REVIEWS

# The formation of the first stars and galaxies

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**Observations made using large ground-based and space-borne telescopes have probed cosmic history from the present day to a time when the Universe was less than one-tenth of its present age. Earlier still lies the remaining frontier, where the first stars, galaxies and massive black holes formed. They fundamentally transformed the early Universe by endowing it with the first sources of light and chemical elements beyond the primordial hydrogen and helium produced in the Big Bang. The interplay of theory and upcoming observations promises to answer the key open questions in this emerging field.**

The formation of the first stars and galaxies at the end of the cosmic 'dark ages' is one of the central problems in modern cosmology[1–3]. It is thought that during this epoch the Universe was transformed from its simple initial state into a complex, hierarchical system, through the growth of structure in the dark matter, by the input of heavy elements from the first stars, and by energy injection from these stars and from the first black holes[4,5]. An important milestone in our understanding was reached after the introduction of the now standard cold dark-matter (CDM) model of cosmic evolution, which posits that structure grew hierarchically, such that small objects formed first and then merged to form increasingly larger systems[6]. Within this model, dark-matter 'minihaloes' (see below), forming a few hundred million years after the Big Bang, were identified as the sites where the first stars formed[7]. Building on this general framework, and relying on the development of efficient new computational tools, the fragmentation properties of primordial gas inside such minihaloes were investigated with numerical simulations, leading to the result that the first stars, so-called population III, were predominantly very massive[4,8] (see Box 1 for the terminology used here). Recently, the frontier has progressed to the next step in the hierarchical build-up of structure, to the emergence of the first galaxies whose formation took place after the first stars had formed and affected their common environment. It is very timely to review our current understanding and remaining challenges, as we are just entering an exciting period of discovery, in which new observational probes are becoming available and advances in supercomputer technology enable ever more realistic theoretical predictions.

We begin with the formation of the first stars, discussing the physics underlying the prediction that they were very massive, and how this picture would be modified if the dark matter exhibited non-standard properties on small scales. We next address the feedback effects from the first stars, with one main result being that such feedback might delay subsequent star formation by up to $\sim 10^8$ years. Proceeding to the assembly of the first galaxies, we discuss the important role of turbulence and supernova feedback during their formation. Intriguingly, the cold accretion streams that feed the turbulence in the centres of the primordial galaxies are reminiscent of the recently proposed new model for galaxy formation, in which such cold streams are invoked to explain the build-up of massive galaxies at more recent cosmic times in a smooth, rather than merger-driven, fashion[9]. We conclude with an outlook into the likely key developments over the next decade.

## Formation of the first stars

Whereas dark-matter haloes can originate through the action of gravity alone, the formation of luminous objects, such as stars and galaxies, is a much more complicated process. For star formation to begin, a sufficient amount of cold dense gas must accumulate in a dark halo. In the early Universe, the primordial gas could not efficiently cool radiatively because atoms have excitation energies that are too high, and molecules, which have accessible rotational energies, are very rare. Trace amounts of molecular hydrogen ($H_2$) can be produced via a sequence of reactions, $H + e^- \rightarrow H^- + \gamma$ (where $\gamma$ indicates a photon), followed by $H^- + H \rightarrow H_2 + e^-$ (where $e^-$ indicates an electron), and under the proper conditions this allows the gas to cool and eventually condense to form stars[10].

Numerical simulations[11–13] starting from cosmological initial conditions show that primordial gas clouds formed in dark-matter haloes with virial temperature $\sim$1,000 K and mass $\sim 10^6 M_\odot$

