Mahalo Subaru, Ohako SWIMS, and Aloha TMT!

Taddy Kodama (NAOJ)

Masao Hayashi, Yusei Koyama (NAOJ), Ken-ichi Tadaki (MPE), Ichi Tanaka, Yosuke Minowa (Subaru), Rhythm Shimakawa, Tomoko Suzuki, Moegi Yamamoto (NAOJ/SOKENDAI), et al.

A galaxy cluster RXJ0152 at z=0.83 (Subaru/Suprime-Cam)
Line-up of our on-going/future projects

1. **MAHALO-Subaru**
2. **GANBA-Subaru**
3. **ULTIMATE-Subaru**
4. **SWIMS-18**
5. **WISH-7**
6. **HSC-HSC**
7. **MAHALO2-SCUBA2**
8. **GRACIAS-ALMA**
9. **Aloha-TMT**

⇐ Today's talk
What is the origin of the cosmic habitat segregation?

Morphology- (SFR-) density relation (Dressler 1980)

- Spirals
- Lenticulars
- Ellipticals
- Star-forming (young)
- No/little SF (old)

Nature? (intrinsic)
Biased, earlier galaxy formation in high density regions

Nurture? (external)
Galaxy-galaxy interaction/mergers, gas-stripping
Emergence of the Hubble sequence between $z=3$ and $1$

$z \sim 1$ (8 Gyrs ago)

$z \sim 2-3$ (10-11 Gyrs ago)

$\lambda_{\text{rest}} = 1700 \, \text{Å}, 4300 \, \text{Å}$

LBGs

Hubble Space Telescope

Dickinson (2000), …many!
Ha and [OIII] are better tracers of SF activities than the UV-light at this epoch, because they are less affected by dust extinction.
# MAHALO-Subaru

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

Unique sample of NB-selected SF galaxies across environments and cosmic times

<table>
<thead>
<tr>
<th>environment</th>
<th>target</th>
<th>z</th>
<th>line</th>
<th>λ (μm)</th>
<th>camera</th>
<th>NB-filter</th>
<th>continuum</th>
<th>status (as of Apr 2015)</th>
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<td>Low-(z) clusters</td>
<td>CL0024+1652</td>
<td>0.395</td>
<td>H(\alpha)</td>
<td>0.916</td>
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<td>(z')</td>
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<td>CL0939+4713</td>
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<td>(J)</td>
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<td>Proto-clusters</td>
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<td>H(\alpha)</td>
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<td>[O(\text{II})]</td>
<td>1.189</td>
<td>MOIRCS</td>
<td>NB1190</td>
<td>(J)</td>
<td>observed</td>
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</table>

~20 nights for imaging, >15 nights for spectroscopy  Kodama et al. (2013)
High-z structures revealed by **MAHALO**

(Hayashi+10, 11)  
(Koyama+11)  
(z=0.4)  
(Ha)  

(Hayashi+12)  
(Koyama+13)  
(z=2.2)  
(Ha)  

(Tadaki+12)  
(z=1.5)  
([OII])  

(Koyama+10)  
(z=0.8)  
(Ha)  

(Hayashi+12)  
(z=2.5)  
(Ha)
LSSs (~20Mpc) around two x-ray clusters at z~1.5 traced with [OII] emitters

Suprime-Cam/Subaru 30’ ~ 30-40 Mpc (co-moving) on a side

Hayashi et al. (2011)

CIG.10218(z=1.62)

Tadaki et al. (2012)
The most prominent star-bursting proto-cluster at $z \sim 2.5$

USS1558-003 ($z=2.53$)

Ha imaging with MOIRCS/NB2315
FoV=4′ x 7′
68 Ha emitters detected.
~40 are spec. confirmed.

~20x denser than the general field.
Mean separation between galaxies is ~150kpc in 3D.

Hayashi et al. (2012)
Spatial distributions of HAEs in two proto-clusters at $z>2$

Lots of HAEs live in proto-cluster cores, indicating strong SF activities there.

Red HAEs (dusty starbursts) tend to favor even denser cores/clumps!
2D/3D Views of Proto-Clusters at z>2

They are a mid of vigorous assembly!
HzRGs are not always located at the centers (densest regions).

Spectroscopic confirmation of 40-50 members in each cluster with Subaru/MOIRCS Shimakawa et al. (2014)
[OIII] strong galaxies in proto-clusters at z>2

Kewley’s model (2013) suggests:

- low metallicity and/or
- large sSFR and/or
- large density?

