Cosmological formation of slowly rotating massive elliptical galaxies

Thorsten Naab with ATLAS^{3D}
MPA

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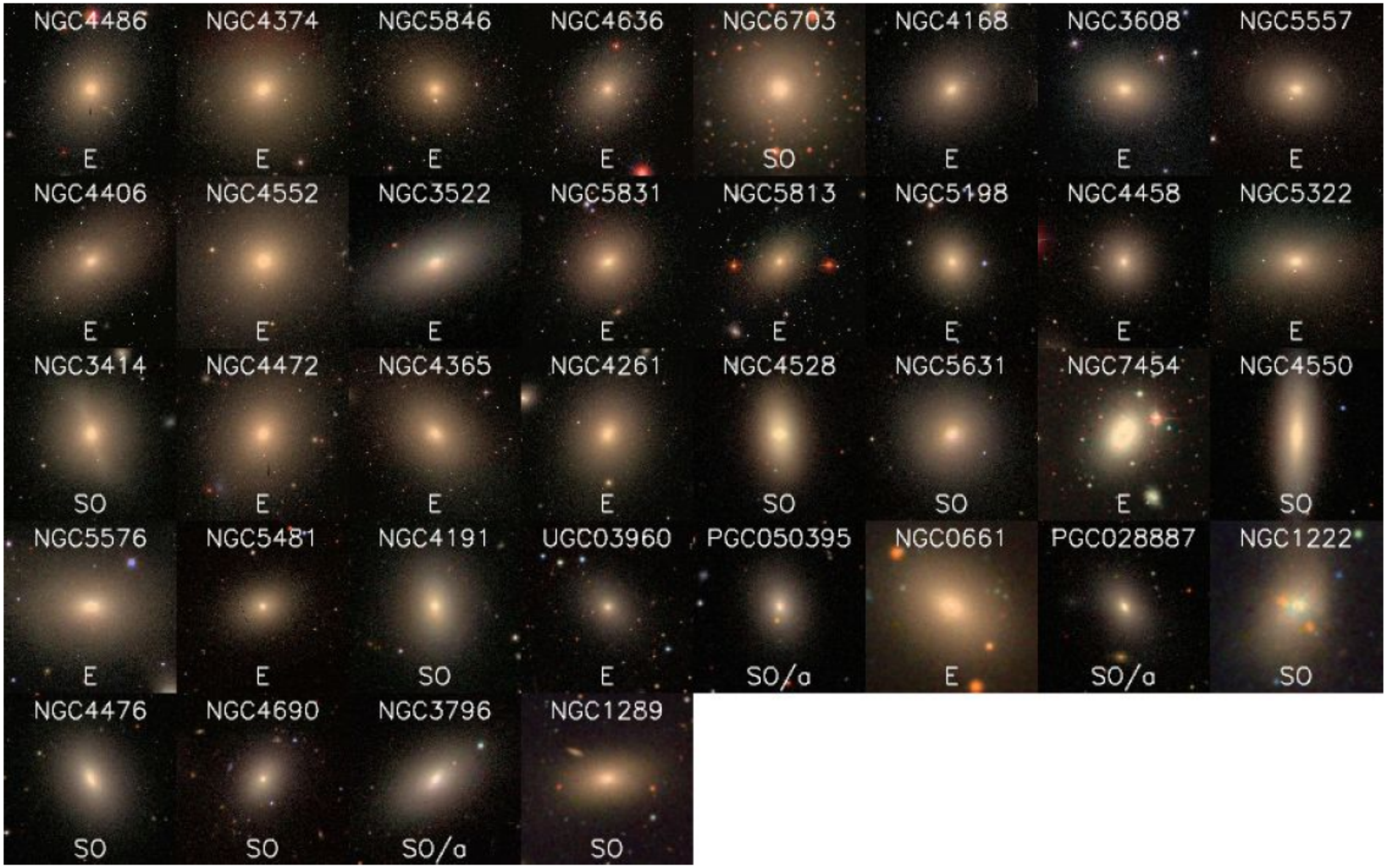
Santa Cruz, August 2011

ATLAS^{3D} - sample

- Multi-wavelength survey of 260 (parent sample of 871) nearby red-sequence early-type galaxies, D < 42 Mpc, $M_K < -21.5$, $M_* > 6 \cdot 10^9 M_\odot$
- Selected visually based on morphology, absence of spiral features and dust lanes
- Radio, millimeter, optical imaging and two-dimensional kinematics of atomic (HI), molecular (CO), and ionized gas (Hβ, [OIII], [NI]), kinematics and populations of stars (Hβ, Fe5015, Mg b)
- Accompanied by semi-analytical modeling, merger simulation and cosmological simulations
- First statistically complete survey with detailed 2D kinematical and photometric information and complete inventory of baryon budget
- Papers on sample (Cappellari et al.), kinematic analysis (Krajnovic et al.), angular momentum (Emsellem et al.), molecular gas content (Young et al.), CO Tully-Fisher relation (Davis et al.), AGN driven outflow (Alatalo et al.), Binary mergers (Bois et al.), Semi-analytical models (Khochfar et al.), and much more...

ATLAS^{3D} - sample



- Slow rotators (36/260), mostly round

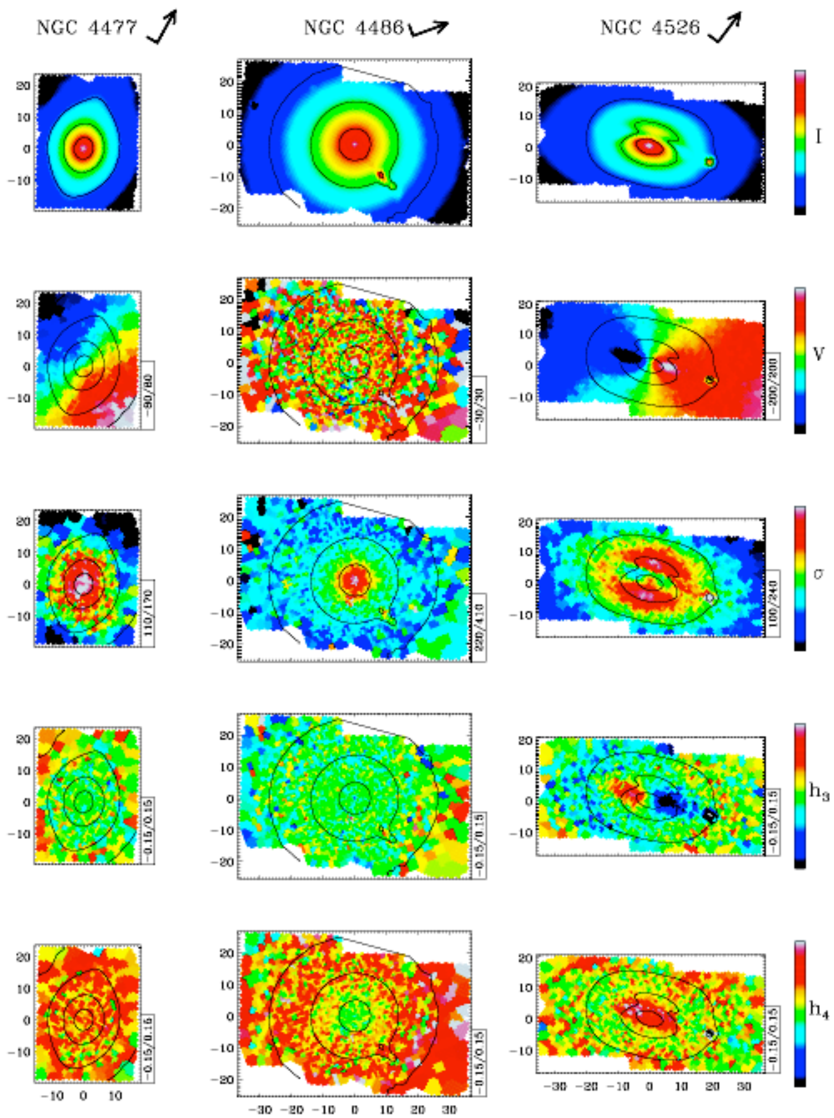
ATLAS^{3D} I: Cappellari, Emsellem, Krajnovic, Mc Dermid et al. 2011

ATLAS^{3D} - sample

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

ATLAS^{3D} I: Cappellari, Emsellem, Krajnovic, Mc Dermid et al. 2011

The SAURON - survey



- Integral field spectroscopy of 48 elliptical and lenticular galaxies

  (Bacon et al. 2001, de Zeeuw et al. 2002, Emsellem et al. 2004, Cappellari et al. 2006)

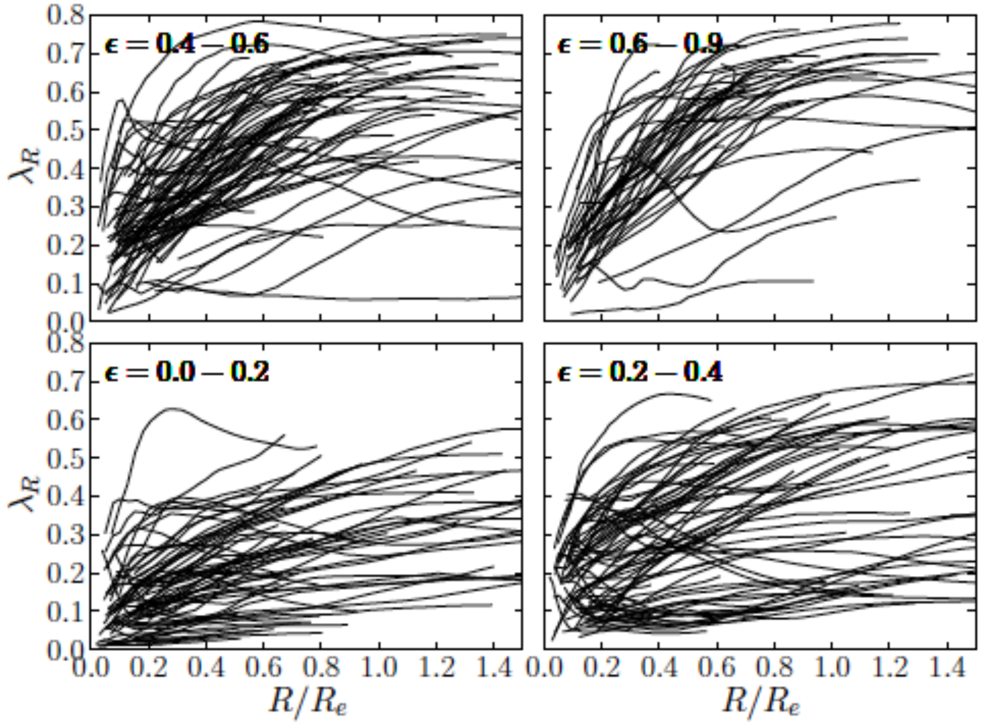
- Wealth of kinematic features like KDCs, KT, two-sigma dispersion profiles

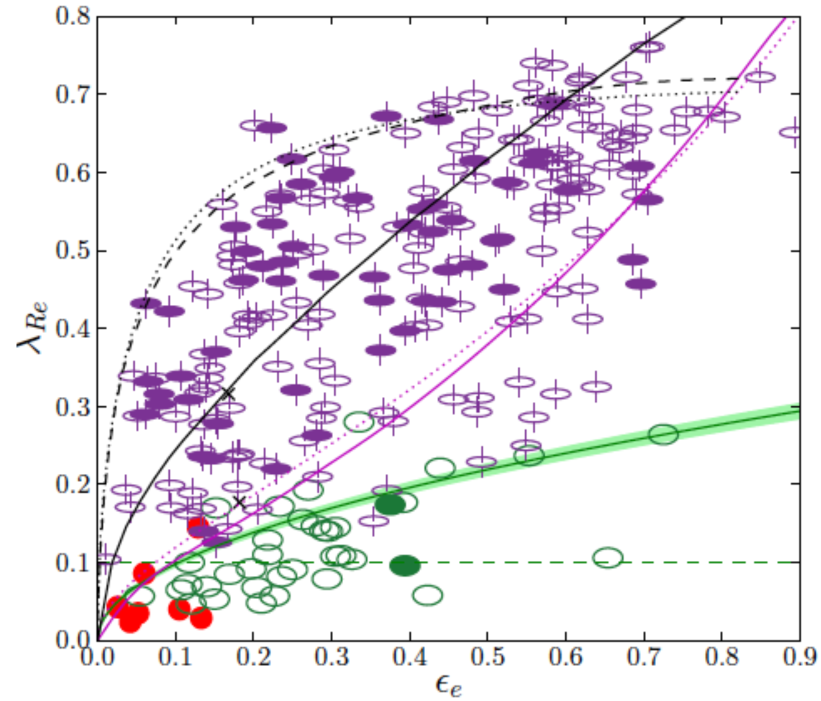
- Measure of the angular momentum of a galaxy: λ_R (Emsellem et al. 2004)

