Neutrino masses and gravitational wave background

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Abstract

We consider the Standard Model with three right-handed neutrinos to generate tiny neutrino masses by the seesaw mechanism. Especially, we investigate the case when one right-handed neutrino has the suppressed Yukawa coupling constants. Such a particle has a long lifetime and can produce an additional entropy by the decay. It is then discussed the impact of the entropy production on the gravitational wave background originated in the primordial inflation. We show that the mass and the coupling constants of the long-lived right-handed neutrino can be probed by the distortion of the gravitational wave spectrum, leading to the information of the mass of the lightest active neutrino.
1 Introduction

Our understanding of neutrinos has been greatly improved from the end of the last century. Various oscillation experiments have provided the evidence of neutrino masses. The observational data are consistent with the flavor oscillations by three active neutrinos $\nu_i$ ($i = 1, 2, 3$) with masses $m_i$. However, unknown properties of neutrinos still exist, including the absolute mass scales, the Dirac or Majorana nature, and the CP violating phases. As for the neutrino masses, there are two possible mass orderings. One is the normal ordering (NO) with $\Delta m^2_{21} = 7.42^{+0.21}_{-0.20} \times 10^{-5}$ eV$^2$ and $\Delta m^2_{31} = 2.517^{+0.026}_{-0.028} \times 10^{-3}$ eV$^2$, and the other is the inverted ordering with $\Delta m^2_{21} = 7.42^{+0.21}_{-0.20} \times 10^{-5}$ eV$^2$ and $\Delta m^2_{32} = -2.498^{+0.028}_{-0.028} \times 10^{-3}$ eV$^2$ [1], which shows that the absolute values of neutrino masses or the mass of the lightest active neutrino, denoted by $m_0$, is undetermined so far. Note that $m_0 = m_1$ or $m_3$ for the NO or IO case. The sum of neutrino masses is $\sum m_i < 0.12$ eV from the cosmological constraints [2], which leads to $m_0 < 0.030$ eV or 0.016 eV for the NO or IO case, respectively.

Furthermore, the mechanism for generating the non-zero neutrino masses is unknown yet. One of the most attractive ways to explain the tiny neutrino masses is the seesaw mechanism by right-handed neutrinos [3–9]. Here we consider the case where the number of right-handed neutrinos is three. In this case the possible region of $m_0$ is below the above bound since there is no reason to select a specific value of $m_0$. Especially, when $m_0 \ll \mathcal{O}(10^{-3})$ eV, the determination of $m_0$ by neutrino experiments becomes very hard.

In such a situation one of three right-handed neutrino, say $N_S$, can have the Yukawa interactions with very suppressed couplings and become a very long-lived particle, and then an additional entropy can be produced by the $N_S$ decays and the universe is reheated again at late epoch after the reheating of the primordial inflation. (See, for example, Refs. [10, 11].) This entropy production dilutes the pre-existing dark matter, baryon asymmetry, and dangerous long-lived particles in cosmology.

In addition, it modifies the thermal history of the universe and the spectrum shape of the primordial gravitational wave (GW) background, which is a good target for the future observations. This issue has been investigated in Refs. [12–23]. It has been shown that the entropy production leads to the suppression of the GW spectrum at high frequencies, from which the reheating temperature $T_R$ of the entropy production and the rate $\Delta S$ between the entropy before and after the decay can be probed by the distortion signature of the GW spectrum.

In this paper we discuss the entropy production by the decays of right-handed neutrino $N_S$ in the seesaw mechanism. Especially, we consider the case when the mass of $N_S$ is heavier than $\mathcal{O}(1)$ TeV and $m_0 < \mathcal{O}(10^{-7})$ eV, and then discuss the impacts on the primordial GW background spectrum. It is then shown that the mass and Yukawa coupling of $N_S$ can be examined by the GW spectrum shape, which results in the determination of $m_0$. Remarkably, the suppression rate of the spectrum is directly related to $m_0$.

The paper is organized as follows. In the next section, we explain the framework of the analysis and

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#1 The mass of the lightest active neutrino is $m_0 = 0$ for the case with two right-handed neutrinos.

#2 There are, of course, possibilities to determine the scale of $m_0$ by introducing an additional mechanism to the theory such as the flavor symmetry.
demonstrate how the decays of right-handed neutrino lead to the late time production of an additional entropy. In section 3, we present the spectrum distortion of the primordial GW background by the entropy production and show what we can learn from it. The final section is devoted to the conclusions.

