Sensitivity of the IceCube Upgrade to Atmospheric Neutrino Oscillations

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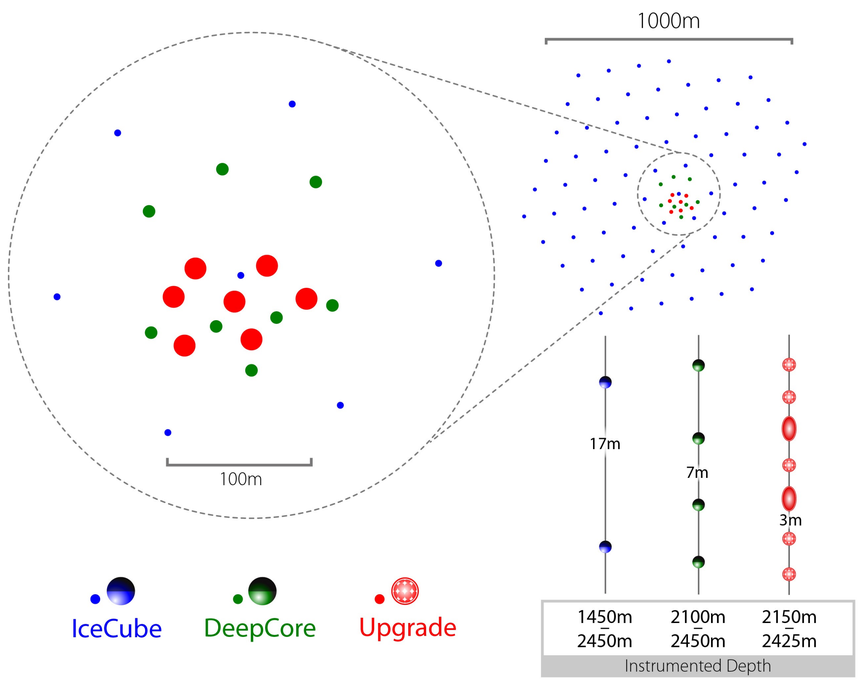
The IceCube Upgrade Detector:

The IceCube Upgrade is an extension of the existing IceCube detector and will be deployed in 2025-26. It features:

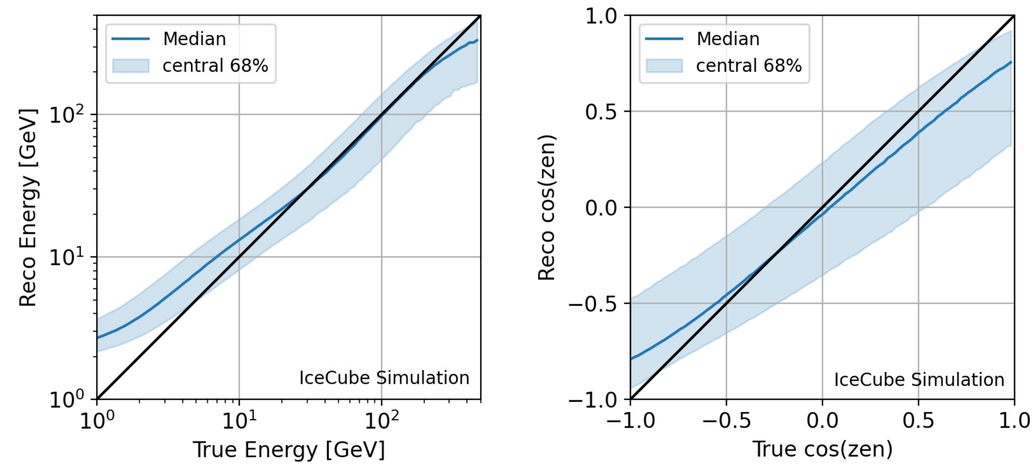
- Seven new strings within the DeepCore volume
- New optical module types (multi-PMT devices)
- New calibration hardware
- Denser module spacing of about 20 m horizontally and 3 m vertically, compared to 40-70 m horizontally and 7 m vertically in DeepCore
- In total more than triple the number of PMT channels with respect to the current IceCube detector configuration

The Upgrade will significantly enhance IceCube's GeV capabilities.