**Box 1 | Definitions and terminology**

We establish here a convention for terminology used in this review. Population III stars are those that initially contain no elements heavier than helium ('metals' in the parlance of astronomers) other than the lithium produced in the Big Bang. Such stars can be divided into first generation stars (population III.1), which form from initial conditions determined entirely by cosmological parameters, and second generation stars (population III.2), which originate from material that was influenced by earlier star formation[25]. According to theory, population III.1 stars formed when almost completely neutral primordial gas collapsed into dark-matter minihaloes, whereas one important class of population III.2 stars formed from gas that was photoionized before the onset of gravitational runaway collapse[33]. Simply put, population III.1 stars are locally the very first luminous objects, whereas population III.2 stars are those metal-free stars formed from gas that was already affected by previous generations of stars. Population II stars have enough metals to affect their formation and/or their evolution. Such stars are classified[100] according to their iron/hydrogen ratio as extremely metal poor for metallicities $10^{-4} < Z/Z_\odot < 10^{-3}$, ultra-metal poor for $10^{-5} < Z/Z_\odot < 10^{-4}$, and hyper-metal poor for $10^{-6} < Z/Z_\odot < 10^{-5}$. Because we know so little about the first galaxies, it is difficult to establish a precise terminology for them. A galaxy is a system of many stars and gas that is gravitationally bound in a dark-matter halo. We define a 'first galaxy' as one composed of the very first system of stars to be gravitationally bound in a dark-matter halo. Such stars could be population III or population II stars with very low metallicities—extremely metal poor or below, according to recent numerical simulations[63,64]. The gas in such galaxies should have similarly low metallicities. Current theory predicts that population III.1 stars are formed in isolation in minihaloes and therefore will not be in galaxies.

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(so-called 'minihaloes'; $M_\odot$, solar mass). In the standard CDM model, the minihaloes that were the first sites for star formation are expected to be in place at redshift $z \approx 20$–30, when the age of the Universe was just a few hundred million years[14]. These systems correspond to (3–4)$\sigma$ peaks in the cosmic density field, which is statistically described as a Gaussian random field. Such high-density peaks are expected to be strongly clustered[15], and thus feedback effects from the first stars are important in determining the fate of the surrounding primordial gas clouds. It is very likely that only one star can be formed within a gas cloud, because the far-ultraviolet radiation from a single massive star is sufficient to destroy all the $H_2$ in the parent gas cloud[16,17]. In principle, a cloud that formed one of the first stars could fragment into a binary or multiple star system[18,19], but simulations based on self-consistent cosmological initial conditions do not show this[20]. Although the exact number of stars per cloud cannot be easily determined, the number is expected to be small, so that minihaloes will not be galaxies (see Box 1).

Primordial gas clouds undergo runaway collapse when sufficient mass is accumulated at the centre of a minihalo. The minimum mass at the onset of collapse is determined by the Jeans mass (more precisely, the Bonnor–Ebert mass), which can be written as:

$$M_J \approx 500 M_\odot \left(\frac{T}{200}\right)^{3/2} \left(\frac{n}{10^4}\right)^{-1/2} \quad (1)$$

for an atomic gas with temperature $T$ (in K) and particle number density $n$ (in $cm^{-3}$). The characteristic temperature is set by the energy separation of the lowest-lying rotational levels of the trace amounts of $H_2$, and the characteristic density corresponds to the thermalization of these levels, above which cooling becomes less efficient[12]. A number of atomic and molecular processes are involved in the subsequent evolution of a gravitationally collapsing gas. It has been suggested that a complex interplay between chemistry, radiative cooling and hydrodynamics leads to fragmentation of the cloud[21], but vigorous fragmentation is not observed even in extremely high-resolution cosmological simulations[11–13,20,22]. Interestingly, however, simulations starting from non-cosmological initial conditions have yielded multiple cloud cores[19,23]. It appears that a high initial degree of spin in the gas eventually leads to the formation of a disk and its subsequent break-up. It remains to be seen whether such conditions occur from realistic cosmological initial conditions.

