Chapter 5

Black hole formation via gas-dynamical processes

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Understanding the formation of earliest supermassive black holes is a question of prime astrophysical interest. In this chapter, we focus on the formation of massive black holes via gas dynamical processes. The necessary requirement for this mechanism are large inflow rates of about 0.1 solar mass per year. We discuss how to obtain such inflow rates via an isothermal collapse in the presence of atomic hydrogen cooling, and the outcome of such a collapse from three dimensional cosmological simulations in subsection 2.2. Alternatives to an isothermal direct collapse are discussed in subsection 3 which include trace amounts of metals and/or molecular hydrogen. In the end, we briefly discuss future perspectives and potential detection of massive black hole seeds via upcoming missions.

1. Introduction

Understanding the formation of supermassive black holes remains an open and fascinating issue, as outlined in detailed reviews on this topic by Volonteri (2010); Volonteri and Bellovary (2012); Haiman (2013); Latif and Ferrara (2016). The three main pathways for the formation of supermassive black holes are: (1) stellar remnants, (2) seed black holes forming in dense stellar clusters via dynamical processes, (3) monolithic collapse of protogalactic gas cloud into a massive black hole so-called direct collapse scenario. In case of stellar remnants, the most promising pathway is likely in

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the context of massive Population III stars, as introduced in the previous chapter 4. Such a mechanism, if it was to produce the observed supermassive black holes, would certainly require a mechanism of super-Eddington accretion, as described in chapter 11, which may however also be present in other scenarios. Black hole formation via collisions in stellar clusters will be discussed in chapter 7, and the observed masses and constraints on the supermassive black hole population at high redshift are reported in chapter 12. In this chapter, the main focus will be on black hole formation via a monolithic collapse.

The idea for the formation of a massive black hole directly via the gas dynamical processes was conceived in the pioneering work of Martin Rees (Rees, 1984). The expectation is that gas in the low spin halos collapses on the viscous time scale, forms a rotationally supported compact disk which later may lead to the formation of a massive black hole (BH) (Loeb and Rasio, 1994; Eisenstein and Loeb, 1995). Similarly, models proposed in the cosmological context suggest that conditions for the formation of a massive black hole are ideal in high redshift protogalaxies with the lowest angular momentum gas (Koushiappas et al., 2004; Volonteri and Rees, 2005; Lodato and Natarajan, 2006). It is proposed that gas can rapidly loose angular momentum via ‘bars within bars’ instabilities and may lead to rapid formation of a self-gravitating core supported by gas pressure. Such a core catastrophically cools by thermal neutrino emission and contracts to potentially form a massive BH (Begelman et al., 2006). The first smoothed particle hydrodynamical simulations starting from idealised initial conditions showed that a low spin metal free halo collapses into a single clump while higher spin halo formed a binary (Bromm and Loeb, 2003).

The key requirement for this scenario is that gas should rapidly collapse by efficiently transporting angular momentum and avoiding fragmentation. The goal is to bring large inflows ($\geq 0.1$ M$_\odot$/yr, see discussion below) of gas into the halo centre within a short time scale of about $\sim 1$ Myr and rapidly build up a massive object of $10^4 - 10^6$ M$_\odot$. Such large inflow rates can be obtained thermodynamically by keeping the gas warm as the inflow rate is $\propto T^{3/2}$ and also via dynamical processes such as ‘bars within bars’ instabilities (Shlosman et al., 1989; Begelman et al., 2006) or in the aftermath of galaxy mergers (Mayer et al., 2010). Depending on the time evolution of mass inflow rates, the central object may form a supermassive star/quasi-star (details are mentioned below) or directly collapse into a massive black hole.
2. Black hole formation in primordial atomic gas

