# Part 5 The first stars/galaxies, EoR the multi-frequency studies

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# Formation of the First Stars and Blackholes

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**Abstract.** Cosmic reionization is thought to be initiated by the first generation of stars and blackholes. We review recent progress in theoretical studies of early structure formation. Cosmic structure formation is driven by gravitational instability of primeval density fluctuations left over from Big Bang. At early epochs, there are baryonic streaming motions with significant relative velocity with respect to dark matter. The formation of primordial gas clouds is typically delayed by the streaming motions, but then physical conditions for the so-called direct collapse blackhole formation are realized in proto-galactic halos. We present a promising model in which intermediate mass blackholes are formed as early as $z = 30$.

**Keywords.** Population III stars, super-massive blackholes, galaxies

## 1. Introduction

The nature of sources of cosmic reionization is largely unknown. Observations of the polarization of the cosmic microwave background radiation suggest the intergalactic medium is ionized at an epoch (called Epoch of Reionization [EoR]) as early as $z \sim 10$. Star-forming galaxies at $z = 6 - 10$ appear to be able to emit a sufficient amount of ultra-violet photons to reionize the IGM (Robertson *et al.* 2015). Most distant galaxies around $z = 6 - 7$ studied so far are well established (e.g., Inoue *et al.* 2016), with significant metal and dust content. There must have been a star formation episode at even earlier epoch.

There remains another important question of the origin of super-massive blackholes (SMBHs) in the early universe. The existence of extremely heavy BHs with masses exceeding $10^9 M_\odot$ poses a serious challenge to the theory of BH formation and evolution (Banados *et al.* 2016). A few mechanisms have been proposed for the formation of BHs with tens to a hundred thousand solarmasses as the seeds for SMBHs, but such models require peculiar conditions either in the formation process or in the growth and mergers of seed BHs. A crucial issue, often overlooked, is that there *should not* be a generic scenario for massive BH formation and efficient growth. The early SMBHs are very rare, with the inferred number density of about 1 per cubic giga-parsec volume. Hence, for a SMBH to exist at $z = 6 - 7$, there must have been an extraordinary process that is however physically possible.

The main driver of cosmic reionizaiton is thought to be star forming galaxies that have not been detected yet directly. However, *James Webb Space Telescope*, to be launched and in operation in 2019, has a capability of detecting exactly such galaxy populations. It is timely to study the properties of most distant galaxies by using a number of diagnostics such as hydrogen/helium lines, metal lines, and dust content. In this contribution, we present the results from recent large-scale simulations of early cosmic structure. We focus three relevant questions to the EoR: (1) the mass distribution of the first generation of stars, (2) the formation of massive blackholes, and (3) the nature of the first galaxies.

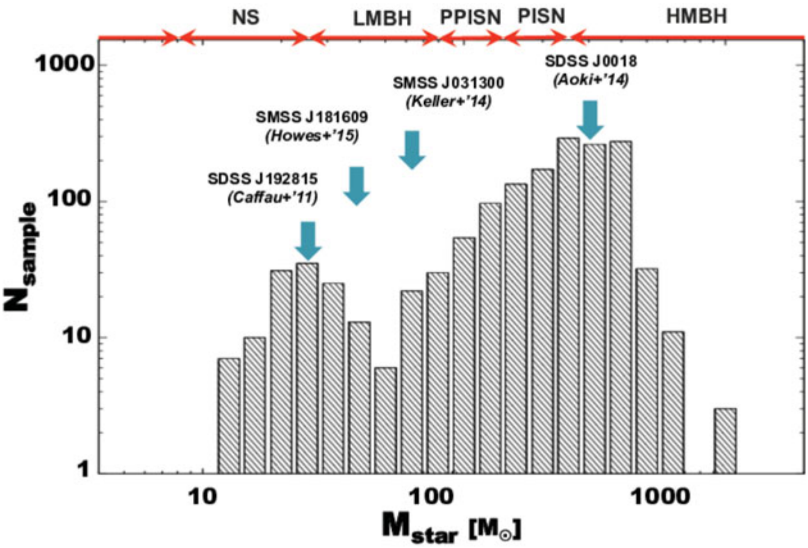

**Figure 1.** The mass distribution of the first stars derived from the simulations of Hirano *et al.* (2015). The arrows indicate the observationally inferred masses of the supernova progenitor stars that had enriched the gas cloud from which the respective second-generation, metal-poor star was born.

