

The transition from population III to population II-I star formation

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ABSTRACT

We present results from the first cosmological simulations which study the onset of primordial, metal-free (population III), cosmic star formation and the transition to the present-day, metal-rich star formation (population II-I), including molecular (H_2 , HD, etc.) evolution, tracing the injection of metals by supernovae (SNe) into the surrounding intergalactic medium and following the change in the initial mass function (IMF) according to the metallicity of the corresponding stellar population. Our investigation addresses the role of a wide variety of parameters (critical metallicity for the transition, IMF slope and range, SN/pair-instability SN metal yields, star formation threshold, resolution, etc.) on the metal-enrichment history and the associated transition in the star formation mode. All simulations present common trends. Metal enrichment is very patchy, with rare, unpolluted regions surviving at all redshifts, inducing the simultaneous presence of metal-free and metal-rich star formation regimes. As a result of the rapid pollution within high-density regions due to the first SN/pair-instability SN, local metallicity is quickly boosted above the critical metallicity for the transition. For this reason, population III stars dominate only during the very first stages of structure formation, with an average contribution to the total star formation rate that reaches a constant value of $\sim 10^{-3}$ at redshift ~ 11 –13. If primordial supernovae consisted only of type II ones, the contribution would be $\sim 10^{-1}$. Interestingly, the above conclusions are independent from many poorly constrained parameters.

Key words: cosmology: theory – dark ages, reionization, first stars – early Universe – large-scale structure of Universe.

1 INTRODUCTION

The standard paradigm of cosmic structure formation relies on the classical approach of Jeans' theory applied to primordial matter fluctuations in the frame of an expanding Universe (Jeans 1902; Gunn & Gott 1972; Peebles 1974; White & Rees 1978; Ciardi & Ferrara 2005). The overall picture agrees with a 'flat' Universe where 'cold dark matter' (CMD) is the dominant fraction of matter and the 'cosmological constant', Λ , is the dominant fraction of the cosmological energy density. Baryonic structures arise from in-fall and condensation of gas into dark-matter potential wells. Recent determinations of the cosmological parameters (Komatsu et al. 2010) suggest a present-day expansion rate $H_0 \simeq 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ this parameter becomes $h \simeq 0.70$), a total-matter density parameter $\Omega_{\text{m}} \simeq 0.272$, with 'baryonic' component $\Omega_{\text{b}} \simeq 0.0456$, and a cosmological-constant density parameter $\Omega_{\Lambda} \simeq 0.728$. The primordial power spectrum of perturbation

is well fitted by a power law with index $n \simeq 0.96$ and normalization via mass variance within $8 \text{ Mpc } h^{-1}$ radius $\sigma_8 \simeq 0.8$. As a reference, it is common to define the standard Λ CDM model the one with the following parameters: $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{m}} = 0.3$, $\Omega_{\text{b}} = 0.04$, $\Omega_{\Lambda} = 0.7$, $\Omega_{\text{tot}} = 1.0$, $n = 1$, $\sigma_8 = 0.9$. It is believed that the very first generation of stars should be characterized by massive objects with typical masses much larger than the presently observed ones (Schwarzschild & Spitzer 1953; Woosley & Weaver 1995; Larson 1998; Chiosi 2000; Heger & Woosley 2002, 2008). These primordial (population III, hereafter popIII) stars are formed out of a pristine environment, where the cooling agents are limited to primordial, H-based molecules only, i.e. H_2 and HD, which are able to cool the gas down to temperatures of $\sim 10^2 \text{ K}$. Therefore, the mass of primordial stars should be relatively large and their spectrum is commonly referred to as 'top-heavy' initial mass function (IMF; Larson 1998). These features imply very short lifetimes (up to $\sim 10^6 \text{ yr}$ only) and final death mostly into black holes (Heger & Woosley 2002). The only mass range where primordial stars can explode as pair-instability supernovae (PISN) and pollute the surrounding medium is $[140, 260 \text{ M}_{\odot}]$ (Heger &

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Woosley 2002).¹ The subsequent star formation events in enriched regions will happen in completely different conditions, because metals allow further cooling and fragmentation to smaller scales (chemical feedback). This results in an initial stellar-mass function peaked at lower masses, similar to the nowadays-observed Salpeter-like (Salpeter 1955) IMF, for common (population II-I, hereafter popII-I) stars, in the local Universe.

A very debated issue is the understanding of the transition from the primordial popIII star formation regime to the standard popII-I regime. In this respect, observations of very metal-poor stars have been done (e.g. Frebel et al. 2010, and references therein) and there are also theoretical evidences for the existence of a critical metallicity, Z_{crit} , at which the modalities of star formation allow such transition (Bromm et al. 2001; Schneider et al. 2002): Z_{crit} is the metallicity at which the metal cooling function dominates over the molecular one. Different studies suggest discrepant values with Z_{crit} varying between $\sim 10^{-6} Z_{\odot}$ (e.g. Schneider et al. 2006b) and $\sim 10^{-3} Z_{\odot}$ (e.g. Bromm & Loeb 2003).² The main uncertainty on the determination of Z_{crit} is the presence of dust at high redshift, revealed from observations of Ly α systems (Pettini, Boksenberg & Hunstead 1990), and quasar emissions in the millimeter wavelengths (McMahon et al. 1994). Dust is commonly formed in long-lived, low-mass stars during their asymptotic giant branch phase. However, if early SNe were able to produce dust (e.g. Bertoldi et al. 2003; Maiolino et al. 2004, 2007), then star formation in the primordial Universe and the level of Z_{crit} would be influenced, as well. Indeed, when the metallicity of star forming regions is still below $\sim 10^{-6} Z_{\odot}$ the only relevant coolants are molecules, mainly H₂ and HD, while above $\sim 10^{-4}$ – $10^{-3} Z_{\odot}$ gas cooling is fully dominated by metal fine-structure transitions (e.g. Maio et al. 2007) and cloud fragmentation can happen down to subsolar scales (e.g. Bromm et al. 2001; Schneider et al. 2002; Schneider, Ferrara & Salvaterra 2004). In between, cooling capabilities depend mainly on the amount of metals depleted on to dust grains. The conclusion of many investigations³ (e.g. Kozasa, Hasegawa & Nomoto 1991; Todini & Ferrara 2001; Nozawa et al. 2003; Bianchi & Schneider 2007; Dwek, Galliano & Jones 2007; Dwek et al. 2008) is that first, massive stars could spread in the early Universe a substantial amount of dust during the final phase of their evolution (as either SNII or PISN).

Semi-analytic studies – not always in agreement with each other – have been made and they generally support the patchiness of metal enrichment and the possibility of continue forming popIII stars at low redshift (e.g. Scannapieco, Schneider & Ferrara 2003; Furlanetto & Loeb 2005; Greif & Bromm 2006; Schneider et al. 2006a; Wyithe & Cen 2007; Trenti & Stiavelli 2009; Trenti, Stiavelli & Michael Shull 2009). The predicted duration of the epoch dominated by popIII star formation and, more in general, the contribution of popIII stars to the intergalactic medium

(IGM) metal enrichment, are generally discordant and dependent on the specific recipes or techniques adopted. To give more accurate and robust answers it is necessary to explore the problem via numerical simulations by consistently following gas chemistry, star formation and feedback effects. Several works investigating metal pollution are present in the literature (like Raiteri, Villata & Navarro 1996; Gnedin 1998; Mosconi et al. 2001; Lia, Portinari & Carraro 2002b,a; Kawata & Gibson 2003; Kobayashi 2004; Ricotti & Ostriker 2004; Scannapieco et al. 2005; Tornatore et al. 2007b; Oppenheimer et al. 2010): heavy elements produced by stars are included via tabulated yields; some works compute primordial chemistry evolution (e.g. Ricotti & Ostriker 2004); Tornatore et al. (2007b) includes, for the first time, the possibility of having multiple IMFs, based on the underlying gas metallicity. None of them, though, follows, at the same time, the three processes: molecule formation from early, non-equilibrium gas chemistry; metal pollution from stellar sources; different IMFs for different stellar populations. This is what we do in this work.

More specifically, we aim at investigating the birth of the first stars, the following cosmic metal enrichment from their explosive death and the transition to the standard, presently observed, star formation regime. We focus on how such transition and the associated features are affected by different choices of Z_{crit} , IMF, post-SN metal yields, star formation density thresholds, box dimension and resolution. We implement gas primordial, molecular chemistry, star formation and feedback effects, metal pollution and different IMFs for different stellar populations.

Throughout the paper we will refer to ‘popIII regime’ and ‘popII-I regime’ when the metallicity is below or above the critical level, respectively. In addition, we will adopt the standard Λ CDM cosmological model.

The paper is organized as follows. We describe the code and the simulations in Section 2, results are given in Section 3, and parameter dependence is addressed in Section 4 (4.1, 4.2 and 4.3). We discuss and conclude in Section 5.

2 SIMULATIONS

The simulations were performed in the frame of the standard Λ CDM cosmological model, by using the GADGET-2 code (Springel 2005). The initial conditions for the reference simulations were generated sampling $0.7 \text{ Mpc } h^{-1}$, comoving (but see also discussion on larger boxes in Section 4.3) of the cosmic fluid at redshift $z = 100$, with 320^3 particles per gas and dark matter species, having masses of 116 and $755 \text{ M}_{\odot} h^{-1}$, respectively. We perform the numerical simulations including primordial molecular evolution (Maio et al. 2006, 2007; Maio 2009), star formation prescriptions (Maio 2009; Maio et al. 2009), and metal pollution from stars (Tornatore et al. 2007b). We choose the stellar IMF according to the value of the gas metallicity Z : if $Z < Z_{\text{crit}}$ a top-heavy IMF is assumed, otherwise a Salpeter one.

More in detail, we include in the code the whole set of chemistry reactions leading to molecule creation or destruction and metal pollution, with the corresponding cooling functions. We follow the abundances of the H- and He-based chemistry, involving e[−], H, H⁺, H[−], He, He⁺, He⁺⁺; H₂-chemistry following H₂, H₂⁺ (Yoshida et al. 2003) and deuterium chemistry with D, D⁺, HD and HeH⁺ (Maio et al. 2007). While in principle an arbitrary number of metals can be accounted for by the scheme for metallicity tracking (Tornatore et al. 2007b), in this work we focus on C, O, Mg, S, Si and Fe, since they are the most abundant metals produced during stellar evolution. We assume, as initial chemical composition, a primordial neutral

¹ At masses of ~ 100 – 140 M_{\odot} there can be some mass loss before collapse (pulsational pair SN). The key uncertainty here is primary nitrogen production and the dredge up of carbon and oxygen. In particular, if the stellar atmosphere is highly CNO enhanced there may be substantial mass loss, but zero metallicity should still be a good first approximation for such stellar flows (Woosley, private communication).

