Quasi-Dirac neutrinos and the baryon asymmetry of the universe

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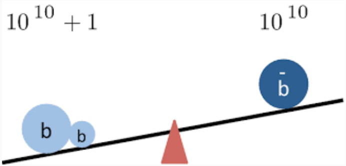
based on [C.S. Fong, T. Gregoire, AT, 2007.09158]

Motivations

Motivations

- Tiny neutrino masses and baryon asymmetry are two of the biggest puzzles in particle physics and both require the presence of Beyond the Standard Model physics



- Leptogenesis is an elegant mechanism that explains the baryon asymmetry in connection with neutrino masses
- In this work we propose a novel leptogenesis model with quasi-Dirac neutrinos that can be tested in oscillation experiments

Neutrino masses

Nature of neutrinos

Neutrinos can be:

- Majorana $(m_L \,\text{and/or}\, m_R \neq 0)$
- Dirac $(m_L = m_R = 0)$
- Quasi-Dirac $(m_L, m_R \ll m_D)$

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R^c\end{pmatrix}\begin{pmatrix}m_L & m_D \\ m_D & m_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix} + \text{h.c.}$$

Quasi-Dirac states are almost degenerate Majorana fermions

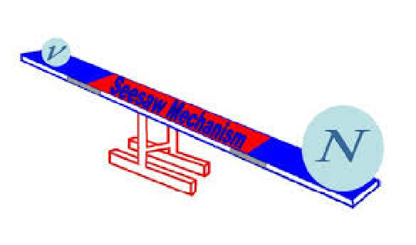
$$m_L, m_R \ll m_D \quad \Rightarrow \begin{cases} m_{1,2} \simeq m_D(1 \pm \epsilon) \\ \nu_{1,2} \simeq \frac{1(i)}{\sqrt{2}}[(\pm 1 + \theta)\nu_L + (1 \mp \theta)\nu_R^c] \end{cases}$$

with $\epsilon = \frac{m_L + m_R}{2m_D} \ll 1$ and $\theta = \frac{m_L - m_R}{4m_D} \ll 1$ (in the limit $m_L, m_R \to 0$ one recovers the Dirac case)

Seesaw mechanisms with HNL

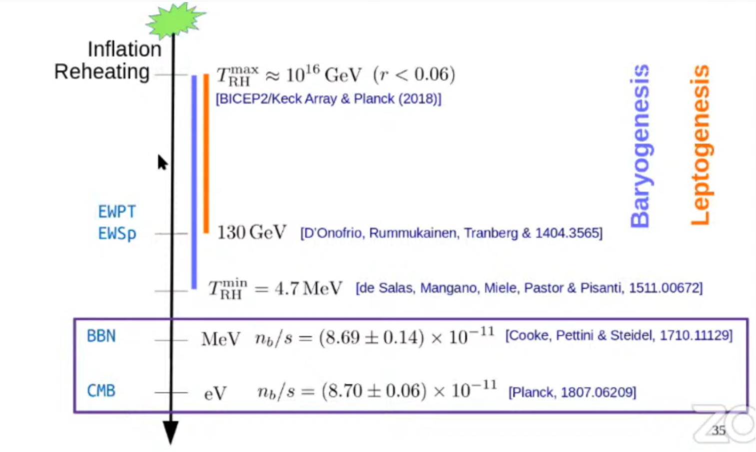
Elegant way to explain light neutrino (ν) masses due to the presence of Heavy Neutral Leptons (N)

Type	light ν	Heavy N	Content
Type I	Majorana	Majorana	ν_L, N_R
Inverse/Linear	Majorana	quasi-Dirac	ν_L, N_R, N'_R
Extended	quasi-Dirac	Majorana	ν_L, ν_R, N_R
Dirac	Dirac	Dirac	ν_L, ν_R, N_R, N'_R
quasi-Dirac	quasi-Dirac	quasi-Dirac	ν_L, ν_R, N_R, N'_R



Leptogenesis

Leptogenesis



The lepton asymmetry generated by the decay of Heavy Neutral Leptons (N) is converted into a baryon asymmetry by $B + L$-violating sphalerons [M. Fukugita and T. Yanagida Phys. Lett. B 174 (1986) 45]

Quasi-Dirac leptogenesis

The model *[CS Fong, T. Grgoire, AT, 2007.09158]*

Inspired by mirror world models (copy of SM)

