Stringent constraint on CPT violation with the synergy of T2K-II, NOvA extension, and JUNO

Son Cao, IFIRSE

Based on our recent works arXiv:2210.13044 (accepted to publish on PRD)

in collaboration w/ T. V. Ngoc, N. T. H. Van, and P.T. Quyen

2023 Jan. 8, **“Theory Meeting Experiment”, ICISE, Quy Nhon**

Outline

- Progress in neutrino study (from neutrino oscillation)
- CPT in neutrino oscillation: recent investigation
- CPT sensitivity with T2K-II, NOvA extension, and JUNO
- Summary

Adapted "The Growing Excitement of Neutrino Physics " by APS

★ 1930: On-paper appearance as "desperate" remedy by W. Pauli

★ 1956: Anti-ν_e first experimentally discovered by Reines & Cowan

★ 1962: ν_μ existence confirmed by Lederman *et al*

★ 1986: Existence of ν_τ was established

★ 1998: Atmospheric ν oscillations discovered by Super-K

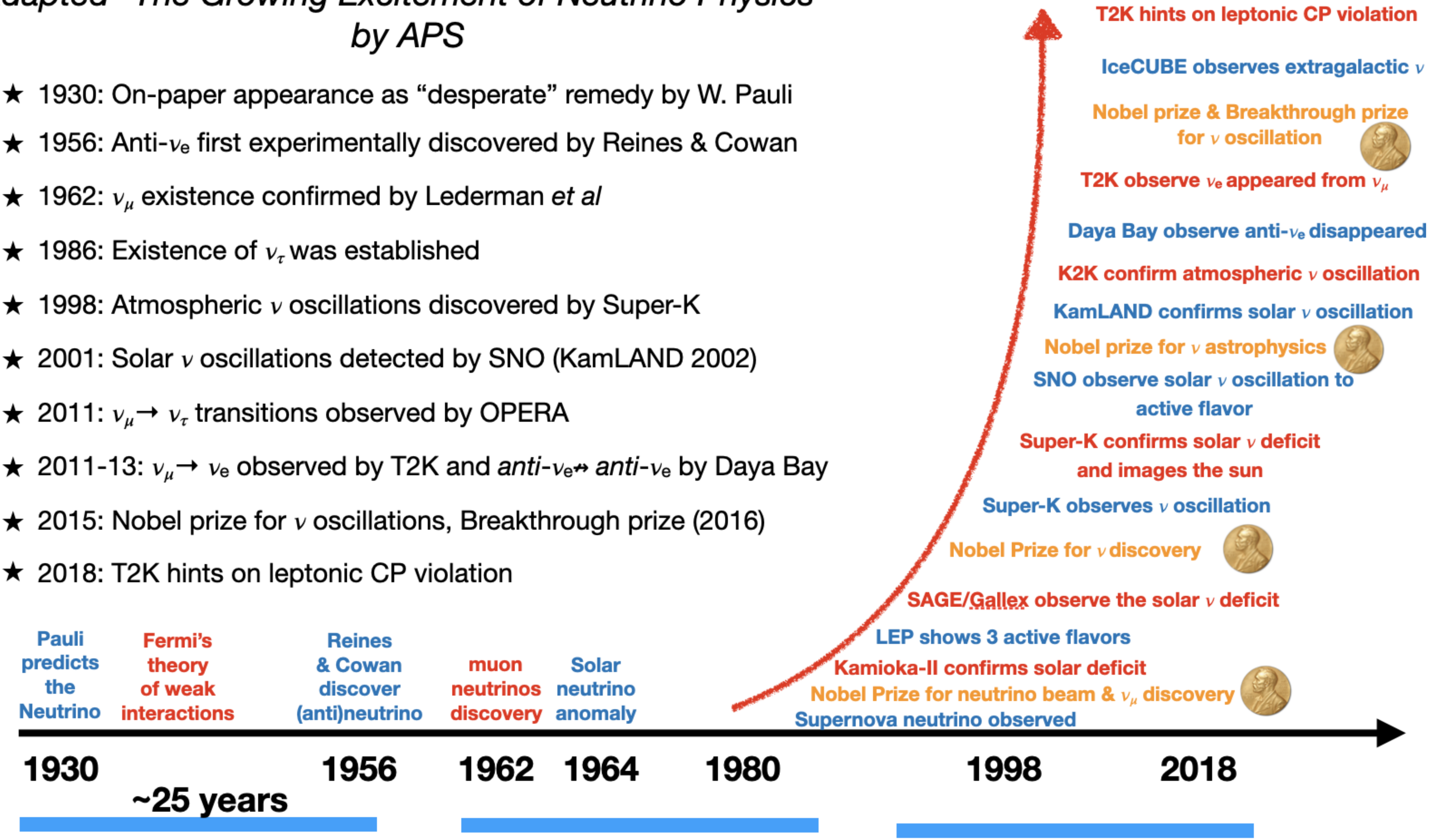
★ 2001: Solar ν oscillations detected by SNO (KamLAND 2002)

★ 2011: $\nu_\mu \rightarrow \nu_\tau$ transitions observed by OPERA

★ 2011-13: $\nu_\mu \rightarrow \nu_e$ observed by T2K and *anti-*ν_e ↮ *anti-*ν_e by Daya Bay

★ 2015: Nobel prize for ν oscillations, Breakthrough prize (2016)

★ 2018: T2K hints on leptonic CP violation



T2K hints on leptonic CP violation

IceCUBE observes extragalactic ν

Nobel prize & Breakthrough prize for ν oscillation

T2K observe ν_e appeared from ν_μ

Daya Bay observe anti-ν_e disappeared

K2K confirm atmospheric ν oscillation

KamLAND confirms solar ν oscillation

Nobel prize for ν astrophysics

SNO observe solar ν oscillation to active flavor

Super-K confirms solar ν deficit and images the sun

Super-K observes ν oscillation

Nobel Prize for ν discovery

SAGE/Gallex observe the solar ν deficit

LEP shows 3 active flavors

Kamioka-II confirms solar deficit

Nobel Prize for neutrino beam & ν_μ discovery

Supernova neutrino observed

Pauli predicts the Neutrino

Fermi's theory of weak interactions

Reines & Cowan discover (anti)neutrino

muon neutrinos discovery

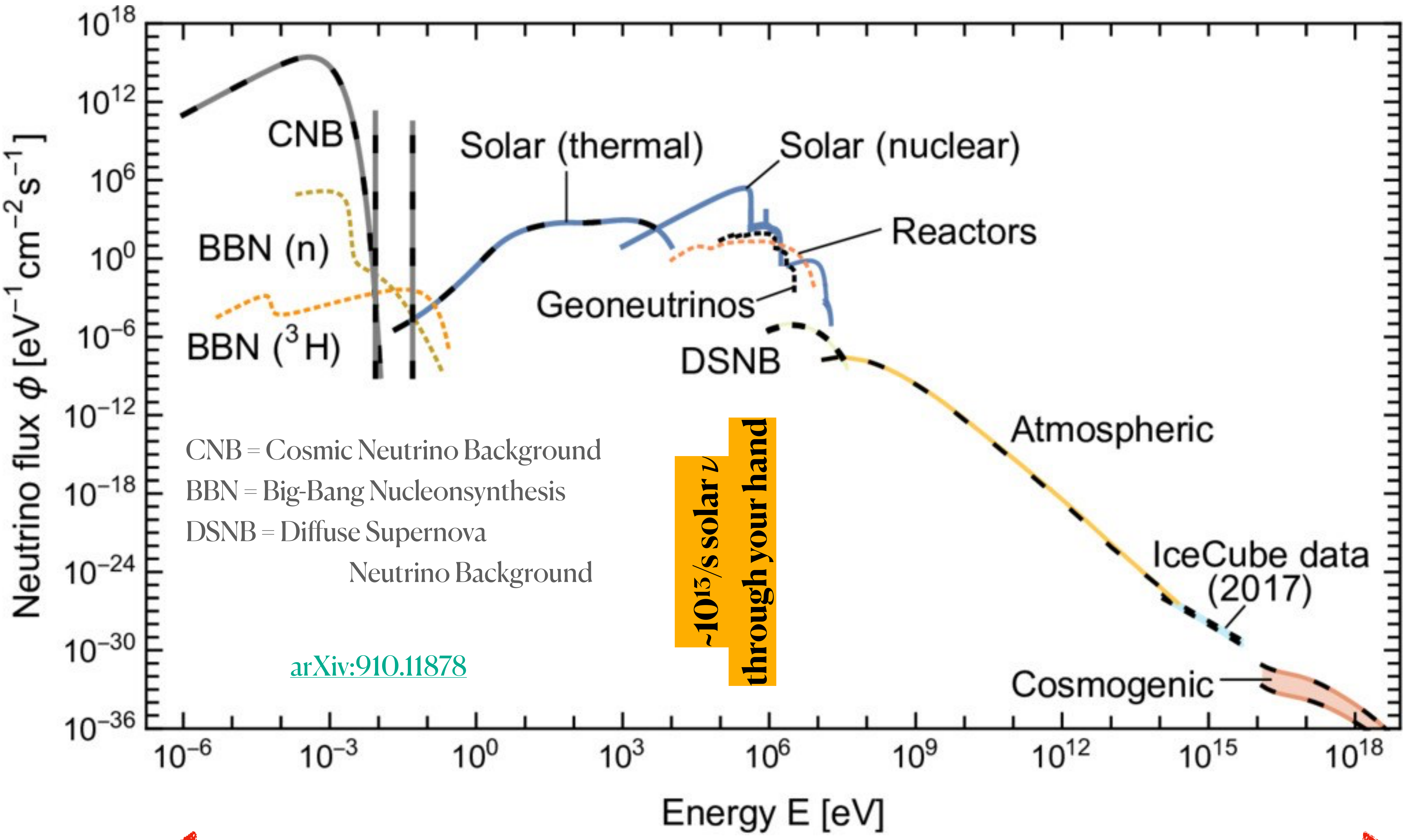
Solar neutrino anomaly

1930 **1956** **1962** **1964** **1980** **1998** **2018**

~25 years

More detail: https://neutrino-history.in2p3.fr/neutrinos-milestones-and-historical-events/

Here, there, every where…tiny, elusive but mighty

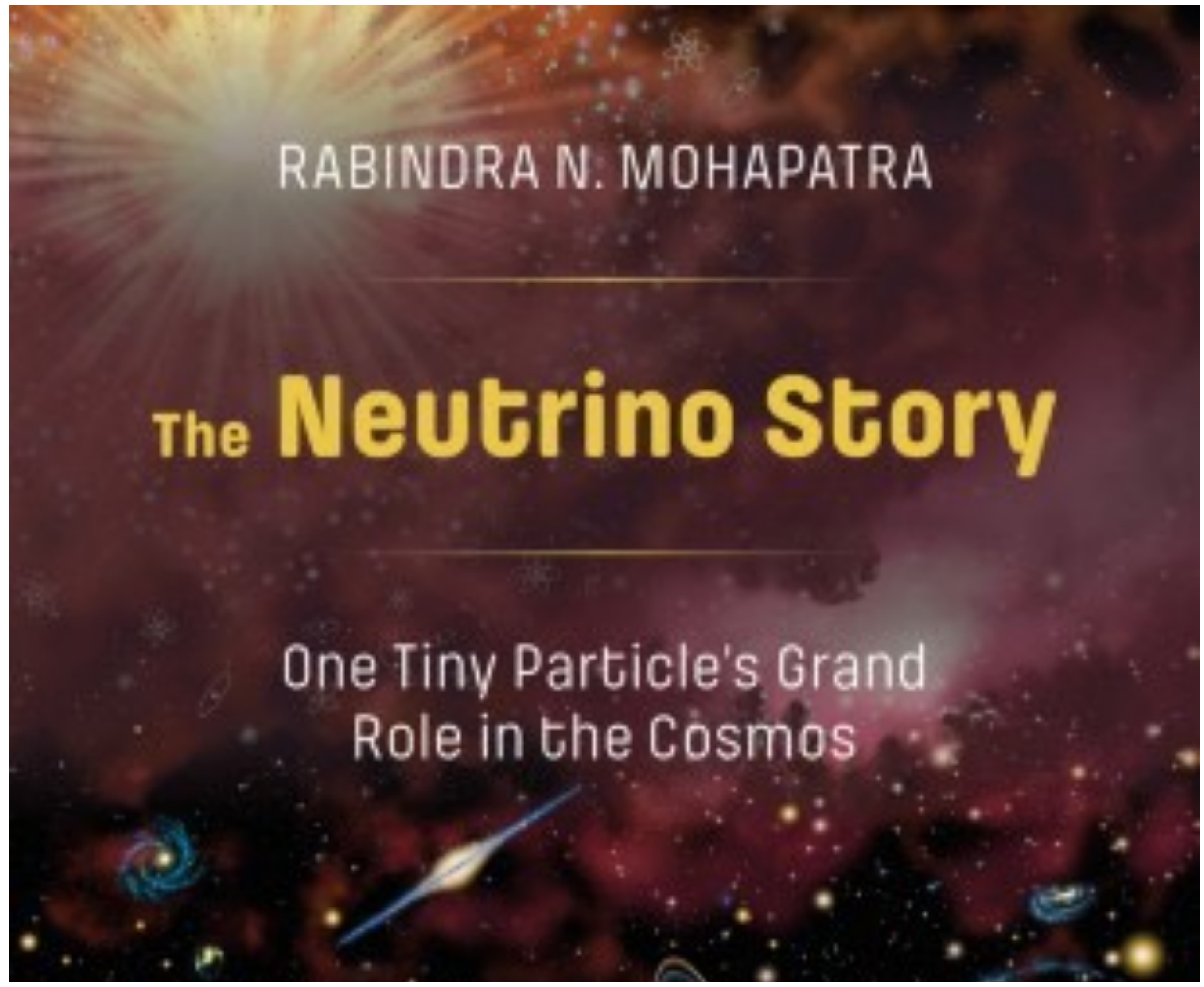


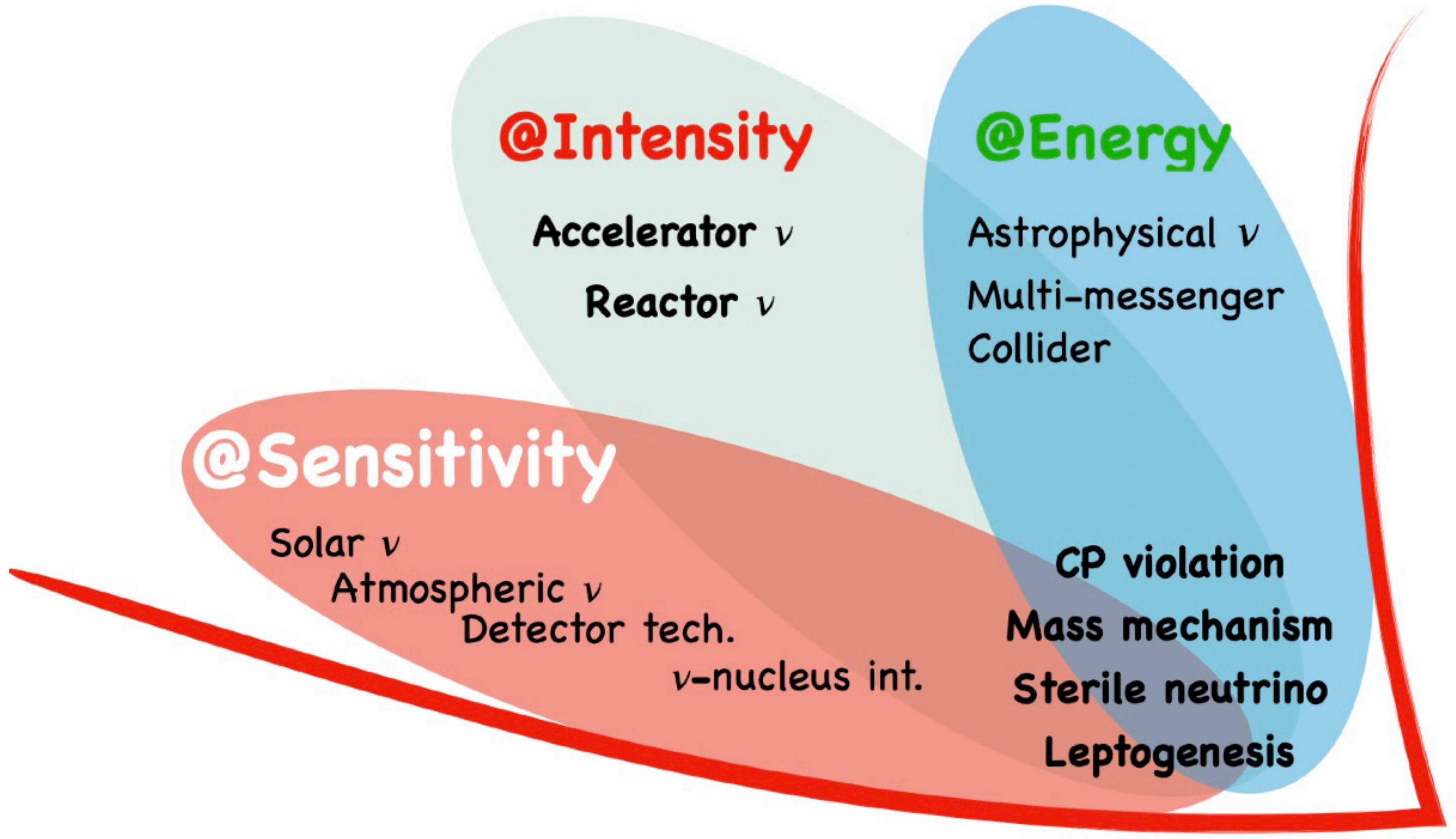
CNB = Cosmic Neutrino Background
BBN = Big-Bang Nucleonsynthesis
DSNB = Diffuse Supernova Neutrino Background

arXiv:910.11878

~10^{13}/s solar ν through your hand

Span ~ 24 order of energy magnitude





@Intensity
Accelerator ν
Reactor ν

@Energy
Astrophysical ν
Multi-messenger
Collider

@Sensitivity
Solar ν
Atmospheric ν
Detector tech.
ν-nucleus int.

