Population III Star Formation in an X-ray background: I. Critical Halo Mass of Formation and Total Mass in Stars

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ABSTRACT

The first luminous objects forming in the universe produce radiation backgrounds in the FUV and X-ray bands that affect the formation of Population III stars. Using a grid of cosmological hydrodynamics zoom-in simulations, we explore the impact of the Lyman-Warner (LW) and X-ray radiation backgrounds on the critical dark matter halo mass for Population III star formation and the total mass in stars per halo. We find that the LW radiation background lowers the H$_2$ fraction and delays the formation of the Population III stars. On the other hand, X-ray irradiation anticipates the redshift of collapse and reduces the critical halo mass, unless the X-ray background is too strong and gas heating shuts down gas collapse into the halos and prevents star formation. Therefore, an X-ray background can increase the number of dark matter halos forming Population III stars by about a factor of ten, but the total mass in stars forming in each halo is reduced. This is because X-ray radiation increases the molecular fraction and lowers the minimum temperature of the collapsing gas (or equivalently the mass of the quasi-hydrostatic core) and therefore slows down the accretion of the gas onto the central protostar.

Key words: stars: formation – stars: Population III

1 INTRODUCTION

The first stars (or Pop III stars) have an important role for the formation of the first galaxies and black holes. They produce the heavy elements required for the formation of the second-generation stars (Greif et al. 2010; Abe et al. 2021), but their formation rate is uncertain because it is self-regulated by complex chemical and radiative feedback loops (Ricotti et al. 2002b; Wise & Abel 2008). For instance, the radiation backgrounds they produce affect their formation rate on cosmological scales (Ricotti 2016, hearer R16). There has been significant progress in detecting high-z galaxies (e.g. Bouwens et al. 2019), but our understanding of their formation is still limited to the brightest galaxies at redshifts below $z \approx 6 - 10$. With James Webb Space Telescope (JWST), however, we will be able to look further and learn more on the formation processes of the first objects. For this reason, a better understanding of the formation of Pop III star and their impact on second-generation stars is timely. The formation of the first intermediate mass black hole (IMBHs) remnants of Pop III stars is also poorly understood because regulated by similar feedback processes as Pop III stars (Regan et al. 2020), but the IMBHs census can now be better constrained by the LIGO (Abbott et al. 2016) gravitational wave detectors.

The first Pop III stars form in dark matter (DM) haloes of $\sim 10^6$ M$_\odot$ (called minihaloes) at $z \approx 30$ (Tegmark et al. 1997). In the early Universe, there are no heavy elements that can cool the gas in virialized minihaloes with $T_{\text{vir}} \lesssim 10^4$ K (corresponding roughly to minihalo masses $< 10^8$ M$_\odot$). Therefore, the formation of Pop III stars relies on molecular hydrogen (H$_2$) formation via the H$^-$ catalyst. This implies that the radiation regulating the amount of H$_2$ is crucial to their formation. For instance, FUV radiation in the Lyman-Werner bands (LW, $11.2 - 13.6$ eV) emitted by Pop III stars dissociates H$_2$ (Omukai 2001), suppressing gas cooling in minihaloes. The mean free path of LW radiation in the intergalactic medium (IGM) is roughly ~ 150 times smaller than the particle horizon (Ricotti et al. 2001, R16), and much greater than the mean free path of ionizing UV radiation ($\gtrsim 13.6$ eV). Therefore, LW photons can travel far and build a radiation background that dominates the radiation from local sources, and it is able to delay or suppress the formation of Pop III stars (Haiman et al. 2000; Regan et al. 2020). Another radiation background that affects the H$_2$ fraction is the X-ray radiation ($\gtrsim 0.2$ keV, Venkatesan et al. 2001; Xu et al. 2016). The IGM is relatively transparent to photons in this energy range. An X-ray radiation background partially ionizes the pristine gas and increases the amount of H$_2$ that forms via H + H$^-$ $\rightarrow$ H$_2$ + e$^-$. In the early Universe, high-mass X-ray binaries (HMXBs), accreting IMBHs, or supernova/hypernova explosions of Pop III stars are possible sources of an X-ray radiation background (Jeon et al. 2014; Xu et al. 2016, R16).

The role of the X-ray background in regulating the formation of Pop III stars is still debated. Using zoom-in simulations, Jeon et al.
Figure 1. Snapshots of the gas density in Halo 1, Halo 1 and Halo 3 (columns from left to right, respectively) for the case without radiation backgrounds. Each row shows the gas density at three different scales (see label on the left).

(2014) studied the effect of X-ray radiation emitted by local sources and found negligible effects on the Pop III star formation rate. On the other hand, through a self-consistent modelling of sources and the background they produce on IGM scales, R16 found that X-ray emission from the first sources has a positive-feedback on the number of Pop III stars because of the enhanced \( \text{H}_2 \) formation and cooling. However, when the mean X-ray emission per source is above a critical value, the number of Pop III stars per comoving volume is reduced because X-ray heating of the IGM becomes the dominant feedback effect. At the critical X-ray luminosity per source, the number of Pop III stars per comoving \( \text{Mpc}/h^3 \) at \( z \approx 15 \) is \( \sim 400 \), that is far larger than \( \sim 10 \) Pop III stars found in the same volume without X-rays (i.e., with only LW radiation background). The limit of this model is that it considers global feedback loops but neglects local feedback effects and galaxy-scale gas dynamics.

The initial mass function (IMF) of Pop III stars is also an important open question in Pop III star formation theory, and has been studied numerically by many authors (Hirano et al. 2014; Susa et al. 2014; Stacy et al. 2016). Using a number of radiative hydrodynamics (RHD) simulations, Hirano et al. (2014) and Hirano et al. (2015, hereafter HR15) explored the final masses of Pop III stars, taking into account photodissociation of \( \text{H}_2 \) by LW background, but neglecting the effect of X-ray radiation. Simulating a large sample of minihaloes, they found correlations between the final mass of Pop III stars and properties of gas cloud or host halo, such as the gas accretion rate. Hummel et al. (2015, hereafter HM15) explored the role of an X-ray background in determining the number of Pop III stars and their final masses.

In this work, the first in a series, we investigate how the X-ray and LW radiation backgrounds affect the formation of Pop III stars using a set of zoom-in cosmological simulations of minihaloes. First, we study the impact of the backgrounds on the redshift of collapse and therefore the critical mass of the dark matter minihalo when Pop III stars form. This is tightly related to the number of Pop III stars and pair-instability supernovae (PISNs) that will be able to be detected with JWST and the Nancy Grace Roman space telescope (Whalen et al. 2014). Furthermore, we explore how the total mass in Pop III stars depends on the intensity of the radiation backgrounds. In a companion paper (Park et al. 2021, hereafter Paper II), we study the effect of X-ray irradiation on the properties and fragmentation of protostellar discs, the multiplicity, mass function and separation of Pop III stars.

