Gravitational wave background from Population III binary black holes consistent with cosmic reionization

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ABSTRACT

The recent discovery of the gravitational wave source GW150914 has revealed a coalescing binary black hole (BBH) with masses of $\sim 30 M_\odot$. Previous proposals for the origin of such a massive binary include Population III (PopIII) stars. PopIII stars are efficient producers of BBHs and of a gravitational wave background (GWB) in the $10 - 100$ Hz band, and also of ionizing radiation in the early Universe. We quantify the relation between the amplitude of the GWB ($\Omega_{gw}$) and the electron scattering optical depth ($\tau_e$), produced by PopIII stars, assuming that $f_{\text{esc}} \approx 10\%$ of their ionizing radiation escapes into the intergalactic medium. We find that PopIII stars would produce a GWB that is detectable by the future O5 LIGO/Virgo if $\tau_e \gtrsim 0.07$, consistent with the recent Planck measurement of $\tau_e = 0.055 \pm 0.09$. Moreover, the spectral index of the background from PopIII BBHs becomes as small as $0.5$ at $f \gtrsim 30$ Hz, which is significantly flatter than the value $\sim 2/3$ generically produced by lower-redshift and less-massive BBHs. A detection of the unique flattening at such low frequencies by the O5 LIGO/Virgo will indicate the existence of a high-chirp mass, high-redshift BBH population, which is consistent with the PopIII origin. A precise characterization of the spectral shape near $30 - 50$ Hz by the Einstein Telescope could also constrain the PopIII initial mass function and star formation rate.

Key words: gravitational waves – black hole physics – stars: Population III

1 INTRODUCTION

Advanced LIGO (AdLIGO) announced the first direct detection of gravitational waves. The source, GW150914, is inferred to be a merging binary black hole (BBH) with masses of $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-3} M_\odot$ at $z = 0.09^{+0.04}_{-0.03}$ \citep{Abbott2016bbh}. The origin of such massive and compact BBHs are of astrophysical interest, and several pathways have been proposed for their formation. One channel is massive binary evolution in a metal-poor environment \citep{Bond1984, Belczynski2004, Kulczycki2006, Dominik2012, Kimura2016, Kowalska2016}, hereafter K14, K16; \cite{Belczynski2016}, including rapid rotation and tides \citep{Mandel2016}, or assisted by accretion discs in active galactic nuclei \citep{Bartos2016, Stone2016}. Alternative formation channels include stellar collisions in dense clusters \citep{PortegiesZwart2000, OLeary2016}, or the collapse of rapidly rotating massive stars \citep{Loeb2016}. Given the estimated BBH merger rate of $\sim 2 - 400$ Gpc$^{-3}$ yr$^{-1}$ \citep{Abbott2016bbh}, these scenarios may be distinguished in the near future by their chirp mass distributions.

Another way to probe the star and BH formation history of the Universe by GWs is via the stochastic background (GWB) from numerous unresolved BBH mergers. Here we focus on one promising source, binary Population III (hereafter PopIII) stars formed in the early Universe at $z \gtrsim 6$. PopIII stars are thought to be massive \citep{Bromm2011}, and references therein), and their binary fraction is expected to be at least as high as for present-day massive stars \citep{Stacy2013}. Thus PopIII stars may form massive BBHs effectively \citep{Bromm2011}. The vast majority of these BBHs merge at high redshifts and contribute to the GWB \citep{Kowalska2012}. A small minority merge after a delay comparable to the Hub-

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1 For the purposes of this paper, "PopIII" refers to any stellar population with unusually high typical mass, forming predominantly at high redshift ($z > 6$), and contributing to reionization at these redshifts. The IMF as a function of metallicity is poorly understood, and these properties may also be satisfied for an extreme "PopII" stellar population, enriched to low, but non-zero metallicity (e.g. $Z < 0.1 Z_\odot$; see \cite{KowalskaLeszczynska2016} \cite{Belczynski2016}).
ble time, inside the detection horizon of AdLIGO. Recent PopIII binary population synthesis calculations predicted the event rate at $z = 0$ to be $\sim 1 - 100 \text{Gpc}^{-3} \text{yr}^{-1}$, and the chirp mass distribution to peak at $\sim 30 \Msun$ ($\text{K14}$, $\text{K16}$), in near-perfect agreement with GW150914.

