from the first black holes to the first quasars

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Outline

- Introduction
- The nature of BH seeds: Pop III remnants or head-on start?
- From the first BHs to the first QSOs: planting seeds along hierarchical structure formation
- Co-evolution of the first BH and galaxies: dominance, symbiosis or adjustment? Clues from chemical properties of the host galaxies
- Conclusions
**Time since the Big Bang**

- $z \approx 1000$
  - 380,000 yr

- $z \approx 30 - 20$
  - 100-200 Myr

- $z \approx 6 - 7$
  - 1 Gyr

- $z = 0$
  - 13.6 Gyr

**Big Bang**
- the universe is filled with a hot plasma

**Recombination**
- the universe becomes neutral
- small density fluctuations grow by gravitational amplification

**Formation of the first stars**
- mini-halos $10^6 \, M_\odot$ at $z = 20$
- Proto-galaxies $10^8 \, M_\odot$ at $z = 10$

**Reionization is complete**

- QSOs $10^{12} - 10^{13} \, M_\odot$ at $z = 6 - 7$

**Present-day Universe**

- SXDF-NB1006-2
  - LAE @ $z = 7.215$
  - Shibuya+2012

- ULAS J112001.48

- QSO @ $z = 7.085$
  - Mortlock+2011
growing the first quasars

\[ M(t) = M(0) \exp \left( \frac{1 - \epsilon}{\epsilon} \frac{t}{t_{\text{Edd}}} \right) \]

- \( t_{\text{Edd}} = 0.45 \text{ Gyr} \)
- \( \epsilon \approx 0.1 \)

- \( z = 7.085 \), \( t = 0.77 \text{ Gyr} \) \( \Rightarrow M_{\text{seed}} > 400 \ M_{\odot} \)
- \( z = 6.42 \), \( t = 0.87 \text{ Gyr} \) \( \Rightarrow M_{\text{seed}} > 80 \ M_{\odot} \)
growing the first quasars

\[ M(t) = M(0) \exp \left( \frac{1 - \epsilon}{\epsilon} \frac{t}{t_{\text{Edd}}} \right) \]

\[ t_{\text{Edd}} = 0.45 \text{ Gyr} \]

\[ \epsilon \approx 0.1 \]

\[ z = 7.085 \quad \Delta t = 0.67 \text{ Gyr} \quad M_{\text{BH}} = 2 \times 10^9 M_{\odot} \quad \rightarrow \quad M_{\text{seed}} > 3000 M_{\odot} \]

\[ z = 6.42 \quad \Delta t = 0.77 \text{ Gyr} \quad M_{\text{BH}} = 3 \times 10^9 M_{\odot} \quad \rightarrow \quad M_{\text{seed}} > 500 M_{\odot} \]
seed BHs formation scenarios

- Remnants of Population III stars forming in primordial mini-halos at $z \approx 20 - 30$
- Direct-collapse in the first proto-galaxies at $z \approx 10$
- Formation in stellar clusters at $z \approx 10$
the formation of the first stars

theory for the formation of the first Pop III stars predict an IMF dominated by high-mass stars

- collapse of \(\approx 10^6 M_{\odot}\) mini-halos at \(z \approx 20 - 30\)
- \(H_2\) cooling
- gas cloud becomes Jeans unstable \(M_{\text{Jeans}} \approx 10^3 M_{\odot}\)

\[
\text{accretion rate } \frac{dM}{dt} = \frac{M_\odot}{t_{\text{ff}}} = c_s^3/G = T^{3/2} \times 100 \text{ larger than } Z_{\odot}\]

\[
\text{accreted gas mass } M_\star \approx [40 - 100] M_{\odot}\]

Omukai & Palla 2003; Bromm et al 2004; O'Shea et al. 2007; Tan & McKee 2004; McKee & Tan 2008; Hosokawa et al. 2011
BH seeds as Pop III stellar remnants?

Pop III IMF?

$M_{\text{ch}} = 40 - 100 \, M_{\odot}$

pair-instability SN

core collapse SN

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

$M_{\text{BH}} \ll 100 \, M_{\odot}$

$M_* > 260 \, M_{\odot}$

$M_{\text{BH}} > 150 \, M_{\odot}$

→ may be too small for $z \sim 6 - 7$ QSOs
what happens next?

