Status of the Precision IceCube Next Generation Upgrade (PINGU)

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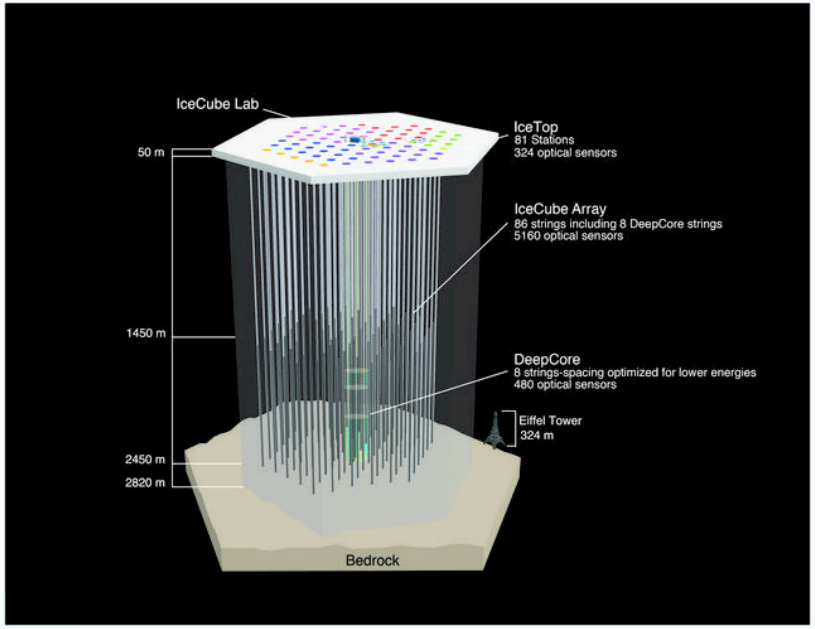
5th Open Meeting for the Hyper-Kamiokande Project
Vancouver
July 20, 2014

The IceCube–PINGU Collaboration

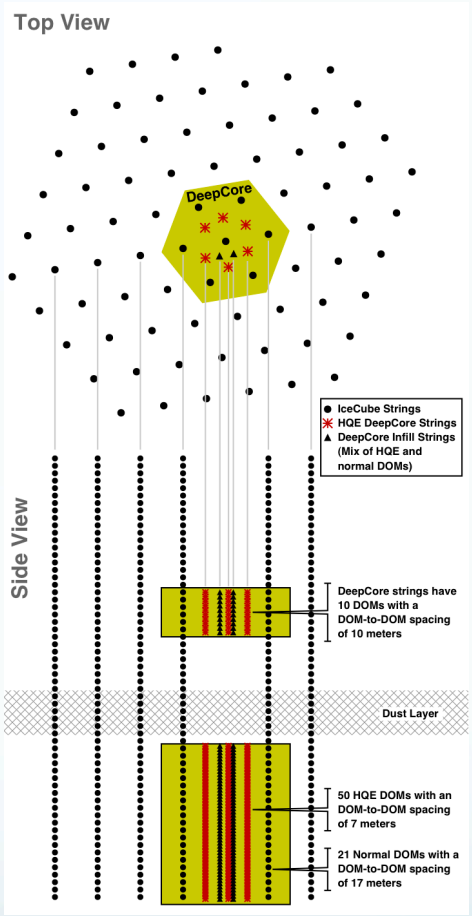
International Funding Agencies

Fonds de la Recherche Scientifique (FRS–FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube and DeepCore



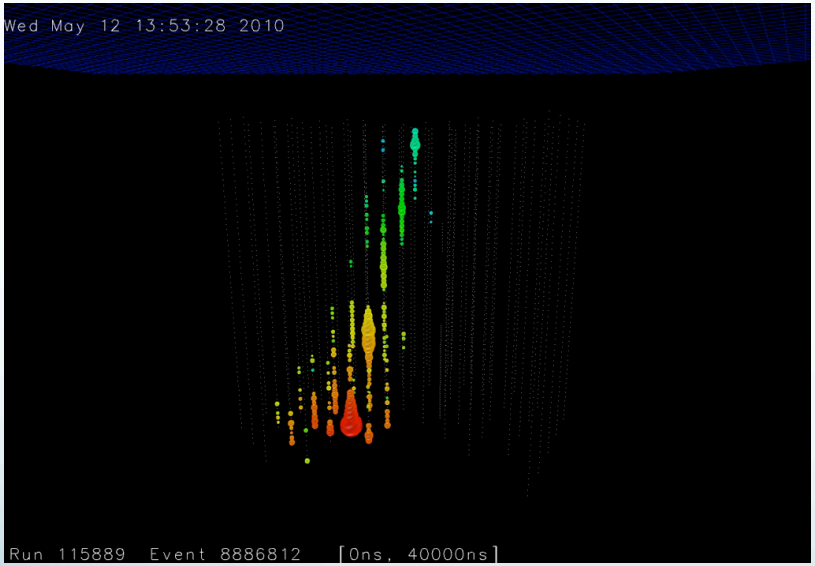
86 strings with 60 Digital Optical Modules (DOMs)
Deployed between 1450 and 2450 m depth
81 IceTop surface stations
Construction complete December 2010



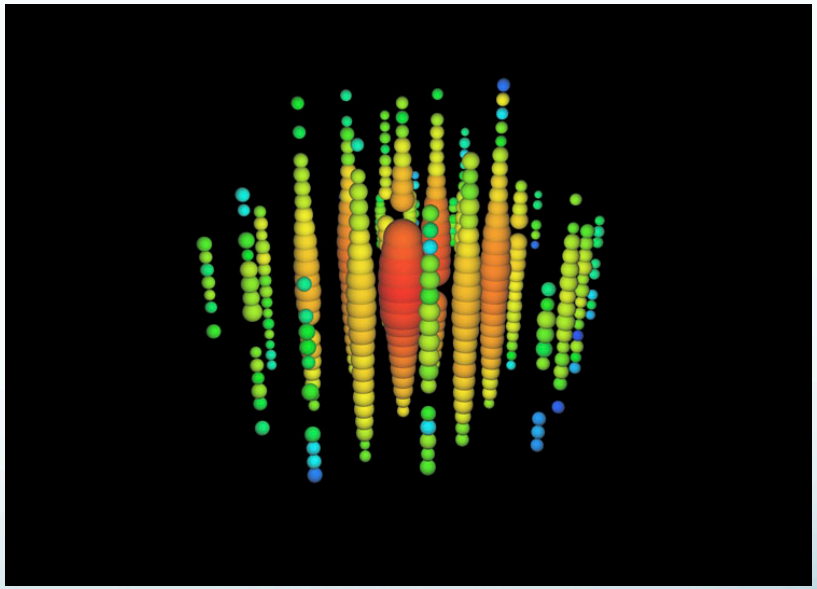
8 strings with more densely spaced, higher quantum efficiency DOMs in the clearest ice at the center of IceCube

