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

International workshop on neutrino masses and mixing

Decmeber 17-19 2006, Shizuoka, Japan

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hep-ph/0607072

# Outline

# Introduction:

**Motivation for postulating the existence of singlet neutrinos:**

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

**What happen if the sterile neutrinos exist ?**

- $\nu_s$ can mix with $\nu_a$ $\Longrightarrow$ 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
  - Responsibe 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 $\Longrightarrow$ encounters gravitino problem in SUSY SM.

$\Longrightarrow$ **Low scale seesaw is desirable !**

- A successful scenario for a low scale leptogenesis $\Longrightarrow$ 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 appears 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 :

  typical seesaw model + equal # gauge singlet neutrinos

  $\Longrightarrow$ 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

$$\mathcal{L} = M_{R_i} N_i^T N_i + Y_{D_{ij}} \bar{\nu}_i \phi N_j + Y_{S_{ij}} \bar{N}_i \Psi S_j - \mu_{ij} S_i^T S_j + h.c. \ ,$$

  - $\nu_i$ : $SU(2)_L$ 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

$$M_\nu = \begin{pmatrix} 0 & m_{D_{ij}} & 0 \\ m_{D_{ij}} & M_{R_{ii}} & M_{ij} \\ 0 & M_{ij} & -\mu_{ij} \end{pmatrix},$$

where $m_{D_{ij}} = Y_{D_{ij}} < \phi >, M_{ij} = Y_{S_{ij}} < \Psi >$.

- 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,

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

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

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 $m_D^2/M_R \implies$ cancelled out.
- Sterile neutrino mass is approximately given as

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

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

$$\tan 2\theta_s \simeq \sin 2\theta_s \simeq \begin{cases} \frac{2m_D}{M} & \left(\text{for } M^2 > 4\mu M_R : \textbf{Case A}\right), \\ \frac{m_D}{M} & \left(\text{for } M^2 \simeq 4\mu M_R : \textbf{Case B}\right), \\ \frac{m_D M}{2\mu M_R} & \left(\text{for } M^2 < 4\mu M_R : \textbf{Case C}\right), \end{cases}$$

$$m_s \simeq \begin{cases} \frac{M^2}{4M_R} & \left(\textbf{Case A}\right), \\ 2\mu & \left(\textbf{Case B}\right), \\ \mu & \left(\textbf{Case C}\right). \end{cases}$$

## 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 $\Longrightarrow$ observable consequences for cosmology & astrophyics.
- $m_s$ and $\theta_s$ $\Rightarrow$ subject to the cosmological and astrophysical bounds.
- Some laboratory bounds $\Longrightarrow$ 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 $m_s$, $\Longrightarrow$ 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 $\implies$
  their abundance to be smaller than the predictions in thermal equilibrium.
- A few keV sterile neutrino $\implies$ 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:
  $\Longrightarrow \qquad \sin^2\theta_s \lesssim 10^{-9}$ .

- 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 $\Longrightarrow$
  responsible for peculiar properties of the lepton mixing such as tri-bimaximal mixig (Smirnov, Funchal '06).

- Sterile neutrinos with mass 1-100 MeV $\Longrightarrow$ 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, <u>we will focus on MeV sterile neutrinos</u>.

- Similarly, we can realize keV sterile neutrinos (unnatural).

# Low Scale Leptogenesis

- 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 $\Longrightarrow$ 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 :

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

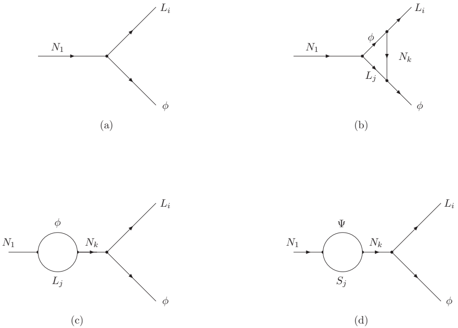
  where

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

- The introduction of $S$ $\Longrightarrow$ 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 :




- In addition to (a-c), there is a new daigram (d) arisen due to the new Yukawa interaction $Y_S \bar{N} \Psi S$.

- Assuming $m_\phi, m_\Psi, m_S << m_{R_1}$, to leading order,

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

- The lepton asymmetry :

$$\boxed{\varepsilon_1 = \frac{1}{8\pi}\sum_{k\neq 1}\left([g_V(x_k)+g_S(x_k)]\mathcal{T}_{k1} + g_S(x_k)\mathcal{S}_{k1}\right),}$$

where

- $g_V(x) = \sqrt{x}\{1-(1+x)\ln[(1+x)/x]\}$,
- $g_S(x) = \sqrt{x_k}/(1-x_k)$ with $x_k = M^2_{R_k}/M^2_{R_1}$ for $k \neq 1$,
- $\mathcal{T}_{k1} = \frac{\mathrm{Im}[(Y_\nu Y_\nu^\dagger)^2_{k1}]}{(Y_\nu Y_\nu^\dagger + Y_s Y_s^\dagger)_{11}}$
- $\mathcal{S}_{k1} = \frac{\mathrm{Im}[(Y_\nu Y_\nu^\dagger)_{k1}(Y_s^\dagger Y_s)_{1k}]}{(Y_\nu Y_\nu^\dagger + Y_s Y_s^\dagger)_{11}}$ : coming from interference of the tree diagram with (d).

- For $x \gg 1$, vertex diagram becomes dominant :

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

- 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 $m_\nu$, $m_{\nu_3} \simeq \sqrt{\Delta m^2_{atm}}$ 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, $\varepsilon_1$ :

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

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

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

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

$\Longrightarrow$ 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

  $\Longrightarrow$ the second term of $\varepsilon_1$ can dominate over the first one and thus the size of $\varepsilon_1$ 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 :

$$\boxed{|\kappa|^2 M_{R_2} \sqrt{\Delta m^2_{atm}} R / 16\pi v^2}$$

- 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 $M^2_{R_2}/M^2_{R_1} \sim 10$.

- The generated B-L asymmetry : $\boxed{Y^{SM}_{B-L} = -\eta\varepsilon_1 Y^{eq}_{N_1}}$

  where $Y^{eq}_{N_1} \simeq \frac{45}{\pi^4}\frac{\zeta(3)}{g_* k_B}\frac{3}{4}$

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

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

- The new process of type $S\Psi \to l\phi \quad \Longrightarrow$

  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 $\quad\Longrightarrow\quad$ similar to the case of the typical seesaw model with $M_{R_1} \sim 10^4$ GeV and $\tilde{m}_1 \simeq 10^{-3}$ eV,

  $\Longrightarrow \quad \varepsilon_1 \sim 10^{-6}$

# Numerical Estimation

- Let us examine how both $m_{\nu_i}$ of order $0.01 \sim 0.1$ eV and $m_s$ of order 100 MeV can be simultaneously realized (without being in conflict with the constraints on the mixing $\theta_s$).
- For hierarchical neutrino spectrum, the largest $m_\nu$ : $\sqrt{\Delta m^2_{atm}} \simeq 0.05$ eV and next largest : $\sqrt{\Delta m^2_{sol}} \simeq 0.01$ eV.
- Low scale seesaw $\Rightarrow$ achieved by taking $m_D$ to be 1-100 MeV.
- For our numerical analysis, $\sin^2\theta_s \simeq 10^{-9}$, allowed by the constraints for $m_s \sim$ a few 100 MeV.

Case A : For $M^2 > 4\mu M_R$:

- $\sin^2\theta_s \simeq (m_D/M)^2$ and $m_{\nu_i} \simeq 0.5\sin^2\theta_s \mu_i$.
- $m_{\nu_i} \simeq 0.01$ (0.1) eV $\Longrightarrow$ $\mu_i \simeq 20$ (200) MeV.
- Since $M_i = m_{D_i} \times \sqrt{10^9}$, $M_1 \sim 30$ GeV for $m_{D_1} \sim 1$ MeV.
- $m_{s_1} \simeq 250$ MeV $\Longrightarrow$ realized by taking $M_{R_1} \simeq 1$ TeV.
- Successful leptogenesis could be achieved for $M^2_{R_2} \simeq 10\ M^2_{R_1}$, and thus in order to obtain $m_{\nu_2} = 0.01$ eV and $m_{s_2} \simeq 250$ MeV, we require $M_{R_2} \simeq 3$ TeV and $M_2 \simeq 50$ 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 $\Longrightarrow$ $\mu_i \simeq 5\ \ (50)$ 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 $m_{\nu_i} \simeq 0.01$ $\Longrightarrow$ 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 $\Longrightarrow$ achieved for quasi-degenerate $m_{\nu_i}$ of order 0.1 eV.
- $M_R = M^2/(4\mu) \simeq 6\times 10^7 m_D^2/\mu \simeq 0.12 m_D^2/m_\nu$ $\Longrightarrow$
  $M_R \simeq 1.2$ TeV for $m_D \simeq 1$ MeV and $\nu \simeq 0.1$ eV.

## Case C : For $4\mu M_R > M^2$:

- $\tan 2\theta_s \simeq 2\sin\theta_2 \simeq m_D M/(2\mu M_R) \implies$

$$\sin\theta_s = \frac{m_D^3}{8 m_\nu M M_R}.$$

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