CP violation
Mass mechanism
Sterile neutrino
Leptogenesis

~ 340 neutrinos/cm³, the second most abundant elementary particles, (*the most abundant massive particles*)

Significant progress from a century of neutrino study,
but…

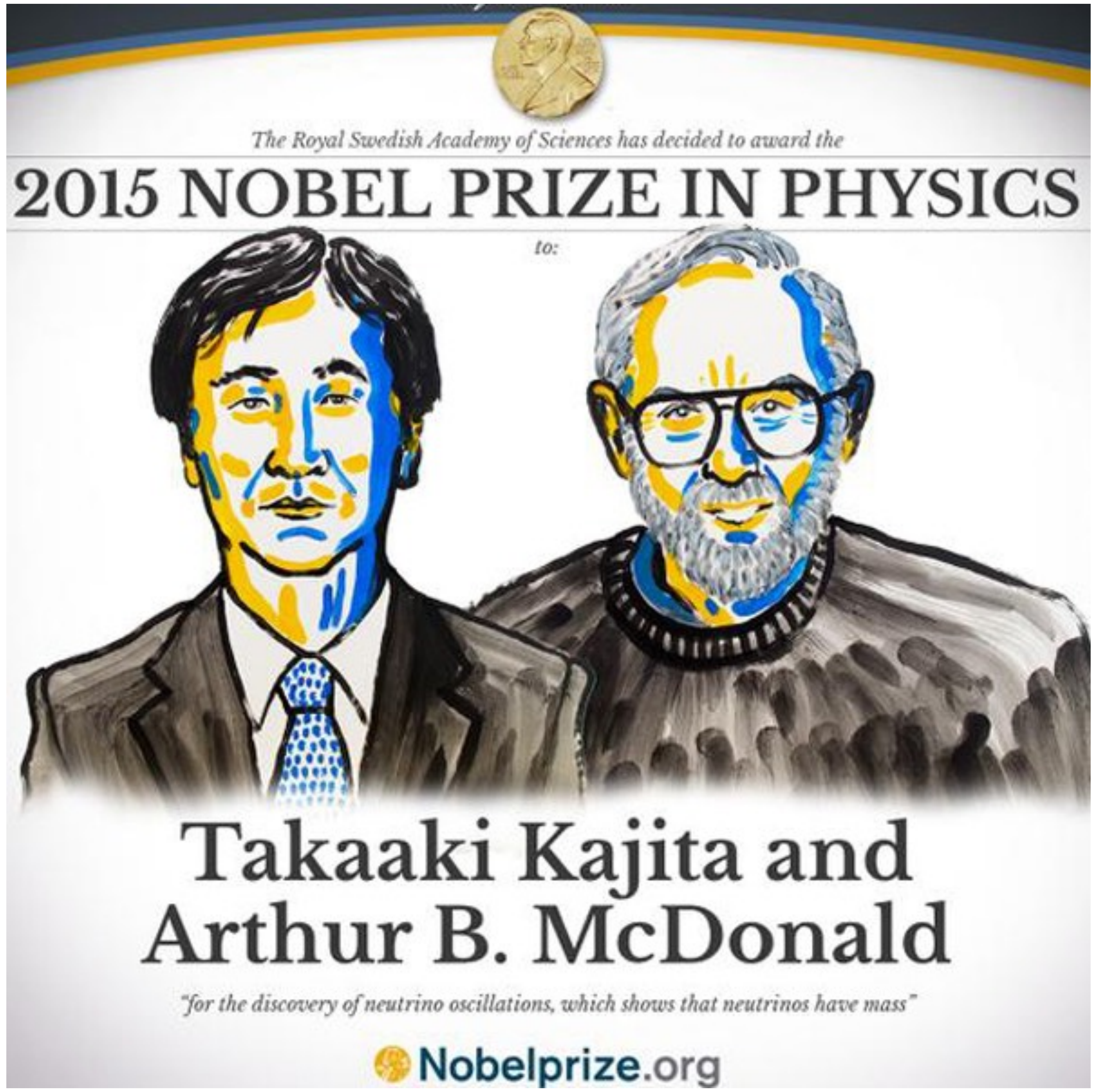
Still, neutrino is the most mysterious particles

Three known unknown in the particle physics (*at observable level*) and all relates to Neutrino

- Neutrino mass spectrum (both absolute scale and mass ordering)
- CP-violation phase in the leptonic mixing matrix
- Whether the leptonic mixing angle θ_{23} maximal or not

Neutrinos are "special" particles and they may break the fundamental rules (*quantum mechanics, relativity, non-standard interaction …*).

Neutrino oscillations: *A game-changer*



The Royal Swedish Academy of Sciences has decided to award the

2015 NOBEL PRIZE IN PHYSICS

to:

Takaaki Kajita and
Arthur B. McDonald

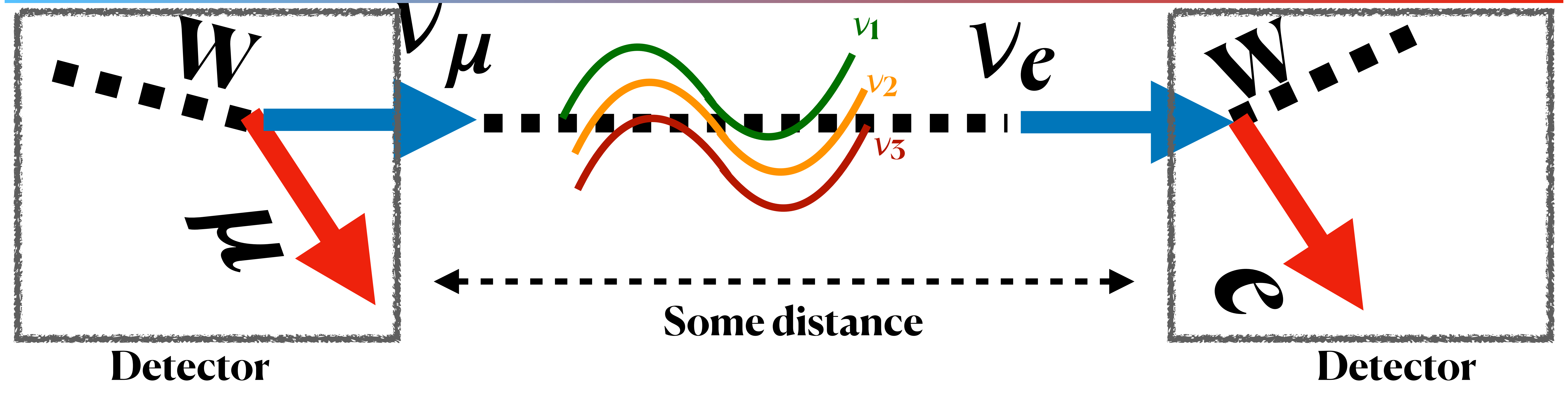
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Nobelprize.org

"...for the discovery of *neutrino oscillations*, which shows that neutrinos have mass"

Neutrino oscillations *in briefing*

Neutrino can be detected with different flavors than the original one when give it time to propagate



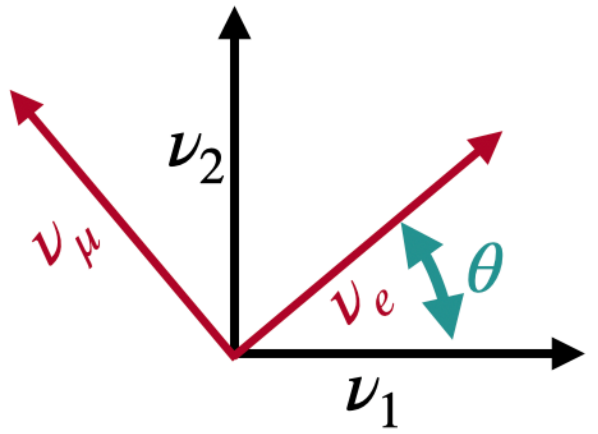
- **Neutrino oscillations** require an existence of **neutrino mass spectrum**, i.e mass eigenstate ν_i with definite mass m_i (where *i* is 1, 2, 3* at least)
- It requires flavor eigenstate with definite flavor, ν_α (where α is e, μ, τ) must be **superpositions** of the mass eigenstates, *a fundamental quantum mechanic phenomenon*

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

flavor eigenstate

PMNS leptonic mixing matrix**

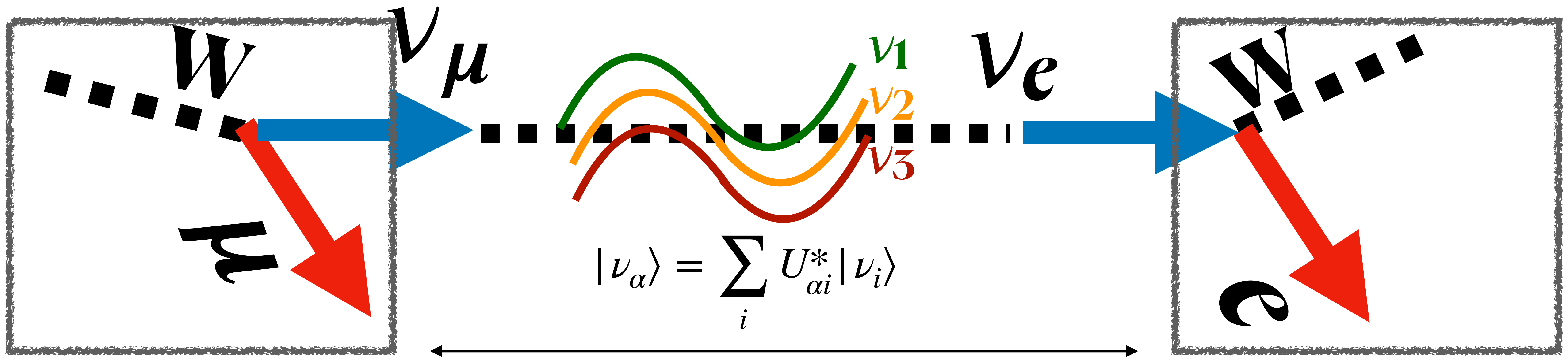
mass eigenstate



**It's still possible that there are more than 3 mass eigenstates*

***PMNS is shorted for Pontecorvo-Maki-Nakagawa- Sakata*

Neutrino oscillation: *charmed* tool to sense the Elusive



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

Detector

Some distance

Detector

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right)$$

$$+2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

where

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

neutrino energy

By measuring the oscillation pattern/probability, it enables us to unravel the neutrino mass spectrum and determine the leptonic mixing matrix

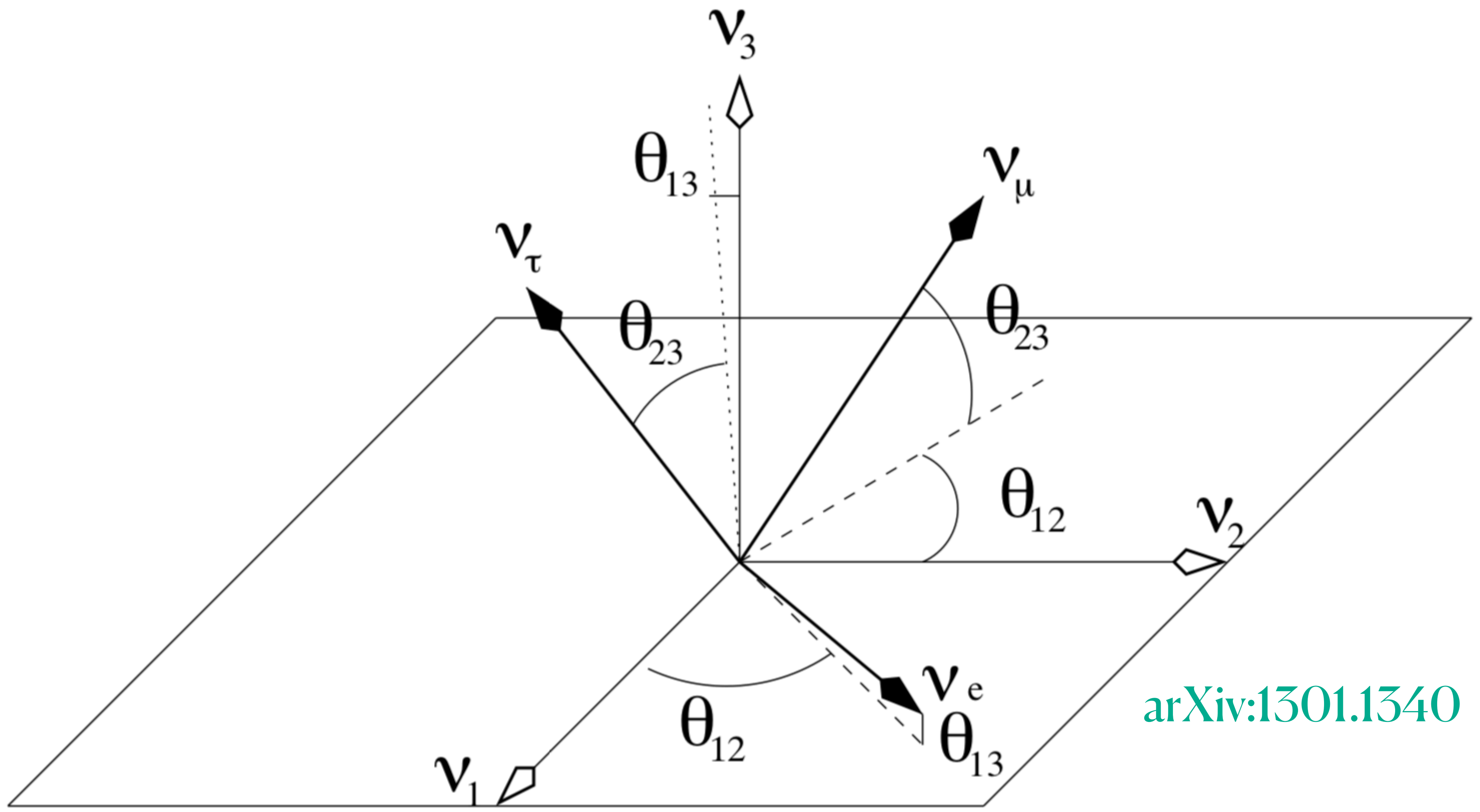
PMNS leptonic mixing matrix

Unitarity & 3 ν mass eigenstates are assumed

$$c_{ij} = \cos\theta_{ij},\ \ s_{ij} = \sin\theta_{ij}$$

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix} \text{Diag}(e^{i\rho_1}, e^{i\rho_2}, 0)$$

- U_{PMNS} is 3x3 unitary matrix and parameterized with **3 mixing angles (θ_{12}, θ_{13}, θ_{23})** and **one irreducible Dirac CP-violation phase (δ_{CP})**, *similar to CKM matrix of quark mixing*
- If neutrino is **Majorana particle**, there are **two additional CP-violation phases (ρ_1, ρ_2)**, *which play no role in neutrino oscillations*