2 Seesaw mechanism and entropy production

We consider the Standard Model which is extended by three right-handed neutrinos $\nu_{RI}$ ($I = 1, 2, 3$) with Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + i \bar{\nu}_{RI} \gamma^\mu \partial_\mu \nu_{RI} - \left( F_{aI} \bar{L}_a H \nu_{RI} + \frac{M_I}{2} \bar{\nu}_{RI} \nu_{RI} + h.c. \right),$$

where the Higgs and left-handed lepton doublets are denoted by $H$ and $L_\alpha$ ($\alpha = e, \mu, \tau$), respectively. $F$ is the Yukawa coupling matrix and $M_I$ are the Majorana masses of right-handed neutrinos. Note that we take the basis in which the mass matrices for charged leptons and right-handed neutrinos are diagonal.

We assume the hierarchy between the Dirac masses $|M_D|_{aI} = |F_{aI}| \langle H \rangle$ and $M_I$ for the seesaw mechanism. The mass matrix of active neutrinos $\nu_i$ ($i = 1, 2, 3$) is given by

$$[M_\nu]_{\alpha\beta} = -[M_D]_{aI}[M_D]_{\beta I} M_I^{-1},$$

and the diagonalization of $M_\nu$ gives the neutrino mixing matrix $U$, called PMNS matrix, as $U^\dagger M_\nu U = D_\nu = \text{diag}(m_1, m_2, m_3)$ where $m_i$ is the mass for $\nu_i$. On the other hand, the heavier states $N_I \simeq \nu_{RI}$, called as heavy neutral leptons (HNLs), have the mixing with left-handed leptons as $\nu_{La} = U_{aI} \nu_i + \Theta_{aI} N^c_I$ where $\Theta_{aI} = [M_D]_{aI}/M_I$. Their mass matrix is $D_N = \text{diag}(M_1, M_2, M_3)$. The Yukawa coupling matrix can be parameterized as [24]

$$F = \frac{i}{\langle H \rangle} U D^{1/2}_\nu \Omega D^{1/2}_N,$$

where $\Omega$ is the $3 \times 3$ complex orthogonal matrix ($\Omega \Omega^T = 1$).

In this analysis we consider the case when the lightest active neutrino is much lighter than other active neutrinos:

$$m_3 > m_2 \gg m_1 = m_0 \quad \text{for the NO case,} \quad m_2 > m_1 \gg m_3 = m_0 \quad \text{for the IO case.} \quad (3)$$

In addition, one of HNLs denoted by $N_S$ ($I = S$) is assumed to have the very suppressed Yukawa coupling constants and we take $\Omega_{1S} \simeq 1$ and $\Omega_{iS} \simeq 0$ ($i = 2, 3$) for the NO case and $\Omega_{3S} \simeq 1$ and $\Omega_{iS} \simeq 0$ ($i = 1, 2$) for the IO case, respectively. In this case we obtain

$$F^2_S = (F^\dagger F)_{SS} \simeq \frac{M_S m_0}{\langle H \rangle^2},$$

and the Yukawa interaction of $N_S$ becomes very suppressed as $m_0$ becomes very small.
When the mass of \( N_S \) is larger than the Higgs boson mass, it mainly decays into pairs of Higgs and lepton and the lifetime is estimated as
\[
\tau_{N_S} = \frac{8\pi}{F_S^2 M_S} \approx \frac{8\pi \langle H \rangle^2}{m_0 M_S^2} \approx 5.0 \times 10^{-7} \text{ sec} \left( \frac{10^{-9} \text{ eV}}{m_0} \right) \left( \frac{1 \text{ TeV}}{M_S} \right)^2 .
\] (5)

It is seen that the lifetime is rather long if the mass and Yukawa coupling constants of \( N_S \) are both sufficiently small. Interestingly, such a long-lived \( N_S \) can dominate the energy of the universe and release an additional entropy by its decay. Note that the \( N_S \) decay becomes out of equilibrium if the Yukawa coupling constant is small as
\[
F_S^2 \lesssim \frac{M_S}{M_P} ,
\] (6)
where \( M_P \) is the (reduced) Planck mass, which corresponds to extremely small \( m_0 < \mathcal{O}(10^{-5}) \) eV. If this is the case, an additional entropy of the universe is produced and its reheating temperature is given by
\[
T_R \sim 1 \text{ GeV} \left( \frac{m_0}{10^{-10} \text{ eV}} \right)^{1/2} \left( \frac{M_S}{1 \text{ TeV}} \right) .
\] (7)

See Fig. 1. Note that the reheating temperature is bounded from below by the cosmological constraints (see, for example the recent analysis in Ref. [25] and references therein).

