Observations made using large ground-based and space-borne telescopes have probed cosmic history all the way from the present-day to a time when the Universe was less than a tenth of its present age. Earlier on 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. 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. 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\textsuperscript{6}. Within this model, dark matter ‘minihalos’ (see below), forming a few hundred million years after the Big Bang, were identified as the sites where the first stars formed\textsuperscript{7}. Building on this general framework, and relying on the development of efficient new computational tools, the fragmentation properties of primordial gas inside such minihalos were investigated with numerical simulations, leading to the result that the first stars, so-called Population III (Pop III), were predominantly very massive\textsuperscript{4,8} (see the Box for the terminology used in this review). 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, since we are just entering an exciting period of discovery, where new observational probes are becoming available, and where 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 (SN) feedback during their formation. Intriguingly, the cold accretion streams that feed the turbulence in the centers of the primordial galaxies are reminiscent of the recently proposed new paradigm 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\textsuperscript{9}. We conclude with an outlook into the likely key developments over the next decade.
Formation of the first stars

While dark-matter halos 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 cannot 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$^-$ → H$^-$ + γ, followed by H$^-$ + H → H$_2$ + e$^-$, 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 halos with virial temperature $T_{\text{vir}} \sim 1,000$ K and mass $\sim 10^6 M_\odot$ (so-called ‘minihalos’). In the standard CDM model, the minihalos that were the first sites for star formation are expected to be in place at $z \sim 20 - 30$, 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 UV 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 forms 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 minihalos will not be galaxies (see Box).

Primordial gas clouds undergo runaway collapse when sufficient mass is accumulated at
the center 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

$$M_J \simeq 500M_\odot \left(\frac{T}{200\,\text{K}}\right)^{3/2} \left(\frac{n}{10^4\,\text{cm}^{-3}}\right)^{-1/2}$$

for an atomic gas with temperature $T$ and particle number density $n$. The characteristic temperature is set by the energy separation of the lowest-lying rotational levels of the trace amounts of $\text{H}_2$, and the characteristic density corresponds to the thermalisation 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 guess 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\(^{20}\) (see Fig. 1). However, the ultimate mass of the star is determined both by the mass of the cloud out of which the star forms and by a number of feedback processes that occur during the evolution of the protostar. In numerical simulations, the final mass of a Pop 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. While
protostellar feedback effects are well studied in the context of the formation of contemporary stars\textsuperscript{24}, they differ in several important respects in primordial stars\textsuperscript{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\textsuperscript{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 ionising luminosities\textsuperscript{27}.

State-of-the-art numerical simulations of the formation of the first (Pop III.1) stars represent a computational \textit{tour de force}, in which the collapse is followed from cosmological (comoving Mpc) 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 generalising a theory for contemporary massive star formation\textsuperscript{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\textsuperscript{29}. Several feedback effects determine the final mass of a first star\textsuperscript{25}. Photodissociation of H\textsubscript{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 \(20 - 30M_{\odot}\), but cannot significantly reduce the accretion rate.
The expansion of the H II region produced by the large flux of ionising 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 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 proto-stellar disk, although their strength is uncertain, and may play an important role in the accretion phase. Cosmic rays and other external ionisation sources, if they existed in the early Universe, could significantly affect the evolution of primordial gas. A partially ionised 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.

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. 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 $4000 - 10^4$ K, well below those for conventional Pop 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 buildup 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 impact primordial star formation on large scales. The enormous fluxes of ionising radiation and H$_2$-dissociating Lyman-Werner (LW) radiation emitted by massive Pop III stars$^{27,41}$ dramatically influence their surroundings, heating and ionising the gas within a few kpc of the progenitor and destroying the H$_2$ within a somewhat larger region$^{17,33,42–44}$. Moreover, the LW radiation emitted by the first stars could propagate across cosmological distances, allowing the build-up of a pervasive LW background radiation field$^{45,46}$. The impact of radiation from the first stars on their local surroundings has important implications for the numbers and types of Pop III stars that form. The photoheating of gas in the minihalos hosting Pop III.1 stars drives strong outflows, lowering the density of the gas in the minihalos and delaying subsequent star formation by up to 100 Myr$^{47}$. Furthermore, neighbouring minihalos may be photoevaporated, delaying star formation in such systems as well$^{48–50}$. The photodissociation of molecules by LW 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\textsuperscript{51}.