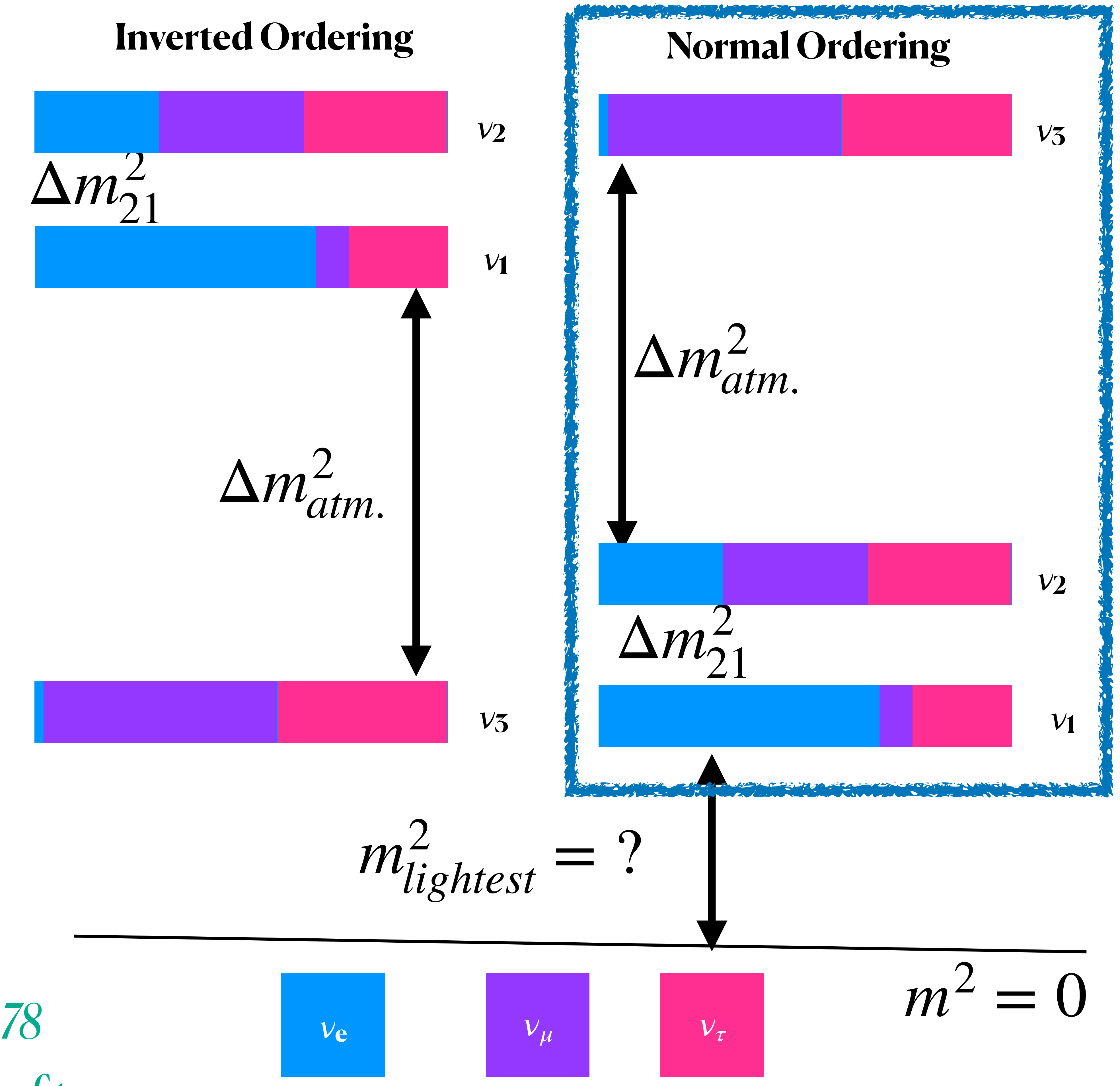


arXiv:1301.1340

Neutrino oscillation measurement can't tell whether neutrino is Dirac or Majorana particle. Unitarity of mixing matrix must be tested

Present landscape of neutrino mass fr. Neutrino Oscillation Exp.

CPT invariance is assumed



JHEP 09 (2020) 178

Global neutrino exp. fit

MINOS, T2K, NOvA; Daya Bay, RENO, Double Chooz, KamLAND; SNO, Borexino; IceCube, Super-K

There are at least two mass square levels, mean there exists at least three mass eigenstates

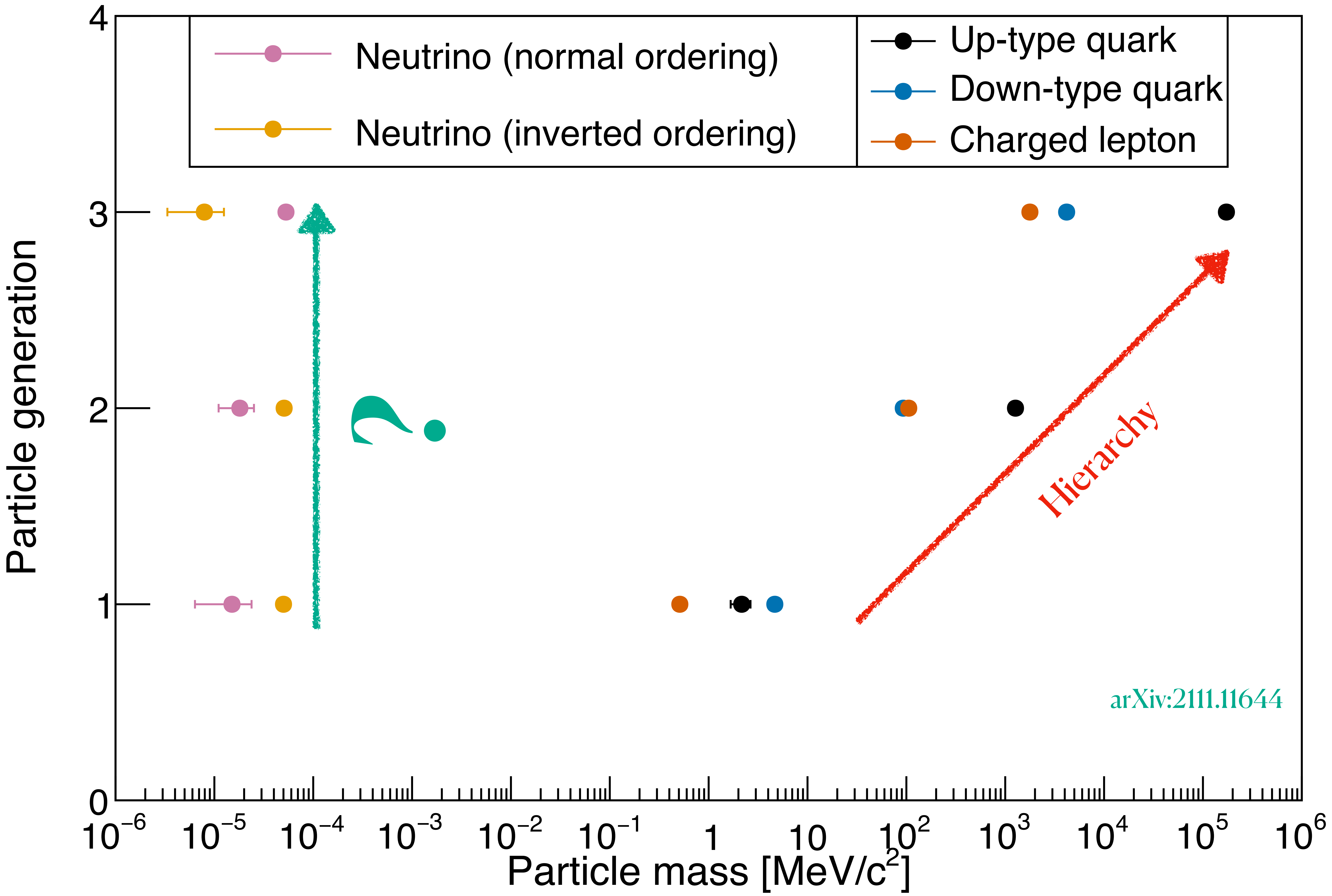
$$|\Delta m^2_{31}| = 2.514^{+0.028}_{-0.027} \times 10^{-3} eV^2$$

$$\Delta m^2_{21} = 7.42^{+0.21}_{-0.20} \times 10^{-5} eV^2$$

Do NOT know if neutrino mass spectrum is in normal or inverted ordering

Do NOT know the absolute mass either (*some constraint fr. cosmology or beta decay*)

The latest update at NEUTRINO 2022 https://neutrino2022.org
The situation is not much different.



The mass of neutrinos is much smaller than that of other charged fermions, and their spectra show no "familiar" pattern.

Present landscape of leptonic mixing parameters

PMNS matrix

$$c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

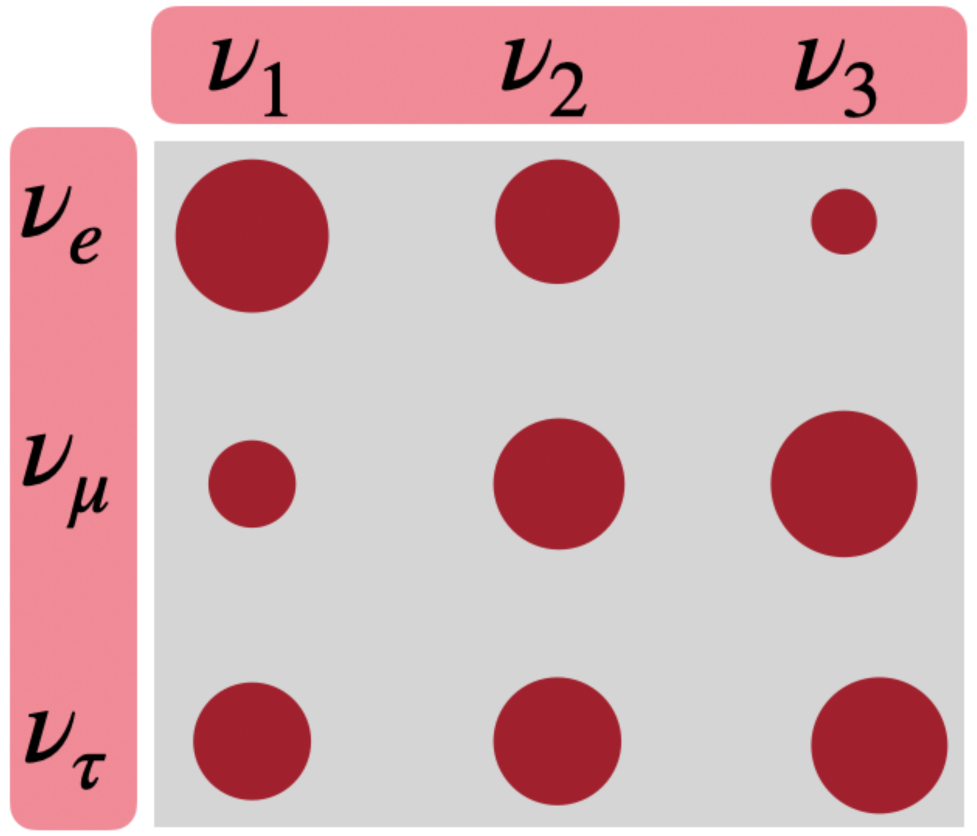
CPT invariance is assumed

$\theta_{23} = 49.0^{+1.1}_{-1.4}$

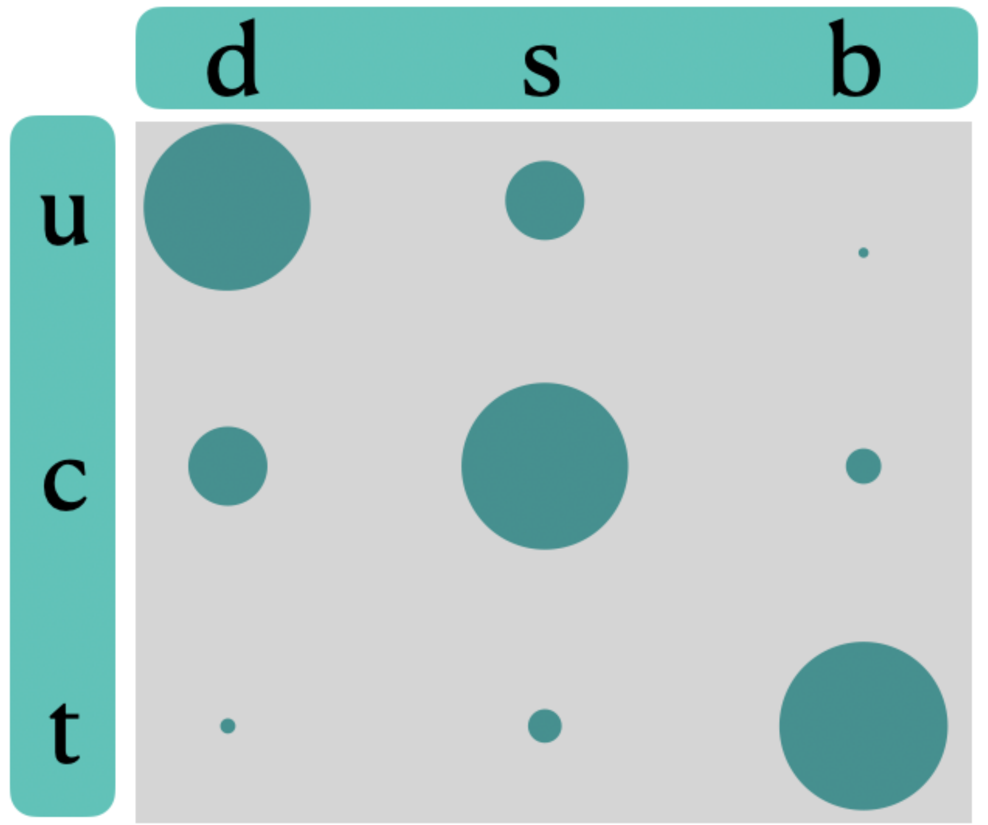
$\theta_{13} = 8.57^{+0.13}_{-0.12}$ $(\delta_{CP} = 195^{+51}_{-25})$

$\theta_{12} = 33.44^{+0.78}_{-0.75}$

*Dot area is proportional to the matrix element amplitude



Leptonic PMNS mixing matrix



Quark CKM mixing matrix

What's behind the *difference in the mixing patterns of quark and lepton* is **unknown and must be understood**

JHEP 09 (2020) 178

Global neutrino exp. fit

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The latest update at NEUTRINO 2022 https://neutrino2022.org
The situation is not much different.

CPT in neutrino oscillation

CPT in Neutrino Oscillation

$$(\nu_\alpha \to \nu_\beta) \xrightarrow{\text{CPT}} (\overline{\nu}_\beta \to \overline{\nu}_\alpha)$$

If CPT invariance is hold

$$P(\nu_\alpha \to \nu_\beta) = P(\overline{\nu}_\beta \to \overline{\nu}_\alpha)$$

If CPT invariance is violated

$$P(\nu_\alpha \to \nu_\alpha) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\alpha)$$

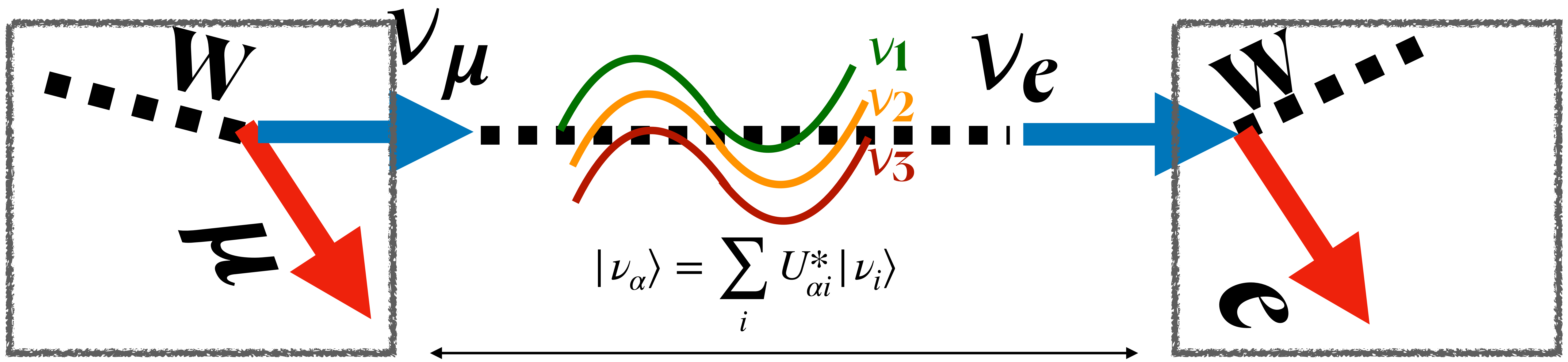
$$m_i \neq \overline{m}_i$$

(Different mass spectra)

$$U_{\alpha i} \neq \overline{U}_{\alpha i}$$

(Different mixing matrix)

