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Flash Ionization of the Early Universe by Population III.1 Supermassive Stars

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Abstract

The Population III.1 theory for supermassive black hole formation predicts that a substantial fraction of the early Universe was ionized by supermassive stars at redshifts $z \sim 20$–30, an era we refer to as "The Flash." This is followed by recombination to a mainly neutral state within a few tens of Myr. Here we discuss the implications of this ionization for the scattering optical depth of the cosmic microwave background (CMB), τ. We find a fiducial contribution of $\tau_{\rm PopIII.1} \sim 0.04$. Combining this with the contribution to reionization by standard galaxy populations at $z \lesssim 10$ with $\tau_{\rm gal} \simeq 0.06$, yields a total of $\tau \simeq 0.10$. As noted recently by several authors, such a value may help resolve apparent "problems" faced by ΛCDM of discrepant CMB-based measures of the Hubble constant ("Hubble tension"), as well as negative neutrino masses and dynamical dark energy that have been implied by recent baryonic acoustic oscillation results from the Dark Energy Spectroscopic Instrument. In addition, free–free emission from The Flash boosts the cosmic radio background, which could help explain the large 21 cm absorption depth reported by the Experiment to Detect the Global EoR Signature.

Unified Astronomy Thesaurus concepts: Reionization (1383); Early universe (435); Population III stars (1285); Cosmic microwave background radiation (322)

1. Introduction

The Population III.1 theory for supermassive black hole (SMBH) formation (N. Banik et al. 2019; J. Singh et al. 2023; V. Cammelli et al. 2025a; see J. C. Tan et al. 2024 for a review) predicts that a substantial fraction of the early Universe is flash ionized by rapidly expanding (R-type) H II regions powered by SMBH-progenitor supermassive stars at redshifts $z \sim 20$–30. These stars are born in "Population III.1" dark matter minihalos, i.e., with $\sim 10^6\,M_\odot$, which are defined to be the metal-free first-collapsed structures to form in their local region of the Universe such that they are not impacted by external feedback, especially ionizing feedback, from astrophysical sources (C. F. McKee & J. C. Tan 2008). Metal-free minihalos that have been ionized or partially ionized, i.e., "Population III.2" sources, are expected to have elevated abundances of H_2 and HD, catalyzed by the presence of free electrons, which enhance cooling and thus fragmentation in the minihalo (e.g., T. H. Greif & V. Bromm 2006). The process of weakly interacting massive particle (WIMP) dark matter annihilation in the Population III.1 protostar, which requires significant adiabatic contraction of the dark matter density in a slowly contracting undisturbed minihalo, can affect the stellar structure (D. Spolyar et al. 2008; A. Natarajan et al. 2009), in particular keeping the protostar in a large, relatively cool state (T. Rindler-Daller et al. 2015; D. Nandal et al. 2025), which then may allow it to avoid photoevaporation feedback that typically truncates accretion if there is contraction to the zero-age main sequence (C. F. McKee & J. C. Tan 2008; J. C. Tan et al. 2010; T. Hosokawa et al. 2011; S. Hirano et al. 2014; H. Susa et al. 2014). Thus, the protostar may be able to grow to $\sim 10^5\,M_\odot$, with this mass scale set by the baryonic content of the dark matter minihalo, followed by a phase of stellar evolution involving a high production rate of H-ionizing photons.

Key motivating features of the Population III.1 model include the prediction that all SMBHs form early in the Universe, i.e., by $z \sim 20$, as "heavy" seeds with $\sim 10^5\,M_\odot$ and with the ionizing feedback from pre-SMBH supermassive Population III.1 stars setting the cosmic abundance of SMBHs, with fiducial values of $n_{\rm SMBH} \sim 10^{-1}\,{\rm cMpc}^{-3}$ (M. J. Hayes et al. 2024; V. Cammelli et al. 2025b). We note that alternative models of heavy seed formation via "direct collapse" in metal-free irradiated or turbulent atomically cooled ($\sim 10^8\,M_\odot$) halos struggle to reach this level of abundance by several orders of magnitude (e.g., S. Chon et al. 2016; J. H. Wise et al. 2019; M. A. Latif et al. 2022; H. O'Brennan et al. 2025).

