New Physics & (vector, scalar, dark) NSI's

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SFG, Stephen J. Parke, Phys.Rev.Lett. 122 (2019) no.21, 211801 [arXiv:1812.08376]

SFG, Hitoshi Murayama [arXiv:1904.02518]

Neutrino Oscillation = Mass + Interaction

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Neutrino oscillations in matter

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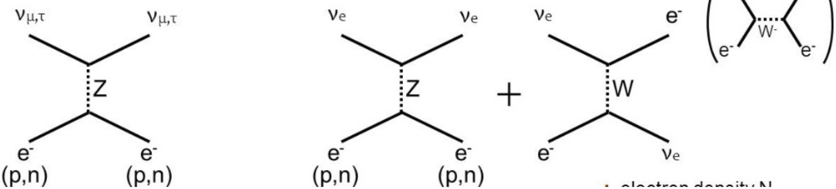
The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

$$\mathcal{H} = \frac{\mathbf{M}\mathbf{M}^\dagger}{2E_\nu} \pm \mathbf{V}\,.$$

muon, tau neutrinos

electron neutrinos

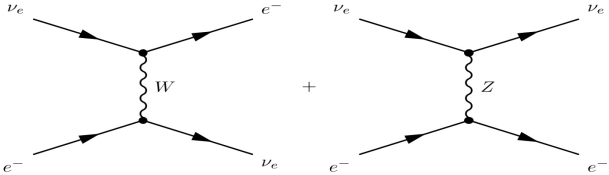


Fierz Transformation for Unifying CC & NC

- Using **Fierz transformation**, the effective Lagrangian becomes

$$\mathcal{L}^{\rm eff}_{\rm cc} = \frac{g_{\alpha\rho} g^*_{\beta\sigma}}{2} \frac{1}{q^2_V - m^2_V} \left(\overline{\nu_\alpha} \gamma_\mu P_L \nu_\beta\right) \left(\overline{\ell}_\sigma \gamma^\mu P_L \ell_\rho\right) ,$$

which can account for both **charged & neutral currents**



- **The matter potential is defined by not just Lagrangian, but also external states!** When expanding $\boxed{\langle out | \mathcal{S} \equiv e^{-i \int \mathcal{L}^{\rm eff}_{\rm cc}} | in \rangle}$ to leading order

$$\boldsymbol{\delta\Gamma_{\alpha\beta}} = -\langle \nu_\alpha e | \mathcal{L}^{\rm cc}_{\rm eff} | \nu_\beta e \rangle , \qquad \boldsymbol{\delta\overline{\Gamma}_{\alpha\beta}} = -\langle \bar\nu_\alpha e | \mathcal{L}^{\rm cc}_{\rm eff} | \bar\nu_\beta e \rangle ,$$

for **neutrino** & **anti-neutrino** modes.

Forward Scattering & Effective Lagrangian

- **Standard Model Lagrangian**

$$\mathcal{L}_{cc} = \frac{\mathbf{g}_{\alpha\rho}}{\sqrt{2}} V^+_\mu \bar{\nu}_\alpha \gamma^\mu P_L \ell_\rho + h.c.$$

To be general, let's keep **non-universal couplings $\mathbf{g}_{\alpha\rho}$**.

- The **effective Lagrangian** for **forward scattering without momentum transfer**

$$\mathcal{L}^{\rm eff}_{cc} = \frac{\mathbf{g}_{\alpha\rho}\mathbf{g}^*_{\beta\sigma}}{2} \frac{\mathbf{1}}{-\mathbf{m}^2_{\mathbf{V}}} \left(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\rho\right) \left(\bar{\ell}_\sigma \gamma_\mu P_L \nu_\beta\right) ,$$

where $\boxed{\frac{\mathbf{1}}{\mathbf{q}^2_{\mathbf{V}} - \mathbf{m}^2_{\mathbf{V}}} = \frac{\mathbf{1}}{-\mathbf{m}^2_{\mathbf{V}}}}$ from the V propagator with **vanishing $\mathbf{q}_{\mathbf{V}}$**.

It seems like effective operator, but not really!

Dispersion Relation & Effective Hamiltonian

- **Dispersion Relation** **Only γ_0 term survives!**

$$(E \pm \mathbf{V})^2 = \vec{p}^2 + \mathbf{MM}^\dagger$$

- **Effective Hamiltonian**

$$\mathcal{H} = \sqrt{\vec{p}^2 + \mathbf{MM}^\dagger} \pm \mathbf{V} \approx |\vec{p}| + \frac{\mathbf{MM}^\dagger}{2E} \pm \mathbf{V}$$

Since the **leading term is universal**, it would not affect neutrino oscillation and hence can be omitted. The neutrino oscillation is determined by the **effective Hamiltonian**

$$\mathcal{H}_{\rm eff} = \frac{\mathbf{MM}^\dagger}{2E} \pm \mathbf{V}$$

Note that neutrino oscillation is described by $\mathcal{H}_{\rm eff}$ but the anti-neutrino one by $\mathcal{H}^*_{\rm eff}$. Since the neutrino energy E is a constant, it is equivalent to use $\mathbf{2E}\mathcal{H}$ for describing neutrino oscillation.

Neutrino Oscillation in Absence of Mass Term

In this paper we show that even if all neutrinos are massless it is possible to have oscillations occur when neutrinos pass through matter. This can happen as a result of coherent forward scattering provided that this scattering is partially off diagonal in neutrino type. The phenomenon is analogous to the regeneration of K_S from a K_L beam passing through matter, A simple model is given in Sec. II from which it is seen that the oscillation length in matter of normal density is of the order 10^9 cm or larger. One of the proposed ex-

$$\sin^2\left(\frac{\delta m_{ij}^2 L}{4E_\nu}\right) \to \sin^2\left(\frac{1}{2}VL\right)$$

Wolfenstein 78'

Standard & Non-Standard Interactions

- **Effective Hamiltonian**

$$\mathcal{H}_{\rm eff} = \frac{\mathbf{M}\mathbf{M}^\dagger}{2E} \pm \mathbf{V} = \frac{\mathbf{M}\mathbf{M}^\dagger}{2E} \pm \mathbf{V}_{\rm SI} \pm \mathbf{V}_{\rm NSI}$$

- **Standard Interactions**

$$\mathbf{V}_{\rm SI} = \mathbf{V}_{\rm cc} \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} + \mathbf{V}_{\rm nc} \mathbb{I}_{3\times 3}$$

- **Non-Standard Interactions**

$$\mathbf{V}_{\rm NSI} = \mathbf{V}_{\rm cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

In the same way as Standard Interactions through **vector boson mediation**.

NSI already appeared in Wolfenstein 78' Paper

$$H_w = \frac{G}{\sqrt{2}} L_\lambda J_\lambda , \tag{1}$$

$$L_\lambda = \cos^2\alpha[\overline{\nu}_a\gamma_\lambda(1+\gamma_5)\nu_a + \overline{\nu}_b\gamma_\lambda(1+\gamma_5)\nu_b] + \sin^2\alpha[\overline{\nu}_a\gamma_\lambda(1+\gamma_5)\nu_b + \overline{\nu}_b\gamma_\lambda(1+\gamma_5)\nu_a] , \tag{2a}$$

$$J_\lambda = g_p \overline{p}\gamma_\lambda p + g_n \overline{n}\gamma_\lambda n + \overline{g}_e \overline{e}\gamma_\lambda e + \cdots , \tag{2b}$$

where the ellipses represent terms in J_λ of no interest for our present considerations. The essential term in H_w is the off-diagonal term proportional to $\sin^2\alpha$, where ν_a and ν_b are neutrino types defined by the charged-current interaction. We have also assumed $\nu_a - \nu_b$ symmetry, which simplifies the discussion and maximizes the effect of interest.

Extra New Physics from Scalar NSI

- **Vector NSI**

$$\mathcal{L}_{\rm cc}^{\rm eff} = \frac{g_{\alpha\rho} g^*_{\beta\sigma}}{2} \frac{1}{-m_V^2} \left(\overline{\nu_\alpha} \gamma_\mu P_L \nu_\beta\right) \left(\bar{\ell}_\sigma \gamma^\mu P_L \ell_\rho\right) ,$$

which is **vector-vector type vertex**.

- **Scalar Mediator**

$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + Y_{\alpha\beta} \phi \bar{f}_\alpha f_\beta + h.c. ,$$

Due to **forward scattering**, the **effective Lagrangian** is

$$\mathcal{L}_{\rm eff}^s \propto y_{\alpha\beta} Y_{ee} \left[\bar{\nu}_\alpha(p_3) \nu_\beta(p_2)\right] \left[\bar{e}(p_1) e(p_4)\right] ,$$

which is a **scalar-scalar type vertex** $\Rightarrow$ **significant phenomenological consequences**.

SFG, Stephen J. Parke, Phys.Rev.Lett. 122 (2019) no.21, 211801 [arXiv:1812.08376]

EOM & Effective Hamiltonian with Scalar NSI

- **Two-Point Correlation Function**

$$\delta\Gamma_S = \frac{y_{\alpha'\beta'} y_{ee}}{m_\phi^2} \langle \nu_\alpha | \bar{\nu}_{\alpha'} \nu_{\beta'} | \nu_\beta \rangle \langle e | \bar{e} e | e \rangle \,,$$

$$\delta\bar{\Gamma}_S = \frac{y_{\beta'\alpha'} y_{ee}}{m_\phi^2} \langle \bar{\nu}_\alpha | \bar{\nu}_{\alpha'} \nu_{\beta'} | \bar{\nu}_\beta \rangle \langle e | \bar{e} e | e \rangle \,.$$

- **Equation of Motion**

$$\bar{\nu}_\beta \left[i\partial_\mu \gamma^\mu + \left(M_{\beta\alpha} + \frac{\mathbf{n_e y_e Y}_{\alpha\beta}}{\mathbf{m}_\phi^2} \right) \right] \nu_\alpha = 0 \,,$$

- **Effective Hamiltonian**

$$\mathcal{H} \approx E_\nu + \frac{(M + \mathbf{M_S})(M + \mathbf{M_S})^\dagger}{2E_\nu} \pm V_{\mathrm{SI}} \,,$$

Mass Scale & Unphysical CP Phases in Oscillation

- The **effective mass term** is a combination

$$\mathbf{M}\mathbf{M}^\dagger \to (\mathbf{M} + \mathbf{M_S})(\mathbf{M} + \mathbf{M_S})^\dagger = \mathbf{M}\mathbf{M}^\dagger + \mathbf{M}\mathbf{M_S}^\dagger + \mathbf{M_S}\mathbf{M}^\dagger + \mathbf{M_S}\mathbf{M_S}^\dagger$$

- The **absolute neutrino mass** can enter neutrino oscillation!

$$\mathbf{M}\mathbf{M_S}^\dagger + \mathbf{M_S}\mathbf{M}^\dagger$$

- The **unphysical CP phases** can also enter neutrino oscillation!

$$M \equiv R_\nu D_\nu R_\nu^\dagger \quad \& \quad R_\nu \equiv P_\nu U_\nu Q_\nu$$

The **Majorana rephasing matrice** $Q_\nu = \{e^{i\delta_{\rm M1}/2}, 1, e^{i\delta_{\rm M3}/2}\}$ can be absorbed, $Q_\nu D_\nu Q_\nu^\dagger = D_\nu$ while the **unphysical rephasing matrix** $P_\nu \equiv \{e^{i\alpha}, e^{i\beta}, e^{i\gamma}\}$ can not be simply rotated away now:

$$M \to \widetilde{\mathbf{M}} = \mathbf{U}_\nu \mathbf{D}_\nu \mathbf{U}_\nu^\dagger\,, \qquad M_S \to \widetilde{\mathbf{M}}_\mathbf{S} = \mathbf{P}_\nu^\dagger \mathbf{M_S} \mathbf{P}_\nu$$

Parametrization & Constant Density Subtraction

- Use **characteristic scale Δm_a^2** to parametrize scalar NSI

$$\widetilde{M}_S \equiv \sqrt{\Delta m_a^2} \begin{pmatrix} \eta_{ee} & \eta_{\mu e}^* & \eta_{\tau e}^* \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\tau\mu}^* \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix},$$

  where $\Delta m_a^2 \equiv \Delta m_{31}^2 = 2.7 \times 10^{-3}\,\text{eV}^2$.

- We first need **input** for $\widetilde{M}$ which is not directly measured.

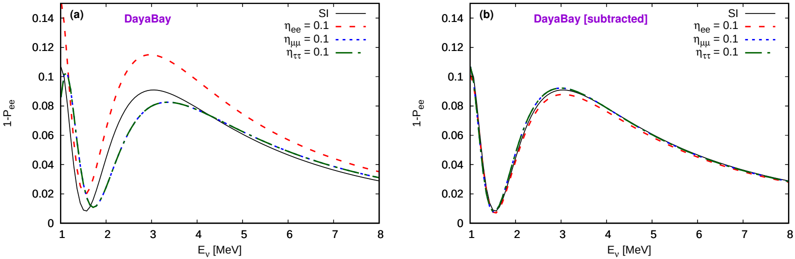
- However, the one directly measured from terrestial experiments is always a combination, $\widetilde{M} + \widetilde{M}_S(\rho_s \approx 3\text{g/cm}^3)$. It is then necessary to first substract a constant term:

$$\widetilde{M} \to \widetilde{M} + \widetilde{M}_S \frac{\rho - \rho_s}{\rho_s}$$

  where $\widetilde{M} = U_\nu D_\nu U_\nu^\dagger$ is **reconstructed** in terms of the measured mixing matrix while $\widetilde{M}_S$ is the scalar NSI @ typical constant **subtraction density ρ_s**.

Density Subtraction for Reactor Anti-Neutrinos

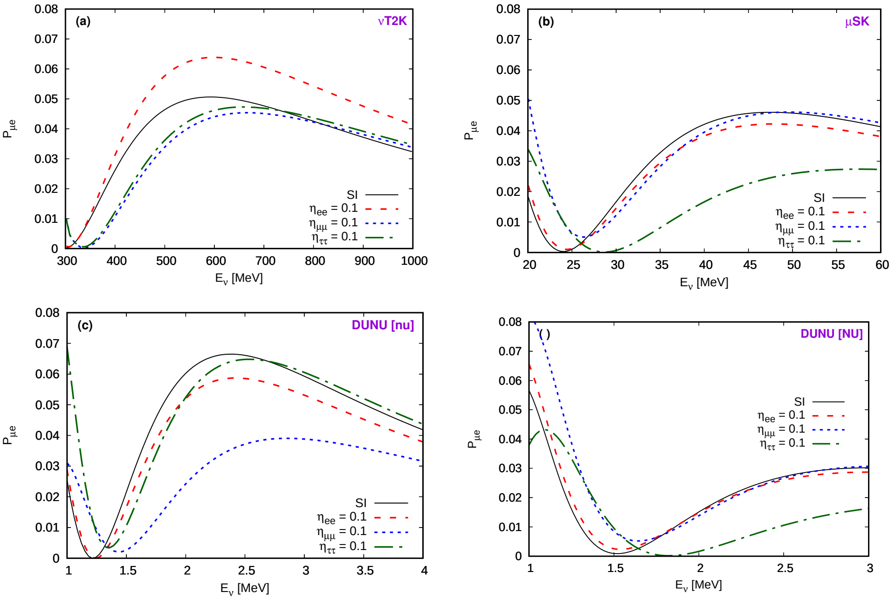
- Since the reactor anti-neutrino experiments (**Daya Bay** & **JUNO**) are the most precise ones, we do substraction according to them:



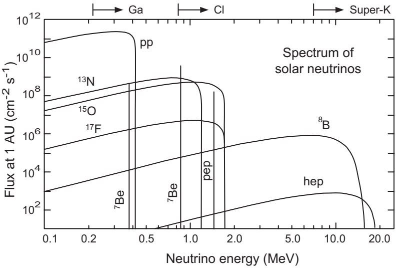
$$\widetilde{M} \to \widetilde{M} + \widetilde{\mathbf{M}}_{\mathbf{S}} \frac{\rho - \rho_{\mathbf{s}}}{\rho_{\mathbf{s}}}$$

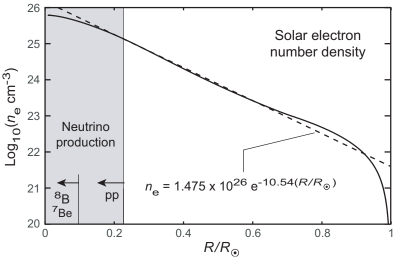
- Then **no constraint** on **scalar NSI** from reactor experiments!

Scalar NSI @ Accelerator Neutrino: TNT2K

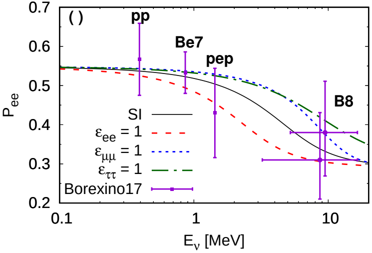


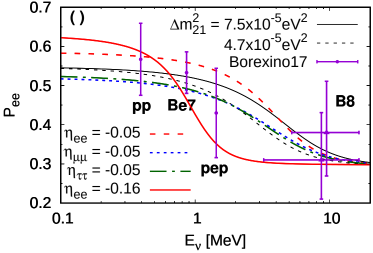
Scalar NSI @ Solar Neutrino Oscillation



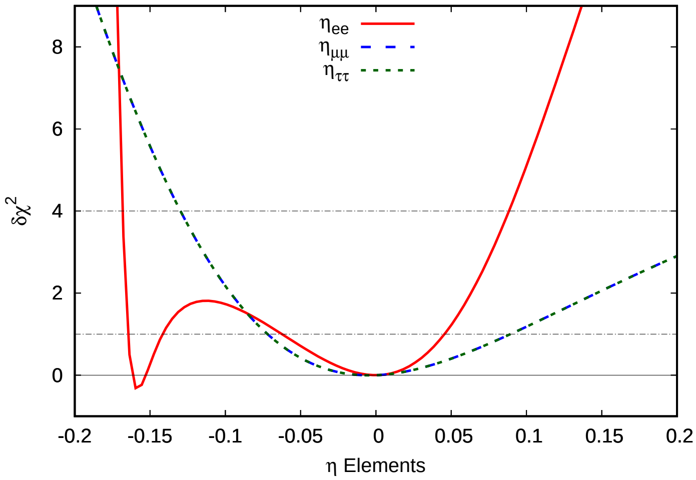


$$P_{ee}^{\rm sun} = \left| U_{ei}^{\rm prod} (U_{ei}^{\rm vac})^* \right|^2$$





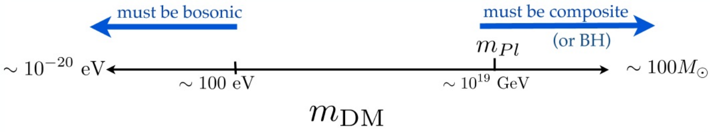
Fitting the Borexino 2017 Data



Light Dark Matter

SFG, Hitoshi Murayama [arXiv:1904.02518]

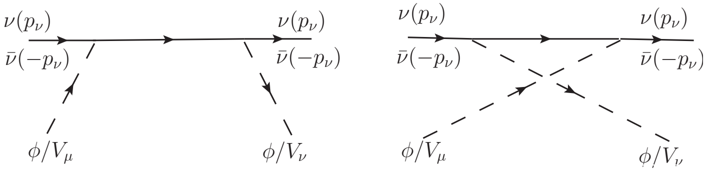
- **The DM mass can span almost 100 orders**



- For **light bosonic DM**

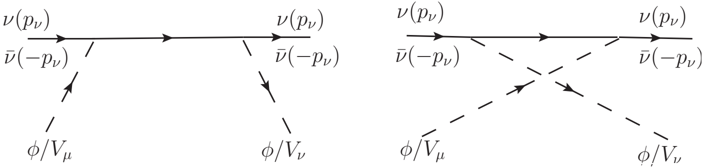
$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + h.c.,$$

leading to **forward scattering**



Effective Mass Correction from Dark Matter

- The **forward scattering** with the **DM background**



- modifies the neutrino **kinetic term**

$$i\delta\Gamma_{\alpha\beta} = \frac{i\rho_\phi(\mathbf{v}_\phi)}{m_\phi^2}\sum_j y_{\alpha j} y^*_{j\beta}\left[\frac{\not{p}_\nu + \not{\mathbf{p}}_\phi + m_\nu}{p_\phi^2 + 2\mathbf{p}_\nu\cdot\mathbf{p}_\phi} + \frac{\not{p}_\nu - \not{\mathbf{p}}_\phi + m_\nu}{p_\phi^2 - 2\mathbf{p}_\nu\cdot\mathbf{p}_\phi}\right]$$

with $\mathbf{p}_\phi \sim \mathbf{m}_\phi(\mathbf{1}, \tilde{\mathbf{v}}_\phi)$, the correction

$$\boldsymbol{\delta\Gamma}_{\alpha\beta} \approx \sum_j y_{\alpha j} y^*_{j\beta}\frac{\rho_\chi}{m_\phi^2 \mathbf{E}_\nu}\gamma_0$$

appears as **dark potential**.

SFG, Hitoshi Murayama [arXiv:1904.02518]

Dark NSI

SFG, Hitoshi Murayama [arXiv:1904.02518]

- The **dark potential**

$$\delta\Gamma_{\alpha\beta} \approx \sum_j y_{\alpha j} y^*_{j\beta} \frac{\rho_\chi}{m^2_\phi \mathbf{E}_\nu} \gamma_0$$

is a correction to the Hamiltonian, same as the matter potential.

- Due to $1/E_\nu$ **dependence**, the **dark potential** is promoted to mass correction

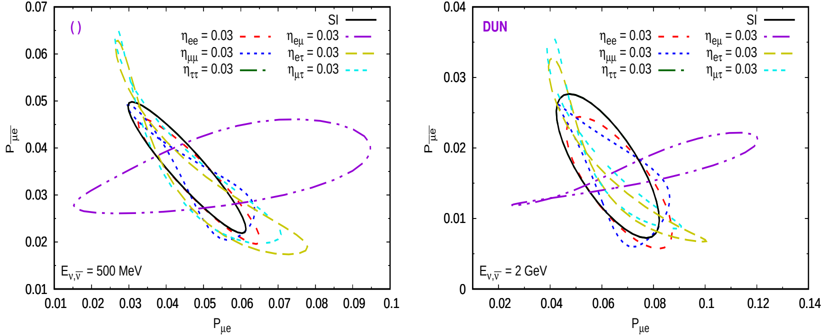
$$H = \frac{M^2}{2E_\nu} - \frac{1}{\mathbf{E}_\nu} \sum_j y_{\alpha j} y^*_{j\beta} \frac{\rho_\chi}{m^2_\phi} \equiv \frac{M^2 + \delta \mathbf{M}^2}{2\mathbf{E}_\nu}$$

which is totally different from the scalar NSI.

- **With mass term correction, any neutrino oscillation cannot see the original variables. Neutrino oscillation can happen even if the original mass term M^2 vanishes.**

Dark NSI & Faked CP

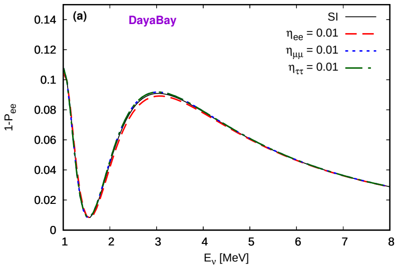
- With just 3% of dark NSI

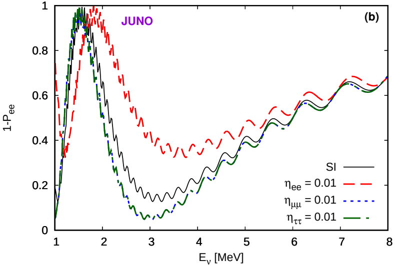


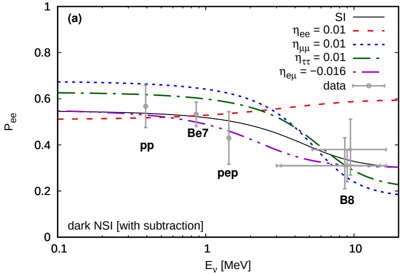
- The biprobability contour can totally change.

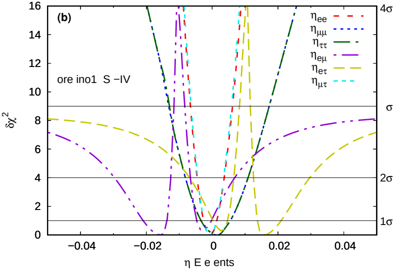
SFG, Hitoshi Murayama [arXiv:1904.02518]

Dark NSI @ Low Energy Exps









SFG, Hitoshi Murayama [arXiv:1904.02518]

Summary

- **Neutrino oscillation** = **Mass** + **Interaction**
  - **Mass** → **vacuum mixing & oscillation**
  - **Interaction** → **matter effect**
- **Both are important**
  - **Yukawa** coupling → **Mass**
  - **Gauge** coupling → **Interaction**
- **Crossing & Hybrid** of the two → **scalar NSI**
  - Appears as **NSI**, but contribute as **mass term correction**.
  - The effect of scalar NSI is **not suppressed by neutrino energy**.
  - Can completely **disguise the original oscillation parameters**.
  - Neutrino **mass scale** & **unphysical CP phases** can enter oscillation.
  - **Matter density variation** can help to identify scalar NSI;
- **Dark NSI** – Scalar NSI is not alone!

$$\mathcal{H} = \frac{(M + \mathbf{M_S})(M + \mathbf{M_S})^\dagger + \delta\mathbf{M}^2}{2E_\nu} + V_{\rm SI} + \mathbf{V}_{\rm NSI}$$

The scalar or dark NSI can fake the neutrino mass term!

Thank You!

Sign Difference between Neutrino & Anti-Neutrino

- Altogether

$$\delta\Gamma_{\alpha\beta} \propto \langle 0|a_\alpha(a^\dagger_{\alpha'}\bar{u}_{\alpha'} + b_{\alpha'}\bar{v}_{\alpha'})\gamma_\mu P_L(a_{\beta'}u_{\beta'} + b^\dagger_{\beta'}v_{\beta'})a^\dagger_\beta|0\rangle$$

$$= \langle 0|\underbrace{a_\alpha a^\dagger_{\alpha'}}\bar{u}_{\alpha'}\gamma_\mu P_L \underbrace{a_{\beta'}u_{\beta'}a^\dagger_\beta}|0\rangle ,$$

$$\delta\overline{\Gamma}_{\alpha\beta} \propto \langle 0|b_\alpha(a^\dagger_{\alpha'}\bar{u}_{\alpha'} + b_{\alpha'}\bar{v}_{\alpha'})\gamma_\mu P_L(a_{\beta'}u_{\beta'} + b^\dagger_{\beta'}v_{\beta'})b^\dagger_\beta|0\rangle$$

$$= \langle 0|b_\alpha b_{\alpha'}\bar{v}_{\alpha'}\gamma_\mu P_L b^\dagger_{\beta'}v_{\beta'}b^\dagger_\beta|0\rangle .$$

- **0** permutation for **neutrino** vs **1** permutation for **anti-neutrino**

$$\delta\Gamma_{\alpha\beta} = +\frac{g_{\alpha e}g^*_{\beta e}}{2m_V^2}(\bar{u}_\alpha\gamma_\mu P_L u_\beta)\langle e|\bar{e}\gamma_\mu P_L e|e\rangle ,$$

$$\delta\overline{\Gamma}_{\alpha\beta} = -\frac{g_{\beta e}g^*_{\alpha e}}{2m_V^2}(\bar{v}_\beta\gamma_\mu P_L v_\alpha)\langle e|\bar{e}\gamma_\mu P_L e|e\rangle ,$$

MSW Effect

- Take **2-neutrino oscillation** as an example

$$\frac{1}{2E}\begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}m_1^2 & \\ & m_2^2\end{pmatrix}\begin{pmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{pmatrix}+\begin{pmatrix}\mathbf{V}_{\rm cc} & 0 \\ 0 & 0\end{pmatrix}$$

- The lagrangian can be described by effective matter term

$$\mathcal{H}_{\rm eff}^{\rm vac}=\frac{1}{2E}\begin{pmatrix}\cos\widetilde{\theta} & \sin\widetilde{\theta} \\ -\sin\widetilde{\theta} & \cos\widetilde{\theta}\end{pmatrix}\begin{pmatrix}\widetilde{m}_1^2 & \\ & \widetilde{m}_2^2\end{pmatrix}\begin{pmatrix}\cos\widetilde{\theta} & -\sin\widetilde{\theta} \\ \sin\widetilde{\theta} & \cos\widetilde{\theta}\end{pmatrix}$$

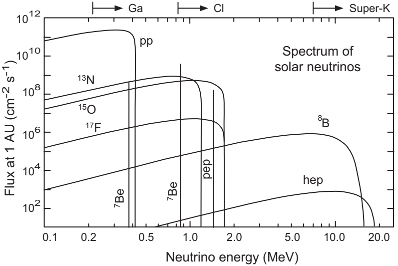
- **Resonance** if $\boxed{V_{\rm cc}\Delta m^2 > 0}$

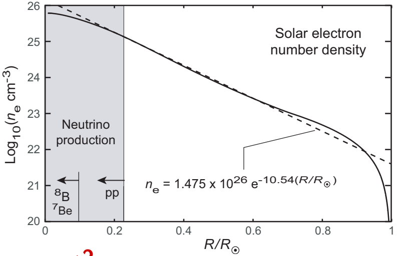
$$\sin 2\widetilde{\theta} = \frac{\sin 2\theta}{\sqrt{\sin^2 2\theta + (\cos 2\theta - 2E\mathbf{V}/\mathbf{\Delta m^2})^2}}$$

$$\mathbf{\Delta\widetilde{m}^2} = \Delta m^2\sqrt{\sin^2 2\theta + (\cos 2\theta - 2E\mathbf{V}/\mathbf{\Delta m^2})^2}$$

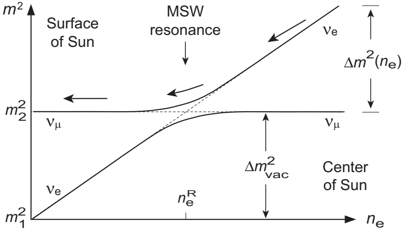
- Energy modulation: $\boxed{\mathcal{H}\rightarrow 2\mathbf{E}\mathcal{H}}$

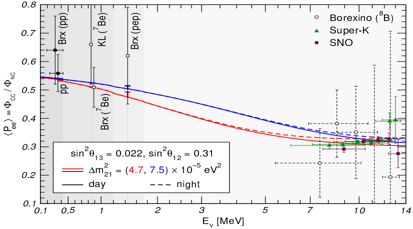
Adiabatic Evolution of Solar Neutrinos





$$P^{\rm sun}_{ee} = \left| U^{\rm prod}_{ei} (U^{\rm vac}_{ei})^* \right|^2$$





Guidry & Billings [arXiv:1812.00035]; Maltoni & Smirnov [arXiv:1507.05287]