IceCube Matter-Enhanced Sterile Neutrino Searches

TeVPA 2022 – Ben Smithers

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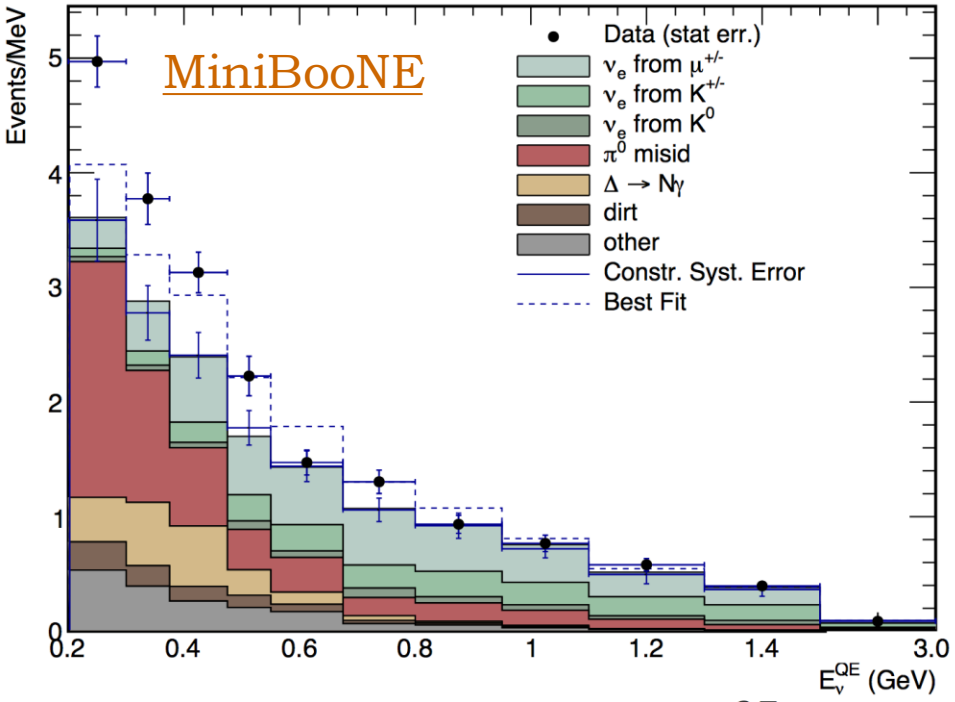
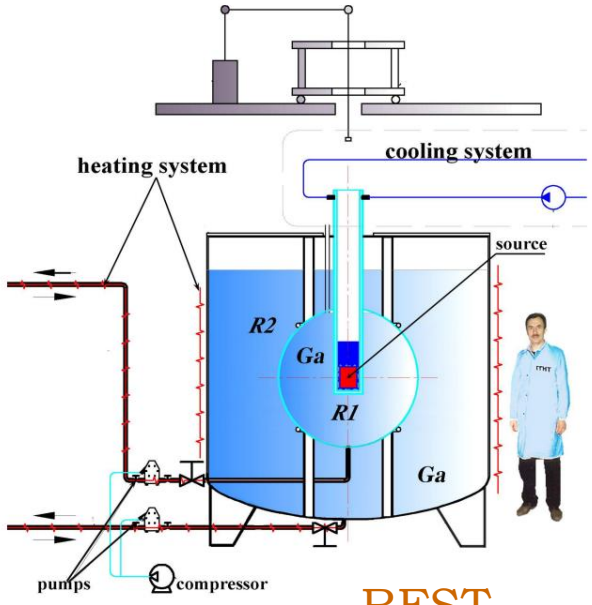
IceCube South Pole Neutrino Observatory

Photo: Martin Wolf, IceCube/NSF

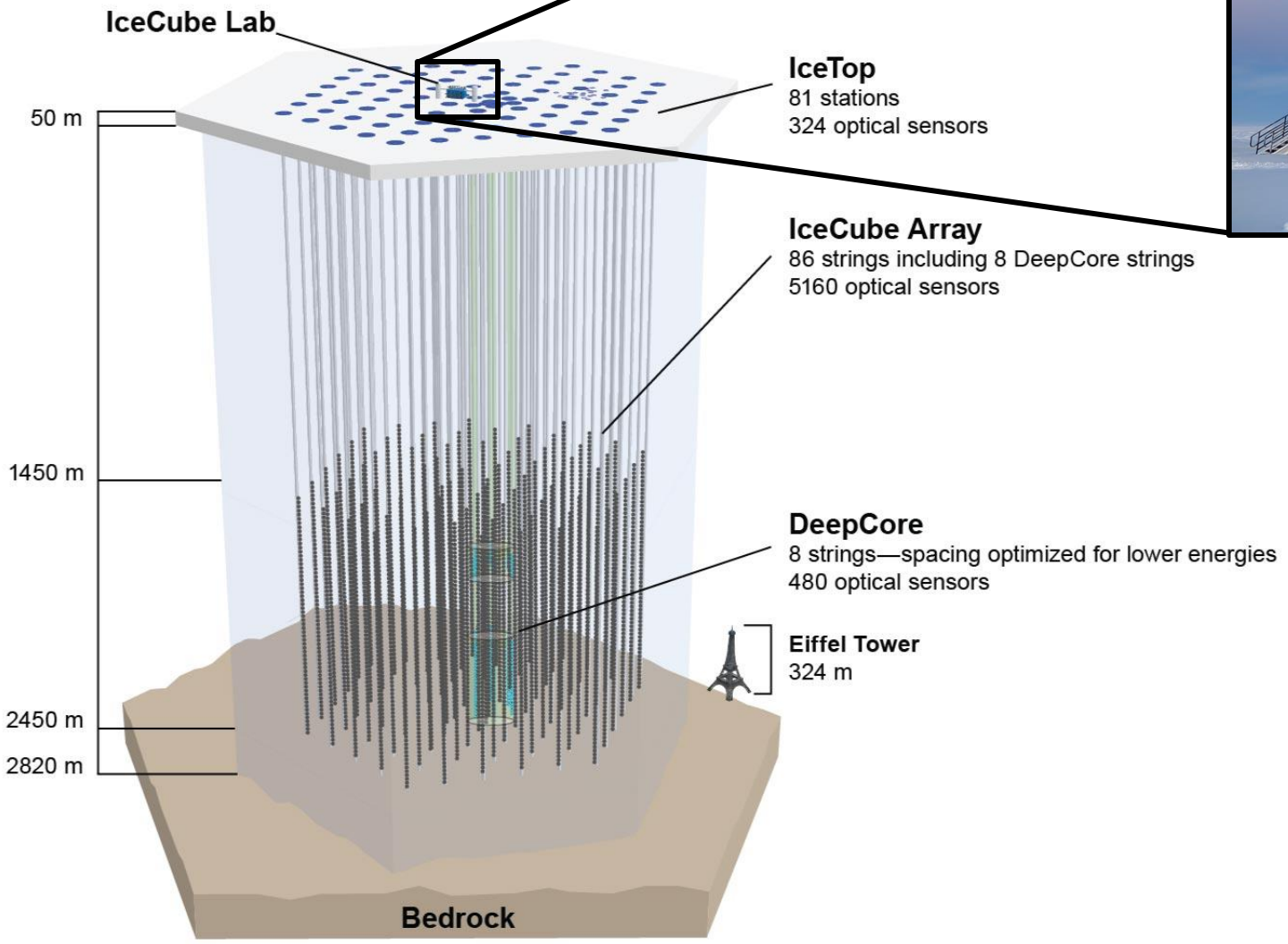
Motivations

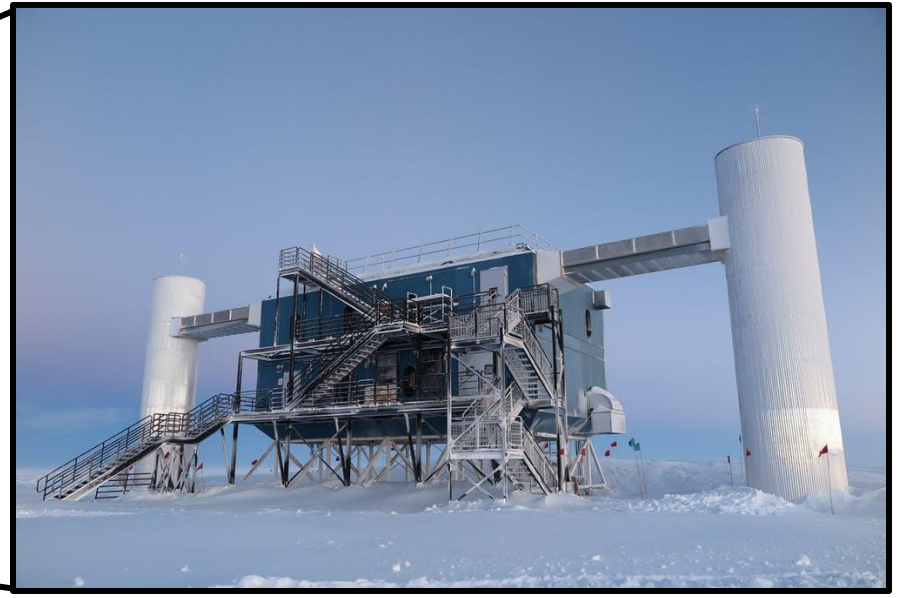
- Anomalous MiniBooNE nu-e appearance results
- Could be addressed with 3+1 sterile neutrino model
  - Non-interacting flavor states,
  - “Light” mass-squared splitting ~1eV^2
- Many, many, more anomalous results since then





