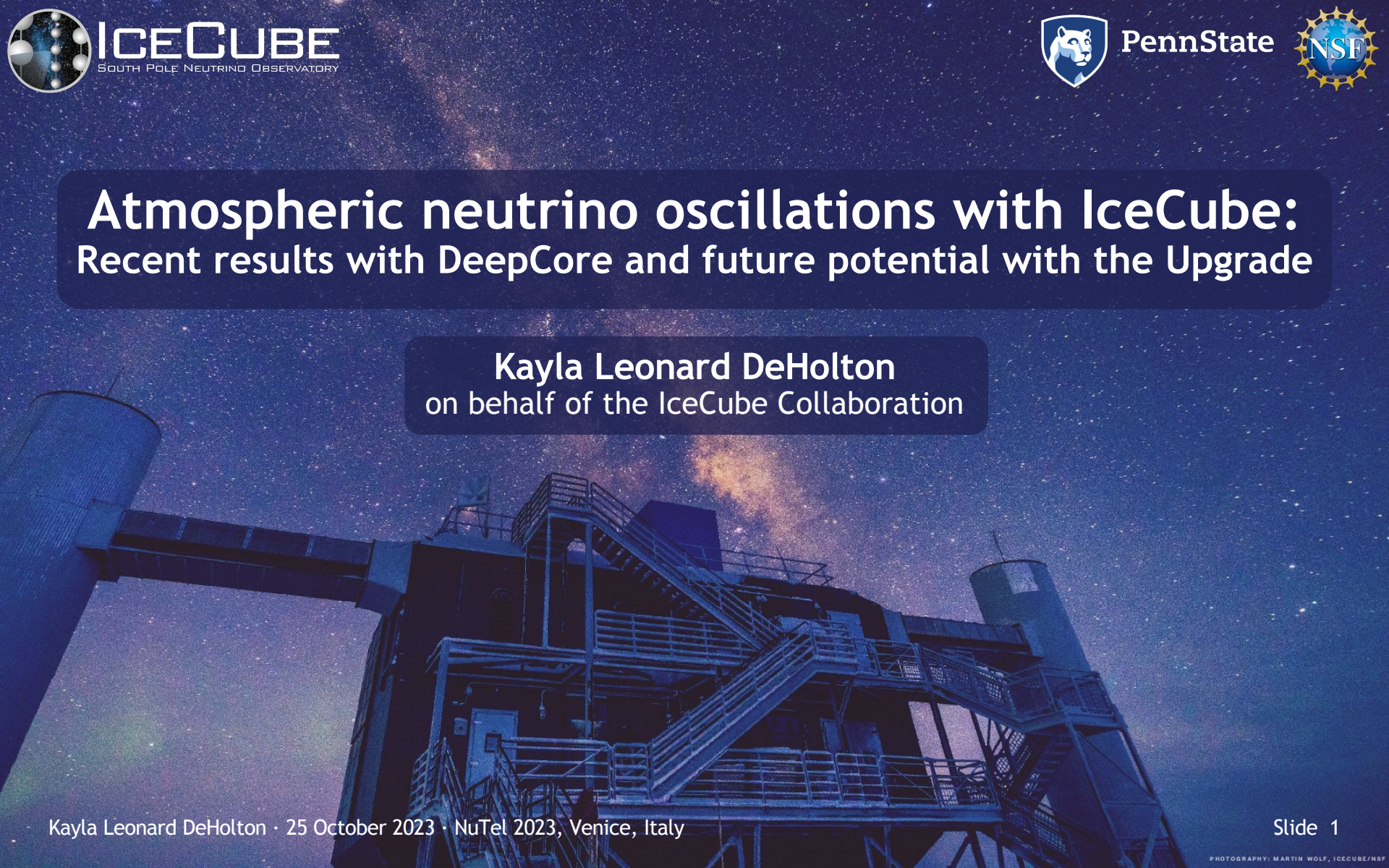
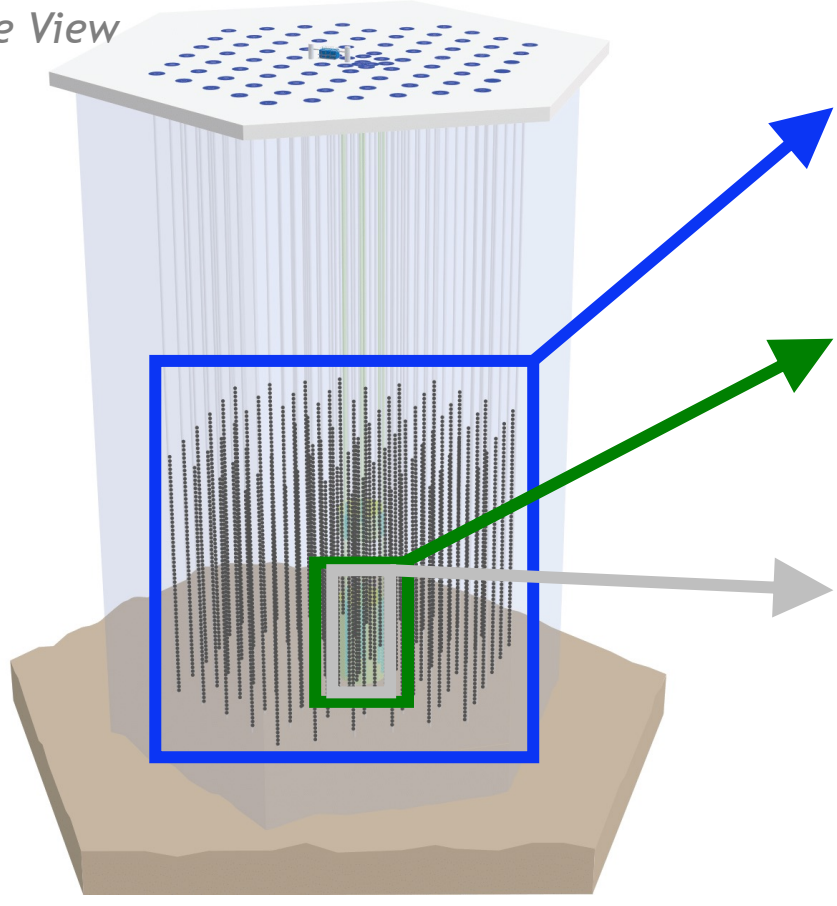
Atmospheric neutrino oscillations with IceCube:
Recent results with DeepCore and future potential with the Upgrade

Kayla Leonard DeHolton
on behalf of the IceCube Collaboration



IceCube, DeepCore, and the Upgrade



IceCube

- 1 km^3 detector located at the South Pole
- 5,160 modules across 86 strings
- Optimized for TeV-PeV

DeepCore

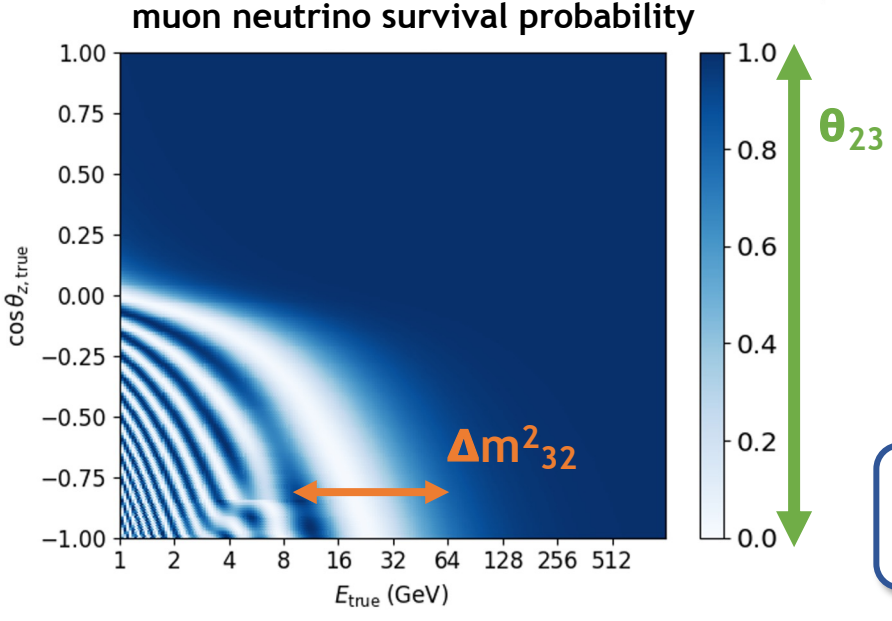
- 8 dedicated strings with denser spacing
- High quantum efficiency modules
- Optimized for GeV
- In operation for more than a decade

