UNIVERSITY OF TEXAS ARLINGTON

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

νRES

OVERVIEW AND RESULTS

THE 8-YEAR HIGH ENERGY NON-STANDARD INTERACTIONS ANALYSIS

TeVPA 2021 Parallel 10/28/21

GRANT K. PARKER
grant.parker@mavs.uta.edu

The IceCube Neutrino Observatory

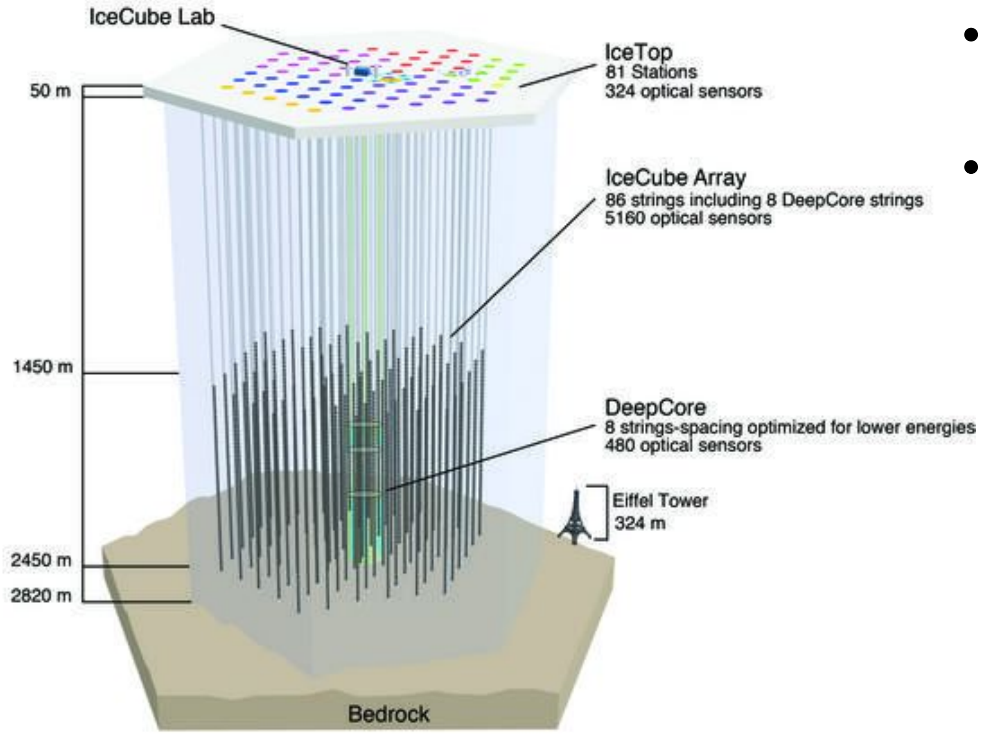


Figure: The IceCube neutrino observatory. DeepCore is an additional collection of strings that allow for signals as low as 5 GeV.

- World's largest-volume neutrino detector and telescope, located under the ice at the South Pole
- Detection mechanism:
  - Neutrino interaction with ice produces charged products.
  - Interaction products have sufficient energy to generate Cherenkov radiation along their trajectory.
  - Collected light allows for neutrino direction and energy reconstruction.
- Two event types: tracks (linear trajectories) and cascades (blob-like signal).
- **DeepCore** is collection of specialized center strings that lower the event energy threshold to ~5 GeV

Non-Standard Interactions

NSI arise in accounting for mass effects on neutrino oscillations

- Standard Model (SM) cannot account for neutrino masses
- If neutrino masses are Majorana, they can be added as a dim(5) Weinberg operator
- In many theories, a dim(6) operator accompanies the dim(5) operator, from which NSI arise
- In a basic model, coupling strength $\varepsilon \sim g_X^2 m_W^2 / m_X^2$, so for natural values of *g*, the mediator > 1TeV

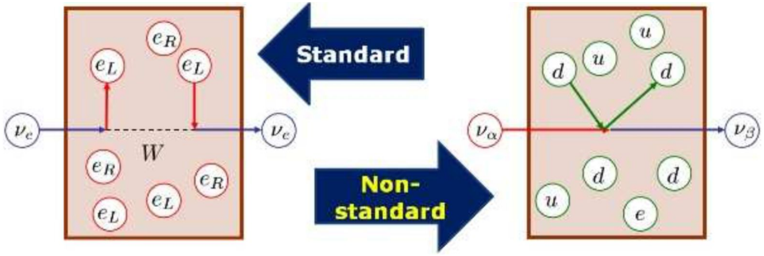


Figure: Diagramed neutrino-matter interactions for SM and NSI [Ohlsonn 2013 arXiv 1209.2710].

Neutrino oscillations are only sensitive to neutral-current NSI:

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P f) \quad \Rightarrow \quad \varepsilon_{\alpha\beta} = \sum_{f,P} \varepsilon_{\alpha\beta}^{fP} \frac{N_f}{N_e} \quad \Rightarrow \quad H_{\text{mat}} = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1 + \varepsilon_{ee}(x) & \varepsilon_{e\mu}(x) & \varepsilon_{e\tau}(x) \\ \varepsilon_{e\mu}^*(x) & \varepsilon_{\mu\mu}(x) & \varepsilon_{\mu\tau}(x) \\ \varepsilon_{e\tau}^*(x) & \varepsilon_{\mu\tau}^*(x) & \varepsilon_{\tau\tau}(x) \end{pmatrix}$$

Generalize the coefficients by summing over fermion and chiral contributions

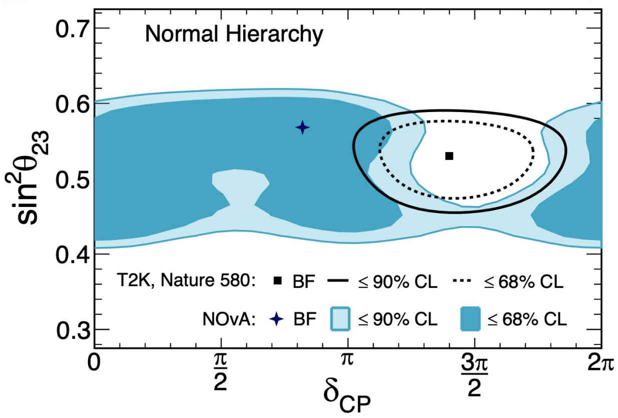
Add the NSI matrix to the standard matter Hamiltonian

Now we have a general parameterization. Oscillations experiments are not sensitive to diagonal parameters in this model.

