Three Twin Neutrinos: Evidence from LSND and MiniBooNE

Parallel Talk, Pheno 2016

Benjamin Stefanek

University of Wisconsin, Madison

May 9th, 2016

Phys. Rev. D 93, 073004 [arXiv:1512.05357]

Yang Bai, Ran Lu, Sida Lu, Jordi Salvado, and Ben A. Stefanek

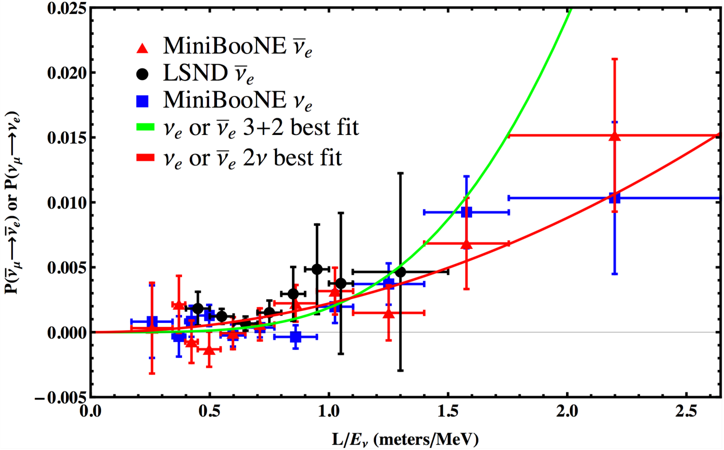
Introduction

The past decade has seen a series of anomalies emerge in short baseline (SBL) neutrino oscillation experiments which cannot be explained within the three active neutrino framework of the Standard Model (SM).

- MiniBooNE experiment at Fermilab (806 ton $\mathrm{CH_2}$ Cherenkov detector)
- Liquid Scintillator Neutrino Detector (LSND)
- Reactor Antineutrino Anomalies
- Radioactive Source Experiments (Gallium Anomaly)

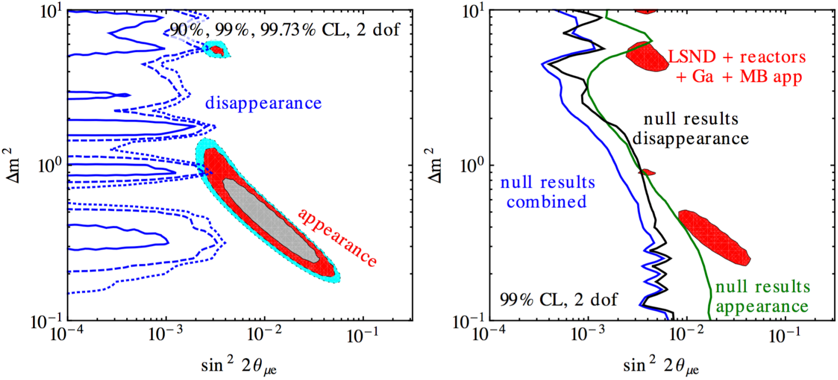
SBL refers to experiments with $L/E_\nu \sim 1\,\mathrm{m/MeV}$, which are sensitive to neutrino oscillations involving mass squared splittings $\Delta m^2 \sim 1\,\mathrm{eV}^2$.

MiniBooNE/LSND Neutrino Appearance



MiniBooNE Collaboration, Phys. Rev. Lett. 110 (2013) 161801, [arXiv:1207.4809]

3 Active Neutrinos + 1 Sterile Neutrino (3+1) Global Fit



$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

$$\Delta m^2 = \Delta m^2_{41} = m_4^2 - m_1^2$$

Kopp, Machado, Maltoni, and Schwetz, JHEP 05 (2013) 050, [arXiv:1303.3011]

Twin Neutrino Model

We construct a 3+3 neutrino model embedded within the Twin Higgs framework, which has the following features

- Full or partial copy of the SM gauge group and particle content makes a 3+3 neutrino scenario natural to consider.
- Couplings in the SM (A) and Twin (B) sectors are related by a discrete $\mathbb{Z}_2$ symmetry which exchanges $A \longleftrightarrow B$.
- SM Higgs field is a pseudo-Nambu Goldstone boson (PNGB) associated with spontaneous breaking of an approximate global $SU(4)$ symmetry.
- The twin $\mathbb{Z}_2$ symmetry forbids quadratically divergent corrections to the SM Higgs mass at the one-loop level.

$$\Delta V_{\mathcal{H}} = \tfrac{9\Lambda^2}{64\pi^2}(g_A^2 H_A^\dagger H_A + g_B^2 H_B^\dagger H_B) = \tfrac{9\Lambda^2}{64\pi^2} g^2 \mathcal{H}^\dagger \mathcal{H}$$

Sterile Neutrino Mass Operators

The sterile neutrinos can be given masses via the following twin $\mathbb{Z}_2$ and $SU(4)$ invariant operators

$$\frac{y_\nu^{ij}}{\Lambda_S}\mathcal{L}_i^T\widetilde{\mathcal{H}}\,\mathcal{C}\,\widetilde{\mathcal{H}}^T\mathcal{L}_j + \mathrm{h.c.} \qquad \text{(Majorana)}$$

$$y_\nu^{ij}\,\widetilde{\mathcal{H}}\,\overline{\mathcal{L}}\,(\nu_{A,R} + \nu_{B,R}) + \mathrm{h.c.} \qquad \text{(Dirac)}$$

$$\mathcal{L} \equiv (L_A, L_B) \qquad \widetilde{\mathcal{H}}^T \equiv (\widetilde{H}_A^T, \widetilde{H}_B^T) \qquad \widetilde{H}_{A,B}^T \equiv -i\sigma_2 H_{A,B}^T$$

In the Majorana case, after the Higgs doublets acquire VEVs defined as $\langle H_A\rangle = v$ and $\langle H_B\rangle = f$, the linear combinations $v\,\nu_{A,L}^i + f\,\nu_{B,L}^i$ are massive and correspond to the three sterile neutrino mass eigenstates. The orthogonal linear combinations corresponding to the active neutrinos remain massless.

Active Neutrino Mass Operators

The active neutrinos can be given masses via the following twin $\mathbb{Z}_2$ invariant and $SU(4)$ breaking operators

$$\frac{y_\nu^{ij}}{\Lambda_\phi^2}\,\phi\,L_{A\,i}^T\,\widetilde{\mathcal{H}}_A\,\mathcal{C}\,\widetilde{\mathcal{H}}_B^T\,L_{B\,j} + \mathrm{h.c.} \qquad \text{(Majorana)}$$

$$\frac{y_\nu^{ij}}{\Lambda_\phi}\,\phi\,\widetilde{\mathcal{H}}_A\,\overline{L}_A\,\nu_{B,R} + \mathrm{h.c.} \qquad \text{(Dirac)}$$

The scalar field ϕ is a gauge singlet and carries both SM and Twin lepton numbers. We also define a parity under which

$$\phi \to -\phi, \qquad L_B \to -L_B, \qquad L_A \to L_A.$$

This parity will forbid additional operators involving ϕ coupling only to SM leptons.

Neutrino Masses and Mixing

After the scalars acquire VEVs ($\langle\phi\rangle = f_\phi$), the mass matrix is (in the Majorana case)

$$M = \frac{1}{\Lambda_S}\begin{pmatrix} v^2 & vf\left[1+\frac{f_\phi \Lambda_S}{\Lambda_\phi^2}\right] \\ vf\left[1+\frac{f_\phi \Lambda_S}{\Lambda_\phi^2}\right] & f^2 \end{pmatrix} \otimes y_\nu^{3\times 3}$$

$$= \mathcal{U}^T \mathrm{diag}\left(m_{\nu_a^1}, m_{\nu_a^2}, m_{\nu_a^3}, m_{\nu_s^1}, m_{\nu_s^2}, m_{\nu_s^3}\right)\mathcal{U}\,.$$

The generalization of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix in our model is

$$\mathcal{U}^{6\times 6} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \otimes U_{\mathrm{PMNS}}^{3\times 3}\,, \qquad \theta \approx \frac{v}{f} = \mathcal{O}(0.1)\,.$$

$$r \equiv \frac{m_i}{m_{i+3}} = \frac{m_{\nu_a^i}}{m_{\nu_s^i}}$$

Majoron Interactions and Sterile Neutrino Decay

In our model, there is a PNGB associated with the global symmetry breaking of $U(1)_{L_A} \times U(1)_{L_B} \to U(1)_L$. The relevant Yukawa couplings for the Majoron particle φ, defined as $\phi \equiv e^{i\varphi/f_\phi}$ in our model are (in the Majorana case)

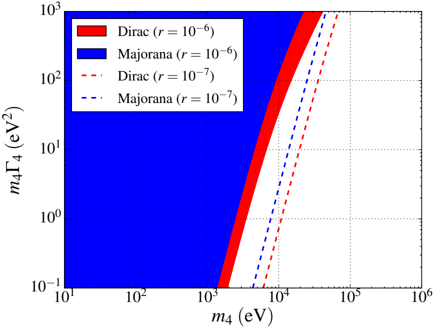
$$\lambda^i_{as}\, i\varphi\, \nu^{i\,T}_{a,L}\mathcal{C}\nu^i_{s,L} \equiv \bar{y}^i_\nu\, \frac{vf}{2\Lambda^2_\phi}\, i\varphi\, \nu^{i\,T}_{a,L}\mathcal{C}\nu^i_{s,L}$$

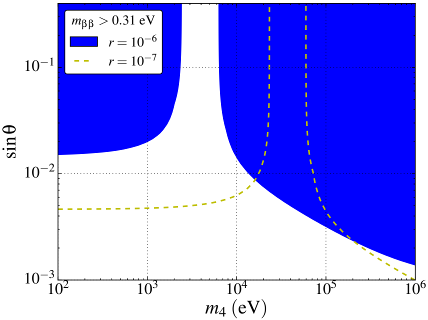
$$\lambda^i_{aa}\, i\varphi\, \nu^{i\,T}_{a,L}\mathcal{C}\nu^i_{a,L} \equiv \theta\, \bar{y}^i_\nu\, \frac{vf}{2\Lambda^2_\phi}\, i\varphi\, \nu^{i\,T}_{a,L}\mathcal{C}\nu^i_{a,L}\, .$$

So, our sterile neutrinos are not stable particles and have the decay widths of

$$\Gamma[\nu^i_s] = 2\,\Gamma[\nu^i_s \to \nu^i_a(\bar{\nu}^i_a) + \varphi] \approx \frac{(\lambda^i_{as})^2\, m_{\nu^i_s}}{4\pi} = \frac{(\lambda^3_{as})^2}{4\pi}\frac{m^3_{\nu^i_s}}{m^2_{\nu^3_s}}\, .$$

Model Parameter Constraints

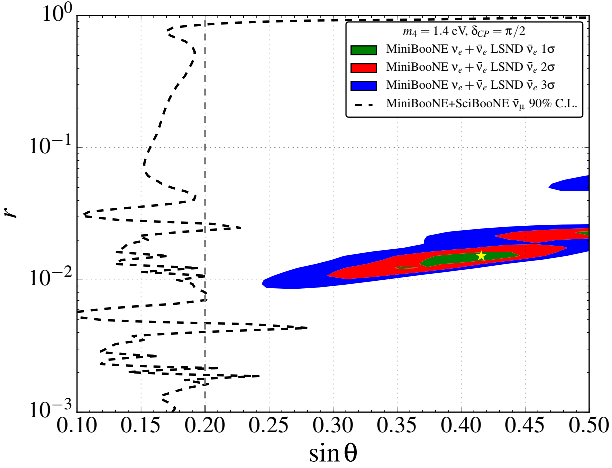




$$(g^2)_{ee} < 3.0 \times 10^{-5}$$

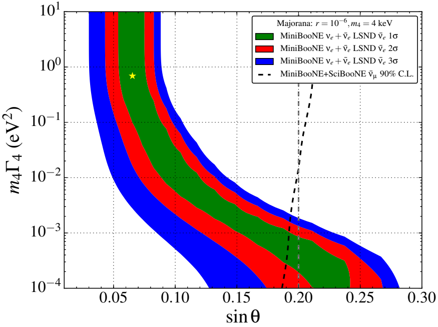
$$|\langle m_{\beta\beta} \rangle| \equiv \left| \sum_{i=1}^{6} m_i \, \mathcal{U}_{ei}^2 \right| < 0.31\,\mathrm{eV}$$

Fit to LSND, MiniBooNE, and SciBooNE Data: Oscillation without Decay



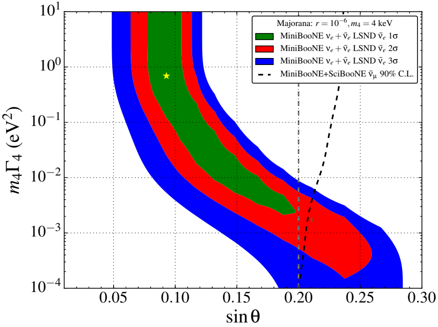
Fit to LSND, MiniBooNE, and SciBooNE Data: Oscillation with Decay

Dirac



$$\Delta\chi^2 = 18.7 \rightarrow 3.9\sigma$$

Majorana



$$\Delta\chi^2 = 22.5 \rightarrow 4.4\sigma$$

Conclusions

- We construct a 3+3 Twin Neutrino model embedded in the well established Twin Higgs paradigm.
- The model predicts identical lepton Yukawa structures in the SM and Twin sectors due to the twin parity.
- The heavy twin neutrinos decay within the experimental lengths into active neutrinos plus a long lived Majoron. This prompt decay scenario can provide a good fit, at around the 4σ confidence level (relative to the background-only fit) to the LSND and MiniBooNE appearance data while simultaneously satisfying the disappearance constraints.

