Revealing the build-up of large scale structures and galaxy populations therein with PFS$^2$

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HSC$^2$ and PFS$^2$ teams

A galaxy cluster CL0024 at z=0.4 (Subaru/Suprime-Cam)
What is Subaru (昴) in Japanese?

“Subaru” is “Pleiades” (a star cluster M45) or “Makalii”. “Subaru” originally means “assemble/cluster” (verb) in old Japanese. 「統（す）まる」

“Subaru” Telescope is “Cluster” Telescope!

“Pleiades” are Atlas’s 7 daughters in the Greek Myths.
Key science with PFS: quenching history since $z \sim 1.7$

- **Redshift (z)**
  - cosmic age (Gyr)
  - 14  12  10  8  6  4  2  0

- **Star formation rate density**
  - **First galaxies**
  - **Reionization**
  - **Morphology of galaxies established**
  - **Formation of galaxy clusters**
  - **Formation of the Earth**
  - **Quenching**
  - **Peaking**
  - **Accelerating**

- **HSC, PFS**
- **ULTIMATE, TMT**
80-100% $f_{\text{AGN}}$ and 60-75% $f_{\text{AGN-outflow}}$ at the highest mass bin irrespective of above/on/below MS.

Sharp rise at log $M/M_\odot$~10.7-10.9 ~Schechter mass at 0.6<$z$<2.7

Forster-Schreiber+ (2018)
Mergers induce starburst first, but then lose or use up the gas, and star formation is truncated sharply.

Ram-pressure strips gas from the system and terminates SF.
HSC+PFS is extremely 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
A gigantic (~100Mpc) structure at z~0.9 hosting CL1604 cluster revealed by Subaru/HSC.
HSC$^2$

Hybrid Search for Clusters with HSC

HSC-SSP (Deep and Ultra-Deep layers; 27 deg$^2$)

Two galaxy populations

<table>
<thead>
<tr>
<th>NB</th>
<th>$\lambda$ [Å]</th>
<th>$z$ ([OII])</th>
<th>$z$ ([OIII])</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB816</td>
<td>8160</td>
<td>1.19±0.02</td>
<td>0.63±0.01</td>
</tr>
<tr>
<td>NB921</td>
<td>9210</td>
<td>1.47±0.02</td>
<td>0.84±0.01</td>
</tr>
<tr>
<td>NB101</td>
<td>10095</td>
<td>1.71±0.02</td>
<td>1.02±0.01</td>
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</table>

The conventional red seq. technique alone will bias your sample of galaxy clusters.

HSC$^2$ is a large, systematic cluster survey with little selection bias to $z$~1.7
Red sequence galaxies at 0.8<z<0.9

UD_COSMOS

Panoramic large scale structures!

[OIII] line emitters at $0.82 < z < 0.86$

**UD_COSMOS**

Blue peaks do not necessarily host red seq. galaxies.

Close-up views of two examples at $z=0.84$ in COSMOS

**Dual cluster**

*Excesses both in red galaxies and [OIII] emitters*

**Blue-dominated cluster**

*no excess in red galaxies*

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

We have $\sim 1,000$ of candidates, and systematic and intensive spectroscopic confirmation with PFS is critical (cluster mass function can also compare with cosmological models).

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Transition of galaxy spectra from SFGs through RQGs and to QGs

Star forming galaxies (SFGs/SBGs)

Shortly after quenching (0.1-1Gyr)

Key population!

Rare, short-lived galaxies (~5%)

Recently quenched galaxies (RQGs)

Strong Balmer absorption lines (A-type stars)

Quenched galaxies (QGs)

Some time after quenching (>1Gyr)

Merger? AGN? Size?
RQGs are short-lived, and thus rare (2~5%) objects. Need wide-field survey to make a statistical sample → HSC-SSP is ideal!
Massive RQGs tend to be found in cluster outskirts \( \rightarrow \) PFS spectroscopic follow-up! while less massive RQGs tend to be seen in the cluster core (ram-pressure stripping?).
Stacking analysis at $z=0.6$ in COSMOS

**Quenching Efficiency (QE)**

\[ QE \equiv \frac{N(RQG)}{N(SFG)} \]

- **Low mass** ($M_* < 10^{9.6}M_\odot$)
- **High mass** ($M_* > 10^{9.6}M_\odot$)

Preliminary results (Mao, TK, et al. in prep.)
Absorption line diagnostic of RQGs
- to constrain the timescales of star-formation/quenching -

Balmer absorption lines (A-type stars)
→ timescale of quenching, existence of starburst

Mg/Fe ratio
→ timescale of SF before quenching

Couch & Sharples (1987)

Truncation w/ starburst
Simple truncation w/o starburst

Kriek+ (2016)

z=2.1 galaxy
z=1.6 stack
z=1.4 galaxy

[Mg/Fe]=0.0
[Mg/Fe]=0.5

α-enhancement
→ short SF timescale

Δ3C 295

We can access to these lines back to z=1.5 (Mg/Fe) ~ z=2 (Hδ) with PFS
Emission line diagnostic of SFGs

Environmental dependence of gaseous metallicities

Based on stacking analysis of N2=[NII]/Hα

with Subaru/MOIRCS

Cluster > Field at low-mid mass

But highly controversial!

