

Abstract

In particle physics there exist two regions: the Standard Model which is fairly complete and the new physics sector which is completely unknown. Inbetween 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.

Knowns and Unknowns in Neutrinos

Peter B. Denton

MIT

October 23, 2023



Brookhaven™
National Laboratory



Speaking from [Massachusetts](#) land

Approach

1. Brief pedagogical **review** of neutrino oscillations
2. Where we are **today** with oscillations
3. What kinds of other **new physics** might be out there

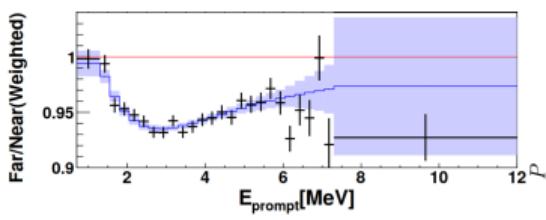
Neutrino oscillations: how it works

Do neutrinos have mass?

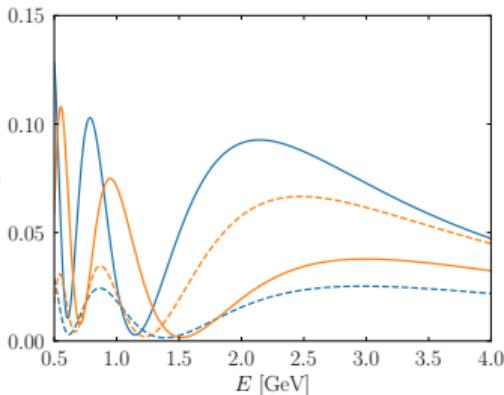
- ▶ Neutrinos seemed to be massless
- ▶ Direct kinematic searches have still not yielded any indication for a mass

KATRIN [2105.08533](#)

Do neutrinos have mass?



Daya Bay [1809.02261](#)

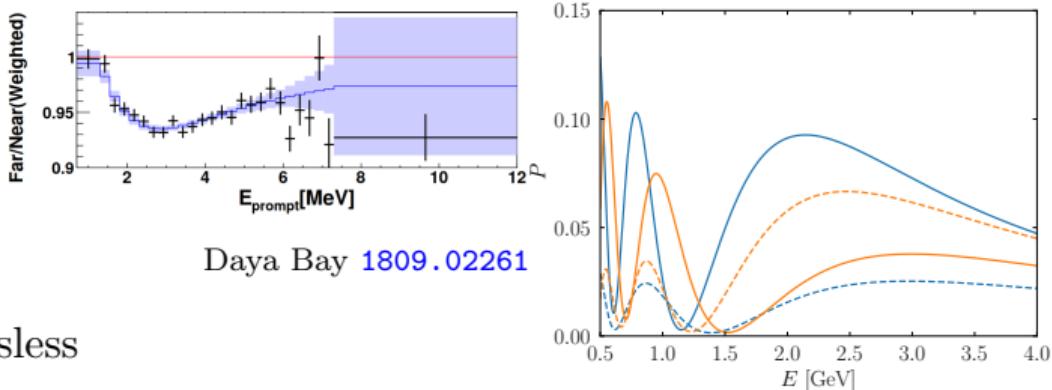


KATRIN [2105.08533](#)

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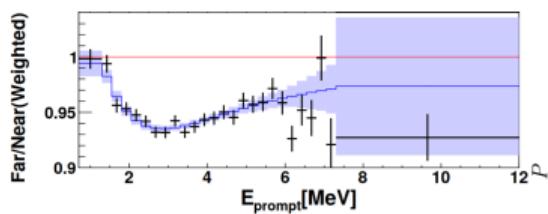


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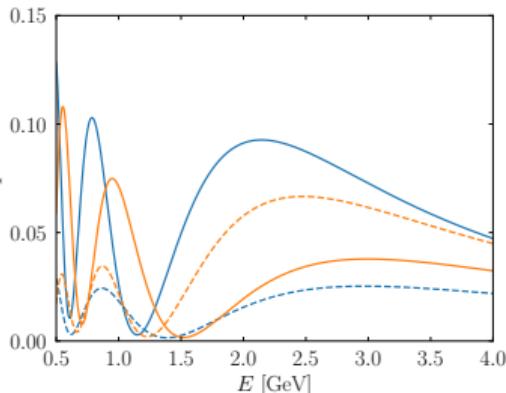
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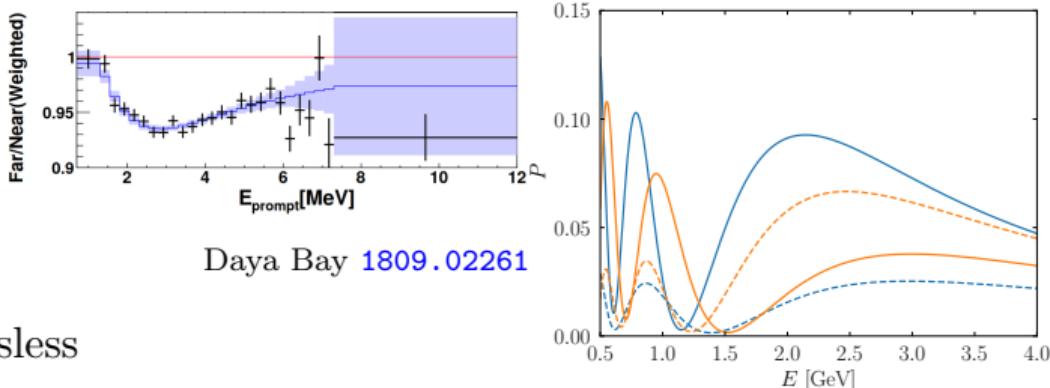
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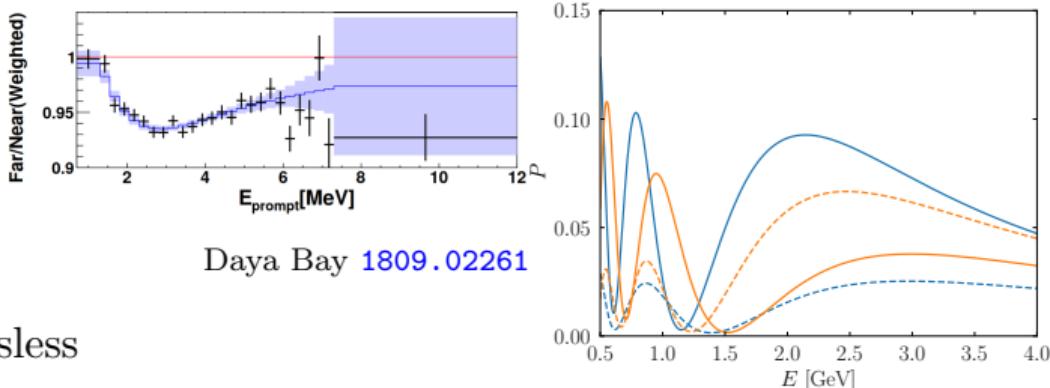
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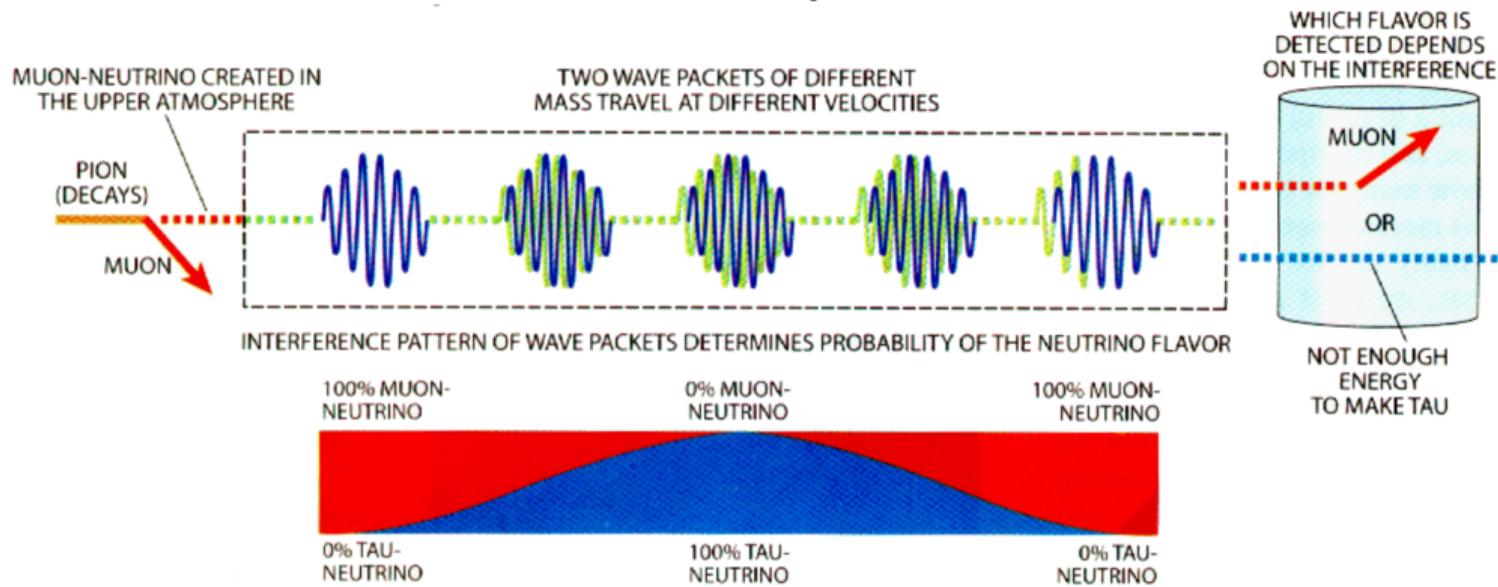
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Neutrinos oscillate!

- ▶ 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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$$H = \begin{pmatrix} E_1 & & \\ & E_2 & \\ & & E_3 \end{pmatrix}$$

$$|\nu_i(t)\rangle = e^{-iEt} |\nu_i(0)\rangle$$

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Subtract a common phase pt from all:

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

Some neutrino oscillation theory

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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 neutrinos in a different basis

QM superposition!

In the flavor/interaction basis:

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

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

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

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U_{PMNS} is: complex, 3×3 , unitary; 4 parameters: θ_{23} , θ_{13} , θ_{12} , δ

Many different ways to parameterize matrix:

PBD, R. Pesles [2006.09384](#)

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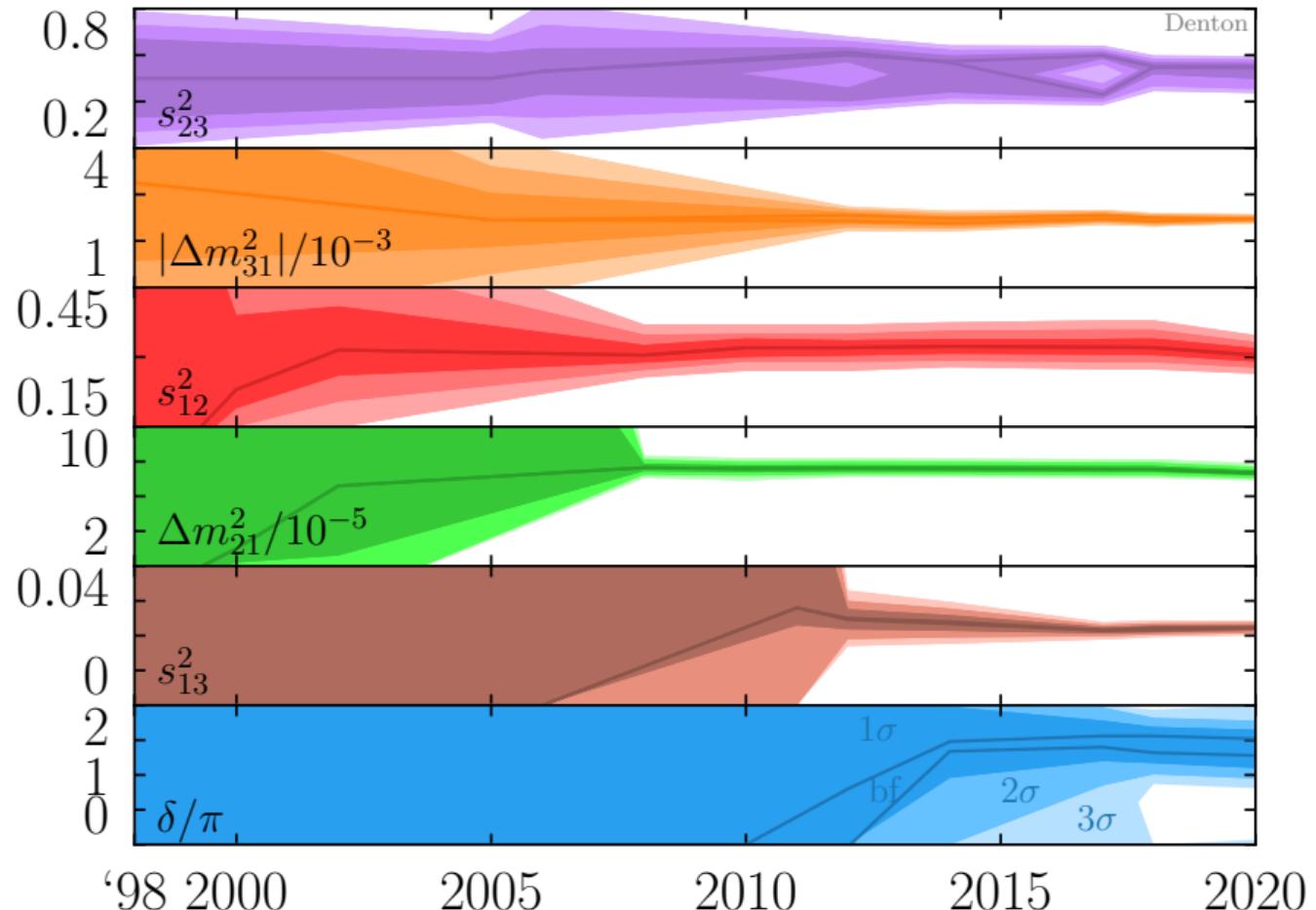
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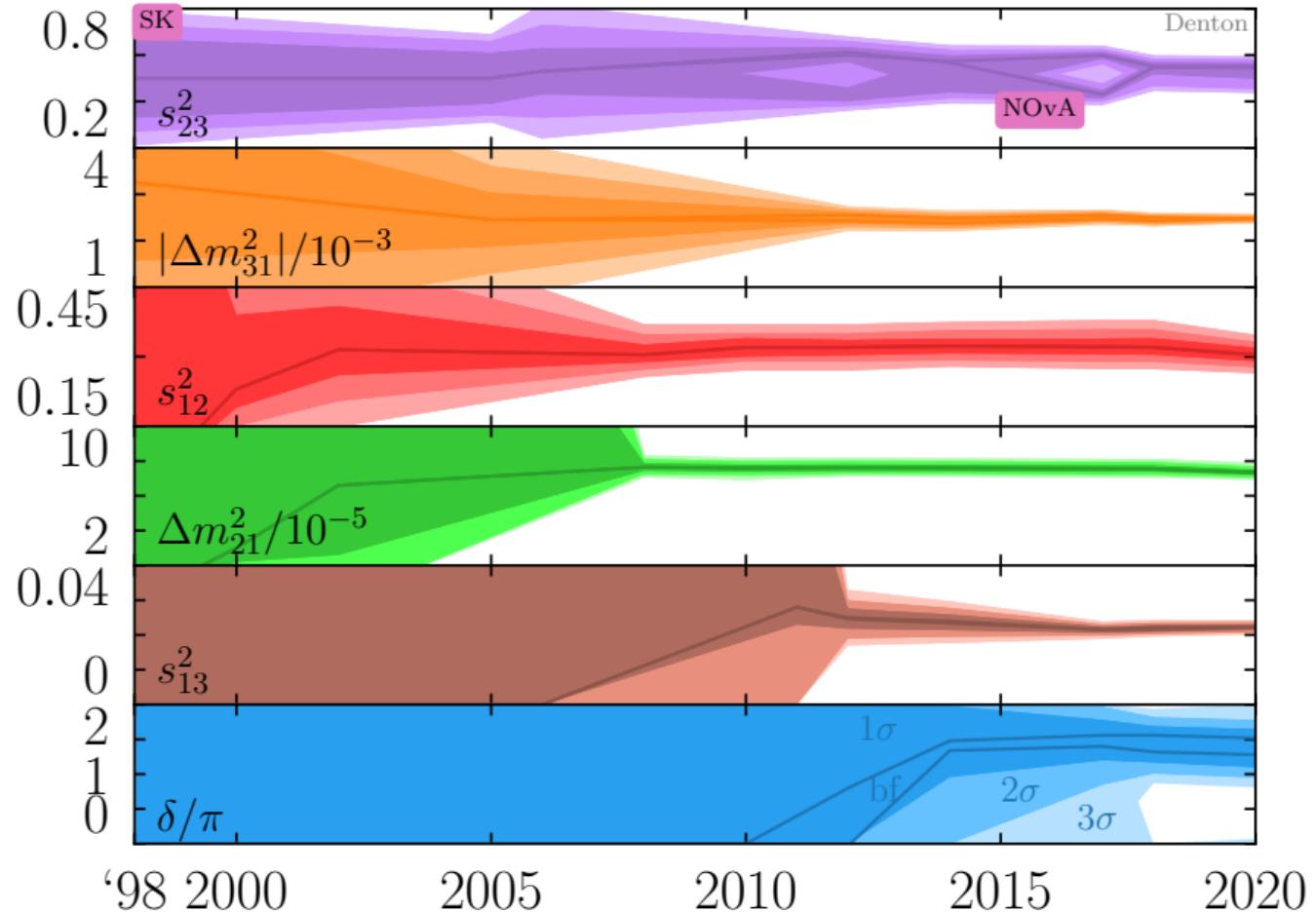
$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_{i=1}^3 U_{\alpha i}^* e^{-im_i^2 L/2E} U_{\beta i} \right|^2$$