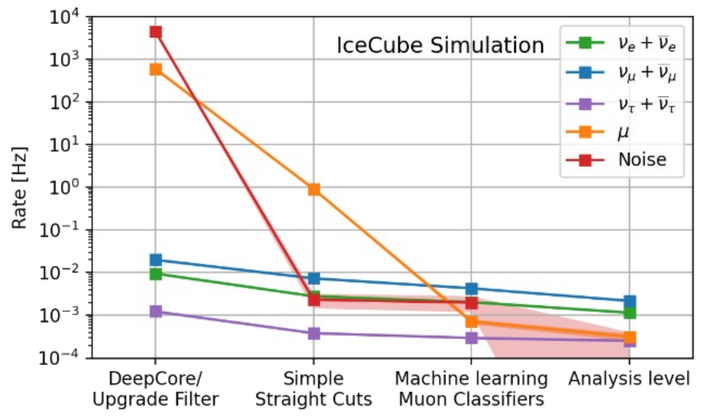


New tools for Upgrade physics:

- **Noise Cleaning:** The Upgrade modules have more channels and an increased number of unwanted noise hits. Using GraphNeT [1], we train a Graph Neural Network (GNN) model to reject such noise pulses. It removes >95% of noise while keeping about 95% of the signal hits.
- **Event Reconstruction:** A similar GNN is used on the cleaned data to predict analysis observables: energy, zenith angle, and track vs. cascade classification (PID). The plots below show the reconstruction performance for neutrinos of all flavors, with energies between 1-500 GeV. Our primary signal region is at 25 GeV.



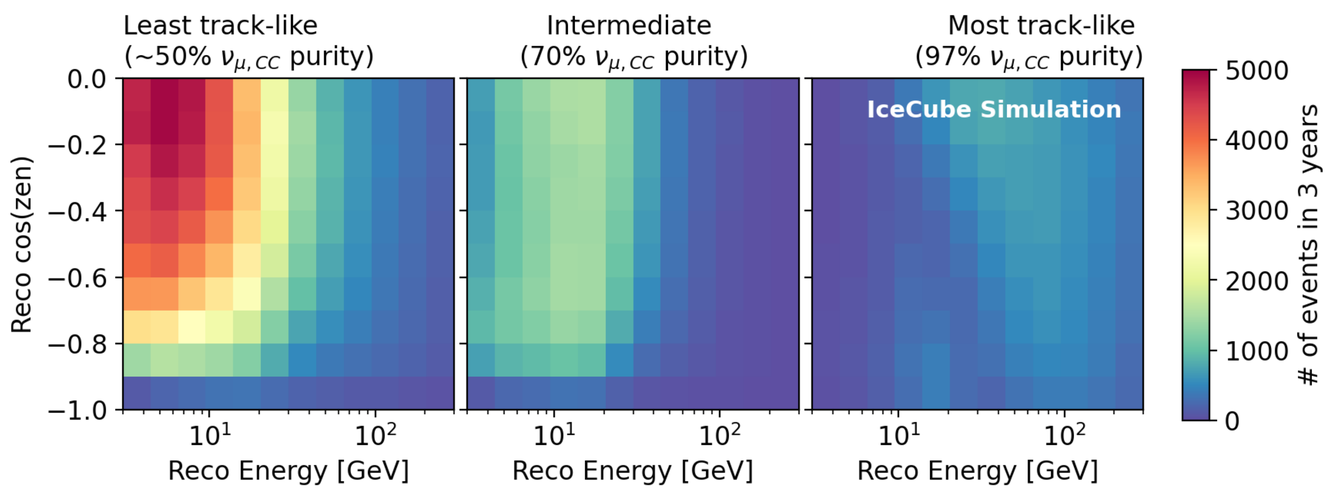
- **Event Selection:** A series of cuts on low-level event variables and Machine Learning classifiers reduce background from pure noise events and atmospheric muons to a level below the expected neutrino rate. The shaded bands correspond to the statistical uncertainty.



