

## 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. In this colloquium I will discuss some algorithmic and theoretical advances to improve our understanding of three-flavor oscillations. I will also discuss how new physics can complicate the oscillation picture. Finally, I will show how astrophysical environments can tell us more about neutrinos and how neutrinos can tell us more about astrophysical environments.

# Nu Theory

Peter B. Denton

University of Tennessee

April 20, 2026



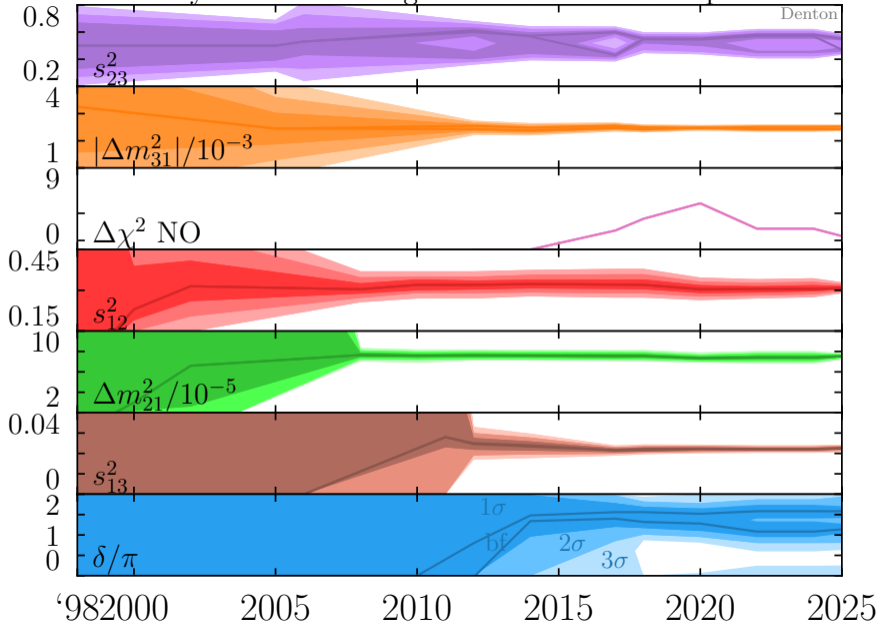
**Brookhaven**<sup>™</sup>  
National Laboratory

The BSM

Physicists

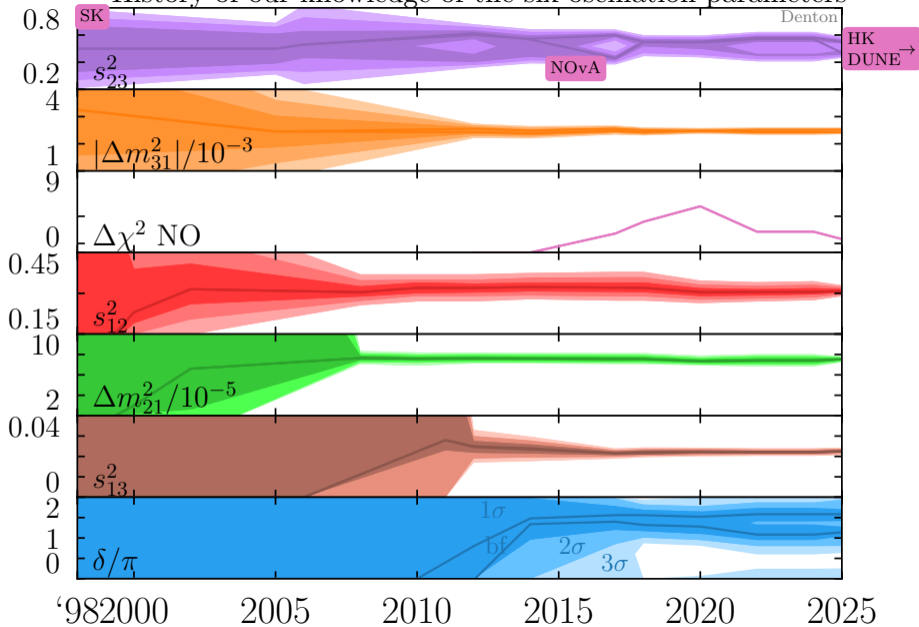


# History of our knowledge of the six oscillation parameters

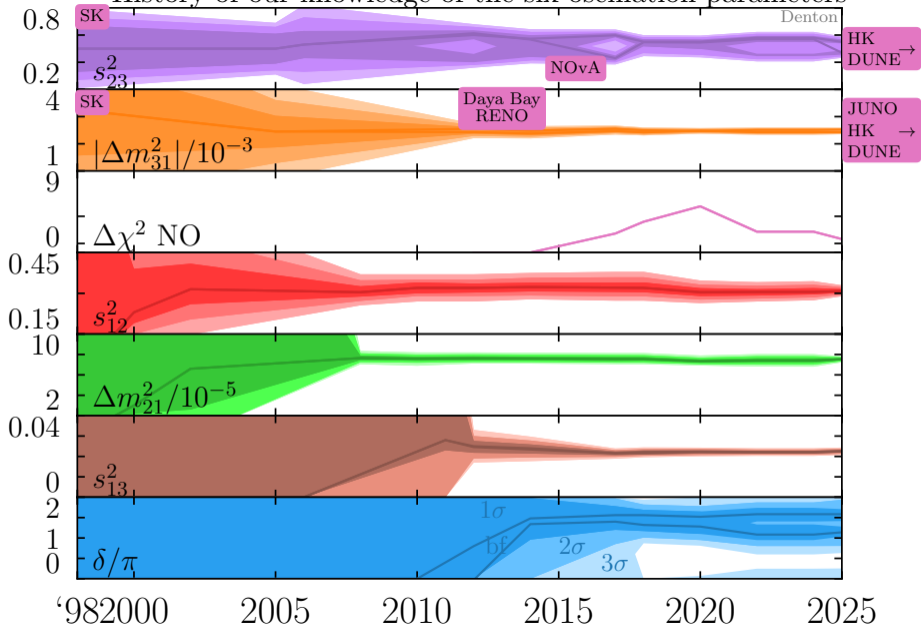


Denton

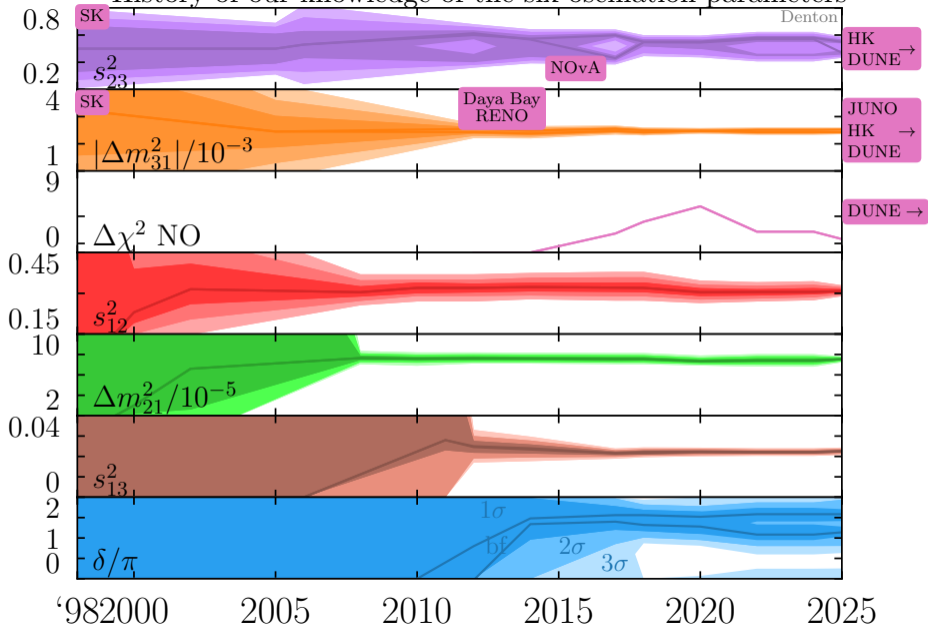
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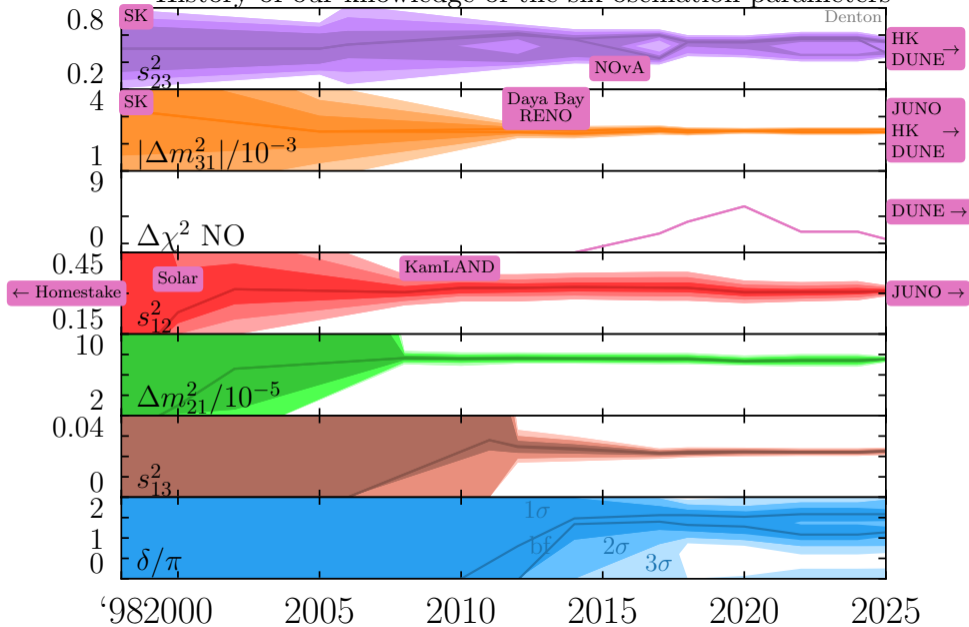
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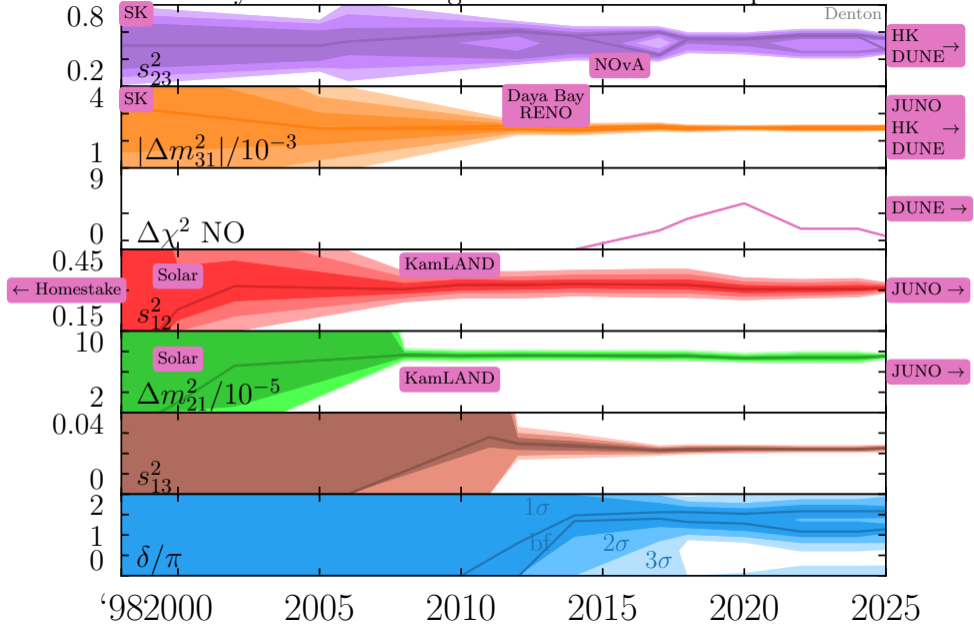
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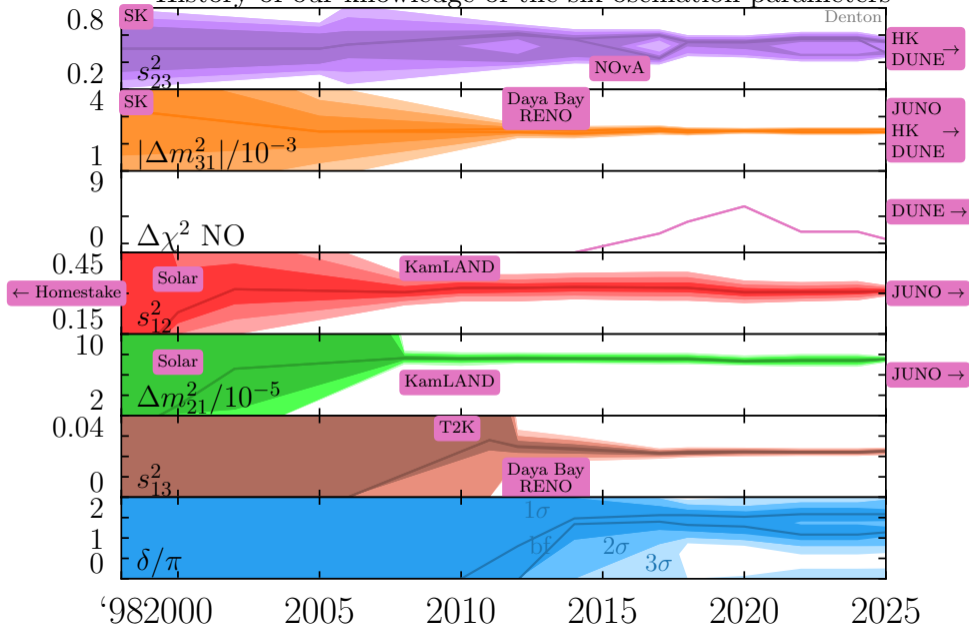
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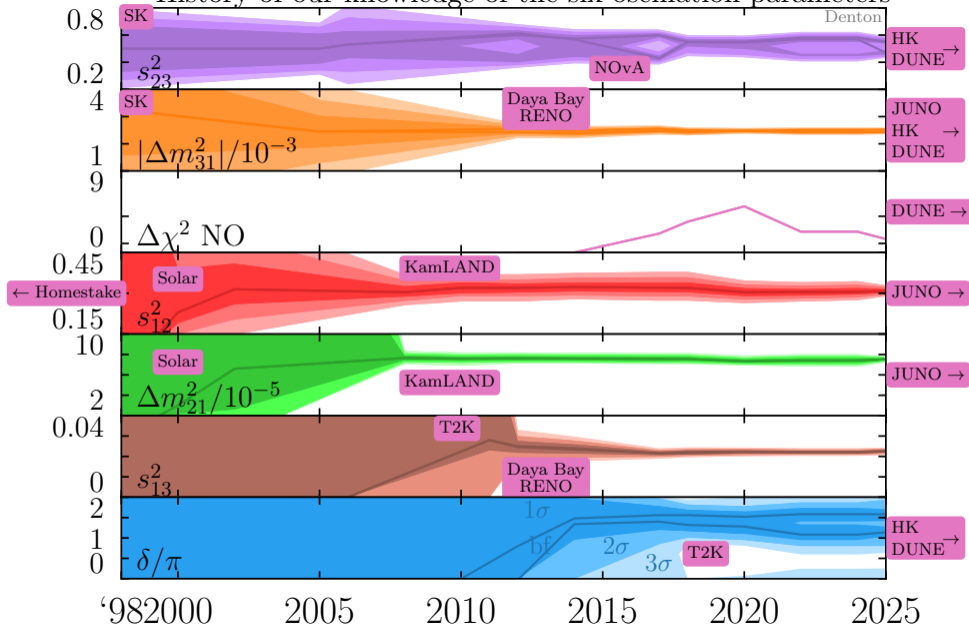
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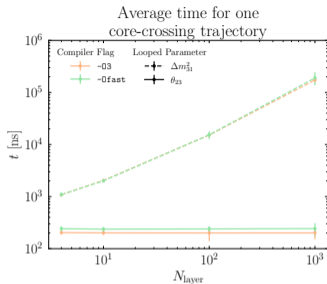