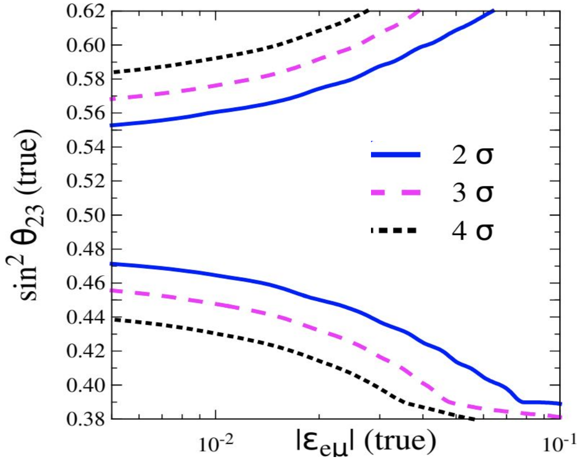
Non-Standard Interactions

If NSI exist:

- NSI **fit better** than the SM to some measurements of data, suggesting the alleviation of tensions
  - **Example Tension (Top Right)**: Constraints on $\boldsymbol{\delta}_{CP}$ from T2K and NOvA [A. Himmel for the NOvA Collaboration (plenary)]



- However, NSI also introduce **degeneracies** to parameters such as $\boldsymbol{\theta}_{23}$ and $\boldsymbol{\delta}_{CP}$
  - **Example Degeneracy (Bottom Right)**: Loss of $\boldsymbol{\theta}_{23}$ octant sensitivity as a function of $|\varepsilon_{e\mu}|$ [Agarwalla et. al. 2016 arXiv:1607.01745]

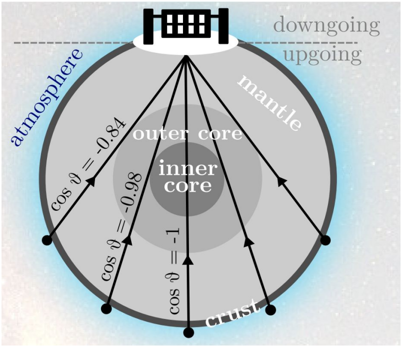


Therefore, NSI are very compelling to study!

NSI in IceCube

NSI are a modification to the matter potential:

- IceCube atmospheric neutrinos
  - Various energies + various matter baselines (right) = optimal sample for BSM oscillations searches through **muon track appearance and disappearance**
- The rate of detected atmospheric neutrinos far exceeds backgrounds and other signal types (bottom)



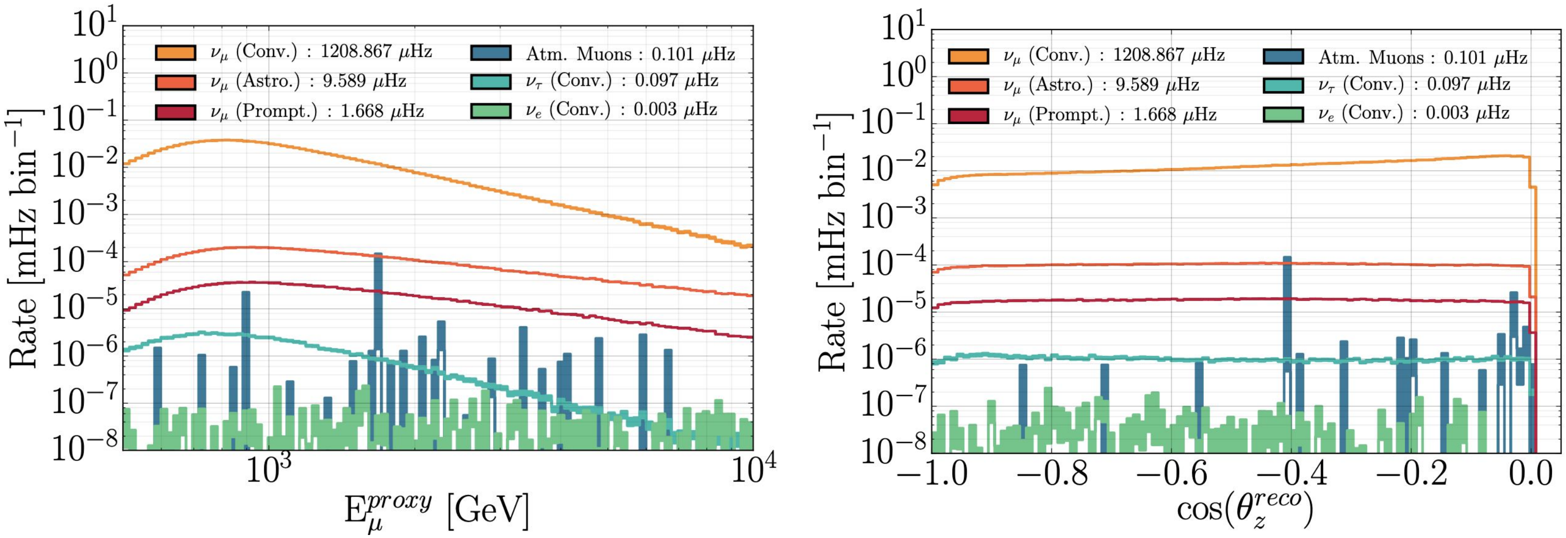


Figure: (Top) Model of neutrinos reaching IceCube from multiple atmospheric sites (Credit: E. Lohfink for the IceCube Collaboration). (Bottom) Rates of neutrinos from different sources (S. Axani for the IceCube Collaboration).

Other IceCube Analyses:

- The 8-year DeepCore analysis (ongoing):
  - Fit on ***all*** complex NSI parameters
  - Different parameterization that allows for constraining the differences between the diagonal Hamiltonian elements
- Sample: ~5-300 GeV, 8.2 years of data, ~300,000 events
  - Binning in energy, zenith, and topology (tracks and cascades)
- DeepCore analysis 3-year (Phys. Rev. D **104**, 072006) : 50k events

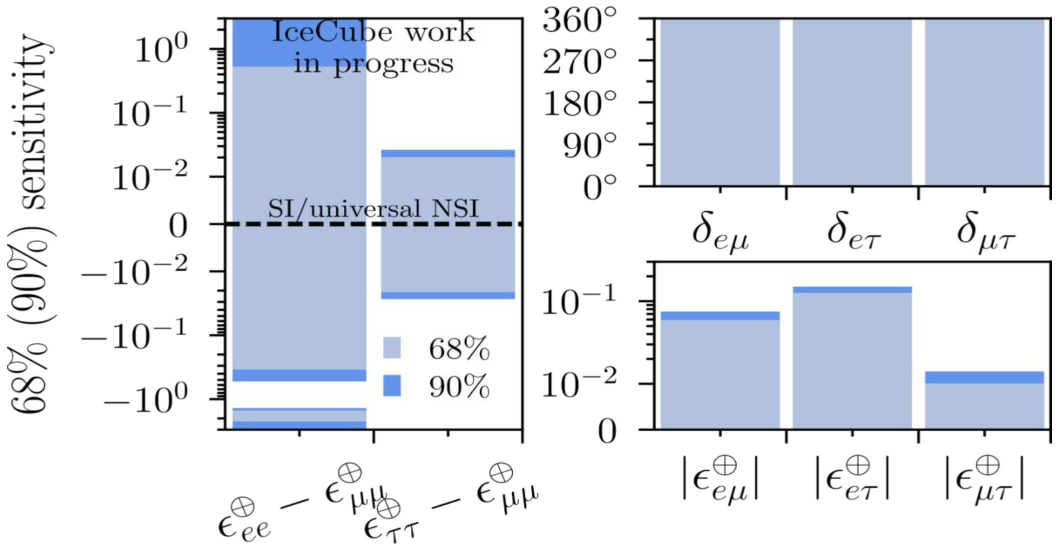


Figure: Sensitivities for the upcoming 8-year low-energy NSI result. Credit: E. Lohfink for the IceCube collaboration.

