New Physics in Neutrino CP Measurement

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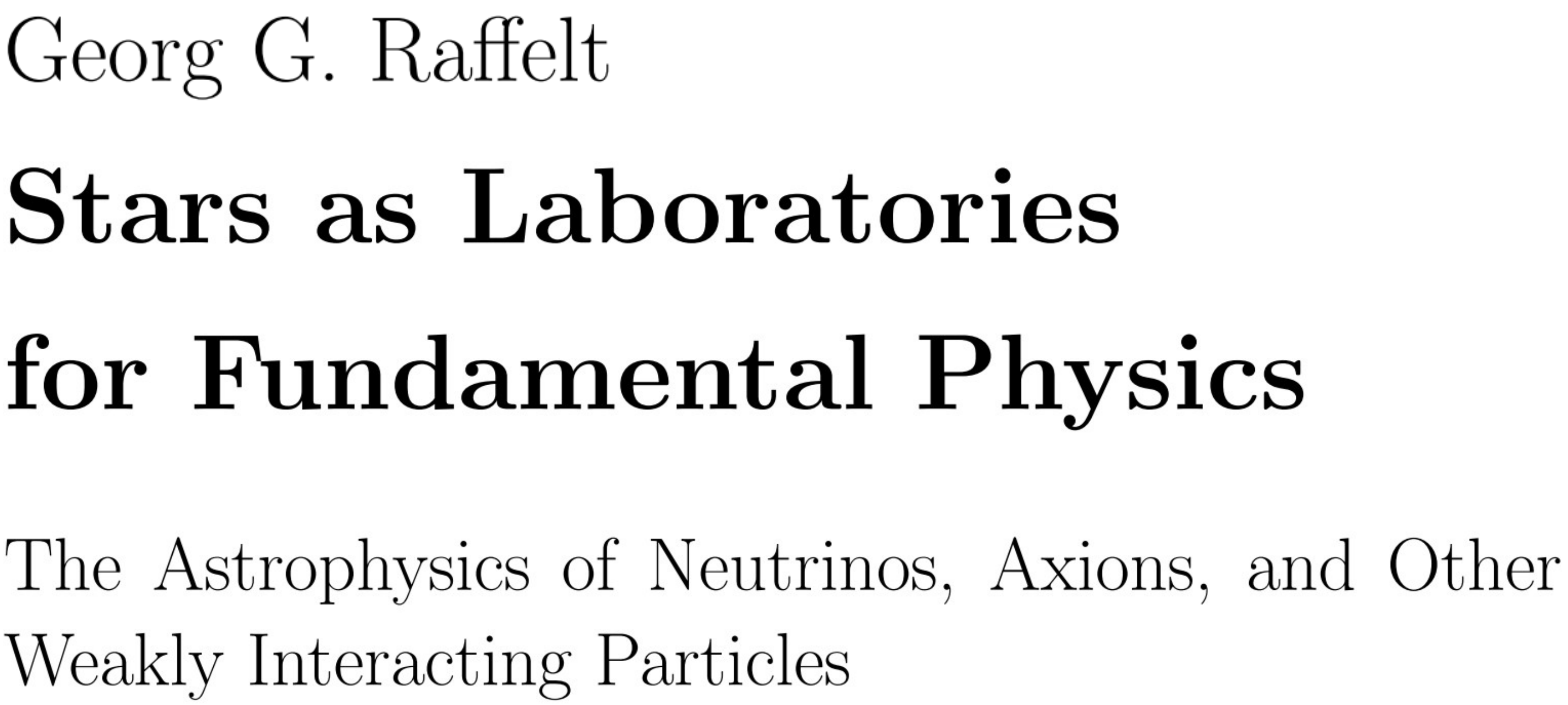
李政道研究所
Tsung-Dao Lee Institute

Outline

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

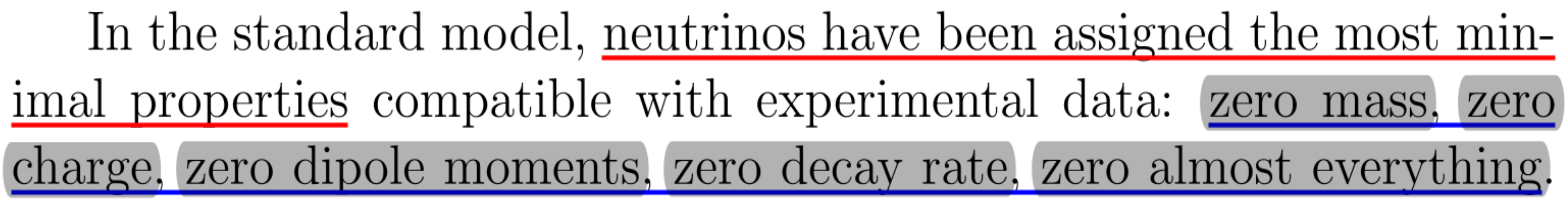
Minimal Neutrinos



Georg G. Raffelt

Stars as Laboratories for Fundamental Physics

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



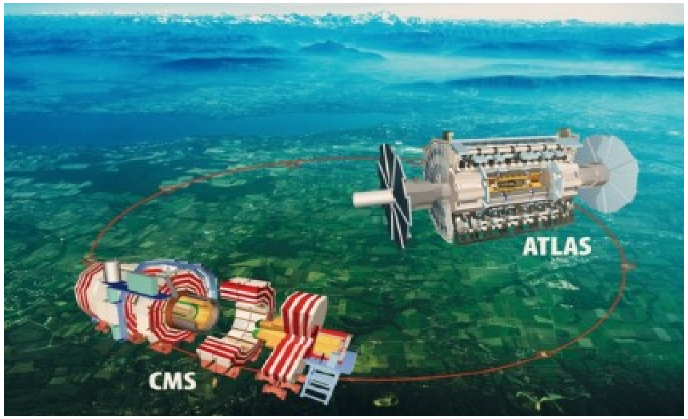
In the standard model, neutrinos have been assigned the most minimal properties compatible with experimental data: zero mass, zero charge, zero dipole moments, zero decay rate, zero almost everything.

Why neutrino mixing is so important?

Neutrino vs Higgs

- **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**



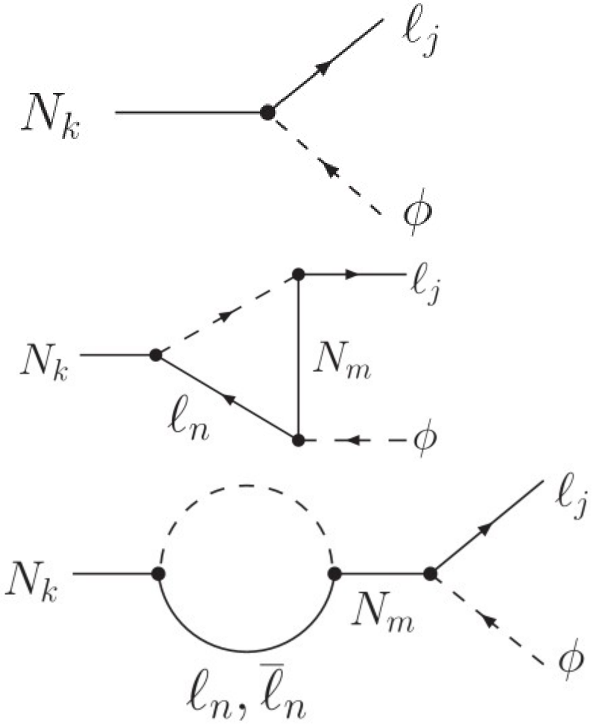
LHC @ **July 4, 2012**

Seesaw & Leptogenesis

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**

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

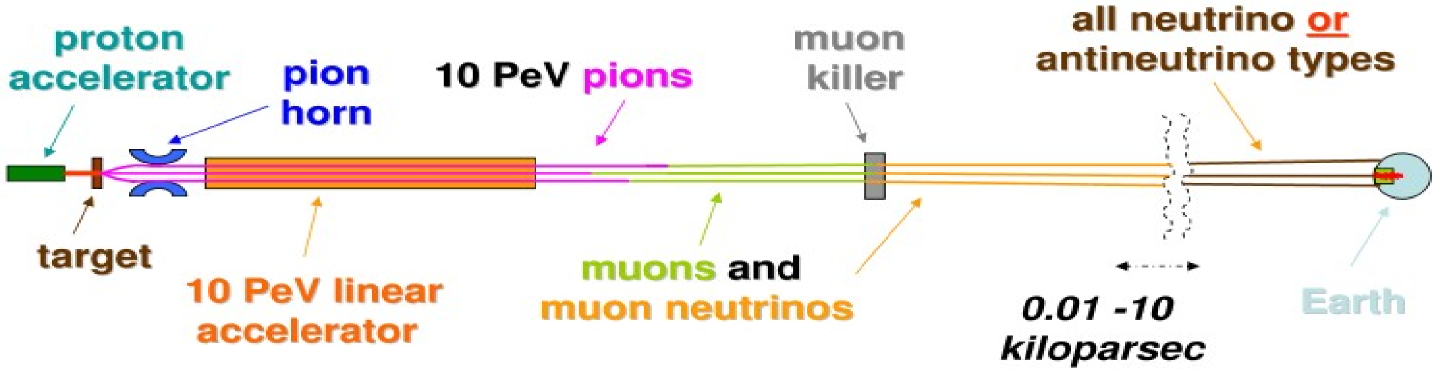
The matter-antimatter asymmetry needs Dirac/Majorana CP phases.

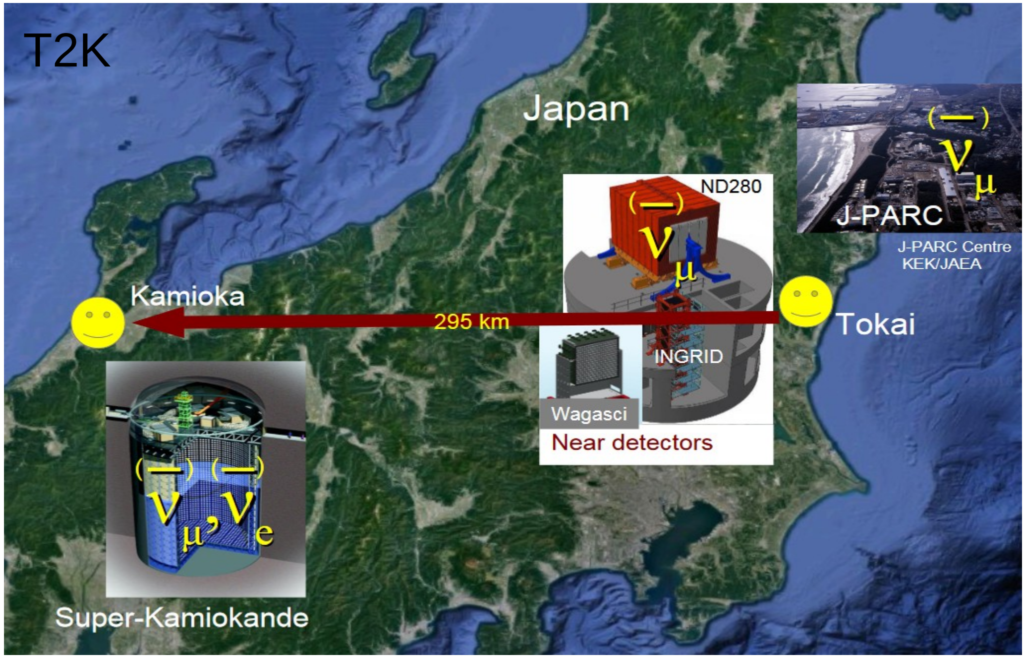
Yanagida

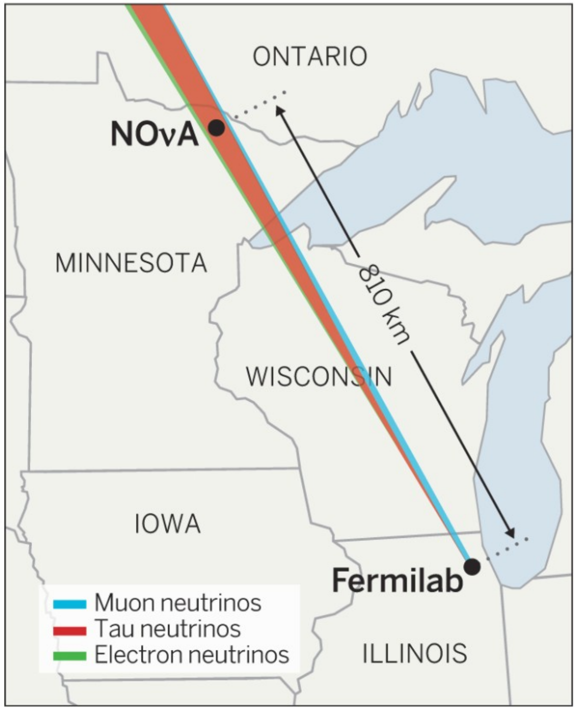
Fukugita

Accelerator ν Experiments

Pion Accelerator Neutrino Beam Concept

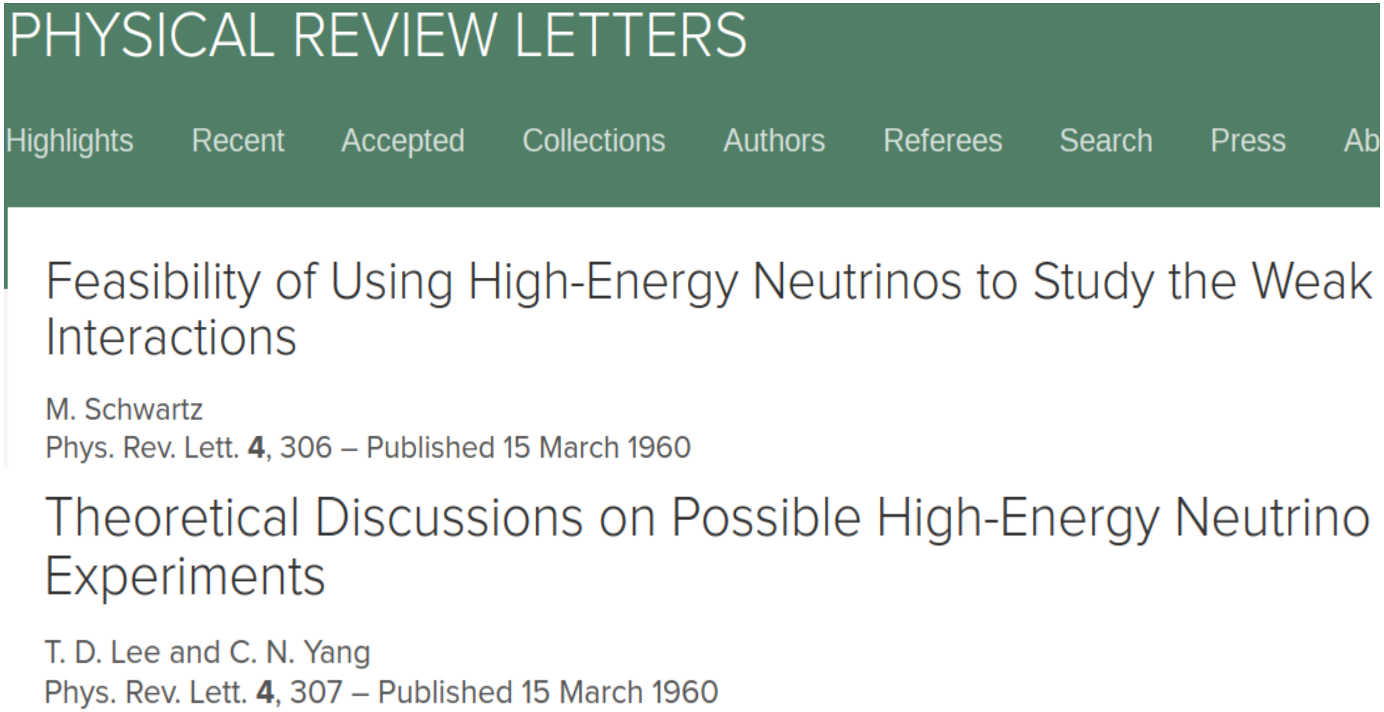






K. Engman, Science 345, 6204

Accelerator ν’s vs Lee & Yang



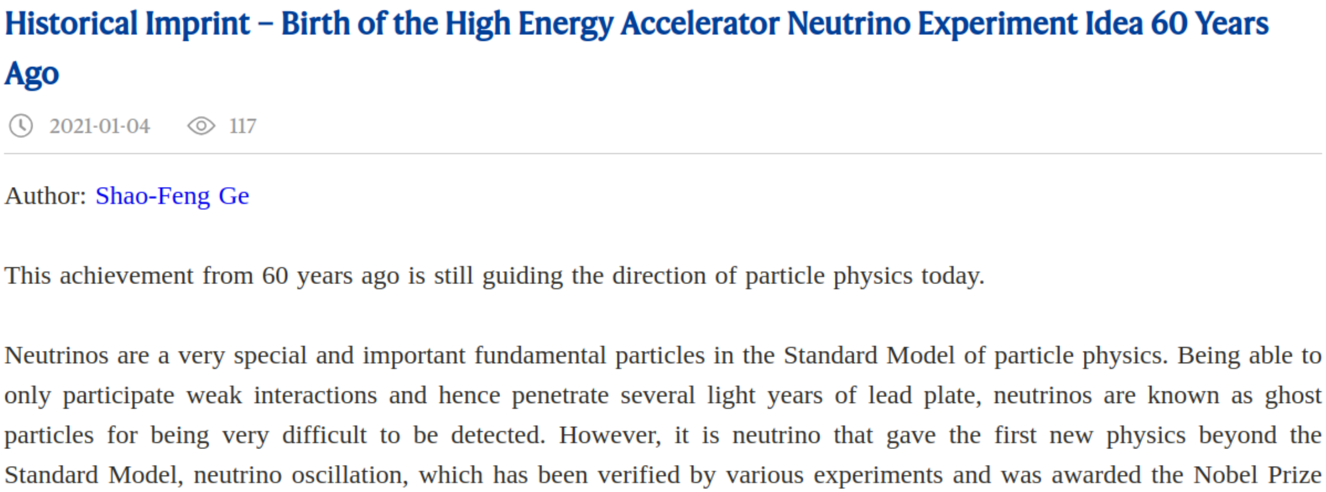
PHYSICAL REVIEW LETTERS

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



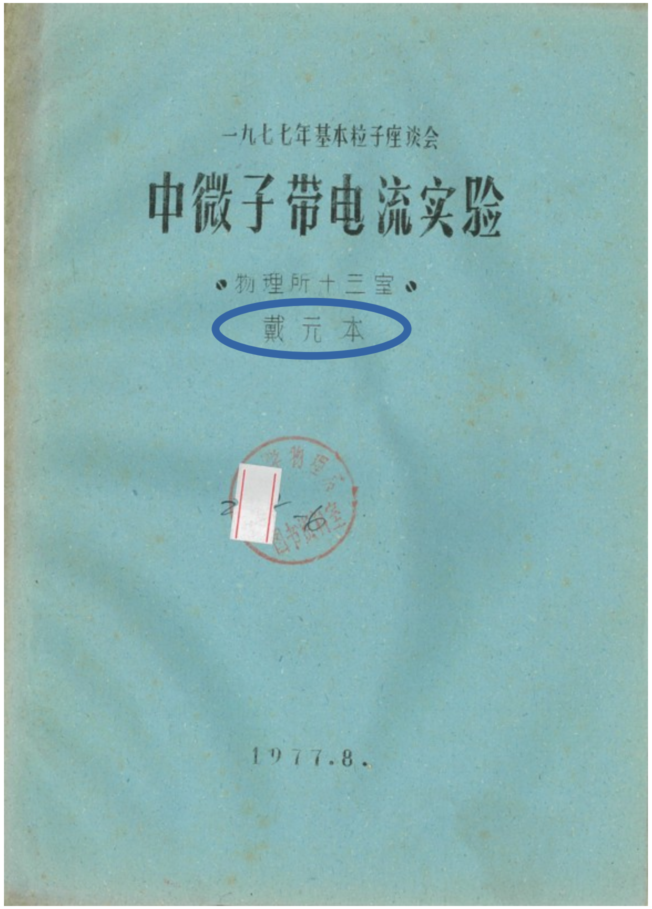
Historical Imprint – Birth of the High Energy Accelerator Neutrino Experiment Idea 60 Years Ago

2021-01-04 117

Author: Shao-Feng Ge

This achievement from 60 years ago is still guiding the direction of particle physics today.