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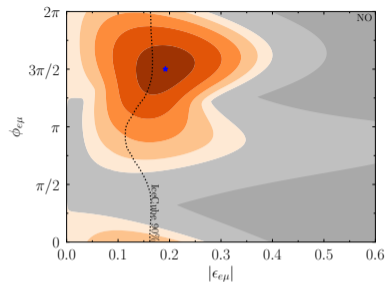
## Part 1:

### Standard Three-Flavor Oscillations



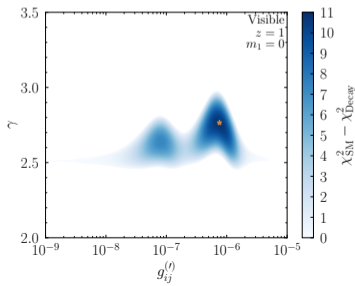
## Part 2:

### New Physics in Neutrinos



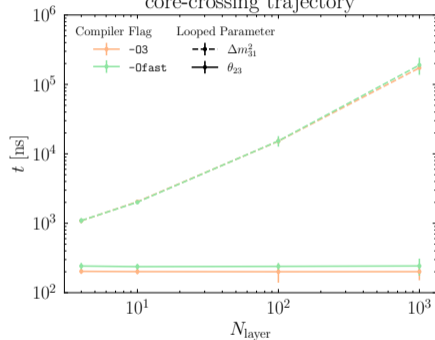
## Part 3:

### Neutrinos in Space



# Part 1: Standard Three-Flavor Oscillations

Average time for one  
core-crossing trajectory



# Neutrino Oscillation Probabilities, Fast

## NuFast

Constant density: [github.com/PeterDenton/NuFast-LBL](https://github.com/PeterDenton/NuFast-LBL)

Varying density: [github.com/PeterDenton/NuFast-Earth](https://github.com/PeterDenton/NuFast-Earth)

# Fermilab computing experts bolster NOvA evidence, 1 million cores consumed

July 3, 2018 | Marcia Teckenbrock

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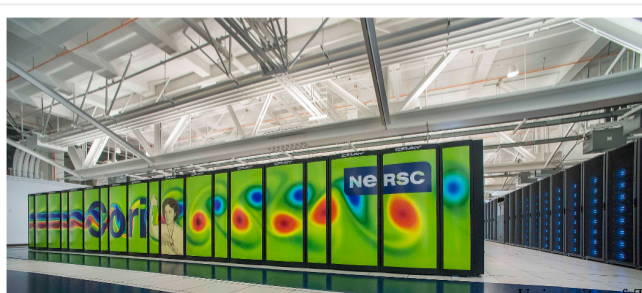
## Array

How do you arrive at the physical laws of the universe when you're given experimental data on a renegade particle that interacts so rarely with matter, it can cruise through light-years of lead? You call on the power of advanced computing.

The NOvA neutrino experiment, in collaboration with the Department of Energy's Scientific Discovery through Advanced Computing (SciDAC-4) program and the HEPcloud program at DOE's Fermi National Accelerator Laboratory, was able to perform the largest-scale analysis ever to support the [recent evidence of antineutrino oscillation](#), a phenomenon that may hold clues to how our universe evolved.

Using Cori, the newest supercomputer at the [National Energy Research Scientific Computing Center \(NERSC\)](#), located at Lawrence Berkeley National Laboratory, NOvA used over 1 million computing cores, or CPUs, between May 14 and 15 and over a short timeframe one week later. This is the largest number of CPUs ever used concurrently over this duration — about 54 hours — for a single high-energy physics experiment. This unprecedented amount of computing enabled scientists to carry out some of the most complicated techniques used in neutrino physics, allowing them to dig deeper into the seldom seen interactions of neutrinos. This Cori allocation was more than 400 times the amount of Fermilab computing allocated to the NOvA experiment and 50 times the total computing capacity at Fermilab allocated for all of its rare-physics experiments. A continuation of the analysis was performed on NERSC's Cori and Edison supercomputers one week later. In total, [nearly 35 million core-hours were consumed by NOvA](#) in the 54-hour period. Executing the same analysis on a single desktop computer would take 4,000 years.

FNAL Newsroom



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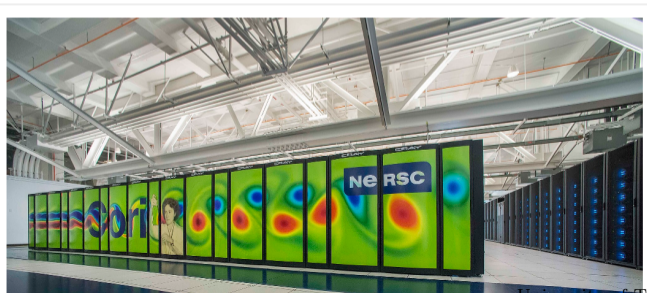
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Benchmarking showed that most of the time was spent computing probabilities

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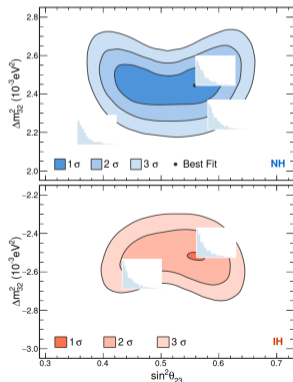


# Monte-Carlo Estimates of Statistical Significances

Wilks' theorem is often wrong

At each point in parameter space, simulate the experiment many times

“many” means  $\gg 1/p$  for a desired  $p$ -value  
This is sometimes called Feldman-Cousins  
G. Feldman, R. Cousins [physics/9711021](#)



NOvA/T2K are  $\sim 3\sigma$  experiments,  
but DUNE/HK will be  $\gtrsim 5\sigma$  experiments!

NOvA: compute the probabilities “a gazillion times”  
DUNE: compute the probabilities “a zillion times”

# Algorithm for Constant Density (Long-Baseline Accelerator)

Need:

1. Eigenvalues
2. Eigenvectors
3. Construct the probability

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NuFast-LBL approach:

1. Approximate one eigenvalue:  $\lambda_3$ 
  - ▶ Can iteratively improve precision rapidly with Newton's method
2. Get other two via two of the Cayley-Hamilton conditions
3. Actually only need  $|V_{\alpha i}|^2$  of the eigenvectors

PBD, S. Parke, X. Zhang [1907.02534](#) (PRD)

- ▶ Leverages NHS identity for the CP violating part

V. Naumov [IJMP 1992](#)  
P. Harrison, W. Scott [hep-ph/9912435](#)

4. Use *Eigenvector-Eigenvalue Identity* to get  $|V_{\alpha i}|^2$  from eigenvalues
5. Combine to probabilities

$$\lambda_3 \approx \Delta m_{31}^2 + \frac{1}{2} \Delta m_{ee}^2 \left( x - 1 + \sqrt{(1-x)^2 + 4x s_{13}^2} \right)$$
$$x \equiv \frac{a}{\Delta m_{ee}^2} \quad \Delta m_{ee}^2 \equiv \Delta m_{31}^2 - s_{12}^2 \Delta m_{21}^2$$

H. Minakata, S. Parke [1505.01826](#)  
PBD, H. Minakata, S. Parke [1604.08167](#) (JHEP)

# Algorithm for Constant Density (Long-Baseline Accelerator)

Need:

1. Eigenvalues
2. Eigenvectors
3. Construct the probability

$$|V_{\alpha i}|^2 = \frac{\prod_{k=1}^{n-1} (\lambda_i - \xi_k^\alpha)}{\prod_{k=1; k \neq i}^n (\lambda_i - \lambda_k)}$$

PBD, S. Parke, T. Tao, X. Zhang [1908.03795](#) (BAMS)  
 $\xi_k^\alpha$  are submatrix eigenvalues: easy to compute

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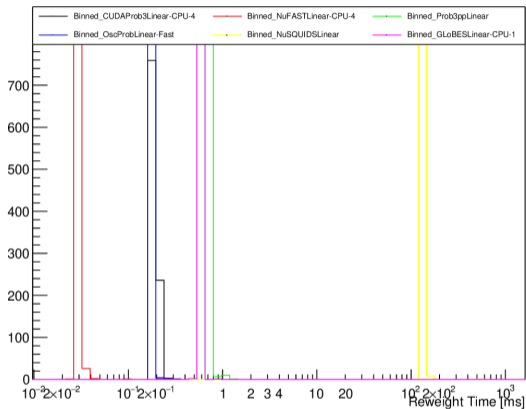
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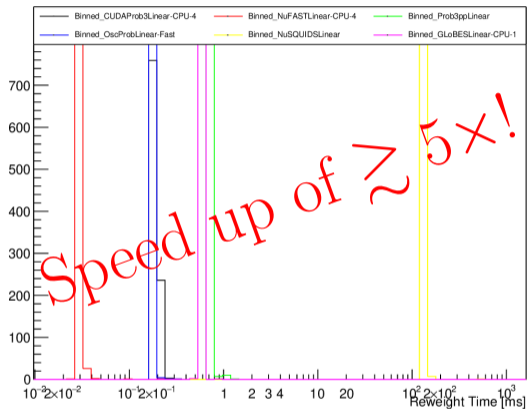
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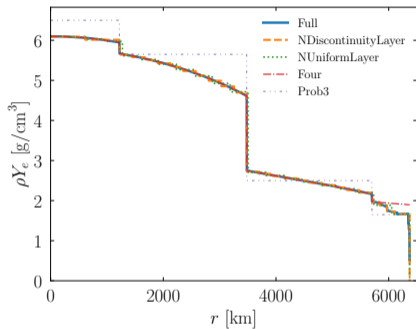


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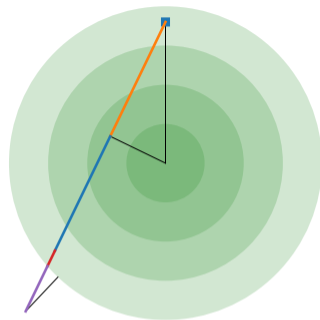
# Atmospherics and Solar are Harder

1. Propagate through the sharply varying Earth
  - ▶ Cannot rewrite probability in terms of  $|V_{\alpha i}|^2$
2. Need many more computations than LBL
  - ▶ Many Earth layers necessary to accurately model Earth
  - ▶ Broader energy range
  - ▶ Varying  $\cos \theta_z$  instead of fixed  $L$
3. High precision necessary to avoid aliasing in solar

# Earth Trajectories



- ▶ Various Earth density profiles
- ▶ Varying or constant density in each shell



Trajectory goes from:

1. Production height to surface
2. Surface to detector depth
3. Detector depth to deepest point
4. Deepest point to detector depth:  
this is the transpose of #3

# New Innovations for Atmospheric

1. Same approach for eigenvalues
2. New approach for eigenvectors: advanced Eigenvector-Eigenvalue identity

PBD, S. Parke, T. Tao, X. Zhang [1908.03795](#) (BAMS)  
A. Abdullahi, S. Parke [2212.12565](#)

3. Pull out  $U_{23}(\theta_{23}, \delta)$  from computation
  - ▶ Hamiltonian is real in new basis
4. Cache computations
  - ▶ Trajectories
  - ▶ Eigenvalue and eigenvector information
  - ▶ Amplitude through the Earth
5. Apply  $\theta_{23}, \delta$ , production height in atmosphere at end

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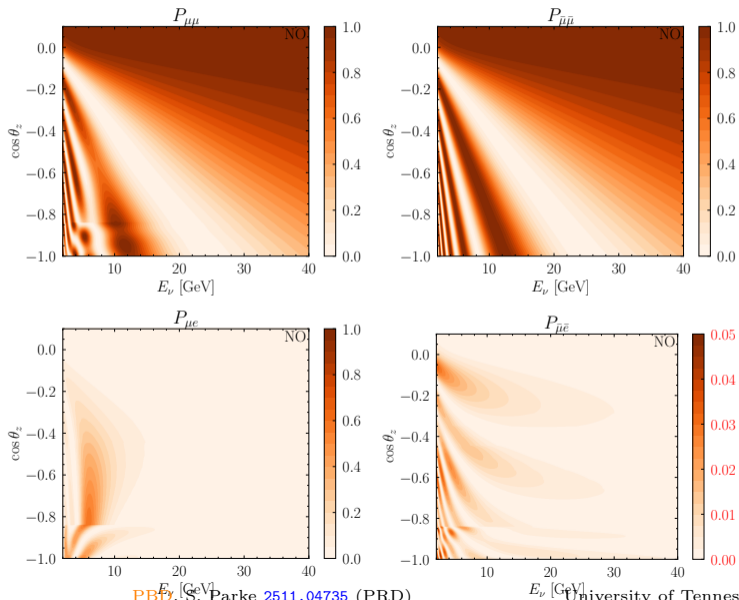
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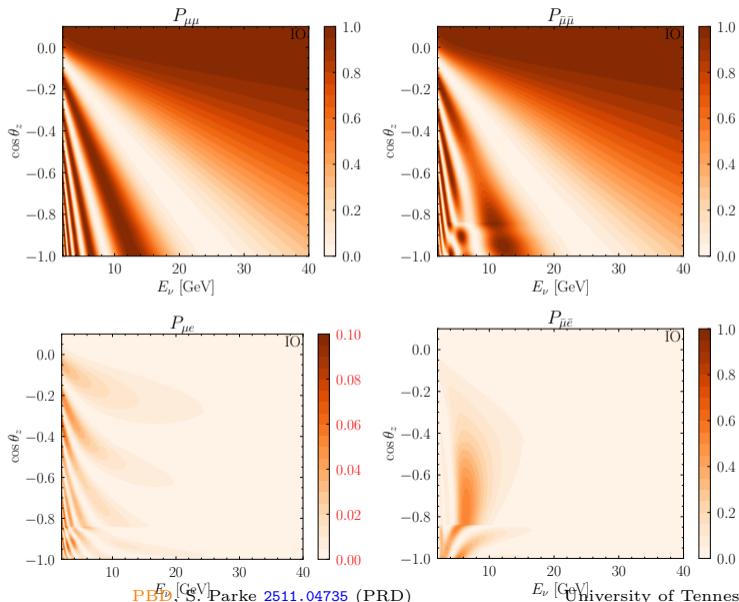
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Varying  $\theta_{23}$ ,  $\delta$ , and production height is essentially free:  
Put on inside of loops

# Atmospheric Results: NO



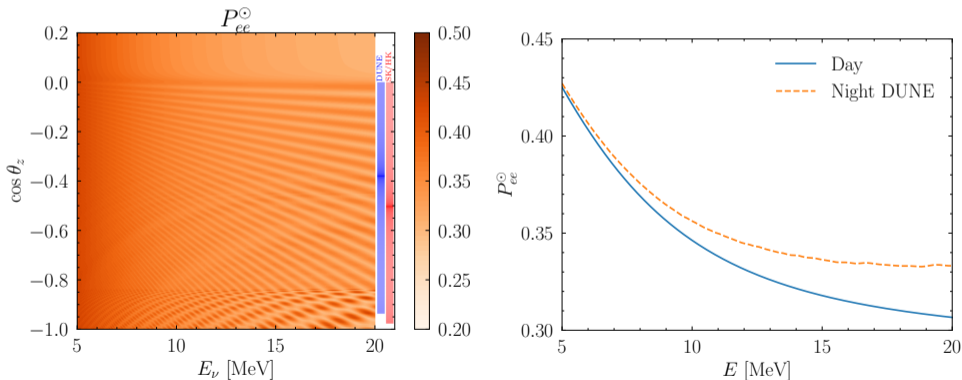
# Atmospheric Results: IO



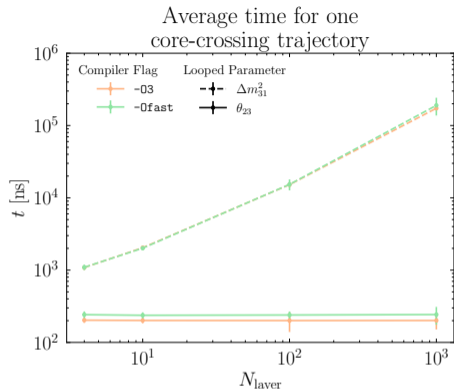
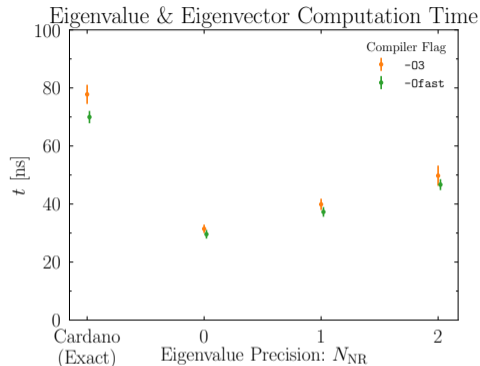
# Nighttime Solar Neutrinos

At night solar neutrinos experience regeneration:  
There are more  $\nu_e$ 's from the Sun at night than during the day!

