The search for the most distant clusters with Spitzer: synergies with \textit{WFIRST~AFTA}

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**Galaxy clusters** trace baryon and dark matter content and distribution.

The redshift distribution of detected high redshift clusters in a deep, large survey is highly sensitive to the dark energy equation of state.

In combination with low-z clusters, following redshift evolution breaks parameter degeneracy.

Mohr et al. 2003
**Abundance of rich clusters** as a function of mass and redshift allows to trace the growth rate of structure.

Key uncertainty in this approach is accurate calibration of cluster mass scale.

WFIRST deep lensing observations will determine accurate mass determination of clusters.

Cluster abundances can then be used to determine the effects of dark energy on the growth rate.
Galaxy Clusters, tools for WFIRST-AFTA cosmology : hosts of Type Ia SNe

- Type Ia SNe provided the first strong evidence for cosmological acceleration (Riess et al. 1998; Perlmutter et al. 1999)

- By targeting massive galaxy clusters at \(0.9 < z < 1.5\), a threefold improvement:
  - in the efficiency of finding SNe (compared to an HST field survey)
  - and a factor of three improvement in the total yield of SN detections in relatively dust-free red-sequence galaxies.

- Decouple the effects of host-galaxy extinction and intrinsic color in high-redshift SNe, reducing one of the largest systematic uncertainties in SN cosmology

Sixteen new SNe were discovered at \(z>0.95\)!


P.I.: Perlmutter
Galaxy Clusters as Cosmic telescopes: Discovery and study of first galaxies with WFIRST

CLASH has lead the way in coupling the gravitational lensing power of massive galaxy clusters with space-based enhanced panchromatic imaging capabilities.

Test of structure formation models with unprecedented precision.

Discovery of very distant galaxies with unprecedented details.
## Motivation

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<thead>
<tr>
<th>Tools for cosmology</th>
<th>Redshift distribution, baryon and dark matter content</th>
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<tr>
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<td>( \sigma_8 ), dark energy, universe’s equation of state</td>
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<td>Hosts of type Ia Supernovae, dark energy</td>
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| Cosmic telescopes   | Discovery and study of first galaxies |

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<tr>
<th>Tools for galaxy evolution studies</th>
<th>mode and epoch of massive galaxy formation</th>
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<td>environmental effects, baryon-dark matter interaction</td>
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## Goal

Finding large samples of mass-selected clusters at high-redshift \((1.3 < z < 2)\)
Current Generation of $z \geq 1$ Cluster Surveys

**Infrared**
- ISCS/IDCS (IRAC Shallow/Distant Cluster Survey)
- SpARCS (Spitzer Adaptation of Red-sequence Cluster Survey)
- UKIDSS DXS (UKIRT Infrared Deep Sky Survey Deep Extragalactic Survey)
- SSDF (Spitzer SPT Deep Field Survey)
- CARLA (Clusters around Radio-Loud AGN)
- MaDCoWS (Massive Distant Clusters of WISE Survey)

**Optical**
- DES (DARK ENERGY SURVEY)

**Sunyaev-Zel’dovich Effect**
- ACT (Atacama Cosmology Telescope)
- SPT (South Pole Telescope)
- Planck

**X-ray**
- XMM-XXL
- XMM-LSS (XMM Large-Scale-Structure Survey)
- XCS (XMM Cluster Survey)
- XDCP (XMM-Newton Distant Cluster Project)
- eROSITA (extended Roentgen Survey with an Imaging Telescope Array) (Launch 2015)

**Future Near-Infrared Survey**
- EUCLID
- WFIRST
Large, homogeneous Spitzer high redshift cluster surveys:

- provide exciting targets for WFIRST

- provide a training set to identify additional clusters outside of the Spitzer footprint

Eisenhardt et al. 2008
**SSDF: Spitzer-SPT Deep Field survey**

**Cycle-8 Warm-Spitzer Exploratory Program**
- 94deg\(^2\)
- [3.6], [4.5] mag
- 120s depth
- 5\(\sigma\) lim: [4.5]<21.46 AB ; [3.6]<21.75 AB

- Coverage of 23h field of the SPT Survey

- **Why SPT ?**
  - SZ-effect Masses – (Reichardt+2013)
  - SPTpol (ongoing) will provide SZ-masses up to z\(\sim\)2

**PI: Stanford (UC-Davis)**

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*Ashby+2013*
SSDF Clusters Working Group

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D. Stern (JPL)

+ SSDF Team
Large Area *Spitzer* Surveys

Ashby+2013
- **BCS survey** ~50deg (PI: Desai–griz photometry, 23 AB mag, Bleem et al. 2014)
- **XXM-XXL survey** ~25deg$^2$ (PI: Pierre – Xray Masses)
- **XXL-DECam survey** ~25deg$^2$ (PI: Lidman – ugriz photometry, 25 AB mag)
- **VISTA (VHS Survey)** ((McMahon et al. – shallow JHK photometry, ~20-21 AB mag)
- **Herschel/SPIRE** (Holder et al. 2013)
- **ATCA** (16cm, down to 40μJy/beam)
- **DES Survey** (24 AB mag)
Spitzer selection of $z > 1.3$ galaxies: 1.6 μm stellar ‘bump’

Simple color cut: $[3.6] - [4.5] > -0.1$ (AB)

Muzzin+2013a

Papovich (2008)
The SuperCOSMOS Sky Surveys (SSS) archive holds the object catalogue data extracted from scans of photographic Schmidt survey plates (i.e., POSS II + UKST) in B, R, I bands.

Homogeneous coverage over the entire 94 deg² Spitzer survey down to $I = 20.45$ (AB)
High-z Clusters Search Algorithm

- Counts in cell analysis

- $\Delta N =$ Completeness-corrected excess number of objects with respect to the local background with:
  
  - $[3.6] - [4.5] > -0.1,$
  - $19.5 < [4.5] < 21.46$
  - $I > 20.45$

within 1.0′ radius

Rettura et al. 2014
Sample Purity

- Determine purity, $f_{\text{pure}}$, as a function of the detection significance $X_f$, defined as:

$$f_{\text{pure}}(X_f) = \frac{N_{\text{real}}}{N_{\text{tot}}} = 1 - \frac{N_{\text{false}}}{N_{\text{tot}}},$$

- We run our cluster finding algorithm on comparable-depth observations from the IRAC Shallow Cluster Survey (ISCS) (Eisenhardt et al. 2004), matched with SuperCOSMOS data.

- The ISCS is a wide-field IR-selected galaxy cluster survey carried out using 90s Spitzer /IRAC imaging of the 8.5 deg$^2$ Boötes field of the NOAO Deep, Wide-Field Survey (NDWFS, Jannuzi & Dey 1999).

- We estimate a purity of $\sim 80\%$ at $z>1.3$ from comparison with accurate photozs (11bands) and large specz campaign in Boötes that resulted in 18 confirmed $1.0 < z < 1.9$ clusters (Brodwin+11).

$$X_f = 5.2 \rightarrow f_{\text{pure}} = 0.80$$
SSDF cluster finding algorithm applied to Boötes field

IDCS J1426.5+3508 @ z=1.75

ISCS J1438.1+3414 @ z = 1.41

ISCS J1432.4+3250 @ z=1.49
SSDF cluster finding algorithm applied to SWIRE

SWIRE-CDFS (7.8deg²)

- SpARCS CDFS-44 (left)
  - $z_{\text{spec}} = 1.626$
  - 2\textsuperscript{nd} most significant overdensity in field

- SpARCS CDFS-41
  - $z_{\text{spec}} = 1.368$
  - 6\textsuperscript{th} most significant overdensity in field

SWIRE XMM  (9.1 deg$^2$)

- J022427-032354 (right)
  - $z_{\text{spec}} = 1.63$
  - 1$^{\text{st}}$ most significant overdensity in field.

Muzzin et al. 2013
SWIRE ELAIS-S1 (6.8 deg$^2$)

- GCLASSJ0035
  - z_spec = 1.335
  - 1st most significant overdensity in field.

Wilson et al. 2009
Other SWIRE fields

- **Lockman Hole**
  - 11.1 deg$^2$
  - SpARCS Lockman-77
    - $z_{spec} = 1.4$

- **ELAIS-N1**
  - 9.3 deg$^2$
  - No $z > 1.3$
  - Spectroscopically confirmed clusters yet.

- **ELAIS-N2**
  - 4.1 deg$^2$
  - No $z > 1.3$
  - Spectroscopically confirmed clusters yet.
Cluster Candidates at $z>1.3$ in the SSDF

279 candidates

$X_f > 5.2$

Rettura et al. 2014
SSDF-CL J2339-5531
SSDF-CL J2340-5403
Sample properties: Redshift Distribution

Derived SSDF clusters redshifts distribution

Spectroscopic and Photometric Data from COSMOS UltraVista Catalog (Muzzin et al. 2013b)

Rettura et al. 2014
Sample properties: Clustering (of Clusters) Analysis

Angular Correlation Function

Strong clustering signal

Number density and $r_0$ are consistent with $\Lambda$CDM predictions (Springel et al. 2005)

<table>
<thead>
<tr>
<th>$n_c$ ($10^{-7}h^3$Mpc$^{-3}$)</th>
<th>$0.7^{+6.3}_{-0.6}$</th>
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<tr>
<td>$M_{\text{min}}$ ($10^{14}h^{-1}M_\odot$)</td>
<td>$1.5^{+0.9}_{-0.7}$</td>
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<tr>
<td>$M_{\text{mean}}$ ($10^{14}h^{-1}M_\odot$)</td>
<td>$1.9^{+1.0}_{-0.8}$</td>
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<tr>
<td>$b_c$</td>
<td>$10.8 \pm 2.5$</td>
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<tr>
<td>$r_0$ ($h^{-1}$Mpc)</td>
<td>$32 \pm 7$</td>
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Rettura et al. 2014
Sample properties: Mass-Redshift Distribution

- No detections in 1\textsuperscript{st} generation SPT cluster catalog (Reichardt et al. 2013)

\(\rightarrow\) The two samples do not overlap in mass-redshift space

- SPTpol will soon detect most of them?

Reichardt et al. 2013
Present:

• New sample of cluster candidates of galaxies at $1.3 < z < 2.0$ over the 94 deg$^2$ Spitzer survey of the SPT field.

• 120s of Spitzer data and Scans of photographic plates finds clusters up to $z \sim 2$ with an 80% purity.

• Strong clustering

• $n_c$, $r_0$ values are consistent with previous observational studies and match expectations based on $\Lambda$CDM high-resolution simulations.

• The sample has a mean mass $M_{\text{mean}} = 1.9 \times 10^{14} M_\odot$.

→ Will evolve into massive clusters ($> 5 \times 10^{14} M_\odot$) at $z = 0.2$

Near Future Directions:

• Magellan/IMACS spectroscopy data taken to assign cluster membership (data reduction ongoing)

• VLT/KMOS spectroscopy (Mei’s talk) of Photoz-selectted in the 25deg$^2$ overlapping area with deep DECam optical data (data reduction ongoing)

CONCLUSION:

Ongoing large Spitzer cluster surveys will provide high-redshift targets for WFIRST:
- enabling unique, exciting, synergic, multi-wavelength studies of the Spitzer-selected sample
- providing training sets to identify additional high-redshift clusters outside of the Spitzer footprint.