- Early-type galaxies are fast rotators ($\lambda_R > 0.1$) or slow rotators ($\lambda_R < 0.1$)

$$\lambda_R = \frac{\langle R|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle}$$

ATLAS^{3D} – kinematical analysis

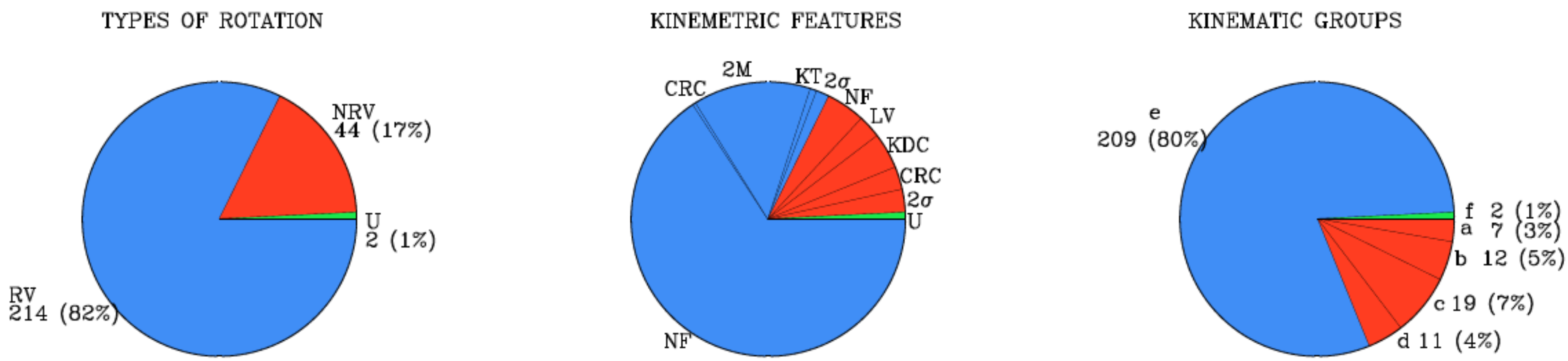




- Most massive early-type galaxies tend to be round and slow rotators
- Division line between slow rotators and fast rotators is $0.31 \cdot \sqrt{\varepsilon}$

ATLAS^{3D} III: Emsellem et al. 2011

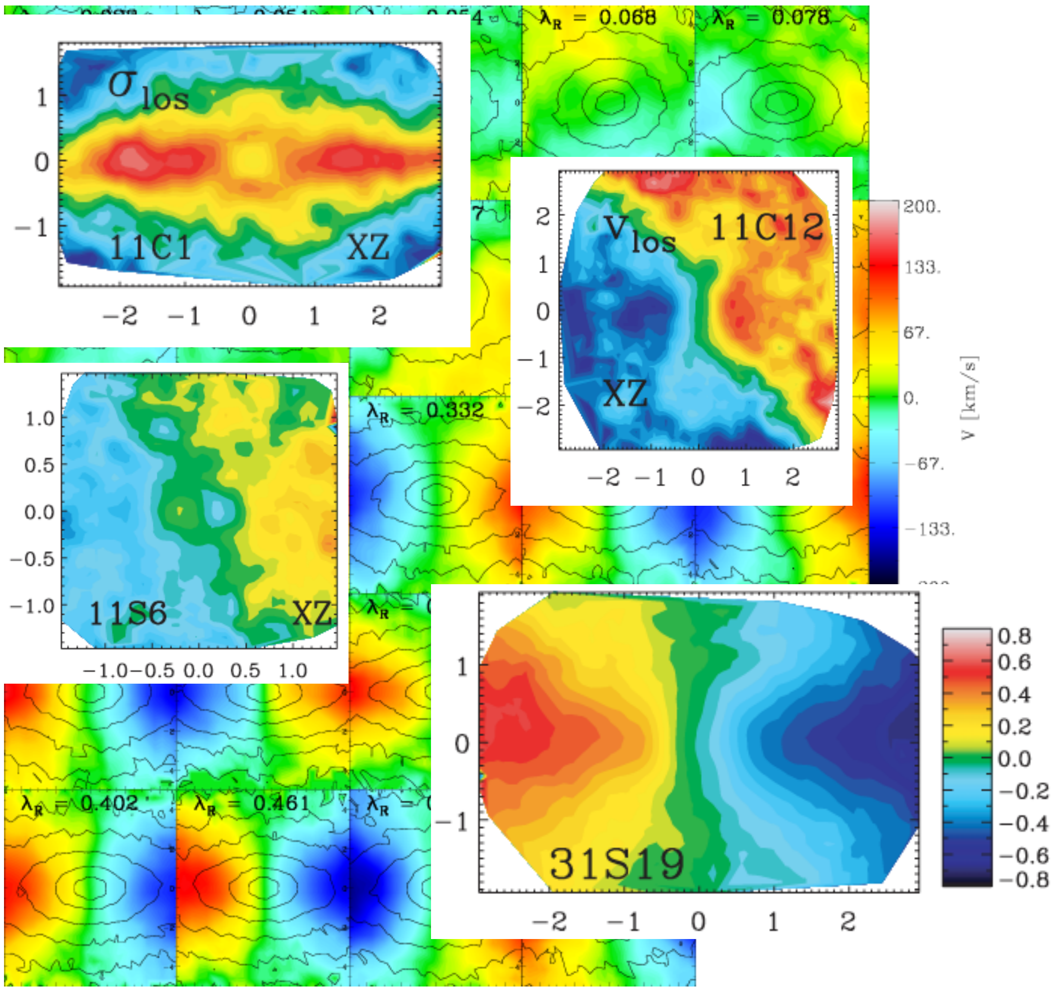
ATLAS^{3D} – kinematical analysis



- Most galaxies have (214, 82%) regular velocity fields, 44% show non-regular rotation (dense environments, massive), KDCs (7%), 2σ (4%)
- Bars & rings (30%), dust structures (16%), blue nuclear colors (6%), interaction (8%)
- 90% have aligned ($\Psi < 5°$) photometric and kinematic major axes (axisymmetric), rest is misaligned within r_e (10%) and triaxial

ATLAS^{3D} II: Krajnovic et al. 2011

Binary mergers of disks

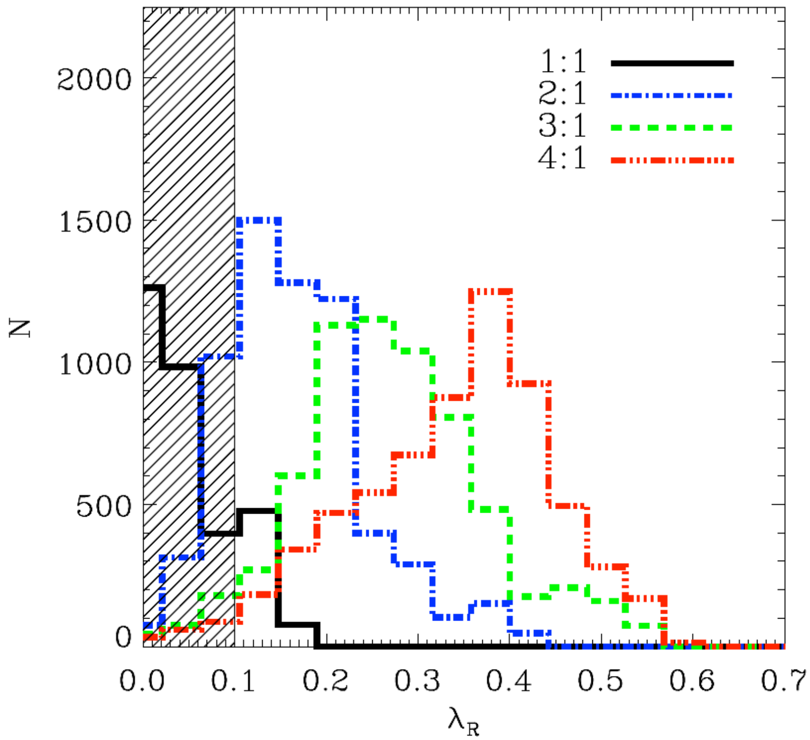


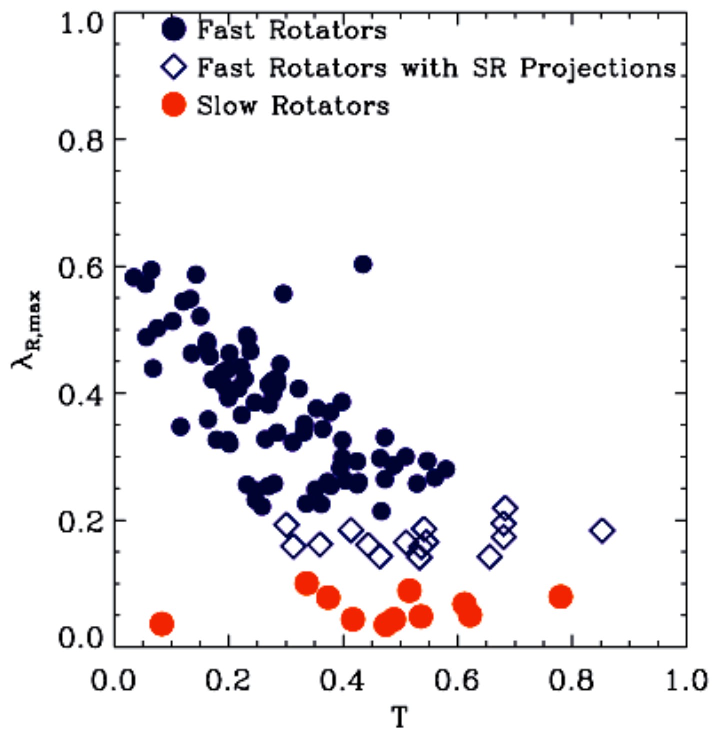
- Velocity fields of disk merger remnants resemble observed velocity fields
- Kinematic misalignment, CRCs, KDCs, 2σ, regular rotation
- Only 1:1 and 2:1 remnants show irregular features

Model	Comment	i_1	i_2	ω_1	ω_2
11C1	High σ by counter-rotation	0	0	180	0
11C3	Regular rotation	0	0	71	−30
11C5	Low rotation	−109	−60	180	0
11C8	Surface-density change	−109	−60	71	90
11C12	Kinematic misalignment	−109	0	71	90
31C6	Regular rotation	−109	−60	71	30
11S2	Low σ ring	0	0	71	30
11S6	CRC in stars	−109	−60	71	30
11GS4	σ double peak	−109	−60	71	30
11GS9	Polar ring	−109	0	180	0
11GS16	CRC in gas	−109	60	71	90
31GS19	σ dumbbell	0	0	71	−30

Jesseit, Naab, Peletier & Burkert 2007

Lambda & binary mergers



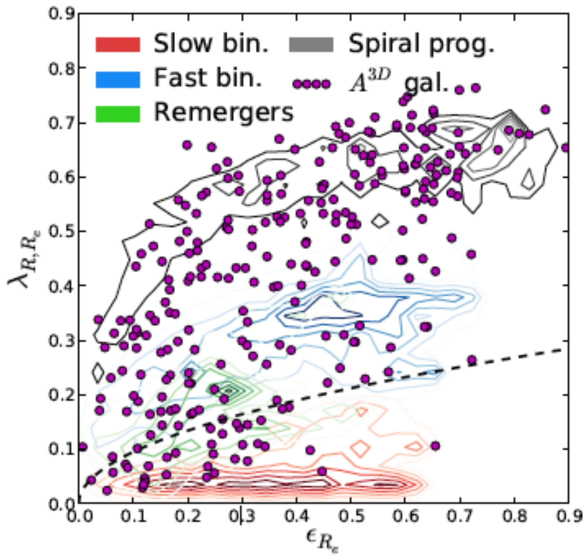


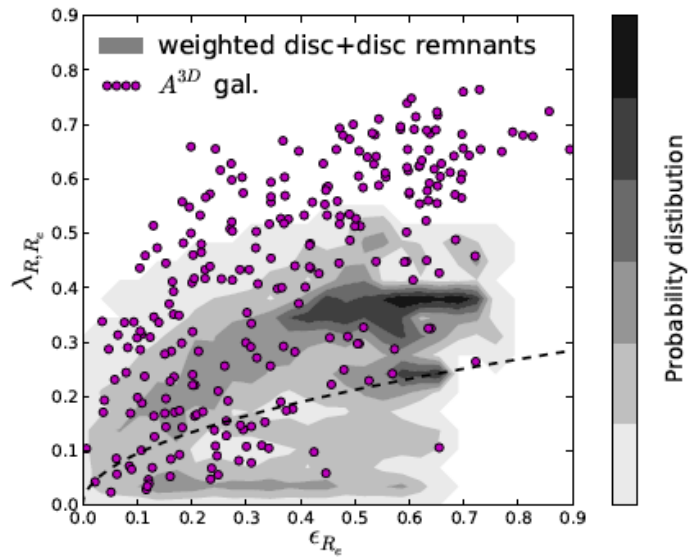
Merger simulations including star formation

In the idealized world: mass ratio is the decisive factor for slow/fast rotators
Re-mergers can make slow rotators

Jesseit et al. 2009

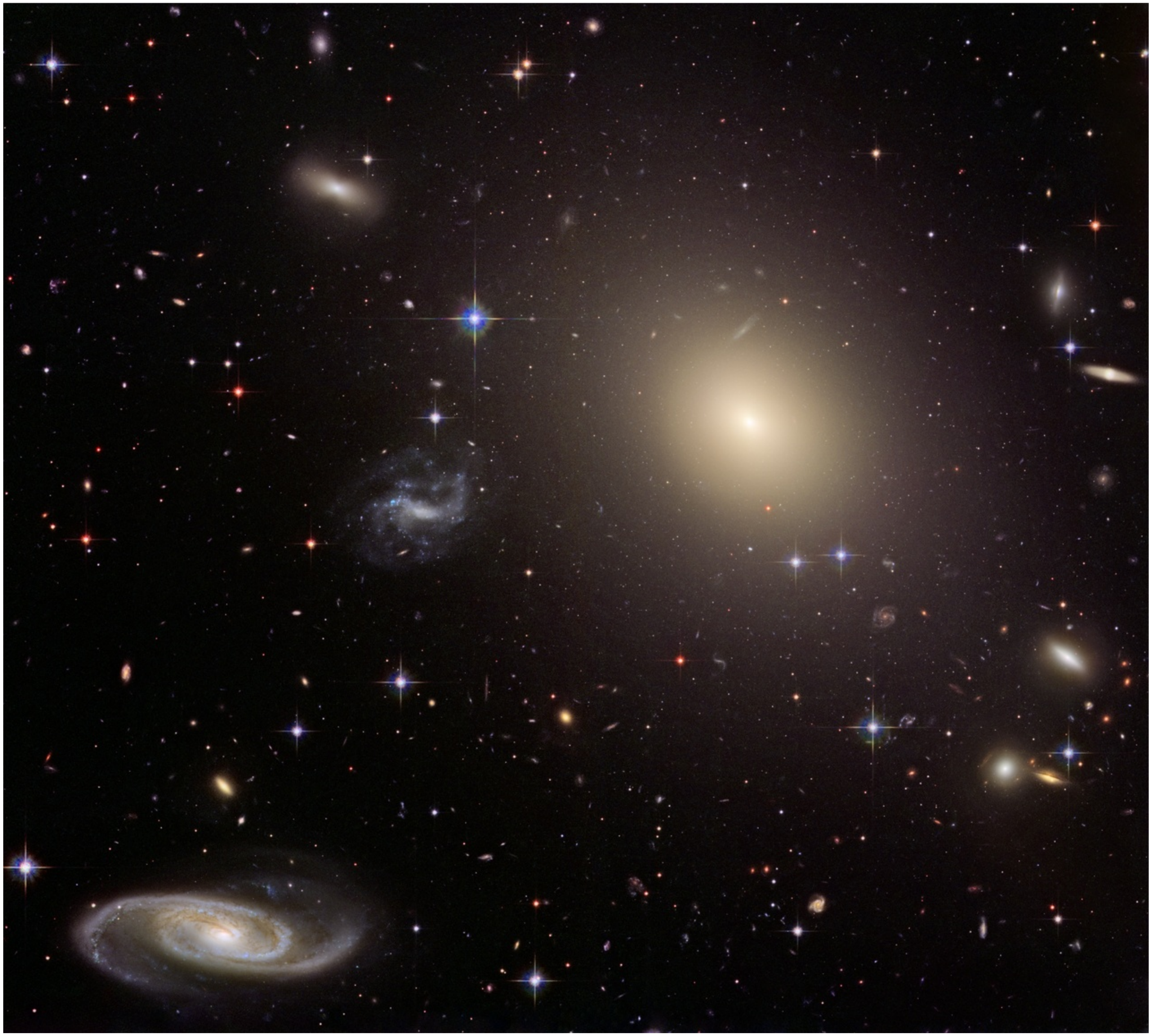
Rotation in merger remnants





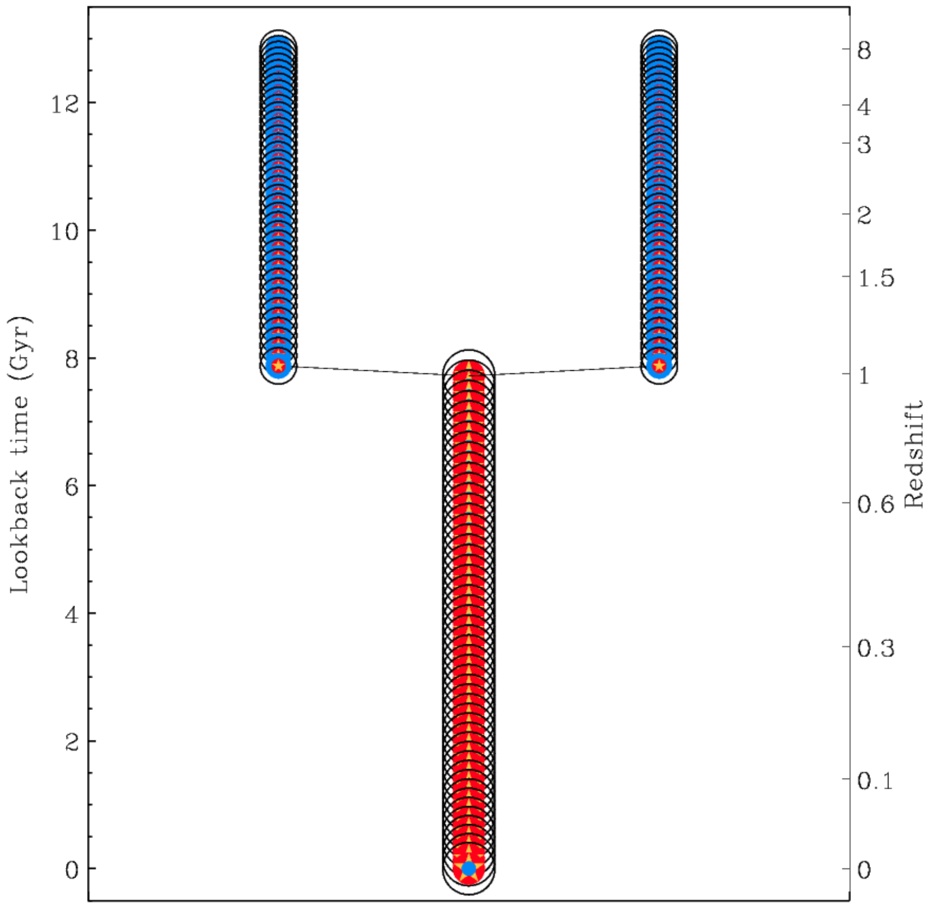
- Equal-mass merger remnants can produce slow rotators
- Slow rotators eventually too flattened
- Upper envelope of fast rotators cannot be explained with major mergers
- Re-mergers do not consistently form slow rotators and destroy KDCs
- Weighted with reasonable probabilities, 1:1 – 6:1 disk mergers cannot account for all early-type galaxies

ATLAS^{3D} VI: Bois et al. 2011



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

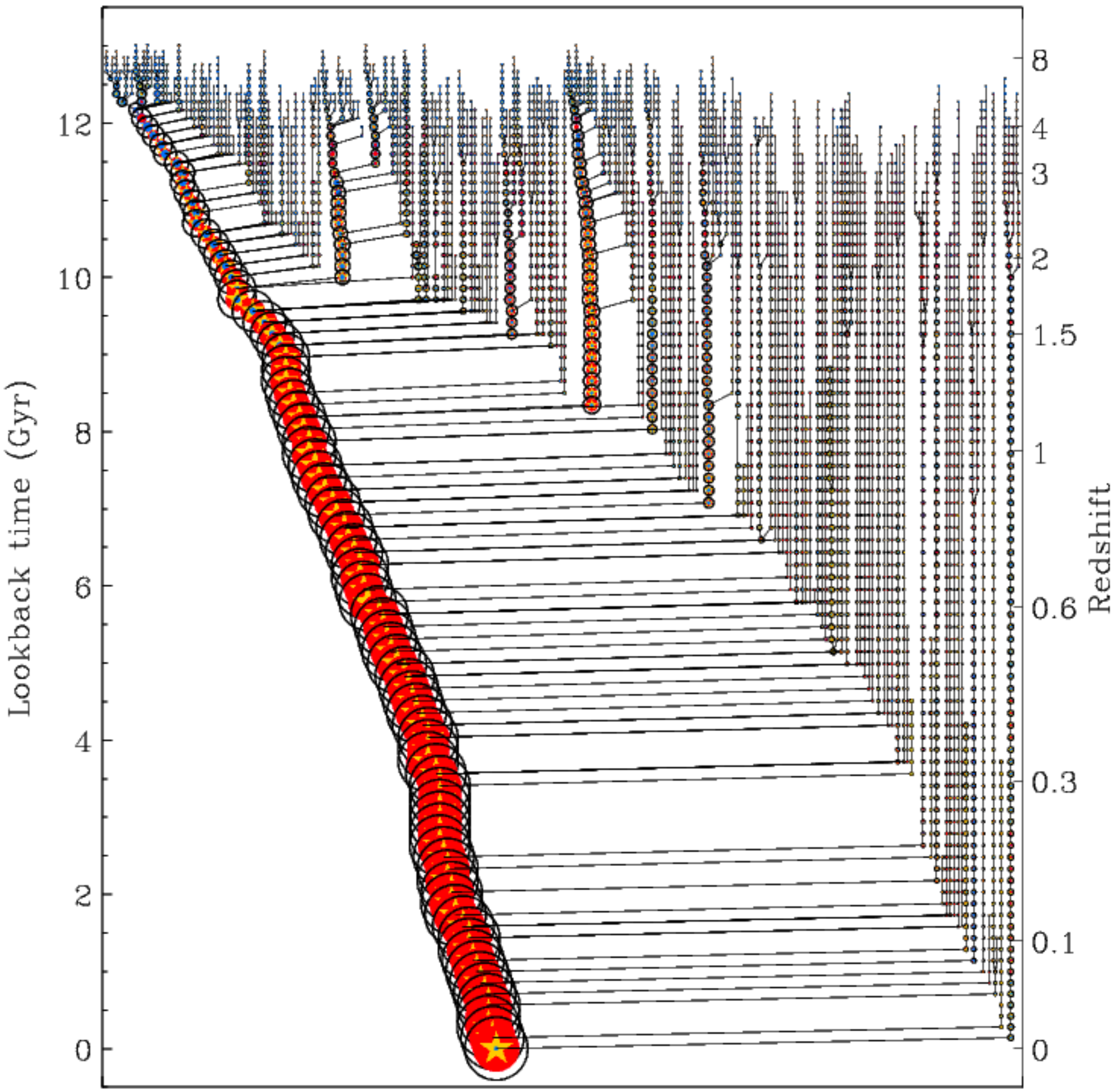
The binary merger-tree



- 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)

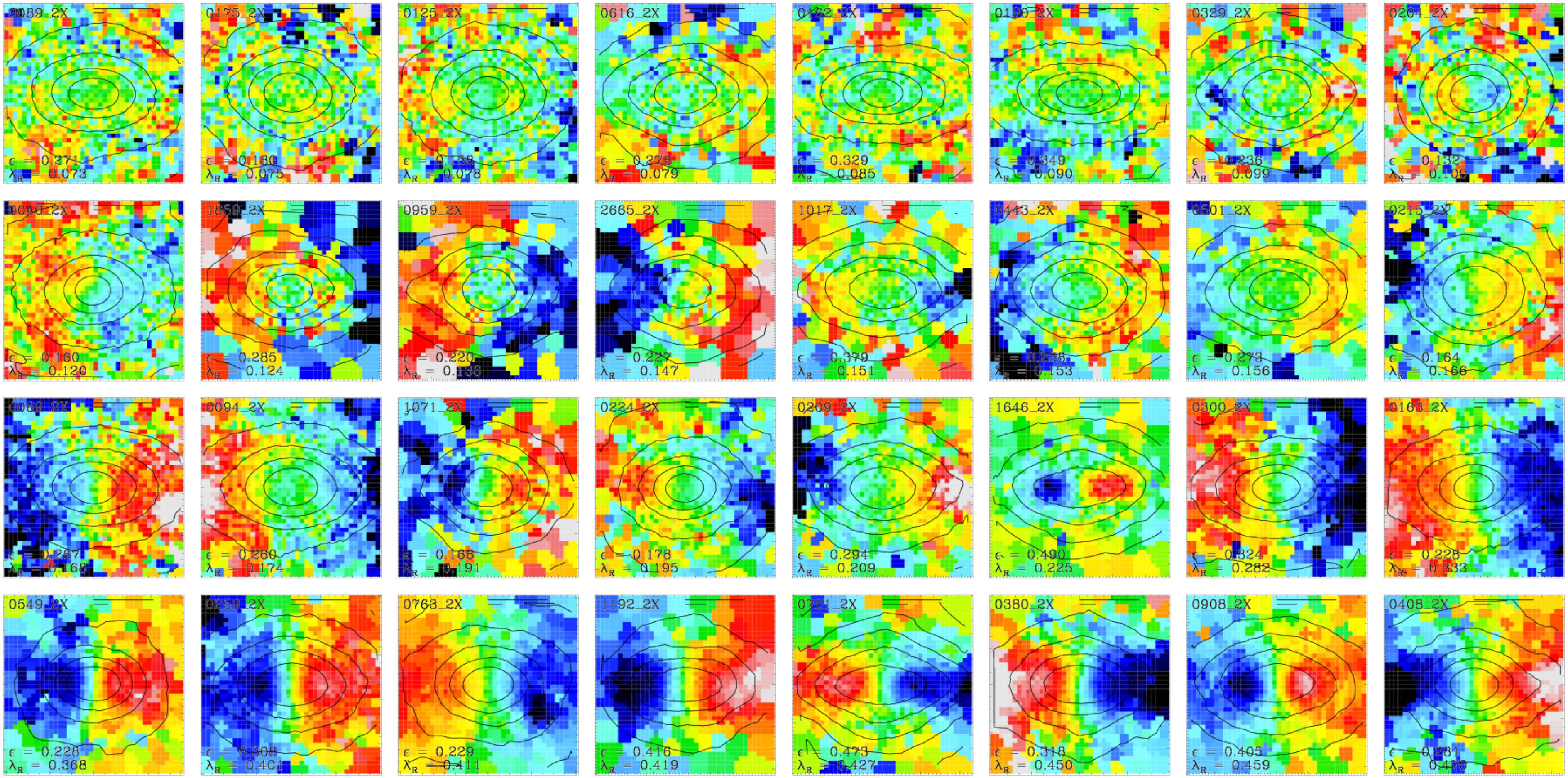
The two phases of galaxy formation

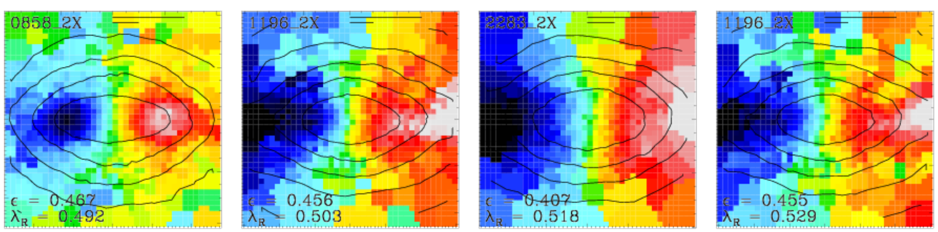


- Typical contribution of mergers (> 1:4) in massive galaxies since z=2 is 30% - 40%

Hirschmann et al. 2011

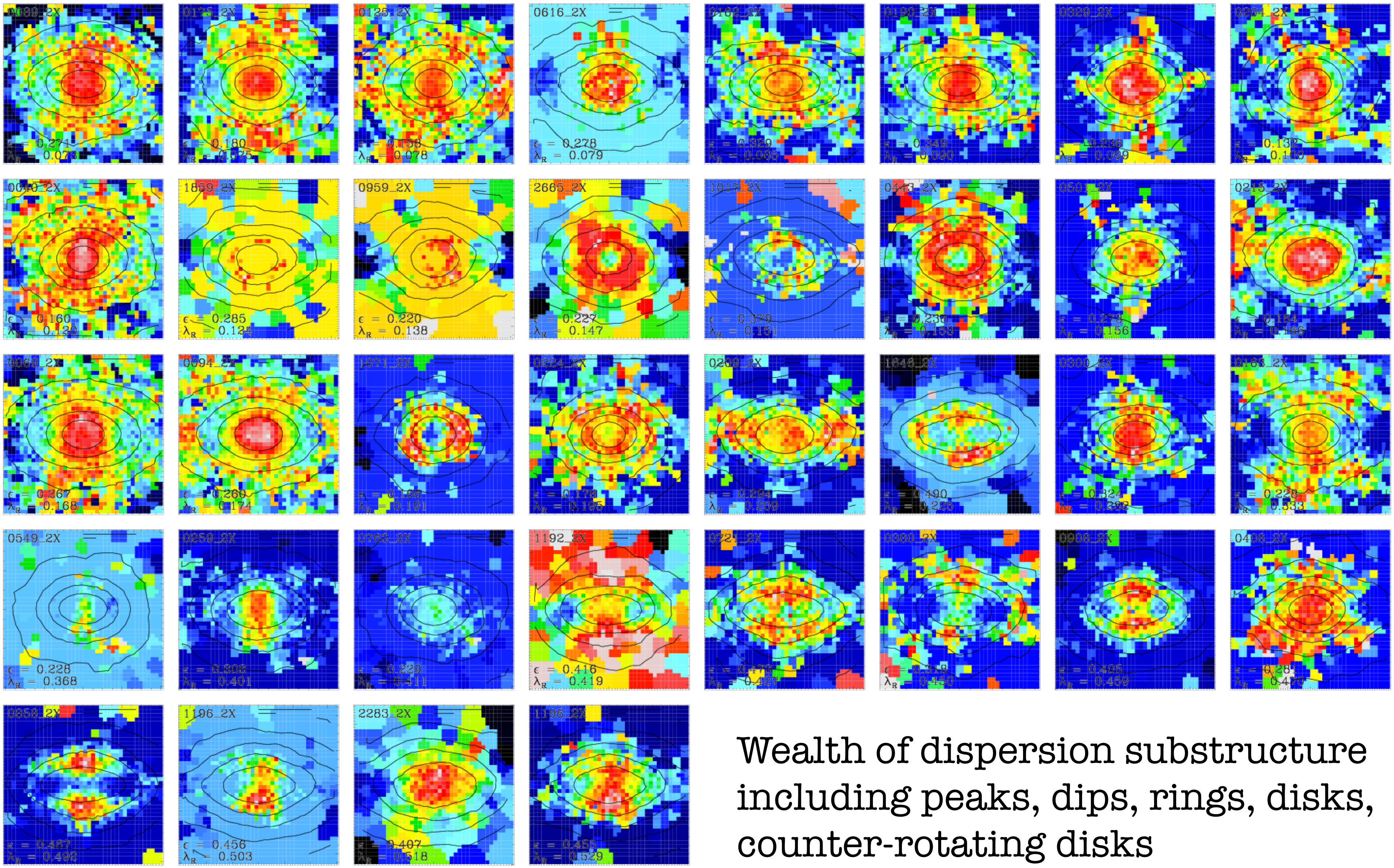
Gallery of cosmological-simulations





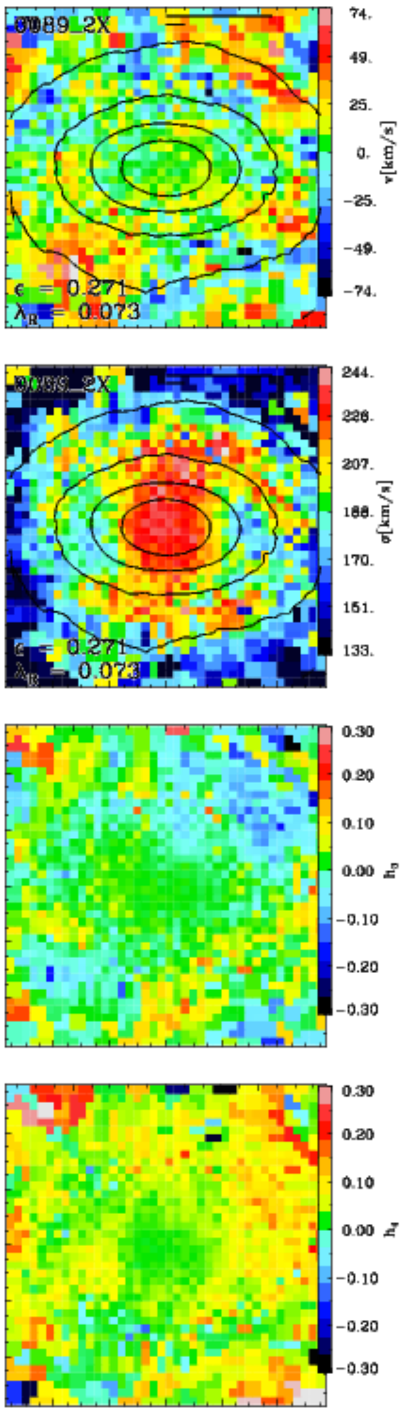
Wealth of velocity structure including slow rotation, KT, disk-like rotation, peaks, KRC?

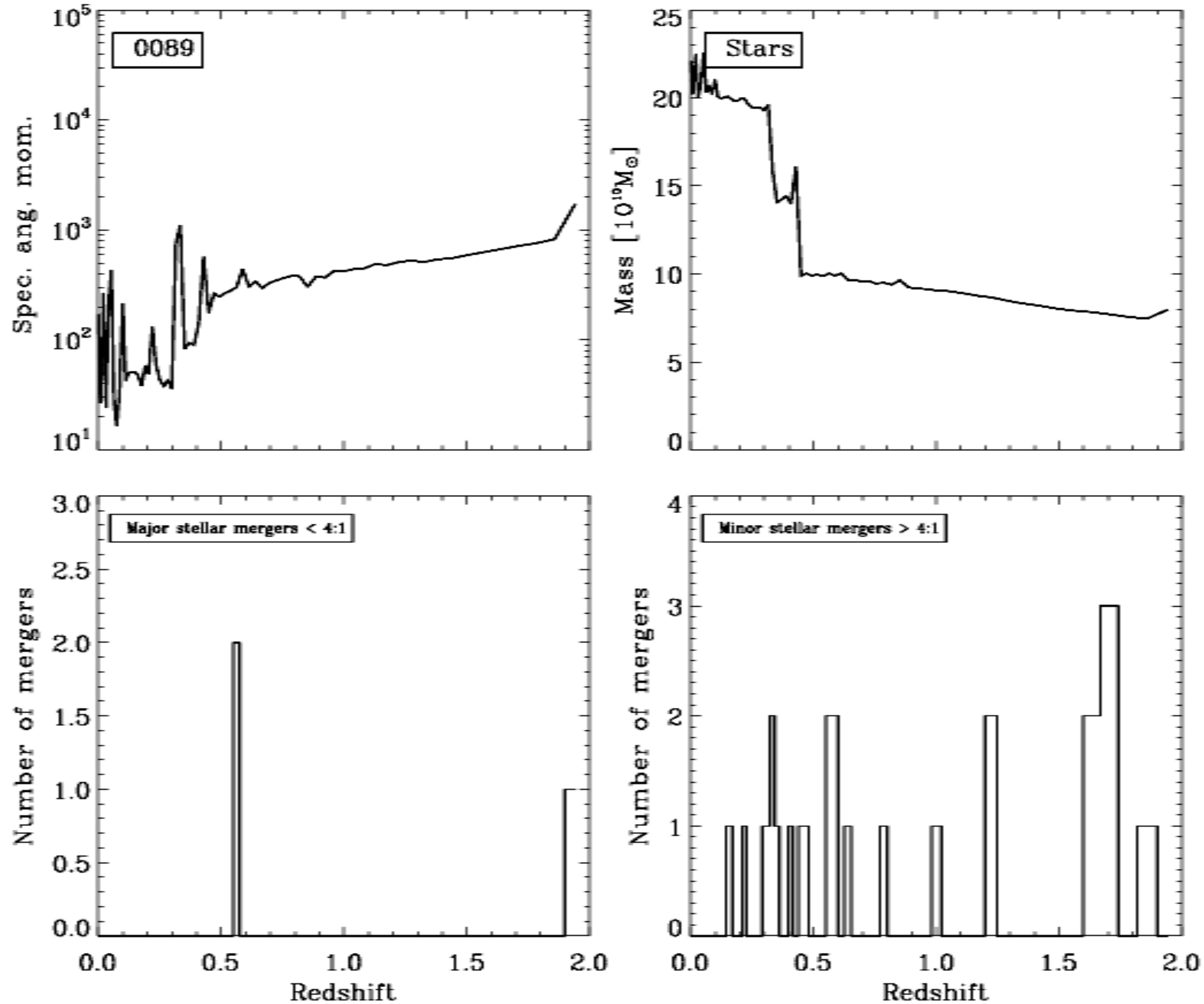
Gallery of cosmological-simulations



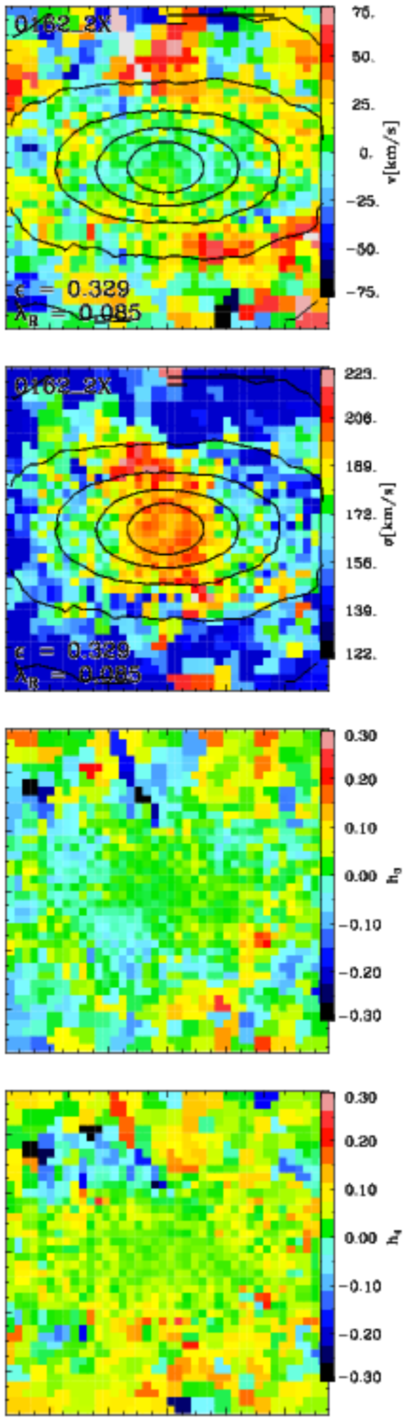
Wealth of dispersion substructure including peaks, dips, rings, disks, counter-rotating disks

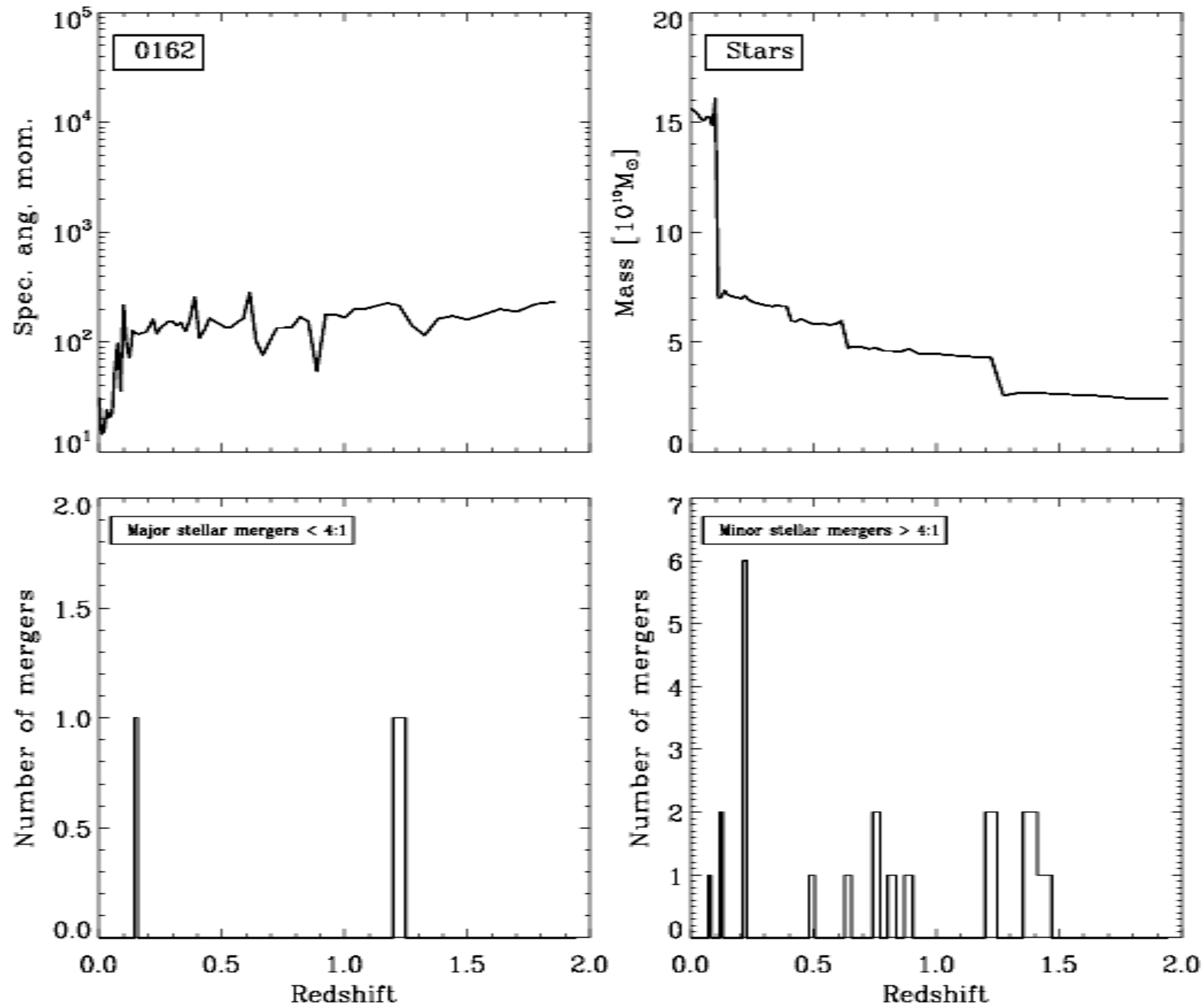
Stellar merger history and angular momentum



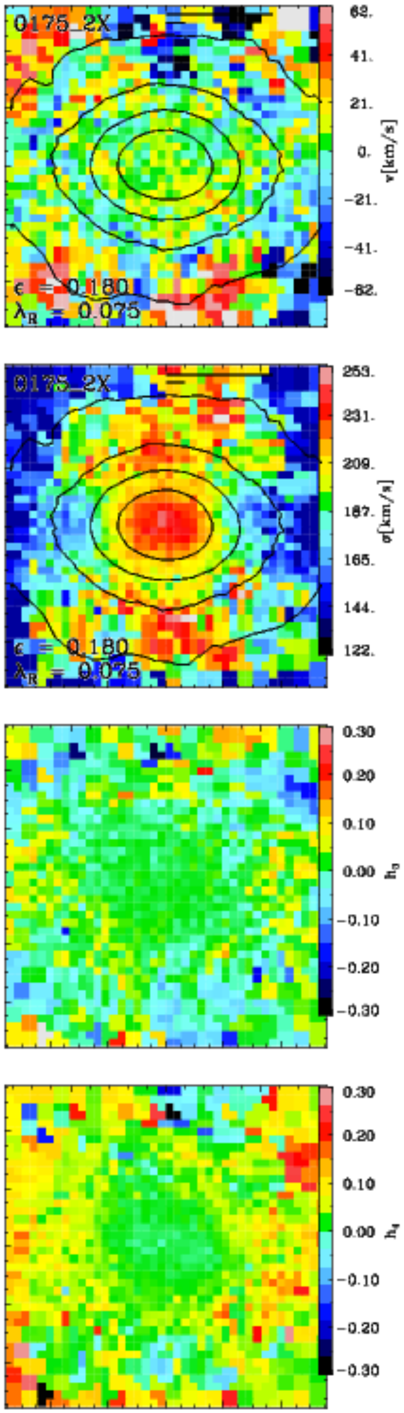


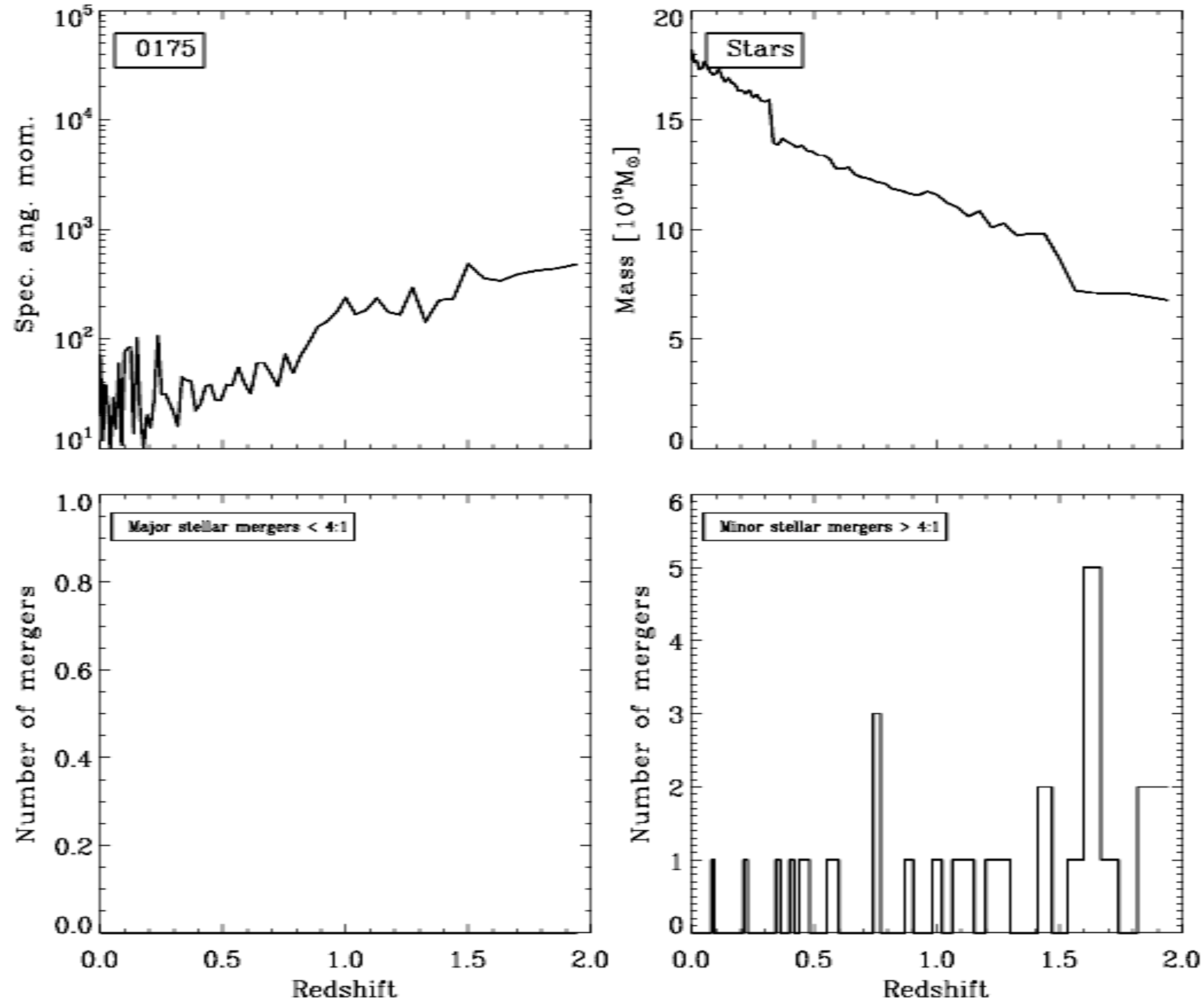
Stellar merger history and angular momentum





