UNIVERSITY OF TEXAS ARLINGTON

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

νRES Neutrino Rare Event Searches

Beyond-Standard-Model Neutrino Oscillations Studies in IceCube

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Overview

- A quick introduction to IceCube
  - Detector design
  - Signal principles

- BSM oscillations studies
  - Sterile neutrinos
  - Neutrino decoherence
  - Neutrino-matter non-standard interactions
    - High-Energy
    - Low-Energy

- Concluding Remarks

Credit: IceCube/NSF

The Detector

The IceCube Neutrino Observatory

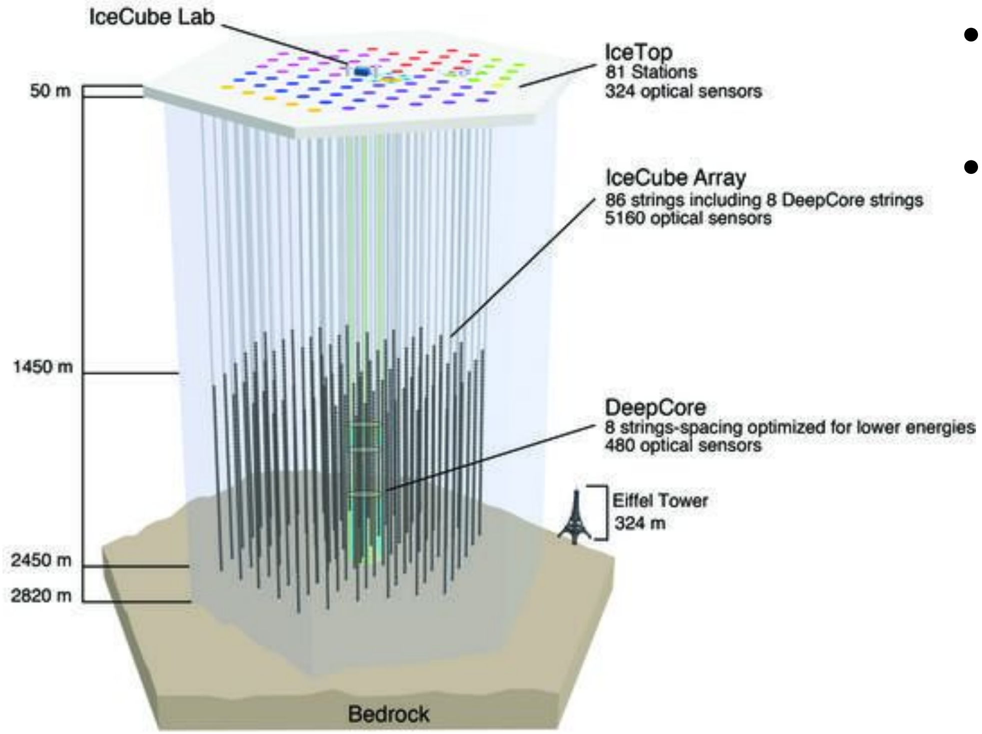


Figure: The IceCube neutrino observatory. DeepCore is an additional collection of strings that allow for signals as low as 5 GeV.

- 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 produces have sufficient energy to produce Cherenkov radiation.
  - Collected light allows for neutrino direction and energy reconstruction.
- Two event types: tracks (linear trajectories) and cascades (blob-like signal).

Atmospheric Neutrinos as Data

- Oscillations studies often require large baselines and as high of a sample as possible.
  - IceCube meets both of these requirements by detecting atmospheric neutrinos generated across the Earth
- Some BSM signals rely on matter effects in addition to the MSW effect, in which case the Earth provides a suitably large medium
  - Hence, samples can often consist of “upgoing” neutrinos

