Massive Galaxy Evolution in the *Spitzer/IRAC* Shallow Cluster Survey

M. Brodwin (JPL/Caltech)
Massive Galaxies over Cosmic Time II
November 3, 2006
# Collaborators

## Core Cluster Search Team:
- M. Brodwin (JPL/Caltech)
- P. R. Eisenhardt (JPL/Caltech)
- A. H. Gonzalez (U. Florida)
- S. A. Stanford (UC Davis)
- D. Stern (JPL/Caltech)

## Surveys

<table>
<thead>
<tr>
<th>Surveys</th>
<th>Data</th>
<th>PI(s)</th>
</tr>
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<tbody>
<tr>
<td>IRAC Shallow Survey</td>
<td>Imaging: 3.6/4.5/5.8/8.0 μm</td>
<td>P. R. Eisenhardt (JPL/Caltech)</td>
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<td>NOAO Deep Wide-Field Survey (NDWFS)</td>
<td>Imaging: Deep B_w/R/I/K</td>
<td>A. Dey (NOAO)</td>
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<td>B. T. Jannuzi (NOAO)</td>
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Origin of Stars in Massive Galaxies

Treu et al (2005)

Massive Galaxies in Clusters at $1 < z < 2$

Questions:

1. What are the formation redshifts of massive galaxies in rich environments, from low-mass groups to rich clusters?
   - When were the stars formed?
   - When were the galaxies assembled?

2. What is the contribution of LIRGs/ULIRGs to the stellar mass budget? What is the AGN fraction?

3. When are the red-sequence, morphology-density relation and Hubble sequence established?
The Spitzer Advantage

- Bruzual & Charlot model
  - 0.1 Gyr Burst, $z_f = 3$
  - $H_0=70; \Omega_M = 0.3; \Omega_\Lambda = 0.7$

- Red galaxies quickly fade in optical due to strong K-correction

- Near-IR better; hard to get deep, large areas

- Mid-IR best, with flat sensitivity at $0.7 < z < 2+$. Wide-field mapping efficient with Spitzer.
Spitzer/IRAC Shallow Survey

4.5 µm image
8.5 sq degrees
3 x 30 sec/position

Eisenhardt et al 2004 ApJS 154, 54

z = 6.1 Quasar
Stern et al 2006 submitted

z = 1.41 Galaxy Cluster

Field T4.5 Brown Dwarf
Stern et al 2006 submitted
Photometric Redshifts

Vital Stats:

\[ \sigma = 0.101 \]

\[ \sigma / (1+z) = 0.059 \]

- AGES Survey
- In-house surveys


Optical + Mid-IR

$\langle z \rangle = 1.24$
Optical + Mid-IR

$\langle z \rangle = 1.41$

$\langle z \rangle = 1.11$

$\langle z \rangle = 1.24$

$\langle z \rangle = 1.37$

$\langle z \rangle = 1.41$
292 @ $0 < z < 2$

93 @ $z > 1$

$\langle z \rangle = 1.41$

$\langle z \rangle = 1.26$

$\langle z \rangle = 1.24$

Relative Size of Moon

9.1 Billion Light Years

8.7 Billion Light Years

8.6 Billion Light Years

Distant Galaxy Cluster IR Survey

Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / M. Brodwin (JPL)
Color Evolution of Galaxy Clusters over $0 < z < 1.5$

$z_f = 3$ PE Model

$\langle I - [3.6] \rangle$ vs. Redshift
Relative to No Evolution

\[ L > L^* \]

\[ \Delta(\text{Blue}-K) \]

\[ \Delta(j-K) \]

Redshift

k-corrected \(< I - [3.6] >\)


Eisenhardt, Brodwin et al. in prep
Uber Follow-up

- **Data in Hand**
  - Cycle 14 *HST/ACS* data for 8 $z>1$ clusters from SNe program (PI: Perlmutter).

- **Allocated Time in Spring 2007**
  - GO-3 *Spitzer/IRAC+MIPS* joint with *HST/ACS* in Cycle 15.
    → **Deep IRAC, MIPS, and ACS imaging on 18 $z>1$ clusters**
  - Cycle 15 *HST/NICMOS* on 5 $z>1.2$ clusters

- **Proposals Spring 2007**
  - Continuing Keck campaign
  - XMM imaging on 5 $z>1$ clusters
  - Palomar near-IR imaging for 13 non-NICMOS $z > 1$ ACS clusters
  - KNPO/MARS MOS to get velocity dispersions for 27 clusters at $0.4 < z < 1.2$
\[ z = 1.37 \]
\[ z = 1.41 \]
\[ \text{confirmed } z > 1 \]
\[ \text{clusters so far} \]