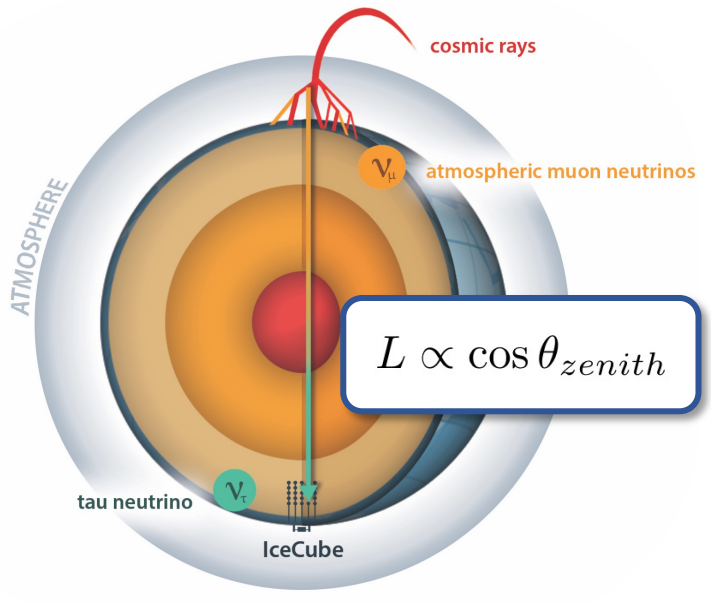
Upgrade

- 7 additional strings with denser spacing
- Multi-PMT modules
- Fully-funded & will be constructed in 2025-26

Atmospheric Neutrino Oscillations

- Neutrinos produced in cosmic ray air showers are dominated by $\overline{(\nu_\mu)}$, then $\overline{(\nu_e)}$
- Predominantly ν_μ oscillating to ν_τ
- Strongest oscillation signal near 25 GeV





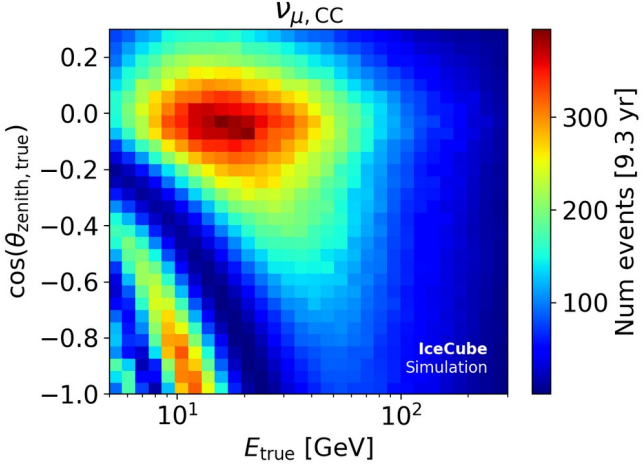
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \frac{\Delta m^2_{32} L}{E}\right)$$

Typical Analysis Procedure

- Remove backgrounds of atmospheric muons and detector noise
- Apply flux + oscillations + cross sections + detector response
- Perform a binned analysis varying physics & nuisance parameters in templates

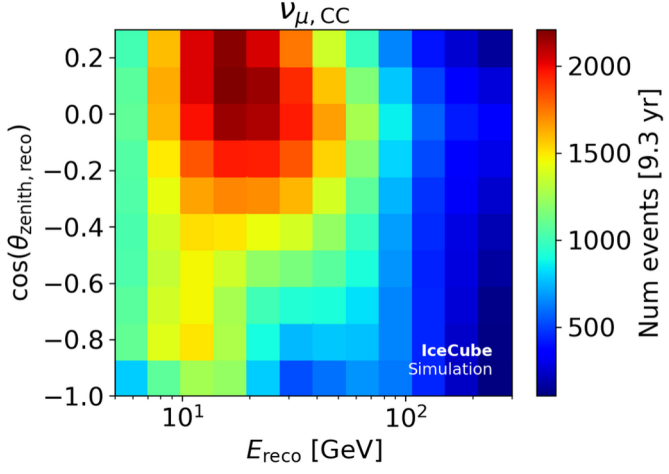
True

Oscillation peaks and valleys are visible in truth level information



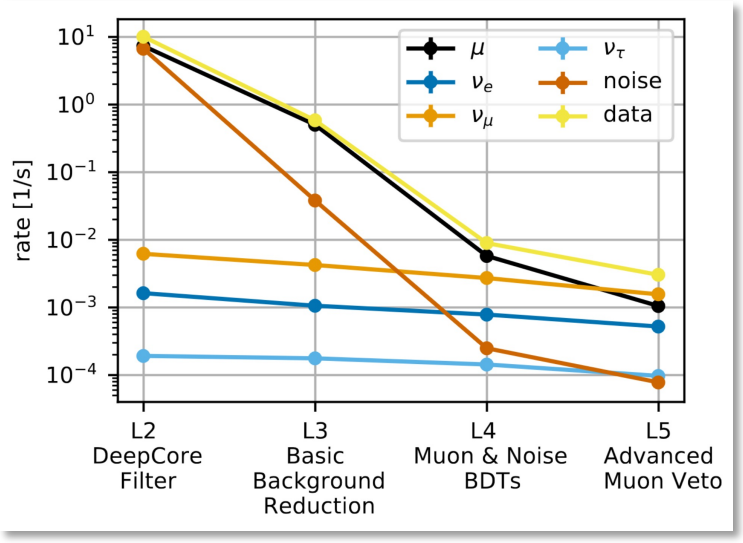
Reconstructed

Smeared out by detector resolution and finite analysis binning



Current Generation Samples

- Common:
  - Event selection to suppress backgrounds by several orders of magnitude
  - Improved treatment of many systematic uncertainties
  - Analysis tools
- Then sample specific reconstructions and analyses:



Sub-sample	Full Sample
High quality events	High statistical power
~22k events	~150k events
Fast reconstructions can only be applied to certain high-quality events	CNN-based reconstruction [J. Micallef, DOI:10.25335/pg10-es32] can be applied to almost any event
Published this year: PRD 108, 012014 (2023)	**Publication preparation in progress** Preliminary results shown next

Systematic uncertainties considered

- **Flux uncertainties**
  - Cosmic ray spectrum
  - Pion & Kaon production uncertainties (Barr et al 2006)

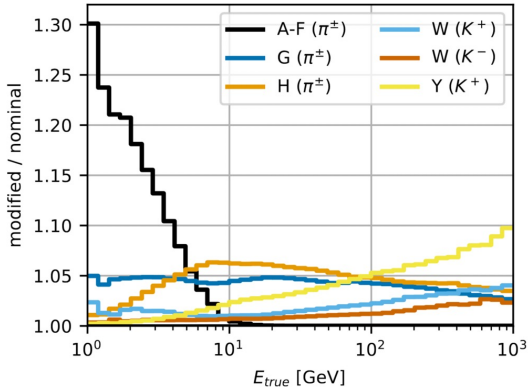
- **Cross sections**
  - DIS cross section transformation between GENIE and CSMS
  - Axial mass uncertainties for non-DIS events

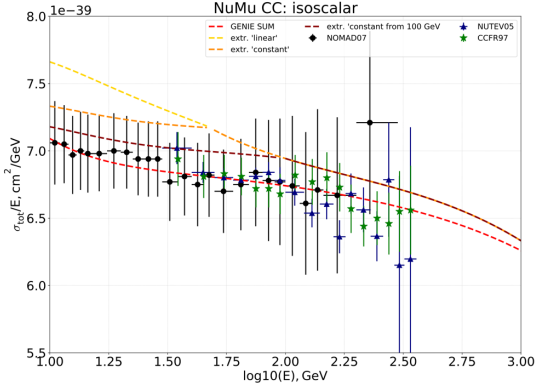
JHEP **08**, 042 (2011)

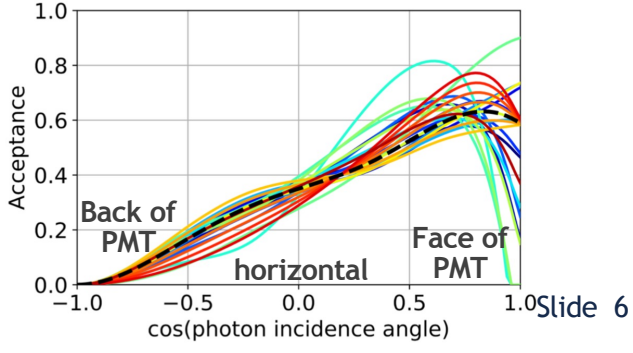
- **Detector and Ice Properties**
  - Improved treatment for modeling the optical properties of ice
  - PMT charge calibration