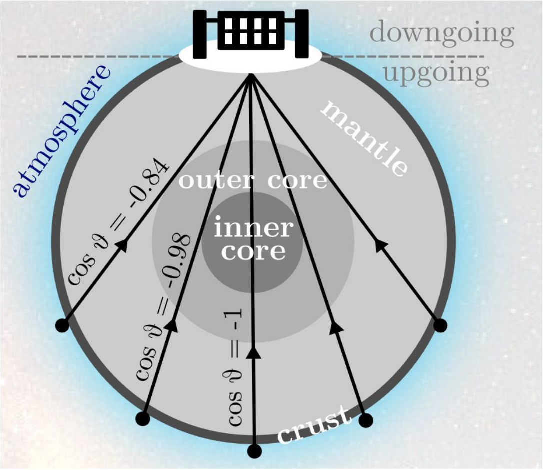
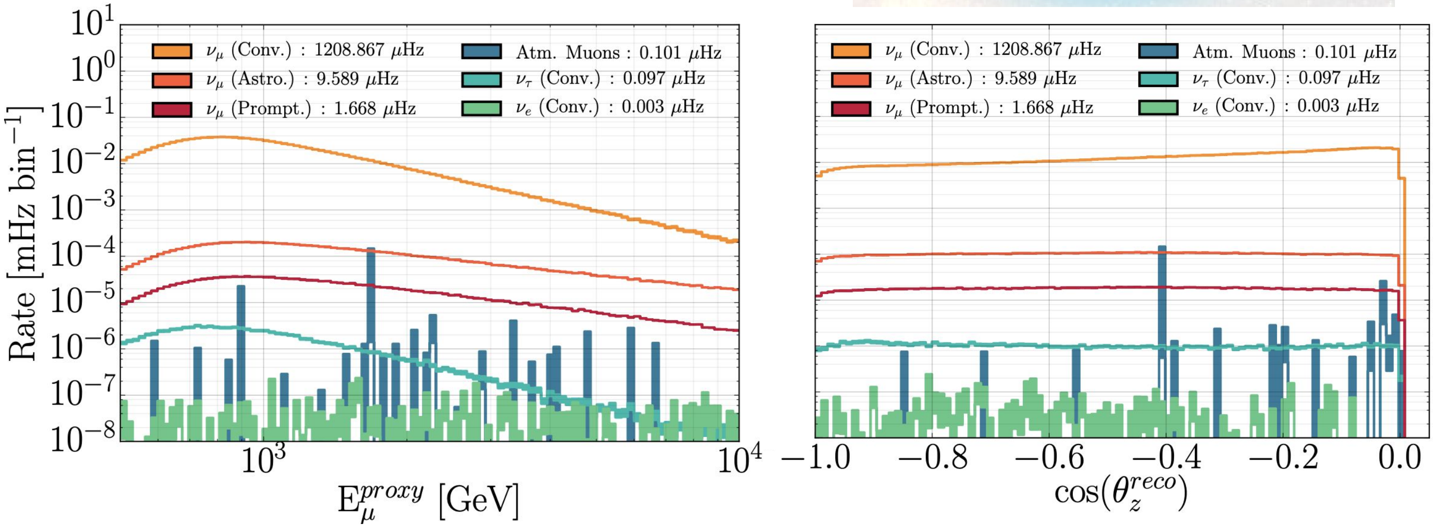


Figure: (Bottom) Distributions of reconstructed neutrino signals and backgrounds at IceCube binned in muon energy (left) and zenith (right). Atmospheric (light orange) have the highest rate [Aartsen et al 2020]. (Top Right) Diagram demonstrating how neutrinos produced across the planet can travel through various baselines and densities to reach IceCube. Credit: E. Lohfink for the IceCube collaboration.



BSM Analyses

Sterile Neutrinos with and without Decay

Sterile Neutrino Analysis

- IceCube has undertaken several sterile neutrino searches, most recently setting new limits last year (Aartsen et al 2020).
- Analysis description:
  - 305,705 CC ν and $\overline{\nu}$ track events (8 years)
  - Muon energy proxy: 500 - 9976 GeV
  - Baseline MC: 500 years equivalent livetime
  - Studies on scaling-up systematic uncertainties
  - Sample is composition:
    - Gold filter events (IC79/86 Diffuse Analysis and IC86.2011 HE Analysis)
    - Diamond filter events (new triggers regarding DeepCore, direct photons, and zenith allow for additional events).

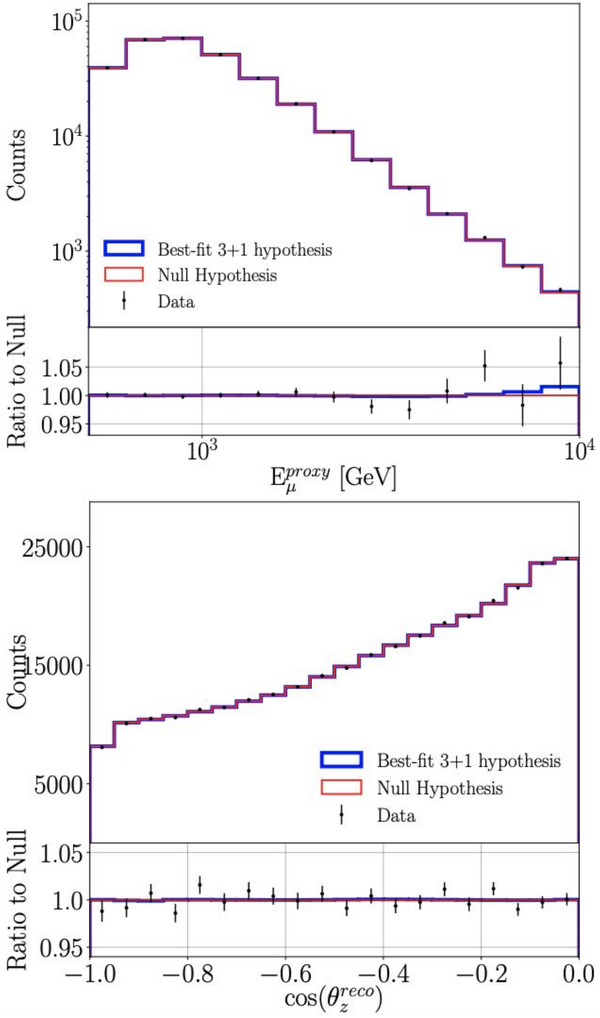


Figure: Reconstructed muon energy (top) and zenith (bottom) distributions [Aartsen et al 2020]