² We adopt $Z_{\odot} \simeq 0.0201$ (Anders & Grevesse 1989; Grevesse & Sauval 1998). See, however, Asplund et al. (2009) for a recently updated value of $Z_{\odot} \simeq 0.0134$.

³ Despite the differences between the dust mass fractions deriving from SNII (2–5 per cent) and PISN (10–15 per cent), the dust-to-metal mass ratios (or ‘depletion factors’) turn out to be ~ 0.3 – 0.7 in both cases and, for metal poor SNII progenitors with masses of 25 M_{\odot} – 30 M_{\odot} , it is up to ~ 1 .

Table 1. Parameters adopted for the simulations. From left to right, we list: model name, box side, number of particles, gas particle initial mass, dark-matter particle mass, critical metallicity, star formation density threshold, popIII IMF range, reference to the stellar-yield tables for SN and PISN.

Model	Box side (Mpc h^{-1})	Number of particles	Mean inter-particle separation (kpc h^{-1})	$M_{\text{gas}}(\text{M}_{\odot} h^{-1})$	$M_{\text{dm}}(\text{M}_{\odot} h^{-1})$	Z_{crit}	$n_{\text{H,th}}$ (cm^{-3})	PopIII IMF range (M_{\odot})	Massive yields
Zcrit3	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-3} Z_{\odot}$	70	[100, 500]	HW02 ^a
Zcrit4	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-4} Z_{\odot}$	70	[100, 500]	HW02 ^a
Zcrit5	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-5} Z_{\odot}$	70	[100, 500]	HW02 ^a
Zcrit6	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-6} Z_{\odot}$	70	[100, 500]	HW02 ^a
Zcrit4-r8-100	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-4} Z_{\odot}$	70	[8, 100]	HW08 ^b
Zcrit4-r0.1-100	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-4} Z_{\odot}$	70	[0.1, 100]	HW08 ^b
Zcrit4-HW8-40	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-4} Z_{\odot}$	70	[0.1, 100]	HW08 ^b
Zcrit4-WW8-40	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-4} Z_{\odot}$	70	[0.1, 100]	WW95 ^c
Zcrit4-th7	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-4} Z_{\odot}$	7	[100, 500]	HW02 ^a
Zcrit4-th1	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-4} Z_{\odot}$	1	[100, 500]	HW02 ^a
Zcrit4-th01	0.7	2×320^3	2.187	1.16×10^2	7.55×10^2	$10^{-4} Z_{\odot}$	0.1	[100, 500]	HW02 ^a
Zcrit4-5th7	5.0	2×320^3	15.62	4.23×10^4	2.75×10^5	$10^{-4} Z_{\odot}$	7	[100, 500]	HW02 ^a
Zcrit4-10th7	10.0	2×320^3	31.25	3.39×10^5	2.20×10^6	$10^{-4} Z_{\odot}$	7	[100, 500]	HW02 ^a

^aData tables from Heger & Woosley (2002).^bData tables from Heger & Woosley (2008).^cData tables from Woosley & Weaver (1995).

gas with residual electron and H^+ fractions (Galli & Palla 1998) $x_{\text{e}} \simeq x_{\text{H}^+} \simeq 4 \times 10^{-4}$, H_2 fraction $x_{\text{H}_2} = 10^{-6}$, H_2^+ fraction $x_{\text{H}_2^+} = 3 \times 10^{-21}$, D fraction $x_{\text{D}} = 3.5 \times 10^{-5}$, D^+ fraction $x_{\text{D}^+} = 4 \times 10^{-9}$, HD fraction $x_{\text{HD}} = 7 \times 10^{-10}$, HeH^+ fraction $x_{\text{HeH}^+} = 10^{-14}$. Individual metals are set to zero initial abundance.

The natural gas evolution, with the initial in-fall into the dark-matter potential wells and the shock-heating phase, is fully self-consistently followed through the attainment of the isothermal turnover and the subsequent cooling regime. This stage is very important at early times, as it represents the state when gas cooling balances and takes over heating. Resolving the isothermal phase in primordial-chemistry simulations is fundamental to account for the early molecular cooling of the gas (as already discussed and shown in Maio et al. 2009). For this reason, we assume that stars are formed roughly at the end of the gas cooling process, when a suitable physical density threshold for early star formation of $\sim 10^2 \text{ cm}^{-3}$ (more exactly 70 cm^{-3}) is reached (Maio 2009; Maio et al. 2009). The often used low-density threshold of $\sim 0.1 \text{ cm}^{-3}$ (e.g. Katz 1992; Katz, Weinberg & Hernquist 1996) would induce spurious time anticipation of the onset of star formation (Maio et al. 2009). Hereafter, stars evolve and die according to their characteristic lifetimes, possibly expelling newly created metals into the surrounding gas and modifying its cooling properties either at low (e.g. Maio et al. 2007) and at high temperatures (e.g. Sutherland & Dopita 1993; Wiersma, Schaye & Smith 2009; Cantalupo 2010).

For the very first bursts (and those happening in gas of metallicity smaller than Z_{crit}) we adopt a ‘Salpeter-like’ IMF, in the mass range [100, 500 M_{\odot}], with a slope of -1.35 . The stellar life-times lie between $\sim 3 \times 10^6$ yr, for the 100 M_{\odot} stars, and ~ 0 yr (instantaneous death), for the hundreds-solar-masses stars. As mentioned in Section 1, the relevant mass range for metal pollution is approximately [140, 260 M_{\odot}], because of the formation of PISN. We point out that in our approach each star forming smoothed particle hydrodynamics (SPH) particle can be assimilated to a simple stellar population, with coeval stars formed out from the same environment. Once the particle (i.e. stellar population) metallicity reaches the critical value, Z_{crit} , popII-I star formation is assumed to set in, in place of popIII, and subsequent stars will have masses in the range [0.1, 100 M_{\odot}], distributed according to a Salpeter IMF. PopII-I stel-

lar life-times are usually much longer than those of popIII, ranging between $\sim 2 \times 10^{10}$ yr, for the 0.1 M_{\odot} stars, and $\sim 3 \times 10^6$ yr, for the 100 M_{\odot} .

Yields of popIII stars (see discussion in Section 4.1) are assumed accordingly to Heger & Woosley (2002), while for popII-I stars we follow Woosley & Weaver (1995) for massive stars (SNII), van den Hoek & Groenewegen (1997) for mass loss of low- and intermediate-mass stars, and Thielemann et al. (2003) for SNIa.

In order to describe properly stellar evolution, it is important to take into account feedback effects which deal with those physical processes that are not resolved because of numerical limitations. In our simulations star forming particles are subject to wind kinetic feedback⁴ with velocities of 500 km s^{-1} . These particles produce metals which are smoothed over the neighbours according to the SPH kernel.

We perform four numerical simulations considering critical metallicities of $Z_{\text{crit}} = 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6} Z_{\odot}$, which span the full range found in the literature (see Section 1). In Sections 4.1, 4.2 and 4.3 we will also investigate how the results are affected by a different choice for the popIII IMF, the post-SN yields, the critical star formation threshold and the box dimension/resolution. A schematic description of the simulations is given in Table 1.

3 RESULTS

In this section, we present results related to the early phases of cosmological metal enrichment and the transition from popIII to popII-I regime. The results refer to the 0.7 Mpc h^{-1} side box described in the previous section, with varying Z_{crit} , the most significant parameter in the calculation.

The strength of our results is that they are physically well motivated and self-consistent. In fact, as described previously, we followed in detail early, non-equilibrium chemistry, metal pollution from stars, and adopted the proper IMF for the actual star formation regime. The inclusion of both molecular and metal cooling is a very

⁴ For a different metal/feedback approach, see also treatments based on thermal feedback (e.g. Scannapieco et al. 2005).

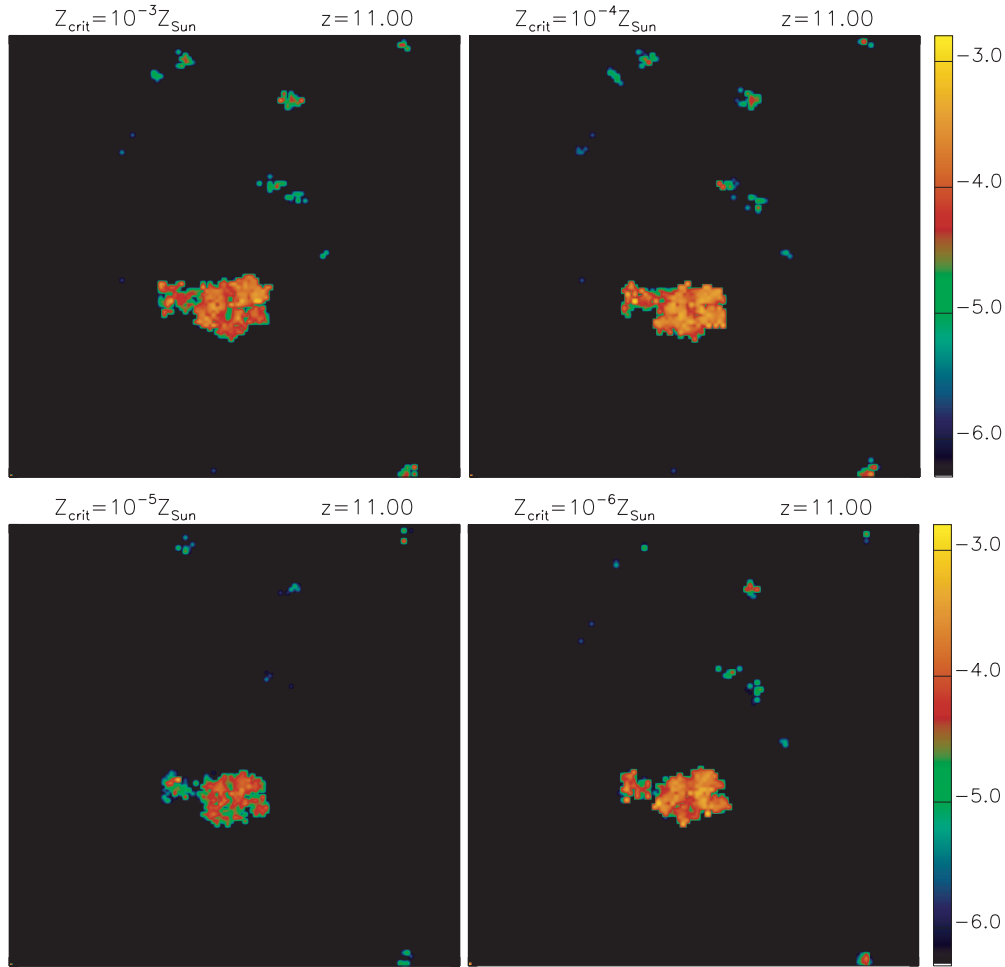


Figure 1. Metallicity maps at redshift $z = 11$ for the $0.7 \text{ Mpc } h^{-1}$ side box, with $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ (top-left panel), $10^{-4} Z_{\odot}$ (top-right panel), $10^{-5} Z_{\odot}$ (bottom-left panel) and $10^{-6} Z_{\odot}$ (bottom-right panel). The maps are obtained by projecting the whole simulation box.

relevant issue, mostly in high resolution simulations like these, as it leads to gas collapse at any time, and in any star forming environment. The subsequent metal-enrichment properties, are, instead, related to the feedback model.

