Super Massive Black Holes in the early Universe

Simona Gallerani

in collaboration with:

Barbara Balmaverde, Paramita Barai, Stefano Carniani, Claudia Cicone, Andrea Ferrara, Roberto Gilli, Luca Graziani, Roberto Maiolino, Maria Carmela Orofino, Andrea Pallottini, Enrico Piconcelli, Livia Vallini, Cristian Vignali, Luca Zappacosta

“QUANTUM GASES, FUNDAMENTAL INTERACTIONS, AND COSMOLOGY”
Pisa, 25th October 2017
Super Massive Black Holes in the early Universe
(z ≈ 6; t < 1Gyr)

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The local $M_{BH} - M_*$ relation

SMBHs ($M_{BH} \approx 10^6 - 10^{10} M_{\text{sun}}$) are present in the center of massive galaxies, including the Milky Way.

What is the origin of the local $M_{BH} - M_*$ relation?
**Active Galactic Nuclei**

**BLACK HOLE ACCRETION**

Gas in the host galaxy is **accreted** onto the black hole

\[
\dot{M}_{BH} = \alpha \frac{4\pi G^2 M_{BH}^2 \rho_{gas}}{(c^2 + v_{BH-gas}^2)^{3/2}}
\]

(Bondi & Hoyle 1944; Hoyle & Lyttleton 1939)

**AGN RADIATION**

A fraction of the accreted rest-mass energy is **radiated away**

\[
L_{rad} = \varepsilon_{rad} \dot{M}_{BH} c^2 \quad \varepsilon_{rad} \approx 10\%
\]

**AGN FEEDBACK**

A fraction of this radiated energy is **returned** to the surrounding gas in terms of **thermal/kinetic energy**

\[
\dot{E}_{feed} = \varepsilon_{feed} L_{rad} = \varepsilon_{feed} \varepsilon_{rad} \dot{M}_{BH} c^2 \quad \varepsilon_{feed} \approx 5\%
\]

**AGN feedback can explain the origin of the local \( M_{BH} - M_\star \) relation**
AGN feedback in the local Universe

Mrk 231: the closest quasar known

Broad wings extended up to ± 750 km/s in the CO(1-0) line

Evidence of molecular outflows in the local Universe
Quasar feedback in $z \approx 6$ quasars

$[\text{CII}] (^{2}P_{3/2} - ^{2}P_{1/2})$ @158 $\mu$m

- The most important coolant of the ISM
- Detectable with sub-mm facilities at $z > 4$
- Detected in all $z \approx 6$ quasars

Broad wings extended up to $\pm 1300$ km/s in the [CII] line

Evidence of fast moving gas flowing out of the host galaxy
Metal-rich fast outflowing gas is distributed on ≈20 - 30 kpc

How does the $M_{\text{BH}} - M_*$ relation evolve at high redshift?
Black hole mass measurements in $z \approx 6$ quasars

The Mg II emission line arises from the AGN innermost region ($< 1$ pc)

$$M_{BH} = 10^{6.86} \left[ \frac{FWHM(MgII)}{1000 \text{ km s}^{-1}} \right]^2 \left[ \frac{\lambda L_\lambda}{10^{44} \text{ ergs}^{-1}} \right]_{\lambda=0.3 \mu}$$
Black hole mass measurements in $z \approx 6$ quasars

Tens of $z \approx 6$ quasars

(e.g. Barth et al. 2003; Jiang et al. 2007; Wang et al. 2010; Wu et al. 2015)

$M_{BH} = (0.02 - 1.10) \times 10^{10} M_{\text{Sun}}$

How SMBHs have formed in less than 1 Gyr?
Possible pathways for the origin of SMBH seeds

Assumptions:
The BH is radiating at $L_{\text{EDD}}$ for all the time spent accreting
$\epsilon = 0.1$

\[ \dot{M}_{\text{BH}} = \frac{(1-\epsilon)L_{\text{EDD}}}{\epsilon c^2} \]
Possible pathways for the origin of SMBH seeds

(1) PopIII remnants
collapse of primordial stars
($M_{\text{PopIII}}>100 \, M_{\odot}$)
in DM minihalos
($M_{\text{DM}} \approx 10^6 \, M_{\odot}$)

