

Dark Matter Halo Environment for Primordial Star Formation

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11 October 2012

ABSTRACT

We study the statistical properties (such as shape and spin) of high- z halos likely hosting the first (PopIII) stars with cosmological simulations including detailed gas physics. In the redshift range considered ($11 < z < 16$) the average sphericity is $\langle s \rangle = 0.3 \pm 0.1$, and for more than 90% of halos the triaxiality parameter is $T \lesssim 0.4$, showing a clear preference for oblateness over prolateness. Larger halos in the simulation tend to be both more spherical and prolate: we find $s \propto M_h^{\alpha_s}$ and $T \propto M_h^{\alpha_T}$, with $\alpha_s \approx 0.128$ and $\alpha_T = 0.276$ at $z = 11$. The spin distributions of dark matter and gas are considerably different at $z = 16$, with the baryons rotating slower than the dark matter. At lower redshift, instead, the spin distributions of dark matter and gas track each other almost perfectly, as a consequence of a longer time interval available for momentum redistribution between the two components. The spin of both the gas and dark matter follows a lognormal distribution, with a mean value at $z = 16$ of $\langle \lambda \rangle = 0.0184$, virtually independent of halo mass. This is in good agreement with previous studies. Using the results of two feedback models (MT1 and MT2) by McKee & Tan (2008) and mapping our halo spin distribution into a PopIII IMF, we find that at high- z the IMF closely tracks the spin lognormal distribution. Depending on the feedback model, though, the distribution can be centered at $\approx 65M_\odot$ (MT1) or $\approx 140M_\odot$ (MT2). At later times, model MT1 evolves into a bimodal distribution with a second prominent peak located at $35 - 40M_\odot$ as a result of the non-linear relation between rotation and halo mass. We conclude that the dark matter halo properties might be a key factor shaping the IMF of the first stars.

1 INTRODUCTION

The formation of first, metal-free (often referred to as PopIII) stars in the Universe represents a milestone during cosmic evolution, marking the end of the Dark Ages and producing the first heavy elements (Ciardi & Ferrara 2005; Yoshida et al. 2008; Bromm et al. 2009; Bromm & Yoshida 2011; de Souza et al. 2011, 2012; Johnson et al. 2012). Thus, a key problem in physical cosmology is to understand the origin and evolution of such objects, born out of the pristine conditions leftover by the Big Bang. More specifically, the most urgent question concerns their Initial Mass Function (IMF), which, despite its relevance, remains at best a poorly known quantity due to the lack of direct observations. Consequently, our knowledge is based mainly on theoretical models (e.g., Dopcke et al. 2012).

Until recently, studies based on the standard Λ CDM cosmological model¹ for structure formation predicted that

the first stars formed when the age of the Universe was less than a few hundred million years, and that they were predominantly massive (Abel et al. 2002; Omukai & Palla 2003; Yoshida et al. 2006). Clark et al. (2011), Greif et al. (2011) and Prieto et al. (2011) have now performed cosmological simulations using a sink particle technique to follow the evolution of a primordial protostellar accretion disk. They find that instead of forming a single massive object, the gas typically fragments into a number of protostars with a range of different masses. However, high resolution radiation-hydrodynamics simulations by Hosokawa et al. (2011) indicate a typical mass of PopIII stars of $\sim 43M_\odot$. Even more recently, similar results was found by Stacy et al. (2012), which suggests radiative feedback will lower the final mass attainable by a PopIII star. With an estimative of $30M_\odot$ for a PopIII mass as a lower

¹ Throughout the paper we assume a standard Λ CDM cosmological model, with current total-matter density parameter $\Omega_m = 0.3$,

cosmological constant density parameter $\Omega_\Lambda = 0.7$, baryonic-matter density parameter $\Omega_b = 0.04$, expansion rate in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $h = 0.7$, spectral normalization $\sigma_8 = 0.9$, and primordial spectral index $n = 1$.

limit. Greif et al. (2012), using a different numerical scheme without need to insert sink particles, found that the keplerian disc around the primary protostar fragments into a number of secondary protostars, confirming previous results using sink particles. Clearly, these theoretical results are far from being conclusive, mostly due to the astonishing difficulty involved in simulating the large dynamical range required and the complex physics involved. Note that these studies, with few exceptions (e.g. Turk et al. 2012), largely neglect the possible effects of a magnetic field in the fragmentation properties of the gas.

In spite of this unsettled situation, a broad consensus exists on the fact that rotation of the protogalactic cloud is the key factor in determining the final outcome of the collapse. The importance of rotation has been fully appreciated after the fundamental paper by McKee & Tan (2008, MT08), who studied the dependence of primordial protostar accretion in the presence of rotation (fostering the formation of an accretion disk) and radiative feedback from the protostar. In their study MT08 concluded that the final stellar mass depends mainly on the entropy of the gas accreting from large radii, as well as its specific angular momentum. As the gas is bound in the gravitational potential of the dark matter halo, it follows that the angular momentum of the gas is linked to that of the parent halo. Hence, it is important to turn our attention to the properties of the dark matter halos that host the first stars to put the entire problem on a solid basis.

The distribution of the angular momentum enters a broad range of problems, from the halo mass function itself (e.g. Macciò et al. 2007; Del Popolo 2009), to the formation and evolution of central black holes (e.g. Eisenstein & Loeb 1995; Volonteri & Rees 2005; Volonteri 2010), to semi-analytical models of galaxy formation (e.g. Benson 2012). Simulations of isolated dwarf galaxies suggest that angular momentum leads to more continuous star formation histories than non-rotating cases by preventing large-scale oscillations in the star formation rate (Schroyen et al. 2011). For this reason, much effort has been done to explore the spin distribution of halos in different redshift and mass ranges, to characterize its probability distribution, as well as the dependence on mass, shape, merger rate and other halo properties (e.g. Bett et al. 2007; D’Onghia & Navarro 2007; Antonuccio-Delogo et al. 2010).

Another fundamental characteristic of halos is their shape. Spherical halos are very rare, and their collective properties cannot be approximated using spherical symmetry (Allgood et al. 2006). They are usually described in terms of ellipsoids characterized by three principal axes. Many authors have explored ways to estimate the shape of halos and the correlations with other halo properties (e.g. Zemp et al. 2011). Using a pure dark matter N-body simulations, Jang-Condell & Hernquist (2001) analyzed the primordial halo characteristics and found no significant difference between their results and simulations of large-scale structure formation at low redshift. Kazantzidis et al. (2004) found that halos in cosmological simulations including gas cooling are considerably more spherical than those found in adiabatic simulations. This shows that the inclusion of detailed gas physics is fundamental, since the back-reaction effects of baryons on dark matter halos change their density profiles as well as their mass distribution (Cui et al.

2012). Observationally, weak gravitational lensing is probably the most common approach to reconstruct the shape of halos (e.g. Corless & King 2008; Bett 2012; van Uitert et al. 2012). The method does not depend on the presence of optical tracers and can be applied to a large range of scales.

The purpose of the present paper is to explore the properties (such as spin and shape) of the high- z halos likely to host the first stars, with an unprecedented inclusion of detailed gas physics. Although previous works that have investigated the correlation between halo parameters exist (e.g., Jeon-Daniel et al. 2011; Skibba & Macciò 2011), this is the first attempt to determine the characteristics and correlations of the low-mass end of the halo mass function including gas physics.