The 8-Year High-Energy Analysis

- **Our analysis fits at much higher energies (500 GeV - 10 TeV) than DeepCore:**
  - Only muon tracks, 300k events, 7.6 years of data
  - This is to constrain a **single parameter, $\epsilon_{\mu\tau}$**
    - $\epsilon_{\mu\tau}$ has the predominant effect on expected fluxes at high energies (right figure)

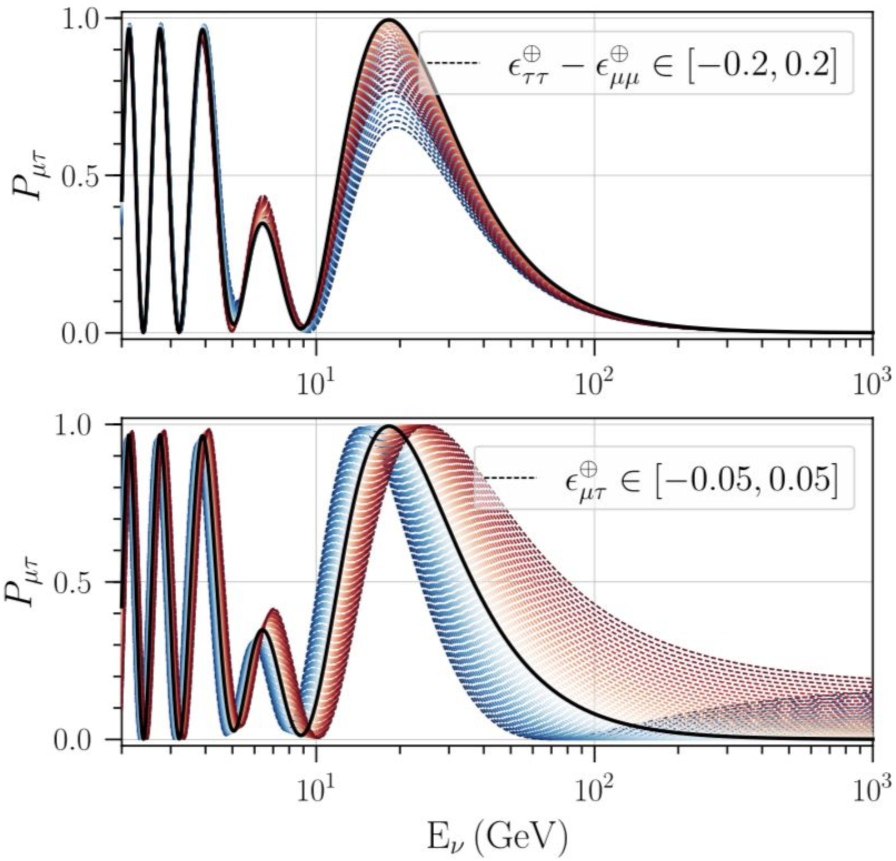


Figure: Neutrino oscillation probabilities with NSI. Red represents positive NSI values, while blue represents negative values. Credit: E. Lohfink for the IceCube Collaboration.

Analysis Predecessor

IceCube's latest sterile neutrino search <u>published last year</u>:

- 305,891 CC ν and $\overline{\nu}$ muon track events (7.64 years)
- Muon energy proxy: 500 - 9976 GeV
- Baseline MC: 500 years equivalent livetime
- **<u>Muon anti/neutrino disappearance shape signal</u>**

The larger data set was met with an updated analysis framework:

- MC Treatment with compactification abilities
- New analysis software for weighting and fitting
- Improved systematic treatment for larger sample
- Optimized event selection with reduced background and boosted statistics

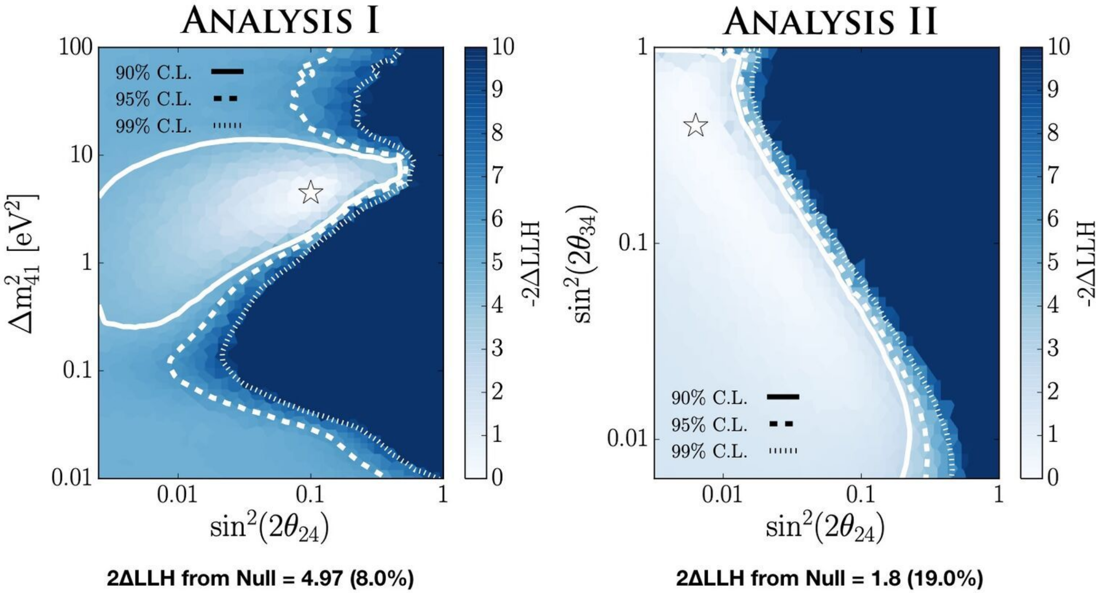


Figure: Results of Analysis I (left) and Analysis II (right), each presenting best-fits and CL contours for their respective parameter spaces. [arXiv:2005.12943]

