Physical Properties of the Highest-redshift SMBHs and how Lynx will detect their missing lower-mass counterparts and seeds

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with: Hagai Netzer (Tel-Aviv U.), Paulina Lira (U. Chile), Claudia Cicone (INAF Brera), Roberto Maiolino (Cambridge), Ohad Shemmer (U. North Texas), Marta Volonteri (AIP), Priyamvada Natarajan (Yale)

and the “First Accretion Light” SWG

from Chandra to Lynx meeting, Cambridge, 10-Aug-2017
SMBHs at all cosmic epochs

ULAS J1120  
z=7.1  
Mortlock+11

Wide-field optical/IR surveys (SDSS, DES, UKIDSS, Pan-STARRS...) found 100s of quasars at $z \geq 5$, when the universe was less than 1 Gyr old.
The highest-\(z\) quasars: normal unobscured AGNs?

Mortlock+11
ULAS J1120+9641, \(z=7.085\)
SDSS composite, \(z\sim 2.5\)
(N=169)

deviation from "expected" X-ray emission

Nanni+17

observed wavelength [\(\mu\)m]
How to grow a SMBH in ~1 Gyr?

1 Gyr after BB

plot adapted from
Trakhtenbrot & Netzer 12
reviews on BH seeds:
Volonter 10, Natarajan 11

black hole mass, $M_{BH}$

redshift, $z$

BH seed formation

Direct Collapse
Stellar Mergers
Pop-III

z=2 SDSS (Trakhtenbrot & Netzer 2012)
$\equiv$ z=2-3.5 (Shemmer+2004, Netzer+2007)
$\equiv$ z=3.5 (Trakhtenbrot+2016)
$\equiv$ z=4.8 (Trakhtenbrot+2011)
$\equiv$ z=6.2 (Kurk+2007, Willott+2010)
How to grow a SMBH in ~1 Gyr?

$\tau_\bullet \sim 0.4 \text{ Gyr} \frac{\eta}{(1 - \eta)} \frac{1}{L/L_{\text{Edd}} \times f_{\text{active}}}$

plot adapted from Trakhtenbrot & Netzer 12

reviews on BH seeds:
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Large-scale environments of early SMBHs

• Simulations suggest early BH mass growth favors over-dense environments
• Can be tested by counting the number of galaxies around SMBH hosts
• So far, few systems studied, with ambiguous results
  (Willott+05, Overzier+06, Kim+09, Utsumi+10, Husband+13, Banados+13, Simpson+14, Kikuta+17…)

Simulations from
Costa+14

see also:
Dekel+09
Di-Matteo+12
Dubois+12

average density, z~6

high density, z~6

HST/ ACS FOV
The epoch of fastest growth of the most massive BHs

The highest-redshift quasars are powered by fast-growing SMBHs, with $M_{\text{BH}} \sim 10^9 M_\odot$ and $L/L_{\text{Edd}} \sim 1$
How to grow a SMBH in ~1 Gyr?

\[ \tau_0 \approx 0.4 \text{ Gyr} \frac{\eta}{1 - \eta} \frac{1}{L/L_{\text{Edd}} \times f_{\text{active}}} \]

- M87
- MW

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The highest-redshift quasars are consistent with Eddington-limited, radiatively efficient, thin-disk accretion flows powering $z\sim 5-7$ quasars.

Applying (over?) simplified thin accretion disk models to derive $\dot{M}_{\text{disk}}$ and $\eta$.

The highest-redshift quasars are consistent with Eddington-limited, radiatively efficient, thin-disk accretion.
Hosts of fast-growing SMBHs at $z \sim 5$, with ALMA

Six fast-growing $z \sim 4.8$ SMBHs observed w/ALMA (cycle-2, band-7, $\sim 0.3''$)

- ALMA resolves the dusty, star-forming host galaxies of early SMBHs

Trakhtenbrot+17 (ApJ, 836, 8)
Hosts of fast-growing SMBHs at $z\sim5$, with ALMA

Six fast-growing $z\sim4.8$ SMBHs observed w/ALMA (cycle-2, band-7, ~0.3")

SMBH host galaxy at $z=4.8$, sub-mm cont. $\rightarrow$ SFR $= 360 \, M_\odot$ / yr

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sub-mm cont. $\rightarrow$ SFR $= 360 \, M_\odot$/yr

$[\text{CII}]$ line $\rightarrow M_{\text{dyn}} \approx 7 \times 10^{10} \, M_\odot$

The highest-$z$, fast-growing SMBHs are hosted in high-SFR, dust-rich galaxies

Trakhtenbrot+17

SMBH host galaxy at $z=4.8$

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The emerging $M_{\text{BH}}-M_{\text{host}}$ relation at $z\sim5-7$

[CII]-based dyn. host masses at $z\sim5$

High-$z$, fast-growing SMBHs are slightly “over-massive” w.r.t. hosts
Environments of fast-growing SMBHs at $z \sim 5$, with ALMA

