Flavor Models for the νMSM

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Some overlap with

T.A. & Li Yufeng(IHEP), PRD85, 065016.

Outline

- νMSM and its parameter space
  - dark matter abundance
  - neutrino masses (seesaw)
  - baryon asymmetry of the universe

  based on [Canetti etal, arXiv: 1208.4607 [hep-ph]]

- Flavor Models
  - Flavor symmetries
  - model - I
  - model - II
- Summary

vMSM

The νMSM

νMSM = **n**eutrino **M**inimal **S**tandard **M**odel

The extended SM by three RHNs with masses smaller than the EW scale ($M_R < 100 \text{ GeV}$) :

$$\mathcal{L}_{\nu\text{MSM}} = \mathcal{L}_{\text{SM}} + i\overline{N_R}\,\partial\!\!\!/ N_R + \left(-Y_{ij}\overline{L}_i \tilde{H} N_{Rj} - \frac{M_{Ri}}{2}\overline{N^c_{Ri}} N_{Ri} + h.c. \right)$$

$M_1 \sim \text{keV}$ → (Warm) Dark Matter Candidate

$M_{2,3} \sim \text{GeV}$ → Tiny Neutrino Masses and BAU

Three big mysteries, which cannot be explained within the SM, can be addressed simultaneously!!

The νMSM ~parameters~

The diagonal basis of the right-handed (sterile) neutrinos:

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM}}$$

$$+i\overline{N_R}\,\partial\!\!\!/ N_R + \left(-Y_{ij}\overline{L}_i \tilde{H} N_{Rj} - \frac{M_{Ri}}{2}\overline{N^c_{Ri}} N_{Ri} + h.c. \right)$$

Dirac $m_{ij} = v_{\mathrm{ew}} Y_{ij}$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & m_{12} & m_{12} & m_{13} \\ & 0 & 0 & m_{22} & m_{22} & m_{23} \\ & & 0 & m_{32} & m_{32} & m_{33} \\ & & & M_1 & 0 & 0 \\ & & & & M - \Delta M & 0 \\ & & & & & M + \Delta M \end{pmatrix}$$

Majorana

The vMSM ~parameters~

The diagonal basis of the right-handed (sterile) neutrinos:

$$\mathcal{L}_{\nu\text{MSM}} = \mathcal{L}_{\text{SM}} + i\overline{N_R}\,\not\partial N_R + \left(-Y_{ij}\overline{L}_i\tilde{H}N_{Rj} - \frac{M_{Ri}}{2}\overline{N^c_{Ri}}N_{Ri} + h.c.\right)$$

$$m_{ij} = v_{\text{ew}}Y_{ij}$$

$Y_{i1}\ \overline{\nu}_{Li}\ h\ N_{R1}$

active – sterile mixing

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & m_{12} & m_{12} & m_{13} \\ & 0 & 0 & m_{22} & m_{22} & m_{23} \\ & & 0 & m_{32} & m_{32} & m_{33} \\ & & & M_1 & 0 & 0 \\ & & & & M-\Delta M & 0 \\ & & & & & M+\Delta M \end{pmatrix}$$

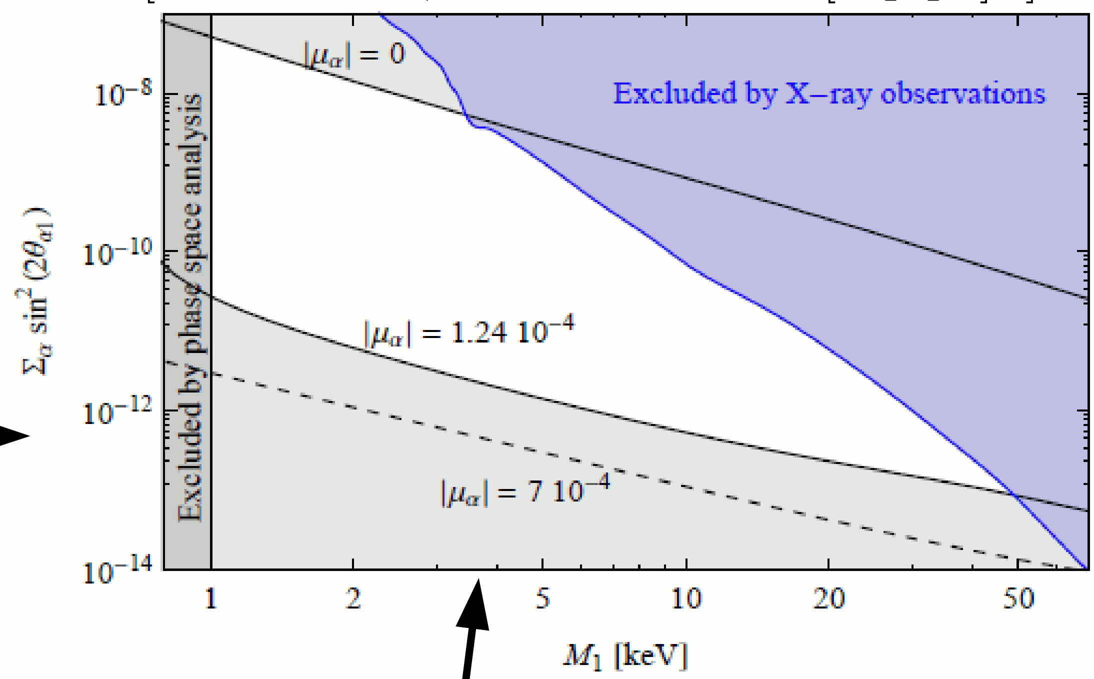
(warm) DM candidate

The νMSM ~dark matter~

The N1 (wDM) abundance was generated via active-sterile mixing with lepton number asymmetry.

$$\begin{pmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{pmatrix}$$

[Canetti etal, arXiv: 1208.4607 [hep-ph]]



$$y_{i1} \sim 10^{-12} \quad \text{for} \quad M_1 = 1\ \text{keV}$$
$$y_{i1} \sim 10^{-13} \quad \text{for} \quad M_1 = 30\ \text{keV}$$

$$\begin{pmatrix} M_1 & 0 & 0 \\ 0 & M - \Delta M & 0 \\ 0 & 0 & M + \Delta M \end{pmatrix}$$

The νMSM ~parameters~

The diagonal basis of the right-handed (sterile) neutrinos:

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM}}$$

$$+ i\overline{N_R}\,\partial\!\!\!/ N_R + \left(-Y_{ij}\overline{L}_i \tilde{H} N_{Rj} - \frac{M_{Ri}}{2}\overline{N^c_{Ri}} N_{Ri} + h.c. \right)$$

$$\begin{pmatrix} 0 & 0 & 0 & \overbrace{m_{12} \quad m_{12} \quad m_{13}}^{m_{ij} = v_{\mathrm{ew}} Y_{ij}} \\ & 0 & 0 & m_{22} \quad m_{22} \quad m_{23} \\ & & 0 & m_{32} \quad m_{32} \quad m_{33} \\ & & & M_1 \quad 0 \quad 0 \\ & & & \quad M - \Delta M \quad 0 \\ & & & \quad\quad M + \Delta M \end{pmatrix}$$

Masses of the active neutrinos via the seesaw mechanism.

