Galaxy Formation and Evolution Explored with Subaru, ALMA, and TMT

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What are galaxies?

Our Galaxy contains hundreds of billions of stars like the sun. The size of disk is about 30K light years, and the sun is located at 25K light years away from the galaxy center.

Milky Way is the edge-on view of our Galaxy!
Present-day galaxies

“Hubble sequence” of galaxies

Elliptical galaxies

Lenticular galaxies

Spiral galaxies

There are ~100 billion galaxies in the Universe.
Clusters of galaxies

A cluster of galaxies consists of 100s -1000s of galaxies.

CL0024 cluster (4.2 Gyr), Subaru Telescope
radius ~ 3M l.y. – 10M l.y.

Abell1689 cluster (2.2Gyr), Hubble Telescope
Mass ~ $10^{14-15} M_\odot$
Super-Clusters (Large Scale Structures)

Clusters are also connected to form even larger structures in the Universe.

Real Universe

Computers

VIRGO simulation (C. Frenk etc)

Stars → Galaxies → Clusters → Super-clusters

Hierarchical Universe

CfA Survey (Gellar & Huchra 1986)
From Uniformity to Complexity

400,000yr ($z=1100$) (recombination era)

Very uniform
$\Delta \rho/\rho = 10^{-5}$

Present-day ($z=0$)

Lots of structures
$\Delta \rho/\rho = 1 \sim 1000$

How did the present-day complex (non-uniform) Universe come from the extremely uniform early Universe?
Origin of the cosmic habitat segregation

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

Nature? (intrinsic)
earlier galaxy formation and evolution in high density regions

Nurture? (external)
galaxy-galaxy interaction/mergers, gas-stripping

Star-forming (young)
Spirals

No/little SF (old)
Ellipticals
Lenticulars

log surface density (Mpc⁻²)
z~0
55 Cluster Sample - all

Morphology-density relation

field galaxy
cluster core

Nature? (intrinsic)

earlier galaxy formation and evolution in high density regions

Nurture? (external)
galaxy-galaxy interaction/mergers, gas-stripping
Hierarchical structure formation (Theory)

http://4d2u.nao.ac.jp/

Small objects form first, they drag each other by gravity, merge together, and grow to more massive objects with cosmic times.
Time-Machine takes you to the past

Galaxy evolution
7 Gyrs ago

Galaxy formation
10 Gyrs ago

Normal galaxies

Dark age
13.5 Gyrs ago

Big Bang
13.7 Gyrs ago

The further away in distance you see, the farther away in the past you look into.
→ Astronomy is the Ultimate Archeology!
Subaru Telescope (Optical-NIR) (Mauna kea, Big island, Hawaii; 4200m)

Mauna Kea Observatories
- CFHT (USA, Canada, Australia) (Canada, France, Hawaii)
- Keck (USA)
- UKIRT (UK)
- Subaru (Japan)
- JCMT (UK)
- CSO (USA)
- SMA (USA)

Elevation: 4200m (~60% oxygen)

Subaru Telescope
- (height: 22.2m, diameter: 8.2m)

Observation bldg.
ALMA (Submm-Radio)
(Atacama, Chile; 5000m)

International collaboration among Japan-USA-Europe

Gigantic interferometer with 66 antennas in total, consisting of 50 antennas of 12m diameter and Morita Array (ATC; 4 antennas of 12 m and 12 antennas of 7 m).

High sensitivity and high spatial resolution (0.01-0.1")
Thirty Meter Telescope (TMT; optical-NIR) (Mauna kea, Hawaii; 4200m)

First light expected in 2021

A large international collaborations among USA, Japan, Canada, India, and China
The three big projects that NAOJ pursues

**Subaru (optical, NIR)**
Hawaii, D=8.2m
resolution: 0.1-1.0”

**TMT (optical, NIR)**
Hawaii, D=30m
resolution: 0.015”

**ALMA (Submm, radio)**
Chile, D=12m x 54, 7m x 12
resolution: 0.01-0.1”
What Subaru and TMT can see in the optical-NIR regime

Stars (a major component of galaxies) and ionized gas (HII region) with emission lines.

