Three-flavor oscillations and beyond the Standard Model physics with IceCube DeepCore

Finn Mayhew on behalf of the IceCube Collaboration

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Funding from NSF

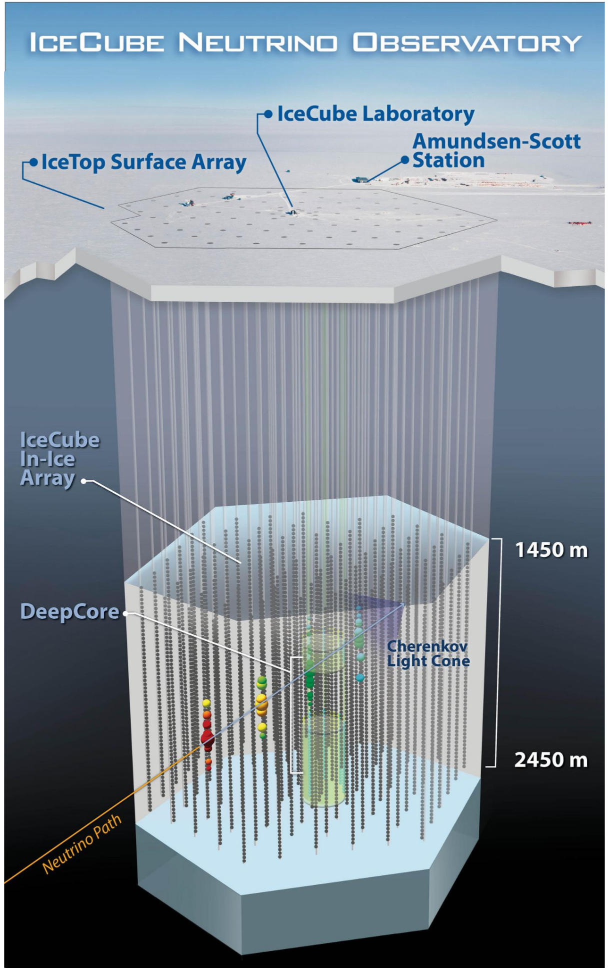
Michigan State University Founded 1855

IceCube

IceCube

- The IceCube Neutrino Observatory is a cubic-kilometer ice Cherenkov detector located at the south pole
- Consists of 5,160 photomultiplier tubes (PMTs) housed in digital optical modules (DOMs) buried 1.5-2.5 km deep under the glacial ice
- Operating continuously since 2011

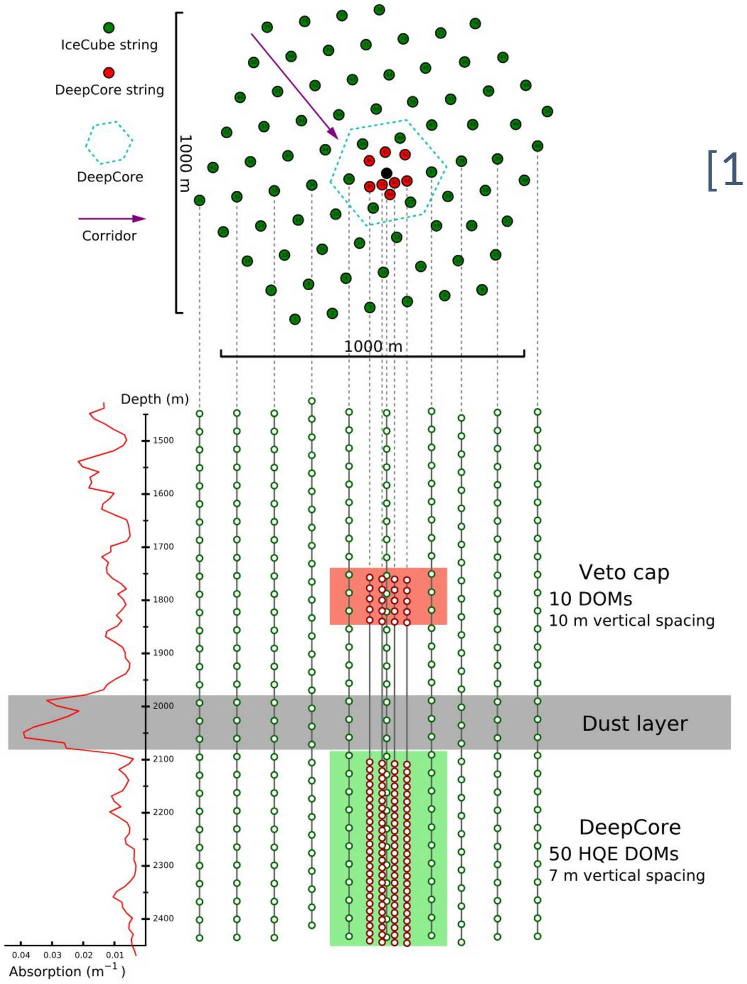
[1]



IceCube DeepCore

- Cosmic rays strike the atmosphere and produce neutrinos (mostly ν_μ's) that travel through the Earth and arrive at the detector from all upgoing directions ⇔ many baselines
- DeepCore consists of eight densely instrumented strings at the center of the array
- Gives the detector sensitivity to GeV-scale neutrinos => oscillation physics

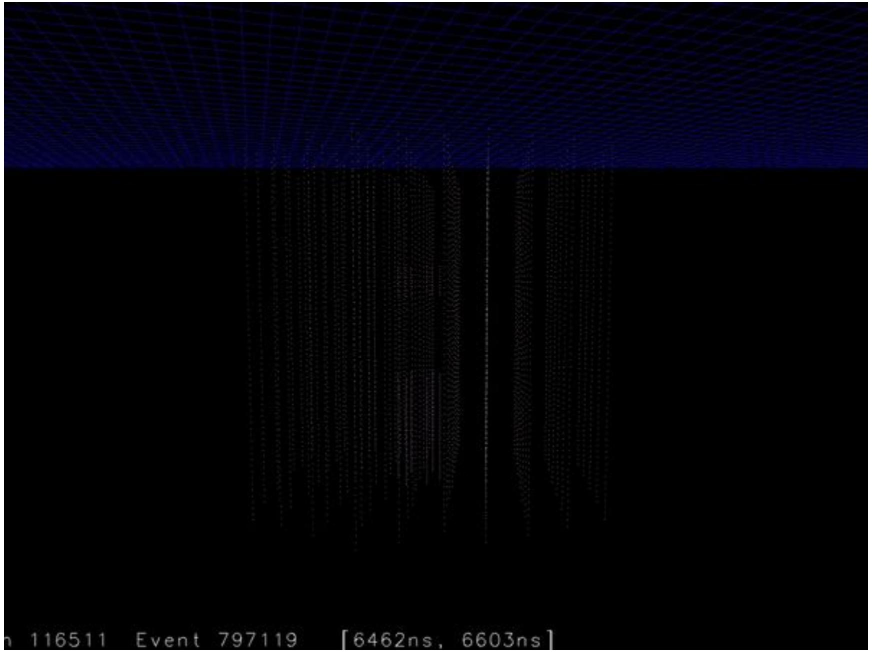
[2]



[1]

Events

- Amount of light deposited in the detector gives us a handle on neutrino energy
- Relative hit timing from DOMs allows reconstruction of neutrino direction
    - Direction parametrized as θ_{zenith}, direction's angle from vertical
    - Determines neutrino's baseline
- Topology/PID is the characteristic pattern of light in the detector
    - "Tracks" are characteristic of ν_μ CC interactions, all other interactions are "cascades"



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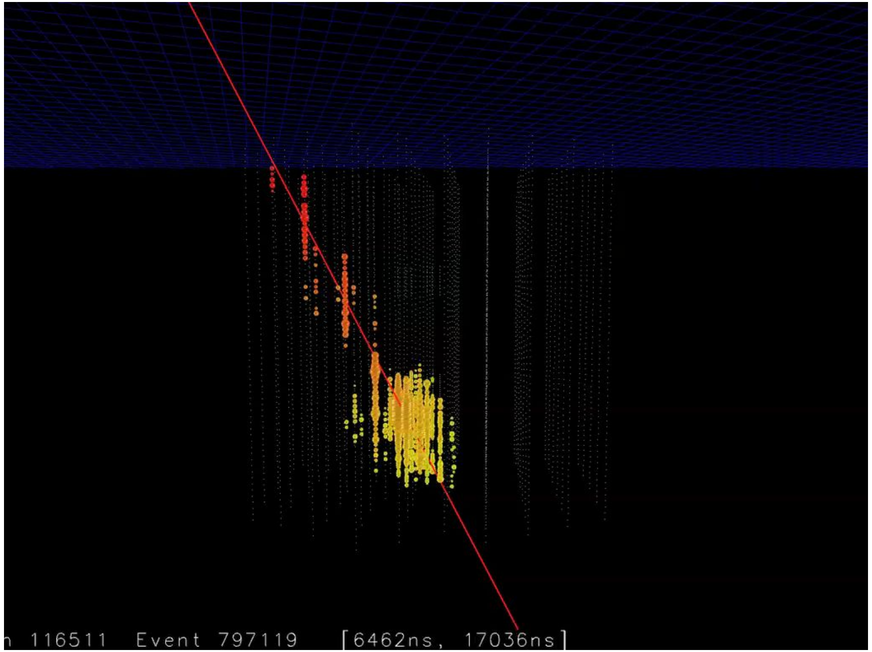
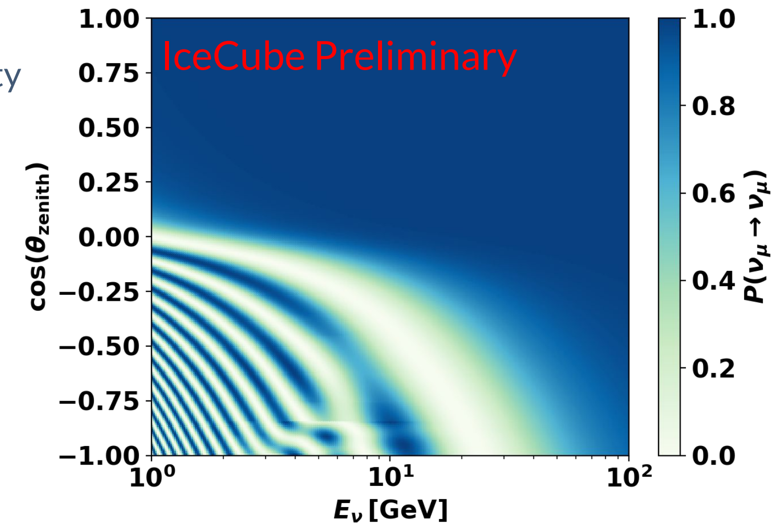
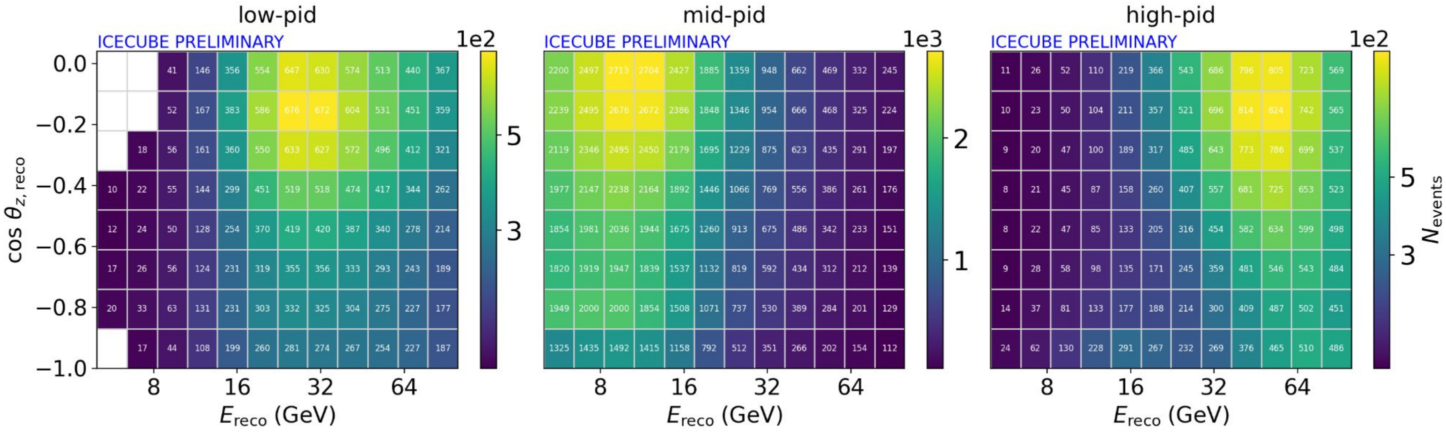