The entropy production rate \( \Delta S \) is defined by the ratio between the entropy densities with or without the \( N_S \) decay. We estimate \( \Delta S \) numerically (see, for example, Ref. [26]) and the result is also shown in Fig. 1. It is seen that \( \Delta S \) is roughly given by
\[
\Delta S \sim 10 \left( \frac{10^{-10} \text{ eV}}{m_0} \right)^{1/2} ,
\] (8)
which is almost independent on $M_S$. In this estimation we have not specified the production mechanism of $N_S$ which may be related to the inflation dynamics, but assumed the thermal abundance. We find that, when the lightest active neutrino mass becomes smaller than $\mathcal{O}(10^{-7})$ eV, the additional entropy can be produced by the $N_S$ decay. It should be noted that the cosmological lower bound on $T_R$ gives the upper bound on $\Delta S$.

### 3 Gravitational wave background and neutrino masses

Now let us discuss the impacts of the entropy production on the primordial GW background. First, we briefly summarize the spectrum of the GWs. The energy density of the GWs is given by \[ \rho_{GW} = \frac{1}{32 \pi G} \langle (\dot{h}_{ij})^2 \rangle, \] (9) where $h_{ij}$ is the tensor metric perturbation which satisfies the transverse-traceless condition $\partial^i h_{ij} = h^{ij} = 0$, and the bracket indicates the spacial average. The GW spectrum is expressed as

\[ \Omega_{GW}(k) = \frac{1}{\rho_{cr}} \frac{d \rho_{GW}}{d \ln k} = \frac{1}{12} \left( \frac{k}{aH} \right)^2 \mathcal{P}_T(k), \] (10)

where $\rho_{cr}$ is the critical density and $\mathcal{P}_T(k)$ is the tensor power spectrum expressed as

\[ \mathcal{P}_T(k) = T^2_T(k) \mathcal{P}^{\text{prim}}_T(k), \] (11)

where $T^2_T(k)$ denotes the transfer function and we use here the results in Ref. [19]. The primordial tensor power spectrum is parameterized as

\[ \mathcal{P}^{\text{prim}}_T(k) = A_T(k_*) \left( \frac{k}{k_*} \right)^{n_T}, \] (12)

where $A_T(k_*)$ and $n_T$ are the amplitude and the spectrum index at $k = k_* = 0.05$ Mpc$^{-1}$. The amplitude is given by $A_T(k_*) = r \mathcal{P}^{\text{prim}}_S(k_*)$ where the power spectrum of the scalar perturbation is measured precisely as $\mathcal{P}^{\text{prim}}_S(k_*) = 2.0989 \times 10^{-9}$ and the tensor-to-scalar ratio $r$ is bounded as $r < 0.063$ [28].

The thermal history of the universe is encoded in the transfer function. When the entropy production at late time occurs by the $N_S$ decay, the energy starts to be dominated by $N_S$ at some moment and the matter dominated universe is realized after the reheating of the primordial inflation, and then its decay into radiations leads to the reheating again. Consequently, the GW spectrum is suppressed at frequencies higher than $f_R$ compared with the case without the entropy production [12].

In Fig. 2 we show the spectrum $\Omega_{GW}$ for the case when $M_S = 10$ TeV and $m_0 = 10^{-14}, 10^{-12}$ and $10^{-10}$ eV. Here we take $r = 0.06$, $T_{RI} = 10^5$ TeV (the reheating temperature of the primordial inflation), and $n_T = 0$ and 0.5. For reference we also present the result without the entropy production. It is seen that $\Omega_{GW}$ is suppressed for the higher frequencies $f \gtrsim f_R$, where the critical frequency is given by

\[ f_R \sim 10^{-11} \text{ Hz} \left( \frac{T_R}{10 \text{ MeV}} \right). \] (13)
Figure 2: Spectra of the primordial GW background $\Omega_{GW}$ for the case when $M_S = 10$ TeV and $m_0 = 10^{-14}$, $10^{-12}$ and $10^{-10}$ eV by black-solid lines. We also show the spectrum without the entropy production by black-dashed line. We take $r = 0.06$, $T_R = 10^5$ TeV, and $n_T = 0$ (left) and 0.5 (right). The shaded regions are excluded from BBN [30], LIGO-Virgo [31] and NANOGrav [32]. The dotted lines show the sensitivities by the GW observations (see the details in the text).

