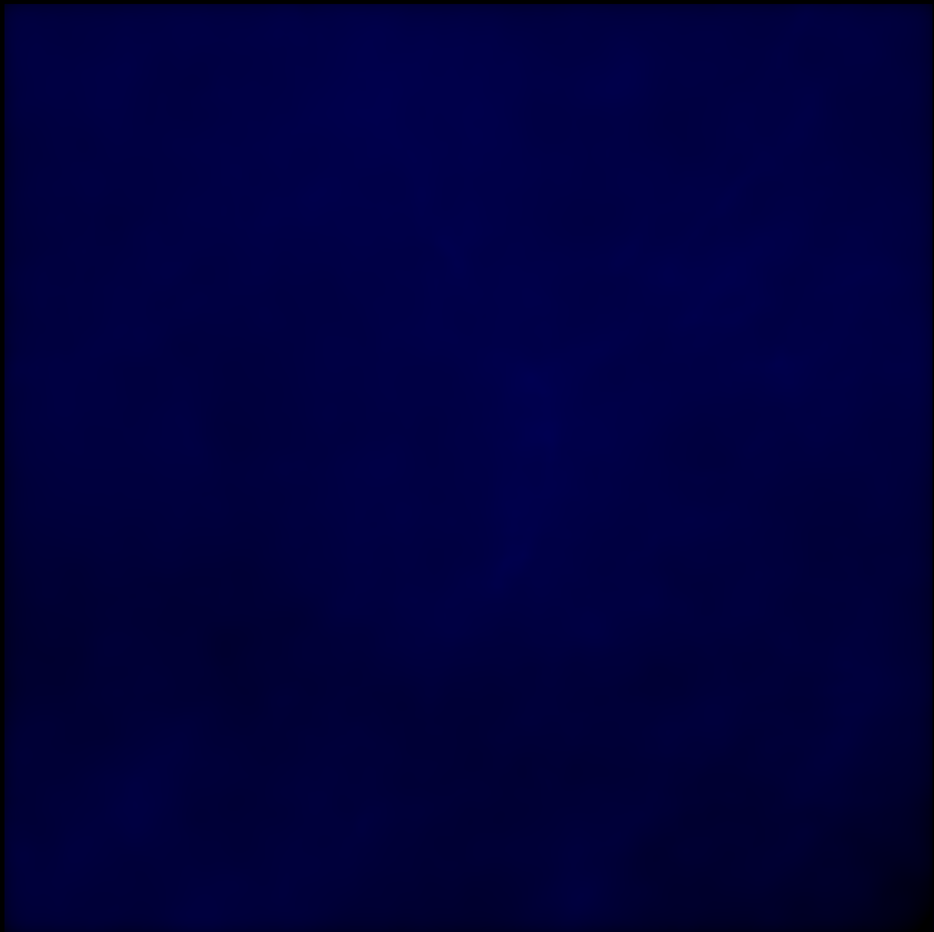
100^3 Mpc, 512^3 particles dark matter only & with gas and simple star formation & feedback, 100 snapshots (WMAP3: $\Omega_m = 0.26$, $\Omega_\Lambda = 0.74$, $h = 0.72$)

Re-simulation of a large number of individual halos from 10^{10}-10^{13} (M_{gas}: 10^6, 10^5, 10^4) without gas, with star formation & evtl. feedback (Springel & Hernquist 2003)

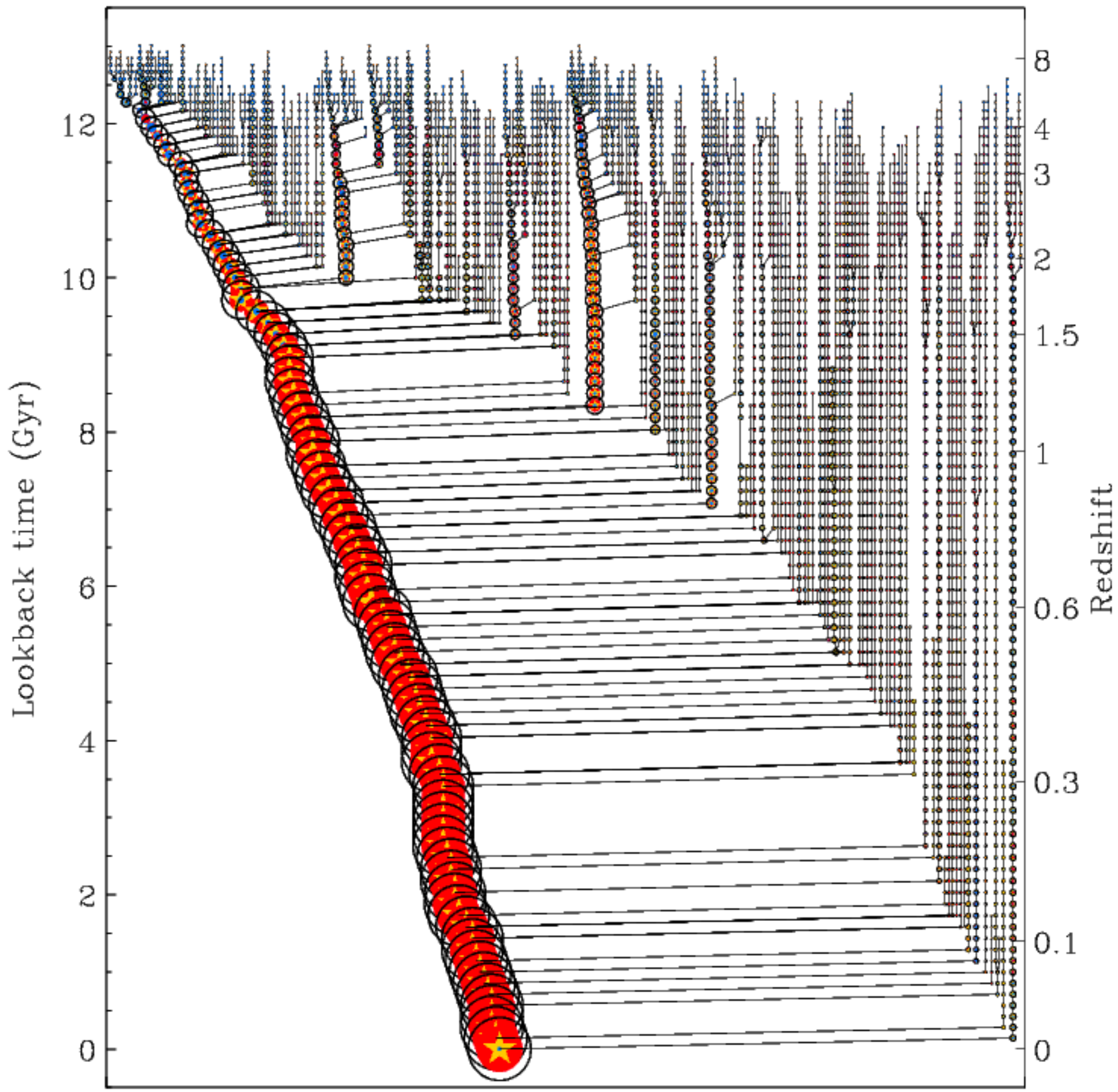
Efficient ICs avoiding massive intruders: e.g. follow the virial region of target halos and resolve all interactions (Oser, Naab, Johansson et al. 2010). 30% - 45% of high-res particles end up in the final virial radius