Shimakawa et al. (2015a)
Higher sSFR
Lower metallicity
Larger e-density in high-z SFGs.

Shimakawa et al. (2015a)
Inside-out growth of galaxy clusters

MAHALO-Subaru

$z = 0$

$z \sim 0.5$

$z \sim 1$

$z \sim 2$

Illustrated by Yusei Koyama

- Red circle: passive red galaxy
- Blue star: normal SF galaxy
- Orange star: dusty SF / AGN

Illustrated by Yusei Koyama
Evolution of integrated SFRs and growth of dynamical mass in cluster cores

Rapid increase of integrated SFR per unit cluster mass with increasing $z$

Numerical simulations suggest that these proto-clusters will grow to $\sim 10^{15} M_\odot$ clusters by the present-day

Our sample is tracking a typical mass growth history of Coma-class rich clusters.
Environmental effects at high-z

(Physical Processes)

• **Merger, Interaction**
  - Frequency, Mode of SF (starburst)
• **Gas inflow**
  - Filamentary cold streams vs. spherical accretion
• **Gas outflow, stripping**
  - IGM pressure confinement, R-P/Tidal Stripping

(Consequences)

• **Star formation activity**
  - Scatter of the SF main sequence (boost/truncation)
• **AGN activity**
  - Frequency, Co-activation with star formation
• **Internal structure**
  - Disturbance, Location/Compactness/Dustiness of SF, Clumpiness
Hypothetical galaxy evolution on the SFR vs. $M^*$ diagram

- Star-forming main sequence
- Dusty starburst (mergers?)
- Starburst mode is more prevalent in proto-clusters?
- Scatter of the main sequence is larger in proto-clusters?
SF galaxies in the proto-cluster at z~2 follow the same “main sequence” as the field one. However, the galaxy distributions on the sequence are different in the sense that the proto-cluster contains more massive, higher-SFR, and probably dustier galaxies. Also, a caveat is that the $M^*$-scaled dust correction may not be applied for cluster galaxies.

Koyama et al. (2013a)  
see also Hatch et al. (2011) and Cooke et al. (2014)
MAHALO-Spec
Environmental dependence of gaseous metallicity at z>2

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

Cluster > Field at low-mid mass

High-z < Low-z

1. Sample selections? HAEs in clusters tend to be more evolved than LBGs in the field.
2. Accelerated, hence more advanced chemical evolution in clusters, and smaller f(gas)?
3. Stripping of metal poor gas from the reservoir, and stopping dilution of metals.
4. Recycling of enriched and once ejected gas? (Dave+ ’11; Kulas+ ’13)

Shimakawa et al. (2015a)
Inflow and outflow processes may well depend on environment!

**General field**
- Stochastic, rapid, cold gas accretion through filaments
- Ejecting enriched gas selectively
- Metal dilution by primordial gas inflow

**(Proto)cluster**
- Recycling of metal enriched gas
- Stripping of metal poor gas from the reservoir
  - Steady but slow (?) gas accretion from a common halo
- Enriched gas falls back
- Stripping outer metal-poor gas

(Dave+ ’11; Kulas+ ’13)  
© Rythm Shimakawa
“Cold Streams” along filaments (Inflow)

Efficient gas supply to form a massive galaxy on a short time scale at high-z.

Rapid gas accretion forms a gas rich disk which becomes gravitationally unstable and fragmented.

Dekel et al. (2009, Nature)

Goerdt et al. (2010)
Environmental dependence of gas in-/out-flow processes is expected and should be explored!
→ another key aspect of the environmental effects on top of merger?

Inflow (cold streams):
- can be different between common haloes in clusters and isolated haloes in the field?
- may affect internal structures (clumpiness)?

Outflow:
- suppressed by IGM pressure?
- selective stripping of outer metal poor gas?

→ Gaseous metallicity (MOSFIRE spectroscopy),
  Gas fraction and effective chemical yield (ALMA), and
  Galaxy anatomy (AO+NB imaging, IFU) will tell us more.
"Clumpy" SFGs at the cosmic noon

Clumpy structure is common (~40%)  Mergers or Fragmentation?
Massive clumpy galaxies tend to have a red clump, and be detected at 24μm.
Numerical simulation

→ The red clumps may be the site of nucleated dusty starburst to form a bulge?
→ Environmental dependence?