## 2. Structure formation in the early universe

We begin with a brief introduction to formation of the first cosmic structure in the context of the standard cosmological model based on cold dark matter and a cosmological constant. The standard model predicts that early structure forms via gravitational instability of tiny density fluctuations that are generated through a brief period of rapid expansion of the universe called inflation. The first baryonic objects are primordial gas clouds with masses of about $1000 M_\odot$ that are hosted by small-mass dark matter halos (Yoshida *et al.* 2003a). These first objects are formed typically at $z = 15 - 30$, but the formation epoch sensitively depends on the exact shape of the primordial density perturbation power spectrum and its amplitude.

Although the current observations cannot probe directly the earliest epoch of star formation nor the physical state of the intergalactic gas at Cosmic Dawn, observational constraints on them can potentially provide invaluable information on the nature of dark matter. Non-standard dark matter models predict different formation epochs, and abundances and clustering amplitudes of primordial gas clouds. Such variants include warm dark matter (Yoshida *et al.* 2003b), ultra-light dark matter (Hirano *et al.* 2018), and annihilating dark matter (Valdes *et al.* 2013). Future 21 cm observations hold promise to probe the large- to small-scale structure of the intergalactic hydrogen and the distribution of reionization sources, and hence possibly to reveal the nature of dark matter (Cohen *et al.* 2017).

Regardless of the exact nature of dark matter, physics and chemistry of a primordial gas remains essentially the same, and the characteristic mass of the host dark halo and the formation epoch do not much affect primordial star formation. An exception is probably formation of filamentary gas clouds, realized either in warm dark matter models or under peculiar conditions in the standard model (Hirano *et al.* 2017), which may lead to interesting consequences including the formation of star clusters and massive star (hence blackhole) binaries.

The existence of early baryonic streaming motions, a consequence of purely cosmological origin, is suggested by Tseliakhovich & Hirata (2010), and its effects on first star formation have been studied extensively in the past several years. Owing the relative streaming velocity (SV) of gas with respect to dark matter, the baryon fraction of small mass dark halos is reduced (Naoz, Yoshida, Gnedin 2013). Primordial star formation is delayed typically by $\Delta z$ of a few, and thus the host dark halos grow to have slightly larger masses than predicted in simulations without SV. We discuss a very important effect in the context of blackhole formation later again in Section 4.

## 3. The mass distribution of the first stars

There have been a number of theoretical studies that address the important question of the characteristic mass of the first stars. Some authors argue that stars as massive as one thousand solar-masses can be formed (Omukai & Palla 2003, Yoshida *et al.* 2006), whereas others suggest that low-mass stars can be formed via circum-stellar disk fragmentation (Clark *et al.* 2011). There are two important physical processes that determine the final mass of a primordial star. One is fragmentation of the parent gas cloud, and the other is gas accretion onto a protostar. The former is largely governed by the detailed thermodynamics and chemistry in a primordial gas, whereas the latter is a hard radiation hydrodynamics problem.

Hirano *et al.* (2014) perform cosmological simulations of the formation and growth of primordial stars for more than one hundred samples of mini-halos. An even larger sample of the subsequent study of Hirano *et al.* (2015) shows a broad range of stellar masses from ten to a thousand solar-masses (Fig. 1). There are a variety of gas clouds with disk fragmentation and even with binary gas clouds. However, because of technical limitations. the evolution of only the primary, central star is followed in their calculations. It thus remains unclear whether or not low mass stars are formed in the star-forming gas clouds. It is necessary to follow the long-term evolution of small-mass fragments (protostars) under the influence of radiation from the central star. Susa *et al.* (2014) and Stacy *et al.* (2016) use sink particles to represent multiple protostars in their hydrodynamics simulations and follow their growth. All of these simulations show a broad range of mass "spectrum" of the first stars.

