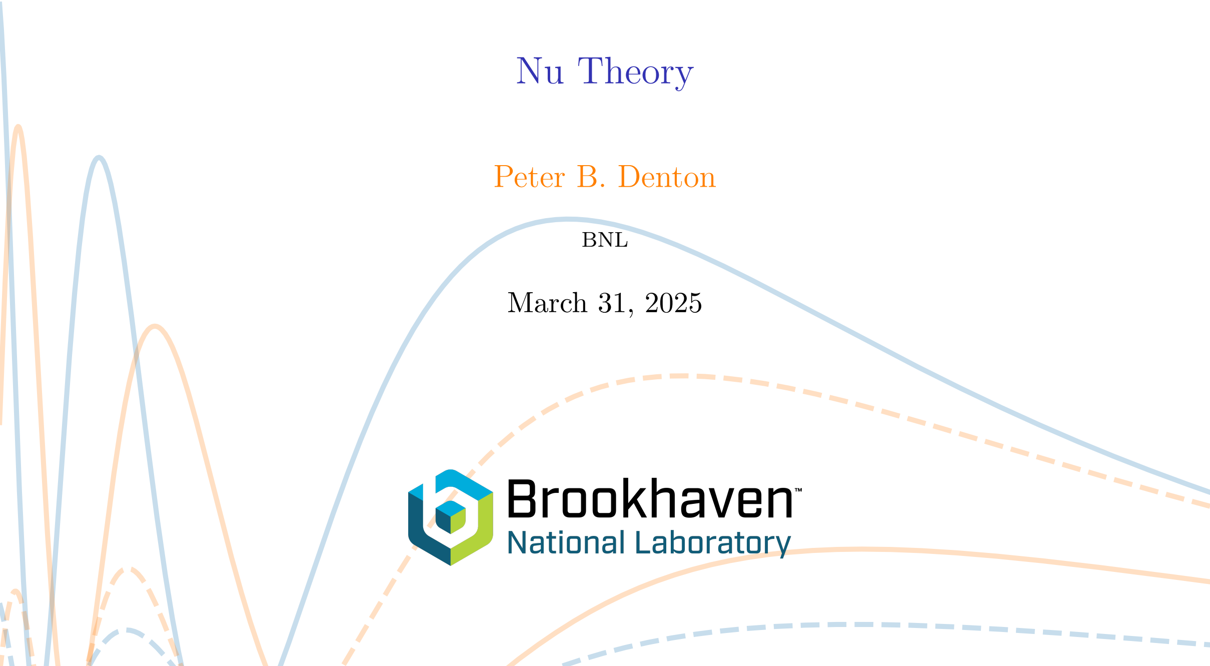
Abstract

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.



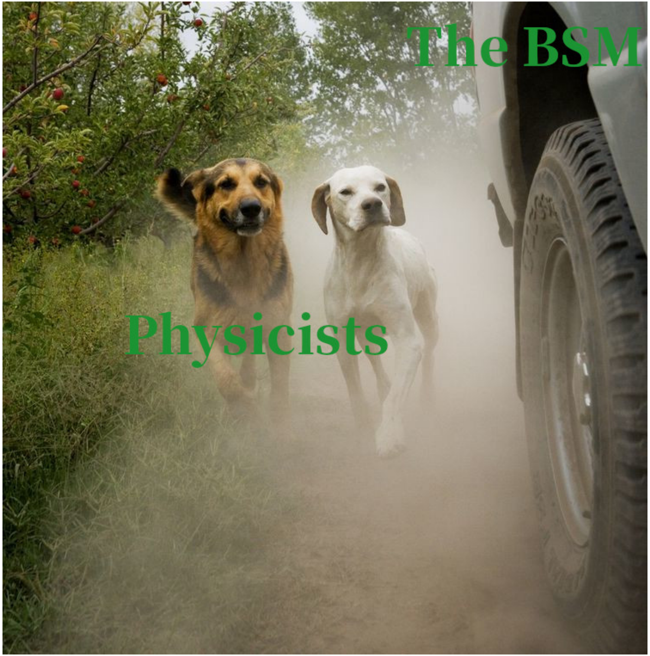
Nu Theory

Peter B. Denton

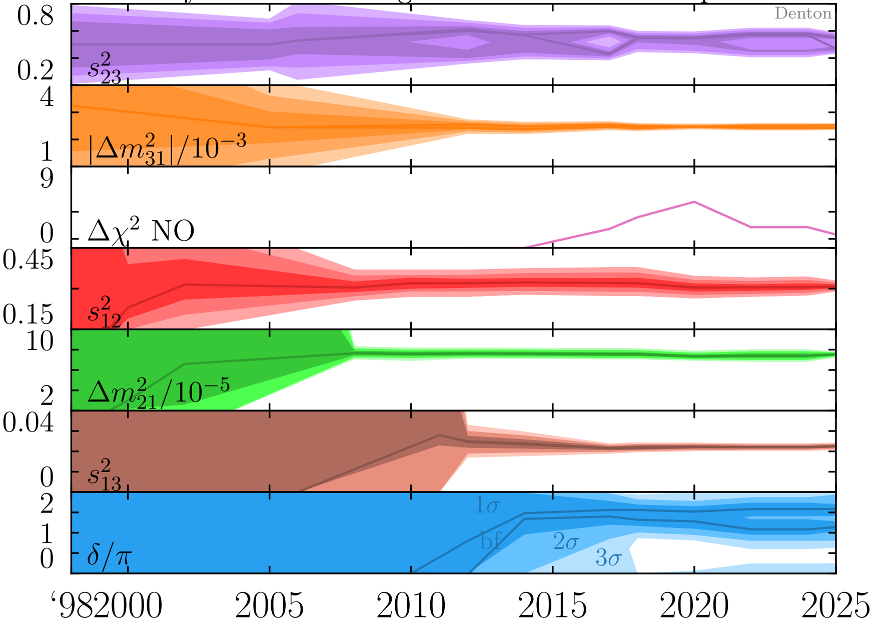
BNL

March 31, 2025

Brookhaven National Laboratory


The BSM
Physicists

History of our knowledge of the six oscillation parameters



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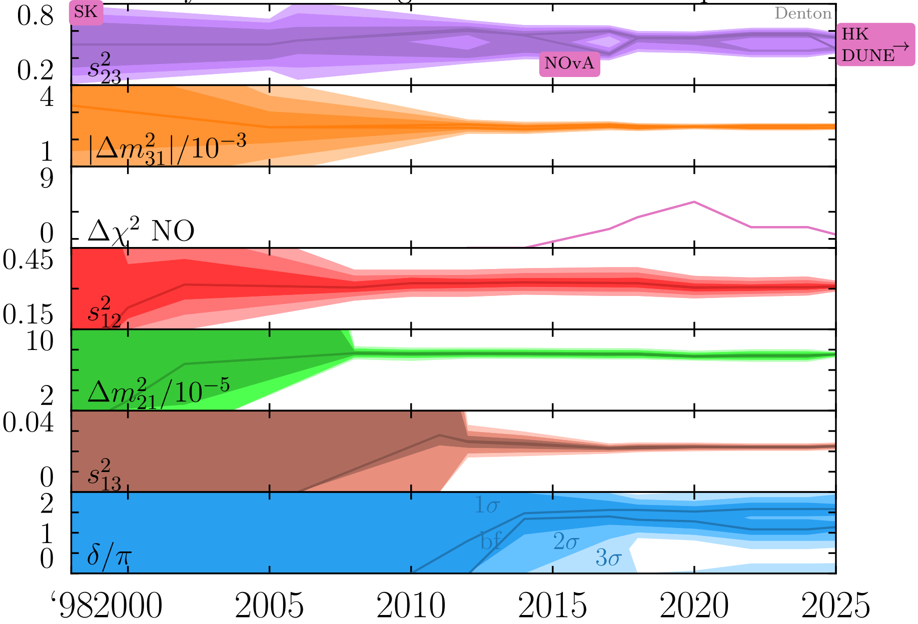

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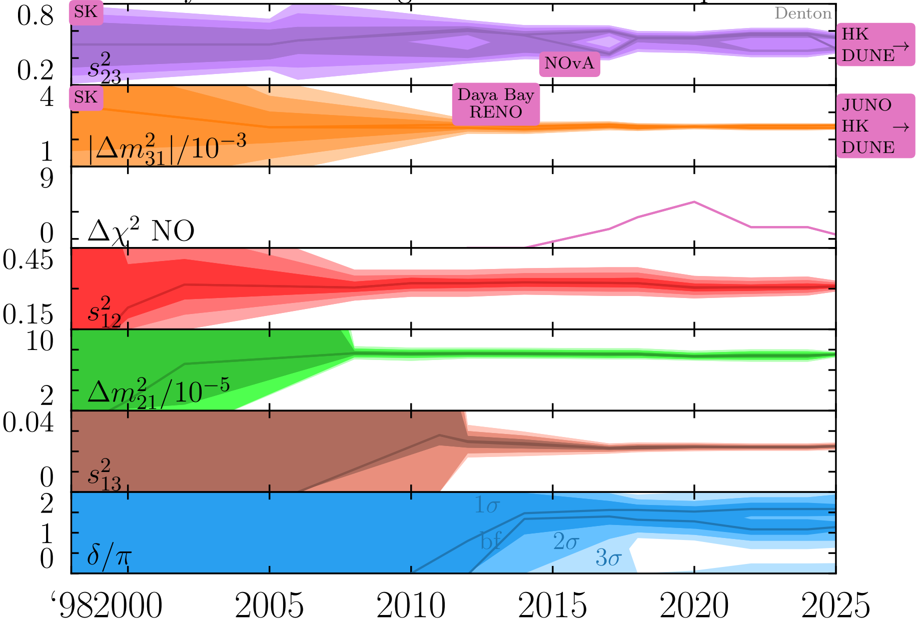

PBD, et al. 2212.00809 & PBD 2501.08374

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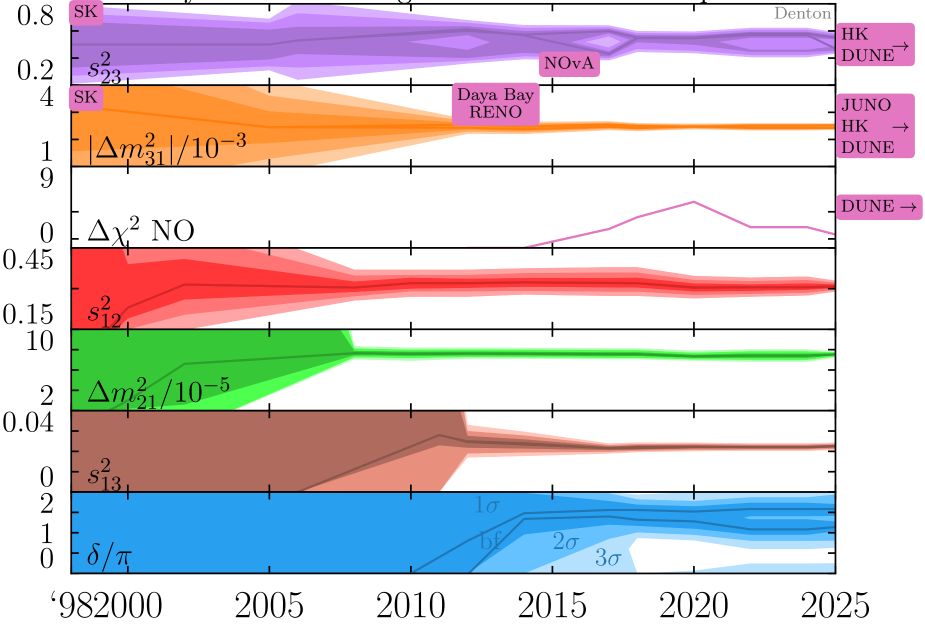

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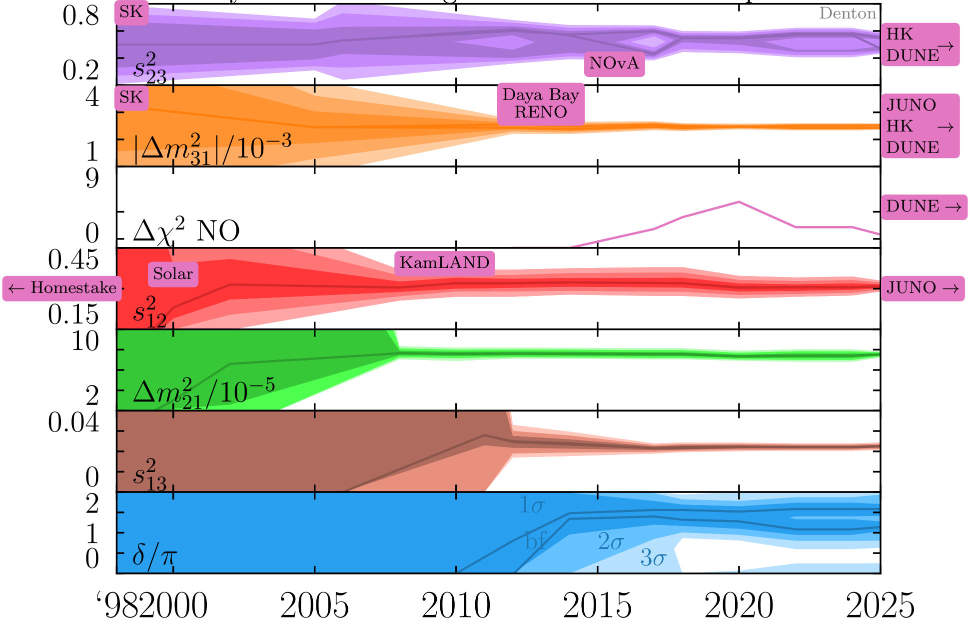

