TNT2K for CP Measurement & Non-Standard Interactions

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Jarah Evslin, **SFG**, Kaoru Hagiwara, JHEP **1602** (2016) 137 [arXiv:1506.05023]
SFG, Pedro Pasquini, M. Tortola, J. W. F. Valle, PRD **95** (2017) No.3, 033005 [arXiv:1605.01670]
SFG, Alexei Smirnov, JHEP **1610** (2016) 138 [arXiv:1607.08513]
SFG [arXiv:1704.08518]
SFG, Stephen Parke, Phys.Rev.Lett. **122** (2019) no.21, 211801 [arXiv:1812.08376]
SFG, Hitoshi Murayama [arXiv:1904.02518]

Minimal Neutrinos

Georg G. Raffelt

Stars as Laboratories for Fundamental Physics

The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles

In the standard model, neutrinos have been assigned the most minimal properties compatible with experimental data: zero mass, zero charge, zero dipole moments, zero decay rate, zero almost everything.

Neutrinos are not just invisible but very boring!

Lazy Neutrino

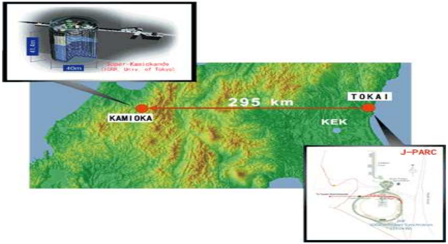
Nothing can interest me!!!

Daya Bay & LHC changed Physics in 2012

- **Higgs boson** $\Rightarrow$ electroweak symmetry breaking & mass.
- **Chiral symmetry breaking** $\Rightarrow$ majority of mass.
- **The world seems not affected by the tiny neutrino mass?**
    - Neutrino mass $\Rightarrow$ Mixing
    - 3 Neutrino $\Rightarrow$ possible **CP violation**
    - CP violation $\Rightarrow$ **Leptogenesis**
    - **Leptogenesis** $\Rightarrow$ **Matter-Antimatter Asymmetry**
    - There is something left in the Universe.
    - Baryogenesis from quark mixing is not enough.
- Majorana $\nu \Leftrightarrow$ **Lepton Number Violation**
- **Residual $\mathbb{Z}_2$ Symmetries:** $\cos\delta_D = \dfrac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r}$ 1108.0964 1104.0602

CP Measurement @ Accelerator Exps

- T2K



- NOνA

- DUNE/T2KII/T2HK/T2HKK/T2KO; MOMENT/ADS-CI/DAEδALUS; Super-PINGU

The Dirac CP Phase δ_D @ Accelerator Exp

- To leading order in $\alpha = \frac{\delta M^2_{21}}{|\delta M^2_{31}|} \sim 3\%$, the oscillation probability relevant to measuring δ_D @ **T2(H)K**,

$$P_{\substack{\nu_\mu \to \nu_e \\ \overline{\nu}_\mu \to \overline{\nu}_e}} \approx 4 s_a^2 c_r^2 s_r^2 \sin^2 \phi_{31}$$
$$- 8 c_a s_a c_r^2 s_r c_s s_s \sin \phi_{21} \sin \phi_{31} \left[\cos \delta_D \cos \phi_{31} \pm \sin \delta_D \sin \phi_{31} \right]$$

for ν & $\overline{\nu}$, respectively. $[\phi_{ij} \equiv \frac{\delta m^2_{ij} L}{4 E_\nu}]$

- $\nu_\mu \to \nu_\mu$ Exps measure $\sin^2(2\theta_a)$ precisely, but not $\sin^2 \theta_a$.

- Run both ν & $\overline{\nu}$ modes @ first peak $[\phi_{31} = \frac{\pi}{2}, \phi_{21} = \alpha \frac{\pi}{2}]$,

$$P_{\overline{\nu}_\mu \to \overline{\nu}_e} + P_{\nu_\mu \to \nu_e} = 2 s_a^2 c_r^2 s_r^2 ,$$
$$P_{\overline{\nu}_\mu \to \overline{\nu}_e} - P_{\nu_\mu \to \nu_e} = \alpha \pi \sin(2\theta_s) \sin(2\theta_r) \sin(2\theta_a) \cos \theta_r \sin \delta_D .$$

The Dirac CP Phase δ_D @ Accelerator Exp

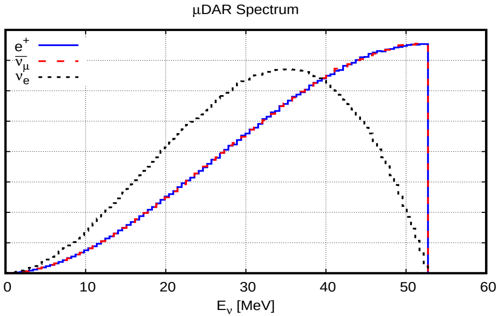
Accelerator experiment, such as **T2(H)K**, uses off-axis beam to compare ν_e & $\overline{\nu}_e$ appearance @ the oscillation maximum.

