

## Abstract

In particle physics there exist two regions: the Standard Model which is fairly complete and the new physics sector which is completely unknown. In between and overlapping with both of these is neutrino physics. Neutrinos exist within the Standard Model but are not explained by it due to the discovery of neutrino oscillations. In this colloquium I will discuss where we stand with neutrino oscillations, where we might go with them, and how we might learn about the nature of neutrinos. I will discuss several new physics ideas such as non-standard neutrino interactions and unitarity violation from theoretical and phenomenological points of view. I will also show how neutrinos can be used as a tool to probe opaque environments.

# Neutrino Oscillations: Unveiling Mysteries

Peter B. Denton

Virginia Tech

February 5, 2025



Brookhaven  
National Laboratory

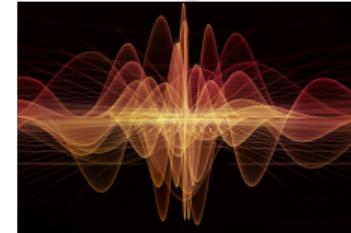


# Outline

1. Pedagogical **review** of neutrino oscillations



2. Where we are **today** with oscillations



3. What kinds of other **new physics** might be out there



4. **Alternative uses** for neutrinos



## Neutrino oscillations: how it works

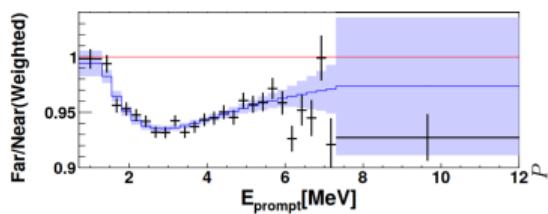


# Do neutrinos have mass?

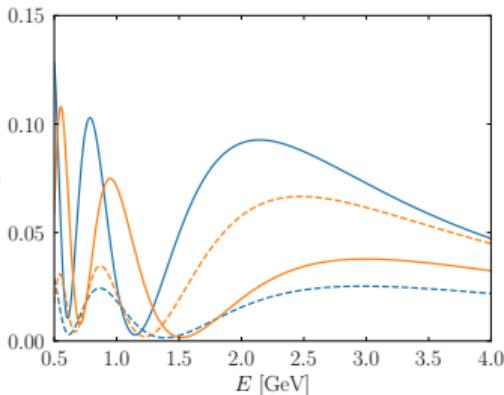
- ▶ Neutrinos seemed to be massless
- ▶ Direct kinematic searches have still not yielded any indication for a mass

KATRIN [2406.13516](#)

# Do neutrinos have mass?



Daya Bay 1809.02261

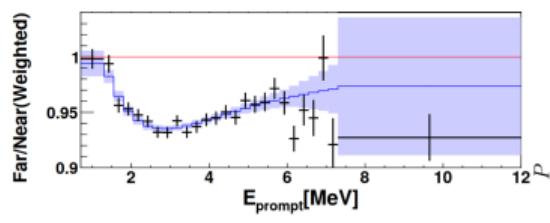


KATRIN 2406.13516

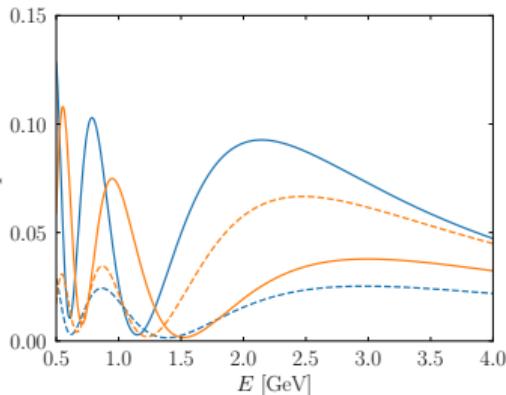
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Neutrinos oscillate!

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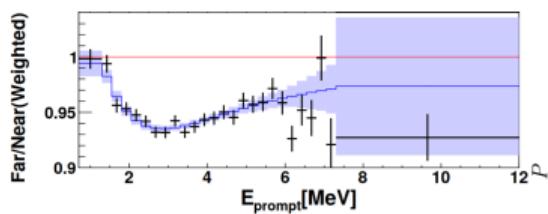
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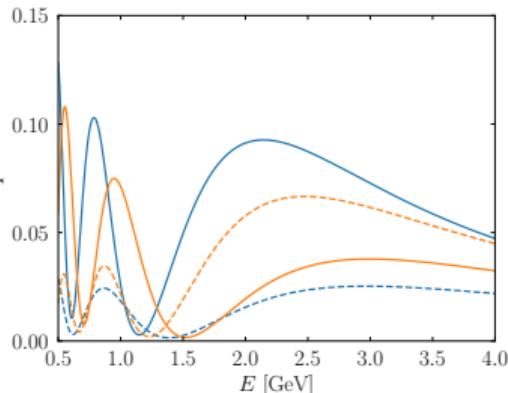
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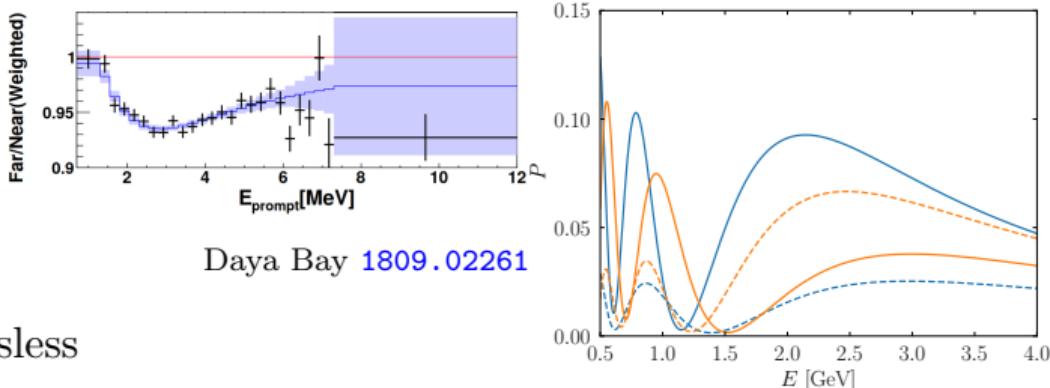
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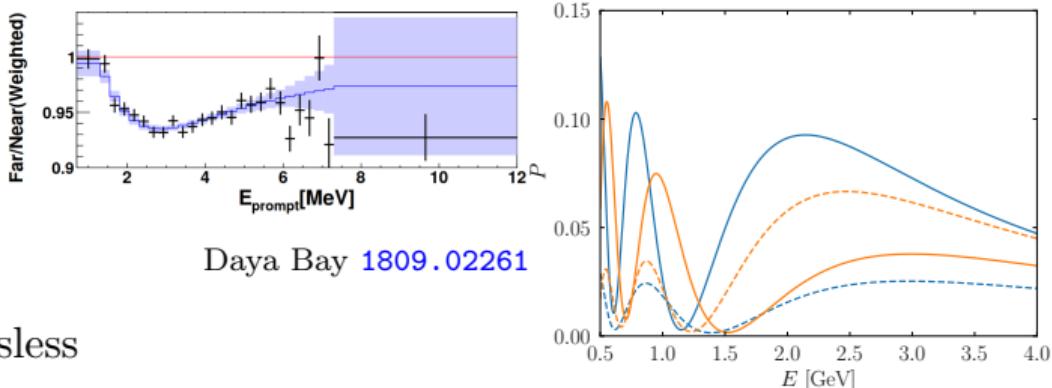
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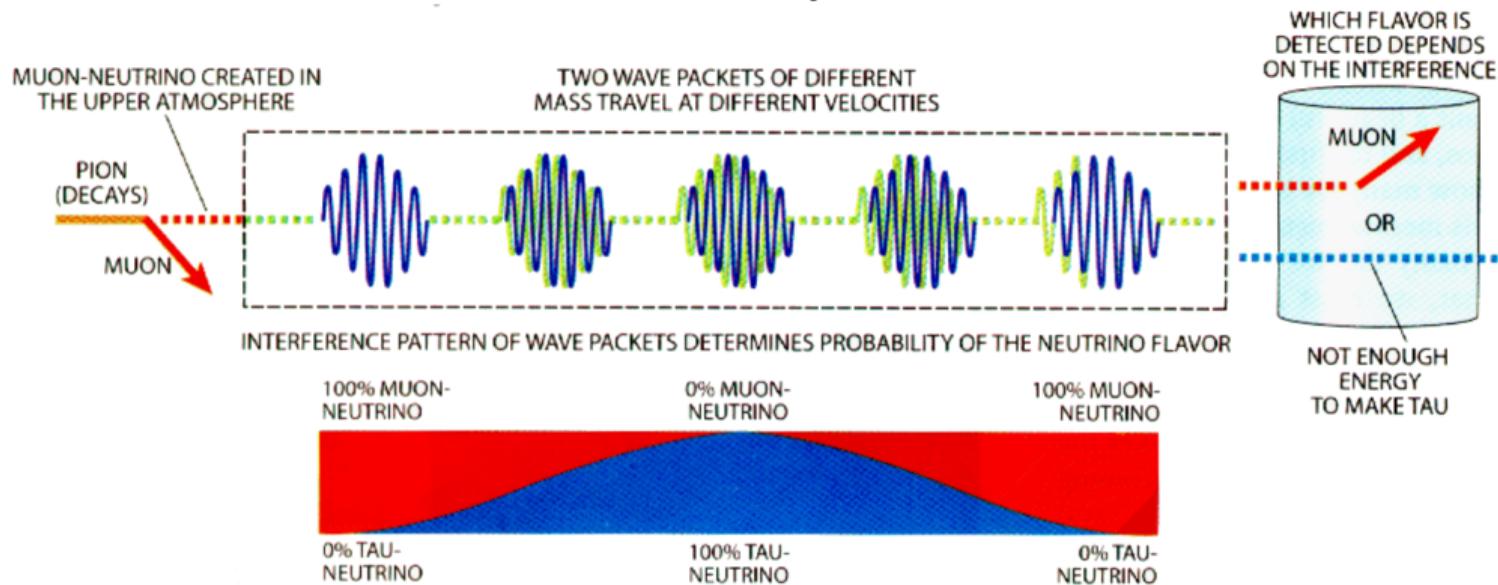
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Neutrinos oscillate!

- ▶ Since they act differently at different times, they must have mass
- ▶ Masses are  $> 1,000,000$  times smaller than the electron
- ▶ Their masses are still unknown!
- ▶ The mechanism by which they get mass is unknown!

# How does oscillation work?

A schematic for many environments:



# Some neutrino oscillation theory

Quantum mechanics exercise:

$$i \frac{\partial}{\partial t} |\nu_i\rangle = H |\nu_i\rangle$$

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Note that switching  $E \simeq p$  and  $x \simeq t$  is potentially problematic  
Full QFT calculation gives the same answer

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Subtract a common phase  $pt$  from all:

$$|\nu_i(t)\rangle = e^{-im_i^2 L/2E} |\nu_i(0)\rangle \quad \text{No oscillations!}$$

Note that switching  $E \simeq p$  and  $x \simeq t$  is potentially problematic  
Full QFT calculation gives the same answer

## Production and detection

Need to produce & detect neutrinos in a different basis

In the flavor/interaction basis:

QM superposition!

$$i \frac{\partial}{\partial t} |\nu_\alpha\rangle = H_f |\nu_\alpha\rangle$$

$$\alpha = e, \mu, \tau$$

$$H_f = \frac{1}{2E} U_{\text{PMNS}} \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} U_{\text{PMNS}}^\dagger$$

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$U_{\text{PMNS}}$  is: complex,  $3 \times 3$ , unitary; 4 parameters<sup>1</sup>:  $\theta_{23}, \theta_{13}, \theta_{12}, \delta$

<sup>1</sup>Plus two complex phases that don't affect oscillations  $\propto (m_\nu/E_\nu)^2$

Many different ways to parameterize matrix:

PBD, R. Pesles [2006.09384](#) (JHEP)

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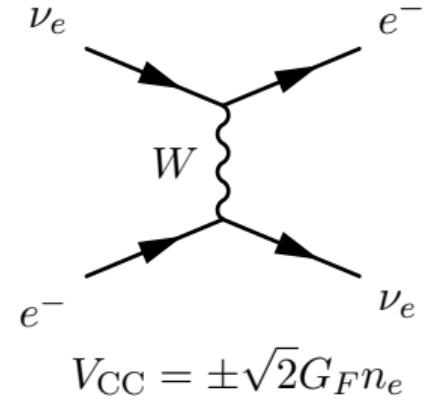
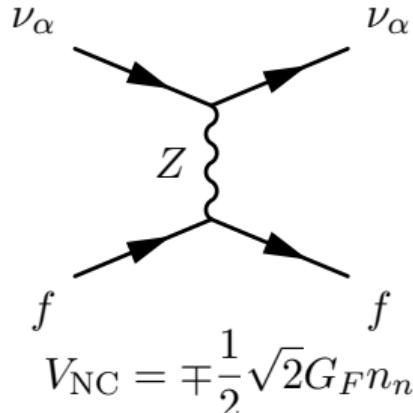
$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_{i=1}^3 U_{\alpha i}^* e^{-im_i^2 L/2E} U_{\beta i} \right|^2$$

Only  $m_i^2 - m_j^2$  contribute

Oscillations!

## Neutrinos in matter

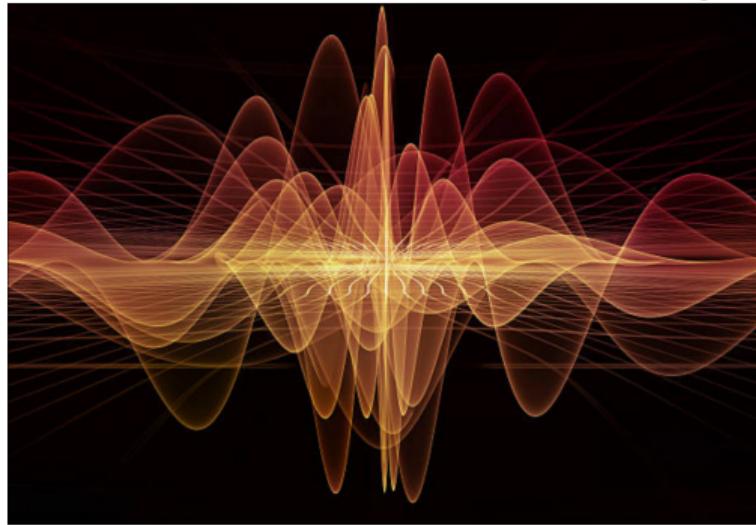
1. Neutrinos propagate through Earth/Sun/... largely unobstructed
2. But the presence of matter modifies how they propagate!
3. Weak interaction tells neutrinos what basis to be in by modifying energy levels

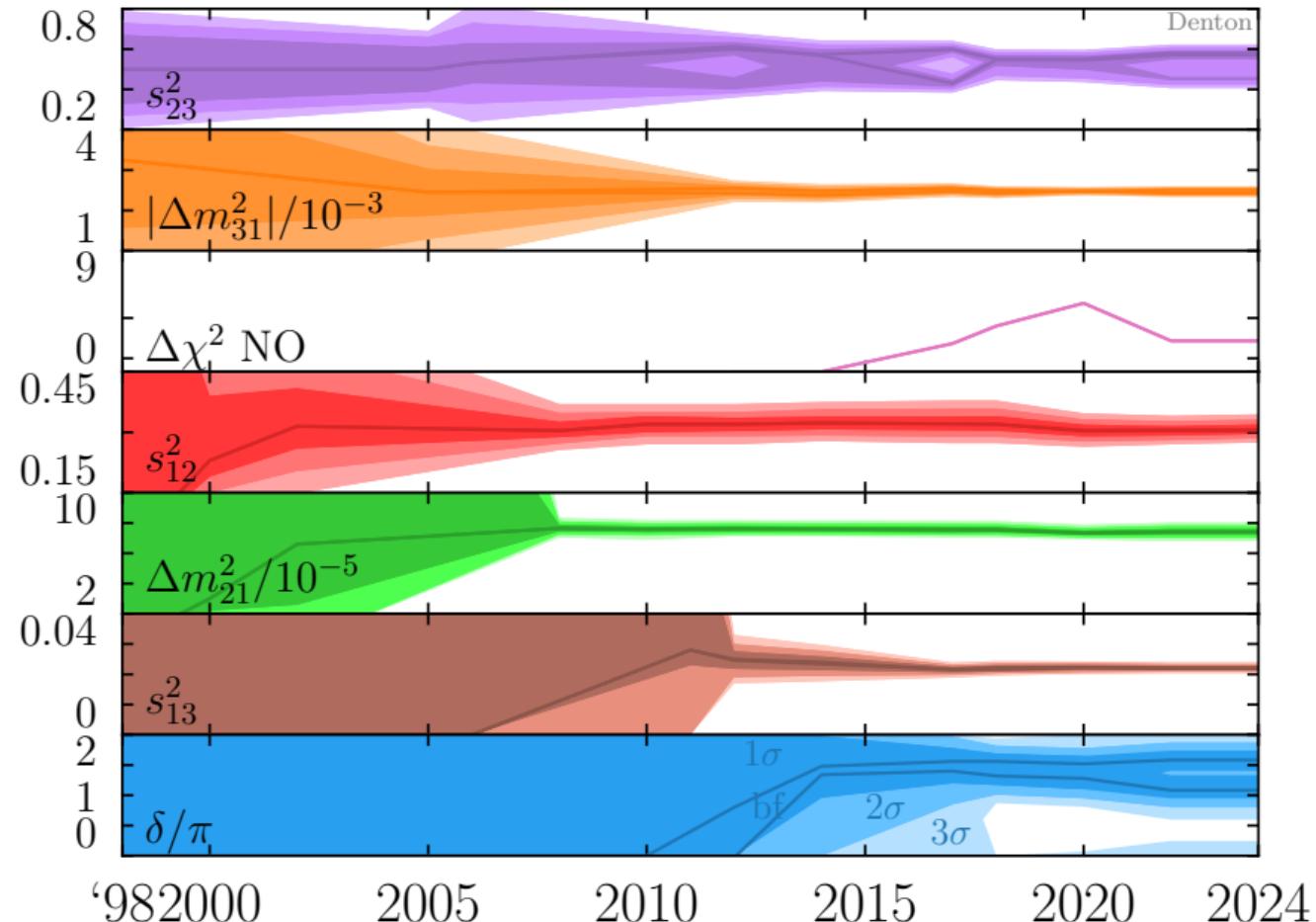


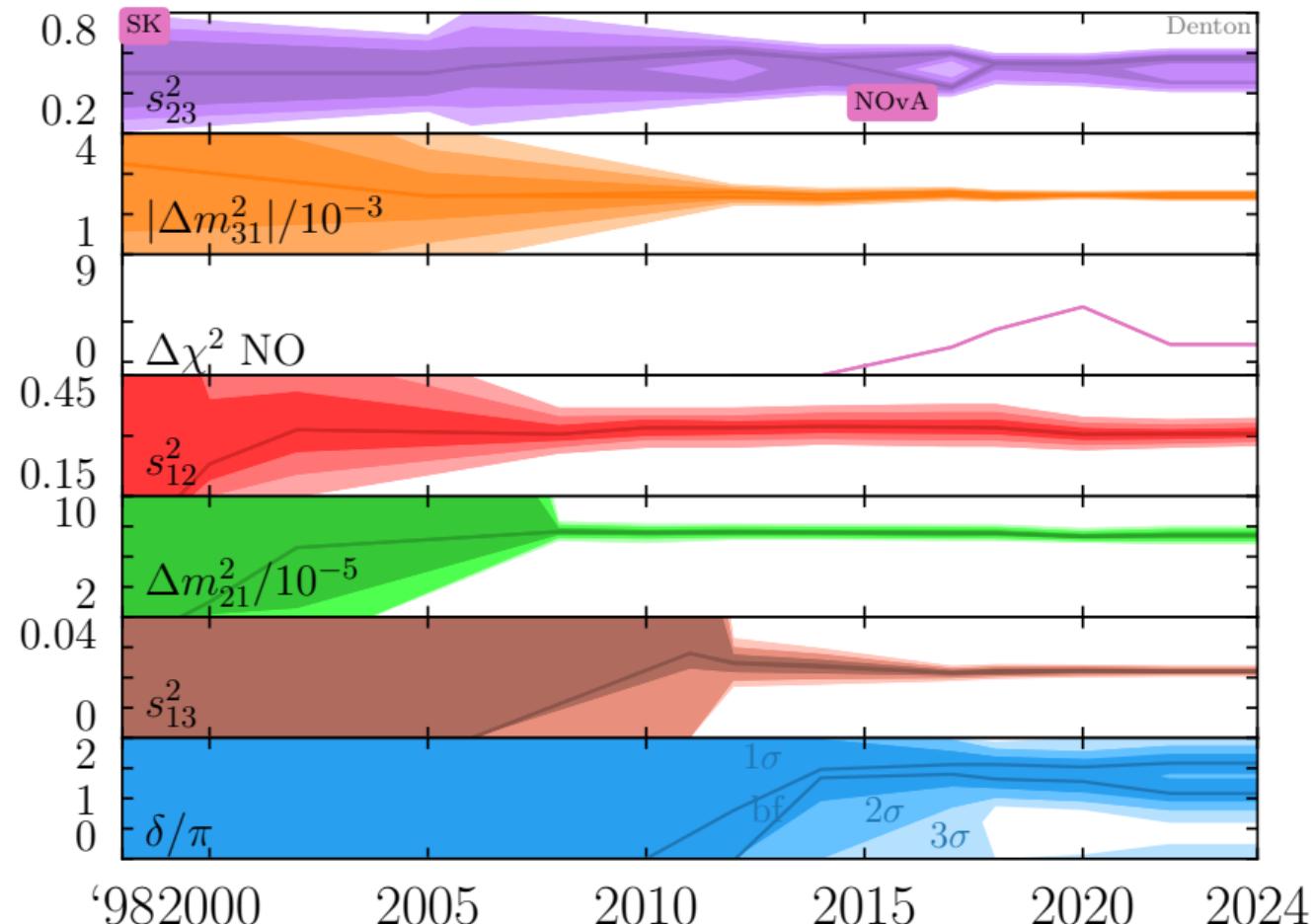
L. Wolfenstein, PRD 17 (1978)

