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Curvature perturbation from velocity modulation

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Abstract

We propose a new variant model of the modulated reheating. If particles have large scale fluctuations on their velocities, or equivalently their Lorentz factors, the decay rate also fluctuates and the curvature perturbation is induced via their decay processes in analogy with modulated reheating. For example, if they are produced nonthermally by the decay of another field with its mass fluctuating on large scales, such a situation is realized. We explicitly calculate the resulting curvature perturbation and non-linearity parameters and show that the effect of velocity-modulation is not negligible if the particles are semi-relativistic at the decay.

I. INTRODUCTION

High accuracy measurements of the cosmic microwave background (CMB) anisotropy revealed that the cosmological density perturbations obey the nearly scale-invariant power spectrum [1]. The inflaton, which drives the inflationary expansion of the very early Universe, has quantum fluctuations on large scales and it is a prime candidate for the origin of the nearly scale invariant curvature perturbation [2].

However, it was recognized that the curvature perturbation can be generated without invoking the quantum fluctuation of the inflaton itself. There may be many scalar fields in the physics beyond the standard model, and some of which may be light during inflation and obtain quantum fluctuations. In the curvaton mechanism [3–7], such a light scalar other than the inflaton, called curvaton, is responsible for the curvature perturbation. Another possibility is to make the inflaton decay rate fluctuate due to another light scalar having large scale perturbations [8, 9]. Then the radiation produced by the inflaton decay has curvature perturbation even if the inflaton itself does not have enough fluctuations. This is called the modulated reheating scenario. Mechanisms for generating the curvature perturbation which shares a similar idea to the modulated reheating have been proposed [10–20].

In this paper we propose a new mechanism to generate the curvature perturbation, which is a variant type of the modulated reheating scenario. The idea is that if a particle velocity is fluctuating on large scales, its decay rate also does since the lifetime of a particle receives a spatially fluctuating Lorentz boost. Therefore, the modulated reheating is realized even if an intrinsic decay rate does not depend on some fluctuating scalar fields as in the original modulated reheating scenario.

As a concrete example, such a large scale fluctuation in the particle velocity is generated if it is produced nonthermally by the decay of a heavier particle whose mass depends on another light scalar with large scale fluctuations.[1] In this setup, modulated reheating

[1] Here the fluctuation of the particle velocity should not be confused with the "velocity perturbation" usually used in the cosmological context. The former refers to the velocity of each particle while the

occurs at two stages : one is at the decay of a heavier particle with a fluctuating mass, the other is at the decay of a daughter particle whose velocity is fluctuating. The final curvature perturbation receives both of the two contributions, as well as that generated by the inflaton. We will systematically calculate the resulting curvature perturbation and estimate the non-Gaussianity, and find that the effect of modulated velocity is important if the velocity at the decay is not much smaller than the speed of light.

II. BASIC IDEA

Let us suppose that a particle σ has a decay width of $\bar{\Gamma}_\sigma$ at the σ rest frame and that its velocity is given by v in the laboratory frame. Due to the time delay effect, the effective decay rate of σ in the laboratory looks like $\Gamma_\sigma = \bar{\Gamma}_\sigma/\gamma$ where $\gamma = (1-v^2)^{-1/2}$.

Then let us imagine a situation that the σ particles are non-interacting and have a monochromatic velocity distribution within a small patch of the Universe but on large scales their velocities fluctuate. More precisely, we assume that the velocities of σ-particles have large scale fluctuations on the decay hypersurface ($H(\vec{x}) = \Gamma_\sigma(\vec{x})$ in the sudden decay approximation where H is the Hubble parameter). On this surface, σ has a velocity of

$$v(\vec{x}) = \bar{v} + \delta v(\vec{x}). \tag{1}$$

Finally the σ-particles decay into radiation. Since the decay hypersurface does not coincide with the uniform density hypersurface due to the fluctuated Lorentz factor, the curvature perturbation is induced at the σ-decay. In this setup, the curvature perturbation is estimated as

$$\zeta \sim \Omega_\sigma \frac{\delta\Gamma_\sigma}{\Gamma_\sigma} = -\Omega_\sigma \frac{\delta\gamma}{\gamma} = \Omega_\sigma \gamma^2 \bar{v} \delta v, \tag{2}$$

where Ω_σ is the energy density of the σ at the decay relative to the total energy density and $\delta\Gamma_\sigma(\vec{x}) \equiv \Gamma_\sigma(\vec{x}) - \Gamma_\sigma$. Thus the large scale fluctuation on the velocity can be converted to the curvature perturbation via the modulated reheating. Obviously, if the σ particles are non-relativistic ($v \to 0$), such an effect is negligible. Also in the ultra-relativistic

latter is the average velocity as the fluid. In the present paper we are interested in the former.

limit ($v \to 1$), the curvature perturbation is not generated since the equation of state of the Universe does not change across the σ-decay. Therefore, this effect is expected to be important if the σ particles are semi-relativistic $v \sim \mathcal{O}(1)$. If the δv is a Gaussian random variable, then the corresponding curvature perturbation is also Guassian at the linear order in δv.