Fitting

- Binning: neutrino energy, $\cos(\theta_{zenith})$, topology
- For non-analytic systematics, generate Monte Carlo (MC) at different hypotheses and interpolate between predicted event counts
- Minimize a likelihood function (forward folding)

Atmospheric ν_μ survival probability



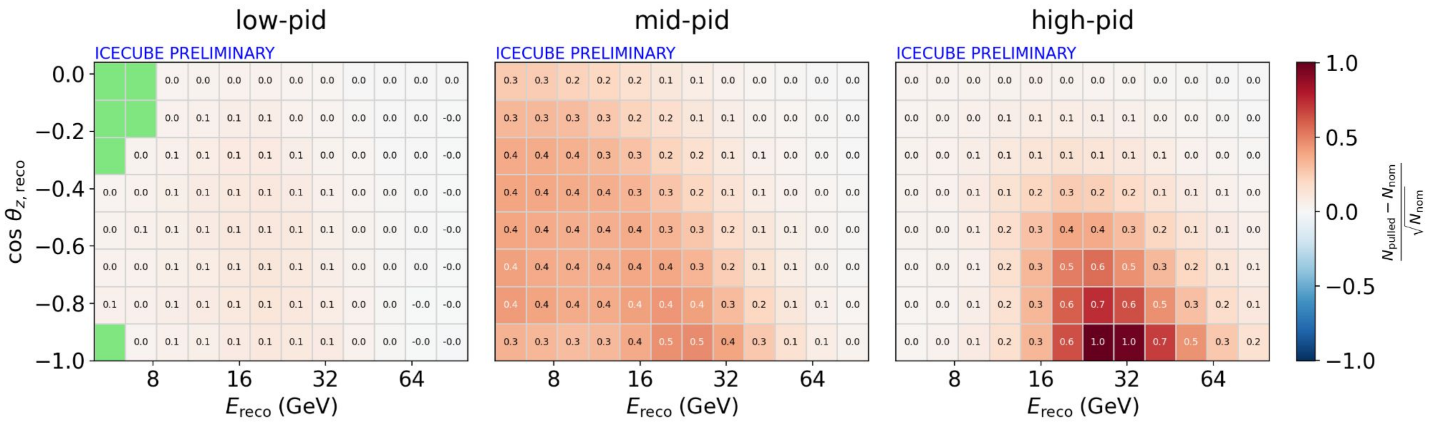


Nominal MC in the CNN-based ν_μ disappearance analysis (described shortly)

Fitting

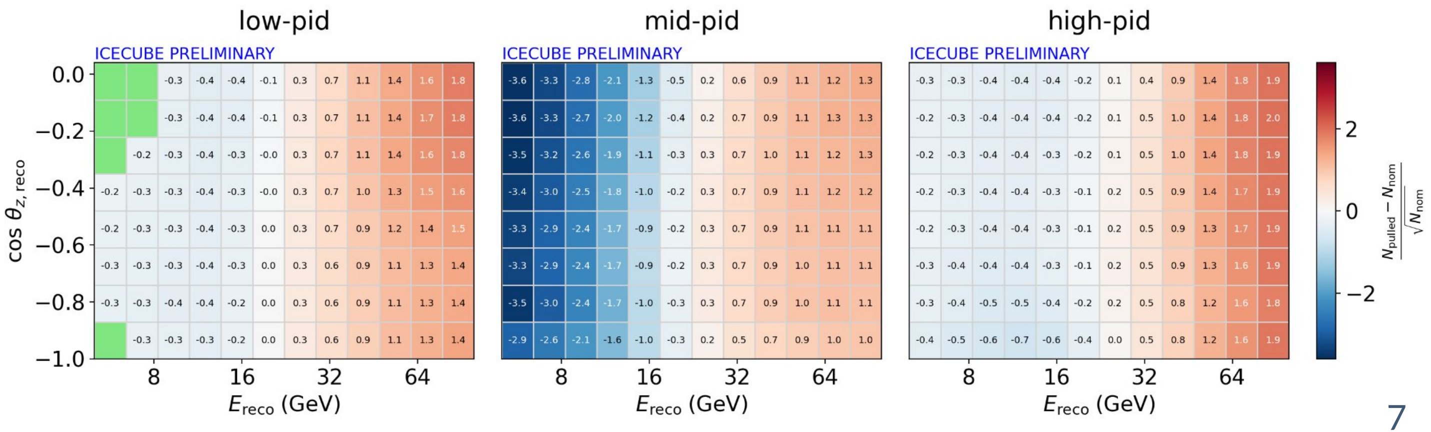
Physics signature example

Effect of pulling θ_{23} 5° from nominal in the CNN-based ν_μ disappearance analysis



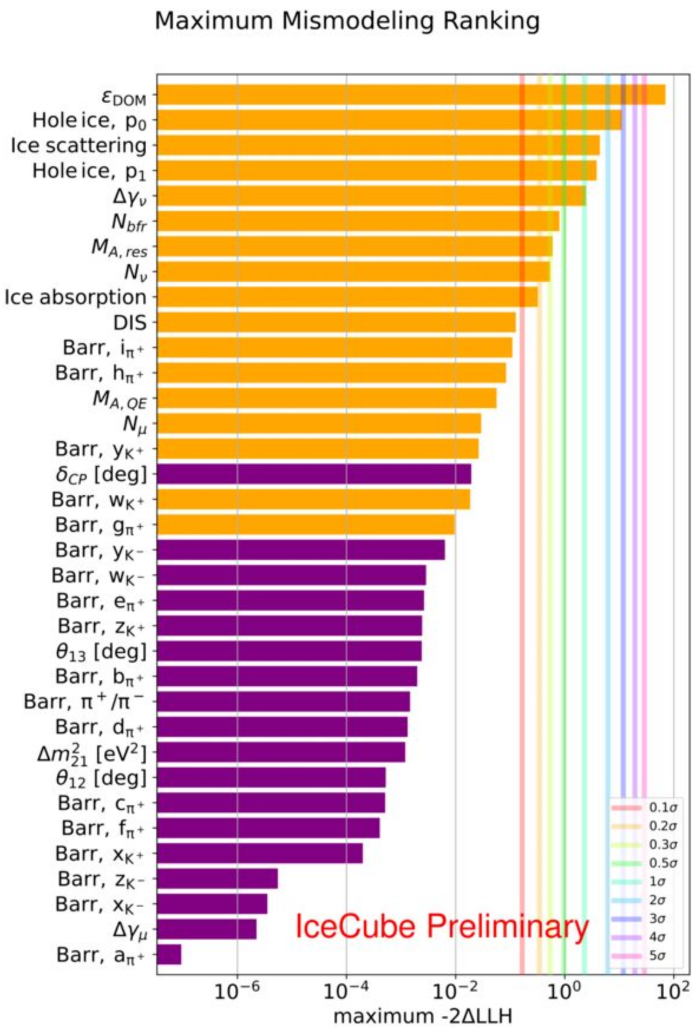
Systematic signature example

Effect of pulling the flux shape parameter $\Delta\gamma_\nu$ 0.1 (1σ)



Systematics

- Flux, cross section, detector response, ice properties
- Detector response and ice properties are the most impactful
- Orange systematics are left free in the CNN-based ν_μ disappearance fit and purple are held fixed

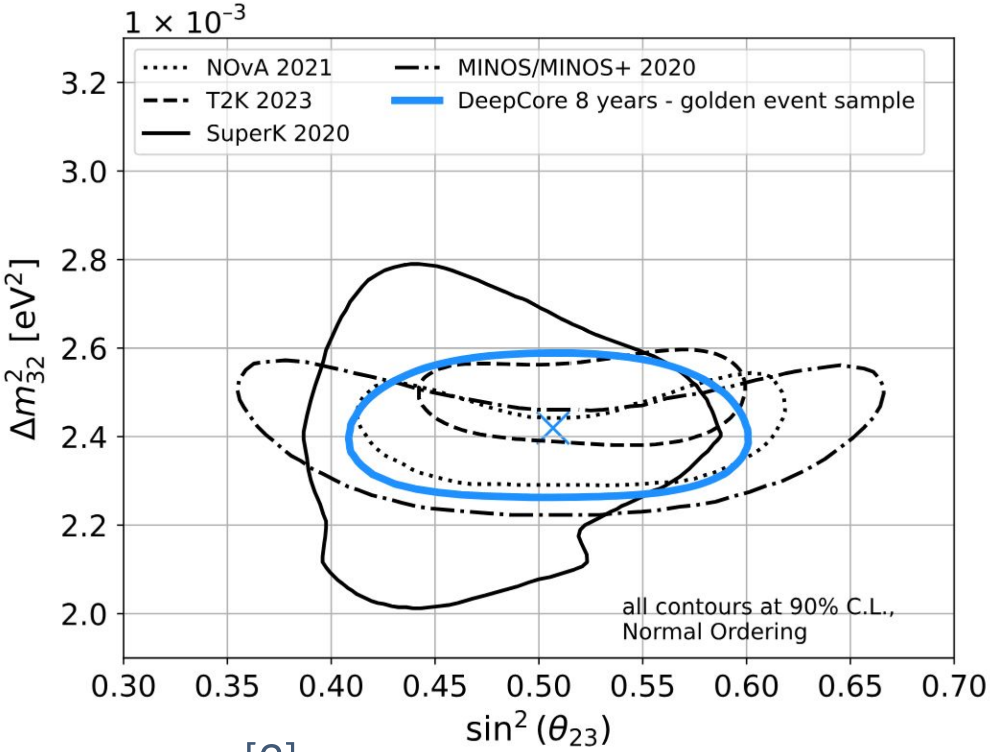


Systematics ranked, for the CNN-based ν_μ disappearance analysis, in order of the maximum difference in test statistic between fits where the physics parameters are free and fits where the physics parameters are fixed to the injected truth in the case that the systematic is held fixed at nominal in the fits while being off-nominal in the injected truth.