IceCube

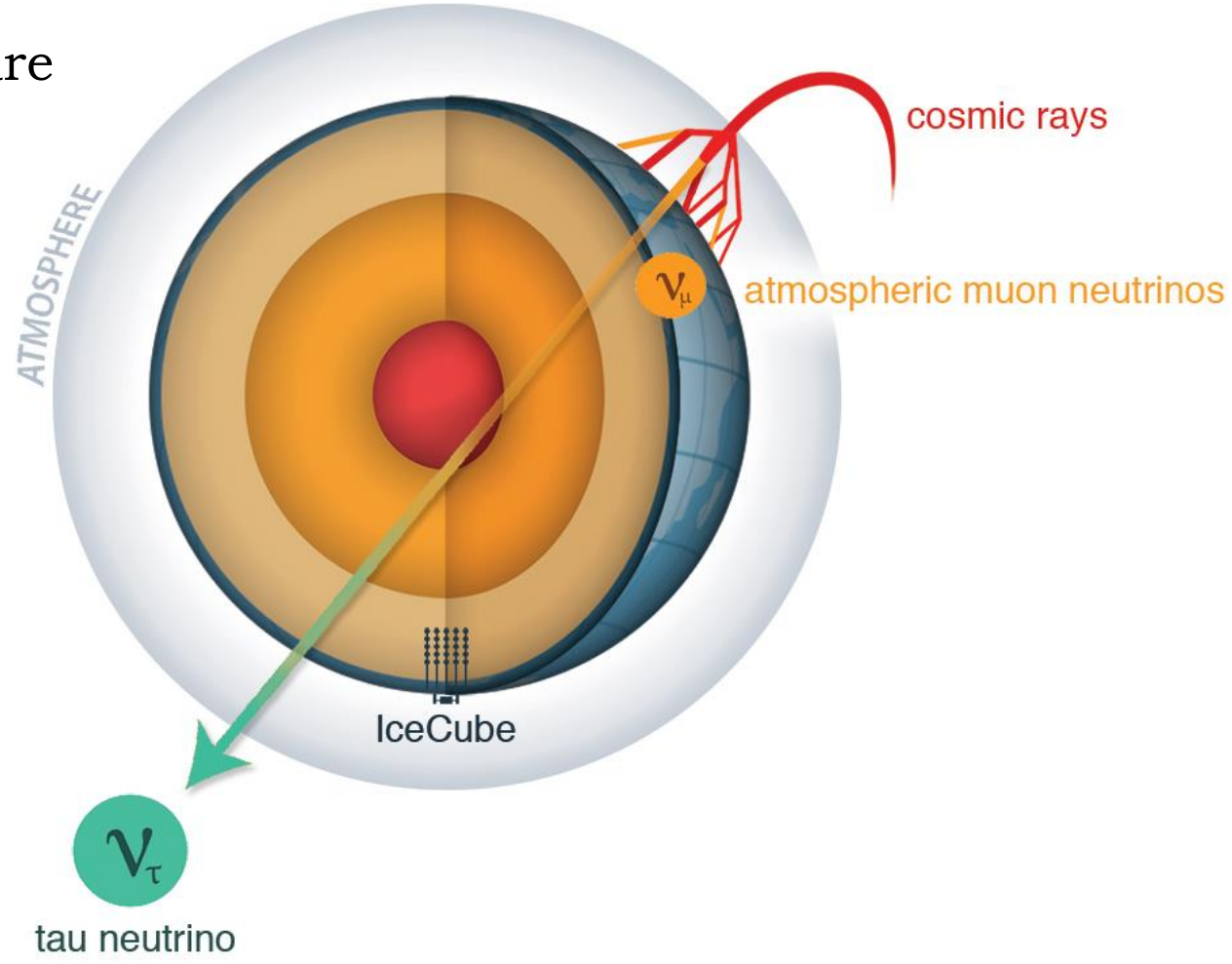




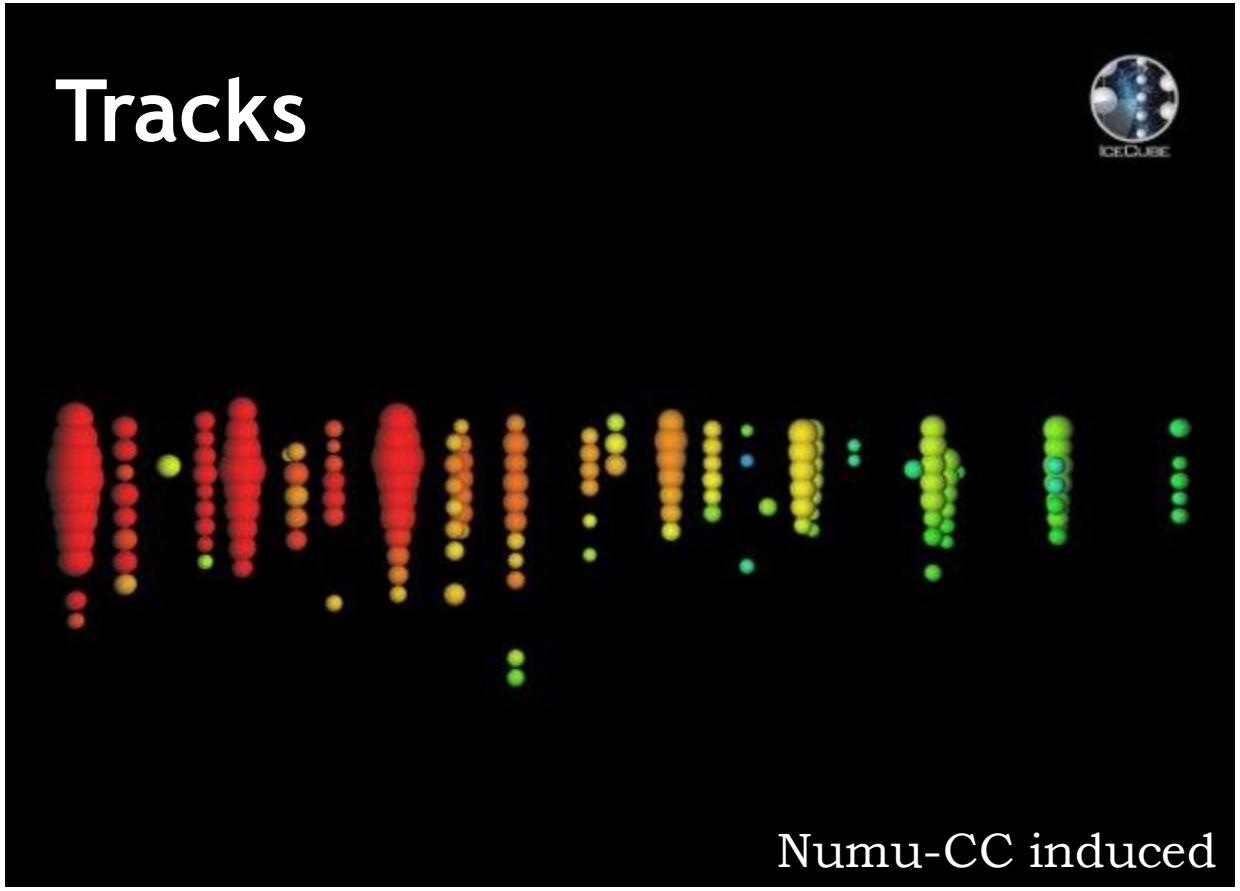
- Array of 5160 light-sensing DOMs instrumented in south pole ice
- More densely instrumented region called DeepCore – sensitive to low-E oscillations
- Sparsely instrumented section sensitive to higher-E oscillations
- Great for TeV PA

Oscillations in IceCube

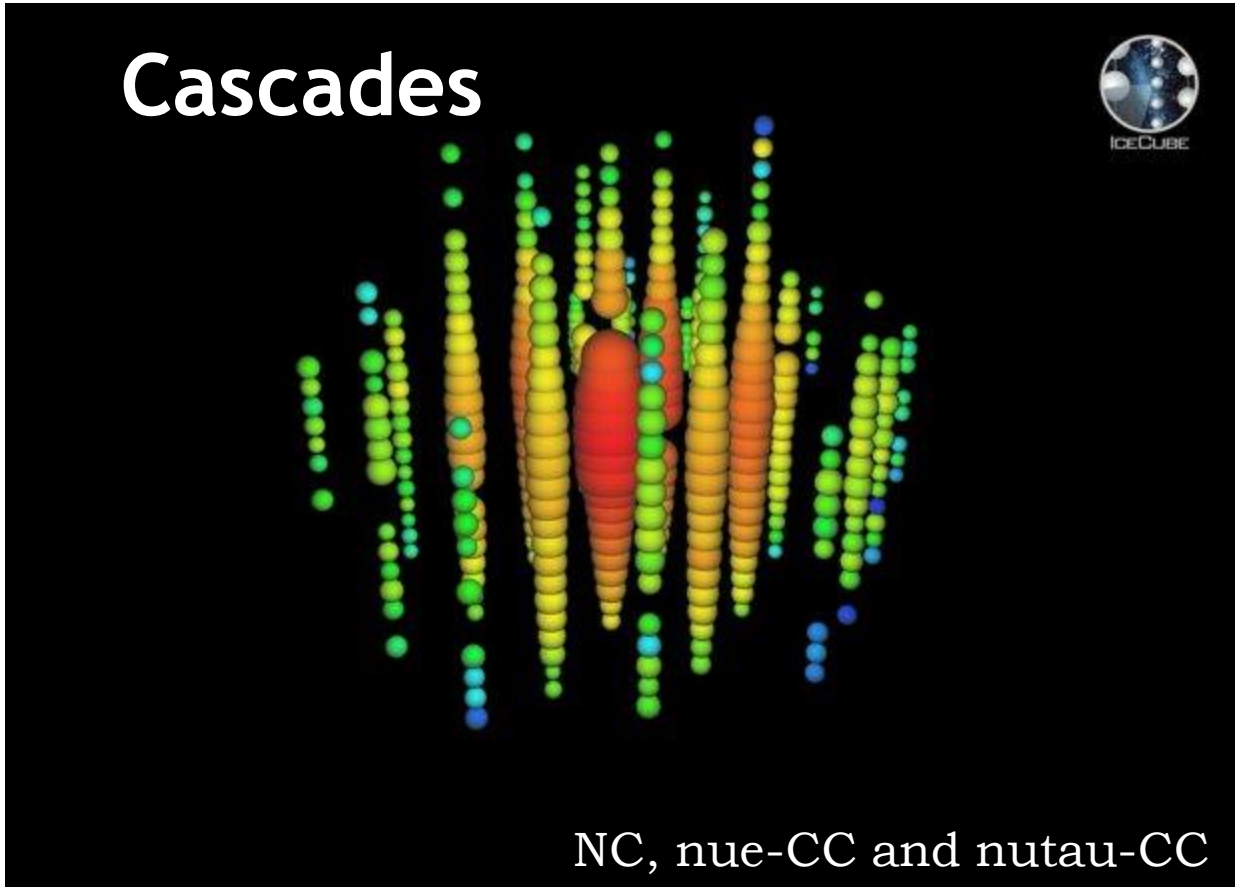
- The Earth is the baseline, cosmic rays are our neutrino source
- Energy spectrum effected by
  - Cosmic ray flux
  - Atmospheric conditions (temperature/density)
  - Hadronic production rates
- Muon-neutrino dominated
- Baseline from zenith angle
- Varying matter effects from different layers of the Earth



