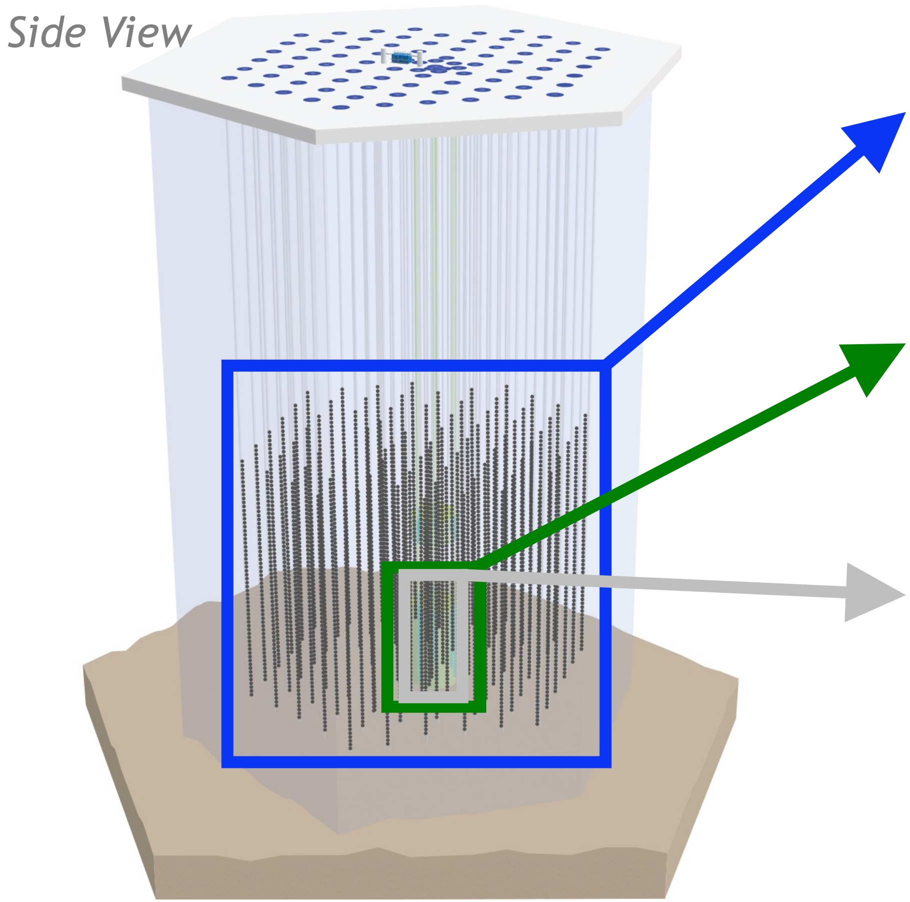
Atmospheric neutrino oscillations with IceCube:
Recent results with DeepCore and future potential with the Upgrade

Kayla Leonard DeHolton

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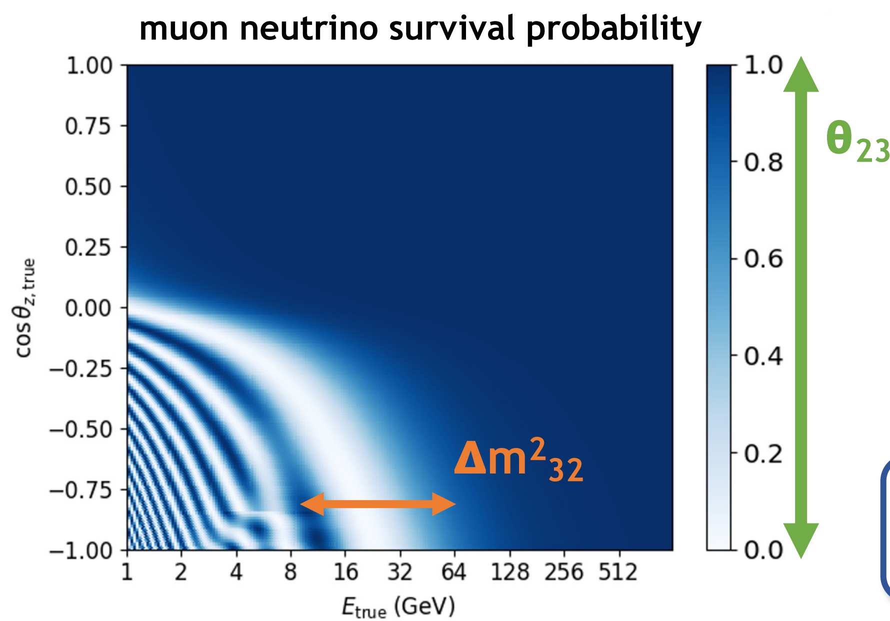
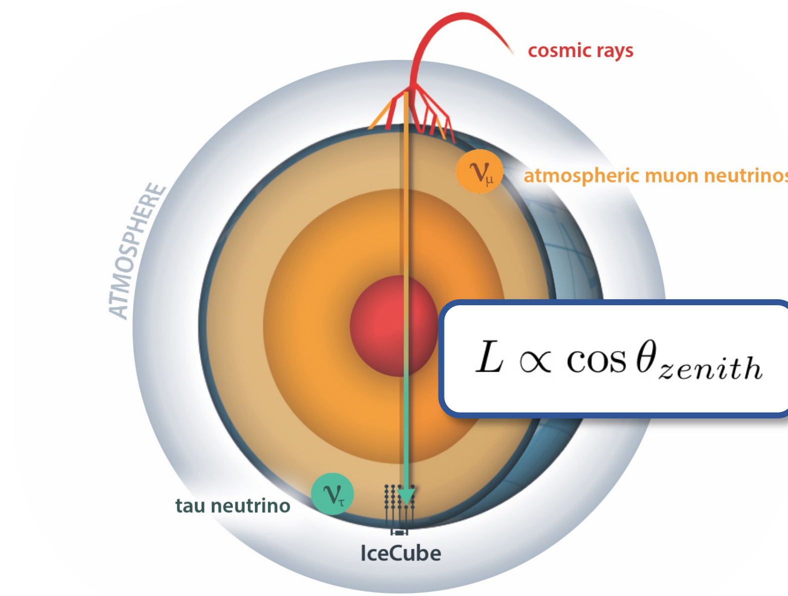
Upgrade
- 7 additional strings with denser spacing
- Multi-PMT modules
- Fully-funded & will be constructed in 2025-26