Another key feature of the Population III.1 seeding of SMBHs is that it can naturally explain why there appears to be a characteristic minimum mass scale of the SMBH population, i.e., a dearth of intermediate mass black holes (IMBHs) in the mass range $\sim 10^2$–$10^4\,M_\odot$ (e.g., J. E. Greene et al. 2020), or a break in the power-law distribution of SMBH masses below $\sim 10^6\,M_\odot$ (A. Mummery & S. van Velzen 2025), with this being related to the baryonic mass content of Population III.1 minihalos. On the other hand, models of SMBH formation via "light" seeds, especially via collisional growth in dense star clusters (e.g., M. A. Gürkan et al. 2004; D. R. G. Schleicher et al. 2022), tend to produce many more IMBHs than SMBHs.

As discussed by J. C. Tan et al. (2024), a key prediction of the Population III.1 seeding theory is the presence of ionized bubbles around Population III.1 supermassive stars at redshifts $z \sim 20$–30. Fiducial values of H-ionizing photon luminosities of $S \sim 10^{53}\,{\rm s}^{-1}$ from supermassive stars with WIMP-enhanced lifetimes of $t_* \sim 10$ Myr lead to R-type expanding H II regions that propagate into the intergalactic medium (IGM) for distances of $R_R \simeq 1.10 t_{*,10}^{1/3} S_{53}^{1/3}$ cMpc, independent of redshift. These regions that have been flash ionized are then no longer able to form Population III.1 SMBH progenitors, but rather much lower mass Population III.2 stars. However, while the particular sizes of the R-type H II regions impact the overall number density of SMBHs, i.e., given by $n_{\rm SMBH}= 3/(4\pi R_R^3) \rightarrow 0.18/(t_{*,10}S_{53})$ cMpc^{-3}, a generic feature of the model is that a large fraction of the Universe is ionized, regardless of the detailed properties of the Population III.1 stars, i.e., ionizing luminosities, lifetimes, and thus sizes of their H II regions. Thus, our primary goal in this Letter is to carry out a simple estimate, independent of detailed individual source properties, for the contribution of this predicted early phase of reionization to the scattering optical depth of cosmic microwave background (CMB) photons.

The later phase of reionization powered by "standard" galaxy populations has been modeled in many studies (e.g., B. E. Robertson et al. 2015; B. Greig & A. Mesinger 2017), with the general finding that the Universe transitions to a mostly ionized state around $z \sim 8$, with the process largely complete by $z \sim 5$. While these models contain a number of uncertainties, especially the assumed values of the initial mass function (IMF) of stars or properties of active galactic nuclei (AGN) that produce the ionizing photons and their escape fractions from their host galaxies to the IGM, they are guided and constrained by observations of galaxy populations. The particular model presented by B. E. Robertson et al. (2015) was mainly constrained by data probing the end of the reionization era, but it remains largely consistent with the latest James Webb Space Telescope (JWST) observations out to higher redshifts, $z \sim 10$, with the IGM neutral fraction approaching values close to unity by these redshifts (M. Tang et al. 2024; Y. Kageura et al. 2025; R. A. Meyer et al. 2025; A. Pahl et al. 2025; R. Ellis 2025, private communication).

The ionized IGM produced from these standard galaxy populations is found to contribute a scattering optical depth to CMB photons of $\tau_{\rm gal} \simeq 0.06$, which is consistent with the latest published results from the Planck Collaboration (Planck Collaboration et al. 2020), who found $\tau = 0.054 \pm 0.007$. A more recent analysis by R. de Belsunce et al. (2021) found $\tau = 0.063 \pm 0.005$. Parametric reionization histories that are fit to these CMB data indicate that reionization began at $z \sim 10$–12 and ended at $z \sim 5$.

However, a number of recent papers have argued for a larger value of $\tau \simeq 0.09$, i.e., significantly larger than the above CMB-inferred values (e.g., I. J. Allali et al. 2025; T. Jhaveri et al. 2025; N. Sailer et al. 2025). Such higher values would help alleviate tensions arising from CMB-based estimates of the Hubble constant (i.e., "Hubble tension") and from recent baryonic acoustic oscillation (BAO) measurements from the Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration 2025), which, combined with Planck CMB results, manifest as a preference for negative neutrino masses and evolving, i.e., dynamical, dark energy. However, as has been pointed out by the above authors, the measurement of τ from the CMB faces a number of challenging systematic uncertainties, i.e., instrumental systematic effects and astrophysical foregrounds, which might yet allow compatibility with a larger value.

