Neutrino CP Phase & New Physics

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vSTEP @ HIAS

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

李政道研究所
Tsung-Dao Lee Institute

Outline

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- CP Violation in the Precision Era
- Dirac CP Phase & New Physics
  1. Non-Standard Interactions (NSI)
  2. Scalar NSI
  3. Dark NSI
  4. Non-Unitary Mixing (NUM)
  5. RG Running
- Accelerator + μDAR for Better CP Measurement
  1. TNT2K
  2. μTHEIA

Minimal Neutrinos

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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.

Neutrino vs Higgs

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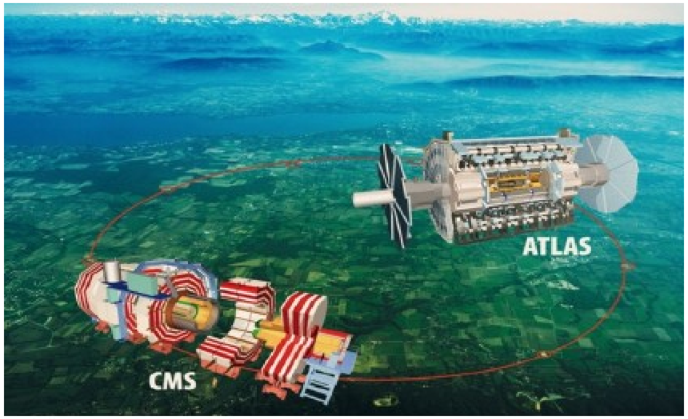
- **Higgs boson** ⇒ electroweak symmetry breaking & mass. ~ O(100)GeV
- **Chiral symmetry breaking** ⇒ majority of mass.
- The world seems not affected by the tiny neutrino mass?
  - Neutrino mass ⇒ Mixing
  - 3 Neutrino ⇒ possible **CP violation**
  - CP violation ⇒ **Leptogenesis**
  - ⇒ **Matter-Antimatter Asymmetry**
  - There is something left in the Universe.
  - **EW Baryogenesis** is not enough.

Daya Bay @ **March 8, 2012**



LHC @ **July 4, 2012**

Seesaw & Leptogenesis

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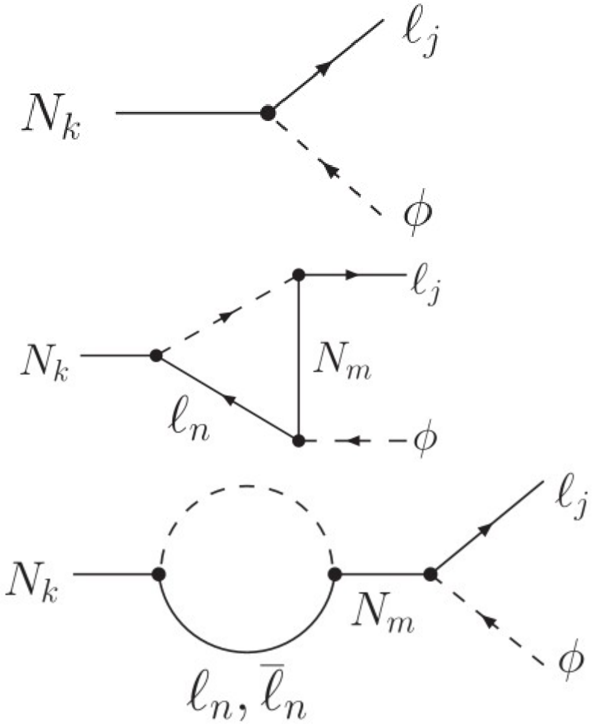
With decreasing temperature, heavy N decays to light SM particles.

$$N_k \to \begin{cases} \ell_j + \overline{\phi} \\ \overline{\ell}_j + \phi \end{cases}$$



Matter-Antimatter Asymmetry

- **Interference between tree & loop diagrams**

$$\begin{aligned} \Gamma &= \Gamma_{\rm tree} + \Gamma_{\rm loop}(+\delta_D, +\delta_M) \\ \overline{\Gamma} &= \Gamma_{\rm tree} + \Gamma_{\rm loop}(-\delta_D, -\delta_M) \end{aligned}$$

The matter-antimatter asymmetry needs Dirac/Majorana CP phases.

Yanagida

Fukugita

Current Status of ν Oscillation

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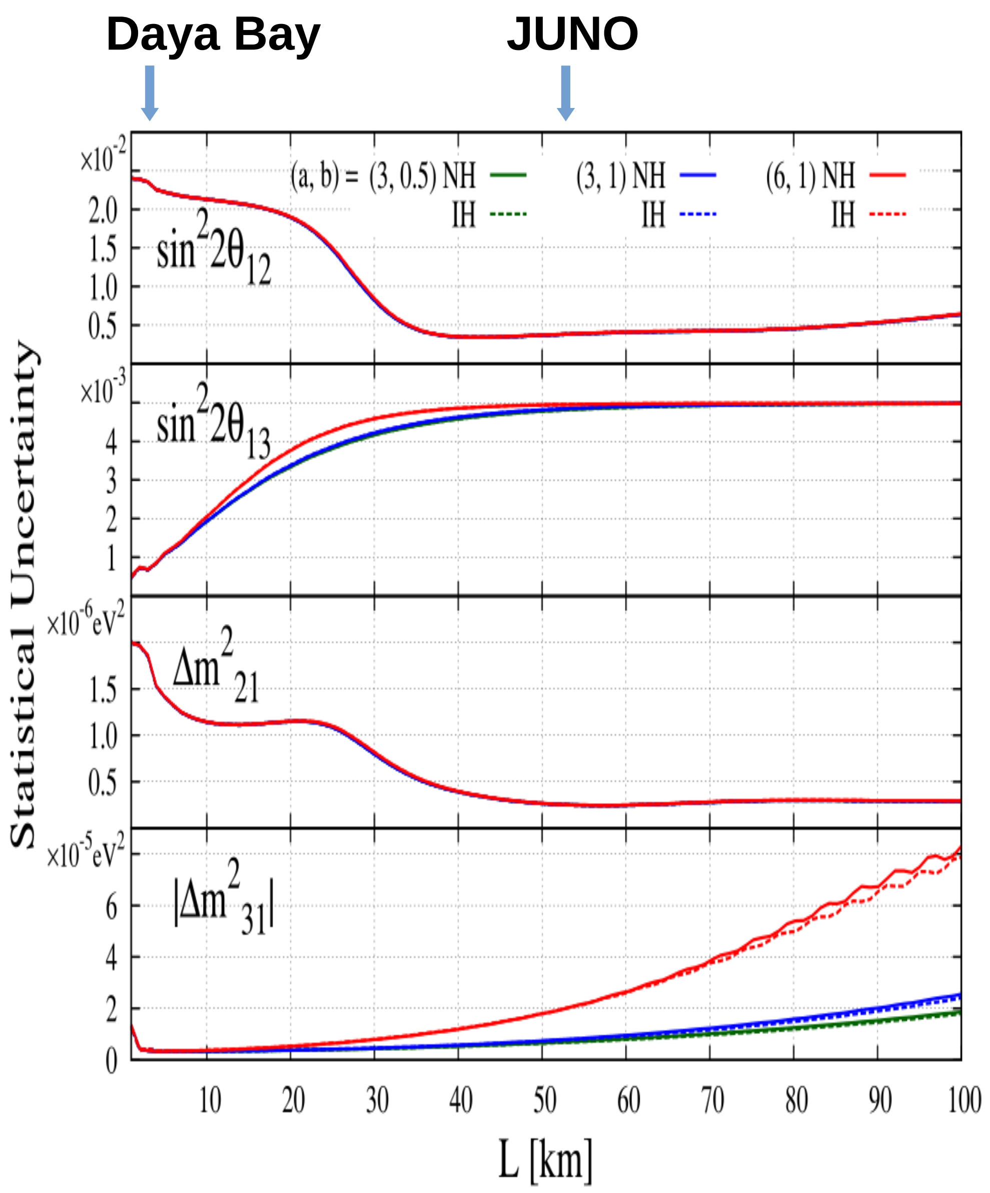
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

Gonzalez-Garcia, Maltoni & Schwetz [2111.03086]

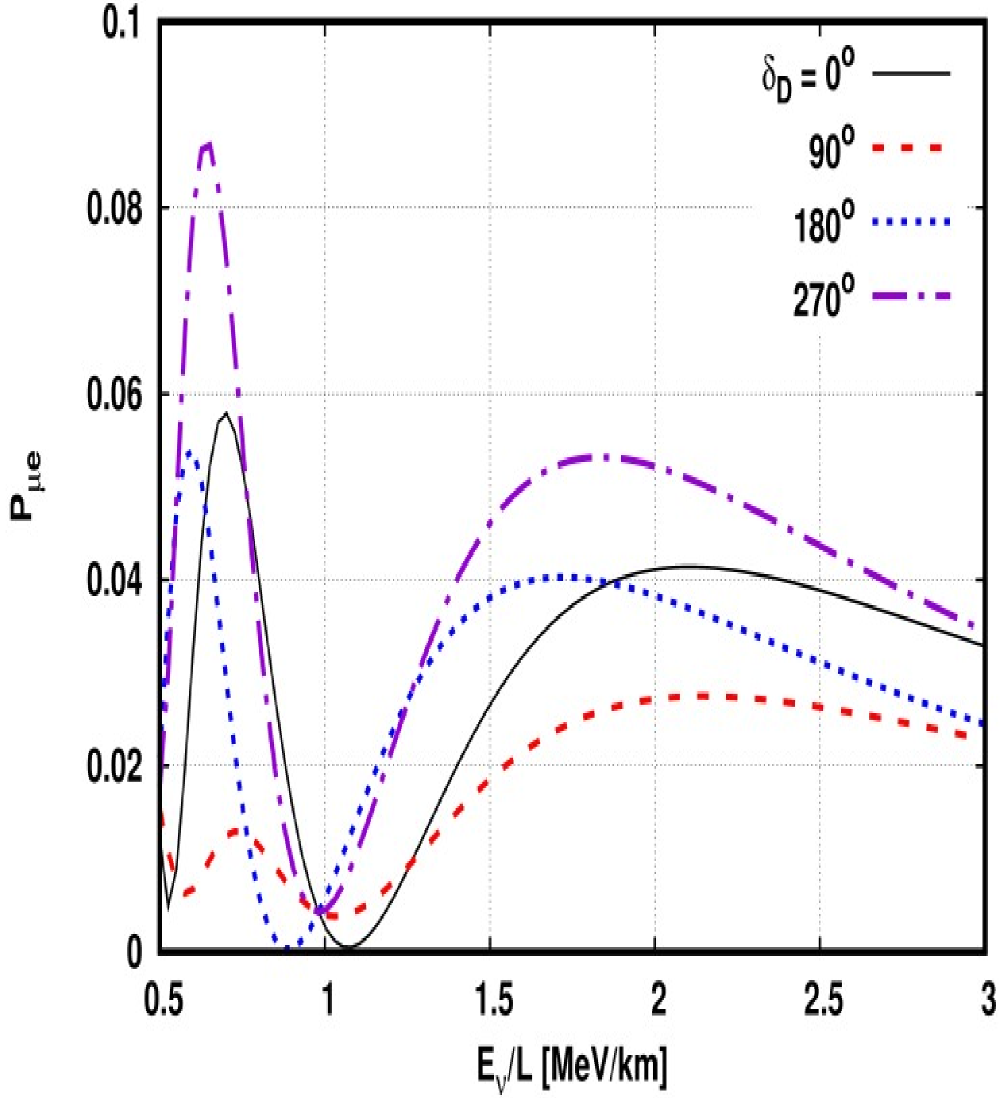
Daya Bay heralded a new era of precision measurement in 2012!

Kam-Biu Luk @ Neutrino 2022

Precision Era of ν Oscillation



SFG, Hagiwara, Okamura & Takaesu [1210.8141]



SFG & Smirnov [1607.08513]

Current Status of CP Measurement

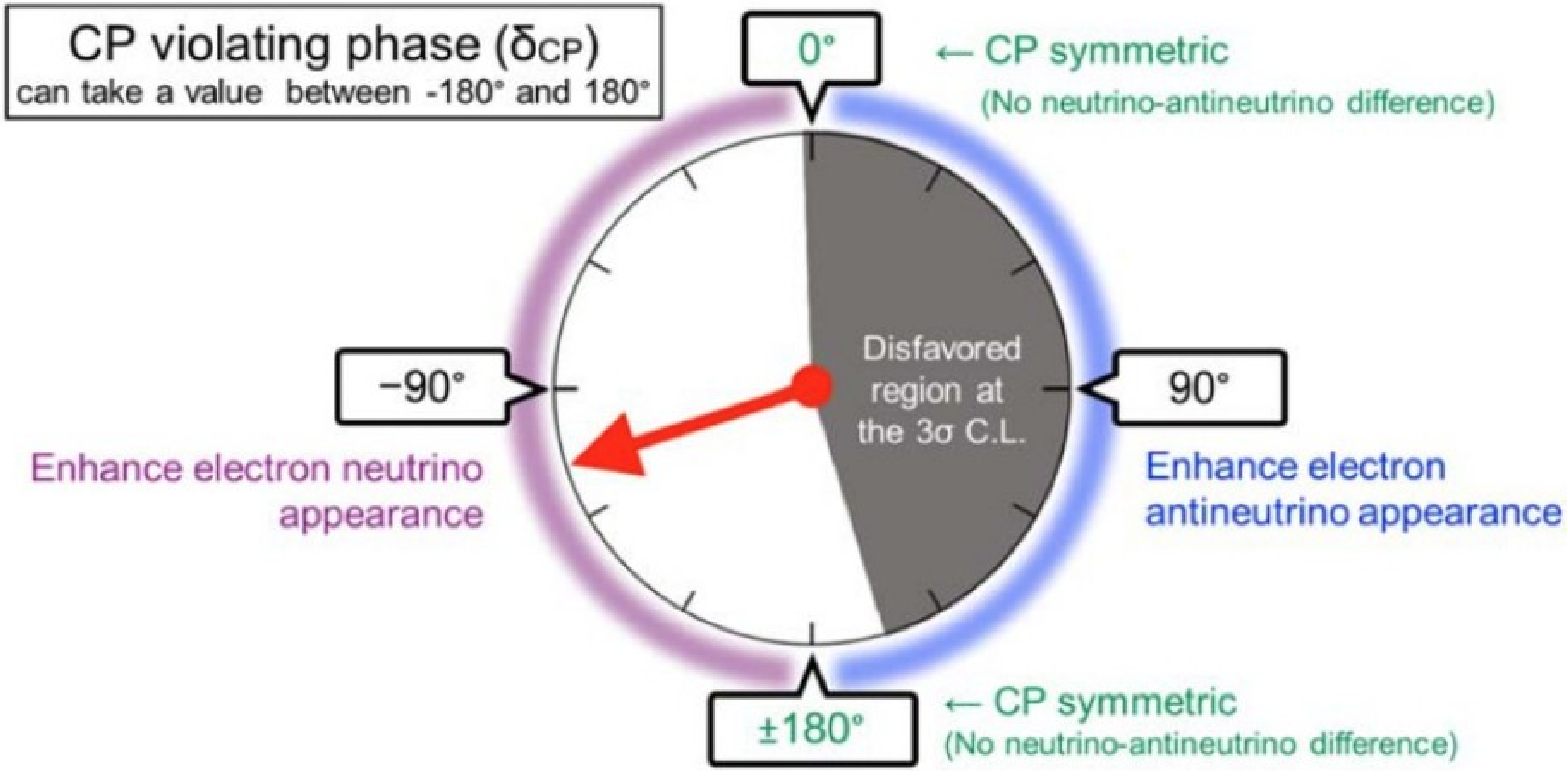


Fig.1 The arrow indicates the value most compatible with the data. The gray region is disfavored at 99.7% (3σ) confidence level. Nearly half of the possible values are excluded.