Six fast-growing $z \sim 4.8$ SMBHs (ALMA cycle-2)

SMBH host galaxy at $z=4.8$
$M_{\text{dyn,QSO}} \approx 7 \times 10^{10} \, M_{\odot}$, SFR = 360 $M_{\odot}$ / yr

$[C\,\text{II}] 158\mu$m line spectrum

SMBH host galaxy at $z=4.8$

$M_{\text{dyn,SMG}} \approx 2 \times 10^{10} \, M_{\odot}$, SFR = 150 $M_{\odot}$ / yr

Trakhtenbrot+17
Environments of fast-growing SMBHs at $z \sim 5$, with ALMA

- A high fraction of companion (interacting) SMGs: $\sim 50\%$
- Separations of $\sim 15-50$ kpc and $< 500$ km/s from quasar hosts
- All are “major mergers”; not seen in previous Spitzer/IRAC data

The highest-redshift quasars are found in over-dense environments
Environments of fast-growing SMBHs at $z \sim 6$, with ALMA

Decarli+17: ALMA observations of 25 quasars at $z \sim 6$
4 of the 25 have nearby companions (~8-60 kpc)

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The highest-redshift quasars are found in over-dense environments
Dual fast-growing SMBHs at $z \sim 5$, in sub-mm and X-ray?

BR 1202-0725
luminous quasar, $z=4.7$
$S_{900} \sim 30-60$ mJy

Omont+96
16 hours, PdBI

Wagg+12
25 minutes, ALMA SV
Environments of fast-growing SMBHs at \( z \sim 6 \), in sub-mm

Plateau de Bure observations of \([\text{CII}]158\) in J1048 (\( z = 6.4 \))

The highest-redshift quasars drive large-scale gas outflows

\cite{Cicone+15}
More $z > 5$ quasars are coming...

adapted from Niel Brand’s talk and Aird et al (2013; *Athena* science case)
Summary: \( z \sim 5-7 \) quasars

<table>
<thead>
<tr>
<th>Property</th>
<th>Known ( z \sim 5-7 ) quasars</th>
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are we missing anything?
"Missing AGNs" at high-\(z\): deep Chandra surveys

Chandra COSMOS Legacy Survey: >1.5 deg\(^2\), 160 ks
(Civano+16, Marchesi+16a,b)

The space density of lower-L AGN drops beyond \(z\sim3\)
“Missing AGNs” at high-$z$: deep Chandra surveys

Chandra Deep Field South (0.13 deg$^2$, 7 Ms) and North (2Ms) (Luo+16, Vito+16,17…)

The space density of lower-L AGN drops beyond $z$~3

Vito et al. (2017)
But *should* we expect faint AGNs at $z \sim 5-7$?

Yes! progenitors of $z \sim 3$ AGNs… ... but we do *not* see them

are the missing AGNs obscured? low BH occupation fraction? low duty cycle? (“flickering”)

Fig. from Trakhtenbrot+16
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Weigel+15
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Chandra sees no sign of AGN in (stacks of) typical $z>5$ galaxies

"Missing AGNs" at high-$z$: deep Chandra surveys

230 galaxies
1.35 Giga-sec

453 galaxies
2.65 Giga-sec

Chandra sees no sign of AGN in (stacks of) typical $z>5$ galaxies
Lynx will detect the faint/low-M counterparts of the highest-redshift quasars, and will trace progenitors back to the BH seed population.

\[ L_{\text{bol}} < L_{\text{Edd}} \approx 1.3 \times 10^{38} \ M_{\text{BH}} \]

\[ M_{\text{BH}} > \frac{L_{\text{bol}}}{1.3 \times 10^{38}} \]
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Faint AGN and BH seeds: prospects for Lynx

\[ \tau_\bullet \sim 0.4 \text{ Gyr} \frac{\eta}{(1-\eta)} \frac{1}{L/L_{\text{Edd}} \times f_{\text{active}}} \]

plot adapted from Trakhtenbrot & Netzer 12
reviews on BH seeds: Volonter 10, Natarajan 11
Summary

• Wide-field optical/IR surveys have identified 100s of quasars at $z > 5$
These SMBHs had to grow continuously and/or from massive seeds

• We learned that the highest-redshift quasars are growing *fast* in
massive, gas-rich, high-SFR hosts, located in *rare* over-dense regions.
Are these SMBHs the rare “lucky ones”? 

• The deepest Chandra surveys suggest we’re missing the fainter / lower-
mass counterparts of these quasars - the progenitors of $z\sim3-4$ systems.
Why can’t we see AGN signature in “typical” high-$z$ galaxies?

• *Lynx* will detect extremely faint/low-mass AGN out to $z\sim10$, tracing the
high-$z$ AGN population back to the epoch of massive BH seed formation.