- **Overall normalizations** for neutrinos and muons

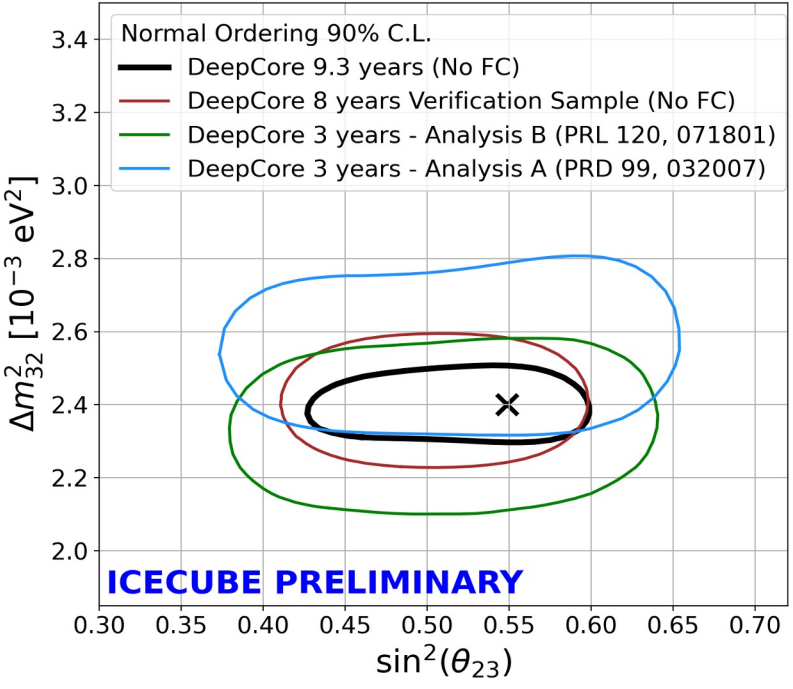
→ In total, about **40** systematic parameters are studied; approx. half are included as nuisance parameters in fit







Latest measurement of atm. oscillation parameters



- High statistics and high purity
  - 150,000 neutrinos
  - >99% purity
- Competitive with long baseline accelerators
- Complementary to accelerator measurements
  - probes higher energies
  - deep inelastic scattering regime
  - above tau lepton production threshold for ν_τ CC
  - different systematics at production and detection

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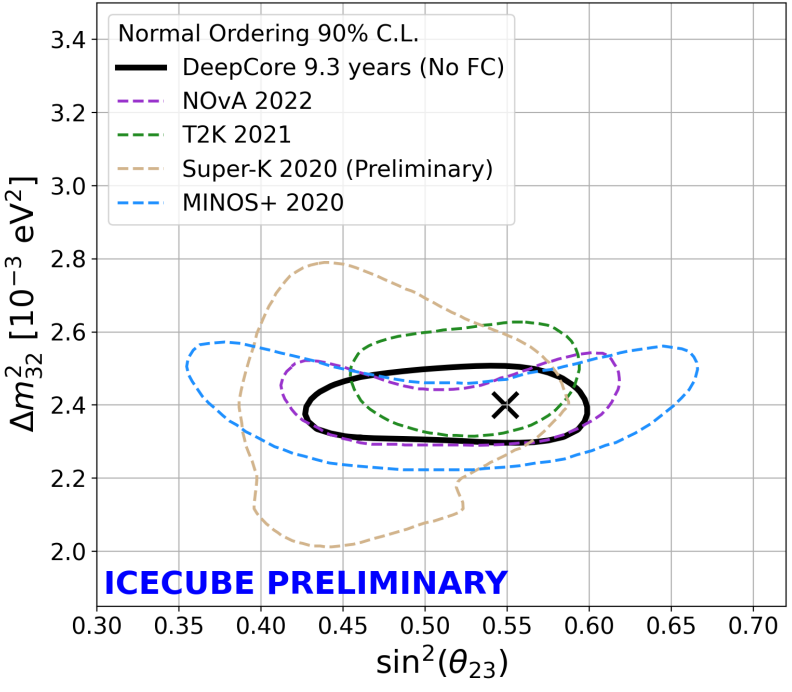

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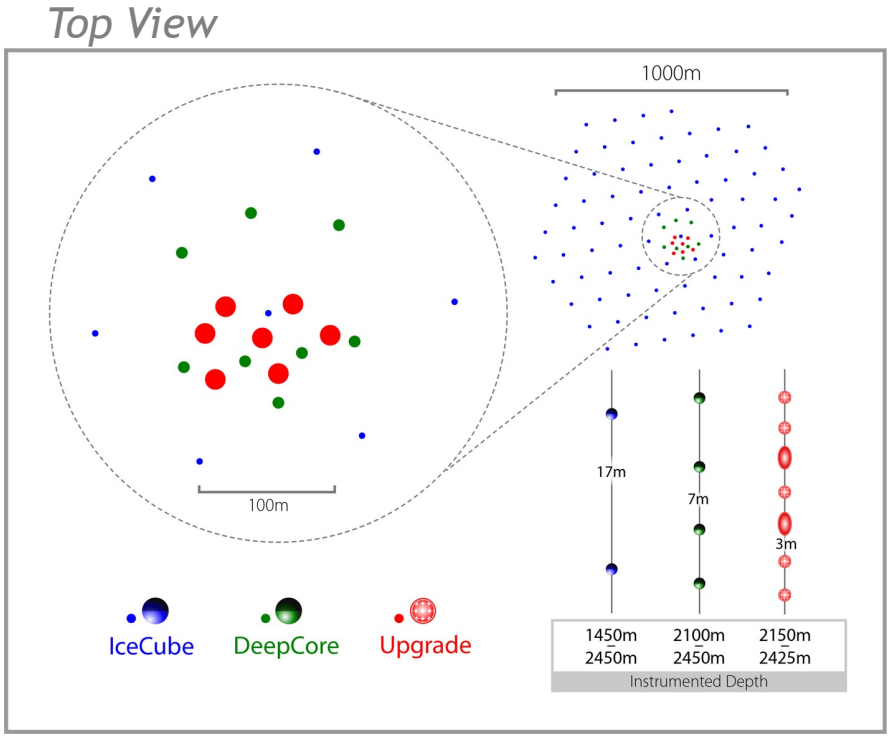
IceCube, DeepCore, and the Upgrade



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The IceCube Upgrade

Advantages: Higher density of modules & multi-PMT info

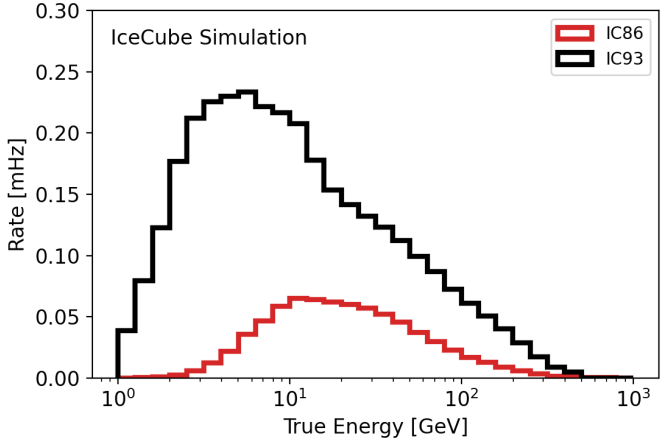
- Lower energy detection threshold
- 3-5 times more events in energy range of interest
- More hits (information) ⇒ better reconstruction and classification

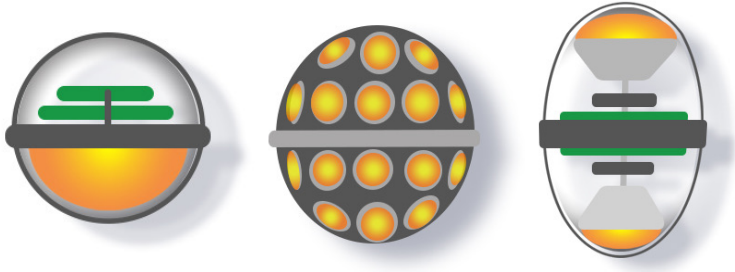
Challenges: Higher rates

- More noise with multi-PMT modules
- Higher background rates

New ML-based tools to address higher rates (GNNs) :