- L-conserving lagrangian $(i, j = 1, .., N_f)$

$$\begin{aligned}\mathcal{L} &= i\bar{N}_{Ri}\partial\!\!\!/ N_{Ri} + i\bar{N}'_{Ri}\partial\!\!\!/ N'_{Ri} - M_i \bar{N}_{Ri} N'^{c}_{Ri} + \text{h.c.} \\ &\quad - y_{\alpha i}\bar{l}_{L\alpha}\tilde{\Phi} N_{Ri} - y'_{\alpha i}\bar{l'}_{L\alpha}\tilde{\Phi}' N'_{Ri} + \text{h.c.}\end{aligned}$$

- Small L-violating terms $(m, m' \ll M, \tilde{y} \ll y, \tilde{y}' \ll y')$

$$\begin{aligned}\mathcal{L}\!\!\!/ &= -\frac{1}{2} m_{ij} \bar{N}^{c}_{Ri} N_{Rj} - \frac{1}{2} m'_{ij} \bar{N}'^{c}_{Ri} N'_{Rj} \\ &\quad - \tilde{y}_{\alpha i}\bar{l}_{L\alpha}\tilde{\Phi} N'_{Ri} - \tilde{y}'_{\alpha i}\bar{l'}_{L\alpha}\tilde{\Phi}' N_{Ri} + \text{h.c.}\end{aligned}$$

In the limit $m, m', \tilde{y}, \tilde{y}' \to 0$ the total baryon minus lepton number

$$\Delta_{\text{tot}} = (B - L) - (B' - L')$$

is a good symmetry of the model

$N_f = 1$ case

We have a pair of Heavy Neutrinos N_R and N_R'. In the limit $m, m' \ll M$ we get the following mass eigenstate

$$\begin{pmatrix} N_1 \\ N_2 \end{pmatrix} = U^\dagger \begin{pmatrix} N_R \\ N_R' \end{pmatrix} \qquad \begin{matrix} N_1 \simeq (N_R + N_R')/\sqrt{2} \\ N_2 \simeq i(-N_R + N_R')/\sqrt{2} \end{matrix}$$

with quasi-degenerate masses

$$M_{1,2}^2 \simeq M^2 \left(1 \mp \frac{|m' + m^*|}{M}\right)$$

The heavy singlet fermions split into quasi-Dirac pairs and CP violation in their decays can naturally be enhanced to realize resonant leptogenesis

N decays and CP violation

- Lagrangian ($Y_{\alpha i} = y_\alpha U_{1i} + \tilde{y}_\alpha U_{2i}$ and $Y'_{\alpha i} = \tilde{y}'_\alpha U_{1i} + y'_\alpha U_{2i}$)

$$-(\mathcal{L} + \not{\mathcal{L}}) \supset \frac{1}{2} M_i \bar{N}_i^c N_i + Y_{\alpha i} \bar{l}_{L\alpha} \tilde{\Phi} N_i + Y'_{\alpha i} \bar{l'}_{L\alpha} \tilde{\Phi}' N_i + \mathrm{h.c.}$$

- Total decay width

$$\Gamma_i = \frac{M_i}{8\pi} \left[(Y^\dagger Y)_{ii} + (Y'^\dagger Y')_{ii} \right]$$

- CP violating parameters

$$\epsilon_i \equiv \frac{\sum_\alpha \Gamma(N_i \to l_\alpha \Phi) - \Gamma(N_i \to \bar{l}_\alpha \bar{\Phi})}{\Gamma_i}$$

$$\epsilon'_i \equiv \frac{\sum_\alpha \Gamma(N_i \to l'_\alpha \Phi') - \Gamma(N_i \to \bar{l}'_\alpha \bar{\Phi}')}{\Gamma_i}$$

Resonant enhancement

- Resonant enhancement occurs when the mass splitting is of the order of the decay width *[Pilaftsis and Underwood 0309342]*

$$|M_1 - M_2| \simeq |m' + m^*| \simeq \frac{\Gamma}{2}$$

- We consider Z_{2D} symmetric limit

$$m = m' \qquad y = y' \qquad \tilde{y} = \tilde{y}'$$

- Maximum CP parameters ($y^2 \equiv \sum_\alpha y_\alpha^2$ and $y'^2 \equiv \sum_\alpha y_\alpha'^2$ and $w \equiv \sum_\alpha y_\alpha \tilde{y}_\alpha$)

$$|\epsilon_1^{\max}| = |\epsilon_1'^{\max}| \simeq \frac{|\mathrm{Re}\, w|}{y^2} \sim \frac{\tilde{y}}{y}$$

