The two phases of massive galaxy formation

Master-Untertitelformat bearbeiten

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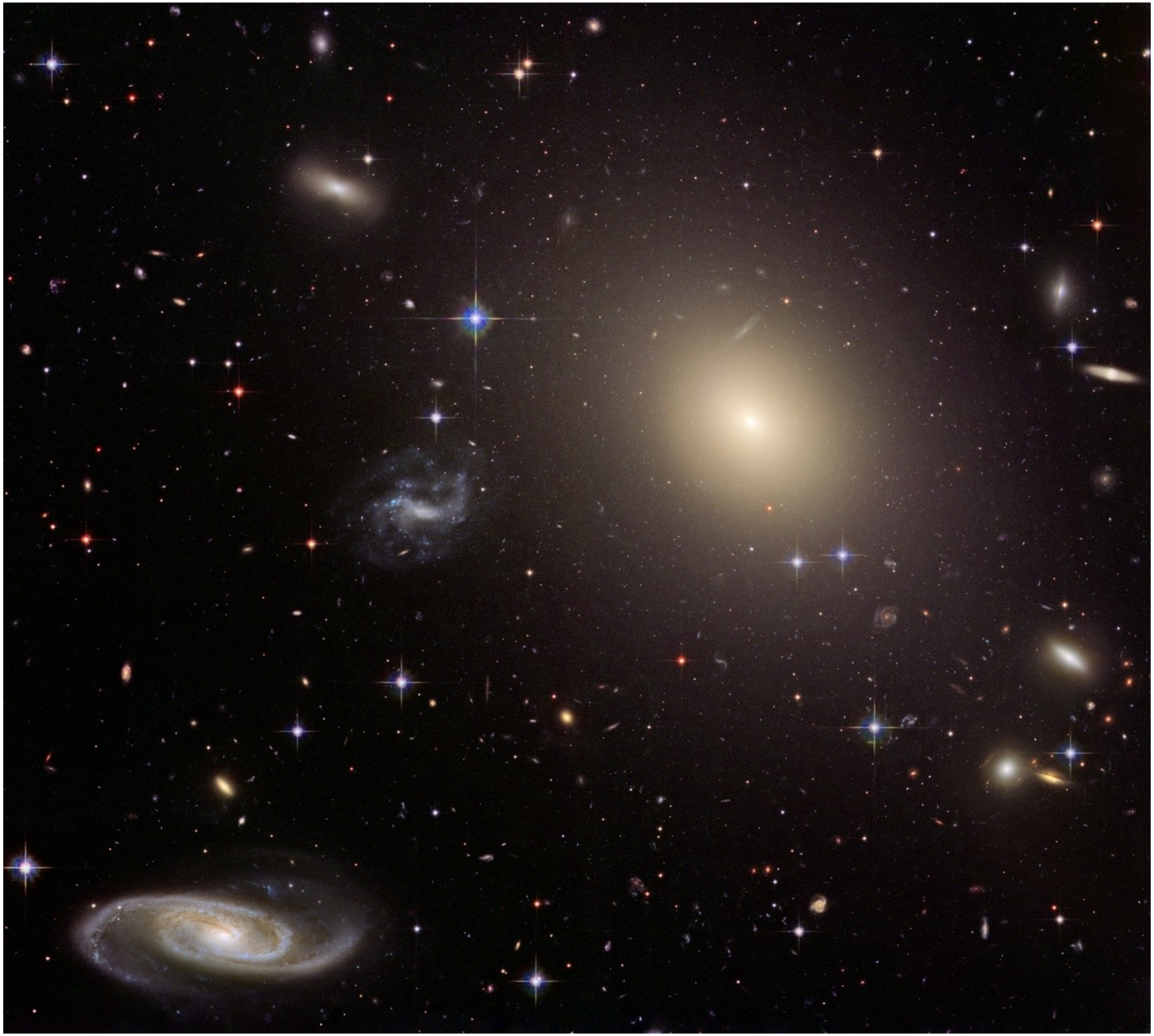
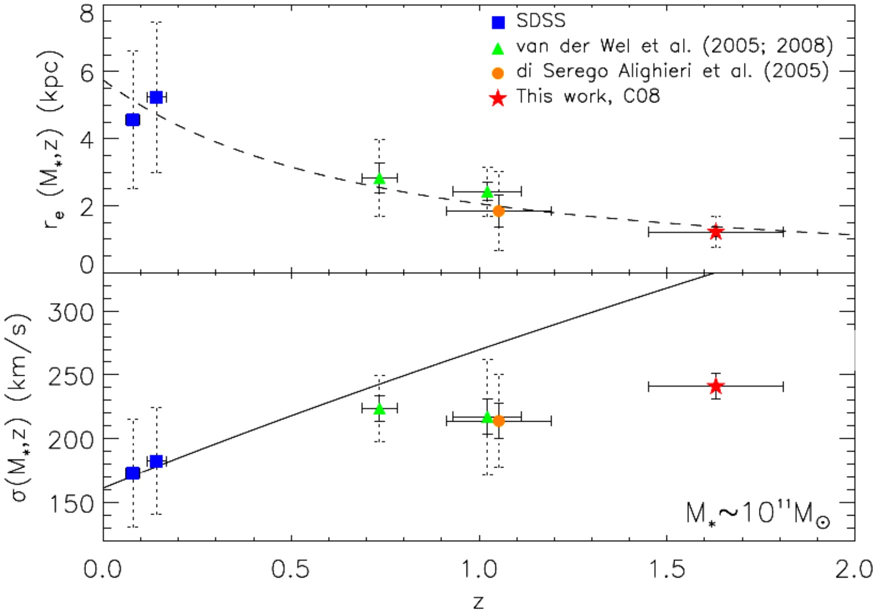


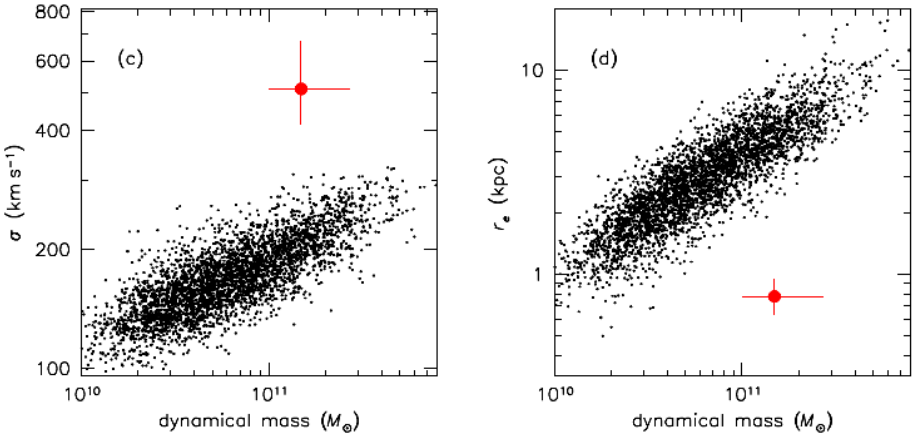
Size, mass (distribution) and velocity dispersion…..

Constraints: ‘Observations’ of early-type galaxies

- SIZE MATTERS! Insight into cosmic history of galaxy assembly, opening a window to the Universe when only a few Gyrs old
- All ellipticals/bulges have old metal-rich (Z=0.03) homogenous stellar populations with zform> 2 making up ½ - ¾? of all stars at z=0 (Ellis et al., Bell et al., Thomas et al., Gadotti 2009)
- Ellipticals are the oldest and most massive galaxies - downsizing
- Follow tight scaling relations, e.g. the Fundamental Plane (Djorgovski & Davis 1987, Dressler et al. 1987, Bender et al. 1992, Bolton et al. 2008)
- Direct observations of massive ≥ 1011 M⊙, compact, evolved galaxies up to high redshifts z ≥ 2 (e.g. Daddi et al. 2005, Kriek et al. 2006, Cimatti et al. 2007, Franx et al. 2008 and many more)
- Strong evolution in size, density, weak evolution in dispersion…

Size and dispersion evolution since z≈2





- Size evolution for massive early-type galaxies proportional to (1+z)α, α=-1.22 (Franx et al. 2008) , -1.48 (Buitrago et al. 2008) , -1.17 (Williams et al. 2010)

- Mild evolution of ≈1011M⊙ ellipticals from 240km/s at z≈1.6 (240km/s) to 180 km/s at z=0 (Cenarro & Trujillo 2009) from stacked spectra of 11 GMASS ellipticals (Cimatti et al. 2008)

- High velocity dispersion of a z=2.168 galaxy – 512 km/s indicates high dynamical mass consistent with mass (2×1011M⊙) and compactness (0.78 kpc) of photometric data

- Add large galaxies to the population: faded spirals?