SuperK has  $\sim 2\sigma$  evidence for this effect; DUNE and HK aim to measure it well



# NuFast-Earth Speed



OscProb takes 40 000 ns per trajectory at 44 layers (compare to 6000 ns or 200 ns)

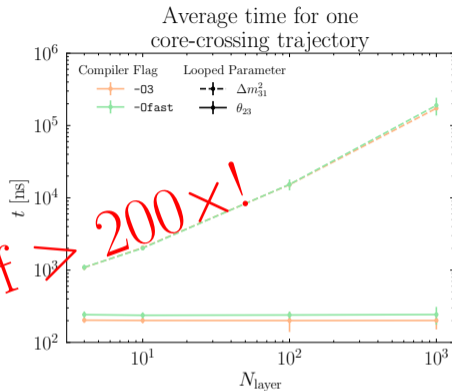
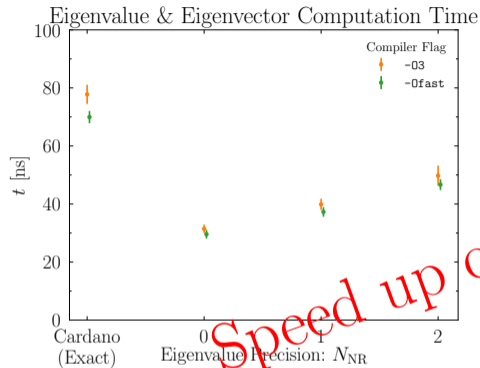
J. Coelho, R. Pestes, et al. [github.com/joaoabcoelho/OscProb](https://github.com/joaoabcoelho/OscProb)

nuSQuIDS takes >1M ns per trajectory

C. Argüelles, J. Salvado, C. Weaver [2112.13804](https://arxiv.org/abs/2112.13804)

Other codes are designed with different goals in mind

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# CP violation in neutrinos

## $\delta$ 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

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

J. Christenson, J. Cronin, V. Fitch, R. Turlay [PRL 1964](#)  
CKMfitter [1501.05013](#)

3. Lepton mass matrix: ?

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

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

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

# The Role of Appearance and Disappearance

- ▶ Disappearance ( $\nu_\alpha \rightarrow \nu_\alpha$ ) are CP even ← nearly all experiments
- ▶ Appearance ( $\nu_\alpha \rightarrow \nu_\beta$ ) have CP even and CP odd parts ← only two

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- ▶ Appearance is the best way to measure  $\delta$  and CPV  
... given known oscillation parameters, systematics, and realistic experiments
  - ▶ Probes mostly  $\sin \delta$  not  $\cos \delta$
  - ▶ Don't need both  $\nu$  and  $\bar{\nu}$  (but systematics)

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- ▶ **Disappearance can measure  $\delta$  and determine if CP is violated or not**
  - ▶ CPV can be discovered with only disappearance measurements
  - ▶ Probes mostly  $\cos \delta$  not  $\sin \delta$
  - ▶ Requires measurements of two flavors
  - ▶ “Works through unitarity” (as do nearly all oscillation measurements)

# Direct Analytic Calculation

Disappearance experiments measure various  $|U_{\alpha i}|^2$  terms  
Suppose 4 are measured:  $|U_{e2}|^2$ ,  $|U_{e3}|^2$ ,  $|U_{\mu 2}|^2$ ,  $|U_{\mu 3}|^2$

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Can show that if any one  $|U_{\alpha i}|^2 = 0 \Rightarrow J = 0$

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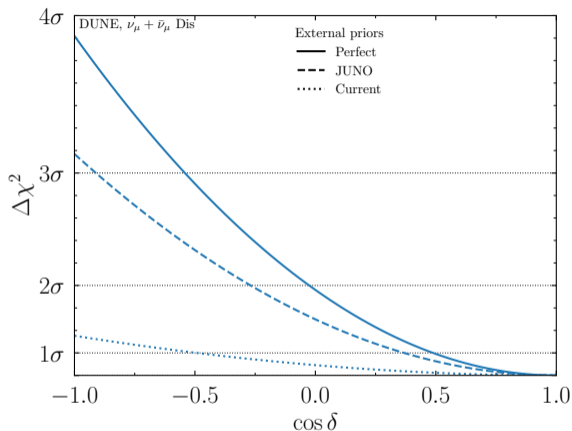
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Can show that if any one  $|U_{\alpha i}|^2 = 0 \Rightarrow J = 0$

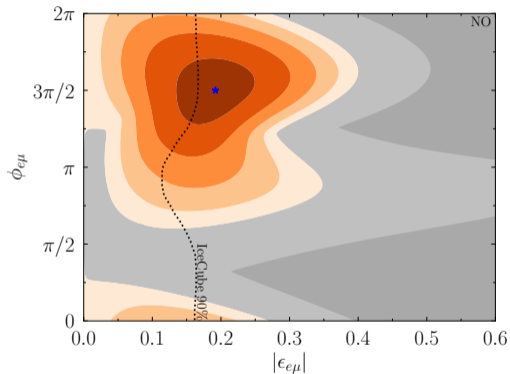
Disappearance can tell us if CP is violated,  
but not if Nature prefers  $\nu$ 's or  $\bar{\nu}$ 's

# JUNO and DUNE Disappearance Combined Sensitivities



Different systematics  $\Rightarrow$  crucial cross check of  $\delta$

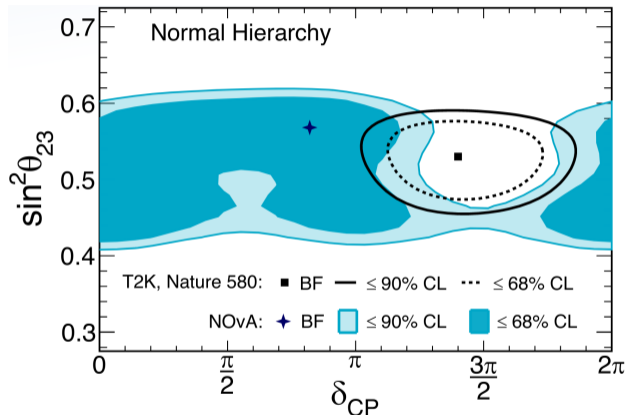
## Part 2: New Physics in Neutrinos



# CP Violation at NOvA and T2K?

T2K wants  $\delta \sim 3\pi/2$  and  $\sin^2 \theta_{23}$  large

NOvA wants anything else



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

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

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

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

Matter potential  $a \propto G_F \rho E$

## Estimate Size of Effect: Magnitude

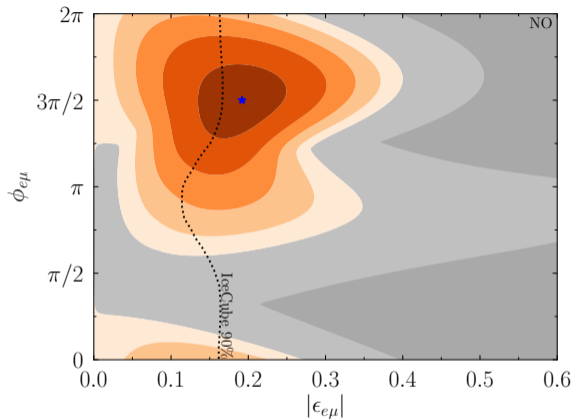
$$|\epsilon_{e\beta}| \approx \frac{s_{12}c_{12}c_{23}\pi\Delta m_{21}^2}{2s_{23}w_\beta} \left| \frac{\sin \delta_{T2K} - \sin \delta_{NOvA}}{a_{NOvA} - a_{T2K}} \right| \approx \begin{cases} 0.22 & \text{for } \beta = \mu \\ 0.24 & \text{for } \beta = \tau \end{cases}$$

$a \propto \rho E$   
Requires  $\phi_{e\beta} \sim \pm\pi/2$   
 $w_\beta = s_{23}, c_{23}$  for  $\beta = \mu, \tau$   
Assumed upper octant  $\theta_{23} > 45^\circ$

Consistency checks:

- ▶  $\sin \delta_{NOvA} = \sin \delta_{T2K} \Rightarrow |\epsilon| = 0$
- ▶  $\sin \delta_{NOvA} \neq \sin \delta_{T2K}$  and  $a_{NOvA} = a_{T2K} \Rightarrow |\epsilon| \rightarrow \infty$
- ▶ 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 \(2019\)](#)  
IceCube [2106.07755](#)

New physics, degeneracies,  
and the impossibility of determining the mass ordering

# 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**, Y. Farzan, I. Shoemaker [1804.03660](#) (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, and DM direct detection can close all loopholes

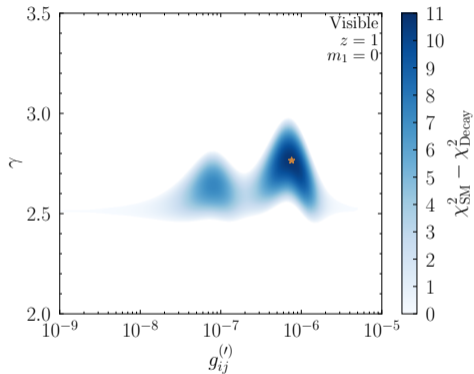
# Many Interesting New Physics Scenarios in Oscillations

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. Pestes [2008.01110](#) (PRL)  
PBD, J. Gehrlein [2008.06062](#) (JHEP), [2204.09060](#) (PRD)  
PBD, A. Giarnetti, D. Meloni [2210.00109](#) (JHEP), [2409.15411](#) (JHEP)
3. Non-standard neutrino self interactions Barenboim, PBD, Oldengott [1903.02036](#) (PRD)
4. Neutrino decay  
with visible or invisible final states  
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

## Part 3: Neutrinos in Space



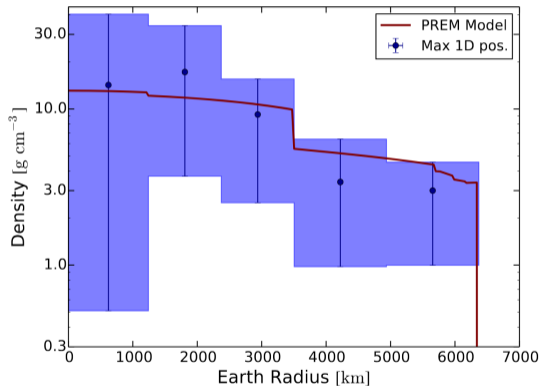
“Ask not what your country can do for you –  
ask what you can do for your country”

What can neutrinos do for you  
**and**  
what you can do for neutrinos

# Neutrinos shine a flashlight in opaque environments

# Terrestrial Tomography

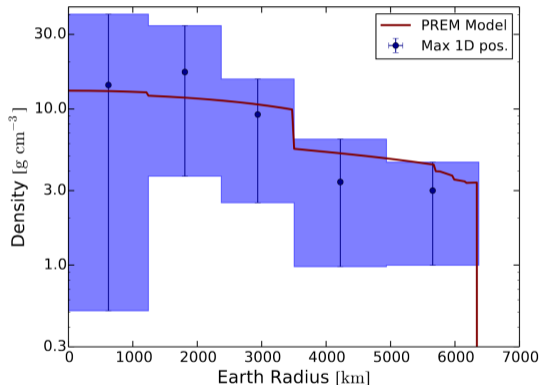
HE neutrinos are absorbed in the Earth  
Assumes isotropic flux



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

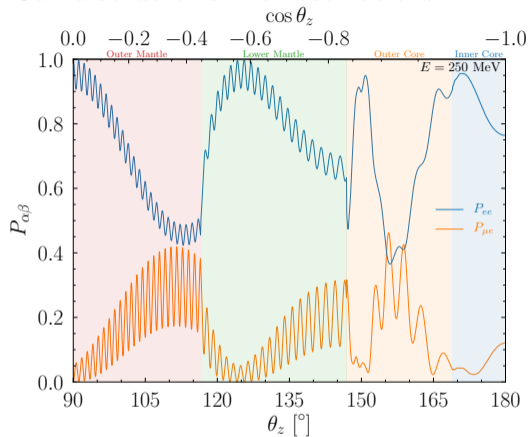
# Terrestrial Tomography

HE neutrinos are absorbed in the Earth  
Assumes isotropic flux



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

Can also do this with oscillations



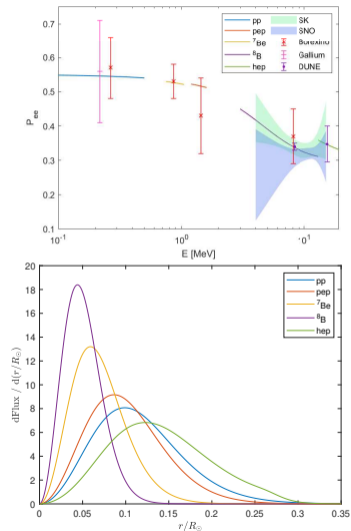
[PBD, R. Pestes 2110.01148](#) (PRD)

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

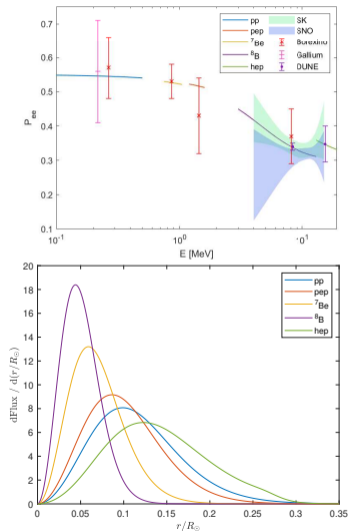
See also K. Kelly, et al. [2110.00003](#)

