Formation of the first stars

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Abstract
From studying the cosmic microwave background, we know our Universe started out very simple. It was by and large homogeneous and isotropic, with small fluctuations that can be described by linear perturbation theory. In stark contrast, the Universe today is highly structured on a vast range of length and mass scales. In the evolution towards increasing complexity, the formation of the first stars marks a primary transition event. The first generation of stars, the so-called Population III (or Pop. III) build up from truly metal-free primordial gas. They have long been thought to live short, solitary lives, with only one massive star forming per halo. However, in recent years this simple picture has undergone substantial revision, and we now understand that stellar birth in the early Universe is subject to the same complexity as star formation at present days. In this chapter, I review the current state of the field. I begin by introducing the basics concepts of star-formation theory and by discussing the typical environment in which Pop. III stars are thought to form. Then I argue that the accretion disk that builds up in the center of a halo is likely to fragment, resulting in the formation of a cluster of stars with a wide range of masses, and I speculate about how this process may be influenced by stellar feedback, the presence of magnetic fields, the energy input from dark matter annihilation, and the occurrence of large-scale streaming velocities between baryons and dark matter. Finally, I discuss direct and indirect constraints on Pop. III star formation from high-redshift observations and from the search for extremely metal-poor stars in the Milky Way and its satellites.
1 Introduction

The appearance of the first stars marked a primary transition in cosmic history. Their light ended the so-called ‘dark ages’, and they played a key role in cosmic metal enrichment and reionization, thereby shaping the galaxies and their internal properties as we see them today. Understanding high-redshift star formation is thus important for many areas of modern astrophysics. However, studying stellar birth in the primordial Universe is a relatively young area of astrophysical sciences. Only with the advent of new numerical methods and powerful supercomputers did the numerical modeling of early star formation become feasible. As a consequence, there is still little consensus on the physical processes that govern stellar birth at high redshifts. This chapter aims at providing a concise overview of the current state of the field.

The first generation of stars, the so-called Population III (or Pop. III) built up from truly metal-free primordial gas. They have long been thought to live short, solitary lives, with only one extremely massive star forming in each dark matter halo with about 100 solar masses or more (Omukai 2001; Abel et al. 2002; Bromm et al. 2002; O’Shea and Norman 2007). The idea was that first star formation is simple and one only needs to know the initial Gaussian density perturbations of material at very high-redshift which are very well understood, e.g. from measuring the cosmic microwave background, see Planck Collaboration et al. (2016), the growth of cosmological structures, and the heating and cooling processes in the primordial gas, which are thought to be very simple because of the lack of elements heavier than hydrogen and helium. In addition, the early numerical models had considerable limitations. First, they only followed the collapse of the very first object in the first halo to form, since the hydrodynamic timestep decreases as the gas collapses, and so the simulations effectively grind to a halt once the protostar has formed. Second, most calculations did not include the effects of protostellar feedback, which may substantially reduce the accretion rate onto the protostar by dumping energy and/or momentum into the infalling gas.

The ever increasing capabilities of modern supercomputers allow us now to perform significantly improved numerical simulations of early star formation that reveal a much more complex picture. The introduction of numerical techniques to first star formation studies that have been standard repertoire in present-day star formation lead to the conclusion that fragmentation is a widespread phenomenon in first star formation (Clark et al. 2011a; Greif et al. 2012), and that Pop. III stars form as members of multiple stellar systems with separations as small as the distance between the Earth and the Sun, see Turk et al. (2009); Clark et al. (2011b); Greif et al. (2011); Smith et al. (2011); Stacy and Bromm (2013). Studies that do include radiative feedback (Hirano et al. 2014; Hosokawa et al. 2016), magnetic fields (Machida et al. 2006, 2008; Schleicher et al. 2009; Sur et al. 2010, 2012; Turk et al. 2012; Schober et al. 2012a, 2012b; Bovino et al. 2013), dark matter annihilation (Smith et al. 2012; Stacy et al. 2014), as well as the primordial streaming velocities (Tseliakhovich and Hirata 2010; Greif et al. 2011; Maio et al. 2011b; Stacy et al. 2011) add to this complexity. All of these processes are relevant and need to be included in any realistic model. There is agreement now that primordial star formation is equally dynamic and difficult to understand as stellar birth at present days.

For further reading on primordial star formation, we refer to the reviews of Bromm and Larson (2004); Yoshida et al. (2012); Bromm (2013), or to the book by Loeb (2010). A good overview with specific focus on the astrochemistry of first star formation is provided by Glover (2005, 2013). The current numerical frontier of high-redshift star formation is summarized by Greif (2015). For further reading on the transition to the second generations of stars and build up of the first galaxies
we recommend Bromm and Yoshida (2011) or the textbook by Loeb and Furlanetto (2013). As we calibrate our understanding of primordial star formation with what we know about stellar birth at present days, we also recommend the reviews by Mac Low and Klessen (2004); McKee and Ostriker (2007); Zinnecker and Yorke (2007); Padoan et al. (2014); Krumholz (2015); Klessen and Glover (2016) on different aspects of this subject.

In this chapter we try to provide a brief summary of primordial star formation theory, we discuss some of the difficulties we face in this context and speculate about possible observational constraints from the high-redshift Universe as well as from our local neighborhood in the Galaxy. Next, in Section 2 we introduce some of the basic concepts that are behind any theory of star formation. The environment of Pop. III star formation and the thermodynamic behavior of primordial gas are discussed in Section 3. Section 4 illustrates the complexity of stellar birth in the early Universe. We start with simple one-dimensional collapse models, but then argue that the accretion disks around the first stars are highly susceptible to fragmentation. We also speculate about how stellar feedback, magnetic fields, possible dark matter annihilation, and large-scale streaming velocities between baryons and dark matter may influence the stellar mass spectrum. In Section 5 we discuss indirect constraints on the properties of the first stars from high-redshift observations and from stellar archeology in the solar neighborhood, and we speculate about the possible detection of genuine low-mass Pop. III stars in the Universe today. We summarize and conclude in Section 6.

2 Basic concepts

The mean density of the Sun is $1.4 \text{ g cm}^{-3}$, and the numbers for other stars are very similar (Kippenhahn et al., 2012). In contrast to that, the mean density of the gas in the Milky Way at the solar radius is $\sim 10^{-23} \text{ g cm}^{-3}$ (Ferrière et al., 2007), and the mean baryon density of the Universe at present days is with $5 \times 10^{-31} \text{ g cm}^{-3}$ even less (Planck Collaboration et al., 2016). The formation of stars therefore requires a density increase by many orders of magnitude. The only way nature can achieve such enormous density contrasts is by gravitational collapse. All other fundamental forces are either short range, as the strong and weak nuclear forces, or cancel out on average. The electromagnetic force plays no role on global scales because the Universe as a whole is charge neutral and so there is no net force between positive and negative charges. And so it is by far the weakest of the four fundamental forces, gravity, that dominates the large-scale dynamics, simply because it is the only one that is purely attractive and has infinite reach.