The mass inflow rate ($\dot{M}$) of collapsing gas is related to its thermodynamical properties, as $\dot{M} \sim c_s^3/G \sim 0.1 \, M_\odot/yr \left( \frac{T}{8000 \, K} \right)^{3/2}$, where $c_s$ is the sound speed and $T$ is the gas temperature. The higher the sound speed the larger the mass inflow rate. Therefore, the thermodynamical requirement for getting large inflows is that gas should not cool down to lower temperatures, otherwise it will fragment and form ordinary stars. The cooling ability of the gas strongly depends on its chemical composition. In the presence of a trace amount of dust/metals, the gas cools down to a few tens of Kelvin by radiating away its thermal energy and forming stars. Even in primordial gas, molecular hydrogen cooling can bring the gas temperature down to $\sim 200$ K and induces star formation. In the absence of molecular hydrogen, primordial gas remains in the atomic phase, cools mainly via atomic line radiation and the gas temperature remains around 8000 K. In atomic primordial gas collapse is expected to proceed isothermally with $T \sim 8000$ K and large mass inflow rates of the order of $0.1 \, M_\odot/yr$ can be achieved easily. Therefore, the conditions for forming a massive object are ideal in massive primordial halos with $T_{\text{vir}} \geq 10^4$ K cooled only via atomic lines. Such halos have masses of a few times $\geq 10^7 \, M_\odot$, formed at $z > 10$ and their gravitational potentials are sufficiently deep to allow the rapid collapse. Therefore, massive primordial halos deprived of $\text{H}_2$ cooling are the potential cradles for the formation of massive black holes.

The prerequisites for the formation of massive black holes in atomic cooling halos are that they should be metal-free and the formation of molecular hydrogen remains suppressed. In the next sub-section, we discuss in detail how to quench the molecular hydrogen formation which could be detrimental for forming massive black holes via isothermal direct collapse (DC).

2.1. Conditions to keep the gas primordial and atomic

Our understanding of structures in the cosmos is based on the hierarchical paradigm of structure formation according to which minihalos of $10^5 - 10^6 \, M_\odot$ were formed first at $z \sim 30 - 40$ which later merged to form larger halos. According to the Big Bang theory, the gas in the Universe initially has a primordial composition of predominantly hydrogen and helium. The first stars, so-called Population III stars, will then form out of a primordial gas in these minihalos. As structure formation proceeds, depending on the their mass, these stars end their lives as supernovae and pollute the ambient...
medium with metals. At earlier cosmic times, a few hundred Myrs after the Big Bang, the metal enrichment is expected to be patchy and also found from the large scale numerical simulations (Trenti et al., 2009; Maio et al., 2011; Ritter et al., 2015; Pallottini et al., 2014; Habouzit et al., 2016b). Therefore, some of the halos may remain pristine until their masses reach the atomic cooling regime (above $10^7 M_\odot$). Indeed, there is observational evidence that pockets of metal free gas can exist down to $z=7$ (Simcoe et al., 2012) and even at $z=3$ (Fumagalli et al., 2011). The estimates about the fraction of metal free halos computed from cosmological simulations including self-consistently star formation and supernova feedback suggest that about 40% of halos remain metal free down to $z=10$ (Latif et al., 2016a; Habouzit et al., 2016a), see figure 1.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Fraction of halos with metallicity below the given value in the figure legged and masses between $2 \times 10^7 - 10^8 M_\odot$. Adopted from Latif et al. (2016a), ©AAS. Reproduced with permission.}
\end{figure}
As we discuss below, due to the requirement of a strong UV flux, a DC halo may form in the surroundings of an intensely star forming galaxy. This may affect the abundance of DC halos by metal pollution from supernova winds from a nearby star forming halo (Dijkstra et al., 2014; Habouzit et al., 2016b). Even such pollution can be avoided in a synchronised pair of halos where the halo which is the radiation source forms first while a rapid collapse in the DC halo helps in avoiding the metal pollution (Visbal et al., 2014). Moreover, cosmological hydrodynamical simulations starting from first principles show that metal ejection preferentially occurs in the low density regime (Ritter et al., 2015; Pallottini et al., 2014) and neighboring halos may remain metal free. In a nutshell, metal pollution is not a bottleneck in the formation of DCBHs.

The second main constraint for DCBHs is that the formation of H$_2$ should remain suppressed in DC halos. Trace amount of H$_2$ can be formed via gas phase reactions where a residual fraction of electrons from the recombination epoch acts as a catalyst. As discussed in the previous chapter on the chemistry of the early universe, the main pathway for the formation of H$_2$ is the following:

$$\text{H} + \text{e}^- \rightarrow \text{H}^- + \gamma$$  \hspace{1cm} (1)

$$\text{H} + \text{H}^- \rightarrow \text{H}_2 + \text{e}^-.$$  \hspace{1cm} (2)

The H$_2$ can be dissociated either directly or indirectly by UV radiation depending on on the stellar spectra. The low energy photons with 0.75 eV can photo-detach H$^-$ which is the main channel for the formation of H$_2$. The photons with energy between 11.2-13.6 eV, so-called Lyman Werner (LW) photons directly photo-dissociate molecular hydrogen via the Solomon process. The dissociation processes are described by the following reactions:

$$\text{H}_2 + h\nu \rightarrow \text{H} + \text{H}$$  \hspace{1cm} (3)

$$\text{H}^- + h\nu \rightarrow \text{H} + \text{e}^-.$$  \hspace{1cm} (4)

The competition between the formation and dissociation timescales defines the critical value of UV flux (hereafter $J_{21}^{crit}$) above which the formation of H$_2$ remains quenched. Pop. III stars with $T_{rad} = 10^5$ K produce more high energy photons and are very effective in directly dissociating H$_2$ while normal stars with $T_{rad} = 10^4$ K photo-detach H$^-$. The previous studies employed idealized spectra to compute the $J_{21}^{crit}$ and found that it varies from 30-300 for $T_{rad} = 10^4$ K and 1000 for $T_{rad} = 10^5$ K (Omukai,
recent estimates of $J_{21}^{crit}$ for a realistic spectra of the first galaxies suggest that it has no single value but it depends on the stellar age, metallicity and mode of star formation (Sugimura et al., 2014; Agarwal and Khochfar, 2015; Agarwal et al., 2016a). Moreover, such spectra can be mimicked with $T_{rad} = 2 \times 10^4 - 10^5$ K. The values of $J_{21}^{crit}$ from cosmological simulations for a realistic spectra of first galaxies found that it further depends on the properties of the host halos and varies between 20,000-50,000 considering a uniform background UV flux (Latif et al., 2015) or anisotropic flux (Regan et al., 2014, 2016a). X-rays catalyse H$_2$ formation by boosting electron fraction and consequently the value of $J_{21}^{crit}$ may further get enhanced (Latif et al., 2015; Inayoshi and Tanaka, 2015; Regan et al., 2016b), see figure 2. The accurate treatment of H$_2$ self-shielding is also necessary to calculate $J_{21}^{crit}$ (Wolcott-Green et al., 2011; Hartwig et al., 2015).

Estimate of $J_{21}^{crit}$ and the fraction of metal free halos are crucial to estimate the number density of direct collapse black holes and to assess the feasibility of this scenario. A detailed assessment of its dependence on

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**Fig. 2.** Estimates of the critical value of the UV flux ($J_{21}^{crit}$) both from one zone models and 3D simulations including variations from halo to halo, dependence on the radiation spectra and the impact of X-ray ionization. Adopted from Latif et al. (2015), reproduced by permission of Oxford University Press / on behalf of the RAS.
2.2. Outcome of an isothermal collapse

In this section, we discuss the outcome of an isothermal collapse in massive primordial halos with $T_{\text{vir}} \geq 10^4$ K illuminated by a strong LW flux above the critical strength. Numerical cosmological simulations performed under these conditions confirm that the gas collapses isothermally in dark matter potentials with $T \sim 8000$ K in a self-similar way and the density profile follows an $R^{-2}$ behaviour (Bromm and Loeb, 2003; Wise et al., 2008; Regan and Haehnelt, 2009; Latif et al., 2011b, 2013a; Inayoshi et al., 2014; Becerra et al., 2015; Latif et al., 2016b). The gas continues to cool by Lyman alpha radiation and keeps collapsing. At densities of $10^8$ cm$^{-3}$, cooling due to H$^-$ comes into play and brings the gas temperature down to 5000 K (Van Borm et al., 2014; Latif et al., 2016b). Above $10^{16}$ cm$^{-3}$, the gas cloud becomes optically thick to both Lyman alpha and H$^-$ cooling, and the temperature starts to rise as shown in figure 3. The collisional ionization cooling becomes important and maintains the gas temperature close to $10^4$ K. Eventually, at densities higher than $10^{20}$ cm$^{-3}$, the gas cloud becomes completely opaque and collapses adiabatically.

Under isothermal conditions, the gas is expected to collapse monolithically without fragmentation. Previous low resolution studies employing a fixed Jeans resolution of four cells confirmed this hypothesis (Regan and Haehnelt, 2009; Latif et al., 2011b). However, recent work employing a detailed chemical model, resolving the collapse to unprecedentedly high densities of $10^{21}$ cm$^{-3}$ with a Jeans resolution of 32 cells shows that fragmentation occasionally occurs depending on the properties of host halos, but does not prevent the formation of a massive central object (Becerra et al., 2015; Latif et al., 2016b). The clumps forming due to the fragmentation on small scales quickly migrate inwards and merge with the central object (Inayoshi and Haiman, 2014; Latif and Schleicher, 2015a). Analytical models of primordial disks around the central object suggest that in the presence of large inflows and rapid rotation, viscous heating stabilises the disk and helps in the formation of a massive central object (Latif and Schleicher, 2015b; Schleicher et al., 2016). Similarly, magnetic fields amplified via the so-called small scale dynamo reach the equipartition field strength within a dynamical timescale and provide a support against gravity. Such strong fields further help in suppressing the fragmentation in atomically
Fig. 3. Spherically averaged and radially binned profiles of density, temperature, mass and mass inflow rates are depicted here. The simulated halos are metal free and illuminated by a strong LW flux above the $J_{21}^{crit}$. Consequently, $\text{H}_2$ formation remains suppressed and cooling proceeds via atomic lines. Adopted from Latif et al. (2016b), reproduced by permission of Oxford University Press / on behalf of the RAS.

One of the salient features of forming DCBHs through isothermal collapse is that large inflow rates of $0.1 - 1 \, M_\odot/\text{yr}$ are easily available, see bottom right panel of figure 3. If these inflow rates can be sustained for about one Myr then the formation of a massive object of $\sim 10^4 - 10^5 \, M_\odot$ is feasible. In fact, it has been confirmed from cosmological numerical simulations that a massive central object of $10^5 \, M_\odot$ can be formed within a Myr after the initial collapse (Latif et al., 2013c; Shlosman et al., 2016), though these simulations did not employ the feedback from a supermassive proto-star. In fact, stellar evolution calculations show that for large mass accretion rates $\dot{m}$ of $\geq 0.1 \, M_\odot/\text{yr}$, the radius of the star monotonically increases with mass because of the short accretion time compared to the Kelvin Helmholtz contraction timescale (Hosokawa et al., 2012; Schleicher et al., 2013). These stars have low surface temperatures of about 5000 K like supergiants and do not produce strong UV flux. Due to the short accretion time in comparison with the nuclear burning time, the core of such
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Fig. 4. Averaged density along the line of sight in the central 20 AU for two halos (top and bottom). The simulated halos are metal free and illuminated by a strong LW flux above the $J_{21}^\text{crit}$. Therefore, cooling proceeds via atomic lines and an isothermal collapse occurs. Adopted from Latif et al. (2016b), reproduced by permission of Oxford University Press / on behalf of the RAS.

a supermassive star may collapse into a BH provided that sufficiently large accretion rates can be retained (Begelman et al., 2008; Begelman, 2010). Such stars with a BH at their centre are called quasi-stars and it has been found that $\dot{m} > 0.14 M_\odot/\text{yr}$ is required for their formation (Schleicher et al., 2013). These supermassive/quasi-stars may collapse into a BH via general relativistic instabilities (Volonteri and Begelman, 2010; Ball et al., 2011; Johnson et al., 2014; Ferrara et al., 2014) and are the potential embryos of massive black holes forming via direct collapse. A more detailed picture on the evolution of such supermassive stars is provided in chapter 8.