# Solar Tomography

Solar neutrinos constrain Sun's density at different radii

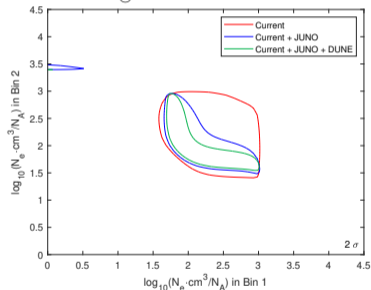


# Solar Tomography

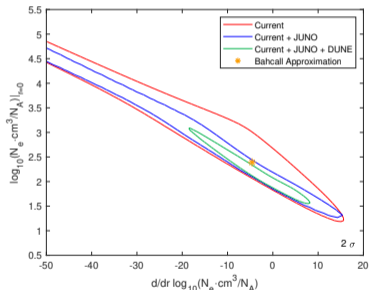


Solar neutrinos constrain Sun's density at different radii

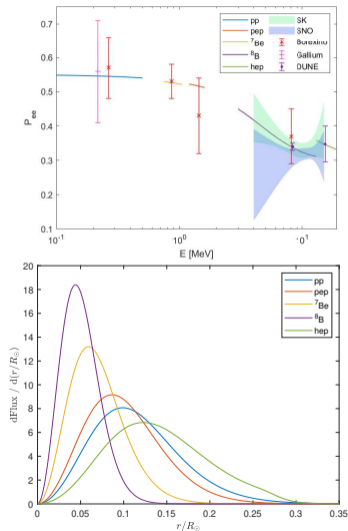
Bin 1:  $\frac{r}{R_\odot} \in [0, 0.05]$   
 Bin 2:  $\frac{r}{R_\odot} \in [0.05, 0.1]$



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

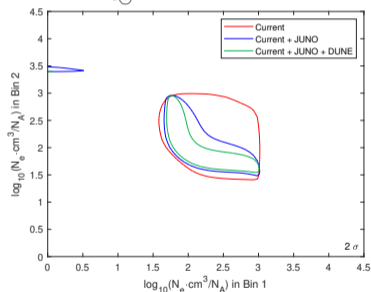


# Solar Tomography

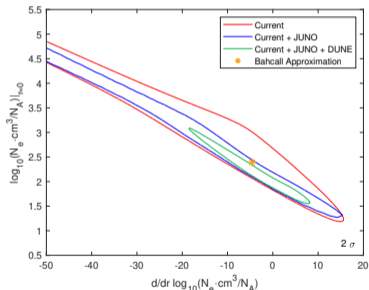


Solar neutrinos constrain Sun's density at different radii

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



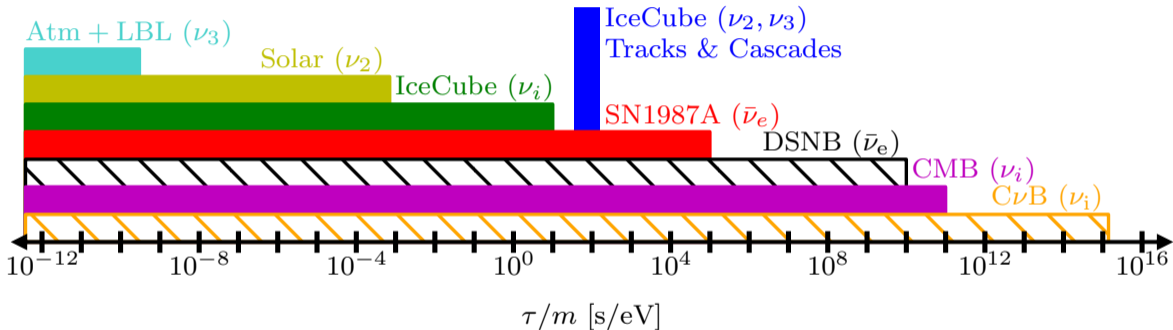
$$\log_{10} N_e = Ar + B$$



First determination of Sun's density with neutrinos  
 Only way to probe innermost 5% of the Sun

# New particle physics in neutrinos from astrophysics

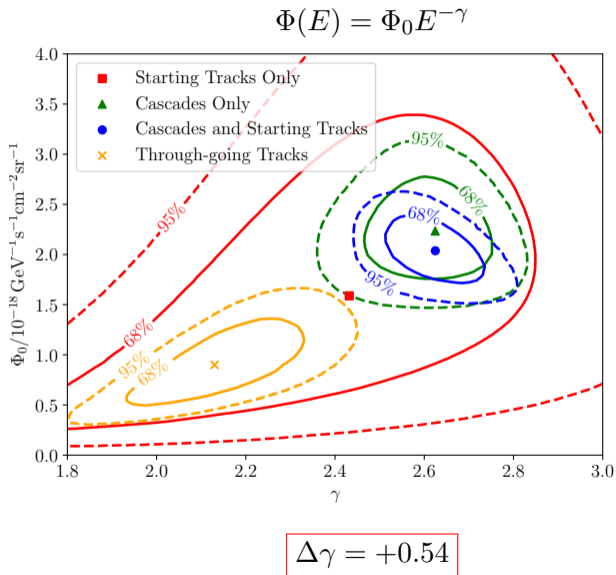
# Invisible $\nu$ Decay Constraints and Evidence



M. Gonzalez-Garcia and M. Maltoni 0802.3699  
 J. Berryman, A. de Gouvea, D. Hernandez 1411.0308  
 G. Pagliaroli, et al. 1506.02624  
 PBD, I. Tamborra 1805.05950 (PRL)

Kamiokande-II, PRL 58 1490 (1987)  
 S. Ando hep-ph/0307169  
 S. Hannestad, G. Raffelt hep-ph/0509278  
 A. Long, C. Lunardini, E. Sabancila 1405.7654

# Tension



“The p-value for obtaining the combined fit result and the result reported here from an unbroken powerlaw flux is  $3.3\sigma$ , and is therefore in significant **tension**.”

IC 1607.08006

“This [cascade] fit [is] in **tension** with previous results based on through-going muons”

IC 1808.07629

“[with cascades] we reject spectral indices  $\gamma \leq 2.28$  [latest track index] at  $\geq 3\sigma$  level.”

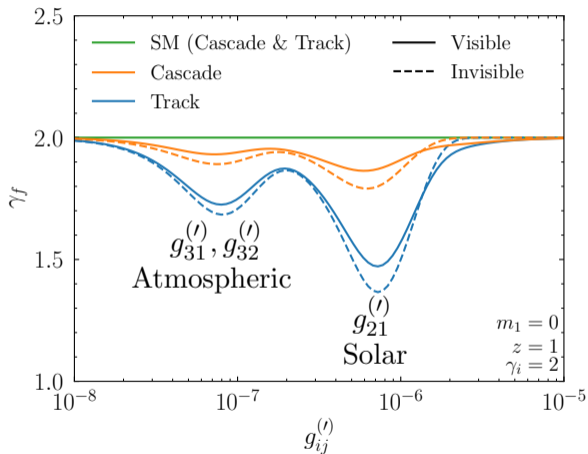
IC 2001.09520

# Spectral Indices at IceCube

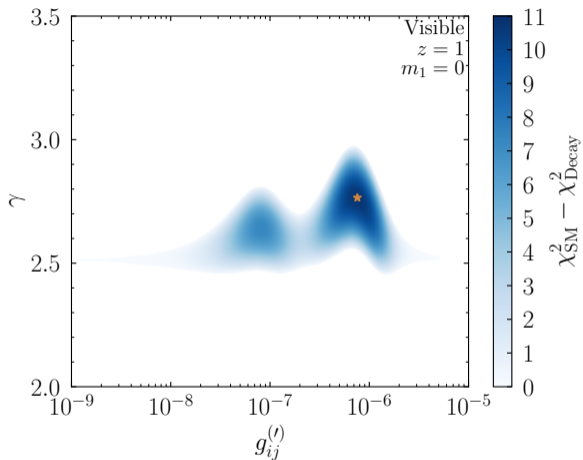
1. Neutrino decay completely removes tension
2. Is preferred over SM at  $> 3\sigma$
3. Either visible or invisible works
4. Requires normal mass ordering
5. Decay only shifts the spectra one way:

$$\gamma_c > \gamma_t$$

this is the direction of the tension



## Preferred Region: Visible



► Consistent with astro constraints including SN1987A

► Terrestrial constraints at  $g \sim 10^{-2}$

$$\pi \rightarrow \ell\nu\phi, K \rightarrow \ell\nu\phi$$

B. Dev, et al. [2407.12738](#)

► Some tension with cosmology;  
possible to evade

[github.com/PeterDenton/Astro-Nu-Decay](https://github.com/PeterDenton/Astro-Nu-Decay)

## Other Astroparticle Projects

1. Tensions with 1 eV sterile anomalies reduced with ultralight scalar

H. Davoudiasl, [PBD 2301.09651](#) (PRD)  
[PBD 2301.11106](#) (PLB)

2. Galactic supernova has information about absolute neutrino masses

[PBD](#), Y. Kini [2411.13634](#) (PRD)

3. NANOGrav may be seeing first order phase transition in GWs;  
this would also show up in supernova

H. Davoudiasl, [PBD](#), A. Suliga [2510.23713](#)

4. Ultralight scalars can boost 100% of the DM at the Earth making DUNE,  
SuperK, and IceCube the relevant DM direct detectors for  $m_\chi < \text{GeV}$

H. Davoudiasl, [PBD](#), J. Gehrlein [2007.04989](#) (PRD)  
J. Acevedo, J. Berger, [PBD 2407.01670](#) (JHEP)

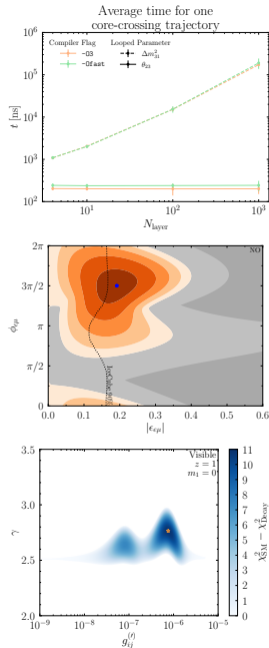
5. Disfavored ultralight boson DM via black hole measurements

H. Davoudiasl, [PBD 1904.09242](#) (PRL)

⋮

# Neutrino Theory Summary

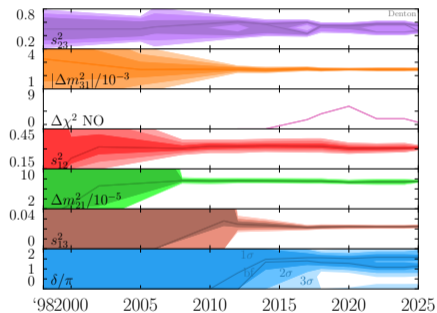
- ▶ Fast probabilities are important; NuFast is fast
- ▶ More ways to get at CPV in neutrinos; systematics
- ▶ Data may be pointing to flavor-changing CPV NSI; can understand analytically
- ▶ Parameter space for LMA-Dark is closing fast; mass ordering robustness
- ▶ Neutrinos can probe opaque environments
- ▶ IceCube can probe particle BSM,  $> 3\sigma$  for  $\nu$  decay



Thanks!

# 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](#)

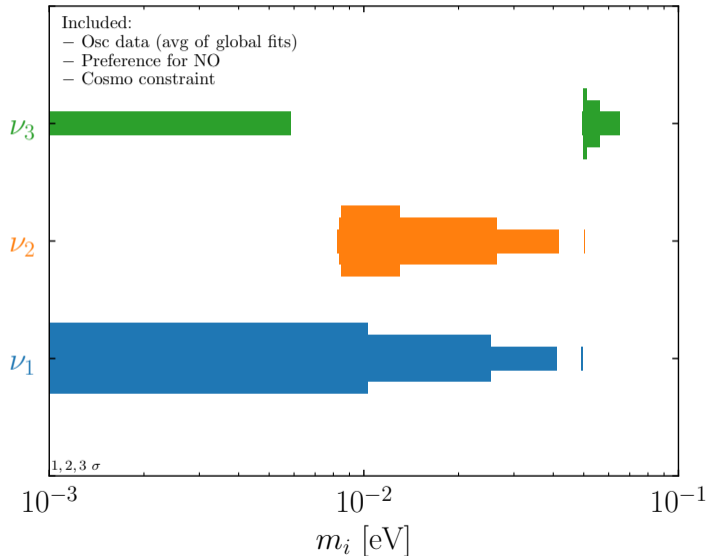
D. Forero, M. Tortola, J. Valle [1405.7540](#)

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

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

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

# Absolute Masses



# Optimal Structure of the Probability for Long-Baseline

1. Amplitude requires four trig functions of kinematic variables ( $\Delta m_{ij}^2 L/4E$ ) ✗
2. Writing the probabilities out requires three trig functions ✓
3. Disappearance structure is straightforward:

$$P_{\alpha\alpha} = 1 - 4 \sum_{i>j} |V_{\alpha i}|^2 |V_{\alpha j}|^2 \sin^2 \frac{\Delta\lambda_{ij}L}{4E}$$

$H$  in matter has eigenvalues  $\lambda_i$  and eigenvectors  $V_{\alpha i}$

# Optimal Structure of the Probability for Long-Baseline

## 4. Appearance structure:

$T$  conserving:

$$P_{\mu e}^{TC} = 2 \sum_{i>j} (|V_{\tau k}|^2 - |V_{\mu i}|^2 |V_{e j}|^2 - |V_{\mu j}|^2 |V_{e i}|^2) \sin^2 \frac{\Delta \lambda_{ij} L}{4E}$$

Fun fact:

$$\begin{aligned} & 2\Re(V_{\alpha i} V_{\beta j}^* V_{\alpha j}^* V_{\beta i}) \\ &= |V_{\alpha k}|^2 |V_{\beta k}|^2 - |V_{\alpha i}|^2 |V_{\beta i}|^2 - |V_{\alpha j}|^2 |V_{\beta j}|^2 \\ &= |V_{\gamma k}|^2 - |V_{\alpha i}|^2 |V_{\beta j}|^2 - |V_{\alpha j}|^2 |V_{\beta i}|^2 \end{aligned}$$

$T$  violating:

$$P_{\mu e}^{TV} = -8J \frac{\Delta m_{21}^2 \Delta m_{31}^2 \Delta m_{32}^2}{\Delta \lambda_{21} \Delta \lambda_{31} \Delta \lambda_{32}} \sin \frac{\Delta \lambda_{21} L}{4E} \sin \frac{\Delta \lambda_{31} L}{4E} \sin \frac{\Delta \lambda_{32} L}{4E}$$

Leverages NHS identity:

V. Naumov [IJMP 1992](#)

P. Harrison, W. Scott [hep-ph/9912435](#)

# Account for Matter in Long-Baseline

1. Need the eigenvalues  $\lambda_i$
2. For eigenvectors, naively need  $\Re(V_{\alpha i} V_{\beta j}^* V_{\alpha j} V_{\beta i})$
3. Given our form, need only the  $|V_{\alpha i}|^2$  and  $J$ 
  - ▶ Don't need any phase information of the eigenvectors!

Leverages [PBD](#), S. Parke, X. Zhang [1907.02534](#) (PRD)

4. Can compute the  $|V_{\alpha i}|^2$  from the  $\lambda_i$  and submatrix eigenvalues (requires only a square root) using Eigenvector-Eigenvalue Identity

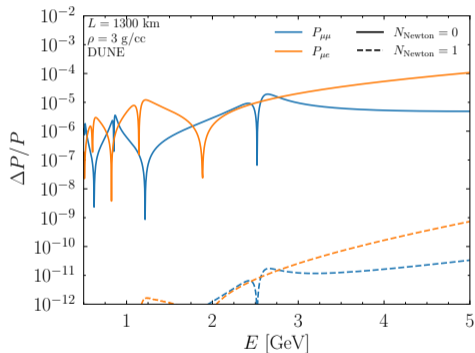
$$|V_{\alpha i}|^2 = \frac{\prod_{k=1}^{n-1} (\lambda_i - \xi_k^\alpha)}{\prod_{k=1; k \neq i}^n (\lambda_i - \lambda_k)}$$

See e.g. [PBD](#), S. Parke, T. Tao, X. Zhang [1908.03795](#) (BAMS)  
Can actually avoid the  $\sqrt{\phantom{x}}$  in practice

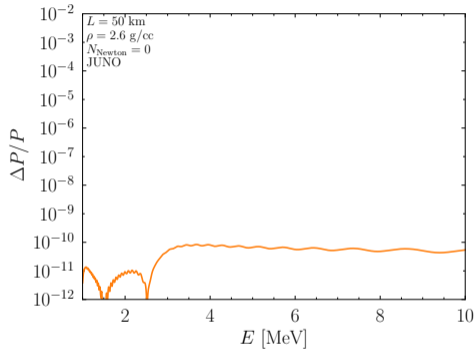
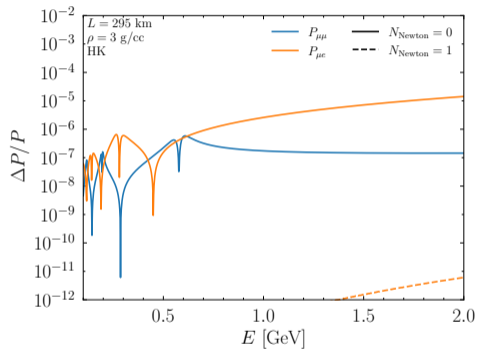
# NuFast-LBL Precision

Is this approximation okay?

DUNE requires  $\lesssim 1\%$  level precision



# Precision



# NuFast-LBL: The Code

- ▶ Code is on github: [github.com/PeterDenton/NuFast-LBL](https://github.com/PeterDenton/NuFast-LBL)
- ▶ Implementations in c++ and f90

---

```
// NuFast.cpp
// Calculate the probabilities:
Probability_Matter_LBL(s12sq, s13sq, s23sq, delta,
    Dmsq21, Dmsq31, L, E, rho, Ye, N_Newton,
    &probs_returned);
// Print out the probabilities to terminal
for (int alpha = 0; alpha < 3; alpha++)
{
    for (int beta = 0; beta < 3; beta++)
    {
        printf("%d %d %g\n", alpha, beta,
            probs_returned[alpha][beta]);
    } // beta, 3
} // alpha, 3
```

---

- ▶  $\bar{\nu}$ :  $E < 0$ ; IO:  $\Delta m_{31}^2 < 0$
- ▶ Folder called **Benchmarks** to make the plots and speed tests in the paper
- ▶ Used in [NuOscillator](#), [MaCh3](#), [GUNDAM](#), and theory papers
- ▶ Speed up of  $\gtrsim 5\times$  over state-of-the-art in realistic usage

# Optimal Structure of the Probability for Atmospherics

1. Cannot apply the previous tricks through the Earth
2. Must compute the amplitude in Each layer

$$\prod_j \mathcal{A}_j$$

# Optimal Structure of the Probability for Atmosphericics

3. Work in the tilde basis with  $\theta_{23}$  and  $\delta$  pulled out

► Can shift  $\delta$  from  $\theta_{13}$  to  $\theta_{23}$

$$\begin{pmatrix} 1 & & \\ c_{23} & s_{23} & \\ -s_{23} & c_{23} & \end{pmatrix} \begin{pmatrix} c_{13} & s_{13}e^{-i\delta} & \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} R_{12} \rightarrow \begin{pmatrix} 1 & & \\ c_{23} & s_{23}e^{i\delta} & \\ -s_{23}e^{-i\delta} & c_{23} & \end{pmatrix} \begin{pmatrix} c_{13} & s_{13} & \\ & 1 & \\ -s_{13} & & c_{13} \end{pmatrix} R_{12}$$

# Optimal Structure of the Probability for Atmosphericics

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▶  $U_{23}$  commutes with the matter potential

$$(2E)H_f = U_{23}(\theta_{23}, \delta) \left[ R_{13}R_{12} \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} R_{12}^T R_{13}^T + \begin{pmatrix} a & & \\ & 0 & \\ & & 0 \end{pmatrix} \right] U_{23}^\dagger(\theta_{23}, \delta)$$

$$H_f = U_{23}(\theta_{23}, \delta) \tilde{H} U^\dagger(\theta_{23}, \delta)$$

# Optimal Structure of the Probability for Atmosphericics

3. Work in the tilde basis with  $\theta_{23}$  and  $\delta$  pulled out

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$$\begin{pmatrix} 1 & & \\ c_{23} & s_{23} & \\ -s_{23} & c_{23} & \end{pmatrix} \begin{pmatrix} c_{13} & s_{13}e^{-i\delta} \\ & 1 \\ -s_{13}e^{i\delta} & c_{13} \end{pmatrix} R_{12} \rightarrow \begin{pmatrix} 1 & & \\ c_{23} & s_{23}e^{i\delta} & \\ -s_{23}e^{-i\delta} & c_{23} & \end{pmatrix} \begin{pmatrix} c_{13} & s_{13} \\ & 1 \\ -s_{13} & c_{13} \end{pmatrix} R_{12}$$

►  $U_{23}$  commutes with the matter potential

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$$H_f = U_{23}(\theta_{23}, \delta) \tilde{H} U^\dagger(\theta_{23}, \delta)$$

$$\mathcal{A} = \prod_j \mathcal{A}_j = \prod_j e^{-iH_{f,j}L_j} = U_{23}(\theta_{23}, \delta) \left( \prod_j e^{-i\tilde{H}_jL_j} \right) U_{23}^\dagger(\theta_{23}, \delta)$$

$$U_{23}U_{23}^\dagger = 1$$

# Optimal Structure of the Probability for Atmosphericics

3. Work in the tilde basis with  $\theta_{23}$  and  $\delta$  pulled out

► Can shift  $\delta$  from  $\theta_{13}$  to  $\theta_{23}$

$$\begin{pmatrix} 1 & & \\ c_{23} & s_{23} & \\ -s_{23} & c_{23} & \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} R_{12} \rightarrow \begin{pmatrix} 1 & & \\ c_{23} & s_{23}e^{i\delta} & \\ -s_{23}e^{-i\delta} & c_{23} & \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} \\ & 1 & \\ -s_{13} & & c_{13} \end{pmatrix} R_{12}$$

►  $U_{23}$  commutes with the matter potential

$$(2E)H_f = U_{23}(\theta_{23}, \delta) \left[ R_{13}R_{12} \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} R_{12}^T R_{13}^T + \begin{pmatrix} a & & \\ & 0 & \\ & & 0 \end{pmatrix} \right] U_{23}^\dagger(\theta_{23}, \delta)$$

$$H_f = U_{23}(\theta_{23}, \delta) \tilde{H} U^\dagger(\theta_{23}, \delta)$$

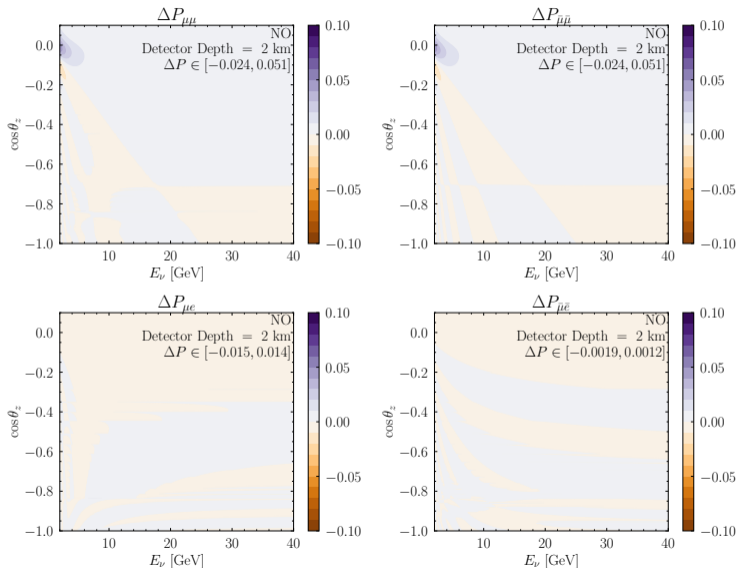
$$\mathcal{A} = \prod_{\tilde{j}} \mathcal{A}_j = \prod_j e^{-iH_{f,j}L_j} = U_{23}(\theta_{23}, \delta) \left( \prod_j e^{-i\tilde{H}_j L_j} \right) U_{23}^\dagger(\theta_{23}, \delta)$$

$\tilde{H}$  is real! And doesn't depend on  $\theta_{23}$  or  $\delta$

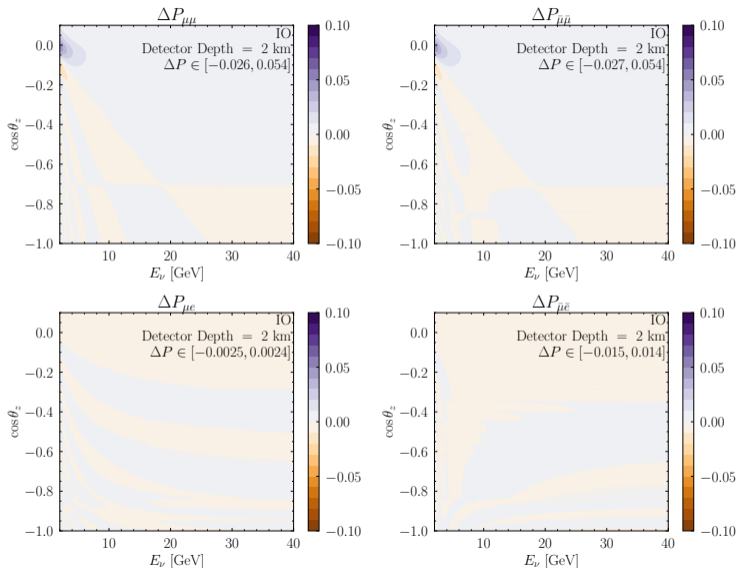
Reduces many unnecessary computations

$$U_{23}U_{23}^\dagger = 1$$

# Atmospheric Results: Detector Depth: NO



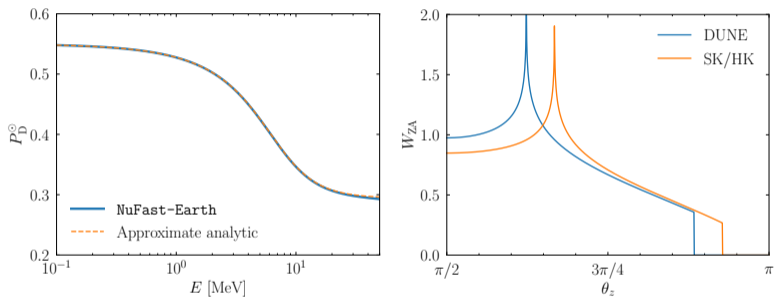
# Atmospheric Results: Detector Depth: IO



# Atmospheric Results: Detector Depth: Summary

$\max  \Delta P $	$\nu_\mu \rightarrow \nu_\mu$		$\nu_\mu \rightarrow \nu_e$	
	$\nu$	$\bar{\nu}$	$\nu$	$\bar{\nu}$
NO	5.1%	5.1%	1.5%	0.2%
IO	5.4%	5.4%	0.3%	1.5%

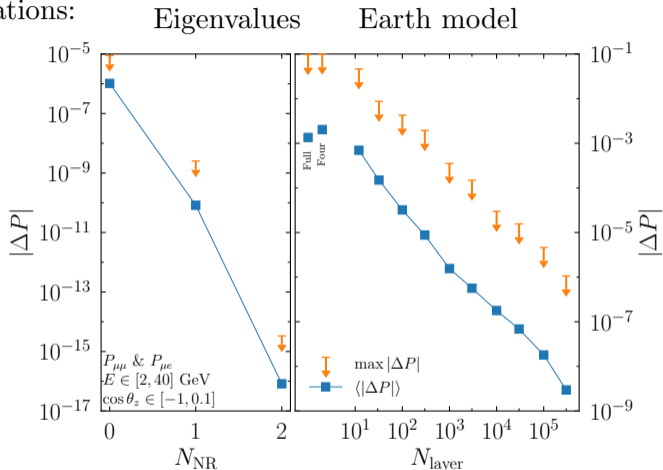
# NuFast-Earth Solar Neutrino Validation



Analytically understand the small deviation at high energy

# NuFast-Earth Precision

Two approximations:



“True” has exact eigenvalues and 1M layers

Calculate  $|\Delta P|$  across  $100 \times 100$  grid in energy and angle

# NuFast-Earth Speed Example of Caching

## Ingredients

1. 44 layer Earth
2. Single core-crossing trajectory:  $\cos \theta_z = -1$

Does not take advantage of reused eigen- calculations

3. 100  $\Delta m_{31}^2$  points and 100  $\theta_{23}$  points

## Run time:

1. OscProb:

$$100 \times 100 \times (4 \times 10^4 \text{ ns}) = 0.4 \text{ s}$$

2. NuFast-Earth wrong order (loop  $\Delta m_{31}^2$  first):

$$100 \times 99 \times (6 \times 10^3 \text{ ns}) + 100 \times (2 \times 10^2 \text{ ns}) = 0.06 \text{ s}$$

6.7×

3. NuFast-Earth right order (loop  $\theta_{23}$  first):

$$100 \times (6 \times 10^3 \text{ ns}) + 100 \times 99 \times (2 \times 10^2 \text{ ns}) = 0.002 \text{ s}$$

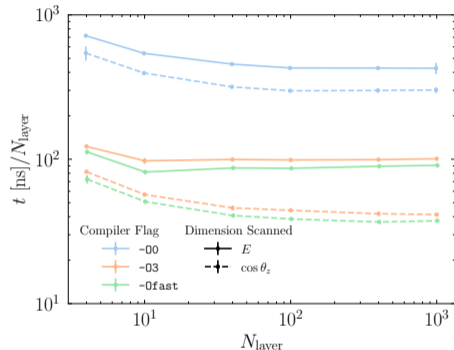
200×

## NuFast-Earth Speed: Grid

Number of eigenvalue and eigenvector computations:  $N_{\text{layer}} \times N_E$

Time per Earth layer for one core-crossing trajectory:

- ▶ 100 energy by 1 zenith grid (solid)
- ▶ 100 zenith by 1 energy grid (dashed)



Zenith angle bins  $\sim 2\times$  faster than energy bins

Cost of computing eigenvalues and eigenvectors comparable to converting to amplitudes and multiplying matrices (which also depend on  $L$  and thus  $\cos \theta_z$ )

# NuFast-Earth Fast Parameters

Four fast parameters for insides of loops:

- ▶  $\theta_{23}$ : `Set_s23sq`
- ▶  $\delta$ : `Set_delta`
- ▶ Production height: `Set_Production_Height`
- ▶ Density at production in Sun/supernova: `Set_rhoYe_Sun`