The νMSM ~seesaw~

Consider the basis $M_R = \mathrm{Diag}(M_1, M-\Delta M, M+\Delta M)$
and integrate out the right-handed neutrinos:

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM}}$$
$$+i\overline{N_R}\,\partial\!\!\!/ N_R + \left(-Y_{ij}\overline{L}_i\tilde{H}N_{Rj} - \frac{M_{Ri}}{2}\overline{N^c_{Ri}}N_{Ri} + h.c.\right)$$

$$m_D = vY$$

$$\begin{pmatrix} 1-\frac{1}{2}\xi\xi^\dagger & -\xi \\ \xi^\dagger & 1-\frac{1}{2}\xi\xi^\dagger \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} 1-\frac{1}{2}\xi^*\xi^T & \xi^* \\ -\xi^T & 1-\frac{1}{2}\xi^T\xi^* \end{pmatrix}$$

$$\xi = m_D M_R^{-1} \ll 1$$

Active: $m_\nu = \xi M_R \xi^T \sim \mathcal{O}(\mathrm{eV})$

Sterile: $M'_R = M_R + \frac{1}{2}\left(\xi^\dagger\xi M_R + M_R^T\xi^T\xi^*\right)$

The νMSM ~seesaw~

In the diagonal basis of the sterle neutrinos

$$M_R = \begin{pmatrix} M_1 & & \\ & M-\Delta M & \\ & & M+\Delta M \end{pmatrix} \quad Y_{ij} = \begin{pmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{pmatrix}$$

GeV

$m_\nu = v^2 Y M_R^{-1} Y^T \simeq 10^{-2}\ \mathrm{eV}$ requires that

$$y_{i2},\ y_{i3} \sim 10^{-7.5} \quad \text{for} \quad M_{2,3} = 1\ \mathrm{GeV}.$$

The constraints $y_{i1} \sim 10^{-12}$ for $M_1 = 1\ \mathrm{keV}$ result in

$$m_\nu^{\text{lightest}} \sim 10^{-5}\ \mathrm{eV}.$$

The lightest active neutrino mass is negligibly-small !!

The νMSM ~seesaw~

The sterile neutrino mixing may be enhanced.

Sterile: $$M'_R = M_R + \frac{1}{2}\left(\xi^\dagger \xi M_R + M_R^T \xi^T \xi^*\right)$$

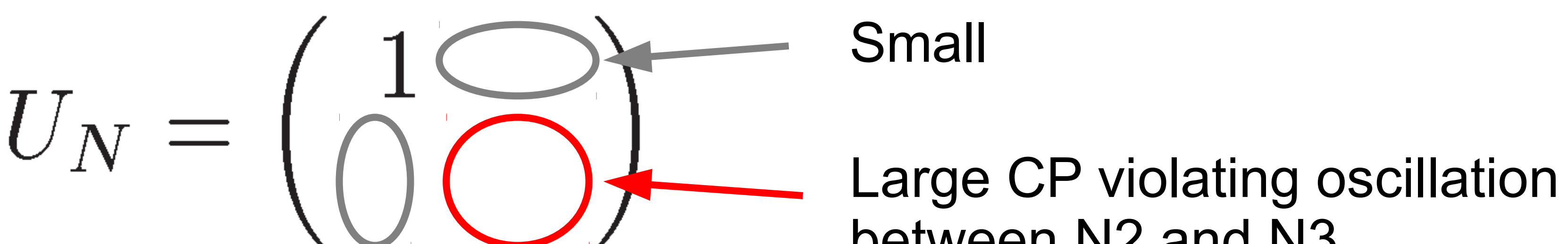
cannot be neglected!

$$U_N^\dagger M'_R U_N^* = \mathrm{Diag}(M_1, M_2, M_3)$$

$$M_{2,3} = M + \frac{1}{2M}\mathrm{Re}\left[\mathrm{tr}(m_D^\dagger m_D)\right] \pm \delta M \equiv \tilde{M} \pm \delta M$$

$$(\delta M)^2 = \left\{\frac{1}{2M}\left(\mathrm{Re}[m_D^\dagger m_D]_{33} - \mathrm{Re}[m_D^\dagger m_D]_{22}\right) + \Delta M\right\}^2 + \frac{1}{M^2}\mathrm{Re}[m_D^\dagger m_D]_{23}^2$$

$\delta M \ll M$ and thus $M_2 \simeq M_3$, but U_N is not necessarily small because of the degeneracy.

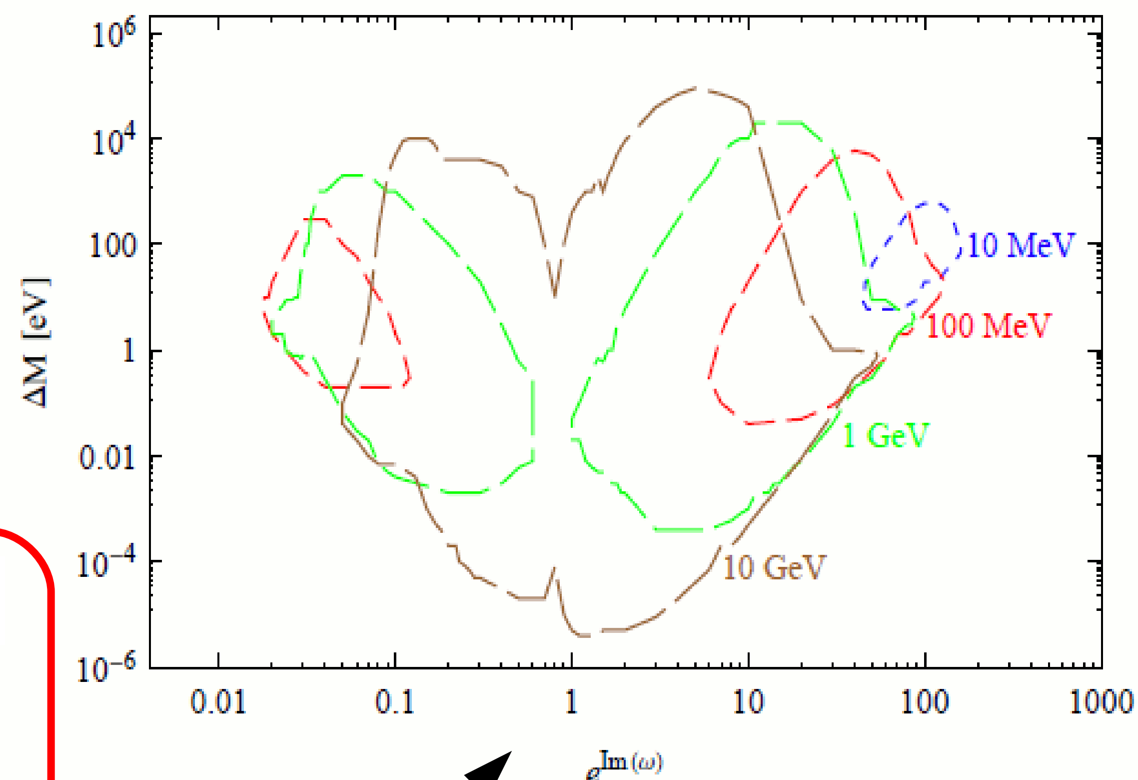


The νMSM ~BAU~

Lepton asymmetry was produced via N2-N3 oscillation, and it was converted into baryon asymmetry.