3.1 Metallicity distribution

In order to have a visual representation of the simulations we show maps at redshift $z = 11$ for the projected metallicity distribution (Fig. 1) for all the cases considered: $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ (upper-left panel), $10^{-4} Z_{\odot}$ (upper-right panel), $10^{-5} Z_{\odot}$ (bottom-left panel) and $10^{-6} Z_{\odot}$ (bottom-right panel). The metallicity is defined as the metal mass fraction of each SPH particle: for each SPH particle with total mass m_{tot} , we track the mass of the individual species considered (see Section 2), sum up the contribution of all the heavy elements, m_Z , and assign the metallicity, Z , according to its definition, $Z = m_Z/m_{\text{tot}}$.

Metal enrichment is very patchy and there are regions which are very strongly polluted and others which preserve their pristine, metal-free composition. The main pollution events happen around the densest regions, where star formation takes place. We stress that the differences in the distribution and level of metallicities are only due to the value of Z_{crit} adopted. In particular, the metallicity of the gas reaches a slightly higher value and wider distribution for the $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ case than for the other cases. This is due to the longer time needed to reach the critical level, Z_{crit} . Once

this happens, popII-I star formation sets in and further delays metal pollution, because the SNI from popII-I stars release about one fourth of metals per unit mass than the popIII ones, on a time-scale at least ~ 10 times longer. When $Z_{\text{crit}} = 10^{-6} Z_{\odot}$, pollution above the critical metallicity threshold is immediate and most of the regions rapidly move into the popII-I star formation regime. This transition gets delayed as Z_{crit} increases.

In Fig. 2, we compare metal enrichment at different redshifts. The maps refer to $z = 11$ (upper row), 12 (central row) and 13 (bottom row), for $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ (left-hand column) and $10^{-5} Z_{\odot}$ (right-hand column). The process is quite fast as inferred from the rapid growth of metal-enriched bubbles, and allows for high metal pollution within very short time (see also Section 3.2). More enrichment is found in the center of the star forming regions, and less in the periphery. Sometimes, there are areas with lower Z in the cores of such structures: this is due to projection effects.

To highlight the differences between popIII and popII-I star forming regions, we plot in Fig. 3 the corresponding two-population maps⁵ projecting the whole box. They show very well how the star formation regime evolves according to metallicity (see further discussion in Section 3.3). From a more quantitative analysis of the figure, some distinctive behaviour emerges. For $Z_{\text{crit}} = 10^{-6} Z_{\odot}$,

⁵ In this case, data are not smoothed on the edges of the pixels.

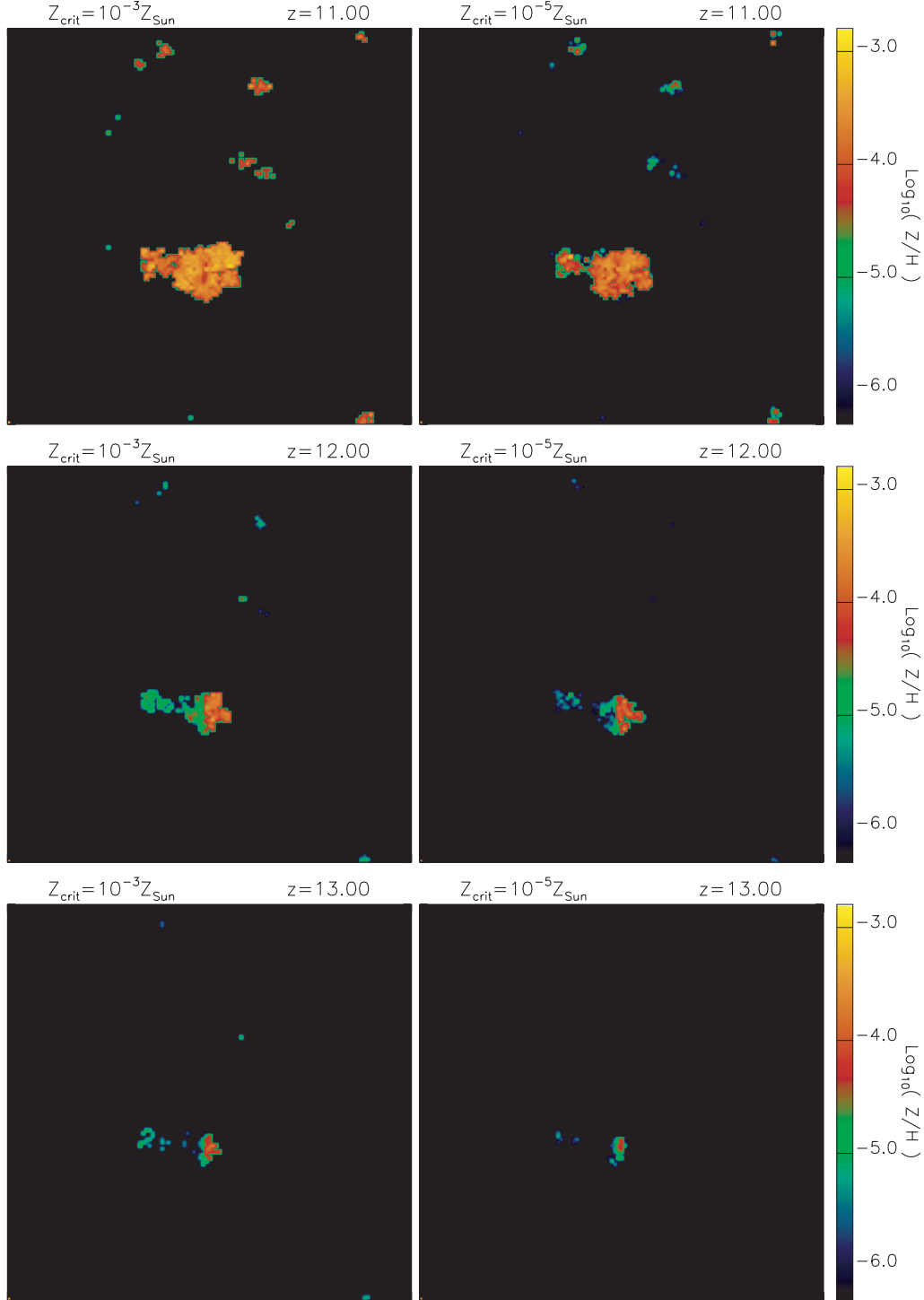


Figure 2. Comparison of the metallicity maps at redshift $z = 11$ (upper row), 12 (central row) and 13 (bottom row), for the $0.7 \text{ Mpc } h^{-1}$ side box with $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ (left-hand column) and $10^{-5} Z_{\odot}$ (right-hand column). The maps are obtained by projecting the whole simulation box.

almost all the polluted areas reach the critical metallicity already in $\sim 0.1 \text{ Gyr}$ (~ 98 per cent at $z = 13$, ~ 99 per cent at $z = 12$ and ~ 100 per cent at $z = 11$). In the other cases we observe a similar quick enrichment: for $Z_{\text{crit}} = 10^{-5}$, 10^{-4} and $10^{-3} Z_{\odot}$ the percentage of areas with $Z \geq Z_{\text{crit}}$ is respectively ~ 72 , 49 and 32 per cent at $z = 13$; ~ 86 , 70 and 39 per cent at $z = 12$; and ~ 99 , 97 and 97 per cent at $z = 11$. We note as well that, at fixed redshift, the fraction of popII-I star formation regions decreases with increasing

Z_{crit} , because of the higher enrichment level needed to allow the transition from $Z < Z_{\text{crit}}$ to $Z \geq Z_{\text{crit}}$.

As the enrichment process is very localized, also the transition to a different star formation regime strongly depends on location. This means that it is possible to find coexistence of population III and population II-I, with stronger pollution in the central regions of star formation sites and weaker pollution in the outermost ones (see maps in Figs 1 and 2). It is in fact evident that the preferential

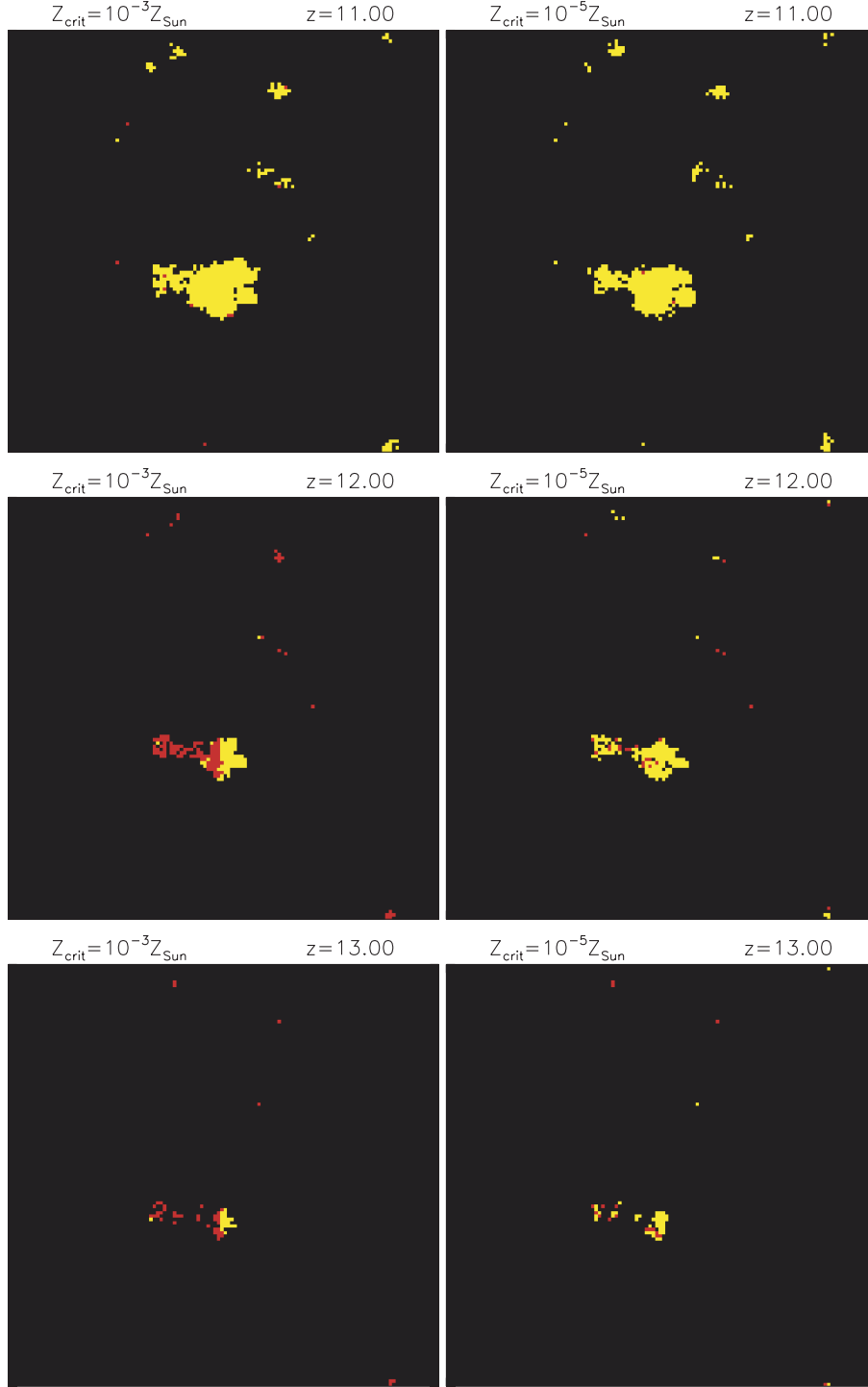


Figure 3. Comparison of the two-population metallicity maps at redshift $z = 11$ (upper row), 12 (central row), and 13 (bottom row), for the $0.7 \text{ Mpc } h^{-1}$ side box with $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ (left-hand column) and $10^{-5} Z_{\odot}$ (right-hand column). The yellow areas refer to polluted regions with metallicity higher than Z_{crit} , while the red ones to those with metallicity lower than Z_{crit} . The maps are obtained projecting the whole box.