Stars (a major component of galaxies) and Ionized gas (HII region) with emission lines.

Star forming galaxies

(ionized gas)
What ALMA can see in the Submm-radio regime

Molecular gas (from which stars form) and Dust (ejected from young stars)

Star bursting galaxies

Mergers

Internal kinematic structures

Wang et al. (2013)
Subaru’s Unique Wide-Field Imaging Capability

Subaru (30arcmin=Full moon)  HST (3arcmin)

Subaru’s Field of View (area of sky observed at once) is 100 times bigger!

Subaru Prime-Focus Camera (Suprime-Cam)

Digital camera with 84M pixels
Subaru’s new gigantic camera

Hyper Suprime-Cam

Field of view is 7 times larger than Suprime-Cam. 870M pixels, 3 tons

Hangs on there!
Panoramic Universe explored by Subaru

Subaru’s unique wide-field instruments will map out the distant Universe, as well as discover rare objects.

- Suprime-Cam (34’ × 27’) optical imaging
- Hyper Suprime-Cam (1.5° Φ) optical imaging
- MOIRCS (7’ × 4’) NIR imaging and spectroscopy
- FMOS (30’Φ) NIR spectroscopy
- PFS (1.5° Φ) optical and NIR spectroscopy
Subaru’s powerful wide-field instruments

Final cluster with $M=6 \times 10^{14} \, M_\odot$, $20 \times 20 \text{Mpc}^2$ (co-moving) (Yahagi et al. 2005; $\nu \text{GC}$)
Panoramic Views of Distant Clusters

Panoramic Imaging and Spectroscopy of Cluster Evolution with Subaru (PISCES)

Subaru/Suprime-Cam view of CL0939 cluster at z=0.41 (4.3Gyrs ago)

30’ corresponds to 30M light yrs at the cluster distance.

Kodama et al. (2001)
Panoramic Views of Cluster Assembly

(4.3 Gyrs ago, z=0.41)

Resemble to numerical simulations

Dominant central body and surrounding filamentary structures along which many groups of galaxies are aligned.

Kodama et al. (2001)
A Huge Cosmic Web at $z=0.55$ over 50 Mpc
(80’x80’ by 7 S-Cam ptgs.)

CL0016 cluster ($z=0.55$)

Dots: red sequence galaxies in V-I
Red: spectroscopically confirmed members
Blue: spectroscopically confirmed non-members

~1200 secure redshifts!

Hyper Suprime-Cam (HSC)

Millenium Simulation (Springel et al. 2005)

Tanaka, M. et al. (2009b)
Cosmic Noon: $1 < z < 3 \ (6 > T_{\text{Gyr}} > 2)$
(in analogy to cosmic dawn at $z > 6$)

Peak epoch of galaxy formation and AGN activities in the Universe

This also coincides with the appearance of the Hubble sequence of galaxies.

The most important epoch for galaxy formation when the grand design of galaxies are established.

Cosmic Star Formation History

AGN activities (QSO number density)

Hopkins and Beacom (2006)

Fan et al. (2006)
How can we sample forming galaxies?

It consists of blue stellar continuum and many emission lines from ionized gas.

Kinney et al. (1996)
Narrow-band imaging survey will efficiently sample star forming galaxies at high-$z$.

Flux ratio between narrow-band (NB921) and broad-band ($z'$).

$\text{SFR}_\text{H}\alpha > 0.3 M_\odot/\text{yr}$

$\lambda$ [Å]

$z'$

NB921

$\text{H}\alpha (6563\text{Å})@z=0.4$

Koyama et al. (2011)

Magnitudes in NB
Subaru Wide-Field Survey of Narrow-Band Emitters ([OII], [OIII] and Hα) at 0.4<z<2.5

Suprime-Cam (optical; 34'x27')

MOIRCS (NIR; 7'x4')

