Can Population III stars survive to the present day?

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ABSTRACT

In recent simulations of primordial star-forming clouds, it has been shown that a number of primordial protostars are ejected from the cluster of their origin with the velocity exceeding their escape velocity. There is a possibility that some of these protostars can enter the main sequence and survive until the present epoch. We develop a semi-analytical model guided by results of cosmological simulations to study the mass accretion by these protostars as a function of the original stellar mass, and other parameters such as angular momentum and gravitational drag due to ambient gas. We aim to determine whether the protostars can remain sufficiently low-mass and long-lived to survive to the present day. This requires that the protostars stop accreting before being ejected from the cluster, and have a final mass less than 0.8 $M_\odot$. Assuming the protostars obey the spherical Bondi-Hoyle flow while interacting with the ambient gas medium, we show that Pop III protostars which initially form within a certain range of mass $M \leq 0.65 M_\odot$ and velocity larger than the escape velocity may survive with a mass lower than the cutoff. Hence, these may even be found in our Milky Way or its satellites.

Key words: stars: Population III – accretion – hydrodynamics – instabilities – methods: numerical

1 INTRODUCTION

The emergence of the very first stars in the Universe, also known as Population III (or Pop III) stars, has become an important topic of research in modern astrophysics and cosmology (see e.g., Lacey & Cole 1993; Haiman et al. 1996; Tegmark et al. 1997; Omukai & Nishi 1998; Madau 2000). Hierarchical structure formation leads to formation of the smaller gravitationally bound objects, such as matter peaks containing the first stars, and these subsequently merge with gas and dark matter to form bigger objects like galaxies and clusters (Abel et al. 2000; Madau, Ferrara & Rees 2001; Barkana & Loeb 2001; Heger & Woosley 2002; Umeda & Nomoto 2003). These structures emit ultra-violet radiation that ionized the surrounding inter-galactic medium (IGM), thereby terminating the cosmic dark ages (for a review see Bromm & Larson 2004; Glover 2005; Gnedin 2015 and references therein).

Various analytical as well as advanced 1D–3D numerical simulations have led to the current consensus that the very first stars in the universe formed in small halos (also called minihalos) of $\sim 10^5–10^6 M_\odot$ at redshift $\sim 15–30$ (e.g., Yoshida et al. 2006; O’Shea & Norman 2007; Wise & Abel 2008; Turk et al. 2009; Komiya, Suda, & Fujimoto 2015). Other simulations have shown that Pop III stars can still form down to the redshift $z \sim 2.5$ (e.g., Scannapieco, Schneider & Ferrara 2003; Dawson et al. 2004; Weinmann & Lilly 2005; Furlanetto & Loeb 2005; Haiman 2005; Xu et al. 2008; 2016; Barrow et al. 2017). Pop III stars by definition formed within metal-free gas never enriched by previous stellar generations. Subsequently, the supernova explosions of a subset of Pop III stars provided the metallicity for the second generation of metal-poor stars (Omukai et al. 2005; Schneider et al. 2006; Tornatore et al. 2007). Although Pop III stars are considered to be metal-free (i.e., formed out of the pristine atomic hydrogen and helium, see e.g., Glover & Abel 2008; O’Shea et al. 2008), the metallicity for the transition from Pop III to Pop II depends on the cooling mechanism that is ultimately responsible for the gas fragmentation (Trenti & Stiavelli 2009; Schneider & Omukai 2010; Wise et al. 2012).

Given the complex nature of the non-linear collapse process, many important details associated with the formation of these stars remain uncertain. One such aspect is the mass...
distribution of the first generation of stars, commonly denoted as initial mass function (IMF). It has been argued that the formation of these objects depends on H$_2$ cooling, but that there is a lower limit to gas temperature ($\sim$200 K) because of the lack of a permanent dipole moment of the hydrogen molecule. This led to the idea that the first generation of stars should have masses of $\sim$100 M$_\odot$ (Abel & Bryan 2007; Gao et al. 2007; Yoshida Omukai & Hernquist 2008; Bromm et al. 2009), based upon the higher Jeans mass of warmer gas as compared to, e.g., present-day star formation in the Milky Way. This would make them have a short lifetime, possibly exploding as a pair-instability supernovae (see e.g., Heger & Woosley 2002; Heger et al. 2003; Whalen & Fryer 2010; Kasen et al. 2011). This is in stark contrast to the typical masses of stars at the present epoch (Kroupa 2002; Chabrier 2003; Andersen et al. 2009; van Pieter & Conroy 2010), whose initial mass function (IMF) peaks at $\sim$1 M$_\odot$ due to metal and dust cooling.

Results from early simulations of Pop III stars suggested that these have very large masses, however this was likely due to computational inability to follow the evolution of gas physics for adequately long periods of time at sufficiently high resolution. The computational time-step decreases rapidly as gas density increases, causing the simulations to become more computationally intensive and costly. It is an onerous task to follow the gas up to very high densities due to time steps becoming of the order of $10^{-3}$ years (see e.g., Abel et al. 2002). Thus the early simulations could not have seen fragmentation in the gas. However, recent 3D simulations (e.g., Stacy et al. 2010; Clark et al. 2011), circumvent this issue by introducing sink particles above a certain density threshold. Only then it became possible to follow the evolution of the gas cloud and the formation of the first protostar. In this case, multiple stars can form in a given minihalo, and the secondary protostars can be much smaller in mass (e.g., Greif et al. 2012; Machida & Oguri 2013); Hirano et al. 2014; Hartwig et al. 2015; Bland-Hawthorn, Sutherland, & Webster 2015). However, the fate of these fragments is still uncertain. There might be two possibilities: Fragments can migrate on the viscous timescale over which angular momentum is lost (Hosokawa et al. 2016), and move towards the center and merge with the primary protostar on a scale $\sim 10^4$ AU (Hirano & Bromm 2016). The other possibility is that the secondary protostars can escape the potential well of the bound system due to gravitational interactions with other objects, or with the surrounding medium (Susa et al. 2014; Johnson 2015; Dutta 2016a; Stacy Bromm & Lee 2016). Escape of stars may also be possible without any interactions if they are born with a sufficiently high velocity. These studies showed that a fraction of the original protostars can be ejected from the cluster of origin, with speeds $\sim 10^{-20}$ km s$^{-1}$, comparable to or larger than the escape speed of the system. If this happens then it is plausible that the first generation of stars can survive for a long time, provided they are unable to accrete significant mass before being finally ejected.