- Grow the population by major/minor mergers, expansion and other effects? Minor mergers are favored (Bezanzon et al. 2009, Hopkins et al. 09/10, Naab et al. 2009)

Minor mergers and the virial theorem

Mf = (1+η)*Mi and assume η=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

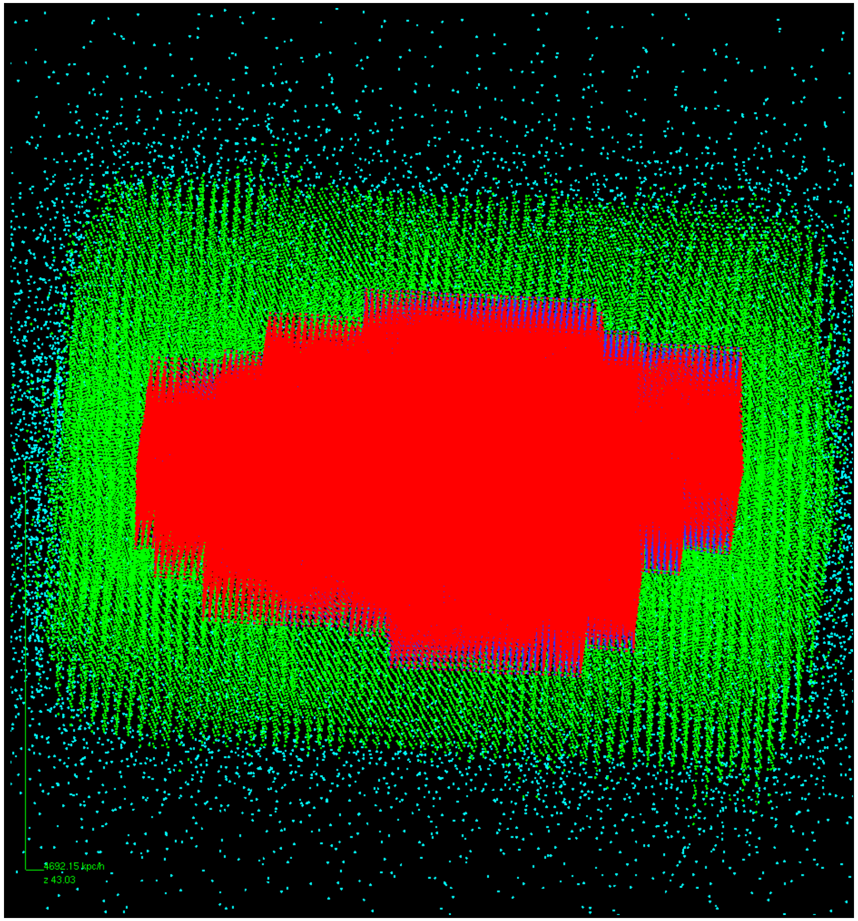
$$\frac{\rho_f}{\rho_i} = \frac{(1+\eta\epsilon)^3}{(1+\eta)^5}$$

Density can decrease by factor 32

more complex: gas, dark matter, dynamics

Naab, Johansson & Ostriker 2009

The tool: re-simulations



1003 Mpc, 5123 particles dark matter only & with gas and simple star formation & feedback, 100 snapshots (WMAP3: Ωm = 0.26, ΩΛ = 0.74, h = 0.72)

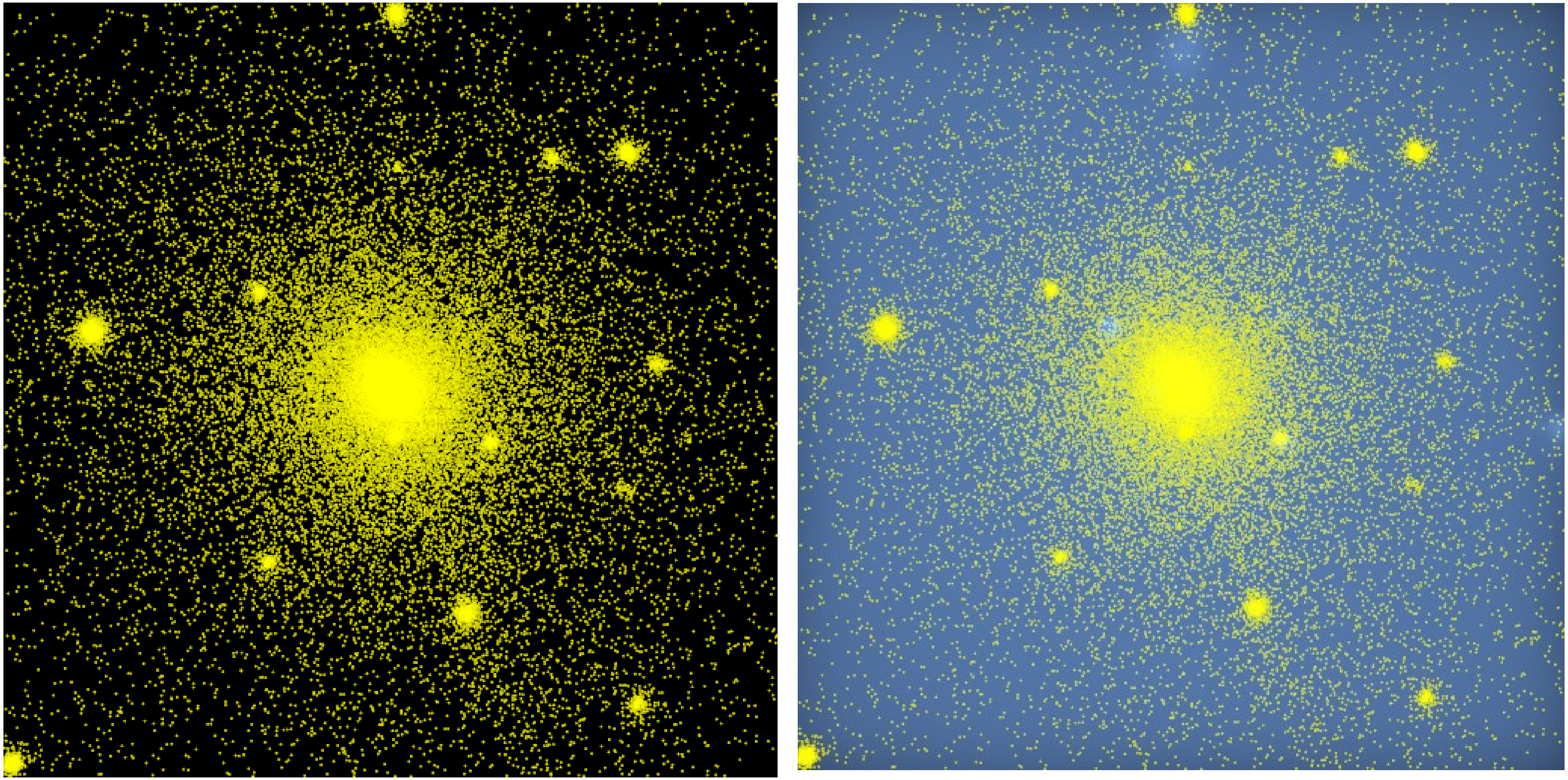
Re-simulation of a large number of individual halos from 1010-1013 (Mgas: 106, 105, 104) without gas, with star formation & evtl. feedback (Springel & Hernquist 2003)

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 (Hirschmann, Naab et al. in prep) also for detailed comparison with semi-analytical predictions

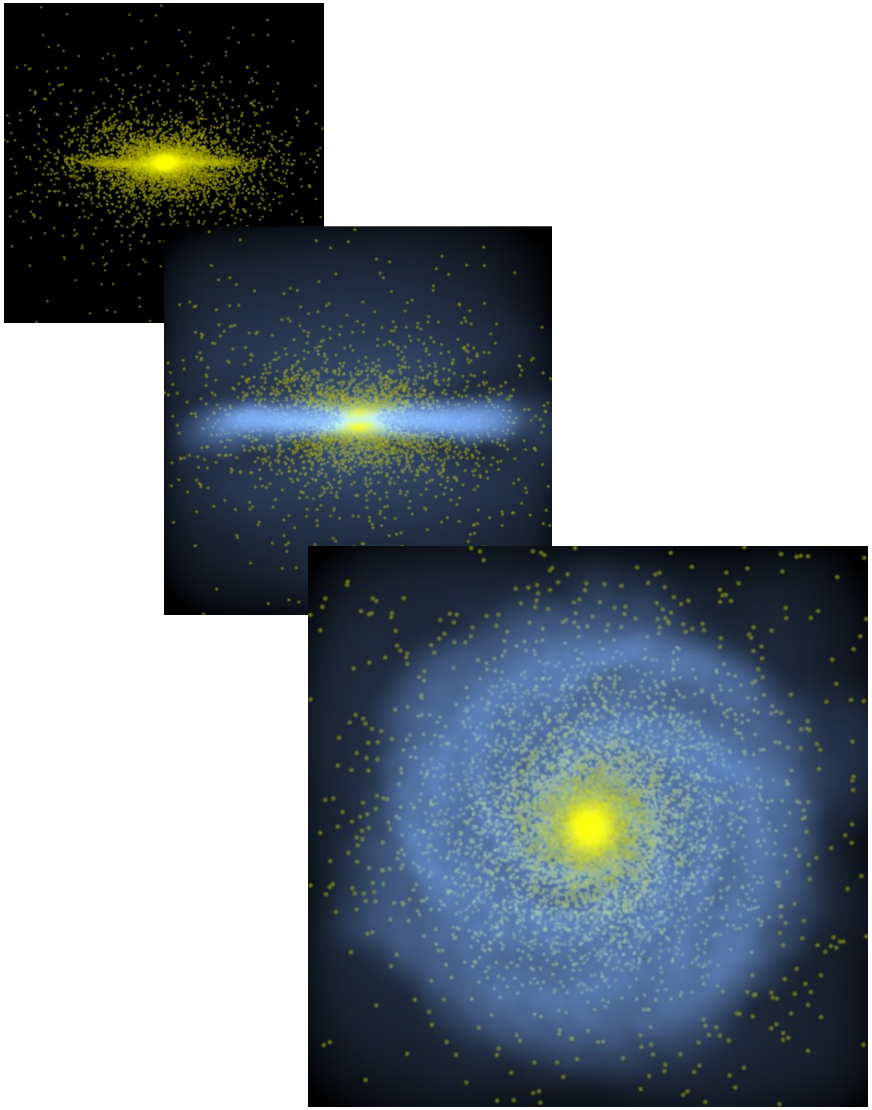
≈55 halos simulated so far and used for analysis presented here