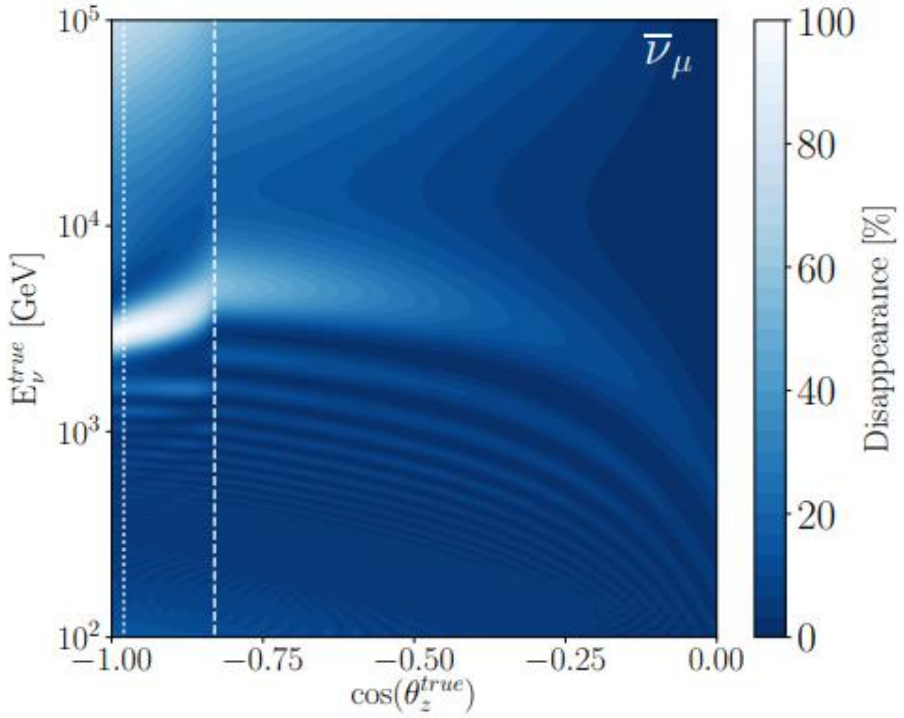
Event Morphologies

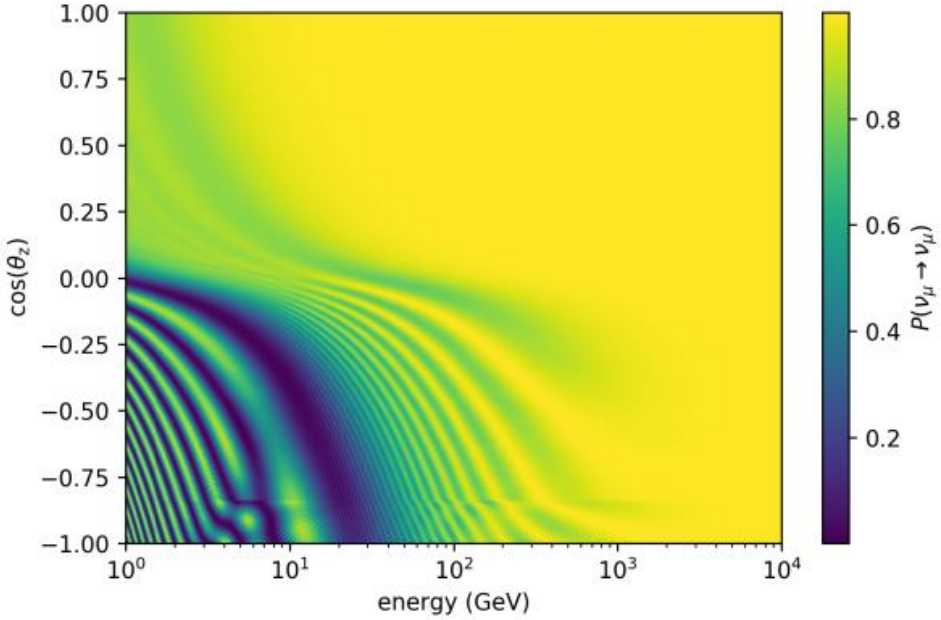


High stats, high angular resolution



High energy resolution





Dominant Oscillations

- High Energies
  - ~500GeV to 10 TeV
  - Whole detector
  - BSM oscillations dominate
  - Both atmospheric and astrophysical

- Low Energies
  - ~5-50 GeV
  - DeepCore
  - Both BSM and regular effects intermingle
  - Atmospheric nu

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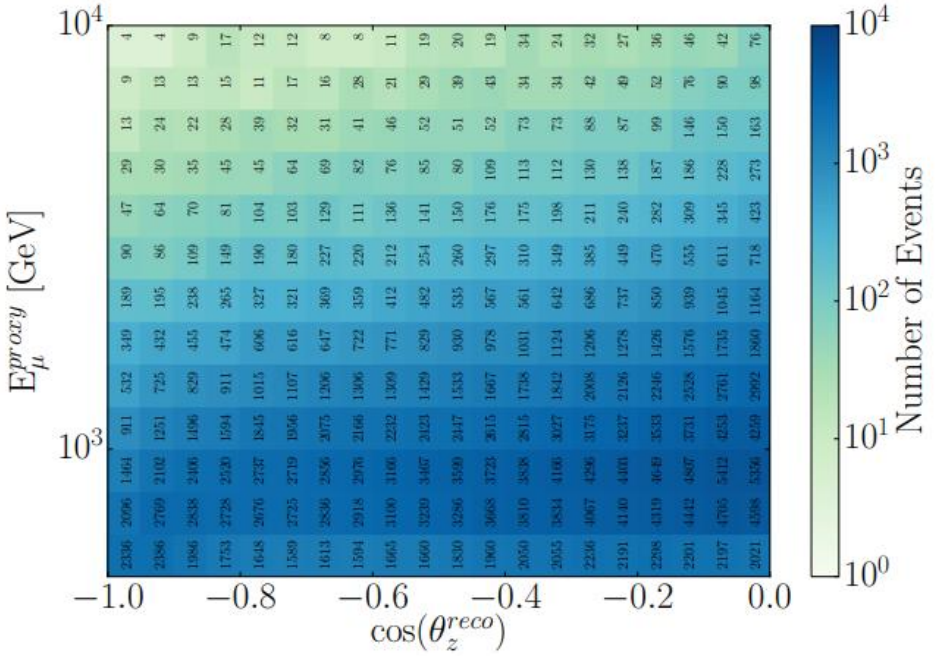
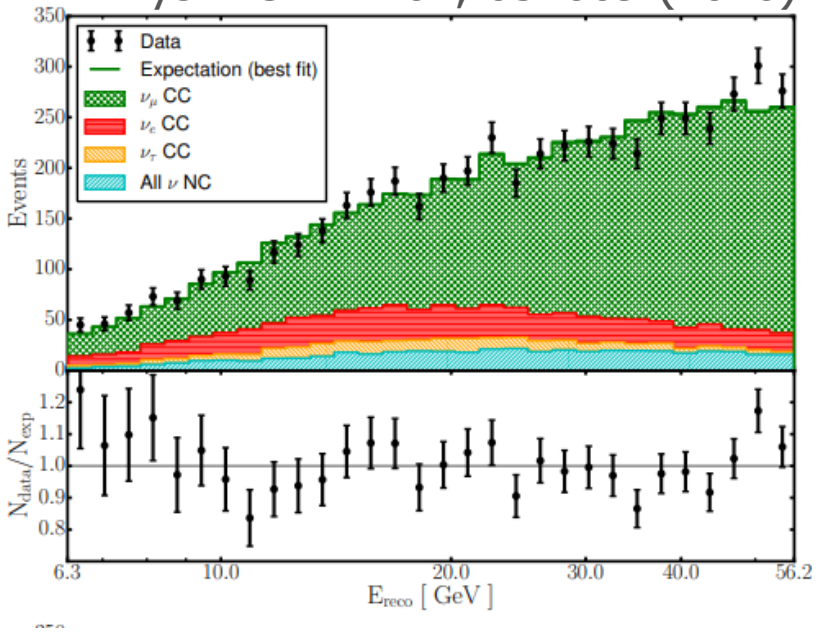
Past Analyses

Two Regimes

- High-energy, ~500GeV to 10 TeV, with
  - 8 years of IceCube
  - 305,735 up-going muon neutrino events
  - **High-energy cascades analysis on the way**
- Low-energy, ~5-50 GeV, with
  - 3 years of DeepCore
  - Approx 5118 events, assorted
  - **Full 8-year analysis with ~260k events, coming soon**
  - **IceCube Upgrade will improve low-E sensitivity with a dense infill**



