Overcooled haloes at $z \geq 10$: a route to form low-mass first stars

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ABSTRACT
It has been shown by Shchekinov and Vasiliev (SV06) that HD molecules can be an important cooling agent in high redshift $z \geq 10$ haloes if they undergo mergers under specific conditions so suitable shocks are created. Here, we build upon Prieto et al. who studied in detail the merger-generated shocks, and show that the conditions for HD cooling can be studied by combining these results with a suite of dark matter only simulations. We have performed a number of dark matter only simulations from cosmological initial conditions inside boxes with sizes from 1 to 4 Mpc. We look for haloes with at least two progenitors of which at least one has mass $M \geq M_{\text{cr}}(z)$, where $M_{\text{cr}}(z)$ is the SV06 critical mass for HD overcooling. We find that the fraction of overcooled haloes with mass between $M_{\text{cr}}(z)$ and $10^{0.2} M_{\text{cr}}(z)$, roughly below the atomic cooling limit, can be as high as $\approx 0.6$ at $z \approx 10$ depending on the merger mass ratio. This fraction decreases at higher redshift reaching a value $\approx 0.2$ at $z \approx 15$. For higher masses, i.e. above $10^{0.2} M_{\text{cr}}(z)$ up to $10^{0.6} M_{\text{cr}}(z)$, above the atomic cooling limit, this fraction rises to values $\approx 0.8$ until $z \approx 12.5$. As a consequence, a non-negligible fraction of high redshift $z \geq 10$ mini-haloes can drop their gas temperature to the cosmic microwave background temperature limit allowing the formation of low-mass stars in primordial environments.

Key words: turbulence – stars: formation – galaxies: formation – large-scale structure of Universe.

1 INTRODUCTION
In the current Λ cold dark matter ($\Lambda$CDM) cosmological paradigm, dark matter (DM) overdensities are the building blocks of cosmic structures. These DM overdensities grow due to gravity forming DM haloes in a hierarchical way, i.e. from the smaller to the bigger ones, and mergers play an important role in this process.

For the formation of the first luminous objects to become possible, the baryonic content of the haloes must be able to cool. Cooling of primordial gas is driven by molecular hydrogen ($\text{H}_2$) which can form inside DM mini-haloes of mass $\geq 10^6 \, \text{M}_\odot$. Once $\text{H}_2$ formation is triggered, rovibrational transitions of the $\text{H}_2$ molecule are able to cool primordial gas down to temperatures of $\sim 200$ K (Haiman, Thoul & Loeb 1996; Tegmark et al. 1997; Abel, Bryan & Norman 2002), see also the Barkana & Loeb (2001) review. At lower temperatures, the $\text{H}_2$ lines become insufficient to cool the gas further.

The $\text{H}_2$ cooling temperature floor ($T \approx 200$ K) and its saturation number density (n $\approx 10^4$ cm$^{-3}$ i.e. the density for local thermal equilibrium at which $\text{H}_2$ cooling is inefficient) yield a Jeans mass:

$$M_J \approx 500 \, \text{M}_\odot \left( \frac{T}{200 \, \text{K}} \right)^{3/2} \left( \frac{10^4 \, \text{cm}^{-3}}{n} \right)^{1/2} .$$

1 But see Greif et al. (2011) and Stacy & Bromm (2013b) for lower masses primordial stellar binary-multiple systems.

This sets a mass scale for gravitationally bounded objects in the primordial gas, suggesting that the first stars were massive.$^1$

Because the HD number density depends on the $\text{H}_2$ abundance through $\text{H}_2 + D^+ \rightarrow \text{HD} + H^+$ (Palla, Galli & Silk 1995; Galli & Palla 2002) and the $\text{H}_2$ abundance depends on the free electron number density through $e^- + H \rightarrow H^- + e^-$ followed by $H^- + H \rightarrow H_2 + e^-$ (Peebles & Dicke 1968), if the gas presents a high ionization fraction it is possible to increase the HD abundance. It has been shown that such high ionization fraction conditions are common in post-shocked gas inside DM haloes (Greif et al. 2008; Prieto, Jimenez & Martí 2012). In fact, the DM halo growing process involves violent merger events. These mergers are able to produce violent merger events. These mergers are able to produce
strong shock waves which both compress the halo baryonic content and increase the ionization fraction. This drives an enhancement in the formation rate of HD molecules with the consequent overcooling of the primordial gas, as shown in Greif et al. (2008) and Prieto et al. (2012).

