Early-type galaxies in a cluster at $z=2$

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Evolutionary paths in galaxy morphology, Sydney 2013
... why going to redshift 2

![Graph showing the average SFR (M_⊙ Gyr⁻¹) / M_stellar versus lookback time (Gyr) with redshift on the x-axis.](image)

**De Lucia+ 2006**

**Bowens+ 2011**

- $10^{15}$
- $10^{13}$
- $10^{12}$
Cl J1449+0856

- “IRAC selected” (3.6-4.5μm), with a strong overdensity of red (Y-K>2) galaxies [Gobat et al. 2011]
- now spectroscopically confirmed at z=2 with >20 spectroscopic members [Gobat et al. 2013]
- an a-posteriori 3.5σ detection of extended X-ray emission [Gobat et al. 2011]
- a sub-$10^{14}M_\odot$ system, evolving into a typical massive cluster today
- wide multi-wavelength coverage including Subaru/VLT/HST/Spitzer optical/NIR, XMM, Chandra, Spitzer MIPS, Herschel PACS and SPIRE, APEX LABOCA, ALMA, JVLA, GMRT

Results presented here based on optical/NIR Imaging.
Cl J1449 as described by its galaxies

- a clear projected overdensity of (candidate) members
- a clear overdensity in redshift space

Projected $\Sigma_3$ density of $m_{140} < 25.7$ (candidate) members

![Projected Density Map]

![Histograms]

- $m_{F140W} < 24.5$
- $m_{F140W} < 25.7$
Cluster galaxies at redshift two

- a population of massive, quiescent early-type galaxies in the cluster core
- but cluster core hosts at the same time still actively forming galaxies

\textit{quiescent} or \textit{star-forming} cluster members (phot or spec), $m_{140} < 24.5$

Cluster galaxies at redshift two

- a population of massive, quiescent early-type galaxies in the cluster core
- **but** cluster core hosts at the same time still actively forming galaxies
- galaxy structure and stellar populations are already well correlated (as observed also in the field)

@log(M/M☉) > 10.4, ≈70% (⁺¹⁰⁻²₀) of passive (candidate) members have n>2 (similar in the field passive sample), wrt ≈10% (⁺²⁰⁻⁴) of SF members. In turn, ≈75% (⁺⁹⁻²⁰) of early-type (candidate) members are passive.

Cluster galaxies at redshift two

- quiescent fraction is already enhanced in the most dense regions

Compared to z≈1 clusters (e.g. Muzzin+ 2012) quiescent fractions appear to be lower (but beware of caveats!), at least for <10^{11} M_\odot galaxies. Already similar quiescent fraction for most massive core galaxies (see also e.g. Raichoor & Andreon 2012).

Quiescent fraction ≈15% (+15,-5) at log(M/M_\odot)<10.5, increasing to ≈30% at log(M/M_\odot)≈10.5-11, and ≈80% beyond 10^{11} M_\odot (also e.g. Kodama+ 2004, De Lucia+ 2007, Rudnick+ 2012,...)
Early-type galaxies in Cl J1449

- Cluster early-types appear smaller (by a factor 2-3) than z≈0 similarly massive early-types


- Cluster early-types might be \textit{larger (≈2x)} than z≈2 field early-types of similar mass

(see also Papovich+2012, Zirm+ 2012, Tanaka+ 2012 – perhaps more controversial results in lower redshift groups, e.g. Cooper+ 2012, Huertas-Company+ 2013)

Median ellipticity of cluster early-types close to low-z values (≈0.3, e.g. Holden+ 2009).
Early-type galaxies in Cl J1449

- Size difference between cluster and field early-types doesn’t seem to be due to systematic age differences (at face value...!)

see also spectral analysis Gobat+ 2013

e.g. Bernardi+ 2010, Valentinuzzi+ 2010, Saracco+ 2011... but see also e.g. Cimatti +2012, Onodera+ 2012, Whitaker+ 2012)
Early-type galaxies in Cl J1449

In principle, size evolution might indicate further structural evolution at later times, but... too many caveats to discuss here, including:

- local reference
- “progenitor bias”
- biases in stellar masses and sizes


![Graph showing size evolution vs. age and stellar mass](image)
The red sequence at $z=2$

New WFC3 F105W observations

Observed F105-F140 probes rest-frame U-B

= spec members

Kodama & Arimoto (1997) models ($z_f=3, 5, 10$)
The red sequence at $z=2$

New WFC3 F105W observations

Observed F105-F140 probes rest-frame $U-B$

- $d \leq 200$ kpc
- spec members
- $z_f = 3, 5, 10$

Kodama & Arimoto (1997) models ($z_f = 3, 5, 10$)
The red sequence at $z=2$

New WFC3 F105W observations

Observed F105-F140 probes rest-frame U-B

- $\odot$ = spec members
- $\square$ = $d \leq 200$ kpc

Kodama & Arimoto (1997) models ($z_f=3,5,10$)

Some “red sequence” galaxies are likely dusty SF (as expected)
The red sequence at $z=2$

![Graph showing the red sequence at $z=2$](image)

- **spec members**
- **$d \leq 200$ kpc**
Red sequence vs Main sequence
Star formation and quenching in Cl J1449

• Not quite there yet...
• In both plots, difficult to identify quenching galaxies
• Need dust-unbiased SFR tracer reaching close to $10^{10} \text{M}_\odot$...
summary

• Only few galaxy clusters discovered at z≈2. Cl J1449 may be an example of typical cluster progenitor at this redshift. We likely see what we might expect:
  • most dense regions already host a concentration of massive passive galaxies
  • these share the cluster core with younger siblings still in their very active age
  • their structure might be more evolved than in the field

• BUT:
  • beware of the (tons of) caveats! (uncertainties, systematics, selection effects, very poor statistics, ....)
  • likely large cluster-to-cluster differences at this epoch

• (among the) other things we are looking for:
  • an accurate mapping of star formation, to constrain the “reversal of fortune”
  • cold gas reservoirs, fueling star formation and affecting structural evolution
  • structural vs stellar population evolution
  • the early red sequence and the drop off the main sequence (ongoing quenching, and constraints on the early formation of first cluster early-types)