Most of the previous work studying the evolution of a supermassive star used constant mass accretion rates. However, recent studies employing time dependent accretion rates show that if the time interval between to consecutive episodes of accretion ($\Delta t_{\text{acc}}$) is longer than 1000 years then star can sufficiently contract and produces strong UV flux which may halt further accretion (Sakurai et al., 2015). It is expected that accretion onto the supermassive protostar will be episodic due to the possible fragmentation of proto-stellar disk and clumps inward migration. Under isothermal conditions, $\Delta t_{\text{acc}}$ is expected to be much shorter in 1000 years (Sakurai et al.).
Therefore, intermittent accretion does not halt the formation of a potential supermassive star. As mentioned earlier, due to the requirement of a strong LW flux, the host halos of DCBHs are expected to form in the close vicinity of actively star forming galaxy and some of these DC halos get tidally disrupted by the nearby massive halos and can not host a DCBH (Chon et al., 2016). Recently, radiation hydrodynamical simulations investigating the impact of ionising radiation on the formation of DCBHs found that rich structures such as filaments and clumps between DC halo and star forming galaxy shield it from ionising photons (Chon and Latif, 2017). So, the formation of DCBHs is expected to continue under these conditions.

2.3. Outcome of collapse under less idealized conditions

Various alternatives to isothermal direct collapse mediated by a strong LW flux have been proposed. For large columns ($\geq 10^{20}$ cm$^{-2}$) of neutral hydrogen, the escape time for Lyman alpha photons becomes longer than the cloud collapse time scale. Consequently, Lyman alpha photons get trapped inside the cloud, the equation of state gets stiffened, the temperature of the gas cloud starts to increase and eventually collapse proceeds adiabatically (Spaans and Silk, 2006). However, later studies found that cooling still proceeds via 2s-1s transition and collapse becomes isothermal identical to the Lyman alpha cooling case (Schleicher et al., 2010b; Latif et al., 2011a). Similarly, large baryonic streaming motions (3 $\sigma$ fluctuations) produced prior to the epoch of recombination naturally increase the critical mass for H$_2$ cooling until it reaches the atomic cooling limit. Such motions may also collisionally dissociate H$_2$ molecules and avoid metal enrichment by suppressing in-situ star formation (Tanaka et al., 2013; Tanaka and Li, 2014). However, it was found that streaming motions are not effective in quenching H$_2$ formation and may require the ubiquity of a strong LW flux (Latif et al., 2014b).

The large inflow rates of the gas required to assemble massive back holes can be obtained dynamically via ‘bars within bars’ instabilities, and fragmentation even in metal rich gas may be suppressed via supersonic turbulence (Begelman and Shlosman, 2009). However, studies of contemporary star formation show that supersonic turbulence locally compresses the gas and induces star formation in molecular clouds (Federrath et al., 2010, 2011). During galaxy mergers, gravitational torques drive large inflows of about $10^3 - 10^4$ $M_\odot$/yr to the halo centre and form a compact
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The circumnuclear disk which later may coalesce into a massive BH (Mayer et al., 2010). The cooling timescale of such disk is very short, of the order of 100 years, and hence the resulting mass scale is still controversial (Ferrara et al., 2013). In a recent study, improving on their previous work of galaxy mergers, Mayer et al. (2015) found that the gas becomes optically thick to cooling radiation and the central stable core may directly collapse into a massive BH via general relativistic instabilities. In this scenario, the central core collapse must avoid the stellar phase otherwise it will blow away most of the mass via stellar winds as the mass loss from star is directly proportional to the metallicity of the gas.

So far, we have mainly focused on the isothermal direct collapse with emphasis on keeping the halo metal free and devoid of H$_2$. The studies of primordial star formation suggest that although the protostellar disk forming in natal primordial clouds fragments, most of the clumps migrate inward, leading to intermittent accretion and merging with the central protostar. The typical accretion rates in primordial minihalos are $10^{-2} - 10^{-4}$ M$_\odot$/yr which is about 3-4 orders of magnitudes larger than the present day star formation in molecular clouds. Moreover, the accretion rate in the bursty mode exceeds $10^{-2}$ M$_\odot$/yr, which keeps the stellar envelope bloated up and consequently the supermassive star produces weak UV feedback. Thus, even in the presence of H$_2$, massive stars up to 1000 M$_\odot$ or even higher may form (Hirano et al., 2014; Latif and Schleicher, 2015a; Hosokawa et al., 2016).