Nature vol. 580, pages 339-344(2020)

https://www.kek.jp/en/newsroom/attic/PR20200416_T2K_E.pdf

T2K+NOvA Joint Analysis

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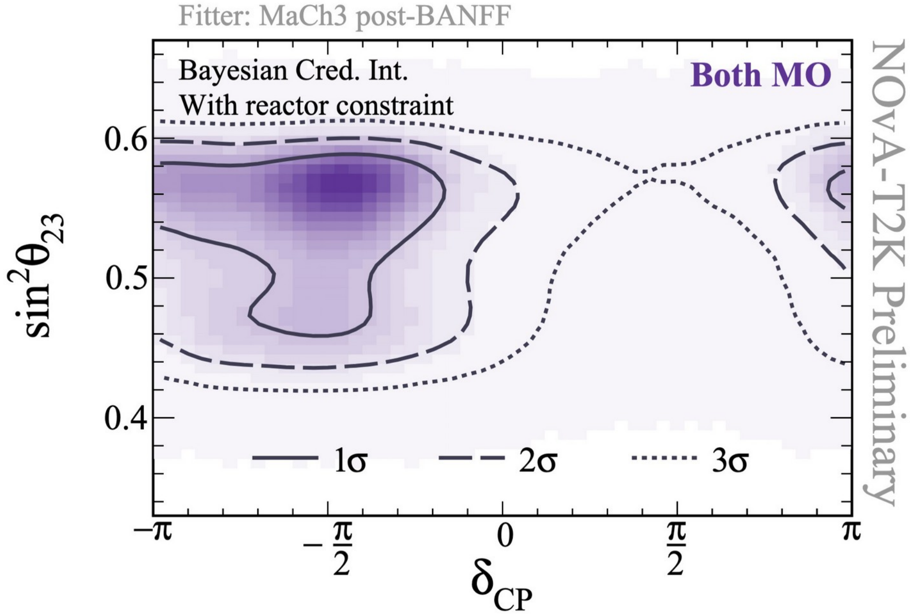

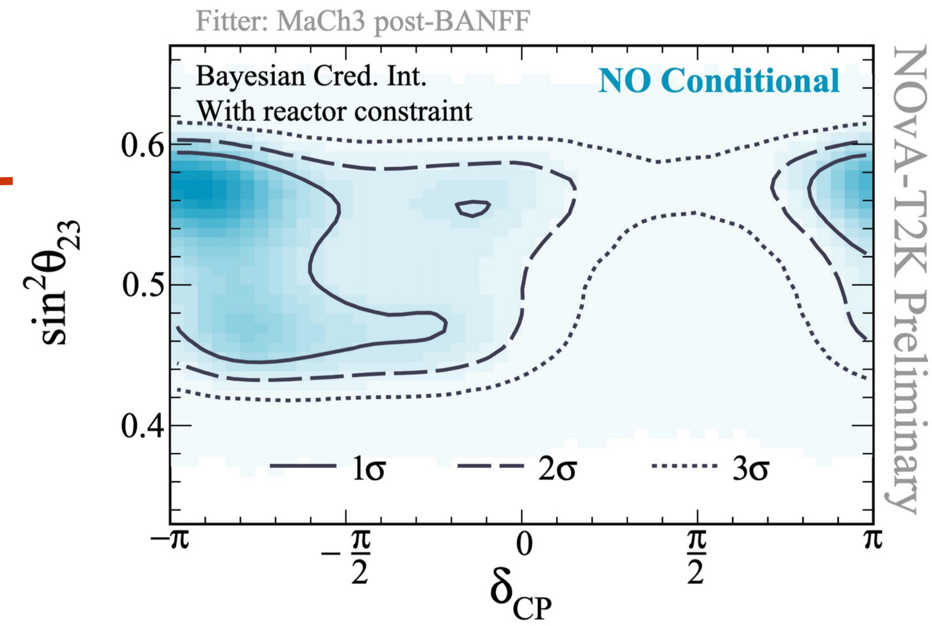

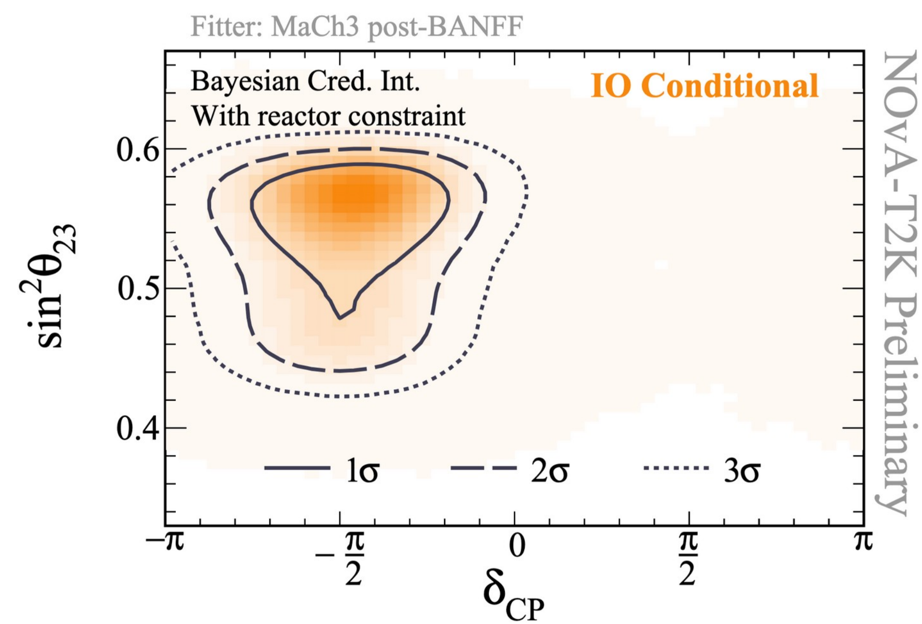

Zoya Vallari [On behalf of NOvA & T2K Collaborations], Feb/16, 2024
Joint Experimental-Theoretical Physics Seminar, Fermilab

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Tension between T2K & NOvA

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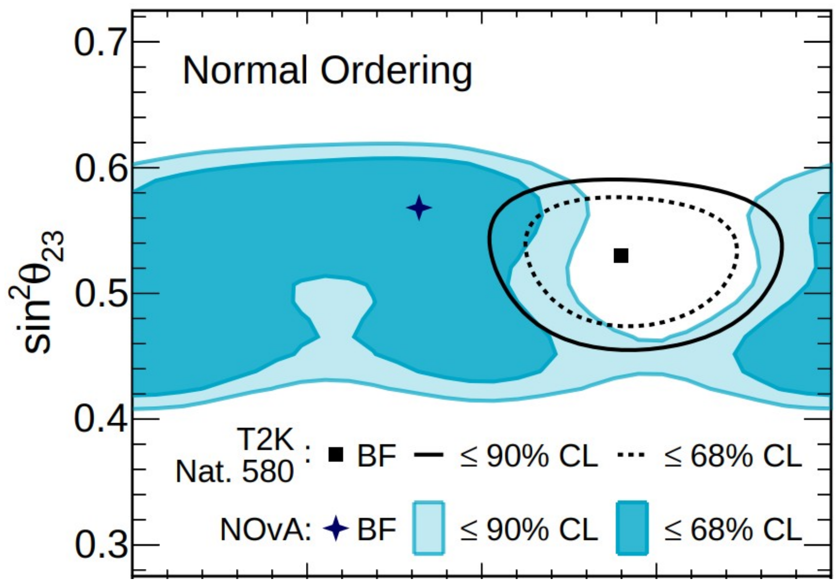

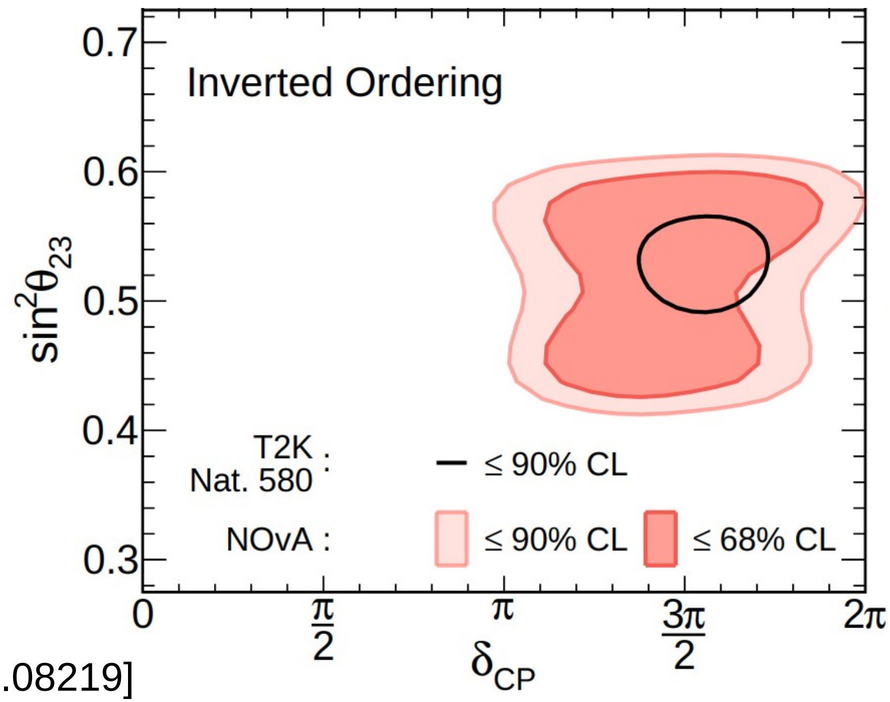

NovA, Phys.Rev.D 106 (2022) 3, 032004 [arXiv:2108.08219]

- **Non-Standard Interactions** — Denton, Gehrlein & Pestes [2008.01110]
- **Non-Unitary Mixing** — Rahaman, Razzaque & Sankar [2201.03250]
- **Lorentz Violation**
- **Sterile Neutrinos** — Chatterjee & Palazzo [2005.10338]

1. Non-Standard Interaction (NSI)

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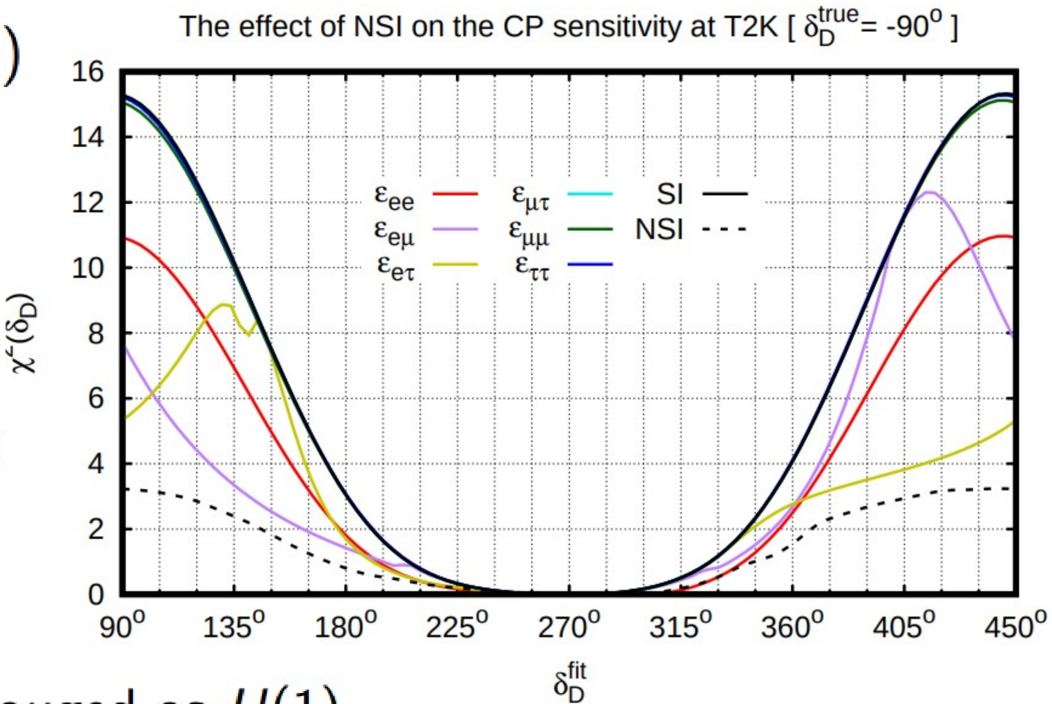
$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* &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

- 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
  - $g_{Z'} \sim 10^{-5}$

2. Scalar NSI

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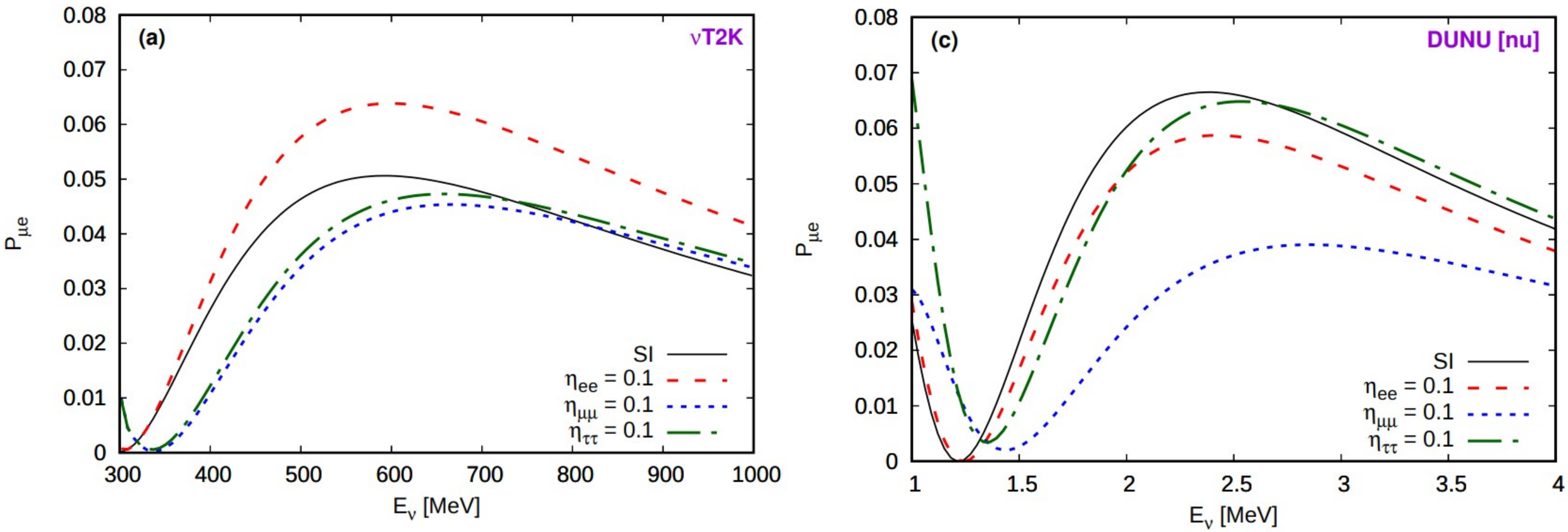
- **Vector NSI** $$\mathcal{L}_{\rm cc}^{\rm eff} = \frac{g_{\alpha\rho} g^*_{\beta\sigma}}{2} \frac{1}{-m_V^2} \left(\overline{\nu_\alpha}\gamma_\mu P_L \nu_\beta\right)\left(\overline{\ell}_\sigma \gamma^\mu P_L \ell_\rho\right)$$
- **Scalar NSI** $$\mathcal{L}^s_{\rm eff} \propto y_{\alpha\beta} Y_{ee} \left[\bar\nu_\alpha(p_3)\nu_\beta(p_2)\right]\left[\bar e(p_1) e(p_4)\right]$$

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

SFG, Stephen Parke, Phys.Rev.Lett. 122 (2019) 21, 211801 [arXiv:1812.08376]



3. Dark NSI with Forward Scattering

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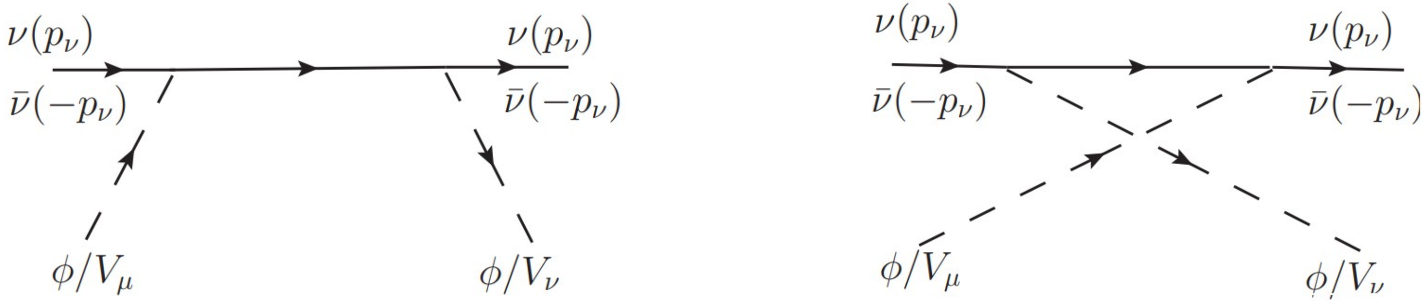
$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + h.c.$$

- **Forward scattering in DM medium**



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

- **With 1/E$_\nu$ dependence, the dark potential is promoted to mass**

Dark NSI can fake neutrino mass!

SFG, Chui-Fan Kong, Alexei Smirnov [2404.17352]

SFG, Murayama [1904.02518]
SFG, PoS NuFact2019 (2020) 108
SFG, J.Phys.Conf.Ser. 1468 (2020) 1, 012125

4. Non-Unitarity Mixing (NUM)

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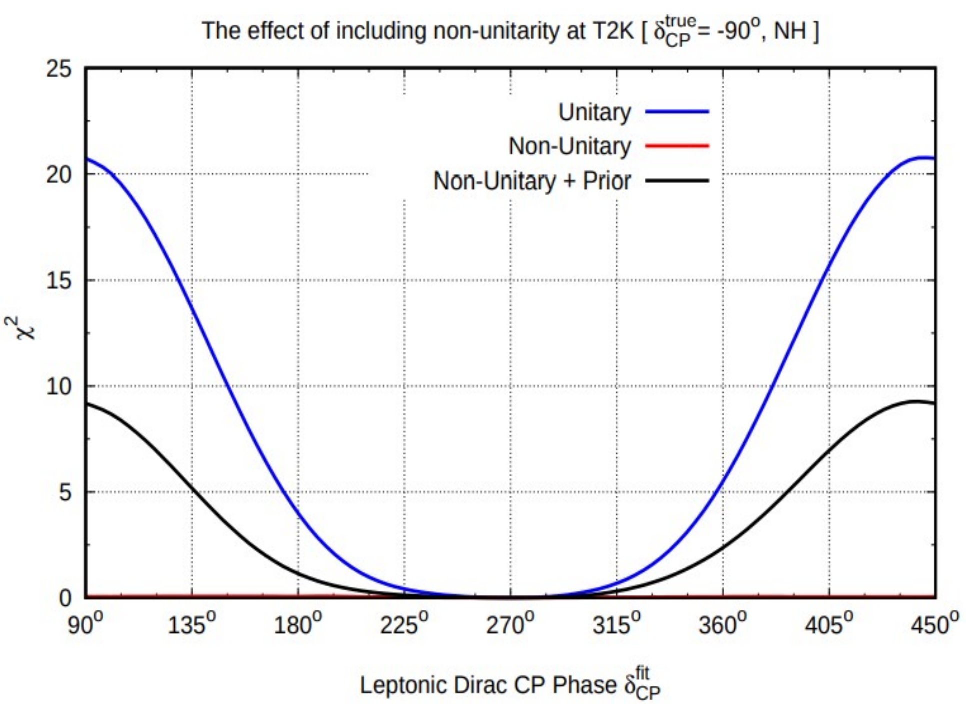
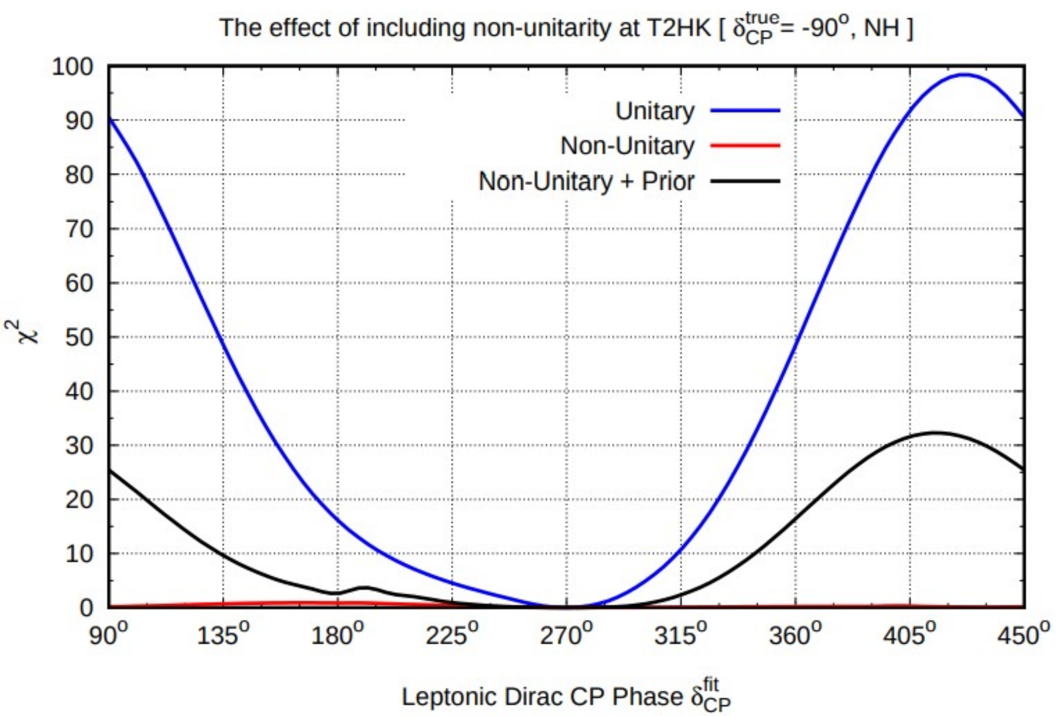
$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

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





SFG, Pasquini, Tortola & Valle [1605.01670]

4. NUM vs Seeaw Mechanism

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- **Heavy Neutrinos**

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

The diagonalization of the full mass matrix

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \Rightarrow M_\nu = -M_D \frac{1}{M_N} M_D^T$$

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

NUM is not exotic at all!

5. RG Running

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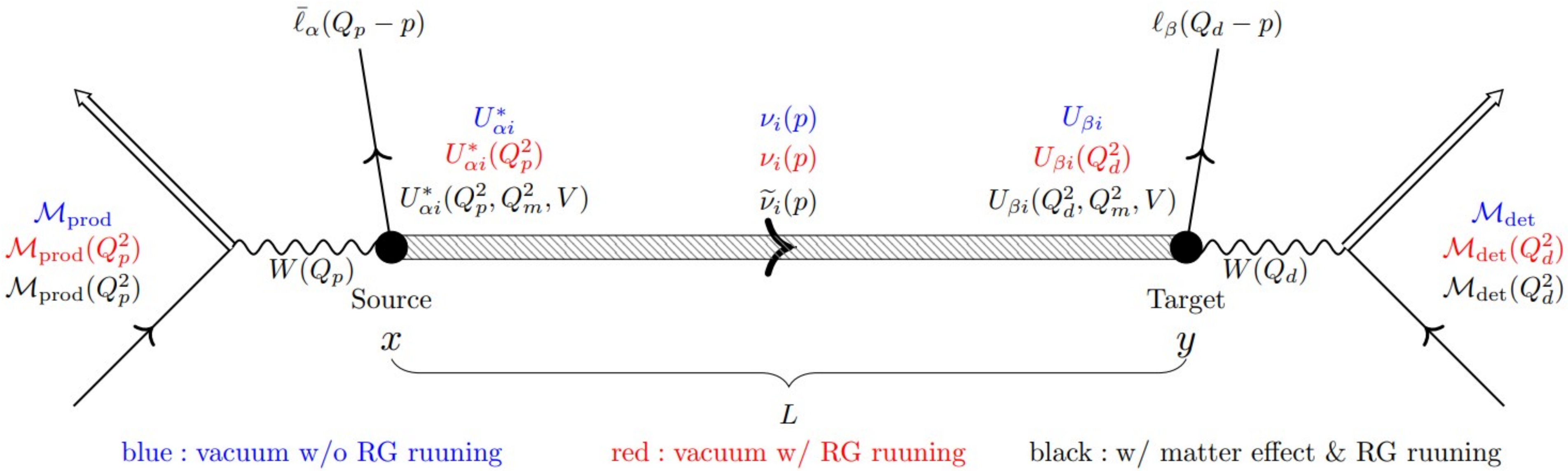
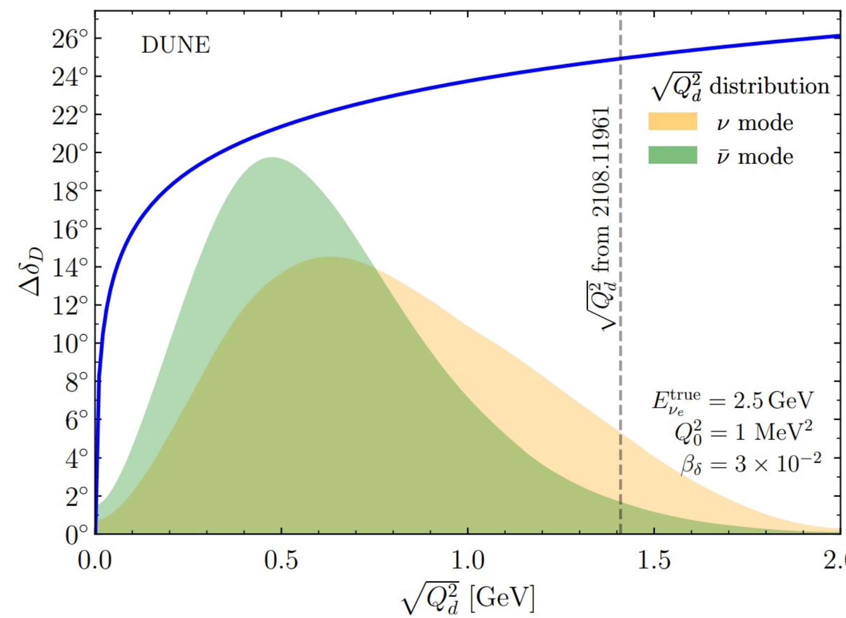


- **Mismatched Momentum**

$$\mathcal{A}^{\rm osc}_{\beta\alpha} = U_{\beta i}(Q_d^2) e^{-iL\frac{m_i^2}{2E_\nu}} U^*_{\alpha i}(Q_p^2)$$

$$P_{\alpha\beta} = \left| \left[U(Q_d^2) U^\dagger(Q_p^2) \right]_{\beta\alpha} \right|^2$$



SFG, Chui-Fan Kong, Pedro Pasquini [arXiv:2310.04077]

5. RG Running & CP Measurement

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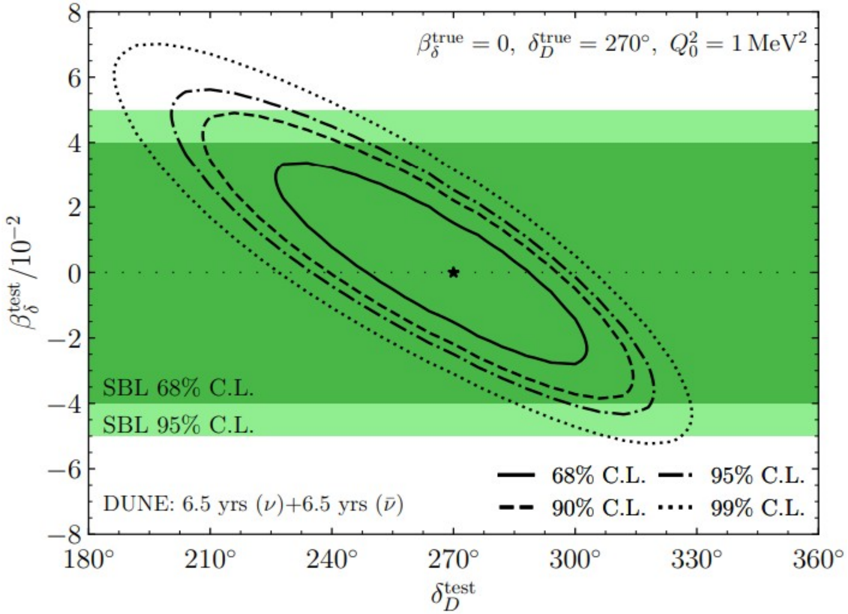
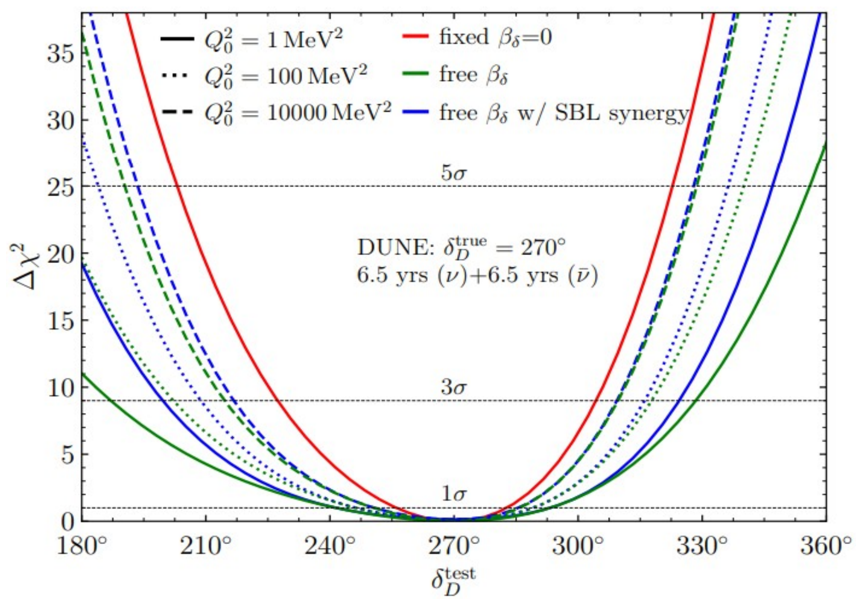




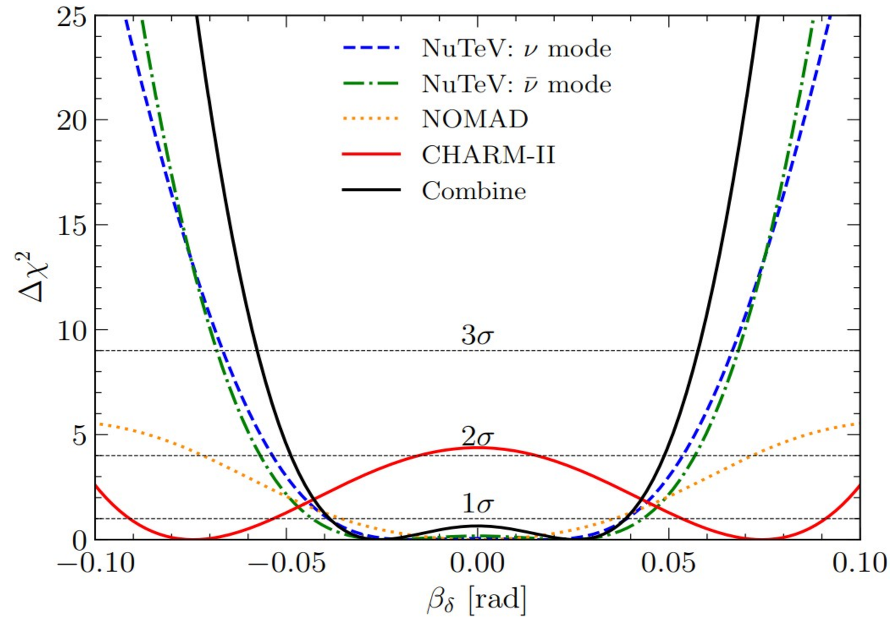
SFG, Chui-Fan Kong, Pedro Pasquini [arXiv:2310.04077]

- ## Zero Distance Effect

$$P_{ee}(Q_{d,p}^2) = 1 - \sin^2\left(\frac{\Delta\delta_D}{2}\right)\sin^2 2\theta_{13}$$

$$P_{\mu e}(Q_{d,p}^2) = \sin^2\left(\frac{\Delta\delta_D}{2}\right) s_{23}^2 \sin^2 2\theta_{13}$$

Short-Baseline Experiment (SBL):



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Accelerator ν Experiments

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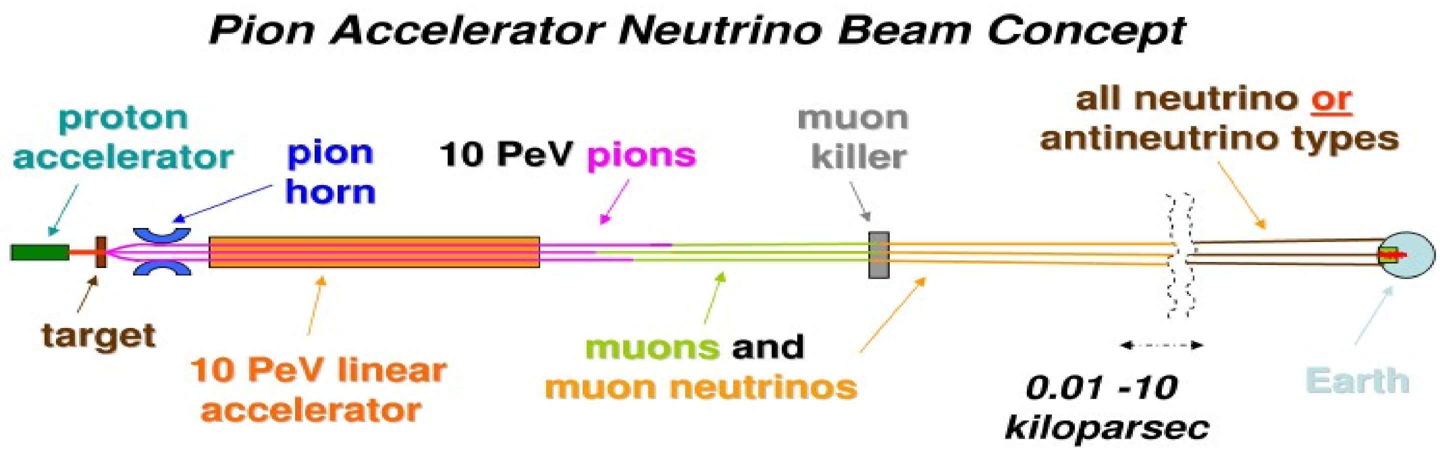

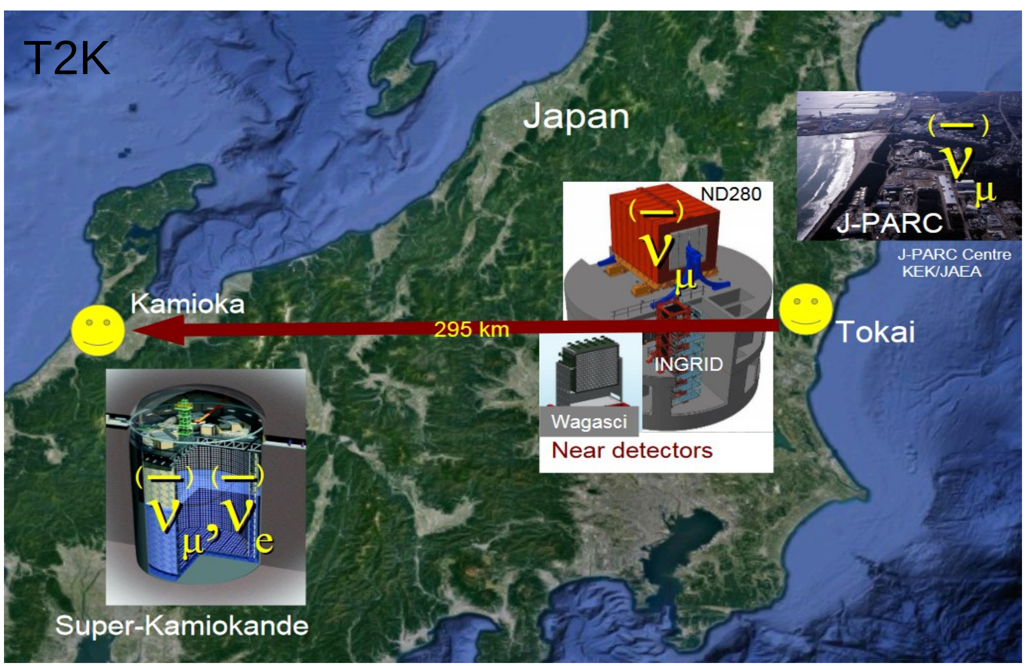

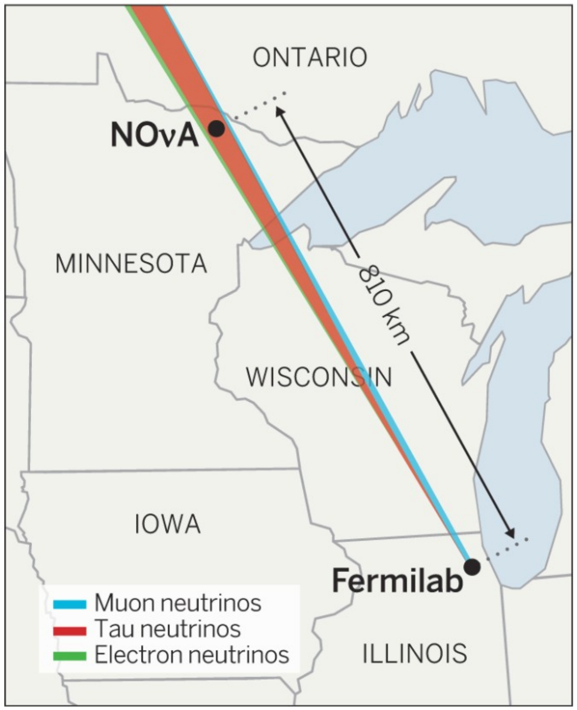

K. Engman, Science 345, 6204

Accelerator ν's by Lee & Yang

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Feasibility of Using High-Energy Neutrinos to Study the Weak Interactions

M. Schwartz
Phys. Rev. Lett. **4**, 306 – Published 15 March 1960

Theoretical Discussions on Possible High-Energy Neutrino Experiments

T. D. Lee and C. N. Yang
Phys. Rev. Lett. **4**, 307 – Published 15 March 1960

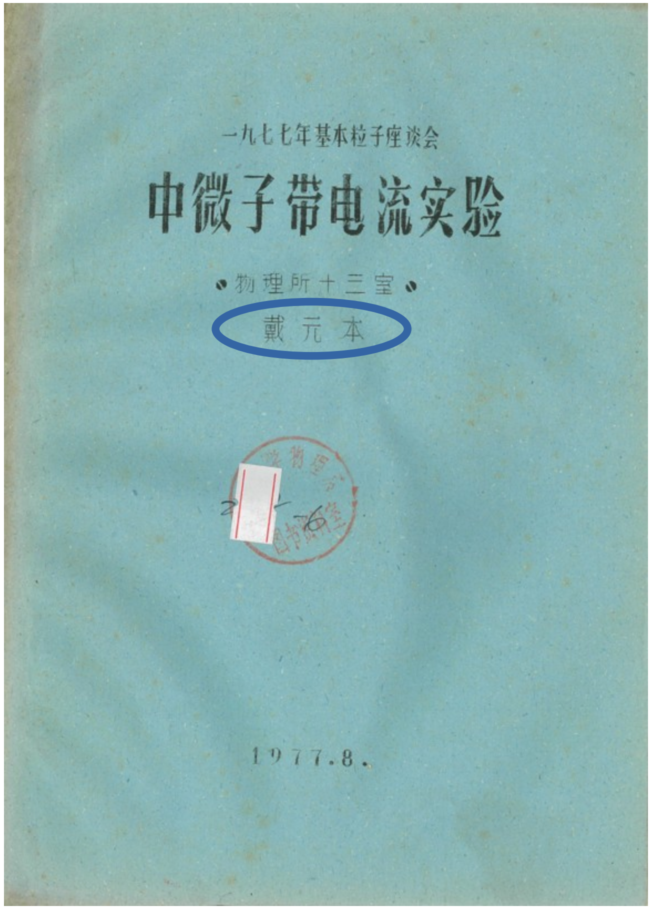
历史印记——60年前高能加速器中微子实验原理诞生

2021-01-04 50

作者：葛韶锋

这项60年前的工作，今天还在为粒子物理研究指引着前进的方向

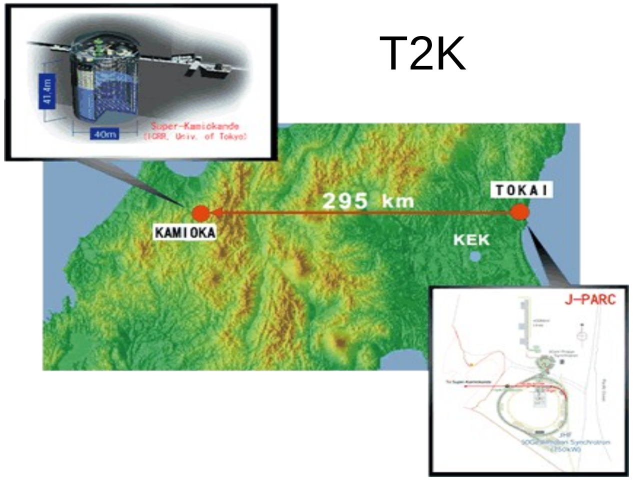
中微子是粒子物理标准模型中非常独特而重要的基本粒子。中微子只参与弱相互作用，能够穿透几光年的铅板，是非常难以探测的鬼魅粒子。然而，恰恰是中微子率先给出了超出标准模型的第一个新物理现象——中微子振荡——这已经得到大量实验的证实，并于2015年获诺贝尔物理学奖，成为指引超出标准模型新物理研究的重要线索。在上世纪五六十年代粒子物理发展的黄金期，施瓦兹、李政道与杨振宁提出的高能加速器中微子实验原理，是一个非常革命性的思想，一直在有力地推动着包括中微子在内的粒子物理不断向前发展。

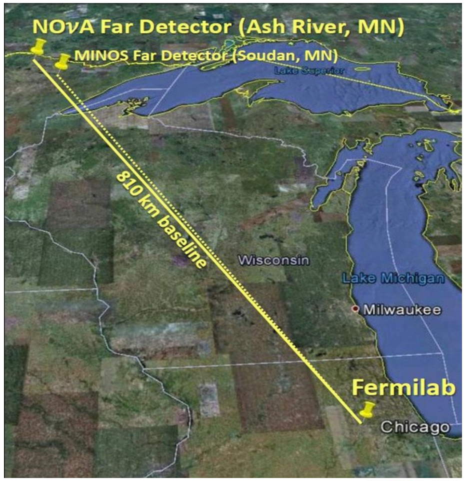


何小刚，李政道先生和现代中微子物理，《现代物理知识杂志》2021

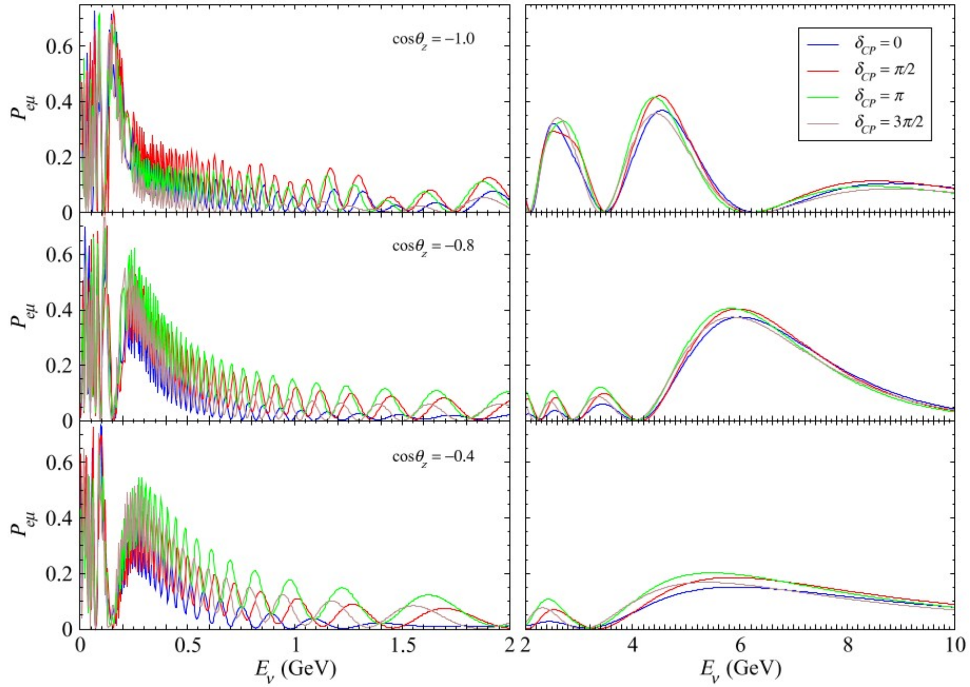
https://tdli.sjtu.edu.cn/CN/customize/436?columnId=35

Future Accelerator Exps





- Flux upgrade: **T2K-II**, **NOvA-II**?
- Detector upgrade: **T2HK**
- Baseline upgrade: **T2KK**, **T2KO**
- **MOMENT** — Cao et al [1401.8125] Tang et al [1909.01548]
- In China? — Tang, Vihonen & Xu [2202.13595] Li et al [2204.11871, 2205.15350, 2301.02493]
- Atmospheric



Super-PINGU: Razzaque & Smirnov [1406.1407]

JUNO: An et al [1507.05613], 2310.06281

DUNE: Kelly, Machado, Martinez-Soler, Parke & Perez-Gonzalez [1904.02751]

Super-ORCA: Hofestadt, Bruchner & Eberl [1907.12983]

狄拉克 CP 相角 δ_D

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- Oscillation probabilities @ Accelerator Neutrino Exps

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

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

- Run both ν & $\overline{\nu}$ modes @ first peak $[\phi_{31} = \frac{\pi}{2}, \phi_{21} = \alpha \frac{\pi}{2}]$, $\alpha = \frac{\delta M_{21}^2}{|\delta M_{31}^2|} \sim 3\%$

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

中微子、反中微子的振荡概率之间的差别 → 测量 CP 相角 δ_D。

CP Measurement & Issues

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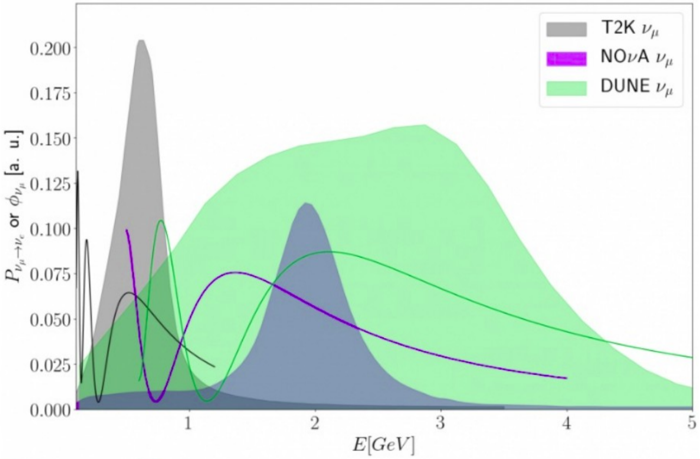
$$P_{\overline{\nu}_\mu \to \overline{\nu}_e} - P_{\nu_\mu \to \nu_e} = \alpha\pi \sin(2\theta_s)\sin(2\theta_r)\sin(2\theta_a)\cos\theta_r \sin\delta_D$$

@ 1st oscillation peak

- **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.



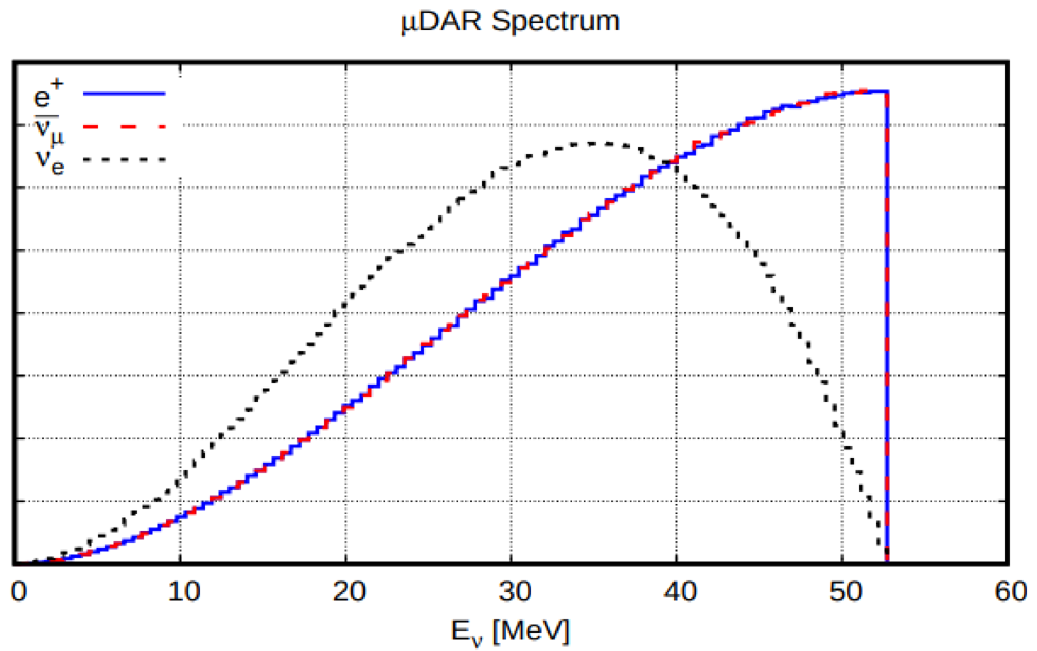
- **Degeneracy**:
  - Only $\sin\delta_D$ appears in $P_{\nu_\mu\to\nu_e}$ & $P_{\overline{\nu}_\mu\to\overline{\nu}_e}$.
  - Cannot distinguish δ_D from $\pi - \delta_D$.

- **CP Uncertainty** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos\delta_D \Rightarrow \Delta(\delta_D) \propto 1/\cos\delta_D$

SFG [1704.08518, PoS NuFact2019 (2020) 108]

Solution: Muon Decay at Rest

- 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: $\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e$



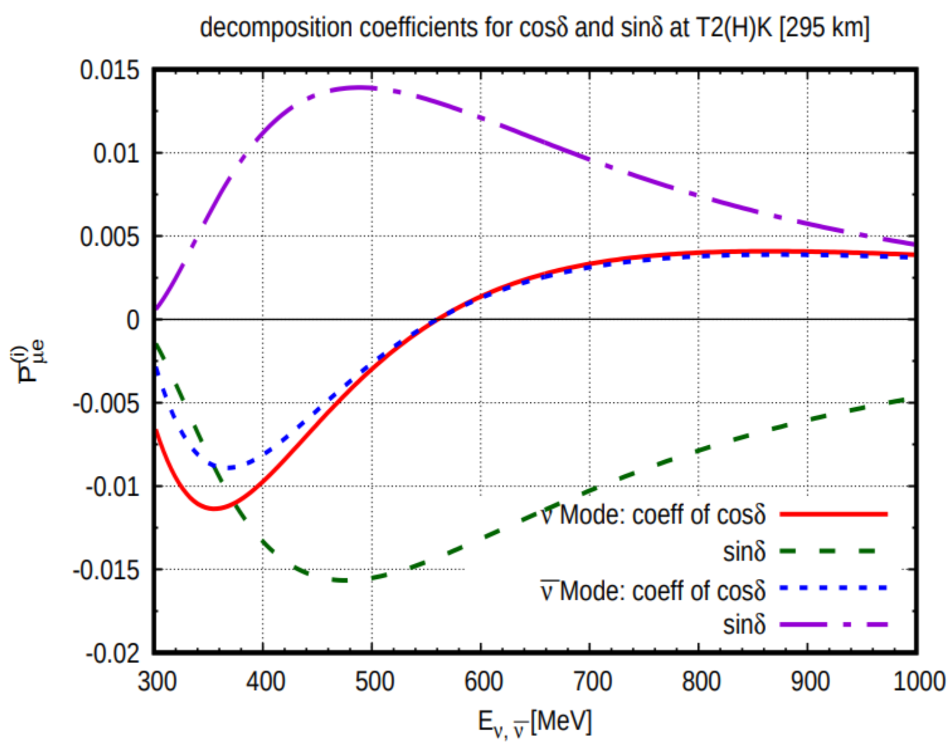
Well predicted spectrum!

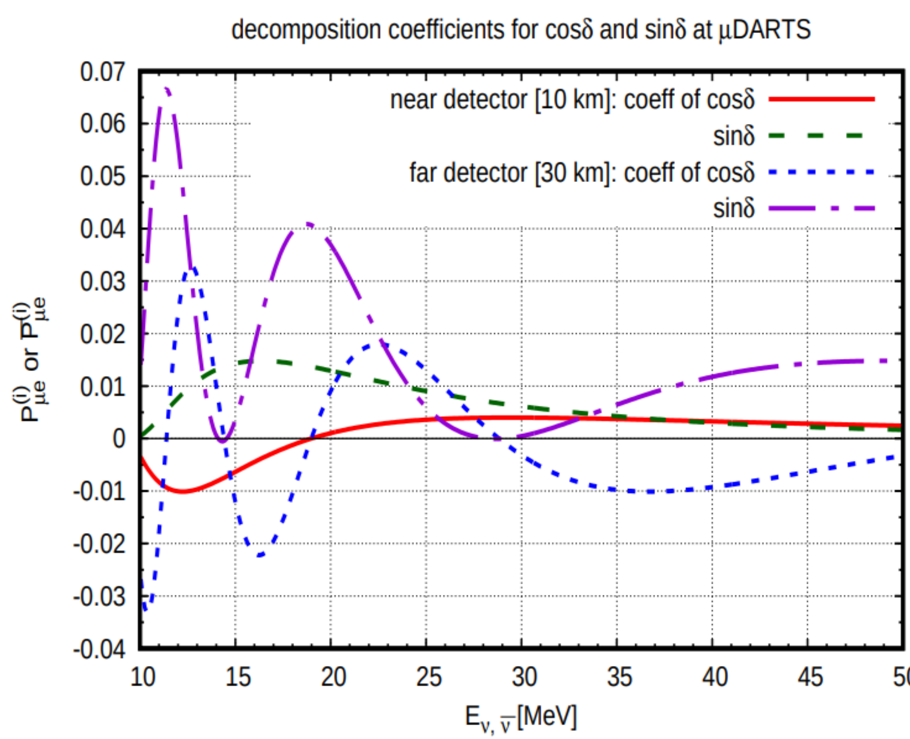
- $\overline{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_e$ from $\overline{\nu}_\mu \to \overline{\nu}_e$ **oscillation**.

μDAR & Accelerator ν

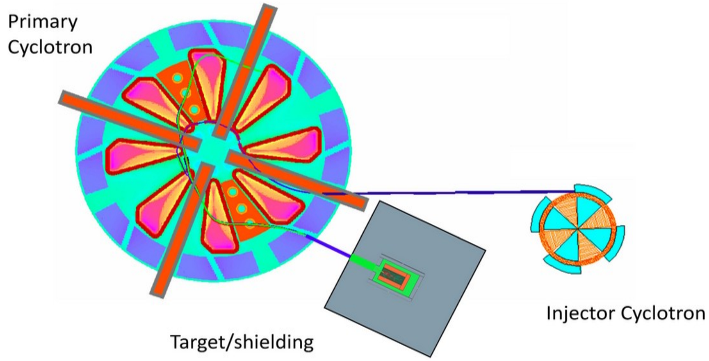
Combining $\nu_\mu \to \nu_e$ @ **accelerator** [narrow **peak @ 550 MeV**] & $\overline{\nu}_\mu \to \overline{\nu}_e$ @ μ**DAR** [wide **peak ∼ 45 MeV**] solves the 2 problems:

- **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])

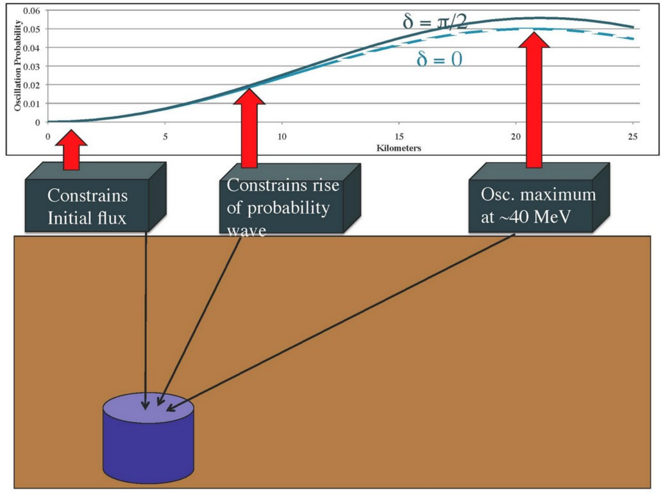




DAEδALUS with μDAR



$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$



戴达罗斯（希腊神话中的建筑师、工匠）

- **Disadvantages**:
  - The scattering lepton from IBD @ low energy is **isotropic**.
  - **Cannot** distinguish $\bar{\nu}_e$ from different sources
  - Baseline **cannot be measured**.
  - Cyclotrons **cannot** run simultaneously (20∼25% duty factor).
  - **Large** statistical uncertainty.
  - **Higher intensity** is necessary.
  - **Expensive** & Technically **challenging**.

$$\bar{\nu}_e + p \to e^+ n$$

Conrad & Shaevitz [0912.4079]

Agarwalla, Huber, Link & Mohapatra [1005.4055]

DAEdALUS [1006.0260, 1307.2949]

New Proposal

Tsung-Dao Lee Institute

1 μDAR source + **2** detectors

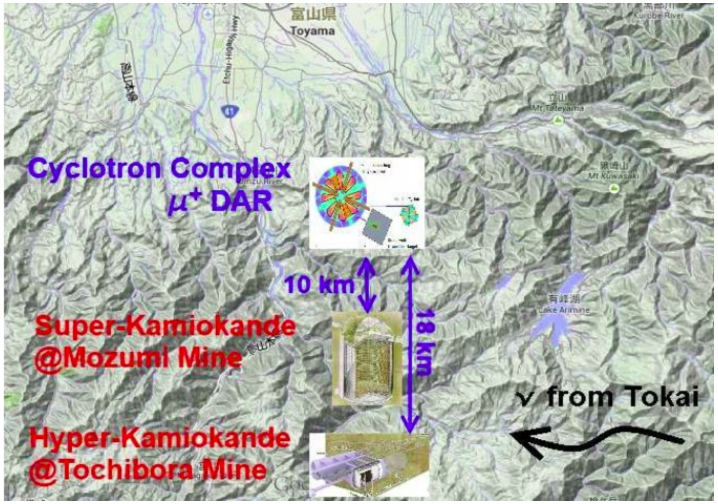
Advantages

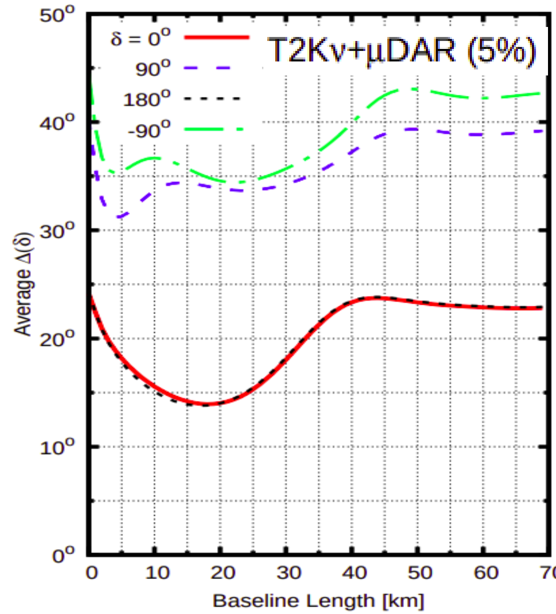
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**$\times$ lower than DAEδALUS]
- Not far beyond the current state-of-art technology of cyclotron [**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
  - Only one cyclotron.
  - Lower intensity.

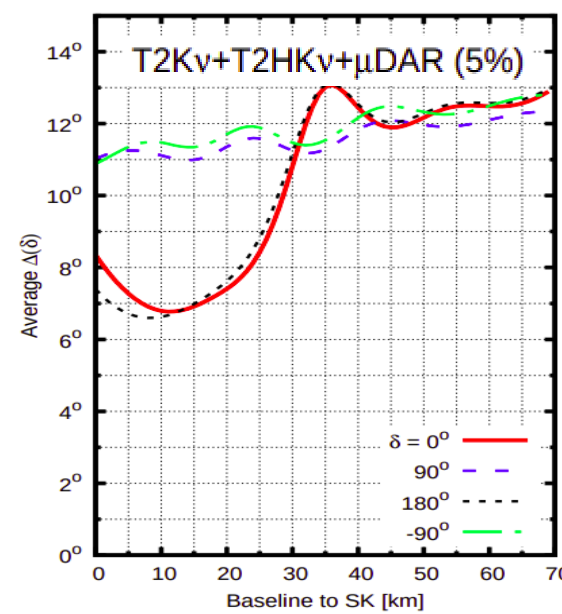
Disadvantage: **A second detector!**

- $\boldsymbol{\mu}$**DAR** with **T**wo **S**cintillators (μ**DARTS**) [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







1 μDAR source + 2 detectors

Evslin, **SFG**, Hagiwara [1506.05023]
SFG, Pasquini, Tortola, Valle [1605.01670]
SFG, Smirnov [1607.08513]

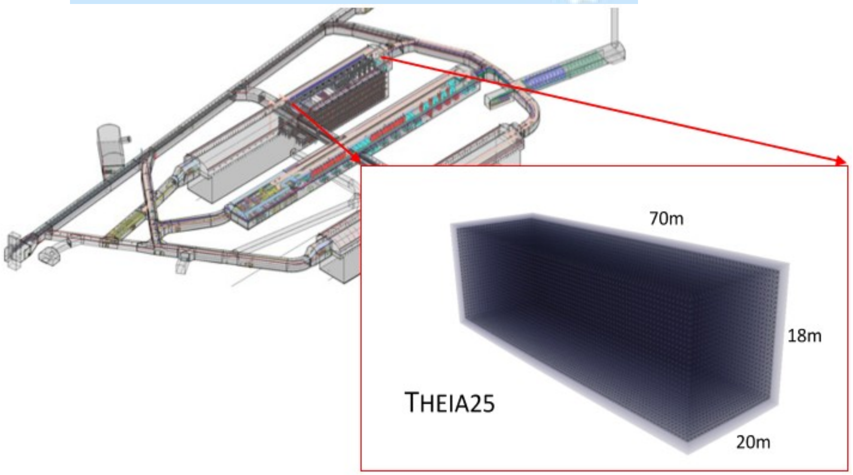
Advantages

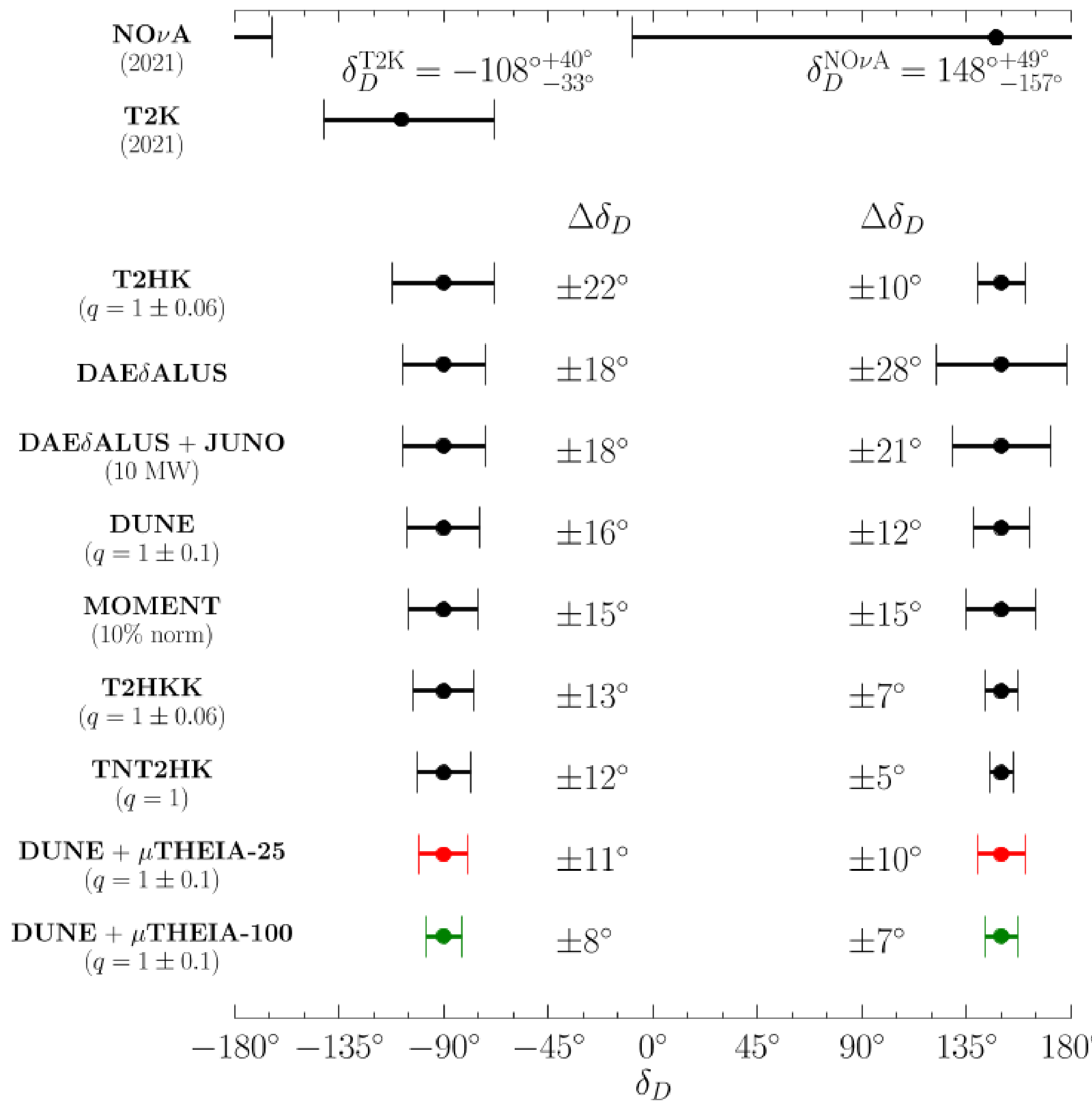
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**$\times$ lower than DAEδALUS]
- Not far beyond the current state-of-art technology of cyclotron [**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
  - Only one cyclotron.
  - Lower intensity.

Disadvantage: A second detector!

Harnik, Kelly & Machado [1911.05088]

μTHEIA+DUNE





THEIA [1911.03501, 2202.12839]

SFG, Kong, Pasquini, Eur.Phys.J.C 82 (2022) 6, 572 [2202.05038]

Guarantee CP against NSI

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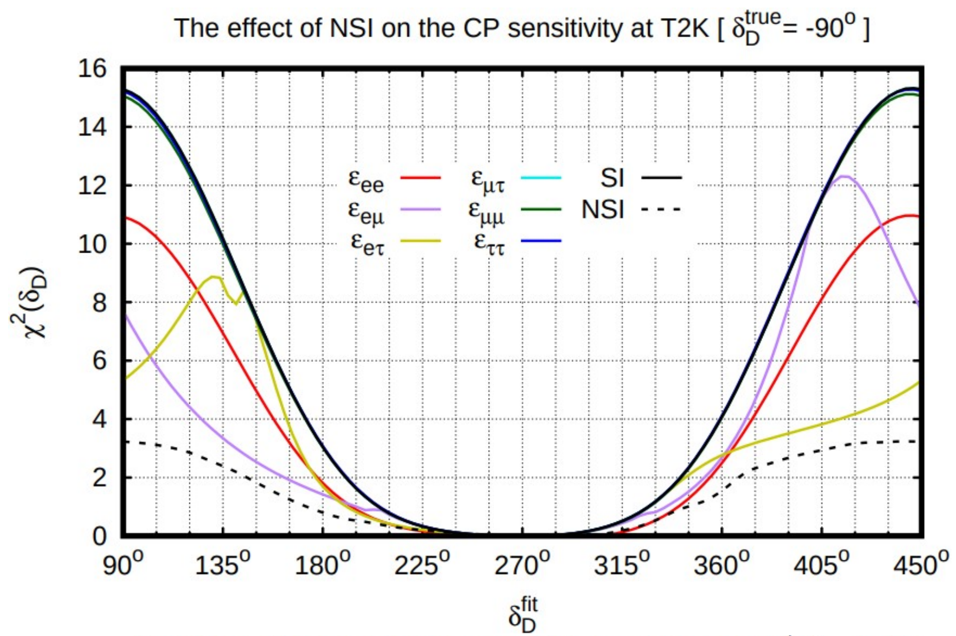

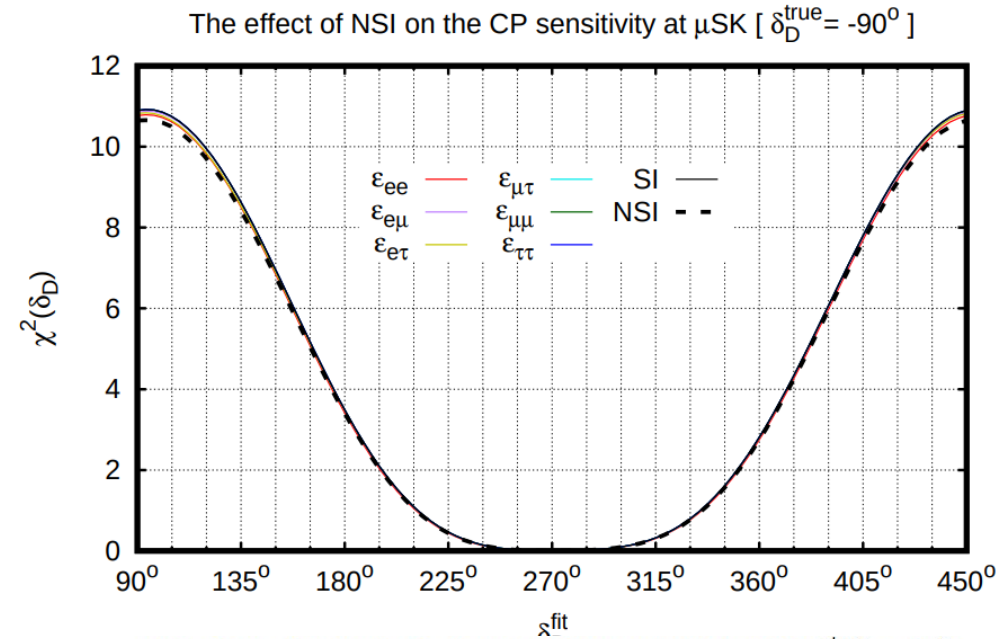

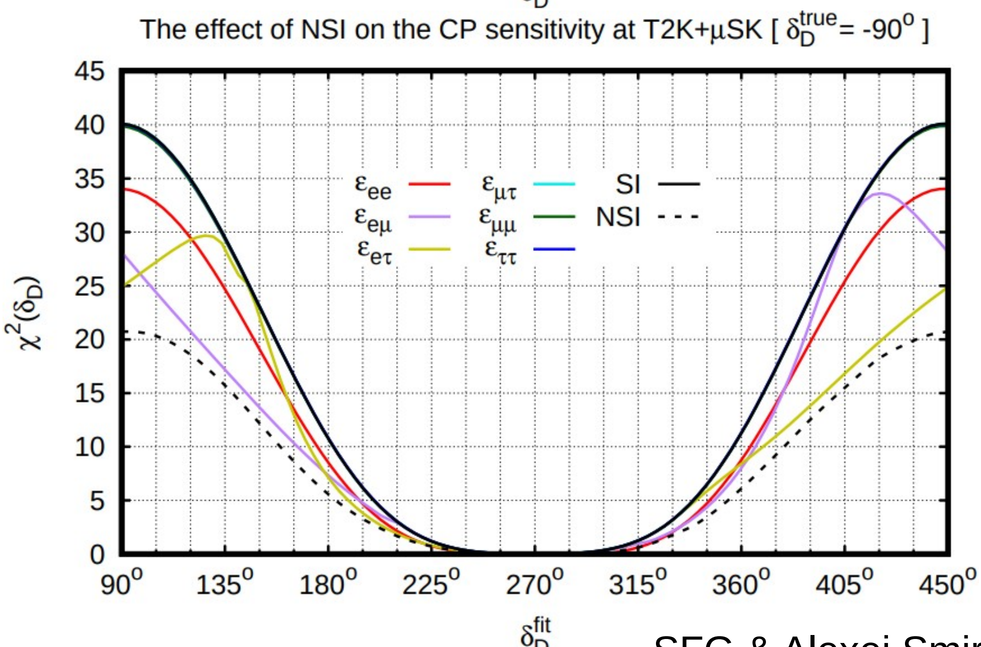

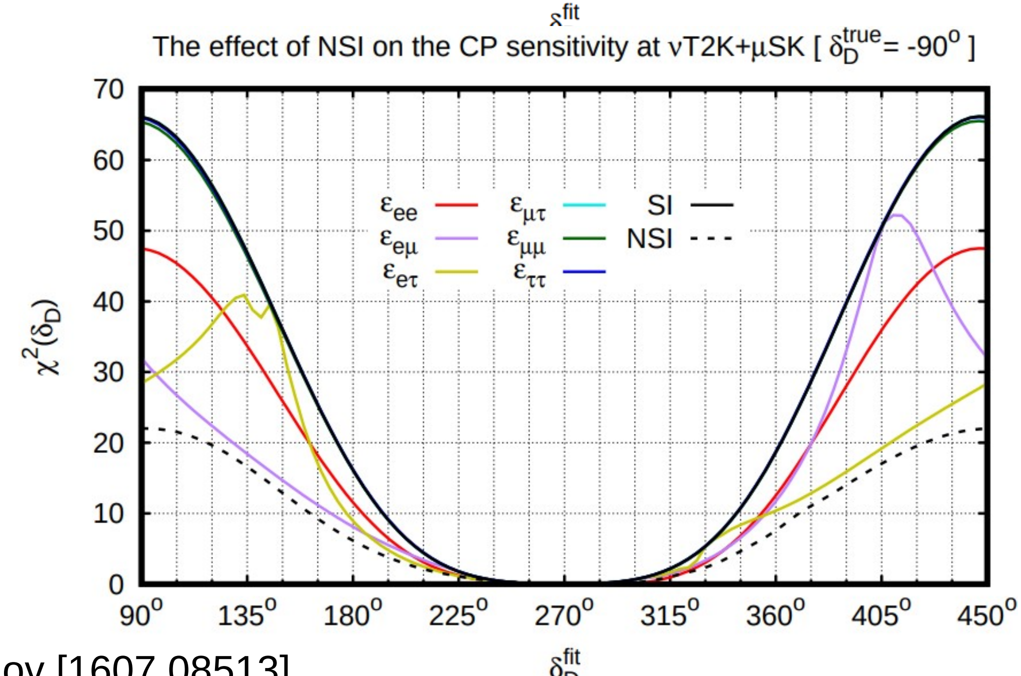

SFG & Alexei Smirnov [1607.08513]