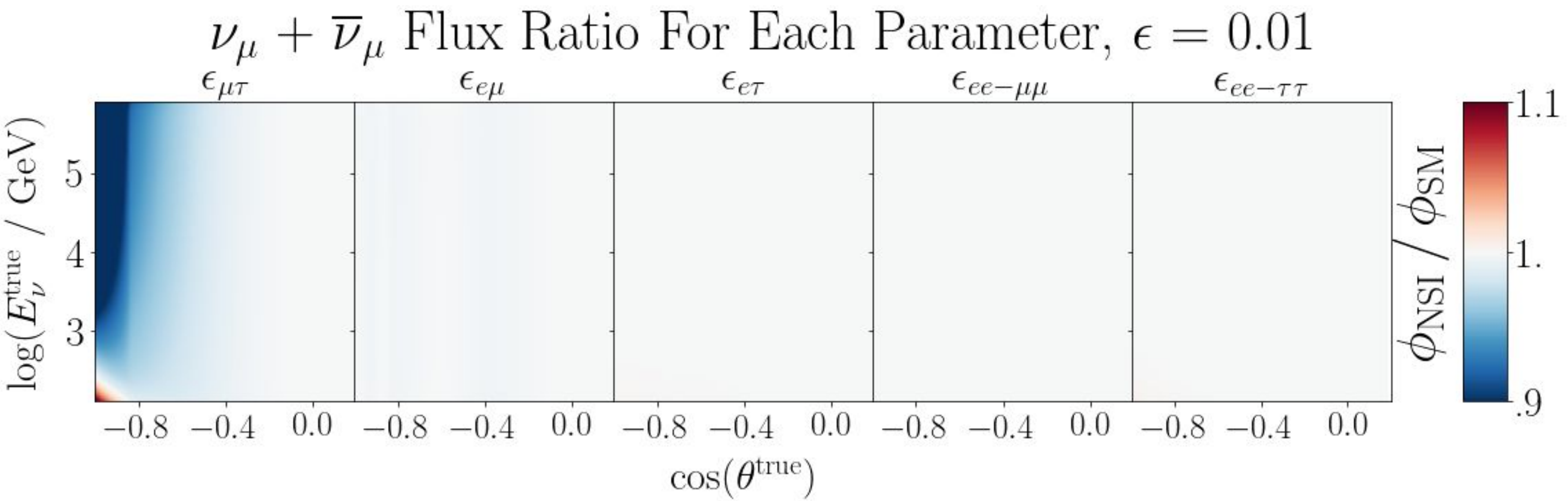
Parameter of Interest for This Analysis:

- At the energies and baselines of this analysis, ν_e decouples from oscillation and vacuum terms are suppressed.
  - Leads to only mu-tau oscillation, which means the mu-tau NSI parameter becomes predominant (Right)

- This is seen in simulated fluxes— all parameters except $\varepsilon_{\mu\tau}$ only enhance/suppress fluxes at O(10%) for parameter strength 0.01 (Below)

$$P(\nu_\mu \to \nu_\tau) \simeq$$

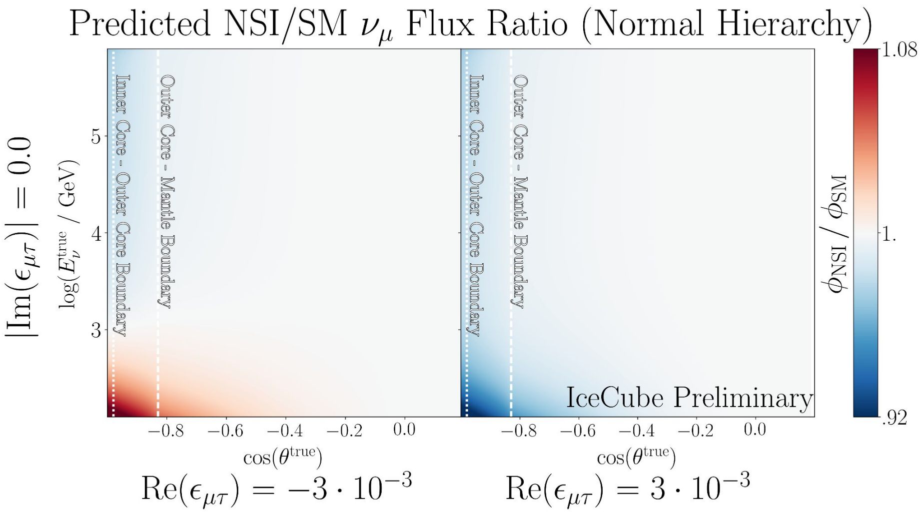
$$\left(\sin 2\theta_{23}\, \frac{\Delta m^2_{31}}{2\,E_\nu} + 2\,V_d\,\varepsilon_{\mu\tau}\right)^2 \left(\frac{L}{2}\right)^2$$



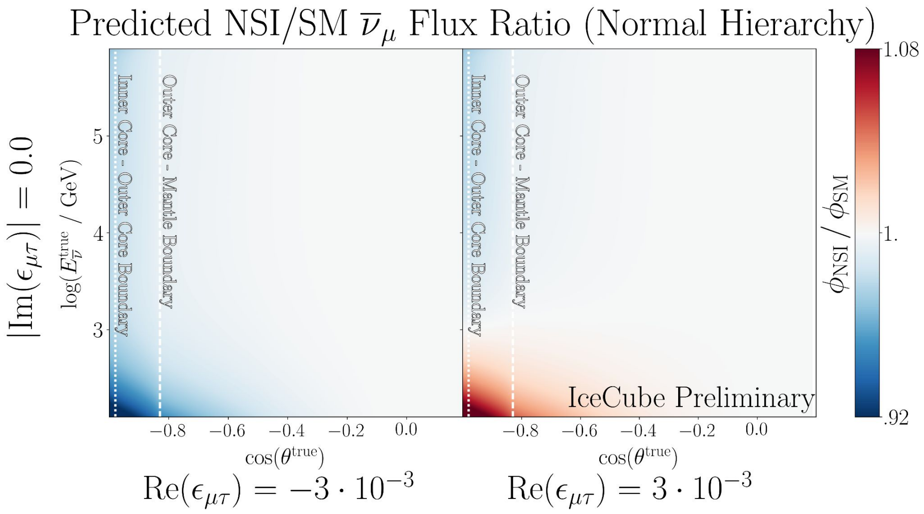
Signal Prediction

When we simulate neutrino and antineutrino fluxes independently, we see:

NEUTRINO



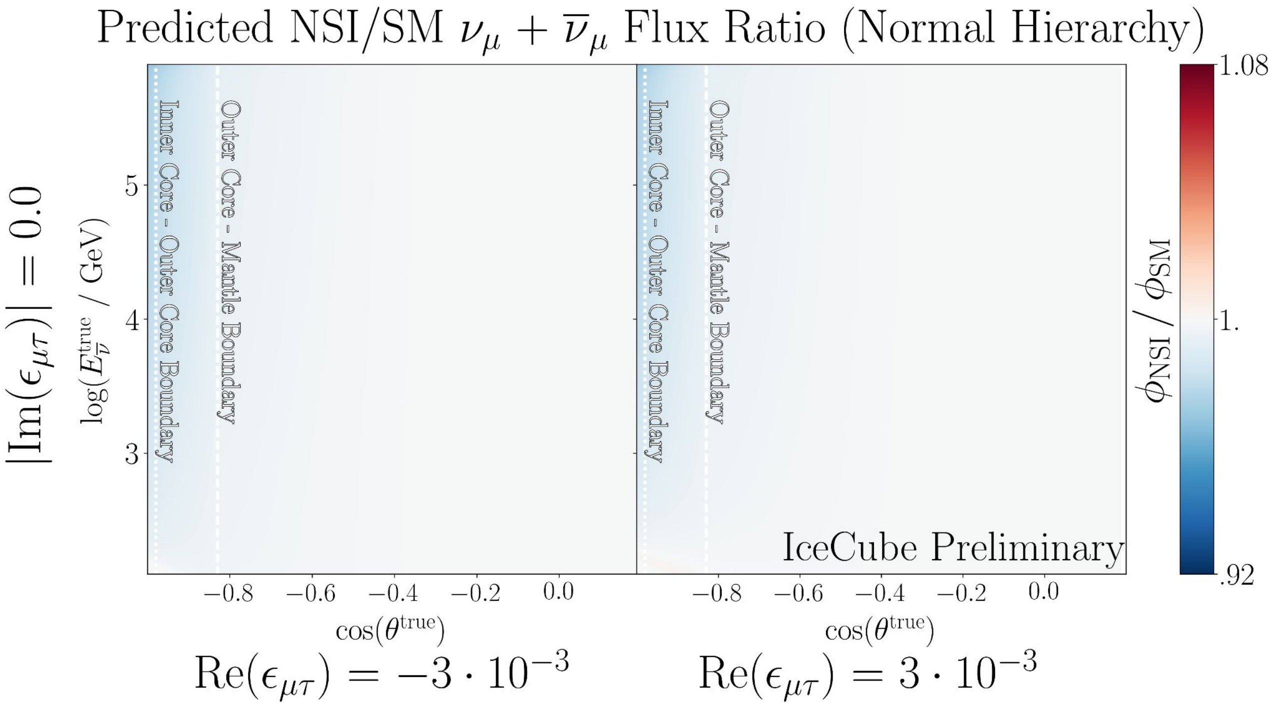
ANTINEUTRINO



This confirms the theory prediction: that as the sign of the matter potential changes between anti/neutrinos, signal shapes switch between +/- Re($\epsilon_{\mu\tau}$)

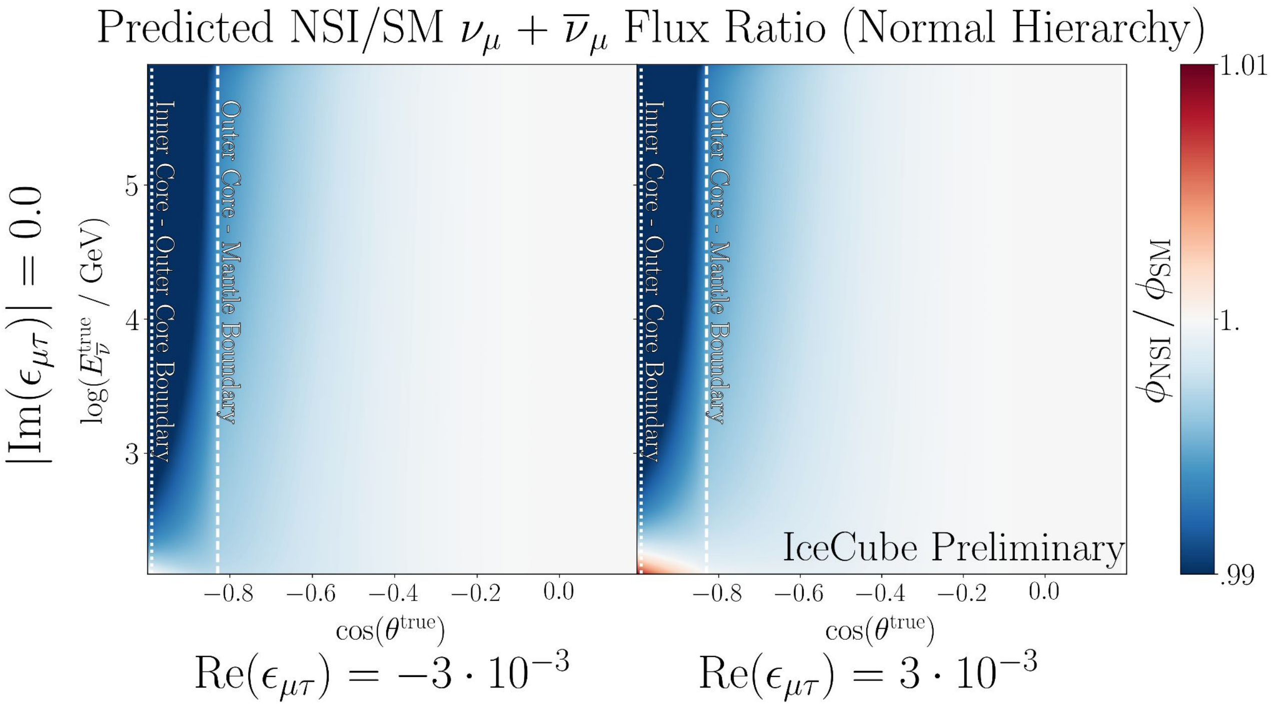
Signal Prediction

Combining the ν and $\overline{\nu}$ effects, the expected signal at IceCube is predominantly disappearance, and is much weaker than a pure ν or $\overline{\nu}$ flux.