The numerical experiments exploring collapse in massive primordial halos with T$_{vir} \geq 10^4$ K irradiated by moderate strength of LW flux found that a trace amount of molecular hydrogen forms in the halo centre surrounded by warm gas with $T \sim 8000$ K. It was found that fragmentation occasionally occurs but clumps migrate inward and merge with the central star. Large inflow rates of $\sim 0.1$ M$_\odot$/yr are generated in halos which have recently gone through a major merger (Latif et al., 2014c; Latif and Volonteri, 2015). Under these conditions, the central star may reach $10^4$ M$_\odot$ within 1 Myr even if in situ star formation occurs in these halos. Estimates about the mass of the central object for various strengths of LW flux below $J_{21}^\text{crit}$ are shown in figure 5. These findings suggest that a massive central object/star of $10^3 - 10^4$ M$_\odot$ can be formed within 1 Myr after the initial collapse for moderate LW flux. Even if in situ star formation occurs, the gas flow to the central star may still continue until stars reach the main-sequence and blow away the gas. This study was performed assuming that the spectra of Pop. II stars is soft with T$_\text{rad} = 10^4$ K. However, similar
results are expected for a realistic spectra of Pop. II stars.

In the presence of a strong LW flux, star formation within the halo remains suppressed but the halo may be polluted by supernova winds from a nearby star forming galaxy. It has been found that for a trace amount of metals/dust as low as $Z = 10^{-6}Z_\odot$, where $Z$ is the metallicity of the halo and $Z_\odot$ is the solar metallicity, dust cooling becomes important at densities above $10^8 - 10^{12}$ cm$^{-3}$ and lowers the gas temperature to a few hundred K (Omukai et al. 2008; Latif et al. 2016a). For very low metallicities $\leq 10^{-5}$ and a strong LW flux, cooling remains confined to the central 10 AU and large inflows of gas are available. The density structure for two halos illuminated by a strong LW flux and polluted by a trace amount of metals are shown in figure 6. It has been found that for $Z/Z_\odot = 10^{-4}$, due to the efficient dust cooling, a filamentary structure emerges and gravitationally bound clumps form. While for $Z/Z_\odot = 10^{-5}$, the density structure remains
spherical and gravitationally unbound sub-solar clumps are observed. The clumps for the cases with $Z/Z_\odot \leq 10^{-5}$ cases may migrate inwards and merge with the central object. In the case of efficient fragmentation, a dense stellar cluster is expected to form as fragmentation occurs in the very inner part of the halo. It is expected that the run-away collisions in such a dense cluster may lead to the formation of a very massive central star which may later collapse into a massive BH of about a thousand solar masses. So, the conditions for growing a massive object in very metal poor halos with $Z \leq 10^{-5} Z_\odot$ and illuminated by a strong UV flux are still favourable (Latif et al. 2016a).

Fig. 6. Average gas density along x-axis for metallicities of $Z/Z_\odot = 10^{-6}, 10^{-5}, 10^{-4}$ and is shown for the central 4000 AU of a halo. Each row represents a halo (halo 1 on top and halo 2 on bottom) and each column represents metallicity (increasing from left to right). Adopted from Latif et al. (2016a), ©AAS. Reproduced with permission.

3. Future outlook

Despite the tremendous progress made regarding our understanding of massive black hole formation during the past decade, there are still many open questions. It is yet not clear what is the final outcome of an isothermal collapse, if it is always a supermassive star or a quasi-star or a direct massive black hole. The final result depends on the long term sustainability of the mass accretion rates and the amount of angular momentum retained during the end stages of gravitational collapse. Both of these quantities
remain uncertain and are not fully comprehended due to the numerical constraints. In the future, numerical simulations starting from ab initio initial conditions should be performed to assess the feasibility of both parameters and to determine the ultimate fate of direct collapse. Similarly, stellar evolution calculations of supermassive proto-star formation ignored the role of rotation which may impede the collapse and may shut further mass accretion.

