The $z > 3$ AGN population in the Chandra Deep Fields

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BH and galaxies co-evolve

- SFRD and BHAD track each other
- $M_{\text{BH}}$ vs $M_{\text{bulge}}$ relation
- Downsizing

Do these relations hold at high redshift? And how are they established?

e.g. “overmassive” high-M BH (e.g. Walter+04, Wang+13, Barnett+15), “undermassive” low-M BH (from simulations, e.g. Habouzit+16)?
High-z QSOs

~90 QSOs known at $z > 6$
(SDSS, CFHTQS, PSO, ULAS, ATLAS, VIKING, DES)
with $M_{1450} \leq -25$

...but they are the extreme tail
($M_{BH} = 1-10 \times 10^9 \, M_\odot$, e.g. Wu+15)
of the underlying population.
Galaxy vs. AGN luminosity functions

Need to improve our knowledge of AGN at high-z/low-L!
Why X-rays?

1) Ubiquitous in AGN

2) Obscuration

3) Galaxy dilution

Clean and less biased selection (especially at high-z)!
But optical/IR data needed for identification
High-z (3<z<5) AGN in X-ray surveys: space density evolution

For $L \geq L^*$, $\log \Phi$ declines as $(1+z)^{-6}$, similarly to optical QSOs (e.g. McGreer+13). At lower luminosities, uncertain evolution.

(e.g. Brusa+09, Civano+11, Hiroi+12, Vito+13, Kalfountzou+14, Vito+14, Marchesi+16)
Different combinations of the physical parameters driving the formation and growth of BH seeds (e.g. seed mass, occupation fraction, Eddington ratio distribution, etc.) produce different shapes of the AGN XLF faint end!
High-z (3<z<5) AGN in X-ray surveys: obscured AGN fraction

\( F_{\text{obs}} \) at high-L evolves strongly from low-z to z>3

Larger covering angles and/or longer obscured phases due to, e.g., larger gas reservoirs, higher merger rate?

Does the anti-correlation invert at high-z?
The data-set
7 Ms CDF-S (Luo+17)

- Deepest X-ray survey to date! $F_{\text{lim}} \sim 6.4 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$
- $A \sim 484$ arcmin$^2$
- Deep radio-UV coverage (e.g. CANDELS/GOODS-S)
- 1008 X-ray sources
- $\sim98.5\%$ multi-wavelength identification,
- $\sim98\%$ redshift ($\sim65\%$ spec-z, phot-z from Straatman+16, Santini+15, Hsu+14, Skelton+14, etc.)

2 Ms CDF-N (Xue+16)

- Second deepest X-ray survey to date!
  $F_{\text{lim}} \sim 1.2 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$
- $A \sim 447$ arcmin$^2$
- Deep radio-UV coverage (e.g. CANDELS/GOODS-N)
- 683 X-ray sources
- $\sim98\%$ multi-wavelength identification,
- $>93\%$ redshift (>50\% spec-z, phot-z from Yang+14, Skelton+14, Kodra+ in prep.)

We used only areas $(330+215$ arcmin$^2$) with $>1$Ms Chandra exposure
Redshift distribution

101.6 sources at $3 \leq z < 6$

$\sim 30\%$ spec. $z$
(spectroscopic fraction can be increased with future JWST/ELT/ALMA)
Parameter distributions

Spectral analysis
(absorbed power-law with $\Gamma = 1.8$) + Eddington bias correction

$logN_H = 23.77^{+0.15}_{-0.16}$

$logF_{0.5 - 2\text{keV}} = -15.59^{+0.08}_{-0.08}$

$logL_{2 - 10\text{keV}} = 44.41^{+0.17}_{-0.27}$
Parameter distributions

Unobscured

Obscured

observed
0.5-7 keV

Rest-frame
2-40 keV

at z=3-6

L* at z\approx3
Obscured fraction ($F_{\text{obsc}}$) vs $L_X$

Strong evolution from low $z$, especially at high $L$
AGN X-ray luminosity function

\[ \phi [\text{Mpc}^{-3} \text{dex}^{-1}] \]

\[ \log L_{2-10\text{keV}} [\text{erg s}^{-1}] \]

- This work (3.0 \leq z < 3.6)
- Habouzit+16 (z=3.5)
- Buchner+15 (3.2 < z < 4)
- Georgakakis+15 (z = 3.3)
- Ueda+14 (z = 3.3)
- Vito+14 (z = 3.3)
- Aird+10 (z = 3.3)
- Volonteri+17 (z=4)
- Habouzit+16 (z=5)
- Buchner+15 (4 < z < 7)
- Volonteri+17 (HMXB, z=4)
- Georgakakis+15 (z = 4.1)
- Giallongo+15 (z=4.25)
- Ueda+14 (z = 4.1)
- Vito+14 (z = 4.1)
- Aird+10 (z = 4.1)

Vito+16, z \sim 4
AGN space density

Decline at high-L driven by evolution of number of massive galaxies?

Hints for steepening at low-L (not matched by low-mass galaxies): change of the accretion parameters (Eddington ratio, occupation fraction, etc.).
Enhancing *Chandra* sensitivity: stacking analysis

Stacking: A Romantic Example

Stacked image of 30 candles with 1/1000 sec exposure.