4 narrow-band filters

7 narrow-band filters

FWHMs correspond to ±1500-2000km/s

Cluster N-body+SAM simulation
(Yahagi et al. 2005; ν GC)
20×20 Mpc² box (co-moving)
"MAHALO-Subaru"
MApping 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>
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<td>z'</td>
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<td>NB912,921</td>
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<td>Hayashi+’10,’11</td>
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<td>Hα</td>
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<td>Ks</td>
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<td>USS1558–003</td>
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<td>Hα</td>
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<td>NB2315</td>
<td>Ks</td>
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<td>z&gt;2 field</td>
<td>GOODS-N</td>
<td>2.19</td>
<td>Hα, Hβ</td>
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<td>NB2095</td>
<td>Ks</td>
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<td></td>
<td>(70 arcmin²)</td>
<td></td>
<td>[OII]</td>
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<td>H</td>
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<td>SXDF-CANDELS</td>
<td>2.19</td>
<td>Hα, Hβ</td>
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<td>NB2095</td>
<td>K</td>
<td>Tadaki+’13</td>
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<td></td>
<td>(92 arcmin²)</td>
<td>2.53</td>
<td>Hα, [OII]</td>
<td>2.315</td>
<td>MOIRCS</td>
<td>NB2315</td>
<td>Ks</td>
<td>Tadaki+’13</td>
</tr>
</tbody>
</table>

18 nights for imaging, >15 nights for spectroscopy
A Prominent Star-Bursting Proto-Cluster at z~2.5

USS1558-003 (z=2.53)

Ha imaging with MOIRCS/NB2315

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**

(Ha emitters)

Proto-clusters are filamentary/clumpy, in the mid of vigorous assembly!

Red Ha emitters (dusty starbursts?) tend to favor higher density regions!

(=key populations under the influence of environmental effects)
Spatial distribution of star-forming galaxies in clusters

- **Ha** emitters at $z=0.81$ (RXJ1716)
- **[OII]** emitters at $z=1.46$ (XCS2215)

Clusters Grow Inside-Out!

- Lx$=2.7 \times 10^{44}$ erg/s
  - Koyama, et al. (2011)
- Lx$=4.4 \times 10^{44}$ erg/s
  - Hayashi, et al. (2010)
Dynamical masses and Integrated SFRs 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

Shimakawa et al. (2014a)
Inside-out growth of galaxy clusters as revealed by MAHALO-Subaru project

Dusty starbursts (red HAEs/IR galaxies) should hold the key to understanding the environmental effects!

Illustrated by Yusei Koyama

- **passive red galaxy**
- **normal SF galaxy**
- **dusty SF / AGN**
MOIRCS multi-object spectroscopy of two proto-clusters at z>2

27 new members (totally 49 members)

36 members

40-50 spectroscopically confirmed members in each cluster!

Dynamical mass of the cluster core is $\sim 1-2 \times 10^{14} M_\odot$
(assuming local virialization)

<table>
<thead>
<tr>
<th>Cluster Name</th>
<th>New Members</th>
<th>$\langle \Delta V \rangle$ [km/s]</th>
<th>$\sigma_{cl}$ [km/s]</th>
<th>$R_{200}$ [Mpc]</th>
<th>$M_{cl}$ [$10^{14} M_\odot$]</th>
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<tr>
<td>PKS1138 all</td>
<td>27</td>
<td>-41</td>
<td>$882^5$</td>
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<tr>
<td>PKS1138 C1</td>
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<td>+9</td>
<td>$683^5$</td>
<td>$0.53^5$</td>
<td>$1.71^5$</td>
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<td>USS1558 all</td>
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<td>-717</td>
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<td>284</td>
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<td>$0.10$</td>
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<td>-1042</td>
<td>574</td>
<td>$0.38$</td>
<td>$0.87$</td>
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</table>

Shimakawa et al. (2014a)
3-D Views of Proto-Clusters at $z>2$

Shimakawa et al. (2014a)
[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. (2014b)
Clumpy structures are common (~40%) in HAEs at z~2 (Field)

HST images (V_{606},I_{814},H_{160}) from the CANDELS survey

less massive clumpy galaxies
\( (M_{\text{star}}<10^{10}M_\odot) \)

massive clumpy galaxies
\( (M_{\text{star}}=10^{10-11}M_\odot) \)

Massive clumpy galaxies tend to have a red clump, and they tend to be detected with MIPS 24μm.