PopIII stars are also efficient producers of ionizing radiation in the early Universe. Recently, the optical depth of the universe to electron scattering was inferred from the cosmic microwave background (CMB) anisotropies by the Planck satellite to be $\tau = 0.066 \pm 0.016$ ($\text{Ade et al.} 2013$). This value is lower than previous estimates from WMAP (Komatsu et al. 2011), placing tight constraints on the formation history of PopIII stars ($\text{Visbal, Haiman & Bryan} 2011$, hereafter VHB15).

In this paper, we show that a PopIII BBH population that is consistent with the Planck optical depth measurement produces a GWB dominating over other BBH populations at $10 - 100$ Hz. As a result, the stochastic GWB may be detectable sooner than previously expected. We also find that the spectral index of the GWB due to PopIII BBHs becomes significantly flatter at $f \gtrsim 30$ Hz than the value $d \ln \Omega_{gw}/d \ln f \approx 2/3$ generically produced by the circular, GW-driven inspiral of less massive and/or lower-$z$ BBHs ($\text{Phinney} 2001$). This flattening can not be mimicked by eccentric orbits or dissipative processes, and could be detected by the observing run O5 by AdLIGO/Virgo. Such a detection would provide robust evidence for a high-chirp-mass, high-redshift BBH population, and would yield information about the initial mass function (IMF) and star formation rate (SFR) of PopIII stars, and about cosmic reionization.

2 MASSIVE BINARY FORMATION RATE AT HIGH-REDSHIFTS

2.1 PopIII stars ($z = 0$)

PopIII stars are the first generation of stars in the Universe, beginning to form from pristine gas in mini-halos with masses of $10^{5-7} \Msun$ at redshifts $z \sim 20 - 30$. These stars are likely to be massive, because of inefficient cooling via molecular hydrogen ($\H_2$), resulting in a top-heavy IMF covering the mass range $\sim 10 - 300 \Msun$ (e.g. $\text{Hirano et al.} 2014$). Massive PopIII stars produce a strong Lyman-Werner (LW) radiation background, which dissociates $\H_2$ in mini-halos and suppresses subsequent star formation (e.g. $\text{Haiman, Rees & Loeb} 1997$). Including this self-regulation, the history of early star-formation has been investigated in semi-analytical studies (e.g. $\text{Haiman, Abel & Rees} 2004$, $\text{Sobacchi & Mesinger} 2013$) and in cosmological simulations (e.g. $\text{Ricotti, Gnedin & Shull} 2002$, $\text{Ahn et al.} 2012$).

The Planck measurement of the optical depth from the CMB ($\tau = 0.066 \pm \Delta \tau_0$, where $\Delta \tau_0 = 0.016$ is the $1\sigma$ error; $\text{Ade et al.} 2013$) tightly constrains the PopIII star formation history. VHB15 estimated an upper limit on the total mass density of PopIII stars as $\rho_{\ast, \text{hi}} \sim 10^5 \Msun \text{Mpc}^{-3}$, consistent with the Planck result. They assumed a top-heavy IMF, with PopIII stars as massive as $\sim 200 \Msun$, for which the number of H-ionizing and LW photons perstellar baryon are both $\eta_{\ion} \simeq \eta_{\text{LW}} \simeq 8 \times 10^3$; the escape fraction of ionizing photons from mini-halos was assumed to be $f_{\text{esc,m}} = 0.5$.

We compute the dependence of $\rho_{\ast, \text{hi}}$ on $\eta_{\ion(LW)}$, $f_{\text{esc,m}}$ and $\tau_0$. We consider two cases for a flat and a Salpeter IMF with $10 - 100 \Msun$. The ionizing photon number per baryon is $\eta_{\ion} = 7.1 (5.1) \times 10^3$ for the flat (Salpeter) IMF ($\text{Schaerer} 2002$). Note that the value of $\eta_{\ion}$ is almost constant for a higher maximum mass of the IMF with $M_{\text{max}} > 100 \Msun$.

We assume $\eta_{\ion} = \eta_{\text{LW}}$, which is a good approximation for these IMFs. We consider two values of the escape fraction, $f_{\text{esc,m}} = 0.1$ and 0.5. The higher value corresponds to halos with $10^5 - 10^6 \Msun$ ($\text{Kitayama et al.} 2004$), while the lower value corresponds to more massive halos with $\gtrsim 10^7 \Msun$ ($\text{Wise et al.} 2014$). In fact, the typical mass of halos forming PopIII stars is $\sim 10^7 - 10^8 \Msun$ at $z \sim 10$, because once a LW background develops it disables H$_2$ cooling in smaller halos. We thus adopt $f_{\text{esc,m}} = 0.1$ as our fiducial model.

Fig. 1 shows the cumulative (comoving) mass density of PopIII stars for different IMFs and escape fractions. All other model ingredients, apart from an overall normalization of the SFR, follow the fiducial model of VHB15.

The normalization is chosen to produce an optical depth of $\tau_0 = 0.066 \pm \Delta \tau_0$ (solid and dotted curves) and $0.066 \pm 2\Delta \tau_0$ (dashed curve). In all cases, the mass density of PopIII stars is saturated at $z \lesssim 8$, where the PopIII star formation is shut down because of LW feedback, metal enrichment and reionization. The saturated value can be given approximately by

$$\rho_{\ast, \text{hi}} \simeq 8.2 \times 10^5 \Msun \text{Mpc}^{-3} \times (\frac{\eta_{\ion}}{5 \times 10^3})^{-1} (\frac{f_{\text{esc,m}}}{0.1})^{-1} (\frac{\tau_0 - 0.066}{\Delta \tau_0}),$$

for the range we consider here. Note that $\text{K14}$ estimated the GW event rate from PopIII binaries adopt-
ing a higher comoving density of \( \rho_{\text{III}} \approx 2 \times 10^5 \, M_\odot \, \text{Mpc}^{-3} \) (de Souza, Yoshida & Ioka 2011).

Next, we estimate the number density of massive PopIII binary stars which potentially evolve into PopIII BBHs. The distribution function of the mass ratio \( q \equiv M_2/M_1 \) of binary stars is assumed to be \( \Phi(q) = \text{const} \), where \( M_{1(2)} \) is the mass of the primary (secondary) star. This distribution is consistent with the slope \( d\ln \Phi/d\ln q = -0.1 \pm 0.6 \), observed for present-day massive binary stars (Sana et al. 2012). The mass ratio range for a fixed \( M_1 \) is \( q_{\text{min}} = (M_{\text{min}}/M_1) \lesssim q \lesssim q_{\text{max}} = (M_{\text{max}}/M_1) \). Thus, the number fraction of stars which form massive binaries with \( M_{1(2)} \geq M_{\text{crit}} = 25 \, M_\odot \), above which a star is assumed to collapse into a BH (Heger & Woosley 2002), is estimated for a given IMF as

\[
\begin{align*}
N_{\text{MB,III}} &= \frac{\rho_{\text{III}}}{(M_*)} \frac{1}{1 + f_{\text{bin}}/f_{\text{MB}}} \\
&= 1.6 \times 10^3 \, \text{Mpc}^{-3} \left( \frac{\eta_{\text{bin}}}{50000} \right)^{-1} \left( \frac{f_{\text{esc,m}}}{0.1} \right)^{-1} \\
&\times \left( \frac{\langle M_* \rangle}{20 \, M_\odot} \right)^{-1} \left( \frac{f_{\text{bin}}/0.7}{1 + f_{\text{bin}}/0.7} \right) \left( \frac{f_{\text{MB}}}{0.1} \right),
\end{align*}
\]

where \( \langle M_* \rangle \) is the average mass of single stars, \( f_{\text{bin}} \equiv N_{\text{binary}}/N_{\text{single}} \) is the binary fraction, and the fiducial \( f_{\text{bin}} = 0.7 \) is based on the binary fraction \( 0.69 \pm 0.09 \) measured for present-day massive stars (Sana et al. 2012). Thus, the number density of PopIII BBHs is estimated as \( N_{\text{MB,III}} \approx 2.7 (1.4) \times 10^3 \, \text{Mpc}^{-3} \) for the flat (Salpeter) IMF.

Fig. 2 shows the number of massive binaries per ionizing photon, a quantity directly connecting the GWB to reionization, from PopIII stars for the flat (blue) and Salpeter (red) IMF with \( 5 \, M_\odot \leq M_{\text{min}} \leq 25 \, M_\odot \). Note that stars with \( M > 25 \, M_\odot \) contribute both BHs and ionizing photons, while stars in the range \( 5 - 25 \, M_\odot \) add significant ionizing photons without any additional BBHs. As long as PopIII stars are massive, with \( M_{\text{min}} \geq 10 \, M_\odot \), our results are relatively insensitive to the slope of the IMF (less than a factor of two). However, if \( M_{\text{min}} \lesssim 10 \, M_\odot \), normalizing the ionizing emissivity to match the Planck optical depth implies fewer massive binaries, and the precise value also depends more strongly on the IMF slope.