This is a generic idea and may have a potential of broad applications. In the next section we provide a concrete setup which results in the velocity fluctuation and induces the curvature perturbation.

III. A MODEL OF VELOCITY MODULATION AND CURVATURE PERTURBATION

A. Outline

We consider a situation that non-relativistic scalar condensate of the Σ field decays into relativistic σ-particles and subsequently σ-particles decay into radiation[2]. Our key assumption is that the mass of Σ spatially fluctuates. This can be achieved if the mass is dependent on a light scalar field which acquired spatial fluctuations during inflation. Such fluctuations of the mass result in the generation of the primordial curvature perturbations through two different processes. In the following, let us roughly estimate the resulting curvature perturbation. More detailed calculations will be given later.

If the mass of Σ spatially fluctuates, then generically the decay rate does too. Let us suppose that σ is a fermion. The Σ decays into a σ pair through the yukawa interaction,

$$\mathcal{L} = y\Sigma\sigma\bar{\sigma}, \tag{3}$$

where y is the yukawa coupling constant, then the decay rate is given by

$$\Gamma(\Sigma \to \sigma\bar{\sigma}) \equiv \Gamma_\Sigma = \frac{y^2}{8\pi} m_\Sigma. \tag{4}$$

[2] The assumption that Σ is a scalar field is not essential to achieve the velocity modulation. The mechanism can work for the cases where Σ is not a scalar field as well.

If σ is a scalar, Σ can decay into them through the three point interaction,

$$\mathcal{L} = \mu \Sigma \sigma \sigma, \tag{5}$$

where μ is a coupling constant having mass dimension one. Then the decay rate is given by

$$\Gamma(\Sigma \to \sigma\sigma) \equiv \Gamma_\Sigma = \frac{\mu^2}{8\pi m_\Sigma}. \tag{6}$$

It is clear from these equations that fluctuation of m_Σ is taken over by Γ_Σ. For concreteness we assume σ is a fermion in the following, although qualitative arguments do not depend on whether it is a fermion or scalar. The density fluctuations of σ are produced when Σ decays;

$$\frac{\delta\rho_\sigma}{\rho_\sigma} \simeq \frac{\delta m_\Sigma}{m_\Sigma}. \tag{7}$$

This is exactly the same mechanism of generating the curvature perturbation in the modulated reheating scenario.

Since each σ-particle has an energy $m_\Sigma/2$ when it is produced, velocity of the produced σ-particle is given by

$$v_0 = \frac{\sqrt{m_\Sigma^2 - 4m_\sigma^2}}{m_\Sigma}. \tag{8}$$

It is clear that the velocity v also fluctuates if m_Σ fluctuates. We assume that the interaction of σ-particle is sufficiently weak so that it does not take part in thermal bath and the velocity remains constant except for the redshift by the cosmic expansion.[3] Otherwise, the σ-particles obey thermal distribution with a background temperature of the radiation and the velocity fluctuation will be smoothed out as long as σ is subdominant. Now, let us suppose that the velocity of σ-particle has dropped to v_1 due to the cosmological redshift when σ-particles decay. Taking into account the effect of time delation, the decay rate of σ is given by

$$\Gamma(\sigma \to \text{radiation}) \equiv \Gamma_\sigma = \bar{\Gamma}_\sigma \sqrt{1 - v_1^2}, \tag{9}$$

[3] The σ-particles can scatter off themselves by the exchange of Σ. This process is suppressed if the coupling constant between Σ and σ is small and/or the Σ is heavy enough.

where $\bar{\Gamma}_\sigma$ is the decay rate measured at the rest frame. Since v_1 is position dependent, this equation manifests that the decay rate of σ spatially fluctuates too;

$$\frac{\delta \Gamma_\sigma}{\Gamma_\sigma} \simeq v_1^2 \frac{\delta m_\Sigma}{m_\Sigma}. \tag{10}$$

Again, the modulation of Γ_σ gives additional contribution to the curvature perturbation. Denoting by Ω_σ a fraction of σ-particles when they decay, we expect that the final curvature perturbation ζ is given by

$$\zeta \simeq \Omega_\sigma \frac{\delta \rho_\sigma}{\rho_\sigma} + \Omega_\sigma \frac{\delta \Gamma_\sigma}{\Gamma_\sigma} \simeq \Omega_\sigma (1 + v_1^2) \frac{\delta m_\Sigma}{m_\Sigma}. \tag{11}$$

Therefore, if σ-particles are still relativistic when they decay, i.e. $v_1 = \mathcal{O}(1)$, then the effect of the velocity modulation on the final curvature perturbation cannot be neglected.