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

We need to spatially resolve star forming activities within galaxies.
“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)
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
\[ \downarrow \]
Gas rich disk
\[ \downarrow \]
Fragment to clumps
\[ \downarrow \]
Migrate towards center
\[ \downarrow \]
Formation of a bulge

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

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

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

Contours: Hα images

Tadaki et al. (2013b)
High-z Galaxy Anatomy

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)
Galaxy Anatomy with 3D spectroscopy
(Integral Field Unit)

VLT(UT4) / SINFONI

Keck/OSIRIS
Gemini/NIFS

No such NIR instrument on Subaru unfortunately!
rotation dominated

D3a 6004 (2.39)

D3a 15504 (2.38)

BX 610 (2.21)

M1-41 (2.17)

K20-8 (2.22)

SA12 6192 (1.51)

BX 599 (2.33)

D3a 6397 (1.51)

ZC 1101592 (1.41)

K20-5 (2.23)

SA12 6339 (2.29)

13a 7144 (1.65)

GK 2471 (2.43)

BM 1163 (1.41)

GK 167 (2.58)

K20-9 (2.04)

K20-6 (2.24)

BX 405 (2.03)

SA12 8768 (2.19)

D3a 4751 (2.27)

GK 2303 (2.45)

1” (8 kpc)

merger

SINS Survey

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

Foerster-Schreiber et al. (2009)
“GANBA-Subaru”

Galaxy Anatomy with Narrow-Band AO-imaging with Subaru

Narrow-band Hα imaging with IRCS + AO188 (0.1-0.15” seeing)

A star forming galaxy at z~2

K-band (continuum)
Stellar mass distribution

Narrow-band (Hα)
Star formation distribution

Ganba!

Struggling with terrible weather at MK :-(
Ultra-wide-field Laser Tomographic Imager and MOS with AO for Transcendent Exploration by SUBARU telescope.
Future key instruments of Subaru Telescope

鼎(tripod pot)

PEPSI (opt)  HSC (opt)  ULTIMATE (NIR)
"ULTIMATE-Subaru": GLAO + Wide-Field NIR Instr.

Ultra-wide Laser Tomographic Imager and MOS with AO for Transcendent Exploration

High resolution (0.2"~1.5kpc) and Wide-field (13.5’)

NIR: Narrow-band imaging and Multi-object IFU / MOS

NB imaging in between OH sky lines is competitive to JWST (wins by 20x FoV !)

Lyα emitters at z=8-10

and

spatially resolved Hα, [OIII] emitters at 1<z<3.5
“Mahalo–Subaru”
MApping HAIpha and Lines of Oxygen with Subaru

“Gracias–ALMA”
GRAphing CO Intensity And Submm with ALMA

Mol. Gas. CO(3→2) @100GHz → gas mass ($M_{\text{gas}}$)
Dust cont. @450 μm–1.1 mm → hidden SFR
spatial resolution (<0.1”), velocity resolusion (~50km/s)

Mol. Gas fraction ($M_{\text{gas}}/M_{\text{gas}}+M_{\text{star}}$)
SF efficiency (SFR/$M_{\text{gas}}$)
Spatial distribution and Kinematics

Proto-clusters are excellent targets for ALMA
**“GRACIAS-ALMA”**

**GRAphing CO Intensity And Submm with ALMA**

Mapping/resolving **molecular gas** and **dust** contents of high-z SF galaxies

cycle-2 sensitivities

- CO line @ Band-3 (~100GHz)  
  SFR~50M$_\odot$/yr (2.7hrs, 5σ) @1<z<3
- Dust continuum@ Band-6-9 (450 μm–1.1 mm)  
  SFR~15M$_\odot$/yr (50min, 5σ)

Spatial resolution: 0.01-0.1” (↔ 0.1-1kpc) (0.18-0.4” in cycle-2)

<table>
<thead>
<tr>
<th>target</th>
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<th>Mahalo-Subaru</th>
<th>Gracias-ALMA</th>
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<td>2.19</td>
<td>Hα</td>
<td>2.094</td>
<td>NB2095</td>
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</table>

We can **spatially resolve dusty star formation directly within galaxies.**

f(gas) and SFE(=SFR/M$_{\text{gas}}$) are essential quantities to characterize the mode of SF.