Studies of Nuisance Parameters

- **Bulk Ice**: Scattering and absorption of glacial ice at different depths has wide uncertainty.
  - **New method developed to study correlation effects via perturbed central MC**
- **Hole Ice**: Ice in sensor column has different scattering and absorption.
  - **Broken into two parameters-- central MC selected after testing different parameter values on angular acceptance**
- **DOM Efficiency**: Optimal module photon detection efficiency.
  - **5 distinct DOM efficiency sets were used to create a splined continuous parameterization fit to zenith and energy reconstructions**
- **Atmospheric Neutrino Flux**: Neutrino production factors and uncertainties.
  - **Switched from discrete CR + hadronic models to continuous parameterizations of physically-motivated variables (Barr hadronic parameterization, CR spectral slope, conventional normalization, kaon-nuclei x-section, atmospheric density)**
- **Cosmic Ray and Neutrino Flux**: The cosmic ray spectral index and neutrino flux normalization have parameterized uncertainties.
  - **Normalization and spectral index with correlated uncertainties to fit IceCube's measurements**

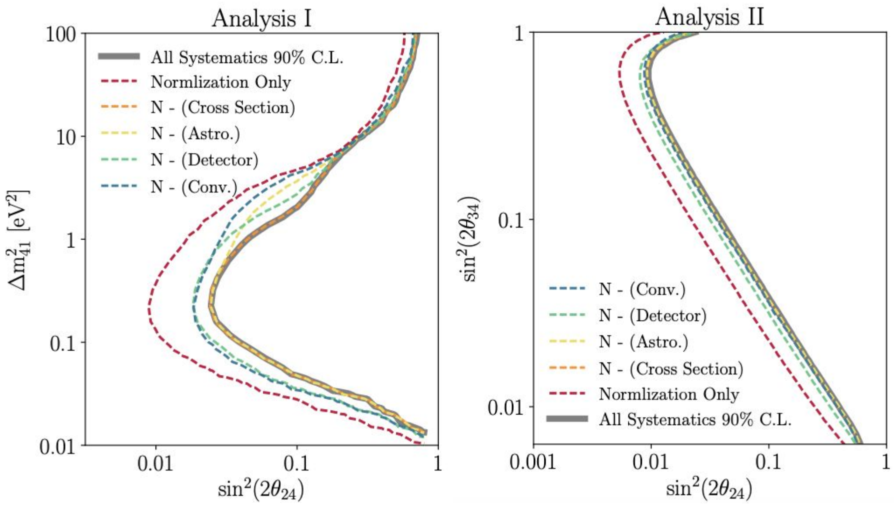
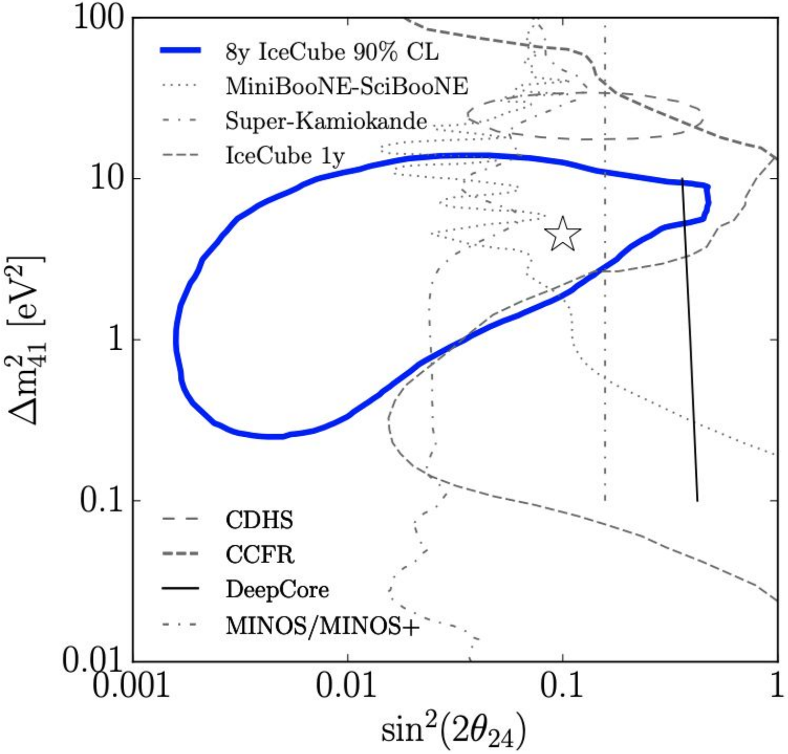
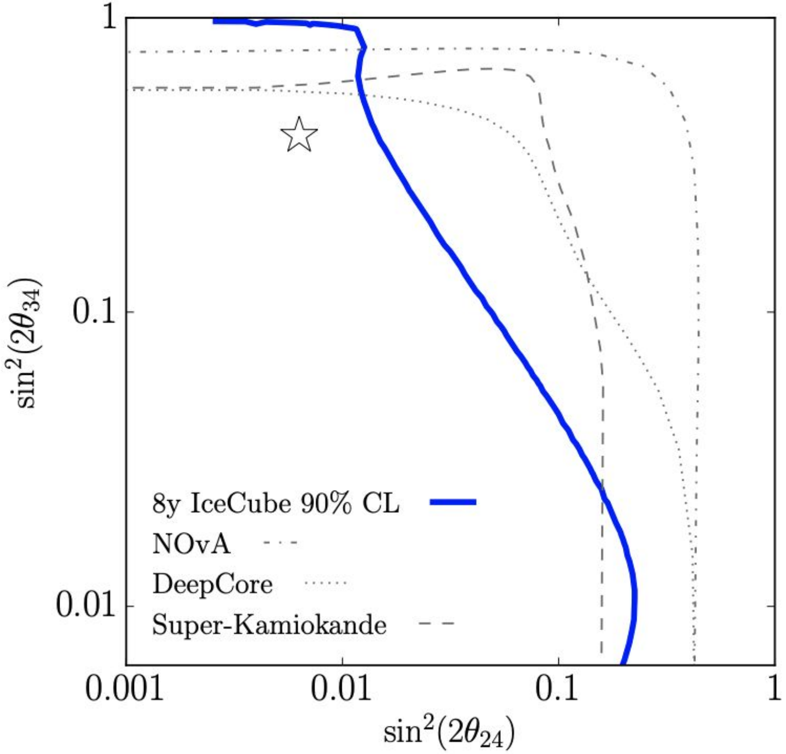