The photoionisation of primordial gas, however, can also stimulate star formation by fostering the production of abundant molecules within the relic H\textsc{ii} regions surrounding the remnants of Pop III.1 stars\textsuperscript{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\textsuperscript{54}. However, some robust conclusions have emerged from the recent simulations. First, the LW feedback is much less ‘suicidal’ than was originally thought\textsuperscript{55}. It is now believed that star formation in neighbouring minihalos is not completely suppressed, but merely delayed. Second, the ionising 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 Pop III stars and on the SNe they produce has been based on the assumption that the stars are not rotating\textsuperscript{56}. For initial stellar masses in the range $25M_\odot \lesssim M_\ast \lesssim 140M_\odot$ and $M_\ast \gtrsim 260M_\odot$, Pop III stars end their lives by collapsing into black holes with relatively little ejection of heavy elements. Pop III stars in the range $140 - 260M_\odot$ explode as pair-instability supernovae (PISNe), which disrupt the entire progenitor, with explosion energies ranging from $10^{51} - 10^{53}$ erg, and nucleosynthetic yields, defined as the heavy element mass fraction, up to 0.5. Such SNe 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\textsuperscript{57}. On the other hand, the PISN signature may exist in a tiny fraction of the stars with intermediate metallicity ($\sim 0.01Z_\odot$), because the enrichment from even a single PISN already endows the surrounding material with heavy elements to levels that are above the regime typically probed by surveys of metal-poor stars\textsuperscript{58}. 
The first stars may have been born rapidly rotating, however, and rotation can entirely modify these results\textsuperscript{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 SN, it is possible to produce a long gamma-ray burst (GRB) or a jet-induced energetic supernova/hypernova\textsuperscript{60,61}, with significant effects on the abundances of the ejected metals\textsuperscript{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 Pop III stars have been investigated with a number of detailed calculations\textsuperscript{63–69}. The key question is how the initially metal-free Universe was enriched with the first heavy chemical elements\textsuperscript{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 SN blast wave expansion\textsuperscript{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 virialised halos\textsuperscript{71}.

**Assembly of the first galaxies**

The characteristic mass of the first star formation sites has been determined to be $\sim 10^6 M_\odot$\textsuperscript{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 halos, with $\sim 10^8 M_\odot$ and virial temperatures greater than $\sim 10^4$ K so that atomic line cooling is efficient, as their formation sites\textsuperscript{73,74}. The simulations, starting from cosmological initial conditions, are just now approaching the resolution and physical realism to investigate whether atomic cooling halos fulfill 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*. While substantial uncertainties in the overall formation efficiency of the first stars still remain, it is possible, and perhaps probable, that most first galaxies hosted at least one primordial star earlier\(^\text{75}\). If the early generation stars were massive, \(\gtrsim 10M_\odot\), 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 SNe of the first stars is 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\(^\text{76}\) and detailed numerical simulations\(^\text{47,77}\) both show that the gas re-incorporation time is as long as a hundred million years, roughly corresponding to the dynamical time for a first-galaxy halo to be assembled.

Chemical enrichment by the first SNe 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 Pop II star-forming regions in the first galaxies. The concept of a ‘critical metallicity’ has been introduced to characterise the transition of the star-formation mode from predominantly high-mass, Pop III or Pop II, to low-mass Pop II stars\(^\text{78}\). 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\(^\text{79}\), whereas others argue that the cooling efficiency at low densities\(^\text{80}\) is crucial and is significantly enhanced only above one ten-thousandth of solar-metallicity \((Z \gtrsim 10^{-4}Z_\odot)\). Since the enrichment from even a single PISN by a very massive Pop III star likely leads to metallicities of \(Z > 10^{-2}Z_\odot\)\(^\text{63}\), well in
excess of any predicted value for the critical metallicity, these arguments might be somewhat academic. The characteristic mass of prestellar gas clumps is likely determined by a number of physical processes (e.g., 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.