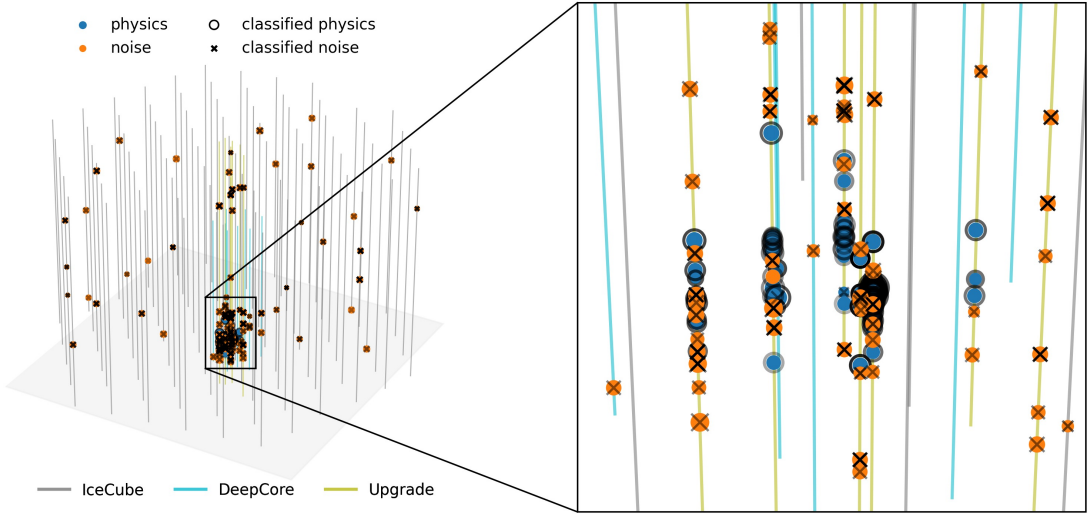
- Very efficient at removing noise
- Very fast to run which can handle the higher rates





GNN cleaning, reconstruction, and classification

- GraphNeT: Graph neural networks for neutrino telescope event reconstruction
  - Open source framework: https://github.com/graphnet-team/graphnet
    DOI:10.21105/joss.04971
- Connects each pulse to its 8 nearest neighbor pulses
  - GNNs can easily handle the irregular geometry of the strings
- Used for many tasks
  - Reject noise hits
  - Rejecting backgrounds
  - Reconstructing energy and direction
  - Classifying ν event types

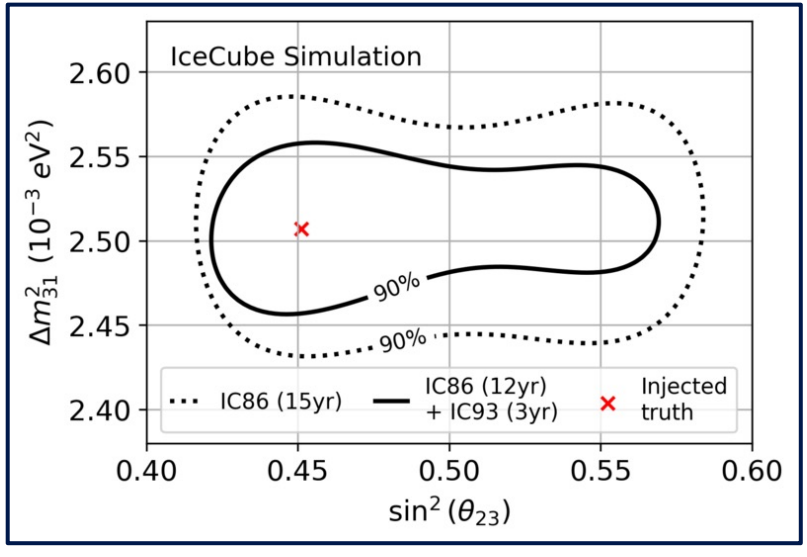


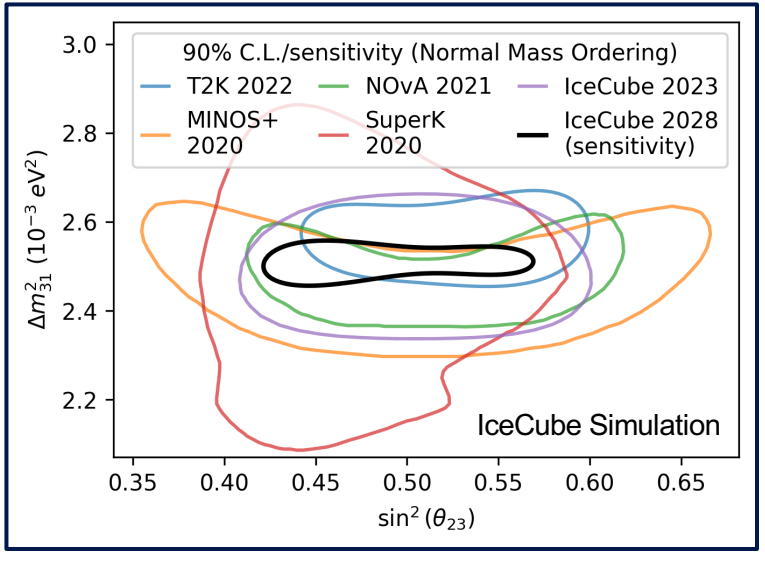
Atm. Neutrino Oscillations w/ the IceCube Upgrade

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \frac{\Delta m^2_{32} L}{E}\right)$$

Refer to: arXiv:2307.15295

- Combined sensitivities for 12 years of DeepCore + 3 years of Upgrade
- Compared to 15 years of DeepCore-only, and to current measurements

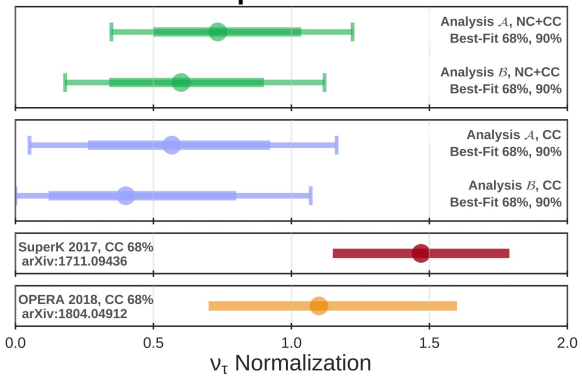




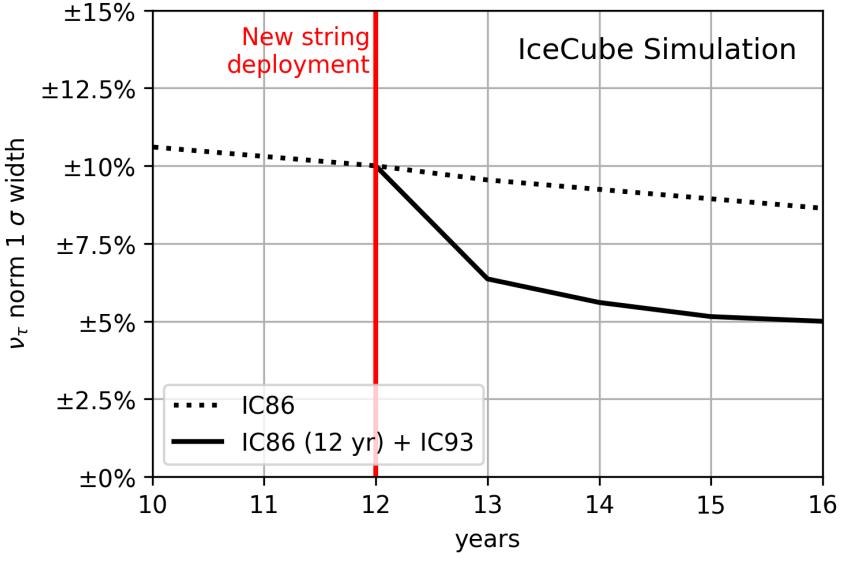
Tau Neutrino Appearance w/ the IceCube Upgrade

- Constraining the number of detected ν_τ via an overall scaling factor "ν_τ normalization"
- Current implementation looks for deviations from expectation of unitarity of the PMNS matrix or from the expected ν_τ cross-section
- Current experimental constraints ±25%
  DeepCore is expected to be about ±10%
  IceCube Upgrade will get to about ±5%

Current experimental status:

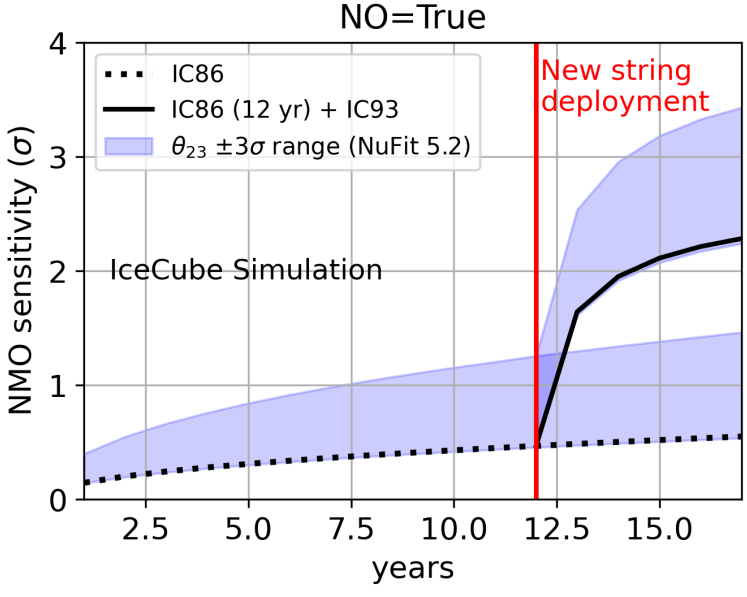


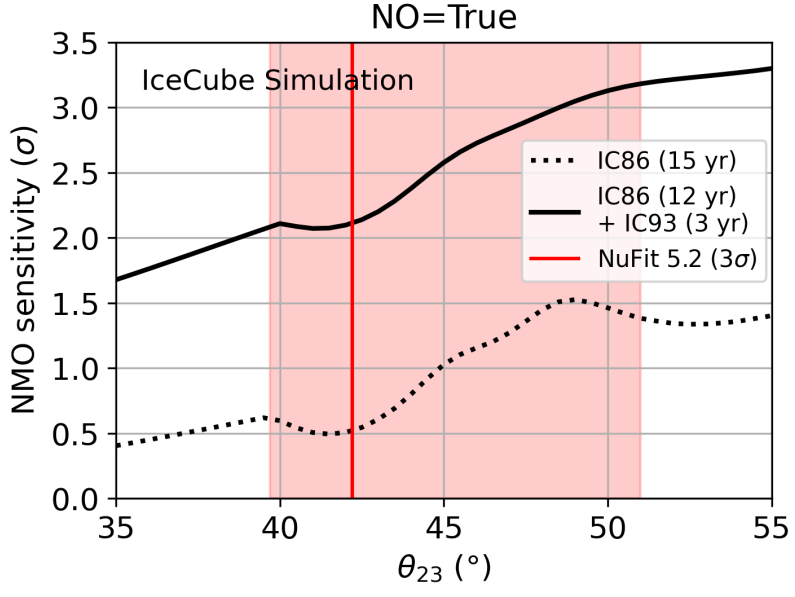
Expected with the Upgrade:



Neutrino Mass Ordering w/ the IceCube Upgrade

- Determining if $\nu_1 < \nu_2 < \nu_3$ (normal ordering) or $\nu_3 < \nu_1 < \nu_2$ (inverted ordering)
- New strings will significantly enhance our sensitivity to NMO
  - 2-3σ sensitivity expected within a few years
  - Strongly depends on the true value of θ_{23}





Summary & Outlook

IceCube DeepCore

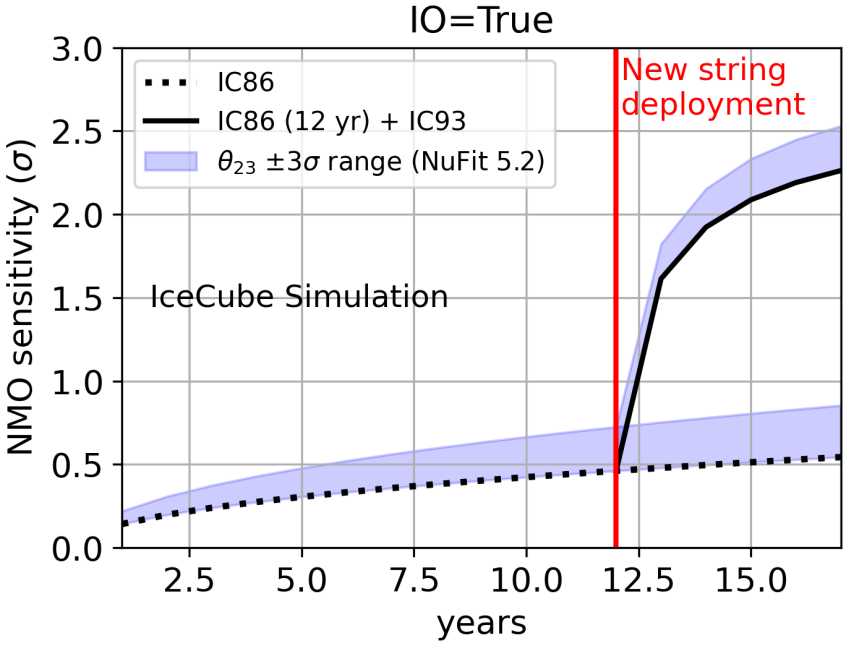
- Last results include almost a decade of DeepCore data
- Provides a unique view of oscillations to complement long baseline experiments
- **The most precise measurement of $\boldsymbol{\theta_{23}}$ and $\boldsymbol{\Delta m^2_{32}}$ using atmospheric neutrinos to date**

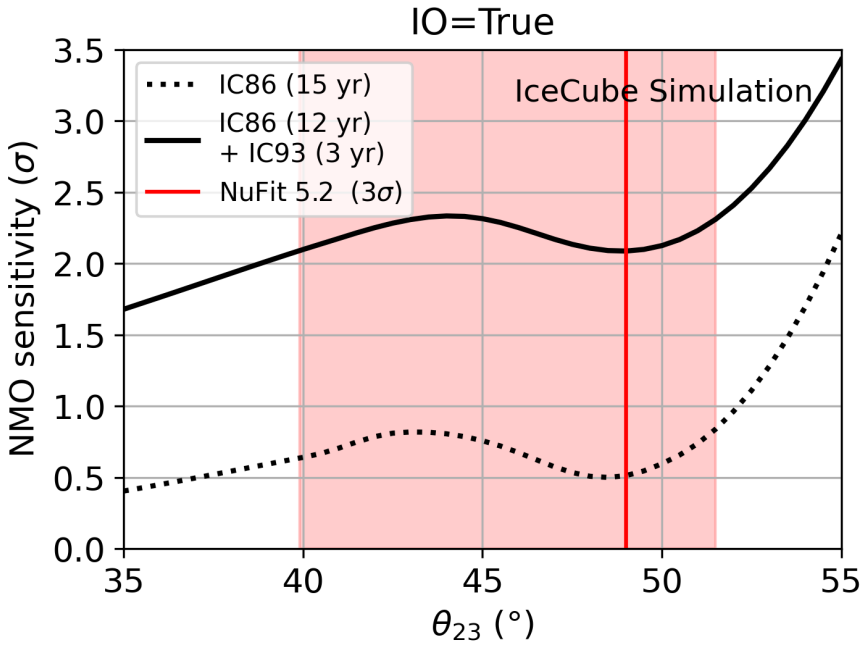
IceCube Upgrade

- Fully-funded and will be constructed in 2025-26
- Significant enhancement in our GeV capabilities
- Latest sensitivity improvements leverage new tools like GNN noise cleaning and reconstruction and combine with 12 years of DeepCore data
- Further improvements are expected when leveraging improvements in calibration, combinations with reactor experiments, and more

