PFS Deep Survey
for
Galaxy Formation and Cosmic Reionization

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Prime Focus Spectrograph (PFS)

- Suprime-Cam → HSC (obs. area x7) from 2011-
- FOCAS → PFS (obs. area x200, multiplicity x100) from 2016?-

Complementary to the other 8m-telescope and ELT spectrographs

→ PFS could revolutionalize spec. studies of highz galaxies reachable with >8m telescopes. No competing studies.
Magnitude limit surveys do not reach galaxies up to $z \sim 7$

<table>
<thead>
<tr>
<th>mag</th>
<th>N(1FoV)</th>
<th>Exp(total;hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_z &lt; 23.0$</td>
<td>76000</td>
<td>10</td>
</tr>
<tr>
<td>$m_z = 23.0 - 23.5$</td>
<td>32000</td>
<td>11</td>
</tr>
<tr>
<td>$m_z = 23.5 - 24.0$</td>
<td>45000</td>
<td>42</td>
</tr>
<tr>
<td>$m_z = 24.0 - 24.5$</td>
<td>64000</td>
<td>128</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td></td>
<td><strong>191(hr)</strong></td>
</tr>
</tbody>
</table>

For 1 FoV (WFMOS) $\sim 30$ nights (for 2008 WFMOS Kona meeting)

The brightest $z \sim 7$ galaxy in 0.5 deg$^2$ have $m \sim 25.5$

(Ouchi et al. 2009)

Targeting color selected galaxies for high redshifts
Perfect Targets Supplied from HSC Deep/Ultra-Deep surveys (Japan-Princeton-Taiwan)

- High-z galaxies: Lyman break galaxies (LBGs) and Lya emitters (LAEs). Bright in optical bands $\rightarrow$ Ideal for PFS optical spectroscopy. Nearly ‘complete’ spectroscopy down to a given UV-continuum magnitude or Lya flux.
Candidates from HSC (being designed)

- Tentative plans
  - Deep survey (i~27mag, NB~25mag) for \(~30\text{deg}^2\)
  - Ultra deep survey (i~28mag, NB~26mag) for \(~3.5\text{deg}^2\)
  \(\rightarrow\) 10k-1M LBGs and 1k-10k LAEs at \(z=2-7\). # of galaxy candidates is boosted by 10-100x.

- 10-100 times more spec. targets will be waiting for spectroscopy. Large enough for PFS spectroscopy.
Deep PFS Surveys
Four Science Drivers (TBD)

1. **Mass assembly** of massive galaxies. What is the major process, accretion or mergers? Is stellar (or dark mass) assembly first?

2. **Chemical and dynamical evolution** of intense star-forming galaxies

3. Galaxy, AGN, and **proto-cluster formation** in large scale structure at early stage

4. **Cosmic reionization** probed with galaxies
1) Mass Assembly of Massive Galaxies
Mergers or cold accretion?

• Violent SF at $z>2$, but mostly no merger signatures
• Galaxies acquired most of baryon ($\sim 70\%$!) at $z\sim 2$-3 via cold accretion (e.g. Katz+03, Keres+09, Dekel+09)?
• Is this true? Any observational signatures?
Testing Cold Accretion Hypothesis

• No signature of cold gas accretion, but outflow based on 89 LBGs at z~2, (Steidel et al. 2010).
• But, consistent with cold accretion models, because a covering factor of cold accretion gas is very small \( \sim 1-2\% \) (Faucher-Giguere+10), and a signal can be obtained when a cold filament is exactly aligned with the line of sight, Kimm +10). → need very large optical+NIR spectroscopic sample of LBGs.
1) Targeting LBGs at $z=2.1-2.4$
Sweet Spot of PFS Galaxy Survey

- Three channels; Blue(3800-6700A), Red(6500-10000A), and IR(10000-13000A)
- Blue+IR channels $\rightarrow$ UV spectra (Lya, IS absorption lines) and [OII] lines for LBGs at $z=2.1-2.4$.
  1. Absorption lines in UV cont and Lya $\rightarrow$ inflow/outflow indicators
  2. [OII] lines $\rightarrow$ systemic velocities

Signature of cold accretion and/or constraints on a covering factor of accretion gas with a 10-100x larger sample than prev. study
Driving mechanism of galaxy evolution in hierarchical structure formation
Relates to starburst, AGN activity, formation of early-type galaxies

Few measurements at z>1 using close pairs
(eg, Ryan+08, Bluck+09, Cooke+10)
very small statistics
mostly based on phot-z

cf. method using morphology
is complementary but has
a limitation

Study with PFS
Identify physically associated close pairs from large LBG+LAE samples. (Exploiting the positive correlation of stellar-mass and UV luminosity, e.g. Papovich+01, Yabe+09)
- N~1000 close pairs with spec-z
- merger fraction at different z, SFR, stellar mass
Dark mass assembly: connecting stars (baryon) and dark halos

- Precision measurements of LF and CF
  - Largest uncertainties → sample contamination and N(z)
  - Constraining star-forming galaxies with numerical simulation, halo occupation distribution (HODs) and conditional luminosity func. models

z=4 LBG correlation function fit by HOD model (Ouchi+06, Hamana+06)

z=4 Mass-luminosity relation by conditional luminosity func. model (Cooray&Ouchi 06)
Star-Formation Duty Cycle
(intermittent SF history for stellar-mass buildup?)

