論　文

Fluctuation of cosmic background radiation from interstellar dust emission of forming dwarf galaxies

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Abstract

We predict the contribution from interstellar dust emission of very young metal-poor low-mass galaxies（*forming dwarf galaxies*）at $z>4$ to the fluctuation of cosmic background radiation（CBR）at observed wavelengths of 200 μm–2.1 mm. For this purpose, we constructed a semi-analytic model of galaxy formation based on the cosmological hierarchical structure formation scenario combined with the model of dust emission of forming dwarf galaxies. Since the small dust grain sizes in forming dwarf galaxies make the appearance of their rest-frame infrared（IR）spectral energy distribution（SED）significantly different from that of nearby more evolved galaxies, we adopt a new model for the evolution of dust content and the IR SED of lowmetallicity, extremely young galaxies. Though the contribution from forming dwarf galaxies to the CBR intensity is small compared with that of giant submillimeter sources at $z=1$–3, the fluctuation signal at high-ℓ in multipole expansion（$\ell \geq 3\times10^4$, or $\theta \leq 20''$）is unique to these forming dwarf populations. Our predictions are useful to construct observational strategies for future facilities, e.g., like ALMA.

1. Introduction

One of the most challenging issues in modern cosmology is to explain the formation of structure in the universe. Especially, star formation and metal enrichment in a very early stage of galaxies are of great importance to establish a coherent view of the cosmic history.

With the aid of a variety of new observational techniques and large facilities, studies on such young galaxies are being pushed to higher redshifts. The Lyman-break galaxy（LBG）is one of the most successfully identified species of galaxies at high-z（$z=2$–5）(e.g. [1]). Even in LBGs, there is clear evidence that they contain non-negligible amount of interstellar dust (e.g. [1, 6]). Dust grains absorb stellar light and re-emit it in the infrared（IR), hence it is very important to evaluate the intensity and spectrum of FIR emission from galaxies for understanding their star formation properties.

Then, how about further, younger galaxies in the early universe at $z \geq 4$? It is often assumed, without deliberation, that the effect of dust is negligible for such young galaxies, because of their low metallicities. However, low metallicity does not necessarily mean low dust emission. Thus, it is an important issue to explore the possibility of observing the dust emission from very early, metal-poor phase of galaxy evolution. Though a direct measurement of dust emission in individual galaxies at very high redshift ($z \geq 5$) is still beyond the ability of present and forthcoming instruments, their integrated light, i.e., the cosmic background radiation (CBR) in the IR - millimeter (mm) wavelength range has been already observed and has given new impetus to the related field (e.g. [18, 12, 29, 15]). The fluctuation of the CBR includes important information of the large-scale distribution of forming galaxies at a distant universe (e.g. [11, 19, 24, 28]).

In this work, we predict the properties of the CBR and its fluctuation in the IR/mm from interstellar dust emission of very young metal-poor low-mass galaxies (*forming dwarf galaxies*) at high redshift, $z > 4$. In order to calculate the CBR from galaxies, we need to know the cosmological evolution of number density of galaxies and the spectral energy distributions (SEDs) of each galaxy. Therefore, we employ a semi-analytic galaxy formation model (SA-model) of Enoki et al. [7] (an extended model of Nagashima et al. [20]) based on the cosmological hierarchical structure formation scenario. Then, we combine an SED model of dust emission of very young metal-poor galaxies recently developed by Takeuchi et al. [30, 32] with the SA-model.

There exist some SA-models that try to reproduce galaxy properties in the IR/mm wavelength range (e.g. [10, 9, 2, 4, 16]). We here stress that there is an important aspect that has never treated properly in these previous studies. Dust is known to be produced mainly in the late stage of stellar evolution: supernovae (Type I and II), red giants, and asymptotic giant branch stars. In a very early phase of galaxy evolution, dust supply is dominated by Type II supernovae (SNe II). On the other hand, for evolved galaxies at $z \leq 3$, other kind of evolved stars (SNe Ia, red giants, asymptotic giant branch stars) also contribute to the dust supply. Thus the size distributions of dust grains in forming dwarf galaxies may be significantly different from those observed in the Galaxy or local aged galaxies, and hence we expect IR SEDs of forming dwarf galaxies to be quite different from those of nearby older galaxies. Takeuchi et al. [30], for the first time, treated the dust size distribution properly and constructed the model for the evolution of dust content and the IR SED of low-metallicity, extremely young galaxies. Unlike the previous works, we consider the properties of very young metal-poor galaxies at $z \geq 4$, and therefore our SED model must take into account the appropriate size distribution of dust grains in the early universe. We here adopt Takeuchi et al. [32] model (the updated version of Takeuchi et al. [30]) in this work because this model successfully reproduced the peculiar SED of a local metal-poor dwarf galaxy SBS 0335–052, which are regarded as an analogue of genuine young galaxies at very high redshift ($z \geq 4$).

This work focuses on the contribution of dust emission from forming dwarf galaxies at $z > 4$ to the fluctuation of the CBR in IR/mm, and discuses the observability. Fluctuation analysis is one of the effective methods to explore the deep universe below the detection limit of the observations, and theoretical prediction gives supplementary information to this kind of analysis (e.g. [31]). Such calculations are also important for the studies of the small-scale anisotropies of the cosmic microwave background (CMB).

This paper is organized as follows: In Section 2 we review the statistical descriptions of the fluctuation of CBR from galaxies. In Section 3 we briefly describe our SA-model and SED model of forming dwarf galaxies. Results are presented in Section 4 and discussion about the observability of the CBR from dust emission of forming dwarf galaxies in Section 5. Section 6 is devoted to summary and conclusions.

In this study, the adopted cosmological model is a low-density, spatially flat cold dark matter (ΛCDM universe with the present density parameter, $\Omega_{\mathrm{m}} = 0.3$, the cosmological constant $\Omega_\Lambda = 0.7$, the Hubble constant $h = 0.7$ ($h \equiv H_0/100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$) and the present rms density fluctuation in spheres of $8h^{-1}$Mpc radius $\sigma_8 = 0.90$.

2. Cosmic background radiation from galaxies

2.1 CBR intensity and its fluctuation

First we introduce the Hubble parameter at redshift z is given as

$$H^2(z) = H_0^2[\Omega_{\mathrm{m}}(1+z)^3 + (1-\Omega_{\mathrm{m}}-\Omega_\Lambda)(1+z)^2 + \Omega_\Lambda]. \tag{1}$$

We define the CBR intensity as a total detected flux density per steradian, without an extraction of point sources. Then, the mean background intensity is written as

$$I_{\nu_0} = \frac{1}{4\pi}\int_0^\infty \frac{c j_{\mathrm{eff}}(\nu_0, z)}{(1+z)^2 H(z)} dz \tag{2}$$

where

$$j_{\mathrm{eff}}(\nu_0, z) \equiv \int_0^\infty \Phi(L_{\nu_0}, z) K(L_{\nu_0}, z) L_{\nu_0} dL_{\nu_0} \tag{3}$$

is the effective volume emissivity density of galaxies at redshift z. Here, $L_{\nu0}$ is the monochromatic luminosity at the observed frequency ν_0, $\Phi(L_{\nu0}, z)$ is the luminosity function at z and $K(L_{\nu0}, z)$ is the K-correction defined as $K(L_{\nu0}, z) \equiv (1+z)L_{(1+z)\nu0}(L_{\nu0})$.

The observed intensity at frequency ν_0 in the direction Ω is $I(\Omega, \nu_0) = I_{\nu0} + \delta I_{\nu0}(\Omega)$. The fluctuation of the CBR, $\delta I_{\nu0}(\Omega)$, is straightforwardly obtained from eq. (2), as

$$\delta I_{\nu_0}(\Omega) = \frac{1}{4\pi}\int_0^\infty \frac{c}{(1+z)^2 H(z)}\left[\int_0^\infty \delta\Phi(\Omega, L_{\nu_0}, z)K(L_{\nu_0}, z)L_{\nu_0}dL_{\nu_0}\right]dz. \quad (4)$$

We adopt an assumption of the universal luminosity function, i.e., $\delta\Phi(\Omega, L_{\nu0}, z) = \Phi(L_\nu, z)\delta_n(\Omega, z)$, where $\delta_n(\Omega, z) = \delta n(\Omega, z)/n(z)$ is the number density fluctuation of galaxies. Then the angular correlation function of the CBR intensity fluctuation, $C_I(\theta, \nu_0)$, is defined as

$$\begin{aligned} C_I(\theta, \nu_0) &\equiv \langle \delta I_{\nu_0}(\Omega)\delta I_{\nu_0}(\Omega')\rangle \\ &= \frac{1}{(4\pi)^2}\int_0^\infty \frac{c j_{\rm eff}(\nu_0, z)}{(1+z)^2 H(z)} \\ &\times \left[\int_0^\infty \frac{c j_{\rm eff}(\nu_0, z')}{(1+z')^2 H(z')}\langle\delta_n(\Omega, z)\delta_n(\Omega', z')\rangle dz'\right]dz. \end{aligned} \quad (5)$$

Here we use the other assumption, called 'small separation approximation', i.e., $\theta \ll 1$ and a correlation takes place only at $z \simeq z'$, which leads $\langle\delta_n(\Omega, z)\delta_n(\Omega', z')\rangle \simeq \xi_{\rm gal}(r, z)$ at $z \simeq z'$. $\xi_{\rm gal}(r, z)$ is the space correlation function of number density fluctuation of galaxies. $r^2 = u^2/[1-(1-\Omega_{\rm m}-\Omega_\Lambda)x^2]^2 + x^2\theta^2$ and $u = x - x'$ is the comoving radial separation between two positions at x and x' (e.g. [23]). Then, after some algebra, we finally obtain the formula for a spatially flat universe $(\Omega_{\rm m} + \Omega_\Lambda = 1)$,

$$C_I(\theta, \nu_0) \simeq \frac{1}{(4\pi)^2}\int_0^\infty \frac{j_{\rm eff}(\nu_0, z)^2}{(1+z)^4 H(z)}\left[\int_{-\infty}^\infty \xi_{\rm gal}(r, z)du\right]dz. \quad (6)$$

2.2 Power spectrum of temperature fluctuation

The temperature fluctuation of CMB in the direction Ω is approximately related the intensity fluctuations of the CMB as $\delta T_{\rm CMB}(\Omega) = \delta I_{\rm CMB}(\Omega)(\partial B_0/\partial T_0)^{-1}$. Here, B_0 is the Plank function with temperature T_0, which is the mean observed temperature of CMB. In order to compare the CMB with the other background, it is convenient to convert other intensity fluctuations into temperature fluctuations in the analogous way. Hence, we define the temperature fluctuations as following:

$$\delta T(\Omega, \nu_0) \equiv \delta I_{\nu_0}(\Omega)\left[\frac{\partial B_0(\nu_0, T_0)}{\partial T_0}\right]^{-1}. \quad (7)$$

Therefore, the angular correlation function of temperature fluctuation is

$$\begin{aligned} C_T(\theta, \nu_0) &\equiv \langle \delta T(\Omega, \nu_0) \delta T(\Omega', \nu_0) \rangle \\ &= C_I(\theta, \nu_0) \left[\frac{\partial B_0(\nu_0, T_0)}{\partial T_0} \right]^{-2}. \end{aligned} \tag{8}$$

Since $C_T(\theta, \nu_0)$ is a function of angle θ, it can be expressed as

$$C_T(\theta, \nu_0) = \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} C_\ell(\nu_0) P_\ell(\cos\theta) \tag{9}$$

where $P_l(\cos\theta)$ are the Legendre polynomials. The multipole expansion coefficients $C_\ell(\nu_0)$ are given by

$$C_\ell(\nu_0) = 2\pi \int_0^\pi d\cos\theta \, P_\ell(\cos\theta) C_T(\theta, \nu_0). \tag{10}$$

The angular power spectra of temperature fluctuation $\delta T_{\nu 0,\ell}$ are defined as $\delta T_{\nu 0,\ell} \equiv [\ell(\ell+1) C_\ell(\nu_0)/2\pi]^{1/2}$.

2.3 Clustering of galaxies

As discussed above, a theoretical model for the evolution of the space correlation function of galaxies $\xi_{\rm gal}(r, z)$ is required to obtain the property of the fluctuation of CBR from galaxies. By assuming that the biases are independent of the scale, $\xi_{\rm gal}(r, z)$ is given by

$$\xi_{\rm gal}(r, z) = b_{\rm eff}^2(z) \xi_{\rm DM}(r, z), \tag{11}$$

where $b_{\rm eff}(z)$ is the effective bias and $\xi_{\rm DM}(r, z)$ is the space correlation function of the mass density fluctuation of dark matter. We proceed this calculation using the halo bias model [3, 7], as follows.

The evolution of $\xi_{\rm DM}(r, z)$ is derived via the formula given by Peacock & Dodds [22]. Then, the effective biases is given by

$$b_{\rm eff}(z) = \frac{\int b_{\rm DH}(M, z) \langle N_{\rm gal}(M, z) \rangle n_{\rm DH}(M, z) {\rm d}M}{\int \langle N_{\rm gal}(M, z) \rangle n_{\rm DH}(M, z) {\rm d}M}, \tag{12}$$

where $\langle N_{\rm gal}(M, z) \rangle$ is the mean number of galaxies that satisfy the selection criteria in a dark matter halo (*dark halo*) of mass M at z, $n_{\rm DH}(M, z)$ is the dark halo mass function at z and $b_{\rm DH}(M, z)$ is the bias parameter for dark halos of mass M at z. The mean number of galaxies in a dark halo $\langle N_{\rm gal}(M, z) \rangle$ is provided by our model described in the next section. For the mass function of dark halos $n_{\rm DH}(M, z)$, we adopted the Press–Schechter function [25], and for the bias parameter for dark halos $b_{\rm DH}(M, z)$, we used the formula given by [14].

3 Model for Forming Dwarf Galaxies

As shown in the previous sections, to calculate the CBR intensity and its fluctuation from galaxies, we must know the luminosity functions of galaxies (see e.g. eq. (2) and (3)). Given the number densities and SEDs of galaxies, we can obtain the luminosity functions. In order to calculate these quantities from forming dwarf galaxies, we adopt a SA-model for galaxy formation and a SED of young metal-poor galaxies.

3.1 Galaxy formation model

In the standard hierarchical structure formation scenario in a cold dark matter universe, dark halos cluster gravitationally and merge together. In each of merged dark halos, a galaxy is formed as a result of radiative gas cooling, star formation, and supernova feedback. Several galaxies in a common dark halo sometimes merge together and a more massive galaxy is assembled. In SA-models for galaxy formation, merging histories of dark halos are realized using a Monte-Carlo algorithm and evolution of baryonic components within dark halos is calculated using simple analytic models for gas cooling, star formation, supernova feedback, galaxy merging and other processes. SA-models have successfully reproduced a variety of observed features of galaxies, such as their luminosity functions, color distributions, and so on (see the recent review [5] and references therein).

In this study, we employ a SA-model for galaxy formation given by Nagashima et al. [20] and Enoki et al. [7]. Using this SA-model, we can obtain the star formation rates (SFRs) of each galaxy and the number of galaxies in a dark halo. Combined the mass function of the dark halo and the SED of each galaxy, we can calculate the luminosity functions of galaxies. From the SFRs, we can obtain the IR luminosity of each galaxy as explained in the next subsection. Finally, we can calculate $\langle N_{\mathrm{gal}}(M, z)\rangle$.

3.2 Star formation and dust production in low-metallicity, young galaxies

In order to treat the dust emission from young metal-poor galaxies, we should calculate the amount of dust and the strength of radiation field from the properties of galaxies. We adopt the updated version of Takeuchi et al. [30] model (see [32]) for the evolution of dust content and the IR SED of low-metallicity, extremely young galaxies. The SED depends on the SFR of galaxy. The SFR is given by the SA-model. We adopt the radius of the star forming region $r_{\mathrm{SF}} = 30$ pc. Dust grains are roughly divided into silicate and carbonaceous ones. Todini & Ferrara [33] have presented that the sizes of silicate and carbonaceous grains formed in SN II ejecta to be

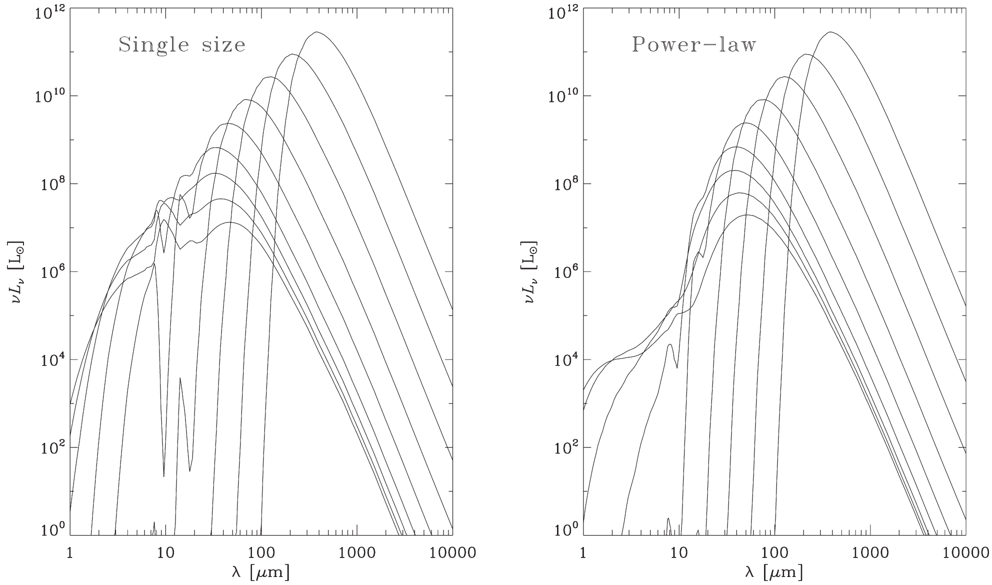

Figure 1: The IR SED we used in this work. We calculated these SEDs based on Takeuchi et al. [30, 31]. The left panel is for the IR SEDs calculated for galaxies of the single sized model, while the right panel is for IR SEDs of those with the power-law model. In each panel, lines represent SFR as $\log(\mathrm{SFR}/M_\odot \mathrm{yr}^{-1}) = -2, -1.6, -1.2, -0.8, -0.4, 0.0, 0.4, 0.8$ and 1.2 from left to right at large wavelength ($\lambda \geq 1000\ \mu$m).

about 10 Å and 300 Å, respectively. In this case, the discrete and small grain sizes make the appearance of the IR SED of young galaxies drastically different from that of aged normal galaxies. We call this "single size model". On the other hand, recently Nozawa et al. [21] have proposed a drastically different picture of dust size distribution from SNe II. They showed that, under some condition, dust grains can grow large even within the expansion timescale of SNe ejecta. Consequently, their size distributions of grains have a broken power-law shape, with a smaller fraction of very small dust grains (radius $a < 100$ Å) than that of Galactic dust. For comparison, we also consider this case by using the simplified distribution

$$\frac{d\mathcal{N}}{da} \propto \begin{cases} a^{-2.5} & 4\ \text{Å} \leq a \leq 100\ \text{Å}, \\ a^{-3.5} & 100\ \text{Å} < a \leq 1\ \mu\text{m}, \\ 0 & \text{otherwise.} \end{cases} \tag{13}$$

for both grain species, i.e., silicate or carbonaceous dust. We call this "power-law model".

In Figure 1, we show the IR SEDs for galaxies with the single size model and for those with the power-law model. Compared with the single-size model, the power law model produces larger dust grains. Thus, the amount of small dust grains in galaxies of the power-law model is smaller than that of the single-size model. As a result, the emissivity of galaxies of the power-

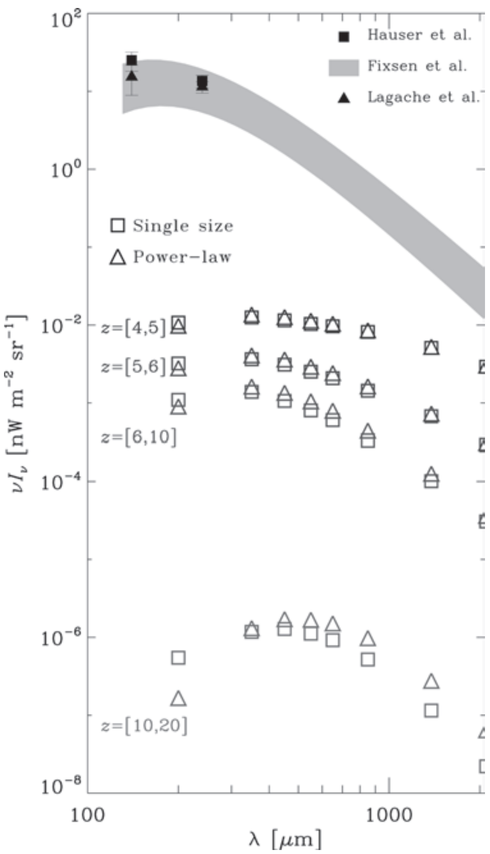

Figure 2: The contribution from dust emission of forming dwarf galaxies to the CBR intensity, $\nu_0 I_{\nu_0}$, at submm and mm wavelengths. Open symbols represent the contributions to the CBR from forming dwarf galaxies at different redshifts. Filled symbols and hatched are the measured CBR spectra by COBE [13, 8, 17].

law model is smaller in a shorter rest wavelength regime ($\lambda \leq 30-40$ μm) and larger in a longer rest wavelength regime ($\lambda \geq 40-50$ μm).

4. Results

4. 1 Background intensity from forming dwarf galaxies

We present the contributions to the CBR intensity, $\nu_0 I_{\nu_0}$, from dust emission of forming dwarf galaxies at different redshifts in Figure 2. This figure shows the main contribution to the CBR from forming dwarf galaxies at $z \sim 4$–6. Open symbols depict the forming dwarf galaxy contribution to the CBR. Observational data are taken from COBE measurements [13, 8, 17]. Clearly its intensity is very small compared to the total observed CBR spectrum. This is consistent with the picture that the CBR is dominated by dusty giant galaxies lying at $z=1$–3.

4. 2　Clustering of forming dwarf galaxies

The effective bias b_{eff} is calculated with a certain effective flux density detection limit. We put the limit flux density, 10^{-8} Jy. The evolution of $b_{\mathrm{eff}}(z)$ is presented in Figure 3. From these figures, we can see that the bias parameter becomes larger and larger in higher redshifts, and that the bias parameter of galaxies of power-law model is larger than that of single size model at longer observed wavelengths ($\lambda_0 > 200\ \mu$m). Since these are bias parameters of galaxies in flux limited sample, more luminous galaxies are selected in higher redshifts. The luminous galaxies tend to populate in large dark halos. Thus, the bias parameter becomes larger in higher redshift. The emissivity of the galaxies of the power-law model is larger than that of single size model at longer rest wavelengths ($\lambda \geq 40$–$50\ \mu$m). Thus, the number of galaxies of the power-law model in a dark halo is larger than that of single size model at longer observed wavelengths ($\lambda_0 \geq 350\ \mu$m). As a result, the effective bias parameter of power-low model is smaller than that of single size model in a longer wavelength regime.

Combining the evolutions of the effective bias parameter $b_{\mathrm{eff}}(z)$ and the space correlation function of dark matter $\xi_{\mathrm{DM}}(r, z)$, we obtain the evolution of the space correlation function of forming dwarf galaxies, $\xi_{\mathrm{gal}}(r, z)$. We show $\xi_{\mathrm{DM}}(r, z)$ in Figure 4 and $\xi_{\mathrm{gal}}(r, z)$ in Figure 5. $\xi_{\mathrm{DM}}(r, z)$ grows larger and larger with evolution, but $b_{\mathrm{eff}}(z)$ of forming dwarf galaxies gets smaller and smaller. Consequently, $\xi_{\mathrm{gal}}(r, z)$ increases with redshift as opposed to the evolution of $\xi_{\mathrm{DM}}(r, z)$ at large scales ($r \geq 1.0$ Mpc).

4. 3　Fluctuations of background radiation from dust in forming dwarf galaxies

Angular correlation functions of the fluctuation of CBR, $C_I(\theta, \nu_0)$, from dust in forming dwarf galaxies at $z=4$–20 are presented in Figure 6. Clustering signals of the power-law model case are slightly larger than those of the single size model case except at 200 μm, that is, in longer wavelength regime. This reflects the difference of galaxy correlation functions in two models.

In Figures 7 and 8, we show the contribution of the forming dwarf galaxies over $z=4$–20 to the angular power spectra of temperature fluctuation of CBR, $\delta T\nu_{0,\ell}$, from submm to mm wavelengths. The CMB power spectrum is calculated by CMBFAST [27]. The hatched areas are the total contribution of dusty galaxies predicted by Perrotta et al. [24]. The dashed curves represent the CMB power spectrum, and dotted lines depict the foreground contribution of the Galactic dust. For the Galactic dust, upper lines are the approximation of the mean dust fluctuation in the sky area at high Galactic latitude ($|b| > 80°$) estimated by Perrotta et al. [24], while

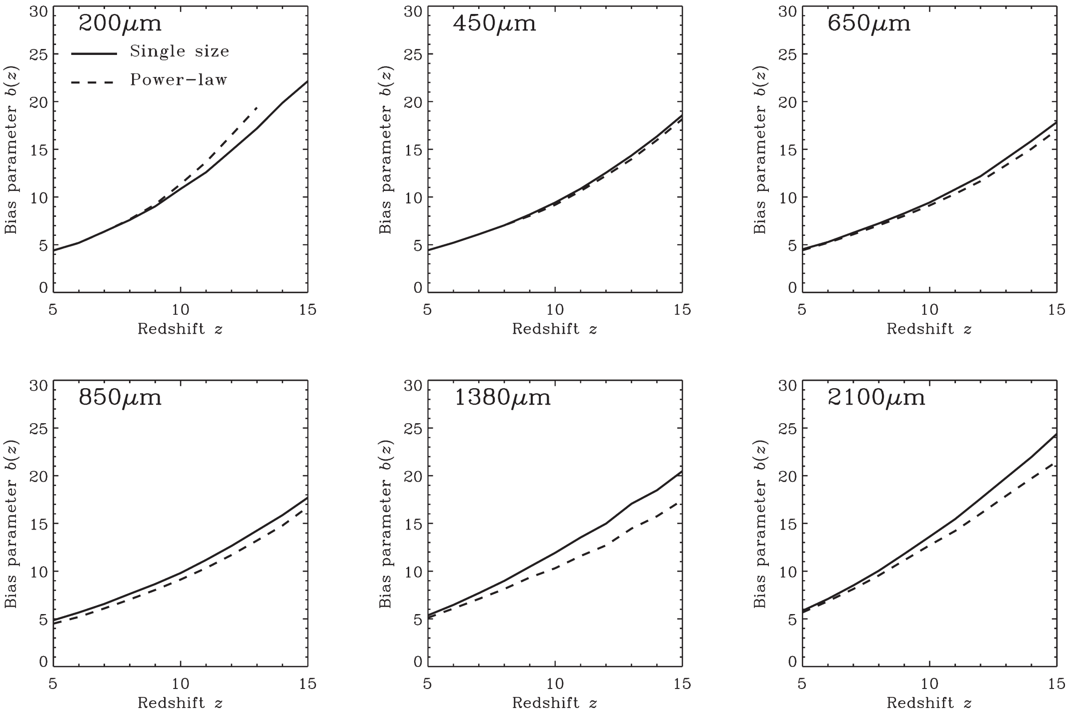

Figure 3: Evolution of the effective bias parameter $b_{\rm eff}$ for several observed wavelengths. We only show the case of the effective detection limit of flux density, 10^{-8} Jy. Solid lines represent the case of the single size model, while dashed lines show the case of the power-law model.

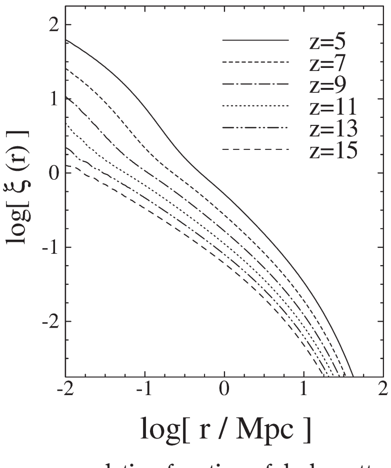

Figure 4: Evolution of the space correlation function of dark matter, $\xi_{\rm DM}(r, z)$. Lines give redshifts with interval 2 as $z = 15, 13, 11, \ldots, 5$ from bottom to top.

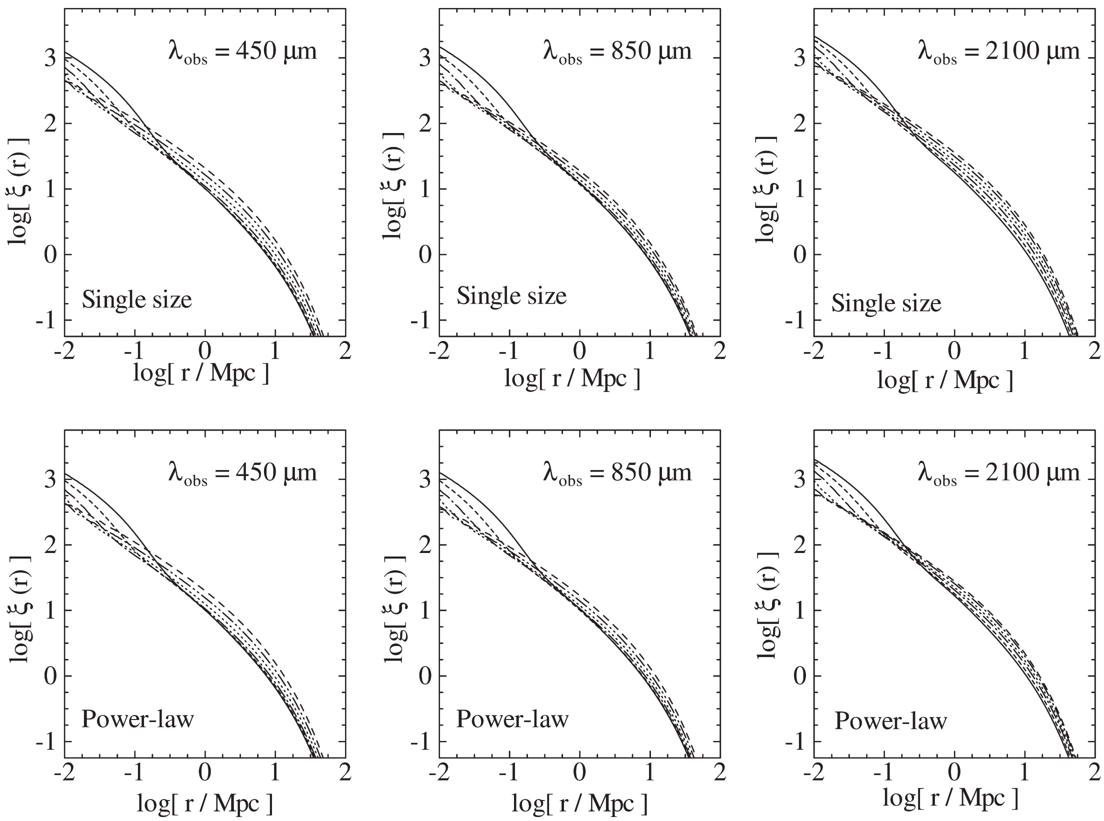

Figure 5: Evolution of space correlation functions of forming dwarf galaxies $\xi_{gal}(r, z)$ for several observed wavelengths and the case of the effective detection limit of flux density, 10^{-8} Jy. The top three panels are for galaxies of single sized model, while the bottom three are for those of power-law model. In each panel, lines give redshifts with interval 2 as $z = 15, 13, 11, \ldots, 5$ from top to bottom at large scales ($r \geq 1.0$ Mpc) as opposed to Figure 4.

the lower lines are the lowest dust column density regions (e.g., Lockman Hole). In the lowest dust column density regions, the signals from dust in forming dwarf galaxies at longer wavelengths ($\lambda_0 \geq 650\ \mu$m) and at high-ℓ in multipole expansion ($\ell \geq 3 \times 10^4$) are over the signal of the foreground contribution of the Galactic dust.

4.4 Effects of dust size distribution

Compared with a galaxy of the single sized model, a galaxy of the power-law model produces larger dust grains. Thus, the amount of small dust grains of the power-law model is smaller than that of the single-size model. As a result, the emissivity of the power-law model is smaller in a shorter rest wavelength regime ($\lambda \leq 30$–$40\ \mu$m), but larger in a longer rest wavelength regime ($\lambda \geq 40$–$50\ \mu$m). Therefore, the number of galaxies of the power-law model in limited flux

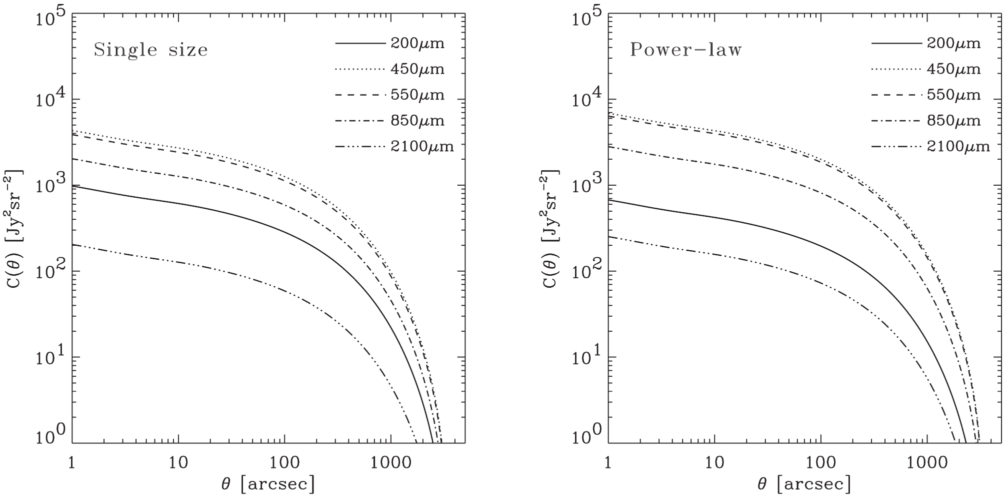

Figure 6: Angular correlation functions of the CBR fluctuation $C_I(\theta, \nu_0)$ from dust in forming dwarf galaxies at $z = 4$–20 for several observed wavelengths. Left panel is for galaxies of single size model, while right panel is for galaxies of power-law model.

sample in a dark halo is smaller than that of single size model at shorter observed wavelengths ($\lambda_0 \leq 200\ \mu$m), but larger at longer observed wavelength ($\lambda_0 \geq 350\ \mu$m). This affects the properties of clustering of forming dwarf galaxies and CBR from dust emission of forming dwarf galaxies.

However, as seen in the previous subsections, the difference of dust size distribution affects the results little for all of the observable considered here. It means that these observations are not useful to constrain the size distribution of the dust grains. On the other hand, it also suggests that these predictions are quite robust against the difference of grain size distributions, or assumed SEDs.

5. Observability of CBR fluctuation from dust emission of forming dwarf galaxies

5. 1 Comparison with other contributors to the CBR fluctuation

The longer the wavelength is, the signal from dust in forming dwarf galaxies becomes weaker. Hence, we should take into account another source of fluctuation. One source is gravitational lensing of the CMB. Zaldarriaga [34] calculated the lens-distorted power spectrum of the CMB temperature fluctuation. His result shows that the effect is generally small compared to the signal of dust emission in forming dwarf galaxies at the submm regime, and only at the mm regime, lensing fluctuation power would be important.

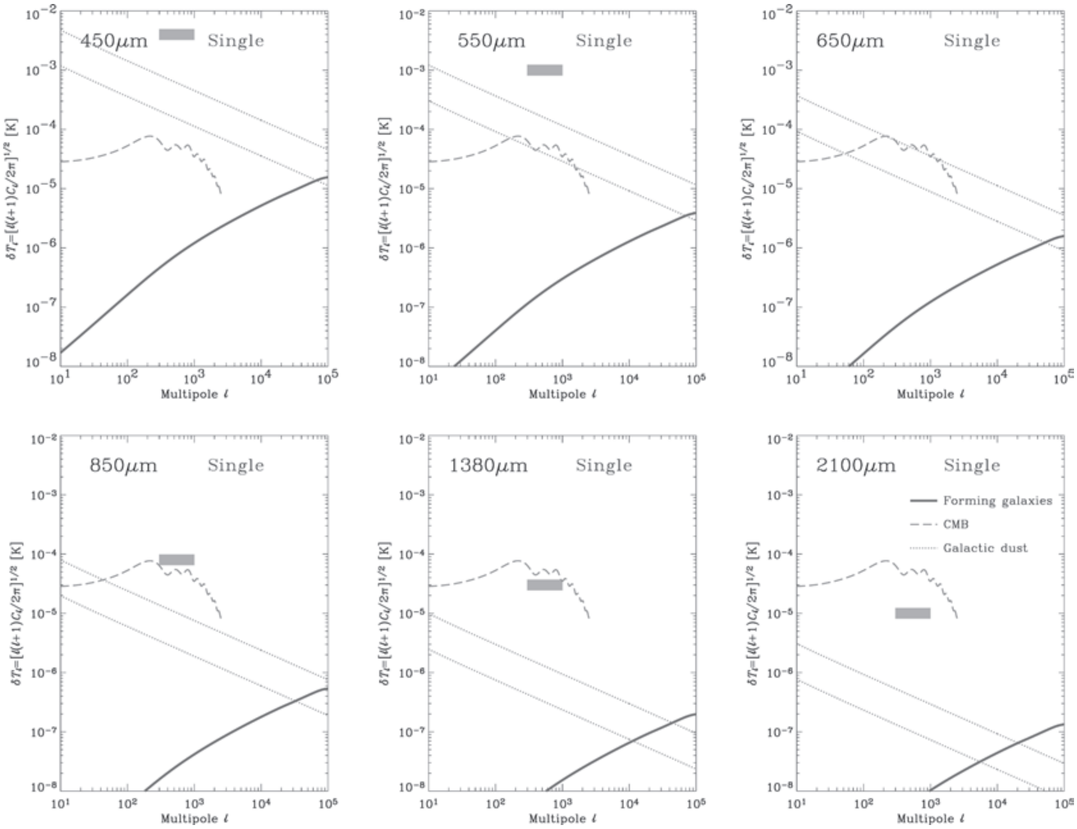

Figure 7: The contribution of dust emission of the forming dwarf galaxies over $z = 4$–20 to angular power spectra of temperature fluctuation of CBR, $\delta T_{\nu_0,\ell}$, from submm to mm wavelengths. The dust size distribution is single-sized. The hatched areas are the total contribution of dusty galaxies predicted by Perrotta et al. [24]. The dashed curves represent the CMB power spectrum, and dotted lines depict the foreground contribution of the Galactic dust. For the Galactic dust, upper lines are the approximation of the mean dust fluctuation in the sky area at high Galactic latitude (|b|>80°) estimated by Perrotta et al. [24], while the lower lines are the lowest dust column density regions (e.g., Lockman Hole).

The thermal and kinetic Sunyaev-Zel'ovich (SZ) effects are the dominant CBR sources at arcmin scales. Thermal SZ effects can be extracted using multifrequency cleaning for observation at 217 GHz. Zhang et al. [35] show that the contribution from kinetic SZ effects is about $\delta T_l \sim 3 \times 10^{-6}$K at $3000 < l < 10000$. The effect of the inhomogeneous intergalactic medium reionization is also the CBR sources at $l \geq 4000$. Salvaterra et al. [26] show that the signal due to patchy reionization is also $\delta T_l \sim 10^{-6}$K at $3000 < l < 10000$. These values are comparable with our predictions at $650 \leq \lambda_0 \leq 850$ μm and larger at $\lambda_0 \geq 1000$ μm. Therefore, it may be difficult to observe the fluctuation from dust emission of forming dwarf galaxies. At least, the signal from dust emission in forming dwarf galaxies would be a *noise source* for measurement of kinetic SZ

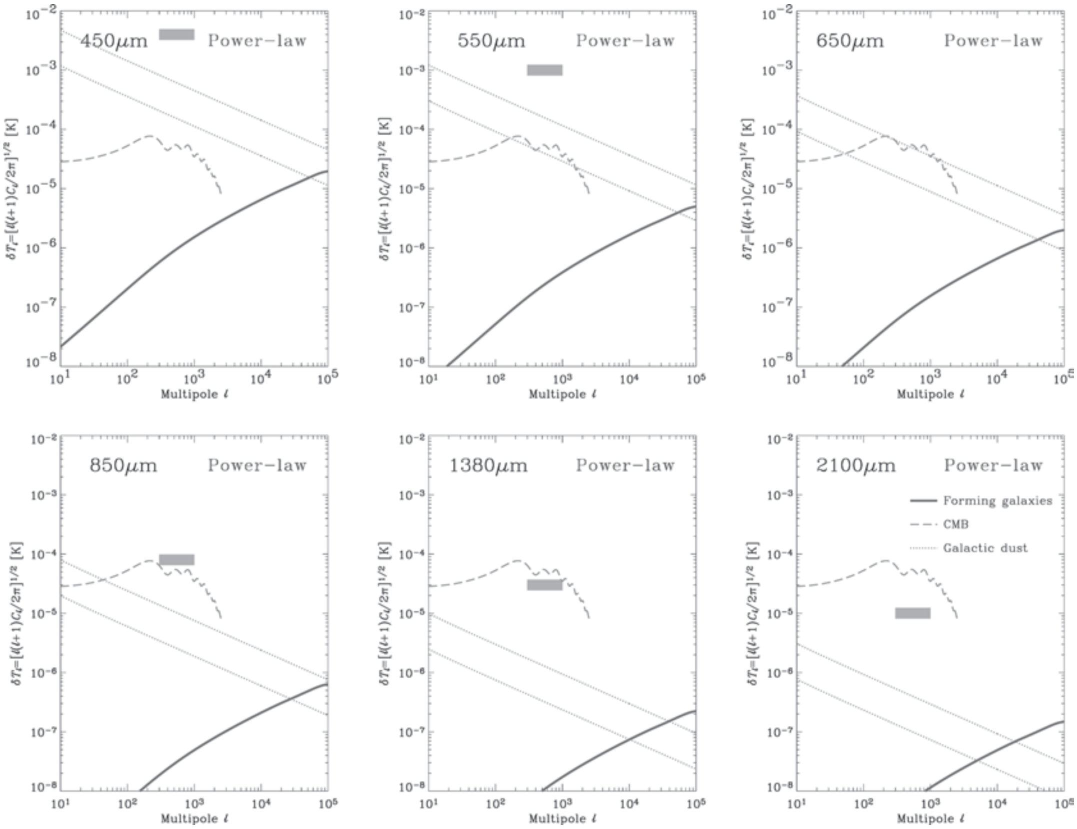

Figure 8: The same as Fig. 7 but the dust size distribution is power-law.

effects. However, the amplitude dependence on wavelengths of forming dwarf galaxies is different from that of kinetic-SZ effects. Therefore, it is not impossible to detect signal from dust emission in forming dwarf galaxies. The subtraction of different wavelength images is a valid method for detecting the signal.

5. 2 Suggestion to the observational strategy

Our model predicts that the fluctuation signal at high-ℓ in multipole expansion ($\ell \geq 3\times10^4$, or $\theta \leq 20''$) is over the signal of foreground contribution from Galactic dust. Interferometry is clearly the best way for such a high angular-resolution observation. Since the sensitivity of an interferometer to a diffuse radiation is essentially determined by the ratio between the observed wavelength λ_0 and the length of the longest baseline B, λ_0/B, we should make a configuration with baselines short enough to resolve the required angular scale.

Here we should note that, of course, we cannot configure the antennas closer than their diameter. To overcome this problem, there are two strategies: One is to use a small diameter antenna, and the other is to map the sky by one antenna and use the obtained data as very short-baseline ($B \simeq 0$) data. The first method will be used by ALMA ACA. It has an additional advantage that we can have a larger field-of-view because of the small diameter. The second one is realized by BIMA array and NRAO 12-m radio telescope, and VLA and GBT 100m.

6. Summary and conclusions

We constructed a new SA model of the evolution of interstellar dust emission of forming dwarf galaxies based on the cosmological hierarchical clustering scenario. By its construction, our model naturally includes the formation of dark halos and the evolution of baryonic structures in a quite simple but consistent way. Using this model, we predict the contribution from dust emission of forming dwarf galaxies at $z > 4$ to the fluctuation of CBR in the IR - mm. Since the small grain sizes in young metal-poor galaxies make the appearance of their IR SED quite different from that of nearby older galaxies, we adopt a new model for the evolution of dust content and the IR SED of low-metallicity, extremely young galaxies.

Though the contribution to the CBR intensity is small compared with that of giant submillimeter sources at $z = 1$–3, fluctuation signal at high-ℓ in multipole expansion ($\ell \geq 3 \times 10^4$, or $\theta \leq 20''$) is unique to these forming populations. Considering the wavelength dependence of the power spectra of CBR fluctuation from dust emission of forming galaxies, the emission from the Galactic dust and other fluctuation source such as SZ effects, the signal could be detected in the submm and mm channels. At least, the signal from dust emission in forming dwarf galaxies would be a noise source for measurement of kinetic SZ effects. However, the amplitude dependence on wavelengths of forming dwarf galaxies is different from that of kinetic SZ effects. Hence, comparing our predictions with forthcoming future observations will provide crucial information to constrain the physical processes of galaxies in their early formation phase. It is also useful to construct observational strategies for future facilities, e.g., like ALMA.

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