- FInal baryon asymmetry

$$Y_B \propto \epsilon_1$$

Quasi-Dirac seesaw mechanism

- Integrating out the Heavy Ns we get the following mass matrix in the basis (ν_L, ν'_L)

$$M_\nu = -m_D \hat{M}^{-1} m_D^T \qquad m_D \equiv \begin{pmatrix} \upsilon Y \\ f Y' \end{pmatrix}$$

- Diagonalization

$$U_\nu^T M_\nu U_\nu = \mathrm{diag}(m_-, m_+, 0, 0, 0, 0)$$

- Non-zero quasi-Dirac mass eigenstates

$$m_\mp = m_\nu \mp \delta m$$

with $\delta m \ll m_\nu$

$$m_\nu \equiv \frac{y y' \upsilon f}{M} \qquad \delta m \simeq \left| \frac{w^* \upsilon^2 + w' f^2}{M} \right|$$

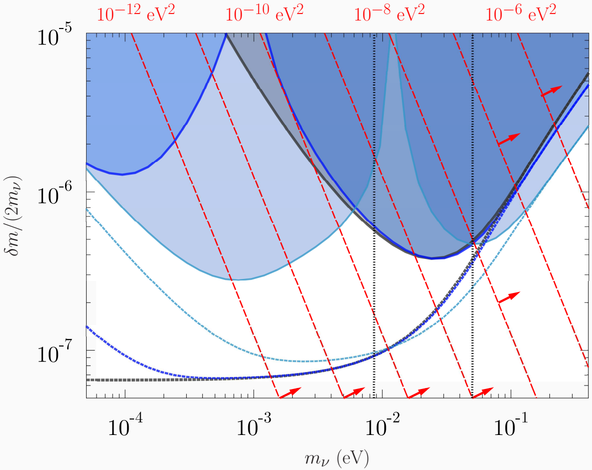
- In the Z_{2D} symmetric limit we have

$$\delta m = 2|\mathrm{Re}\, w| \upsilon^2 / M = 2 m_\nu |\mathrm{Re}\, w| / y^2$$

Light neutrinos are quasi-Dirac and there exist an intriguing relation between the CP parameter and light neutrino mass splitting

$$|\epsilon_1^{\max}| \simeq \frac{\delta m}{2m_\nu}$$

Results Z_{2D} symmetric limit



$M \gg 1\,\mathrm{TeV}$ (gray), $M = 1\,\mathrm{TeV}$ (blue) and $M = 500\,\mathrm{GeV}$ (light blue).
Dashed red lines indicate isocurves of constant $m_+^2 - m_-^2 \equiv \varepsilon^2 = 4m_\nu\delta m$

Quasi-Dirac oscillations

- Phenomenological study *[Anamiati, Fonseca, Hirsch 1710.06249]*

$$m_{i\mp}^2 = m_i^2 \mp \frac{\varepsilon^2}{2}$$

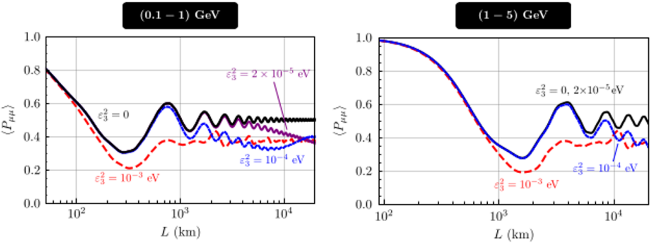


Figure 2: Averaged atmospheric muon neutrino survival probability for neutrinos with energies E_ν = (0.1 − 1) GeV (left) and E_ν = (1 − 5) GeV (right), as a function of distance (L), for different choices of ε_3^2. Lower neutrino energies are more sensitive to small ε_3 values. This plot is calculated with the simplifying assumptions of $\sin^2\theta_{23} = 1/2$, $\theta_{13} = 0$ and $\Delta m_\odot^2 = 0$.