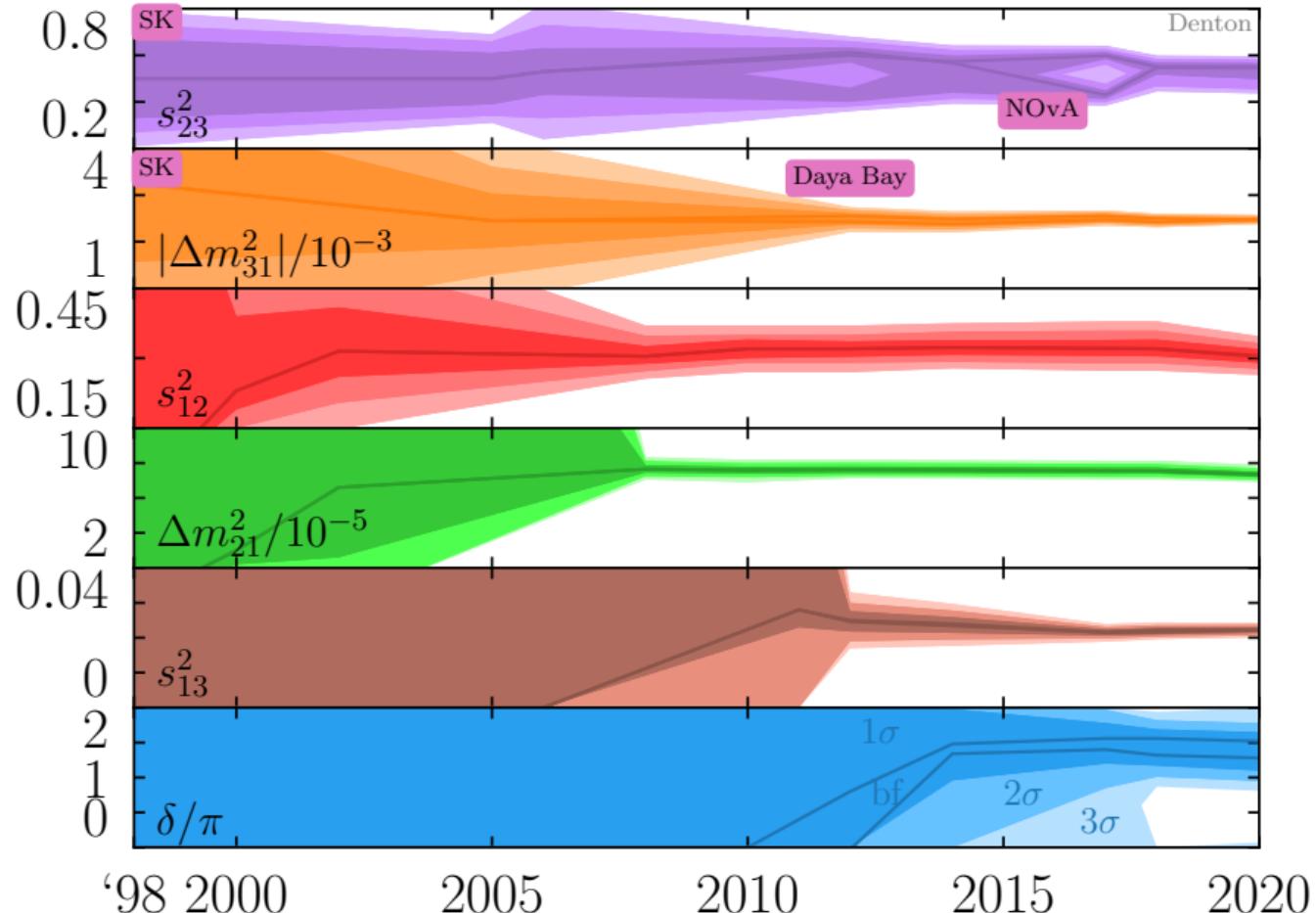
Only $m_i^2 - m_j^2$ contribute

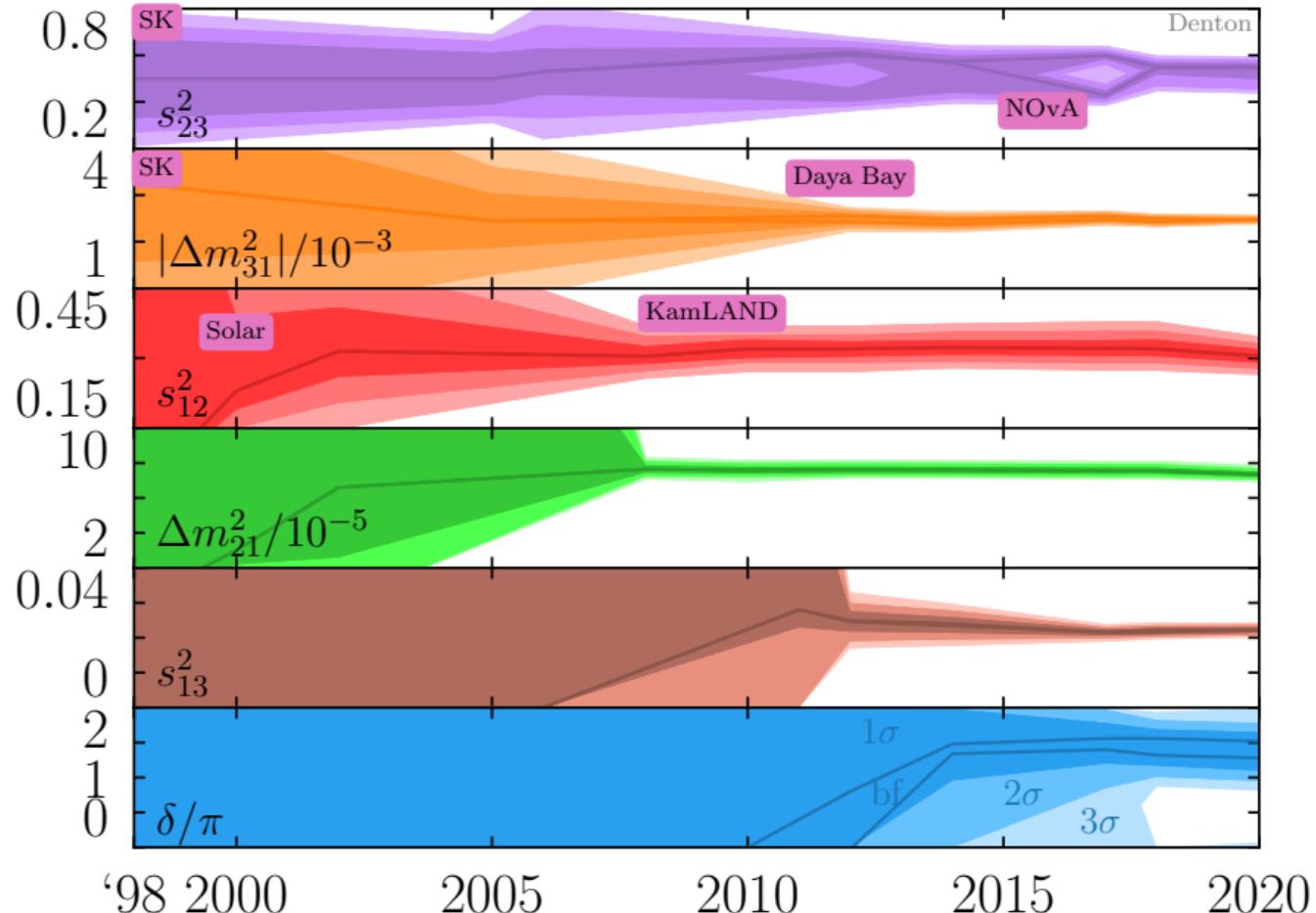
Oscillations!