Also zenith grid points are  $\sim 2\times$  faster than energy grid points

# NuFast-Earth Flow

```

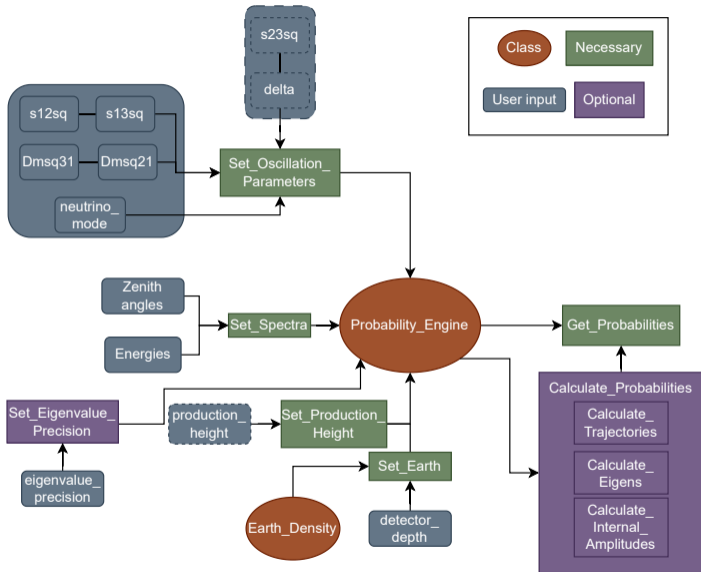
// Initialize the engine
Probability_Engine probability_engine;

// Set the oscillation parameters to nu-fit 6 best fit
// values:
probability_engine.Set_Oscillation_Parameters(0.307,
0.02195, 0.561, 177 * M_PI / 180, 7.49e-5, 2.534e-3,
true); //(s12sq, s13sq, s23sq, delta, Dmsq21, Dmsq31,
neutrino_mode)

// Set energy and zenith angle arrays
std::vector<double> energies = {1, 2, 3, 4, 5}; // GeV
std::vector<double> coszs = {-1, -0.5, 0, 1}; // core-
crossing to horizontal to down-going
probability_engine.Set_Spectra(energies, coszs);

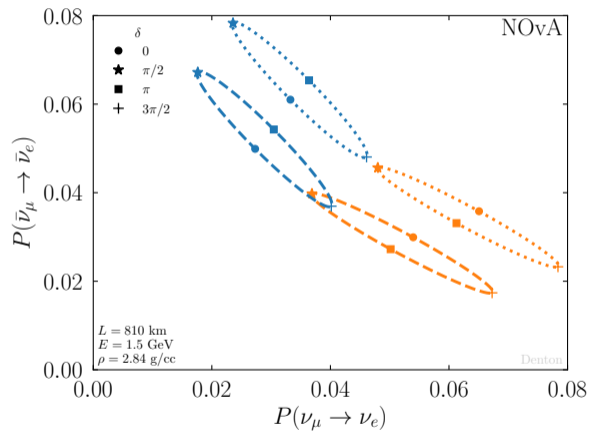
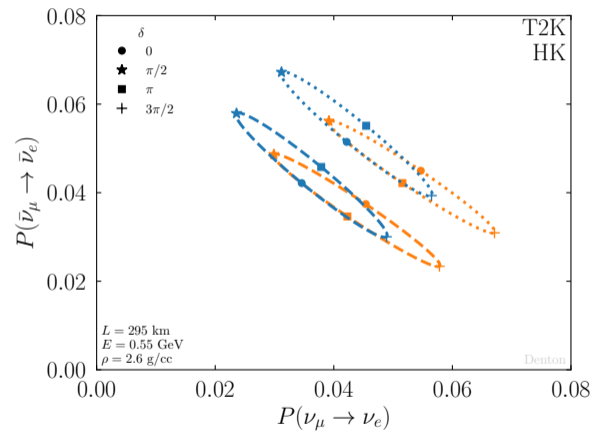
// Create Earth model instance
PREM_NDiscontinuityLayer earth_density(2, 10, 10, 5); //
2 layers in the inner core, 10 layers in the outer
core, 10 layers in the inner mantle, and 5 layers in
the outer mantle
// Set Earth details
probability_engine.Set_Earth(2, &earth_density); //
detector depth in km
// Set production height (optional)
probability_engine.Set_Production_Height(10); // km,
recalculations after changing this are fast

// Do the calculations
std::vector<std::vector<Matrix3r>> probabilities =
probability_engine.Get_Probabilities();
    
```



Dashed boxes = fast!

# $\delta$ : What is it Really?



## $\delta$ : 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](#)

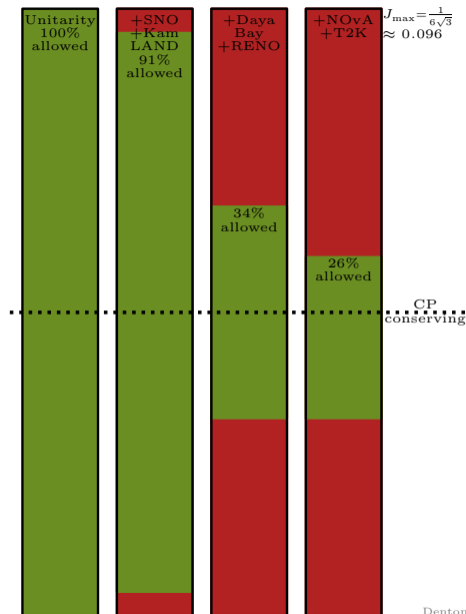
K. Moffat, et al. [1809.08251](#)

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

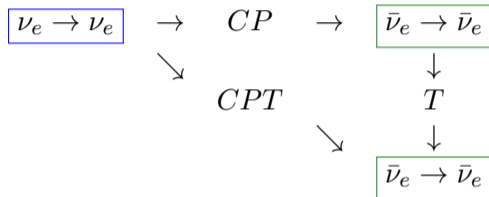
# $\delta, J$ : Current Status

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



# CP, T: Disappearance

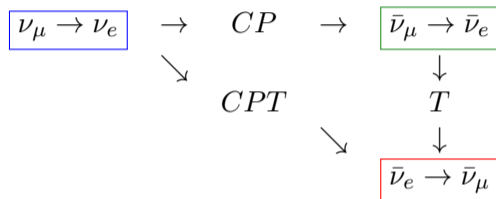


Disappearance measurements are even eigenstates of  $CP$

$$CP[P(\nu_e \rightarrow \nu_e)] = P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \stackrel{CPT}{=} P(\nu_e \rightarrow \nu_e)$$

Assume that CPT is a good symmetry

## CP, T: Appearance



Appearance measurements are not eigenstates of  $CP$

# Appearance and Disappearance, CP Even and CP Odd Terms

**Disappearance:**

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

**Appearance:**

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta) &= -4\Re[U_{\alpha 1}U_{\beta 1}^*U_{\alpha 2}^*U_{\beta 2}] \sin^2 \Delta_{21} \\ &\quad - 4\Re[U_{\alpha 1}U_{\beta 1}^*U_{\alpha 3}^*U_{\beta 3}] \sin^2 \Delta_{31} \\ &\quad - 4\Re[U_{\alpha 3}U_{\beta 3}^*U_{\alpha 2}^*U_{\beta 2}] \sin^2 \Delta_{32} \\ &\quad \pm 8J_{CP} \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32} \\ &= P_{\alpha\beta}^{CP+} + P_{\alpha\beta}^{CP-} \end{aligned}$$

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

Sign depends on  $\alpha, \beta$

# Parameter Counting

1. Four parameters in the PMNS matrix

Majorana phases are irrelevant in oscillations

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$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - 4 \sum_{i>j} C_{ij}^\alpha \sin^2 \Delta_{ij}$$

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

$$C_{ij}^\alpha = |U_{\alpha i}|^2 |U_{\alpha j}|^2$$

$$|U_{\alpha i}| = \left( \frac{C_{ij}^\alpha C_{ik}^\alpha}{C_{jk}^\alpha} \right)^{1/4}$$

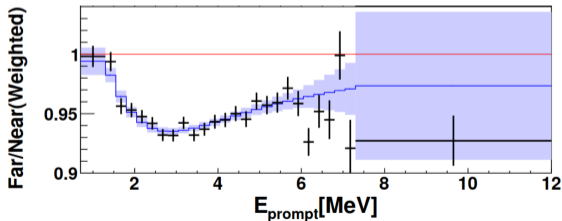
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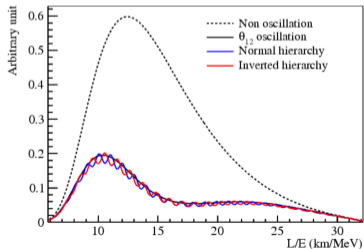
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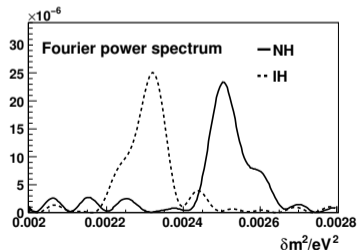
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JUNO [1507.05613](#)

PBD [2309.03262](#) (PRL)



L. Zhan, et al. [0807.3203](#)

University of Tennessee: April 20, 2026 71/44

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3. Only two parameters for one flavor are independent

4. Given good measurements of the  $\nu_e$  and  $\nu_\mu$  disappearance, 4 independent parameters will be measured

- ▶ Any row can be “simple” (e.g.  $c_{12}c_{13}$ ,  $s_{12}c_{13}$ , ...)  $\Rightarrow$  no one row is ever enough
- ▶ That is, CPV is physical and cannot depend on parameterization

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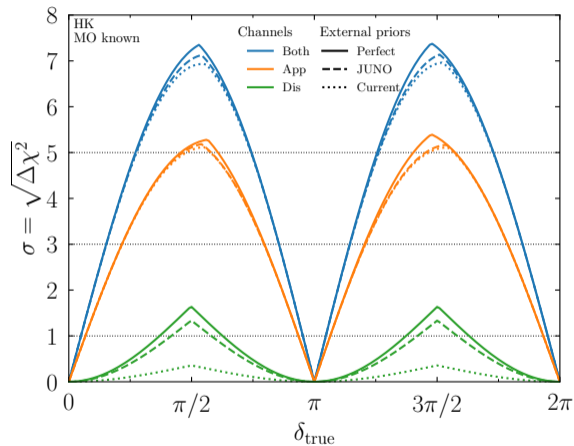
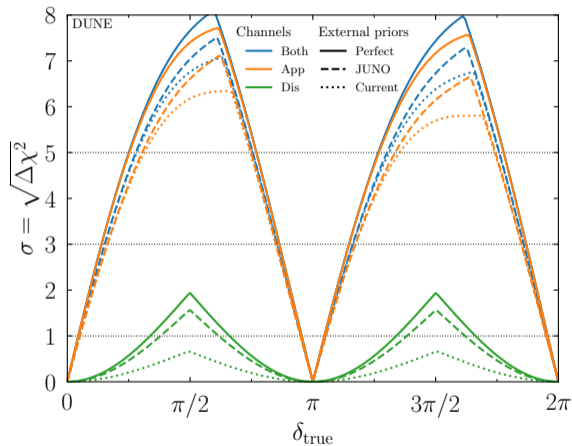
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5. This is sufficient to constrain  $\cos \delta$  and three mixing angles

6. If we determine  $\cos \delta \neq \pm 1 \Rightarrow$  CP is violated!

# JUNO and HK Disappearance Sensitivities



## $\delta$ : Future Sensitivities

Possible to get at CPV with CPC processes

Disappearance probability:

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

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

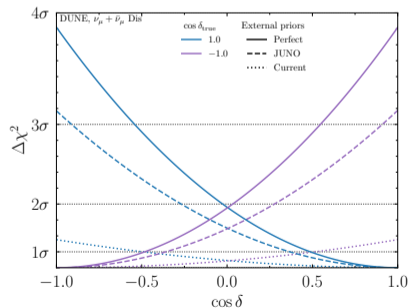
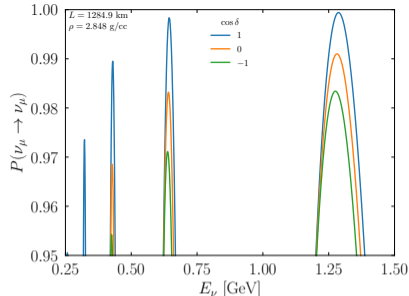
Can measure all three coeffs of each frequency  $\Rightarrow$  2 dofs  
 $\delta$  (and CPV) needs 4 dofs  $\Rightarrow$  two dis measurements

$\nu_e$ : Daya Bay and KamLAND/JUNO

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

Important cross check

Different and cleaner systematics than appearance



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

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

however

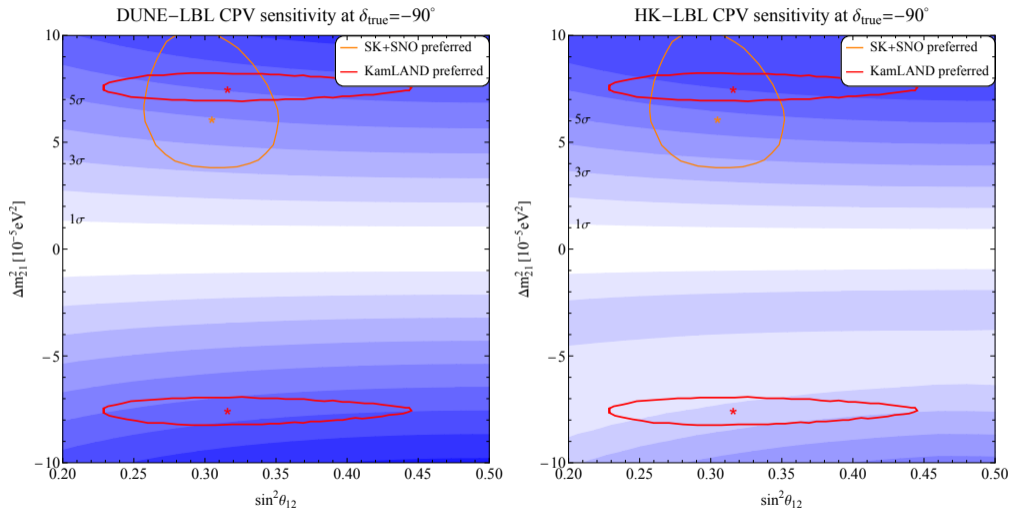
If the goal is **measuring the parameters** one must use  $\delta$

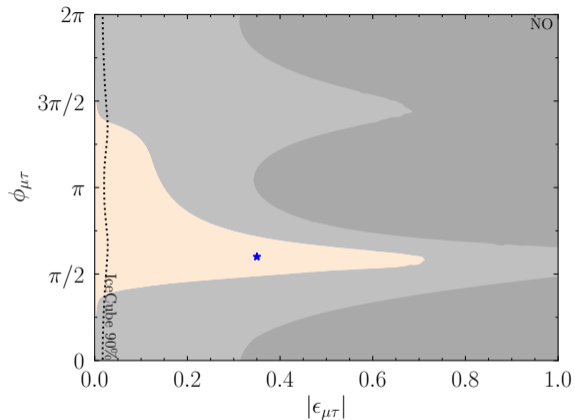
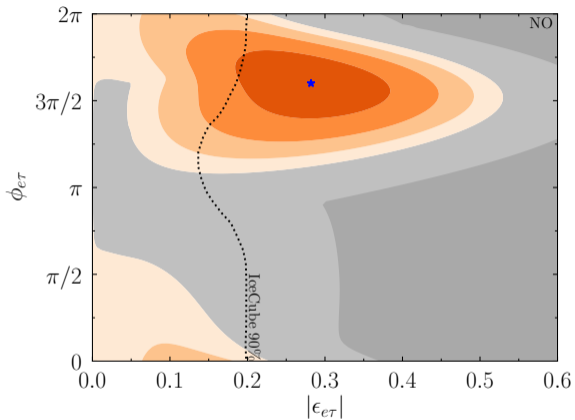
Given  $\theta_{12}$ ,  $\theta_{13}$ ,  $\theta_{23}$ , and  $J$ , I can't determine the sign of  $\cos \delta$  which is physical

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

- ▶ 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

# Impact of the True Solar Parameters on $\delta$





# Other CP Violating NSI Constraints

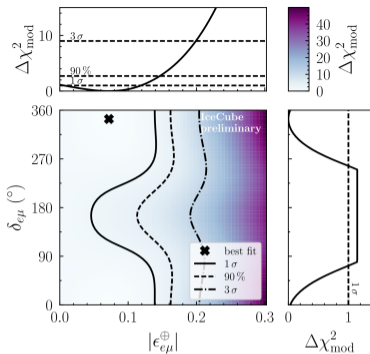
NSI effects grow with energy, density, and distance