Atmospheric Neutrino Oscillations

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



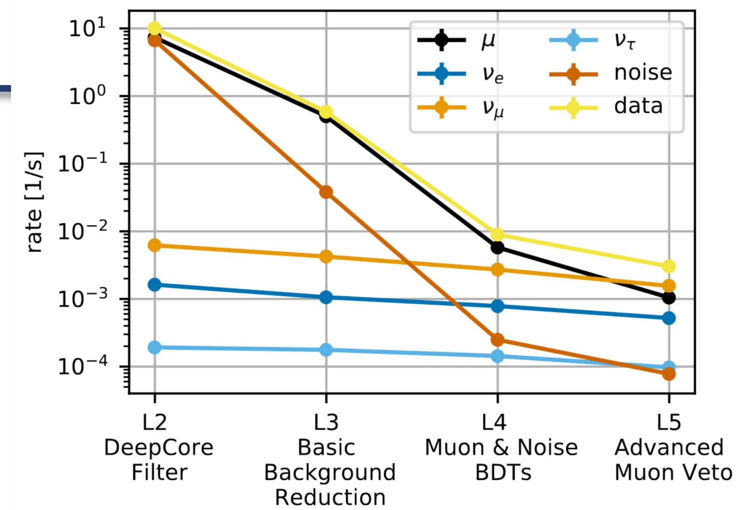


$$L \propto \cos\theta_{zenith}$$

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

Current Generation Samples

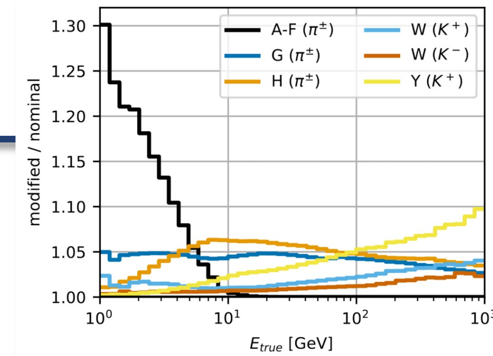
- Common:
  - Event selection to suppress backgrounds by several orders of magnitude
  - Improved treatment of many systematic uncertainties
  - Analysis tools
- Then sample specific reconstructions and analyses:



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 last year: PRD 108, 012014 (2023)	**Publication submitted last week:** arXiv:2405.02163

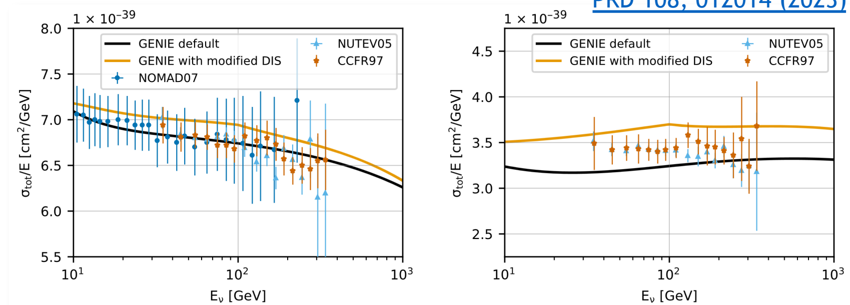
Systematic uncertainties considered

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

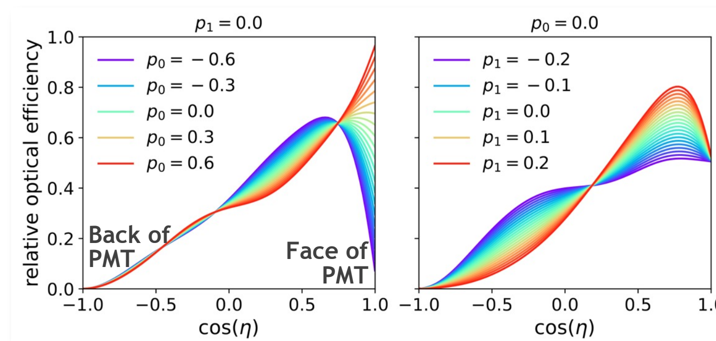


PRD 108, 012014 (2023)

- **Cross sections**
  - DIS transformation between GENIE & CSMS
    JHEP **08**, 042 (2011)
  - Axial mass uncertainties for non-DIS events



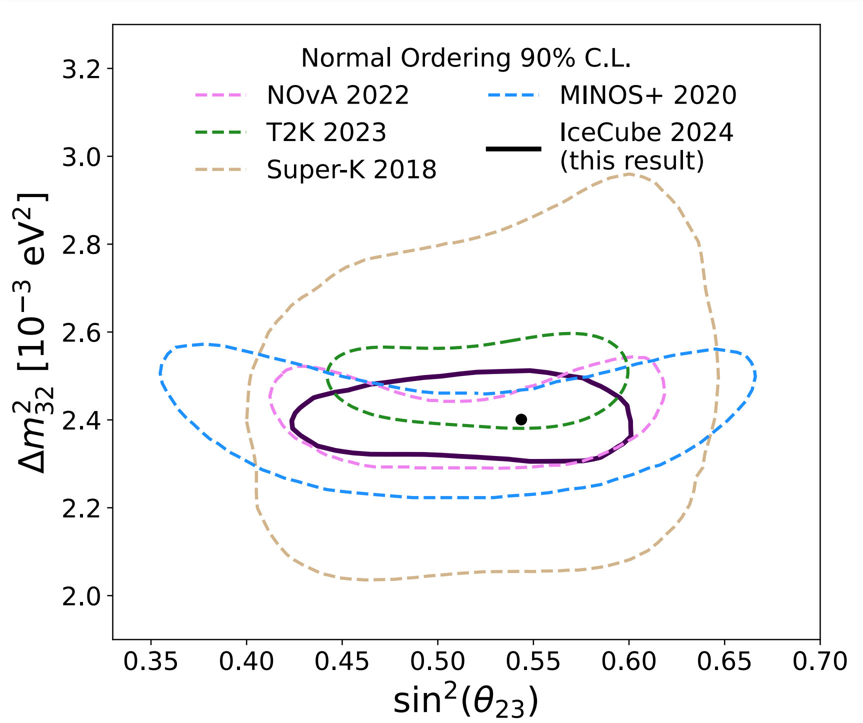
- **Detector and Ice Properties**
  - Improved treatment for modeling the optical properties of ice
  - PMT charge calibration



