Galaxy evolution in the cosmic web: galaxy clusters

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Color-Magnitude Relation - Red sequence $z \sim 0$

**FIGURE 1.** Color-magnitude distributions. (a): Observed bimodal distribution, corrected for incompleteness. The contours are

SDSS, Baldry et al. 2004
**Color-Magnitude Relation - Red sequence z~0**

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SDSS, Baldry et al. 2004
Color-Magnitude Relation

ACS GTO, Mei et al. 2009
Color-Magnitude Relation

Kodama et al. 2008, see also Zirm et al. 2008
Cluster Galaxy Morphology

Dressler 1980; Dressler et al. 1996

Morphology density relation

55 Cluster Sample – all, with area cut
Cluster Galaxy Morphology

**ATLAS 3D KINEMATICS** Cappellari et al. 2011

**Morphology density relation**

Dressler 1980; Dressler et al. 1996

55 Cluster Sample – all, with area cut

- E
- S0
- Sp
Morphology-Density Relation Evolution

Postman et al. 2005
Dependence on halo mass, role of groups

Figure 1. Morphological fractions within 0.6 $R_{200}$ vs. rest-frame cluster velocity dispersion for galaxies with a passively evolving absolute magnitude limit $M_V < -19.5$ at the WINGS redshift. Nearby clusters (WINGS) are black circles. Average Poissonian error bars for WINGS are shown in each panel on

Predictions from McGee et al. 2009, De Lucia et al. 2012: 40-50% galaxies in local clusters have been pre-processed in groups in the past
Early-Type Fraction evolution, dependence on galaxy stellar mass

The fraction of massive ETG is constant up to $z \sim 1.3$

Holden et al. 2007

Mei et al. 2011, 2012

selected in mass ($M > 10^{10.6} M_\odot$) and in density regions ($\Sigma > 500 Mpc^{-2}$)
Dependence on galaxy mass and environment

Local Universe - Calvi, Poggianti et al. 2011,
Dependence on galaxy mass and environment

Local Universe - Calvi,
Evolution of morphological fractions and the stellar mass function: mass/environment

ULTRAVISTA - Ilbert et al. 2013

Vulcani et al. 2011

X-ray selected 25 clusters - Raichoor & Andreon 2012
Evolution of morphological fractions and the stellar mass function

UltraVista, Ilbert et al. 2013
see also Muzzin et al. 2013
Environment

• Galaxy interactions with the cluster potential well. Time scale $10^8 - 10^9$ yrs

• Galaxy-Galaxy interactions - tidal friction mergers, dry major mergers (low speed - few Gyrs), harassment ($10^8$ yrs)

• Galaxy interactions with the ICM (e.g. Ram-pressure stripping, stripping of the ICM) - Decrease of star formation - Starvation. Ram-pressure stripping short time scales ($\sim 10^7 - 10^8$ yrs), Starvation few Gyrs

Local observations up to z~1, point mainly to starvation and harassment for satellite and mass-dependent and merger episodes for centrals

Treu et al. 2003; z=0.4
Evolution of morphological fractions and the stellar mass function

UltraVista, Ilbert et al. 2013
see also Muzzin et al. 2013
Galaxy Mass-Size Relation

z~0 ATLAS 3D Cappellari et al. 2012, see also e.g., Bernardi et al. 2012, Shen et al. 2003
Early-type galaxies (ETGs) double their size from $z \approx 1$ to the present, quadruple it from $z \approx 2$.

