Atmospheric Neutrino Oscillations with 8 years of data from IceCube DeepCore

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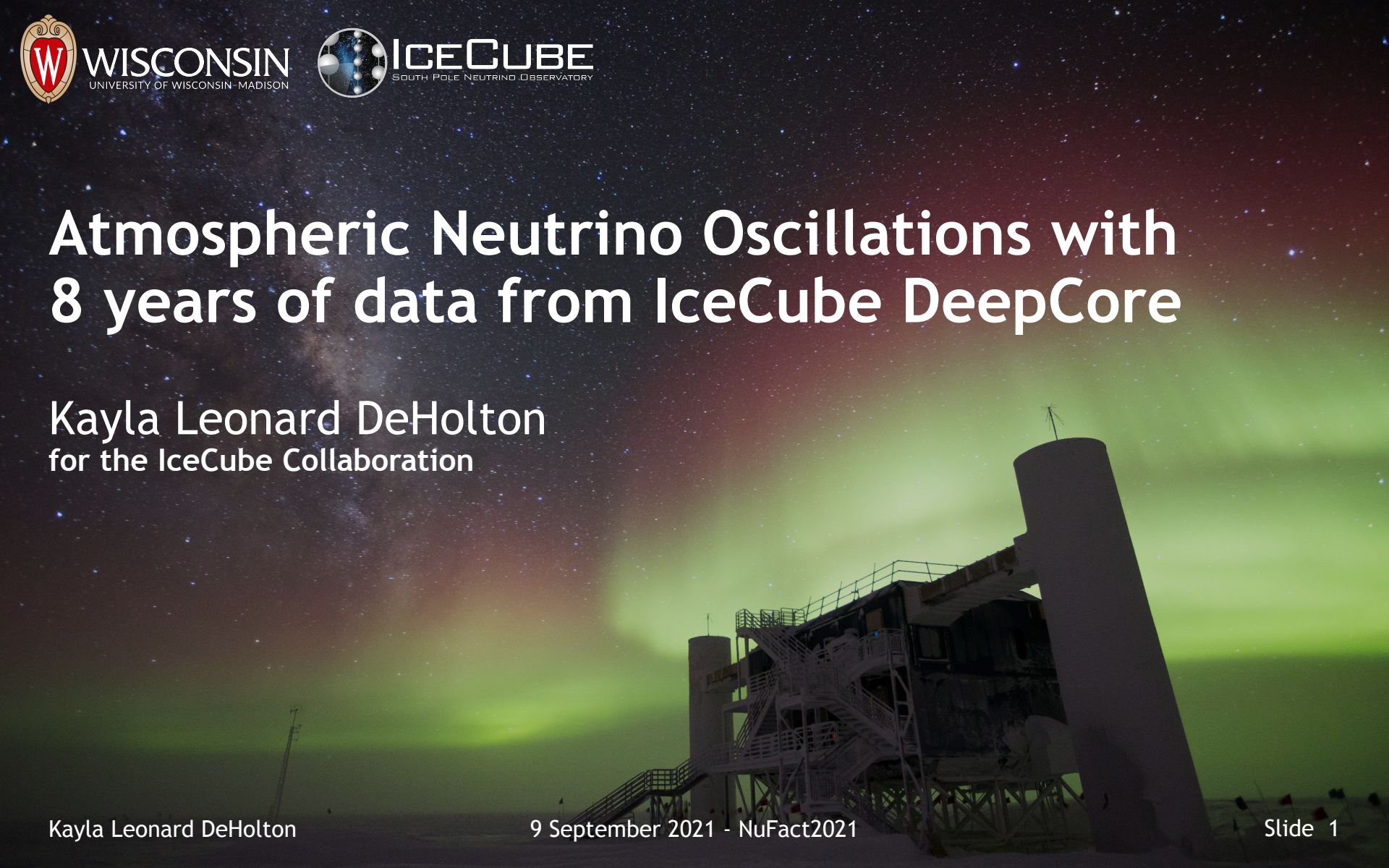
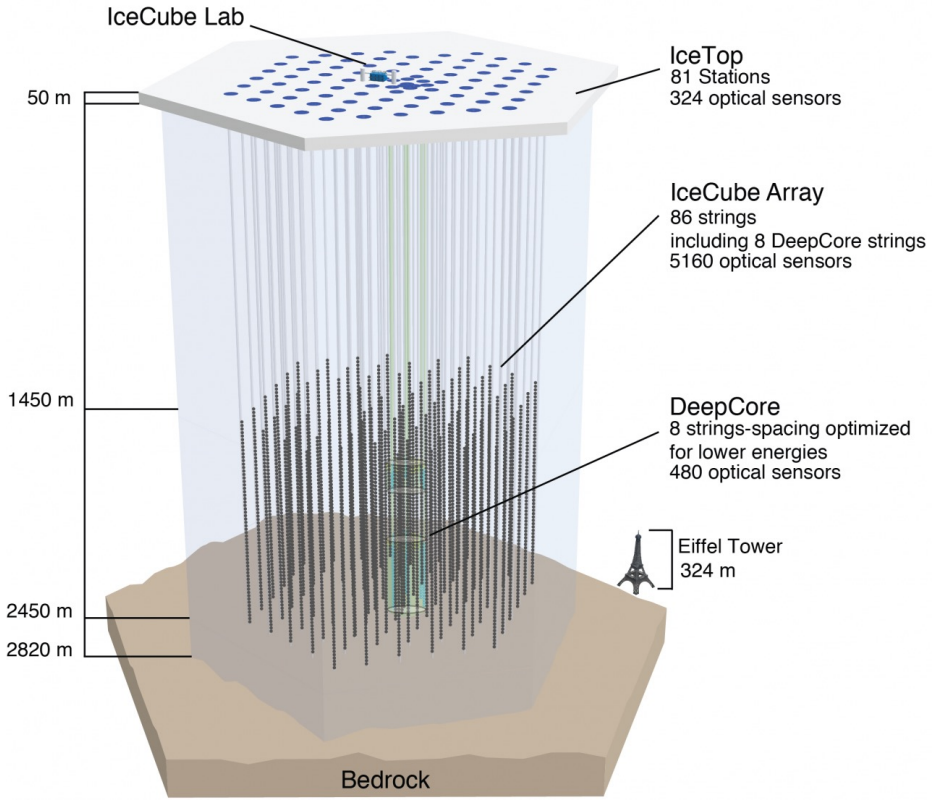
for the IceCube Collaboration