Neutrinos are a very special and important fundamental particles in the Standard Model of particle physics. Being able to only participate weak interactions and hence penetrate several light years of lead plate, neutrinos are known as ghost particles for being very difficult to be detected. However, it is neutrino that gave the first new physics beyond the Standard Model, neutrino oscillation, which has been verified by various experiments and was awarded the Nobel Prize



一九七七年基本粒子座谈会

中微子带电流实验

•物理所十三室•

戴元本

1977.8.

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/EN/customize/436?columnId=35

Current Status of CP Measurement

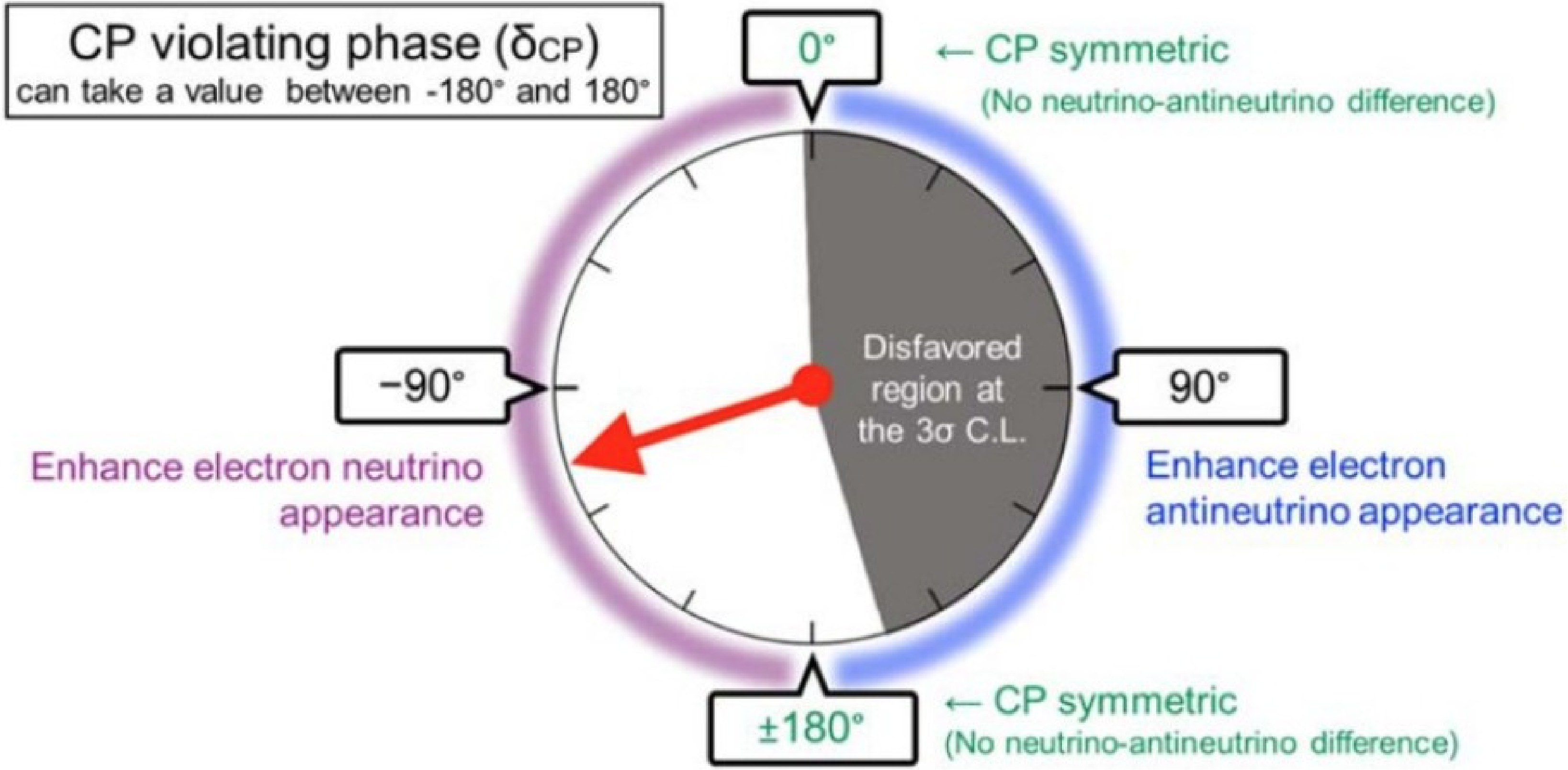
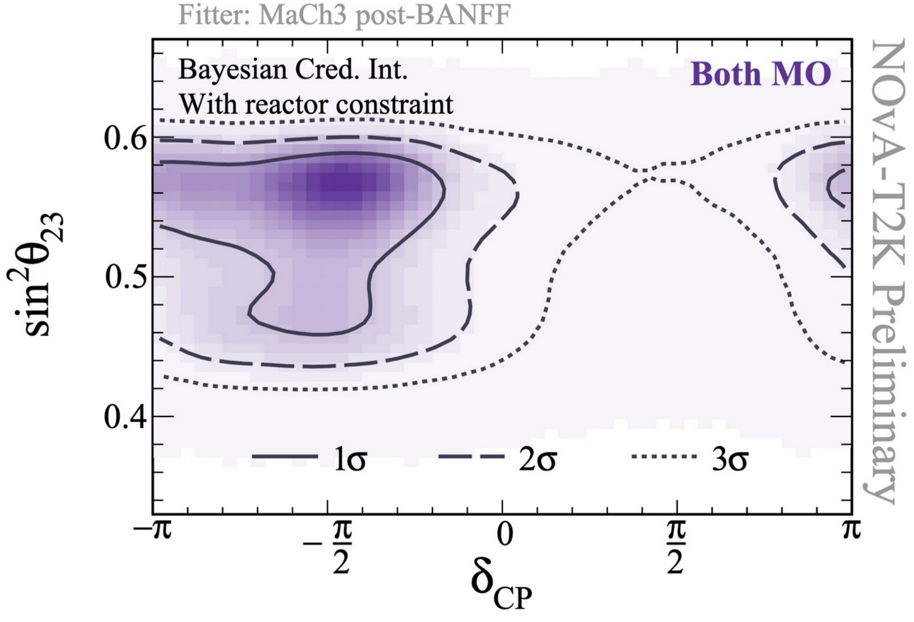


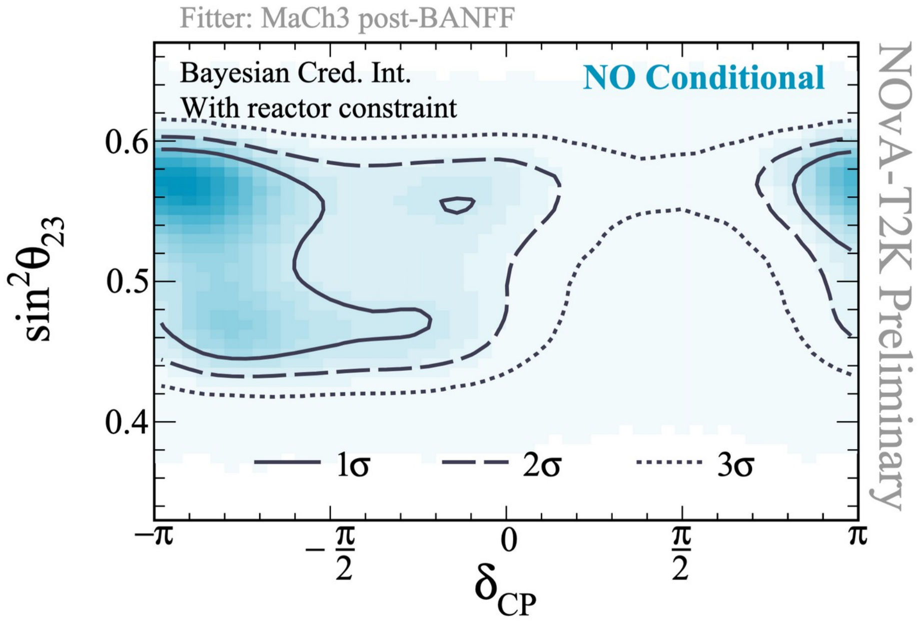
Fig.1 The arrow indicates the value most compatible with the data. The gray region is disfavored at 99.7% (3σ) confidence level. Nearly half of the possible values are excluded.

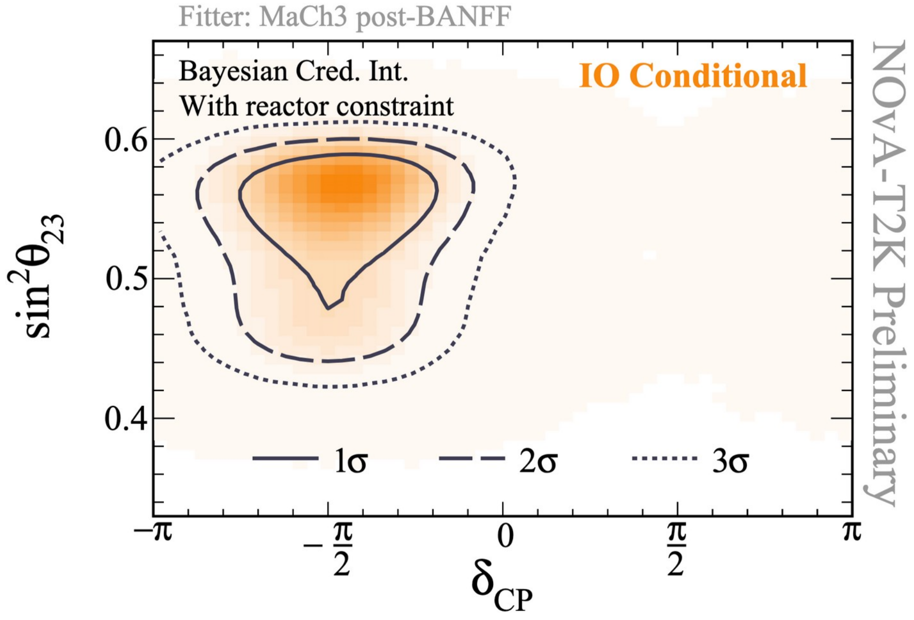
Nature vol. 580, pages 339-344(2020)

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

T2K+NOvA Joint Analysis







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

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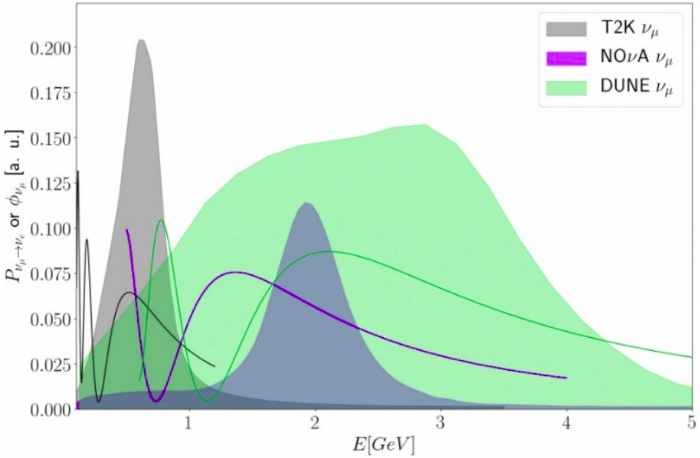
CP Measurement & Issues

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

@ 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 [$\mathbf{T}_{\overline{\nu}} : \mathbf{T}_\nu = \mathbf{2 : 1}$].
  - Undercut statistics ⇒ Difficult to reduce the uncertainty.



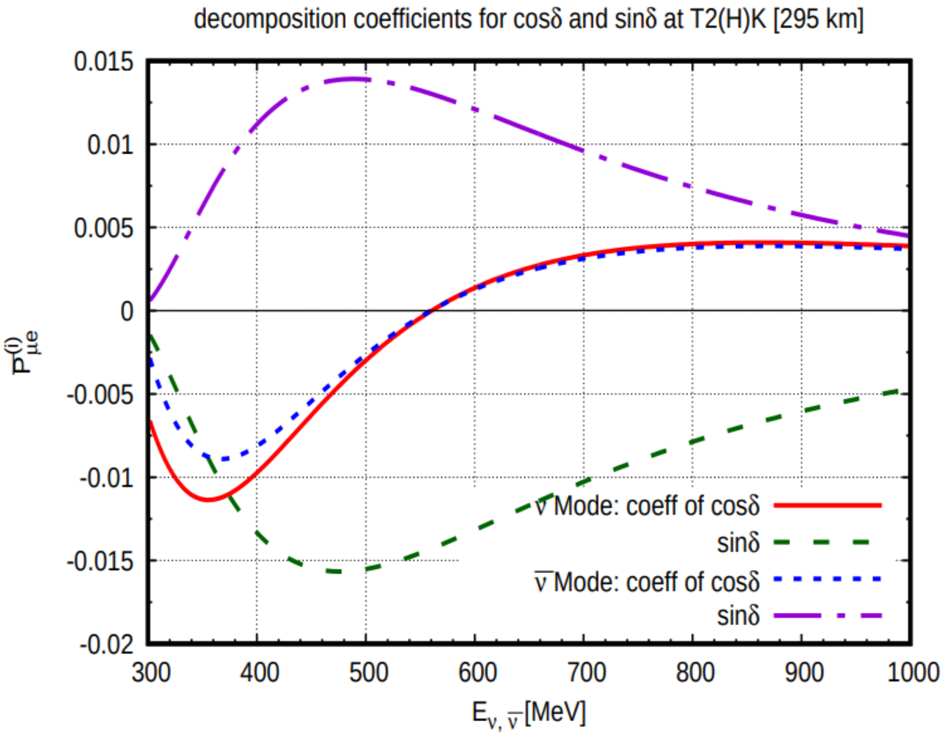
- **Degeneracy**:
  - Only $\sin\delta_D$ appears in $P_{\nu_\mu \to \nu_e}$ & $P_{\overline{\nu}_\mu \to \overline{\nu}_e}$.
  - Cannot distinguish δ_D from $\pi - \delta_D$.
- **CP Uncertainty** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos\delta_D \Rightarrow \Delta(\delta_D) \propto 1/\cos\delta_D$

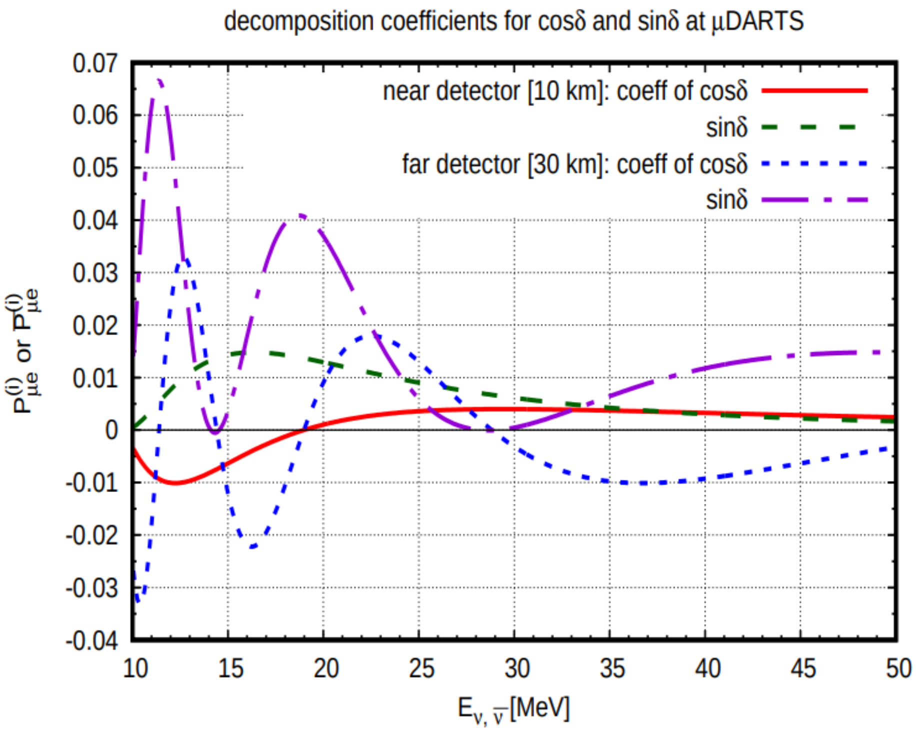
SFG [1704.08518, PoS NuFact2019 (2020) 108]

μDAR & Accelerator ν

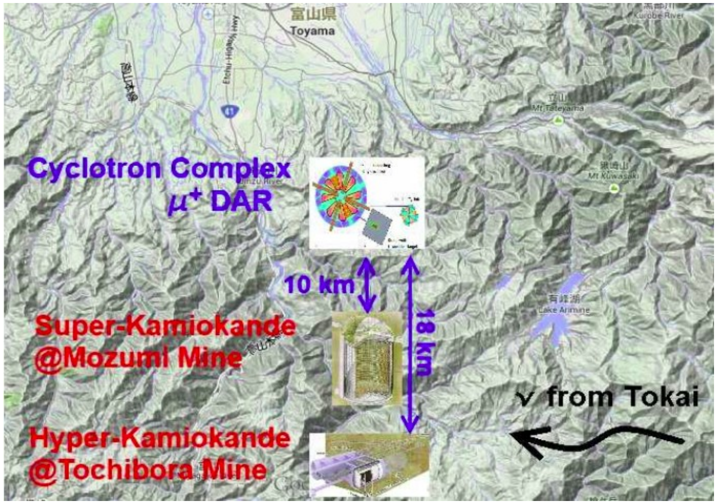
Combining $\nu_\mu \to \nu_e$ **@ accelerator** [narrow **peak @ 550 MeV**] & $\overline{\nu}_\mu \to \overline{\nu}_e$ **@ μDAR** [wide **peak $\sim$ 45 MeV**] solves the 2 problems:

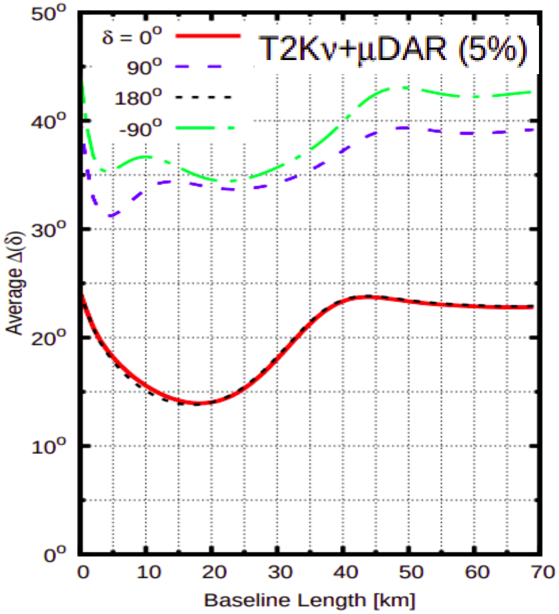
- **Efficiency**:
  - $\overline{\nu}$ @ high intensity, μDAR is plentiful enough.
  - Accelerator Exps can devote all run time to the ν mode. With same run time, the statistical uncertainty drops by $\sqrt{3}$.
- **Degeneracy**: (**decomposition in propagation basis** [1309.3176])

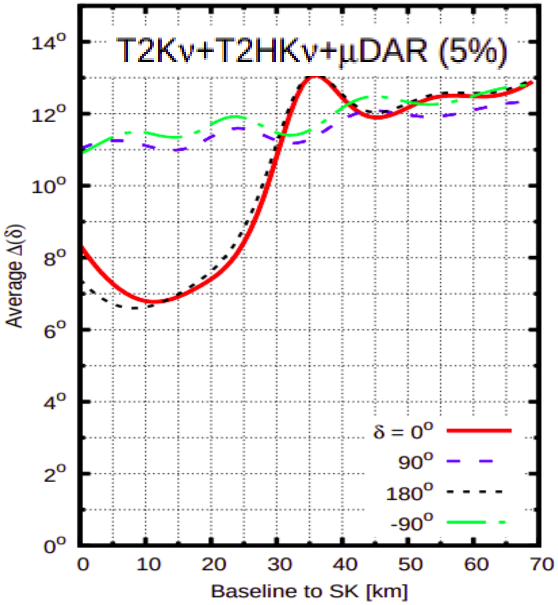

decomposition coefficients for cosδ and sinδ at T2(H)K [295 km]


decomposition coefficients for cosδ and sinδ at μDARTS

TNT2K







1 μDAR source + 2 detectors

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

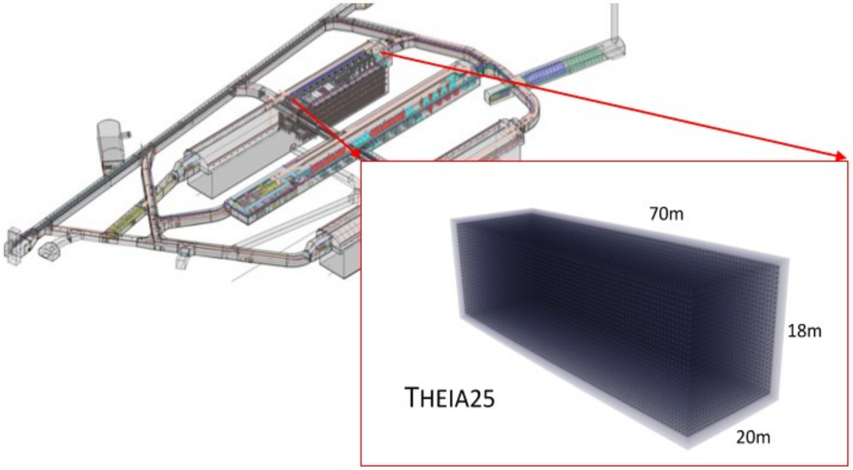
Advantages

- 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!**

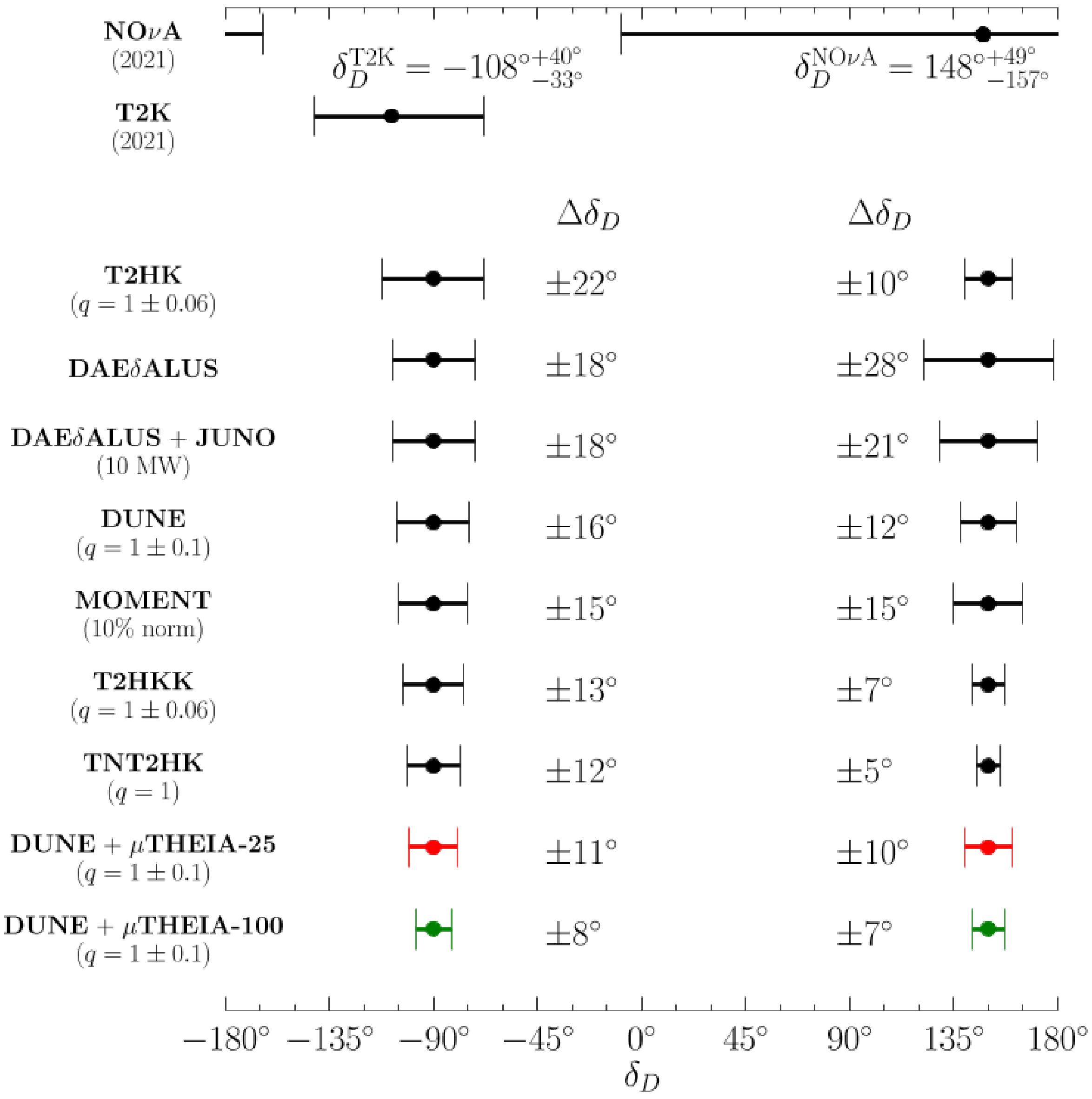
Harnik, Kelly & Machado [1911.05088]

μTHEIA+DUNE



THEIA [1911.03501, 2202.12839]

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



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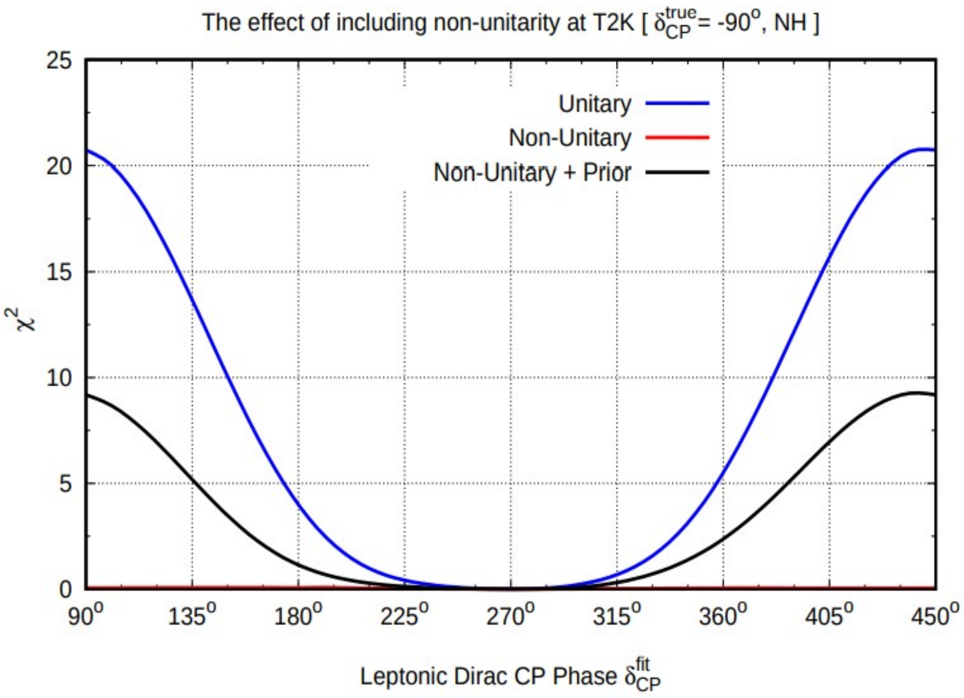
1. Non-Unitarity Mixing (NUM)

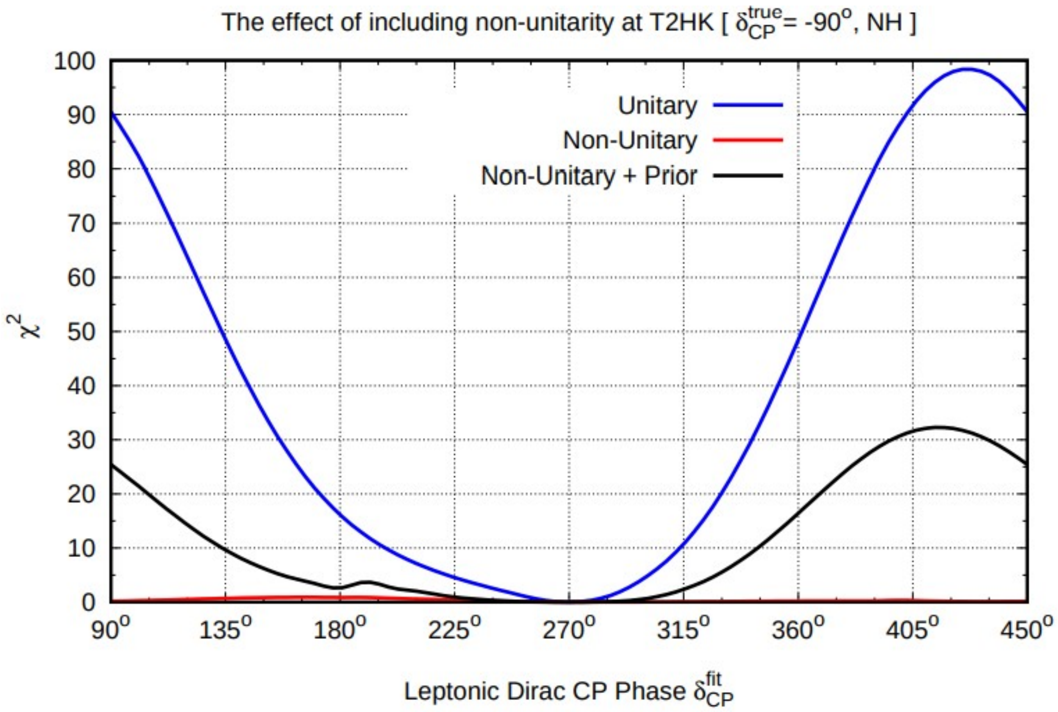
$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

U is unitary

$$P^{NP}_{\mu e} = \alpha_{11}^2 \left\{ \alpha_{22}^2 \left[c_a^2 |S'_{12}|^2 + s_a^2 |S'_{13}|^2 + 2 c_a s_a (\cos\delta_{\rm D} \mathbb{R} - \sin\delta_{\rm D} \mathbb{I})(S'_{12} S'^*_{13}) \right] + |\alpha_{21}|^2 P_{ee} \right.$$

$$\left. + 2\alpha_{22}|\alpha_{21}| \left[c_a (c_\phi \mathbb{R} - s_\phi \mathbb{I})(S'_{11} S'^*_{12}) + s_a (c_{\phi+\delta_{\rm D}}\mathbb{R} - s_{\phi+\delta_{\rm D}}\mathbb{I})(S'_{11} S'^*_{13}) \right] \right\} .$$





SFG, Pasquini, Tortola & Valle [1605.01670]

1. NUM vs Seeaw Mechanism

- **Heavy Neutrinos**

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

The diagonalization of the full mass matrix

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

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

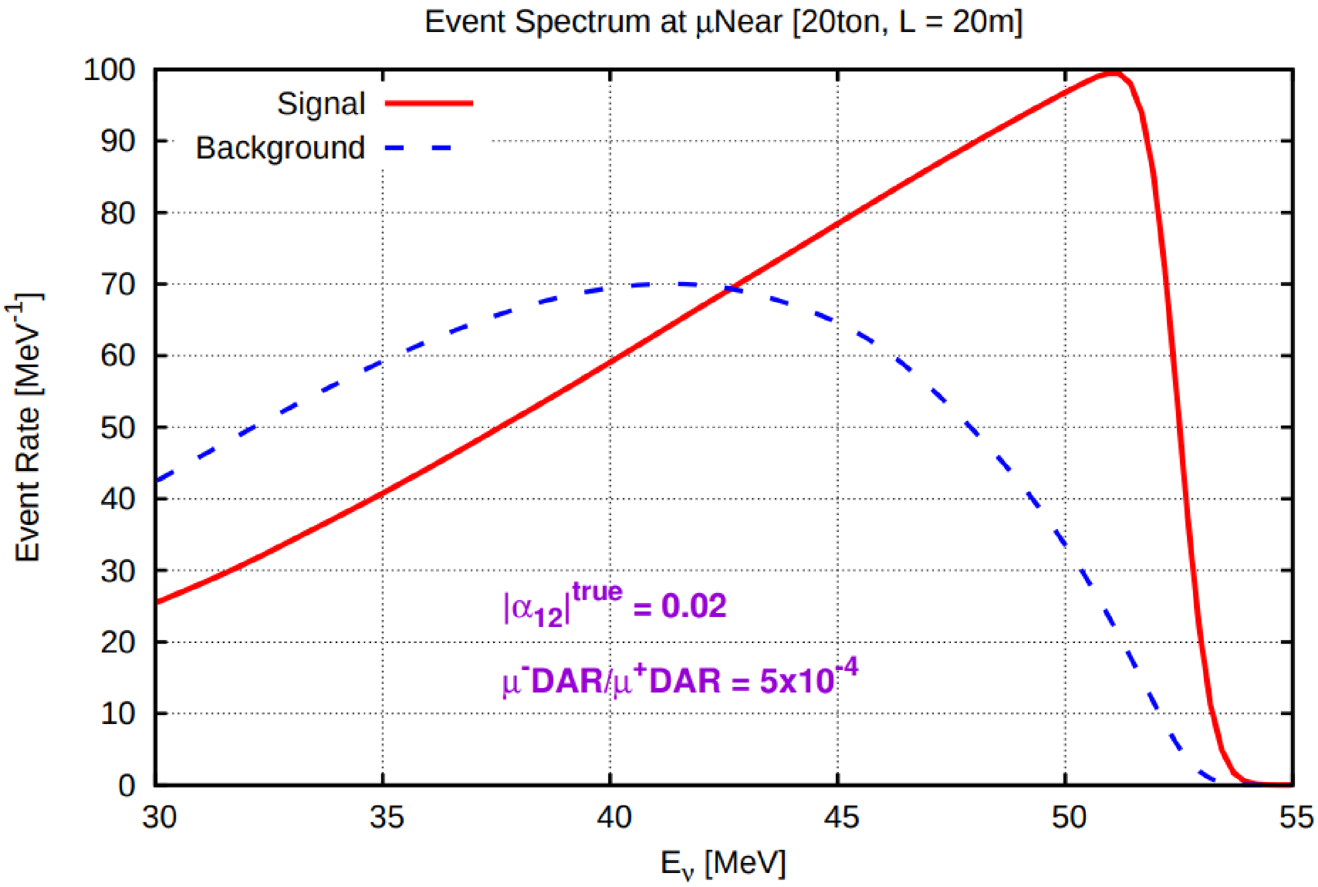
NUM is not exotic at all!

1. NUM Zero Distance Effect

Tsung-Dao Lee Institute

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

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

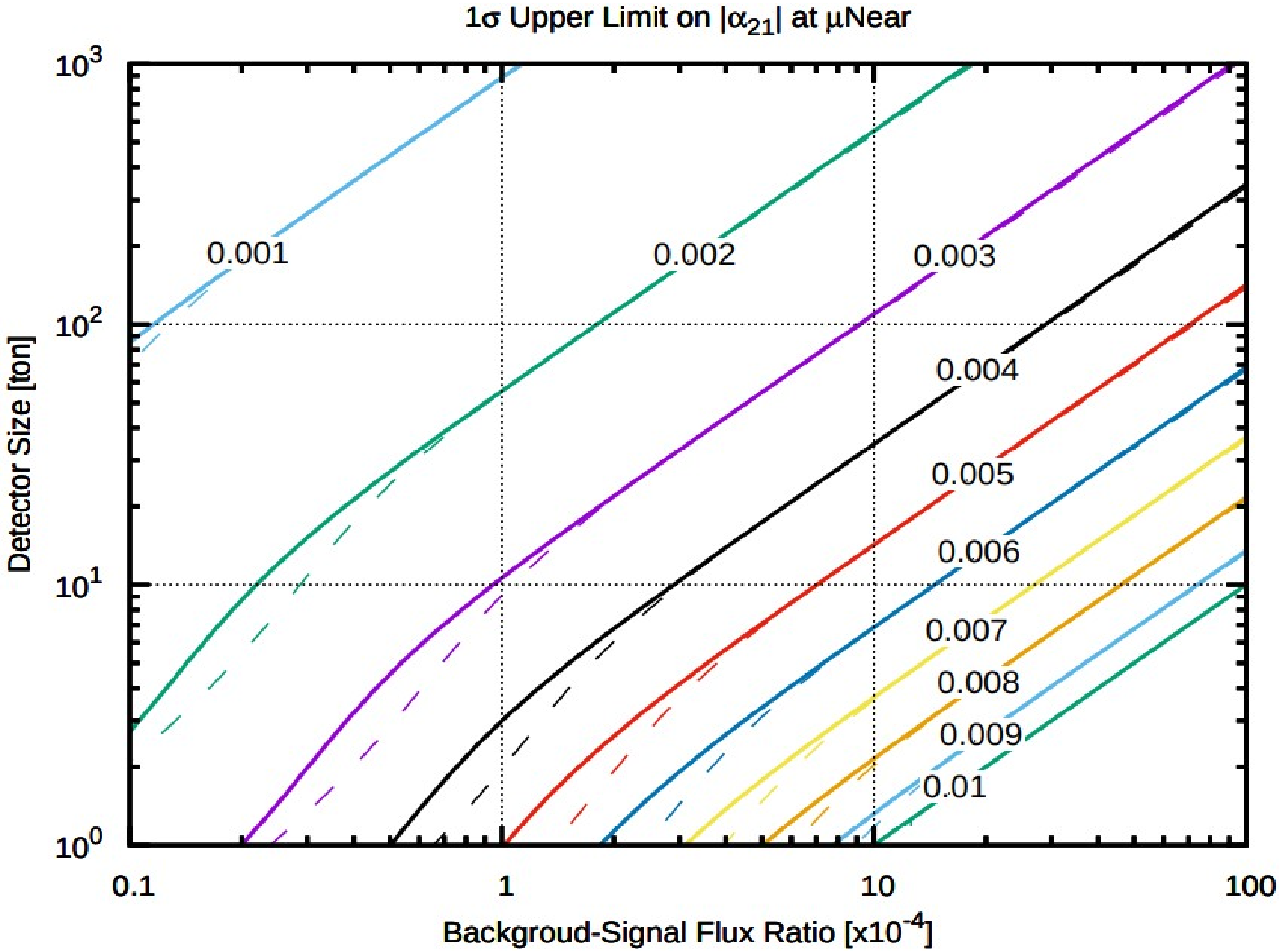


Transition @ L → 0

SFG, Pasquini, Tortola & Valle [1605.01670]

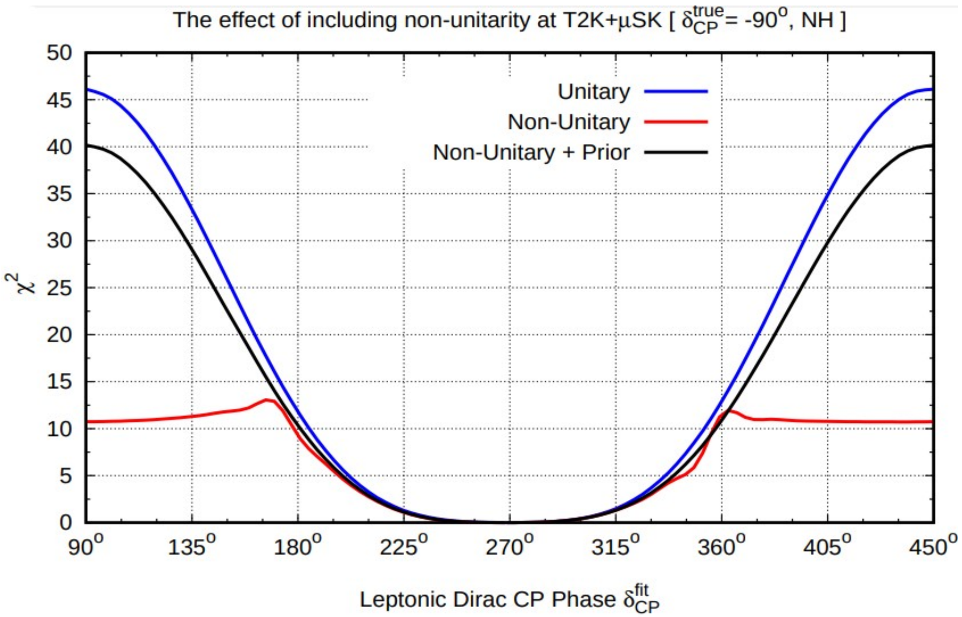
1. μNear @ μDAR

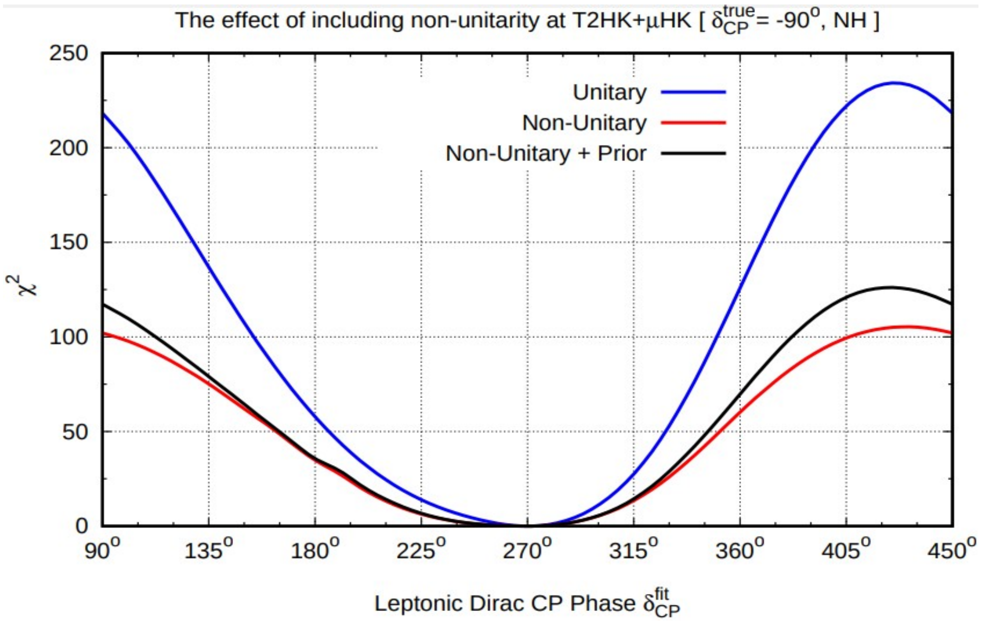
$$P^{NP}_{\mu e}(L \to 0) = \alpha^2_{11}|\alpha_{21}|^2 P_{ee} \approx \alpha^2_{11}|\alpha_{21}|^2 \approx |\alpha_{21}|^2$$

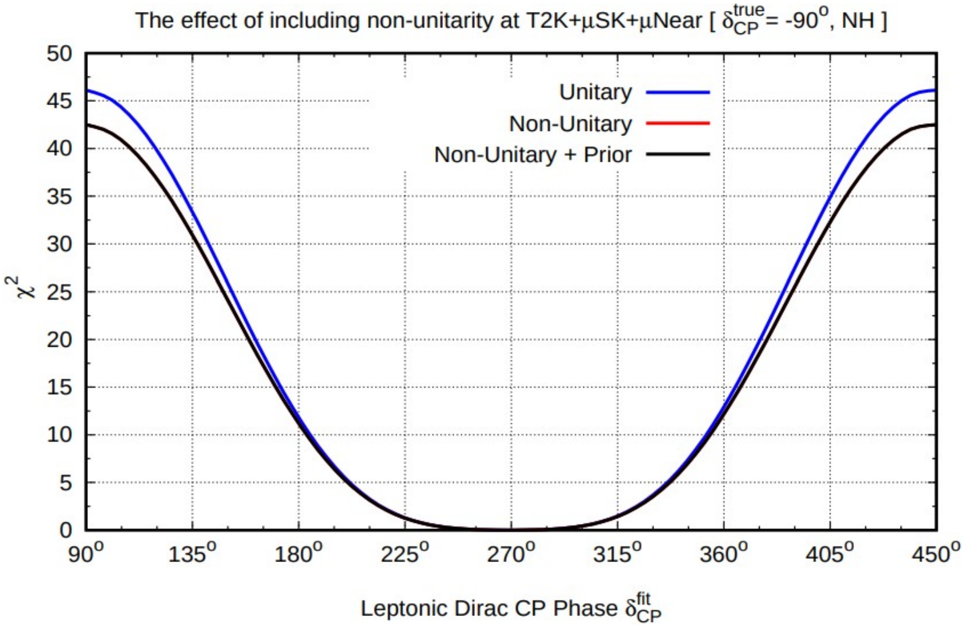


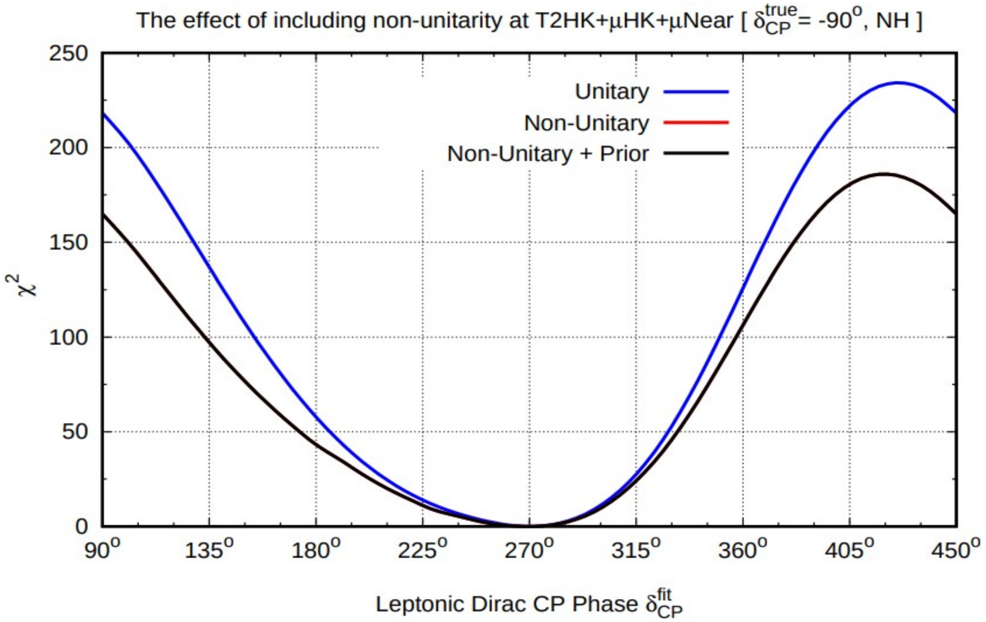
SFG, Pasquini, Tortola & Valle [1605.01670]

1. TNT2K + μNear



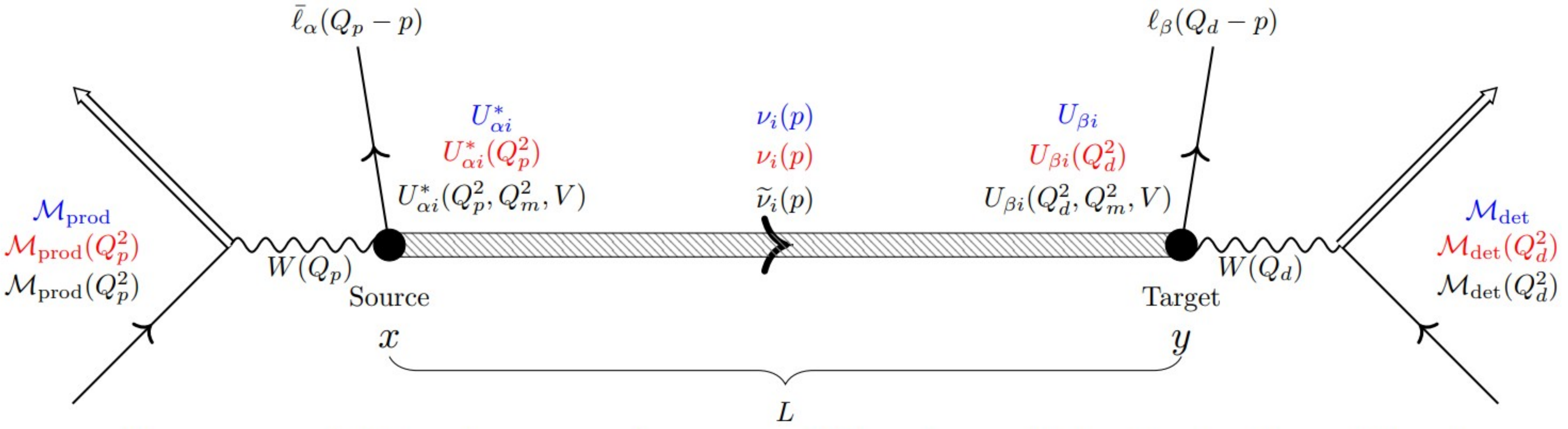






SFG, Pasquini, Tortola & Valle [1605.01670]

2. RG Running

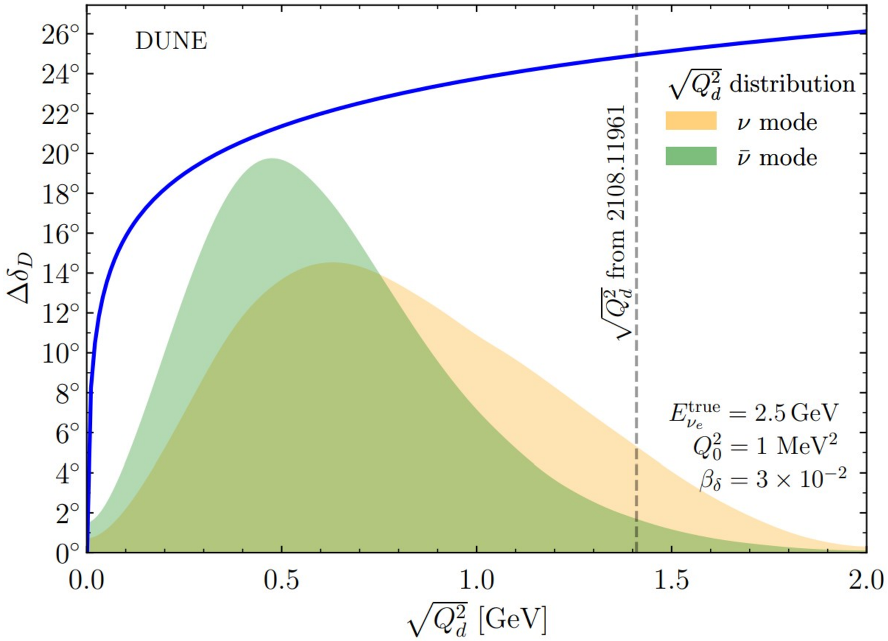


blue : vacuum w/o RG ruuning red : vacuum w/ RG ruuning black : w/ matter effect & RG ruuning

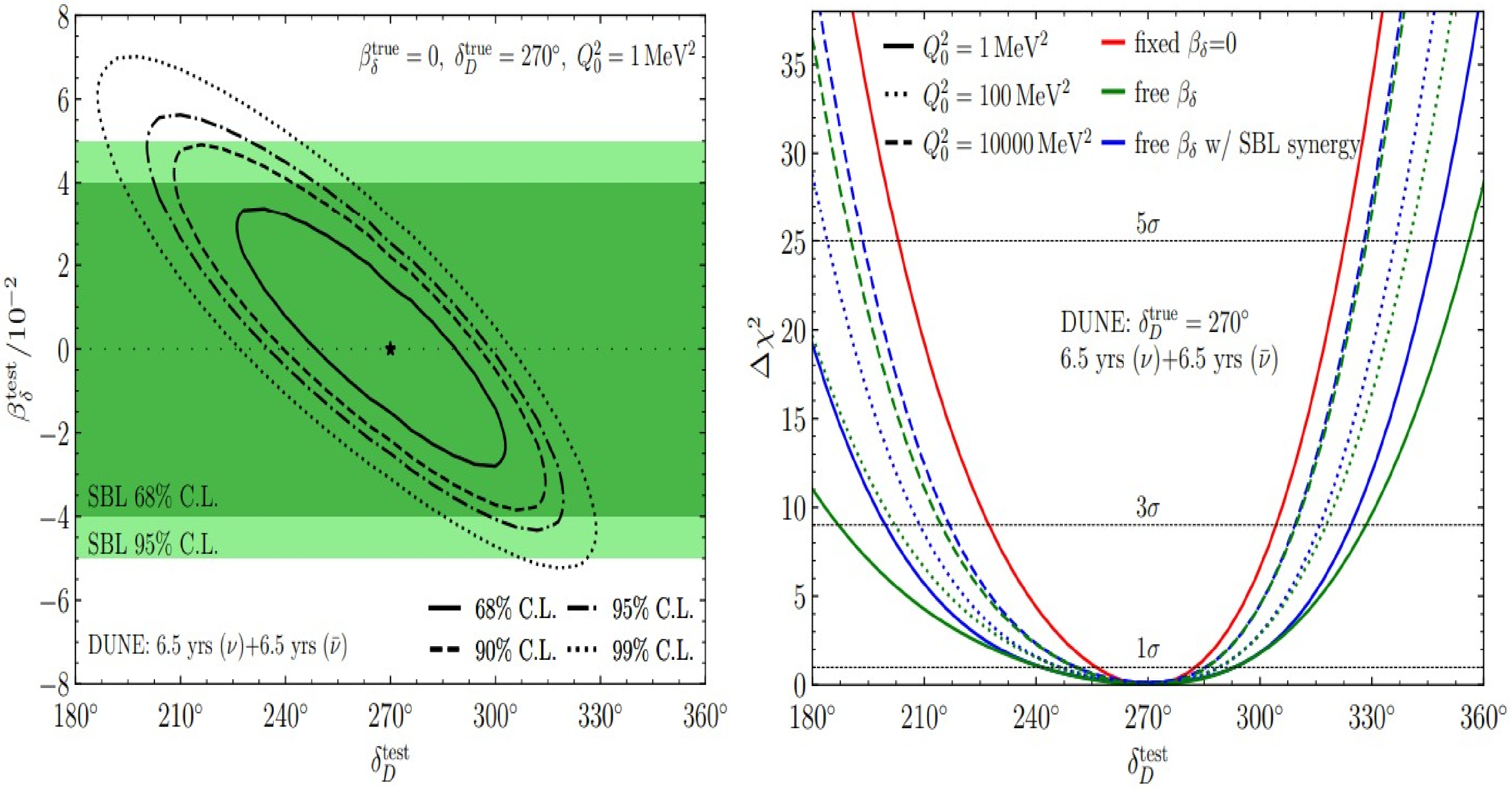
$$\mathcal{A}^{\text{osc}}_{\beta\alpha} = U_{\beta i}(Q_d^2) e^{-iL\frac{m_i^2}{2E_\nu}} U^*_{\alpha i}(Q_p^2)$$

Mismatched Momentum

SFG, Chui-Fan Kong, Pedro Pasquini
Phys. Rev. D 110, 015003 [arXiv:2310.04077]



2. RG Running & CP Measurement



SFG, Chui-Fan Kong, Pedro Pasquini, Phys. Rev. D 110, 015003 [arXiv:2310.04077]

2. Zero Distance Effect

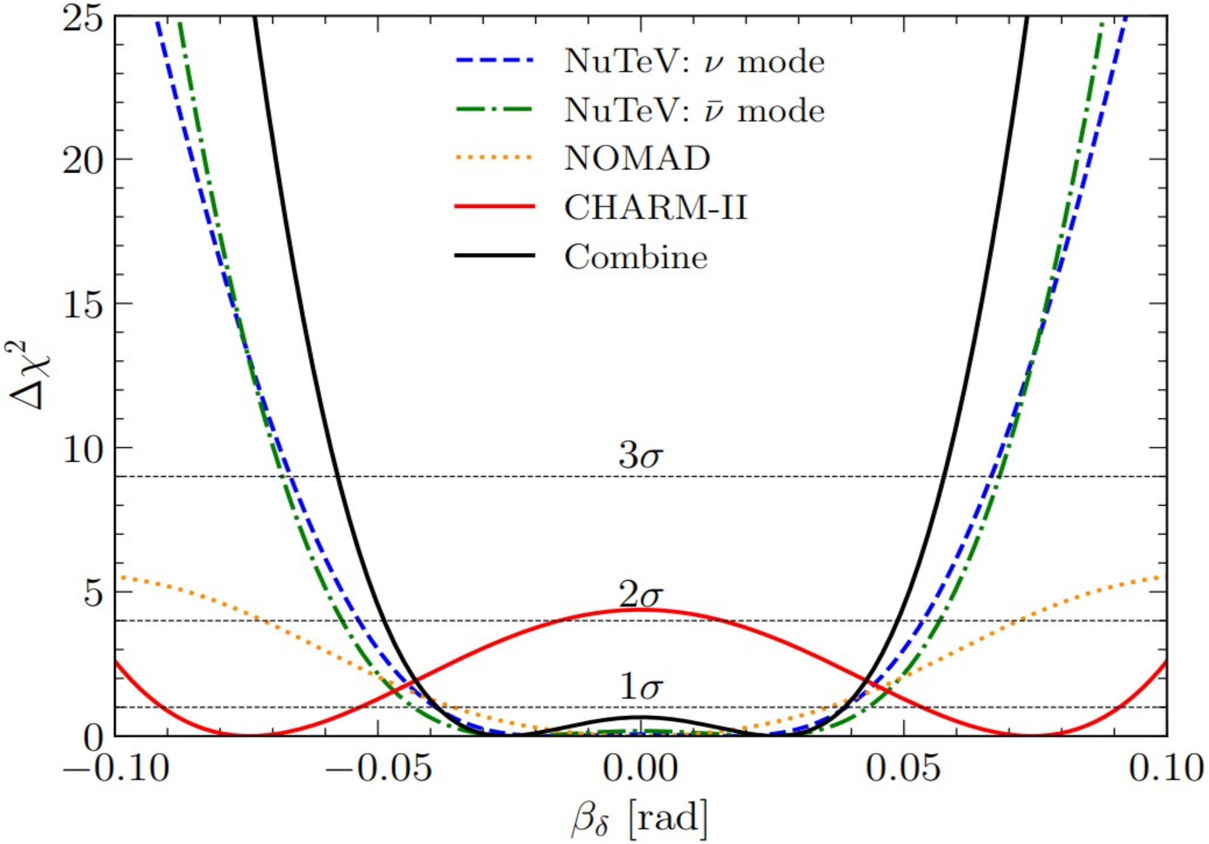
Tsung-Dao Lee Institute

$$\mathcal{A}^{\rm osc}_{\beta\alpha} = U_{\beta i}(Q^2_d) e^{-iL\frac{m_i^2}{2E_\nu}} U^*_{\alpha i}(Q^2_p) \quad \Rightarrow \quad P_{\alpha\beta} = \left| \left[U(Q^2_d) U^\dagger(Q^2_p) \right]_{\beta\alpha} \right|^2$$

Transition @ L → 0

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

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

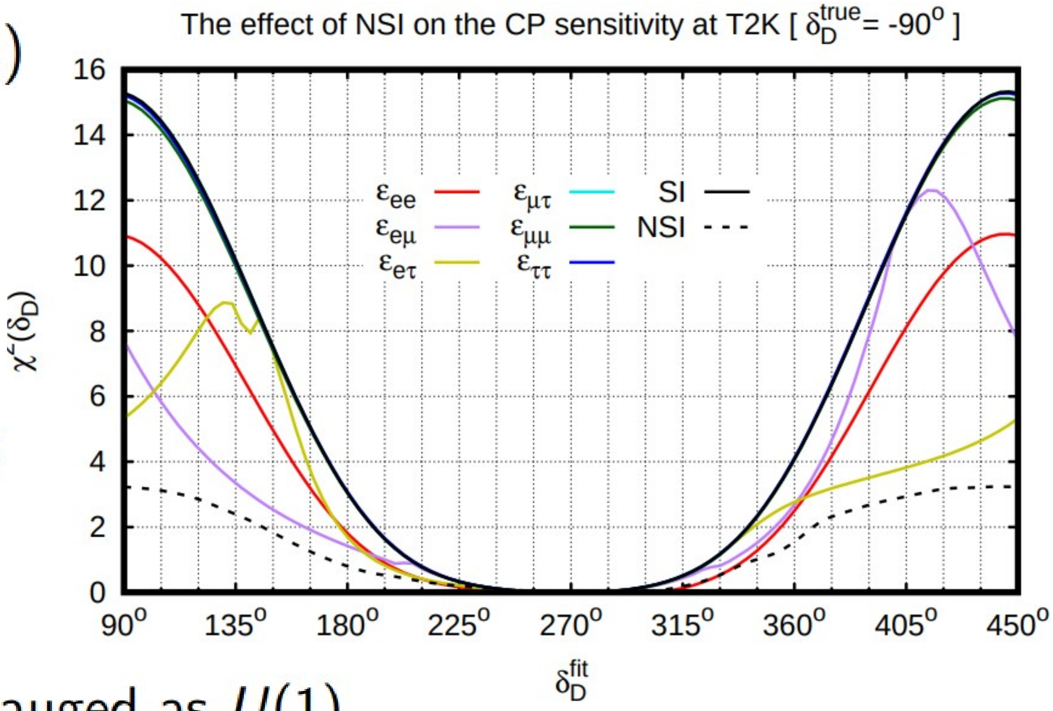


SFG, Chui-Fan Kong, Pedro Pasquini
Phys. Rev. D 110, 015003 [arXiv:2310.04077]

3. Non-Standard Interaction (NSI)

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

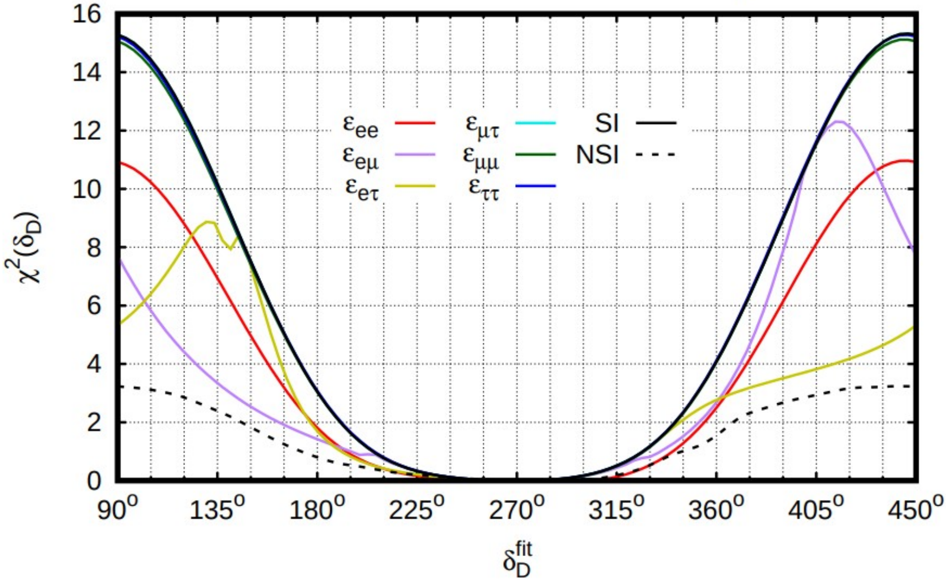
- Standard Interaction – V_{cc} (also V_{nc})
- Non-Standard Interaction – $\epsilon_{\alpha\beta}$
  - **Diagonal $\epsilon_{\alpha\alpha}$ are real**
  - **Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex**
  - **Both can fake CP**



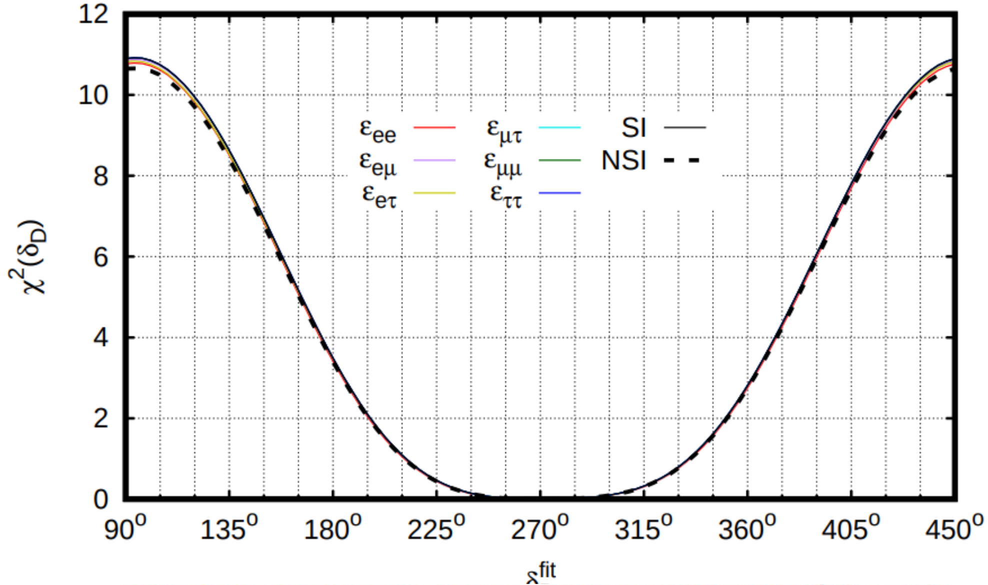
- Z' in LMA-Dark model with $L_\mu - L_\tau$ gauged as $U(1)$
  - $M_{Z'} \sim \mathcal{O}(10)$MeV
  - $g_{Z'} \sim 10^{-5}$

3. Guarantee CP against NSI

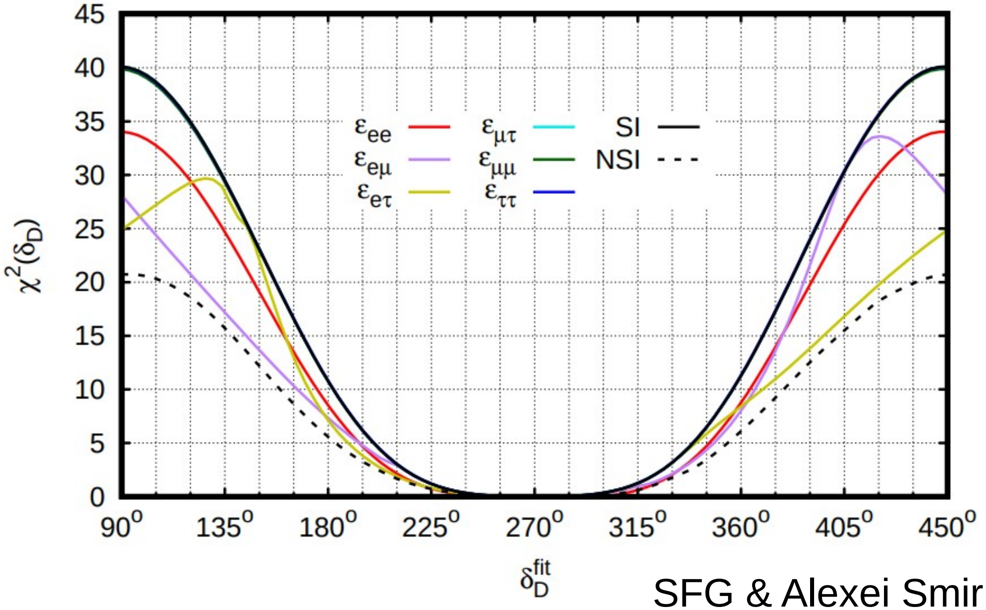
The effect of NSI on the CP sensitivity at T2K [δ_D^{true}= -90^o]



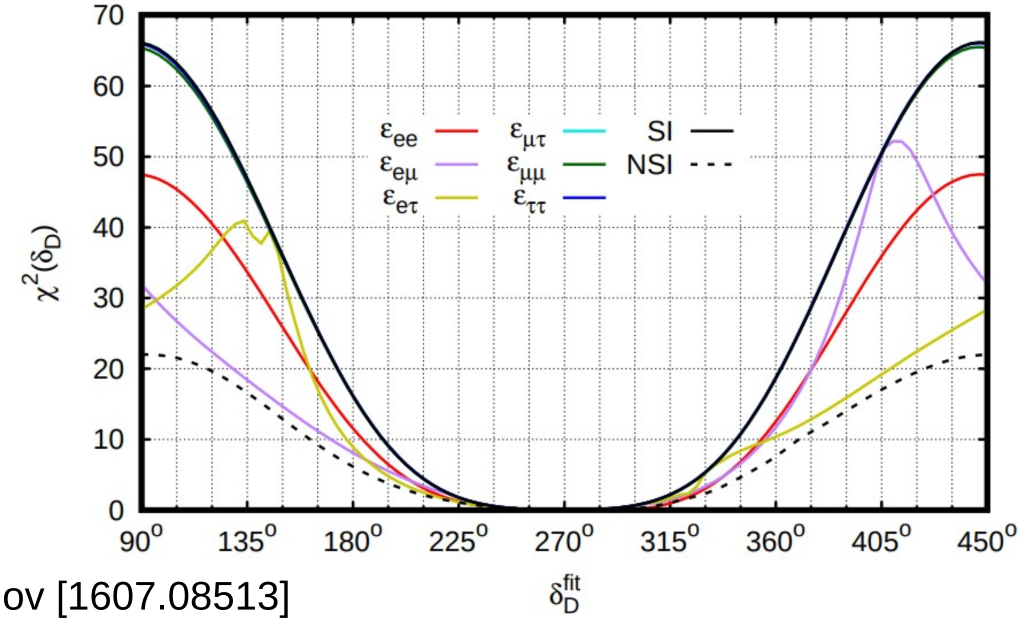
The effect of NSI on the CP sensitivity at μSK [δ_D^{true}= -90^o]



The effect of NSI on the CP sensitivity at T2K+μSK [δ_D^{true}= -90^o]



The effect of NSI on the CP sensitivity at νT2K+μSK [δ_D^{true}= -90^o]



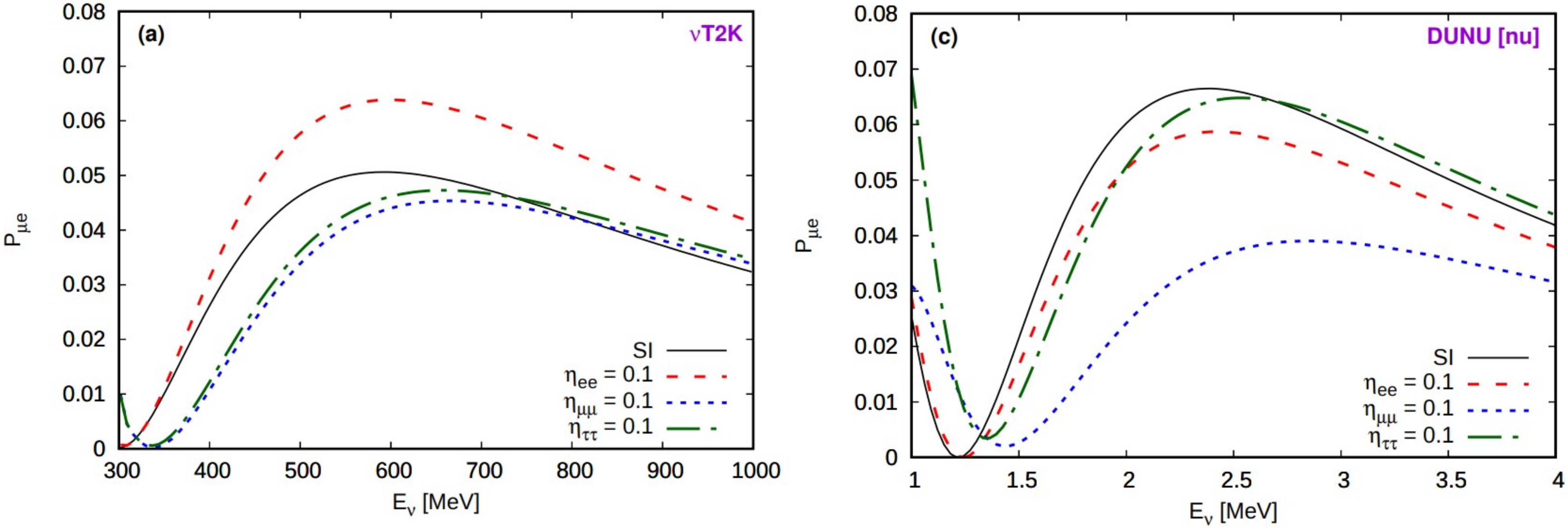
SFG & Alexei Smirnov [1607.08513]

4. Scalar NSI

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

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

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



5. Dark NSI with Forward Scattering

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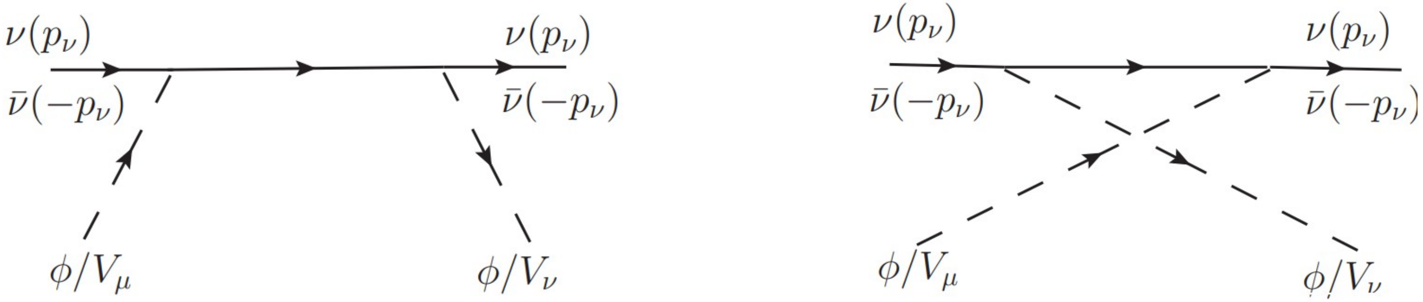
$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + h.c.$$

- 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/Eν 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

Summary

- Leptonic CP Violation

CP has profound importance for matter-antimatter asymmetry!

- Accelerator + μDAR for better CP measurement

Intrinsic defects & precision measurement

- Dirac CP Phase & New Physics

1. Non-Unitary Mixing (NUM)
2. RG Running
3. Non-Standard Interactions (NSI)
4. Scalar NSI
5. Dark NSI

Multiple new physics!

《 Physics Letters A 》

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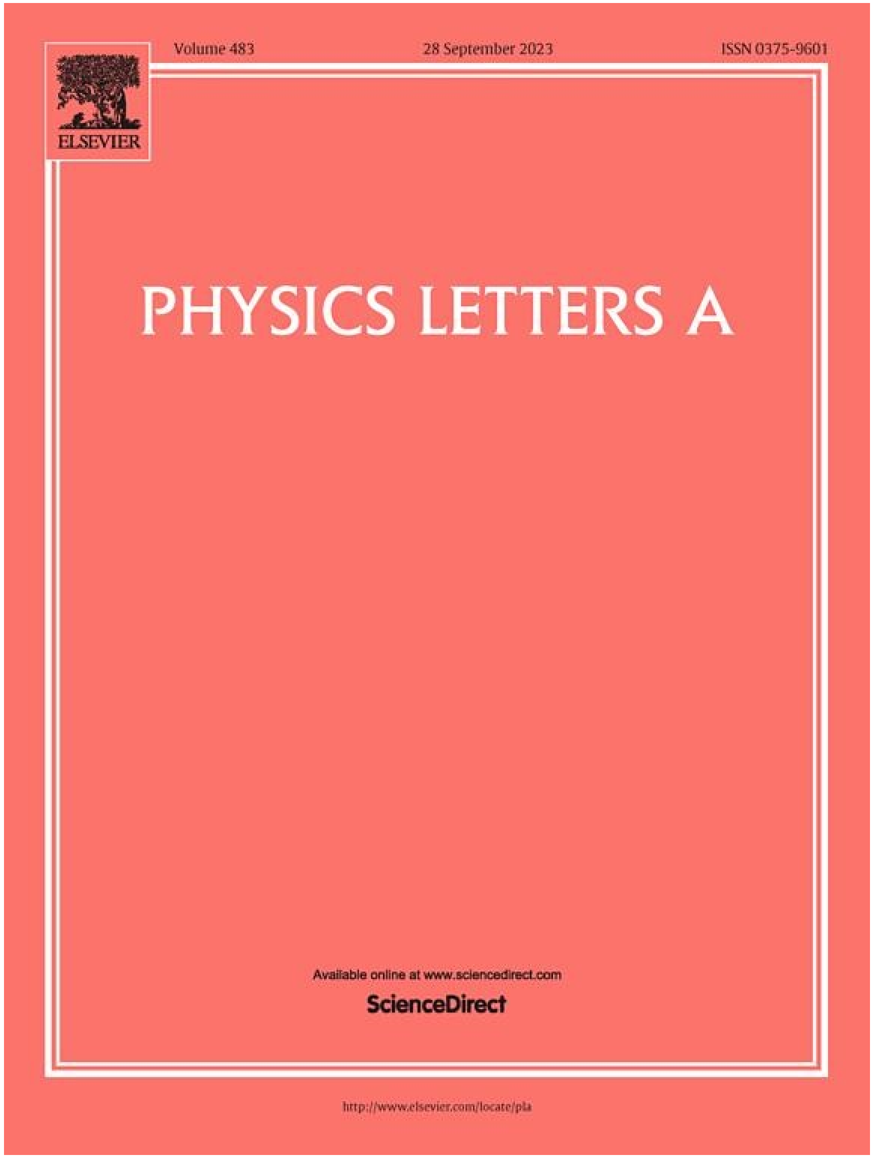

Volume 483 28 September 2023 ISSN 0375-9601

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PHYSICS LETTERS A

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Aims & Scope

- Nonlinear science,
- Statistical physics,
- Mathematical and computational physics,
- AMO and physics of complex systems,
- Plasma and fluid physics,
- Optical physics,
- General and cross-disciplinary physics,
- Biological physics and nanoscience,
- Astrophysics, Particle physics and Cosmology.

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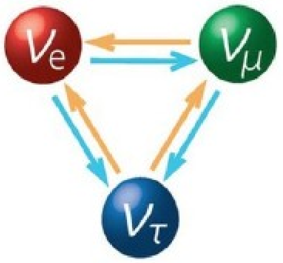
Thank You

Neutrino Oscillation

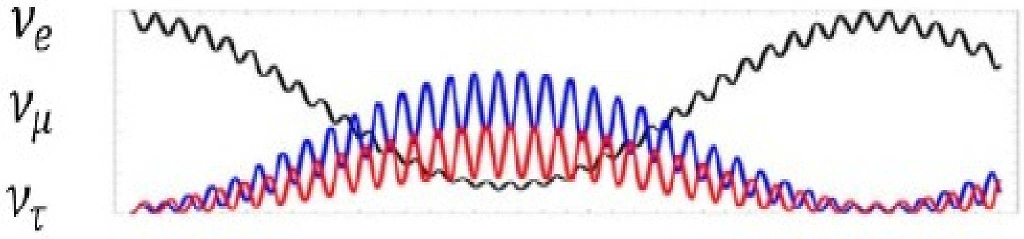
- **PMNS Matrix**



$$U_{\mathrm{PMNS}} = \mathcal{P} \begin{pmatrix} c_s c_r & s_s c_r & s_r e^{-i\delta_D} \\ -s_s c_a - c_s s_a s_r e^{i\delta_D} & +c_s c_a - s_s s_a s_r e^{i\delta_D} & s_a c_r \\ +s_s s_a - c_s c_a s_r e^{i\delta_D} & -c_s s_a - s_s c_a s_r e^{i\delta_D} & c_a c_r \end{pmatrix} \mathcal{Q}$$

with $\mathcal{P} \equiv \mathrm{diag}(e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3})$ & $\mathcal{Q} \equiv \mathrm{diag}(e^{i\delta_{M1}}, 1, e^{i\delta_{M3}})$
[$(s, a, r) \equiv (12, 23, 13)$ for (**solar, atmospheric, reactor**) angles]

- **Oscillation**



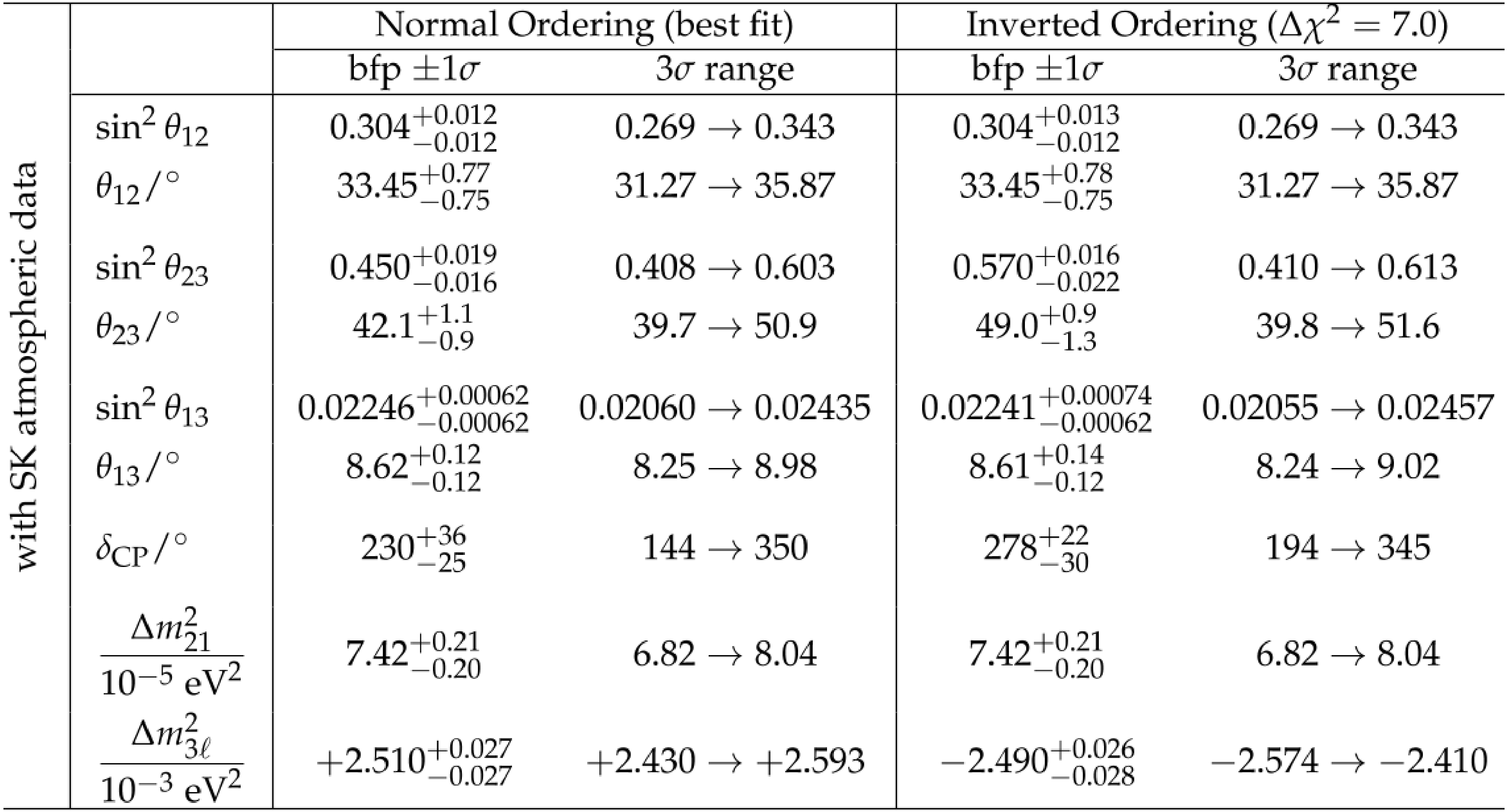
Mass Splitting + **Mixing**

Neutrino Oscillation

$$P_{\alpha\beta}\big|_{\alpha\neq\beta} \equiv |A_{\alpha\beta}|^2 = \sin^2 2\theta \sin^2\left(\delta m^2 \frac{L}{4E}\right)$$

Amplitude **Frequency**

Current Status of ν Oscillation



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

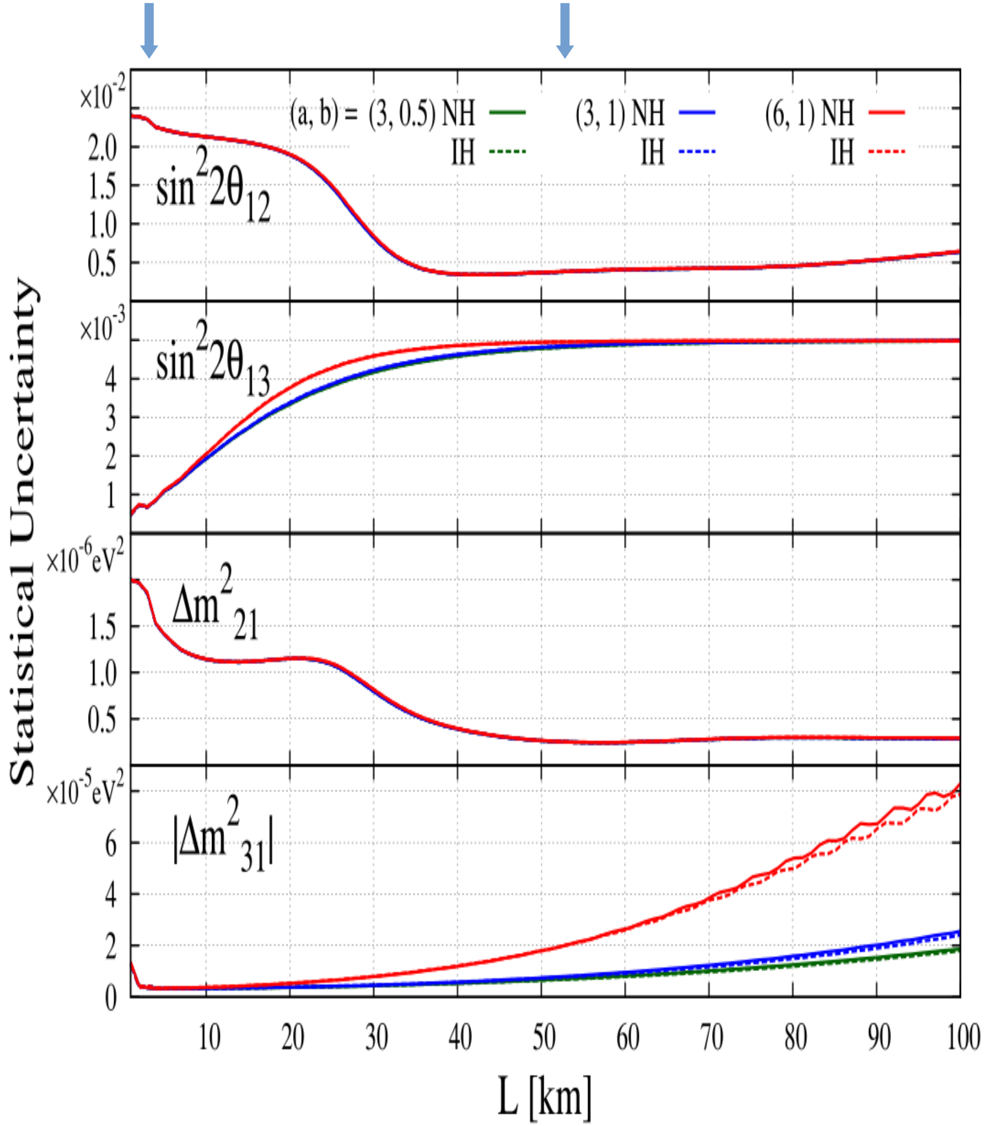
Gonzalez-Garcia, Maltoni & Schwetz [2111.03086]

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

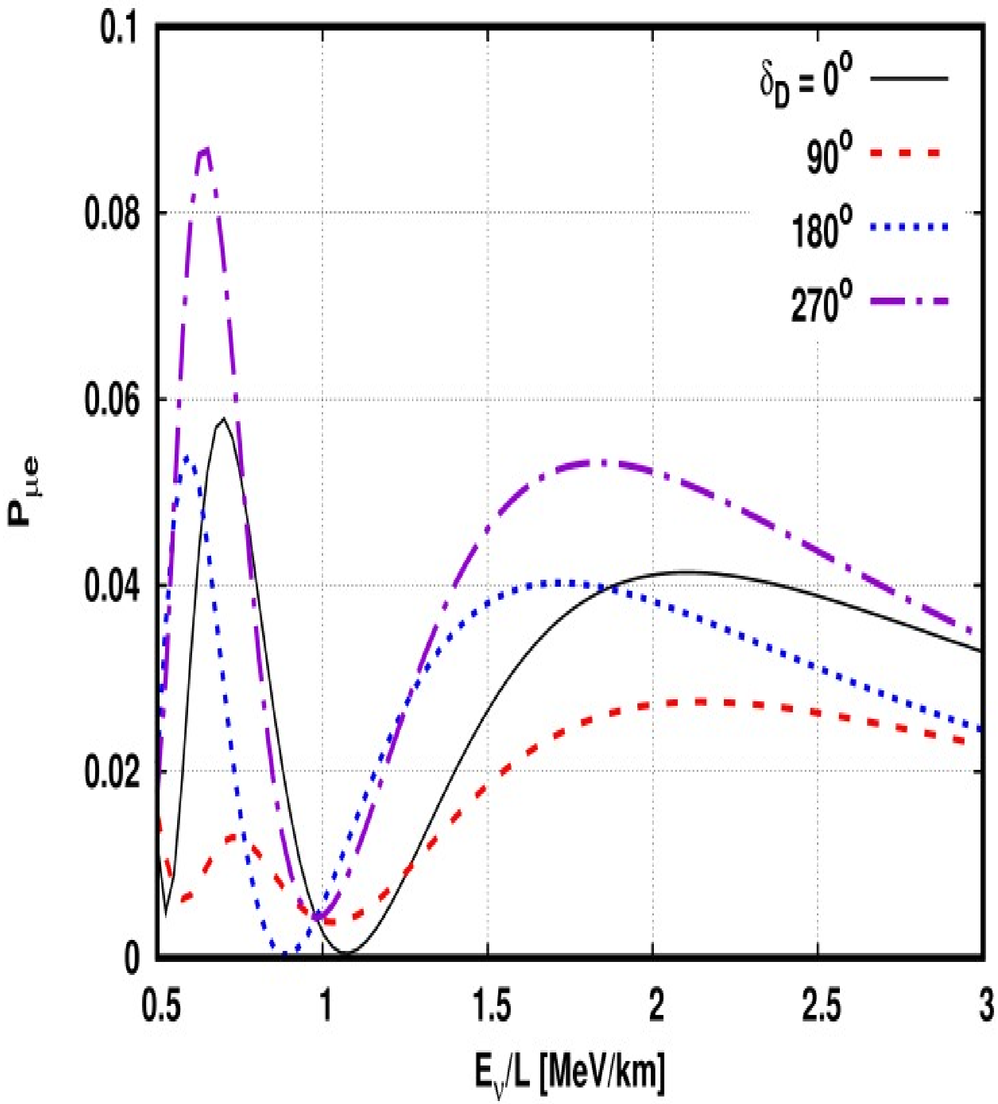
Kam-Biu Luk @ Neutrino 2022

Precision Era of ν Oscillation

Daya Bay **JUNO**

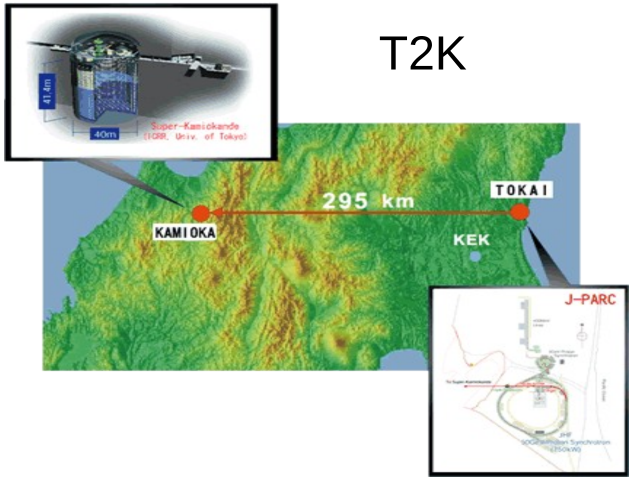


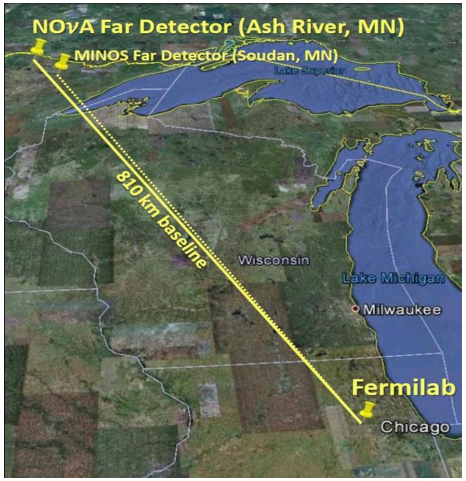
SFG, Hagiwara, Okamura & Takaesu [1210.8141]

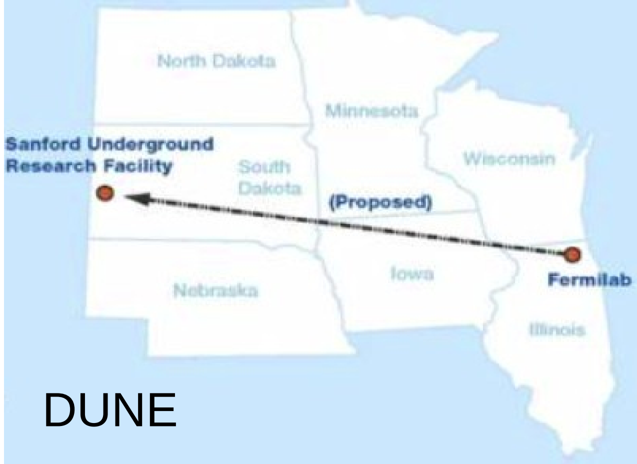


SFG & Smirnov [1607.08513]

Future Accelerator Exps


T2K




DUNE

- **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?

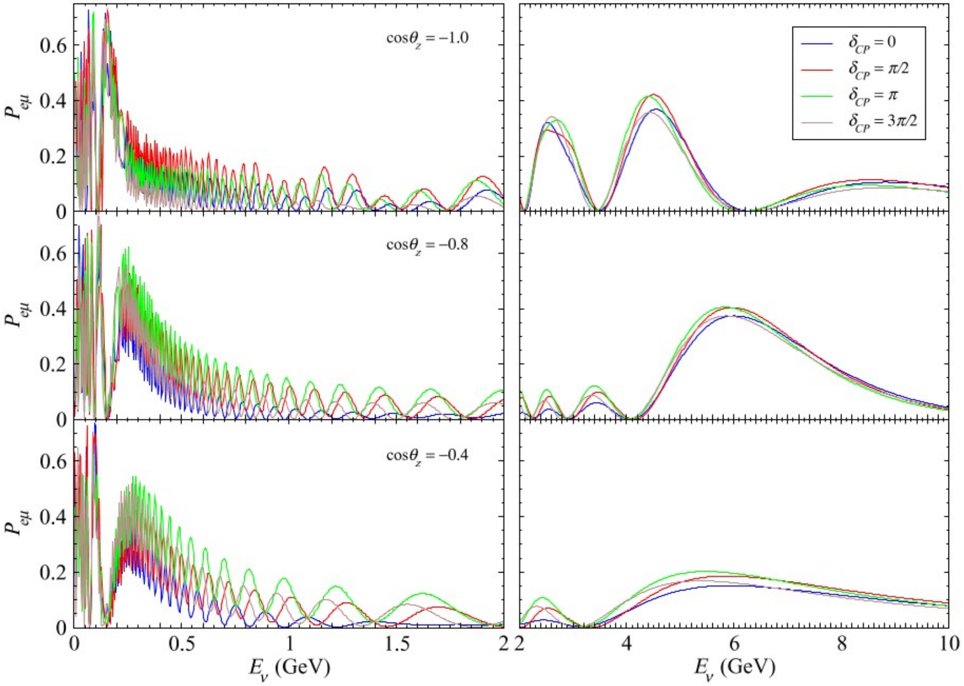
  Tang, Vihonen & Xu [2202.13595]
  Li et al [2204.11871, 2205.15350, 2301.02493]
- Atmospheric

  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]



Dirac CP Phase δ_D

- Oscillation probabilities @ Accelerator Neutrino Exps

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

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

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

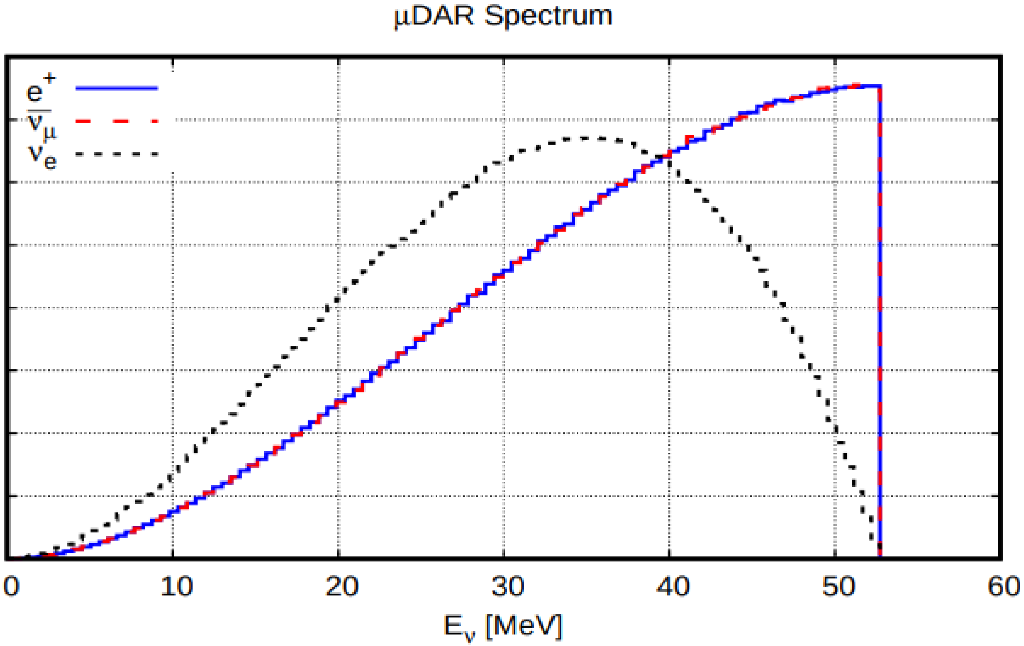
$$P_{\overline{\nu}_\mu\to\overline{\nu}_e} + P_{\nu_\mu\to\nu_e} = 2 s_a^2 c_r^2 s_r^2 \,,$$

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

Difference in ν & νbar osc. probilities → infer CP phase δ_D

Solution: Muon Decay at Rest

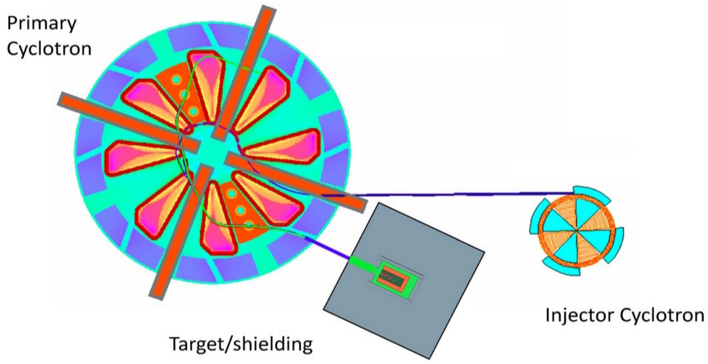
- A cyclotron produces 800 MeV proton beam @ fixed target.
- Produce $\pi^\pm$ which stops &
  - π^- is absorbed,
  - π^+ decays @ rest: $\pi^+ \to \mu^+ + \nu_\mu$.
- μ^+ stops & decays @ rest: $\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e$



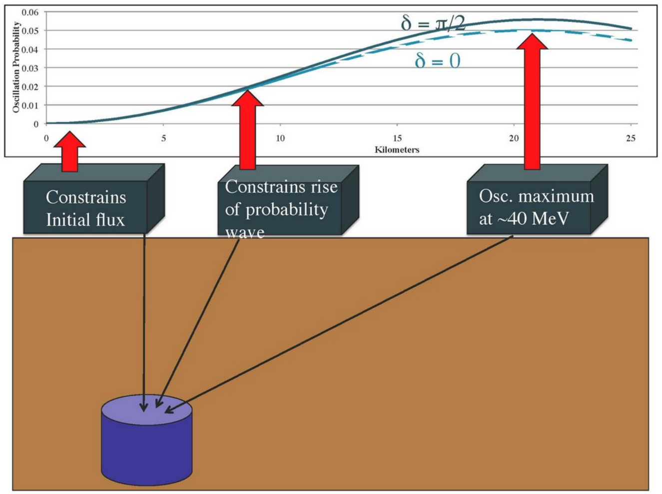
Well predicted spectrum!

