中微子理论进展

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高能物理年会 @ 大连
August 9, 2022

上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

李政道研究所
Tsung-Dao Lee Institute

Outline

Tsung-Dao Lee Institute

- Neutrino Oscillation & Mixing Patterns
- CP Measurement & New Physics
- Neutrino Properties (Dirac vs Majorana)
- Neutrino vs Dark matter
- Neutrino with Beams

    1) Neutrino @ Collider exps

    2) Neutrino trident production & beam dump

    3) Neutrino collider

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}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

Gonzalez-Garcia, Maltoni & Schwetz [2111.03086]

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

Kam-Biu Luk @ Neutrino 2022

Neutrino Mixing Models

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- **Discrete flavor symmetries** S_3, A_4, S_4, $\Delta(27)$, ……

Harrison et al., 02
Xing , 02
He, Zee, 03

$$U_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Daya Bay → Nonzero θ_{13}
Beyond Tri-Bimaximal

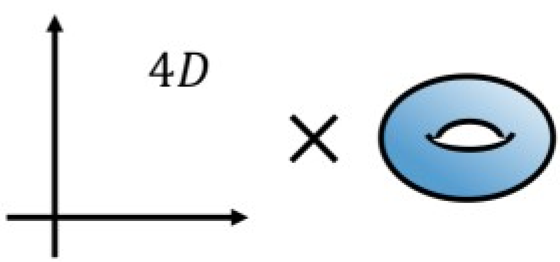
Z.Z. Xing [Phys.Rept. 854 (2020) 1-147]

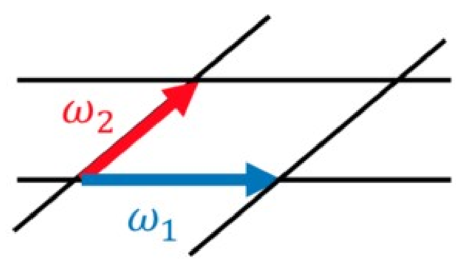
- **CP-like flavor symmetries** S_4 x CP, Z_2 x CP, ……

$$m_\nu^*(\phi) = X_l^T m_\nu(X_\phi \phi^*) X_l \qquad X_\phi \phi^* \neq \phi$$

- **Modular invariances**

Liu & Ding [2112.14761]





$$\tau \to \gamma\tau \equiv \frac{a\tau + b}{c\tau + d}$$

- **Gauged flavor symmetries**

Feruglio & Romanino [Rev.Mod.Phys. 93 (2021) 1, 015007]

- (**Symmetry-assisted**) **anarchy models**

SFG, Kusenko, Yanagida [1803.03888]
Barrie, **SFG**, Yanagida [1911.07430]

Flavor Symmetry Approaches

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- **Full symmetry has to be broken & not the one dictating mixing**

$$\begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \in \left(2, -\frac{1}{2}\right)$$ **Same doublet** ⇒ $$U_\ell^\dagger U_\nu = I$$

Many other things (Yukawa couplings, VEVs) may enter.

- **Bottom-Up vs Top-Down**

Lam, PRL101:121602(2008), PRD78:073015(2008)

$\mathcal{H} \equiv \mathcal{G} \times \mathcal{F}$	$\mathcal{G}$	$\mathcal{F}$
S_4	$\mathbb{Z}_2^s \times \mathbb{Z}_2^{\mu\tau}$	$\mathbb{Z}_3 \equiv \{I, F, F^2\}$
$\{G_1, G_3, F\}$	$G_1(G_2), G_3$	$F \equiv \text{diag}\,(1, \omega, \omega^2)$

Bottom-Up $\Uparrow$ $\Downarrow$ **Top-Down**

See also Smirnov et. al., [1204.0445, 1212.2149, 1510.00344]

Residual vs Custodial symmeties

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- If mixing is determined by symmetry, it has to be the residual one

$$\mathbf{G}_\nu^T \mathbf{M}_\nu \mathbf{G}_\nu = \mathbf{M}_\nu$$
$$\mathbf{V}_\nu^T \mathbf{M}_\nu \mathbf{V}_\nu = \mathbf{D}_\nu$$
$$\mathbf{D}_\nu = \mathbf{d}_\nu^T \mathbf{D}_\nu \mathbf{d}_\nu$$

$$\Rightarrow \quad \mathbf{G}_\nu = \mathbf{V}_\nu \mathbf{d}_\nu \mathbf{V}_\nu^\dagger$$

$$\nu_i: \quad \mathcal{G} \equiv \mathbb{Z}_2^s(\overline{\mathbb{Z}}_2^s) \times \mathbb{Z}_2^{\mu\tau} \quad \text{for} \quad d_\nu^i = \text{diag}\,(\pm 1, \pm 1, \pm 1)$$

$$\ell_i: \quad \mathcal{F} \in U(1) \times U(1) \quad \text{for} \quad d_\ell^i = \text{diag}\,(e^{i\beta_1}, e^{i\beta_2}, e^{i\beta_3})$$

- Analogy with custorial symmetry

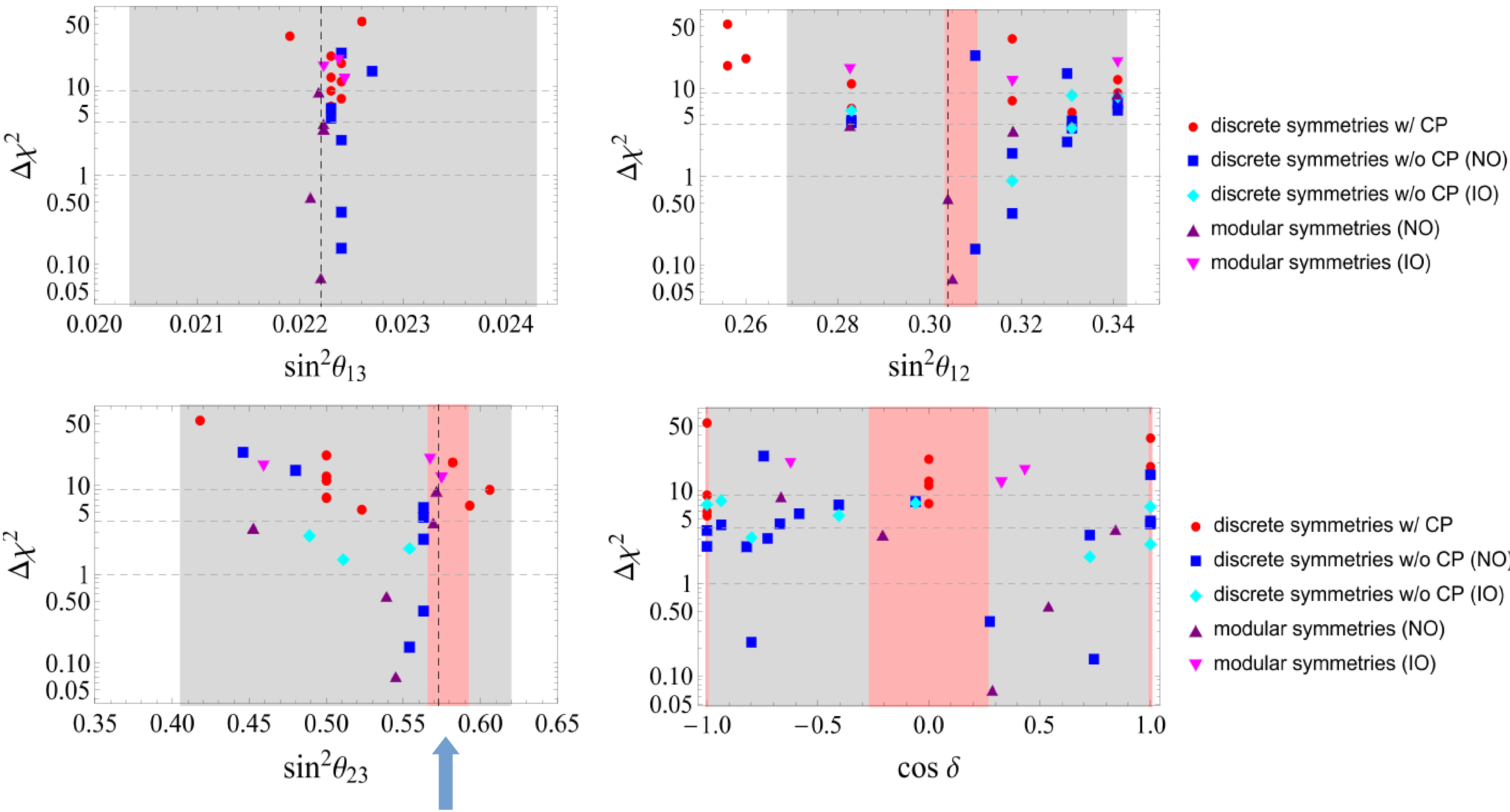
$$\cos\delta_D = \frac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r} \quad \text{vs} \quad \rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

Sum rules

SFG, Dicus, Repko [1104.0602, 1108.0964]

Precision measurement of the leptonic CP phase is important!

Experimental Tests



3σ

Petcov [1711.10806]; Gehrlein, Petcov, Spinrath & Titov [2203.06219]

大亚湾 & LHC in 2012

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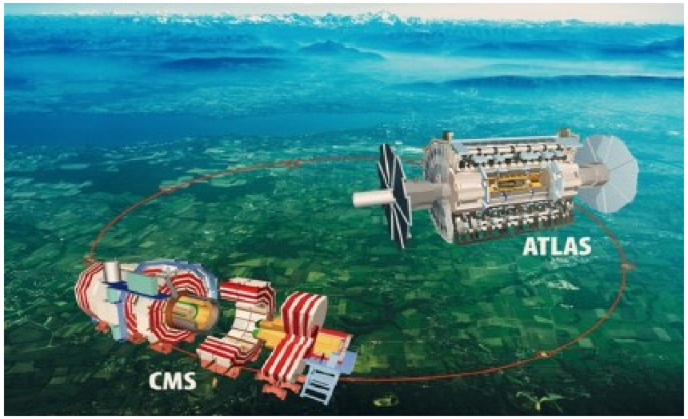
- **Higgs boson** ⇒ electroweak symmetry breaking & mass. ~ O(100)GeV
- **Chiral symmetry breaking** ⇒ majority of mass.
- The world seems not affected by the tiny neutrino mass?
  - Neutrino mass ⇒ Mixing
  - 3 Neutrino ⇒ possible **CP violation**
  - CP violation ⇒ **Leptogenesis**
  - ⇒ **Matter-Antimatter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

大亚湾实验 @ **March 8, 2012**



LHC @ **July 4, 2012**

中微子 CP 相角 δ_D 的测量现状

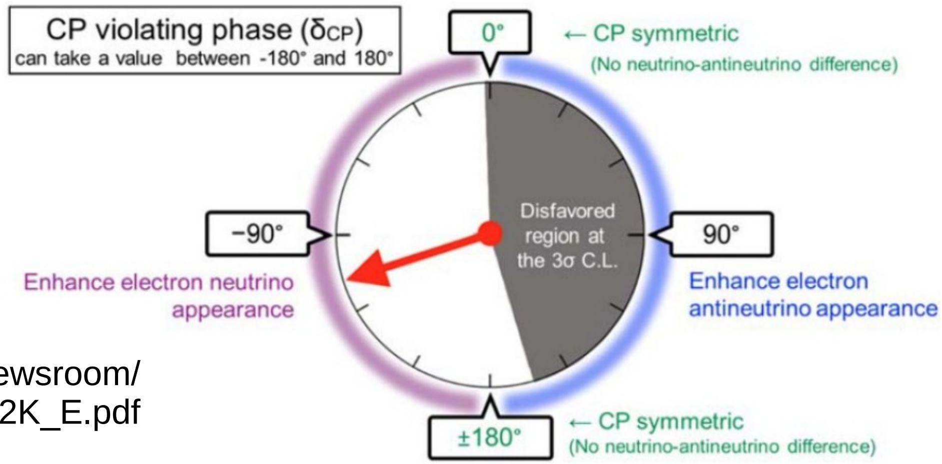
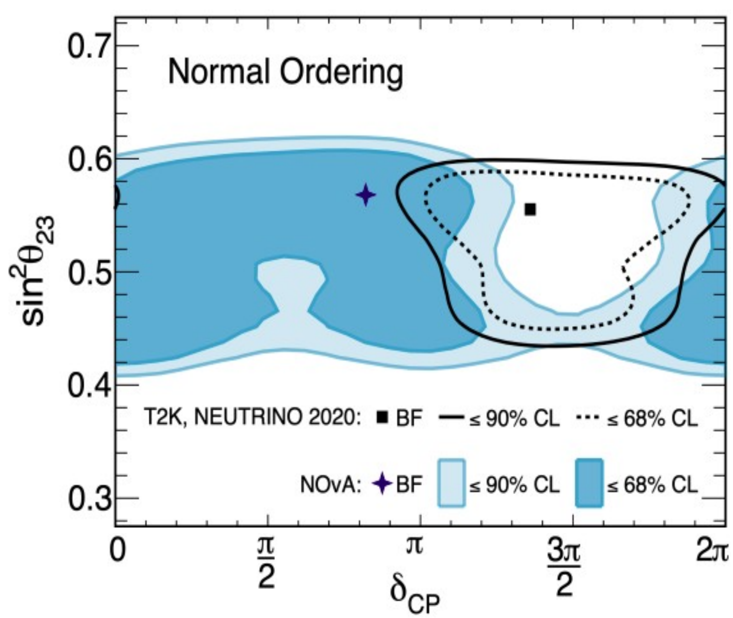