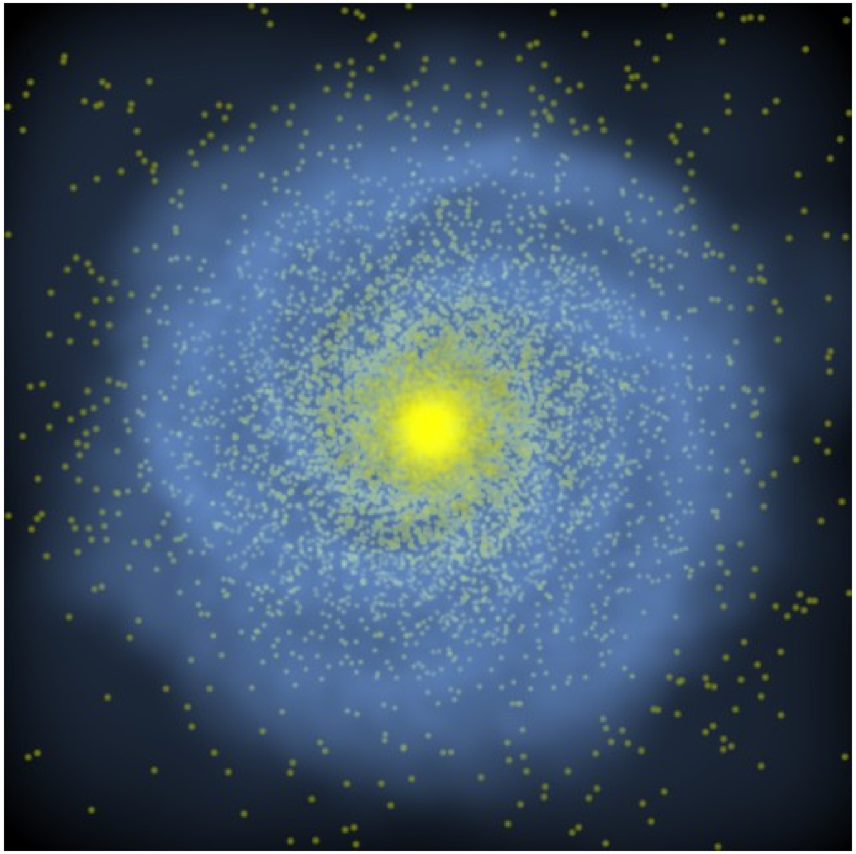
Galaxy gallery



M* = 8*1011 M⊙

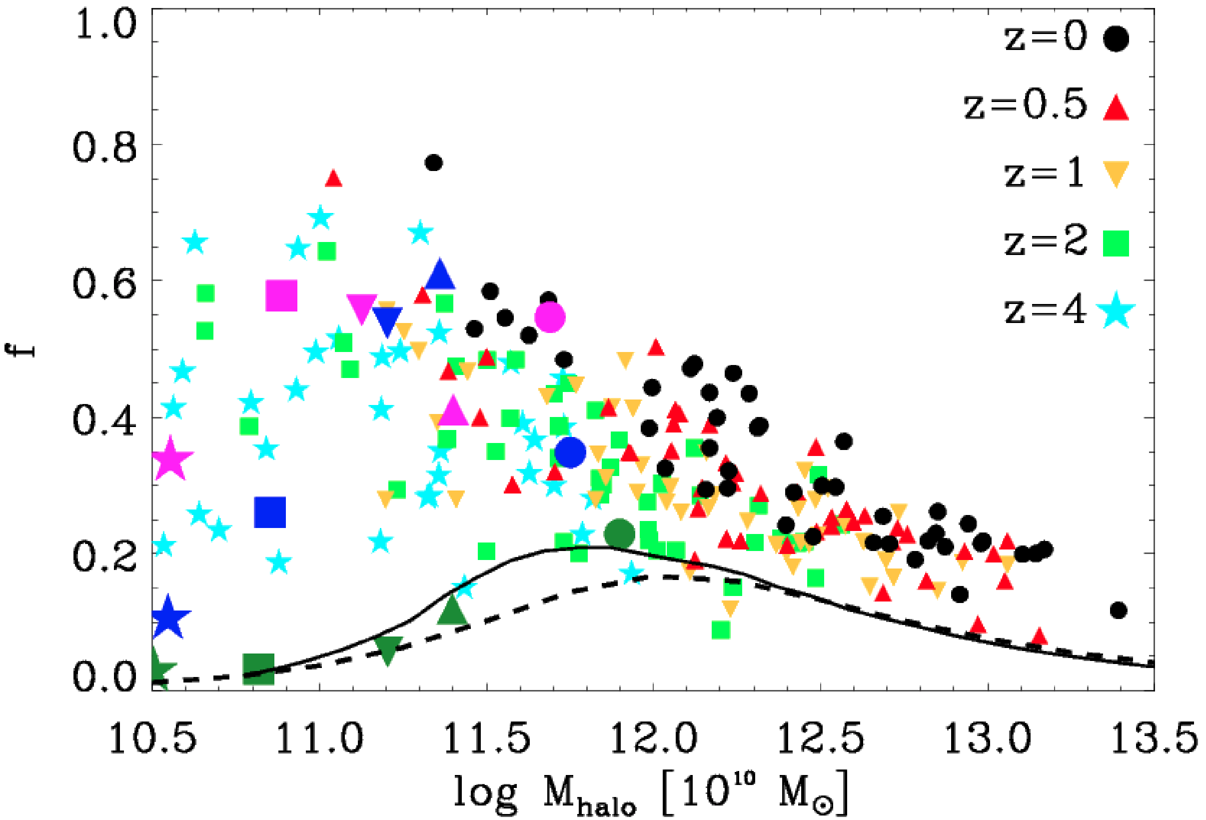
Galaxy gallery





$M^* = 1.5*1010\ M_\odot$

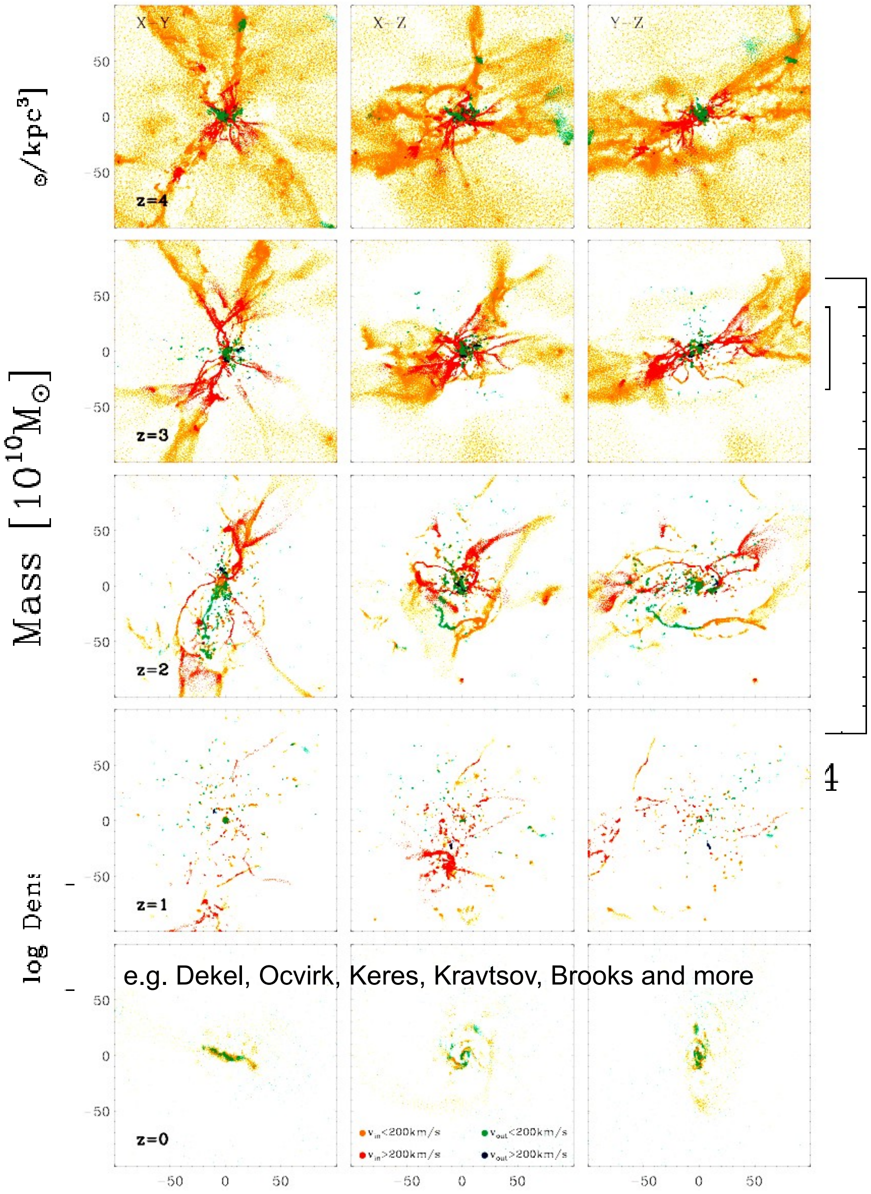
The stellar mass budget



- ◦Conversion efficiencies are slightly lower at higher redshifts
- ◦Agreement with 'observations' for low mass galaxies is worse than for high mass galaxies (Wechsler et al., Guo et al. 2010, Moster et al. 2010, Trujillo-Gomez et al. 2010)
- ◦IMF? AGN feedback? Stellar mass loss? Star formation driven winds? etc…

Grossi et al. in prep.