Relations between **red clumps ~ dusty starbursts ~ bulge formation ~ environment**
Unique targets to test the effects of environment on galaxy formation

USS1558 proto-cluster (z=2.53)

Clusters are efficient targets for ALMA especially at Band-3 as multiple targets can be observed by a single pointing (1’).

HST images (Hayashi et al.) are being taken NOW!
(Clumpy fraction, size evolution)

Chandra 100ks X-ray data (Martini et al.) have just been taken.
(AGN fraction, distribution)
ALMA Takes Off

A detection of nebular emission line from a distant, heavily obscured galaxy at z=5.3 in a protocluster. Now expecting molecular gas observations (CO) from those systems.
“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 (x 15) for point sources and
~1.5 mag deeper (x 4) for extended sources
compared to Subaru (8.2m diameter)

0.015”@2μm ⇔ ~0.1kpc @z>1

TMT can resolve stars and ionized gas with high resolution
which is comparable to ALMA (molecular gas and dust)!
Central concepts of galaxy formation are yet to be explored.

→ Bright future but hard competition!
More Future Surveys of the Cosmic Noon and Beyond

- HSC hybrid blind cluster survey (0.4-1.0μm; z<1.7)
- SWIMS-18 (0.9-2.5μm; z<5)
- WISH-7 (1-5μm; z<8)
HSC Hybrid Blind Cluster Survey to z~1.5-1.7

“blue sequence” survey (SF galaxies)
NB [OII] emitter survey to z~1.7

“red sequence” survey (passive galaxies)
phot-z (or color-color) survey to z~1.5

<table>
<thead>
<tr>
<th>Filter</th>
<th>CW</th>
<th>FWHM</th>
<th>$z(\text{Ly}\alpha)$</th>
<th>$z([\text{OII}])$</th>
<th>$z(\text{H}\beta)$</th>
<th>$z([\text{OIII}])$</th>
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<td>120</td>
<td>5.711±0.049</td>
<td>1.189±0.016</td>
<td>0.679±0.012</td>
<td>0.630±0.012</td>
<td>0.243±0.009</td>
</tr>
<tr>
<td>NB921</td>
<td>9210</td>
<td>131</td>
<td>6.574±0.054</td>
<td>1.471±0.018</td>
<td>0.895±0.013</td>
<td>0.839±0.013</td>
<td>0.403±0.010</td>
</tr>
<tr>
<td>NB973</td>
<td>9730</td>
<td>138</td>
<td>7.002±0.057</td>
<td>1.611±0.019</td>
<td>1.002±0.014</td>
<td>0.943±0.014</td>
<td>0.483±0.011</td>
</tr>
<tr>
<td>NB101</td>
<td>10095</td>
<td>143</td>
<td>7.302±0.059</td>
<td>1.709±0.019</td>
<td>1.077±0.015</td>
<td>1.016±0.014</td>
<td>0.538±0.011</td>
</tr>
</tbody>
</table>
Large-scale (~20Mpc) structures at z~1.5 unveiled by [OII]λ3727 emitter survey with S-Cam

Hayashi et al. (2011)

