Non-Standard Interaction of Solar Neutrinos in Dark Matter Detectors

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Outline

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    - Transition probability of solar neutrino
    - Current constrains
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    - Oscillation effects
3. Future work and conclusion
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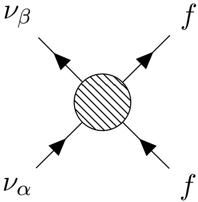
Non-standard interactions of neutrinos

General four fermion interaction:

$$\mathcal{L}_{int} = 2\sqrt{2}G_F\bar{\nu}_{\alpha L}\gamma^{\mu}\nu_{\beta L}\left(\epsilon^{fL}_{\alpha\beta}\bar{f}_L\gamma_{\mu}f_L + \epsilon^{fR}_{\alpha\beta}\bar{f}_R\gamma_{\mu}f_R\right)$$



$= SM + BSM$

Differential cross section

Differential cross section of $\nu_\beta + f \to \nu_\alpha + f$ as a function of recoil energy E_r:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} = \frac{2}{\pi} G_F^2 m_f \times \left[\left|\epsilon_{\alpha\beta}^{fL}\right|^2 + \left|\epsilon_{\alpha\beta}^{fR}\right|^2 \left(1 - \frac{E_r}{E_\nu}\right)^2 - \frac{1}{2}\left(\epsilon_{\alpha\beta}^{fL*}\epsilon_{\alpha\beta}^{fR} + \epsilon_{\alpha\beta}^{fL}\epsilon_{\alpha\beta}^{fR*}\right)\frac{m_f E_r}{E_\nu^2}\right]$$

Cross section on nucleus

$$\epsilon^{L}_{\alpha\alpha} \to \frac{1}{2} Z \epsilon^{pV}_{\alpha\alpha} + \frac{1}{2}\left(Z_{+} - Z_{-}\right)\epsilon^{pA}_{\alpha\alpha} + \frac{1}{2} N \epsilon^{nV}_{\alpha\alpha} + \frac{1}{2}\left(N_{+} - N_{-}\right)\epsilon^{nA}_{\alpha\alpha}$$

$$\epsilon^{R}_{\alpha\alpha} \to \frac{1}{2} Z \epsilon^{pV}_{\alpha\alpha} - \frac{1}{2}\left(Z_{+} - Z_{-}\right)\epsilon^{pA}_{\alpha\alpha} + \frac{1}{2} N \epsilon^{nV}_{\alpha\alpha} - \frac{1}{2}\left(N_{+} - N_{-}\right)\epsilon^{nA}_{\alpha\alpha}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \to \frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \times F^2\left(Q^2\right)$$

$$\epsilon^{pV}_{\alpha\alpha} = \frac{1}{2} - 2\sin^2\theta_w + 2\epsilon^{uV}_{\alpha\alpha} + \epsilon^{dV}_{\alpha\alpha}$$

$$\epsilon^{pA}_{\alpha\alpha} = \frac{1}{2} + 2\epsilon^{uA}_{\alpha\alpha} + \epsilon^{dA}_{\alpha\alpha}$$

$$\epsilon^{nV}_{\alpha\alpha} = -\frac{1}{2} + \epsilon^{uV}_{\alpha\alpha} + 2\epsilon^{dV}_{\alpha\alpha}$$

$$\epsilon^{pA}_{\alpha\alpha} = -\frac{1}{2} + \epsilon^{uA}_{\alpha\alpha} + 2\epsilon^{dA}_{\alpha\alpha}$$

Transition probability of solar neutrino

The propagation of neutrino is described by:

$$\mathcal{H}_{\beta\alpha} = \left[U \mathrm{diag}\left(0, \frac{\Delta m_{21}^2}{2E}, \frac{\Delta m_{31}^2}{2E}\right) U^\dagger \right]_{\beta\alpha} + \sqrt{2} G_F \sum_f n_f \left(\delta^{ef} \delta_{e\alpha} + \epsilon_{\beta\alpha}^f \right)$$

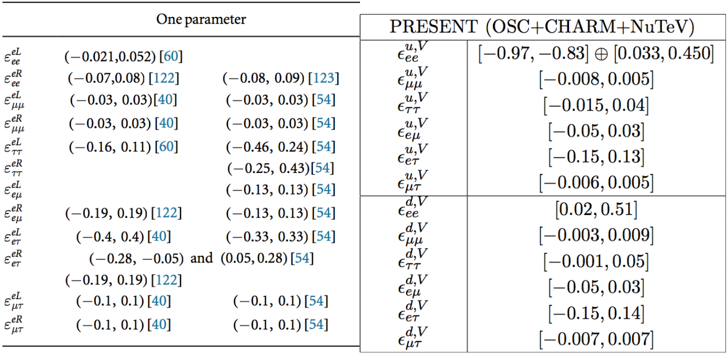
U: mixing matrix, $\Delta m_{ij}^2 = m_i^2 - m_j^2$, n_f: number density of fermion f.

Neutrino propagates through the sun adiabatically (diagonalize $\mathcal{H}$ into $\tilde{U} diag \tilde{U}^\dagger$):

$$P_{\beta\to\alpha} = \left|\tilde{U}\left(t\right)_{\alpha k}\right|^2 \left|A_{jk}^1\right|^2 \left|A_{ij}^2\right|^2 \left|\tilde{U}\left(0\right)_{\beta i}\right|^2$$

A: transition probability between mass eigenstate when resonance happens.

Current constraints



	One parameter	
ε_{ee}^{eL}	(−0.021,0.052) [60]	
ε_{ee}^{eR}	(−0.07,0.08) [122]	(−0.08, 0.09) [123]
$\varepsilon_{\mu\mu}^{eL}$	(−0.03, 0.03)[40]	(−0.03, 0.03) [54]
$\varepsilon_{\mu\mu}^{eR}$	(−0.03, 0.03) [40]	(−0.03, 0.03) [54]
$\varepsilon_{\tau\tau}^{eL}$	(−0.16, 0.11) [60]	(−0.46, 0.24) [54]
$\varepsilon_{\tau\tau}^{eR}$		(−0.25, 0.43)[54]
$\varepsilon_{e\mu}^{eL}$		(−0.13, 0.13) [54]
$\varepsilon_{e\mu}^{eR}$	(−0.19, 0.19) [122]	(−0.13, 0.13) [54]
$\varepsilon_{e\tau}^{eL}$	(−0.4, 0.4) [40]	(−0.33, 0.33) [54]
$\varepsilon_{e\tau}^{eR}$	(−0.28, −0.05) and (0.05, 0.28) [54] (−0.19, 0.19) [122]	
$\varepsilon_{\mu\tau}^{eL}$	(−0.1, 0.1) [40]	(−0.1, 0.1) [54]
$\varepsilon_{\mu\tau}^{eR}$	(−0.1, 0.1) [40]	(−0.1, 0.1) [54]

PRESENT (OSC+CHARM+NuTeV)	
$\epsilon_{ee}^{u,V}$	$[-0.97, -0.83] \oplus [0.033, 0.450]$
$\epsilon_{\mu\mu}^{u,V}$	$[-0.008, 0.005]$
$\epsilon_{\tau\tau}^{u,V}$	$[-0.015, 0.04]$
$\epsilon_{e\mu}^{u,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.13]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.006, 0.005]$
$\epsilon_{ee}^{d,V}$	$[0.02, 0.51]$
$\epsilon_{\mu\mu}^{d,V}$	$[-0.003, 0.009]$
$\epsilon_{\tau\tau}^{d,V}$	$[-0.001, 0.05]$
$\epsilon_{e\mu}^{d,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{d,V}$	$[-0.15, 0.14]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.007, 0.007]$

(a) Gonzalez-Garcia et al, arXiv:1307.3092

(b) Coloma et al, arXiv:1701.04828

Figure: Current constraints

Electron scattering $\nu_\beta + e \rightarrow \nu_\alpha + e$

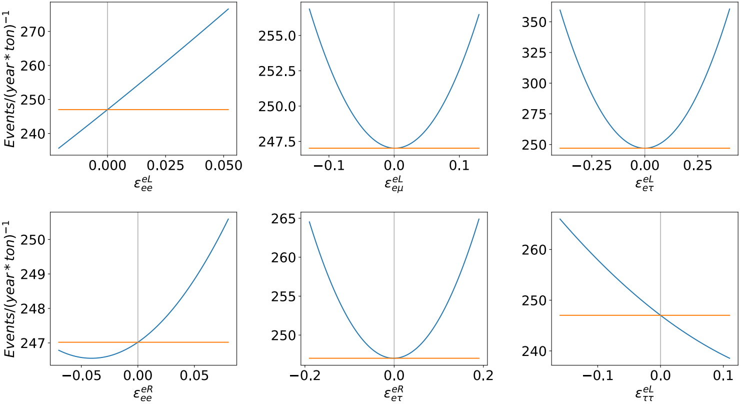


Figure: Number of events above an equivalent electron recoil energy threshold of 1 keV as each ϵ varies over its allowable range (blue curves). Orange curve: SM contribution.

Nucleus scattering $\nu_\beta + N \rightarrow \nu_\alpha + N$

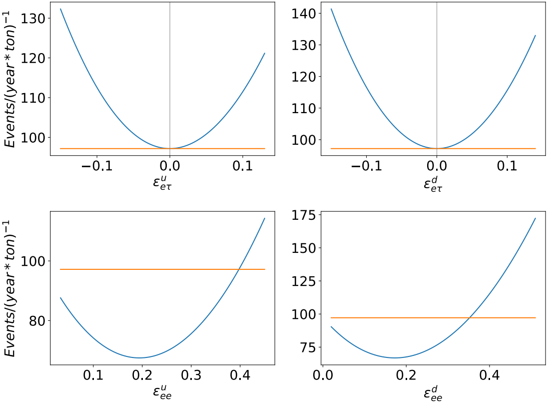


Figure: Number of events above an equivalent nucleus recoil energy threshold of 1 keV as each ε varies over its allowable range (blue curves). Orange curve: SM contribution.

LMA-Dark solution

$$\theta_{12} \to \frac{\pi}{2} - \theta_{12}$$

$$\theta_{13} \to \pi - \theta_{13}$$

$$\delta \to \pi - \delta$$

$$\Delta m^2_{31} \to -\Delta m^2_{32}$$

$$\epsilon \to -\epsilon^*$$

$$H \to -H^*$$

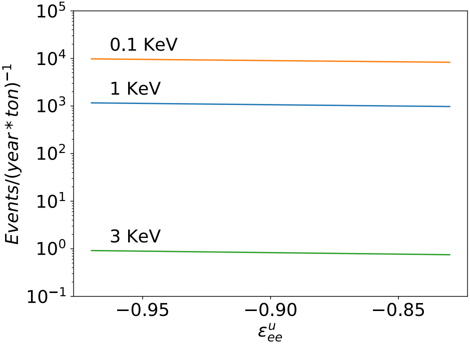


Figure: Number of events for LMA-d solution with different threshold energies.

Threshold

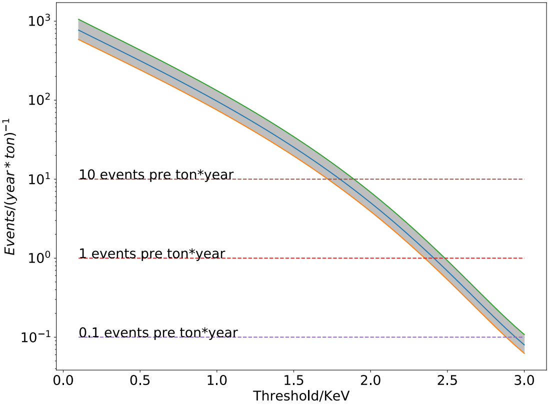


Figure: Number of events with different threshold energies.

Oscillation vs. no oscillation

	$\epsilon_{ee}^{eL} = 0.052$	$\epsilon_{ee}^{u} = 0.2$	$\epsilon_{ee}^{d} = 0.17$
$U\Delta m U^\dagger + \sqrt{2}G_f\text{diag}\,(1,0,0) + \sqrt{2}G_f\epsilon$	1.10	0.69	0.69
$U\Delta m U^\dagger + \sqrt{2}G_f\text{diag}\,(1,0,0) +$ ~~$\sqrt{2}G_f\epsilon$~~	1.12	0.67	0.67
$U\Delta m U^\dagger +$ ~~$\sqrt{2}G_f\text{diag}\,(1,0,0) + \sqrt{2}G_f\epsilon$~~	1.13	0.44	0.44
~~$U\Delta m U^\dagger + \sqrt{2}G_f\text{diag}\,(1,0,0) + \sqrt{2}G_f\epsilon$~~	1.72	3.88×10^{-5}	1.18×10^{-3}

Table: Ratio to only SM prediction N/N_{SM}

Survival probability due to NSI

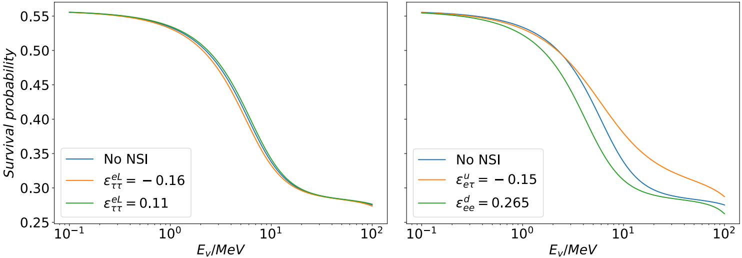


Figure: Electron neutrino survival probability for the SM (blue) compared to cases in of NSI.

Oscillations

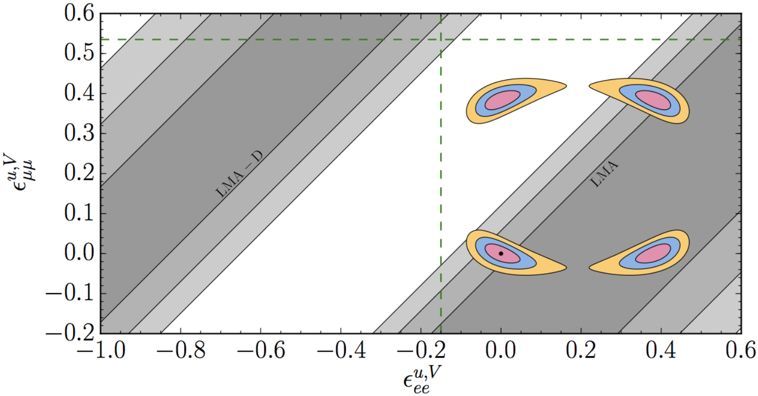
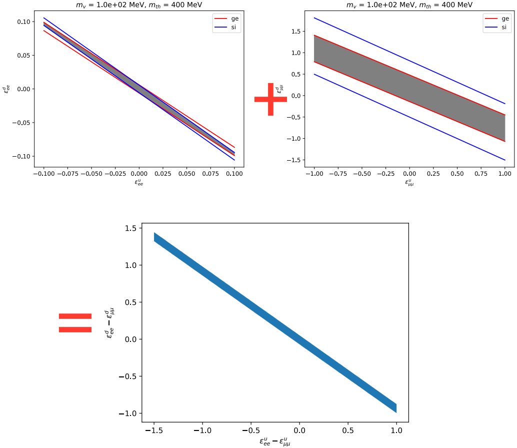


Figure: Oscillation experiment can only detect $\epsilon_{ee} - \epsilon_{\mu\mu}$, Coloma et al. 2017

Complementarity of various experiments

Reactor + SNS + Solar-DM = constraints on $\epsilon_{ee} - \epsilon_{\mu\mu}$? u and d degeneracy?



Conclusion

1. Direct dark matter searches are able to probe NSI parameter space that cannot be probed by current neutrino experiments.
    1. A low threshold detector is more likely to be able to observe significant number of events
    2. Due to interference between SM and BSM, number of observed events can be lower than SM expectations.
2. Uncertainties of additional NSI parameters will not only affect the detection side, but also affect the solar neutrino flux.