Satellite quenching was not important for $z>1$ clusters: most quenching occurred during infall.

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Quenching times are short but ages are old

Low-z galaxy clusters

- Environmental vs mass quenching (Peng+10)
- Studies of quenching timescales suggest that galaxies quench after 4-6 Gyr they enter the cluster

High-z galaxy clusters

Quenching timescales are estimated using the fraction of excess quenched galaxies in clusters with respect to the field. It is assumed that galaxies that fall in the clusters have similar properties than "field" galaxies.

However, there are two scenarios that we should consider:

- Preprocessing
- Protocluster galaxies differ

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**Sample - GOGREEN data**

Are protocluster (infall) galaxies different from the field?

| Name            | RA (J2000) | Dec (J2000) | Redshift | $\sigma$ (km/s) | $R_{200}$ (Mpc) |
|-----------------|------------|-------------|----------|-----------------|-----------------|
| SpARCS0034      | 8.675      | -43.132     | 0.867    | 700             | 0.58            |
| SpARCS0036      | 9.188      | -44.181     | 0.869    | 750             | 1.06            |
| SpARCS1613      | 243.311    | 56.825      | 0.871    | 1350            | 1.54            |
| SpARCS1047      | 161.889    | 57.687      | 0.956    | 660             | 0.91            |
| SpARCS0215      | 33.850     | -3.726      | 1.004    | 640             | 0.88            |
| SpARCS1051      | 162.797    | 58.301      | 1.035    | 689             | 0.84            |
| SPT0546         | 86.640     | -53.761     | 1.067    | 977             | 1.15            |
| SPT2106         | 316.519    | -58.741     | 1.131    | 1055            | 1.21            |
| SpARCS1616      | 244.172    | 55.753      | 1.156    | 782             | 0.92            |
| SpARCS1634      | 248.654    | 40.364      | 1.177    | 715             | 0.85            |
| SpARCS1638      | 249.715    | 40.645      | 1.196    | 564             | 0.73            |
| SPT0205         | 31.451     | -58.480     | 1.323    | 678             | 0.85            |
| SpARCS0219      | 34.931     | -5.525      | 1.325    | 810             | 0.98            |
| SpARCS0035      | 8.957      | -43.207     | 1.335    | 840             | 0.90            |
| SpARCS0335      | 53.765     | -29.482     | 1.368    | 542             | 0.69            |

Total of 15 galaxy clusters $0.85 < z < 1.5$

Cluster SPT 0546

Data: photometric and spectroscopic redshifts, stellar masses and U, V, J rest frame colours

Passive galaxies:

- $U - V > 1.3$
- $V - J < 1.5$
- $U - V > 0.88 \times (V - J) + 0.59$

Thank GOGREEN team for making the data public!

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Classifying Galaxies

We classified the galaxies as:

**Cluster galaxies**

\[ \frac{|z_{phot} - z_{cl}|}{1 + z_{phot}} < 0.08 \]

\[ r < R_{200} \]

**Infall galaxies**

\[ \frac{|z_{phot} - z_{cl}|}{1 + z_{phot}} < 0.08 \]

\[ R_{200} < r < 3R_{200} \]

**Control galaxies**

\[ 0.15 < \frac{|z_{phot} - z_{cl}|}{1 + z_{phot}} < 0.30 \]

\[ r > 1 \text{Mpc} \]
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What are the quiescent fractions for the clusters, infall and control?
Quenched Fraction Excess

- Comparison with other values in the literature
- Our method is different but the results are in agreement with van der Burg+20

\[ QFE_{2-1} = \frac{f_{q,2} - f_{q,1}}{1 - f_{q,1}} \]
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- Satellite quenching is **not** mass dependent
- Other works consider that the QFE is mass dependent but they only use cluster and field data
- When we use field and cluster data we have the same results as these works

Field cannot be used as a proxy for infall when estimating QFEs and quenching timescales

Caveats: mass limit and QFE is uncertain for higher masses

What fraction of infall galaxies are quenched when they enter the cluster?

QFE between cluster and infall is constant

Satellite quenching is 40%
Fraction of environmentally quenched

- Fraction of environmentally quenched galaxies *in the cluster*
- Half of low mass galaxies were quenched in the clusters but high mass galaxies arrived in the clusters already quenched

\[ f = \frac{f_{q,cls} - f_{q,proto}}{f_{q,cls}} \]
- QFE between infall and control is strongly mass dependent
- Massive infall galaxies are quenched more efficiently than similar mass galaxies in the control sample

This is not an evolutionary sequence! We are comparing them, but field galaxies will not become protocluster galaxies.
Satellite quenching was not important for z>1 clusters; most quenching occurred during infall

- Cluster and control QFE is misleading
- It suggests that high mass galaxies quenched more rapidly than low mass galaxies
- Control != Infall
- In the cluster all infall galaxies quench at the same speed
- Infall and control QFE is mass dependent
- We now explore why...
Environment of massive galaxies

We estimate the environment by measuring the satellites around each massive galaxy in the protocluster and control as Kawinwanichakij 2014.

Kawinwanichakij +14

Statistically estimated contaminants

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Satellite Galaxies

- Are massive galaxies being quenched because of satellite galaxies?
- Protocluster galaxies have 3x more satellites than the control.

Number of satellites around massive galaxies and around random points.

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Satellite Galaxies

- They have different $r_s$ (scale radius) \(\sim\) halo mass
- This is the first observational detection that the halo mass function in protoclusters is top-heavy

\[
\Sigma(x) = \begin{cases} 
  n(x^2 - 1)^{-1} \left( 1 - \frac{2}{\sqrt{x^2 - 1}} \arctan \sqrt{\frac{x-1}{x+1}} \right) & (x > 1) \\
  n/3 & (x = 1) \\
  n(x^2 - 1)^{-1} \left( 1 - \frac{2}{\sqrt{1-x^2}} \arctanh \sqrt{\frac{1-x}{1+x}} \right) & (x < 1)
\end{cases}
\]
Quenching Scenarios

How do infall galaxies quench?

- Preprocessing: higher number of satellites in massive halos compared to the control sample – groups falling inside the cluster ('overconsumption', ram-pressure stripping, strangulation or suffocation)
- Halo quenching model (Dekel & Birnboim 2006): infalling intergalactic medium is shock heated in the outskirts of haloes above a critical mass.
We find that protocluster galaxies differ from the control and cluster galaxies, in terms of stellar mass distribution and quiescent fraction.

We find that massive protocluster galaxies are surrounded by three times more satellites distribute according to an NFW profile with a larger scale radius than the control field.

We infer that the protocluster region contains a top-heavy halo mass function compared to the control. This may cause the excess quenching compared to the field.

**SUMMARY**

1. quenching timescales using field are wrong
2. environmental quenching is independent of stellar mass

**Implications**

Most of the excess quiescent galaxies present in high redshift clusters were quenched at an earlier phase when galaxies evolved in the protocluster environment.