Review
Formation of the first generation of stars and blackholes in the Universe

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Abstract: Modern sky surveys using large ground-based telescopes have discovered a variety of celestial objects. Prominent structures such as galaxies and galaxy clusters are found virtually everywhere, and their collective distribution forms the large-scale structure of the Universe. It is thought that all of the rich content in the present-day Universe developed through gravitational amplification of primeval density fluctuations generated in the very early phase of cosmic evolution. The standard theoretical model based on an array of recent observations accurately predicts the physical conditions in the early Universe, and powerful super-computers allow us to simulate in detail the formation and evolution of cosmic structure to the present epoch. We review recent progress in the study on the first generation of stars and blackholes. We focus on the physics of early structure formation, while identifying several key issues and open questions. Finally, we discuss prospects for future observations of the first stars, galaxies and blackholes.

Keywords: stars, cosmology, blackholes

1. Introduction

A number of distant astronomical objects have been discovered by wide-field sky surveys since the late 1990’s. Such objects include massive galaxies and super-massive blackholes that were in place when the Universe was less than one billion years old. The current excitement concerning studies on the early Universe is due to the recent rapid progress in observational astronomy. Large ground-based telescopes are probing an impressive fraction of the entire cosmic history, and future observational facilities are aimed at detecting not only light from the distant Universe, but also high-energy cosmic rays, neutrinos, and gravitational waves.

Space-borne telescopes have been used to probe the state of the infant Universe, about 380,000 years after the Big Bang, through observations of the cosmic microwave background (CMB) radiation. Precise measurements of CMB temperature fluctuations have established the currently standard cosmological model, which provides an excellent account for the evolution of the Universe. The remaining frontier of cosmology lies in the so-called Dark Ages, when the Universe was about several hundred million years old.

Soon after the so-called recombination epoch when the cosmic primordial gas became neutral and decoupled from photons, the mean CMB photon energy shifted to infrared, and then the Universe was left in complete darkness. About a hundred million years had to pass until the first generation of stars were born, which lit up the Universe once again and terminated the cosmic Dark Ages. The first stars were the first sources of light, and also synthesized heavy elements that enabled the formation of later generations of stellar populations and planets, and, ultimately, the emergence of life.

In this article, we review recent progress in the theory of structure formation in the early Universe. We focus on physical processes relevant to the formation of the first stars. We also introduce the results from state-of-the-art computer simulations. There are two major reasons that we expect supercomputer simulations to play an important role in
studies of early cosmic structure formation: (1) the initial conditions, as determined through a broad range of astronomical observations, are well-established, so that an accurate representation of the early Universe can be generated as a complete computer model, and (2) the important basic physics such as gravitation, hydrodynamics, and chemical reactions in a cosmic primordial gas are identified and understood. In principle, it is possible to understand purely theoretically the formation of early structure and of the first stars in an expanding Universe. We describe the basic elements in such super-computer simulations. The implications of the obtained results are discussed.

2. The standard cosmological model

We begin with a brief introduction to the standard cosmological model. Recent observations of the cosmic microwave background radiation, distant supernovae, and the large-scale galaxy and matter distributions suggest that the present-day Universe consists of about 70 percent of dark energy and 25 percent of dark matter, with the remaining small fraction being 5 percent contributed by ordinary matter. Dark energy permeates the Universe and acts to accelerate its expansion, whereas dark matter drives the formation of galaxies as the major source of gravity. Remarkably, very accurate numbers have been derived for the respective energy densities. The latest result from the Planck mission suggests that the present matter density is \( \Omega_m = 0.308 \), whereas the corresponding dark energy density is \( \Omega_{\Lambda} = 0.692 \). These values indicate the fractions with respect to the critical density that makes the present-day Universe geometrically flat.

The so-called A Cold Dark Matter model is widely accepted as the standard model, for it is consistent with an array of observations of cosmic structure. According to the model, all of the structure is seeded in an exponentially expanding phase of the early Universe, called inflation. The inflationary Universe models predict primordial density fluctuations with very simple characteristics. The density field is represented by a Gaussian random field, whose power spectrum is given by a nearly power-law of \( P(k) \propto k^n \) as a function of the wavenumber \( k \), and \( n \) is very close to unity. Such density fluctuations have progressively larger amplitudes on smaller length scales, and hence structure formation is expected to proceed in a hierarchical manner. Figure 1 shows one such example of early structure. The complex matter distribution with prominent filaments and nearly empty voids resembles the distribution of galaxies in the local Universe, although with an overall much smaller physical size. The resemblance manifests the hierarchical nature of structure formation mentioned in the above. At the intersections of the large filaments, massive clumps of dark matter are formed through nonlinear gravitational collapse. Such dark matter “halos” assemble, by the action of gravity, the surrounding primordial gas, which eventually provides the material of star nurseries.