Neutrino and anti-neutrino oscillations



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

Detector

Some distance

Detector

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right)$$

where

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Assume CPT invariance

for anti-neutrino, this changes to (—) →

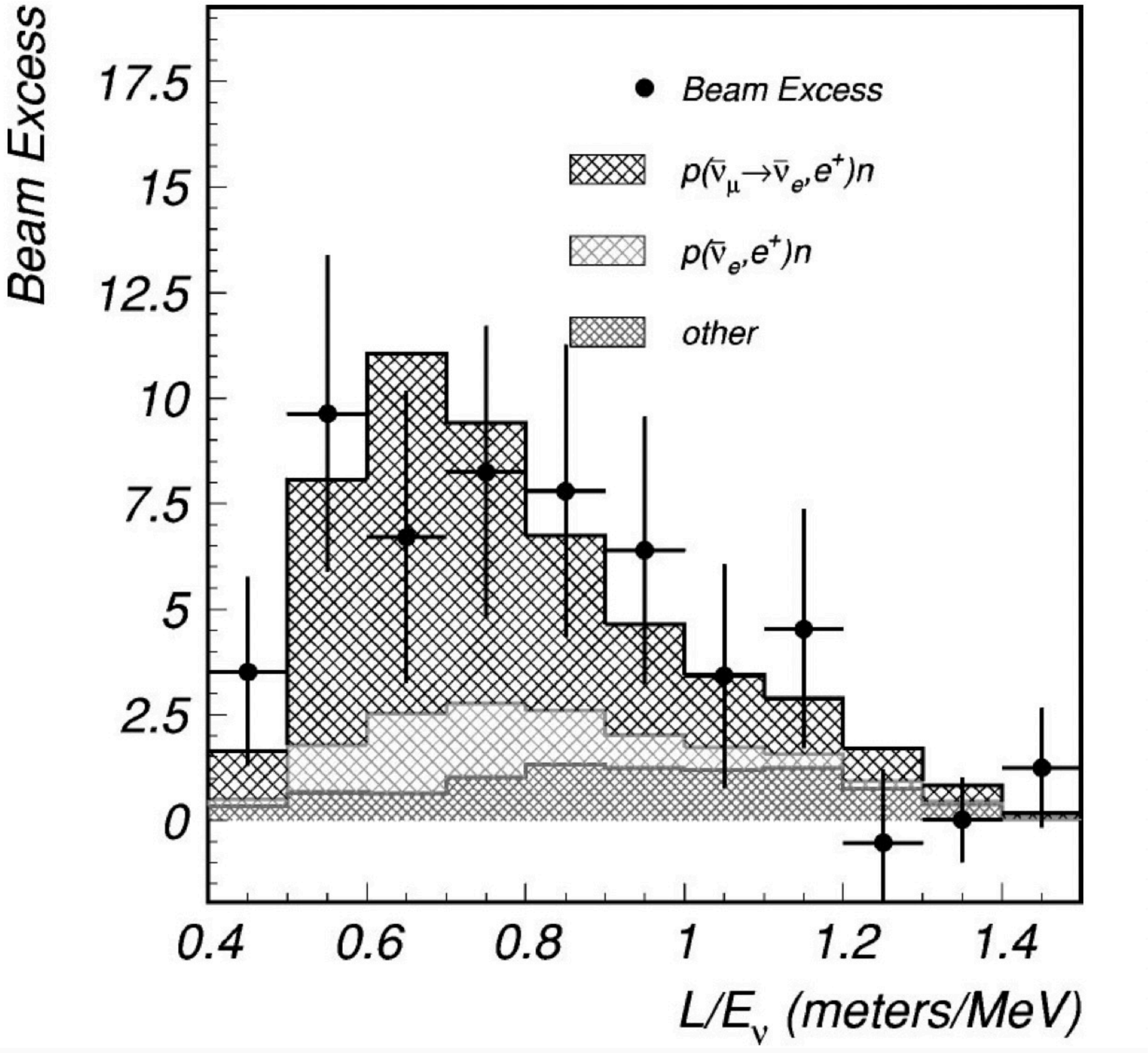
$$+2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

neutrino energy

CPT invariance is built in the Standard Neutrino Model. CPT violation, if discovered, is revolutionary!

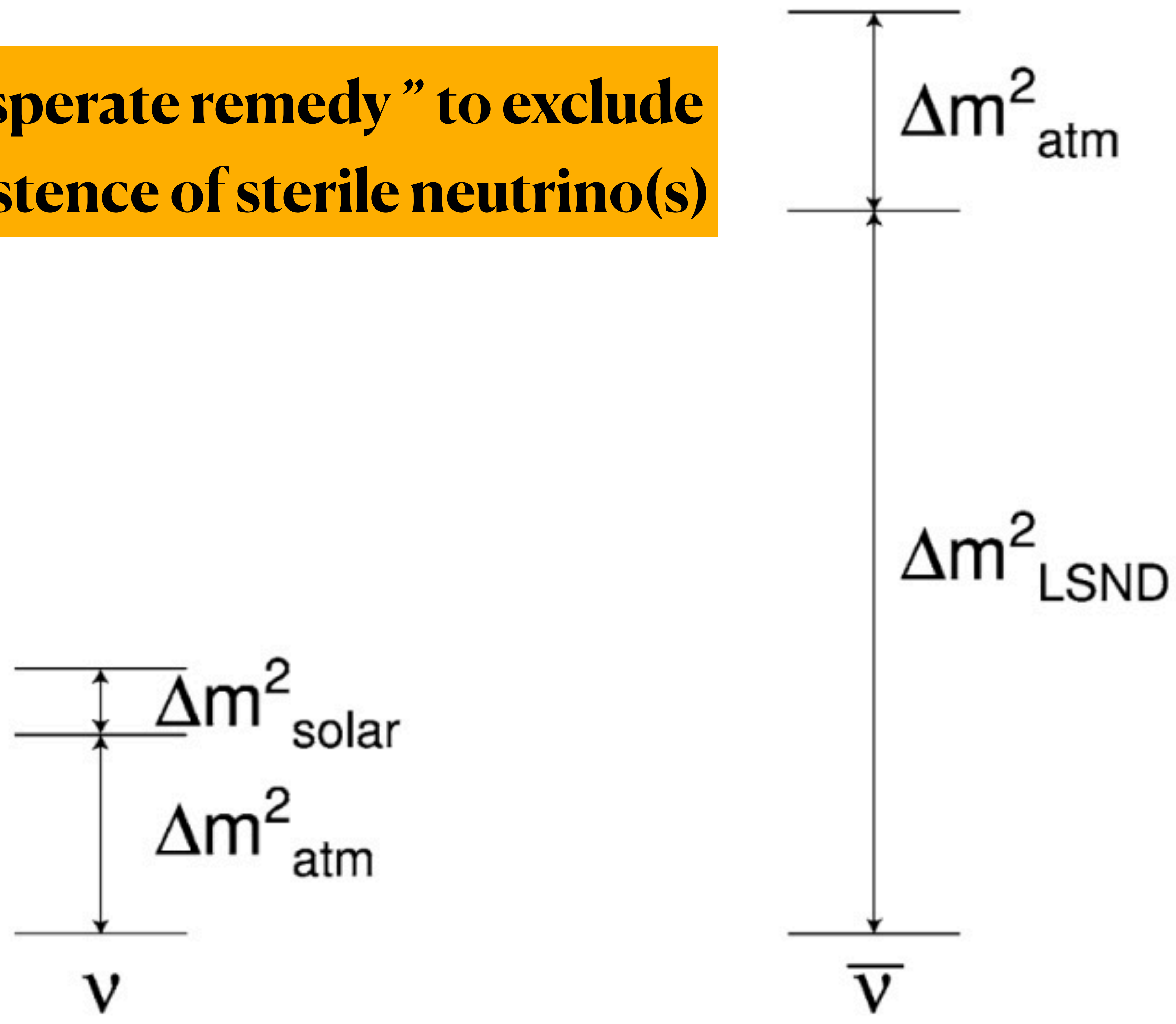
Early work: LSND anomaly and CPT-violation suggested

LSND, PRD.64.112007 (2001)



H. Murayama, PhysLett.B. 520 (2001) 263-268

"As desperate remedy" to exclude the existence of sterile neutrino(s)



*Later measurement of KamLAND with reactor antineutrinos shows that the anti-neutrinos mass spectrum here is not supported although the LSND anomaly (also MiniBooNE anomaly) is still unsolved.

Empirical approach to test CPT

If CPT invariance is violated

$$P(\nu_\alpha \to \nu_\alpha) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\alpha)$$

$f(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{21}, \Delta m^2_{31})$

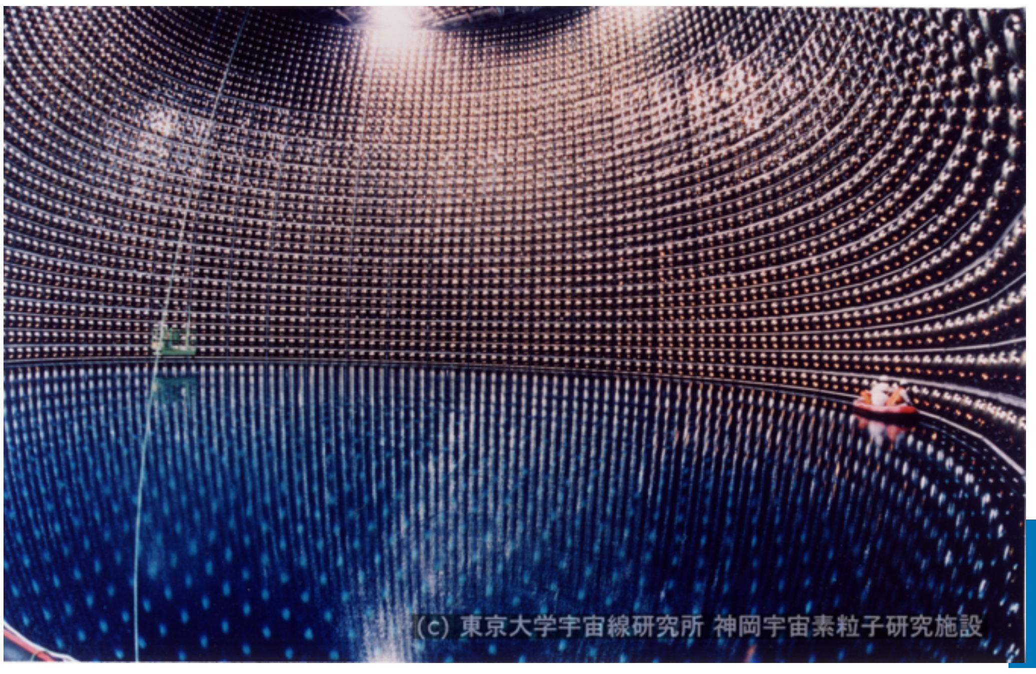
$f(\overline{\theta}_{12}, \overline{\theta}_{23}, \overline{\theta}_{13}, \overline{\delta}_{CP}, \Delta \overline{m}^2_{21}, \Delta \overline{m}^2_{31})$

- We assume neutrino and antineutrino oscillations are governed by independent parameter sets
- Some challenges in measuring precisely the neutrino/antineutrino parameters
  - Statistics is low due to weak interaction of neutrinos; understanding (natural/man-made) neutrino source
  - Detector capability to detect all flavors and measure precisely neutrino energy
  - Parameter degeneracy presented in oscillation probability (*e.g different parameter sets give same probabilities*)
  - Each measurement is sensitive to a subset of parameters, not all; few channels can be measured

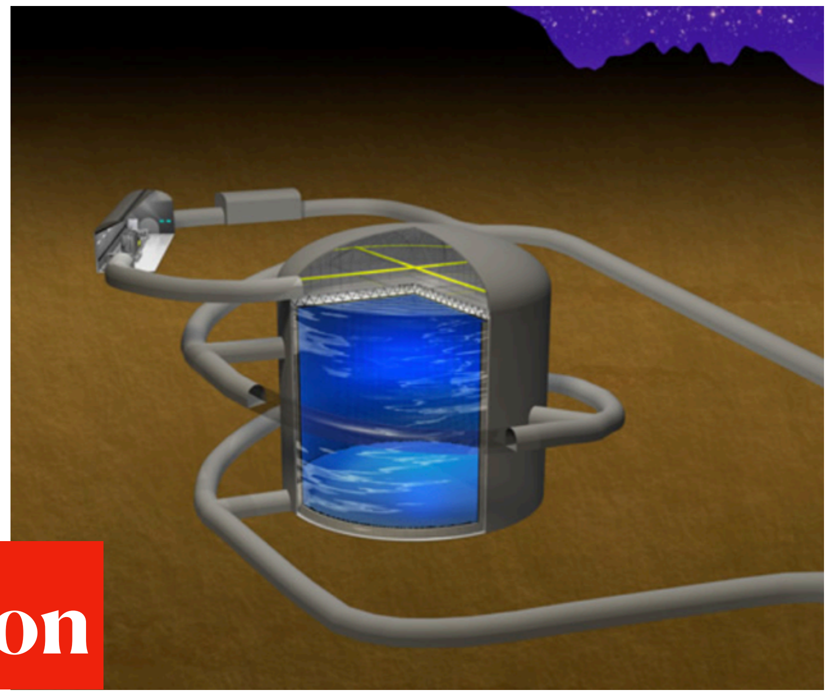
Generations of Accelerator-based Long-baseline Exp.

50 kton

K2K, JP (1999-2004)



T2K (-II) , JP(2010-)



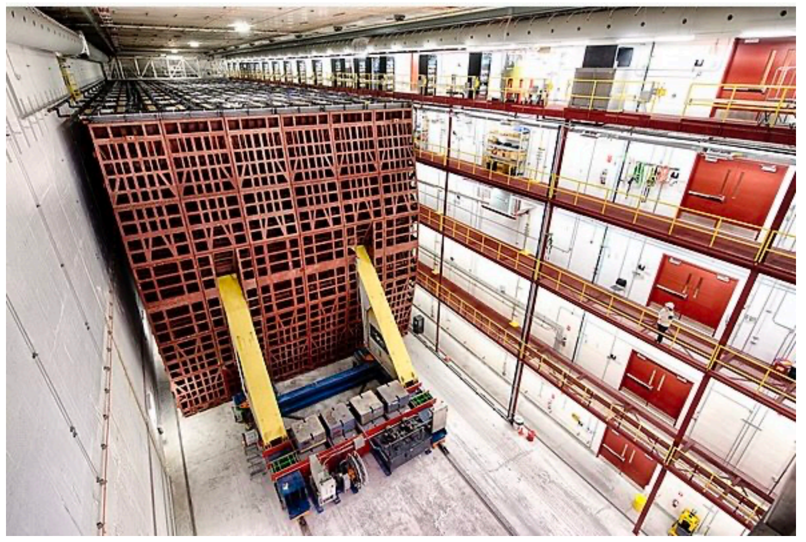
187 kton

Hyper-K , JP(~2027 -)

2000 **2010** **2030**

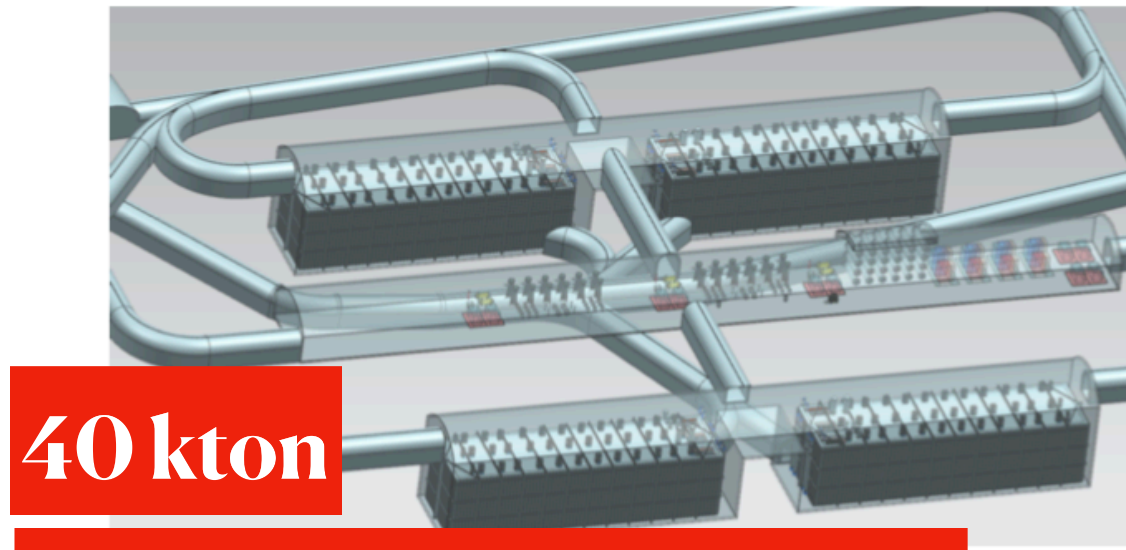
5.4 kton

MINOS(+), US (2005-2016)



14 kton

NOvA (-II), US (2013-)



40 kton

DUNE, US (~2028 -)