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

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

1 μDAR source + **2** detectors

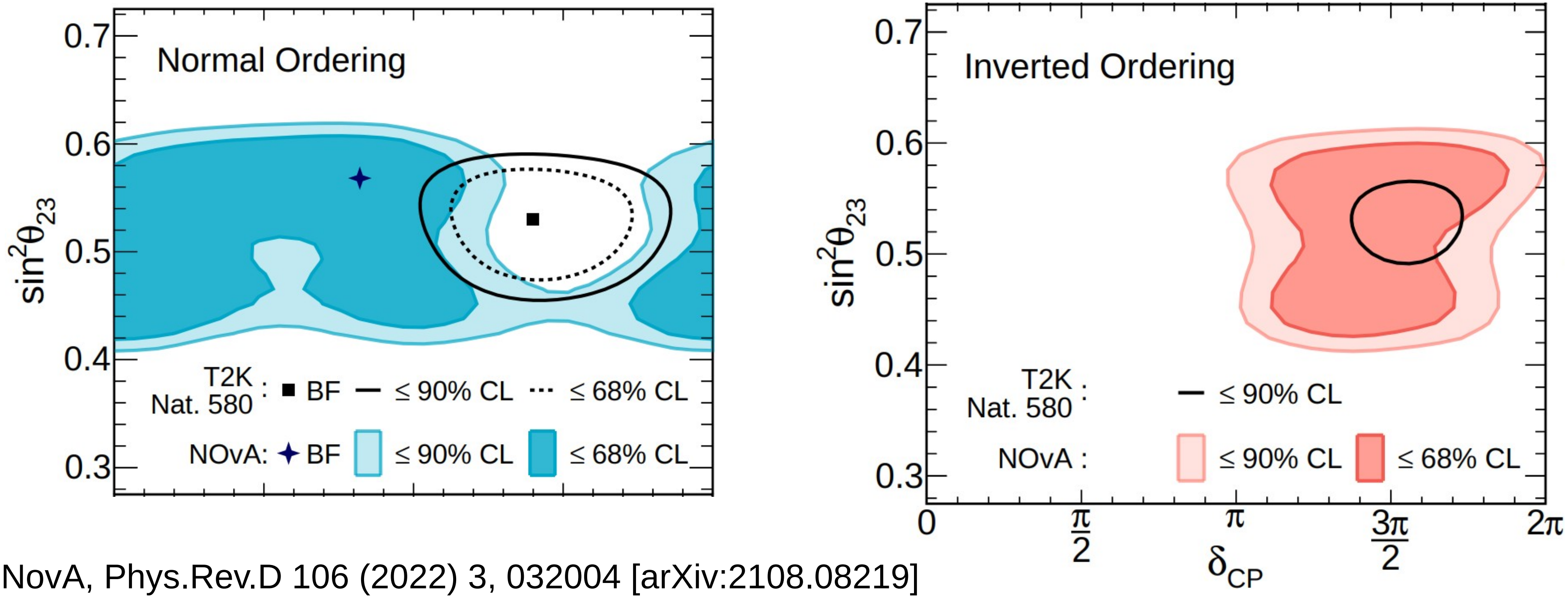
Advantages

- 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]

Tension between T2K & NOvA



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

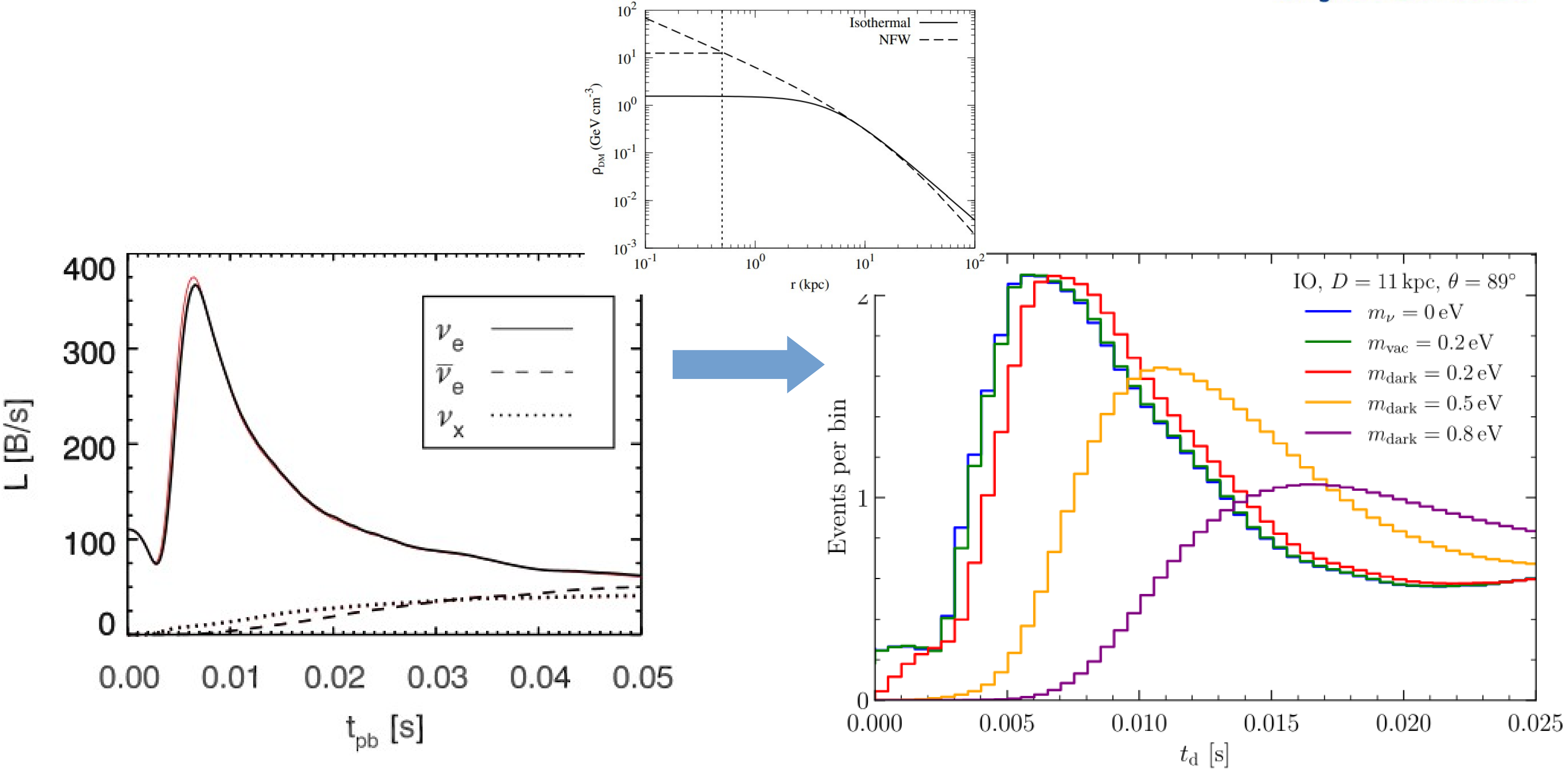
- **Non-Standard Interactions**
- **Non-Unitary Mixing**
- **Lorentz Violation**
- **Sterile Neutrinos**

Denton, Gehrlein & Pestes [2008.01110]

Rahaman, Razzaque & Sankar [2201.03250]

Chatterjee & Palazzo [2005.10338]

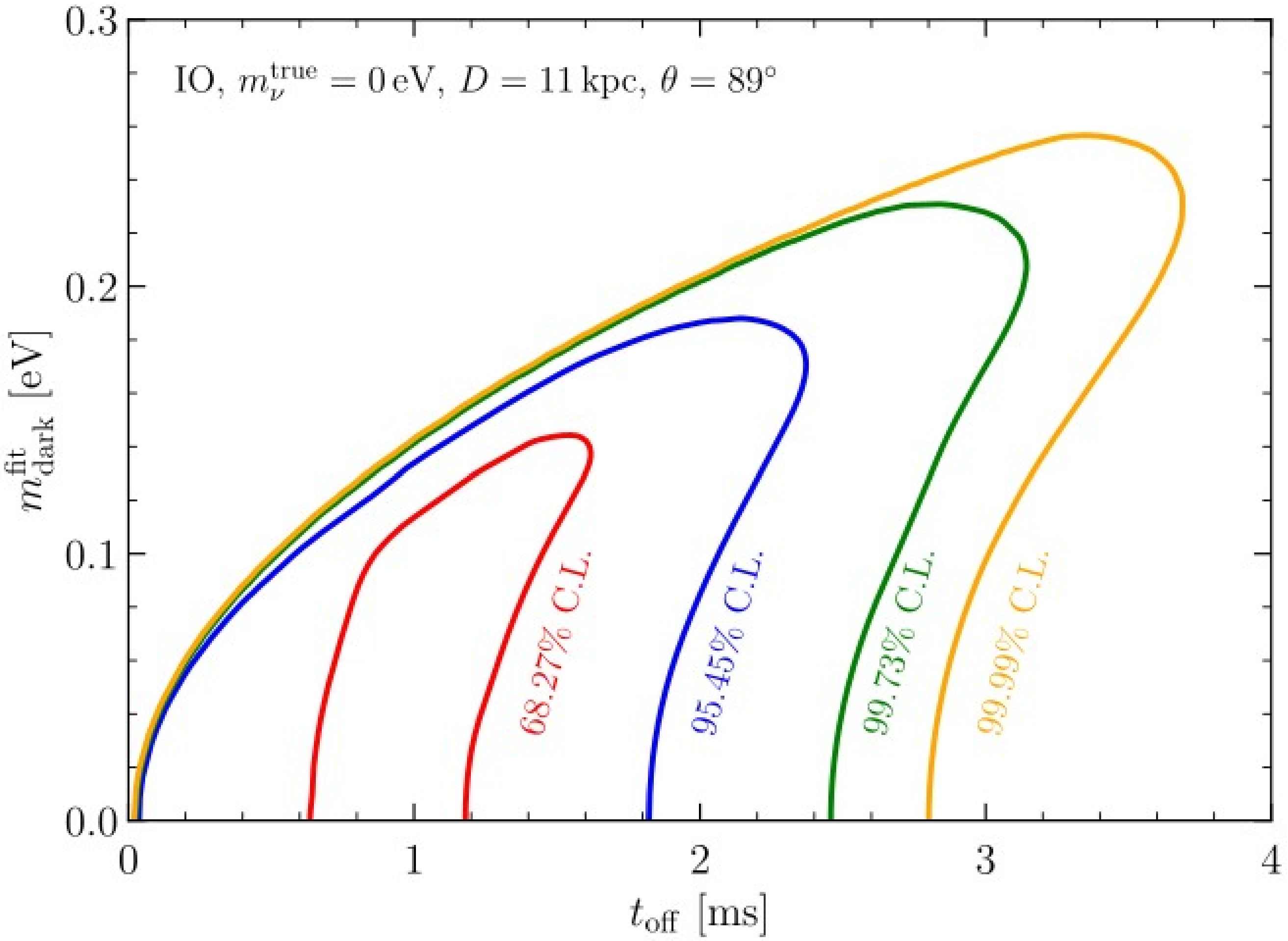
Dark Mass with SN



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

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

Dark Mass with SN

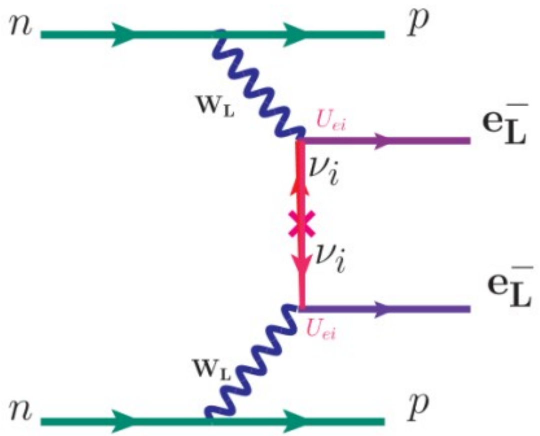


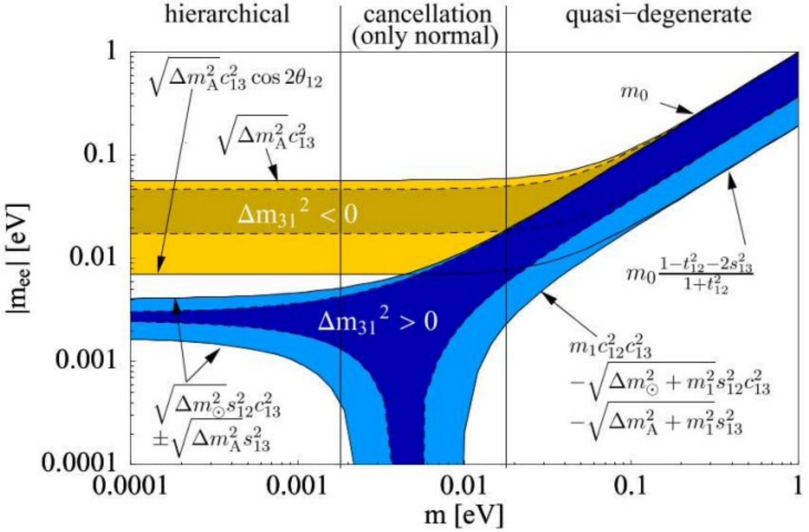
$$\Delta t_{\rm dark} = \frac{m^2_{\rm dark}(\mathbf{x}_\odot) D}{2E_\nu^2} \frac{\int_{\mathbf{x}_\star}^{\mathbf{x}_\odot} \rho_\phi(\mathbf{x})|d\mathbf{x}|}{D\rho_\phi(\mathbf{x}_\odot)} \equiv \Delta t_\odot \frac{\overline{\rho_\phi}(\mathbf{x}_\star)}{\rho_\phi(\mathbf{x}_\odot)}$$

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

Neutrinoless Double Beta Decay

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





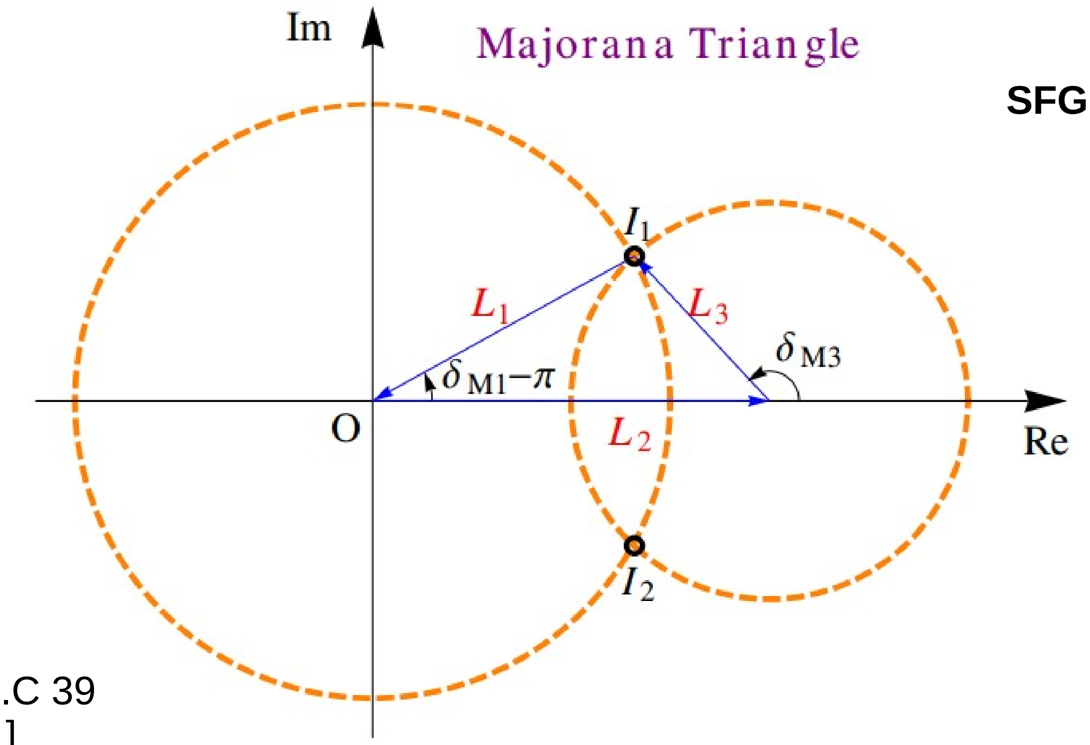
- **Mass Suppression**

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

- **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]

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

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

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

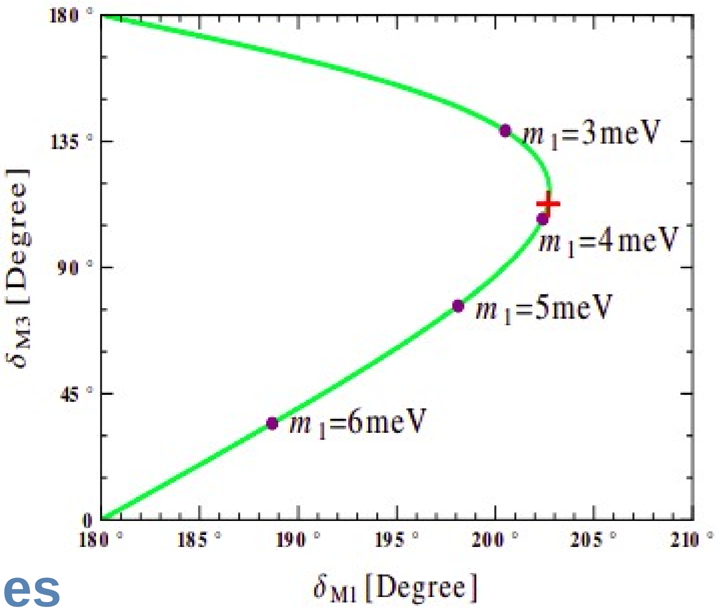
$$\overrightarrow{L_3} \equiv m_3 U_{e3}^2 = \sqrt{m_1^2 + \Delta m_a^2} s_r^2 e^{i\delta_{\rm M3}} .$$

Catching 2 Majorana CP Phases

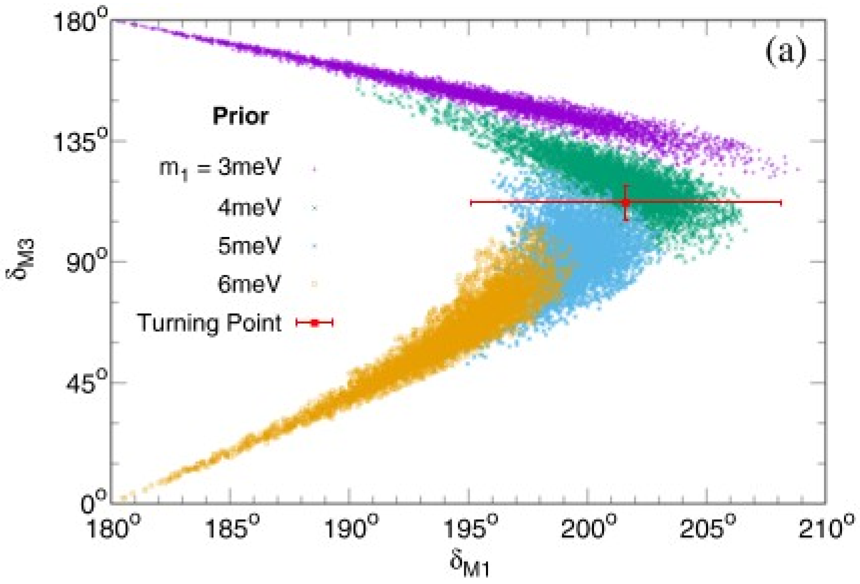
Tsung-Dao Lee Institute

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

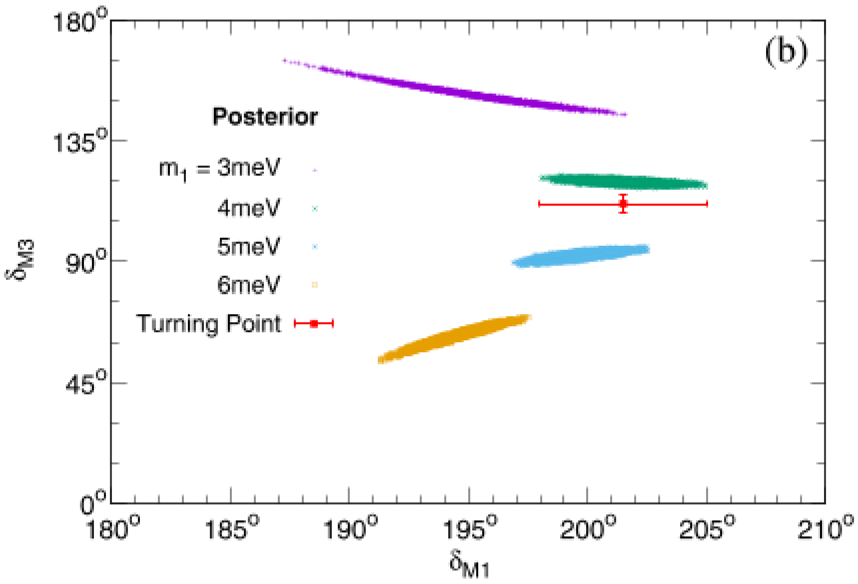
$$\cos \delta_{M3} = +\frac{m_1^2 c_r^4 c_s^4 - m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_2 m_3 c_r^2 s_r^2 s_s^2}$$



- **JUNO can significantly reduce uncertainties**



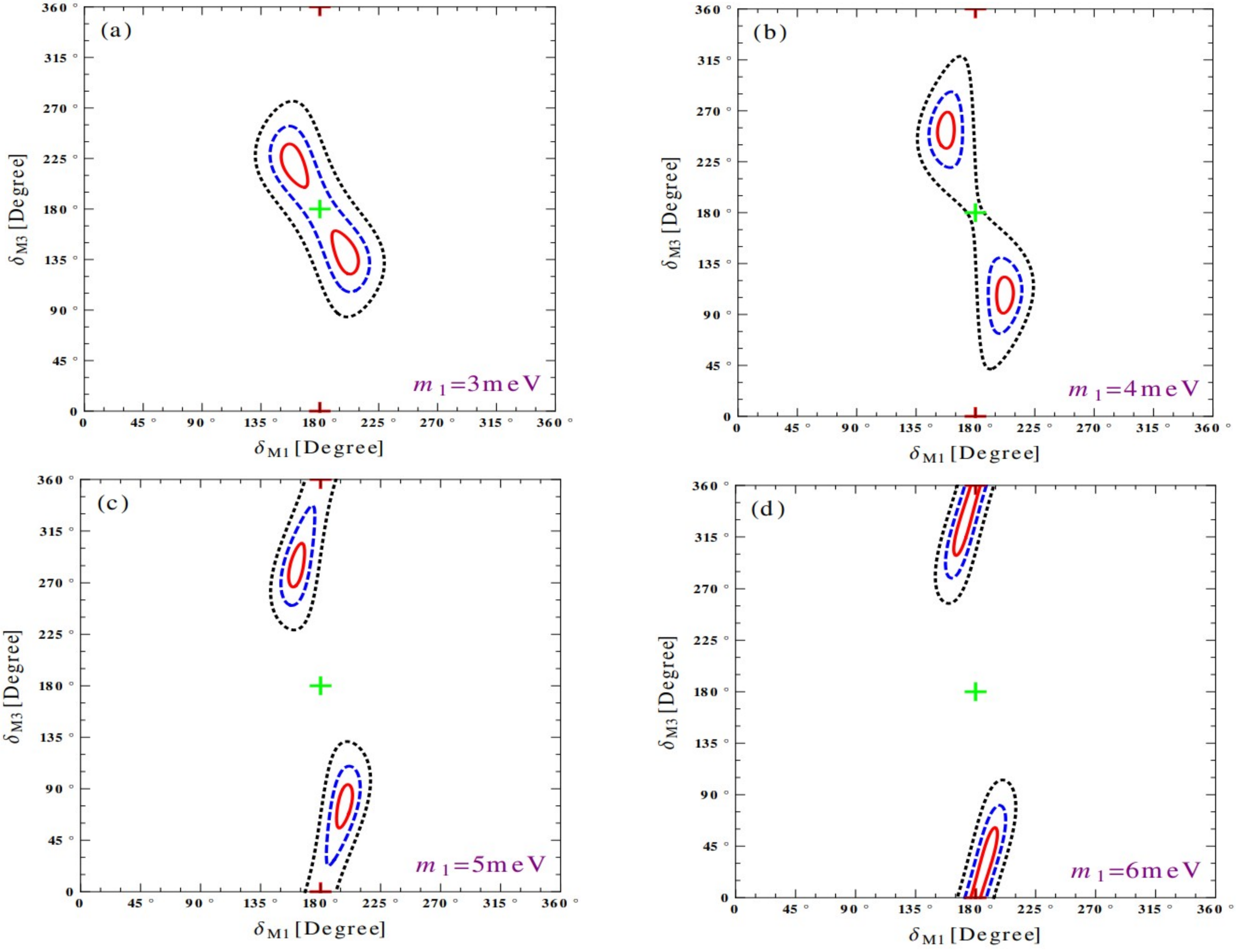
SFG & Manfred Lindner, [1608.01618]



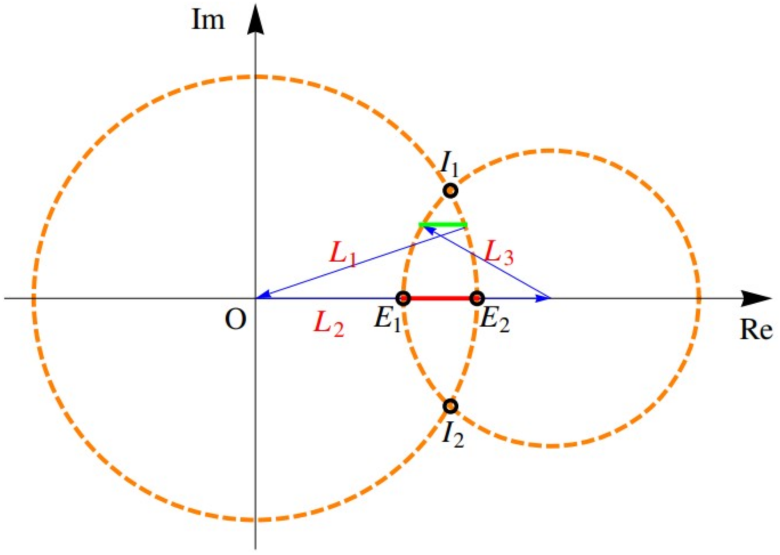
see also **SFG** & Rodejohann [1507.05514]

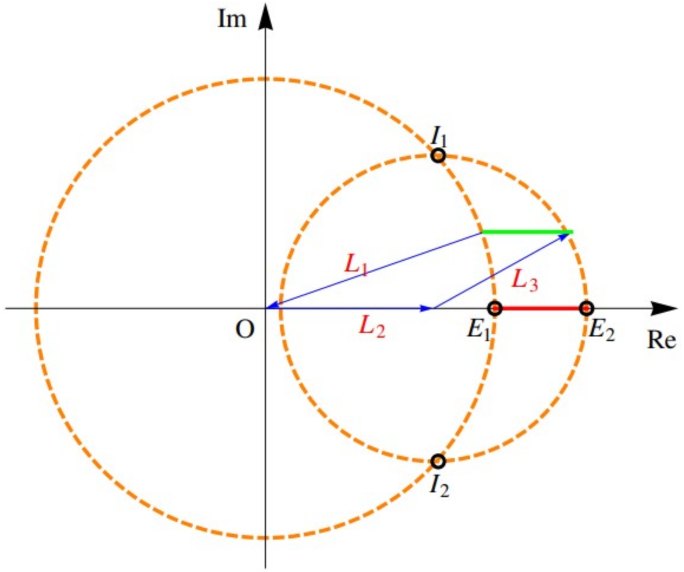
Uncertainty from m_{ee}

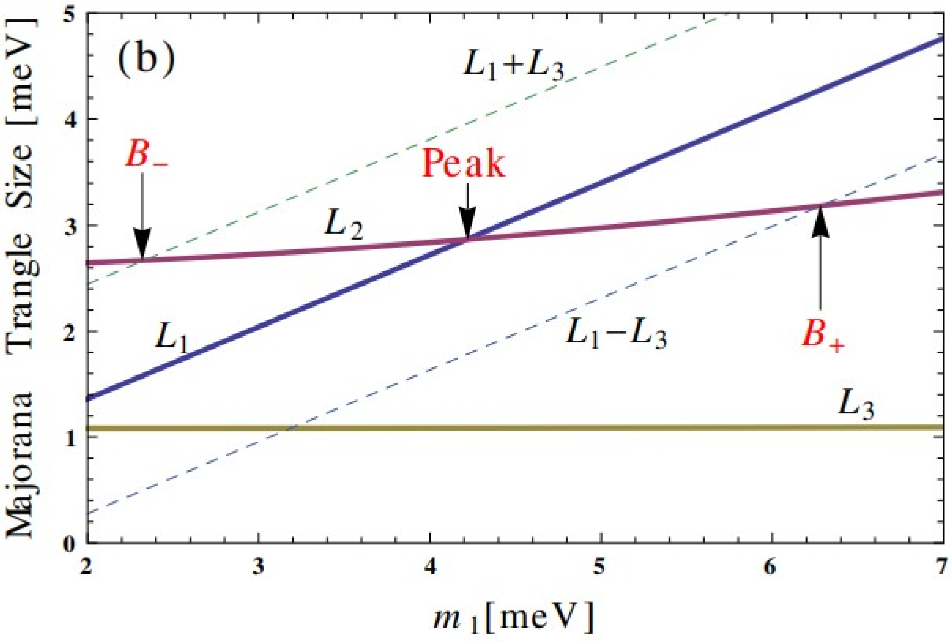
Tsung-Dao Lee Institute

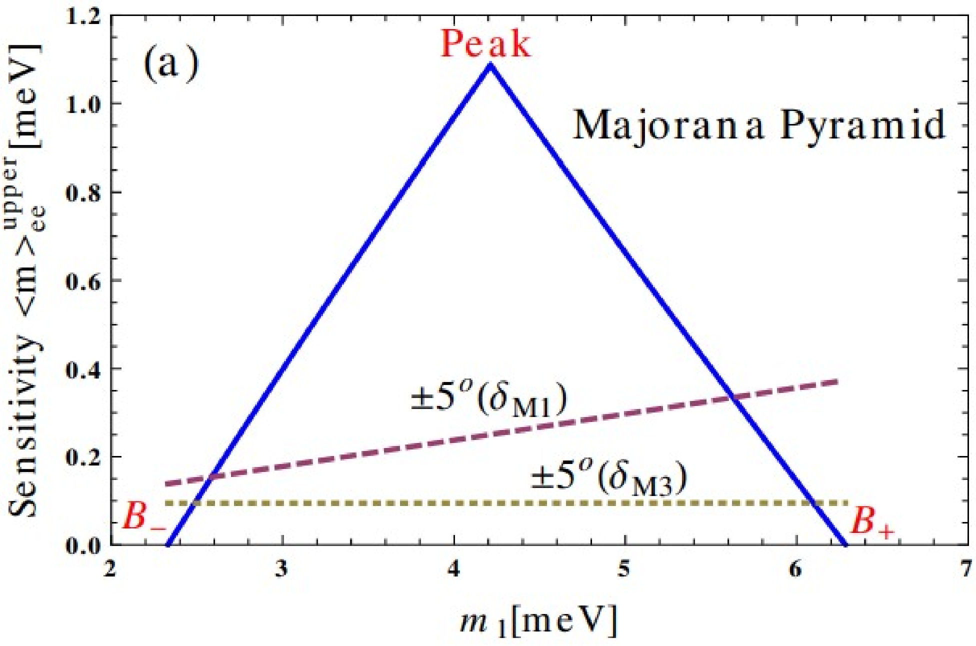


Majorana Pyramid

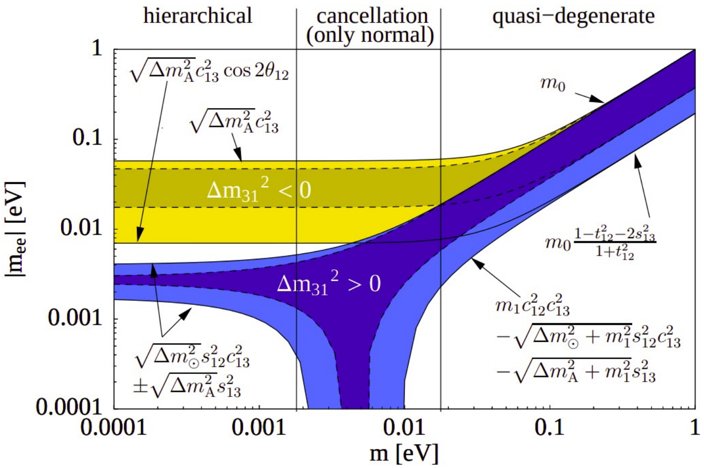








1meV frontier of 0ν2β



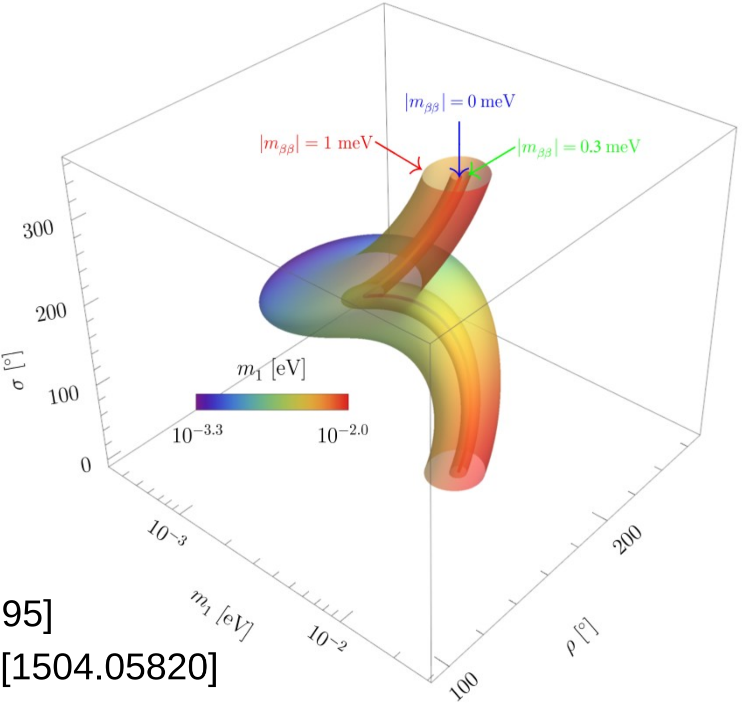
- **Nonzero → only 1 Majorana CP**

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

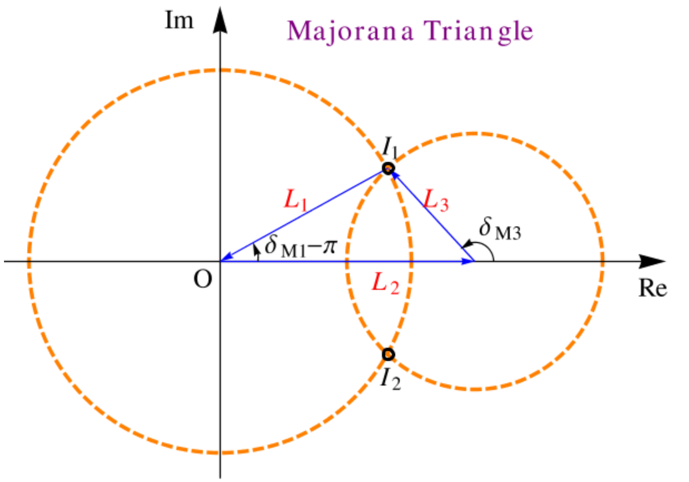
- **Zero → 2 Majorana CP phases**

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

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



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



Xing [hep-ph/0305195]

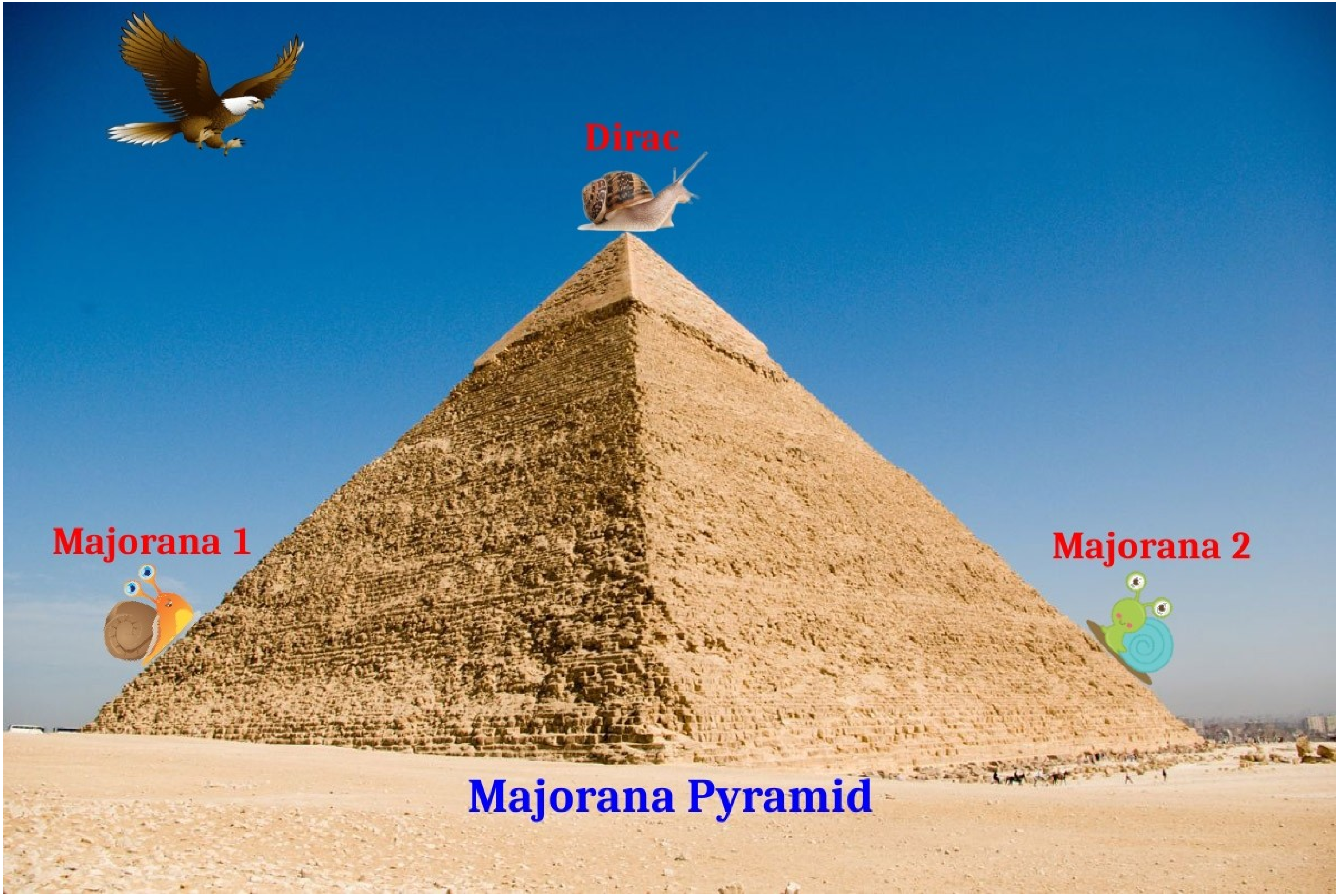
Xing, Zhao & Zhou [1504.05820]

Xing & Zhao [1612.08538]

Cao, Huang, Li, Wang, Wen, Xing, Zhao & Zhou [1908.08355]

SFG & Manfred Lindner, [1608.01618]

Prey of Leptonic CP Phases



Confusion from New Physics

- 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]

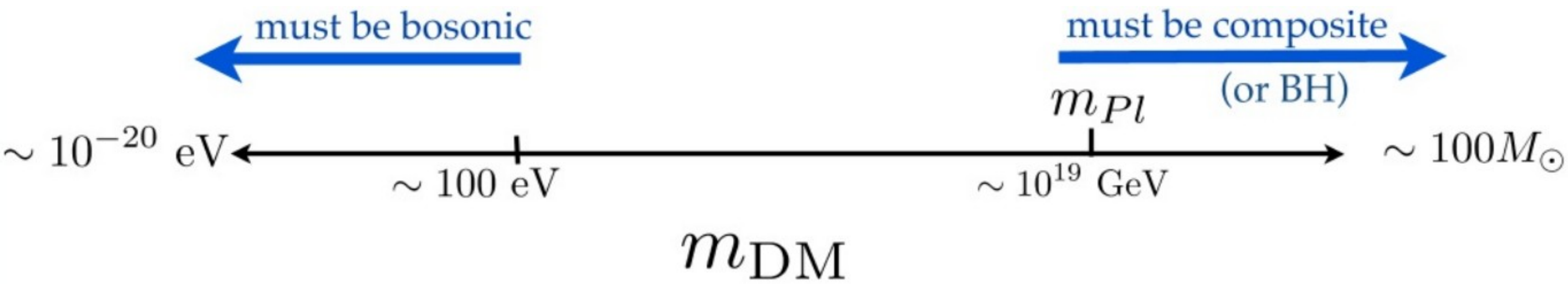
SFG, Murayama [1904.02518]

SFG, PoS NuFact2019 (2020) 108

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

3. Dark NSI

- **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!