- **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

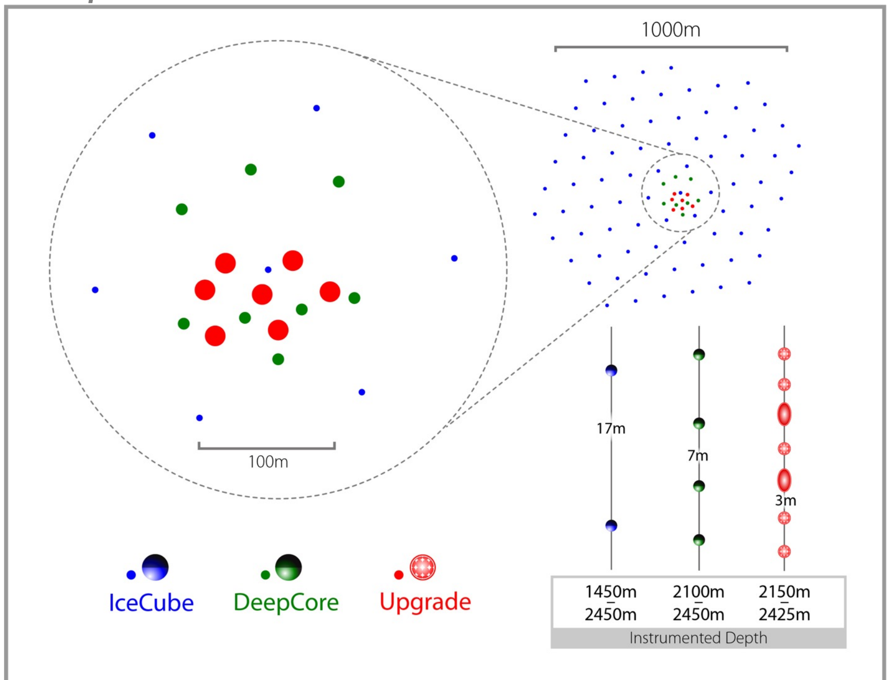


Just posted last week! arXiv:2405.02163

- 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

IceCube, DeepCore, and the Upgrade

Top View



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The IceCube Upgrade

Advantages: Higher density of modules & multi-PMT info

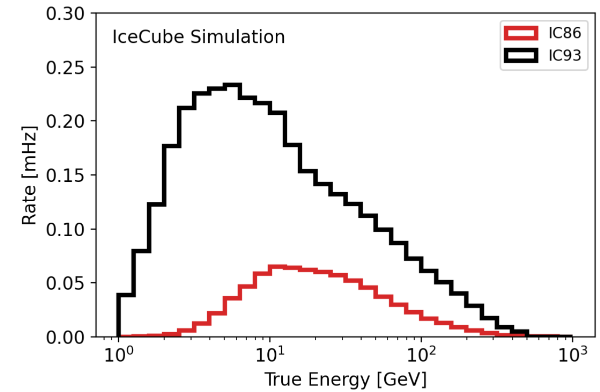
- Lower energy detection threshold
- 3-5 times more events in energy range of interest
- More hits (information) ⇒ better reconstruction and classification

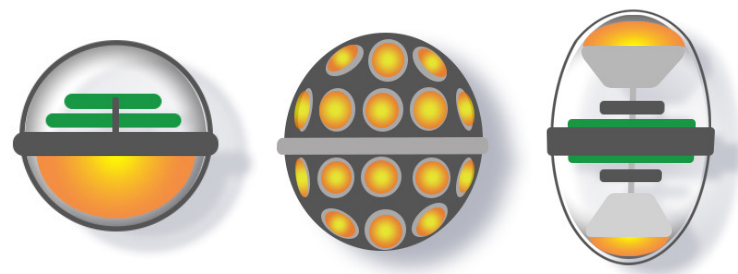
Challenges: Higher rates

- 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





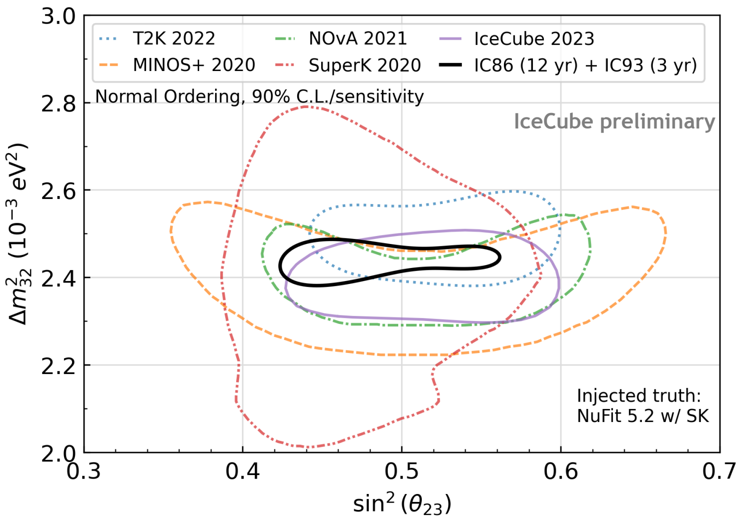
GraphNeT
Deep Learning for Neutrino Telescopes

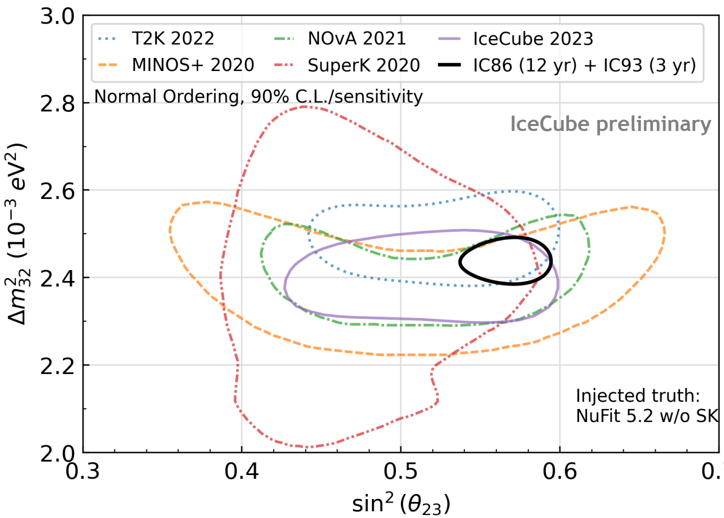
Atm. Neutrino Oscillations w/ the IceCube Upgrade

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

Refer to: arXiv:2307.15295

- Combined sensitivities for 12 years of DeepCore + 3 years of Upgrade
- Injected truth value(s) from NuFit 5.2





Tau Neutrino Appearance w/ the IceCube Upgrade

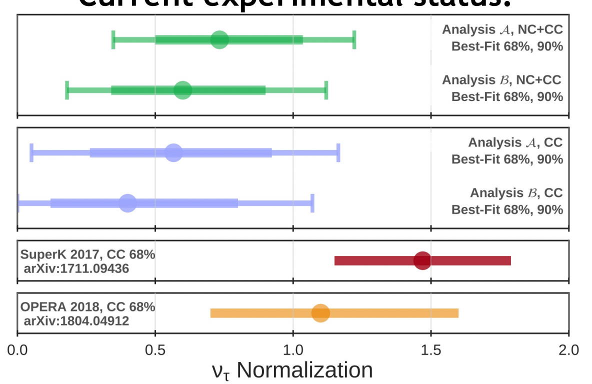
- Constraining the number of detected ν_τ via an overall scaling factor "ν_τ normalization"
- Current implementation looks for deviations from expectation of unitarity of the PMNS matrix or from the expected ν_τ cross-section
- Current experimental constraints ±25%