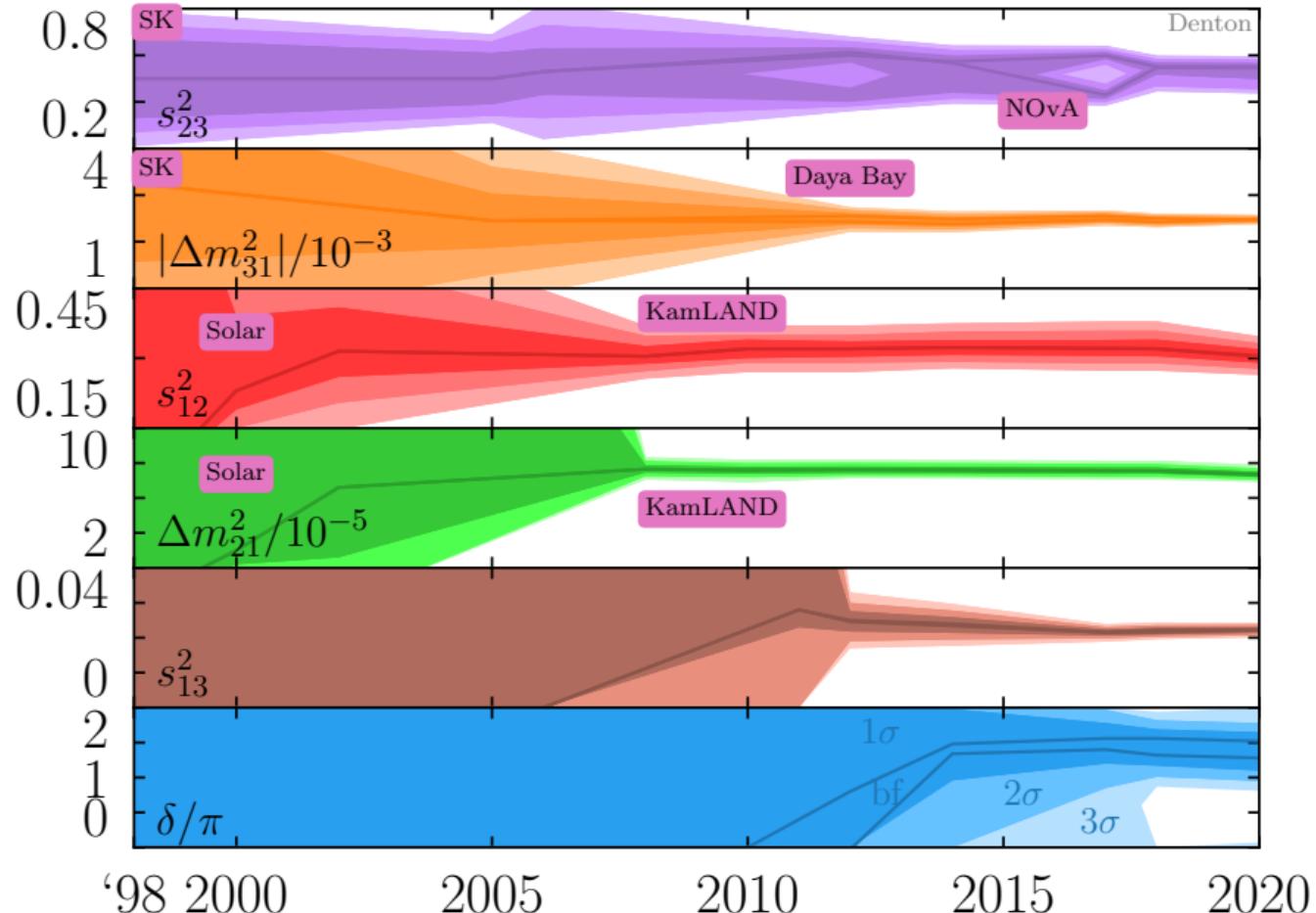
Neutrino oscillations: today

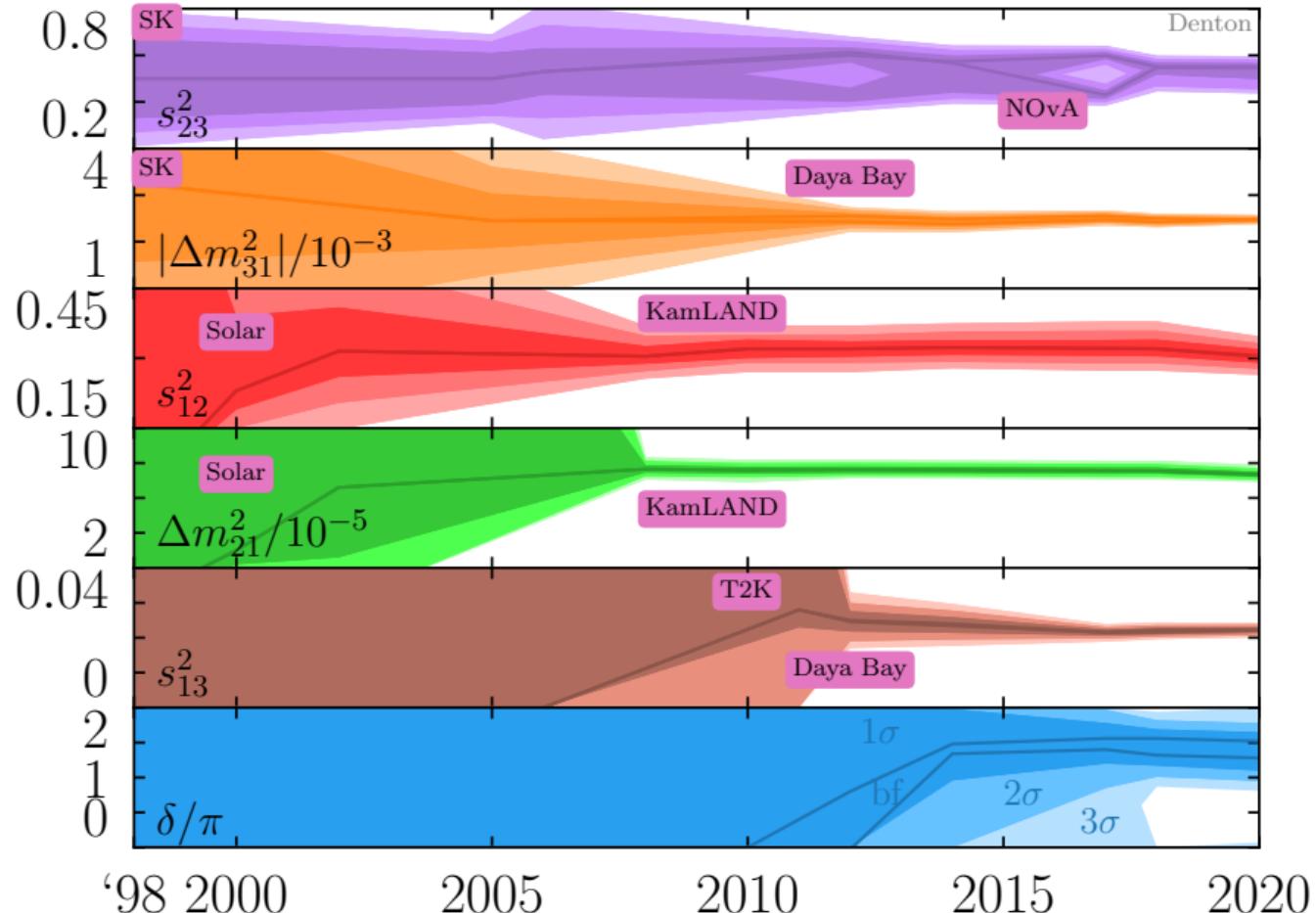


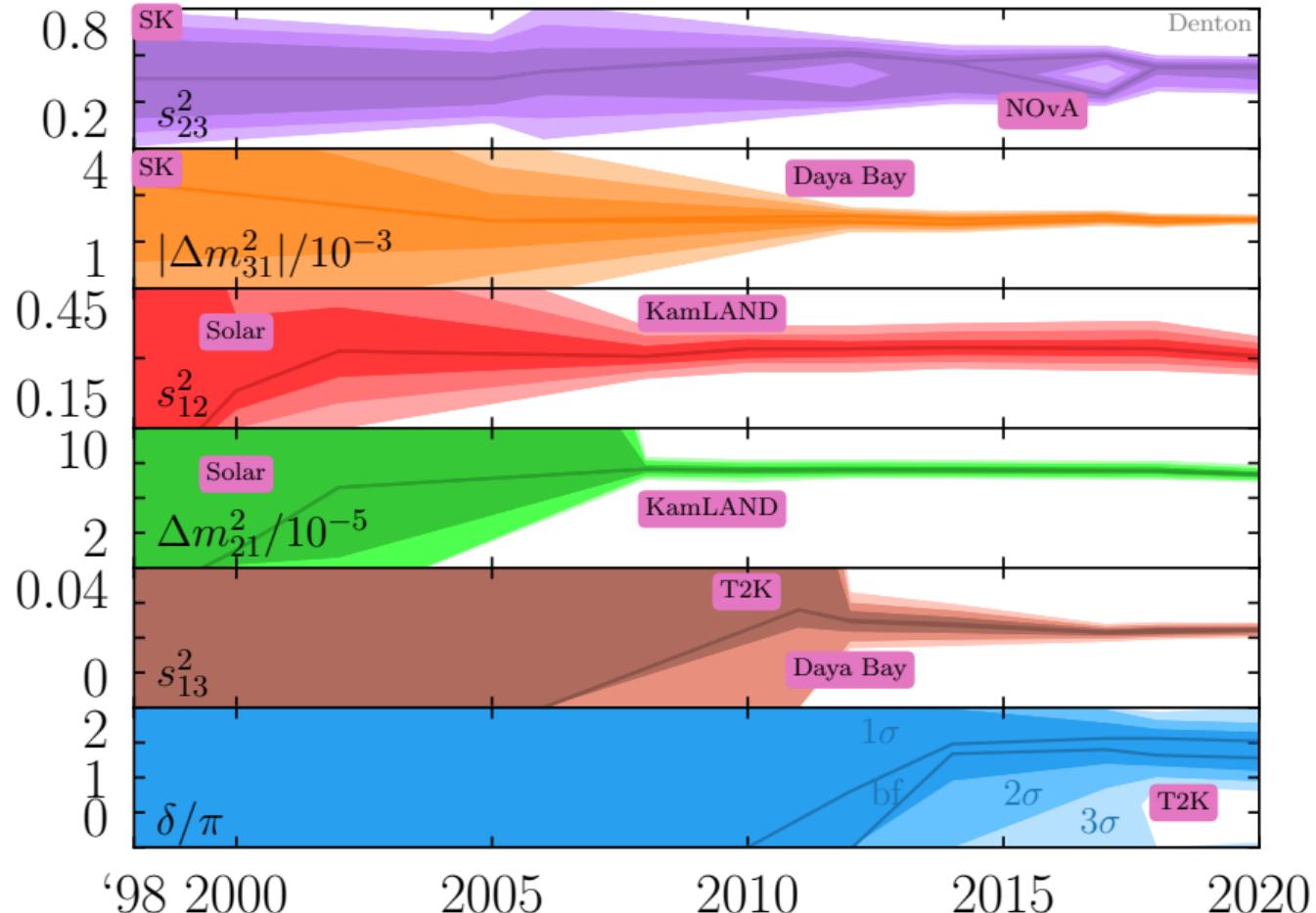




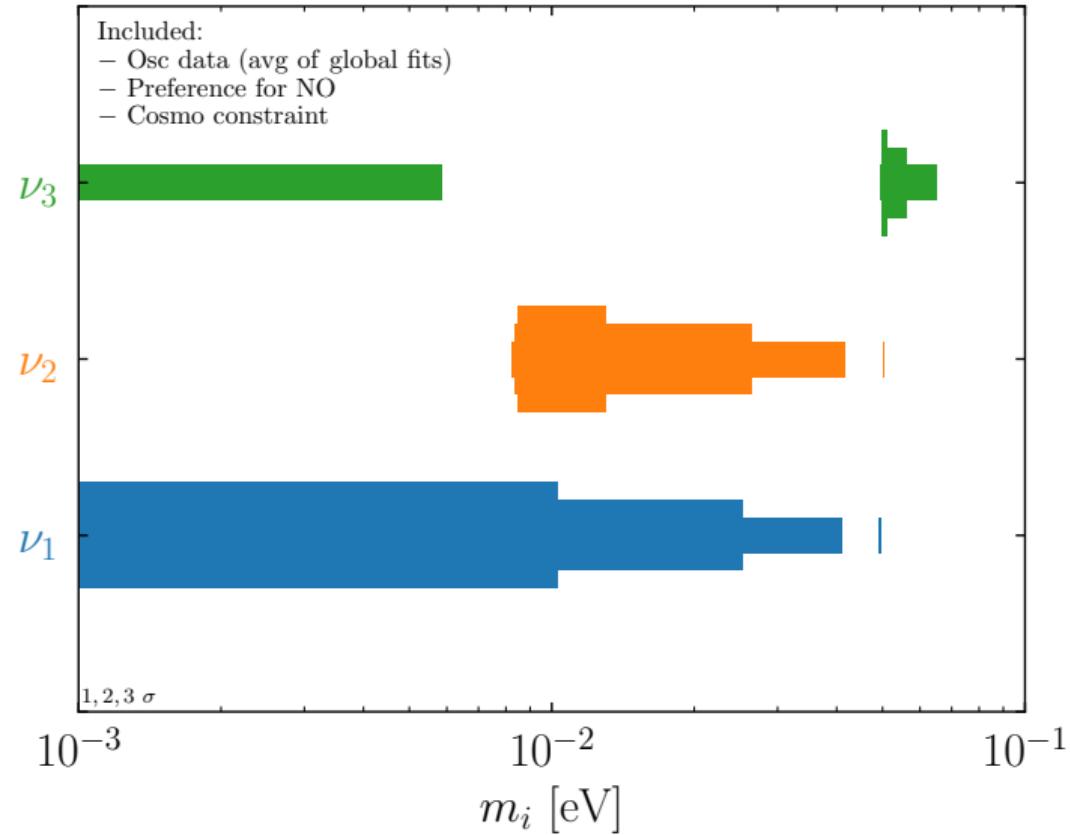








Absolute masses



Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

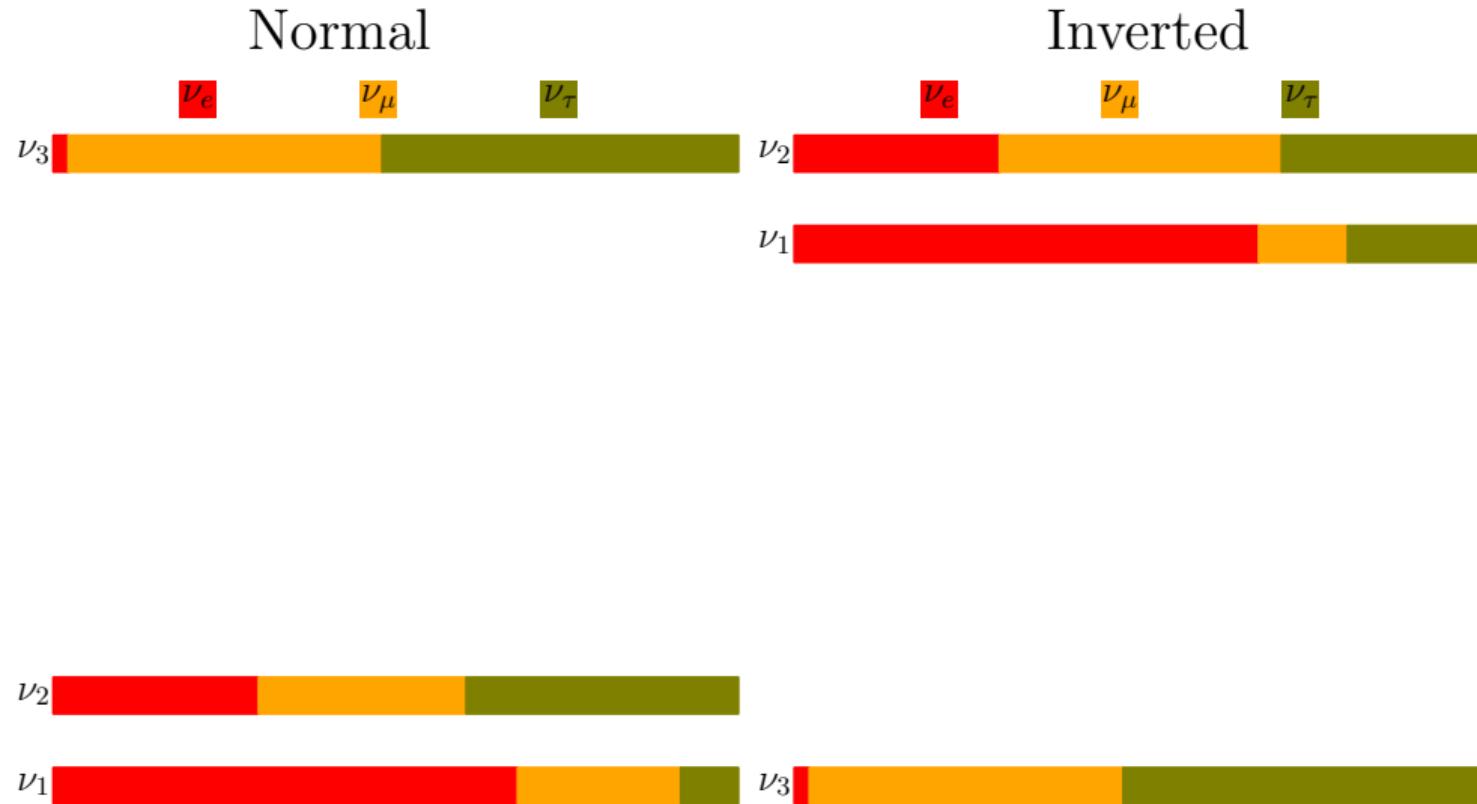
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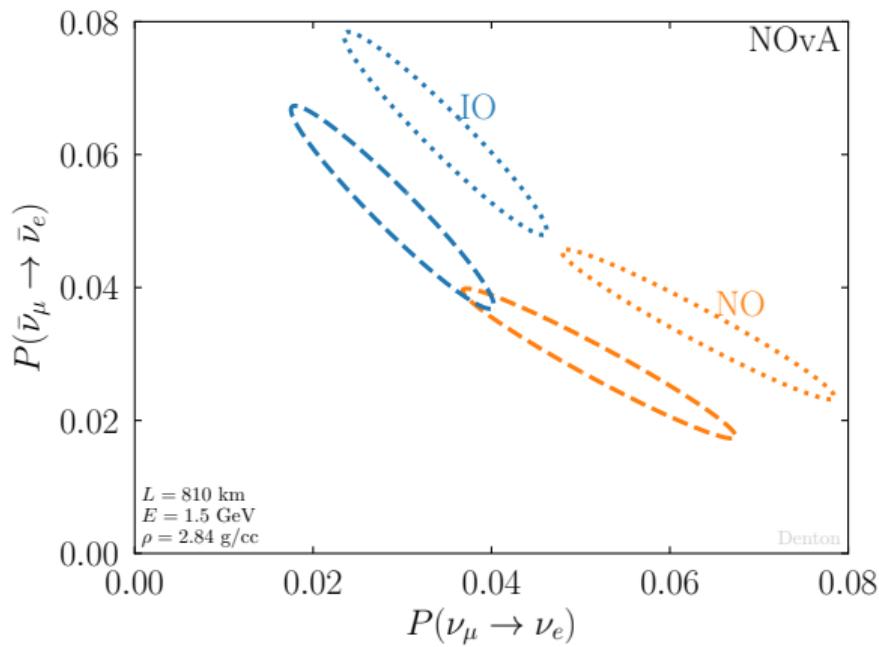
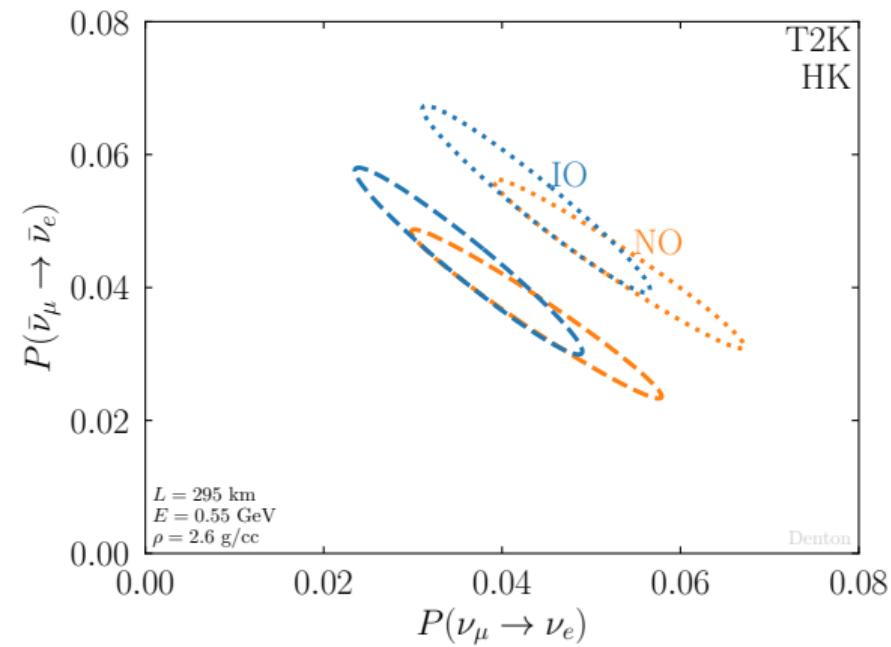
Cosmology, scattering, $0\nu\beta\beta$, ...

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**
4. NOvA+T2K+SK still prefers **NO** over **IO**
5. + Daya Bay & RENO \Rightarrow slight preference **NO**
6. $= 2.5 - 2.7\sigma$

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

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

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

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

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

Mass ordering current status: all

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, ...

From oscillations:

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

See also KATRIN [2105.08533](#)

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PRIORS?

Some claim “decisive” Bayesian evidence for normal

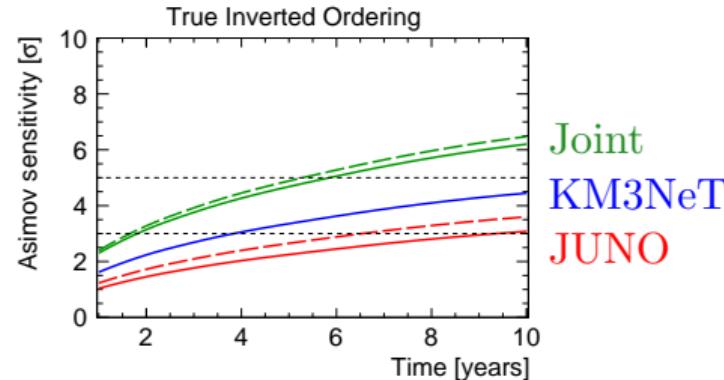
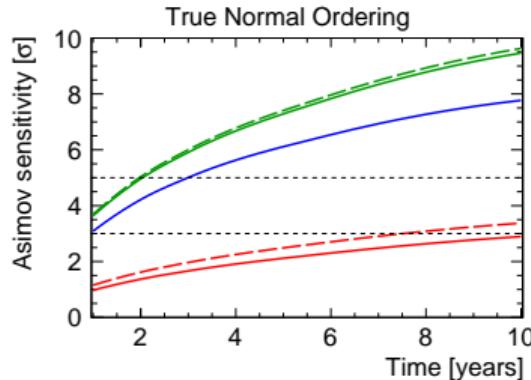
R. Jimenez, et al. [2203.14247](#)

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

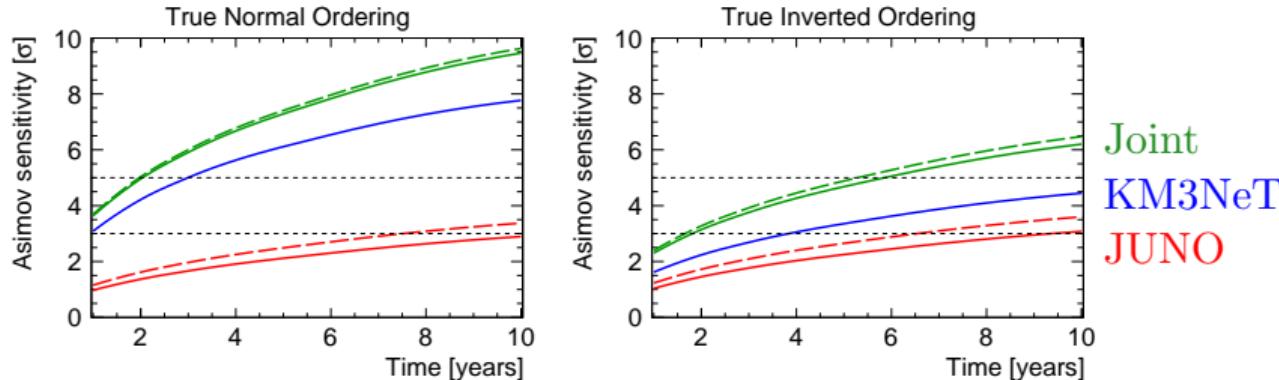


JUNO, KM3NeT [2108.06293](#)

JUNO, IceCube [1911.06745](#)

Note: if lower octant, KM3NeT is less sensitive

Mass ordering: future sensitivities



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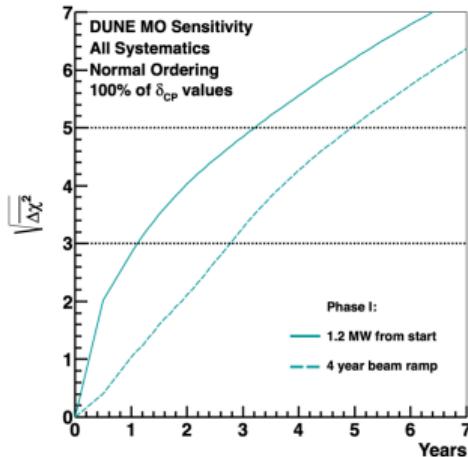
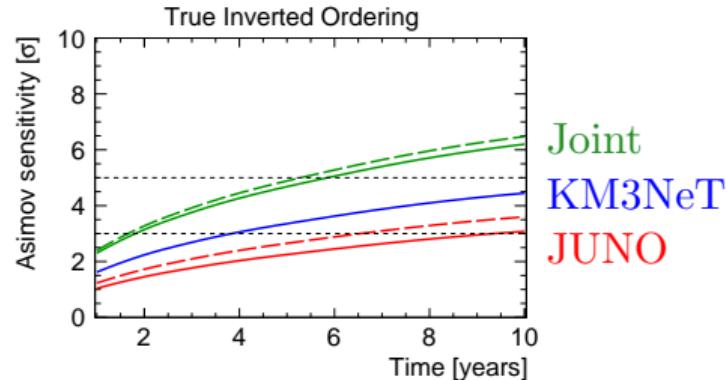
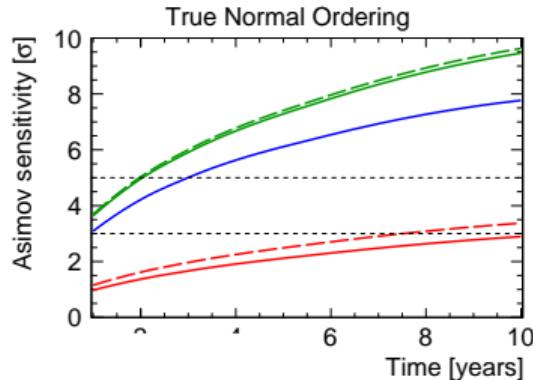
$$\Delta m_{ee}^2 = c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2$$

