Cosmological formation of slowly rotating massive elliptical galaxies

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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 ($H\beta$, [OIII], [NI]), kinematics and populations of stars ($H\beta$, 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...
Slow rotators (36/260), mostly round

ATLAS$^{3D}$ I: Cappellari, Emsellem, Krajnovic, Mc Dermid et al. 2011
Fast rotators (224/260), some pretty flat

**ATLAS$^3$D**  
I: Cappellari, Emsellem, Krajnovic, McDermid et al. 2011
Integral field spectroscopy of 48 elliptical and lenticular galaxies

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

Measure of the angular momentum of a galaxy: $\lambda_R$ (Emsellem et al. 2004)

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

$$\lambda_R = \frac{\langle R | V | \rangle}{\langle R \sqrt{V^2 + \sigma^2} \rangle}$$
Most massive early-type galaxies tend to be round and slow rotators.

Division line between slow rotators and fast rotators is $0.31 \cdot \sqrt{\epsilon}$

ATLAS$^{3D}$ III: Emsellem et al. 2011
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 ($\Psi < 5^\circ$) photometric and kinematic major axes (axisymmetric), rest is misaligned within $r_e$ (10%) and triaxial.

ATLAS$^3$D II: Krajnovic et al. 2011
Binary mergers of disks

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

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$^3$D VI: Bois et al. 2011
Size, mass (distribution) and velocity dispersion.....
The binary merger-tree

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).

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

![Diagram showing stellar merger history and angular momentum](image-url)
Stellar merger history and angular momentum

- **2283**:
  - Mass [10^3 M_☉]
  - Spec. ang. mom.
  - Redshift

- **Stars**
  - Mass [10^3 M_☉]

- **Major stellar mergers < 4:1**
  - Number of mergers
  - Redshift

- **Minor stellar mergers > 4:1**
  - Number of mergers
  - Redshift
Profiles are in qualitative and quantitative agreement with observations.
More massive systems are slower rotators
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 \((1+z)^\alpha\), \(\alpha=-1.22\) (Franx et al. 2008), -1.48 (Buitrago et al. 2008), -1.17 (Williams et al. 2010).

- Mild evolution of \(\approx10^{11}M_\odot\) ellipticals from 240 km/s at \(z\approx1.6\) (240 km/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...

\[
\eta = \frac{M_a}{M_i}, \quad \epsilon = \frac{\langle v_a^2 \rangle}{\langle v_i^2 \rangle}
\]

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

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

\[ r \sim M^\alpha, \quad \alpha = 1 \text{ for major mergers}, \quad \alpha = 2 \text{ for minor mergers} \]

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 $\sim 2$
- Size increase by a factor of $\sim 4$
- $r \sim M^\alpha$, $\alpha \geq 2$
- 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.
- 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.