Recent cosmological simulations have demonstrated that star formation inside the first galaxies is strongly influenced by gravitationally-driven supersonic turbulence that was generated during the virialisation process. This is in marked difference to the rather quiescent, quasi-hydrostatic situation in minihalos (see Fig. 5). It thus appears possible that the first galaxies harbour 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 (IMF). It is an open question as to whether the first galaxies could harbour 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 CMB optical depth to Thomson scattering, the near-IR background, high-redshift GRBs, the possibility of scrutinising the nature of the first stars by metals found in the oldest Galactic halo stars, dubbed ‘stellar archaeology’, and various facilities now being deployed to map reionisation using the redshifted 21 cm line of neutral hydrogen. The *James Webb Space Telescope (JWST)* will carry out a number of observations designed to test key assumptions of our current theory of the first stars and galaxies. How could the existence of massive Pop III stars be unambiguously inferred? The most clear-cut diagnostic is the
ratio of recombination lines emitted from the H II regions around single Pop III stars, or clusters thereof, to be measured with ultra-deep near-IR and mid-IR spectroscopy. Due to the high effective temperature of the Pop III stellar continuum, \( \sim 10^5 \) K, strong He II \( \lambda 1640 \) line emission 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-\( z \) SNe\(^{96} \) through deep broadband near-IR imaging. One key objective is to search for possible PISN 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 drawing within reach, and the pace of progress is likely to be rapid.
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Acknowledgments The authors are grateful for the hospitality of KITP, University of California Santa Barbara. This work was supported in part by NSF and NASA.

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This manuscript was prepared with the AAS \LaTeX\ macros v4.0.
Fig. 1.— Projected gas distribution around a primordial protostar\textsuperscript{20}. Shown are, (A) the large-scale gas distribution around the cosmological minihalo (300 pc on a side), (B) a self-gravitating, star-forming cloud (5 pc on a side), (C) the central part of the fully molecular core (10 astronomical units on a side), and (D) the final protostar (25 solar-radii on a side).
Fig. 2.— Feedback limited accretion\textsuperscript{25}. The accretion rate vs. protostellar mass is shown in the cases of “no feedback” and “with feedback”. 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. The intersection of the two curves determines the final Pop III mass.
Fig. 3.— Dark matter properties and early star formation\textsuperscript{98}. Projected gas distribution in CDM (\textit{left}) and warm dark matter (WDM) simulations (\textit{right}) 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 warm dark matter\textsuperscript{99}, gas collapses into filaments, which might then fragment into multiple stellar cores. The abundance of star-forming halos is significantly reduced in this model.
Fig. 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 catalyzes 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 Pop III.2 stars after these regions have re-collapsed so that gas densities are sufficiently high again for gravitational instability to occur. The latter process takes of order the local Hubble time, thus imposing a $\sim 100$ 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 LW photons over physical distances of the order of several kpc. The development of a high optical depth to LW 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 LW photons over cosmological scales may be very high, acting to suppress the build-up of a background LW radiation field, and mitigating negative feedback on star formation. Note the strongly clustered nature of early star formation.
Fig. 5.— Turbulence inside the first galaxies\textsuperscript{74}. Shown is the Mach number in a slice through the central 40 kpc (comoving) of the galaxy. The dashed line denotes the virial radius of \( \approx 1 \) 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 \( \approx 10 \), resulting in strong turbulent flows in the galactic center.
Box: Definitions and Terminology

We here establish a convention for terminology to be used in this review. Pop 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 (Pop III.1), which form from initial conditions determined entirely by cosmological parameters, and second generation stars (Pop III.2), which originate from material that was influenced by earlier star formation. According to theory, Pop III.1 stars formed when almost completely neutral primordial gas collapsed into dark-matter minihalos, whereas one important class of Pop III.2 stars formed from gas that was photoionised prior to the onset of gravitational runaway collapse. Simply put, Pop III.1 stars are locally the very first luminous objects, whereas Pop III.2 stars are those metal-free stars formed from gas that was already affected by previous generations of stars. Pop II stars have enough metals to affect their formation and/or their evolution. Such stars are classified according to their iron/hydrogen ratio as extremely metal poor (EMP) for metallicities $10^{-4} < Z/Z_\odot < 10^{-3}$, ultra-metal poor (UMP) for $10^{-5} < Z/Z_\odot < 10^{-4}$, and hyper-metal poor (HMP) $10^{-6} < Z/Z_\odot < 10^{-5}$. 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 comprised of the very first system of stars to be gravitationally bound in a dark matter halo. Such stars could be Pop III or Pop II stars with very low metallicities—EMP or below according to recent numerical simulations. The gas in such galaxies should have similarly low metallicities. Current theory predicts that first generation Pop III stars (Pop III.1) are formed in isolation in minihalos and therefore will not be in galaxies.