Event Signatures in IceCube

Tracks from charged current muon neutrino interactions



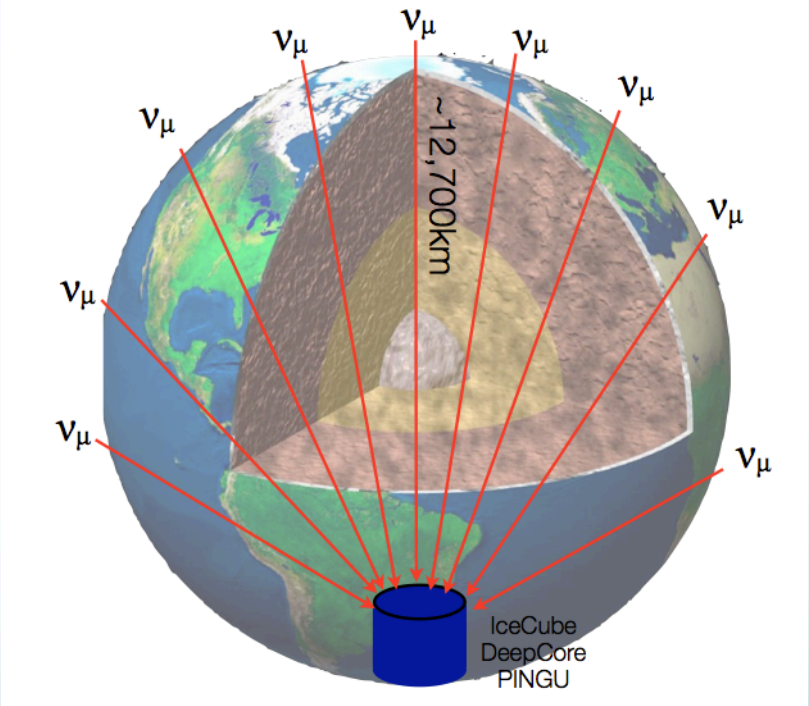
Cascades from charged current electron and tau neutrinos and neutral current interactions of all flavors



Use deposited light to reconstruct energy, position, direction, time

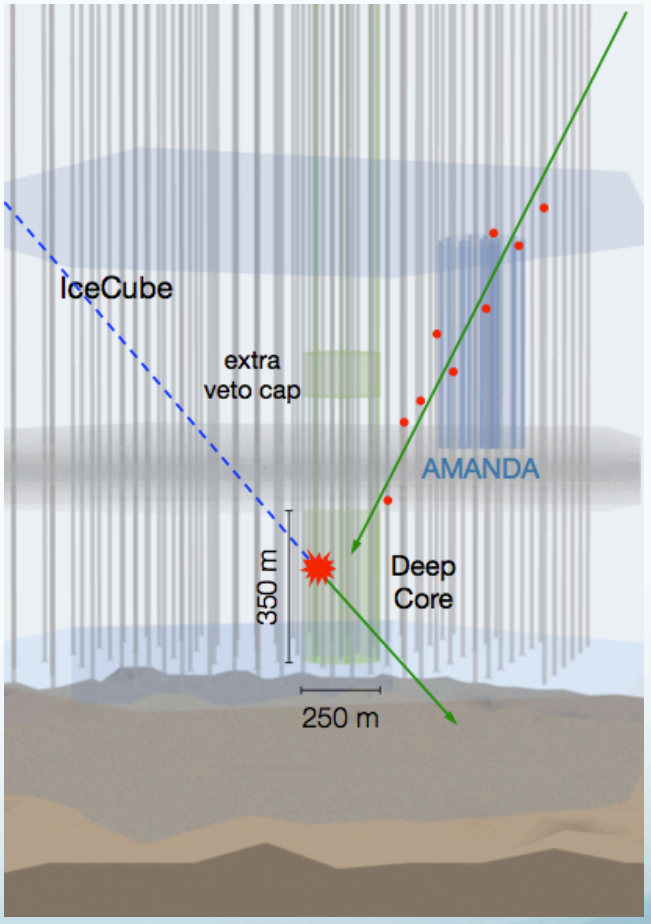
Atmospheric Neutrinos in IceCube/DeepCore

- IceCube designed for astrophysical neutrino detection
- DeepCore extends IceCube's physics capability at lower energies
- Using neutrinos from cosmic rays interacting with the atmosphere
- Range of baselines and energies to control systematics
- Neutrino oscillation in the Earth enhanced by MSW effect, strongest effects below ~10 GeV

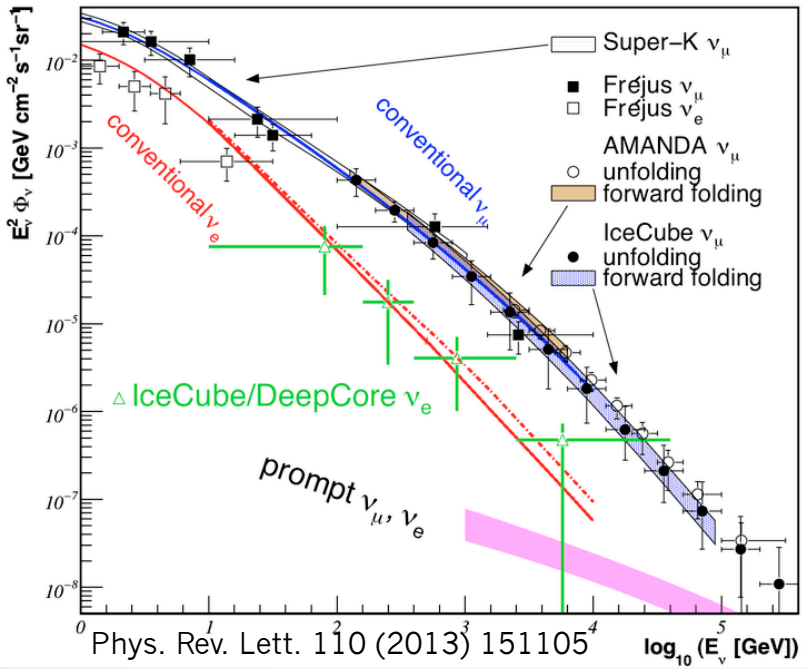


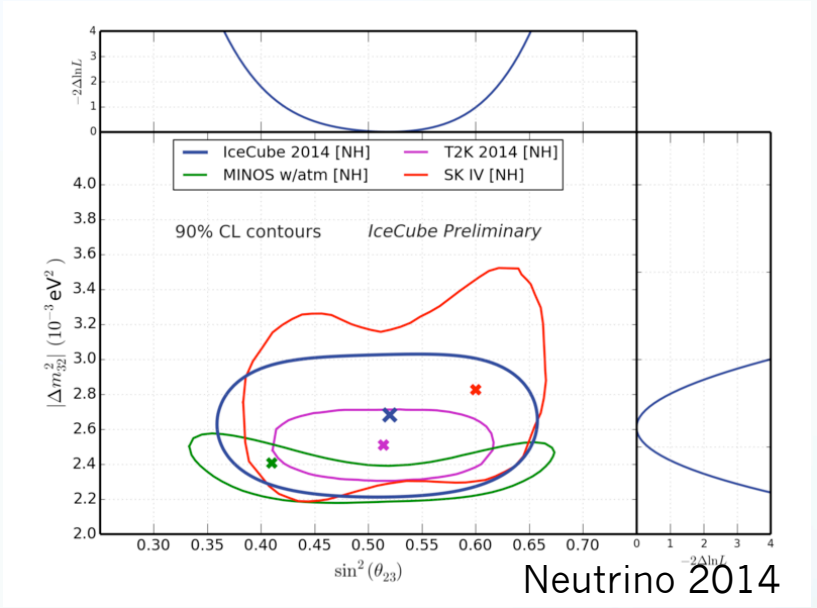
IceCube as a Veto

- **Substantial background from cosmic ray induced muons**
  - **~3 kHz at trigger level in IceCube**
  - **Rate of atmospheric neutrinos is a few hundred per day in IceCube**
  - **=> Veto efficiency of 10^6 required**
- **Outer IceCube strings act as active veto for DeepCore to eliminate atmospheric muon background**