Figure: 90% CL sensitivities for analyses I and II with individual nuisance parameter groups removed. Grey is the original sensitivity [Aartsen et al 2020]

Sterile Results

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





Sterile Neutrinos With Decay

- With the sterile analysis sample and tools, a collection of successor analyses are underway.
  - The first such analysis, nearing completion, is a search for sterile neutrinos with invisible decay.
- Motivation: if a fourth neutrino state exists, nothing in theory prevents it from decaying.
  - Sterile models with decay have improved fits compared to standard 3+1 models (see [Diaz et all 2019]).
- The lifetime of ν_4 is related to coupling constant g via:

$$\frac{1}{\tau} = \Gamma = \frac{g^2 m_4}{16\pi}$$

- The analysis fits to Δm^2_{41}, $\sin^2(\theta_{24})$, and g^2.

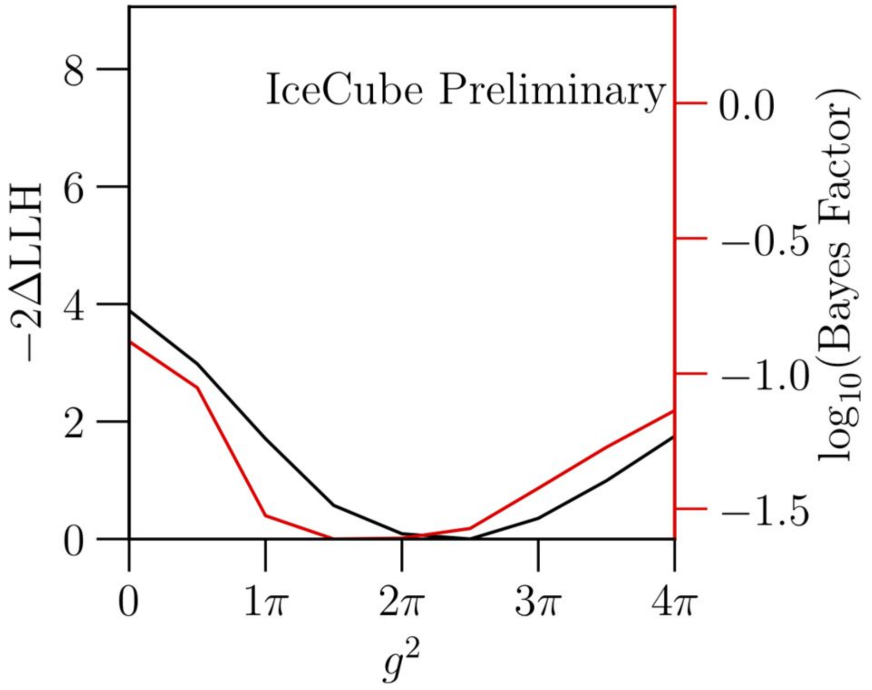


Figure: Profiled -2ΔLLH, plotted on the left y-axis, and log10(Bayes factor), plotted on the right y-axis, versus g2. Credit: M. Moulai for the IceCube Collaboration.

Neutrino Decoherence from Quantum Gravitational Space-Time Fluctuations

Decoherence Analyses

- Spacetime fluctuations at the quantum scale may produce virtual black holes (VBHs), a form of quantum foam.
- Neutrino-VBH interactions are an excellent probe for this type of physics

- Decoherence can be introduced as an operator in the quantum system formalism:

$$\dot{\rho} = -i[H, \rho] + \mathcal{D}[\rho] \Rightarrow \mathcal{D}[\rho] = (D_{\mu\nu}\rho^{\nu})b^{\mu}$$

$$D_{\text{phase perturbation}} = \text{diag}\,(0\ \Gamma\ \Gamma\ \Gamma\ \Gamma\ \Gamma\ \Gamma\ \Gamma\ \Gamma)$$

$$D_{\text{state selected}} = \text{diag}\,(0\ \Gamma\ \Gamma\ 0\ \Gamma\ \Gamma\ \Gamma\ \Gamma\ 0)$$

$$D_{\text{neutrino lost}} = \text{diag}\,(\Gamma\ \Gamma\ \Gamma\ \Gamma\ \Gamma\ \Gamma\ \Gamma\ \Gamma\ \Gamma)$$

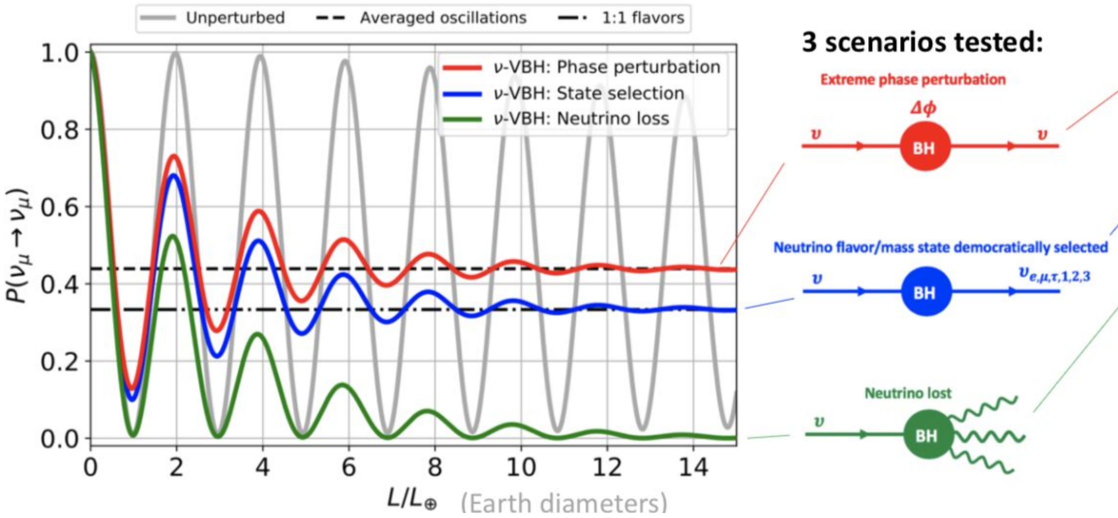


Figure: (Left) Modified neutrino survival probabilities as a function of coherence length for the 3 tested decoherence scenarios. (Center) Diagramed neutrino-VBH interactions for the 3 scenarios. (Right) The operator matrix representation for each scenario. Credit: T. Stuttard for the IceCube collaboration.

Decoherence Analyses

- Coherence length L_{coh} is the interaction mean free path for a given scenario. It is defined as $1/\Gamma$, where Γ is the damping factor inside the decoherence operator.
- With no accepted model of quantum gravity, a method to probe decoherence is to test multiple scenarios at different energy dependencies.
- Defining the damping factor as

$$\Gamma(E) = \zeta_{\mathrm{Planck}} \frac{E^n}{M_{\mathrm{Planck}}^{n-1}}$$

with ζ_{Planck} a dimensionless free parameter that characterizes the decoherence strength, we now have a parameter to constrain with IceCube fluxes.

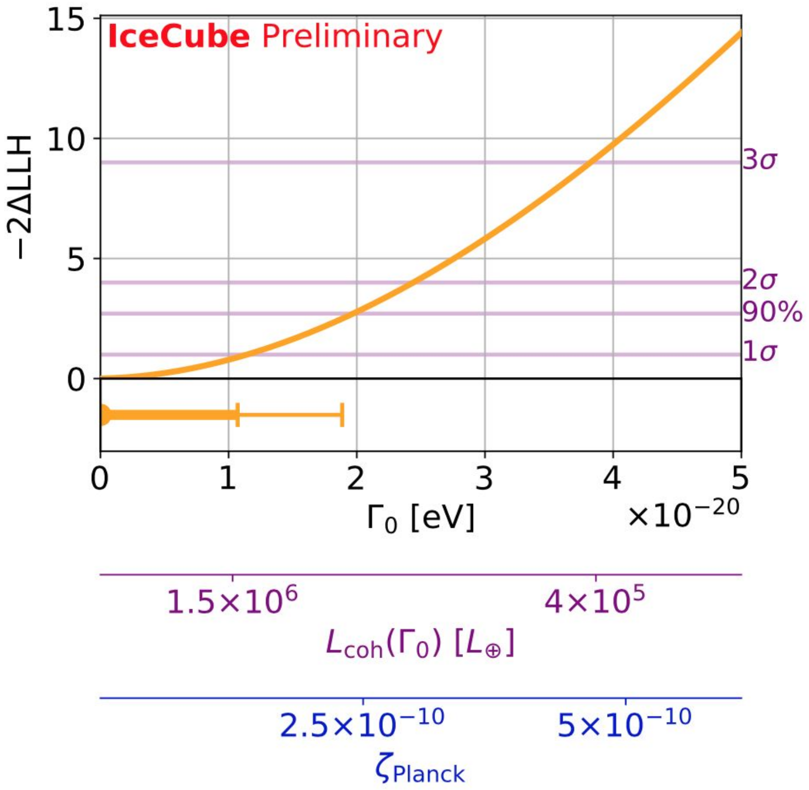


Figure: IceCube sensitivity to Γ_0 , L_{coh}, and ζ_{Planck} for an n=0 in the “democratic selection scenario. [Stuttard T., Jensen M. 2020]

<u>Low-Energy</u>
Neutrino-Matter
Non-Standard-Interactions

Analysis Motivation

- Wolfenstein postulated NSI when describing mass effects on neutrino oscillations.
  - **Standard Model (SM) cannot account for neutrino masses**
  - NSI originate from adding a dimension-6 operator to the SM