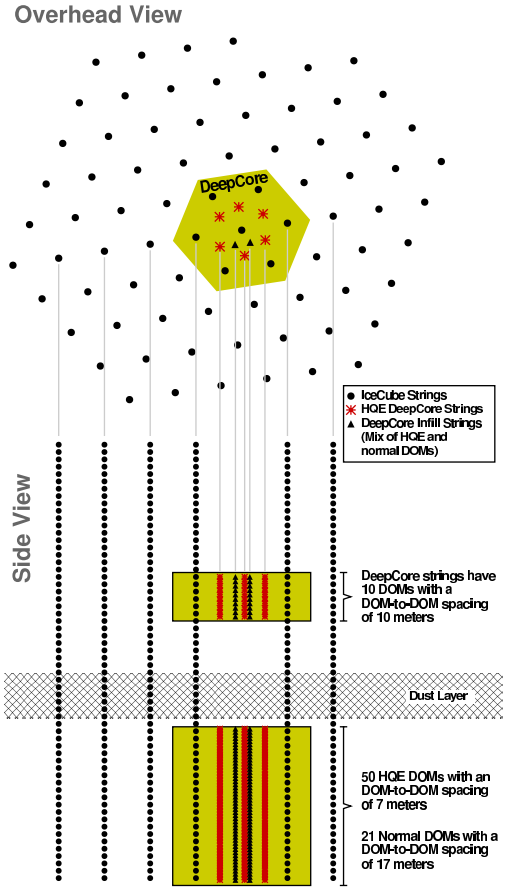


The IceCube Detector



- Located in Antarctica at the South Pole
- 1 km^3 of ice
- Array of 5,160 modules to detect Cherenkov light
- DeepCore Subarray has module density 5x greater than the rest of IceCube