Neutrino Physics with DeepCore



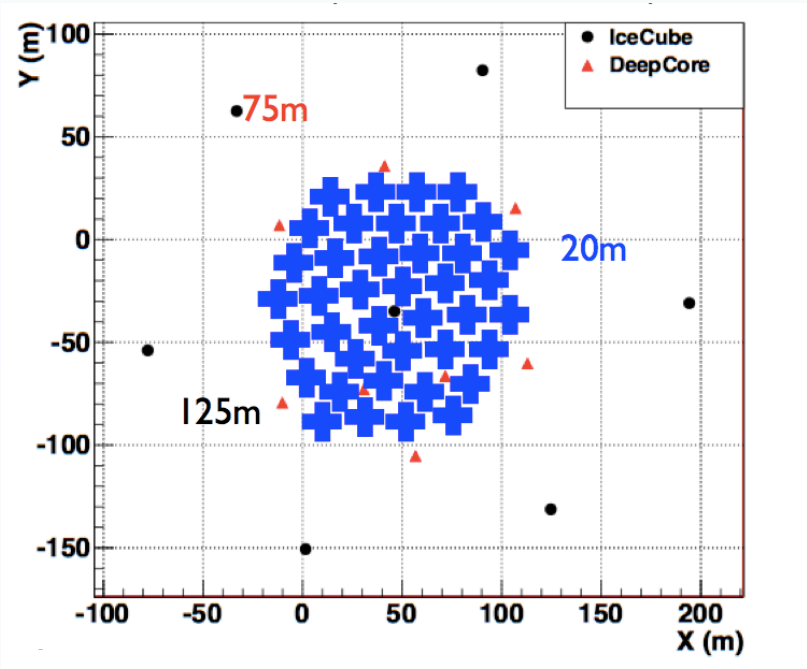


IceCube veto allowed DeepCore to measure atmospheric electron neutrino flux from 80 GeV to 6 TeV for the first time

Muon neutrino disappearance measurement
3 years of full IceCube data
5293 events in 953 days
Competitive with world's best measurements
Results compatible with world average values of θ_{23} and $|\Delta m^2_{23}|$

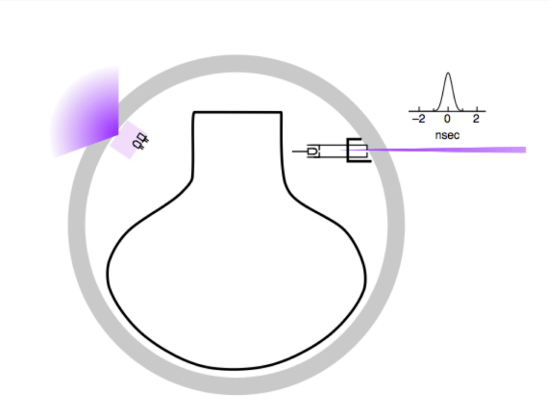
PINGU

- Proposed infill extension of IceCube/DeepCore
  - Physics goals: neutrino mass hierarchy, tau neutrino appearance, indirect dark matter detection, supernovae neutrinos
- Baseline geometry: 40 strings with 60 PDOMs per string
  - Still being optimized
- 20 m string-to-string spacing, ~15x higher instrument density
- Relatively modest cost and rapid construction for a NMH measurement
- IceCube experience shows that drilling 40 strings in 2-3 years is feasible

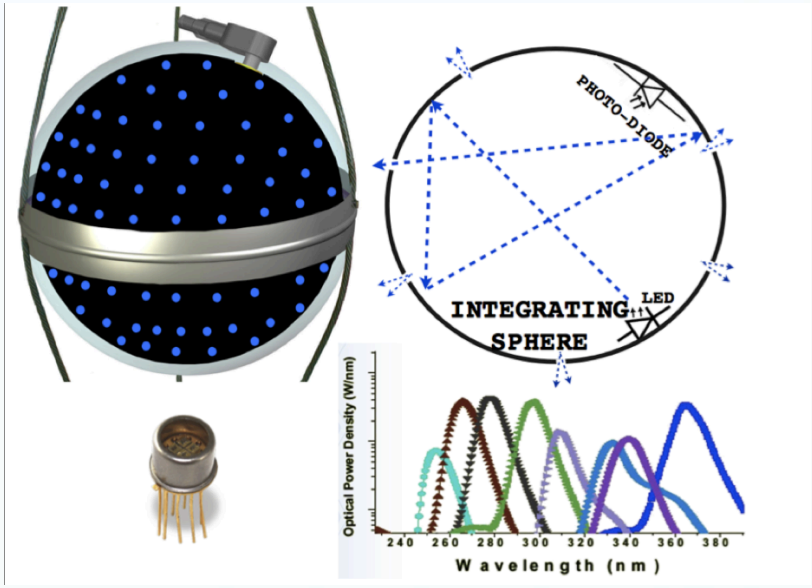


- Improvements to IceCube design
  - Single digitizer channel
  - Remove "local coincidence" condition
  - Feature extraction in ice
  - Improve measurement of ice properties and DOM sensitivity with dedicated calibration devices
  - De-gassing of drill water to mitigate bubbles in refrozen hole ice

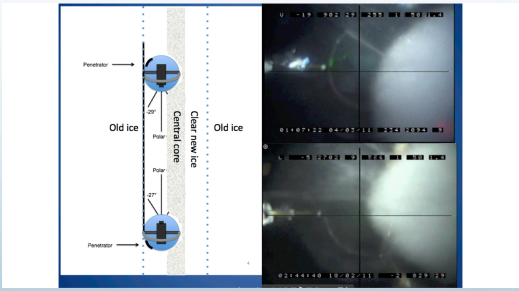
Calibration Devices



Flasher LEDs to be deployed with every pDOM: already used in IceCube to measure ice properties



Under development: Precision Optical Calibration Module: diffuse multiwavelength source