The paper is organized as follows. In Section 2 we introduce our simulations and methods. In Section 3 and 4 we discuss how
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2 SIMULATIONS

We use the RHD RAMSES-RT cosmological code (Rosdahl et al. 2013). Its original version RAMSES (Teyssier 2002) is an N-body + hydrodynamic code using an adaptive mesh refinement (AMR) technique. In order to simulate the growth of haloes, gas collapse and development of discs from cosmological initial conditions, we perform zoom-in simulations. First, we run two DM-only simulations of 1 and 2 Mpc/h^3 boxes. We select two haloes (Halo 1 and Halo 3) from the 1 Mpc/h^3 box and one halo (Halo 2) from the other. Halo 1 is at the centre of a group while Halo 2 and Halo 3 are in sparsely populated regions.

Inside each zoom-in region, the mass of DM particles is ~ 800 M⊙. The cells within the zoom regions are refined if they contain at least 8 DM particles or if their Jeans lengths are not resolved with at least N_J cells. For the latter condition, a widely adopted value is N_J = 4 (Truelove et al. 1997), but we adopt the value of N_J adaptively. At small-scales where the circumstellar disc fragments and star forms (cell size smaller than ~ 1 pc/h, comoving), we adopt N_J = 16 in order to prevent any possible artificial fragmentation and better resolve possible turbulent motions. If the size of a cell is greater than ~ 30 pc/h (comoving), we adopt N_J = 4 to save computational time. Any cells between these two scales are refined with N_J = 8. The size of a smallest cell is 0.00375 pc/h (comoving). At z=20, this corresponds to a physical size of 2.63 × 10^-3 pc (or 54 au). The corresponding AMR levels are shown in Table 1. The initial conditions of the DM-only and zoom-in simulations are generated with MUSIC (Hahn & Abel 2011). The assumed cosmological parameters are h = 0.674, Ω_M = 0.315, Ω_b = 0.685, Ω_b = 0.0493, σ_8 = 0.811 and n_s = 0.965 (Planck Collaboration 2018).

| M_{DM} (zoom-in) | M_{DM} (z=15.7) | Box size | l_{max} |
|------------------|------------------|----------|---------|
| Halo 1 7.9 × 10^6 M⊙ | 800 M⊙ | 1 Mpc/h^3 | 28 |
| Halo 2 4.4 × 10^6 M⊙ | 800 M⊙ | 2 Mpc/h^3 | 29 |
| Halo 3 7.0 × 10^5 M⊙ | 800 M⊙ | 1 Mpc/h^3 | 28 |

Table 1. Summary of the simulations.

Snapshots of the haloes are presented in Figure 1 and a summary of the three simulations is given in Table 1. In Figure 2 we plot the virial masses of the haloes as a function of redshift. Halo 1 is more massive than the other two, and its mass reaches ~ 2.4 × 10^7 M⊙ at z ~ 15. Halo 2 and Halo 3 end up being haloes of ~ 7 × 10^6 and 2 × 10^6 M⊙ at z ~ 10. In a strong LW radiation background the collapse of the gas is delayed to when the mass of the minihalo is ≥ 10^5 M⊙ close to the critical mass at which Ly α cooling becomes dominant and approaching a regime thought to be the main formation channel of direct-collapse-black holes (Regan et al. 2020). Excluding this extreme case, the formation of Pop III stars in our simulations occurs when the masses of the minihaloes are between 10^5 M⊙ to ~ 2 × 10^6 M⊙. In this range of the masses of the three haloes grow in different ways. Halo 1 grows rapidly between redshift z ~ 30 to z ~ 22 and Pop III star formation happens during this time. Halo 3 also grows rapidly from z ~ 19 to z ~ 17 and the redshift of star formation in many simulations fall in this range. On the other hand, the mass of Halo 2 increases slowly, by a factor of two from z ~ 25 and 20, and most of the star formation happens during this time.

2.1 Chemistry

RAMSES-RT incorporates the chemistry of hydrogen/helium ions and molecular hydrogen. In this study, the formation and destruction of H_2 are treated following Katz et al. (2017) with some modifications. Our revised model is accurate up to gas densities n_H ± 10^12 H cm^-3. Improvements and validation of the primordial chemistry/cooling model with respect to the original RAMSES version are shown in Appendix A. The H_2 formation rate is,

\[ \frac{dN_{H_2}}{dt} = -C_{coll} x_{H_2} - k_{photo} x_{H_2} + R n_{H_2}. \]  

where x_{H_2} is the H_2 fraction, n_{H_2} is the H I number density, C_{coll} is the collisional dissociation rate, k_{photo} is the photodissociation rate and R is the production rate. The term C_{coll} is the sum of the collisional dissociation rates of H_2 colliding with H, H_2, e^-, He and H^+ (Glover & Abel 2008; Glover et al. 2010). Its definition is

\[ C_{coll} = \sum_{i} k_{coll,i} n_i \]  

where i means one of five chemical species (H, He, e^-, H^+ and H_2). The term k_{coll,i} is the collisional dissociation rate for species i and n_i is its number density. The photodissociation rate is,

\[ k_{photo} = 4\pi \int_{13.6 eV}^{11.2 eV} \frac{J_\nu}{h \nu} \frac{1}{P_{H_2}} d\nu. \]
\[ h \sigma_{\text{LW}} = 2.47 \times 10^{-18} f_{\text{shd}} \text{ cm}^2, \]

where \( f_{\text{shd}} \) is the shielding factor. To compute \( f_{\text{shd}} \), we adopt the formula in Wolcott-Green & Haiman (2019):

\[
f_{\text{shd}} = \frac{0.965}{(1 + x/b_2)^{\alpha(n,T)}} + \frac{0.035}{(1 + x)^{0.5}} \times \exp \left[ -8.5 \times 10^{-4} (1 + x)^{0.5} \right],
\]

where

\[
\alpha(n,T) = A_1 \times \exp \left( -0.2856 \times \log(n/cm^3) \right) + A_2(T),
\]

\[
A_1(T) = 0.8711 \times \log(T/K) - 1.928,
\]

\[
A_2(T) = -0.9639 \times \log(T/K) + 3.892.
\]

Here, \( x \equiv N_{\text{HI}}/5 \times 10^{14} \text{ cm}^{-2} \), where \( N_{\text{HI}} \) is the H\(_2\) column density. One difference with respect to the formula in Gnedin et al. (2009) is the doppler broadening factor \( b_2 = b_1/10^5 \text{ cm s}^{-1} \). For each cell, the value of \( b_2 \) is computed with \( b_2 = (b_2^{\text{turb}} + b_2^{\text{thermal}})^{1/2} \), where \( b_2^{\text{turb}} = 7.1 \times 10^2 \text{ cm s}^{-1} \) is the turbulent broadening factor (Krumholz 2012) and \( b_2^{\text{thermal}} = (2k_B T/m_{\text{HI}})^{1/2} \) is the thermal broadening factor (Richings et al. 2014). For the latter, \( m_{\text{HI}} \) is the mass of an H\(_2\) molecule, \( T \) is the temperature of the cell, and \( k_B \) is the Boltzmann constant.

The rate of production of H\(_2\) is,

\[
R = \frac{k_1 k_2 x_e}{k_2 + k_5 x_{\text{HII}} + k_{13} x_e} + \left( R_{3,1} n_{\text{HII}} x_{\text{HII}} + R_{3,2} n_{\text{HII}} x_{\text{HII}} \right),
\]

where \( x_{\text{HII}} \) is the ionized H\(_2\) fraction, \( x_e \) is the electron fraction, and \( n_{\text{HII}} \) is the H\(_2\) number density. The term on the right-hand side of the equation is the production rate through the H\(^{-}\) channel. In this work, contrary to the other schemes, we do not track the out-of-equilibrium H\(^{-}\) abundance, instead we calculate the equilibrium value using the four reaction rates of H\(^{-}\) formation from \( k_1, k_2, k_5 \) and \( k_{13} \) from Glover et al. (2010)\) as in Katz et al. (2017). At densities higher than \( 10^8 \text{ cm}^{-3} \), the three-body interaction (the second term in equation 7) is the dominant channel of H\(_2\) formation. \( R_{3,1} \) is the production rate from the reaction H\(_{-}\) \( \longrightarrow \) H\(_2\) + H (Forrey 2013) and \( R_{3,2} \) is that from 2 H\(_{-}\) \( \longrightarrow \) 2 H\(_2\) (Palla et al. 1983).

We make use of the results of Glover & Abel (2008) and Glover (2015) to calculate the gas cooling rate due to the collisions of H\(_2\) with H, H\(_2\), e\(^-\), He and H\(^+\). The low-density limit follows equation (37) and Table 8 of Glover & Abel (2008) and we adopt equation (30) of Glover (2015) to calculate the LTE limit. The rate of cooling by H\(_2\) is,

\[
\Lambda_{\text{H}_2} = \frac{\Lambda_{\text{H}_2, \text{LTE}}}{1 + \Lambda_{\text{H}_2, \text{LTE}}/\Lambda_{\text{H}_2, n \rightarrow 0}},
\]

where \( \Lambda_{\text{H}_2, \text{LTE}} \) is the LTE limit and \( \Lambda_{\text{H}_2, n \rightarrow 0} \) is the low density limit.

At high-density, H\(_2\) line emission is trapped by the optically thick gas, so the cooling rate is affected by the escape probability of the radiation. The cooling rate is multiplied by the following factor.

\[
\xi_{\text{esc}} = \frac{1}{(1 + N_{\text{H}_2}/N_e)^{\alpha}}.
\]

The equation and parameters \((N_e, \alpha)\) are defined in Fukushima et al. (2018).
while in a highly ionized gas, photo-electrons collide with other photo-electrons collide with neutral hydrogen and ionize the gas, This can be understood as in a neutral gas (low increasing when the gas is almost neutral and its value converges to zero with increasing a neutral gas (close to 0.1) and converges to 1 with increasing .

The secondary ionization fraction is the photo-electron ionization is photo-ionization rate ( follows Shull & van Steenberg (1985) and Ricotti et al. (2002a). The ionization rate of species is:

\[
\frac{dx_i}{dt} = x_i \zeta_i + \sum_{j \neq i} f_{\text{ion},j} \zeta_j \langle \Phi(E_i^0, x_e) \rangle,
\]

(10)

where \( f_{\text{ion},i} \) is the secondary ionization fraction of species \( i \), \( E_i^0 = h\nu - I_i \) is the photo-electron energy and \( \langle \Phi(E_i^0, x_e) \rangle \) is the average number of secondary ionization per primary electron of species \( j \) (see Ricotti et al. 2002a). \( I_i \) is the ionization potential and \( \zeta_i \) is the photo-ionization rate

\[
\zeta_i = 4\pi \int_{h\nu}^{\infty} \frac{J_\nu}{h\nu} \sigma_i d\nu,
\]

(11)

where \( \sigma_i \) is the ionization cross-section of \( i \) (Verner et al. 1996). The rate of heating due to species \( i \) is

\[
\frac{de}{dt} = 4\pi \int_{h\nu}^{\infty} \frac{J_\nu}{h\nu} \sigma_i E_b \langle E_i^0, x_e \rangle d\nu,
\]

(12)

where \( e \) is the internal energy. A fraction of the energy of photo-electrons is used to ionize the gas and therefore the heating of the gas is less efficient (Ricotti et al. 2002a). This effect is considered with the factor \( E_b \langle E_i^0, x_e \rangle \). The photoheating rate neglecting secondary photo-electron ionization is

\[
\Gamma_i = 4\pi \int_{h\nu}^{\infty} \frac{J_\nu}{h\nu} (h\nu - I_i) \sigma_i d\nu.
\]

(13)

The secondary ionization fraction \( f_{\text{ion},i} \) is large (e.g. \( f_{\text{ion},\text{H I}} \sim 17.3 \)) when the gas is almost neutral and its value converges to zero with increasing \( x_e \). On the contrary, the heating fraction \( f_{\text{heat},i} \) is low in a neutral gas (close to 0.1) and converges to 1 with increasing \( x_e \). This can be understood as in a neutral gas (low \( x_e \)), most of the photo-electrons collide with neutral hydrogen and ionize the gas, while in a highly ionized gas, photo-electrons collide with other electrons and thermalize.

2.3 Tracking Clumps

We impose that the Jeans length is resolved with at least \( N_J = 16 \) cells up to the maximum AMR level near the halo centre. Once the maximum level is reached, however, we cannot refine them further. In order to prevent artificial fragmentation at the maximum refinement level caused by a decreasing Jeans length, we suppress the cooling of cells with the maximum refinement level following the method in Hosokawa et al. (2016). This is done by multiplying the cooling function by the factor

\[
C_{\text{limit}} = \exp \left[ -\left( \frac{\xi - 1}{0.1} \right)^2 \right] \quad \text{(if } \xi > 1),
\]

(14)

where \( \xi = f_{\text{limit}}(\Delta x/\lambda_J) \) with the cell size \( \Delta x \) and Jeans length \( \lambda_J \). We assume \( f_{\text{limit}} = 12 \) as in Hosokawa et al. (2016).

To investigate the growths of protostars and the initial mass function, many studies employ sink particles/cells and calculate the gas accretion onto and radiative feedback from them (e.g. HR15; S20). In this study, we do not use sink particles, hence we neglect accretion and feedback physics associated with them. Our goal is to perform many simulations for various radiation backgrounds to capture the effects of X-rays on the collapse and fragmentation. Instead of using sink particles, we flag cells with \( C_{\text{limit}} < 10^{-4} \) in each run. Using a friends-of-friends algorithm, we link neighboring cells together to identify dense clumps. Each clump represents a quasi-hydrostatic core that would collapse to form a star if we did not impose limitations to cooling rate and the resolution. Throughout this article, we use each clump as a proxy for a single Pop III star.

3 RESULTS: I. CRITICAL MINIHALO MASS FOR POP III FORMATION

In a gas of primordial composition, formation of \( \text{H}_2 \) is inefficient in minihaloes below a critical mass due to the low electron fraction produced by collisional ionization during virialization (Tegmark et al.
However, pristine gas can cool more efficiently, even in small mass minihaloes, if an X-ray radiation background enhances the electron fraction. Figure 4 demonstrates the effectiveness of the X-ray background in promoting Pop III star formation. When the halo is irradiated by a constant (as a function of time) LW background (top panels), the maximum gas density in the minihalo at redshift \( z = 22.6 \) is below \( 10^5 \) H cm\(^{-3} \), and the gas collapses to form a dense core at \( z \approx 16.5 \), when the mass of the minihalo is \( 1.6 \times 10^6 \) M\(_\odot\). If the halo is exposed to the same LW background but also an X-ray background (bottom panels), the gas at the halo centre cools more efficiently (the right panels show the temperature) thanks to the enhanced H\(_2\) fraction (see the third panel from the left). The cooling enables the formation of a dense core at \( z = 22.6 \), when the halo mass is \( 1.5 \times 10^5 \) M\(_\odot\), a critical mass about ten times lower than the case without X-ray irradiation.

To quantify the effect of the X-ray background we define the critical mass as the mass of a minihalo at the redshift when the Pop III star forms. To this end, we define the parameter \( z_a \), that is the redshift at which the central gas density reaches \( 10^6 \) H cm\(^{-3} \). For example, if the central gas density reaches \( 10^5 \) H cm\(^{-3} \) at \( z = 25 \) and \( 10^6 \) H cm\(^{-3} \) at \( z = 23, z_1 = 25 \) and \( z_8 = 23 \), respectively. In this section, we assume that Pop III stars form at \( z_{10} \). From the time of formation of the protostellar core, it takes roughly \( 10^4 - 10^5 \) years for feedback to halt gas accretion and reach the final Pop III star mass (S20). This time-scale is much shorter than the typical variations of the formation time caused by different intensities of the LW or X-ray radiation backgrounds. The later phases of evolution of the gas (\( n_H > 10^{10} \) H cm\(^{-3} \)), when a protostellar disc is formed, are discussed later in Sections 4 and Paper II.

The three panels in Figure 5 show \( z_1, z_3 \) and \( z_{10} \), respectively, for Halo 1 for the \( 7 \times 7 \) grid of radiation backgrounds. The middle and right panels are nearly identical, meaning that once the gas reaches a density above \( 10^5 \) H cm\(^{-3} \), for the range of backgrounds considered here, the collapse cannot be halted and proceeds rapidly to densities \( \sim 10^{10} \) H cm\(^{-3} \). The panel on the left shows that the gas density reaches \( 10^1 \) H cm\(^{-3} \) by \( z \approx 24 \) for any value of the LW background, unless the X-ray intensity is larger than \( J_{\text{X},21} > 10^{-3} \) and \( J_{\text{LW},21} > 10 \). This is because the core gas density of Halo 1 at virialization is \( \sim 10^3 \) H cm\(^{-3} \) even without any core contraction due to gas cooling (see Ricotti 2009, for the calculation of the core gas density assuming an isothermal equation of state and \( T \approx T_{\text{vir}} \)). Therefore \( z_1 \) is always reached by Halo1 unless the X-ray background is strong enough (\( J_{\text{X},21} > 10^{-3} \)) to heat the IGM to \( T_{\text{IGM}} > T_{\text{vir}} \) and cooling from H\(_2\) formation (that is increased by X-ray photo-ionization) does not offset significantly the X-ray heating (\( J_{\text{LW},21} > 10 \)).

Let’s now focus on the right panel, showing the redshift of Pop III star formation. In a zero background (the bottom left corner), the Pop III star forms at \( z \approx 24 \) when the halo mass is \( 7 \times 10^5 \) M\(_\odot\), increasing the LW background intensity to \( J_{\text{LW},21} \approx 10 \) delays Pop III formation to \( z \approx 14 \) when the halo mass exceeds \( 2 \times 10^7 \) M\(_\odot\) (label A). The figure also shows that \( z_{10} \) increases, and the critical mass decreases, with increasing X-ray intensity. This is consistent with HM15 that also find earlier onset of gas collapse in an X-ray background. We find that the X-ray background is particularly effective in offsetting the negative feedback effect of a strong LW background. In a weak X-ray background, LW intensity \( J_{\text{LW},21} \approx 10 \) delays the formation of Pop III stars to \( z \approx 14 \) (label A in the figure), but if an X-ray background \( J_{\text{X},21} \approx 10^{-3} \) is present, the central gas can collapse to form Pop III stars at \( z \approx 22 \) (label B) when the mass of the halo is below \( 1.8 \times 10^8 \) M\(_\odot\). Compared to \( 2 \times 10^7 \) M\(_\odot\) at \( z \approx 14 \), this is a reduction of the critical mass by one order of magnitude. In a cosmological context, a reduction of the critical mass by an order of magnitude implies that the number of minihaloes that are able to form Pop III stars will increase by roughly the same factor. As a side note, Regan et al. (2020) found that LW radiation backgrounds with \( J_{\text{LW},21} \approx 0.1 \) – 10 suppresses the formation of Pop III stars and allows direct-collapse-black holes to form in atomic cooling haloes (with mass > \( 10^8 \) M\(_\odot\)).
results suggest that a strong X-ray background may offset this effect enabling Pop III star formation even in a strong LW background.

Figure 6 shows the same results as Figure 5, but for Halo 2 and Halo 3, respectively. At all redshifts, Halo 2 is smaller in mass than Halo 1, and Halo 3 is the smallest halo (see Figure 2). The results for these two haloes are qualitatively similar to Halo 1, with some quantitative differences explained below. For these smaller mass haloes, when both the LW and X-ray intensity are large, the gas density fails to reach $10^9 \text{H cm}^{-3}$ (label A in the figure). This is because, due to their lower masses and virial temperatures, the core densities of these haloes at virialization are $< 10^9 \text{H cm}^{-3}$, hence sufficiently rapid cooling is necessary to reach that density. A
The reduced critical mass of Pop III stars in Halo 2 compared to Halo 3 is due to the absence of X-ray irradiation. In Halo 1, significant delay of Pop III star formation occurs due to high LW radiation. In all the haloes, the reduction of the critical minihalo mass produced by an increasing X-ray background is largest in an intense LW background. The suppression of cool, dense gas by X-rays becomes more pronounced: in Halo 2, the critical mass is lower by more than a factor of 10 for Halo 3. In Halo 3, a strong LW background, Pop III stars fail to form before $z \approx 13$ ($z \approx 10$) for Halo 2. The positive feedback by an X-ray background is also observed in Halo 2 and Halo 3. Without any LW or X-ray radiation backgrounds, the critical mass is about $10^{6}$ $M_{\odot}$ (location B). In a strong X-ray background ($J_{\text{X},21} = 10^{-3}$, location C), the critical mass decreases to $9.5 \times 10^{5}$ $M_{\odot}$ (while it decreases by a factor of $3$ for Halo 3). When LW radiation is stronger ($J_{\text{X},21} \sim 0.1$), the effect of X-rays becomes more pronounced: in Halo 3 Pop III star does not form without X-ray irradiation (location G) and in Halo 2 the critical mass is $1.6 \times 10^{6}$ $M_{\odot}$ ($z_{10} = 16.50$, location D). Adding X-ray radiation (location E and H), the critical mass is lower by more than a factor of 10 for Halo 2 ($1.2 \times 10^{5}$ $M_{\odot}$, $z_{10} = 23.11$) and is about $3.0 \times 10^{5} - 10^{6}$ $M_{\odot}$ for Halo 3.

If the X-ray intensity increases further, however, the heating of the IGM becomes the dominant feedback mechanism, suppressing the formation of Pop III stars as in the analytic models of R16. Increasing the X-ray intensity by a factor of 10 (location F) suppresses gas collapse and Pop III star formation does not occur until $z = 12.60$ when the halo mass is $6.6 \times 10^{6}$ $M_{\odot}$. If $J_{\text{X},21} = 0.1$, the heating by a radiation background shuts down gas collapse completely and the formation of a Pop III star is suppressed until $z = 10$.

In all the haloes, the reduction of the critical minihalo mass produced by an increasing X-ray background is largest in an intense LW background. The collapse of gas to higher densities (from $a = 3$ to 10) follows the same trend as that of Halo 1. An increase in the LW intensity suppresses the formation of H$_2$ and delays Pop III star formation. Compared to Halo 1, however, significant delay of Pop III star formation occurs for a weaker LW radiation background. In fact, $z_{10}$ of Halo 1 decreases dramatically between $J_{\text{LW},21} = 1$ and 10 while this occurs between $J_{\text{X},21} = 0.1$ and 1 and for Halo 2 and $J_{\text{LW},21} = 0.01$ and 0.1 for Halo 3. In a strong LW background, Pop III stars fail to form before $z \approx 13$ ($z \approx 10$) for Halo 2.

The Schematic diagram shows the region on the grid where the formation of Pop III stars is allowed. The left panel shows the formation of Pop III stars in Halo 2 (Halo 3) and the critical mass decreases to $10^{6}$ $M_{\odot}$ (location B). In a strong X-ray background ($J_{\text{X},21} = 10^{-3}$, location C), the critical mass decreases to $9.5 \times 10^{5}$ $M_{\odot}$ (while it decreases by a factor of $3$ for Halo 3). When LW radiation is stronger ($J_{\text{X},21} \sim 0.1$), the effect of X-rays becomes more pronounced: in Halo 3 Pop III star does not form without X-ray irradiation (location G) and in Halo 2 the critical mass is $1.6 \times 10^{6}$ $M_{\odot}$ ($z_{10} = 16.50$, location D). Adding X-ray radiation (location E and H), the critical mass is lower by more than a factor of 10 for Halo 2 ($1.2 \times 10^{5}$ $M_{\odot}$, $z_{10} = 23.11$) and is about $3.0 \times 10^{5} - 10^{6}$ $M_{\odot}$ for Halo 3.

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In all the haloes, the reduction of the critical minihalo mass produced by an increasing X-ray background is largest in an intense LW background. This can be readily understood because no matter how strong is the boosting of H$_2$ formation by X-rays, there is a floor to the lowest critical mass, that is dictated by the inefficient cooling rate of H$_2$ in gas with temperature below $\sim 100 - 200$ K. Hence, virialized gas in minihaloes with $T_{\text{vir}} < 100 - 200$ K cannot cool rapidly even if the gas has high molecular fraction. A rough estimate of this floor critical mass of dark matter minihaloes is,

$$M_{\text{cr}}(\text{min}) \approx 10^{5} M_{\odot} \left( \frac{1 + z_{\text{vir}}}{20} \right)^{-3/2},$$

where we have assume $T_{\text{vir}} = 200$ K. This limiting minimum mass could be significantly reduced by HD cooling, that is neglected in our work.

In order to better understand the common qualitative features described above for the three haloes, in Figure 7 we show a sketch of the region on the grid in which Pop III stars can form. The sketch on the left is based on the analytical model in R16, while the sketch on the right illustrates the results of this study based on hydrodynamical simulations.

When an X-ray background is intense (top line in the sketch), gas photo-heating is the dominant feedback process. In this case the temperature of the IGM ($T_{\text{IGM}}$) and the halo virial temperature ($T_{\text{vir}}$) determine the formation of Pop III stars. If $T_{\text{vir}} < T_{\text{IGM}}$ the gas in the halo cannot collapse until the halo mass grows enough and $T_{\text{vir}}$ exceeds $T_{\text{IGM}}$. R16 assumed that only haloes with $T_{\text{vir}} < T_{\text{IGM}}$ can form Pop III stars and this is represented as an horizontal line in the left panel. In the hydrodynamics simulations, however, the formation of Pop III stars in a strong X-ray radiation shows a dependence on the intensity of the LW radiation and thus this line is slanted. We speculate that this is due to the additional cooling by H$_2$ in the absence of a strong LW background. The position of the
Figure 8. Properties of the gas in Halo 1 when the central density reaches $10^7$ H cm$^{-3}$. The X-ray intensity $J_{X0,21}$ is color-coded and the LW intensity is zero. Panel (a): The gas density profile, $n_H$, as a function of the distance from the halo centre, $R$. Panel (b): The $H_2$ fraction profile as a function of $R$. Panel (c): The gas phase diagram constructed from the temperature and density profiles. Each dot represents the minimum temperature of the gas. Panel (d): The ratio of the enclosed mass to the Bonnor-Ebert mass as a function of the enclosed mass. Each peak defines the characteristic radius and it is marked by a triangle. We use the same symbols in Panel (e) and (f) to show the characteristic radii. Panel (e): The Bonnor-Ebert mass versus the enclosed mass. Panel (f): The rate of gas accretion (the left axis) and the corresponding final mass (using Equation 16). The symbols indicate the accretion rate at the characteristic radii, and define the final mass of Pop III stars.

line on the diagram is shifted upward (to higher $J_{X0,21}$) if the halo is more massive and has higher virial temperature.

The lower part of the diagram can be understood considering the degree of X-ray ionization and $H_2$ formation. If the X-ray radiation is weak (below the dashed line) the fraction of electrons produced by X-ray photoionization ($x_{e,\text{back}}$) is lower than the residual electron fraction from the epoch of recombination and the electron fraction produced by collisional ionization in the virialized halo ($x_{e,\text{vir}}$). In this region the positive feedback by the X-ray background is negligible. The position of the line is mostly determined by the growth rate of the halo. Halo 1, that grows quickly and becomes more massive than the other two, has higher virial temperature and thus higher collisional ionization rate. In addition, the halo is irradiated for a shorter period of time before the formation of Pop III stars. Therefore, the mass of the X-ray background must be higher ($J_{X0,21} \sim 10^{-5}$) for Halo 1, see Figure 5 to increase sufficiently $x_{e,\text{back}}$ and have an influence on the critical mass of the halo. On the other hand, the position of the dashed line is lower for Halo 2 and 3 ($J_{X0,21} \sim 10^{-6}$, Figure 6) because they are irradiated by X-rays for a longer time, hence weaker X-ray background is sufficient to produce $x_{e,\text{back}} > x_{e,\text{vir}}$.

Above the dashed line the X-ray photoionization is the dominant positive feedback. In this region of the parameter space, the increase $H_2$ fraction from X-ray ionization compensates the $H_2$ dissociation by the LW background, making the formation of Pop III stars possible in a stronger LW background. The slanted line on the right side the region shows this trend. The slope of the isocountour lines in this region is roughly linear: $J_X \propto J_{LW}$. This can be understood in the context of the R16 model in which the critical mass was found to depend on the parameter $\beta$, that is the ratio of the energies in two energy bins in the mean spectrum of the sources $\beta \equiv E_X/E_{LW} \sim J_X/J_{LW}$.

In conclusion, considering the finite sampling in the $J_{LW,21}$, $J_{X0,21}$ plane due to the limited number of simulations in this work, our results are in good qualitative agreement with the analytic model in R16, although the simulations show that the R16 model neglects some physical processes that are important when the X-ray irradiation is strong, and/or when minihaloes masses grow rapidly. In absence of radiation backgrounds the critical halo mass we find is in agreement with R16 (about $10^6 M_\odot$). We note that in R16 the smallest mass halo in which Pop III stars can form is $\sim 3 \times 10^4 M_\odot$, obtained when a strong X-ray irradiation is considered at very high redshift. In this work we find a minimum mass about three times larger ($\sim 10^5 M_\odot$). This is in agreement with the estimate of the minimum critical mass in equation (15), given that the analytical work considers also very rare haloes forming at $z > 30$.

4 RESULTS: II. TOTAL MASS IN POP III STARS

Our simulations follow the collapse of protostars for $5 \times 10^4$ – $10^5$ years after the time of formation, defined here when the core
density reaches $10^{10}$–$10^{11}$ H cm$^{-3}$. However, we neglect radiation feedback from the accreting protostars that can dissociate H$_2$ (FUV radiation) and produce winds powered by photo-heating from hydrogen and helium ionization. Therefore the masses of the Pop III stars at the end of our simulations are (in most cases) overestimated and provide an upper limit to the Pop III mass. Without radiation feedback the masses of the Pop III stars grow at an early constant rate and provide an upper limit to the Pop III mass. Without radiation feedback themasses of the Pop III stars grow at an early constantrate and provide an upper limit to the Pop III mass. Without radiation feedback the masses of the Pop III stars grow at a nearly constant rate from the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation.

In order to estimate the effect of radiation feedback in reducing the final masses of Pop III stars, we use an empirical relationship based on previous work by HR15 that includes UV radiation feedback. HR15 provides a relation between the final mass of Pop III stars at the end of our simulations as (in most cases) overestimated and provide an upper limit to the Pop III mass. Without radiation feedback the masses of the Pop III stars grow at a nearly constant rate from the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation. Radiation feedback is expected to both reduce the accretion rate and halt the accretion after the time of formation.
ionization rate and is irradiated for a shorter period of time before
the discussion in Section 3. A bigger halo has higher collisional
star formation, the figure shows the general trend of a decreasing
Although the three haloes are different in mass and redshift of Pop III
sources of X-rays are HMXBs; the spectrum is expected to be harder.
have used a relatively soft power-law spectrum, but if the dominant
J
\text{X}\text{0,21} \leq 10^{-3}, showing a roughly constant \( T_{\text{min}} \). This is consistent
with the discussion in Section 3. A bigger halo has higher collisional
ionization rate and is irradiated for a shorter period of time before
forming Pop III stars. For these reasons, the threshold of the positive
X-ray feedback is higher (dashed lines in Figure 7).

The accretion rate at the critical radius can be estimated
analytically (Hirano et al. 2014) assuming spherical symmetry and
simple dimensional analysis: \( \frac{dM}{dt} \sim \frac{M_{\text{f}}}{t_{\text{ff}}} \), where \( M_{\text{f}} = (4\pi/3)\rho(c_s t_{\text{ff}})^3 \) is the Jeans mass
of the quasi-hydrostatic core at temperature \( T_{\text{min}} \) and \( t_{\text{ff}} = 1/(\sqrt{4\pi\rho}) \) is the free-fall time. Hence,

\[
\frac{dM}{dt} \sim 3.4 \times 10^{-3} \ M_{\odot} \ yr^{-1} \ \frac{\left( \frac{T_{\text{min}}}{200 \ K} \right)^{3/2}}{\left( \frac{\mu}{1.22} \right)^{-3/2}}. \tag{18}
\]

showing that the accretion rate depends only on the gas sound speed
or temperature of the collapsing core. Since the gas is nearly neutral
(\( \mu = 1.22 \)), using equation (16) we obtain the relationship between
\( T_{\text{min}} \) and the final Pop III mass:

\[
M_{\text{final}} \approx 287 \ M_{\odot} \ \left( \frac{T_{\text{min}}}{200 \ K} \right)^{1.05}. \tag{19}
\]

We found that a strong X-ray radiation background lowers \( T_{\text{min}} \) and the
Jeans mass, reducing the mass of the collapsing core (HM15), thus reducing the accretion rate.

Figure 10 shows the accretion rates at the critical radius and
final mass in Pop III stars for all the simulations forming Pop III
stars, as a function of the minimum temperature \( T_{\text{min}} \). The different
symbols refer to the three haloes we have simulated and the colors
refer to the X-ray background intensity (see legend in the left
panel of the figure). As we discuss with Figure 9 they all follow a
similar relationship: \( T_{\text{min}} \) decreases with increasing X-ray intensity
and this leads to a slower gas accretion and hence lower mass of
the Pop III star. The dashed lines in the left and right panels show
the result of the simple analytic model for the accretion rate (equation
18) and Pop III mass (equation 19), respectively. The accretion
rates from the simulations are consistent with this simple model,
but the uncertainties in determining the location of the characteristic
radii (and thus the accretion rates) produces a significant scatter
with respect to the analytic calculation, especially for strong X-ray

\[ M_{\text{final}} = \frac{3.4 \times 10^{-3}}{\left( \frac{T_{\text{min}}}{200 \ K} \right)^{3/2}}. \]

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irradiation. The accretion rate $dM/dt$ and $M_{\text{final}}$ for Halo 2 (crosses) and Halo 3 (triangles) show a much tighter relationship with $T_{\text{min}}$, probably because these two haloes grow relatively slowly and do not experience major perturbations. On the other hand, Halo 1 (circles), that grows rapidly and experiences a major merger at some point, shows a larger scatter and $dM/dt$ is slightly biased to be lower than the other cases at a given temperature.

Figure 11 shows that the total mass of the protostellar cores grows roughly linearly as a function of time. In other words, the accretion rate is roughly constant as a function of time, and its value decreases with increasing X-ray intensity similarly to $M_{\text{final}}$. The trend is quite robust, for instance, when $J_{X0,21} \geq 10^{-2}$ (orange and red lines in the top panels) the protostars grow at a significantly slower rate and the total mass in Pop III stars is lower at any given time. Again, deviations from the general trend are observed (green lines) in Halo 1 and Halo 3. As discussed in earlier in the section, a halo interaction may cause the rapid gas accretion. When Halo 3 is irradiated by X-ray background of $J_{X0,21} = 10^{-1}$ (the orange line in the upper right panel) the growth of the clump stagnates after it reaches $\sim 50 M_\odot$. We observe that a bar-like structure develops inside the characteristic radius. Due to the increase in the accretion rate the clump at the centre grows in $\sim 10$ kyr but does not grow as most of the disc gas is consumed.

The bottom row in Figure 11 shows the total mass as a function of time for different intensities of the LW backgrounds (see legend) keeping fixed the X-ray intensity ($J_{X0,21} = 10^{-4}$). We do not observe any dependence of the protostellar core growth rate on the LW intensity. Probably this can be explained by H$_2$ self-shielding (equation 4) that increases rapidly when the gas density exceeds $\sim 10^3 - 10^5$ H cm$^{-3}$. Hence, after the formation of the protostar the LW radiation is shielded and does not play a significant role in determining $T_{\text{min}}$ and thus the final Pop III mass. The effect of the LW background is limited to setting the redshift of Pop III star formation. Because the protostar forms and accretes at different redshifts (for the same halo but with different radiation backgrounds), other factors such as the mass of the halo or mergers with other minihaloes are more important in determining the Pop III star mass growth than the gas cooling physics. An extreme example of this is the case of Halo 1 irradiated by a very strong LW background ($J_{LW,21} = 100$, red line in the bottom-left panel). The gas in the halo starts condensing when the mass of the halo reaches $\sim 2 \times 10^7$ M$_\odot$ (the virial temperature $\sim 9,000$ K), when Ly $\alpha$ atomic cooling start to become important. The accretion rate is very rapid and both $M_{\text{final}}$ and the core mass exceed $10^4$ M$_\odot$. This is consistent with Regan et al. (2020) in that a LW background allows black hole seeds to form by suppressing the formation of Pop III stars in small mass minihaloes below the atomic cooling limit.

Since the accretion rate onto the protostar is fairly constant, the final mass in Pop III stars increases linearly with time. In order to determine the final mass in Pop III stars we therefore need to...
estimate the typical timescale for feedback to halt the accretion. This can be derived from equation (16) as long as the accretion rate remains constant and equal to the value \( \frac{dM}{dt}_{\text{crit}} \) estimated at the critical core radius at \( n_1 = 10^7 \text{ H cm}^{-3} \):

\[
\tau_{\text{SF}} = \frac{M_{\text{final}}}{\frac{dM}{dt}_{\text{crit}}} = 89 \text{ kyrs} \left( \frac{\frac{dM}{dt}_{\text{crit}}}{2.8 \times 10^{-3} \text{ M}_\odot \text{yr}^{-1}} \right)^{-0.3}.
\]  

In Figure 12 we show the ratio between the average growth rate of the protostar \( \langle \frac{dM}{dt} \rangle = M(t_c)/t_c \), where we use \( t_c = 50 \text{ kyrs} \) for this period and the accretion rate \( \frac{dM}{dt}_{\text{crit}} \) at \( n_1 = 10^7 \text{ H cm}^{-3} \),

\[
\eta = \frac{\langle \frac{dM}{dt} \rangle}{\frac{dM}{dt}_{\text{crit}}}
\]

as a function of \( \frac{dM}{dt}_{\text{crit}} \). The ratio \( \eta \) is of the order of unity with a spread within a factor of two (shaded region) in most cases. Since these two accretion rates are nearly the same, the final mass in Pop III stars estimated as \( M(\tau_{\text{SF}}) \) is the same as \( M_{\text{final}} \) in equation (16).

5 SUMMARY AND DISCUSSION

The first stars have an important effect on the formation of the first galaxies by regulating the formation of metal-enriched stars (Ricotti et al. 2002b, 2008; Wise & Abel 2008). LW and X-ray photons can travel large distances without being absorbed in the early Universe, building up a radiation background. In addition, X-rays can penetrate deep into star forming clumps producing both heating and ionization. Each photo-electron has high energy but in a mostly neutral gas fast photo-electrons deposit a large fraction of their kinetic energy into secondary ionizations (Shull & van Steenberg 1985). Because of these properties, it is thought that early objects (first stars and their remnants such as SNe, PISNe, HMXBs, and IMBHs) built a LW and X-ray radiation backgrounds that self-regulates their formation (Venkatesan et al. 2001; Jeon et al. 2014; Xu et al. 2016, R16).

In this study, using zoom-in simulations of three minihaloes with different mass and irradiated by different intensities of the LW and X-ray backgrounds, we investigate the effect of X-ray/LW radiation on the formation of the first stars and on their characteristic mass. Below we summarize the key results of the simulations.

(i) We confirm qualitative results of previous analytic models (R16), that an X-ray radiation background promotes the initial gas collapse in small mass minihaloes, while a LW background delays it by regulating the amount of H\(_2\) formation. If the X-ray background is too intense, the feedback effect by gas heating suppresses Pop III star formation in haloes with virial temperature \( T_{\text{vir}} < T_{\text{gas}} \). Below this threshold X-ray intensity, the increase in \( H_2 \) formation due to the increased ionization fraction of the gas, reduces the mass above which a minihalo can host a Pop III star (the critical mass) to \( \sim 10^5 \text{ M}_\odot \). The positive feedback effect of X-rays is most important when it offsets the negative feedback of an intense H\(_2\)-dissociating LW radiation background. For example, X-rays can reduce the critical mass by a factor of \( \sqrt{2} \) in a weak LW intensity, while the reduction is by a factor of ten when \( J_{\text{W},21} = 10^{-1} \). Hence, X-ray radiation can increase the number of Pop III stars forming in the early Universe by about a factor of ten.

(ii) X-ray irradiation produces a net cooling effect on the collapsing protostellar core by increasing the \( H_2 \) fraction. Efficient gas cooling reduces the gas sound speed and consequently the accretion rate on collapsing protostellar cores. Therefore the final mass in Pop III stars is lower in X-ray irradiated minihaloes.

The results in this work constitute a first step to understand the self-consistent evolution of the number of Pop III stars forming in the early universe. As shown in R16 using analytic calculations, the critical minihalo mass above which Pop III stars can form and the intensity of the radiation backgrounds are self-regulated by a feedback loop on cosmological scales. While this work considers only a grid of assumed values of the background, the lower value of the critical mass we derive is roughly a factor of 3 higher than the value found in R16 (~ \( 3 \times 10^5 \text{ M}_\odot \)). Although cosmological simulations are required to make solid predictions, a simple scaling argument using Press-Schechter formalism (Press & Schechter 1974; Sheth & Tormen 1999), suggests that the number of Pop III stars according to our simulation results would be a factor of 3–4 lower than in R16: \( \sim 100 \) instead of \( \sim 400 \) in 1 Mpc/h estimated by R16.

In addition, following R16, we assume that soft X-ray (\( \sim 0.2 – 2.0 \text{ keV} \)) is the dominant source of ionization and our spectra do not cover harder X-ray (\( \sim 2.0 – 10 \text{ keV} \)). Whether adding photons in this energy bin has positive or negative feedback will be studied in the future.

The model of R16 assumes that one halo has only one Pop III star. As other simulations (S20; Turk et al. 2009; Clark et al. 2011) and this work suggest, however, the formation of multiple Pop III stars in one halo. This implies that the prediction of a radiation background depends on the IMF of Pop III stars. Due to their high masses, they are emitting at Eddington rate \( 1.25 \times 10^{38} \text{ ergs s}^{-1} (\text{M}_\odot^{-1}) \) (Bromm et al. 2001) so the LW intensity per halo depends on the total mass of the stars. On the contrary, if they explode as PISNe with similar energy (\( \sim 10^{52} \text{ ergs} \)), the X-ray intensity per halo depends on the number of Pop III stars. Furthermore, the fraction of HMXBs (~ 35%, Stacy & Bromm 2013) can be affected by the X-ray background. This suggests the number density of Pop III stars or their explosions that JWST (Whalen et al. 2014) will detect may provide constraints of the IMFs and X-ray physics.

Figure 12. The dimensionless ratio \( \eta \) of two accretion rates (see Equation (21)) as a function of \( \frac{dM}{dt}_{\text{crit}} \), defined when the central density is \( 10^7 \text{ H cm}^{-3} \). The parameter \( \eta \) is the ratio of the average accretion rate on the Pop III star (i.e., the total mass at \( t_c = 5 \times 10^4 \text{ years} \), divided by \( t_c \)) to \( \frac{dM}{dt}_{\text{crit}} \). Different symbols refer to different host halos and \( J_{\text{W},21} \) is color-coded. To guide the eye, the shaded region encompasses a change of a factor of two around unity: \( 0.5 \leq \eta \leq 2.0 \). Simulations with critical mass of the host halos larger than \( 10^8 \text{ M}_\odot \) are omitted.
HM15 finds that the X-ray radiation background is shielded by the dense central gas and therefore plays a minor role in determining the IMF of Pop III stars. Since the self-shielding of the X-ray background is not considered in our simulations, we perform a test run with Halo 2 to investigate if it is an important factor. In this simulation, we assume that radiation is shielded completely if the density of a cell exceeds $10^4 \, \text{H cm}^{-3}$ since the optical depth of X-rays becomes close to unity at this radius. This simple prescription overestimates the shielding effect since the optical depth monotonically increases with decreasing radius. The test run gives results similar to those of the original one. The redshift of Pop III star formation is $z = 24.597$, the same as in runs neglecting self-shielding (24.595). In addition, the total mass in Pop III stars at $z = 50$ kyr after the formation of the first clump are very close ($\approx 220 \, M_\odot$ versus $240 \, M_\odot$ in the fiducial run). Finally, the multiplicity of Pop III stars is two in the original run, while in the run with X-rays self-shielding a third small mass Pop III star is formed. We speculate the causes of the similar results are the following. First, as discussed in Section 4, the size of the quasi-hydrostatic core (at $n_H \sim 10^4 \, \text{H cm}^{-3}$) determines the accretion rate and the properties of Pop III stars. For this reason, X-ray photons do not change the later evolution even if they do not penetrate to the centre of the halo. Secondly, the collapse to a higher densities occurs on a timescale comparable to the ionization/recombination timescales. Hence, the dense gas retains a memory of the temperature and ionization fraction at lower densities, as shown by panel (c) of Figure 8 up to densities $\sim 10^7 \, \text{H cm}^{-3}$. We confirm that this behaviour continues up to densities $n_H \sim 10^{10} \, \text{H cm}^{-3}$. At densities $n_H > 10^8 \, \text{H cm}^{-3}$, the gas temperature raises with increasing density, hence compression heating (or viscous heating in discs at densities $> 10^{10} \, \text{H cm}^{-3}$, Kimura et al. 2021) dominates over photoionization heating. As HM15 has pointed out, however, this result may be sensitive to the column density of the halo. So what matters to the X-ray shielding is the growth history of the host halo.

This work does not include two potentially important physical processes: HD cooling and radiative feedback from protostars. HD provides additional cooling at low temperatures ($\sim 100 \, \text{K}$) and thereby can reduce the characteristic mass of Pop III stars (Yoshida et al. 2007). Its formation rate is proportional to that of H$_2$ which is regulated by an X-ray background. Furthermore, Figure 8 and 9 show the minimum temperature is a function of X-ray. Therefore, X-ray radiation can be crucial to the onset of HD cooling. The role of X-ray radiation in HD formation has been explored by Nakauchi et al. (2014), but not tested yet with hydrodynamics simulation. Finally, a full treatment of radiation feedback from accreting protostars, rather than the semi-empirical approximation used in this work, is important for a more accurate determination of the final masses of Pop III stars (S20; Hosokawa et al. 2011, 2016). Therefore, including the neglected or approximated physical processes mentioned above (X-ray self-shielding, HD cooling and radiation feedback) will be the focus of future work.

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APPENDIX A: VALIDATION OF PRIMORDIAL CHEMISTRY AND COOLING IN RAMSES

In Figure A1 we show the phase diagram for one-zone calculations (cooling balances compression heating, e.g. Omukai 2001) for successive improvements of the primordial chemistry/cooling module in RAMSES. The different lines (see legend) illustrate how the original primordial cooling calculation in RAMSES is improved with the addition of each of the physical processes discussed in Section 2. We also compare the results with that of a former work (S20), indicated by the solid line with label "SFUMATO". Figure A2 shows the H$_2$ (left panel) and electron fraction (right panel) for the same one-zone calculation. One of the major differences in this work is produced by lowering the minimum floor for the ionization fraction. As can be seen in the right panel of Figure A2 the electron fraction is lower than $10^{-6}$ at $n_H \gtrsim 10^4$ H cm$^{-3}$. In the original version, however, the floor is set to $10^{-6}$ and thus the electron fraction is always higher than this threshold. For this reason, the simulation (orange dashed line) shows the H$_2$ fraction abnormally higher than it is supposed to be (right panel of Figure A1). In the current version of our code, the value of the floor is $10^{-12}$ and therefore the validity of the model is guaranteed up to $n_H \sim 10^{14}$ H cm$^{-3}$. With three-body H$_2$ formation, the models are consistent with each other up to densities $n_H = 10^9$ H cm$^{-3}$ and other improvements of the physics in the high-density regime reduces the error up to $\lesssim 10^{14}$ H cm$^{-3}$.

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Figure A1. Phase diagram (temperature as a function of hydrogen number density) for a one-zone calculation in which compression heating balances molecular hydrogen cooling. The different lines (see legend) refer to incremental improvements of the model with respect to the original implementation in RAMSES. The validation of the result is done by comparing our implementation in RAMSES to published results by S20 using the AMR code SFUMATO. Our results are accurate to densities \( n_\text{H} \sim 10^{12} \, \text{H cm}^{-3} \), but the error remains relatively small (< 15 per cent) up to densities \( n_\text{H} \sim 10^{14} \, \text{H cm}^{-3} \).

Figure A2. Same calculations as in Figure A1 but showing the molecular hydrogen abundance (left panel) and the electron fraction (right panel).