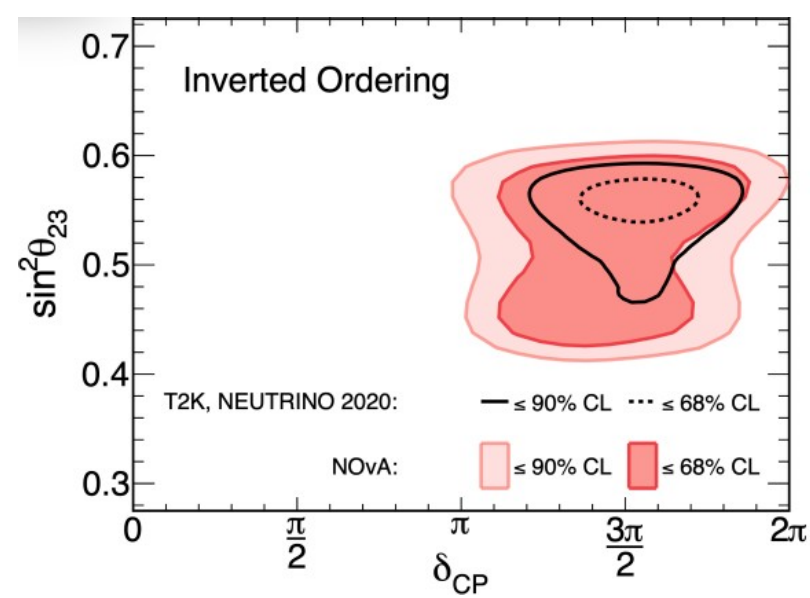
Fig.1 The arrow indicates the value most compatible with the data. The gray region is disfavored at 99.7% (3σ) confidence level. Nearly half of the possible values are excluded.

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

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

- **Exclude almost half parameter space @ 3σ**
- **Best-fit value close to maximal CP (-90º)**
- **In tension with NOvA**





NOvA [2108.08219]

Future Accelerator Exps

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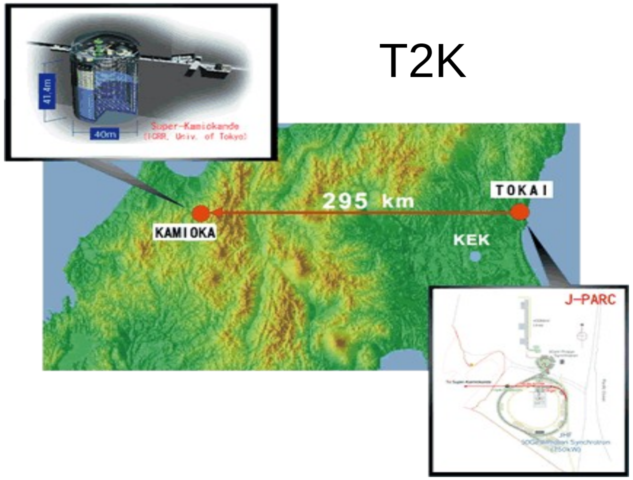
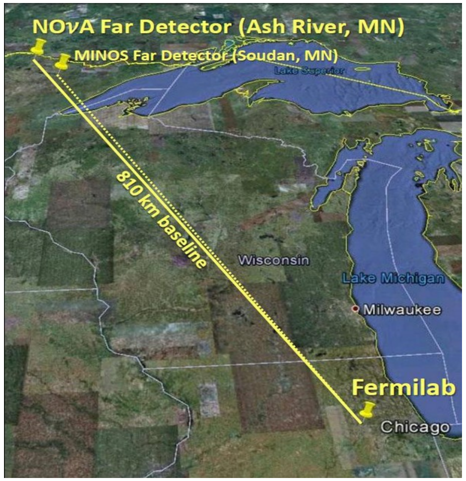
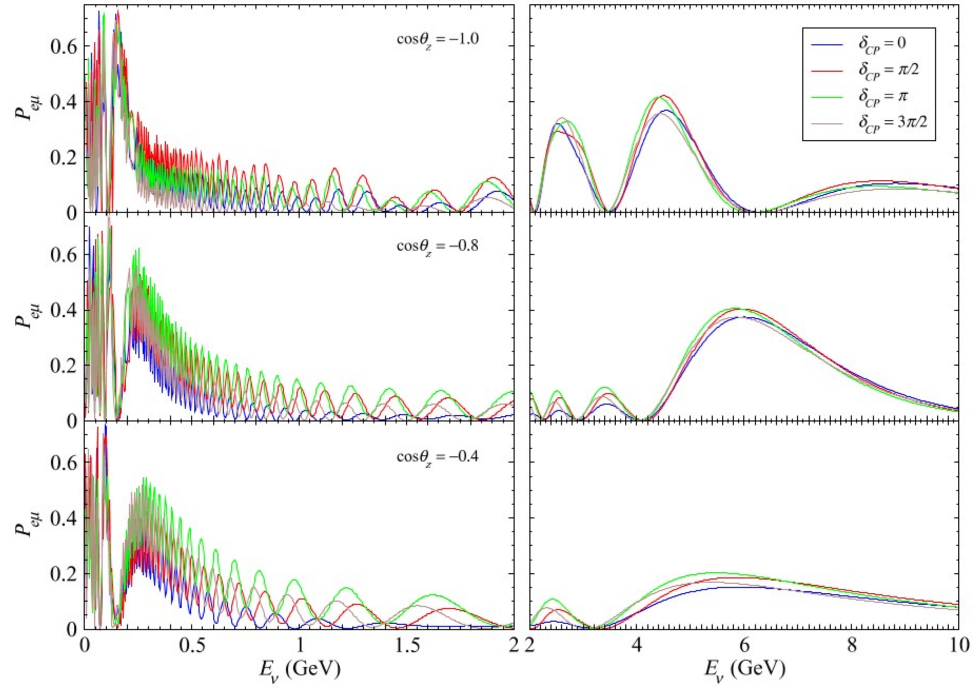




- Flux upgrade: **T2K-II**, **NOvA-II**?
- Detector upgrade: **T2HK**
- Baseline upgrade: **T2KK**, **T2KO**
- **MOMENT**
  Cao et al [1401.8125]
  Tang et al [1909.01548]
- In china? Tang, Vihonen & Xu [2202.13595]
- Atmospheric



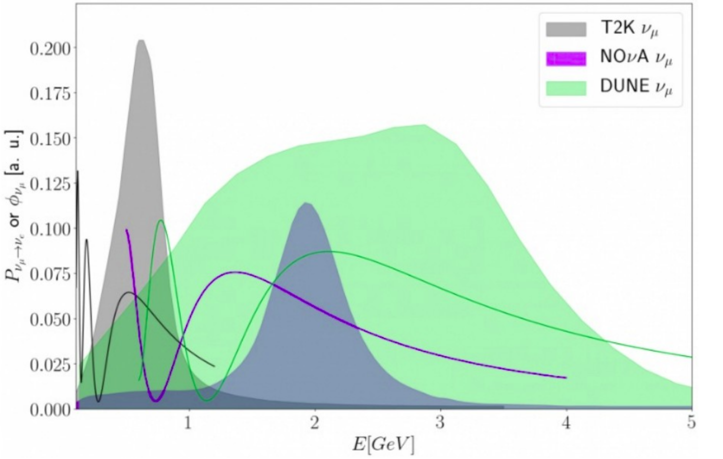
Super-PINGU: Razzaque & Smirnov [1406.1407]
JUNO: An et al [1507.05613]
DUNE: Kelly, Machado, Martinez-Soler, Parke & Perez-Gonzalez [1904.02751]
Super-ORCA: Hofestadt, Bruchner & Eberl [1907.12983]

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 $[\mathbf{T}_{\overline{\nu}} : \mathbf{T}_\nu = \mathbf{2} : \mathbf{1}]$.
  - 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** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos\delta_D \Rightarrow \Delta(\delta_D) \propto \mathbf{1}/\cos\delta_D$

SFG [1704.08518, PoS NuFact2019 (2020) 108]

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]

Tension between T2K & NOvA

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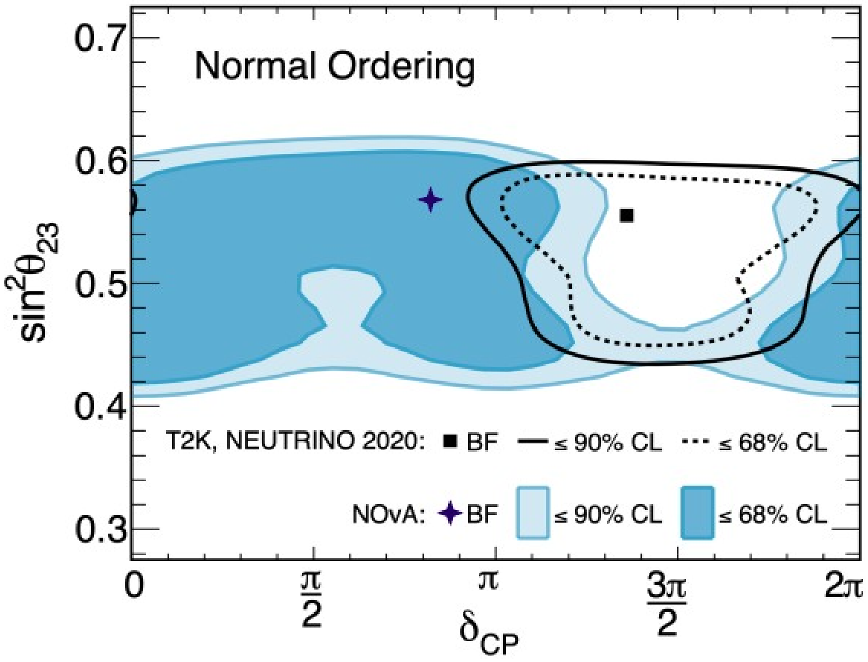
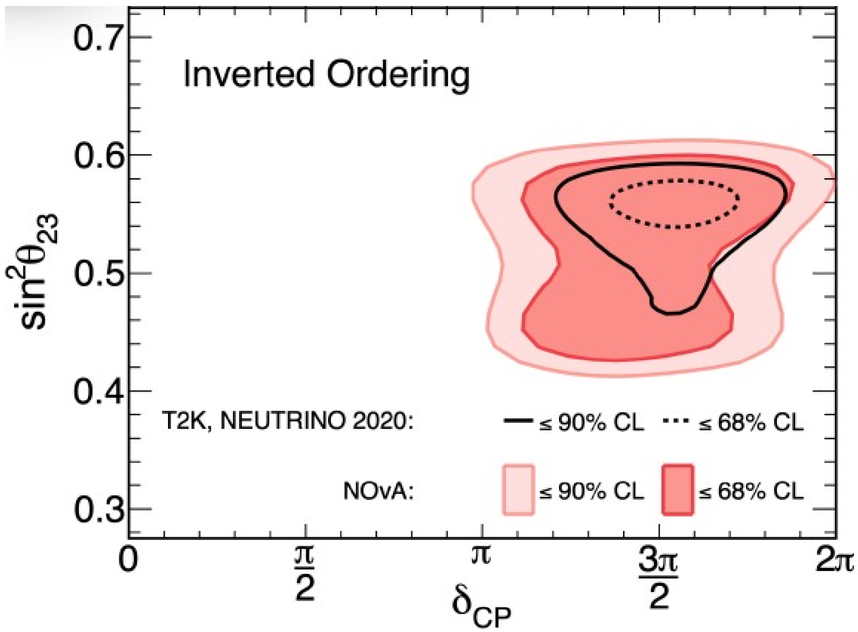
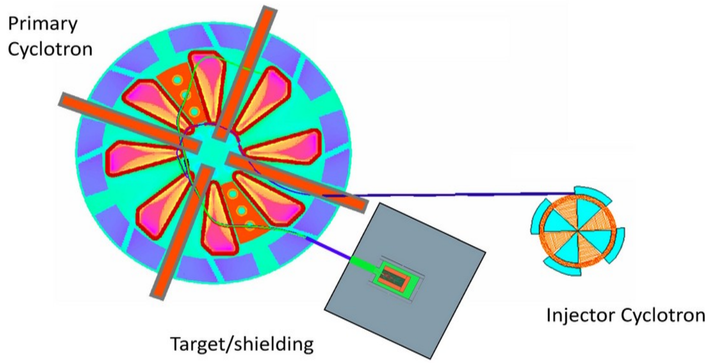