Stellar merger history and angular momentum





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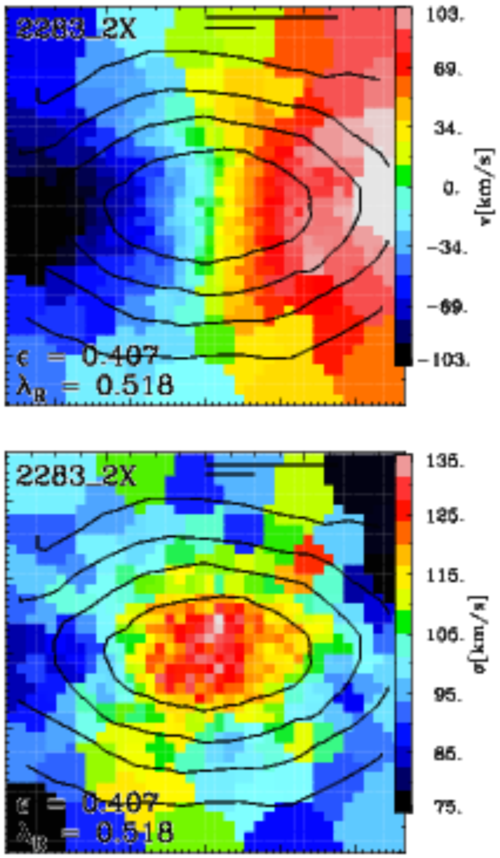
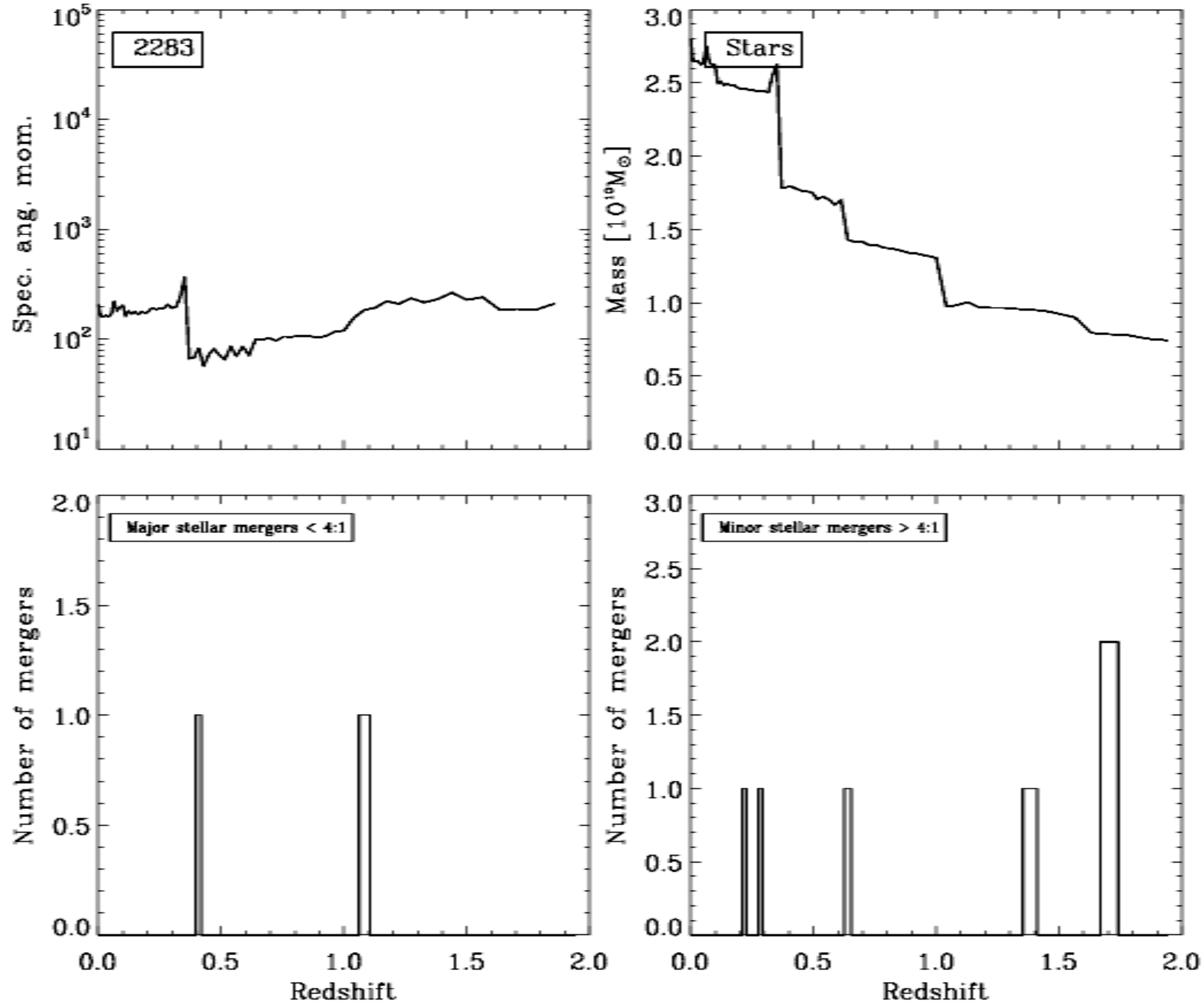
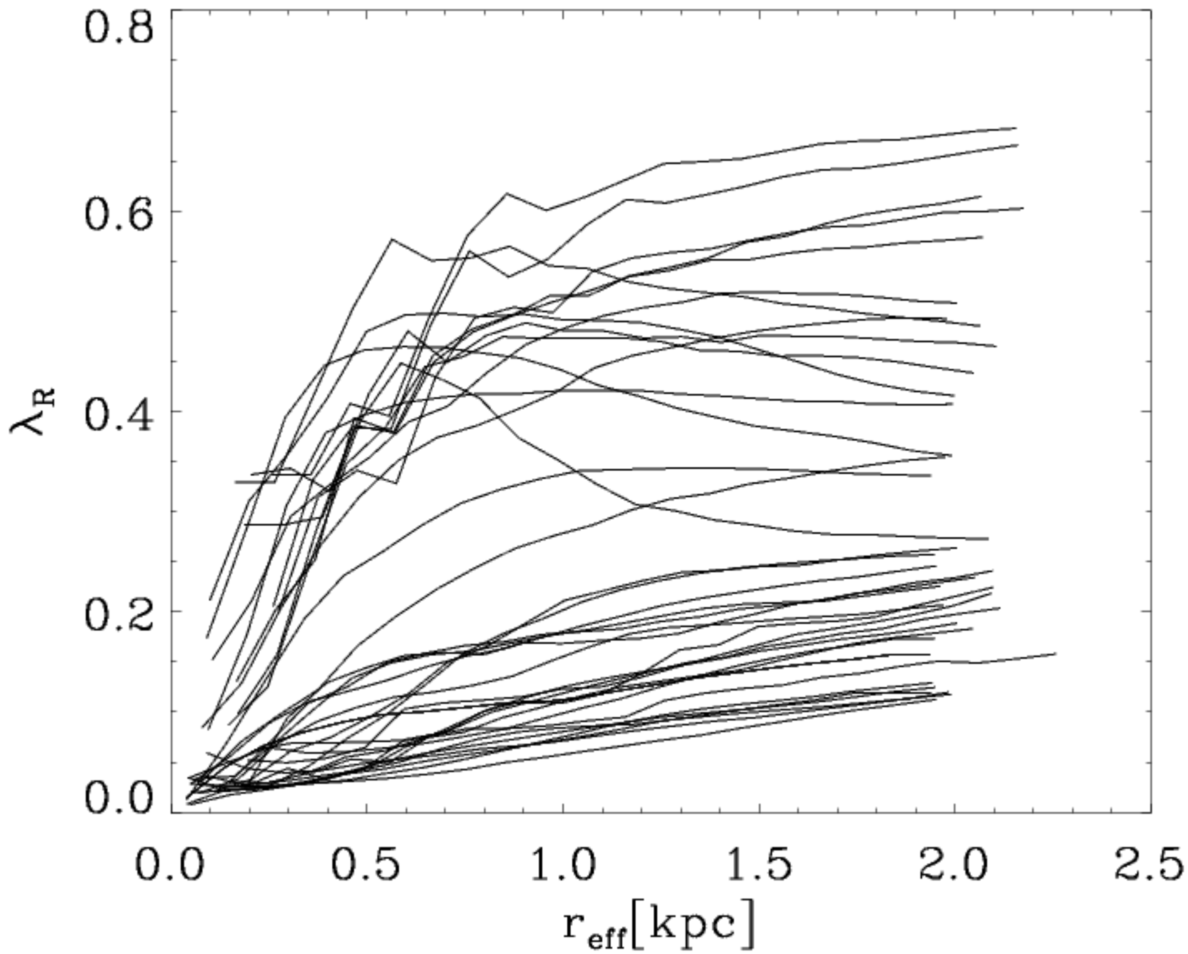


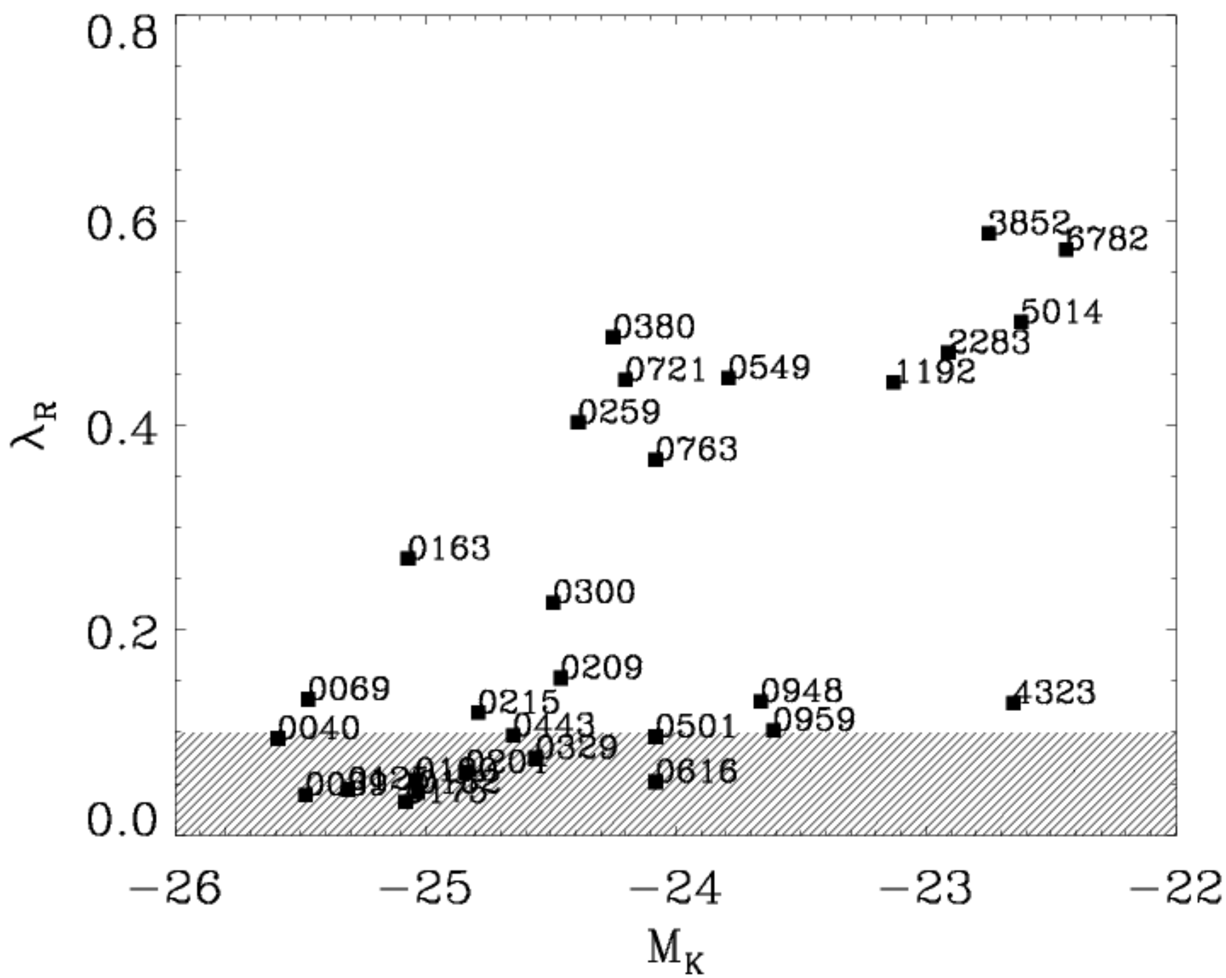


Profiles



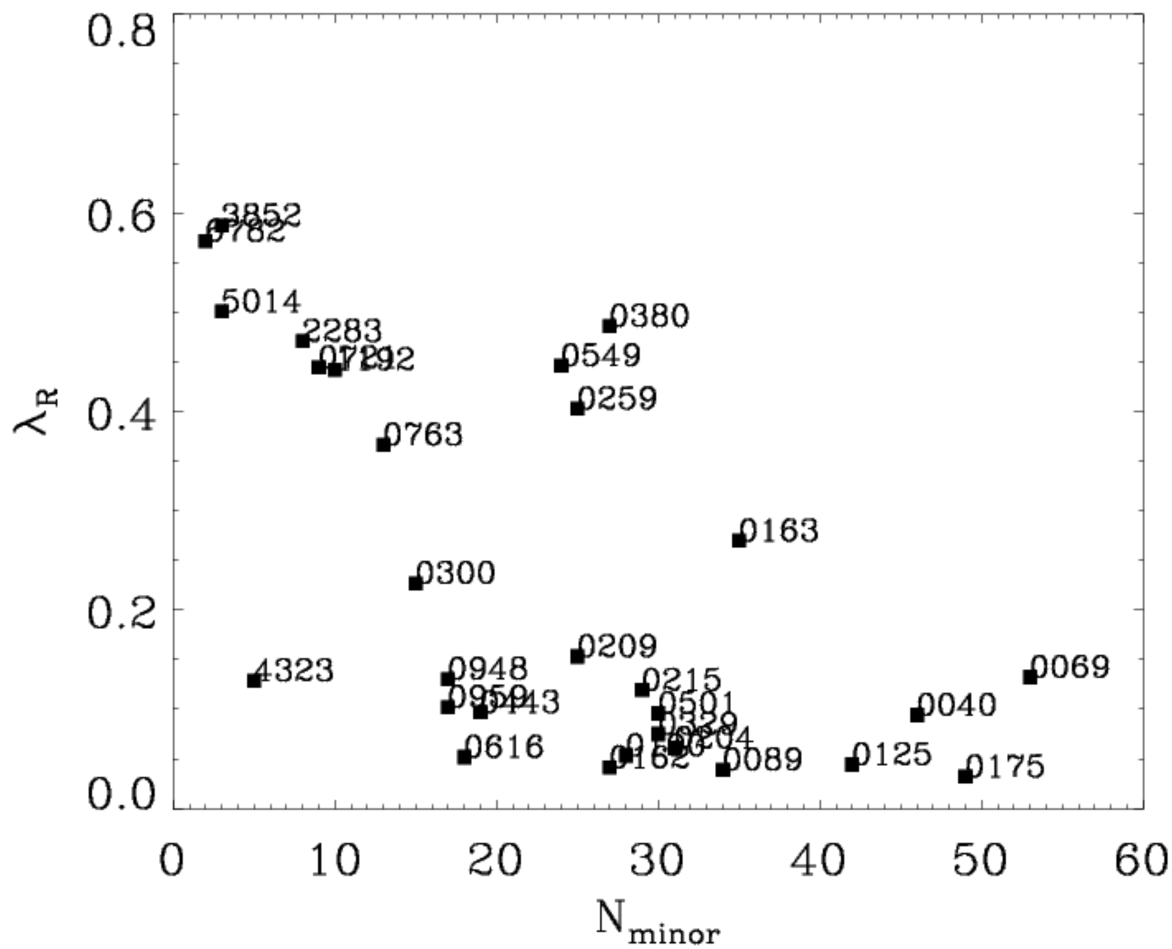
✓Profiles are in qualitative and quantitative agreement with observations

Correlations with λ_R



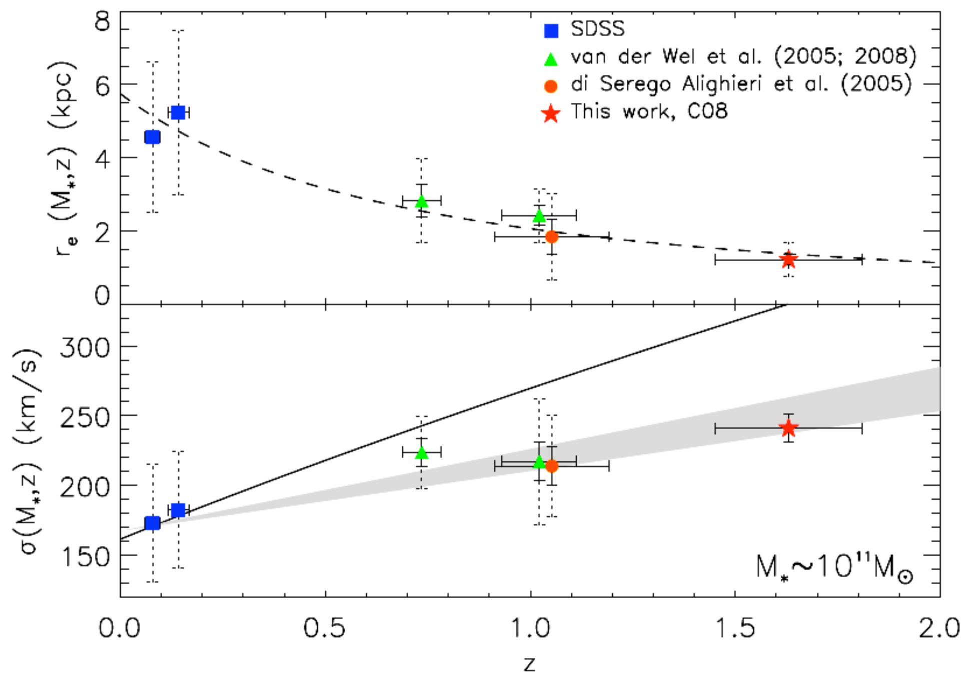
✓More massive systems are slower rotators

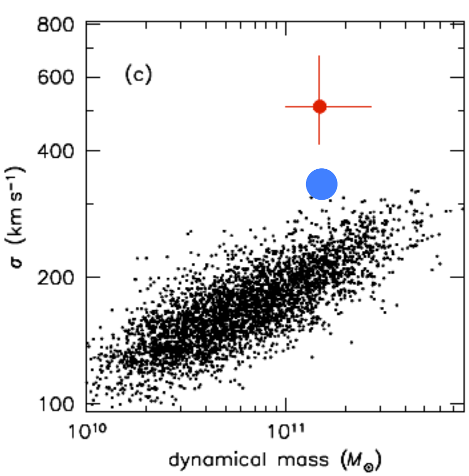
Correlations with λ_R: theory

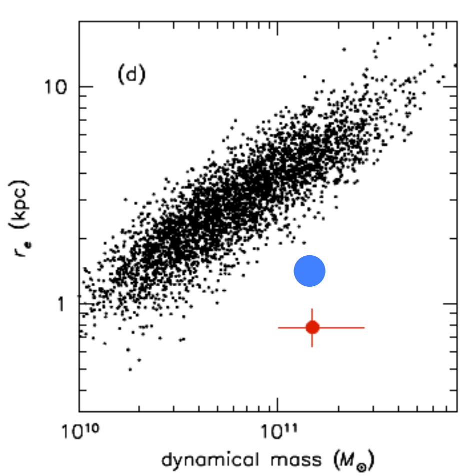


✓Galaxies with most minor mergers are slow rotators, major mergers do not matter!

Size and dispersion evolution since z≈2







- 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)
- Mild evolution of $\approx 10^{11} M_\odot$ 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 ($2\times10^{11} M_\odot$) 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)

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

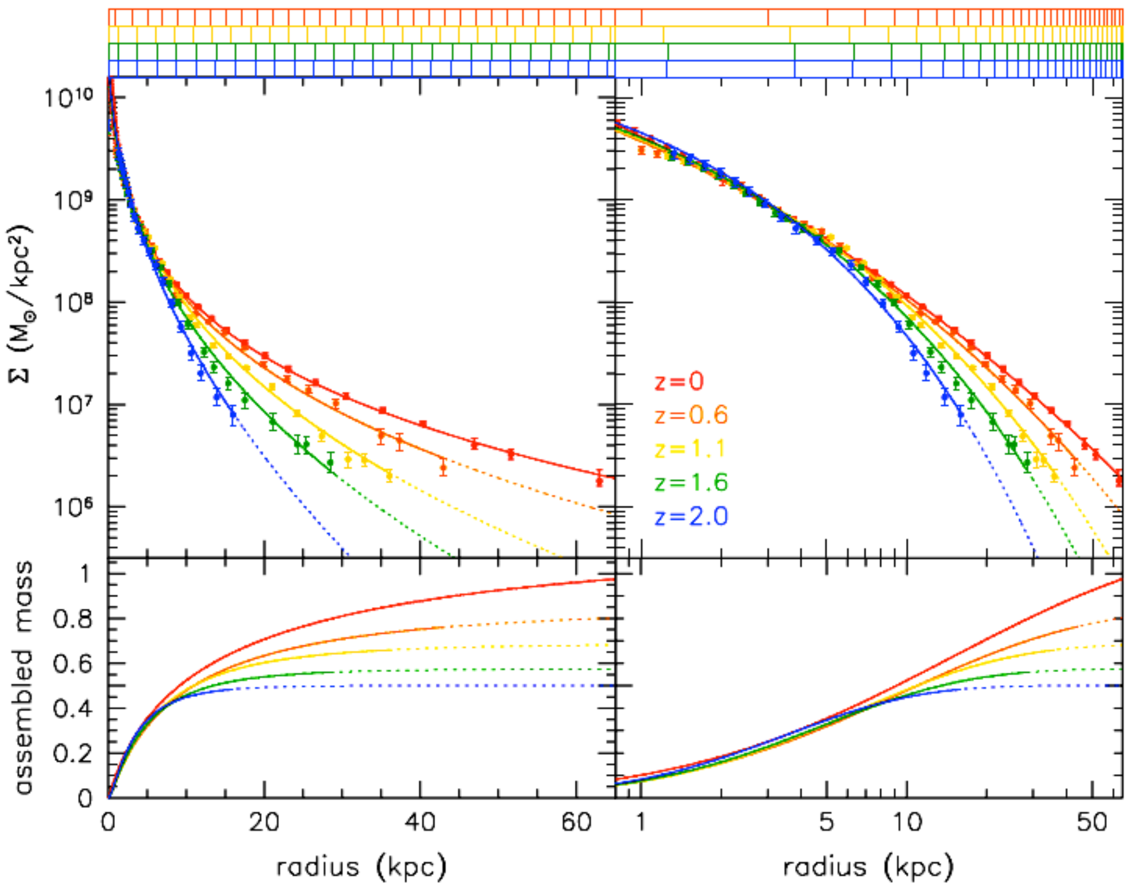
$$\frac{\rho_f}{\rho_i} = \frac{(1+\eta\epsilon)^3}{(1+\eta)^5}$$

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, cosmology

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

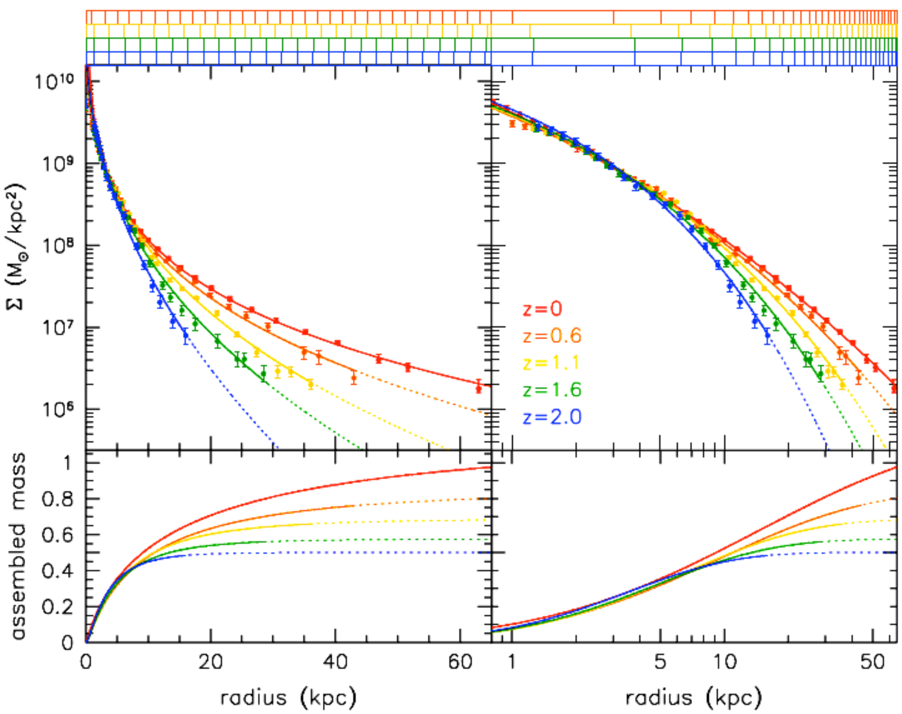
Inside-out growth since z = 2

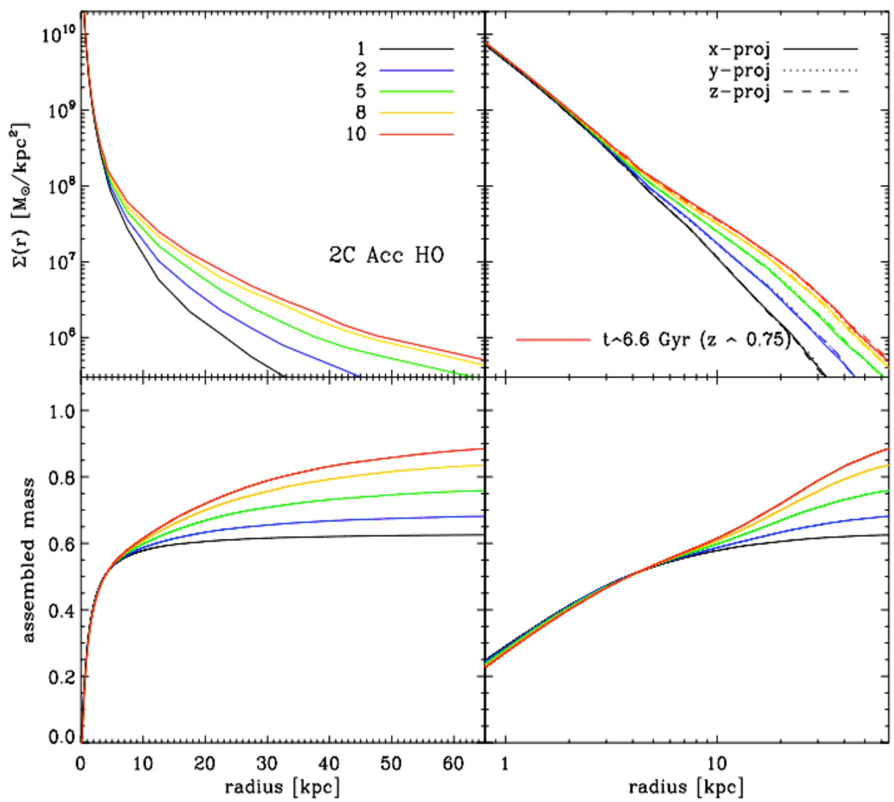


- Stacks of 70-80 galaxies at different redshifts
- Inside-out growth of ellipticals since z=2
- Mass increase by a factor of ~ 2
- Size increase by a factor of ~ 4
- $r \sim M^{\alpha}$, $\alpha \geq 2$
- Mass increase dominated by stellar accretion – energy conserving process

van Dokkum et al. 2010

Inside-out growth since z = 2

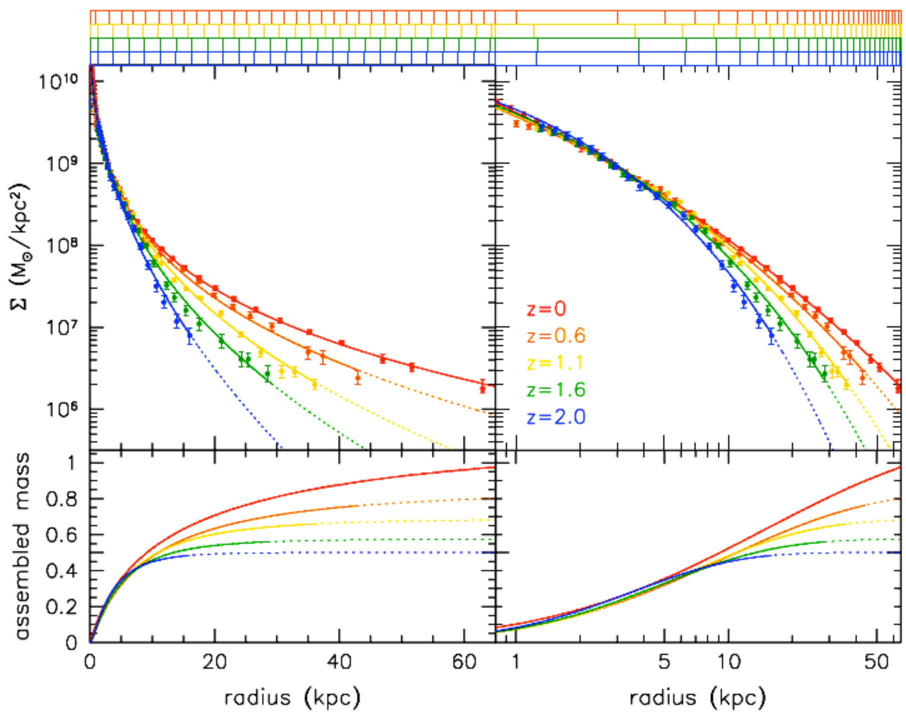


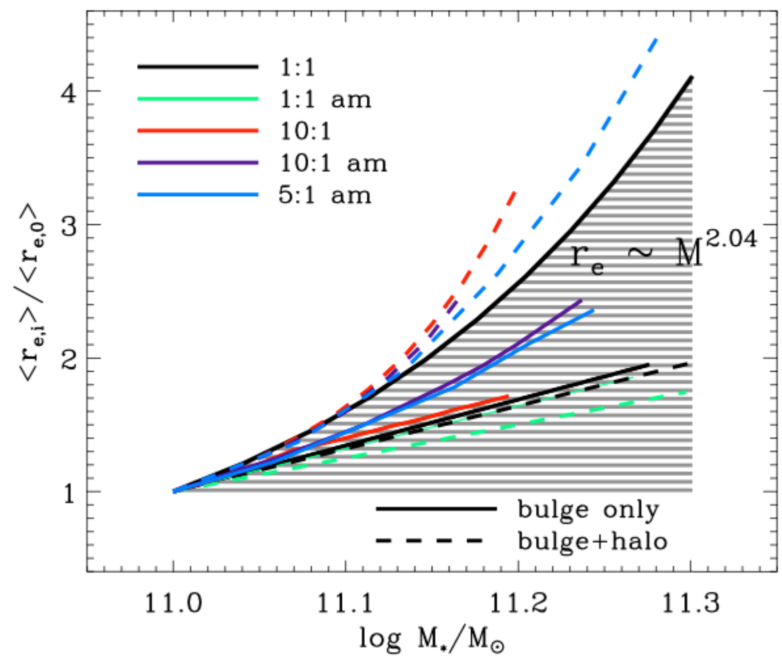


- Isolated 1:1 (mm) and 10:1 (acc) mergers of spheroidal galaxies without (1C) and with (2C) dark matter
- Only minor mergers with dark matter result in inside-out growth

Hilz et al. 2011, in prep.

Inside-out growth since z = 2

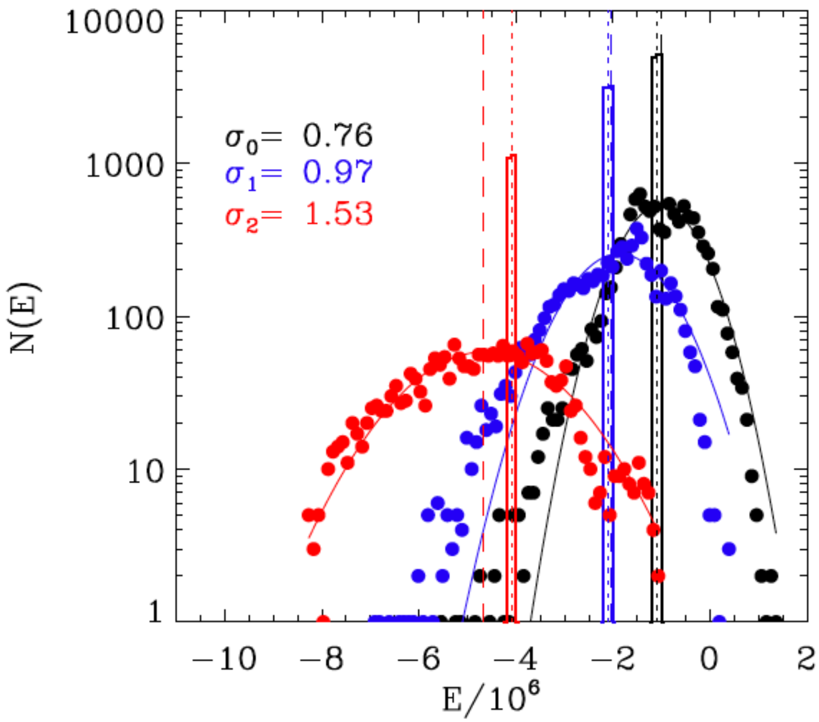


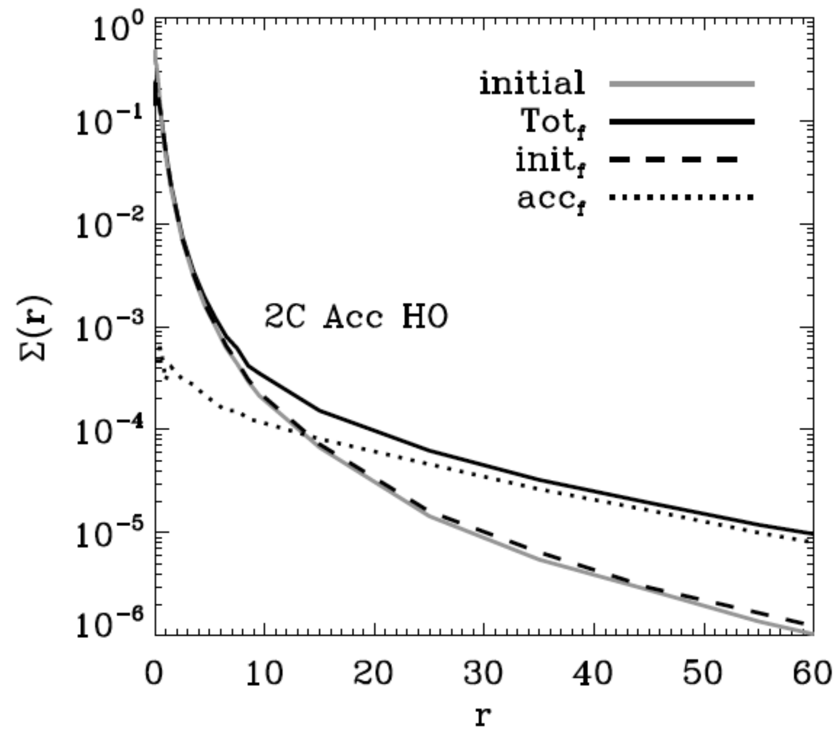


- Isolated 1:1 (mm), 5:1, and 10:1 (acc) mergers of spheroidal galaxies without (1C) and with (2C) dark matter
- Only minor mergers with! dark matter result in inside-out growth

Hilz et al. 2011, in prep.

Merger dynamics



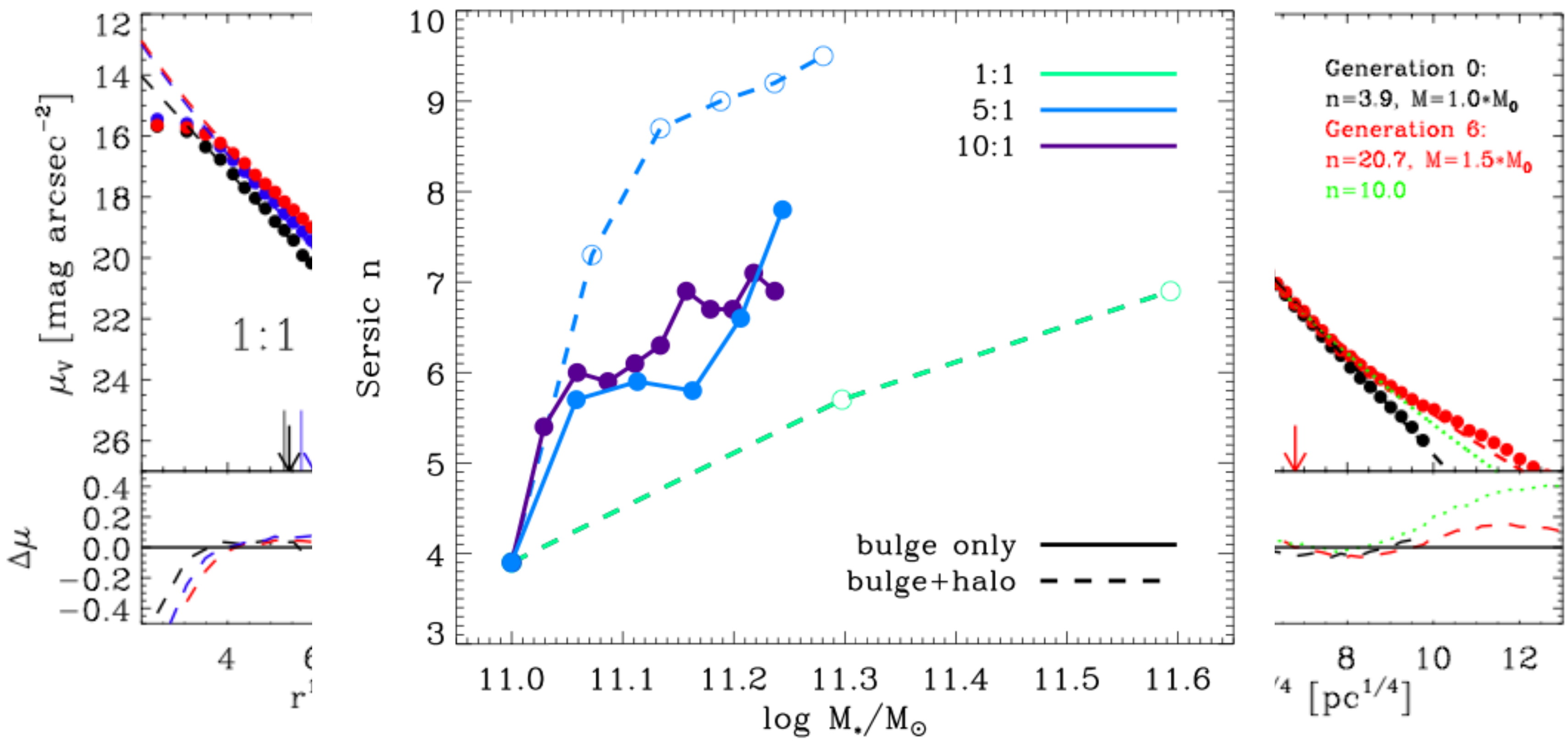


○ Violent relaxation – in major mergers - scatters particles in energy space to more bound and less bound – change in homology

○ Additional strong effect of stripping in minor mergers

Hilz et al. 2011, in prep.

Surface density profiles...



○ Minor mergers with dark matter can rapidly increase the Sersic index

○Rapid size evolution and the simultaneous evolution in Sersic index can be explained by minor mergers of galaxies surrounded by massive dark matter halos

Hilz et al. 2011, in prep.