3. Formation of primordial gas clouds

The formation of dark matter halos that host early star-forming gas clouds can be described in terms of basic physics. Over-dense regions in the initial density field grow to become denser and denser, and each of them finally collapses gravitationally when the mean density within it exceeds a certain threshold value. Such a collapsed object relaxes toward dynamic equilibrium through the so-called virialization process, and then forms a dense clump of dark matter. Because of its hierarchical nature originating from the initially stochastic density fluctuations, the formation of dark matter halos proceeds in essentially the same manner regardless of the mass and size.

Unlike the formation of dark halos, which is driven solely by gravity, star formation involves a number of physical processes. First of all, for star formation to begin in the early Universe, a sufficient amount of cold dense gas must accumulate. The gas in a dark halo can cool and condense only if radiative cooling operates efficiently. A crucial difference between the present-day inter-stellar medium and a primordial gas is whether or not their contents include efficient coolants. The inter-stellar medium in the Galaxy contains heavy element atoms, their ions, molecules, and dust grains that all enable radiative cooling through various processes. Contrasting, a primordial gas contains mostly neutral hydrogen and helium atoms, and only a trace amount of lithium atoms and ions. None of these acts as an efficient coolant at low gas temperatures of \( T < 1000 \) K. Hence the very first step of primordial gas cloud formation is to produce coolants.

Hydrogen molecules (H\(_2\)) can form via a sequence of gas-phase reactions:

\[
\begin{align*}
\text{H} + e^- \rightarrow \text{H}^- + \gamma, & \quad [1] \\
\text{H}^- + \text{H} \rightarrow \text{H}_2 + e^-. & \quad [2]
\end{align*}
\]

Molecules, once formed, collide with other atoms and molecules, and change their quantum rotational and
vibrational levels. Excited molecules return to the lower or ground states by emitting photons. This allows the gas to lose its thermal energy and condense to form a dense gas cloud. The early formation phase of the first cosmological objects is dictated by the physics of a primordial gas (Fig. 2). Its thermal and chemical evolution specifies a few important mass scales, such as the Jeans mass at the onset of collapse.

Before describing the physics of primordial star formation further in detail, it is worth discussing here the nature of dark matter and related cosmological implications. Although dark matter interacts with gas only through gravity, the particle nature of dark matter critically determines how and when early star-forming gas clouds are assembled. The standard cosmological model generally posits that dark matter consists of heavy elementary particles, which have very small random velocities in the early Universe (hence named cold dark matter). This means that dark matter can clump together by its self-gravity to produce numerous small objects, possibly even those of stellar/planetary sizes. If dark matter particles are light and stream fast with a substantial velocity dispersion, the matter density fluctuations are damped at smaller length scales than the particle free-streaming length. A smooth gas distribution is realized in such “warm” dark matter models, and star-forming gas clouds tend to be formed and aligned in a filamentary structure, rather than being embedded in dark matter halos. The fragmentation
of such filaments can lead to the formation of star clusters including stellar binaries. Essentially the same features are found in a theoretical model with extremely light dark matter. Understanding the differences originating from the small-scale clustering of dark matter opens an intriguing possibility that future observations of the distribution of the first stars can probe the particle nature of dark matter.

4. Protostar formation

Cosmological hydrodynamics simulations have been used extensively to study the distribution and the statistical properties of primordial star-forming clouds. In this section, we describe in detail the evolution of a gravitationally collapsing pre-stellar gas cloud. There are multiple steps from a cloud to a star, which are all explained in terms of microscopic physical processes.

One-dimensional hydrodynamics simulations of spherical gas collapse show that the overall evolution is well described by a self-similar collapse model. Recently, three-dimensional cosmological simulations were performed by several groups. They achieve a large dynamic range, and do not assume any a priori equation of state for the gas, unlike many other hydrodynamics simulations of different kinds. Instead, the simulations incorporate primordial gas chemistry and associated radiative processes, and the thermal evolution is followed in a direct manner.

To a good approximation, a primordial gas cloud contracts roughly isothermally through a number of atomic and molecular processes. Figure 2 shows that the gas density increases over twenty orders of magnitude from a diffuse gas to a protostar, whereas the temperature increases only by a factor of about ten. The thermal evolution can be described in terms of physical processes as follows. The collected primordial gas in a small dark halo first cools by molecular hydrogen cooling to a temperature of a few hundred Kelvin. A sufficient amount of molecular gas is accumulated at the halo center, and the gravitational Jeans instability sets in when the particle number density reaches \( n \approx 10^4 \text{ cm}^{-3} \). At lower densities, the molecular cooling rate is proportional to the density squared, because hydrogen molecules can be rotationally excited by two-body impacts with other atoms and molecules. At \( n \approx 10^4 \text{ cm}^{-3} \) the level population of hydrogen molecules is set by the local thermodynamic equilibrium, rather than by collisional excitation and the subsequent radiative de-excitation, and then the molecular hydrogen cooling rate saturates. The characteristic mass of the cloud at this density is given by the Jeans mass,

\[
M_J \approx 500 M_\odot \left( \frac{T}{200 K} \right)^{3/2} \left( \frac{n}{10^4 \text{ cm}^{-3}} \right)^{-1/2}.
\]

The cloud thereafter undergoes run-away collapse. In the contracting gas cloud core, a series of thermal and
chemical processes operate to keep the temperature roughly constant at around 1000 Kelvin, while the density continues increasing. Rapid three-body reactions convert almost all of the hydrogen atoms to molecules at a density of $n \sim 10^{10} \text{cm}^{-3}$. When the central density reaches $n \sim 10^{18} \text{cm}^{-3}$, the gas becomes optically thick even to continuum radiation in infrared, and radiative processes cannot cool the gas any more. Only one possible cooling mechanism is chemical cooling through the dissociation of hydrogen molecules, but this cooling operates only temporarily until full-scale dissociation. Afterwards, adiabatic contraction quickly heats the gas to above several thousand Kelvin. In the final phase, the central core contracts very slowly owing to the increasing thermal pressure, and hydrodynamic shocks are generated at the surface where supersonically infalling gas is suddenly stopped. A protostar is formed at this moment. It has a small mass of about one percent of that of the Sun, which should be compared with the cloud mass of about five hundred solar-masses (Equation [3]). The central particle number density of the protostar is $\sim 10^{21} \text{cm}^{-3}$ and the post-shock temperature is higher than 10,000 Kelvin.

A critical issue is whether or not a star-forming gas cloud undergoes fragmentation to yield multiple protostars. Chemo-thermal instability can be triggered when rapid chemical reactions and gas cooling drives the cloud core to contract further. Direct three-dimensional simulations show that, throughout the pre-stellar collapse phase, density perturbations grow only slowly compared to the gravitational collapse. Hence, the cloud core does not fragment into multiple clumps, but its collapse is accelerated by the chemo-thermal instability.

In the later accretion phase after the central protostar is formed, gravitational instability can trigger fragmentation in the circumstellar disk. The process shall be discussed in the next section in the context of low-mass star formation. It is worth summarizing here the physical conditions under which primordial protostars are formed. The facts that the cloud does not fragment, that the gas temperature is high, and that there is little source of opacity such as dust, all suggest favourable conditions for the formation of massive, even very massive, stars in the early Universe. The second condition suggests that, to first order, the gas mass accretion rate ($\dot{M}$) scales with temperature ($T$) as $\dot{M} \sim T^{3.5}$. Hence a large accretion rate is expected in a “hot” primordial gas cloud. The third condition implies that radiation from the central protostar does not significantly affect gas accretion. The final stellar mass is actually set when the growth of a protostar ends, and thus the remaining key question is whether or not, and how, gas accretion is stopped.

5. The mass of the first stars

The fundamental property of a star is its mass. A star’s luminosity, lifetime, and the final fate are determined by its mass. Hence, the characteristic mass or the mass distribution of the first stars is of primary interest and importance. Unfortunately, there are no direct observations of the first stars, whereas it is extremely difficult to predict the mass of a primordial star from only theory and computer simulations. The gas mass accretion rate onto a protostar is a critical element, but it is determined by the complex interplay of the accretion process through the circumstellar disk and protostellar feedback effects. Photoevaporation of the surrounding gas is thought to be a decisive process to halt gas accretion. In order to determine the final stellar mass, one needs to follow a long-term evolution of a protostar until the main-sequence phase for over one hundred-thousand years.