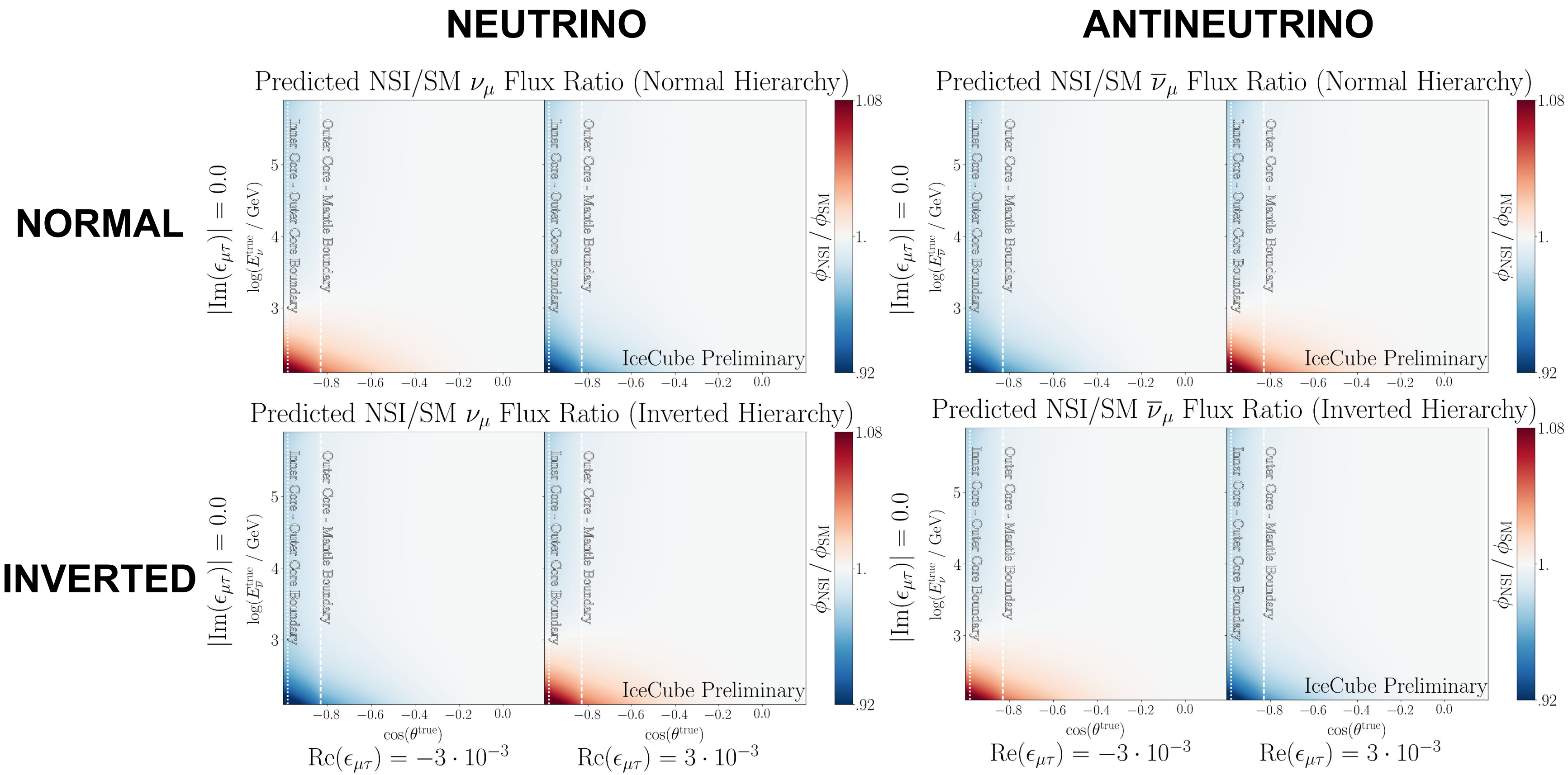


Signal Prediction

Let's rescale to look at the signal shape:



Inverted Hierarchy Prediction



Sensitivity and Impact of Systematic Uncertainties

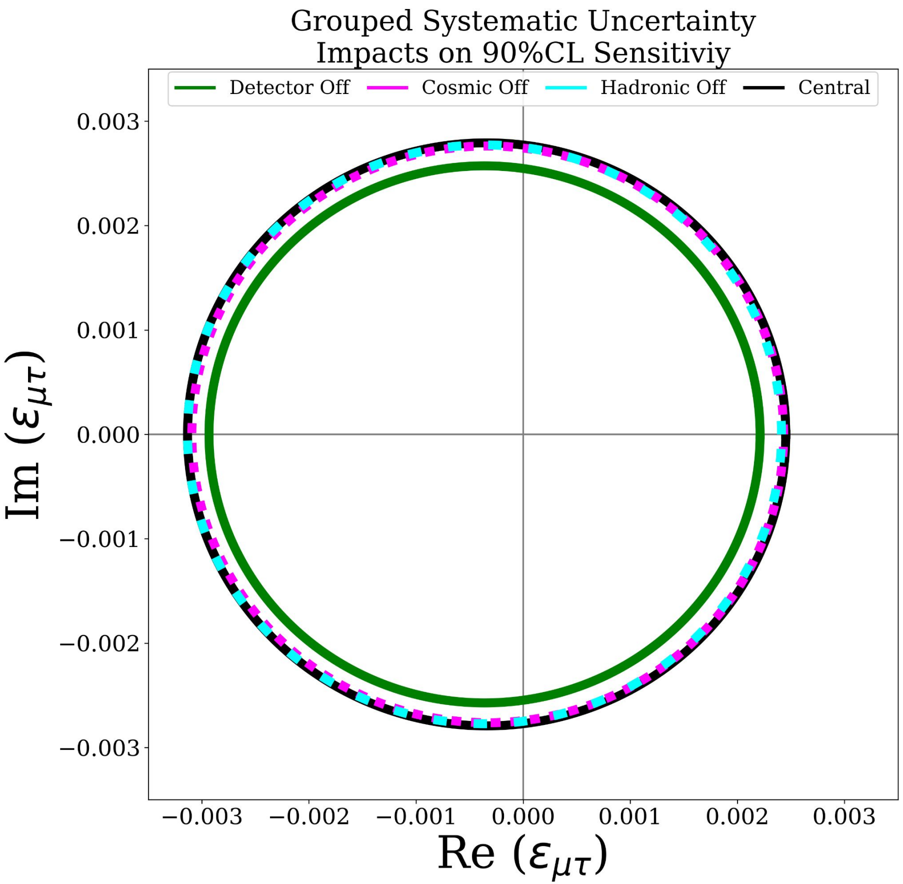
The 90% CL sensitivity is given in black ("central").

Impact of Systematic Uncertainties:

- **Individual systematic uncertainties have have little impact on the sensitivity.**
- **For testing, we group uncertainties by type, then turn them off individually to measure their impact (right).**

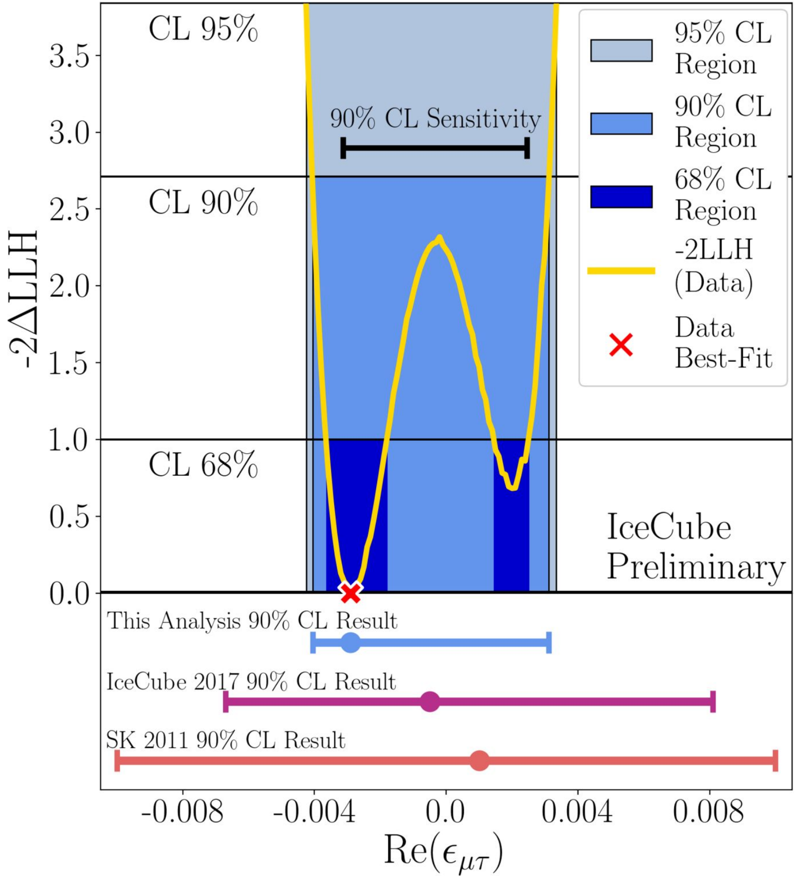
<u>Breakdown of Categorizations</u>

- **Bulk Ice: Uncertainties from the optical properties of South Pole glacial ice.**
- **Hole Ice: Uncertainties from the optical properties of refrozen ice in the drilled sensor column**
- **DOM Efficiency: How well the light sensors operate post-installation**
- **Atmospheric Neutrino Flux: Uncertainties in the production factors for atmospheric neutrinos**
- **Cosmic Ray and Astrophysical Neutrino Flux: Uncertainties regarding the fluxes of cosmic rays and astrophysical neutrinos**



