Impact of Hole-Ice Calibration on High Energy Event Reconstruction with the IceCube Upgrade

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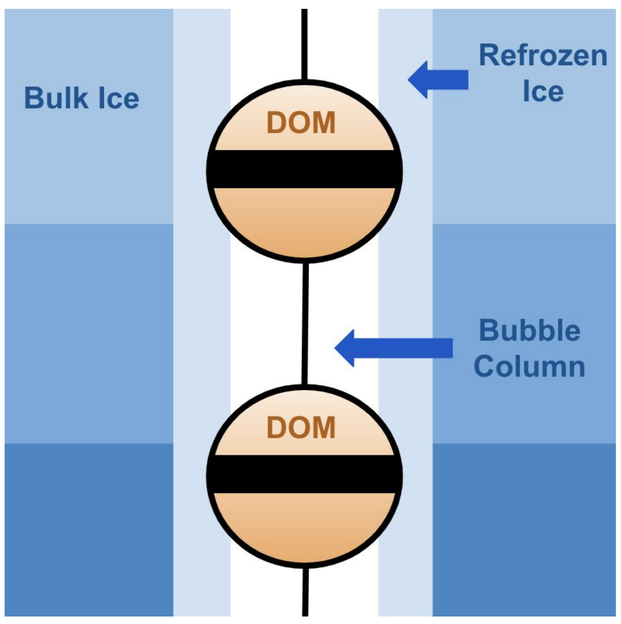
ICRC 2025

Motivation

Concept of Hole Ice



- Each IceCube deployment hole created with a hot water drill.
- Refreezing creates a vertical column of ice that is optically clearer than the surrounding glacial ice.
- Drilling introduces **bubbles** and impurities that are pushed toward the hole center during refreezing and stick to glass housing of Digital Optical Modules (DOMs) [1].
- **Camera footage** reveals the bubble column has much shorter scattering and absorption lengths than surrounding ice.

Why do we need a precise calibration of hole ice?

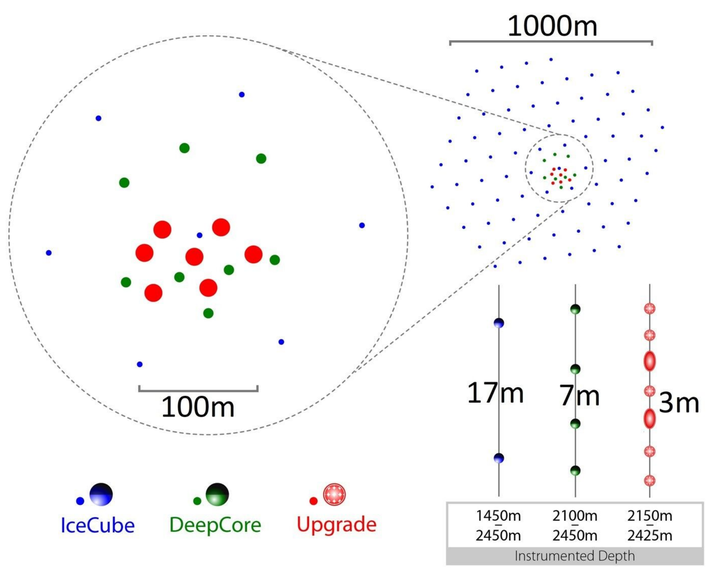
Reconstruction accuracy at TeV - PeV energies is constrained by systematic uncertainties, particularly those from photon propagation through hole ice.

Better calibration translates to better reconstruction performance.

The IceCube Upgrade

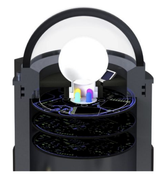
The IceCube Upgrade [2] is the upcoming low-energy extension to the existing IceCube detector. Some of its features are:

- Seven new strings within the DeepCore volume.
- Denser instrumentation, with horizontal & vertical inter-module spacings at ~30 m and 3 m respectively.
- **Novel calibration devices** contained inside mDOMs, DEggs, and POCAMs [2], will allow a detailed study of hole ice optical properties.



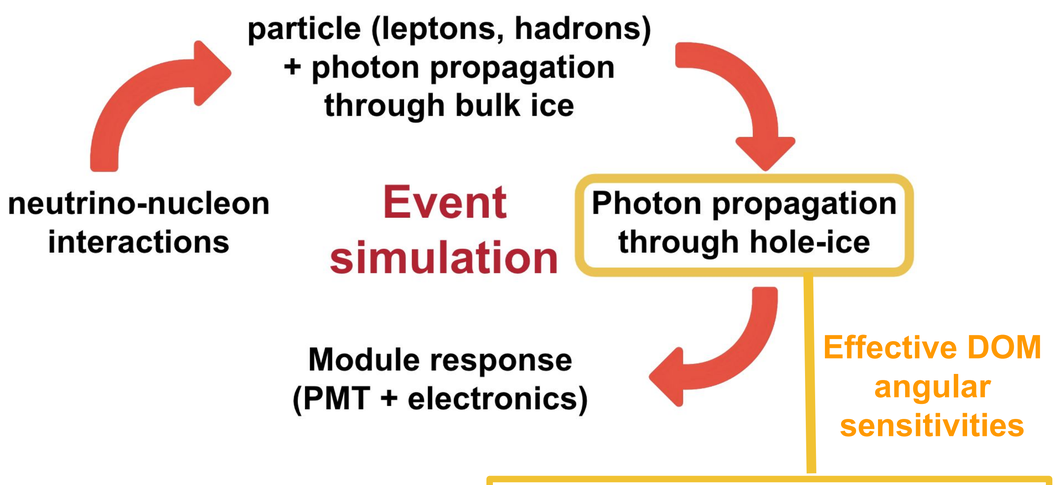

mDOM


DEgg

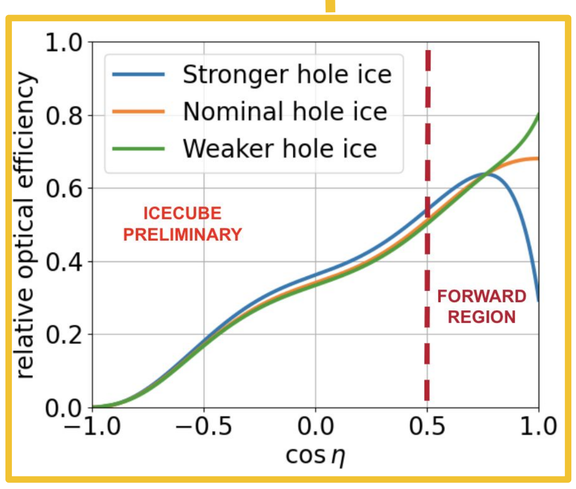

POCAM

Event Simulation

- Brief overview of the simulation chain for IceCube events:



- The bubble column absorbs photons approaching from the front of the PMT → reduced sensitivity in the forward region.
- Modeled by reducing the forward sensitivity in the angular response curves [3].
- Nominal hole ice derived from simulated photon tables.



- Simulations use real event selections, with photon propagation re-simulated with different hole-ice models to mimic parameter knowledge bias.
- Signal yield mismatch ⇒ degraded reconstruction performance.

Reconstruction procedure

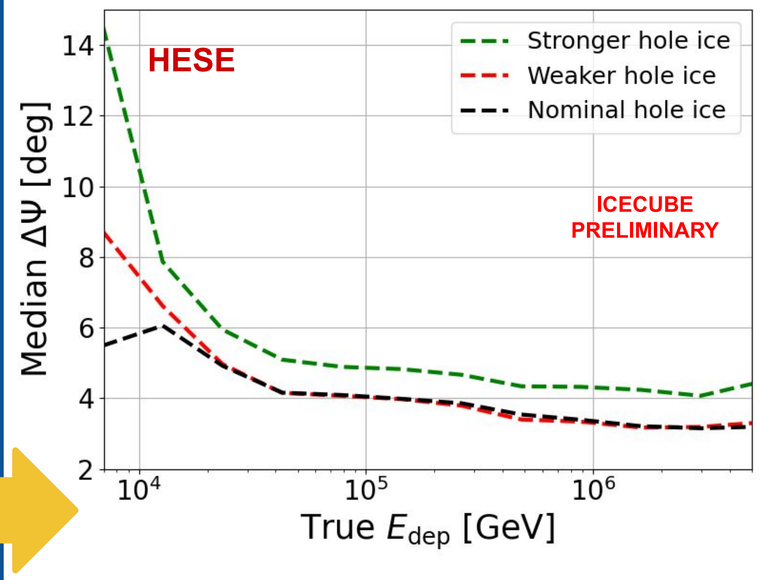
- Parameter of interest is the incoming **zenith angle of neutrinos**.
- **Cascade-like events** are modeled with a single-cascade fit to obtain initial parameter estimates. A two-cascade fit further models the longitudinal extent of high-energy showers, and improves reconstruction accuracy [4].
- **Track-like events** are segmented into cascade-like sources created by processes such as bremsstrahlung. Maximum likelihood fit to photon arrival times in hit modules yields best-fit muon direction [5].

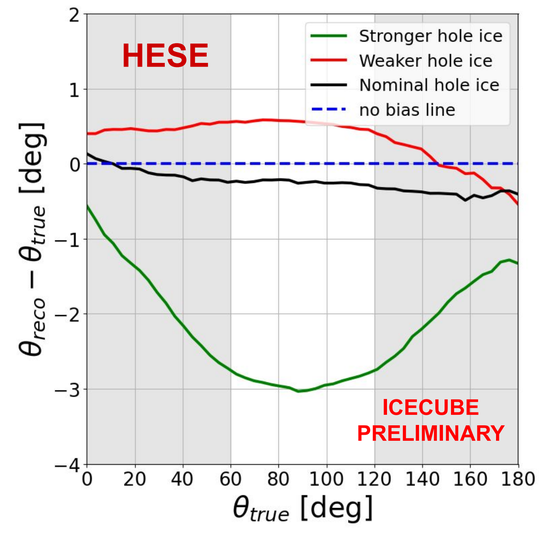
Results

- Previous studies [6,7] with systematic fits to MC data show that Upgrade can achieve a **precision of ~1%** in the forward region of effective angular sensitivity curves.
- Impact of improved hole ice calibration on directional reconstruction evaluated on:

Dataset	Event type	Energy Range
HESE [8]	Contained electron-neutrino cascades	[10 TeV, 1 PeV]
DNN Cascades [9]	Partially contained all-flavor cascades	[1 TeV, 1 PeV]
ESTES [10]	Tracks starting within the detector volume	[1 TeV, 1 PeV]

- A weaker hole ice model shows a negligible impact across all datasets.
- **Contained cascades:** stronger hole ice assumption results in reconstruction resolution loss of ~ 4^0 at 10 TeV and ~ 1^0 above 100 TeV of deposited energies; directional bias degrades upto 3^0 for horizontal cascades ($\theta_{true} \approx 90^0$).
- **Partially contained cascades**: minimal resolution degradation at TeV energies and modest 1^0 degradation in the PeV range; directional bias degrades upto 3^0 for horizontal cascades.
- **Tracks:** No significant impact on reconstruction or directional bias.





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