Adam Muzzin (Leiden), Chris Lidman (AAO), Howard Yee (Toronto), Ricardo Demarco (Concepcion), Alessandro Rettura (UC Riverside), Michael Balogh (Waterloo), Douglas Burke (Chandra/CfA), Erica Ellingson (Colorado), David Gilbank (Waterloo), Hendrik Hildebrandt (UBC), Henk Hoesktra (Leiden), Mark Lacy (NRAO), J.-C. Mauduit (SSC/IPAC), Julie Nantais (Concepcion), Allison Noble (McGill), Jason Surace (SSC/IPAC), Eelco van Kampen (ESO), Ludovic van Waerbeke (UBC), Tracy Webb (McGill), Joseph Cox (UCR), Andrew DeGroot (UCR), Alireza Farahmandi (UCR), Ryan Foltz (UCR), Andrew Crooks (UCR), Michael Cooper (UCI), Michael Boylan-Kolchin (UCI)
Stellar Mass of Brightest Cluster Galaxies

Lidman, Suherli, Muzzin, Wilson, et al., 2012, in prep

The Role of Environment (and Self-Regulation) in Galaxy Evolution

The SpARCS Survey (PI Wilson)

- Spitzer Adaptation of the Red-sequence Cluster Survey
- Deep-wide z’-band survey combined with Spitzer SWIRE 50 deg$^2$ survey
- Clusters are selected based on z’-[3.6] color (gives photo-z)*
- 200 new cluster candidates $z > 1$ with estimated $M > 1 \times 10^{14} M_{\odot}$

Wilson et al. (2009), Muzzin et al. (2009), Demarco et al. (2010)

SAMPLES OF CLUSTERS !!
SpARCS Fields

Survey summarized in

“Northern Fields”

ELAIS-N1
ELAIS-N2
XMM-LSS
Lockman Hole

“Southern Fields”

ELAIS-S1
CDFS

<table>
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<tr>
<th>Field</th>
<th>R.A. J2000</th>
<th>Decl. J2000</th>
<th>SWIRE 3.6 μm Area (deg²)</th>
<th>SpARCS z' Area (deg²)</th>
<th>Usable Area (deg²)</th>
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<td>55.4</td>
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http://www.faculty.ucr.edu/~gillianw/SpARCS
Ten of the most massive halos at $z=1$ from 50 deg$^2$
Brightest Cluster Galaxies

BCGs are easy to identify, observationally and in simulations => an attractive target for testing our understanding of the processes that drive evolution, albeit in the most massive galaxies of the Universe.
Stellar Mass of BCG versus Redshift

Observations
- Whiley et al. 2008
- Collins et al. 2009
- Stott et al. 2010

find no increase in SM since z~1

Simulations
- de Lucia & Blaizot 2007

predict that BCGs increase their SM by a factor of three since z~1
BCG K-band magnitude versus Redshift

Notice how all models overpredict the flux of high-redshift BCGs.
Stellar mass of BCG scales with cluster mass

Previous observations did not properly take account of Mass of Cluster
Stellar Mass of BCG versus Redshift

Lidman et al., 2012, in prep

Simulations

de Lucia & Blaizot 2007

predict that BCGs increase their SM by a factor of three since z~1
The Role of Environment (and Self-Regulation) in Galaxy Evolution

Mass versus Environment
(“nature” versus “nurture” debate)
The GCLASS Survey (PIs Wilson/Yee)

- Spectroscopic survey of 10 rich clusters at $z \sim 1$ ($0.87 < z < 1.34$) with Gemini/GMOS

- The Gemini CLuster Astrophysics Spectroscopic Survey “GCLASS”

- Low-res: $R=450 = 17\text{Å} = 400\text{km/s}$
- 4 to 6 masks per cluster (45 total)
- 3.6µm selected sample of galaxies

- Nod + Shuffle mode with microslits

- Observational goal: Spectroscopy of 50 members in each cluster(!)

- 222 hr (25 night) multi-semester project with Gemini/GMOS
MOS observation of the yellow region from a Keck/LRIS mask using standard length (~10") slits, and a band-shuffle mask on GMOS. More than 4x more slits can be placed within the cluster virial radius using GMOS vs. LRIS, a significant improvement in efficiency.
No “Reversal of SFR-Density Relation” in $z=1$ Clusters

Stacked spectra (~500 members), as a fn of clustercentric distance (left) and SM (right)  

Star formation decreases with increasing density (left) and increasing mass (right)
At $z\sim1$, galaxies are strongly influenced both by environment AND stellar mass
Effect of Environment and SM on SF Fraction:
SF fraction as a function of SM in four environments (left) and as a function of environment for three SMs (right)

Even at fixed environment (left), the SF fraction is correlated with SM
& at fixed SM (right), the SF fraction is correlated with environment

Both environment and SM play an important and causal role in quenching of galaxies at $z=1$
Separation of Environmental and SM Evolution:
SSFR of SF galaxies as a function of SM in four environments (left) and as a function of environment for three SMs (right)

SSFR is correlated with SM in all environments; but is independent of environment for all SMs

Stellar mass is the primary factor determining SSFR of SF galaxies

See also Balogh et al., 2004, Kauffmann et al., 2004, Peng et al., 2010
To Recap

• Both environment and stellar mass play an important and causal role in the quenching of galaxies at $z \sim 1$
• The SSFR of star-forming galaxies is correlated with their stellar mass, but this correlation is independent of the environment they live in.
• This is a surprising result!
  If both stellar mass and environment are responsible for quenching star formation it might be expected that the SSFRs of star-forming galaxies should decrease both as a function of environment and stellar mass, not just stellar mass alone.
Separation of Environmental and SM Evolution:
D4000 of quiescent (upper) and SF (lower) galaxies as a function of SM in four environments (left) and as a function of environment for three SMs (right).

D4000 is correlated with SM in all environments; but is independent of environment for all SMs.

Stellar mass is the primary factor determining age of a galaxy.
What does Environment do?

It quickly quenches SF in galaxies, rapidly transforming SF galaxies into quiescent galaxies.

The timescale over which environment quenches star formation in galaxies is very rapid.

It must be a rapid process because no dependence of the SSFR of SF galaxies on environment is seen => environmental quenching moves galaxies out of the SF classification and into the quiescent classification before a drop in their SSFRs is measured.

Can we test this idea?
What does Environment do?

It quickly quenches SF in galaxies, rapidly transforming SF galaxies into quiescent galaxies

Corroborating Evidence from Poststarburst (K+A) Population

= the subset of galaxies with weak [OII] emission and strong H\(\delta\) absorption-line strength. The lack of [OII] emission is an indicator of a lack of ongoing star formation, and the strong H\(\delta\) absorption is indicative of a population of A-stars which have lifetimes of \(\sim 1\) Gyr. Therefore, K+A galaxies can be considered to have no ongoing star formation but a young stellar population less than 1 Gyr old.
What does Environment do?

It quickly quenches SF in galaxies, rapidly transforming SF galaxies into quiescent galaxies.

Corroborating Evidence from Poststarburst Population

Mean stacked spectrum of candidate poststarburst galaxies with $1.0 < Dn(4000) < 1.45$ and no detectable [OII] emission.
What does Environment do?

It quickly quenches SF in galaxies, rapidly transforming SF galaxies into quiescent galaxies.

Corroborating Evidence from Poststarburst Population

Fraction of poststarburst galaxies is a function of stellar mass AND environment. Poststarbursts are more (3x) common in the high-density cluster environment.
What does Environment do?

It quickly quenches SF in galaxies, rapidly transforming SF galaxies into quiescent galaxies.

Corroborating Evidence from Poststarburst Population

Excess of poststarburst galaxies in the high-density cluster environment more direct evidence for the importance of environmental quenching of SF at $z \sim 1$

Environmental quenching sufficiently abrupt to create the poststarburst signature in galaxies
Are Baryons “pre-processed” in Groups?

While most cluster mass is thought to be accreted from groups (large grey circles), most cluster galaxies are thought to be accreted from the field (blue circles), and not pre-processed in groups (from Bullock et al. 2010).

But see McGee et al. 2009, Balogh & McGee 2010
The End