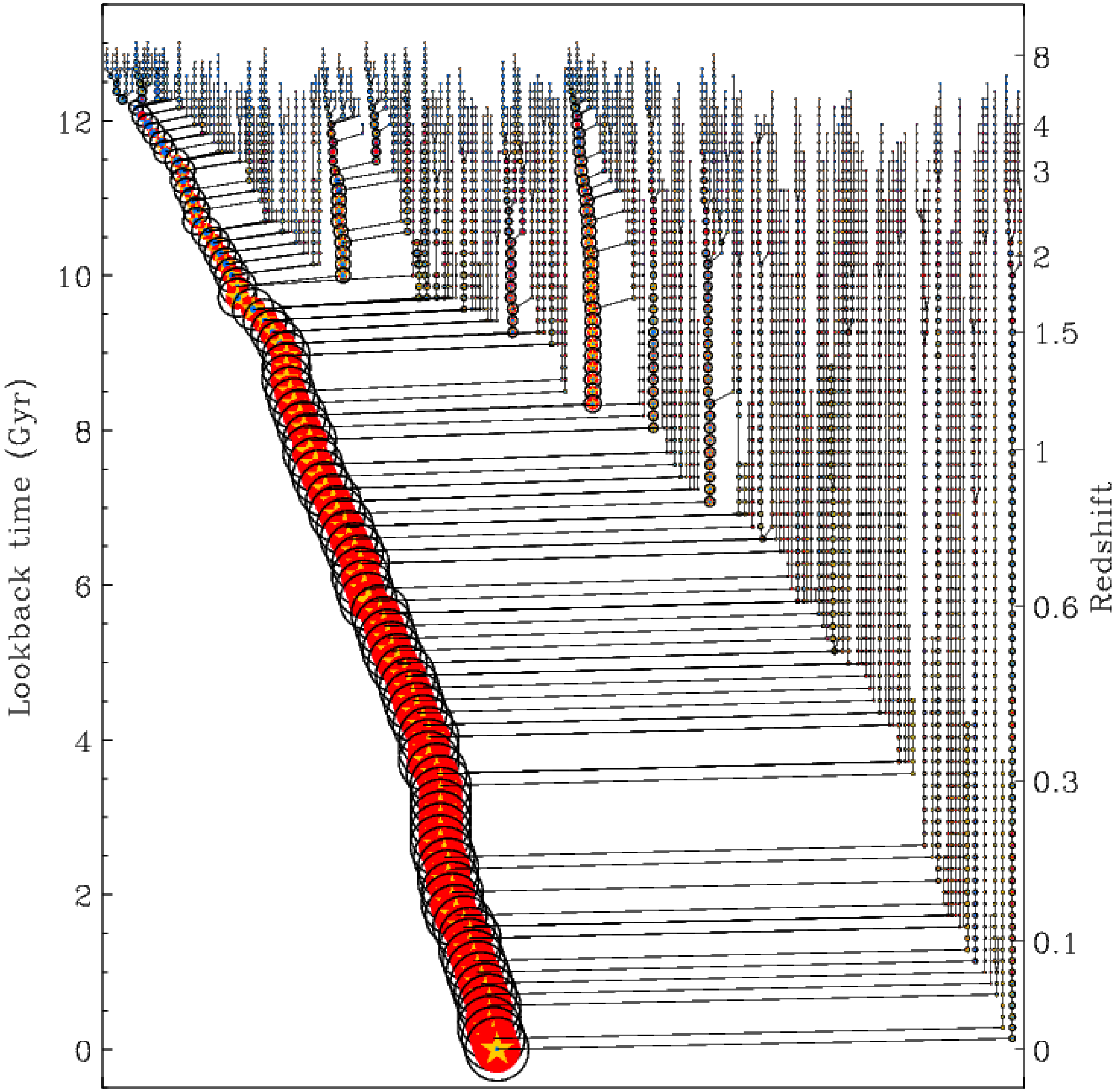
Size evolution in a high resolution simulation



e.g. Dekel, Ocvirk, Keres, Kravtsov, Brooks and more

- 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*1010M⊙
  ρeff = 1.6*1010M⊙/kpc3
  σeff= 240 km/s
- z≈0: M=15*1010M⊙
  ρeff = 1.3*109M⊙/kpc3
  σeff= 190 km/s
- Consistent with accreted mass being responsible for size increase

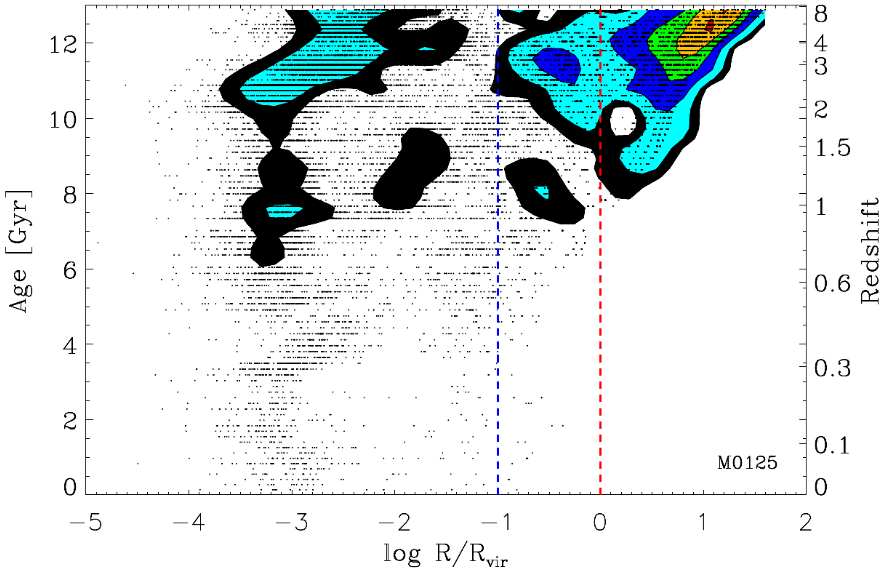
The two phases of galaxy formation

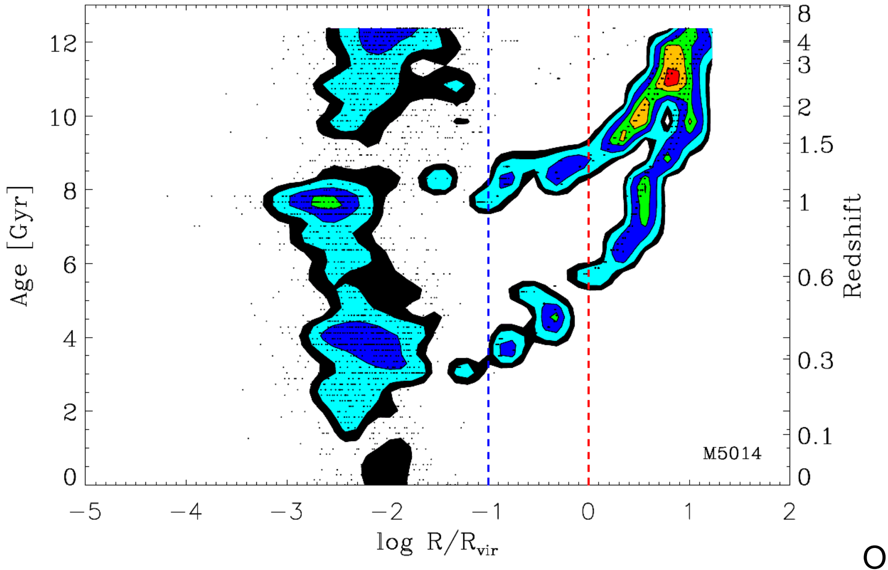


- ◦Typical contribution of stellar mergers (>1:4) in massive galaxies since z=2 is 40% - 50%

Hirschmann, Naab, Somerville et al., in prep

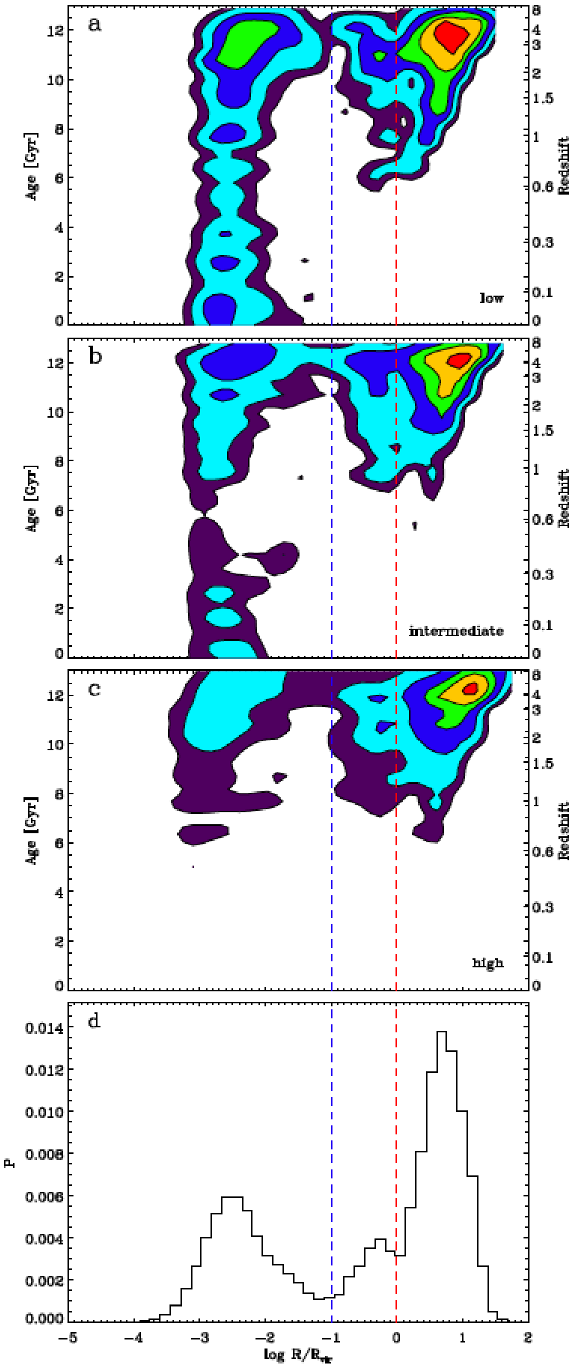
The origin of stars in galaxies

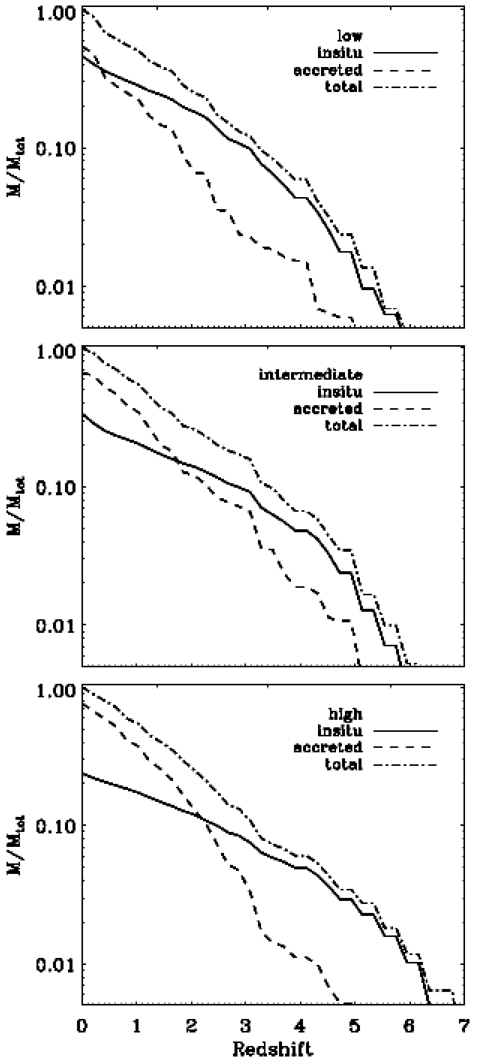




- Stellar origin diagrams indicate when and at which radius a star ending up in a present day galaxy was born
- In massive galaxies most stars are made at high redshift in-situ in the galaxy and even more ex-situ outside the galaxies virial radius with a low fraction of in-situ formation at low redshift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

Oser, Ostriker, Naab, Johansson & Burkert 2010, submitted

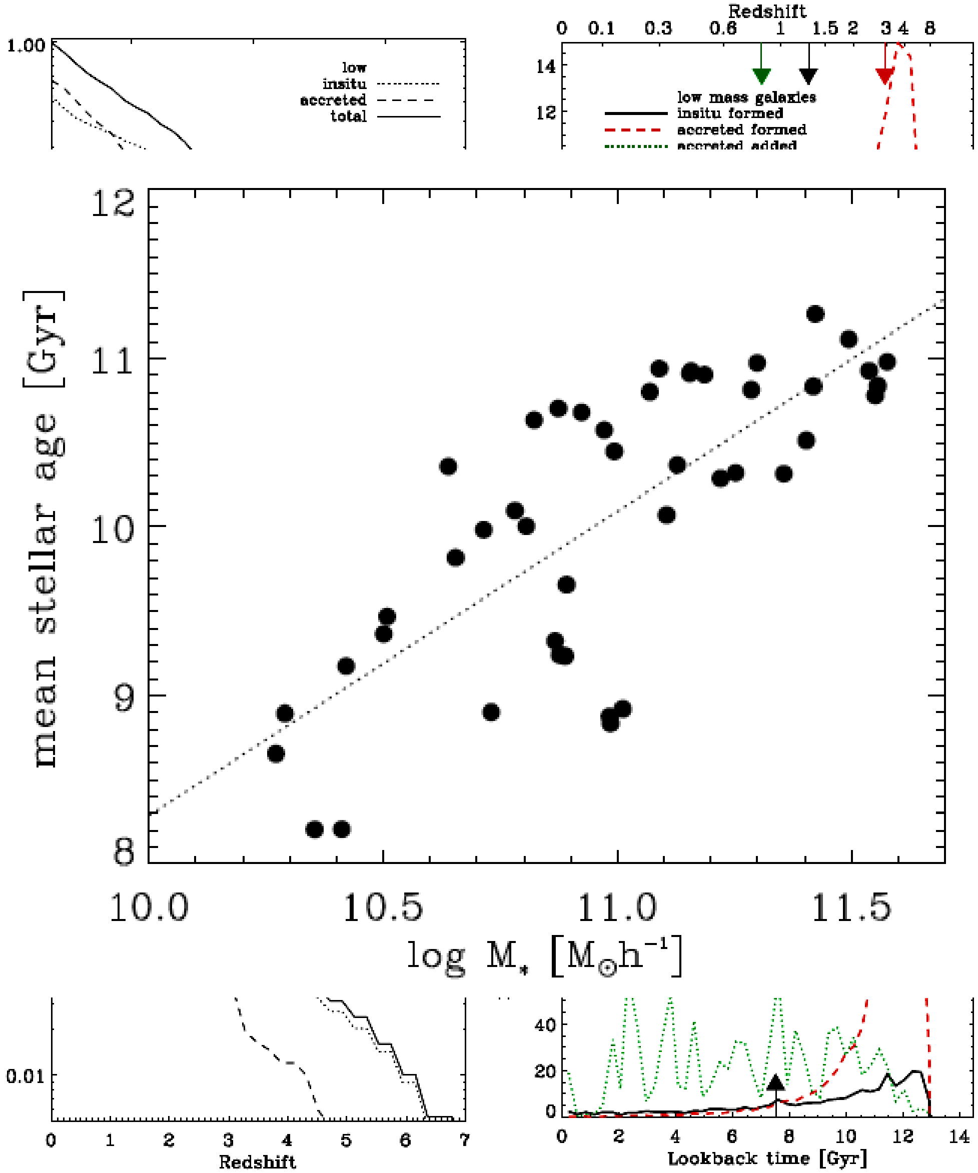




- 45 simulations stacked in mass bins
- Early assembly is dominated by in-situ formation, more so in massive galaxies (6 > z > 3)
- Low mass galaxies assemble half their mass by in-situ formation
- The late assembly of massive galaxies is dominated by accretion (up to 80%) of stellar system (3 > z >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

The two phases of galaxy formation

The origin of stars in galaxies



◦Ex-situ stars form at high redshift (z=4)