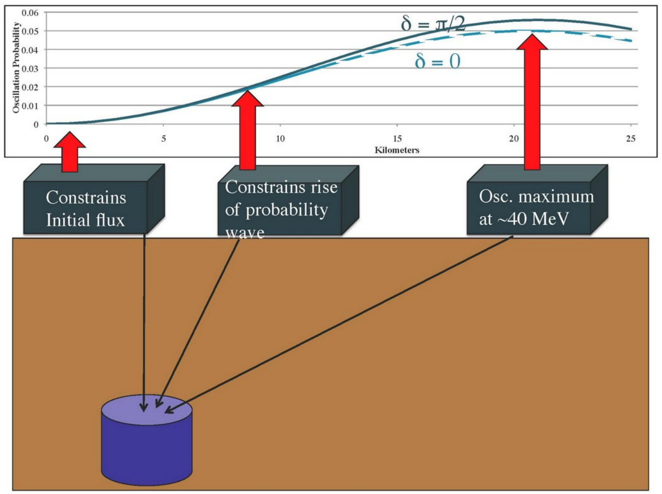
NOvA [2108.08219]

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

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

TNT2K

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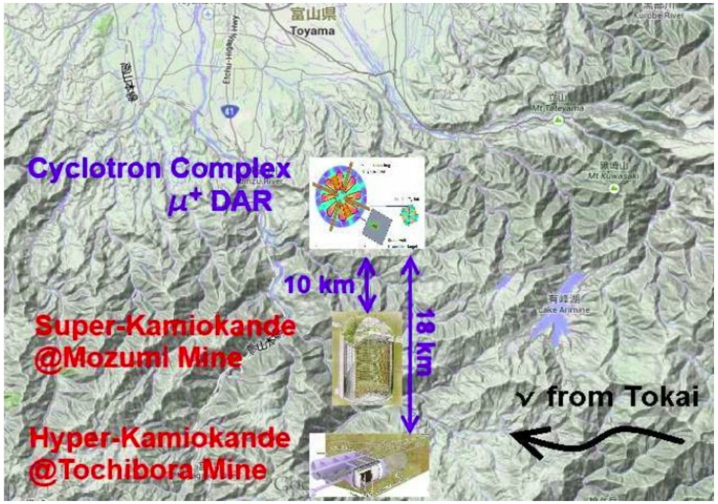
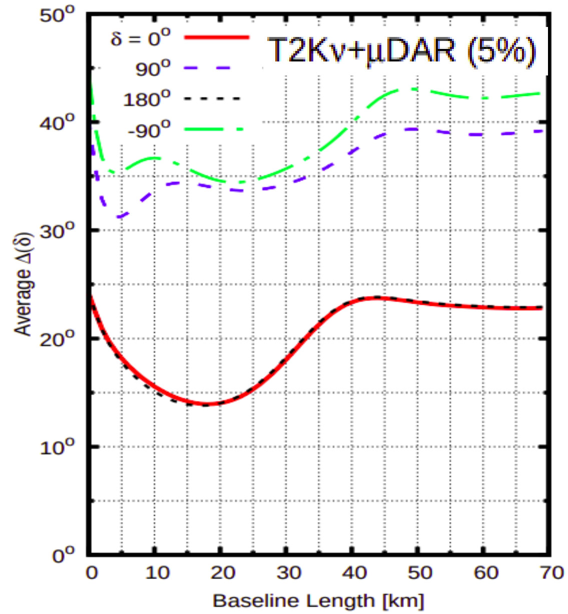
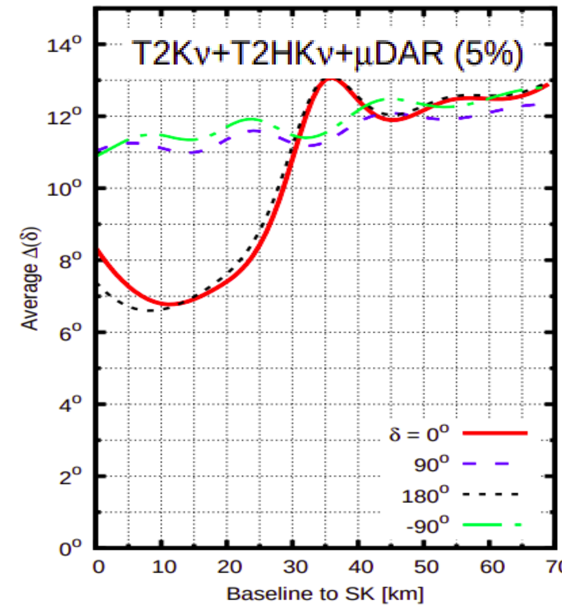






1 μDAR source + **2** detectors

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

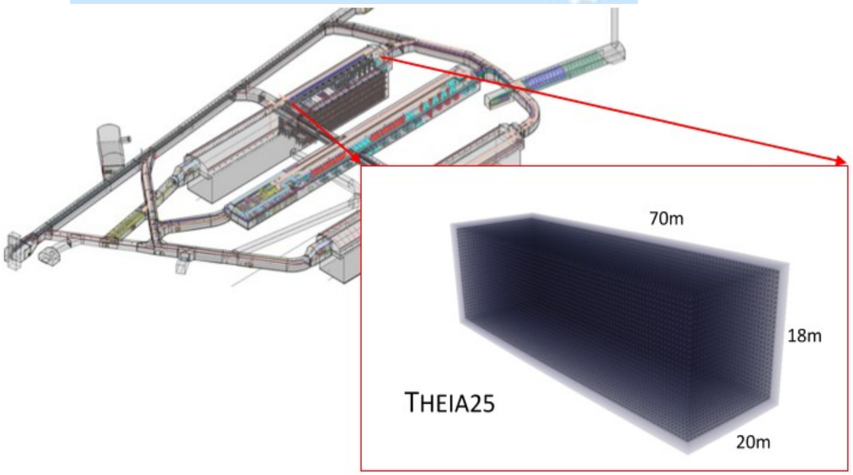
Advantages

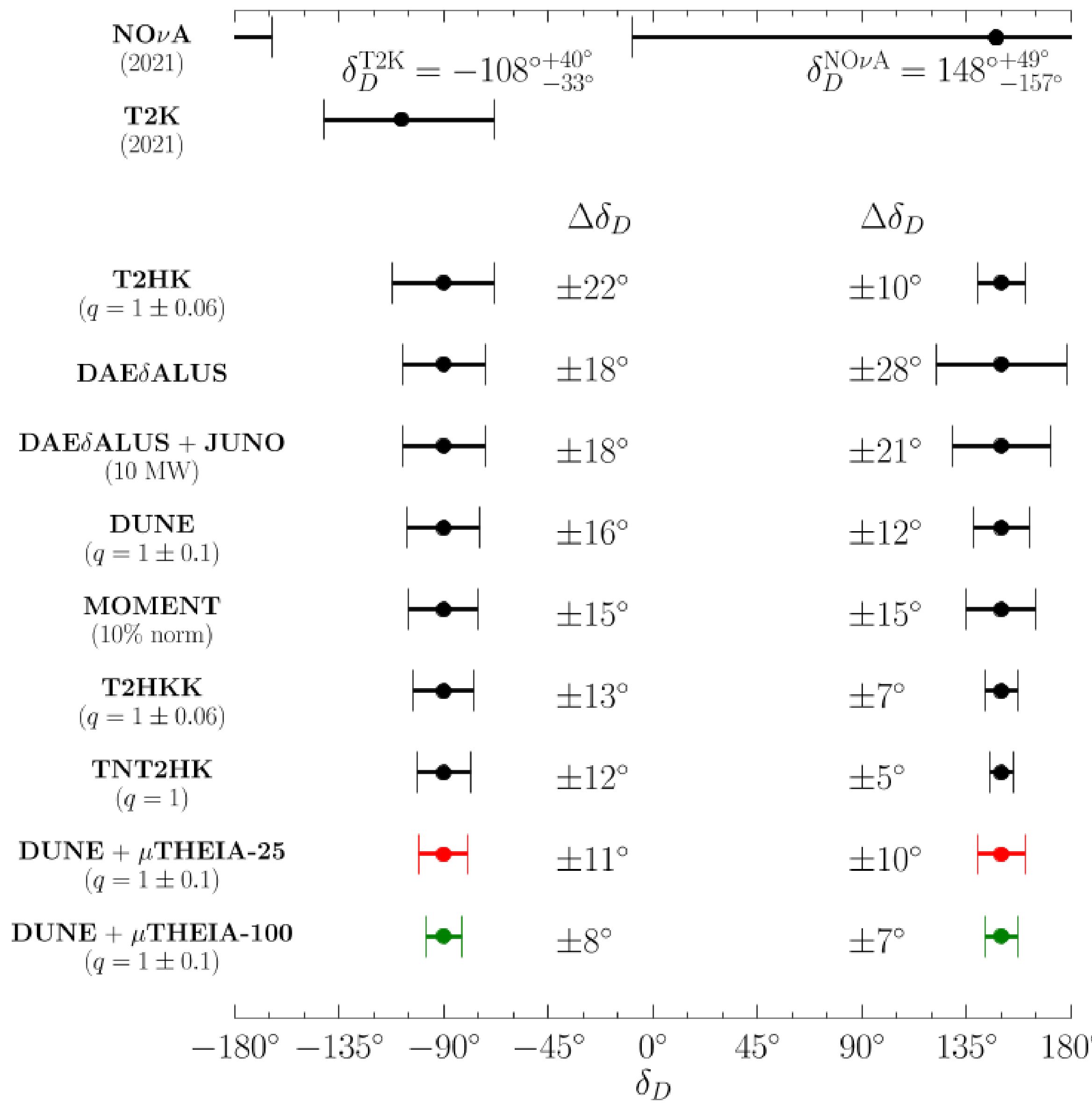
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**$\times$ lower than DAEδALUS]
- Not far beyond the current state-of-art technology of cyclotron [**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
  - Only one cyclotron.
  - Lower intensity.

Disadvantage: A second detector!