- K2K confirmed the neutrino oscillations (pioneered by Super-K, SNO...)
- MINOS: measure precisely $\nu_\mu \to \nu_\mu$; indicated $\nu_\mu \to \nu_e$; 1st neutrino vs. anti-neutrino oscillations
- T2K make observation of $\nu_\mu \to \nu_e$; hint on CP violation; precision measurement w/ (anti-)neutrino
- NOvA provide evidence of $\bar{\nu}_\mu \to \bar{\nu}_e$; CP search; precision measurement
- Hyper-K/DUNE for definite answers for last 3 unknowns in neutrino oscillation and beyond

Four main measurement channels

$$P(\nu_\mu \to \nu_\mu) \sim 1-\Big(\underbrace{\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}}_{\text{Leading-term}}+\underbrace{\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}}_{\text{Next-to-leading}}\Big)\cdot\sin^2\frac{\Delta m_{31}^2\cdot L}{4E}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & \boxed{4c_{13}{}^2 s_{13}{}^2 s_{23}{}^2 \sin^2\Delta_{31}} && \text{Leading term} && \boxed{\theta_{13}} \\ & +8c_{13}{}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} && && \boxed{\text{CPC}} \\ & \boxed{-8c_{13}{}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}} && && \boxed{\text{CPV}} \\ & +4s_{12}{}^2 c_{13}{}^2(c_{12}{}^2 c_{23}{}^2 + s_{12}{}^2 s_{23}{}^2 s_{13}{}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21} && && \boxed{\text{Solar}} \end{aligned}$$

$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$

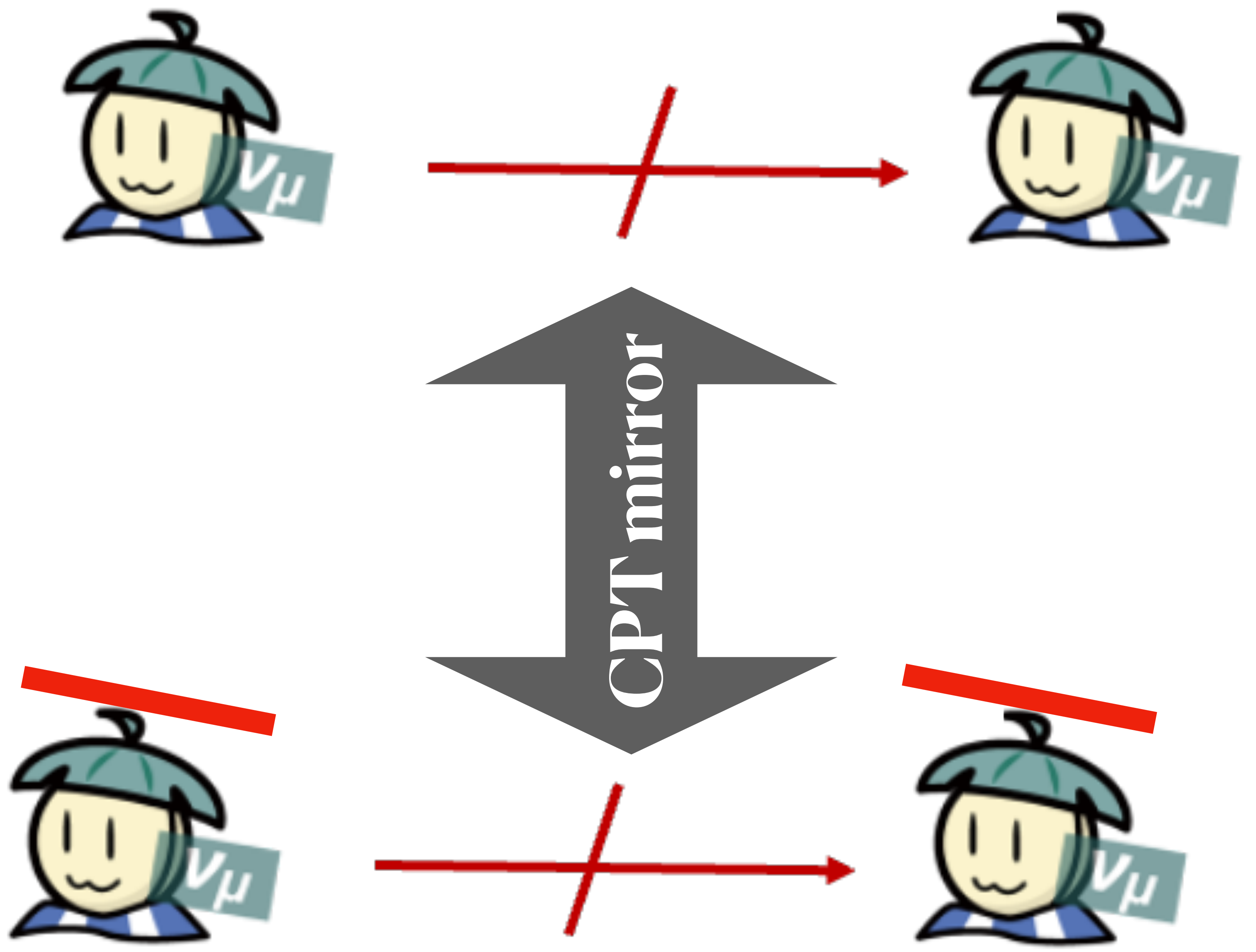
$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$

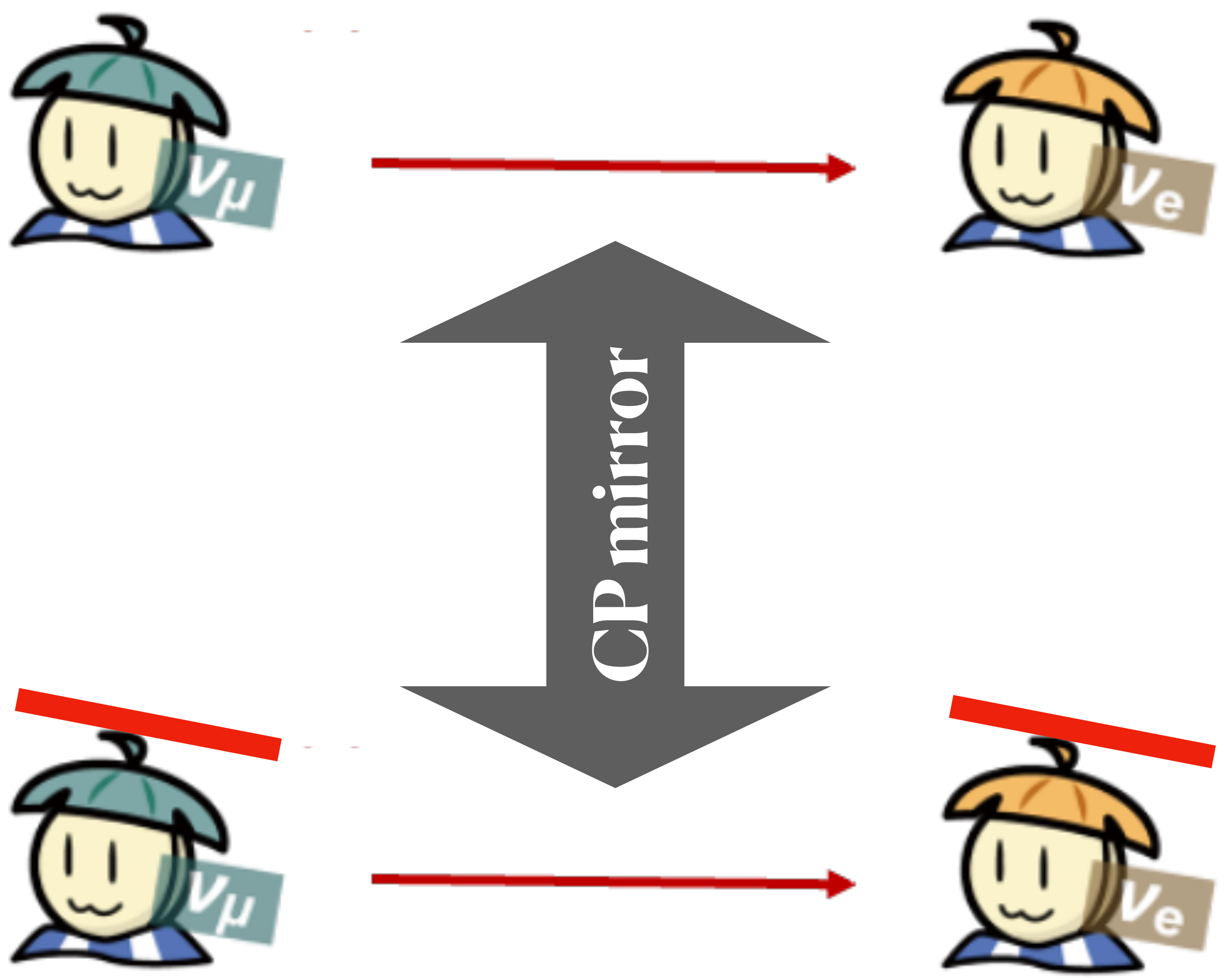
replace δ by –δ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

CP violating term introduced by interference among three-flavor mixing

Neutrinos

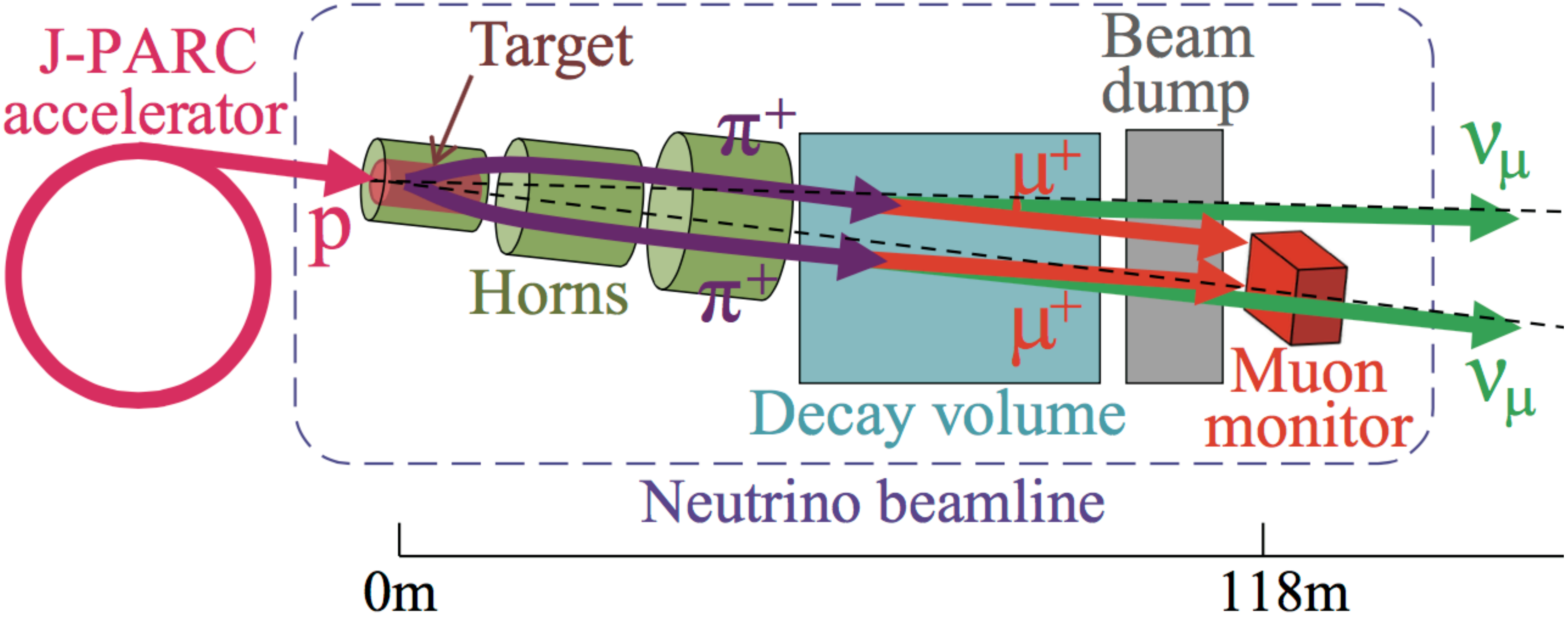
Anti-Neutrinos





*Focus on accelerator-based neutrino experiments

Magnetic horn system is essential



Flexibility to change the horn current → capability to select the meson charge → allow to produce highly pure of neutrino or antineutrino