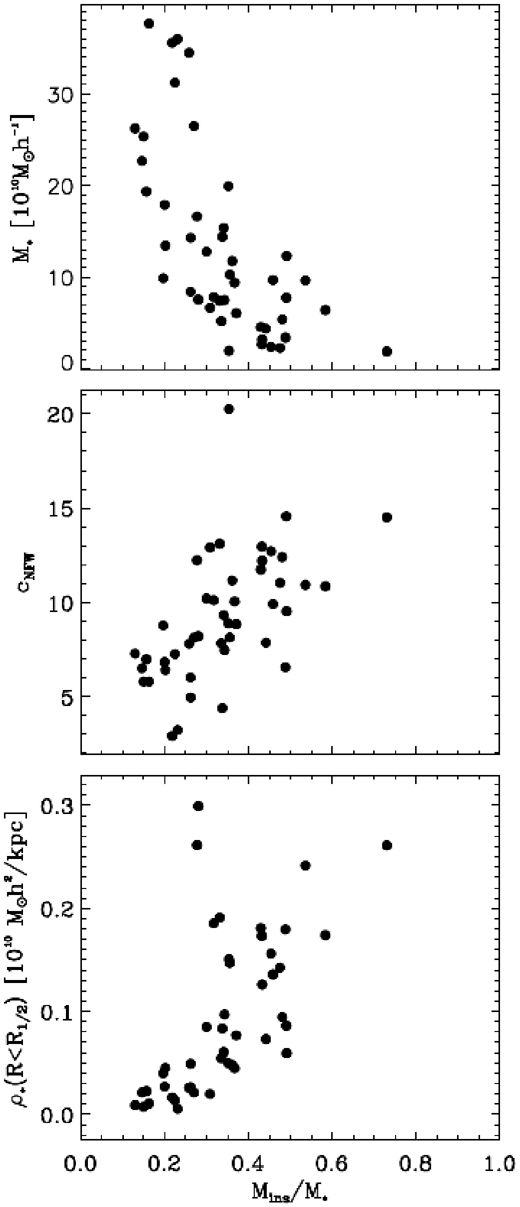
◦Ex-situ stars are accreted below z ≈1 at high rates for massive galaxies

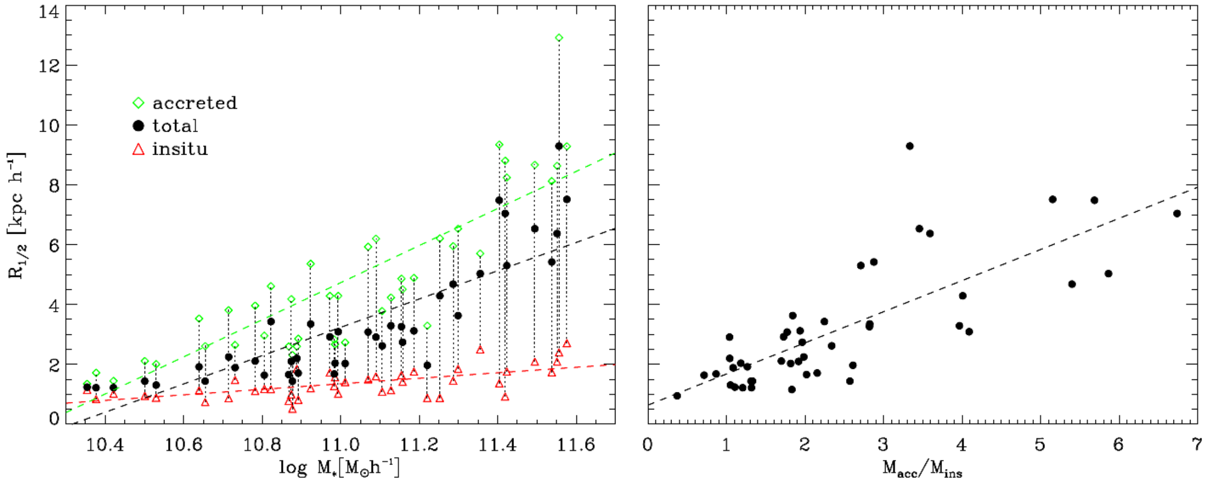
◦In-situ stars start forming at high redshift and continue to contribute to the growth of low mass galaxies until the present day

◦Galaxies assemble half their mass at z ≈1

◦More massive galaxies are older ➔ downsizing (Keres et al. 2009)

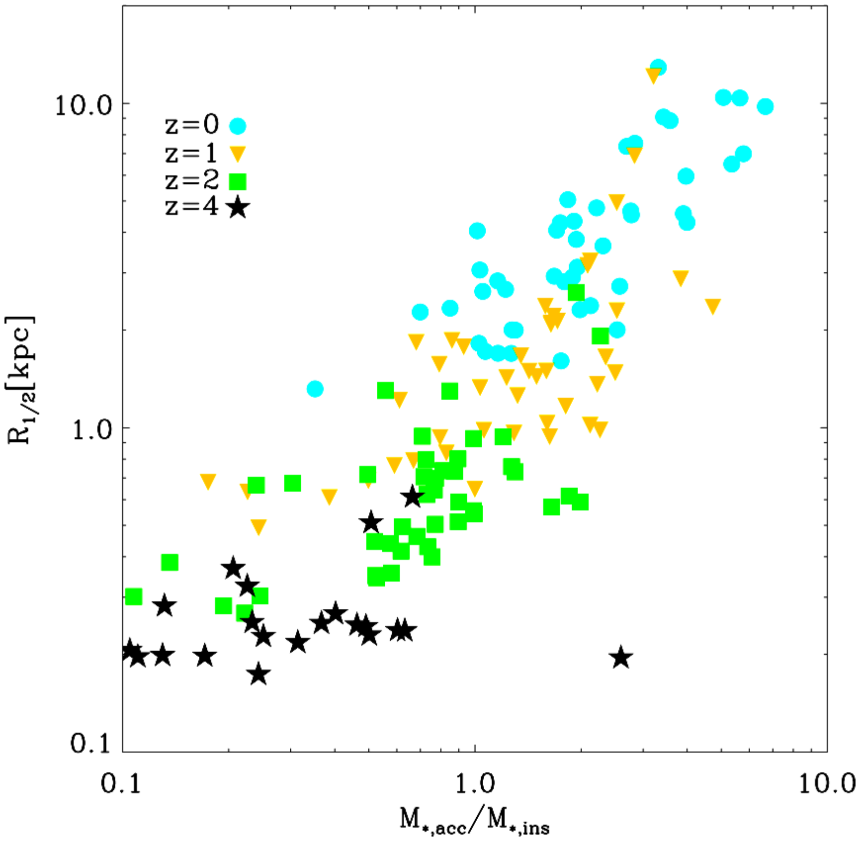
… and some more consequences

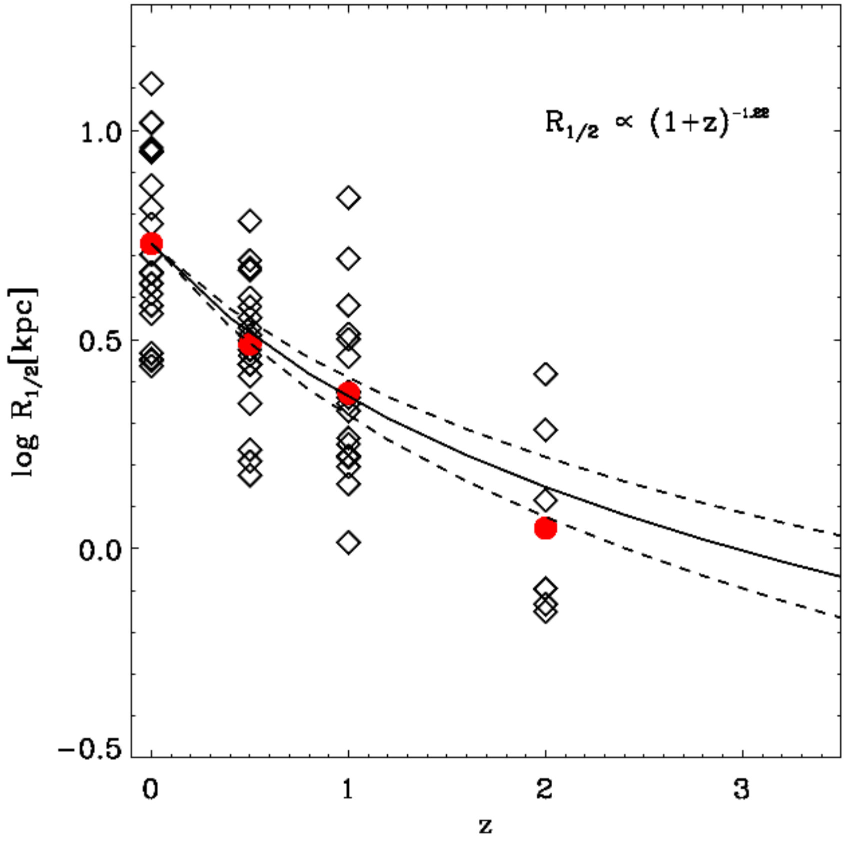




- More massive galaxies had more accretion
- Galaxies formed by more dissipation have more concentrated dark matter halos
- Galaxies formed by more dissipation have denser galaxies
- Mass-size relation is driven by accretion

The rapid size evolution of spheroids

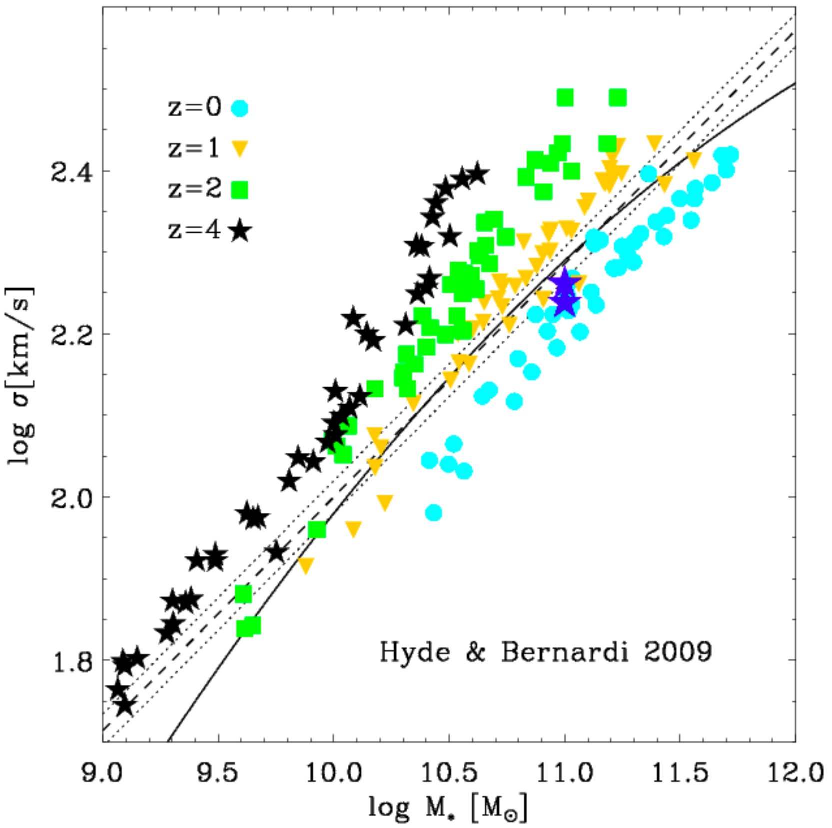


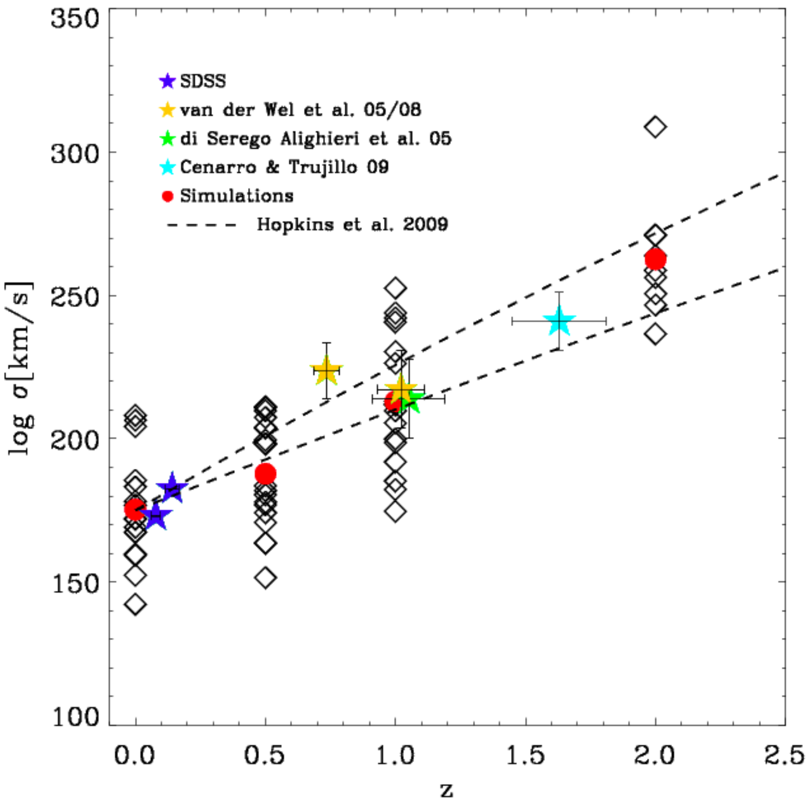


Good agreement with observed strong size evolution for massive early-type galaxies proportional to (1+z)α, α=−1.22 (Franx et al. 2008) , -1.48 (Buitrago et al. 2008) , -1.17 (Williams et al. 2010)

Naab, Oser, Ostriker, Johansson 2010

Compact massive ellipticals at z≈2





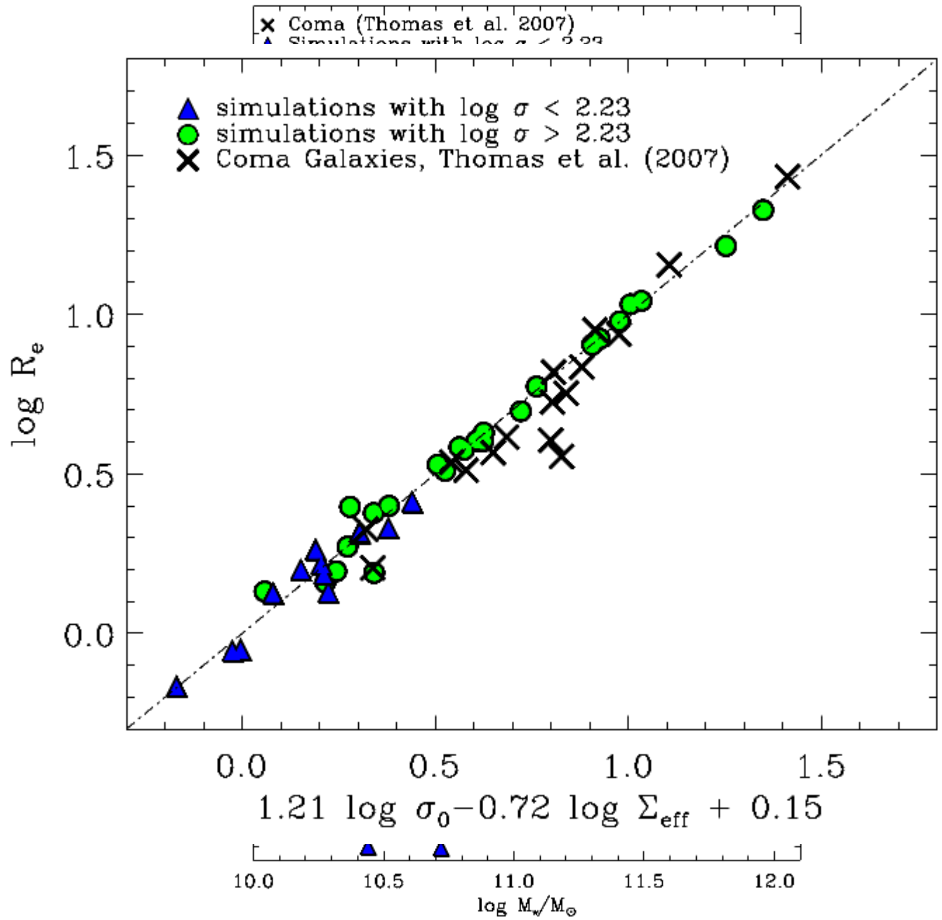
Galaxies at higher redshift have higher velocity dispersions but move onto the local correlations – detailed merger analysis is ongoing

Naab, Oser, Ostriker, Johansson 2010

Conclusions

- The formation 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 ('monolithic collapse') (Keres et al. 2005, Dekel et al. 2009, Hopkins et al. 2009) 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 ('dry mergers') of old stars (≈ 10 kpc) - all mass ratios, minor mergers dominate, major mergers have a more dramatic effect
- Effect of accretion can explain the mass-size relation and can be the key to the observed strong size evolution!!!
- Simulated central galaxies follow the fundamental mass plane with reasonable central dark matter fractions – reasonable models for ellipticals

The ‘dynamical’ mass FP



◦Dynamical modeling of Coma early-type galaxies (Thomas et al. 2007)

◦Direct estimate of total stellar mass within re

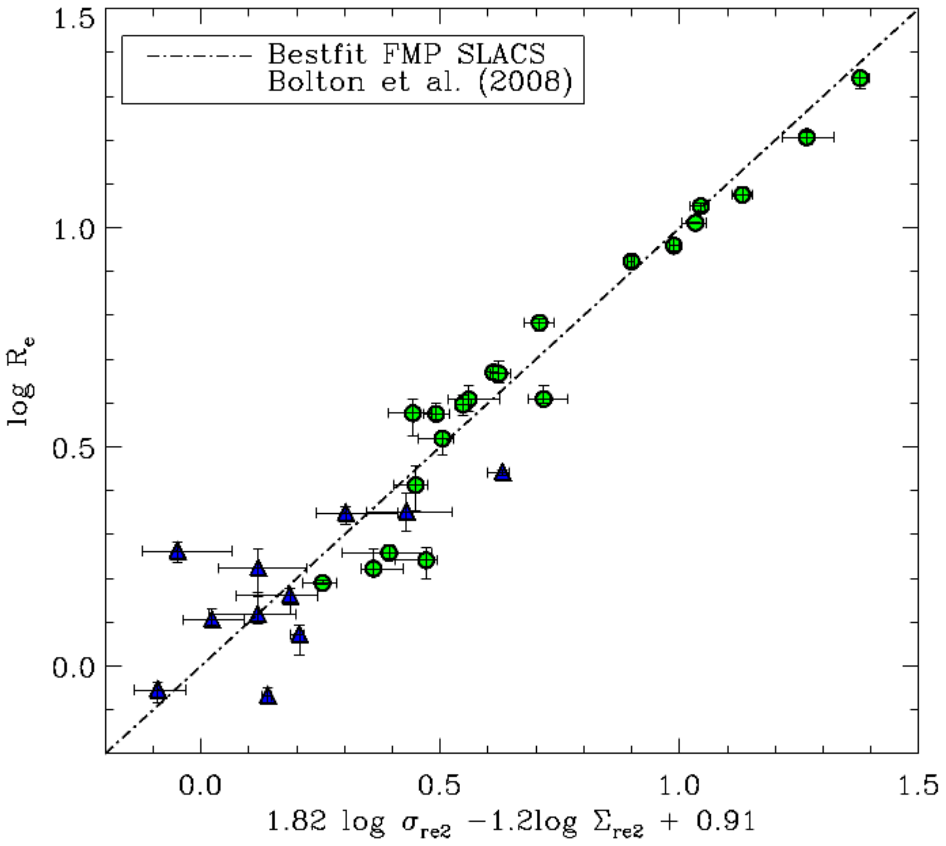
◦Modeling includes dark matter

◦Modeling for cluster galaxies is compared to isolated ellipticals. For central properties a reasonable comparison

Simulated galaxies are reasonable spheroidals with respect to dynamical mass scaling relations

Jesseit, Naab, Oser, Ostriker, Grillo et al. 2010, in prep.

