Constraint on the early-formed dark matter halos using the free-free emission in the Planck foreground analysis

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We provide a new constraint on the small-scale density fluctuations, evaluating the diffuse background free-free emission from dark matter halos in the dark ages. If there exists a large amplitude of the matter density fluctuations on small scales, the excess enhances the early formation of dark matter halos. When the virial temperature is sufficiently high, the gas in a halo is heated up and ionized by thermal collision. The heated ionized gas emits photons by the free-free process. We would observe the sum of these photons as the diffuse background free-free emission. Assuming the analytical dark matter halo model including the gas density and temperature profile, we calculate the intensity of the diffuse background free-free emission from early-formed dark matter halos in the microwave frequency range. Comparing with the recent foreground analysis on cosmic microwave background, we obtain the constraint on the excess of the density fluctuations on small scales. Our constraint corresponds to $P_{\xi} \lesssim 10^{-7}$ for $k \approx 1 - 100$ $\text{Mpc}^{-1}$ with assuming the delta-function-type curvature power spectrum. Therefore, our constraint is the most stringent constraint on the perturbations below 1 $\text{Mpc}$ scales.

I. INTRODUCTION

The primordial perturbations are the initial seeds of various cosmological structures: the temperature anisotropies of the Cosmic Microwave Background (CMB), the Large-Scale Structure (LSS), clusters of galaxies, galaxies, and so on. Therefore, the statistical properties of the primordial perturbations are well studied. In particular, the power spectrum of the primordial perturbations is one of the important statistics to understand the cosmological structure formation. It is thoroughly measured on large length scales through the observations of the CMB on $10^{-3}$ $\text{Mpc}^{-1} \lesssim k \lesssim 10^{-1}$ $\text{Mpc}^{-1}$ [1] and the LSS (e.g., galaxy clustering, weak lensing, Ly-\(\alpha\) forest and so on) on $k \sim 1$ $\text{Mpc}^{-1}$ [2–7].

These observations have revealed that the amplitude of the power spectrum is in order of $P_{\xi} \sim 10^{-9}$ on those scales and is almost scale-invariant. These statistical properties are consistent with the primordial perturbations predicted in the inflationary paradigm [8, 9]. On the other hand, on smaller scales with $k > 1$ $\text{Mpc}^{-1}$, the primordial perturbations are not known well. Many studies suggest that the excess power on small scales can be induced by a lot of mechanisms in the early universe: multi-field inflation [10], phase transition [11, 12], early matter-dominated era [13], fast-rolling scalar field domination [14], and so on. Therefore, the investigation of the primordial perturbations on small scales can improve our knowledge of the primordial universe.

One of the powerful probes for the small-scale perturbations is the CMB distortion [15–17]. The small-scale primordial perturbations are drown out by the Silk damping, however, instead, the distortion of the CMB energy spectrum would be created. Therefore, measurements of the CMB distortion lead us to further understanding of the primordial perturbations [18–22]. For example, Ref. [19] has pointed out that the CMB distortion measurement by COBE/FIRAS [23, 24] provides the constraint in order of $P_{\xi} \lesssim 10^{-5}$ for the wave number range, $k \approx 1 - 10^4$ $\text{Mpc}^{-1}$, and next-generation CMB measurements like PIXIE [25] can be a probe of the level of the scale-invariant spectrum, $P_{\xi} \lesssim 10^{-8}$. Another hopeful measurement is future redshifted 21-cm observations which are expected to explore the density perturbations on smaller scales than the Silk scale [26]. Since the 21-cm signal comes from neutral hydrogen, the measurements of the spatial fluctuations in the redshifted 21-cm signal can trace the density fluctuations before the epoch of reionization. In order to measure the fluctuations of 21-cm signals from high redshifts, the radio interferometer telescope, the Square Kilometre Array (SKA), is now constructing.

The large amplitude of the perturbations on small scales promotes the structure formation and produces substantial collapsed objects in the early universe. One of such collapsed objects is a primordial black hole (PBH) [27]. PBHs are considered to be responsible for a non-negligible fraction of dark matter (DM) compositions [28, 29]. Furthermore, they are attracting attention, because of the recent detection of gravitational wave (GW) events via LIGO and Virgo collaboration [30], as sources of GWs. The abundance of PBHs has been studied in a wide range of the PBH mass scale [31]. Since the PBH mass scale corresponds to the scale of the overdense region collapsing to PBHs, the constraint on the PBH abundance can be converted to the limit on the perturbations in the wide range of the scale [32]. However, the PBH formation requires large amplitude of curvature power spectrum as $P_{\xi} \sim 10^{-2} - 10^{-1}$. Therefore, their constraint on the perturbations is relatively not so tight.

The density fluctuations are induced by the primor-
dial perturbations and grow gravitationally well after the matter-radiation equality. In the growth, the overdense region on small scales finally collapses into the nonlinear structures called ultra-compact minihalos or minihalos in higher redshifts than the standard hierarchical structure formation due to the scale-invariant primordial perturbations [33]. With the self-annihilating DM model, the abundance of these early-formed DM halos is constrained by the present gamma-ray observations. Accordingly, the limit on the primordial perturbations can be obtained with the formation scenario [34–36]. However, the constraint on the primordial perturbations highly depends on the parameters of the self-annihilating DM. The constraint on the early-formed DM halo abundance, which is independent of the DM model can be obtained from redshifted 21-cm observations. Depending on their mass, early-formed DM halos can host abundant neutral hydrogen gas. Therefore, redshifted 21-cm observations can probe the abundance of early-formed DM halos [37]. Several studies have shown that SKA can provide the stringent limit on the abundance of early-formed collapsed objects and the amplitude of the primordial perturbations [38–41].

In this paper, we discuss the diffuse background free-free emission in the CMB frequency range from early-formed DM halos. In the formation of DM halos, baryonic gas is collapsed into them. During the collapse, the gas is heated up by the gravitational potential and ionized by the collisions between gas particles if the halo virial temperature is high enough, as $T_{\text{vir}} \gtrsim 10^4$ K. Such hot ionized gas can emit photons via free-free emission, and they would be observed as the diffuse background free-free emission.

The diffuse background free-free emission has already been identified as one of the important foreground components in the CMB analysis [42, 43]. Although most of the observed free-free emission is believed to be Galactic origin, a lot of cosmological free-free emitters can be considered, for example, the intergalactic medium (IGM) [44], the galaxy groups and clusters after the reionization [45], and the structure formation during the reionization [46]. The estimated amplitude is roughly 10% level of the observed free-free emission component.

Here, we focus on the early-formed DM halos with $M_{\text{halo}} \sim 10^7 - 10^{13} M_\odot$ and estimate the contribution to the observed free-free emission component in the CMB frequency range. These mass scales roughly correspond to the perturbation scales $k \sim 1 - 100$ $\text{Mpc}^{-1}$ and there is a possible window for the excess of the primordial perturbations to produce DM halos much earlier than in the standard hierarchical structure formation scenario. Comparing our estimation of the diffuse background free-free emission with the observed free-free emission component [42, 43], we obtain the constraint on the primordial density fluctuations on small scales.

The rest of this paper is organized as follows. In section II, we provide the halo model describing the density, temperature, and ionization fraction of gas by assuming the hydrostatic equilibrium, and the collisional-ionization equilibrium with isothermal gas. Then, we calculate the intensity of the free-free emission from individual halos for different mass $M_{\text{halo}}$ and formation redshift $z_f$. Next, in section III, considering the halo formation history, we formulate the diffuse background intensity which is the sum of the free-free emission from early-formed halos. The results are shown in section IV. We also discuss the application of our results to the constraint on the primordial curvature perturbations and obtain the limit by comparing the intensity of the observed free-free emission in the CMB frequency range. We conclude in section V. Throughout this letter, we take the flat $\Lambda$CDM model with: $(\Omega_m, \Omega_b, h, n_s, \sigma_8) = (0.32, 0.049, 0.67, 0.97, 0.81)$ [47].

II. FREE-FREE EMISSION FROM THE INDIVIDUAL HALO

In this section, we estimate the intensity of the free-free emission from individual halos. It depends on the number density and temperature profiles of ionized gas. First, we construct the simple analytical model of ionized gas in a DM halo with mass $M_{\text{halo}}$.

A. gas structure of DM halo

Suppose that a DM halo forms with a mass of $M_{\text{halo}}$ in a redshift $z_f$. We assume that, after the virialization, the DM density profile is given by the NFW profile [48],

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{r_s \left(1 + \frac{r}{r_s}\right)^2},$$  

where $r_s$ is the scale radius, which is related to the virial radius

$$R_{\text{vir}}(M_{\text{halo}}) = \left(\frac{3M_{\text{halo}}}{4\pi\Delta_c \rho_m(z_f)}\right)^{1/3},$$  

with the matter density $\rho_m(z)$ and the concentration parameter, $c_s \equiv R_{\text{vir}}/r_s$.

The scale density $\rho_s$ is given by

$$\rho_s = \frac{M_{\text{halo}}}{4\pi r_s^3 F(c_s)} = \frac{c_s^3}{3F(c_s)} \Delta_c \rho_m(z_f),$$  

where $\Delta_c = 18\pi^2$ is the spherical overdensity of the halo, and the function $F(x)$ is described as

$$F(x) = \ln(1 + x) - \frac{x}{1 + x}. $$

The concentration parameter $c_s$ varies depending on the mass and redshift of the halo. Although no simulation covers both the mass and redshift range we are interested in this paper, Ref. [49] has performed N-body
In this work, we assume that DM halos do not host any stars in themselves for simplicity. In the absence of ionization photon sources including stars, collisional ionization is a possible process to ionize the gas in a DM halo. Since the collisional ionization and recombination timescales are sufficiently shorter than the cosmological timescale, we may assume that halo gas is in the steady-state, by balancing between the collisional ionization and the case-B recombination. In such a case, the ionization fraction in a DM halo with the temperature $T_{\text{halo}}$ is determined by

$$x_e(T_{\text{halo}}) = \frac{\dot{C}_{\text{coll}}}{C_{\text{coll}} + \dot{A}_{\text{rec}}},$$

where $\dot{C}_{\text{coll}} = C_{\text{coll}}/(1 - x_e)$, and $C_{\text{coll}}$ is the electron-collisional ionization rate which is given by the fitting formula [53],

$$C_{\text{coll}} \approx 5.85 \times 10^{-9} T_4^{1/2} e^{-T_4/H_{\text{halo}}} n_{\text{gas}}(1 - x_e) \text{ cm}^3/\text{s}.$$  

Here, $T_H \approx 1.58 \times 10^5$ K and $T_4 \equiv T_{\text{halo}}/10^4$ K. In Eq. (11), $\dot{A}_{\text{rec}} = A_{\text{rec}}/x_e$, and $A_{\text{rec}}$ is the recombination rate obtained by

$$A_{\text{rec}} = -\alpha_H n_{\text{gas}} x_e,$$

where $\alpha_H$ is the case-B recombination coefficient for hydrogen and fitted by Ref. [54] as

$$\alpha_H = 1.14 \times 10^{-13} \frac{aT_4^5}{1 + cT_4^4} \text{ cm}^3/\text{s}$$

with the fitting parameters, $a = 4.309$, $b = -0.6166$, $c = 0.6703$, and $d = 0.5300$. In our model, the ionization fraction is only controlled by the gas temperature. When the gas temperature is larger than $10^4$ K, the ionization fraction goes up close to the unity.

Although the gas becomes hot by the virial shock at the formation of the DM halo, the gas will be cooled down by the cooling mechanism related to baryon physics. Assuming the cooling timescale $t_{\text{cool}}$, the temperature is expressed at a given redshift $z$,

$$T_{\text{halo}}(M_{\text{halo}}, z, z_f) = T_{\text{vir}}(M_{\text{halo}}, z_f) \exp \left(-\frac{\Delta t(z, z_f)}{t_{\text{cool}}}, \right)$$

where $\Delta t$ is the cosmic time duration in the redshift range $[z, z_f]$ in the matter dominated epoch,

$$\Delta t \approx \frac{2}{3} \left( \frac{1}{H(z)} - \frac{1}{H(z_f)} \right),$$

with the Hubble parameter $H(z)$.

The main cooling mechanism depends on the redshift and the gas properties including the gas density, temperature, and ionization fraction. One of the main cooling mechanisms is the free-free emission cooling. The
timescale might be defined by
\[ t_{\text{ff}}(M, z) = \frac{3/2n_{\text{gas}}T_{\text{halo}}}{\int d\nu \epsilon_{\nu}^\text{ff}}. \tag{16} \]
where \( \epsilon_{\nu}^\text{ff} \) is the efficiency of free-free emission which is defined in the following subsection, especially in Eq. (18).

When the gas is ionized (even if partially), the Compton cooling by CMB photons also can be the main cooling mechanism. In this case, the cooling timescale depends only on the redshift,
\[ t_{\text{Comp}}(z) = \frac{3m_e c}{4 \sigma_T \rho_\gamma} f_{\text{cool}} \approx 1.4 \times 10^7 f_{\text{cool}} \left( \frac{1+z}{20} \right)^{-4} \text{ yr}, \tag{17} \]
where \( m_e \) is the mass of electron, \( \rho_\gamma \) is the CMB energy density, and \( f_{\text{cool}} \equiv (1+x_e)/2x_e \) represents the dependence on the ionized fraction. Here we assume that the baryon is composed of only hydrogen atoms.

Through the paper, we adopt the cooling timescale for the smaller value of Eqs. (16) and (17), that is, \( t_{\text{cool}} = \min(t_{\text{ff}}, t_{\text{comp}}) \). Because of the cooling, even if the gas temperature is high enough to ionize the gas at the formation time, the temperature decreases, and finally the gas becomes neutral by following Eq. (10).

As we mentioned above, we assume that stars are not formed in DM halos, and we consider only the Compton cooling as the cooling process. However, when the virial temperature is larger than \( 10^4 \) K, the atomic cooling becomes effective and leads to further collapsing of the gas and the star formation. Stars could heat up and ionize the gas in such massive DM halos substantially. While that can lead to enhance the free-free emission, the timescale and the efficiency of the star formation are still uncertain. Therefore, we do not include these effects.

### B. Free-free emission

When the gas in DM halos has a high temperature enough for the collisional ionization, the ionized gas can emit radiation through thermal free-free emission. The emissivity of the thermal free-free emission at a frequency \( \nu \) is given by [55]
\[ \epsilon_{\nu}^\text{ff} = \frac{2^3 e^6}{3 m_e c^3} \left( \frac{2\pi}{3 m_e k_B T_{\text{halo}}} \right)^{1/2} \]
\[ \times \chi_2^2 k_B^2 \exp(-h_{\nu}^p/k_B T_{\text{halo}}) \tilde{g}_f, \tag{18} \]
where \( h_p \) is the Planck constant. In this paper, we are interested in the CMB frequency range or below them. Since these frequencies are much smaller than the halo temperature for the free-free emission, \( h_{\nu}^p \ll k_B T_{\text{halo}} \), we take \( \exp(-h_{\nu}^p/k_B T_{\text{halo}}) \approx 1 \). In Eq. (18), \( \tilde{g}_f \) is a velocity-averaged Gaunt factor. Ref. [56] has provided the fitting formula for the \( \tilde{g}_f \),
\[ \tilde{g}_f = \log \left\{ \exp \left[ 5.960 - \sqrt{3}/\pi \log \left( \nu_0 T_4^{-3/2} \right) \right] + e \right\}, \tag{19} \]
where \( \nu_0 \equiv \nu/(1 \text{ GHz}) \), and \( e \) is the Napier’s constant.

Since, in our gas model, the number density has radial dependence, the emissivity also depends on the radius in a DM halo.

Now we calculate the mean intensity of the free-free emission from a DM halo. When the optical depth of the free-free absorption is negligible, the mean intensity of the free-free emission induced by an individual halo is obtained by
\[ I_{\nu}^\text{ind}(z, z_i, M_{\text{halo}}) = \frac{\int dV \epsilon_{\nu}^\text{ff} s_{\text{halo}}}{S_{\text{halo}}}, \tag{20} \]
where \( S_{\text{halo}} \) is the physical cross section of a DM halo on the sky, \( S_{\text{halo}} = \pi R_{\text{vir}}^2 \).

Since the gas profile depends on the redshift of the emission \( z \), the formation redshift \( z_i \), and the mass of the DM halos \( M_{\text{halo}} \), Eq. (20) depends on these parameters.

III. DIFFUSE BACKGROUND FREE-FREE EMISSION

Now we consider the diffuse background intensity emitted from DM halos with mass \( M_{\text{halo}} \) residing spherical shell between from \( z \) to \( z + dz \). This intensity is obtained by integrating the contributions from the DM halos formed until redshift \( z \).
\[ dI_{\nu}^\text{ff}(z, M_{\text{halo}}) = \left( \int_z^\infty f_{\text{sky}} I_{\nu}^\text{ind} \frac{d\nu_{\text{halo}}}{dz_{\text{red}}} d\nu_{\text{halo}} \right) \frac{dV_{\text{com}}}{dz} dz. \tag{21} \]

Here, we omit the dependencies of \( f_{\text{sky}} \) and \( I_{\nu}^\text{ind} \) on \( (z, z_i, M_{\text{halo}}) \). In Eq. (21), \( V_{\text{com}} \) is the total comoving volume out to redshift \( z \), and \( \nu_{\text{halo}} \) is the comoving number density of halos with mass \( M_{\text{halo}} \) at a redshift \( z \), which we discuss later. Additionally, \( f_{\text{sky}} \) in Eq. (21) is the sky fraction of the DM halos formed at \( z_i \) with mass \( M_{\text{halo}} \) and given by
\[ f_{\text{sky}} = \frac{\Omega_{\text{halo}}}{4\pi}, \tag{22} \]
where the solid angle \( \Omega_{\text{halo}}(z, z_i, M_{\text{halo}}) \) of a DM halo is given by \( \Omega_{\text{halo}} = \pi((1+z)R_{\text{vir}})^2/\chi^2 \) with the comoving distance \( \chi \), from \( z = 0 \) to \( z \).

Taking into account the redshift effect due to the cosmological expansion, the diffuse background intensity at the observed frequency \( \nu_{\text{obs}} \) is calculated by
\[ I_{\nu_{\text{obs}}} = \int_{z_{\text{cut}}}^\infty dz \frac{1}{(1+z)^3} \frac{dI_{\nu}^\text{ff}(z, M_{\text{halo}})}{dz}, \tag{23} \]
where \( \nu_{\text{em}} = (1+z)\nu_{\text{obs}} \), and \( z_{\text{cut}} \) is the lower limit of the redshift. We are interested in the free-free emission from DM halos created by the excess fluctuations from the scale-invariant spectrum. Therefore, we set \( z_{\text{cut}} \) to the redshift at which the mass variance due to the scale-invariant spectrum reaches the critical density contrast.
\[ \delta_c = 1.69, \text{ so that } \delta_c = \sigma_1(z, M_{\text{halo}}), \text{ where } \sigma_1(z, M) \text{ is the mass variance calculated from the scale-invariant spectrum at } z. \]

**A. DM halo number density**

In order to calculate the number density of DM halos in Eq. (21), we assume that the density fluctuations obey Gaussian statistics. We represent the mass variance with mass \( M_{\text{halo}} \) at the present epoch as \( \sigma_0(M_{\text{halo}}) \). The mass variance at a redshift \( z \) is \( \sigma(z, M_{\text{halo}}) = D(z) \sigma_0(M_{\text{halo}}) \) with the linear growth rate \( D(z) \) which is normalized as \( D(0) = 1 \) at the present. Using the spherical collapse model, at a redshift \( z_f \) in the matter dominated epoch, the mass fraction of DM halos with mass \( > M_{\text{halo}} \) is given by

\[ f_{\text{coll}}(z_f, M_{\text{halo}}) = \text{erfc}\left(\frac{\nu_c}{\sqrt{2}}\right), \quad (24) \]

where \( \nu_c \equiv \delta_c / \sigma(z, M_{\text{halo}}) \).

The mass distribution of DM halos depends on the shape of the mass variance as a function of \( M_{\text{halo}} \). However, in this work, instead of specifying the shape of the mass variance, we simply assume that the number density of DM halos with mass \( M_{\text{halo}} \) is given by

\[ n_{\text{halo}}^{\text{com}}(z_f, M_{\text{halo}}) = \Omega_m \frac{\rho_{\text{crit}}}{M_{\text{halo}}} f_{\text{coll}}(z_f, M_{\text{halo}}). \quad (25) \]

Since the mass fraction, \( \sigma(M_{\text{halo}}) \) includes the contribution from not only dark matter halos with \( M_{\text{halo}} \) but also with \( M > M_{\text{halo}} \), this evaluation leads to overestimate the number density of \( M_{\text{halo}} \). In other words, we neglect the DM halos with \( M > M_{\text{halo}} \) in the above treatment. However, the free-free intensity is larger for massive halos than that for lighter mass. We discuss this point in the next section. Therefore, the obtained intensity is the lowest signals of the free-free emission for the given mass variance with a single mass \( M_{\text{halo}} \). Consequently, the limit on the primordial curvature perturbations would be estimated conservatively.

Accordingly, the derivative of the number density with respect to the formation redshift, \( z_f \) is

\[ \frac{dn_{\text{halo}}^{\text{com}}}{dz_f} = \sqrt{2} \frac{\Omega_m \rho_{\text{crit}}}{M_{\text{halo}}} \nu_{c,0} \exp\left(-\frac{\nu_c^2}{2}\right), \quad (26) \]

where \( \nu_{c,0} = \delta_c / \sigma_0(M_{\text{halo}}) \). Through this halo number density, the diffuse background intensity from early-formed DM halos depends on the density fluctuations, whose statistical property we represent by two parameters \( (M_{\text{halo}}, \sigma_0(M_{\text{halo}})) \).

In the next section, we demonstrate that the observation of the all-sky averaged free-free emission is a powerful probe of the density fluctuations on small scales, calculating the amplitude of the diffuse background intensity with different sets of two parameters \( (M_{\text{halo}}, \sigma_0(M_{\text{halo}})) \).

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**IV. RESULTS AND DISCUSSION**

In Fig. 1, we show the dependence of the diffuse background intensity from early-formed DM halos at \( \nu = 70 \text{ GHz} \) on the mass variance \( \sigma_0(M) \) for different \( M = M_{\text{halo}} \). It is worth mentioning that, in the standard \( \Lambda \text{CDM} \) model consistent with the Planck data, the mass variance are \( \sigma_0(M) = 12.0, 6.5 \) and \( 3.5 \) for \( M = 10^{10}, 10^{11} \), and \( 10^{12} \), respectively. When \( \sigma_0(M) \) becomes large, the formation of DM halos with mass \( M \) would start in higher redshifts, and the number density of DM halos emitting the free-free emission would increase. Therefore, the large \( \sigma_0(M) \) enhances the amplitude of the diffuse background intensity in these mass scales. Fig. 1 tells us that more massive halos emit the stronger free-free intensity than less massive halos. This reason can be interpreted that the massive halos have higher virial temperature at their formation time, and they survive longer until the cooling down and the neutralization of the baryon gas.

Additionally, Fig. 2 shows the redshift distribution of the diffuse background intensity with at each redshift for \( M_{\text{halo}} = 10^{9}, 10^{10}, \) and \( 10^{12} \). In this figure, we fix the mass variance as \( \sigma_0 = 24.8, 19.5, \) and \( 14.2 \), respectively.

Fig. 3 presents the frequency dependence of the diffuse background intensity in the CMB frequency range. These frequencies are smaller than \( k_B T_{\text{halo}} / h_p \). Therefore, the frequency dependence comes from only the Gaunt factor.
FIG. 2. The redshift distribution of the diffuse background intensity induced by early-formed halos with mass and mass variance \( M_{\text{halo}}[M_\odot], \sigma_0 \approx (10^8, 24.8), (10^{10}, 19.5), (10^{12}, 14.2) \). The color and line styles are the same as in Fig. 1.

of Eq. (19). The dependence is the same as in the free-free emission component in the CMB data analysis [42].

In the Planck CMB analysis, the free-free emission component has been separated from other diffuse foreground emissions. The obtained intensity map of the free-free emission tells us that the emission is strongly anisotropic. At low galactic latitude, the emission is strong, while the emission becomes weak as the galactic latitude increases. From the Planck data, the all-sky averaged free-free emission component is identified as \( I_\nu \approx 10^3 \) Jy/str at the frequency \( \nu = 70 \) GHz [42, 43]. To avoid the contamination from the Galactic disk, we also calculate the intensity of the observed free-free emission component by masking the region at galactic latitude \( |b| < b_{\text{cut}} \). Fig. 4 shows the dependence of the averaged intensity on the cutoff galactic latitude \( b_{\text{cut}} \) at \( \nu = 70 \) GHz. The averaged intensity becomes small as \( b_{\text{cut}} \) increases, and we have found that when we set \( b_{\text{cut}} > 60 \) deg., so that the region with \( |b| < b_{\text{cut}} \) is masked, the resultant averaged intensity observed by Planck drops down roughly to 70 Jy/str (in the brightness temperature, \( T_b \sim 0.7 \times (\nu/70 \text{ GHz})^{-2} \text{ K} \)). For comparison, we plot the intensity of the all-sky averaged free-free emission \( I_\nu \approx 10^3 \) Jy/str, and only in high galactic latitude, \( I_\nu \approx 70 \) Jy/str as black dotted and dash-dotted lines, respectively, in Figs. 1 and 3.

Since the diffuse background intensity from early-formed DM halos cannot exceed the intensity of the observed free-free emission, we can obtain the constraint on \( \sigma_0(M_{\text{halo}}) \). Fig. 5 represents the upper limit on the allowed \( \sigma_0(M_{\text{halo}}) \) for each mass \( M_{\text{halo}} \). The parameter sets in the colored region show the excluded ones where the diffuse background intensity is larger than the measured signal. It is noted that the dependence of the signal amplitude on the DM halo mass \( M_{\text{halo}} \) is weak in the mass range between \( 10^{12} \) \( M_\odot \) and \( 10^{13} \) \( M_\odot \). This is because the free-free emission from individual halos gets higher as the halo mass increases, while the number density of DM halos decreases for a fixed \( M_{\text{halo}} \). For halos with mass \( 10^{11} \) \( M_\odot \lesssim M_{\text{halo}} \lesssim 10^{12} \) \( M_\odot \), the diff-

FIG. 3. The diffuse background intensity induced by early-formed halos with mass \( M_{\text{halo}} = 10^{12} M_\odot \). The thick lines with different color and line types represent the diffuse background intensity with different amplitude of \( \sigma_0 \). From bottom to top, the lines are for \( \sigma_0(i) = (12.7, 41.7, 59.2, 73.0) \) with \( (i=I,I,II,III,IV) \). The thin black dotted line and the thin black dash-dotted line are the same as in Fig. 1.

FIG. 4. The averaged intensity of the free-free emission from the Planck foreground map. The horizontal axis represents the absolute galactic latitude \( |b_{\text{cut}}| \) for masking the Galactic disk component. The orange line is the fitting curve for illustrative purposes.
fuse background intensity weakly depends on the mass variance \(20 \lesssim \sigma_0 \lesssim 50\), as shown in Fig. 1. Therefore, the constraint on \(\sigma_0(M_{\text{halo}})\) strongly changes on these mass scales. Finally, in the lightest mass range as \(M_{\text{halo}} \lesssim 10^8 M_\odot\), the virial temperature is not high enough to ionize the gas inside DM halos. Therefore, the signal strength decreases, and resultantly, the constraint on \(\sigma_0(M_{\text{halo}})\) quickly becomes weak.

We find that the fitting formula of the limitation of \(\sigma_0(M_{\text{halo}})\) by the intensity of the observed free-free emission averaged in all-sky is

\[
\log_{10} \sigma_0 < -0.0061 x^3 + 0.21 x^2 - 2.56 x + 12.43,
\]

where \(x = \log_{10} M_{\text{halo}}\). We mention that this fitting function can be adopted in the mass region \(M_{\text{halo}} = (10^8 M_\odot, 10^{13} M_\odot)\).

We have obtained the constraint on the mass variance on \(M_{\text{halo}}\). It is also worth discussing this constraint in terms of the primordial curvature perturbations. The mass variance is calculated from the power spectrum of the curvature perturbations \(P_\zeta\) by

\[
\sigma_0^2(M) = \int d \log k \frac{4}{25} \frac{k^4}{\Omega_m^2 H_0^4} P_\zeta(k) T^2(k) W^2(k R_{\text{M}}(M)),
\]

where \(W(k)\) is the Fourier component of the top-hat window function, and \(R_{\text{M}}(M)\) is the comoving scale in which the mass \(M\) is enclosed with the background matter density \(\Omega_m \rho_c\). Besides, we adopt the transfer function for the matter density fluctuations \(T(k)\) as

\[
T(k) = \frac{45 \Omega_m^2 H_0^2}{2 \Omega_r k^2} \left( -\frac{7}{2} + \gamma_E + \ln \left( \frac{4 \sqrt{\Omega_r k}}{\sqrt{3} \Omega_m H_0} \right) \right),
\]

with the Euler-Mascheroni constant \(\gamma_E \approx 0.577\). Since we would like to constrain the excess of the fluctuations from the scale-invariant spectrum on small scales, we implicitly assume the blue-tilted power spectrum on these scales. In this case, \(P_\zeta(k) W^2(kR)\) in Eq. (28) has a maximum value at \(k = 2\pi/R\). Therefore, Eq. (28) can be approximated to

\[
\sigma_0^2(M) \approx \frac{4}{25} \frac{k^4}{\Omega_m^2 H_0^4} P_\zeta(k) T^2(k) W^2(k R_{\text{M}}(M)) \bigg|_{k = k_p},
\]

where \(k_p = 2\pi/R_{\text{M}}(M_{\text{halo}})\) and we adopt the sharp-k filter, \(k = k_p\).

Using Eq. (30), we rewrite our constraint on \(\sigma_0(M_{\text{halo}})\) in Fig. 5 to the limit on the amplitude of the delta-function type primordial curvature power spectrum, \(P_\zeta\) as a function of different \(k\). Fig. 6 is a summary of our constraint on the amplitude of the curvature perturbations. On scales \(1 \text{ Mpc}^{-1} \leq k \leq 100 \text{ Mpc}^{-1}\), our constraint is stronger than the previous ones.

At the last of this section, we discuss the dependence of our results on the gas profile. The diffuse background intensity is proportional to the square of the number density of gas particle as shown in Eq. (18). We have evaluated the diffuse background intensity with the gas profile based on the hydrostatic equilibrium and the isothermal condition. In order to estimate the model uncertainty of the gas profile, we also calculate with the different gas profile model (KS model) suggested in Ref. [58]. In the KS model, without the isothermal condition, the gas density and temperature profiles are obtained from the hydrostatic equilibrium and the condition that the shape of the gas density profile becomes the same as the one of DM in the outer region of the DM halo. Calculating the diffuse background intensity with this model and we find out that the signals become smaller than in the isothermal case. Although it depends on halo mass, the extent of the signal suppression is a factor of two in the mass range between \(10^{12} M_\odot < M < 10^{13} M_\odot\). Comparing the free-free emission at the high galactic latitude, we obtain the constraint in the case of the KS model and plot it in Figs. 5 and 6. Because of the signal suppression, the constraint in the KS model is weaker than in the isothermal case as well.

V. CONCLUSION

In this work, we have estimated the diffuse background free-free emission due to the early formation of DM halos. If there are a large amplitude of density fluctuations on
small scales, DM halos form efficiently after the matter-radiation equality. Inside DM halos with high virial temperature, the gas is ionized by the thermal collision and can emit photons by the free-free process.

First, we construct the gas model in DM halos, assuming isothermal gas with the hydrostatic equilibrium and calculate the free-free emission from individual halos. In our model, the gas is heated up to the virial temperature at the halo formation and cooled down by the Compton scattering with CMB photons. The ionization of gas is achieved by thermal collisional ionization. The gas with a large virial temperature is ionized and can emit radiation through free-free emission. However since the Thomson scattering cooled down the gas, the gas quickly becomes neutral and terminates the free-free emission. The intensity is completely determined by the halo mass and the formation redshift.

Next, assuming the excess of density fluctuations from the scale-invariant power spectrum on small scales, we have computed the diffuse background intensity.

Since it depends on the formation history of DM halos, the intensity is sensitive to the density fluctuations. We have found that the large mass variance promotes the DM halo formation at high redshifts, and increases the diffuse background intensity.

By comparing the intensity of the free-free emission observed by the Planck satellite, we have put an upper limit on the mass variance at the present epoch, \( \sigma_0(M) \). The observed free-free emission is highly anisotropic and the intensity averaged only in high galactic latitude region is lower than that of the all-sky averaged free-free emission. We have shown that the comparison with the emission at high galactic latitude makes the constraint stronger. The obtained constraint on the mass variance from intensity averaged only in high galactic latitude region is \( \sigma_0 < 20 \) in the mass range \( 10^{12} M_\odot < M < 10^{13} M_\odot \). This constraint allows us to provide the limit on the amplitude of the delta-function-type primordial curvature power spectrum, \( P_\zeta(k) \lesssim 10^{-7} \) for \( 1 \text{ Mpc}^{-1} \lesssim k \lesssim 100 \text{ Mpc}^{-1} \).

We have demonstrated that the measurements of the diffuse background free-free emission can probe the abundance of early-formed DM halos. However, there are several theoretical uncertainties related to the nonlinear structure formation in our estimation. One of such uncertainties is the baryon gas profile in DM halos. In order to investigate this uncertainty, we calculate the diffuse background intensity with a different gas profile model as in Ref. [58]. We have found that the difference of the gas profile models provides the suppression of the signal by a factor of two.

One way to improve the theoretical prediction of the diffuse background free-free emission is to perform numerical simulations of the early structure formation including baryon physics. Not only the gas profile mentioned above but also the star formation in early-formed DM halos can affect the diffuse background intensity because radiation from stars can heat up and ionize baryon gas inside halos. In addition, the further improvement of the constraint is expected by combining the other observational probes, 21-cm line observations, thermal and kinetic Sunyaev-Zel’dovich (SZ) effect, and so on. We leave them for our future work.

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