Extended double seesaw model for neutrino masses and low scale leptogenesis.

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Summary
Introduction:

Motivation for postulating the existence of singlet neutrinos:

- Smallness of neutrino masses ⇒ introducing heavy singlet neutrinos: seesaw mechanism.
- Sterile neutrinos ⇒ a viable candidate for dark matter
- LSND experiment ⇒ need a sterile neutrino

What happen if the sterile neutrinos exist?

- $\nu_s$ can mix with $\nu_a$ ⇒ such admixtures: contribute to various processes forbidden in the SM
- They affect the interpretations of cosmological and astrophysical observations.
Virtue and Vice of the Seesaw Mechanism:

- Accomplishment of smallness of neutrino masses
- Responsible for baryon asymmetry of our universe
- Seesaw scale $10^{10\sim14}$ GeV: impossible to probe at collider
- High scale thermal leptogenesis $M > 10^9$ GeV $\Rightarrow$ encounters gravitino problem in SUSY SM.

$\Rightarrow$ Low scale seesaw is desirable!

A successful scenario for a low scale leptogenesis $\Rightarrow$ Resonant leptogenesis with very tiny mass splitting of heavy Majorana neutrinos with $M_1 \sim 1$ TeV. (Pilaftsis)

$$((M_2 - M_1)/(M_2 + M_1) \sim 10^{-6})$$

However, such a very tiny mass splitting may appear somewhat unnatural due to the required severe fine-tuning.
Motivation and Aim of this work

- In order to remedy above problems, we propose a variant of the seesaw mechanism.

- Our model:

  \[
  \text{typical seesaw model} + \text{equal } \# \text{ gauge singlet neutrinos} \Rightarrow \text{a kind of double seesaw model}
  \]

- Unlike to the typical double seesaw model,
  
  - Permit both tiny neutrino masses and relatively light sterile neutrinos of order MeV.
  
  - Accommodate very tiny mixing between $\nu_a$ and $\nu_s$ demanded from the cosmological and astrophysical observations.

- We show that a low scale thermal leptogenesis can be naturally achieved.
Extended Double Seesaw Model

- The Lagrangian we propose in the charged lepton basis as
  \[ \mathcal{L} = M_{Ri} N_i^T N_i + Y_{Dij} \bar{\nu}_i \phi N_j + Y_{Sij} \bar{N}_i \psi S_j - \mu_{ij} S_i^T S_j + h.c. , \]

- \( \nu_i : SU(2)_L \) doublet, \( N_i : \) RH singlet neutrino
- \( S_i : \) newly introduced singlet neutrinos
- \( \phi : SU(2)_L \) doublet Higgs
- \( \psi : SU(2)_L \) singlet Higgs

- The neutrino mass matrix after \( \phi, \psi \) get VEVs becomes
  \[ M_\nu = \begin{pmatrix}
0 & m_{Dij} & 0 \\
 m_{Dij} & M_{Rii} & M_{ij} \\
0 & M_{ij} & -\mu_{ij}
\end{pmatrix} , \]
  where \( m_{Dij} = Y_{Dij} \langle \phi \rangle, M_{ij} = Y_{Sij} \langle \psi \rangle. \)

- Here we assume that \( M_R > M \gg \mu, m_D. \)
After integrating out $N_R$ in $\mathcal{L}$, we obtain the following effective lagrangian,

\[
-\mathcal{L}_{\text{eff}} = \frac{(m_D^2)_{ij}}{4M_R} \nu_i^T \nu_j + \frac{m_{D_{ik}} M_{kj}}{4M_R} (\bar{\nu}_i S_j + \bar{S}_i \nu_j)
\]

\[
+ \frac{M_{ij}^2}{4M_R} S_i^T S_j + \mu_{ij} S_i^T S_j.
\]

After block diagonalization of the effective mass terms in $\mathcal{L}_{\text{eff}},$

1. The light neutrino mass matrix :

\[
m_\nu \simeq \frac{1}{2} \frac{m_D}{M} \mu \left( \frac{m_D}{M} \right)^T,
\]

2. Mixing between the active and sterile neutrinos :

\[
\tan 2\theta_s = \frac{2m_D M}{M^2 + 4\mu M_R - m_D^2}.
\]
Note: typical seesaw mass $m_D^2/M_R \Rightarrow$ cancelled out.