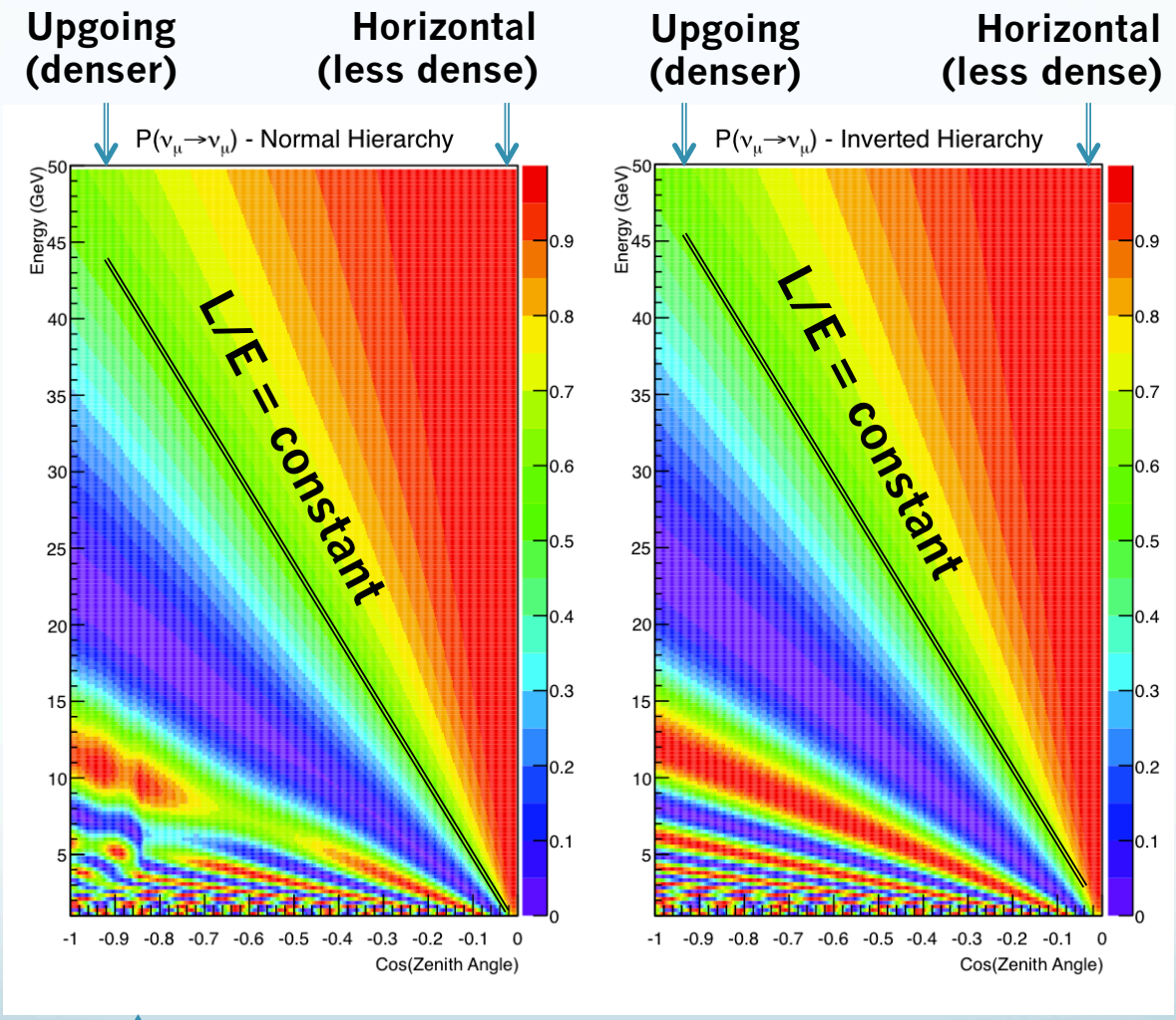


Cameras to investigate refrozen ice in the hole, verify degassing, check orientation of pDOM

NMH Signature in PINGU

$$\sigma(\nu) \sim 2\sigma(\bar{\nu})$$

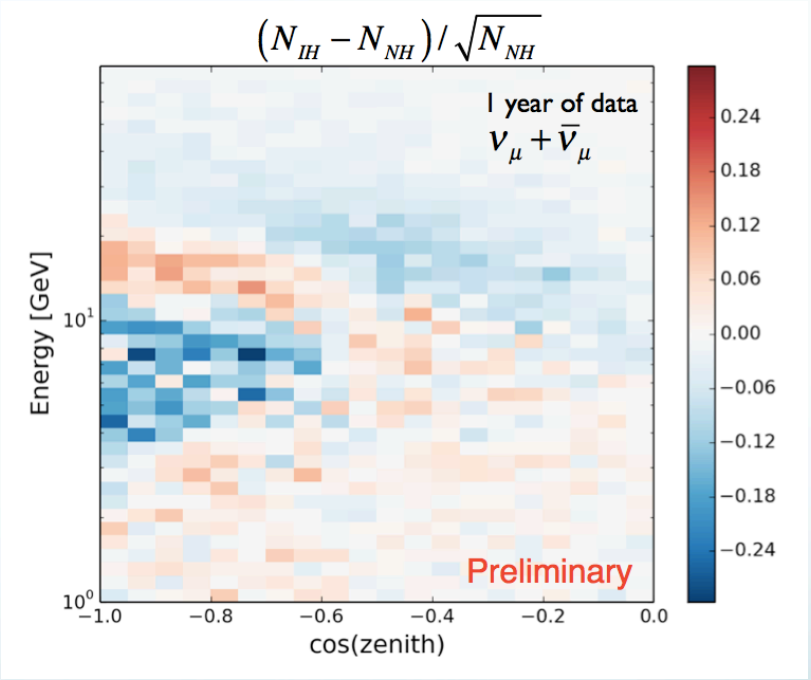
$$\phi(\nu) > \phi(\bar{\nu})$$



Matter effects are hierarchy-dependent
Relatively large value of θ_{13} makes it possible to measure hierarchy