It would be fair to state that the formation of massive primordial stars with 10-1000 solar-masses may well be just a theoretical product. However, observations of the elemental abundance patterns of several Galactic extremely metal-poor (EMP) stars allow us to infer the masses of the progenitor stars which are thought to have chemically enriched the second-generation gas clouds. Namely, it is possible to determine the mass of the first generation of stars although in a model-dependent way. Recent results are shown in Fig. 1. The number of EMP stars is still small, but it is remarkable that the predicted broad range, or the diversity in the final stellar mass, is consistent with the observations.

There has been another interesting hint from the detection of gravitational waves. The existence of massive blackhole binaries provide strong evidence that there were conditions in the distant universe under which massive stars, even twins of them, were formed. This could be realized in a low-metallicity environment in general, but zero-metal, Population III stars are also promising candidates as progenitors of massive BHs.

## 4. The origin of early supermassive blackholes

Virtually all the realistic formation paths of supermassive blackholes have been suggested by Martin Rees already in late 1960's. In modern context, there are three promising

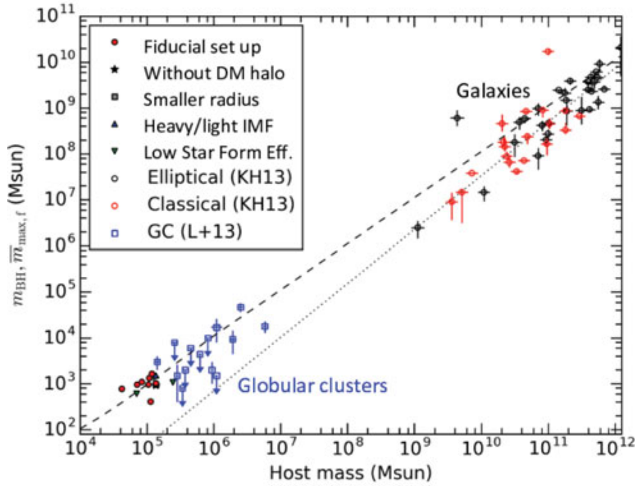

**Figure 2.** We plot the blackhole mass against host halo mass. Observational data are also over-plotted for ellipticals and classical bulges, and globular clusters. The IMBHs formed in the first star cluster simulations lie on the same relation, although at significantly lower mass scales (red circles in the lower-left portion), as SMBH-galaxies in the present-day universe.

pathways for the formation of seed BHs. The first path is the formation of stellar-mass BHs as remnants of the first stars, the second is via stellar collisions in dense star clusters, and the third is direct gravitational collapse of massive primordial gas clouds. The first path was advocated as one of the natural outcomes the formation of massive primordial stars (Madau & Rees 2001), but it was soon realized, after the standard model of early structure formation was explored, that strong radiative feedback processes of the first stars effectively evacuate the surrounding gas out of the shallow gravitational potential well of small mass dark halos. This 'self-termination' hampers the remnant stellar-mass blackholes from growing for a significantly long period of time. Thus the first path is disfavored in the hierarchical structure formation model. The second path is interesting in that essentially the same process might have occurred in some star clusters in the present-day universe (Ebisuzaki *et al.* (2001)). Katz *et al.* (2015) and Sakurai *et al.* (2017) study dynamical evolution of the first star clusters in a realistic cosmological context. Both the studies conclude that blackholes as massive as a thousand solar-masses can be formed via runaway stellar collisions at the center of dense star clusters (Fig. 3). The conclusion appears fairly robust, regardless of the details of the adopted stellar IMF, star formation efficiency, and the radii of low-metallicity stars that are highly uncertain.

The third path attracted much attention in recent years. The so-called direct collapse model posits that a primordial gas cloud irradiated by a nearby galaxy contracts nearly isothermall at a temperature of $\sim 8000-10000$ K. The key is suppression of molecular hydrogen cooling by photo-dissociation of the coolant, hydrogen molecules. Unfortunately, a few crucial conditions need to be met for the mechanism to work, and this fact makes the scenario rather uncertain. It is possible that the radiation-driven direct collapse is triggered in the early universe in, for example, a pair of nearby dark halos, but the model itself cannot predict the abundance or the overall occurance rate.

A promising scenario has been proposed by Hirano *et al.* (2017), who show that the early baryonic streaming motions drive the formation of massive blackholes. The key is surpression of star formation in early minihalos. In a region under a fast baryonic stream, small mass halos cannot trap the gas and hence gas condensation is delayed until a large

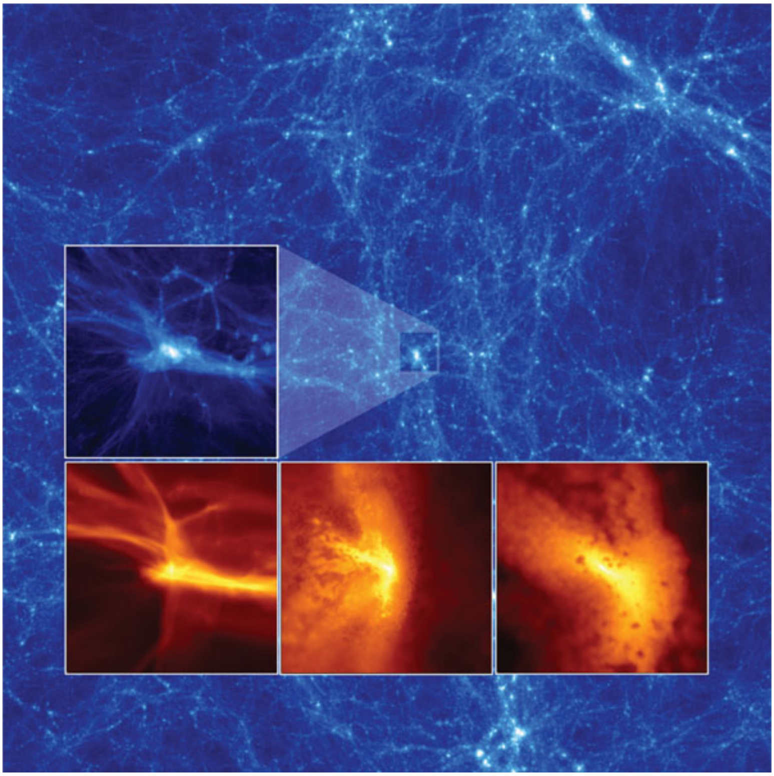

**Figure 3.** The large-scale dark matter distribution (background) and the gas distribution (lower insets) around the supermassive star in the streaming gas driven collapse model. The initial streaming velocity is set in the direction from left to right in the panels.

mass halo is assembled. The gas streams generate strong turbulence and the star-forming gas cloud collapses rapidly, to provide an excellent condition for massive star formation (Fig. 3).

Conventionally, the onset of molecular hydrogen cooling has been thought to be a failure of direct collapse, but the simulation of Hirano *et al.* 2017 shows that the cloud collapse continues in a highly complicated manner. Fragmentation of the collapsing cloud is suppressed by far-UV, photodissociating radiation from the central star, but the circumstellar disk fragments to yield many clumps. The importance of fragmentation is highlighted not by the possibility of the survival of low-mass fragments, but rather by causing stochastic accretion “bursts”. A series of accretion bursts with short time intervals keep the structure of the central star being that of highly bloated one (Sakurai *et al.* 2016).

In the streaming gas driven collapse model, the final stellar masses lie within the range of a few thousand to a hundred thousand solar-masses. Such massive accreting stars undergo gravitational collapse as soon as the central fuel – hydrogen – is exhausted in about a million years. Interestingly, Umeda *et al.* (2016) show that the so-called general relativistic instability is triggered during hydrogen-burning stage only in the extremely high accretion case. In the other cases, supermassive stars go through ordinary core evolution and collapse, when hydrogen is exhausted, to leave massive blacholes. Such intermediate mass blackholes formed at $z \sim 30$ are priomising seeds for the formation of supermassive blackholes at $z \sim 6 - 7$.

## 5. High-redshift galaxies and intensity mapping

Detecting and studying the most distant galaxies is a fundamental quest in modern astronomy. Conventionally, a combination of multi-band observations in optical and infrared have been used as a primary method to identify distant galaxies via the so-called drop-out technique. Recently, submillimeter observations with ALMA made a breakthrough by detecting metal lines such as $C_{\rm II}$ 158 $\mu$m (Aravena *et al.* 2016) and $O_{\rm III}$ 88 $\mu$m (Inoue *et al.* 2016). The bright $C_{\rm II}$ 158 $\mu$m has been an excellent target for ALMA detection, but initial attempts to detect the emission from known bright (but distant) galaxies left curious facts. Several star forming galaxies lie off from the empirical $C_{\rm II}$ luminosity - star formation rate relation. It could be attributed to an extraordinary low metal and dust contents of the galaxy, and the physical conditions of the $C_{\rm II}$ emitting regions are largely unknown yet. A pilot project of blind survey resulted in success; two plausible candidates are detected as possible high-redshift $C_{\rm II}$ emitters (Hayatsu *et al.* 2017). $O_{\rm III}$ 88 $\mu$m emission line may be a promising target because it originates from HII regions and because oxygen is also one of the most abundant heavy elements in the normal ISM. Locating high-redshift far-infrared line emitters is an important step forward to more detailed observations using JWST. Intensity mapping is a powerful technique to study the early galaxy population at EoR, which are likely the driver of cosmic reionization (Gong *et al.* 2011). So far, CO lines and $C_{\rm II}$ line are suggested as potential targets (see the contribution from G. Lagache to this volume), but it is conceivable that essentially the same technique can be applied to $O_{\rm III}$ intensity mapping at shorter wavelengths, or at higher redshifts.

## 6. Future observations

Direct observation of the first stars is yet to be achieved by future telescopes, but there have been already an array of indirect observations of early generation of stars. Elemental abundances of Galactic EMP stars provide invaluable information on the first generation of stars. Analyses so far suggest that the progenitor stars are typically massive, with masses of a few to several tens solarmasses (Fig. 2).

There was a hope that probing the reionizaion history through observations of the cosmic microwave background radiation would place tight constraint on the constribution from the first stars to early reionizaion. Unfortunately, the most recent measurement of the Thomson optical depth is rather low with $\tau = 0.65$, and hence it is difficult to infer the relative contribution from the first stars. Visbal *et al.* (2015) conclude that individual first stars in minihalos formed at $z > 10$ contributed little to global reionization. Ultimately, global 21cm signature can be used to probe the thermal state of the inter-galactic medium and hence star-formation at very high redshifts.

In 2015, Sobral *et al.* 2015 reported that a high-redshift galaxy without any signature of metal line was detected. The galaxy, named CR7 at $z = 7$, showed a prominent $He_{\rm II}$ line emission. Later detailed observations confirm, however, that CR7 consists of a few components and signatures of heavy elements are found (Matthee *et al.* 2017).

Cosmological simulations have been playing a vital role in theoretical study on the formation of the first stars. A standard picture is emerging that suggests that the first stars are formed in primordial gas clouds under the influence of early baryonic streaming motions. Radiation hydrodynamics simulations are capable of even predicting the final stellar masses. In future work, it is highly desired to follow the evolution of binary or multiple stellar systems. Such need is highlighted especially after the detection of gravitational waves from massive BH binaries. Finally, future space-borne gravitational wave observatories such as eLISA will be able to detect the signals from mergers of massive blackholes in the early universe (Salcido *et al.* 2016). It will be possible to discriminate a few models of seed BH formation and their growth.

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