Sterile neutrino mass is approximately given as

$$m_s \simeq \mu + \frac{M^2}{4M_R}.$$ 

Depending on the relative sizes among $M, M_R, \mu, \Rightarrow \theta_s$ and $m_s$ are approximately given by

\[
\begin{align*}
tan 2\theta_s & \simeq \sin 2\theta_s \\
\frac{2m_D}{M} & \quad (\text{for } M^2 > 4\mu M_R : \text{ Case A}), \\
\frac{m_D}{M} & \quad (\text{for } M^2 \simeq 4\mu M_R : \text{ Case B}), \\
\frac{m_D M}{2\mu M_R} & \quad (\text{for } M^2 < 4\mu M_R : \text{ Case C}),
\end{align*}
\]

\[
\begin{align*}
m_s & \simeq \\
\frac{M^2}{4M_R} & \quad (\text{Case A}), \\
2\mu & \quad (\text{Case B}), \\
\mu & \quad (\text{Case C}).
\end{align*}
\]
Note on the above formulae:

- For $M^2 \leq 4 \mu M_R$, the size of $\mu$ is mainly responsible for $m_s$.

- The value of $\theta_s$ is suppressed by the scale of $M$ or $M_R$.

- Thus, very small mixing angle $\theta_s$ can be naturally achieved in our seesaw mechanism.

- For Case A and Case B, constraints on $\theta_s$ leads to constraints on the size of $m_\nu/\mu$. 
Constrains on the active-sterile mixing

- Existence of a relatively light sterile neutrino \( \Rightarrow \) observable consequences for cosmology & astrophysics.

- \( m_s \) and \( \theta_s \) \( \Rightarrow \) subject to the cosmological and astrophysical bounds.

- Some laboratory bounds \( \Rightarrow \) typically much weaker than the astrophysical and cosmological ones.

- In the light of laboratory experimental as well as cosmological and astrophysical observations, there exist two interesting ranges of \( m_s \), \( \Rightarrow \) order keV and order MeV.
keV sterile neutrino

- A viable “warm” dark matter candidate.

- For \( \sin \theta_s \sim 10^{-6} - 10^{-4} \), sterile neutrinos were never in thermal equilibrium in the early Universe \( \Rightarrow \) their abundance to be smaller than the predictions in thermal equilibrium.

- A few keV sterile neutrino \( \Rightarrow \) important for the physics of supernova, which can explain the pulsa kick velocities (Kusenko).

- In addition, some bounds on \( m_s \) from the possibility to observe \( \nu_s \) radiative decays from X-ray observations and Lyman \( \alpha \)–forest observations of order of a few keV.
MeV sterile neutrinos

- There exists high mass region $m_s \gtrsim 100$ MeV restricted by the CMB bound, meson decays and SN1987A cooling: $\Rightarrow \sin^2 \theta_s \lesssim 10^{-9}$.

- Such a high mass region may be very interesting in the sense that induced contributions to the neutrino mass matrix due to the mixing between $\nu_a$ and $\nu_s$ can be dominant $\Rightarrow$ responsible for peculiar properties of the lepton mixing such as tri-bimaximal mixing (Smirnov, Funchal '06).

- Sterile neutrinos with mass 1-100 MeV $\Rightarrow$ a dark matter candidate for the explanation of the excess flux of 511 keV photons if $\sin^2 2\theta_s \lesssim 10^{-17}$.

- In this work, we will focus on MeV sterile neutrinos.

- Similarly, we can realize keV sterile neutrinos (unnatural).
We propose a scenario that a low scale leptogenesis can be successfully achieved without severe fine-tuning such as very tiny mass splitting between two heavy Majorana neutrinos.

In our scenario, the successful leptogenesis achieved by the decay of the lightest RH Majorana neutrino before the scalar fields get VEVs.

In particular, a new contribution to the lepton asymmetry mediated by the extra singlet neutrinos.
Without loss of generality, taking a basis where the mass matrices $M_R$ and $\mu$ real and diagonal.

In this basis, the elements of $Y_D$ and $Y_S$ are in general complex.

The lepton number asymmetry required for baryogenesis:

$$\varepsilon_1 = - \sum_i \left[ \frac{\Gamma(N_1 \rightarrow \bar{l}_i \bar{H}_u) - \Gamma(N_1 \rightarrow l_i H_u)}{\Gamma_{\text{tot}}(N_1)} \right],$$

where

- $N_1$ : the lightest RH neutrino
- $\Gamma_{\text{tot}}(N_1)$ : the total decay rate.

The introduction of $S$ $\implies$ a new contribution which can enhance $\varepsilon_1$. 


As a result of such an enhancement, low scale leptogenesis is successful without severe fine-tuning.

Diagrams contributing to lepton asymmetry:

(a) \[ N_1 \rightarrow L_i \phi \]

(b) \[ N_1 \rightarrow \phi N_k \rightarrow L_i \phi \]

(c) \[ N_1 \rightarrow \phi N_k \rightarrow L_i \phi \]

(d) \[ N_1 \rightarrow \Psi S_j \rightarrow L_i \phi \]

In addition to (a-c), there is a new diagram (d) arisen due to the new Yukawa interaction \( Y_S \bar{N} \Psi S \).
Assuming $m_{\phi}, m_{\psi}, m_S \ll m_{R_1}$, to leading order,

$$\Gamma_{\text{tot}}(N_i) = \frac{(Y_\nu Y_\nu^+ + Y_s Y_s^+)^{ii}}{4\pi} M_{R_i}$$

The lepton asymmetry:

$$\epsilon_1 = \frac{1}{8\pi} \sum_{k \neq 1} (g_V(x_k) + g_S(x_k)) T_{k1} + g_S(x_k) S_{k1},$$

where

- $g_V(x) = \sqrt{x} \{1 - (1 + x) \ln[(1 + x)/x]\}$,

- $g_S(x) = \sqrt{x_k}/(1 - x_k)$ with $x_k = M_{R_k}^2/M_{R_1}^2$ for $k \neq 1$,

- $T_{k1} = \frac{\text{Im}[(Y_\nu Y_\nu^+)^{k1}]}{(Y_\nu Y_\nu^+ + Y_s Y_s^+)^{11}_{11}}$

- $S_{k1} = \frac{\text{Im}[(Y_\nu Y_\nu^+ Y_s^+ Y_s^{k1})]}{(Y_\nu Y_\nu^+ + Y_s Y_s^+)^{11}_{11}}$: coming from interference of the tree diagram with (d).
For $x \gg 1$, vertex diagram becomes dominant:

$$\varepsilon_1 \simeq -\frac{3M_{R_1}}{16\pi v^2} \frac{\text{Im}[(Y_\nu^* m_\nu Y_\nu^\dagger)_{11}]}{(Y_\nu Y_\nu^\dagger + Y_s Y_s^\dagger)_{11}},$$

it is bounded as (Davidson, Ibarra)

$$|\varepsilon_1| < \frac{3}{16\pi} \frac{M_{R_1}}{v^2} (m_{\nu_3} - m_{\nu_1}),$$

For hierarchical $m_\nu$, $m_{\nu_3} \simeq \sqrt{\Delta m^2_{\text{atm}}}$ and then it is required: $M_{R_1} \geq 2 \times 10^9$ GeV

To see how much the new contribution can be important, let's consider a case: $M_{R_1} \simeq M_{R_2} < M_{R_3}$. 
In this case, $\varepsilon_1$:

$$
\varepsilon_1 \simeq -\frac{1}{16\pi} \left[ \frac{M_{R_2}}{v^2} \frac{\text{Im}[(Y_{\nu}^* m_{\nu} Y_{\nu}^{\dagger})_{11}]}{(Y_{\nu} Y_{\nu}^{\dagger} + Y_{s} Y_{s}^{\dagger})_{11}} + \frac{\sum_{k \neq 1} \text{Im}[(Y_{\nu} Y_{\nu}^{\dagger})_{k1}(Y_{s} Y_{s}^{\dagger})_{1k}]}{(Y_{\nu} Y_{\nu}^{\dagger} + Y_{s} Y_{s}^{\dagger})_{11}} \right] R ,
$$

where $R \equiv \frac{|M_{R_1}|}{(|M_{R_2}| - |M_{R_1}|)}$.

Denominator of $\varepsilon_1$ constrained by $\Gamma_{N_1} < H |_{T=M_{R_1}}$:

- the corresponding upper bound on $(Y_{s})_{1i}$:

$$
\sqrt{\sum_{i} |(Y_{s})_{1i}|^2} < 3 \times 10^{-4} \sqrt{M_{R_1}/10^9 \text{GeV}}.
$$

The first term (>> 2nd term) : bounded as

$$
(M_{R_2}/16\pi v^2) \sqrt{\Delta m_{atm}^2} R
$$

$\Rightarrow$ TeV scale leptogenesis achieved by $R \sim 10^{6-7}$ (implying severe fine-tuning).
However, since $(Y_s)_{2i}$ is not constrained by the out-of-equilibrium condition, large value of $(Y_s)_{2i}$ is allowed.

\[ \Rightarrow \text{the second term of } \varepsilon_1 \text{ can dominate over the first one and thus the size of } \varepsilon_1 \text{ can be enhanced.} \]

For example, assuming $(Y_\nu)_{2i}$ is aligned to $(Y_s^*)_{2i}$, i.e. $(Y_s)_{2i} = \kappa (Y_\nu^*)_{2i}$, the upper limit of the second term:

\[ |\kappa|^2 M_{R_2} \sqrt{\Delta m_{atm}^2} R / 16\pi v^2 \]

Successful leptogenesis can be achieved for $M_{R_1} \sim$ a few TeV, provided that $\kappa = (Y_s)_{2i} / (Y_\nu^*)_{2i} \sim 10^3$ and $M_{R_2}^2 / M_{R_1}^2 \sim 10$. 
- The generated B-L asymmetry:

\[
Y_{B-L}^{SM} = -\eta \varepsilon_1 Y_{N_1}^{eq}
\]

where \( Y_{N_1}^{eq} \approx \frac{45}{\pi^4} \frac{\zeta(3)}{g_* k_B} \frac{3}{4} \)

- The efficient factor \( \eta \), to a good approximation, depends on the effective neutrino mass \( \tilde{m}_1 \) given

\[
\tilde{m}_1 = \frac{(Y_\nu Y_\nu^\dagger + Y_s Y_s^\dagger)^{11}}{M_{R_1}} \nu^2.
\]

- The new process of type \( S \Psi \rightarrow l \phi \) \( \implies \) wash-out of the produced B-L asymmetry.

- Wash-out factor for \( (Y_s)_{1i} \sim (Y_\nu)_{1i} \), \( (Y_s)_{2i}/(Y_\nu)_{2i} \sim 10^3 \) and \( M_{R_1} \sim 10^4 \) GeV \( \implies \) similar to the case of the typical seesaw model with \( M_{R_1} \sim 10^4 \) GeV and \( \tilde{m}_1 \sim 10^{-3} \) eV, \( \implies \varepsilon_1 \sim 10^{-6} \)
Numerical Estimation

- Let us examine how both $m_{\nu_i}$ of order $0.01 \sim 0.1 \text{ eV}$ and $m_s$ of order $100 \text{ MeV}$ can be simultaneously realized (without being in conflict with the constraints on the mixing $\theta_s$).

- For hierarchical neutrino spectrum, the largest $m_{\nu}$:
  \[ \sqrt{\Delta m^2_{atm}} \approx 0.05 \text{ eV} \] and next largest:
  \[ \sqrt{\Delta m^2_{sol}} \approx 0.01 \text{ eV}. \]

- Low scale seesaw $\Rightarrow$ achieved by taking $m_D$ to be $1$-$100 \text{ MeV}$.

