Past 20 years of panoramic studies of distant clusters with Subaru (+ALMA) and the Future

Taddy Kodama (Tohoku Univ.)
PISCES, Mahalo-Subaru, Gracias-ALMA, HSC$^2$, SWIMS-18, and ULTIMATE-Subaru teams

A galaxy cluster CL0024 at $z=0.4$ (Subaru/Suprime-Cam)
Panoramic view of the growth of massive cluster

★ PISCES: ~12 X-ray clusters at 0.4<z<1.6

★ MAHALO-Subaru: ~14 clusters/proto-clusters at 0.4<z<3.6

★ HSC²: ~27 sq. deg. survey at 0.4<z<1.7

Final cluster with $M=6 \times 10^{14} \, M_\odot$, $20 \times 20$Mpc² (co-moving) (Yahagi et al. 2005; ν GC)
Intermediate density regions (cluster outskirts and groups) are the quenching site at $z<1$.

Star-forming activity abruptly drops (by nearly one order) in groups in the outer regions of clusters, before galaxies enter cluster cores.

CL0939 cluster ($z=0.41$)

Suprime-Cam imaging (Vri’z’)

Kodama et al. (2001)
Some obvious mergers tend to be seen in the cluster outskirts.

Galaxy-galaxy interactions/mergers may be playing key roles in shaping galaxies!

RXJ1716 cluster (z=0.81) Koyama et al. (2008)

Subaru (z') mergers

AKARI (15μm) star-bursts
Environmental dependence of the down-sizing red/blue galaxies

RXJ0152 (z=0.83)  CL0016 (z=0.55)  SDSS (z=0)

HSC, PFS, ULTIMATE, SWIMS are powerful to probe LSSs
1.3° = 75 Mpc (z=1), 100 Mpc (z=1.5), 118 Mpc (z=2) in co-moving

CL0016 cluster (z=0.55)
(Tanaka, M. et al. 2009)

Millenium Simulation
(Springel et al. 2005)

~1,200 redshifts from spectroscopy
red are cluster members, while blue are non-members
**HSC²**

**Hybrid Search for Clusters with HSC**

HSC-SSP (Deep and Ultra-Deep layers; 27 deg²)

Two galaxy populations

Hybrid cluster finder

<table>
<thead>
<tr>
<th>NB</th>
<th>$\lambda$ [Å]</th>
<th>$z$ ([OII])</th>
<th>$z$ ([OIII])</th>
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<td>NB816</td>
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<td>1.71±0.02</td>
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The conventional red seq. technique alone will bias your sample of galaxy clusters. HSC² is a large, systematic cluster survey with little selection bias to $z \sim 1.7$.
Two cluster examples at $z=0.84$ in COSMOS

Dual cluster

Blue-dominated cluster

New class of objects discovered by HSC$^2$, which would have been missed by the red sequence technique alone.

Poster #43
A gigantic ($\sim 100\text{Mpc}$) structure at $z \sim 0.9$ hosting CL1604 cluster revealed by Subaru/HSC.
Hα imaging of CL1604-D at z~0.9

SWIMS NB imaging (NB1261) (a part of engineering run), combined with existing Spitzer(MIPS), HST(ACS), Keck spec. data

26 Hα emitters are identified


Asano, TK, et al., in prep.

Figure 2. Redshift distribution of the CL1604 supercluster.

MIPS sources

matched for Hα line
Spatial and kinematical structures in CL1604-D

Combined with Spitzer (MIPS), HST (ACS), and Keck spec. data

A virialized core and two infalling groups. The groups show high starburst and merger fractions.

Asano, TK, et al., in prep.
Starbursts and Mergers are both enhanced during the course of galaxy group accretion to the cluster core.

CL1604 super-cluster (around cluster D)

<table>
<thead>
<tr>
<th></th>
<th>Field</th>
<th>SW Filament</th>
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<th>Core</th>
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<td>Star formation</td>
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<td>○</td>
<td>○</td>
<td>X</td>
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<tr>
<td>Starburst</td>
<td>☆ 25%</td>
<td>○ 54%</td>
<td>○ 17%</td>
<td>X 0%</td>
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<tr>
<td>Merger</td>
<td>△ 8%</td>
<td>○ 23%</td>
<td>○ 50%</td>
<td>X 8%</td>
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</table>

Outside of the cluster: Younger accreting group | Older accreting group | Cluster core

Asano, TK, et al., in prep.
## MAHALO–Subaru

**MApping HAlpha and Lines of Oxygen with Subaru**

Wide-field survey of line emitters (Hα, [OII], [OIII]) in and around 14 clusters at 0.4<z<3.6 and major general fields. PI: Kodama, T.

<table>
<thead>
<tr>
<th>environment</th>
<th>target</th>
<th>z</th>
<th>line</th>
<th>λ</th>
<th>camera</th>
<th>NB-filter</th>
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<td>MOIRCS</td>
<td>NB2315</td>
<td>K_s</td>
<td>partly observed</td>
<td></td>
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</table>
Inside-out growth/quenching of galaxy clusters revealed by MAHALO-Subaru

$$\Sigma_{\text{SFR}}(R<R_{200}) / M_{200} \sim (1+z)^6$$

(Shimakawa et al. 2014)

c.f. Field: $$\sim (1+z)^3$$

Illustrated by Yusei Koyama

- : passive red galaxy
- : normal SF galaxy
- : dusty SF / AGN
A dense proto-cluster in assembly USS1558-003 at $z=2.53$

Subaru/MOIRCS, NB2315 (H$\alpha$) imaging

107 H$\alpha$ emitters across the 4’x7’ field.
36 are spectroscopically confirmed.

Densest “super-group” (~20x) $M_{\text{dyn}}=10^{14} M_\odot$

Galaxy haloes are likely to be overlapping.