Note that $f_R$ is sensitive to $T_R$, and hence to $m_0$ and $M_S$ as shown in Eq. (7). On the other hand, the magnitude of the spectrum suppression is expressed as

$$\Delta \Omega_{GW} = \frac{\Omega_{GW}|_{wEP}}{\Omega_{GW}|_{woEP}}$$

where $\Omega_{GW}|_{wEP}$ and $\Omega_{GW}|_{woEP}$ are the GW spectrum for $f \gg f_R$ with and without the entropy production, respectively. This suppression factor has been estimated as [12]

$$\Delta \Omega_{GW} \simeq \frac{1}{\Delta S^{4/3}}.$$  

It is then found from Eq. (8) that $\Delta \Omega_{GW}$ gives the information of $m_0$.

In Fig. 2, we also show the upper bounds on $\Omega_{GW}$ from BBN [29,30], LIGO-Virgo [31] and NANOGrav [32]. In addition, we show the sensitivities by the future GW observations: SKA [33], LISA [34], ET [35], BBO [36], (B-)DECIGO [37,38] and Ultimate-DECIGO [39]. It is found that, when the mass of $N_S$ is $\mathcal{O}(10)$ TeV and $n_T$ is a relatively large value, the predicted $f_R$ can be probed by the pulsar time array observations for $m_0 = \mathcal{O}(10^{-14})$–$\mathcal{O}(10^{-10})$ eV, and $\Delta \Omega_{GW}$ can be probed by the GW interferometers. On the other hand, we show in Fig. 3 the GW spectrum $\Omega_{GW}$ with $M_S = 10^3$, $10^6$ and $10^9$ TeV by taking $m_0 = 10^{-12}$ eV. It is found that the effect by $N_S$ with masses $M_S > \mathcal{O}(10^6)$ TeV can be probed by the future GW observations if $n_T$ is a relatively large.

As shown above, the distortion of the GW spectrum due to the entropy production by $N_S$ can be probed by the future observations. Importantly, we can reconstruct the masses of the lightest active
neutrino $m_0$ and the right-handed neutrino $N_S$ if $f_R$ and $\Delta \Omega_{GW}$ will be provided by the observations. It should be noted that the Yukawa coupling $F_S$ can be determined from $m_0$ and $M_S$ as shown in Eq. (4). This point is represented in Fig. 4, where we present the indicated values of $m_0$ and $M_S$ for given $f_R$ and $\Delta \Omega_{GW}$. The result for the range $M_S = 1$ TeV to $10^{12}$ TeV is shown. We find that the mass of the lightest active neutrino with $m_0 < \mathcal{O}(10^{-7})$ eV can be probed which is very difficult to examine by the neutrino experiments.

Before closing this section, we mention the mass range of the right-handed neutrino $N_S$. We have considered the case when $M_S > \mathcal{O}(1)$ TeV so far. The extension to the lighter mass region can be done in a straightforward way by taking into account the appropriate decay modes of $N_S$. This issue will be discussed elsewhere [40].

4 Conclusions

We have considered the Standard Model with three right-handed neutrinos which realizes the seesaw mechanism for the observed tiny neutrino masses. Especially, we have investigated the case that one of three right-handed neutrinos, $N_S$, have very suppressed Yukawa coupling $F_S$, and the lightest neutrino mass $m_0$ becomes smaller than $\mathcal{O}(10^{-7})$ eV. In this case the late-time entropy production occurs by the $N_S$ decay and can modify the spectrum of the primordial gravitational wave background significantly. The spectrum can be suppressed for the frequencies $f > f_R$ by the factor $\Delta \Omega_{GW}$. We have shown that the observational data of $f_R$ and $\Delta \Omega_{GW}$ determines both the mass of the lightest active neutrino $m_0$ and...
Figure 4: The indicated values of the masses of the lightest active neutrino \( m_0 \) (red-solid lines) and the right-handed neutrino \( M_S \) (blue-dashed lines) in terms of the critical frequency \( f_R \) the suppression factor \( \Delta \Omega_{GW} \). Gray-shaded regions are excluded by the BBN bounds (\( T_R \geq 1 \) and 5 MeV).

the \( N_S \) mass \( M_S \), which leads to the determination of the Yukawa coupling \( F_S \). It has been found that the very small value of \( m_0 < \mathcal{O}(10^{-7}) \) eV, which is very difficult to test by the neutrino experiments, can be probed by the GW spectrum shape by the future gravitational wave detection projects and the pulsar timing arrays.

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