Right-handed neutrinos in the vMSM

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Introduction: \(\nu\text{MSM}\)

[T.Asaka, S.Blanchet, M.Shaposhnikov (‘05), T.Asaka, M.Shaposhnikov (‘05)]

- Problems of the Standard Model
  - The neutrino mass
  - The dark matter of the universe
  - The baryon number asymmetry

- \(\nu\text{MSM} : \text{SM} + 3 \text{ Right-Handed Neutrinos (}\nu_R\text{)}\)

\[
\mathcal{L}_{\nu\text{MSM}} = \mathcal{L}_{\text{SM}} + \bar{\nu}_R i \partial_\mu \gamma^\mu \nu_R - F_{\alpha I} \bar{L}_\alpha \tilde{\Phi} \nu_{RI} - \frac{1}{2} (M_M)_{IJ} \bar{\nu}_{RI}^c \nu_{RJ} + \text{h.c.}
\]

Assumption: \(|M_D| = F\langle \Phi \rangle \ll M_M < \Lambda_{\text{EW}} \sim O(100\text{GeV})\)

- See-saw mechanism
  - Mass eigenstates
    - Light neutrinos: \(\nu_1, \nu_2, \nu_3\)
    - Heavy neutrinos: \(N_1, N_2, N_3\)

- Play of the Heavy neutrinos
  - \(N_1\): Dark Matter candidate
  - \(N_2, N_3\): Neutrino mass, BAU
Motivation 1 – Constraint on DM candidate

The DM candidate $N_1$

Mass : $O(1\text{keV})$

$N_1$ acts as WDM.

- Free-streaming length

$$\lambda_{FS} = 0.2\text{Mpc} \left(\frac{1\text{keV}}{M_{DM}}\right) \left(\frac{T_{DM}}{T_{\nu}}\right) \left[\ln\left(\frac{t_{EQ}}{t_{NR}}\right) + 2\right]$$

$(t_{EQ} \sim 10^{11}\text{sec}, \ t_{NR} \sim 10^{7}\text{sec})$

- The lower limit of the DM mass (Lyman-α)

$$M_1 > 8\text{keV} \quad [A. \ Boyarsky, \ et \ al, \ arXiv.0812.0010]$$

$$[M. \ Laine, \ M. \ Shaposhnikov, \ (’08)]$$

Considering the X-ray and Lyman-α constraints, the allowed region of DM is very limited.
Motivation 1 – Impact of Entropy Production

There is a possibility that the entropy production is induced by the N$_{2,3}$ decay before BBN.

If N$_{2,3}$ decay increase the entropy by $\Delta S$, the $\lambda_{FS}$ becomes suppressed as,

$$\lambda_{FS}^{EP} = \frac{\lambda_{FS}^{wo\ EP}}{\Delta S}$$

The lower limit of DM mass from structure formation is relaxed.

$$M_N > 8 \text{keV} \frac{1}{\Delta S^{1/3}}$$

We would like to know how large $\Delta S$ is obtained in the vMSM.
Motivation 2 – Evaluation of the previous work

In the previous work, $\Delta_S$ have been evaluated.

[T.Asaka, M. Shaposhnikov, A. Kusenko (’06)]

The maximal value of $\Delta_S$ in the previous work

- $\Delta_S = 29 \left( T_R = 0.7\text{MeV} \right)$
- $\Delta_S = 10 \left( T_R = 4\text{MeV} \right)$

However, there were the unsatisfactory points.

- Evaluation of the lifetime of the $N_{2,3}$ was incomplete. (In particular the decay modes into meson were not included.)
- Only specific Yukawa coupling constant is considered.

We would like to solve these points.

Purpose of study:

Reevaluating the Entropy Production in the universe by the $N_{2,3}$ decay and Discussing its impact on DM physics in the vMSM
Entropy Production by $N_{2,3}$ decay

$N_{2,3}$ decoupled from the thermal bath and acted as non-relativistic particles in the early universe.

In order to evaluate quantitatively the entropy production, we should investigate if $N_{2,3}$ lifetime can be sufficiently long.

⇒ $N_{2,3}$ energy could dominate that of the universe.

⇒ The Entropy Production could occur by the $N_{2,3}$ decay.
Interactions and decay modes of N

Neutrino Mixing: $\nu_{L\alpha} = U_{\alpha i} \nu_i + \Theta_{\alpha I} N_I^C$

$N_{2,3}$ have the suppressed interactions.

⇒ We can expect that their lifetime can be long.

Decay Modes

$N_{2,3} \rightarrow \nu \nu \nu$
$\rightarrow \nu l^+ l^-$
$\rightarrow \nu \gamma$
$\rightarrow \pi^0 \nu, \pi^+ l^-$
$\rightarrow K^+ l^-$
$\rightarrow \rho \nu$
$\rightarrow \eta \nu, \eta' \nu$
$\rightarrow D^+ l^-, D_s^+ l^-$
$\rightarrow B^+ l^-, B_c^+ l^-$

The main decay mode changes according to the mass.
We need the values of Yukawa coupling constant and the mass.

To decide these values,

- Using the center value of $\theta_{ij}$, $\Delta m_{ij}^2$ of the neutrino oscillation
- Assuming $M_N = M_{N2} = M_{N3}$
- Varying the free parameters in possible range

$\tau_N$ lifetime

Evaluating the upper limit of $\tau_N$

![NH lifetime](image1.png)

$\tau_N$ upper limit

![IH lifetime](image2.png)

$\tau_N$ upper limit
Evaluation of Entropy Production rate $\Delta_S$

Evaluation formula of Entropy Production rate $\Delta_S$

$$\Delta_S = \frac{S_f}{S_i} = \left[ 1 + \left( \frac{1.37 M_N^2 \tau_N}{M_{pl}(g_*(T_D))^2} \right)^{\frac{3}{4}} \right] \propto M_N \sqrt{\tau_N}$$

$T_D$ : Decoupling Temperature


$g_*(T_D) = 10.75$

The upper limit of $\tau_N \Rightarrow$ The upper limit of $\Delta_S$

![NH](image1.png)

$\Delta_S$ upper limit

![IH](image2.png)

$\Delta_S$ upper limit
Constraint on lifetime from CMB

Usually light neutrino energy density $\rho_\nu$ is calculated as their decoupling from the thermal bath occurs at $T \sim O\ (\text{MeV})$.

\[ \Rightarrow \text{Relativistic neutrino effective number} \]

\[ N_{\text{eff}} = 3.046 \]

\[ N_{\text{eff}} = \frac{\rho_\nu}{\rho_{\nu^*}} \]

$\rho_{\nu^*}$: 1-flavor neutrino energy density

If $N_{2,3}$ lifetime is too long, light neutrinos that are produced by their decay were not thermalized completely and there is a possibility that $N_{\text{eff}}$ deviates from 3.

\[ \Rightarrow \text{We can get the upper limit of } \tau_N. \]

\[ \tau_N < 0.12\text{sec} \]

Constraint on lifetime from CMB

\[ \Delta_S < 24 \]  [T. Asaka, K. T (2013)]
In the direct search such as Beam-Dump experiments (PS191, CHARM), no positive evidence of N has been found so far.

We can get the upper limit of $|\Theta|^2$.

The event number of $e^+$ and $e^-$ is proportional to $|\Theta|^4$.

We consider the mass range $M_N \leq 400\text{MeV}$.
Constraint on lifetime from direct search of $N$
The lower limit of DM mass is relaxed to 2.8keV maximally if the entropy production can realize.
Summary

We consider the vMSM that introduces 3 right-handed neutrinos into the SM and discuss the **Entropy Production** by $N_2, N_3$ decays.

- **Evaluation of the Entropy Production rate**
  - We calculated the decay rate for possible decay modes of $N_{2,3}$ and their lifetime.
  - We evaluated the entropy production rate $\Delta S$ by considering the free parameter on Yukawa coupling constant.
  - Constraint from CMB $\Rightarrow$ entropy production rate $\Delta S < 24$
  - Constraint from the direct searches $\Rightarrow$ the lower limit of $\Delta S$ at $M_N \leq 400$ MeV

- **Impact on DM physics**
  - $\lambda_{FS}$ is suppressed. $\Rightarrow$ The lower limit of DM mass is relaxed.
Back Up
Yukawa coupling constant

\[ F = \frac{i}{\nu} U D^{1/2}_\nu \Omega D^{1/2}_N \]

\[
U = \begin{pmatrix}
  c_{12} c_{13} & s_{12} s_{13} & s_{13} e^{-i\delta} \\
  -c_{23} s_{12} - s_{23} c_{12} s_{13} e^{i\delta} & c_{23} c_{12} - s_{23} s_{12} s_{13} e^{i\delta} & s_{23} c_{13} \\
  s_{23} s_{12} - c_{23} c_{12} s_{13} e^{i\delta} & s_{23} c_{12} - c_{23} s_{12} s_{13} e^{i\delta} & c_{23} c_{13}
\end{pmatrix} \times \text{diag}(1, e^{i\eta}, 1)
\]

\[ D_\nu = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) \quad D_v = \text{diag}(M_{N_2}, M_{N_3}) \]

\[
\Omega = \begin{pmatrix}
  0 & 0 \\
  \cos \omega & -\sin \omega \\
  \xi \sin \omega & \xi \cos \omega
\end{pmatrix}
\]

\[ \xi = \pm 1 \quad \omega = \text{Re} \omega + \text{Im} \omega \]

NH \quad 0 = m_{\nu_1} < m_{\nu_2} < m_{\nu_3}

IH \quad 0 = m_{\nu_3} < m_{\nu_1} < m_{\nu_2}
Parameter on Yukawa coupling constant

Free parameter : $M_{N2}, M_{N3}, \delta, \eta, \text{Re}\omega, \text{Im}\omega, \xi$

Observed parameter : $\theta_{12}, \theta_{13}, \theta_{23}, m_{\nu1}, m_{\nu2}, m_{\nu3}$