Early growth of typical high redshift black holes seeded by direct collapse

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ABSTRACT
Understanding the growth of high redshift massive black holes (MBHs) is a problem of great astrophysical interest. The most luminous quasars at $z > 6$ are frequently observed but they represent only the tip of the iceberg as the majority of the low luminosity AGN population remains undetected. In the present study, we perform a radiation hydrodynamics cosmological simulation to study the growth of “normal” black holes in the high redshift universe. In our simulation we model the formation of Pop III and Pop II stars along with their chemical, mechanical and radiative feedback. We consider both UV and X-ray emission from an accreting BH to simulate its radiative feedback. The selected halo has a mass of $3 \times 10^{10} M_\odot$ at $z = 7.5$ and we turn on radiative feedback from a MBH seed of $10^5 M_\odot$ along with in-situ star formation at $z = 12$ when the halo mass reaches well above the atomic cooling limit. We find that the MBH accretes only about $2200 M_\odot$ during 320 Myr and the average mass accretion onto the MBH is a few times $10^{-6} M_\odot$/yr. Our results suggest that the stunted growth of MBH is a consequence of supernovae in tandem with MBH feedback which drive large outflows and evacuate the gas from MBH vicinity. This may explain why a population of low luminosity AGN has not been detected so far at $z > 6$; the large contrast between the star formation rate and the MBH accretion rate may make them hard to detect even in upcoming deep surveys.

Key words: methods: numerical – cosmology: theory – early Universe – high redshift black holes– black holes physics-galaxies: formation

1 INTRODUCTION
Supermassive black holes (SMBHs) of millions to billions of solar masses are common at the centers of present day galaxies and may have co-evolved with their hosts (see Kormendy & Ho (2013) and references therein). On the other hand, high redshift surveys have detected dozens of quasars at $z \geq 6$ powered by the accretion onto SMBHs of a few billion solar masses within the first Gyr after the Big Bang (Fan et al. 2003; Willott et al. 2007; Jiang et al. 2009; Mortlock et al. 2011; Banados et al. 2014; Venemans et al. 2015; Wu et al. 2015; Bañados et al. 2017). These quasars represent the tip of the iceberg as many low luminosity active galactic nuclei (AGN) may have gone undetected in present surveys due to current observational constraints. Therefore, the population and growth of BHs remain elusive at earlier cosmic epochs. Understanding their formation and growth mechanisms are questions of a prime astrophysical interest.

Seeds of SMBHs may have formed at high redshift and evolved via accretion or merging to reach a billion solar masses for the most extreme cases. The main pathways for SMBH formation are a collapse of a massive star, run-away collisions in stellar clusters and a direct collapse of gas cloud into a massive BH, see a recent review on this topic by Latif & Ferrara (2016). The mass of seed BH depends on the formation channel and varies from $10$ to $10^5 M_\odot$ (Volonteri 2010; Haiman 2013). Large scale cosmological simulations exploring the growth of BHs commonly employ thermal feedback without proper radiation transfer calculations and use Bondi prescription with a resolution of about a kpc (Booth & Schaye 2009; Sijacki et al. 2015; Di Matteo et al. 2017) except Dubois et al. (2012) with a resolution of about 10 pc. They may overestimate the mass accretion onto a MBH by not resolving the Bondi radius (Gaspari et al. 2013; Gaspari & Sadowski 2017; Negri & Volonteri 2017; Johnson & Haardt 2016). Numerical experiments exploring the growth of a stellar mass BH including a detailed treatment for its feedback show that gas in the surrounding gets photo-evaporated and...
leads to its stunted growth shortly after its formation (Johnson & Bromm 2007, Milosavljevic et al. 2009, Alvarez et al. 2009, Park & Ricotti 2011). Similarly, Jeon et al. (2012) and Jeon et al. (2014) found that BH feedback strongly suppresses its growth in minihalos and also influences the star formation in the host galaxies. These studies either employed idealized initial conditions or focused on the growth of low mass BHs in the first minihalos forming at $z = 10 - 30$, using cosmological simulations.