Backup 1

- Because of the fairly large interaction strength ($\lambda_{as}^3 \sim 0.01$) among sterile neutrinos, active neutrinos and the Majoron particle, both sterile neutrinos and the Majoron particles stay within the supernova core.
- Sterile neutrinos with a mass below around $\sim$ 1 MeV contribute to additional relativistic degrees of freedom and are constrained by measurements of the CMB and BBN. There have been suggestions that these constraints can be avoided if the sterile neutrinos are charged under a new $U(1)'$ gauge symmetry which is spontaneously broken such that the corresponding gauge boson acquires an MeV-scale mass. In this type of scenario, the coupling of the sterile neutrinos to the new MeV-scale gauge boson can generate a large temperature dependent potential which effectively suppresses the mixing angle between active and sterile neutrinos in the thermal bath.
- It is possible that the Majoron introduced in our model could play a similar role to this new massive gauge boson, but with the caveat that it will decay later due to its eV scale mass. This means it will contribute to N_{eff} as an approximately massless boson, yielding a $\Delta N_{\text{eff}} \sim 4/7$, which is only marginally contrained by the most recent Planck data.

Backup 2

- In the past decades, the majority of the reactor experiments have observed less neutrino flux than predicted. The Daya Bay experiment recently published the result of its 217-day run and found a measured-predicted ratio of $0.943 \pm 0.008 \pm 0.025$.
- These deficits of about 5% can be easily explained in the twin neutrino scenario by active-sterile mixing. The sterile and active components are produced with a ratio of $\sin^2\theta : \cos^2\theta$, and the sterile components evade the detection of far detector, which implies $\sin^2\theta \sim 0.05$. The corresponding $\sin\theta$ value is on the boundary of our allowed parameter space.
- On the other hand, our model cannot explain the Gallium anomalies. The deficit there is about $15\% \pm 5\%$, and would require $\sin\theta > 0.3$, which is outside our allowed parameter space.

Backup 3

$$P(\nu_\alpha \to \nu_\beta) = 4\sin^4\theta \sum_{j=2}^{3}\sum_{k=1}^{j-1} |U_{\beta j}U^*_{\alpha j}U^*_{\beta k}U_{\alpha k}| \sin\left(\frac{\Delta m^2_{jk} L}{2\,r^2 E}\right) \sin\left(\phi_{\beta\alpha jk} - \frac{\Delta m^2_{jk} L}{2\,r^2 E}\right)$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta) \sum_{j=1}^{3} |U_{\alpha j}|^2 \sin^2\left(\frac{\Delta m^2_{j+3,1} L}{2\,E}\right)$$

For the case in which sterile neutrino decay effects dominate, and in the limit of $|\Delta m^2_{45,56,46}| \gg \Gamma_j m_j$, the appearance probability is

$$\frac{dP_{\nu_\alpha \to \nu_\beta}(E_{\nu_\alpha})}{dE_{\nu_\beta}} = \frac{c}{2}\sin^2\theta\, W_{E_{\nu_\alpha} \to E_{\nu_\beta}} \sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2 \left(1 - e^{-\frac{m_{j+3}\Gamma_{j+3} L}{E_{\nu_\alpha}}}\right)$$

Backup 4

- For the best fit point of the Majorana neutrino model, the six neutrino masses are 0.004 eV, 0.0096 eV, 0.050 eV, 4 keV, 9.56 keV, 50.0 keV.
- The three sterile neutrino widths are $\Gamma_4 = 0.0001$ eV, $\Gamma_5 = 0.0019$ eV and $\Gamma_6 = 0.27$ eV.
- The decay Yukawa coupling: $\lambda_{as}^3 \approx 0.008$.

$$(g^2)_{ee} = c \sum_{i=1}^{3} U_{ei} \frac{32\pi \, \Gamma_{\nu_s^i \to \nu_a^i + \varphi}}{m_{\nu_s^i}} U_{ie}^T < 3.0 \times 10^{-5}$$