A semi-analytic model of protostellar evolution suggests that a primordial protostar can grow to be typically as massive as 100–200 solar-masses, but the final mass depends on the initial angular momentum of the infalling gas and the contraction time scale of the central star itself. The first radiation-hydrodynamics simulation of protostellar evolution is presented in ref. 30. In their simulation, a growing protostar exerts strong radiation feedback to the surrounding gas, and terminates the gas mass accretion when its mass is about $40 M_\odot$. Strong radiation from the central protostar also affects the dynamics and the gravitational stability of the circumstellar disk.

The environmental dependence of the stellar mass has been explored by a large set of simulations of star-forming gas clouds located in a cosmological simulation. The result shows a wide mass distribution extending from 10 to 1000 solar-masses (Fig. 3). The derived distribution, however, should not be regarded as being an estimate of the initial mass function, because it represents the sum of stars formed in different gas clouds (halos), rather than that of multiple stars formed in a single cloud. Nevertheless, the wide mass distribution, or the diversity in the evolution process, can be tested, or at least compared, with observations.
One can infer the mass of an “ancestor” primordial star from the elemental abundance pattern of a second-generation star. Promising candidates of such second-generation stars are ultra-metal-poor or hyper-metal-poor stars recently discovered in the Galaxy. For example, SMSS J031300.36-670839.3 is the most iron-poor star known to date, whose peculiar elemental abundance pattern suggests that the progenitor primordial star had a mass of 60 times that of the Sun, and died as an energetic supernova. The underlying assumption is that a single supernova enriched with heavy elements the parent gas cloud from which the metal-poor star was born. Similar observations for several other low-metallicity stars are available; the collected results are shown in Fig. 3. The number of samples is still small, but so far the theoretically derived wide mass distribution appears to be consistent. Systematic studies of a number of metal-poor stars and the analyses of the abundance patterns will allow us to infer the mass distribution of the first stars in the Universe.

There is an intriguing possibility that low-mass stars are formed from a primordial gas. Gravitational instability of the circumstellar disk around a protostar triggers fragmentation. This process may lead to the formation of low-mass stars, but such small fragments do not necessarily remain small while orbiting and migrating in a dense gas disk. However, technically it is difficult to determine the fate and the final mass of such fragments. There is an observational constraint on the formation efficiency of low-mass primordial stars. The lack of evidence for zero-metallicity stars in our Galaxy, despite decades-long searches, already suggests that there are only a small number of, if they ever existed, low-mass zero-metallicity stars. Future surveys of metal-poor stars that examine millions stars hold promise to place tighter constraints on the formation of low-mass primordial stars.

6. The first light

The first generation of stars transform the Universe from a simple state with darkness to a complex one, but with light and heavy elements. The first stars emit ultra-violet photons and ionize the surrounding gas. The inter-galactic medium (IGM) becomes a plasma from its initially neutral state (after recombination), and it also becomes warmed up. This process is called cosmic reionization, which is currently a topical subject of numerous studies, both theoretical and observational ones, in modern cosmology.

Observations of polarization of the cosmic microwave background radiation suggest that the IGM is largely ionized at an epoch as early as $z \sim 10$. Star-forming galaxies in the early Universe...
are thought to be the major sources that drive reionization, but most likely it is individual massive primordial stars that initiated the process. Interestingly, the farthest galaxies detected to date show distinct metal line emission features, and thus they are thought to have already been well-developed when the age of the Universe was several hundred million years.\textsuperscript{39} There must have been significant star-formation activities at an even earlier epoch.

Massive stars synthesize a substantial fraction of their mass into heavy elements both during and at the end of their lives. The subsequent supernova (SN) explosions disperse the heavy elements while “polluting” the IGM.\textsuperscript{40} Also, SNe are plausible sources of high-energy photons and cosmic rays, neutrinos, and gravitational waves. Even a trace amount of heavy elements such as carbon, oxygen and iron promotes radiative cooling in a gas cloud,\textsuperscript{41} and also enables the formation and growth of dust grains that in turn enhances further gas cooling at high gas densities. Hence, the heavy element content affects, and can even regulate, star formation in a low-metallicity gas. It has been suggested that there is some critical metallicity, above which the formation of low-mass stars is enabled. This is, however, still a matter of debate. Small mass fragments can be formed even in a purely primordial gas cloud (Section 5), whereas efficient radiative cooling in a low-density gas mediated by atomic carbon and oxygen does not necessarily lower the Jeans mass to sub-solar masses (see Equation [3]). Identifying the decisive process that promotes the formation of low-mass stars remains as an outstanding challenge.