Effective stacked exposure of \((30 \times \frac{1}{1000} \text{ sec}) = \frac{3}{100} \text{ sec}\).
Results from stacking analysis

Vito+16
BHAD dominated by X-ray detected AGN: most of the BH growth happens during the “bright” AGN phase

Low-rate accretion not enough for observations to match simulations

What causes the different slopes of BHAD and SFRD? (see also Aird+15; complex combination of parameters, e.g., occupation fraction, duty cycle, Eddington ratio distribution, etc…)
XLF faint end at high-z as a tool to study BH seed formation and growth

Need to push at lower-L and higher-z! E.g. Lynx
Lynx  (Weisskopf et al. 2015)

- *Chandra*-like spatial resolution
- 10x f.o.v.
- 50x sensitivity

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Detection threshold @ 4Msec (0.5-2 keV) (for known locations)</td>
<td>$3.0 \times 10^{-19}$ erg/s/cm$^2$</td>
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<tr>
<td></td>
<td>($1.1 \times 10^{-19}$)</td>
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<tr>
<td>2–10 keV luminosity at z=10 assuming $\Gamma=1.7$</td>
<td>$3.7 \times 10^{41}$ erg/s</td>
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<tr>
<td></td>
<td>($1.35 \times 10^{41}$)</td>
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<tr>
<td>Bolometric luminosity at z=10, assuming 10% correction</td>
<td>$3.7 \times 10^{42}$ erg/s</td>
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<tr>
<td></td>
<td>($1.35 \times 10^{42}$)</td>
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<tr>
<td>Black Hole Mass assuming Eddington rate</td>
<td>29,000 Msun</td>
</tr>
<tr>
<td></td>
<td>(11,000 Msun)</td>
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</tbody>
</table>

Credits: Alexey Vikhlinin
Under reasonable assumptions on space density (from Habouzit+16 and Volonteri+17 or from DM halo arguments) and physical parameters ($\lambda_{Edd}=1, K_{bol}=10\%$), we expect to detect $\sim1000$ accreting BH at $z=8-9$ with $\log L_x \geq 41$ and $\log (M_{BH}/M_\odot) \geq 4$ in $\sim 1 \text{ deg}^2$.

On behalf of the Lynx "first accretion light” working group:

Credits: Alexey Vikhlinin
\[ \sim 1000 \text{ accreting BH at } z=8-9 \]
with \( \log L_x \gtrapprox 41 \) and \( \log (M_{\text{BH}}/M_\odot) \gtrapprox 4 \)
in \( \sim 1 \text{ deg}^2 \)

Enough to sample accurately the XLF and place tight constraints to physical parameters regulating BH seed formation and growth
(e.g. Volonteri+12,+16; Haiman+13; Johnson&Haardt+16, and references therein)

Volonteri+15

1. seed mass distribution
   (light or heavy seeds?)
2. occupation fraction
3. \( \lambda_{\text{Edd}} \) distribution
4. feedback
5. etc.

Multi-\( \lambda \) data can help breaking the degeneracies
(e.g. Pacucci+15; Natarajan+17)
~1000 accreting BH at \( z=8-9 \) with \( \log L_x \geq 41 \) and \( \log (M_{\text{BH}}/M_\odot) \geq 4 \) in \( \sim 1 \text{ deg}^2 \)

Enough to sample accurately the XLF and place tight constraints to physical parameters regulating BH seed formation and growth

But significant uncertainties due to…

1. modelling
   (e.g. factors of several in space density)
2. XRB contribution/confusion
3. ancillary data
   (i.e. NIR/MIR with JWST/WFIRST, we need rest-frame UV m\~30)

Work in progress here!

https://wwwastro.msfc.nasa.gov/lynx/
Conclusions

• Largest sample of $3<z<6$ X-ray detected AGN with $L>L^*$, thanks to the use of the deepest Chandra surveys

• Large fraction of obscured AGN at $\log L_X>43$ ($F_{\text{obsc}}\sim 0.6-0.8$), less clear at low-$L$

• Strong evolution of $F_{\text{obsc}}$ from low-$z$

• Best constraints on the $L<L^*$ AGN XLF at $z>3$

• Space density of luminous AGN evolves similarly to (is caused by?) that of massive galaxies

• Hints for a steeper evolution of the space density of low-$L$ AGN than high-$L$ AGN, while flattening of density of low-mass galaxies: evolution of accretion parameters (duty cycle, Eddington ratio, etc)?

• BHAD due mostly to luminous AGN, and steeper evolution than SFRD: higher BH-to-galaxy mass ratio at high $z$?

• Lynx will probe the AGN population down to $\log M_{BH}\sim 4$ up to $z\sim 10$
Back-up slides
High-z (3<z<5) AGN in X-ray surveys: faint end of XLF

Flattening?
(e.g. Georgakakis+15)

Steepening?
(e.g. Fiore+12, Giallongo+15)

No slope evolution?
(e.g. Vito+14)

(possible high AGN contribution to cosmic reionization)
AGN number counts at high-z

Soft-band detected sources only
Larger population of obscured AGN than expected!
Obscured fraction ($F_{\text{obsc}}$) vs z

No significant evolution from z=3 to z=6
Stacked X-ray emission dominated by XRB?

Stacked emission consistent with being produced ~entirely by XRB