Johnson et al. (2011) performed a 3D smoothed particle hydrodynamical simulation with a ray tracing algorithm to model radiative feedback from a MBH in an atomic cooling halo. They found that accretion rate onto the BH drops down to $10^{-3}$ $M_\odot$/yr in about one Myr due to the photo-heating and radiation pressure. However, these simulations were performed for primordial gas composition collapsing isothermally with no in-situ star formation. The impact of heating and radiation pressure. However, these simulations were performed for primordial gas composition collapsing isothermally with no in-situ star formation. The impact of X-ray feedback from a MBH seed on its growth was explored via cosmological radiation transfer simulations by employing the adaptive mesh refinement (AMR) technique in a halo of $\sim 10^6$ $M_\odot$ (Aykutalp et al. 2013, 2014). They found that X-ray feedback from BH self-regulates its growth and also induces star formation. Recently, Smidt et al. (2017) performed radiative transfer cosmological simulations to explore the role of X-ray feedback on its growth assuming a single frequency bin at 1 keV in the context of the most luminous high redshift quasars. They found that dense cold accretion flows feed MBH which grows up to billion solar masses by $z = 7$ and may explain the existence of $z > 6$ quasars.

In this study, we focus on the growth of “normal” BHs, not the extreme population such as the brightest quasars at $z > 6$ in the early universe. To accomplish this goal, we perform an AMR cosmological simulation coupled with radiative transfer algorithm MORAY (Wise & Abel 2011). We model feedback from a MBH by including both UV and X-ray (11.2 eV - 1.1 keV) emission from an accreting BH of $10^5$ $M_\odot$. We also follow the formation of Population III (Pop III) and Population II (Pop II) stars along with their radiative, chemical and mechanical feedback. For star formation, we employ recipes for Pop III and Pop II from Wise et al. (2012) which allows transition to second generation of stars for $Z/Z_\odot > 10^{-4}$. Pushing the state of the art in this field, this work provides better insight about the growth of normal black holes at high redshift ($z > 6$).

This article is organised in the following way. In section 2, we describe in detail the simulation setup and prescriptions for feedback from MBH/stars as well as recipes for star formation. We present our main results in section 3 and confer our conclusions in section 4.

2 NUMERICAL METHODS

We conduct the simulation using the public version of cosmological hydrodynamical code ENZO (Bryan et al. 2014). It is an AMR grid based code which makes use of the message passing interface (MPI) to run on parallel systems. The equations for hydrodynamics are solved with the piece-wise parabolic method (PPM) and we employed the HLLE Riemann solver to capture strong shock and rarefaction waves. The code makes use of a particle-mesh based N-body solver to compute dark matter (DM) dynamics. A multi-grid Poisson solver is used for self-gravity calculations.

