Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs)

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on behalf of the SHELLQs collaboration
SHELLQs
Subaru High-z Exploration of Low-Luminosity Quasars

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High-z quasars - Unique probe of the early Universe

Fundamental questions we aim to answer:

**Why do supermassive black holes (SMBHs) exist?**
★ When were they born?
★ What were their seeds?
★ How did they grow in the early and late epochs of the cosmic history?

[Observational signatures]
- What are the luminosity/mass functions of quasars/SMBHs?
- Are $10^9 \, M_\odot$-class SMBHs common or exceptional at $z > 6$?
- How do the luminosity/mass functions evolve towards lower redshift?

**How did the host galaxies form and (co-)evolve?**
★ When and how did the first stellar-mass assembly happen?
★ Did SMBHs impact the host galaxy evolution? If so, how?
★ Do they mark the highest density peaks of the underlying matter distribution?

[Observational signatures]
- What are the current and past star formation activities, inferred from the amount and kinematics of the gas, current SFR, and chemical enrichment?
- Do we find special (e.g., over-dense) environments around the quasars/host galaxies?

**When and how was the Universe re-ionized?**
★ When did re-ionization start and complete?
★ How did it proceed, as a function of space and time?
★ What provided the ionizing photons?

[Observational signatures]
- How does the IGM neutral fraction change along redshift and transverse direction?
- Do low-luminosity quasars emit enough UV photons to re-ionize the Universe?

and many more!

"Illuminating the dark ages: Quasars and galaxies in the reionization epoch" (Heidelberg; June 27 - July 1, 2016)
Past/ongoing surveys and their immense legacy value

- SDSS 2.5m
- CFHT 3.6m
- UKIDSS/VIKING 4m
- Pan-STARRS1 1.8m
- DES 4m

~100 quasars known at z > 5.7:
- only a few (one) at z > 6.5 (z > 7)
- or $M_{1450} > -24$ mag

A wide variety of follow-up observations with

- ALMA for FIR-based SFR, gas and dust masses, gas kinematics, dynamical galaxy mass, ...
- Subaru and other large optical/near-IR telescopes (→ELTs) for SMBH mass, metallicity distribution, IGM properties, ...
- HST (→JWST) for the morphology, UV-based SFR, etc. in the host galaxies, surrounding ionized gas, ...
- Chandra and XMM-Newton (→ATHENA) for intrinsic mass accretion rate, Eddington ratio, absorbers, ...

Luminosity function

Comparison with theoretical models
**Subaru Hyper Suprime-Cam SSP survey**

**Hyper Suprime-Cam (HSC)**
- 116 2K x 4K Hamamatsu FD CCDs (104 CCDs are used for science exposures)
- Circular FoV of 1°.5 diameter
- Installed on the Subaru 8.2-m telescope
- Miyazaki et al. (2016, in prep.)

**The HSC SSP (Subaru Strategic Program) survey**
- 300 Subaru nights over 5 years, started in early 2014.
  - Wide: $r_{AB} < 26.1$ mag over 1400 deg$^2$
  - Deep: $r_{AB} < 27.1$ mag over 27 deg$^2$
  - UDeep: $r_{AB} < 27.7$ mag over 3.5 deg$^2$
- Filters: ($g$, $r$, $i$, $z$, $y$) in Wide, + NBs in Deep & UDeep
- The Wide has just reached the full-depth, full-color area of 200 deg$^2$.

**Table 7: Quasar Samples**

<table>
<thead>
<tr>
<th>redshift</th>
<th>Wide (1400 deg$^2$)</th>
<th>Deep (27 deg$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mag. range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r &lt; 23.0$</td>
<td>$i &lt; 24.0$</td>
<td>$z &lt; 24.0$</td>
</tr>
<tr>
<td>number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>3500</td>
<td>280</td>
</tr>
</tbody>
</table>
Candidate selection and confirmation

HSC database search for red point sources

Near-IR catalogs (UKIDSS, VIKING)

Simple color cuts

SED fitting

Bayesian probabilistic

\[ P_{\text{Q}}(d) = \frac{W_{Q}(d)}{W_{Q}(d) + W_{0}(d)} \]

\[ W_{Q/D}(d) = \int S(\phi) \Pr(\det|\phi) \Pr(\bar{d}|\phi) \, d\bar{d} \]

Eye inspection

Additional quality checks (detection, photometry, shape, ...)
with SExtractor, using both stacked and per-visit images.

"Illuminating the dark ages: Quasars and galaxies in the reionization epoch" (Heidelberg; June 27 - July 1, 2016)
Progress to date

- Candidate selection has been completed for the first ~100 deg$^2$ of the Wide fields (i.e., all the area included in the latest internal data release).

- Spectroscopic observations are underway.

  - Subaru/FOCAS
  - GTC/OSIRIS
  - Gemini/GMOS

- Results so far (preliminary!)

<table>
<thead>
<tr>
<th>Candidates ($z_{AB} &lt; 24.5$, $y_{AB} &lt; 24.0$)</th>
<th>86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectroscopy done</td>
<td>48</td>
</tr>
<tr>
<td>Quasars at $z \geq 6$</td>
<td>22</td>
</tr>
<tr>
<td>Galaxies at $z \sim 6$</td>
<td>14</td>
</tr>
<tr>
<td>[O III] emitters at $z \sim 0.8$</td>
<td>2</td>
</tr>
<tr>
<td>Brown dwarfs</td>
<td>4</td>
</tr>
<tr>
<td>Moving/transient</td>
<td>6</td>
</tr>
</tbody>
</table>

Our uniqueness and challenges

* We are going down to $z_{\text{AB}} \sim 24.5$ mag, deeper than any previous wide-field (1,000-deg$^2$ scale) survey has reached.

* Spectroscopic identification needs a-few-hour integration per object, even with 8-10 m telescopes.

* We are starting to find many $z \sim 6$ galaxies contaminating to the quasar candidates.

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$Illuminating the dark ages: Quasars and galaxies in the reionization epoch$ (Heidelberg; June 27 - July 1, 2016)
Future Prospects

- The HSC-SSP survey will continue to observe the planned 1,400 deg$^2$ in the Wide component, until 2019-2020. The observed area, in the full color and full depth, has just reached 200 deg$^2$.
- We will continue high-z quasar candidate selection in lock-step with the HSC survey.
- We will also soon start to look at the Deep (27 deg$^2$) and the Ultra-Deep (3.5 deg$^2$) fields.

- Spectroscopic observations will continue.
  - “Subaru Intensive program” has been approved for our project; 20 nights awarded in the 16B - 18A semesters.
- Various follow-up studies are underway.
  - luminosity function
  - IGM neutral fraction through GP and damping-wing measurements (deep optical spectroscopy proposed)
  - SMBH mass and Eddington ratio distributions (near-IR spectroscopy proposed)
  - metallicity and chemical evolution (near-IR spectroscopy proposed)
  - star formation, dust, and gas in the host galaxies (ALMA observations proposed)
  - Ly$\alpha$ halos (HST narrow-band imaging proposed)
- Subaru Prime Focus Spectrograph (PFS) will come on stage at ~2019, and will start a massive spectroscopic survey over the HSC survey area.