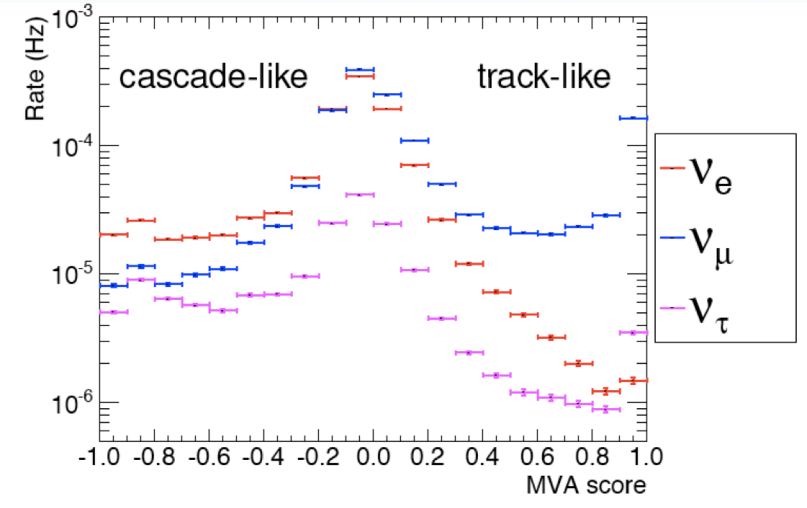
NMH Signature in PINGU

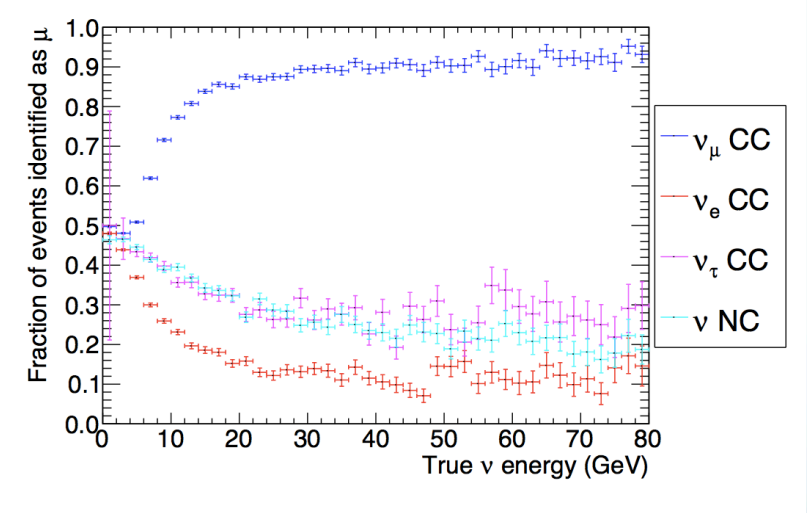
- **Distinguishability metric (Akhmedov *et al.*, JHEP 2013(02) pp. 1-39) used to show NMH pattern in PINGU data**
- **Use energy/zenith angle pattern to reduce impact of systematic errors**



Reconstructed energy $\Delta E/E \sim 0.27$ at $E_{true} = 5$ GeV
Reconstructed zenith angle $\sigma_\theta \sim 13°$ at $E_{true} = 5$ GeV
No particle ID included yet

Particle ID in PINGU



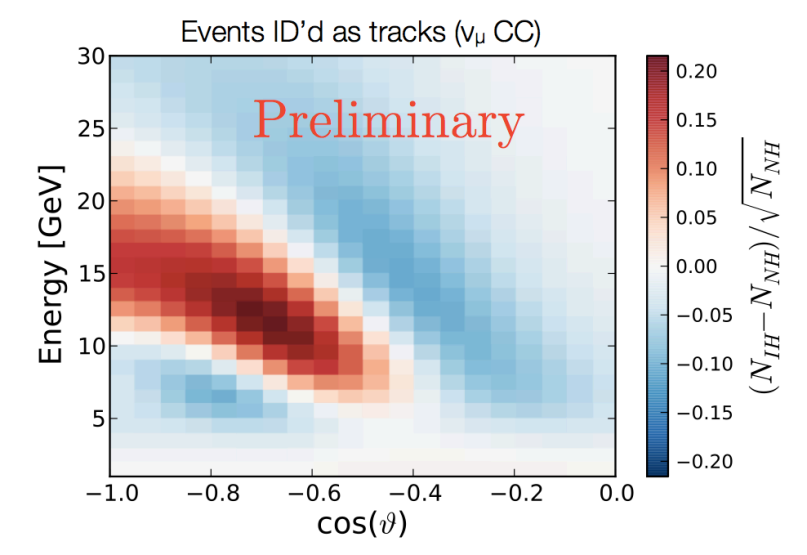


Use time distribution of hits to identify outgoing tracks, separate ν_μ CC from all NC, ν_e, ν_τ CC

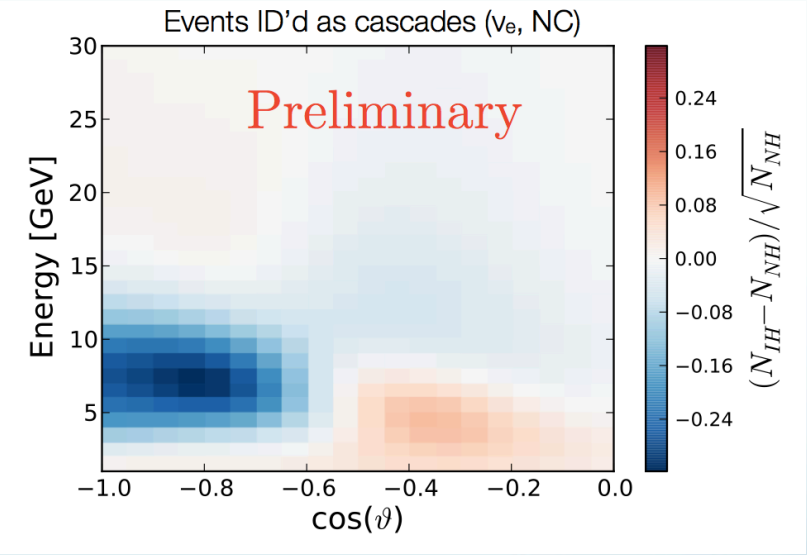
Efficiency for particle ID in PINGU simulation Also agrees well with DeepCore data