As a final step, we embed our results into theoretical models of first star formation to unveil the links between dark matter halo properties and the PopIII IMF.

The outline of this paper is as follows. In Sec. 2, we briefly describe the N-body/hydrodynamical simulations used to derive the halo properties; Sec. 3 describes the methodology used to calculate the quantities of interest (halo spin and shape). In Sec. 4, we show the results and provide useful fits for correlations between different quantities. Finally, Sec. 5 discusses the possible implications for the PopIII IMF. Sec. 6 contains a summary of the results.

2 SIMULATIONS

We analyze the output of the N-body/hydrodynamical simulations described in Maio et al. (2010), which were performed using the Gadget-2 code (Springel 2005). The simulations include the evolution of e^- , H, H^+ , H^- , He, He^+ , He^{++} , H_2 , H_2^+ , D, D^+ , HD, HeH^+ (Yoshida et al. 2003; Maio et al. 2006, 2007, 2009), PopIII and PopII/I star formation and metal pollution (Tornatore et al. 2007), gas cooling from resonant and fine-structure lines (Maio et al. 2007, 2009) and feedback effects (Springel & Hernquist 2003). There are evidences for the existence of a critical metallicity, Z_{crit} , which allow the transition between PopII/I and Pop III star formation modes (Omukai 2000; Bromm et al. 2001). The transition from the PopIII to the PopII/I regime is determined by the value of the gas metallicity, Z , compared to the critical value $Z_{crit} = 10^{-4} Z_{\odot}$. The value of this minimum level is very uncertain, but is likely to be between 10^{-6} and $10^{-4} M_{\odot}$ and can be strongly dependent of the efficiency of dust formation in first-generation supernova ejecta (Schneider et al. 2003, 2006) and the fine-structure line cooling of singly-ionized carbon or neutral atomic oxygen (Bromm & Loeb 2003). If $Z < Z_{crit}$ a Salpeter IMF (i.e. with a slope of -1.35) is assumed in the mass range 100-500 M_{\odot} , otherwise the same Salpeter slope is adopted in the mass range 0.1-100 M_{\odot} . The chemical model follows the detailed stellar evolution of each SPH particle. At every time-step, the abundances of various heavy elements (C, O, Mg, S, Si and Fe) are consistently derived, according to the lifetimes and metal yields of the stars in the given mass range.

The cosmological field is sampled at redshift $z = 100$, with dark-matter and baryonic-matter species. We consider snapshots in the range $11 < z < 16$, within a cubic volume of comoving side 1 Mpc h^{-1} and 320^3 particles per gas

and dark matter species, corresponding to particle masses of $116 M_\odot h^{-1}$ and $755 M_\odot h^{-1}$, respectively. The identification of the simulated objects is done by applying a Friends of Friends (FoF) technique; substructures are identified by using a SubFind algorithm (Dolag et al. 2009), which discriminates among bound and non-bound particles. For more details on the simulations we refer the reader to the original paper (Maio et al. 2010).

3 HALO PROPERTIES DERIVATION

In the following we describe the method used to derive the halo properties of interest here, as its shape and spin, along with a number of ancillary quantities defined below.

3.1 Shape

The halo shape is estimated based on its mass distribution, which can be directly derived using the eigenvalues of the inertia tensor \mathcal{I} (e.g., Springel et al. 2004; Allgood et al. 2006; Bett et al. 2007),

$$\mathcal{I}_{jk} = \sum_{i=1}^N m_i (\mathbf{r}_i^2 \delta_{j,k} - r_{i,j} r_{i,k}), \quad (1)$$

where \mathbf{r}_i and m_i are the position vector and mass of the i -th particle, $\delta_{j,k}$ is the Kronecker delta and the sum is performed over the total number of particles inside the halo, N .

An alternative way to measure the shape is by using the second moment of the mass distribution, i.e. the shape tensor

$$\mathcal{S}_{jk} = \frac{1}{N} \sum_{i=1}^N r_{i,j} r_{i,k}. \quad (2)$$

As the eigenvalues of \mathcal{S} and \mathcal{I} are the same, the two definitions are totally equivalent for halo shape studies. We then restrict our discussion to the shape tensor.

The eigenvalues of the diagonalised shape tensor define an ellipsoid, which represents the equivalent homogeneous shape of the halo in terms of the principal axis ratios, with the convention $a \geq b \geq c$. It is customary to refer to the axis ratios in terms of sphericity, $s = c/a$ (with $s = 0$ meaning aspherical and $s = 1$ spherical), oblateness, $q = b/a$ and prolateness, $p = c/b$. With these definitions, the triaxiality parameter can be conveniently written as

$$T = \frac{1 - q^2}{1 - s^2}; \quad (3)$$

hence a prolate (oblate) halo has $T = 1$ ($T = 0$).

A slightly different way to calculate the shape tensor was introduced by Allgood et al. (2006),

$$\mathcal{S}_{jk} = \frac{1}{N} \sum_{i=1}^N \frac{r_{j,i} r_{k,i}}{d_i^2}, \quad (4)$$

where $d_i^2 = x_i^2 + y_i^2/q^2 + z_i^2/s^2$ is the elliptical distance in the eigenvector coordinate system from the center to the i -th particle and q and s are found iteratively. More generally,

a weight factor, $w(r)$, can be introduced

$$\mathcal{S}_{jk} = \frac{1}{N} \sum_{i=1}^N \frac{w(r) r_{j,i} r_{k,i}}{d_i^2}. \quad (5)$$

A critical review of the different approaches can be found in Zemp et al. (2011). They explore six methods, differing by the integration volume and the choice of the weight functions, $w(r) = 1$, $w(r) = 1/r^2$, $w(r) = 1/d_i^2$. They conclude that using weights can introduce a systematic bias in the measured axis ratios, in addition to blurring the physical interpretation of the shape tensor. Thus, using $w(r) = 1$ and integrating over the enclosed ellipsoidal volume appears to be the most unbiased method. This choice is also preferred for halos with lower number of particles and if the main interest is in deriving the global rather than local (i.e. as a function of distance) shape. Hereafter, all calculations are done using eq. 2 integrated over the enclosed ellipsoidal volume.

3.2 Spin

The spin parameter is a measure of the amount of coherent rotation in a system compared to random motions. For a spherical object, it corresponds approximately to the ratio of its own angular velocity to the angular velocity needed for it to be supported against gravity solely by rotation (see e.g. Padmanabhan 1993). The halo spin can be characterized by a dimensionless parameter λ ,

$$\lambda \equiv \frac{J|E|^{1/2}}{GM^{5/2}}, \quad (6)$$

where J , E , and M are the total angular momentum, energy, and mass of the system, and G is the gravitational constant. The (specific) angular momentum per unit mass is

$$\mathbf{j} = \frac{1}{N} \sum_{i=1}^N \mathbf{r}_i \times \mathbf{v}_i, \quad (7)$$

with r_i and v_i being the position and velocity of i -th particle relative to the halo center and halo center of momentum, respectively; N is again the total number of particles inside the halo. The kinetic, E_k , and potential, E_p , energies are calculated on-the-fly during the simulation as

$$\begin{aligned} E_k &= \frac{1}{2} \sum_{i=1}^N m_i v_i^2, \\ E_p &= \left(\frac{N^2 - N}{N_u^2 - N_u} \right) \left(\frac{-Gm_p^2}{\eta} \right) \sum_{i=1}^{N_u-1} \sum_{j=i+1}^{N_u} -W(r_{ij}/\eta), \end{aligned} \quad (8)$$

where η is the softening length and $W(u)$ is the softening kernel. If the halo contains more than 1000 particles, the potential is calculated using $N_u = 1000$ randomly selected particles (for more details see Springel 2005; Bett et al. 2007).