B. Calculation of the curvature perturbation

Now let us evaluate the curvature perturbation based on the δN-formalism [21, 22]. We adopt the so-called sudden decay approximation in which the decay of Σ or σ-particles is assumed to occur instantaneously when the decay rate becomes equal to the Hubble expansion rate [23].

Let us take a hypersurface just before the Σ field decays on which the total energy density is spatially uniform (uniform density hypersurface). We here assume that Σ begins to oscillate in a period between the end of inflation and the completion of reheating where the universe expands like a matter-dominated universe and that the initial amplitude is constant. In this case the energy density of the Σ condensation does not fluctuate on the uniform density slice even if its mass fluctuates.[4] Since no fluctuations exist before Σ decays, this hypersurface coincides with the spatially flat hypersurface. Let us denote by δN_1 a required e-folding number from the flat hypersurface to the decay hypersurface

[4] If, otherwise, the Σ begins to oscillate during the radiation-dominated era after the reheating, the energy density of Σ itself also has fluctuations. We do not consider such a case since it only makes the following analyses more complicated.

on which Σ decays into σ-particles. Since Γ_Σ spatially fluctuates, δN_1 does too. Thus we have

$$\bar{\rho}_r e^{-4\delta N_1} + \bar{\rho}_\Sigma e^{-3\delta N_1} = \bar{\rho}_{\rm tot}\left(1+\frac{\delta\Gamma_\Sigma}{\Gamma_\Sigma}\right)^2, \qquad (12)$$

where ρ_r and ρ_Σ denote the energy densities of the radiation and Σ at the Σ-decay. The total energy density is given by $\rho_{\rm tot} = \rho_r + \rho_\Sigma$. Quantities with bars represent the background values. This is rewritten in the form as

$$(1-\Omega_\Sigma)e^{-4\delta N_1} + \Omega_\Sigma e^{-3\delta N_1} = \left(1+\frac{\delta\Gamma_\Sigma}{\Gamma_\Sigma}\right)^2. \qquad (13)$$

where $\Omega_\Sigma \equiv \bar{\rho}_\Sigma/\bar{\rho}_{\rm tot}$ at the Σ-decay. Let us next consider a hypersurface just after the Σ decays on which ρ_σ is spatially uniform and denote by δN_2 a required e-folding number from the decay hypersurface to uniform ρ_σ hypersurface. Then equation for δN_2 is given by

$$e^{-3\delta N_1} e^{-3(1+w_0)\delta N_2} = 1, \qquad (14)$$

where w_0 is the effective equation of state parameter $w_0 = P_\sigma/\rho_\sigma$ of σ evaluated on the decay surface. According to the δN formalism, the sum of δN_1 and δN_2 gives the curvature perturbation of the uniform ρ_σ hypersurface;

$$\zeta_\sigma = \delta N_1 + \delta N_2. \qquad (15)$$

Eqs. (13), (14) and (15) allow us to express ζ_σ in terms of $\delta\Gamma_\Sigma$, which we defer. Unless w_0 is zero, ζ_σ is non-vanishing, as it should be. Since σ-particles do not interact with the other particles, ζ_σ is conserved until σ-particles decay into radiation. On the other hand, ζ_r, the curvature perturbation on the uniform ρ_r hypersurface, is zero since we assume that Σ decays only into σ-particles.

Now we consider a difference between a hypersurface on which σ-particles decay into radiation and a one on which ρ_σ is uniform. Let us denote by δN_3 a required e-folding number from uniform ρ_σ hypersurface to σ decay hypersurface. Then we obtain

$$\bar{\rho}_\sigma e^{-3(1+w_1)\delta N_3} + \bar{\rho}_r e^{-4(\zeta_\sigma+\delta N_3)} = \bar{\rho}_{\rm tot}\left(1+\frac{\delta\Gamma_\sigma}{\Gamma_\sigma}\right)^2. \qquad (16)$$

This is rewritten as

$$\Omega_\sigma e^{-3(1+w_1)\delta N_3} + (1-\Omega_\sigma) e^{-4(\zeta_\sigma+\delta N_3)} = \left(1+\frac{\delta\Gamma_\sigma}{\Gamma_\sigma}\right)^2, \tag{17}$$

where $\Omega_\sigma \equiv \bar{\rho}_\sigma/\bar{\rho}_{\rm tot}$ on the σ-decay surface and w_1 is the effective equation of state parameter of σ on this hypersurface. Let us next consider a hypersurface just after the σ-particles decay on which radiation energy density is spatially uniform and denote by δN_4 a required e-folding number from the σ decay hypersurface to the uniform density hypersurface. Then we have the following relation

$$e^{4\delta N_4} = \left(1+\frac{\delta\Gamma_\sigma}{\Gamma_\sigma}\right)^2. \tag{18}$$

The final curvature perturbation is given by

$$\zeta = \zeta_\sigma + \delta N_3 + \delta N_4. \tag{19}$$

From Eqs. (17) and (18), we can express both δN_3 and δN_4 as a function of $\delta\Gamma_\sigma$. Therefore, ζ can be written in terms of $\delta\Gamma_\Sigma$ and $\delta\Gamma_\sigma$. Note that Ω_Σ and Ω_σ are related through

$$\Omega_\sigma = \frac{\Omega_\Sigma}{\Omega_\Sigma + (1-\Omega_\Sigma)\exp\left[\int 3H(1+w(t))dt - 4N\right]}, \tag{20}$$

where the e-folding number N measures the duration between the Σ and σ decay hypersurfaces and $w(t)$ denotes the time-dependent equation of state of the σ particle. The integral in the exponent starts from the time of Σ-decay and ends at the σ-decay. It is soon seen that in the relativistic limit $w=1/3$, Ω_σ remains constant as is expected. The equation of state of σ at its production (w_0) and decay (w_1) are also related. First note that the equation of state of the σ is given by

$$w(t) = \frac{P_\sigma}{\rho_\sigma} = \frac{p^2(t)}{3(p^2(t)+m_\sigma^2)}, \tag{21}$$

because it has a monochromatic momentum distribution in the sudden decay approximation, where $p(t)$ is the momentum of the σ particle. Then we obtain

$$w_1 = \frac{w_0}{(1-3w_0)e^{2N}+3w_0}. \tag{22}$$

Since each σ-particle has an energy of $m_\Sigma/2$ at the time of their creation, w_0 can be written as

$$w_0 = \frac{m_\Sigma^2 - 4m_\sigma^2}{3m_\Sigma^2}. \tag{23}$$

To get the final expression for the curvature perturbation, we need to express $\delta\Gamma_\Sigma$ and $\delta\Gamma_\sigma$ as the functions of δm_Σ. As for the former, it is already given by Eq. (4). As for the latter, the decay rate of σ is calculated from

$$\Gamma_\sigma = \bar{\Gamma}_\sigma \sqrt{1 - 3w_1}. \tag{24}$$

Through Eqs. (24), (22) and (23), we see that Γ_σ is related to m_Σ. To third order in δm_Σ, we find

$$\frac{\delta\Gamma_\sigma}{\Gamma_\sigma} = -\frac{w_1}{w_0}\frac{\delta m_\Sigma}{m_\Sigma} - \frac{(w_0 - 3w_1)w_1}{2w_0^2}\left(\frac{\delta m_\Sigma}{m_\Sigma}\right)^2 + \frac{(3w_0 - 5w_1)w_1^2}{2w_0^3}\left(\frac{\delta m_\Sigma}{m_\Sigma}\right)^3. \tag{25}$$

Using these results obtained above, we can Taylor-expand ζ in terms of δm_Σ to any order. To third order, it is given by

$$\zeta = A_1\frac{\delta m_\Sigma}{m_\Sigma} + \frac{1}{2}A_2\left(\frac{\delta m_\Sigma}{m_\Sigma}\right)^2 + \frac{1}{6}A_3\left(\frac{\delta m_\Sigma}{m_\Sigma}\right)^3, \tag{26}$$

where A_1 is given by

$$A_1 = \frac{\Omega_\sigma\left[12w_0^2(w_1+1) - w_1(w_0+1)(3w_1-1)(\Omega_\Sigma - 4)\right]}{2w_0(w_0+1)(\Omega_\Sigma - 4)((3w_1 - 1)\Omega_\sigma + 4)}. \tag{27}$$

The other expansion coefficients A_2 and A_3 are given in the appendix. Let us confirm that apart from the $\mathcal{O}(1)$ numerical factors, Eq. (27) reproduces the naive expectation Eq. (11). First, we see that A_1 is proportional to Ω_σ (It can be confirmed that A_2 and A_3 are also proportional to Ω_σ.). Therefore, ζ of Eq. (26) is proportional to Ω_σ and vanishes in the limit $\Omega_\sigma \to 0$, which is also true for the naive expectation. Secondly, let us expand A_1 in terms of w_1;

$$A_1 = \frac{3\Omega_\sigma}{8(\Omega_\sigma - 4)} + \frac{9\Omega_\sigma}{2(\Omega_\sigma - 4)^2}w_1 + \mathcal{O}(w_1^2), \tag{28}$$

where we have set $\Omega_\Sigma = 0,\ w_0 = 1/3$ for simplicity.[5] We see that the first term remains even if we set $w_1 = 0$. Therefore, this term represents the contribution of $\delta\rho_\sigma$ in Eq. (11),

[5] Actually Ω_σ and Ω_Σ are related through Eq. (20). We can always take $\Omega_\Sigma \ll \Omega_\sigma$ by choosing N and w_0.

which originates from the modulation of Γ_Σ. On the other hand, the second term in Eq. (28) is proportional to w_1 and hence proportional to v_1^2. This corresponds to the second term in Eq. (11) and is due to the modulation of Γ_σ.

From Eq. (26), the scalar spectral index, n_s, is calculated as [24]

$$n_s = 1 - 2\epsilon - \frac{4\epsilon - 2\eta}{1 + 2M_P^2 \epsilon N_\chi^2}, \tag{29}$$

where we have defined N_χ through $A_1 \delta m_\Sigma / m_\Sigma \equiv N_\chi \delta\chi$ with χ being the light field giving spatial modulation to the Σ mass, M_P denotes the reduced Planck scale, and ϵ and η are inflationary slow-roll parameters [2]. If the inflaton dominantly contributes to the curvature perturbation, we recover the standard formula, $n_s = 1 - 6\epsilon + 2\eta$. Otherwise, it approaches to $n_s = 1 - 2\epsilon$, similarly to the curvaton case.

C. Non-linearity parameters

In this paper, we consider the simplest case where δm_Σ is a gaussian variable. For simplicity, let us assume that Σ is subdominant when they decay, i.e., $\Omega_\Sigma \ll 1$ and σ-particles are relativistic when they are created, i.e., $w_0 = 1/3$. Hereafter we neglect the contribution of the inflaton fluctuation to the curvature perturbation and the dominant contribution to the curvature perturbation comes from the fluctuation of m_Σ. With these assumptions, the non-linearity parameters are given by[6]

$$\begin{aligned} f_{\rm NL} = \ & \frac{20}{9(3w_1(4w_1-1)+1)^2 \Omega_\sigma((3w_1-1)\Omega_\sigma+4)} \\ & \times \Big[w_1(36w_1(2w_1-1)+5)+1)(\Omega_\sigma - 3w_1\Omega_\sigma)^2 \\ & + 2(w_1(3w_1(24w_1(6w_1-7)+35)+10)-7)\Omega_\sigma \\ & + 2w_1(9w_1(8w_1(6w_1+5)-21)+22)+22 \Big], \end{aligned} \tag{30}$$

$$\tau_{\rm NL} = \frac{36}{25} f_{\rm NL}^2, \tag{31}$$

[6] The non-linearity parameters for the standard modulated reheating case are given in Ref. [25].

$$g_{\rm NL} = \frac{800}{243(3w_1(4w_1-1)+1)^3\Omega_\sigma^2(-3w_1\Omega_\sigma+\Omega_\sigma-4)^2}$$
$$\times \Big[(3w_1-1)(w_1(3w_1(27w_1(4w_1(96w_1(2w_1-3)+127)-75)-43)-97)+41)\Omega_\sigma^3$$
$$+3(w_1(3w_1(9w_1(w_1(12w_1(8w_1(36w_1+19)-413)+2579)-416)+262)-500)+133)\Omega_\sigma^2$$
$$+2(w_1(36w_1(3w_1-1)(4w_1-1)+1)+1)(\Omega_\sigma-3w_1\Omega_\sigma)^4$$
$$+2(w_1(3w_1(3w_1(3w_1(12w_1(12(37-12w_1)w_1+133)-5177)+4570)-728)+674)-517)\Omega_\sigma$$
$$+4(w_1+1)(9w_1(w_1(12w_1(36w_1(4w_1+9)-181)+265)-2)+209)\Big]. \qquad (32)$$

In Fig. 1 and 2, we show plots of $f_{\rm NL}$, $\tau_{\rm NL}$ and $g_{\rm NL}$ as a function of w_1 for three cases $\Omega_\sigma = (0.2,\ 0.5,\ 1.0)$. From this, we see that $f_{\rm NL}$ is always positive. For fixed w_1, the smaller Ω_σ is, the larger $f_{\rm NL}$ is. Actually, we can easily show from Eq. (30) that $f_{\rm NL} \simeq \Omega_\sigma^{-1}$ when Ω_σ is small. The mechanism of this boost of $f_{\rm NL}$ is exactly the same as that in the curvaton model in which $f_{\rm NL}$ is inversely proportional to curvaton fraction evaluated at the time when the curvaton decays. For fixed Ω_σ, $f_{\rm NL}$ has a maximum at $w_1 \simeq 0.1$ and that the maximum value is roughly two times larger than $f_{\rm NL}$ at $w_1 = 0$. Therefore, if the motion of σ-particles are mildly relativistic, then the effect of the velocity modulation can double $f_{\rm NL}$.

We also find that $g_{\rm NL}$ is always positive and $\tau_{\rm NL}$ is always larger than $g_{\rm NL}$. Noticing that their difference is less than a factor 2 and using Eq. (31), we have $g_{\rm NL} = \mathcal{O}(f_{\rm NL}^2)$. Therefore, in this model, both $\tau_{\rm NL}$ and $g_{\rm NL}$ become large when $f_{\rm NL}$ is large.

IV. CONCLUSIONS AND DISCUSSION

We have shown that the curvature perturbation can be sourced by the decay of particles with velocity modulation. We have given a concrete setup for realizing such a scenario. A class of modulated reheating scenario in which the mass of decaying particle fluctuates generates a velocity modulation of daughter particles, which may result in the additional source of curvature perturbation. The non-Gaussian signatures may also be enhanced due to the velocity-modulation effects.

One can easily construct a variant model. For example, let us suppose that the mass of

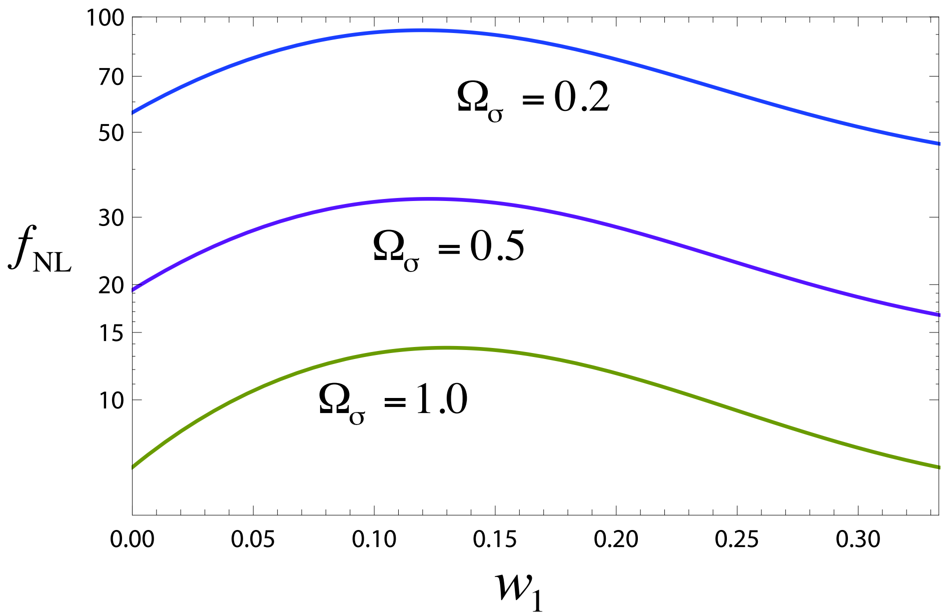

FIG. 1: Plots of $f_{\rm NL}$ as a function of w_1 for three cases $\Omega_\sigma = (0.2,\ 0.5,\ 1.0)$.

Σ does not fluctuate but the σ-mass does. The velocity of σ, produced by the Σ-decay, also fluctuates in this case and the velocity modulation can generate the curvature perturbation at the σ-decay in a same manner.

The same mechanism may generate the CDM/baryon isocurvature perturbation if the σ-decay produces CDM/baryon. Actually σ can be identified with the right-handed neutrino N_R while Σ with a scalar field giving the mass for N_R. The relevant interaction Lagrangian is given by

$$\mathcal{L} = \left(y_i \Sigma N_{Ri} \bar{N}^c_{Ri} + y^{(\nu)}_{ij} H L_i \bar{N}_{Rj} + \text{h.c.} \right) - V(\Sigma), \tag{33}$$

where i, j are generation indices and the scalar potential of Σ is taken to be

$$V(\Sigma) = -\mu_\Sigma^2 |\Sigma|^2 + \lambda |\Sigma|^4. \tag{34}$$

Here H is the standard model Higgs boson and L_i is the lepton doublet. The Σ mass around the vacuum, $m_\Sigma = 2\mu_\Sigma$, is assumed to depend on another light scalar having large scale fluctuations. This model possesses a global $\mathrm{U}(1)_L$ or gauged $\mathrm{U}(1)_{B-L}$ symmetry

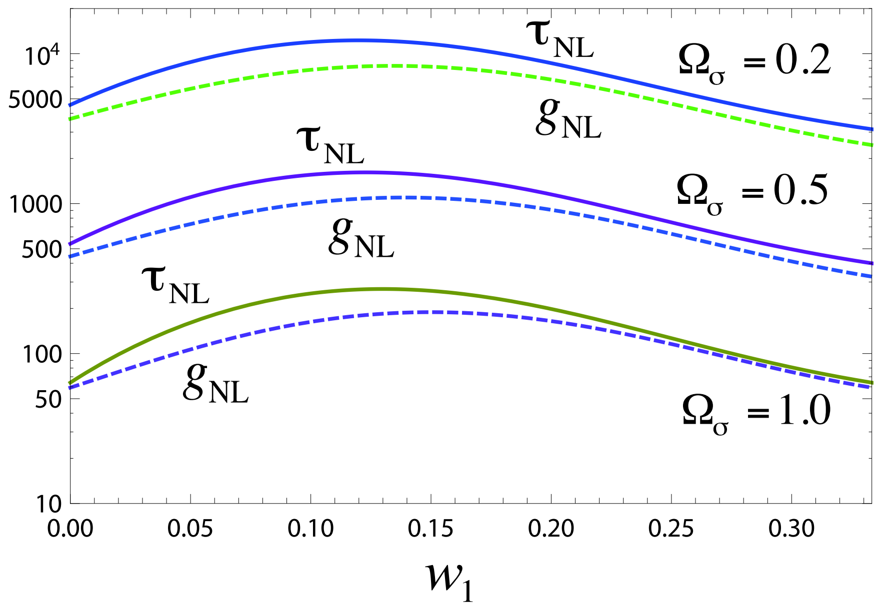

FIG. 2: Plots of $\tau_{\rm NL}$ and $g_{\rm NL}$ as a function of w_1 for three cases $\Omega_\sigma = (0.2,\ 0.5,\ 1.0)$.

which is spontaneously broken by the VEV of Σ.[7] In this model Σ decays into the N_R-pair, and subsequently N_R decays into the Higgs boson and lepton, generating the lepton asymmetry (which is converted to the baryon asymmetry through the sphaleron process) if the CP angle is nonzero [27]. Since N_R has a large scale velocity modulation, the baryon number created by its decay also has fluctuations. If the Σ or N_R decay gives dominant curvature perturbation, there is no baryonic isocurvature perturbation. On the other hand, if the curvature perturbation is dominantly sourced by the inflaton fluctuation, this results in the baryonic isocurvature perturbation.

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[7] In the case of global symmetry, there exists a Goldstone mode, called the majoron [26]. It does not have significant cosmological and astrophysical effects if the breaking scale is sufficiently large.

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Appendix A: Expressions for A_2 and A_3

Here we give expressions for A_2 and A_3 in Eq. (26).

$$\begin{aligned}
A_2 = & \frac{1}{12w_0^5(w_1+1)^2\Omega_\sigma^2((3w_1-1)\Omega_\sigma+4)}\Big[8A_1^3w_0^3(w_0+1)^2((3w_1-1)\Omega_\sigma+4)^3 \\
& +4A_1^2w_0^2\Omega_\sigma\left(w_0^3(w_1+1)\left(63w_1^2\Omega_\sigma^2-6w_1\left(7\Omega\sigma^2-20\Omega_\sigma-8\right)+7\Omega_\sigma^2-104\Omega_\sigma+160\right)\right. \\
& +w_0^2\left(9w_1^2+4w_1+7\right)(-3w_1\Omega_\sigma+\Omega_\sigma-4)^2+6w_0w_1(3w_1-1)(-3w_1\Omega_\sigma+\Omega_\sigma-4)^2 \\
& \left.+3w_1(3w_1-1)(-3w_1\Omega_\sigma+\Omega_\sigma-4)^2\right)+2A_1w_0\Omega_\sigma^2\left(6w_0^4(w_1+1)^2+14w_0^3w_1\left(3w_1^2+2w_1-1\right)\right. \\
& \left.+w_0^2w_1\left(27w_1^3+24w_1^2+31w_1-14\right)+6w_0(1-3w_1)^2w_1^2+3(1-3w_1)^2w_1^2\right)((3w_1-1)\Omega_\sigma+4) \\
& +w_1^2(3w_1-1)\Omega_\sigma^3\left(w_0^3\left(33w_1^2+38w_1+5\right)+w_0^2\left(9w_1^3+15w_1^2+15w_1-7\right)+2w_0(1-3w_1)^2w_1\right. \\
& \left.+(1-3w_1)^2w_1\right)\Big], \qquad \text{(A1)} \\
A_3 = & A_{3,1}+A_{3,2}+A_{3,3}, \qquad \text{(A2)}
\end{aligned}$$

where

$$A_{3,1} = \frac{3(3w_1-1)w_1(w_0-3w_1)(16A_1w_0(\Omega_\sigma-1)+w_1\Omega_\sigma(-3w_1\Omega_\sigma+\Omega_\sigma-4))}{2w_0^3((3w_1-1)\Omega_\sigma+4)^2} + \frac{w_0f_1}{w_0+1} - \frac{w_1^3}{w_0^3} + \frac{3(3w_1-1)w_1^2\Omega_\sigma(3w_0-5w_1)}{2w_0^3((3w_1-1)\Omega_\sigma+4)}, \tag{A3}$$

$$A_{3,2} = \frac{2}{3w_0^6(w_0+1)(w_1+1)^4\Omega_\sigma^4((3w_1-1)\Omega_\sigma+4)}\Big[12(w_0+1)w_0^3(w_1+1)^4(\Omega_\sigma-1)\Omega_\sigma^4(2A_1w_0+w_1)^3 - 12(w_0+1)w_0^3(w_1+1)^4\Omega_\sigma^2(2A_1w_0(\Omega_\sigma-1)+w_1\Omega_\sigma)^3 + 6f_1w_0^7(\Omega_\sigma-1)(w_1\Omega_\sigma+\Omega_\sigma)^4\Big], \tag{A4}$$

$$A_{3,3} = \frac{2}{3w_0^6(w_0+1)(w_1+1)^4\Omega_\sigma^4((3w_1-1)\Omega_\sigma+4)}\Big[(w_0+1)(w_1+1)(1-\Omega_\sigma)\Omega_\sigma(2A_1w_0+w_1) \Big\{(2A_1w_0((3w_1-1)\Omega_\sigma+4)+w_1(3w_1-1)\Omega_\sigma)\,(2A_1w_0(w_0+1)((3w_1-1)\Omega_\sigma+4) + \Omega_\sigma\left(w_0^2(w_1+1)+w_0w_1(3w_1-1)+w_1(3w_1-1)\right))\,(2A_1w_0(w_0+1)((3w_1-1)\Omega_\sigma+4) + \Omega_\sigma\left(6w_0^2(w_1+1)+w_0w_1(3w_1-1)+w_1(3w_1-1)\right)) - \frac{72f_2w_0^5(w_1+1)^3\Omega_\sigma^3}{(3w_1-1)\Omega_\sigma+4}\Big\} - \frac{54f_2w_0^5(w_0+1)(w_1+1)^5\Omega_\sigma^4(2A_1w_0(\Omega_\sigma-1)+w_1\Omega_\sigma)}{(3w_1-1)\Omega_\sigma+4}\Big], \tag{A5}$$

and f_1 and f_2 are defined by

$$f_1 = \frac{3w_1^2(3w_1-1)\Omega_\sigma(3w_0-5w_1)}{2w_0^3((3w_1-1)\Omega_\sigma+4)}, \tag{A6}$$

$$f_2 = \frac{3w_1(3w_1-1)(w_0-3w_1)(16A_1w_0(\Omega_\sigma-1)+w_1\Omega_\sigma(-3w_1\Omega_\sigma+\Omega_\sigma-4))}{2w_0^3(-3w_1\Omega_\sigma+\Omega_\sigma-4)^2}. \tag{A7}$$

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