Particle ID in PINGU

NMH distinguishability using tracks



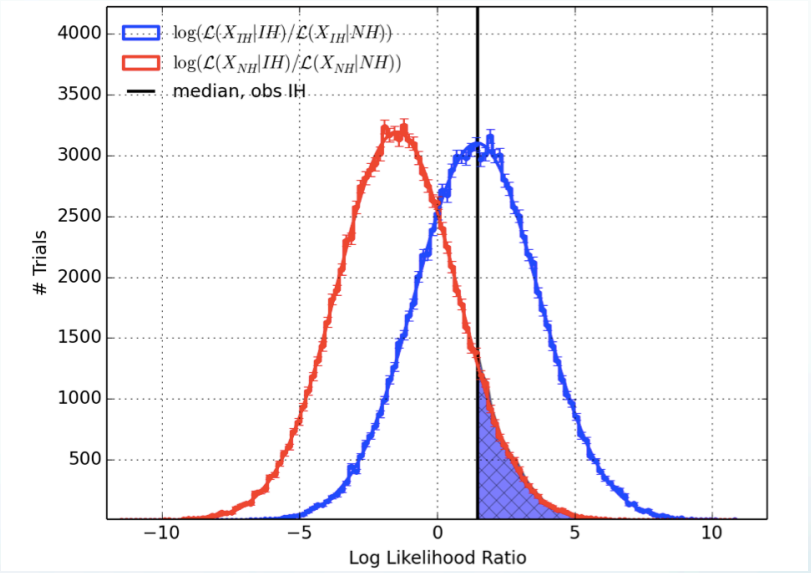
NMH distinguishability using cascades



Detector efficiency, reconstruction and particle ID included

NMH Sensitivity

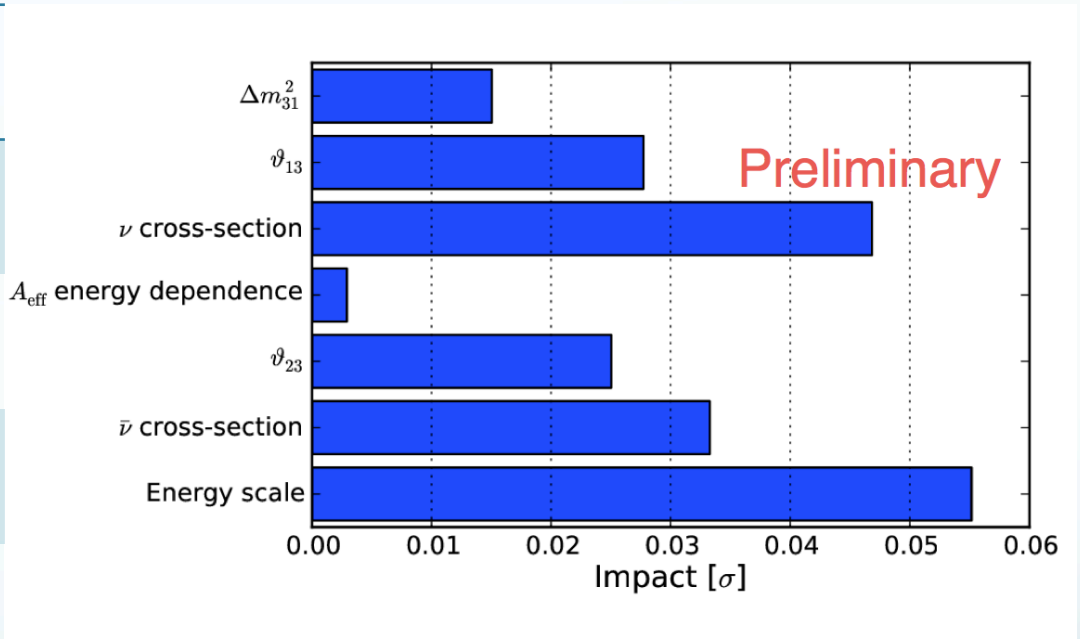
- Use energy-zenith angle histograms to calculate PINGU's sensitivity to the NMH
- Calculate sensitivity with three methods
  - Fisher information matrix
  - Asimov approach
  - Log likelihood ratio
- Methods agree with each other



Likelihood ratio analysis

Systematic Effects

$\Delta(m_{31})^2$	$\pm 1\sigma$
θ_{13}	$\pm 1\sigma$
θ_{23}	$\pm 1\sigma$
Cross section	**±15%**
E_{reco}/E_{true}	**5%**
A_{eff}	**Dependence on E, σ**

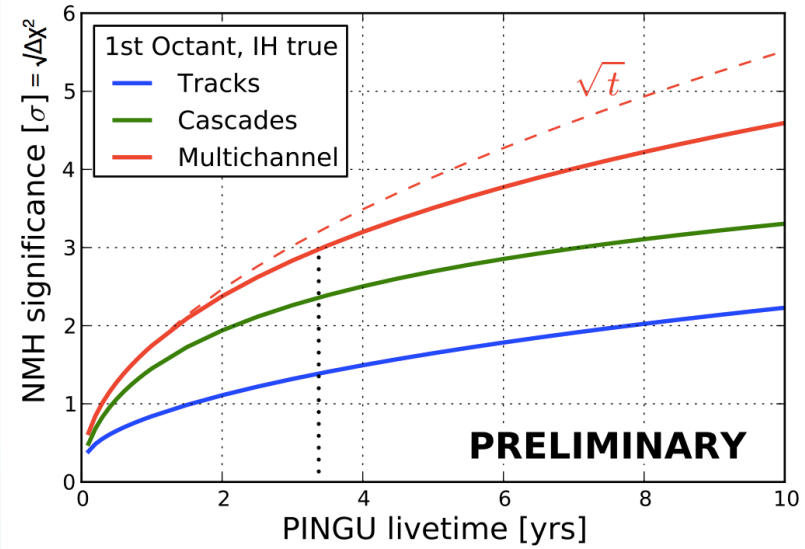


Still to be added: ice properties, particle ID

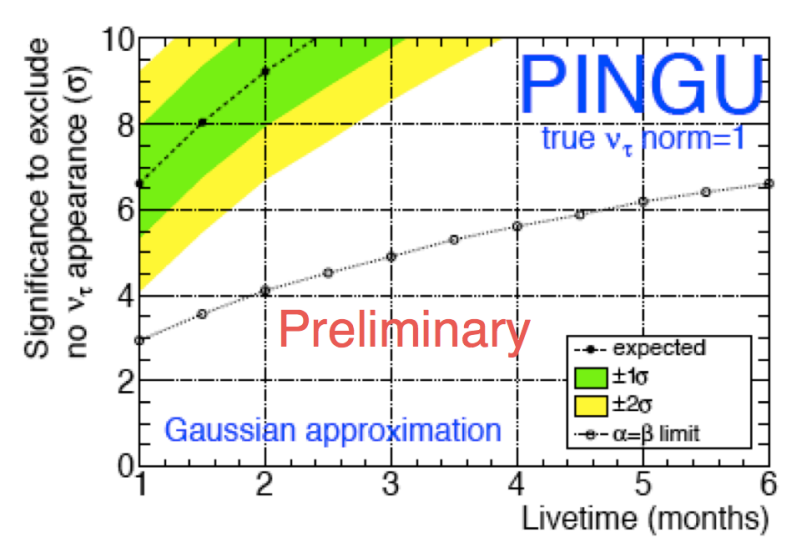
Minimal effect from δ_{CP}

Significance vs Time

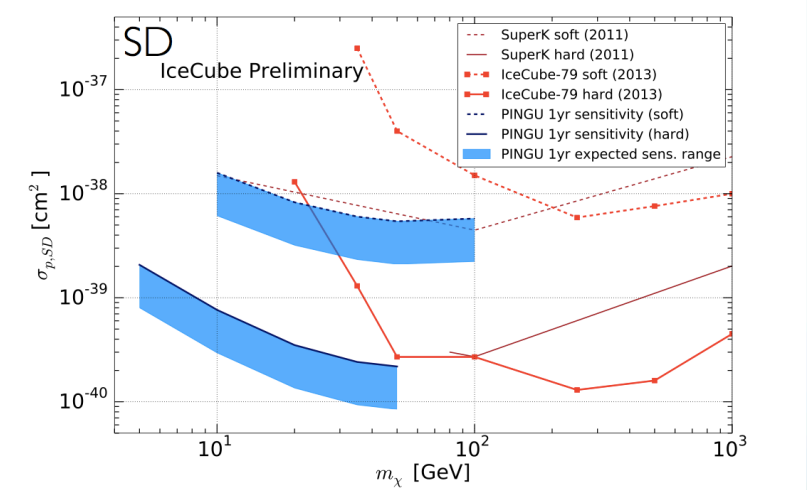
- Significance shown using parametric model of detector response
  - Includes systematics and particle ID
- With inverted hierarchy, reach 3σ in 3.5 years
  - Not including data collected during construction
- Geometry optimization, further systematic studies and refinement of particle ID ongoing