We start our simulation at $z = 150$ with cosmological initial conditions generated from the MUSIC package (Hahn & Abel 2011) and use the latest Planck data with $\Omega_m = 0.3089$, $\Omega_\Lambda = 0.6911$, $H_0 = 67.74$ to generate initial conditions (Planck Collaboration et al. 2016). Our periodic box has a size of comoving 8 Mpc/h on each side, we select the most massive halo forming in our computational volume and place it at the center of the simulation box. We employ nested grid initial conditions with a root grid resolution of 256$^3$ cells, an equal number of DM particles and two additional nested grids with 256$^3$ cells, resulting in an effective resolution of 1024$^3$. This setup provides us an effective DM resolution of $\sim 53,000$ $M_\odot$. We further employ 8 additional dynamic refinement levels during the course of simulation which yields a maximal physical resolution of 3.6 pc at $z = 11$. Our resolution criteria is based on the baryonic overdensity of 4, the particle mass resolution of $\rho_{\text{DM}} \Delta^3 r^{\gamma}$ where $\rho_{\text{DM}}$ is the dark matter density, $\Delta$ is the root grid cell size, $r$ is the refinement factor, $\gamma$ is the refinement level, and $\alpha = -0.3$ makes the refinement super-Lagrangian and a fixed Jeans resolution of at least four cells, similar to Latif et al. (2016). The simulated halo has a mass of $3 \times 10^{10} M_\odot$ and $6.2 \times 10^9 M_\odot$ at $z = 7.5$ and $z = 6$, respectively. The virial radius of the halo at $z = 7.5$ is 21.5 kpc. We follow its formation from $z = 14$ down to $z = 7.5$, turn on star formation and feedback from the MBH at $z = 12$ when the halo mass is $\sim 10^9 M_\odot$ and it is resolved by 20,000 DM particles. We did not allow star formation in the halo before $z = 12$ assuming that one of its progenitors formed a MBH of $10^9 M_\odot$ via direct collapse (Latif et al. 2013, Johnson et al. 2013). We mention the consequences of such delayed star formation in the discussion section.

We employ a non-equilibrium time dependent chemical model which solves rate equations of nine primordial species H, H+, H−, He, He+, He++, H2, H3+, e−. Our chemical model is mainly based on Anninos et al. (1997) and Abel et al. (1997). It includes cooling due to the collisional excitation, collisional ionization, radiative recombination, Bremsstrahlung radiative, H2 cooling and Compton heating/cooling. In addition to primordial cooling, we also include metallicity dependent metal lines (C, N, O, Si etc) cooling from Glover & Jappsen (2007) which operates in the regime $10^4 - 10^8$ K, above $10^4$ K, the cooling function of Sutherland & Dopita (1993) is employed. We only consider metal line cooling from metals produced by Pop III stars and ignore the effect of cooling by metals produced by Pop II stars, doing so we may underestimate the stellar mass by a factor of two, for further details see Wise et al. (2012). We assume a constant H2 dissociating flux of strength $J_2 = 500$, where $J_2$ is in units of $10^{-23}$erg/cm$^2$/Hz. Our chemistry solver is coupled with the radiative transfer module MORAY to take into account heating from photoionization and secondary ionization heating (Shull & van Steenberg 1985) from X-rays emitted by a MBH.

2.1 Star formation

Our star formation criteria are primarily based on Wise & Abel (2008) and Wise et al. (2012) for Pop III and Pop II stars, respectively, which we briefly summarise here. We
model the formation of both Pop III and Pop II stars and distinguish them based on the metalliclicity of gas cloud. Pop II stars in our simulation are formed for $Z/Z_\odot > 10^{-4}$, otherwise Pop III stars form. A Pop III star particle is allowed to form when a cell has an over density of $5 \times 10^4 (10^3 \text{ cm}^{-3}$ at $z = 10$), a molecular hydrogen ($H_2$) fraction of $\geq 5 \times 10^{-4}$ and the flow is convergent ($\nabla \cdot \vec{v}_\text{gas} < 0$). Each Pop III star particle represents a single star and its mass is randomly sampled from the initial mass function (IMF) with mass range between 1-300 $M_\odot$ with the following shape,

$$f(\log M) dM = M^{-1.3} \exp \left(-\left(\frac{M}{M_{\text{char}}}\right)^{1.6}\right) dM$$

where $M_{\text{char}}$ is the characteristic mass and is set to 100 $M_\odot$. The chosen IMF behaves as a Salpeter IMF above $M_{\text{char}}$ and has an exponential cutoff below it. The Pop II star formation criterion is similar to Pop III but the requirement for minimum $H_2$ is removed as gas in the presence of metals can cool down even in the presence of a UV background. Pop III star particles are restricted to form in cells with temperature $< 1000$ K. Contrary to a Pop III star particle, a Pop II star particle represents a star cluster with a minimum mass of 1000 $M_\odot$ with a Salpeter IMF. Pop II star particles that are born with $< 1000$ $M_\odot$ continue to accrete gas until they cross this threshold. For cells meeting this criteria, 7 % of the cold gas ($T < 1000$ K) within a sphere over a dynamical timescale of about 3 Myr ($\rho_{\text{gas}} \sim 1000 \mu \text{ cm}^{-3}$) is converted into stars. Both newly forming Pop III and Pop II star particles are merged within a radius of 10 pc in a single timestep.

### 2.2 Stellar feedback

Star particles are treated as point sources of radiation, and the radiative feedback from stars is modelled using the adaptive ray tracing scheme based on HEALPix framework (Abel & Wadsley 2002, Wise & Abel 2011) which is self-consistently coupled with the hydrodynamics. Moreover, star particles emit ionising radiation with a monochromatic spectrum. The $H_2$ dissociating radiation ( LW) from radiation sources is modelled with an inverse-square profile around them, optically thin limit. The mass dependent hydrogen ionizing and LW luminosities of Pop III stars are taken from Schaerer (2002). For Pop III stars, we take a monochromatic spectrum with an energy of 29.6 eV suit- able for stars with surface temperatures of $10^4$ K, while for Pop II stars, we take a fixed spectrum of 21.6 eV appropriate for low metallicity stars (Schaerer 2003). Pop II stars emit 6000 hydrogen ionizing photons per stellar baryon for 20 Myr, or equivalently $2.4 \times 10^{47}$ photons s$^{-1} M_\odot^{-1}$.

Depending upon their mass, Pop III stars end their lives either as a supernovae (SNe) or collapse into a BH. We model SN energy and also X-ray feedback from a stellar mass black holes via ray tracing module mentioned above. Pop III stars with masses between 11-40 $M_\odot$ and 140-260 $M_\odot$ die as Type II SNe and pair-instability SNe (PISNe), respectively (Heger et al. 2003). While Pop III stars with mass between 40-140 $M_\odot$ and above 260 $M_\odot$ are expected to directly collapse into a BH (Heger & Woosley 2002, Heger et al. 2003). The typical energy for type II SNe from 11-20 $M_\odot$ stars is $10^{51}$ erg s$^{-1}$ and for 20-40 $M_\odot$ stars energy is taken from Nomoto et al. (2006) while for PISNe is $10^{51} - 10^{53}$ erg s$^{-1}$ (Heger & Woosley 2002). Pop II star clusters generate $6.8 \times 10^{48}$ erg s$^{-1} M_\odot^{-1}$ from SNe 4 Myr after their formation, which is distributed in a sphere of radius 10 pc.

### 2.3 Massive black hole feedback

We insert a massive black hole (MBH) seed of $10^5 M_\odot$ at the halo center at $z = 12$ possibly formed via direct collapse (Latif et al. 2013) and treat it as collisionless sink particle that can grow via accretion. For the spectral energy distribution (SED) of a MBH, we compute multicomponent spectrum which includes both the multi-color black body and a power law component $\propto E^{-\alpha}$ with $\alpha = 1$ Shakura & Sunyaev (1973) Sazonov et al. (2004). We model both UV and X-ray feedback from an accreting MBH by considering the energy range from 11.2 eV-1100 eV. Four energy bins at 13.6 eV, 24.6 eV, 54.4 eV and 1 keV are used when generating the photons. We treat the MBH particle as a radiation source and perform 3D radiative transfer calculations to model its radiative feedback by making use of radiative transfer module MORAY that couples it with hydrodynamics. We have extended the implementation of a radiative feedback from a MBH by adding more energy bins, originally from Kim et al. (2011). The luminosity of an accreting black hole can be estimated as:

$$L_{\text{BH}} = \epsilon_0 M_{\text{BH}} c^2$$

where $\epsilon_0$ is the radiative efficiency, assumed to be 0.1, $M_{\text{BH}}$ is the MBH accretion rate and $c$ is the speed of light. We estimate the total number of ionizing photons from MBH as $L_{\text{BH}} \times \Delta t_{\text{BH}} / E_{\text{ion}}$ where $\Delta t_{\text{BH}}$ is the radiation transport timestep and $E_{\text{ion}}$ is the average energy in the given frequency bin. These photons interact with the surrounding gas by photo-ionizing hydrogen and helium atoms, even causing secondary ionizations via suprathermal electrons, and photo-heating the gas. For a detailed description about these processes, we refer the reader to Kim et al. (2011). We model the gas accretion onto the MBH following the prescription of Kim et al. (2011) and estimate $M_{\text{BH}}$ using the Eddington limited Bondi-Hoyle equation as follows:

$$M_{\text{BH}} = \min(M_{\text{BH}, M_{\text{Edd}}}) = \min\left(\frac{4\pi G M_{\text{BH}} c^2}{\sigma_T c^2}, \frac{4\pi G M_{\text{BH}} m_p}{c^2} \epsilon_0 G \frac{m_p c^2}{E_{\text{ion}}}ight)$$

where $G$ is the gravitational constant, $M_{\text{BH}}$ the black hole mass, $\rho_B$ is the density at the Bondi radius, $c$ is the sound speed, $m_p$ is the proton mass, $\sigma_T$ is the Thomson scattering cross-section. The Bondi accretion radius is given by:

$$R_B = \frac{2GM_{\text{BH}}}{\epsilon_0 c^2}$$

A portion of gas with mass $M_{\text{BH}} M_{\text{BH}}$ inside the Bondi radius is accreted onto a MBH and is uniformly subtracted from grid cells within the Bondi sphere. The maximum resolution in our simulation is 3.6 pc, which is close to the Bondi radius for $10^5 M_\odot$ black holes sitting in T $\sim$ 8000 K gas (i.e. 8.6 pc). Therefore, the Bondi radius is resolved at most times, when the gas temperature is allowing us to probe the gas dynamics onto accreting MBH.

### 3 RESULTS

In this section we present results from a 3D cosmological radiation hydrodynamical simulation performed to explore
the growth of “normal” BHs within the first Gyr after the Big Bang. The simulated halo has a mass of $3 \times 10^{10} M_\odot$ at $z = 7.5$ and we follow its formation from $z = 14$ down to $z = 7.5$. We insert a MBH particle of $10^5 M_\odot$ at $z = 12$ when halo mass reaches $\sim 10^9 M_\odot$, well above the atomic cooling limit, and turn on radiation feedback from the MBH. The merger history of the simulated halo shows that it has gone through three major mergers (mass ratio greater than 1:2) at cosmic times of 425 Myr, 586 and 645 Myr, respectively, and many minor mergers. Our simulation does not resolve star formation in halos below $\sim 10^9 M_\odot$ at $z > 12$ and we discuss its implications in the caveats section.

### 3.1 Star formation

In our simulation Pop III stars begin to form in pristine H$_2$ clouds self-shielded from the MBH radiation, 2-3 Myr after turning on the star formation which is restricted to the main halo. They explode as supernovae within a few Myr after their formation due to high masses and enrich the interstellar medium with metals. The first Pop II star cluster forms 3 Myr after the birth of Pop III stars, immediately after SNe. Both Pop III and Pop II stars continue to form but Pop II stellar mass overtakes the Pop III stellar mass after 5 Myr. The decline in Pop III stellar mass by a factor of a few after 13 Myr is due to the death of massive stars, and it later on increases up to $10^5 M_\odot$. Pop III stars keep forming in metal free minihalos and at the same time they continue to explode as SNe. Figure 1 shows that the average Pop III stellar mass over the simulated time is $\sim 10^5 M_\odot$ while wiggles on the Pop III stellar mass plot indicate the epochs of starburst and massive SNe going off. Peaks in the Pop III stellar mass correspond to the mergers of minihalos occurring at those epochs. Star formation mainly occurs in the primary halo and remains inhibited in the surrounding halos due to the feedback from primary halo.

A large number of SNe generate massive galaxy-wide outflows and particularly these outflows are observed at 450 Myr, 497 Myr, 560 Myr and 640 Myr, where time is the age of the universe, as shown in Figure 2. SNe along with AGN feedback heat the gas above $10^4 K$ already at $z = 10$. Highly anisotropic HII regions are formed at these epochs which propagate through the interstellar medium and heat the surrounding gas. By $z = 7.5$, the HII region extends out to 20 kpc. These SNe keep enriching the halo with metals, and the Pop II stellar mass increases over time due to the efficient metal cooling, culminating in $\sim 10^9 M_\odot$ of Pop II stars by $z = 7.5$. As soon as first Pop III star goes SNe, it enriches the medium with metallicity of $10^{-2} Z_\odot$ well above the critical metallicity and a Pop III star cluster forms, see the top left panel of Figure 3. The average metallicity enhancement from Pop III stars alone is about $10^{-2} Z_\odot$ and our estimates for the metallicity from Pop III stars are shown in Figure 3. Metal enrichment is very inhomogeneous and extends beyond the virial radius. Also, pockets of metal poor (Z/Z$_\odot \leq 10^{-4}$) gas exist down to $z = 7.5$ in filaments.

The density structure inside the halo is quite clumpy and turbulent which leads to chaotic accretion, also see [Gaspari et al. (2017)](https://doi.org/10.3847/1538-4357/aa5d8f). The state of gas density at various epochs is shown in Figure 4 which depicts the occurrence of major merger between $z = 8.8$ and $z = 7.5$. The peak density is about $10^5 cm^{-3}$ while the typical gas density is about $10 – 100 cm^{-3}$. The overall density structure in the halo becomes filamentary by the end of the simulation, shown in Figure 3. The average star formation rate (SFR) in our simulations for Pop III stars is $10^{-3} M_\odot/yr$ while the average SFR for Pop II stars is a few $M_\odot/yr$ and peaks around 10 $M_\odot/yr$. The Pop II SFR falls below 1 $M_\odot/yr$ during the strong outflows of massive SNe.
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 a few times \( 10^8 - 10^{10} \, M_{\odot} \) 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
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 a low density medium. In the meantime the first Pop III 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 increased accretion onto the MBH.
start again after a few Myr. 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, it's 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 ignored 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 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 per-

![Figure 6](https://example.com/figure6.png)
form radiative transfer calculations to model the radiative feedback from both stars and the central MBH.

Recently, it was found from BLUETIDES simulations that MBH can grow up to a few times \(10^8 M_\odot\) already at \(z = 8\) in halos sitting in low tidal fields (Di Matteo et al. 2017). It should be noted that the halo mass in our simulation is a factor of ten lower compared to Di Matteo et al. (2017) but the spatial resolution is about 50 times higher. Moreover, they employed thermal feedback to model feedback from MBHs while we performed radiative transfer calculations. MBH does not grow much in our case, most likely the differences arise from the environment of the halo, its merger history and the sub-grid physics. The other works exploring the growth of MBH had a spatial resolution of about few hundred pc (Feng et al. 2014; Costa et al. 2014; Schaye et al. 2015; Feng et al. 2016) and used thermal feedback from MBH. Doing so, they may have overestimated the mass accretion onto MBH, see Negri & Volonteri (2017) for a comparison of different resolutions and consequences of variations in the implementation of thermal feedback recipes.

4 DISCUSSION AND CONCLUSIONS

We have performed a cosmological radiation hydrodynamical simulation to explore the growth of “normal” BHs in the first Gyr after the Big Bang. To accomplish this goal, we selected a halo of \(3 \times 10^{10} M_\odot\) at \(z = 7.5\). Our simulation includes both UV and X-ray feedback from an accreting BH and in-situ star formation along with their chemical, mechanical and radiative feedback. Our recipes for Pop III and Pop II star formation are based on Wise et al. (2012) and we insert a MBH of \(10^8 M_\odot\) at \(z = 12\) by turning on its feedback when halo mass reaches well above the atomic cooling limit.

- Our results show that the MBH has accreted only about 2200 \(M_\odot\) over the course of 320 Myr and the average mass accretion rate onto the MBH is a few times \(10^{-6} M_\odot/yr\).
- The stunted growth of the MBH is a consequence of large outflows driven by SNe in tandem with AGN feedback which expel the gas out of its surroundings.
- Pop III SNe quickly enrich the ISM with metals in about a few Myr.
- The average SFR during the simulation is \(~ 1 M_\odot/yr\) and SFR mainly occurs in the primary halo.

The mass accretion rate onto MBH is highly intermittent and peaks around \(10^{-4} M_\odot/yr\). Interestingly, our results are comparable to the delayed cooling case of high resolution cosmological simulation of Dubois et al. (2015) (hereafter called S15) where strong SN feedback halts the growth of MBH down to \(z = 3.5\). Their simulations have effective resolution of 8.7 pc and halo mass of \(10^{12} M_\odot\) at \(z = 2\). They employed simple thermal feedback prescription for MBH accretion (for a detailed description see S15). In our case energetic SNe from massive stars along with AGN feedback effectively heat the gas to high temperatures and yield results similar to the delayed cooling case of S15.

Pop III stars quickly enrich the medium with metals and the first Pop II star cluster formed 3 Myr after the birth of Pop III stars in our simulation. The latter have a top heavy initial mass function and thus shorter lives and are initially more effective in removing the gas from the central potential and regulating the growth of a MBH. The maximum total Pop III stellar mass in our simulation is \(~ 10^8 M_\odot\) and the average Pop III stellar mass at any given time is \(~ 10^6 M_\odot\). The Pop II stellar mass becomes greater than Pop III mass after first 5 Myr and reaches up to \(~ 10^9 M_\odot\) by the end of our simulation. The average SFR is \(~ 1 M_\odot/yr\) and peaks around 10 \(M_\odot/yr\). The MBH to stellar mass ratio is \(10^{-3}\) for the first 50 Myr and approaches \(10^{-2}\) in about 100 Myr after the beginning of simulation which is roughly consistent with the observed BH-stellar mass relation in low mass galaxies in the local universe by Reines & Volonteri (2015).

The peak bolometric luminosity from the MBH is \(~ 4 \times 10^{41} \text{erg/s}\) while the corresponding X-ray luminosity is \(~ 10^{37} \text{erg/s}\). This is about two orders of magnitude lower than the Chandra Deep Field South detection limits for an exposure of 4 Ms. The Eddington ratio is \(~ 10^{-3}\) much lower compared to the luminous quasars. This may explain why such faint sources have not been detected so far. The local analogs of these sources are low-luminosity AGNs provided that the stellar mass-BH relation holds at high redshift (Overzier et al. 2009; Jia et al. 2011; Alexandroff et al. 2012). These findings are consistent with current observations of high redshift AGN (Willott 2011; Giallongo et al. 2015; Weigel et al. 2015). We have estimated the flux from the AGN in the near infrared (NIR) band (1-2.2 micron) assuming a bolometric correction of \(~ 7\%\) in the NIR. The estimated flux is \(~ 10^{-21} \text{erg/s/cm}^2\) which is about three orders of magnitude lower than the observational limit for the James Webb Space telescope with NIRCAM for \(S/N = 10\) and integration time of 10 ks. However, SFR is about 6 orders of magnitude higher than mass accretion rate onto the MBH. Therefore it will be difficult to distinguish the AGN from the stellar population (Volonteri et al. 2017). Depending upon the line of the sight, the average column density is \(10^{20} \text{cm}^{-2}\) which is below the Compton thick limit for obscured AGN. Therefore, the simulated AGN is not Compton thick but too faint to be detected with current surveys. This may explain the paucity of AGN in high redshift Lyman Break galaxies.

In our simulation we activated star formation and their feedback at \(z = 12\) when halo mass is \(10^8 M_\odot\). Doing so, star formation was delayed as Pop III stars are expected to form in \(~ 10^8 M_\odot\) halos under moderate LW flux which is a shortcoming of our simulation. We expect that if Pop III stars were formed in the progenitor halos they would have enriched their hosts and neighboring halos with metals and led to earlier transition from Pop III to Pop II stars. Also MBH could not have formed via direct collapse due to early metal enrichment. Such prior star formation may have lowered the gas content in the halo, preheated the gas and consequently the impact of starburst may have been lower. However, we expect that role of such prior Pop III star formation to be only important during the early phases of galaxy formation.

The direct collapse BHs are expected to form in metal free halos of \(~ 10^8 M_\odot\) at \(~ z > 10\) but in our simulation we inserted MBH in \(10^8 M_\odot\) halo due to the high computational demand of the radiative transfer calculation. If we had to insert MBH into \(~ 10^8 M_\odot\) halo, we had to refine even larger region to resolve the progenitors of the halos. We also assumed here that the MBH formed in one of the progenitor halos via direct collapse which mandates that the host halo.
of $\sim 10^8 M_\odot$ was metal free and irradiated with a strong LW flux. These conditions should be assessed in future studies to explore their feasibility. In such a scenario, the impact of prior star formation would be less important as it naturally suppresses the star formation in the host halo. If the MBH was formed via accretion/merging of stellar mass black holes then the feedback from such a BH would have expelled gas from the halo and regulated the star formation in the host galaxy. Future simulations should self-consistently model the formation of MBH along with star formation to better understand their role in galaxy assembly and BH growth in the early universe.

One of the shortcomings of the present work is that cooling is considered only from metals produced by Pop III stars. Consequently, the galaxy stellar mass is expected to be lower by a factor of two compared to the metal cooling both from Pop III and Pop II stars (see Wise et al., 2012; for a detailed discussion). Furthermore, we employed the Bondi-Hoyle formalism for accretion onto the MBH which assumes spherical symmetry and is only an approximation for low resolution simulations. In reality, gas around the MBH settles in a rotationally supported disk which cannot be resolved in the present-day numerical simulations. The maximum resolution in our simulation is a few pc which is far from resolving the accretion disk and flow around the event horizon of a MBH. Recently Sugimura et al. (2017) performed 2-D radiation hydrodynamical simulations to explore the impact of an isotropic radiation feedback on BH growth. They found that radiation feedback is mainly confined to the bi-polar region while accretion still continues from the equatorial plane. This results in higher accretion rate onto the BH compared to the an isotropic case and even exceeds the Eddington value. However, other studies found that as the disk wind opening angle increases, winds kinematically get coupled with the surrounding gas and lead to an isotropic flow, see Novak et al. (2011) and Ciotti et al. (2017) for a detailed discussion. It is expected that radiative feedback may become already isotropic by the time it reaches the resolution limit (a few parsecs) of our simulation.

Due to the resolution constraints, we employed a Bondi-Hoyle prescription for MBH accretion which does not take into account the angular momentum of the gas (Debier et al., 2010; Power et al., 2010; Hopkins & Quataert, 2011), and provides only an approximate solution to the real accretion inflow, which can at times be underestimated or overestimated. When the accretion radius is close to the Bondi radius, however, the Bondi formalism provides a good estimate of the mass flux (Negri & Volonteri, 2017). In future studies, alternative approaches considering the angular momentum transport should be explored. In this study, we only considered the coupling of X-rays with primordial gas chemistry and ignored the interaction of X-rays with metals. The presence of metals can attenuate X-rays and may impact the formation of HII region as well as the growth of MBH (see Aykutalp et al., 2013).

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