The IceCube DeepCore Detector



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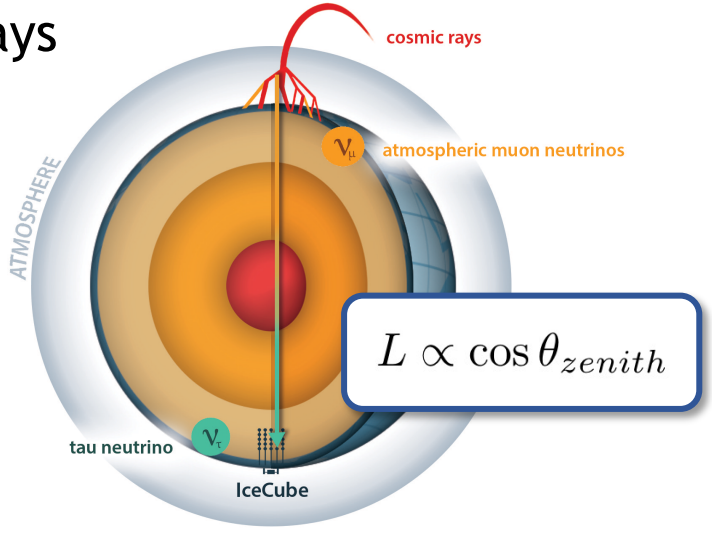
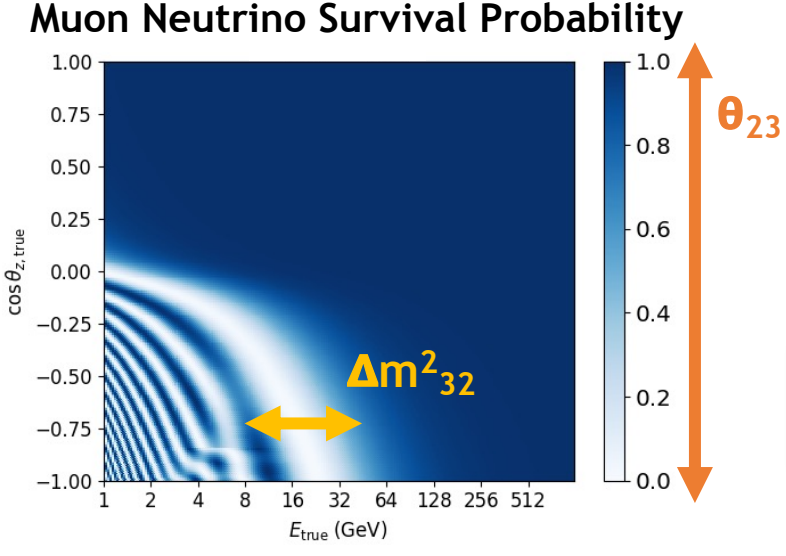
Neutrino Flavor Oscillations in DeepCore

- Atmospheric neutrinos produced by cosmic rays
- Predominantly ν_μ oscillating to ν_τ
- Oscillation maximum at 25 GeV



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



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

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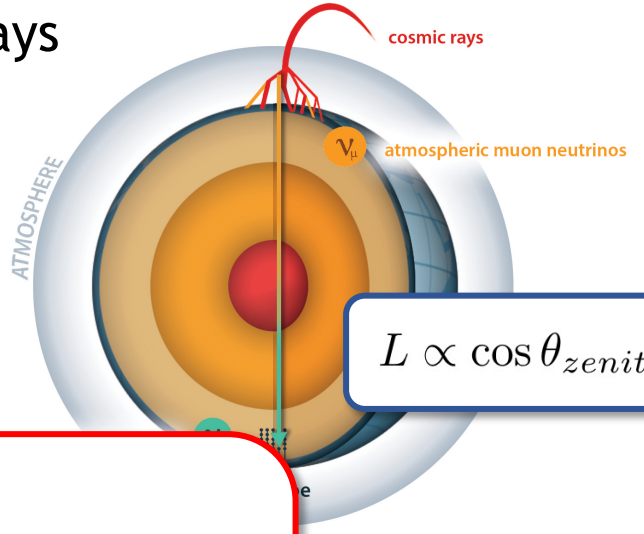