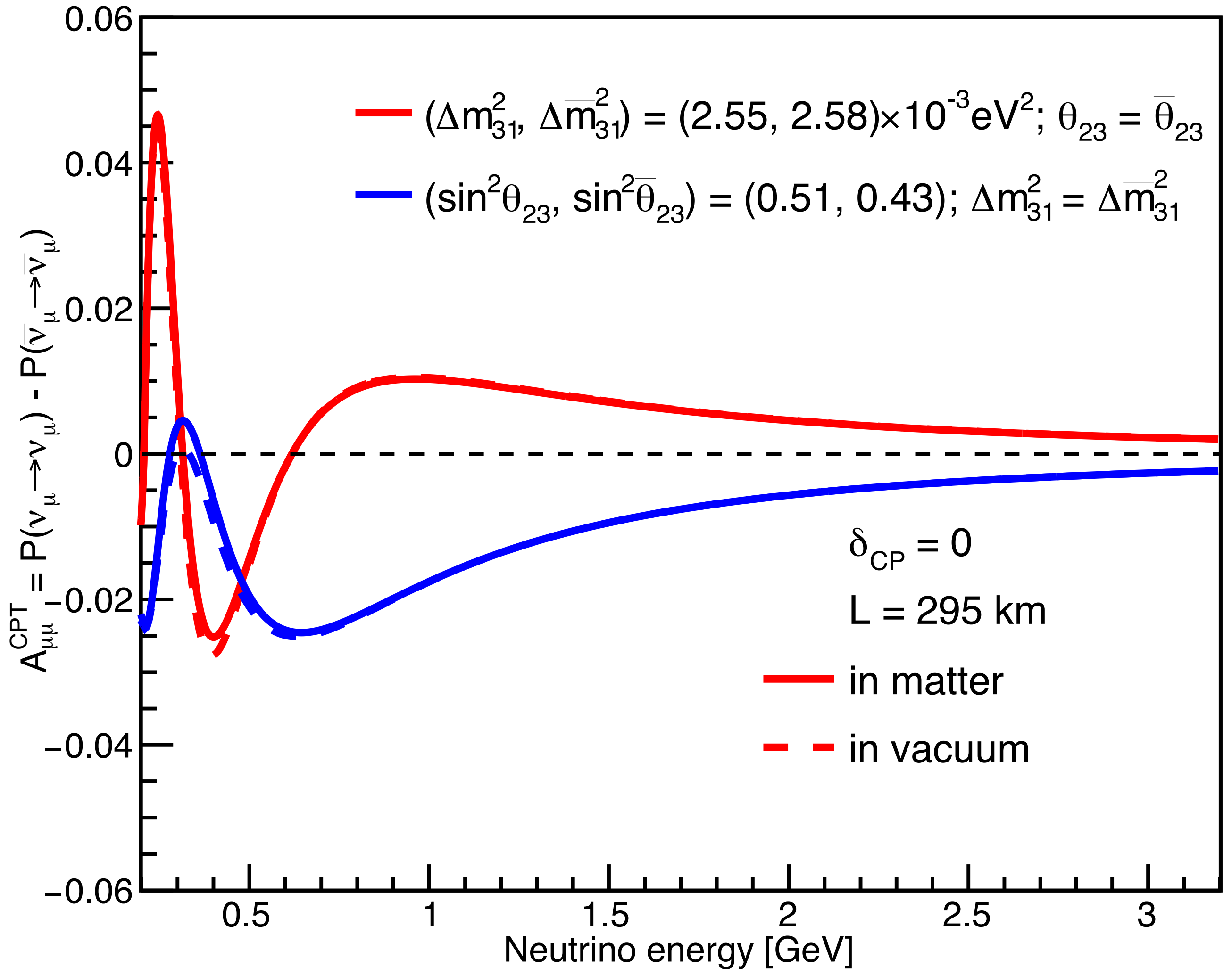
Parameterize the CPT asymmetry

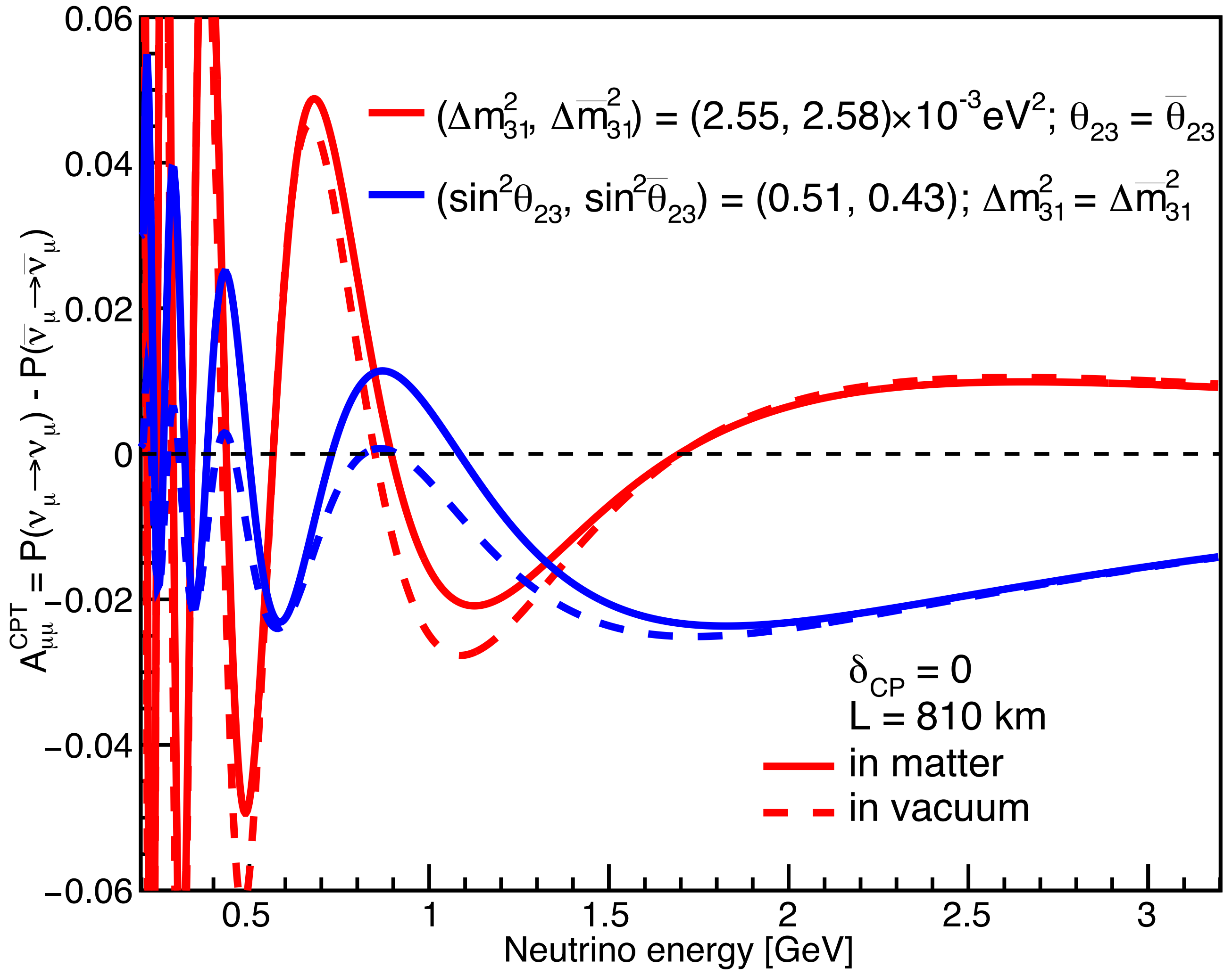
$$\mathscr{A}^{\mathrm{CPT}}_{\nu\bar{\nu}} = P\left(\nu_\mu \to \nu_\mu\right) - P\left(\bar{\nu}_\mu \to \bar{\nu}_\mu\right)$$

$$\approx \left(\delta_{\nu\bar{\nu}}(\Delta m^2_{31}),\ \delta_{\nu\bar{\nu}}(\sin^2\theta_{23})\right)$$

$$P(\nu_\mu \to \nu_\mu) \sim 1-(\underbrace{\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}}_{\text{Leading-term}}+\underbrace{\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}}_{\text{Next-to-leading}})\cdot\sin^2\frac{\Delta m^2_{31}\cdot L}{4E}$$

where $\delta_{\nu\bar{\nu}}(X) = X - \overline{X}$





- Propagation of neutrino/antineutrino in matter of the Earth induces “extrinsic” CPT effect, but insignificant w/ experimental setup of T2K and NOvA
- This channel is governed mainly by 2 parameters $\left(\Delta m^2_{31},\ \sin^2\theta_{23}\right)$; doesn’t depend on the poorly-measured δ_{CP} phase

Present global constraints on CPT

CPT constraints from neutrinos

G. Barenboim et al,
JHEP 2020 (2020)

at 3σ C.L. :

$$|\,\delta_{\nu\overline{\nu}}(\Delta m^2_{31})\,| < 2.5\times10^{-4}\ \mathrm{eV}^2$$

$$|\,\delta_{\nu\overline{\nu}}(\sin^2\theta_{23})\,| < 0.19$$

One of the best CPT constraints in neutral kaon system

$$\left|\frac{m(K^\circ)-m(\overline{K}^\circ)}{m_K}\right| < 6\times10^{-19}\ \text{at}\ 90\,\%\ \text{C. L.}$$

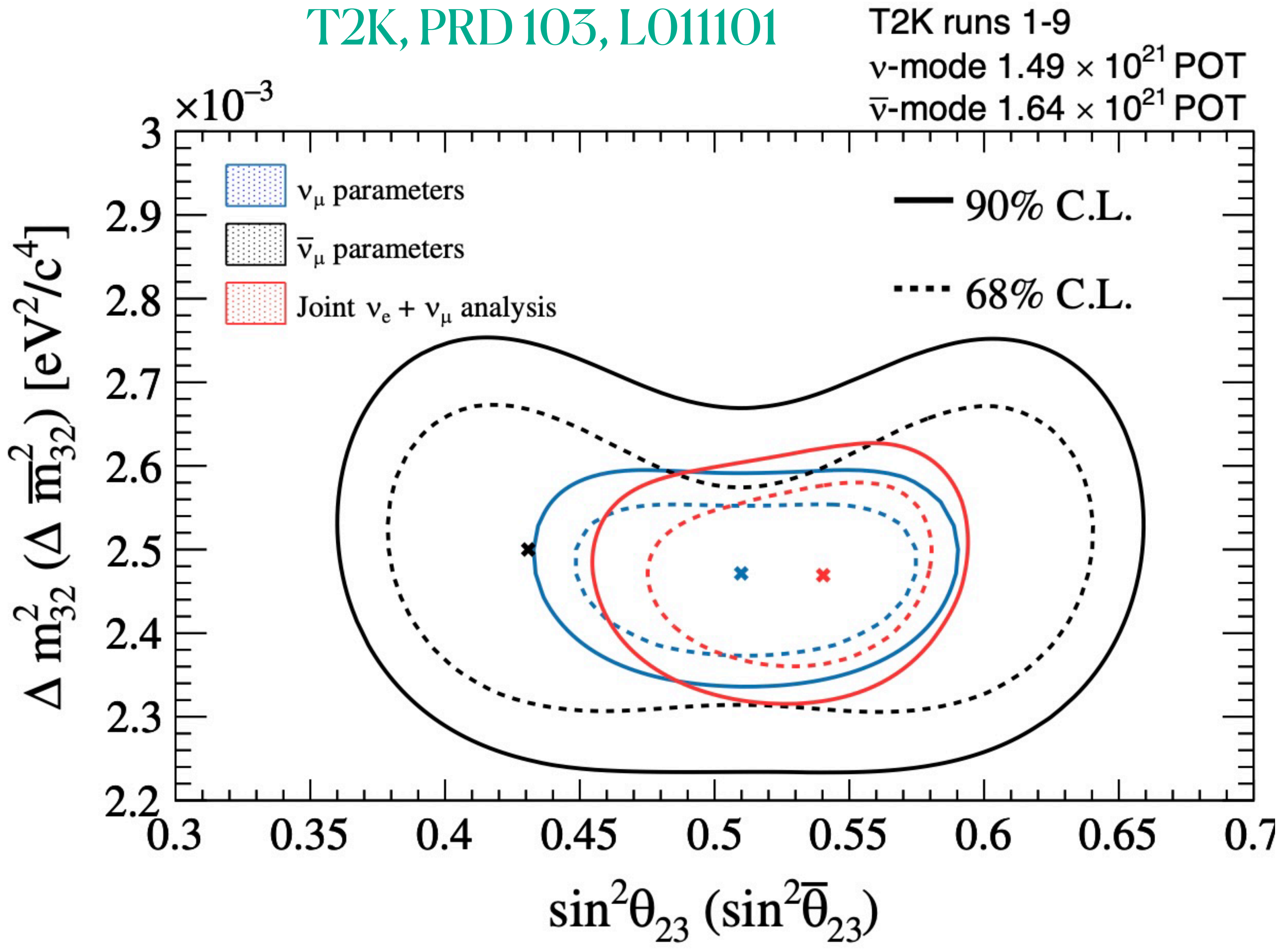
$$\Downarrow$$

$$|\,m^2(K^\circ)-m^2(\overline{K}^\circ)\,| < 0.3\ \mathrm{eV}^2\,.$$

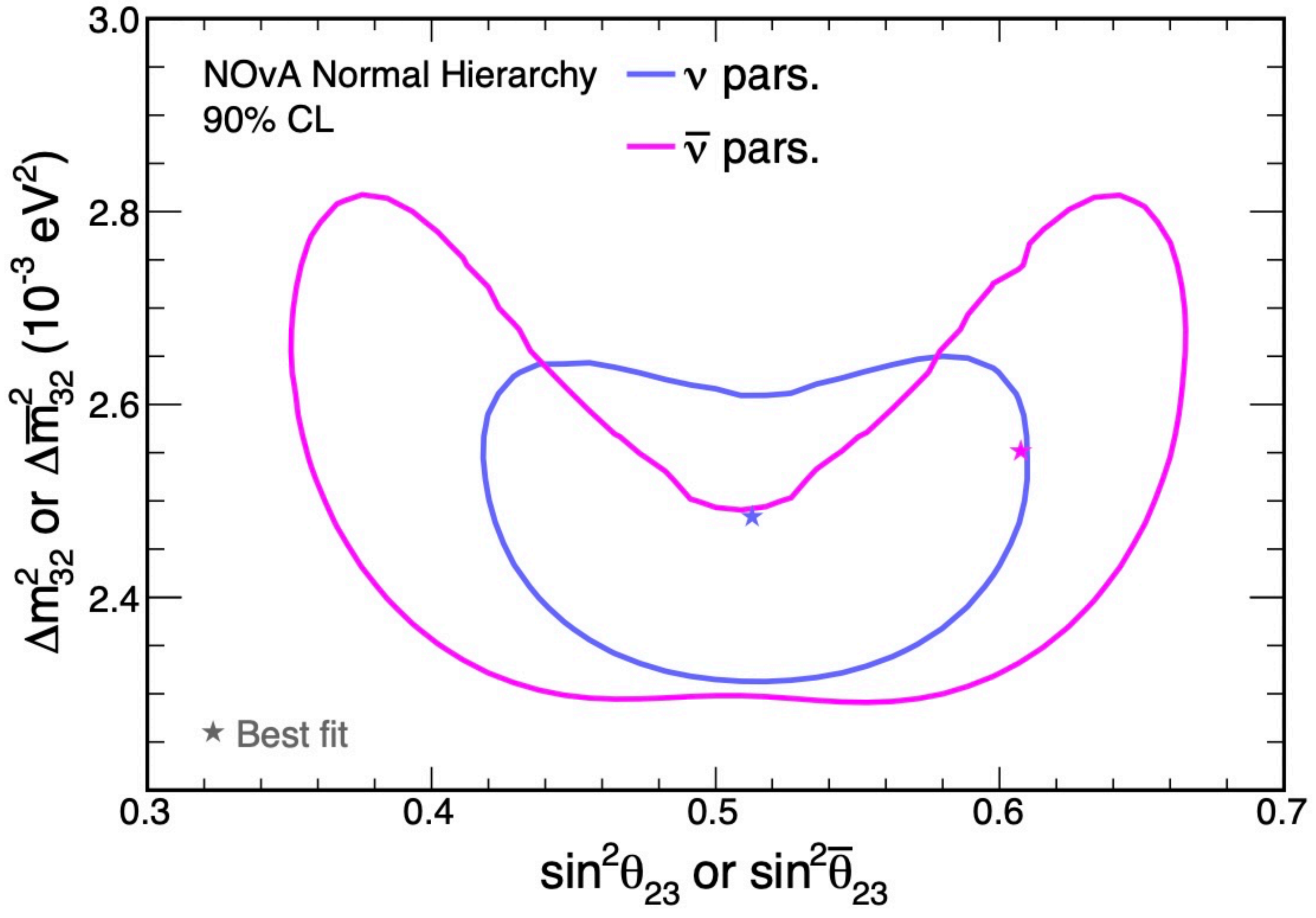
Neutrino oscillation can provide the best constraints on CPT violation in term of the mass-squared difference.

CPT testing w/ accelerator-based long-baseline exp.

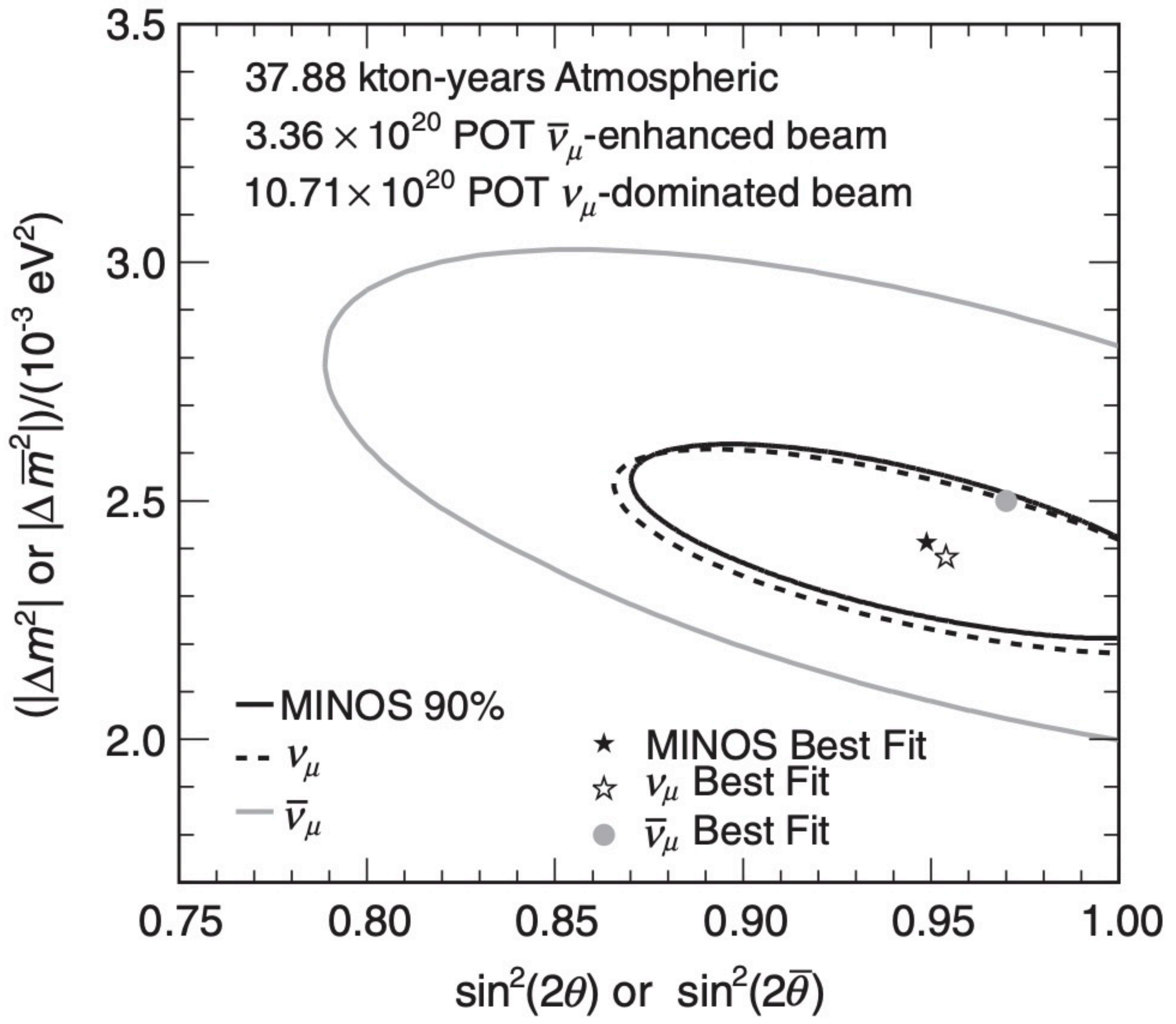
T2K, PRD 103, L011101



NOvA, D. P. Mendez thesis (2019)



MINOS exp. , PRL 110, 251801 (2013)