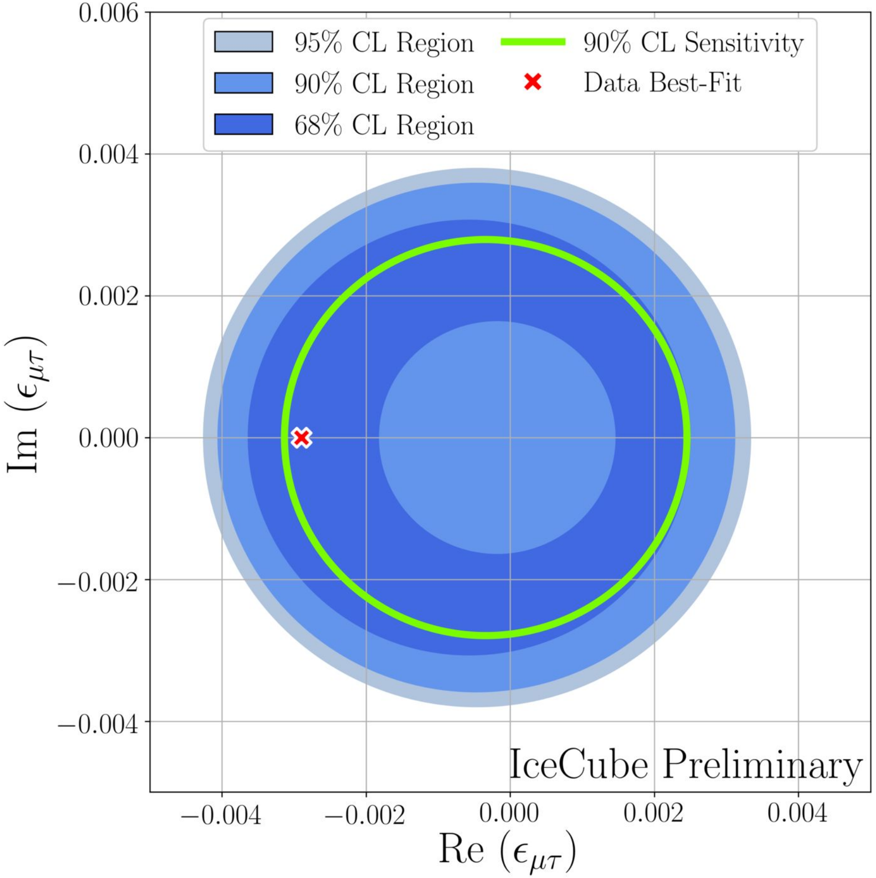
Results (Real-Only)

- **Figure (Top)**
  - Re($\boldsymbol{\varepsilon}_{\mu\tau}$) results for this analysis, including the -2LLH profile for the data and the obtained CL intervals
- **Figure (Bottom)**
  - Comparison of the Re($\boldsymbol{\varepsilon}_{\mu\tau}$) result from this analysis to other leading analyses that constrain Re($\boldsymbol{\varepsilon}_{\mu\tau}$) only
- **Best-Fit:**
  - $\boldsymbol{\varepsilon}_{\mu\tau}$ = -0.0029
- **Significance:**
  - p-value = 0.252
  - Result is 0.68 $\boldsymbol{\sigma}$ from the mean NSI value recovered from 1000 null hypothesis (no NSI) trials
- **90% CL Limits:**
  - $-0.0041 < \boldsymbol{\varepsilon}_{\mu\tau} < 0.0031$
- **IceCube obtains a new world-leading limit**



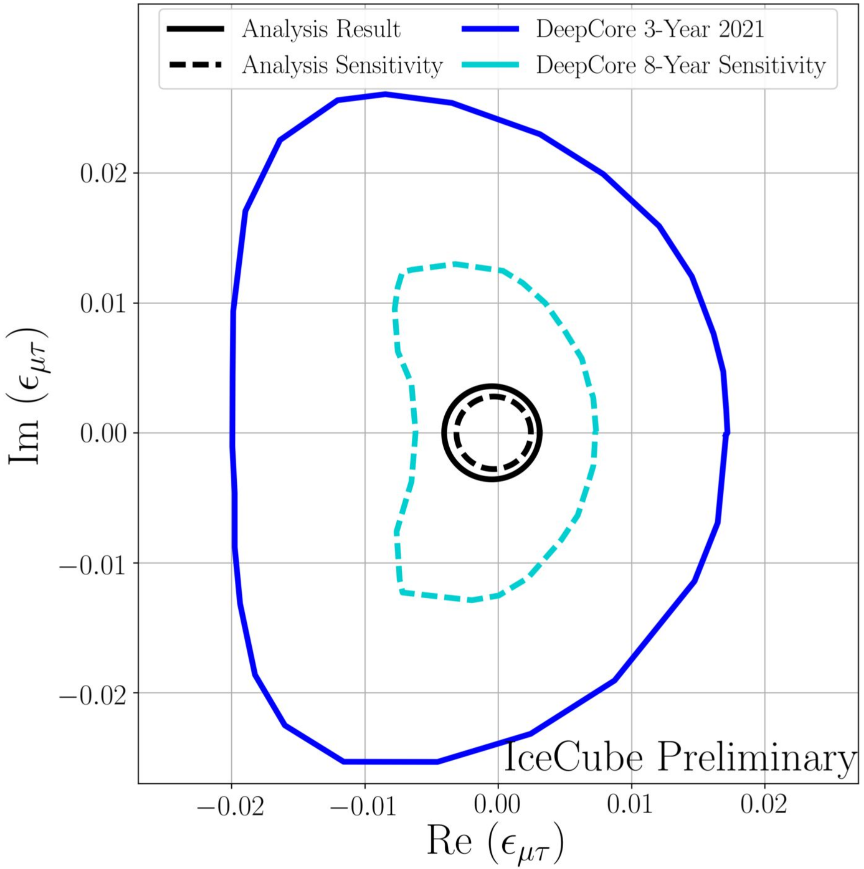
Results (Complex)

- **Figure:**
  - CL regions for complex $\boldsymbol{\varepsilon}_{\mu\tau}$
  - The Im($\boldsymbol{\varepsilon}_{\mu\tau}$) component is degenerate for a given Re($\boldsymbol{\varepsilon}_{\mu\tau}$) (see slide 21)
  - Due to the degeneracy, we fit only along Re($\boldsymbol{\varepsilon}_{\mu\tau}$) and infer the Im($\boldsymbol{\varepsilon}_{\mu\tau}$) limits. This has the advantages of faster computing time and one less degree of freedom to fit to.