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

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](#)

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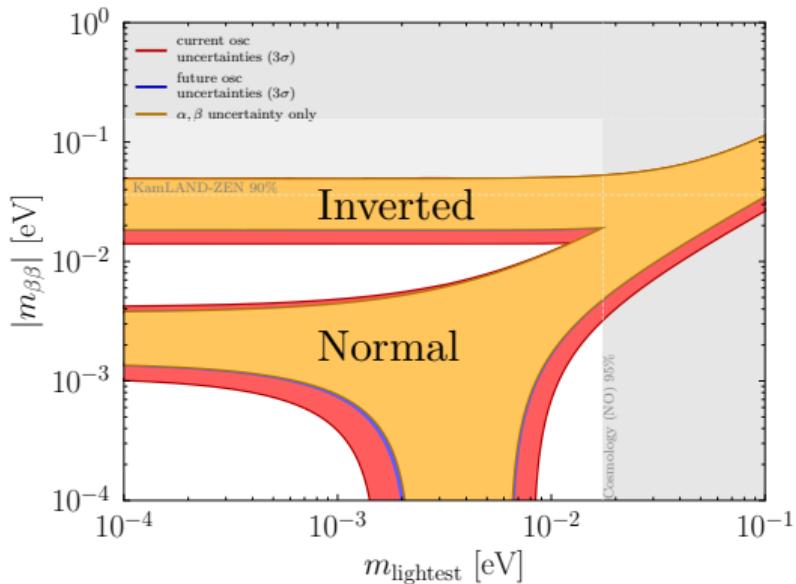
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Mass ordering: broad implications

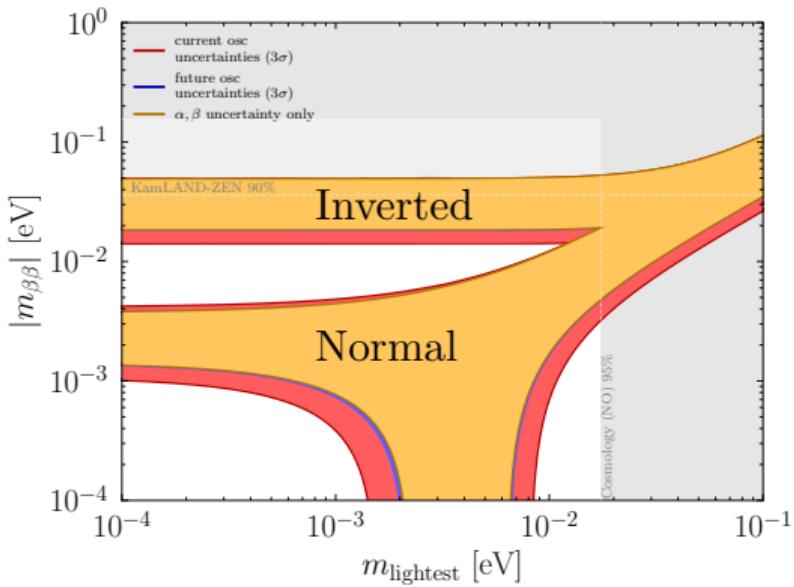
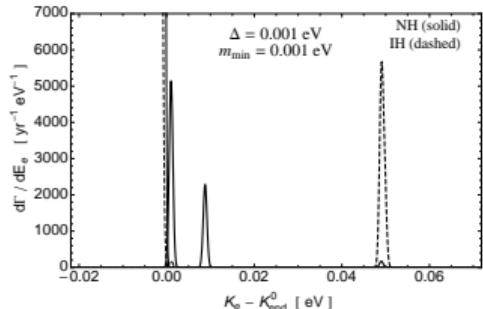
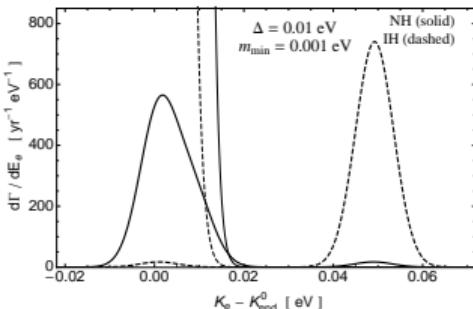
- ▶ Affects cosmology
- ▶ Affects $0\nu\beta\beta$
- ▶ Affects end point measurements
- ▶ Affects $C\nu B$



PBD, J. Gehrlein [2308.09737](#)

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PBD, J. Gehrlein [2308.09737](#)

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](#)

PBD, S. Parke [2106.12436](#)

PBD, J. Gehrlein [2204.09060](#)



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

PBD, et al. [1701.04828](#)

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

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

3. Dresden-II for any mediator mass

PBD, J. Gehrlein [2204.09060](#)

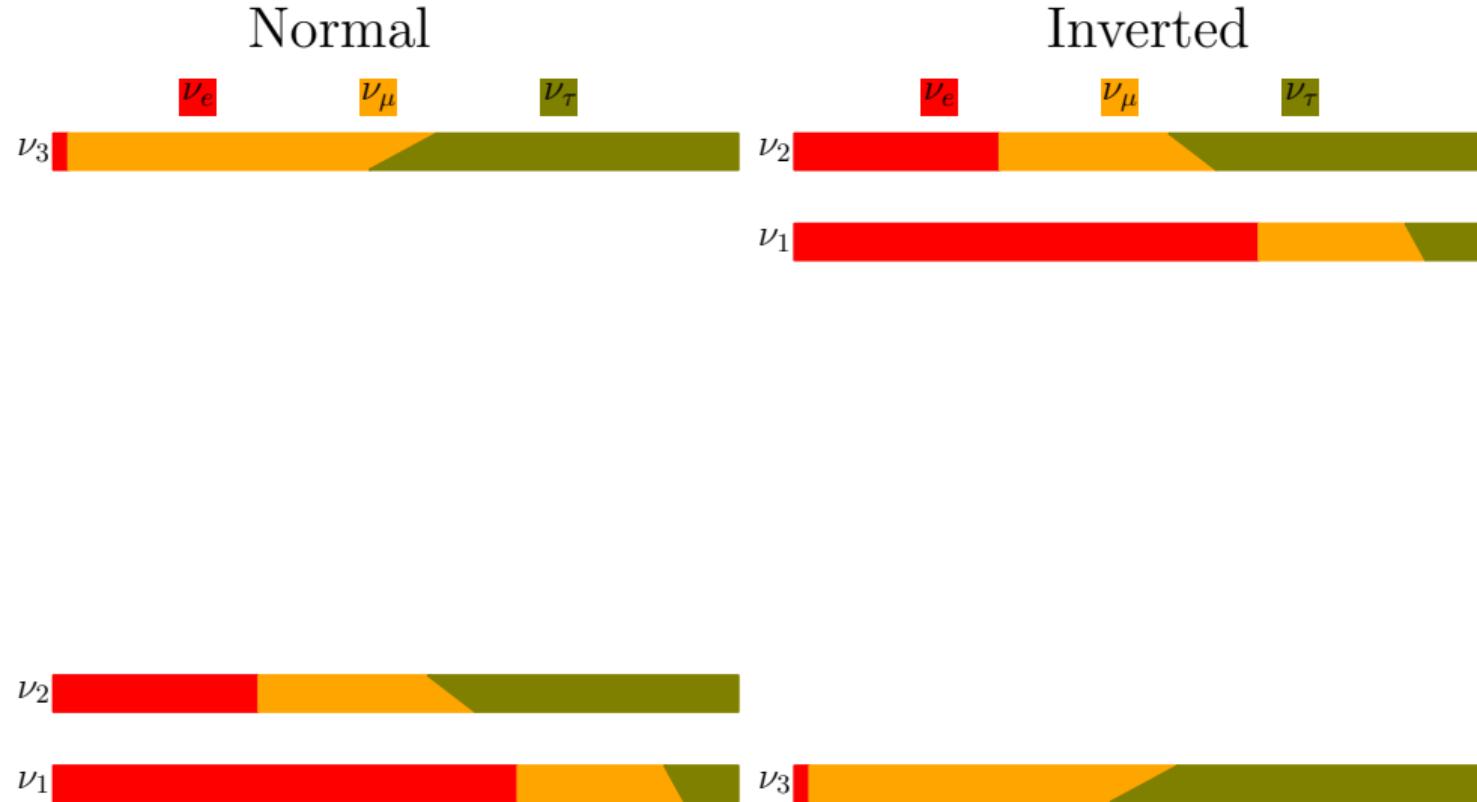
4. Can still evade with specific flavor structures

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

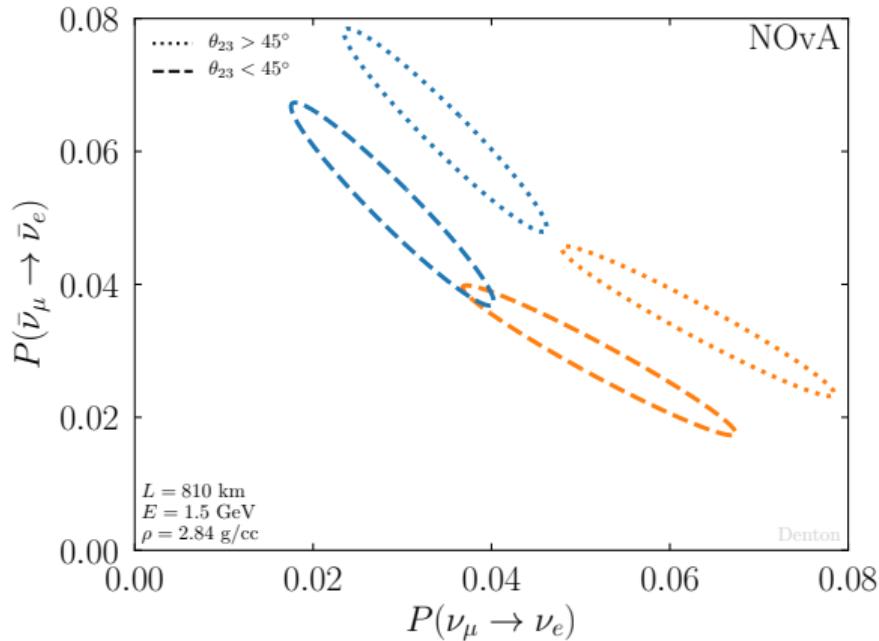
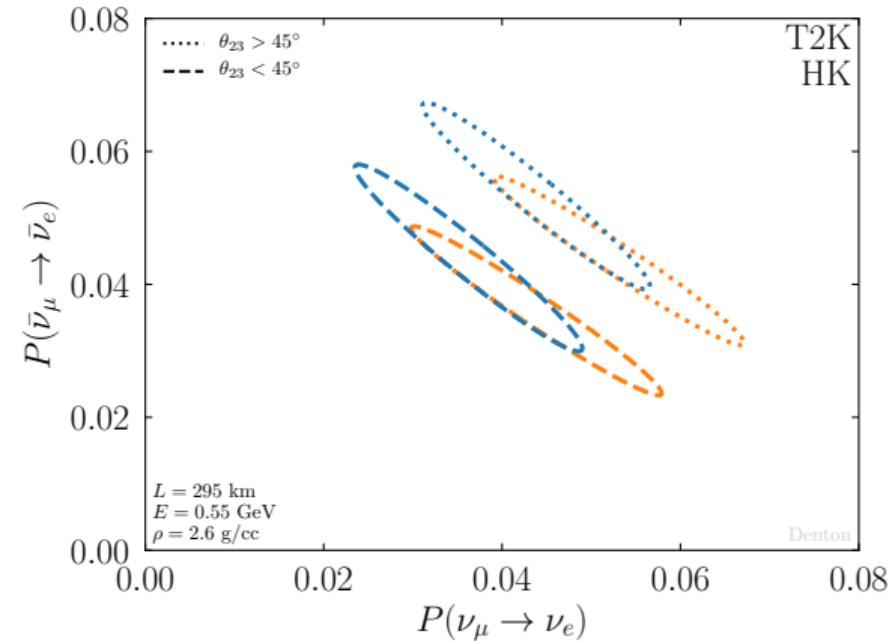
5. CCM & COHERENT can close all loopholes

θ_{23} octant

θ_{23} octant: what is it?

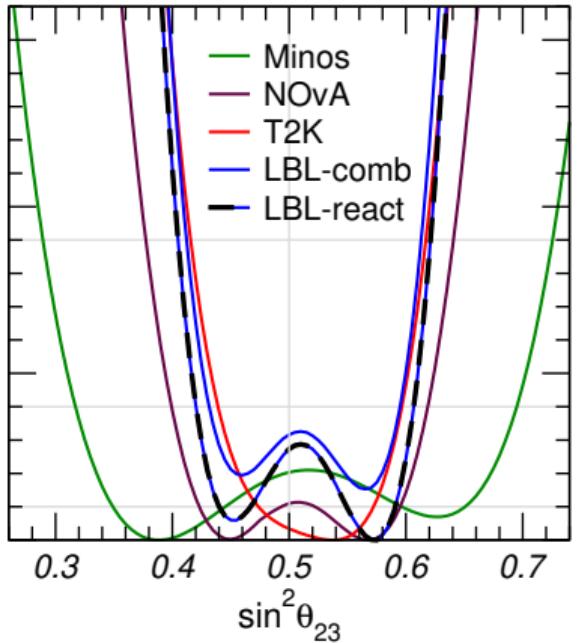


θ_{23} octant: what is it really?

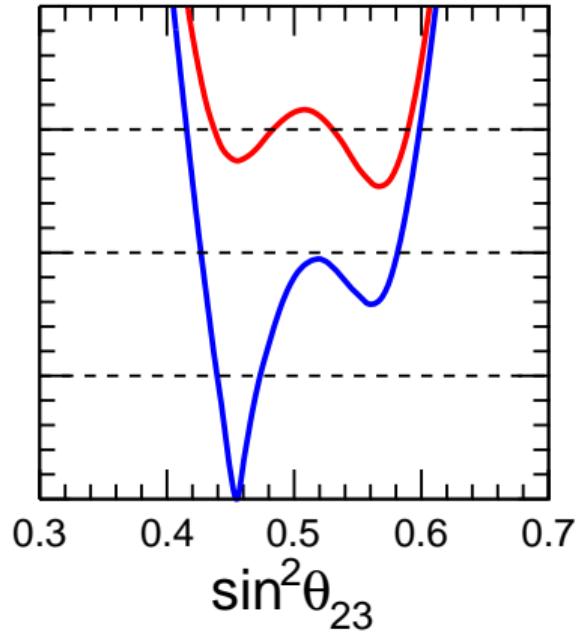


Lower octant more “normal” than upper octant

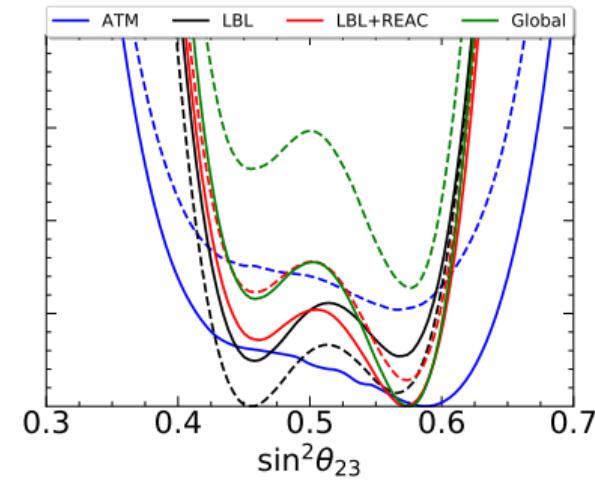
θ_{23} octant: current status



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



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



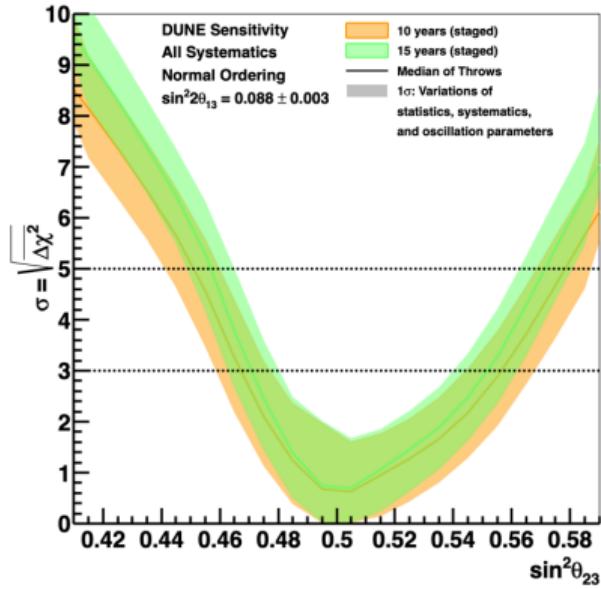
P. de Salas, et al. [2006.11237](#)

Prefers **upper** at $< 1\sigma$

Prefers **lower** at $\sim 1.5\sigma$

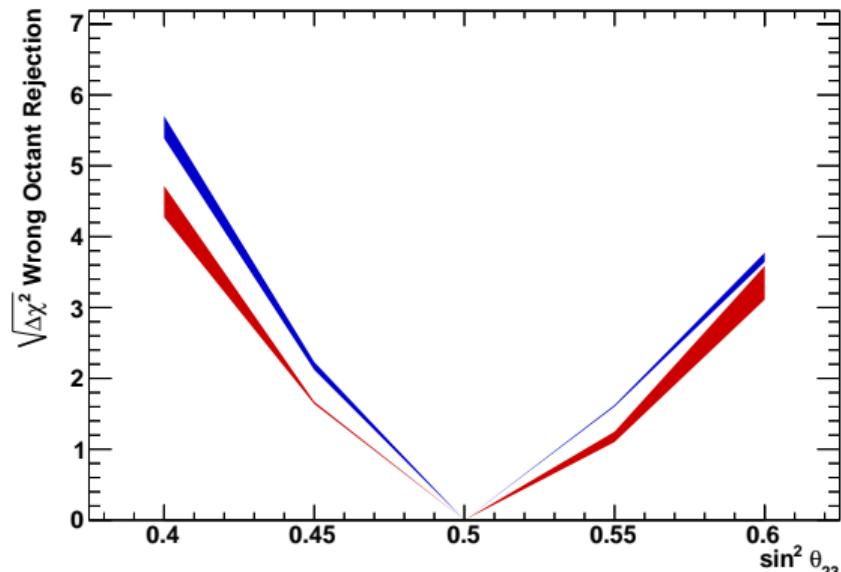
Prefers **upper** at $> 2\sigma$

θ_{23} octant: future sensitivities



$\sim 3 - 5\sigma$

DUNE 2002.03005



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

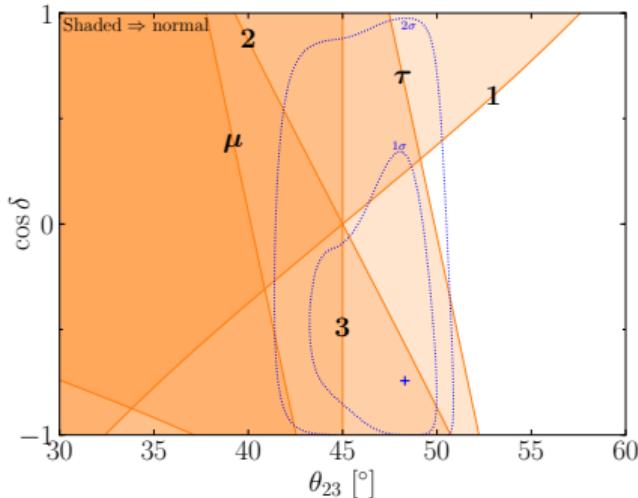
HK 1805.04163

θ_{23} : broader implications

μ - τ interchange/reflection symmetry

Normalcy

Is the heaviest neutrino mostly ν_τ ?
Is the lightest neutrino least ν_τ ?



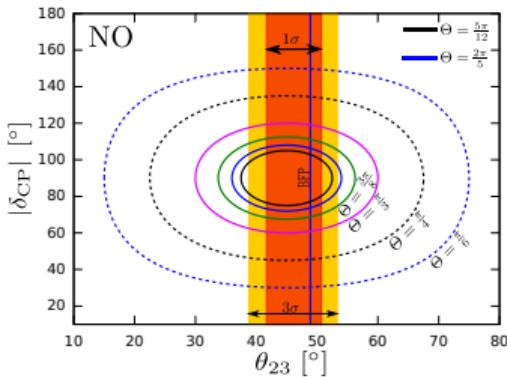
Quarks easily satisfy normalcy PBD 2003.04319

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

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

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

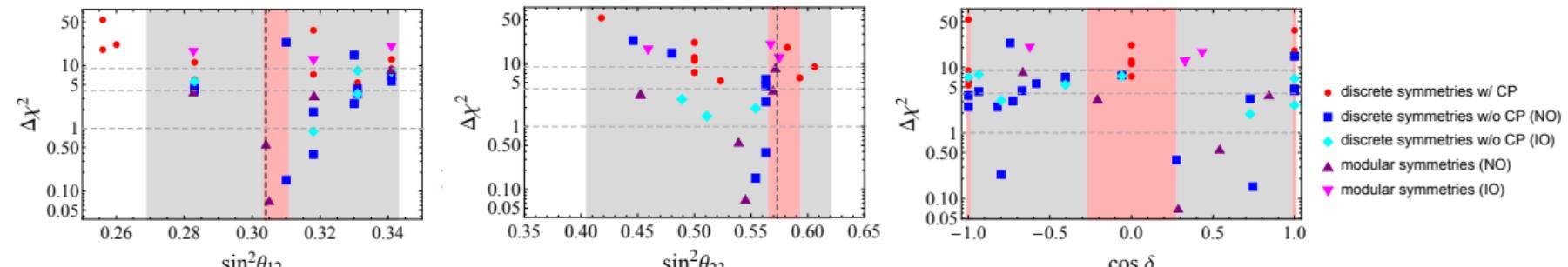
Predicts: $\theta_{23} = 45^\circ$, often $\theta_{13} = 0$



P. Chen, et al. 1512.01551

Parameter interplay

Models predict specific correlations among the parameters



J. Gehrlein, et al. [2203.06219](https://arxiv.org/abs/2203.06219) (Snowmass)

Complex phase

δ and CP violation

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

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



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

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](#)

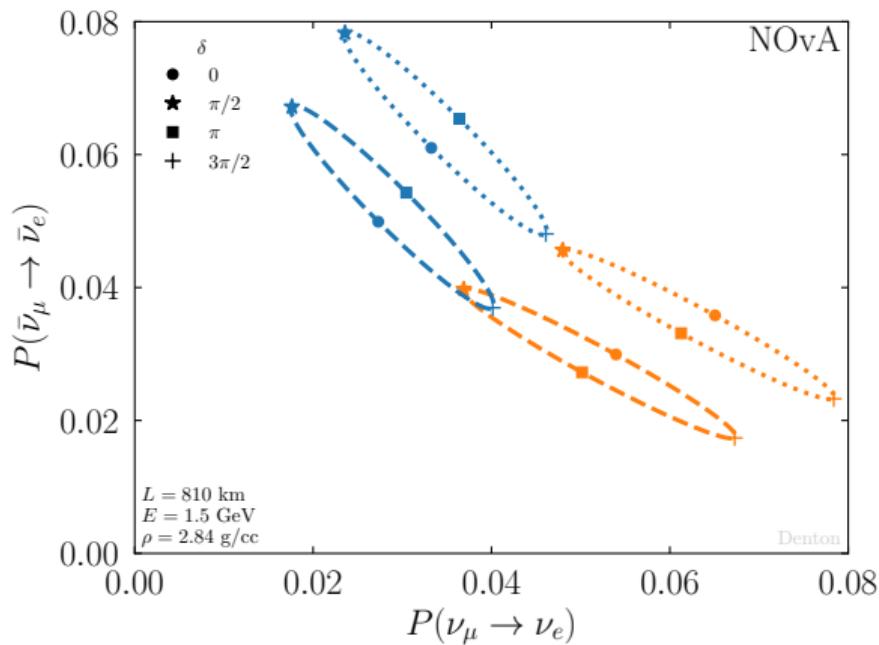
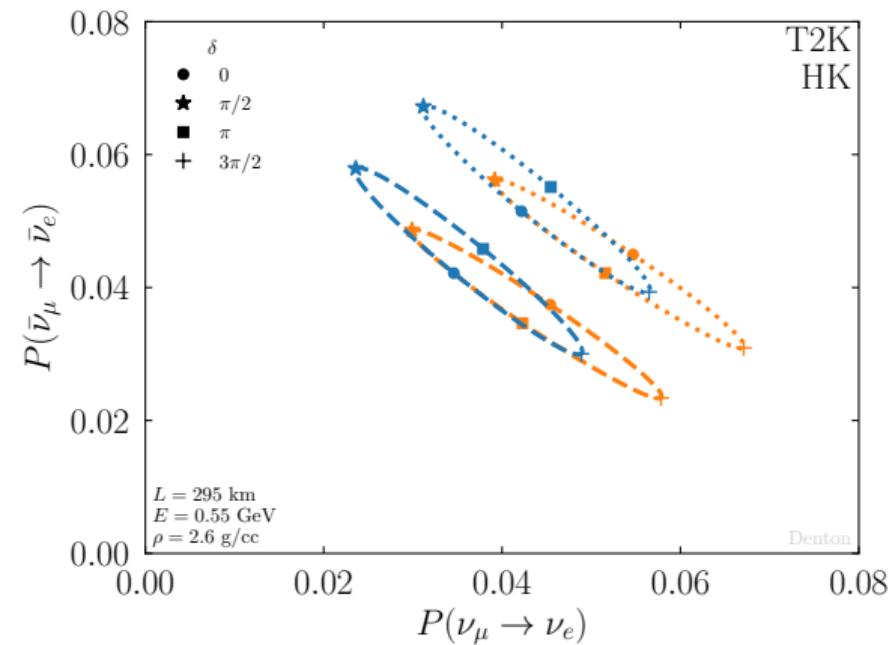
3. Lepton mass matrix: ?

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

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

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

δ : what is it really?



δ : what is it not?

$\delta \not\Rightarrow$ Baryogenesis

The amount of leptogenesis is a function of:

1. δ
2. the heavy mass scale
3. α, β (Majorana phases)
4. CP phases in the RH neutrinos
5. ...

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

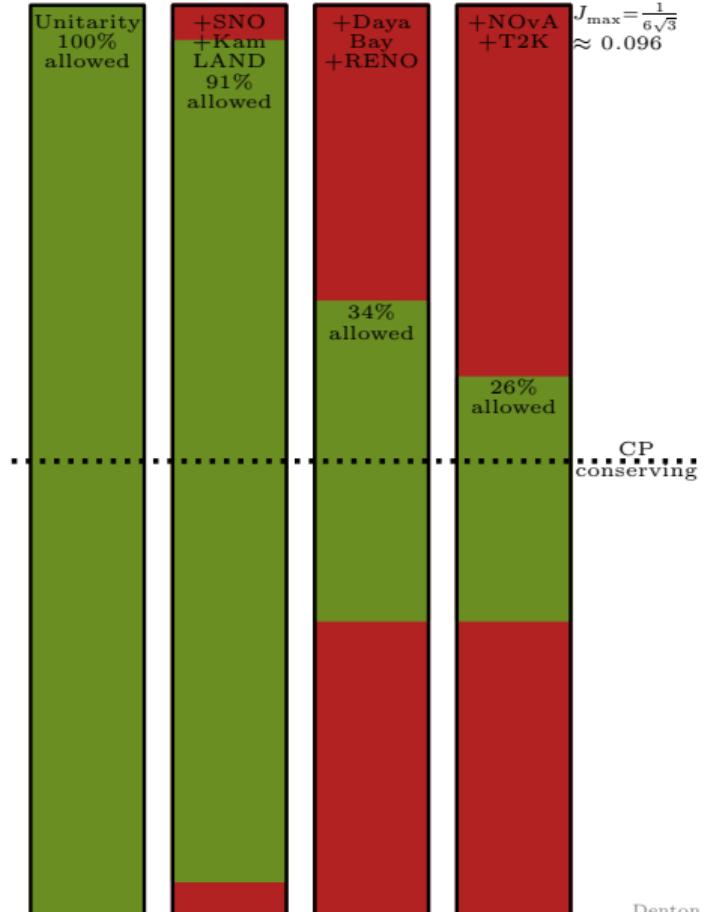
K. Moffat, et al. [1809.08251](#)

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

δ, J : current status

Maximal CP violation is already ruled out:

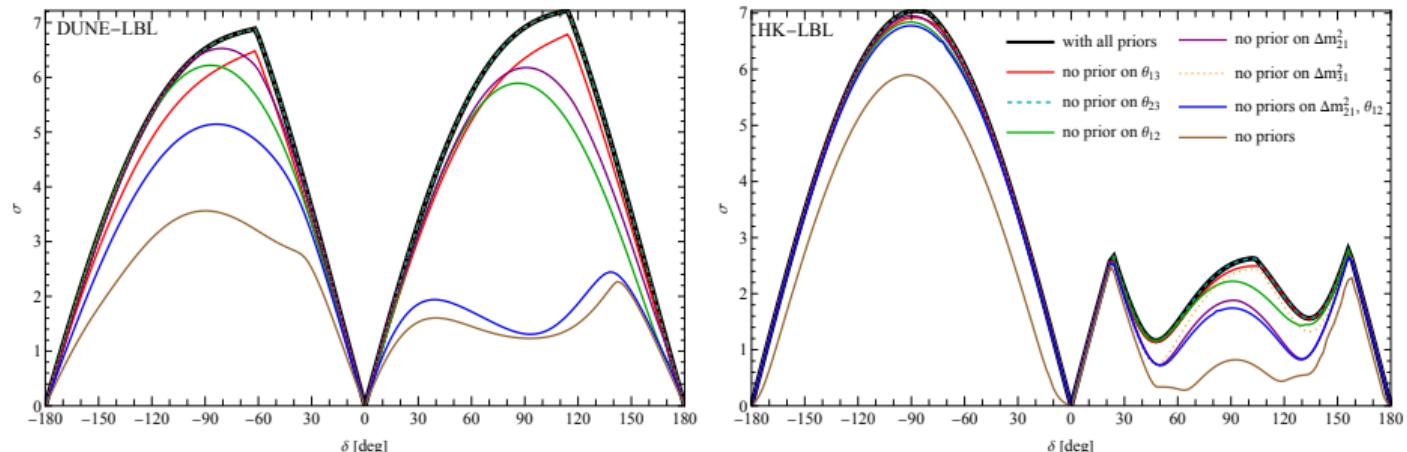
1. $\theta_{12} \neq 45^\circ$ at $\sim 15\sigma$
2. $\theta_{13} \neq \tan^{-1} \frac{1}{\sqrt{2}} \approx 35^\circ$ at many (100) σ
3. $\theta_{23} = 45^\circ$ allowed at $\sim 1\sigma$
4. $|\sin \delta| = 1$ allowed



δ : 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



PBD, J. Gehrlein [2302.08513](#)

Need to know solar parameters to measure δ !

Current solar knowledge: okay
Future (JUNO): excellent

δ : future sensitivities

Appearance is best

Disappearance works too

Disappearance probability:

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

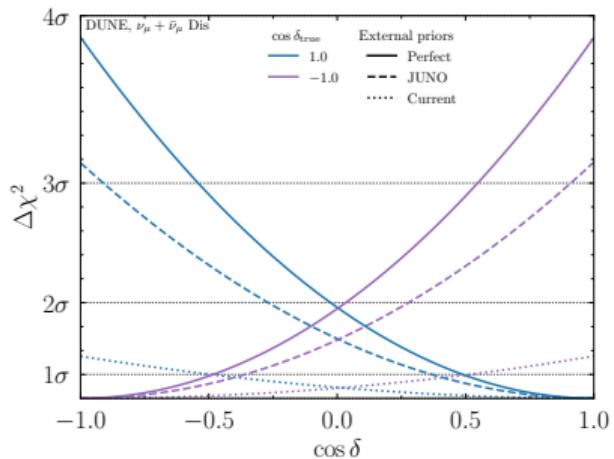
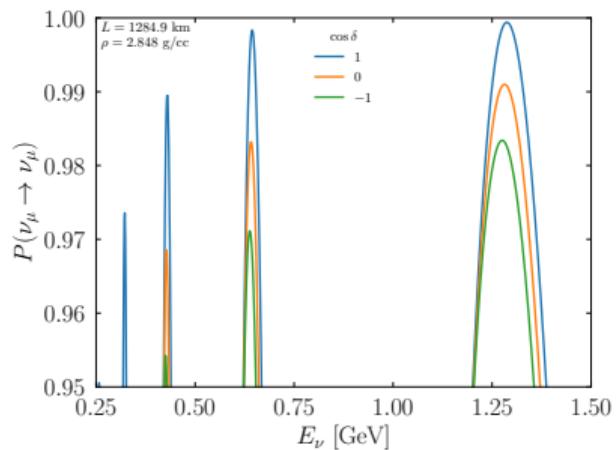
$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E$$

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

ν_e : Daya Bay and KamLAND/JUNO

ν_μ : precision at DUNE/HK

See backups for more



PBD 2309.03262

Neutrinos: more new physics?