Although the mass triggering the first runaway collapse is well-determined, it provides only a rough estimate of the mass of the star(s) to be formed. Standard star-formation theory predicts that a tiny protostar forms first and subsequently grows by accreting the surrounding gas to become a massive star. Indeed, the highest-resolution simulations of first-star formation verify that this also occurs cosmologically[20] (Fig. 1). However, the ultimate mass of the star is determined both by the mass of the cloud out of which it forms and by a number of feedback processes that occur during the evolution of the protostar. In numerical simulations, the final mass of a population III star is usually estimated from the density distribution and velocity field of the surrounding gas when the first protostellar fragment forms, but this may well be inaccurate even in the absence of protostellar feedback. Whereas protostellar feedback effects are well studied in the context of the formation of contemporary stars[24], they differ in several important respects in primordial stars[25].

First, primordial gas does not contain dust grains. As a result, radiative forces on the gas are much weaker. Second, it is generally assumed that magnetic fields are not important in primordial gas because, unless exotic mechanisms are invoked, the amplitudes of magnetic fields generated in the early Universe are so small that they never become dynamically significant in primordial star-forming gas[26]. Magnetic fields have at least two important effects in contemporary star formation: they reduce the angular momentum of the gas out of which stars form, and they drive powerful outflows that disperse a significant fraction of the parent cloud. It is likely that the pre-stellar gas has more angular momentum in the primordial case, and this is borne out by cosmological simulations. Third, primordial stars are much hotter than contemporary stars of the same mass, resulting in significantly greater ionizing luminosities[27].

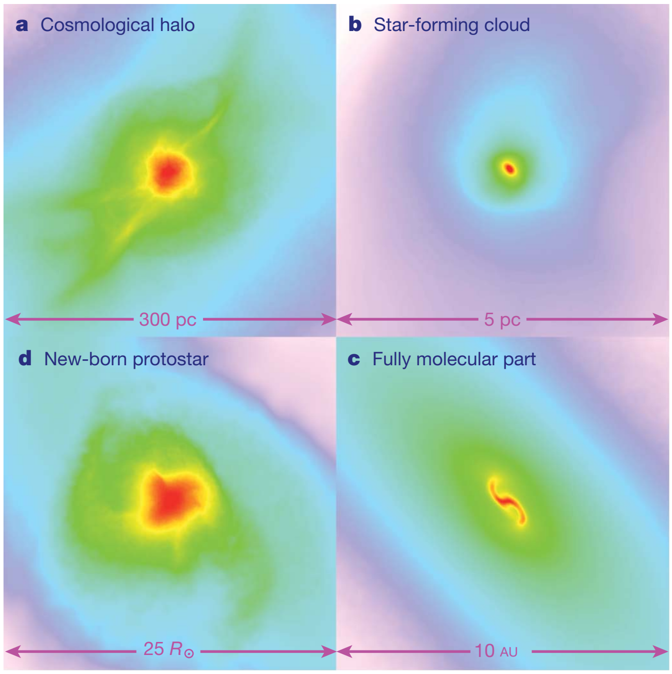


**Figure 1 | Projected gas distribution around a primordial protostar.** Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming cloud; **c**, the central part of the fully molecular core; and **d**, the final protostar. Reproduced by permission of the AAAS (from ref. 20).

State-of-the-art numerical simulations of the formation of the first (population III.1) stars represent a computational *tour de force*, in which the collapse is followed from cosmological (comoving megaparsec) scales down to protostellar (sub-astronomical-unit) scales, revealing the entire formation process of a protostar. However, further growth of the protostar cannot be followed accurately without implementing additional radiative physics. For now, inferring the subsequent evolution of the protostar requires approximate analytic calculations. By generalizing a theory for contemporary massive-star formation[28], it is possible to approximately reproduce the initial conditions found in the simulations and to then predict the growth of the accretion disk around the star[29]. Several feedback effects determine the final mass of a first star[25]: photodissociation of $H_2$ in the accreting gas reduces the cooling rate, but does not stop accretion. Lyman-$\alpha$ radiation pressure can reverse the infall in the polar regions when the protostar grows to 20–30 $M_\odot$, but cannot significantly reduce the accretion rate. The expansion of the H II region produced by the large flux of ionizing radiation can significantly reduce the accretion rate when the protostar reaches 50–100 $M_\odot$, but accretion can continue in the equatorial plane. Finally, photoevaporation-driven mass loss from the disk[30] stops the accretion and fixes the mass of the star (see Fig. 2). The final mass depends on the entropy and angular momentum of the pre-stellar gas; for reasonable conditions, the mass spans 60–300 $M_\odot$.

