SHELLQs-ALMA: submm properties of galaxies hosting less-luminous quasars at $z > 6$

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→ Izumi et al. to be submitted
Co-evolution of SMBH and galaxy

- $M_{\text{BH}}$ is tightly correlated with $M_{\text{bulge}}$ and $\sigma^*$ → **Co-evolution**

- Favoured scenario: Merger-induced starburst & AGN, and subsequent “AGN feedback” to regulate the star formation (e.g., Hopkins et al. 2008; Fabian 2012, ARA&A, 50, 455)

- **When, how, and where the relation has arisen?**

Reveal (i) SMBH feeding/feedback and (ii) galaxy growth over the cosmic time
Host galaxy properties of high-z quasars

- Luminous quasars at $z \sim 6$ ($L_{\text{bol}} > 1 \times 10^{14} L_{\odot}$)
- ULIRG/SMG-class star formation!
- Rapid, vigorous, and coeval SMBH and galaxy growths (SF time scale < 100 Myr)

<table>
<thead>
<tr>
<th>Typical value</th>
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</thead>
<tbody>
<tr>
<td><strong>SFR</strong></td>
</tr>
<tr>
<td><strong>$M_{\text{gas}}$</strong></td>
</tr>
<tr>
<td><strong>$M_{\text{dust}}$</strong></td>
</tr>
<tr>
<td><strong>$M_{\text{BH}}$</strong></td>
</tr>
</tbody>
</table>

Early co-evolution: likely a biased one

- $M_{\text{BH}}$ of some optically-luminous $z > 6$ quasars are over-massive → SMBH earlier, galaxies later?

- But we should care about a selection bias to prefer luminous ($\sim$ massive) objects

$\sigma$ (km/s)

$M_{\text{BH}}$ (M$_{\odot}$)

- Gas-$\sigma$ is used instead of stellar $\sigma$ in quasars


Local galaxies, Tremaine02
Quasars at $1.4 \leq z \leq 5$
$z \sim 6$ Quasars, $\sigma=$FWHM/2.35
$z \sim 6$ Quasars, $\sigma$ based on Ho (2007a)
Probing-down low luminosity objects → Depict less-biased mass distribution!
SHELLQs

Subaru High-z Exploration of Low-Luminosity Quasars

Members

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### ALMA Cycle 4 observations

<table>
<thead>
<tr>
<th>Quasar</th>
<th>$z_{\text{opt}}$</th>
<th>$M_{1450}$</th>
<th>$L_{\text{Bol}}$ ($L_{\odot}$)</th>
<th>BAL</th>
<th>$\theta$ ([CII])</th>
<th>$1\sigma$ (mJy/b), dV=50 km/s</th>
<th>$1\sigma$ (μJy/b): cont.</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0859+0022</td>
<td>6.39</td>
<td>-23.56</td>
<td>3.9E+12</td>
<td>N</td>
<td>0.64” x 0.47”</td>
<td>0.12</td>
<td>9.5</td>
</tr>
<tr>
<td>J1152+0055</td>
<td>6.37</td>
<td>-24.91</td>
<td>1.4E+13</td>
<td>N</td>
<td>0.52” x 0.47”</td>
<td>0.24</td>
<td>20.7</td>
</tr>
<tr>
<td>J2216-0016</td>
<td>6.10</td>
<td>-23.56</td>
<td>3.9E+12</td>
<td>Y</td>
<td>0.54” x 0.43”</td>
<td>0.18</td>
<td>13.2</td>
</tr>
<tr>
<td>J1202-0057</td>
<td>5.93</td>
<td>-22.44</td>
<td>1.4E+12</td>
<td>N</td>
<td>0.79” x 0.71”</td>
<td>0.12</td>
<td>8.8</td>
</tr>
</tbody>
</table>

- Four HSC quasars at $z\sim6$ (from Matsuoka+16)
- Aimed at detecting the [CII] and underlying rest-FIR continuum emission
Band 6 full spectrum: J2216 (example)

~0.18 mJy @dV = 50 km/s (on-source time ~ 1.7h)
Results: Spatial distribution

Color = [CII]
Contour = FIR continuum

J0859+0022
$\theta = 0.64'' \times 0.47''$

J1152+0055
$\theta = 0.52'' \times 0.47''$

J2216-0016
$\theta = 0.54'' \times 0.43''$

J1202-0057
$\theta = 0.79'' \times 0.71''$
**FIR properties of the HSC-quasars**

- **LIRG-class objects @ z > 6**!
- Moderate SFR (23-40 M$_{\text{sun}}$/yr; L$_{\text{IR}}$-based)
  - c.f., SFR ~ 100-1000 M$_{\text{sun}}$/yr for optically luminous quasars @ z > 6

<table>
<thead>
<tr>
<th></th>
<th>$M_{\text{dust}}$ (1E7 M$_{\text{sun}}$)</th>
<th>SFR$<em>{\text{IR}}$ (M$</em>{\text{sun}}$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0859</td>
<td>5.0 ± 0.7</td>
<td>28 ± 4</td>
</tr>
<tr>
<td>J1152</td>
<td>6.0 ± 1.0</td>
<td>34 ± 6</td>
</tr>
<tr>
<td>J2216</td>
<td>4.1 ± 0.8</td>
<td>23 ± 5</td>
</tr>
<tr>
<td>J1202</td>
<td>7.1 ± 0.3</td>
<td>40 ± 2</td>
</tr>
</tbody>
</table>
Size of the emitting region

- FWHM ~ a few kpc
- Comparable to the sizes of optically-luminous quasars (SFR ~ 100-1000 \( M_{\text{sun}}/\text{yr} \); \( M_{\text{dust}} > 1e8 \ M_{\text{sun}} \))
  - An order of mag. difference in \( \Sigma_{\text{ISM}} \)
  - Key parameter of \( \text{SMBH accretion} \) (e.g., Hopkins & Quataert 2010)
Discussion:
Star-forming nature and early co-evolution in the HSC quasars

$v^2$GC simulation (SAM)
Ishiyama et al. 2015, Shirakata et al. in prep. (P5-07)

Volume: $1.12 \, h^{-1} \, cGpc$
DM resolution: $2.2E8 \, M_{\odot}$
Particles: $8192^3$

from $v^2$GC simulation (Ishiyama et al. 2015)
Star formation levels

![Graph showing star formation rates (SFR) versus stellar mass for galaxies at z ~ 6. The graph includes data points for high-redshift quasars (cyan stars), the Somerville+08 (MS) model, and the Salmon+15 (MS) model. The artificial effect due to low signal-to-noise (S/N) is shown with red diamonds, and the quasi-stellar object (QSO) J1152+0055 is highlighted.]
These HSC quasars are on or below the MS@z~6: They are transforming to quiescent galaxies

Star formation levels

![Graph showing the relationship between SFR and Stellar Mass for HSC quasars at z~6.]

- **SFR (M⊙/yr)**
- **Stellar Mass (M⊙)**

Key points:
- **HSC quasar**
- **z > 5.7 luminous quasar**
- **Somerville+08 (MS)**
- **Salmon+15 (MS)**

Legend:
- Red diamonds: z > 5.7 luminous quasar
- Blue stars: HSC quasar
- Green circles: v2GC Model
- Black dashed line: Somerville+08 (MS)
- Blue solid line: Salmon+15 (MS)
Early co-evolution in z ~6 quasars

Fig. 8. M\textsubscript{BH} vs host galaxy M\textsubscript{dyn} for z > ∼6 quasars. The HSC quasars are shown as cyan stars along with ν\textsuperscript{2}GC model predictions at z ∼6 (white circles). The diagonal dashed line indicates the local M\textsubscript{BH}–M\textsubscript{bulge} relationship with its intrinsic scatter in the shaded region (Kormendy & Ho 2013). We equate M\textsubscript{dyn} and M\textsubscript{bulge} in this plot. Also shown are z > ∼optically luminous (M\textsubscript{1450} < −25, mostly < −26) quasars (red diamonds) and less-luminous (M\textsubscript{1450} > −25; similar to the HSC quasars) ones (blue triangles). The less-luminous quasars, including the HSC ones, lie close to the local relation, whereas the luminous quasars show departures particularly at M\textsubscript{dyn} < 10\textsuperscript{11}M\textsubscript{☉}. Among the four HSC quasars, Mg\textsuperscript{II}-based M\textsubscript{BH} is available for J0859+0022 and J2216-0016, whereas the Eddington-limited accretion is assumed for the rest (see Table 4). For these two, M\textsubscript{BH} with the Eddington ratio = 0.6 are also plotted for reference.

Our study highlights the importance of probing lower M\textsubscript{BH} (∼10\textsuperscript{8}M\textsubscript{☉}) SMBHs to understand the unbiased early co-evolutionary relation reflecting the bulk of the AGN-host galaxies in this epoch.

Finally, we compare the observed distributions of z ∼6 quasars on the plane with simulated galaxies from the ν\textsuperscript{2}GC model, which are also plotted in Figure 8. Here, we selected all galaxies containing M\textsubscript{BH} ≥ 10\textsuperscript{7}M\textsubscript{☉} SMBHs at z ∼6 as we focused on massive quasars. The simulation traces the SMBH growth from the seed mass of 10\textsuperscript{3}M\textsubscript{☉} 10\textsuperscript{5}M\textsubscript{☉}. Changing the seed BH mass to 10\textsuperscript{5}M\textsubscript{☉} does not affect the results at the high M\textsubscript{BH} or high M\textsubscript{bulge} regions, primarily because the ν\textsuperscript{2}GC model allows super-Eddington accretion (Shirakata et al. 2016) relation. It is thus natural that the simulated galaxies follow the local relation. Note that we use M\textsubscript{dyn} returned by the model, which indicates either (i) total mass within a half-mass radius (bulge-dominated galaxy) or (ii) total mass within a disk effective radius (disk-dominated galaxy). The mass of the dark matter would not be important at these spatial scales (Genzel et al. 2017). Thus, our comparison with observed data is fair.

It is therefore remarkable that most of the low-luminosity quasars (HSC + CFHQS) follow the local relation. This implies, based on the ν\textsuperscript{2}GC model, that these quasars could have been formed through the standard, quasi-synchronized galaxy–SMBH formation scenario (e.g., Di Matteo et al. 2005; Hopkins et al. 2006), although we cannot exclude other evolutionary scenarios. This argument still holds if we re-estimate the M\textsubscript{BH} of the two HSC quasars without Mg\textsuperscript{II}-based calibration (J1152+0055 and J1202-0057) with an Eddington ratio of 0.6 (expected mean for z ∼6 quasars including lower-luminosity ones as well, Willott et al. 2010a), which are also plotted in Figure 8. On the other hand, it is still quite challenging to form massive-end galaxies (M\textsubscript{dyn} > ∼5 × 10\textsuperscript{10}M\textsubscript{☉}) that contain M\textsubscript{BH} > ∼2.5 × 10\textsuperscript{8}M\textsubscript{☉} SMBHs (i.e., values comparable to optically luminous ones).
Early co-evolution in z ~6 quasars

Merger-induced synchronized SMBH-galaxy formation (dM_{BH}/dt = f \times SFR_{bulge}); v2GC model

Figure 8.
Early co-evolution in $z \sim 6$ quasars

![Graph showing co-evolution of black hole mass ($M_{\text{BH}}$) vs. host galaxy dynamical mass ($M_{\text{dyn}}$) for quasars at $z \sim 6$. The graph includes data points and model predictions, with different symbols representing HSC quasars, luminous quasars, low-luminosity quasars, and $\nu$2GC model predictions. The graph highlights two groups of quasars, Group-1 and Group-2, with one group showing departures from the local $M_{\text{BH}}$–$M_{\text{bulge}}$ relation.

The text explains that the study focuses on probing lower SMBH masses ($\sim 10^8 M_\odot$) to understand the unbiased early co-evolutionary relation reflecting the bulk of the AGN-host galaxies in this epoch. The study compares the observed distributions of high-redshift quasars with simulated galaxies from the $\nu$2GC model.

Key points:
- The HSC quasars are shown as cyan stars along with $\nu$2GC model predictions at $z \sim 6$ (white circles).
- The diagonal dashed line indicates the local $M_{\text{BH}}$–$M_{\text{bulge}}$ relationship with its intrinsic scatter in the shaded region.
- Optically luminous quasars ($M_{1450} < -25$, mostly $< -26$) and less-luminous ones ($M_{1450} > -25$) are also shown.
- The less-luminous quasars, including the HSC ones, lie close to the local relation, whereas the luminous quasars show departures particularly at $M_{\text{dyn}} < 10^{11} M_\odot$.
- Among the four HSC quasars, Mg II-based $M_{\text{BH}}$ is available for J0859+0022 and J2216-0016, where the Eddington-limited accretion is assumed for the rest (see Table 4).
- The Eddington ratio for these two quasars is assumed to be 0.6 for reference.

The study highlights the importance of probing lower SMBH masses to understand the unbiased early co-evolutionary relation reflecting the bulk of the AGN-host galaxies in this epoch. Finally, the observed distributions are compared with simulated galaxies from the $\nu$2GC model, which traces the SMBH growth from the seed mass of $10^3 M_\odot$. The galaxy bulge and the central SMBH gain masses while maintaining the relation.

Key equations:
\[
\Delta M_{\text{BH}} = f_{\text{BH}} \Delta M^*_{\text{burst}}
\]
where $\Delta M^*_{\text{burst}}$ is the total mass of stars newly formed during an SB episode, $\Delta M_{\text{BH}}$ is the total SMBH mass growth, and $f_{\text{BH}}$ is a constant (= 0.01) selected to match the local $M_{\text{BH}}$–$M_{\text{bulge}}$ relation.

Changing the seed BH mass to $10^5 M_\odot$ does not affect the results at the high $M_{\text{BH}}$ or high $M_{\text{bulge}}$ regions, primarily because the $\nu$2GC model allows super-Eddington accretion.

The comparison with observed data is fair, as our study highlights the importance of probing lower SMBH masses to understand the unbiased early co-evolutionary relation reflecting the bulk of the AGN-host galaxies in this epoch.

Finally, the observed distributions are compared with simulated galaxies from the $\nu$2GC model, which traces the SMBH growth from the seed mass of $10^3 M_\odot$. The galaxy bulge and the central SMBH gain masses while maintaining the relation.
Early co-evolution in z ~6 quasars

Group-1
- Roughly follow the local relation
  → merger-induced, synchronised
SMBH-galaxy evolution model may explain (although many of them
must live in quite massive halos)

Group-2
- Quite hard to reproduce with the ν2GC scheme; another scheme
- Appear as over-massive $M_{BH}$ at $z$ ~ 0 as well?
Summary

- ALMA follow-up of four low-luminosity HSC quasars at $z > 6$.
- LIRG-like FIR properties ($L_{\text{FIR}}, L_{\text{[CII]}}, M_{\text{dust}}$) in their hosts.
  - SFR $\sim 20-40$ M$_{\text{sun}}$/yr
    → Clear contrasts to those of the previously discovered quasar-hosts (~ULIRG/SMG-class star formation)
- The HSC quasars are on or below the MS at $z \sim 6$
  → Rapid transition phase to quiescent galaxies?
- Low-luminosity quasars follow the local co-evolutionary relations
- Adding lower-luminosity (lower-mass) quasars enhances the likely existence of two quasar populations,
  (i) those roughly following the local relation ← standard model :)
  (ii) those showing clear enhancement in $M_{\text{BH}}$ ← another scheme?