Some other works find no environmental dependence and some the other works find opposite trend.
Environmental Impacts on Gas Flows and Metallicity
Shimakawa et al. (2015a)

Isolated galaxies (Field)

(Inflow)
Stochastic, rapid, cold gas accretion through filaments
→ Metal dilution by accreting pristine gas

(Outflow)
Gas removal due to feedback (SN, AGN)
→ Selective ejection of metal rich gas

(Proto-)Cluster galaxies

(Inflow)
A common halo is formed and gas is shock heated to its virial temperature.
→ Inefficient gas accretion compared to isolated galaxies.

(Outflow)
Fall back of gas due to deeper potential wells and ICM pressure (see also Dave+11, Klus+13)
→ Recycling of gas (further enrichment)

(Outflow)
Gas stripping (tidal or ram-pressure)
→ Removal of outer metal poor gas
Emission line diagnostic (gaseous metallicity)

- to explore environmental dependence of SFH and gas in/outflows -

Separation between ionization parameter (q) and metallicity (O/H)

\[
\frac{\text{[OIII]}}{\text{[OII]}} \quad \text{vs.} \quad \frac{\text{[OIII]}}{\text{H}\beta} \quad \text{vs.} \quad \frac{\text{[NII]}}{\text{[SII]}}
\]

\[
= \frac{([\text{OIII}]+[\text{OII}])}{\text{H}\beta}
\]

Nakajima+ (2013)

z<1.5 with PFS

Kewley+ (2015b)

z<0.9 with PFS
Emission line diagnostic (AGNs) - to explore AGN quenching -
AGN quenching may also be related to environmental quenching if AGN activities are enhanced in clusters (e.g. interactions/mergers!)

**Line ratios**

BPT-diagram

Separation between SFGs and AGNs

z<0.9 with PFS

AGNs are rare (a few %) objects. PFS is ideal to make a statistical sample!

**Line width**

Low-mass (log M*<10.9)
SFR driven outflow (Δv\_broad\sim300 km/s)

High-mass (log M*<10.9)
AGN driven outflow

SINFONI/VLT
Genzel et al. (2014)

PFS: R=3000-5000 ⇔ ΔV=60-100 km/s
Physical quantities to be derived from spectra

Weak lines can be explored by stacking of many galaxies (PFS can easily do it!)

- Resolving Star Formation History in Fine Time Scales
  - Hα, Hβ + Balmer absorption + SED
  - 10^7 yr, 10^8-9 yr, >10^9 yr
  - Starburst? Truncation timescale? → Physical mechanisms

- Accurate Dust Extinction
  - Hα/Hβ (Balmer decrement) → Dust extinction
  - z(Hα/Hβ) < 0.92

- Chemical Evolution of Interstellar Gas
  - N2, R23, [SII]/[NII], [OIII]λλ4959,5007/[OIII]λ4363 (T_e) → Metallicity
  - z(S2N2) < 0.87
  - z(R23) < 1.52

- Ionization States, AGN / SB Separation
  - [OIII]/[OII], [OIII]/Hβ-[SII]/[NII], BPT → Ionization parameter, AGN
  - z(O32) < 1.52

- Electron Density
  - [OII]λ3726,3729, [SII]λ6716,6731 → e- density of HII-R and PDR
  - z([OII]) < 2.38
Absorption lines and continua analyses

→ Key to understanding quenching history

A simulated PFS spectrum of a PSB galaxy with J=19 at z=1 (5 hrs integration)

PFS throughput~30%

Credit: M. Onodera

Recovery of age and metallicity

Stacking analyses will also help a lot here!
Simulation of fiber allocation and progress of the survey

J<22.8 (as in SSP) \rightarrow \log (M^*/M_*)>10 at z=0.7

Exp. Times: BCS (blue cloud survey) clusters =5 hrs, RSS (red sequence survey) clusters =10 hrs

Completeness (fiber-hour-based)

The fraction of fiber hours of finished targets

The observing time (hours)

Preliminary!

Yabe, K., et al.

Depends highly on the “priorities” in the fiber allocation process.

(overlapping galaxies between SSP samples and cluster samples are double counted!)
**Summary**

**Panoramic Follow-up Spectroscopy with PFS** ($\text{PFS}^2$)

| Confirming our large samples of HSC$^2$ cluster candidates and |
| Revealing the full quenching history of galaxies since $z=1.7$ |

**Key targets:** Unique sample of galaxy clusters (~1,000) from our HSC$^2$ survey. Rare objects such as RQGs, SBGs, and AGNs across Environments and $M^*$

**Key questions:** when, where, and in what galaxies (mass/size) do they appear and why? We can put constraints on the recent star formation histories (quenching time-scale, starbursts), chemical evolution (gas flows), AGN contribution, and their environmental dependences.

**A possible issue:**

*$\text{PFS-SSP may not sample galaxies in high density regions very efficiently due to fiber collisions (minimum separation between fibers = 30")}$.*

Do we want a separate dedicated program on cluster samples (e.g. intensive program)?

→ Need a fiber allocation simulation with the real galaxy distributions.