A variety of physical processes can affect and possibly substantially alter the picture outlined above. Magnetic fields generated through the magneto-rotational instability may become important in the protostellar disk[31], although their strength is uncertain, and may play an important role in the accretion phase[18]. Cosmic rays and other external ionization sources, if they existed in the early Universe, could significantly affect the evolution of primordial gas[32]. A partially ionized gas cools more efficiently because the abundant electrons promote $H_2$ formation. Such a gas cools to slightly lower temperatures than a neutral gas can, accentuating the fractionation of D into HD so that cooling by HD molecules becomes important[33–36].

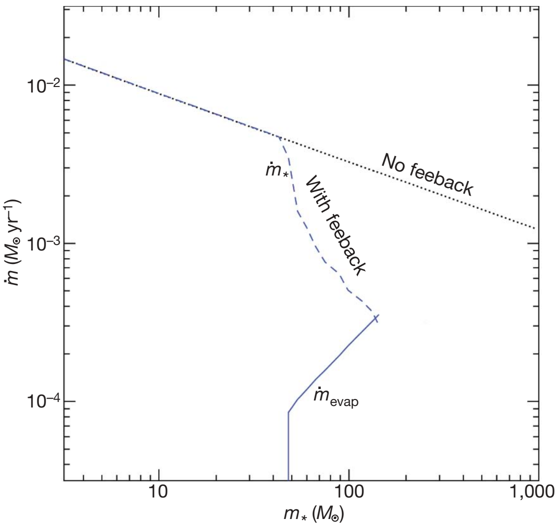


**Figure 2 | Feedback-limited accretion.** Change in mass ($\dot{m}$) versus protostellar mass ($m_*$) for a number of key processes. The protostellar accretion rate ($\dot{m}_*$) is shown in the cases of 'no feedback' (black dotted line) and 'with feedback' (blue dashed line). Even as an H II region is built up, accretion continues through an accretion disk, which is eventually destroyed via photoevaporation. Also shown is the corresponding rate ($\dot{m}_{evap}$; blue solid line). The intersection of the blue dashed and solid curves determines the final population III mass. Reproduced by permission of the AAS (from ref. 25).

More significant modifications to the standard model result if the properties of the dark matter are different from those assumed above (see Fig. 3). A key assumption in the standard model is that the dark matter interacts with the baryons only via gravity. However, dark matter can indirectly affect the dynamics of a pre-stellar gas. A popular candidate for CDM is the neutralino, for which the self-annihilation cross-section is large. Neutralino dark matter is thus expected to pair-annihilate in very dense regions, producing high-energy particles such as pions and electron–positron pairs and high-energy photons. These annihilation products may effectively heat collapsing primordial gas clouds when the density is sufficiently high, thereby arresting the collapse[37]. Calculation of the structure of stars with dark-matter annihilation suggest that they can undergo a phase of evolution in which they have temperatures of 4,000–10,000 K, well below those for conventional population III stars[38,39]. The magnitude of this effect depends sensitively on details such as the dark-matter concentration and the final products of neutralino annihilation. Furthermore, calculations to date have assumed spherical symmetry, whereas it is possible that the angular momentum of both the baryons (which leads to the formation of an accretion disk[29]) and of the dark matter could significantly impede the build-up of the high dark-matter densities required to power the stellar luminosity via dark-matter annihilation. Nevertheless, if neutralinos are detected in the appropriate mass range[40], early star formation models may need to include the effect of dark-matter annihilation.

## Feedback from the first stars

Some of the feedback processes described above that affect the formation of individual stars also influence primordial star formation on large scales. The enormous fluxes of ionizing radiation and $H_2$-dissociating Lyman–Werner radiation emitted by massive population III stars[27,41] dramatically influence their surroundings, heating and ionizing the gas within a few kiloparsecs of the progenitor and destroying the $H_2$ within a somewhat larger region[17,33,42–44]. Moreover, the Lyman–Werner radiation emitted by the first stars could propagate across cosmological distances, allowing the build-up of a pervasive Lyman–Werner background radiation field[45,46]. The effect of radiation from the first stars on their local surroundings has important implications for the numbers and types of population III stars that form. The photoheating of gas in the minihaloes hosting population III.1 stars drives strong outflows, lowering the density of the gas in the minihaloes and delaying subsequent star formation by up to 100 Myr (ref. 47). Furthermore, neighbouring minihaloes may be photoevaporated, delaying star formation in such systems as well[48–50]. The photodissociation of molecules by Lyman–Werner photons emitted from local star-forming regions will, in general, act to delay star formation by destroying the main coolants that allow the gas to collapse and form stars[51].

The photoionization of primordial gas can, however, also stimulate star formation by fostering the production of abundant molecules within the relic H II regions surrounding the remnants of population III.1 stars[44,47,52,53] (see Fig. 4). It is still debated whether this radiative feedback is positive or negative in terms of its overall impact on the cosmic star formation rate[54]. However, some robust conclusions have emerged from the recent simulations. First, the Lyman–Werner feedback is much less 'suicidal' than was originally thought[55]. It is now believed that star formation in neighbouring minihaloes is not completely suppressed, but merely delayed. Second, the ionizing radiation from the first stars is initially very disruptive because it substantially decreases the density in the host minihalo. This effect leads to the substantial gap between the formation of the first and second generations of stars. In each region of space, the drama of 'first light' thus occurred in two clearly separated stages.

Most of the work on the evolution of population III stars and on the supernovae they produce has been based on the assumption that the stars are not rotating[56]. For initial stellar masses in the range $25M_\odot \lesssim M_* \lesssim 140M_\odot$ and $M_* \gtrsim 260M_\odot$, population III stars end their lives by collapsing into black holes with relatively little ejection of heavy

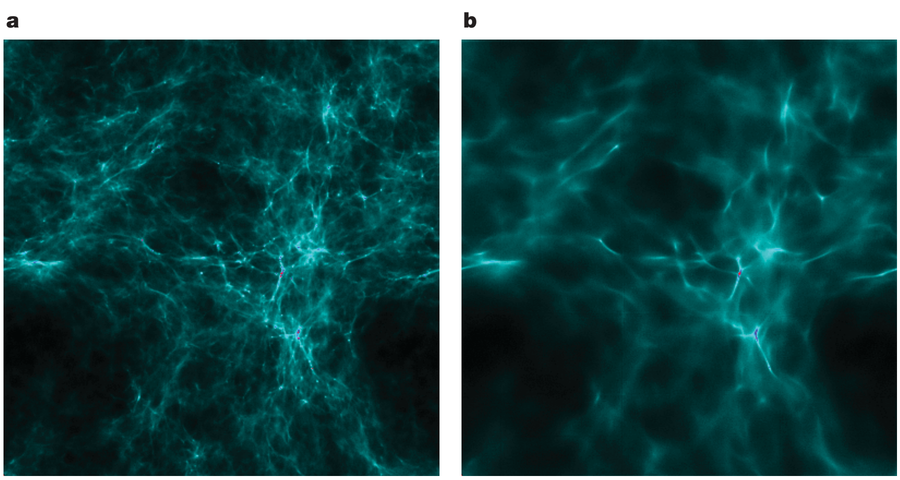


**Figure 3 | Dark-matter properties and early star formation.** Projected gas distribution in CDM (**a**) and warm dark matter (WDM; **b**) simulations at $z = 20$. If the power in the primordial density spectrum is reduced on small scales, the first stars will form much later than in the standard CDM-based scenario. If the dark matter is warm, having a substantial velocity dispersion, density perturbations on small length scales are smoothed. The hierarchy of structure formation is then truncated at a corresponding mass scale, and the first cosmological objects could be more massive than $10^6 M_\odot$. For the case of light WDM[98], gas collapses into filaments, which might then fragment into multiple stellar cores. The abundance of star-forming haloes is significantly reduced in this model. Reproduced by permission of the AAS (from ref. 99).

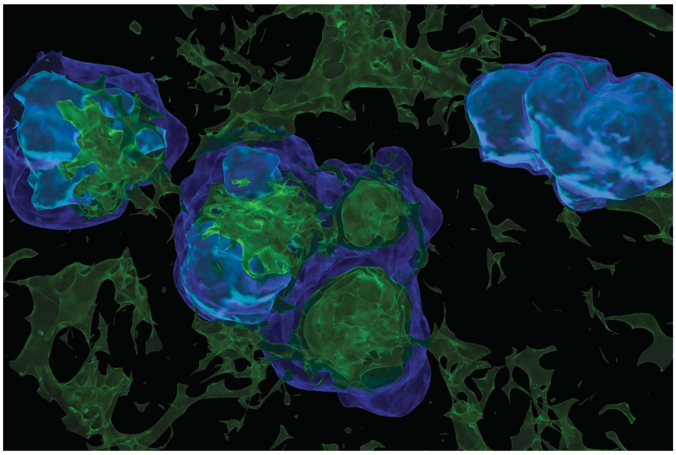

**Figure 4 | Radiative feedback around the first stars.** Ionized bubbles are shown in blue, and regions of high molecule abundance in green. The large residual free electron fraction inside the relic H II regions, left behind after the central star has died, rapidly catalyses the reformation of molecules. The abundance of HD molecules allows the primordial gas to cool to the temperature of the CMB, possibly leading to the formation of population III.2 stars after these regions have re-collapsed so that gas densities are sufficiently high again for gravitational instability to occur[77]. The latter process takes of the order of the local Hubble time, thus imposing a ~100 Myr delay in star formation. The relatively high molecule abundance in relic H II regions, along with their increasing volume-filling fraction, leads to a large optical depth to Lyman–Werner photons over physical distances of the order of several kiloparsecs (ref. 47). The development of a high optical depth to Lyman–Werner photons over such short length-scales, combined with a rapidly increasing volume filling fraction of relic H II regions, suggests that the optical depth to Lyman–Werner photons over cosmological scales may be very high, acting to suppress the build-up of a background Lyman–Werner radiation field, and mitigating negative feedback on star formation[75]. Note the strongly clustered nature of early star formation. Visualization courtesy of the Texas Advanced Computing Center (based on data from ref. 47).

elements. Population III stars in the range 140–260 $M_\odot$ explode as pair-instability supernovae, which disrupt the entire progenitor, with explosion energies ranging from $10^{51}$ erg to $10^{53}$ erg, and nucleosynthetic yields, defined as the heavy-element mass fraction, up to 0.5. Such supernovae exhibit an odd-even effect in the nuclei produced that is much greater than observed in any star to date, and as a result they cannot make a significant contribution to the metals observed in very low-metallicity stars today[57]. On the other hand, the pair-instability supernova signature may exist in a tiny fraction of the stars with intermediate metallicity (~$0.01Z_\odot$, where $Z_\odot$ indicates solar metallicity), because the enrichment from even a single pair-instability supernova already endows the surrounding material with heavy elements to levels that are above the regime typically probed by surveys of metal-poor stars[58].

The first stars may have been born rapidly rotating, however, and rotation can entirely modify these results[59]. For sufficiently high rotation rates, rotationally induced mixing is able to render the cores chemically homogeneous; mixing of heavy elements to the surface in the late stages of evolution can lead to substantial mass loss. If the cores maintain a sufficiently high rotation at the time of the supernova, it is possible to produce a long γ-ray burst or a jet-induced energetic supernova/hypernova[60,61], with significant effects on the abundances of the ejected metals[62]. Large uncertainties remain in the evolutionary calculations owing to the effects of dynamo-generated magnetic fields.

The strong mechanical and chemical feedback effects exerted by explosions of population III stars have been investigated with a number of detailed calculations[63–69]. The key question is how the initially metal-free Universe was enriched with the first heavy chemical elements[70]. Recently, it has become feasible to address this process with realistic three-dimensional simulations that start from cosmological initial conditions, and that resolve the detailed physics of the supernova blast wave expansion[63,64]. These simulations have shown that early enrichment is very inhomogeneous, as the low-density voids are enriched before any metals can reach into the denser filaments and virialized haloes[71].

## Assembly of the first galaxies

The characteristic mass of the first star formation sites has been determined to be ~$10^6 M_\odot$ (refs 14, 72), whereas the critical mass for hosting the formation of the first galaxies is still not known with any certainty. A promising theoretical *Ansatz* is to explore atomic cooling haloes—with ~$10^8 M_\odot$ and virial temperatures greater than ~$10^4$ K so that atomic line cooling is efficient—as their formation sites[73,74]. The simulations, starting from cosmological initial conditions, are just now approaching the resolution and physical realism required to investigate whether atomic cooling haloes fulfil the criteria for a first galaxy as defined above. Quite generically, in such models, the first generation of stars forms before galaxies do, and feedback effects from the first stars are expected to play a key role in determining the initial conditions for the formation of the first galaxies. Although substantial uncertainties in the overall formation efficiency of the first stars still remain, it is possible, and perhaps probable, that at least one primordial star had formed in the region that was destined to eventually become a first galaxy[75]. If the early generation stars were massive, $\gtrsim 10 M_\odot$, the feedback effects described in the previous section would shape the conditions for subsequent star formation in the region.

The gas expelled by the H II regions and supernovae of the first stars would have been too hot and diffuse to allow further star formation until it had time to cool, as well as to reach high densities again in the course of being reincorporated in a growing dark-matter halo. Both cooling and re-collapse occur rather slowly, thus rendering star formation intermittent in the early formation phase of the first galaxies. Analytic models[76] and detailed numerical simulations[47,77] both show that the gas re-incorporation time is as long as $10^8$ years, roughly corresponding to the dynamical time for a first-galaxy halo to be assembled.

Chemical enrichment by the first supernovae is among the most important processes in the formation of the first galaxies. Efficient cooling by metal lines and dust thermal emission regulate the temperature of already metal-enriched population II (see Box 1) star-forming regions in the first galaxies. The concept of a 'critical metallicity' has been introduced to characterize the transition of the star-formation mode from predominantly high-mass, population III or population II, to low-mass population II stars[78]. However, this critical gas metallicity is still poorly determined. It is not even clear if there exists such a sharp transition. Some studies show that even a slight quantity of metals in a gas may be enough to change the gas thermal evolution significantly[79], whereas others argue that the cooling efficiency at low densities[80] is crucial and is significantly enhanced only above $10^{-4} Z_\odot$. As the enrichment from even a single pair-instability supernova by a very massive population III star probably leads to metallicities of $Z > 10^{-2} Z_\odot$ (ref. 63), well in excess of any predicted value for the critical metallicity, these arguments might be somewhat academic. The characteristic mass of pre-stellar gas clumps is probably determined by a number of physical processes (for example, turbulence and, possibly, dynamo-amplified primordial magnetic fields) other than radiative cooling. The overall effect of gas metallicity on star formation may well be limited[81].

Recent cosmological simulations have demonstrated that star formation inside the first galaxies was strongly influenced by gravitationally driven supersonic turbulence that was generated during the virialization process[64,73,74]. This is in marked contrast to the rather quiescent, quasi-hydrostatic situation in minihaloes (see Fig. 5). It thus appears possible that the first galaxies harboured the first stellar clusters, if present-day star formation offers any guide here, where it is widely believed that gravo-turbulent fragmentation is responsible for shaping the initial mass function[24,82]. It is an open question as to whether the first galaxies could have harboured the first globular clusters, which are the oldest star clusters known.

## Future empirical probes

Studying the formation of the first stars and galaxies will be at the frontier of astronomy and cosmology in the next decade. Astronomers will muster a comprehensive arsenal of observational probes. The most prominent among these concern the optical depth to Thomson scattering of cosmic microwave background photons off free electrons[83–85], the near-infrared background[86], high-redshift $\gamma$-ray bursts[87–89], the possibility of scrutinizing the nature of the first stars by metals found in the oldest Galactic halo stars, dubbed 'stellar archaeology'[90,91], and various facilities now being deployed to map reionization using the redshifted 21 cm line of neutral hydrogen[92–94]. The James Webb Space Telescope (JWST) will perform a number of observations designed to test key assumptions of our current theory of the first stars and galaxies[95]. How could the existence of massive population III stars be unambiguously inferred? The most clear-cut diagnostic is the ratio of recombination lines emitted from the H II regions around single population III stars, or clusters thereof, to be measured with ultra-deep near-infrared and mid-infrared spectroscopy. Owing to the high effective temperature of the population III stellar continuum, $\sim10^5$ K, strong He II line emission at a rest-frame wavelength of 1,640 Å is predicted, with a ratio compared to Lyman-$\alpha$ that is one to two orders of magnitude larger than for normal stars[41]. A second crucial observational campaign aims at a census of very high-$z$ supernovae[96] through deep broadband near-infrared imaging. One key objective is to search for possible pair-instability supernova events, which would clearly stand out owing to their extreme intrinsic brightness, as well as their very long durations—a few years in the observer frame[97]. The goal of making useful predictions for the high-redshift frontier is now clearly moving within reach, and the pace of progress is likely to be rapid.

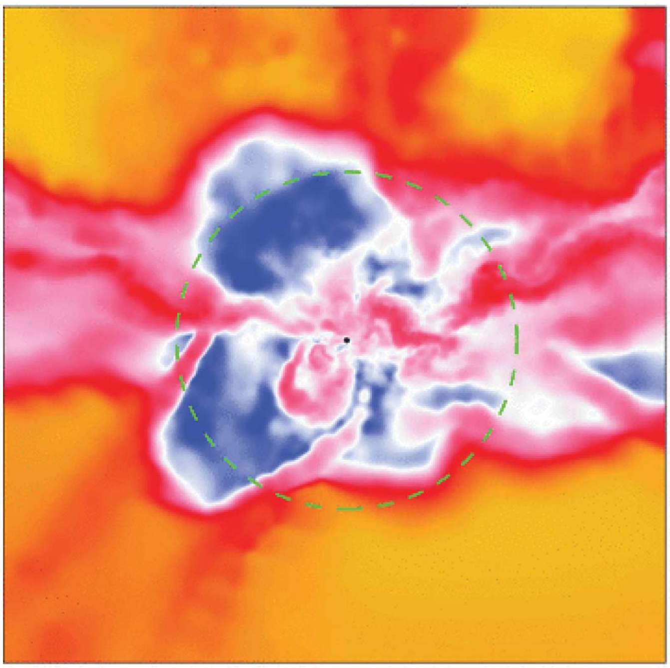


**Figure 5 | Turbulence inside the first galaxies.** Shown is the Mach number (Ma) in a slice through the central 40 kpc (comoving) of the galaxy. The dashed line denotes the virial radius of ~1 kpc. The Mach number approaches unity at the virial shock, where the accreted gas is heated to the virial temperature. Inflows of cold gas along filaments are supersonic by a factor of ~10, resulting in strong turbulent flows in the galactic centre. The age of the Universe at redshift $z \approx 10$ is given by $t_H$. Reproduced by permission of Wiley-Blackwell (from ref. 74).

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