The cosmic frontier:
Formation and growth of the earliest supermassive black holes

James Aird
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Cosmic frontier backyard: ubiquity of massive BHs

Black holes with $M_{BH} \sim 10^6 - 10^{10} M_\odot$ are found at the centres of most (if not all) galaxies in the local Universe

Kormendy & Ho 2013

(N.B. Francesco Shankar talk => biased sampling of BHs?)
X-ray surveys (Chandra + XMM-Newton): track the **growth** of these black holes by accretion

Growth tracked by AGN Luminosity Function

e.g. Aird+15
(see also: e.g. Ueda+14, Buchner+15, Miyaji+15, Fotopoulou+16, Ranalli+16, Georgakakis+17, Ananna+19)
X-ray surveys (*Chandra* + *XMM-Newton*): track the **growth** of these black holes by accretion

Bulk of this growth occurred at $z \sim 1-3$, primarily in moderate-luminosity **obscured** sources (revealed by X-ray observations).
X-ray surveys (Chandra + XMM-Newton): track the **growth** of these black holes by accretion

Accretion growth (primarily at $z \sim 1-3$) accounts for the BH mass density in the local Universe

Measured BHMF in local Universe

**Growth by accretion**

$z=0$

$z=1$

$z=2$

$z=3$

$z=4$

$z=5$

Ueda+14

log (BH mass function) $[\text{Mpc}^{-3} \text{dex}^{-1}]$

log $M_{\text{BH}}/M_{\odot}$
X-ray surveys (Chandra + XMM-Newton): track the growth of these black holes by accretion

Cosmic X-ray background
(integrated emission from BH growth over the lifetime of the Universe)

- >90% resolved by Chandra at soft energies (<2 keV)
- ~35% resolved by NuSTAR at energies >8keV
- Population synthesis models (based on Chandra/XMM surveys at 0.5-10keV) =>
  - produced by SMBH accretion, primarily at z<2
  - successfully recover full shape and peak at ~20-30 keV - dominated by obscured AGN

Aird+15 (adapted).
See also e.g. Gilli+07, Triester+09, Ballantyne+11, Akylas+12, Ueda+14, Ananna+19, Mackenzie Jones talk
Open questions regarding the **bulk** of BH growth

- Connection to **galaxy** properties? (triggering/fuelling mechanisms, impact of AGN *feedback* on galaxy evolution)

- Contribution of **Compton-thick** AGN?

- **Physics** of the accretion process? (structure of accretion disk+corona, winds/jets, BH *spin*, super-Eddington accretion)
Where do these supermassive black holes come from?
SMBH seed mechanisms

Grow by merging and accretion

- SMBH seed mechanisms
  - Pop III star remnants
  - Direct gravitational collapse
  - Stellar cluster collapse

- Gas cools very slowly forming a stable disc
- Globally unstable gas falls rapidly toward the galaxy center and a supermassive star forms
- Locally unstable gas flows toward the galaxy center

- First stars: maybe one star per galaxy, up to several hundred times larger than the Sun
- The stellar core collapses into a small black hole, embedded in what is left of the star
- Gas fragments into stars, and a dense star cluster forms

- If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of the Sun
- The black hole swallows the envelope, growing up to ~one million solar masses
- Stars merge into a very massive star that collapses into a black hole ~1000 times more massive than the Sun

- $M_{BH} \sim 100 \, M_\odot$
  - $z \sim 20-30$

- $M_{BH} \sim 10^5 \, M_\odot$
  - $z \sim 15$

- $M_{BH} \sim 1000 \, M_\odot$
  - $z \sim 10$

- $M_{BH} \sim 10^6 - 10^{10} \, M_\odot$
  - $z \sim 6$ and below

from Volonteri (2012)
Massive black holes in the early (z>6) Universe - optical/near-IR searches

- Searches for rare, luminous QSOs at z>6
  - Require large-area, deep optical + NIR imaging, search for “drop-outs” due to absorption by neutral hydrogen

Bañados et al. 2018
Massive black holes in the early (z>6) Universe - optical/near-IR searches

~146 known quasars at z>6 (4 at z>7)

Bañados+16 (and references therein), Mazzucchelli+17, Matsuoka+19a,19b
Optical spectra of luminous $z>7$ quasars

$z=7.54$ (Bañados et al. 2018)

Composites of 75 broad-line and 18 narrow-line quasars at $5.7<z<7$ from Subaru High-z Exploration of Low-Luminosity Quasars (SHELLLQs)

(Matsuoka+19b)
X-ray properties of luminous z>6 quasars

Chandra 0.5-7keV image of J1342+0928, z=7.54 (Bañados et al. 2018b)

see upcoming talks by Fabio Vito and Ricardo Nanni
Building high redshift QSOs - constraints on growth rates and seed masses

- Black hole mass grows as:

\[ M_{\text{BH}}(t) = M_0 \exp \left( \frac{1 - \eta}{\eta} \frac{L_{\text{bol}}}{L_{\text{Edd}}} \frac{t}{0.45 \text{Gyr}} \right) \]

The seed of J1342 (z=7.54, \( M_{\text{BH}} \approx 8 \times 10^8 M_\odot \)) could have formed by:

- direct collapse at \( z \sim 15 \), but requires growth at \( \sim \) Eddington limit for entire lifetime

- from a PopIII remnant at \( z < 20 \), but requires growth at \( \sim \) Eddington limit for entire lifetime and low radiative efficiency (maintain low spin = chaotic accretion?)
Building high redshift QSOs - constraints on growth rates and seed masses

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HSC-J1243 (z=7.07, \( M_{\text{BH}} \approx 3.3 \times 10^8 M_\odot \)):

- also consistent with direct collapse or PopIII if accreting at Eddington limit
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To constrain the early growth of SMBHs, need to probe the "typical" \( z > 6 \) AGN (lower mass black holes, lower luminosities, obscured sources \( \Rightarrow \) determine the extent and distribution of the bulk of early BH growth)
Current X-ray searches for early AGN

X-ray surveys:
- probe a broad range in luminosity
- find fainter AGN, generally not identified by optical or IR selection
- identify obscured AGN

Chandra 7Ms flux limit

x Chandra detections

- CDFS 7Ms (Luo+ 17)
- COSMOS Legacy (Marchesi+16)
- AEGIS (Nandra+15)

- only a handful at z>5
- faint counterparts, uncertain photo-z
The evolution of the space density of X-ray detected AGN

- Strong decline in space densities at $z > 3$ for **all** luminosities

Data points = Miyaji et al. (2015)
Lines+shading = Aird et al. (2015)

Vito et al. (2018)
(see also Brusa+09, Civano+12, Ueda+14, Vito+14, Weigel+15, Georgakakis+15, Khorunzhev+18)
X-ray searches for the earliest SMBHs

- “sub-threshold” detections

  • deep NIR+optical imaging (HST/CANDELS) provides moderate samples of galaxies at z>5

  • Attempt to improve X-ray source identification using galaxy positions

Giallongo et al. (2019)

identifies additional AGN =>

• constraints on faint end of UV luminosity function (connection to opt+IR selected quasars)
• role of AGN in re-ionization,

• see also Fiore+12, Giallongo+15, Cappelluti+16
X-ray searches for the earliest SMBHs

- stacking

- deep NIR+optical imaging (HST/CANDELS) provides moderate samples of galaxies at z>5

  • Stack the X-ray data at the galaxy positions

  

  e.g. Vito+16

  • X-ray signal likely dominated by star formation processes
  • Places upper limits on BH accretion density due to low-Lx AGN in these very high-z galaxies
X-ray searches for the earliest SMBHs

- what’s left…?

• Background fluctuations!

• correlation between infrared and X-ray background fluctuations
  => tracer of early BHs

see next talk by Nico Cappelluti
Tracking the early growth of SMBHs with *Athena*

- Current surveys (Chandra) have the sensitivity to detect low-to-moderate $L_X$ AGN ($10^{43-44}$ erg s$^{-1}$) at $z>6$, but lack the area coverage

**Athena:**
- large-collecting area (1.4m$^2$)
- large field-of-view (40'x40')
- PSF ~5” HEW across the FOV
- survey speed up to 100 times faster than Chandra

$\sim 22.5$ Ms survey programme (tentative plan):
  $4 \times 1.3$Ms + $8 \times 950$ks + $108 \times 90$ks
Tracking the early growth of SMBHs with *Athena*

- **Athena WFI survey**
- **Chandra/XMM surveys**
- **CDFS 7Ms (Luo+ 17)**
- **COSMOS Legacy (Marchesi+16)**
- **AEGIS (Nandra+15)**

- **Chandra detections**
- **Athena predicted high-z detections (~25Ms multi-tiered survey)**
Counterparts to Athena X-ray sources (in the early 2030s)

- ~50 deg\(^2\) Athena ‘shallow’ (~90ks) surveys will be well matched in depth/area to forthcoming deep optical/near-infrared surveys (e.g. Euclid, HyperSuprimeCam, LSST)

- JWST imaging required to identify counterparts in deep Athena surveys (~6 deg\(^2\), 950ks)

- *Athena* will pinpoint (low-L/obscured) AGNs within samples of early (z>6) galaxies - efficiently tracing SMBH accretion activity

- Further follow-up with ELTs, ALMA, JWST for
  - spectroscopic redshifts
  - host properties (stellar mass, star formation rates, dust masses etc.)
Athena constraints vs. models

Comparison of the high-z AGN luminosity function from a range of hydrodynamic and semi-analytic simulations vs. predicted Athena constraints

- models often high vs. empirical predictions (extrapolations) - also true at lower z!
- order of magnitude differences between models - Athena will provide vital constraints!
- some models do not extend to highest $L_X$ - volume limitations?

see also: Ricarte+18, Valiante+18, DeGraf+19, Griffin+19
Athena constraints vs. models

- Detection of an AGN with \( L_X = 10^{43} \text{ erg s}^{-1} \) at \( z = 6 \)
  \[ \Rightarrow M_{\text{BH}} \gtrsim 2 \times 10^6 M_{\odot} \]
  (assuming \( \sim \)Eddington limited)

- Detection of an AGN with \( L_X = 10^{44} \text{ erg s}^{-1} \) at \( z = 8 \)
  \[ \Rightarrow M_{\text{BH}} \gtrsim 2 \times 10^7 M_{\odot} \]
  (assuming \( \sim \)Eddington limited)

_Athena will not_ identify SMBH seeds immediately after their formation _but_ samples _will_ constrain the extent of early mass growth, where this growth occurs within the \( z > 6 \) galaxy population, and the _possible_ seed mechanisms, ruling out certain classes of models.

Aird, Comastri et al. 2013, models by Marta Volonteri
Beyond *Athena*: AXIS and Lynx

To detect accreting $\sim10^{4-5} M_\odot$ black holes in the $z\sim6-10$ Universe, requires $\sim1''$ resolution.
Summary

• Bulk of the mass growth of supermassive black holes is due to accretion at $z<3$ and is well-characterised.

• But initial seeds likely formed in particular environments at very high $z>10$, with subsequent growth by merging but (mostly) accretion.

• Latest optical/NIR surveys starting to sample quasar population at $z>6$ - challenges for seed models to build most massive black holes.

• Current X-ray surveys reveal strong drop in space density of AGN at all luminosities at $z>3$ - very few sources found at $z>5$ even though Chandra has the sensitivity to detect them.

• To characterise early growth need to reach deepest Chandra flux limits over large sky areas (6-50 deg$^2$) coverage => ATHENA.

• To directly see the initial growth of $\sim 10^{4-5} M_\odot$ black holes requires order of magnitude improvement in sensitivity and wide-area coverage => LYNX.