	MINOS(+)	T2K	NOνA	Daya Bay
$\Delta m^2_{31}/10^{-3}\text{eV}^2$	$2.48^{+0.08}_{-0.09}$	$2.55^{+0.08}_{-0.09}$	$2.56^{+0.07}_{-0.09}$	-
$\Delta \overline{m}^2_{31}/10^{-3}\text{eV}^2$	$2.55^{+0.23}_{-0.25}$	$2.58^{+0.18}_{-0.13}$	$2.63^{+0.12}_{-0.13}$	$2.53^{+0.06}_{-0.06}$
$\sin^2\theta_{23}$	$0.43^{+0.20}_{-0.04}$	$0.51^{+0.06}_{-0.07}$	$0.51^{+0.06}_{-0.06}$	-
$\sin^2\overline{\theta}_{23}$	$0.41^{+0.05}_{-0.08}$	$0.43^{+0.21}_{-0.05}$	$0.41^{+0.04}_{-0.03}$	-

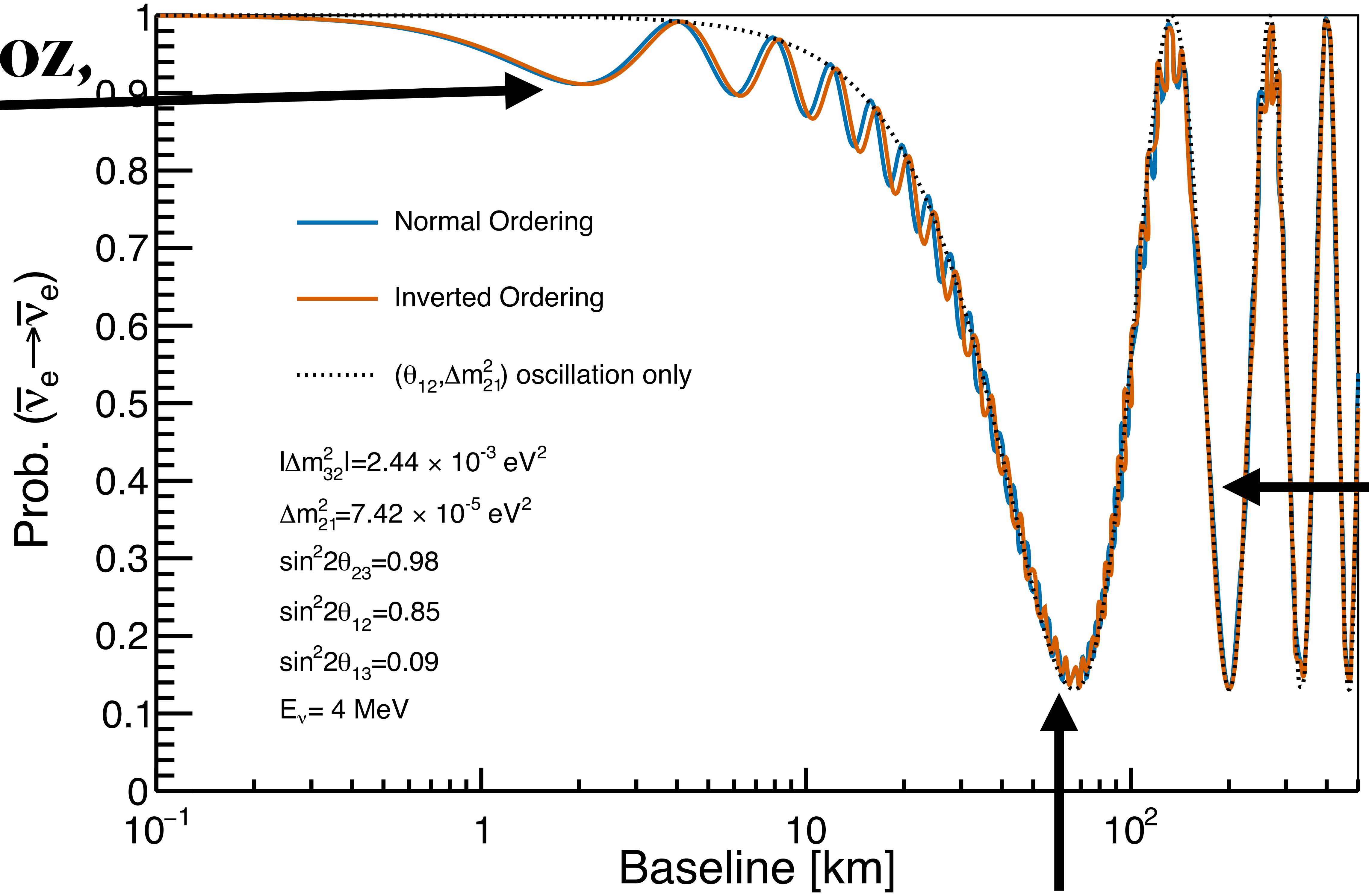
No hint for CPT violation. Precision test is dominatedly limited by statistics of anti-neutrino samples

Reactor-based experiments and JUNO

DayaBay, Double Chooz, RENO…

Precisely measure

$\bar{\theta}_{13},\ |\Delta \bar{m}^2_{32}|$

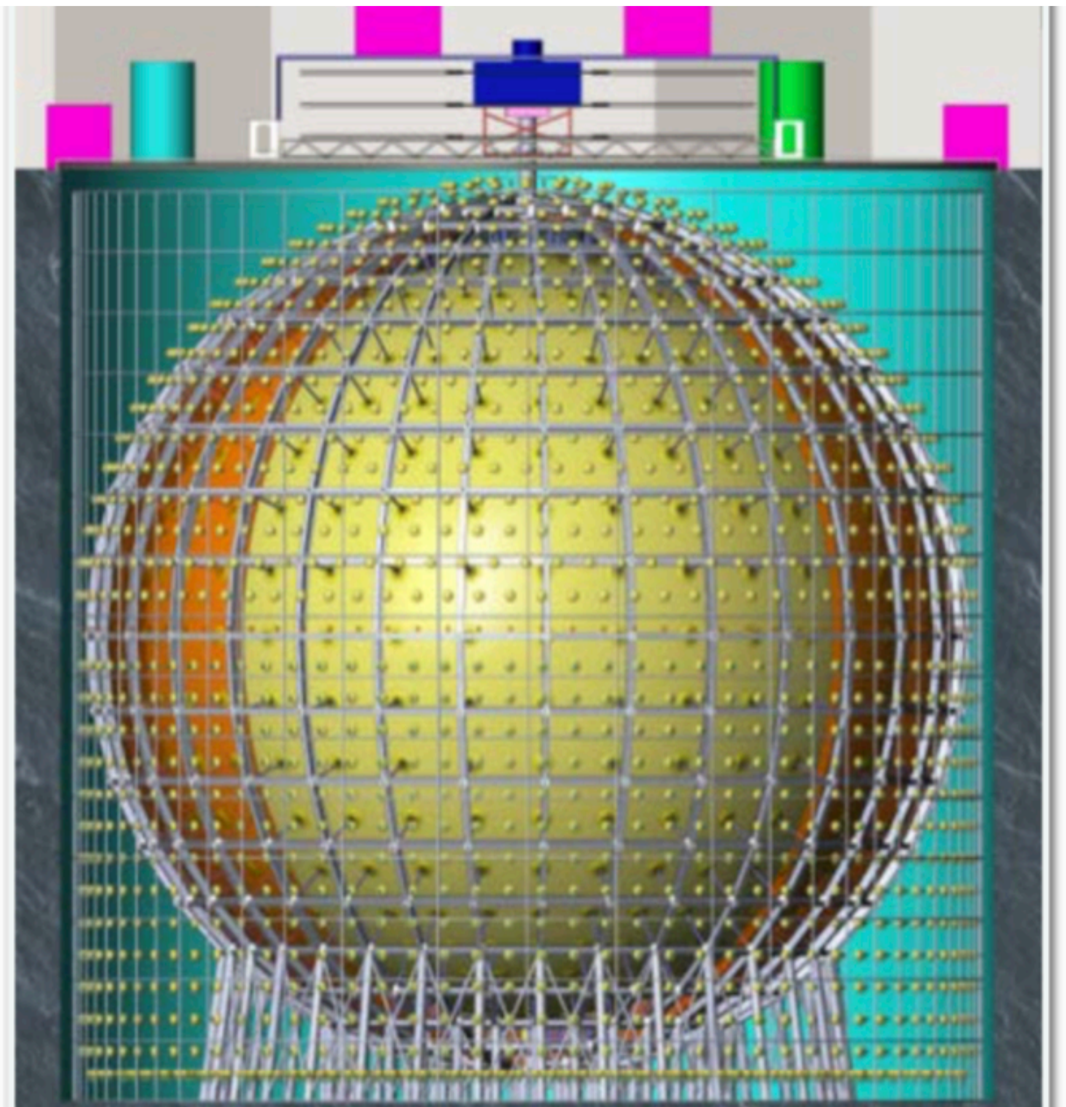


KamLAND, Japan (now KamLAND-Zen)

- First oscillation pattern (as function of energy) w/ man-made source
- Precisely measure $\Delta \bar{m}^2_{21}$
- First investigation on geoneutrino

JUNO, China ~20kton liquid scintillator detector, *plan to take data from 2024*,

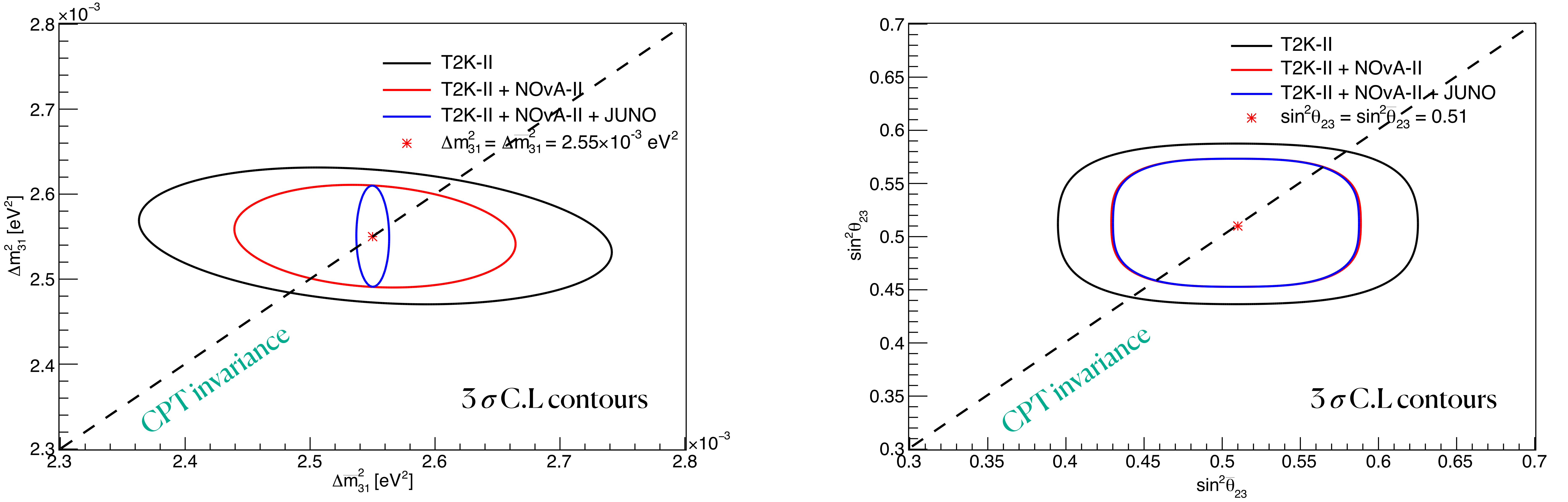
- 3σ sensitivity to mass hierarchy (after 6-year operation)
- Sub-percent precision on $\bar{\theta}_{12},\ \Delta \bar{m}^2_{32},\ \Delta \bar{m}^2_{21}$



Prospects on CPT test w/ T2K-II, NOvA extension, and JUNO

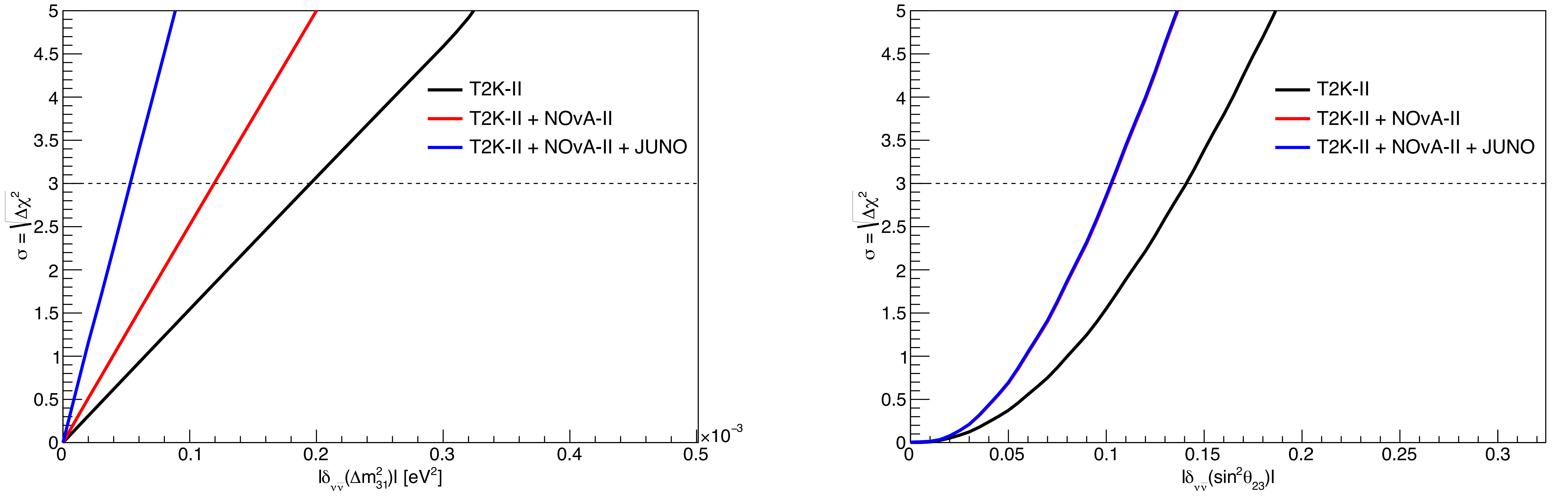
- T2K-II: T2K operation until 2027, collecting 10e21 Protons-on-target (POT) (collected 3.6e21 POT; $\nu : \overline{\nu} \sim 1.2 : 1.0$)
- NOvA extension or NOvA-II: NOvA operation until 2024, collecting 7.2e21 POT (collected 2.6e21 POT; $\nu : \overline{\nu} \sim 1.0 : 1.0$)
- JUNO: 6 years operation with 36 GW thermal reactor power

Sensitivity to CPT testing: Improvement w/ joint analysis



- It is expected that a combination of T2K-II and NOvA-II improves both the CPT-violation sensitivity in the mass-squared difference and in the in mixing angle
- JUNO will help the sensitivity in the mass-squared difference but not in the mixing angle