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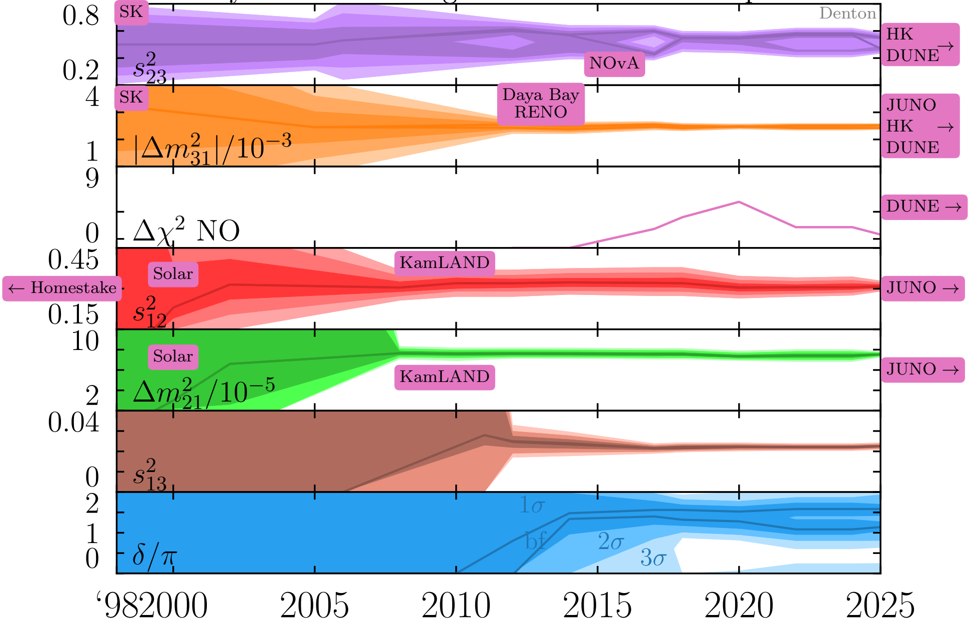

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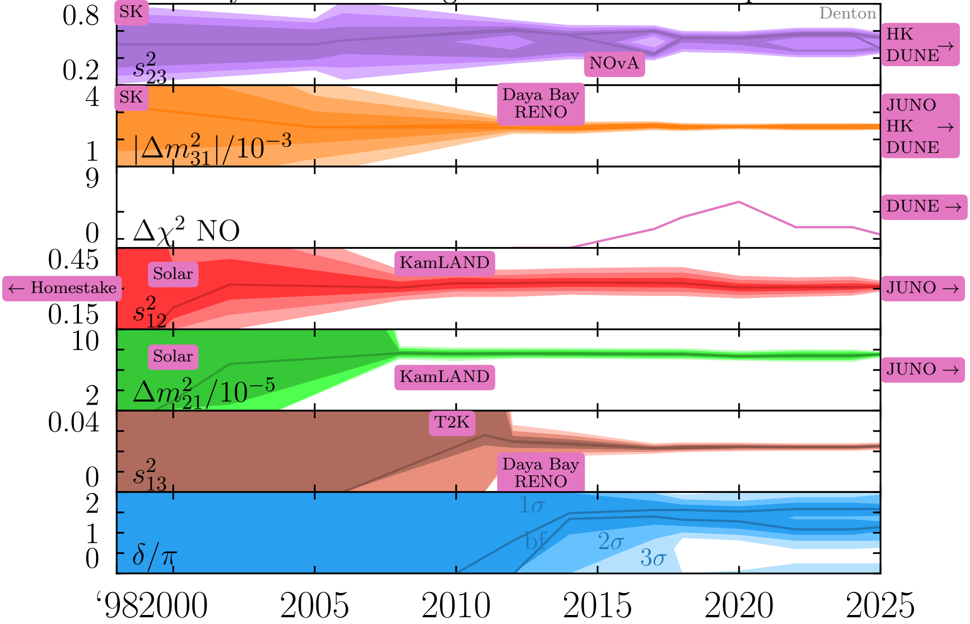

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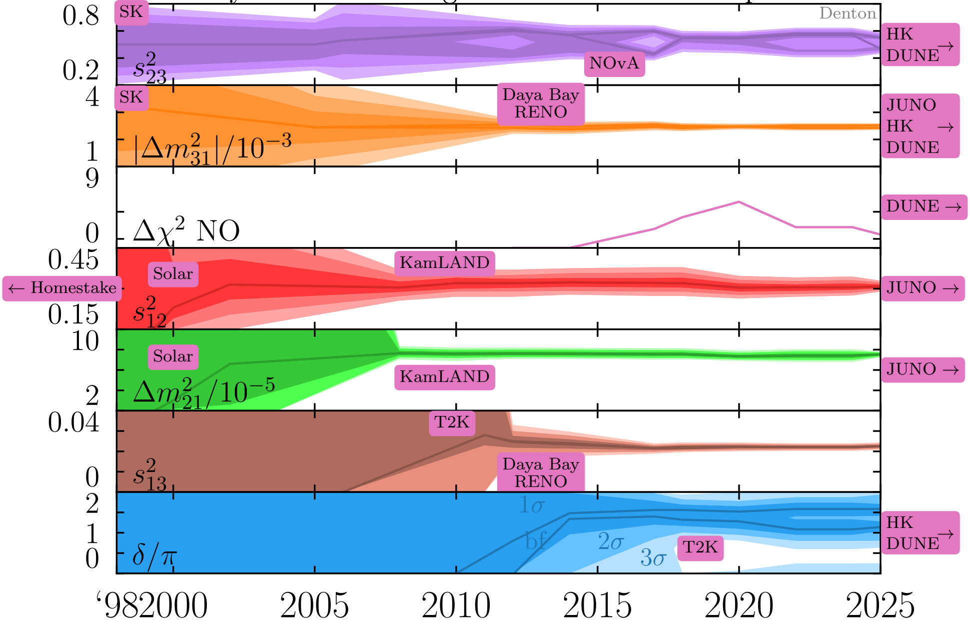

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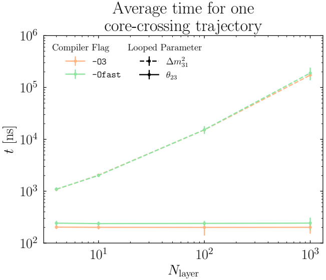
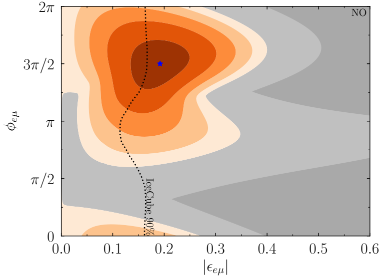
Part 1:
Standard Three-Flavor Oscillations

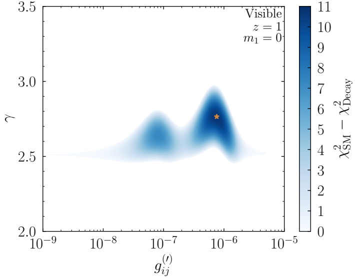


Average time for one core-crossing trajectory

Part 2:
New Physics in Neutrinos



Part 3:
Neutrinos in Space



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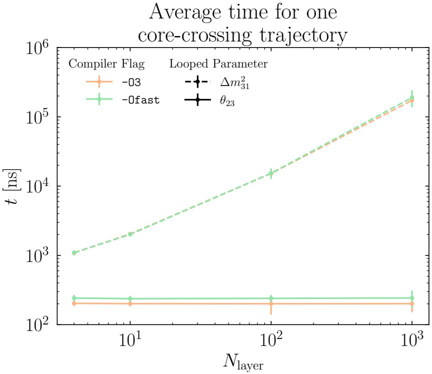
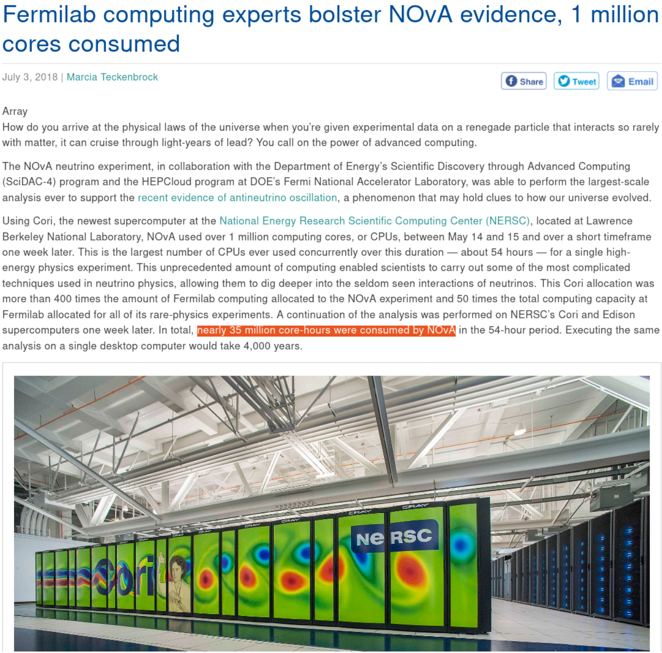


Neutrino Oscillation Probabilities, Fast

`NuFast`

Constant density: github.com/PeterDenton/NuFast-LBL
Varying density: github.com/PeterDenton/NuFast-Earth



Fermilab computing experts bolster NOvA evidence, 1 million cores consumed

July 3, 2018 | Marcia Teckenbrock

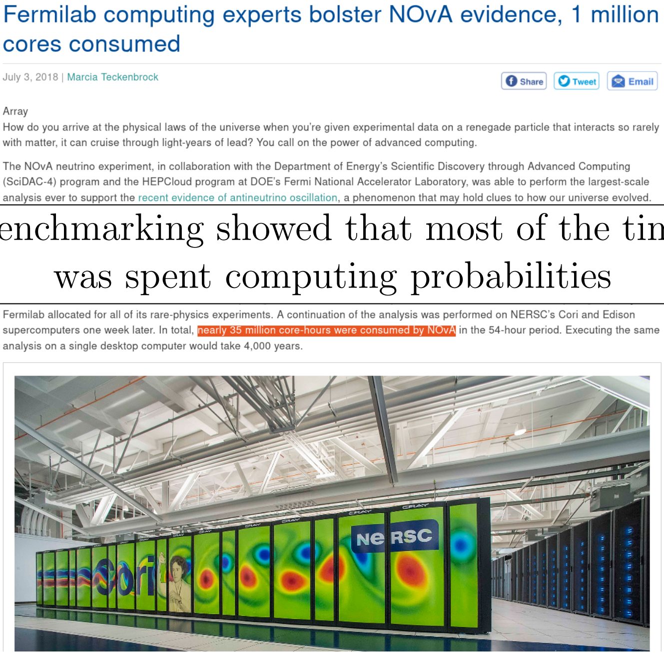
Array

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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Benchmarking showed that most of the time was spent computing probabilities

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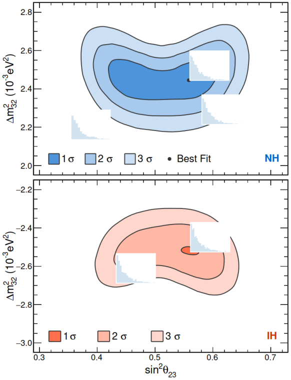
FNAL Newsroom

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

Need:

1. Eigenvalues
2. Eigenvectors
3. Construct the probability

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$$\lambda_3 \approx \Delta m^2_{31} + \frac{1}{2}\Delta m^2_{ee}\left(x - 1 + \sqrt{(1-x)^2 + 4xs^2_{13}}\right)$$

$$x \equiv \frac{a}{\Delta m^2_{ee}} \qquad \Delta m^2_{ee} \equiv \Delta m^2_{31} - s^2_{12}\Delta m^2_{21}$$

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

`NuFast-LBL` approach:

1. Approximate one eigenvalue: λ_3
   - Can iteratively improve precision rapdily 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

Algorithm for Constant Density

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)
ξ_k^α are submatrix eigenvalues: easy to compute

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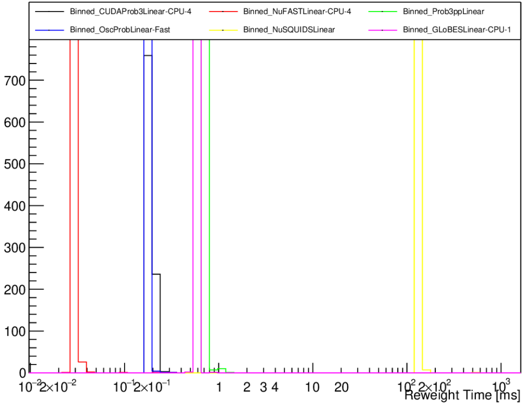
NuFast-LBL is Fast



D. Barrow, et al. NuOscillator

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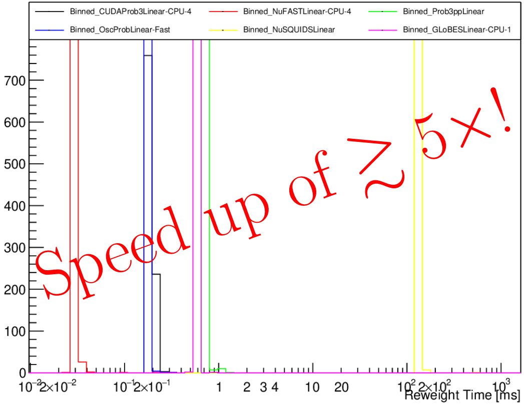


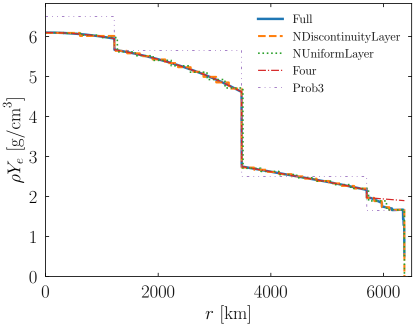
Speed up of $\gtrsim 5\times$!

