# The Ultimately Large Telescope: What Kind of Facility Do We Need to Detect Population III Stars? 

Anna T. P. Schauer ${ }^{1,3}$ (1), Niv Drory ${ }^{2}$ (1D, and Volker Bromm ${ }^{1}$ (1)<br>${ }^{1}$ Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA; anna.schauer@utexas.edu<br>${ }^{2}$ McDonald Observatory, University of Texas at Austin, Austin, TX 78712, USA<br>Received 2020 July 6; revised 2020 September 24; accepted 2020 September 26; published 2020 November 27


#### Abstract

The launch of the James Webb Space Telescope (JWST) will open up a new window for observations at the highest redshifts, reaching out to $z \approx 15$. However, even with this new facility, the first stars will remain out of reach, as they are born in small minihalos with luminosities too faint to be detected even by the longest exposure times. In this paper, we investigate the basic properties of the Ultimately Large Telescope, a facility that can detect Population III star formation regions at high redshift. Observations will take place in the near-infrared and therefore a Moon-based facility is proposed. An instrument needs to reach magnitudes as faint as $39 \mathrm{mag}_{\mathrm{AB}}$, corresponding to a primary mirror size of about 100 m in diameter. Assuming JWST NIRCam filters, we estimate that Population III sources will have unique signatures in a color-color space and can be identified unambiguously.


Unified Astronomy Thesaurus concepts: Population III stars (1285); Early universe (435); Infrared telescopes (794)

## 1. Introduction

The current record-holding observation of a high-redshift galaxy was performed by Oesch et al. (2016), reaching $z \sim 11$ with a stellar mass of $M_{\star} \sim 2 \times 10^{9} M_{\odot}$ and a star formation rate of $\sim 25 M_{\odot} \mathrm{yr}^{-1}$. The upcoming James Webb Space Telescope (JWST) is targeting the first galaxies and expected to push this barrier to even earlier times. The JWST targets highredshift sources, as their emitted light is redshifted into the near-infrared (NIR) wavelength bands. JWST filters reach flux limits of a few nanoJanskys, thus opening up the observational window for galaxies out to a redshift of $z \geqslant 15$ (Gardner et al. 2006). Small galaxies with stellar masses of a few $\geqslant 10^{7} M_{\odot}$ will be detectable out to redshifts of $z \sim 12$ (Barrow et al. 2017; Ceverino et al. 2019) in relatively large numbers (e.g., 60 objects in a single deep pointing between $z=8$ and 11 ; Hainline et al. 2020).

However, to understand the formation of the first stars and the early universe as a whole, we need to observe so-called minihalos, the formation site of Population III stars with virial masses of $10^{5}-10^{7} M_{\odot}$ (Hirano et al. 2015; Schauer et al. 2019a). The luminosities of these objects are much smaller, and we expect a total mass in Population III stars of a few hundred to a few thousand solar masses (Xu et al. 2013; Hirano et al. 2014). None of the existing nor planned missions will be able to detect an individual minihalo with a standard Population III stellar mass (Zackrisson et al. 2011, 2015), even more massive first galaxies at $z \sim 8$ with $M_{\star}<10^{6} M_{\odot}$ are out of reach for JWST (Jeon \& Bromm 2019), unless observed during a starburst.
In this paper, we investigate what kind of telescope is necessary to observe such minihalos, and therefore the formation sites of Population III stars or star clusters. Two physical parameters are important: the number density of such minihalos, translating into constraints on the field of view, and the stellar properties that determine the luminosity of a single object, and our analysis will focus on them. With the nextgeneration Ultimately Large Telescope (ULT), the entire

[^0]cosmic star formation history would become accessible, completing astronomy's centuries old pursuit to push the frontier of the observable universe.

## 2. Minihalo Models

### 2.1. Stellar Populations

The mass of the first stars is still under debate. Earlier pioneering studies showed that a single, very massive Population III star forms per minihalo with masses reaching 300-1000 $M_{\odot}$ (Abel et al. 2002; Bromm et al. 2002). In more recent simulations, however, the central gas core exhibits a rotating disk that is breaking up into several lower-mass stars (Clark et al. 2011; Greif et al. 2011a; Stacy et al. 2016; see however Hirano et al. 2014). The resulting spectral energy distribution (SED) of the stars depends on additional input physics that is uncertain, such as the contribution from nebula emission (Zackrisson et al. 2011). To account for the different possibilities, we study a range of models, including two limiting cases for Population III:

1. Population III MS star. We assume that a single, massive star forms with a mass of $\sim 1000 M_{\odot}$, staying on the main sequence (MS) throughout. As the luminosity per stellar mass is approximately constant for stars $>100 M_{\odot}$ (Bromm et al. 2001b), it is unimportant if we have, say, three $300 M_{\odot}$ stars or one $900 M_{\odot}$ star. We use the spectrum in Bromm et al. (2001b), which does not take into account nebula emission.
2. Population III + nebula + evolution. To mimic a stellar population that is composed of very massive stars, we choose the Population III. 1 Yggdrasil model by Zackrisson et al. (2011) with an extremely top-heavy initial mass function (IMF), within $50-500 M_{\odot}$ and a Salpeter slope, including nebula emission, and the effect of stellar evolution.
3. Population II SED. For a Population II counterpart, we assume that a small cluster of stars forms with continuous star formation over 30 Myr in each minihalo. Here, we choose the Population II Yggdrasil model (Zackrisson
et al. 2011) with a Kroupa IMF between 0.1 and $100 M_{\odot}$, a covering fraction of $50 \%$ (equivalent to a nebula emission fraction of $50 \%$ ), and a metallicity of $Z=0.0004 Z_{\odot}$ (corresponding roughly to the critical metallicity $Z=10^{-3.5} Z_{\odot}$ that divides the Population III from the Population II formation regime; see Bromm et al. 2001a).
As the total mass in stars per minihalo varies, we have some fundamental scatter (which, in nature, also comes from different realizations of the IMF). For this proof-of-concept paper, we take a simplistic approach, where we set the fiducial mass per minihalo to $1000 M_{\odot}$, and assume that the stellar mass follows a logarithmically normal distribution with a standard deviation of 0.5 dex. As typical star-forming minihalos have a virial mass of around $10^{6} M_{\odot}$ (Schauer et al. 2019b), our fiducial star formation efficiency (SFE) is $0.1 \%$, with $95 \%$ of halos having an SFE between $0.01 \%$ (accounting for the single star case in a minihalo) and $1 \%$ (accounting for efficient SF). These numbers lie in the range of SF limits inferred from the 21 cm signal (Fialkov \& Barkana 2019; Schauer et al. 2019a).

The Population III MS star model is time independent. However, the two other models change their flux over time, as more massive stars have a shorter lifetime and the nebula reprocessing changes. Below, we show the flux either explicitly at defined times, or we consider average fluxes over the entire time evolution, e.g., when discussing the fraction of observable sources.

### 2.2. Number of Luminous Minihalos

For the number density of minihalos that currently host Population III stars, we have to rely on theoretical models. We take some of the most recent simulation results and work "backward" from a star formation rate density (SFRD) to obtain the number of luminous minihalos per redshift. We choose Jaacks et al. (2019, hereafter J19) and Visbal et al. (2020, hereafter V20), who present global Population III SFRDs based on their simulations (see the top panel of Figure 1). In their models, they assume a transition to Population II at critical metallicities of $10^{-4} Z_{\odot}$ and $10^{-3.5} Z_{\odot}$, values often assumed in the literature.

We can translate the $\operatorname{SFRD}, \Psi(z)$, into a comoving number density of halos with luminous Population III stars via

$$
\begin{equation*}
n_{\text {halo }}(z)=\Psi(z) \times t_{\star} / M_{\star}(z) \tag{1}
\end{equation*}
$$

where $t_{\star}$ is the stellar lifetime. We consider two values for $t_{\star}$ (Schaerer 2002): 20 Myr (lifetime of a $9 M_{\odot}$ star) and 3 Myr (lifetime of a $80 M_{\odot}$ star). For $M_{\star}(z)$ in J19, we take their fiducial average value of $M_{\star}^{\text {ave }} \sim 550 M_{\odot}$. V20 links the stellar mass to the halo mass, via $M_{\star}(z)=0.001\left(\Omega_{b} / \Omega_{m}\right) \times M_{\mathrm{vir}}(z)$. We retrace their steps for the minimum halo mass, and choose the most likely streaming velocity region of the universe with $v_{\mathrm{bc}}=0.8 \sigma$ (see, e.g., Fialkov 2014 for a review on streaming velocities).

The resulting halo mass functions of luminous halos are shown in the middle panel of Figure 1. We see a large spread in minihalo number density, which is mainly due to the two different star formation descriptions. While $M_{\star}$ is constant in J19, its mass increases by more than one order of magnitude in V20 for lower redshifts. The two models hence span a wide range of physical possibilities.

## 3. Observing Population III Stars

### 3.1. Field of View

We can translate the number density of luminous Population III halos, $n_{\text {halo }}$, into the expected number of luminous halos per square arcminute on the sky, $N_{\text {halo }}$. Integrating over the redshift interval $z_{1}$ to $z_{2}$, we have

$$
\begin{equation*}
N_{\text {halo }}=\int_{z_{\min }}^{z_{\max }} d z n_{\text {halo }} \frac{c(1+z)^{2} d_{A}(z)^{2}}{H_{0} E(z)} \Delta \Omega \tag{2}
\end{equation*}
$$

We show our results for the J19 and V20 data in the bottom panel of Figure 1. Even for the short lifetime of the $80 M_{\odot}$ star within the V20 model, we expect to observe more than 20 minihalos per square arcminute per unit redshift. Comparing, e.g., to the $\sim 10 \operatorname{arcmin}^{2}$ NIRCam field of view on JWST, we can conclude that there will be a large number of objects visible, and that the detection of minihalos will never be limited by too low a number of sources, as long as the ULT is able to probe sources that are faint enough.

### 3.2. Sensitivity

As a next step, we calculate the observed flux of our Population III stellar sources. As seen in more recent simulations (Chiaki et al. 2018), the ionization front around the central source hardly breaks out of the virial radius, and therefore the nebula reprocessing assumed in the Population III + nebula + evolution model is the more realistic case. The upcoming JWST is designed to probe sources at high redshifts with the NIRCam instrument (Rieke et al. 2005; Beichman et al. 2012). For simplicity, we adopt the same filters and assume the same filter throughput as in the NIRCam wide-field filters. We assume that the filter technology will only advance toward higher sensitivities, such that our results can be seen as conservative limits.

From the Yggdrasil- luminosities $L_{\lambda}$, we can infer the observed flux of the star or stellar population:

$$
\begin{equation*}
f_{\lambda}=\frac{L_{\lambda}}{4 \pi d_{c}^{2}(1+z)^{3}}, \tag{3}
\end{equation*}
$$

where $d_{c}$ is the comoving distance to redshift $z$. Applying the NIRCam-filter response functions, $R(\lambda)$, the integrated flux in the observed frame is

$$
\begin{equation*}
\left\langle F_{\lambda}\right\rangle=\frac{\int \lambda f_{\lambda} R(\lambda) d \lambda}{\int \lambda R(\lambda) d \lambda} \tag{4}
\end{equation*}
$$

As most sensitivity limits refer to specific frequency, we can translate our observed flux $\left\langle F_{\lambda}\right\rangle$ from wavelength to frequency space $\left\langle F_{\nu}\right\rangle$ via the pivot wavelength

$$
\begin{equation*}
\left\langle F_{\nu}\right\rangle=3.34 \times 10^{10} \mathrm{Jy}\left(\frac{\lambda}{\mu \mathrm{~m}}\right)^{2}\left\langle F_{\lambda}\right\rangle . \tag{5}
\end{equation*}
$$

We show the flux in the NIRCam filters as a function of redshift in Figure 2 for our three stellar models. For higher redshifts, the flux in the longer wavelength filters becomes the dominant component. To enable observations at redshift $z \geqslant 15$, one needs a filter with a wavelength of at least $\lambda \geqslant 2.0 \mu \mathrm{~m}$. The three different models vary by more than an order of magnitude in the expected flux. The Population III SED with a nebular contribution (middle panel of Figure 2) has


Figure 1. Top panel: population III SFRD from select simulations (J19 and V20; see the main text). We show both the original data (dotted lines) and after we applied a smoothing algorithm (solid lines). Middle panel: number density of luminous halos per comoving volume, derived from the SFRDs. Bottom panel: number of luminous halos per observed field of view, normalized to $1 \operatorname{arcmin}^{2}$.


Figure 2. Observed flux as a function of redshift for our three stellar population models. For the Population III + nebula + evolution and the Population II SED models, we include two (or three) time intervals: $0 \mathrm{Myr}, 3 \mathrm{Myr}$ (and 80 Myr ).
the highest flux. The stars without nebula (top panel of Figure 2) are less luminous at wavelengths larger than $\mathrm{Ly} \alpha$, and the Population II model that includes many less-luminous stars (bottom panel of Figure 2) is the faintest. As shown in Section 3.4, a telescope with a detection limit of $39 \mathrm{mag}_{\mathrm{AB}}$ can be feasible. Here again, we use the NIRCam-filter specifications for our estimates. For example, the F150 filter has a 0.17 lower magnitude limit than the F200 filter, so in our case,
$m_{\mathrm{AB}}^{200}=39$ mag leads to $m_{\mathrm{AB}}^{150}=38.83$ mag. The other filter we will base our predictions on is F444, with $m_{\mathrm{AB}}^{444}=37.965 \mathrm{mag}$.

In Figure 3, we show the density distribution of our three stellar models in color-magnitude diagrams for the neighboring filter pair F200 and F444 (top row) and for the distant combination of F150 and F200 (bottom row). One can immediately see that for both filter combinations, the majority of sources in the two Population III models can be observed (lie above the red solid line), whereas very few Population II sources are bright enough in both bands. As the dropout of the F150 filter occurs around $z \approx 13$ (see Figure 2), we show our sources in the redshift range $10 \leqslant z \leqslant 13$.

The estimated number of observable objects with ULT as a function of redshift can be seen in Figure 4. For the lower wavelength filters (left panels), the dropout happens around redshift $z \approx 12.5$, whereas the number remains roughly constant for the longer wavelength filters (middle panels). Both filter pairs combined (right panels) reflect the dropout at $z \approx 12.5$, and Population II sources are only visible for a short redshift interval around $z=11$. As noted before, the number of detectable Population II sources is much smaller than for either the Population III MS star or Population III + nebula + evolution model.
Finally, for further diagnostic power, we show a color-colordiagram in Figure 5. Our three models occupy distinct regions in this diagram, composed of the three filters F150, F200, and F444. The different positions of the two Population III models are mainly the result of the nebula emission that is present in the Population III + nebula + evolution model, but not in the Population III MS star one. With our two Population III models, we span the whole parameter space between maximal and zero nebula contribution. Both of these extreme cases can be detected with the ULT. With the proposed ULT, we can therefore distinguish between different Population III host environments. The Population II SED model lies between these extremes, and may thus masquerade as a Population III model with partial nebula reprocessing. However, as shown in Figure 3, the Population II sources have much lower flux, especially in the F200 filter.

### 3.3. Confusion from Other Sources

In addition to deriving the ULT capabilities for observing Population III stellar regions in minihalos, we need to make sure that the sources are unique and cannot be confused with other celestial objects. We evaluate a list of possible contaminants with literature data:

1. Population II galaxies. Population II galaxies are the first galaxies forming out of metal-enriched gas, and are typically more massive than minihalos. To first order, we can distinguish Population II galaxies by dint of their typically lower redshift with the dropout technique, e.g., $z \geqslant 9.8$ galaxies would drop out of the F 115 W filter (Hainline et al. 2020). For Population II stars forming in galaxies at similar redshift as the considered Population III models, we can use the color-color diagram of the Population II SED and compare it to the Population III MS star and Population III + nebula + evolution models. The Population II sources occupy a distinct region in color-color space, and are in addition much fainter than the two Population III models.


Figure 3. Color-magnitude density diagrams for our three models. The top row shows the longer wavelength filter combination of F200 and F444, the bottom row the shorter wavelength filter combination of F150 and F200. Here, we include the redshift interval $z=10$ to 13, as higher redshifts drop out of the F150 filter. Lower redshifts can be found toward the left of all panels, and higher redshifts toward the right. All sources above the solid red line would be observable with our proposed ULT.


Figure 4. Number density of luminous sources for the two SFRD models by Visbal et al. (2020) (top panels) and Jaacks et al. (2019) (bottom panels). On the left, we show the F150-F200 filter combination; in the middle, the F200-F444 filter combination; and on the right, the combination of all three filters.
2. Pair-instability supernovae (PISNe). Some of the brightest sources in the universe are single PISNe, with bolometric luminosities outshining an underlying Population III stellar population by a factor of $\sim 100$. The brightness of these sources declines rapidly, however, and $\sim 1 \mathrm{yr}$ after the explosion, they are indistinguishable from the underlying stellar population. Even with an
optimal strategy, 50,000 exposures per year of 600 s each are necessary to detect one PISN with JWST (Hartwig et al. 2018). Given that we target a small field of view, confusion with a PISN is highly unlikely.
3. Brown dwarfs. Due to their red color, brown dwarfs are a common contaminant for high-redshift sources. The number density of brown dwarfs is, similar to the PISNe


Figure 5. Color-color diagram of our three models, from $z=10$ (blue) to $z=13$ (yellow). The Population III + nebula + evolution and the Population II SED models consider stellar evolution and are therefore more spread out than the Population III MS star model. All three high-redshift models occupy distinct regions in this color-color diagram and can be distinguished. Overplotted in gray are very cloudy brown dwarfs from Saumon \& Marley (2008)—other brown dwarfs have a positive F200-F400 color and lie outside the range considered here.
discussed above, small. Assuming that there are 25-100 billion brown dwarfs in the Milky Way (Mužić et al. 2017), and that they follow the ratio of stars in the halo to stars in the whole Galaxy of $10 \%-30 \%$ (Pillepich et al. 2014), we can estimate their observed number density on the
$\Sigma_{\mathrm{BD}}=f_{\text {halo }} \times N_{\mathrm{BD}} / A_{\text {sky }} \approx 0.2 \times 5 \times 10^{10} /$
$(4 \pi \mathrm{sr}) \approx 70 \mathrm{arcmin}^{-2}$, lower than what is predicted by both J19 and V20. We calculate the colors in the NIRCam filters with models by Saumon \& Marley (2008). Only very cloudy brown dwarfs have a higher flux in the F200 than the F444 filter, mildly cloudy or noncloudy ones are too red to even appear in our colorcolor diagram in Figure 5. These very cloudy brown dwarfs show only a small flux difference in the F150 to F200 filter, and hence very few objects will occupy an overlapping region with the Population III + nebula + evolution model.

In summary, we expect the ULT to unambiguously detect Population III sources. We have investigated other sources, but they are either very rare or emit flux at lower wavelengths than minihalos at $z \geqslant 10$, and can thus be neglected here.

### 3.4. Technical Feasibility

From the previous sections we conclude that an instrument with a field of view of few $\operatorname{arcmin}^{2}$ and a sensitivity of $39 \mathrm{mag}_{\mathrm{AB}}$ for pointlike sources in the F150 and F200 bands will suffice to detect tens to hundreds of minihalos at redshifts $10-15$. The halos are $<1 \mathrm{kpc}$ in physical size, with the lightemitting region likely at least a factor of 10 smaller. Simulations show that the region of active star formation is $\ll 1 \mathrm{pc}$ (Greif et al. 2011b) while the size of the light-emitting HII region might reach 80 pc maximum size (Schauer et al. 2017). The angular scale at the redshifts of interest $(z \sim 15)$ is $\sim 3 \mathrm{kpc} \operatorname{arcsec}^{-1}$ and the diffraction limit for a 100 m aperture
is 5 mas at $2 \mu \mathrm{~m}$, or 15 pc . While the star-forming regions and the star clusters they contain will be unresolved, the nebular region at peak size might be just resolved by this largest of telescopes given perfect optics. For the purpose of this paper, we can assume that we are dealing with unresolved emission sources.

A telescope capable of reaching these limits has been proposed, for example, by Angel et al. (2008) in the form of a cryogenic liquid-mirror telescope on the surface of the Moon. However, as the authors mention, a liquid mirror might face some challenges, as it is unclear what effect lunar dust would have on the instrument and the observations.

To avoid an articulating mount, the telescope would be placed at the lunar pole, constantly pointing at the zenith. To assure thermal isolation, it would be located in the permanent shadow in a lunar crater. The limit on exposure time is then given by the precession of the Moon, and is of the order of several days. This can only be extended by the addition of some active tracking facility, for example, a moving prime focus platform. However, to reach the sensitivities we require, a mirror diameter of 100 m is necessary. We note that Angel et al. (2008) do consider mirror sizes of 20 up to 100 m in their preliminary design studies. While 100 m is evidently challenging, it is within the realm of possibility for mid-century technology.

## 4. Summary and Conclusions

In this paper, we have explored the requirements for a possible observation of Population III stars-thus providing a vista into the future beyond JWST. We find that we need to reach an $A B$ magnitude of $\approx 39$ in order to detect these first luminous objects in the universe, which would be possible with a 100 m diameter mirror on the Moon (Angel et al. 2008). The number density of Population III sources is very high, so even a small field of view of a few $\operatorname{arcmin}^{2}$ will be sufficient to
observe hundreds of minihalos. We find that a Population III stellar population with nebula emission can be observed more easily than a single, massive Population III star on the main sequence, and that both show distinct colors and magnitudes from contaminants such as Population II stellar populations and brown dwarfs.

In our analysis, we do not explicitly consider streaming velocities (Tseliakhovich \& Hirata 2010). These relative velocities between gas and dark matter vary over large (Mpc) scales and are known to offset the halo mass for star formation to larger masses (Schauer et al. 2019a). In regions of the universe with a high (low) streaming velocity, we expect an under (over) density of star-forming minihalos. These spatial variations are beyond the scope of this paper. In addition, we explore here two extreme cases for Population III stars with maximal and completely absent nebula emission. While the proposed ULT can detect both, more precise statistical predictions of nebula properties will lead to better predictions of the Population III observability and the optimal survey strategy, closer to the actual telescope design. A full radiativetransfer model of Population III sources is further beyond the scope of this study.

Another possibility to observe fainter objects can be achieved by strong gravitational lensing. Magnifications of factors of tens to hundreds could be reached at high redshift, and a Population III candidate object has recently been detected (Vanzella et al. 2020). However, the sky area with these high magnifications is very small, and-if at all-only a few objects would be observable within survey volumes as large as 100 $\operatorname{deg}^{2}$ (Zackrisson et al. 2015). With the proposed ULT, hundreds of Population III star-forming regions in minihalos are expected to be detected.

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## ORCID iDs

Anna T. P. Schauer (©) https://orcid.org/0000-0002-2220-8086

Niv Drory © https://orcid.org/0000-0002-7339-3170
Volker Bromm (©i) https://orcid.org/0000-0003-0212-2979

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[^0]:    ${ }^{3}$ Hubble Fellow.