See also all references above, Valentinuzzi et al. 2010, Mancini et al. 2010, Cassata et al. 2011, Cimatti et al. 2012, van de Sande et al. 2013, and more...
Inside-out size growth

How to increase ETG sizes

- Quasar feedback for massive galaxies and stellar winds for less massive galaxies ($M < 10^{10} M_\odot$) - e.g., Fan et al. 2009. Size increases fast, mass does not increase

- Major mergers - Galaxy mass and size grow together

- Minor mergers (van Dokkum 2010) - Size increases more than mass

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Size and Environment

Huertas-Company, Shankar, Mei et al. 2013
z~0 SDSS
Yang et al. 2007 group sample; sizes from Bernardi et al. 2012

see also Poggianti et al. 2013
Size and Environment

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Cosmos X-ray groups $0.2 < z < 1$ (George et al. 2011)

- X-ray detected groups in the Cosmos field (Finoguenov et al. 2007), with weak lensing mass estimates (Leauthaud et al. 2007) in the range $10^{13} \text{ - } 10^{14} M_\odot$

- 298 group and 384 field quiescent early-type galaxies with stellar masses $> 10^{10.5} M_\odot$. Photometric redshifts from Ilbert et al. 2009: $0 < z < 1$. Galaxy sample purity ~70% - 85% within $0.5 \times R_{200}$

- Spectroscopic redshifts from zCOSMOS, Keck, MMT, SDSS, and our own VLT/FORS 2 spectroscopic follow-up of BCGs, bright satellites and galaxy mergers (P.I. Mei)

- Galaxy masses from Bundy et al 2007 and independent estimation by LePhare using BC03 stellar population models
Cosmos X-ray group E mass-size relation

**Huertas-Company, Mei et al. 2013**

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Cosmos X-ray group E mass-size relation

Huertas-Company, Mei, Shankar et al. 2013
see also Newman et al. 2012, Bluck et al. 2011
Clusters $0.8 < z < 1.5$

<table>
<thead>
<tr>
<th>Cluster</th>
<th>$z_{cl}$</th>
<th>$\sigma_{vel}$ (km/s)</th>
<th>$T$ (keV)</th>
<th>$M_{200}^X$ $(10^{14} , M_\odot)$</th>
<th>$R_{200}$ (Mpc)</th>
<th>$M_{200}^L$ $(10^{14} , M_\odot)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXJ0152-1357</td>
<td>0.84</td>
<td>$919 \pm 168^a$</td>
<td>$6.7 \pm 1.0^1$</td>
<td>$7.3_{-1.7}^{+1.8}$</td>
<td>$1.17_{-0.06}^{+0.09}$</td>
<td>$4.4_{-0.5}^{+0.7}$</td>
</tr>
<tr>
<td>RCS2319+0038</td>
<td>0.90</td>
<td>$1202 \pm 233^b$</td>
<td>$6.2_{-0.8}^{+0.92}$</td>
<td>$5.4_{-1.0}^{+1.2}$</td>
<td>$1.22_{-0.13}^{+0.15}$</td>
<td>$5.8_{-1.6}^{+2.3}$</td>
</tr>
<tr>
<td>XMMJ1229+0151</td>
<td>0.98</td>
<td>$683 \pm 62^c$</td>
<td>$6.4_{-0.6}^{+0.73}$</td>
<td>$5.7_{-0.8}^{+1.0}$</td>
<td>$1.12_{-0.10}^{+0.11}$</td>
<td>$5.3_{-1.2}^{+1.7}$</td>
</tr>
<tr>
<td>RCS0220-0333</td>
<td>1.03</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>$1.09_{-0.11}^{+0.12}$</td>
<td>$4.8_{-1.3}^{+1.8}$</td>
</tr>
<tr>
<td>RCS2345-3633</td>
<td>1.04</td>
<td>$670 \pm 190^d$</td>
<td>...</td>
<td>...</td>
<td>$0.87_{-0.10}^{+0.11}$</td>
<td>$2.4_{-0.7}^{+1.1}$</td>
</tr>
<tr>
<td>XMMJ0223-0436</td>
<td>1.22</td>
<td>$799 \pm 129^e$</td>
<td>$3.8_{-1.9}^{+4}$</td>
<td>$2.4_{-1.5}^{+1.0}$</td>
<td>$1.18_{-0.12}^{+0.11}$</td>
<td>$7.4_{-2.5}^{+2.5}$</td>
</tr>
<tr>
<td>RDCSJ1252-2927</td>
<td>1.23</td>
<td>$747_{-84}^{+74}f$</td>
<td>$7.6_{-1.2}^{+1.5}$</td>
<td>$4.4_{-1.0}^{+1.1}$</td>
<td>$1.14_{-0.06}^{+0.08}$</td>
<td>$6.8_{-1.0}^{+1.2}$</td>
</tr>
<tr>
<td>XMMU2235-2557</td>
<td>1.39</td>
<td>$802_{-48}^{+84}g$</td>
<td>$8.6_{-1.2}^{+1.36}$</td>
<td>$6.1_{-1.2}^{+1.0}$</td>
<td>$1.13_{-0.07}^{+0.08}$</td>
<td>$7.3_{-1.4}^{+1.7}$</td>
</tr>
<tr>
<td>XMMJ2215-1738</td>
<td>1.45</td>
<td>$720 \pm 110^h$</td>
<td>$4.1_{-0.9}^{+0.67}$</td>
<td>$2.0_{-0.6}^{+0.5}$</td>
<td>$0.9_{-0.14}^{+0.17}$</td>
<td>$4.3_{-1.7}^{+3.0}$</td>
</tr>
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*Delaye, Huertas-Company, Mei et al. 2013*

