Lepton Number Violating Interactions and Neutrino Oscillations in Matter

(Warning: Very Much a Work in Progress)

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Motivation

Project title – "Probing Exotic Neutrino Interactions"

But where are they!? In the SM:

- Three two-component left-handed neutrino fields $\nu_{\alpha L} \Rightarrow$ massless and couple only via CC and NC interactions
- No mixing in lepton sector

Observables:

- Interactions: (Quasi)elastic electron/nucleon scattering, DIS from nucleons, hadron decays
- Oscillations: Reactor, accelerator, atmospheric, solar, supernovae neutrinos
- Cosmological constraints: Dark Matter, matter/antimatter

Explaining the Observed Mixing

Require a neutrino mass? One remedy – add ν_R to SM:

$$\begin{aligned}\mathcal{L}_{\text{mass}}^{\text{D+M}} &= -\left(Y_{s\alpha}^{\nu}\overline{\nu_{sR}}\widetilde{H}^{\dagger}L_{\alpha L} + \text{h.c.}\right) - \frac{1}{2}M_R\left(\overline{\nu_{sR}^{c}}\nu_{s'R} + \text{h.c.}\right) \\ &\overset{\text{EW}}{=} -\frac{1}{2}\begin{pmatrix}\overline{\nu_{\alpha L}^{c}} & \overline{\nu_{sR}}\end{pmatrix}\begin{pmatrix}0 & M_D^T \\ M_D & M_R\end{pmatrix}\begin{pmatrix}\nu_{\beta L} \\ \nu_{s'R}^{c}\end{pmatrix} + \text{h.c.}\end{aligned} \tag{1}$$

If the v_R are sufficiently heavy, generate seesaw. Quadratic seesaw ($M_R = \mathcal{M}I_{N_s\times N_s}$):

$$\mathcal{L}_{\text{mass}}^{\text{eff}} \overset{\text{EW}}{=} -\frac{1}{2}\frac{(M_D^T M_D)_{\alpha\beta}}{\mathcal{M}}\left(\overline{\nu_{\alpha L}^{c}}\nu_{\beta L} + \text{h.c.}\right) \tag{2}$$

- A variety of models based on different possible M_R

Standard Model Effective Field Theory

SMEFT $\Rightarrow$ describe NP at low energy (e.g. heavy sterile $\nu_R \Rightarrow$ light active Majorana ν_L) via high-dim operators:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} \ldots \tag{3}$$

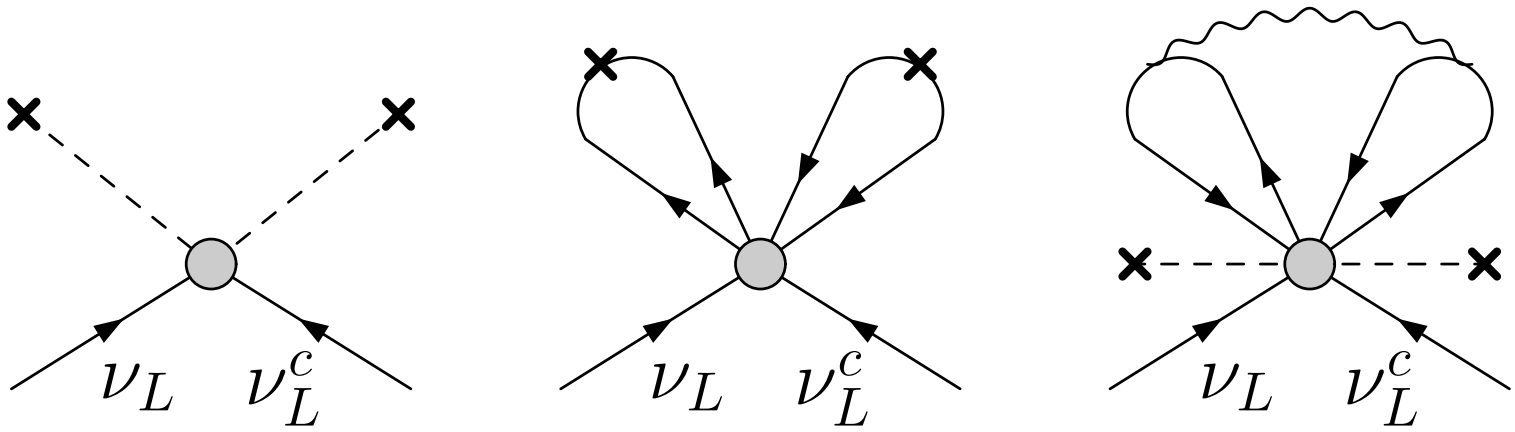
At dimension-five, Weinberg operator:

$$\mathcal{L}^{(5)} = \frac{\widetilde{C}^{(5)}_{\alpha\beta}(\overline{L^c_{\alpha L}}\widetilde{H}^*)(\widetilde{H}^\dagger L_{\beta L})}{\Lambda_{\text{NP}}} \tag{4}$$

- Odd dimensional operators are generally LNV

Generating a Majorana Mass

Higher-dimensional LNV operators $\Rightarrow$ radiative Majorana neutrino mass



d = 5 **d = 9** **d = 11**

- Assume $\Lambda_{\rm NP}$ is the scale at which $U(1)_{B-L}$ (the only non-anomalous global symmetry of the SM) is broken

Lepton Number Violating Neutrino Oscillations

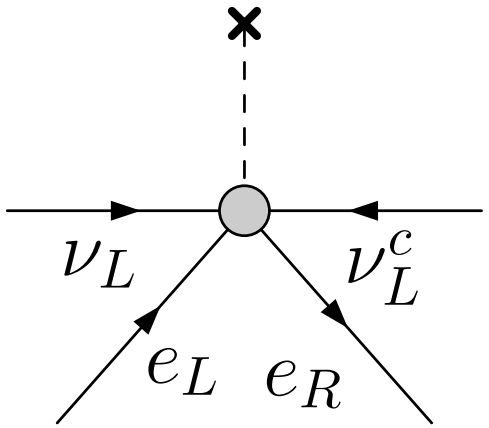
Pontecorvo: $\nu_\alpha \to \bar{\nu}_\beta$ oscillation? In vacuum, helicity flip suppresses this transition probability by $(\frac{m_i}{E})^2 \lesssim 10^{-12}$

$$P(\nu_\alpha \to \bar{\nu}_\beta) = \left| \sum_i U^*_{\alpha i} U^*_{\beta i} \frac{m_i}{E} \exp\left(-i \frac{m_i^2}{2E} L \right) K \right|^2 \qquad (5)$$

- Contains term proportional to $\mathrm{Im}(U_{\alpha i} U_{\beta i} U^*_{\alpha j} U^*_{\beta j}) \Rightarrow$ varies under rephasing of neutrino fields
- Majorana phases and effective mass $\langle m \rangle_{\alpha\beta}$ important
- See arXiv:1301.7654 for a description of the corresponding CP properties

Lepton Number Violating Matter Oscillations

The effective operator $L^i L^j L^k e^c H^l \epsilon_{ij} \epsilon_{kl}$ could induce a LNV interaction between neutrinos and electrons in matter:



- Effective matter potential coupling ν_α to $\bar{\nu}_\beta$? Non-unitary evolution of $\nu_\alpha \to \nu_\beta$ and $\bar{\nu}_\alpha \to \bar{\nu}_\beta$ systems?

$$V_7 \sim \left(\frac{\tilde{C}^{(7)}}{\Lambda_{\rm NP}^3}\right)\left(\frac{m_e}{E_e}\right) v N_e \sim \left(\frac{N_e}{N_A \cdot {\rm cm}^{-3}}\right) \times 10^{-14}\ {\rm eV} \qquad (6)$$

Matter Effect

Toy model – 2 ν and 2 $\bar{\nu}$ mixing in matter, coupled via V_7:

$$i\frac{d}{dt}\begin{pmatrix} \boldsymbol{\nu} \\ \bar{\boldsymbol{\nu}} \end{pmatrix} = \mathcal{H}_{\rm F}\begin{pmatrix} \boldsymbol{\nu} \\ \bar{\boldsymbol{\nu}} \end{pmatrix} \tag{7}$$

$$\begin{aligned} \mathcal{H}_{\rm F} = \frac{\Delta m^2}{4E}&\begin{pmatrix} -c_{12} & s_{12} & 0 & 0 \\ s_{12} & s_{12} & 0 & 0 \\ 0 & 0 & -c_{12} & s_{12} \\ 0 & 0 & s_{12} & c_{12} \end{pmatrix} \\ +&\begin{pmatrix} \sqrt{2}G_F N_e & 0 & V_7 & 0 \\ 0 & 0 & 0 & 0 \\ V_7 & 0 & -\sqrt{2}G_F N_e & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{aligned} \tag{8}$$

where $c_{12} = \cos 2\theta$, $s_{12} = \sin 2\theta$, N_e – electron number density.
Propagation medium neither CP nor CPT invariant

Matter Effect

Assume $V_7 \ll \sqrt{2} G_F N_e$ – obtain perturbative expansion around standard uncoupled solution (after diagonalizing $\mathcal{H}_{\rm F}$):

$$\Delta\widetilde{m}^2_{\rm M} = \Delta m^2_{\rm M}\left\{1 \mp \frac{(\Delta m^2 c_{12} \mp A_{\rm CC})V_7^2}{8A_{\rm CC}(\Delta m^2_{\rm M})^2} + \mathcal{O}(V_7^4)\right\} \tag{9}$$

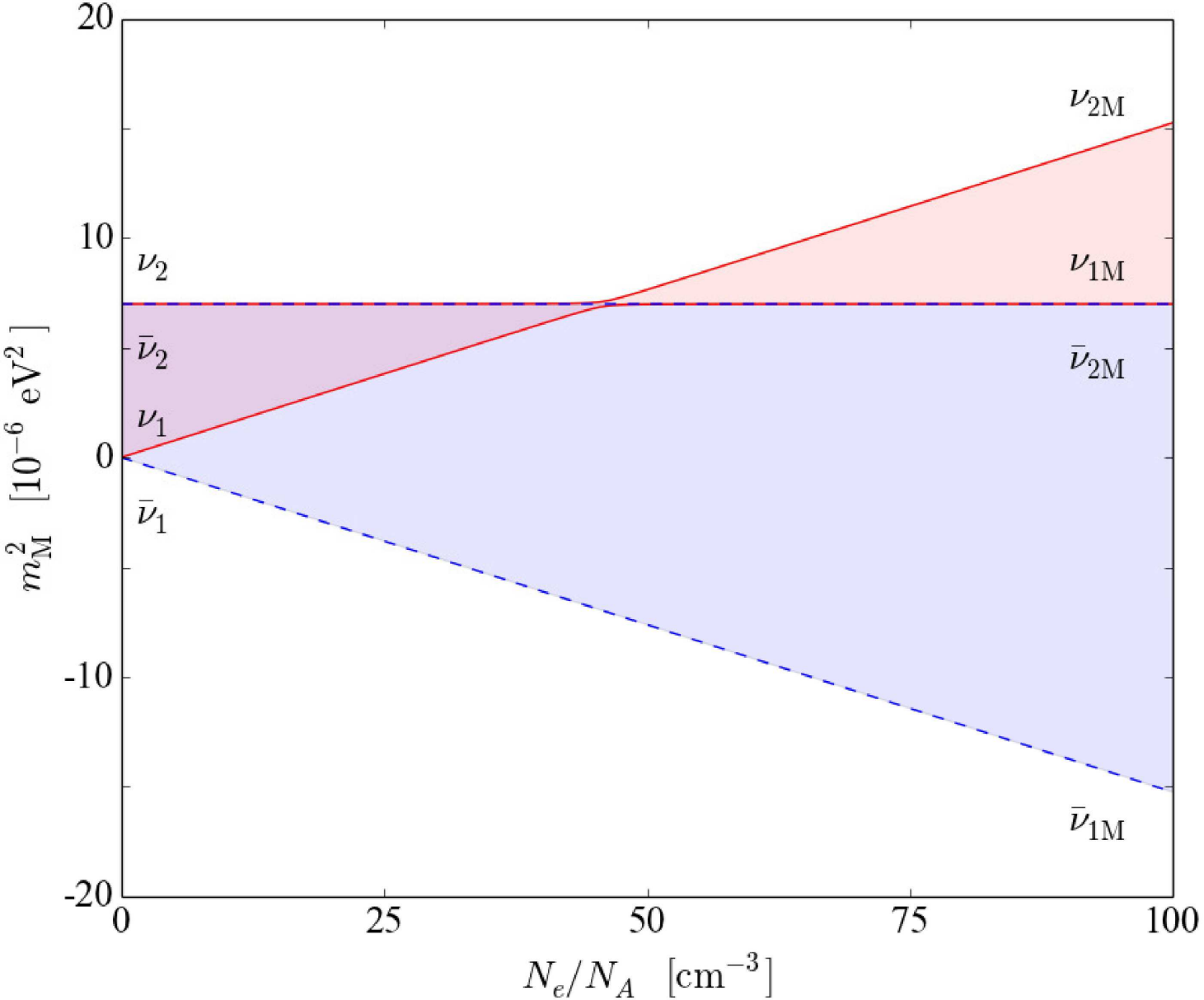
$$\sin 2\widetilde{\theta}_{\rm M} = \sin 2\theta_{\rm M}\left\{1 \pm \frac{(\Delta m^2 c_{12} \mp A_{\rm CC})V_7^2}{8A_{\rm CC}(\Delta m^2_{\rm M})^2} + \mathcal{O}(V_7^4)\right\} \tag{10}$$

where

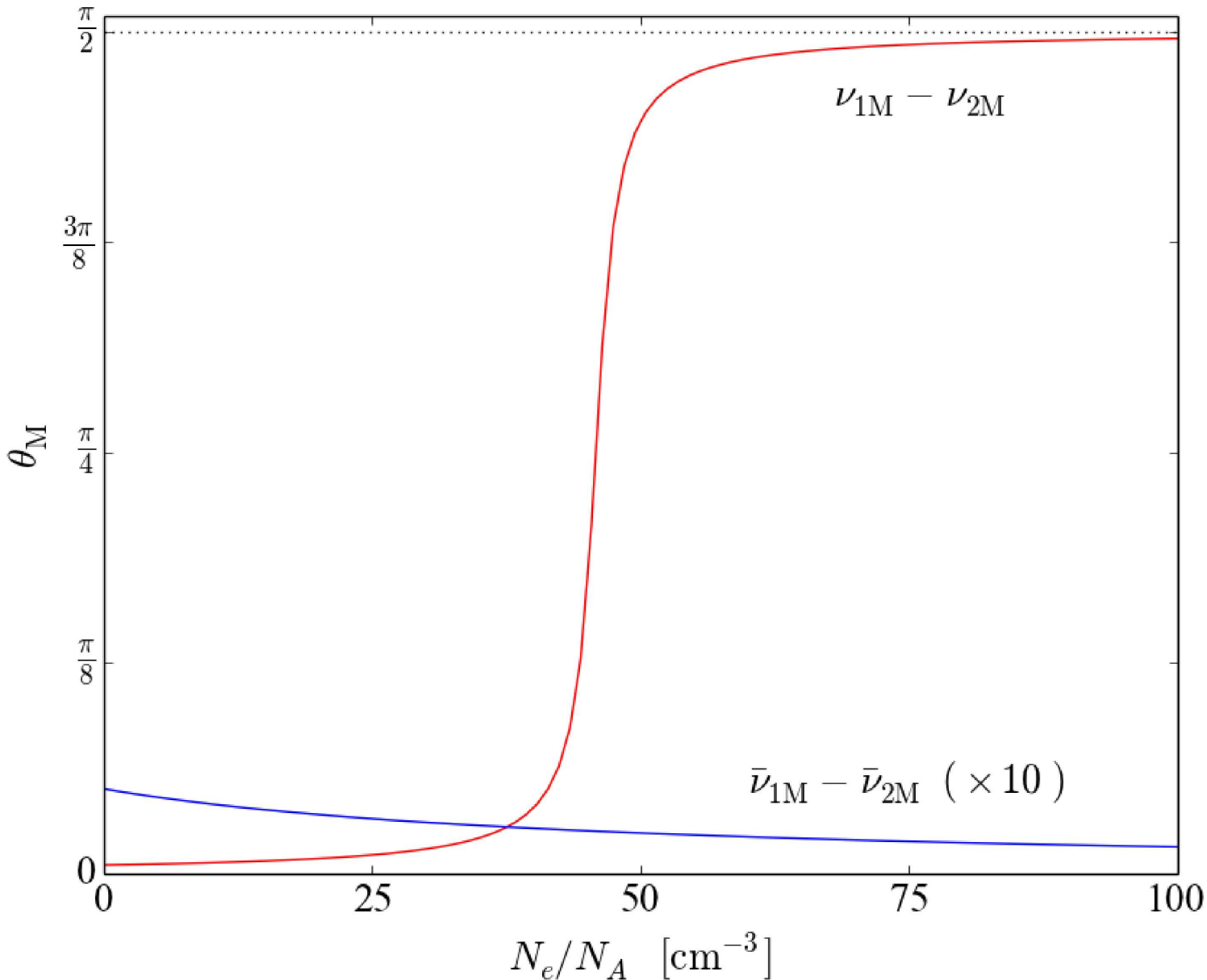
$$\begin{aligned} A_{\rm CC} &= 2\sqrt{2} E G_F N_e \\ \Delta m^2_{\rm M} &= \sqrt{(\Delta m^2 c_{12} \mp A_{\rm CC})^2 + (\Delta m^2 s_{12})^2} \\ \sin 2\theta_{\rm M} &= \frac{\Delta m^2 s_{12}}{\Delta m^2_{\rm M}} \end{aligned} \tag{11}$$

($\pm, \mp \Rightarrow$ top – neutrinos, bottom – antineutrinos)

Matter Neutrino Mass Eigenstates



Matter Mixing Angle



Outlook

Aims

- Further investigate magnitude of LNV effects in matter oscillations – are they sizeable enough?
- If so, explore phenomenology at higher precision upcoming experiments: JUNO, DUNE, Hyper-K...
- LNV in extreme environments – stellar collapse?

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Thanks for your attention

For Further Reading I


A. de Gouvêa and J. Jenkins
A Survey of Lepton Number Violation Via Effective Operators
arXiv:0708.1344 [hep-ph]


S. Bergmann, H. V. Klapdor-Kleingrothaus and H. Pas
Lepton number violating interactions and their effects on neutrino oscillation experiments
hep-ph/0004048


Z. Z. Xing
Properties of CP Violation in Neutrino-Antineutrino Oscillations
arXiv:1301.7654 [hep-ph]


S. Hollenberg, O. Micu and P. B. Pal
Lepton number violating effects in neutrino oscillations
arXiv:1112.1523 [hep-ph]

For Further Reading II

C. S. Fong, H. Minakata and H. Nunokawa
Non-unitary evolution of neutrinos in matter and the leptonic unitarity test
arXiv:1712.02798 [hep-ph]

M. Blennow, P. Coloma, E. Fernandez-Martinez, J. Hernandez-Garcia and J. Lopez-Pavon
Non-Unitarity, sterile neutrinos, and Non-Standard neutrino Interactions
arXiv:1609.08637 [hep-ph]