Tadaki et al. (2012)
## Subaru-HSC Legacy Surveys

<table>
<thead>
<tr>
<th>Layer</th>
<th>Area [deg$^2$]</th>
<th># of HSC fields</th>
<th>Filters &amp; Depth</th>
<th>Comoving volume [h$^{-3}$Gpc$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>1400</td>
<td>916</td>
<td>grizy ($r \approx 26$)</td>
<td>$\sim 4.4 \ (z &lt; 2)$</td>
</tr>
<tr>
<td>Deep</td>
<td>27</td>
<td>15</td>
<td>grizy+3NBs ($r \approx 27$)</td>
<td>$\sim 0.5 \ (1 &lt; z &lt; 5)$</td>
</tr>
<tr>
<td>Ultradeep</td>
<td>3.5</td>
<td>2</td>
<td>grizy+3NBs ($r \approx 28$)</td>
<td>$\sim 0.07 \ (2 &lt; z &lt; 7)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>survey</th>
<th>area</th>
<th>cluster number (dn/dz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSC-Deep</td>
<td>27 deg$^2$</td>
<td>200 (&gt;10$^{14}$ M$_\odot$) at z=1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$6 (&gt;10^{14.5}M_\odot)$ at z=1</td>
</tr>
<tr>
<td>HSC-Wide</td>
<td>1400 deg$^2$</td>
<td>10,000 (&gt;10$^{14}$ M$_\odot$) at z=1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$300 (&gt;10^{14.5}M_\odot)$ at z=1</td>
</tr>
</tbody>
</table>
SWIMS-18 Survey

Unique, comprehensive imaging survey of the Cosmic 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 2015-2017.

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

<table>
<thead>
<tr>
<th>Narrow-Band</th>
<th>Medium-Band</th>
<th>Broad-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>$\lambda_0$ ($\mu$m)</td>
<td>FWHM ($\mu$m)</td>
</tr>
<tr>
<td>NB1244</td>
<td>1.244</td>
<td>0.012</td>
</tr>
<tr>
<td>NB1261</td>
<td>1.261</td>
<td>0.012</td>
</tr>
<tr>
<td>NB1630</td>
<td>1.630</td>
<td>0.016</td>
</tr>
<tr>
<td>NB1653</td>
<td>1.653</td>
<td>0.016</td>
</tr>
<tr>
<td>NB2137</td>
<td>2.137</td>
<td>0.021</td>
</tr>
<tr>
<td>NB2167</td>
<td>2.167</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Simultaneous observations of blue (<1.4$\mu$m) and red (>1.4$\mu$m) channels!

Blue | Red
---|---
NB1244 (6h) | NB1630 (3h) | NB2137 (3h)
NB1261 (6h) | NB1653 (3h) | NB2167 (3h)
Y (3h) | H1 (2h) | K1 (1h)
J1 (3h) | H2 (2h) | K2 (1h)
J2 (3h) | H3 (2h) | K3 (1h)
J (1.5h) | H (1h) | K_s (0.5h)
SWIMS-18 Medium-Band Filters (9)

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

<table>
<thead>
<tr>
<th>MB filters</th>
<th>$\lambda_c$ (μm)</th>
<th>FWHM (μm)</th>
<th>$z_s$(Bal.Lim.) 3645Å</th>
<th>$z_s$(D4000) 4000Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>1.05</td>
<td>0.10</td>
<td>1.74</td>
<td>1.50</td>
</tr>
<tr>
<td>J1</td>
<td>1.17</td>
<td>0.12</td>
<td>2.05</td>
<td>1.78</td>
</tr>
<tr>
<td>J2</td>
<td>1.29</td>
<td>0.12</td>
<td>2.37</td>
<td>2.08</td>
</tr>
<tr>
<td>H1</td>
<td>1.50</td>
<td>0.12</td>
<td>2.95</td>
<td>2.60</td>
</tr>
<tr>
<td>H2</td>
<td>1.62</td>
<td>0.12</td>
<td>3.28</td>
<td>2.90</td>
</tr>
<tr>
<td>H3</td>
<td>1.74</td>
<td>0.12</td>
<td>3.61</td>
<td>3.20</td>
</tr>
<tr>
<td>K1</td>
<td>2.03</td>
<td>0.14</td>
<td>4.38</td>
<td>3.90</td>
</tr>
<tr>
<td>K2</td>
<td>2.17</td>
<td>0.14</td>
<td>4.76</td>
<td>4.25</td>
</tr>
<tr>
<td>K3</td>
<td>2.31</td>
<td>0.14</td>
<td>5.14</td>
<td>5.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BB filters</th>
<th>$\lambda$ (μm)</th>
<th>$\lambda_c$ (μm)</th>
<th>FWHM (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>1.17–1.33</td>
<td>1.25</td>
<td>0.16</td>
</tr>
<tr>
<td>H</td>
<td>1.48–1.78</td>
<td>1.63</td>
<td>0.30</td>
</tr>
<tr>
<td>$K_s$</td>
<td>1.99–2.30</td>
<td>2.15</td>
<td>0.30</td>
</tr>
</tbody>
</table>

NEWFIRM survey (KPNO) with 5 MBs + $K_s$

Will open a new window to 3.5<z<5 with K1,K2,K3 !

