High-redshift \((z > 6)\) accreting SMBHs in the X-rays

F. Vito
PUC (Chile) / CASSACA (China)

with W.N. Brandt, F.E. Bauer, F. Calura, R. Gilli, B. Luo, O. Shemmer, C. Vignali, G. Zamorani, M. Brusa, F. Civano, A. Comastri, R. Nanni, N. Cappelluti, M. Volonteri

Testing self-similarity of QSO accretion physics up to \(z > 6\)

Witnessing SMBH accretion as close as possible to the initial conditions of SMBH formation
>200 QSOs discovered so far at z>6 (i.e. <1 Gyr after the Big Bang), thanks to wide area (>1000 deg²) optical/NIR surveys

(Banados+16, +18, Mazzucchelli+17, Reed+17, +19, Tang+17, Wang+17, +18a, +18b, Chehade+18, Matsuoka+18a,+18b, +19, Yang+18, Fan+19, Pons+19)

(only ~15 z>6 QSOs with X-ray data, <8% of the known population)
Selection of high-z QSO candidates

Figure 1. Photometry and combined Magellan/FIRE and Gemini/GNIRS near-infrared spectrum of the quasar J1342+0928 at $z = 7.54$. The FIRE data were taken on 11–12 March 2017 for a total integration time of 3.5 hours.

- Ly$\alpha$ forest ($\lambda < 1216$ Å)
- Lyman break ($\lambda < 912$ Å)
- Blue continuum emission (by selection only Type I QSOs!)
- Virial BH mass estimate
Optically selected $z \approx 6$ QSOs are extremely massive!

$log(M_{BH}/M_{\odot}) \sim 9-10$ (with large uncertainties)

(e.g., Mortlock+11, Wu+15, Banados+18)

How can you form such massive BH in $<1$Gyr??
Models require fast accretion (i.e., high Eddington ratio $\lambda_{\text{edd}}$), possibly in heavily obscured conditions, to match the observed $M_{\text{BH}}$ at $z=6-7.5$. 

Onoue+19

Initial $M_{\text{BH}}$ predicted by models

---

Pacucci+15

Valiante+18

Obscuration

Direct Collapse

Eddington limited accretion

Pop – III
Different accretion modes at high \( L/L_{\text{Edd}} \)?

(e.g. Jiang+17, Mayer+18, and reference therein)

Higher fraction of WLQs at \( z>6 \) suggesting a change in the accretion mode?

(see also Shen+19, Bañados+16)
Testing accretion mode (accretion disk + hot corona)

\[ \alpha_{ox} = 0.38 \times \log \frac{L_{2\text{keV}}}{L_{2500\text{Å}}} \]

(Tananbaum+1979 and many others since)

\( \alpha_{ox} \) and other parameters are illustrated in the diagram. The corona and accretion disk are shown with their respective fluxes and luminosities.
\[ \alpha_{ox} \propto -0.15 \times \log L_{2500 \AA} \]

(e.g., Steffen+06, Just+07, Lusso+10,+16, Nanni+17)

Hot corona contribution decreases at high luminosity

No (strong) evolution with redshift

(e.g. Lusso&Risaliti 2017)

but poorly sampled at \(z>6!!\)

Possible implications for cosmology

(Risaliti&Lusso 2018)
X-ray photon index ($\Gamma$) as a probe of accretion

$N(E) \propto E^{-\Gamma}$

$\Gamma$ includes information on the physical conditions (e.g. temperature) of the hot corona and its interplay with the accretion disk.

e.g., Shemmer+08, Brightman+13, Fanali+13, but see also Trakhtenbrot+17

No (strong) evolution with redshift (e.g. Lusso&Risaliti 2017)

but poorly sampled at $z>6$!!
**New Chandra observations of 10 z>6 QSOs**

*Chandra* Cycle 19 Large Program (~430 ks, PI: Brandt)

Table 1. Physical properties of the $z > 6$ QSOs with new or archival X-ray observations.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>DEC</th>
<th>$z$</th>
<th>$M_{1450A}$ (m$_{1450A}$)</th>
<th>log($L_{bol}$/L$_{CO}$)</th>
<th>log($M_{BH}$/M$_{BH}$)</th>
<th>$\lambda_{Edd}$</th>
<th>Ref. (disc./z/MBH)</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFHQSJ0050+3445</td>
<td>00:50:06.67</td>
<td>+34:45:21.05</td>
<td>6.253 (Mg II)</td>
<td>-26.70 (20.11)</td>
<td>13.45</td>
<td>9.41</td>
<td>0.34</td>
<td>W10/W10/W10</td>
<td>&lt; 11.4</td>
</tr>
<tr>
<td>VIKJ0109-3047</td>
<td>01:09:53.13</td>
<td>-30:47:26.3</td>
<td>6.7909 (C II)</td>
<td>-25.64 (21.30)</td>
<td>13.06</td>
<td>9.12</td>
<td>0.27</td>
<td>V13/V16/M17</td>
<td>&lt; 34.1</td>
</tr>
<tr>
<td>PSOJ036+03</td>
<td>02:20:01.87</td>
<td>+03:02:59.4</td>
<td>6.541 (C II)</td>
<td>-27.33 (19.55)</td>
<td>13.67</td>
<td>9.48</td>
<td>0.48</td>
<td>V15/B15/M17</td>
<td>&lt; 2.1</td>
</tr>
<tr>
<td>VIKJ0305-3150</td>
<td>03:05:16.92</td>
<td>-31:55:55.5</td>
<td>6.6145 (C II)</td>
<td>-26.18 (20.72)</td>
<td>13.26</td>
<td>8.95</td>
<td>0.63</td>
<td>V13/V16/M17</td>
<td>&lt; 20.0</td>
</tr>
<tr>
<td>SDSSJ0842+1218</td>
<td>08:42:29.43</td>
<td>+12:18:50.5</td>
<td>6.0763 (C II)</td>
<td>-26.91 (19.86)</td>
<td>13.52</td>
<td>9.29</td>
<td>0.53</td>
<td>dR11/D18/dR11*</td>
<td>&lt; 1.3</td>
</tr>
<tr>
<td>PSOJ167-13</td>
<td>11:10:33.98</td>
<td>-13:29:45.6</td>
<td>6.5148 (C II)</td>
<td>-25.57 (21.25)</td>
<td>13.03</td>
<td>8.48</td>
<td>1.11</td>
<td>V15/M17/M17</td>
<td>&lt; 34.3</td>
</tr>
<tr>
<td>CFHQSJ1509-1749</td>
<td>15:09:41.78</td>
<td>-17:49:26.8</td>
<td>6.1225 (C II)</td>
<td>-27.14 (19.64)</td>
<td>13.61</td>
<td>9.47</td>
<td>0.42</td>
<td>W07/D18/W08</td>
<td>&lt; 1.2</td>
</tr>
<tr>
<td>PSOJ3338+29</td>
<td>22:32:55.14</td>
<td>+29:30:32.3</td>
<td>6.666 (C II)</td>
<td>-26.14 (20.78)</td>
<td>13.24</td>
<td>9.43</td>
<td>0.20</td>
<td>V15/M17/M17</td>
<td>&lt; 21.0</td>
</tr>
<tr>
<td>SDSSJ2310+1855</td>
<td>23:10:38.89</td>
<td>+18:55:19.9</td>
<td>6.0031 (C II)</td>
<td>-27.80 (18.95)</td>
<td>13.85</td>
<td>9.62</td>
<td>0.52</td>
<td>Wa13/Wa13/J16</td>
<td>&lt; 3.9</td>
</tr>
</tbody>
</table>

**New observations**

**Archival data**

**Vito+19b.**

Now we have 25 $z>6$ QSOs with sensitive X-ray data and can start doing robust statistical analysis.
New Chandra observations of 10 $z>6$ QSOs

Detected (P>0.99)

<table>
<thead>
<tr>
<th>QSO</th>
<th>soft band 0.5-2 keV</th>
<th>hard band 2-7 keV</th>
<th>full band 0.5-7 keV</th>
<th>Vito+19b</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0050+3445</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J0109-3047</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J036+03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J0305-3150</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J0842+1218</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Undetected

<table>
<thead>
<tr>
<th>QSO</th>
<th>soft band 0.5-2 keV</th>
<th>hard band 2-7 keV</th>
<th>full band 0.5-7 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>J167-13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1509-1749</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1641+3755</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J338+29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J2310+1855</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
X-ray luminosity derived assuming “standard” $\Gamma = 2$ (e.g., Shemmer+06, Nanni+17)

<table>
<thead>
<tr>
<th>ID</th>
<th>$L_{2-10 \text{keV}}$ [10^{44} \text{erg s}^{-1}]</th>
<th>$\sigma_{\text{ox}}$</th>
<th>$\Delta \sigma_{\text{ox}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFHQSJ0050+3445</td>
<td>6.68±3.67</td>
<td>-1.71±0.07</td>
<td>-0.02±0.07</td>
</tr>
<tr>
<td>VIKJ0109−3047</td>
<td>&lt; 3.29</td>
<td>&lt; -1.67</td>
<td>&lt; -0.04</td>
</tr>
<tr>
<td>PSOJ036+03</td>
<td>8.20±5.05</td>
<td>-1.77±0.08</td>
<td>-0.05±0.08</td>
</tr>
<tr>
<td>VIKJ0305−3150</td>
<td>&lt; 3.79</td>
<td>&lt; -1.72</td>
<td>&lt; -0.06</td>
</tr>
<tr>
<td>SDSSJ0842+1218</td>
<td>4.34±3.26</td>
<td>-1.81±0.09</td>
<td>-0.11±0.09</td>
</tr>
<tr>
<td>PSOJ167−13</td>
<td>&lt; 2.21</td>
<td>&lt; -1.72</td>
<td>&lt; -0.09</td>
</tr>
<tr>
<td>CFHQSJ1509−1749</td>
<td>10.34±5.10</td>
<td>-1.71±0.07</td>
<td>0.01±0.07</td>
</tr>
<tr>
<td>CFHQSJ1641+3755</td>
<td>33.39±5.07</td>
<td>-2.82±0.03</td>
<td>0.32±0.03</td>
</tr>
<tr>
<td>PSOJ338+29</td>
<td>5.92±2.96</td>
<td>-1.64±0.07</td>
<td>0.01±0.08</td>
</tr>
<tr>
<td>SDSSJ2310+1855</td>
<td>6.93±3.34</td>
<td>-1.87±0.11</td>
<td>-0.12±0.11</td>
</tr>
</tbody>
</table>
No evidence for strong evolution of $\alpha_{ox}$ vs. $L_{UV}$ relation at $z>6$
\[ \Delta \alpha_{\text{ox}} = \alpha_{\text{ox}}(\text{obs}) - \alpha_{\text{ox}}(\text{expect.}) \]
No evidence for strong evolution of $\alpha_{\text{ox}}$ vs. $L_{\text{UV}}$ relation at $z>6$.

Compared also with “ultra-clean” $z=2$ QSO sample by Gibson+08.

No apparent relation b/w $\alpha_{\text{ox}}$ and $M_{\text{BH}}$ or $\lambda_{\text{EDD}}$, but small sample size and large uncertainties.
Bolometric correction: $L_{\text{bol}} / L_X$

Larger $K_{\text{bol}}$ at higher luminosities, in agreement with steeper $\alpha_{\text{ox}}$ at higher luminosities.

Populate the luminosity regime b/w “normal” AGN and hyper-luminous QSOs, and extend at $z>6$.

Change of the accretion-disk/hot-corona physics/geometry at high luminosities/$\lambda_{\text{edd}}$ but same change at all redshifts.
Average QSO photon index as a function of $z$

$$\langle \Gamma \rangle \approx 2.1-2.2$$ for $z>6$ QSOs

Consistent with $z=1-6$ results (but hint of a steepening?)

Assumed simple power-law emission, i.e. no reflection (ok for luminous type-1 QSOs, e.g. Comastri+92, Picconcelli+05, Shemmer+05)

"Universal" accretion mode ($\lambda_{EDD}$ dependent, redshift independent)
Conclusion: No significant change of the QSO accretion physics at $z>6$

Same dependence on luminosity (i.e., $\lambda_{\text{edd}}$?) at all redshifts

Possible implications for cosmology

Risaliti&Lusso 2019
PSO167-13 (z=6.515): first heavily obscured QSO candidate at z>6!

Relative emission is soft and hard bands gives indications of absorption level.

3 photons (P=0.9996, Weisskopf+07)

Vito+19b
PSO167-13 (z=6.515): first heavily obscured QSO candidate at z>6!

- Soft band: 0.5-2 keV
- Hard band: 2-7 keV
- Full band: 0.5-7 keV

\[ N_H > 2 \times 10^{24} \text{ cm}^{-2} \] at 68% confidence level

\[ N_H > 6 \times 10^{23} \text{ cm}^{-2} \] at 90% confidence level

First heavily obscured QSO candidate at z>6!
PSO167-13 (z=6.515): first heavily obscured QSO candidate at z>6!

X-ray to optical/sub-mm offset of ~1 arcsec, but significant positional uncertainty.

Why an optically type I QSO is heavily obscured in X-rays?
• WLQ?
• BALQSO?
• Changing look QSO?

see Mazzucchelli+19

HST F140w

ALMA [C II] + continuum (0.25'' ang. res.)

see Willott+17, Decarli+18, Neeleman+19

Δz=0.0035

1 arcsec
PSO167-13 ($z=6.515$): first heavily obscured QSO candidate at $z>6$!

XSHOOTER (11h) to obtain a rest-frame UV spectrum with a higher SNR.

*Chandra* (120ks) to confirm large $N_H$ and improve positional accuracy.

See Mazzucchelli+19, Venemans+15, Vito+19a, Willott+17, Decarli+18, Neeleman+19.
Obscured QSOs at $z>6$: how many are there?

Models require fast accretion (i.e., high Eddington ratio $\lambda_{\text{EDD}}$), possibly in heavily obscured conditions, to match the observed $M_{\text{BH}}$ at $z=6-7.5$.
Obscured QSOs at $z>6$: how many are there?

Extrapolate AGN X-ray LF at $z \sim 4$ and compare with QSO UV LF at $z \sim 6$

$z \sim 4$ AGN XLF (Vito+14,+18)
- Includes ~all obscured AGN
- normalization $\propto (1 + z)^{-6}$

$z \sim 6$ QSO UV LF (Matsuoka+18)
- Includes ~only unobscured QSOs

---

![Graph showing the extrapolation of AGN X-ray LF at $z \sim 4$ and comparison with QSO UV LF at $z \sim 6$.]
Obscured QSOs at $z>6$: how many are there?
Obscured QSOs at $z>6$: how many are there?
Obscured QSOs at $z>6$: how many are there?

XLF consistent with UV LF assuming ~85% obscured QSOs at $z\sim 6$
(modulo extrapolation, LF uncertainties, etc.)
Huge discovery space for current and future X-ray observatories!

XLF consistent with UV LF assuming ~85% obscured QSOs at z~6 (modulo extrapolation, LF uncertainties, etc.)