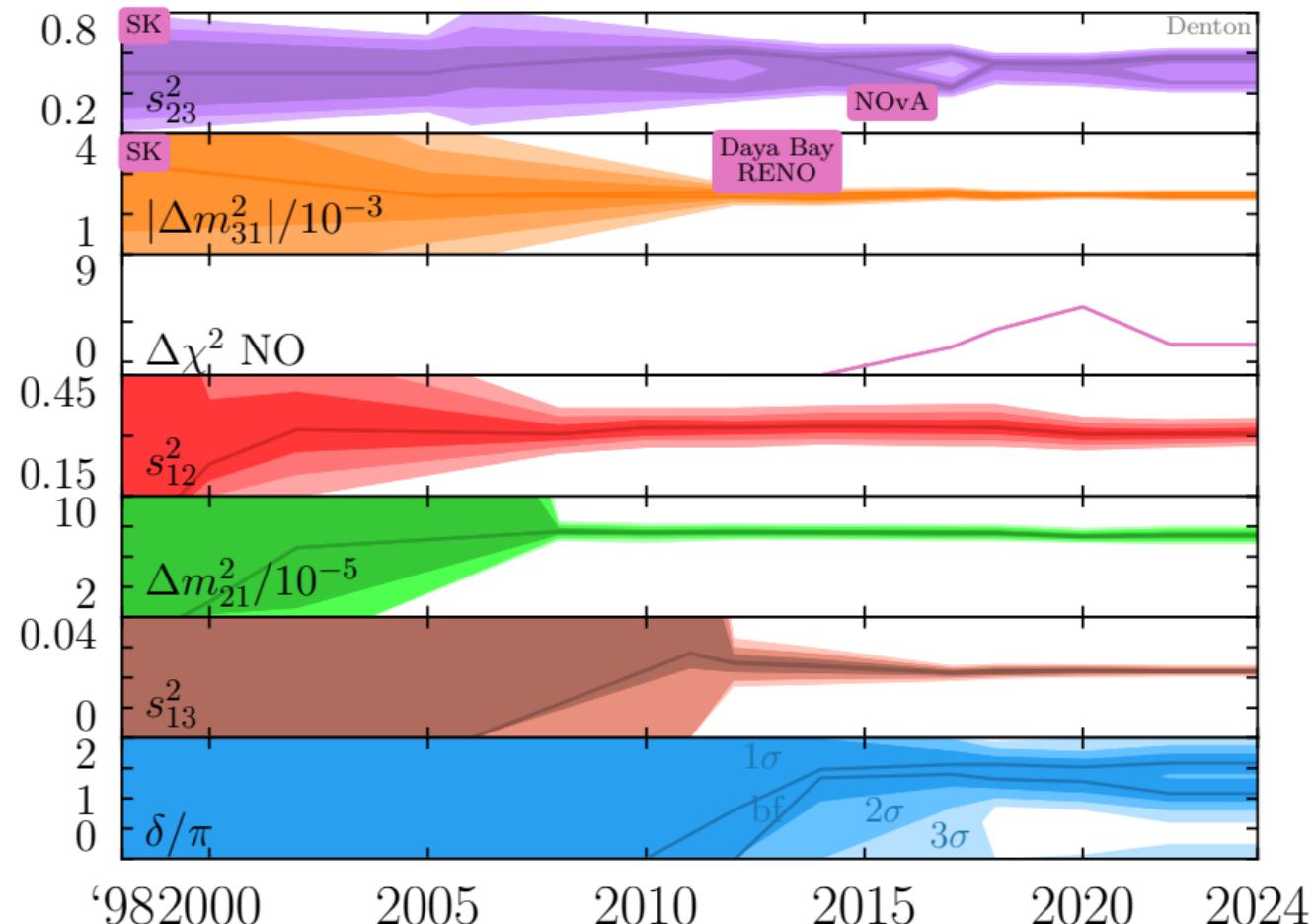
$$H_f = \frac{1}{2E} \left[ U M^2 U^\dagger + \begin{pmatrix} 2EV_{\text{CC}} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right]$$

