# Neutrino CP Violation


Shao-Feng Ge

葛韶锋

gesf@sjtu.edu.cn


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FIND CPV @ USTC


上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

李政道研究所
Tsung-Dao Lee Institute

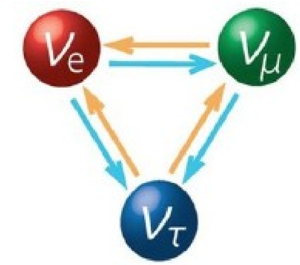
# Outline

李政道研究所 Tsung-Dao Lee Institute

- CP Violation in the Neutrino Sector
- Dirac CP Phase & New Physics
- Accelerator + μDAR for better CP measurement
- Majorana CP Phase
- Neutrino Electromagnetic Properties

# Neutrino Oscillation

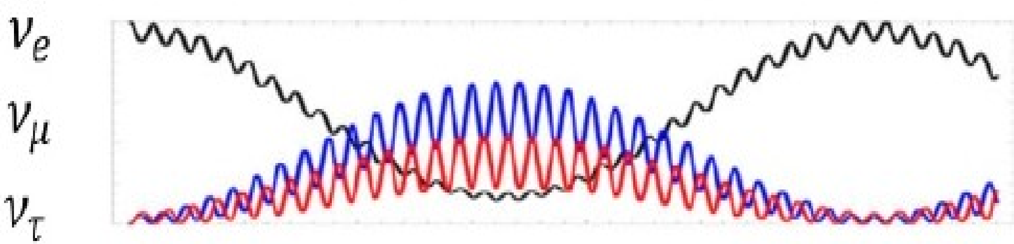
- **PMNS Matrix**



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

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

- **Oscillation**



**Mass Splitting** + **Mixing**

**Neutrino Oscillation**

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

**Amplitude** **Frequency**

# Current Status of ν Oscillation

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

Gonzalez-Garcia, Maltoni & Schwetz [2111.03086]

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

Kam-Biu Luk @ Neutrino 2022

# Seesaw Mechanism

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- **Heavy neutrinos (*N*)**

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

required by **Grand Unification Theory (大统一理论)**

- **Seeaw Mechanism**

The diagonalization of the full mass matrix

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

$M_D \sim O(100)$ GeV, $M_N \sim O(10^{15})$ GeV $\rightarrow M_\nu \sim O(0.01)$ eV


柳田勉、何小刚：
**大家一起来玩跷跷板！**

**Light neutrino mass $M_\nu$ is suppressed by the heavy ones**

# Neutrino vs Higgs

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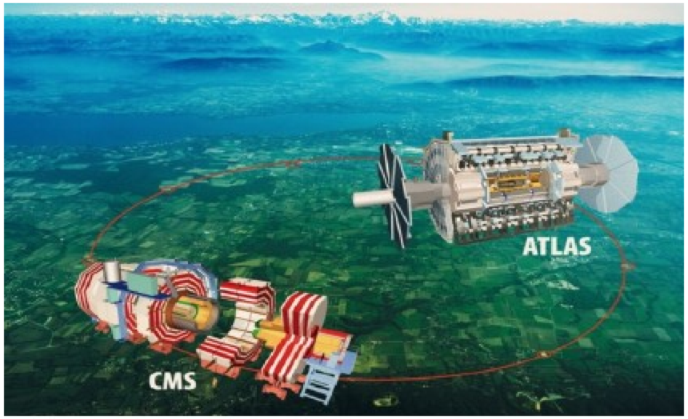
- **Higgs boson** ⇒ electroweak symmetry breaking & mass. ~ O(100)GeV
- **Chiral symmetry breaking** ⇒ majority of mass.
- The world seems not affected by the tiny neutrino mass?
  - Neutrino mass ⇒ Mixing
  - 3 Neutrino ⇒ possible **CP violation**
  - CP violation ⇒ **Leptogenesis**
  - ⇒ **Matter-Antimatter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


Daya Bay @ **March 8, 2012**




LHC @ **July 4, 2012**

# Leptogenesis

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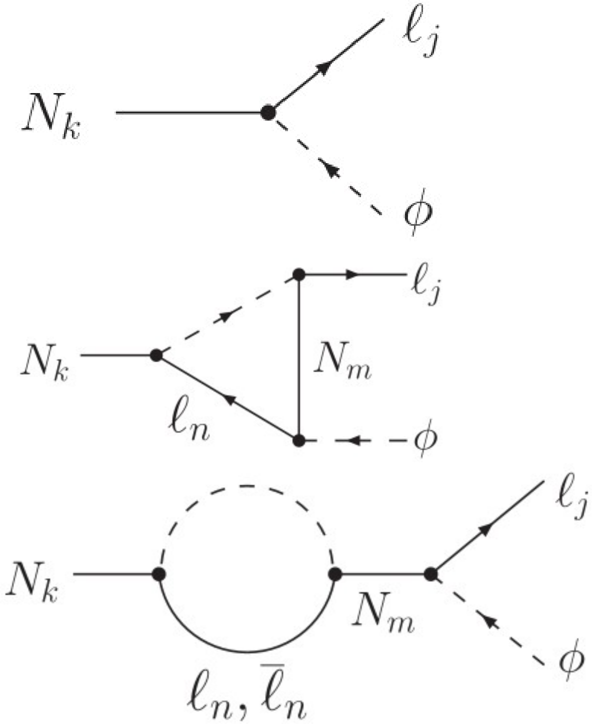
With decreasing temperature, heavy N decays to light SM particles.

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




**Matter-Antimatter Asymmetry**

- **Interference between tree & loop diagrams**

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

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

**Yanagida**

**Fukugita**

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# Current Status of CP Measurement

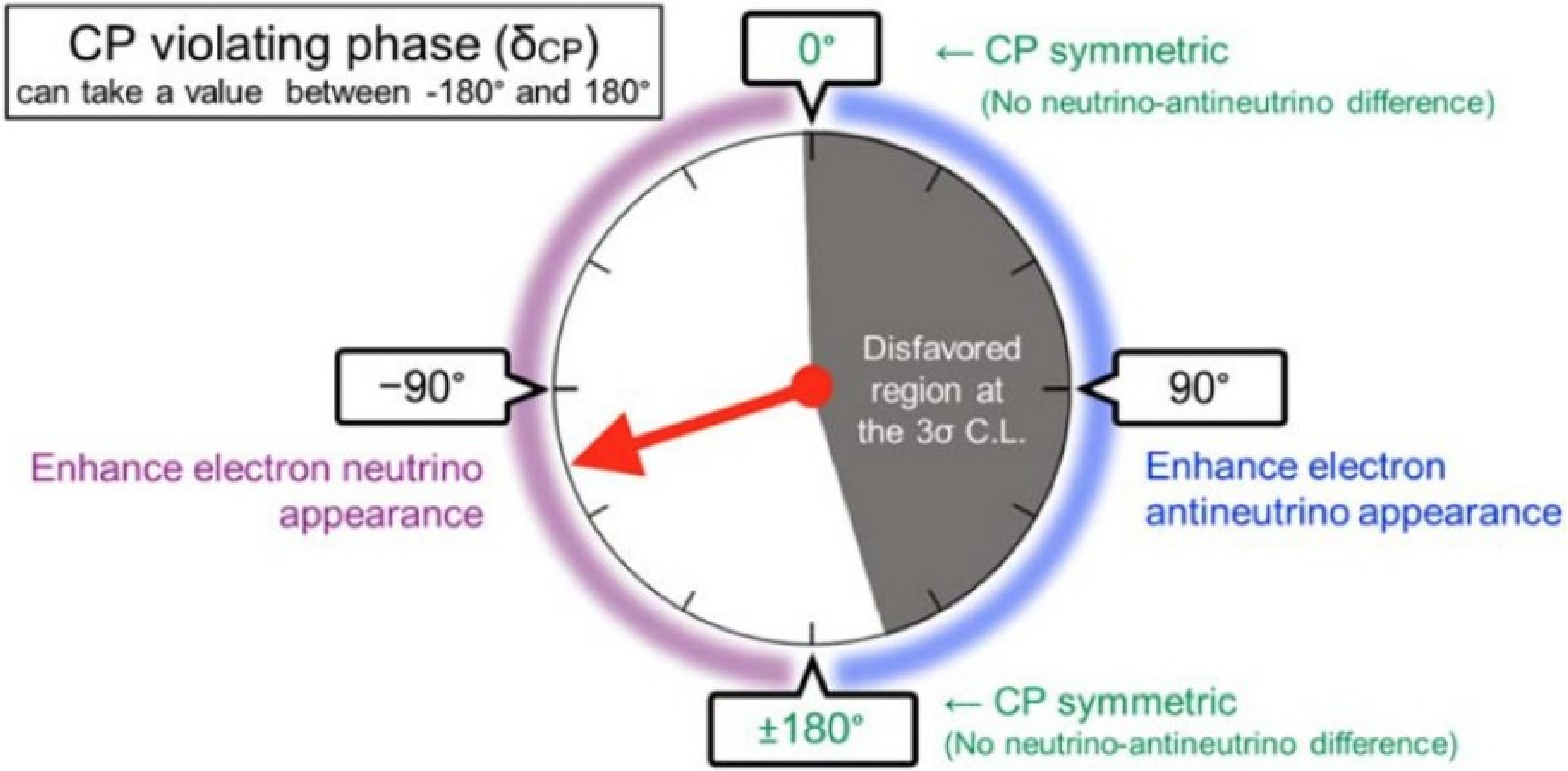


*Fig.1 The arrow indicates the value most compatible with the data. The gray region is disfavored at 99.7% (3$\sigma$) confidence level. Nearly half of the possible values are excluded.*

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

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

# Accelerator ν's by Lee & Yang

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PHYSICAL REVIEW LETTERS

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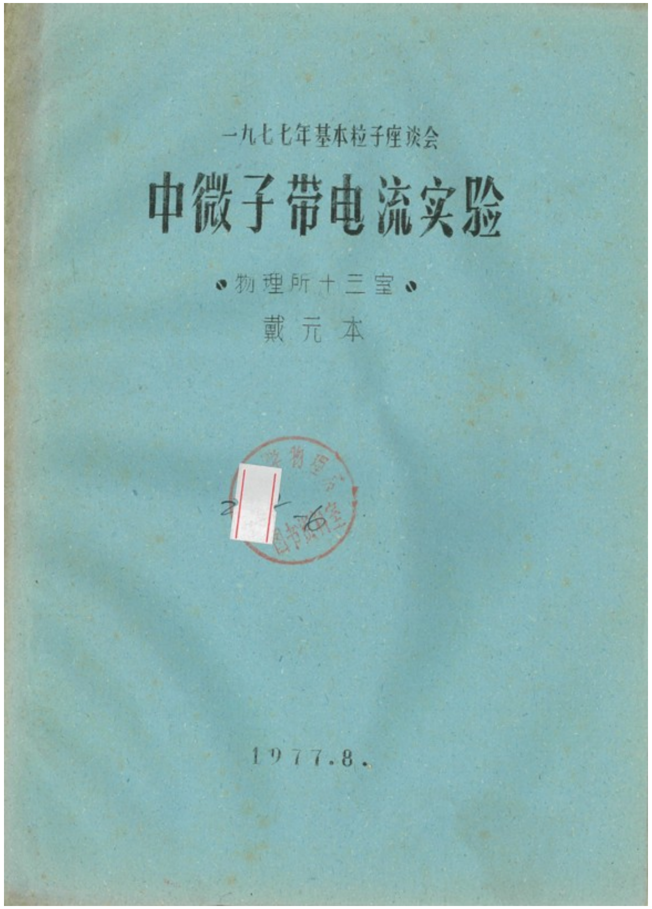
## Feasibility of Using High-Energy Neutrinos to Study the Weak Interactions

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

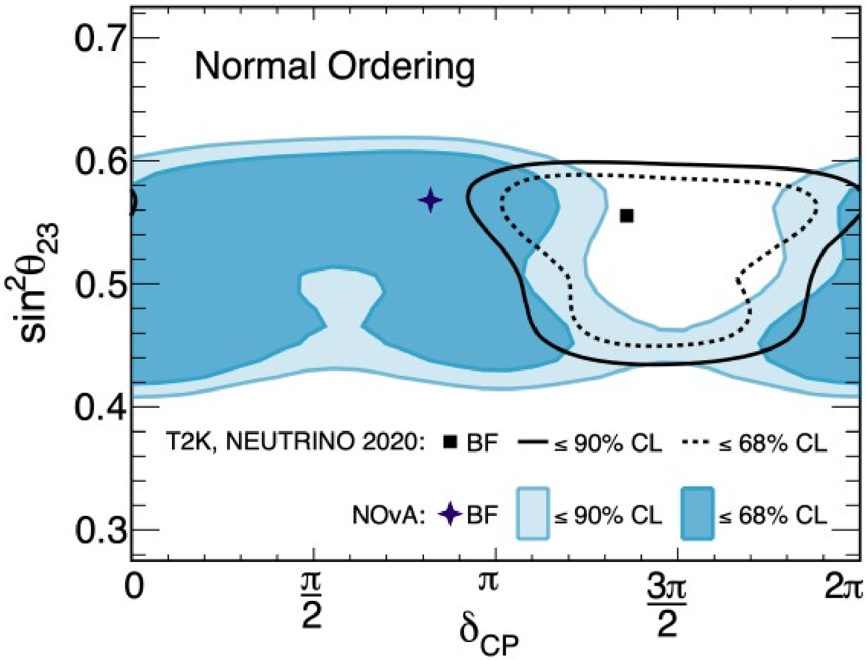
中微子是粒子物理标准模型中非常独特而重要的基本粒子。中微子只参与弱相互作用，能够穿透几光年的铅板，是非常难以探测的鬼魅粒子。然而，恰恰是中微子率先给出了超出标准模型的第一个新物理现象——中微子振荡——这已经得到大量实验的证实，并于2015年获诺贝尔物理学奖，成为指引超出标准模型新物理研究的重要线索。在上世纪五六十年代粒子物理发展的黄金期，施瓦兹、李政道与杨振宁提出的高能加速器中微子实验原理，是一个非常革命性的思想，一直在有力地推动着包括中微子在内的粒子物理不断向前发展。

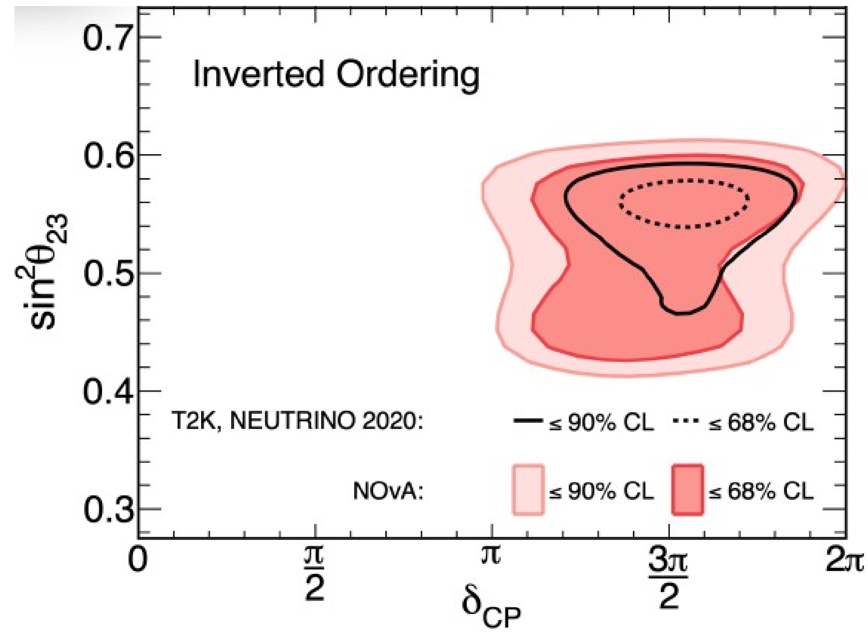
何小刚，李政道先生和现代中微子物理，《现代物理知识杂志》2021

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

# Tension between T2K & NOvA






NOvA [2108.08219]

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

# 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]

# Non-Standard Interactions (NSI)

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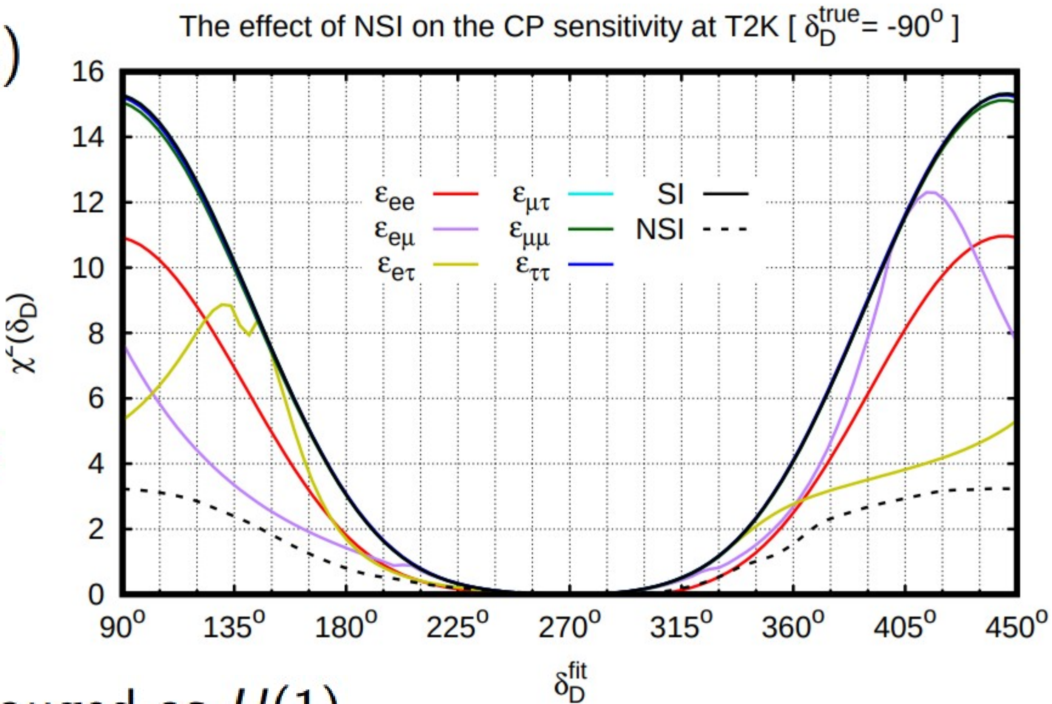
$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* &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

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

# Non-Unitarity Mixing (NUM)

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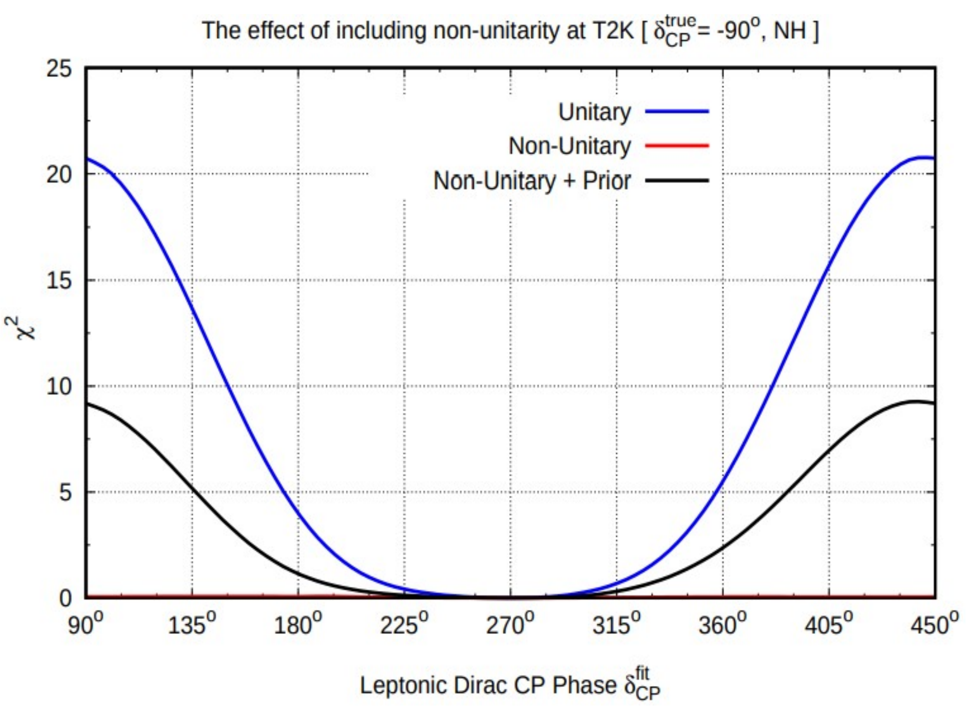
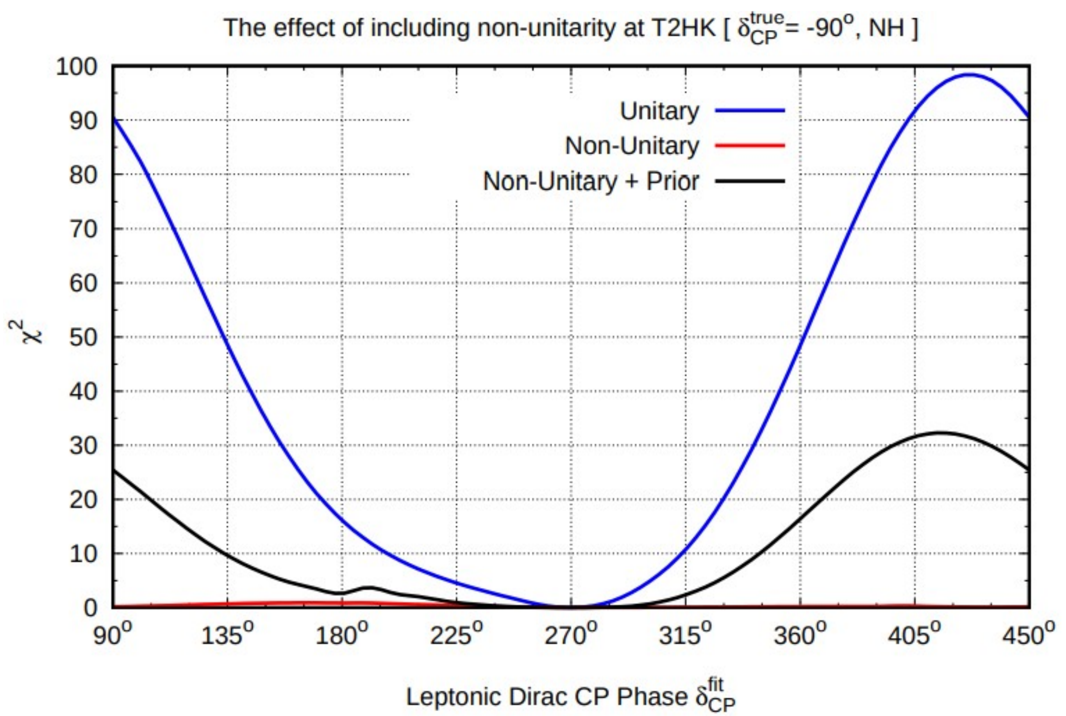
$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

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




SFG, Pasquini, Tortola & Valle [1605.01670]

# NUM vs Seeaw Mechanism

- **Heavy Neutrinos**

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

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!**

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# CP Measurement & Issues

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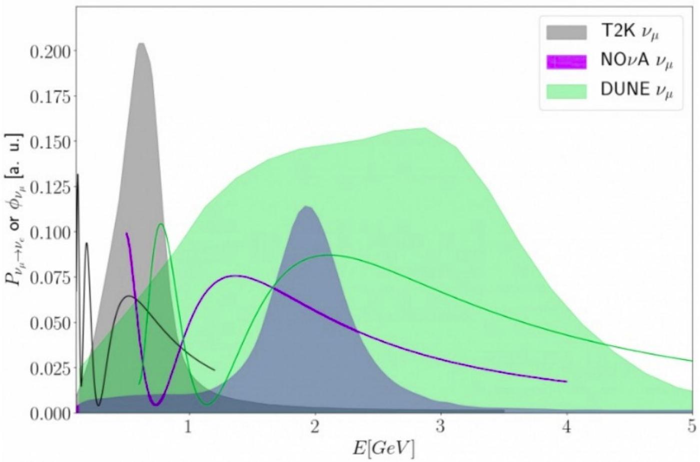
$$P_{\overline{\nu}_\mu \to \overline{\nu}_e} - P_{\nu_\mu \to \nu_e} = \alpha\pi \sin(2\theta_s)\sin(2\theta_r)\sin(2\theta_a)\cos\theta_r \sin\delta_D$$

@ 1st oscillation peak

- **Efficiency**:
  - Proton accelerators produce $\nu$ 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 $\delta_D$ 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

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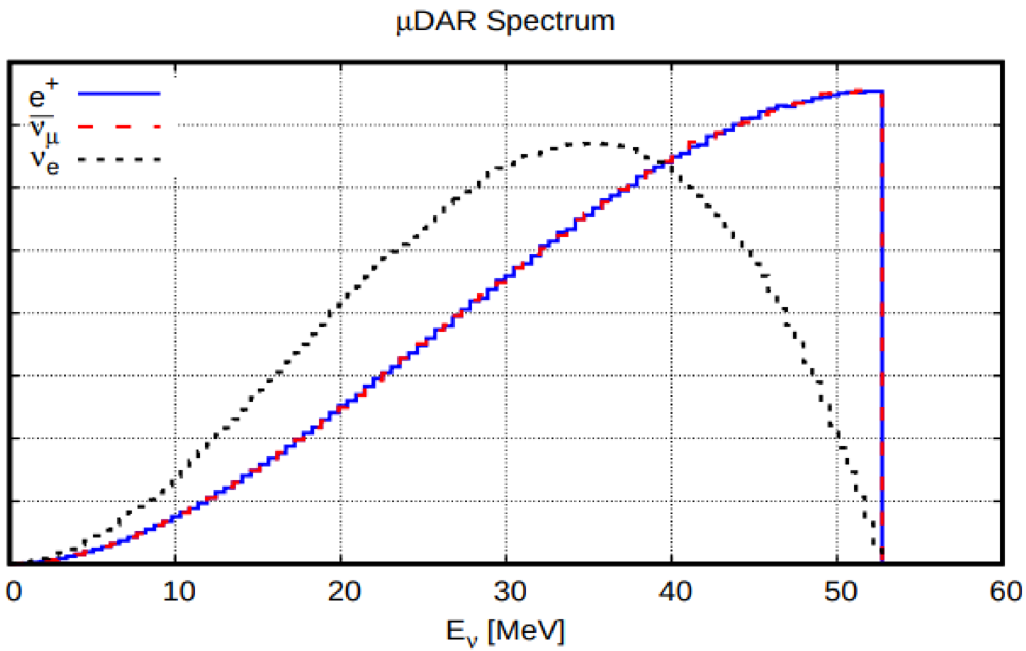
- A cyclotron produces 800 MeV proton beam @ fixed target.
- Produce $\pi^\pm$ which stops &
  - $\pi^-$ is absorbed,
  - $\pi^+$ decays @ rest: $\pi^+ \to \mu^+ + \nu_\mu$.
- $\mu^+$ stops & decays @ rest: $\boldsymbol{\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e}$



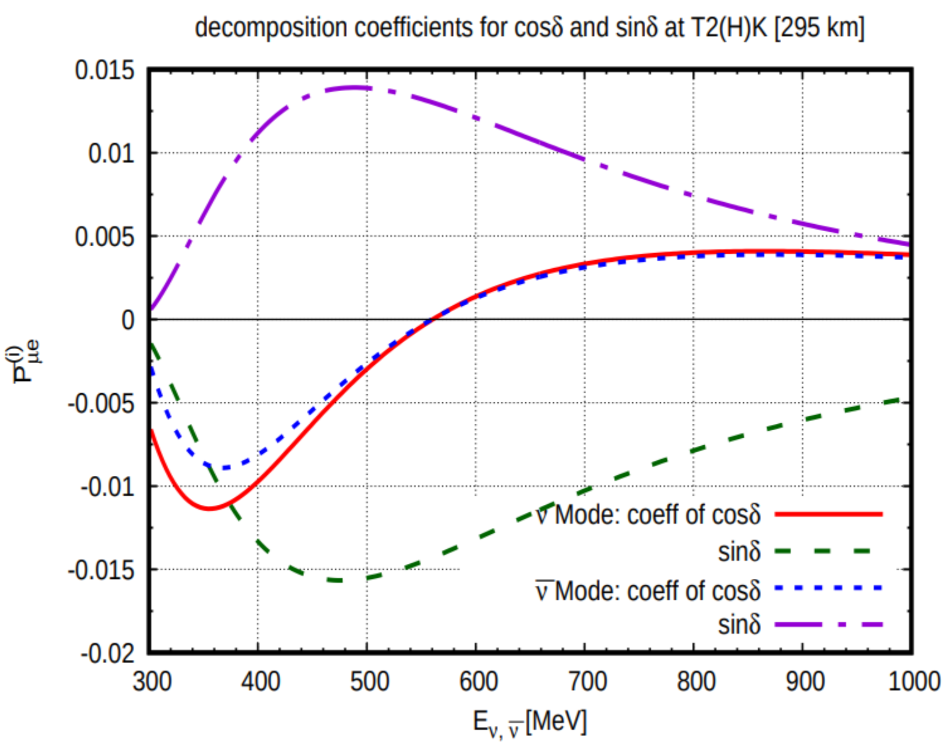

Well predicted spectrum!

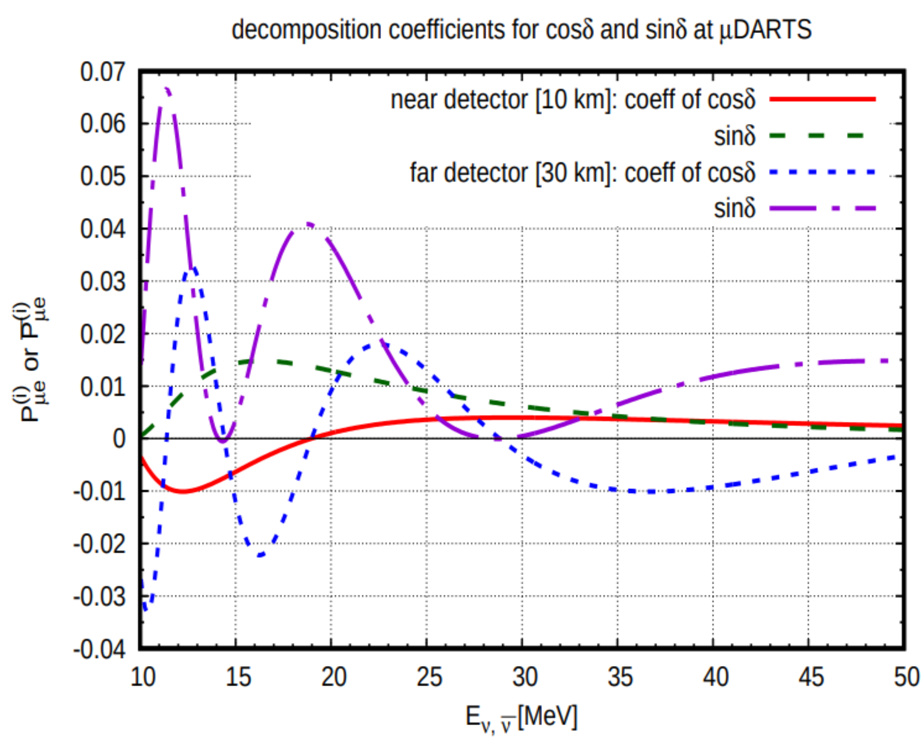
- $\overline{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_e$ from $\boldsymbol{\overline{\nu}_\mu \to \overline{\nu}_e}$ **oscillation**.

# μDAR & Accelerator ν

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

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



# TNT2K

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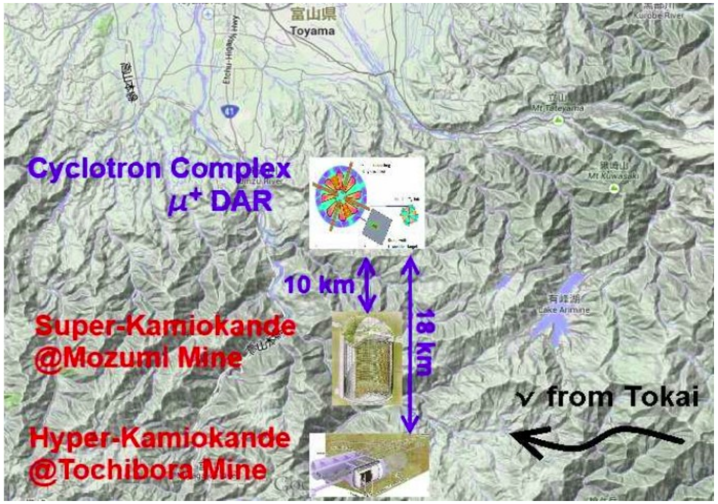


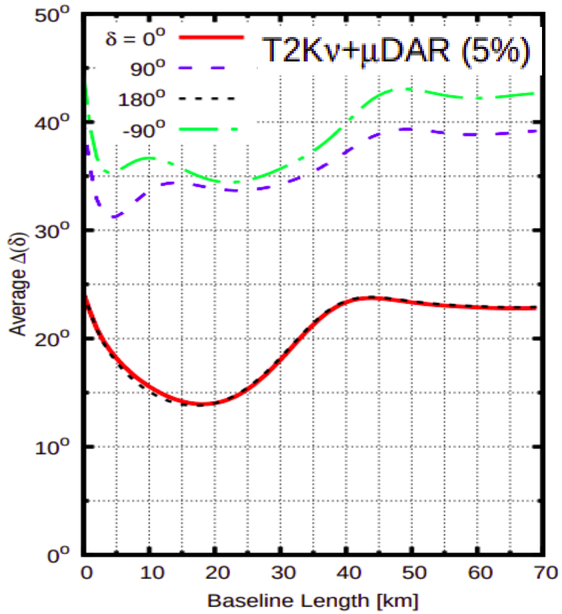


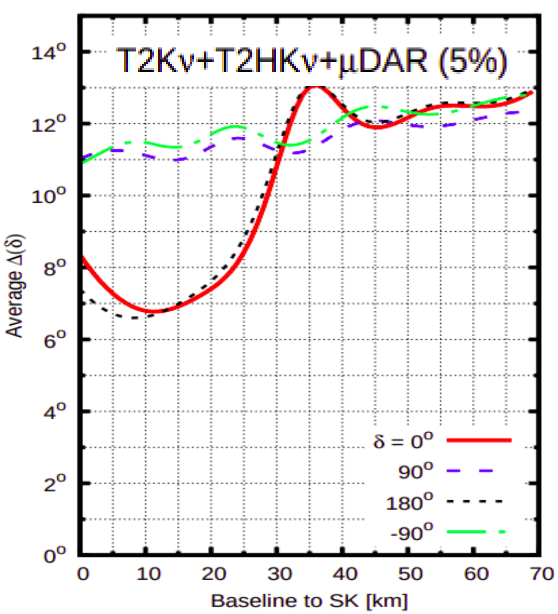


1 $\mu$DAR source + 2 detectors

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 DAE$\delta$ALUS]
- 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]

# Guarantee CP against NSI

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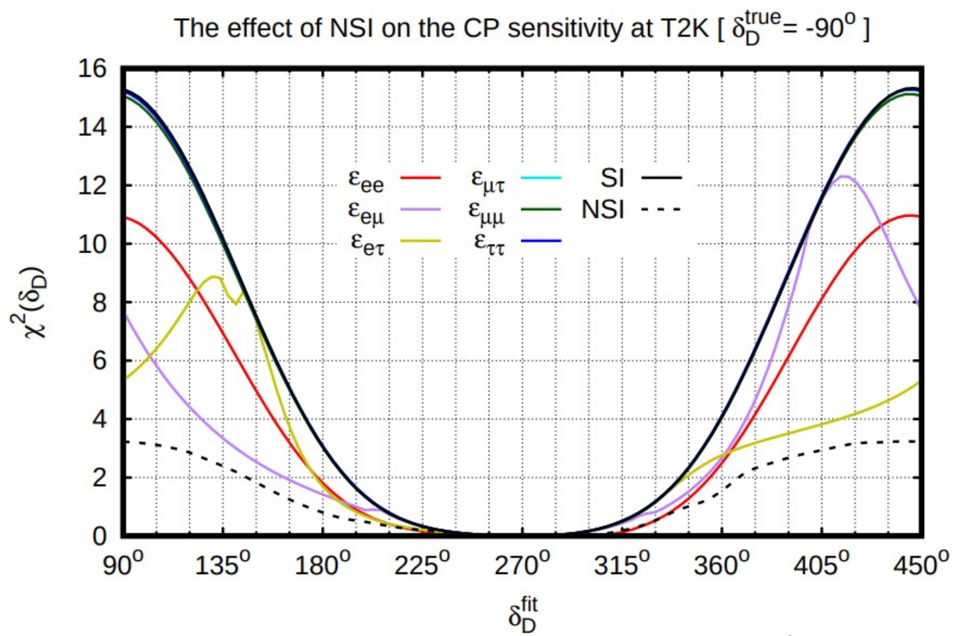


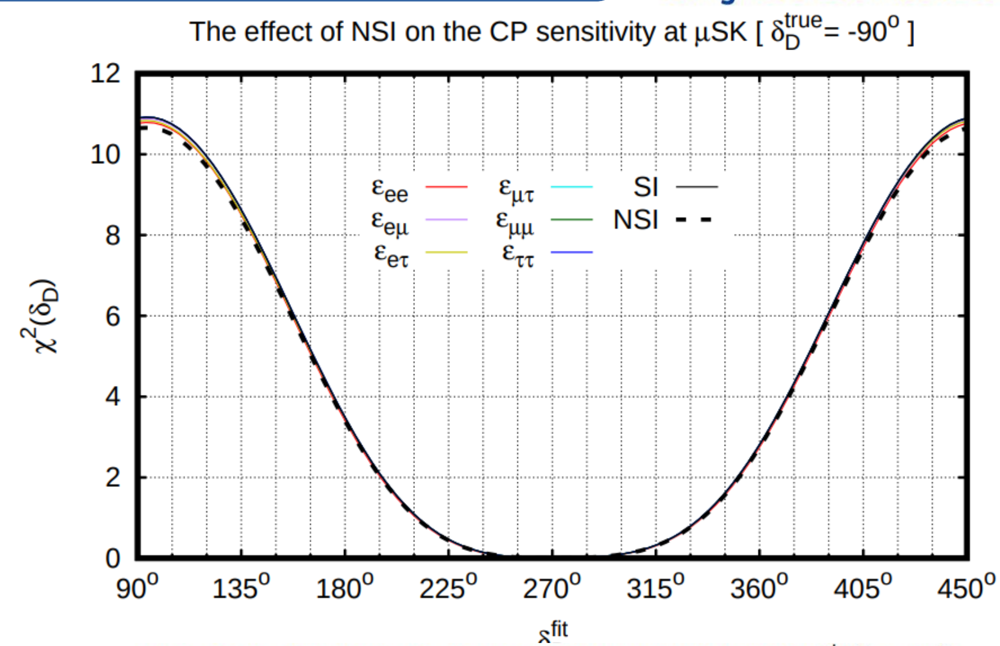


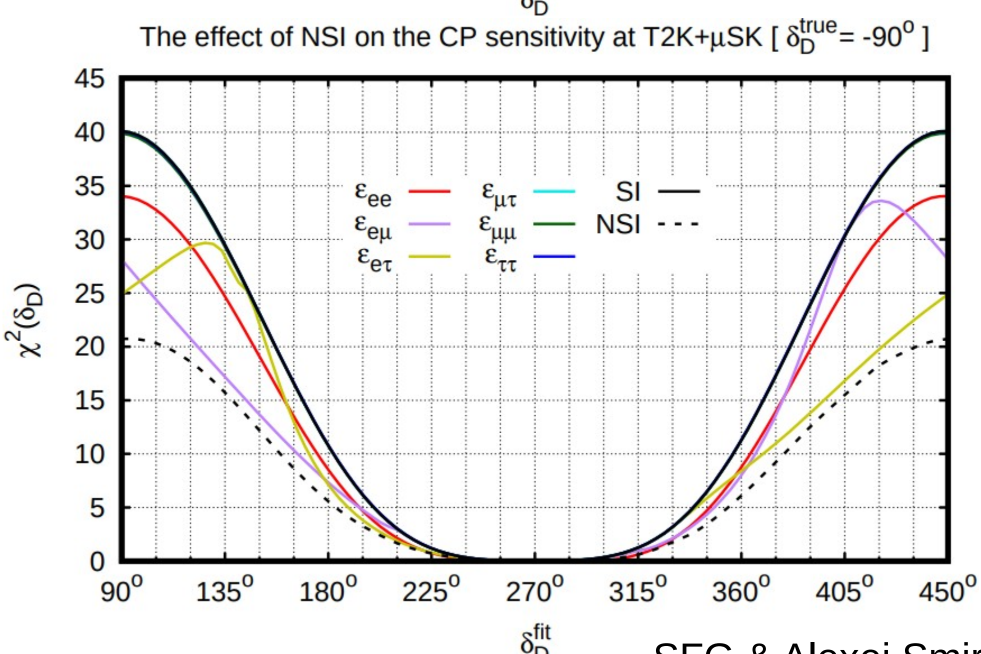


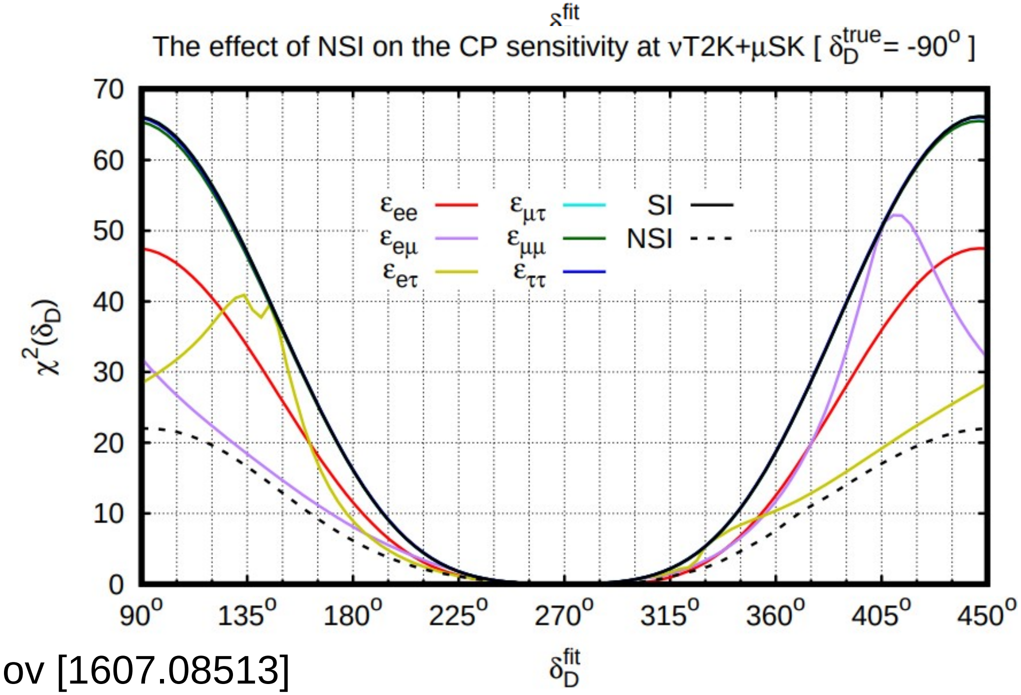


SFG & Alexei Smirnov [1607.08513]

# NUM Zero Distance Effect

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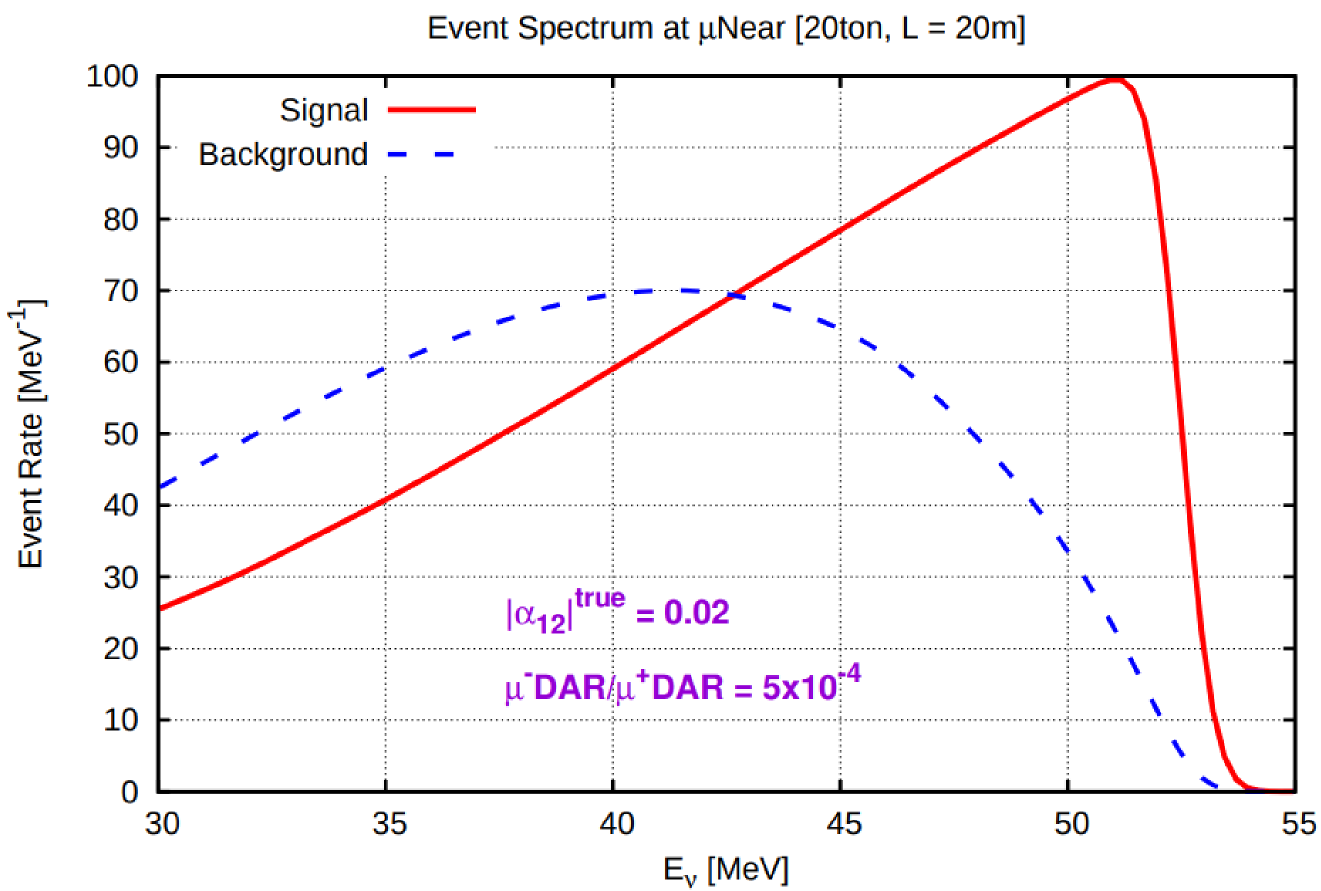
$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

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




**Transition @ L → 0**

SFG, Pasquini, Tortola & Valle [1605.01670]

# μNear @ μDAR

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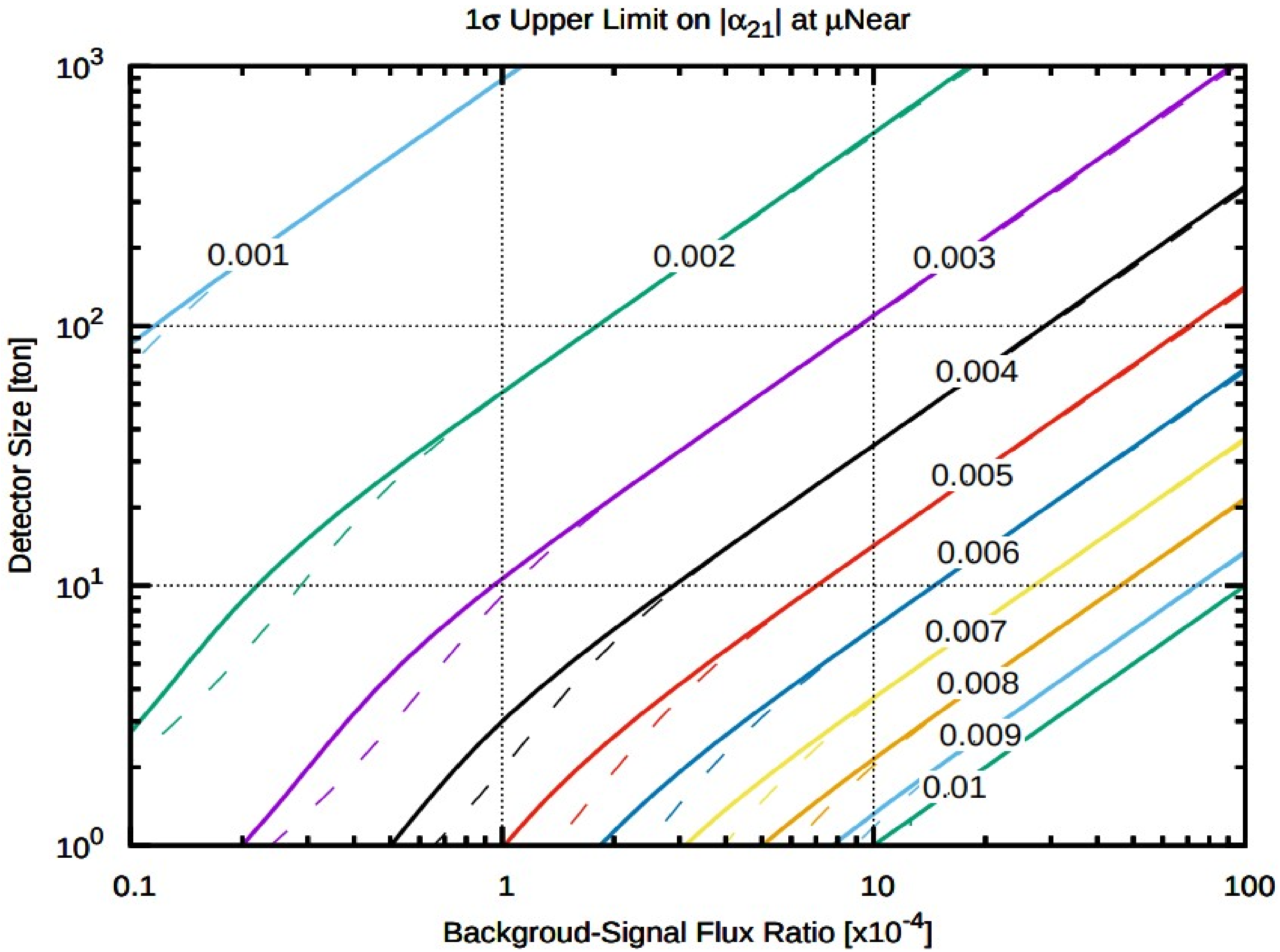
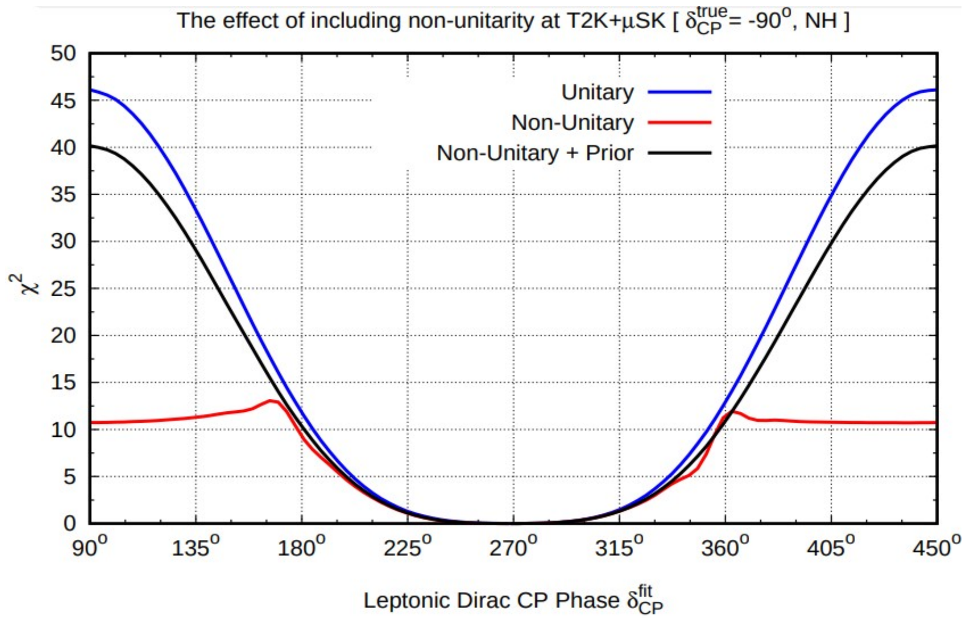
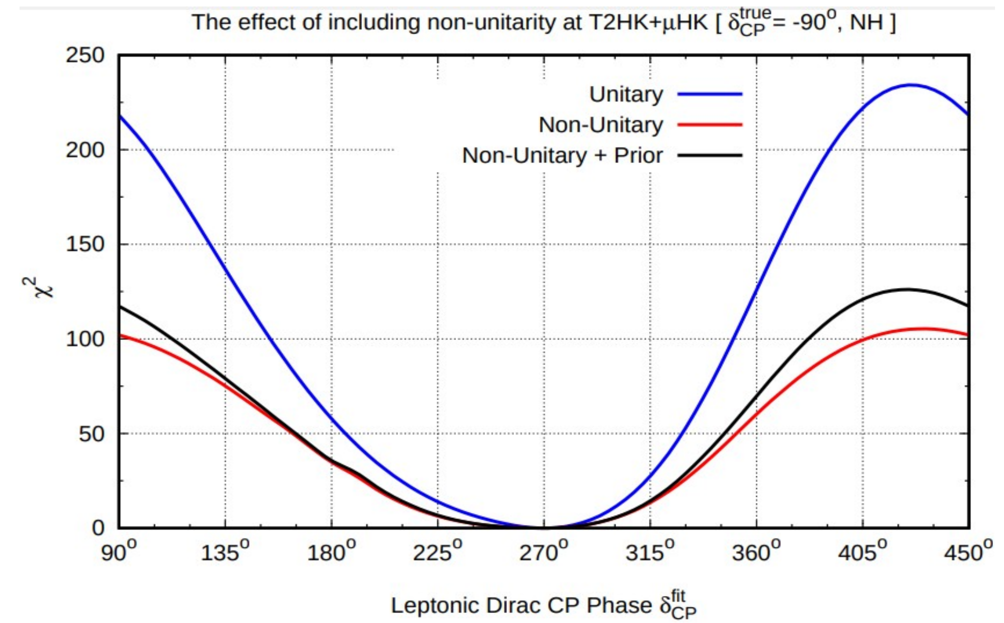
$$P^{NP}_{\mu e}(L \to 0) = \alpha^2_{11}|\alpha_{21}|^2 P_{ee} \approx \alpha^2_{11}|\alpha_{21}|^2 \approx |\alpha_{21}|^2$$

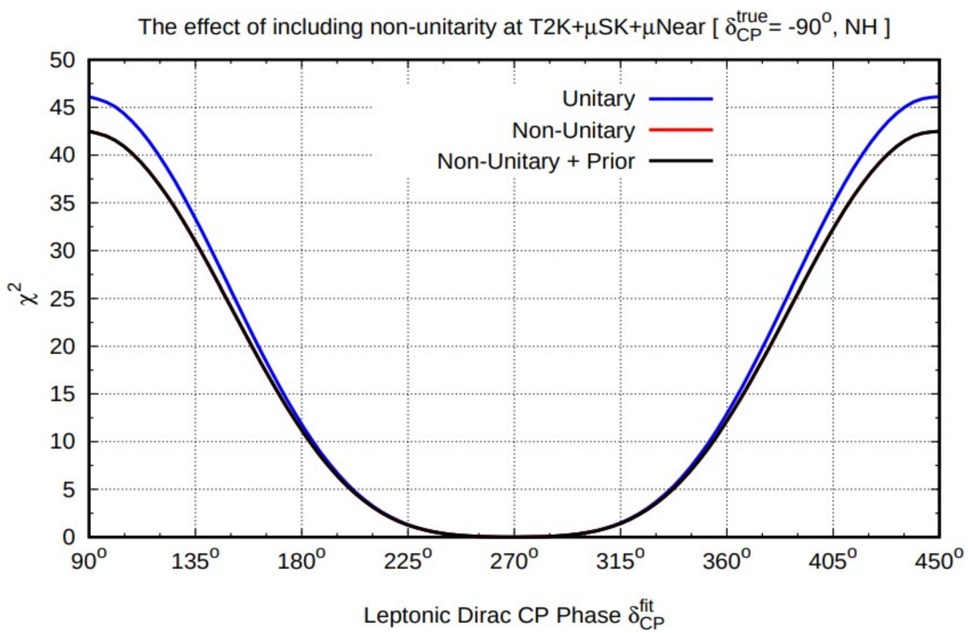


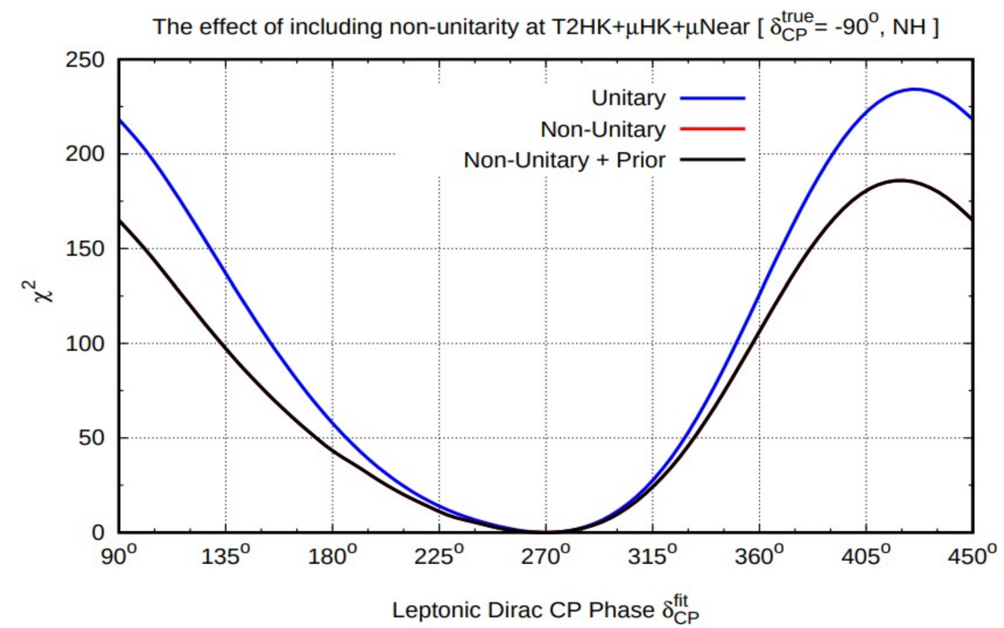

SFG, Pasquini, Tortola & Valle [1605.01670]

# TNT2K + μNear



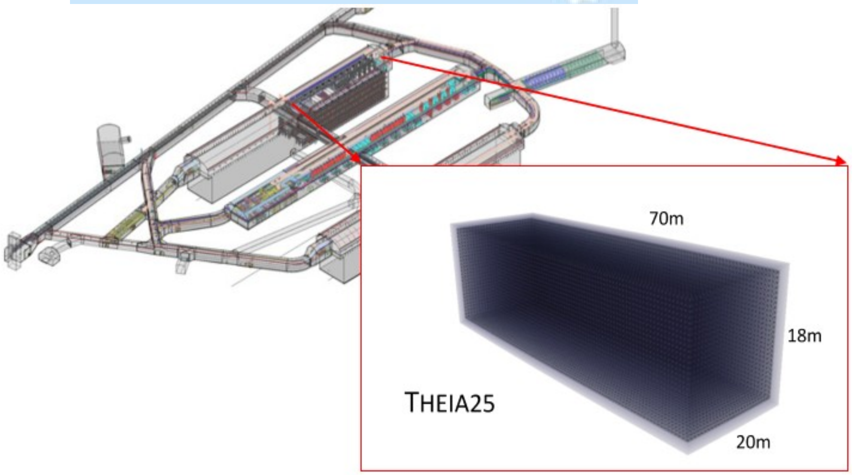



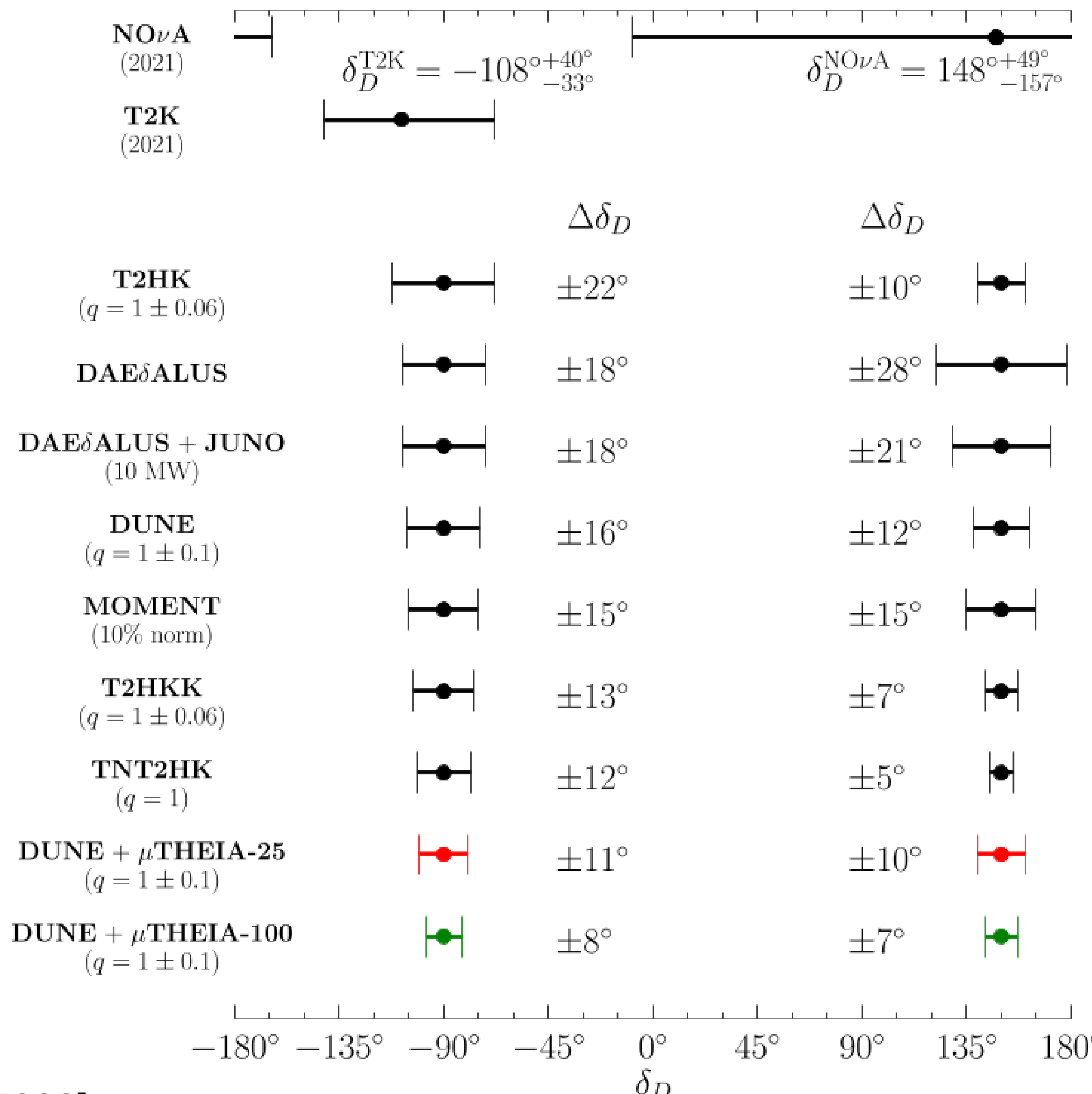




SFG, Pasquini, Tortola & Valle [1605.01670]

# μTHEIA+DUNE


**THEIA** [1911.03501, 2202.12839]




**SFG**, Kong, Pasquini [2202.05038]

# Outline

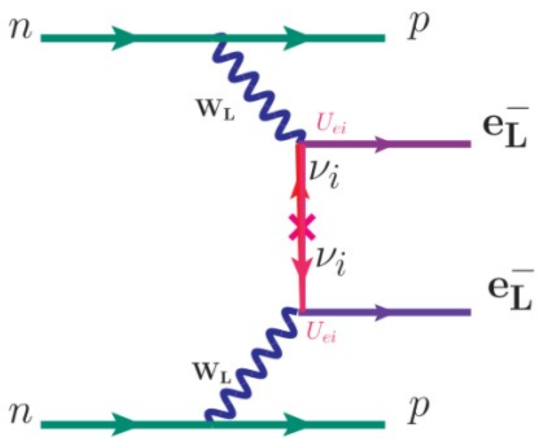
李政道研究所
Tsung-Dao Lee Institute

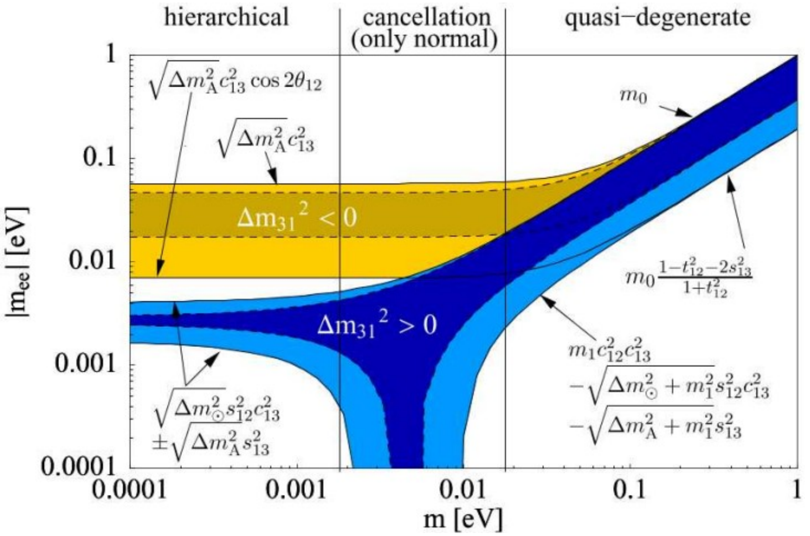
- CP Violation in the Neutrino Sector
- Dirac CP Phase & New Physics
- Accelerator + μDAR for better CP measurement
- Majorana CP Phase
- Neutrino Electromagnetic Properties

# Neutrinoless Double Beta Decay

李政道研究所 Tsung-Dao Lee Institute

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




- **Mass Suppression**

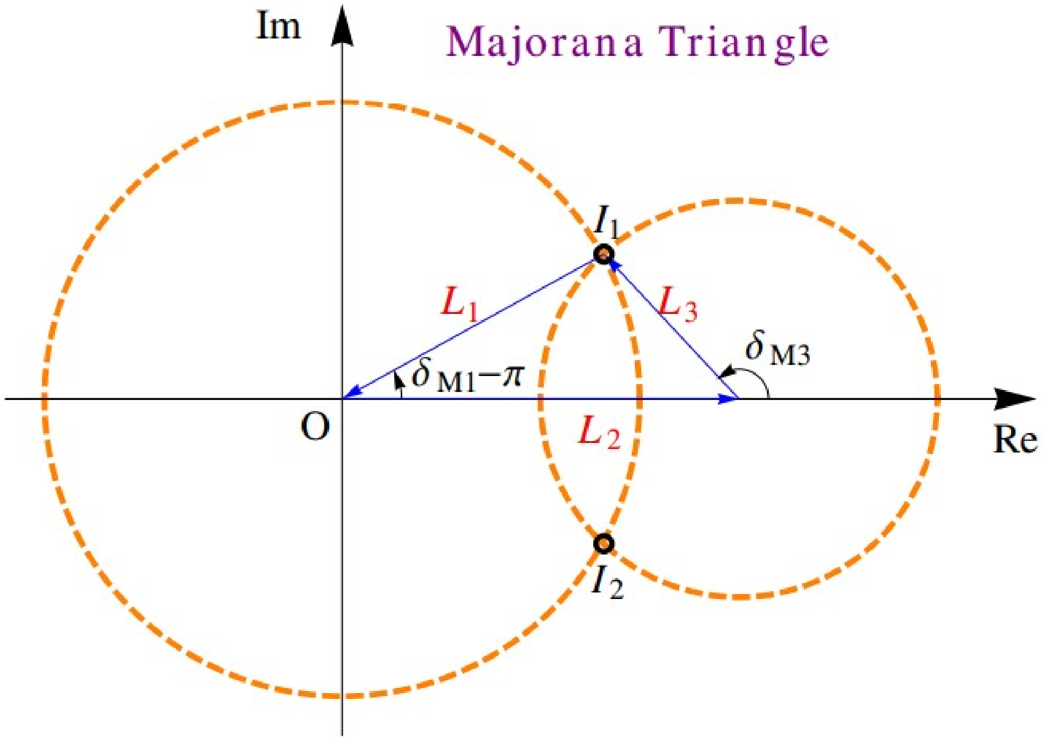
$$\mathcal{M} \propto \sum_i U_{ei} \frac{i}{\not{p} - m_i} U_{ei} \approx \sum_i U_{ei} \frac{m_i}{p^2} U_{ei}$$

- **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

李政道研究所 Tsung-Dao Lee Institute




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

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

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

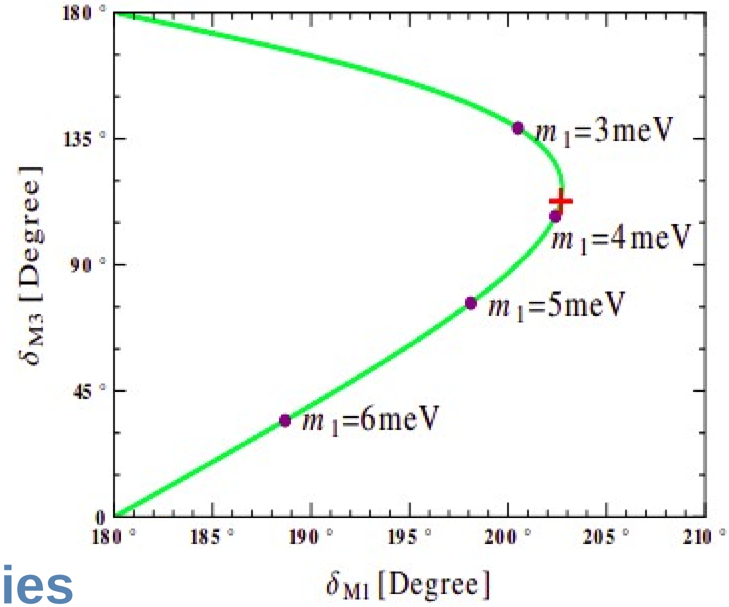
$$\overrightarrow{L_3} \equiv m_3 U_{e3}^2 = \sqrt{m_1^2 + \Delta m_a^2} s_r^2 e^{i\boldsymbol{\delta_{\mathrm{M3}}}} .$$

# Catching 2 Majorana CP Phases

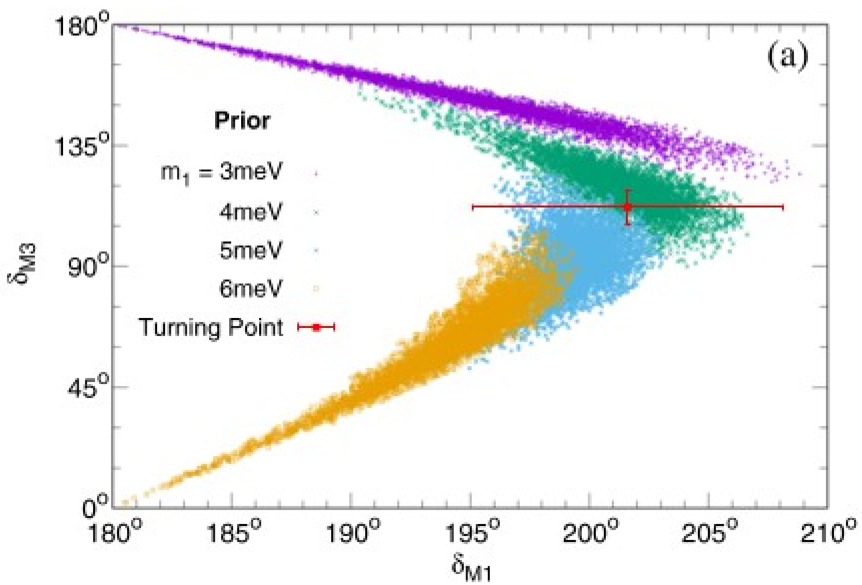
Tsung-Dao Lee Institute

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

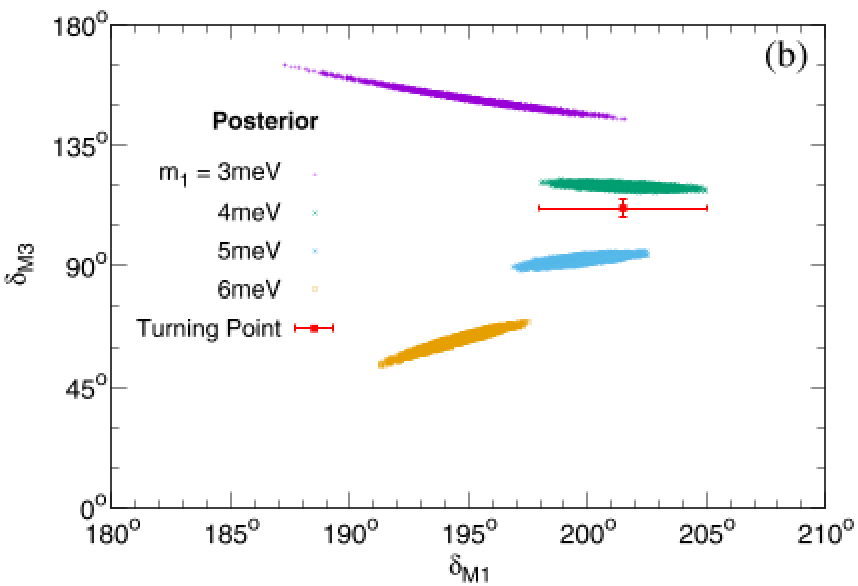
$$\cos \delta_{\rm M3} = +\frac{m_1^2 c_r^4 c_s^4 - m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_2 m_3 c_r^2 s_r^2 s_s^2}$$




- **JUNO can significantly reduce uncertainties**




**SFG** & Manfred Lindner, [1608.01618]




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

# Uncertainty from $m_{ee}$

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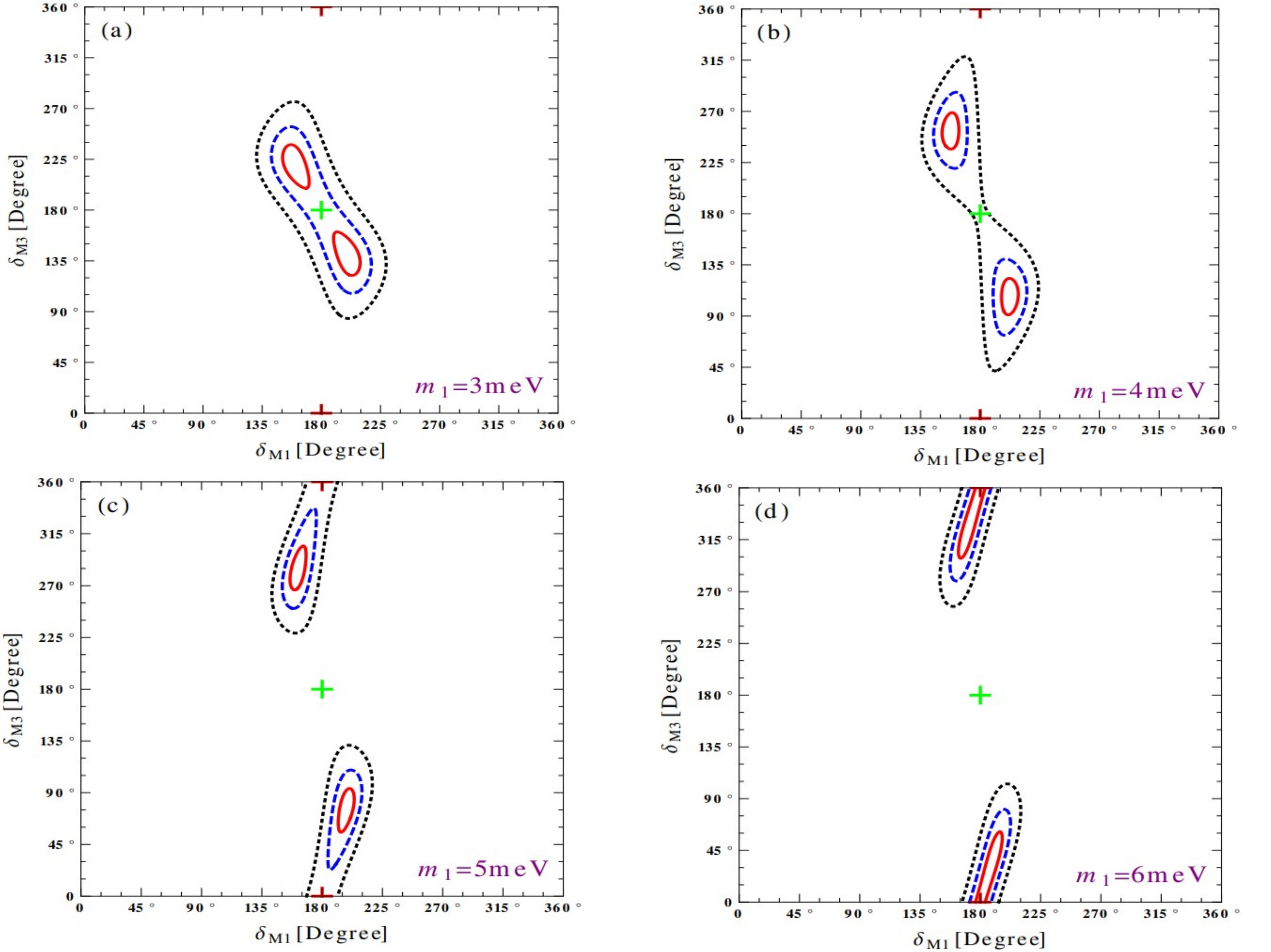
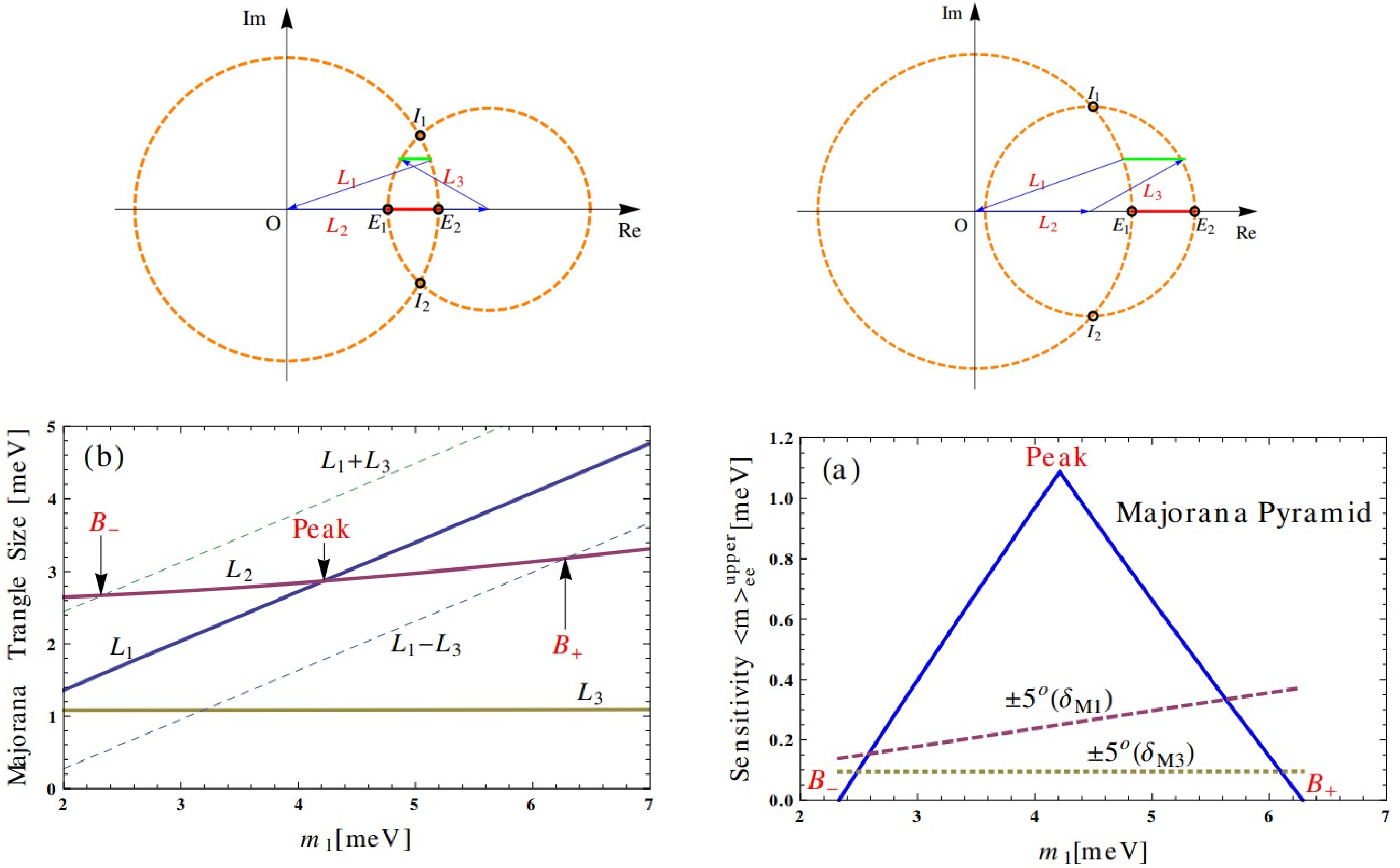
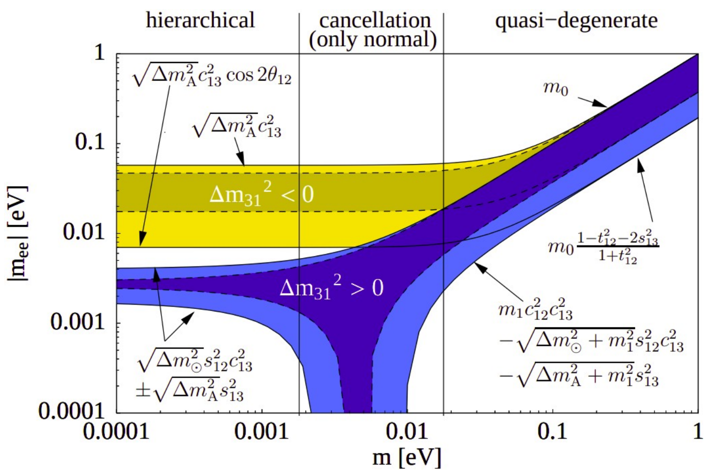


# Majorana Pyramid



# 1meV frontier of 0ν2β

Tsung-Dao Lee Institute



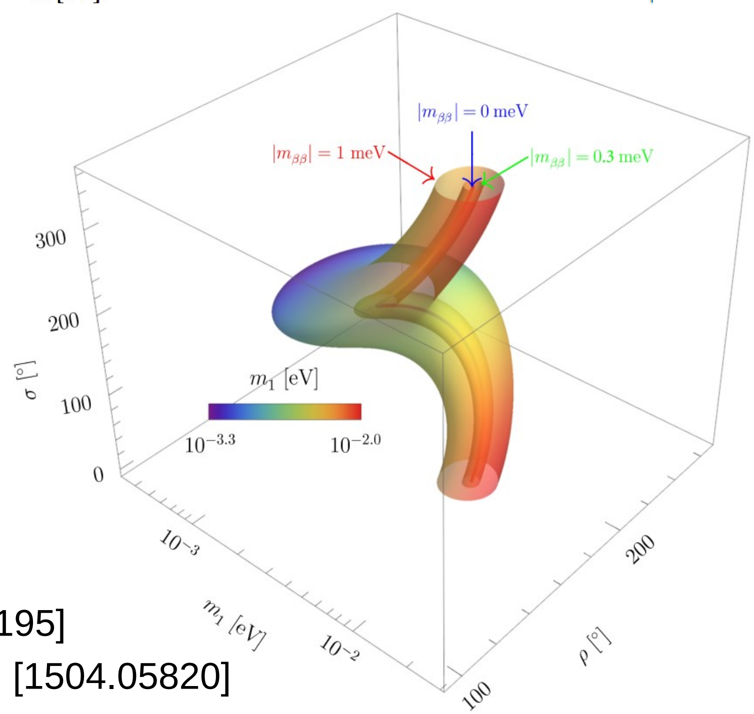

- **Nonzero → only 1 Majorana CP**

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

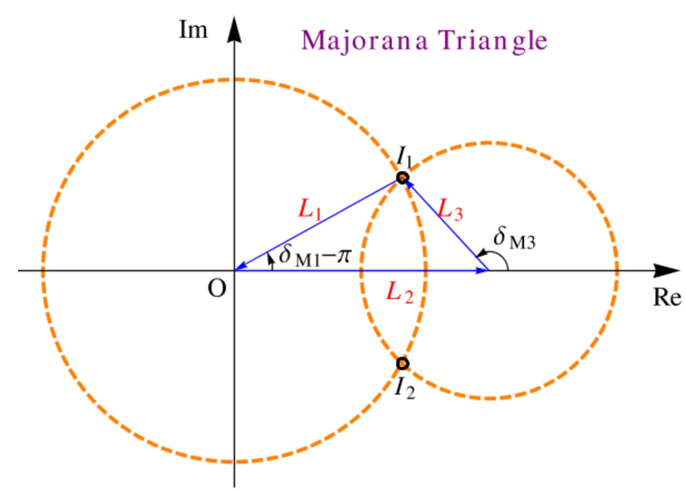
- **Zero → 2 Majorana CP phases**

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

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




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




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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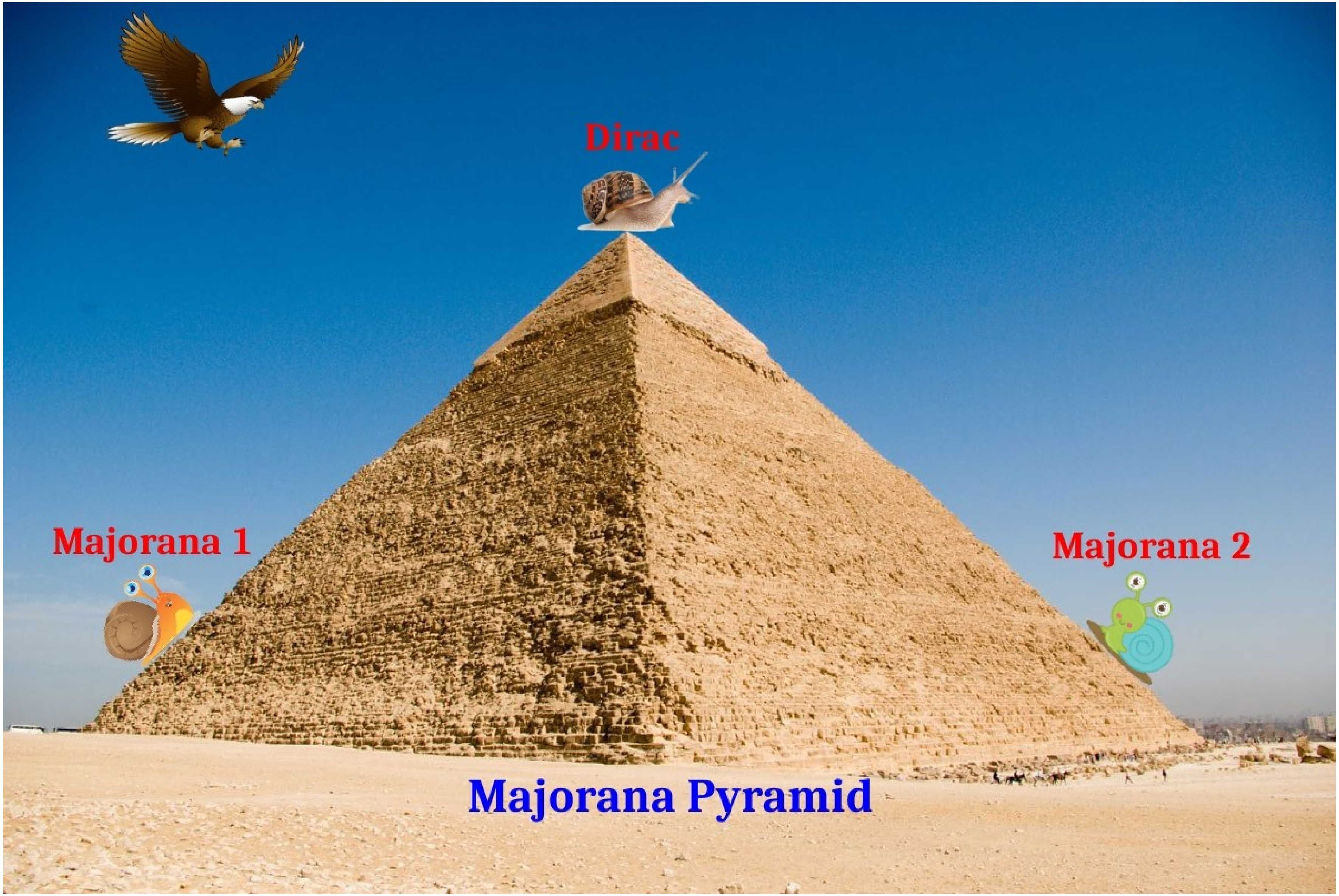

# Outline

Tsung-Dao Lee Institute

- CP Violation in the Neutrino Sector
- Dirac CP Phase & New Physics
- Accelerator + μDAR for better CP measurement
- Majorana CP Phase
- **Neutrino Electromagnetic Properties**

# Electric & Magnetic Moments

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Tsung-Dao Lee Institute

- **Being neutral, neutrino does not have charge**
- **But can have electric & magnetic moments**

$$H_M = \bar{\nu}\left[-f_M(q^2) i \sigma_{\mu\nu} q^\nu + f_E(q^2)\sigma_{\mu\nu} q^\nu \gamma_5\right] \nu A^\mu(q)$$

Magnetic Moment Electric Moment

1) Majorana neutrinos $(\mu_\nu)_{ij} = -(\mu_\nu)_{ji}$ and $(\epsilon_\nu)_{ij} = -(\epsilon_\nu)_{ji}$

2) Dirac neutrinos nonzero diagonal $(\epsilon_\nu)_{ii}$ also indicates CP violation

- **Possible tests**

$$(\mu_{\alpha\beta}^{\text{eff}})^2 \equiv \sum_j \left| \sum_k U_{\alpha k}^* \left[(\mu_\nu)_{jk} - i(\epsilon_\nu)_{jk}\right] \right|^2$$

**Scattering & recoil**

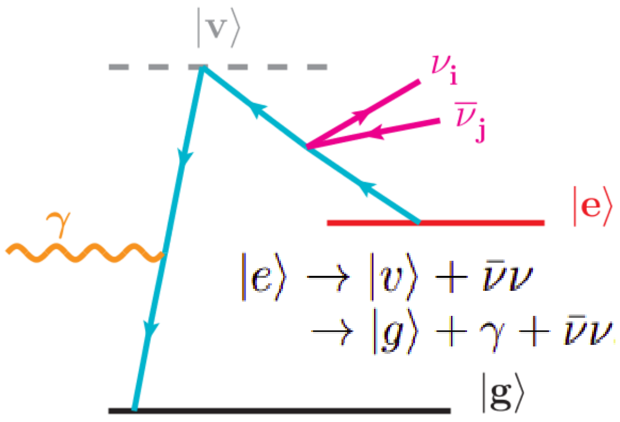
$$(\mu_\nu^\odot)^2 \equiv \sum_{ij} |(\mu_\nu)_{ij}|^2 + |(\epsilon_\nu)_{ij}|^2$$

**Stellar processes**

Giunt & Studenikin [1403.6344]

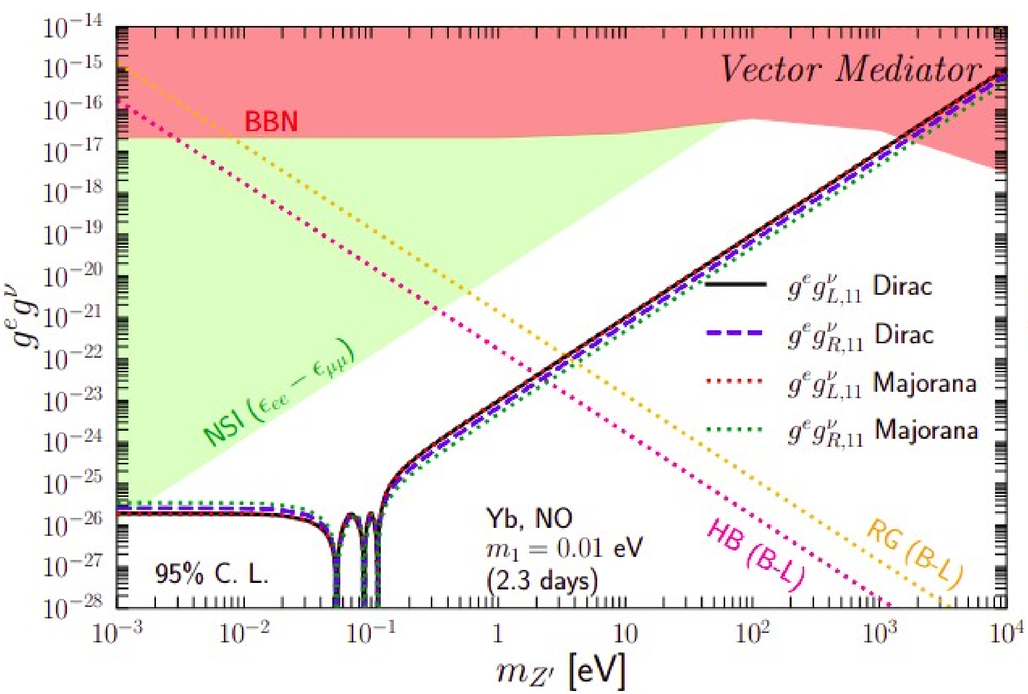
# Light mediator @ ν Pair Emission

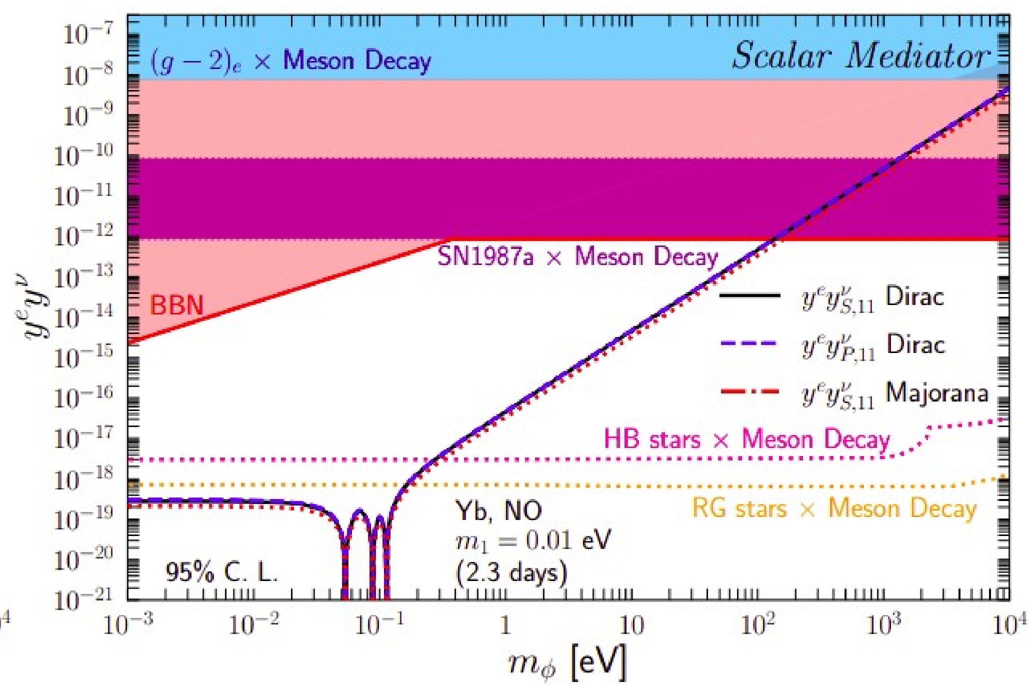
Tsung-Dao Lee Institute




Fukumi et al [1211.4904]

1) **Mass** Song et al [1510.00421]; Zhang & Zhou [1604.08008]
2) **CP phase** Yoshimura & Sasao [1506.08003]
3) **Dirac vs Majorana** Dinh, Petcov, Sasao, Tanaka & Yoshimura [1209.4808]
4) **Unitarity** Huang, Sasao, Xing & Yoshimura [1904.10366]
5) **Sterile neutrino** Dinh & Petcov [1411.7459]
6) **Axion** Huang & Zhou [1905.00367]
7) **Dark photon** Bhoonah, Bramante & Song [1909.07387]

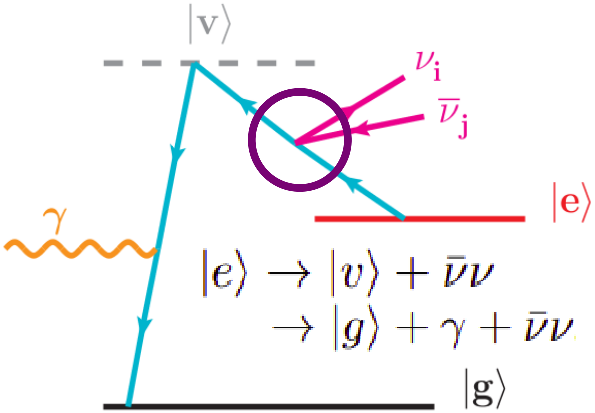


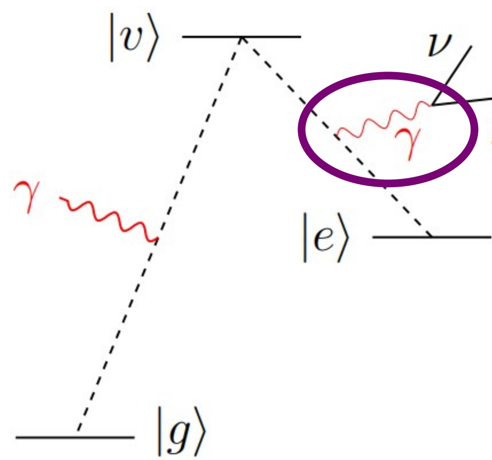




**SFG** & Pasquini [2110.03510]

# ν Moments @ ν Pair Emission

李政道研究所 Tsung-Dao Lee Institute

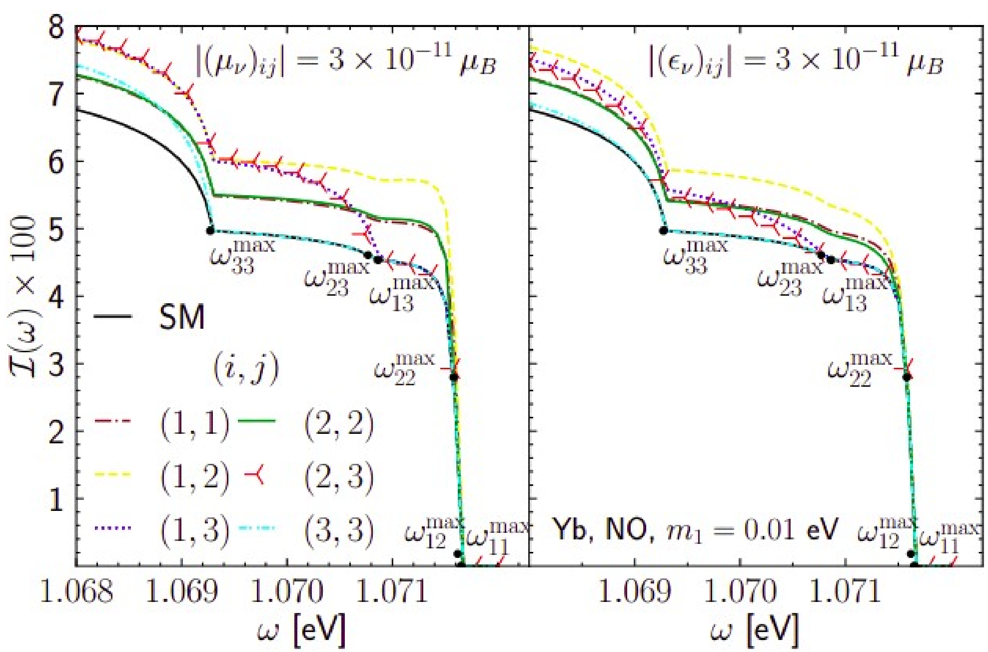


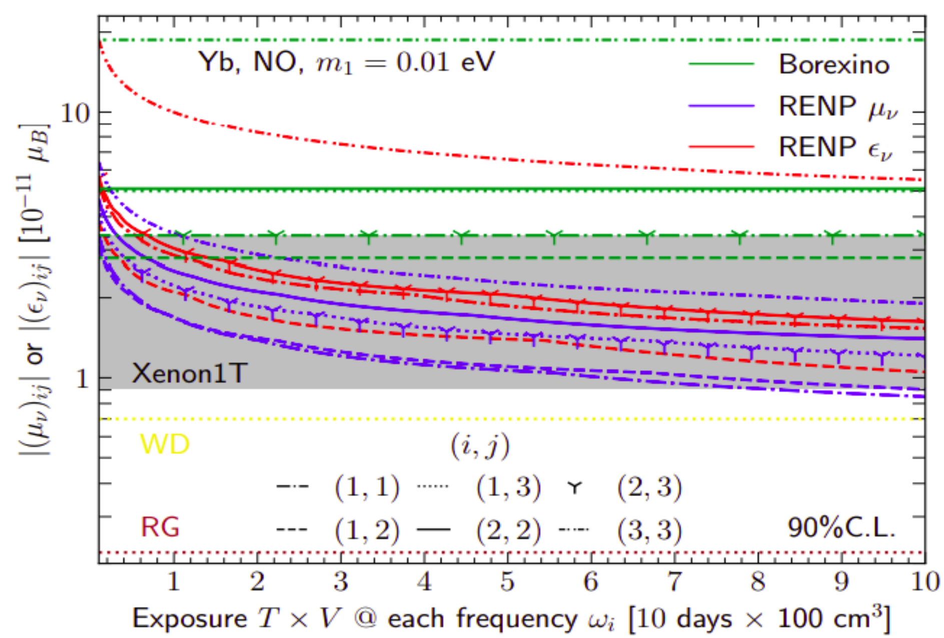




$$\omega_{ij} = \frac{E_{eg}}{2} - \frac{(m_i + m_j)^2}{2E_{eg}}$$

$$\mathcal{I}_{\substack{M\\E}} \equiv \sum_{ij} \left(\frac{\mu_B}{G_F}\right)^2 \frac{\omega^2 \Delta_{ij} \Theta(\omega - \omega_{ij}^{\max})}{9(E_{vg} - \omega)^2}$$

$$\times \left[1 + \frac{(m_i \pm m_j)^2 \pm 4 m_i m_j}{q^2} - 2\left(\frac{\Delta m^2_{ji}}{q^2}\right)^2\right]$$



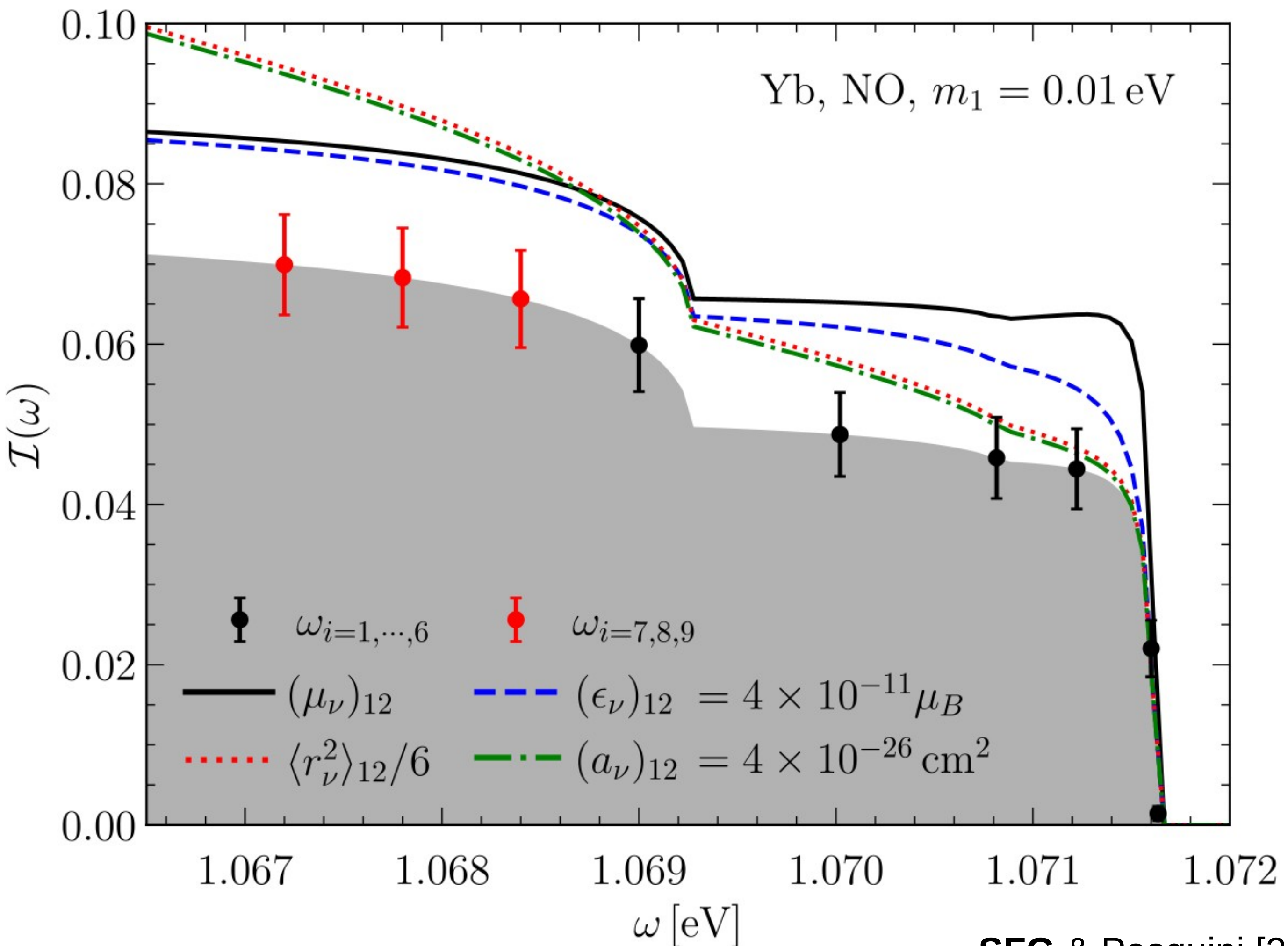

**Can disentangle EDM & MDM elements!**

**SFG** & Pasquini [2206.11717]

# ν EM Properties @ ν Pair Emission

李政道研究所 Tsung-Dao Lee Institute

$$H_{EM} = \overline{\nu}\left[-i\sigma_{\mu\nu}q^{\nu}\left(\mu_\nu + i\epsilon_\nu\gamma_5\right) + \left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2}\right) q^2 \left(\frac{\langle r_\nu^2\rangle}{6} + a_\nu\gamma_5\right)\right]\nu A^\mu(q),$$




**SFG** & Pasquini [2306.12953]

# Summary

李政道研究所
Tsung-Dao Lee Institute

- **CP Violation in the Neutrino Sector**

  **Important consequence for explaining matter-antimatter asymmetry.**

- **Dirac CP Phase & New Physics**

  **Needs to exclude multiple theoretical uncertainties.**

- **Accelerator + μDAR for better CP measurement**

  **Combination of high- and low-energy neutrino sources.**

- **Majorana CP Phases**

  **No-loss for 0v2b measurements.**

**Thank You**

- **Neutrino Electromagnetic Properties**

  **Atomic RENP (radiative emission of neutrino pair) is a unique probe.**

李政道研究所
Tsung-Dao Lee Institute

# Backup Slides

# 狄拉克 CP 相角 $\delta_D$

- Oscillation probabilities @ Accelerator Neutrino Exps

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

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

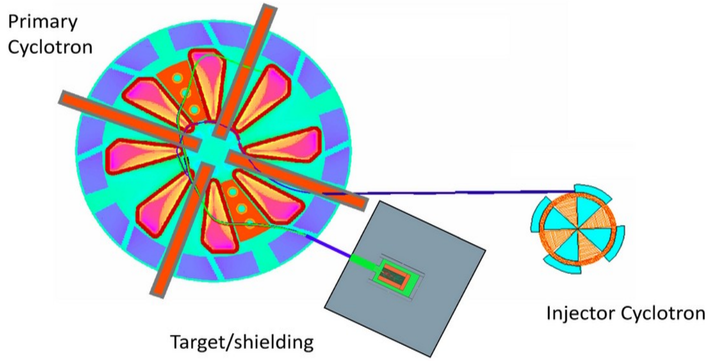
- Run both $\nu$ & $\overline{\nu}$ modes @ first peak $[\phi_{31} = \frac{\pi}{2}, \phi_{21} = \alpha\frac{\pi}{2}]$, $\alpha = \frac{\delta M_{21}^2}{|\delta M_{31}^2|} \sim 3\%$

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

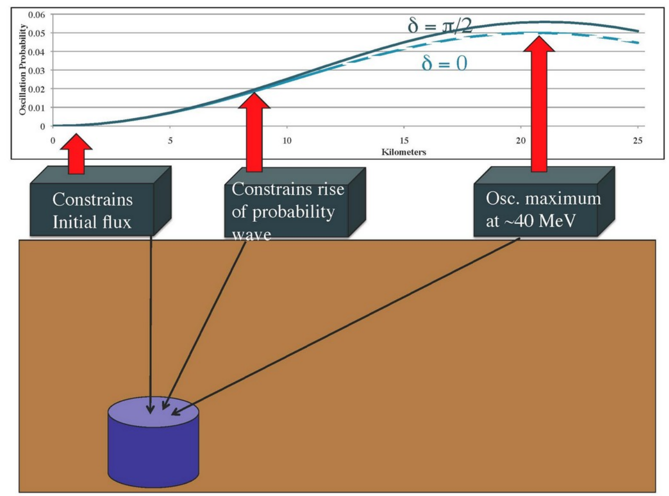
$$P_{\overline{\nu}_\mu \to \overline{\nu}_e} - P_{\nu_\mu \to \nu_e} = \alpha\pi \sin(2\theta_s) \sin(2\theta_r) \sin(2\theta_a) \cos\theta_r \sin\delta_D.$$

**中微子、反中微子的振荡概率之间的差别 → 测量 CP 相角 $\delta_D$。**

# 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 $\quad \bar{\nu}_e + p \to e^+ n$
  - Baseline **cannot be measured**.
  - Cyclotrons **cannot** run simultaneously (20∼25% duty factor).
  - **Large** statistical uncertainty.
  - **Higher intensity** is necessary.
  - **Expensive** & Technically **challenging**.

Conrad & Shaevitz [0912.4079]
Agarwalla, Huber, Link & Mohapatra [1005.4055]
DAEdALUS [1006.0260, 1307.2949]

# New Proposal

Tsung-Dao Lee Institute

**1** $\mu$DAR source + **2** detectors

## Advantages

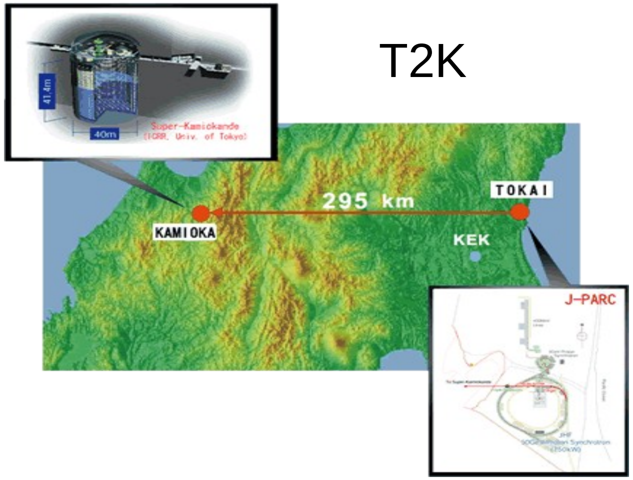
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**$\times$ lower than DAE$\delta$ALUS]
- Not far beyond the current state-of-art technology of cyclotron [**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
  - Only one cyclotron.
  - Lower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

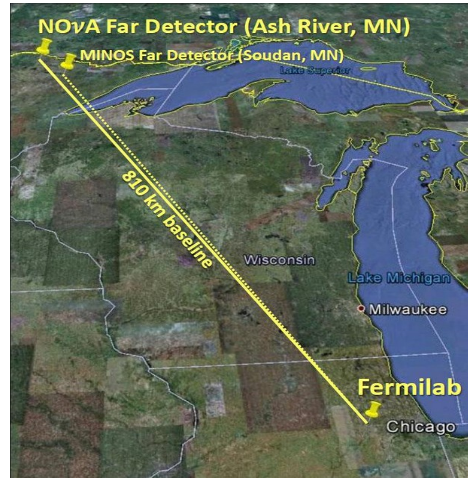
## Disadvantage: **A second detector!**

- **$\mu$DAR** with **T**wo **S**cintillators (**$\mu$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]

# Future Accelerator Exps

T2K





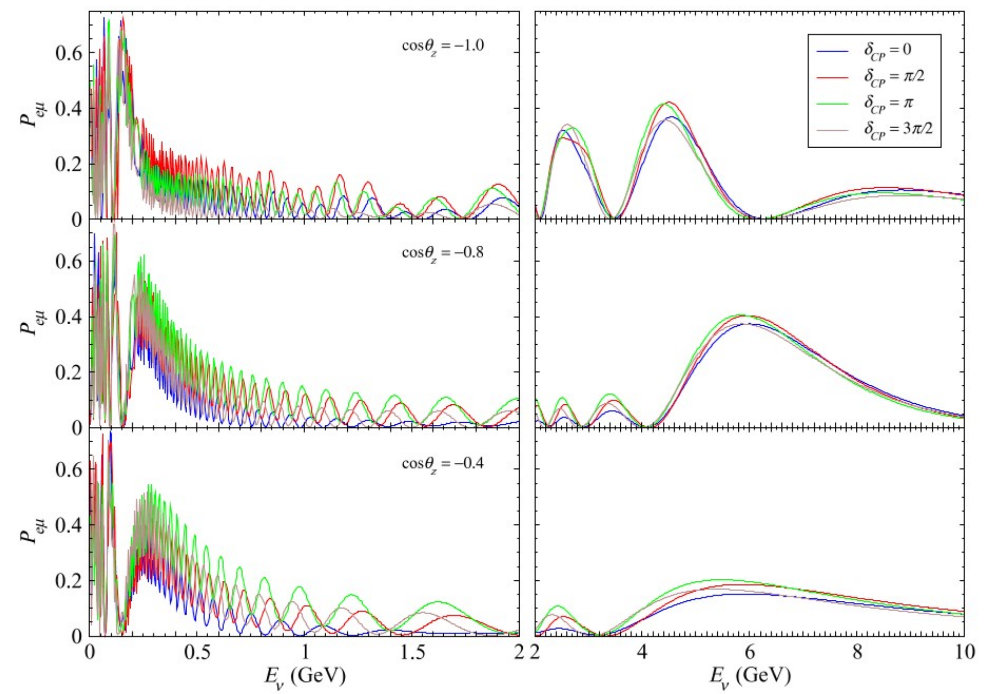
- Flux upgrade: **T2K-II**, **NOvA-II**?
- Detector upgrade: **T2HK**
- Baseline upgrade: **T2KK**, **T2KO**
- **MOMENT** Cao et al [1401.8125] Tang et al [1909.01548]
- In china? Tang, Vihonen & Xu [2202.13595]
- Atmospheric

  **Super-PINGU**: Razzaque & Smirnov [1406.1407]

  **JUNO**: An et al [1507.05613]

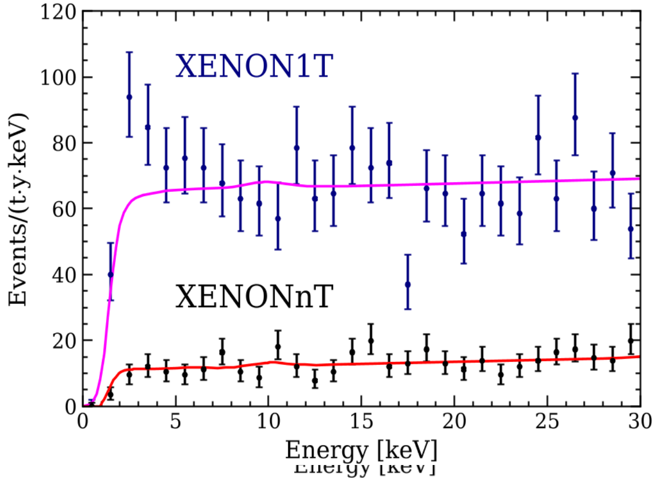
  **DUNE**: Kelly, Machado, Martinez-Soler, Parke & Perez-Gonzalez [1904.02751]

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

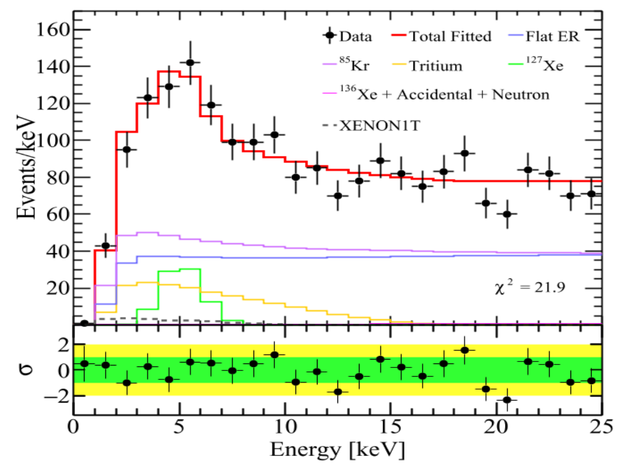


# ν Magnetic Moments @ DM Exps

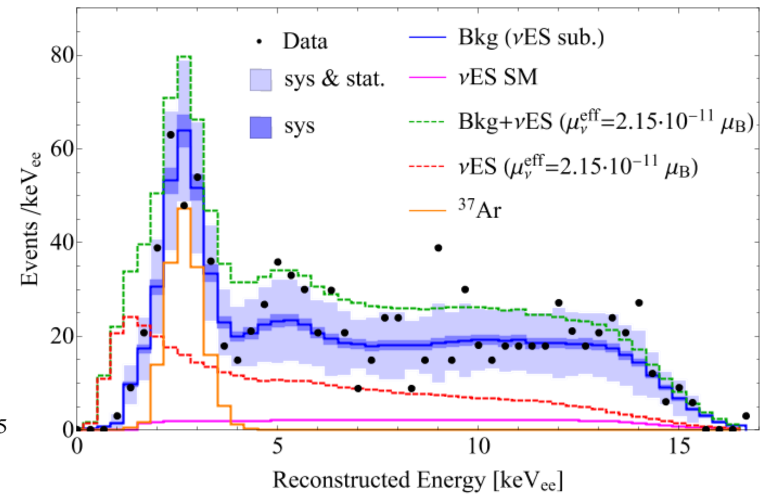
Tsung-Dao Lee Institute



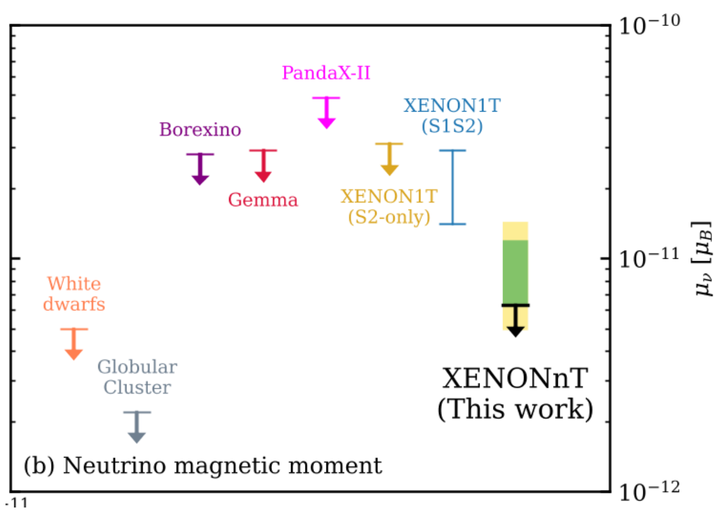

Xenon1T [2006.09721]



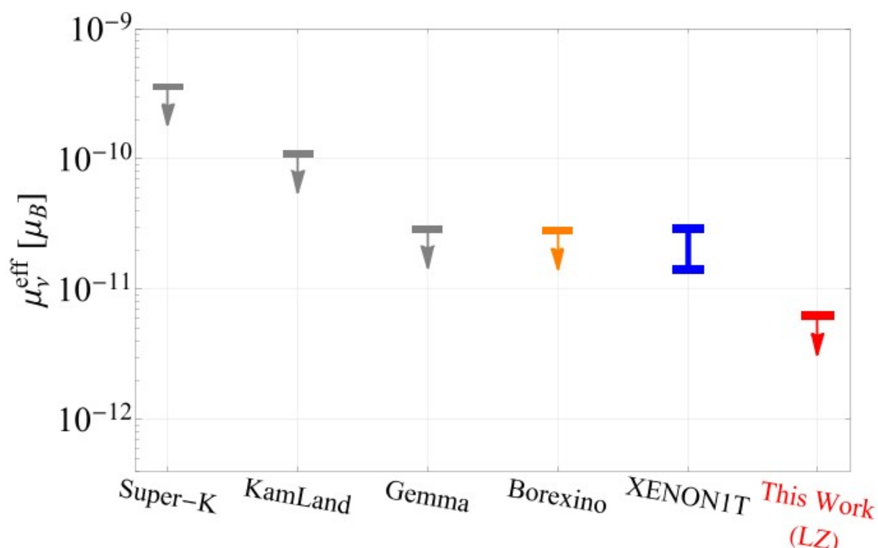

PandaX-II [2008.06485]




LZ [2207.03764]




XENONnT [2207.11330]




Corona, Bonivento, Cadeddu, Cargioli & Dordei [2207.05036]