Back Up Slides

NMO Sensitivity - Inverted Ordering

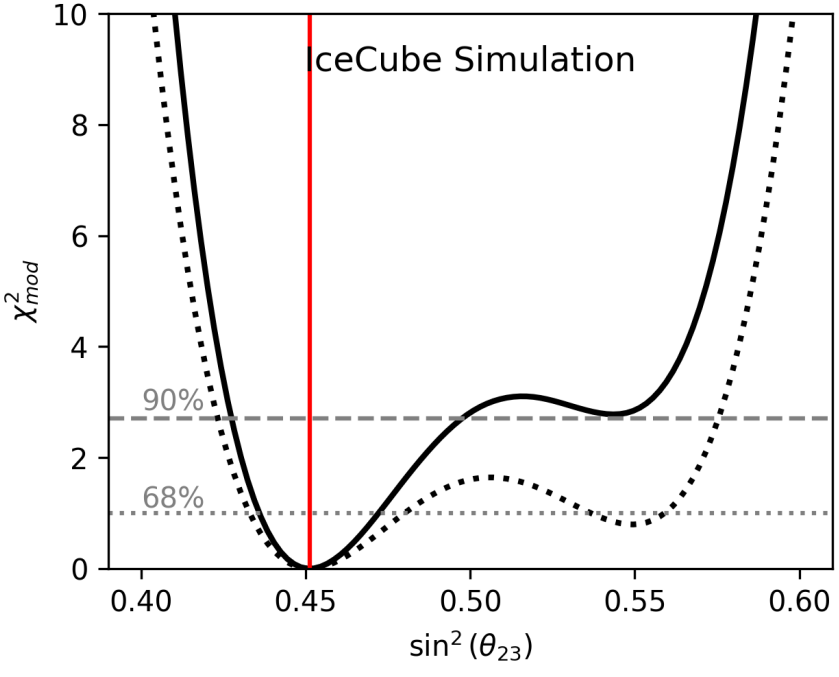




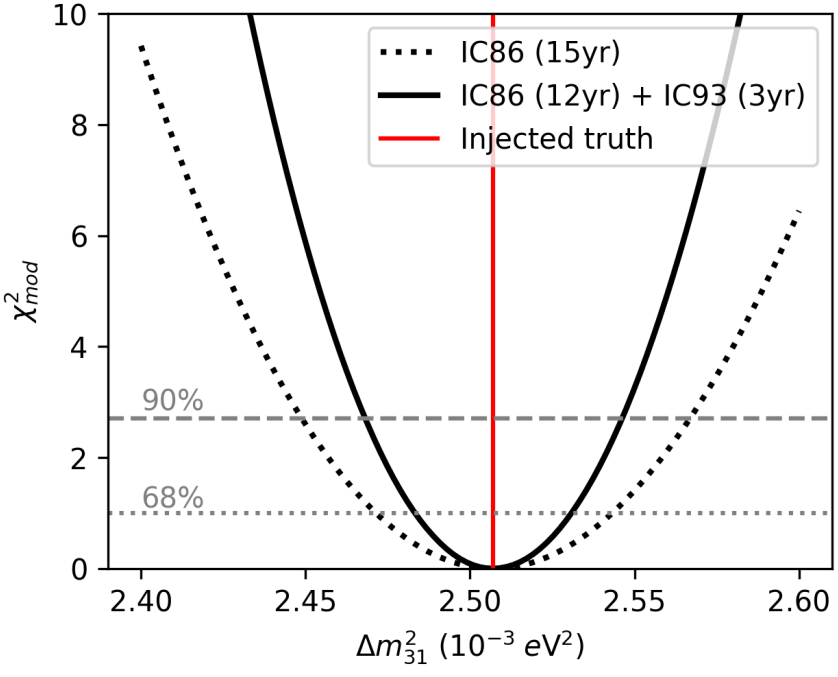
1d projections - Upgrade

- 1 sigma uncertainty

±4% for $\sin^2(\theta_{23})$

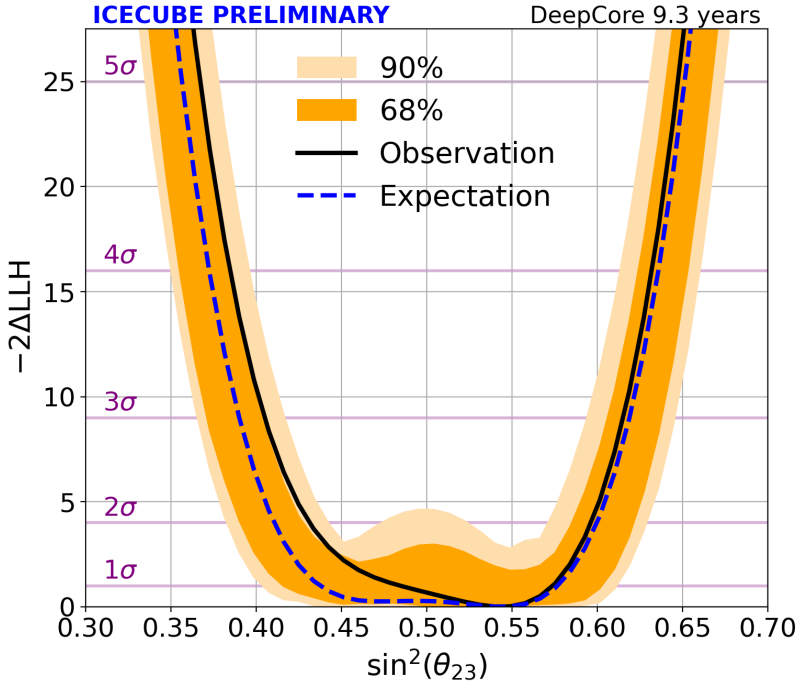


±1% for Δm^2_{32}

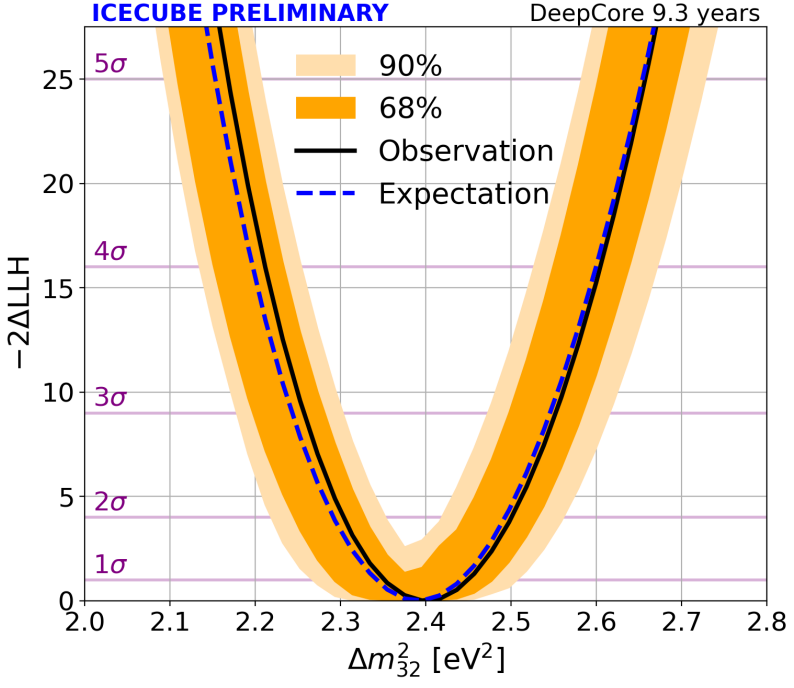


1d projections - DeepCore

- 1 sigma uncertainty

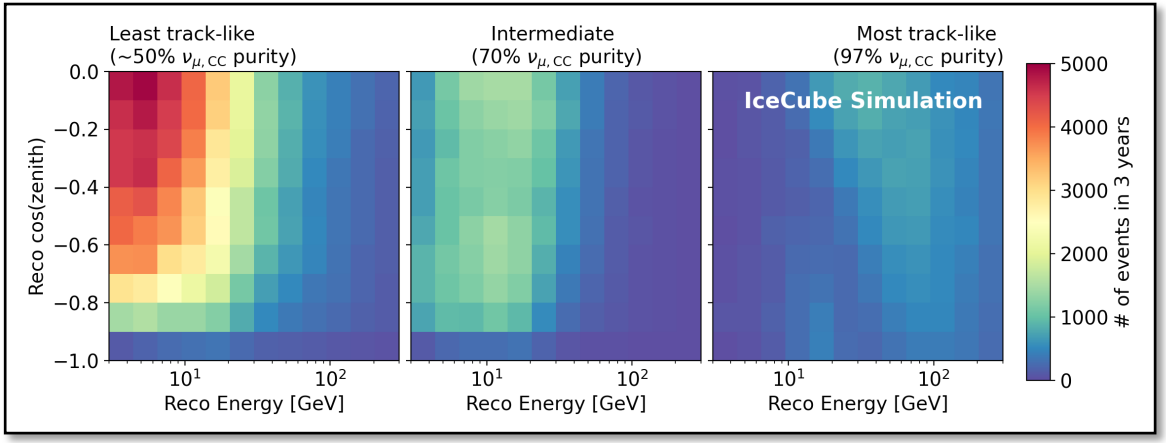


±2% for Δm^2_{32}

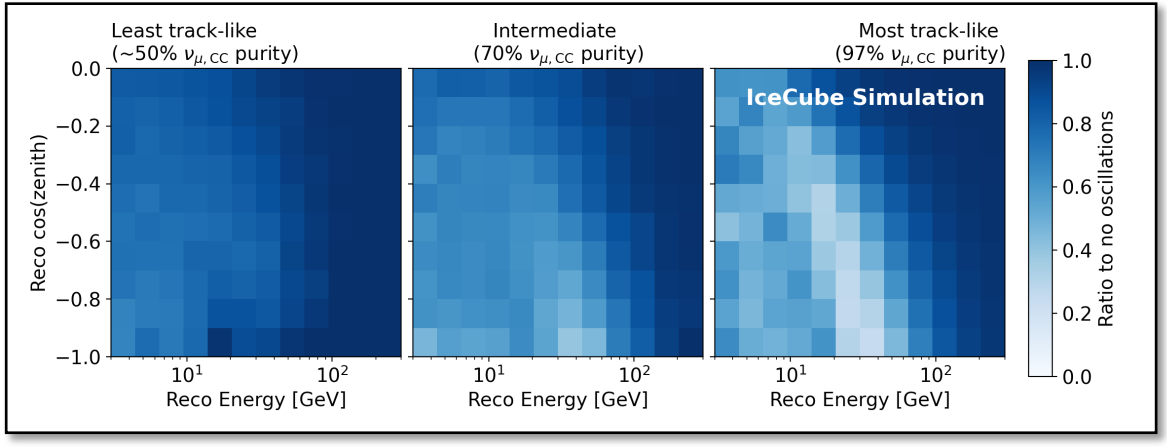


Event distributions with the IceCube Upgrade

Expected event distribution w/ 3 years of Upgrade:

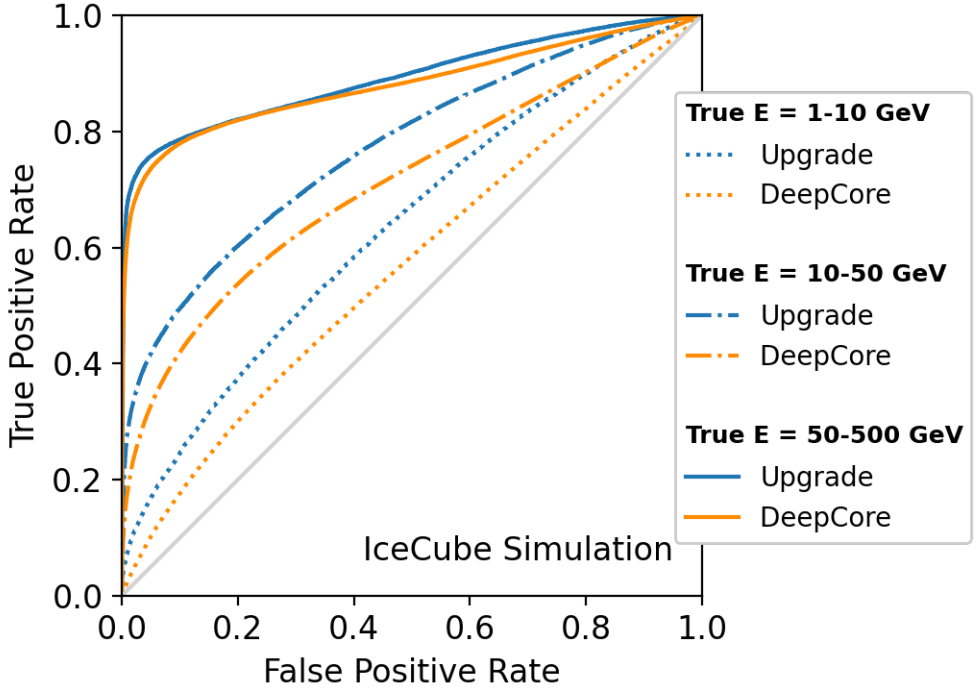


Ratio to no oscillations:



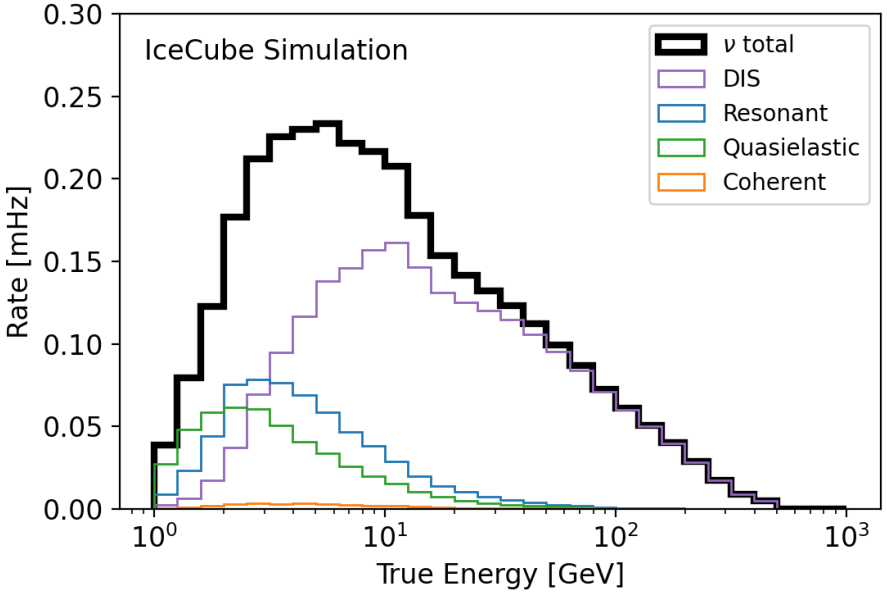
“PID” - Track vs. Cascade Classification Performance

- Similar performance for energies above standard oscillation region
- Improved performance for energies relevant for oscillations

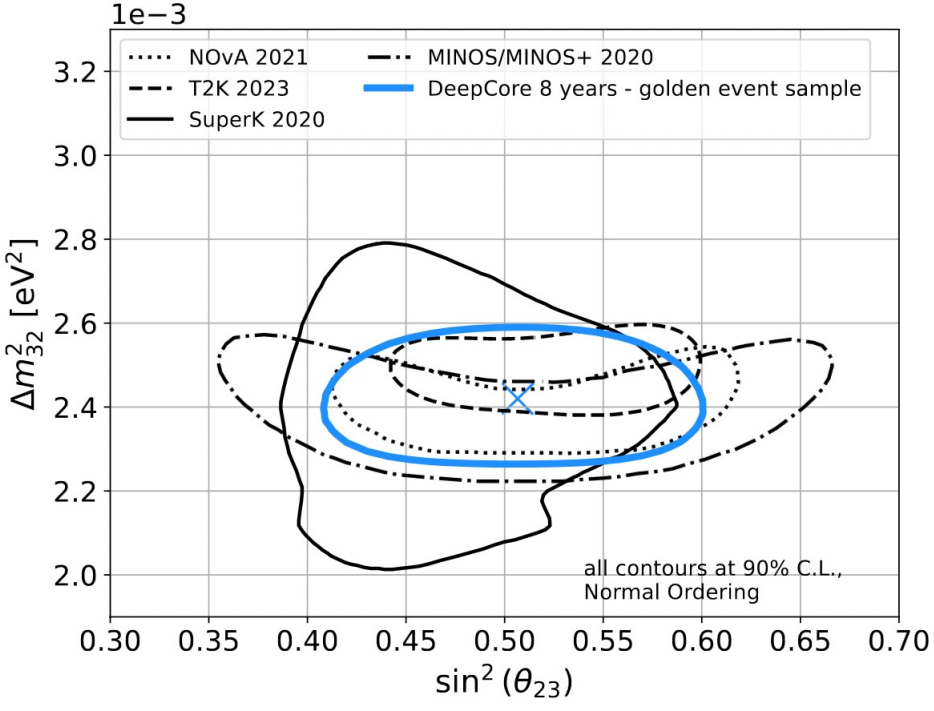


Interaction types

- Still dominated by DIS interactions; non-DIS interactions dominate below ~3 GeV
- Uncertainty in DIS cross-section handled by allowing interpolation between 2 models (Genie and CSMS)
- Uncertainties in non-DIS cross-sections handled by axial masses M_A

