The deepest X-ray view of high-redshift galaxies: constraints on low-rate black-hole accretion

Fabio Vito
Penn State University (US)
INAF-OABo (IT)
UNIBO-DIFA (IT)

fvito@psu.edu

F. Vito, R. Gilli, C. Vignali, W.N. Brandt, A. Comastri, G. Yang, B.D. Lehmer, B. Luo, A. Basu-Zych, F.E. Bauer, N. Cappelluti,
Massive BH at high redshift are very massive!

ULASJ1120+0641 is the highest redshift ($z = 7.1$) QSO ever discovered and has $M_{BH} \gtrsim 10^9 M_\odot$

$z = 7.1 \ll 1$ Gyr after Big Bang

Other SMBH at $z > 6$ discovered

(e.g. Willott+03,+09, Fan+06a,+06b, Venemans+13, Banados+14, Wu+15)
SMBH seed formation models

Introduction

SMBH seed formation models

Collapsing halo

Z=0

'minihalo'

PopIII star

$40 \, M_\odot < M_* < 140 \, M_\odot$

$M_* > 260 \, M_\odot$

MBH formation

Gas cooling -> disc formation

Dynamical instability

Inflow

Suppressed star formation

Strong inflow

VMS/quasistar+ MBH formation

Cluster formation

Runaway collisions VMS+MBH formation

Volonteri+10

LIGHT SEEDS

$(M_{BH} \sim 100 \, M_\odot)$

HEAVY SEEDS

$(M_{BH} \sim 10^4 - 10^6 \, M_\odot)$
Faint end of high-z LF can help in discriminating the models

Examples of high-z HXLF predicted from models of light and heavy seeds (Hirschmann+12)

Need to sample the faint end of the LF at high-z!
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Introduction

AGN Population Evolution

$z < 3$: AGN "downsizing" (LDDE, e.g. Miyaji+00, Ueda+03, Hasinger+05, La Franca+05, Silverman+08, Ebrero+09, Yencho+09, Ueda+14; LADE, Aird+10; FDPL, Aird+15)

$z > 3$: not well assessed

Ueda+14
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**Introduction**

**High-Redshift AGN Population Evolution**

![Graph showing the decline of luminosity with redshift](image)

- **Vito+14**
- **Marchesi+16**

**logL_X \geq 44**

Decline at \( z > 3 \) (e.g. Brusa+09, Civano+11, Hiroi+12, Kalfountzou+14)

\[ \Phi \propto (1 + z)^p \]

\[ p = -6.0 \pm 0.9 \Rightarrow \text{Factor} \sim 10 \text{ from } z=3 \text{ to } 5 \]

**logL_X \lesssim 44**

???
Goals of the work

Stacking X-ray emission from $z > 4$ CANDELS galaxies to look for signatures of accretion onto SMBH.

Trying to give estimates of:

- **Black Hole Accretion Rate Density (BHAD)**
- **Star Formation Rate Density (SFRD)**
- **Faint end of the AGN LF**
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Exploiting the best X-ray and optical/NIR data: 7 Ms CDFS + CANDELS

～7 Ms CDFS (～480 arcmin^2)

PI: W.N. Brandt, Luo et al. in prep.

Deepest X-ray survey ever!

(and great spatial resolution!)

+ Deep HST catalogs in GOODS-S (CANDELS + ERS + HUDF; Guo+13, Santini+15)

Limit mag F160w ≤ 30

+ Multiwavelength data, high quality spec. and phot. z, dedicated SED-fitting campaigns (M*, SFR, etc.)
Stacking: A Romantic Example

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

Effective stacked exposure of $(30 \times 1/1000 \text{ sec}) = 3 / 100 \text{ sec}$. 

Courtesy of Bret Lehmer
X-ray stacking analysis in previous works: black-hole accretion and star formation (XRB)

Cowie+12 (X-ray emission from individually undetected galaxies mainly due to star formation)

Treister+13

Basu-Zych+13
The samples of high-z galaxies

<table>
<thead>
<tr>
<th>$z$ bin</th>
<th>mass sample</th>
<th>N</th>
<th>$\langle z^w \rangle$</th>
<th>Effective Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.5 \leq z &lt; 4.5$</td>
<td>all</td>
<td>1393</td>
<td>3.90</td>
<td>$8.16 \times 10^9$ s $\sim$ 260 yr</td>
</tr>
<tr>
<td></td>
<td>massive</td>
<td>662</td>
<td>3.91</td>
<td>$3.86 \times 10^9$ s $\sim$ 120 yr</td>
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<tr>
<td>$4.5 \leq z &lt; 5.5$</td>
<td>all</td>
<td>453</td>
<td>4.90</td>
<td>$2.65 \times 10^9$ s $\sim$ 85 yr</td>
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<tr>
<td></td>
<td>massive</td>
<td>217</td>
<td>4.92</td>
<td>$1.26 \times 10^9$ s $\sim$ 40 yr</td>
</tr>
<tr>
<td>$5.5 \leq z &lt; 6.5$</td>
<td>all</td>
<td>230</td>
<td>5.93</td>
<td>$1.35 \times 10^9$ s $\sim$ 43 yr</td>
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<tr>
<td></td>
<td>massive</td>
<td>111</td>
<td>5.93</td>
<td>$0.65 \times 10^9$ s $\sim$ 20 yr</td>
</tr>
</tbody>
</table>

cf. 7 Ms $\sim$ 0.2 yrs !!
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Stacking X-ray data