NUM Zero Distance Effect

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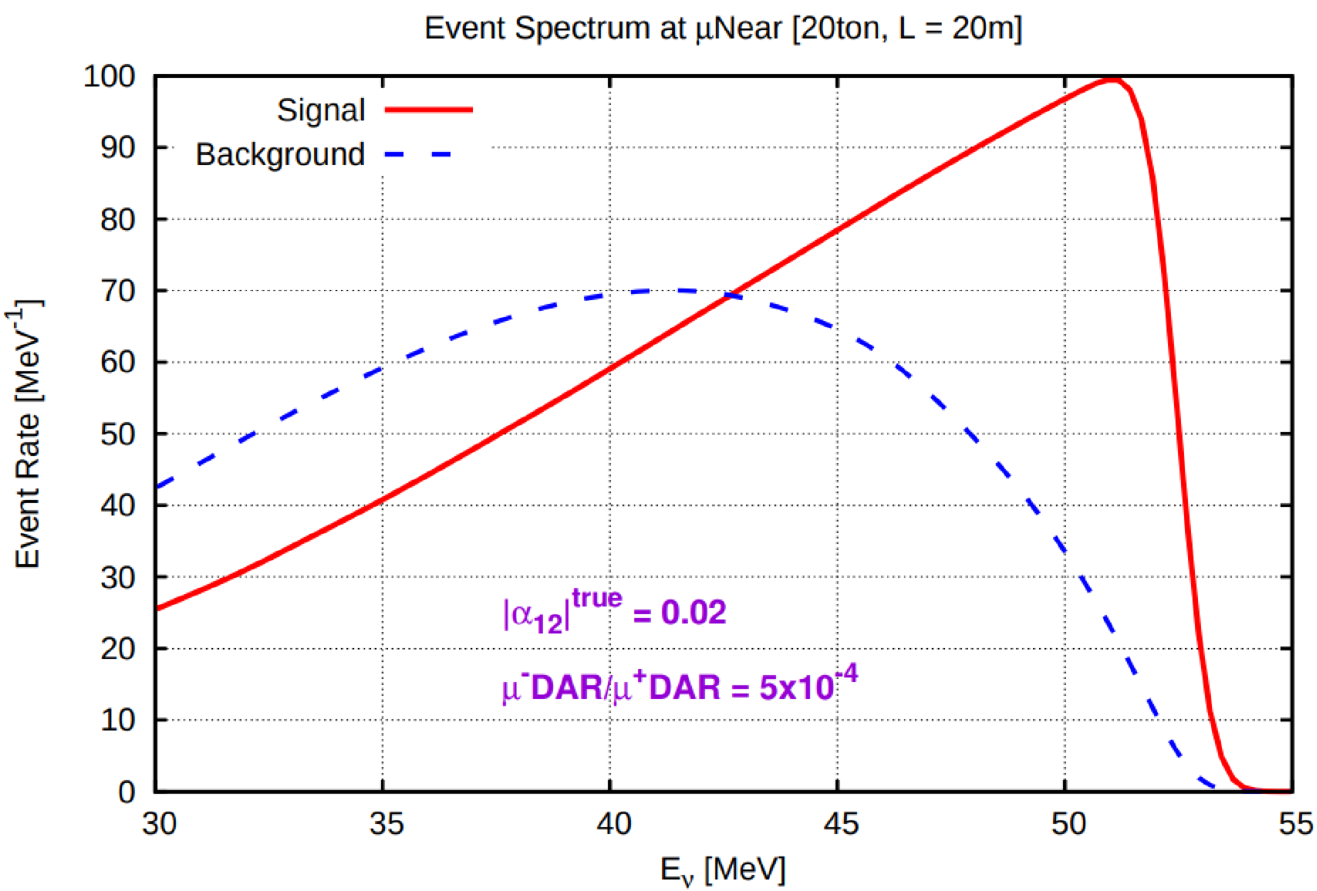
$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

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



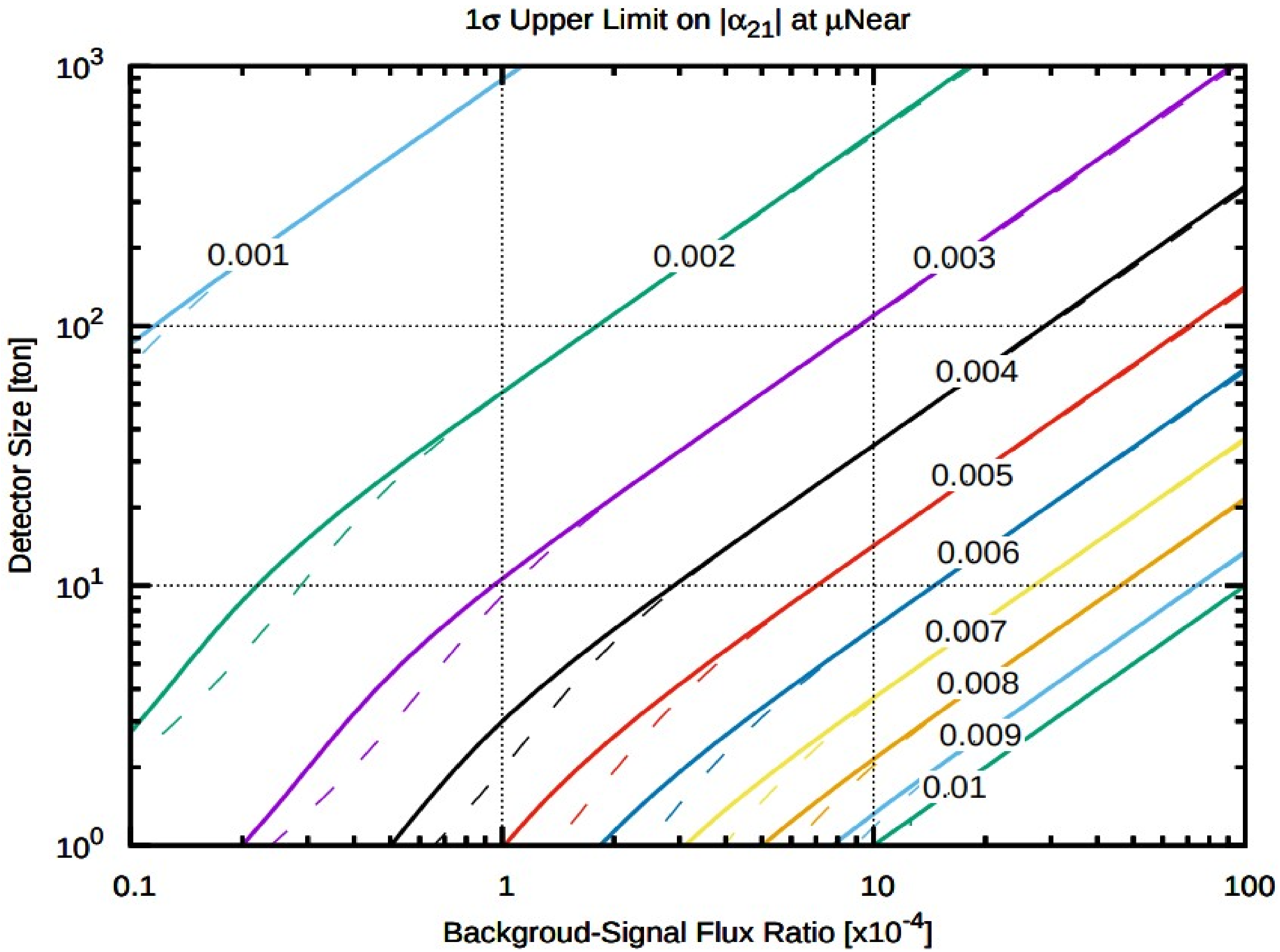
Transition @ L → 0

SFG, Pasquini, Tortola & Valle [1605.01670]

μNear @ μDAR

Tsung-Dao Lee Institute

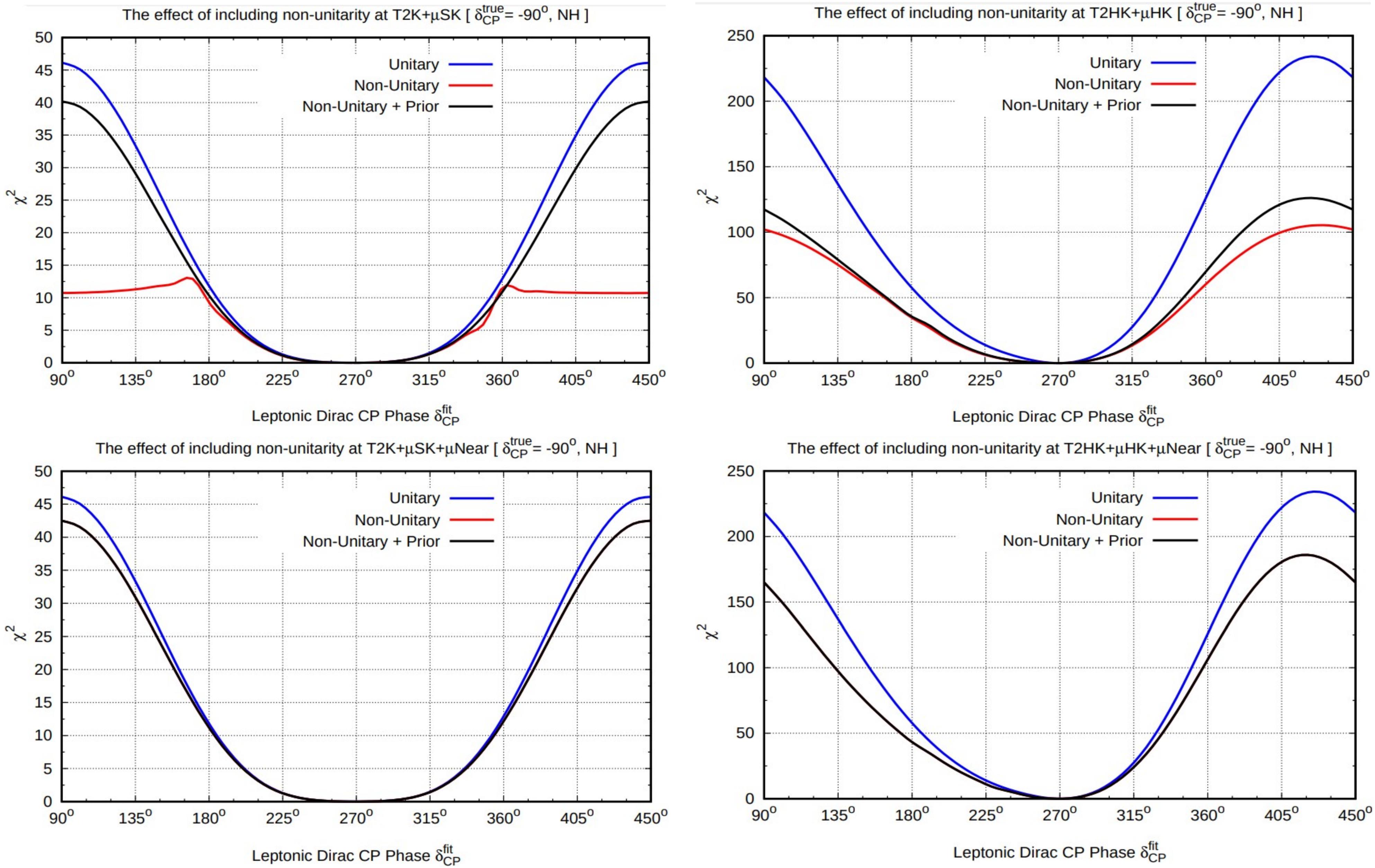
$$P^{NP}_{\mu e}(L \to 0) = \alpha_{11}^2 |\alpha_{21}|^2 P_{ee} \approx \alpha_{11}^2 |\alpha_{21}|^2 \approx |\alpha_{21}|^2$$



SFG, Pasquini, Tortola & Valle [1605.01670]

TNT2K + μNear

Tsung-Dao Lee Institute



SFG, Pasquini, Tortola & Valle [1605.01670]

Summary

- CP Violation in the Precision Era
- Dirac CP Phase & New Physics
  1. Non-Standard Interactions (NSI)
  2. Scalar NSI
  3. Dark NSI
  4. Non-Unitary Mixing (NUM)
  5. RG Running
- Accelerator + μDAR for better CP measurement
  1. TNT2K
  2. μTHEIA

Thank You

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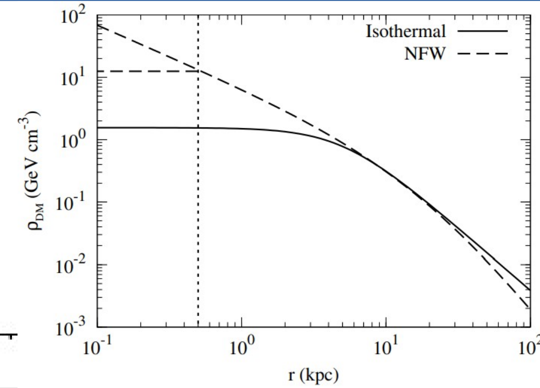
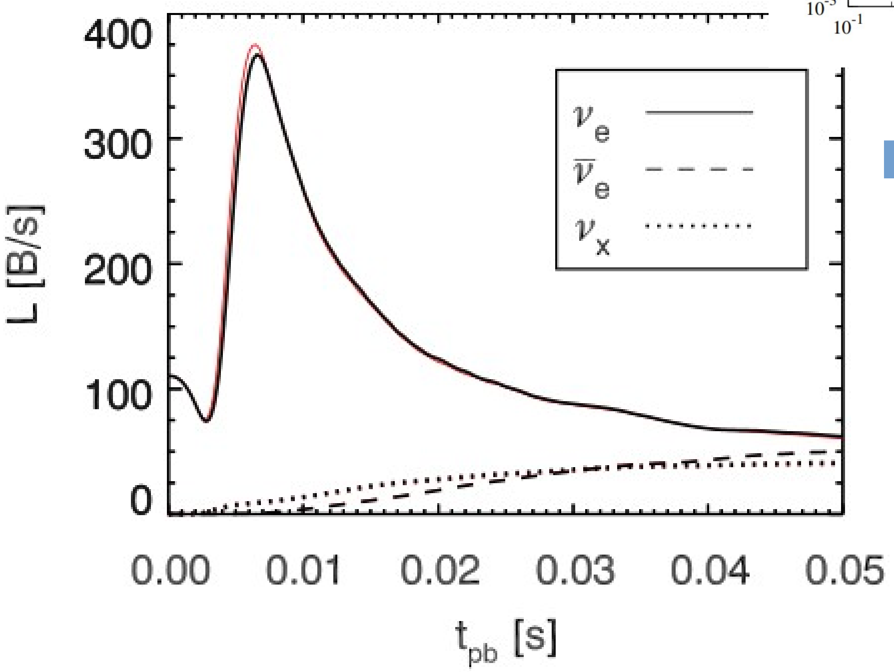
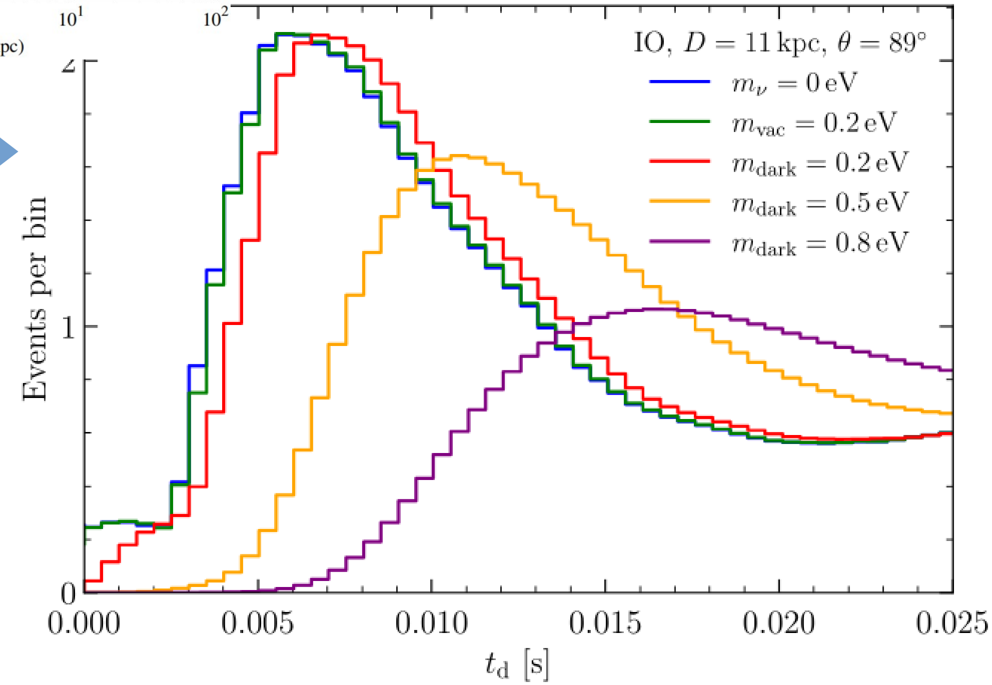
Backup Slides

Dark Mass with SN



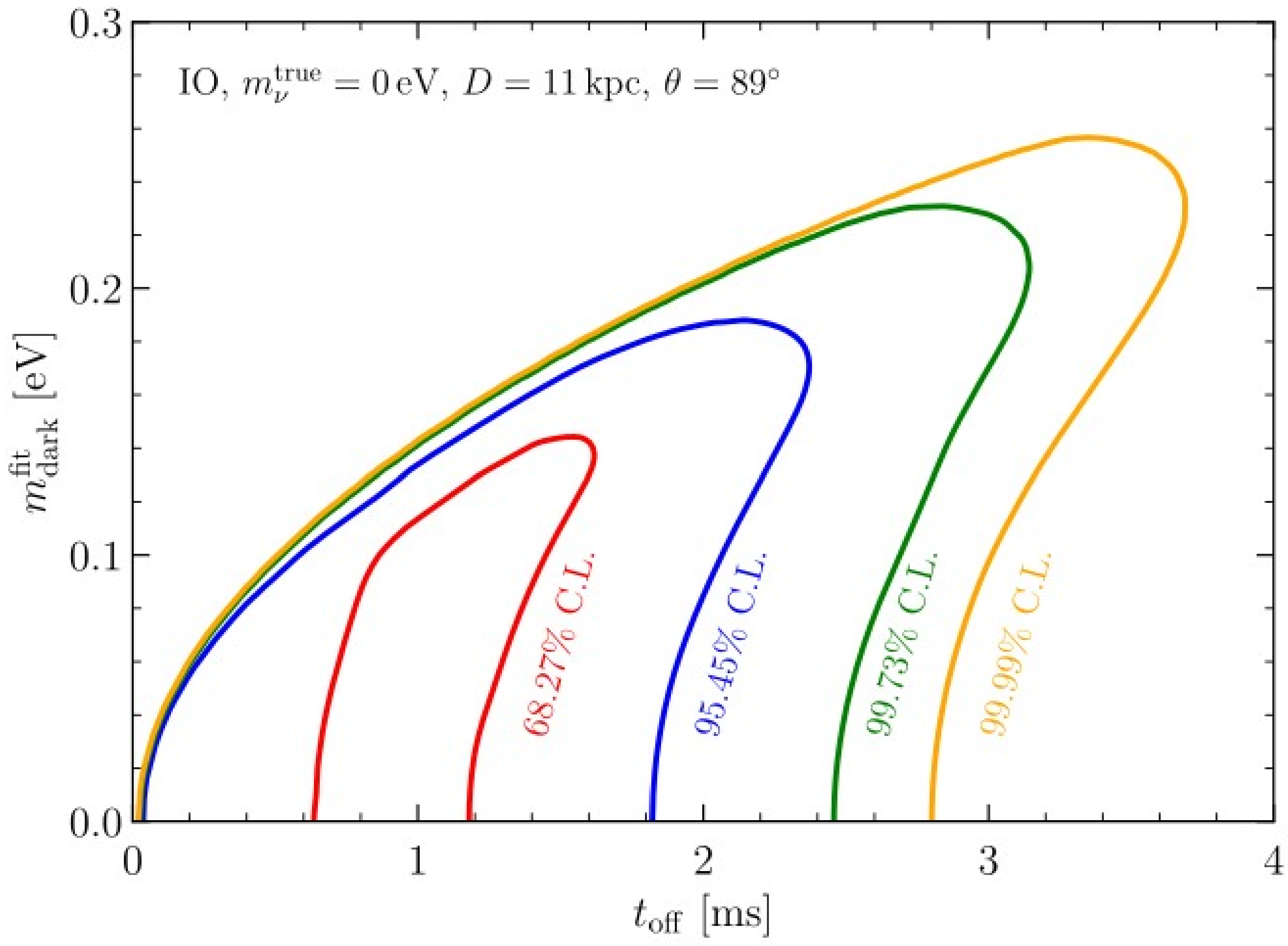




$$\Delta t_{\rm dark} = \frac{m^2_{\rm dark}(\mathbf{x}_\odot) D}{2E^2_\nu} \frac{\int_{\mathbf{x}_\star}^{\mathbf{x}_\odot} \rho_\phi(\mathbf{x})|d\mathbf{x}|}{D\rho_\phi(\mathbf{x}_\odot)} \equiv \Delta t_\odot \frac{\overline{\rho_\phi}(\mathbf{x}_\star)}{\rho_\phi(\mathbf{x}_\odot)}$$

SFG, Chui-Fan Kong, Alexei Smirnov [2404.17352]

Dark Mass with SN

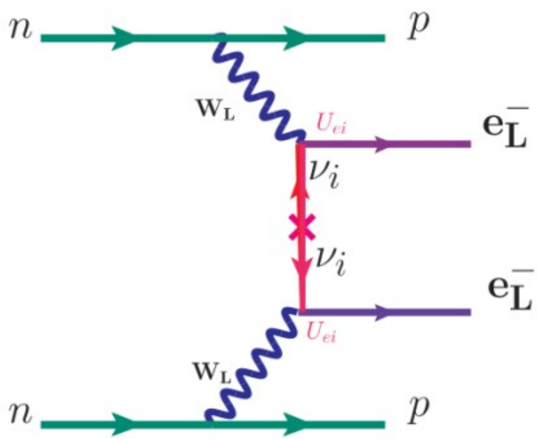


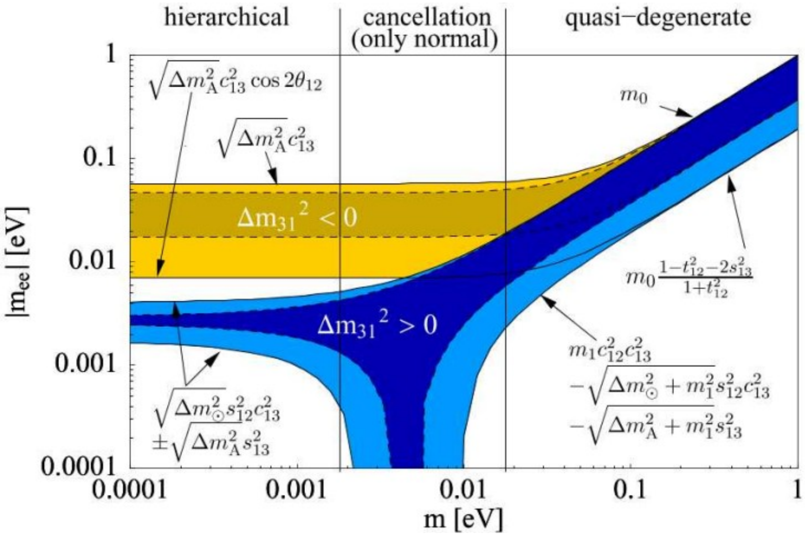
$$\Delta t_{\rm dark} = \frac{m^2_{\rm dark}(\mathbf{x}_\odot) D}{2E_\nu^2} \frac{\int_{\mathbf{x}_\star}^{\mathbf{x}_\odot} \rho_\phi(\mathbf{x})|d\mathbf{x}|}{D\rho_\phi(\mathbf{x}_\odot)} \equiv \Delta t_\odot \frac{\overline{\rho_\phi}(\mathbf{x}_\star)}{\rho_\phi(\mathbf{x}_\odot)}$$

SFG, Chui-Fan Kong, Alexei Smirnov [2404.17352]

Neutrinoless Double Beta Decay

- Mediated by **Majorana Neutrino** + **Lepton # Violation**





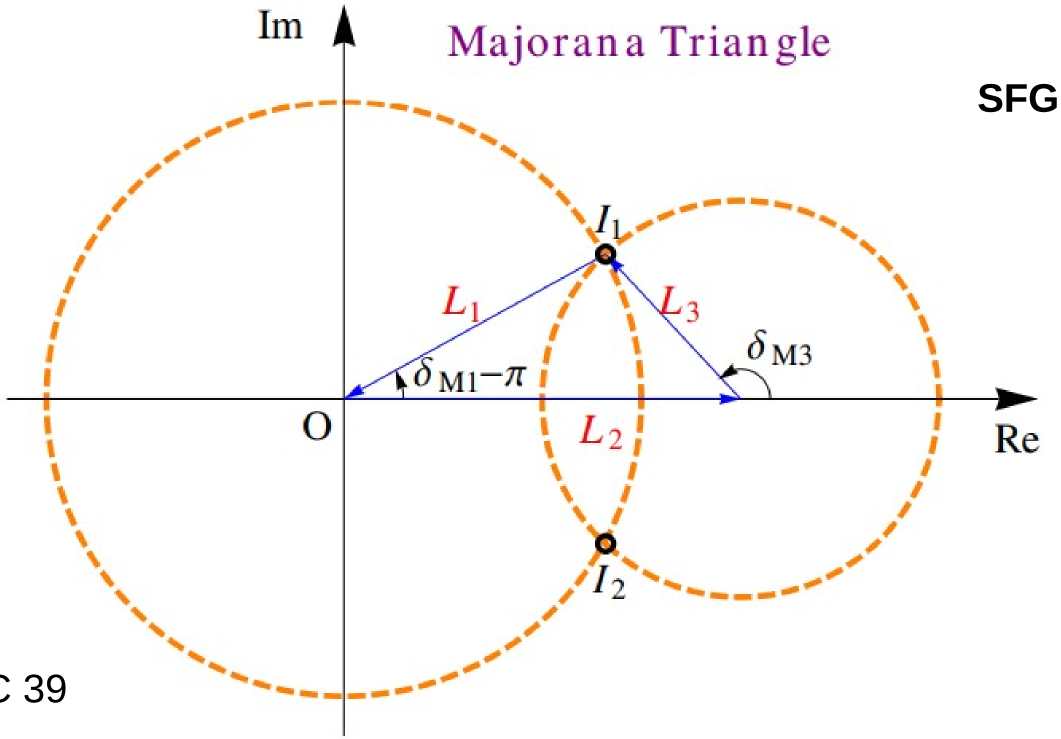
- **Mass Suppression**

$$\mathcal{M} \propto \sum_i U_{ei} \frac{i}{\not{p} - m_i} U_{ei} \approx \sum_i U_{ei} \frac{m_i}{p^2} U_{ei}$$

- **Effective Mass**

$$\langle m \rangle_{ee} \equiv \left| \sum_i m_i U_{ei}^2 \right| = \left| c_s^2 c_r^2 m_1 e^{i\delta_{M1}} + s_s^2 c_r^2 m_2 + s_r^2 m_3 e^{i\delta_{M3}} \right|$$

Majorana Triangle



SFG & Manfred Lindner, PRD 95 (2017) No.3, 033003 [arXiv:1608.01618]

Xing & Zhou, Chin.Phys.C 39 (2015) [arXiv:1404.7001]

$$\langle m \rangle_{ee} \equiv \overrightarrow{L_1} + \overrightarrow{L_2} + \overrightarrow{L_3}$$

$$\overrightarrow{L_1} \equiv m_1 U_{e1}^2 = m_1 c_r^2 c_s^2 e^{i\delta_{M1}} ,$$

$$\overrightarrow{L_2} \equiv m_2 U_{e2}^2 = \sqrt{m_1^2 + \Delta m_s^2} c_r^2 s_s^2 ,$$

$$\overrightarrow{L_3} \equiv m_3 U_{e3}^2 = \sqrt{m_1^2 + \Delta m_a^2} s_r^2 e^{i\delta_{M3}} .$$

Catching 2 Majorana CP Phases

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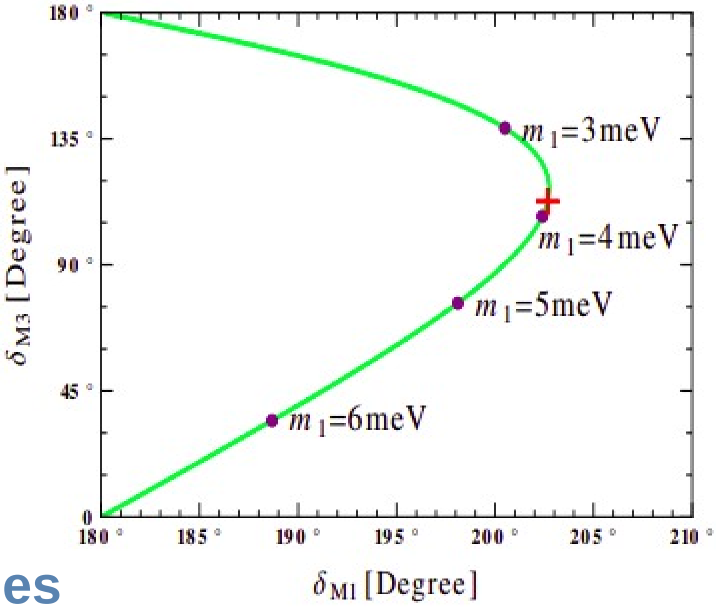
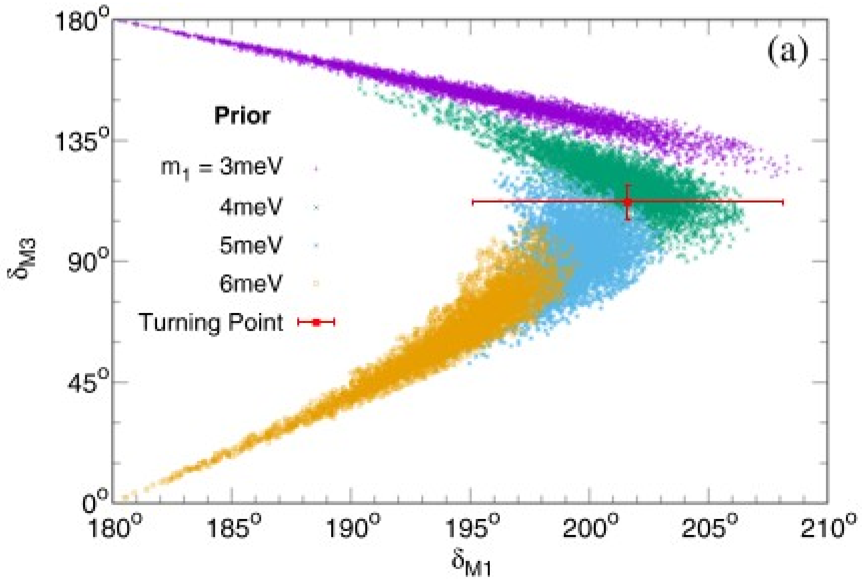
$$\cos \delta_{M1} = -\frac{m_1^2 c_r^4 c_s^4 + m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_1 m_2 c_r^4 c_s^2 s_s^2}$$

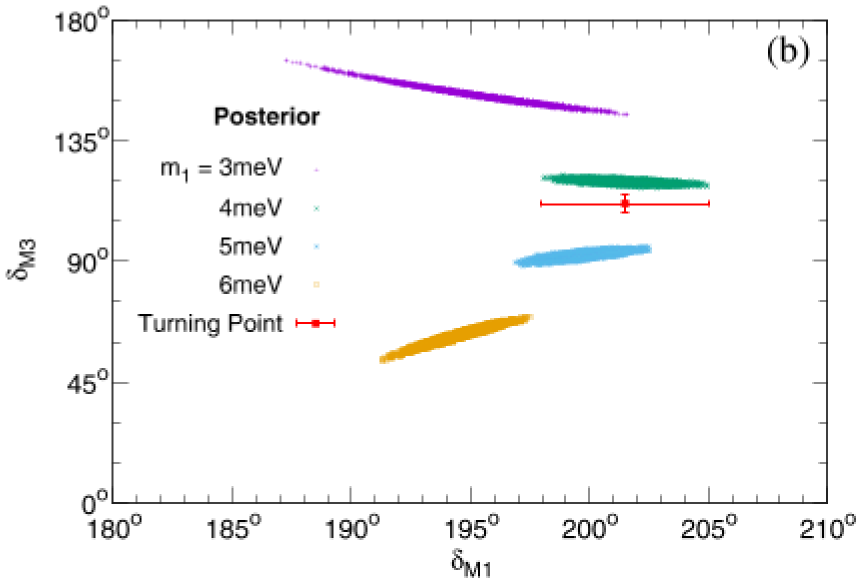
$$\cos \delta_{M3} = +\frac{m_1^2 c_r^4 c_s^4 - m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_2 m_3 c_r^2 s_r^2 s_s^2}$$



- JUNO can significantly reduce uncertainties



SFG & Manfred Lindner, [1608.01618]



see also **SFG** & Rodejohann [1507.05514]

Uncertainty from m_{ee}

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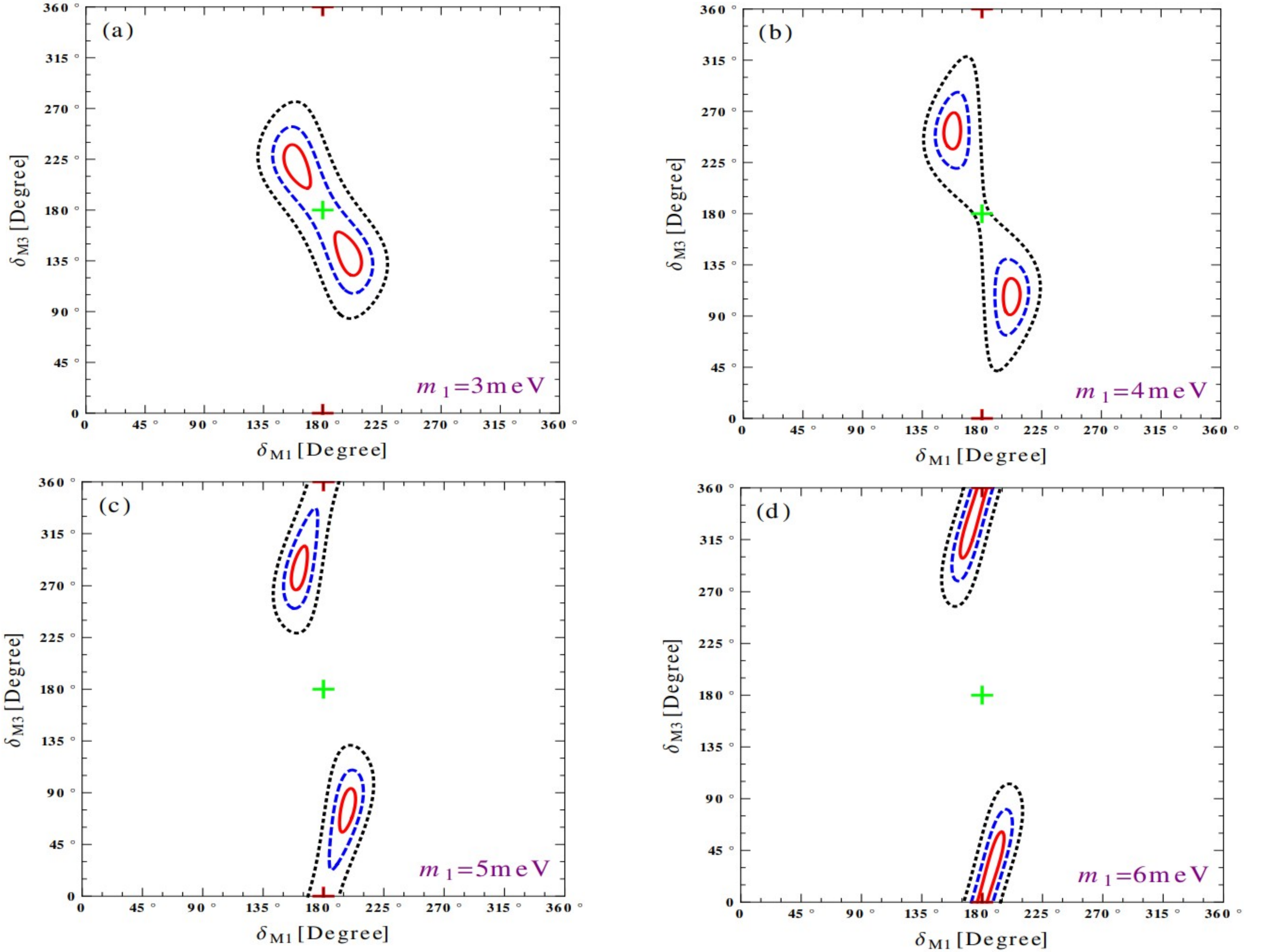
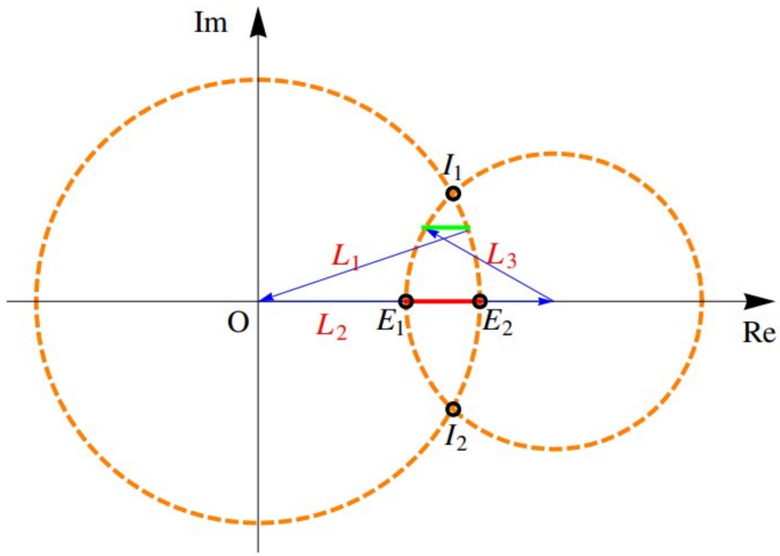
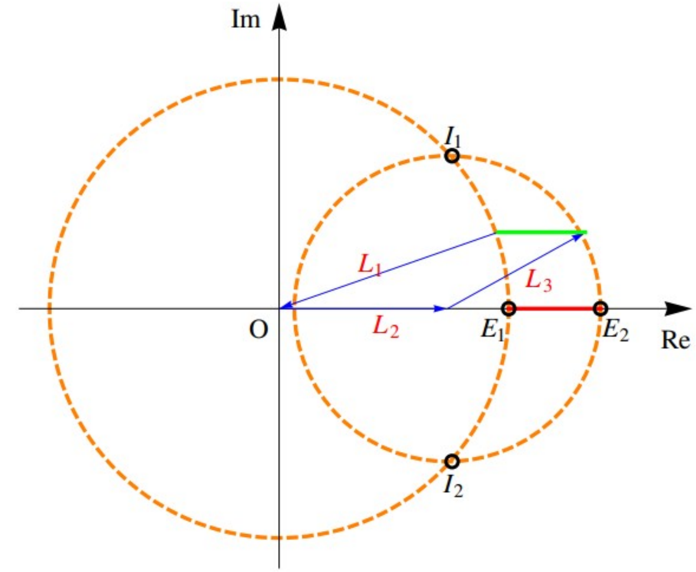
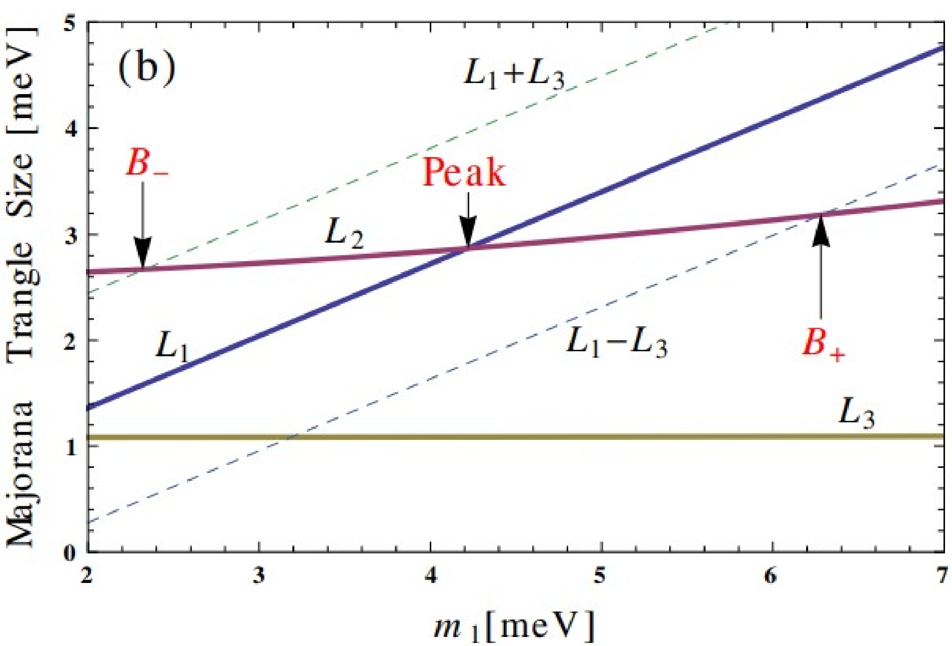
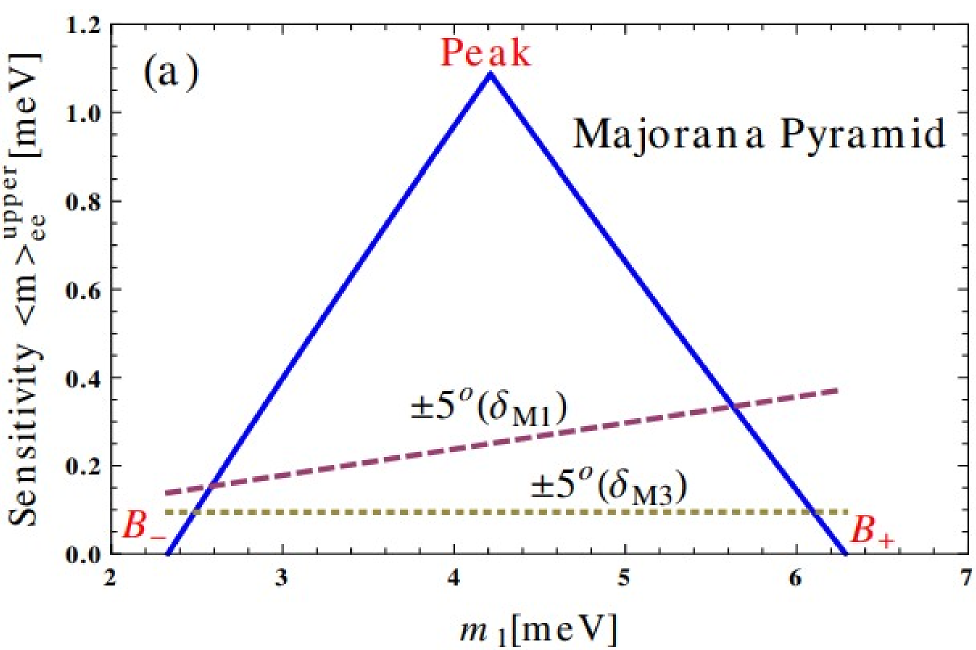


Majorana Pyramid









1meV frontier of 0ν2β

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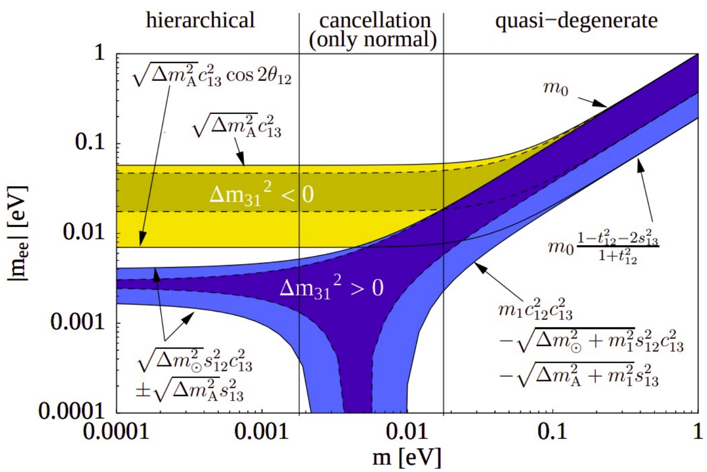


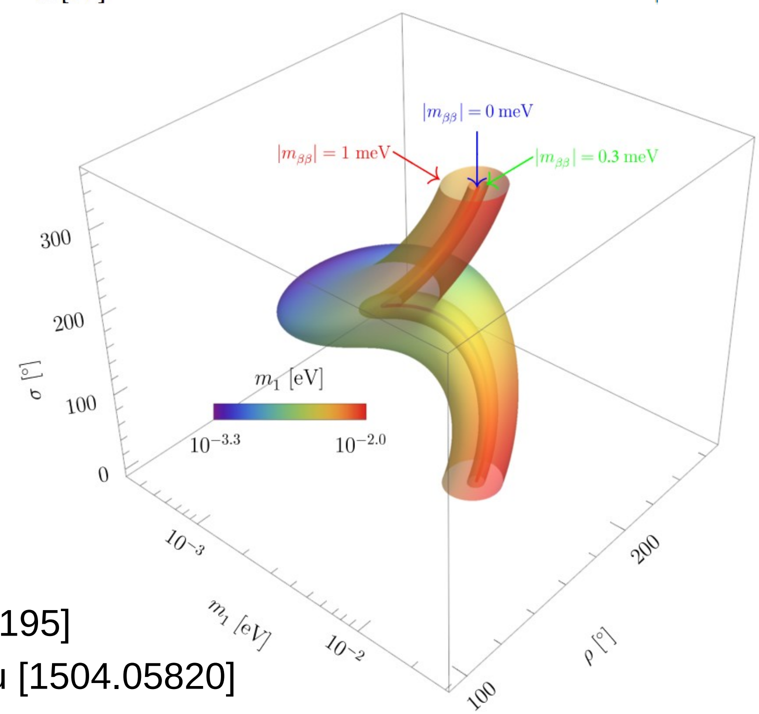
- **Nonzero → only 1 Majorana CP**

$$|m_{ee}| = f$$

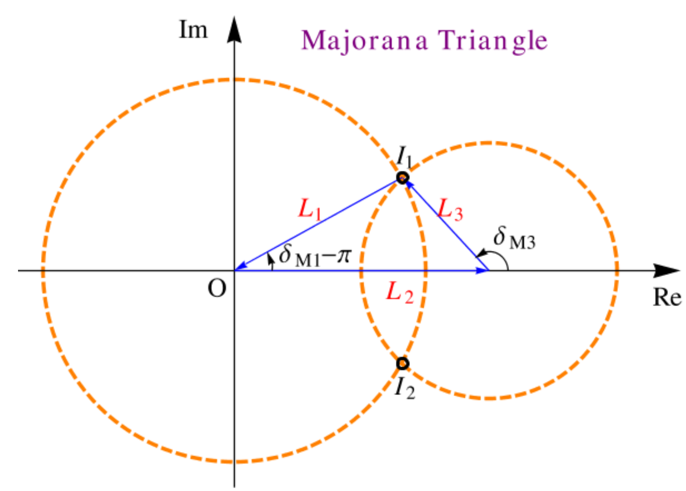
- **Zero → 2 Majorana CP phases**

$$|m_{ee}| = 0 \quad \Rightarrow \quad \mathbb{R}(m_{ee}) = \mathbb{I}(m_{ee}) = 0$$

$$|m_{ee}| < f \quad \Rightarrow \quad \mathbb{R}(m_{ee}) < f \quad \mathbb{I}(m_{ee}) < f$$



$$m_{ee} = c_r^2 c_s^2 m_1 e^{i\tilde{\delta}_{M1}} + c_r^2 s_s^2 m_2 + s_r^2 m_3 e^{i\tilde{\delta}_{M3}}$$



Xing [hep-ph/0305195]
Xing, Zhao & Zhou [1504.05820]
Xing & Zhao [1612.08538]
Cao, Huang, Li, Wang, Wen, Xing, Zhao & Zhou [1908.08355]

SFG & Manfred Lindner, [1608.01618]

Prey of Leptonic CP Phases

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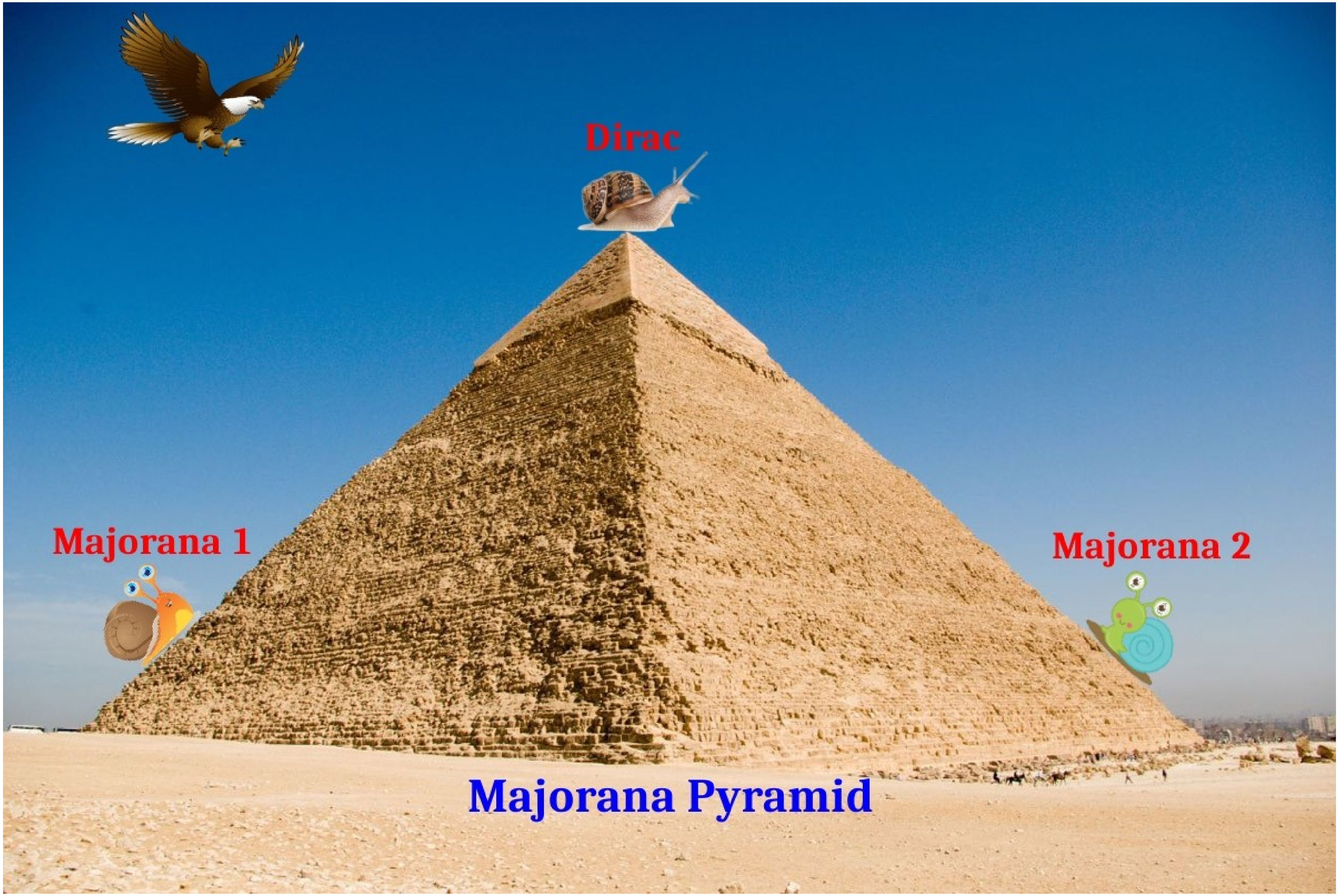

Confusion from New Physics

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- **Non-Standard Interactions**

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

Du, Li, Tang, Vihonen & Yu [2011.14292, 2106.15800]

Tang & Zhang [1705.09500]

Du, Li, Tang, Vihonen & Yu [2106.15800]

Scalar NSI: **SFG** & Parke [1812.08376]   Smirnov & Xu [1909.07505]

- **Non-Unitary Mixing**

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

SFG, Pasquini, Tortola & Valle [1605.01670]

Tang, Zhang & Li [1708.04909]

Hu, Ling, Tang & Wang [2008.09730]

- **Sterile neutrinos** — Chatterjee & Palazzo [2005.10338]

- **Lorentz violation** — Rahaman, Razzaque & Sankar [2201.03250]

- **Dark NSI**

Berlin [1608.01307]

Zhao [1701.02735]

Brdar, Kopp, Liu, Prass & Wang [1705.09455]

Liao, Marfatia & Whisnant [1803.01773]

Chao, Hu, Jiang & Jin [2009.14703]

SFG, Murayama [1904.02518]

SFG, PoS NuFact2019 (2020) 108

SFG, J.Phys.Conf.Ser. 1468 (2020) 1, 012125

3. Dark NSI

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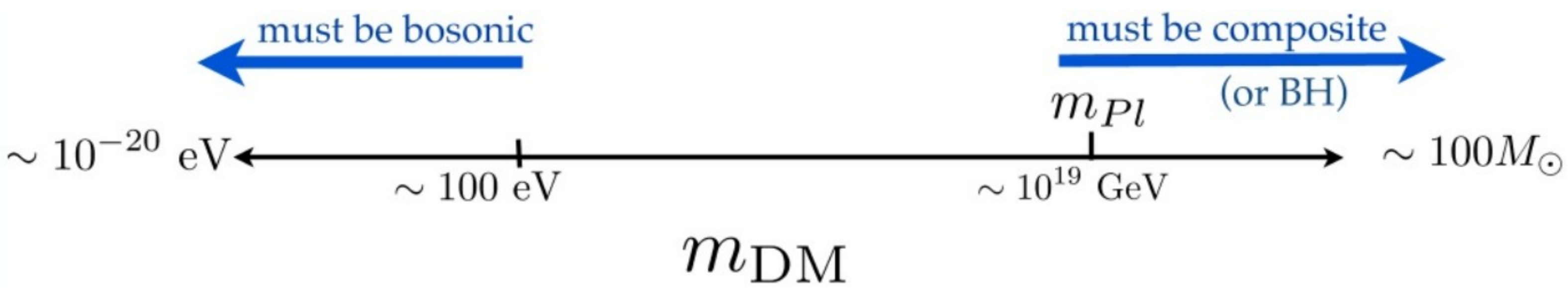
- **Wave DM can be as light as 10^{-22} eV**



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

- **Bose-Einstein Condensation** $\langle \phi \rangle \neq 0$

$$\phi(x) \simeq \frac{\sqrt{2\,\rho_{\rm DM}(x)}}{m_\phi} \cos\left[m_\phi \left(t - \vec{v} \cdot \vec{x} \right) \right]$$

Berlin [1608.01307]

Zhao [1701.02735]

Brdar, Kopp, Liu, Prass & Wang [1705.09455]

Time-Varying oscillation probabilities!