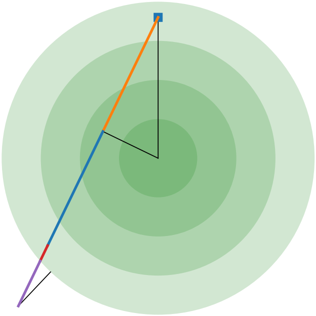
D. Barrow, et al. `NuOscillator`

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 Atmospherics

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 θ_{23}, δ, production height in atmosphere at end

PBD, S. Parke `2511.04735` (PRD)

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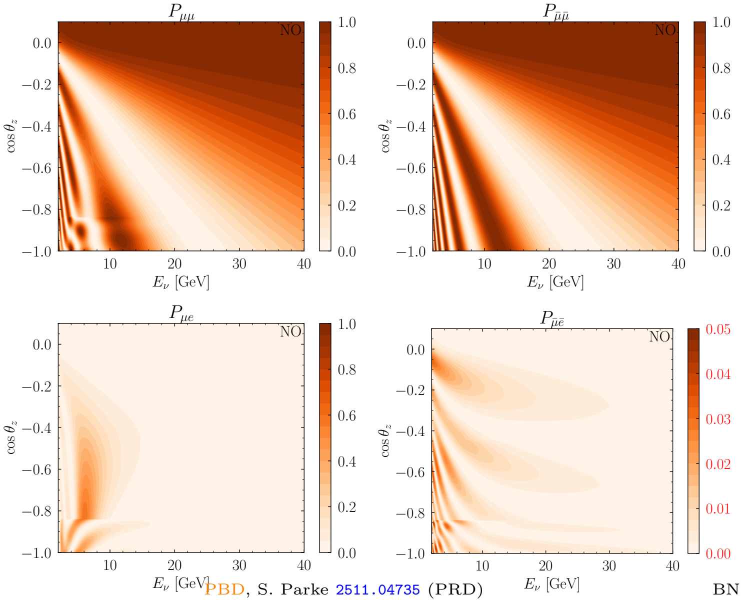
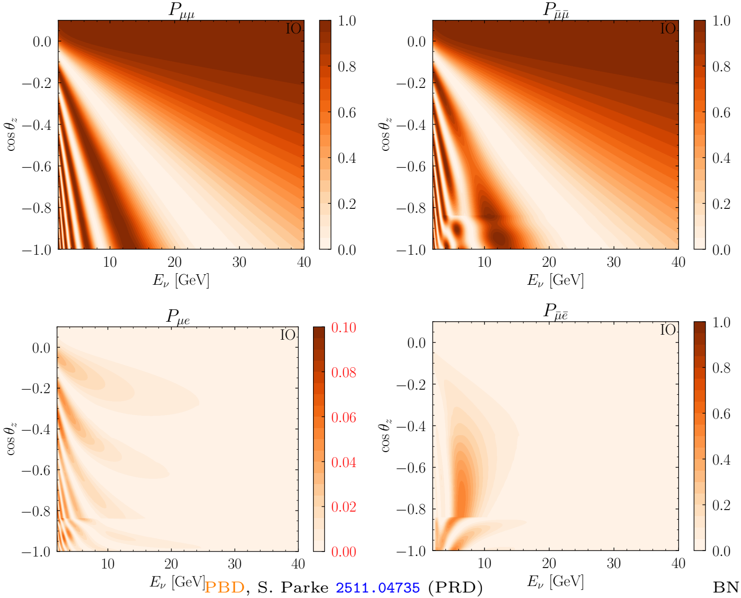
Varying θ_{23}, δ, and production height is essentially free:
Put on inside of loops

PBD, S. Parke 2511.04735 (PRD)

Atmospheric Results: NO



Atmospheric Results: IO

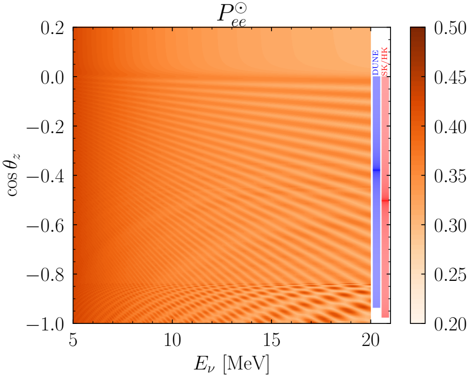


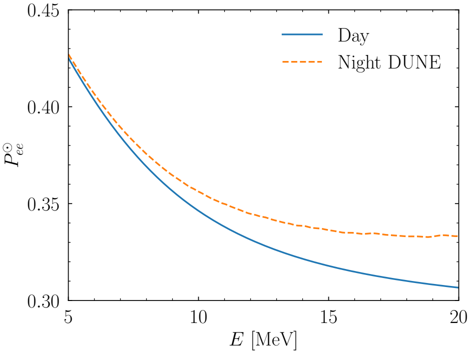
PBD, S. Parke 2511.04735 (PRD)

Nighttime Solar Neutrinos

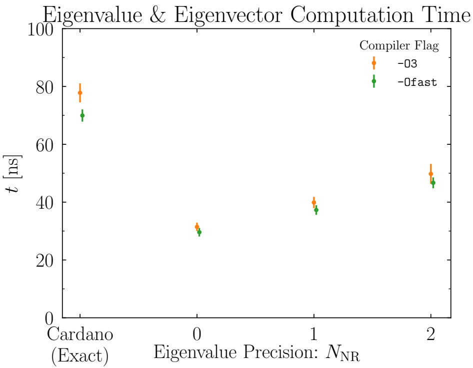
At night solar neutrinos experience regeneration:
There are more ν_e's from the Sun at night than during the day!

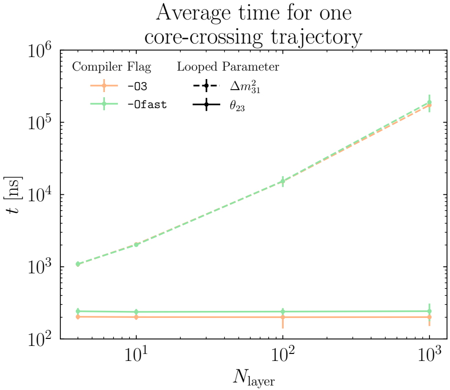
SuperK has $\sim 2\sigma$ evidence for this effect; DUNE and HK aim to measure it well





`NuFast-Earth` Speed





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

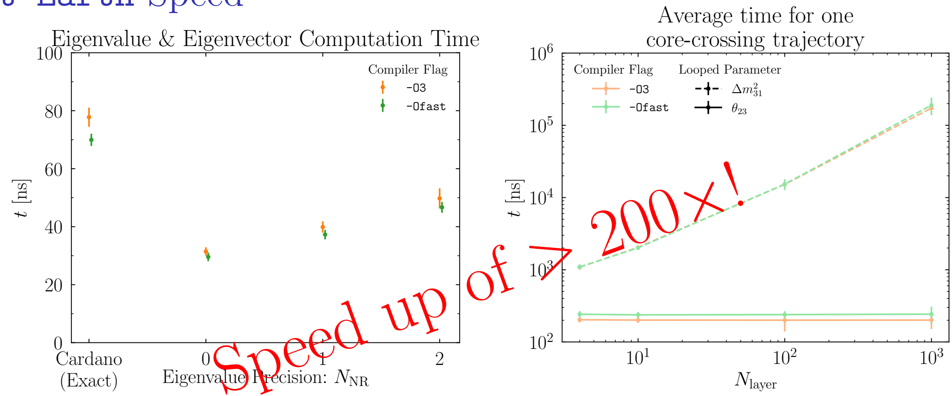
J. Coelho, R. Pestes, et al. github.com/joaoabcoelho/OscProb

`nuSQuIDS` takes >1M ns per trajectory

C. Argüelles, J. Salvado, C. Weaver 2112.13804

Other codes are designed with different goals in mind

`NuFast-Earth` Speed



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CP violation in neutrinos

δ and CP Violation

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

C. Jarlskog PRL 55, 1039 (1985)

δ and CP Violation

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C. Jarlskog PRL 55, 1039 (1985)

1. Strong interaction: no observed EDM ⇒ 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

$$\frac{|J_{\rm CKM}|}{J_{\rm max}} = 3\times10^{-4}$$

J. Christenson, J. Cronin, V. Fitch, R. Turlay PRL 1964
CKMfitter `1501.05013`

3. Lepton mass matrix: **?**

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

PBD, J. Gehrlein, R. Pestes `2008.01110` (PRL)

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

The Role of Appearance and Disappearance

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

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…given known oscillation parameters, systematics, and realistic experiments

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- **Disappearance can measure δ 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: $|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu2}|^2$, $|U_{\mu3}|^2$

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$$\boxed{\begin{aligned} J_{CP}^2 = {} & |U_{e2}|^2|U_{\mu 2}|^2|U_{e3}|^2|U_{\mu 3}|^2 \\ & -\frac{1}{4}\left(1-|U_{e2}|^2-|U_{\mu 2}|^2-|U_{e3}|^2-|U_{\mu 3}|^2+|U_{e2}|^2|U_{\mu 3}|^2+|U_{e3}|^2|U_{\mu 2}|^2\right)^2 \end{aligned}}$$

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

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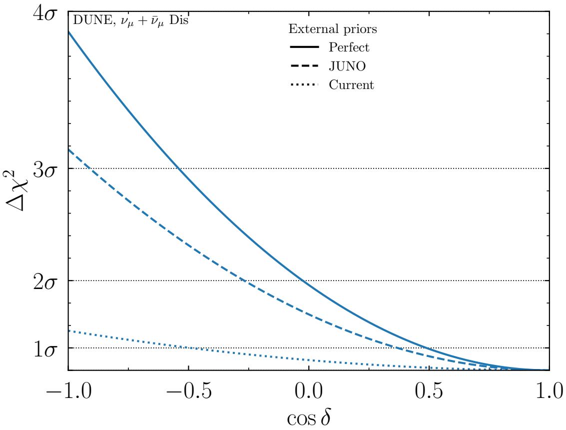
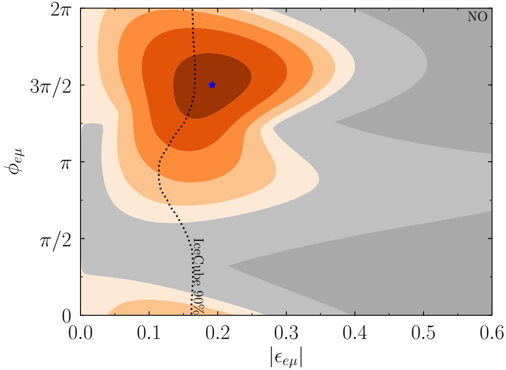
Disappearance can tell us if CP is violated,
but not if Nature prefers ν's or $\bar\nu$'s

JUNO and DUNE Disappearance Combined Sensitivities

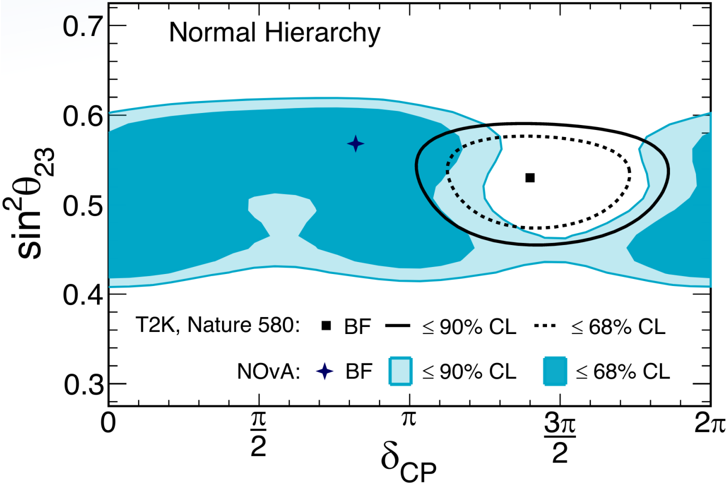


Different systematics $\Rightarrow$ crucial cross check of δ

Part 2: New Physics in Neutrinos



CP Violation at NOvA and T2K?