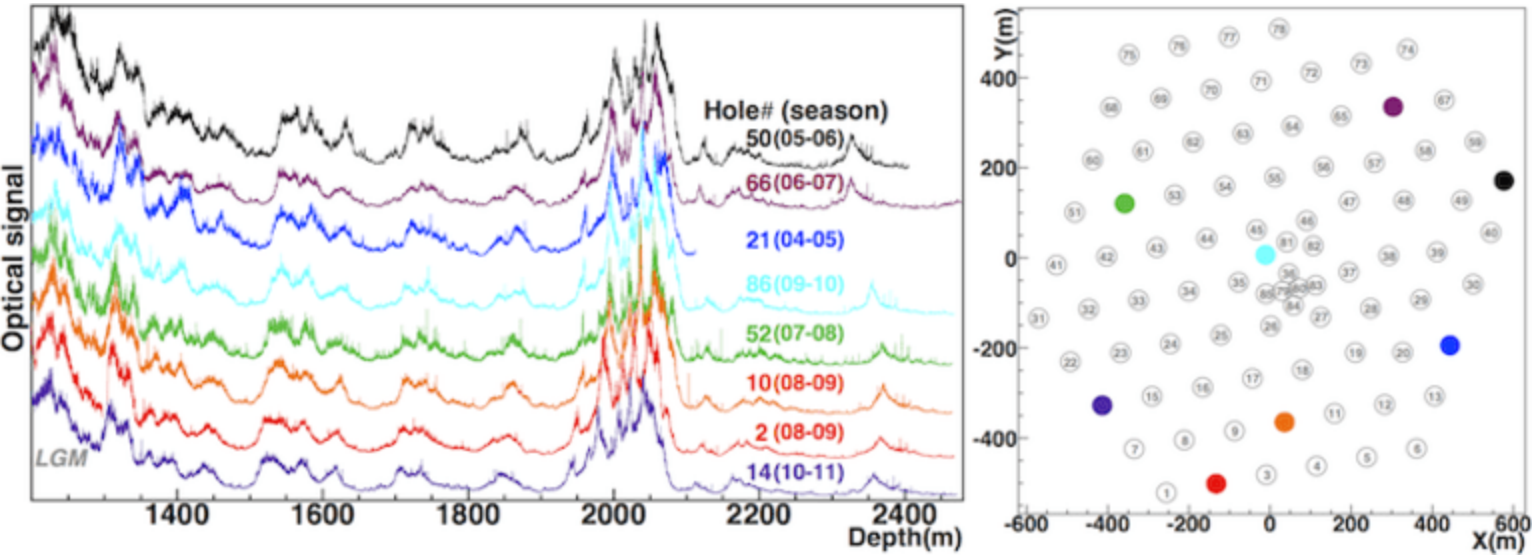
Phys. Rev. D 102, 052009 (2020)

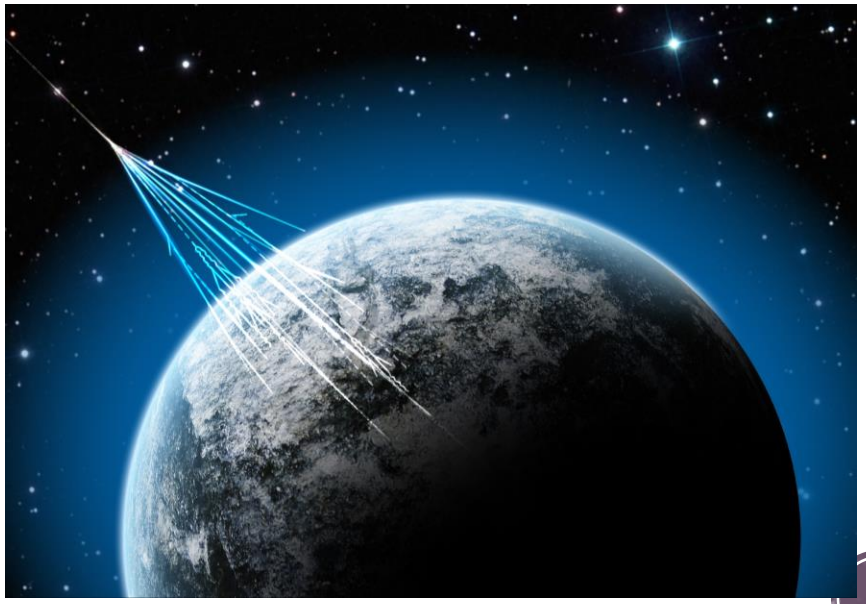


Phys. Rev. D 95, 112002 (2017)

Systematic uncertainties

- High-energy, ~500GeV to 10 TeV
  - Hole Ice, Absorption/Scattering
  - DOM efficiency
  - Cross sections
  - Flux normalizations, slope
  - Barr parameters, atmospheric density
  - Kaon energy loss rates
- Low-energy, ~5-50 GeV
  - Hole ice effects, Absorption/Scattering
  - DOM efficiency
  - Cross sections
  - Flux normalization, slope
  - nu/anu ratios



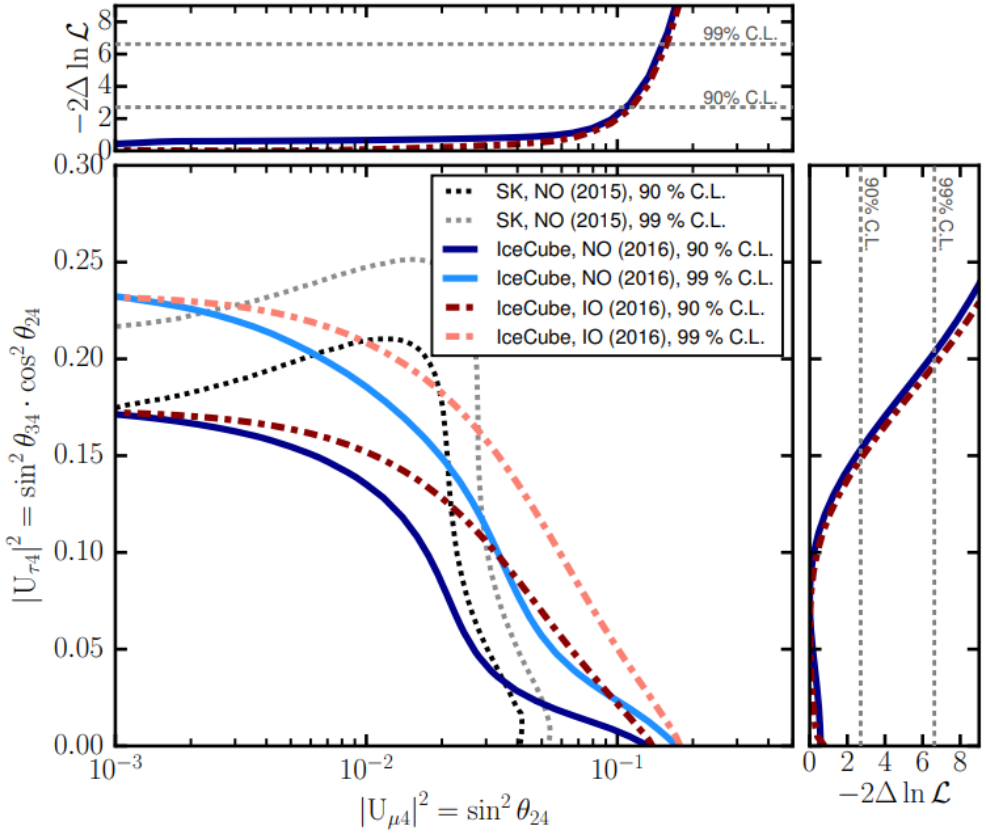


DeepCore Results (~5-50 GeV)

- Low-Energy DeepCore analysis
- All-flavor, all-interaction, up-going
- Fit to standard nu mixing parameters,

$$\Delta m^2_{32} = 2.52 \cdot 10^{-3}\ \mathrm{eV}^2, \sin^2\theta_{23} = 0.541$$

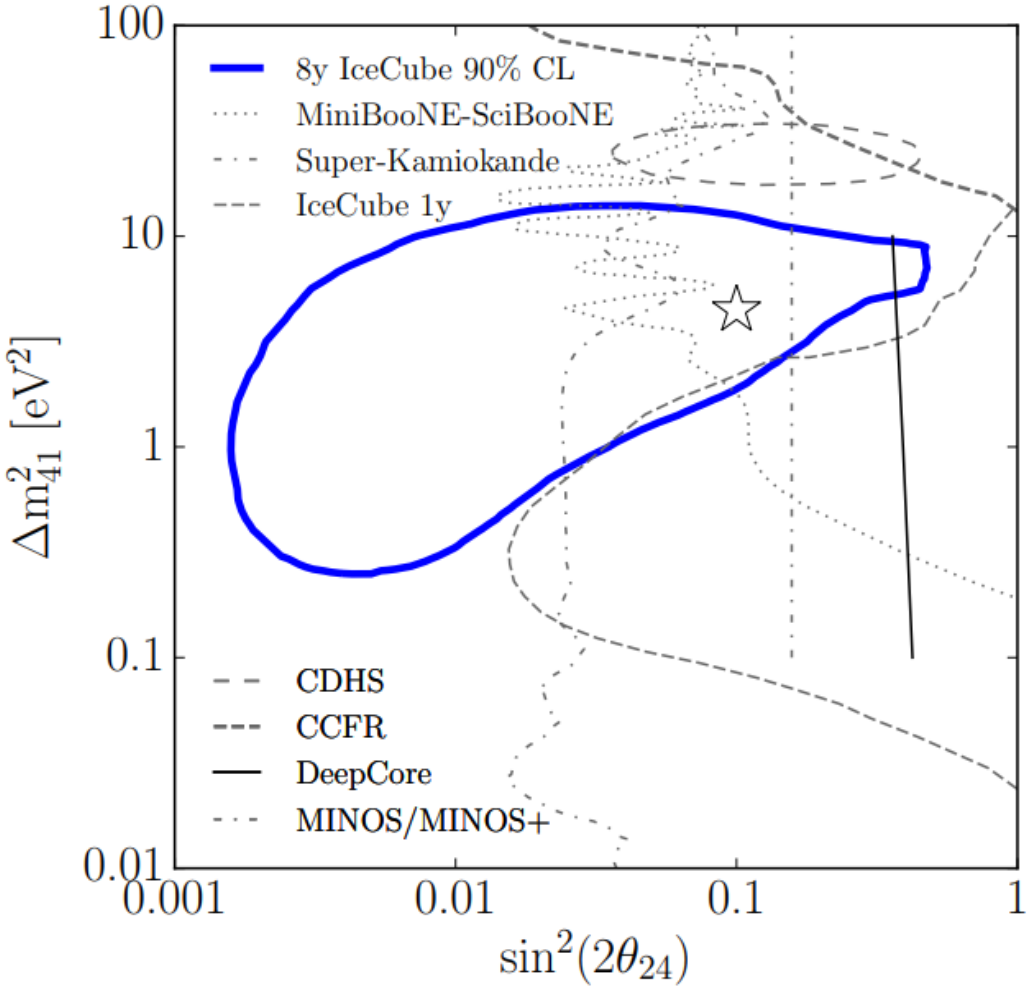
- First results consistent with 3-neutrino model
- Nuisance parameters fit near nominal values



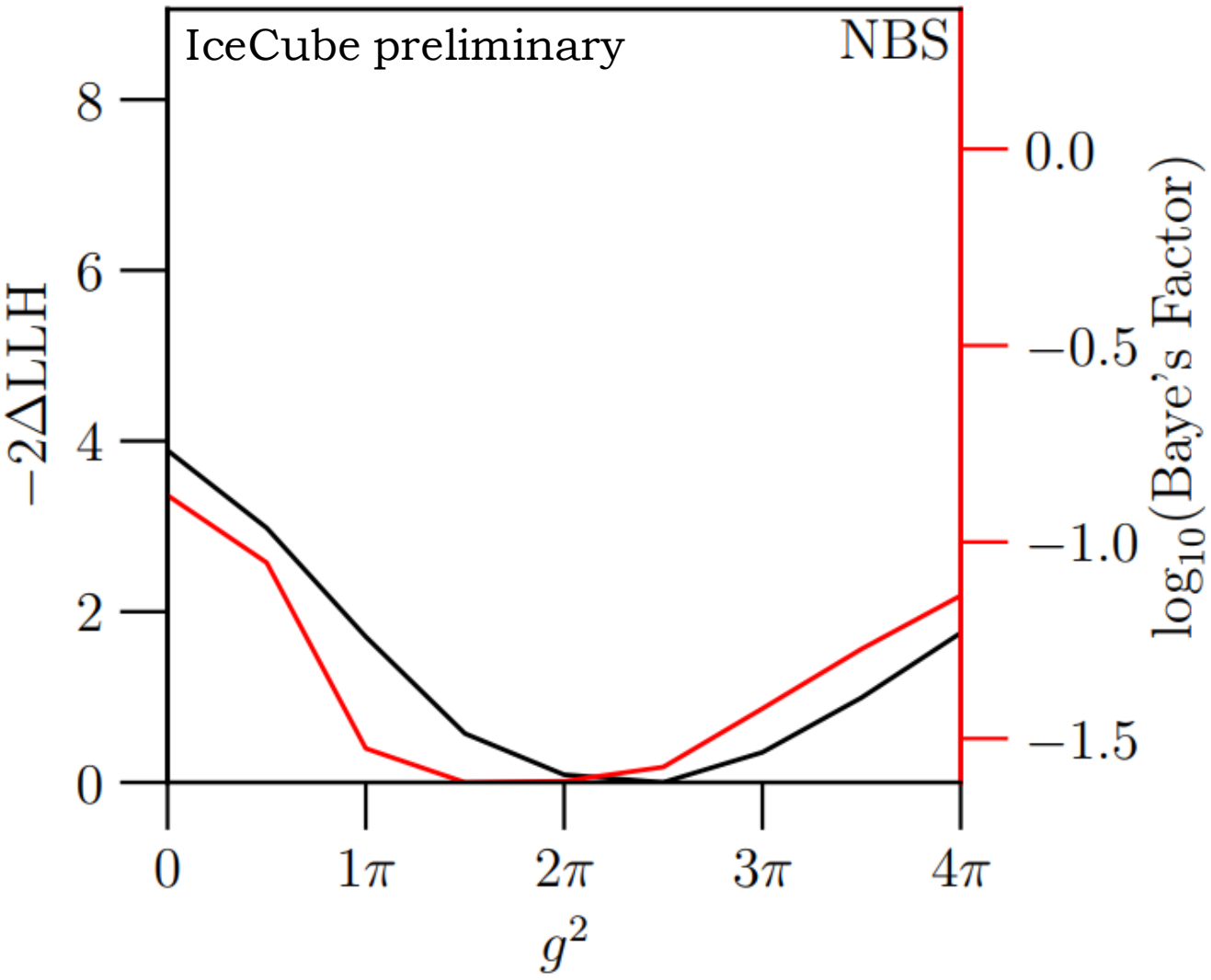
Phys. Rev. D 95, 112002 (2017)

High-E Results (~500 GeV – 10TeV)

- High Energy, matter effect
- Fits to all nuisance parameters
- Closed contour, best fit
  - $\mathrm{Sin}^2(2\theta_{24})=0.10$, $\Delta\, m_{41}^2=4.5\mathrm{eV}^2$
- Exclusion contour at 99% CL
- Potentially statistically weak signal hint at 90%CL
- Motivates cross-checking in other channels



Phys. Rev. D 102, 052009 (2020)
Phys. Rev. Lett. 125, 141801 (2020)



Sterile Decay Sensitivity

- An additional mass, flavor state with decay
- Same 8-year through-going muon sample
- Sterile state with lifetime

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

- Analysis fits to, $\Delta m^2_{41}, \sin^2(\theta_{24}), g^2$ frequentist and Bayesian model comparison

arxiv.org/abs/2110.02351

NonStandard Interactions

- Also, same 8-year through-going muon sample
- New dimension-6 operator to SM Lagrangian introducing neutrino NSI
- Modified neutrino flavor transition probability

$$P(\nu_\mu \to \nu_\tau) = \left|\sin(2\theta_{23})\frac{\Delta m^2_{31}}{2E_\nu} + 2V_d\epsilon_{\mu\tau}\right|^2 \left(\frac{L}{2}\right)^2$$

- Factor of 2 improvement beyond previous leading NSI constraints

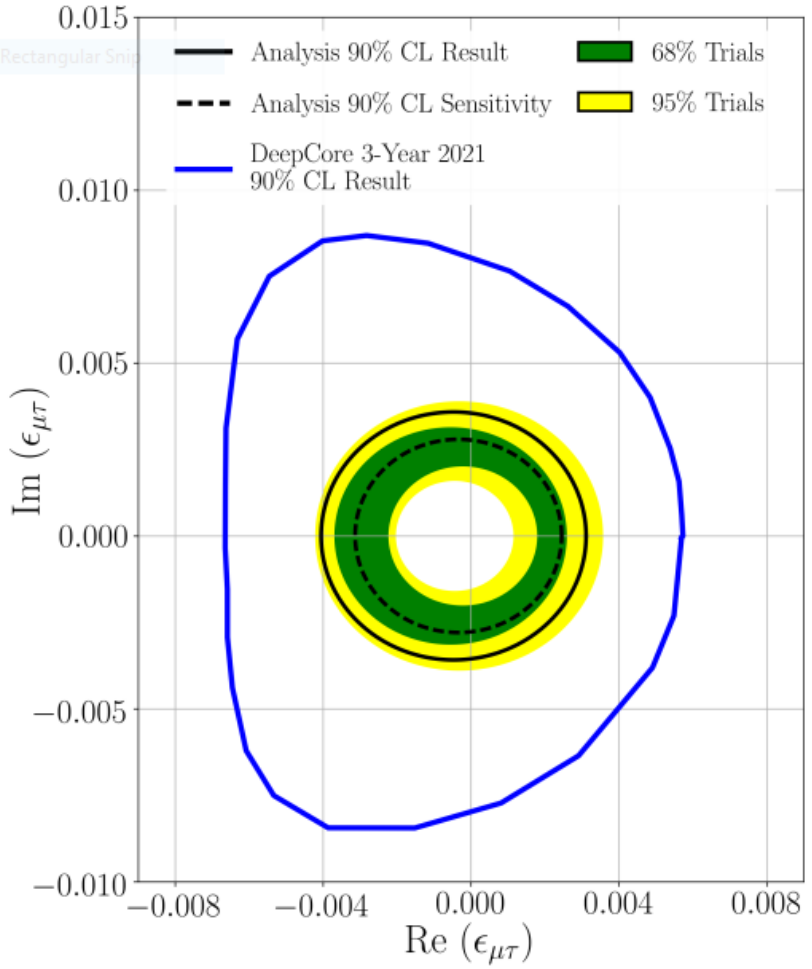


FIG. 4. ***Global comparison.*** Comparison of the analysis 90% CL sensitivity and result to the DeepCore 3-year, 5.6-100 GeV result [23]. Green and yellow regions represent 90% CL sensitivity envelopes of symmetrically-counted 68% and 95% (respectively) regions calculated from 1,000 pseudoexperiment trials.

Phys. Rev. Lett. **129**, 011804 – Published 29 June 2022

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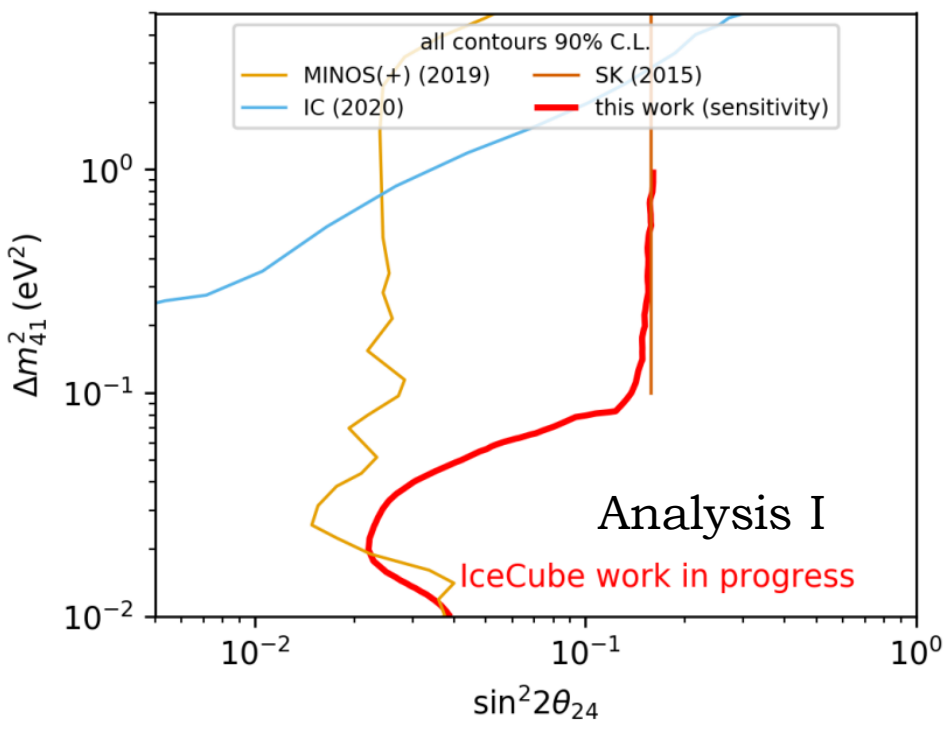
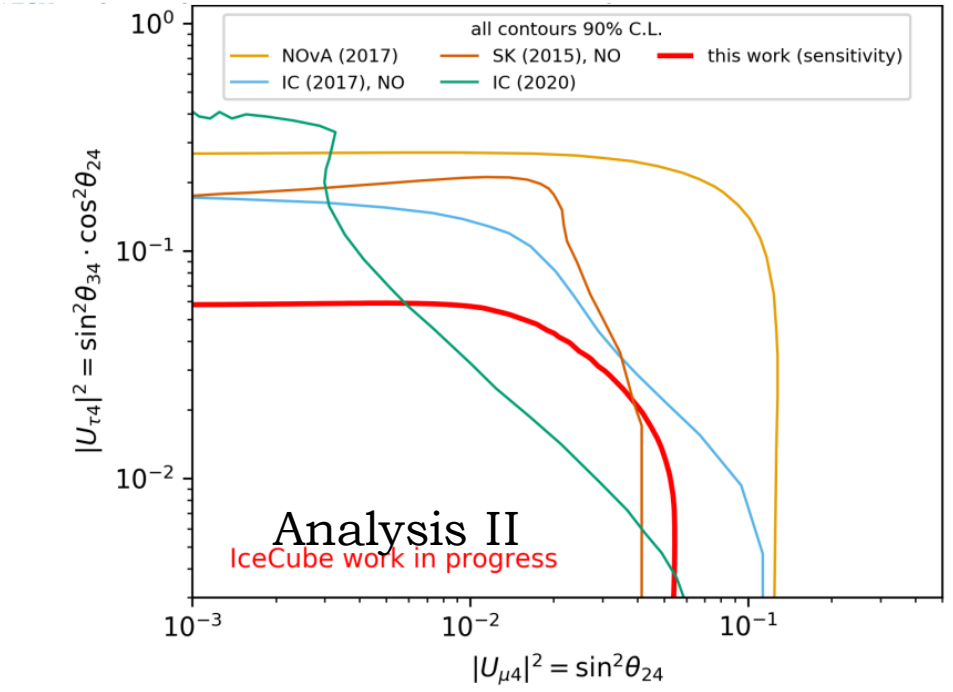
Upcoming analyses

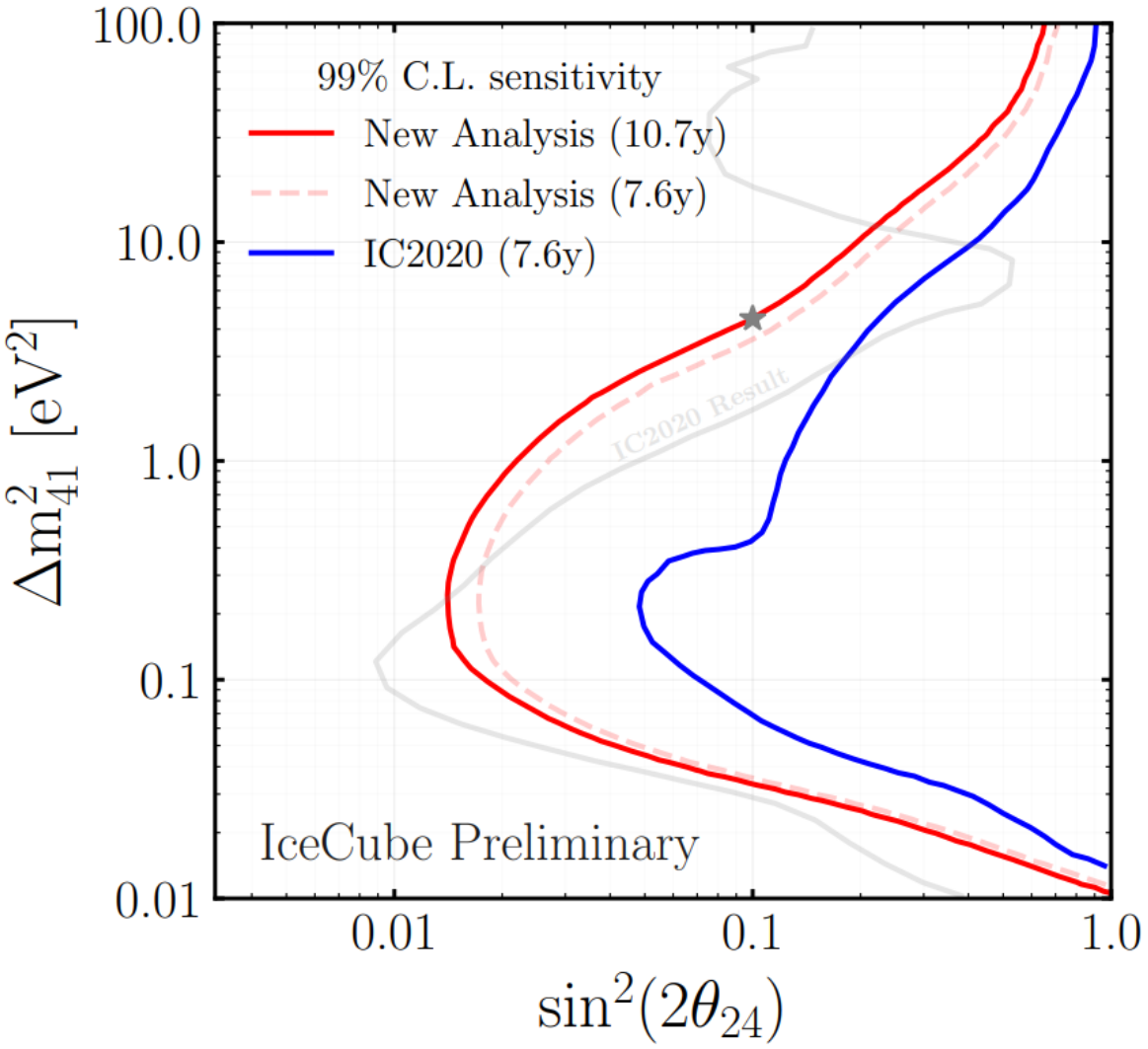
OscNext Analysis

- Full 8 years of DeepCore data
- 5-300 GeV analysis
- 260k events in total
- Multiple sub-analyses
  - In both, $\Delta m^2_{32}, \theta_{23}$ free
  - Analysis II - δ_{24} free
- Improved systematic uncertainties
  - Interpolation between GENIE and CSMS DIS cross-sections
  - DOM eff, hole/bulk ice





From a talk at VLVnT, A. Trettin



High Energy +Starting Muons

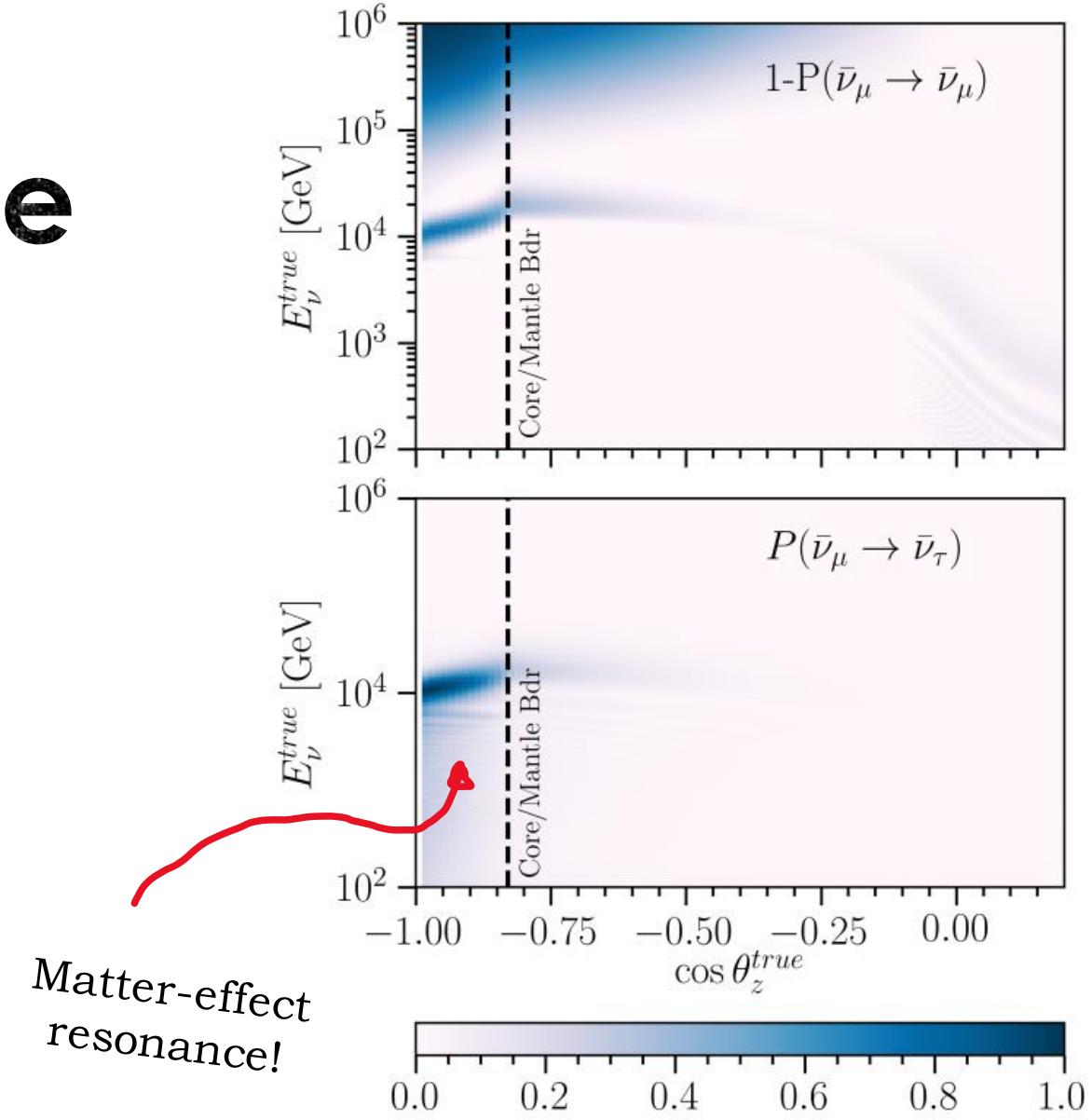
- Previously – suboptimal track energy reconstruction limited analysis sensitivity
- New BDT-based event selection and NN-based reconstruction
  - Improved energy range
  - Starting-event Inclusive
- Significant improvements to sterile neutrino oscillations sensitivity