ν_μ disappearance with the golden event sample

- Oscillation parameters $\sin^2(\theta_{23})$ and Δm^2_{32} constrained
- Using an 8-year smaller sample (18k ν_μ CC events) optimized to contain mostly direct photons and high ν_μ CC purity
- Validates modern calibration and achievability of good data/MC agreement with modern selection and analysis tools

[3]



[3]

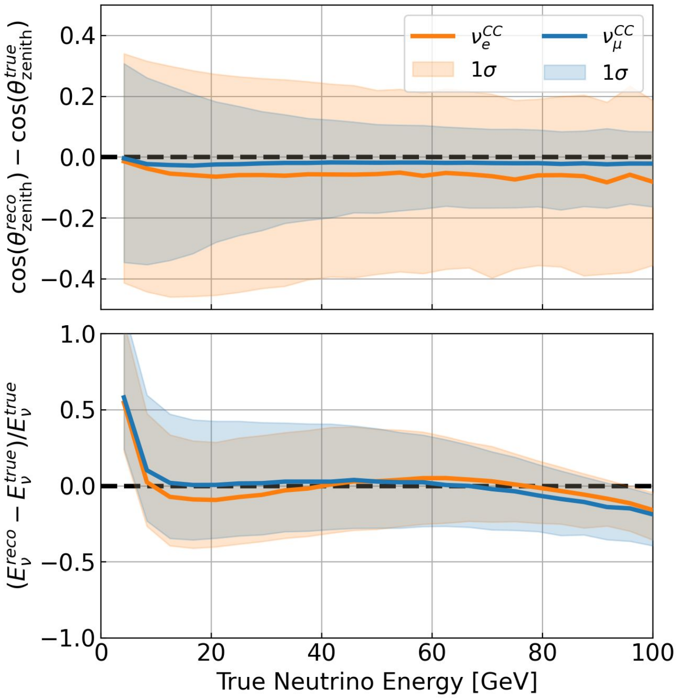
New convolutional neural network (CNN) reconstruction

- Allows for higher statistics (88k ν_μ CC events)
- Used in the most recent ν_μ disappearance analysis

[4]

	N_{events}(9.3yrs)	% of MC sample
ν_μ CC	88306	58.8
ν_e CC	35296	23.5
ν_τ CC	8772	5.8
ν NC	16981	11.3
atm. μ	917	0.6
Total MC	150272	-
data	150257	-

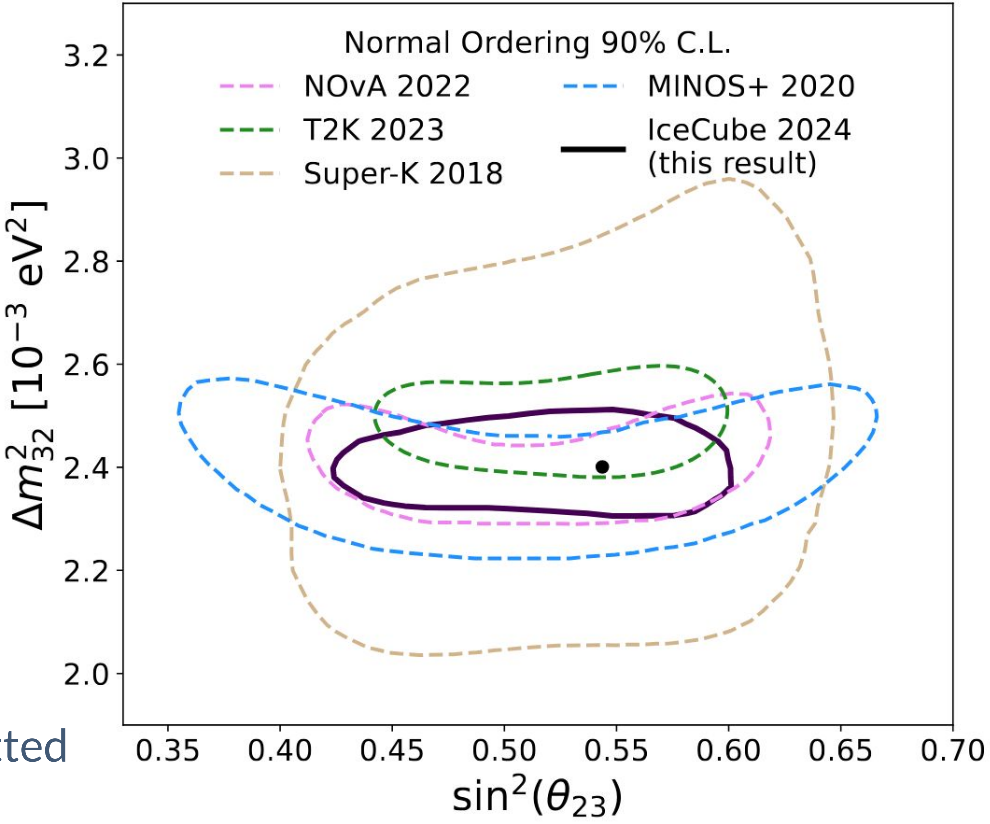
Resolution for neutrino energy and cos(θ_{zenith})



ν_μ disappearance with the CNN-based sample

- World-competitive constraints on oscillation parameters

[4]



[4] and submitted to PRL

Data vs MC by L/E for the CNN-based ν_μ disappearance analysis

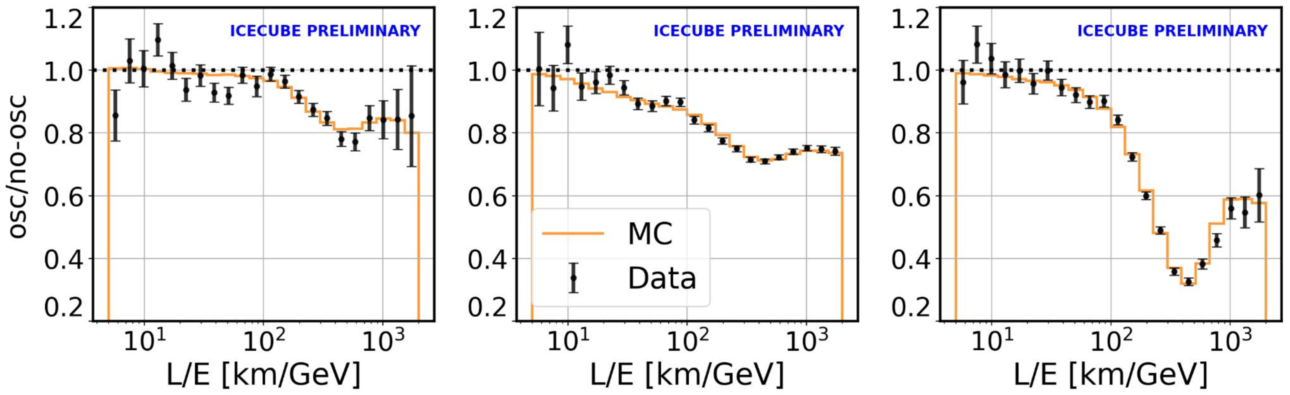
- Good data/MC agreement

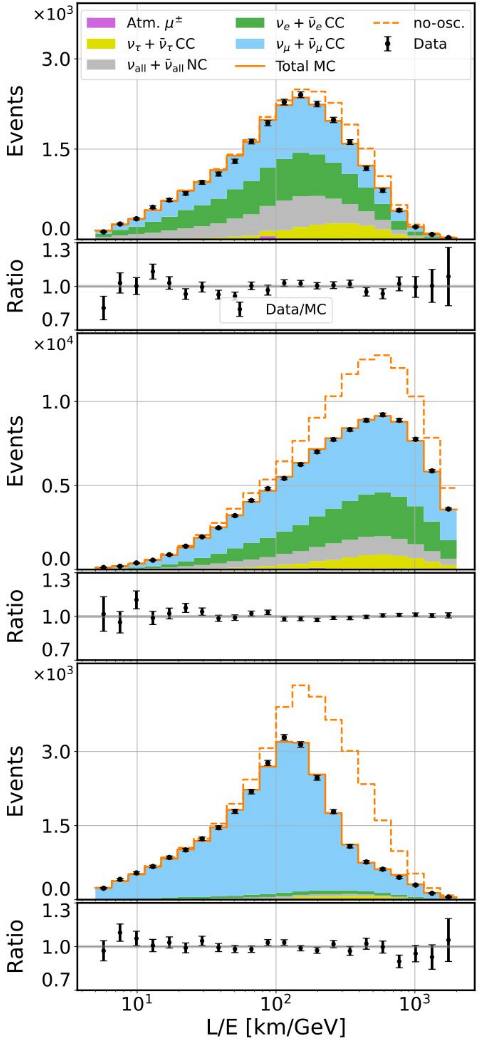
[4]

Left/top: cascade-like topology bin

Middle: mixed topology bin

Right/bottom: track-like topology bin





Light sterile neutrinos

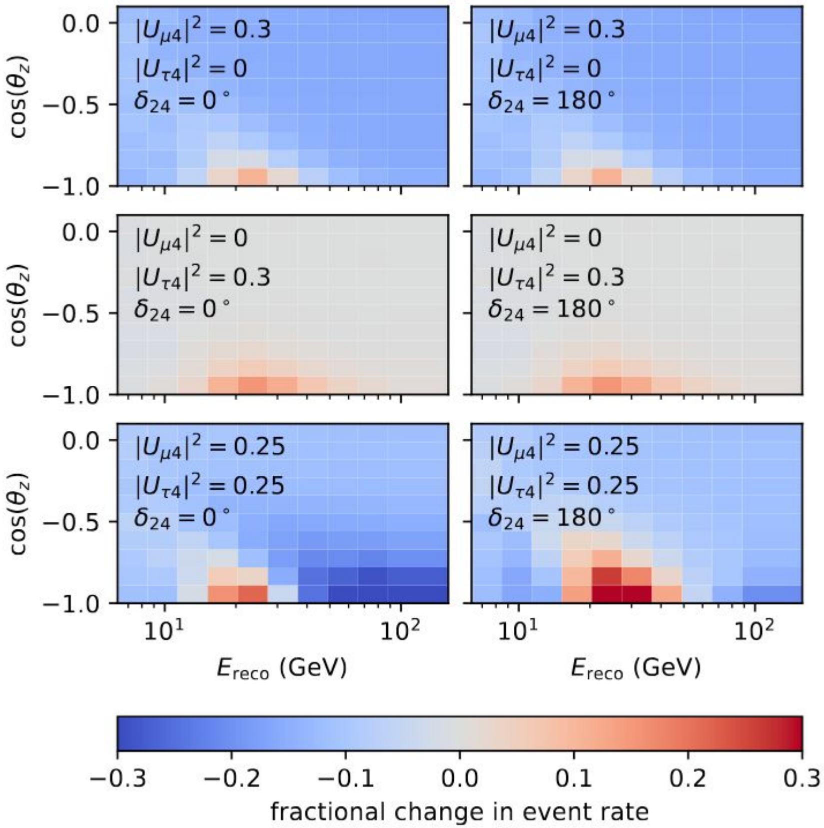
- Experimental anomalies can be explained by a noninteracting "sterile" neutrino with eV-scale mass splitting with respect to the other flavors
- Extension of the PMNS matrix:

$$U^{3+1}_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- Signal is less disappearance of ν_μ's that pass through Earth's core

[5]

Signal in track-like topology bin [5]