Great improvement in phot-z such as $\Delta z/(1+z) < 0.02$

van Dokkum et al. (2009)
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>$\lambda_c$ ((\mu m))</th>
<th>FWHM ((\mu m))</th>
<th>$z(\text{H}\alpha)$</th>
<th>$z([\text{OIII}])$</th>
<th>$z(\text{H}\beta)$</th>
<th>$z([\text{OII}])$</th>
<th>$z(\text{Pa}\alpha)$</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 H\(\alpha\)) Survey with Pair NB filters (4 pairs)
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>$M^*<em>\text{-limit} (M</em>\odot)$</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 (2015-2017)
WISH Space Telescope

WISH is a planned 1.5m diameter space telescope mission for 1-5µm (NIR) with a FoV of 0.24 sq. deg.

Proposing NB filters for WISH

<table>
<thead>
<tr>
<th>NB Filter</th>
<th>Wavelength (µm)</th>
<th>Redshift (Hα, OIII)</th>
<th>SFR (Msun/yr)</th>
<th>Number / FoV</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB217</td>
<td>2.17</td>
<td>2.3, 3.3</td>
<td>7</td>
<td>~1500</td>
</tr>
<tr>
<td>(same as SWIMS-18)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NB284</td>
<td>2.84</td>
<td>3.3, 4.7</td>
<td>20</td>
<td>~200</td>
</tr>
<tr>
<td>NB335</td>
<td>3.35</td>
<td>4.1, 5.7</td>
<td>30</td>
<td>~150</td>
</tr>
<tr>
<td>NB441</td>
<td>4.41</td>
<td>5.7, 7.8</td>
<td>90</td>
<td>~20</td>
</tr>
<tr>
<td>NB497</td>
<td>4.97</td>
<td>6.6, 8.9</td>
<td>250</td>
<td>??</td>
</tr>
</tbody>
</table>

6hrs exp. (5σ), 1mag extinction of Hα

NB filters at 2.5 ~ 5 µm will be the key for WISH!
Pair filters ([OIII], Hα) to z~6!
**WISH-7 Survey**

for $1.5 < z < 8$

- 「7」 sq. deg.
  \[ \sim 7 \times 10^7 \text{ Mpc}^3 / (\Delta z=1) \]
  \[ \sim 10 \text{ progenitors of Coma class clusters at every } z \]
  NB: $3.5-7 \times 10^6 \text{ Mpc}^3 / (\Delta z=0.05-0.1)$
  \[ \sim 1 \text{ progenitor of Coma class cluster per filter} \]
  30 WISH pointings (0.24 sq. deg. / FoV)

- Exposure times needed
  BB: $1 \text{ hrs} \times 6 \text{ filters} \times 30 \ p = 180 \text{ hrs}$
  NB: $6 \text{ hrs} \times 4 \text{ filters} \times 30 \ p = 720 \text{ hrs}$
  900 hrs in total (or 1200 hrs including overheads)
Summary

• **Mahalo-Subaru** has been mapping out star formation activities across cosmic times (0.4<z<3) and environments.

• **Clusters grow inside-out**, and the SF activity in cluster cores drops rapidly as \((1+z)^6\). Dusty starbursts are more prevalent in proto-clusters, and the key populations under the influence of environmental effects.

• **Clumpy nature** of SFGs at z~2 (in particular, red dusty clumps) maybe closely related to a bulge formation.

• **Galaxy Anatomy with NB+AO (Ganba-Subaru), Gracias-ALMA** and **ULTIMATE-Subaru** will reveal the physical processes of galaxy formation.

• **HSC** will make a large, statistical sample of clusters to z~1.7. **SWIMS-18** will be sensitive up to z~5, and **WISH** will extend the frontier of SFR- and Mass-limited samples to z~6-8.