- Precision measurements of high-z galaxy luminosity function and correlation function →
  hosting halo mass+HOD+duty cycle (Ouchi et al. 2004, Lee et al. 2009, Ouchi et al. 2010)
- Halo mass determination (just an accuracy of an order—a factor of ~5)
- Duty cycle of dropout and Lya emitting population is ~10% and ~1%, respectively (just an
  accuracy of an order). Constraints on SF history and Lya production mechanism.
2) Constraints on Metallicity at z~2-6 with Metal Absorption Lines

- Metallicity estimated from low-ionization IS lines (Heckman et al. 1998), CIV-index (Mehlert et al. 2003) etc.
- Composite spectra of very faint LBGs → metallicity of very faint/less-massive galaxies (~300 m telescope science)
- Complementary to ELT(z<2-4) and JWST(bright) studies
2) Do z~2-7 Galaxies include PopIII starbursts?

- Hell is an indicator of forming galaxies (ionized by massive stars).
- Composite spectra → no Hell emission (no signature of popIII/cooling radiation)
  - 3σ upper limits: \( f(\text{HeII})/f(\text{LyA}) < 2\% \) at \( z=3.13 \) (Ouchi et al. 2008)
- No signatures of popIII SF.
- PFS observations for 10k high-z galaxies → identifying popIII SB comp. with a top heavy IMF.

Hardness of flux expressed by the ratio of He+ to H ionising flux (Schaerer 2003)
3) Large-scale structures and proto-clusters at $z>4$

- Searching for large-scale structures and proto-clusters in a volume 100x larger than the previous Subaru surveys. (cf. the filamentary LSSs+proto-cluster at $z\sim3-6$ Shimasaku+03, Hayashino+04, Ouchi et al. 2005). (100 proto-clusters at $z\sim5-6$)
- 3D maps of high-z universe for charting large scale structures
4) Cosmic Reionization

Tight Relation with Galaxy Formation

Ionized IGM (orange), neutral IGM (green), and Galaxies (blue)

Ly-continuum photons to ionize the universe

Intense UV background to suppress dwarf-galaxy formation

M(halo) = 6e7 Mo, z_c = 1.7

M(halo) = 6e8 Mo, z_c = 7.6

Susa & Umemura+04
Open Questions (1)

Evolution of Neutral Hydrogen Fraction

- $z \sim 6$: QSO Gunn-Peterson test
- $z \sim 11$: CMB Thomson scattering optical depth

sharp reionization or extended reionization (Dunkley+09)?
Is significant minihalo ($M_h \sim 10^6 M_\odot$) contribution (Choudhury+08) required?

Choudhury+08 models

$M_h(\text{lim}) \sim 10^9 M_\odot$
$M_h(\text{lim}) \sim 10^8 M_\odot$
$M_h(\text{lim}) \sim 10^6 M_\odot$

Ouchi et al. (2010)
Open Questions (2)

Ionization process

Inside-out? Outside-in?  Or filament-last?

The ionization process: How did the ionized regions extend?

• Depending on distribution of ionizing sources and IGM density
• Inside-out (e.g. Furlanetto et al. 2004), outside-in (e.g. Miralda-Escude et al. 2000), or filament-last (Finlator et al. 2009).

Not enough S/N with the present 21cm-obs facilities such as LOFAR
Reionization and Physical Processes

- Physical processes from topology (inside-out, outside-in, filament-last?)
- Clustering of Lya emitters: imprints of neutral fraction and ionized bubble topology (McQuinn et al. 2007)
The clustering of Lya emitters at $z \approx 7$ is not well constrained with the present Subaru studies, due to small statistics. (phot. sample $\sim 200$, spec. sample $\sim 30$ at $z=6.6$) $\rightarrow x_{HI} < \sim 0.5$ at $z=6.6$. None for the ionized bubble topology

- PFS+HSC $\rightarrow \sim 100$ x larger sample ($\sim 10k$ LAEs) $\rightarrow x_{HI}$ and topology

PFS: Composites of Lya line profiles in a few 10Mpc area. Spatial variance of line broadening/Lya-FWHM relation for reionization test.
At $z \sim 7$, did galaxies produce ionizing photons enough for ionizing the hydrogen IGM?

- Galaxies alone may not reionize the universe or
- Universe is already ionized by galaxies, but these galaxies have higher escape fraction (>0.2), (lower metallicity top-heavy IMF) or undetected faint galaxy population ($\alpha \sim -1.9$).

- The determination of $\alpha$ with PFS+HSC data, HUDF, and the forthcoming CANDLES data.
OBSERVATIONS AND REQUIREMENTS
PFS Observations (TBD)

- PFS 12 hour (6 hour each) integration/pos. for 30 deg$^2$
  - Covering HSC DS area (30 deg$^2$): ~60 nights incl. overhead+weather with PFS
  - Goals: logL>42.7-42.8 erg/s; 6000 LAEs at z=5.7-6.6 and >10000 LBGs+LAEs at z=2-7
Required PFS Performance

• Faint limits of PFS performance, this survey requires good→ high sensitivities with good sky subtraction. The high throughput (10-20%) is indispensable. Moreover, for good sky subtraction and less smearing of signals, we request a stability of spectrograph ideally as high as Keck/LRIS and DEIMOS.

• A half of sensitivity → twice of Subaru nights (or probably more, due to the systematics)

• Fiber diameter should be optimized. High S/N for a point source is desirable.
Summary

PFS Deep Survey for Galaxies at z=2-7
Spectroscopic follow-up of ~30 deg^2 HSC D/UD fields

1. Mass assembly of massive galaxies. (Cold accretion or mergers?)
2. Chemical and dynamical evolution of intense star-forming galaxies
3. Galaxy, AGN, and proto-cluster formation in large scale structure at early stage
4. Cosmic reionization probed with galaxies

Required nights (~60-120 nights; TBD)
Required performance→high sensitivity (incl. stability)