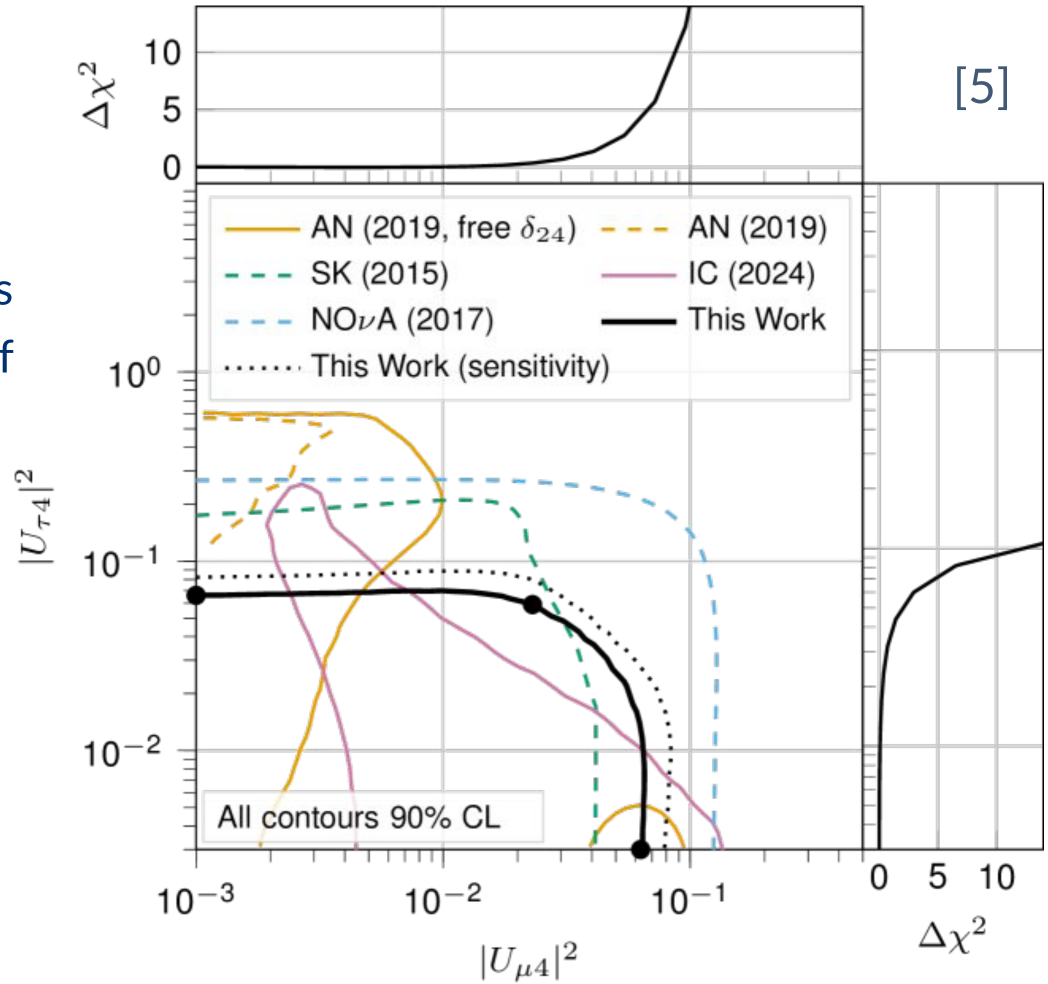


Light sterile neutrinos

[5]

- New result with world-competitive constraints
- Does not measure the value of the mass splitting due to sensitivity to average oscillation effects only

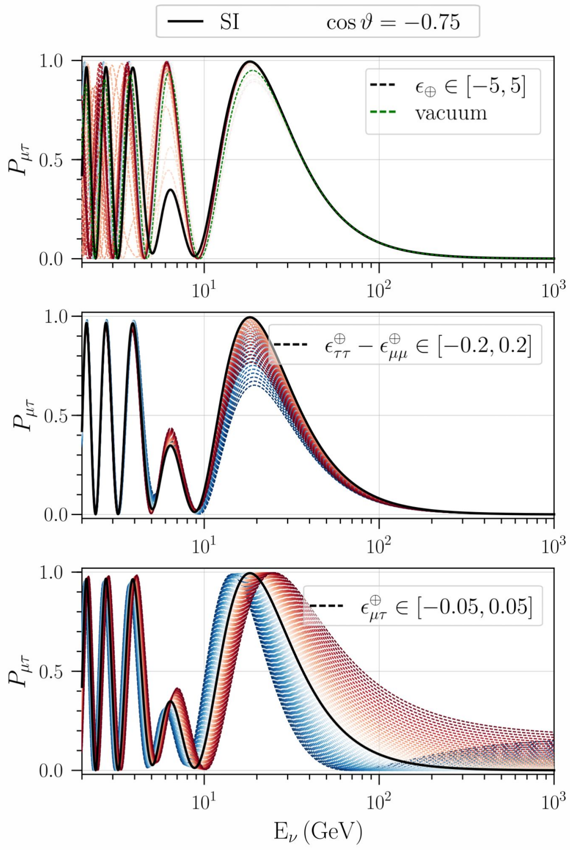
[5]



Non-standard interactions (NSI)

- Given that neutrino masses are so small, it's possible that they get their mass from a mechanism outside of the standard model
- This mechanism may imply the existence of a new boson that interacts with neutrinos
- Neutrinos traveling through the Earth would then interact with the Earth through this boson, affecting their oscillations

[6]



[6]

Effect of variations of three NSI parameters on neutrino oscillation

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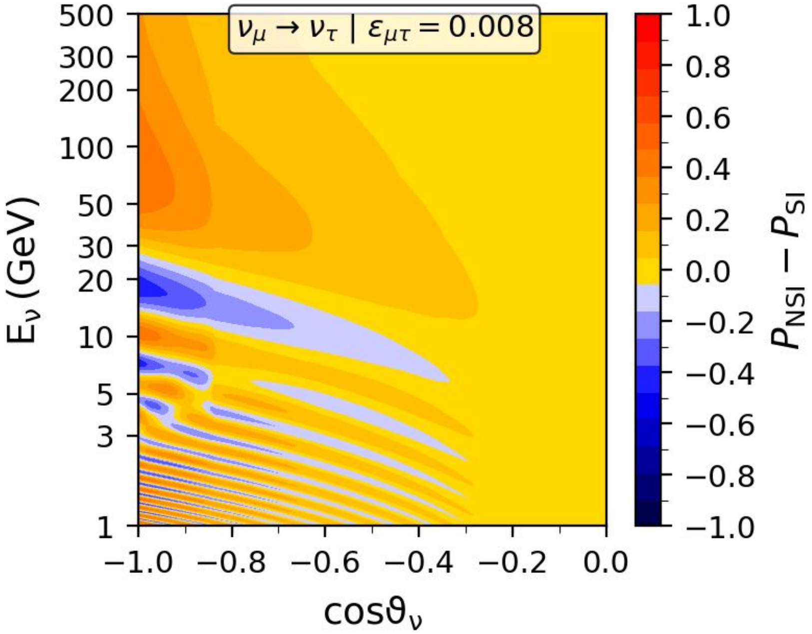


Difference in atmospheric $\nu_\mu \to \nu_\tau$ probabilities between the standard interactions case and an NSI case

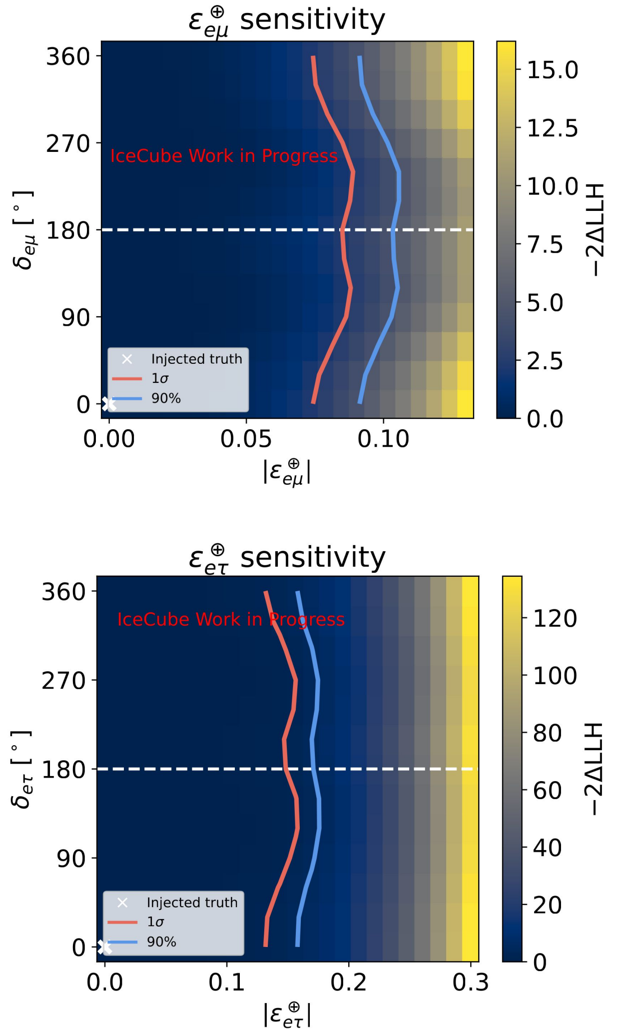
NSI, standard parametrization

- Parametrize possible effects generally as perturbations on the matter Hamiltonian (in the flavor basis):

$$\mathcal{H}_{\text{mat}} = V_{\text{CC}}(x) \begin{pmatrix} 1 + \epsilon_{ee}^{\oplus} - \epsilon_{\mu\mu}^{\oplus} & \epsilon_{e\mu}^{\oplus} & \epsilon_{e\tau}^{\oplus} \\ \epsilon_{e\mu}^{\oplus *} & 0 & \epsilon_{\mu\tau}^{\oplus} \\ \epsilon_{e\tau}^{\oplus *} & \epsilon_{\mu\tau}^{\oplus *} & \epsilon_{\tau\tau}^{\oplus} - \epsilon_{\mu\mu}^{\oplus} \end{pmatrix}$$

- ϵ's are fit one by one, assuming all others are zero
- An analysis with 9.28 years of data is ongoing

[8]



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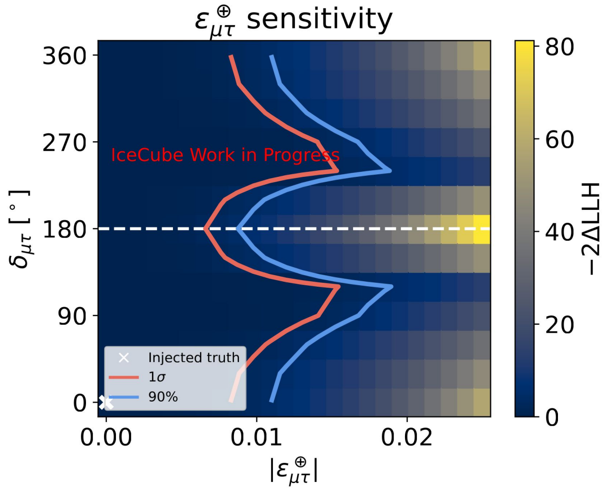

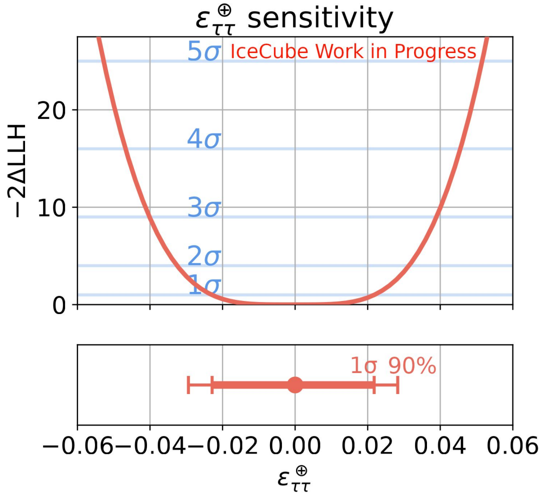

NSI, generalized matter potential parametrization

- Alternative parametrization:

$$H_{\text{mat}}(x) = Q_{\text{rel}} U_{\text{mat}} D_{\text{mat}}(x) U^\dagger_{\text{mat}} Q^\dagger_{\text{rel}} \ ,$$

$$D_{\text{mat}}(x) = V_{\text{CC}}(x)\text{diag}(\epsilon_\oplus, \epsilon'_\oplus, 0) \ ,$$

$$U_{\text{mat}} = R_{12}(\varphi_{12}) R_{13}(\varphi_{13}) \tilde{R}_{23}(\varphi_{23}, \delta_{\text{NS}}) \ ,$$

$$Q_{\text{rel}} = \text{diag}\left(e^{i\alpha_1}, e^{i\alpha_2}, e^{-i(\alpha_1+\alpha_2)}\right) \ .$$

