The Phase-Space of z~1 Clusters: A View from Spitzer and Herschel

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How does Environment Influence Galaxy Evolution?

Hierarchical Structure Formation

Discrete Galaxy Populations within Clusters

galaxies accreted at early times vs galaxies accreted recently

Credit: Volker Springel - MPIA
Stellar Mass/Environment Covariance

<table>
<thead>
<tr>
<th>Nature vs Nurture</th>
<th>Mass</th>
<th>Environment</th>
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<tbody>
<tr>
<td>Fraction of star-forming galaxies</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>SFR per unit mass (SSFR)</td>
<td>✓</td>
<td>✗</td>
</tr>
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- e.g., Kauffmann+ 2004
- Peng+ 2010
- Muzzin+ 2012
- Wetzel+ 2012
Stellar Mass/Environment Covariance

Nature vs Nurture

Mass

- Fraction of star-forming galaxies ✓ ✓
- SFR per unit mass ✓ ✗
- Age of star-forming galaxies ✓ ✗

Environment

- Rapid Quenching of Star Formation?

E.g., Kauffmann+ 2004
Peng+ 2010
Muzzin+ 2012
Wetzel+ 2012
Stellar Mass/Environment Covariance

Nature vs Nurture

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| SFR per unit mass               | ❗    | ❗           |
| Age of star-forming galaxies    | ✓    | ❗           |

How well do we understand “environment”? e.g., Kauffmann+ 2004, Peng+ 2010, Muzzin+ 2012, Wetzel+ 2012
The Next Step

How does cluster environment shape galaxy evolution at $z>1$?

How we accomplish this

• a homogenous sample of high-z clusters, with spectroscopy
  $\rightarrow$ SpARCS/GCLASS

• accurate star formation rates
  $\rightarrow$ 24um-Spitzer, 100/160/250/350/500um-Herschel

• develop a dynamical definition for environment
  $\rightarrow$ accretion histories can isolate dynamically distinct galaxy populations
SpARCS Cluster Survey/GCLASS

- >200 massive infrared-selected cluster candidates
- 42 sq. deg. survey with deep $z'$ band imaging
- **GCLASS**: 10 spectroscopically confirmed clusters from $0.86 < z < 1.34$ with ~500 members above $2 \times 10^9 M_\odot$

Figure 1. $g_z[3.6\mu m]$ color images of the nine GCLASS clusters used in this analysis. The field of view of each image is $7' \times 7'$, which is approximately the area covered by the spectroscopic observations and corresponds to 3.5 Mpc on a side at $z=1$. Rich clusters at $z\sim 1$ show a range of morphologies, from roughly spherical and centrally concentrated with a clear central galaxy (e.g., SpARCS J003645$-$441050, $z=0.869$) to asymmetric with filamentary-like structure and no clear central galaxy (e.g., SpARCS 104737$+$574137, $z=0.956$). (A color version of this figure is available in the online journal.)

Muzzin et al. 2012

Noble et al 2013

Muzzin et al 2012
Results: $z=0.871$ Star-Forming Cluster Galaxies

Integrated SFR per total stellar mass of all cluster members increases with radius, but...

SSFR of star-forming galaxies is flat with radius

$\rightarrow$ rapid quenching?

Noble et al 2013
Results: $z = 0.871$ **Star-Forming Cluster Galaxies**

- MIPS cluster members
- Star-forming galaxies

**Integrated SFR per total stellar mass** of all cluster members increases with radius, but...

**SSFR of star-forming galaxies** is flat with radius

→ rapid quenching?

Are we truly sampling **star-forming galaxies** in distinct environments?
Isolating Accretion Histories with Simulations

Haines et al. 2012

Line-of-sight velocity ($v/\sigma$) vs. Clustercentric radius ($r/r_{500}$)

Redshift at which galaxy is accreted by cluster

- $0.21$
- $0.28$
- $0.36$
- $0.46$
- $0.56$
- $0.69$
- $0.83$
- $0.99$

see also:
- Biviano+ 2002
- Mamon+ 2004
- Gill+ 2005
- Mahajan+ 2011
- Oman+ 2013
Isolating Accretion Histories with Simulations

Haines et al 2012

Line-of-sight velocity ($v/\sigma$)

Clustercentric radius ($r/r_{500}$)

Redshift at which galaxy is accreted by cluster

Caustic profiles kinematically isolate different accretion histories

Isolating Accretion Histories in Phase-Space

Noble et al. 2013
**Conclusion:** An accretion-based definition of environment yields a $\sim 1$ dex depression of SSFR at low values of $r \times \Delta v$. 

**Diagram:** Specific SFR versus $r \times \Delta v$ at $z=0.871$.
Stacked Specific SFR versus $r \times \Delta v$ at $z \sim 1.2$

Same depression of SSFR at low values of $r \times \Delta v$ (early accretion) with larger sample and MIPS sample.
Dust Temperature versus $r \times \Delta v$

Intermediate phase-space bin has coolest dust temperature

Noble et al in prep
A Possible Quenching Model?

Strangulation
removal of warm gas/dust;
gradual or no decline in SFR

Ram-pressure stripping
removal of cold atomic disk gas;
delayed then rapid quenching of star formation

Noble et al in prep
Conclusions

• a dynamical definition for environment based on phase-space trumpet profiles \((r \times \Delta v)\) offers a unique snapshot of distinct galaxy populations that have been accreted at different periods of cluster formation

• we see a decline in the specific SFR of cluster star-forming galaxies with caustic environment - moving from regions of recently accreted galaxies to earliest accreted galaxies

• we see a slight decline in the dust temperature for galaxies in the intermediate phase-space bin

• we suggest one plausible quenching model with combination of strangulation and ram-pressure stripping