$z \approx 20-30$

$M_{\text{seed}} \approx 50-100 \, M_{\odot}$

(e.g. Tegmark et al. 1997; Madau & Rees 2001; Bromm et al. 2002)
Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

- Collapse of primordial stars
  $(M_{\text{PopIII}} > 100 \, M_{\odot})$
  in DM minihalos
  $(M_{\text{DM}} \approx 10^6 \, M_{\odot})$

  $z \approx 20-30$

(2) Compact nuclear star clusters

- Star collisions
  can lead
to the formation of VMSs

  $z \approx 10-20$

$M_{\text{seed}} \approx 1000 \, M_{\odot}$

$M_{\text{seed}} \approx 50-100 \, M_{\odot}$

(e.g. Schneider et al. 2006; Clark et al. 2008; Devecchi et al. 2012)

(e.g. Tegmark et al. 1997; Madau & Rees 2001; Bromm et al. 2002)
Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

- Collapse of primordial stars
  \( (M_{\text{PopIII}} > 100 \, M_\odot) \)
- In DM minihalos
  \( (M_{\text{DM}} \approx 10^6 \, M_\odot) \)

\[ z \approx 20-30 \]

\( M_{\text{seed}} \approx 10^5-10^6 \, M_\odot \)

\( M_{\text{seed}} \approx 1000 \, M_\odot \)

\( M_{\text{seed}} \approx 50-100 \, M_\odot \)

(2) Compact nuclear star clusters

- Star collisions
  can lead
  to the formation of VMSs

\[ z \approx 10-20 \]

(3) Direct Collapse Black Holes

- Primordial gas
  irradiated by LW radiation
  in atomic-cooling halos

\[ z > 10 \]

\( M_{\text{seed}} \approx 1000 \, M_\odot \)

\( M_{\text{seed}} \approx 10^5-10^6 \, M_\odot \)

QSO observations

(e.g. Haehnelt & Rees 1993; Yue et al. 2013; Pallottini et al. 2017; Pacucci et al. 2017)

(e.g. Schneider et al. 2006; Clark et al. 2008; Devecchi et al. 2012)

(e.g. Tegmark et al. 1997; Madau & Rees 2001; Bromm et al. 2002)
Cosmological simulations of a $z \approx 6$ quasar

GADGET-3 (Springel 2005)

$100 > z > 6$

$L_{\text{box}} \approx 2 \, h^{-1} \, \text{c Mpc}$

$m_{\text{DM}}^{\text{res}} = 4 \times 10^6 \, M_{\text{sun}}$

$\lambda_{\text{smooth}} = 1 \, h^{-1} \, \text{c kpc}$

$M_{\text{DM}}^{\text{tot}} \approx 4 \times 10^{12} \, M_{\text{sun}}$

Star formation

$(n > 0.1 \, \text{cm}^{-3})$

BLACK HOLE SEEDING: $10^5 \, M_{\text{sun}}$ BH in $M_{\text{DM}} > 10^9 M_{\text{sun}}$

BLACK HOLE GROWTH: Gas accretion and galaxy merging

QUASAR FEEDBACK: Kinetic energy deposition
Cosmological simulations of a $z \approx 6$ quasar

Quasar feedback energy is distributed as kinetic energy

We have assumed a bi-conical and spherical geometry

Surrounding *gas is driven outward*

$$(v_{\text{outflow}}, \dot{M}_{\text{outflow}}) \quad v_{\text{outflow}} = 10^4 \text{ km/s}$$

$$\frac{1}{2} \dot{M}_{\text{outflow}} v_{\text{outflow}}^2 = \dot{E}_{\text{feed}}$$

$$\dot{M}_{\text{outflow}} = 2 \varepsilon_{\text{feed}} \varepsilon_{\text{rad}} \dot{M}_{\text{BH}} \left( \frac{c}{v_{\text{outflow}}} \right)^2$$
Cosmological simulations of a $z \approx 6$ quasar

At $z \approx 6$ a SMBH with $M_{\text{BH}} \approx 10^8$-$10^9$ $M_{\odot}$ is formed, in agreement with BH mass measurements obtained from the Mg II emission line.
Quasar feedback effects on the host galaxy

GAS DENSITY

GAS TEMPERATURE

Barai et al. (2017)
Quasar feedback effects on the host galaxy

The gas density and temperature maps shows the location and extension of the outflowing gas

Barai et al. (2017)
Quasar feedback effects on the host galaxy

In the AGN run, particles reach very large velocities (up to 1000 km s\(^{-1}\))
Quasar feedback effects on the host galaxy

Star formation is quenched due to the shock-heated low density gas.