A. Garcia – NuFact 2022

Tau Appearance

- $\nu_\mu \rightarrow \nu_s \rightarrow \nu_\tau$ resonance expected for non-zero θ_{24}, θ_{34}
- Up-going antineutrinos, passing through the Earth's core

- Leads to muon disappearance, tau appearance
- Potential for cascade appearance, direct tau appearance

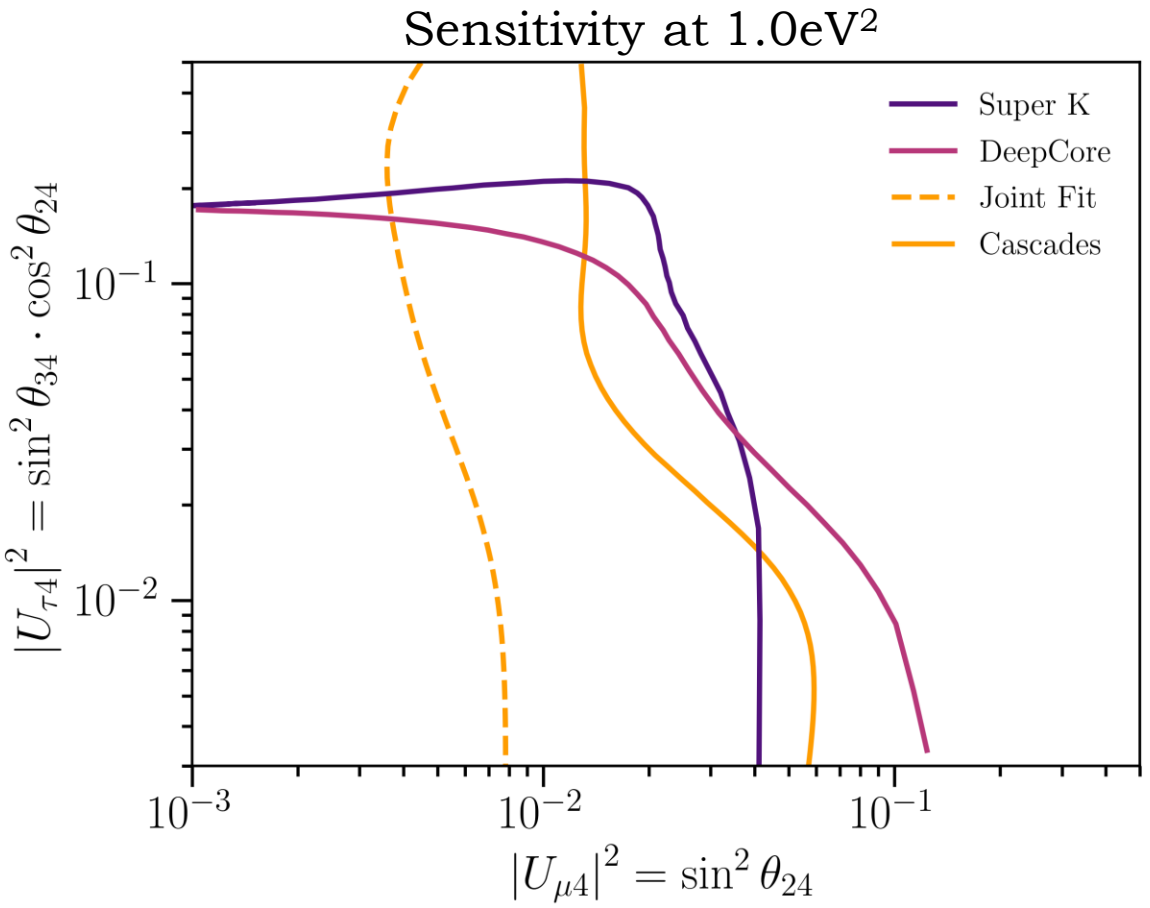


Matter-effect resonance!

Phys. Rev. D 105, 052001 (2022)

Calculated Sensitivity

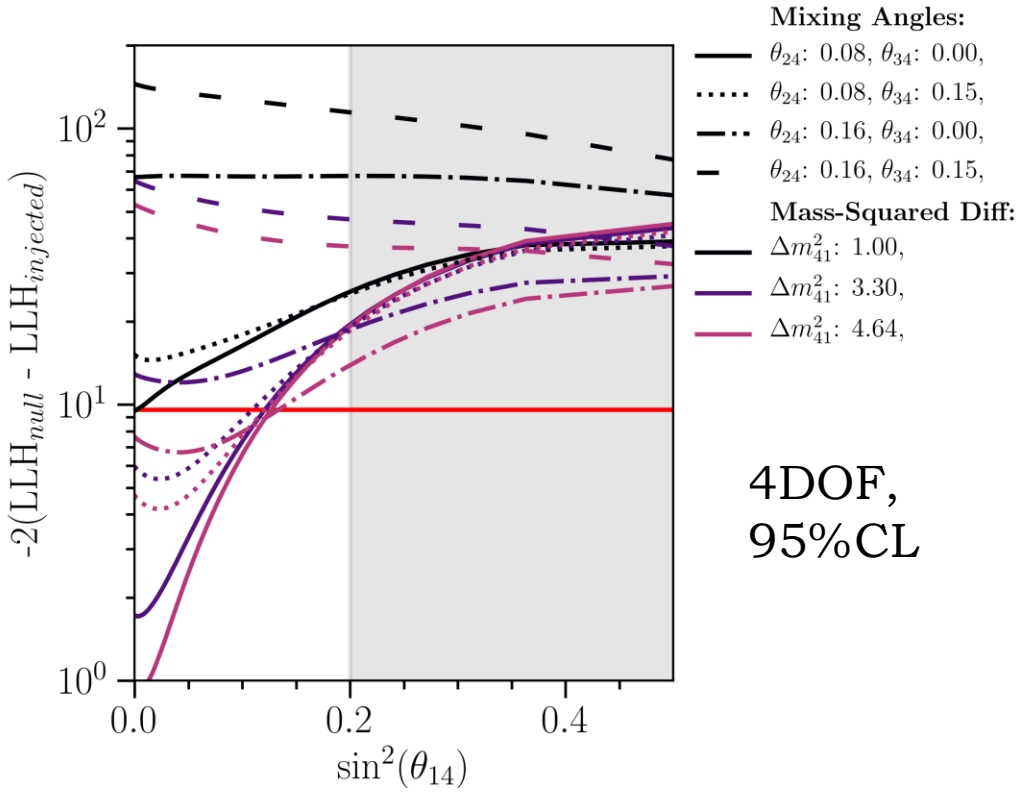
- Calculated using public IC effective areas, reconstruction efficiency
- Could discover signatures in ν_τ appearance
- Preliminary sensitivity
- Joint track + cascade fit for strongest constraints



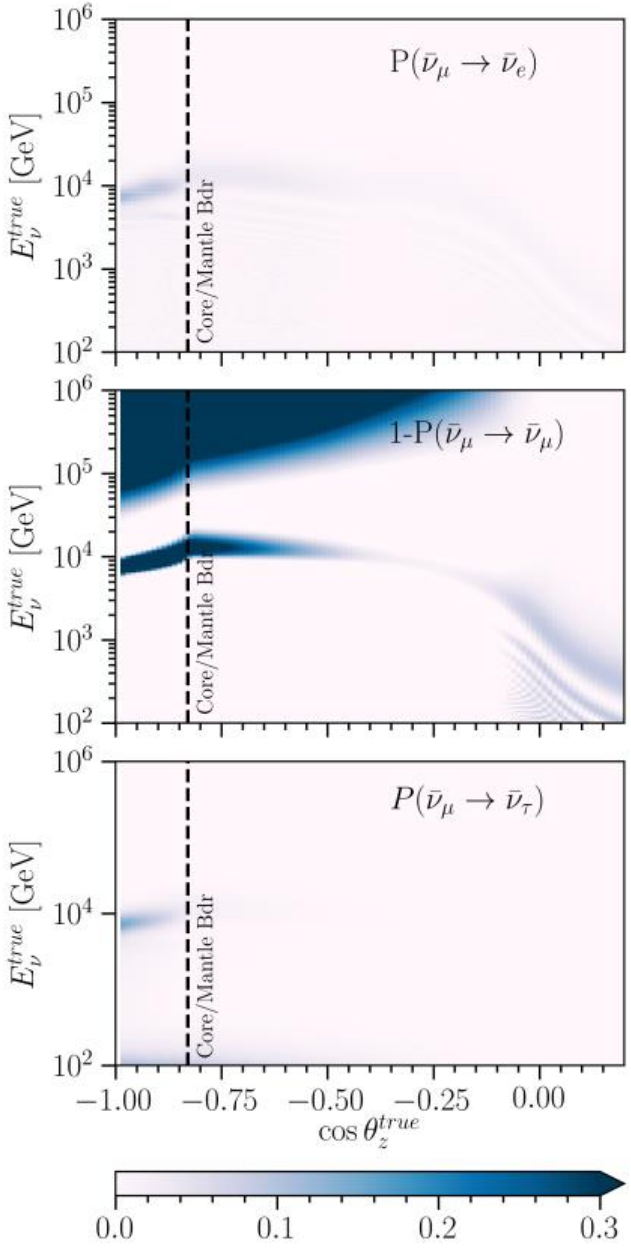
Phys. Rev. D 105, 052001 (2022)

Probing θ_{14}

- Recent BEST results further support gallium anomaly
- Non-zero $\theta_{14}, \theta_{24}, \theta_{34}$could lead to similar resonant ν_e, ν_τ appearance
- Will be able to probe BEST anomaly



4DOF, 95%CL



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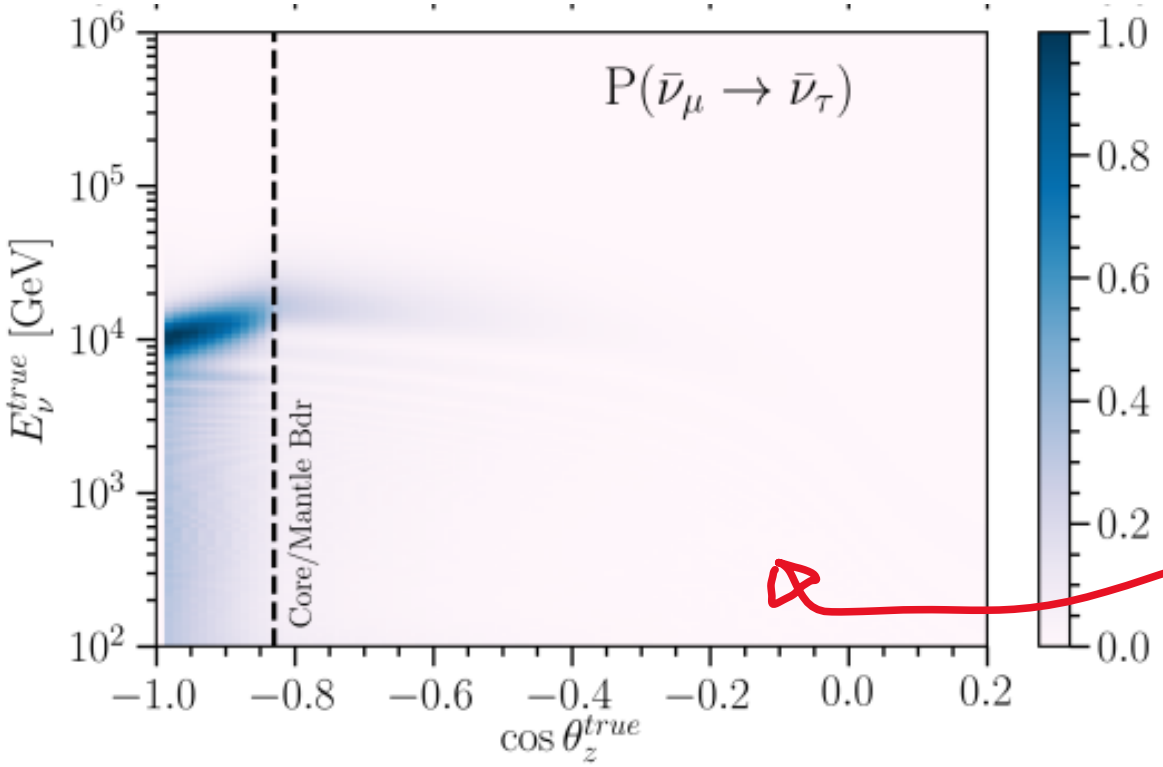
Outlook

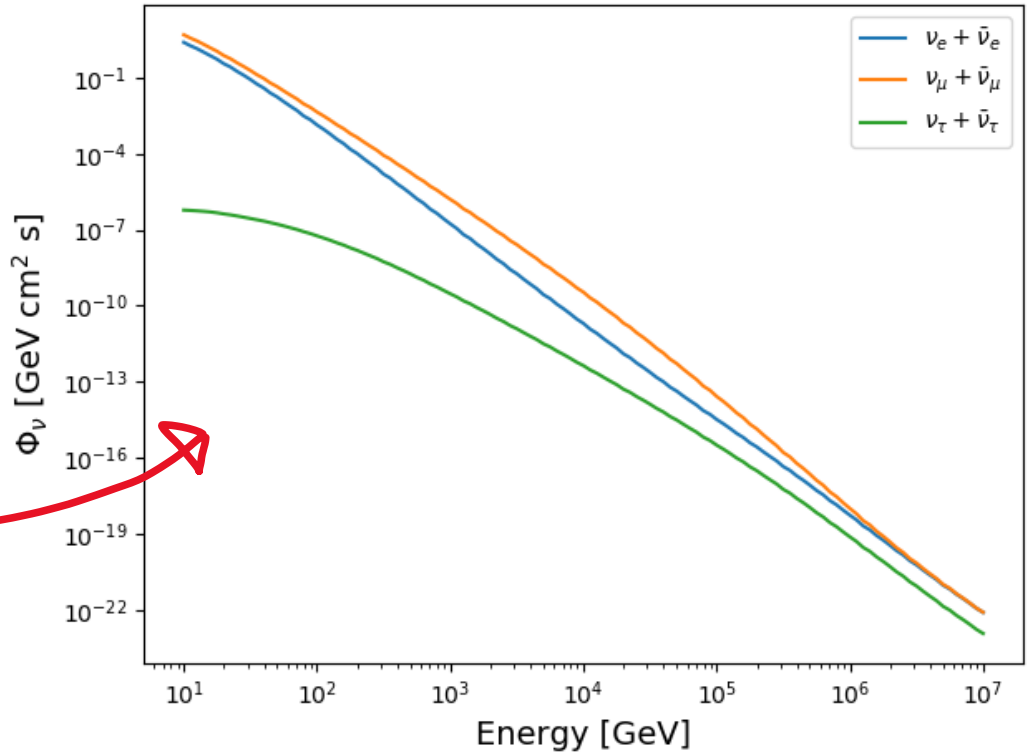
- Upcoming "low"-energy IceCube analysis will improve upon previous 3yr DeepCore analysis
- Upcoming High-Energy analyses incorporating cascade events
- IceCube poised to make direct tau-appearance measurement
- IceCube will be able to probe the BEST anomaly

Thank you for your time!
Questions?

Expected True Fluxes

- MCEq (arxiv 1503.00544)
  - Cosmic ray flux model, Hillas Gaisser H3a
  - Numerically evaluate Matrix Cascade Equations describing air showers
    - SYBILL 2.3c
  - Get neutrino rates at the Earth's surface

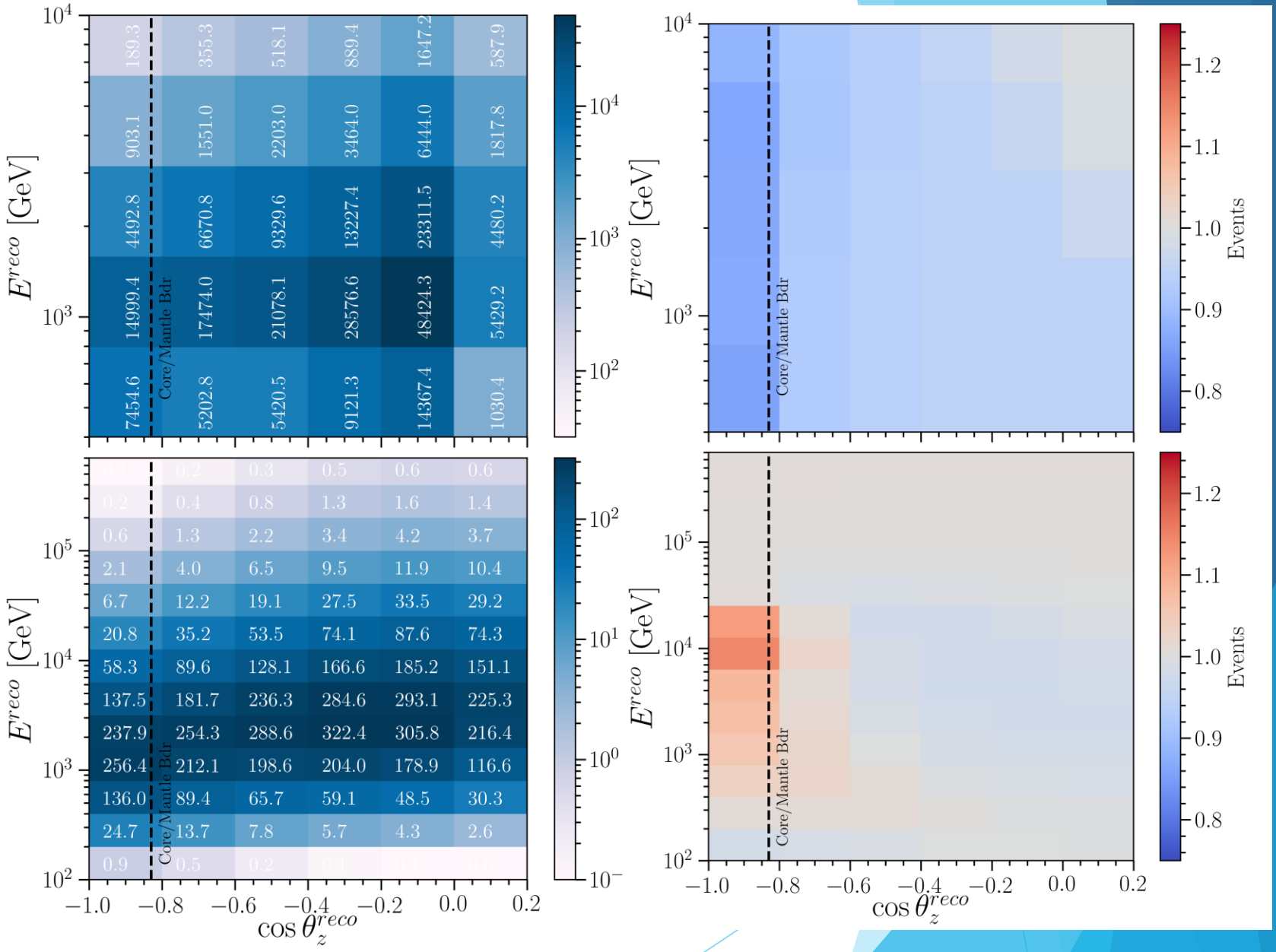




- nuSQuIDS (arxiv 2112.13804)
  - Neutrino propagation, oscillation
  - Absorption, tau regeneration
  - Example made with possible sterile neutrino oscillation params

Expected Rates

- Apply publicly available IceCube effective areas for cascades
- Smear fluxes according to published reconstruction efficiencies
- IceCube one-year sterile MC data release used for event rates of tracks



3-neutrino predictions

Sterile / Null Ratio