If τ is in fact closer to 0.09, then it has major implications for the reionization history of the Universe. In particular, it would require an extra phase of ionization that is not specifically included in most current astrophysical models (e.g., B. E. Robertson et al. 2015) (see also Z. Haiman & G. L. Bryan 2006; E. Visbal et al. 2015). While models of so-called "double reionization" have been explored previously (e.g., R. Cen 2003; Z. Haiman & G. P. Holder 2003; J. S. B. Wyithe & A. Loeb 2003; S. R. Furlanetto & A. Loeb 2005), they generally treated an early Population III phase via simple extensions of normal galactic models, e.g., by varying the IMF (and thus the ionizing efficiency per baryon) and required simple parameterizations for the transition from Population III to Population II sources. Furthermore, various studies (e.g., Z. Haiman & G. P. Holder 2003; S. R. Furlanetto & A. Loeb 2005) concluded that a distinct early phase of reionization was unlikely because the transition from Population III to Population II would occur in a spatially inhomogeneous and temporally extended manner.

Given that the observed IGM ionization fraction is near unity at $z \sim 10$ (e.g., M. Tang et al. 2024), the results of S. R. Furlanetto & A. Loeb (2005) indicate that an early phase of increased IGM ionization fraction would require a very distinct high redshift population of ionizing sources. Population III.1 supermassive stars could be such sources, and since an early phase of flash ionization is a key feature and prediction of the Population III.1 cosmological model of SMBH seeding, we are thus motivated to present a first, simple calculation of its basic properties, including duration and expected contribution to τ.

2. Contribution to τ of Population III.1 Ionization in "The Flash"

We construct a simple model for reionization by supermassive Population III.1 stars. We assume these stars all form together at a redshift $z_{\rm form}$, which leads to a subsequent peak level of ionization in their H II regions, $f_{i,\rm peak}$, occurring at redshift $z_{\rm flash}$. These H II regions are assumed to fill a significant fraction of the volume of the Universe at this epoch, $f_{i,\rm vol}$. Based on the cosmological volume SMBH seeding models of N. Banik et al. (2019) and J. Singh et al. (2023) that explored and developed the Population III.1 scenario, we consider two cases: $z_{\rm flash} = 20$ and $z_{\rm flash} = 25$. Note that these values are constrained by the need to form enough Population III.1 sources to seed a cosmic population of SMBHs with $n_{\rm SMBH} \sim 10^{-2}$–$10^{-1}$ cMpc^{-3} (M. J. Hayes et al. 2024; V. Cammelli et al. 2025b), requiring isolation distance parameters in the range $d_{\rm iso} \simeq 50$–75 pkpc, i.e., $\simeq$1–2 cMpc at these redshifts. Similar results apply when the isolation distance is set to be equal to the H II region radius around Population III.1 supermassive stars (J. C. Tan et al. 2024; M. Sanati et al. 2025; M. Petkova et al. 2025, in preparation).

For our fiducial case, we will consider values of $f_{i,\rm peak} = 0.5$ and $f_{i,\rm vol} = 0.5$. We note there is simple linear degeneracy between these parameters for the total contribution to τ. However, in the context of the Population III.1 model, we require $f_{i,\rm vol}$ to be near unity. Similarly, H II regions undergoing R-type evolution are expected to have ionization fractions of order unity when the star is shining, since the mean free path of ionizing photons is relatively short, i.e., $\lambda_{\rm mfp} = (n_{\rm H}\sigma_{\rm p.i.})^{-1} = 9.0(n_{\rm H}/n_{{\rm H},z=30})^{-1}(h\nu/13.6 \quad {\rm eV})^3 \quad {\rm pc}$, where $\sigma_{\rm p.i.}$ is the photoionization cross section of H and we have normalized to the mean IGM density at $z = 30$, i.e., $n_{{\rm H},z=30} = 5.72 \times 10^{-3}$ cm^{-3}. However, after the star dies and is no longer a significant source of ionizing photons, the ionization fraction drops, even as the R-type H II region front is still expanding. So the average ionization fraction in the H II region at its maximum extent is expected to be moderately lower than unity.