Fast outflowing metals are distributed on >10 kpc scales in agreement with [CII] observations of high-z quasars.
The $M_{\text{BH}}-M_*$ relation at high redshift
The $M_{\text{BH}}-M_*$ relation at high redshift

Agreement with the local $M_{\text{BH}}-M_*$ relation
The $M_{\text{BH}}$-$M_*$ relation at high redshift

- Agreement with the local $M_{\text{BH}}$-$M_*$ relation
- Deviation from the local $M_{\text{BH}}$-$M_*$ relation

In the high redshift range, the $M_{\text{BH}}$-$M_*$ relation shows a tendency towards outflow bi-conical geometry, as opposed to the local spherical geometry. For instance, at $z \approx 6$, $M_{\text{BH}} = 10^9 M_{\odot}$ deviates from the local relation, while $M_{\text{BH}} = 10^8 M_{\odot}$ and $10^7 M_{\odot}$ agree with the local relation.
The $M_{\text{BH}}-M_*$ relation at high redshift

Are quasar feedback in $z \approx 6$ quasars more efficient than in local Universe counterparts?
Super Massive Black Holes in the early Universe

• $z \approx 6$ quasars are powered by $10^8$-$10^{10}$ Msun BH

• Quasar feedback are in place at high-$z$

• Cosmological simulations can reproduce the BH observed masses starting from massive seeds ($M_{\text{seed}} = 10^5$ Msun)

• Quasar feedback quenches star formation expelling the surrounding gas out of the host galaxy

• The $M_{\text{BH}}$-$M_*$ does not evolve with $z$ for $M_{\text{BH}}=10^7$ - $10^8$ $M_{\odot}$

• Above this mass range the BH grows faster than $M_*$
Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

- Collapse of primordial stars
  \((M_{\text{PopIII}} > 100 \, M_{\odot})\)
  in DM minihalos
  \((M_{\text{DM}} \approx 10^6 \, M_{\odot})\)

  \(z \approx 20-30\)

(2) Compact nuclear star clusters

- Star collisions can lead to the formation of VMSs
  in \(H_2\)-cooling halos
  \((T_{\text{vir}} < 10^4 \, K)\)

  \(z \approx 10-20\)

(3) Direct Collapse Black Holes

- Primordial gas irradiated by LW radiation
  in atomic-cooling halos
  \((T_{\text{vir}} > 10^4 \, K)\)

  \(z > 10\)

(4) Primordial Black Holes

- Direct collapse of primordial density inhomogeneities

  \(z > 2.3 \times 10^4 h^2 \Omega_m\)
  (radiation-dominated era)

DM candidates

\[ M_{\text{seed}} \approx 50-100 \, M_{\odot} \]
\[ M_{\text{seed}} \approx 10^5-10^6 \, M_{\odot} \]
\[ M_{\text{seed}} \approx 1000 \, M_{\odot} \]
Gravitational wave detection from merging BHs

The measured BH masses (10-40 $M_{\odot}$) and event rate (2-53 $\text{Gpc}^{-3}\text{yr}^{-1}$) provide important constraints on the hypothesis that PBHs can be constituents of DM.
Gravitational Waves constraints on PBHs as DM

**Assumption:** a fraction $f_{\text{DM}}$ of Dark Matter in the Galactic Ridge is constituted by PBHs

**Method:** Model of gas accretion onto PBHs; predictions of X-ray and radio emission

**Result:** 30 $M_{\odot}$ PBHs cannot constitute more than 10% of DM in our galaxy.
Quasar-driven feedback: Gas metallicity

Barai et al. (2017)

Metals are distributed on very large scale (≥ virial radius) possibly being ejected in the inter-galactic medium.
[CII] emission in J1148 at $z \approx 6.4$

Evidence of strong quasar feedback at $z \approx 6$

Broad wings extended up to $\pm 1300$ km/s

indication of a powerful outflow

Maiolino et al. (2012)