Harnik, Kelly & Machado [1911.05088]

μTHEIA





THEIA [1911.03501, 2202.12839]

SFG, Kong, Pasquini [2202.05038]

LMA-Dark Solution

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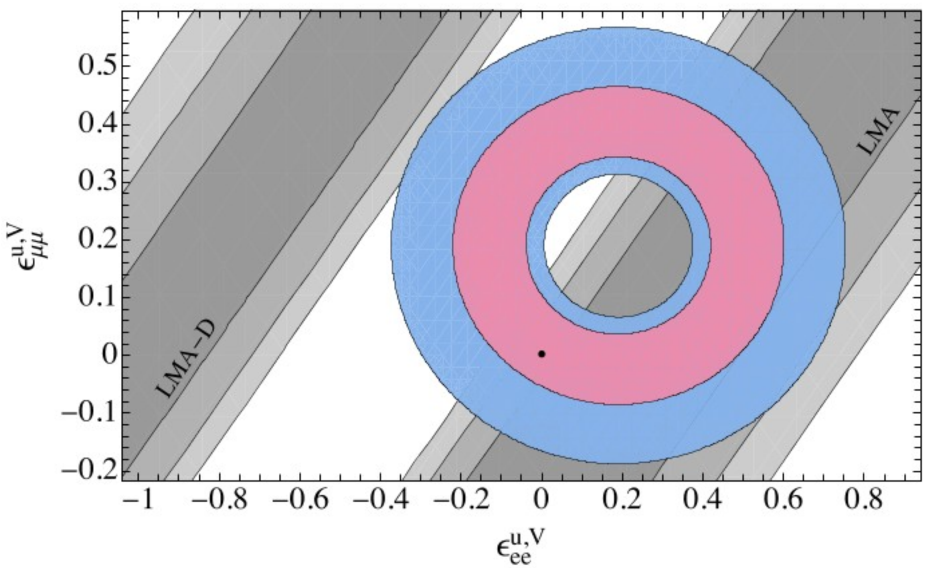
- **Degeneracy between oscillation parameters & NSI**

$$H = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau}\end{pmatrix}\right]$$

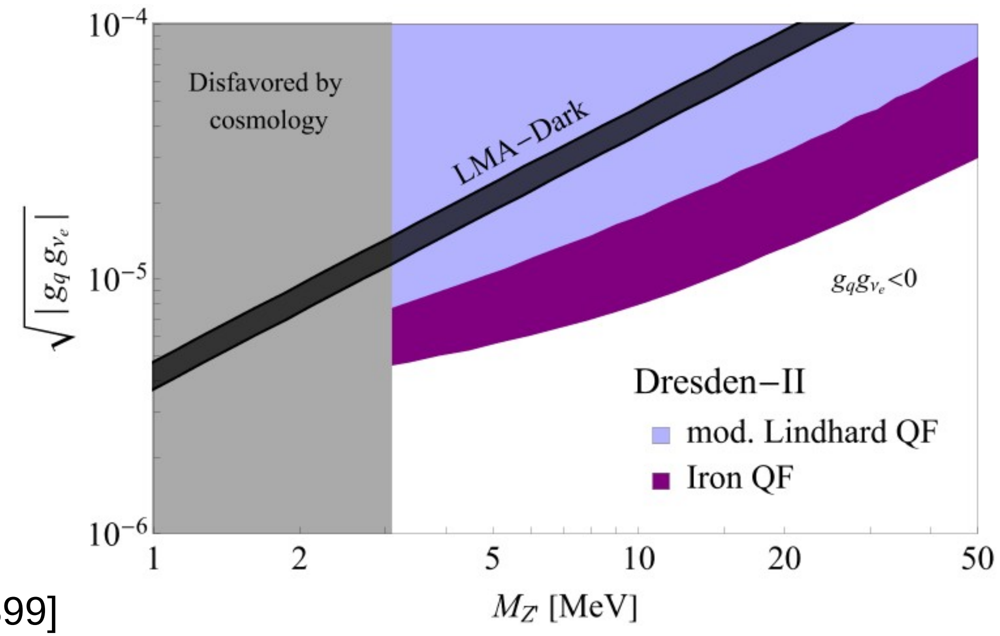
$$\begin{aligned}\sin\theta_s &\leftrightarrow \cos\theta_s\,,\\ \delta_D &\to \pi-\delta_D\,,\\ \Delta m_a^2 &\to -\Delta m_a^2+\Delta m_s^2\,,\\ \epsilon_{ee} &\to -2-\epsilon_{ee}\,,\end{aligned}$$

Problem solved!



Coloma, Gonzalez-Garcia, Maltoni & Schwetz [1708.02899]

Farzan, Lindner, Rodejohann & Xu [1802.05171]

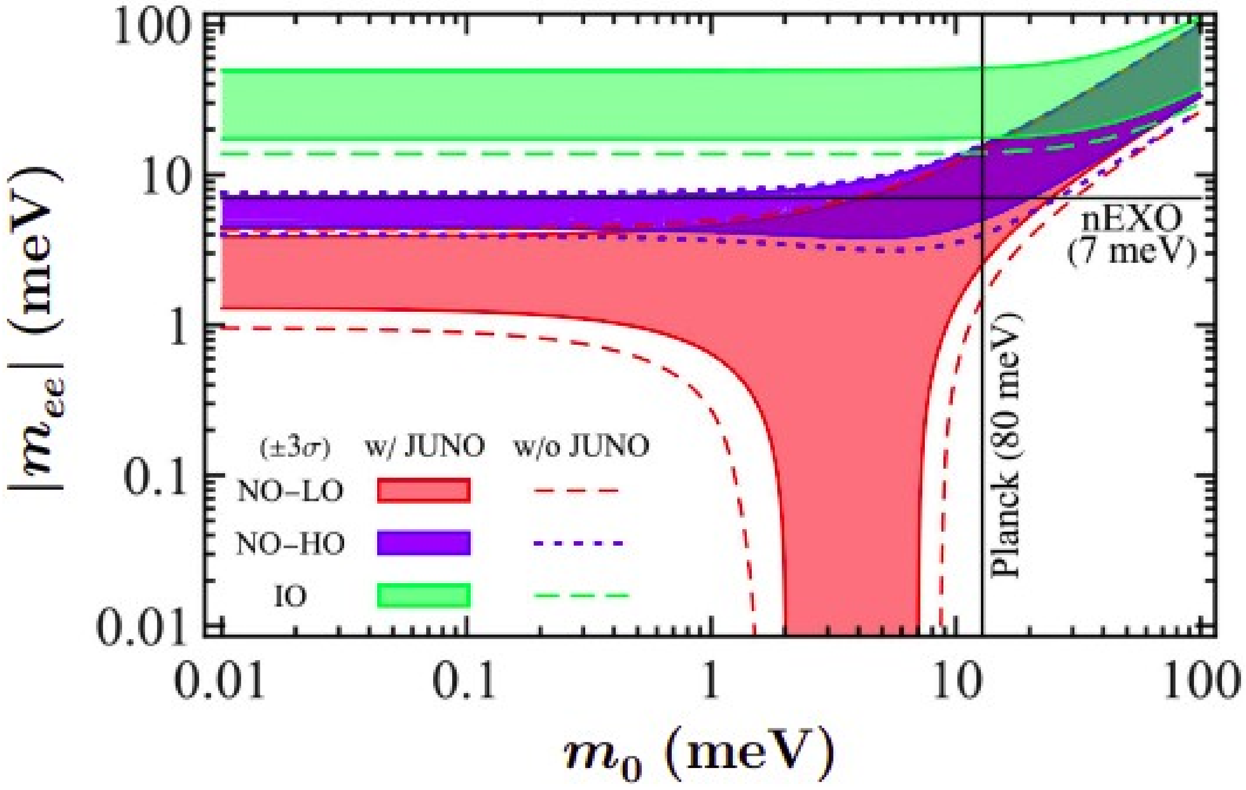


Denton & Gehrlein [2204.09060]

LMA-Dark vs 0ν2β

- **LMA-Dark affects solar octant** $\sin\theta_s \leftrightarrow \cos\theta_s$

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



Independent check with 0ν2β!

SFG & Jing-Yu Zhu [arXiv:1910.02666]
Vishnudath, Choubey & Goswami [1901.04313]

1meV frontier of 0ν2β

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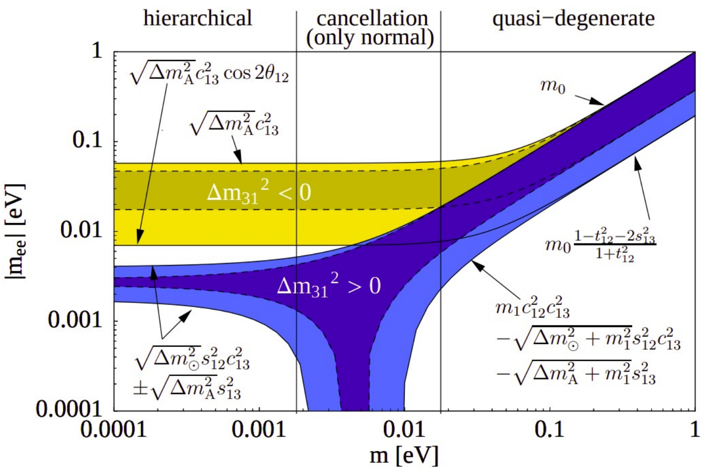


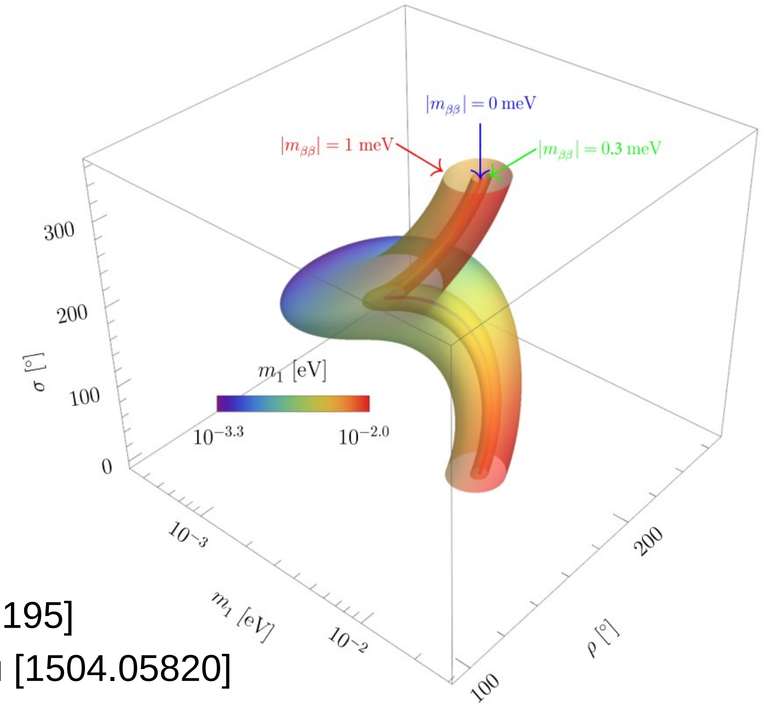
- **Nonzero → only 1 Majorana CP**

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

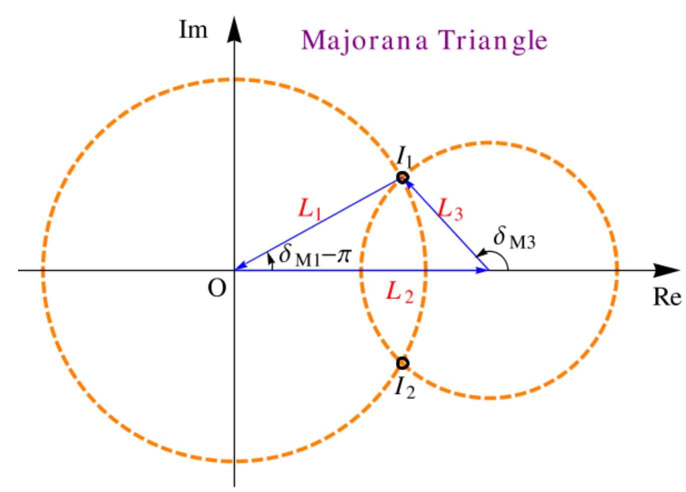
- **Zero → 2 Majorana CP phases**

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

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



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



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, [arXiv:1608.01618]

Catching 2 Majorana CP Phases

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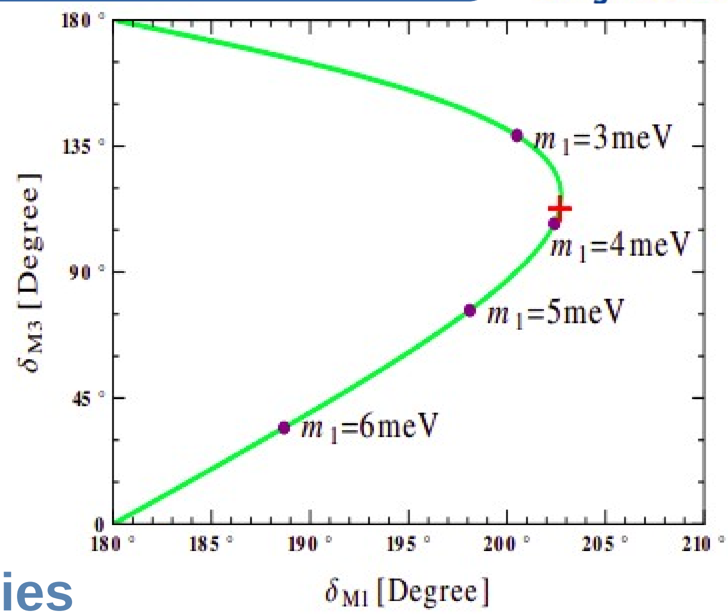
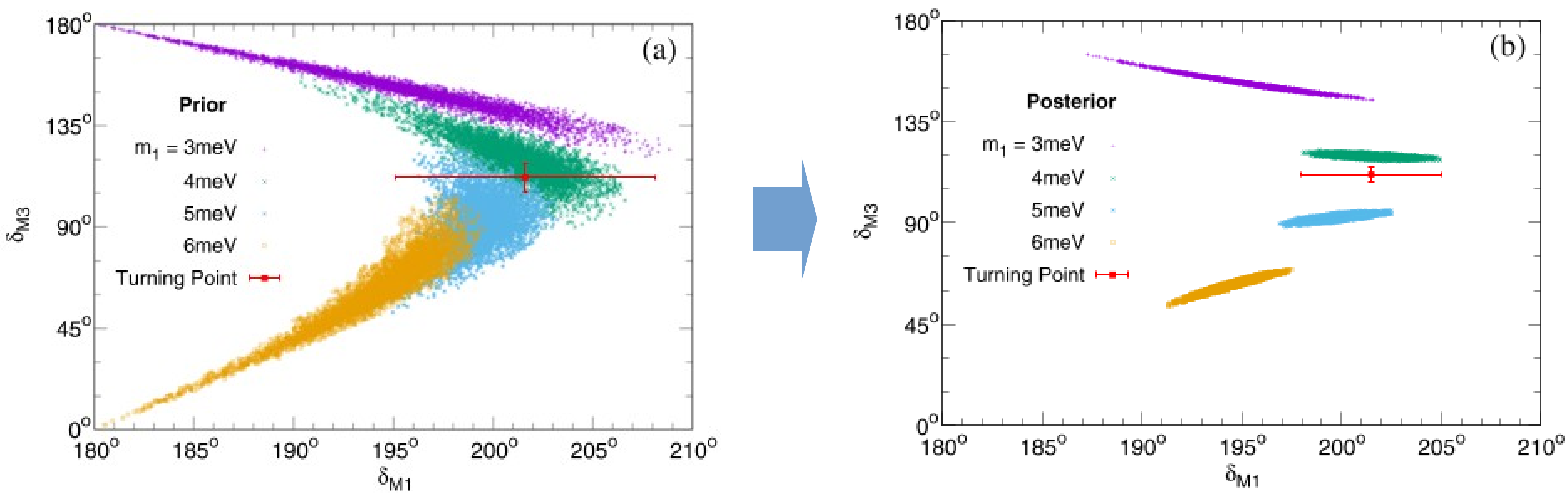
$$\cos \delta_{M1} = -\frac{m_1^2 c_r^4 c_s^4 + m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_1 m_2 c_r^4 c_s^2 s_s^2}$$

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



- JUNO can significantly reduce uncertainties



SFG & Manfred Lindner, [arXiv:1608.01618]

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

Models for Vanishing m_{ee}

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- **In seesaw mechanism**

$$m_{\rm eff} = \sum_i m_i U_{ei}^2 + \sum_I f_\beta(M_I) M_I \Theta_{eI}^2$$

$$f_\beta(M_I) = \frac{\langle p^2 \rangle}{\langle p^2 \rangle + M_I^2}$$

$$\sqrt{\langle p^2 \rangle} = 200 \text{ MeV}$$

↓

$$m_{\rm eff} = \sum_i m_i U_{ei}^2$$

↓

$$M_{\rm eigen} = U^\dagger \begin{pmatrix} 0 & M_D \\ M_D^T & M_I \end{pmatrix} U^*$$

$$m_{\rm eff} = 0$$

Asaka, Ishida & Tanaka [2012.12564, 2012.13186, 2101.12498]

Fang, Li & Zhang [2112.12779]

Zhao, Zhen-Hua [2205.01021]

Independent check: CνB

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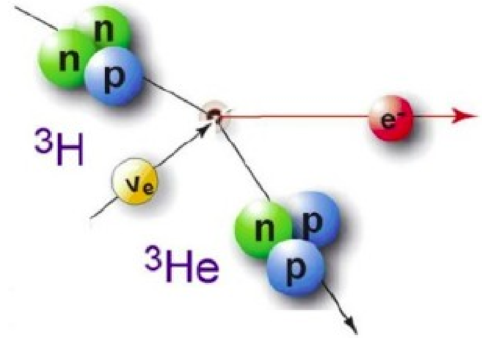
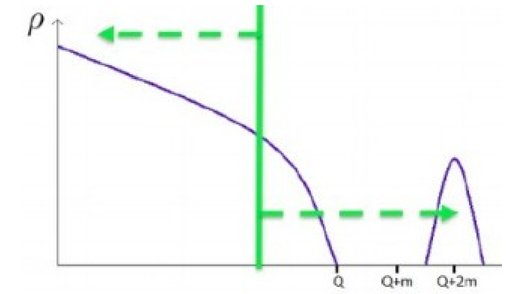
粒子物理 + 宇宙学的**双前沿！**

必然存在，**没有问题更大！**





- **Fermi-Dirac Distribution**

$$dn_\nu = \frac{d^3p(z)}{(2\pi)^3}\frac{1}{e^{p(z)/T_\nu(z)}+1}, \qquad p(z) = \frac{1+z}{1+z_{fo}}p_{fo}$$

currently $n_\nu \approx$ **56/cm³**.

- **Detection Cross Section**

	ν_L	ν_R	$\bar\nu_L$	$\bar\nu_R$
Weak Interactions	✓	×	×	✓
Density	$n_\nu(z)$	0	0	$n_\nu(z)$
Helicity $(\mathrm{p}\cdot\boldsymbol{\sigma}/\lvert\mathrm{p}\rvert)$	$-$	$+$	$+$	$-$
Today	$n_- = n_\nu(z)$	0	0	$n_+ = n_\nu(z)$
Dirac ν Detection	✓	×	×	×
Majorana ν Detection	✓	×	×	✓

$$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} = 2\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}}$$

Long, Lunardini & Sabancilar [1405.7654]

Zhang & Zhang [1712.01153]

- **Test new physics**

Thermal vs nonthermal productions

Huang & Zhou [1610.01347]

Electric & Magnetic Moments

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- **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**

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

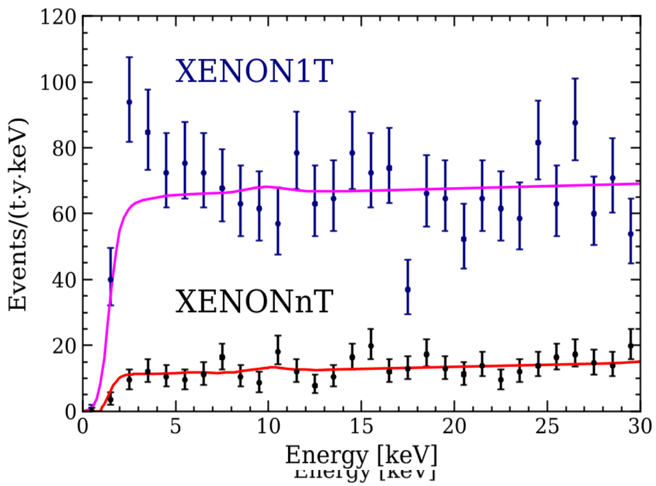
Scattering & recoil

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

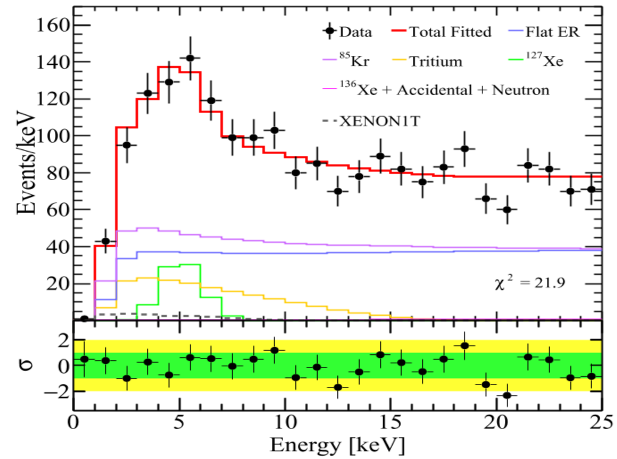
Stellar processes

Giunt & Studenikin [1403.6344]

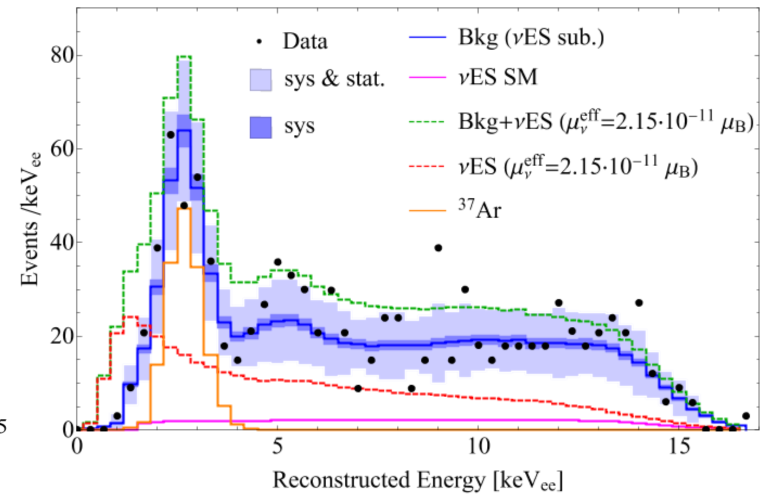
ν Magnetic Moments @ DM Exps



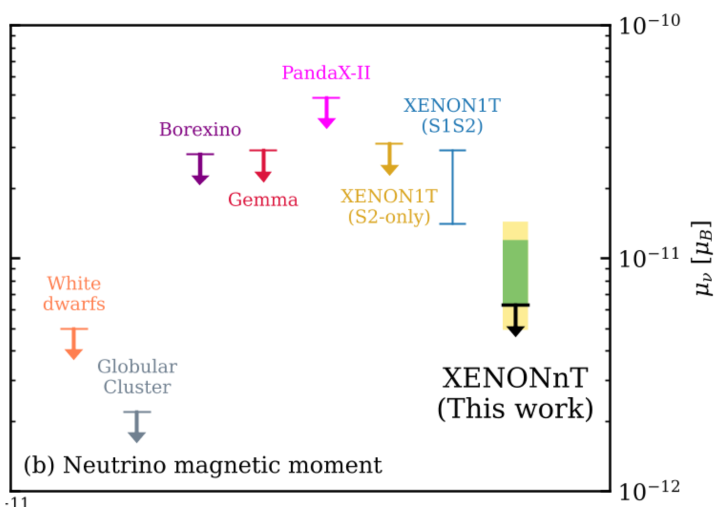
Xenon1T [2006.09721]



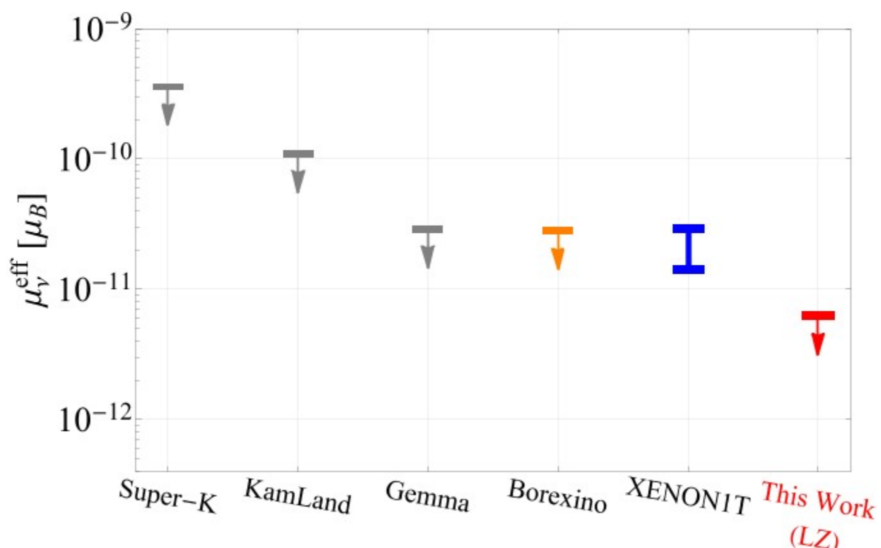
PandaX-II [2008.06485]



LZ [2207.03764]



XENONnT [2207.11330]



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

Light mediator @ ν Pair Emission

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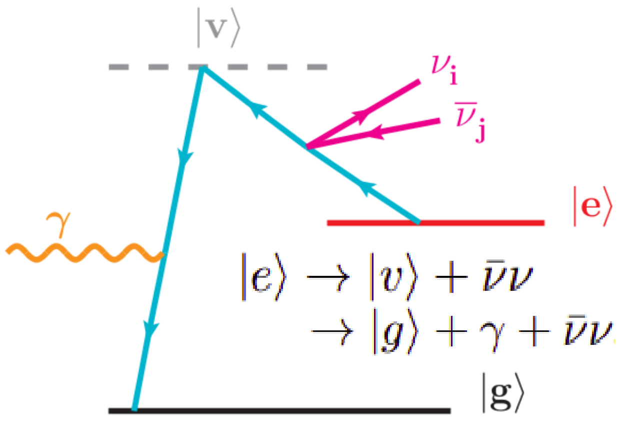
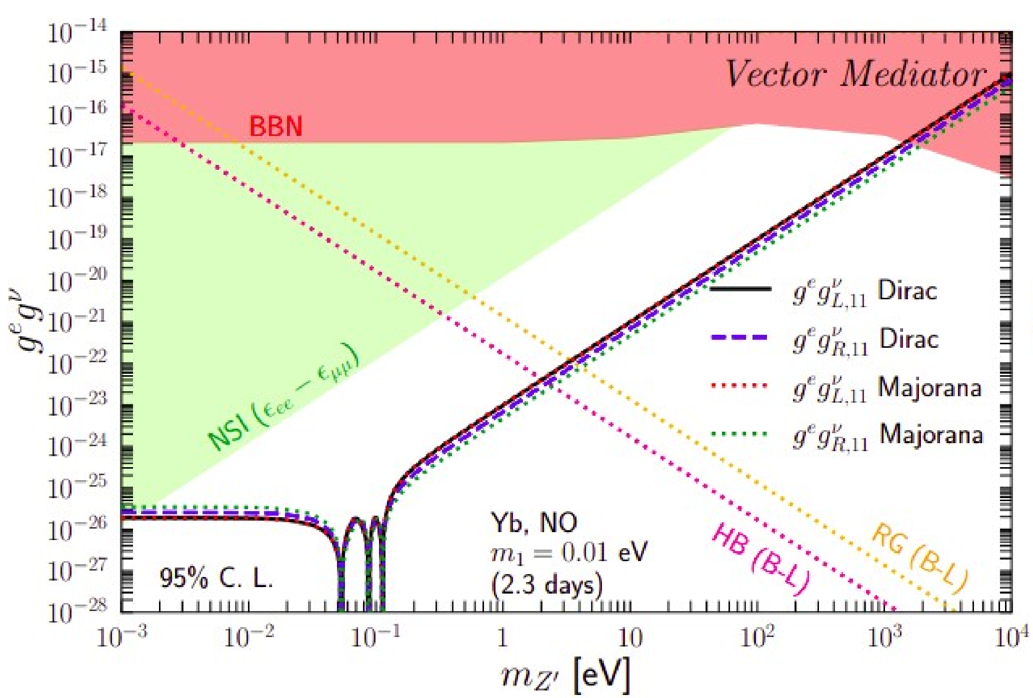
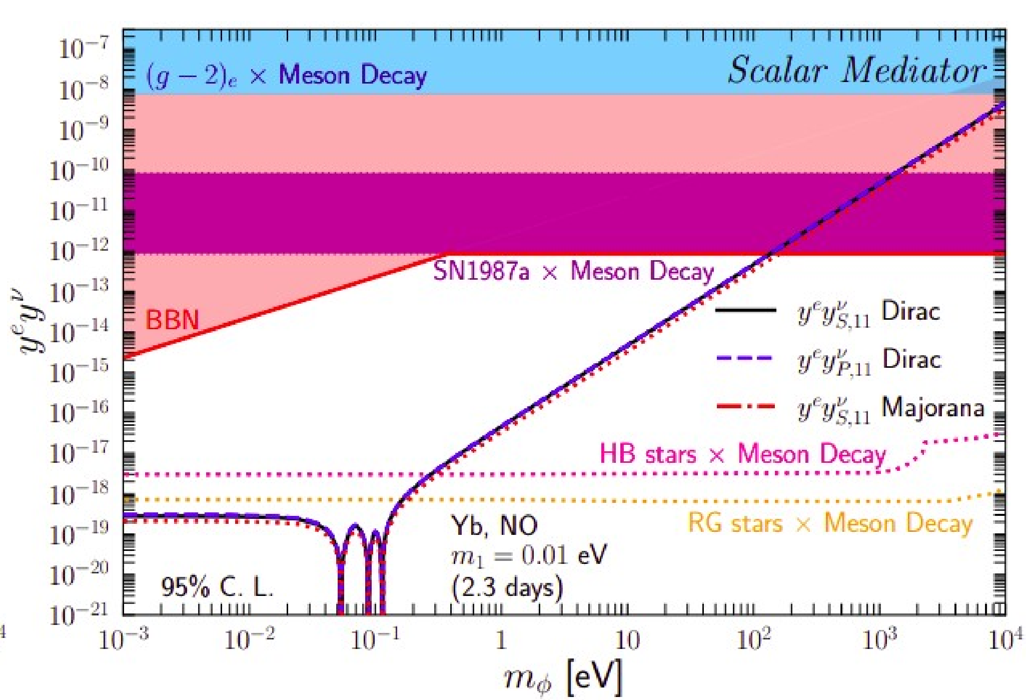


Fukumi et al [1211.4904]

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

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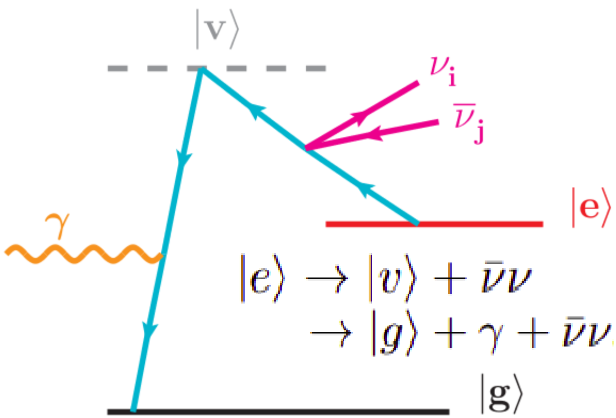
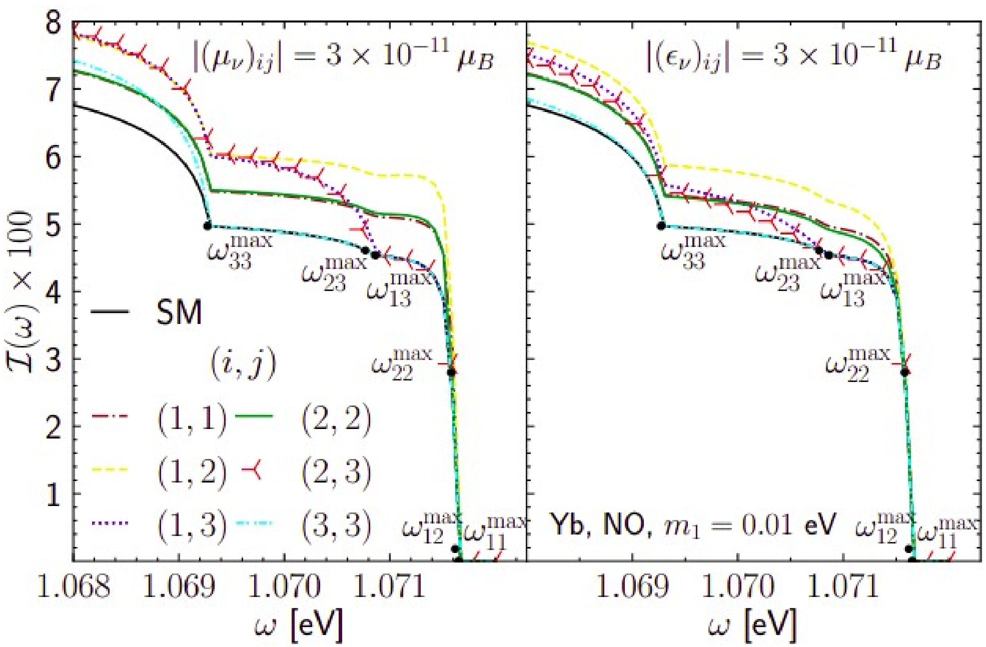
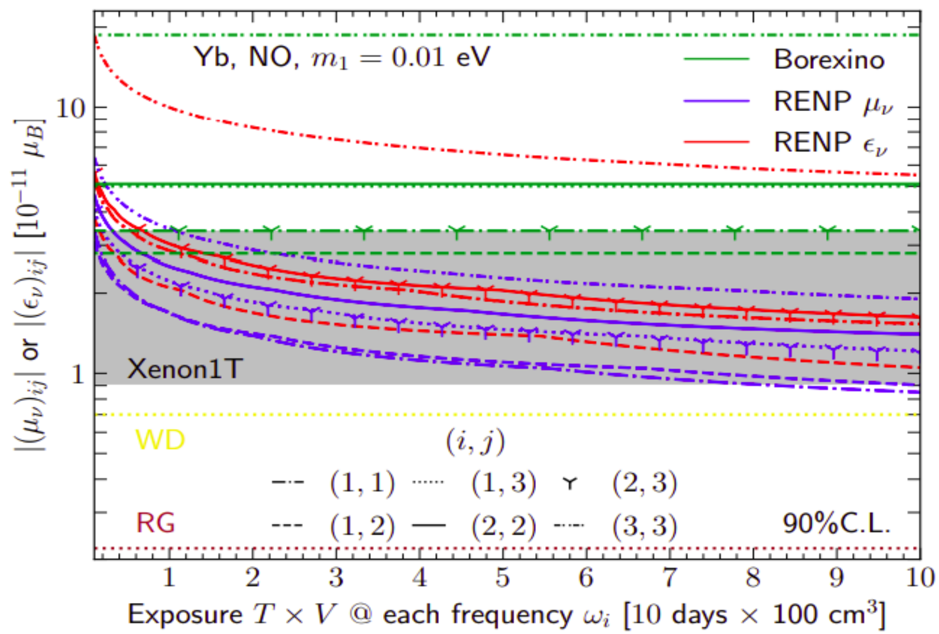


Fukumi et al [1211.4904]

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

$$\mathcal{I}^M_E \equiv \sum_{ij} \left(\frac{\mu_B}{G_F}\right)^2 \frac{\omega^2 \Delta_{ij} \Theta(\omega - \omega^{\max}_{ij})}{9(E_{vg} - \omega)^2} \times \left[1 + \frac{(m_i \pm m_j)^2 \pm 4 m_i m_j}{q^2} - 2\left(\frac{\Delta m^2_{ji}}{q^2}\right)^2\right] \quad ($$



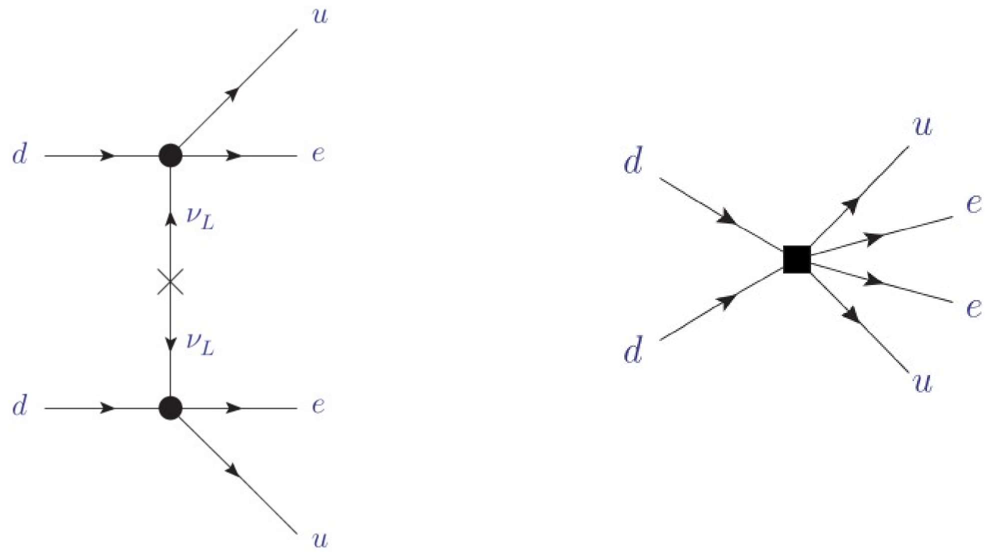


Can disentangle EDM & MDM elements!

SFG & Pasquini [2206.11717]

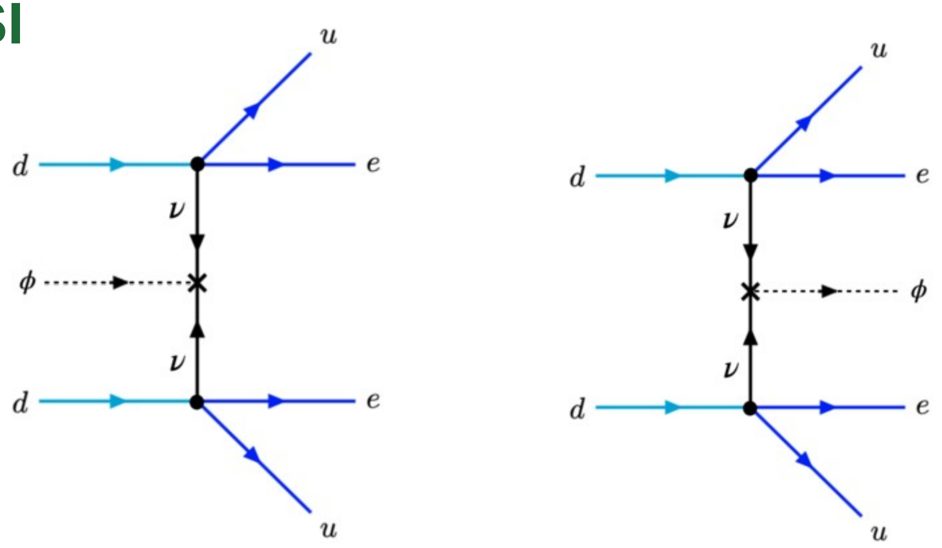
Faked 0ν2β

- **Cancellation between Majorana masses**



Gu, Pei-Hong [2101.00212]

- **Dark NSI**



Enviromental effect!

Huang & Nath [2111.08732]

ν Oscillation vs Dark Matter

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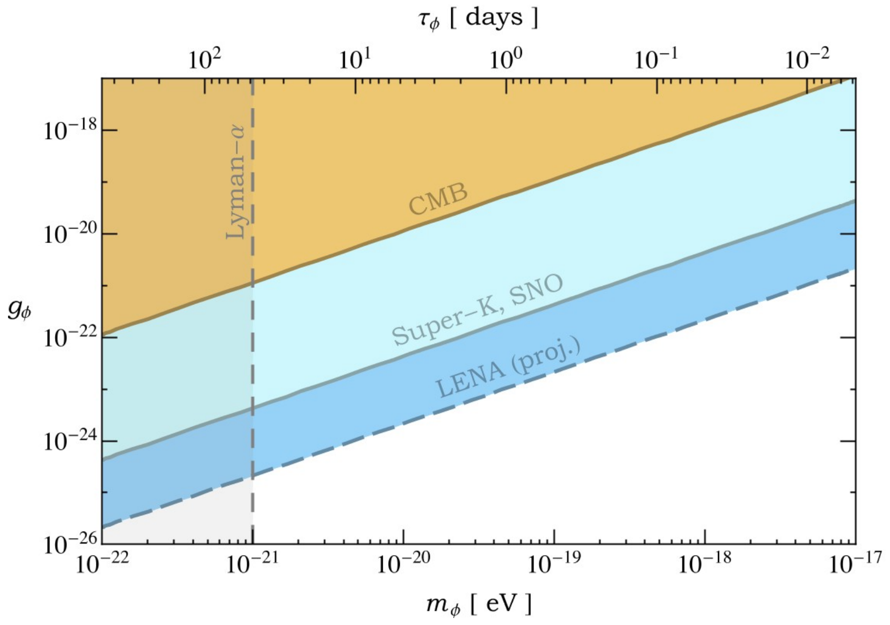
- **ν-DM coupling + Fuzzy DM**

$$-\mathcal{L} \supset \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} m_i \bar{\nu}_i \nu_i + g_\phi \phi \bar{\nu}_1 \nu_2 + \cdots$$

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



- **Neutrino oscillation parameters receive corrections**

Dark NSI

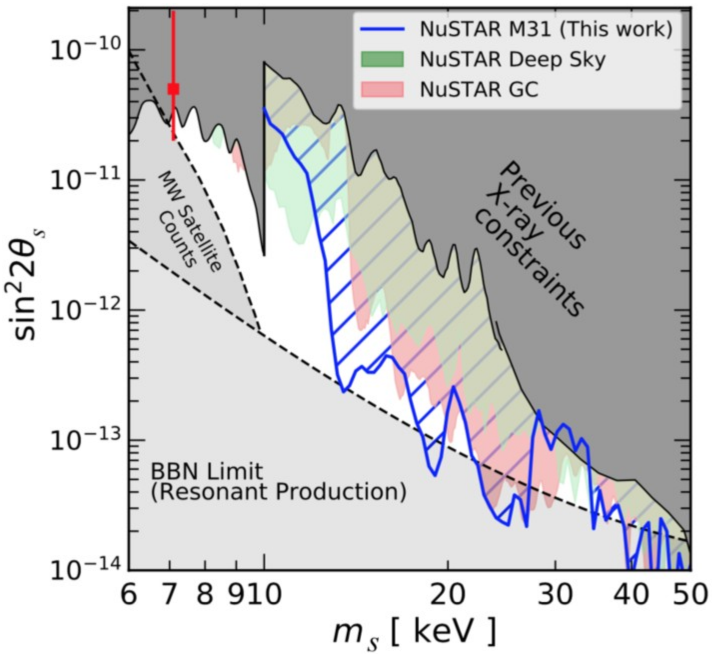
$$\sin\theta_{12}(t) \simeq \sin\theta_{12} + \frac{\cos\theta_{12}}{\Delta m_{12}} \frac{g_\phi \sqrt{2\rho_{\rm DM}}}{m_\phi} \cos m_\phi t$$

Berlin [1608.01307]
Zhao [1701.02735]

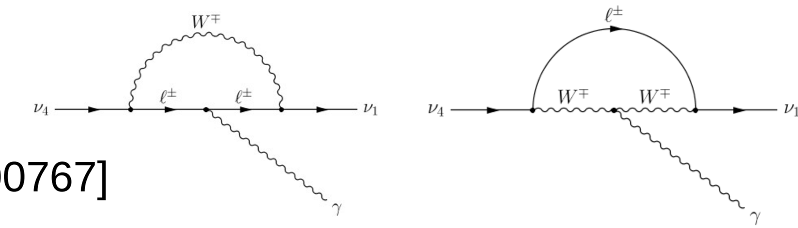
Brdar, Kopp, Liu, Prass & Wang [1705.09455]
Liao, Marfatia & Whisnant [1803.01773]

Chao, Hu, Jiang & Jin [2009.14703]
SFG, Murayama [1904.02518]

Sterile Neutrino Dark Matter

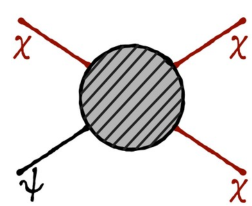


$$\left(\frac{\partial}{\partial t} - H\,E\,\frac{\partial}{\partial E}\right) f_s(E,t) = \left[\frac{1}{2}\sin^2(2\theta_M(E,t))\Gamma(E,t)\right] f_a(E,t)$$



Kopp [2109.00767]

- **Original Dodelson-Widrow mechanism excluded by X-ray constraints**
- **MSW resonant production** Shi & Fuller, PRL99
- **Pandemic production**



Bringmann et al [2103.16572; 2206.10630]

- **Dark NSI**

$$\sin^2 2\theta_m \simeq \frac{\Delta^2 \langle \sin^2 2\theta_{\rm eff}\rangle}{\Delta^2 \langle \sin^2 2\theta_{\rm eff}\rangle + (\Delta - V_T)^2}$$

Berlin & Hooper [1610.03849]

- **Neutrino self-interactions**

Gouvea, Sen, Tangarife & Zhang [1910.04901]

Kelly, Sen, Tangarife & Zhang [2005.03681]

Chen, Sen, Tangarife, Tuckler & Zhang [2207.14300]

- **Pseudo-Dirac Sterile DM**

Chao, Jiang, Wang & Zhou [2112.14527]

Neutrino @ Collider

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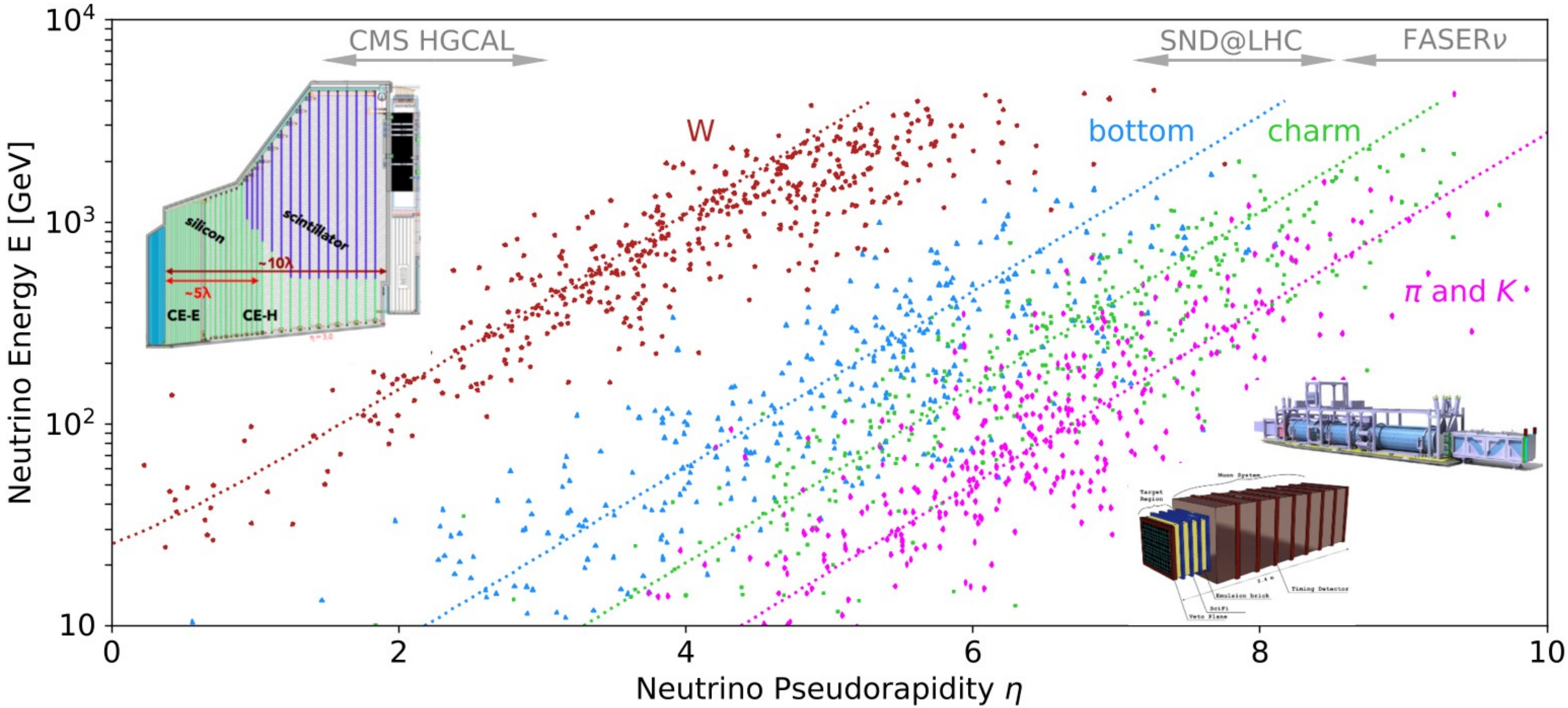

- **FASERν** [1908.02310]
- **SND@LHC**

Scattering and neutrino detector of ShiP [2002.08722]

- **CMS** Foldenauer, Kling & Reimitz [2108.05370]

Neutrino Trident Production

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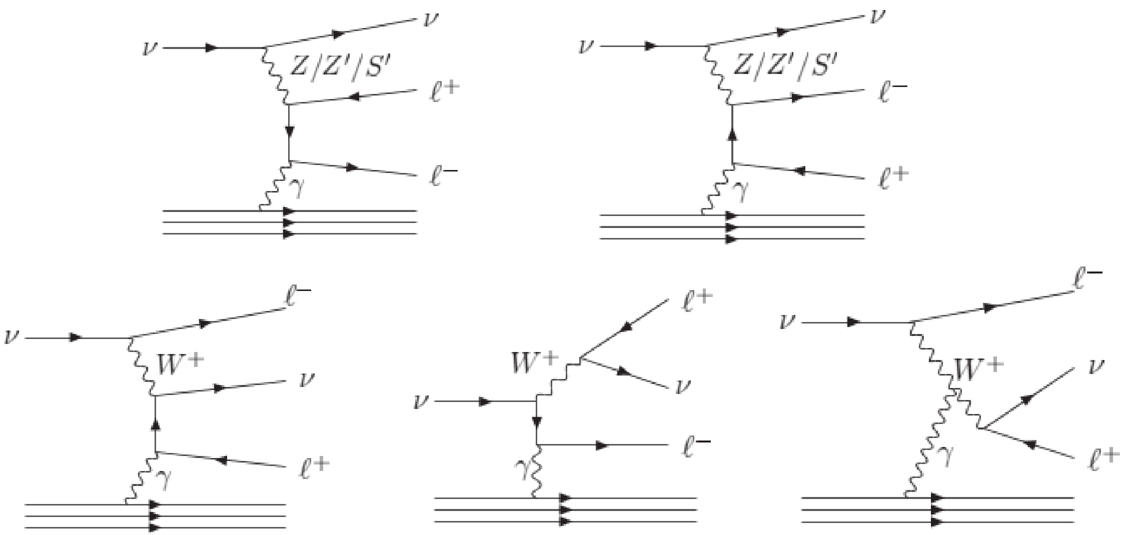
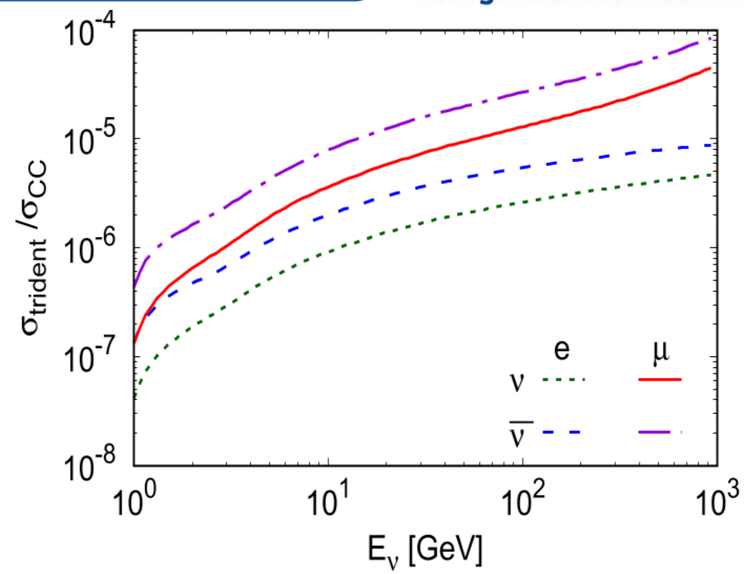
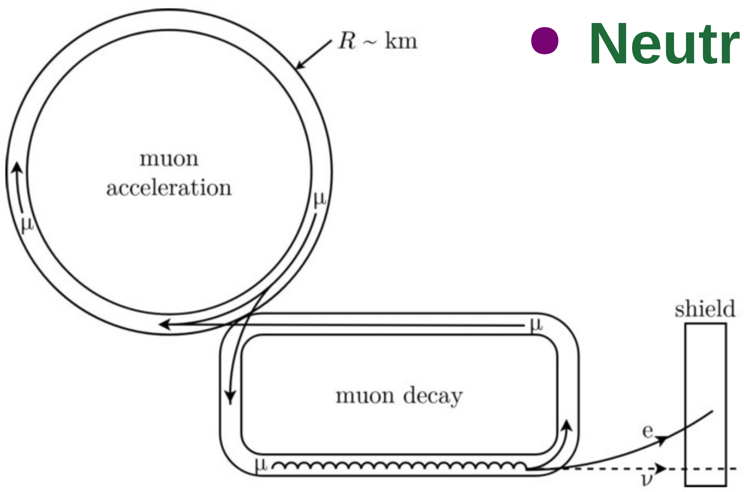




- **Existing CHARM-II, CCFR, NuTeV** — Altmannshofer, Gori, Pospelov & Yavin [1406.2332]
- **DUNE near detector** — Magill & Plestid [1612.05642, 1710.08431]; Ballett et al [1807.10973, 1902.08579]; Altmannshofer, Gori, Martin-Albo, Sousa & Wallbank [1902.06765]
- **Atmospheric neutrinos** — **SFG**, Lindner & Rodejohann [1702.02617]
- **Even higher energy** — Zhou & Beacom [1910.08090, 1910.10720]; Sun, Zhang, Hu, Xu & Gao [2201.03580]
- **Models** — Shimomura & Uesaka [2009.13773]; Cheng, He, Huang & Li [2204.05031]

Snowmass, Dark Sector Studies with Neutrino Beams [2207.06898]

Neutrino Collider



- **Neutrino from muon beam**

With a TeV scale $\mu^+ \to e^+ \nu_e \tilde{\nu}_\mu$ beam, if the collision beams from the other side are of e^-, e^+ and μ^-, respec-

Yang, Qian, Deng, Xiao, Gao, Levin, Li, Lu & You [2204.11871, 2205.15350]

- **Neutrino from (proton, muon & pion) beams**

1) Neutrino + Quark; **2)** Neutrino + Lepton; **3)** Neutrinos

Schwienhorst [0708.0160]

- **Neutrino from reactor**

$\bar{\nu}_\mu$ appearance experiment:

✓ reactor ($\bar{\nu}_e \to \bar{\nu}_\mu$) +accelerator $p \to \mu^+ + n$

✓ $E_{th} = 19$ GeV

Ichikiawa @ NuFact 2018

总结

Tsung-Dao Lee Institute

- **Neutrino Oscillation & Mixing Patterns**
- **CP Measurement & New Physics**
- **Neutrino Properties (Dirac vs Majorana)**
- **Neutrino vs Dark matter**
- **Neutrino with Beams**

  1) Neutrino @ Collider exps

  2) Neutrino trident production & beam dump

  3) Neutrino collider

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谢谢！

CP Measurement

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

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

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

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

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

Majorana Pyramid

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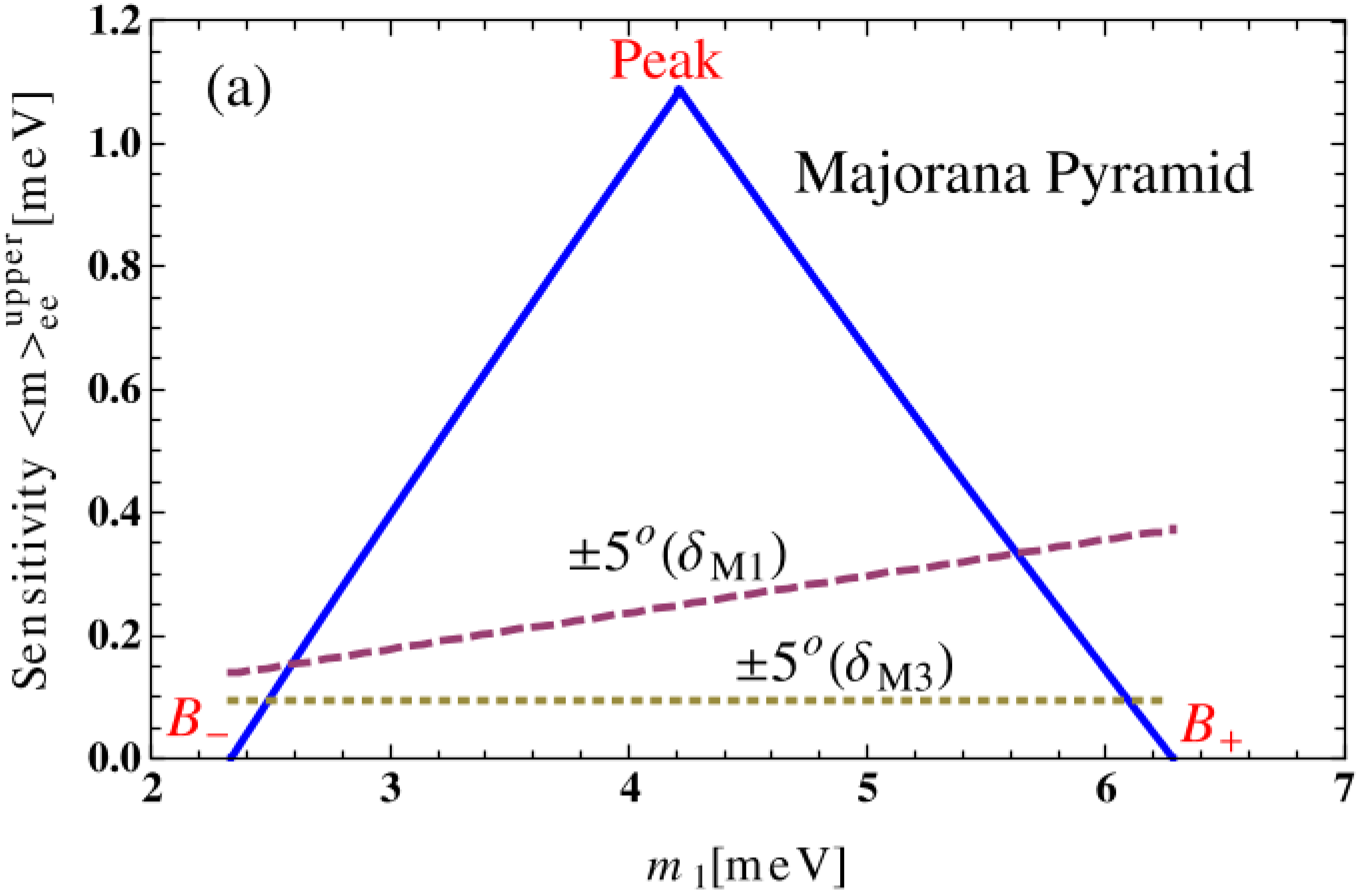

SFG & Manfred Lindner, [arXiv:1608.01618]

Majorana Pyramid

SFG & Manfred Lindner, [arXiv:1608.01618]