The timescale for the ionization fraction to rise up to its peak value, $t_{\rm rise}$, is assumed to be intermediate between the lifetime of the ionizing source, i.e., with fiducial value of 10 Myr for the lifetime of a supermassive star that is somewhat prolonged by WIMP annihilation heating (see discussion by J. C. Tan et al. 2024), and the time to establish a Strömgren sphere, $t_{\rm ion}$, in gas that has a density similar to that of the mean IGM density. The value of $t_{\rm ion}$ assuming mean cosmic density is

$$t_{\rm ion} = \frac{4}{3}\pi R_S^3 \frac{n_{\rm H}}{S} = \frac{1}{\alpha^{(2)} n_{\rm H}} = 51.3\left(\frac{1 + z_{\rm form}}{31}\right)^{-3} {\rm Myr}, \quad (1)$$

where R_S is the radius of the Strömgren sphere, $n_{\rm H}$ is number density of H nuclei, $\alpha^{(2)} = 1.08 \times 10^{-13} T_{3e4}^{-0.8}\,{\rm cm^3\,s^{-1}}$ is the recombination rate to excited states of ionized H at a fiducial temperature of 30,000 K that is expected in metal-free gas, $S_{53} \equiv S/10^{53}\,{\rm s^{-1}}$, and the final calculation adopts the mean number density of H at $z = 30$. Note also that for simplicity, we have ignored the reionization of He. Population III.1 sources are expected to form in moderately overdense regions. For example, in the simulations of M. Sanati et al. (2025), the average density in the H II region around a Population III.1 supermassive star is a factor of about 3 times greater than the cosmic average. From such simulations of ionizing feedback, it is also seen that when $t_{\rm ion} > t_*$, the R-type ionization front continues to propagate after the star has ended its life. Given the above considerations, we adopt a fiducial value for $t_{\rm rise} = 30$ Myr. We note that this implies Population III.1 stars would actually have started shining at $z_{\rm form} \simeq 23$ and 30 for our cases of $z_{\rm flash} = 20$ and 25, respectively. We also note that $t_{\rm rise}$ can thus additionally be interpreted as encompassing a modest spread in formation redshifts of Population III.1 stars that is similar in magnitude to these differences.

After reaching a peak ionization fraction in The Flash, we assume this level then decreases exponentially on a timescale equal to the recombination timescale in the H II regions, i.e., given by Equation (1), but adopting an overdensity compared to the mean IGM of a factor of 3. Note, given the R-type nature of the H II regions, there is a limited impact on the density structure of the gas due to the ionizing feedback. For our cases of $z_{\rm flash} = 20$ and 25, these recombination times are 55 and 29 Myr, respectively.

For the above reionization histories, we then integrate along a line of sight to evaluate the contribution of each interval to the Thomson optical depth, τ. For this calculation, a helpful reference is that, given the Thomson cross section $\sigma = 6.6525 \times 10^{-25}\,{\rm cm^2}$, the contribution from each comoving Mpc of mean density IGM that is fully ionized is $d\tau = 3.7875 \times 10^{-4}\,{\rm cMpc^{-1}}$. Furthermore, the comoving radial distance from $z = 20$ to 30 is about 620 cMpc.

Figure 1 shows the contributions to τ from our two example Population III.1 models with $z_{\rm flash} = 20$ and 25. They have been added to the contribution from "standard" galaxies and AGN, as calculated by B. E. Robertson et al. (2015). A representative estimate for τ based on the analysis of Planck CMB data, i.e., $\tau_{\rm Planck} = 0.06 \pm 0.005$ (Planck Collaboration et al. 2020; R. de Belsunce et al. 2021), is shown by the lower shaded bar. A representative estimate for τ that is needed to alleviate negative neutrino masses and dynamical dark energy, i.e., $\tau_{\rm high} = 0.09 \pm 0.01$ (T. Jhaveri et al. 2025; N. Sailer et al. 2025), is shown by the upper shaded bar. We see that the example Population III.1 models give similar contributions of $\tau_{\rm PopIII.1} \simeq 0.04$, which then yields total values of $\tau \simeq 0.1$. Such optical depths are consistent with the estimates of $\tau_{\rm high}$ that are needed to resolve negative neutrino masses and dynamical dark energy.