Lots of 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. Neutrino – dark matter interactions
7. Decoherence
8. Lorentz invariance or CPT violation

Lots of interesting new physics scenarios in oscillations

1. Sterile neutrinos

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

PBD [2111.05793](#)

2. Non-standard neutrino interactions (NSI)

with any Lorentz structure: SPVAT

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

P. Coloma, PBD, M. Gonzalez-Garcia, M. Maltoni, T. Schwetz [1701.04828](#)

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

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

3. Non-standard neutrino SELF interactions

G. Barenboim, PBD, I. Oldengott [1903.02036](#)

4. Neutrino decay

PBD, I. Tamborra [1805.05950](#)

PBD, A. Abdullahi [2005.07200](#)

PBD [2109.14576](#)

PBD, J. Gehrlein [2109.14575](#)

6. Neutrino – dark matter interactions

A. Dev, et al. [2205.06821](#)

C. Boehm, P. Fayet, R. Schaeffer [astro-ph/0012504](#)

7. Decoherence

T. Stuttard, M. Jensen [2007.00068](#)

A. Gouv  a, V. Romeri, C. Ternes [2104.05806](#)

8. Lorentz invariance or CPT violation

S. Ge, H. Murayama [1904.02518](#)

Three BSM scenarios:

Non-standard neutrino interactions (NSI)

Light sterile neutrinos (~ 1 eV)

Unitarity violation (UV)

Three BSM scenarios:

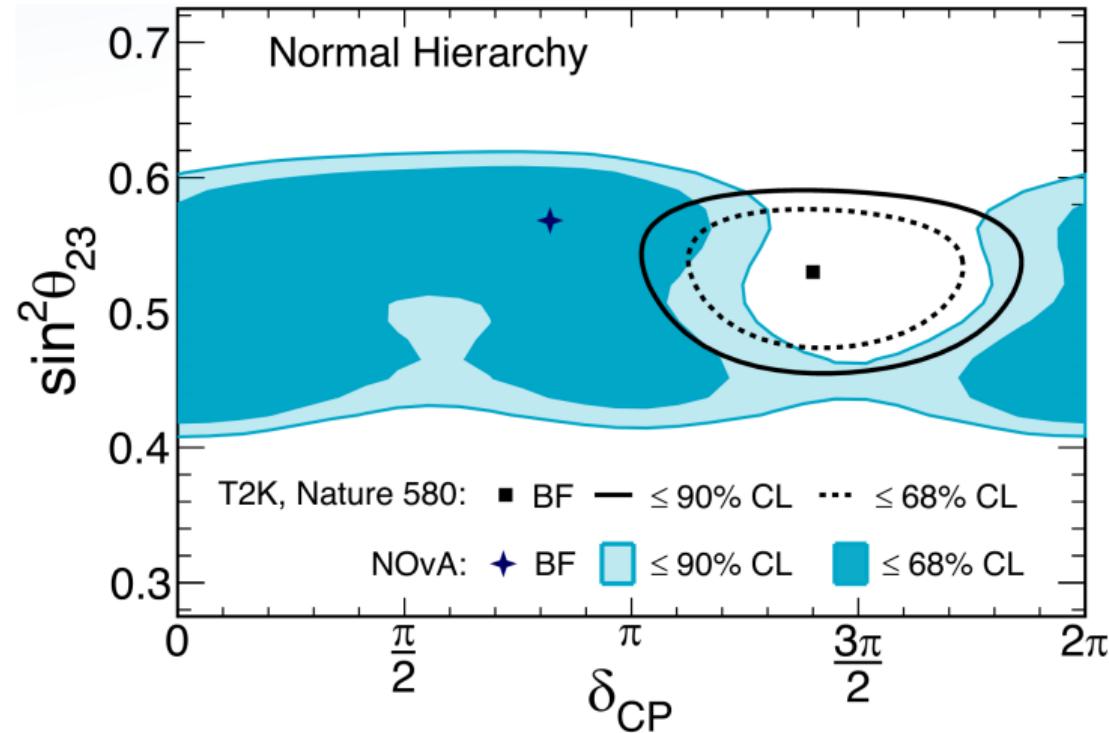
Non-standard neutrino interactions (NSI)

Light sterile neutrinos (~ 1 eV)

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CP violation at NOvA and T2K?

Excitement at Neutrino2020!



A. Himmel for NOvA [10.5281/zenodo.3959581](https://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](#)
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U. Dey, N. Nath, S. Sadhukhan [1804.05808](#) Y. Farzan [1912.09408](#)

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

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

$a \propto \rho E$

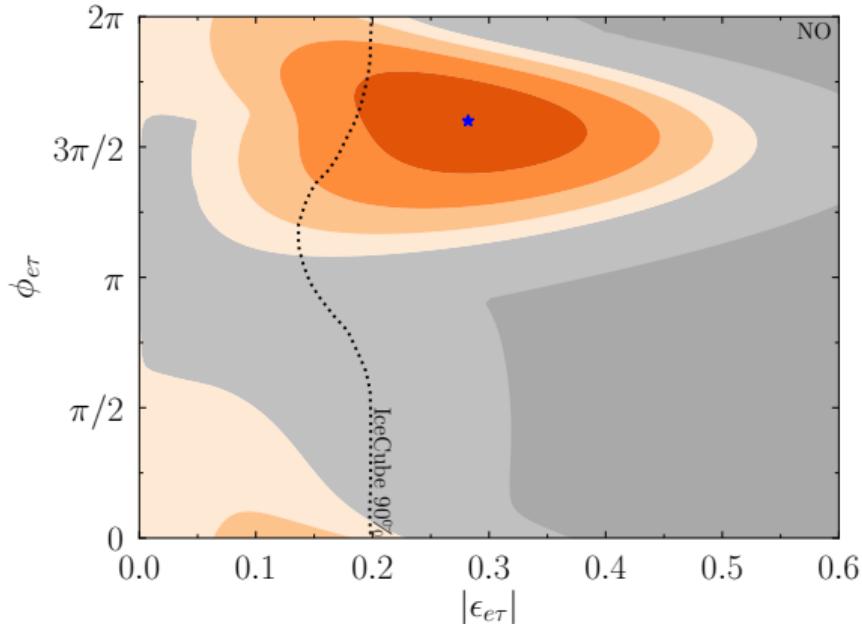
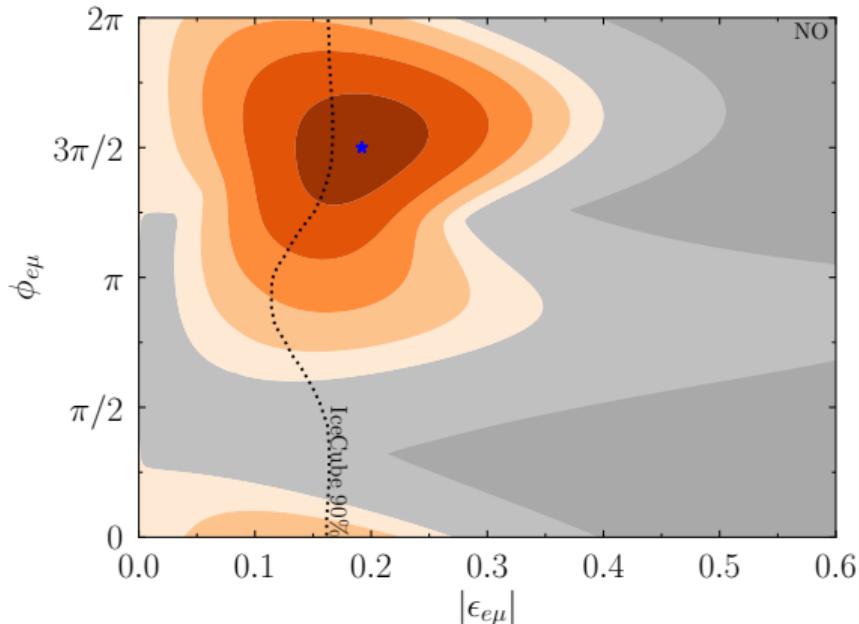
$w_\beta = s_{23}, c_{23}$ for $\beta = \mu, \tau$

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 ν_3
 2. Upper octant $\Rightarrow \nu_3$ is more ν_μ
 3. More $\nu_\mu \Rightarrow$ need less new physics coupling to ν_μ 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

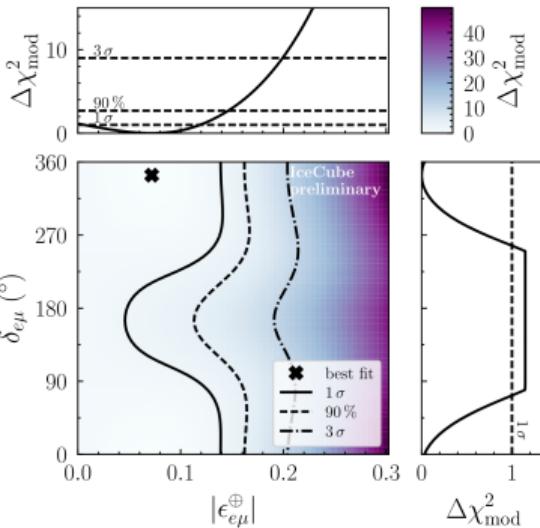
NSI effects grow with energy, density, and distance

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 $\sim 1\sigma$



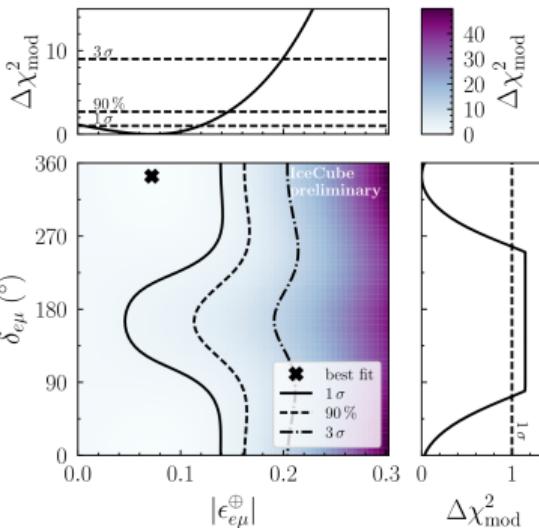
T. Ehrhardt, IceCube [PPNT \(2019\)](#)

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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](#)
PBD, J. Gehrlein [2008.06062](#)

Three BSM scenarios:

Non-standard neutrino interactions (NSI)

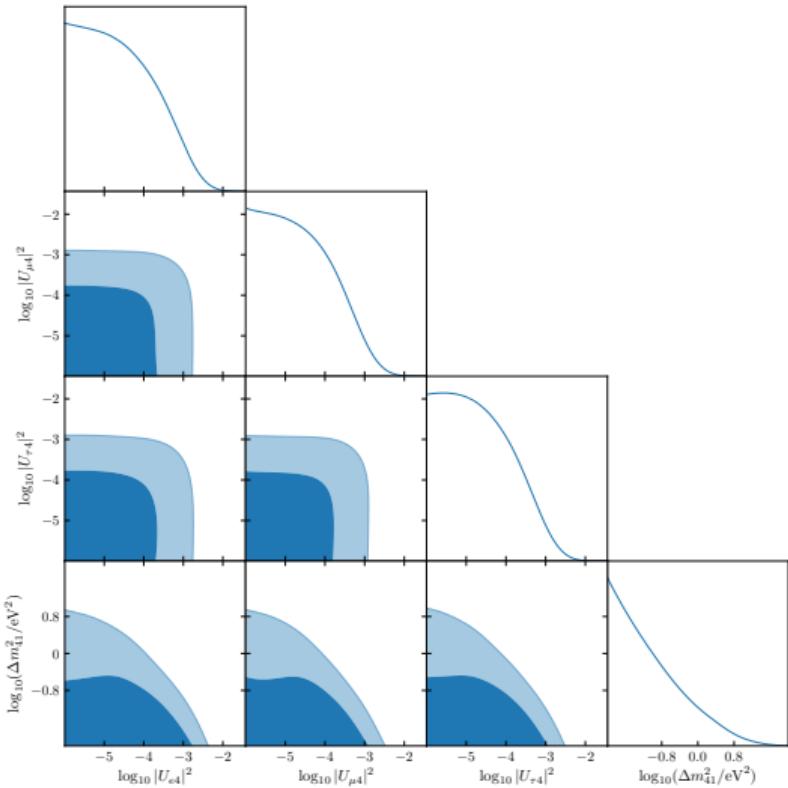
Light sterile neutrinos (~ 1 eV)

Unitarity violation (UV)

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
- ▶ Lots of hints pointing to $m_4 \sim 1 \text{ eV}$
- ▶ Cosmology?

Cosmological bounds

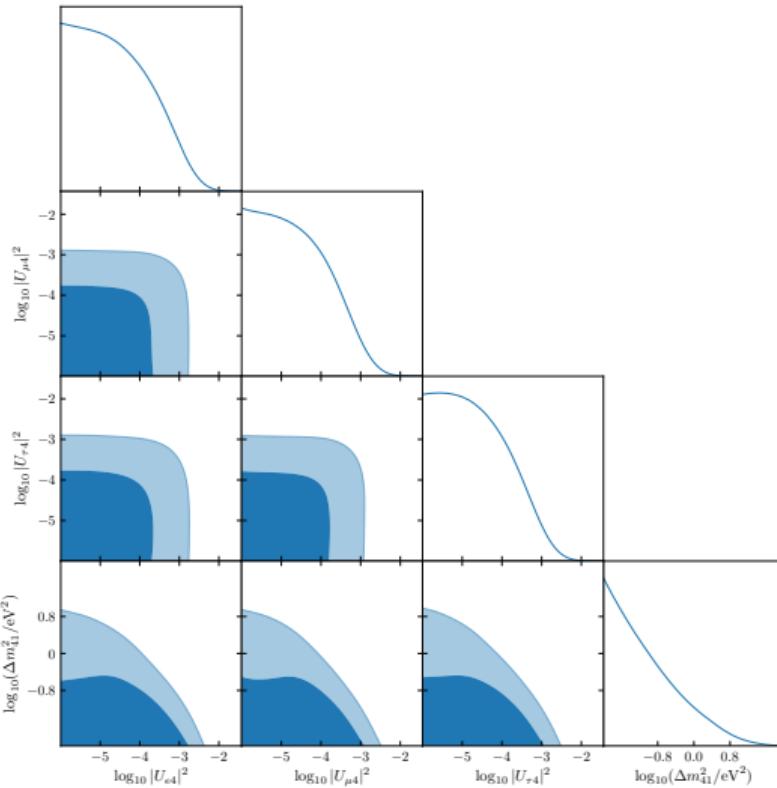


$1\sigma, 2\sigma$

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

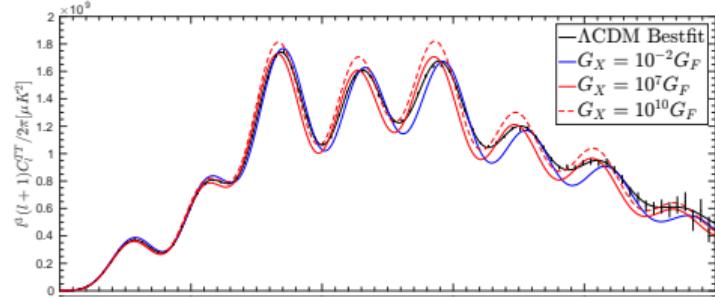
Cosmological bounds



$1\sigma, 2\sigma$

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_{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 ν_e than expected:

3.0σ : C. Giunti, M. Laveder [1006.3244](#)

2.3σ : 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](#)

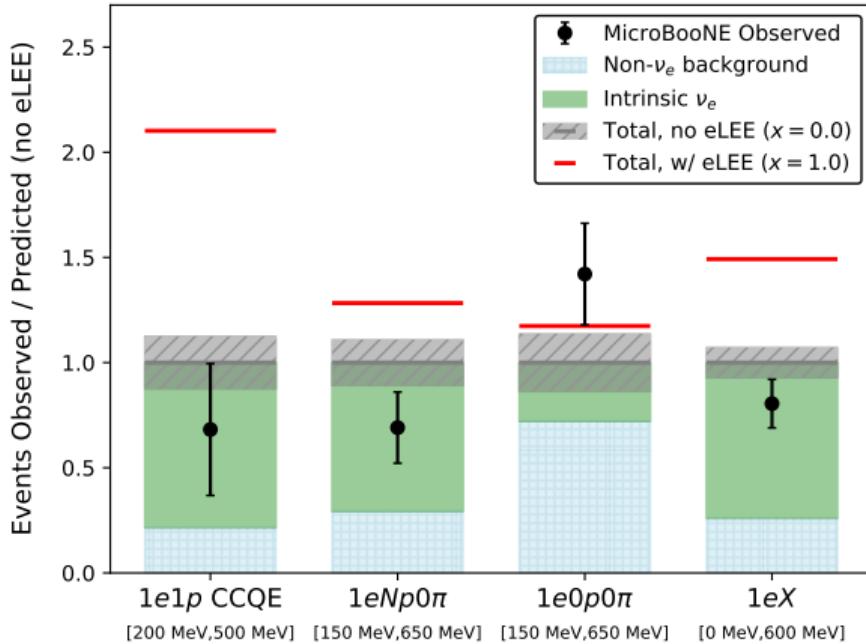
W. Haxton, et al. [2303.13623](#)