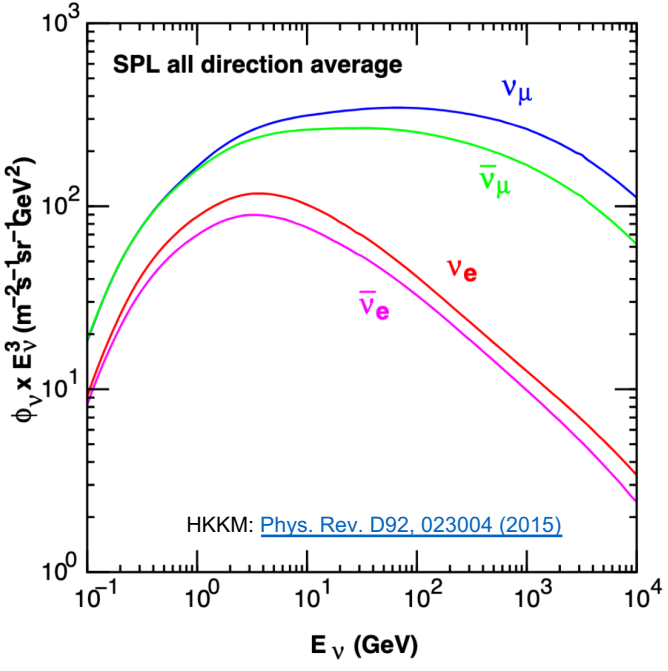


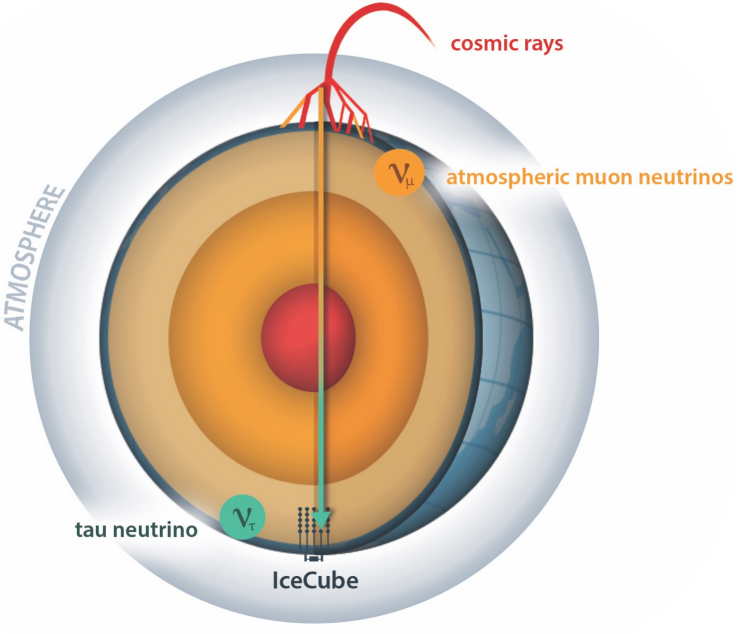
Results from PRD 108, 012014 (published 2023)



Atmospheric Neutrinos

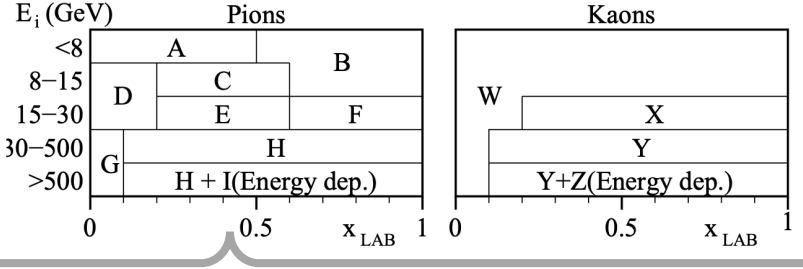
- Neutrinos produced in cosmic ray air showers via pions and kaons
- Dominated by ν_μ , also some ν_e

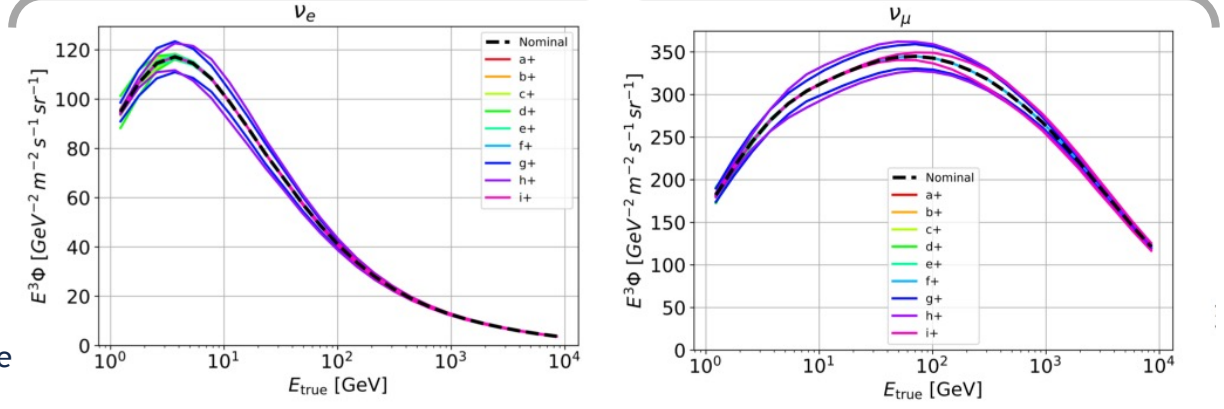




Flux Systematics

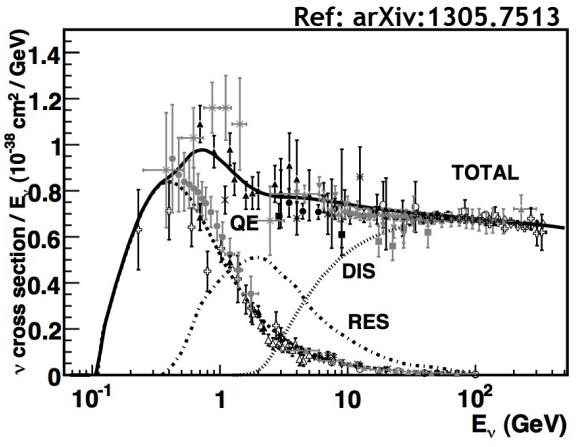
- **Nominal Flux:** Honda 2015 model [arXiv:1502.03916, PRD 92, 023004]
- **Uncertainties:**
  - Change in Spectral Index $\Delta\gamma_\nu$
  - Barr Parameterization [arXiv:astro-ph/0611266, PRD 74, 094009]

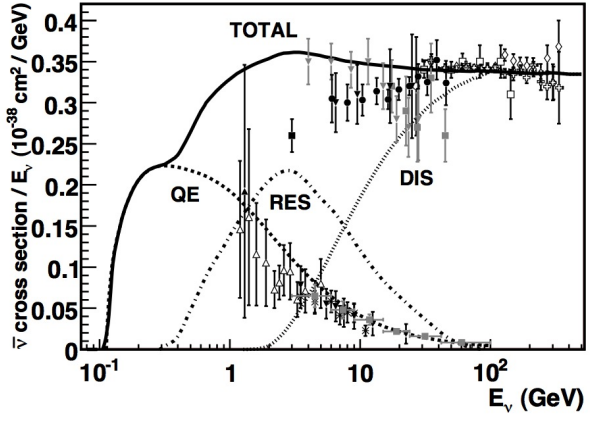


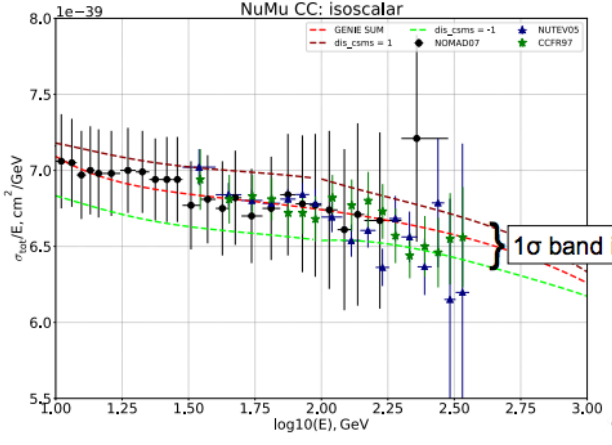


Cross-section Systematics

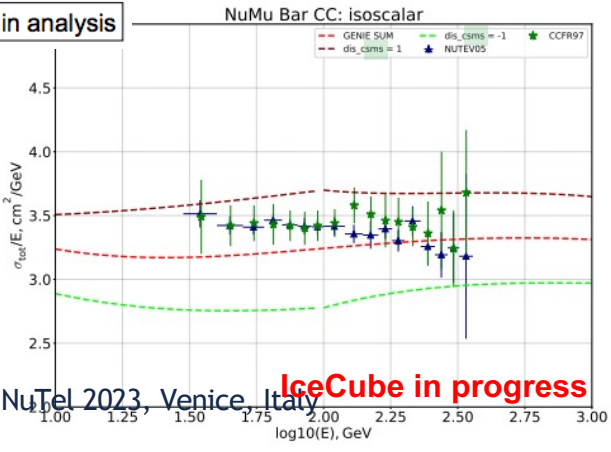
- Predominantly in the DIS region
- Uncertainty to account for different models (GENIE vs. CSMS)
- Also include systematic for $M_{A,QE}$ and $M_{A,Res}$







1σ band in analysis



--- GENIE ● NOMAD07
--- CSMS ▲ NuTEV05
★ CCFR97

IceCube in progress