- For our numerical analysis, $\sin^2 \theta_s \approx 10^{-9}$, allowed by the constraints for $m_s \sim$ a few $100 \text{ MeV}$.
Case A : For $M^2 > 4\mu M_R$ :

- $\sin^2 \theta_s \simeq \left( \frac{m_D}{M} \right)^2$ and $m_{\nu_i} \simeq 0.5 \sin^2 \theta_s \mu_i$.

- $m_{\nu_i} \simeq 0.01 \,(0.1) \text{ eV} \implies \mu_i \simeq 20 \,(200) \text{ MeV}$.

- Since $M_i = m_{D_i} \times \sqrt{10^9}$, $M_1 \sim 30 \text{ GeV}$ for $m_{D_1} \sim 1 \text{ MeV}$.

- $m_{s_1} \simeq 250 \text{ MeV} \implies$ realized by taking $M_{R_1} \simeq 1 \text{ TeV}$.

- Successful leptogenesis could be achieved for $M_{R_2}^2 \simeq 10 \, M_{R_1}^2$, and thus in order to obtain $m_{\nu_2} = 0.01 \text{ eV}$ and $m_{s_2} \simeq 250 \text{ MeV}$, we require $M_{R_2} \simeq 3 \text{ TeV}$ and $M_2 \simeq 50 \text{ GeV}$.
Case B: For $M^2 = 4\mu M_R$:

- $\tan 2\theta_s \simeq 2\sin\theta_s \simeq m_D/M$ and $m_{\nu_i} \simeq 0.5\sin^2\theta_s\mu_i$. 
  
  $m_{\nu_i} \simeq 0.01\ (0.1)\ eV \implies \mu_i \simeq 5\ (50)\ MeV$.

- $m_{s_i} \simeq 2\mu_i$ 
  $m_s \simeq 100\ MeV$ is achieved for $m_{\nu_i} \simeq 0.1$, whereas 
  $m_s \simeq 10\ MeV$ for $m_{\nu_i} \simeq 0.01 \implies$ hierarchical light 
  neutrino spectrum disfavors 100 MeV sterile neutrinos.

- Thus, low scale leptogenesis in consistent with neutrino data as well as 100 MeV sterile neutrino 
  achieved for quasi-degenerate $m_{\nu_i}$ of order 0.1 eV.

- $M_R = M^2/(4\mu) \simeq 6 \times 10^7 m_D^2/\mu \simeq 0.12 m_D^2/m_\nu \implies M_R \simeq 1.2\ TeV$ for $m_D \simeq 1\ MeV$ and $\nu \simeq 0.1\ eV$. 
Case C: For $4\mu M_R > M^2$:

- $\tan 2\theta_s \simeq 2 \sin \theta_2 \simeq m_D M/(2\mu M_R) \implies \sin \theta_s = \frac{m_D^3}{8m_\nu M M_R}$.

- The size of $M M_R \implies 4 \times 10^5 (4 \times 10^{11})$ GeV$^2$ for $\sin^2 \theta_s \simeq 10^{-9}$ and $m_D = 1 \text{ (100)}$ MeV.

- $m_s$ strongly depends on $\mu$ as long as $4\mu M_R >> M^2$.

- Note: for smaller values of $\theta_s$, larger value of $\mu$ is demanded so as to achieve the required $m_{\nu_i}$. 
Summary

- We have considered a variant of seesaw mechanism by introducing extra singlet neutrinos and investigated how the low scale leptogenesis is realized without fine-tuning and gravitino problem.

- We have shown that the introduction of the new singlet fermion leads to a new contribution to lepton asymmetry and it can be enhanced for certain range of parameters.

- We have also examined how both the light neutrino mass spectrum and relatively light sterile neutrinos of order a few 100 MeV can be achieved without being in conflict with the constraints on $\theta_s$. 