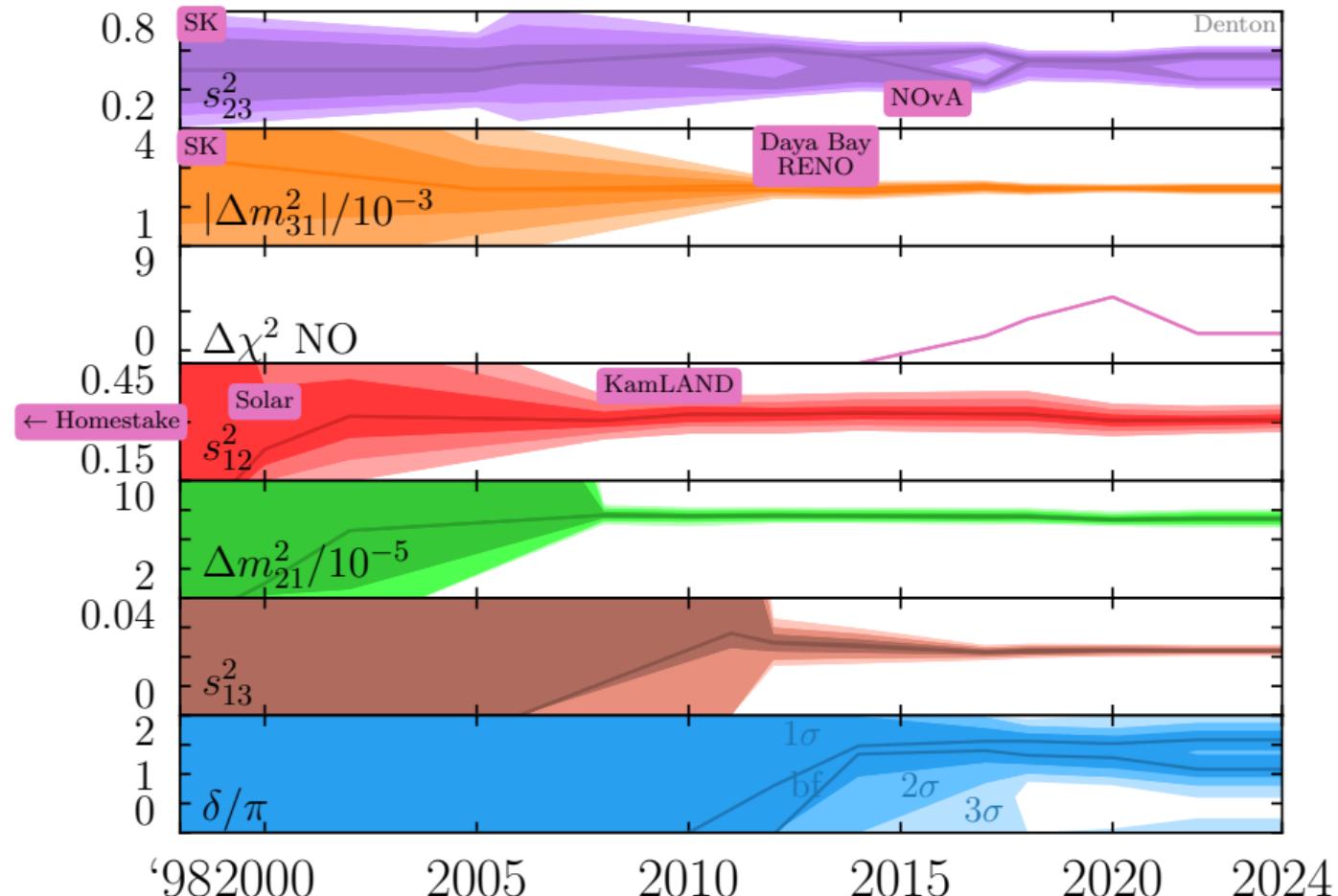
## Neutrino oscillations: today

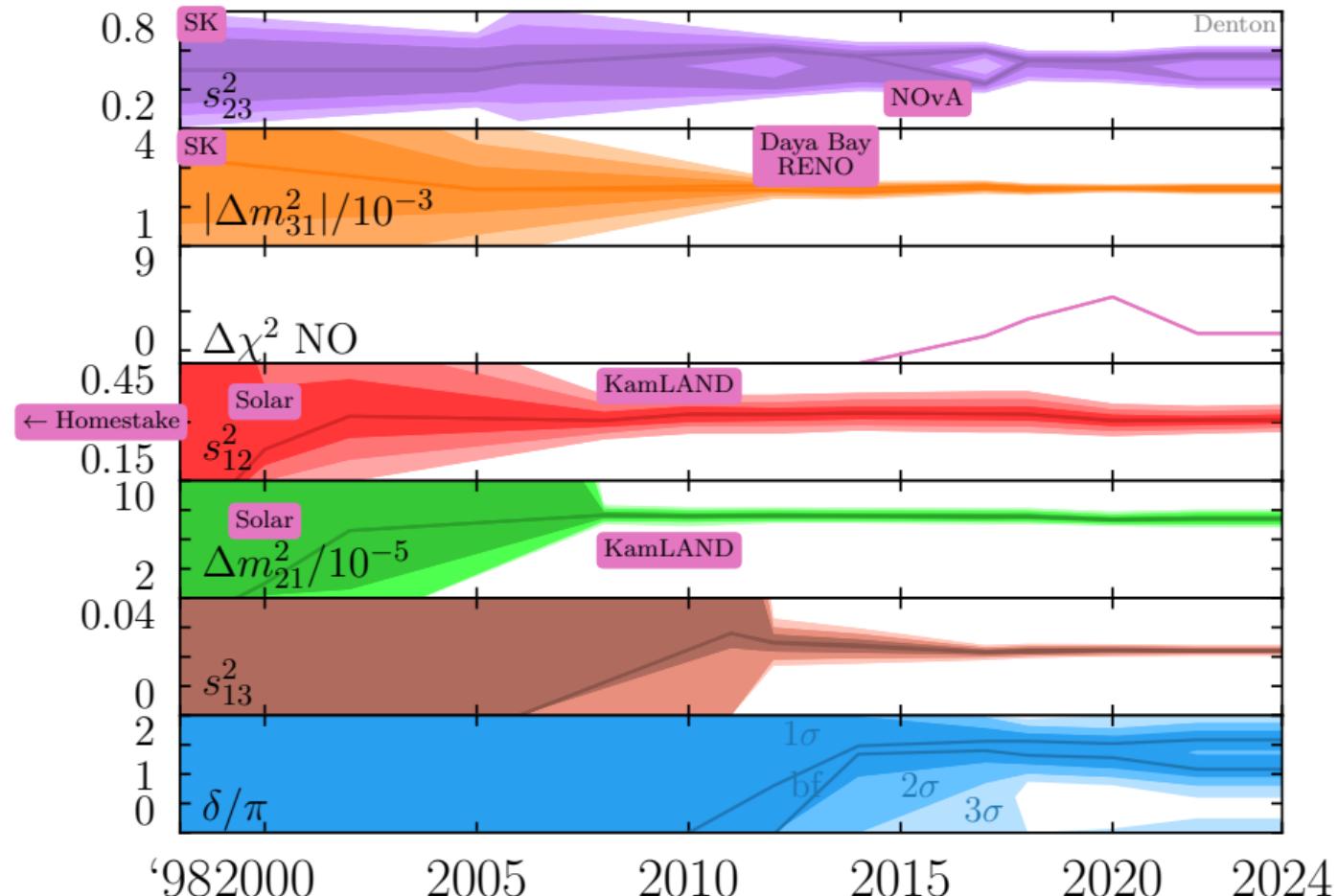


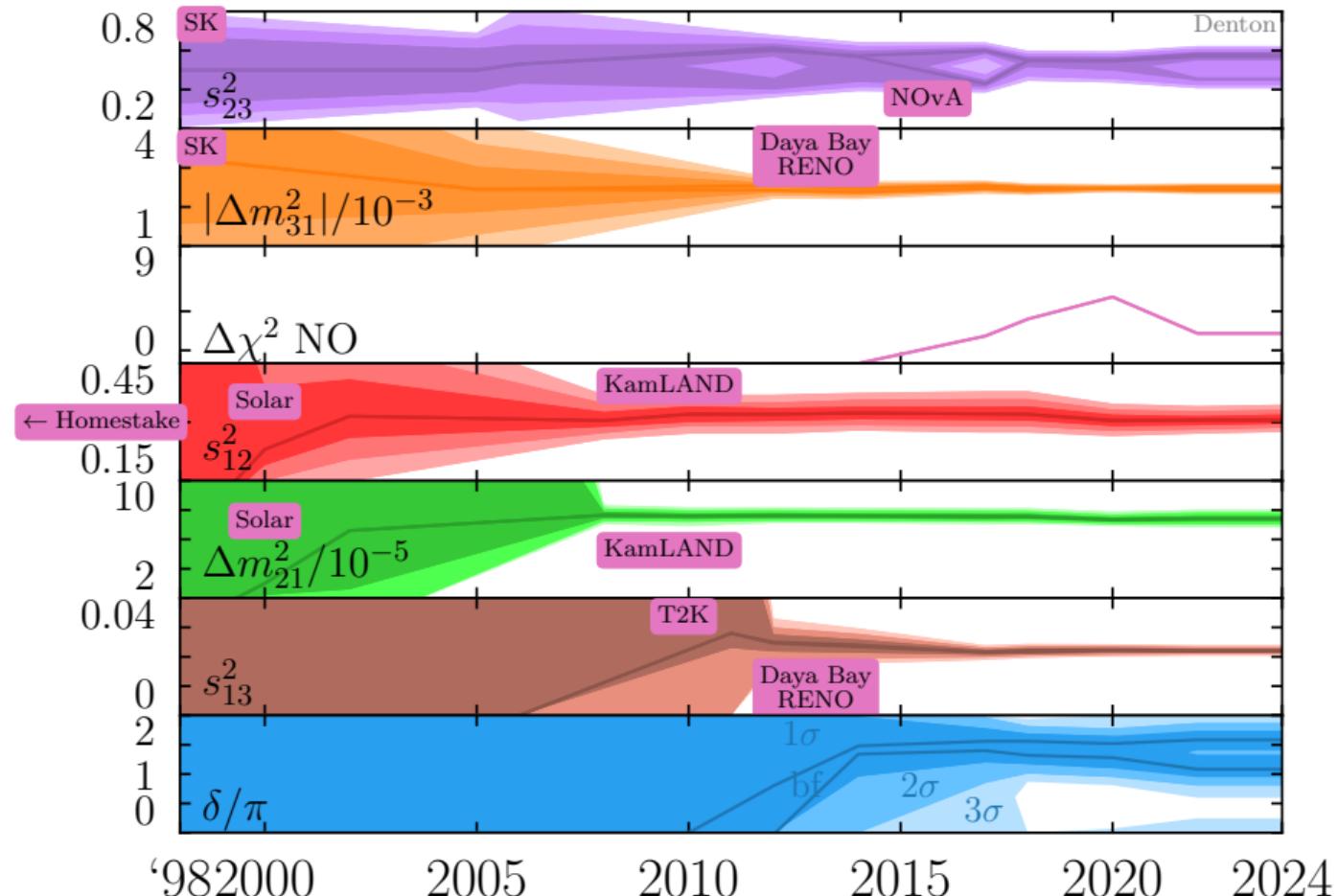


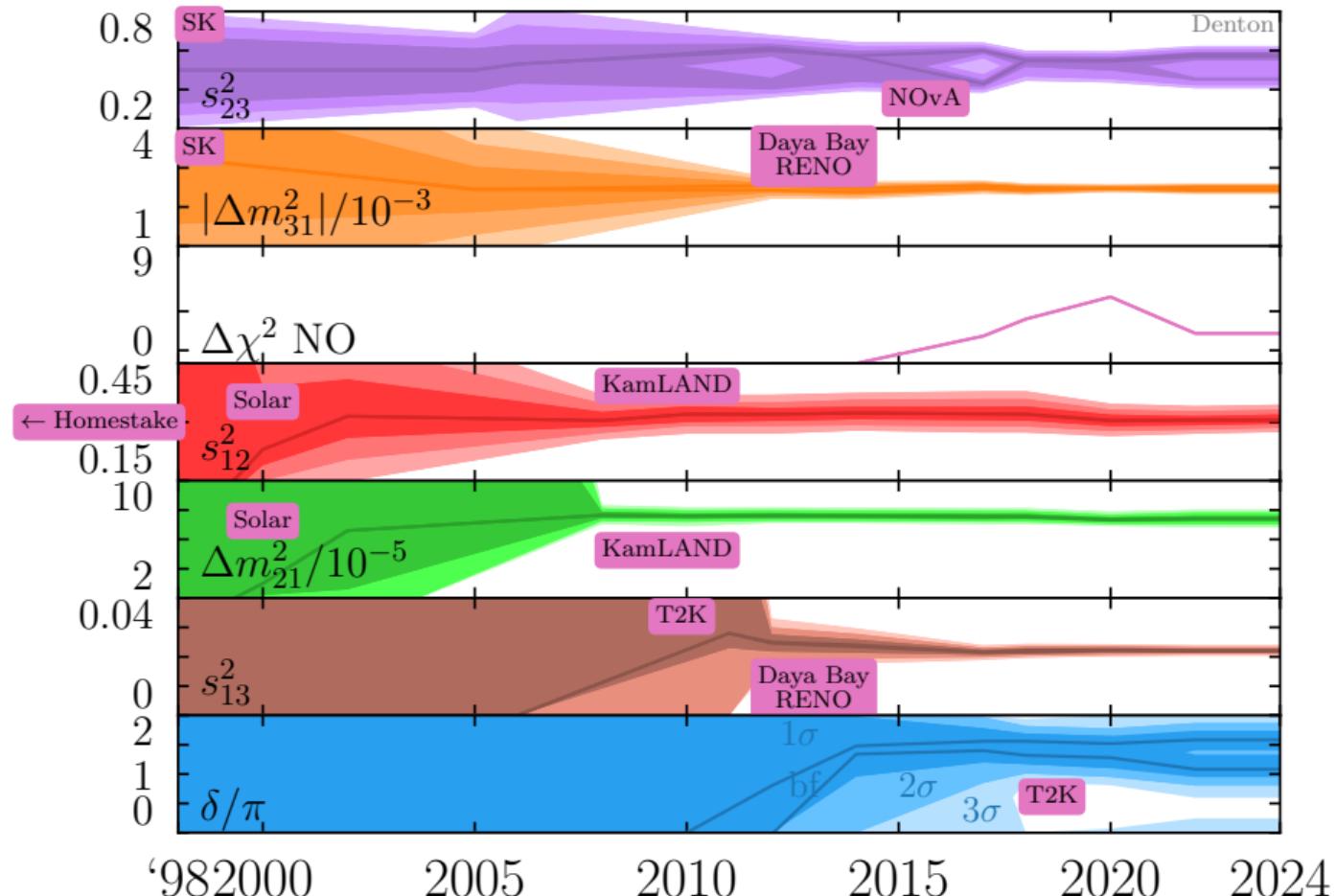




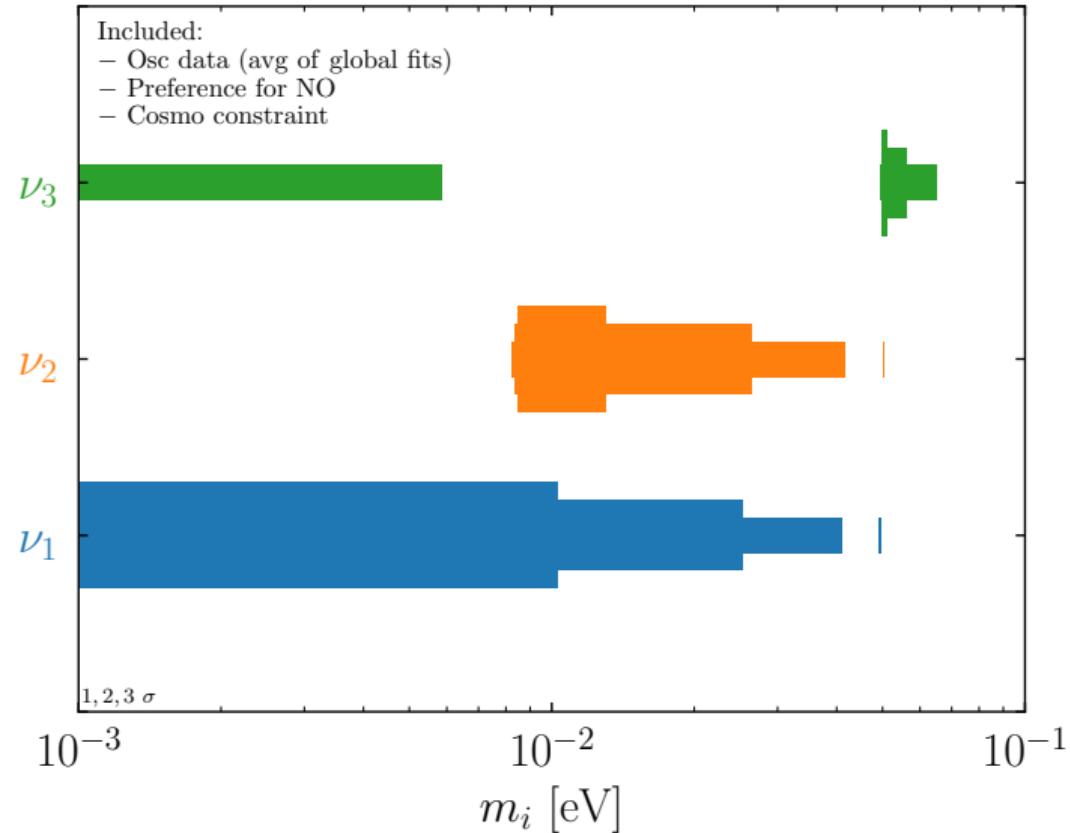








# Absolute masses



Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

$\theta_{23}$  octant

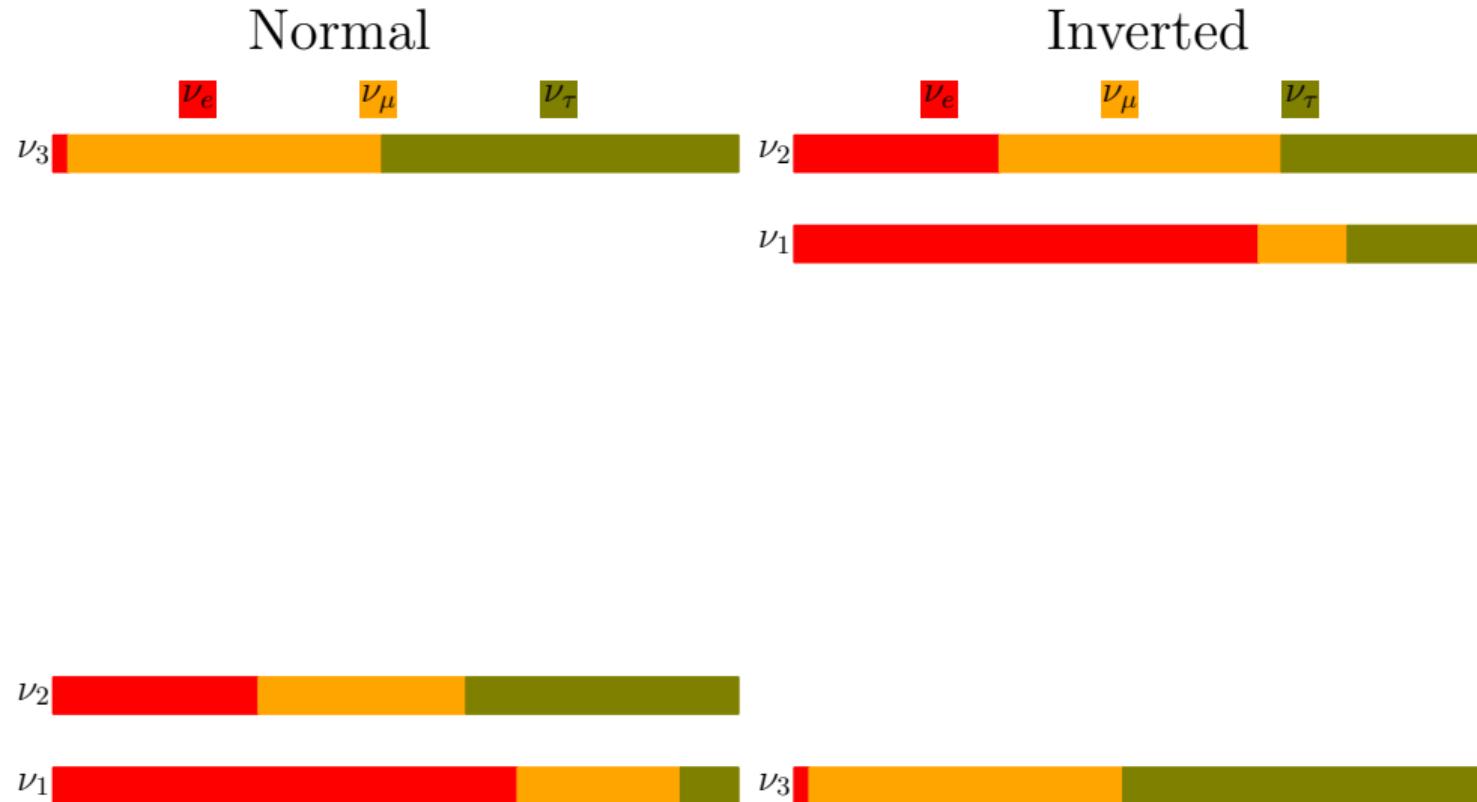
Complex phase

Absolute mass scale

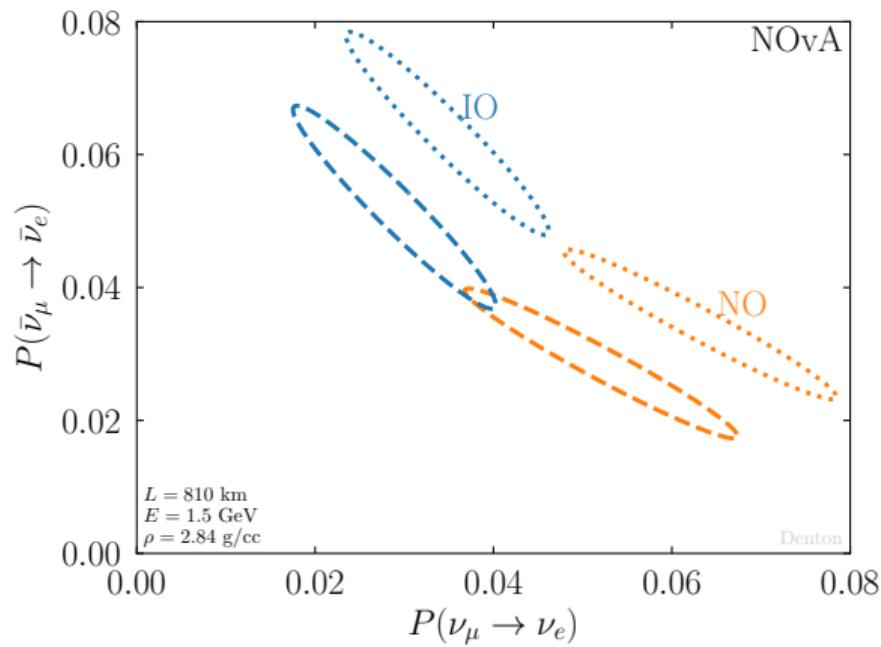
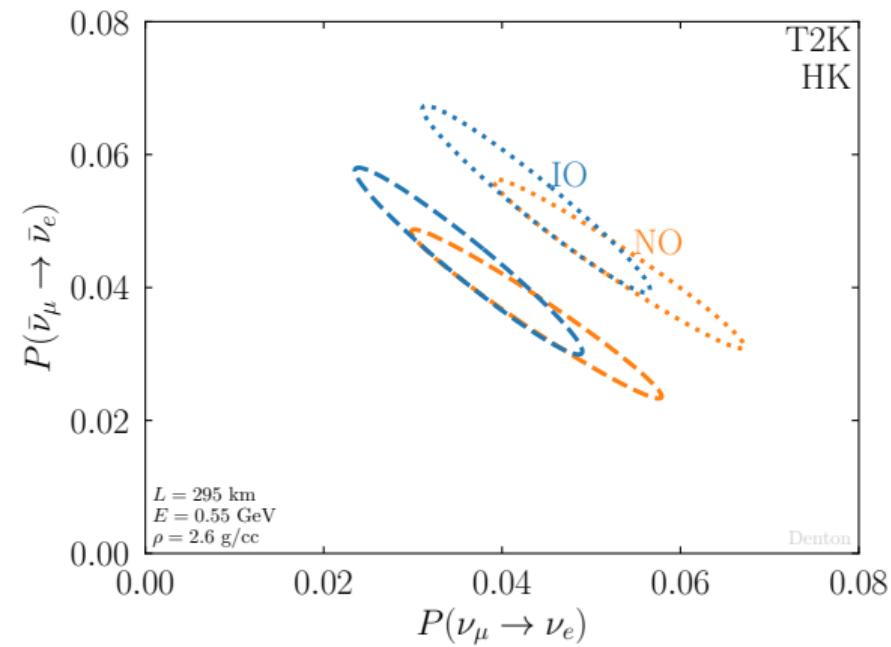
Cosmology, scattering,  $0\nu\beta\beta$ , ...

# Atmospheric mass ordering

# Mass ordering: what is it?



# Mass ordering: what is it really?



# Mass ordering current status: oscillations

1. NOvA and T2K both prefer **NO** over **IO**
2. NOvA+T2K prefers **IO** over **NO**
3. SK still prefers **NO** over **IO** – statistics complicated
4. NOvA+T2K+SK still prefers **NO** over **IO**
5. + Daya Bay & RENO  $\Rightarrow$  slight preference **NO**
6. = no significant preference either way; with SK  $\sim 2\sigma$

**PBD**, J. Gehrlein, R. Pestes [2008.01110](#) (PRL)

K. Kelly, et al. [2007.08526](#)

I. Esteban, et al. [2007.14792](#)

F. Capozzi, et al. [2107.00532](#)

P. de Salas, et al. [2006.11237](#)

I. Esteban, et al. [2410.05380](#)

# Mass ordering current status: all

From oscillations:

Normal :  $m_1 + m_2 + m_3 > 60$  meV      Inverted :  $m_1 + m_2 + m_3 > 100$  meV

Cosmology:  $m_1 + m_2 + m_3 < 90$  meV at 95% CL

E. Valentino, S. Gariazzo, O. Mena [2106.15267](#)

→ 20 meV precision with DESI, EUCLID, ...

Pushing to very low (negative?) masses!?

N. Craig, et al. [2405.00836](#)

Many caveats: T. Bertólez-Martínez, et al. [2411.14524](#)

See also KATRIN [2406.13516](#)

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## PRIORS?

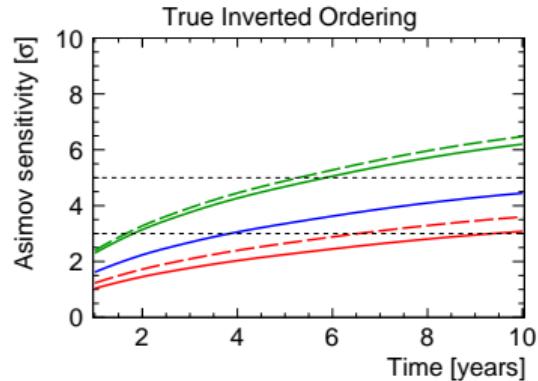
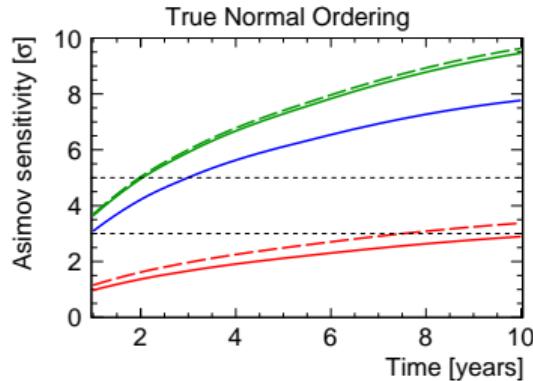
Some claim “decisive” Bayesian evidence for normal

R. Jimenez, et al. [2203.14247](#)

More general prior assumptions ⇒ no significant information from cosmology

S. Gariazzo, et al. [1801.04946](#)  
S. Gariazzo, et al. [2205.02195](#)

# Mass ordering: future sensitivities

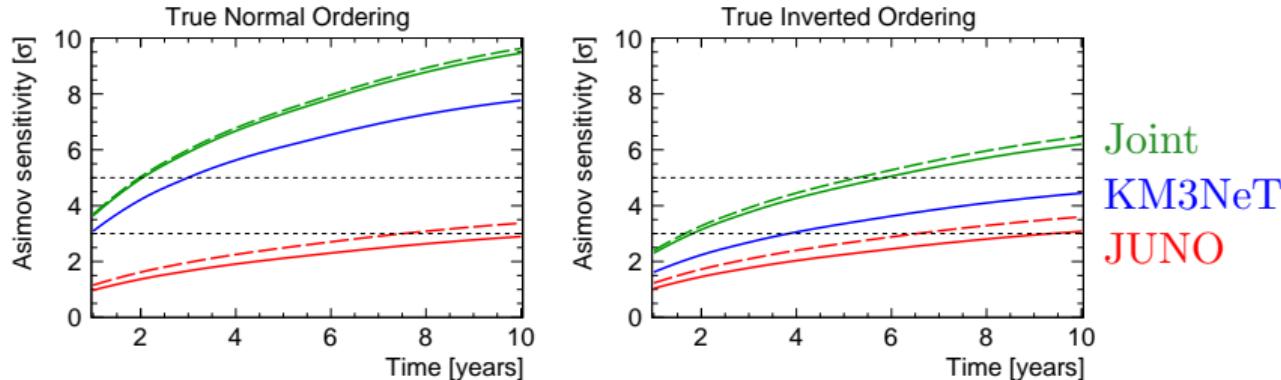


JUNO, KM3NeT [2108.06293](#)

JUNO, IceCube [1911.06745](#)

Note: if lower octant, KM3NeT is less sensitive

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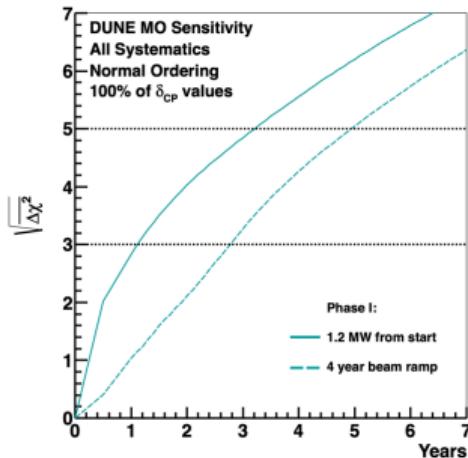
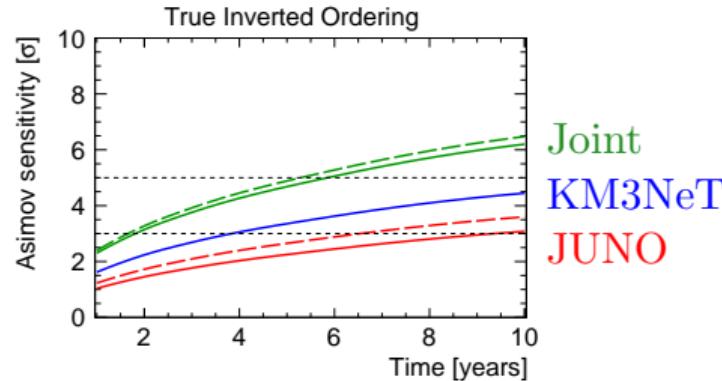
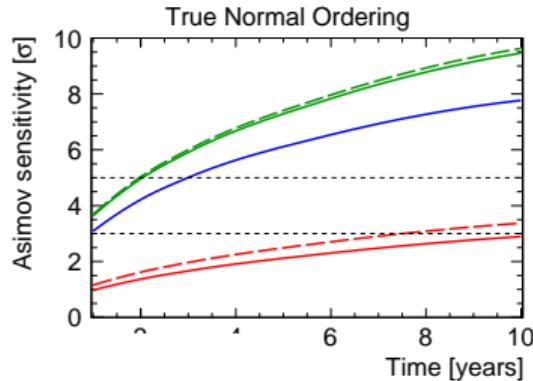
$$\Delta m_{ee}^2 = c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2$$

$$\Delta m_{\mu\mu}^2 = s_{12}^2 \Delta m_{31}^2 + c_{12}^2 \Delta m_{32}^2 + \mathcal{O}(s_{13}\Delta m_{21}^2)$$

Differ by  $\pm \sim 1.1\%$  in each mass ordering

H. Nunokawa, S. Parke, R. Funchal [hep-ph/0503283](#)

# Mass ordering: future sensitivities



Matter effect  $\Rightarrow$  DUNE [2203.06100](#)

JUNO, KM3NeT [2108.06293](#)

JUNO, IceCube [1911.06745](#)

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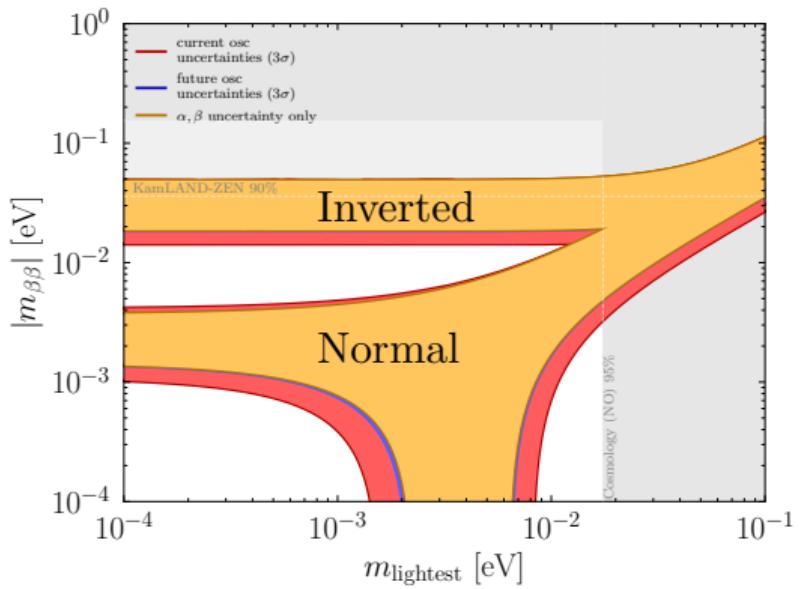
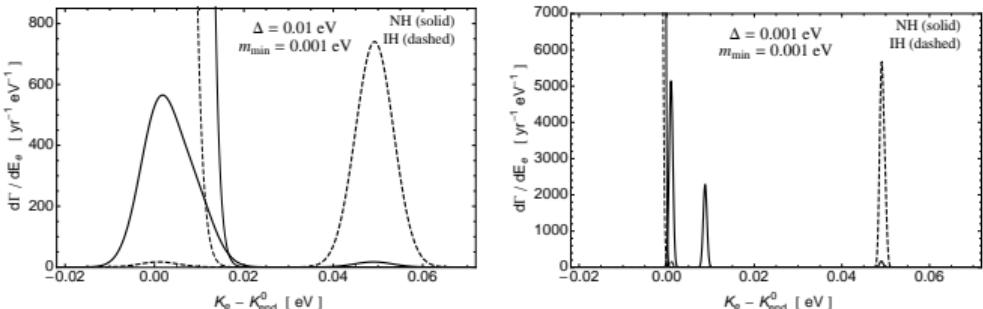
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H. Nunokawa, S. Parke, R. Funchal [hep-ph/0503283](#)

# Mass ordering: broad implications

- ▶ Affects cosmology
- ▶ Affects  $0\nu\beta\beta$
- ▶ Affects end point measurements
- ▶ Affects  $C\nu B$



PBD, J. Gehrlein [2308.09737](#) (PRD)

A. Long, C. Lunardini, E. Sabancilar [1405.7654](#)

# Mass ordering: new physics degeneracies

In the presence of new physics such as NSI we have:

$$[\text{NO}] + [\epsilon = 0] \equiv [\text{IO}] + [\epsilon_{ee} = -2]$$

$$[\text{IO}] + [\epsilon = 0] \equiv [\text{NO}] + [\epsilon_{ee} = -2]$$

Equivalences hold even if all oscillation probabilities are *perfectly* measured

P. Bakhti, Y. Farzan [1403.0744](#)

P. Coloma, T. Schwetz [1604.05772](#)

P. Coloma, [PBD](#), et al. [1701.04828](#) (JHEP)

[PBD](#), S. Parke [2106.12436](#) (PRD)

[PBD](#), J. Gehrlein [2204.09060](#) (PRD)



This is known as the **LMA-Dark** solution

# Is the mass ordering robust?

Need scattering to break



Can probe same NC  $\epsilon = -2$  process in scattering, but...

1. CHARM and NuTeV for  $M_{Z'} \gtrsim 10$  GeV

P. Coloma, PBD, et al. [1701.04828](#) (JHEP)

2. COHERENT for  $M_{Z'} \gtrsim 50$  MeV and cosmology for  $M_{Z'} \lesssim 5$  MeV

PBD, Y. Farzan, I. Shoemaker [1804.03660](#) (JHEP)

3. Dresden-II for  $\epsilon_{ee}$  for any mediator mass

PBD, J. Gehrlein [2204.09060](#) (PRD)

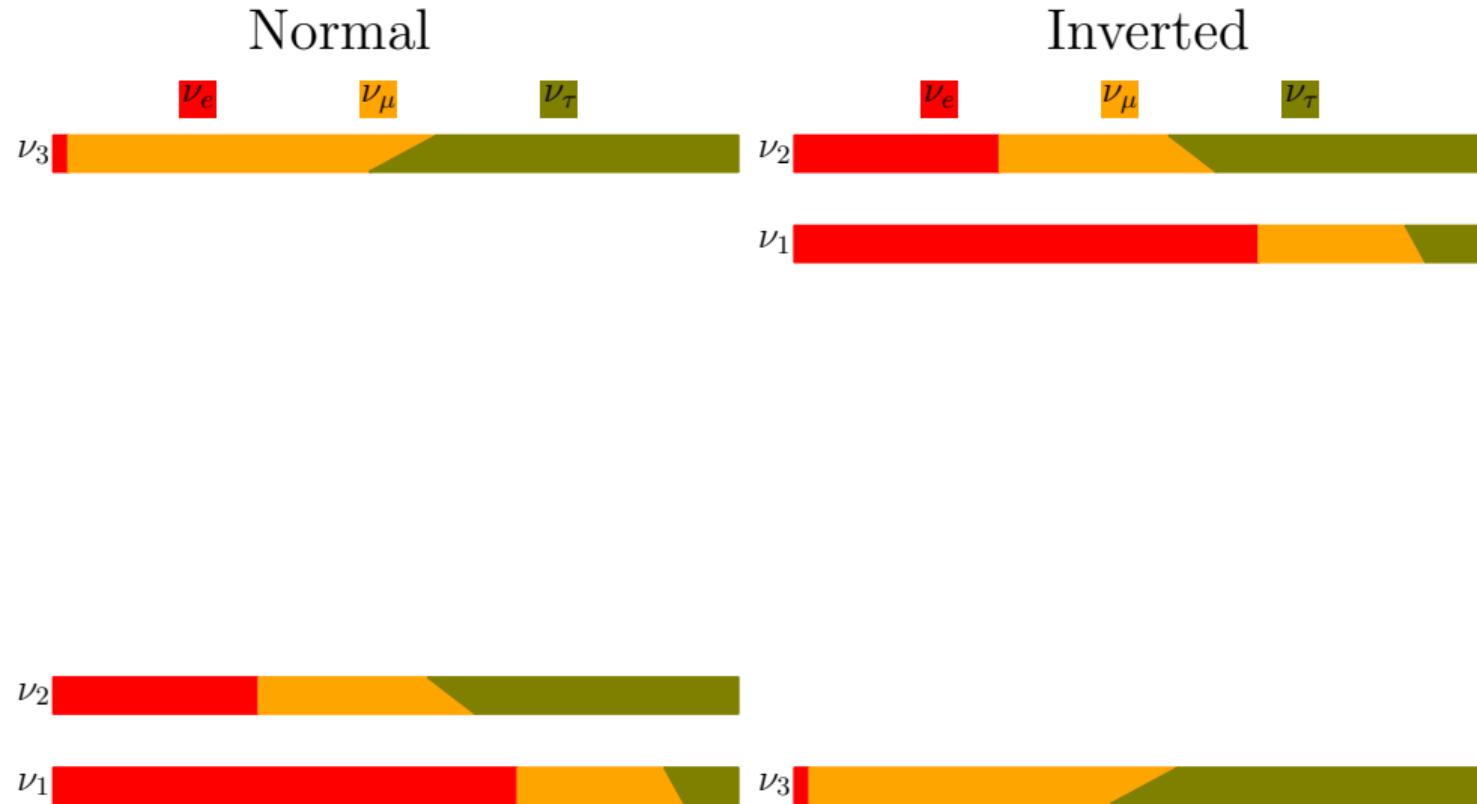
4. Can still evade with specific flavor structures

$\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$  or certain  $u / d$  combinations

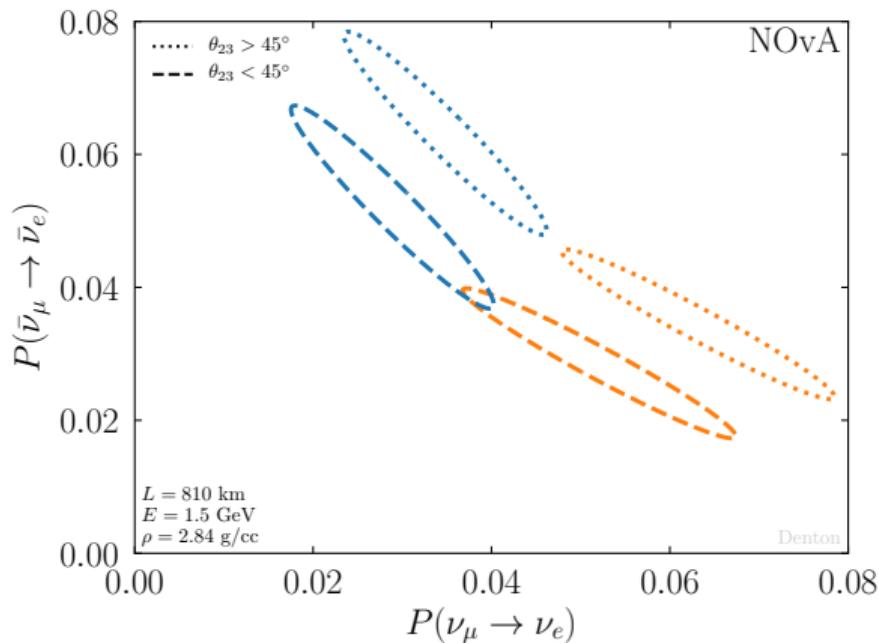
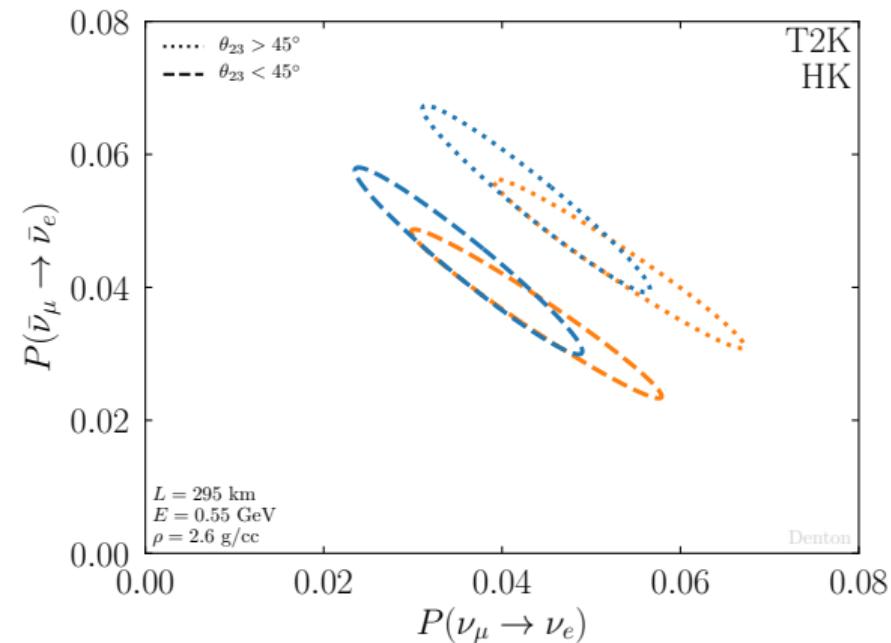
5. CCM & COHERENT can close all loopholes

$\theta_{23}$  octant

# $\theta_{23}$ octant: what is it?

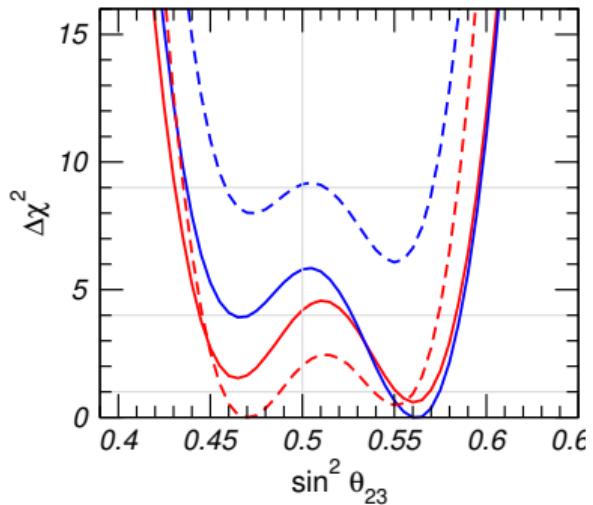


# $\theta_{23}$ octant: what is it really?

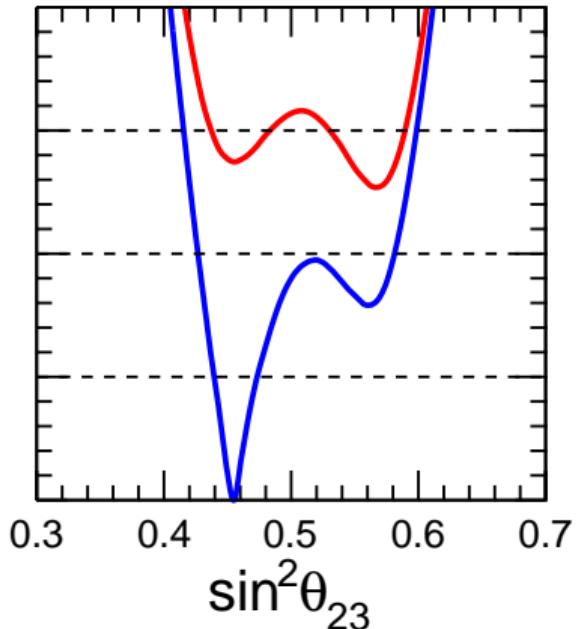


Lower octant more “normal” than upper octant

## $\theta_{23}$ octant: current status



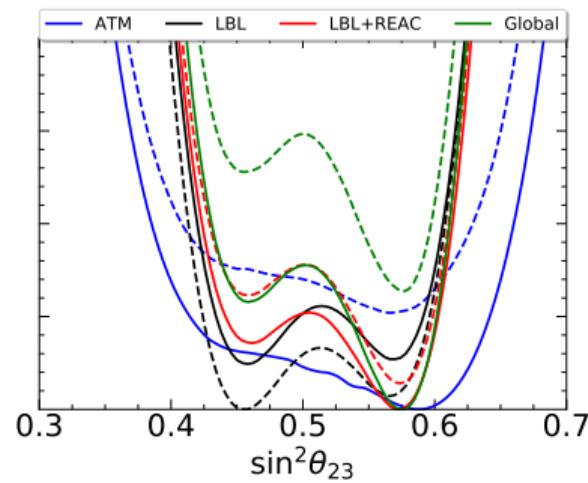
I. Esteban, et al. [2410.05380](#)



F. Capozzi, et al. [2107.00532](#)

Upper/lower at  $\sim 1\sigma$

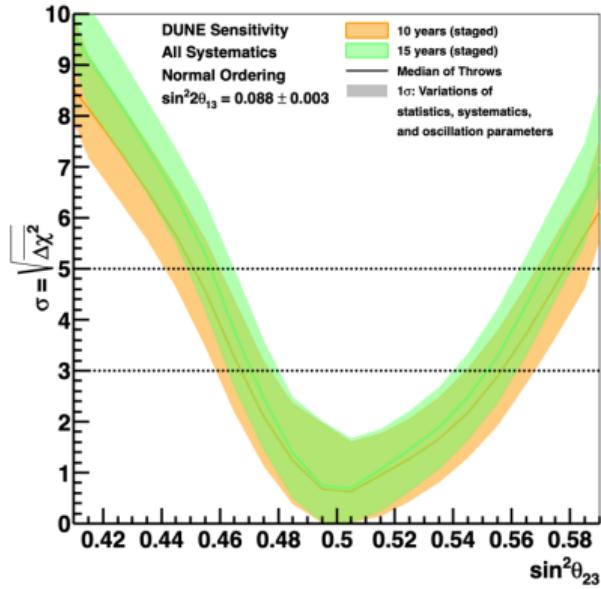
Prefers lower at  $\sim 1.5\sigma$



P. de Salas, et al. [2006.11237](#)

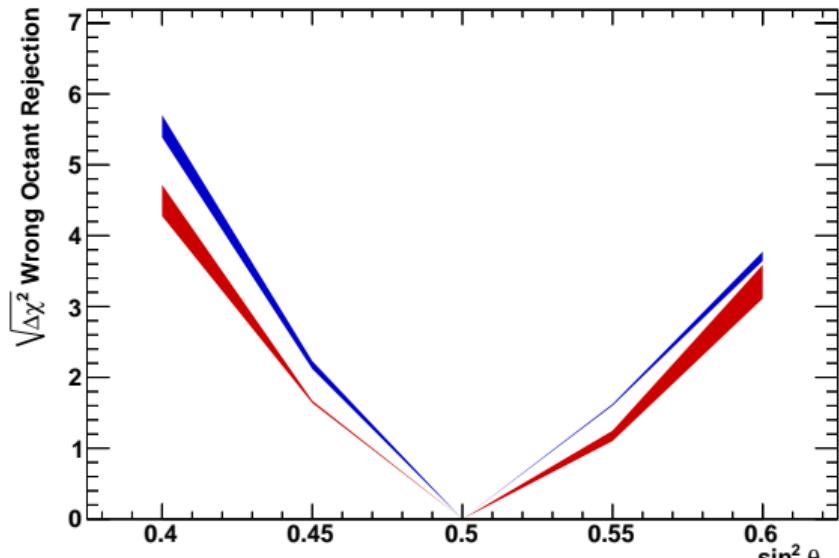
Prefers upper at  $> 2\sigma$

# $\theta_{23}$ octant: future sensitivities



$\sim 3 - 5\sigma$

DUNE 2002.03005

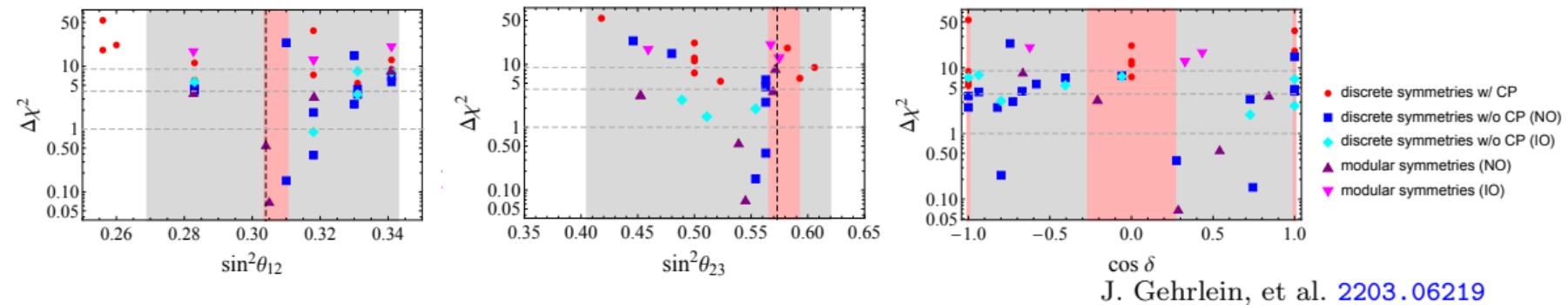


Beam+Atm  $\Rightarrow \sim 3 - 6\sigma$

HK 1805.04163

# Parameter interplay

Models predict specific correlations among the parameters



# Complex phase

# $\delta$ and CP violation

$$J_{CP} = s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23} \sin \delta$$

C. Jarlskog [PRL 55, 1039 \(1985\)](#)



# $\delta$ and CP violation

$$J_{CP} = s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23} \sin \delta$$

C. Jarlskog [PRL 55, 1039 \(1985\)](#)



1. Strong interaction: no observed EDM  $\Rightarrow$  CP (nearly) **conserved**

$$\frac{\bar{\theta}}{2\pi} < 10^{-11}$$

J. Pendlebury, et al. [1509.04411](#)

2. Quark mass matrix: non-zero but **small** CP violation

$$\frac{|J_{CKM}|}{J_{\max}} = 3 \times 10^{-4}$$

CKMfitter [1501.05013](#)

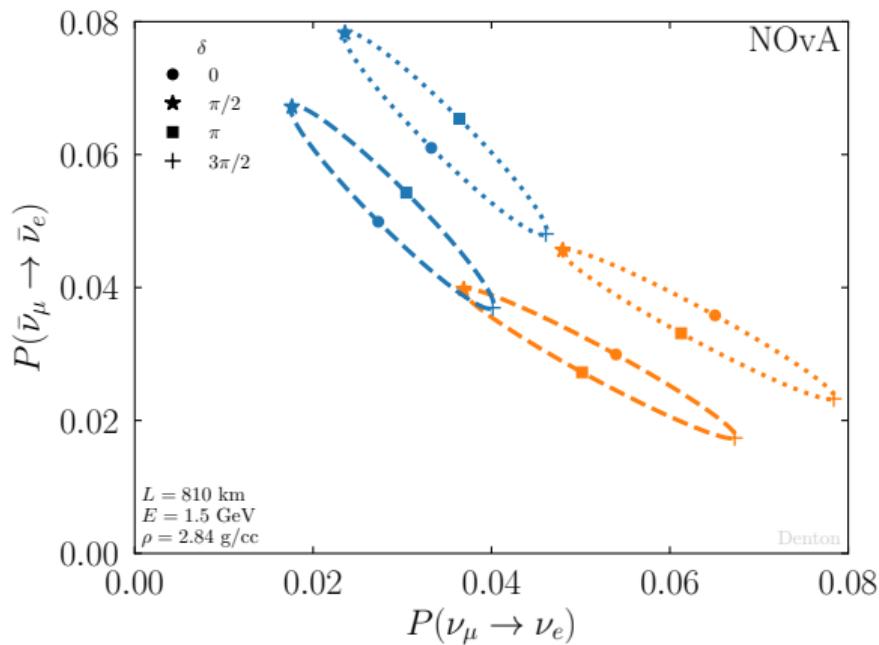
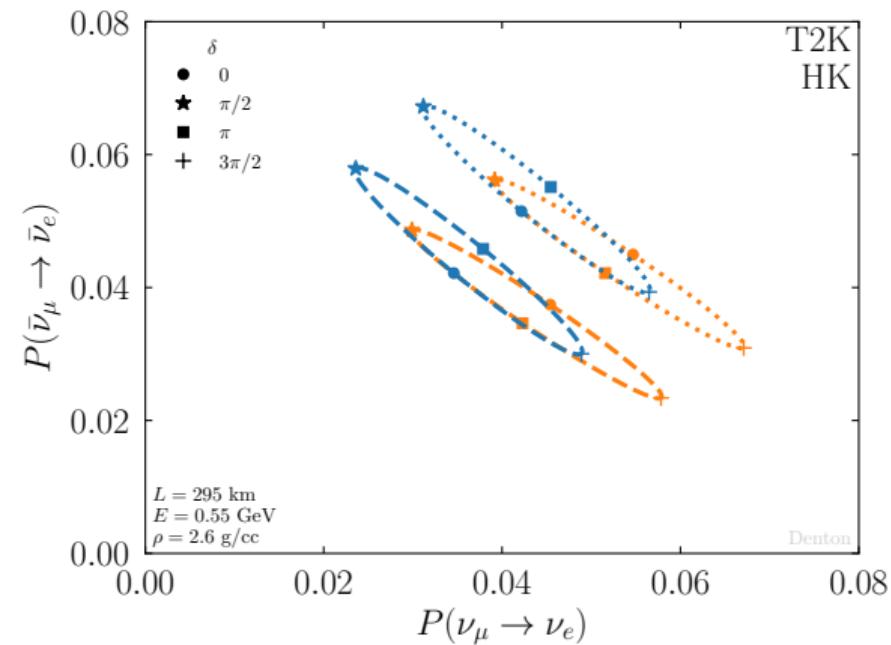
3. Lepton mass matrix: ?

$$\frac{|J_{PMNS}|}{J_{\max}} < 0.34$$

**PBD**, J. Gehrlein, R. Pestes [2008.01110](#) (PRL)

$$J_{\max} = \frac{1}{6\sqrt{3}} \approx 0.096$$

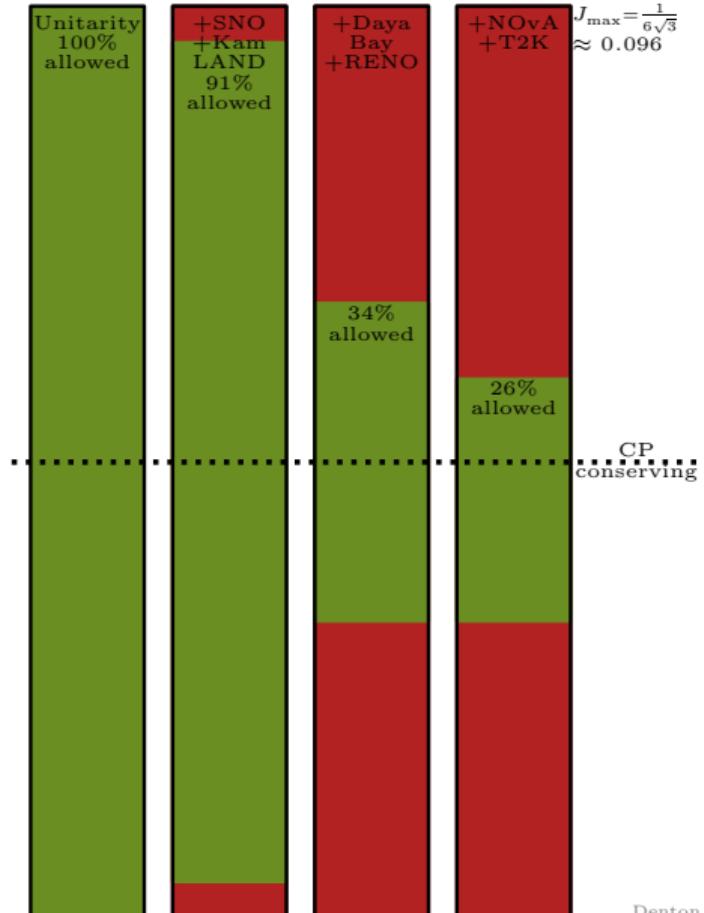
# $\delta$ : what is it really?



# $\delta, J$ : current status

Maximal CP violation is already ruled out:

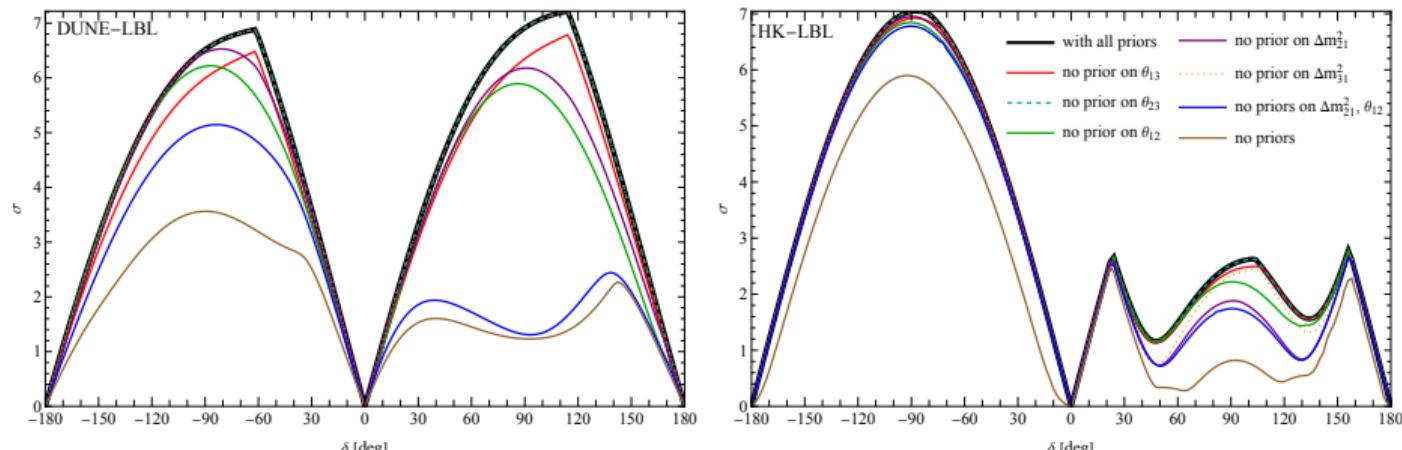
1.  $\theta_{12} \neq 45^\circ$  at  $\sim 15\sigma$
2.  $\theta_{13} \neq \tan^{-1} \frac{1}{\sqrt{2}} \approx 35^\circ$  at many (100)  $\sigma$
3.  $\theta_{23} = 45^\circ$  allowed at  $\sim 1\sigma$
4.  $|\sin \delta| = 1$  allowed



# $\delta$ : future sensitivities

DUNE and HK will make great measurements via appearance  $\nu_\mu \rightarrow \nu_e$

$\nu + \bar{\nu}$  helps systematics but isn't strictly necessary



Need to know solar parameters to measure  $\delta$ !

Current solar knowledge: okay  
Future (JUNO): excellent

## $\delta$ : future sensitivities

Possible to get at CPV with CPC processes

Disappearance probability:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\alpha) &= 1 - 4|U_{\alpha 1}|^2|U_{\alpha 2}|^2 \sin^2 \Delta_{21} \\ &\quad - 4|U_{\alpha 1}|^2|U_{\alpha 3}|^2 \sin^2 \Delta_{31} \\ &\quad - 4|U_{\alpha 2}|^2|U_{\alpha 3}|^2 \sin^2 \Delta_{32}, \end{aligned}$$

$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E$$

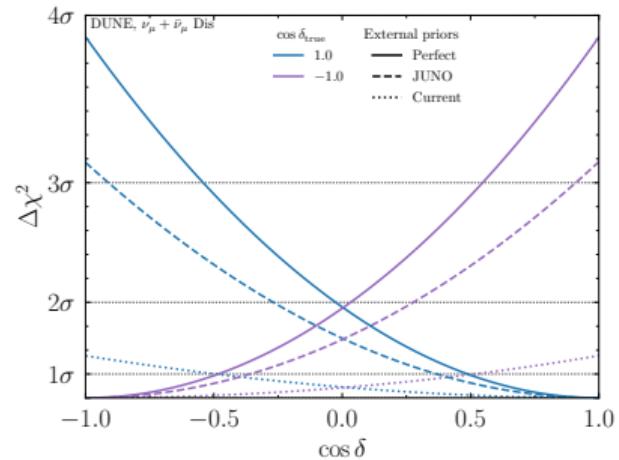
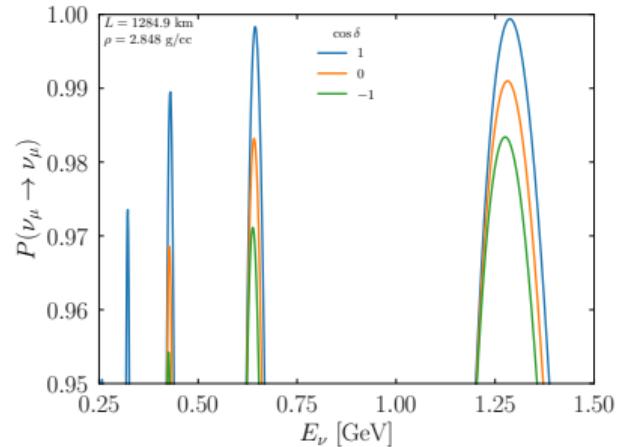
Can measure all three coeffs of each frequency  $\Rightarrow$  2 dofs  
 $\delta$  (and CPV) needs 4 dofs  $\Rightarrow$  two dis measurements

$\nu_e$ : Daya Bay and KamLAND/JUNO

$\nu_\mu$ : precision at DUNE/HK

Important cross check

Different and cleaner systematics than appearance



# Neutrinos: more new physics?



# Many interesting new physics scenarios in oscillations

1. Sterile neutrinos
2. Non-standard neutrino interactions (NSI)  
with any Lorentz structure: SPVAT
3. Non-standard neutrino self interactions
4. Neutrino decay  
with visible or invisible final states
5. Unitarity violation
6. Many others: neutrino – dark matter interactions, environmental decoherence, and Lorentz invariance or CPT violation

# Many interesting new physics scenarios in oscillations

## 1. Sterile neutrinos

PBD, Y. Farzan, I. Shoemaker [1811.01310](#) (PRD)

PBD [2111.05793](#) (PRL)

H. Davoudiasl, PBD [2301.09651](#) (PRD)

## 2. Non-standard neutrino interactions (NSI)

with any Lorentz structure: SPVAT

PBD, Y. Farzan, I. Shoemaker [1804.03660](#) (JHEP)

P. Coloma, PBD, et al. [1701.04828](#) (JHEP)

PBD, J. Gehrlein, R. Peses [2008.01110](#) (PRL)

PBD, J. Gehrlein [2008.06062](#) (JHEP), [2204.09060](#) (PRD)

PBD, A. Giannetti, D. Meloni [2210.00109](#) (JHEP), [2409.15411](#) (JHEP)

## 3. Non-standard neutrino self interactions

Barenboim, PBD, Oldengott [1903.02036](#) (PRD)

## 4. Neutrino decay

PBD, I. Tamborra [1805.05950](#) (PRL)

PBD, A. Abdullahi [2005.07200](#) (PRD)

## 5. Unitarity violation

PBD [2109.14576](#) (PRD)

PBD, J. Gehrlein [2109.14575](#) (JHEP)

## 6. Many others: neutrino – dark matter interactions, environmental decoherence, and Lorentz invariance or CPT violation

Two new physics scenarios:  
Non-standard neutrino interactions (NSI)  
Unitarity violation (UV)

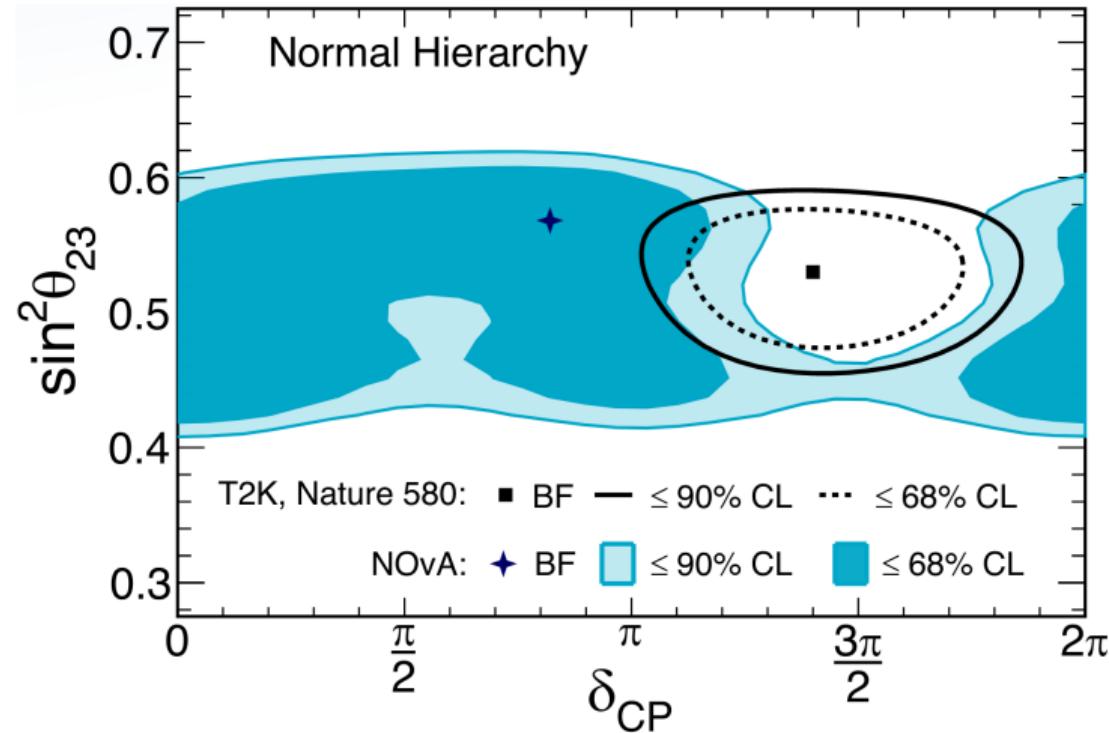
Two new physics scenarios:

**Non-standard neutrino interactions (NSI)**

Unitarity violation (UV)

# CP violation at NOvA and T2K?

Excitement at the Neutrino conference!



A. Himmel for NOvA [10.5281/zenodo.3959581](https://doi.org/10.5281/zenodo.3959581)

# NSI review

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu \nu_\beta) (\bar{f} \gamma_\mu f)$$

Models with large NSIs consistent with CLFV:

Y. Farzan, I. Shoemaker [1512.09147](#)   Y. Farzan, J. Heeck [1607.07616](#)   D. Forero and W. Huang [1608.04719](#)  
K. Babu, A. Friedland, P. Machado, I. Mocioiu [1705.01822](#)   **PBD**, Y. Farzan, I. Shoemaker [1804.03660](#) (JHEP)  
U. Dey, N. Nath, S. Sadhukhan [1804.05808](#)   Y. Farzan [1912.09408](#)   N. Bernal, Y. Farzan [2211.15686](#)  
S. Abbaslu, Y. Farzan [2407.13834](#)

Affects oscillations via new matter effect

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

Matter potential  $a \propto G_F \rho E$

B. Dev, K. Babu, **PBD**, P. Machado, et al. [1907.00991](#)

## Estimate size of effect: magnitude

$$|\epsilon_{e\beta}| \approx \frac{s_{12}c_{12}c_{23}\pi\Delta m_{21}^2}{2s_{23}w_\beta} \left| \frac{\sin \delta_{\text{T2K}} - \sin \delta_{\text{NOvA}}}{a_{\text{NOvA}} - a_{\text{T2K}}} \right| \approx \begin{cases} 0.22 & \text{for } \beta = \mu \\ 0.24 & \text{for } \beta = \tau \end{cases}$$

$a \propto \rho E$

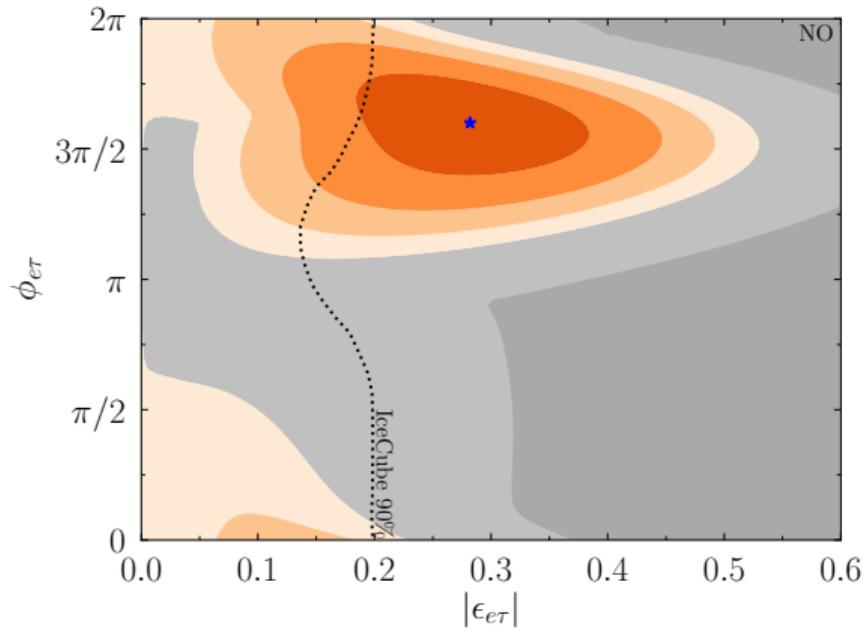
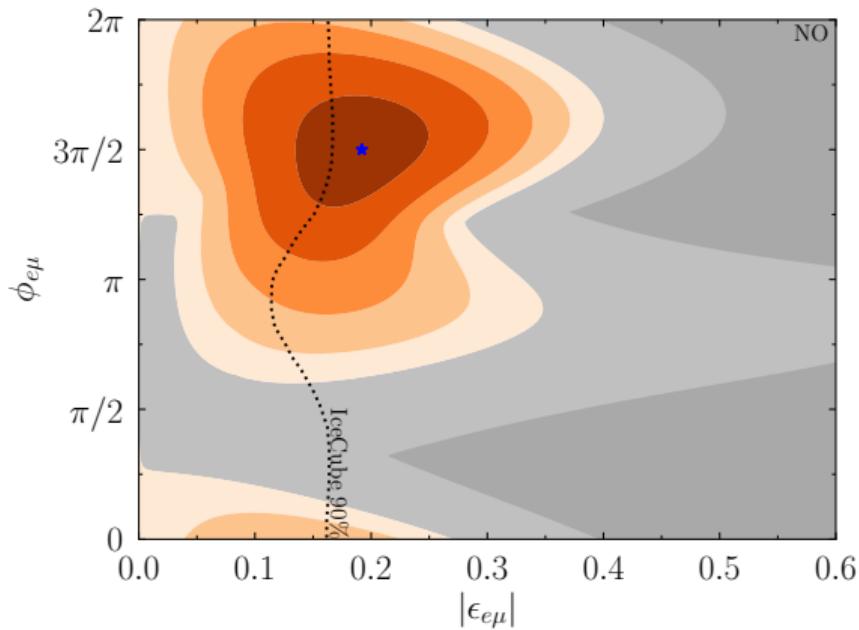
$w_\beta = s_{23}, c_{23}$  for  $\beta = \mu, \tau$

Assumed upper octant  $\theta_{23} > 45^\circ$

Consistency checks:

- ▶  $\sin \delta_{\text{NOvA}} = \sin \delta_{\text{T2K}} \Rightarrow |\epsilon| = 0$
- ▶  $\sin \delta_{\text{NOvA}} \neq \sin \delta_{\text{T2K}}$  and  $a_{\text{NOvA}} = a_{\text{T2K}} \Rightarrow |\epsilon| \rightarrow \infty$
- ▶ Octant:
  1. LBL is governed by  $\nu_3$
  2. Upper octant  $\Rightarrow \nu_3$  is more  $\nu_\mu$
  3. More  $\nu_\mu \Rightarrow$  need less new physics coupling to  $\nu_\mu$  to produce a given effect

# NSI parameters



Orange is preferred over SM at integer values of  $\Delta\chi^2$ , dark gray is disfavored at 4.61

T. Ehrhardt, IceCube [PPNT \(2019\)](#)

$\epsilon_{\mu\tau}$ , IO in backups

## Other CP violating NSI constraints

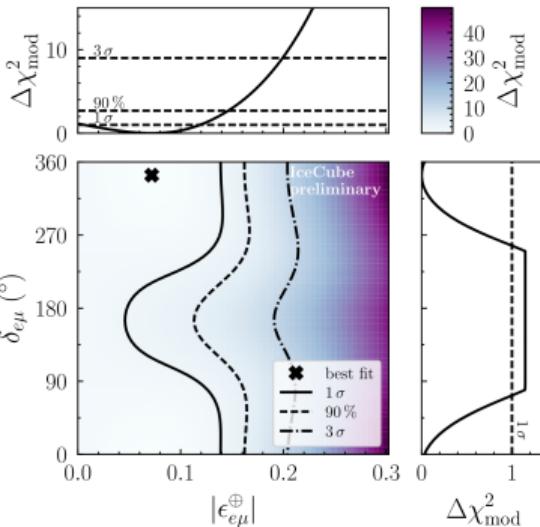
NSI effects grow with energy, density, and distance

# Other CP violating NSI constraints

NSI effects grow with energy, density, and distance

Best probes:

- ▶  $\epsilon_{\mu\tau}$ : atmospheric
- ▶  $\epsilon_{e\mu}, \epsilon_{e\tau}$ : LBL appearance, atmospheric
- ▶ IceCube
  - ▶ Constraint is at LBL best fit with 3 yrs  
10 yrs of data in the bank
  - ▶ Prefers non-zero  $|\epsilon_{e\mu}|$  at  $\sim 1\sigma$



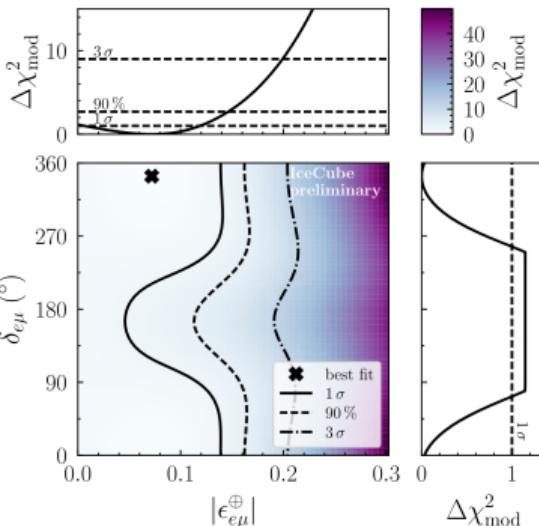
T. Ehrhardt, IceCube [PPNT \(2019\)](#)

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T. Ehrhardt, IceCube [PPNT \(2019\)](#)

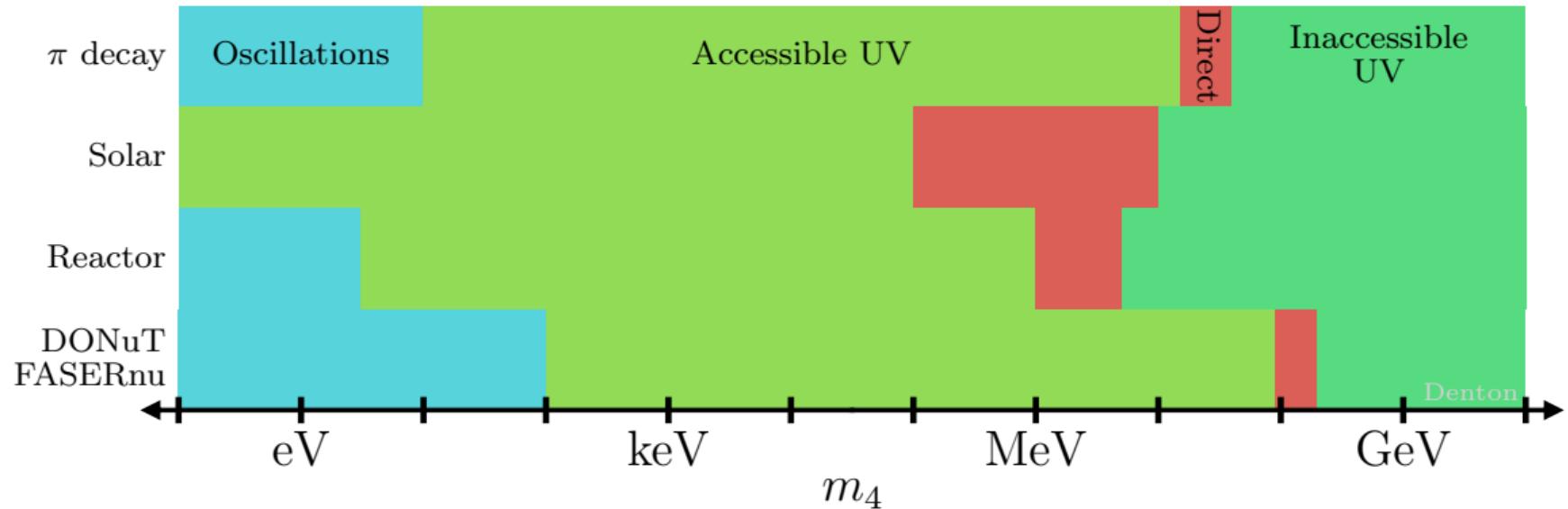
- ▶ Super-K
  - ▶ Only consider real NSI
  - ▶ Comparable sensitivity as IceCube
- ▶ COHERENT
  - ▶ Only applies to NSI models with  $M_{Z'} \gtrsim 10$  MeV
  - ▶ NSI  $u, d, e$  configuration matters
  - ▶ Comparable constraints

Super-K [1109.1889](#)

COHERENT [1708.01294](#)  
PBD, Y. Farzan, I. Shoemaker [1804.03660 \(JHEP\)](#)  
PBD, J. Gehrlein [2008.06062](#)

Two new physics scenarios:  
Non-standard neutrino interactions (NSI)  
**Unitarity violation (UV)**

# Unitarity violation: a tale of two regimes



\*Details depends on the specific experiment/channel

# Unitarity violation: how to calculate

Kinematically **accessible** states

1. Unitary calculation of full  $n \times n$  matrix
2. Oscillation averaged:

$$\sin^2 \frac{\Delta m_{41}^2 L}{4E} \rightarrow \frac{1}{2}$$

$$\sin \frac{\Delta m_{41}^2 L}{4E} \rightarrow 0$$

3. No matter effect:

$$H^{\text{mat}} = \text{diag}(V_{\text{CC}} + V_{\text{NC}}, V_{\text{NC}}, V_{\text{NC}}, 0, \dots)$$

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3. No matter effect:

$$H^{\text{mat}} = \text{diag}(V_{\text{CC}} + V_{\text{NC}}, V_{\text{NC}}, V_{\text{NC}}, 0, \dots)$$

Kinematically **inaccessible** states

1. Nonunitary calculation of  $m \times m$  matrix  
 $m =$  number of kinematically accessible states
2. Rescale probability:

$$P_{\alpha\beta} = \frac{|\sum_{i=1}^{\text{acc}} U_{\alpha i}^* e^{i P_i L} U_{\beta i}|}{(\sum_{i=1}^{\text{acc}} U_{\alpha i}^* U_{\alpha i})(\sum_{i=1}^{\text{acc}} U_{\beta i}^* U_{\beta i})}$$

3. Cannot subtract multiples of  $\mathbb{1}$
4. Rescale cross section/flux as appropriate
5. Rescale  $G_F$  in matter effect

# Unitarity violation status from oscillations

$3\sigma$  maximal deviations from unitarity

Leptons		
	Hu+	Ellis+
$\nu_e$ row	0.003	0.05
$\nu_\mu$ row	0.02	0.04
$\nu_\tau$ row	0.2	0.82
$\nu_1$ col	0.06	0.22
$\nu_2$ col	0.09	0.27
$\nu_3$ col	0.12	0.40

Quarks		
	$u$ row	$c$ row
$d$ col	0.0015	$\sim 2.2\sigma$ tension
$s$ col	-	0.06
$b$ col	0.005	-

Lepton constraints don't include anomalies

Care is required

S. Ellis, K. Kelly, S. Li [2008.01088](#)

Z. Hu, et al. [2008.09730](#)

S. Parke, M. Ross-Lonergan [1508.05095](#)

PDG

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S. Ellis, K. Kelly, S. Li [2008.01088](#)

Z. Hu, et al. [2008.09730](#)

Vastly different mixing angle hierarchy



Like comparing apples and steak

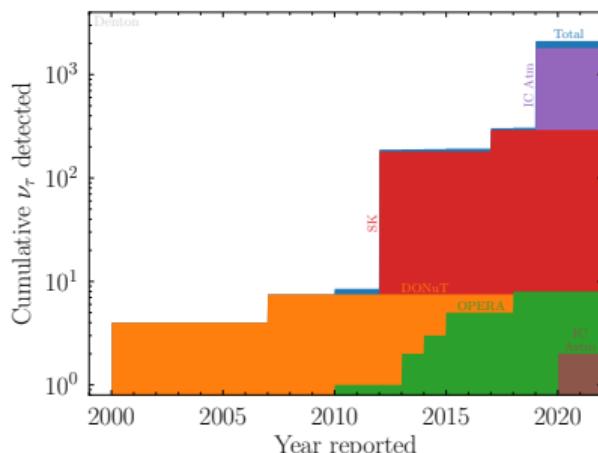
S. Parke, M. Ross-Lonergan [1508.05095](#)

PDG

# Unitarity violation: tau row

Leptons: tau row is the weakest

1. Existing global analyses use OPERA and SNO
2. More data from atmospheric  $\nu_\tau$  appearance!



Also astrophysical  $\nu_\tau$  appearance; weak but distinct!

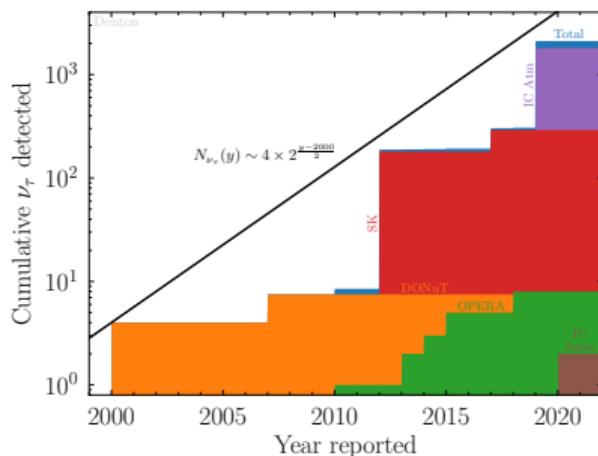
Atmospheric works because  $\tau$  is in **direct** region

PBD, et al. [2203.05591](#) (whitepaper)

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Also astrophysical  $\nu_\tau$  appearance; weak but distinct!

Atmospheric works because  $\tau$  is in **direct** region

Tau neutrino data set doubles every two years!

PBD, et al. [2203.05591](#) (whitepaper)

## Alternative uses for neutrinos

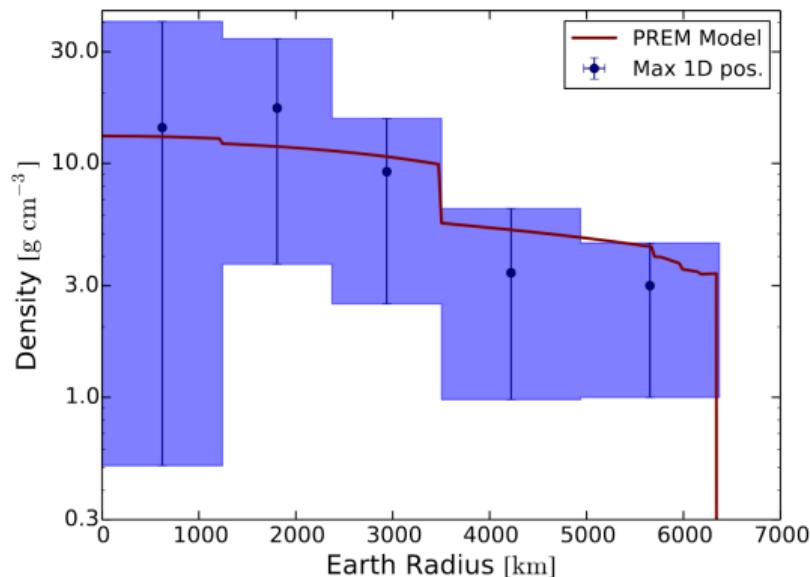


## Alternative uses for neutrinos



# Terrestrial tomography

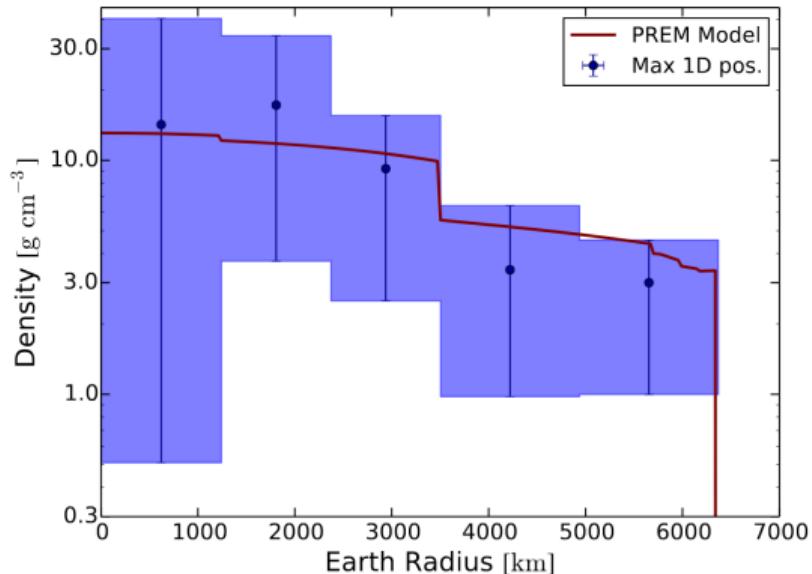
HE neutrinos are absorbed in the Earth  
Assumes isotropic flux



A. Donini, S. Palomares-Ruiz, J. Salvado [1803.05901](#)

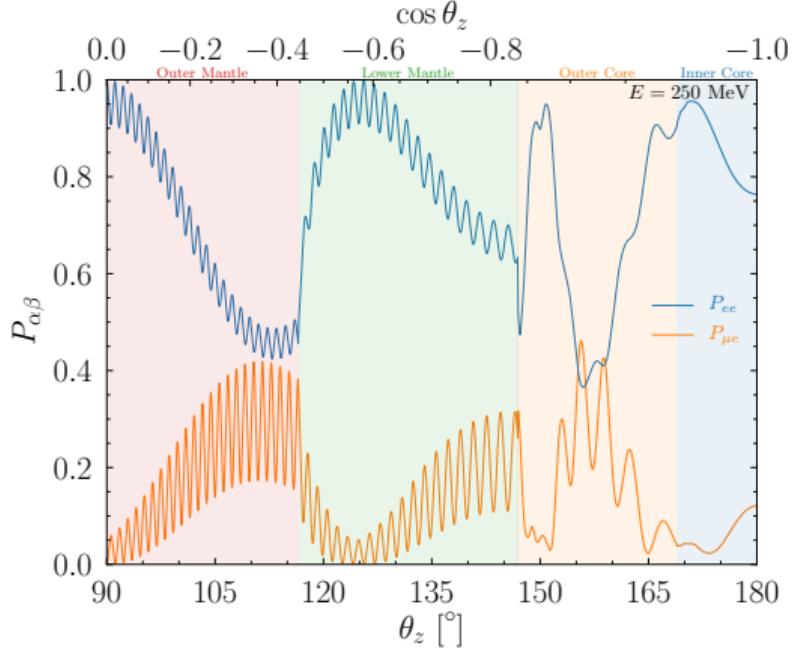
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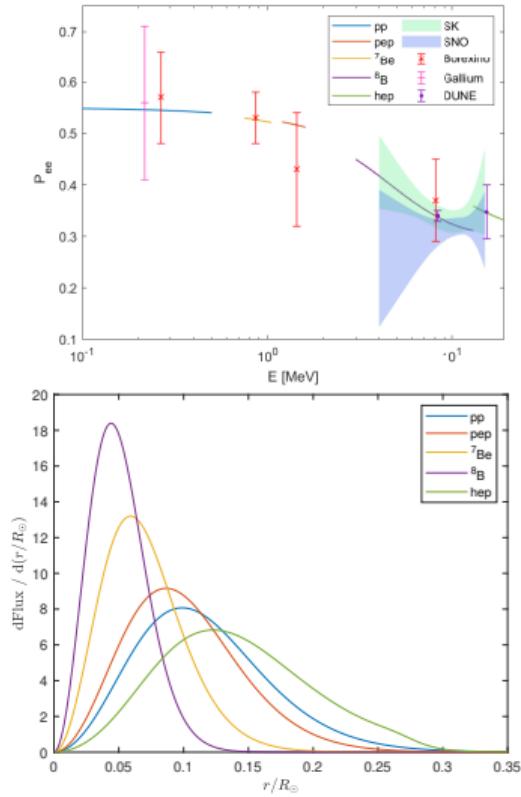
Can also do this with oscillations



DUNE-atm can measure  $r_{\text{core}}^{\oplus}$  to 9%

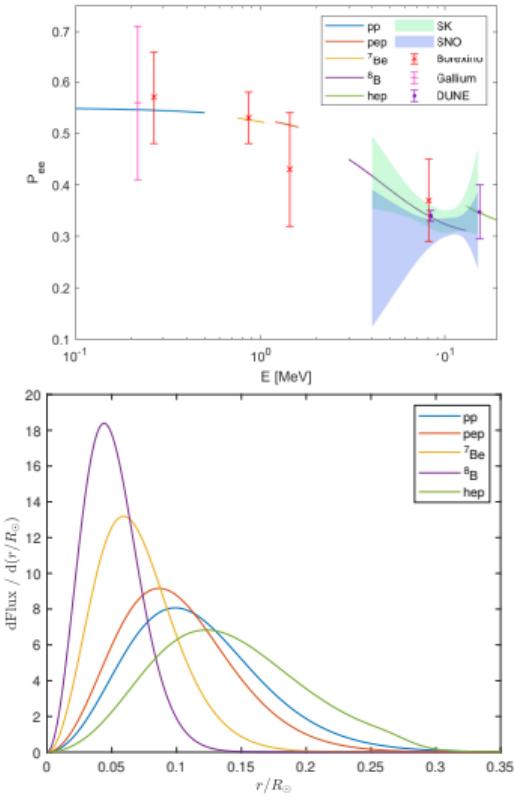
See also K. Kelly, et al. [2110.00003](#)

# Solar tomography



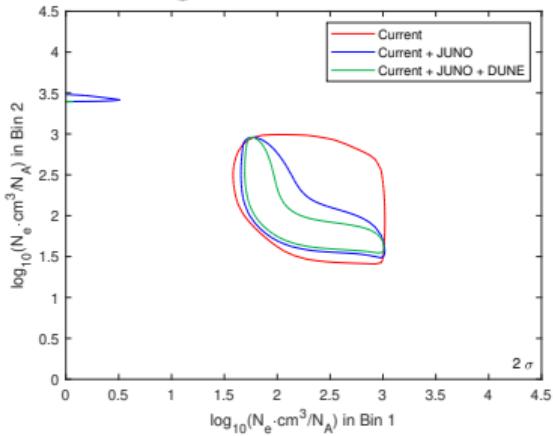
Solar neutrinos constrain Sun's density at different radii

# Solar tomography

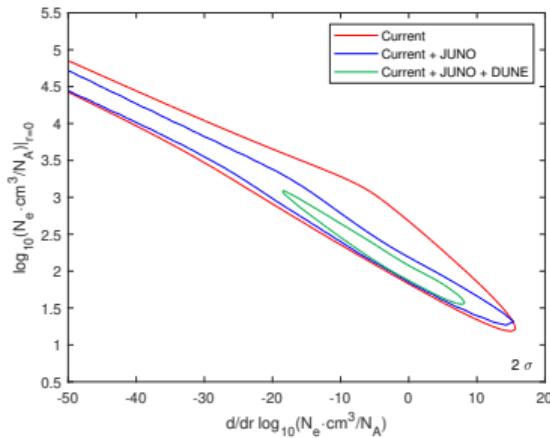


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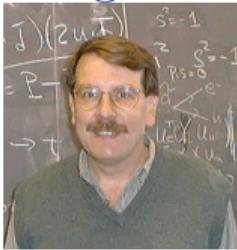
Bin 1:  $\frac{r}{R_\odot} \in [0, 0.05]$   
Bin 2:  $\frac{r}{R_\odot} \in [0.05, 0.1]$



$$\log_{10} N_e = Ar + B$$



# Colleagues



Stephen  
Parke



Julia  
Gehrlein



Hooman  
Davoudiasl



Yasaman  
Farzan



Yves Kini



Rebekah  
Pestes

Peter B. Denton (BNL)



Ian  
Shoemaker



Tom Weiler

Many thanks to these and other great colleagues!

# Neutrino oscillation summary

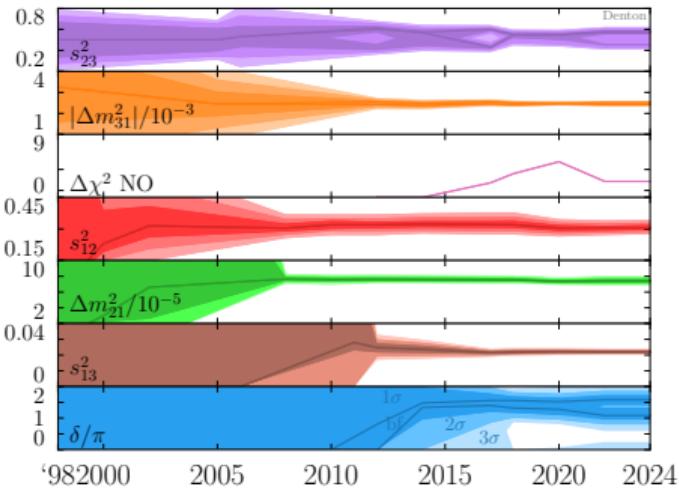
- ▶ Four known unknowns in particle physics: all neutrinos
- ▶ Mass ordering will be measured (robustness?)
- ▶  $\theta_{23}$  octant is important for flavor models
- ▶  $\delta$  could shed light on CP violation
- ▶ Hints of new physics pointing towards NSI, steriles, ...
- ▶ Unitarity violation is phenomenologically very rich
- ▶ Lots of existing tau neutrino information to be utilized!
- ▶ Neutrinos can shine a flashlight into opaque environments



Thanks for the hospitality  
Virginia Tech physics department!

# Backups

# References



SK [hep-ex/9807003](#)

M. Gonzalez-Garcia, et al. [hep-ph/0009350](#)

M. Maltoni, et al. [hep-ph/0207227](#)

SK [hep-ex/0501064](#)

SK [hep-ex/0604011](#)

T. Schwetz, M. Tortola, J. Valle [0808.2016](#)

M. Gonzalez-Garcia, M. Maltoni, J. Salvado [1001.4524](#)

T2K [1106.2822](#)

D. Forero, M. Tortola, J. Valle [1205.4018](#)

D. Forero, M. Tortola, J. Valle [1405.7540](#)

P. de Salas, et al. [1708.01186](#)

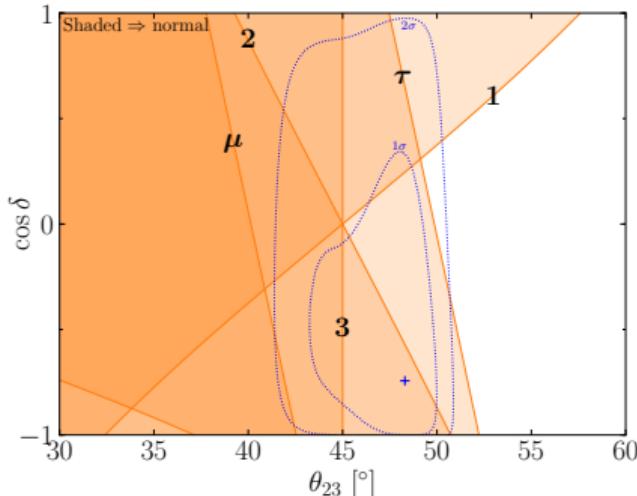
F. Capozzi et al. [2003.08511](#)

# $\theta_{23}$ : broader implications

$\mu$ - $\tau$  interchange/reflection symmetry

Normalcy

Is the heaviest neutrino mostly  $\nu_\tau$ ?  
Is the lightest neutrino least  $\nu_\tau$ ?



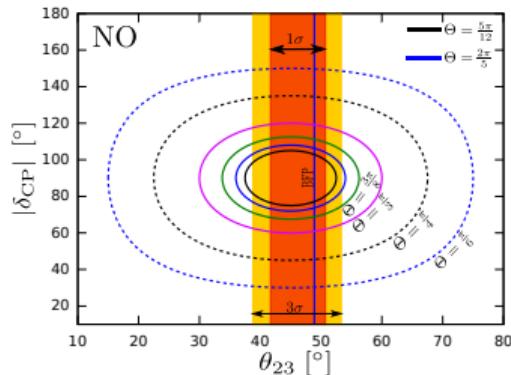
Quarks easily satisfy normalcy PBD 2003.04319

$$\nu_\mu \leftrightarrow \nu_\tau$$

$$M_\nu^* = X M_\nu X^T \quad X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$M_\nu \equiv U D_\nu U^\dagger$$

Predicts:  $\theta_{23} = 45^\circ$ , often  $\theta_{13} = 0$



P. Chen, et al. 1512.01551

$\delta$ : what is it not?

# $\delta \not\Rightarrow$ Baryogenesis

The amount of leptogenesis is a function of:

1.  $\delta$
2. the heavy mass scale
3.  $\alpha, \beta$  (Majorana phases)
4. CP phases in the RH neutrinos
5. ...

C. Hagedorn, et al. [1711.02866](#)

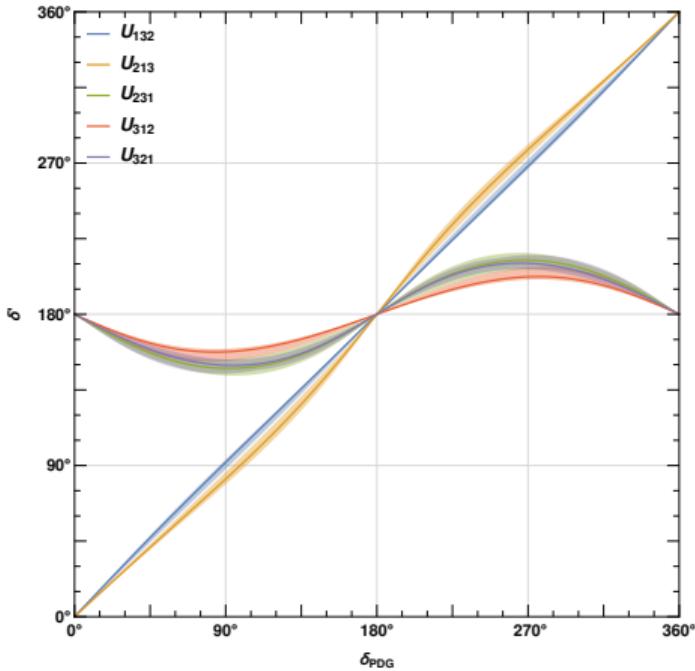
K. Moffat, et al. [1809.08251](#)

Measuring $\delta = 0, \pi$	$\not\Rightarrow$	no leptogenesis
Measuring $\delta \neq 0, \pi$	$\not\Rightarrow$	leptogenesis

# Complex phase in different parameterizations

- ▶ Can relate the complex phase in one parameterization to that in another
- ▶  $U_{132}$  and  $U_{213}$  similar to  $U_{123}$
- ▶  $\delta$  constrained to  $\sim [150^\circ, 210^\circ]$  in  $U_{231}$ ,  $U_{312}$ ,  $U_{321}$
- ▶ Bands indicate  $3\sigma$  uncertainty on  $\theta_{12}$ ,  $\theta_{13}$ ,  $\theta_{23}$
- ▶ “50% of possible values of  $\delta$ ”  
⇒ parameterization dependent

DUNE TDR II [2002.03005](#)



## Quark mixing

From the PDG,  $V_{\text{CKM}}$  in the  $V_{123}$  parameterization is

$$\theta_{12} = 13.09^\circ \quad \theta_{13} = 0.2068^\circ \quad \theta_{23} = 2.323^\circ \quad \delta_{\text{PDG}} = 68.53^\circ$$

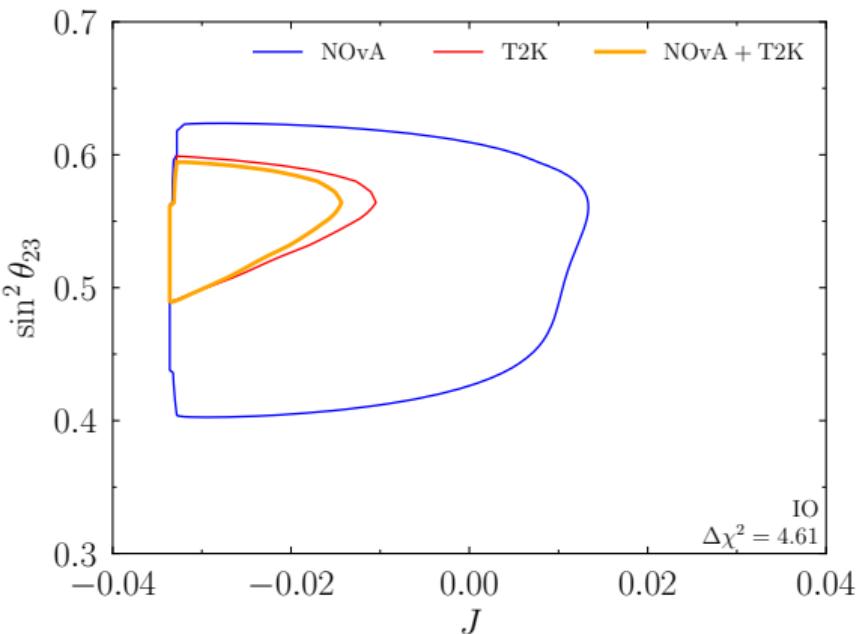
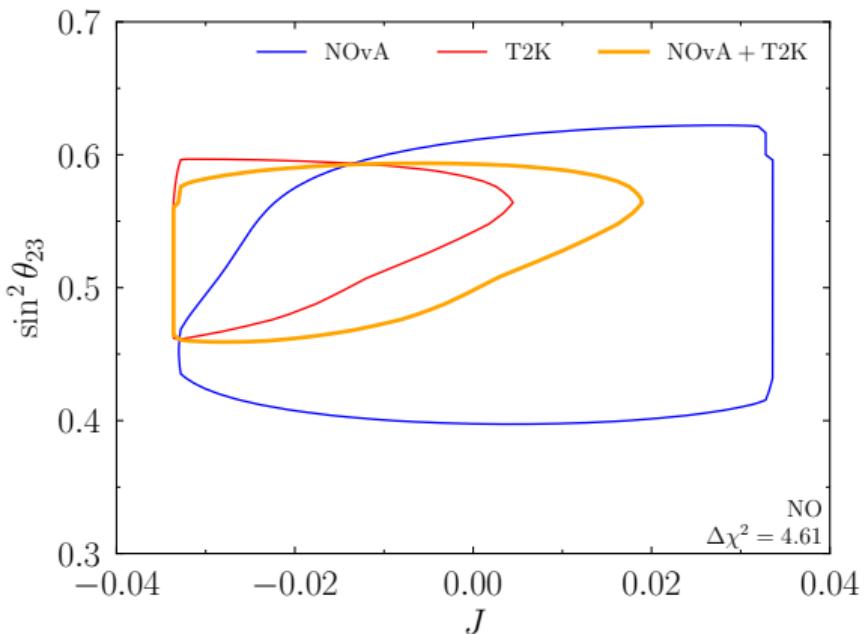
Looks like “large” CPV:

$$\sin \delta_{\text{PDG}} = 0.93 \sim 1$$

yet  $J_{\text{CKM}}/J_{\text{max}} = 3 \times 10^{-4}$ .

Switch to  $V_{212}$  parameterization,  $\Rightarrow \delta' = 1^\circ$  and  $\sin \delta' = 0.02$ .

# Standard oscillation parameters



Can see that the combination doesn't like the NO while it does like the IO  
IO preferred over NO at  $\Delta\chi^2 = 2.3$

# CP violation in oscillations

In vacuum at first maximum:

$$P_{\mu e} - \bar{P}_{\mu e} \approx 8\pi J \frac{\Delta m_{21}^2}{\Delta m_{32}^2}$$

$$J \equiv s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23} \sin \delta$$

C. Jarlskog [PRL 55, 1039 \(1985\)](#)

- ▶ Extracting  $\delta$  from data requires every other oscillation parameter
- ▶  $J$  requires only  $\Delta m_{21}^2$  (up to matter effects)

Matter effects are easily accounted for

$$\hat{J} \simeq \frac{J}{\sqrt{(c_{212} - c_{13}^2 a / \Delta m_{21}^2)^2 + s_{212}^2} \sqrt{(c_{213} - a / \Delta m_{ee}^2)^2 + s_{213}^2}}$$

[PBD](#), S. Parke [1902.07185](#)

[PBD](#), H. Minakata, S. Parke [1604.08167](#)

## When $\delta$ and when $J$ ?

If the goal is **CP violation** the Jarlskog invariant should be used

however

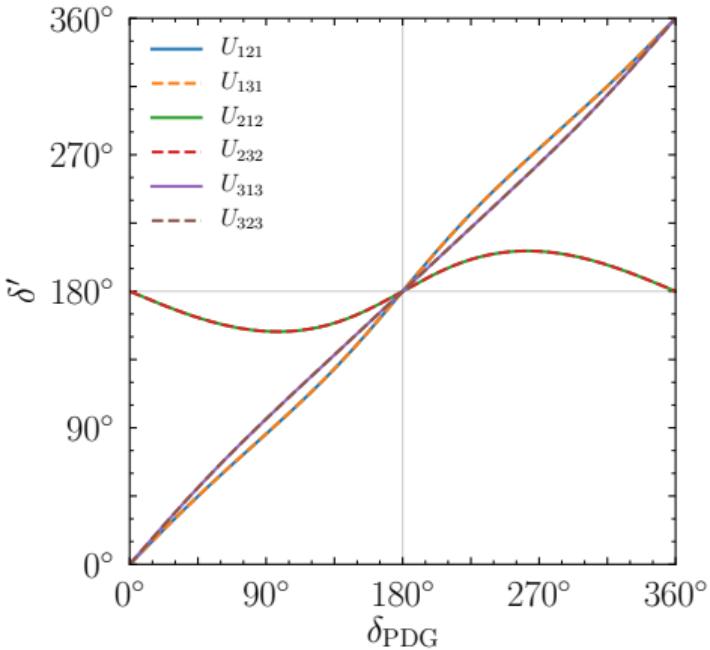
If the goal is **measuring the parameters** one must use  $\delta$

Given  $\theta_{12}$ ,  $\theta_{13}$ ,  $\theta_{23}$ , and  $J$ , I can't determine the sign of  $\cos \delta$  which is physical

e.g.  $P(\nu_\mu \rightarrow \nu_\mu)$  depends on  $\cos \delta$  a tiny bit  
[PBD 2309.03262](#)

- ▶ T2K/HK are mostly sensitivity to  $\sin \delta$ ; they should focus on  $J$   
T2K does this now!
- ▶ NOvA/DUNE has modest  $\cos \delta$  sensitivity; both  $J$  and  $\delta$  should be reported

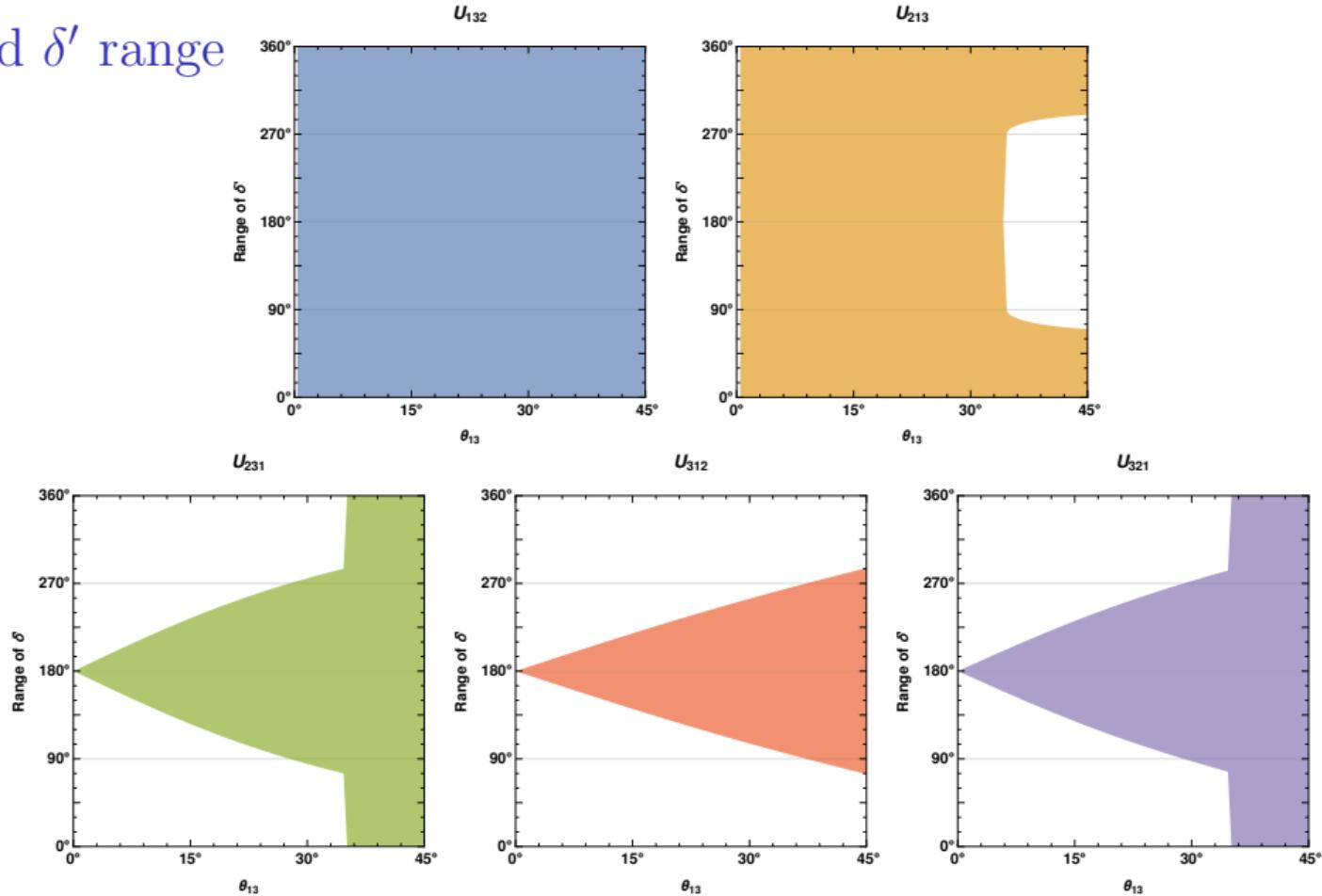
# Repeated rotations



	$U_{121}$	$U_{131}$	$U_{212}$	$U_{232}$	$U_{313}$	$U_{323}$
$ U_{e2} $	✓	✓	✓	✓	✗	✗
$ U_{e3} $	✓	✓	✗	✗	✓	✓
$ U_{\mu 3} $	✗	✗	✓	✓	✓	✓

Note that  $e^{i\delta}$  must be on first or third rotation

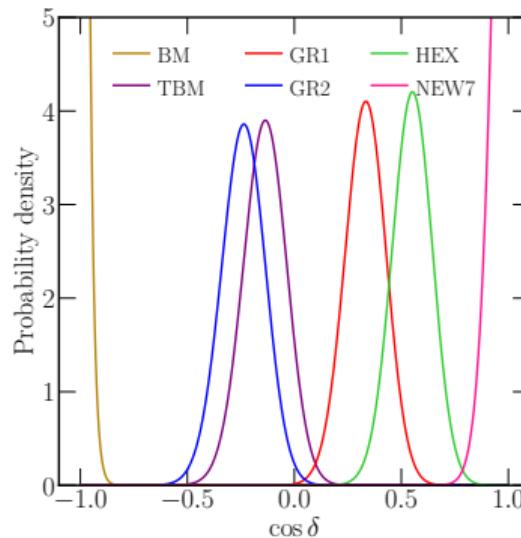
# Allowed $\delta'$ range



# The importance of $\cos \delta$

- ▶ If only  $\sin \delta$  is measured  $\Rightarrow$  sign degeneracy:  $\cos \delta = \pm \sqrt{1 - \sin^2 \delta}$
- ▶ Most flavor models predict  $\cos \delta$

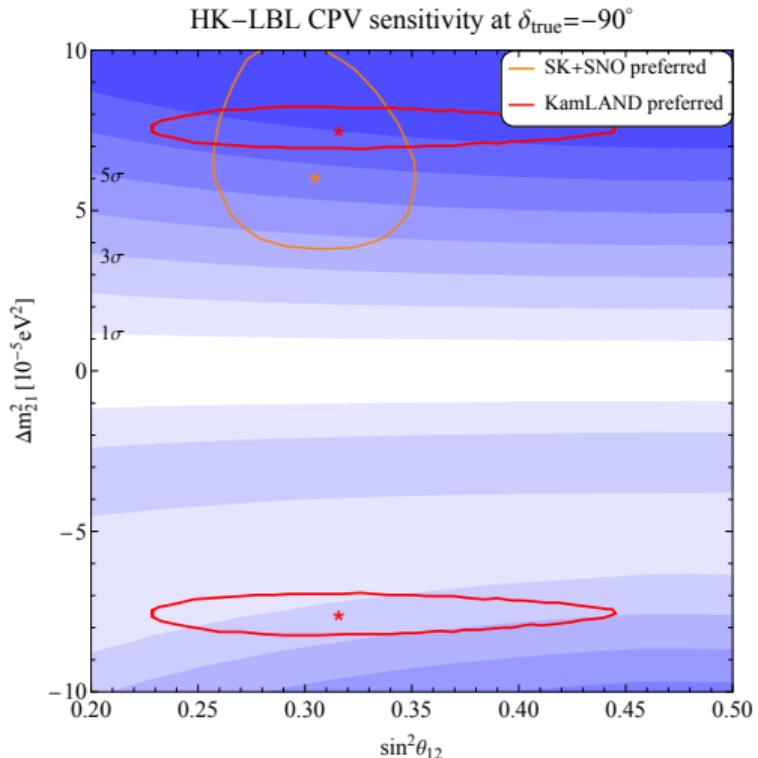
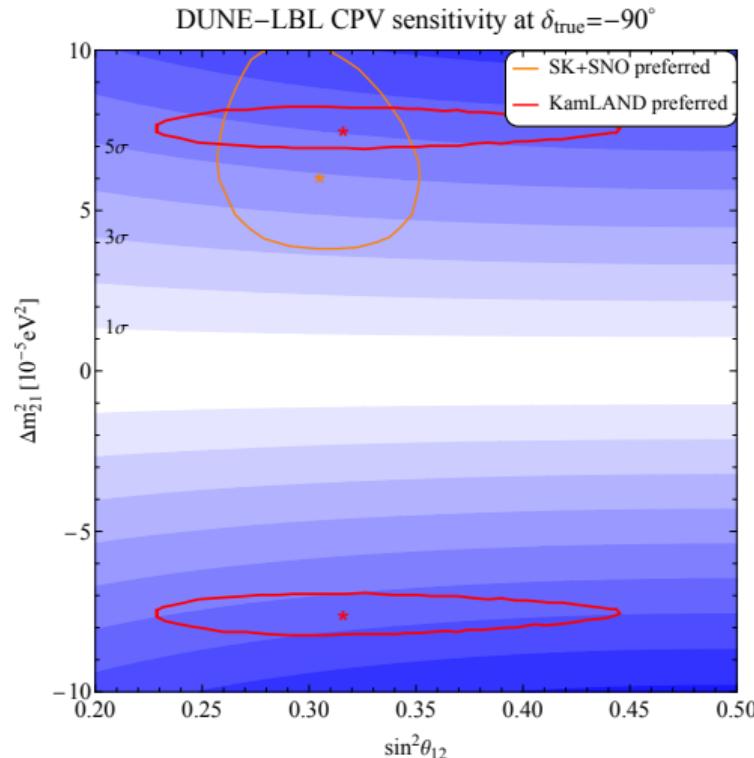
J. Gehrlein, et al. [2203.06219](#)



L. Everett, et al. [1912.10139](#)

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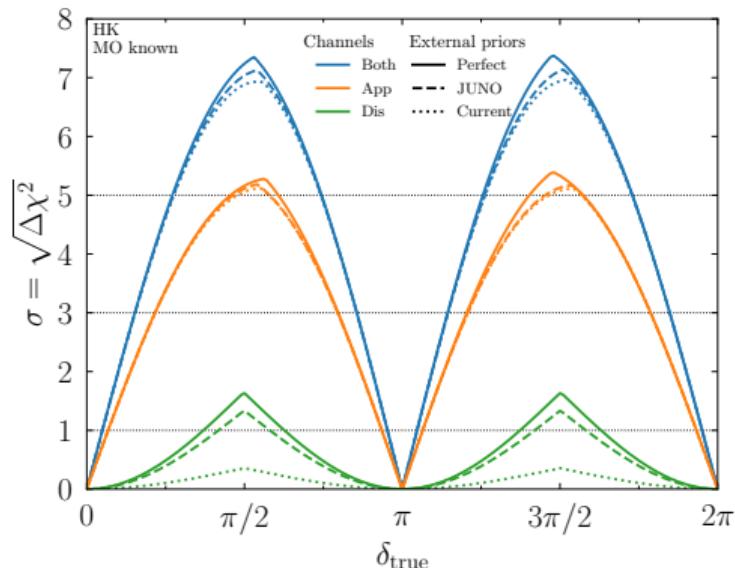
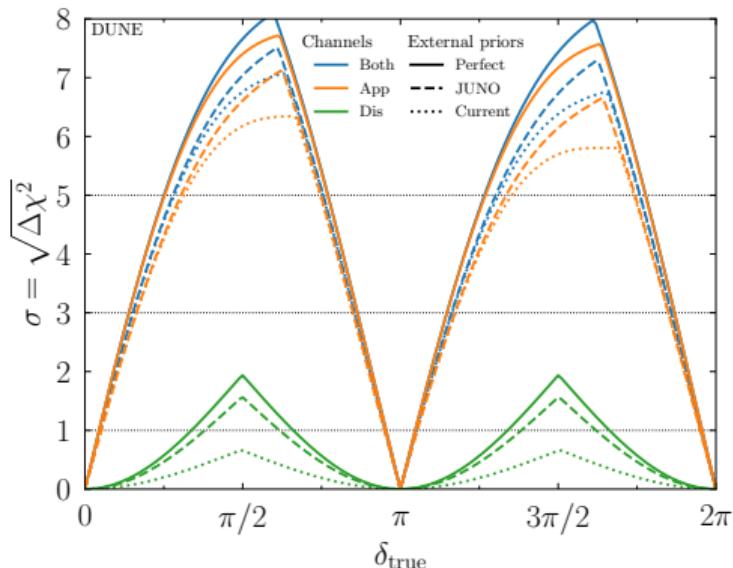
# Impact of the true solar parameters on $\delta$



PBD, J. Gehrlein [2302.08513](#)

# CP violation discovery with disappearance

Need JUNO and DUNE or HK



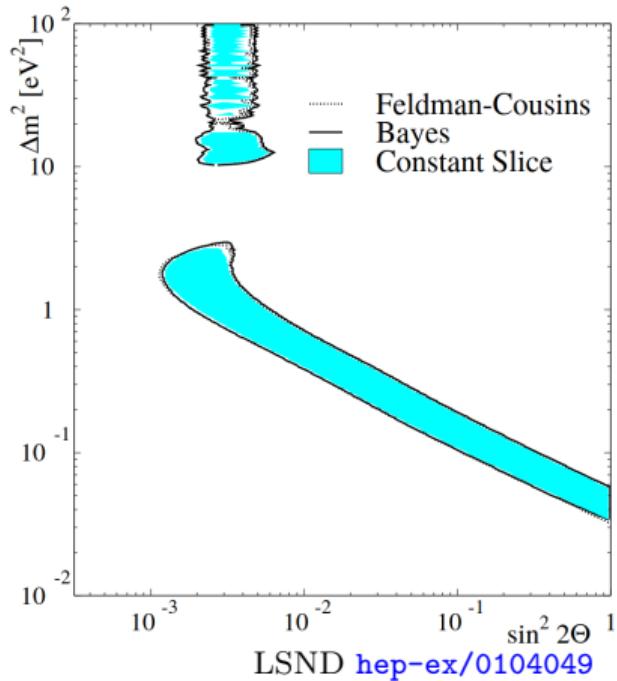
PBD 2309.03262

# Light sterile neutrinos

- ▶ Sterile neutrinos are a generic prediction of most neutrino mass models
- ▶ Sterile neutrinos at  $m_4 \sim \text{keV}$  could be dark matter
- ▶ Nobody asked for steriles at  $m_4 \sim 1 \text{ eV}$
- ▶ Would lead to new oscillations
- ▶ Many hints pointing to  $m_4 \sim 1 \text{ eV}$
- ▶ Cosmology?

# Accelerator: LSND

- ▶ LSND ran from 1993-1998
- ▶  $E_{\bar{\nu}_\mu} \in [20, 53]$  MeV
- ▶  $L = 30$  m
- ▶ Looked for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  appearance
- ▶ Excess of:  $87.9 \pm 22.4 \pm 6.0 \Rightarrow 3.8\sigma$  (1 dof)
- ▶ Interesting region:
  - ▶  $\Delta m_{41}^2 \sim 1$  eV<sup>2</sup>
  - ▶  $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sim 0.002$   
OPERA, ICARUS disfavor  $\sin^2 2\theta_{\mu e} \gtrsim 0.02$

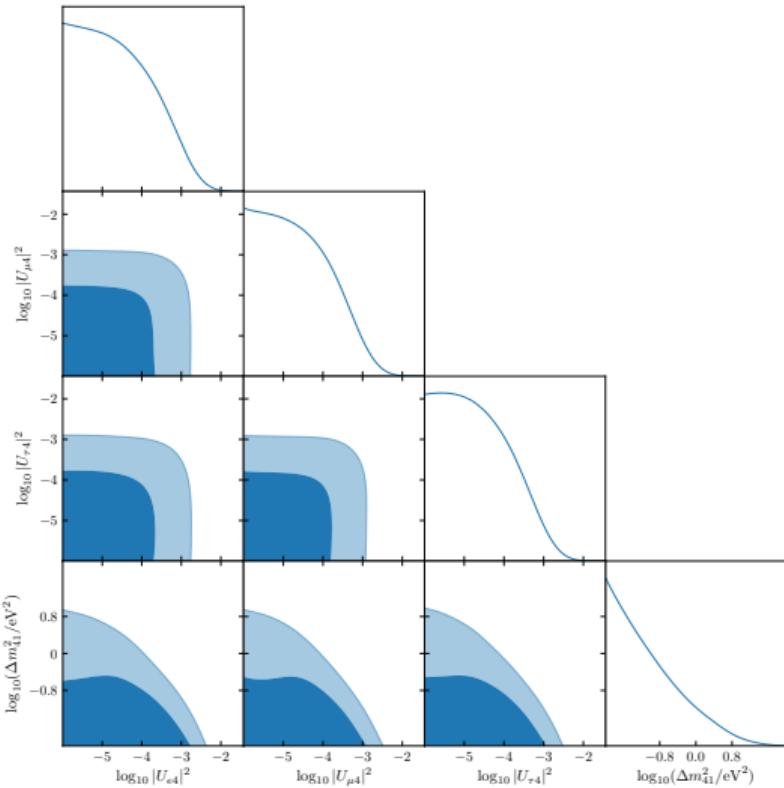


## Accelerator: MiniBooNE

- ▶ Built to test LSND, higher energy, longer baseline, similar  $L/E$ , both  $\nu, \bar{\nu}$
- ▶  $E_{\nu_\mu} \sim 500$  MeV
- ▶  $L = 541$  m
- ▶ Excesses:
  - ▶  $\nu_e$ :  $381.2 \pm 85.2 \Rightarrow 4.5\sigma$  (1 dof)
  - ▶  $\bar{\nu}_e$ :  $79.3 \pm 28.6 \Rightarrow 2.8\sigma$  (1 dof)
  - ▶ Combined:  $4.7\sigma$  (1 dof)
  - ▶ Excesses consistent with LSND under sterile hypothesis
  - ▶ Combined with LSND:  $\Rightarrow 6.0\sigma$  (1 dof)

MiniBooNE [1805.12028](#)

# Cosmological bounds

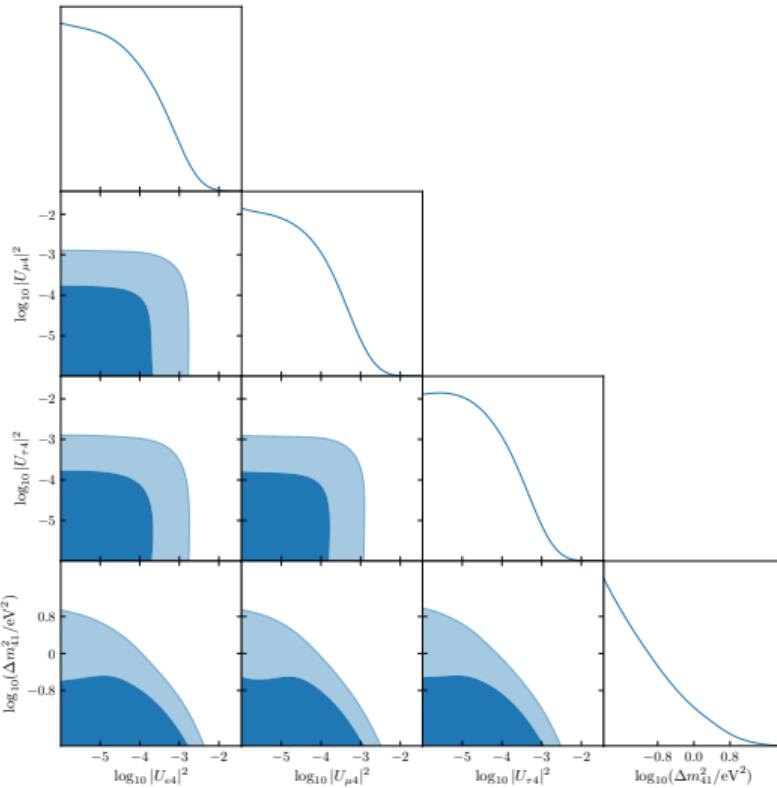


$1\sigma, 2\sigma$

S. Hagstotz, et al. [2003.02289](#)

- ▶ Includes CMB temperature, polarization, and lensing, and BAO
- ▶ No local  $H_0$  constraint
- ▶ Bounds independent of flavor
- ▶ To be consistent with data must have small mixing **and** small mass

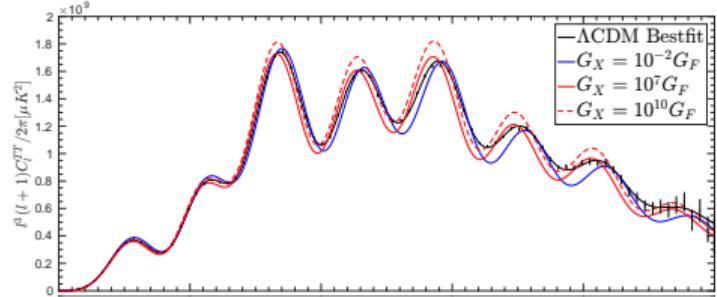
# Cosmological bounds



$1\sigma, 2\sigma$

S. Hagstotz, et al. [2003.02289](#)

- ▶ Includes CMB temperature, polarization, and lensing, and BAO
- ▶ No local  $H_0$  constraint
- ▶ Bounds independent of flavor
- ▶ To be consistent with data must have small mixing **and** small mass
- ▶ Much more than just  $N_{\text{eff}}$  and  $\sum m_\nu$
- ▶ Just adding a new interaction is not straightforward



N. Song, M. Gonzalez-Garcia, J. Salvado [1805.08218](#)

# Gallium experiments

- ▶ Low energy solar neutrino experiments measure the  $pp$  flux
  - ▶ Consistent with KamLAND

SAGE [0901.2200](#)

GALLEX [1001.2731](#)

- ▶ Callibrate detectors with intense radioactive sources
- ▶ See fewer  $\nu_e$  than expected:

$3.0\sigma$ : C. Giunti, M. Laveder [1006.3244](#)

$2.3\sigma$ : J. Kostensalo, et al. [1906.10980](#)

$> 4\sigma$ : BEST [2109.11482](#)

- ▶ Cannot be easily explained with SM physics

C. Giunti, et al. [2212.09722](#)

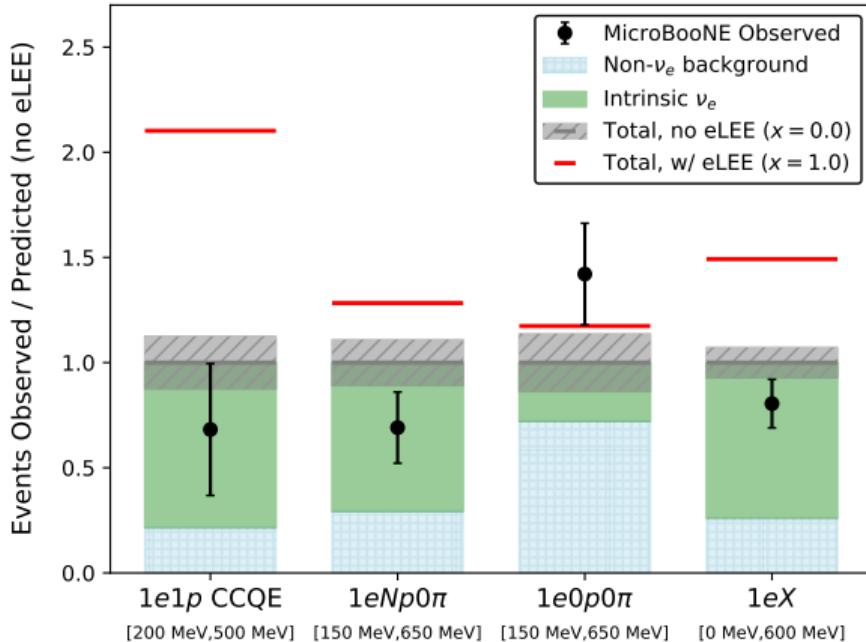
V. Brdar, J. Gehrlein, J. Kopp [2303.05528](#)

W. Haxton, et al. [2303.13623](#)

- ▶ Prefers:

- ▶  $\Delta m_{41}^2 \gtrsim 0.5 \text{ eV}^2$
- ▶  $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2) \sim 0.4$

# MicroBooNE



- ▶ Three analysis teams:
  1. Wire-Cell
  2. Deep Learning
  3. Pandora
    - ▶ With 0 protons
    - ▶ With 1+ protons
- ▶ Underfluctuation compared to no-oscillations
- ▶ Disfavors MiniBooNE's best fit LEE hypothesis at  $3.75\sigma$

MicroBooNE [2110.14054](#)

# MicroBooNE disappearance

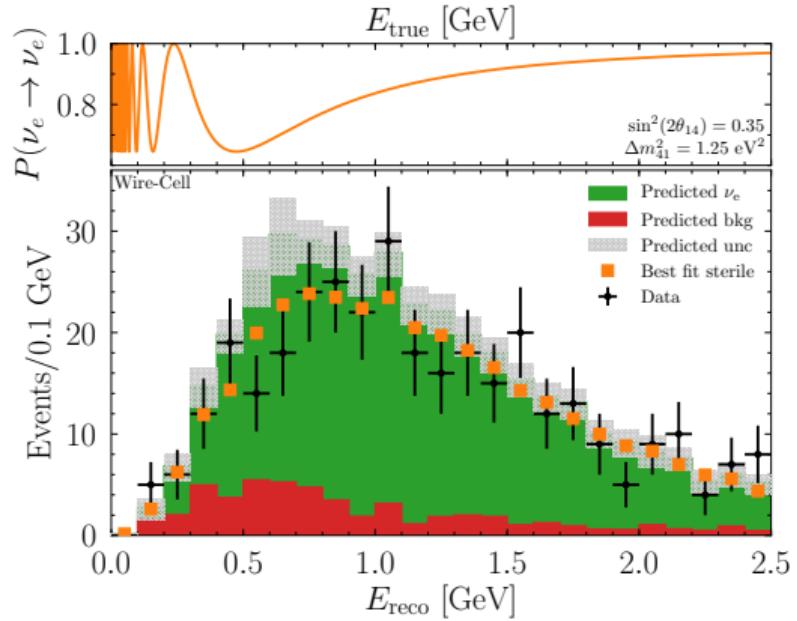
MicroBooNE is focused on  $\nu_e$  appearance  
Can do  $\nu_\mu$  and  $\nu_e$  disappearance too!

See also D. Cianci, et al. [1702.01758](#)

MiniBooNE backgrounds too big, plus anomaly

# Dip hunting

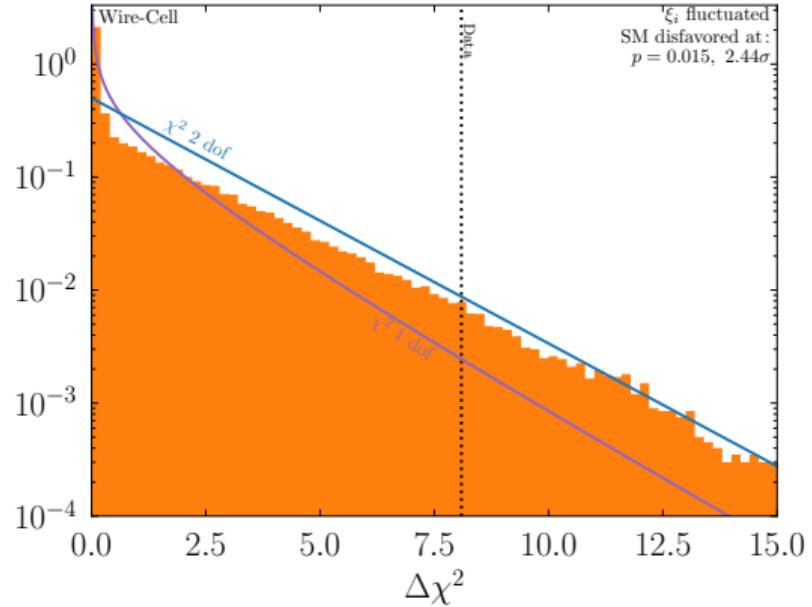
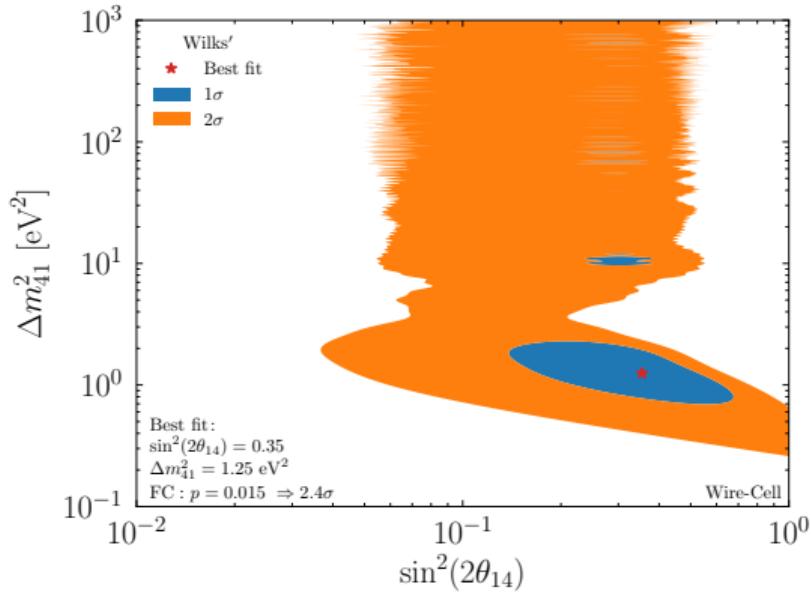
- ▶ 4 analysis channels
  - ▶ Wire cell has most statistics
  - ▶ Analyses not fully independent
- ▶ Dip appears in multiple analyses



# Analysis procedure

1. Take systematics as fully uncorrelated bin to bin
2. Unfold predicted spectrum to spectrum in true energy
  - ▶ Use a derivative regulator
3. Apply oscillation probability
4. Reapply energy smearing
5. Compare to data with LLR-Poisson with pull terms
6. Apply Feldman-Cousins
  - ▶ Fluctuate systematics
  - ▶ Literature suggests this is conservative
  - ▶ Verified that it is conservative in this case
7. Get contours via Wilks'
  - ▶ FC contours are very similar

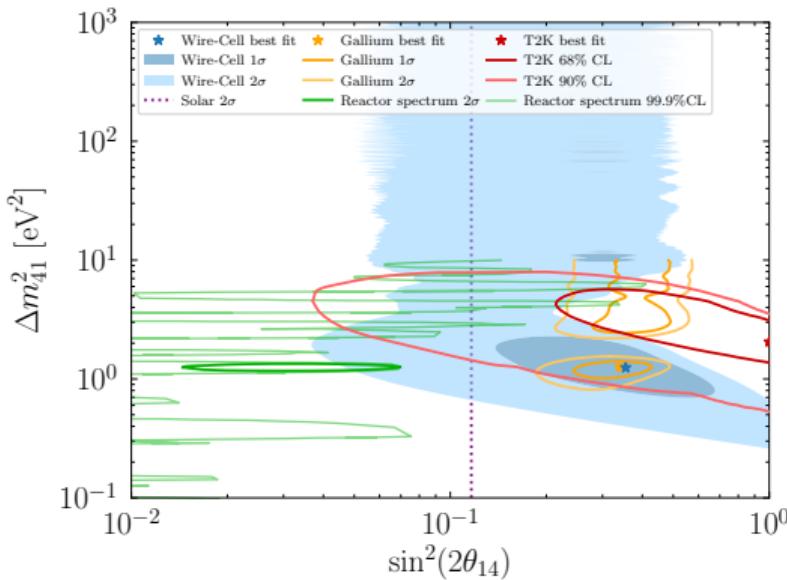
# Results and Monte Carlo significance



## Other MicroBooNE analysis channels

Analysis	$\sin^2(2\theta_{14})$	$\Delta m_{41}^2$ (eV $^2$ )	$N\sigma$ (FC)
Wire-Cell	$0.35^{+0.19}_{-0.16}$	$1.25^{+0.74}_{-0.39}$	2.4
Deep-Learning	$0.88^{+0.12}_{-0.41}$	$3.91^{+0.40}_{-0.40}$	1.8
Pandora-Np	$0.81^{+0.19}_{-0.47}$	[1.28,2.44]	2.4
		$6.73^{+1.75}_{-0.90}$	
Pandora-0p	$1^{-0.29}$	$2.21^{+0.82}_{-0.60}$	1.8
		$\vdots$	

# Global $\nu_e$ disappearance picture



- ▶ MicroBooNE and gallium regions agree
- ▶ Constraints from solar and reactor
- ▶ Cosmology disfavors entire plane!

# Shape-shifting sterile neutrinos

How to evade constraints?

# Shape-shifting sterile neutrinos

## How to evade constraints?

Suppose:

1. Sterile neutrinos talk to dark matter  
DM is ultralight boson
2. Dark matter talks to baryons

Then:

1. Sterile neutrinos aren't abundantly produced in the early universe
2. Mixing angle in the Sun is suppressed
3. Reactor constraints still exist

H. Davoudiasl, [PBD 2301.09651](#)

[PBD 2301.11106](#)

# Unitarity violation

Consistency of the three-flavor oscillation picture?

and/or

Searches for unitarity violation?

# Unitarity violation

Consistency of the three-flavor oscillation picture?

and/or

Searches for unitarity violation?

Not the same!

Lots of models to test standard three-flavor picture:  
Sterile, unitarity violation, NSI, neutrino decay, decoherence, ...

# Unitarity violation: what is it?

Our  $3 \times 3$  matrix isn't unitary:

$$U_3 U_3^\dagger \neq \mathbb{1}$$

Addition of new flavor states  $\nu_a, \nu_b, \nu_c, \dots$  and new mass states  $\nu_4, \nu_5, \nu_6$

$$U \rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \textcolor{red}{U_{e4}} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \textcolor{red}{U_{\mu 4}} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \textcolor{red}{U_{\tau 4}} & \cdots \\ \textcolor{red}{U_{a1}} & \textcolor{red}{U_{a2}} & \textcolor{red}{U_{a3}} & U_{a4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Unitarity Violation  $\Rightarrow$

New mass states not directly accessible by oscillations or decay

Thus check if  $U_3$  is what it should be

## Unitarity constraints

Unitary violation: the study of how  $U_{3 \times 3}$  is not unitary independent of  $m_4, m_5, \dots$   
Constraints vary considerably in the literature:

$$1 - |U_{e1}|^2 - |U_{e2}|^2 - |U_{e3}|^2 < \begin{cases} 0.05 & \text{at } 2\sigma \\ 0.001 & \end{cases}$$

S. Parke, M. Ross-Lonergan [1508.05095](#)

Z. Hu, et al. [2008.09730](#)

## Unitarity constraints

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Constraints vary considerably in the literature:

$$1 - |U_{e1}|^2 - |U_{e2}|^2 - |U_{e3}|^2 < \begin{cases} 0.05 & \text{at } 2\sigma \\ 0.001 & \end{cases}$$

All analyses *assume* unitarity

Throw out LSND, MiniBooNE, RAA, gallium, etc.

S. Parke, M. Ross-Lonergan [1508.05095](#)

Z. Hu, et al. [2008.09730](#)

## Unitarity violation

- ▶ Could conceivably differentiate: 2 new states from 1, but not 3+ from 2
- ▶ Zero distance effect  $\Rightarrow$  near detector **with flux prediction**
  - E.g. RAA, Gallium
- ▶ Numerous parameterizations:  $\alpha$  matrix,  $\eta$  matrix, submatrix & Cauchy-Schwartz
  - All apply to the inaccessible cases only
- ▶ There is an approximate correspondence to sterile and NSI

$$\alpha_{ee} \approx \frac{1}{2}(s_{14}^2 + s_{15}^2 + s_{16}^2) \approx -\epsilon_{ee}, \quad \dots$$

M. Blennow, et al. [1609.08637](#)

Applies one experiment at a time

- ▶ Additional EW precision information: W, Z,  $\pi$ ,  $\mu$ ,  $\tau$  decays

Care is required

S. Antusch, et al. [hep-ph/0607020](#)

S. Antusch, O. Fischer [1407.6607](#)

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# Unitarity violation: mass ranges for tau neutrinos

experiment	(4,4) ( $m_4$ )	(5,3) ( $m_4$ )
atmospheric $\nu_\mu$ disappearance	$\in [10 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
atmospheric $\nu_\tau$ appearance	$\in [10 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
astrophysical $\nu_\tau$ appearance	$\lesssim 15 \text{ MeV}$	$\gtrsim 40 \text{ MeV}$
solar ${}^8\text{B}$	$\lesssim 5 \text{ MeV}$	$\gtrsim 20 \text{ MeV}$
DONuT/FASERnu	$\in [100 \text{ eV}, 90 \text{ MeV}]$	$\gtrsim 200 \text{ MeV}$
LBL $\nu_\tau$ appearance (OPERA)	$\in [1 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
LBL $\nu_\tau$ appearance (DUNE)	$\in [0.1 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
LBL $\nu_\mu$ disappearance (DUNE)	$\in [0.1 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
CEvNS	$\in [10 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$

PBD, J. Gehrlein [2109.14575](#)