The first supernovae start cosmic metal enrichment

mass-averaged metallicity $Z = \frac{M_{\text{met}}}{M_{\text{gas}}}$

→ second generation stars may form in clouds that have been polluted by metals and dust grains

→ cooling and fragmentation properties of star-forming gas change

Tornatore et al 2007
Star formation with the first heavy elements and dust grains

metal-line cooling:
\[ Z > 10^{-4} \, Z_{\text{sun}} \]
\[ M_{\text{jeans}} > 10 \, M_{\text{sun}} \]


dust cooling:
\[ Z > 10^{-6} \, Z_{\text{sun}} \]
\[ M_{\text{jeans}} < 1 \, M_{\text{sun}} \]

Can fragmentation be avoided?

Yes, preventing the gas to cool!
- sub-critical metallicities $Z < Z_{cr}$
- inefficient $H_2$ cooling $\leftrightarrow$ photo-dissociation by a strong UV flux

$$J_{21} = J/10^{-21} \text{ erg cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \text{ Hz}^{-1} > J_{21,\text{crit}} \approx 10^2 - 10^3$$

Thermal evolution of $Z = 0$ gas in a protogalaxy ($T_{\text{vir}} > 10^4$K)

Omukai, RS, Haiman (2007)
BH seeds: rapid direct collapse

- overcome rotational support by gravitational instabilities
- rapid collapse due to deep potential well and large accretion rates $> 1 \, \text{M}_{\text{sun}}/\text{yr}$

$M_{\text{BH}} \sim 10^5 - 10^6 \, \text{M}_{\text{sun}}$ @ $z = 10$

Can fragmentation be avoided?

No, if progenitors of the first galaxies have experienced SF
- super-critical metallicities $Z \geq Z_{\text{cr}}$
- inefficient $H_2$ cooling $\leftrightarrow$ photo-dissociation by a strong UV flux

$$J_{21} = J/10^{-21} \text{ erg cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \text{ Hz}^{-1} > J_{21,\text{crit}} \approx 10^2 - 10^3$$

Thermal evolution of $Z \geq 10^{-6} Z_{\text{sun}}$ gas in a protogalaxy ($T_{\text{vir}} > 10^4$K)

Omukai, RS, Haiman (2007)
BH seeds: formation in a dense stellar cluster

- dust-induced fragmentation leads to the formation of a dense stellar cluster:
  ~ 1000 fragments with mass \( M_{\text{frag}} \sim 0.1 \, M_{\odot} \) in a 0.01 pc region with free-fall time \( \sim 300 \, \text{yr} \)

- dynamical friction timescale: \( t_{\text{fric}} \sim 1.6 \times 10^3 \, \text{yr} \left( \frac{M_R}{10^2 M_{\odot}} \right) \)

Very Massive Star forms by stellar mergers if \( t_{\text{fric}} < 4 \, \text{Myr} \) (Portegies-Zwart et al. 2004)

\[ M_{\text{BH}} \sim 10^2 - 10^3 \, M_{\odot} @ z = 10 \]

Omukai, RS, Haiman (2008),
Devecchi & Volonteri (2009),
Devecchi et al. (2010), Devecchi et al. (2012)
Oh & Haiman (2002), Bromm & Loeb (2003),
nature of BH seeds

Dark Matter Halo
- $T_{\text{vir}} < 10^4 \text{ K}$
- $T_{\text{vir}} > 10^4 \text{ K}$
- $Z < Z_{\text{crit}}$
- $Z > Z_{\text{crit}}$

mini-halo
- Pop III star
  - $40 \ M_{\odot} < M_* < 140 \ M_{\odot}$
  - $M_* > 260 \ M_{\odot}$
  - $\rightarrow$ MBH

proto - galaxy
- dynamical instability
  - suppressed star formation
    - UV, B field, shocks…
  - Star formation dense cluster
    - direct collapse
      - $\rightarrow$ MBH
    - run-away collisions
      - $\rightarrow$ MBH

adapted from Volonteri, ARAA (2010)
From the first BHs to the first QSOs: planting and growing seeds

Co-evolution of the first BH and galaxies: dominance, symbiosis or adjustment?