ACS (F850LP+F775W)

\[ z = 1.24 \]

8.6 Billion Light Years
8 members: $\sigma = (920 \pm 230) \text{ km/s}$ (Elston, Gonzalez et al. 2006)
7 members: $\sigma \sim 600$ km/s; preliminary WL mass of $\sim 1-2 \times 10^{14}$ Msun
Next Steps

- Forthcoming deeper *Spitzer* and *HST* data will allow us to:
  - Observe the mass assembly history of massive cluster galaxies over 2/3 of the lifetime of the Universe.
  - Measure the evolution of the merger rate and the quantify the dry merger fraction
  - Probe the Cluster/ULIRG connection at the era of peak star formation
  - Compare WL and dynamical masses, calibrate $z>1$ mass-richness relation.
Summary

- Using a probabilistic multi-\( \lambda \) (0.4-5\( \mu \)m) photometric redshift technique, we have identified 300 new galaxy clusters and groups, of which almost 100 are at \( z > 1 \), a 6-fold increase.

- To date 8 \( z > 1 \) clusters between 1.06 < \( z < 1.41 \) have been spectroscopically confirmed with at least 5 members.

- Mean colors of clusters at 0 < \( z < 1.5 \) are consistent with simple PE models with high formation redshifts (\( z_f \sim 3 \)).

- Evidence of mass-metallicity relation in clusters at \( z = 1.5 \)

- Incidence of disturbed morphologies increases over the range 1.1 < \( z < 1.4 \). Elliptical fraction appears to be decreasing as well. Quantitative results TBD.
Cluster "Masses"?
Thank you!
Photometric Redshifts

Vital Stats:

\[ \sigma = 0.101 \]
\[ \sigma / (1 + z) = 0.059 \]

Results

- 292 candidate clusters and groups at $0 < z < 2$ over 8.5 deg$^2$ in Boötes.

- Of these 93 are at $z > 1$, a 6-fold increase over the number of confirmed high-z clusters in the literature.

- To date 8 confirmed at $z > 1$ ($1.06 < z < 1.41$).
Redshift Probability Functions

<table>
<thead>
<tr>
<th>Confidence Interval</th>
<th>Correct Within Confidence Interval</th>
<th><strong>Observed Fraction</strong></th>
<th>Gaussian Expectation</th>
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<tbody>
<tr>
<td>( \leq 1\sigma )</td>
<td>9722/13043</td>
<td>74.5%</td>
<td>68.3%</td>
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<tr>
<td>( \leq 2\sigma )</td>
<td>12335/13043</td>
<td>94.6%</td>
<td>95.4%</td>
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<tr>
<td>( \leq 3\sigma )</td>
<td>12848/13043</td>
<td>98.5%</td>
<td>99.7%</td>
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<tr>
<td>&gt; 3( \sigma )</td>
<td>195/13043</td>
<td>1.5%</td>
<td>0.3%</td>
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</table>
Cluster Probability Density Map

1.1 < z < 1.3
## Spectroscopic Confirmation

### Keck 2005/2006
- Observed 10 clusters to date
- 8 confirmed with 5+ members within 2000 km/s in the rest-frame (approx \( \Delta z \pm 0.015 \))
- Cl26 and Cl79: Many objects with faint, red continua, no lines
- Cl90: Evidence of projection. Line-of-sight structure at \( z = 1.46 \)

### Subaru 2006
not yet reduced

<table>
<thead>
<tr>
<th>ID</th>
<th>Phot-z</th>
<th>&lt;Spec-z&gt;</th>
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<td>1.00</td>
<td>1.06</td>
<td>7</td>
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<tr>
<td>13</td>
<td>1.09</td>
<td>1.11</td>
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<tr>
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<td>1.11</td>
<td>1.16</td>
<td>5</td>
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<tr>
<td>283</td>
<td>1.18</td>
<td>1.24</td>
<td>7</td>
</tr>
<tr>
<td>27</td>
<td>1.17</td>
<td>1.26</td>
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<td>90</td>
<td>1.36</td>
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<td>29</td>
<td>1.25</td>
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<td>79</td>
<td>1.41</td>
<td>-</td>
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Relative to $z_f = 3$ Model

Redshift

$\langle I - [3.6] \rangle$ relative to PE ($z_f = 3$)

$L > L^*$

$z_f = 100$

$z_f = 5$

$z_f = 4$

$z_f = 3$

$z_f = 2$

$z_f = 1.5$
confirmed $z > 1$ clusters so far

ACS (F850LP+F775W)

$z = 1.24$

$z = 1.37$

$z = 1.41$

8.6 Billion Light Years