Mem. S.A.It. Vol. 88, 671

Memorie della

The first stars: our evolving theoretical picture

V. Bromm

Department of Astronomy, University of Texas, 2511 Speedway, Austin, TX 78712, U.S.A.
e-mail: vbromm@astro.as.utexas.edu

Abstract. This brief review will discuss what we have learned about the formation, properties, evolution and death of the first stars, the so-called Population III (Pop III). It is crucial to embed the problem into its proper cosmological context, including insights into the particle-physics nature of dark matter. This is a good time to reflect on where we are, just ahead of the *James Webb Space Telescope (JWST)* launch, and of the imminent arrival of a suite of next-generation observational facilities. How can we test our emerging theoretical picture with observations both in-situ, at high redshifts, and in our local cosmic neighborhood? This may indeed be our main challenge for the near future, given that individual Pop III stars cannot be directly observed, unless we get very lucky, and catch them at the moment of their death as transient events. We therefore need powerful diagnostics that make use of an increasingly rich data set of indirect clues.

Key words. Cosmology: theory – Galaxies: formation – Galaxies: high-redshift – Stars: formation – Stars: Population II – Hydrodynamics – Galaxies: observations

1. Introduction

The end of the cosmic dark ages marks the fundamental transition in the history of the universe from the simple initial conditions of the inflationary fireball to a state of ever increasing complexity (Loeb & Furlanetto 2013; Wiklind et al. 2013). This great cosmic metamorphosis is specifically brought about by the formation of the first stars, the so-called Population III (Pop III), a few hundred million years after the Big Bang (Barkana 2016). When they finally appear on the scene, they crucially impact subsequent cosmic history through their copious emission of ionizing UV photons, thus initiating the prolonged process of reionization (Robertson et al. 2010), and through the production and dispersal of the first heavy chemical elements (Karlsson et al. 2013). The detailed physics involved is largely governed by the Pop III initial mass function (IMF). Although our picture remains incomplete and uncertain, a theoretical consensus has developed over the last decade, or so, leading to the current "standard model" of first star formation, positing that the primordial IMF was overall top-heavy (Bromm 2013).

The challenge now is to empirically test this emerging theoretical framework. This is a timely endeavor, given the imminent arrival of a suite of next-generation observational facilities. Immediately ahead is the launch of the *James Webb Space Telescope (JWST)*, providing us with unprecedented, sub-nJy imaging sensitivity in the near- and mid-IR. The adaptive optics (AO) enhanced spectroscopic capabilities of the extremely large ground-based telescopes, the GMT, the TMT, and the E-ELT, are ideally complementary to the *JWST* imaging. Excitingly, we already now are granted occasional "previews" into the very high-redshift frontier, such as with the gravitational lensing-amplified Hubble Frontier Fields, or with gamma-ray bursts (GRBs) at $z > 5$, detected by *Swift* (Toma et al. 2016). Indirectly, the Advanced-LIGO gravitational wave (GW) observatory is probing the coalescence of massive black hole binaries, some of them may be fossils of the first stars (see below). Further ahead, other frontier missions, such as the planned *Origins Space Telescope*, will continue to expand our horizon.

Francesco Palla has deeply touched many areas of astronomy. This is very much the case for the first stars field, as well. Indeed, he has been one of the initial pioneers of this exploration, going back to the "Palla-Stahler-Salpeter trilogy" of the 1980s, where a number of key ideas were first presented. Among them are the role of three-body reactions in converting the primordial gas into fully molecular form (Palla et al. 1983), and the protostellar and pre-main sequence evolution of stars under the peculiar conditions of the early universe, where temperatures are high and dust grains are absent (Stahler et al. 1986a,b). All of these ideas have stood the test of time. As many of the participants of this conference have recalled, this "trilogy" has served as the vital training set that got us started into first stars research, and we all hold these papers close to our hearts. Since then, Francesco has continued to make important contributions to the field, among them are the papers on primordial chemistry with Daniele Galli (Galli & Palla 1998, 2013), and the work with Kazu Omukai on the build-up process of massive Pop III protostars (Omukai & Palla 2001, 2003). The letter sequence in many regards constitutes an update to the original "trilogy", now taking into account the more recent advances in the underlying cosmological model.

The outline for this brief review is as follows. We will begin with a discussion of the Pop III formation physics, first within the context of standard cosmology, and then of non-standard ideas for the nature of dark matter. We will follow with some notes on how first star formation leads to first galaxy formation, a process which is governed by Pop III feedback effects, most crucially due to supernova (SN) explosions. We conclude with a quick survey of empirical probes of our theoretical picture.

2. Formation of the first stars

The key challenge here is to understand how primordial gas behaves when it collapses into newly virialized dark matter potential wells, where cooling and fragmentation proceeds in the absence of the metal coolants that dominate star formation in the interstellar medium of present-day galaxies. The only available coolants then are the rather inefficient H_2 molecule, and possibly the rare deuterium hydride (HD) one. It was realized a long time ago that this will result in primordial star forming regions that are significantly hotter than those in the present-day universe. This realization is ultimately behind the zero-order prediction that the first stars were typically more massive than their present-day counterparts, as the higher temperatures translate into larger Jeans masses (Bromm & Larson 2004).

Beyond that, the detailed physics of primordial star formation depends on the large-scale, cosmological initial conditions, including any assumptions on the particle physics nature of dark matter. If the cosmology is the ΛCDM model, now calibrated to high precision by the *WMAP* and *Planck* satellites, we arrive at the "standard model" of Pop III star formation. Part of ΛCDM is often the assumption that the dark matter is a WIMP-like particle, predicted by supersymmetry. Recently, however, cosmology has begun to explore alternatives to the WIMP dark matter, as direct detection experiments have failed so far to find any hints of the WIMP. Any non-standard ideas for the particle nature of dark matter impact the small-scale nature of cosmic structure formation, such that the initial conditions for Pop III star formation would also be modified, possibly greatly affecting the process. We will briefly discuss these two scenarios, standard and non-standard cosmology, in turn.

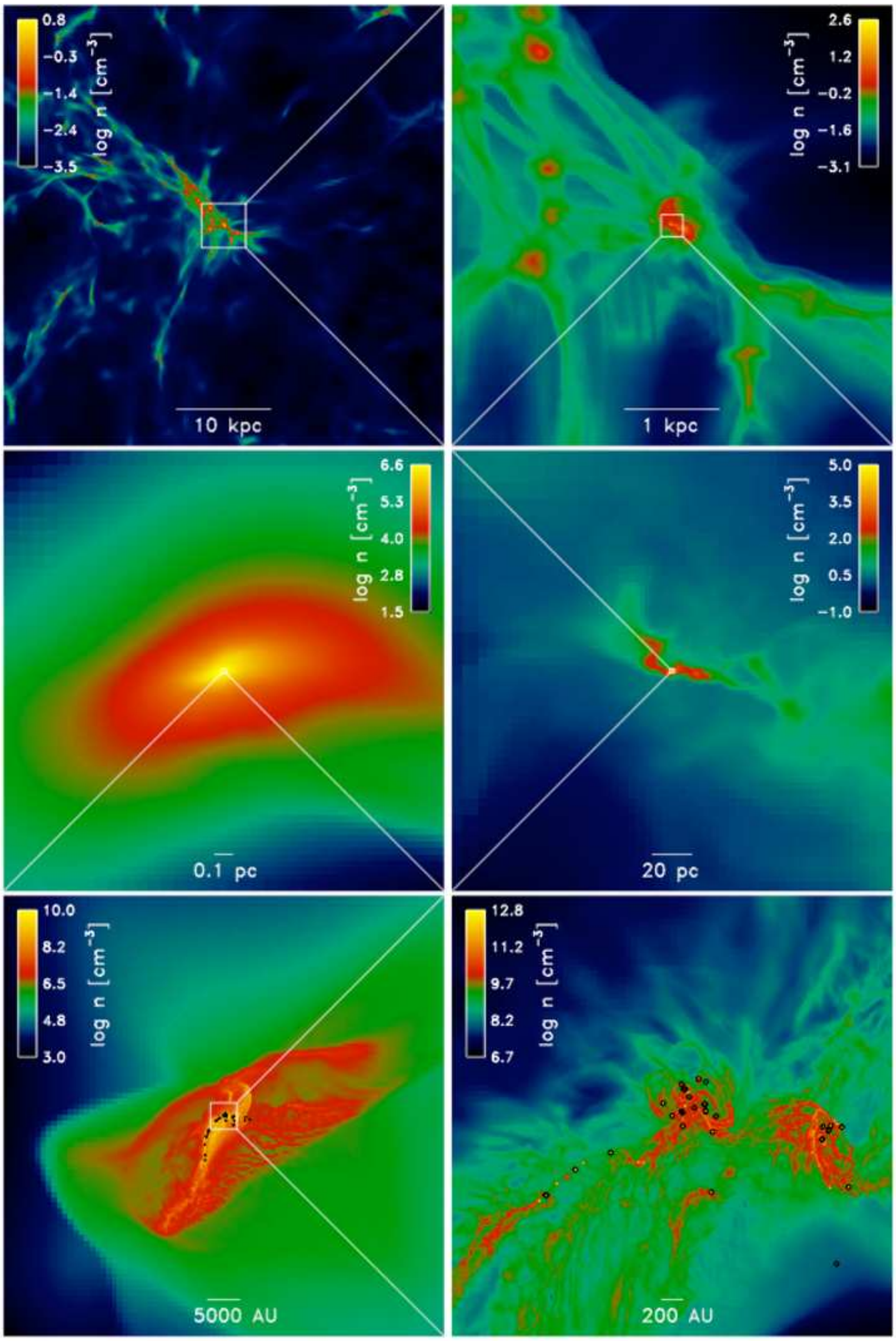

Fig. 1. Star formation inside the first galaxies (from Safranek-Shrader et al. 2014a,b). This zoom-in sequence shows how the initial generation of metal-enriched (Pop II) stars forms inside one of the first galaxies. The simulation spans an extreme range of scales, from the cosmological initial conditions at large scales (*top left panel*) to the scale of individual protostars (*bottom right panel*).

2.1. Standard model

Among the robust predictions of the "standard model" is that Pop III stars form inside of dark matter minihalos, with total (virial) masses of $\sim 10^6 M_\odot$ at redshifts $z \simeq 20-30$. A second, seemingly robust, element of this model has emerged more recently, stating that Pop III star formation is mediated via accretion disks that are inevitably driven towards gravitational instability (Clark et al. 2011; Greif et al. 2012). The first stars, thus, typically form as members of small multiple groups, including a high incidence of binaries (Stacy & Bromm 2013). Such stellar multiplicity in turn has crucial implications for the evolutionary pathways of Pop III stars, their modes of nucleosynthesis, and those of their deaths.

The current frontier of the formation problem is to determine the "end-game", the termination of the protostellar accretion process due to the radiative feedback exerted by the protostars once they begin to emit UV ionizing photons. This gets us into the regime of radiation-hydrodynamics, which still pushes existing computational resources to the limit. What we have learned so far is that negative radiative feedback is eventually effective in limiting the mass growth of Pop III stars, either by choking off the accretion disks (McKee & Tan 2008; Stacy et al. 2012; Hosokawa et al. 2011, 2016; Hirano et al. 2014), or by impacting the mass inflow via radiation pressure (Stacy et al. 2016). However, those processes cannot prevent the stars from becoming quite massive, resulting in typical masses of a few $10 M_\odot$, but with the possibility that growth might occasionally extend to $> 100 M_\odot$. Those terminal masses in turn determine the final fate encountered by a Pop III stars. Based on the current results, Pop III stars are thus predicted to typically die in a core-collapse SN, or a massive black hole (BH) remnant. In rare cases, they might also explode as pair-instability supernova (PISN), for progenitor masses in excess of $\sim 150 M_\odot$ (Heger & Woosley 2002).

The current standard model does not consider any magneto-hydrodynamic (MHD) effects. During the initial stages of collapse, where the weak primordial seed fields are not yet dynamically significant, this neglect is justified. However, dynamo action is likely to amplify magnetic fields at later stages of the accretion process, so that future simulations should be carried out in a full MHD context (Latif & Schleicher 2016).

2.2. Dark matter alternatives

Despite their many theoretically attractive features, supersymmetric WIMPs may not exist. In anticipation of such a possibility, particle physics is seriously exploring alternative scenarios to account for dark matter, including models that postulate a completely dark sector, where dark matter only interacts with normal matter via gravity. If that were the case, the only way to test such dark sector models is to figure out the astronomical, macroscopic consequences.

Recently, increased attention has been focused on models where the dark matter is constituted by ultra-light axions. Such ultralight particles would be endowed with quantum deBroglie wavelenghts of order a kpc, thus imprinting quantum effects onto the macroscopic scale of entire (dwarf) galaxies. In the context of cosmological structure formation, such models are termed *fuzzy* dark matter (FDM), and they are attractive, since they would naturally avoid some of the well-known small-scale problems of ΛCDM, by suppressing any sub-kpc structure in the dark matter distribution. As Pop III star formation is very sensitive to the DM small-scale structure, it is instructive to compare the host regions for Pop III within FDM and ΛCDM (Hirano et al. 2017). The result is that within FDM, first star formation occurs inside the filaments or sheets of the cosmic web, and not the roughly spherical halos of standard ΛCDM, with a much higher star formation efficiency.

3. Towards the first galaxies

When do *bona fide* galaxies, defined as long-lived stellar systems within the confining potential well of a dark matter halo, first arise, and what were their properties (Bromm & Yoshida 2011)? This question is intimately tied to the properties of Pop III stars, in particular their IMF. Since Pop III stars arise in DM minihalos, the emergence of the first galaxies is delayed to later times, and to more massive host halos within hierarchical, bottom-up structure formation. This delay is determined by the timescale over which a region can 'recover' from the negative feedback from Pop III star formation (Jeon et al. 2014). If this feedback is severe, such as in the wake of a hyper-energetic PISN event, second-generation star formation is delayed for 100 Myr, of order the local Hubble time, and there is a substantial delay before the first galaxies emerge. If the feedback, on the other hand, is less violent, such as for less energetic core-collapse SNe, recovery is 'prompt', and the first galaxies arise quicker, in less massive systems (Ritter et al. 2012). Thus, as it were, the Pop III IMF is mapped into the luminosity function of the first galaxies. And the latter can be measured, even if the Pop III IMF is beyond direct observational reach.

3.1. Second-generation stars

Once the first SNe disperse heavy chemical elements into the pristine intergalactic medium (IGM), the physics of star formation fundamentally changes. Subsequently, gas cooling can proceed more efficiently, and down to lower temperatures, provided that the enrichment exceeds a threshold value, termed the 'critical metallicity' (Bromm & Loeb 2003). Under such conditions, low-mass stars can form, and indeed the IMF is expected to transition from top-heavy to the 'normal', Salpeter-like bottom-heavy case. The precise threshold metallicity depends on the role of dust cooling, but any suggested values are so low that even a single Pop III SN event will render the local IGM 'super-critical' (Ji et al. 2014).

It is now possible, with efficient adaptive mesh-refinement (AMR) codes, to directly simulate the formation of Population II (Pop II) star clusters inside the first galaxies, out of the material that was previously enriched by Pop III SNe (see Fig. 1). This requires to cover a huge dynamical range in spatial scales, from the large-scale IGM of the cosmic web, to the scale of individual protostars, and simulations still need to impose idealizing simplifications, such as limits to the time that the protostellar accretion can be followed. However, the existing simulations already provide some key lessons. One lesson is that second-generation star formation is governed by supersonic turbulence, in difference from the sub- or transonic conditions in the Pop III minihalo case, but similar to the standard situation in present-day galaxies (Mac Low & Klessen 2004). Related to this, the IMF of the second-generation stars is already quite similar to the standard, bottom-heavy Salpeter-like case. Thus, we have the peculiar prediction that the stellar IMF is indeed near universal, and was already in place very early in cosmic history. The only exception would then be the 'singularity' of the initial Pop III case. The latter, however, would be effectively hidden from view, and may only manifest itself indirectly, in terms of observational probes (see below).

4. Observational probes

The theoretical framework for Pop III star formation is now being subject to an increasing number of observational tests. This is a truly exciting development, and it marks the transition to a mature field of astrophysics. One strategy is to look for signs of Pop III *in situ*, that is at high redshifts, close to their epoch of formation. This will be attempted with the *JWST*, in the planned deep field campaigns (Pawlik et al. 2011, 2013). The problem here, however, is that individual Pop III stars, or even the predicted small groups thereof, are too faint for direct detection. The possible exception is to catch a Pop III star at the moment of its violent death, as a hyper-energetic SN, or a GRB (Hummel et al. 2012; Whalen et al. 2013). To go beyond this serendipitous approach, a powerful alternative strategy is to probe for fossil remains of the first stars in the local universe, where observations can be carried out with high precision, and at moderate cost. This approach is sometimes termed 'stellar archaeology', or more generally, 'near-field cosmology' (Freeman & Bland-Hawthorn 2002). We will here briefly touch on two examples of the latter, fossil approach.

4.1. Gravitational wave sources

Since the initial discovery of gravitational waves (Abbott et al. 2016), the Advanced-LIGO detector has now detected three cases of massive BH-BH mergers. How can one account for the surprisingly large masses involved? A number of source origins has been suggested, including exotic scenarios, such as primordial BH dark matter. More conventional explanations invoke stellar pathways, either the capture of pre-existing BHs in dense stellar clusters, or the formation of massive binary progenitor systems that subsequently evolve into BH binaries. As a subset of the latter class of sources, it is intriguing to explore whether LIGO may even have detected fossils of Pop III stars. The inferred BH mass scale well resonates with the predictions for Pop III remnant masses; and a large fraction of Pop III stars is predicted to form in binaries (see the discussion above). When modeling the likely merger rate of such Pop III binary BHs as a function of cosmic time, however, the likelihood to account for the existing LIGO detections is less than 1 per cent (Hartwig et al. 2016; Belczynski et al. 2017). It would be difficult to uniquely infer a Pop III origin for any future LIGO source, unless the inferred masses would exceed $\sim 100 M_{\odot}$, in which case a Pop III interpretation would be near inescapable.

4.2. Stellar archaeology

One of the most promising ways to test the Pop III theory is to scrutinize the detailed pattern of chemical abundances in metal-poor stars in our immediate cosmic neighborhood (Beers & Christlieb 2005). Traditionally, the focus has been on the Milky Way stellar halo. More recently, a complementary approach has honed in on the lowest-luminosity satellite (dwarf) galaxies, the so-called ultra-faint dwarfs (UFDs). These systems sometimes comprise only a few hundred stars, so that in principle a census of their entire stellar content is within reach, in terms of obtaining high-resolution spectra. With the advent of the extremely-large ground-based telescopes (GMT, TMT, E-ELT), and their unprecedented spectroscopic capabilities, such surveys will become a reality. Such a complete census, impossible for the Galactic halo, would then also give us the complete picture of the chemical enrichment history of these primitive galaxies. Indeed, the most primitive of them may provide a true snapshot of "Pop III SN enrichment only" conditions, or "one-shot" conditions (Frebel & Bromm 2012).

This approach becomes truly exciting, rendering it into a version of high-precision cosmology, when coupled with state-of-the-art cosmological simulations of the assembly history of such small dwarf galaxies, 'one star at a time' (Jeon et al. 2017). With the simulations, we can translate any assumptions on the underlying Pop III IMF into detailed predictions for the stellar chemical content in the local dwarf galaxies. These predictions can then be compared with the rich spectroscopic data sets of future surveys. In an iterative cycle, we can thus infer the Pop III IMF in great detail and robustness. Stellar archaeology is clearly 'big data' science, and will thus benefit from all the developments in this ever accelerating endeavor.

5. Quo vadis?

Until now, the first star field has largely been dominated by theory, enabled and enhanced by supercomputer simulations. With the advent of the *JWST* and other next-generation facilities, the character of this pursuit will fundamentally change. We will soon enter a new phase of maturity, where observations and theory inform and propel each other. This will greatly accelerate the pace of discovery, and, crucially, it will provide wonderful opportunities for all of us to learn important lessons on how star and galaxy formation got going at the dawn of time. It will be extremely interesting to see how much our current theoretical framework has to change to accommodate this golden age of discovery.

Acknowledgements. This was a very special conference, pervaded throughout by the deep sense of gratitude that all of us feel for Francesco. I would like to thank the organizers for giving me the chance to be a part of this event. Support from NSF grant AST-1413501 is gratefully acknowledged.

References

Abbott, B. P., et al. 2016, Phys. Rev. Lett., 116, 061102
Barkana, R. 2016, Phys. Rep., 645, 1
Beers, T. C., & Christlieb, N. 2005, ARA&A, 43, 531
Belczynski, K., et al. 2017, MNRAS, 471, 4702
Bromm, V., & Loeb, A. 2003, Nature, 425, 812
Bromm, V., & Larson, R. B. 2004, ARA&A, 42, 79
Bromm, V., & Yoshida, N. 2011, ARA&A, 49, 373
Bromm, V. 2013, Rep. Prog. Phys., 76, 112901
Clark, P. C., Glover, S. C. O., Smith, R. J., et al. 2011, Science, 331, 1040
Frebel, A., & Bromm, V. 2012, ApJ, 759, 115
Freeman, K., & Bland-Hawthorn, J. 2002, ARA&A, 40, 487
Galli, D., & Palla, F. 1998, A&A, 335, 403
Galli, D., & Palla, F. 2013, ARA&A, 51, 163
Greif, T. H., Bromm, V., Clark, P. C., et al. 2012, MNRAS, 424, 399
Hartwig, T., Volonteri, M., Bromm, V., et al. 2016, MNRAS, 460, L74
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Hirano, S., Hosokawa, T., Yoshida, N., et al. 2014, ApJ, 781, 60
Hirano, S., Sullivan, J. M., & Bromm, V. 2018, MNRAS, 473, L6
Hosokawa, T., et al. 2011, Science, 334, 1250
Hosokawa, T., et al. 2016, ApJ, 824, 119
Hummel, J. A., et al. 2012, ApJ, 755, 72
Jeon, M., Pawlik, A. H., Bromm, V., & Milosavljević, M. 2014, MNRAS, 444, 3288
Jeon, M., Besla, G., & Bromm, V. 2017, ApJ, 848, 85
Ji, A. P., Frebel, A., & Bromm, V. 2014, ApJ, 782, 95
Karlsson, T., Bromm, V., & Bland-Hawthorn, J. 2013, Rev. Mod. Phys., 85, 809
Latif, M. A., & Schleicher, D. R. G. 2016, A&A, 585, A151
Loeb, A., & Furlanetto, S. R. 2013, The First Galaxies in the Universe (Princeton Univ. Press, Princeton)
Mac Low, M.-M., & Klessen, R. S. 2004, Rev. Mod. Phys., 76, 125
McKee, C. F., & Tan, J. C. 2008, ApJ, 681, 771
Omukai, K., & Palla, F. 2001, ApJ, 561, L55
Omukai, K., & Palla, F. 2003, ApJ, 589, 677
Palla, F., Salpeter, E. E., & Stahler, S. W. 1983, ApJ, 271, 632
Pawlik, A. H., Milosavljević, M., & Bromm, V. 2011, ApJ, 731, 54
Pawlik, A. H., Milosavljević, M., & Bromm, V. 2013, ApJ, 767, 59
Safranek-Shrader, C., Milosavljević, M., & Bromm, V. 2014a, MNRAS, 438, 1669
Safranek-Shrader, C., Milosavljević, M., & Bromm, V. 2014b, MNRAS, 440, L76
Ritter, J. S., Safranek-Shrader, C., Gnat, O., et al. 2012, ApJ, 761, 56
Robertson, B. E., Ellis, R. S., Dunlop, J. S., et al. 2010, Nature, 468, 49
Stacy, A., Greif, T. H., & Bromm, V. 2012, MNRAS, 422, 290
Stacy, A., & Bromm, V. 2013, MNRAS, 433, 1094
Stacy, A., Bromm, V., & Lee, A. T. 2016, MNRAS, 462, 1307
Stahler, S. W., Palla, F., & Salpeter, E. E. 1986a, ApJ, 302, 590
Stahler, S. W., Palla, F., & Salpeter, E. E. 1986b, ApJ, 308, 697
Toma, K., Yoon, S.-C., & Bromm, V. 2016, Space Sci. Rev., 202, 159
Whalen, D. J., Fryer, C. L., Holz, D. E., et al. 2013, ApJ, 762, L6
Wiklind, T., Mobasher, B., & Bromm, V. 2013, The First Galaxies (Springer, Berlin), ASSL, 396