A. Himmel for NOvA 10.5281/zenodo.3959581

NSI Review

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

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 $a \propto G_F \rho E$

B. Dev, K. Babu, PBD, P. Machado, et al. 1907.00991

Estimate Size of Effect: Magnitude

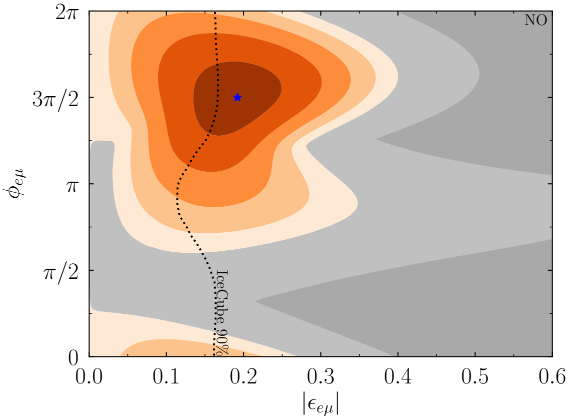
$$\boxed{|\epsilon_{e\beta}|\approx\frac{s_{12}c_{12}c_{23}\pi\Delta m^2_{21}}{2s_{23}w_\beta}\left|\frac{\sin\delta_{\rm T2K}-\sin\delta_{\rm NOvA}}{a_{\rm NOvA}-a_{\rm T2K}}\right|\approx\begin{cases}0.22 & \text{for }\beta=\mu\\0.24 & \text{for }\beta=\tau\end{cases}}$$

$a\propto\rho E$
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:

- $\sin\delta_{\rm NOvA}=\sin\delta_{\rm T2K}\Rightarrow|\epsilon|=0$
- $\sin\delta_{\rm NOvA}\neq\sin\delta_{\rm T2K}$ and $a_{\rm NOvA}=a_{\rm T2K}\Rightarrow|\epsilon|\to\infty$
- Octant:
  1. LBL is governed by ν_3
  2. Upper octant $\Rightarrow$ ν_3 is more ν_μ
  3. More ν_μ $\Rightarrow$ 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)
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:

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

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

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 ϵ_{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

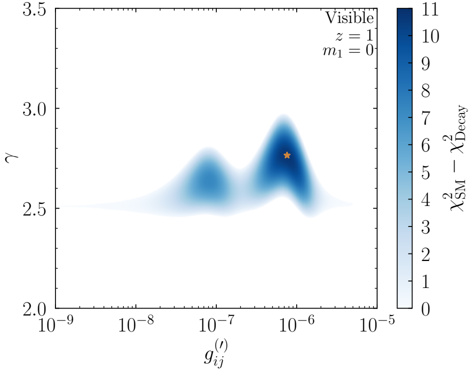
   PBD, I. Tamborra 1805.05950 (PRL)
   PBD, A. Abdullahi 2005.07200 (PRD)

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”

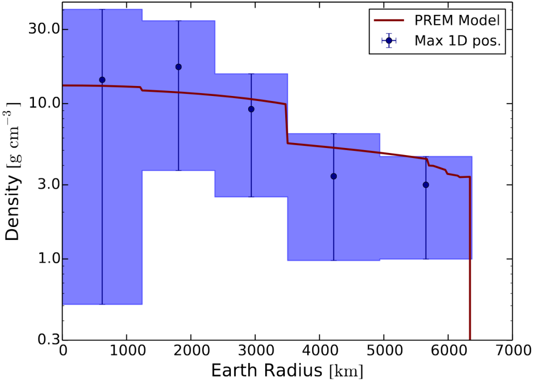
What can neutrinos do for you
and
what you can do for neutrinos

Neutrinos shine a flashlight in opaque environments

Terrestrial Tomography

HE neutrinos are absorbed in the Earth

Assumes isotropic flux

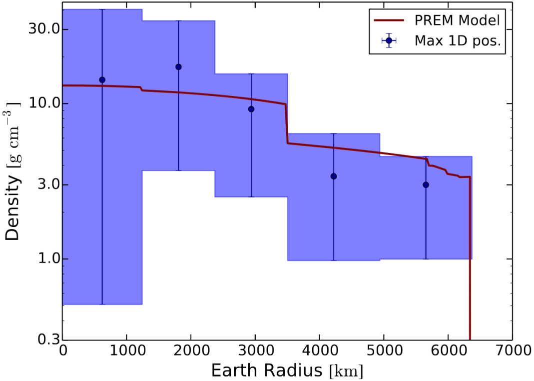


A. Donini, S. Palomares-Ruiz, J. Salvado 1803.05901

Terrestrial Tomography

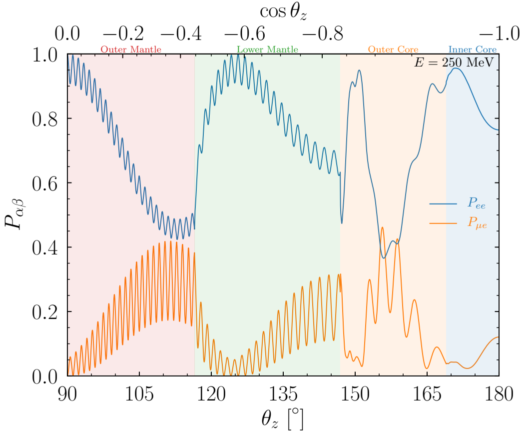
HE neutrinos are absorbed in the Earth

Assumes isotropic flux



A. Donini, S. Palomares-Ruiz, J. Salvado 1803.05901

Can also do this with oscillations

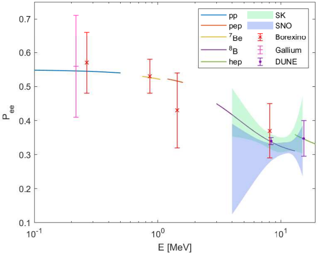


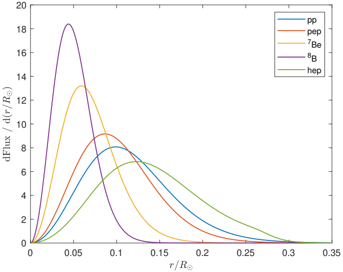
PBD, R. Pestes 2110.01148 (PRD)

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

See also K. Kelly, et al. 2110.00003

Solar Tomography

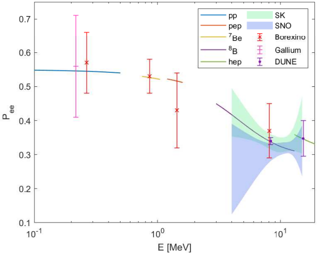


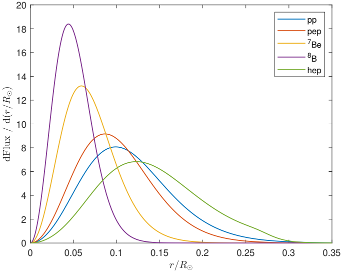


Solar neutrinos constrain Sun’s density at different radii

Solar Tomography

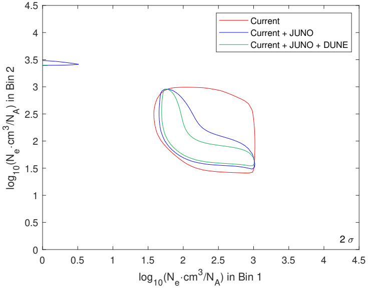
Solar neutrinos constrain Sun's density at different radii



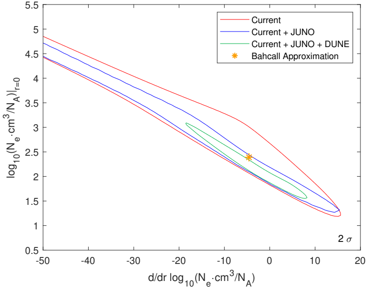


Bin 1: $\frac{r}{R_\odot} \in [0, 0.05]$

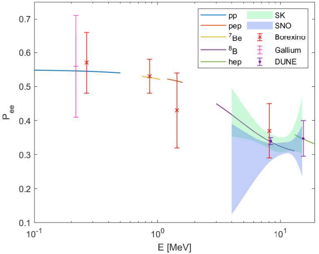
Bin 2: $\frac{r}{R_\odot} \in [0.05, 0.1]$

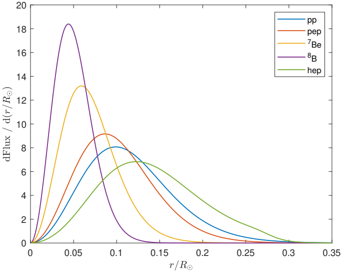


$$\log_{10} N_e = Ar + B$$



Solar Tomography



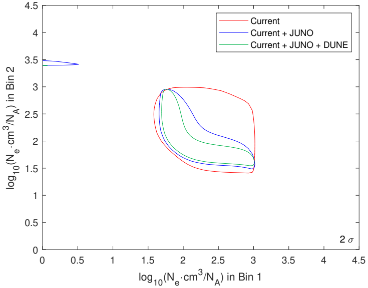


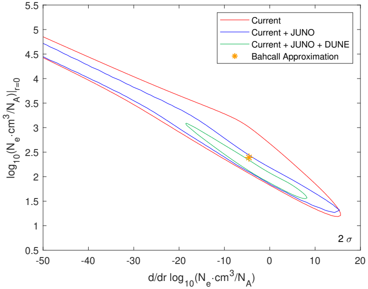
Solar neutrinos constrain Sun's density at different radii

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

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

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



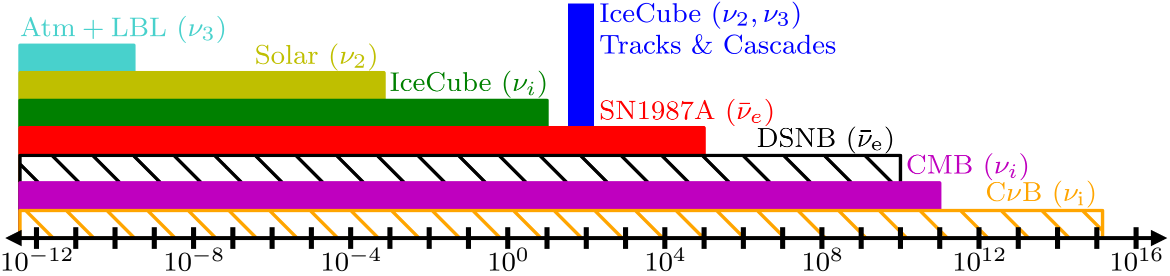


First determination of Sun's density with neutrinos
Only way to probe innermost 5% of the Sun

PBD, C. Gourley 2502.17546 (PLB)

New particle physics in neutrinos from astrophysics

Invisible ν Decay Constraints and Evidence



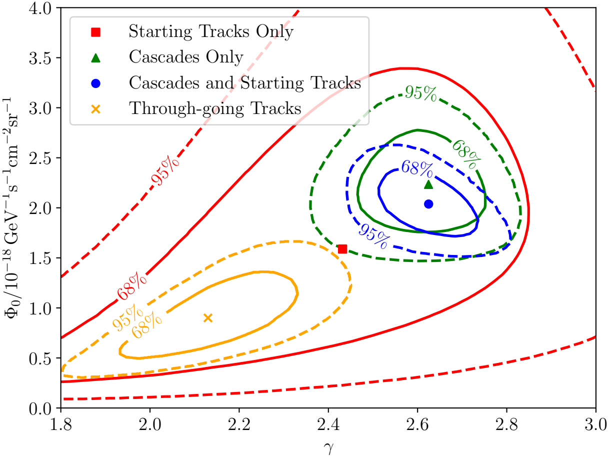
τ/m [s/eV]

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

$$\Phi(E) = \Phi_0 E^{-\gamma}$$



$$\boxed{\Delta\gamma = +0.54}$$

"The p-value for obtaining the combined fit result and the result reported here from an unbroken powerlaw flux is 3.3σ, and is therefore in significant **tension**."

IC 1607.08006

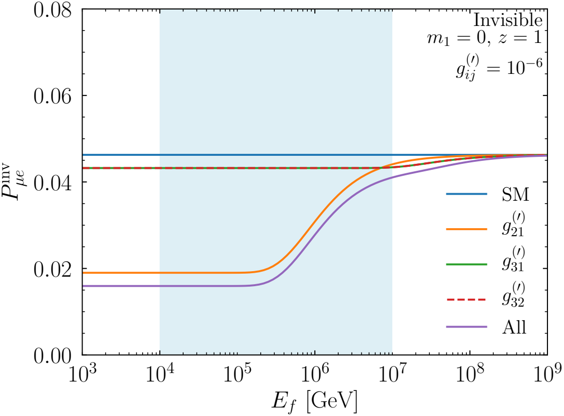
"This [cascade] fit [is] in **tension** with previous results based on through-going muons"

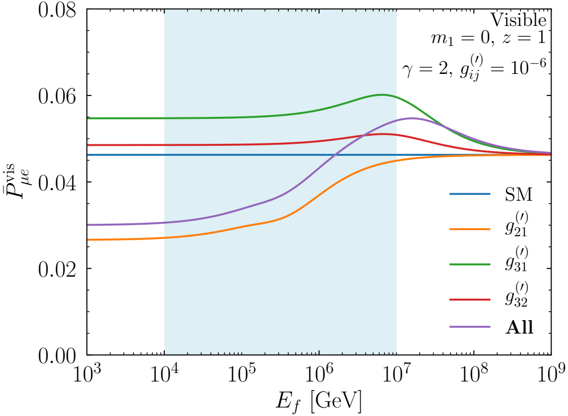
IC 1808.07629

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

IC 2001.09520

Invisible vs. Visible Decay



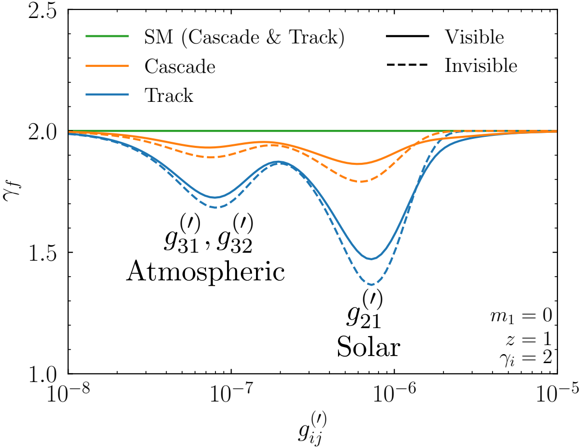


Spectral Indices at IceCube

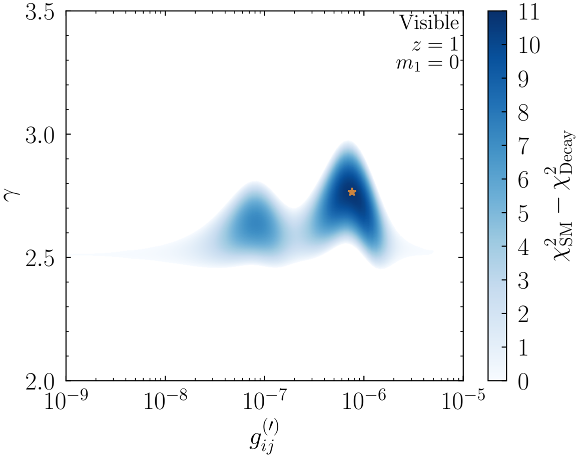
1. Neutrino decay completely removes tension
2. Is preferred over SM at $> 3\sigma$
3. Either visible or invisible works
4. Requires normal mass ordering
5. Decay only shifts the spectra one way:

$$\gamma_c > \gamma_t$$

this is the direction of the tension



Preferred Region: Visible



- Consistent with astro constraints including SN1987A
- Terrestrial constraints at $g \sim 10^{-2}$

$$\pi \to \ell\nu\phi, \;\; K \to \ell\nu\phi$$

B. Dev, et al. 2407.12738

- Some tension with cosmology; possible to evade

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 $m_\chi <$GeV

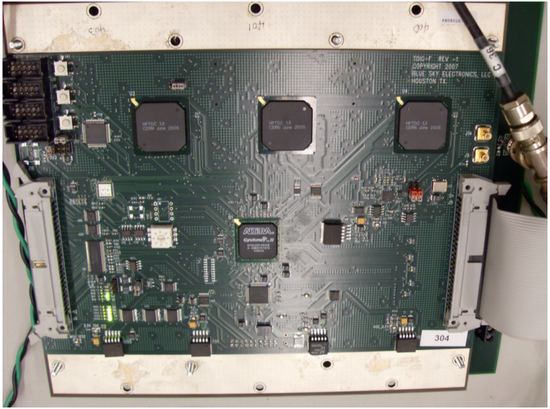
   H. Davoudiasl, PBD, J. Gehrlein `2007.04989` (PRD)
   J. Acevedo, J. Berger, PBD `2407.01670` (JHEP)

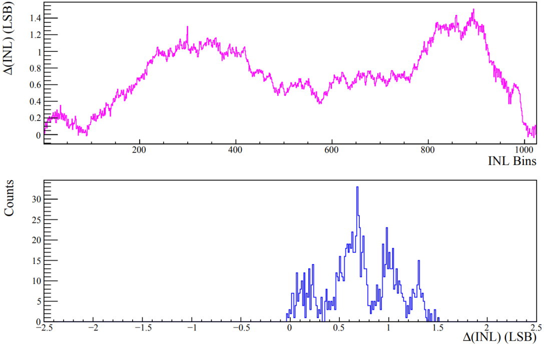
5. Disfavored ultralight boson DM via black hole measurements

   H. Davoudiasl, PBD `1904.09242` (PRL)

⋮

STAR-TOF TDIG Boards Calibration at Rice in 2008

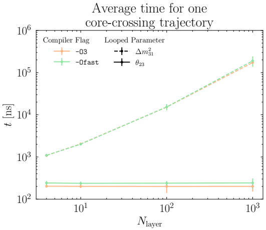


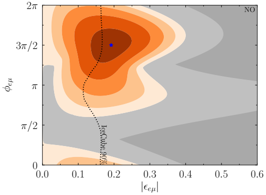


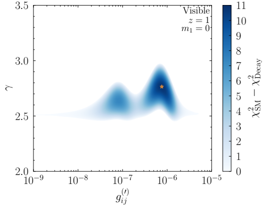
D. McDonald, MSc Thesis

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 ν decay

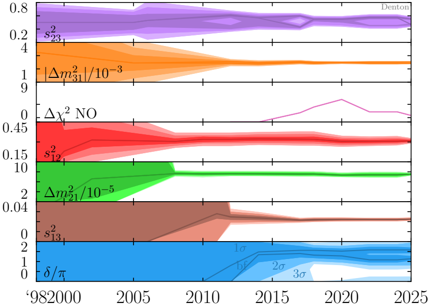






Backups

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

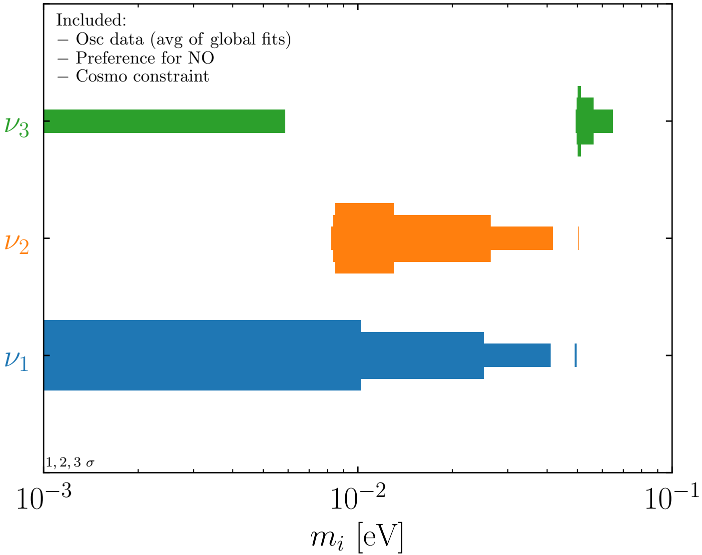
D. Forero, M. Tortola, J. Valle 1405.7540

P. de Salas, et al. 1708.01186

F. Capozzi et al. 2003.08511

I. Esteban, et al. 2007.14792

Absolute Masses



PBD, J. Gehrlein 2308.09737 (PRD)

Optimal Structure of the Probability for Long-Baseline

1. Amplitude requires four trig functions of kinematic variables ($\Delta m^2_{ij}L/4E$) ✗
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 λ_i and eigenvectors $V_{\alpha i}$

Optimal Structure of the Probability for Long-Baseline

4. Appearance structure:
   T conserving:

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

Fun fact:

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

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 λ_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 λ_i and submatrix eigenvalues (requires only a square root) using Eigenvector-Eigenvalue Identity

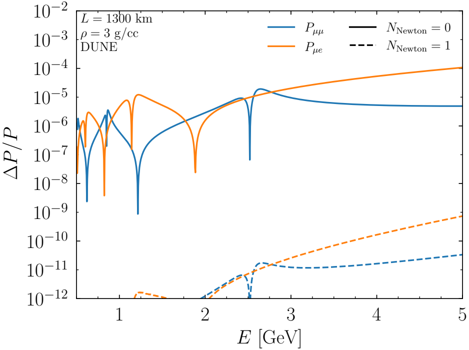
$$|V_{\alpha i}|^2 = \frac{\prod_{k=1}^{n-1}(\lambda_i - \xi_k^\alpha)}{\prod_{k=1;k\neq i}^{n}(\lambda_i - \lambda_k)}$$

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

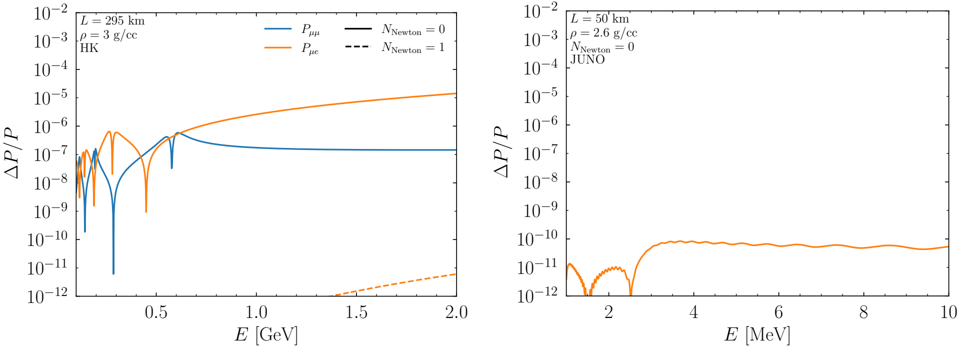
`NuFast-LBL` Precision

Is this approximation okay?

DUNE requires $\lesssim 1\%$ level precision



Precision


$L = 295$ km
$\rho = 3$ g/cc
HK
$P_{\mu\mu}$
$P_{\mu e}$
$N_{\rm Newton} = 0$
$N_{\rm Newton} = 1$
$\Delta P/P$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0.5
1.0
1.5
2.0
E [GeV]
$L = 50$ km
$\rho = 2.6$ g/cc
$N_{\rm Newton} = 0$
JUNO
$\Delta P/P$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
2
4
6
8
10
E [MeV]

NuFast-LBL: The Code

- Code is on github: 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: $\Delta m^2_{31} < 0$
- 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 Atmospherics

3. Work in the tilde basis with θ_{23} and δ pulled out
    - Can shift δ from θ_{13} to θ_{23}

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

Optimal Structure of the Probability for Atmospherics

3. Work in the tilde basis with θ_{23} and δ pulled out
   - Can shift δ from θ_{13} to θ_{23}

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

   - U_{23} commutes with the matter potential

$$(2E)H_f=U_{23}(\theta_{23},\delta)\left[R_{13}R_{12}\begin{pmatrix}0&&\\&\Delta m^2_{21}&\\&&\Delta m^2_{31}\end{pmatrix}R^T_{12}R^T_{13}+\begin{pmatrix}a&&\\&0&\\&&0\end{pmatrix}\right]U^\dagger_{23}(\theta_{23},\delta)$$

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

Optimal Structure of the Probability for Atmospherics

3. Work in the tilde basis with θ_{23} and δ pulled out
   - Can shift δ from θ_{13} to θ_{23}

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

   - U_{23} commutes with the matter potential

$$(2E)H_f=U_{23}(\theta_{23},\delta)\left[R_{13}R_{12}\begin{pmatrix}0&&\\&\Delta m^2_{21}&\\&&\Delta m^2_{31}\end{pmatrix}R^T_{12}R^T_{13}+\begin{pmatrix}a&&\\&0&\\&&0\end{pmatrix}\right]U^\dagger_{23}(\theta_{23},\delta)$$

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

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

$$U_{23}U^\dagger_{23}=\mathbb{1}$$

Optimal Structure of the Probability for Atmospherics

3. Work in the tilde basis with θ_{23} and δ pulled out
    - Can shift δ from θ_{13} to θ_{23}

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

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

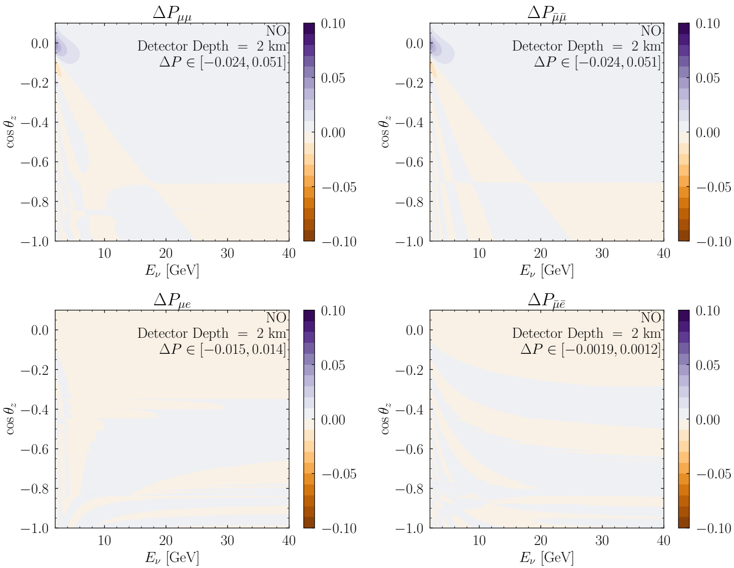
$$\mathcal A=\prod_j\mathcal A_j=\prod_j e^{-iH_{f,j}L_j}=U_{23}(\theta_{23},\delta)\left(\prod_j e^{-i\tilde H_jL_j}\right)U^\dagger_{23}(\theta_{23},\delta)$$

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

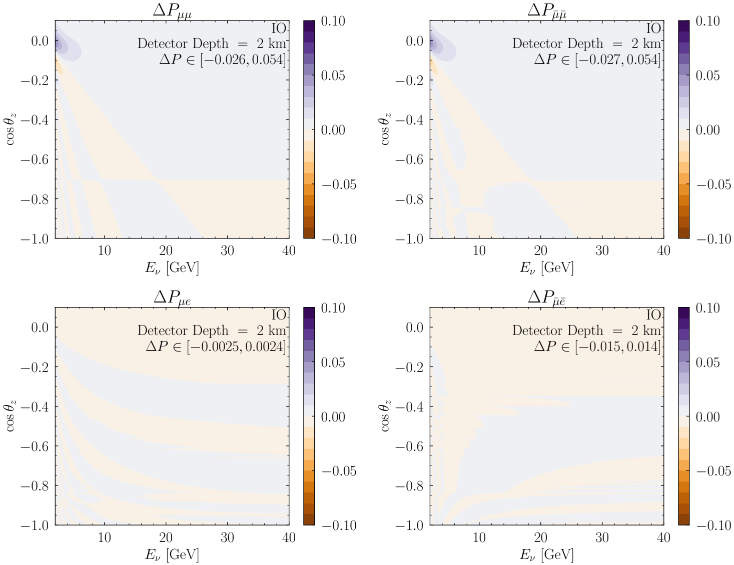
$U_{23}U^\dagger_{23}=\mathbb{1}$

Reduces many unnecessary computations

Atmospheric Results: Detector Depth: NO



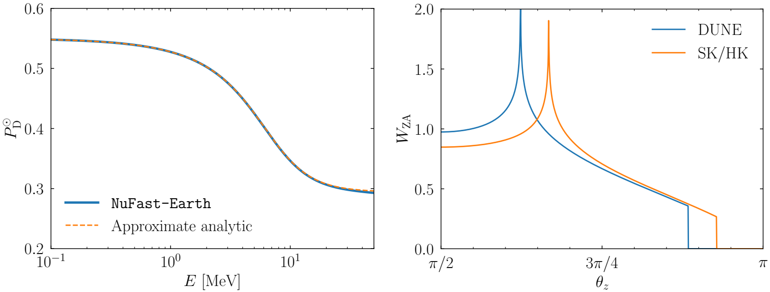
Atmospheric Results: Detector Depth: IO



Atmospheric Results: Detector Depth: Summary

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

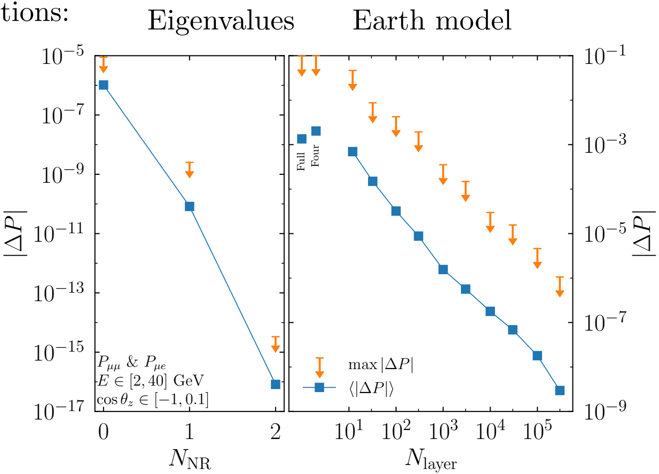
NuFast-Earth Solar Neutrino Validation



Analytically understand the small deviation at high energy

NuFast-Earth Precision

Two approximations:



"True" has exact eigenvalues and 1M layers

Calculate $|\Delta P|$ across 100×100 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 Δm^2_{31} points and 100 θ_{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 Δm^2_{31} 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 θ_{23} first):

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

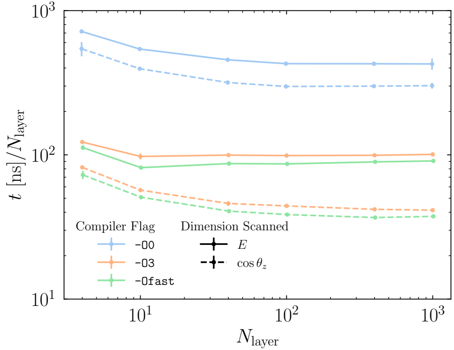
200×

`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

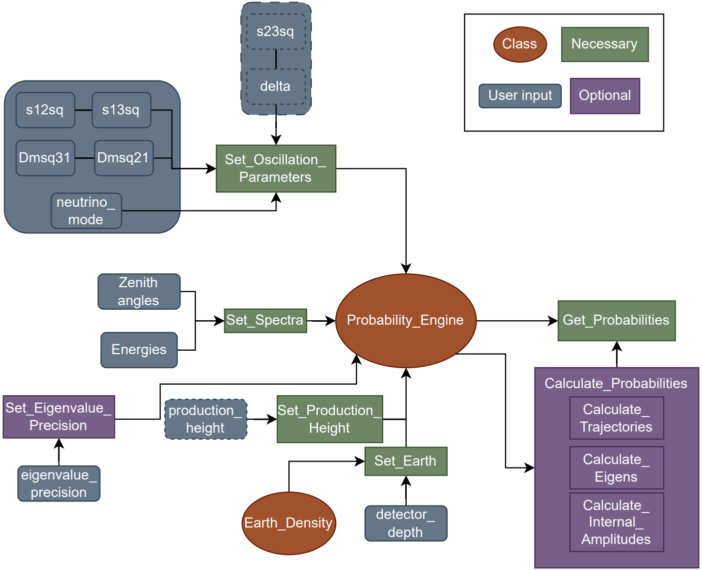
Four fast parameters for insides of loops:

- θ_{23}: `Set_s23sq`
- δ: `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