Shchekinov & Vasiliev (2006, hereafter SV06) studied the necessary (thermochemical) conditions for HD cooling to switch on. They argue that such conditions are fulfilled in merging DM haloes with a total system mass above a critical value, so suitable shocks form. The post-shocked gas with an enhanced HD molecular fraction is able to drop its temperature to the CMB floor of \( T_{\text{CMB}} \approx 2.73(1 + z) \).

SV06, however, only considered a straw-man head-on collision of two primordial clouds of equal mass, but, clearly the physical state of the post-shock gas depends on many factors that are not captured by this simplified scenario. Prieto et al. (2012) produced numerical DM + baryons simulations that capture enough physics to study the physical state of the post-shock gas. They find that as a result of the hierarchical merging process, turbulence is generated and the production of coolants is enhanced, so much that even the HD molecule becomes an important coolant in some regions. Yet, their simulations are not sufficient to assess how generic this is, that is, how these regions are associated with the distribution of mini-haloes. This is what we set up to do here.

In this paper, we use a set of DM cosmological simulations to compute the fraction of haloes able to produce overcooling of the primordial gas due to mergers at high redshift as predicted by SV06 using the recipe developed in Prieto et al. (2012). This paper is organized as follows. In Section 2, we describe our methodology. In Section 3, we show our numerical results and discuss about them. In Section 4, we present our summary and conclusions.

## 2 METHODOLOGY

In principle, to compute the fraction of haloes able to overcool their baryonic content due to mergers at high redshifts, we would want to have multiple hydrodynamic simulations, which model both DM and baryonic physics and chemothermal evolution of primordial gas, for cosmological initial conditions, reaching a resolution of \( \sim 1 \) pc at \( z = 10 \). This ambitious goal was achieved in Prieto et al. (2012), but only for a single 1 Mpc size box, and in there the formation and baryonic matter accretion process of a single halo was simulated at full resolution: a region of 2 kpc (at \( z = 10 \)) with \( \sim 2 \) pc resolution (at \( z = 10 \)). The average CPU time for one of such systems is \( \sim 180,000 \) CPU h. This makes it computationally very expensive to replicate the Prieto et al. (2012) runs for multiple haloes in a cosmological context. However, this complex problem can be broken in three ingredients which can be studied independently. The first ingredient is the thermochemical conditions for the HD cooling to switch on which were studied in SV06. The second ingredient is the physical conditions of the primordial gas (turbulence and shocks) which was studied in Prieto et al. (2012). They find that post-shock regions are able to produce both \( H_2 \) and HD molecules very efficiently even in small mini-haloes (\( M \sim 10^6 M_\odot \)) if they accrete on, or merge with, a more massive but still relatively low-mass halo (\( M \sim 10^7 M_\odot \simeq M_{\text{cr}} \)). The remaining ingredient is how frequently this happens in a cosmological context. This last step, however, can be addressed with DM-only simulations under minimal assumptions, and this is what we set up to do here.

The critical mass to trigger HD molecular overcooling at redshift \( z \) is defined by SV06 as

\[
M_{\text{cr}}^{\text{SV06}}(z) = 8 \times 10^7 \left( \frac{20}{1 + z} \right)^2 M_\odot.
\]

(2)

Following SV06, this is the total mass of the system, i.e. DM plus baryonic mass. Because we have to work with DM-only simulations, we have to make an assumption regarding the baryonic matter. To take into account the gas inside the DM haloes, we assume that these primordial haloes host the universal baryon fraction

\[
\frac{M_b}{M_{\text{DM}} + M_b} = \frac{\Omega_b}{\Omega_m} \equiv f_b,
\]

(3)

where \( M_b, M_{\text{DM}}, \Omega_b, \Omega_m \) and \( f_b \) are the baryonic mass content of the halo, the dark mass content of the halo, the current average baryonic matter density in the Universe in units of the critical density, the current average DM density in the Universe in units of the critical density and the universal baryonic mass fraction of the Universe, respectively. Using this approximation, the necessary (but not yet sufficient) condition for a DM halo at redshift \( z \) to become an overcooled (OC) halo is that it must have a DM mass above a critical mass

\[
M_{\text{cr}}^B(z) = (1 - f_b) \times M_{\text{cr}}^{\text{SV06}}(z);
\]

(4)

hereafter, we will refer to \( M_{\text{cr}}^B \) as \( M_{\text{cr}} \).

We use the cosmological hydrodynamical code RAMSES (Teyssier 2002) to perform 75 DM-only simulations. The cosmological initial conditions are produced with the MPGRACIF code (Prunet et al. 2008) and the initial redshift for each run is set to \( z_i \approx 65 \). The cosmological parameters are those of the concordance CDM model from Komatsu et al. (2009, 2010): \( \Omega_m = 0.258 \), \( \Omega_L = 0.742 \), \( h = 0.719 \), \( \sigma_8 = 0.796 \), \( n_s = 0.963 \) and the transfer function of Eisenstein & Hu (1998) with \( \Omega_b = 0.0441 \).

Using the AHF halo finder (Knollmann & Knebe 2009), we identified DM haloes (i.e. objects with a density contrast \( \delta \geq 200 \)) with mass above or equal to the critical mass to enhance the HD molecular cooling \( M_{\text{cr}} \), at several redshifts \( z \geq 10 \). For reference, in the cosmology adopted here, \( f_b = 0.1709 \), and thus

\[
M_{\text{cr}}(z) = 6.63 \times 10^7 \left( \frac{20}{1 + z} \right)^2 M_\odot.
\]

(5)

In the set-up chosen for the AHF halo finder the minimum particle number per halo was set to \( N_{\text{min}} = 20 \). We adopted this low number because we are not interested in characterizing the haloes based on their internal radial features. This corresponds closely to the minimum number of particles per critical mass halo \( N_{\text{p,cr}} \) at the highest redshift of interest in the lower resolution run.

Table 1 shows the details of each simulation. From the first column to the last one: the simulation name, referring to both the box size and the particle number, the number of simulations \( N \), the box size\(^2 \) \( L_{\text{box}} \) in Mpc, the number of particles per simulation \( N_p \), the particle mass \( m_p \) and the number of particle per critical mass halo \( N_{p,\text{cr}} \) at two reference redshift \( z = 10 \) and 17.5.

As we will show in the next section, the most reliable results come from runs where \( M_{\text{cr}} \) is defined by \( N_{p,\text{cr}} \geq 1310 \) particles at \( z \leq 17.5 \), i.e. runs with a particle mass \( m_p \leq 5.88 \times 10^5 M_\odot \). In these runs, the DM haloes are found consistently in successive snapshots. Furthermore, it is worthwhile to note that in these reliable

\(^2 \text{Note that we adopt the value } h = 0.719 \text{ therefore here length are in Mpc and masses in } M_\odot.\)
runs the primordial perturbation distance scale $\lambda_{M_{cr}}$ associated with the critical mass $M_{cr}$, is well defined by a number of particles (>10) when the simulation starts. The Prieto et al. (2012) findings indicate that a necessary and sufficient condition for triggering HD cooling is that a halo with mass greater than $M_{cr}$ (recall that at the redshifts of interest $M_{cr} \sim 10^7 M_\odot$) undergoes a merger or accretes baryonic material funnelled in the halo along filaments. Even in subcritical haloes ($M \sim 10^6 M_\odot$) HD cooling can be triggered if they accrete on a critical one, as the relevant physical condition driving the turbulence is the relative velocity, which is set by the potential well created by the supercritical halo. In the supercritical halo, if it is not disrupted by a major merger, the turbulence triggered by accretion is enough to enhance the creation of H$_2$ and HD, and therefore kickstart overcooling.

Informed by the above findings, here we impose the conditions for overcooling to happen as follows.

We construct the merger trees for each simulation using the AHF merger tree tool, we identify DM haloes at redshift $z_i$ with mass $\geq M_{cr}(z_i)$ that subsequently undergo merging to form a bigger halo at $z_f$ (with $z_f \geq z_i$).

We define the OC halo merger as the process in which an existing halo at $z_1$ has at least two progenitors, of which at least one with mass $M_{DM} \geq M_{cr}(z_i)$ and after the merger keeps at least a mass fraction $f_{\text{mg}}$ of the most massive progenitor. We vary the factor $f_{\text{mg}}$ from 0.6 to 0.9 in order to study how the OC haloes fraction depends on it.

Our parameters of the halo finder routine imply that the minimum halo mass (which sets therefore the definition of merger) is somewhat resolution dependent ranging from $1.47 \times 10^5 M_\odot$ in simulation S1Mpc512 to $7.54 \times 10^5$ in simulation S4Mpc256.

Here, we want to stress that we do not impose a minimum merger mass ratio in our strategy to look for OC haloes. The method described above is suitable to address the question: What is the fraction of DM haloes able to overcool their baryonic content (and thus potential site for low-mass star formation) due to mergers and accretion at high redshift? Indeed, the condition $M \geq M_{cr}$ ensures that the interaction between haloes will be strong enough to trigger the enhancement of the HD formation. On the other hand, a study based on the merger mass ratio could give us information about the amount of OC gas, and then could help answer a different question: What is the amount of OC gas in haloes at high redshift? Our simulation set-up and our methodology cannot quantify the amount of OC gas, but it is suitable to estimate the fraction of OC haloes at high redshift. This is the goal of this work.

### 3 RESULTS AND DISCUSSION

Table 2 shows some example combinations of redshifts $z_1$ and $z_2$ used in building our merger tree, and the ranges of the three halo mass bins (at $z_2$) we consider. The mass bins labelled by $i = 1, 2, 3$ have been chosen so that bin mass lower and upper boundaries are $10^{9.2(1-i)} M_{cr}(z_2)$ and $10^{9.2(1+i)} M_{cr}(z_2)$, respectively. Thus, the three mass bins are centred around, 1, 3, 2 and $3 M_{cr}(z_2)$, respectively. With this choice, the mass range spanned by the three bins covers the transition from H$_2$ cooling haloes to atomic cooling ones.

![Figure 1. The mass scales involved.](image)

| $z_1$ | $z_2$ | Mass bin 1 in $10^7 M_\odot$ | Mass bin 2 in $10^7 M_\odot$ | Mass bin 3 in $10^7 M_\odot$ |
|-------|-------|----------------------------|----------------------------|----------------------------|
| 10.0  | 10.2  | 2.10–3.33                  | 3.33–5.28                  | 5.28–8.36                  |
| 11.0  | 11.4  | 1.73–2.74                  | 2.74–4.34                  | 4.34–6.88                  |
| 12.3  | 12.7  | 1.41–1.81                  | 1.81–2.87                  | 2.87–4.55                  |
| 14.9  | 15.4  | 0.99–1.57                  | 1.57–2.49                  | 2.49–3.94                  |
| 17.2  | 17.9  | 0.74–1.17                  | 1.17–1.85                  | 1.85–2.94                  |

Table 3 reports the total number of OC haloes $N_{OC}$ and the total number of haloes $N_h$ at $z_i = 10$ for the three different mass bins in the less restrictive case $f_{\text{mg}} = 0.6$ and for the highest resolution simulations with $m_p \leq 5.88 \times 10^3 M_\odot$. The reported number is the sum of all OC haloes (all haloes) in the N simulations considered, i.e.
Table 3. Total number of OC haloes (i.e. the sum over the N realizations) and total number of haloes (N) in a given mass bin with \( f_{mg} = 0.6 \) and \( m_p \leq 5.88 \times 10^3 \, M_\odot \) at \( z_1 = 10 \).

| Sim. name | Mass bin 1 \( N_{OC}(N_h) \) | Mass bin 2 \( N_{OC}(N_h) \) | Mass bin 3 \( N_{OC}(N_h) \) | Total volume \( (\text{Mpc}^3) \) |
|-----------|-----------------|-----------------|-----------------|-----------------|
| S1Mpc512  | 5 (7)           | 4 (4)           | 3 (3)           | 5               |
| S1Mpc256  | 25 (46)         | 14 (15)         | 11 (12)         | 20              |
| S2Mpc512  | 88 (132)        | 56 (57)         | 37 (38)         | 40              |

5 simulations of S1Mpc512, 20 for S1Mpc256 and 5 for S2Mpc512. The effective volume for finding these OC haloes is therefore 5, 20 and 40 Mpc\(^3\), respectively.

Figs 2–4 show the fraction of OC haloes \( f_{HD}^{OC} \) for four different values of \( f_{mg} \) and for the three halo mass bins as a function of redshift. These results are shown for our two different \( N_p \) (in different columns) and different box sizes \( L_{box} \) (in different rows). The error bars correspond to the standard deviation between the \( N \) simulations at a given redshift. The error on the mean would be smaller by a factor \( \sqrt{N} \).

As we expected, the higher the \( f_{mg} \) the lower the OC fraction \( f_{HD}^{OC} \). This trend shows that after a merger process it is very difficult for the resulting halo to keep 100 per cent of its progenitor’s mass: some of the progenitor’s mass is always removed from the parent halo after the merger. The resulting \( f_{HD}^{OC} \) shows a very weak dependence (or no dependence at all) on \( f_{mg} \) for \( 0.6 \leq f_{mg} \leq 0.8 \).

Our results show a clear resolution dependence for \( m_p \geq 4.70 \times 10^4 \, M_\odot \), i.e. runs S4Mpc512, S4Mpc256 and S2Mpc256. In these runs, it is possible to see a monotonic growth of the OC fraction with the simulation resolution, which is particularly marked in the \( f_{mg} = 0.6 \) case: we, thus, discuss numerical convergence before further interpreting Figs 2–4.

Numerical convergence is investigated further in Fig. 5 where it is possible to identify a mass-resolution-dependent trend. Simulations S1Mpc512, S2Mpc512 (and S1Mpc512) have particle masses below \( m_p = 5.88 \times 10^3 \, M_\odot \) and thus a mass threshold for OC halo merger \( M = 1.2 \times 10^5 \, M_\odot \) or mass merger ratios below 1 : 65. These simulations correspond to the (red) plus symbols, (blue) asterisk symbols and (green) ‘x’ symbols. At this resolution results for \( f_{HD}^{OC} \) appear to converge. On the other hand, simulations S2Mpc256, S4Mpc512 and S4Mpc256 with \( m_p \geq 4.70 \times 10^4 \, M_\odot \), (magenta) open square symbols, (cyan) filled square symbols and (yellow) open circle symbols, do not show numerical convergence. This can be understood as the mass threshold for merger in these simulations is high (> 9.4 \times 10^5 \, M_\odot) and the merger mass ratios are larger than 1 : 2.

In what follows, we will focus on these three higher mass resolution simulations because they have the most reliable results based on both, convergence and number of particles per DM halo.
Figure 3. Same as Fig. 2 but for the second mass bin centred around $M = 2M_{cr}(z_2)$. See Table 2.

Figure 4. Same as Fig. 2 but for the third mass bin centred around $M = 3.2M_{cr}(z_2)$. See Table 2.
In Fig. 2, corresponding to the first mass bin (see Table 2), and for mass resolution \( m_p \leq 5.88 \times 10^6 \, M_\odot \) (i.e. top two panels, and middle-right panel) our results show that at \( z = 10 \) the fraction of OC haloes is \( f_{OC}^{HD} \geq 0.5 \) in the case with \( m_{mg} \leq 0.7 \). This fraction tends to decrease at higher redshift (\( z \lesssim 12.5 \)), but is always above 20 per cent (for \( m_{mg} \leq 0.7 \)) showing that a non-negligible fraction of DM haloes in this mass bin is able to overcool their gas content due to mergers at high redshift. At higher redshifts, i.e. \( z \gtrsim 15 \), the fraction decreases \( f_{OC}^{HD} \lesssim 0.2 \). This last result comes from S2Mpc512, the only simulation with data above \( z \gtrsim 15 \) in this mass bin.

In Fig. 3, we show the second mass bin centred around \( M = 2 M_{\odot}(z_2) \). For runs with mass resolution \( m_p \leq 5.88 \times 10^3 \, M_\odot \) (top two panels, and middle-right panel) the OC fraction at \( z = 10 \) is \( f_{OC}^{HD} \gtrsim 0.9 \) for \( m_{mg} \lesssim 0.7 \) and it can reach \( f_{OC}^{HD} \sim 1.0 \). At higher redshift (\( z \lesssim 12.5 \)) the fraction remains significant, \( f_{OC}^{HD} \gtrsim 0.8 \). As expected the OC fraction increases with the mass of the halo.

Fig. 4 shows our results for the third mass bin centred around \( M = 3.2 M_{\odot}(z_2) \). The OC fraction keeps increasing with halo mass.

In summary, these figures show that a non-negligible fraction of DM haloes above the critical mass \( M_c \) are able to overcool their gas content due to mergers at high redshift.

To illustrate how the OC merger proceeds, Fig. 6 shows the evolution of two randomly chosen OC haloes from our catalogue at four different redshift \( z_1 \). In the first column, we show an OC halo of \( M = 6.41 \times 10^6 \, M_\odot \) (computed at \( z = 10 \)) from the third bin mass and in the second column an \( M = 2.53 \times 10^6 \, M_\odot \) (computed at \( z = 10 \)) OC halo from the first mass bin. The difference in size of the objects reflects the different mass bins.

As an additional study, we have computed the probability distribution function for the halo spin parameter \( \lambda \) defined by Bullock et al. (2001a), and we have found that it follows log-normal distribution characterized by a standard deviation \( \sigma \approx 0.5 \) and an average spin parameter \( \lambda \approx 0.04 \) in good agreement with previous works, e.g. Davis & Natarajan (2009). Despite the low number of haloes in the most reliable runs (see Table 3), we recover a log-normal distribution (for S1Mpc256 and S2Mpc512) characterized with the parameters shown above. This fact supports our claim on the reliability of our results.

While the \( N \)-body simulations for this work were running, new results on cosmological parameters, derived from the Planck satellite observations, were released (Planck Collaboration 2013). The Planck’s best-fitting \( \Lambda \)CDM cosmological parameters are somewhat different from Wilkinson Microwave Anisotropy Probe’s (WMAP) ones. Because our results can be cosmology dependent, let us elaborate on the possible effect of the Planck results. Planck’s \( \Omega_m \) value is slightly higher than WMAP’s and \( \Omega_b \) slightly lower. This affects directly the computation of the DM critical mass \( M_{cr}(z) \) decreasing it by a 2 per cent, approximately. Furthermore, because the Planck’s value of the Hubble constant is lower, each redshift in our calculations has to be increased by about 4 per cent and so the box size \( L_{box} \). Thus, the changes associated with the new best-fitting cosmological parameters have a negligible effect on our results.

4 SUMMARY AND CONCLUSIONS

We have performed 75 DM-only cosmological simulations with two different particle numbers (256\(^3\) and 512\(^3\)) and inside three different box sizes \( L_{box} = 1, 2 \) and 4 Mpc in order to quantify the fraction of haloes able to overcool their baryonic content due to mergers at high redshift as predicted by SV06.

As shown in Prieto et al. (2012) accretion and (minor) mergers on to a halo of mass above the critical value defined by SV06, \( M_c(z) \) produce supersonic turbulence and a shocked environment, where \( H_2 \) and HD molecules are formed efficiently. There, regions are able to (over)cool below the \( H_2 \) cooling temperature floor.

To identify the fraction of haloes where the above conditions are verified, we computed the progenitor’s mass for each halo at a given redshift inside a bin mass, specified in Table 2. This mass range spans the transition between \( H_2 \) molecular cooling to atomic
cooling haloes. Every halo with more than one progenitor of which at least one has a mass above \( M_{\text{cr}}(z) \), was counted as an OC halo.

Our results show that a non-negligible fraction of the mini-haloes formed at \( z \geq 10 \) OC their primordial gas due to the process outlined above. The fraction of OC haloes at \( z = 10 \) is \( f_{\text{HD}}^{\text{OC}} \gtrsim 0.5 \) for masses roughly below the atomic cooling limit: \( 1 \times 10^7 \lesssim M/M_\odot \lesssim 3 \times 10^7 \). At higher redshift, \( z \lesssim 12.5 \), the fraction \( f_{\text{HD}}^{\text{OC}} \gtrsim 0.2 \) and it is below 0.2 for \( z \gtrsim 15 \). The fraction of OC haloes rises with halo mass. For haloes above the atomic cooling limit, \( 2 \times 10^7 \lesssim M/M_\odot \lesssim 8 \times 10^7 \), the fraction of OC haloes at \( z \lesssim 12.5 \) is \( f_{\text{HD}}^{\text{OC}} \gtrsim 0.8 \).

The existence of a non-negligible fraction of OC haloes at high redshift has interesting consequences for the star formation process in primordial environments. As predicted by SV06 the HD molecular cooling drops the gas temperature to the CMB limit \( T_{\text{CMB}}(z) \approx 2.73(1 + z) \) allowing the formation of low-mass primordial stars (Prieto et al. 2011, 2012). Their low mass makes these primordial (Population III) stars very long lived, opening a window for the potential detection of primordial stars in the local Universe.

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