- Assuming no CP violation and that the experiment has most sensitivity to ν_μ disappearance, reduce to involving only ε, ϕ_{12}, and ϕ_{13}, which are fit simultaneously
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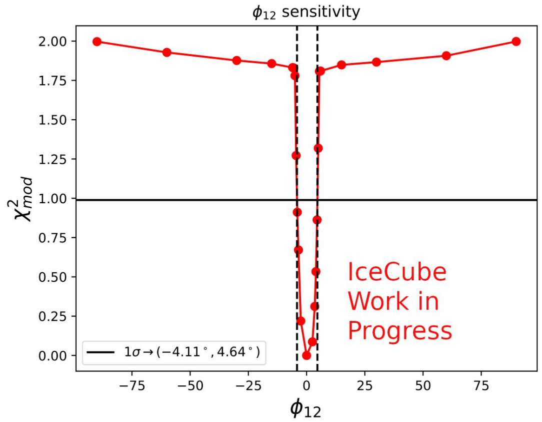

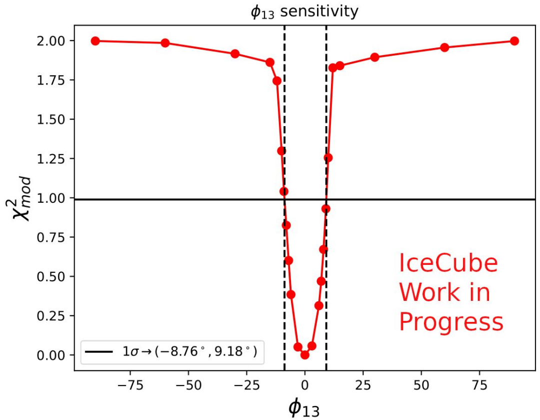

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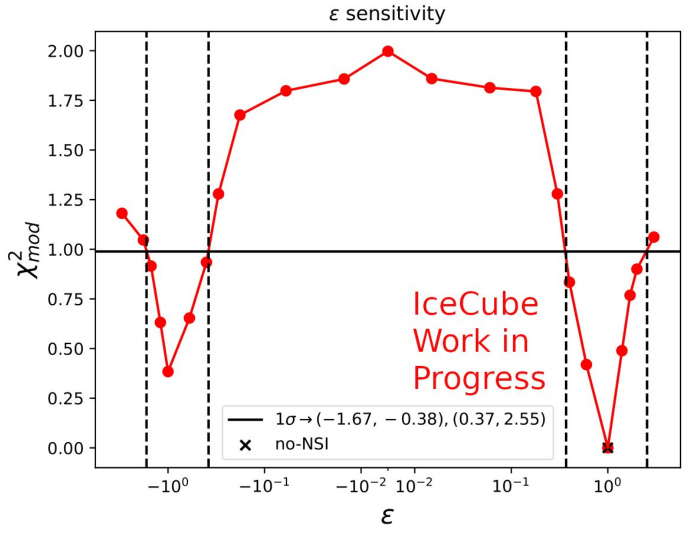


[8]

Preview: probing the interior of the Earth

Three analyses described more fully in the backup:

1. Quantify DeepCore's ability to see the Earth through oscillations
2. Verify that the Earth has a layered structure
   - Result: Earth's uniformity excluded at 1.4σ
3. Use neutrino data to improve the constraints on the densities of Earth's layers placed by Earth's mass and moment of inertia

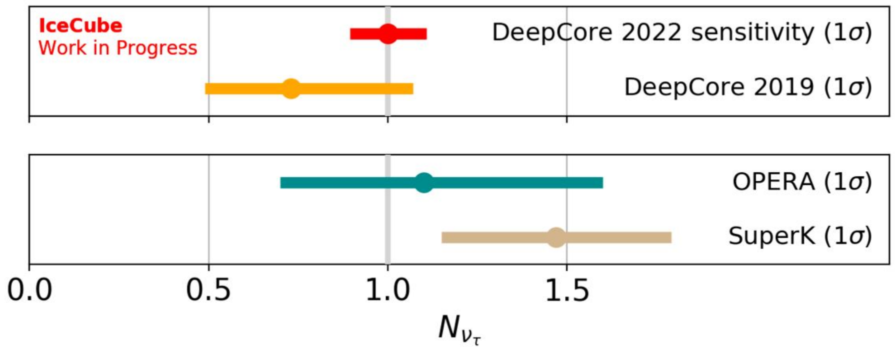
Conclusion

- IceCube DeepCore probes a variety of physics questions
- Many world-competitive results have come or are coming soon, stay tuned!
- NMO results coming soon
- Results in backup: **decoherence**, **heavy neutral leptons**, **layered structure of the Earth**
- Sensitivities in backup: $\boldsymbol{\nu_\tau}$ **appearance**, **long-range interactions**, **invisible decay**, **Earth's matter effect**, **mass of the Earth**, **density of layers of the Earth**
- See Josh Peterson's talk tomorrow for IceCube's projected sensitivities with the coming Upgrade!

Backup

ν_τ appearance

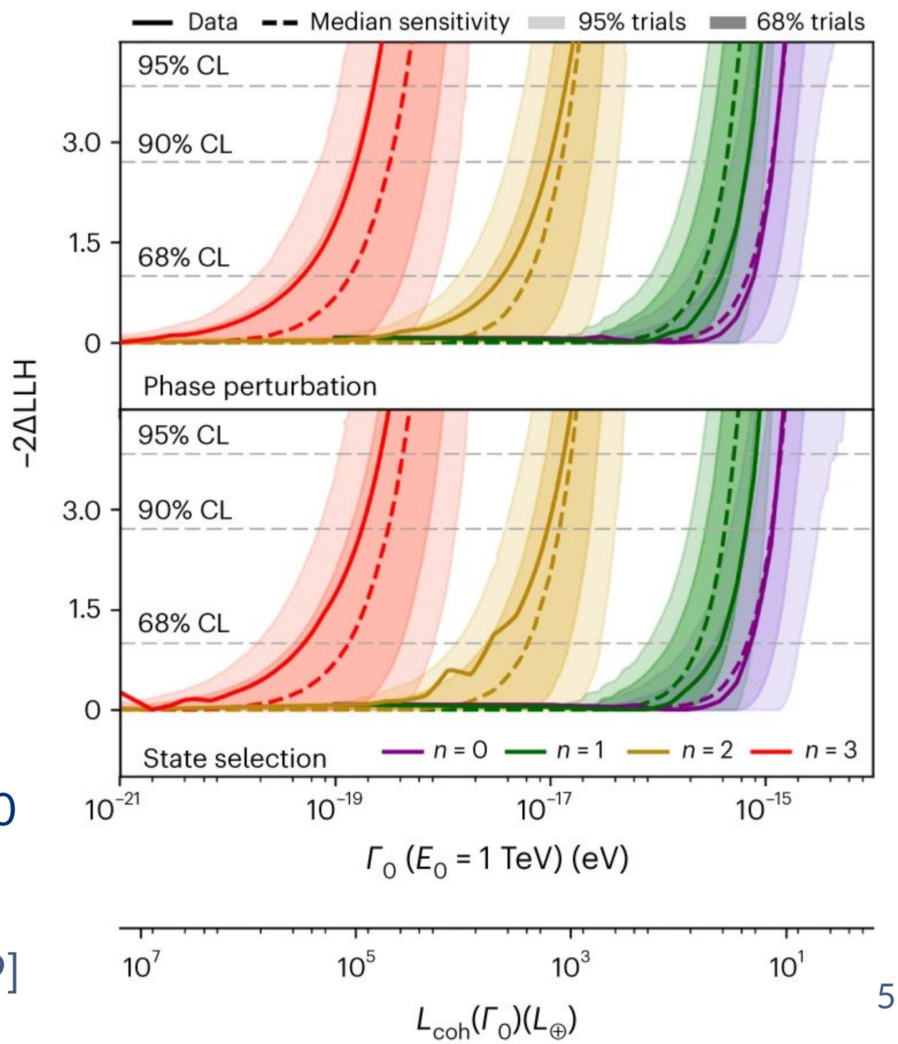
- Ongoing analysis to measure the appearance of ν_τ's following atmospheric ν_μ oscillation
  - Standard oscillations case is $N_{\nu\tau} = 1$
- Signal is an excess of cascade-like events over the no-ν_τ hypothesis
- Uses a high-statistics maximum likelihood reconstructed sample
  - An analysis using the CNN-based sample is also ongoing
- Projected to have world-leading sensitivity



Decoherence

- If the metric of spacetime has a quantum description, its fluctuations would introduce quantum decoherence in neutrinos that pass through them
- This would impact oscillations at long baselines and high energies
- Signal is less flavor transition and non-unitary flavor evolution
- Previous limits improved by a factor of 30

[9]



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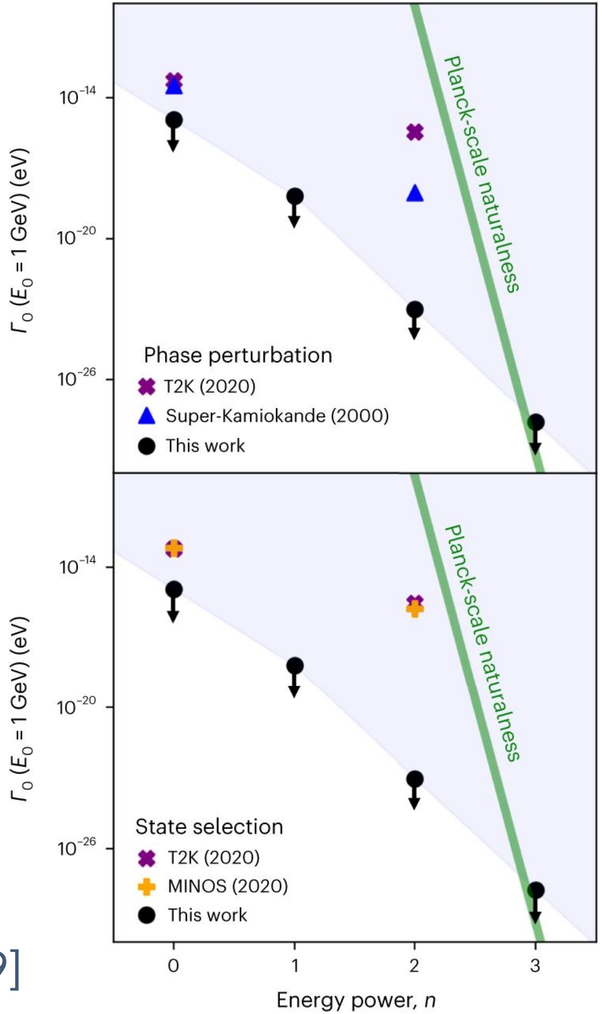
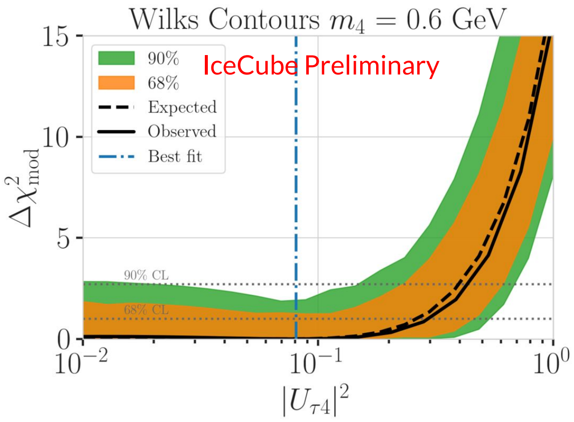


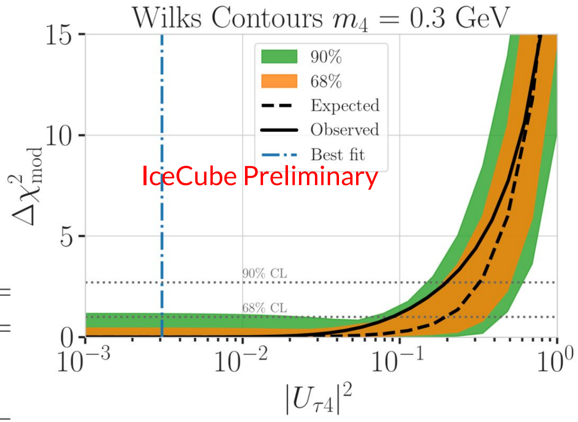
[9]

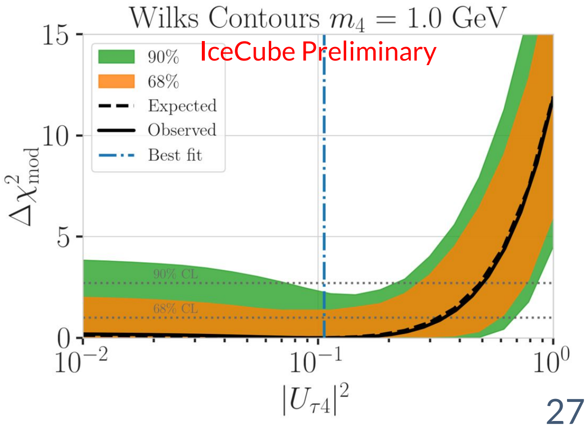
Heavy neutral leptons (HNLs)

- Search for steriles produced via ν_τ upscattering
- Theoretical signature is a low-energy double cascade
  - This analysis searched for an excess of single cascades because identifying double cascades is not feasible with current tools
- Constraints placed for three HNL masses (m_4)
- Proof of concept for HNL searches in IceCube

[10]



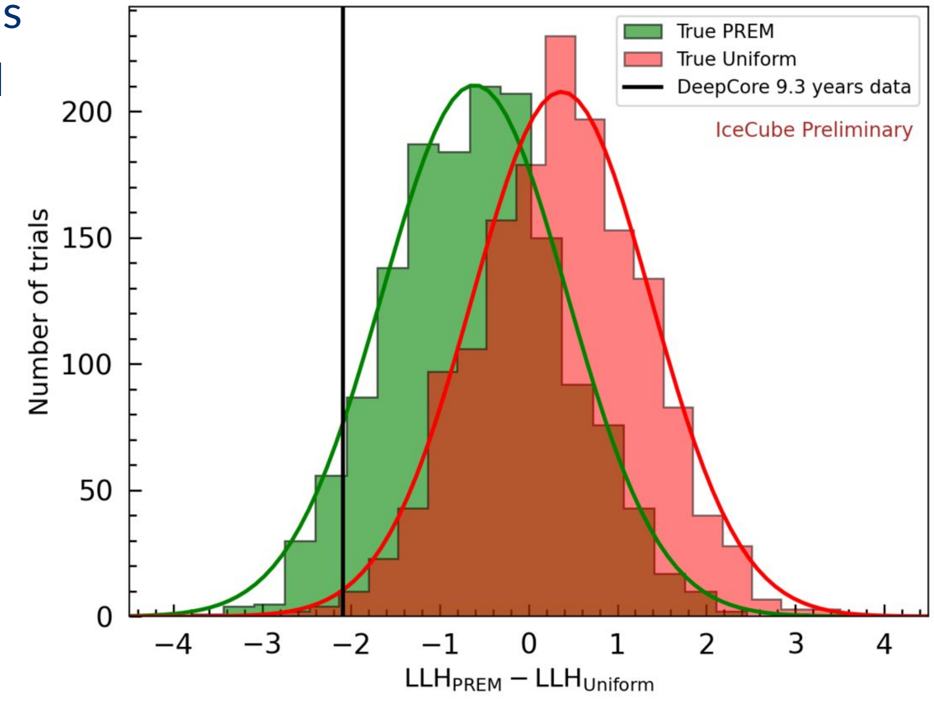




HNL mass	$\lvert U_{\tau4}\rvert^2$	68 % CL	90 % CL	NH p-value
0.3 GeV	0.003	0.09	0.19	0.97
0.6 GeV	0.080	0.21	0.36	0.79
1.0 GeV	0.106	0.24	0.40	0.63

Layered structure of the Earth

- Gravitational and seismic studies give us the Preliminary Reference Earth Model (PREM) for Earth's radial density [11]
- Earth's matter effect is modified by its layered density structure
- Comparing the PREM hypothesis and the hypothesis that the Earth is uniformly dense, DeepCore rejects the uniform hypothesis at 1.4σ
- See [12] for more info



[13]

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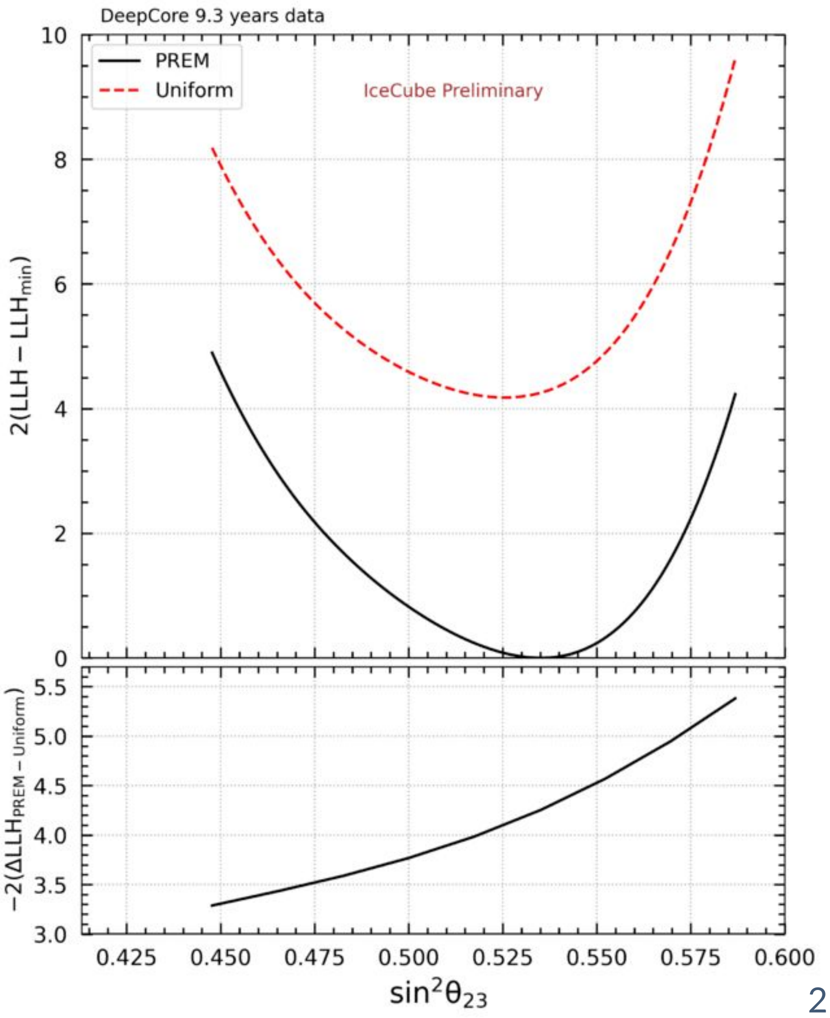
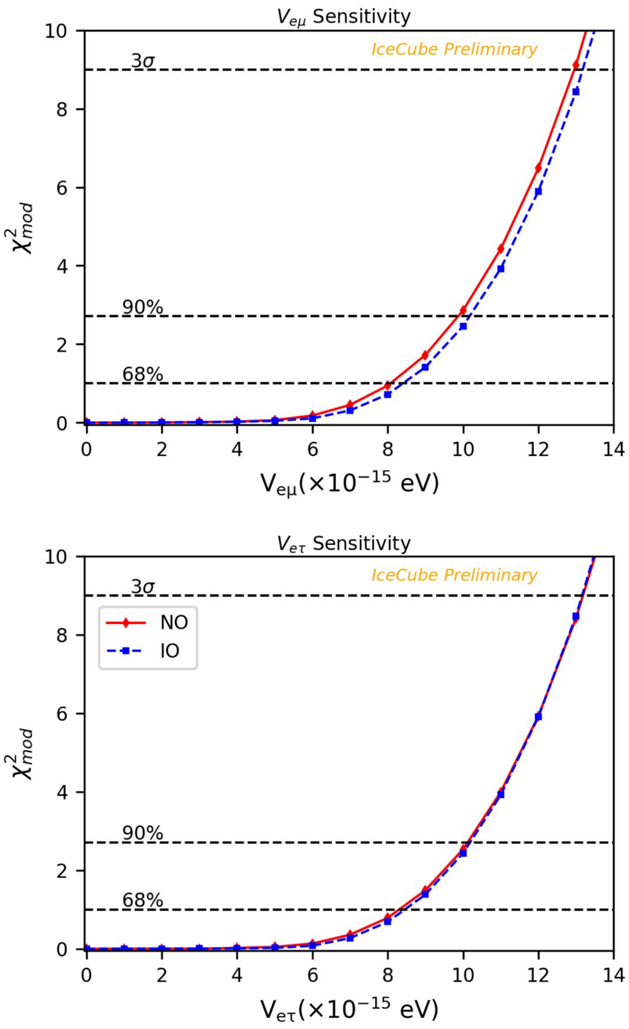


Long-range interactions (LRI)

- If there is an undiscovered light boson that interacts differently with the different neutrino flavors and has a large interaction range, large quantities of matter (like the sun) could affect the oscillations of neutrinos
- Ongoing analysis to constrain the strengths of these interactions

[14]



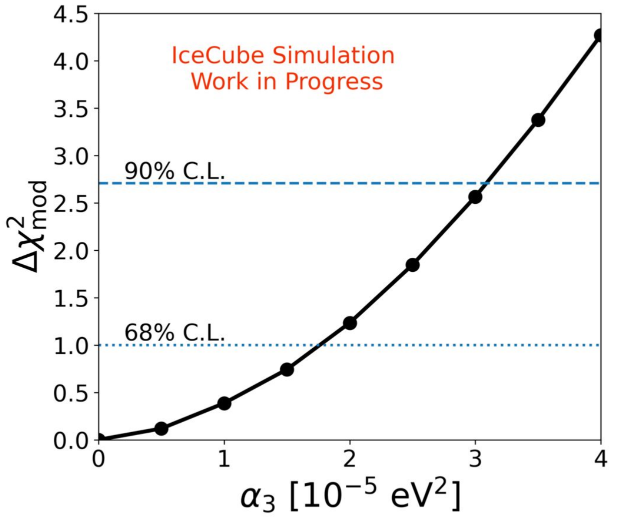
Invisible neutrino decay

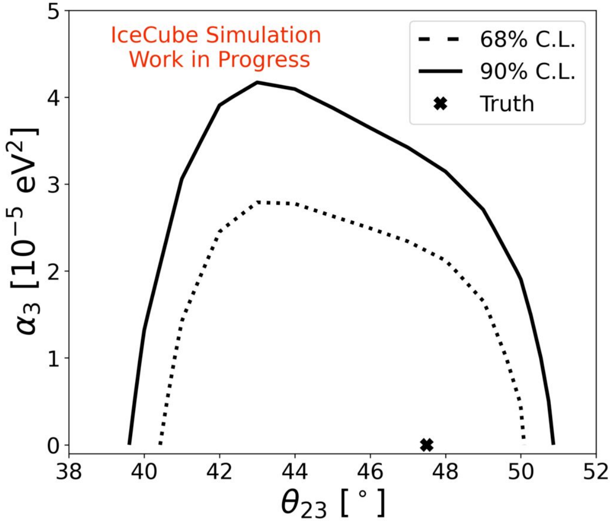
- Ongoing analysis to constrain the possibility of neutrinos decaying into sterile neutrinos that do not mix with the known neutrinos
- Considering the case that ν_3 decays into a sterile
- Modify the Hamiltonian to include $\alpha_3 = m_3/\tau_3$:

$$H_{\text{Total}} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + U\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & -i\alpha_3\end{pmatrix}U^\dagger\right] + \begin{pmatrix}V & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

$$V = \pm\sqrt{2}N_e G_F \qquad \alpha_3 = \mathrm{m}_3/\tau_3$$

[15]