sites of popIII star formation are isolated areas and often peripheric regions not strongly contaminated by nearby bursts. Our findings are consistent with the study by Tornatore, Ferrara & Schneider (2007a). We note that changes in Z_{crit} can only slightly alter the whole enrichment scenario, as, after $\Delta z \sim a \text{ few}$, just few regions which undergo popII-I star formation for $Z_{\text{crit}} = 10^{-5} Z_{\odot}$ are undergoing popIII star formation for $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ (e.g. Fig. 3). In fact, the star forming environment is chemically ‘sterilized’ by one

or a few subsequent popIII generations, and some differences are only visible during the very initial phase of metal pollution.

3.2 Metallicity evolution

From the previous results, it emerges that metal enrichment is a very patchy and inhomogeneous phenomenon. Never the less, as an indicative estimate of the global enrichment history of the

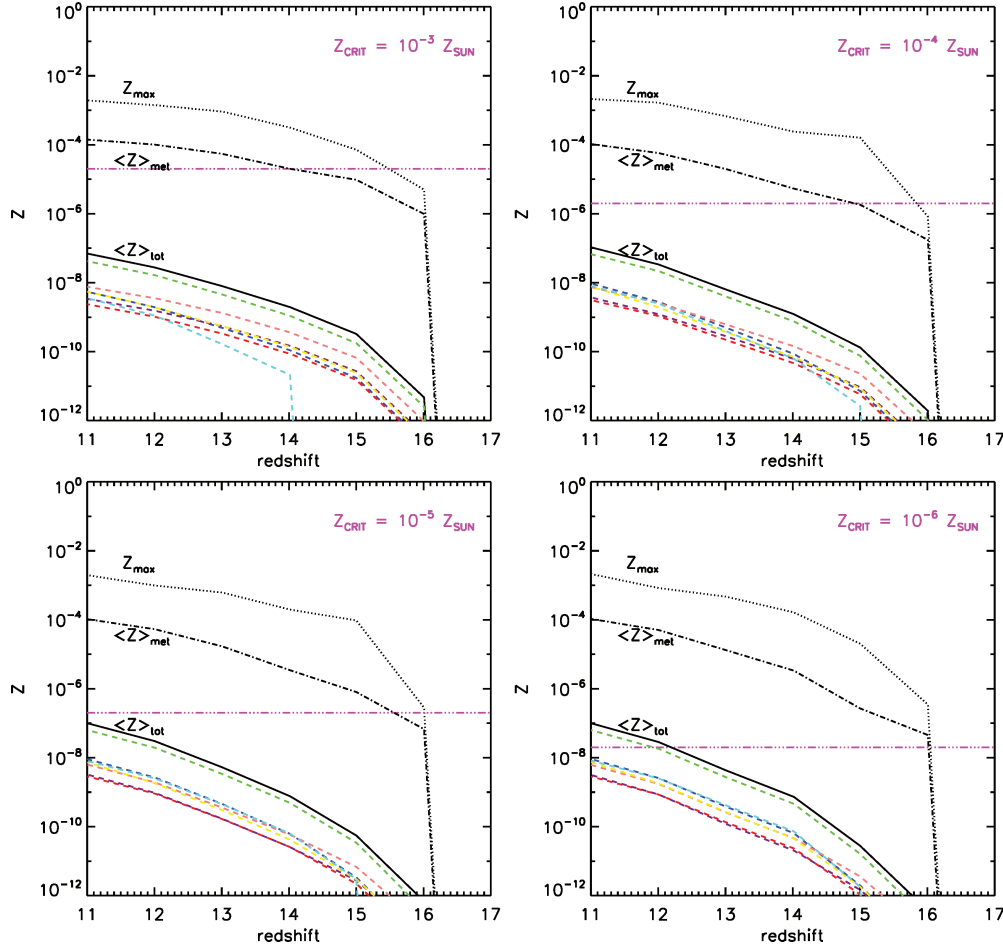


Figure 4. Metal evolution as function of redshift for the $0.7 \text{ Mpc } h^{-1}$ side box simulations, with $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ (upper-left panel), $10^{-4} Z_{\odot}$ (upper-right panel), $10^{-5} Z_{\odot}$ (bottom-left panel) and $10^{-6} Z_{\odot}$ (bottom-right panel) case. The magenta horizontal dot-dot-dot-dashed line indicates, in each panel, the critical metallicity; the dotted line is the maximum metallicity; the dot-dashed line is the average metallicity of the spread metals; the solid line is the total metallicity averaged over the whole simulation box and the dashed lines the corresponding individual metallicities: oxygen (green), carbon (blue), magnesium (red), sulphur (purple), silicon (pink), iron (yellow), other metals (cyan) – see also text in Section 2.

Universe, we present the evolution of the average metallicities found in the simulations (Fig. 4). Following previous discussions, we expect large fluctuations⁶ around the mean values reported here. In particular, for each Z_{crit} (labelled on the upper-right corner and shown by the horizontal dot-dot-dot-dashed line in each panel), we show the maximum metallicity reached at any redshift (dotted lines), the average metallicity of the enriched regions (dot-dashed lines), the average metallicity in the whole simulation box including primordial unpolluted zones (solid line) and the corresponding individual metallicities for the different metals tracked by the code (dashed lines).

The first metals spread during the final stages of stellar evolution leads to typical metallicities in the surrounding ISM of $Z \sim (10^{-5} - 10^{-4}) Z_{\odot}$, which, shortly after, rise to values of $Z \sim (10^{-4} - 10^{-3}) Z_{\odot}$, between redshift $z \sim 16$ and $z \sim 15$. Therefore, the critical metallicity Z_{crit} is easily overtaken, despite its precise, actual determination. The leading element is always oxygen, as it is the most abundant one produced by SNII and PISN explosions.

For higher Z_{crit} the popIII regime lasts longer, so that more massive star explosions take place which can pollute the medium up

to higher metallicities, before popII-I star formation regime sets in. This results in a quicker Z increase in the very early stages – the difference between the $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ and $Z_{\text{crit}} = 10^{-6} Z_{\odot}$ cases is more than one order of magnitude at $z \sim 15$.

Broadly speaking, a metallicity of $10^{-6} - 10^{-5} Z_{\odot}$ is locally reached after only $\sim 10^5$ yr. In $\sim 5 \times 10^6$ yr, it is possible to get $Z \sim 10^{-4} Z_{\odot}$ or even $Z \sim 10^{-3} Z_{\odot}$. An average pollution of $Z \sim Z_{\text{crit}}$ is always obtained in a few 10^7 yr (i.e. $\Delta z \sim 1$, at $z \sim 16$) after the onset of star formation (Fig. 4). Once the critical metallicity is reached, popII-I star formation sets in and contributes (on longer time-scales) to metal enrichment, as well.

3.3 Star formation from population III and population II-I stellar generations

In Fig. 5, we plot the average⁷ popIII star formation rate, SFR_{III} , and the average total star formation rate, SFR_{tot} . For all the simulations the onset of star formation is at $z \simeq 16.3$, when the Universe is about 2.3×10^8 yr old (independently from Z_{crit} , which plays a

⁶ Variances are comparable to the averages.

⁷ The average is the arithmetic average of the star formation rates taken at each time-step and binned over 50 bins in redshift.

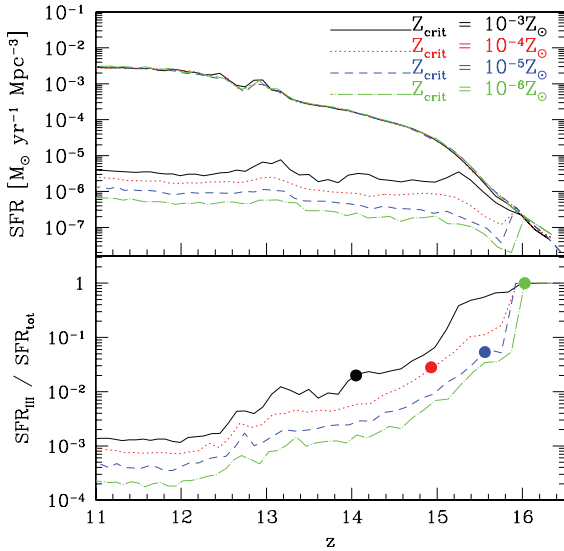


Figure 5. Upper panel: redshift evolution of the average star formation rate densities (in $M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$) for the $0.7 \text{ Mpc } h^{-1}$ side box simulations. The four upper lines are the total star formation rate densities for $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ (solid line), $10^{-4} Z_{\odot}$ (dotted line), $10^{-5} Z_{\odot}$ (dashed line), and $10^{-6} Z_{\odot}$ (dotted-dashed line). The four lower lines are the corresponding popIII contributions. Bottom panel: evolution of the ratio between the average popIII star formation rate density (SFR_{III}) and the total star formation rate density (SFR_{tot}), $\text{SFR}_{\text{III}}/\text{SFR}_{\text{tot}}$. The bullets correspond to the redshift at which the average metallicity of the enriched particles equals the value of Z_{crit} (as in Fig. 4).

role only in the following epochs). As shown in Fig. 5, at the very beginning popIII contribution is dominant, but rapidly fades away and the popII-I regime is established.