- ▶ 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

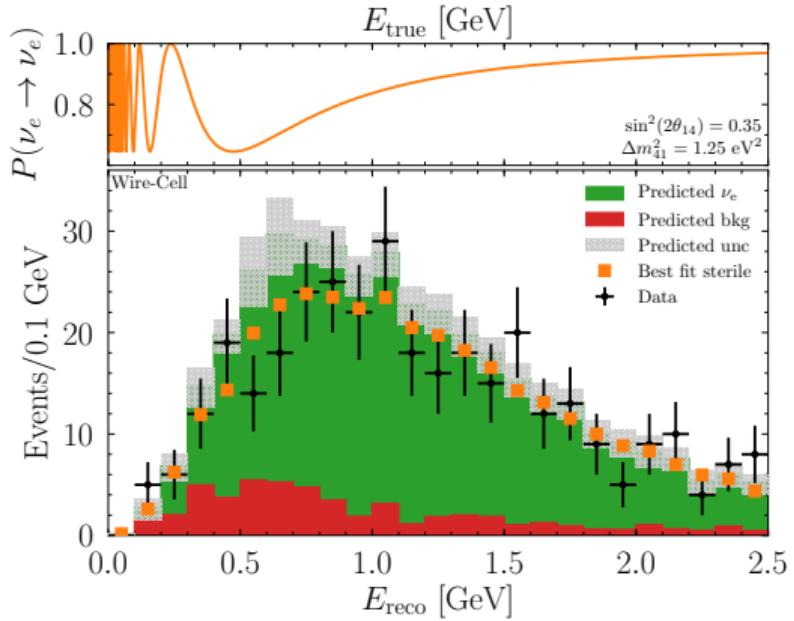


- ▶ Three analysis teams:
 1. Wire-Cell
 2. Deep Learning
 3. Pandora
 - ▶ With 0 protons
 - ▶ With 1+ protons
- ▶ Underfluctuation compared to no-oscillations
- ▶ Disfavors MiniBooNE's best fit LEE hypothesis at 3.75σ

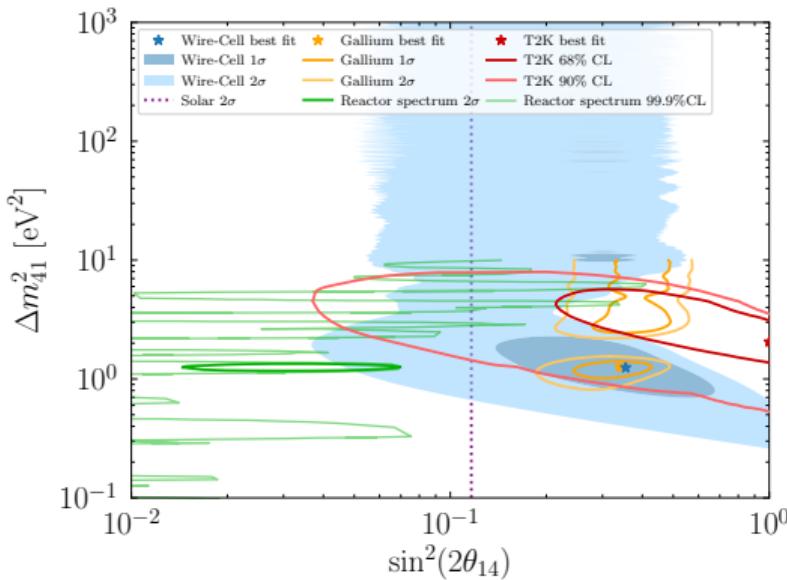
MicroBooNE [2110.14054](#)

Dip hunting

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



Global ν_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](#)

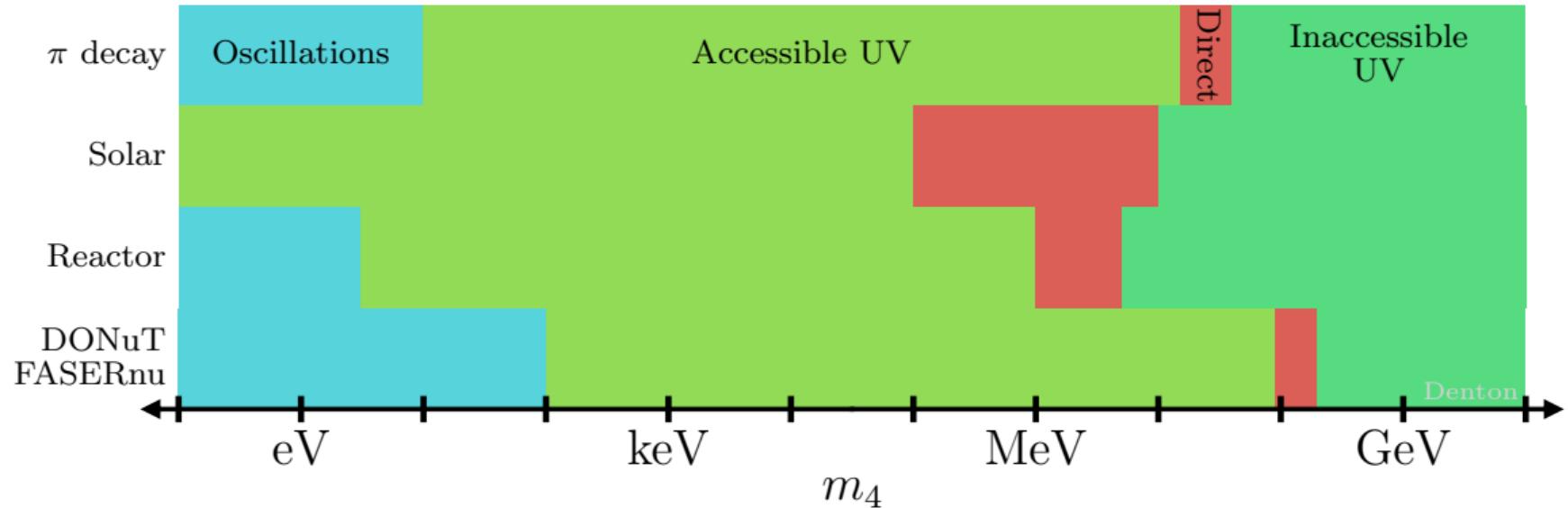
Three BSM scenarios:

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Light sterile neutrinos (~ 1 eV)

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Unitarity violation: a tale of two regimes



*Details depends on the specific experiment/channel

Unitarity violation: what is it?

Our 3×3 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 ν_4, ν_5, ν_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 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:

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

Unitarity violation: how to calculate

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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

3σ maximal deviations from unitarity

Leptons		
	Hu+	Ellis+
ν_e row	0.003	0.05
ν_μ row	0.02	0.04
ν_τ row	0.2	0.82
ν_1 col	0.06	0.22
ν_2 col	0.09	0.27
ν_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

Unitarity violation status from oscillations

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PDG

Vastly different mixing angle hierarchy



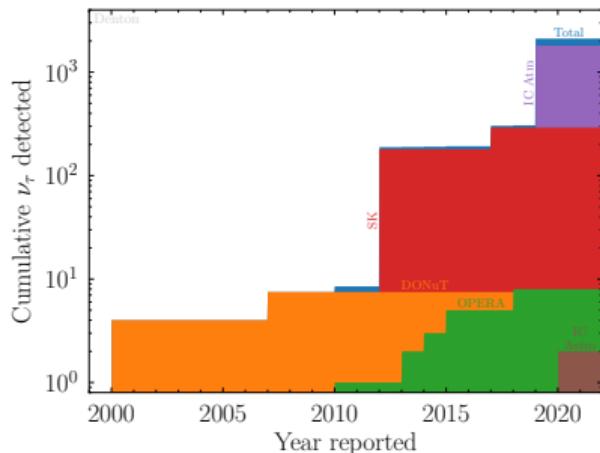
Like comparing apples and steak

Unitarity violation: tau row

Leptons: tau row is the weakest

1. Existing global analyses use OPERA and SNO
2. More data from atmospheric ν_τ appearance!

PBD [2109.14576](#)



Also astrophysical ν_τ appearance; weak but distinct!

PBD, J. Gehrlein [2109.14575](#)

Atmospheric works because τ is in **direct** region

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

[2109.14575](#) & [2109.14576](#)

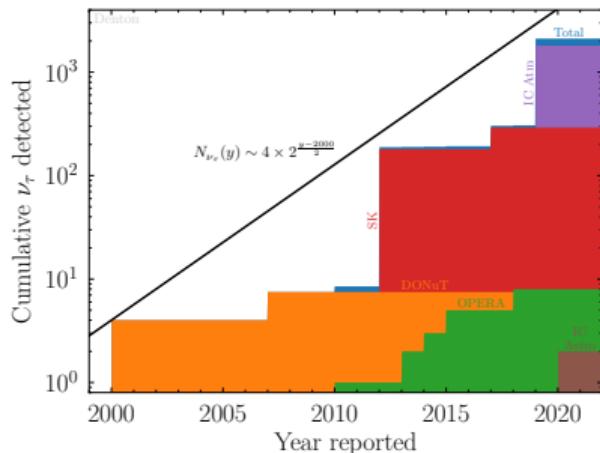
MIT: October 23, 2023 56/58

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Tau neutrino data set doubles every two years!

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

[2109.14575](#) & [2109.14576](#)

Other topics adjacent to neutrino oscillations

1. Lots of other new physics scenarios
2. How do neutrinos get mass?

Seesaw? ...

3. How do we learn what mass mechanism is right?

Neutrinoless double beta decay, cosmology, collider, ... ?

4. Why are the mixings and masses what they are?
5. How do you actually detect neutrinos?

Talk to your experimentalist friends

6. How do you produce sources of neutrinos?

Talk to your experimentalist friends

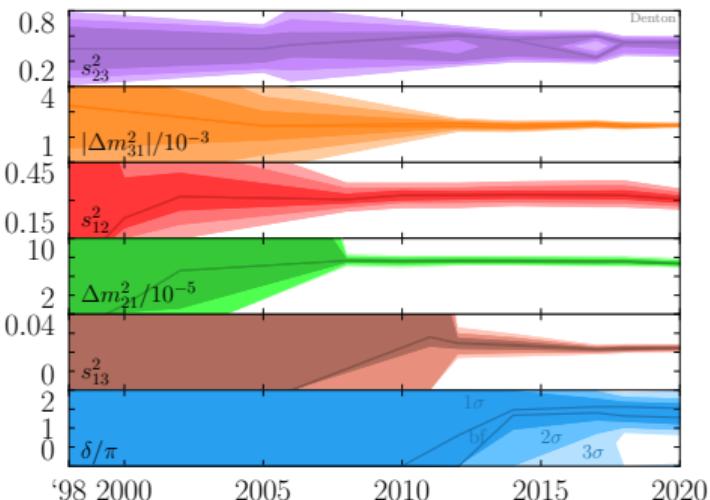
Neutrino oscillation summary

- ▶ Four known unknowns in particle physics: all neutrinos
- ▶ Mass ordering will be measured (robustness?)
- ▶ θ_{23} octant is important for flavor models
- ▶ δ 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!

Precision is coming to neutrinos!

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](#)

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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](#)

NSI review

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

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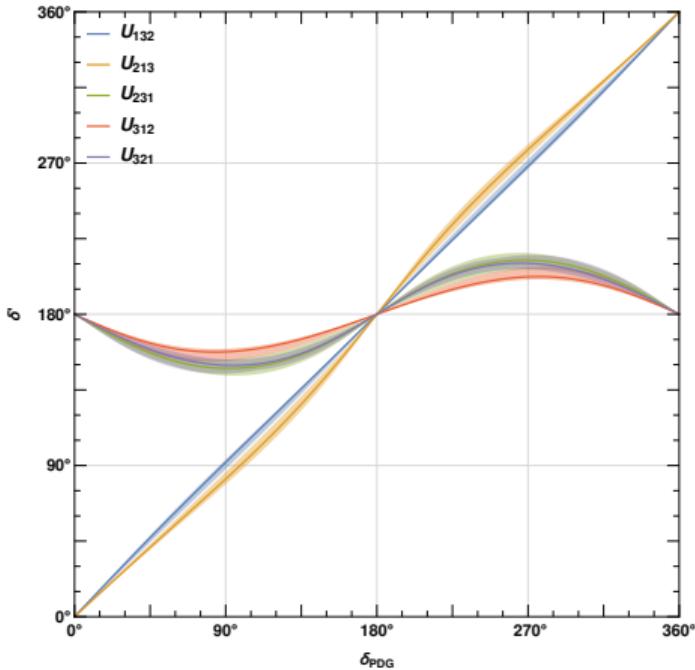
Matter potential $a \propto G_F \rho E$

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

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}
- ▶ δ constrained to $\sim [150^\circ, 210^\circ]$ in U_{231} , U_{312} , U_{321}
- ▶ Bands indicate 3σ uncertainty on θ_{12} , θ_{13} , θ_{23}
- ▶ “50% of possible values of δ ”
⇒ parameterization dependent

DUNE TDR II [2002.03005](#)



Quark mixing

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

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

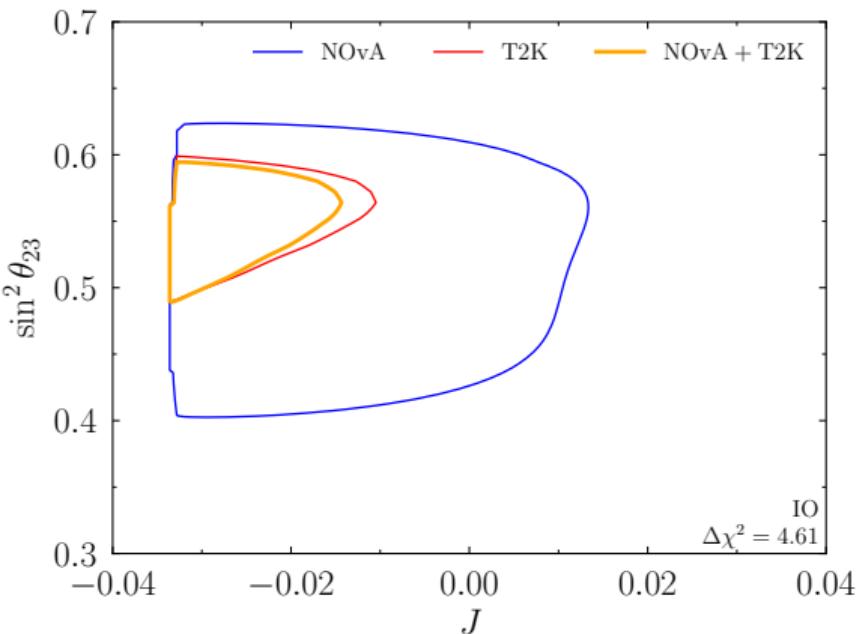
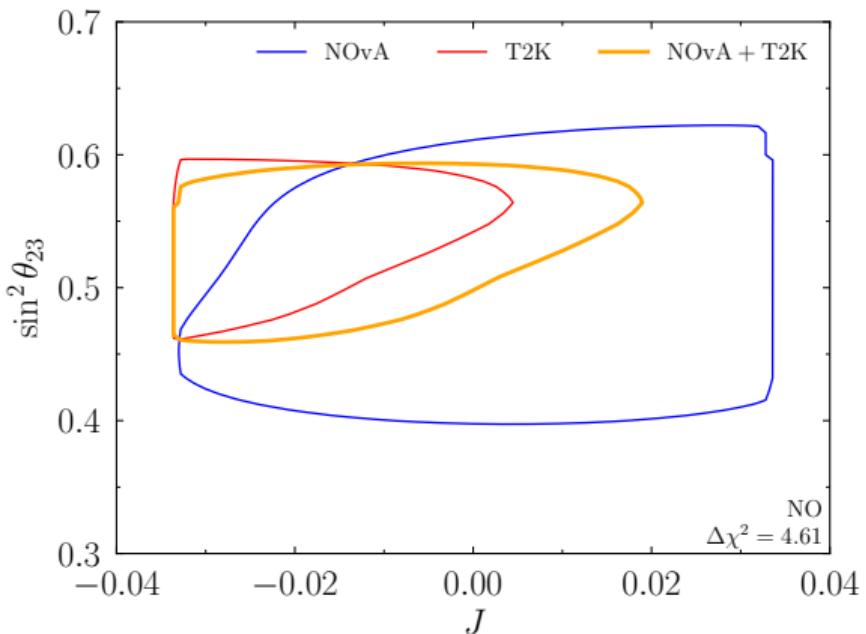
Looks like “large” CPV:

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

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 δ from data requires every other oscillation parameter
- ▶ J requires only Δm_{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 δ and when J ?

