Early Growth of typical Massive Black Holes

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Supermassive black holes with \( \sim 10^9 \) solar masses have been observed at \( z > 6 \).

The highest-redshift black hole currently observed is at \( z = 7.085 \) and has \( 2 \times 10^9 M_\odot \) (Mortlock et al. 2011).

The most massive black of \( 1.3 \times 10^{10} \ M_\odot \) at \( z = 6.3 \) (Wu et al. Nature 2015)
Direct collapse scenario

★ Provides massive seeds of $10^5$–$10^6$ \( M_\odot \)

★ Key requirement is to have large inflow rate of > 0.1 \( M_\odot/yr \)

★ Isothermal direct collapse with \( T \sim 8000 \) K

★ Primordial gas composition

★ Requires strong LW flux to quench $H_2$ formation

See review by Latif & Ferrara 2016

Regan et al 2009
Supergiant protostar

The protostar never contracts to reach the ZAMS stage, but largely expands with very rapid accretion, $>0.01 \, M_\odot/yr$.

- Large radius $\rightarrow$ low effective temperature $\rightarrow$ weak UV feedback

Turbulent, magnetized black hole formation

BH growth: simulation setup

- 3D radiation hydrodynamics cosmological simulation
- Halo mass of $3 \times 10^{10} M_\odot$ at $z = 7.5$
- Coming periodic box of 8 Mpc/h
- DM resolution of $\sim 53,000 M_\odot$
- Physical resolution of 3.6 pc
Pop III/II Star Formation

- An Overdensity of $5 \times 10^5$ ($\sim 10^3$ cm$^{-3}$ at $z = 10$)
- A converging gas flow ($\nabla \cdot V_{\text{gas}} < 0$)
- Molecular hydrogen fraction ($f_{\text{H}_2} > 5 \times 10^{-4}$)
- The mass is randomly sampled from IMF with mass range between 1-300 M$\odot$
- For $Z/Z_\odot > 10^{-4}$ Pop II star cluster of $\sim 1000$ solar masses are allowed to form

Wise & Abel 2012
Stellar feedback

★ Radiative feedback is modelled using the ray tracing scheme

★ We take a monochromatic spectrum with an energy of 29.6 eV for Pop III stars

★ For Pop II stars, we take a fixed spectrum of 21.6 eV appropriate for low metallicity stars

★ We model both Type II and PINSN
Massive black hole feedback

- Insert a massive black hole (MBH) seed of $10^5 M_\odot$ at the halo center at $z = 12$

- We model both UV and X-ray feedback from an accreting MBH

- Four energy bins at 13.6 eV, 24.6 eV, 54.4 eV and 1 keV are used when generating the photons

- We model the gas accretion onto the MBH following the prescription of Kim et al. (2011) and estimate mass accretion onto BH using the Bondi-Hoyle recipe
Growth of a DCBH in Atomic cooling halo

3D Radiation Hydrodynamical simulations
Include both UV & X-ray feedback (0.1eV-1.1 KeV) from a BH

Also see Johnson et al. 2011
Aykutalp et al. 2014
Stellar mass

Latif, Volonteri & Wise 2018
Star formation rate

Salmon et al. 2015 at z=6.5

Latif, Volonteri & Wise 2018
Figure 2. Projections of density-weighted temperature along the y-axis at various redshifts for the central 14 kpc region. The left panel shows the moment when first SN goes off while other panels depict the epochs when large outflows are produced by the SNe in tandem with MBH feedback.

Figure 3. Projections of density-weighted metallicity originating from Pop III SNe along the y-axis at the same redshifts as figure 2 for the central 14 kpc region.

Flows as they evacuate gas from the halo. Overall, the average SFR is $\sim 2 M_\odot/yr$ and peaks in SFR correspond to the mergers occurring at those epochs. Most of the SF occurs inside the primary halo. These results are comparable to the SFR main sequence at $z = 6.5$ from the CANDELS survey (Salmon et al. 2015, see Fig. 2). The typical star formation rates observed in the CANDELS survey are between $1 - 100 M_\odot/yr$, with stellar masses of time $10^8 - 10^{10} M_\odot$ and $z$ between 3.5 - 6.5. Although, the simulated galaxy is at $z=7.5$, at slightly higher redshift, but its stellar mass and the SFR are close to the observed range at $z=6.5$. Such a comparison confirms that the simulated galaxy is a typical, not completely off the main sequence observed at $z > 6$ and agree with predictions from theoretical models (Behroozi et al. 2013; Davé et al. 2013; Somerville et al. 2012).

3.2 Black hole growth

The initial mass accretion rate onto the MBH is $\sim 10^{-5} M_\odot/yr$ and continues to increase for about first 3 Myr. The X-ray...
Latif, Volonteri & Wise 2018

Figure 4. Projections of density-weighted gas density along the y-axis at the same redshifts as figure 2 for the central 14 kpc region.

Figure 5. The black hole mass evolution (top panel) and the mass accretion rate onto the MBH (bottom panel) over the cosmic time in Myr after the Big Bang, showing the lack of the growth of "normal" BHs in the early universe.

and UV feedback from the MBH photo-dissociate molecular hydrogen and photo-ionize hydrogen and helium atoms in its surrounding. Such energy deposition photo-evaporates the clumpy gas and forces it away from the MBH. The luminosity from young stars exceeds the MBH luminosity within the central kpc region which further heats and expels the gas from the central potential. As a result the temperature of gas rises to \( \geq 10^4 \) K, and the expanding HII region leaves behind old dense medium. In the mean time the first PopII SN occurs that further pushes the gas away from the MBH and generates an outflow. Consequently, mass accretion onto the MBH drops below \( 10^{-6} M_\odot/yr \) as shown in Figure 5. In the aftermath of SN, metal cooling brings the gas temperature down to \( \leq 10^4 \) K and increases accretion to the MBH.
Comparison of BHAR vs SFR

Figure 6. The MBH accretion rate against star formation rate is shown here. The green squares represent Pop III SFRs while orange triangles correspond to Pop II SFRs. They are plotted for all halo progenitors at all redshifts. The grey-shaded region shows the range of SFR found in Salmon et al. 2015.

Accretion onto the MBH continues until many SNe explode. They in tandem with MBH feedback expel the gas from MBH neighborhood and drive large outflows. On a few occasions the MBH gets trapped inside SN remnants. Subsequently, the accretion rate drops significantly and the growth of the MBH is halted for a few Myr. As mentioned above, large outflows observed at about 400 Myr, 450 Myr, 480 Myr, 560 Myr and 640 Myr strongly influence the MBH growth and particularly their impact is severe when the stellar mass is less than $10^8 M_\odot$.

The mass accretion onto the MBH reaches brief maxima of $10^{-4} M_\odot/yr$, but starbursts generate large kpc-wide outflows and regulate the growth of MBH. This trend has been observed particularly for the first 150 Myr of simulation similar to previous works (Dubois et al. 2012; Habouzit et al. 2016; Prieto et al. 2017). The ratio of the MBH mass accretion rate to the Eddington accretion rate, so-called the Eddington ratio, increases up to a $\sim 0.03$ in the first 20 Myr and declines during the massive outflows generated by SNe. The average Eddington ratio during the simulation is $\sim 10^{-3}$.

In our simulation the MBH never accretes at the Eddington limit.

The average accretion rate onto the MBH is a few times $10^{-6} M_\odot/yr$ and remains highly intermittent throughout the simulation. In total about 2200 $M_\odot$ are accreted onto the MBH during 320 Myr out of which about 1000 $M_\odot$ is accreted during the first 40 Myr. Over time, the halo and stellar mass increase as the potential well gets deeper. Therefore, the average density in the halo increases as well as the average temperature due to the continuous heating of gas by SNe and AGN feedback. Consequently, the growth of the MBH tends to be faster during the last 50 Myr. In Figure 6, we plot the accretion rate onto the MBH against the SFR. The ratio between MBH accretion rate and SFR is $\sim 10^{-3}$ for Pop III stars and $\sim 10^{-6}$ for Pop II stars; this confirms that the MBH grows much more slowly than its host galaxy, since SFR and therefore stellar mass are dominated by Pop II stars. Unless MBH accretion becomes more consistent, the MBH-galaxy system will drift towards a smaller ratio between MBH and stellar mass, creating a MBH "undermassive" with respect to its galaxy. The large ratio between SFR and MBH accretion rate would also make it difficult to detect the AGN, its luminosity likely swamped by that of the stellar population (see Volonteri et al. 2017).

Overall, the stunted growth of MBH is a consequence of SNe in tandem with BH feedback which expel gas from the MBH surroundings and quench its growth. These findings are consistent with previous works exploring the growth of BHs at early cosmic times (Dubois et al. 2012, 2015; Habouzit et al. 2016; Prieto et al. 2017; Di Matteo et al. 2017; Angles-Alcazar et al. 2017; Smidt et al. 2017; Biermann et al. 2017). They also found that MBH does not grow efficiently in high redshift galaxies when stellar mass is below $10^9 M_\odot$. These studies ignore the formation and feedback from Pop III stars which can be important during the early stages of galaxy formation. By following the formation and feedback from Pop III stars, we found that it makes the growth of MBH even more difficult as massive Pop III stars could produce PISNe which are more effective in ejecting the gas from central potential, being 10-100 times more energetic than Type II SNe. Consequently, in comparison with earlier findings, the mean accretion rate onto the MBH is about two orders of magnitude smaller. These differences arise from modeling the feedback from Pop III stars and inclusion of both UV and X-ray feedback from the MBH. Our results are more robust than previous estimates as we...
Key Findings

- SNe in combination with feedback from MBH quench its growth
- PISNe are more effective in removing the gas from BH vicinity
- The average SFR during the simulation is \( \sim 1 \, M_{\odot}/yr \)
- This may explain the paucity of low luminosity AGN at \( z > 6 \)
The formation of the first supermassive black holes is one of the main open questions in our understanding of high-redshift structure formation. In this book, we aim to provide a summary on the state of art of modern research on this topic, exploring the formation of massive black holes from a fluid dynamical, stellar dynamical and chemical perspective. The book thus provides a solid theoretical foundation, and includes a comparison with current observations and future perspectives, including modern topics such as the potential of the Square Kilometre Array, the European Extremely Large Telescope, the Euclid satellite or possible detections via gravitational waves.