  DeepCore is expected to be about ±10%

  IceCube Upgrade will get to about ±5%

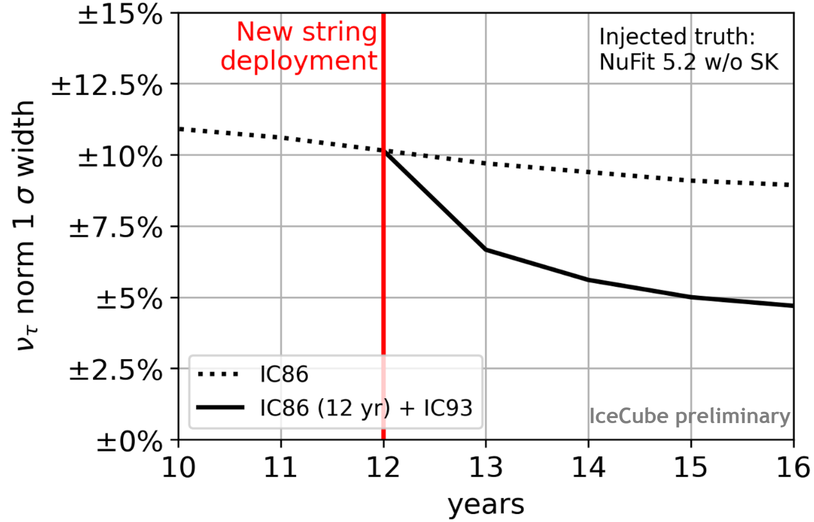
Refer to: arXiv:2307.15295

Current experimental status:



PRD 99, 032007 (2019)

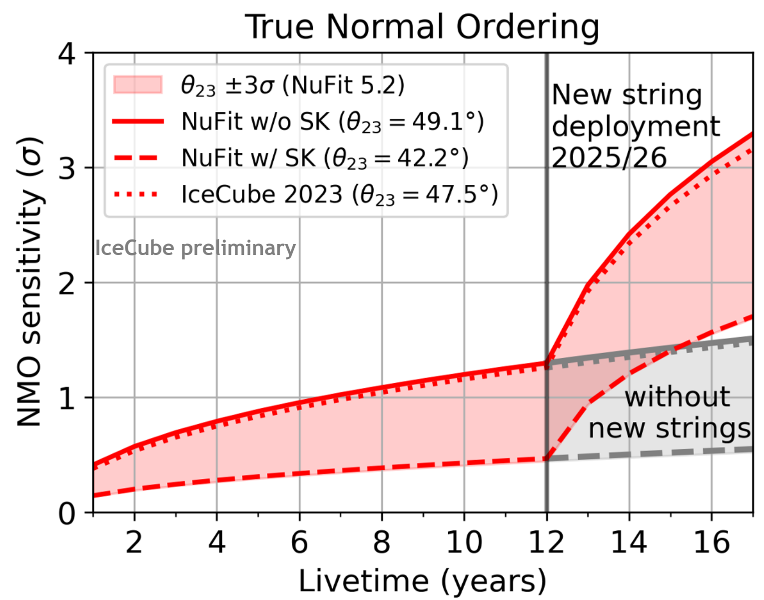
Expected with the Upgrade:

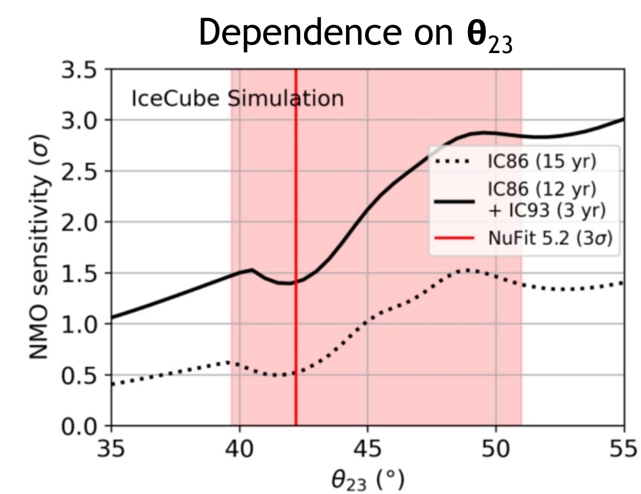


Neutrino Mass Ordering w/ the IceCube Upgrade

- 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
  - 1.5-3σ sensitivity expected within a few years
  - Strongly depends on the true value of θ_{23}

Refer to: arXiv:2307.15295





Summary & Outlook

IceCube DeepCore

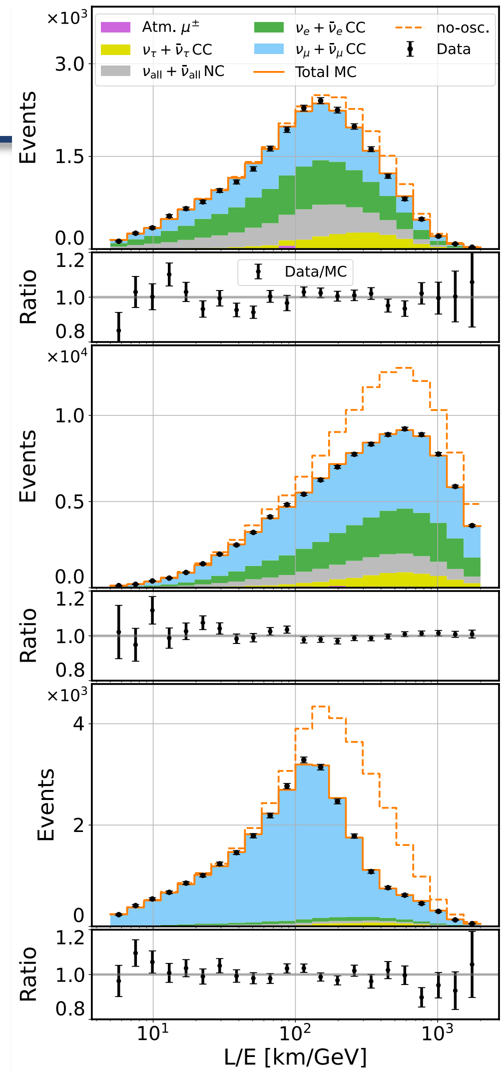
- Latest results include almost a decade of DeepCore data
- Provides a unique view of oscillations to complement long baseline experiments
- **The most precise measurement of θ_{23} and Δm^2_{32} using atmospheric neutrinos to date**