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

however

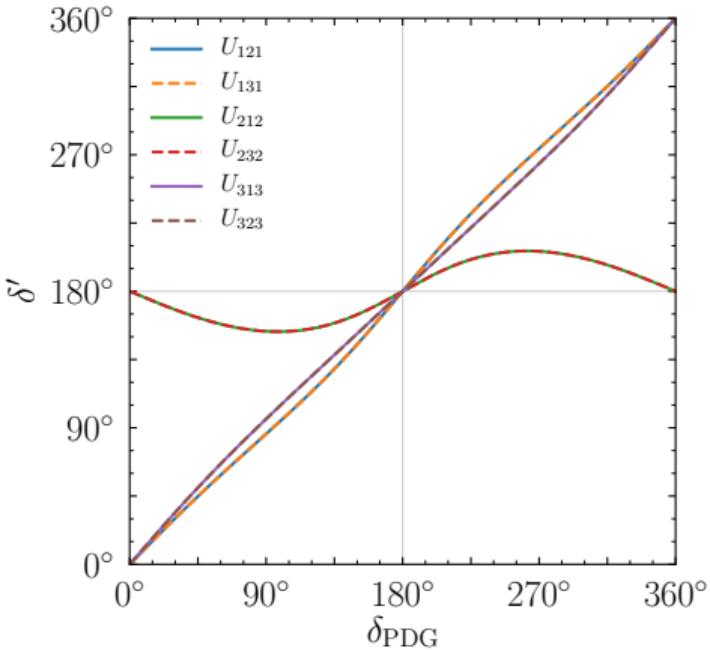
If the goal is **measuring the parameters** one must use δ

Given θ_{12} , θ_{13} , θ_{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 δ should be reported

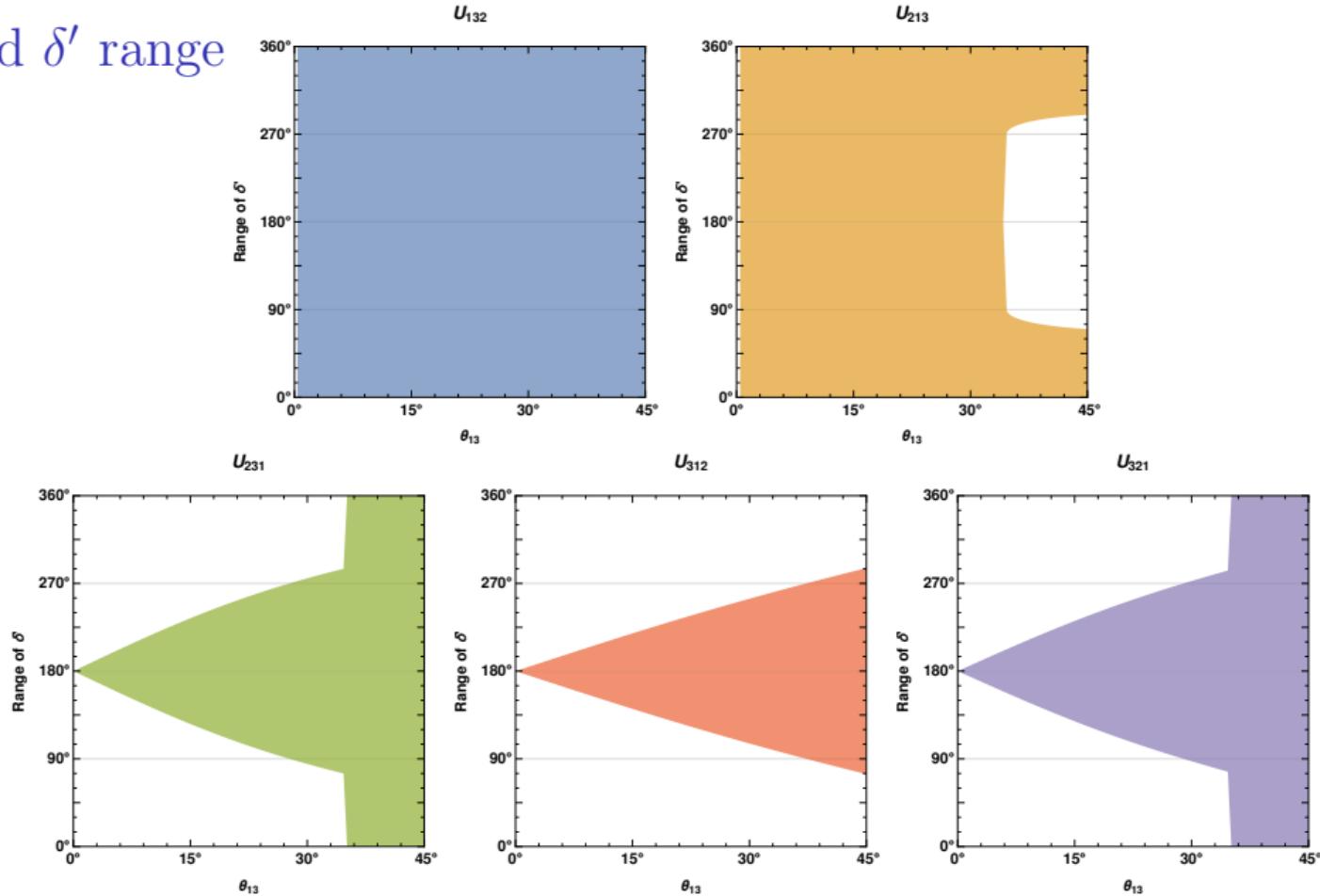
Repeated rotations



	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

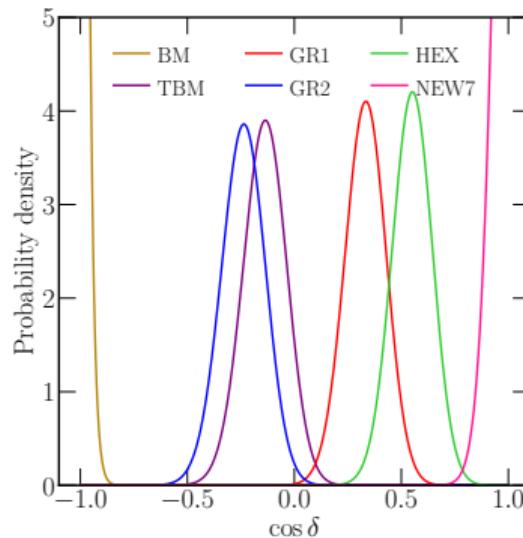
Allowed δ' range



The importance of $\cos \delta$

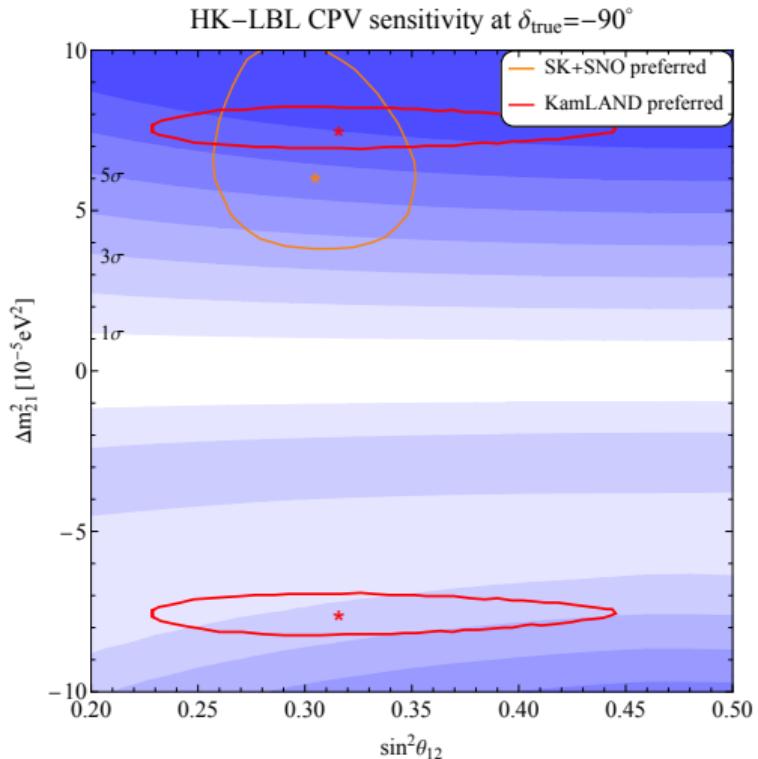
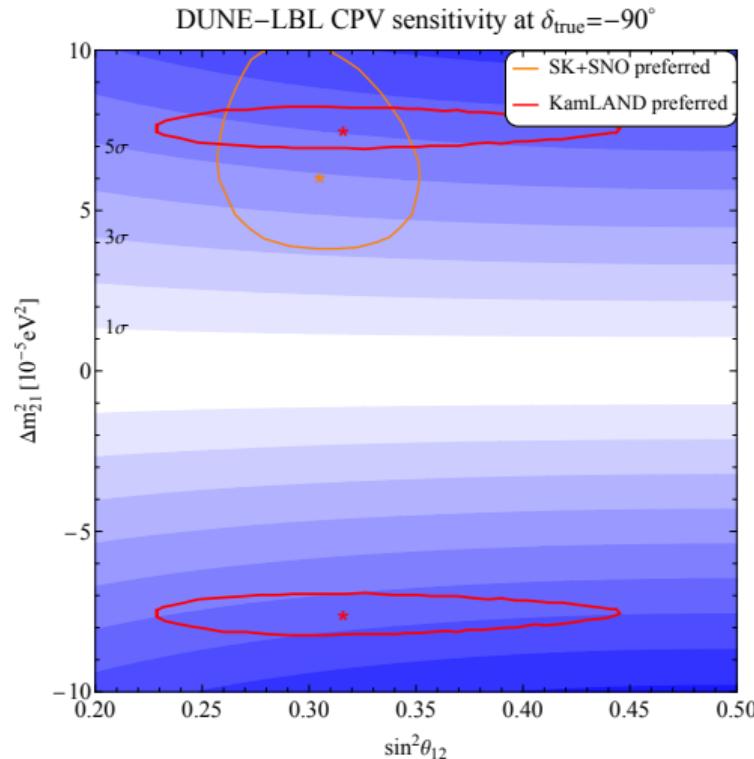
- ▶ If only $\sin \delta$ is measured \Rightarrow sign degeneracy: $\cos \delta = \pm \sqrt{1 - \sin^2 \delta}$
- ▶ Most flavor models predict $\cos \delta$

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



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

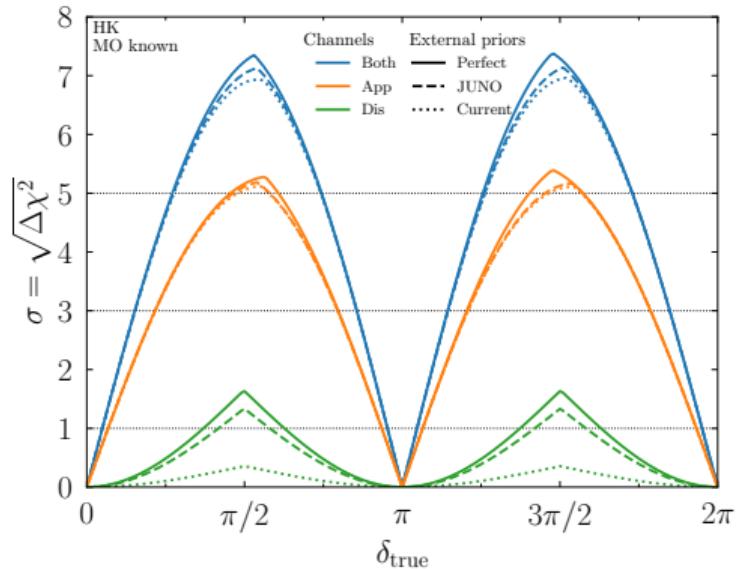
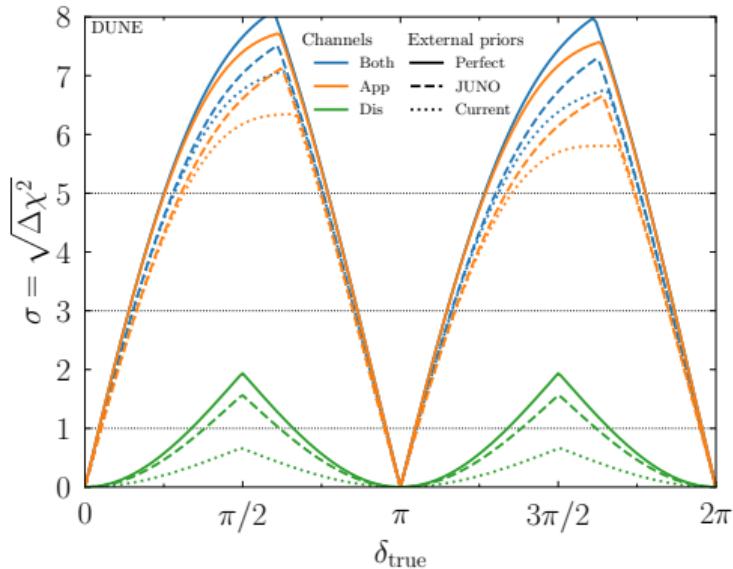
Impact of the true solar parameters on δ



PBD, J. Gehrlein [2302.08513](#)

CP violation discovery with disappearance

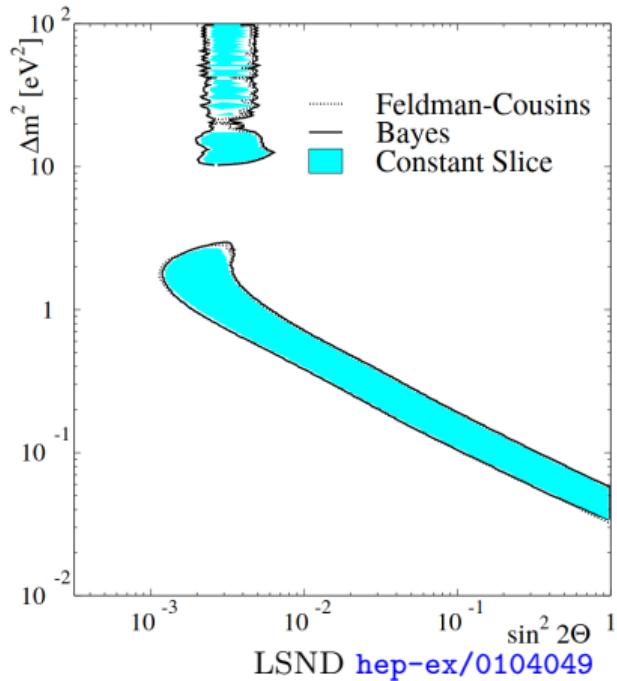
Need JUNO and DUNE or HK



PBD 2309.03262

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:
 - ▶ $\Delta m_{41}^2 \sim 1$ eV²
 - ▶ $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sim 0.002$
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:
 - ▶ ν_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: 4.7σ (1 dof)
 - ▶ Excesses consistent with LSND under sterile hypothesis
 - ▶ Combined with LSND: $\Rightarrow 6.0\sigma$ (1 dof)

MiniBooNE [1805.12028](#)

MicroBooNE disappearance

MicroBooNE is focused on ν_e appearance
Can do ν_μ and ν_e disappearance too!

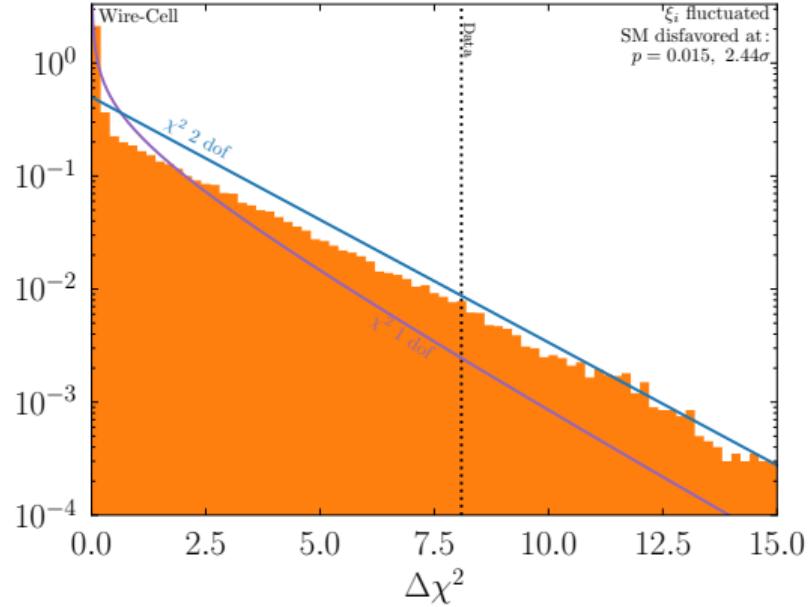
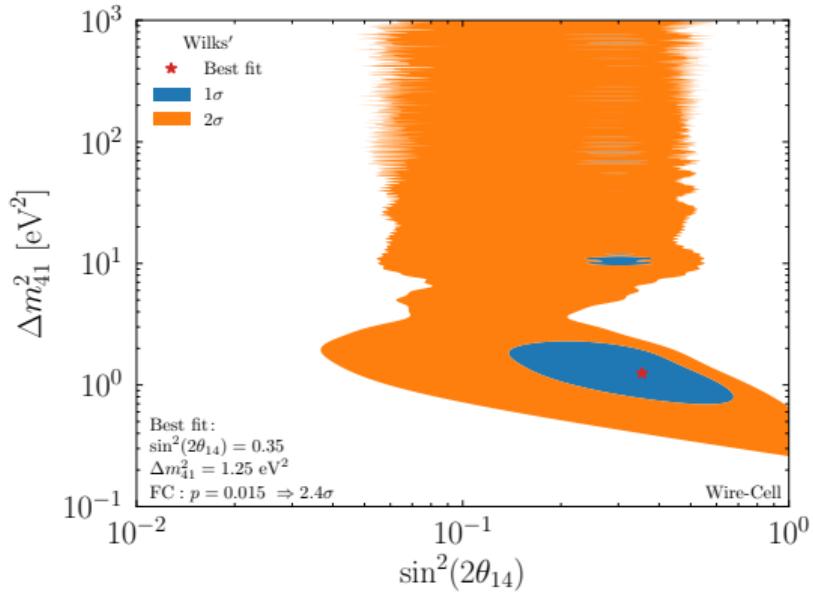
See also D. Cianci, et al. [1702.01758](#)

MiniBooNE backgrounds too big, plus anomaly

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	$\sin^2(2\theta_{14})$	Δm_{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	$0.81^{+0.19}_{-0.47}$	[$1.28, 2.44$] $6.73^{+1.75}_{-0.90}$	2.4
		\vdots	
Pandora-0p	$1^{-0.29}$	$2.21^{+0.82}_{-0.60}$ \vdots	1.8

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 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](#)

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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: α matrix, η 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, π , μ , τ decays

Care is required

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

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

Unitarity violation: mass ranges for tau neutrinos

experiment	(4,4) (m_4)	(5,3) (m_4)
atmospheric ν_μ disappearance	$\in [10 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
atmospheric ν_τ appearance	$\in [10 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
astrophysical ν_τ 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 ν_τ appearance (OPERA)	$\in [1 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
LBL ν_τ appearance (DUNE)	$\in [0.1 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
LBL ν_μ 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](https://arxiv.org/abs/2109.14575)