Altogether, the first stars play a vital role in setting the scene for galaxy formation. In the standard cosmological model, the first galaxies are assembled in a hierarchical manner, through mass accretion and mergers of smaller objects. Then strong turbulence is generated dynamically, which likely changes star-formation process from a quiescent one to highly complicated, but organized one. Combined effects of strong turbulence and metal-enrichment may drive the mode of star formation to be close to that in the present-day star-forming regions.\textsuperscript{42}

7. Origin of super-massive blackholes

The origin of super-massive blackholes (SMBHs) that reside at the centers of virtually all galaxies is largely unknown. The apparent tight correlation of the BH mass and the host galaxy’s bulge mass suggests that BHs and galaxies evolved together through mutual interaction,\textsuperscript{43} but it remains almost a mystery how exactly the central blackhole \textit{shapes} the host galaxy that is much larger in size and mass. There is yet another, and even deeper, puzzle. The existence of many SMBHs at $z > 6$, when the age of the Universe was less than one billion years,\textsuperscript{44} poses serious challenges to the theory of BH formation and evolution. Massive BHs could have formed by, for example, collisions of massive galaxies,\textsuperscript{45} but it is unclear if the merger product can promptly build a central BH as heavy as a few billion times that of the Sun.

There are two major issues regarding the long-standing problem of SMBH formation: there must have been a seed BH, and there must also be physical mechanisms that drive the growth of such a seed(s). A natural seed candidate is the remnant of a massive primordial star. Theory of stellar evolution suggests that a star with mass greater than a few tens solar-masses leave a BH at the end of its evolution. If a very massive primordial star exceeding $\sim 300 M_\odot$ is formed, the whole star collapses gravitationally at the end of its life, and leaves a BH with the same mass. Hence, the first stars appear to provide timely seeds for the formation of SMBHs.\textsuperscript{46} However, it is known to be extremely difficult for such a seed to grow to be as massive as a billion solar-masses in a short period of several hundred million years. A variety of feedback effects of the first stars (see Section 2) make the surroundings of the remnant BHs unfavorable for efficient growth. This is considered to be a severe bottleneck of the initial growth of the seed BHs.

An alternative scenario is provided by the so-called Direct-Collapse Black Hole formation model. A massive, hot gas cloud can gravitationally collapse rapidly to yield a super-massive star in a short period of time.\textsuperscript{47} It is thought that such a hot gas collapses to a single central object without fragmentation, if its temperature stays at around 8000–10000 Kelvin. The question is how such a massive gas cloud can be kept hot. Plausible conditions can be realized if there exists a bright galaxy near a massive star-forming gas cloud. Intense ultra-violet radiation from the galaxy continues dissociating hydrogen molecules in the gas cloud to inhibit molecular cooling.\textsuperscript{48} Recent cosmological simulations show that, in a few rare cases out of many, there are massive gas clouds contracting near star-forming galaxies at $z \sim 15$.\textsuperscript{49}

There is yet another formation path of massive (seed) BHs proposed already in late 1970’s.\textsuperscript{50} At the center of a dense star cluster, stellar dynamical instabilities can drive run-away collisions of the stars,
and eventually produce an intermediate mass BH. This third possibility has not been explored as much as the other two formation scenarios. It has been suggested that some star clusters in the present-day Universe contain inter-mediate mass blackholes, perhaps as the products of run-away stellar collisions. A similar process might have occurred in the early Universe when the first star clusters were formed. Recent direct \(N\)-body calculations show that BHs with a mass of a few thousand solar-masses can actually be formed at the center of the first star clusters.

Before discussing the individual theoretical models of early blackhole formation, it may be appropriate to give a cautionary remark here. An intrinsic difficulty in understanding the formation of SMBHs is that there must not be a generic mechanism for a seed BH to grow efficiently. The number density of luminous quasars at \(z > 6\), which are believed to be powered by SMBHs, is very small, on the order of one per comoving giga-parsec volume. Hence, any successful model of SMBH formation must also explain the extremely small number density. All of the models introduced in the above present the possibility of seed BH formation, but additional conditions are often required; the radiation-driven DC model assumes the existence of a star-forming galaxy in the vicinity of the host gas cloud, whereas run-away stellar collisions occur only in initially very dense star clusters.