More PINGU Science Goals



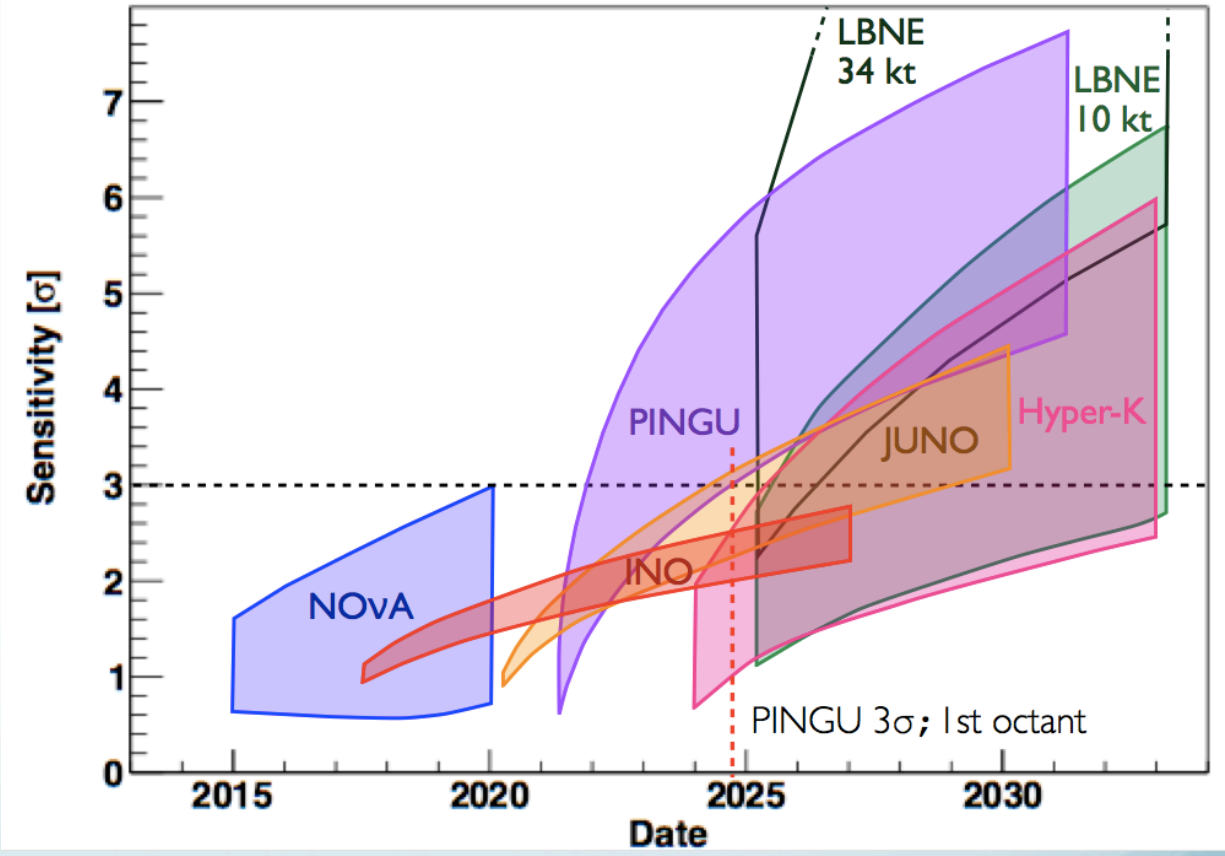
Tau neutrino appearance: 5 σ exclusion of no tau neutrino appearance in one month of PINGU data



Best limits on spin-dependent WIMP detection down to 5 GeV

Sensitivity to NMH in Upcoming Neutrino Experiments

- **Widths indicate main physics uncertainty**
  - **PINGU/INO/ HyperK: θ_{23}**
  - **LBNE/NOνA: δ_{CP}**
  - **JUNO: σ_E**



Blennow et al., arxiv:1311.1822, LBNE-doc-8087-v10, Hyper-K from arXiv:1109.3262 (2011)
Hyper-K start date is 2025 (ICHEP14)

Summary

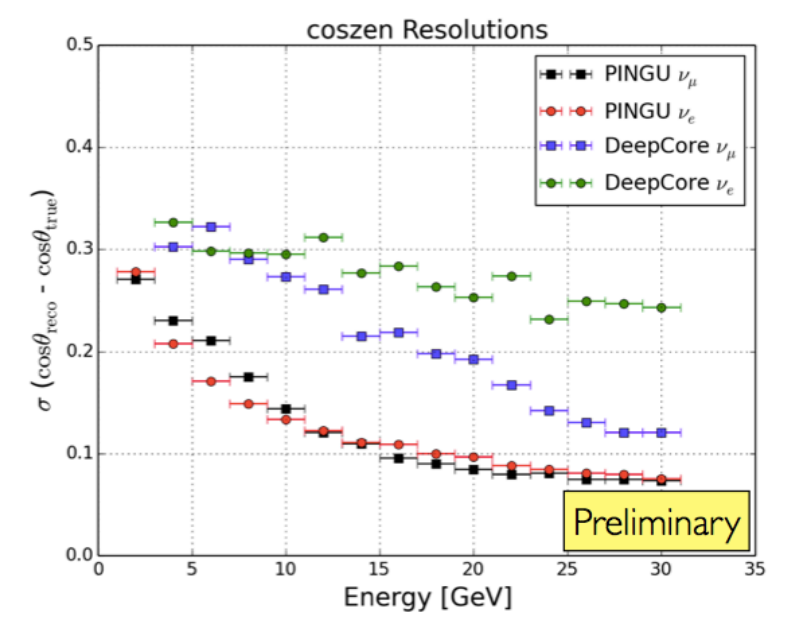
- IceCube with DeepCore has demonstrated sensitivity to atmospheric neutrino physics
- PINGU infill extension could measure NMH at 3σ in 3.5 years
  - Technology has been proven with IceCube, relatively low cost
  - Analysis still being improved
  - Complementary to long baseline accelerator experiments
  - Lead the way for further IceCube extensions
  - PINGU physics program also includes indirect dark matter detection, tau appearance
- MREFC proposal in preparation, CFI proposal submitted and under review, other countries in the process of applying for funding
- Letter of intent on the archive, to be updated this fall