2.1 Stability of spherical gas clouds – Jeans criterion

As argued above, any theory of star formation needs to be based on the competition between gravitational attraction and a large number of dispersing processes ranging from gas pressure, to the coupling between matter and radiation, magnetic fields, turbulence, cosmic rays to name some of the most important ones (Mac Low and Klessen 2004; McKee and Ostriker 2007). In its most basic form, a criterion for gravitational collapse goes back to Jeans (1902), who studied the stability
of self-gravitating isothermal gas spheres. He found that these systems have a critical mass,

\[ M_J = \frac{\pi^{5/2}}{6} \left(\frac{1}{G}\right)^{3/2} \rho^{-1/2} c_s^3 \]

\[ = \frac{\pi^{5/2}}{6} \left(\frac{k}{G}\right)^{3/2} \left(\frac{1}{\mu m_H}\right)^2 n^{-1/2} T^{3/2} \]

\[ \approx 50 M_\odot \mu^{-2} \left(\frac{n}{1\text{cm}^{-3}}\right)^{-1/2} \left(\frac{T}{1\text{K}}\right)^{3/2}, \]

where the proportionality factor depends on Boltzmann’s constant \( k \), on the gravitational constant \( G \), on the proton mass \( m_H \), and on the mean molecular weight of the gas particles \( \mu \). Recall that \( \mu \approx 1.22 \) for primordial atomic gas, and that \( \mu \approx 2.33 \) for molecular gas. If this critical mass is exceeded, gravity overwhelms pressure gradients and the systems collapses. If the mass is smaller, then gas pressure wins and the sphere expands. The Jeans mass \( M_J \) depends inversely on the square root of the density \( \rho \) and on the third power of the sound speed \( c_s \). Because of \( \rho = \mu m_H n \) and \( c_s = (kT/\mu m_H)^{1/2} \), we can also write this expression in term of the number density \( n \) and the temperature \( T \) as \( M_J \propto n^{-1/2} T^{3/2} \).

In summary, the larger the density the smaller is the critical mass for collapse, and the higher the temperature the more stable is the system.

The concept of the Jeans mass (1) can be extended to include additional physics by introducing an 'effective' density (say when dealing with multi-component fluids) and an 'effective' temperature or sound speed. For example when the gas is turbulent on scales much smaller than the dynamical scales of interest then the velocity dispersion \( \sigma \) can be simply added to the sound speed,

\[ c_{s,\text{eff}} = (c_s^2 + \sigma^2)^{1/2}. \]

Similar has been proposed for the presence of magnetic fields, then we add half of the Alfvén velocity squared, \( v_A^2 = B^2/4\pi \rho \), in Equation (2), see e.g. Federrath and Klessen (2012). In order to trigger star formation in an otherwise stable medium, either the density needs to increase (say, due to an external compression) or the temperature needs to decrease (by some cooling process). Consequently, a significant fraction this chapter focuses on a discussion of the various astrophysical processes that can lead to this behavior.

We note that the Jeans criterion can also be formulated in terms of energies. If the absolute value of the potential energy \( W \) is more than twice the integral over the pressure \( U \), which is closely related to the internal energy of the system, then collapse occurs. We get

\[ \eta_{\text{vir}} = \frac{|W|}{U} = \frac{5}{2} \int d^3 x \rho(x) \phi(x) \phi(x) > 1/2, \]

where \( \phi \) is the potential and \( P \) is the pressure. This is simply the scalar virial theorem. Another alternative is to look at typical timescales. If the free-fall time, \( \tau_{\text{ff}} \), is smaller than the sound crossing time, \( \tau_s \), then the system collapses. Otherwise sound waves travel fast enough to wipe out inhomogeneities and the system is stable. Both times are defined as

\[ \tau_{\text{ff}} = \left(\frac{3\pi}{32G\rho}\right)^{1/2} \quad \text{and} \quad \tau_{\text{sound}} = \frac{R}{c_s}, \]


where $R$ is the radius of the sphere.

We can obtain a crude estimate of the accretion rate onto the center of the halo from combining Equations (1) and (4) as

$$
\dot{M} = \zeta \frac{M_J}{\tau_{ff}} \propto \frac{c_s^3}{G},
$$

(5)

where the factor $\zeta$ can take values of up to several tens depending on the actual density profile and on how much the gas mass $M$ exceeds the Jeans mass $M_J$, for the classical studies, see Shu (1977); Larson (1969); Penston (1969); Whitworth and Summers (1985). Note that the accretion rate for isothermal collapse only depends on the gas temperature.

### 2.2 Stability of rotating disks – Toomre criterion

In systems that are supported by rotational motions, like protostellar accretion disks or spiral galaxies, the criterion for gravitational instability takes a slightly different form. Besides gas pressure now also the stabilizing effect of shear in the disk needs to be taken into account (Toomre, 1964). The criterion for instability reads

$$
Q = \frac{\kappa c_s}{\pi G \Sigma} \lesssim 1,
$$

(6)

with the surface density $\Sigma$ and the epicyclic frequency $\kappa$, which for Keplerian disks takes the simple form $\kappa = \Omega$, where $\Omega$ is the rotational frequency, see the review by Kratter and Lodato (2010). The criterion was originally derived for infinitesimally thin disks, but it can be extended to thick disks with multiple components (Rafikov, 2001; Elmegreen, 2002) which introduces correction factors of order unity to Equation (6). Again, there are two main pathways towards disk fragmentation. If the mass load onto the disk by accretion from the enclosing gas cloud exceeds its capability to transport material inwards by viscous stresses, $\Sigma$ increases beyond the critical value and the disk becomes unstable. First, spiral arms form and speed up the inward transport. If this is not enough, these arms become non-linear and interact with each other with run-away collapse occurring in the interception regions. By a similar token, also in the absence of accretion an initially stable disk will become unstable if it is able to cool rapidly enough compared to the viscous time scale, see Gammie (2001).

For accretion disks that are continuously fed by infalling gas from an extended envelope, in our case from the gas that is further out in the halo, the Toomre criterion can be extended. Kratter et al. (2010), for example argue that two dimensionless parameters can be used to address the stability of mass-loaded disks. The primary parameter,

$$
\xi = \frac{\dot{M}_{\text{in}}}{\dot{M}_{\text{disk}}} = \frac{c_{s,\text{halo}}^3}{c_{s,\text{disk}}^3} \frac{G}{T_{\text{halo}}^{3/2} / T_{\text{disk}}^{3/2}},
$$

(7)

compares the effective sound speed, or equivalently the effective temperature, in the halo with the corresponding value in the disk. Effective means here that the normal thermal sound speed could be increased by the presence of microturbulence or by the presence of magnetic fields, see Equation (3). The effective temperature is then simply $T_{\text{eff}} = \rho c_{s,\text{eff}}^2 / k$. Equation (7) makes use of the fact that in isothermal collapse models the accretion rate scales as $c_s^3 / G$, see Equation (5). This relation can also be used to characterize the mass flow through disks in steady state (Kratter 2010).
The interpretation of (7) is simple, if the mass load onto the disk from the halo (numerator) exceeds the accretion from the disk onto the central protostar (denominator), then the disk becomes Toomre unstable and will fragment. With other words, instability is likely to occur if the halo gas is effectively hotter than the disk material, say because of the presence of strong microturbulence in the halo or because the disk is so dense that additional cooling processes can work there, see the reviews [Glover, 2005, 2013]. Numerical simulations indicate critical values of $\xi \geq 3$ for fragmentation to set in [Offner et al., 2010].

A secondary parameter,

$$\Gamma = \frac{M_{\text{in}}}{M_{\text{disk}}} \Omega,$$  \hspace{1cm} (8)

compares the infall timescale $M_{\text{disk}}/M_{\text{in}}$ to the orbital timescale $\Omega$ in the disk. If $\Gamma \ll 1$ then the disk radius is governed by the angular momentum of the infalling material and not by viscous spreading. Roughly speaking the parameter $\Gamma$ compares the relative strength of gravity versus rotation in the halo.

If these concepts are applied to the accretion disks around the first stars, it is found that fragmentation is a widespread phenomenon and that first stars typically form as members of multiple systems with a wide range of masses (see section 4.2).