## 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 \(2019\)](#)  
IceCube [2106.07755](#)

# Other CP Violating NSI Constraints

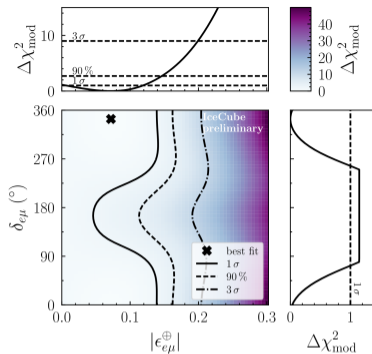
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  - ▶ Constraint is at LBL best fit with 3 yrs
  - ▶ 10 yrs of data in the bank
  - ▶ Prefers non-zero  $|\epsilon_{e\mu}|$  at  $\sim 1\sigma$

- ▶ 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



T. Ehrhardt, IceCube [PPNT \(2019\)](#)  
IceCube [2106.07755](#)

Super-K [1109.1889](#)

COHERENT [1708.01294](#)

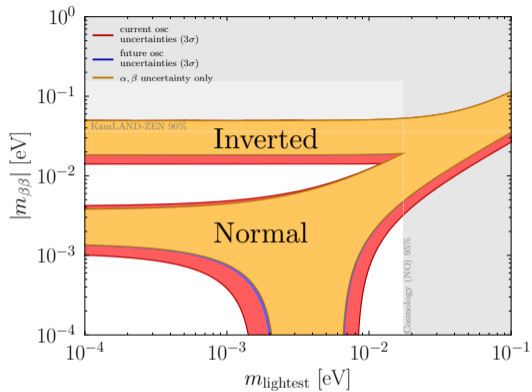
[PBD](#), Y. Farzan, I. Shoemaker [1804.03660](#) (JHEP)

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

University of Tennessee: April 20, 2026 77/44

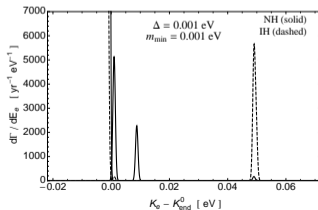
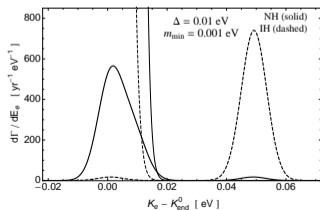
# Mass Ordering: Broad Implications

- ▶ 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](#)



# Neutrino Decay

Since neutrinos have different masses, they decay

- ▶ Loop suppressed
- ▶ Long lifetime:  $\tau \gtrsim 10^{35}$  years

Test this!

Typical Lagrangian for  $\nu_i \rightarrow \nu_j + \phi$  with  $m_i > m_j$

$$\mathcal{L} \supset \frac{g_{ij}}{2} \bar{\nu}_j \nu_i \phi + \frac{g'_{ij}}{2} \bar{\nu}_j i \gamma_5 \nu_i \phi$$

# Neutrino Decay Phenomenology

Neutrino decay is phenomenologically classified into:

- ▶ **Invisible decay:**

- ▶ The decay products are sterile or too low energy to be detected
- ▶ Results in a *depletion* of the flux below the relevant energy

- ▶ **Visible decay:**

- ▶ Decay products are detected
- ▶ In addition to depletion, there is *regeneration*
- ▶ Regeneration happens at a lower energy than depletion

# Why IceCube for Neutrino Decay

- ▶ DSNB and  $C\nu B$  are still some time off
- ▶ The next galactic supernova could come tomorrow, or in fifty years
- ▶ If  $\nu_1$  is stable SN1987A isn't too relevant (25 events + theory uncertainties)

- ▶ Mass ordering looks to be normal at  $\sim 3 - 3.5 \sigma$

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

- ▶ Texture in the  $\nu - \phi$  mixing matrix

- ▶ Early universe constraints mostly constrain the typical decay diagram

G. Dvali and L. Funcke [1602.03191](#)

M. Escudero and M. Fairbairn [1907.05425](#)

- ▶ IceCube measures **all three flavors** over  $> 1$  decade in energy
- ▶ Astrophysical uncertainties seem like a problem, aren't really

# How to Calculate Visible Neutrino Decay

## Ingredients:

1. Oscillation averaged/decohered SM contribution
2. Depletion component
  - ▶ This takes us to invisible decay
3. Regeneration component at lower energies
  - ▶ This takes us to visible decay

## Steps:

1. Integrate over decay location
2. Integrate over initial energy spectrum due to regeneration
3. Include multiple decays
4. Include cosmology
5. Mix thoroughly, let bake for an hour



M. Lindner, T. Ohlsson, W. Winter [astro-ph/0105309](#)

J. Beacom et al. [hep-ph/0211305](#)

P. Baerwald, M. Bustamante, W. Winter [1208.4600](#)

## SM Contribution: How to Calculate

First we define a “probability”

$$P_{\alpha\beta}(E_f) \equiv \frac{\Phi_{\alpha\beta}^E(E_f)}{\Phi_{\alpha}^S(E_f)}$$

Not actually a probability as it can be more than 1, but is probability-like and is useful  
Over large distances the mass states decohere and/or the wave packets separate

$$\frac{\Delta m^2 L}{E} \gg 1$$

This is easily satisfied for extragalactic sources

Wave packet separation results in an identical flux to oscillation averaging:

$$\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \rightarrow \frac{1}{2}$$

## SM Contribution: The Probability

Given the usual Hamiltonian,

$$H = U_{\text{PMNS}} \begin{pmatrix} 0 & & \\ & \frac{\Delta m_{21}^2}{2E} & \\ & & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U_{\text{PMNS}}^\dagger$$

The SM oscillation probability is:

$$P_{\alpha\beta}^{\text{SM}} = \left| U_{\alpha 1}^* U_{\beta 1} + U_{\alpha 2}^* U_{\beta 2} e^{-i \frac{\Delta m_{21}^2 L}{2E}} + U_{\alpha 3}^* U_{\beta 3} e^{-i \frac{\Delta m_{31}^2 L}{2E}} \right|^2$$

When averaged/decohered:

$$\bar{P}_{\alpha\beta}^{\text{SM}} = \sum_{i=1}^3 |U_{\alpha i}|^2 |U_{\beta i}|^2$$

No interference terms.

## Depletion Component: How to Calculate

$$H = U_{\text{PMNS}} \begin{pmatrix} 0 & & \\ & \frac{\Delta m_{21}^2}{2E} - \frac{i}{2}\Gamma_2 & \\ & & \frac{\Delta m_{31}^2}{2E} - \frac{i}{2}\Gamma_3 \end{pmatrix} U_{\text{PMNS}}^\dagger$$

Assume here and throughout that  $\nu_1$  is stable (no lighter sterile neutrino) and the normal ordering

# Depletion Component: How to Calculate

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Assume here and throughout that  $\nu_1$  is stable (no lighter sterile neutrino) and the normal ordering

The partial width including scalar and pseudo-scalar as well as  $\nu \rightarrow \nu$  and  $\nu \rightarrow \bar{\nu}$

$$\Gamma_{ij} = \frac{m_i m_j}{16\pi E_i} \{ g_{ij}^2 [f(x_{ij}) + k(x_{ij})] + g'_{ij}{}^2 [h(x_{ij}) + k(x_{ij})] \}$$

$$f(x) = \frac{x}{2} + 2 + \frac{2}{x} \log x - \frac{2}{x^2} - \frac{1}{2x^3}$$

$$h(x) = \frac{x}{2} - 2 + \frac{2}{x} \log x + \frac{2}{x^2} - \frac{1}{2x^3}$$

$$k(x) = \frac{x}{2} - \frac{2}{x} \log x - \frac{1}{2x^3}$$

$$\begin{aligned} \Gamma_i &= \sum_j \Gamma_{ij} \\ \tau_i &= m_i / E_i \Gamma_i \\ x_{ij} &\equiv m_i / m_j \end{aligned}$$

See slide 95 on  $\nu/\bar{\nu}$

## Depletion Component: The Probability

$$\bar{P}_{\alpha\beta}^{\text{dep}}(E, L) = -|U_{\alpha 2}|^2 |U_{\beta 2}|^2 (1 - e^{-\Gamma_2 L}) - |U_{\alpha 3}|^2 |U_{\beta 3}|^2 (1 - e^{-\Gamma_3 L})$$

The invisible probability is:

$$\bar{P}_{\alpha\beta}^{\text{inv}} = \bar{P}_{\alpha\beta}^{\text{SM}} + \bar{P}_{\alpha\beta}^{\text{dep}}$$

$$\bar{P}_{\alpha\beta}^{\text{inv}} = |U_{\alpha 1}|^2 |U_{\beta 1}|^2 + |U_{\alpha 2}|^2 |U_{\beta 2}|^2 e^{-\Gamma_2 L} + |U_{\alpha 3}|^2 |U_{\beta 3}|^2 e^{-\Gamma_3 L}$$

## Further Details

Full calculation is much more involved:

1. Regeneration: requires integrating over decay point and initial energy
2. Multiple decays possible:  $\nu_3 \rightarrow \nu_2 \rightarrow \nu_1$
3. Cosmology affects energy at production, decay point(s), and to the Earth

# Summary of Parameters

More important

1.  $\gamma$ : harder spectra  $\Rightarrow$  large regeneration component
2.  $m_1$ : higher mass scale  $\gtrsim 0.1$  eV  $\Rightarrow$  large regeneration component
3.  $g_{ij}$ : different features depending on the texture

Less important

4. Redshift evolution  $\Rightarrow$  small effect
5. Scalar/Pseudo-scalar  $\Rightarrow$  small effect
6.  $\nu \rightarrow \nu, \nu \rightarrow \bar{\nu} \Rightarrow$  small effect

## Regeneration Component: Analytic Limits

- ▶ Verify that as  $E_f \rightarrow \infty$ ,  $\bar{P}_{ij}^{\text{reg}} \rightarrow 0$  as expected

SM

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Full decay

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Degenerate masses

$$\lim_{\substack{E_f \rightarrow 0 \\ m_1 \rightarrow \infty}} \bar{P}_{ij}^{\text{reg}}(E_f, L) = 1$$

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- ▶ As  $m_1 \rightarrow 0$

Depends on nature of interaction!

$$\lim_{\substack{E_f \rightarrow 0 \\ m_1 \rightarrow 0}} \bar{P}_{ij}^{\text{reg}}(E_f, L) = \frac{1}{\gamma}$$

# Regeneration Component: Analytic Limits with Cosmology

Full decay:

► As  $m_1 \rightarrow \infty$

$$\lim_{\substack{E_f \rightarrow 0 \\ m_1 \rightarrow \infty}} \bar{P}_{ij}^{\text{reg}}(E_f, L) = (1+z)^{-2\gamma}$$

$$\lim_{\substack{E_f \rightarrow 0 \\ m_1 \rightarrow \infty}} \bar{P}_{\alpha\beta}^{\text{vis}} = (1+z)^{-\gamma} [ |U_{\alpha 1}|^2 |U_{\beta 1}|^2 + |U_{\alpha 2}|^2 |U_{\beta 2}|^2 + (1+z)^{-\gamma} |U_{\alpha 3}|^2 |U_{\beta 1}|^2 ]$$

# Regeneration Component: Analytic Limits with Cosmology

Full decay:

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$$\lim_{\substack{E_f \rightarrow 0 \\ m_1 \rightarrow \infty}} \bar{P}_{ij}^{\text{reg}}(E_f, L) = (1+z)^{-2\gamma}$$

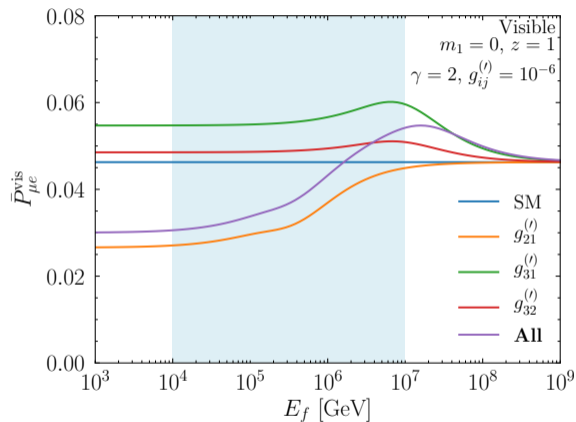
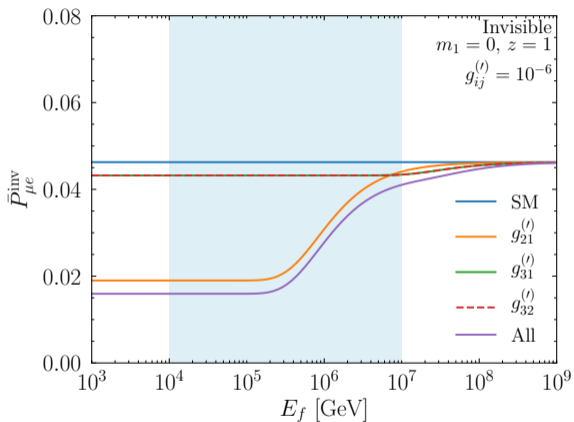
$$\lim_{\substack{E_f \rightarrow 0 \\ m_1 \rightarrow \infty}} \bar{P}_{\alpha\beta}^{\text{vis}} = (1+z)^{-\gamma} \left[ |U_{\alpha 1}|^2 |U_{\beta 1}|^2 + |U_{\alpha 2}|^2 |U_{\beta 2}|^2 + (1+z)^{-\gamma} |U_{\alpha 3}|^2 |U_{\beta 1}|^2 \right]$$

► As  $m_1 \rightarrow 0$

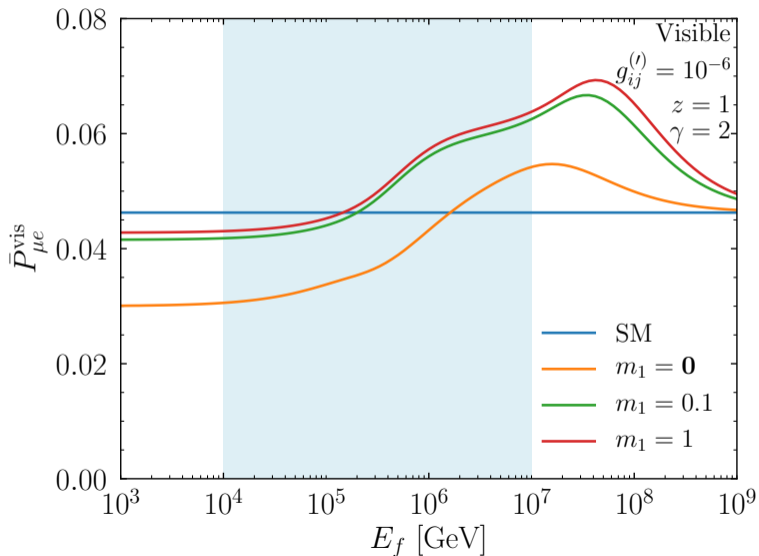
$$\lim_{\substack{E_f \rightarrow 0 \\ m_1 \rightarrow 0}} \bar{P}_{ij}^{\text{reg}}(E_f, L) = \frac{(1+z)^{-2\gamma}}{\gamma}$$

$$\lim_{\substack{E_f \rightarrow 0 \\ m_1 \rightarrow 0}} \bar{P}_{\alpha\beta}^{\text{vis}} = (1+z)^{-\gamma} \left[ |U_{\alpha 1}|^2 |U_{\beta 1}|^2 + |U_{\alpha 2}|^2 |U_{\beta 2}|^2 + \frac{(1+z)^{-\gamma}}{\gamma} |U_{\alpha 3}|^2 |U_{\beta 1}|^2 \right]$$