Stacked images

20x20 arcsec

Normalized to (min,max)=(0,1); smoothed (Gaussian function with $\sigma = 3\, \text{pix}$), power-law scale
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Stacking X-ray data

Stacked (i.e. total) net-count rates

First detection of stacked X-ray emission in $z \sim 5$ galaxies at $2.7\sigma$ (99.7% c.l.) !!
The deepest X-ray view of high-redshift galaxies: constraints on low-rate black-hole accretion

Stacking X-ray data

Black Hole Accretion Rate Density (BHAD)

\[ \psi_{bhar}(z) = \frac{(1-\varepsilon)K_{bol}}{(\varepsilon c^2)} \frac{L_{\text{TOT}}^{AGN}}{V_c^{\text{CANDELS}}} \]

CASE I: max AGN
CASE V: AGN + SF

Black points: all galaxies
Red Points: massive galaxies
Grey points: individually X-ray detected sources (i.e. AGN)

Observational results from: Delvecchio+14, Ueda+14, Vito+14, Aird+15, Georgakakis+15, Miyaji+15
Result I:

X-ray detected AGN dominate the BHAD at high redshift. Continuous low-rate accretion in “normal” (i.e. undetected in the 7 Ms CDF-S) provides a negligible contribution to the total BH mass growth.

(see also Volonteri+16).

Similar to what found at low redshift via the Soltan argument and direct measurements (see Brandt&Alexander 2015).
Star Formation Rate Density (SFRD)

\[ \rho_{sfrd}(z) = \frac{N \times \langle SFR \rangle}{V} \]

\[ \langle SFR \rangle = SFR(L_{X}^{\text{stack}}, M_{*}) \]
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Stacking X-ray data

Star Formation Rate Density (SFRD)

$$\rho_{\text{sfrd}}(z) = \frac{N \times \langle SFR \rangle}{V}$$

Black points: all galaxies
Red Points: massive galaxies
Green points: SFRD from CANDELS
SFR and $M_*$

Observational results from: Bouwens+15, Madau&Dickinson 2014
Result II:

Stacked X-ray emission in high-z galaxies plausibly entirely due to XRB (i.e. star formation) (see also Cowie+12)

or, in other words, we need the stacked X-ray emission in high-z galaxies to be due entirely to XRB in order to match the SFRD found in previous works and the SFRD derived by CANDELS SFRs for the same galaxies.

This strengthens result I. Caveat: SFR-$L_X$ relations not constrained observationally at high-z.
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Stacking X-ray data

Faint end of AGN XLF

\[ N^{AGN}(L) \leq \frac{L^{\text{stack}}_{AGN}}{L} \implies \phi = \frac{dN^{AGN}}{dVd\log L} \]

Blue upper limits:
all galaxies

Red upper limits:
massive galaxies

Georgakakis+15

PDE
LDDE

Vito+14

PDE
LDDE

Georgakakis+15

PDE
LDDE
Result III:

The faint end of the AGN XLF at high-z is fairly flat. First constraints on the XLF at such low luminosities at $z > 3.5$.

This naively supports massive seeds.
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Stacking X-ray data

Faint end of AGN XLF

Testing the AGN contribution to the Cosmic Reionization (Giallongo+15 found a high number of faint X-ray AGN (i.e. steep XLF faint end), Madau&Dickinson2016 used that result to predict a high AGN contribution to the Reionization).

Evidence for flatter AGN XLF faint end! Different analysis, photometric redshift uncertainties, ...

Need to directly probe the AGN XLF faint end!
Conclusions

Stacking X-ray data from 7 Ms CDF-S \( \Rightarrow \sim 10^9 \) s effective exposure.

X-ray detected AGN dominate the BHAD at high redshift. Continuous low-rate accretion in “normal” (i.e. undetected in the 7 Ms CDF-S) provides a negligible contribution to the total BH mass growth.

(see also Volonteri+16).

Stacked X-ray emission in high-z galaxies plausibly entirely due to XRB (i.e. star formation) (see also Cowie+12)

The faint end of the AGN XLF at high-z is fairly flat. First constraints on the XLF at such low luminosities at \( z > 3.5 \).

*Athena, WFXT* and *X-Ray Surveyor* will directly sample the faint end of the AGN XLF at \( z > 4 \).
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Stacking X-ray data

Technical notes

Simulating Chandra PSF:

Best choice for the aperture-photometry region size:
The deepest X-ray view of high-redshift galaxies: constraints on low-rate black-hole accretion

- Stacking X-ray data

The sample

![Graphical representation](image-url)
The deepest X-ray view of high-redshift galaxies: constraints on low-rate black-hole accretion

Stacking X-ray data

The sample
The deepest X-ray view of high-redshift galaxies: constraints on low-rate black-hole accretion

Stacking X-ray data

The sample
The deepest X-ray view of high-redshift galaxies: constraints on low-rate black-hole accretion

Stacking X-ray data

X-ray/optical offset
The deepest X-ray view of high-redshift galaxies: constraints on low-rate black-hole accretion

Stacking random positions

![Graph showing normalized distribution of total net count rate](image-url)
Effect of photometric redshift uncertainties

Signal-to-noise ratio

- 3.5<z<4.5
- 4.5<z<5.5
- 5.5<z<6.5