### 3 Environment of first star formation

Before we discuss further details of protostellar collapse and the evolution of the accretion disks around the first stars let us briefly review the large-scale environment and the thermodynamic properties of the primordial gas.

#### 3.1 Cosmological context

The formation of the first stars in the Universe occurs in systems which have reached sufficiently large masses so that gas cooling becomes important and baryons can go into run-away collapse within a dark matter halo. In the current $\Lambda$CDM paradigm [Planck Collaboration et al., 2016], gravitationally bound objects form in a hierarchical fashion with smaller objects decoupling earlier from the Hubble flow of cosmic expansion (see also chapter ??). Calculations of the growth of density perturbations in an expanding Universe [Barkana and Loeb, 2001] show that the corresponding Jeans mass scales with redshift $z$ as well as cosmological matter and baryon density parameters, $\Omega_m$ and $\Omega_b$, as

$$M_J \approx 5 \times 10^3 M_\odot \left( \frac{\Omega_m h^2}{0.14} \right)^{-1/2} \left( \frac{\Omega_b h^2}{0.022} \right)^{-3/5} \left( \frac{z + 1}{10} \right)^{3/2}.$$  \hspace{1cm} (9)

Here $h$ is the value of the Hubble parameter in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and the parameters are normalized to the 2015 Planck data. However, the criterion for gas to be bound is not sufficient. It also needs to be able to cool for gravitational collapse to set in and lead to first star formation. Considering the various cooling channels of primordial gas described in chapter ??, see also [Glover].
(2005, 2013), this leads to another critical mass scale of

\[ M_{\text{cool}} \approx 6 \times 10^5 M_\odot h^{-1} \Omega_m^{-1/2} \left( \frac{\mu}{1.22} \right)^{-3/2} \left( \frac{z+1}{10} \right)^{3/2}, \]

where again the mean molecular weight \( \mu \) of primordial gas enters the equation.

We note that below a redshift of \( z \approx 40 \) the critical mass from cooling \( M_{\text{cool}} \) becomes larger than \( M_J \) and so we expect a significant number of halos that are not able to form stars, because their gas is not able to cool sufficiently fast (that is within a Hubble time). We also note that there are several processes that can increase the critical mass for collapse even further. For example the relative streaming velocity between baryons and dark matter (Tseliakhovich and Hirata, 2010; Fialkov et al., 2014) is able to add a turbulent contribution to the effective sound speed in Equation (1) and so can delay collapse (section 4.5). Similar holds for the slow build up of background radiation in the Lyman-Werner band with photon energies from 11.2 eV to 13.6 eV or cosmic reionization at later times, where the additional heat input or change of chemical composition may again delay the gravitational collapse of gas in halos with masses that exceed \( M_{\text{cool}} \). Clearly, this is most extreme in the case of halos that lie in close vicinity to sites of first star formation, where this external feedback may lead to the formation of supermassive stars (Agarwal et al., 2012, 2016), which in turn could be the progenitors of the supermassive black holes that we observe in the centers of some galaxies at high redshift (Mortlock et al., 2011; Wu et al., 2015). The latter will be discussed in more detail in chapter ??.

Altogether, first star formation is likely to start at a redshift \( z \gtrsim 30 \) in rare high-sigma fluctuations, then rapidly becomes possible in more and more halos, and reaches a peak rate at redshifts \( z \sim 20 - 15 \). Although the overall cosmic star formation rate continues to increase (Madau et al., 2014), the rate at which metal-free stars form declines again. Regions in the Universe that are not enriched by supernova ejecta from massive stars become increasingly rare. This is the transition to so-called Population II star formation (see section 4.7). When exactly the formation of genuine Population III stars ends is difficult to assess, and different models and numerical simulations give vastly different answers. It is conceivable that some very low-density regions in voids in the cosmic web have not yet been polluted by metals and so the formation of genuine Population III stars is still possible.

A typical example of the formation rate of metal-free stars predicted for regions similar to the Local Group is shown in Figure 1. It shows comoving Pop. III star formation rate densities from Magg et al. (2018). The semi-analytic calculations are based on a suite of 30 Local Group simulations (Griffen et al. 2018) using four different assumptions about stellar feedback and metal enrichment. Panel (a) gives the fiducial model with radiative feedback and metal enrichment from Pop. III supernovae. The star formation rate has two peaks, one at \( z \approx 17 \) and one at \( z \approx 7 \). Panel (b) demonstrates that the metal enrichment from Pop. III supernovae in neighboring halos delays the transition to Pop. II star formation. This model considers only yields from stars within the same halo. Altogether more Pop. III stars are forming. The largest impact comes from switching off ionizing feedback, as illustrated in panel (c). This means that individual halos are able to form Pop. III stars for a longer time and this model leads to the highest Pop. III star formation rates at low redshifts. Panel (d) depicts the model with the most extreme feedback, where star formation is completely shut off inside an ionized region, even in the most massive halos. This model does not allow for Pop. III star formation below a redshift of \( z \approx 7 \). Overall, Figure 1 demonstrates the impact of environmental conditions on the overall rate of Pop. III star formation and provides
some estimate for the uncertainties in the current modeling efforts.

### 3.2 Thermodynamic behavior of primordial gas

As discussed above, the ability of gas to collapse and form stars depends on its thermodynamic behavior as determined by the competition between the available heating and cooling functions. Despite its chemical simplicity several cooling and heating channels exist for zero-metallicity gas, and become important in different density and temperature regimes. All cooling processes are related to hydrogen, either in atomic or molecular form. At high temperatures, collisions can populate the first exited electronic states of H which then de-excite by emitting Ly-α photons. This process is most efficient around temperatures of $\sim 10^4$ K. To reach lower temperatures, molecular hydrogen is needed. Since H$_2$ is a symmetric molecule, it has no permanent dipole moment, and so only quadrupole or higher order transitions are permitted. The corresponding rates are relatively small. In addition, H$_2$ exists in two states with either parallel nuclear spins (para-hydrogen) or anti-parallel spins (ortho-hydrogen). Transitions between para- and ortho-states are forbidden, so that the lowest allowed transition occurs between the $J = 2$ and $J = 0$ rotational levels in the
vibrational ground state of para-hydrogen. The transition energy corresponds to a temperature of $\sim 512$ K. The high-velocity tail in the thermal Maxwell-Boltzmann velocity distribution allows the gas to cool down to about 200 K, see Greif (2014). The temperature can drop even further, if cooling by deuterated hydrogen takes over. The HD molecule has a non-zero dipole moment and it is not separated into para- and ortho-states and so its lowest energy transition from the ground state is between the $J = 1$ to $J = 0$ rotational levels, corresponding to a temperature of $\sim 128$ K. In practice, HD cooling becomes significant only in regions with enhanced fractional ionization, for example in very massive or in externally irradiated halos. In most sites of Pop. III star formation this process is not important. For a more detailed account of the cooling and heating processes in primordial gas, see chapter ?? or the reviews by Glover (2005, 2013).
Figure 2: Upper left panel: mass enclosed as a function of the radial distance from the densest point in the simulation, plotted just before the formation of the first sink particle. The black crosses represent the corresponding values in the simulation presented by Abel et al. (2002). Upper right panel: spherically averaged value of the specific angular momentum, \( L \), plotted at the same time. Crosses represent the values of \( L \) for the indicated enclosed masses in the simulation presented by Abel et al. (2002). Lower left panel: spherically averaged number density profile at the same time, plotted as a function of the enclosed mass. The dashed line represents the power-law behavior of the density, \( n \propto r^{-2.2} \), typically found in simulations of Pop. III star formation. Figure from Clark et al. (2011b).

At low densities, \( \text{H}_2 \) forms mostly by reacting with \( \text{H}^- \) (McDowell 1961; Peebles and Dicke 1968), which itself requires free electrons to form. The reactions are:

\[
\begin{align*}
\text{H} + \text{e}^- &\rightarrow \text{H}^- + \gamma, \quad (11) \\
\text{H}^- + \text{H} &\rightarrow \text{H}_2 + \text{e}^- . \quad (12)
\end{align*}
\]

There is also a contribution from the interaction with \( \text{H}^+ \) as intermediary molecule (Saslaw and Zipoy 1967):

\[
\begin{align*}
\text{H} + \text{H}^+ &\rightarrow \text{H}_2^+ + \gamma, \quad (13) \\
\text{H}_2^+ + \text{H} &\rightarrow \text{H}_2 + \text{H}^+ . \quad (14)
\end{align*}
\]

These channels lead to typical molecular fractions of about \( 10^{-3} \). At high particle densities above
\begin{align} \sim 10^9 \text{cm}^{-3}, \text{ the three-body reaction becomes important} & \text{[Palla et al. 1983]:} \\
H + H + H & \rightarrow H_2 + H. \quad (15)\end{align}

As a result all atomic hydrogen is converted into \( H_2 \) once particle densities of \( n \approx 10^{11} \text{cm}^{-3} \) are reached. This is illustrated in the bottom panel of Figure 2 which is adopted from Yoshida et al. (2006). The top panel of this figure shows the corresponding equilibrium temperature \( T \) as function of \( n \). The labels indicate important phases of the collapse. (A) As the gas begins to flow into the potential well of the dark matter halo, it is compressionally heated to the virial temperature of the system. Once sufficient molecular hydrogen is formed the gas goes into a run-away cooling phase (B), which brings it down to the minimum temperature of \( \sim 200 \text{K} \) (C). At this stage of the collapse cold gas can accumulate in the center of the halo. Bromm et al. (2002) call this a ‘loitering’ phase. When enough gas is accumulated the collapse proceeds and gas slowly heats up again. Eventually three-body \( H_2 \) formation becomes important (D) and the gas turns fully molecular. The gas remains roughly isothermal over several decades in density. As \( n \) increases further, the cloud slowly becomes optically thick (E) and the temperature rises again. At densities \( n \approx 10^{14} \text{cm}^{-3} \) (F) collisional induced emission is an important coolant. When two molecules come close to each other, van der Waals forces can induce a temporary dipole which allows for efficient dipole emission during the interaction time interval, for details see Omukai and Nishi (1998); Ripamonti and Abel (2004). Finally, at temperatures around 2000 K collisional dissociation of \( H_2 \) sets in (G), and the gas becomes molecular again. Altogether, we note that over more than ten orders of magnitude in density, from \( n \approx 10^4 \text{cm}^{-3} \) to \( n \approx 10^{16} \text{cm}^{-3} \), the temperature only rises by a factor of 10 at most. The gas roughly follows a polytropic equation of state, \( P \propto n^{\gamma} \) with effective index \( \gamma \approx 1.08 \) (Omukai et al. 2005). This close to isothermal behavior is essential for allowing the accretion disk in the center of the halo to fragment efficiently (Section 4.2). We note that Figure 2 was calculated in the absence of additional heat sources, the situation may change if radiative feedback from newly formed stars (Section 4.3) or the possible energy input from dark matter annihilation is considered (section 4.6).

4 Stellar birth in the halo center

In this section we investigate how star formation progresses once the combination of gravitational collapse and cooling leads to a strong accretion flow into the center of a high-redshift halo, and we discuss the most important physical processes that govern stellar birth on small scales. We argue that the accretion disk that forms around the first object is likely to fragment, which typically results in the formation of a cluster of stars with a wide range of masses rather than the built-up of a single high-mass object. We then speculate about how stellar feedback, the presence of magnetic fields, the potential energy input from dark matter annihilation and the possible existence of large-scale streaming velocities between baryons and dark matter may influence this picture.

4.1 Simple spherical collapse

The most simple model we can construct for describing primordial star formation is the spherically symmetric continuation of the run-away collapse that sets in when a halo exceeds the critical mass for cooling \( M_{\text{cool}} \) as defined in Equation (10) above. This was modelled extensively in
the early 2000’s, as discussed by Abel et al. (2002), Bromm et al. (2002), and Yoshida et al. (2003). Although the numerical simulations were fully three-dimensional, the halos considered were relatively round and so assuming spherical symmetry and only considering radial profiles was a very good approximation during the early stages of collapse, see also Yoshida et al. (2006, 2008) or Bromm and Larson (2004). Figure 3 adopted from Clark et al. (2011b) shows enclosed mass and number density as function of radius (left), as well as the specific angular momentum and the radial inflow velocity as function of enclosed mass (right). The gas temperature is $\sim 1500$ K and we can use Equation (5) to obtain a good estimate of the measured accretion rate $\dot{M} \approx 2 \times 10^{-3} M_\odot \text{yr}^{-1}$.

These early calculations typically stopped when the object in the center reached number densities of $n \approx 10^{16} \text{cm}^{-3}$ or more, because then the computational timestep became prohibitively small. At this time the protostar has a mass of only $\sim 10^{-3} M_\odot$. At such early stage of evolution the accretion disk has only a small mass and it is strongly sub-Keplerian, meaning that the rotational velocity is smaller than the circular velocity corresponding to centrifugal support, due to the stabilizing influence of large pressure gradients and, if magnetic fields are taken into account, due to the additional support from magnetic pressure and tension. Consequently, this early disk shows no sign of fragmentation at the time these simulations have been stopped. Similar holds for the gas further out in the infalling envelope. The authors of these studies concluded that the same should be true for the entire protostellar accretion history, and so they argued that all the inflowing mass would end up in one single high-mass star, see also Tan and McKee (2004). Clearly this supposition needed to be tested, in particular, because the idea that primordial stars only form in isolation is in tension with present-day star formation where fragmentation is ubiquitous and young stars are typically found in clusters and aggregates Lada and Lada (2003).

4.2 Disk fragmentation

In the Universe today, the process of stellar birth is controlled by the intricate interplay between the self-gravity of the star-forming gas and various opposing agents, such as supersonic turbulence, magnetic fields, radiative and mechanical feedback, gas pressure, and cosmic rays. In particular turbulence has been identified to play a key role, see the reviews by Mac Low and Klessen (2004); McKee and Ostriker (2007); Klessen and Glover (2016). On global scales it provides support, while at the same time it can promote local collapse. This process is modified by the thermodynamic response of the gas, which is determined by the balance between various heating and cooling processes. These in turn depend on the chemical composition of the material. Here, clearly, differences between present-day and primordial star formation are expected (see section 3.2).

The introduction of techniques that had been standard repertoire in present-day star formation studies, in particular the use of sink particles, allowed to continue the numerical simulations beyond the first occurrence of a protostar. In this approach, a contracting high-density region is replaced by a single Lagrangian particle when the resolution limit is reached. The particle inherits the mass as well as the linear and angular momentum of the original region, and it continues to accrete mass that falls in at later times, see Bate et al. (1995); Krumholz et al. (2004); Jappsen et al. (2005); Federrath et al. (2010); Bleuler and Teyssier (2014); Howard et al. (2014); Sormani et al. (2017). This technique enables calculations that model the build-up and long-term evolution of the accretion disk, and that follow the entire protostar mass growth history. These studies unambiguously show that primordial accretion disks are highly prone to fragmentation. They indicate that the standard pathway of Pop. III star formation leads to a stellar cluster with a
Figure 4: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. The prominent two-arm spiral structure is caused by the gravitational instability in the disk, and the resulting gravitational torques provide the main source of angular momentum transport that allows disk material to accrete onto the protostar. Eventually, as mass continues to pour onto the disk from the infalling envelope, the disk becomes so unstable that regions in the spiral arms become self-gravitating in their own right. The disk fragments and a multiple system is formed. Figure adopted from Clark et al. (2011b).

Wide distribution of masses rather than the build-up of one single high-mass object. An example is illustrated in Figure 4, adopted again from Clark et al. (2011b), which shows the evolution of the accretion disks and the build-up of altogether four protostars within only about hundred years after the formation of the first object.

Disk fragmentation on various spatial and temporal scales is also reported by Machida et al. (2008); Greif et al. (2011, 2012); Dopcke et al. (2013); Susa (2013); Susa et al. (2014); Hosokawa et al. (2016); Stacy and Bromm (2013); Stacy et al. (2016); Turk et al. (2009). The reason is always the same. Under typical conditions of Pop. III star formation the mass load onto the disk by accretion from the infalling envelope exceeds its capability to transport this material inwards by gravitational or magnetoviscous torques, that is by spiral arms (Binney and Tremaine 1987) or by the magnetorotational instability (Balbus and Hawley 1998). The mass of the disk grows, and it quickly becomes Toomre unstable (section 2.2). This preferentially occurs at the outer edge of the disk. The instability region moves outwards as the disk grows larger by accretion of higher angular momentum material. And so, fragmentation and the formation of new protostars occurs at larger and larger radii as the evolution progresses, as visible in Figure 4.
This has important consequences for the overall accretion history and the resulting mass spectrum. As matter flows through the disk towards the center, it first encounters the Hill volume of secondary protostars further out and preferentially gets swallowed by these objects. Otherwise, this gas would have continued to move inwards and would eventually be accreted by the central object. Clearly, disk fragmentation limits the mass growth of the primary star in the center, and so this process has been termed 'fragmentation-induced starvation' in the context of present-day star formation (Kratter and Matzner 2006; Peters et al. 2010; Girichidis et al. 2011, 2012b, a). Some of these protostars may get ejected by dynamical encounters with other protostars or fragments while some may move inwards to get accreted by the central object (Clark et al. 2011a; Greif et al. 2012; Smith et al. 2012; Stacy et al. 2016). As a result of these highly unpredictable and stochastic events, the mass spectrum of Pop. III stars is expected to cover a wide range of masses, possibly reaching down into the substellar regime. Possible implications of this are discussed in Section 5.

We note that some numerical studies indicate that fragmentation may also occur on larger scales in the halo, on scales of the star-forming cloud as a whole (Turk et al. 2009; Stacy et al. 2010; Clark et al. 2011b). It may happen when the initial turbulence in the halo gas, that is always present at some low subsonic or transsonic level, gets amplified during gravitational collapse and induces density fluctuations that can go into run-away growth in their own right. This is then very similar to the turbulence-driven mode of star formation that is dominant at present days, for reviews see Mac Low and Klessen (2004); McKee and Ostriker (2007); Krumholz (2015); Klessen and Glover (2016). The importance of this process is enhanced in atomic cooling halos, where cold streams of gas bring dense material towards the center with supersonic velocities (with respect to the cold gas), thereby strongly raising the level of turbulence in the halo (Greif et al. 2008; Wise and Abel 2007; Wise et al. 2008). Similar is also expected in halos that are strongly affected by streaming velocities between baryons and dark matter (section 4.5). It has been suggested that the primordial IMF may be different under more turbulent conditions (McKee and Tan 2008; Clark et al. 2011b; Maio et al. 2011a; Stacy et al. 2011), however, overall the results are not fully conclusive.

4.3 Radiative feedback

Since the protostellar Kelvin-Helmholtz contraction time decreases rapidly with increasing stellar mass, massive stars enter the hydrogen burning main sequence while still accreting (Zinnecker and Yorke 2007; Maeder and Meynet 2012). The properties of the resulting star hereby depend very strongly on the details of the mass growth history. First stars with accretion rates below values of $\dot{M} \approx 10^{-3} \, M_\odot$, as we typically expect in low-mass minihalos at high redshift (section 4.1), are compact and very hot at their surface (Hosokawa and Omukai 2009; Hosokawa et al. 2010, 2012). These stars emit copious amounts of ionizing photons (Schaerer 2002) that can significantly influence their birth environment, as we discuss below. On the other hand, for rates of $\dot{M} \gtrsim 10^{-2} \, M_\odot$ stellar evolution calculations suggest that stars remains bloated and fluffy, and because of the large radius the surface temperature is relatively low. Although very luminous, these stars do not emit much ionizing radiation and could be able to maintain this high accretion flow for a very long time. In the right environment this could possibly lead to the formation of supermassive stars (Hosokawa et al. 2013; Haemmerlé et al. 2016; Umeda et al. 2016; Woods et al. 2017).
Compact and hot Pop. III stars create HII regions which are likely to break out of the parental halo and affect stellar birth in neighboring halos. Many aspects of this problem have been addressed, for example by Kitayama et al. (2004); Whalen et al. (2004); Alvarez et al. (2006); Abel et al. (2007); Yoshida et al. (2007); Greif et al. (2008); Wise et al. (2012b,a); Jeon et al. (2014). Here we focus on the impact of radiative feedback on the immediate birth environment of the star and on the question of how this influences the fragmentation behavior of the disk and the resulting stellar mass spectrum.

As before, we can seek guidance from models of present-day star formation. Radiation hydrodynamic simulations in two and three dimensions that take both non-ionizing and ionizing radiation into account (Yorke and Sonnhalter, 2002; Krumholz et al., 2009; Kuiper et al., 2010; Peters et al., 2011; Commerçon et al., 2011; Rosen et al., 2016) demonstrate that once a protostellar accretion disk has formed, it quickly becomes gravitationally unstable and so material in the disk midplane flows inwards along dense filaments, whereas radiation escapes through optically thin channels above the disk. Even ionized material can be accreted, if the accretion flow is strong enough (Keto, 2007; Peters et al., 2010). Radiative feedback is thought not to be able to shut off the accretion flow onto massive stars. Instead it is the dynamical evolution of the disk material that controls the mass growth of individual protostars. Accretion onto the central object is shut off by the fragmentation of the disk and the formation of lower-mass companions which intercept inward-moving material as argued in the previous section 4.2. This requires three-dimensional simulations, because this fragmentation process is not properly captured in two dimensions.

Due to the lack of metals and dust, protostellar accretion disks around Pop. III stars can cool less efficiently and are much hotter than disks at present days. Similarly, the stellar radiation field couples less efficiently to the surrounding because the opacities are smaller. It is thus not clear how well the above results can be transferred to the primordial case. Insight can be gained from the two-dimensional radiation hydrodynamic simulations of Pop. III star formation by Hosokawa et al. (2011); Hirano et al. (2014, 2015). They follow disk formation and the long-term accretion history of the central object and find that radiative feedback can indeed stop stellar mass growth and blow away the remaining accretion disk, leading to final stellar masses from a few 10 M⊙ up to about 1000 M⊙. However, these calculations cannot capture disk fragmentation and the formation of multiple stellar systems. Three-dimensional calculations have been reported by Stacy et al. (2013); Susa et al. (2013; 2014); Hosokawa et al. (2016). These studies find widespread fragmentation, again with a wide range of stellar masses down to ~ 1 M⊙. These simulations have their own limitations and shortcomings, either in terms of resolution or in the number of physical processes included. And so, any firm conclusions about the resulting mass spectrum of Pop. III stars in the presence of radiative feedback is premature at this stage. This is clearly one of the frontiers of current research in primordial star formation.

### 4.4 Magnetic fields

The presence of dynamically important magnetic fields could significantly alter the picture presented so far. We know that the current Universe is highly magnetized on all scales (Beck et al., 1996) and that this influences the birth of stars and the evolution of the interstellar medium, for the extreme viewpoint of magnetically mediated star formation, see Shu et al. (1987). The properties of the magnetic fields observed today are well explained by a combination of small-scale and large-scale dynamo processes (Brandenburg and Subramanian, 2005). In contrast, our knowl-
edge of magnetic fields at high redshifts is very sparse. Theoretical models predict that magnetic fields could be produced in various ways, for example via the Biermann battery (Biermann 1950), the Weibel instability (Lazar et al. 2009; Medvedev et al. 2004), or thermal plasma fluctuations (Schlickeiser and Shukla 2003). Other theories place their origin in phase transitions that occur during cosmic inflation (Sigl et al. 1997; Grasso and Rubinstein 2001; Banerjee and Jedamzik 2003; Widrow et al. 2012). The resulting fields are thought to be orders of magnitudes too weak to have any dynamical impact, and so, magnetohydrodynamic effects have typically been neglected in numerical simulations of primordial star formation however, see the analytic models by Pudritz and Silk (1989); Tan and McKee (2004); Silk and Langer (2006).

This situation has changed, when people started to realize that the small-scale turbulent dynamo is efficiently amplifying even extremely small primordial seed fields to the saturation level, and that this process is very fast, acting on timescales much shorter than the dynamical free-fall time. An analytic treatment is possible in terms of the Kazantsev model (Kazantsev 1968; Subramanian 1998; Schober et al. 2012a,b) for low as well as large Prandtl numbers. This theory describes how the twisting, stretching, and folding of field lines in turbulent magnetized flows (see Figure 4.3) leads to an exponential growth. The amplification timescale is comparable to the eddy-turnover time on viscous or resistive length scales. This is the kinematic regime. Once backreactions become important, the growth rate slows down, and saturation is reached within a few large-scale eddy-turnover times (Schekochihin et al. 2002, 2004; Schober et al. 2015). Depending on the properties of the turbulent flow the magnetic energy density at saturation is thought to lie between 0.1% and a few 10% of the kinetic energy density (Federrath et al. 2011, 2014).
Magnetic fields with that strength can strongly affect the evolution of protostellar accretion disks. They remove angular momentum from the star-forming gas (Machida et al. 2008; Machida and Doi 2013; Bovino et al. 2013; Latif et al. 2013; 2014b), drive protostellar jets and outflows (Machida et al. 2006), and reduce the level of fragmentation in the disk (Turk et al. 2011; Peters et al. 2014). We expect Pop. III clusters to have fewer members with somewhat higher masses than predicted by purely hydrodynamic simulations (as discussed in section 4.2). However, the details of how magnetic fields influence the overall star-formation process in primordial gas, and how they affect the resulting IMF are not well understood. This remains to be an area of very active research.

4.5 Relative streaming velocities between baryons and dark matter

Prior to recombination, baryons are tightly coupled to photons resulting in a standing acoustic wave pattern (Sunyaev and Zel’dovich 1970). In turn, this leads to oscillations between baryons and dark matter with relative velocities of about 30 km s$^{-1}$ and coherence lengths of several 10 Mpc to 100 Mpc (Silk 1986) at $z \approx 1000$. After recombination, baryons are no longer tied to photons, their sound speed drops to $\sim 6$ km s$^{-1}$, and the velocity with respect to the dark matter component becomes supersonic with Mach numbers of $M \approx 5$. This has been first described by Tseliakhovich and Hirata (2010). In the subsequent cosmic evolution, the relative streaming velocity decays linearly with $z$, and reaches $\sim 1$ km s$^{-1}$ at the onset of first star formation at $z \approx 30$. It is comparable to the virial velocity of the first halos to cool and collapse, and so it has been suggested that this velocity offset strongly influences the star formation process (Tseliakhovich et al. 2011; Fialkov et al. 2012).

Simulations that include streaming velocities indeed suggest that their presence reduces the baryon overdensity in low-mass halos, delays the onset of cooling, and leads to a larger critical mass for collapse to set in (Greif et al. 2011; Stacy et al. 2011; Maio et al. 2011a; Naoz et al. 2012, 2013; O’Leary and McQuinn 2012; Latif et al. 2014a; Schauer et al. 2017). They may also have substantial impact on the resulting 21 cm emission (Fialkov et al. 2012; McQuinn and O’Leary 2012; Visbal et al. 2012). Gas in halos which are located in regions of large streaming velocities will be more turbulent than in more quiescent systems, and so we expect more fragmentation and a bias towards smaller stellar masses (Clark et al. 2008). However, this process has not yet been modeled with sufficient resolution, and so a reliable prediction of the IMF in regions with large streaming velocities is still outstanding.

4.6 Potential impact of dark matter annihilation

Despite its importance for cosmic evolution and structure formation, the true physical nature of dark matter is still unknown. Many models introduce a new class of weakly interacting massive particles, so called WIMPs, as they naturally occur in supersymmetry theories. The lightest supersymmetric particle is expected to be stable and to have properties that agree with the phenomenological requirements on dark matter (Bertone et al. 2005). Specifically, they are self-annihilating Majorana particles, that is they are their own antiparticles, and they interact only weakly with baryons.
In most environments the dark matter density is much too low for this to be significant. However, it has been suggested to be different in star-forming halos in the early Universe. Here the collapse of baryons may drag along dark matter particles. This process is called ‘adiabatic contraction’ (Blumenthal et al., 1986), and it can lead to a density increase of several orders of magnitude in the very center of the halo. As the annihilation rate scales quadratically with the density the corresponding energy input and ionization rate may become large enough to influence the dynamics of the gas. Spolyar et al. (2008); Freese et al. (2009) realize that this process could potentially overcome the cooling provided by H\textsubscript{2}. They speculate that this could halt further collapse and lead to the formation of a dark star, an object of a few AU in size that is powered by dark matter annihilation rather than by nuclear fusion. If dark matter particles also scatter weakly on baryons this could lead to a structure that is stable for a long time. These dark stars are thought to be much larger than normal Pop. III stars, have lower surface temperatures, and are more luminous (Freese et al. 2008; Iocco 2008; Jocco et al. 2008; Yoon et al. 2008; Hirano et al. 2011).

There are several problems with this scenario. First, it is not clear whether collapse stalls once the energy input from dark matter becomes comparable to the cooling rate. Ripamonti et al. (2010), for example argue that this may not be the case because the larger heating rate catalyzes further formation of H\textsubscript{2} and is compensated by the corresponding larger cooling rate. Second, the inherent assumption of perfect alignment between dark matter cusp and gas collapse is most likely violated in realistic star formation conditions. There is always some degree of anisotropy in the halo and there is always some level of turbulence in the infalling gas that make it highly unlikely for the dark matter cusp and the collapsing gas to overlap perfectly. This problem was studied by Stacy et al. (2012, 2014), who indeed found that non-axisymmetric perturbations lead to a separation between dark matter cusp and collapsing gas, rendering the annihilation energy input insignificant for dark star formation. Similar was reported by Smith et al. (2012), who also found no evidence for a dark stellar phase in their calculations, but instead formed more normal Pop. III stars. These authors, however, also reported that dark matter annihilation was able to influence the dynamics of the accretion disk and that the energy input associated with this process lead to a suppression of disk fragmentation. They concluded that dark matter annihilation may reduce the multiplicity of metal-free stars and increase their overall mass. But, as before, the existing simulations are still too premature to draw firm conclusions about the Pop. III IMF.

### 4.7 Second generation star formation

Second generation stars, sometimes termed Population II.5 stars, have formed from material that has been enriched from the debris of the first stars. Unlike the very first stars, for which we have no direct detections yet (section 5.1), members of the second generation have already been found in surveys looking for extremely metal-poor stars in our Milky Way and neighboring satellite galaxies (section 5.3). There are two competing models for their origin based on different low-metallicity cooling channels that determine the ability of the gas to collapse and fragment, and so set the stellar mass spectrum.

Unlike purely primordial gas, where cooling is solely provided by hydrogen in various forms (section 3.2), metal-enriched gas has access to a wide range of different cooling processes. Atomic fine-structure lines from alpha elements such as carbon or oxygen can provide sufficient cooling at number densities around 10\textsuperscript{4} cm\textsuperscript{-3} above a critical metallicity of about 10\textsuperscript{-3} of the solar value (Smith et al. 2009). Details of the element abundance in the Sun are discussed by Asplund et al. 18.
Up to \( n \approx 10^2 \text{cm}^{-3} \) and metallicities of \( \sim 10^{-2} \) solar the cooling rate is dominated by molecular hydrogen (Jappsen et al. 2007, 2009; Glover and Clark 2014). This can be estimated by calculating the amount of heavy elements required to produce a cooling rate equal to the rate of adiabatic compression heating for given halo properties (Bromm and Loeb 2003; Santoro and Shull 2006). Frebel et al. (2009) combined the available abundance measures and introduced a transition criterion, with low-mass stars forming only above a certain threshold. This proposition is challenged by the discovery of SDSS J1029151+172927, a truly primitive star in the constellation of Leo, that falls below this value (Caffau et al. 2011a). The star has elemental abundances in the range \( 10^{-5} \) to \( 10^{-4} \) of the solar value for all of the elements measured in its spectrum, setting it apart from other extremely metal-poor stars which typically have enhanced CNO abundances despite being very iron poor.

Another line of reasoning considers dust cooling as the primary agent for fragmentation, which leads to a lower critical metallicity in the range \( 10^{-5} \) to \( 10^{-6} \) (Omukai et al. 2005; Schneider et al. 2006, 2012; Chiaki et al. 2013b). The existence of SDSSJ1029151+172927 provides evidence for the validity of the dust-induced fragmentation model (Schneider et al. 2012; Klessen et al. 2012; Bovino et al. 2016). The analytical models, based on comparing the strength of various cooling and heating processes in a metal-poor environment, are supported by numerical simulations (Tsuribe and Omukai 2006, 2008; Clark et al. 2008; Dopcke et al. 2013; Chiaki et al. 2014, 2016). These suggest that indeed dust is responsible for a transition to a star formation mode similar to the one observed at present days. This transition occurs at a metallicity of about \( 10^{-5} \) solar and leads to an IMF peaking below 1 M\(_\odot\) with a functional form similar to the one inferred for the solar neighborhood (Kroupa 2002; Chabrier 2003).

5 Observational constraints

Determining the properties of the first population of stars is a difficult task. Most of our current knowledge of Pop. III stars comes from theoretical model building and numerical simulations. To a large degree, this is due to the fact that, unlike in present-day star formation, stringent observational constraints are rare and extremely difficult to obtain. Here we provide a brief overview of possible indirect constraints from the primordial as well as the present-day Universe, and we speculate about possible detections of genuine low-mass Pop. III stars in Galactic archeological surveys.

5.1 Indirect constraints from high redshift observations

Unfortunately, Pop. III stars are very hard to see directly in the high-redshift Universe. They are too faint (Schaerer 2002) to be within reach of the next generation of telescopes. This holds in space for the James Webb Space Telescope (Gardner et al. 2006), Euclid (Laureijs et al. 2011), or the Wide-Field Infrared Survey Telescope (Spergel et al. 2015), and it is true for ground-based observatories such as the European Extremely Large Telescope (Tamai and Spyromilio 2014) or the Thirty Meter Telescope (Skidmore et al. 2015). Constraints on the IMF from high-z observations therefore are indirect at best. For example we can search for the supernova explosions that accompany the end of massive Pop. III stars. Numerical simulations indicate that the light-curves of Pop. III pair-instability supernovae and even less energetic core collapse supernovae will
be within easy reach of JWST or E-ELT out to very high redshifts (Hummel et al., 2012; Kasen et al., 2011; Pan et al., 2012; Whalen et al., 2013a,b). However, because of their narrow field of view, and for the space missions also because of the long slewing time, these telescopes are not suited for large area surveys and will have difficulties to find these supernovae. Lists of suitable target candidates are needed. Here, gravitational lensing might help and bring some of the supernova events above the sensitivity limit of large-area surveys such as planned with LSST, WFIRST or Euclid, see also (Oguri and Marshall, 2010, Rydberg et al., in prep.). Once a candidate is found, JWST or E-ELT can be used for detailed follow-up observations. The detection rates in large surveys furthermore can contribute to distinguish between different cosmological models (Magg et al., 2016).

Studying the high-redshift Universe will only allow us to address the high mass end of the IMF. Information about the low-mass Pop. III stars is completely inaccessible via this route. Similar is true for potential detections of gravitational wave emission from merging Pop. III black hole binaries. The recent discoveries of gravitational waves from three systems with masses of \(62 \, M_\odot, 21 \, M_\odot, \) and \(49 \, M_\odot\) (Abbott et al., 2016a,b, 2017) has demonstrated that this might indeed be possible. Mergers of very massive Pop. III remnants could contribute to the statistical background (Inayoshi et al., 2016; Sasaki et al., 2016) or may even be detected directly (Belczynski et al., 2017; Hartwig et al., 2016; Nakama et al., 2017). More details on detecting mergers of black hole binaries from Pop. III stars via gravitational wave emission will be given in chapter ??.

We should also mention studies by Kulkarni et al. (2013, 2014) who investigate the impact of the chemical enrichment from Pop. III stars on damped Lyman-\(\alpha\) systems and on cosmic reionization, and find that this could be a sensitive probe of the primordial IMF at high redshift.

At the extreme end of the mass spectrum, we note that the discovery of very massive quasars with several \(10^9 \, M_\odot\) at redshifts of \(z \approx 6\) or above (Mortlock et al., 2011; Wu et al., 2015) provides support for the existence of supermassive stars in the early Universe. We note that stellar evolution calculations with very high accretion rates suggest that stars could be stable up to several \(10^5 \, M_\odot\) before the general relativistic instability (Iben, 1963; Chandrasekhar, 1964) leads to the collapse into a black hole of the same mass (Hosokawa et al., 2013; Umeda et al., 2016; Woods et al., 2017). These could be the seeds for the observed very massive quasars when able to maintain high accretion rates close to the Eddington limit down to \(z \approx 6\). The formation of such objects via gravitational collapse will be described in chapter ??, and their subsequent evolution in chapter ??.

5.2 Indirect constraints from observations in the Local Group

More stringent limits on the IMF are likely to come from the study of nearby stars in the Local Group. Current Galactic archeological surveys (Beers and Christlieb, 2005; Caffau et al., 2013; Frebel, 2010) in the halo and bulge of our Milky Way or the analysis of stars in nearby satellite dwarf galaxies (Koch et al., 2013; Salvadori et al., 2015; Kirby et al., 2015; Roederer et al., 2016; Ji et al., 2016a,b) can contribute to our knowledge of primordial stars in several ways. There is a large body of work that uses the abundance pattern determined in extremely metal-poor stars to infer the properties of the progenitor stars which provided the enrichment (Heger and Woosley, 2002, 2010). Assuming that the oldest and most metal-poor stars in the Galaxy have been supplied with heavy elements by only one or at most two supernova explosions (Chan and Heger, 2017), it turns out that the measured relative abundances of heavy elements are most consistent with core collapse supernovae from Pop. III stars in the mass range \(20 - 40 \, M_\odot\) (Aoki et al., 2014; Bonifacio ??).
et al., 2015; Caffau et al., 2012; Cooke and Madau, 2014; Frebel et al., 2005; Iwamoto et al., 2005; Joggerst et al., 2009, 2010; Keller et al., 2014; Lai et al., 2008; Norris et al., 2013. Together with the fact that no genuine signatures of pair-instability supernovae from massive stars in the range of \( \sim 130 \) to \( 250 \, M_\odot \) have been found, this places strong constraints on the high-mass end of the primordial IMF.

5.3 Possible direct detections of low-mass Pop. III stars

The theory of stellar evolution (Kippenhahn et al., 2012) tells us that any low-mass Pop. III star with \( 0.8 \, M_\odot \) or smaller must have survived until the present day. If these stars ever existed, then there is a chance to directly detect some of them in current or future stellar archeological surveys. Even non-detections allow us to put stringent limits on the low-mass end of the Pop. III IMF. For example Hartwig et al. (2015) estimate the expected numbers of low-mass Pop. III stars in the Galactic halo based on semi-analytic models of the early star formation history in Milky Way-like halos. They conclude that if no such object is found in surveys with sample sizes of 4 million stars then we can exclude the existence of low-mass Pop. III stars with masses below \( 0.8 \, M_\odot \) with a confidence level of 68\%. This limit may soon be reached.

On similar grounds, Salvadori et al. (2007, 2010) develop a detailed model of the metallicity distribution function of metal-poor stars in the Galactic halo and suggest that Pop. III stars should be more massive than \( 0.9 \, M_\odot \) when matching their predictions with the observational data. On the other hand, Tumlinson (2006, 2010) argues that the current abundance measurements are not really sufficient to distinguish between different models of the primordial IMF based on studying the chemical evolution during the early build-up of the Galaxy. However, he also suggests that characteristic masses of a few \( 10 \, M_\odot \) provide a better fit to the available data than masses of \( 100 \, M_\odot \) or above, consistent with the supernova yields mentioned above.

Mapelli et al. (2006) focus on the density of Galactic intermediate-mass black holes. They take them as the relics of higher-mass Pop. III stars and derive an upper limit by comparing their model to the non-detection of ultra-luminous x-ray sources in the Galaxy. This constraint, however, does not affect the low-mass end of the primordial IMF. The approach has been extended by de Bennassiti et al. (2014) who also conclude that the Galactic metallicity function and the abundances measured in extremely metal-poor stars in the halo are inconsistent with pair-instability supernovae. Their study indicates that the early enrichment of the Galaxy by Pop. III stars was dominated by core collapse supernovae, and they suggest an IMF that goes all the way down to \( 0.1 \, M_\odot \). Altogether, the prospects of finding surviving low mass first stars in our immediate neighborhood are highly exciting, but at present no clear conclusions are possible.
6 Summary

In this chapter of the book we aimed at providing a concise overview of our current understanding of the physical processes that govern stellar birth in the primordial Universe. As the first stars are too faint to be directly detectable at high redshift, the available observational data give little input and provide very indirect constraints at best. And so, most of the current progress in this rapidly evolving field of astrophysical research has been driven by numerical simulations and theoretical model building.

While early models predicted that the first stars formed in isolation with only one single high-mass star in the center of a halo, the community now acknowledges that the birth of stars in truly metal-free gas is subject to the same complexity and stochasticity that is well known in present-day star formation. Probably the most important development in the past decade is the realization that the accretion disks that build up around the first stars are highly susceptible to fragmentation. The natural formation pathway therefore leads to Population III stars that are members of multiple stellar systems and clusters. This has important consequences for the stellar mass spectrum. Numerical simulations of first star formation that are able to resolve the evolution of the accretion disk and the mass growth of individual protostars with high resolution predict a wide range of masses, with a relatively flat distribution that spans the substellar regime up to several hundred solar masses, and with the most likely values being around a few tens of solar masses. This is different from the IMF observed at present days, which shows a clear peak at $\sim 0.3 \, M_\odot$ and a power-law fall-off towards higher masses. So, one of the key questions is when and where did the transition between the primordial and the current mode of star formation occur, and what is its primary physical cause.

A convincing answer to this question is still outstanding. Besides the lack of a good observational base, the primary reason for this is that all existing calculations have severe shortcomings. And so still very little is actually known about the mass spectrum of Pop. III stars. The current numerical simulations either lack sufficient resolution, or they cover only a short fraction of the overall star formation timescale. Most of them ignore important physical processes, such as protostellar feedback or magnetic fields. It may also be that more speculative phenomena such as heating from dark matter annihilation or the relative streaming velocity between baryons and dark matter are important for the star formation process in the center of a halo. The theoretical and numerical treatment of these processes is still in its infancy. Furthermore, some simulations are two-dimensional, whereas a full three-dimensional approach is required to properly capture gas fragmentation or to fully assess the dynamical impact of stellar radiation on the infaling gas. So, correctly modelling stellar birth in high-redshift halos with high physical fidelity with strong predictive power is still an unsolved problem. It is a true frontier of computational astrophysics.

It is probably fair to say that most researchers in the field agree that the genuine Pop. III stars have formed in binary or higher-order multiple stellar systems and that they most likely had a wide range of masses. Whether the mass scale reached down to low-mass stars or even the sub-stellar regime depends on physical processes that we only now start to consider properly, such as radiative feedback, the level of turbulence in halo gas and accretion disk, properties of the dark matter, or the larger scale environment of the star forming halo. Since low-mass Pop. III stars must have survived until the present days, they should be detectable in stellar archeological surveys in the Milky Way and neighboring satellite galaxies, and so there are good chances that we soon have stringent constraints on the low-mass end of the Pop. III IMF. The abundance patterns we observe...
in extremely metal-poor stars nearby are all consistent with enrichment by core collapse supernovae with progenitor masses of a few tens of solar masses. This is in agreement with the most likely stellar masses from fragmentation calculations of primordial accretion disks. The fact that no signatures of enrichment by pair-instability supernovae are seen, suggests that Pop. III stars with masses above 100 M$_\odot$ must have been extremely rare. How far up the mass range of primordial stars extends is not clear yet. Theoretical limits from including general relativistic instabilities in the stellar structure equations predict an upper mass limit of several 10$^5$ M$_\odot$. Indeed, such stars could be the seeds for the extremely massive quasars with billions of solar masses we observe at redshifts of $z \approx 6$ and higher. However, the density of these objects is only a few per Gpc$^3$, and so our statistical base is scarce.

In this chapter, we have focused on what could be called the standard pathway to Pop. III star formation. We have considered cooling and collapse of truly pristine gas that has not been affected by any form of feedback from earlier episodes of star formation either within the same halo or in neighboring halos. The temperature and composition of the material has not been altered by strong Lyman-Werner or ionizing fluxes, and there was no enrichment from the supernovae of previous stars. These effects are discussed in detail in other chapters of this book. Particularly, the next chapter will discuss the formation of very massive black holes via direct collapse, in situations where the cooling is suppressed by radiation backgrounds. An alternative formation channel via collisions in dense stellar clusters will be presented in chapter , and the evolution of supermassive stars is discussed in chapter . Predictions for gravitational wave emission from black hole binary mergers, including remnants from Pop. III stars, are summarized in chapter .

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