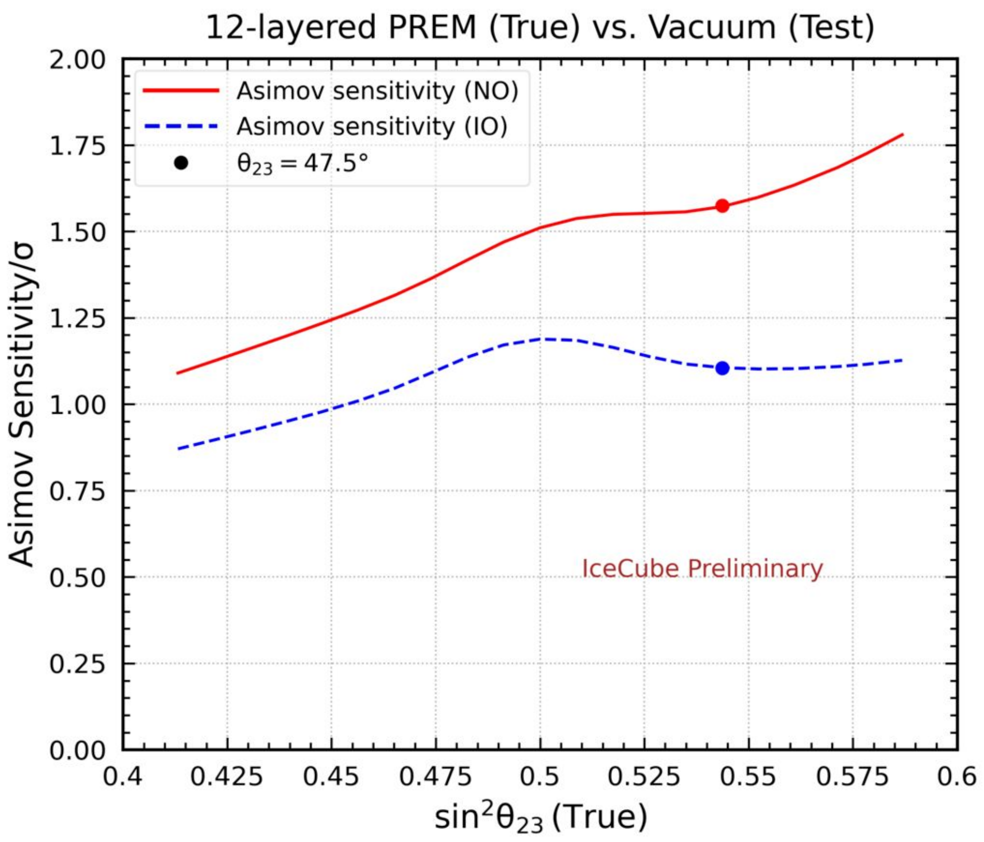




Earth's matter effect

- Ongoing analysis to validate Earth's matter effect
- Compares the PREM hypothesis against the vacuum hypothesis
- Will quantify DeepCore's ability to see Earth's matter effect in oscillations data

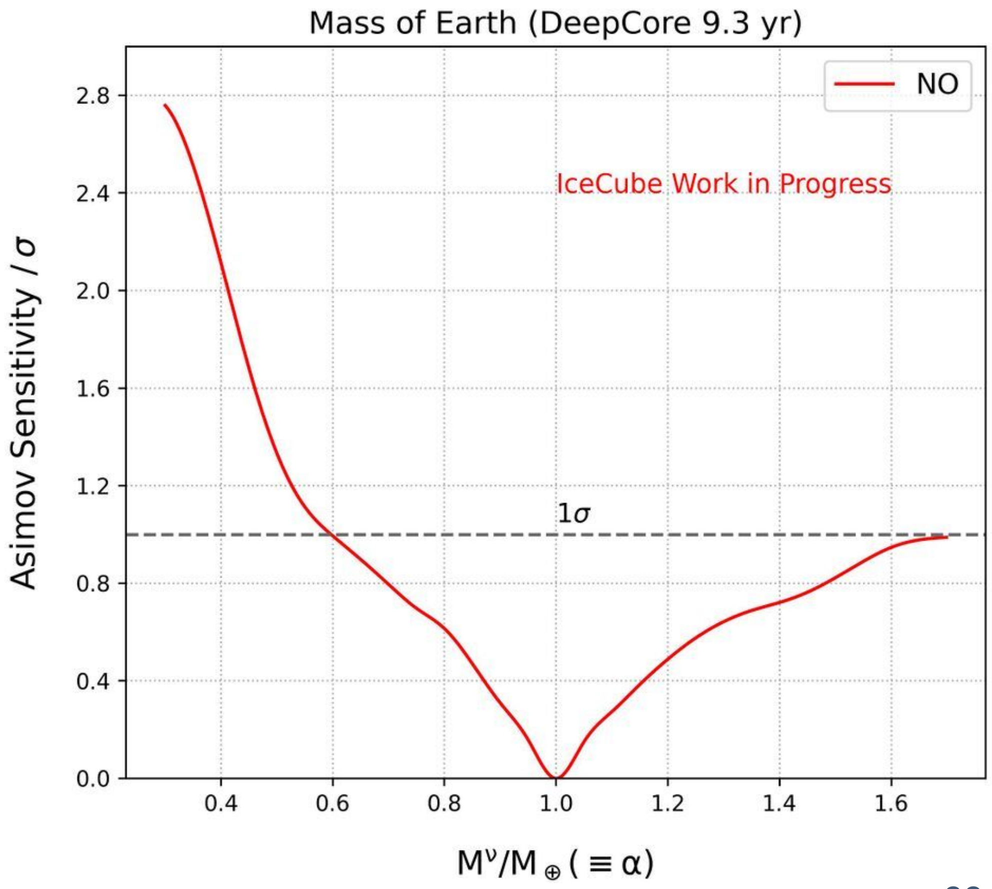
[13]



Mass of the Earth

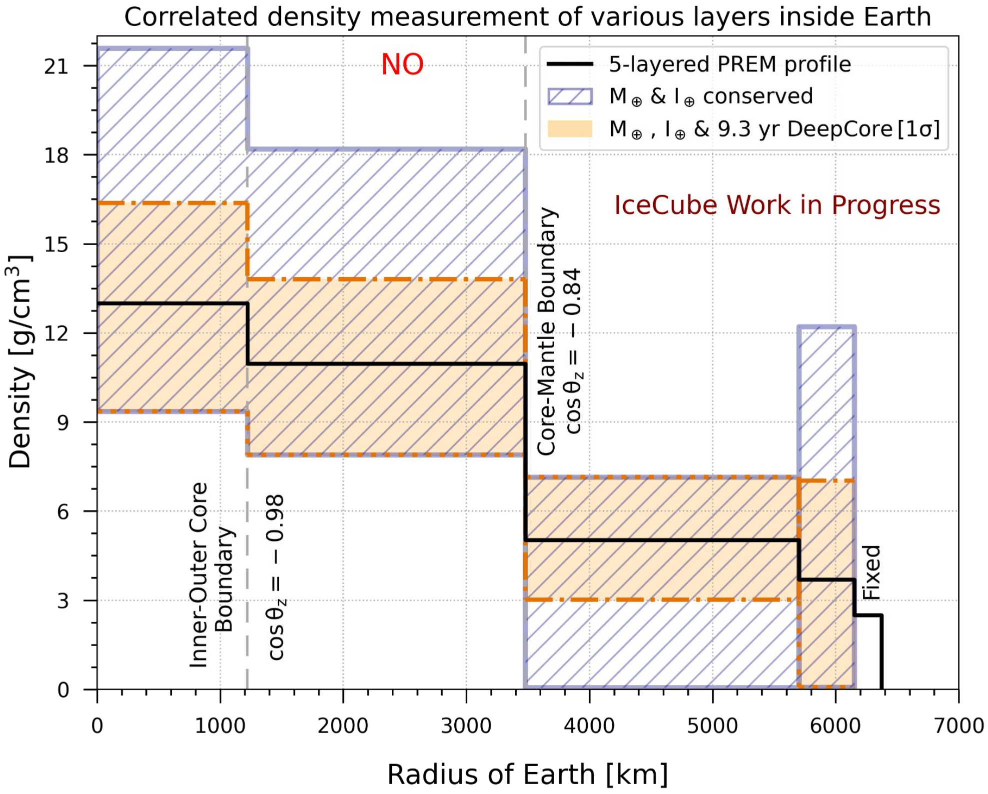
- Ongoing analysis to measure the mass of the Earth
- Compares the PREM hypothesis against a PREM hypothesis with all densities scaled
- M^{ν} is Earth's mass measured from neutrino oscillations, $M_{\oplus}$ is Earth's mass from gravitational measurements

[13]



Density of layers of the Earth

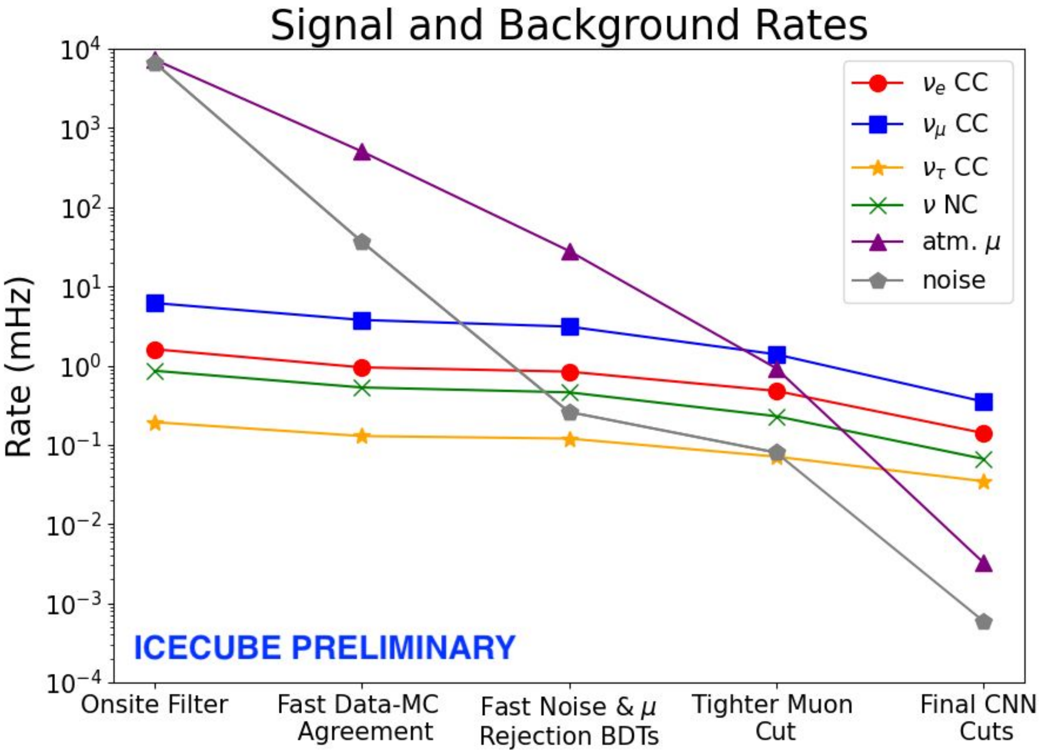
- Ongoing analysis to study how neutrino data can improve upon constraints on the densities of layers of the Earth placed by Earth's mass and moment of inertia
- Compares the 5-layer PREM hypothesis against a 5-layer PREM hypothesis with the layer densities scaled while holding mass and moment of inertia constant



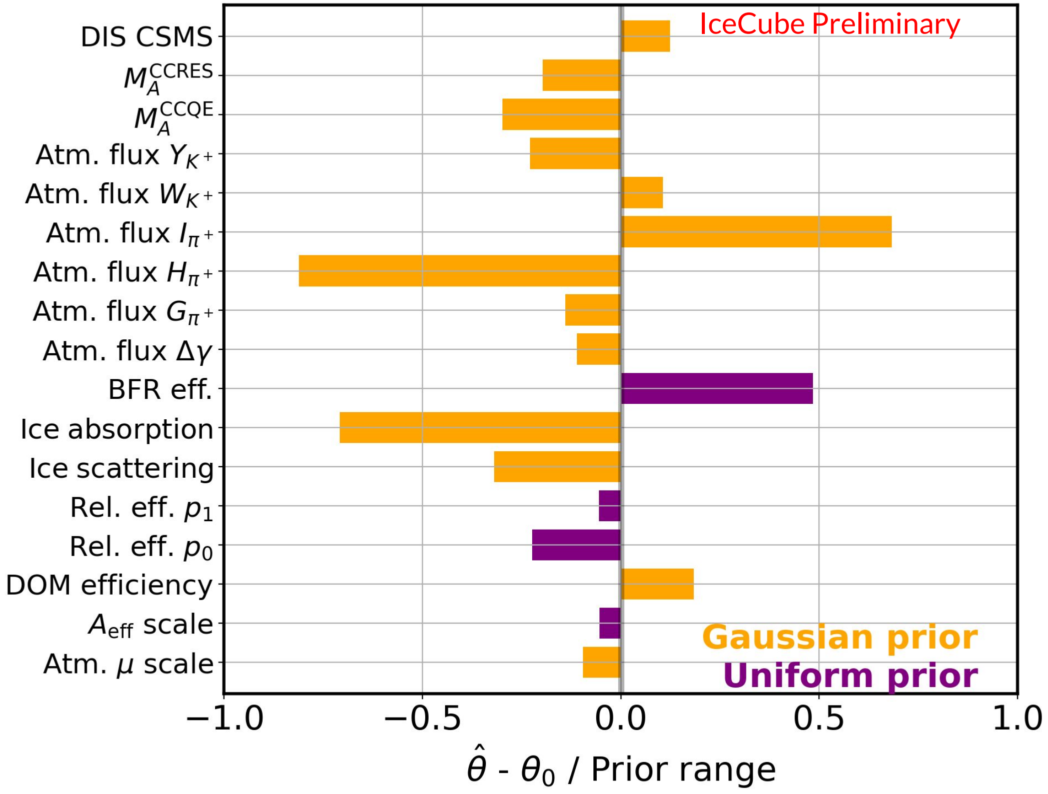
[13]

CNN-based sample ν_μ rates

MC rates by particle and interaction type as a function of event selection stages from the CNN-based ν_μ disappearance analysis

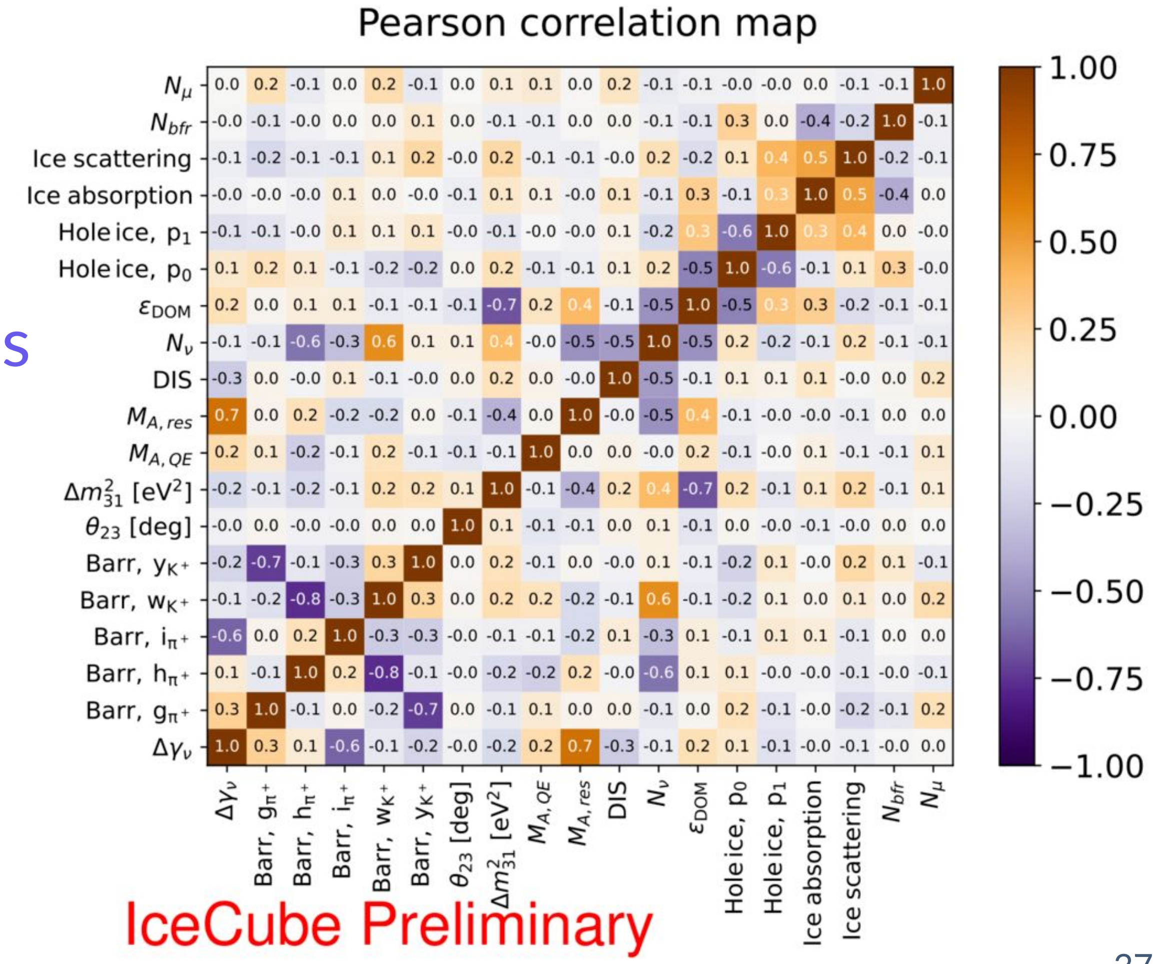


Parameter pulls in CNN-based ν_μ disappearance analysis



[4]

Correlation between systematics in CNN-based ν_μ disappearance analysis



Nuisance parameters left free in the CNN-based ν_μ disappearance analysis

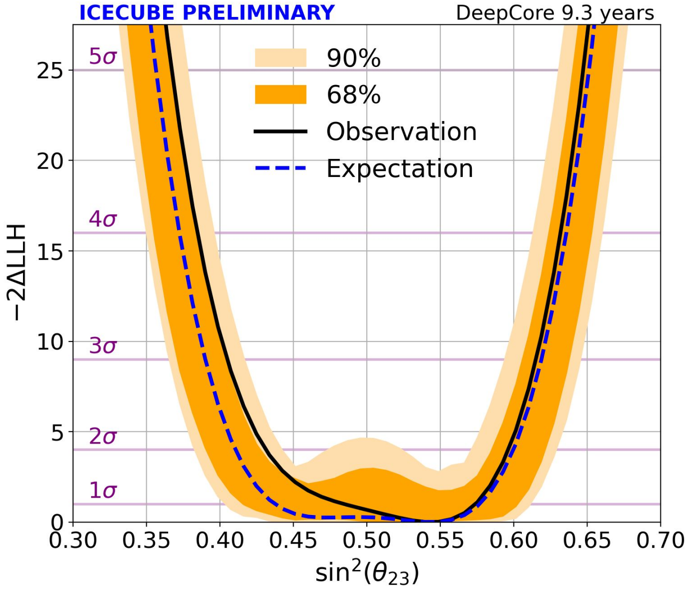
The systematic uncertainty parameters included as nuisance parameters in the data analysis, along with their associated priors. The priors on parameters can either be Gaussian (in which case the value corresponding to ±1σ is listed) or Uniform (in which case the allowed range is listed). [4]

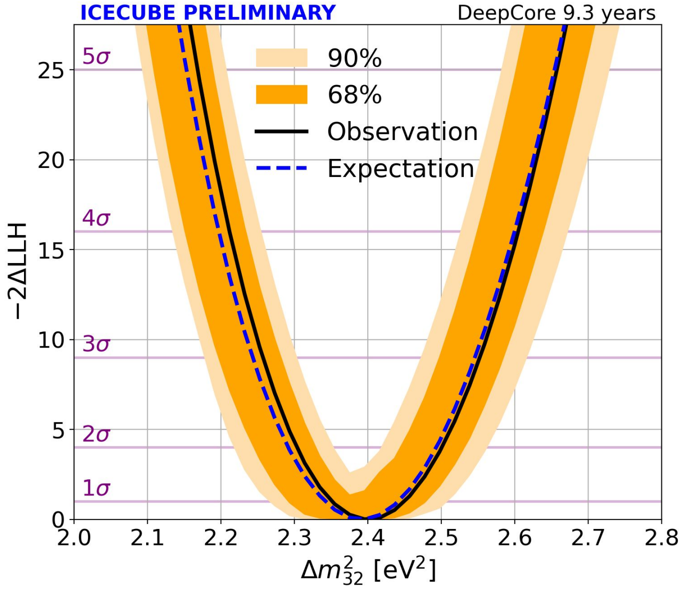
[4]

Parameter	Nominal	Prior width	Fit value	Pull (σ)
Detector:				
DOM efficiency	+0%	±10%	+1.8%	0.18
Ice absorption	+0%	±5%	−3.5%	-0.71
Ice scattering	+5%	±10%	+1.8%	-0.32
Rel. eff. p_0	0.10	[-0.6, 0.5]	-0.14	-
Rel. eff. p_1	-0.05	[-0.2, 0.2]	-0.07	-
BFR efficiency	0.0	[0, 1]	0.48	-
Atm. flux:				
$\Delta\gamma_\nu$	0.0	±0.1	-0.011	-0.11
$\Delta\pi^\pm$ yields I	0.0	±61%	+42%	0.68
$\Delta\pi^\pm$ yields G	0.0	±30%	−4.2%	-0.14
$\Delta\pi^\pm$ yields H	0.0	±15%	−12%	-0.81
ΔK^+ yields W	0.0	±40%	+4.2%	0.11
ΔK^+ yields Y	0.0	±30%	−6.9%	-0.23
Cross-section:				
M_A^{CCQE}	0.99 GeV	$^{+25\%}_{-15\%}$	−4.5%	-0.30
M_A^{CCRES}	1.12 GeV	±20%	−3.9%	-0.20
DIS CSMS	0.0	±1.0	0.12	0.12
Normalization:				
A_{eff} scale	+0%	[−90%, +100%]	−10%	-
Atm. muons:				
Atm. μ scale	+0%	±40%	−3.8%	-0.10

Brazil bands for the CNN-based ν_μ disappearance analysis

Generated by injecting parameters at the best-fit point, applying statistical fluctuations to get pseudotrials, and running a scan of the test statistics over each physics parameter for each pseudotrial. The band shows the 68% and 90% regions of the test-statistic distribution at each scan point.





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