4 RESULTS

4.1 Shape distribution

The shape dependence on halo mass has been considered previously by several authors. Despite they all agree on the

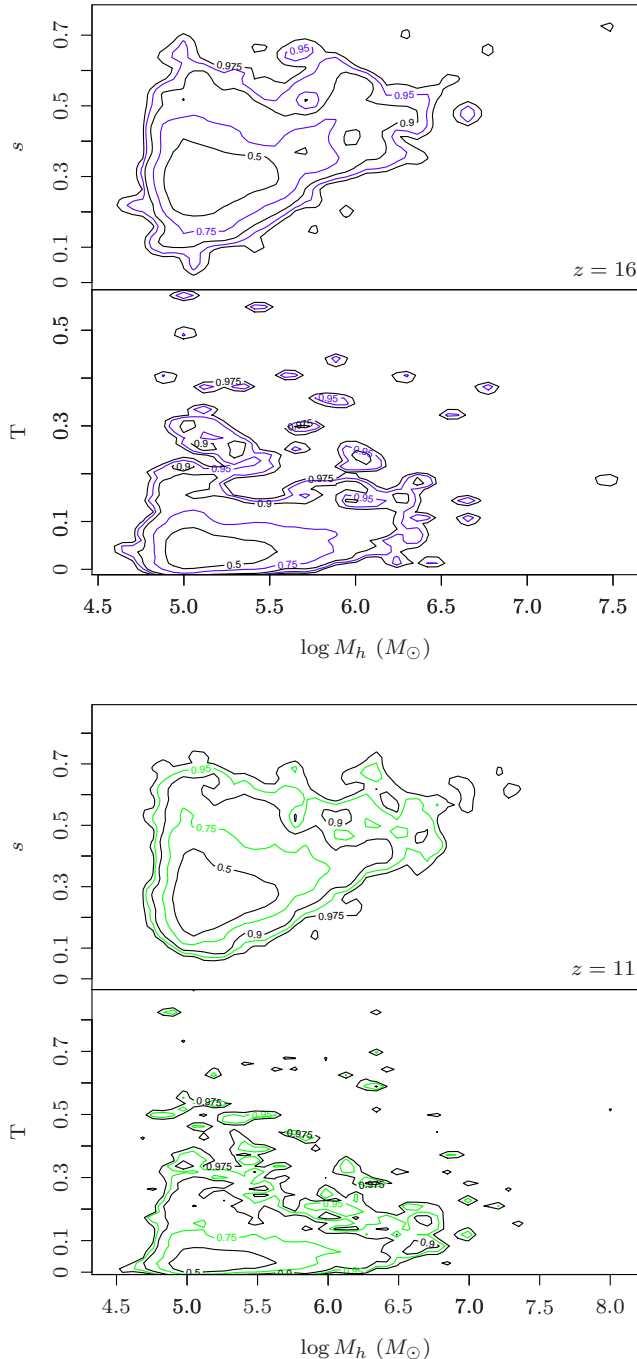


Figure 1. Sphericity s (upper panels), and triaxiality T (lower panels), as a function of total halo mass for halos at $z = 16$ (upper figure) and $z = 11$ (lower). The contour levels represent 50%, 75%, 90%, 95% and 97.5% of the sample.

non-spherical nature of halos, overall conclusions can be different depending on the assumptions made to define halos, the methods to measure shapes or the inclusion of gas physics (Allgood et al. 2006). Bett et al. (2007) found that more massive halos tend to be less spherical and more prolate; Kazantzidis et al. (2004) noticed that halos formed in simulations with gas cooling are more spherical than halos in adiabatic simulations.

To estimate the halo shape, we only use halos with more

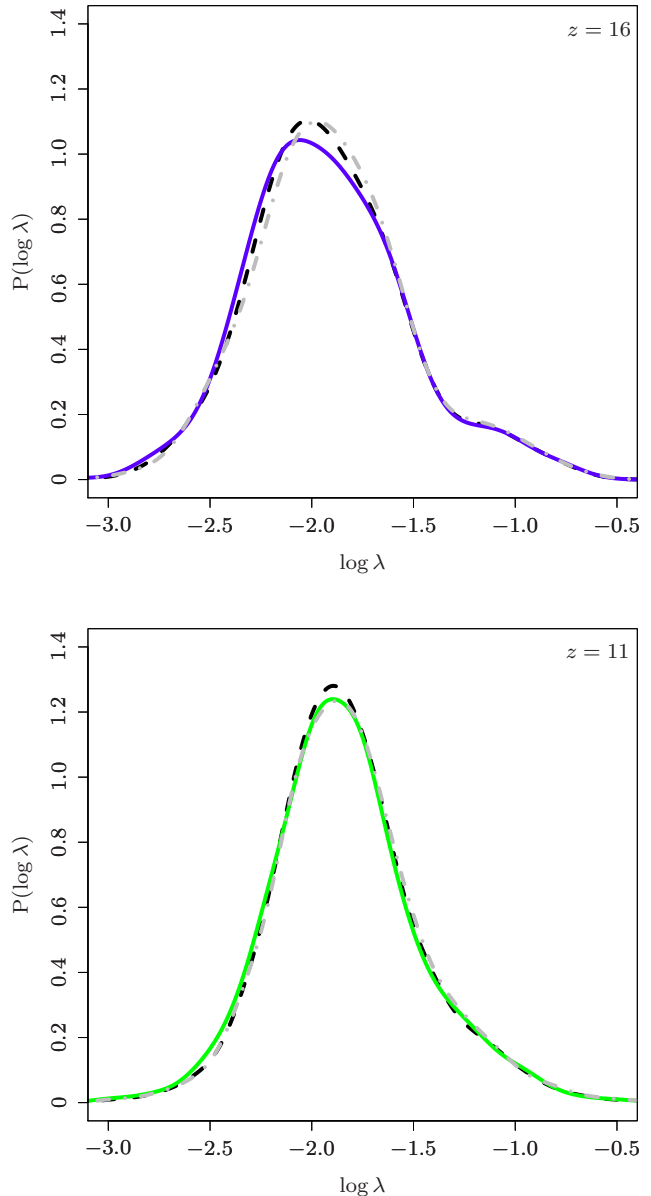


Figure 2. Spin distribution of the total (dark matter + gas) halo (black dashed lines), the dark matter (grey dot-dashed lines) and the gas (solid lines). The upper and lower panels refer to $z = 16$ and 11, respectively.

than 100 particles (gas + dark matter), equivalent to a total mass of $\approx 10^{4-5} M_\odot$. The shape of the halos is described in terms of sphericity, s , and triaxiality, T , as defined in Sec. 3.1. The probability contour levels of s and T as a function of the total halo mass, M_h , are shown in Fig. 1 for $z = 16$ (upper panel) and $z = 11$ (lower panel).

In the entire redshift range considered ($11 < z < 16$) the average sphericity is $\langle s \rangle = 0.3 \pm 0.1$, and for more than 90% of halos $T \lesssim 0.4$, showing a clear preference for oblateness over prolateness. This is markedly different from $z = 0$ halos that tend to be more prolate and spherical: for example, pure collisionless simulations (Allgood et al. 2006) found $\langle s \rangle \approx 0.6 \pm 0.1$ for galaxy mass halos $\sim 10^{12} h^{-1} M_\odot$. Note that constraints from observations of the Sagittarius

tidal streams give best-fit parameters $s \approx 0.67$, $q \approx 0.83$, and $T \approx 0.56$, in agreement with the Galactic model by Law et al. (2009).

Using a non-linear last square method computed with the Gauss-Newton algorithm, and approximating $s \propto M_h^{\alpha_s}$ and $T \propto M_h^{\alpha_T}$, we find $\alpha_s \approx 0.147$ and $\alpha_T = 0.285$ at $z = 16$, and $\alpha_s \approx 0.128$ and $\alpha_T = 0.276$ at $z = 11$. The fits are given below²,

$$\langle s(z) \rangle = \zeta_s \left(\frac{M_h}{h^{-1} M_\odot} \right)^{\alpha_s}, \quad (9)$$

$$\alpha_s = -4.1082 + 0.9834z - 0.0754z^2 + 0.00191z^3,$$

$$\zeta_s = 20.143 - 4.977z + 0.384z^2 - 0.00979z^3,$$

and

$$\langle T(z) \rangle = \zeta_T \left(\frac{M_h}{h^{-1} M_\odot} \right)^{\alpha_T}, \quad (10)$$

$$\alpha_T = -9.7534 + 2.2924z - 0.1727z^2 + 0.00429z^3,$$

$$\zeta_T = 51.720 - 12.500z + 0.946z^2 - 0.0236z^3.$$

The most massive halos in the simulation ($M_h = 10^{6.5-7} M_\odot$) tend to be more spherical and prolate than smaller ones, with weak variation of the mass dependence with redshift.

4.2 Spin distribution

The spin distribution of the total (dark matter + gas) mass, dark matter mass and gas mass is shown in Fig. 2 for $z = 16$ (top panel) and $z = 11$ (low panel). The curve is smoothed using a kernel density estimator for a sample of n elements,

$$f(x, h_s) = \frac{1}{nh_s(x)} \sum_{i=1}^n K \left(\frac{x - x_i}{h_s(x)} \right), \quad (11)$$

with a Gaussian kernel K and an adaptive bandwidth h_s . The distributions of dark matter and gas are considerably different at high redshift ($z = 16$), with the baryons rotating slower than the dark matter, which gives the dominant contribution to the total spin. At lower redshift, instead, the spin distributions of dark matter and gas track each other almost perfectly, as a consequence of a longer time interval available for momentum redistribution between the two components. It is important to notice that the comparisons are done by collecting different dark matter and gas particles of the same halo, thus fully accounting for the back-reaction of baryons on the parent dark matter distribution. It is very common to fit the halo spin distribution with a lognormal function (Bailin & Steinmetz 2005; Davis & Natarajan 2010). However, Bett et al. (2007) found deviations from such functional form when studying a large ($> 10^6$) number of halos in the Millennium simulation. Both the lognormal and Weibull models can be used quite effectively to analyze skewed data sets. Although these two models may provide similar data fit for moderate sample sizes, the inferences based on the model will often involve tail probabilities, where the effect of the model assumptions is very critical. This makes it important to use a quantitative

² Note that all fits hereafter are valid only within the redshift range of the simulation, unless explicitly stated.

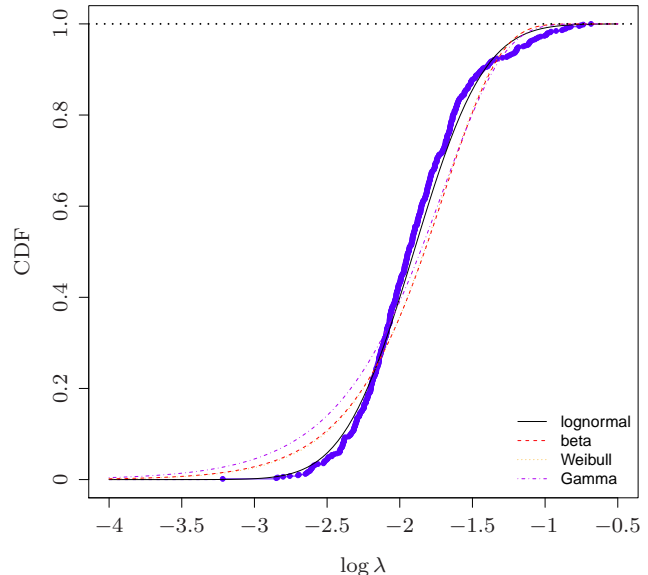


Figure 3. Cumulative distribution function of dark matter spin (thick blue solid line) compared with theoretical distributions at $z = 16$. The theoretical distributions are: lognormal (black solid line), beta (red dashed), Weibull (orange dotted) and Gamma (purple dot-dashed).

diagnostic to quantify the best distribution to use. To do so, we test four classical distributions: lognormal, Gamma, beta and Weibull, whose shapes are given by:

$$f_L(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-(\ln x - \mu)^2 / 2\sigma^2}, \quad (12)$$

$$f_\Gamma(x; k, \theta) = \frac{1}{\theta^k} \frac{1}{\Gamma(k)} x^{k-1} e^{-(1-x)/\theta}, \quad (13)$$

$$f_\beta(x; \alpha, \beta) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1} (1-x)^{\beta-1}, \quad (14)$$

$$f_W(x; k, \lambda) = \frac{k}{\lambda} \left(\frac{x}{\lambda} \right)^{k-1} e^{-(x/\lambda)^k}. \quad (15)$$

In order to choose the most suitable distribution, we fit the spin distribution of halos in our redshift range. Then, we use a Maximum Likelihood test to justify our choice. We obtain the following redshift-averaged values of the reduced chi-square: $(\chi_L^2, \chi_\beta^2, \chi_\Gamma^2, \chi_W^2) = (2.89 \pm 0.94, 11.95 \pm 4.85, 11.38 \pm 4.85, 13.53 \pm 4.34)$. In Fig. 3, we plot the cumulative distribution function for the four distributions above and the one obtained from the simulations. It is clear that the lognormal fits the data at best.

The distribution of spin parameter can be written as

$$P(\lambda) = \frac{1}{\lambda\sigma_0\sqrt{2\pi}} \exp \left[-\frac{\ln^2(\lambda/\lambda_0)}{2\sigma_0^2} \right], \quad (16)$$

where λ_0 is the location parameter and σ_0 is the shape parameter of the distribution. The best fit values for mean and

variance, σ^2 , as a function of redshift are³

$$\begin{aligned} \langle \lambda(z) \rangle &= 1.315 - 3.681 \times 10^{-1} z + 3.903 \times 10^{-2} z^2 \\ &\quad - 1.831 \times 10^{-3} z^3 + 3.206 \times 10^{-5} z^4, \end{aligned} \quad (17)$$

and

$$\begin{aligned} \sigma^2(z) &= 0.1754 - 5.246 \times 10^{-2} z + 5.871 \times 10^{-3} z^2 \\ &\quad - 2.909 \times 10^{-4} z^3 + 5.385 \times 10^{-6} z^4. \end{aligned} \quad (18)$$

While it is well known that the dependence of spin on halo masses is relatively weak (Macciò et al. 2007; Bett et al. 2007), it has not been verified yet whether this holds also for small objects. Therefore, analogously to the shape distribution, in Fig. 4 we show the contour levels of the halo spin as a function of total halo mass at $z = 16$ and 11.

Assuming a power law $\lambda \propto M_h^\alpha$, best fit becomes

$$\begin{aligned} \langle \lambda(z) \rangle &= \zeta_\lambda \left(\frac{M_h}{h^{-1} M_\odot} \right)^{\alpha_\lambda}, \quad (19) \\ \alpha_\lambda &= -1.64 \times 10^2 + 4.97 \times 10^1 z - 5.60 z^2 \\ &\quad + 2.78 \times 10^{-1} z^3 - 5.16 \times 10^{-3} z^4, \\ \zeta_\lambda &= 4.056 - 0.993 z + 0.045 z^2 - 0.004 z^3. \end{aligned}$$

The slope α_λ evolves from -0.023 at $z = 16$, to 0.012 at $z = 11$; both values are consistent with 0, indicating that the spin parameter distribution is essentially independent on halo mass also at the very high redshifts considered here.

5 IMPLICATIONS FOR THE POPIII IMF

In the following we discuss the possibility to connect the host halo properties to the typical mass scale of the collapsed protostar. It is important to keep in mind that all results presented here rely on the best available semi-analytical model to translate the angular momentum distribution into a corresponding stellar IMF. Despite such limitation, our approach provides the best way to statistically analyze a large sample of simulated halos, which could not be performed otherwise. For a detailed study of the properties of the rotation and structure of PopIII stars we refer the reader for the works of Greif et al. (2012); Stacy et al. (2012). They resolve four minihalos down to scales as small as $0.05 R_\odot$. They found little evidence of correlation between the properties of each host minihalo and the spin of its largest protostar or the total number of protostars formed in the minihalo. However due the low number of halos probed, it's difficult reach a statistical significant conclusion.

The IMF is usually defined as a segmented power-law or a log-normal type mass distribution (Kroupa 2001; Chabrier 2003). Both definitions are correlated by

$$dN \propto m_*^{-\alpha} dm_* \quad \text{or} \quad dN \propto m_*^\Gamma d(\log m_*), \quad (20)$$

where $\Gamma = -(\alpha - 1)$ (Bonnell et al. 2007) and N is the number of stars with masses in the range m_* to $m_* + dm_*$. The Salpeter slope (Salpeter 1955) is given by $\alpha = 2.35$, or $\Gamma = -1.35$. As discussed in the Introduction, the PopIII IMF is actually unknown, but there are hints that it could

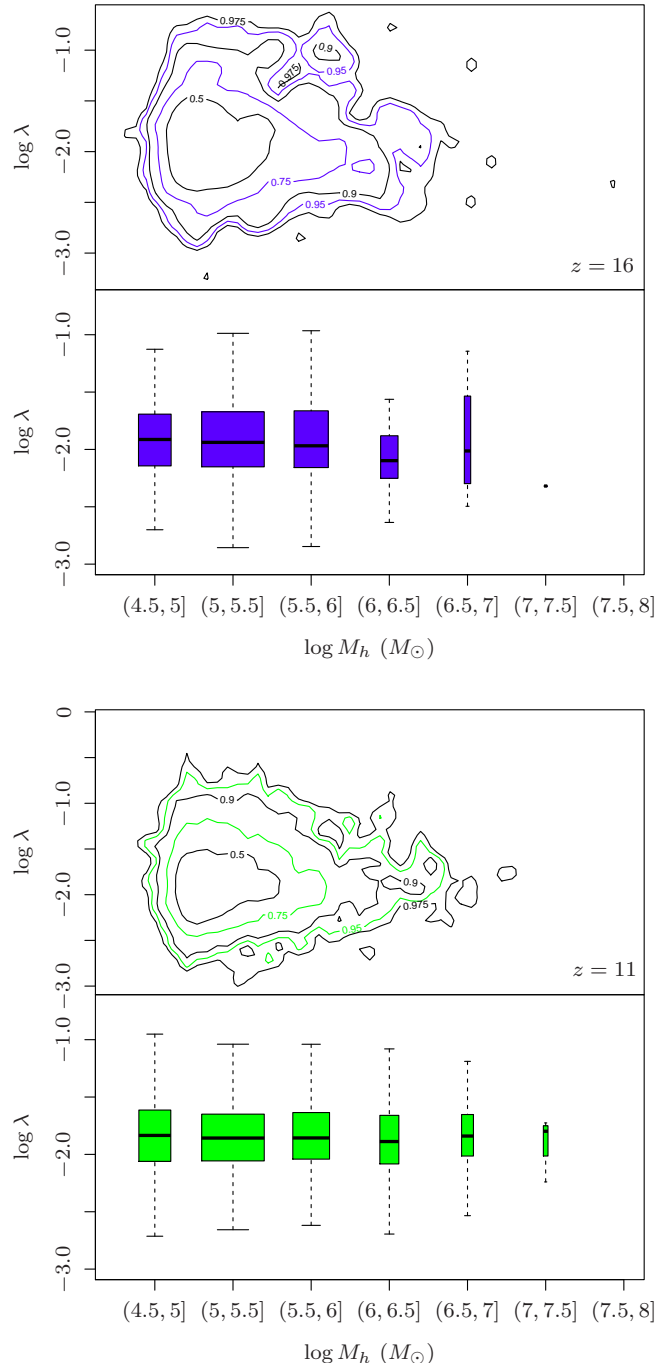


Figure 4. Spin distribution as a function of the total mass for halos at $z = 16$ (top figure) and 11 (bottom). The contour levels in the upper panels represent 50%, 75%, 90%, 95% and 97.5% of the sample, while in the lower panels the median values per bin of mass ($\log M_h = 0.5$) is shown. The width of boxes is proportional to the square root of the number of halos within each bin and the whiskers extend to the most extreme data point, which is within the 50% interquartile range, i.e. the difference between the largest and smallest values in the middle 50% of the dataset.

³ The mean and variance of lognormal distribution are given by $\langle \lambda \rangle = e^{\lambda_0 + \sigma_0^2/2}$ and $\sigma^2 = e^{\sigma_0^2 + 2\lambda_0} (e^{\sigma_0^2} - 1)$.

have been biased towards more massive stars compared to that of PopII/I stars.

One of the important ingredients for the determination of the IMF is the typical rotation of the gas. Extreme ultraviolet radiation from the protostar can ionize infalling neutral gas, creating an H II region whose expansion reduces significantly the accretion of gas onto the star. The radiation would also destroy molecules and inhibit star formation in the surroundings, by affecting accretion onto more distant protostellar cores (see e.g. Ricotti et al. 2002; Ahn & Shapiro 2007; Whalen & Norman 2008; Petkova & Maio 2012). The expansion is facilitated by protostellar cores with higher rotation, as the density in the polar directions tends to be lower; hence the final stellar mass is expected to increase in slowly rotating cores where the effects of feedback are quenched.

In the following we will make a simple estimate for the expected PopIII IMF, based on a combination of results from our simulations and the semi-analytic prescription described in MT08. In addition to studying the dependence of the final stellar mass on several radiative feedback processes such as photodissociation of H₂, Lyman- α radiation pressure, formation and expansion of H II regions, and disk photo-evaporation, the authors investigate the role of gas rotation, which modifies the density distribution in the vicinity of the star. In their fiducial model they assume that accretion is halted when the disk photo-evaporation rate exceeds the accretion rate onto the star-disk system; at that stage the typical PopIII stellar mass is $\sim 137M_{\odot}$.

Such value depends strongly on the assumed rotation rate of the protostellar core, which in their case was taken to be half of the keplerian velocity as suggested by AMR simulations focusing on a single parent halo (Abel et al. 2002; Bromm et al. 2002; O’Shea & Norman 2007). However, high rotational speeds might not be the rule, as we have seen from our previous analysis. Hosokawa et al. (2011) have found qualitatively similar results by means of a 2D hydrodynamic, radiative transfer simulation, showing that the mass accretion is shut down due to the dynamical expansion of the HII region and the photo-evaporation of the circumstellar disk. However, their simulations found systematically lower final masses than MT08. The likely explanation suggested by Hosokawa et al. (2011) for this discrepancy comes from the different model of the stellar feedback. In addition, MT08 assume that after the formation of the HII region mass accretion onto the disk still continues from regions shaded by the disk, which is not in agreement with the simulation picture from Hosokawa et al. (2011).

In the following, we consider the influence of rotation in two different scenarios developed by MT08. In the first (hereafter MT1), the accretion is reduced by the expansion of the H II region around the protostar and sets a typical mass similar to the values found by Hosokawa et al. (2011). In the second (hereafter MT2), the accretion efficiency is reduced as the H II region expands, however, accretion is allowed to continue from directions that are shadowed by the disk photosphere. The accretion stops when the photo-evaporation rate exceeds the accretion rate onto the star-disk system and sets a larger typical mass scale. The comparison between our results and MT08 can be easily done due to the one-to-one relationship between f_{kep} defined below and the stellar mass scale, assuming other parameters

fixed (see Fig. 5, 10 and Table 1 in MT08, where the values to interpolate the one-to-one relationship were taken).

The angular momentum of the gas accreting onto the star-disk system can be characterized by its keplerian parameter:

$$f_{kep}(M_{r_i}) = V_{\phi,i}/V_{kep,i}, \quad (21)$$

where $V_{\phi,i}$ and $V_{kep,i}$ are the rotational and keplerian velocity, respectively, as a function of the total mass enclosed within a radius r_i . Here, r_i is the position vector of the i -th particle relative to the halo centre. The characteristic velocities above are defined as:

$$V_{\phi,i} = j_i/r_i, \quad V_{kep,i} = \sqrt{GM(r_i)/r_i}, \quad (22)$$

where the specific angular momentum, j_i , of the i -th particle is averaged over the spherical shell whose radius is r_i .

The value of f_{kep} averaged over all particles within a halo can be expressed as

$$\langle f_{kep} \rangle = \frac{1}{N} \sum_{i=1}^N \frac{(j_i/r_i)}{V_{kep,i}}. \quad (23)$$

According to McKee & Tan (2008), for $f_{kep} \gtrsim 0.25$ little difference is observed in the final stellar mass, which is set by the balance between the (inner) disk-shadowed accretion and mass loss due to photo-evaporation. For smaller rotation parameters ($f_{kep} \lesssim 0.125$) instead, the mass scale at which accretion is halted strongly depends on the H II region breakout.

To calculate the $\langle f_{kep} \rangle$ distribution, we use the same procedure described in Sec. 4.2 and we show it in Fig. 5 at $z = 16$ and 11. The overall shape of the distribution remains qualitatively similar at different epochs, however the mean value increases towards lower redshifts, from 0.26 at $z = 16$ to 0.61 at $z = 11$.

The typical rotational velocity is in general below the required velocity for rotational support, in agreement with previous calculations (Abel et al. 2002). Using the above distributions we can translate the rotational velocity into a PopIII typical mass using models MT1 and MT2. The result of this exercise is shown in Fig. 6; there are several interesting features that we can deduce from here.

First, at high redshift the IMF tends to closely track the lognormal distribution imprinted by the rotation properties of the halos. Depending on the feedback model, though, the distribution can be centered at $\approx 65M_{\odot}$ (MT1) or $\approx 140M_{\odot}$ (MT2). At later times, model MT1 tends to evolve into a bimodal distribution with a second prominent peak located at $35 - 40M_{\odot}$ in addition to the initial one. The bimodality comes from the non-linear connection between rotation and mass scale. For values of $f_{kep} \gtrsim 0.25$ the rotation has a weak influence on the final stellar mass. As the redshift decreases, so does the width around the second peak of the stellar mass distribution, because the majority of halos have higher values of f_{kep} . A peak at $m_{*} \sim 65M_{\odot}$ is still present due to the slow rotation tail of the $\langle f_{kep} \rangle$ distribution. Model MT2 instead shows a much more gradual and moderate shift of the peak towards lower masses, accompanied by an increasingly narrower width.

Thus, it seems that the $\langle f_{kep} \rangle$ distribution and shift with redshift, governed by the angular momentum evolution of the halos, has an extremely strong influence on the PopIII

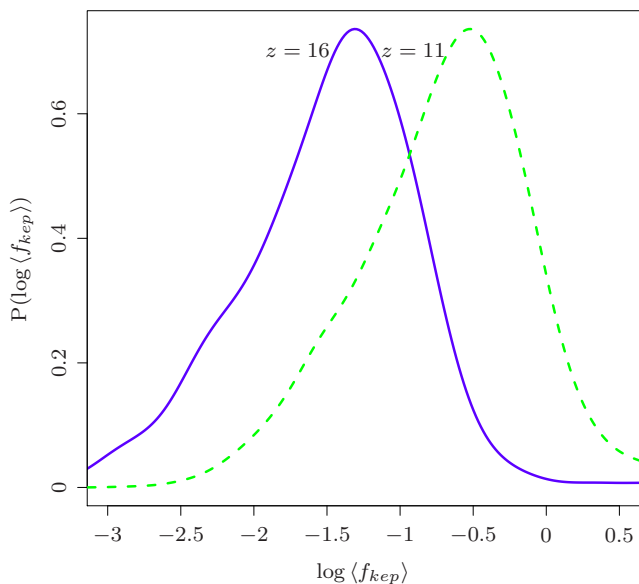


Figure 5. Distribution of $\log\langle f_{kep}\rangle$ at $z=16$ (solid blue line) and 11 (dashed green).

IMF, at least as long as we assume the MT08 feedback models to be correct. However, it is important to emphasize that the gas rotation is also affected by thermal heating from feedback mechanisms, which are expected to be stronger for PopIII stars and in low mass halos, as the ones we are dealing with. In addition, simulations (e.g. Tornatore et al. 2007; Maio et al. 2010, 2011) show that it is common to have multiple star formation sites within the same halo, with a combination of PopIII and PopII/I stars. This means that it is not straightforward nor trivial to assign a single PopIII IMF to a halo.

With the above caveats in mind, we come to the somewhat surprising conclusion that, although on a protostellar basis radiative feedback acting on baryons might be the key factor in determining the mass of the first stars, *it is the angular momentum distribution of the dark matter halos that controls the build-up of the IMF* (see also Schroyen et al. 2011). This process might work in the simple way outlined here as long as there is a one-to-one correlation between the halo and the protostellar core angular momentum and it might break down in larger galaxies in which momentum is dissipated via tidal torques and/or shocks arising from the interaction among different cores or galactic-scale dynamical instabilities. We reiterate that all our calculations include the back-reaction of baryons on the dark matter, and hence they should provide a robust description of the total matter dynamics in a halo.

6 SUMMARY

Our study, following the evolution of dark matter *and* baryonic physics in cosmological simulations, makes possible to study the statistical properties of the high- z , low mass halos that likely hosted the first stars. In addition such simulations include a large number of physical processes (PopIII and PopII/I star formation, metal enrichment, gas cooling

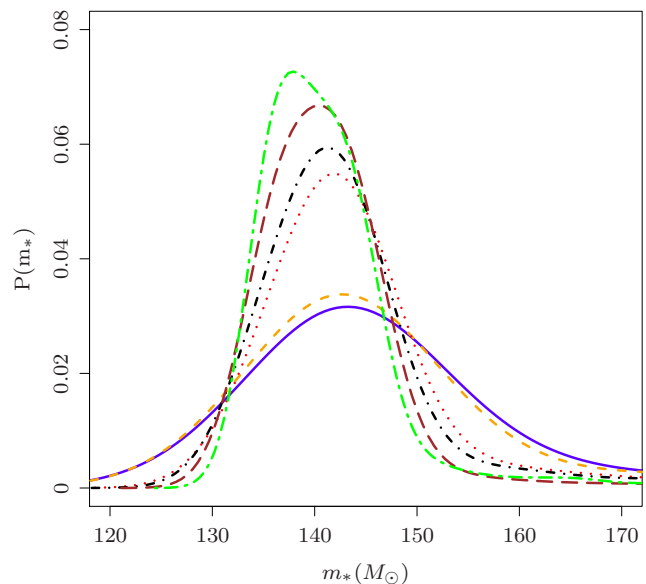
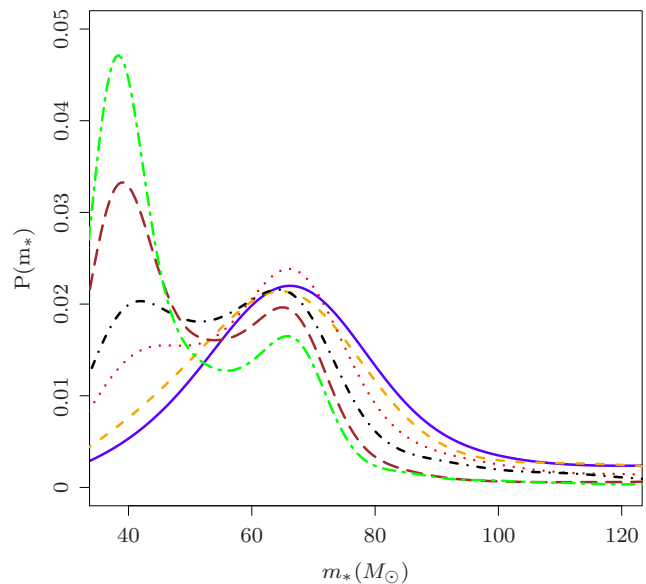


Figure 6. PopIII typical mass distribution for model MT1 (top panel) and MT2 (bottom panel) at redshift $z=16$ (blue solid line), 15 (orange dashed), 14 (red dotted), 13 (black dashed-dot), 12 (brown long-dashed), and 11 (green long dashed-dot).

from resonant and fine-structure lines and feedback effects) and a detailed chemical network following the abundances of key species (e^- , H, H^+ , H^- , He, He^+ , He^{++} , H_2 , H_2^+ , D, D^+ , HD, HeH^+).

In this work we have mostly concentrated on the statistical analysis of two important halo properties, i.e. spin and shape. As these parameters, governing the overall evolution of protostellar cloud collapse, are predicted by modern PopIII formation theories to be related to the mass of the first stars forming in these systems, we then discuss the implications of our findings for the PopIII IMF. Our main results can be summarized as follows:

- In the entire redshift range considered ($11 < z < 16$)

the average sphericity is $\langle s \rangle = 0.3 \pm 0.1$, and for more than 90% of halos $T \lesssim 0.4$, showing a clear preference for oblateness over prolateness, contrary to what found at $z = 0$.

- Larger halos in the simulation tend to be both more spherical and prolate: we find $s \propto M_h^{\alpha_s}$ and $T \propto M_h^{\alpha_T}$, with $\alpha_s \approx 0.128$ and $\alpha_T = 0.276$ at $z = 11$.

- The spin distributions of dark matter and gas are considerably different at $z = 16$, with the baryons rotating slower than the dark matter (giving the dominant contribution to the total spin). At lower redshift, instead, the spin distributions of dark matter and gas track each other almost perfectly, as a consequence of a longer time interval available for momentum redistribution between the two components.

- The spin distribution for both gas and dark matter inside the simulated small halos can be well represented by a lognormal function, with mean and variance at $z = 16$ of 0.0184 and 0.000391, virtually independent on halo mass and in good qualitative agreement with previous results. The mean value of spin parameters is also in agreement within $1-\sigma$ with the median value found by Jang-Condell & Hernquist (2001) for a lognormal distribution in their study of small-scale structures at high- z using a pure dark matter N-body simulation.

- According to most recent theories of PopIII star formation, rotation is the key factor in determining their final mass. Using the results of two feedback models (MT1 and MT2) by McKee & Tan (2008) and mapping our halo spin distribution into a PopIII IMF, we find that at high z the IMF tends to closely track the spin lognormal distribution; depending on the feedback model, though, the distribution can be centered at $\approx 65M_\odot$ (MT1) or $\approx 140M_\odot$ (MT2). At later times, model MT1 tends to evolve into a bimodal distribution with a second prominent peak located at $35 - 40M_\odot$, as a result of the non-linear relation between rotation and halo mass.

While the PopIII IMF is still highly debated (Stacy et al. 2010; Clark et al. 2011; Greif et al. 2011; Prieto et al. 2011; Hosokawa et al. 2011; Greif et al. 2012), the present study offers an intriguing indication that the IMF of the first stars might be tied and controlled by the properties of their parent halos, thus linking in a novel way large scale structure and early star formation. If this is indeed the case, our suggestion could lead to clear and testable predictions (e.g. PISN rates, abundance of pure PopIII galaxies, metal abundance patterns in the IGM and low-mass stars to mention a few) for the number, properties and cosmic evolution of these pristine stellar systems.

ACKNOWLEDGEMENTS

RSS and BC are happy to thank the Scuola Normale Superiore (SNS), Pisa, Italy for hospitality during part of the development of this work. RSS acknowledges financial support from the Brazilian financial agency FAPESP through grant number 2009/05176-4. UM acknowledges the computing center of the Max Planck Society, in Garching bei München (Rechenzentrum Garching, RZG), Germany, for the invaluable technical support, and kind hospitality at the Italian computing center (CINECA), the Scuola Normale Superiore in Pisa, Italy, the University of Bologna, Italy, and the Universidad Autónoma de Madrid, Spain. He

also acknowledges financial contributions from the Project ‘‘HPC-Europa2’’, grant number 228398, with the support of the European Community, under the FP7 Research Infrastructure Programme. We also thank Emille Ishida, Addressa Jendrieck and Jongsoo Kim for fruitful comments. Finally we thank Volker Bromm for the very kindly and fruitful comments as a referee of the present paper.

REFERENCES

- Abel T., Bryan G. L., Norman M. L., 2002, *Science*, 295, 93
- Ahn K., Shapiro P. R., 2007, *MNRAS*, 375, 881
- Allgood B., Flores R. A., Primack J. R., Kravtsov A. V., Wechsler R. H., Faltenbacher A., Bullock J. S., 2006, *MNRAS*, 367, 1781
- Antonuccio-Delogu V., Dobrotka A., Becciani U., Cielo S., Giocoli C., Macciò A. V., Romeo-Velóná A., 2010, *MNRAS*, 407, 1338
- Bailin J., Steinmetz M., 2005, *ApJ*, 627, 647
- Benson A. J., 2012, *New Astronomy*, 17, 175
- Bett P., 2012, *MNRAS*, 420, 3303
- Bett P., Eke V., Frenk C. S., Jenkins A., Helly J., Navarro J., 2007, *MNRAS*, 376, 215
- Bonnell I. A., Larson R. B., Zinnecker H., 2007, *Protostars and Planets V*, pp 149–164
- Bromm V., Coppi P. S., Larson R. B., 2002, *ApJ*, 564, 23
- Bromm V., Ferrara A., Coppi P. S., Larson R. B., 2001, *MNRAS*, 328, 969
- Bromm V., Loeb A., 2003, *Nature*, 425, 812
- Bromm V., Yoshida N., 2011, *ARA&A*, 49, 373
- Bromm V., Yoshida N., Hernquist L., McKee C. F., 2009, *Nature*, 459, 49
- Chabrier G., 2003, *PASP*, 115, 763
- Ciardi B., Ferrara A., 2005, *Space Sci. Rev.*, 116, 625
- Clark P. C., Glover S. C. O., Smith R. J., Greif T. H., Klessen R. S., Bromm V., 2011, *Science*, 331, 1040
- Corless V. L., King L. J., 2008, *MNRAS*, 390, 997
- Cui W., Borgani S., Dolag K., Murante G., Tornatore L., 2012, *MNRAS*, 423, 2279
- Davis A. J., Natarajan P., 2010, *MNRAS*, 407, 691
- de Souza R. S., Krone-Martins A., Ishida E. E. O., Ciardi B., 2012, *A&A*, 545, A102
- de Souza R. S., Yoshida N., Ioka K., 2011, *A&A*, 533, A32
- Del Popolo A., 2009, *ApJ*, 698, 2093
- Dolag K., Borgani S., Murante G., Springel V., 2009, *MNRAS*, 399, 497
- D’Onghia E., Navarro J. F., 2007, *MNRAS*, 380, L58
- Dopcke G., Glover S. C. O., Clark P. C., Klessen R. S., 2012, in Umemura M., Omukai K., eds, *American Institute of Physics Conference Series Vol. 1480 of American Institute of Physics Conference Series, The stellar IMF at very low metallicities*. pp 352–354
- Eisenstein D. J., Loeb A., 1995, *ApJ*, 443, 11
- Greif T. H., Bromm V., Clark P. C., Glover S. C. O., Smith R. J., Klessen R. S., Yoshida N., Springel V., 2012, *MNRAS*, 424, 399
- Greif T. H., Springel V., White S. D. M., Glover S. C. O., Clark P. C., Smith R. J., Klessen R. S., Bromm V., 2011, *ApJ*, 737, 75

- Hosokawa T., Omukai K., Yoshida N., Yorke H. W., 2011, *Science*, 334, 1250
- Jang-Condell H., Hernquist L., 2001, *ApJ*, 548, 68
- Jeeson-Daniel A., Dalla Vecchia C., Haas M. R., Schaye J., 2011, *MNRAS*, 415, L69
- Johnson J. L., Dalla Vecchia C., Khochfar S., 2012, *ArXiv e-prints*
- Kazantzidis S., Kravtsov A. V., Zentner A. R., Allgood B., Nagai D., Moore B., 2004, *ApJ*, 611, L73
- Kroupa P., 2001, *MNRAS*, 322, 231
- Law D. R., Majewski S. R., Johnston K. V., 2009, *ApJ*, 703, L67
- Macciò A. V., Dutton A. A., van den Bosch F. C., Moore B., Potter D., Stadel J., 2007, *MNRAS*, 378, 55
- Maio U., Ciardi B., Dolag K., Tornatore L., Khochfar S., 2010, *MNRAS*, 407, 1003
- Maio U., Ciardi B., Yoshida N., Dolag K., Tornatore L., 2009, *A&A*, 503, 25
- Maio U., Dolag K., Ciardi B., Tornatore L., 2007, *MNRAS*, 379, 963
- Maio U., Dolag K., Meneghetti M., Moscardini L., Yoshida N., Baccigalupi C., Bartelmann M., Perrotta F., 2006, *MNRAS*, 373, 869
- Maio U., Khochfar S., Johnson J. L., Ciardi B., 2011, *MNRAS*, 414, 1145
- McKee C. F., Tan J. C., 2008, *ApJ*, 681, 771
- Omukai K., 2000, *ApJ*, 534, 809
- Omukai K., Palla F., 2003, *ApJ*, 589, 677
- O'Shea B. W., Norman M. L., 2007, *ApJ*, 654, 66
- Petkova M., Maio U., 2012, *MNRAS*, 422, 3067
- Prieto J., Padoan P., Jimenez R., Infante L., 2011, *ApJ*, 731, L38
- Ricotti M., Gnedin N. Y., Shull J. M., 2002, *ApJ*, 575, 49
- Salpeter E. E., 1955, *ApJ*, 121, 161
- Schneider R., Ferrara A., Salvaterra R., Omukai K., Bromm V., 2003, *Nature*, 422, 869
- Schneider R., Salvaterra R., Ferrara A., Ciardi B., 2006, *MNRAS*, 369, 825
- Schroyen J., de Rijcke S., Valcke S., Cloet-Osselaer A., Dejonghe H., 2011, *MNRAS*, 416, 601
- Skibba R. A., Macciò A. V., 2011, *MNRAS*, 416, 2388
- Springel V., 2005, *MNRAS*, 364, 1105
- Springel V., Hernquist L., 2003, *MNRAS*, 339, 289
- Springel V., White S. D. M., Hernquist L., 2004, in *Ryder S., Pisano D., Walker M., Freeman K., eds, Dark Matter in Galaxies Vol. 220 of IAU Symposium, The shapes of simulated dark matter halos.* p. 421
- Stacy A., Greif T. H., Bromm V., 2010, *MNRAS*, 403, 45
- Stacy A., Greif T. H., Bromm V., 2012, *MNRAS*, 422, 290
- Stacy A., Greif T. H., Klessen R. S., Bromm V., Loeb A., 2012, *ArXiv e-prints*
- Tornatore L., Borgani S., Dolag K., Matteucci F., 2007, *MNRAS*, 382, 1050
- Turk M. J., Oishi J. S., Abel T., Bryan G. L., 2012, *ApJ*, 745, 154
- van Uitert E., Hoekstra H., Schrabback T., Gilbank D. G., Gladders M. D., Yee H. K. C., 2012, *A&A*, 545, A71
- Volonteri M., 2010, *A&A Rev.*, 18, 279
- Volonteri M., Rees M. J., 2005, *ApJ*, 633, 624
- Whalen D., Norman M. L., 2008, *ApJ*, 673, 664
- Yoshida N., Abel T., Hernquist L., Sugiyama N., 2003, *ApJ*, 592, 645
- Yoshida N., Omukai K., Hernquist L., 2008, *Science*, 321, 669
- Yoshida N., Omukai K., Hernquist L., Abel T., 2006, *ApJ*, 652, 6
- Zemp M., Gnedin O. Y., Gnedin N. Y., Kravtsov A. V., 2011, *ApJS*, 197, 30

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