- **Disadvantages**:
  - **Efficiency**:
    - Proton accelerators produce ν more efficiently than $\overline{\nu}$ ($\sigma_\nu > \sigma_{\overline{\nu}}$).
    - The $\overline{\nu}$ mode needs more beam time [$\mathbf{T}_{\overline{\nu}} : \mathbf{T}_\nu = \mathbf{2} : \mathbf{1}$].
    - Undercut statistics $\Rightarrow$ Difficult to reduce the uncertainty.
  - **Degeneracy**:
    - Only $\sin \boldsymbol{\delta}_\mathbf{D}$ appears in $P_{\nu_\mu \to \nu_e}$ & $P_{\overline{\nu}_\mu \to \overline{\nu}_e}$.
    - Cannot distinguish $\boldsymbol{\delta}_\mathbf{D}$ from $\boldsymbol{\pi} - \boldsymbol{\delta}_\mathbf{D}$.
  - **CP Uncertainty** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos \delta_D \Rightarrow \Delta(\delta_D) \propto \mathbf{1} / \cos \boldsymbol{\delta}_\mathbf{D}$.
- **Solution**:

  Measure $\overline{\nu}$ mode with μ^+ decay @ rest (μDAR)

μDAR $\bar{\nu}$ Oscillation Experiments

- A cyclotron produces 800 MeV proton beam @ fixed target.
- Produce $\pi^{\pm}$ which stops &
  - π^- is absorbed,
  - π^+ decays @ rest: $\pi^+ \to \mu^+ + \nu_\mu$.
- μ^+ stops & decays @ rest: $\boldsymbol{\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e}$.

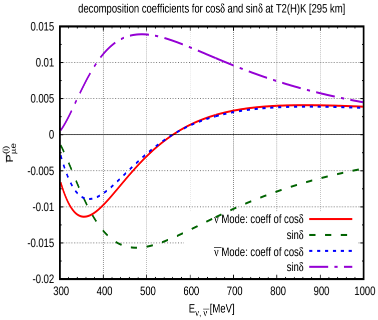


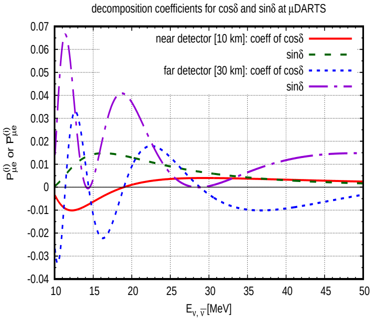
- $\overline{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_e$ from $\boldsymbol{\overline{\nu}_\mu \to \overline{\nu}_e}$ **oscillation**.

Accelerator + μDAR Experiments

Combining $\nu_\mu \to \nu_e$ **@ accelerator** [narrow **peak @ 550 MeV**] & $\overline{\nu}_\mu \to \overline{\nu}_e$ **@ μDAR** [wide **peak $\sim$ 45 MeV**] solves the 2 problems:

- **Efficiency**:
  - $\overline{\nu}$ @ high intensity, μDAR is plentiful enough.
  - Accelerator Exps can devote all run time to the ν mode. With same run time, the statistical uncertainty drops by $\sqrt{3}$.
- **Degeneracy**: (**decomposition in propagation basis** [1309.3176])





DAEδALUS

- It's the **FIRST** proposal along this line:
  - **3** μDAR with **3** high-intensity cyclotron complexes.
  - **1** detector.
  - Different baselines: **1.5**, **8** & **20** km to break degeneracies.
- **Disadvantages**:
  - The scattering lepton from IBD @ low energy is **isotropic**.
  - **Cannot** distinguish $\overline{\nu}_e$ from different sources
  - Baseline **cannot be measured**.
  - Cyclotrons **cannot** run simultaneously (20$\sim$25% duty factor).
  - **Large** statistical uncertainty.
  - **Higher intensity** is necessary.
  - **Expensive** & Technically **challenging**.

New Proposals

1 μDAR source + **2** detectors

Advantages

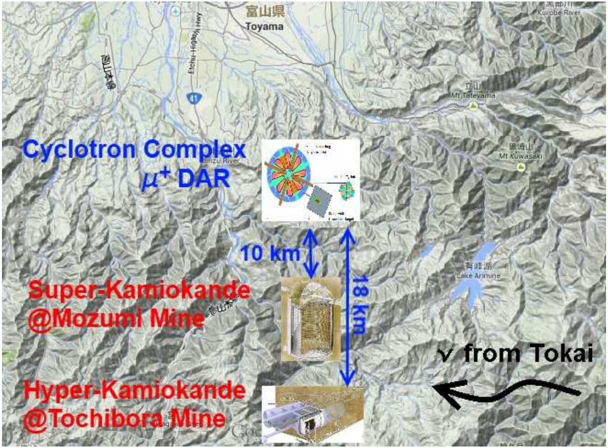
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**$\times$ lower than DAEδALUS]
- Not far beyond the current state-of-art technology of cyclotron [**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
  - Only one cyclotron.
  - Lower intensity.