Some studies suggest that rapid accretion may launch strong winds leading to large mass loss (Dotan et al., 2011; Fiacconi and Rossi, 2016). Also, preliminary work exploring the role of rotation during the quasi-stellar phase indicates that the quasi-stellar phase may be skipped for objects massive than $10^5 \, M_\odot$ (Fiacconi and Rossi, 2017). However, detailed three-dimensional radiation hydrodynamical computations are necessary to support/reject this finding. The dynamical ways to obtain large inflow rates look promising, but it is not completely clear whether such inflows can be maintained down to AU scales. Also, whether metal-enriched gas remains optically thick or radiates away thermal energy to form stars remains to be determined. Detailed investigations exploring this channel will thus be necessary.

One of the biggest uncertainty in assessing the feasibility of direct collapse black holes is their number density which sensitively depends on the value of $J_{21}^{\text{crit}}$. The variation in $J_{21}^{\text{crit}}$ by a factor of a few changes the abundance of direct collapse black holes by an order of magnitude or even larger. Our current understanding suggests that values of $J_{21}^{\text{crit}}$ vary by orders of magnitude and may also change with the age of stars and metallicity. In the future, more realistic estimates of $J_{21}^{\text{crit}}$ are required from 3D radiation hydrodynamical simulations by properly modelling the SED of the source galaxy for different modes of star formation, as also discussed in chapter 6.

Observational evidence is necessary to constrain these models of black hole formation. The first observations of CR7, the brightest Lyman alpha emitter at $z=6.6$, revealed that it shows strong Lyman alpha and He-1640 \AA emission and no signatures of metal lines were observed (Sobral et al., 2015). The drivers of strong Lyman alpha and He-1640\AA can be either a cluster of primordial stars with $10^7 \, M_\odot$ or a direct collapse black hole of $10^6 - 10^7 \, M_\odot$. However, due to the metal enrichment forming such a young massive cluster of primordial stars at redshifts as low as $z=6$ seems infeasible and a black hole of $10^6 \, M_\odot$ possibly forming via DC is more likely source of CR7 (Pallottini et al., 2015; Hartwig et al., 2016; Agarwal et al., 2016; Dijkstra et al., 2016; Smidt et al., 2016; Smith et al., 2016).
The recent deep observations of CR7 show doubly ionized oxygen (O III) emission (Bowler et al., 2017) but the current photometry is still consistent with a mild amount of pollution DCBH site with metals (Hartwig et al., 2016; Pacucci et al., 2015; Agarwal et al., 2017). It is expected that JWST will be able to directly probe the observational signatures of DCBHs in high redshift galaxies.

The future X-ray space observatory ATHENA is expected to detect a few hundred low luminosity active galactic nuclei (AGN) in the early universe with X-ray luminosities of $L_X \geq 10^{43}$ erg/s. These observations will provide direct constraints on the masses and luminosity functions of the first AGN. Also future 21 cm experiments such as SKA and LOFAR will probe the proximity zones of high redshift quasars and help in better understanding their formation and growth mechanisms (Whalen et al., 2017). In the local universe the deep observation of dwarf galaxies may help in tracing the seed BHs forming at high redshift (Reines and Comastri, 2016). The recent detections of BH-BH mergers with LIGO have opened a new window of gravitational waves astronomy and the upcoming European space mission eLISA will be able to detect the merging of massive black holes and help in understanding their formation mechanisms.

In the next chapters, we will clarify uncertainties in the value of $J_{21}^{\text{crit}}$ (chapter 6), which is crucial to quantify the expected number of black holes. Black hole formation through mergers in stellar clusters will then be explored in chapter 7, and the evolution of supermassive stars is described in chapter 8. The growth of seed black holes, potentially forming from the first stars, will be discussed in chapters 10 and 11. Statistical predictions will be provided in chapter 9. A comparison with current observations of high-redshift quasars is given in chapter 12, while predictions on gravitational wave emission are provided in chapter 13, and expectations for future observations are outlined in chapter 14.

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