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

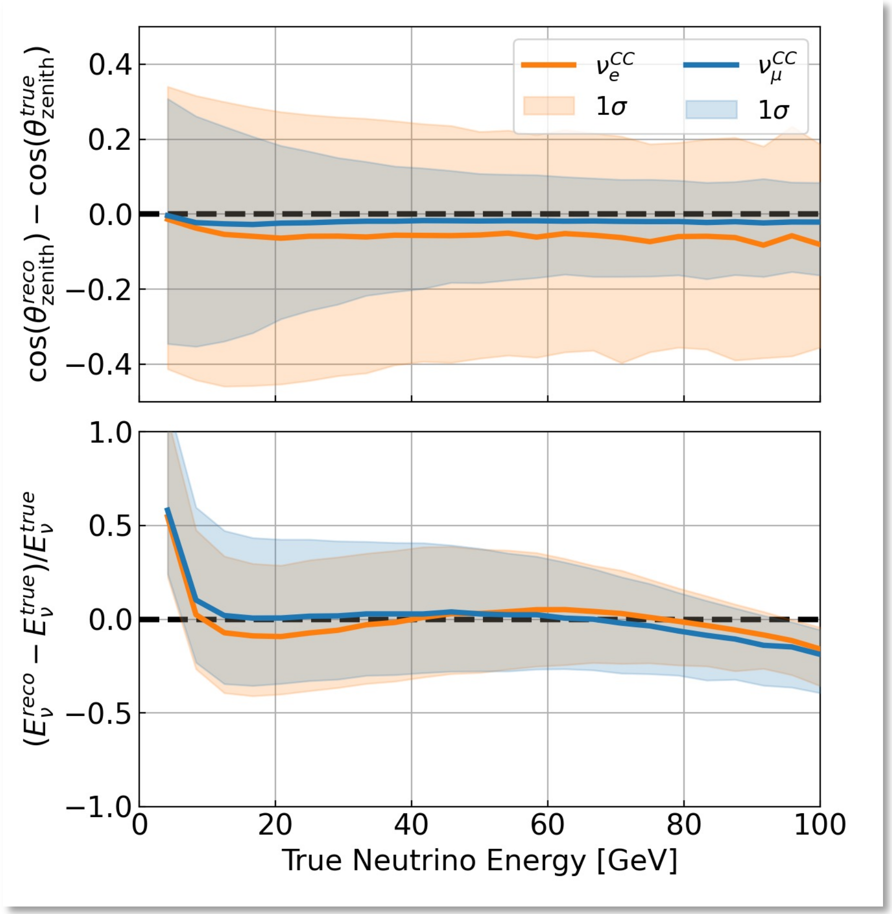
Back Up Slides - DeepCore

L/E



arXiv:2405.02163

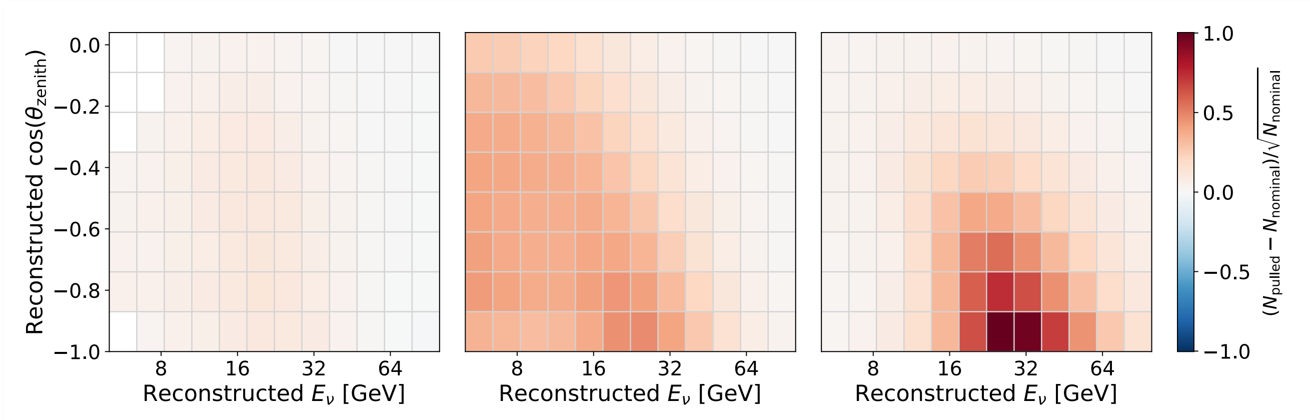
Reconstructed Resolutions



arXiv:2405.02163

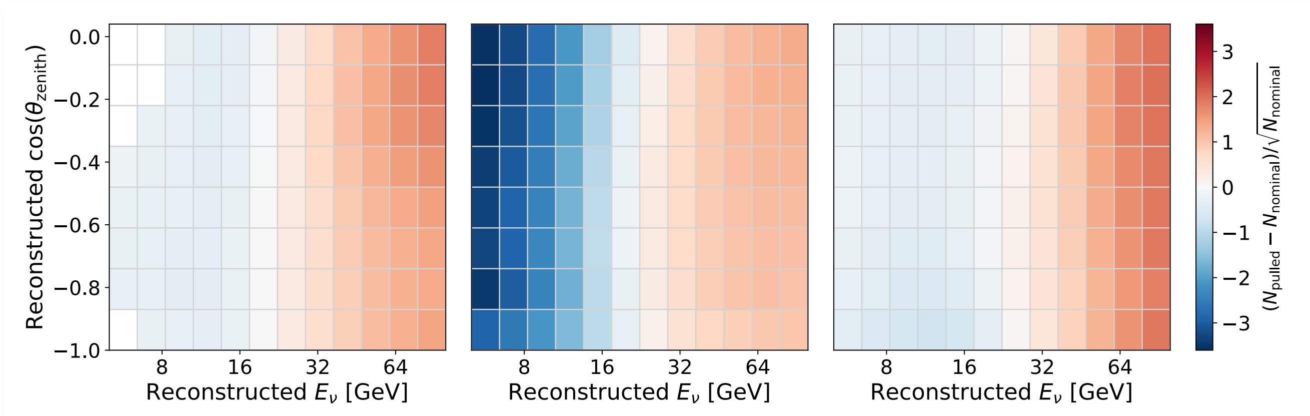
Effect of parameters on analysis templates

Effect of θ_{23}:



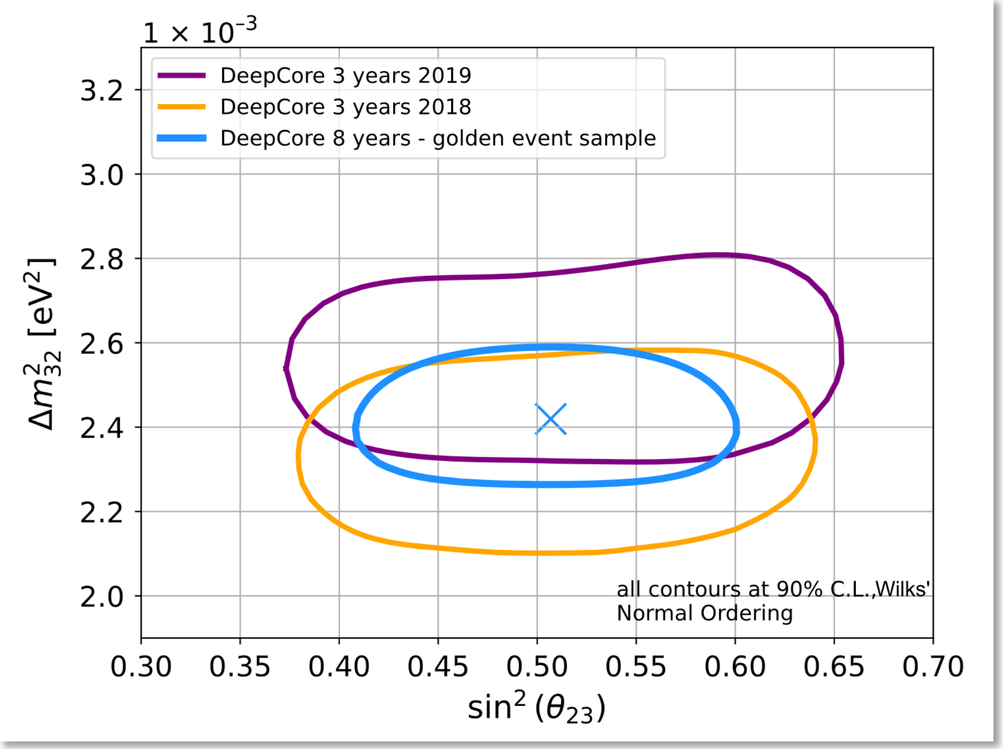
arXiv:2405.02163

Effect of spectral index:



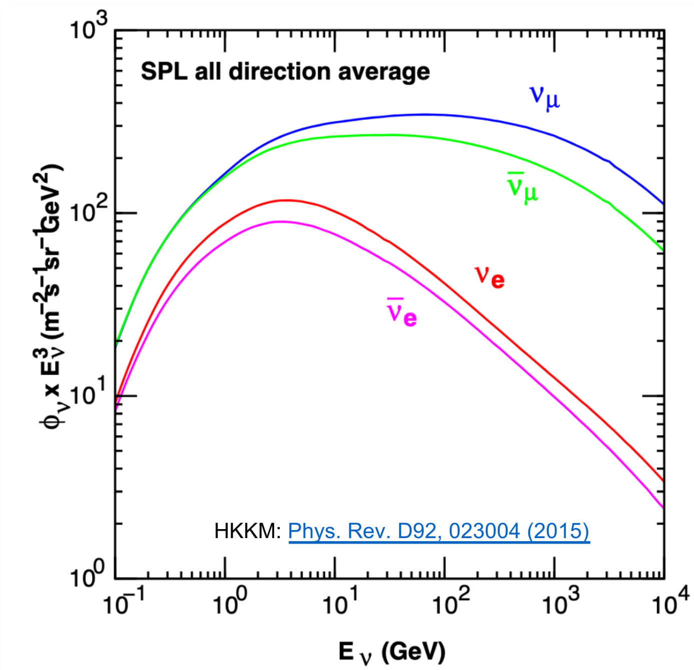
Results from PRD 108, 012014 (2023)

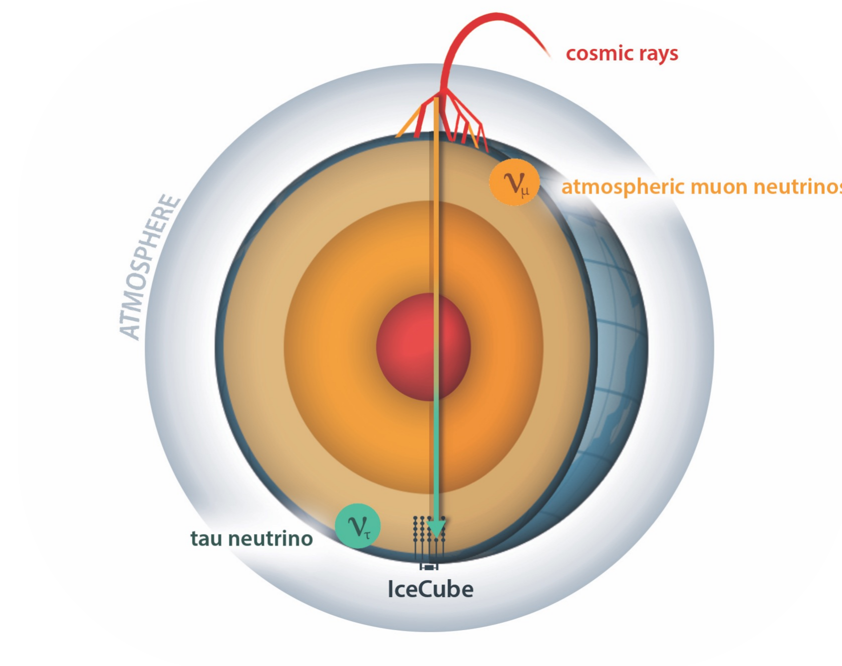
Comparison to previous DeepCore results:



Atmospheric Neutrinos

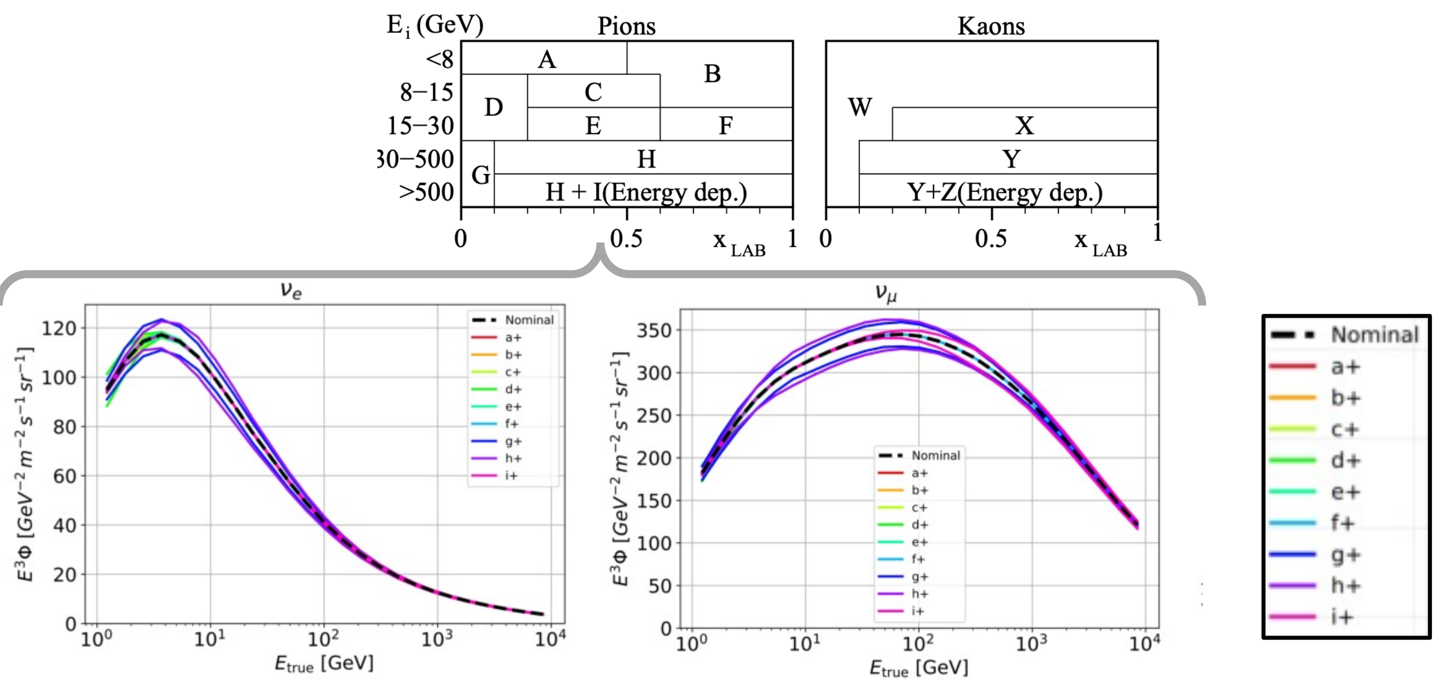
- Neutrinos produced in cosmic ray air showers via pions and kaons
- Dominated by ν_μ , also some ν_e





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]

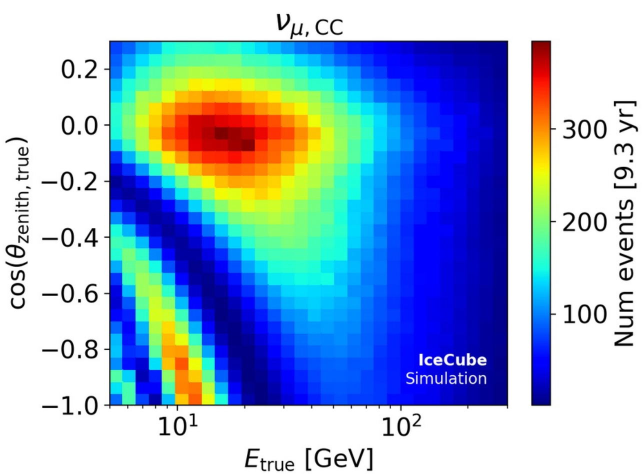


Typical Analysis Procedure

- 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

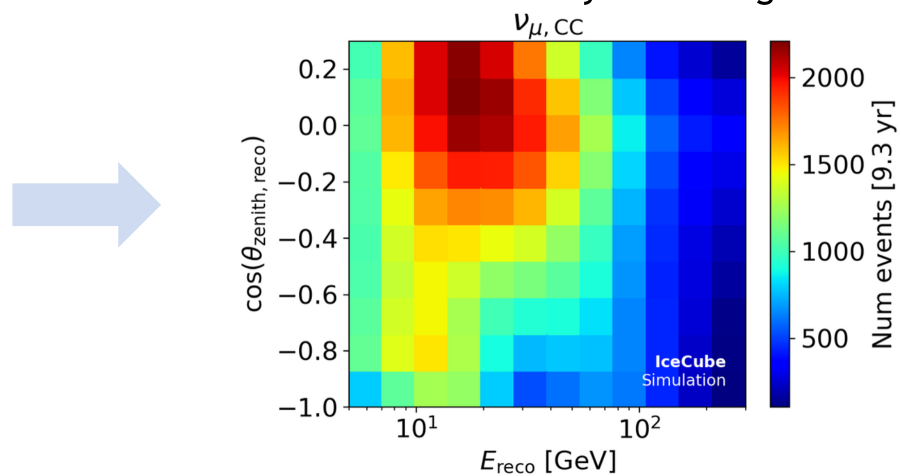
True

Oscillation peaks and valleys are visible in truth level information



Reconstructed

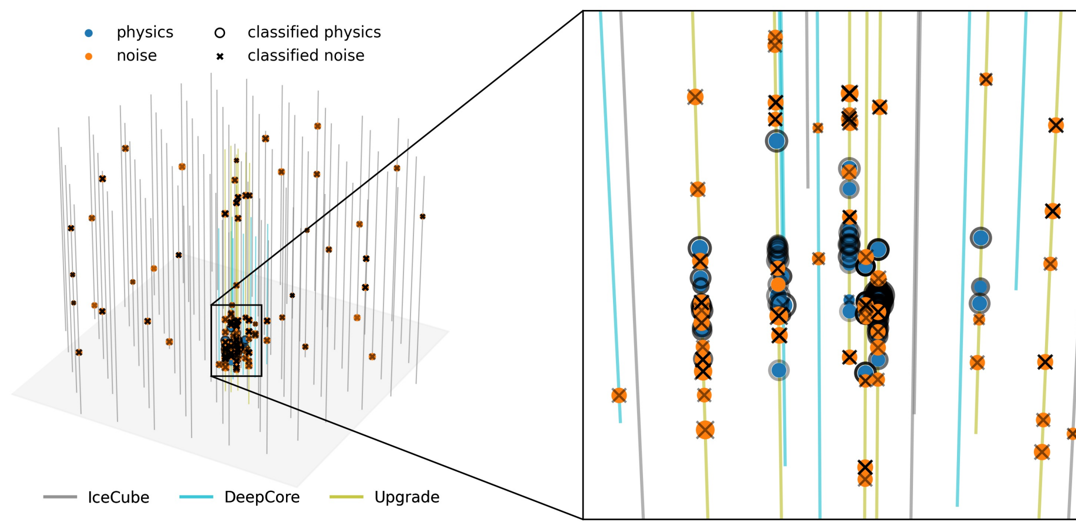
Smeared out by detector resolution and finite analysis binning



