Merger processes: when, what kind, and how frequent, and the impact on the rotation properties of the merger remnants

aka

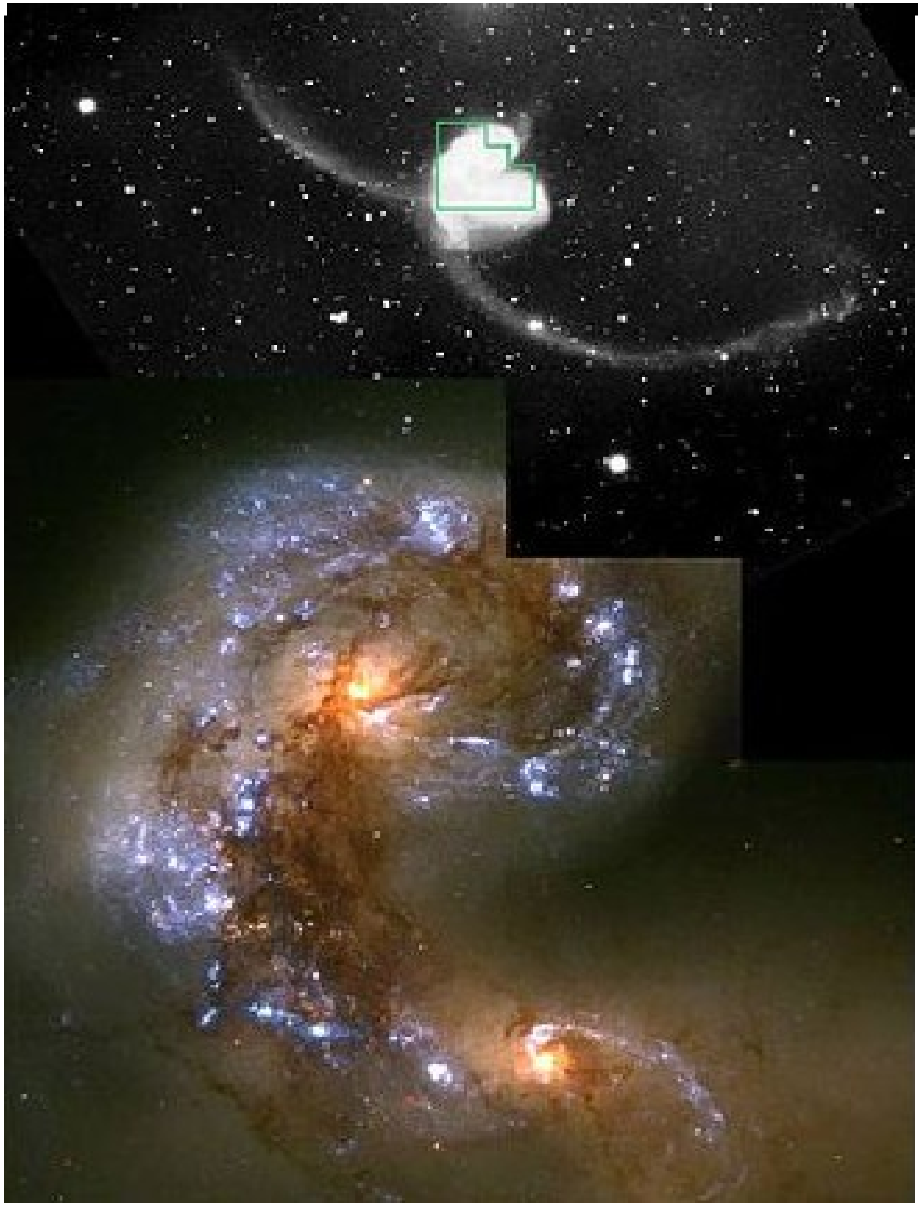
Galactic Collisions

Thorsten Naab
Max-Planck-Institute for Astrophysics

Master-Untertitelformat bearbeiten

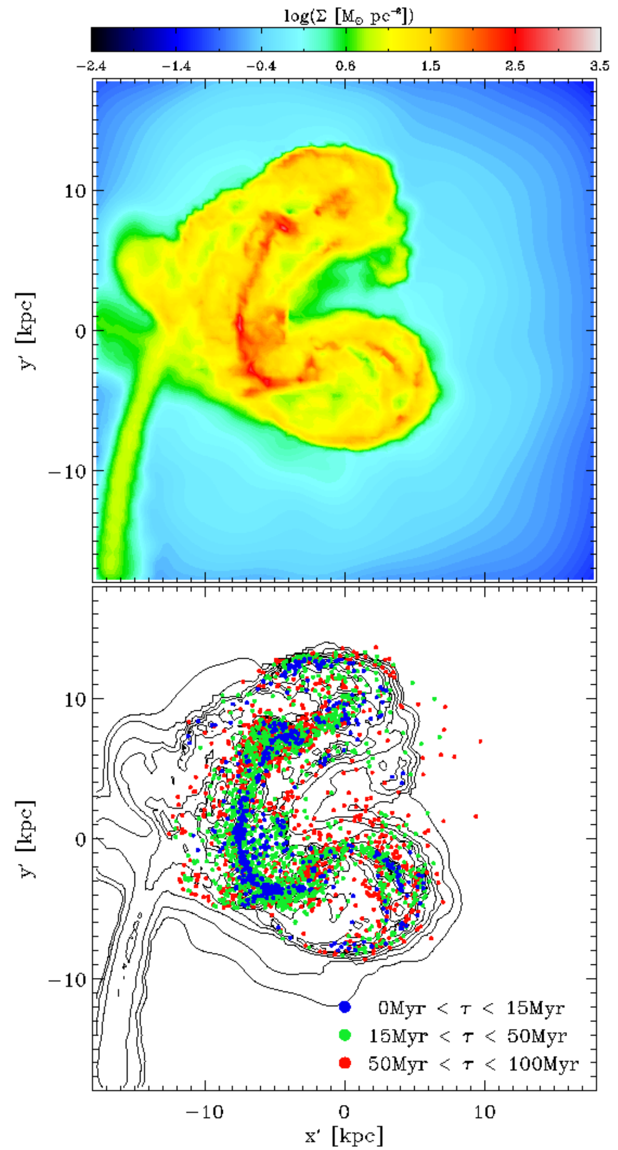
ESO Garching, June 29th

The Antennae galaxies: A key to galactic evolution

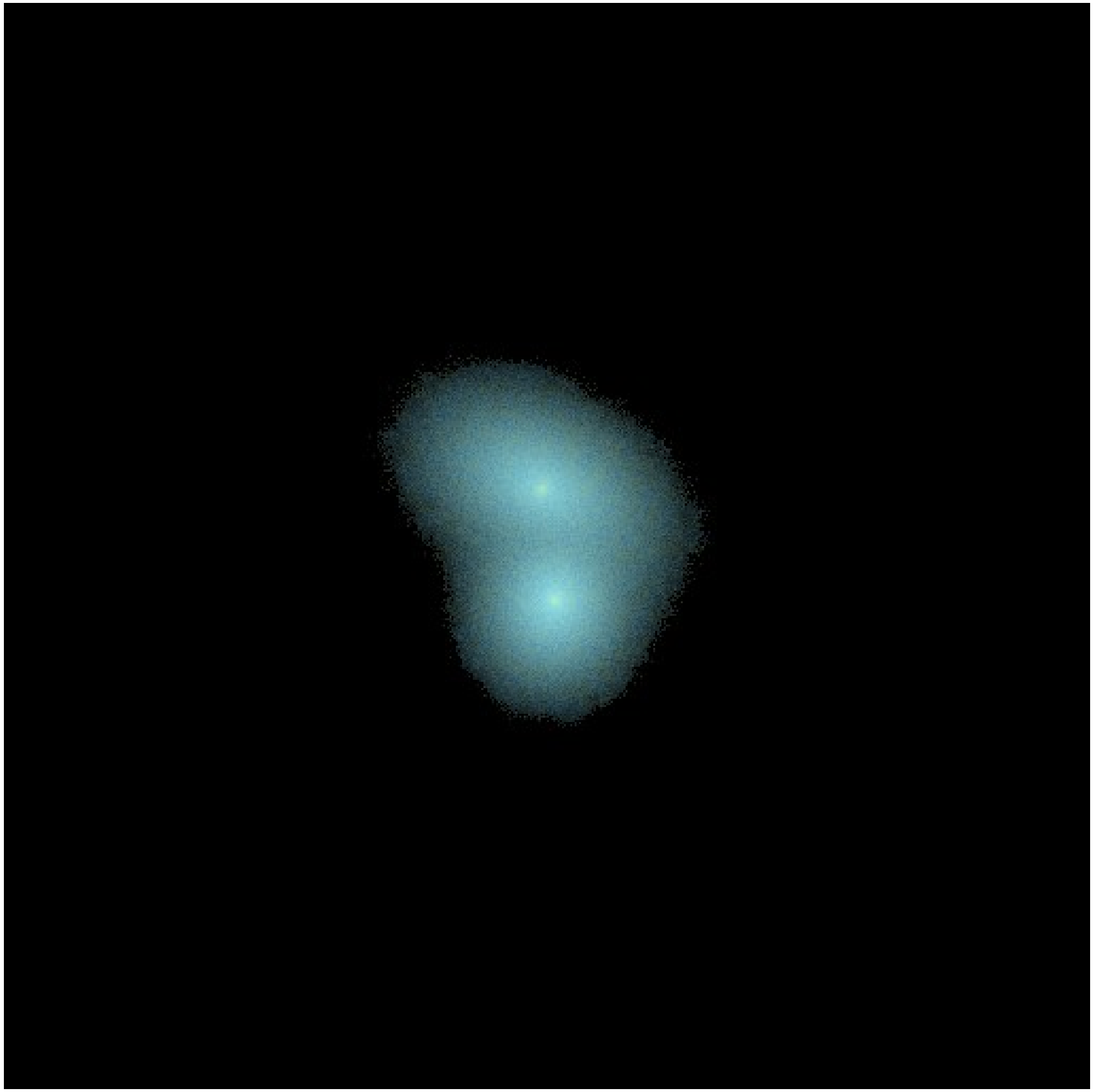


- Mergers are drivers for galaxy evolution at high and low redshift
- Antennae galaxies are the best-studied local major merger system
- ...and are an ideal laboratory to study galaxy properties ISM evolution, and star & cluster formation in galactic mergers

Best match to the central region of the Antennae

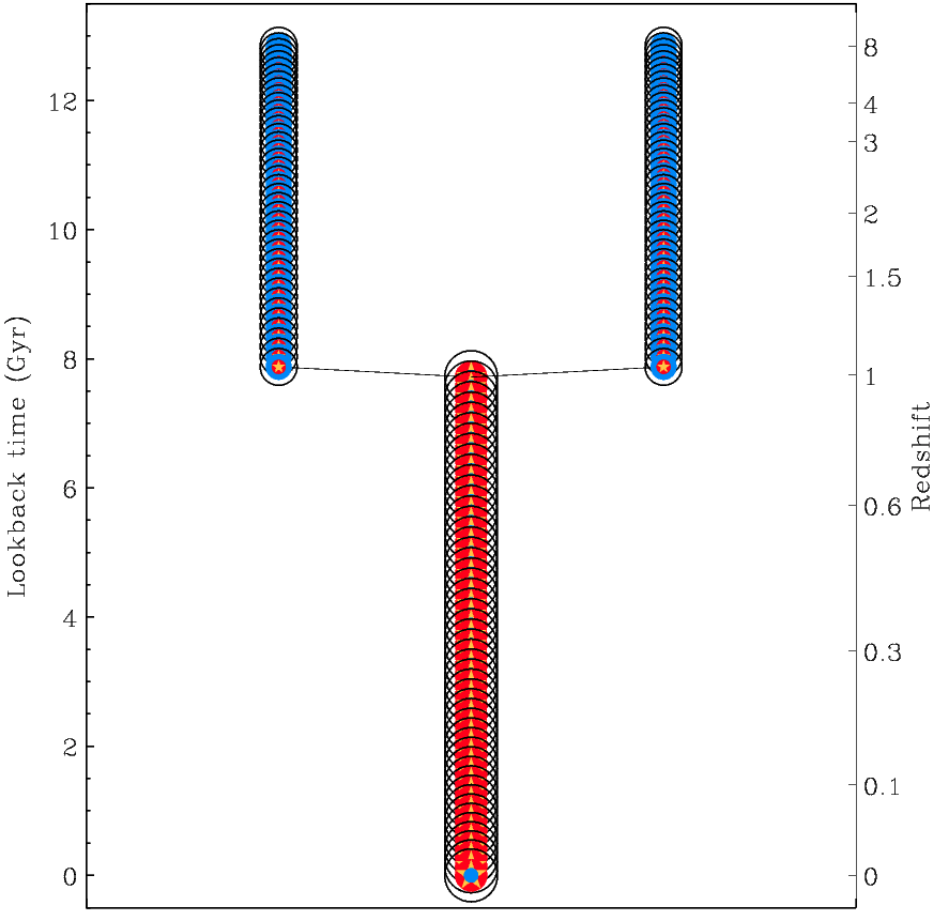


Karl et al. 2010/2011



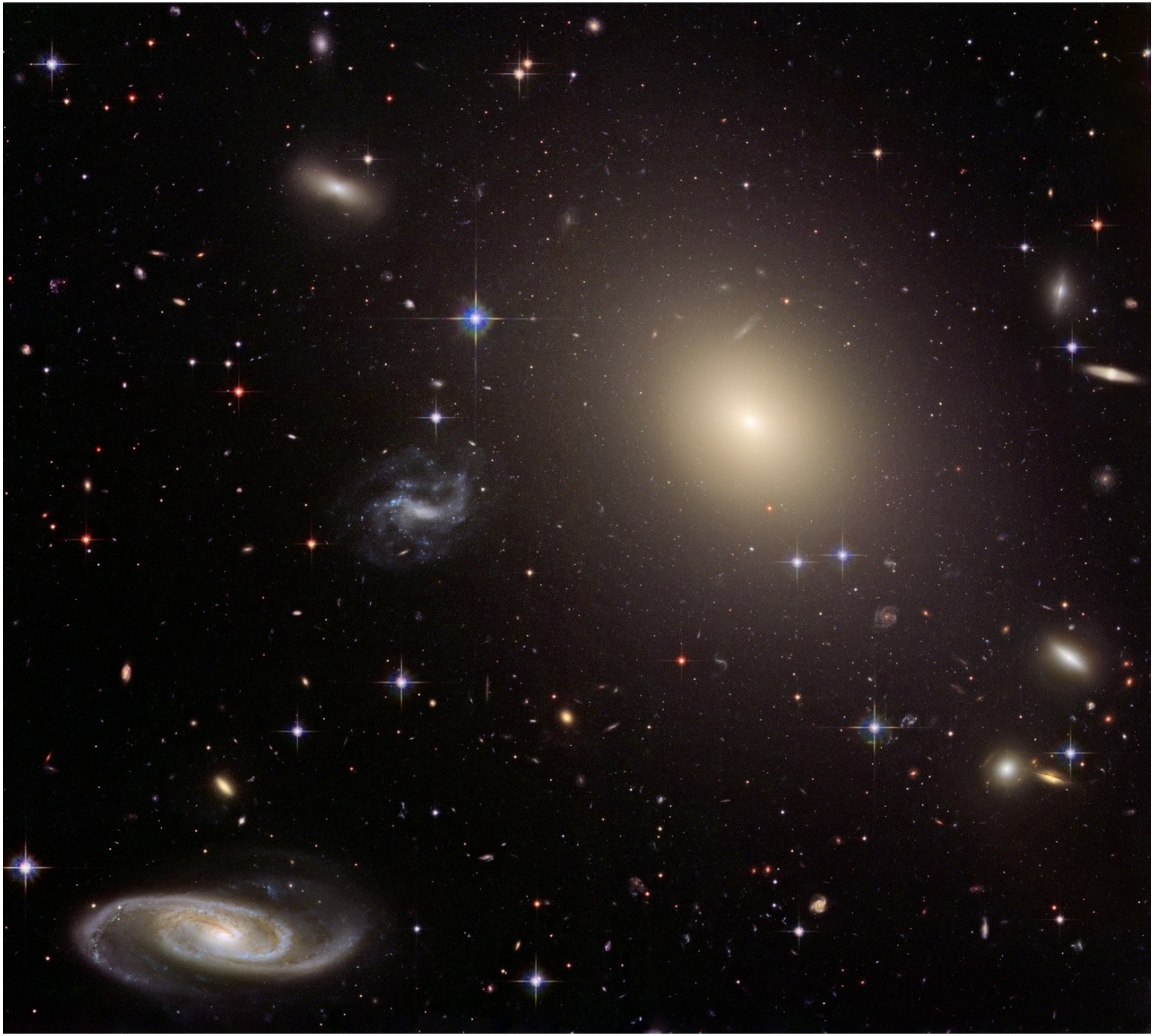
Toomre 1972, Barnes 1988, Mihos et al. 1994, Teyssier et al. 2010

The binary merger-tree



◦Typical contribution of stellar mergers (>1:4) in massive galaxies since z=2 is 100%

The bulk of the stars in present day elliptical galaxies cannot originate from major mergers of present day disk galaxies or major mergers of their progenitors (e.g. Naab & Ostriker 2009, and references therein)



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

Constraints: ‘Observations’ of early-type galaxies

- Ellipticals are the oldest and most massive galaxies in the Universe

- 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)

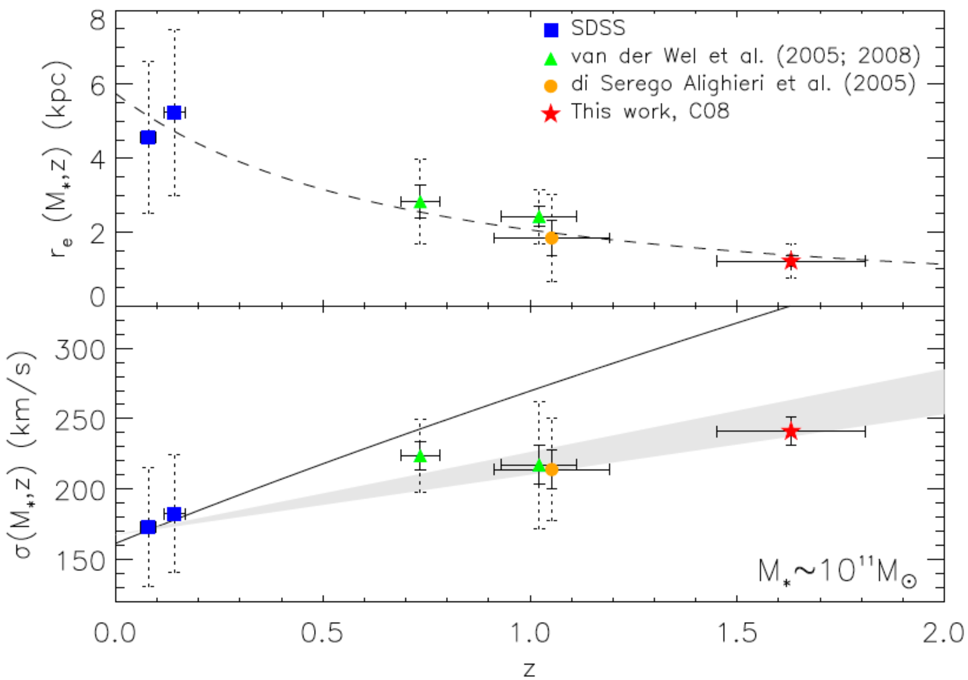
- SIZE MATTERS! Insight into cosmic history of galaxy assembly, opening a window to the Universe when only a few Gyrs old

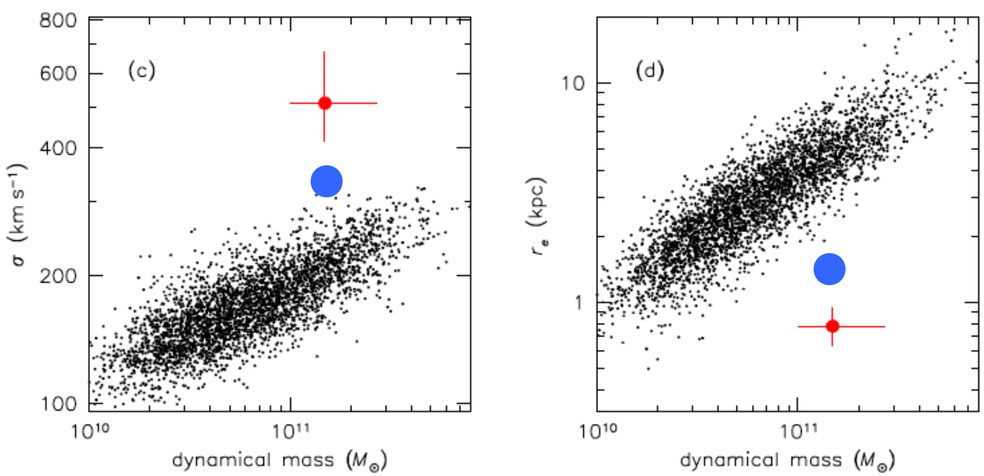
- Hierarchical assembly of elliptical galaxies in CDM cosmologies – assembly time is not formation time (e.g. Kauffmann 1996, de Lucia et al. 2006)

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

- 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)

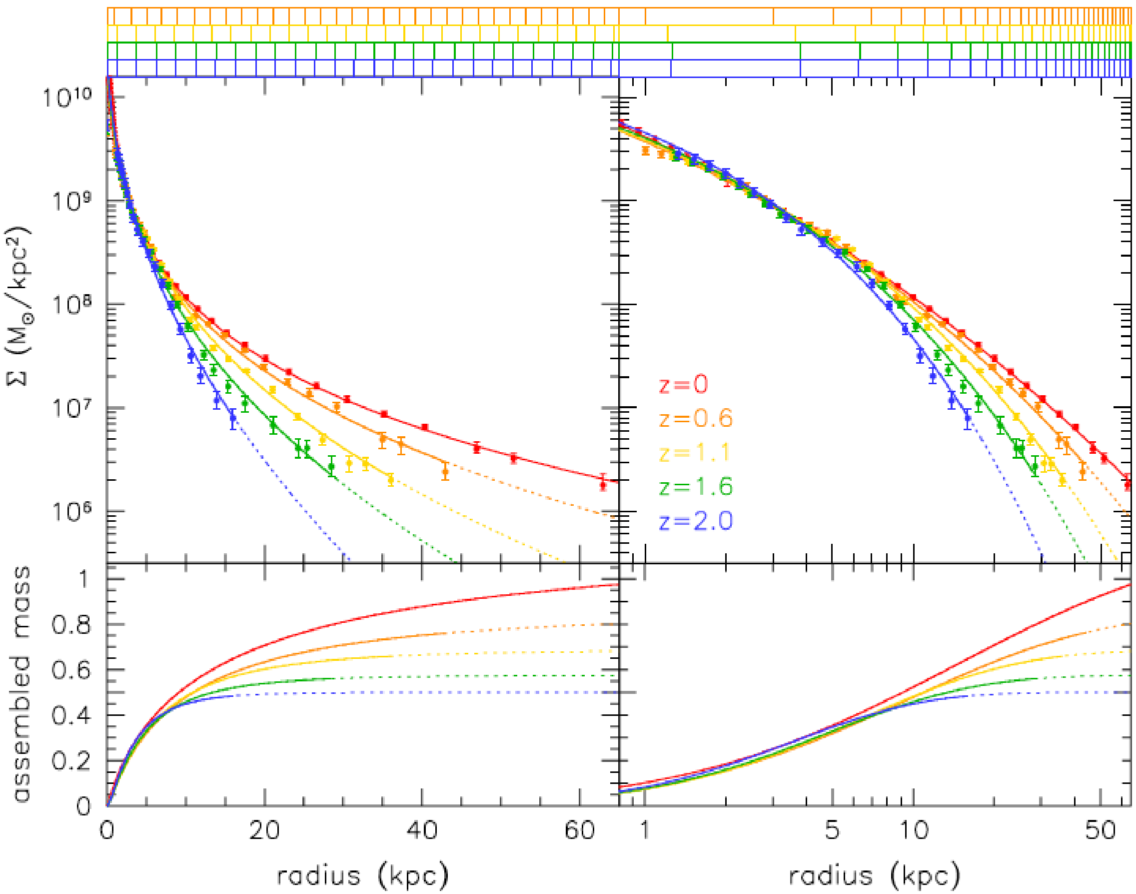
Size and dispersion evolution since z≈2





- 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 (van Dokkum et al. 2009, van de Sande et al. 2011)
- Add large galaxies to the population: faded spirals?
- Grow the population by major/minor mergers, expansion and other effects (e.g. Fan et al.)? Minor mergers are favored (Bezanzon et al. 2009, Hopkins et al. 09/10, Naab et al. 2009, Oser et al. 2010/2011)

Inside-out growth since z = 2



- Stacks of 70-80 galaxies at different redshifts
- Inside-out growth of ellipticals since z=2
- Mass increase by a factor of ~ 2
- Size increase by a factor of ~ 4
- r ~ Mα , α 2
- Mass increase dominated by stellar accretion – energy conserving process

van Dokkum et al. 2010

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

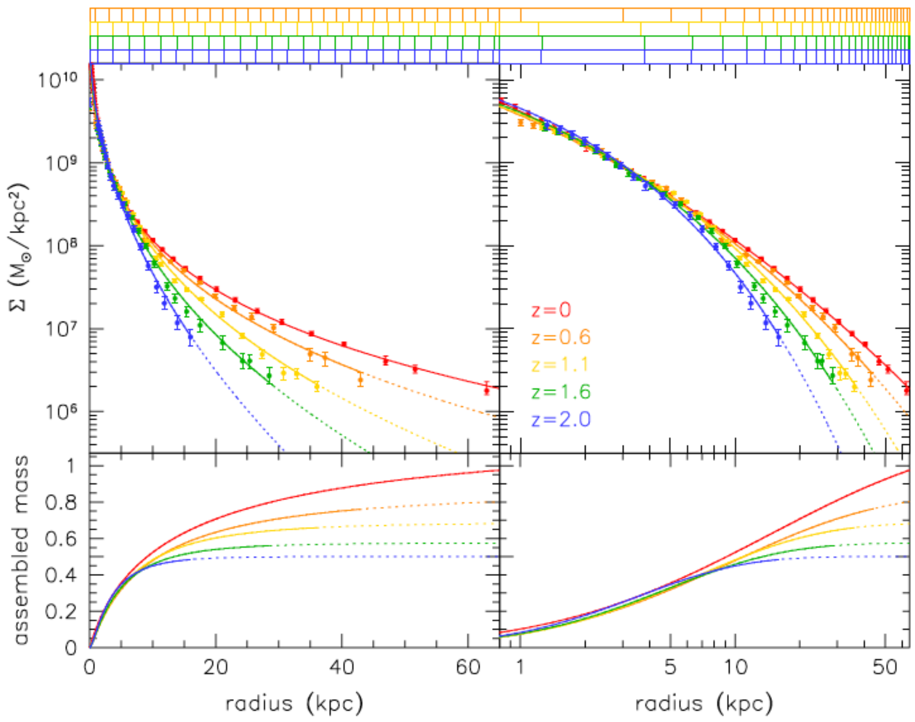
$$\frac{\rho_f}{\rho_i} = \frac{(1+\eta\epsilon)^3}{(1+\eta)^5}$$

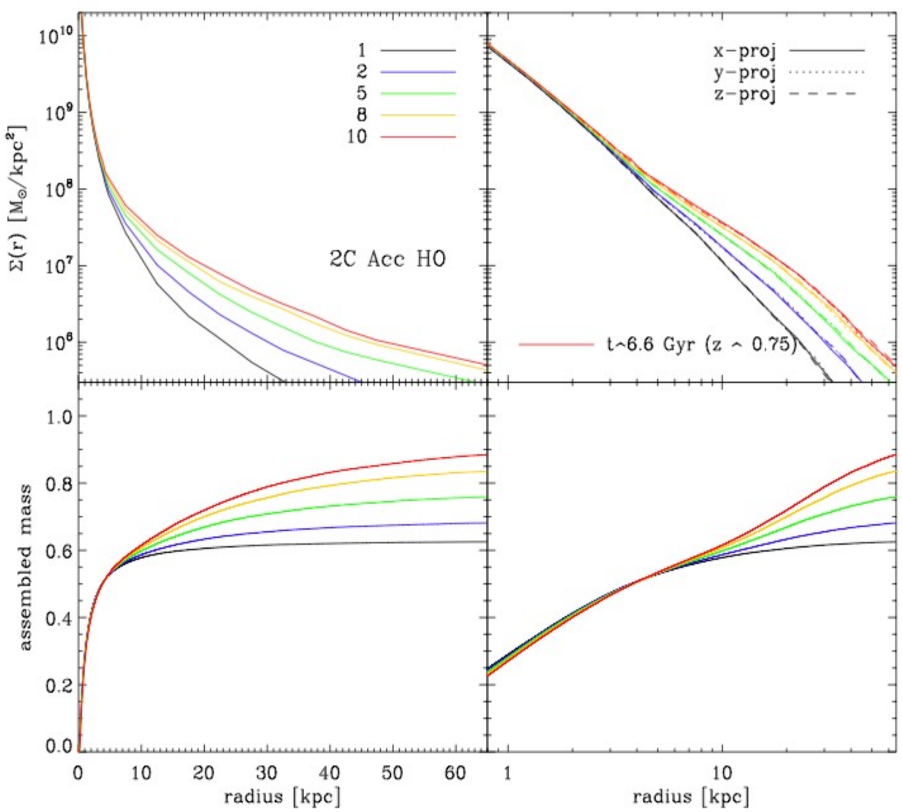
Density can decrease by factor 32

r ~ M^α , $\alpha = 1$ for major mergers , $\alpha = 2$ for minor mergers
more complex: gas, dark matter, dynamics, cosmology

e.g. Cole et al. 2000; Naab, Johansson & Ostriker 2009; Bezanson et al. 2009

Inside-out growth since z = 2

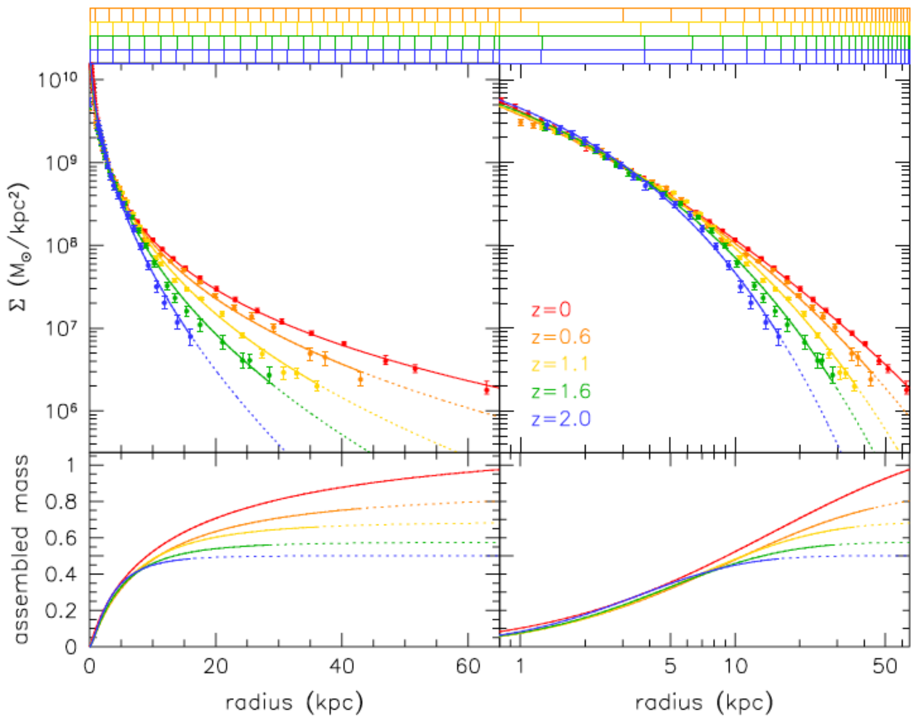


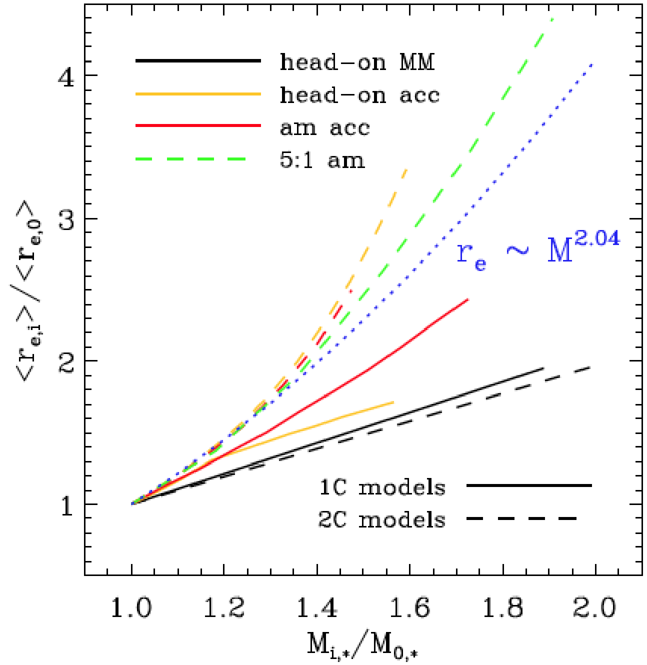


- Isolated 1:1 (mm) and 10:1 (acc) mergers of spheroidal galaxies without (1C) and with (2C) dark matter
- Only minor mergers with dark matter result in inside-out growth

Hilz et al. 2011, in prep.

Inside-out growth since z = 2

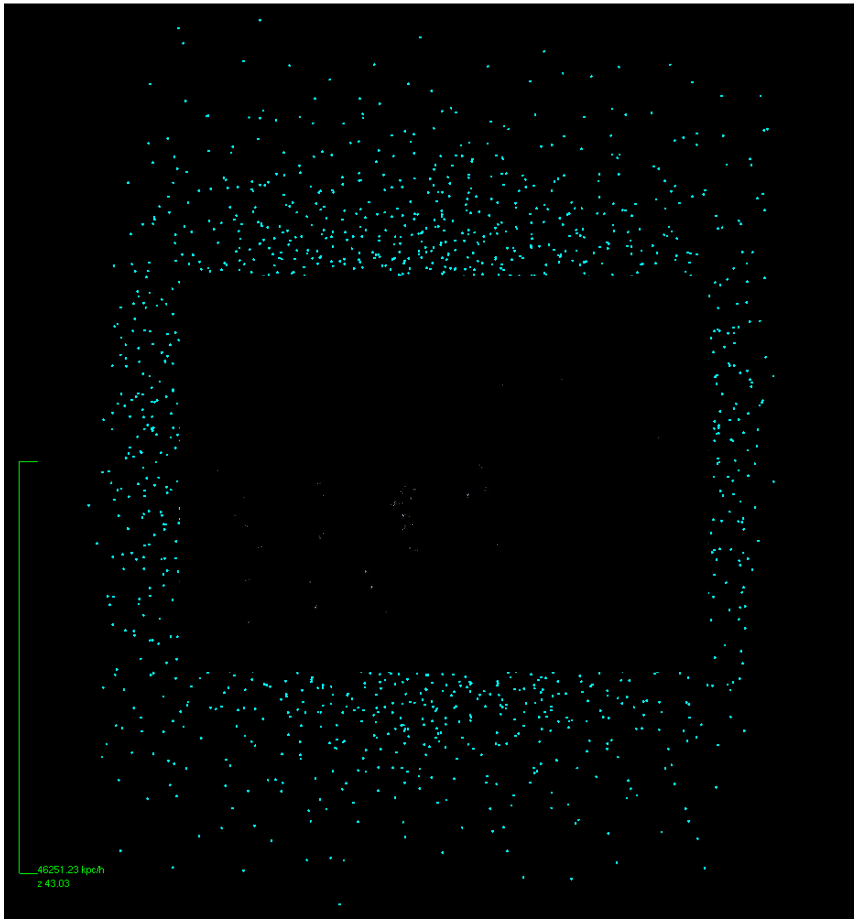




- Isolated 1:1 (mm), 5:1, and 10:1 (acc) mergers of spheroidal galaxies without (1C) and with (2C) dark matter
- Only minor mergers with dark matter result in inside-out growth

Hilz et al. 2011, in prep.

The tool: re-simulations



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

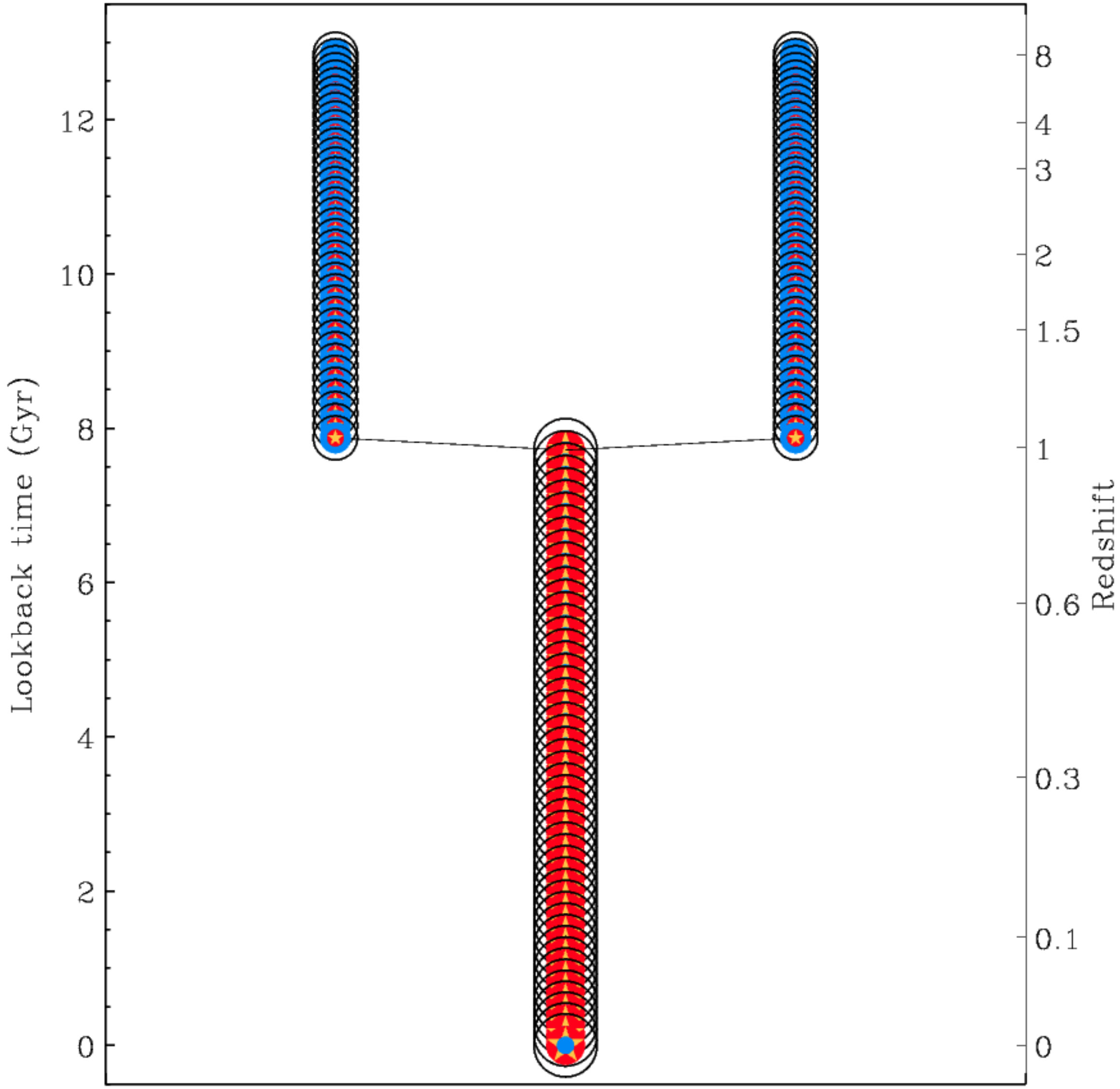
Re-simulation of a large number of individual halos from 1010-1013 (Mgas: 106, 105, 104) without gas, with star formation & evtl. feedback (Springel & Hernquist 2003)

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 (Hirschman et al. 2011, Oser et al. 2011) also for detailed comparison with semi-analytical predictions

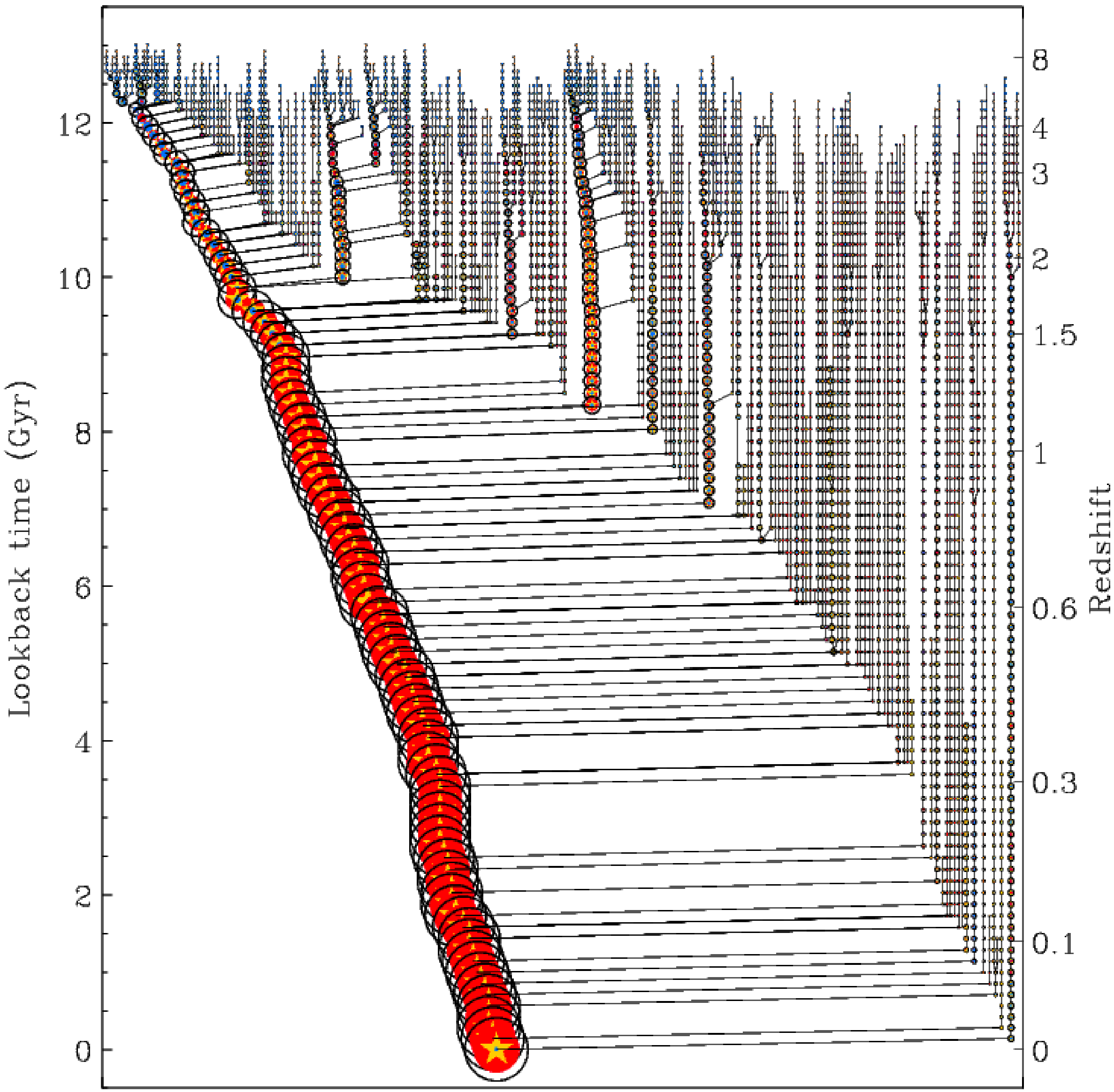
≈45 halos simulated so far and used for analysis presented here

The binary merger-tree



- Typical contribution of stellar mergers (>1:4) in massive galaxies since z=2 is 100%

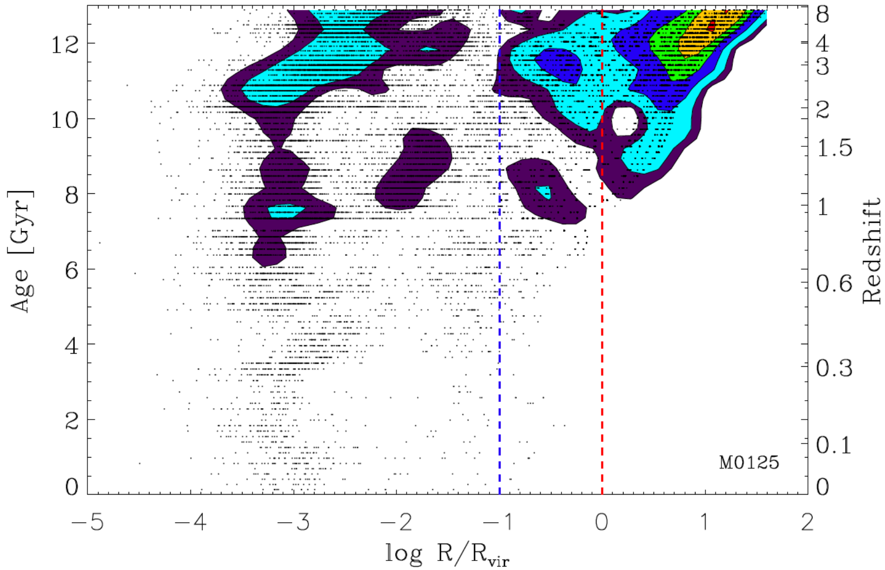
The complex assembly histories

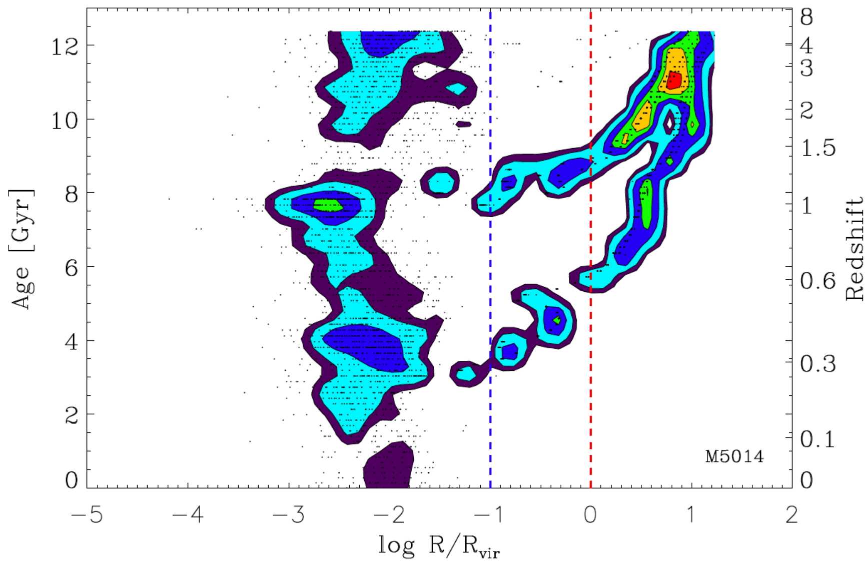


- Typical contribution of mergers (> 1:4) in massive galaxies since z=2 is 30% - 40%
- Extract dark matter and galaxy merger histories for zoom-simulations

Hirschmann et al. 2011, astro-ph

The origin of stars in galaxies





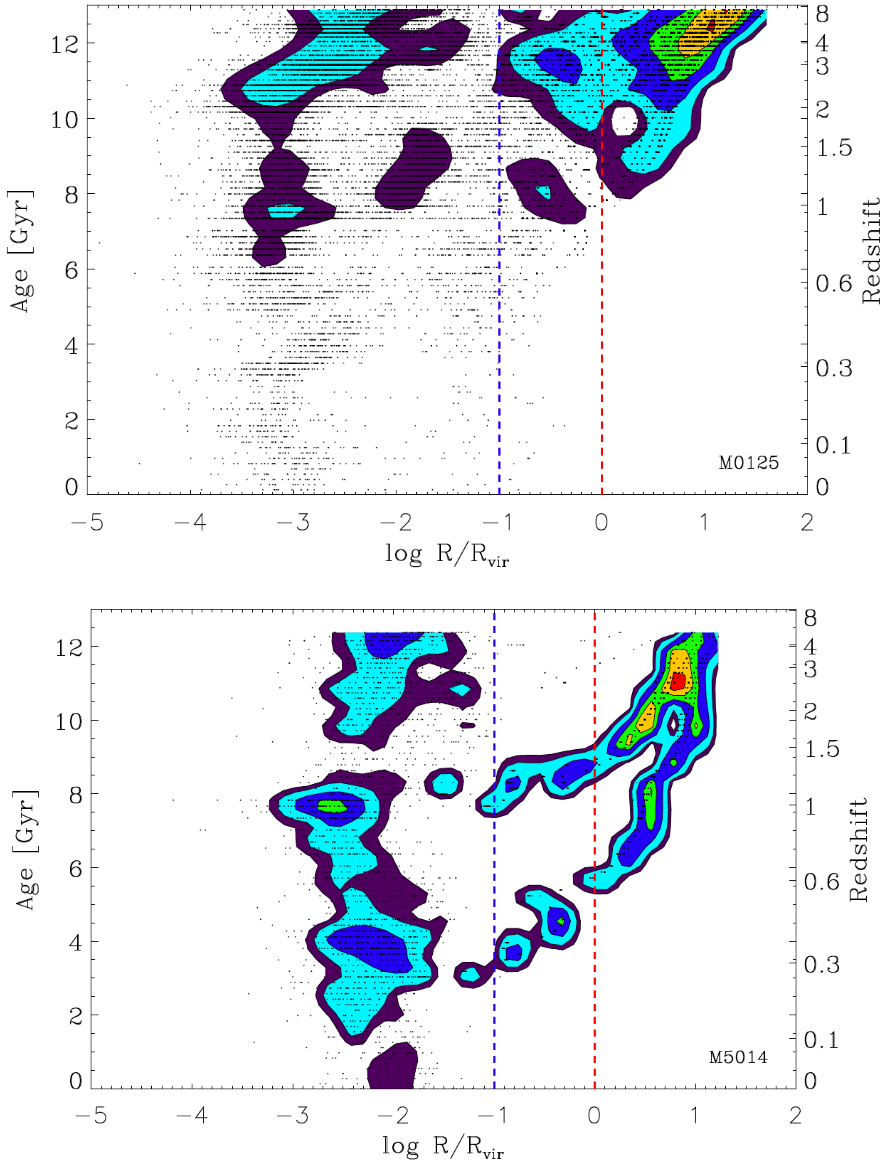
- Stellar origin diagrams indicate when and at which radius a star ending up in a present day galaxy was born

- 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

The origin of stars in galaxies

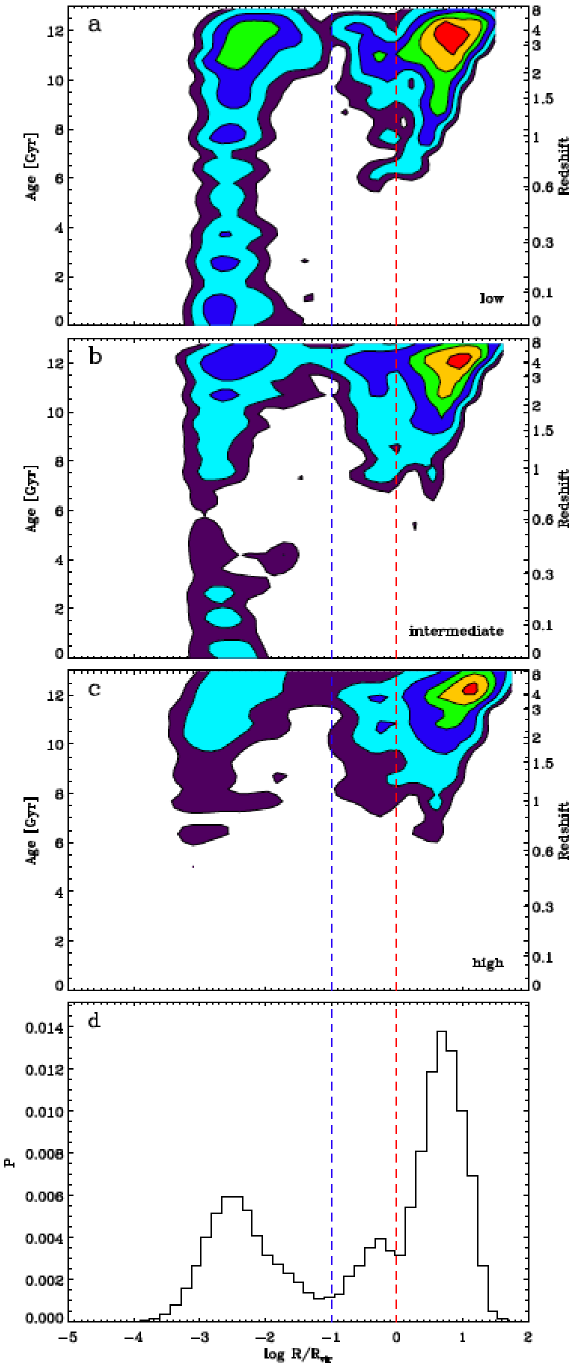


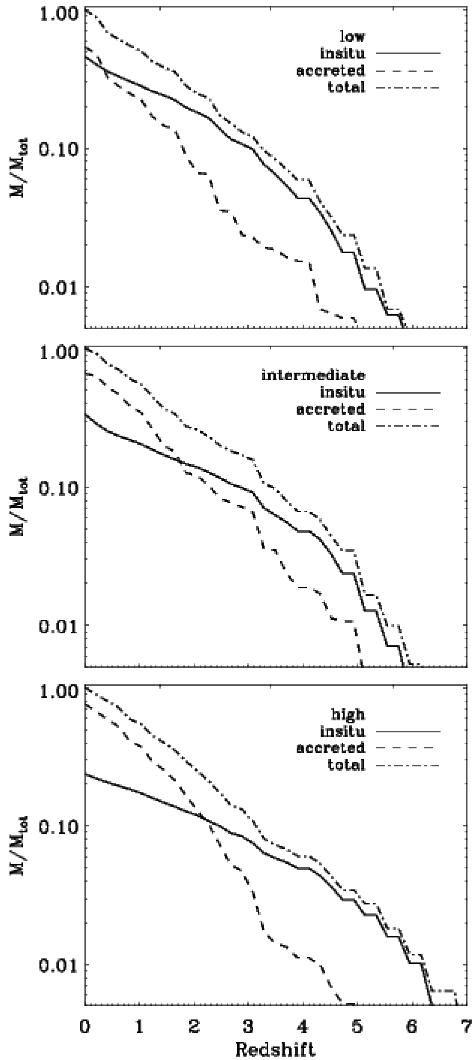
◦Stellar origin diagrams indicate when and at which radius a star ending up in a present day galaxy was born

◦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



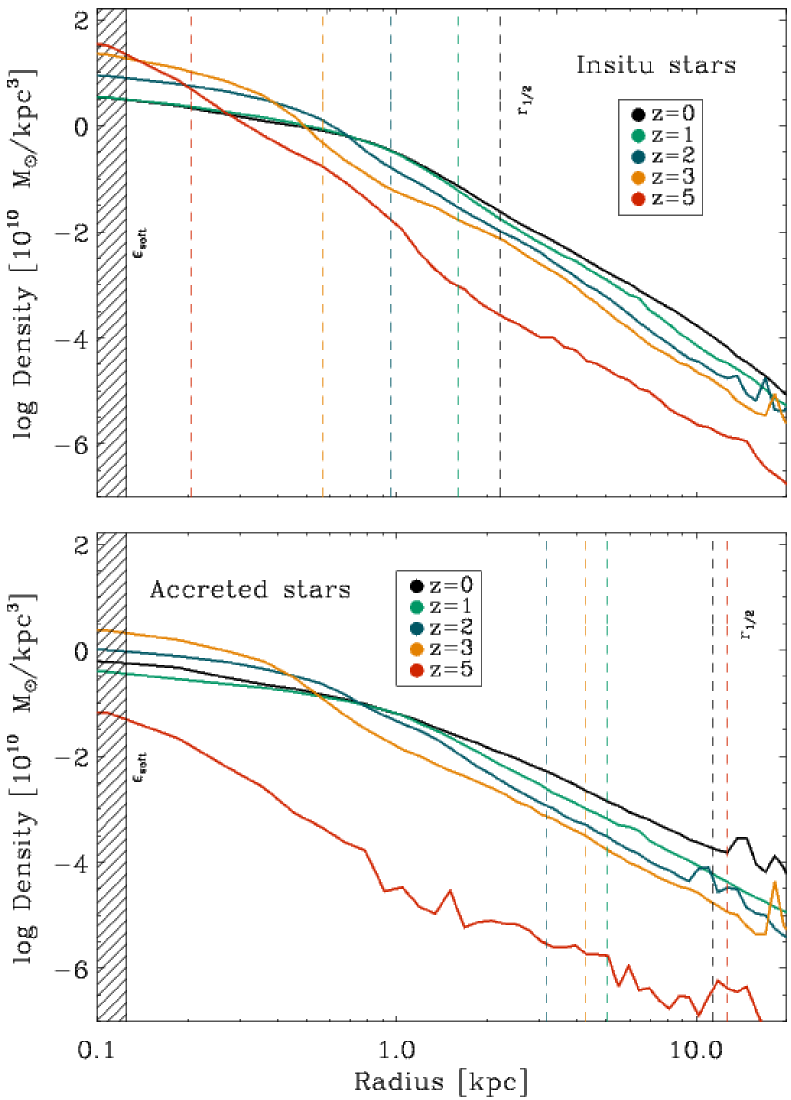


- Simulated galaxies stacked in mass bins
- Early assembly is dominated by in-situ formation, more so in massive galaxies (6 > z > 3)
- Low mass galaxies assemble half their mass by in-situ formation
- The late assembly of massive galaxies is dominated by accretion (up to 80%) of stellar system (3 >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

The two phases of galaxy formation

Oser et al. 2010, see also Feldmann et al. 2010/2011

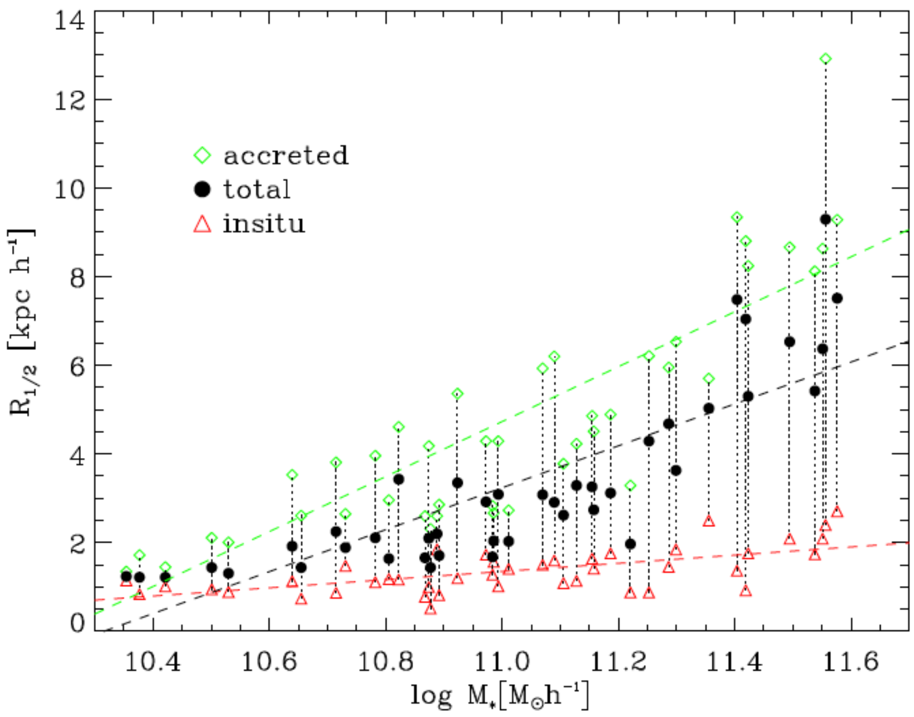
Size evolution in a high resolution simulation

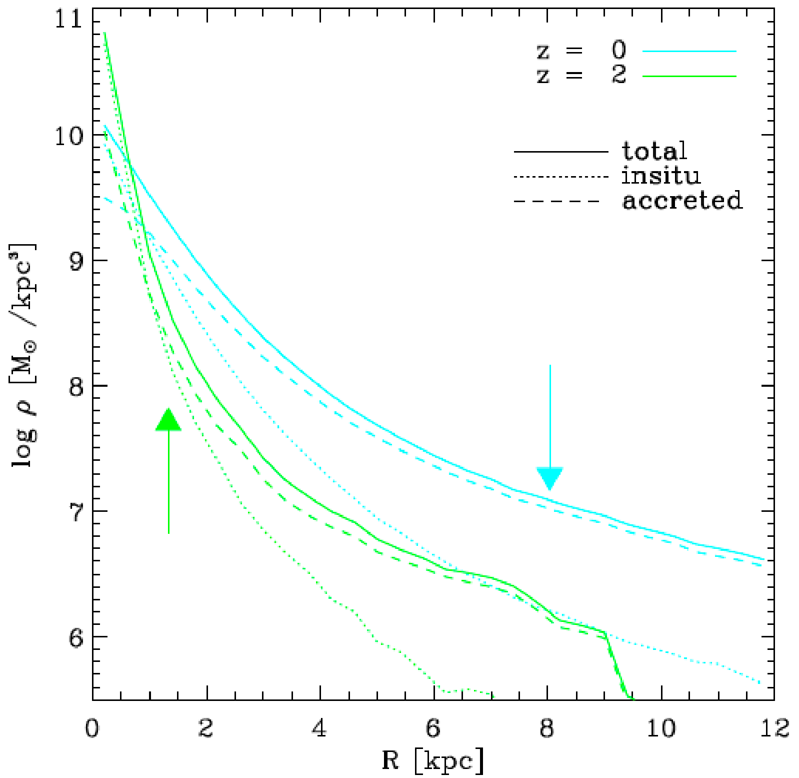


Naab, Johansson & Ostriker 2007/2009

- 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*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

… and some consequences

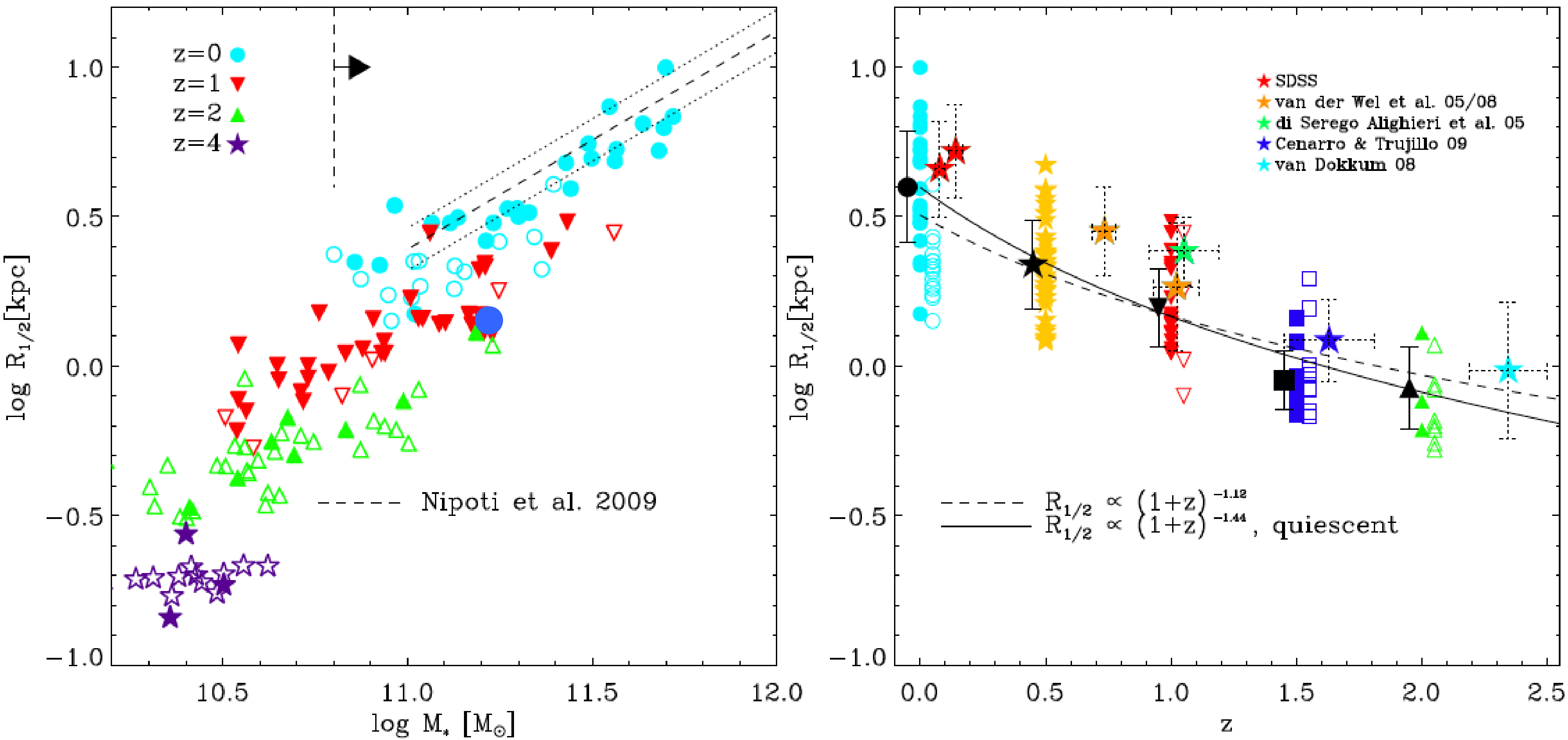




- More massive galaxies had more accretion
- In-situ stars are the core and accreted stars build the outer envelope
- Mass-size relation is driven by accretion

Oser et al. 2010/2011

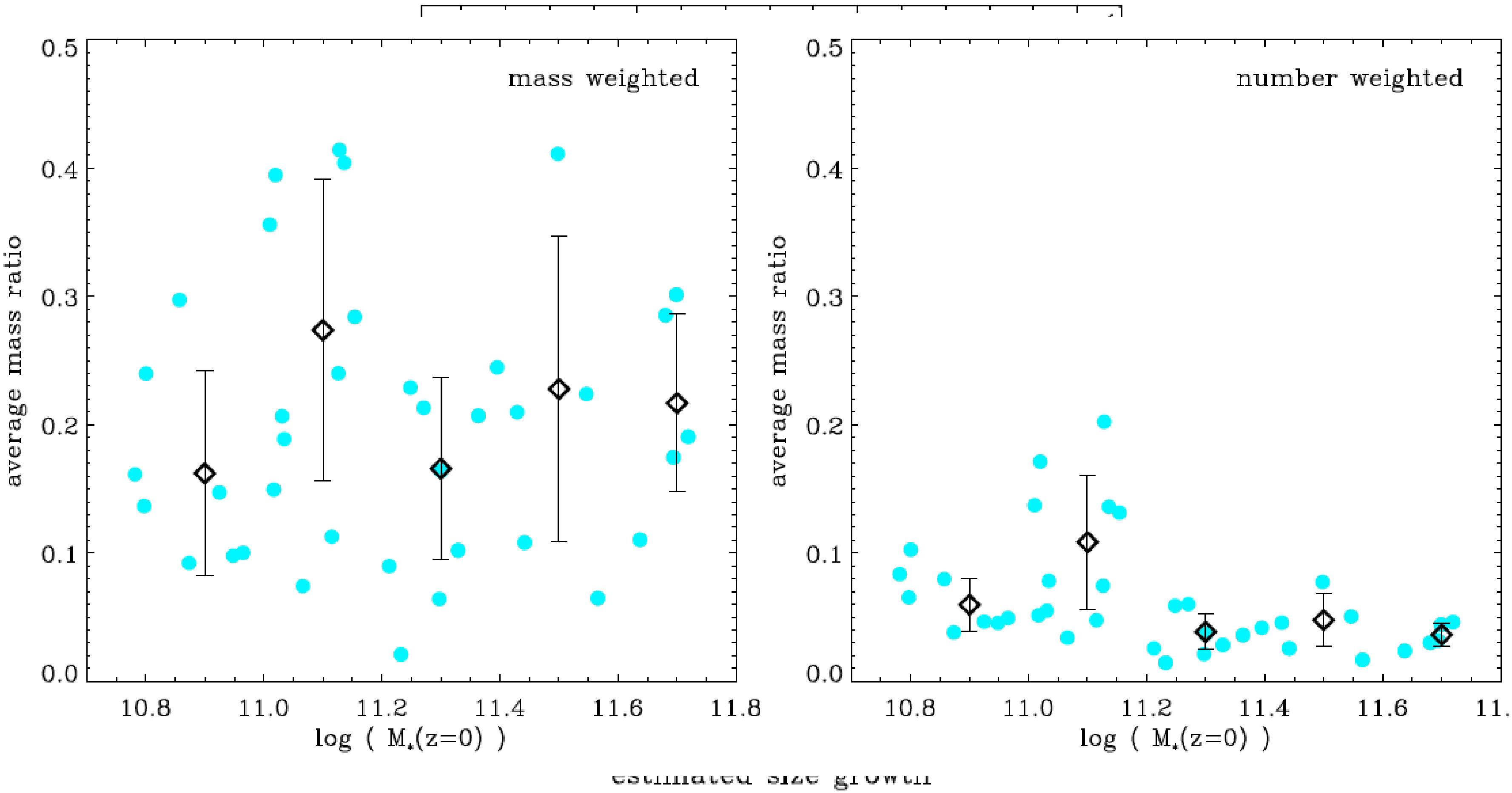
The rapid size evolution of spheroids



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)

Oser et al. 2011, submitted

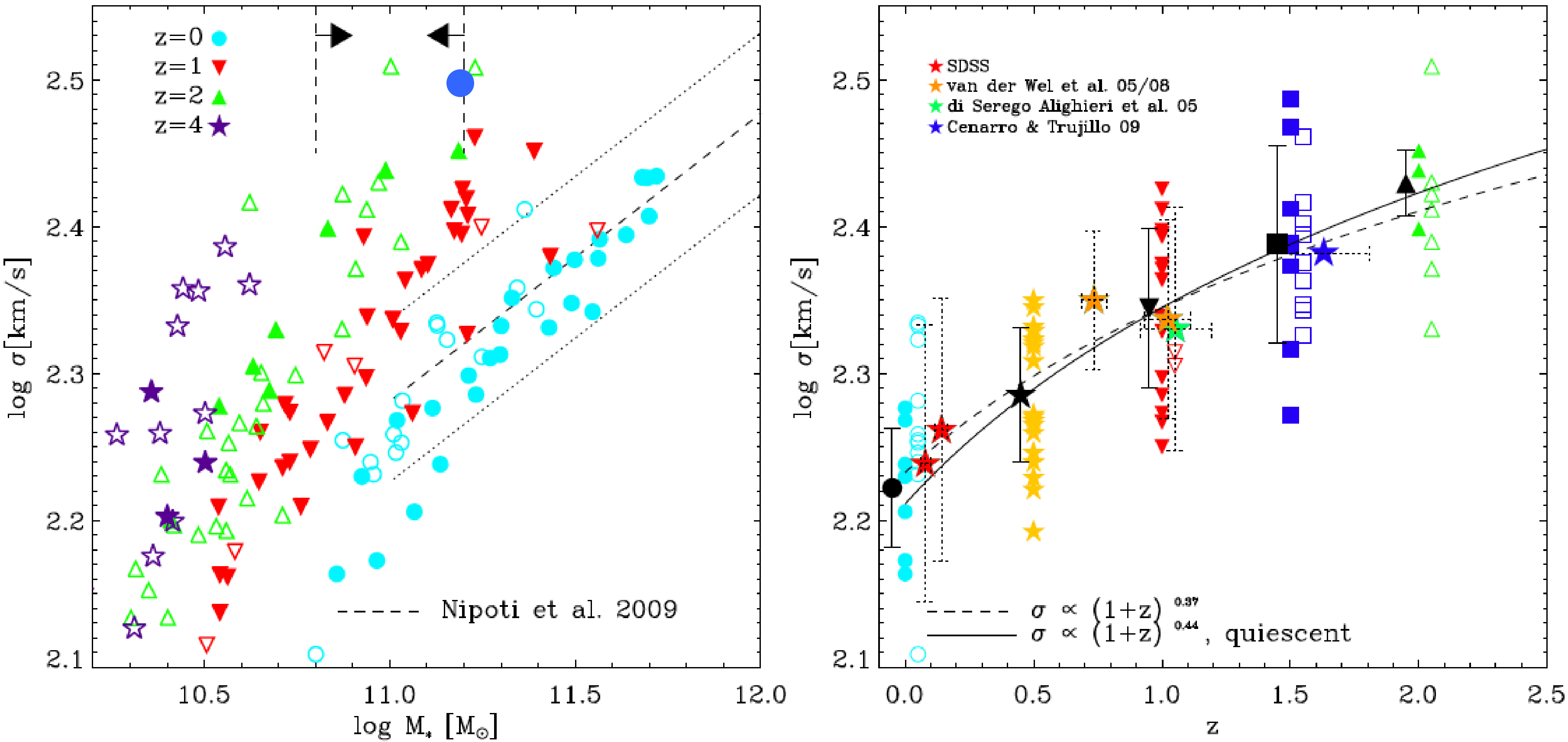
Size evolution and merger history



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

Oser et al. 2011, astro-ph

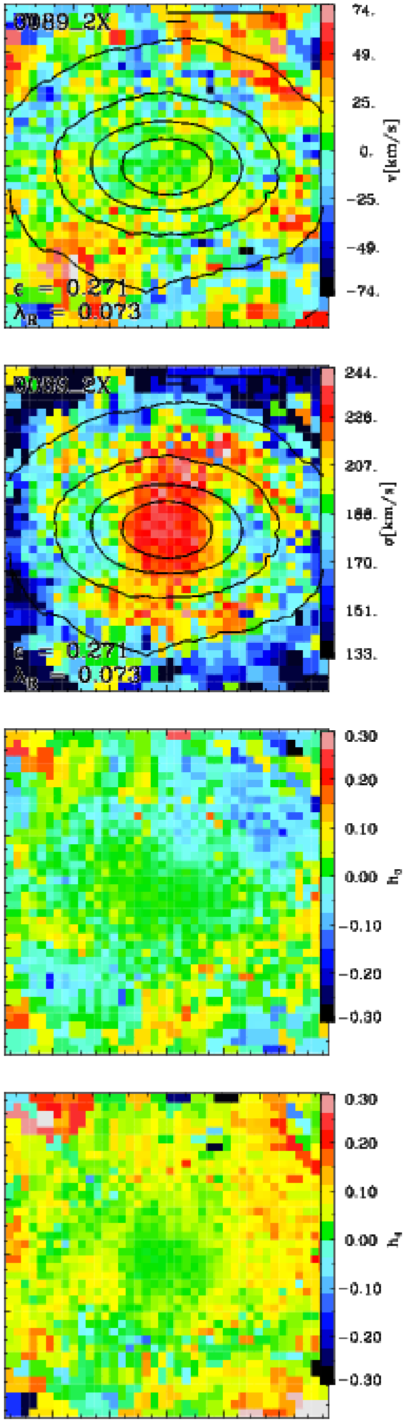
The dispersion evolution of spheroids

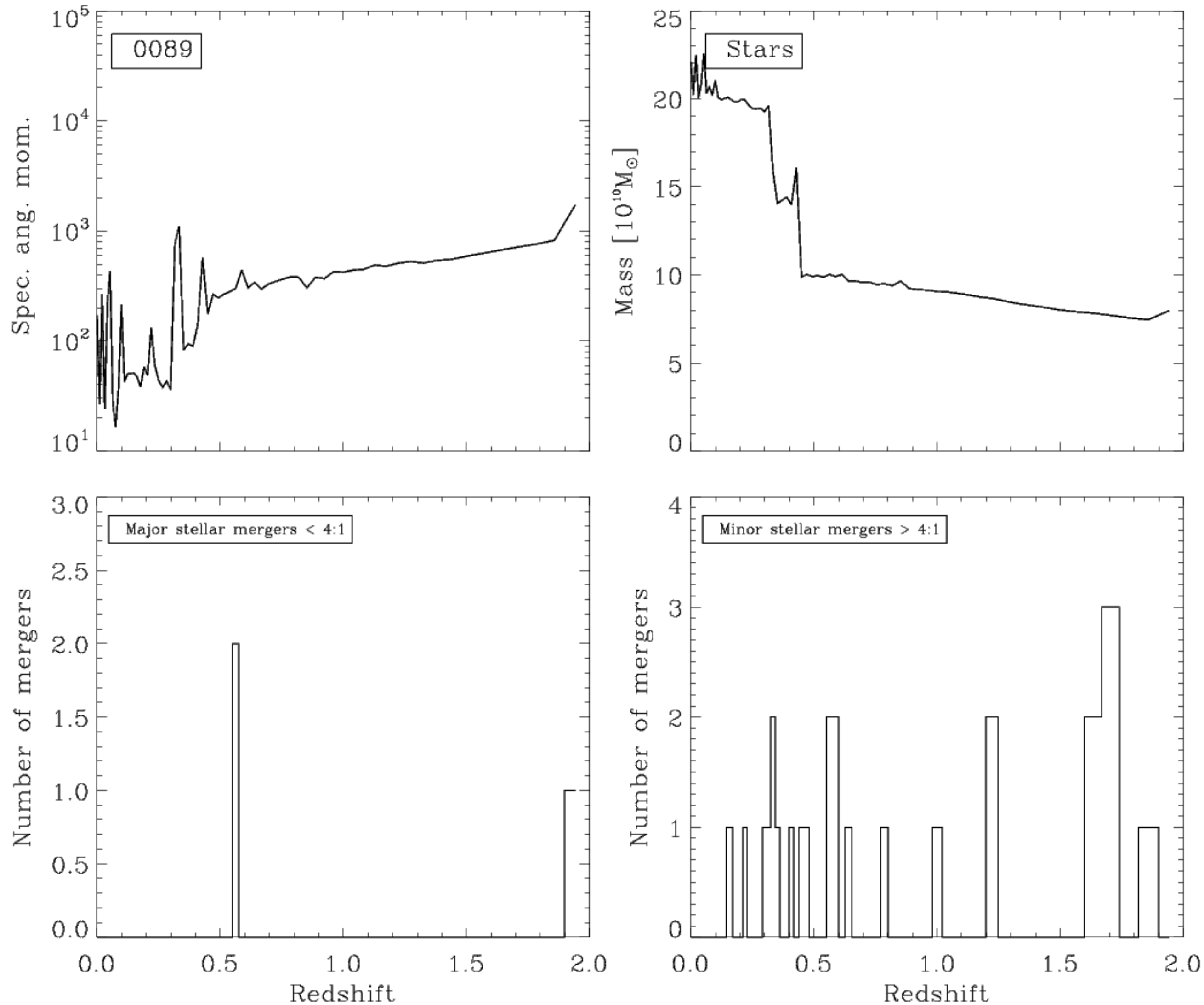


Galaxies at higher redshift have higher velocity dispersions but move onto the local correlations – detailed merger analysis is ongoing

Oser et al. 2011, astro-ph

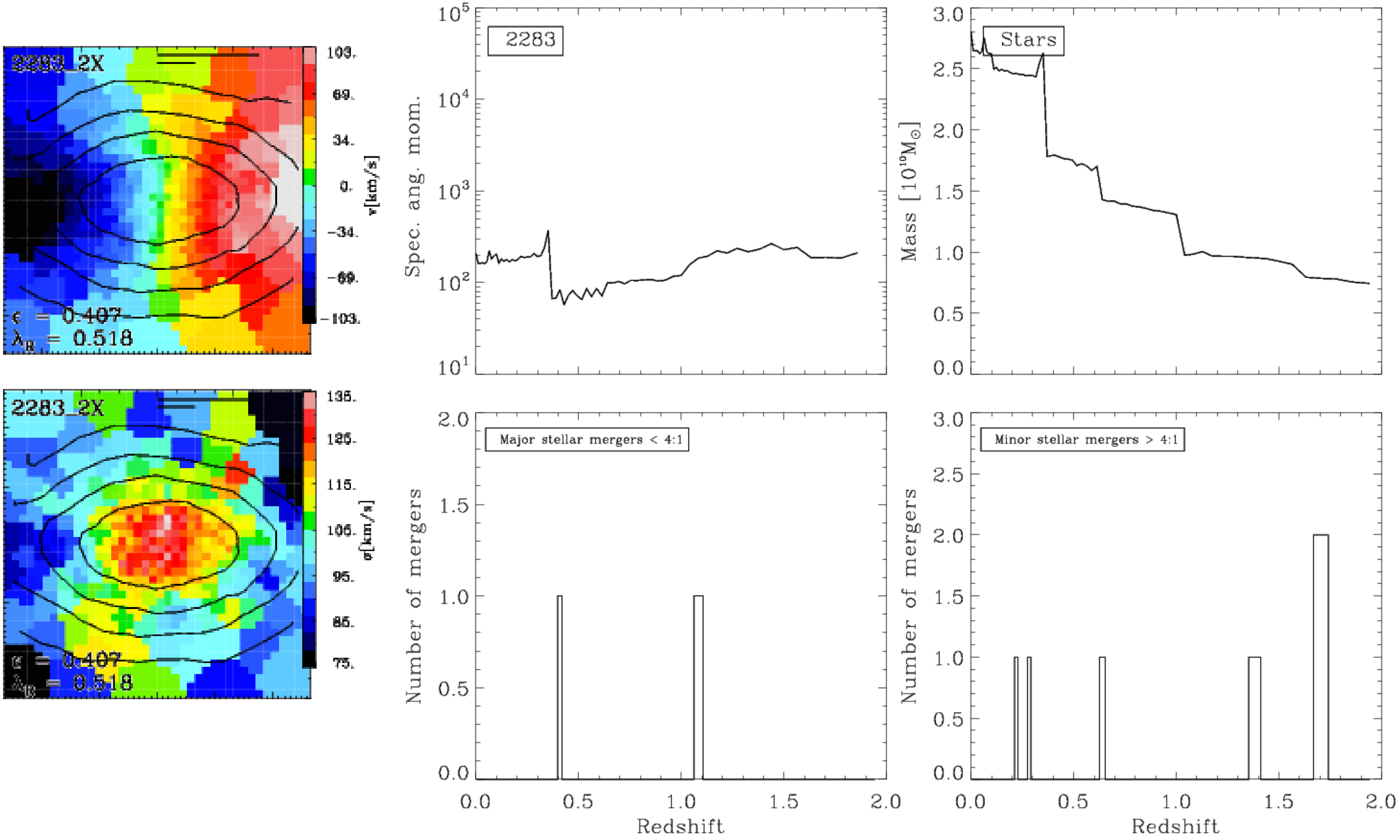
Stellar merger history and angular momentum



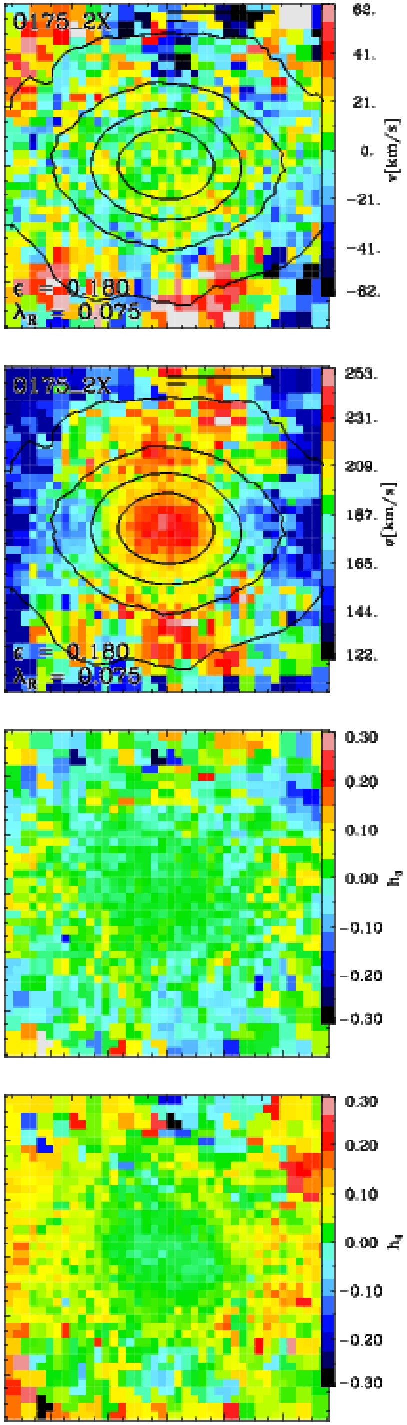


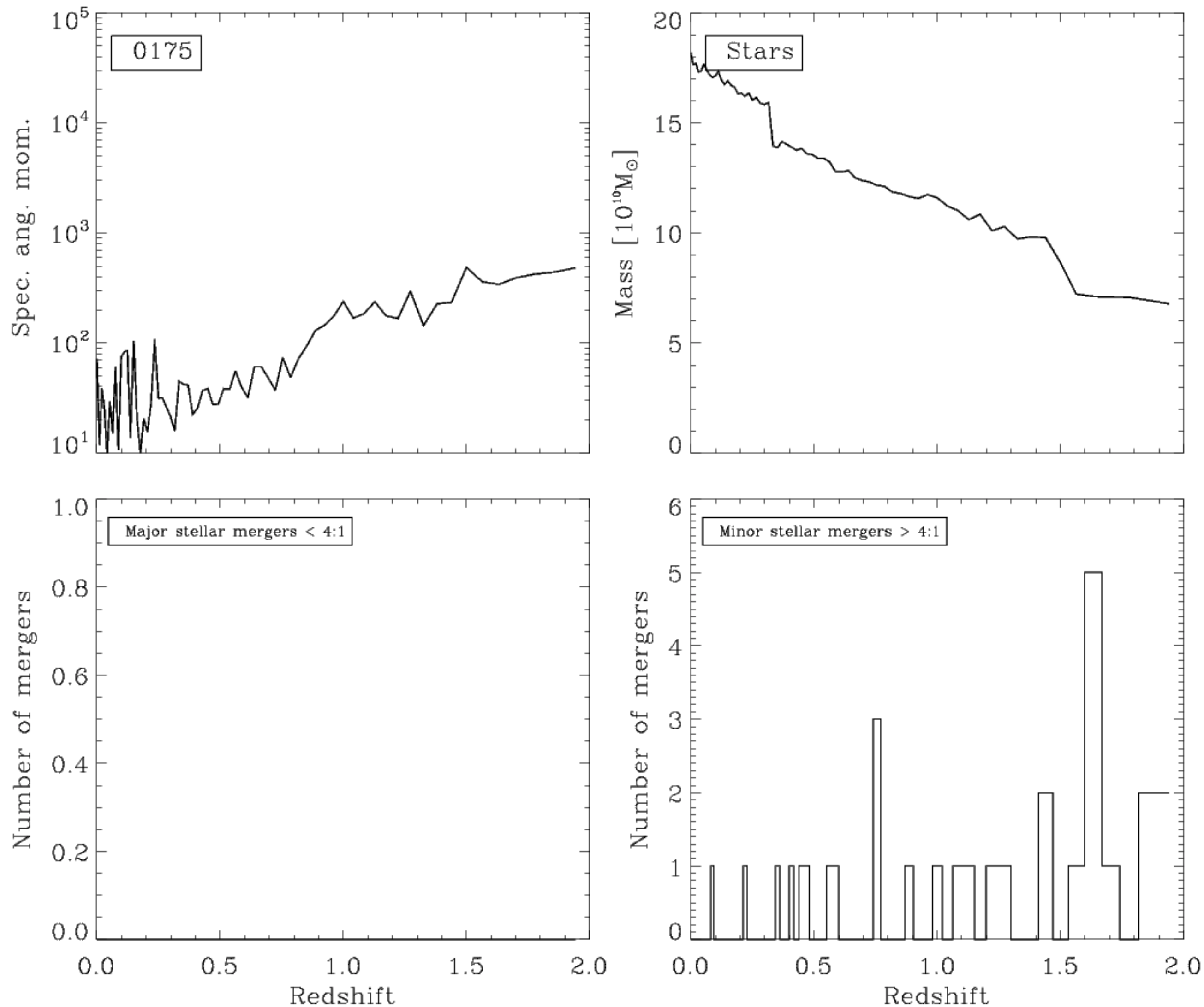
This is in collaboration with the ATLAS3D team!

Stellar merger history and angular momentum

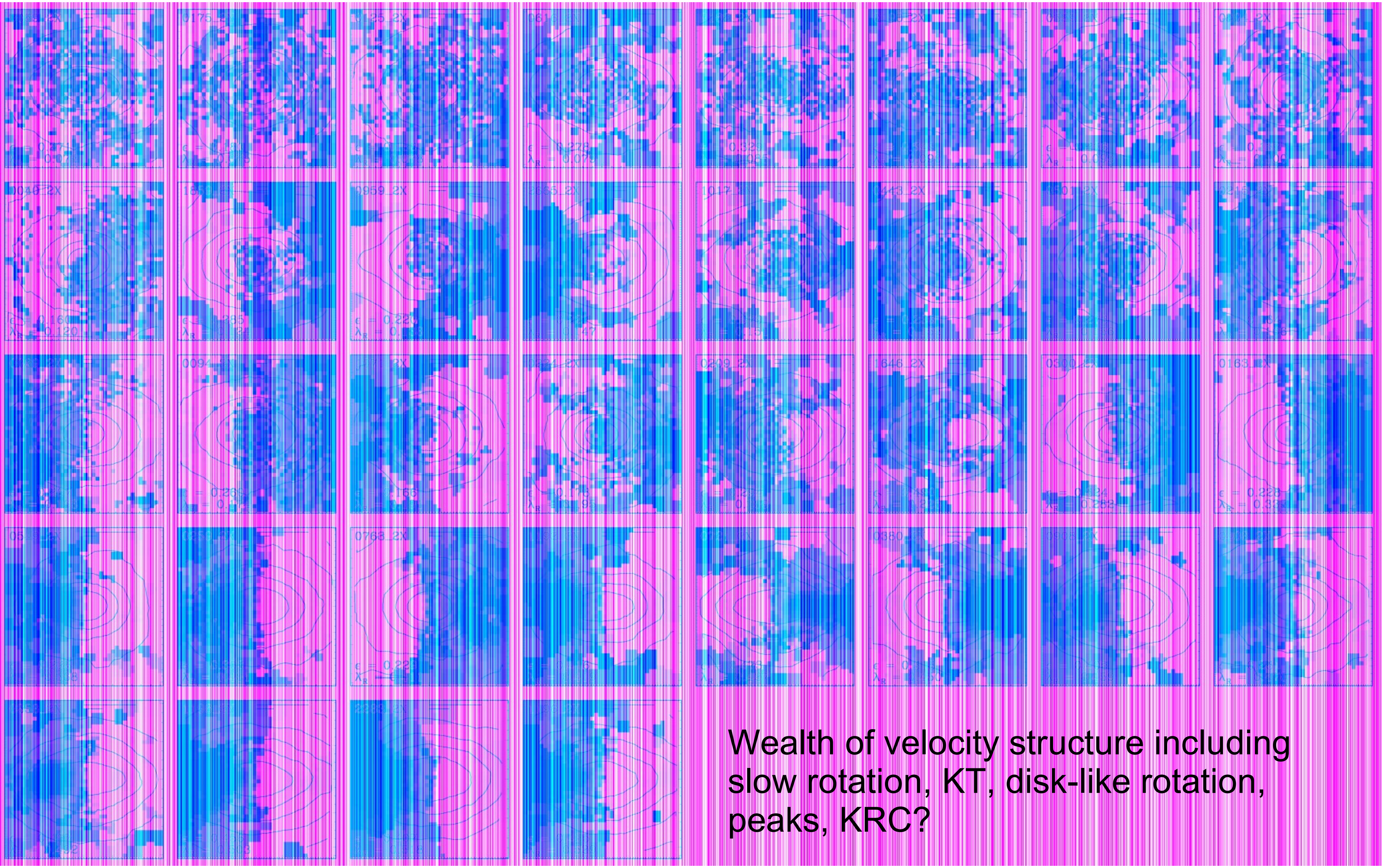


Stellar merger history and angular momentum



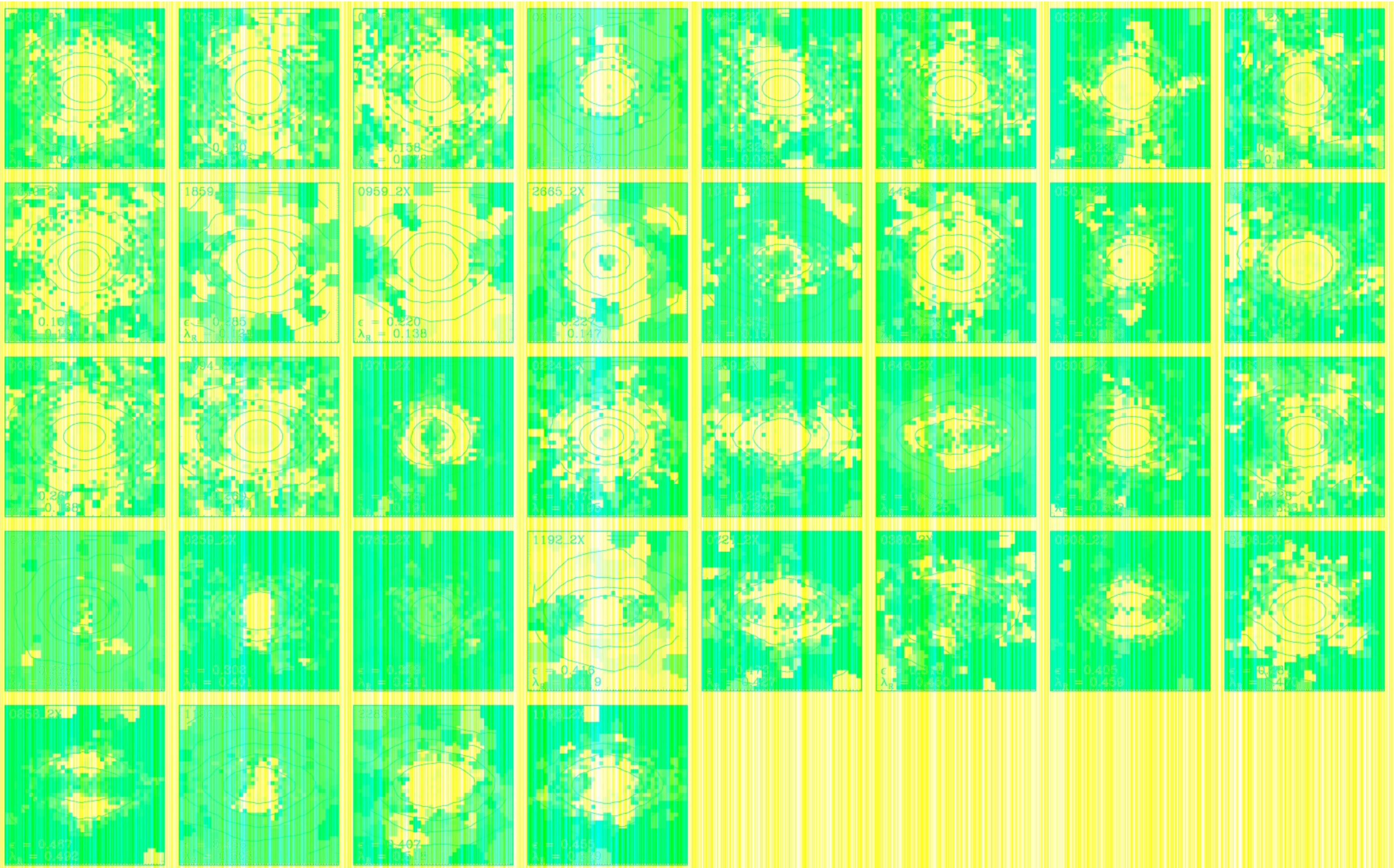


Gallery of cosmological-simulations

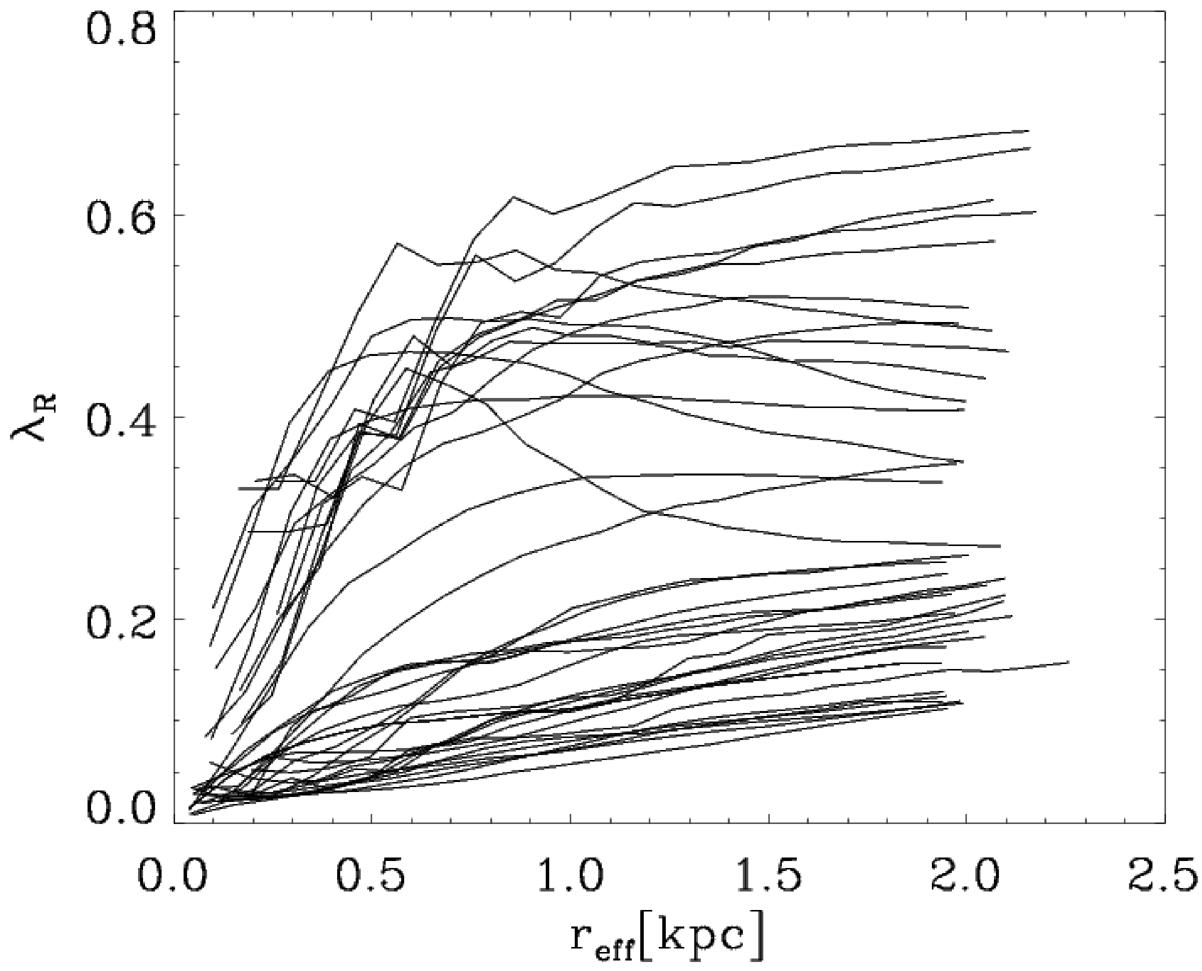


Wealth of velocity structure including slow rotation, KT, disk-like rotation, peaks, KRC?

Gallery of cosmological-simulations

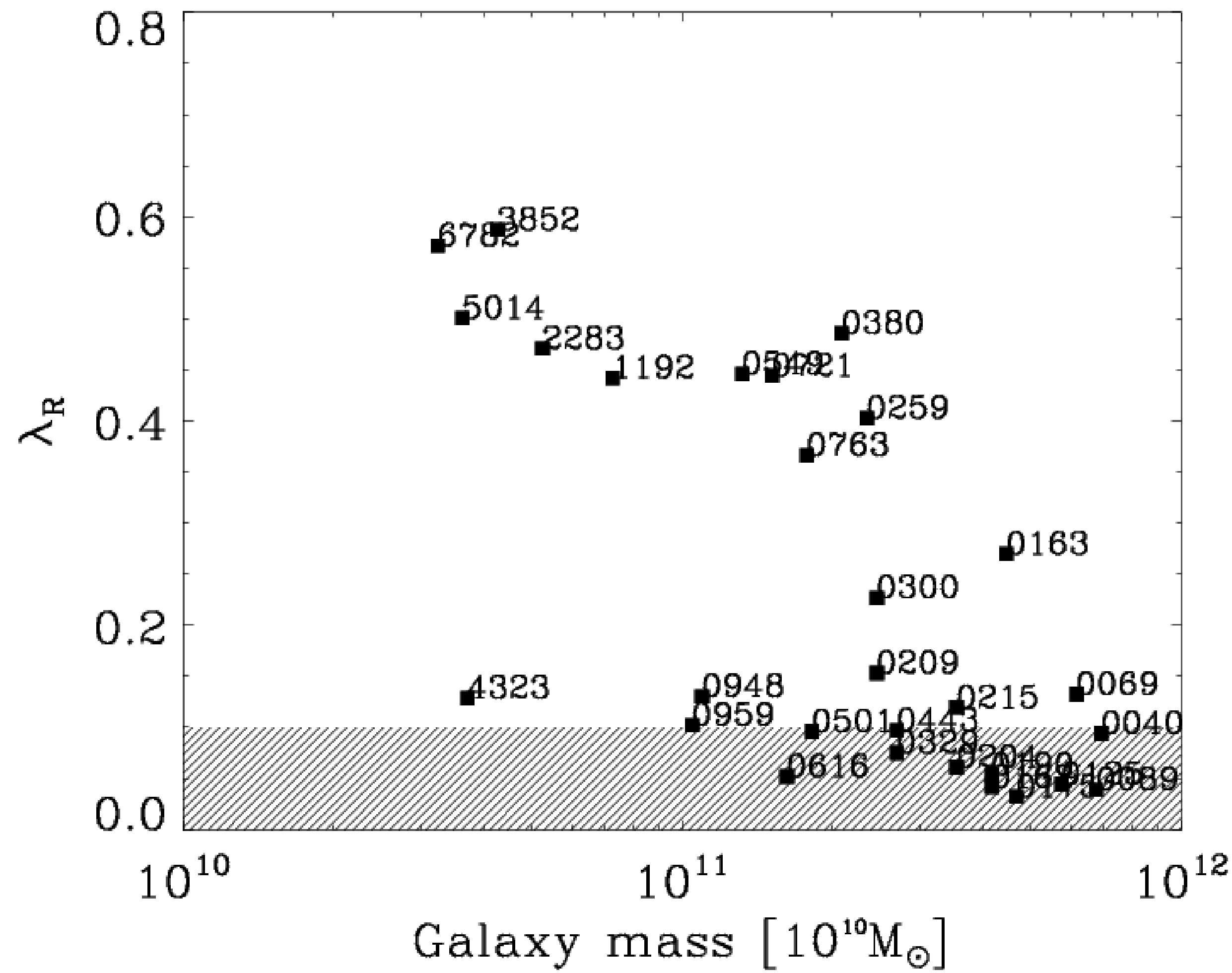


Profiles



ü Profiles are in qualitative and quantitative agreement with observations

Correlations with λR



üMore massive systems are slower rotators

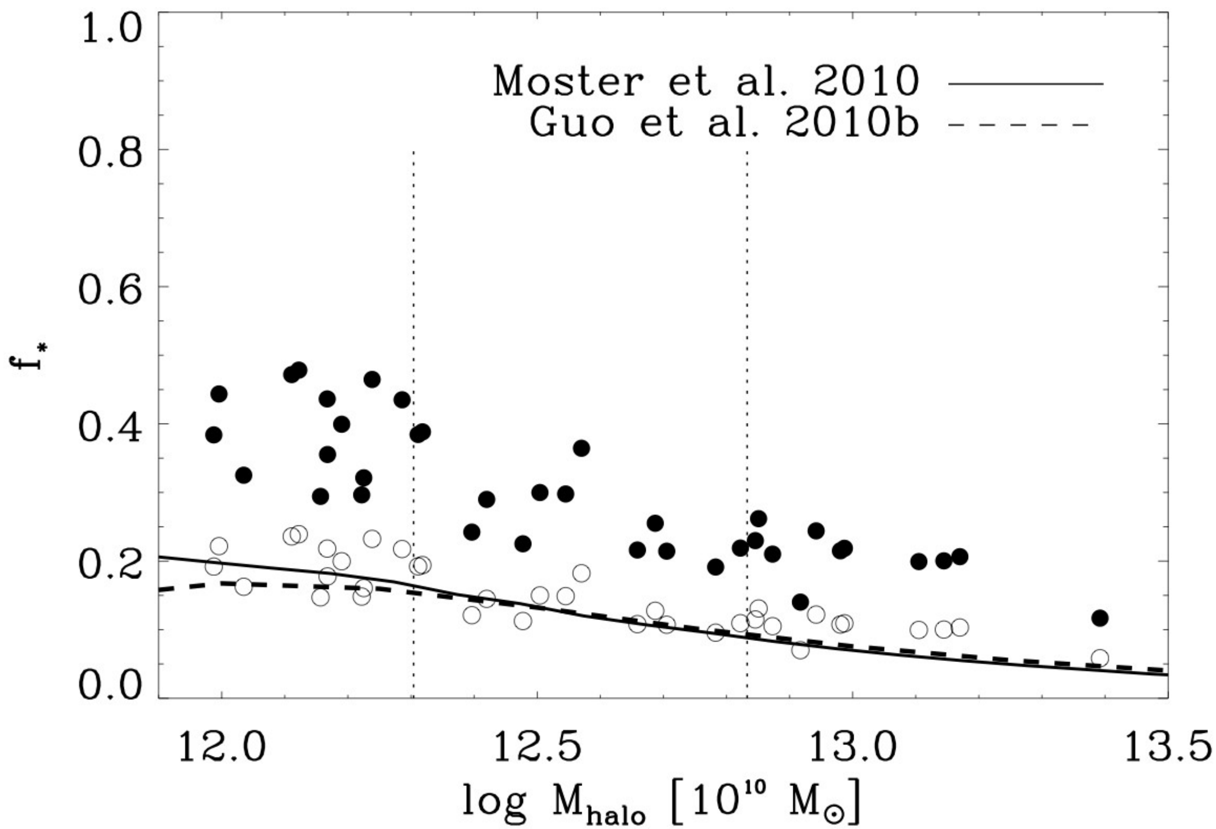
Conclusions

- 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

- The combination of early dissipation and late accretion can explain the observed strong size evolution and the emergence of the present day scaling relations
- More accretion (minor mergers) for massive systems > stronger inside-out growth and higher Sersic-index
- Metallicity gradients in outer parts of galaxies
- Globular cluster dichotomy (red, in-situ, in the inner, blue, accreted, in the outer parts?)
- Merger histories of slow rotators are dominated by minor mergers

- Feedback processes will influence the two phases – tension with HOD models

The stellar mass budget



◦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…

Oser et al. 2010

Analysis

- Construct two-dimensional velocity fields from simulations and perform analysis similar to observers, i.e. Voronoi-binning, LOSVD, Gauss-Hermite, λR (Cappellari et al., van de Ven et al. 2006)

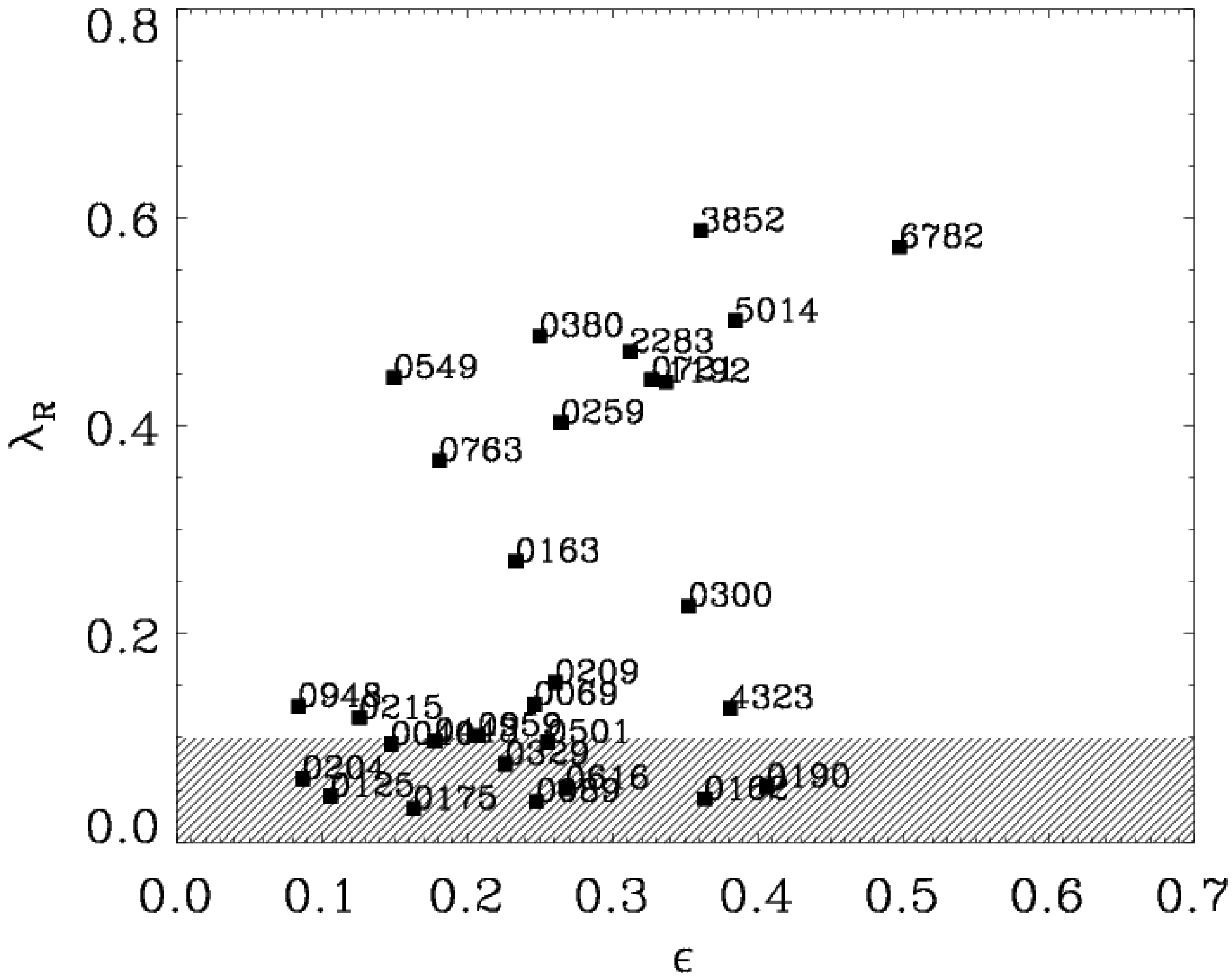
- Follow the formation history of the galaxies, i.e. stellar/halo merger trees, angular momentum build-up, gas accretion etc.

- Analyze stellar populations, metallicities, ages

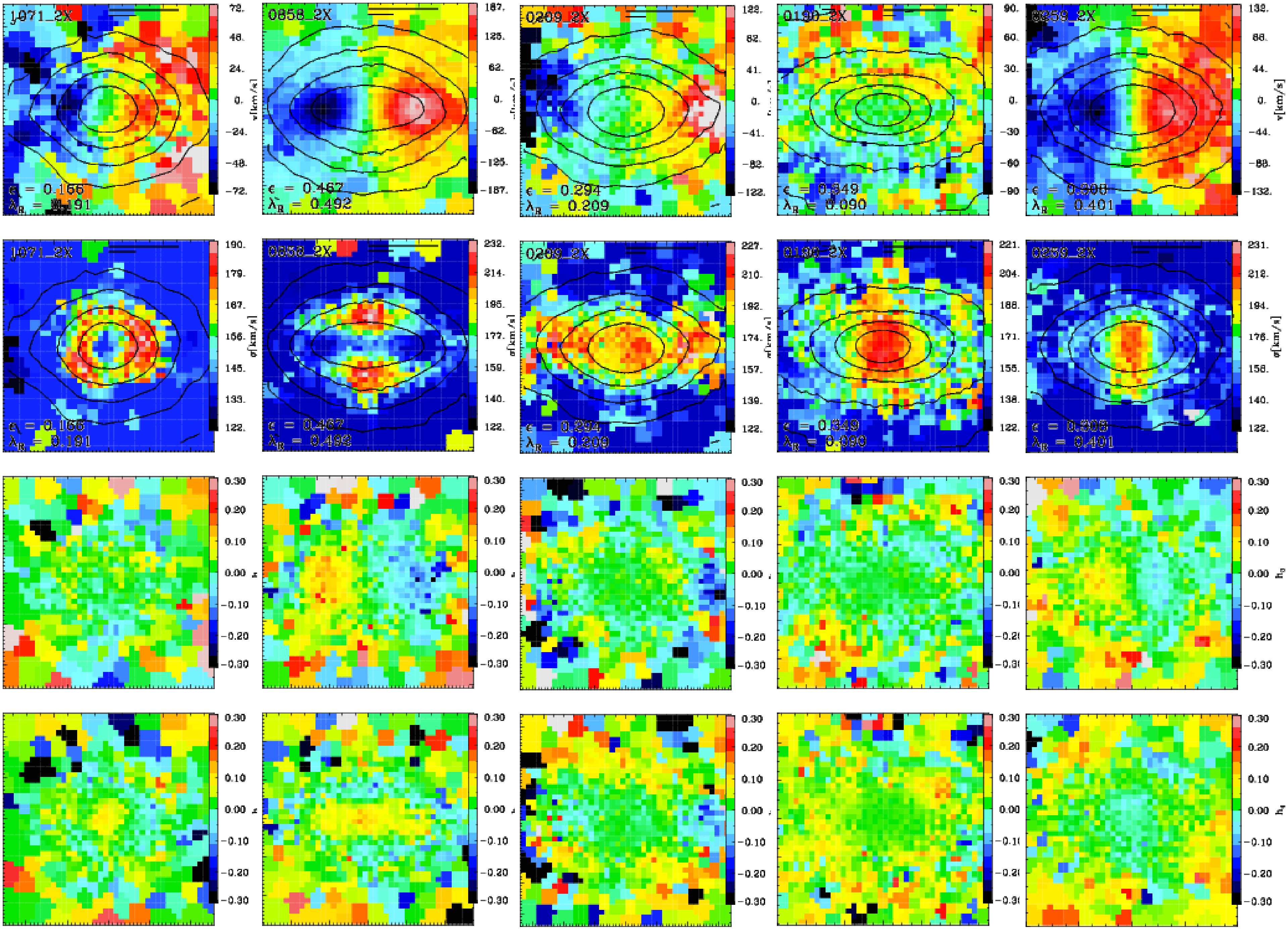
- Cosmological boundaries , more complicated than binary mergers, limited resolution, no full statistics

- Similar environments but so far only central galaxies investigated

Correlations with λR: ‘observations’



üMore flattened systems are fast rotators, slow rotators are round (enough?)



1071_2X
0858_2X
0209_2X
0190_2X
0259_2X
ε = 0.166
λR = 0.191
ε = 0.467
λR = 0.492
ε = 0.294
λR = 0.209
ε = 0.349
λR = 0.090
ε = 0.308
λR = 0.401
v[km/s]
σ[km/s]
h3
h4
72. 48. 24. 0. −24. −48. −72.
187. 125. 62. 0. −62. −125. −187.
122. 82. 41. 0. −41. −82. −122.
90. 60. 30. 0. −30 −60 −90
132. 88. 44. 0. −44. −88. −132.
190. 179. 167. 156. 145. 133. 122.
232. 214. 195. 177. 159. 140. 122.
227. 210. 192. 174. 157. 139. 122.
221. 204. 188. 171. 155. 138. 122.
231. 212. 194. 176. 158. 140. 122.
0.30 0.20 0.10 0.00 −0.10 −0.20 −0.30

Minor mergers and the virial theorem

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

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

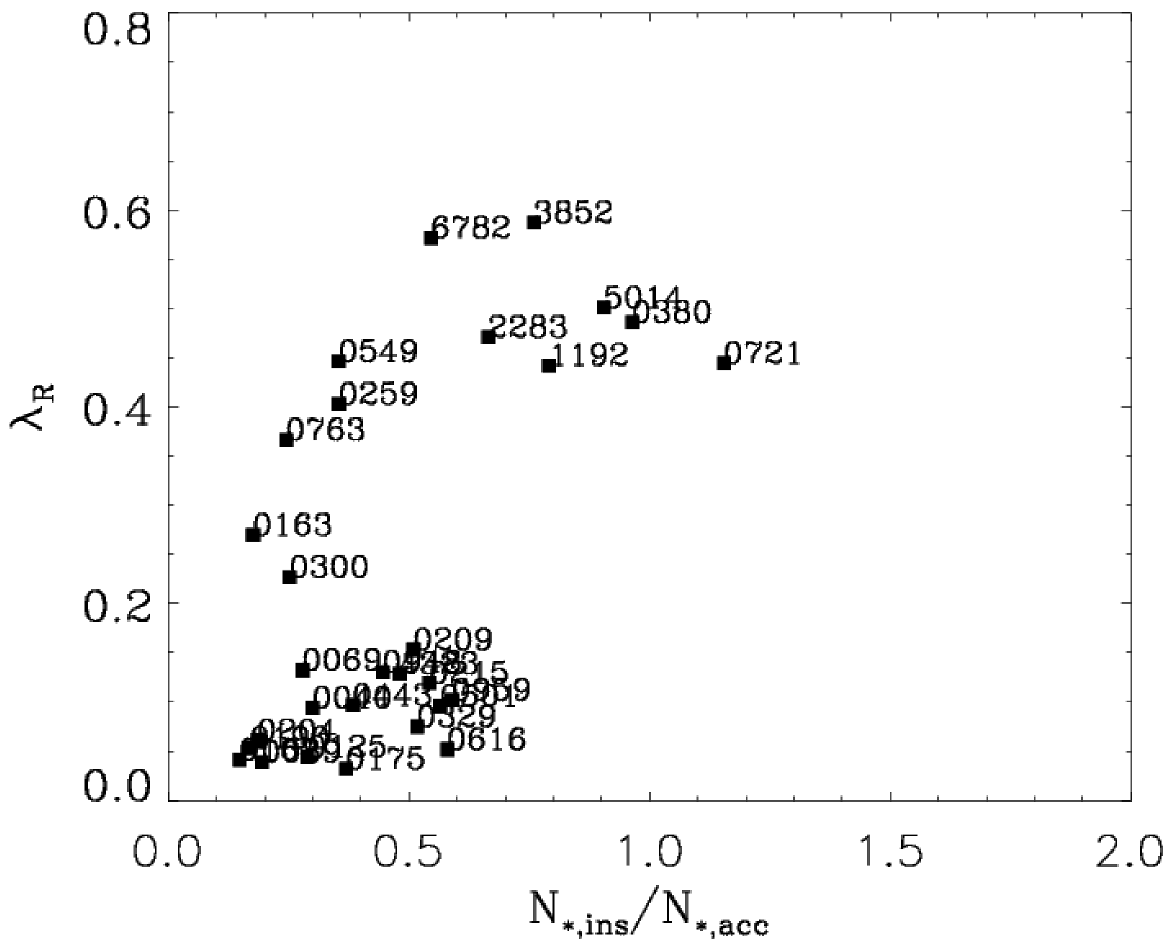
&

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

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

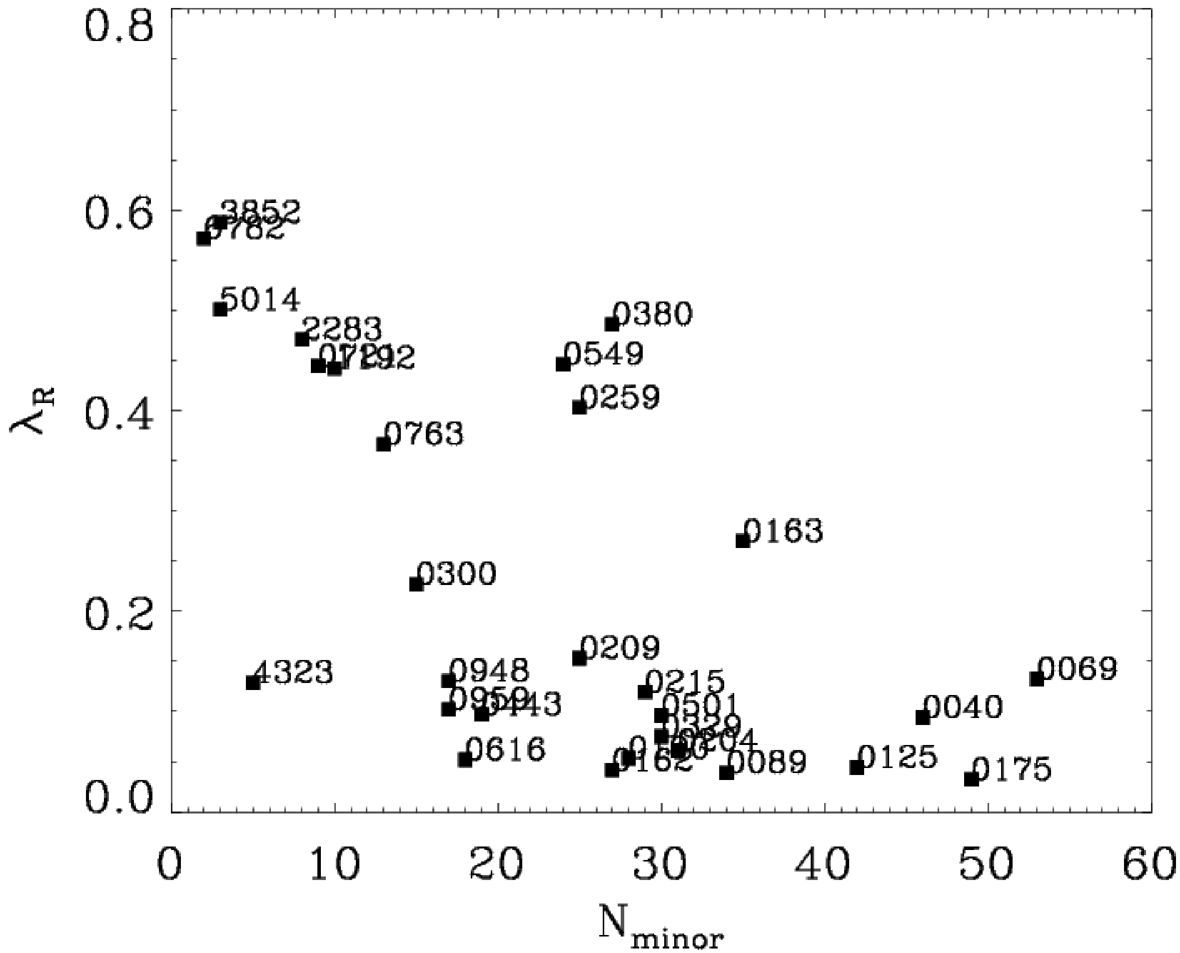
e.g. Cole et al. 2000; Naab, Johansson & Ostriker 2009; Bezanson et sl. 2009

Correlations with λR: theory



- Galaxies with large fraction of in-situ stars are fast rotators

Correlations with λR: theory

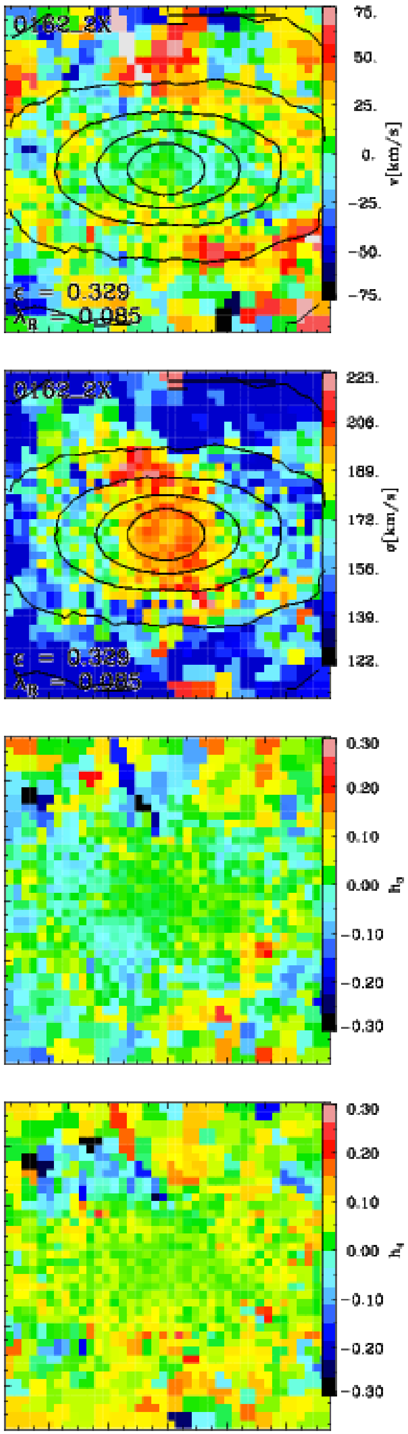


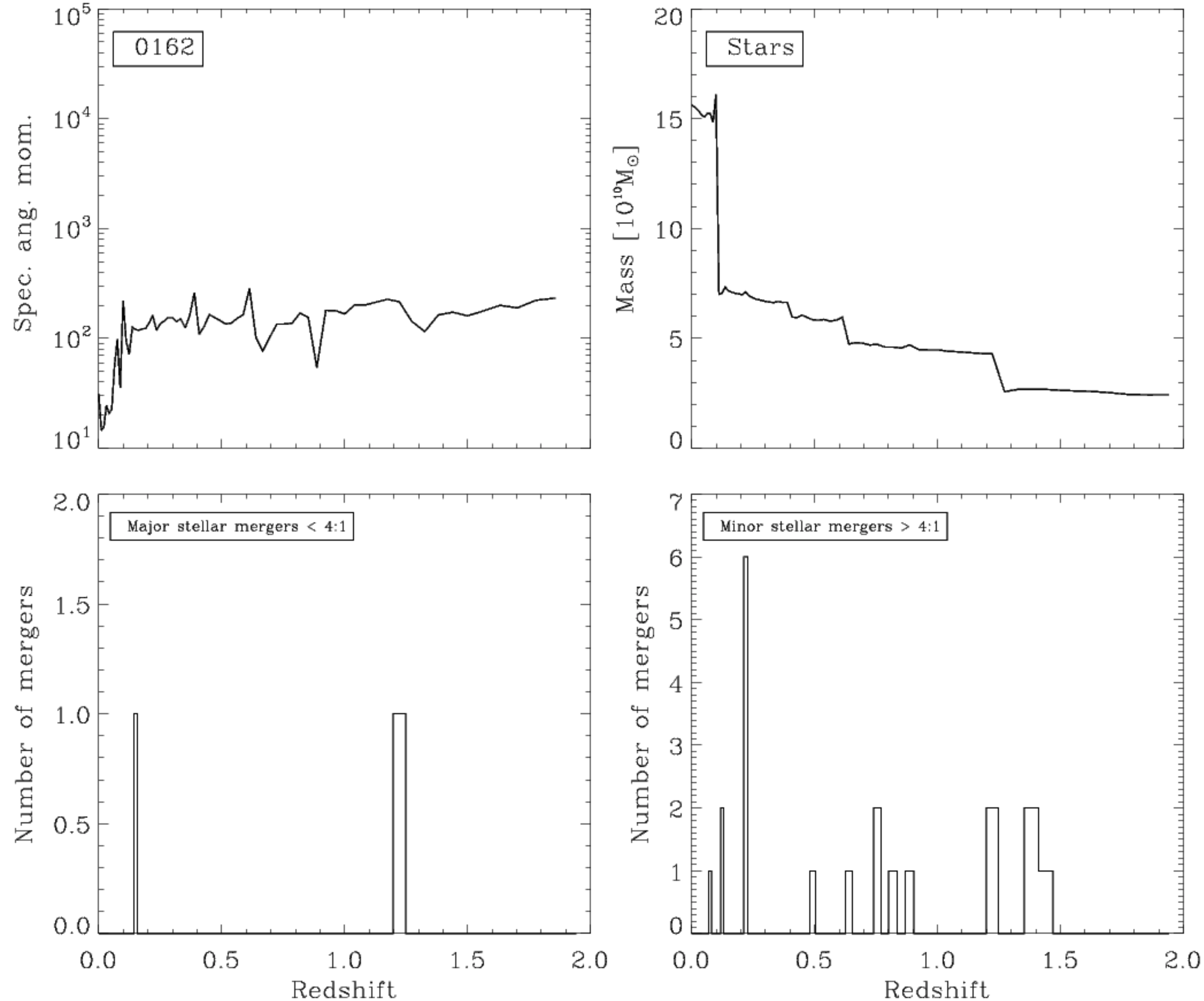
- Galaxies with most minor mergers are slow rotators, major mergers do not matter!

Conclusions

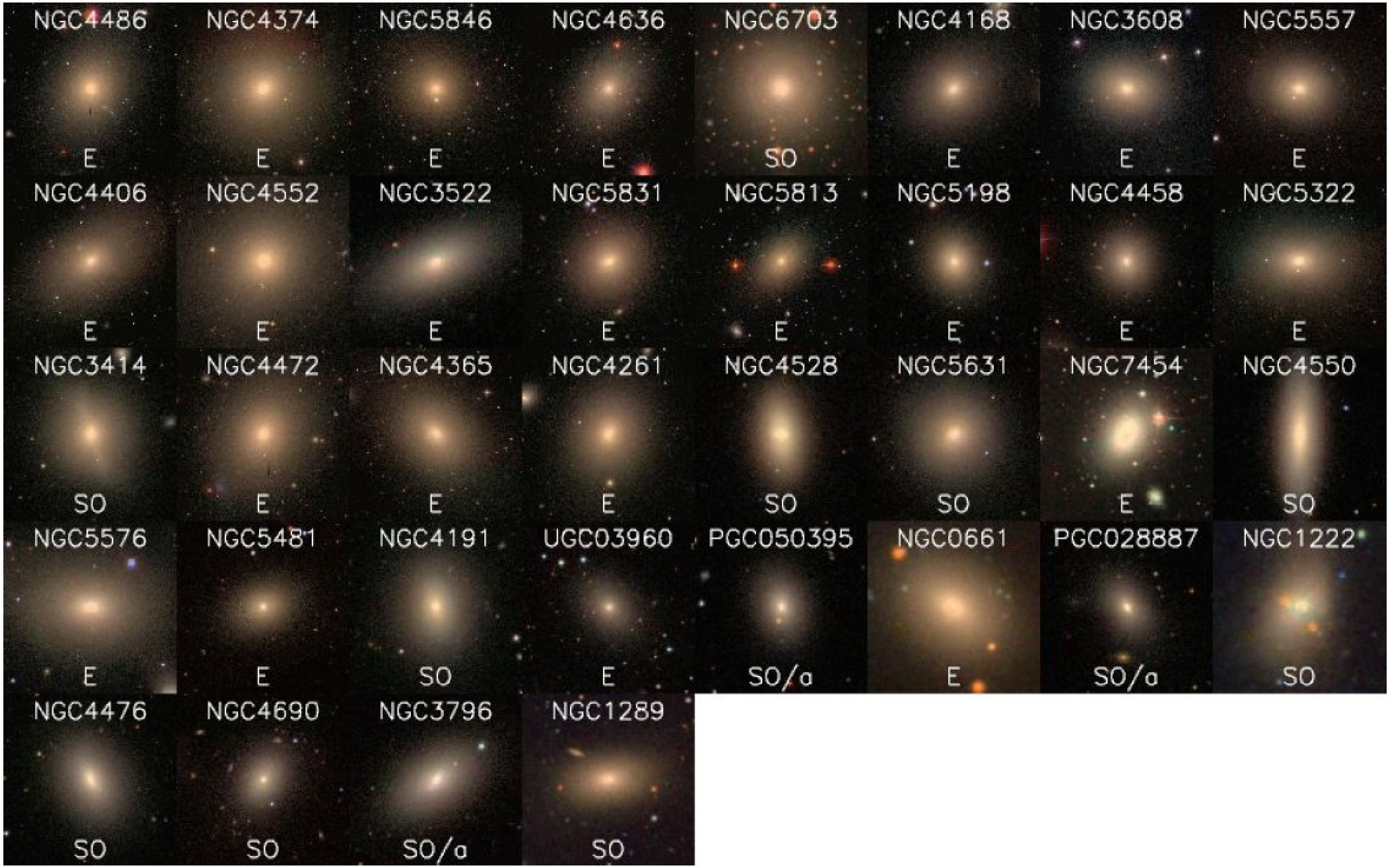
- Cosmological simulations predict kinematic features similar to observations, with proper cosmological boundary conditions
- Rotation properties are determined by the formation and accretion history of the stars – fast rotators are dominated by in-situ formation
- Slow rotators can, maybe, form from equal mass mergers but all galaxies growing by minor mergers are slow rotators, indicating the importance of minor mergers
- Minor mergers are on average from random directions and – on average – reduce the rotation in the galaxies, KDCs are rare
- Investigate gas properties and stellar populations
- Limited sample at the ‘SAURON’ stage, better statistics needed but high-resolution simulations are expensive – we expect more fast rotators for a larger sample
- Currently used sub-grid model favours the early formation of stars, e.g. might over-predict the formation of slow rotators

Stellar merger history and angular momentum





ATLAS3D - sample



- Slow rotators (36/260), mostly round

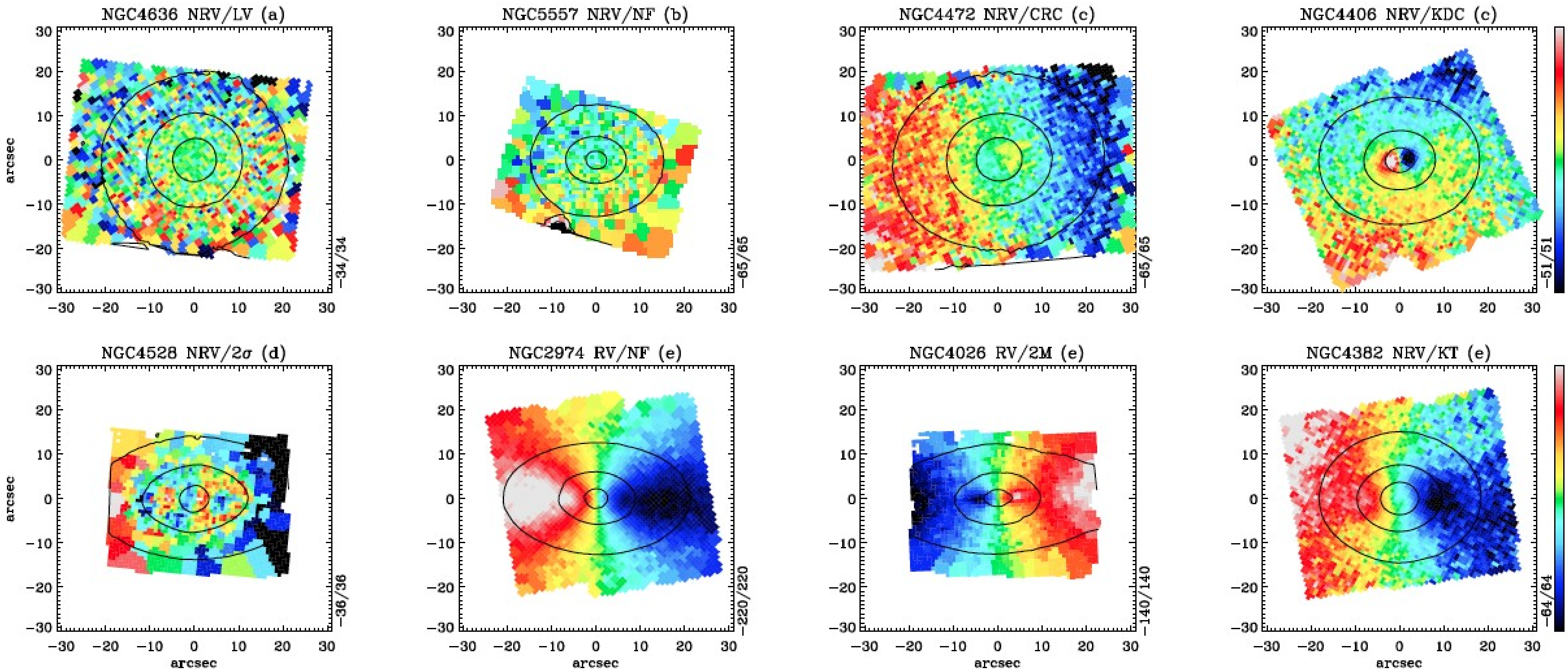
ATLAS3D I: Cappellari, Emsellem, Krajnovic, Mc Dermid et al. 2011

ATLAS3D - sample

- Fast rotators (224/260), some pretty flat

ATLAS3D I: Cappellari, Emsellem, Krajnovic, Mc Dermid et al. 2011

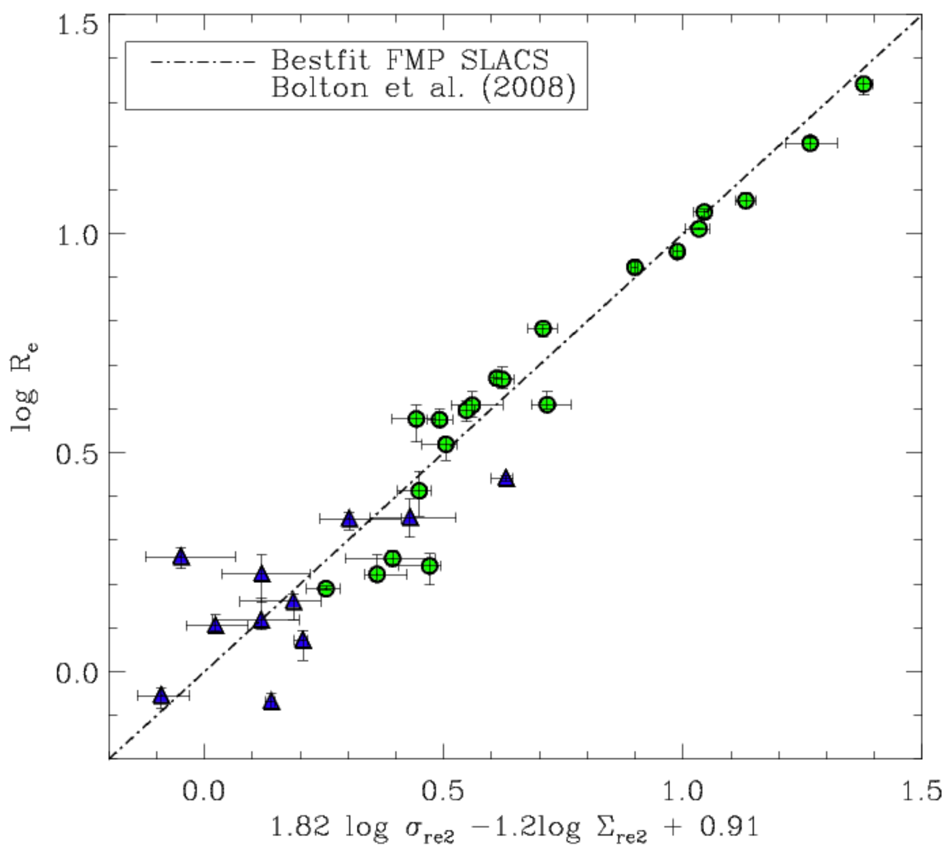
ATLAS3D – kinematical analysis



- Detailed analysis of the two-dimensional velocity fields
- Classification into two main groups and subgroups
- Non-regular velocity fields (NRV) and regular velocity fields (RV) with special features like counter-rotating cores (CRC), kinematically decoupled cores (KDC), kinematic twists (KT), double peak in velocity dispersion (2σ)

ATLAS3D II: Krajnovic et al. 2011

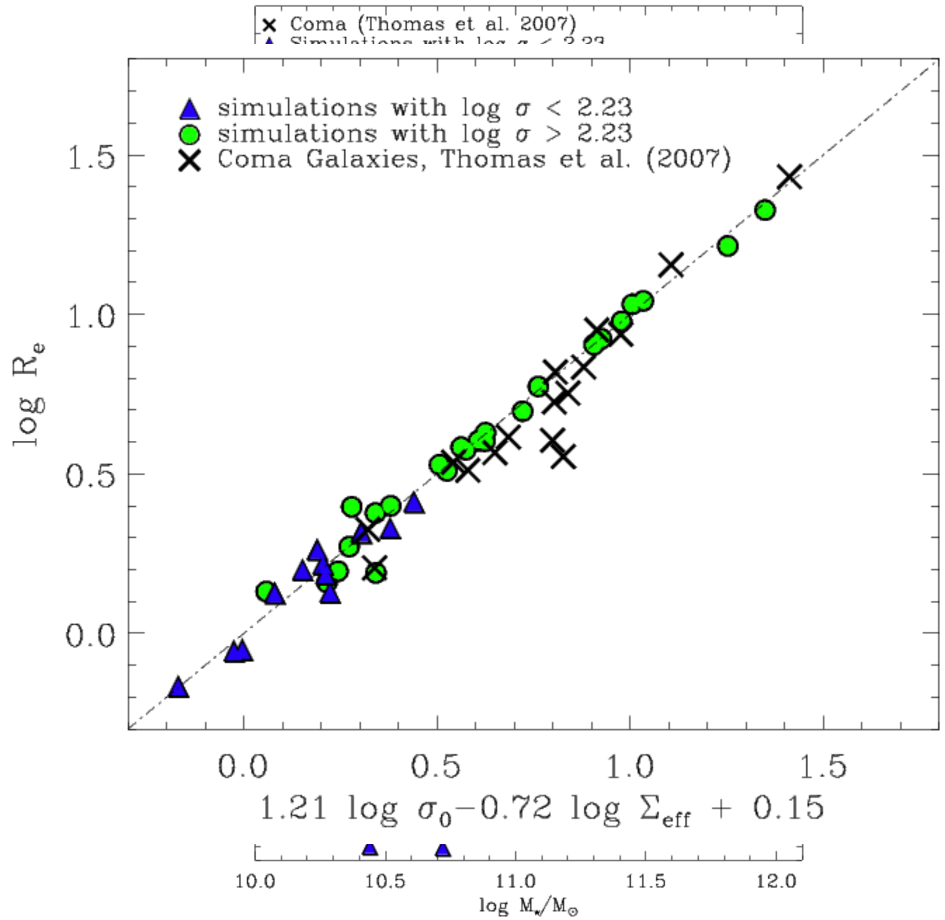
The fundamental mass plane from strong lensing



- 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, observed FP still uncertain…

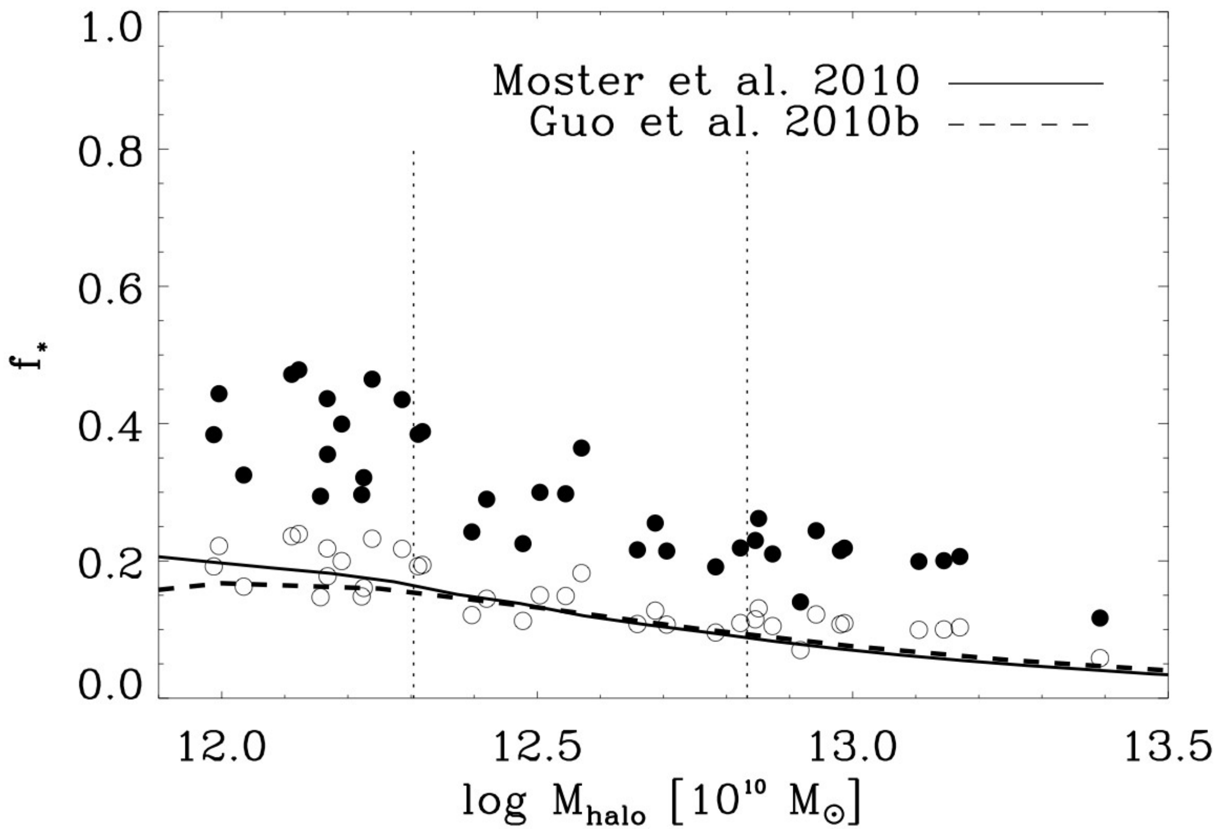
The ‘dynamical’ mass FP from simulations



- 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

The stellar mass budget

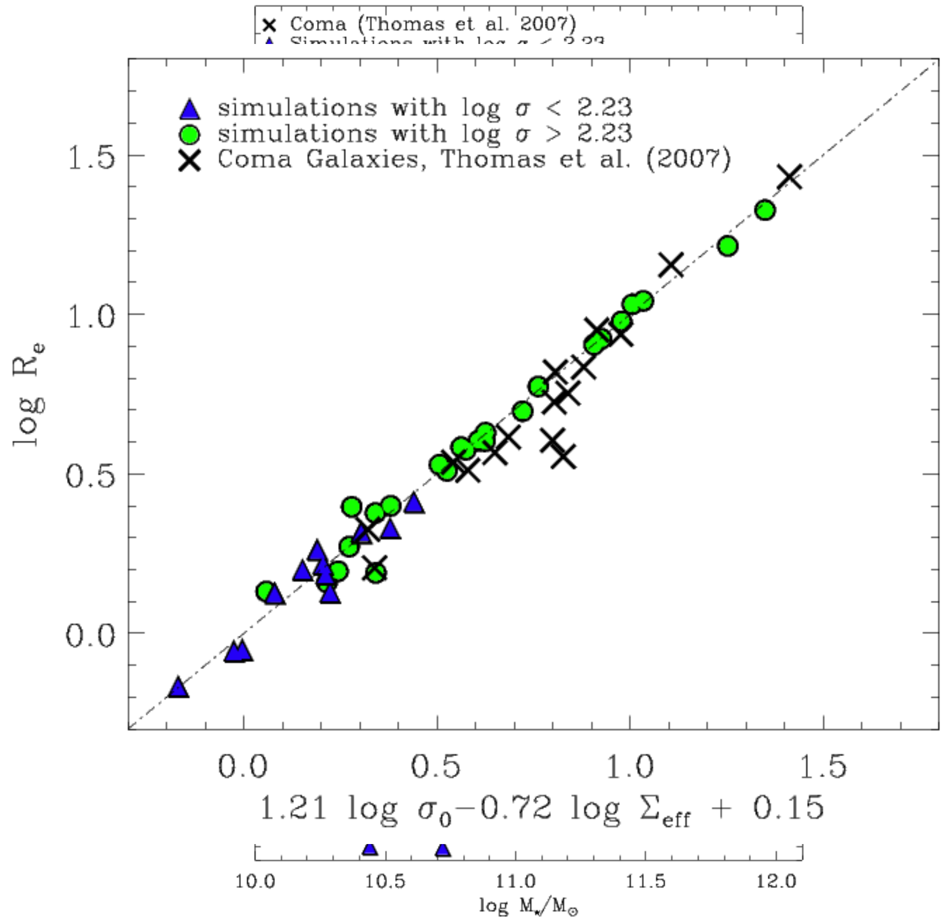


◦Agreement with ‘observations’ for low mass galaxies is worse than for high mass galaxies (Wechsler et al., Guo et al. 2010, Moster et al. 2010, Trujillo-Gomez et al. 2010)

◦IMF? AGN feedback? Stellar mass loss? Star formation driven winds? etc…

Oser et al. 2010

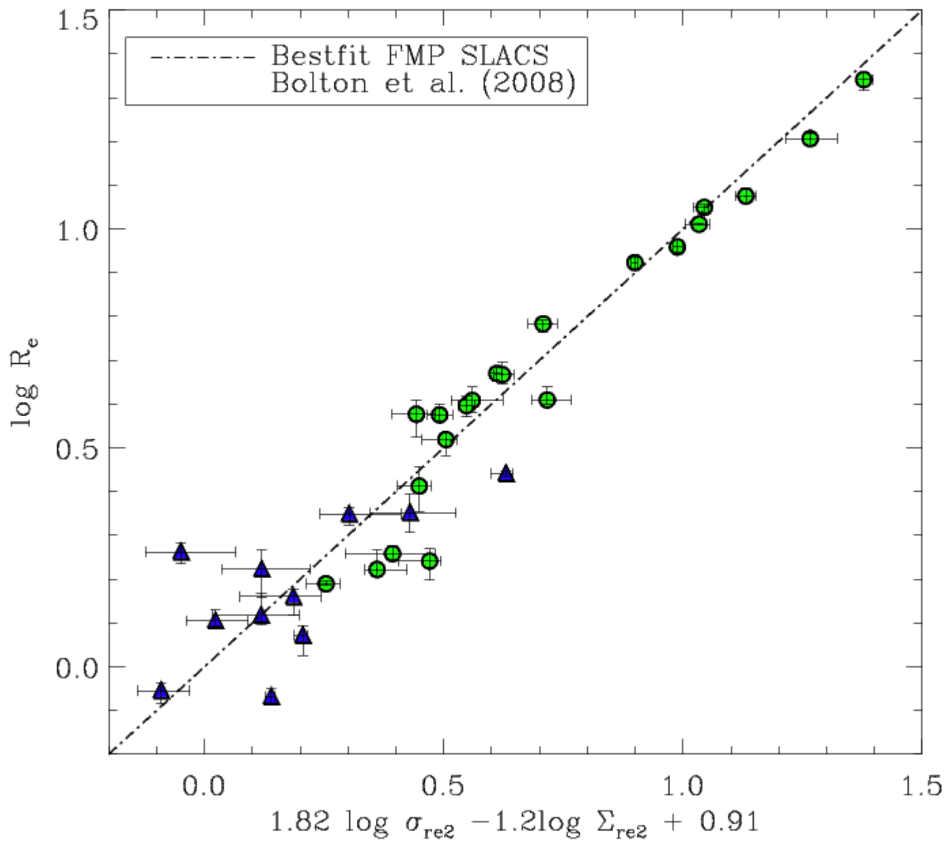
The ‘dynamical’ mass FP from simulations



- 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

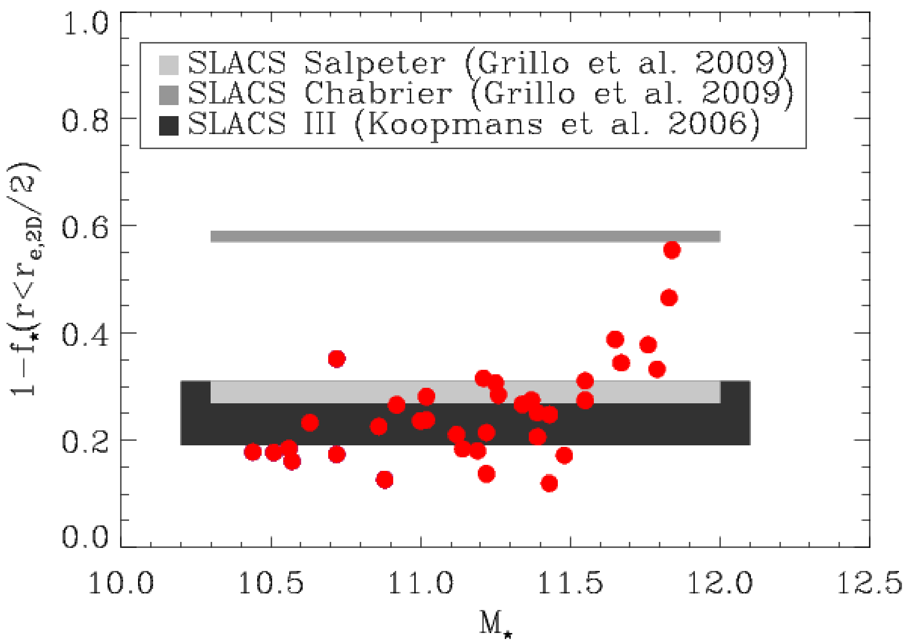
The fundamental mass plane from strong lensing

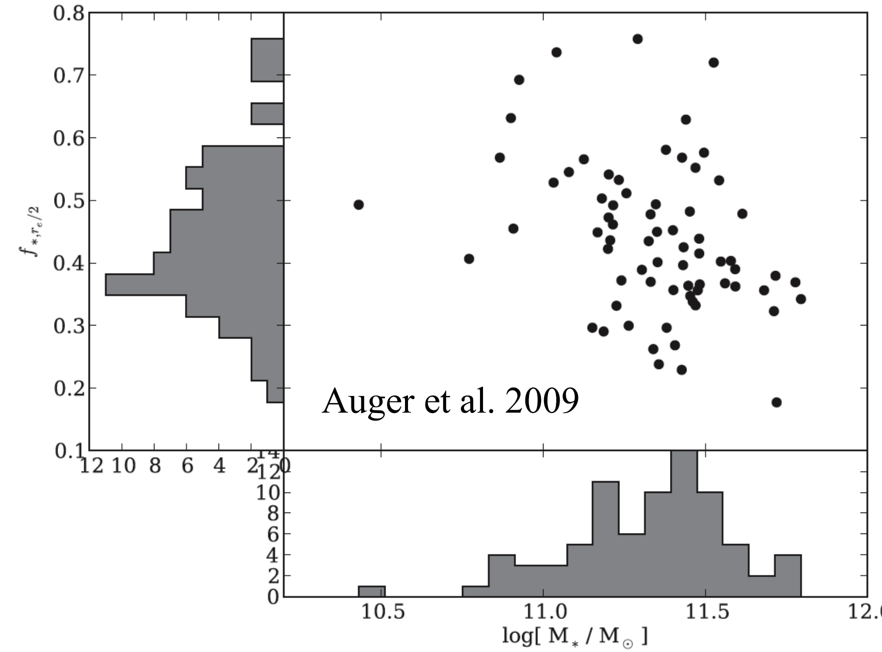


- 53 field early-type strong gravitational lens galaxies from the Sloan Lens ACS (SLACS) survey (Bolton et al. 2008)
- Estimate of the total mass (dark+gas+stars) within re/2
- Representative for early-type galaxies with M*> 1011M (Auger et al. 2009)
- Dynamical mass is a good proxy for the true masses

Our simulations agree well with the observed lensing mass plane, observed FP still uncertain…

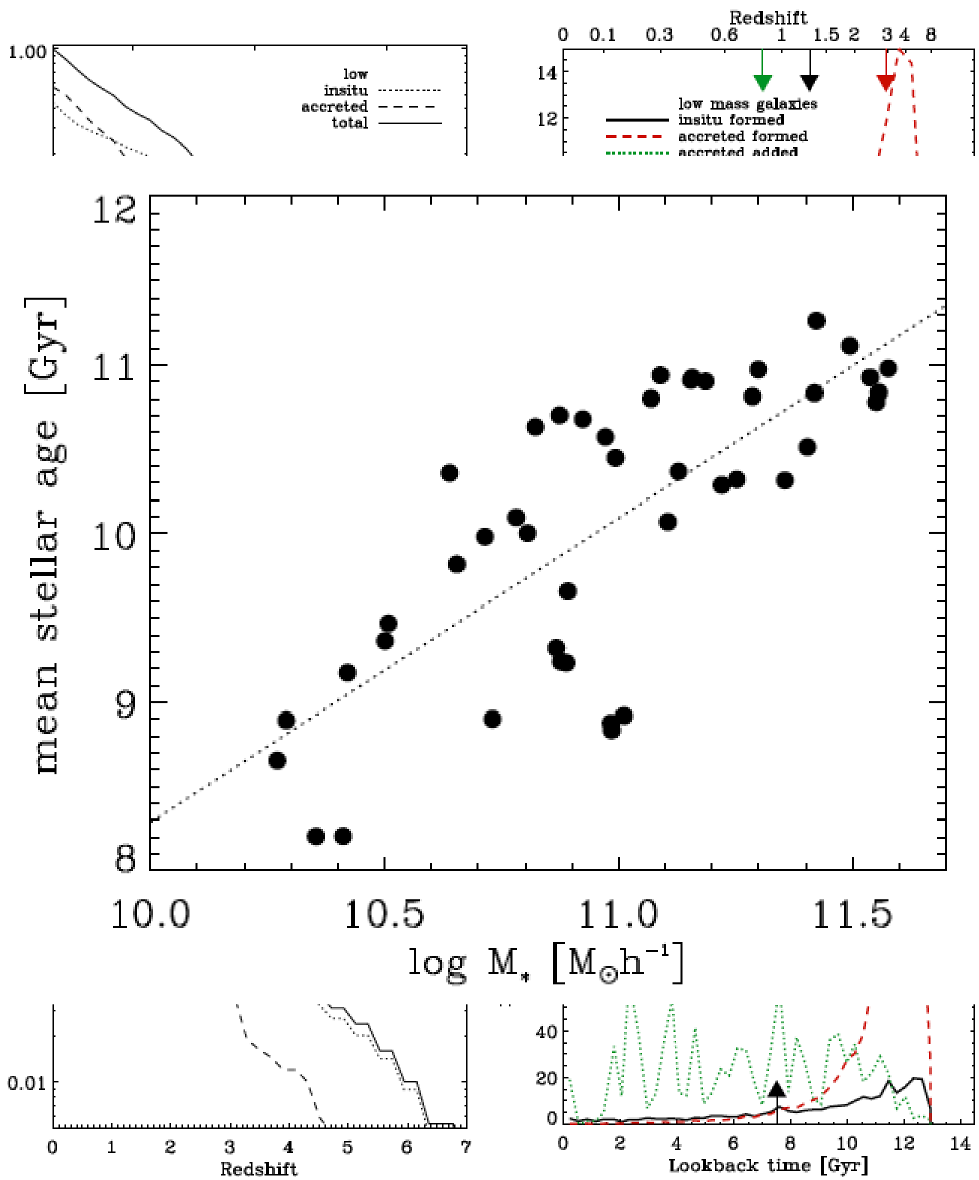
Central dark matter fractions





The average central dark matter fraction agrees with estimates from lensing and dynamical modeling

The origin of stars in massive 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 (see e.g. de Lucia et al. 2006)

Oser et al. 2010

Compact massive ellipticals at z ≥ 2

- Observations show the existence of evolved, massive >1011M□, compact (r1/2 ≈ 1kpc) galaxies with very low star formation rates at z ≥ 2 (Daddi et al. 2005, Trujillo et al. 2006, Toft 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, Damjanov et al. 2008, Bezanson et al. 2009 and others)

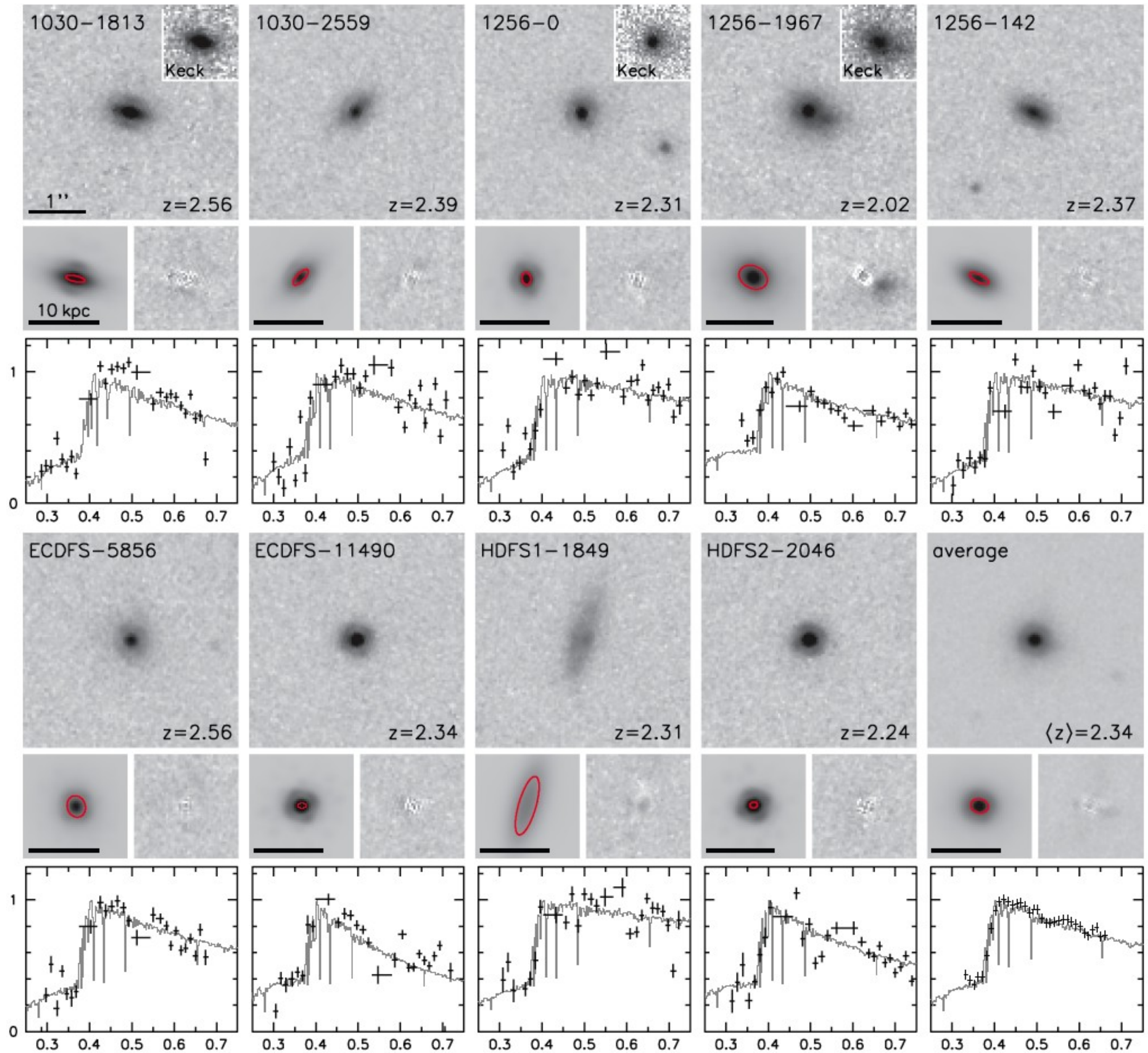
- Systems are a factor three to five smaller than present day ellipticals of similar mass and two orders of magnitude denser within re and 2-3 times denser within 1kpc than z=0 galaxies of similar mass (e.g. Bezanson et al. 2009)

- Galaxies are really compact down to low surface brightness limits (H ≈ 28 mag arcsec-2) with no indications for a faint extended component (Szomoru et al. 2010, van Dokkum et al. 2011)

- Galaxies have higher dispersion – consistent with being more compact (Cenarro & Trujillo 2009, van Dokkum et al. 2009, Cappellari et al. 2009, van de Sande 2011)

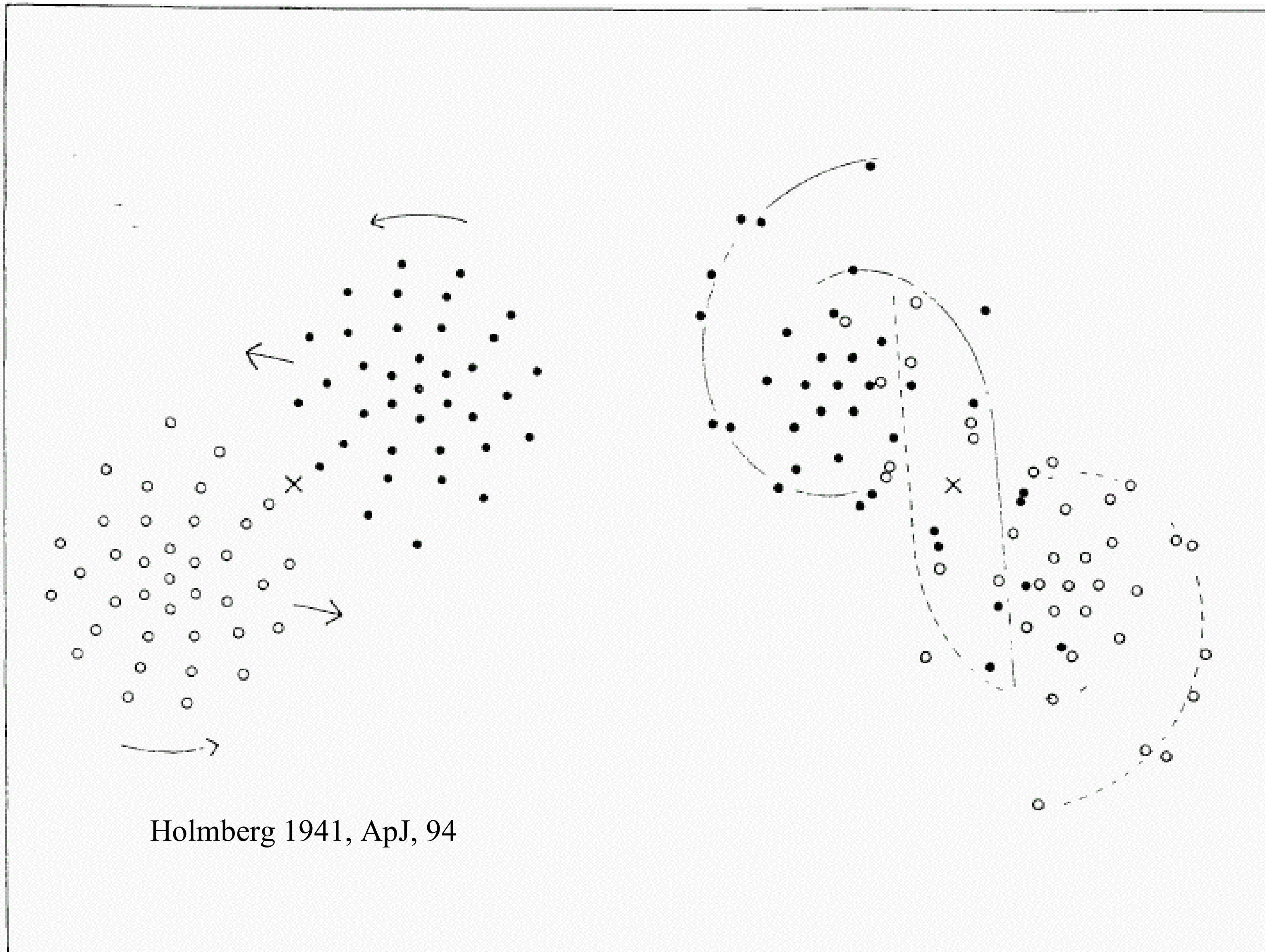
- Massive compact ellipticals are rare (0.03%, at 1011M□ NO?) in the local Universe (Trujillo et al. 2009, Taylor et al. 2010) but make up about half of the general high redshift population (van Dokkum et al. 2006, Kriek et al. 2006, Wiliams et al. 2008)

Compact massive ellipticals at z≈2



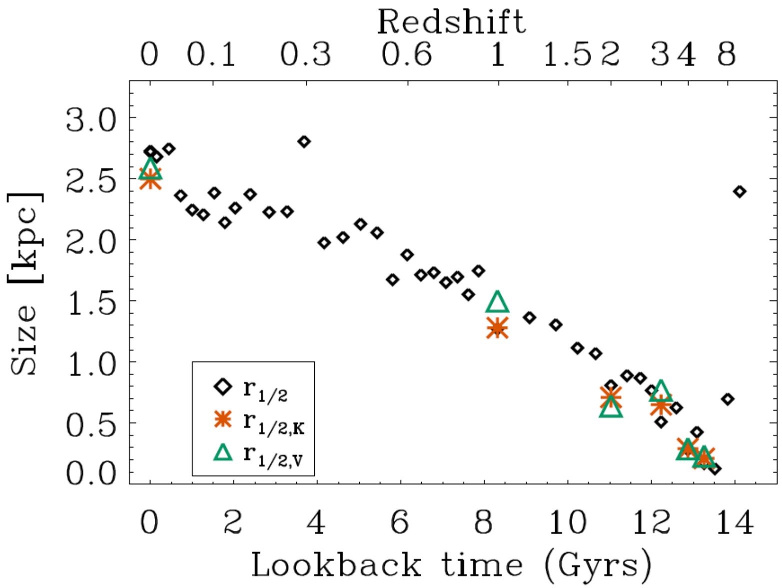
van Dokkum et al. 2008, Kriek et al. 2006

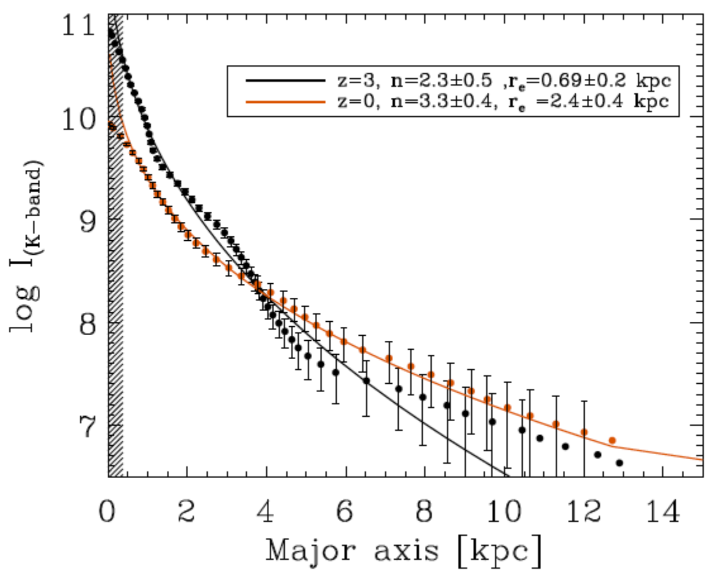
Galactic collisions: It's gravity!



Holmberg 1941, ApJ, 94

Size evolution in a high resolution simulation

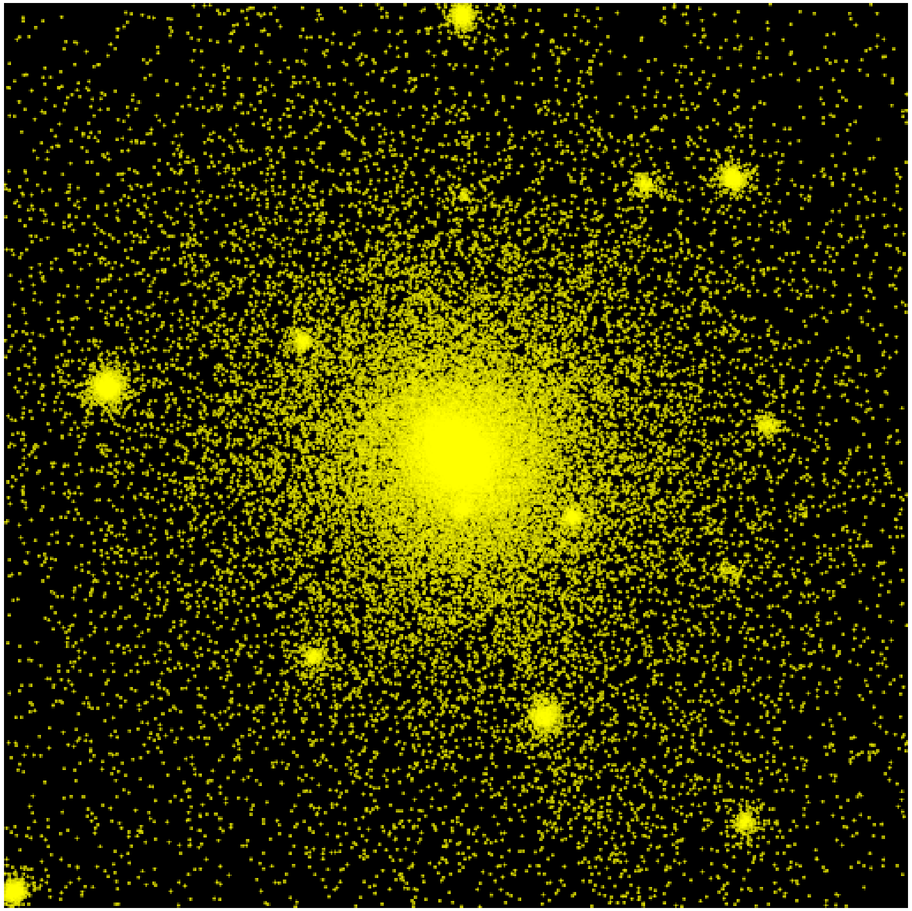


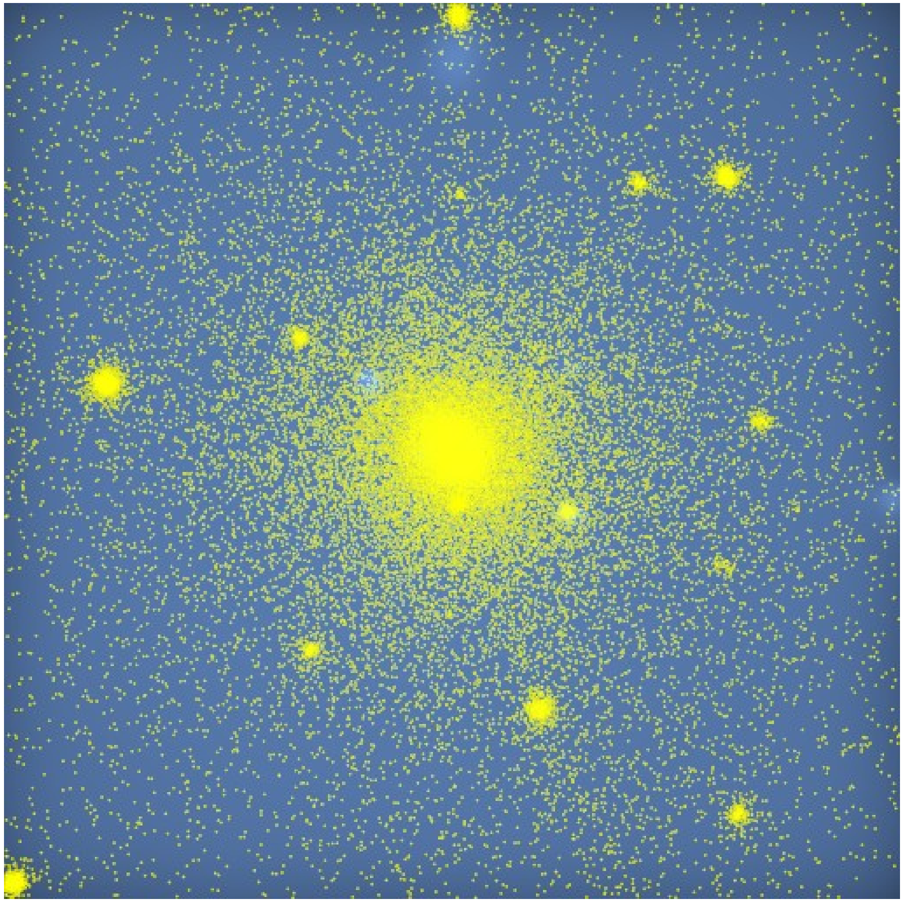


- Size increase of about a factor four from z=3 to z=0; Sersic index increases weakly
- High z system is significantly flattened, whereas low redshift system is round
- Direct evidence from cosmological simulations for minor merger driven evolution
- Elliptical galaxy formation is a two phase process

Naab, Johansson & Ostriker 2009

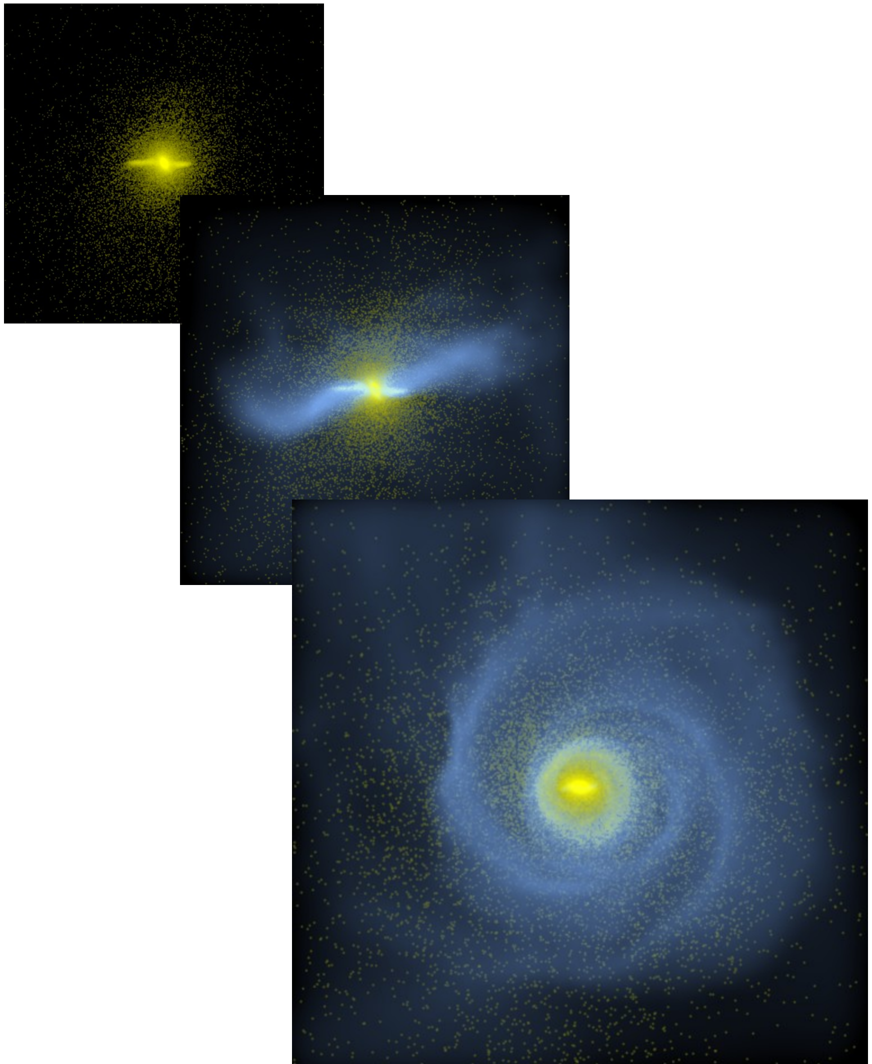
Galaxy gallery

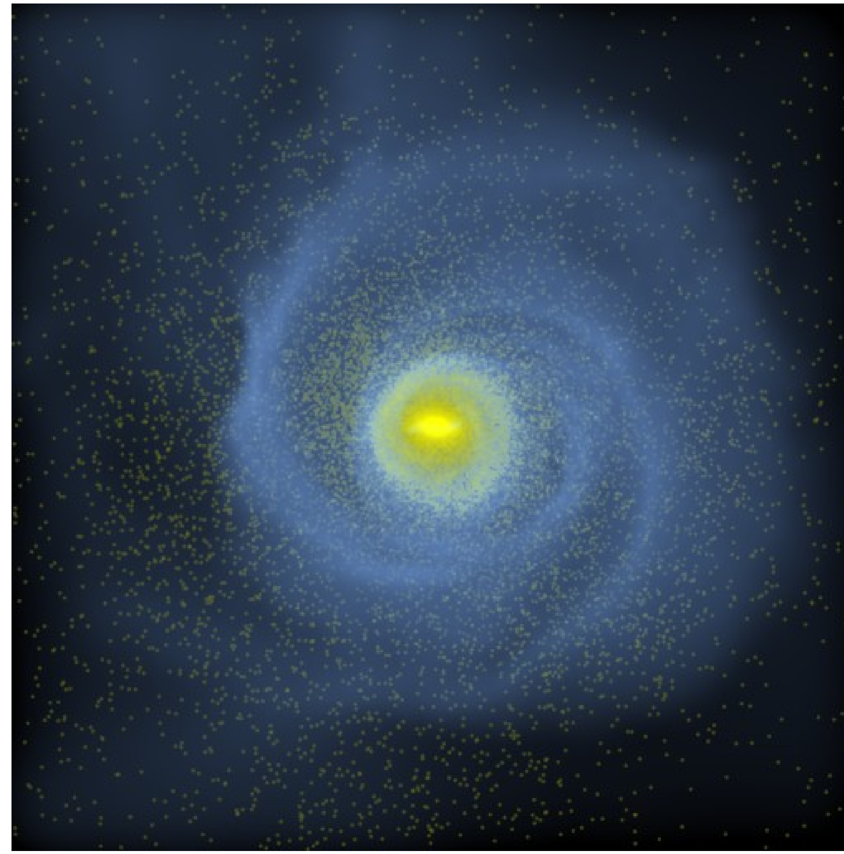




M* = 8*1011 M□

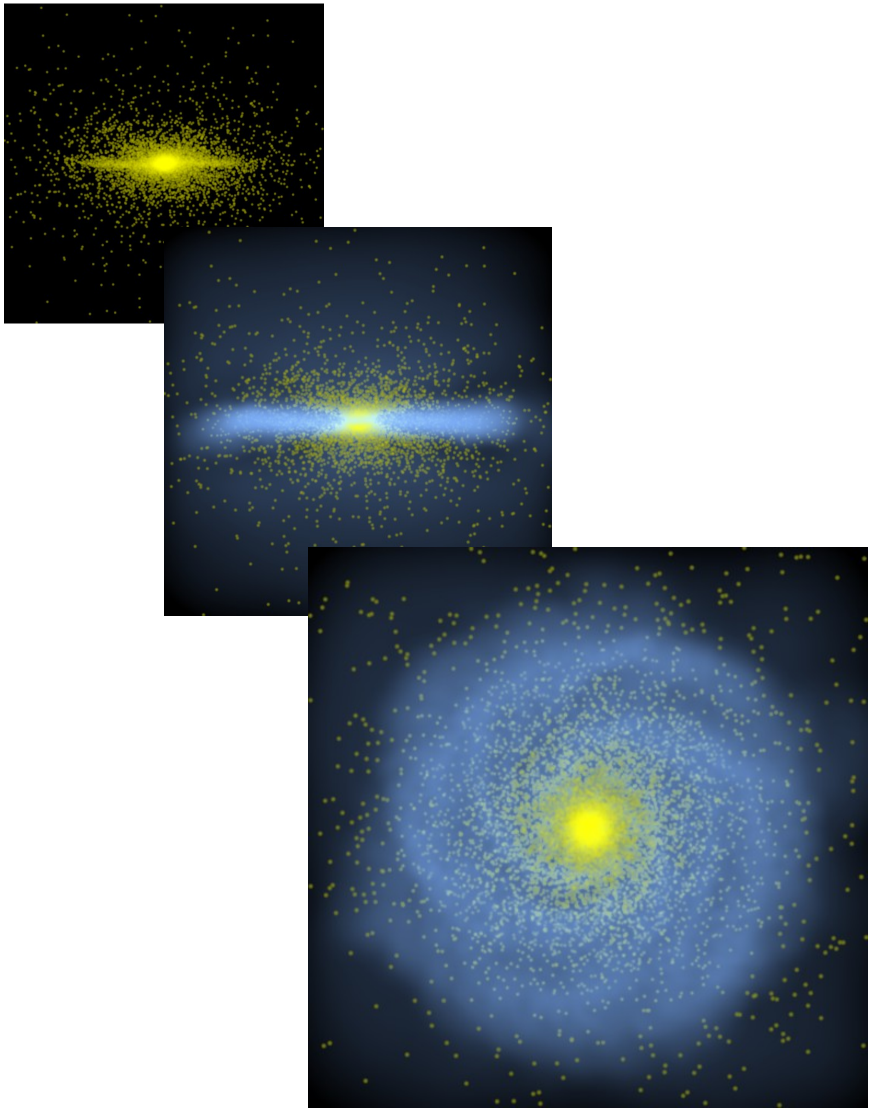
Galaxy Gallery

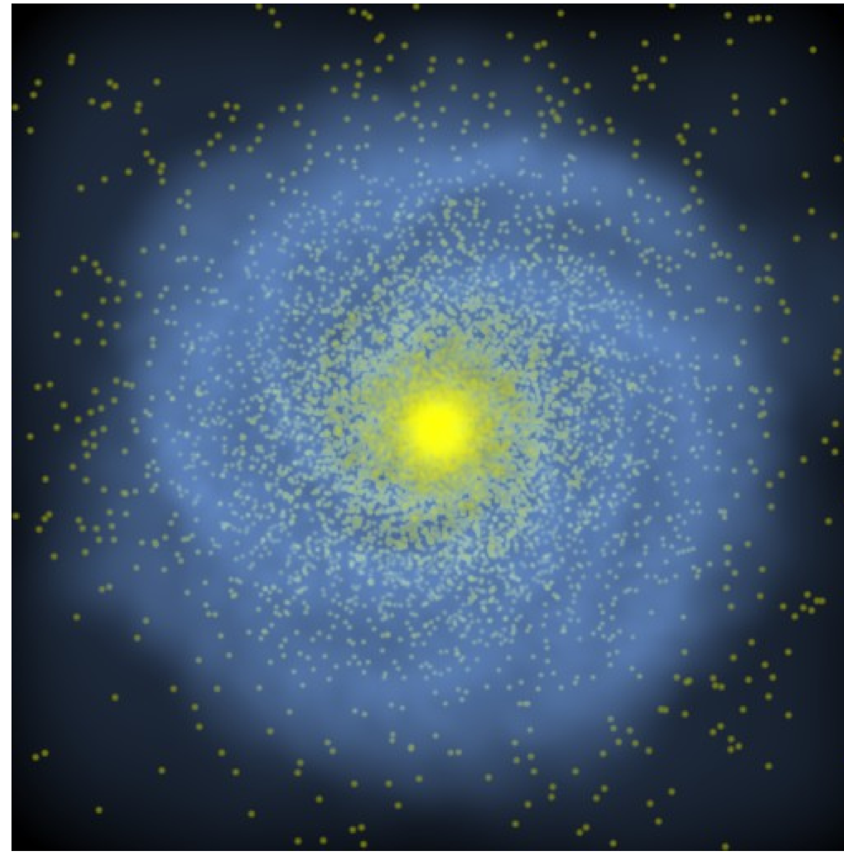




M* = 3.6*1010 M□

Galaxy gallery





$M^* = 1.5*10^{10}\ M_{\odot}$