Volonteri 2012

different pathways reflect BH seeds birth and growth conditions
Co-evolution of the first BH and galaxies: footprints in the $M_{\text{bh}} - M_{\text{bulge}}$ relation at early times?

in AGN-selected samples $M_{\text{bh}}/M_{\text{bulge}}$ evolves to larger values at higher $z$

Walter et al. 2004; Peng et al. 2006; McLure et al. 2006; Riechers et al. 2008; Merloni et al. 2010; Wang et al. 2010

\[
M_{\text{bulge}} = M_{\text{dyn}} - M_{\text{gas}}
\]

\[
M_{\text{dyn}} = 2.3 \times 10^5 \frac{v_{\text{circ}}^2 R}{2}
\]

\[
M_{\text{gas}} = M_{\text{H}_2} \leftarrow L_{\text{CO}}
\]

\[
\frac{v_{\text{circ}}}{v_{\text{FWHM}}} = 0.75 \sin i
\]

$4 < z < 6$ QSOs

Valiante et al. in prep
Co-evolution of the first BH and galaxies: footprints in the $M_{bh} - M_{bulge}$ relation at early times?

BH dominance: rapid growth at early times due to efficient accretion triggered by galaxy mergers

Lamastra et al. 2010
Is the observed off-set of $z \sim 6$ QSOs in the $M_{bh} - M_{bulge}$ relation real?

Selection effects may be very important:

- scatter in the $M_{bh} - M_{bulge}$ relation + steep mass function $\rightarrow z \sim 6$ QSOs preferentially selected in low-mass hosts than what would be in a volume-limited sample (Lauer et al. 2007, Volonteri & Stark 2011)

- galaxy samples selecting starbursts without luminous AGN show a negative $M_{bh}/M_{bulge}$ evolution (Alexander et al. 2008)

- high-$z$ QSOs are preferentially viewed face-on (Ho et al. 2007)

- high-$z$ QSOs observations probe only a smaller (inner) fraction of the host mass (Haiman 2012)
Clues from the chemical properties of the host galaxies

High-z QSOs host galaxies are chemically mature systems: super solar metallicities in BLR/NLRs and $M_{\text{dust}} \sim 10^8 M_{\odot}$

BLRs Nagao+2006, Juarez+2009

NLRs Matsuoka+2009

Valiante et al. in prep
50 merger histories of a $10^{13} M_{\odot}$ halo @ $z = 6.4 \rightarrow$ SDSS J1148

- star formation in quiescent and/or merger-driven bursts

- BH growth via gas accretion and mergers

- BH feedback

- chemical enrichment (metals and dust) on the stellar characteristic timescales
Evolution of high-z QSOs: SDSS J1148


SDSS J1148: testing different evolutionary paths

Evolution of the nuclear black hole mass & accretion rate
Evolution of high-z QSOs: SDSS J1148

SDSS J1148: testing different evolutionary paths

star formation histories
chemical evolution of SDSS J1148 host
Valiante et al. (2011, 2012)

metals and dust are underpredicted by models which reproduce $z \sim 6 M_{\text{bh}} - M_{\text{star}}$
chemical evolution of SDSS J1148 host
Valiante et al. (2011, 2012)

metals and dust are reproduced if $M_{\text{star}}$ is a factor 3 – 10 larger:

$\Rightarrow M_{\text{bh}} - M_{\text{star}}$ consistent with the local correlation
chemical evolution of SDSS J1148 host

Valiante et al. (2011, 2012)

metals and dust are reproduced if $M_{\text{star}}$ is a factor 3 – 10 larger: 

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Valiante et al. (2011, 2012)

chemical properties can be reconciled with $z \sim 6$ $M_{bh} \cdot M_{star}$ for a top-heavy IMF
Summary

- The nature of BH seeds: Pop III remnants are likely to be too “light”... direct collapse scenarios lead to “heavy” seeds but require peculiar environmental conditions

- From the first BHs to the first QSOs: still hard to model accounting for BH dynamics and various radiative and chemical feedback effects

- Tension between the observed mass function of SMBHs @ z = 6 and upper limits on the accreted mass density at z > 5 from the unresolved CXRB? Tension between the observed mass density @ z = 6 and the positive evolution of the locally observed $M_{bh} - M_{star}$ correlation?

- Co-evolution of the first BH and galaxies: dominance, symbiosis or adjustment? Still hard to answer. Selection effects might influence the inferred correlation at z = 6

- Chemical properties of $z \sim 6$ QSOs host galaxies can give important constraints on evolutionary scenarios and on the nature and properties of the stars that dominate the evolution