Disadvantage?

- A second detector!
  - **μDAR** with **T**wo **S**cintillators (**μDARTS**) [Ciuffoli, Evslin & Zhang, 1401.3977] also Smirnov, Hu, Li & Ling [1802.03677, 1808.03795]
  - **T**okai '**N** **T**oyama to(**2**) **K**amioka (**TNT2K**) [Evslin, Ge & Hagiwara, 1506.05023]

TNT2K

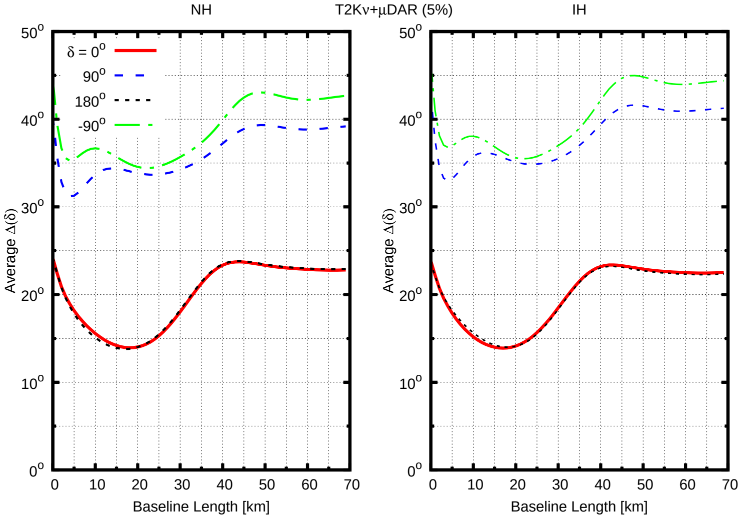
- T2(H)K + μSK + μHK



- μDAR is also useful for **material**, **medicine** industries in Toyama

δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



Simulated by **NuPro**, http://nupro.hepforge.org/

δ_D Precision @ TNT2K

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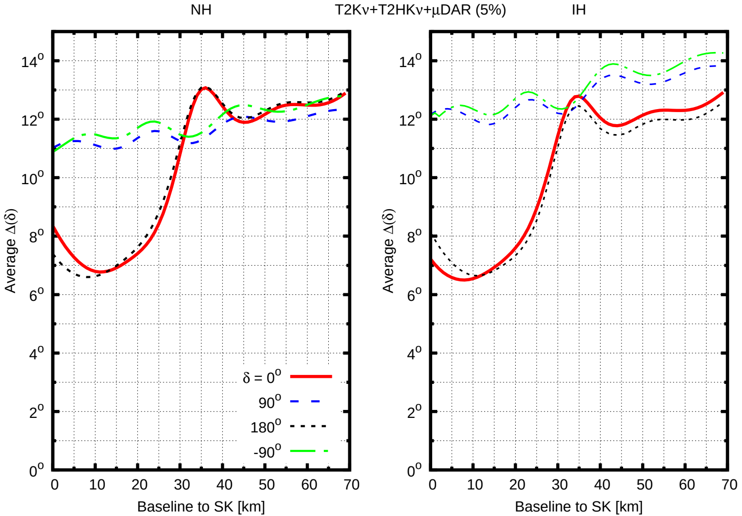


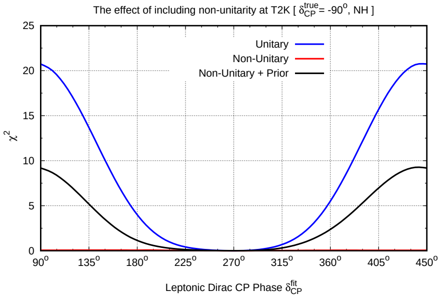
Simulated by **NuPro**, http://nupro.hepforge.org/

Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle [1605.01670]

$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U \,.$$

$$P^{NP}_{\mu e} = \alpha^2_{11} \left\{ \alpha^2_{22} \left[c^2_a |S'_{12}|^2 + s^2_a |S'_{13}|^2 + 2 c_a s_a (\cos \delta_D \mathbb{R} - \sin \delta_D \mathbb{I})(S'_{12} S'^*_{13}) \right] + |\alpha_{21}|^2 P_{ee} \right.$$
$$\left. + 2 \alpha_{22} |\alpha_{21}| \left[c_a \left(c_\phi \mathbb{R} - s_\phi \mathbb{I} \right) \left(S'_{11} S'^*_{12} \right) + s_a \left(c_{\phi + \delta_D} \mathbb{R} - s_{\phi + \delta_D} \mathbb{I} \right) \left(S'_{11} S'^*_{13} \right) \right] \right\} \,.$$



NUM vs Seesaw Mechanism

- **Heavy neutrinos**

$$\bar{\nu} M_D \mathcal{N} + h.c. + \overline{\mathcal{N}} M_N \mathcal{N} = \begin{pmatrix} \bar{\nu} & \overline{\mathcal{N}} \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \begin{pmatrix} \nu \\ \mathcal{N} \end{pmatrix}$$

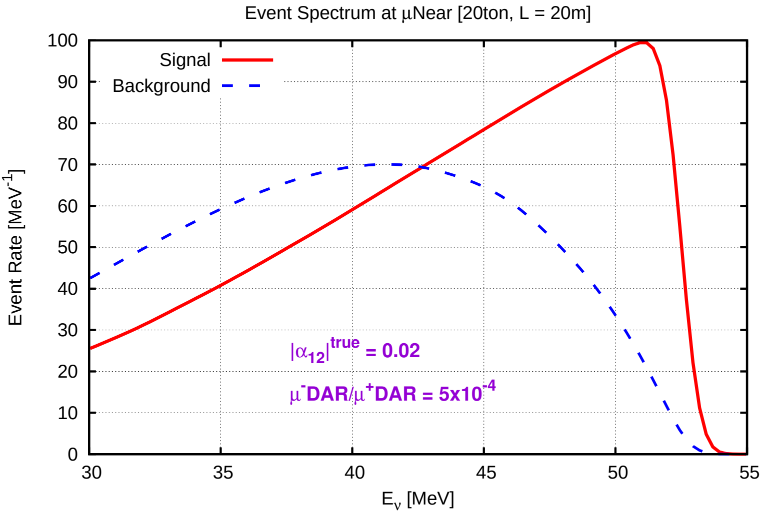
- **Seeaw Mechanism**

$$M_\nu = -M_D M_N^{-1} M_D^T \,, \qquad \nu' = \nu + M_D M_N^{-1} \mathcal{N}$$

μNear at μDAR

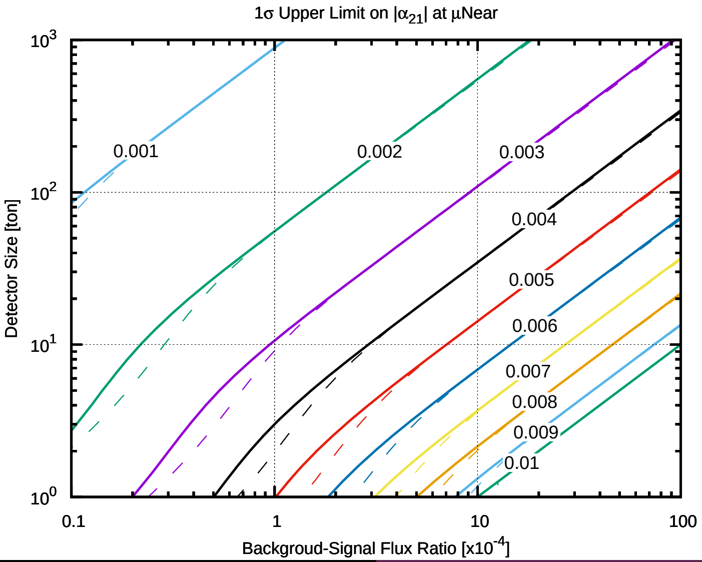
Ge, Pasquini, Tortola & Valle [1605.01670]

$$P^{NP}_{\mu e}(L \to 0) = \alpha_{11}^2 |\alpha_{21}|^2 P_{ee} \approx \alpha_{11}^2 |\alpha_{21}|^2 \approx |\alpha_{21}|^2$$



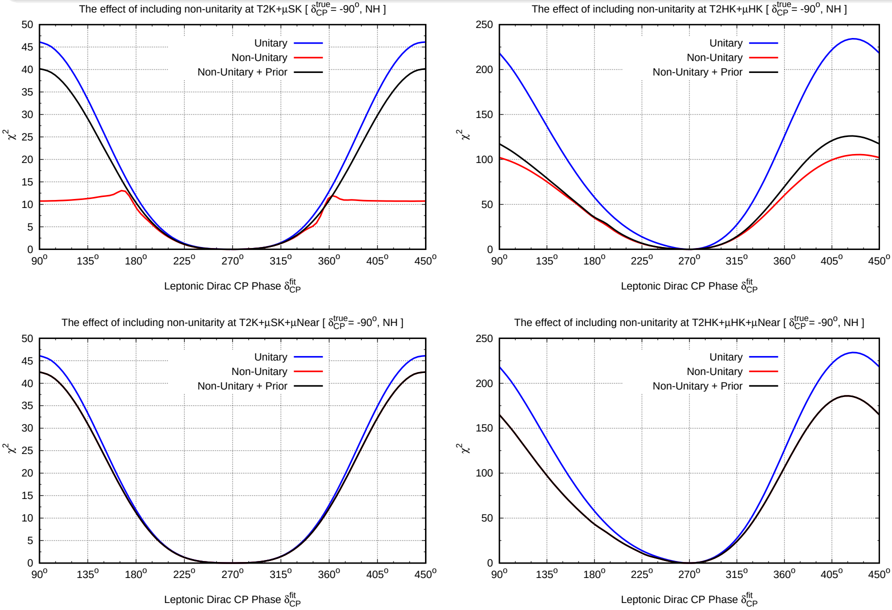
μNear at μDAR

Ge, Pasquini, Tortola & Valle [1605.01670]



TNT2K+μNear

Ge, Pasquini, Tortola & Valle [1605.01670]



Non-Standard Interaction

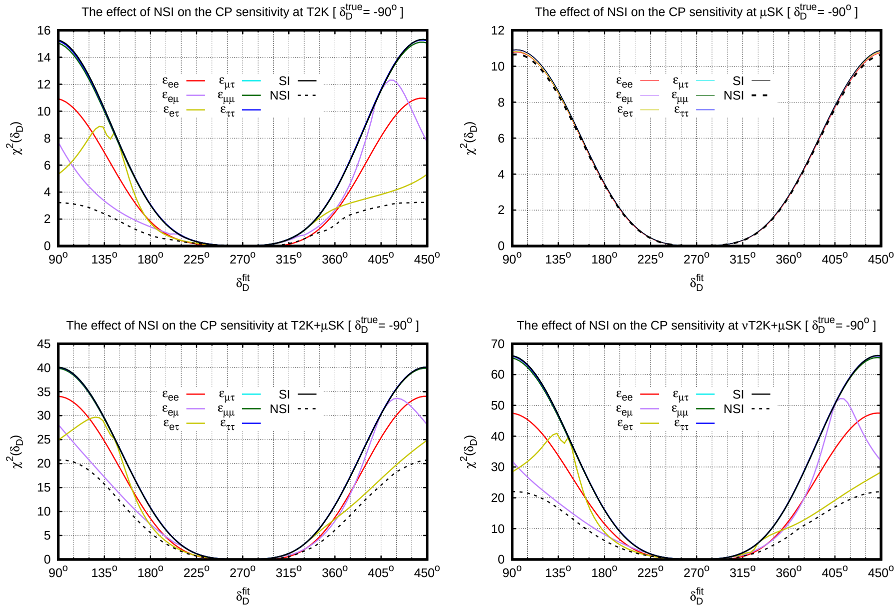
SFG & Alexei Smirnov [arXiv:1607.08513]

$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

- Standard Interaction – V_{cc} (also V_{nc})
- Non-Standard Interaction – $\epsilon_{\alpha\beta}$
  - **Diagonal $\epsilon_{\alpha\alpha}$ are real**
  - **Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex**
  - **Both can fake CP**
- Z' in LMA-Dark model with $L_\mu - L_\tau$ gauged as $U(1)$
  - $M_{Z'} \sim \mathcal{O}(10)$MeV
  - $g_{Z'} \sim 10^{-5}$

CP Sensitivity at T2K & μSK

SFG & Alexei Smirnov [arXiv:1607.08513]



Scalar NSI

SFG & Stephen Parke, Phys.Rev.Lett. **122** (2019) no.21, 211801 [1812.08376]

- **Vector NSI**

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

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

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

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

EOM & Effective Hamiltonian with Scalar NSI

- **Two-Point Correlation Function**

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

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

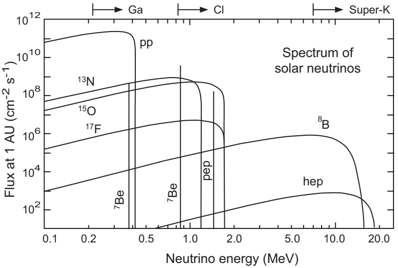
- **Equation of Motion**

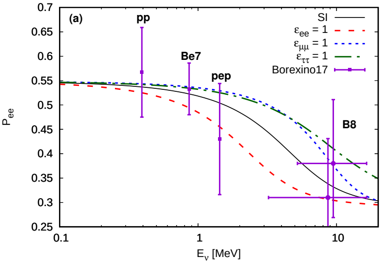
$$\bar{\nu}_\beta \left[i\partial_\mu \gamma^\mu + \left(M_{\beta\alpha} + \frac{\mathbf{n_e y_e Y}_{\alpha\beta}}{\mathbf{m}_\phi^2} \right) \right] \nu_\alpha = 0 \,,$$

- **Effective Hamiltonian**

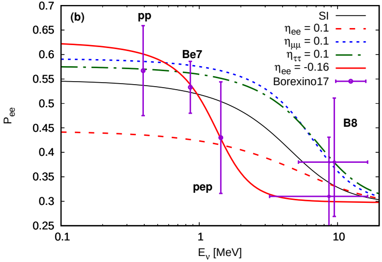
$$\mathcal{H} \approx E_\nu + \frac{(M + \mathbf{M_S})(M + \mathbf{M_S})^\dagger}{2E_\nu} \pm V_{\mathrm{SI}} \,,$$

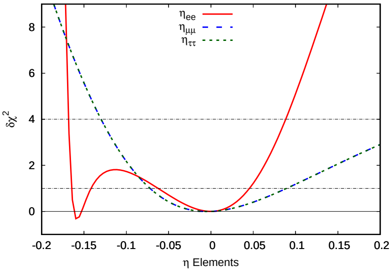
Solar Neutrino



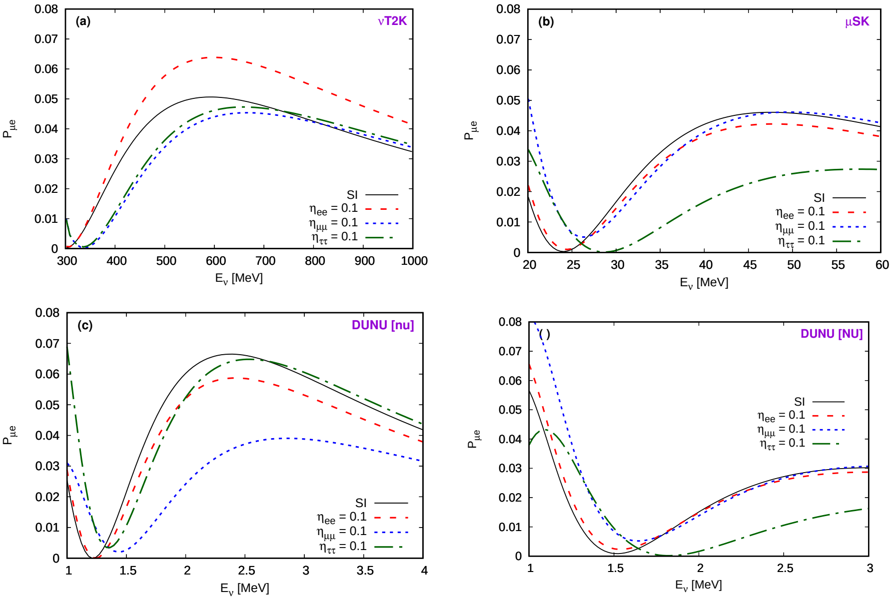


$$P_{ee}^{sun} = \left| U_{ei}^{prod} (U_{ei}^{vac})^* \right|^2$$





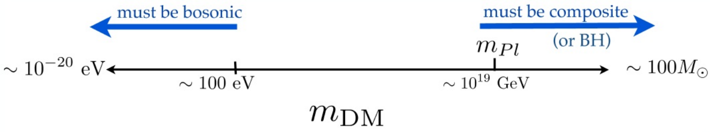
Scalar NSI @ Accelerator Neutrino Oscillation



Light Dark Matter

SFG, Hitoshi Murayama [arXiv:1904.02518]

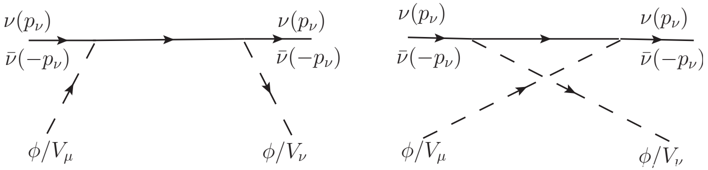
- **The DM mass can span almost 100 orders**



- For **light bosonic DM**

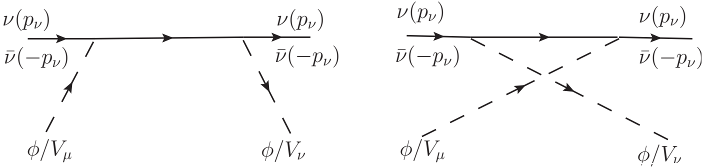
$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + h.c.,$$

leading to **forward scattering**



Effective Mass Correction from Dark Matter

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



- modifies the neutrino **kinetic term**

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

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

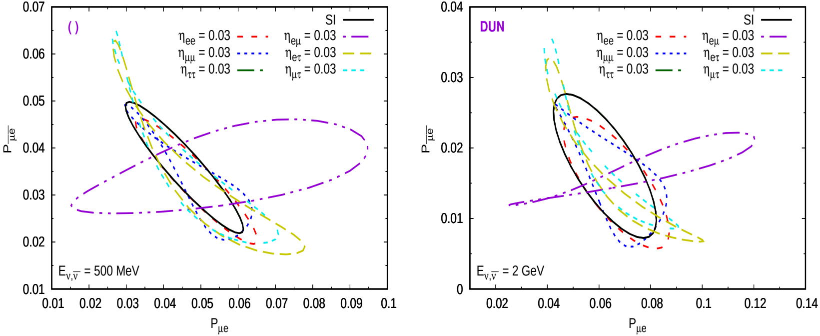
$$H = \frac{M^2}{2E_\nu} \mp \frac{1}{\mathbf{E}_\nu} \sum_j y_{\alpha j} y^*_{j\beta} \frac{\rho_\chi}{m^2_\phi} \equiv \frac{M^2 \pm \delta \mathbf{M}^2}{2\mathbf{E}_\nu}$$

which is totally different from the scalar NSI.

- **With mass term correction, any neutrino oscillation cannot see the original variables.**

Dark NSI & Faked CP

- With just 3% of dark NSI



- The biprobability contour can totally change.

SFG, Hitoshi Murayama [arXiv:1904.02518]

Summary

- **Better CP measurement than T2K**
  - Much larger event numbers
  - Much better CP sensitivity around maximal CP
  - Solve degeneracy between δ_D & $\pi - \delta_D$
  - Guarantee CP sensitivity against NUM
  - Guarantee CP sensitivity against NSI (vector, scalar, dark)
- **Better configuration than DAEδALUS**
  - Only one cyclotron
  - 100% duty factor
  - Much lower flux intensity
  - Much easier
  - Much cheaper
  - Single near detector

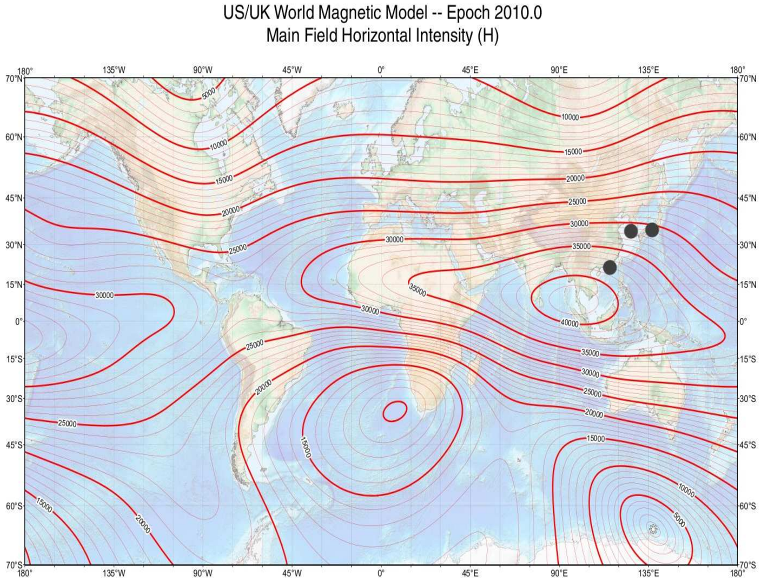
Thank You!

ν Oscillation Data

(for NH)	-1σ	Best Value	$+1\sigma$
$\boldsymbol{\Delta m_s^2} \equiv \Delta m_{12}^2\,(\mathbf{10^{-5}}\mathrm{eV}^{\mathbf{2}})$	7.37	**7.56**	7.75
$\left\lvert\boldsymbol{\Delta m_a^2} \equiv \Delta m_{13}^2\right\rvert\ (\mathbf{10^{-3}}\mathrm{eV}^{\mathbf{2}})$	2.51	**2.55**	2.59
$\sin^2\boldsymbol{\theta_s}\ (\boldsymbol{\theta_s} \equiv \boldsymbol{\theta_{12}})$	0.305 (33.5°)	0.321 (**34.5°**)	0.339 (35.6°)
$\sin^2\boldsymbol{\theta_a}\ (\boldsymbol{\theta_a} \equiv \boldsymbol{\theta_{23}})$	0.412 (39.9°)	0.430 (**41.0°**)	0.450 (42.1°)
$\sin^2\boldsymbol{\theta_r}\ (\boldsymbol{\theta_r} \equiv \boldsymbol{\theta_{13}})$	0.02080 (8.29°)	0.02155 (**8.44°**)	0.02245 (8.62°)
δ_D, δ_{Mi}	?, **??**	?, **??**	?, **??**

Salas, Forero, Ternes, Tortola & Valle, arXiv:1708.01186

Lowest Atmospheric Neutrino Background



Backgrounds to IBD ($\overline{\nu}_e + p \to e^+ + n$)

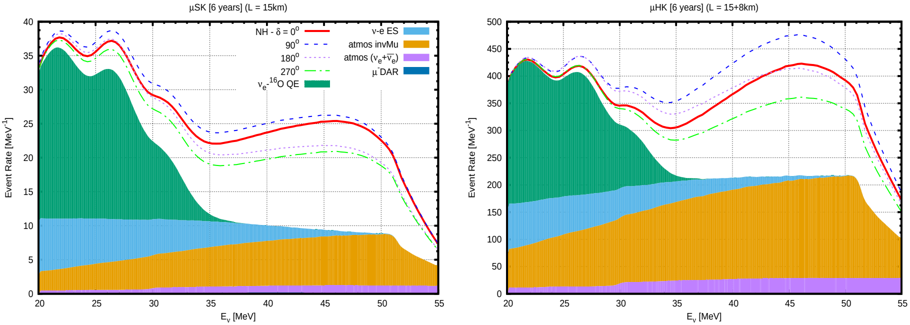
- Reactor $\overline{\nu}_e$: $E_\nu < 10$ MeV
- Accelerator ν_e: $E_\nu > 100$ MeV
- Spallation: $E_\nu \lesssim 20$ MeV
- Supernova Relic Neutrino: $E_\nu \lesssim 20$ MeV

  Cut with 30 MeV $< E_\nu <$ 55 MeV

- Accelerator $\nu_\mu \to$ **Invisible muon**
- Atmospheric Neutrino Background
  - **Invisible muon** (below Cherenkov limit)
    - $E_\mu \lesssim 1.5 \times m_\mu$, $\mu^\pm \to e^\pm$
    - $E_\pi \lesssim 1.5 \times m_\pi$, $\pi^+ \to \mu^+ \to e^+$
    - 1 neutron
    - No prompt photon
  - Irreducible $\overline{\nu}_e$: 30 MeV $\lesssim E_\nu \lesssim$ 55 MeV
  - Reducible ν_e: 60 MeV $\lesssim E_\nu \lesssim$ 100 MeV
    - 1 neutron
    - No prompt photon
  - **Lowest** at μDARTS & TNT2K sites

Event Shape @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]

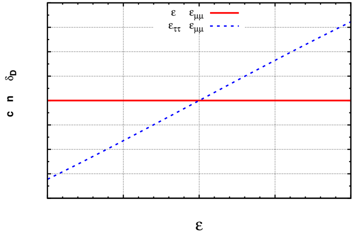


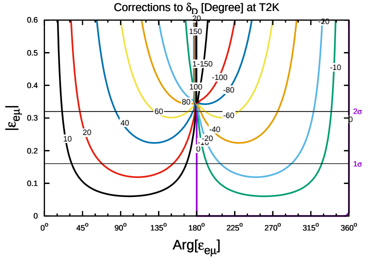
Expected μDAR IBD signal from 6 yrs of running @ SK (15km) & HK (23km) with NH.

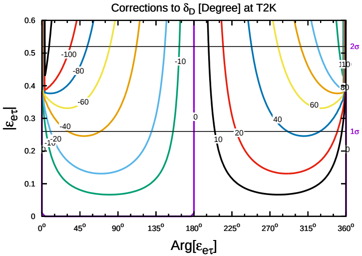
Simulated by **NuPro**, http://nupro.hepforge.org/

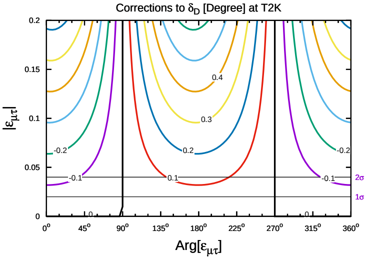
Faked CP with NSI

SFG & Alexei Smirnov [arXiv:1607.08513]









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** $\mathbf{\Delta m_a^2}$ to parametrize scalar NSI

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

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

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

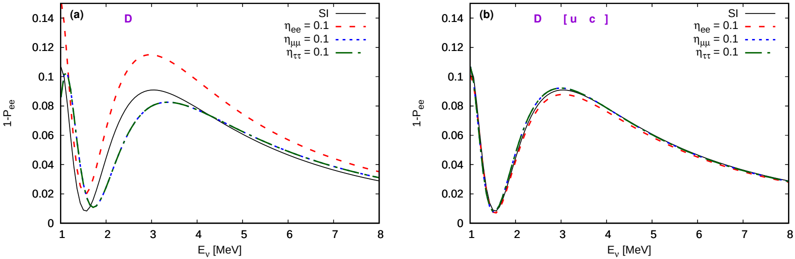
- However, the directly measured from terrestial experiments is always a combination, $\widetilde{\mathbf{M}} + \widetilde{\mathbf{M}}_{\mathbf{S}}(\rho_{\mathbf{s}} \approx \mathbf{3}\mathrm{g/cm}^{\mathbf{3}})$. It is then necessary to first substract a constant term:

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

  where $\widetilde{\mathbf{M}} = \mathbf{U}_\nu \mathbf{D}_\nu \mathbf{U}_\nu^\dagger$ is **reconstructed** in terms of the measured mixing matrix while $\widetilde{M}_S$ is the scalar NSI @ typical constant **subtraction density** $\rho_{\mathbf{s}}$.

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 @ Atmospheric Neutrino Oscillation