The fundamental mass plane from strong lensing



◦53 field early-type strong gravitational lens galaxies from the Sloan Lens ACS (SLACS) survey (Bolton et al. 2008)

◦Estimate of the total mass (dark+gas+stars) within re/2

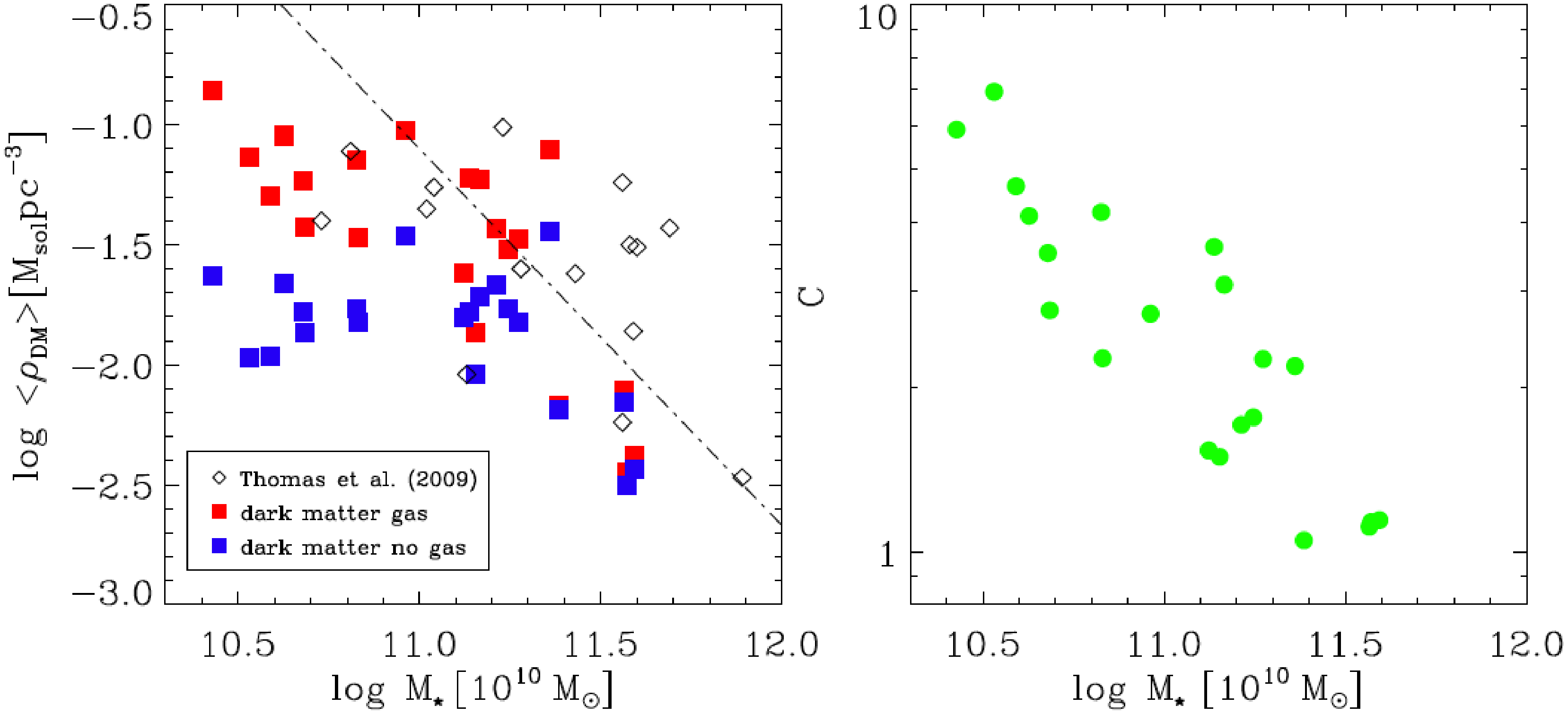
◦Representative for early-type galaxies with M*> 1011M (Auger et al. 2009)

◦Dynamical mass is a good proxy for the true masses

Our simulations agree well with the observed lensing mass plane, total mass profile is isothermal!

Jesseit, Naab et al. 2010

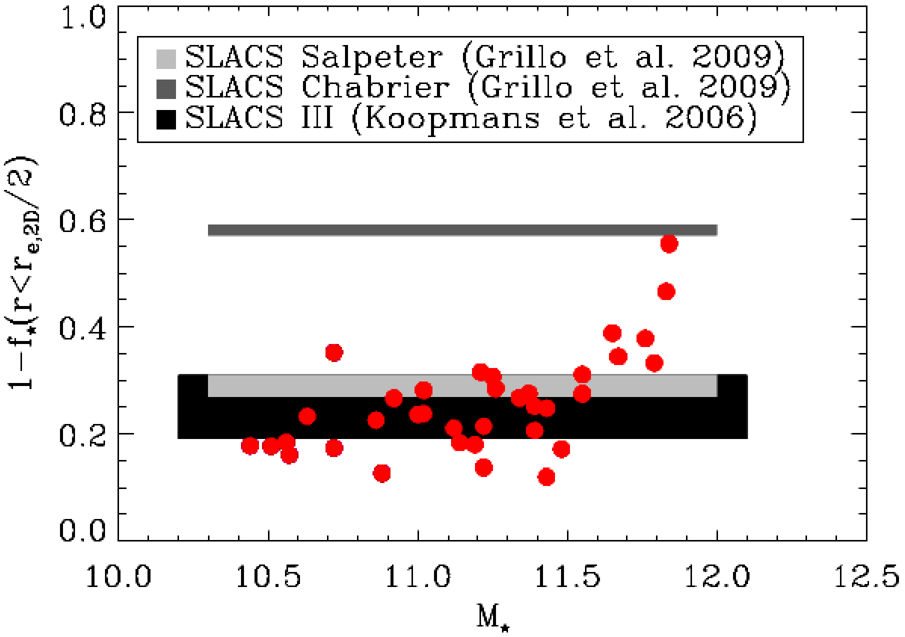
The dark matter content of elliptical galaxies

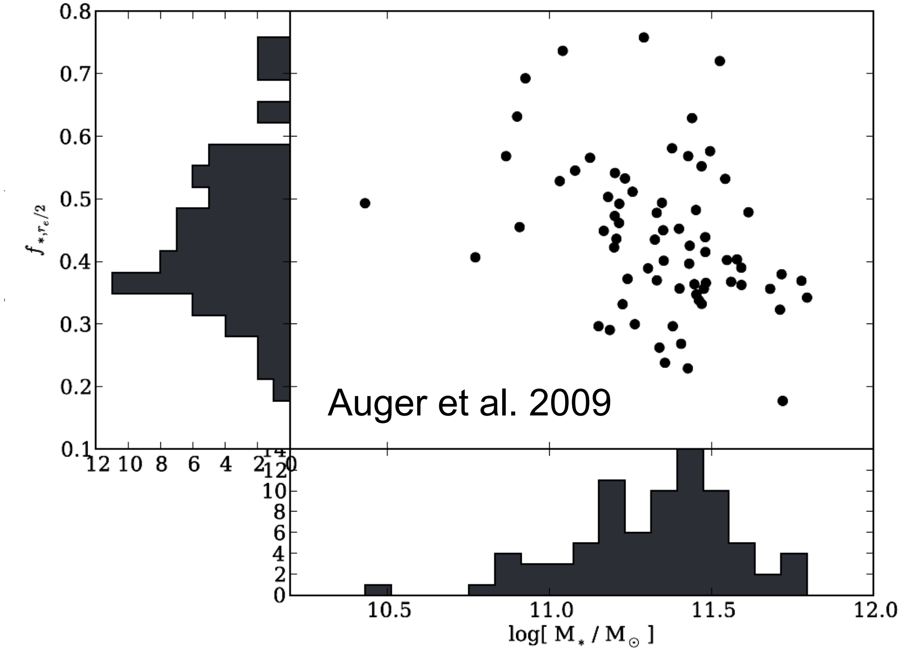


Dark matter densities are consistent with Thomas et al. origin here is not the formation time but the baryonic accretion history

Jesseit, Naab, et al. in prep.

Central dark matter fractions





- ◦The average central dark matter fraction agrees with estimates from lensing and dynamical modeling
- ◦Reasonable models for the mass distribution in massive early-type galaxies at z=0