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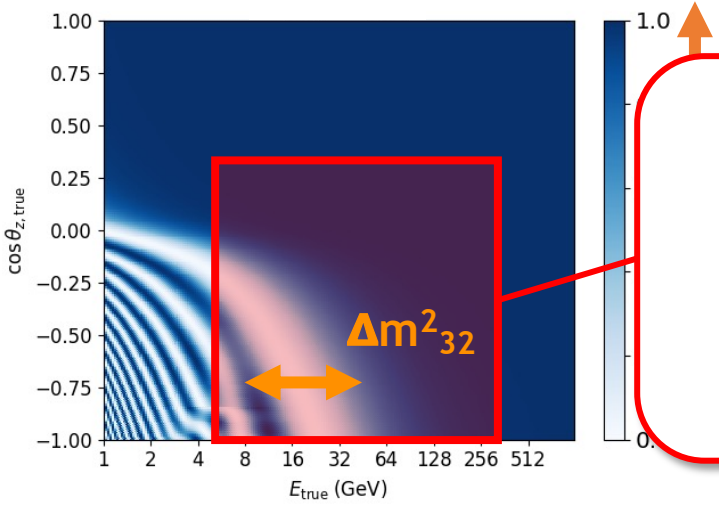
Muon Neutrino Survival Probability



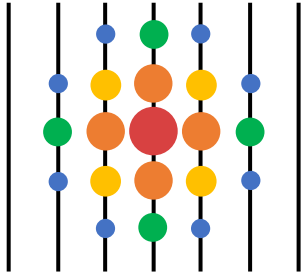
Analysis range

Energy: 5 to 300 GeV
cos(zen): -1.0 to 0.3

$$\left(1.27\frac{\Delta m^2_{32} L}{E}\right)$$

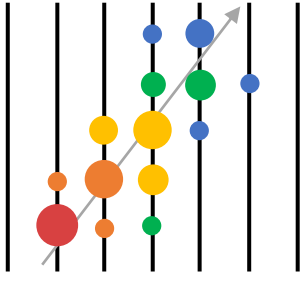
Event Signatures

Cascades



- Spherical
- NC, ν_e CC, ν_τ CC

Tracks



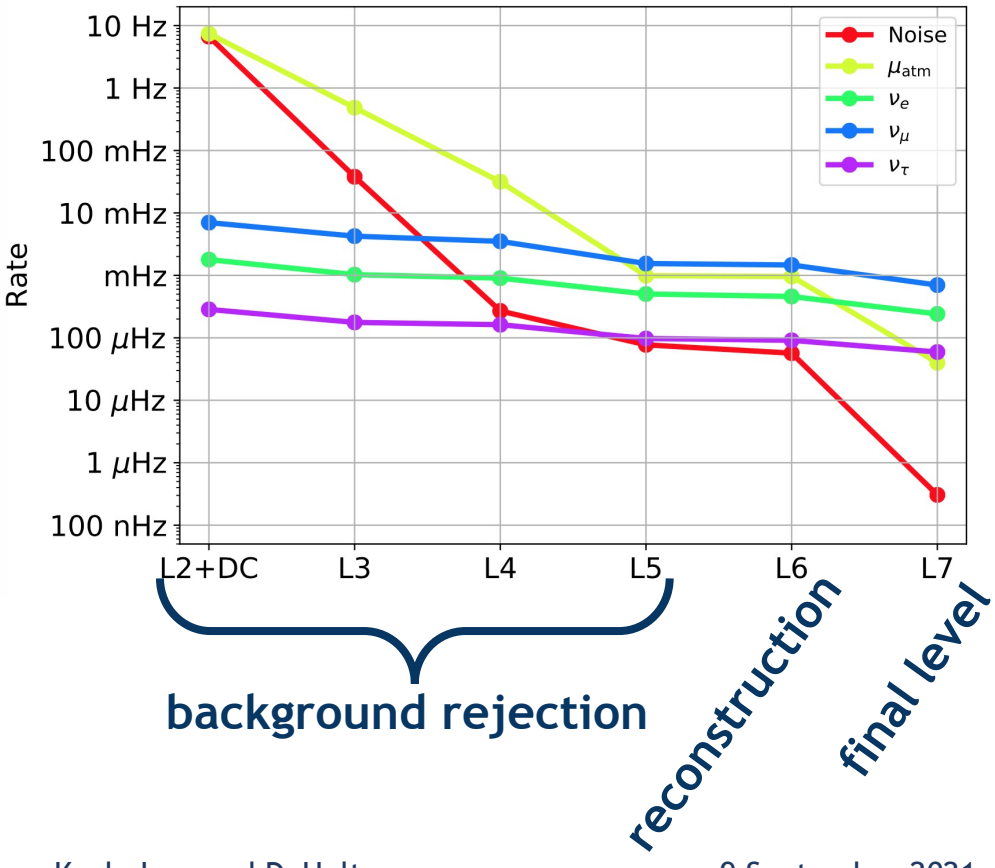
- Elongated
- ν_μ CC

color = time
early hits
late hits

- Difficult to distinguish at low energies
- Newest analyses use Boosted Decision Trees

8 year sample

Background Rejection



Several levels of selection strongly suppress backgrounds

Random Noise Hits

- reduced by 7 orders of magnitude
- <0.03% of final sample

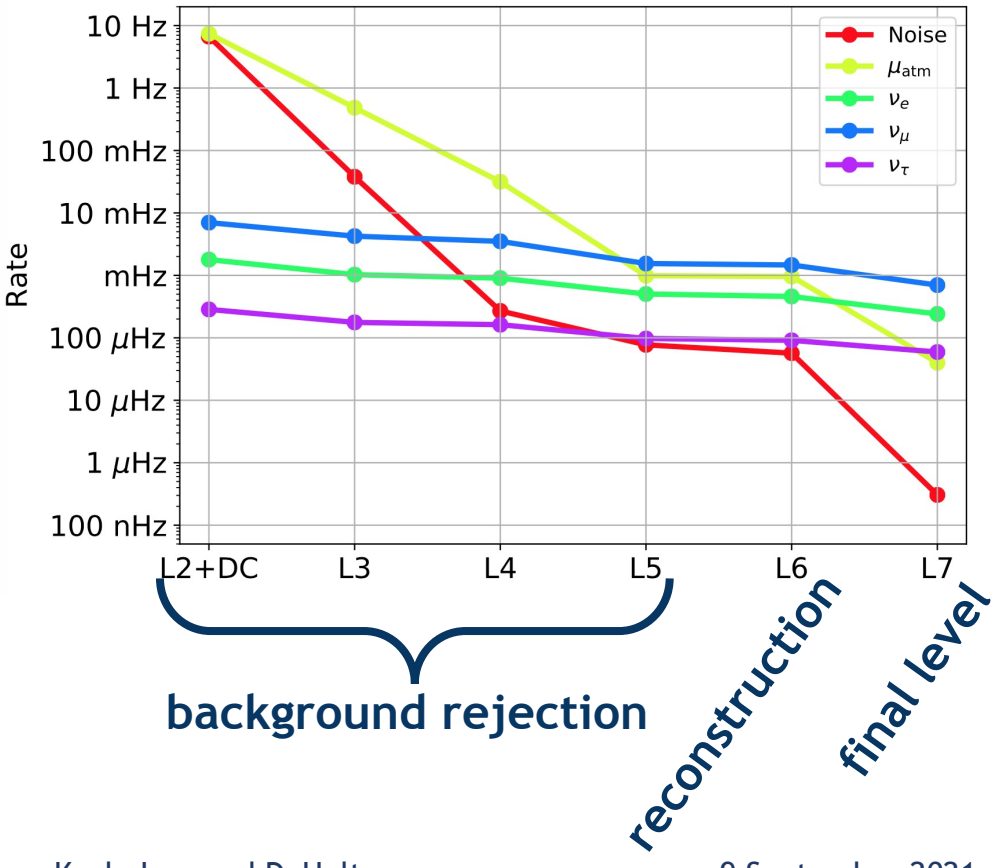
Atmospheric Muons

- reduced by 5 orders of magnitude
- ~3% of final sample

Final neutrino rate ~1 mHz

expect 250,000 neutrinos in 8 year sample

Background Rejection



Levels 2-3

- Fast, simple cuts remove obvious backgrounds (light in veto regions, etc.)

Level 4

- 2 BDTs to target muons and noise

Level 5

- Containment cuts to ensure vertex within DeepCore
- Corridor cut to eliminate “sneaky” muons passing between strings

Final Level

- Post-reconstruction: muon BDT, data quality, containment cut…

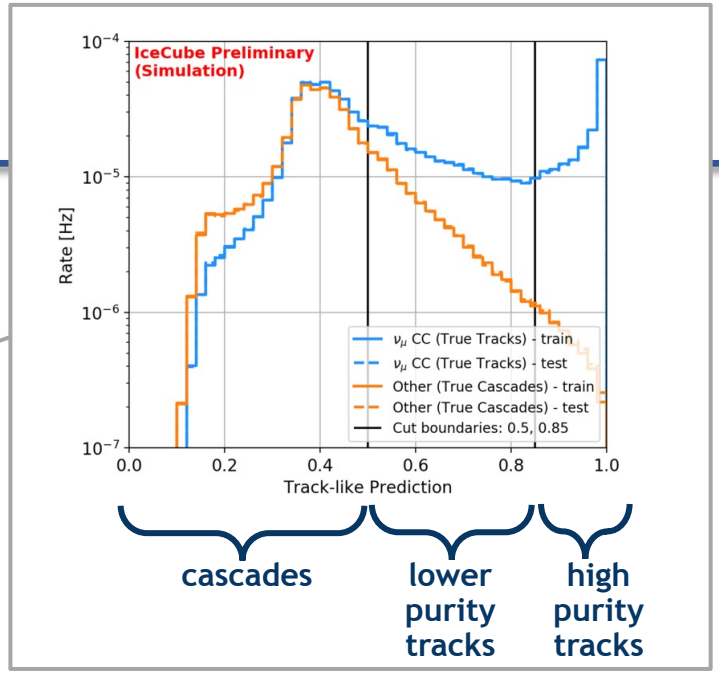
Analysis Strategy

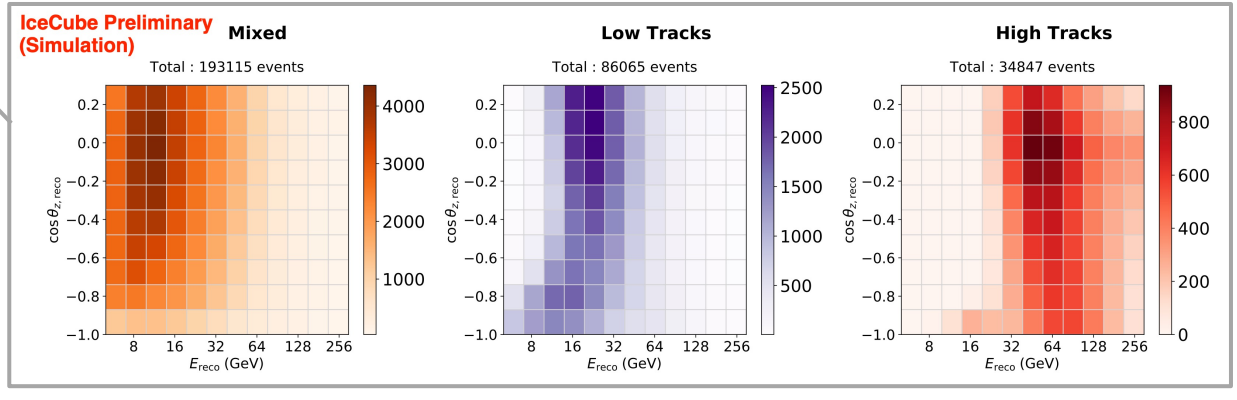
Event selection

Bin in PID classification

Bin in energy and cos(zenith)

Compare templates for data and simulation: fit nuisance and physics parameters





Systematics

Flux

- Neutrino & Muon Flux Normalizations, Spectral Index
- Atmospheric Neutrino Flux (Barr parameters)

Cross Sections

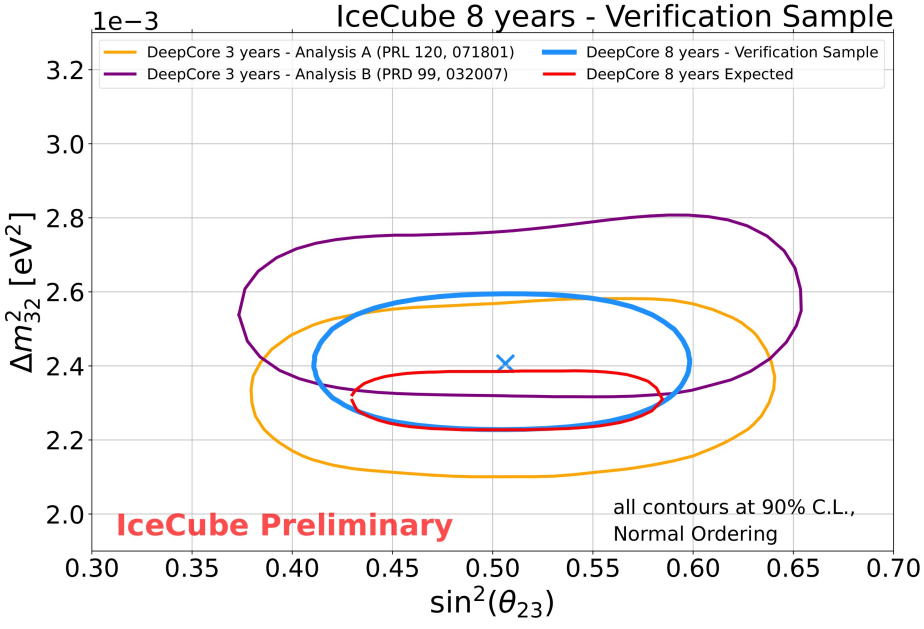
- Deep Inelastic Scattering - Genie vs. CSMS
- Quasielastic & Resonant axial mass

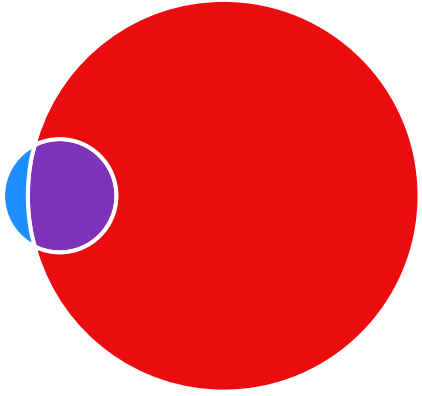
Detector Systematics

- DOM (PMT) Efficiency
- Bulk Ice Properties (scattering & absorption of main glacier)
- Hole Ice Properties (ice near strings refrozen after deployment)

8 Year Verification Sample Result

- Fast reconstruction for events with direct (unscattered) light
- About 10% in size compared to full high statistics sample
- Independent final level selection so most (but not all) events are also in the high stats sample





Verification Sample

~23k events

High Stats Sample

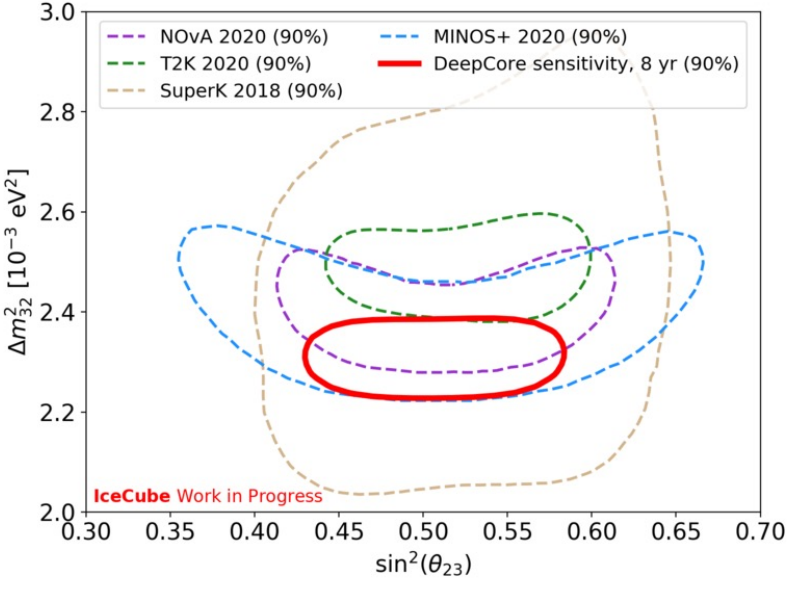
~250k events

$$\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$$

$$\Delta m^2_{32} = 2.41^{+0.084}_{-0.084} \times 10^{-3}\,\mathrm{eV}^2$$

8 Year High Statistics Sample Sensitivity

- Uses a more robust reconstruction which allows more events to be kept
- High statistics sample result expected to follow after the initial verification sample result
- Sensitivity of high statistics sample is competitive with accelerator measurements
- Complementary to accelerator experiments:
  - probes higher energies
  - different systematics at production and detection

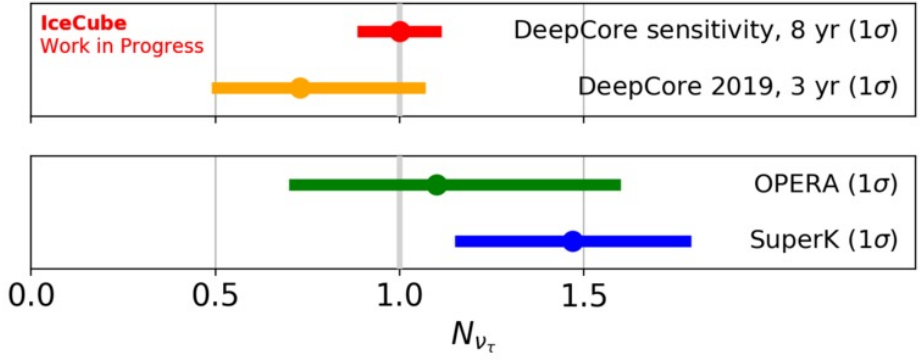


Tau Neutrino Appearance

- DeepCore observes above the tau lepton production threshold for $\boldsymbol{\nu_\tau}$ CC
- $\boldsymbol{\nu_\tau}$ appearance analysis fits a separate normalization $\mathbf{N_{\nu_\tau}}$
- Probes unitarity of the PMNS matrix
- Expect a world leading measurement of the tau neutrino normalization

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1$$



Looking forward

- Additional analyses underway using the high statistics sample
  - Neutrino Mass Ordering
  - Non-standard Interactions
  - Sterile Neutrinos
  - Solar WIMP
  - and more
- IceCube Upgrade scheduled for deployment around 2023
  - Infill even denser than DeepCore
  - Improved resolution, calibration, and lower energy detection threshold

Summary

- Recent results from IceCube DeepCore "Verification Sample" provide measurements of θ_{23} and Δm^2_{32} competitive with accelerator experiments
- High statistics sample will be unblinded soon to take advantage of the full statistical power
- High statistics sample will also provide a world-leading measurement of the tau neutrino normalization probing PMNS unitarity
- Broad collection of additional analyses using the 8 year sample are actively underway

Thank you for listening!