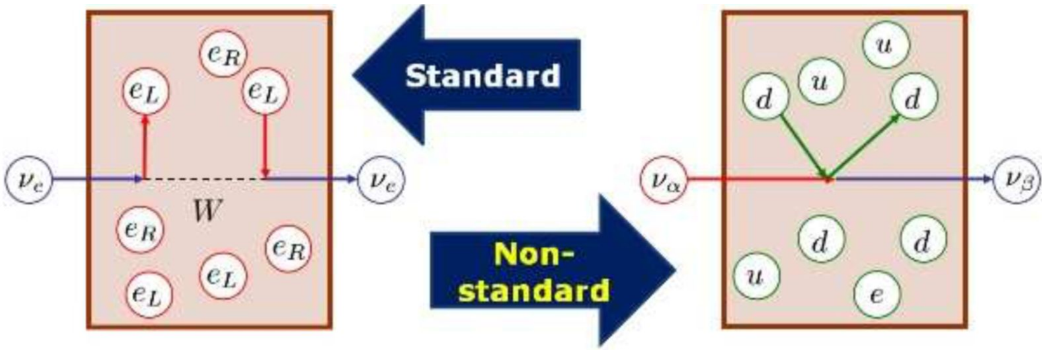


Figure: Diagramed neutrino-matter interactions for SM and NSI (Ohlsonn 2013).

- NSI can **resolve tensions**
  - Solar and KamLAND measurements of Δm_{21}^2 and θ_{12} [Dev et al 2019]

- Complicate neutrino parameter measurements
  - Degeneracies in δ_{CP} and the θ_{23} octant [Esteban et al 2020]

- NSI generalizing non-SM effects + likely neutrino mass - high energy connection = **compelling opportunity to find find new physics**

Formalism

- NSI's come in two types:
    - Neutral-Current (NC)
    - Charged-Current (CC)

- In IceCube we only look for NC NSI:
    - NC affect propagation, so we use the Earth as a large matter filter to search for NSI signals from "upgoing" atmospheric neutrinos that reach IceCube.

Start with the NC NSI Lagrangian

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

Generalize the parameters

$$\varepsilon_{\alpha\beta} = \sum_{f,P} \varepsilon_{\alpha\beta}^{fP} \frac{N_f}{N_e}$$

Add the NSI Hamiltonian to the matter Hamiltonian.

$$H_{\mathrm{mat}} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1+\varepsilon_{ee}(x) & \varepsilon_{e\mu}(x) & \varepsilon_{e\tau}(x) \\ \varepsilon_{e\mu}^*(x) & \varepsilon_{\mu\mu}(x) & \varepsilon_{\mu\tau}(x) \\ \varepsilon_{e\tau}^*(x) & \varepsilon_{\mu\tau}^*(x) & \varepsilon_{\tau\tau}(x) \end{pmatrix}$$

Low-Energy NSI

- The 8-year analysis is a fit on *all* complex NSI parameters with a slightly 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)

- Markov-Chain MC sampling for a fit to a higher-dimensional parameter space

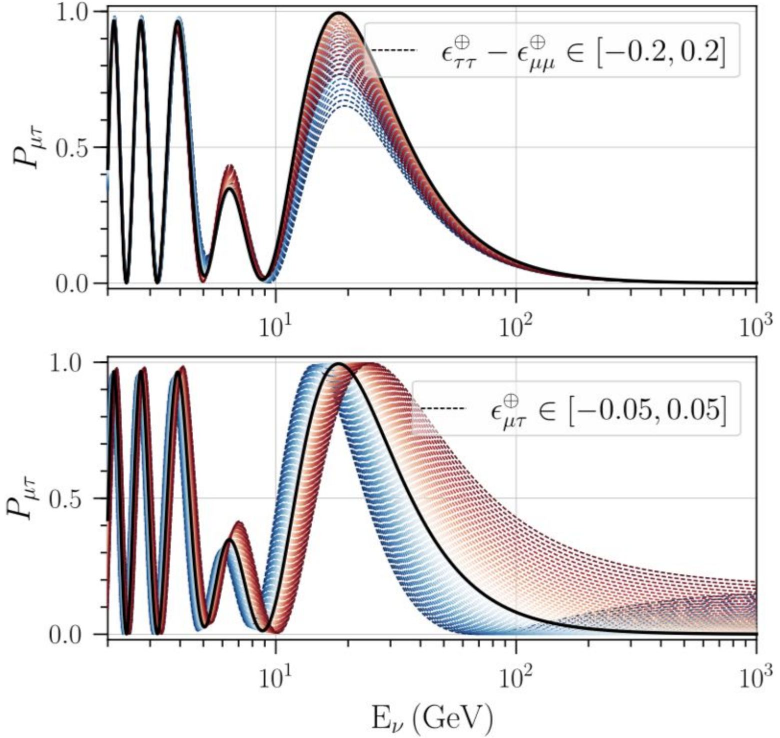


Figure: Neutrino oscillation probabilities with NSI. Red represents positive NSI values, while blue represents negative values. Credit: E. Lohfink for the IceCube Collaboration.