A completely different formation path is explored in ref. 56. Blackhole formation may be enhanced by supersonic gas flows in the early Universe. Baryonic acoustic oscillations that are manifested in the observed CMB temperature fluctuations induce relative motions of the gas with respect to dark matter. At the epoch of cosmological recombination, the soundspeed of the gas drops significantly, but the relative motions remain as supersonic gas flows and suppress gas condensation. Star formation in early dark matter halos is delayed until the host halos grow much larger in mass.

When heavy halos with \(M \sim 10^7 M_\odot\) are assembled, their strong gravity finally traps the streaming gas, and excess kinetic energy is quickly converted to gas random motions to generate turbulence (Fig. 4). The effective Jeans mass for a turbulent gas cloud is given by

\[
M_J = \frac{\pi}{6} \left( \frac{c_s^2 + \sigma^2}{G} \right)^{\frac{1}{2}} \frac{1}{\sqrt{\rho}},
\]

where \(\rho\) is gas density, \(c_s\) is the soundspeed and \(\sigma\) is the turbulence velocity dispersion. Strong turbulence raises effectively the cloud mass at the onset of gravitational collapse. The turbulent cloud collapse is thought to be a promising pathway to the formation of massive stars. In the early Universe, primordial stars formed in massive halos under the influence of supersonic gas flows can become as massive as a few...
to several hundred-thousand solar-masses. Such super-massive stars leave equally massive BHs, which can seed the formation of SMBHs at sufficiently early epochs.

**8. Prospects for future observations**

Many of the planned and ongoing large observational programs are aimed at detecting the first stars and galaxies. We conclude this article by discussing prospects for future observations.

One of the main targets of next-generation telescopes are the first galaxies formed in the first few hundred million years. Direct and indirect information concerning the first stars will be obtained from the first supernovae and γ-ray bursts (GRBs), the CMB polarization and spectral distortion, the near-infrared background radiation, and from the so-called Galactic archeology. In a longer term, radio interferometers will map out the distribution of the inter-galactic hydrogen in the early Universe.

Massive primordial stars are promising progenitors of energetic supernovae and associated GRBs at high redshifts. GRBs are the brightest explosions in the Universe, and are detectable out to redshift 10 and beyond. Recently, the *Swift* satellite has detected a GRB originating at z > 9, thus demonstrating the promise of GRBs as probes of the early Universe. Distant GRBs can be used as backlight to detect and measure the absorption line features in the spectra, from which the neutral gas fraction at different epochs can be probed.

*MJWST*, to be launched in 2021, will be able to discover many supernovae at z > 5. The key question is how to locate and identify such faint, but slowly varying transients. Infrared colors can be used to identify high-redshift supernovae. Recently, a class of very bright objects called super-luminous supernovae were discovered. While the exact explosion mechanisms and the power source are not yet known, it is generally thought that (very) massive stars triggers the super-luminous supernovae at their deaths. If massive primordial stars also explode in the same manner, they can be seen as long-lasting, extremely bright events. There is another possibility, that very massive primordial stars die as pair-instability SNe, among which the most distant one are expected to appear near-infrared sources with year-long variability.

The physical process of early star formation can be revealed through observations of Galactic metal-poor stars (Section 5). When and how such stellar relics were formed are encoded in the elemental abundance patterns. The mass distribution of the first stars can be statistically derived (Section 3), and a large sample of extremely metal-poor stars will allow us to study the details of the early chemical evolution of the Galaxy.

Redshifted 21-cm emission from neutral hydrogen is a direct probe of the topology of reionization. There are already some designated radio interferometers operating, such as *Low Frequency Array*, that can detect signals from the epoch of reionization. A combination of the 21-cm emission/absorption and the clustering of high-redshift galaxies can be used to study the distribution and the topology of reionized regions. Recently, the global 21-cm signature from the primordial gas at z ~ 18 was detected for the first time. In the near future, the superb sensitivity and spectral coverage of the planned *Square Kilometre Array* will allow us to generate a fine map of the distribution of neutral hydrogen in the early Universe, and will probe the cosmic Dark Ages when the first stars were born.

Understanding the formation of the first galaxies is challenging. This is where theoretical, *ab initio* approaches such as those introduced in this article, should match upcoming observations. Direct numerical simulations using state-of-the-art supercomputers will play an ever increasing role to interpret a wealth of data. A number of programs are being planned in the first observation cycle of *James Webb Space Telescope*. It is expected that the spectroscopic features of the first galaxies contain distinct signatures of the first stars and blackholes.

A concerted use of the future observational facilities, with the great help from theoretical studies, will finally fill the gap in our knowledge on the history of the Universe, and will shed new light on cosmology.

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Profile

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