Extracted merger histories of full box and individual halos (Hirschman et al. 2011, Oser et al. 2011) also for detailed comparison with semi-analytical predictions

≈100 halos simulated so far and used for analysis presented here



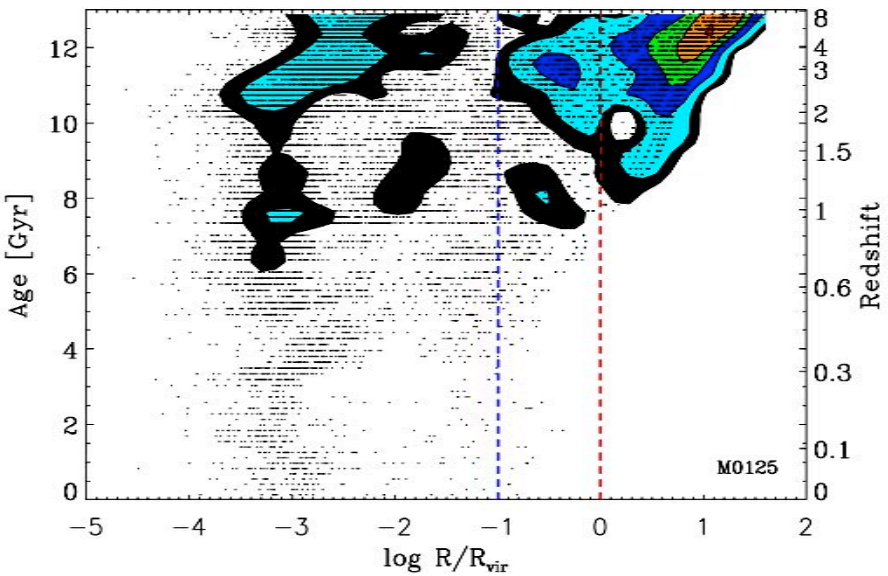
The complex assembly histories

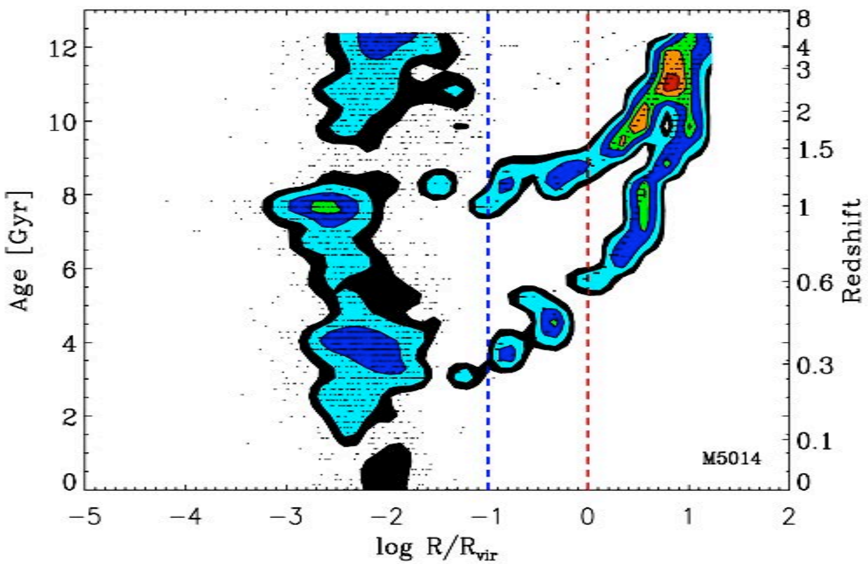


- Typical contribution of mergers (> 1:4) in massive galaxies since z=2 is 30% - 40%
- Extract dark matter and galaxy merger histories for zoom-simulations

Hirschmann et al. 2011

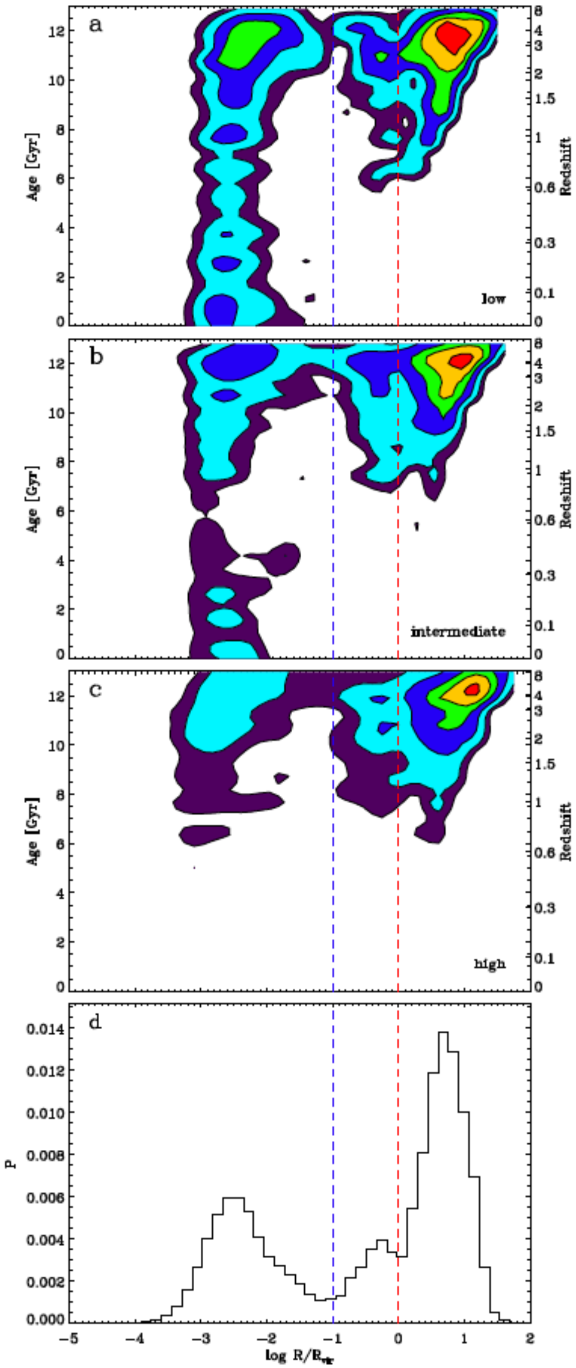
The origin of stars in galaxies

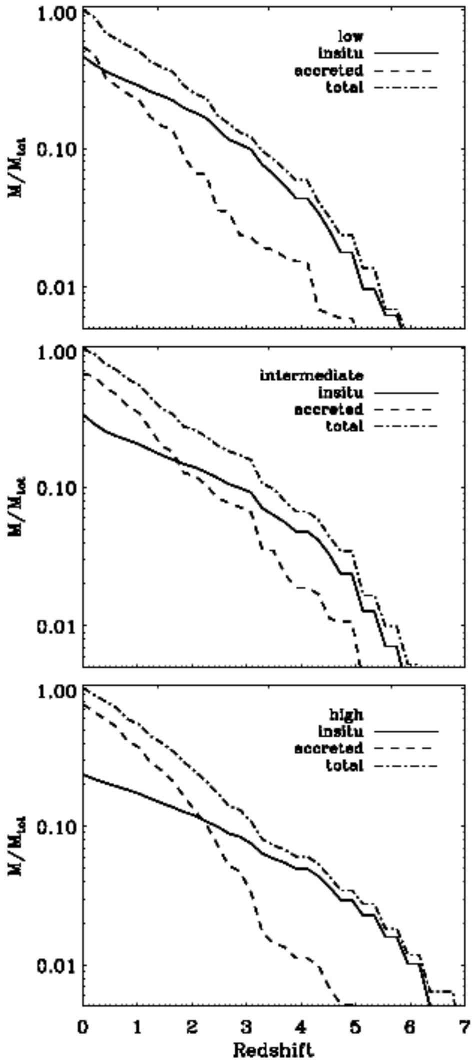




- Stellar origin diagrams indicate when and at which radius a star ending up in a present day galaxy was born
- In massive galaxies most stars are made at high redshift in-situ in the galaxy and even more ex-situ outside the galaxies virial radius with a low fraction of in-situ formation at low redshift
- Lower mass galaxies make a larger fraction of stars at low redshift