Shimakawa et al. (2017)
Enhanced SF (/AGN) activity in the densest “super-group” of the proto-cluster USS1558 at z=2.53

There are some other works which do not see any environmental dependence on the MS diagram.
GRACIAS–ALMA

Galaxy Resolved Anatomy with CO Interferometry And Submm observations with ALMA

+ 4C23.56 (z=2.48)

PKS1138 (z=2.16)  
USS1558 (z=2.53)

Beam size = 59” diameter

○ ALMA CO(3-2) detections (>5σ) 3hrs integration
○ non detected HAEs

Tadaki et al. (2019)

Band-6 data (dust continuum) show more detections in USS1558 (Aoyama et al.).
Enhanced fraction of molecular gas in proto-clusters

Higher gas fraction in proto-cluster galaxies compared to the general field, due to efficient cold gas accretion towards the intersections of filaments at high-z?

Tadaki et al. (2019)

Horizontal lines: \textit{Scaling relation (as a func. of } M^*, \text{ SFR)} by Tacconi+ '18 for \textit{field galaxies}

\textit{field average}

\textit{detection bias}

\textit{z=2−2.5 proto-clusters}
Dual NB emitter survey (Ly$\alpha$, H$\alpha$) of USS1558 at $z=2.53$

Shimakawa et al. (2017)

Suprime-Cam (34' x 27') − NB429 (Ly$\alpha$)
MOIRCS (7' x 4') − NB2315 (H$\alpha$)

Dual NB emitter survey (Ly$\alpha$, H$\alpha$) of USS1558 at $z=2.53$

Shimakawa et al. (2017)

Suprime-Cam (34' x 27') − NB429 (Ly$\alpha$)
MOIRCS (7' x 4') − NB2315 (H$\alpha$)

Dual emitters (LAE&HAE) avoid the dense clumps!

→ Dense cores are enshrouded by HI gas fed by cold streams?
Cold gas accretion through filaments

USS1558 (z=2.5)
Proto-cluster core
Field

Cold gas

Lyα is scattered and attenuated by HI gas
Ha can penetrate through the HI gas

Not transparent

Caution: Lyα is not a good tracer of dense proto-cluster cores!

Shimakawa et al. (2017)
Dual NB Survey (Lyα + Ha)
Lower gas mass fractions in X-ray clusters at z>2

The most distant X-ray cluster at z=2.51 (CLJ1001)

JVLA, CO(1-0) line
14 detections at S/N>3

Wang et al. (2018)

A X-ray cluster at z=1.99 (CLJ1449)

ALMA CO(4-3), CO(3-2)
JVLA CO(1-0)

Coogan et al. (2018)

$\mu_{\text{gas}} \propto M^\ast^{-0.5}$

$M \sim 10^{13.9 \pm 0.2} M_\odot$

$M \sim 5-7 \times 10^{13} M_\odot$
Transition of gas accretion mode in proto-clusters?

As cluster halos grow massive/dense, gas is heated up to high T, and X-ray is emitted. Cold gas is efficiently supplied to proto-clusters with cold streams along filaments.

Credit: R. Shimakawa

Accretion "inefficient" phase

CLJ1001 (z=2.5)  
CLJ1449 (z=2)

X-ray cluster

Accretion "dominated" phase

USS1558 (z=2.5)  
4C23.56 (z=2.5)  
Non-X-ray cluster

But see also Zavala+ (2019) for no environmental dependence in mol. gas for non-X-ray proto-clusters

c.f., Valentino et al. (2015)
High-z Monsters!

Massive quiescent galaxies with strong Balmer abs. lines at z~4

ZF\textsuperscript{-}COSMOS\textsuperscript{-}20115 at z=3.717, $1.5 \times 10^{11} \text{ M}_\odot$, Keck/MOSFIRE: 4 and 7 hours in the H and K band, respectively.

We can extend this survey to z~5 with deep MB imaging with SWIMS/ULTIMATE.

The existence of such massive high-z monsters, and/or their old stellar populations, can put strong constraints on cosmology & galaxy formation theory.
Table 1: SWIMS-18 filters

<table>
<thead>
<tr>
<th>MB filters</th>
<th>$\lambda_c$ (μm)</th>
<th>FWHM (μm)</th>
<th>$z_s$(Bal.Lim.)</th>
<th>$z_s$(D4000)</th>
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<td>Ks</td>
<td>1.99–2.30</td>
<td>2.15</td>
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</table>

Will open a new window to Balmer break galaxies at 4<z<5 with K1,K2,K3 !
Hunting higher-z monsters in the biased HSC proto-clusters

r-dropouts (LBG; $4.4 < z < 5.2$)

HSC/UD-COSMOS

Targets:

g-drop clusters ($3.5 < z < 4$)

r-drop clusters ($4.4 < z < 5.2$)

Investigate the galaxy formation bias in the early Universe by comparing with the field survey.

Medium band survey with (H1, H2, H3) and (K1, K2, K3), respectively, on SWIMS and ULTIMATE (GLAO)
Summary

- Subaru has been mapping large scale structures in and around distant clusters and galaxies therein with the unique wide-field instruments (Suprime-Cam/HSC in optical and MOIRCS in NIR).

- Proto-clusters grow from a cold gas rich phase to a hot phase at the cosmic noon as seen by ALMA and Lyα observations. A young proto-cluster core shows elevated SF, while older X-ray clusters show suppressed SF.

- HSC-selected proto-clusters at z\(\gg\)3 (r-drop) are ideal sites for searching for massive monsters at high-z with SWIMS and ULTIMATE (GLAO) to put strong constraints on the speed of galaxy formation.