Implications of the Dark LMA solution and Fourth Sterile Neutrino for Neutrino-less Double Beta Decay

Based on arXiv:1909.09434

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Abstract

We analyze the effect of the Dark-large mixing angle (DLMA) solution on the effective Majorana mass ($m_{\beta\beta}$) governing neutrino-less double beta decay ($0\nu\beta\beta$) in the presence of one sterile neutrino. We have checked that the MSW resonance in the sun can take place in the DLMA parameter space in this scenario. Next we investigate how the values of the solar mixing angle θ_{12} corresponding to the DLMA region alter the predictions of $m_{\beta\beta}$ by including a sterile neutrino in the analysis. We also compare our results with three generation cases for both standard large mixing angle (LMA) and DLMA. Additionally, we evaluate the discovery sensitivity of the future ^{136}Xe experiments in this context.

Objectives

1. The Large Mixing Angle (LMA) solution solves the solar neutrino problem which corresponds to the standard neutrino oscillation with $\Delta m^2_{21} = 7.5\times10^{-5}eV^2$ and $\sin^2\theta_{12} \simeq 0.3$.
2. There is a degenerate solution of the solar neutrino problem which is called the Dark Large Mixing angle (DLMA) solution which corresponds to the neutrino oscillation parameters $\Delta m^2_{21} = 7.5\times10^{-5}eV^2$ and $\sin^2\theta_{12} \simeq 0.7$ if we allow non standard interaction (NSI) along with the standard oscillation in the theory (JHEP10(2006)008).
3. The LSND/MiniBooNE results motivate us to go beyond three generation neutrino scheme. In this work, we have studied the implications of the DLMA solution to the solar neutrino problem for $(0\nu\beta\beta)$ in the presence of sterile neutrino.
4. Here we have checked that the MSW resonance in the Sun can take place in the DLMA parameter space in this scenario.
5. We investigate how the values of the solar mixing angle θ_{12} corresponding to the DLMA region alter the prediction of $m_{\beta\beta}$ including a sterile neutrino in the hypothesis.

DLMA solution in 3+1 neutrino framework

The neutral current Lagrangian for NSIs in matter is given by the effective dimension 6 four fermion operator as

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu\nu_\beta)(\bar{f}\gamma_\mu P f), \quad (1)$$

The total matter potential including standard and non-standard interactions is governed by the Hamiltonian,

$$H^{sterile+NSI}_{mat} = \sqrt{2}G_F N_e(r)\begin{bmatrix}1&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix} + \frac{G_F N_n}{\sqrt{2}}\begin{bmatrix}0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&1\end{bmatrix} + \sqrt{2}G_F\sum_{f=e,u,d}N_f(r)\begin{bmatrix}\epsilon^f_{ee}&\epsilon^f_{e\mu}&\epsilon^f_{e\tau}&0\\\epsilon^{f*}_{e\mu}&\epsilon^f_{\mu\mu}&\epsilon^f_{\mu\tau}&0\\\epsilon^{f*}_{e\tau}&\epsilon^{f*}_{\mu\tau}&\epsilon^f_{\tau\tau}&0\\0&0&0&0\end{bmatrix}. \quad (2)$$

The Hamiltonian in an effective 2×2 model is $H^{eff} = H^{eff}_{vac} + H^{eff}_{mat}$ where,

$$H^{eff} = \frac{\Delta m^2_{21}}{4E}\begin{bmatrix}-\cos2\theta_{12}&\sin2\theta_{12}\\\sin2\theta_{12}&\cos2\theta_{12}\end{bmatrix} + A_i\begin{bmatrix}c^2_{13}c^2_{14}&0\\0&0\end{bmatrix} + A_j\begin{bmatrix}-k_1&k_2\\k^*_2&k_1\end{bmatrix} + A_i\sum_{f=e,u,d}\frac{N_f}{N_e}\begin{bmatrix}-\epsilon^f_D&\epsilon^f_N\\\epsilon^{f*}_N&\epsilon^f_D\end{bmatrix}. \quad (3)$$

Diagonalizing the above effective Hamiltonian gives the matter mixing angle θ_M as,

$$\tan2\theta_M = \frac{\delta\sin2\theta_{12} + 2A_i\alpha_f\epsilon^f_N + 2A_jk_2}{\delta\cos2\theta_{12} + 2A_i\alpha_f\epsilon^f_D - A_ic^2_{13}c^2_{14} + 2A_jk_1}. \quad (4)$$

Hence, the resonance occurs when,

$$\Delta m^2_{21}\cos2\theta_{12} + Bk_1 = A[c^2_{13}c^2_{14} - 2\alpha_f\epsilon^f_D], \quad (5)$$

where all the terms are defined in arXiv:1909.09434

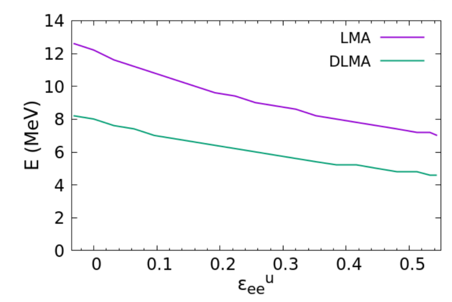

Figure 1: The energies corresponding to resonance for different values of ϵ^u_{ee} for LMA (purple line) and DLMA (green line) solutions.

$0\nu\beta\beta$ in 3+1 scenario

The half life for $0\nu\beta\beta$ in the standard scenario with light neutrino exchange is given by

$$(T_{1/2})^{-1} = G\left|\frac{M_\nu}{m_e}\right|^2 m^2_{\beta\beta}, \quad (6)$$

The expression for the effective Majorana mass $m_{\beta\beta}$ is given by,

$$m_{\beta\beta} = |U^2_{ei}m_i|, \quad (7)$$

Thus, in 3+1 scheme,

$$m_{\beta\beta} = |m_1c^2_{12}c^2_{13}c^2_{14} + m_2s^2_{12}c^2_{13}c^2_{14}e^{i\alpha} + m_3s^2_{13}c^2_{14}e^{i\beta} + m_4s^2_{14}e^{i\gamma}|. \quad (8)$$

For normal hierarchy (NH), m_1 is the lowest mass eigenstate ($m_1 < m_2 << m_3$) and we can express the other mass eigenstates in terms of m_1 as

$$m_2 = \sqrt{m^2_1 + \Delta m^2_{sol}} \quad m_3 = \sqrt{m^2_1 + \Delta m^2_{atm}} \quad m_4 = \sqrt{m^2_1 + \Delta m^2_{LSND}} \quad (9)$$

For inverted hierarchy (IH), m_3 is the lowest mass eigenstate ($m_3 << m_1 \approx m_2$) and the other mass eigenstates in terms of m_3 are,

$$m_1 = \sqrt{m^2_3 + \Delta m^2_{atm}} \quad m_2 = \sqrt{m^2_3 + \Delta m^2_{sol} + \Delta m^2_{atm}} \quad m_4 = \sqrt{m^2_3 + \Delta m^2_{atm} + \Delta m^2_{LSND}}. \quad (10)$$

Here, $\Delta m^2_{sol} = m^2_2 - m^2_1$, $\Delta m^2_{atm} = m^2_3 - m^2_1(m^2_1 - m^2_3)$ for NH(IH) and $\Delta m^2_{LSND} = m^2_4 - m^2_1$.

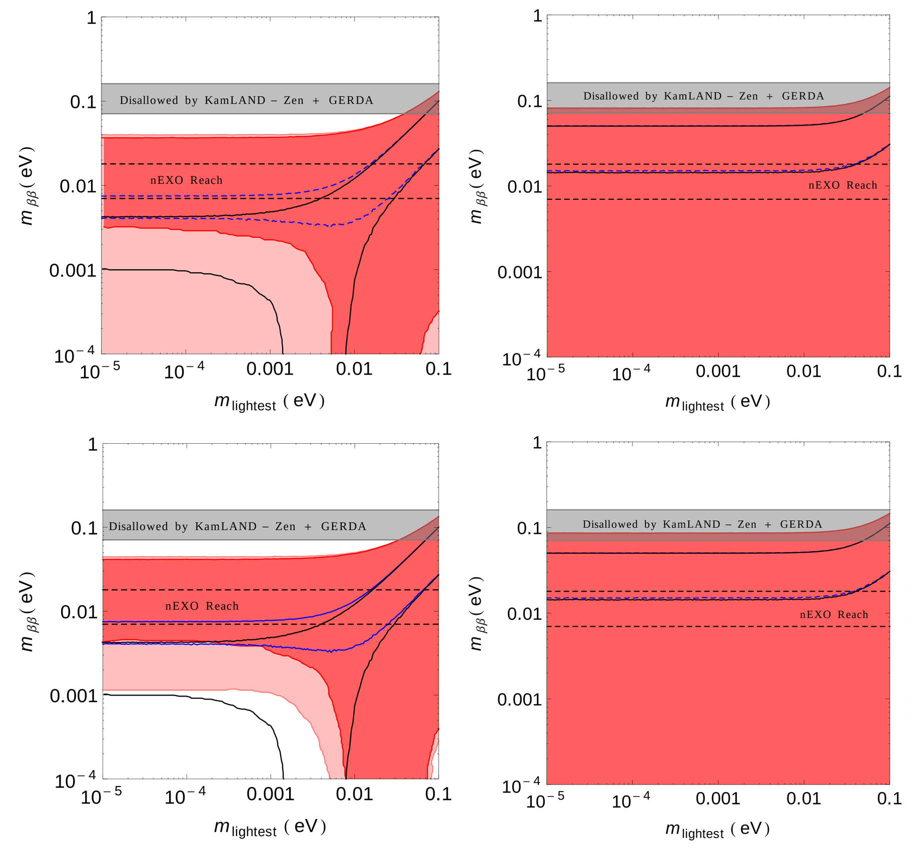

Figure 2: $m_{\beta\beta}$ vs $m_{lightest}$ for NH (left) and IH (right) for $\Delta m^2_{LSND} = 1.3\text{eV}^2$&$1.7\text{eV}^2$. The pink and the red regions represent the predictions for the standard LMA as well as the DLMA solutions for θ_{12} respectively. The gray shaded region represents the current upper bound of $m_{\beta\beta}$ obtained from the combined results of KamLAND-Zen and GERDA experiments and the band defined by the two horizontal black dashed lines represents the future 3σ sensitivity of the nEXO experiment. The black solid lines and the blue dotted lines represent the predictions with the standard three neutrino case for the standard LMA and the DLMA solutions respectively.(arXiv:1909.09434)

Sensitivity in the future experiments

The value of $T_{1/2}$ for which an experiment has a 50% probability of measuring a 3σ signal above the background is defined as the 3σ discovery sensitivity of $T_{1/2}$. It is given as (arXiv:1705.02996),

$$T_{1/2} = \ln2\frac{N_A\epsilon}{m_aS_{3\sigma}(B)} \quad (11)$$

$S_{3\sigma}$ can be obtained from the equation, $1 - CDF_{Poisson}(C_{3\sigma}|S_{3\sigma} + B) = 50\%$. $C_{3\sigma}$ stands for the number of counts for which the cumulative Poisson distribution with mean as B obeys, $CDF_{Poisson}(C_{3\sigma}|B) = 3\sigma$. We use the normalized upper incomplete gamma function to define $CDF_{Poisson}$ as a continuous distribution in C as follows, $CDF_{Poisson}(C|\mu) = \frac{\Gamma(C+1,\mu)}{\Gamma(C+1)}$.

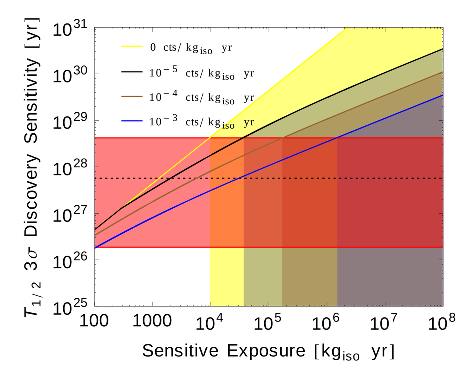

Figure 3: ^{136}Xe discovery sensitivity as a function of sensitive exposure for different sensitive background levels. The yellow, black, brown and blue lines correspond to four different values of the sensitive background levels as shown in the figure.

Isotope	NME (M_ν)	$G(10^{-15}\text{year}^{-1}$	$T_{1/2}$(years)
^{136}Xe	$1.6-4.8$	14.58	$1.87\times10^{26}-4.20\times10^{28}$
^{76}Ge	$2.8-6.1$	2.363	$7.13\times10^{26}-8.47\times10^{28}$
^{130}Te	$1.4-6.4$	14.22	$1.08\times10^{26}-5.63\times10^{28}$

Conclusions

- In the case of IH, the prediction of $m_{\beta\beta}$ remains same for both LMA and DLMA solutions and this is true for both the three as well as four generation.
- These predictions are independent of the values of Δm^2_{LSND}.
- Complete cancellation of $m_{\beta\beta}$ can occur for the entire range of m_3 in the presence of the fourth sterile neutrino, unlike in the three generation case where there is no cancellation region for IH at all. The maximum predicted values for $m_{\beta\beta}$ are higher in the case of four generation.
- Even the non observation of a positive signal for $0\nu\beta\beta$ in the future nEXO experiment will rule out the IH scenario in the case of three generation (arXiv:1901.04313), it can still be allowed in the presence of the fourth sterile neutrino for both LMA and DLMA.
- For NH, complete cancellation can occur for certain values of m_1 for both the standard LMA as well as the DLMA solutions in the four generation case whereas for the three generation case, there is no cancellation region for the DLMA solution.
- The values of $m_{lightest}$ for which complete cancellation of $m_{\beta\beta}$ occurs is larger for the DLMA solution.
- There is more cancellation region for $\Delta m^2_{LSND} = 1.3$ eV^2 compared to that for $\Delta m^2_{LSND} = 1.7$ eV^2. For $\Delta m^2_{LSND} = 1.3$ eV^2 with the standard LMA solution, cancellation is possible in the entire range of $m_{lightest}$. But for the DLMA solution cancellation is possible only for higher values of $m_{lightest}$.
- for the sterile neutrino scenario, there is no desert region between NH and IH unlike in the standard three generation picture. This is true for both LMA and DLMA solutions.
- The prediction of $m_{\beta\beta}$ for three neutrino DLMA picture is in the range (0.004-0.0075) eV while for the sterile DLMA(and LMA) this spans (0.004 - .04) eV (for $m_{lightest} \lesssim 0.005$ eV) for NH. The new allowed region of 0.0075-0.04 eV in the case of NH with four generation is in the complete reach of the future nEXO experiment.