For the $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ case, the contribution is higher and it decreases with Z_{crit} . In fact, the higher Z_{crit} , the higher the number of star forming regions with $Z < Z_{\text{crit}}$. The total star formation rate density is only mildly influenced by the exact value adopted for Z_{crit} , meaning that popIII star formation does not affect the global behaviour significantly and the bulk of star formation is mainly led by popII-I stars. The reason for this is simply understood in terms of time-scales, as popIII stars have shorter lifetimes (at most $\sim 10^6 \text{ yr}$) and heavily pollute the medium up to Z_{crit} via PISN explosions. Therefore, after the first bursts, it is much easier to match the conditions for standard popII-I star formation, rather than metal free star formation. The period over which star formation is dominated by popIII is slightly longer in the $Z_{\text{crit}} = 10^{-3} Z_{\odot}$ case and decreases gradually with Z_{crit} . For $Z_{\text{crit}} = 10^{-3} Z_{\odot}$, ~ 100 per cent of the total SFR is due to popIII stars in the redshift interval $z \sim 15-16$ (equivalent to a time interval of $\sim 2 \times 10^7 \text{ yr}$), while the percentage decreases to an average value of roughly 0.1 per cent at $z \sim 12$. In the $Z_{\text{crit}} = 10^{-6} Z_{\odot}$ case, there is a sudden drop below ~ 10 per cent already at $z \sim 15-16$ and down to ~ 0.01 per cent at $z \sim 12$. The intermediate cases are bracketed by the former two regimes. These trends are consistent, because the time to pollute the IGM to lower Z_{crit} is shorter. The resulting behaviour – the smaller Z_{crit} , the earlier the transition from popIII to popII-I dominated star formation – is expected, because, as mentioned, the time needed to pollute the IGM up to lower Z_{crit} is shorter.

The dots on the lines of the average fractions of popIII star formation rate densities, point to the redshifts when the average enrichment reaches the level of Z_{crit} (i.e. the abscissa of the inter-

secting point between the dotted line and the horizontal line in each panel of Fig. 4) for the different cases. We note that this is only a very indicative comparison because, due to the patchiness of metal enrichment, popII-I stars form before this epoch and popIII stars continue forming after it. At those redshifts, the average contribution of popIII star formation has already dropped of more than one order of magnitude. For the $Z_{\text{crit}} = 10^{-6} Z_{\odot}$ case, Z_{crit} is reached in the polluted regions when $\text{SFR}_{\text{III}}/\text{SFR}_{\text{tot}} \sim 1$ and this ratio steeply decreases afterwards. In the cases with higher Z_{crit} , the popII-I regime develops simultaneously with the popIII regime, and the average popIII contribution to the total star formation rate when $Z \sim Z_{\text{crit}}$ is below ~ 10 per cent.

4 PARAMETER DEPENDENCE

In the following, we will investigate the effects on our results of the main parameters (other than Z_{crit}) adopted in the simulations and choose as reference the one with box dimension $0.7 \text{ Mpc } h^{-1}$, $Z_{\text{crit}} = 10^{-4} Z_{\odot}$, $n_{\text{H,th}} = 70 \text{ cm}^{-3}$ and Salpeter slope for popIII stars in the range $[100, 500 M_{\odot}]$. We have also checked the effects of adopting a different implementation of SPH [the relative pressure SPH (*rp*SPH) according to Abel 2010], which only considers pressure gradients in force calculations and should perform closer to grid-based codes. We found no strong deviations in the general gas state (as also expected from the discussion in section 3.8 of Abel 2010) and even in the star formation rates. Metal pollution at early times is slightly more scattered, due to the capability of the *rp*SPH implementation of better resolving instabilities. Overall, there are no substantial changes in our results.

4.1 Different population III IMFs and yields

In order to account for the uncertainties on the popIII IMF, we explore first the role of its slope, which so far has been fixed to the value $s = -1.35$. There are no robust arguments (neither theoretical nor observational) supporting the above assumption and different slopes or shapes are not excluded. None the less, by changing slope, the expected fraction of PISN is not dramatically modified, as its value, over the mass range $[100, 500 M_{\odot}]$, is always around ~ 0.4 for any s between, roughly, -1 and -3 . Thus, the results on metallicity evolution and star formation rates are not altered at all.

Differently, the chosen mass range and yields of popIII stars could play a more important role, since they directly affect metal pollution and star formation history. The existence of popIII stars with masses below $\sim 10^2 M_{\odot}$ is supported by numerical simulations (e.g. Yoshida 2006; Yoshida, Omukai & Hernquist 2007; Campbell & Lattanzio 2008; Suda & Fujimoto 2010), which find that it is possible to fragment primordial clouds down to $\sim 10 M_{\odot}$. According to Woosley & Weaver (1995), $Z = 0$ massive stars can die as SN if their mass is smaller than $40 M_{\odot}$; above this limit, they collapse into black holes. Recent updates, though, suggest that such stars can die as SN even if their masses are larger, up to $100 M_{\odot}$ (Heger & Woosley 2008). We have investigated the implications of these uncertainties on our results.

In Fig. 6, together with the results for our reference run (dotted lines), we show the trends for different popIII IMF mass ranges (we use the same slope, $s = -1.35$, SNII energy of 10^{51} erg , and PISN energy of 10^{53} erg), assuming metal yields for primordial,

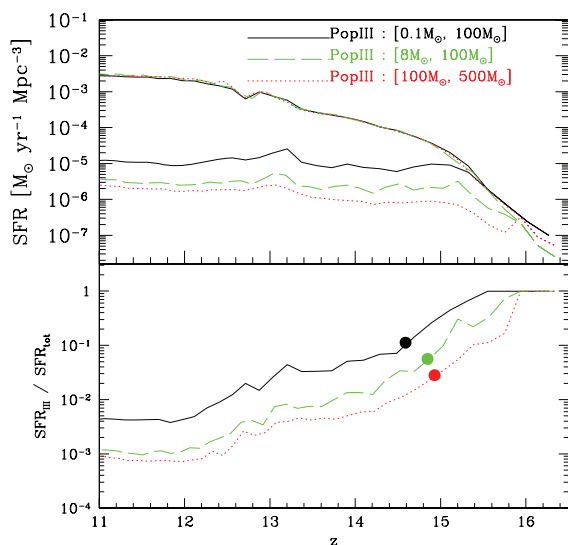


Figure 6. Upper panel: redshift evolution of the average star formation rate densities (in $M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$) for the $0.7 \text{ Mpc } h^{-1}$ side box simulations with $Z_{\text{crit}} = 10^{-4} Z_{\odot}$. The upper lines are the total star formation rate densities for different popIII IMF mass range: $[0.1, 100 M_{\odot}]$ (solid lines), $[8, 100 M_{\odot}]$ (dashed lines) and $[100, 500 M_{\odot}]$ (dotted lines). The lower lines are the corresponding popIII contributions. Bottom panel: evolution of the ratio between the average popIII star formation rate density (SFR_{III}) and the total star formation rate density (SFR_{tot}), $\text{SFR}_{\text{III}}/\text{SFR}_{\text{tot}}$. The bullets correspond to the redshift at which the average metallicity of the enriched particles equals the value of Z_{crit} .

massive SN from Heger & Woosley (2008).⁸ We plot star formation rates and the corresponding popIII contribution for popIII IMF mass ranges of $[0.1, 100 M_{\odot}]$ (solid lines), $[8, 100 M_{\odot}]$ (dashed lines) and $[100, 500 M_{\odot}]$ (dotted lines). The latter case is our reference run and its popIII contribution is always lower than the other ones. The reason is the extremely short lifetime of stars with masses in the range $[100, 500 M_{\odot}]$ (and in particular in the PISN range), which pollute the surrounding medium in a time-lag much shorter than the one needed to longer-living $\sim 10 M_{\odot}$ stars. Therefore, metal pollution and the transition to popII-I regime happen earlier, with a residual popIII contribution of a factor of 3 or 4 smaller. The difference between the extreme case of stellar masses in the range $[0.1, 100 M_{\odot}]$ and the case of stellar masses in the range $[8, 100 M_{\odot}]$ is simply due to the different normalization of the IMF, since yields and massive-SN lifetimes are the same. Indeed, the SN fractions are ~ 0.14 and 1, respectively. Thus, as in the latter case 100 per cent of the stars dies as SN, their enrichment results slightly higher, and the popIII contribution drops faster than in the former one (see also the bullets in the lower panel).

Finally, we investigate the effects of different metal yields, according to Woosley & Weaver (1995) and Heger & Woosley (2008). As the massive-SN mass range differs in the two works, in order to have a fair comparison between the yields only and to exclude normalization effects, we fix the popIII IMF range as $[0.1, 100 M_{\odot}]$ and the massive-SN mass range as $[8, 40 M_{\odot}]$. In Fig. 7, we compare the results for the Woosley & Weaver (1995)’s yields (dashed lines) and for the Heger & Woosley (2008)’s ones (dot-dashed lines). For sake of completeness, we replot also the results for the IMF mass

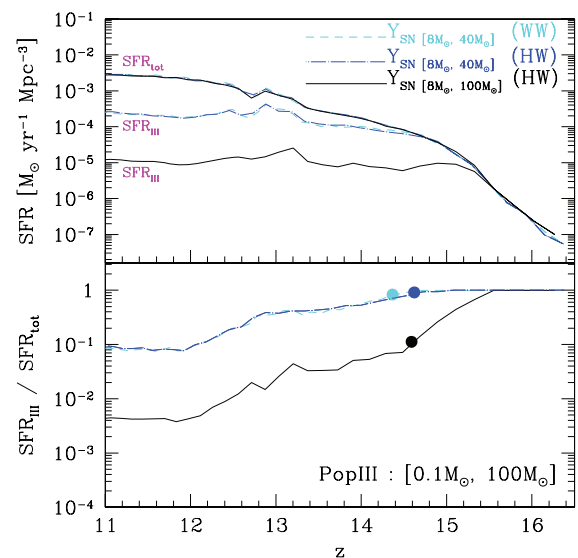


Figure 7. Upper panel: redshift evolution of the average star formation rate densities (in $M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$) for the $0.7 \text{ Mpc } h^{-1}$ side box simulations with $Z_{\text{crit}} = 10^{-4} Z_{\odot}$. The upper lines are the total star formation rate densities for different popIII metal yields, and fixed the popIII IMF mass range at $[0.1, 100 M_{\odot}]$: primordial SN yields for stars of $[8, 40 M_{\odot}]$, according to the case $Z = 0$ in Woosley & Weaver (1995) (dashed lines); primordial SN yields for stars of $[8, 40 M_{\odot}]$ according to Heger & Woosley (2008) (dot-dashed lines); and primordial SN yields for stars of $[8, 100 M_{\odot}]$ according to Heger & Woosley (2008) (solid lines). The lower lines are the corresponding popIII contributions. Bottom panel: evolution of the ratio between the average popIII star formation rate density (SFR_{III}) and the total star formation rate density (SFR_{tot}), $\text{SFR}_{\text{III}}/\text{SFR}_{\text{tot}}$. The bullets correspond to the redshift at which the average metallicity of the enriched particles equals the value of Z_{crit} .

range of $[0.1, 100 M_{\odot}]$ and the massive-SN range of $[8, 100 M_{\odot}]$ (Heger & Woosley 2008). Due to the longer lifetimes of $10\text{--}40 M_{\odot}$ stars (dashed lines and dot-dashed lines), with respect to PISN and $100 M_{\odot}$ star lifetimes (solid lines), the popIII regime can now last longer (compare bullets in Fig. 7 with the ones in Fig. 5 or in Fig. 6), and contribute up to 10 per cent the total SFR at $z \sim 11$: some order of magnitude more than all the other cases. By directly comparing the effects of adopting different yields, in the same mass range, it comes out that their impact is negligible and there are no significant changes in the star formation history.

4.2 Density threshold for star formation

We now address how the transition from popIII to popII-I depends on the choice of the density threshold for star formation. Indeed, it is usual to assume that star formation takes place only in converging flows where a given number density is reached. Because different thresholds lead to different onsets of star formation (see also Maio et al. 2009), this could also affect the properties of the transition. For this reason, we re-run the reference simulation ($n_{\text{H,th}} = 70 \text{ cm}^{-3}$) assuming density thresholds of $n_{\text{H,th}} = 7, 1, 0.1 \text{ cm}^{-3}$. Also in these cases the enrichment is very fast and the critical level in polluted environments is always reached between redshifts ~ 15 and 18, very close to the value of our fiducial case, ~ 15 (see Fig. 4). Obviously, the higher the density threshold the later the onset of star formation, as the gas needs more time to condense.

In Fig. 8, we show the star formation rates and the contribution from popIII stars for different density thresholds. The asymptotic

⁸ We use the tabulated post-SN yields (table 8 in Heger & Woosley 2008) for the $10\text{--}100 M_{\odot}$ stars, explosion energy of 1.2 Bethe, standard mixing prescriptions, $S = 4$ piston parameter (Woosley, private communication).

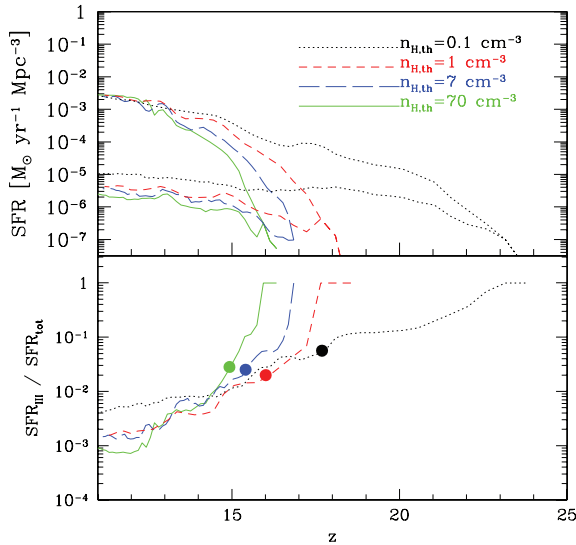


Figure 8. Upper panel: redshift evolution of the average star formation rate densities (in $M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$) for the $0.7 \text{ Mpc } h^{-1}$ side box simulations with $Z_{\text{crit}} = 10^{-4} Z_{\odot}$. The upper lines are the total star formation rate densities for different H-density thresholds for star formation, $n_{\text{H,th}} = 0.1 \text{ cm}^{-3}$ (dotted lines), 1 cm^{-3} (short-dashed lines), 7 cm^{-3} (long-dashed lines) and 70 cm^{-3} (solid lines). The four lower lines are the corresponding popIII contributions. Bottom panel: evolution of the ratio between the average popIII star formation rate density (SFR_{III}) and the total star formation rate density (SFR_{tot}), $\text{SFR}_{\text{III}}/\text{SFR}_{\text{tot}}$. The bullets correspond to the redshift at which the average metallicity of the enriched particles equals the value of Z_{crit} .

amplitude of the total SFR is not affected, but the contribution from popIII stars has different slopes for different $n_{\text{H,th}}$: the higher the threshold, the steeper the evolution of $\text{SFR}_{\text{III}}/\text{SFR}_{\text{tot}}$, with this ratio decreasing of ~ 3 orders of magnitude in redshift intervals of $\Delta z \sim 15, 8, 6, 4$, for $n_{\text{H,tr}} = 0.1, 1, 7, 70$, respectively.

It is evident that the difference between the $70, 7$ and 1 cm^{-3} cases is quite small, with star formation rates almost overlapping since the beginning of the process. The reason is that such values fall in correspondence of the gas cooling branch, which is extremely fast and therefore the effects on the final results are very little. For the 0.1 cm^{-3} case, instead, we find discrepancies at higher redshift due to the unresolved isothermal peak. This is due to the fact that (unphysical) low-density threshold models convert gas into stars quite regularly and smoothly, when it is still shock-heating in the hosting dark-matter potential well. But, if high-density thresholds are used, the dense gas is converted into stars later on, only after the loitering, isothermal phase (during which it just gets accumulated at temperatures around $\sim 10^4 \text{ K}$) and the catastrophic run-away cooling. So, large amounts of particles undergo star formation in a shorter time, after which the SFR catches up and converges to the low-density-threshold cases. In the meantime, the critical metallicity is more quickly reached, as well. This also explains the differences among the slopes of the decrement. The higher the density thresholds, the higher the gas accumulated and catastrophically converted into stars, the higher the enrichment, and the steeper the ratio $\text{SFR}_{\text{III}}/\text{SFR}_{\text{tot}}$.

The popIII/popII-I transition (see bullets) happens in all the cases when the contribution of SFR_{III} has dropped roughly between 10^{-2} and 10^{-1} , and at redshift $z \sim 10$ it is $\sim 10^{-3}$.

These conclusions support the fact that the transition from popIII to popII-I star formation regime is very fast, independently from the detailed numerical parameters, as long as the gas isothermal phase is resolved.

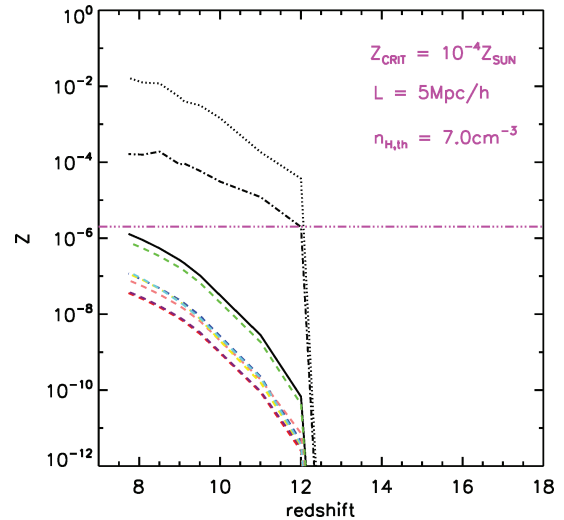


Figure 9. Average metallicities in the simulation of the box with a comoving side length of $5 \text{ Mpc } h^{-1}$ and $Z_{\text{crit}} = 10^{-4} Z_{\odot}$. The density threshold is 7 cm^{-3} . The magenta horizontal dot-dot-dashed line indicates the critical metallicity; the dotted line is the maximum metallicity; the dot-dashed line is the average metallicity of the spread metals; the solid line is the total metallicity averaged over the whole simulation box; and the dashed lines the corresponding individual metallicities (see also Fig. 4).

4.3 Box size

In this section, we discuss the effect on our results of different choices for the box size. In the next, we will show metallicity properties (Section 4.3.1) and star formation rate densities (Section 4.3.2) for simulations with the same parameters used for our reference simulation but with a box size in comoving units of 5 and $10 \text{ Mpc } h^{-1}$. Properties and resolution are also summarized in Table 1. Because of the lower resolution of such boxes (gas particle masses are of the order $\sim 10^4$ – $10^5 M_{\odot} h^{-1}$), we cannot adopt a very-high-density threshold (of $\sim 10^2 \text{ cm}^{-3}$ or more), therefore, to make a meaningful comparison we show results for $n_{\text{H,th}} = 7 \text{ cm}^{-3}$.

4.3.1 Metallicity

The global behaviour is patchy and similar to the maps already shown for the $0.7 \text{ Mpc } h^{-1}$ cases (Figs 1–3). The only difference is the larger sampling of star forming regions with a wider statistical significance.

In Figs 9 and 10, we plot metallicity evolution for the simulations with 5 and $10 \text{ Mpc } h^{-1}$ box side, respectively. In both cases, the critical metallicity is reached quite quickly and metal-rich regions have $Z > Z_{\text{crit}}$ already by redshift ~ 10 . The rapid attainment of Z_{crit} is independent of the resolution, which instead influences the onset of star formation. That is the reason why, in the $10 \text{ Mpc } h^{-1}$ box side, star formation is slightly delayed. As in Fig. 4, we also plot the maximum (dotted lines) and average metallicity in the whole simulation box (solid lines) with the different metal contributions (dashed lines). We find that the first can easily reach solar values, because of strong pollution due to the high PISN metal yields; the second has $Z < Z_{\text{crit}}$ at any redshift above ~ 7 . These fluctuations are reflected in the high patchiness of early metal spreading. The metal pollution histories do not show large discrepancies and, in spite of differences in resolution of more than one order of magnitude for the SPH masses, an overall agreement between larger (5 or $10 \text{ Mpc } h^{-1}$) and smaller ($0.7 \text{ Mpc } h^{-1}$) boxes is reached. Thus, the

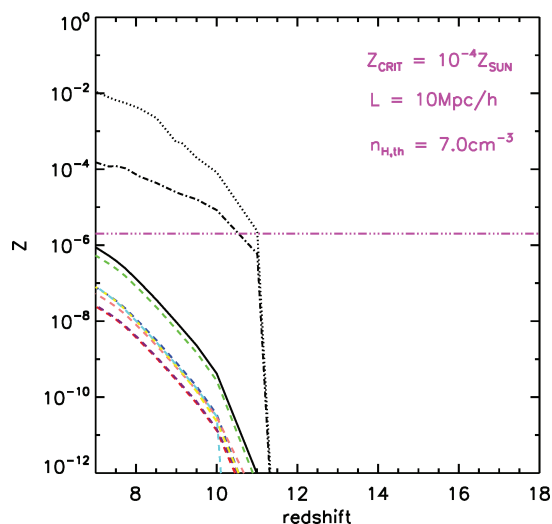


Figure 10. Average metallicities in the simulation of the box with a comoving side length of $10 \text{ Mpc } h^{-1}$ and $Z_{\text{crit}} = 10^{-4} Z_{\odot}$. The density threshold is 7 cm^{-3} . The magenta horizontal dot–dot–dashed line indicates the critical metallicity; the dotted line is the maximum metallicity; the dot–dashed line is the average metallicity of the spread metals; the solid line is the total metallicity averaged over the whole simulation box and the dashed lines the corresponding individual metallicities (see also Fig. 4).

general results are independent from the particular cosmological sampling.

4.3.2 Star formation from population III and population II-I stellar generations

We will now discuss the behaviour of the star formation rates for the simulations previously introduced.

The average star formation rate densities are shown in the upper panel of Fig. 11, for the boxes of $0.7 \text{ Mpc } h^{-1}$ (dashed lines), $5 \text{ Mpc } h^{-1}$ (dotted lines) and $10 \text{ Mpc } h^{-1}$ (solid lines). The upper lines refer to the total star formation rate densities and the ones below to the corresponding popIII star formation rate densities (data points are by Reddy et al. 2008). Overall, they seem to connect fairly well with the observed trend at lower redshift.

In the bottom panel, we present the ratios of popIII versus total star formation rate. Independently from the box size, the popIII contribution is unity at the very beginning (i.e. ~ 100 per cent of the SFR is due to popIII) and, for all the cases, rapidly decreases below ~ 1 per cent at redshift $z \sim 11$, and below ~ 0.1 per cent at redshift $z \lesssim 11$: a time-lag much shorter than a Gyr. This means, consistently with what said in Section 3, that the bulk of popIII episodes happens in a short time after the onset of star formation and it dominates the cosmological SFR for a limited period at high redshift. At lower redshift, only isolated regions could still have pristine environment and host popIII star formation (which is none the less several order of magnitude smaller than the total SFR).

A general feature of the large box simulations is the slight delay of the onset of star formation: this is due to the limited capabilities of the bigger SPH particles to condense, cool, and collapse. Indeed, molecular cooling is not efficient when the SPH masses are so high ($\sim 10^4$ – $10^5 \text{ M}_{\odot} h^{-1}$) and the primordial gas in-fall is not well resolved. The qualitative agreement of these results is encouraging, though. We point out that, the coarse resolution of the larger boxes does not allow to infer much about the fate of primordial H_2 -haloes, since they are not well represented. In the high-resolution runs, in-

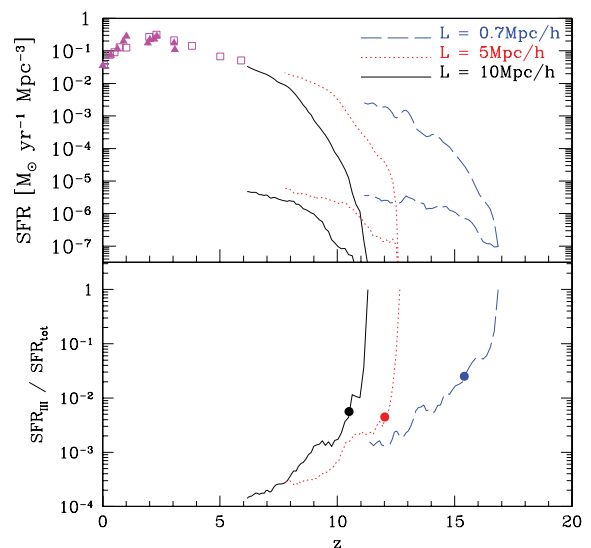


Figure 11. Upper panel: star formation rate densities for the simulations with a comoving box side of $0.7 \text{ Mpc } h^{-1}$ (dashed lines), $5 \text{ Mpc } h^{-1}$ (dotted lines) and $10 \text{ Mpc } h^{-1}$ (solid lines). The density threshold is 7 cm^{-3} . For each of them, we show the total star formation rate density (upper lines) and the popIII one (lower lines). Data points (Reddy et al. 2008) are different determinations of the star formation rate density: square symbols are the UV determinations, triangular symbols are the IR determinations. Bottom panel: evolution of the ratio between the average popIII star formation rate density (SFR_{III}) and the total star formation rate density (SFR_{tot}), $\text{SFR}_{\text{III}}/\text{SFR}_{\text{tot}}$. The bullets correspond to the redshift at which the average metallicity of the enriched particles equals the value of Z_{crit} .

stead, mini-haloes are found with typical masses well-below $\sim 10^6$ – 10^7 M_{\odot} , at redshift $z \sim 16$, and, while their gas is condensing, it is likely that part of them will be polluted by nearby structures, that have already undergone star formation. To estimate the fraction of new haloes experiencing popIII or popII-I star formation, with the corresponding cosmological evolution, more refined studies, beyond the aim of this paper, are needed. In any case, the detailed molecular treatment guarantees that the thermodynamical properties of collapsing gas are followed self-consistently and correctly, and this is particularly relevant at high redshift.

Finally, we can safely state that if we kept the same resolution of the fiducial case (or possibly higher), larger boxes would show star formation histories similar to the fiducial one, with the same, or earlier, onset of star formation. In fact, more modes could be sampled, and these would induce earlier collapse of statistically rare objects.

5 DISCUSSION AND CONCLUSIONS

In this work, we perform numerical simulations of early structure formation, including both primordial, molecular evolution and metal enrichment from stellar death, to study the transition from an early, massive star formation mode to a more standard one, regulated by the gas metallicity. We follow (see details in Maio et al. 2007; Tornatore et al. 2007b) the abundances of e^- , H , H^+ , H^- , He , He^+ , He^{++} , H_2 , H_2^+ , D , D^+ , HD , HeH^+ , C , O , Mg , S , Si , Fe , and use different initial stellar-mass functions, metal yields, and critical metallicities for the transition from a popIII to a popII star formation mode, Z_{crit} . At the present, our work is the only one dealing with detailed chemical evolution, from early molecule creation to the later stages of star formation, and, at the same time, allowing

to trace simultaneous, different stellar populations, according to the underlying metallicity.

Indeed, early structure formation can be accurately modelled only with a proper treatment of both the chemistry of primordial molecules and the metal enrichment. In fact, the main influence of chemical evolution on the following generations of structures is via metal pollution (chemical feedback). This event can completely alter the cooling properties of the gas and thus the modalities of star formation, inducing a transition from a top-heavy to a standard IMF. The transition is believed to happen when the gas is enriched above Z_{crit} , which allows fragmentation below the typical scales determined by primordial molecular cooling. Because of our ignorance of the features of early dust formation and the lack of precision of many atomic and molecular data, the exact determination of Z_{crit} is still elusive; reasonable values should range between $10^{-6} Z_{\odot}$ and $10^{-3} Z_{\odot}$ (Bromm et al. 2001; Schneider et al. 2002).

In our simulations we assume four different values of Z_{crit} in the above range: 10^{-6} , 10^{-5} , 10^{-4} and $10^{-3} Z_{\odot}$. From our investigation, some common features emerge. In general, metal pollution, independently from the parameters adopted in the simulations, is very patchy, with excursions of orders of magnitudes at all redshifts. This is consistent with any simulation including metal enrichment (e.g. Raiteri et al. 1996; Gnedin 1998; Mosconi et al. 2001; Lia et al. 2002b,a; Kawata & Gibson 2003; Kobayashi 2004; Ricotti & Ostriker 2004; Scannapieco et al. 2005; Tornatore et al. 2007b; Oppenheimer et al. 2010).

In addition, the gas is easily enriched above Z_{crit} . For this reason, the average contribution from pristine, metal-free (or $Z < Z_{\text{crit}}$) stars to the total cosmic star formation density is dominant only in the very early phases of structure formation, while it drops below $\sim 10^{-3}$ quite rapidly, after the explosion of the first PISN and their metal ejection. In fact, PISN explosions which follow the death of the first, metal-free or very-metal-poor stars, are responsible for enriching the surrounding medium up to a minimum level of $\sim 10^{-4} Z_{\odot}$. This means that nearby star forming regions have a very high probability of being polluted above Z_{crit} (as seen also in Fig. 4), while popIII star formation can still occur farther away, in rare, isolated regions with pristine or low-metallicity gas (e.g. Fig. 3). None the less, this would not be the dominant star formation regime.

Our findings hold regardless of the value of Z_{crit} , the popIII IMF adopted, and the numerical parameters involved in modelling star formation (as shown in Sections 4.1, 4.2 and 4.3). Differences are found only if different IMF mass ranges for primordial stars are used. Because of the short life and the high metal yields of early, massive SN, the popIII regime contributes, in any case, slightly to the global SFR (as expected by e.g. Ricotti & Ostriker 2004), since the early pollution events quickly raise Z above Z_{crit} .

Finally, we want to comment on the effects of the UV background radiation generated by stellar sources on the popIII star formation. Since the UV background heats mostly the low-density particles of the IGM, it will not influence much the very-dense, star forming regions which are undergoing run-away cooling. Thus, the consequent star formation mode will remain unchanged. We have checked the validity of our statement, by repeating the simulation of the $10 \text{ Mpc } h^{-1}$ side-box with two difference prescriptions based on the UV model by Haardt & Madau (1996): one, assuming the onset of a UV background at redshift $z \sim 6.7$ and the second at $z \sim 13$. We found no relevant deviations from the plots shown previously (e.g. in Fig. 11). This essentially means that the main reason main reason for cosmic popIII star formation to drop down (e.g. Tornatore et al. 2007a) and eventually stop is simply the ongoing metal pollution.

We highlight that Figs 5–8 and 11 clearly predict that popIII star formation reaches a constant value of $\sim 10^{-3}$ the total one at redshift $z \sim 11$ –13. This is a very solid result, which holds independently from many poorly constrained parameters. Only if primordial supernovae were similar to type II ones (i.e. with masses below $40 M_{\odot}$), the contribution could be as high as $\sim 10^{-1}$.

The simulations were performed using a standard Λ CDM cosmology, but slightly different parameters would not change the general picture. We have checked this, by running simulations with $\Omega_{\text{m}} = 0.26$, $\Omega_{\Lambda} = 0.74$, $\Omega_{\text{b}} = 0.0441$, $h = 0.72$, $\sigma_8 = 0.796$ and $n = 0.96$ (WMAP5 data; Hinshaw et al. 2009) and found that the same results hold, albeit shifted by a $\Delta z \sim$ of a few to lower redshift (because of the smaller Ω_{m}).

One last comment about the role of dust production from SNII and/or PISN: one of the main uncertainties in determining Z_{crit} . According to our findings, given the strength and rapidity of metal enrichment (see e.g. Figs 4, 9 and 10), details about dust and its impact on Z_{crit} seem not to be the main drivers of the general process and of our understanding of the transition from primordial, popIII regime to present-day-like, popII-I regime (even if they could be of some interest on very local scales). The entire process, in fact, is dominated by metal pollution and the strong yields of early, massive stars. Although the qualitative, general trends seem not to be affected by Z_{crit} and by dust, some details do rely on them. For example, the ‘residual’ level of popIII star formation does depend on Z_{crit} (see e.g. Fig. 4), and thus on the role of dust.

We have to stress some caveats. Ejection of particles into the IGM is an unknown process. We have assumed winds originated from stars (kinetic feedback), but different mechanisms (like gas stripping, shocks, thermal heating from stellar radiation, etc.) could play a role, as well, mostly at high redshifts, when objects are small and can easily loose part of their baryonic content. In addition, diffusion and conduction will probably alter the smoothness of metal and molecule distribution, but these phenomena have not been extensively studied, yet, and probably will depend on many parameters: e.g. the way metal or gas particles are ejected and mixed, how they are transferred away from the production sites, how strong is the efficiency of such processes, just to mention a few. Some attempts to address such issues have been done (Spitzer 1962; Cowie & McKee 1977; Brookshaw 1985; Sarazin 1988; Monaghan 1992; Cleary & Monaghan 1999; Klessen & Lin 2003; Jubelgas, Springel & Dolag 2004; Monaghan, Huppert & Worster 2005; Wadsley, Veeravalli & Couchman 2008; Greif et al. 2009), but much more realistic and detailed analyses are still strongly needed.

To conclude, we have followed the structure formation process from very early times to first star formation and subsequent metal pollution. In the 1 Mpc side box simulations we have seen that, after $\sim 2 \times 10^8 \text{ yr}$, molecular evolution leads the very first bursts of star formation (popIII), but metal enrichment is extremely fast (Figs 1–3) in inducing the nowadays observed star formation mode (popII-I). In fact, we observe a steep increase of Z , with local values rapidly reaching and overtaking Z_{crit} (Fig. 4). Metal pollution proceeds from the densest cores of star formation outwards, because of SN ejections from high-density to lower-density environments (Figs 2 and 3). Rare, unpolluted regions can still survive, determining the simultaneous presence of the two star formation regimes, and Z_{crit} can affect the level of residual popIII star formation. As a result of this rapid pollution, we find that the average contribution of the popIII component to the total star formation rate density is of a few times $\sim 10^{-4}$ – 10^{-3} (with a maximum of $\sim 10^{-2}$ – 10^{-1}) at $z \sim 11$ (Figs 5–7). This general picture is preserved regardless of the precise value of the metallicity threshold Z_{crit} the slope of the

popIII IMF, and their yields, but is quite sensitive to the popIII mass range. The change of the critical density threshold for star formation influences little these conclusions, but can affect the onset and the decrement of the popIII contribution to the total SFR (e.g. Fig. 8). We have found similar results in larger-box simulations, either in the metal enrichment features (Figs 9 and 10) and in the star formation behaviour (Fig. 11).

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More detailed maps and information can be found at the URL <http://www.mpe.mpg.de/~umaio/maps.html>.

REFERENCES

- Abel T., 2010, preprint (arXiv:1003.0937)
- Anders E., Grevesse N., 1989, *Geochim. Cosmochim. Acta*, 53, 197
- Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, *ARA&A*, 47, 481
- Bertoldi F., Carilli C. L., Cox P., Fan X., Strauss M. A., Beelen A., Omont A., Zylka R., 2003, *A&A*, 406, L55
- Bianchi S., Schneider R., 2007, *MNRAS*, 378, 973
- Bromm V., Loeb A., 2003, *Nat*, 425, 812
- Bromm V., Ferrara A., Coppi P. S., Larson R. B., 2001, *MNRAS*, 328, 969
- Brookshaw L., 1985, *Proc. Astron. Soc. Australia*, 6, 207
- Campbell S. W., Lattanzio J. C., 2008, *A&A*, 490, 769
- Cantalupo S., 2010, *MNRAS*, 403, L16
- Chiosi C., 2000, in Weiss A., Abel T. G., Hill V., eds, *The First Stars*. Springer, Berlin, p. 95
- Ciardi B., Ferrara A., 2005, *Space Sci. Rev.*, 116, 625
- Cleary P. W., Monaghan J. J., 1999, *J. Comput. Phys.*, 148, 227
- Cowie L. L., McKee C. F., 1977, *ApJ*, 211, 135
- Dwek E., Galliano F., Jones A. P., 2007, *ApJ*, 662, 927
- Dwek E. et al., 2008, *ApJ*, 676, 1029
- Frebel A., Simon J. D., Geha M., Willman B., 2010, *ApJ*, 708, 560
- Furlanetto S. R., Loeb A., 2005, *ApJ*, 634, 1
- Galli D., Palla F., 1998, *A&A*, 335, 403
- Gnedin N. Y., 1998, *MNRAS*, 294, 407
- Greif T. H., Bromm V., 2006, *MNRAS*, 373, 128
- Greif T. H., Glover S. C. O., Bromm V., Klessen R. S., 2009, *MNRAS*, 392, 1381
- Grevesse N., Sauval A. J., 1998, *Space Sci. Rev.*, 85, 161
- Gunn J. E., Gott J. R. I., 1972, *ApJ*, 176, 1
- Haardt F., Madau P., 1996, *ApJ*, 461, 20
- Heger A., Woosley S. E., 2002, *ApJ*, 567, 532
- Heger A., Woosley S. E., 2008, preprint (arXiv:0803.3161)
- Hinshaw G. et al., 2009, *ApJS*, 180, 225
- Jeans J. H., 1902, *Philos. Trans. R. Soc. London A*, 199, 1
- Jubelgas M., Springel V., Dolag K., 2004, *MNRAS*, 351, 423
- Katz N., 1992, *ApJ*, 391, 502
- Katz N., Weinberg D. H., Hernquist L., 1996, *ApJS*, 105, 19
- Kawata D., Gibson B. K., 2003, *MNRAS*, 340, 908
- Klessen R. S., Lin D. N., 2003, *Phys. Rev. E*, 67, 046311
- Kobayashi C., 2004, *MNRAS*, 347, 740
- Komatsu E. et al., 2010, preprint (arXiv:1001.4538)
- Kozasa T., Hasegawa H., Nomoto K., 1991, *A&A*, 249, 474
- Larson R. B., 1998, *MNRAS*, 301, 569
- Lia C., Portinari L., Carraro G., 2002a, *MNRAS*, 330, 821
- Lia C., Portinari L., Carraro G., 2002b, *MNRAS*, 335, 864
- McMahon R. G., Omont A., Bergeron J., Kreysa E., Haslam C. G. T., 1994, *MNRAS*, 267, L9
- Maio U., 2009, PhD thesis, Ludwig Maximilian Univ.
- Maio U., Dolag K., Meneghetti M., Moscardini L., Yoshida N., Baccigalupi C., Bartelmann M., Perrotta F., 2006, *MNRAS*, 373, 869
- Maio U., Dolag K., Ciardi B., Tornatore L., 2007, *MNRAS*, 379, 963
- Maio U., Ciardi B., Yoshida N., Dolag K., Tornatore L., 2009, *A&A*, 503, 25
- Maiolino R., Schneider R., Oliva E., Bianchi S., Ferrara A., Mannucci F., Pedani M., Roca Sogorb M., 2004, *Nat*, 431, 533
- Maiolino R. et al., 2007, *A&A*, 472, L33
- Monaghan J. J., 1992, *ARA&A*, 30, 543
- Monaghan J. J., Huppert H. E., Worster M. G., 2005, *J. Comput. Phys.*, 206, 684
- Mosconi M. B., Tissera P. B., Lambas D. G., Cora S. A., 2001, *MNRAS*, 325, 34
- Nozawa T., Kozasa T., Umeda H., Maeda K., Nomoto K., 2003, *ApJ*, 598, 785
- Oppenheimer B. D., Davé R., Kereš D., Fardal M., Katz N., Kollmeier J. A., Weinberg D. H., 2010, *MNRAS*, in press (arXiv:0912.0519)
- Peebles P. J. E., 1974, *ApJ*, 189, L51
- Pettini M., Boksenberg A., Hunstead R. W., 1990, *ApJ*, 348, 48
- Raiteri C. M., Villata M., Navarro J. F., 1996, *A&A*, 315, 105
- Reddy N. A., Steidel C. C., Pettini M., Adelberger K. L., Shapley A. E., Erb D. K., Dickinson M., 2008, *ApJS*, 175, 48
- Ricotti M., Ostriker J. P., 2004, *MNRAS*, 350, 539
- Salpeter E. E., 1955, *ApJ*, 121, 161
- Sarazin C. L., 1988, *X-Ray Emissions from Clusters of Galaxies*, Vol. 76. Cambridge Univ. Press., Cambridge, p. 639
- Scannapieco E., Schneider R., Ferrara A., 2003, *ApJ*, 589, 35
- Scannapieco C., Tissera P. B., White S. D. M., Springel V., 2005, *MNRAS*, 364, 552
- Schneider R., Ferrara A., Natarajan P., Omukai K., 2002, *ApJ*, 571, 30
- Schneider R., Ferrara A., Salvaterra R., 2004, *MNRAS*, 351, 1379
- Schneider R., Salvaterra R., Ferrara A., Ciardi B., 2006a, *MNRAS*, 369, 825
- Schneider R., Omukai K., Inoue A. K., Ferrara A., 2006b, *MNRAS*, 369, 1437
- Schwarzschild M., Spitzer L., 1953, *Observatory*, 73, 77
- Spitzer L., 1962, *Physics of Fully Ionized Gases*, 2nd edn. Wiley, New York
- Springel V., 2005, *MNRAS*, 364, 1105
- Suda T., Fujimoto M. Y., 2010, *MNRAS*, p. 444
- Sutherland R. S., Dopita M. A., 1993, *ApJS*, 88, 253
- Thielemann F.-K. et al., 2003, *Nucl. Phys. A*, 718, 139
- Todini P., Ferrara A., 2001, *MNRAS*, 325, 726
- Tornatore L., Ferrara A., Schneider R., 2007a, *MNRAS*, 382, 945
- Tornatore L., Borgani S., Dolag K., Matteucci F., 2007b, *MNRAS*, 382, 1050
- Trenti M., Stiavelli M., 2009, *ApJ*, 694, 879
- Trenti M., Stiavelli M., Shull J. M., 2009, *ApJ*, 700, 1672
- van den Hoek L. B., Groenewegen M. A. T., 1997, *A&AS*, 123, 305
- Wadsley J. W., Veeravalli G., Couchman H. M. P., 2008, *MNRAS*, 387, 427
- White S. D. M., Rees M. J., 1978, *MNRAS*, 183, 341
- Wiersma R. P. C., Schaye J., Smith B. D., 2009, *MNRAS*, 393, 99
- Woosley S. E., Weaver T. A., 1995, *ApJS*, 101, 181
- Wytke J. S. B., Cen R., 2007, *ApJ*, 659, 890
- Yoshida N., 2006, *New Astron. Rev.*, 50, 19
- Yoshida N., Abel T., Hernquist L., Sugiyama N., 2003, *ApJ*, 592, 645
- Yoshida N., Omukai K., Hernquist L., 2007, *ApJ*, 667, L117

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