Global Comparison

- **Figure:**
  - Few analyses fit to complex $\boldsymbol{\varepsilon}_{\mu\tau}$
    - We compare our result and sensitivity to those of IceCube DeepCore analyses
  - DeepCore analyses are in the low-energy regime (5-300 GeV), where $\boldsymbol{\nu}_e$ **does not** effectively decouple from atmospheric neutrino oscillations
  - While the Im($\boldsymbol{\varepsilon}_{\mu\tau}$) symmetry is still observed, the overall radial symmetry for the contours is lost in the 3-neutrino mixing regime



Conclusions

In the era of high-precision neutrino physics, NSI must be constrained

With 8 years of high-energy muon neutrino data, our result sets 90% CL limits of $\varepsilon_{\mu\tau}$ parameter: $-0.0041 < \varepsilon_{\mu\tau} < 0.0031$

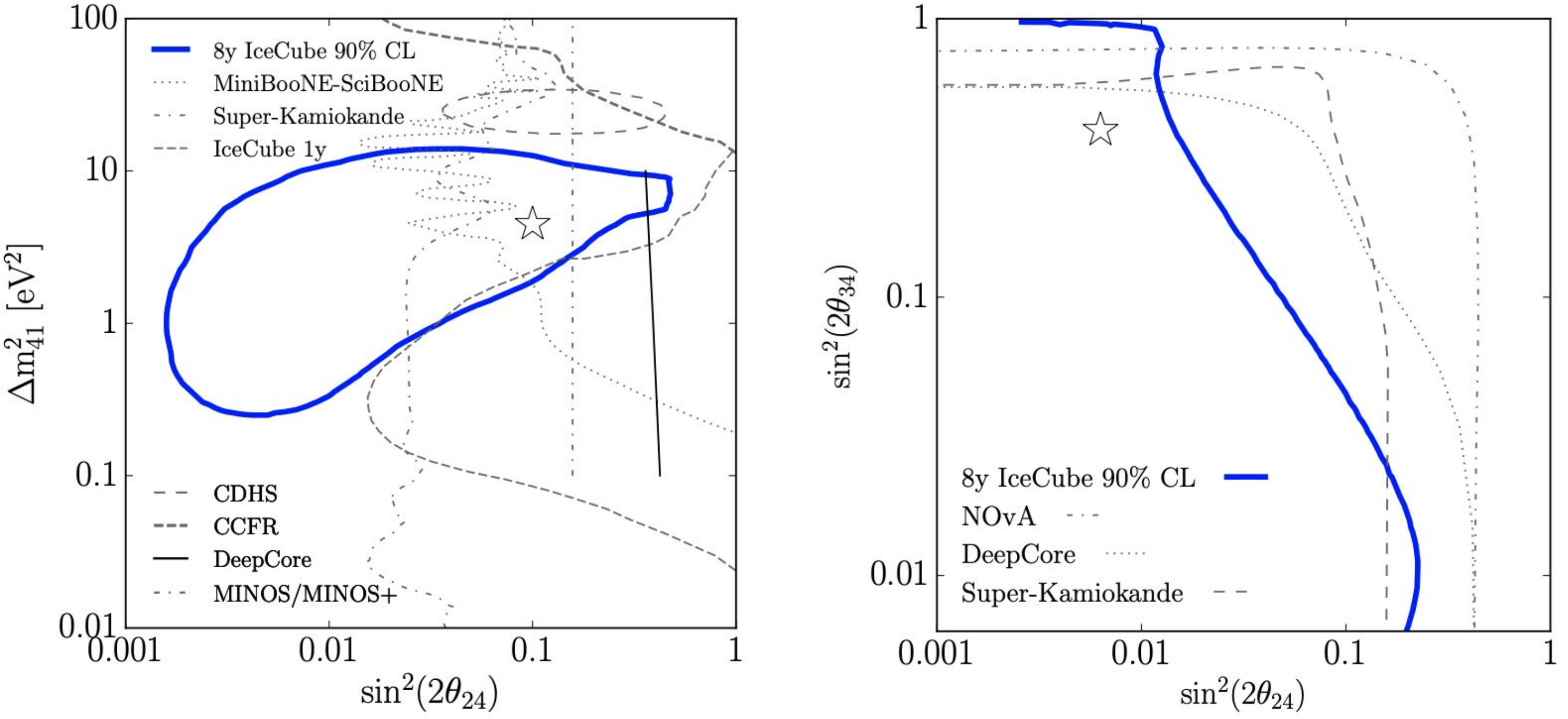
This analysis sets the **tightest constraint on any NSI parameter in any channel globally**, with improvement on the nearest limits of $\varepsilon_{\mu\tau}$ by a factor of ~2

Thank You

Backup Slides

Sterile Results

- Below is the comparison of 90% CL results for Analysis I (left) and Analysis II (right) to other published limits.



Symmetry Between +Im(NSI) and -Im(NSI

- For a given Re, +Im and -Im are identical in the two-neutrino calculation (right)

- Therefore, we can:

  - 1: Scan only the Re axis to get all the information

  - 2: Calculate statistics object for 1 DoF

$$P(+) = \left| \sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} + 2(a+bi)V_d \right|^2 \left(\frac{L}{2} \right)^2$$

$$P(-) = \left| \sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} + 2(a-bi)V_d \right|^2 \left(\frac{L}{2} \right)^2$$

$$P(+)/P(-) = \frac{\left| \sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} + 2(a+bi)V_d \right|^2}{\left| \sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} + 2(a-bi)V_d \right|^2}$$

$$= \frac{\left(\sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} \right)^2 + 4(a)V_d \sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} + 4(a^2+b^2)V_d^2}{\left(\sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} \right)^2 + 4(a)V_d \sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} + 4(a^2+b^2)V_d^2}$$

$$= 1$$

NSI LLH Offset

- At sample energies, the electron flavor state decouples from atmospheric oscillation.
- Below is the approximate calculation of the difference in probabilities for NSI values with equal imaginary components, opposite-sign real components.

$$P(-) - P(+) =$$

$$\left[\left|\sin 2\theta_{23}\frac{\Delta m^2_{31}}{2E_\nu} + 2(-a+bi)V_d\right|^2 - \left|\sin 2\theta_{23}\frac{\Delta m^2_{31}}{2E_\nu} + 2(a+bi)V_d\right|^2\right]\left(\frac{L}{2}\right)^2$$

$$= -aV_d L^2 \sin 2\theta_{23}\frac{\Delta m^2_{31}}{E_\nu}$$

$$= \text{negative value}$$

This confirms what we see in the $-2\Delta\text{LLH}$ distribution, as $-2\Delta\text{LLH}(-a+bi) < -2\Delta\text{LLH}(a+bi)$.

Expected Distributions

Signal in reconstruction space: