Lepton asymmetry production in the νMSM

Shintaro Eijima

(EPFL)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SEWM14, 17, July @EPFL

A flavor symmetry in the νMSM with 7 keV dark matter

Shintaro Eijima

(EPFL)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

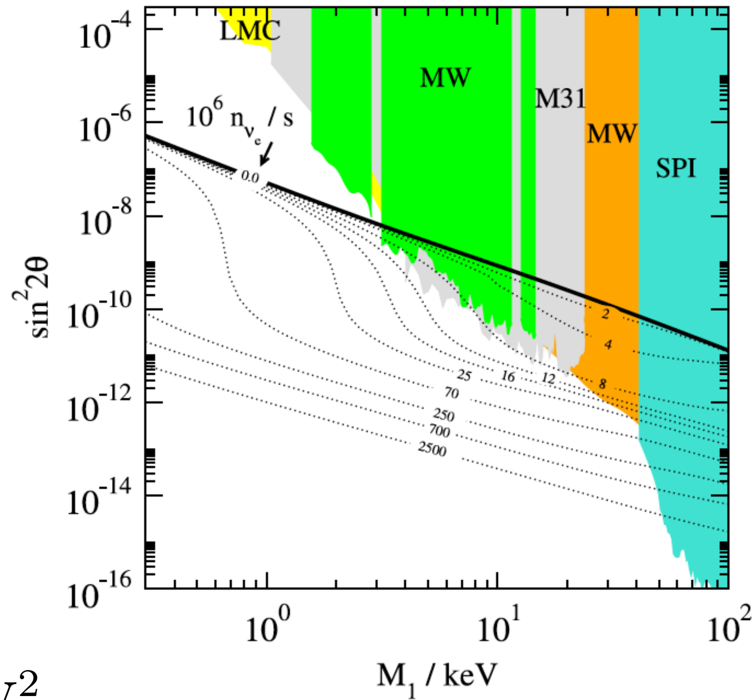
In collaboration with Takehiko Asaka (Niigata University)

SEWM14, 17, July @EPFL

Neutrino Minimal Standard Model (νMSM)

[Asaka, Shaposhnikov ('05)] [Asaka, Blanchet, Shaposhnikov ('05)]

The SM extended by **three right-handed neutrinos with masses smaller than electroweak scale.**



[Laine, Shaposhnikov ('08)]

N_1 DM

$$M_1 \sim \mathcal{O}(10)\mathrm{keV}$$

$$|F_1| \sim \mathcal{O}(10^{-14})$$

$N_{2,3}$ ν Osc.

$$\Delta m^2_{\mathrm{sol}} = 7.54 \times 10^{-5}\mathrm{eV}^2$$

$$\Delta m^2_{\mathrm{atm}} = 2.43 \times 10^{-3}\mathrm{eV}^2$$ [Fogri et al. ('12)]

BAU

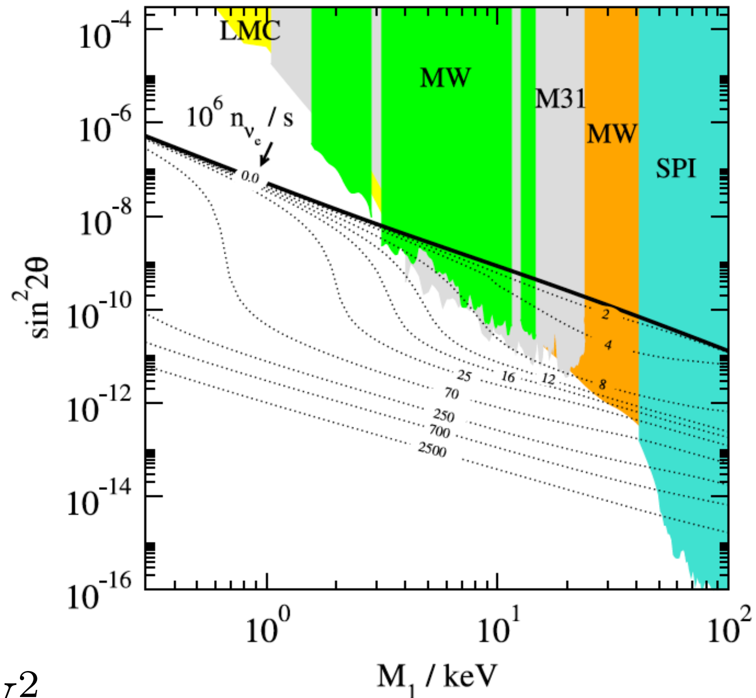
$$Y_B \simeq 8.8 \times 10^{-11}$$ [WMAP collaboration ('10)]

$$M_N \sim \mathcal{O}(1)\mathrm{GeV} \quad \Delta M = \frac{M_3 - M_2}{2} \ll M_N$$

$$F_{2,3} \sim \mathcal{O}(10^{-7})$$

Neutrino Minimal Standard Model (νMSM)

[Asaka, Shaposhnikov ('05)] [Asaka, Blanchet, Shaposhnikov ('05)]



[Laine, Shaposhnikov ('08)]

These particles are testable!

N_1 DM

Through radiative decay

$$N_1 \rightarrow \nu + \gamma$$

$N_{2,3}$ ν Osc. $\Delta m^2_{\rm sol} = 7.54 \times 10^{-5} {\rm eV}^2$

$\Delta m^2_{\rm atm} = 2.43 \times 10^{-3} {\rm eV}^2$ [Fogri et al. ('12)]

BAU $Y_B \simeq 8.8 \times 10^{-11}$ [WMAP collaboration ('10)]

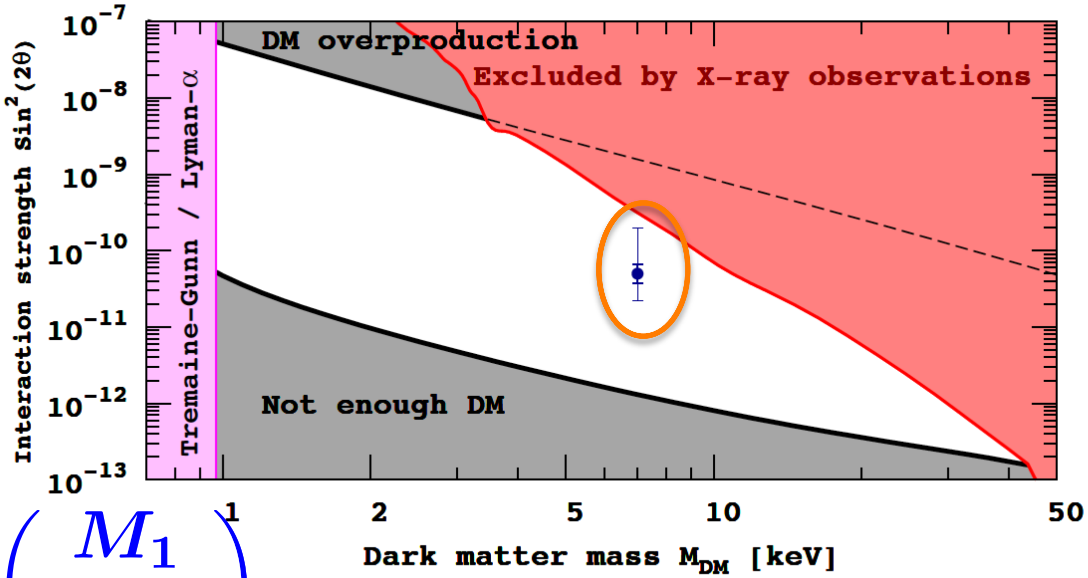
With weak interaction through the neutrino mixing

e.g. $K^+ \rightarrow N_{2,3} + e^+$

$$N_{2,3} \rightarrow e^+ e^- \nu,\ \mu^+ \mu^- \nu,\ \pi^+ e^-,\ \ldots$$

Fine-tunings in the νMSM

3.5 keV line in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster



[Boyarsky, Ruchayskiy, Iakubovskyi, Franse ('14)]

N_1 DM

$$M_1 \simeq 7\mathrm{keV}$$

$$|F_1| \simeq 2 \times 10^{-13} \left(\frac{M_1}{7\mathrm{keV}}\right)$$

$N_{2,3}$

⇕

We discuss a flavor symmetry to explain this fine-tunings

$$M_N \sim \mathcal{O}(1)\mathrm{GeV} \quad \Delta M = \frac{M_3 - M_2}{2} \ll M_N$$

$$F_{2,3} \sim \mathcal{O}(10^{-7})$$

A possible symmetry in the νMSM

[Shaposhnikov ('07)]

Start from the case which all fine-tunings are exactly satisfied

1. $\boldsymbol{M_1 = 0}$ and $\boldsymbol{F_{\alpha 1} = 0}$

   A chiral symmetry : $\boldsymbol{\widetilde{N}_1 \to e^{i\beta_L} \widetilde{N}_1}$

2. $\boldsymbol{M_2 = M_3 \ (\Delta M = 0)}$

   A $\boldsymbol{U(1)}$ symmetry : $\boldsymbol{\widetilde{N}_2 \to e^{-i\alpha_L} \widetilde{N}_2}$

   $$\boldsymbol{\widetilde{N}_3 \to e^{i\alpha_L} \widetilde{N}_3}$$

⇨ Mass matrix : $\boldsymbol{\hat{\widetilde{M}} = \begin{pmatrix} 0 & M_N \\ M_N & 0 \end{pmatrix}}$

These symmetries are equally described by one $\boldsymbol{U(1)_L}$ symmetry

Field	$\widetilde{N}_1$	$\widetilde{N}_2$	$\widetilde{N}_3$
$\mathrm{U}(1)_L$ charge	a	-1	$+1$

$a = 1/n_a \quad (n_a = 2, 3, 4, \ldots)$

Global $U(1)_L$ symmetry

Field	$\widetilde{N}_1$	$\widetilde{N}_2$	$\widetilde{N}_3$	L_α
$\mathrm{U}(1)_L$ charge	a	-1	$+1$	$+1$

$a = 1/n_a \quad (n_a = 2, 3, 4, \ldots)$

$U(1)_L$ exact Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \overline{\widetilde{N}_I} i\partial_\mu \gamma^\mu \widetilde{N}_I - \widetilde{F}_{\alpha 3} \overline{L}_\alpha H \widetilde{N}_3 - \frac{M_N}{2} \overline{\widetilde{N}_2^c} \widetilde{N}_3 + h.c.$$

where $\widetilde{F}_{\alpha 3} = c_{\alpha 3} F_0$

F_0 : Typical Yukawa coupling constant

$c_{\alpha 3}$: Real and order unity

⇨ BSM phenomena can not be explained

DM : No — $M_1 = 0$

ν Osc. : No — All active neutrinos are massless

BAU : No — No CP violation

Global $U(1)_L$ symmetry

Introduce two singlet scalar, χ_2 and χ_a

Field	$\widetilde{N}_1$	$\widetilde{N}_2$	$\widetilde{N}_3$	L_α	χ_2	χ_a
$\mathrm{U}(1)_L$ charge	a	-1	$+1$	$+1$	$+2$	a

Assumption : $M_{IJ} \propto M_N$ and $F_{\alpha I} \propto F_0$ $\qquad a = 1/n_a$

$$
\begin{aligned}
\mathcal{L} \;=\;& \mathcal{L}_{\mathrm{SM}} + \overline{\widetilde{N}_I} i\partial_\mu \gamma^\mu \widetilde{N}_I - c_{\alpha 3} F_0 \overline{L_\alpha} H \widetilde{N}_3 - \frac{M_N}{2} \overline{\widetilde{N}_2^c} \widetilde{N}_3 \\
& - c_{\alpha 1} F_0 \left(\frac{\chi_a^*}{\Lambda}\right)^{n_a - 1} \overline{L_\alpha} H \widetilde{N}_1 - \frac{d_{11} M_N}{2} \left(\frac{\chi_a^*}{\Lambda}\right)^2 \overline{\widetilde{N}_1^c} \widetilde{N}_1 \\
& - \frac{d_{12} M_N}{2} \left(\frac{\chi_a^*}{\Lambda}\right)^{n_a - 1} \overline{\widetilde{N}_1^c} \widetilde{N}_2 - \frac{d_{13} M_N}{2} \left(\frac{\chi_a}{\Lambda}\right)^{n_a + 1} \overline{\widetilde{N}_1^c} \widetilde{N}_3 \\
& - c_{\alpha 2} F_0 \left(\frac{\chi_2}{\Lambda}\right) \overline{L_\alpha} H \widetilde{N}_2 - \frac{d_{22} M_N}{2} \left(\frac{\chi_2}{\Lambda}\right) \overline{\widetilde{N}_2^c} \widetilde{N}_2 \\
& - \frac{d_{33} M_N}{2} \left(\frac{\chi_2^*}{\Lambda}\right) \overline{\widetilde{N}_3^c} \widetilde{N}_3 + h.c.
\end{aligned}
$$

at the leading order of χ

($c_{\alpha I}$, $d_{IJ} = \mathcal{O}(1)$)

Global $U(1)_L$ symmetry breaking

After the symmetry breaking,

Mass matrix

$$\hat{\widetilde{M}} = \begin{pmatrix} \widetilde{M}_{11} & \widetilde{M}_{12} & \widetilde{M}_{13} \\ \widetilde{M}_{21} & \widetilde{M}_{22} & \widetilde{M}_{23} \\ \widetilde{M}_{31} & \widetilde{M}_{32} & \widetilde{M}_{33} \end{pmatrix}$$

The VEVs of χ are normalized by Λ

$$= M_N \begin{pmatrix} d_{11}\langle\chi_a\rangle^2 & d_{12}\langle\chi_a\rangle^{n_a-1} & d_{13}\langle\chi_a\rangle^{n_a+1} \\ d_{21}\langle\chi_a\rangle^{n_a-1} & d_{22}\langle\chi_2\rangle & 1 \\ d_{31}\langle\chi_a\rangle^{n_a+1} & 1 & d_{33}\langle\chi_2\rangle \end{pmatrix}$$

Yukawa coupling constants

$$\widetilde{F}_{\alpha 1} = c_{\alpha 1}\langle\chi_a\rangle^{n_a-1} F_0$$

$$\widetilde{F}_{\alpha 2} = c_{\alpha 2}\langle\chi_2\rangle F_0$$

$$\widetilde{F}_{\alpha 3} = c_{\alpha 3} F_0$$

The structure of mass matrix and hierarchy of Yukawa coupling constants can be induced by the symmetry breaking parameters

Implication from 7 keV dark matter

From the diagonalization of mass matrix,

$$M_1 \simeq \widetilde{M}_{11} \simeq \langle \chi_a \rangle^2 M_N$$

$$\Rightarrow \quad \langle \chi_a \rangle \simeq 2.6 \times 10^{-3} \left(\frac{1\mathrm{GeV}}{M_N} \right)^{\frac{1}{2}} \qquad \text{for } M_1 = 7\mathrm{keV}$$

In this case, $N_1 \simeq \widetilde{N}_1$,

$$|F_{\alpha 1}| \simeq |\widetilde{F}_{\alpha 1}| \simeq \langle \chi_a \rangle^{1-n_a} F_0 \qquad \text{for } |F_{\alpha 1}| = 2 \times 10^{-13}$$

$$\Rightarrow \quad F_0 \simeq \frac{|F_{\alpha 1}|}{\langle \chi_a \rangle^{n_a - 1}} = 2 \times 10^{-13} \langle \chi_a \rangle^{1-n_a}$$

$$\simeq 2 \times 10^{-13} \left(2.6 \times 10^{-3} \left(\frac{1\mathrm{GeV}}{M_N} \right)^{\frac{1}{2}} \right)^{1-n_a}$$

Implication from neutrino oscillation

The dark matter candidate is decoupled from the see-saw mechanism due to the smallness of couplings.

See-saw mass matrix is given by

$$M_\nu \simeq \widetilde{F}_{\alpha 2}\widetilde{F}_{\alpha 3}\frac{\langle H\rangle^2}{M_N} \simeq F_0^2\langle\chi_2\rangle\frac{\langle H\rangle^2}{M_N}$$

When we choose $|M_\nu| = 5\times 10^{-2}\mathrm{eV}$ (atmospheric scale),

$$F_0 \simeq \left(\frac{|M_\nu|M_N}{\langle\chi_2\rangle\langle H\rangle^2}\right)^{\frac{1}{2}} = 4\times 10^{-6}\left(\frac{M_N}{1\mathrm{GeV}}\right)^{\frac{1}{2}}\left(\frac{X}{100}\right)$$

where $X \equiv 1/\sqrt{\langle\chi_2\rangle}$ controls the magnitude of Yukawa coupling.

$$\langle\chi_2\rangle \simeq \frac{|M_\nu|M_N}{F_0^2\langle H\rangle^2} \simeq (4\times 10^{10})(7\times 10^{-6})^{n_a-1}\left(\frac{1\mathrm{GeV}}{M_N}\right)^{n_a-2}$$

Consequence from flavor symmetry

n_a	2	3	4	5
$\langle\chi_2\rangle$	2.9×10^{5}	2	1.4×10^{-5}	9.8×10^{-11}
X	1.9×10^{-3}	0.71	2.7×10^{2}	1.0×10^{5}

for $M_N = 1\text{GeV}$

$n_a = 2,\ 3$ excluded $\langle\chi_2\rangle$ should be much smaller than unity

$n_a = 4$ **OK!**

$n_a \geq 5$ excluded BAU can not be realized due to strong washout

For $n_a = 4$

$$\langle\chi_2\rangle \simeq 1.4\times10^{-5}\left(\frac{1\text{GeV}}{M_N}\right)^2$$

$$X = \langle\chi_2\rangle^{-\frac{1}{2}} \simeq 267\left(\frac{M_N}{1\text{GeV}}\right)$$

$$\Delta M \simeq M_{22} \simeq M_{33} \simeq \langle\chi_2\rangle M_N = 1.4\times10^{-5}\,\text{GeV}\left(\frac{1\text{GeV}}{M_N}\right)$$

$\Longleftrightarrow$

$$\frac{\Delta M}{M_N} \simeq X^{-2}$$

Parameterization of $F_{\alpha I}$ for $N_{2,3}$

From see-saw mass matrix $M_\nu = -M_D M_N^{-1} M_D^T$,

$$F = \frac{i}{\langle H \rangle} U \, D_\nu^{\frac{1}{2}} \, \Omega \, D_N^{\frac{1}{2}}$$

[Casas, Ibarra ('01)]

- $D_\nu^{\frac{1}{2}} = \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})$
- $D_N^{\frac{1}{2}} = \mathrm{diag}(\sqrt{M_2}, \sqrt{M_3}) = \mathrm{diag}(\sqrt{M_N - \Delta M}, \sqrt{M_N + \Delta M})$
- U : PMNS-matrix
- $\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi \sin\omega & \xi \cos\omega \end{pmatrix}$ (*e.g.* NH)

ω :complex parameter

$\xi = \pm 1$

⇨ When $\mathrm{Im}\,\omega \gg 1$,

$F \propto \exp[\mathrm{Im}\,\omega] \equiv X_\omega$

X and X_ω can be identified

Neutrino osc. is guaranteed as long as this parameterization is relevant.

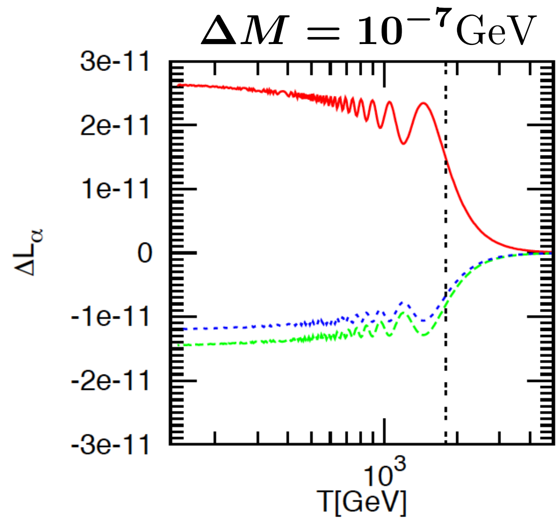
Baryogenesis via RHν Oscillation

[Akhemedov, Rubakov, Smirnov('98)] [Asaka, Shaposhnikov('05)]

In this model, "decay" is not effective because of $M_N \ll T$, but "**Right-handed neutrino oscillation**" can works as the source to produce lepton asymmetry.

$$\Delta L|_{T_{SF}} \propto \sum_{\alpha,\, I} \frac{|F^2_{\alpha I}| A^{\alpha}_{32}}{\Delta M}$$

$$A^{\alpha}_{32} = \mathrm{Im}[F_{\alpha 3}[F^{\dagger} F]_{32} F^{*}_{\alpha 2}]$$

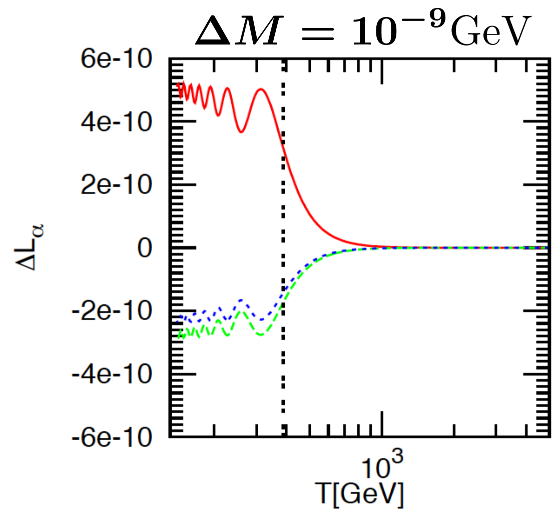


ΔM

- Resonance ⟹ Smaller is favored
- T_{SF} vs. $T_{\mathrm{osc}} = (M_N\, \Delta M\, M_0 \,/\, 3)^{\frac{1}{3}}$

  $(\, M_0 = 7 \times 10^{17}\mathrm{GeV} \,)$

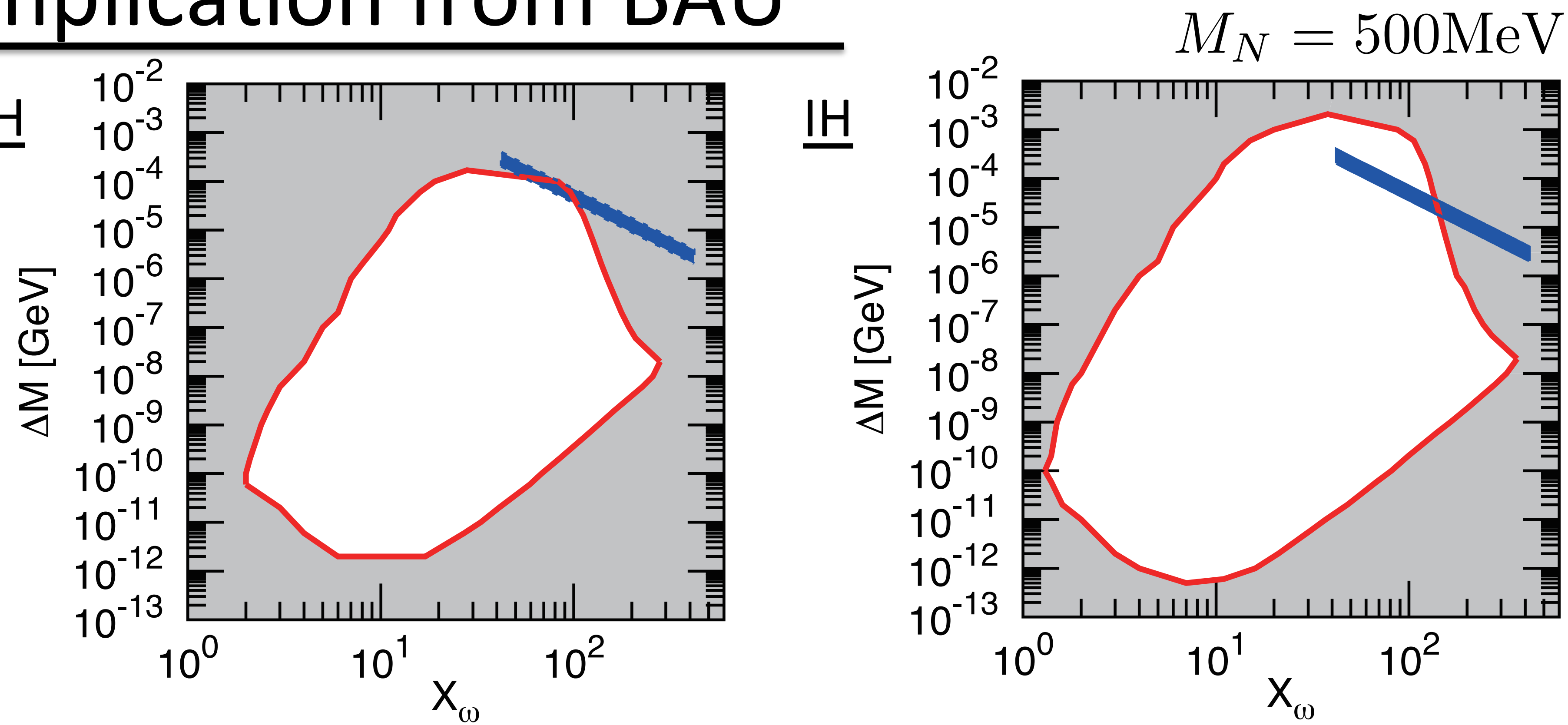
  ⟹ Too small is excluded



X_ω

- Large enhances the asymmetry
- Washout ⟹ Too large is excluded

Implication from BAU

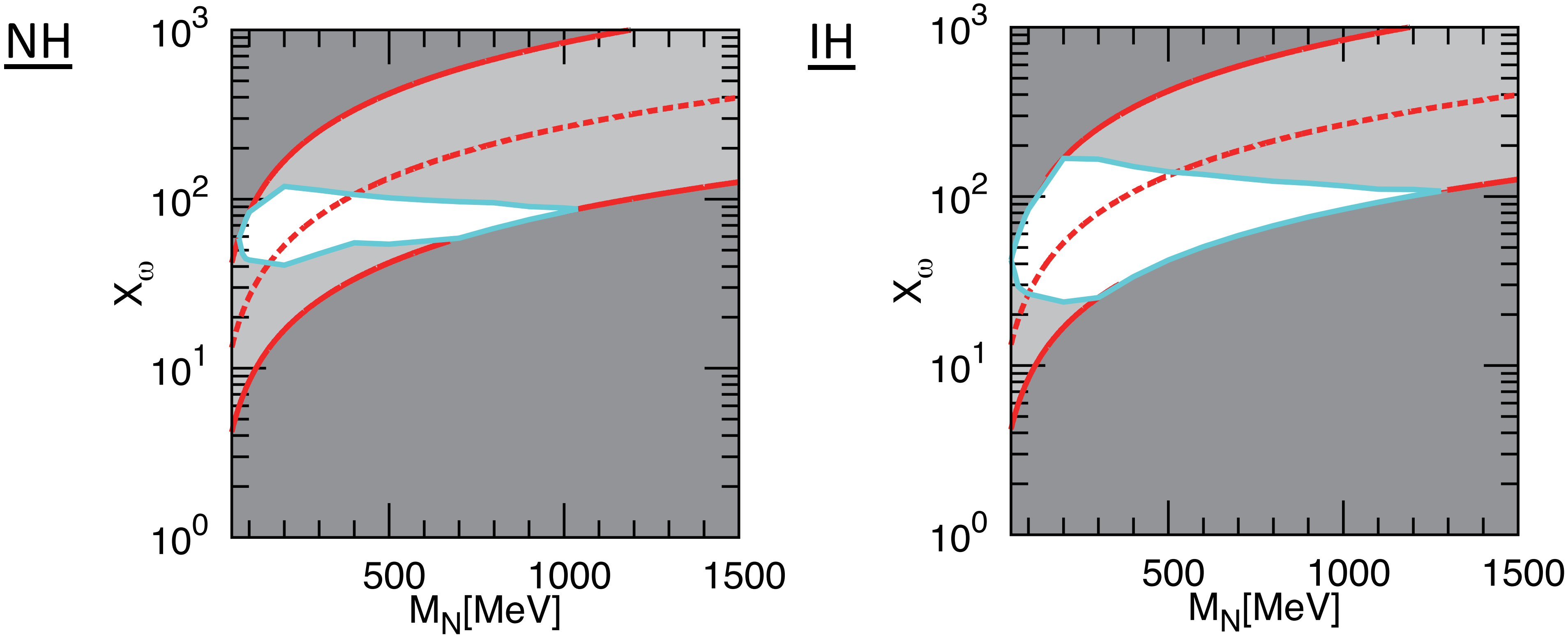


In the region enclosed red line BAU can be explained

The blue band is the suggestion from this flavor symmetry including the theoretical uncertainty, described by

$$\boldsymbol{\Delta M \simeq M_N X_\omega^{-2}}$$

Implication from BAU



The region between red solid lines is the suggestion from this flavor symmetry

In the region enclosed cyan line BAU can be explained

⇨ **This flavor symmetry indicates lighter mass region**

Constraints for $N_{2,3}$

Experimental bounds

So far several experiments (PS191, NuTeV, CHARM, …) have been performed to search the heavy neutral leptons, however the particles have not been discovered yet.

⟹ Upper bounds of interaction strength

⟹ From $|F|^2 \propto X_\omega^2$, **upper bound of X_ω**

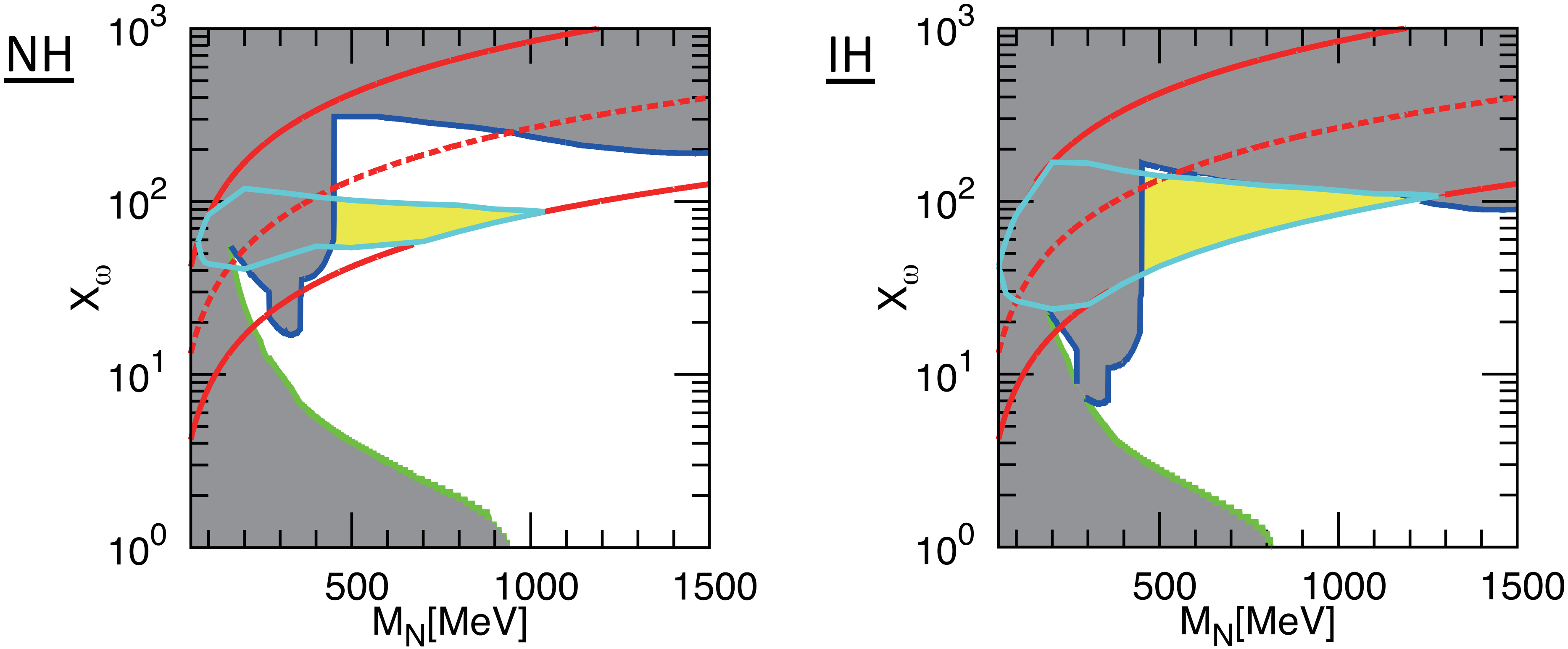
Cosmological bounds

If heavier right-handed neutrinos decay after the beginning of Big Bang Nucleosynthesis (1 sec), the decay products would spoil the prediction of standard BBN.

⟹ Upper limit of lifetime : $\tau_N < 0.1\,\mathrm{sec}$ for $M_N > m_\pi$
(one flavor case)
[Dolgov, Hansen, Raffelt, Semikoz ('00)]

⟹ From $\tau_N^{-1} \propto \Gamma_N \propto F^2$, **lower bound of X_ω**

Result



Blue line : Experimental bound   Green line : BBN bound

In the yellow region heavier right-handed neutrinos are allowed from the two types of constraint, and can also generate observed baryon asymmetry in the parameter space suggested by the flavor symmetry.

Summary

We discuss the global $U(1)_L$ symmetry as a possibility to explain the fine-tunings of Yukawa coupling constants and masses of right-handed neutrino sector in the νMSM.

Taking into account the decaying dark matter with 7 keV mass, the flavor symmetry suggests that the interaction of heavier neutrinos is relatively strong and the mass difference is not too small ($X \simeq 270$, $\Delta M \simeq 10^{-5}$ GeV for $M_N = 1$ GeV) .

We show that the model which is based on the flavor symmetry is consistent with several observations.

Furthermore, heavy neutral leptons in that region might be investigated by near future experiment!

- *Search for Hidden Particle : SHiP*

SHiP

Search for Hidden Particles

Backup

[Asaka, SE, Ishida ('12)]

Explicit expressions for parameters

$$F_0 \simeq \left(\frac{|M_\nu| M_N}{|c_{\alpha 2}||c_{\alpha 3}|\langle\chi_2\rangle\langle H\rangle^2}\right)^{\frac{1}{2}} = \frac{4\times 10^{-6}}{\sqrt{|c_{\alpha 2}||c_{\alpha 3}|}}\left(\frac{M_N}{1\mathrm{GeV}}\right)^{\frac{1}{2}}\left(\frac{X}{100}\right)$$

$$\langle\chi_2\rangle \simeq \frac{|M_\nu| M_N}{|c_{\alpha 2}||c_{\alpha 3}|F_0^2\langle H\rangle^2}$$

$$= \frac{4\cdot 10^{10}\times(7\cdot 10^{-6})^{n_a-1}|c_{\alpha 1}|^2}{|c_{\alpha 2}||c_{\alpha 3}||d_{11}|^{n_a-1}}\left(\frac{1\mathrm{GeV}}{M_N}\right)^{n_a-2}$$

$$\Delta M \simeq |d| M_N\langle\chi_2\rangle \qquad (\, d = d_{22} = d_{33}\,)$$

Parameters for $n_a = 4$

$$\widetilde{F}_{\alpha 1} = 2 \times 10^{-13}$$

$$\widetilde{F}_{\alpha 2} \simeq 1.5 \times 10^{-10} \left(\frac{1\mathrm{GeV}}{M_N}\right)^{\frac{1}{2}}$$

$$\widetilde{F}_{\alpha 3} \simeq 1.1 \times 10^{-5} \left(\frac{M_N}{1\mathrm{GeV}}\right)^{\frac{3}{2}}$$

$$\widetilde{M}_{11} = 7 \times 10^{-6}\mathrm{GeV}$$

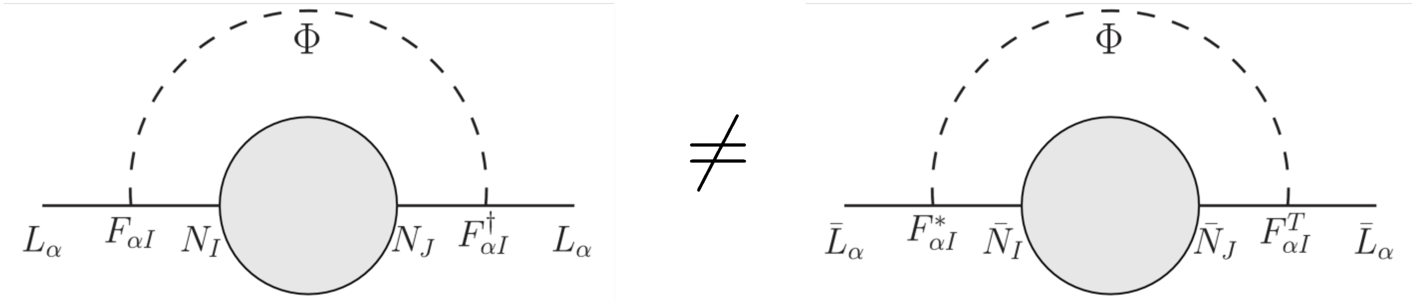
$$\widetilde{M}_{12} \simeq 1.8 \times 10^{-8} \left(\frac{1\mathrm{GeV}}{M_N}\right)^{\frac{1}{2}} \mathrm{GeV}$$

$$\widetilde{M}_{13} \simeq 1.2 \times 10^{-13} \left(\frac{1\mathrm{GeV}}{M_N}\right)^{\frac{3}{2}} \mathrm{GeV}$$

Baryogenesis via RHν Oscillation

[Akhemedov, Rubakov, Smirnov('98)] [Asaka, Shaposhnikov('05)]

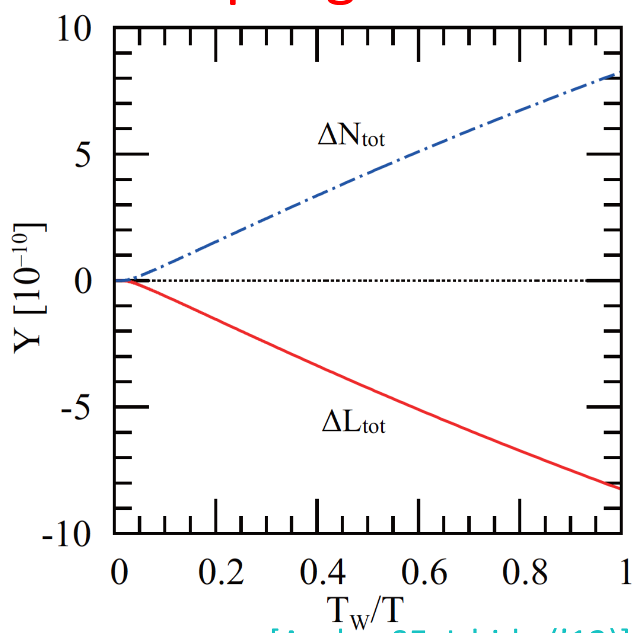
1. Lepton "flavor" asymmetry is generated by flavor changing processes in LH sector



2. "Total" lepton asymmetry is produced in RHν sector by the lepton flavor asymmetry and flavor difference of Yukawa couplings

3. The same amount lepton asymmetry with opposite sign is generated in LH sector due to the lepton number conservation at $T \gg M_N$

4. The lepton asymmetry in LH sector is partially converted to baryon asymmetry by Sphaleron effect



[Asaka, SE, Ishida ('12)]