Experiment	ε_1^2 [eV^2]	ε_2^2 [eV^2]	ε_3^2 [eV^2]
KamLAND	$7.7(3.4)\times10^{-6}$	$1.7(1.0)\times10^{-5}$	–
Solar + KamLAND	$1.7(1.3)\times10^{-11}$	$1.7(1.5)\times10^{-11}$	–
DayaBay + MINOS + T2K	–	$1.5(0.9)\times10^{-4}$	$1.3(0.074)\times10^{-3}$
Super-K + DayaBay + MINOS + T2K	–	$1.9(1.8)\times10^{-5}$	$1.2(1.1)\times10^{-5}$
JUNO	$1.7(0.07)\times10^{-5}$	$2.3(0.09)\times10^{-5}$	$6.0(2.2)\times10^{-5}$

Conclusions

- We proposed a novel model with small $B-L$ breaking where Heavy Neutrinos as well as light neutrinos are split into quasi-Dirac pairs
- This implies a natural realization of resonant leptogenesis
- The parameter space for viable leptogenesis spans over the neutrino mass squared difference in the range $10^{-12} - 10^{-6}\,\mathrm{eV}^2$ which can be probed in solar and atmospheric neutrino oscillation experiments
- From minimality considerations, observation of small mass splitting would strongly suggest that neutrinos are indeed Majorana particles
- More realistic study with $N_f = 2, 3$ needed (in progress)

Thank you

BACK UP

Baryogenesis

Sakarov conditions to dynamically generate the baryon asymmetry

- Baryon number violation
- C and CP violation
- Out of equilibrium dynamics

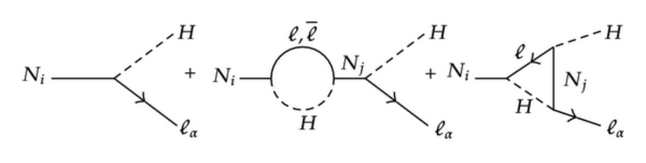
Al three ingredients are present in the SM but no successful mechanism has been found within the SM $\Rightarrow$ NP is needed

Minimal leptogenesis model I

- Type I seesaw lagrangian

$$\mathcal{L}_{\rm NP} = -\frac{1}{2} M_i \bar{N}^c_{Ri} N_{Ri} - y_{\alpha i} \bar{l}_{L\alpha} \tilde{\Phi} N_{Ri} + \text{h.c.}$$

- L-violating and CP-violating decay of heavy N



- CP-violating parameters

$$\epsilon_i \equiv \frac{\sum_\alpha \Gamma(N_i \to l_\alpha \Phi) - \Gamma(N_i \to \bar{l}_\alpha \bar{\Phi})}{\Gamma_{N_i}} \propto \sum_j \text{Im}[(y^\dagger y)^2_{ij}]$$

- Baryon asymmetry (in the limit $M_1 \ll M_{2,3}$)

$$Y_B \simeq -\frac{1}{3}\, \epsilon_1 \, \eta \, Y^{eq}_{N_1}$$

Minimal leptogenesis model II

- Casas-Ibarra parametrization

$$y_\nu = \frac{1}{v} U_\nu^* \sqrt{\hat{m}} R \sqrt{\hat{M}} \quad \Rightarrow \quad m_\nu = v^2 y_\nu M^{-1} y_\nu^T = U_\nu^* \hat{m} U_\nu^\dagger$$

- y_ν has 15 independent parameters, but 6 moduli + 3 phases cannot be probed at low energy
- Davidson-Ibarra bound

$$\epsilon_1 \gtrsim 10^{-6} \quad \Rightarrow \quad M_1 \gtrsim 10^{9-10}\mathrm{GeV}$$

- We can have only circumstantial or supporting evidences through L-violation in $0\nu\beta\beta$ decay and CP-violation in leptonic sector δ_{CP}

Dirac seesaw general idea

i) initial condition (no asymmetry)

$$B = 0 \qquad L = 0 \qquad B' = 0 \qquad L' = 0$$

ii) hierarchical spectrum (leptogenesis dominated by N_1 decay)

$$M_1 \ll M_2, M_3$$

iii) CPV decay of heavy Dirac N_i generates asymmetry in L and L'

$$B = 0 \qquad L = w \qquad B' = 0 \qquad L' = w$$

iv) sphalerons redistribute the asymmetry in $B - L$ and $B' - L'$

$$B = a \qquad L = w + a \qquad B' = a' \qquad L' = w + a'$$

v) all N_i decay, the two sectors decouple and sphaleron freeze out
$\rightarrow B$, L, B', L' separately conserved

Dirac seesaw neutrino masses

- Integrating out the heavy N_i we get

$$\mathcal{L}_{\rm eff} = (yM^{-1}y'^T)_{\alpha\beta}\bar{l}_{L\alpha}\tilde{\Phi}\tilde{\Phi}'^T(l'_{L\beta})^c + \text{h.c.}$$

- after EWSB in both sectors $\qquad \nu_R = (\nu'_L)^c$

$$\mathcal{L}_{mass} = (\mathcal{M}_\nu)_{ij}\,\bar{\nu}_{Li}\nu_{Rj} + \text{h.c.}$$

where (f is the Φ' vev)

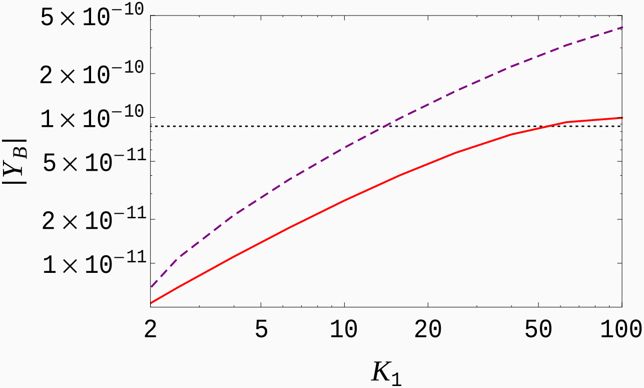
$$\mathcal{M}_\nu = \upsilon f\, yM^{-1}y'^T$$

- DI bound on CP parameter

$$|\epsilon_1| \leq \frac{M_1(m_3 - m_1)}{16\pi}\frac{1}{\upsilon f} = \frac{M_1|\Delta m^2_{\rm atm}|}{16\pi(m_3+m_1)}\frac{1}{\upsilon f} \equiv \epsilon_1^{\rm max}$$

Dirac leptogenesis *[K. Earl, CS Fong, T. Grgoire, AT, 1903.12192]*

Baryon asymmetry as function of $K_1 \equiv \frac{\Gamma_{N_1}}{H(T=M_1)}$



zero initial abundance thermal initial abundance

$M_1 = 8\times10^8$ GeV, $f = 500$ GeV, $m_3 + m_1 = 0.1$ eV, $|\epsilon'_{i\alpha}| >> |\epsilon_{i\alpha}|$

Other low energy tests

- LFV can be induced at one-loop level through loop of heavy quasi-Dirac fermions N, we have ($r \equiv y/y'$)

$$\mathrm{Br}(\mu \to e\gamma) \approx 6 \times 10^{-26} r^2 \left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)^2 \left(\frac{500\,\mathrm{GeV}}{M}\right)^2$$

- Current experimental bound

$$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

- Neutrinoless beta decay rate is prop to

$$(M_\nu)_{ee} \simeq -\frac{2 y_e \tilde{y}_e v^2}{M}$$

- $(M_\nu)_{ee}$ suppressed by $\tilde{y}_e \ll y_e$, not likely to be measured even in the next generation experiments which aim to probe $(M_\nu)_{ee} \sim 10\,\mathrm{meV}$

CP parameters

$\Delta_{\rm tot}$-conserving terms $\epsilon^c_{i\alpha}$ and $\epsilon'^c_{i\alpha}$

$$\epsilon^c_{i\alpha} \equiv \frac{M_i}{(8\pi)^2\Gamma_i}\sum_{j\neq i}\left\{\mathrm{Im}[(Y'^\dagger Y')_{ij}Y^*_{\alpha i}Y_{\alpha j}]f_{ij} + \mathrm{Im}[(Y^\dagger Y)_{ji}Y^*_{\alpha i}Y_{\alpha j}]g_{ij}\right\}$$

$$\epsilon'^c_{i\alpha} \equiv \frac{M_i}{(8\pi)^2\Gamma_i}\sum_{j\neq i}\left\{\mathrm{Im}[(Y^\dagger Y)_{ij}Y'^*_{\alpha i}Y'_{\alpha j}]f_{ij} + \mathrm{Im}[(Y'^\dagger Y')_{ji}Y'^*_{\alpha i}Y'_{\alpha j}]g_{ij}\right\}$$

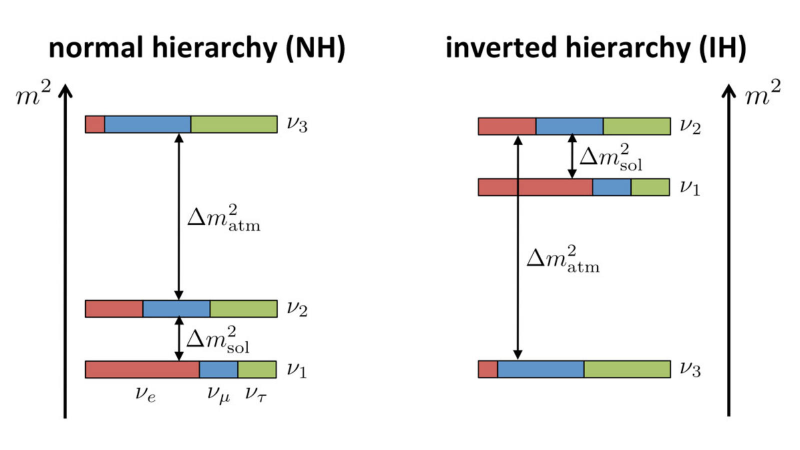
$\Delta_{\rm tot}$-violating terms $\epsilon^v_{i\alpha}$ and $\epsilon'^v_{i\alpha}$

$$\epsilon^v_{i\alpha} \equiv \frac{M_i}{(8\pi)^2\Gamma_i}\sum_{j\neq i}\left\{\mathrm{Im}[(Y^\dagger Y)_{ij}Y^*_{\alpha i}Y_{\alpha j}]f_{ij} + \mathrm{Im}[(Y'^\dagger Y')_{ji}Y^*_{\alpha i}Y_{\alpha j}]g_{ij}\right\}$$

$$\epsilon'^v_{i\alpha} \equiv \frac{M_i}{(8\pi)^2\Gamma_i}\sum_{j\neq i}\left\{\mathrm{Im}[(Y'^\dagger Y')_{ij}Y'^*_{\alpha i}Y'_{\alpha j}]f_{ij} + \mathrm{Im}[(Y^\dagger Y)_{ji}Y'^*_{\alpha i}Y'_{\alpha j}]g_{ij}\right\}$$

The regulated one-loop functions are given by $f_{ij} \equiv \frac{\sqrt{x_{ji}}(1-x_{ji})}{(1-x_{ji})^2+a_{ji}}$ and $g_{ij} \equiv \frac{1-x_{ji}}{(1-x_{ji})^2+a_{ji}}$, with $x_{ji} \equiv M_j^2/M_i^2$ and $a_{ji} \equiv \Gamma_j^2/M_i^2$.

Neutrino mass hierarchy



General neutrino masses

Lagrangian

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{kin} - \frac{1}{2}(m_n)_{ij} n_i n_j - \frac{1}{2}(m'_n)_{ij} n'_i n'_j - (m_D)_{ij} n'_i n_j + \text{h.c.} \\ & -y_{\alpha i}(l\Phi)_\alpha n_i - y'_{\alpha i}(l'\Phi')_\alpha n'_i + \text{h.c.} \\ & -\tilde{y}_{\alpha i}(l\Phi)_\alpha n'_i - \tilde{y}'_{\alpha i}(l'\Phi')_\alpha n_i + \text{h.c.}\end{aligned}$$

Integrating out the heavy n, n' fields

$$\begin{aligned}\mathcal{L}_{eff} &= \left[\frac{-y^2 m'_n - \tilde{y}^2 m_n + 2y\tilde{y}m_D}{2(m_D^2 - m_n m'_n)}\right](l\Phi)^2 \\ &+ \left[\frac{-y'^2 m_n - \tilde{y}'^2 m_{n'} + 2y'\tilde{y}' m_D}{2(m_D^2 - m_n m'_n)}\right](l'\Phi')^2 \\ &+ \left[\frac{-y\tilde{y}' m'_n - y'\tilde{y} m_n + (yy' + \tilde{y}\tilde{y}')m_D}{(m_D^2 - m_n m'_n)}\right](l\Phi)(l'\Phi')\end{aligned}$$

Comments

- With 3 families we have 30 total parameters (5 unobservables Majorana phases): 9 new angles, 12 new phases, 3 ε_k^2

- A two-parameter fit was performed (turning on one ε_k^2 and another new mixing angle at a time), leading to constraints in the range $\varepsilon_k^2 \lesssim 10^{-12} - 10^{-5}\,\mathrm{eV}^2$ for $k = 1, 2$. Larger values of ε_k^2 are also allowed for fine-tuned values of the mixing angle. For $k = 3$, the bound is in general much weaker: $\varepsilon_3^2 \lesssim 10^{-5}\,\mathrm{eV}^2$ *[Anamiati, Fonseca, Hirsch 1710.06249]*

- Solar neutrino experiment are not sensitive to values of $\varepsilon^2 \lesssim 10^{-12}\,\mathrm{eV}^2$, but this could by probed by measuring the flavor content of high-energy astrophysical neutrinos *[A. Esmaili, arXiv:hep-ph/0909.5410]*