Tadaki, TK, et al. (2012)
Numerical simulations (N-body+SPH) reproduce the clumpy nature of star forming galaxies and the bulge formation

Bournaud et al. (2013)

Hypothesis

Massive gas infall ↓
Gas rich disk ↓
Fragment to clumps ↓
Migrate towards center ↓
Formation of a bulge

$M_{\text{dyn}} = 3.5 \times 10^{10} M_\odot$
Spatially resolved Hα line emission in clumpy galaxies

Tadaki et al. (2013b)

Contours: Hα images

Hα emission tends to be stronger in red clumps, suggesting a dusty starburst occurring there.

Some extended HAEs are resolved with natural seeing, but for the majority, we require better resolutions with AO+NB imaging, IFU and ALMA.
GANBA-Subaru

Galaxy Anatomy with Narrow-Band AO imaging with Subaru
AO-assisted narrow-band Hα, [OIII] imaging with IRCS/Subaru

Any environmental dependence in internal structures?

Proto-cluster USS1558-003 (z=2.53)

HST/H-band (0.16")
(Hayashi et al. in prep)

MOIRCS + NB (Hα) (seeing~0.5")

IRCS + AO188 +NB (Hα) (0.16” ~ 1.3 kpc)

Resolved star-forming clumps!

Suzuki et al., in prep.
SWIMS (TAO)

PI: Motohara, K. (IoA, U. Tokyo)

- Wide Field Imager and Multi-Object Spectrograph for TAO 6.5m telescope (IoA, U. Tokyo)
- 2-color (0.9-1.4/1.4-2.4um) simultaneous imaging/spectroscopy
- Initially operated at Subaru (2016~2018?)
SWIMS-18 Survey

Super multi-λ (NIR) imaging survey of the “Cosmic High Noon”

SWIMS is the new wide-field NIR camera and spectrograph to be installed on TAO 6.5m telescope in Chile, and will be mounted on Subaru for 2016-2018.

18 filters (6 NBs, 9 MBs, and 3 BBs) will be available!

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<tr>
<th>Narrow-Band</th>
<th>Medium-Band</th>
<th>Broad-Band</th>
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Simultaneous observations of blue (<1.4\(\mu m\)) and red (>1.4\(\mu m\)) channels!

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<th>Red</th>
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<td>Y (3h)</td>
<td>H1 (2h)</td>
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<td>J1 (3h)</td>
<td>H2 (2h)</td>
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<td>J2 (3h)</td>
<td>H3 (2h)</td>
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<td>J (1.5h)</td>
<td>H (1h)</td>
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<td>K_s (0.5h)</td>
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SWIMS-18 Medium-Band Filters (9)

M*-limited sample of galaxies up to z~4–5

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<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>5.14</td>
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<th>( \lambda_c ) (µm)</th>
<th>FWHM (µm)</th>
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<td>J</td>
<td>1.17–1.33</td>
<td>1.25</td>
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<tr>
<td>H</td>
<td>1.48–1.78</td>
<td>1.63</td>
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<tr>
<td>K_s</td>
<td>1.99–2.30</td>
<td>2.15</td>
<td>0.30</td>
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Will open a new window to 3.5<z<5 with K1,K2,K3 !
Improvement of Photometric Redshifts at 1.5<z<5.5

\[ \Delta z/(1+z) > 0.1 \]

Outlier fraction (%)

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<th>z range</th>
<th>0-0.5</th>
<th>0.5-1.0</th>
<th>1.0-1.5</th>
<th>1.5-2.0</th>
<th>2.0-2.5</th>
<th>2.5-3.0</th>
<th>3.0-4.0</th>
<th>4.0-5.0</th>
<th>5.0-6.0</th>
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<td>w/o SWIMS18</td>
<td>22.7</td>
<td>9.9</td>
<td>7.8</td>
<td>13.0</td>
<td>14.8</td>
<td>11.4</td>
<td>7.2</td>
<td>12.4</td>
<td>26.6</td>
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<tr>
<td>w/ SWIMS18 (Deep)</td>
<td>15.5</td>
<td>7.9</td>
<td>4.1</td>
<td>6.5</td>
<td>6.0</td>
<td>6.9</td>
<td>4.5</td>
<td>8.2</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Tadaki, et al.
SWIMS-18 Narrow-Band Filters (6)

SFR-limited sample of star forming galaxies at 0.9<z<3.3

<table>
<thead>
<tr>
<th>NB filters</th>
<th>$\lambda_c$ (μm)</th>
<th>FWHM (μm)</th>
<th>$z$(Hα)</th>
<th>$z$([OIII])</th>
<th>$z$(Hβ)</th>
<th>$z$([OII])</th>
<th>$z$(Paα)</th>
<th>note</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB1244</td>
<td>1.244</td>
<td>0.012</td>
<td>0.895</td>
<td>1.484</td>
<td>1.559</td>
<td>2.337</td>
<td>–</td>
<td>CL1604+4304 ($z=0.895$)</td>
</tr>
<tr>
<td>NB1261</td>
<td>1.261</td>
<td>0.012</td>
<td>0.922</td>
<td>1.519</td>
<td>1.595</td>
<td>2.384</td>
<td>–</td>
<td>CL1604+4321 ($z=0.920$)</td>
</tr>
<tr>
<td>NB1630</td>
<td>1.630</td>
<td>0.016</td>
<td>1.484</td>
<td>2.256</td>
<td>2.354</td>
<td>3.374</td>
<td>–</td>
<td>※ HST F126N 1.259 0.015</td>
</tr>
<tr>
<td>NB1653</td>
<td>1.653</td>
<td>0.016</td>
<td>1.519</td>
<td>2.302</td>
<td>2.401</td>
<td>3.436</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>NB2137</td>
<td>2.137</td>
<td>0.021</td>
<td>2.256</td>
<td>3.268</td>
<td>3.396</td>
<td>4.734</td>
<td>0.140</td>
<td></td>
</tr>
<tr>
<td>NB2167</td>
<td>2.167</td>
<td>0.021</td>
<td>2.302</td>
<td>3.328</td>
<td>3.458</td>
<td>4.814</td>
<td>0.156</td>
<td></td>
</tr>
</tbody>
</table>

**Dual Emitters ([OIII] and Hα) Survey with Pair NB filters (4 pairs)**

[Images of emission line spectra and galaxy profiles]
Z-FOURGE @Magellan 6.5m (El. 2400m)  
(FourStar Galaxy Evolution Study)

- Four Star Infrared Camera; Hawaii-2RG x 4
- One deep 10.9’x10.9’ field each in COSMOS, CDFS and UDS FourStar; Hawaii-2RG x 4) – 0.1 sq. deg.
- 30,000 galaxies at 1<z<3
- J1,J2,J3 ≈ 25.5, H1, Hs ≈ 25, and Ks ≈ 24.5 (AB, 5σ, total mag for compact sources)
- $\Delta z/(1+z) \sim 0.02$
Why **SWIMS-18 > Z-FOURGE?**

(TAO 6.5m) (Magellan 6.5m)

- **More medium-band filters** (from 5 to 9)
  J1(Y), J2, J3, Hs, Hι → Y, J1, J2, H1, H2, H3, K1, K2, K3
  → Improvement of phot-z accuracy (in particular at z>3), Balmer break up to z<5

- **Existence of narrow-band filters**
  6 narrow-band filters, 4 pairs (Hα and [OIII]), adjacent on/off bands
  → optimized to strong [OIII] emitters at high-z, no contamination

- **Simultaneous observations of two passbands**
  λ<1.4μm (blue channel) and λ>1.4μm (red channel) with a dichroic mirror
  → Survey efficiency is doubled

- **Large amount of time allocation to some dedicated programs**
  → 0.7-1.5 yrs of observing time for 1 sq. deg. (× 10 Z-FOURGE), optimal for environmental studies with clusters of >10¹⁴M☉
Survey Design for SWIMS-18 (imaging)

<table>
<thead>
<tr>
<th>survey layer</th>
<th>area (sq. deg.)</th>
<th># of pointings</th>
<th>observing time (Subaru)</th>
<th>observing time (TAO)</th>
<th>total time for TAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWIMS-18-Wide</td>
<td>1</td>
<td>100</td>
<td>25hrs/FoV</td>
<td>40hrs/FoV</td>
<td>4,000 hrs</td>
</tr>
<tr>
<td>SWIMS-18-Deep</td>
<td>0.1</td>
<td>10</td>
<td>125hrs/FoV</td>
<td>200hrs/FoV</td>
<td>2,000 hrs</td>
</tr>
</tbody>
</table>

SFR-limited sample (HAEs): $7.5 \times 10^5 \text{ Mpc}^3$ at each redshift

<table>
<thead>
<tr>
<th>SFR-limit (M$_\odot$/yr)</th>
<th>expected # of HAEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10(z=1.5)$, $30(z=2.5)$</td>
<td>$8000(z=1.5)$, $4000(z=2.5)$</td>
</tr>
</tbody>
</table>

M$_*$-limited sample: $1.2 \times 10^7 \text{ Mpc}^3$ ($\Delta z=1$)

<table>
<thead>
<tr>
<th>M$<em>*$-limit (M$</em>\odot$)</th>
<th>expected # /($\Delta z=1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{10}(z=1.5)$, $10^{11}(z=3)$</td>
<td>$3000(z=3)$, $300(z=4)$</td>
</tr>
</tbody>
</table>

→ Requires 0.7-1.5 yrs of observing time at TAO
1/10-1/30 of the survey will be done with Subaru as a pilot study when SWIMS is mounted on Subaru for 3 yrs (2016-2018)
Thirty Meter Telescope (TMT; optical-NIR) (Mauna-Kea, Hawaii; 4200m)

Expected first light in early 2020’s

A large international collaborations among USA, Japan, Canada, India, and China
High-z Galaxy Anatomy is "Ohako" for TMT IFU (3D spectroscopy) w/ AO

Rotation of gas-rich clumpy disk of a SFG at z=2.4 resolved with IFU (SINFONI) on VLT Genzel et al. (2011)
High-z Galaxy Anatomy

SINS Survey
z~2 UV selected galaxies; VLT/SINFONI w/o AO; Vc/σ~2-4

Foerster-Schreiber et al. (2009)
“ALOHA-TMT”

Anatomy with Lines of Oxygen and Hydrogen with AO on TMT

Resolving internal structures/kinematics within galaxies under construction

Huge light collecting power (13 × Subaru), and
High spatial resolution (0.015”@2μm with AO)

~3 mag deeper for point sources and
~1.5 mag deeper for extended sources
compared to Subaru (8.2m diameter)

0.015”@2μm ⇔ ~0.1kpc @z>1

TMT can resolve stars and ionized gas in distant galaxies
with high resolution, comparable to ALMA (molecular gas and dust)!
Gas outflows from clumpy galaxies (feedback in action)

Genzel et al. (2011)

Gas outflow from the star-bursting clump-B (~500 km/s)

$F_{\text{broad}}/F_{\text{narrow}}$ (outflow strength) scales with SFR, suggesting “stellar” feedback.
Stacked Hα spectrum of massive SFGs at z=1–3

8 galaxies with log M > 11

The spectra in the central region show a broad component which is a signature of gaseous outflows.

Genzel et al. (2014)
Outflows by Star Formation and AGN (feedback)

Based on stacking analysis now, and with 1kpc resolution at best. With TMT, we can resolve individual galaxies in space (0.1kpc), velocity, and line ratios, which tells us internal physics of galaxy formation such as star formation, inflows, and outflows.

Genzel et al. (2014)
Detection of cold streams (gas feeding)

A major channel of gas accretion at high-z?
Responsible for high SFR and clumpy structures?

However, no convincing evidence discovered yet!

Relative velocity of absorbing gas in the front.
Blueshift $\rightarrow$ outflow (figure above)
Redshift $\rightarrow$ inflow (new!)
Spatially resolved chemical evolution within galaxies

→ Propagation of SF and gas in/outflows

2D map of line ratios (metallicity indicators) such as [OIII]/Hβ and [NII]/Hα

TMT will disentangle between metallicities and ionizing states by applying multiple line diagnostics for individual galaxies!

Low metallicity in the central region → Dilution of metals by gas accretion?
Summary

• **Mahalo-Subaru** has been mapping out star formation activities across cosmic times (0.4<z<3.6) and environments, covering the peak epoch of galaxy formation.

• **SWIMS-18** will be sensitive up to z~5 (Balmer break) and to z~3.3 (Hα, OIII emitters), with unique sets of medium-band/narrow-band filters.

• **Aloha-TMT** will spatially and kinematically resolve galaxies at high-z and tell us internal physics of galaxy formation such as localized SF, feeding, and feedback.