Low-Energy NSI

- Particularly sensitive to $\varepsilon_{\tau\tau}$-$\varepsilon_{\mu\mu}$ and $\varepsilon_{e\mu}$.
- Oscillations experiments are not sensitive to diagonal parameters, so only the difference in diagonal NSI can be constrained.
- Previous all-parameter DeepCore analysis used 3 years of data
  - 50k events -> 300k events

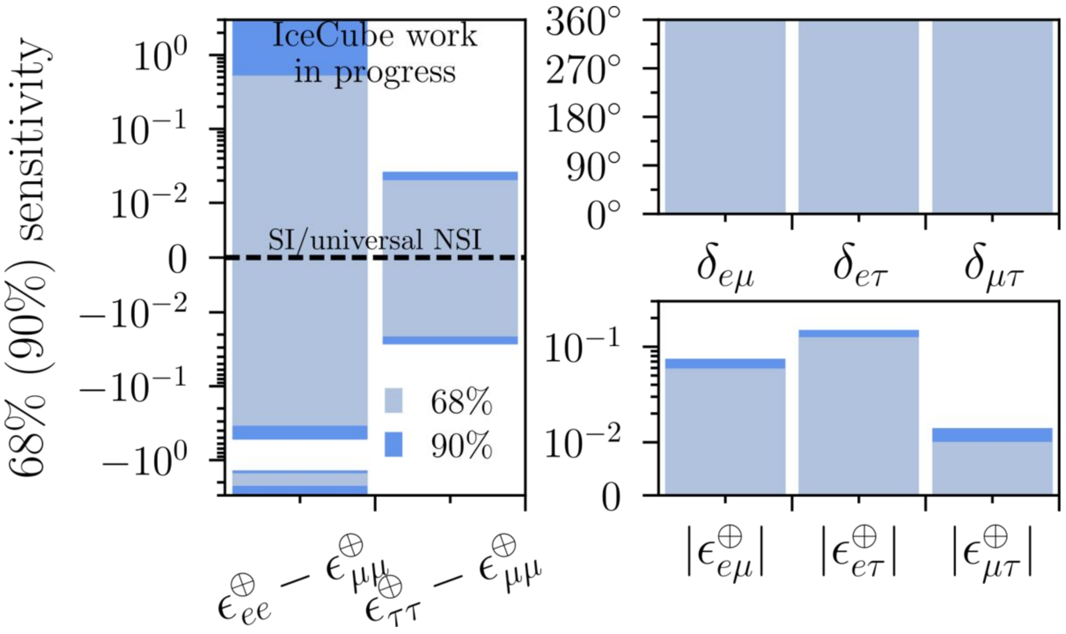
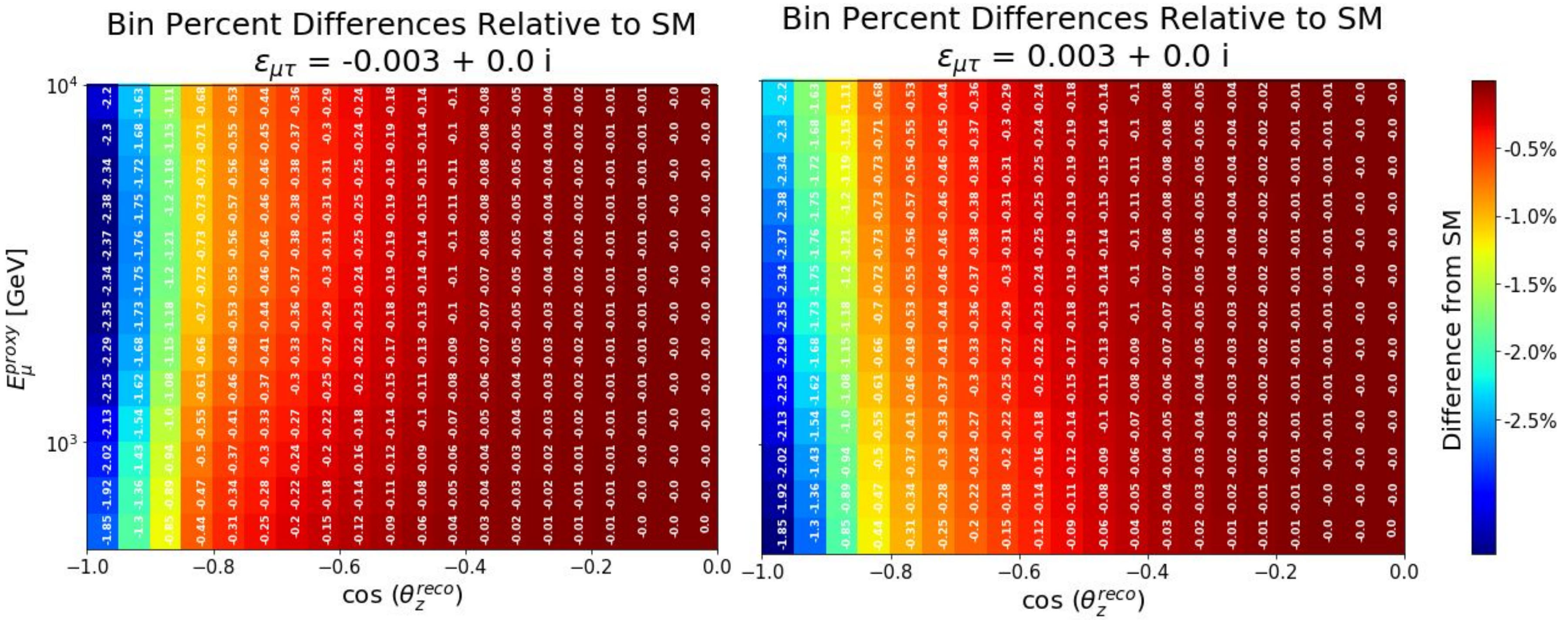


Figure: Sensitivities for the upcoming 8-year low-energy NSI result. Credit: E. Lohfink for the IceCube collaboration.

High-Energy Neutrino-Matter Non-Standard-Interactions

Expectation Distributions

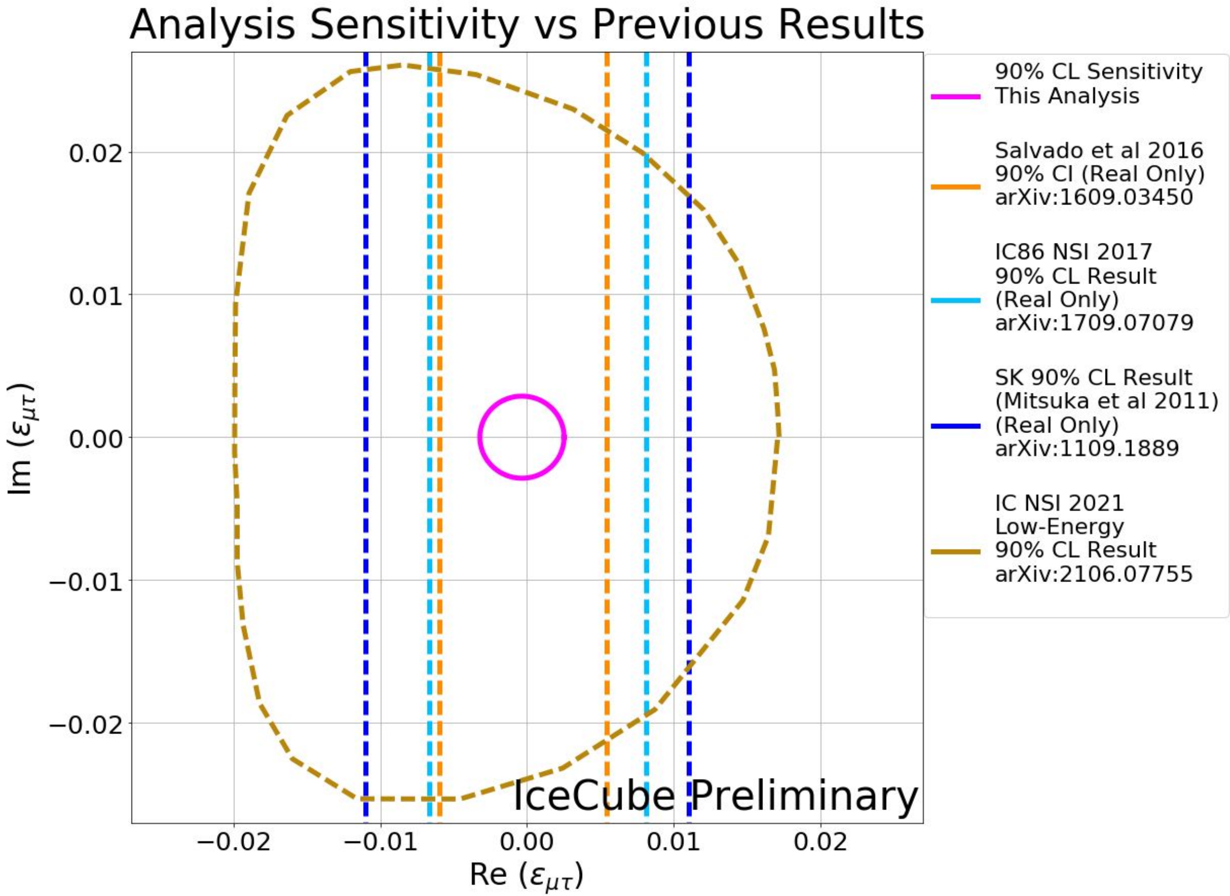
- The HE analysis looks for differences rate and shape (disappearance).
- We can distinguish between positive and negative real NSI due to the offset effect real NSI has on $\mu\tau$ oscillation probabilities.



High-Energy NSI

- With the same high-energy track sample as the sterile and sterile decay analyses, this search is meant to fit only $\boldsymbol{\varepsilon_{\mu\tau}}$.

- LLH's are offset as a feature of non-zero real NSI and symmetric about the imaginary axis due to the form of the probability (see backup).



Concluding Remarks

Concluding Remarks

- After 10 years of runtime, IceCube now has years of data to use in oscillations analyses.

- With the Earth as the ultimate matter baseline, IceCube has many opportunities to explore a vast range of BSM oscillation models and accomplish the following:

    - Leading measurements of sterile neutrino parameters from an extensive study of data filtering, data stability, and nuisance parameters.
    - New sterile decay parameter constraints.
    - A new probe of quantum foam models.
    - Globally competitive NSI parameter constraints.

- As samples, software, and the detector improve, IceCube will continue to pursue these analyses and lead in the oscillations frontier.

Thank You!

Backup

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.

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

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

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

$$= \text{negative value}$$

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