We emphasize that the Population III.1 theory, which is astrophysically motivated to explain the origin of the entire cosmic population of SMBHs, predicts that there is an epoch of early flash ionization of the Universe (J. C. Tan et al. 2024). The models presented here have some uncertainties in their choice of $z_{\rm flash}$ and the combination of $f_{i,\rm peak}$ and $f_{i,\rm vol}$. However, we find that the variation from $z_{\rm flash} = 20$ to 30 leads to very minor differences in $\tau_{\rm PopIII.1}$. Furthermore, for $f_{i,\rm peak}$ and $f_{i,\rm vol}$, we expect values near and bounded by unity, thus motivating our choices of 0.5 for both. For completeness, we note that maximal values of $\tau_{\rm PopIII.1} = 0.16$ ($z_{\rm flash} = 20$) and 0.15 ($z_{\rm flash} = 25$) arise if both $f_{i,\rm peak} = 1$ and $f_{i,\rm vol} = 1$.

3. Conclusions and Discussion

We have presented an estimate for the contribution of Population III.1 supermassive stars to cosmic reionization as measured by the Thomson optical depth experienced by CMB photons. These Population III.1 sources, which are invoked as the progenitors of the entire cosmic SMBH population, are predicted to flash ionize a large volume fraction of the Universe to high ionization fractions at $z \sim 20$–30, in an era we term "The Flash." The duration of The Flash is set, approximately, by recombination of the IGM at these redshifts. The example models that we have presented, including variation of $z_{\rm flash}$ from 20 to 25, yield values of $\tau_{\rm PopIII.1} \simeq 0.04$. When added to the contribution from standard galaxies, $\tau_{\rm gal} \simeq 0.06$, the total optical depth is $\tau \simeq 0.1$. Such a value, while currently larger than allowed by the most recent analyses of Planck CMB data, has found some favor in its potential ability to resolve problems facing ΛCDM of the "Hubble tension," negative neutrino masses, and dynamical dark energy (I. J. Allali et al. 2025; T. Jhaveri et al. 2025; N. Sailer et al. 2025).

The model we have presented is very simple and highly idealized. It can be improved by detailed studies of individual H II regions around Population III.1 supermassive stars (M. Sanati et al. 2025) and semianalytic cosmic volume simulations that treat individual sources (M. Petkova et al. 2025, in preparation; M. la Torre et al. 2025, in preparation). In addition, the model should also be developed to include the contributions to reionization from Population III.2 sources and early-phase AGN, which here have been assumed to be negligible. If these sources make a significant contribution to reionization, then this would lead to a more complex, spatiotemporally extended reionization history, which would blur the two distinct phases shown in Figure 1, as well as leading to an overall increase in τ.

The $E-$mode CMB polarization power spectrum has some sensitivity to the redshift dependence of reionization history (e.g., C. H. Heinrich et al. 2017; M. Millea & F. Bouchet 2018). Future CMB polarization observations, e.g., with LiteBIRD (LiteBIRD Collaboration et al. 2023), are expected to be able to improve on such constraints and thus test the proposed Population III.1 reionization history. Furthermore, future studies of the CMB with the Simons Observatory

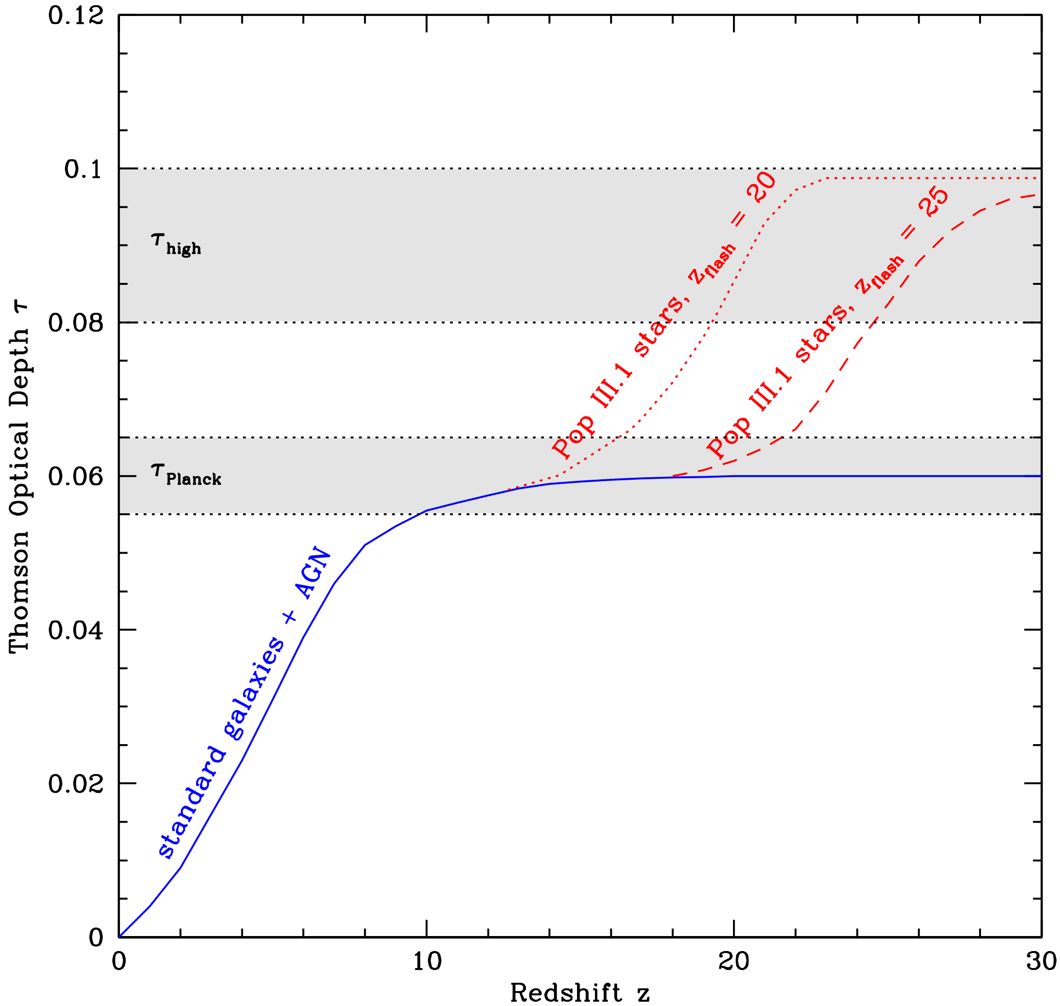

Figure 1. Thomson optical depth to electron scattering, τ, integrated out to redshift, z. The blue solid line is the estimated contribution from "standard" galaxies (B. E. Robertson et al. 2015) and AGN (although note AGN are expected to make only a minor contribution). The red dotted line shows the contribution from Population III.1 supermassive stars with epoch of peak flash ionization at $z_{\rm flash} = 20$. The red dashed line shows the corresponding model for $z_{\rm flash} = 25$ (see the main text). The lower gray shaded area shows $\tau = 0.06 \pm 0.005$, which is representative of values derived from most recent analyses of Planck CMB data (e.g., Planck Collaboration et al. 2020; R. de Belsunce et al. 2021). The upper gray shaded area shows $\tau = 0.09 \pm 0.01$ that is needed to alleviate negative neutrino masses and dynamical dark energy (T. Jhaveri et al. 2025; N. Sailer et al. 2025).

(P. Ade et al. 2019) will be able to further test the Population III.1 prediction of an early phase of flash ionization, especially via observation of the patchy kinematic Sunyaev–Zel'dovich (pkSZ) effect from the peculiar motion of the H II regions around these sources. We note that pkSZ constraints on reionization history, which have been found to be in 2σ tension with values of $\tau \simeq 0.09$ (C. Cain et al. 2025), assume a monotonically decreasing IGM ionization fraction with redshift and so these need to be reevaluated for the case of the Population III.1 scenario with a distinct phase of very early flash ionization. We note that the peculiar motions driving the pkSZ signal are reduced at higher redshifts, so the Population III.1 reionization scenario has the attractive feature of being able to boost τ in a way that minimizes additional pkSZ contributions.

The signatures of ionized bubbles and/or heating effects on neutral gas around Population III.1 sources may also be found in surveys of high-z 21 cm emission. Currently, only upper limits on the power spectrum of redshifted 21 cm brightness temperature fluctuations at $z \gtrsim 15$ have been reported. For example, in the redshift range $z = 19.8$ to 25.2, limits have been reported from the LOw Frequency ARray (LOFAR; M. P. van Haarlem et al. 2013) Low Band Antenna, with these constraints derived on spatial scales corresponding to wavenumbers of $k \sim 0.038\,h\,{\rm cMpc}^{-1}$ (B. K. Gehlot et al. 2019). At slightly lower redshifts, $z = 14.2$–16.5, upper limits from observations with the Murchison Widefield Array (S. J. Tingay et al. 2013) have been reported on scales $0.1h{\rm cMpc}^{-1} \lesssim k \lesssim 1\,h\,{\rm cMpc}^{-1}$ (S. Yoshiura et al. 2021). Using the New Extension in Nançay Upgrading LOFAR (NenuFAR; P. Zarka et al. 2012), limits have been found on emission from $z = 17.0$ to 20.3 on scales of $k \simeq 0.04\,h\,{\rm cMpc}^{-1}$ (S. Munshi et al. 2024, 2025). However, many of these current limits are thought to be mostly set by systematics, such as the impact of bright foreground sources (E. Ceccotti et al. 2025). The forthcoming Hydrogen Epoch of Reionization Array (Z. Abdurashidova et al. 2022) is expected to be able to detect 21 cm emission as far as $z \sim 28$ and may be able to determine if there is a characteristic size of early H II regions, expected to be ∼1 cMpc in the fiducial Population III.1 model. Similarly, the Square Kilometre Array LOW (L. Koopmans et al. 2015) is expected to be able to directly image neutral hydrogen from scales of arcminutes to degrees from $z \sim 6$ to 28, allowing detection of the power spectrum of the cosmological signal and the potential to make tomographic images of H II regions (e.g., M. Bianco et al. 2024).

Finally, the Population III.1 model may be relevant to the sky-averaged (global) 21 cm signal of neutral hydrogen from the early Universe. A tentative detection of this signal from $z \sim 13$ to 27 has been claimed based on analysis of data from the low-band antenna of the Experiment to Detect the Global EoR Signature (EDGES; J. D. Bowman et al. 2018; however, see S. Singh et al. 2022). The signal is centered at $z = 17.2$ and features an absorption depth that is at least twice as strong as predicted by standard astrophysical scenarios in ΛCDM. One potential resolution of this observation involves an enhanced radio background, equivalent to a brightness temperature of 67.2 K, i.e., significantly (≃18 K) greater than that of the CMB at these redshifts with $T_{\rm CMB} = 49.5$ K (e.g., C. Feng & G. Holder 2018; A. Fialkov & R. Barkana 2019).

Free–free emission from The Flash could make a contribution to such a background. The brightness temperature arising from path integrated free–free emission is $T_{B,\rm ff} = 1124\nu_{1.4\rm GHz}^{-0.118}T_{3e4}^{-0.323}[{\rm EM}/({\rm cm}^{-6}\,{\rm pMpc}]$ K, where the emission measure is defined as ${\rm EM} \equiv \int n_e n_p ds$. Evaluating $T_{\rm B,ff}$ with respect to average IGM densities at $z = 25$, for emission weighted overdensity clumping factor of $f_{\rm clump} = 10$, and integrating over a path length of 10 pMpc, yields: $T_{B,\rm ff} = 12.8\nu_{1.4\rm GHz}^{-0.118}T_{3e4}^{-0.323}\;f_{\rm clump,10}^{2}(s/10\;\;{\rm pMpc})[(1+z)/26]^6$ K. Integrating this free–free emission through the reionization histories described in Section 2 yields $T_{B,\rm ff} = 0.91$ and 2.9 K for $z_{\rm flash} = 20$ and 25, respectively. These values would double if we set $f_{i,\rm peak} = 1.0$ and $f_{i,\rm vol} = 0.25$, which keeps the same value of Thomson optical depth. Thus, given the sensitivity of the integrated free–free emission to H II region number density, i.e., $\propto f_{\rm clump}^2(1 + z_{\rm flash})^6$, this process could lead to a significant radio background that may help in the interpretation of the reported absorption signal from EDGES. Conversely, confirmation of the EDGES 21 cm absorption depth would place more stringent constraints on the Population III.1 model, in particular, favoring relatively early formation redshifts that result in higher density H II regions. This further motivates additional exploration of the Population III.1 flash reionization scenario, including its predicted free–free background, via more advanced numerical simulations.

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