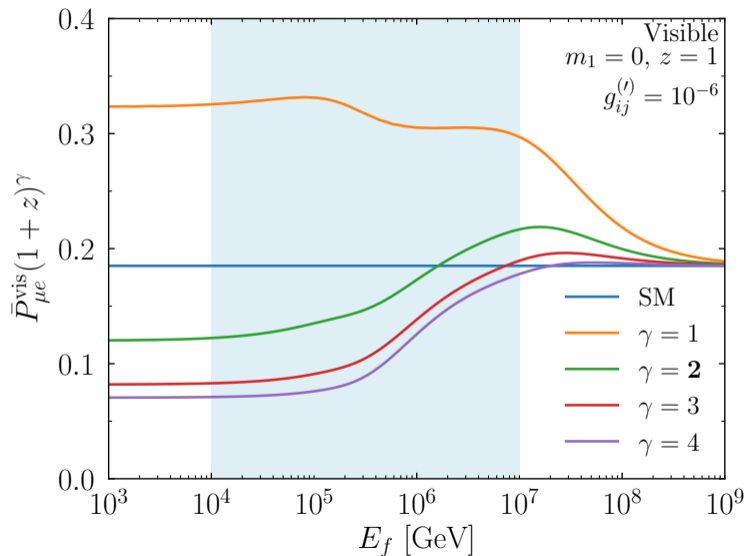
# Invisible vs. Visible Decay



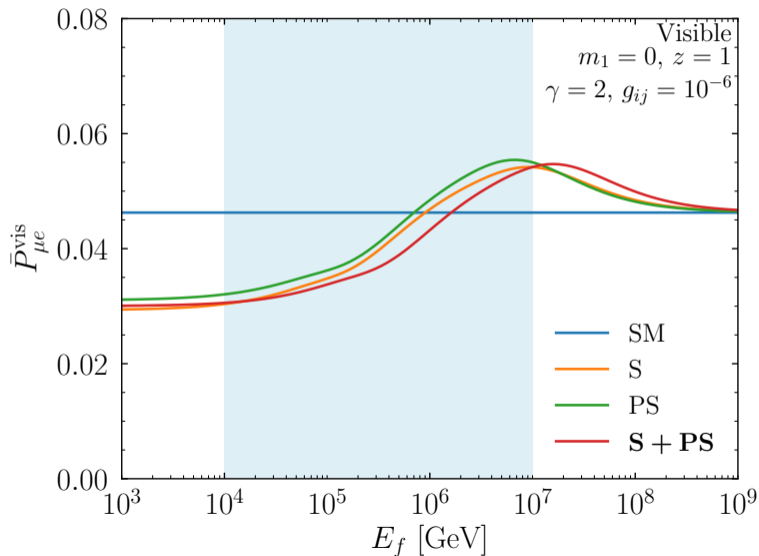
# Results: Visible Decay: Neutrino mass scale



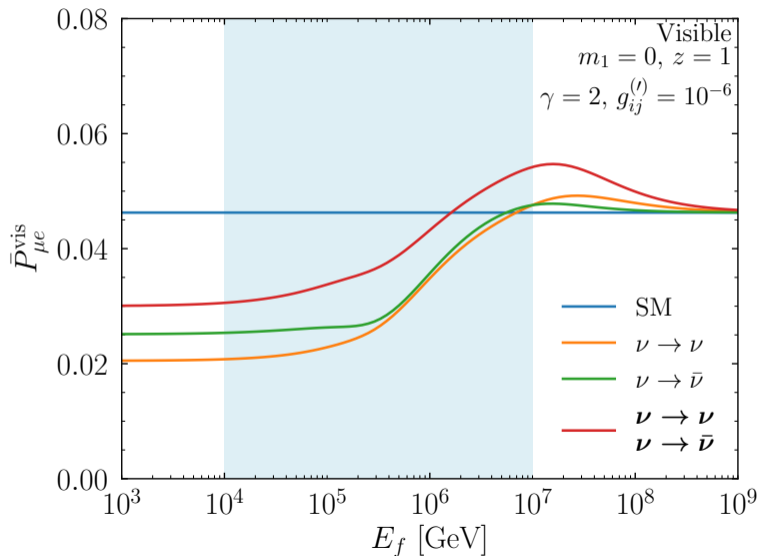
# Results: Visible Decay: Spectral Index



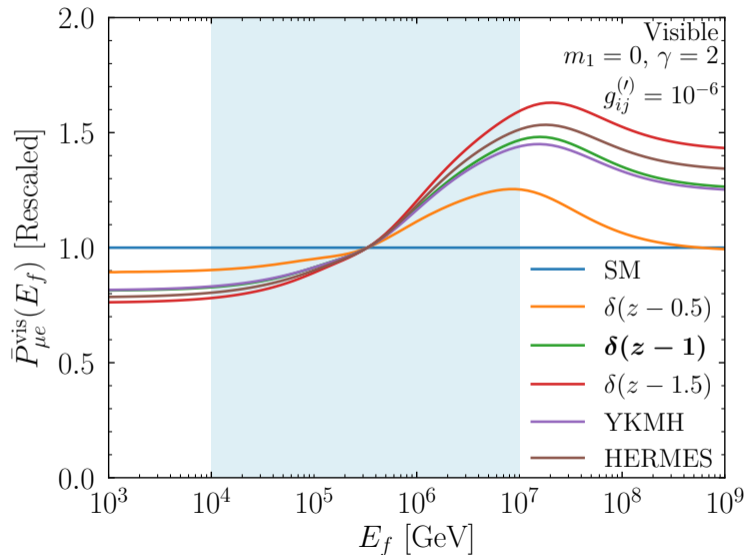
# Results: Visible Decay: Scalar vs. Pseudo-scalar



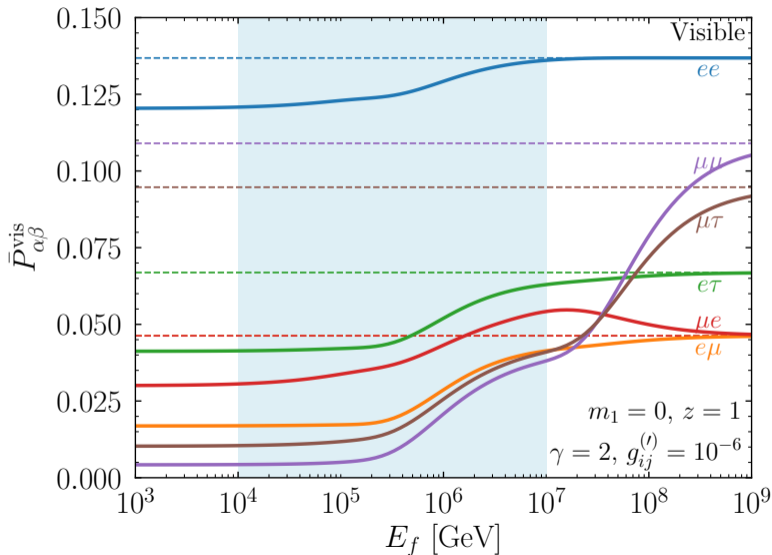
# Results: Visible Decay: Neutrinos vs. Anti-neutrinos



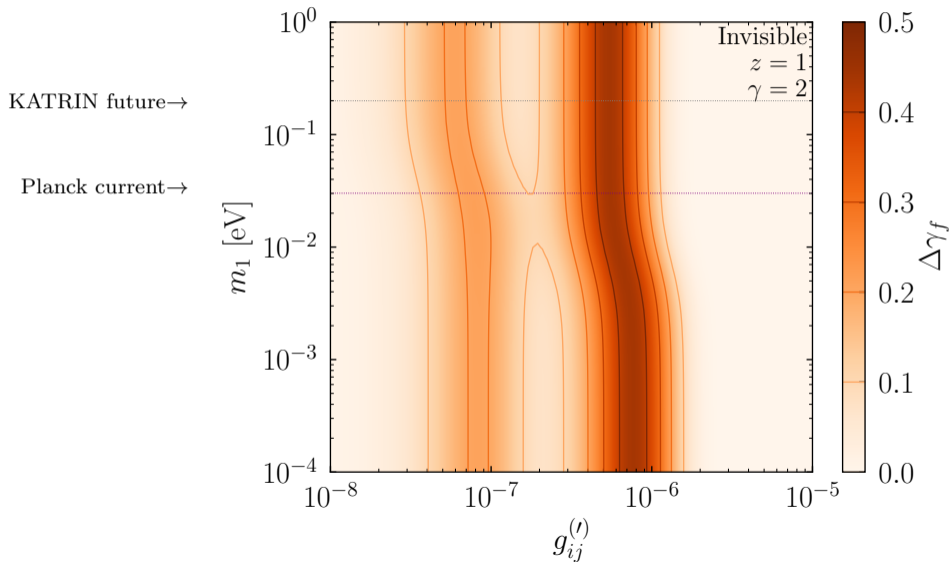
# Visible Decay for Different Redshift Evolution Functions



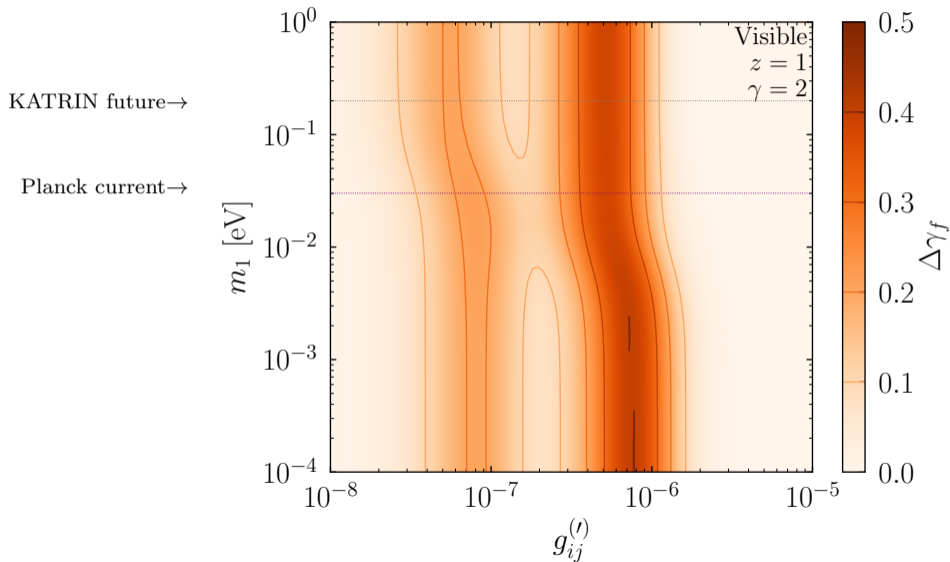
# Results: Visible Decay: Flavors



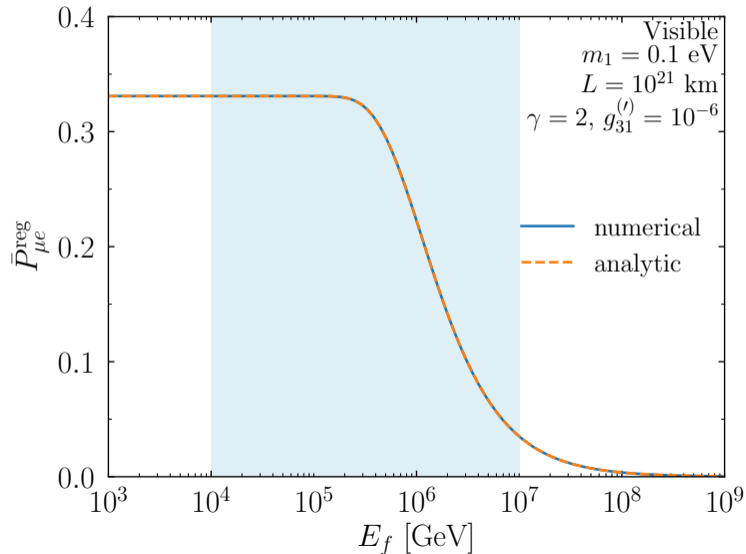
# IceCube Track and Cascade Spectral Index Difference: Invisible Decay



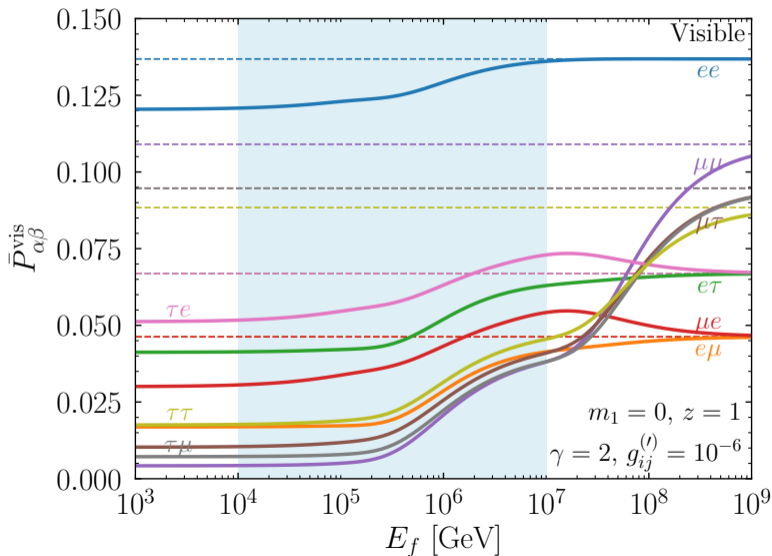
# IceCube Track and Cascade Spectral Index Difference: Visible Decay



# Analytic Validation



# Results: Visible Decay: Flavors with $\nu_\tau$



## IceCube Measures:

- ▶ **Energy**
- ▶ **Flavor(ish)**
- ▶ **Direction**
- ▶ **Time**

## Some Track to Cascade with Decay Observations

- ▶ Decay usually hardens the spectrum
  - ▶ Only  $\bar{P}_{\mu e}^{\text{vis}} > \bar{P}_{\mu e}^{\text{SM}}$  for  $m_1 \sim 0$  and  $\gamma \sim 2$
  - ▶ While  $\bar{P}_{\tau\beta}^{\text{vis}} > \bar{P}_{\tau\beta}^{\text{SM}}$ , no  $\nu_\tau$ 's are produced at the sources
- ▶ The effect is larger for tracks than cascades

$\max \Delta\gamma$	$g_{21}^{(l)}$	$g_{31}^{(l)}$	$g_{32}^{(l)}$	All
Invisible	0.006	0.200	0.200	0.438
Visible	0.042	0.227	0.172	0.400

$$\min \Delta\gamma = -0.01$$

$$\Delta\gamma \equiv \gamma_c - \gamma_t$$

- ▶ This is the same direction of the IceCube data!
- ▶ The other sign (cascades harder than tracks) requires the inverted ordering

# Uncertainties

or “How to muck it all up with astrophysics”

## What doesn't work:

- ▶ Multiple classes of sources with different spectra
- ▶  $pp$  vs.  $p\gamma$  sources
- ▶ Different redshift evolution  $\Rightarrow$  shift the  $g_{ij}$
- ▶ Neutron decay sources
- ▶ Varying the oscillation parameters
- ▶ IceCube track or cascade normalization

## What could work: (other than neutrino decay)

- ▶ Muon damped  $\Rightarrow \Delta\gamma \sim +0.2$
- ▶ Track and cascade spectra are fit over slightly different energy ranges  $\Rightarrow$  broken power law can help
- ▶ Energy misreconstruction (tracks could be susceptible to this)
- ▶ Dark matter?