Oser et al. 2010



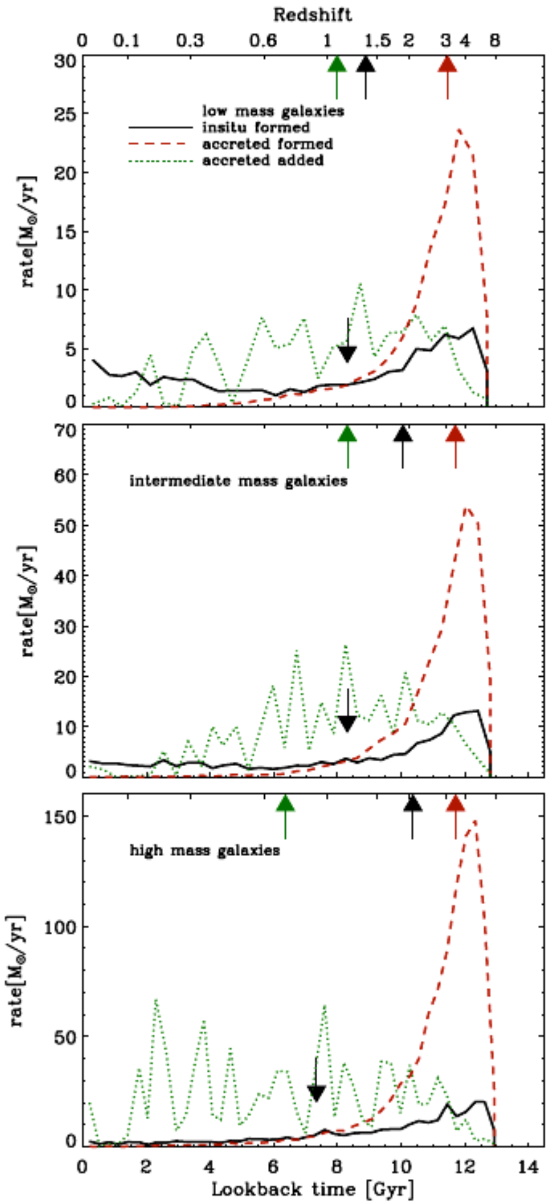


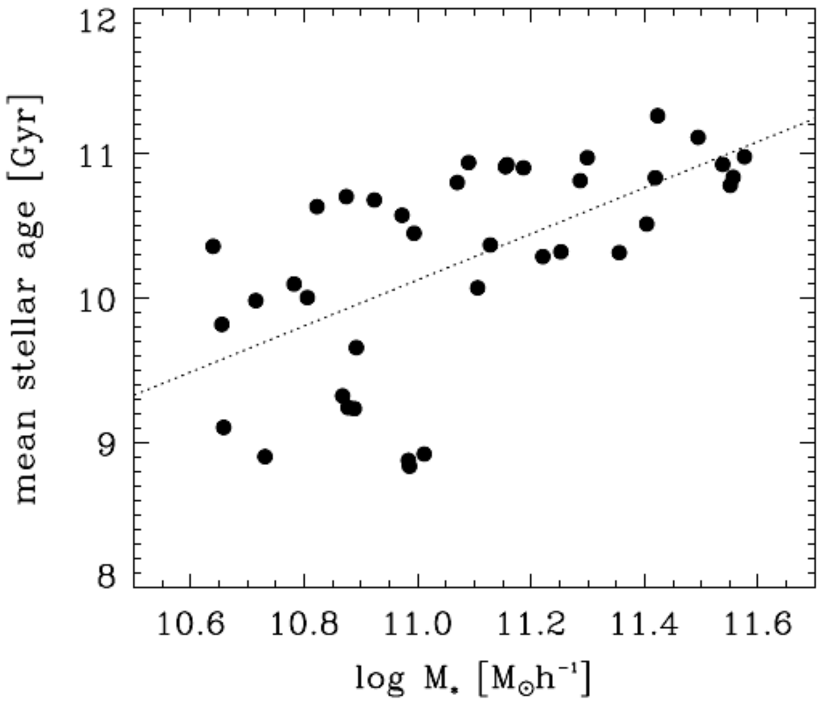
- Simulated galaxies stacked in mass bins
- Early assembly is dominated by in-situ formation, more so in massive galaxies (6 > z > 3)
- Low mass galaxies assemble half their mass by in-situ formation
- The late assembly of massive galaxies is dominated by accretion (up to 80%) of stellar system (3 > z > 0)

The two phases of galaxy formation

Oser et al. 2010

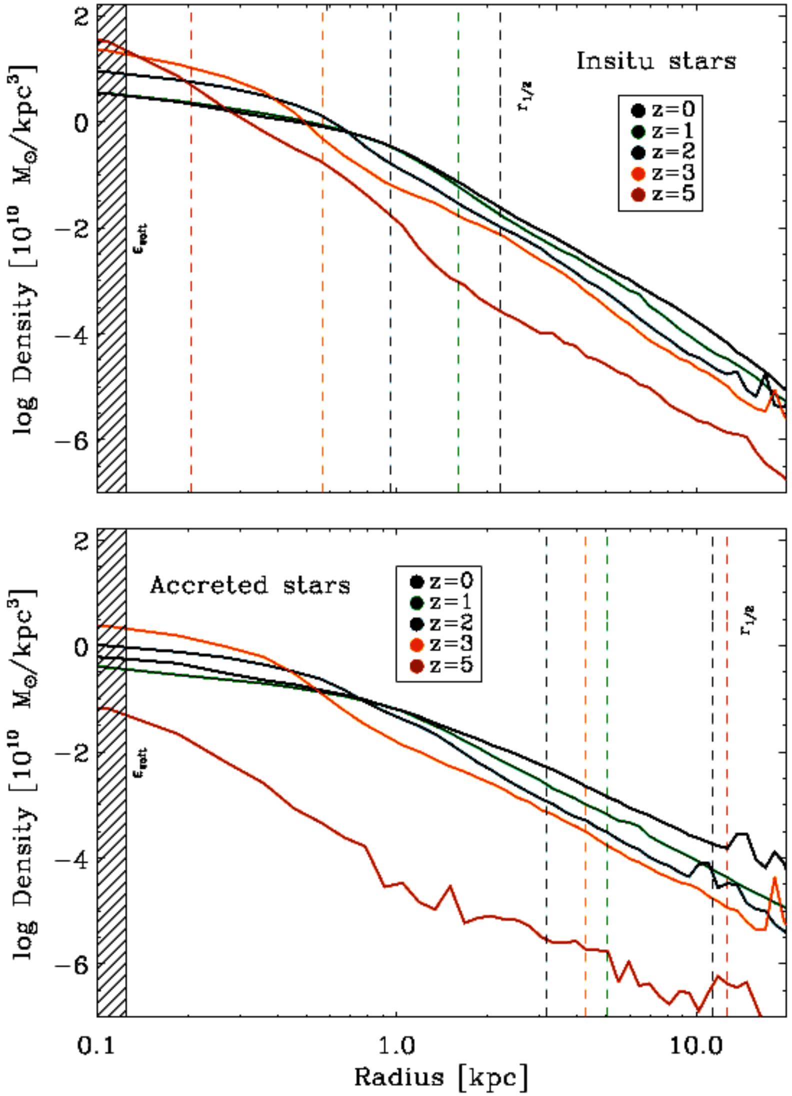
The two phases of galaxy formation





- Ex-situ stars form early and assemble late
- In-situ stars form early – extended star formation in low mass systems
- Archaeological downsizing – the most massive galaxies are the oldest
- Not in contradiction with hierarchical structure formation (de Lucia et al. 2006)

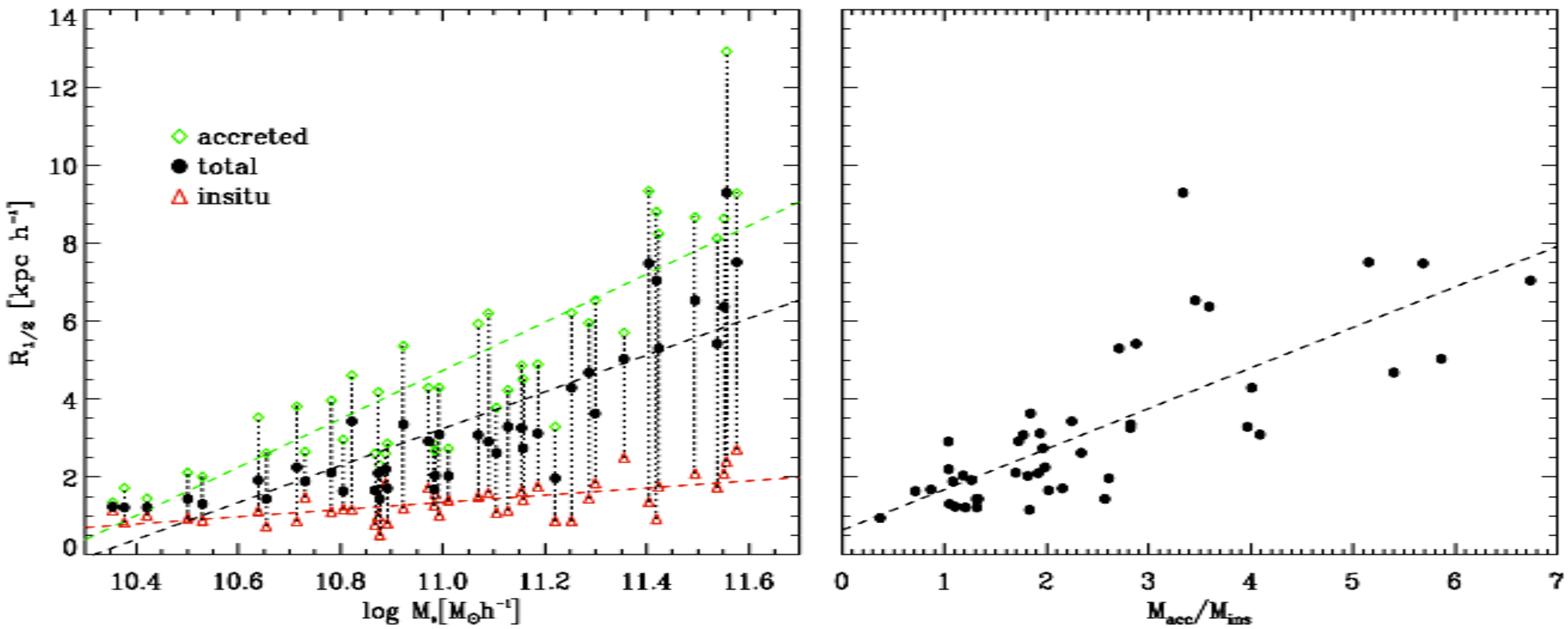
Size evolution in a high resolution simulation



Naab, Johansson & Ostriker 2007/2009

- In-situ stars form a compact high density stellar system
- Accreted stars make extended outer system (see e.g. Hopkins et al. 2009)
- z≈3: $M = 5.5 * 10^{10} M_\odot$
  $\rho_{eff} = 1.6 * 10^{10} M_\odot/kpc^3$
  $\sigma_{eff} = 240$ km/s
- z≈0: $M = 15 * 10^{10} M_\odot$
  $\rho_{eff} = 1.3 * 10^{9} M_\odot/kpc^3$
  $\sigma_{eff} = 190$ km/s
- Consistent with accreted mass being responsible for size increase

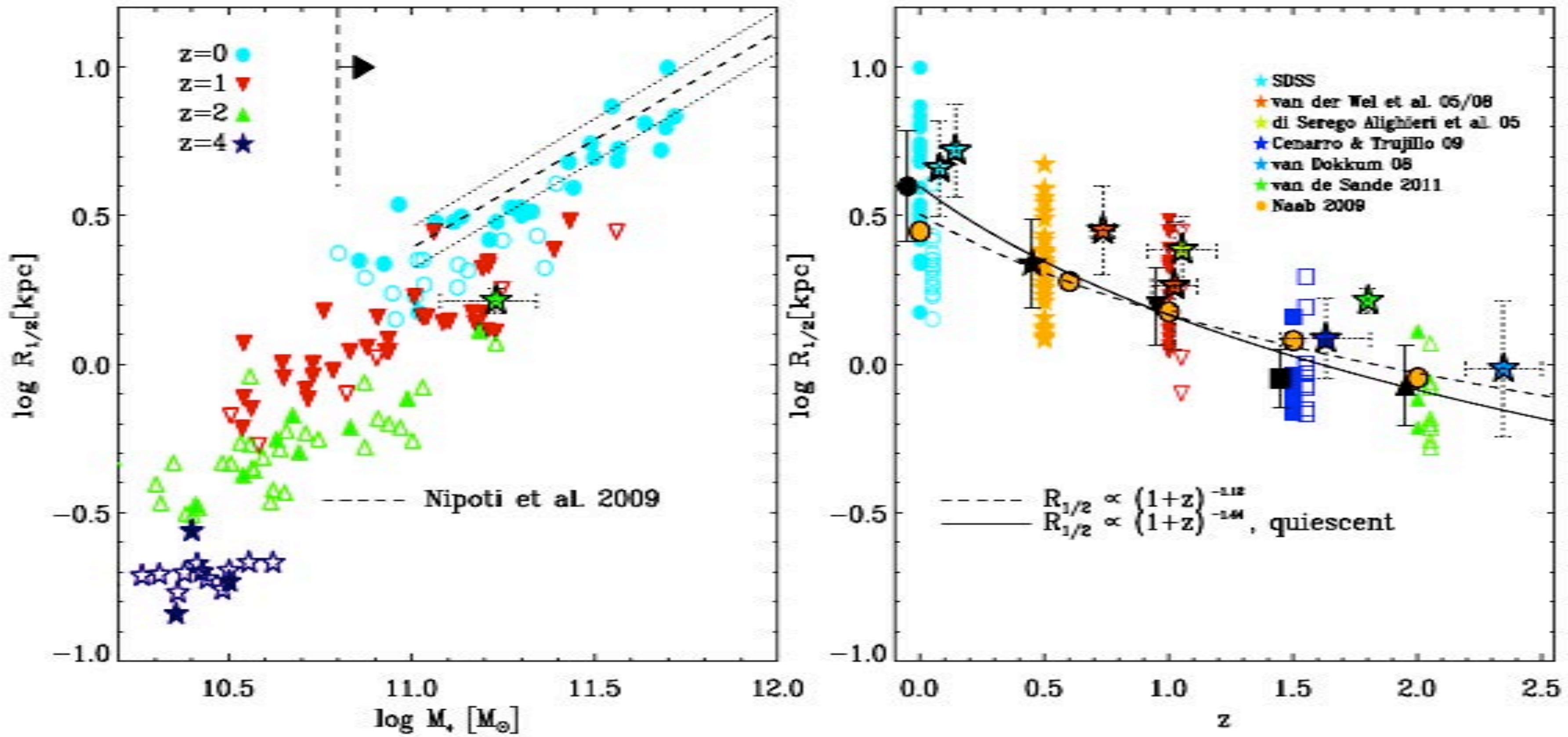
Size evolution ... and some consequences



- More massive galaxies had more accretion
- In-situ stars are the core and accreted stars build the outer envelope
- Mass-size relation is driven by accretion

Oser et al. 2010

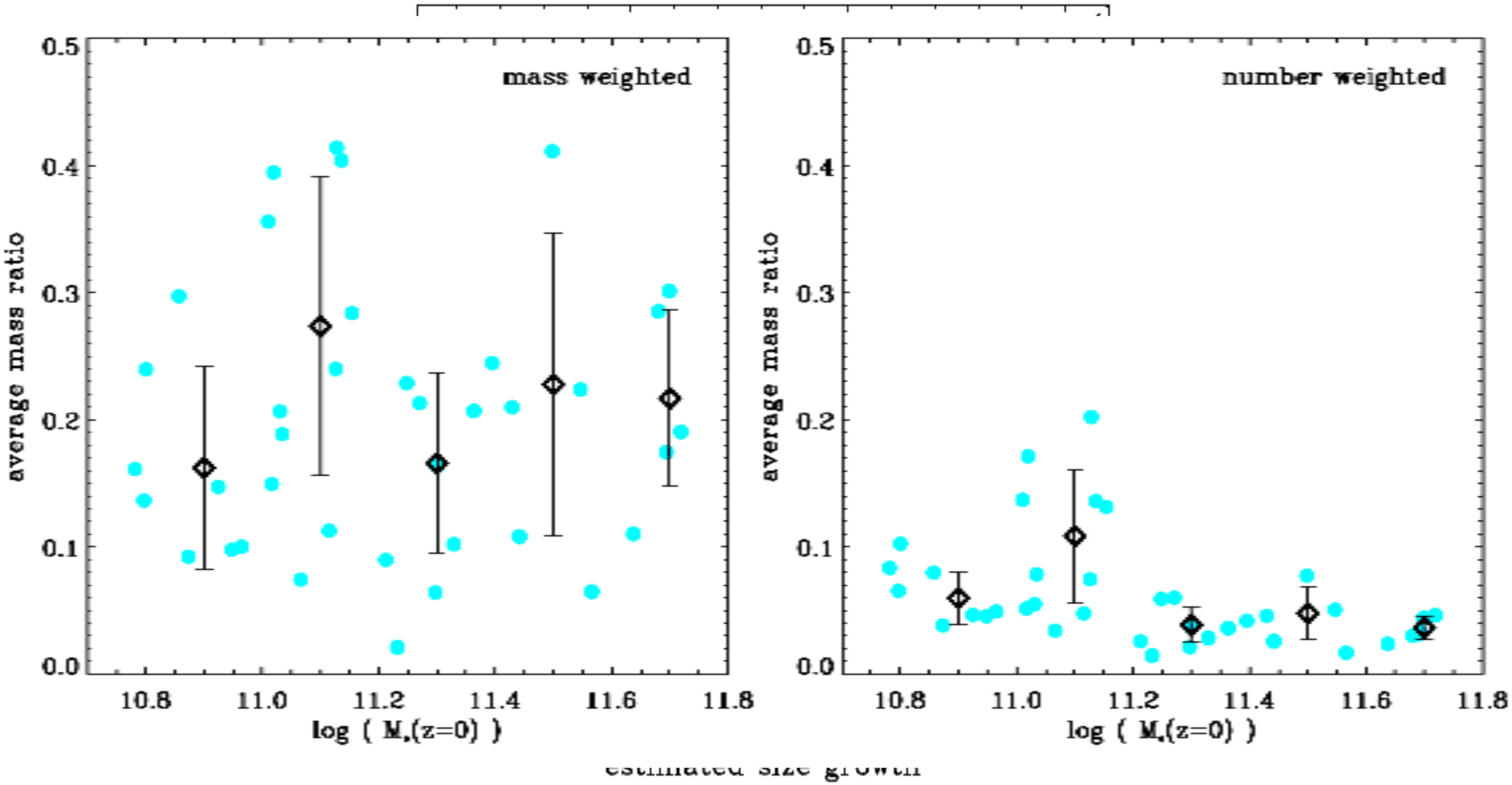
The rapid size evolution of spheroids



Good agreement with observed strong size evolution for massive early-type galaxies proportional to $(1+z)^{\alpha}$, $\alpha=-1.22$ (Franx et al. 2008) , -1.48 (Buitrago et al. 2008) , -1.17 (Williams et al. 2010)

Oser et al. 2012

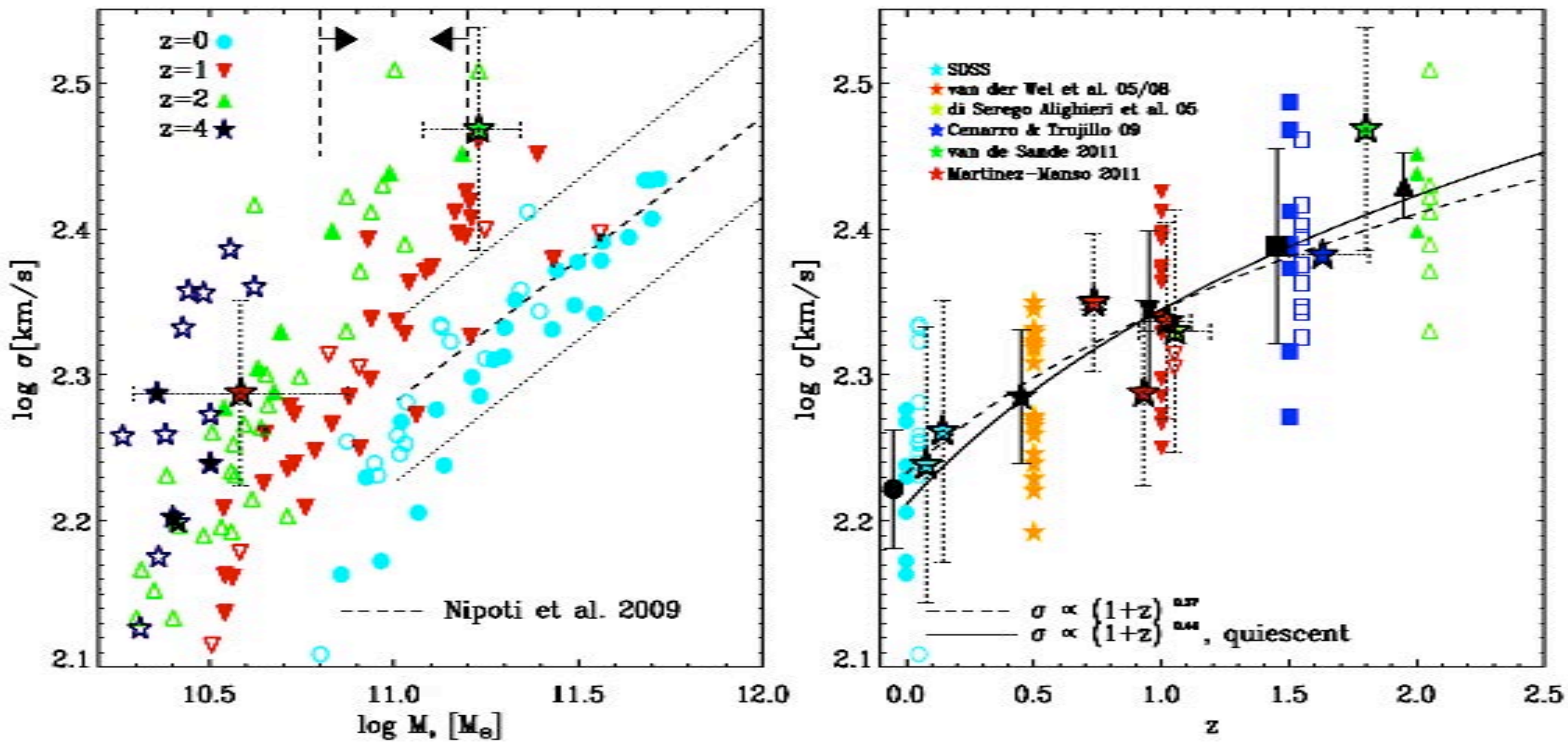
Size evolution and merger history



- The simulated size evolution in a cosmological context agrees with simple virial estimates
- Mass-weighted mass ratio is 5:1

Oser et al. 2012

The dispersion evolution of spheroids



Galaxies at higher redshift have higher velocity dispersions but move onto the local correlations – detailed merger analysis is ongoing

Oser et al. 2011

Central dark matter fractions

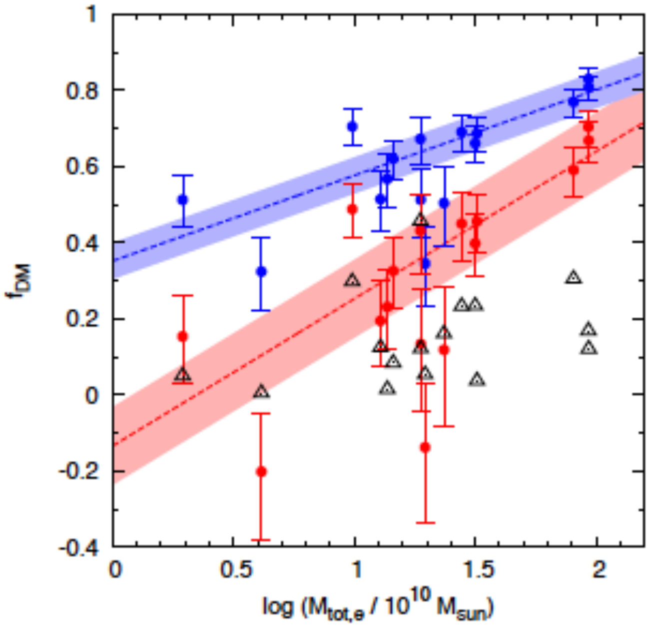
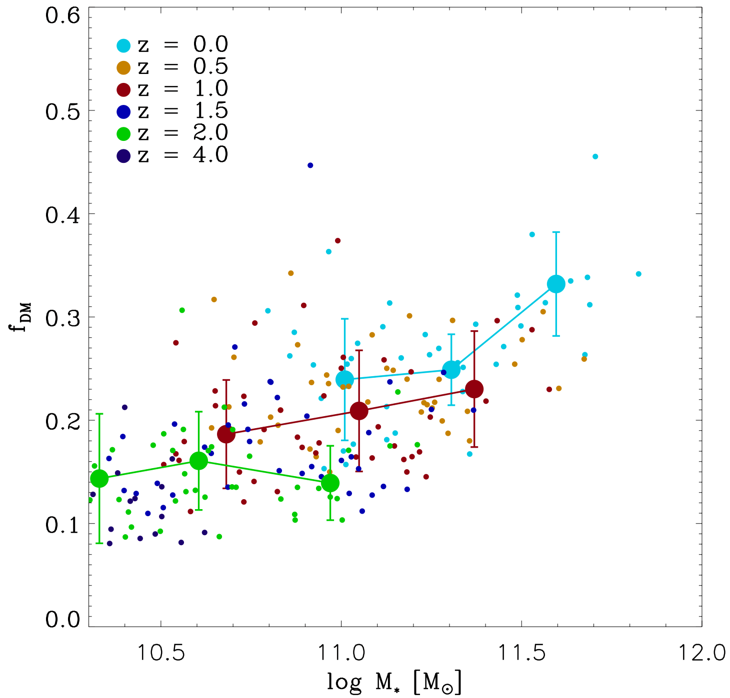


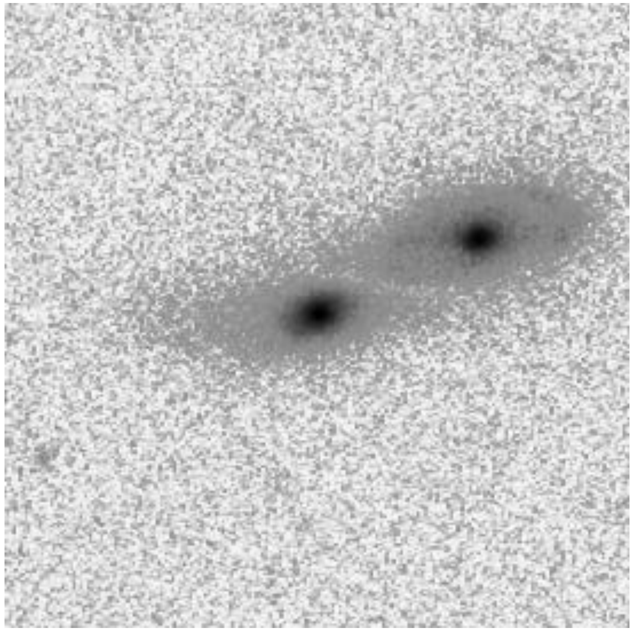
Figure 6. Dark matter fractions versus the total mass enclosed within the three-dimensional radius r_e. The upwards black triangles indicate the dark matter fraction lower limits calculated from the maximum bulge approach. The full circles show the dark matter fractions obtained when luminous masses are determined via SPS analysis, assuming Salpeter (red) or Chabrier (blue) IMFs. The dashed lines are linear fits to the relation, calculated including intrinsic scatter (which is indicated by the coloured bands).

Barnabe et al. 2011

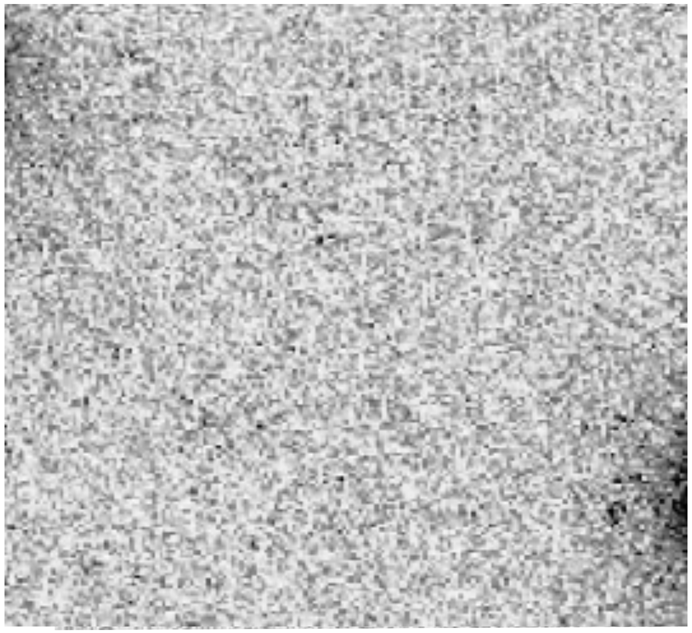


The average central dark matter fractions agree with estimates from lensing and dynamical modeling - see SLACS

Merger rate of elliptical galaxies



GEMS observations



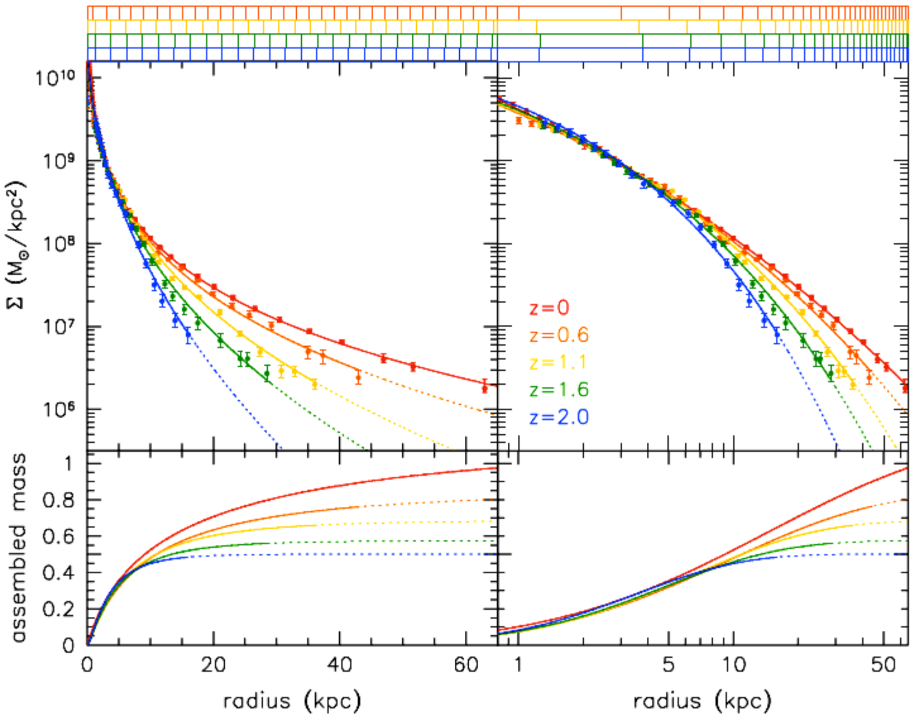
Simulation

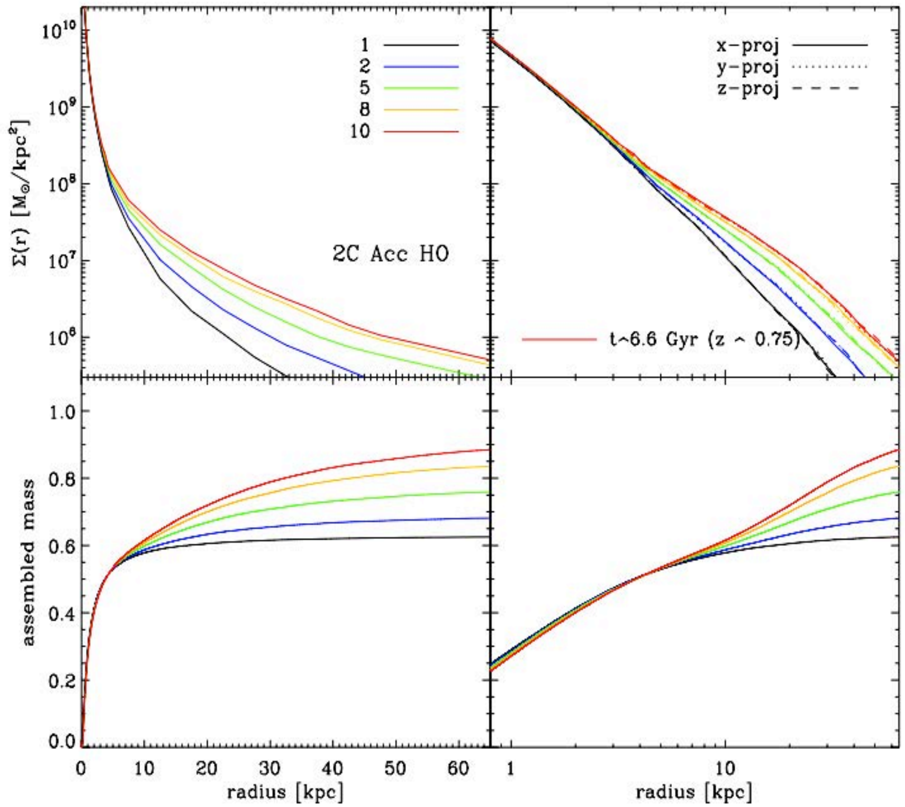
Mergers are visible for approx. 150 Myrs independent of their orbit.

$M_V < -20.5$ galaxies undergo 0.5 -2 major spheroid mergers since z=0.7

Bell, Naab, McIntosh et al. 2006

Inside-out growth since z = 2

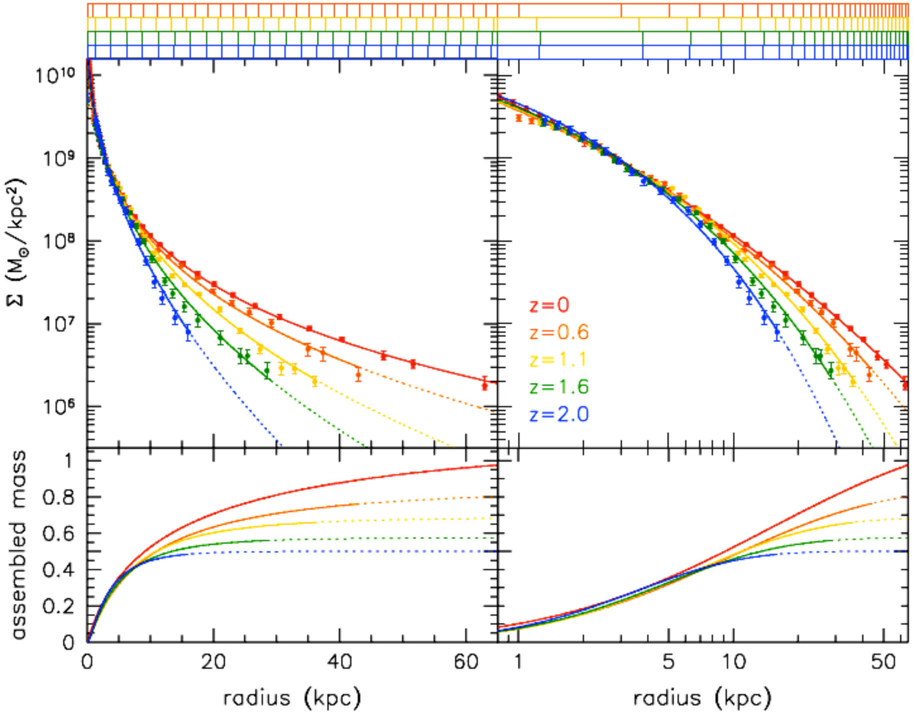


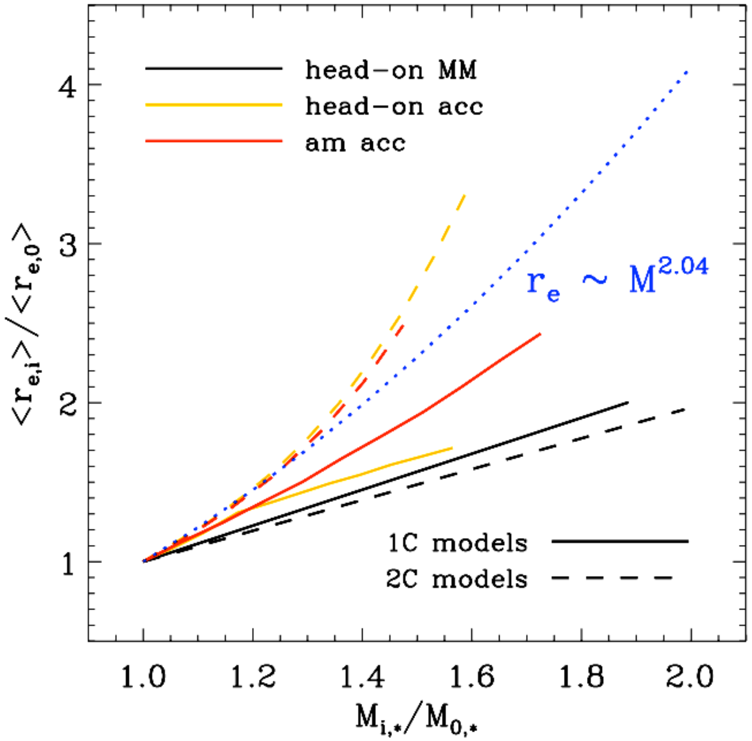


- Isolated 1:1 (mm) and 10:1 (acc) mergers of spheroidal galaxies without (1C) and with (2C) dark matter
- Only minor mergers with dark matter result in inside-out growth

Hilz et al. 2012, in prep.

Inside-out growth since z = 2

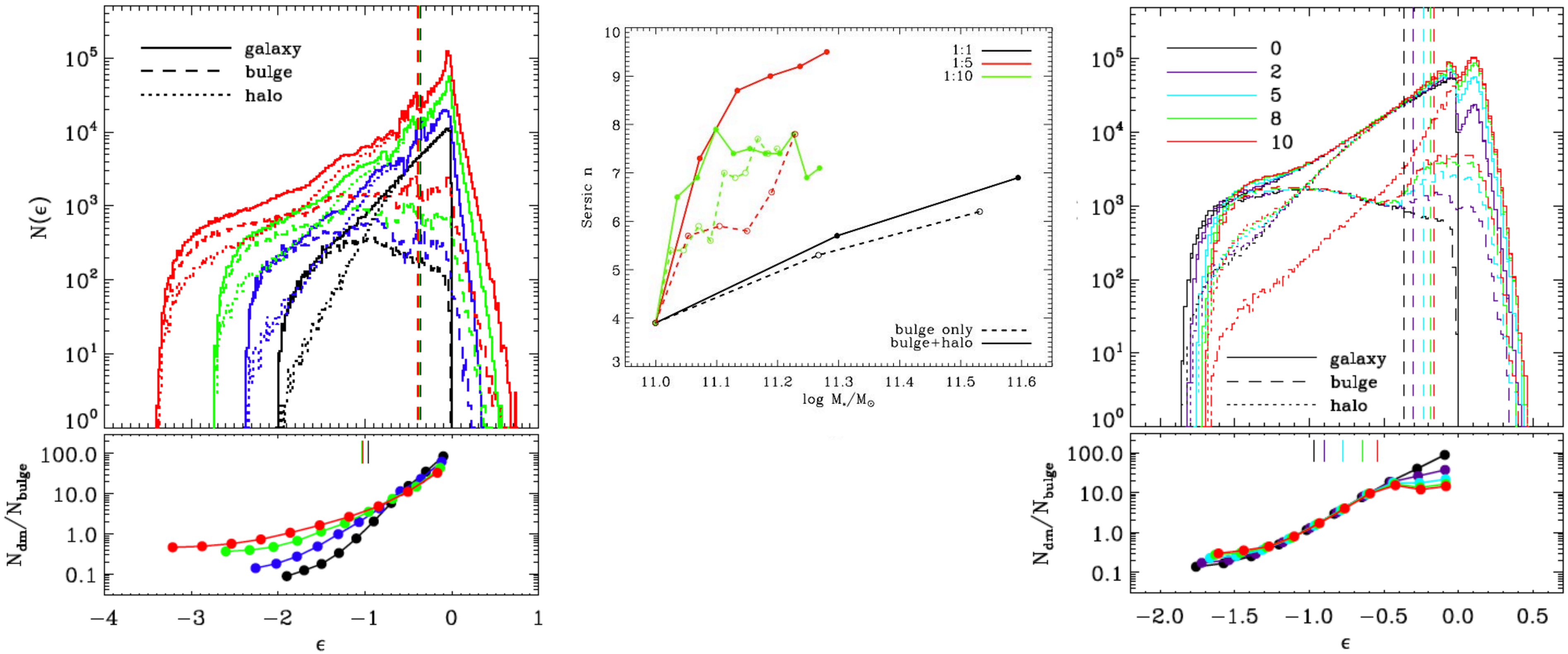




- ○Isolated 1:1 (mm) and 10:1 (acc) mergers of spheroidal galaxies without (1C) and with (2C) dark matter
- ○Only minor mergers with dark matter result in inside-out growth

Hilz et al. 2012, in prep.

Relaxation and Stripping



Major mergers mix dark matter into the center (relaxation)
Minor mergers increase galaxy sizes enclosing more dark matter (stripping)

Hilz et al. 2012, submitted, see e.g. Boylan-Kolchin et al., Libeskind et al. 2011 for M31 & MW

Conclusions

- The formation/assembly of elliptical galaxies is a two phase process

- The cores (≈kpc) of early-type galaxies form at $2 < z < 6$ by dissipation/cold gas flows and by merging of smaller structures of stars/gas at the same time as the halo is building up (e.g. Hopkins et al. 09/10, van Dokkum et al. 2010)

- Ellipticals grow at $0 < z < 3$ by accretion/mergers of old stars (≈ 10 kpc) - all mass ratios, minor mergers dominate, major mergers have a more dramatic effect

- Size growth, the concurrent increase in dark matter fraction, downsizing, profile shape changes are a natural result of the hierarchical assembly of massive galaxies in modern cosmologies

- More work is needed on modelling the details of feedback from SN and AGN