Back Up Slides - Upgrade

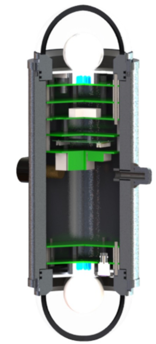
GNN cleaning, reconstruction, and classification

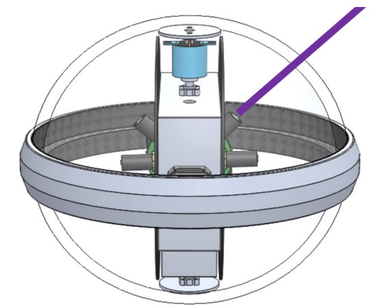
- GraphNeT: Graph neural networks for neutrino telescope event reconstruction
  - Open source framework: https://github.com/graphnet-team/graphnet
    DOI:10.21105/joss.04971
- Connects each pulse to its 8 nearest neighbor pulses
  - GNNs can easily handle the irregular geometry of the strings
- Used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



Future improvements

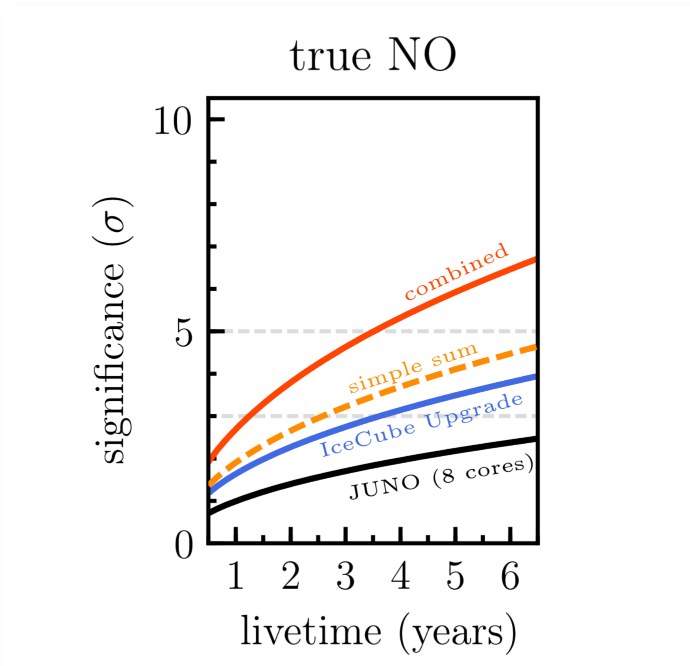
- Calibration Devices
  - Bright, isotropic light
  - Directional laser beam
- Further analysis optimizations
  - Event selection
  - Reconstructions and particle ID
  - Analysis binning
- Newer systematics treatment
  - Flux uncertainties - Phys. Rev. D **107**, 123037 (2023)
  - Ice models
  - DIS cross section treatment



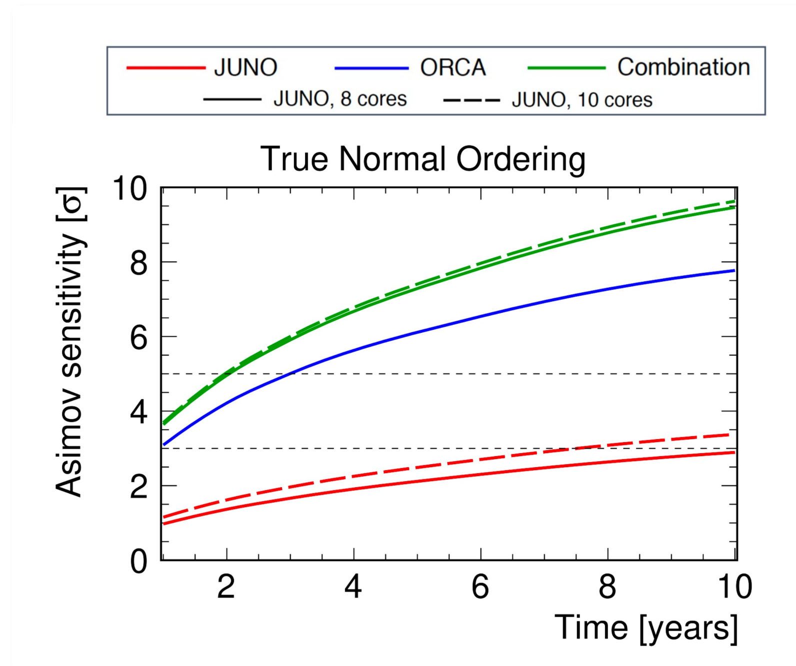


Combining w/ Reactor Experiments

- Synergy effect when combining with reactor experiment
- Future possibility: combining JUNO + IceCube Upgrade + KM3NeT/ORCA



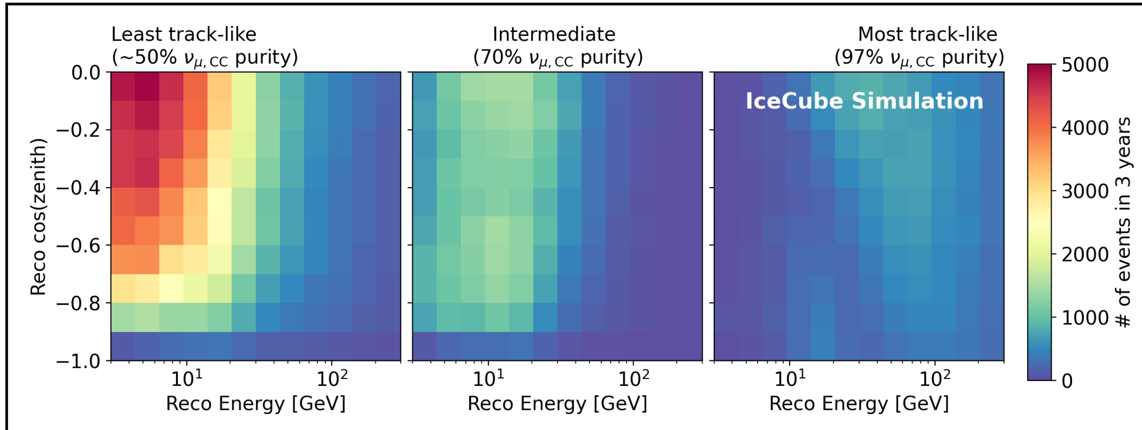
JUNO + IceCube Upgrade. PRD 101, 032006 (2020)



JUNO + KM3NeT/ORCA. JHEP03(2022)055

Event distributions with the IceCube Upgrade

Expected event distribution w/ 3 years of Upgrade:



Ratio to no oscillations: