



## **Sterile Neutrinos in 3+3+3 model eV and keV sterile neutrinos in one scheme**

Arifin Achmad,  
Mirza Satriawan

Physics Departement  
Universitas Gadjah Mada  
Yogyakarta, Indonesia

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# Theory of neutrino oscillation

## Hypothesis: neutrino mixing

(Pontecorvo 1958; Maki, Nakagawa, Sakata 1962)

$\nu_e \nu_\mu \nu_\tau$  are not mass eigenstates but linear superpositions of mass eigenstates  $\nu_1 \nu_2 \nu_3$  with eigenvalues  $m_1 m_2 m_3$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

$\alpha = e, \mu, \tau$  (flavour index)  
 $i = 1, 2, 3$  (mass index )

$U_{\alpha i}$ : unitary mixing matrix

$$|\nu_i\rangle = \sum_\alpha V_{i\alpha} |\nu_\alpha\rangle$$

$$V_{i\alpha} = (U_{\alpha i})^*$$



# Time evolution of a neutrino with momentum $\mathbf{p}$ produced in the flavour eigenstate $\nu_\alpha$ at time $t = 0$

$$|\nu(t)\rangle = e^{i\mathbf{p} \cdot \mathbf{r}} \sum_k U_{\alpha k} e^{-iE_k t} |\nu_k\rangle$$

**Note:**  $|\nu(0)\rangle = |\nu_\alpha\rangle$

$E_k = \sqrt{p^2 + m_k^2}$  the complex phases  $e^{-iE_k t}$   
are different if  $m_j \neq m_k$

**appearance of new flavour**  $\nu_\beta \neq \nu_\alpha$  **at time**  $t > 0$

## Example for two – neutrino mixing

$$|\nu_\alpha\rangle = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle$$

$$|\nu_\beta\rangle = -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle$$

$\theta \equiv$  mixing angle

If  $\nu = \nu_\alpha$  at production ( $t = 0$ ):

$$|\nu(t)\rangle = e^{i(\mathbf{p} \cdot \mathbf{r} - E_1 t)} \left\{ \cos\theta |\nu_1\rangle + e^{-i(E_2 - E_1)t} \sin\theta |\nu_2\rangle \right\}$$

**For  $m \ll p$**   $E = \sqrt{p^2 + m^2} \approx p + \frac{m^2}{2p}$  **(in vacuum!)**



$$\rightarrow E_2 - E_1 \approx \frac{m_2^2 - m_1^2}{2p} \approx \frac{m_2^2 - m_1^2}{2E} \equiv \frac{\Delta m^2}{2E}$$

**Probability to detect  $\nu_\beta$  at time  $t$  if  $\nu(0) = \nu_\alpha$ :**

$$\mathcal{P}_{\alpha\beta}(t) = \left| \langle \nu_\beta | \nu(t) \rangle \right|^2 = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 t}{4E}\right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

**Using units more familiar to experimentalists:**

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta) \sin^2\left(1.267 \Delta m^2 \frac{L}{E}\right)$$

$L = ct$  distance between neutrino source and detector

**Units:**  $\Delta m^2$  [eV<sup>2</sup>];  $L$  [km];  $E$  [GeV] (or  $L$  [m];  $E$  [MeV])

# Status of neutrino oscillations 2018: first hint for normal mass ordering and improved CP sensitivity



P. F. de Salas, D. V. Forero, C. A. Ternes, M. Tórtola and J. W. F. Valle,  
arXiv:1708.01186v2 [hep-ph] 27 Apr 2018

parameter	best fit $\pm 1\sigma$	$2\sigma$ range	$3\sigma$ range
$\Delta m_{21}^2$ [ $10^{-5}$ eV $^2$ ]	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$ \Delta m_{31}^2 $ [ $10^{-3}$ eV $^2$ ] (NO)	$2.50 \pm 0.03$	2.44–2.57	2.41–2.60
$ \Delta m_{31}^2 $ [ $10^{-3}$ eV $^2$ ] (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31–2.51
$\sin^2 \theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/^\circ$	$34.5^{+1.2}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2 \theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99
$\theta_{23}/^\circ$	$47.7^{+1.2}_{-1.7}$	43.1–49.8	41.8–50.7
$\sin^2 \theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98
$\theta_{23}/^\circ$	$47.9^{+1.0}_{-1.7}$	44.5–48.9	42.3–50.7
$\sin^2 \theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41
$\theta_{13}/^\circ$	$8.45^{+0.16}_{-0.14}$	8.2–8.8	8.0–8.9
$\sin^2 \theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44
$\theta_{13}/^\circ$	$8.53^{+0.14}_{-0.15}$	8.3–8.8	8.1–9.0
$\delta/\pi$ (NO)	$1.21^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94
$\delta/^\circ$	$218^{+38}_{-27}$	182–315	157–349
$\delta/\pi$ (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94
$\delta/^\circ$	$281^{+23}_{-27}$	229–328	202–349

# Reactor anomalies (LSND, MiniBooNe and etc)



However, there are hints from the LSND experiment at Los Alamos in the 1990s, and more recently from the MiniBooNE experiment at Fermilab, that there may be (at least) one more light neutrino:

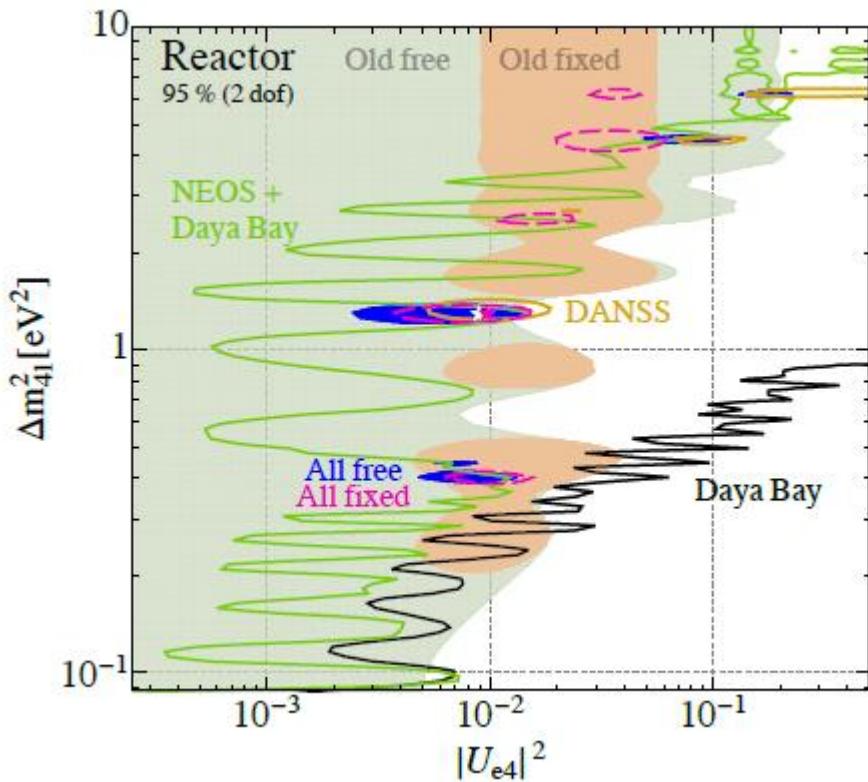
LSND observes a signal from  $\bar{\nu}_\mu - \bar{\nu}_e$  oscillations with  $\Delta m^2 \approx 0.2 - 2 \text{ eV}^2$ ;  
MiniBooNE has a similar signal in  $\bar{\nu}_\mu - \bar{\nu}_e$  oscillations , but not in  $\nu_\mu - \nu_e$  .

The statistical significance is about 3 standard deviations in both experiments.

# Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos



Mona Dentler, Alvaro Hernandez-Cabezudo, Joachim Kopp,  
Pedro Machado, Michele Maltoni, Ivan Martinez-Soler, and  
Thomas Schwetz, arXiv:1803.10661v1 [hep-ph] 28 Mar 2018



$\Delta m_{41}^2 \approx 1.29 \text{ eV}^2$  for free and  
fixed reactor fluxes

$\sin^2 \theta_{14} = 0.0089$  for free  
reactor fluxes  
 $\sin^2 \theta_{14} = 0.0096$  for fixed  
reactor fluxes



$|U_{e4}| \approx 0.1$

The LSND  $\nu_\mu - \nu_e$  oscillation signal with  $\Delta m^2 \approx 0.2 - 2 \text{ eV}^2$  requires the existence of a 4<sup>th</sup> neutrino:

$$(m_2^2 - m_1^2) + (m_3^2 - m_2^2) + (m_1^2 - m_3^2) = 0$$

$$m_2^2 - m_1^2 \approx 7.6 \times 10^{-5} \text{ eV}^2; |m_3^2 - m_2^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$$

$$\rightarrow |m_1^2 - m_3^2| = |m_3^2 - m_2^2| \pm (m_2^2 - m_1^2) \ll 0.2 - 2 \text{ eV}^2$$



Measurement of the Z – boson width at LEP: number of neutrinos  $N_\nu = 2.984 \pm 0.008$   
 $\Rightarrow$  the 4<sup>th</sup> neutrino does not couple to W or Z  $\Rightarrow$  no interaction with matter:  
“sterile neutrino” – the mixing matrix dimensions are at least 4 x 4

$$\nu_\alpha = \sum_{k=1}^4 U_{\alpha k} \nu_k \quad \alpha = e, \mu, \tau, s$$

$$P(\nu_\mu - \nu_e) = \left| \sum_{k=1}^4 U_{ek} U_{\mu k} \exp(-iE_k t) \right|^2 = \left| U_{e1} U_{\mu 1} + \sum_{k=2}^4 U_{ek} U_{\mu k} \exp\left(-i \frac{\Delta_{k1}}{2E} t\right) \right|^2 \quad (\Delta_{k1} = m_k^2 - m_1^2)$$

For the LSND experiment oscillation effects associated with  $\Delta_{12}$  and  $\Delta_{23}$  are negligible:

$$P(\nu_\mu - \nu_e) = \left| \sum_{k=1}^3 U_{ek} U_{\mu k} + U_{e4} U_{\mu 4} \exp\left(-i \frac{\Delta_{41}}{2E} t\right) \right|^2 = 4 \left| U_{e4} U_{\mu 4} \right|^2 \sin^2\left(1.267 \Delta_{41} \frac{L}{E}\right) \quad (L[m]; E[MeV])$$

$\left( \sum_{k=1}^4 U_{e4} U_{\mu 4} = 0 \quad \text{from unitarity} \right)$

   $\sin^2 2\vartheta_{e\mu}$



The MiniBooNE and LSND antineutrino result  
(if confirmed) implies:  
the existence of a 4<sup>th</sup> sterile neutrino or even more

Ekstension of neutrino oscillation, such as

- 3+1 (Carlo Giunti and Marco Laveder, 2014)
- 3+2 (M. Sorel, J. M. Conrad, and M. H. Shaevitz, 2004)
- 1+3+1 (Joachim Kopp *et al.*, 2013)
- 3+3





# X-ray observations

Detection unidentified line from

- galaxy clusters,
- in the individual spectra of nearby galaxy clusters,
- in the Andromeda galaxy,
- in the Galactic Center region

The position of this line is  $E = 3.55 \text{ keV}$  with  
an uncertainty in position  $\sim 0.05 \text{ keV}$

(E. Bulbul *et al.*, 2014)



If the line is interpreted as originating from a two-body decay of a DM particle

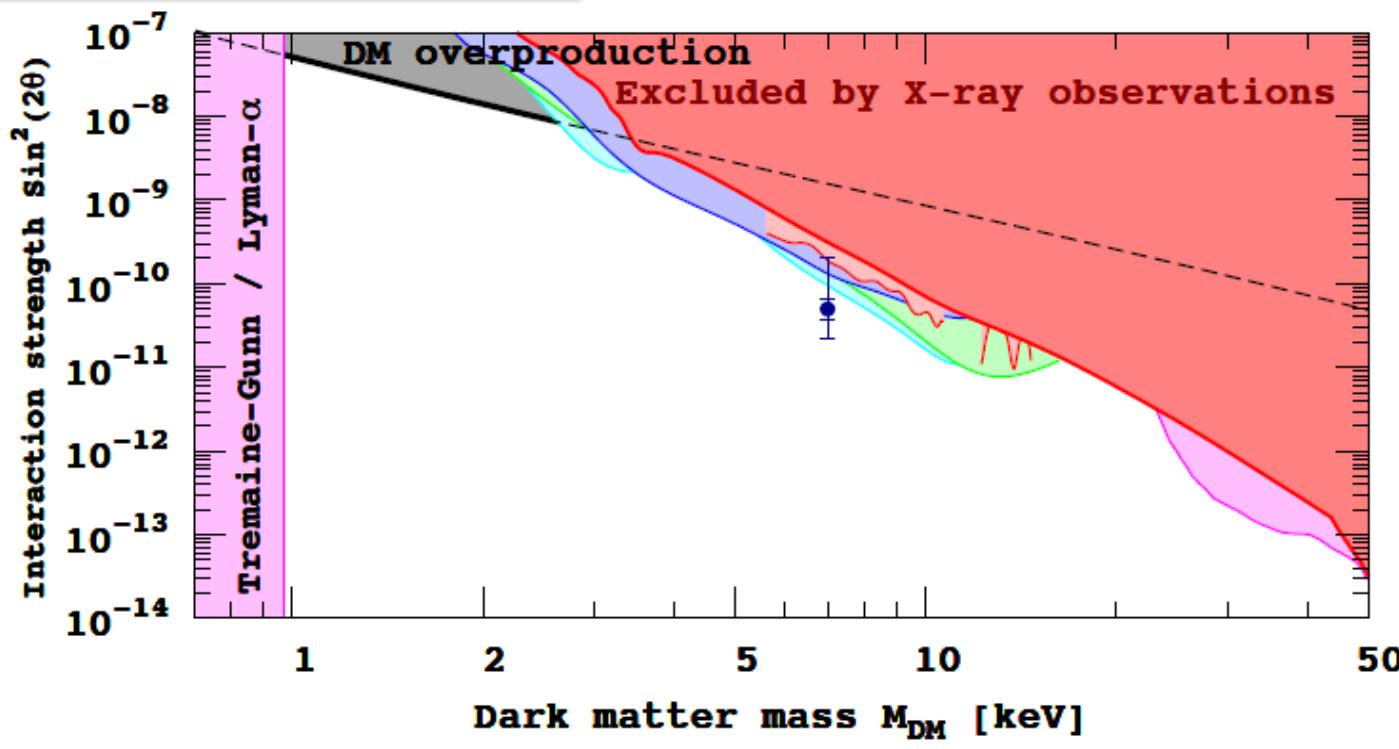


Mass dark matter  $m_S \simeq 7.1 \text{ keV}$  and life time  $\tau_{DM} \sim 10^{27.8 \pm 0.3} \text{ s}$   
(Boyarsky *et. al*, 2014)

Converting the lifetime to the sterile neutrino mixing angle



$\sin^2 2\theta \simeq (2 - 20) \times 10^{-11}$   
(Boyarsky *et. al*, 2014)





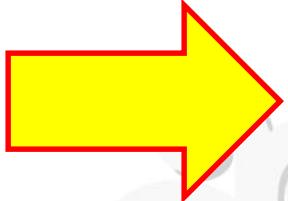
We have possibility of 3 kinds of neutrinos with 3 mass order:

- ❖ **Sub-eV neutrinos** (solar and atmospheric neutrinos or 3 active neutrinos)
- ❖ **eV sterile neutrinos** (SBL neutrino oscillation)
- ❖ **keV sterile neutrinos** (X-ray observation)

- The eV and keV sterile neutrino each of them maybe part of different families
- There maybe several heavier neutrinos for the Seesaw mechanism

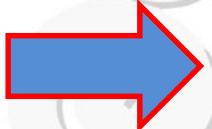


# The Model



Building models that can accommodate 3 order mass in one scheme

## 3+3+3 Model



In order to include the active neutrinos, the eV sterile neutrinos, and the keV sterile neutrinos



# Particles contents

We proposed a model invariant  
under  $SM \otimes SU(2)_R \otimes U(1)_X$

Particle	$U(1)_Y$	$SU(2)_L$	$U(1)_X$	$SU(2)_R$
$\nu_L$	1	2	0	1
$\nu_R$	0	1	0	2
$n_L$	0	1	1	1
$n_R$	0	1	1	2
$N_L$	0	1	$\frac{1}{3}$	1
$N_R$	0	1	$\frac{1}{3}$	2

Scalar	$U(1)_Y$	$SU(2)_L$	$U(1)_X$	$SU(2)_R$
$\varphi$	1	2	0	1
$\chi_1$	0	1	0	2
$\chi_3$	1	2	-1	2
$\chi_5$	0	1	$\frac{1}{3}$	2
$\xi_1$	0	1	0	1
$\xi_2$	0	1	2	1
$\xi_3$	0	1	$\frac{2}{3}$	1



## Relevant Yukawa Lagrangian

$$\begin{aligned}\mathcal{L} \supset & G_1 \phi \bar{\nu}_L \nu_R + G_2 \chi_1 \bar{n}_L n_R + G_3 \chi_1 \bar{N}_L N_R \\ & + G_4 \chi_3 \bar{\nu}_L \nu_R + G_5 \chi_5 \bar{N}_L \nu_R + G_6 \xi_1 \bar{\nu}_R \nu_R^C \\ & + G_7 \xi_2 \bar{n}_R n_R^C + G_8 \xi_3 \bar{N}_R N_R^C + h.c.\end{aligned}$$

After spontaneous symmetry  
Breaking and have VEV's

$$\begin{aligned}\mathcal{L} \supset & m_{e1} \bar{\nu}_L \nu_R + m_2 \bar{n}_L n_R + m_{e2} \bar{N}_L N_R \\ & + m_1 \bar{\nu}_L \nu_R + m_{e3} \bar{N}_L \nu_R + M_1 \bar{\nu}_R \nu_R^C \\ & + M_2 \bar{n}_R n_R^C + M_3 \bar{N}_R N_R^C + h.c.\end{aligned}$$



The mass Lagrangian above can be written as

$$\mathcal{L} \supset \bar{\psi} \mathcal{M} \psi$$

$$\text{With } \psi = (\nu_L + \nu_L^C \ n_L + n_L^C \ N_L + N_L^C \ \nu_R + \nu_R^C \ n_R + n_R^C \ N_R + N_R^C)^T$$

And  $\mathcal{M}$  is neutrino matrix mass,  
given by

$$\mathcal{M} = \begin{pmatrix} 0 & 0 & 0 & m_{e1} & m_1 & 0 \\ 0 & 0 & 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & m_{e3} & 0 & m_{e2} \\ m_{e1} & 0 & m_{e3} & M_1 & 0 & 0 \\ m_1 & m_2 & 0 & 0 & M_2 & 0 \\ 0 & 0 & m_{e2} & 0 & 0 & M_3 \end{pmatrix}$$



## Special case for one generation

Input value of mass neutrino to the neutrino mass matrix ( GeV units )

$$m_{e1} = 1/4000, m_{e2} = 1/2000, m_{e3} = 1/431, m_1 = 1/250, \\ m_2 = 844/1000, M_1 = 4800, M_2 = 10^5, M_3 = 10^7$$

Diagonalize the matrix  $\mathcal{M}$  then gives

$$m_1 \simeq 2.869 \times 10^{-16} \text{ GeV} = 2.869 \times 10^{-7} \text{ eV}$$



Sub-eV neutrino

$$m_2 \simeq 1.1346 \times 10^{-9} \text{ GeV} = 1.1346 \text{ eV}$$



eV sterile neutrino

$$m_3 \simeq 7.124 \times 10^{-6} \text{ GeV} = 7.124 \text{ keV}$$

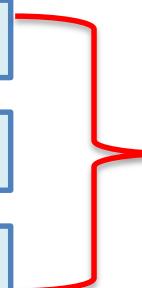


keV sterile neutrino

$$m_4 \simeq 4800 \text{ GeV}$$

$$m_5 \simeq 1.0 \times 10^5 \text{ GeV}$$

$$m_6 \simeq 1.0 \times 10^7 \text{ GeV}$$



3 massive neutrinos



# Oscillations in SBL

➤  $\Delta m_{21}^2$  correspond to  $\Delta m_{41}^2$

$$\Delta m_{21}^2 \approx m_2^2 = 1,287 \text{ eV}^2 \longrightarrow \Delta m_{41}^2 \approx 1.29 \text{ eV}^2$$

➤  $\sin^2 2\vartheta_{e\mu}$  ?

➤  $U_{12}$  corespond to  $|U_{e4}| \approx 0.1$

$$U = \begin{bmatrix} 0.994234 & -0.107125 & -0.00473929 & -5.20833 \cdot 10^{-8} & 3.99404 \cdot 10^{-8} & 2.84975 \cdot 10^{-31} \\ -0.00471201 & 0.000507783 & -0.999989 & 3.84789 \cdot 10^{-19} & 0.00000844000 & 9.89483 \cdot 10^{-48} \\ -0.107126 & -0.994245 & -8.04097 \cdot 10^{-8} & -4.83372 \cdot 10^{-7} & -6.13729 \cdot 10^{-12} & 5.00000 \cdot 10^{-11} \\ -1.14104 \cdot 10^{-12} & 4.86170 \cdot 10^{-7} & 2.46877 \cdot 10^{-10} & -1.00000 & 1.05042 \cdot 10^{-16} & 1.16065 \cdot 10^{-20} \\ 1.60179 \cdot 10^{-18} & -6.82594 \cdot 10^{-13} & 0.00000844009 & 2.18838 \cdot 10^{-15} & 1.00000 & 1.17237 \cdot 10^{-40} \\ 5.35632 \cdot 10^{-12} & 4.97123 \cdot 10^{-11} & 4.02049 \cdot 10^{-18} & 2.41802 \cdot 10^{-17} & 2.32712 \cdot 10^{-32} & 1. \end{bmatrix}$$

# Oscillations active and keV sterile neutrino



- ❖  $m_3$  correspond to  $m_S$

$$m_3 \simeq 7.124 \text{ keV}$$

$$m_S \simeq 7.1 \text{ keV}$$

- ❖  $\sin^2 2\theta$

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \delta_{\alpha\beta}^2 - 2 \sum_{k>j} \Re(U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*) \sin^2 \left( \frac{\Delta m_{kj}^2}{2E} \right) + 2 \sum_{k>j} \Im(U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*) \sin \left( \frac{\Delta m_{kj}^2}{2E} \right)$$

Only sensitive for  $\nu_1 \rightarrow \nu_3$  oscillation

$$P_{\nu_1 \rightarrow \nu_3} = -2 U_{13} U_{33} U_{11} U_{31} \sin^2 \left( \frac{\Delta m_{13}^2}{2E} \right)$$

$$\sin^2 2\theta = 8.118 \times 10^{-11}$$

$$\sin^2 2\theta \simeq (2 - 20) \times 10^{-11}$$



# Conclusions

- This models can accommodate eV and keV sterile neutrinos in one scheme which agree with experimental parameters

## Outlook

- For 3 generation neutrinos



# THANK YOU