[1] JOSS 8(85) 4971, github.com/graphnet-team/graphnet

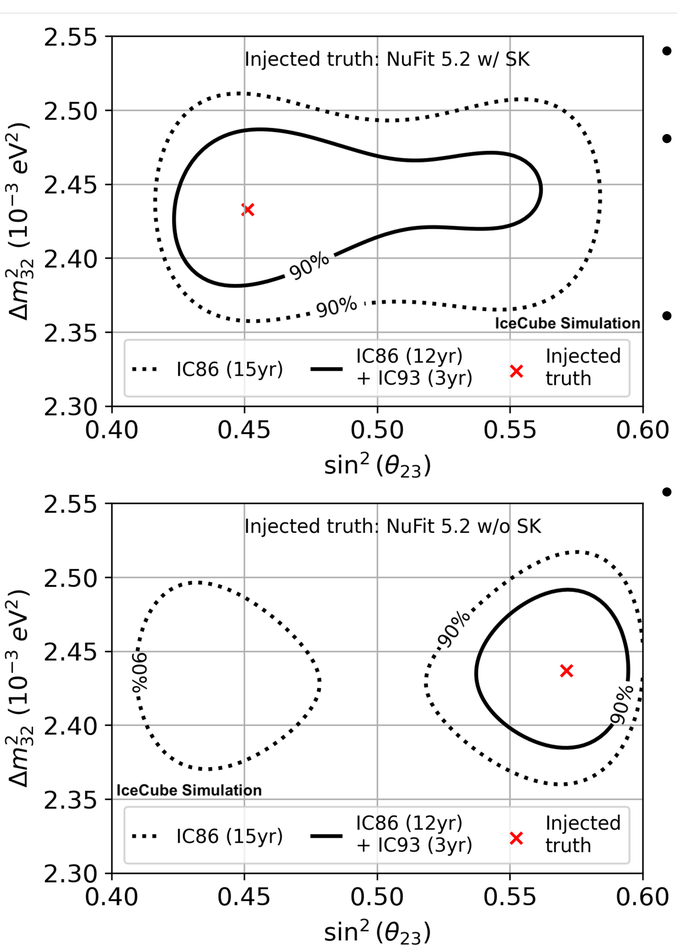
Analysis Techniques:

- **Event sample & analysis histogram:** The simulated event sample contains 315,000 neutrinos using 3 years of the Upgrade. The analysis is performed using histograms binned in energy, cos(zen), and PID. The varying oscillation baselines are given by cos(zen).
- **IC86+IC93 Combined Analysis**: The analysis sensitivities combine the Upgrade (IC93) distribution shown on the right with a similar one that contains events from 12 years of IceCube DeepCore (IC86).
- **Systematic Uncertainties:** The sensitivities include a full set of nuisance parameters accounting for uncertainties in atmospheric flux, cross sections, and detector effects. For more details, see [2].



Expected performance with the IceCube Upgrade:

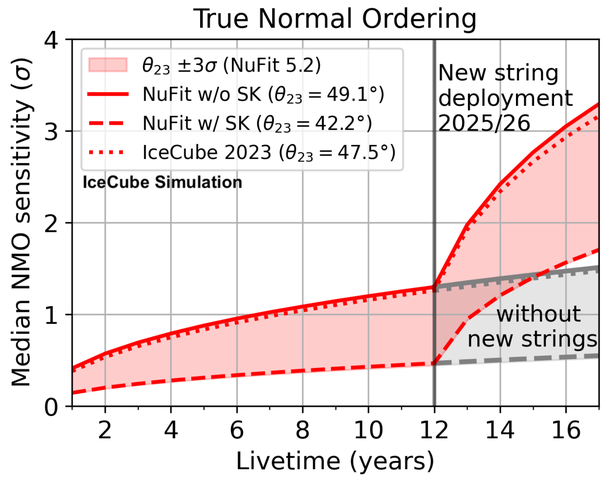
Atmospheric Neutrino Oscillation Parameters



- Sensitivity to the mixing parameters θ_{23} and Δm^2_{32}.
- Combines 12 years of IceCube DeepCore (IC86) with 3 years of the IceCube Upgrade (IC93).
- A scenario w/ (solid) and w/o (dotted) the new strings is compared in each plot.
- We assume two different true scenarios provided by the NuFit global fit: the top plot uses NuFit 5.2 w/ SuperK (SK) as injected truth, while the bottom plot assumes NuFit 5.2 w/o SuperK [3].

[2] arXiv:2307.15295
[3] JHEP 09 (2020) 178, nu-fit.org
[4] Phys. Rev. D 99, 032007 (2019)

Neutrino Mass Ordering (NMO)



- Sensitivity to neutrino mass ordering as a function of livetime for two scenarios: with and without the Upgrade strings.
- The sensitivity strongly depends on θ_{23}.
- The shaded bands correspond to the preferred 3σ range from NuFit 5.2 [3].
- The new strings drastically enhance the sensitivity to NMO. With 4 years of the Upgrade, we expect 1.5-3σ sensitivity.

Tau Neutrino Normalization

- The ν_τ normalization parameter scales the number of ν_τ and represents a deviation from the expectation w.r.t. PMNS unitarity or current ν_τ cross-section uncertainties.
- IceCube constrained the 1σ width of this parameter to about ±25% [4].
- With the IceCube Upgrade, the uncertainty on this parameter will be reduced to about ±5%.