The question of survival of the oldest stars in the Universe becomes even more interesting in the light of recent discoveries of extremely metal poor stars both in the halo of the Milky Way (Beers & Christlieb 2005, and the references therein) as well as in the bulge (Howes et al. 2015). Most interestingly, the possibility of survival of the low-mass Pop III stars has received a boost with the recent discovery of Galactic halo star SDSS J102915+172927, which has a mass less than 0.8 M$_\odot$ and a metallicity of $Z = 4.5 \times 10^{-5}$ Z$_\odot$ (Schneider et al. 2012). Over the last two decades, with the help of advanced observational techniques and surveys, searches have led to a handful of stars with metallicities below [Fe/H] $\leq -4.0$, even down to [Fe/H] $\sim -5.5$ (e.g., Keller et al. 2007; Yanny et al. 2009; Califa et al. 2011; Li et al. 2015; Sobral et al. 2015). The discovery of such low-metallicity stars is in contrast with the estimate of the critical metallicity above which Pop II stars form: this is expected to be of order $10^{-3.5}$ Z$_\odot$ (Ostriker & Gnedin 1996; Omukai 2000; Bromm & Loeb 2003; Furlanetto & Loeb 2003; Tan Wang & Cheng 2016). The lowest metallicity stars then correspond to some of the earliest generations of stars in the universe (see e.g., Tornatore et al. 2007; Smith et al. 2009). The discovery of these low-metallicity stars implies that the critical metallicity is lower than expected. The low metallicity of these small stars suggests that low-mass star formation began by the first episodes of metal-enrichment. While even metal-free gas has been shown in simulations to fragment into low-mass stars, the critical metallicity of the transition from a Pop III IMF to a Pop I/II IMF remains an open question. Another possibility is that these low-metallicity stars are Pop III stars that later went through gas clouds with metallicity and accumulated some metallicity after they reached the ZAMS (Zero Age Main Sequence). Therefore, Pop III stars may or may not be able to accrete metals later in their lifetime to end up ‘masked’ as Pop II stars. (see e.g., Frebel et al. 2007, 2009; Johnson & Khocharf 2011; Tanaka et al. 2017). The photosphere of the stars may also gain some processed metals from a supernova in the vicinity. In any case, these observations therefore prompt one to ask the question whether the first stars could have survived for a long time, e.g. until the present epoch.

The answer to this question lies in the complex interplay between the dynamical interaction of the fragments with the ambient gas and the accretion phenomena. It is necessary to investigate the history of mass accretion by the primordial protostars. Numerical simulations of gravitational collapse of primordial halos that follow the evolution beyond the formation of the first protostar suffers from two major shortcomings. On one hand, our attempts to simulate such a system can be hindered by the susceptibility of the gas to artificial fragmentation if the Jeans length $\lambda_J$ is not adequately resolved. On the other hand, even when $\lambda_J$ is sufficiently well resolved, current highest resolution simulations are incapable of following protostar evolution over a sufficient number of orbital revolutions around its disk (e.g., Clark et al. 2011; Greif et al. 2011, 2012; Becerra et al. 2015). Thus, the final fate of these protostars remains unclear. In these circumstances, it is important to explore the issue using a combination of numerical simulations and semi-analytical methods. This is the approach that we adopt here. Specifically, we begin by using the typical orbital parameters of these protostars and the properties of the clusters, as determined from numerical simulations. Next, we use these parameters as inputs into a simple semi-analytical model of Bondi-Hoyle accretion to explore the maximum mass range of Pop III protostars that could have avoided core collapse and survived to the present day. As we shall see in the subsequent sections, the combination of semi-analytic methods...
and numerical simulations enables us to probe the details of the trajectory of these stars that escape while interacting with the ambient gas in the gravitationally bound system.

The paper is organized in the following manner. In §2 we briefly discuss the relevant physical process with an emphasis on those primordial stars that stay below the critical mass for surviving until the present-day. In §3 we describe the numerical setup along with a comprehensive discussion on the Bondi-Hoyle accretion phenomenon. The details of the mass-velocity relations are outlined in §4, followed by the implication of this study for the possible existence of Pop III stars in §5.

2 BASIC PHYSICAL PROCESS

Before going into the intricate details of the problem, we briefly delineate the basic physical processes starting from the formation of primordial cloud inside dark matter (DM) halos to the build-up of the disk, which then fragments to form a Pop III multiple system.

2.1 Formation of the gas clump inside DM halo

The standard cosmological model predicts that the hierarchical structure formation is based on weakly interacting cold dark matter (CDM; e.g., White & Frenk 1991; Lacey & Cole 1994). The primordial density fluctuations are best described by a Gaussian random field with a power spectrum $P(k) \propto k^n$, where $k$ is the wavenumber with $n \approx 1$ (Subramanian Cen & Ostriker 2000; Navarro & Steinmetz 2000). Evolution in the early universe and differences in the growth rate at different scales leads to its modification as encapsulated in Bardeen et al. (1986); Efstathiou et al. (1982); Eisenstein & Hu (1999). Using TREEPM code (see e.g., Bagla 2002; 2005; Springel et al. 2005), cosmological N-Body simulations have shown that perturbations eventually become amplified and unstable against collapse due to gravitational instability (Smith et al. 2008; Turk et al. 2009; Hahn & Abel 2011). This leads to the formation of virialized dark matter halos. The mass of the virialized halo inside the virial radius is defined as $M_{\text{vir}} \sim \rho_{\text{vir}} r_{\text{vir}}^3$, where the virial density $\rho_{\text{vir}}$ can be taken as $\rho_{\text{vir}} \sim \bar{\rho}(z_{\text{collapse}})\Delta$, with $\bar{\rho}$ and $\Delta$ being the mean matter density and overdensity at the time of virialization. The radius $r_{\text{vir}}$ and temperature of the virialized halos can be calculated as

$$r_{\text{vir}} \approx 200 \text{ pc} \left( \frac{M_{\text{vir}}}{10^9 M_\odot} \right)^{1/3} \left( \frac{1 + z_{\text{collapse}}}{20} \right)^{-1} \left( \frac{\Delta}{200} \right)^{-1/3},$$

$$T_{\text{vir}} \approx 2000K \left( \frac{M_{\text{vir}}}{10^9 M_\odot} \right)^{2/3} \left( \frac{1 + z_{\text{collapse}}}{20} \right),$$

where mass of the collapsing halo corresponding to a 3-σ fluctuation at redshift $z_{\text{collapse}} \sim 20$ is $M_{\text{vir}} \approx 10^9 M_\odot$. This is the characteristic mass of the potential well inside which primordial gas cools and condenses by molecular hydrogen. Here we are ignoring the effect of supersonic large scale flows in baryons (Tseliakhovich & Hirata 2010; Greif et al. 2011a).

2.2 Initial collapse phase

Gas falling into the potential well of DM halo gets heated up, due to shock-heating, to around 1000 K, which is close to the virial temperature of the DM halo. At this point the infalling gas has reached peak densities of $\sim 1$ cm$^{-3}$. Next, theoretical studies (e.g., Susa et al. 1998; Yoshida et al. 2003) have shown that the formation of molecular hydrogen is sufficient to cool the gas down to temperature 200 K, via H$_2$ rotational and vibrational line emission. The gas reaches a density $\sim 10^4$ cm$^{-3}$ where the H$_2$ cooling rate ($\dot{\Lambda}_{\text{H}_2}$) saturates, i.e., there is a transition from $\dot{\Lambda}_{\text{H}_2} \propto n^2$ to $\dot{\Lambda}_{\text{H}_2} \propto n$ (Bromm & Larson 2004). More precisely, the adiabatic heating rate becomes higher than the cooling rate near this critical density $n_{\text{crit}} \sim 10^4$ cm$^{-3}$. The transition from cooling to heating sets a characteristic Jeans length $L_J$, allowing the gas to fragment with the Jeans mass, $M_J$ (Glover 2005), defined as

$$M_J \approx 1000 M_\odot \left( \frac{T}{200 K} \right)^{3/2} \left( \frac{n}{10^4 \text{cm}^{-3}} \right)^{-1/2},$$

$$L_J \approx 2 \text{pc} \left( \frac{T}{200 K} \right)^{1/2} \left( \frac{n}{10^4 \text{cm}^{-3}} \right)^{-1/2}.$$ (4)

As the collapse reaches $\sim 10^7$–$10^8$ cm$^{-3}$, almost all the atomic hydrogen begins to convert to the molecular phase by the three-body H$_2$ formation reaction (e.g., Palla et al. 1983), resulting in the cooling of gas faster than its free-fall time. This is an extremely complicated phase of collapse where various cooling and heating processes occur simultaneously (Glover & Savin 2009; Turk et al. 2011; Dutta 2015b). Continuous collapse leads the gas to go through different high-density cooling processes, such as dissociation cooling and collision-induced emission cooling (Ripamonti & Abel 2004). The gas becomes optically thick and forms an adiabatic hydrostatic core with density as high as $\sim 10^{15}$ cm$^{-3}$ (O'Shea & Norman 2007; Yoshida Omukai & Hernquist 2008). The non-linear collapse process depends significantly on the interplay of dynamical as well as thermal evolution of the unstable gas, which differs among clouds. Studies show that the hydrostatic core typically has mass $\sim 0.1 M_\odot$, length scale of 0.03 AU and a temperature $\sim 2500$ K and is surrounded by a massive dense circumstellar disk. Due to high accretion rates ($\sim 0.1 M_\odot$ yr$^{-1}$), the core mass increases rapidly to form a massive primordial protostar (see e.g., recent reviews by Bromm 2013; Glover 2013).

2.3 Disk fragmentation

The distribution of angular momentum during the collapse of a rotating gas cloud leads to the formation of a disk-like structure that has relative velocity between the spiral-arms. However, both the shear motion and density gradient between the spiral-arms that exert pressure support are unable to counter the disk’s self-gravity, leading the disk to become gravitationally unstable to fragmentation (Stacy et al. 2010; Clark et al. 2011). Simulations use different computational techniques to model the disk fragmentation, such as the sink particle method (Clark et al. 2011a) and artificial opacity (Hirano & Bromm 2016). In the following, we compare the various time scales which are crucial to understand the fragmentation behaviour due to instability in the disk.
To begin with, let us suppose that the gas is being accreted with radial velocity profile \( v(r) \) through a radial gas density profile \( \rho(r) \propto r^{-2.2} \). The accretion timescale is defined as \( t_{\text{acc}} = M(r)/\dot{M}(r) \), where \( M(r) = 4\pi r^2 \rho(r) v(r) \) is the mass accretion rate. The fragmentation timescale is defined as \( t_{\text{frag}} = \dot{M}_{\text{BE}}/\dot{M} \), where the Bonnor–Ebert mass \( (\dot{M}_{\text{BE}}) \) within a certain volume of collapsed gas measures the strength of gravitational instability, and is given by \( \dot{M}_{\text{BE}} = 1.18(c_s^2/G^{3/2}) \rho_{\text{ext}}^{-3/2} \approx 20M_\odot T_3^{3/2}n^{-1/2}\mu^{-2} \gamma^2 \). Here \( c_s \) is the speed of sound, \( P_{\text{ext}} \) is the external pressure that is equal to the local gas pressure, \( \mu \) is the mean molecular weight in units of the proton mass and \( \gamma = 5/3 \) is the well-known adiabatic index. Fragmentation occurs when the dynamical timescale of the central collapse becomes longer than the collapse timescale of the individual density fluctuations, i.e., \( t_{\text{acc}} < t_{\text{frag}} \).

To understand the general stability criteria for differentially rotating disks, one needs to compare the free-fall time \( (t_f = \sqrt{3\pi/32GP}) \) along with both the sound crossing time \( (t_{\text{sound}} = H/c_s) \) and shear timescale \( (t_{\text{shear}} = R/v_{\text{shear}}) \) as defined in recent study by Hirano & Bromm (2016). Here \( R \) is the radius, \( H \) is the scale height and \( v_{\text{shear}} \) is the velocity of shearing motions between the spiral-arms. The gas clumps as well as the disk become unstable when the free-fall timescale due to its self-gravity becomes shorter than both the sound-crossing timescale and shear timescale, i.e., \( t_f < t_{\text{sound}} \) and \( t_f < t_{\text{shear}} \). In other words, \( t_f^2 < t_{\text{sound}}t_{\text{shear}} \) implies,

\[
\frac{c_s(v_{\text{shear}}/d)}{\pi G(\rho H)} \leq \frac{32}{3\pi^2} \sim 1. \tag{5}
\]

If fragmentation happens throughout the disk that has a rotational speed \( v_{\text{rot}} \) such that \( v_{\text{rot}} = \Omega R (\Omega \text{ being the angular velocity}) \), then the local Toomre criteria can be defined as \( Q \equiv c_s\Omega/\pi G \Sigma \sim \Omega^2/\pi G \rho \), where \( \Sigma = \rho H \) is the surface density of the disk.

A number of recent simulations have confirmed that the disk fragments to low-mass Pop III stars, which can have significant impact upon the initial mass function and subsequent generation of stars. Moreover, a fraction of protostars can even be ejected from the cluster due to the dynamical interaction with other stars and gas (Susa et al. 2013; Dutta 2016a; Ishiyama et al. 2016).

### 2.4 Mass of stars \( M_\star \leq 0.8M_\odot \)

Here we provide a simple analytical estimate of the critical mass of the ejected protostars that have evolved over time. Once the Pop III stars enter the pre-main-sequence stage, energy is generated in the core and carried outward to the cooler surface. The flow velocity at each point is constant over time, i.e., becomes stabilized, when the force exerted by pressure gradient is balanced by the gravity. A star that reaches hydrostatic equilibrium must satisfy the following equations: \( dP_\star(r)/dr \propto -G M_\star(r) \rho_\star(r)/r^2 \) and \( dT_\star(r)/dr \propto -(\rho_\star(r)/T_\star^2(r))(L_\star(r)/4\pi r^2) \), where \( L_\star(r) \) is the energy flux or luminosity, \( P_\star(r) \), \( T_\star(r) \), \( M_\star(r) \) and \( \rho_\star(r) \) are respectively, the pressure, temperature, mass and density of the stars in the state of hydrostatic equilibrium. Ignoring the constant term from both equations, and writing \( dP_\star(r)/dr \propto \rho_\star/R_\star \) and \( dT_\star(r)/dr \propto T_\star/R_\star \), where \( R_\star \) is the radius up to which the system is in hydrostatic equilibrium, leads to the following approximate relations for the temperature and mass-luminosity relation: \( T_\star \propto M_\star/R_\star \) and \( L_\star \propto M_\star^4 \). Thus, a more massive star would be much more luminous, and would radiate ionizing photons into the surrounding medium at an enormous rate. For example, the typical number of ionizing photons emitted by an O-type star is in excess of \( 10^{49} \) per second. The lifetime \( (\tau) \) of the Pop III stars is given by \( \tau_\star \propto M_\star/L_\star \propto M_\star^{-2} \) (see, e.g., Binney & Tremaine 1987; Carroll & Ostlie 2006).

According to the \( \Lambda \)CDM model of Big Bang cosmology, the age of the universe is roughly 13.7 billion years whereas, our own Solar system was born just \( \sim 4.6 \) billion years ago. Taking the solar mass as a reference, and \( M_{\text{PopIII}} \) and \( \tau_{\text{PopIII}} \) as mass and lifetime of Pop III stars, we find \( \tau_{\text{PopIII}}/\tau_\odot \approx (M_{\text{PopIII}}/M_\odot)^{-2} \) or \( M_{\text{PopIII}} \approx 0.8M_\odot \). Hence, for a Pop III star to survive for the 13.7 billion years, its mass has to be less than \( 0.8M_\odot \). If a Pop III star is more massive, it will live for a shorter time, i.e. explode as supernovae or collapse into a stellar remnant such as a black hole, neutron star, or white dwarf. But low mass Pop III stars can still exist in our Milky Way.

### 3 NUMERICAL METHOD

In our previous study (Dutta 2016a), we have shown that newly-born protostars, which were formed out of pristine gas clumps with different degrees of rotational support, are distributed in such a way so as to conserve angular momentum. Clumps with higher initial rotation yield more fragments with sufficiently low mass and with a range of radial as well as rotational velocities. Because these fragments continue to accrete material while moving through the gaseous medium in the disk, it is important to investigate the long-term evolution of the multiple system. We thus need a numerical set-up that takes into account the complex interplay between the dynamical interaction of fragments with surrounding gas and accretion phenomenon. To this effect, we describe below the initial conditions of our simulations followed by our implementation of a simple model of accretion, namely Bondi–Hoyle accretion.

### 3.1 Initial Conditions

In order to assess the mass accretion and hence the final mass of the fragments that ultimately forms the stars, one needs to carefully consider the scale at which fragmentation takes place. We have seen in (2) that the size of the small dark matter halo (i.e., \( \rho_{\text{DM}} \approx \rho_{\text{vir}} \)) is 100–200 pc, inside of which gas clumps form of the order 2–5 pc depending on the rotation of the halo. For our study, we have used such halos from the cosmological simulations of (Greif et al. 2011) that employed the hydrodynamic moving mesh code AREPO (Springel 2010). Their simulations start at redshift of \( z_{\text{init}} = 99 \) and are based on standard \( \Lambda \)CDM parameters. We use the snapshots from AREPO simulations at the epoch when the gas density inside these halos reaches around

\[ \frac{\rho_{\text{DM}}}{\rho_{\text{crit}}(z_{\text{init}})} = 0.9 \]
n \sim 10^6 \text{ cm}^{-3}$, i.e., well below the point when the conversion of atomic to molecular hydrogen takes place rapidly resulting in cooling become faster than the free-fall collapse (see e.g., Omukai & Yoshii 2003; Turk et al. 2009; Dutta et al. 2015a; Dutta et al. 2015b; Dutta et al. 2015a). These halos contain gas mass \( \sim 1000 M_{\odot} \) and have central temperature roughly 400–500 K. We call these ‘realistic halos’ so as to differentiate from the artificial gas clumps that we generate from non-cosmological initial conditions. For our study, we have followed the collapse of primordial gas in two ‘realistic halos’ as well as eight artificial gas clumps with different initial rotation. Both realistic and artificial gas clumps have a range of angular momentum (Saigo Tomisaka & Matsumoto 2008; Dutta et al. 2012). The artificial clumps are unstable against self-gravity with a size \( \sim 2.5 \text{ pc} \) and mass around 3000\( M_{\odot} \) that is larger than the Jeans mass \( \sim 1000 M_{\odot} \). Our study therefore investigates gas evolution for a wide range of realizations.

### 3.2 Simulations of primordial gas collapse

We use the sink particle technique and primordial chemical network including Hydrogen, Helium and Deuterium to model the chemical and thermo-dynamical evolution of metal-free gas (Dutta et al. 2015a, Dutta 2015b). We also take into account radiative cooling, collisional emission cooling, dissociation cooling, chemical heating, three-body heating and heating due to contraction (Dutta 2016a) to study thermal evolution during collapse. For both realistic and artificial gas clumps, we have carried out a suite of simulations using the smoothed particle hydrodynamic (SPH) code GADGET-2 that follow the non-linear collapse of primordial gas all the way starting from the density \( n \sim 10^3 \text{ cm}^{-3} \) (formation of unstable clumps) up to \( n \sim 10^{14} \text{ cm}^{-3} \) (density threshold at which sink is formed). It is possible to use the AREPO-snapshots into GADGET-2 code because both GADGET-2 and AREPO are based on the principle of Lagrangian formalism. The mesh-generating points of AREPO are represented as Lagrangian fluid particles, which is similar to the SPH technique. In our GADGET-2 simulation, the mass of a single SPH particle is roughly \( 10^{-4} M_{\odot} \), so the mass resolution for 100 SPH particles (e.g., Bate & Burkert 1997) is \( \approx 10^{-2} M_{\odot} \), whereas the AREPO simulations resolve the Jeans length with 128 cells (Greif et al. 2011), resulting in roughly constant mass particles within the central \( \approx 1000 \text{ AU} \). This is sufficient for our study, as all the fragmentation and accretion take place in the central region of the halos.

Once the collapse reaches the protostellar core density, as discussed in Section 3.1, it is surrounded by a massive circum-stellar disk that is driven towards gravitational instability to form multi-scale fragmentation throughout the disk (as shown in many studies, for example, Susa 2013; Stacy & Bromm 2014; Dutta 2015b). The smallest fragmentation scale is \( \sim 0.03 \text{ AU} \) with a mass of \( \sim 0.01 M_{\odot} \) (Hirano & Bromm 2016), but increases with increasing disk mass, resulting in the formation of protostars. The newly formed protostars for different rotationally supported clouds can have a range of radial velocities as shown in Figure 7A of Dutta 2016a. The typical radial velocities lie within a range of \( 0 \sim 20 \text{ km} \text{ s}^{-1} \) with some of them moving towards the center. Because the protostars keep moving within the bound system and simultaneously accrete gas that in turn opposes their motion, it is therefore important to study the dynamics by incorporating all the relevant processes. We run our GADGET-2 simulations to evolve the system over \( 10^6 \) years after the formation of sink particles to investigate the final protostellar masses within both the realistic and artificial gas clumps. However, to investigate the accretion process and trajectories of each protostar, we use a semi-analytical calculation, discussed in the next sections. The semi-analytical calculation takes the initial mass, position and velocity of the fragments as the initial configuration, and evolves the system by following the dynamics of protostars and their interaction with the surrounding medium for \( 10^6 \) years. We can therefore compare the final outcome from both the 3D-simulations and semi-analytical calculation and validate the latter approach.

### 3.3 Escape velocity

Theoretical calculations and cosmological simulations have shown that the density profile of the gas clumps in which first stars are formed is a power-law of the form \( \rho \propto r^{-2.2} \) (Omukai & Nishi 1998; Abel et al. 2002; Glover 2005). When initializing our artificial halos, we assume a central core of size \( r_o \) in this clump, such that the density profile is given by

\[
\rho(r) = \frac{\rho_0}{(1 + r/r_0)^{2.2}}.
\]

The central particle density is generally taken in the range \( 10^{13} – 10^{14} \text{ cm}^{-3} \), with a mean molecular weight \( \mu = 2.33 \). In our set-up, the core radius is assumed to be \( r_0 = 5 \text{ AU} \), and the gas temperature is taken to be:

\[
T(r) = 1200 \text{K} \times \left(\frac{\rho(r)}{\rho_0}\right)^{0.1}.
\]

Figure 1 shows the initial density and temperature variation as function of radius. The gas density obeys the power-law distribution \( \rho \propto r^{-2.2} \) with the central core radius is \( R_0 = 5 \text{ AU} \). The core temperature is the temperature when first sink is formed.

Starting from the initial conditions as outlined in Section 3.1, we first allow the gas in minihalos to collapse and reach the critical density so as to form a hydrostatic core surrounded by the disk that is gravitationally unstable to fragmentation. We then use this snapshot as our initial conditions for post-processing and compute the escape velocity. Note that the escape velocity is a function of distance from the centre. For this escape velocity function, we then explore a range of parameter space consisting of initial conditions, consisting of an initial distance \( r_i = 1 – 100 \text{ AU} \), i.e., the distances of sinks (i) from the center of the gas clump, an initial azimuthal angle \( \phi = 0 \), and the radial and azimuthal components of the initial velocity, \( v_r,i \) and \( v_\phi,i \), respectively. In our analysis, a star is considered to be ejected out of the system if and when it reaches a radial distance \( r = 2 \text{ pc} \), which is the typical size of the gas clumps. Note that this scale is more than four orders of magnitude larger than the core radius. We start our semi-analytical calculations from this set of initial conditions along with the equation of motion and angular momentum conservation of the central sink as well as the secondary sinks from disk fragmentation. Our aim with the semi-analytical approach is to investigate the motion, mass accretion and final fate of each sink as it encounters
the surrounding gas. In a full 3D simulation, it is extremely difficult to do these calculations because the Jeans length is not adequately resolved and it is computationally expensive to follow the trajectories and evolution of each sink and its interaction with ambient gas. Therefore a validated semi-analytical approach allows us to explore a wider parameter space.

The escape speed corresponding to the assumed density profile is given by,

\[ v_{\text{esc}} = \left[ 8\pi G \rho_0 r_0^2 \frac{(1 + r_0/r)}{r_0} - \frac{1}{(r_0^2)(1 + r_0/r)} - 2 \ln(1 + r_0/r) \right]^{0.5}. \]

In general, protostars born out of the more rapidly rotating clouds are situated away from the center to conserve angular momentum, whereas others are located around the center within few AU to tens of AU. For Pop III stars, the initial core radius is roughly few AU. Thus for a core radius of, e.g., \( r_0 = 5 \) AU, the maximum escape speed is of order \( \sim 10 \) km s\(^{-1}\).

### 3.4 Bondi-Hoyle accretion

The unstable self-gravitating disk is prone to fragmentation leading to the formation of multiple protostars. The protostars together with the ambient gas are trapped in the gravitational potential well. This system can be formally described as a supersonic, compressible flow coupled to multiple gravitating, accreting and potentially radiating bodies. The protostars while moving through this medium will experience a drag force originating from the dynamical friction associated with star-cloud interactions. This drag force can simply cause a change in orbit akin to the case for X-ray binaries (Bobrick, Davies & Church 2017).

Highest resolution numerical simulations available at present are only able to follow a few tens of years of evolution after the formation of the first protostar (Becerra et al. 2015). Thus, integration over realistic number of orbital revolutions is well beyond the existing numerical capabilities. To tide over these limitations, we take recourse to a semi-analytical model of Bondi-Hoyle accretion flow (Bondi & Hoyle 1944, Bondi 1952) to track the long term evolution of the protostars. We note here that in its original form, Bondi-Hoyle accretion considers the evolution of a mass moving through a uniform gas cloud where it accretes material from the surrounding medium. As we shall see in the subsequent sections, the Bondi-Hoyle approximation turns out to be an excellent approximation to describe the evolution of protostars orbiting in the disk while simultaneously accreting material from the disk.

To start with, we consider protostars with initial mass \( M_{*,i} \) that are orbiting with initial azimuthal velocity \( v_{*,i} \), along with a range of radial velocity \( v_{r,i} \). Here the subscript ‘i’ stands for the number of protostars. We use the Bondi-Hoyle accretion formula to determine the time evolution of the stellar mass as,

\[ \frac{dM_*}{dt} = \frac{4\pi G^2 M_*^2 \rho(r)}{[c_s^2 + (v_\phi^2 + v_r^2)]^{1/2}}. \]  
(9)

Here \( \rho(r) \) is the ambient gas density that has power-law profile and \( c_s = \sqrt{5k_B T/(3 \times 2.33 m_p)} \) is the sound speed, \( m_p \) being the mass of a proton. Along with the accretion phenomenon, we solve for the dynamics of the individual protostars and conservation of angular momentum using

\[ \frac{d^2 r}{dt^2} = - \frac{GM_{\text{enc}}(r)}{r^2} + v_{\phi}^2 \frac{1}{r} - \frac{A v_r}{M_* (v_r^2 + v_{\phi}^2)^{3/2}}, \]  
(10)

\[ \frac{d^2 \phi}{dt^2} = \frac{2 c_s \dot{\phi}}{r} - \frac{A \dot{\phi}}{M_* (v_r^2 + v_{\phi}^2)^{3/2}}. \]  
(11)

Here \( A = 4\pi G^2 M_*^2 \rho(r) \) represents the coefficient of drag force \( \vec{F}_{\text{drag}} \) in the direction of \( \vec{n} \), where \( \vec{F}_{\text{drag}} = (A/v^2) \vec{n} \). The enclosed mass \( M_{\text{enc}}(r) \) is integrated over the density regime

\[ M_{\text{enc}}(r) = 4\pi r^2 \int d\rho(r) = 4\pi \rho_0 r_0^3 \int \frac{(r/r_0)^2 d(r/r_0)}{(1 + r/r_0)^{3/2}} dr \]  
(12)

Figure 2 shows the mass distribution and the sound speed as a function of radius. The central core radius is assumed to be \( r_0 = 5 \) AU. The dynamics of the protostars following the above equations is calculated until \( r = 2 \) pc, and the final mass is evaluated at this point. Protostars, once escaping this region, will no longer be part of the gravitationally
In this section, we present our results on the time evolution of the protostars. We will first investigate their trajectories as calculated from the model discussed in previous section. We will then investigate the final mass of the protostars, as calculated from the 3D-numerical simulation using modified GADGET-2 code, for protostars that escape the cluster as well as those that stay inside and merge.

4.1 Semi-analytical approach

Here we examine the trajectories and mass accretion by the protostars while moving around the ambient medium. The protostars are formed from the fragmentation of the disk and assumed to obey the spherical Bondi-Hoyle accretion along with gravitational drag from the surrounding gas.

The evolution of protostars with speed less than and larger than the escape speed are shown in Figure 3. The top panel shows the trajectories of the protostars having different radial velocities for a particular choice of the azimuthal velocity. The black solid line represents a protostar that has a radial velocity equal to the escape speed, i.e., ~10 km s$^{-1}$. The red lines correspond to protostars with speed 20 (dotted), 15 (solid), 12 (dash-dot) and green lines correspond to 9 (dotted), 8 (solid) and 7 (dash-dot) in units of km s$^{-1}$ respectively. We keep the azimuthal velocity comparatively small ~0.01 km s$^{-1}$, because some of the fragments may have lower angular momentum (e.g., Yoshida Omukai & Hernquist 2008; Stacy et al. 2013). Then for each given radial velocity, we increase $v_r$ up to 0.01, 0.1, 0.5, 1, 3, 5, respectively, in units of km s$^{-1}$ (for a given radial velocity), so as to investigate the effect of rotation on the mass accretion phenomenon. The distances $r_{\text{delt}}$ travelled by the protostars are plotted as a function of time evolution (top panel of Fig. 3). The initial masses are chosen in such a way that the final mass is $\lesssim 0.8 M_\odot$ at the time of escaping the cluster. We notice that some of the protostars (red lines) can directly travel the path of 2 pc at around a million years. Different degrees of the radial velocities lead to subtle deviations. For instance, protostars with larger radial component results in a slightly steeper curve, and therefore, leave the cluster earlier. In contrast, protostars with speed $v_r \ll v_{\text{esc}}$ (green lines) keep on orbiting around the central clumps while being slowed down by the gravitational drag from the ambient gas density.

The middle panel shows the mass evolution of the protostars just after fragmentation of the circumstellar disk. The green curves demonstrate that the protostars with even smaller masses and with initial velocity $v_r \ll v_{\text{esc}}$ are able to acquire a mass in the range of $0.1–10$ $M_\odot$ depending on the initial configuration. The mass accretion coincides with initial deceleration as can be seen by comparing the top two panels. The accretion rate is expected to be higher if the protostar is moving with a slower velocity and/or through denser medium. Therefore for $v_r < v_{\text{esc}}$ the protostar accretes a large amount of mass relative to its initial mass, and can even increase its mass by an order of magnitude by the time the orbit is significantly affected by the gravitational drag. They can therefore continuously accrete mass to end up becoming massive stars, or may merge with another star.

In contrast, an initial high speed $v_r \gg v_{\text{esc}}$ (denoted by red lines in the middle panel) ensures that the mass accretion is relatively small before the star escapes the system. In this case the initial mass of the protostars is less than 0.76 $M_\odot$ if they are to end up with a final mass less than 0.8 $M_\odot$. For initial velocity just over the escape velocity, the initial mass may need to be as low as 0.65 $M_\odot$. Thus the net accretion
can be up to about 20% for stars that escape. The bottom panel shows that for the same initial velocity, increase of initial mass leads to trajectories that go out to larger radii. These plots are for stars with initial velocity less than the escape velocity.

In the above discussion, we have explored the trajectories and the time evolution of the masses of the protostars for different values of \( v_r \), for a given choice of \( v_φ \). In Figure 5, we show the evolution of the stellar initial mass \( (m_i) \) and the escape time \( (t_{\text{esc}}) \) taken for evolving protostars as a function of the initial velocity for five different values of the initial \( v_φ \). These values are plotted as the protostars reach a distance of 2 pc with a final mass \( m_f = 0.8 \, M_⊙ \). The azimuthal velocity is varied such that the total velocity \( v = \sqrt{(v_r^2 + v_φ^2)} \) remains the same. The lower panel shows that for low initial \( v_φ \), the escape time varies strongly with \( v \), compared to the case when \( v_φ = 3 \, 5 \, \text{km s}^{-1} \).

Figure 6 has two panels. The top panel shows the growth in mass as a function of the initial mass for protostars that escape the system. Each curve is for a different initial radial velocity. We find that the mass accreted is higher for a lower initial radial velocity. This is to be expected because the accretion rate is higher for a lower velocity and in such a case the protostar spends more time in the core region where the ambient density is higher. Further, we note that the mass accreted is higher for a higher initial mass. This again relates directly to the increased accretion rate. As the radial velocity increases, the final mass vs initial mass curves come closer to the \( y = x \) line shown for reference. It is to be noted that the increase in mass for protostars that escape the system is small and is limited to \( \sim 0.2 \, M_⊙ \). Therefore this process, i.e., the increase in accretion rate near the center of the core, cannot be responsible for a significant increase in mass of stars that escape the cluster where these protostars are born.

The lower panel of Figure 5 presents the same data for protostars that do not escape and hence remain in the cloud. In this case the protostars spend considerable time in the core region of the cloud. In the absence of any realistic feedback process in our simulations, this leads to a large enhancement in mass over time. At low initial mass, the accretion rate is small and hence the net increase in the mass is less efficient than for higher initial mass. Further, we find that the low-mass stars remain closer to the centre and hence are moving faster. This also lowers the mass accretion rate. More massive stars tend to have orbits going to larger distances. This is mainly because the change in momentum due to mass accretion is smaller for more massive stars. Thus we find that the final mass increases with increasing initial mass. At even higher masses, beyond 0.35 \( M_⊙ \), the trend reverses. The stars in this regime have orbits that go out to larger radii. The stars are moving rapidly when they are in regions near the centre and hence do not accrete much, and in regions where the stars are moving slowly, the ambient density is small.

Of course, this semi-analytical approach still leaves out processes that are important in a physically realistic scenario. Radiative and thermal feedback are likely to evaporate the core of the cloud and hence the increase in mass will be less than suggested by the lower panel of Figure 5. It is heartening to note that the final mass in our model is comparable to that seen in other simulations (see, e.g., Greif et al. 2011, Dutta et al. 2015a, Dutta 2016a). The increase in mass is higher for a lower initial radial velocity, as expected from the expression for the accretion rate.

### 4.2 Protostellar mass from simulations

In section 2 and 3, we have described in detail the numerical methods for modeling the complicated gravitational collapse of primordial gas inside dark matter halos. To make sure that our calculations are not biased with any initial configuration, we have investigated the non-linear collapse phenomena with two different types of halos: one from the cosmological simulation and other from the artificial model of halos that have similar initial conditions as the primordial case, but with uniform density distribution.

The unstable gas clumps inside both types of halos start to collapse under their self-gravity once the mass of the clumps exceeds the Jeans mass. This happens when the free-fall time becomes shorter than the sound-crossing time. Each of the gas clumps has differential rotation from their own angular momentum that has to be conserved during collapse. We can model the rotation by mathematically treating the unstable collapsing clumps of the simulation as solid bodies, which are not subject to any internal turbulent motion. We can further characterize the rotation by the parameter \( \beta_0 = \frac{E_{\text{rot}}}{E_{\text{grav}}} \) (Sterzik et al. 2003, Saigo Tomisaka & Matsumoto 2008, Dutta et al. 2012), where \( E_{\text{rot}} \) and \( E_{\text{grav}} \) are the magnitudes of the rotational and the gravitational energies, respectively. The rotation parameter \( \beta_0 \) can be described as the strength of rotational support of the unstable gas clumps. We have performed eight numerical experiments for our artificial gas clumps with \( \beta_0 = 0.005, 0.007, 0.01, 0.02, 0.04, 0.05, 0.07, 0.1 \). The two cosmological gas clumps from arepo simulations are centrally condensed, and have maximum \( \beta_0 = 0.035 \) and 0.042.

The initial time (i.e., \( t = 0 \)) is measured as the time of the formation of first hydrostatic core (also called sink). The dynamical evolution of all the sinks depend on the history of collapse (i.e., chemical and thermal evolution, turbulence and angular momentum conservation) as described in our previous studies (Dutta 2016a). Here we follow the trajectories and mass accretion of all the sinks during evolution. A fraction of the protostars are ejected from the cluster with their velocity exceeding the escape speed, and the remaining protostars orbit around the gravitationally bound system and continue to accrete mass. We have followed the evolution of the small N-Body system till the protostellar mass attains a value of \( \sim 30 M_⊙ \). We have limited our calculations up to this value because it has been extremely difficult to follow the simulations for the fast-rotating clouds (e.g., \( \beta_0 > 0.1 \)) after this stage of evolution. This corresponds to the time roughly \( t \sim 10^5 \) year taken by the protostellar system, although the time varies between the clouds with different rotational support.

In Figure 6, we plot the mass of the sinks as a function of the clump’s rotation quantified by the parameter \( \beta_0 \). Each \( \beta_0 \) value corresponds to a different halo. We see a slight trend that higher \( \beta_0 \) may allow for more low-mass protostars. It is interesting to point out that we get more sinks with \( M_* < 1 M_⊙ \) when we have \( \beta_0 > 0.1 \). It is expected because clouds with a higher rotation exhibits larger disk or
Figure 3. The trajectories (top panel), evolution of the mass (middle panel) and the extra distance travelled for increase of initial mass (bottom panel) of the protostars are plotted as a function of time for two cases: one in which the initial velocity is larger than the escape velocity (red lines) and another in which it is smaller (green lines). The escape region is 2 pc. Protostars with $v_i > v_{esc}$ and certain critical masses are ejected from the cluster at around one million years with a final mass $\lesssim 0.8 M_\odot$. Protostars with a smaller mass $\sim 0.1 M_\odot$ and speed less than $v_{esc} = 10 \text{ km s}^{-1}$ move around the ambient gas against gravitational drag and accrete a sufficient amount of gas to end up becoming massive stars.

arm-like structure that is prone to fragmentation on several scales, whereas slowly-rotating clouds are centrally condensed (see, e.g., Dutta 2016a, Hirano & Bromm 2016, Hosokawa et al. 2016). The final mass of the sinks, after they evolve for million years, can be typically $\sim 0.1–10 M_\odot$.

The results from both the analytical model and 3D-simulations, after the evolution of the protostellar system for approximately one million years, are well matched, which shows that the ejected protostars have a low mass $\lesssim 0.8 M_\odot$ and others can end up having higher mass due to continued accretion. Our comprehensive calculation also reflects that indeed the Bondi-Hoyle accretion is a good approximation for the dynamical evolution of the protostars.

5 SUMMARY AND DISCUSSION

5.1 Overview

We have investigated in detail the collapse of primordial star-forming clouds and the resulting fragmentation of the circumstellar accretion disk. In particular, we focussed on
![Figure 5](image1.png)

**Figure 5.** Top panel: The growth in mass as a function of the initial mass is plotted for protostars that escape the gravitationally bound system. Each curve is for a different initial radial velocity. The mass accretion is higher for a lower initial radial velocity. Bottom panel: Protostars that remain in the cluster spend considerable time in the core region and continue to accrete from ambient gas. In absence of any realistic feedback process in our simulations, this leads to a large enhancement in mass over time.

We assume that the new-born protostars accrete material from the ambient gas through the spherical Bondi-Hoyle accretion while moving through the cluster. In this process, depending on their initial mass and velocity, they acquire enough mass as well as encounter a gravitational drag, which leads them to stop moving as they merge with a larger protostar. They can therefore either continue orbiting around the central core while accreting mass and sinking closer to the centre, or they can escape the system with their velocity exceeding the escape velocity. There is hence a high probability that they can merge with the central protostars below a certain fragmentation scale over which angular momentum is lost (as seen in [Hirano & Bromm 2016]). However, the protostars with speed greater than the escape speed overcome this drag force and accrete only a small amount of mass before being ejected as low-mass Pop III stars ($\leq 0.8 M_\odot$). Ejection can also happen if the primary, more massive star goes supernova and the cloud loses much of its mass, e.g., see [Komiya, Suda, & Fujimoto 2016].

Here we summarize the main findings of our work. The mass accretion of the protostars that escape the cluster is higher for a lower initial radial velocity. On the contrary protostars that remain in the cluster can have typical mass in the range $0.1-10 M_\odot$ depending on their radial and rotational support. The low-mass stars remain closer to the centre and hence are moving faster. This also lowers the mass accretion rate. We also find from our simulations that more massive stars tend to have orbits going to larger distances. This is mainly because the change in momentum due to mass accretion is smaller for more massive stars. Thus we find that the final mass increases with larger initial mass. In addition, we note that the result from our semi-analytical model matches well with the 3D-simulation. Therefore the Bondi-Hoyle accretion employed in our study is a good approximation to understand the evolution of Pop III protostars in an unstable self-gravitating disk.

Although previous work suggests that Pop III survivors can reside in both the bulge and halo, a more careful theoretical approach is needed to settle the issue. Based on our theoretical studies, we can conclude that the low-mass and low-metallicity Pop III stars are likely to exist in the Galaxy and may be in the halo.

Observations of metal poor stars in the halo of the Galaxy suggest a high floor of around $0.5 M_\odot$, i.e., all known
low metallicity stars have masses higher than this threshold. The process of accretion in the parent cloud studied here can lead to an increase in the mass by a small amount. However, stars which escape the parent cloud experience only a very small mass increase. This on its own cannot explain the absence of very low mass stars. The increase in mass for stars that remain in the cloud is fairly large and hence not applicable for stars surviving to the present. In future studies, we plan to consider evolution of a group of stars in a gas cloud and it is possible that many body interactions lead to a more nuanced understanding.

5.2 Caveats

In spite of the involved numerical calculations presented here, we emphasize that we cannot accurately predict the final mass of the primordial protostars. This is because of the fact that we have neglected both the effects of the primordial magnetic fields and radiative feedback from the protostars. Magnetic fields can be amplified by orders of magnitudes over their initial cosmological strengths by a combination of dynamo action and field compression (see e.g., Sur et al. 2010; Schleicher et al. 2010). Magnetic fields may provide support against fragmentation (Machida & Dol 2013; Peters et al. 2014). In addition, sufficiently strong magnetic fields can reduce the Bondi-Hoyle accretion rate from a factor of two up to orders of magnitude below the classical rate (Lee et al., 2014).

The radiative feedback from the eprotostars can significantly change the accretion and can even evaporate the circumstellar disk (Whalen et al. 2010; Hosokawa et al. 2011). In general we expect feedback to lower the accretion of metals on to proto stars (Suzuki 2017) and hence our estimates can be thought of as being upper bounds. Notwithstanding these processes we have not taken into account, our approach to the problem enables us to provide good estimates for the overall trend of the protostars that move around the cluster before being ejected. It is heartening to see that our results match those of more sophisticated simulations. It is important to improve models and study this problem in greater detail and such studies will eventually lead to predictions on probable locations and properties of surviving Pop III stars so that upcoming surveys can target these.

5.3 Possibility of survival of metal-poor stars

Here we discuss the probability of finding those stars in the Milky Way. Earliest work on this was done by Bond (1981). Recent work has considered how many Pop III survivors may currently reside in the Milky Way, and where within the Galaxy they might be found. Recent analysis based on cosmological zoom in simulations suggests that such stars may survive and are likely to be found in massive galaxies (Sharma, Theuns, & Frenk 2017). A more detailed question is whether more survivors are within the bulge or within the Galactic halo, as the Milky Way disk does not contain low-metallicity stars ([Fe/H] < −2.2) (e.g., Freeman & Bland-Hawthorn 2002). Work by Scannapieco et al. (2006) and Brook et al. (2007) suggest that survivors should be spread throughout the entire Galaxy. On the other hand, within ΛCDM cosmology the DM halos grow from the inside out, leading many studies to predict that Pop III survivors are likely to be concentrated towards the Galactic bulge (see, e.g., White & Springel 2000; Diemand, Madau & Moore 2005; Diemand, Moore & Stadel 2006; Bland-Hawthorn & Peebles 2006; Salvador et al. 2010; Tumlinson 2010a,b).

More recent semi-analytic models by Hartwig et al. (2015) indicate that the Milky Way halo is the best region to search for Pop III stars. They point out that the comoving volume of the halo is much larger than that of the bulge, and that the halo contribution dominates the overall Pop III star formation rate. Under their fiducial assumptions, if no survivor is detected within a sample size of $4 \times 10^6$ then the extension of the Pop III IMF to below 0.8 $M_\odot$ can be excluded at a 68% confidence level. Observations within the bulge would require $\sim 10^4$ times more stars to reach similar conclusions.

In a different study, the cosmological simulations of Ishiyama et al. (2016) employ Pop III tracer particles to find a contrasting conclusion that survivors tend to concentrate towards the Galactic center. However, field stars are also more concentrated at low Galactic latitudes. Thus, finding a Pop III survivor will still require a sample size $\sim 100$ times larger for low-latitude and central surveys as opposed to surveys at higher latitudes.

The study by Griffen et al. (2018) similarly uses cosmological simulations, which employ tracer particles to follow Pop III formation sites as they collect into larger halos of approximately Milky Way mass. They find qualitative agreement with Ishiyama et al. (2016) and that the oldest Pop III remnants populate all parts of the Galaxy. They furthermore note that for their sample of 30 Milky Way sized galaxies, there is an order of magnitude scatter in the number density of remnants within the bulge and at large radii. We finally note the Magg et al. (2008) extended these studies to find that low-mass Milky Way satellites are more likely to contain Pop III stars that the Milky Way itself, and that low-mass satellites will serve as promising targets in the search for the Pop III survivors.

The result that the lowest mass protostars are the ones that escape the cloud of formation indicates that these are poorly bound in the halo of formation. It has been shown that Syer & White (1998) in mergers of halos, the most tightly bound objects end up near the centre of the merged halo whereas loosely bound objects in the parent halos end up on the outskirts. In view of the preserved ordering by binding energy in mergers, we expect that these stars are more likely to be found in the halo or loosely bound structures like low-mass satellites.

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