[Canetti etal, arXiv: 1208.4607 [hep-ph]]

$$M_2 = M - \Delta M$$
$$M_3 = M + \Delta M$$



$$\Delta M \sim 10^{-2}\mathrm{eV} - 10\mathrm{keV}$$

for

$$M = 1\ \mathrm{GeV}$$

CP phase in Yukawa couplings.

The νMSM ~thermal history~

Everything happened near or below the EW scale.

$$\mu_\ell \sim 10^{-10}$$

for Baryogenesis
at around the EW.

$$\mu_\ell > 10^{-7}$$

for DM production
at around 100 MeV.

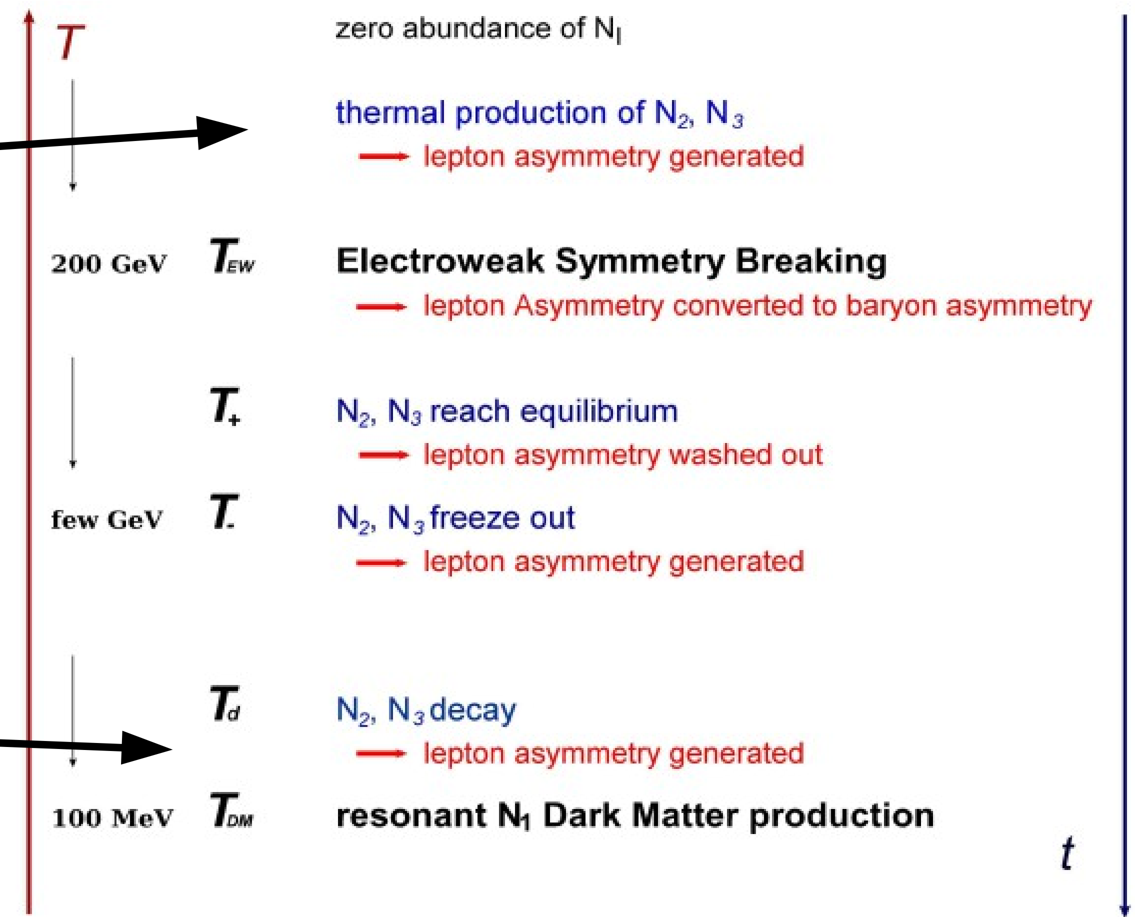


Figure 1: *The thermal history of the universe in the νMSM.*

[Canetti etal, arXiv: 1208.4607 [hep-ph]]

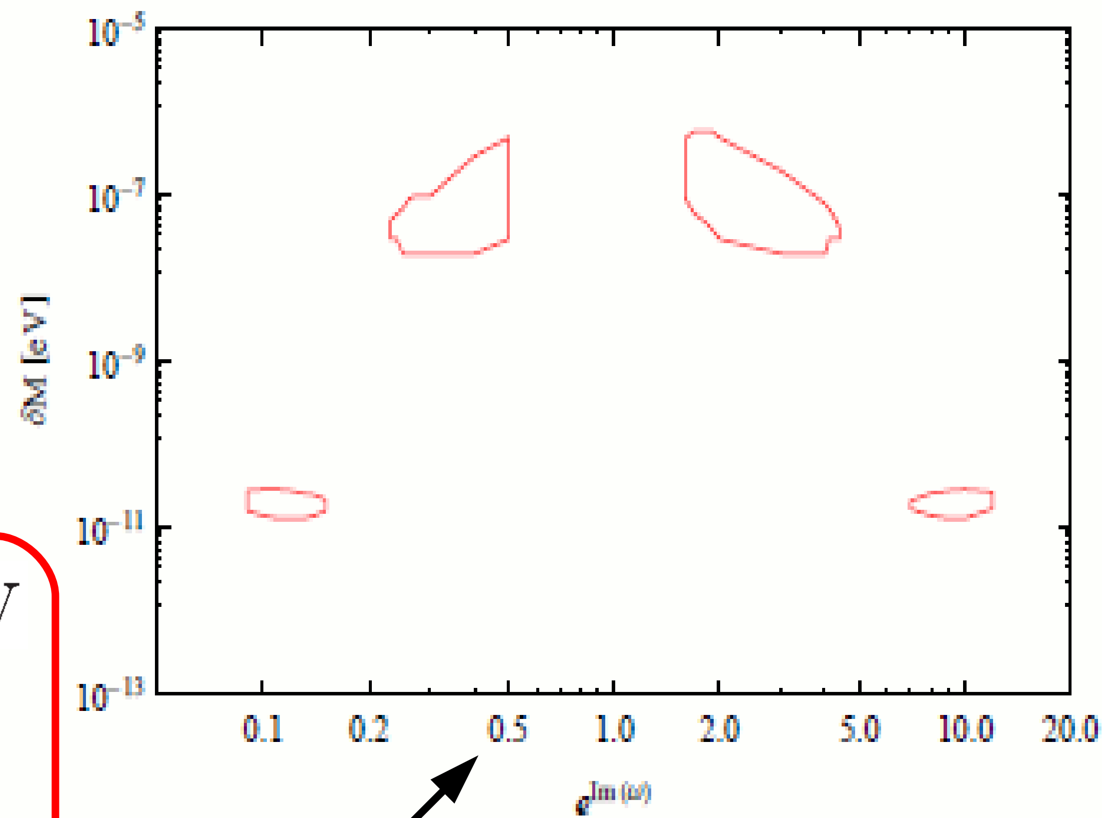
The νMSM ~lepton asym.~

In order to have sufficient amount of baryon asymmetry, large lepton asymmetry is necessary.

$$M_2 = M - \Delta M$$
$$M_3 = M + \Delta M$$

$$\Delta M \sim 10^{-17} - 10^{-15}\mathrm{GeV}$$
for
$$M = 1\ \mathrm{GeV}$$

[Canetti etal, arXiv: 1208.4607 [hep-ph]]



CP phase in Yukawa couplings.

Constraints for the νMSM

Suppose $M_{2,3} = 1$ GeV

$$\begin{pmatrix} M_1 & 0 & 0 \\ 0 & M - \Delta M & 0 \\ 0 & 0 & M + \Delta M \end{pmatrix}$$

Seesaw

$$y_{i2},\ y_{i3} \sim 10^{-7.5}$$
for $M_{2,3} = 1$ GeV

Baryon asymmetry

$$\Delta M \sim 1 - 10 \text{ keV}$$
for $M_{2,3} = 1$ GeV

DM production

$$M_1 \sim (1 - 10) \text{ keV}$$
$$y_{i1} \sim 10^{-13} - 10^{-12}$$

$$\begin{pmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{pmatrix}$$

Constraints for the νMSM

Suppose $M_{2,3} = 1 \ \mathrm{GeV}$

$$\begin{pmatrix} M_1 & 0 & 0 \\ 0 & M - \Delta M & 0 \\ 0 & 0 & M + \Delta M \end{pmatrix}$$

$10^{-6} \ll 1 \ \mathrm{GeV}$?

$10^{-13} \ll 10^{-7.5}$?

$$\begin{pmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{pmatrix}$$

Flavor Model for νMSM

Flavor Symmetries

Q. What do $M_1 \ll M_{2,3}$ and $|M_2 - M_3| \ll 1$ suggest?

(1) The degeneracy seems to indicate that they serve as a doublet representation under a symmetry.

$$\begin{pmatrix} N_2 \\ N_3 \end{pmatrix} \ddagger \ \mathbf{2}\ ? \quad \Rightarrow \quad N_1 \ddagger \ \mathbf{1},\ \mathbf{1}' \cdots$$

(2) Furthermore, if the singlet is complex, one can prohibit N1 from having its bare (Majorana) mass term, leading to

$$\Rightarrow \quad M_R = \mathrm{Diag}(0, M, M).$$

A tiny mass splitting between N2 and N3 and the keV-scale mass of N1 may be obtained after taking higher dimensional operators into account.

Flavor Symmetries

Q. What kind of symmetries do we need?

- The symmetry should be non-abelian.
- The doublet should be real to give bare (Majorana) mass terms for N2 and N3.
- The singlet should be complex to forbid a bare mass term for N1.

The smallest non-abelian discrete group incorporating both of the complex singlet and real doublet is Q_6.

Flavor Symmetries

Q. What is Q_6 ?

Q_6 consists of four singlets and two doublet:

$$\mathbf{1}, \mathbf{1}', \quad \underbrace{\mathbf{1}'', \mathbf{1}'''}_{\text{complex}}, \mathbf{2}, \quad \underbrace{\mathbf{2}'}_{\text{real}}.$$

The multiplication rules are given by

$$\mathbf{1}' \times \mathbf{1}' = \mathbf{1}, \quad \mathbf{1}'' \times \mathbf{1}'' = \mathbf{1}',$$
$$\mathbf{1}' \times \mathbf{1}''' = \mathbf{1}'', \quad \mathbf{1}' \times \mathbf{1}'' = \mathbf{1}''',$$
$$\mathbf{2} \times \mathbf{1}''' = \mathbf{2}', \quad \mathbf{2}' \times \mathbf{1}' = \mathbf{2}',$$
$$\mathbf{1}''' \times \mathbf{1}''' = \mathbf{1}', \quad \mathbf{1}'' \times \mathbf{1}''' = \mathbf{1},$$
$$\mathbf{2} \times \mathbf{1}' = \mathbf{2}, \quad \mathbf{2} \times \mathbf{1}'' = \mathbf{2}',$$
$$\mathbf{2}' \times \mathbf{1}'' = \mathbf{2}, \quad \mathbf{2}' \times \mathbf{1}''' = \mathbf{2}\ .$$

$$\underset{\mathbf{2}}{\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}} \times \underset{\mathbf{2}}{\begin{pmatrix} y_1 \\ y_2 \end{pmatrix}} = \underset{\mathbf{1}}{(x_1y_2 - x_2y_1)} + \underset{\mathbf{1}'}{(x_1y_1 + x_2y_2)} + \underset{\mathbf{2}'}{\begin{pmatrix} -x_1y_2 - x_2y_1 \\ x_1y_1 - x_2y_2 \end{pmatrix}}$$

$$\underset{\mathbf{2}'}{\begin{pmatrix} a_1 \\ a_2 \end{pmatrix}} \times \underset{\mathbf{2}'}{\begin{pmatrix} b_1 \\ b_2 \end{pmatrix}} = \underset{\mathbf{1}}{(a_1b_1 + a_2b_2)} + \underset{\mathbf{1}'}{(a_1b_2 - a_2b_1)} + \underset{\mathbf{2}'}{\begin{pmatrix} -a_1b_1 + a_2b_2 \\ a_1b_2 + a_2b_1 \end{pmatrix}}$$

$$\underset{\mathbf{2}}{\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}} \times \underset{\mathbf{2}'}{\begin{pmatrix} a_1 \\ a_2 \end{pmatrix}} = \underset{\mathbf{1}''}{(x_1a_2 + x_2a_1)} + \underset{\mathbf{1}'''}{(x_1a_1 - x_2a_2)} + \underset{\mathbf{2}}{\begin{pmatrix} x_1a_1 + x_2a_2 \\ x_1a_2 - x_2a_1 \end{pmatrix}}$$

Model - I

	$\overline{L_i}$	e_{Ri}	N_1	N_D	H	D	S
Q_6	1	1	$1''$	$2'$	1	2	$1'$
Z_2	$+$	$+$	$+$	$+$	$+$	$-$	$-$

Q_6 is complemented with an auxiliary Z_2 symmetry.

1. $N_D N_D \ddagger\ (\mathbf{1}, +)$ (singlet by itself)
2. $N_D N_D \ddagger\ (\mathbf{2}', +) \otimes D^2, |D|^2 \ddagger\ (\mathbf{2}', +)$
3. $N_1 N_1 \ddagger\ (\mathbf{1}', +) \otimes D^2 \ddagger\ (\mathbf{1}', +)$
4. $N_1 N_D \ddagger\ (\mathbf{2}, +) \otimes DS, D^* S \ddagger\ (\mathbf{2}, +)$

Note

$< D > \equiv (d_1, d_2)$

$< S > \equiv s$

$\lambda = \frac{d_i}{\Lambda} = \frac{s}{\Lambda}$

$$M_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & M \end{pmatrix} + \lambda^2 \begin{pmatrix} m_s & m_b & m_c \\ m_a & -m_d & m_e \\ m_c & m_e & m_d \end{pmatrix}$$

$m_i, M = \mathcal{O}(1\mathrm{GeV})$

Model - I

Move on to the diagonal basis of M_R.

$$M_R = \begin{pmatrix} \lambda^2 m_s & \lambda^2 m_b & \lambda^2 m_c \\ \lambda^2 m_b & M - \lambda^2 m_d & \lambda^2 m_e \\ \lambda^2 m_c & \lambda^2 m_e & M + \lambda^2 m_d \end{pmatrix}$$

Note

$< D > \equiv (d_1, d_2)$

$< S > \equiv s$

$\lambda = \dfrac{d_i}{\Lambda} = \dfrac{s}{\Lambda}$

Suppose λ is sufficiently small, then

$$R \simeq \begin{pmatrix} 1 & -\eta\, U_R \\ \eta^\dagger & U_R \end{pmatrix}$$

$$\eta = \lambda^2 (m_b, m_c) \begin{pmatrix} M - \lambda^2 m_d & \lambda^2 m_e \\ \lambda^2 m_e & M + \lambda^2 m_d \end{pmatrix}^{-1}$$

$\Rightarrow$

$$M_1 \simeq \lambda^2 m_s + \mathcal{O}(\lambda^4)$$

$$M_2 \simeq M - \lambda^2 m_d + \mathcal{O}(\lambda^4)$$

$$M_3 \simeq M + \lambda^2 m_d + \mathcal{O}(\lambda^4)$$

Given $m_i, M = \mathcal{O}(1\mathrm{GeV})$, $\lambda = 10^{-3}$ results in

$$M_1 \sim 1 \text{ keV} \quad \text{and} \quad \Delta M \sim 1 \text{ keV}.$$

Model - I

	$\overline{L_i}$	e_{Ri}	N_1	N_D	H	D	S
Q_6	1	1	$1''$	$2'$	1	2	$1'$
Z_2	$+$	$+$	$+$	$+$	$+$	$-$	$-$

Q_6 is complemented with an auxiliary Z_2 symmetry.

1. $L_i \tilde{H} N_D \ddagger\ (\mathbf{2}', +) \otimes\ D^2, |D|^2 \ddagger\ (\mathbf{2}', +)$
2. $L_i \tilde{H} N_1 \ddagger\ (\mathbf{1}'', +) \otimes\ D^3 S \ddagger\ (\mathbf{1}''', +)$

Note

$< D > \equiv (d_1, d_2)$

$< S > \equiv s$

$\lambda = \frac{d_i}{\Lambda} = \frac{s}{\Lambda}$

$$Y_D = \lambda^2 \begin{pmatrix} 0 & y_{12} & y_{13} \\ 0 & y_{22} & y_{23} \\ 0 & y_{32} & y_{33} \end{pmatrix} + \lambda^4 \begin{pmatrix} y_{11} & 0 & 0 \\ y_{21} & 0 & 0 \\ y_{31} & 0 & 0 \end{pmatrix}$$

Model - I

In the diagonal basis of M_R

$$Y_D \to \begin{pmatrix} \lambda^4 y_{11} & \lambda^2 y_{12} & \lambda^2 y_{13} \\ \lambda^4 y_{21} & \lambda^2 y_{22} & \lambda^2 y_{23} \\ \lambda^4 y_{31} & \lambda^2 y_{32} & \lambda^2 y_{33} \end{pmatrix} \begin{pmatrix} 1 & -\eta\, U_R \\ \eta^\dagger & U_R \end{pmatrix}$$

$$\eta = \mathcal{O}(\lambda^2) = \mathcal{O}(10^{-6})$$

$$\equiv \begin{pmatrix} \lambda^4 y_{11} + \mathcal{O}(\lambda^4) & \lambda^2 y'_{12} & \lambda^2 y'_{13} \\ \lambda^4 y_{21} + \mathcal{O}(\lambda^4) & \lambda^2 y'_{22} & \lambda^2 y'_{23} \\ \lambda^4 y_{31} + \mathcal{O}(\lambda^4) & \lambda^2 y'_{32} & \lambda^2 y'_{33} \end{pmatrix}$$

Given $y_{ij} \simeq y_\tau \simeq 10^{-2}$, we obtain 10^{-14} and 10^{-8}.

Note that U_R can be large but only mixes the second and third lines of Y_D.

Constraints for the νMSM

Suppose $M_{2,3} = 1 \text{ GeV}$

$$\begin{pmatrix} M_1 & 0 & 0 \\ 0 & M - \Delta M & 0 \\ 0 & 0 & M + \Delta M \end{pmatrix}$$

Seesaw

$$y_{i2},\ y_{i3} \sim 10^{-7.5} \quad \text{for} \quad M_{2,3} = 1 \text{ GeV}$$

Baryon asymmetry

$$\Delta M \sim 1 - 10 \text{ keV} \quad \text{for} \quad M_{2,3} = 1 \text{ GeV}$$

DM production

$$M_1 \sim (1 - 10) \text{ keV}$$

$$y_{i1} \sim 10^{-13} - 10^{-12}$$

$$\begin{pmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{pmatrix}$$

Model - II

	$\overline{L}_{1,2,3}$	$e_{R1,2,3}$	N_1	N_D	H	D	S_1	S_2
Q_6	$1, 1', 1'$	$1, 1', 1'$	$1''$	$2'$	1	2	$1'$	$1'''$
Z_{10}	$0, 0, 1$	$0, 0, -1$	4	0	0	1	3	0

Q_6 is complemented with an auxiliary Z_{10} symmetry.

1. $N_D N_D \ddagger\ (\mathbf{1}, 0)$ (singlet by itself)
2. $N_D N_D \ddagger\ (\mathbf{2}', 0) \quad \otimes \quad |D|^2 \ddagger\ (\mathbf{2}', 0)$
3. $N_1 N_1 \ddagger\ (\mathbf{1}', 8) \quad \otimes \quad D^2 \ddagger\ (\mathbf{1}', 2)$
4. $N_1 N_D \ddagger\ (\mathbf{2}, 4) \quad \otimes \quad (DS_1)^* \ddagger\ (\mathbf{2}, -4)$

Note

$< D > \equiv (d_1, d_2)$

$< S_i > \equiv s_i$

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & M \end{pmatrix} + \frac{1}{\Lambda^2} \begin{pmatrix} m_s(d_1^2 + d_2^2) & m_b d_2 s_1 & m_b d_1 s_1 \\ m_b d_2 s_1 & -m_d(d_1^2 - d_2^2) & 2 m_d d_1 d_2 \\ m_b d_1 s_1 & 2 m_d d_1 d_2 & m_d(d_1^2 - d_2^2) \end{pmatrix}$$

Model - II

	$\overline{L_{1,2,3}}$	$e_{R1,2,3}$	N_1	N_D	H	D	S_1	S_2
Q_6	$1, 1', 1'$	$1, 1', 1'$	$1''$	$2'$	1	2	$1'$	$1'''$
Z_{10}	$0, 0, 1$	$0, 0, -1$	4	0	0	1	3	0

Q_6 is complemented with an auxiliary Z_{10} symmetry.

1. $L_{1,2}\tilde{H}N_D \ddagger\ (\mathbf{2}', 0) \quad \otimes \quad |D|^2 \ddagger\ (\mathbf{2}', 0)$
2. $L_3\tilde{H}N_D \ddagger\ (\mathbf{2}', 1) \quad \otimes \quad D^* S_2 \ddagger\ (\mathbf{2}', -1)$
3. $L_{1,2}\tilde{H}N_1 \ddagger\ (\mathbf{1}'', 4) \quad \otimes \quad D^3 S_1 \ddagger\ (\mathbf{1}''', +)$
4. $L_3\tilde{H}N_1 \ddagger\ (\mathbf{1}''', 5) \quad \otimes$ ~~$D^5 \ddagger\ (\mathbf{1}''', 5)$~~

Note

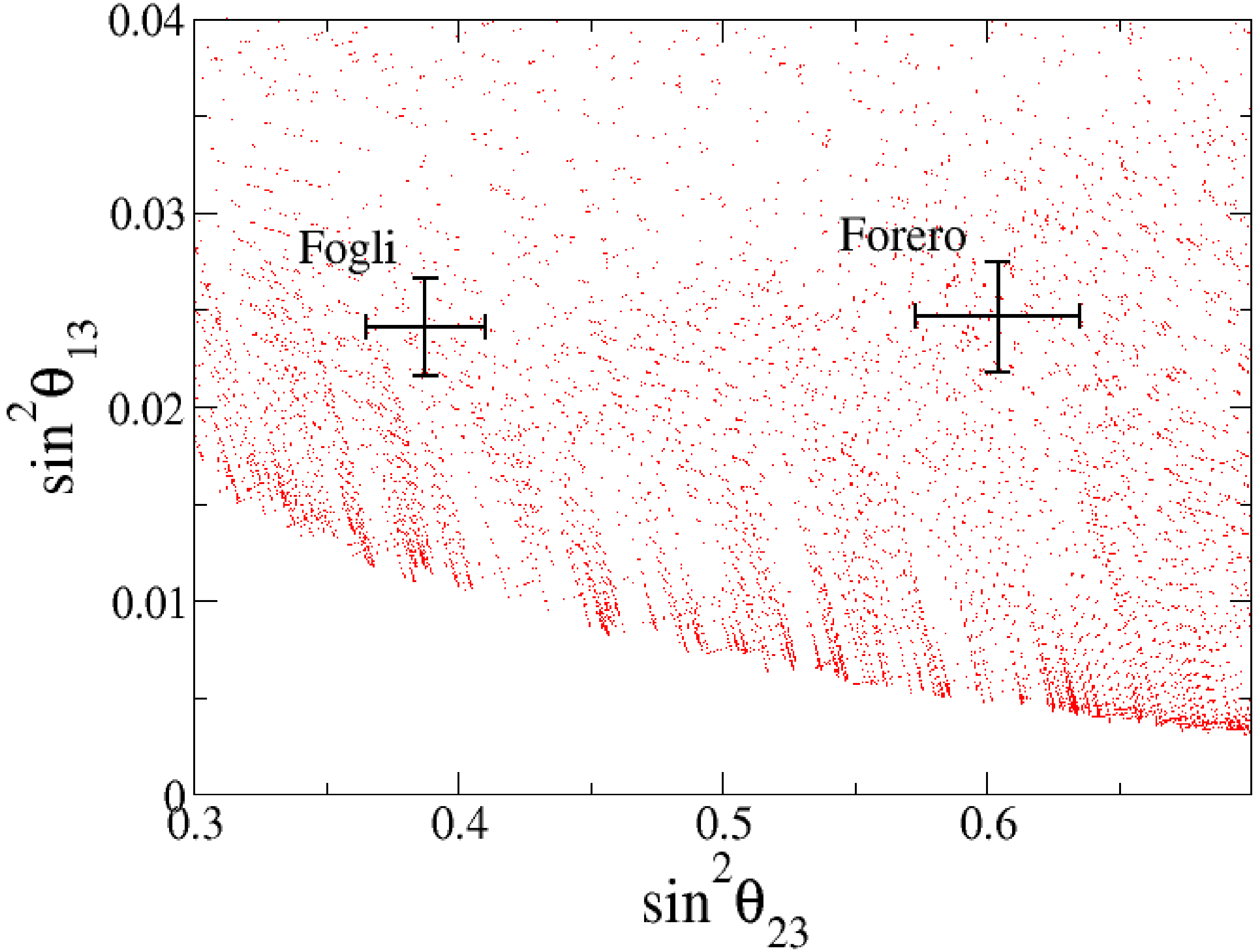
$< D > \equiv (d_1, d_2)$

$< S_i > \equiv s_i$

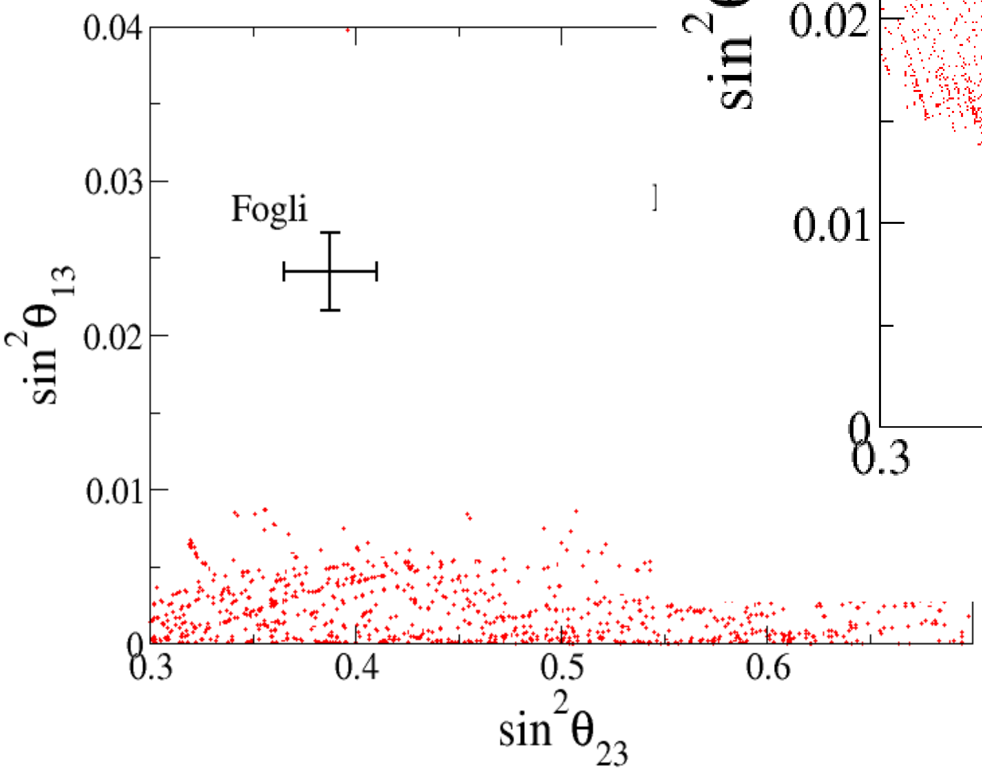
$$\frac{1}{\Lambda^2}\begin{pmatrix} 0 & y_1(d_1^2 - d_2^2) & 2y_1 d_1 d_2 \\ 0 & 2y_2 d_1 d_2 & -y_2(d_1^2 - d_2^2) \\ 0 & y_3 d_2 s_2 & y_3 d_1 s_2 \end{pmatrix} + \frac{1}{\Lambda^4}\begin{pmatrix} y_{11} & 0 & 0 \\ y_{21} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Model - II

Normal Ordering



Inverted Ordering



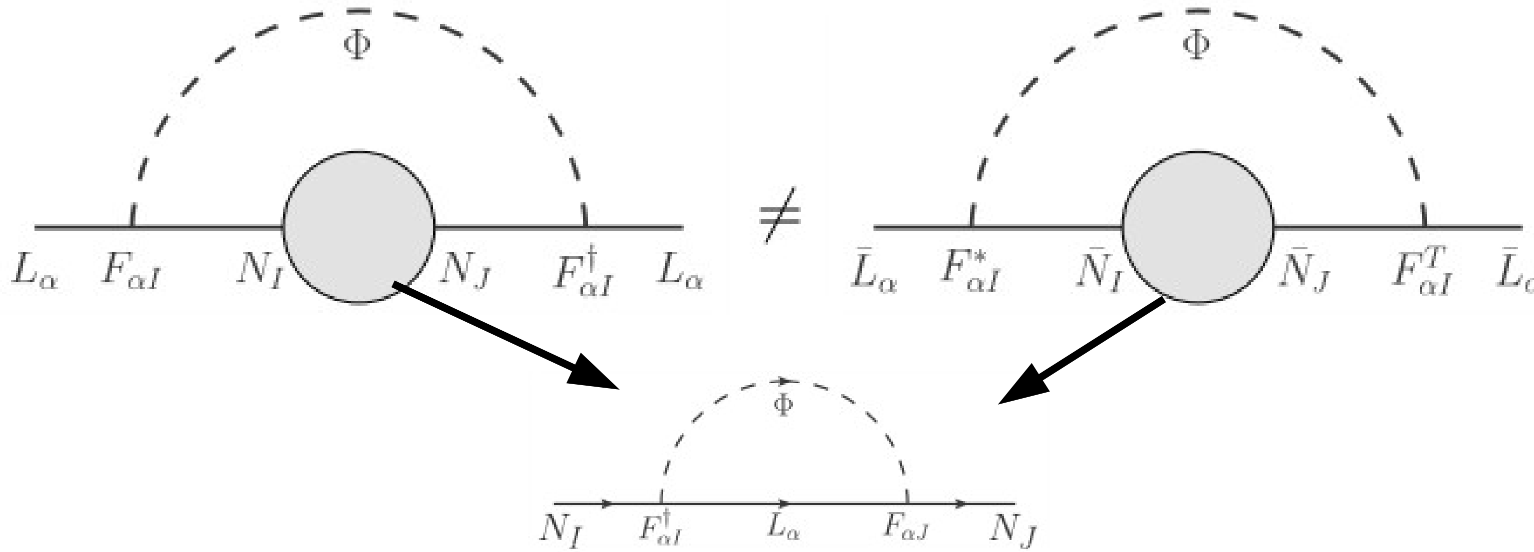
Summary

- The nMSM is one of the most attractive candidates for physics beyond the SM; it may be able to address the observed DM abundance, tiny neutrino masses and the BAU **at the same time**.
- Strong hierarchies and tunings among parameters, however, are necessary; the nMSM cannot explain these issues.
- We have proposed an extension of the nMSM by imposing flavor symmetries and succeeded in explaining some of them.
- Unfortunately, the tight fine-tuning still remains, so far no idea...

Backup Slides

The vMSM ~BAU~

Lepton asymmetry via CP violating N2-N3 oscillations:



$$\Delta L_\alpha = \frac{3^{\frac{2}{3}}\pi^{\frac{3}{2}}\sin^2\phi}{18\Gamma\left[\frac{5}{6}\right]}\frac{M_0^{\frac{4}{3}}}{(\Delta M_{32}^2)^{\frac{2}{3}}}A_{32}^\alpha \qquad A_{32}^\alpha = \mathrm{Im}\left[F_{\alpha I}\left[F^\dagger F\right]_{IJ}F^\dagger_{\alpha J}\right] \neq 0$$

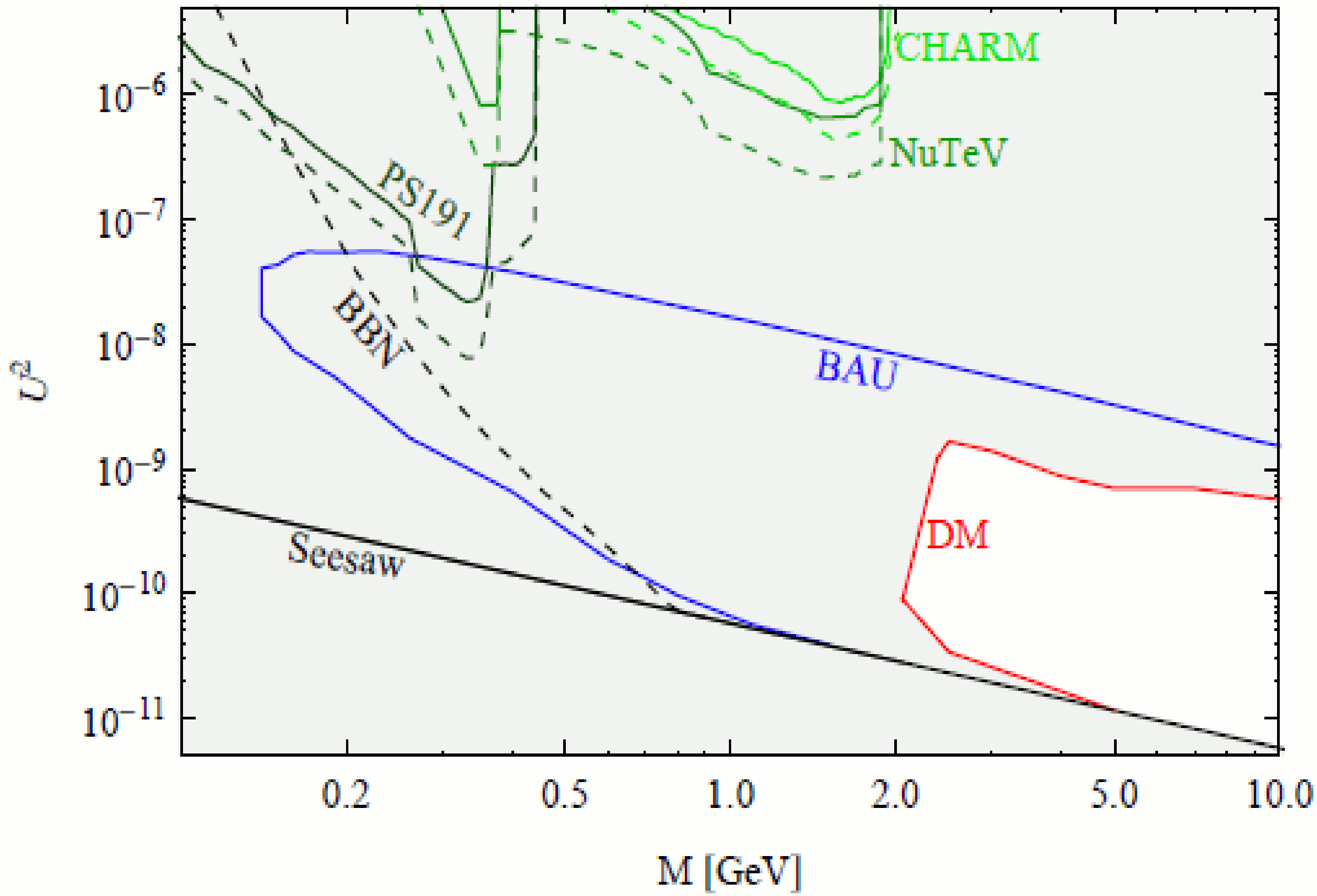
it was converted into baryon asymmetry via Sphalerons:

$$\Delta B = -\frac{28}{79}\sum_\alpha \Delta L_\alpha$$

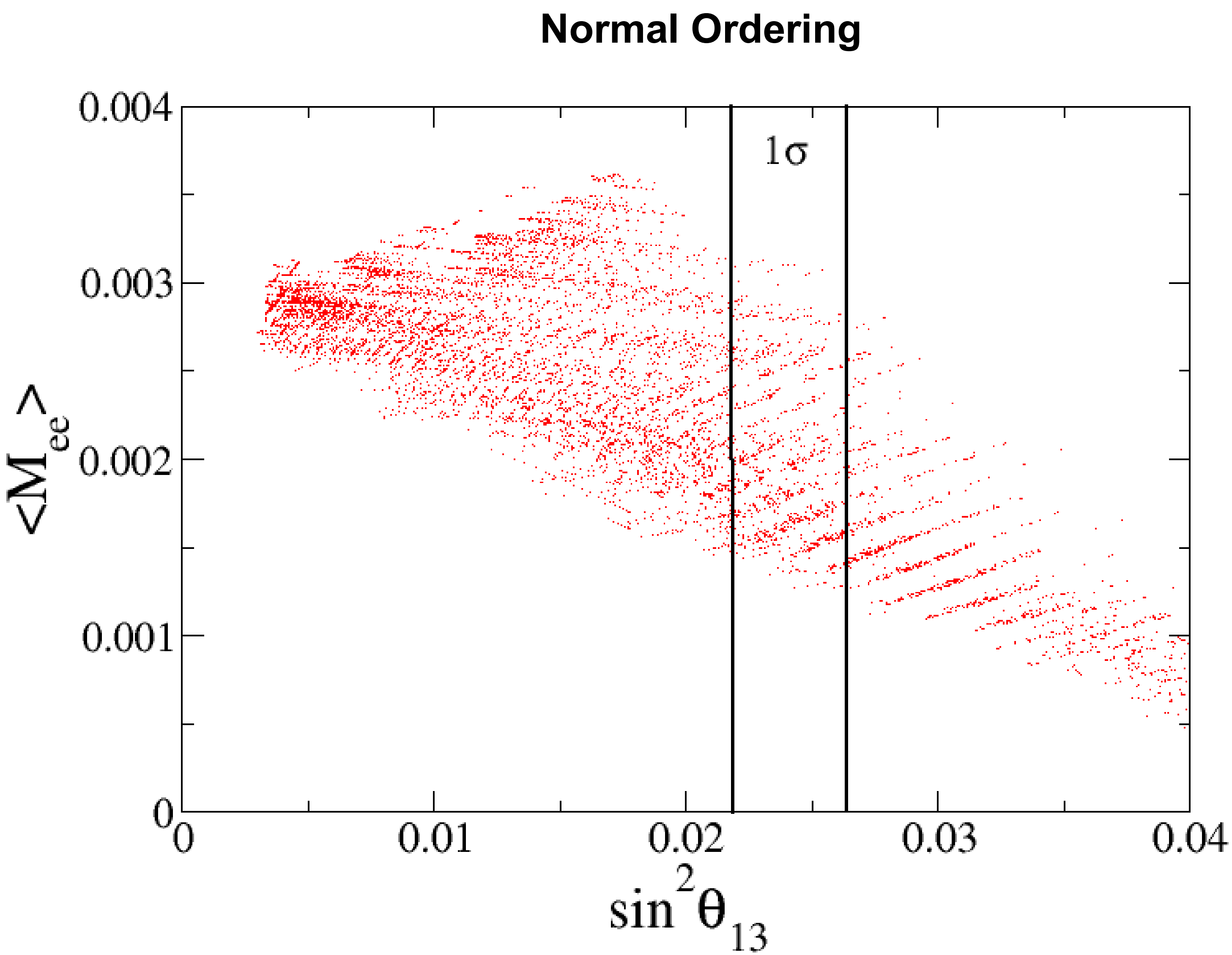
The νMSM ~combined~

Combine all the constraints.

[Canetti etal, arXiv: 1208.4607 [hep-ph]]



0nbb


Normal Ordering
0.004
0.003
0.002
0.001
0
0
0.01
0.02
0.03
0.04
1σ
<Mee>
sin2θ13