Possibly established bounds on CPT violation

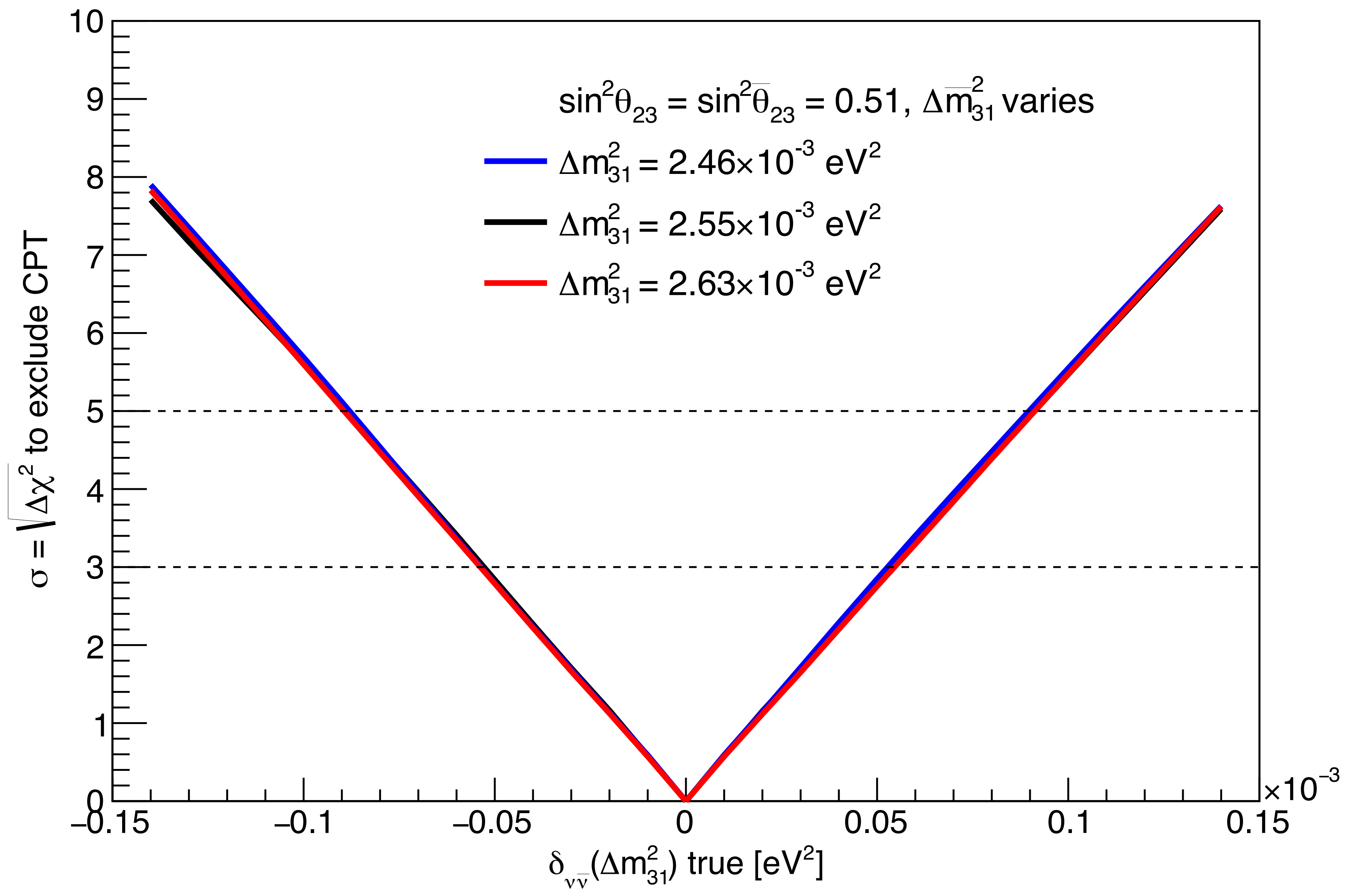


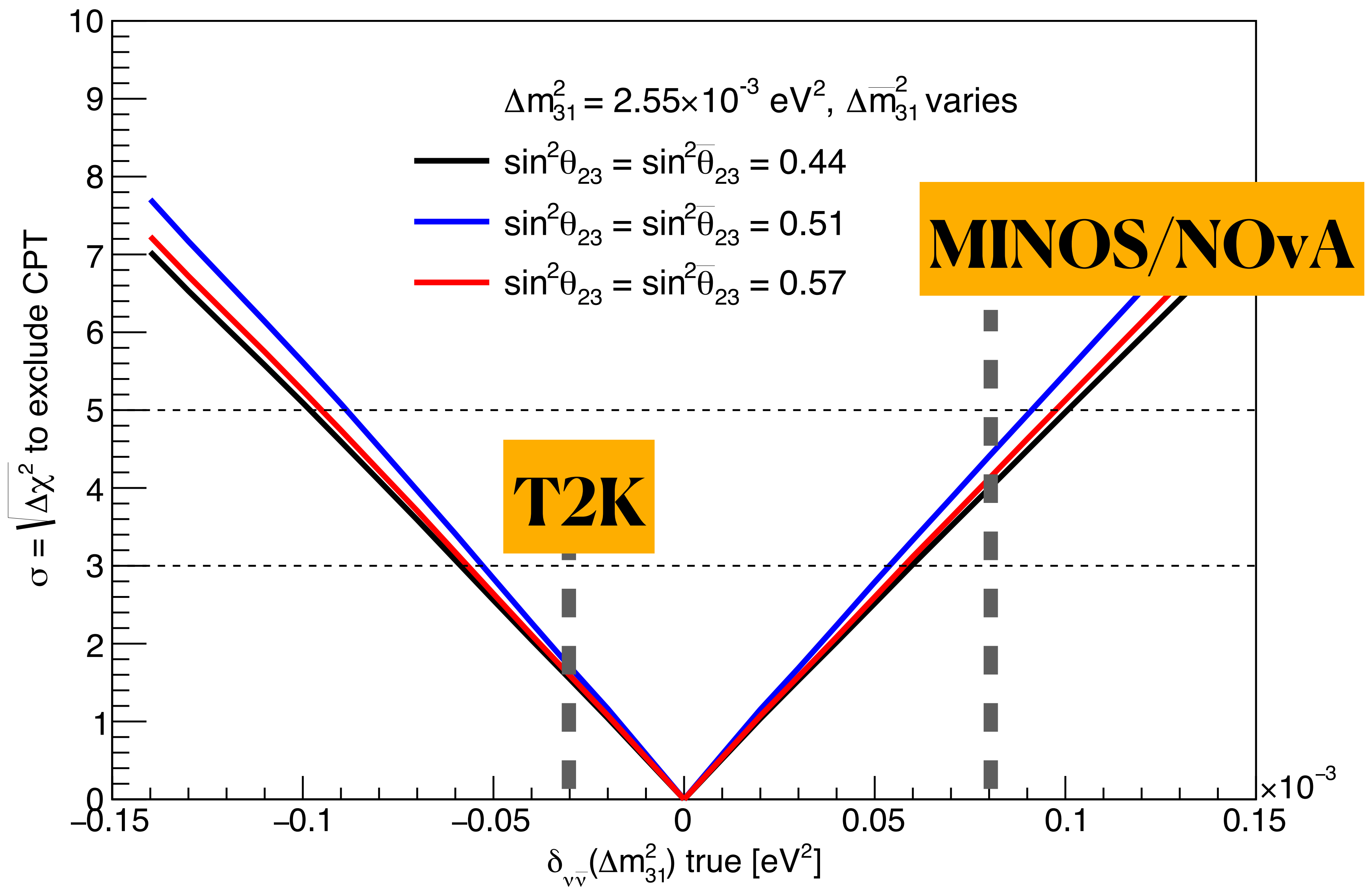
	3σ C. L. upper limits	
Experiments	$\|\delta_{\nu\bar{\nu}}(\Delta m^2_{31})\|$	$\|\delta_{\nu\bar{\nu}}(\sin^2\theta_{23})\|$
T2K-II	2.0×10^{-4} eV^2	0.14
T2K-II+NOνA-II	1.2×10^{-4} eV^2	0.10
T2K-II+NOνA-II+JUNO	5.3×10^{-5} eV^2	0.10

Ref. DUNE $\delta_{\nu\bar{\nu}}\left(\Delta m^2_{31}\right) < 8.1 \times 10^{-5}$ eV^2 at 3σ C.L.

- If CPT is not violated, expect to establish unprecedented bounds
- JUNO will help the sensitivity in the mass-squared difference but not in the mixing angle

Significance of CPT exclusion: dependence and projection



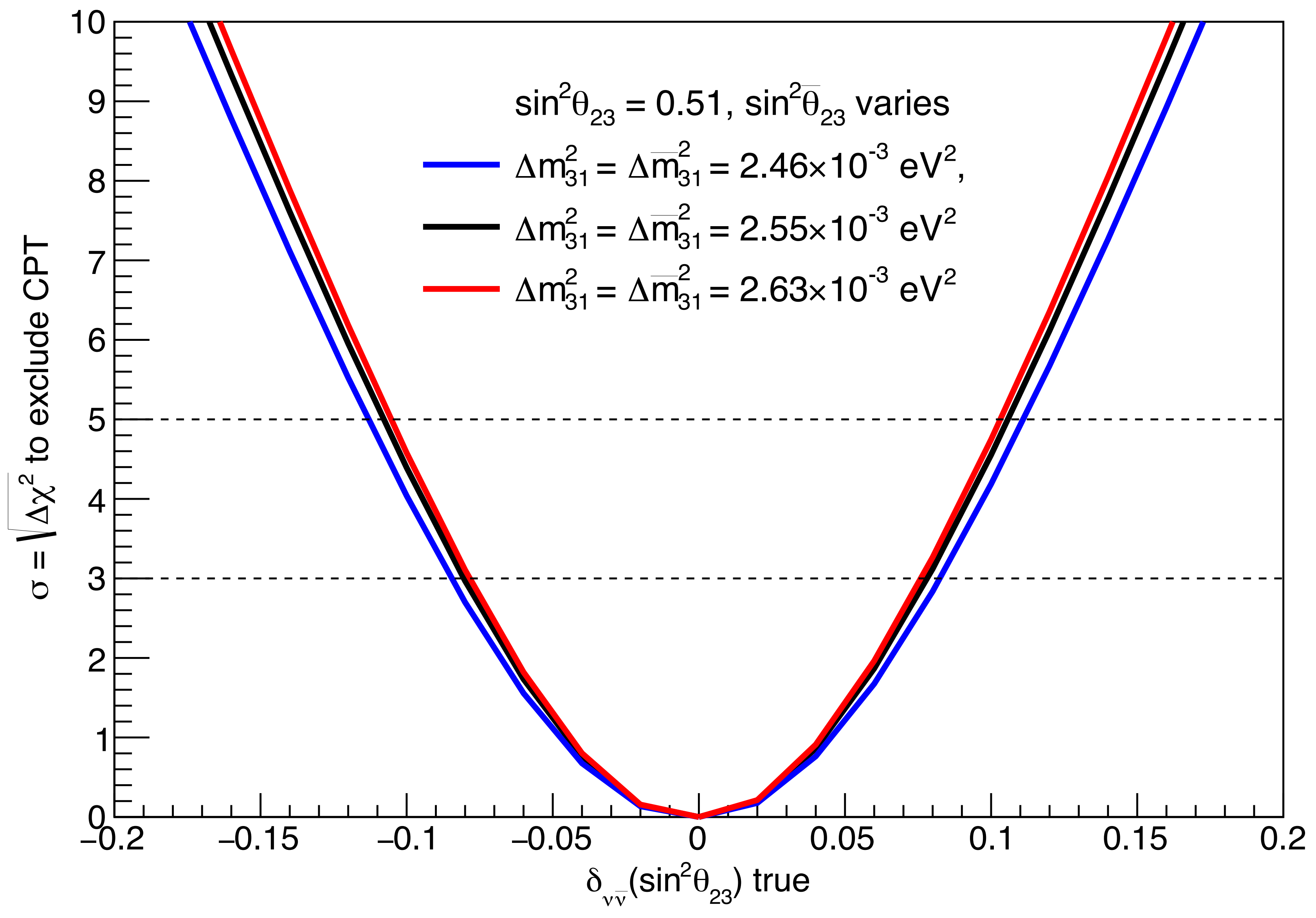


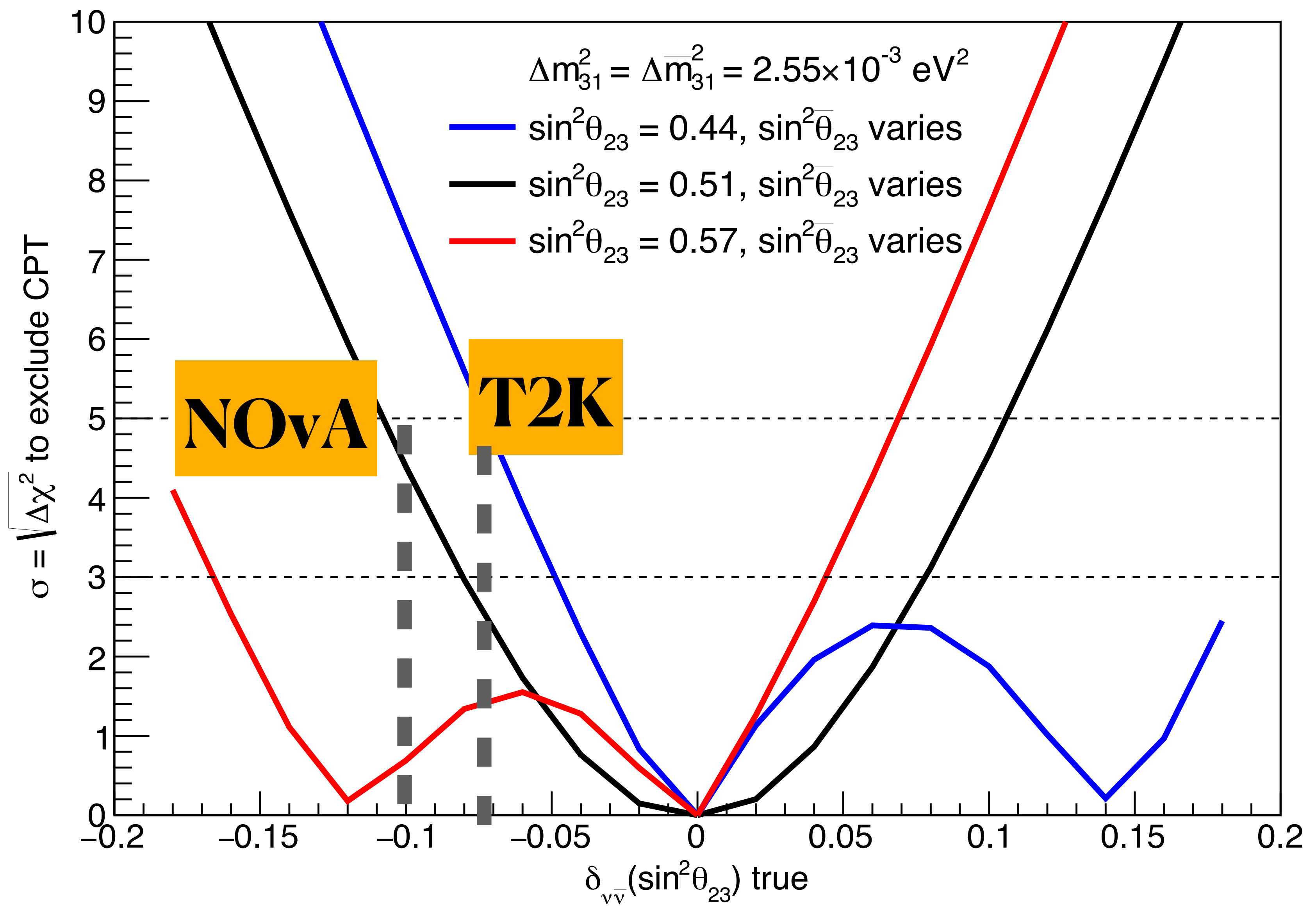
	MINOS(+)	T2K	NOνA
$\Delta m^2_{31}/10^{-3}\mathrm{eV}^2$	$2.48^{+0.08}_{-0.09}$	$2.55^{+0.08}_{-0.09}$	$2.56^{+0.07}_{-0.09}$
$\Delta\overline{m}^2_{31}/10^{-3}\mathrm{eV}^2$	$2.55^{+0.23}_{-0.25}$	$2.58^{+0.18}_{-0.13}$	$2.63^{+0.12}_{-0.13}$

- Dependence of $\delta_{\nu\bar{\nu}}\left(\Delta m^2_{31}\right)$ sensitivity on the true values of underlying parameters is small→the bound is robust against the parameter fluctuation

- If asymmetry in MINOS(+)/NOvA best fit is persisted, expect to have 4σ CPT exclusion

Significance of CPT exclusion: dependence and projection





	MINOS(+)	T2K	NOνA
$\sin^2\theta_{23}$	$0.43^{+0.20}_{-0.04}$	$0.51^{+0.06}_{-0.07}$	$0.51^{+0.06}_{-0.06}$
$\sin^2\overline{\theta}_{23}$	$0.41^{+0.05}_{-0.08}$	$0.43^{+0.21}_{-0.05}$	$0.41^{+0.04}_{-0.03}$

- Dependence of $\delta_{\nu\bar{\nu}}\left(\sin^2_{23}\right)$ sensitivity on the true values of mass-squared difference parameters is relatively small but significant on the mixing angles
- It is due to the octant degeneracy presented in the probabilities of muon (anti-)neutrino disappearance

- If asymmetry in T2K/NOvA best fit is persisted, expect to have 3σ or higher CPT exclusion

Summary

- After ~ a century of study, neutrino is still one of the most mysterious particles
- Neutrino oscillation is a charmed and powerful tool to unravel the neutrino unknown and sense the tiny non-standard effect (such as CPT)
- CPT invariance has been tested directly w/ MINOS, T2K, and NOvA. No signifiant deviation is observed
  - Statistic error in anti-neutrino data sample is the main
  - …But *already provided an encouraging upper limit on CPT in term of mass-squared difference*
- More data with T2K-II, NOvA-II (by ~2027, start of Hyper-K/DUNE) and sub-percent precision measurements from JUNO will provide *unprecedented bounds on the CPT* if no violation is discovered…
  - … or *lead to* 3σ *significance to exclude CPT if present deviation in the T2K/NOvA/MINOS best fit persists*