### 2.2 PopII stars \( (Z \approx 0.1 \, Z_\odot) \)

Population II (PopII) stars are formed in metal-enriched gas clouds once supernovae of massive PopIII stars have produced heavy elements. Because metal/dust cooling is more efficient than H\(_2\) cooling, the IMF of PopII stars is expected to be less top-heavy (e.g. Omukai et al. 2005). We assume that once metal enrichment has occurred, PopII stars form with \( Z \approx 0.1 \, Z_\odot \), although the precise value of this metallicity does not significantly affect our results.

Observations of high-redshift galaxies provide estimates of the stellar mass density (e.g. Pérez-González et al. 2008), which are consistent with cosmological simulations (e.g. Vogelsberger et al. 2013). At \( z \sim 3 \), the (comoving) stellar mass density is \( \rho_* \approx 3 \times 10^{-7} \, M_\odot \, \text{Mpc}^{-3} \). Assuming a Salpeter IMF with \( 1 - 100 \, M_\odot \) and the mass-ratio distribution \( \Phi(q) = \text{const} \), the number fraction of massive binaries with \( M_{1(2)} \geq M_{\text{crit}} = 25 \, M_\odot \) is \( f_{\text{MB}} = 3.8 \times 10^{-4} \), and the number density of PopII BHs is \( N_{\text{MB,II}} \approx 1.5 \times 10^3 \, \text{Mpc}^{-3} \) (for \( f_{\text{bin}} = 0.7 \)). The number density of PopII and PopIII binaries is almost identical, even though the total stellar mass in PopII stars is much higher than in PopIII stars. For comparison, in Fig. 2 we also show the ratio of the number of massive binaries to ionizing photons for a PopII Salpeter IMF with \( 1 - 100 \, M_\odot \) (dashed), where \( \eta_{\text{ion}} = 8710 \) is assumed (Samui, Srianand & Subramanian 2007). This shows that PopII stars produce fewer BBHs per ionizing photon. Nevertheless, with the normalization above, we find that PopII stars produce an ionizing background of \( J_{\text{bg}} \approx 5 \times 10^{-22} \, \text{erg} \, \text{s}^{-1} \, \text{cm}^{-2} \, \text{Hz}^{-1} \, \text{sr}^{-1} \) (in physical units), consistent with \( \sim 50\% \) of the background measured at \( z \sim 3 \) (e.g. Steidel, Pettini & Adelberger 2001). We note that 90% of present-day stars form between \( 0 < z < 3 \); however, the more recent, more metal-rich generations at \( z < 3 \) are not expected to dominate the GWB, assuming a merger rate of BBHs by e.g., Dominik et al. 2013).

### 3 Gravitational waves from PopIII binary black hole mergers

We next consider the evolution of massive binaries to estimate the merger rate of PopIII BBHs. As discussed by K14 in the context of their population synthesis model, most
massive PopIII binaries can evolve into BBHs because in the absence of metals (1) mass loss from the metal-free surface is suppressed, and (2) stars are compact, which suppresses the deleterious effects of stellar binary interactions and mergers. Furthermore, PopIII stars with $\lesssim 30 M_\odot$ are unlikely to evolve into red giants (Marigo et al. 2001), and as a result, the typical chirp mass of PopIII BBHs is $(M_{\text{chirp}}) \approx 30 M_\odot$ for both a flat and a Salpeter IMF with $10^{-5} - 100 M_\odot$.

By comparison, when massive PopII stars experience strong mass loss, they go through a red giant phase. These effects would reduce the average PopII BH chirp mass to $\sim 10 M_\odot$ (Kowalska-Leszczynska et al. 2015), and suppress the formation of BBHs somewhat (Belczynski et al. 2010). Furthermore, the average separation of PopII BBHs which escape mergers during the red giant phases would be larger, and their GW inspiral time is longer, so that only a few percent merges within a Hubble time ($\mathcal{K}14$).

Fig. 3 shows the evolution of the PopIII BBH merger rate $R_{\text{BBH}}$ for the flat (blue) and Salpeter (red) IMF with $10 - 100 M_\odot$. The distribution of the initial binary separation $a$ is assumed to be $\propto a^{-1}$ (Abbott 1983). The rates are normalized using the cumulative mass density of PopIII stars consistent with the Planck $\tau_e$ within the $1\sigma$ (solid) and $2\sigma$ (dashed) error (Eq. 1 for $f_{\text{esc},m} = 0.1$ and $\eta_0 = 5 \times 10^3$).

Fig. 4. Top: spectra of GWB produced by PopIII BBHs for the same IMFs, $f_{\text{esc},m}$ and $\tau_e$ as in Fig. 3 (blue and red curves). We assume binaries with the average chirp mass of $(M_{\text{chirp}}) = 30 M_\odot$ on circular orbits. The background expected from all unresolved PopII+Pop BBHs is shown for reference (solid black curve, Abbott et al. 2016a), their fiducial model. Black dotted curves show the expected sensitivity of AdLIGO/Virgo in the observing runs O2 and O5. The green solid curve is the same as the blue solid curve, but with a higher chirp mass of $(M_{\text{chirp}}) = 50 M_\odot$ and with a lower merging rate by a factor of 3/5. Bottom: the spectral index; open circles mark the frequencies above which $\alpha < 0.3$.

We estimate the spectrum of the PopIII GWB as

$$
\rho c^2 \Omega_{\text{gw}}(f) = \int_{z_{\text{min}}}^{z_{\text{max}}} \frac{R_{\text{BBH}}(f) df}{1+z} \frac{dE_{\text{gw}}}{df} \frac{dz}{f_{\text{esc},m} = 0.1} \text{ (4)}
$$

where $f$ and $f_r$ are the GW frequencies observed at $z = 0$ and in the source’s rest frame, respectively, and $\rho_c$ is the critical density of the Universe. We set the minimum redshift to $z_{\text{min}} = 0.28$, the detection horizon of AdLIGO/Virgo. The GW spectrum from a coalescing BBH is given by

$$
dE_{\text{gw}} = \frac{\rho c^2}{3} \left( \frac{\sigma G}{M_{\text{chirp}}} \right)^{2/3} \frac{dz}{f_{\text{esc},m} = 0.1} \text{ (5)}
$$

where $E_{\text{gw}}$ is the energy emitted in GWs, $M_{\text{chirp}} \equiv (M_1 M_2)^{3/5}/(M_1 + M_2)^{1/5}$ is the chirp mass, and $f_i (i = 1,2,3)$ and $\sigma$ are frequencies that characterize the inspiral-merger-ringdown waveforms. $\omega_{1,2}$ are normalization constants chosen so as to make the waveform continuous, and the Post-Newtonian correction factors of $\mathcal{F}(\sigma)$ (Ajith et al. 2011). We assume that the BBHs have circular orbits because the PopIII BBHs should circularize by the time they move into the LIGO band (see Fig.3 in Abbott et al. 2016a). Note that the background spectrum in the inspiral phase scales with frequency as $\Omega_{\text{gw}}(f) \propto f^{2/3}$. Fig. 4 shows spectra of the GWB produced by PopIII BBHs for the same IMFs, $f_{\text{esc},m}$ and $\tau_e$ as in Fig. 3 (blue and red curves). For the two IMFs with $10 - 100 M_\odot$ and a
flat mass ratio distribution, the typical merger is an equal-mass binary with a chirp mass of \( M_{\text{chirp}} \approx 30 \, M_\odot \) \citep{K16}. For comparison, we show the background produced by all PopIII/I BBHs (black solid curve), which typically merge at \( z \lesssim 2 - 4 \) \citep{Dominik13, Abbott16}. For all cases shown, the GWB from PopIII BBHs is higher than the expected sensitivity of the AdLIGO/Virgo detectors in the observing run O5 (black dotted curves). The typical chirp mass and redshift of PopIII BBHs are both higher than for PopIII/I BBHs \( (\sim 30 \, M_\odot \text{ vs.} \sim 10 \, M_\odot \text{ and} \sim 3 \text{ vs.} \sim 2) \), causing the GW frequency to be redshifted. As a result, the spectrum in the AdLIGO/Virgo band becomes flatter than the canonical \( \Omega_{gw}(f) \propto f^{2/3} \) expected from lower-redshift and lower-mass PopIII/I sources.

As discussed in \cite{Kowalska12}, also have noted the spectral flattening by assuming a different chirp mass distribution and a high PopIII SFR which is inconsistent with the Planck result and does not include important physics \citep[e.g. LW feedback, metal enrichment and reionization. In the bottom panel, the open circles mark the frequencies above which the spectral index falls below 0.3; this critical frequency is 40 Hz, well inside the AdLIGO/Virgo band. The deviation could be detectable with \( S/N \sim 3 \) in the O5 run \citep{Abbott16}. Note that PopIII/I BBHs can produce such a significant flattening of the GWB spectrum at \( \sim 100 \text{ Hz} \) \citep[black curve; see also][]{Kowalska12} that show a similar flattening at \( \gtrsim 70 - 100 \text{ Hz} \), depending on their models.) Although a sub-dominant population of massive PopII BBHs with \( \gtrsim 30 \, M_\odot \) would form, depending on a model of cosmic metal enrichment \citep{Belczynski16}, the severe flattening requires the majority of massive stars, as expected only in the PopIII model (although of course this remains uncertain). Finally, we increase the chirp mass to 50 \( M_\odot \) to see its impact (green solid curve). In this case, the critical frequency shifts to \( \sim 25 \text{ Hz} \), allowing the deviation of the spectral index to be measured more easily. The spectral shape near \( 30 - 50 \text{ Hz} \) would be precisely observed by the Einstein Telescope (ET) \citep{ET} with the expected sensitivity of \( \Omega_{gw} \approx 10^{-10} \text{ to } 10^{-11} \) at \( f \sim 30 \text{ Hz} \).

### 4 SUMMARY AND DISCUSSION

In this paper, we show that GW background produced by PopIII binary BHs can dominate other populations at 10 – 100 Hz, even considering tight constraints on PopIII star formation by the recent Planck optical depth measurement from the CMB. We also find that the spectral index of the background from PopIII BHs becomes significantly flatter at \( \gtrsim 30 \text{ Hz} \) than the canonical value of \( 2/3 \) expected from lower-redshift and lower-mass massive binaries.

As discussed in \cite{Kowalska12}, massive PopIII stars are also sources of ionizing photons in the early Universe. Thus, future observations of reionization and high-redshift galaxies could yield constraints on the PopIII BBH scenario. Fig. 5 shows the amplitude of the PopIII GWB at \( f = 30 \text{ Hz} \) for different values of the CMB optical depth (red solid), assuming \( f_{\text{esc,m}} = 0.1 \), a flat IMF with \( 10 - 100 \, M_\odot \) and \( M_{\text{chirp}} = 30 \, M_\odot \). For our fiducial case, the PopIII GWB would be above the expected sensitivity of AdLIGO/Virgo in the observing run O5 \citep[dotted]{} as long as \( \tau_\text{c} \gtrsim 0.07 \). However, for a small value of \( \tau_\text{c} \lesssim 0.04 \) \citep{Mitra15}, ionizing photons from PopIII stars would contribute negligibly to reionization \citep{Mitra15, VHB16}. A detection of the PopIII GWB by the future observations \citep[for example, Planck 2015; KAGRA \citep{KAGRA} and ET,]{} implies that the IMF of PopIII stars would be more top-heavy, where PopIII stars form more BBHs but produce less ionizing photons \citep[see Fig. 2]{Abbott16}. The GWB (even an upper limit) would provide a useful constraint on the PopIII BBH scenario, combining with theoretical studies of high-z star formation.

The origin of massive BBHs such as GW150914 is still uncertain. Future detections of multiple GW events with a BBH coalescence rate of \( \dot{R}_{\text{BBH}} \sim 10 \text{ Gpc}^{-3} \text{ yr}^{-1} \) and a typical chirp mass of \( 30 \, M_\odot \) would suggest a PopIII BBH scenario. In this case, the GWB could also be detectable, along with a significant flattening of the spectral index. There are three other effects which can cause a deviation of the spectral slope from the canonical value for circular, GW-driven, non-spinning inspirals: (i) environmental effects (interaction of the BHs with nearby gas and/or stars), (ii) high orbital eccentricities and (iii) high BH spins. The first two of these effects would generically steepen the spectral slope because environmental effects remove energy preferentially at large separations, and eccentricities move power from low to high frequencies. In principle, strong BH spins anti-aligned with the orbital angular momentum can flatten the spectrum significantly, but only at high frequencies near the merger \citep[e.g. \cite{Mitra15}].

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4. Recently, new values of \( \tau_\text{c} \) by Planck have been proposed as \( 0.055 \pm 0.009 \) and \( 0.058 \pm 0.012 \) \citep[1σ,]{}. \citep{Adam16, Aghanim16}.

5. A lower escape fraction of ionizing photons from PopIII galaxies \( f_{\text{esc,11}} < 0.1 \) would allow a higher PopIII star (BBH) formation rate, however reducing this escape fraction prevents the completion of reionization by \( z = 6 \).

6. \url{http://gwcenter.icrr.u-tokyo.ac.jp/en/}
Therefore, the detection of a flattening of the spectral index of GWB at frequencies as low as 30 Hz would be an unique smoking gun of a high-chirp mass, high-redshift BBH population, as expected from PopIII stars.

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