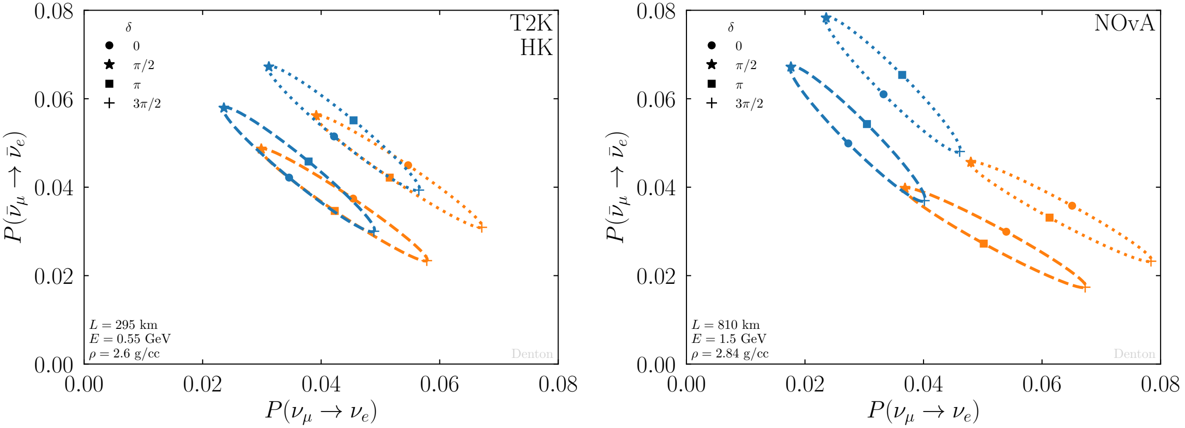
NuFast-Earth Flow

```
// 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_enginge.Set_Production_Height(10); // km,
     recalculations after changing this are fast

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



Dashed boxes = fast!

δ: What is it Really?



δ: What is it Not?

$$\delta \not\Rightarrow \text{Baryogenesis}$$

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

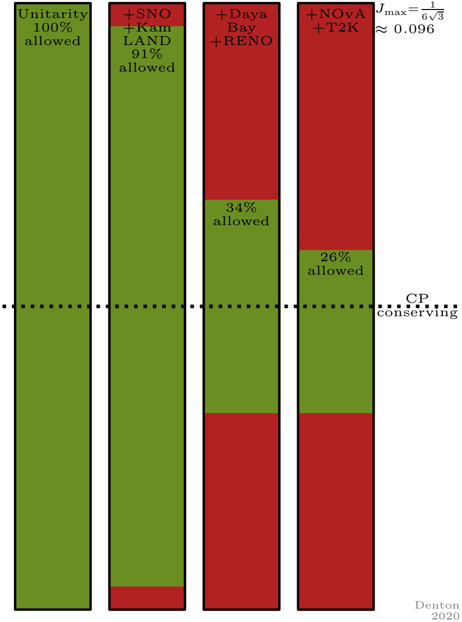
K. Moffat, et al. 1809.08251

$$\boxed{\begin{array}{lcl} \text{Measuring } \delta = 0, \pi & \not\Rightarrow & \text{no leptogenesis} \\ \text{Measuring } \delta \neq 0, \pi & \not\Rightarrow & \text{leptogenesis} \end{array}}$$

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



CP, T: Disappearance

$$\begin{tikzcd} \boxed{\nu_e \to \nu_e} \arrow[rr, "CP"] \arrow[drr, "CPT"'] & & \boxed{\bar{\nu}_e \to \bar{\nu}_e} \arrow[d, "T"] \\ & & \boxed{\bar{\nu}_e \to \bar{\nu}_e} \end{tikzcd}$$

Disappearance measurements are even eigenstates of CP

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

Assume that CPT is a good symmetry

CP, T: Appearance

$$\begin{tikzcd}
\boxed{\nu_\mu \to \nu_e} \arrow[rr, "CP"] \arrow[drr, "CPT"'] & & \boxed{\bar{\nu}_\mu \to \bar{\nu}_e} \arrow[d, "T"] \\
& & \boxed{\bar{\nu}_e \to \bar{\nu}_\mu}
\end{tikzcd}$$

Appearance measurements are not eigenstates of CP

Appearance and Disappearance, CP Even and CP Odd Terms

Disappearance:

$$\begin{aligned} P(\nu_\alpha \to \nu_\alpha) = 1 &- 4|U_{\alpha1}|^2|U_{\alpha2}|^2\sin^2\Delta_{21} \\ &- 4|U_{\alpha1}|^2|U_{\alpha3}|^2\sin^2\Delta_{31} \\ &- 4|U_{\alpha2}|^2|U_{\alpha3}|^2\sin^2\Delta_{32} \\ &= P_{\alpha\alpha}^{CP+} \end{aligned}$$

Appearance:

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) = &- 4\Re[U_{\alpha1}U_{\beta1}^*U_{\alpha2}^*U_{\beta2}]\sin^2\Delta_{21} \\ &- 4\Re[U_{\alpha1}U_{\beta1}^*U_{\alpha3}^*U_{\beta3}]\sin^2\Delta_{31} \\ &- 4\Re[U_{\alpha3}U_{\beta3}^*U_{\alpha2}^*U_{\beta2}]\sin^2\Delta_{32} \\ &\pm 8J_{CP}\sin\Delta_{21}\sin\Delta_{31}\sin\Delta_{32} \\ = &\; P_{\alpha\beta}^{CP+} + P_{\alpha\beta}^{CP-} \end{aligned}$$

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

Sign depends on α, β

Parameter Counting

1. Four parameters in the PMNS matrix

Majorana phases are irrelevant in oscillations

Parameter Counting

1. Four parameters in the PMNS matrix

Majorana phases are irrelevant in oscillations

2. Disappearance experiments of one flavor can measure up to three amplitudes
    - Electron neutrino row:
        - KamLAND/SNO+/JUNO measured one
        - Daya Bay/RENO measured a different one
        - JUNO will measure all three
    - Muon neutrino row:
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$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4\sum_{i>j} C^\alpha_{ij} \sin^2 \Delta_{ij}$$

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

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

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

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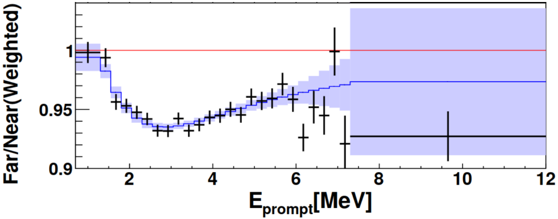

Daya Bay 1809.02261

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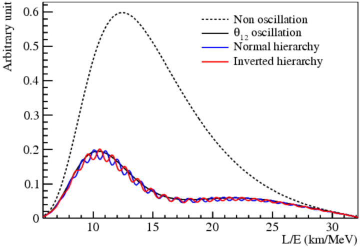
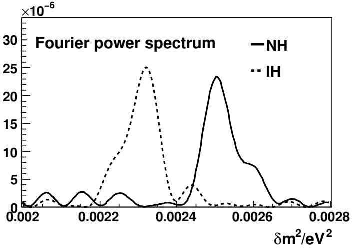


JUNO 1507.05613



L. Zhan, et al. 0807.3203

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3. Only two parameters for one flavor are independent
4. Given good measurements of the ν_e and ν_μ disappearance, 4 independent parameters will be measured
   - Any row can be "simple" (e.g. $c_{12}c_{13}$, $s_{12}c_{13}$, ...) ⇒ no one row is ever enough
   - That is, CPV is physical and cannot depend on parameterization

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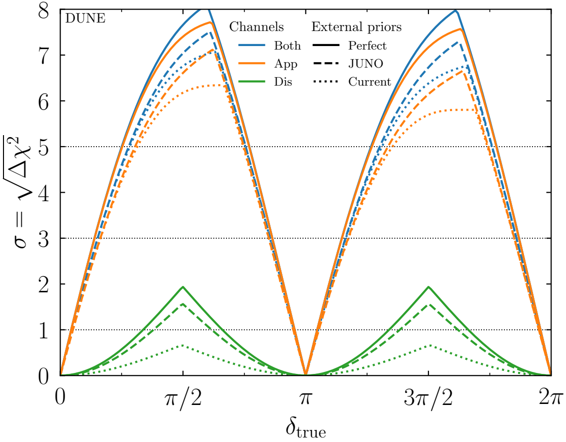
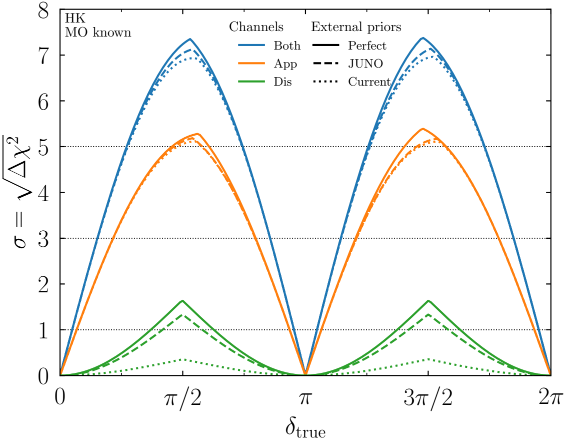
   - That is, CPV is physical and cannot depend on parameterization
5. This is sufficient to constrain $\cos\delta$ and three mixing angles
6. If we determine $\cos\delta \neq \pm 1 \quad \Rightarrow \quad$ CP is violated!

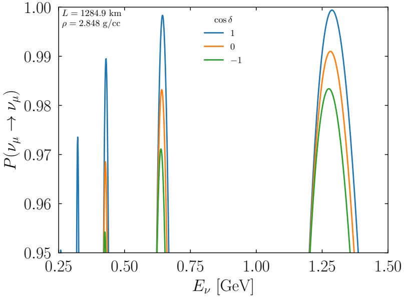
JUNO and HK Disappearance Sensitivities





δ: Future Sensitivities

Possible to get at CPV with CPC processes



Disappearance probability:

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

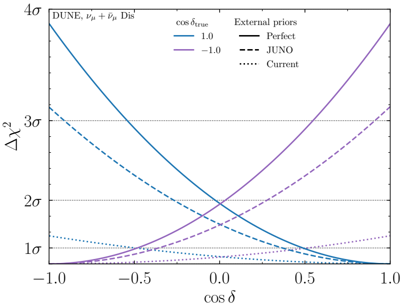
$$\Delta_{ij} = \Delta m^2_{ij} L/4E$$

Can measure all three coeffs of each frequency ⇒ 2 dofs

δ (and CPV) needs 4 dofs ⇒ two dis measurements

ν_e: Daya Bay and KamLAND/JUNO

ν_μ: precision at DUNE/HK



Important cross check

Different and cleaner systematics than appearance

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

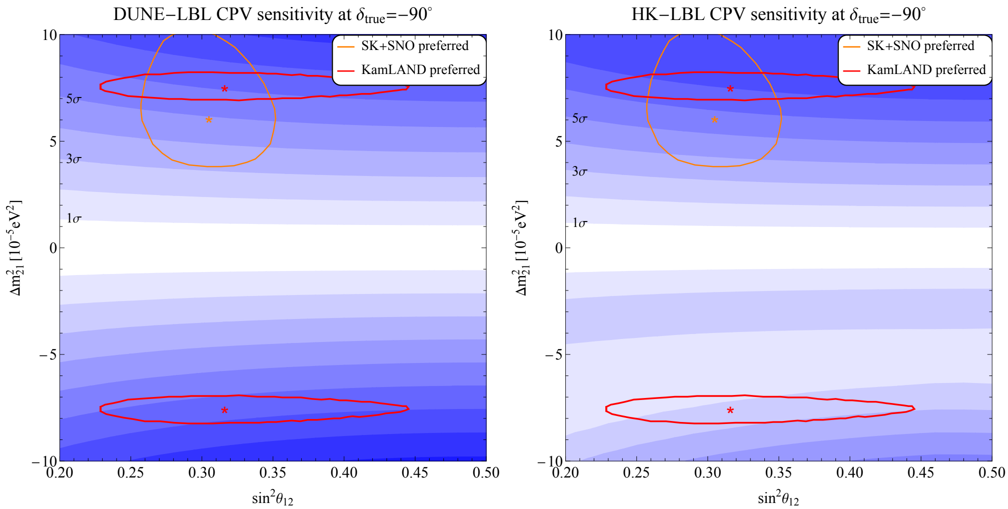
e.g. $P(\nu_\mu \to \nu_\mu)$ depends on $\cos\delta$ a tiny bit
PBD 2309.03262 (PRL)

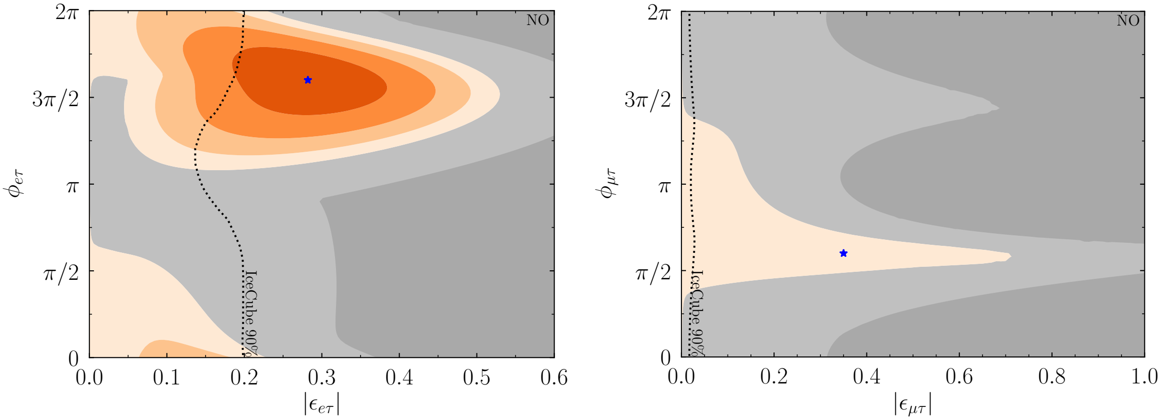
- T2K/HK are mostly sensitivity to $\sin\delta$; they should focus on J

  T2K does this now!

- NOvA/DUNE has modest $\cos\delta$ sensitivity; both J and δ should be reported

Impact of the True Solar Parameters on δ




2π
3π/2
π
π/2
0
$\phi_{e\tau}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
$|\epsilon_{e\tau}|$
NO
IceCube 90%
2π
3π/2
π
π/2
0
$\phi_{\mu\tau}$
0.0
0.2
0.4
0.6
0.8
1.0
$|\epsilon_{\mu\tau}|$
NO
IceCube 90%

Other CP Violating NSI Constraints

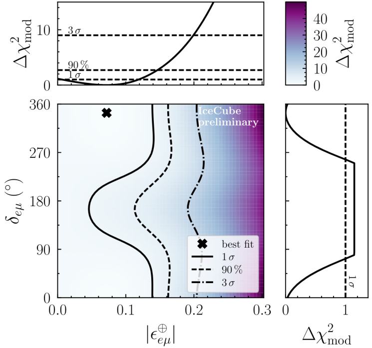
NSI effects grow with energy, density, and distance

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

NSI effects grow with energy, density, and distance

Best probes:

- $\epsilon_{\mu\tau}$: atmospheric
- $\epsilon_{e\mu}$, $\epsilon_{e\tau}$: LBL appearance, atmospheric

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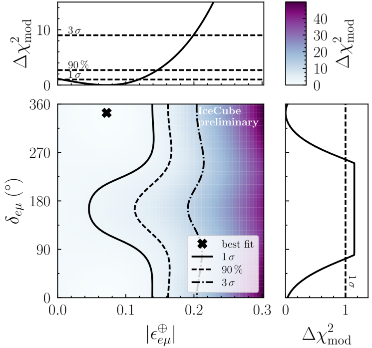


T. Ehrhardt, IceCube PPNT (2019)
IceCube `2106.07755`

- Super-K
  - Only consider real NSI
  - Comparable sensitivity as IceCube

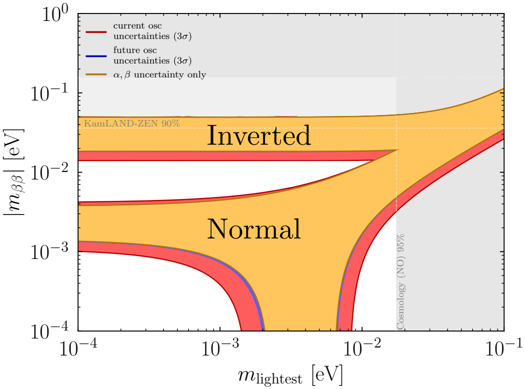
Super-K `1109.1889`

- COHERENT
  - Only applies to NSI models with $M_{Z'} \gtrsim 10$ MeV
  - NSI u, d, e configuration matters
  - Comparable constraints

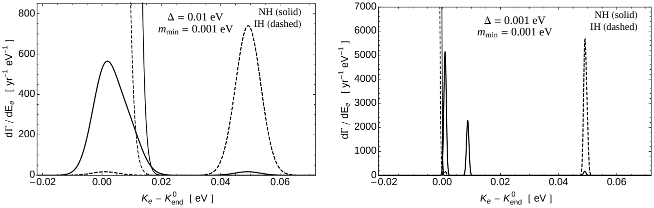
COHERENT `1708.01294`
PBD, Y. Farzan, I. Shoemaker `1804.03660` (JHEP)
PBD, J. Gehrlein `2008.06062` (JHEP)
PBD, J. Gehrlein, R. Pestes `2008.01110` (PRL)

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 $\nu_i \to \nu_j + \phi$ with $m_i > m_j$

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

PBD, I. Tamborra 1805.05950 (PRL) & A. Abdullahi, PBD 2005.07200 (PRD)

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

PBD, I. Tamborra 1805.05950 (PRL) & A. Abdullahi, PBD 2005.07200 (PRD)

Why IceCube for Neutrino Decay

- DSNB and CνB are still some time off
- The next galactic supernova could come tomorrow, or in fifty years
- If ν_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”

$$P_{\alpha\beta}(E_f) \equiv \frac{\Phi^E_{\alpha\beta}(E_f)}{\Phi^S_\alpha(E_f)}$$

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:

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

SM Contribution: The Probability

Given the usual Hamiltonian,

$$H = U_{\text{PMNS}} \begin{pmatrix} 0 & & \\ & \frac{\Delta m^2_{21}}{2E} & \\ & & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger_{\text{PMNS}}$$

The SM oscillation probability is:

$$P^{\text{SM}}_{\alpha\beta} = \left| U^*_{\alpha1} U_{\beta1} + U^*_{\alpha2} U_{\beta2} e^{-i\frac{\Delta m^2_{21} L}{2E}} + U^*_{\alpha3} U_{\beta3} e^{-i\frac{\Delta m^2_{31} L}{2E}} \right|^2$$

When averaged/decohered:

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

No interference terms.

Depletion Component: How to Calculate

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

Assume here and throughout that ν_1 is stable (no lighter sterile neutrino) and the normal ordering

Depletion Component: How to Calculate

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

Assume here and throughout that ν_1 is stable (no lighter sterile neutrino) and the normal ordering

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

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

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

$\Gamma_i = \sum_j \Gamma_{ij}$
$\tau_i = m_i / E_i \Gamma_i$
$x_{ij} \equiv m_i / m_j$
See slide 95 on $\nu/\bar{\nu}$

Depletion Component: The Probability

$$\bar{P}^{\rm dep}_{\alpha\beta}(E,L)=-|U_{\alpha2}|^2|U_{\beta2}|^2(1-e^{-\Gamma_2L})-|U_{\alpha3}|^2|U_{\beta3}|^2(1-e^{-\Gamma_3L})$$

The invisible probability is:

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

$$\bar{P}^{\rm inv}_{\alpha\beta}=|U_{\alpha1}|^2|U_{\beta1}|^2+|U_{\alpha2}|^2|U_{\beta2}|^2e^{-\Gamma_2L}+|U_{\alpha3}|^2|U_{\beta3}|^2e^{-\Gamma_3L}$$

Further Details

Full calculation is much more involved:

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

Summary of Parameters

More important

1. γ: 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. $\nu \to \nu$, $\nu \to \bar{\nu} \Rightarrow$ small effect

Regeneration Component: Analytic Limits

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

SM

Regeneration Component: Analytic Limits

- Verify that as $E_f \to \infty$, $\bar{P}_{ij}^{\rm reg} \to 0$ as expected

SM

- As $E_f \to 0$:

Full decay

$$\lim_{E_f \to 0} \bar{P}_{ij}^{\rm reg}(E_f, L) = \frac{z(x)}{\gamma y(x)} \left(1 - \frac{1}{x^{2\gamma}}\right)$$

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  - As $m_1 \to \infty$

Degenerate masses

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

Regeneration Component: Analytic Limits

- Verify that as $E_f \to \infty$, $\bar{P}_{ij}^{\rm reg} \to 0$ as expected

SM

- As $E_f \to 0$:

Full decay

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  - As $m_1 \to \infty$

Degenerate masses

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

  - As $m_1 \to 0$

Depends on nature of interaction!

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

Regeneration Component: Analytic Limits with Cosmology

Full decay:

- As $m_1 \to \infty$

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

$$\lim_{\substack{E_f \to 0 \\ m_1 \to \infty}} \bar{P}_{\alpha\beta}^{\rm vis} = (1+z)^{-\gamma}\left[|U_{\alpha1}|^2|U_{\beta1}|^2 + |U_{\alpha2}|^2|U_{\beta2}|^2 + (1+z)^{-\gamma}|U_{\alpha3}|^2|U_{\beta1}|^2\right]$$

Regeneration Component: Analytic Limits with Cosmology

Full decay:

- As $m_1 \to \infty$

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

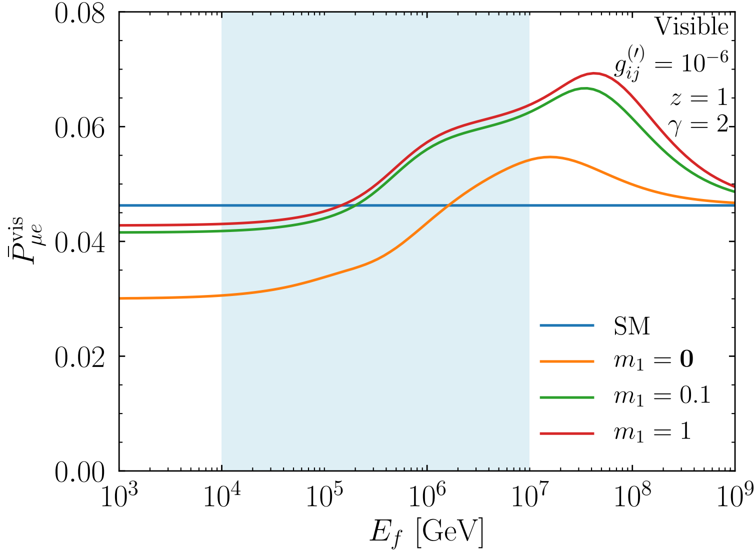
$$\lim_{\substack{E_f \to 0 \\ m_1 \to \infty}} \bar{P}_{\alpha\beta}^{\text{vis}} = (1+z)^{-\gamma}\left[|U_{\alpha 1}|^2|U_{\beta 1}|^2 + |U_{\alpha 2}|^2|U_{\beta 2}|^2 + (1+z)^{-\gamma}|U_{\alpha 3}|^2|U_{\beta 1}|^2\right]$$

- As $m_1 \to 0$

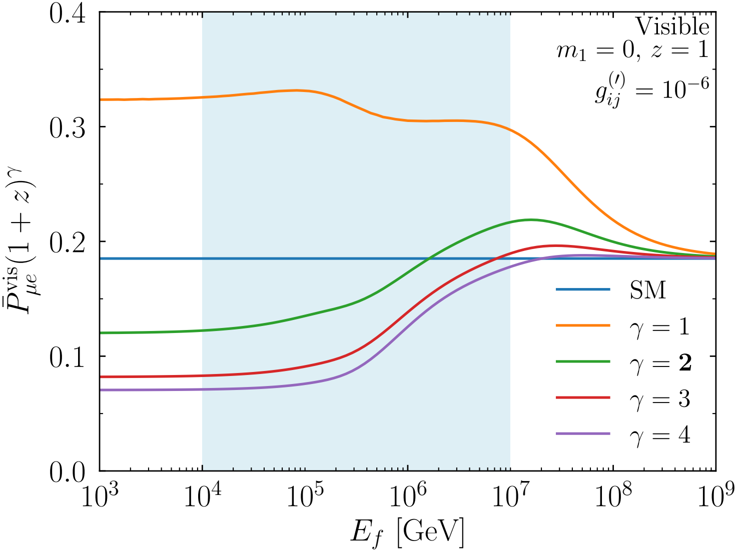
$$\lim_{\substack{E_f \to 0 \\ m_1 \to 0}} \bar{P}_{ij}^{\text{reg}}(E_f, L) = \frac{(1+z)^{-2\gamma}}{\gamma}$$

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

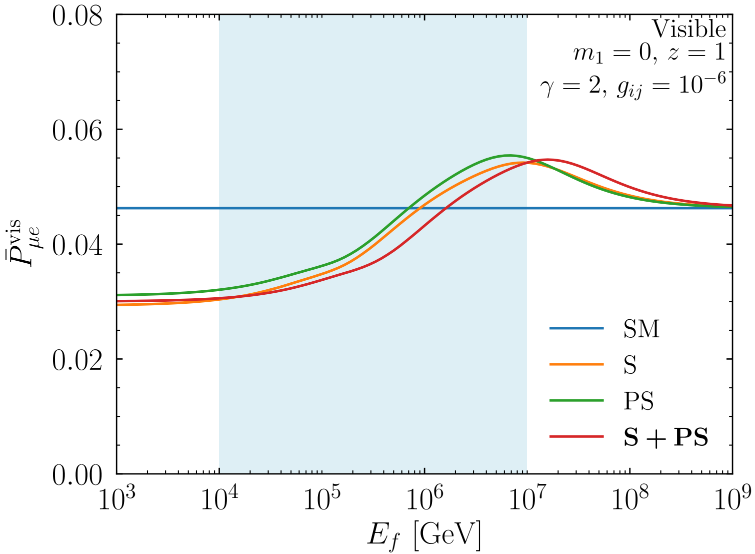
Results: Visible Decay: Neutrino mass scale



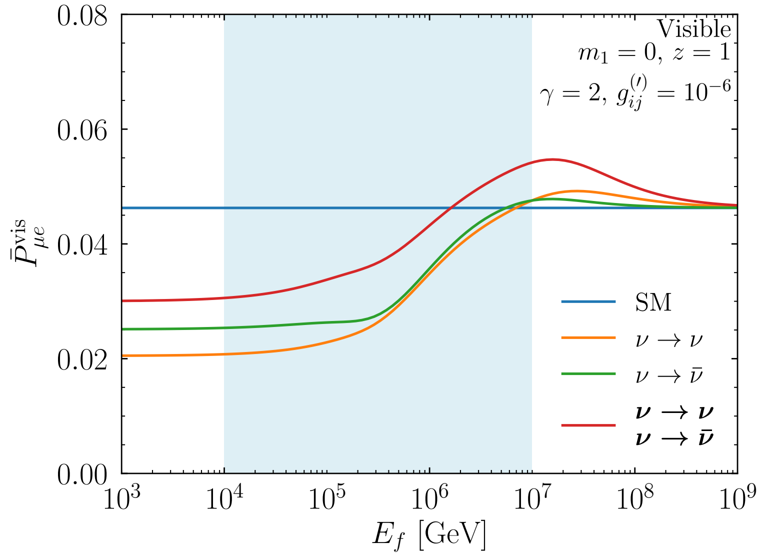
Results: Visible Decay: Spectral Index



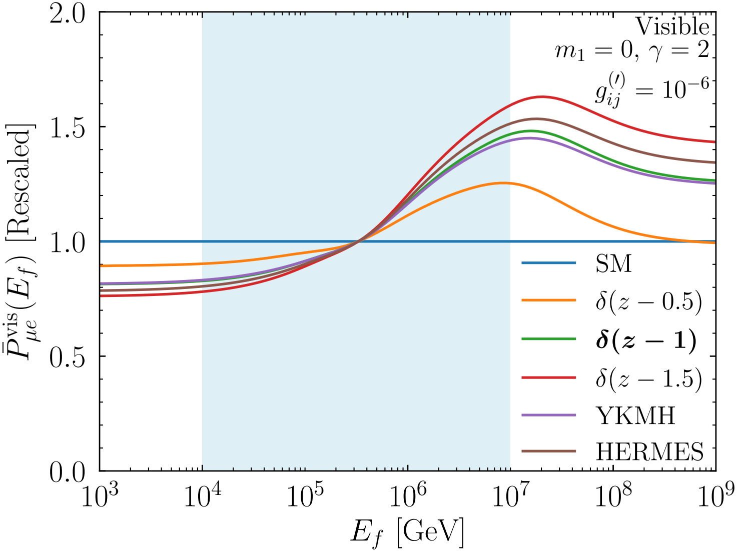
Results: Visible Decay: Scalar vs. Pseudo-scalar



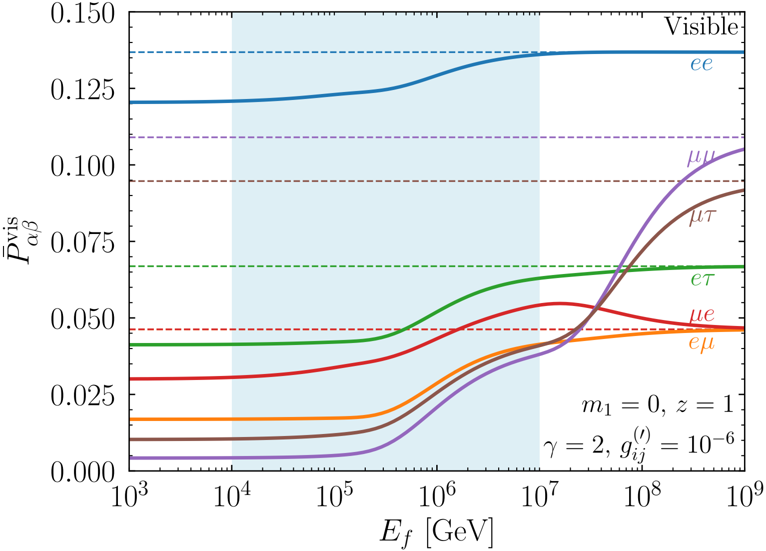
Results: Visible Decay: Neutrinos vs. Anti-neutrinos



Visible Decay for Different Redshift Evolution Functions



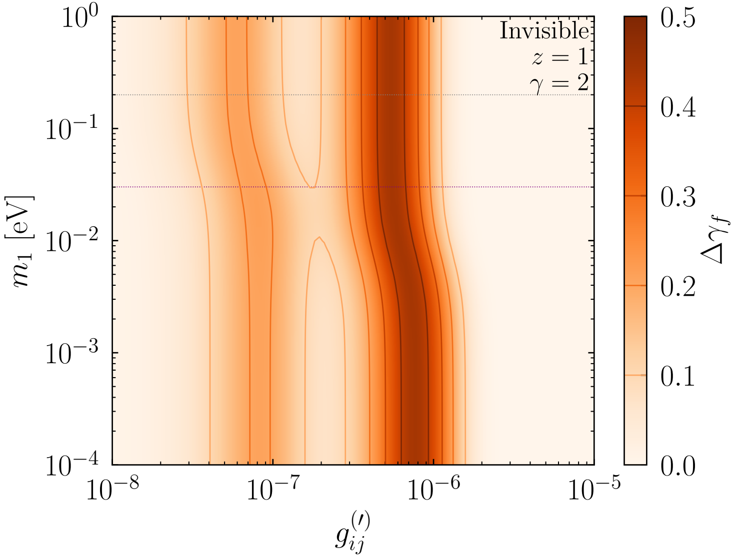
Results: Visible Decay: Flavors



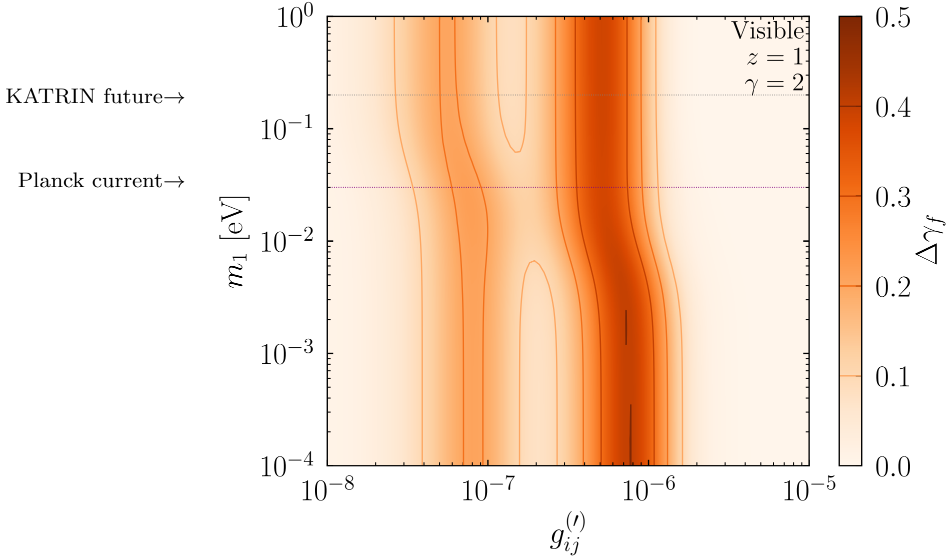
IceCube Track and Cascade Spectral Index Difference: Invisible Decay

KATRIN future→

Planck current→

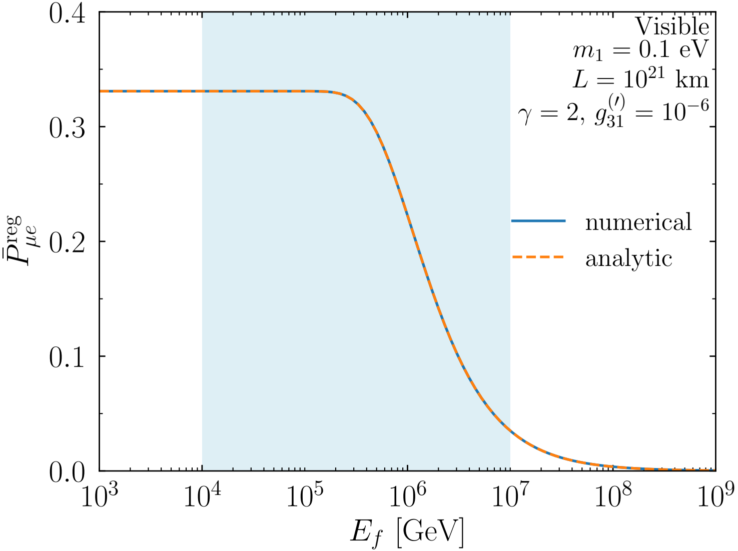


IceCube Track and Cascade Spectral Index Difference: Visible Decay



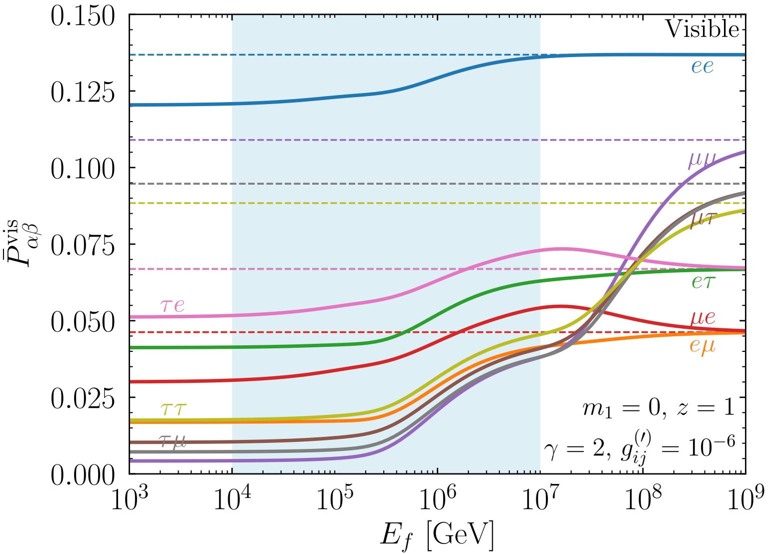
A. Abdullahi, PBD 2005.07200 (PRD)

Analytic Validation



A. Abdullahi, PBD 2005.07200 (PRD)

Results: Visible Decay: Flavors with ν_τ



IceCube Measures:

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

Some Track to Cascade with Decay Observations

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

max $\Delta\gamma$	$g_{21}^{(\prime)}$	$g_{31}^{(\prime)}$	$g_{32}^{(\prime)}$	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 ⇒ 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 ⇒ $\Delta\gamma\sim+0.2$
- Track and cascade spectra are fit over slightly different energy ranges ⇒ broken power law can help
- Energy misreconstruction (tracks could be susceptible to this)
- Dark matter?