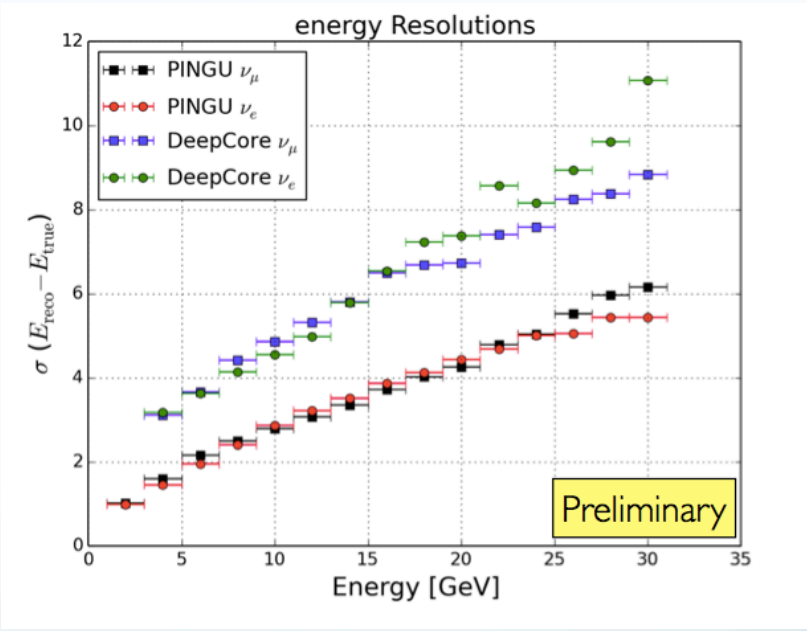
Backup slides

PINGU costs

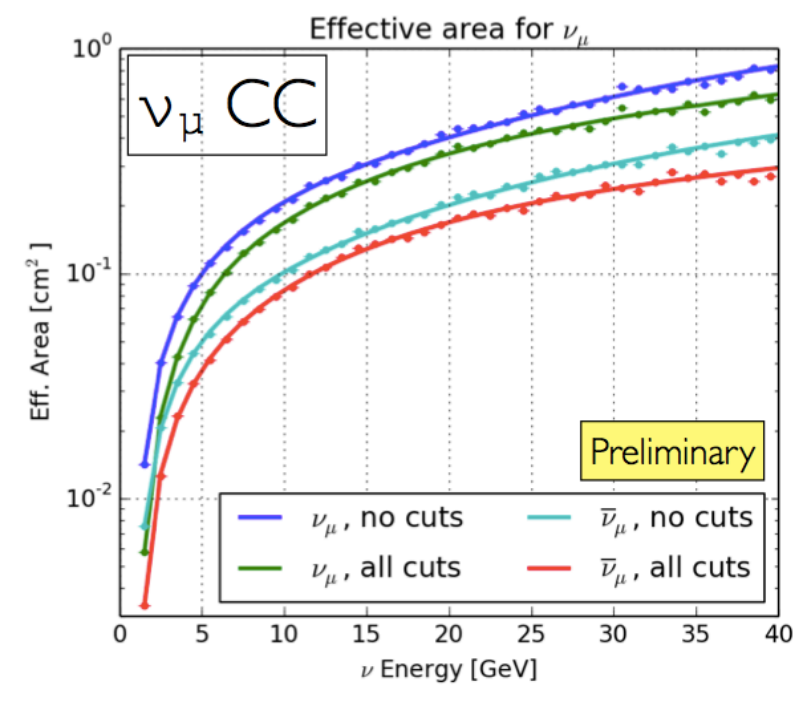
- Standalone PINGU
  - US cost $60m: $21m startup, $1.61m per string
  - Assume $25m non-US contribution
- PINGU as part of a facility at Pole
  - US cost $40m: $7m startup, $1.44m per string
  - Assume $25m non-US contribution
- Additional detectors (increasing from 60 to 96 modules per string) improves the resolution at low energies significantly moving the 3 year significance from 2.8σ to nearly 3.3σ for a 10% increase in project cost

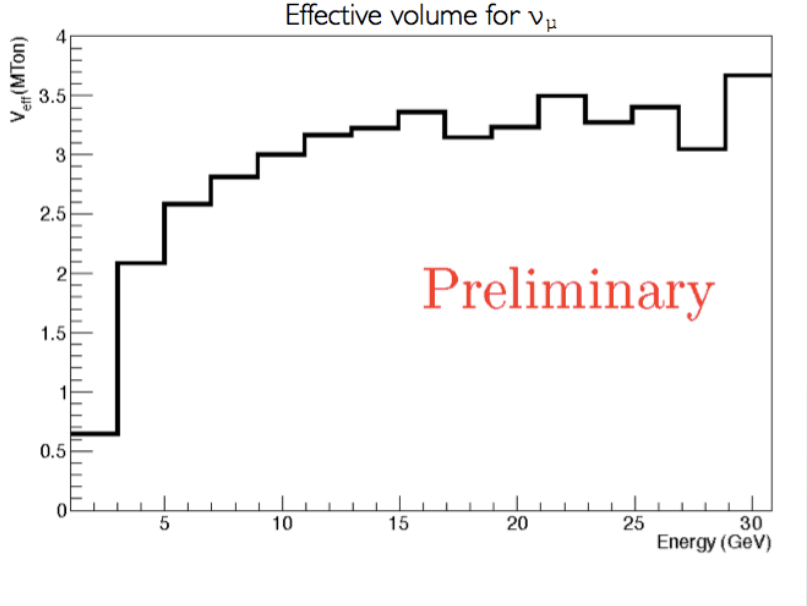
Energy and Zenith Angle Resolution



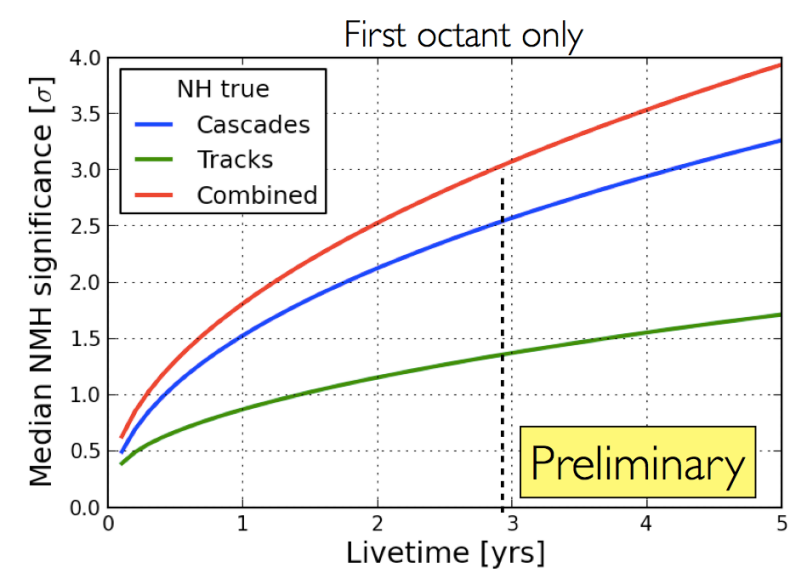


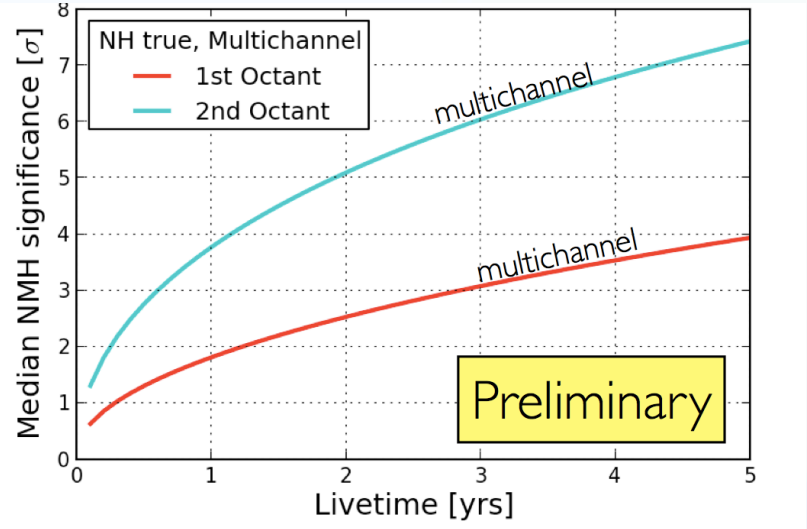
Effective areas





NMH Significance vs. time





Significance vs. time assuming normal hierarchy, first octant- less conservative than assuming inverted hierarchy
3σ in 3 years
Livetime during construction not included

Effect of octant on significance