Nine clusters (ACS GTO, Sparcs, RCS) with $z \sim 0.8-1.5$ and mass in the range $2-7 \times 10^{14} \, M_\odot$ from the HAWKI Cluster survey (Lidman et al. 2013). ~400 ETGs (morphology selected and passive)
Size evolution and Environment

Delaye, Huertas-Company, Mei et al. 2013
see also Carollo et al 2013 for similar results for COSMOS field galaxies
Which galaxies

Low mass suggest environment quenching (and/or different morphology mix)
Accretion of younger, larger galaxies with time

Carollo et al. 2013, see also van der Wel 2010
The progenitors at z~2

Barro et al. 2012
The progenitors at z~2

Barro et al. 2012
## Physical processes and their signature

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DISC INSTABILITIES</strong></td>
<td>Mostly effective if violent and impulsive. Induce more compact bulges in less massive haloes with lower circular velocities</td>
</tr>
<tr>
<td><strong>MERGERS</strong></td>
<td>Only effective (at $z = 0$) if short dynamical friction timescales. More effective (minor) galaxy mergers in more massive host haloes, thus larger centrals</td>
</tr>
<tr>
<td><strong>GAS DISSIPATION</strong></td>
<td>Progressively more effective in less massive haloes with gas-richer progenitors</td>
</tr>
<tr>
<td><strong>SATELLITE EVOLUTION</strong></td>
<td>Overall milder effect. Present if fast quenching/gas stripping, thus proportionally less growth in satellites in lower mass haloes. Induces more compact remnants in less massive haloes</td>
</tr>
</tbody>
</table>

Shankar, Mei et al. 2013
Environment can distinguish predictions from different models

Shankar, Mei, Huertas-Company et al. 2013
Observations are at z~0 from Bernardi et al. 2012, Huertas-Company et al. 2013

**Figure 6.** Predicted median size-stellar mass relation of central galaxies in different bins of halo masses, log $M_{\text{halo}}/M_\odot < 13$, 13 < log $M_{\text{halo}}/M_\odot < 14$, and log $M_{\text{halo}}/M_\odot > 14$, for different models, as labelled. There is a large variation of median sizes up to a factor
Environment can distinguish predictions from different models

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mass, may reduce some of the tension. Despite the observational uncertainties, the data tend to disfavor hierarchical models characterized by strong disc instabilities, strong gas dissipation in major mergers, short dynamical friction timescales, and very short quenching timescales in infalling satellites. We also discuss a variety of additional

Shankar, Mei, Huertas-Company et al. 2013