Neutrino Physics with the Precision IceCube Next Generation Upgrade (PINGU)

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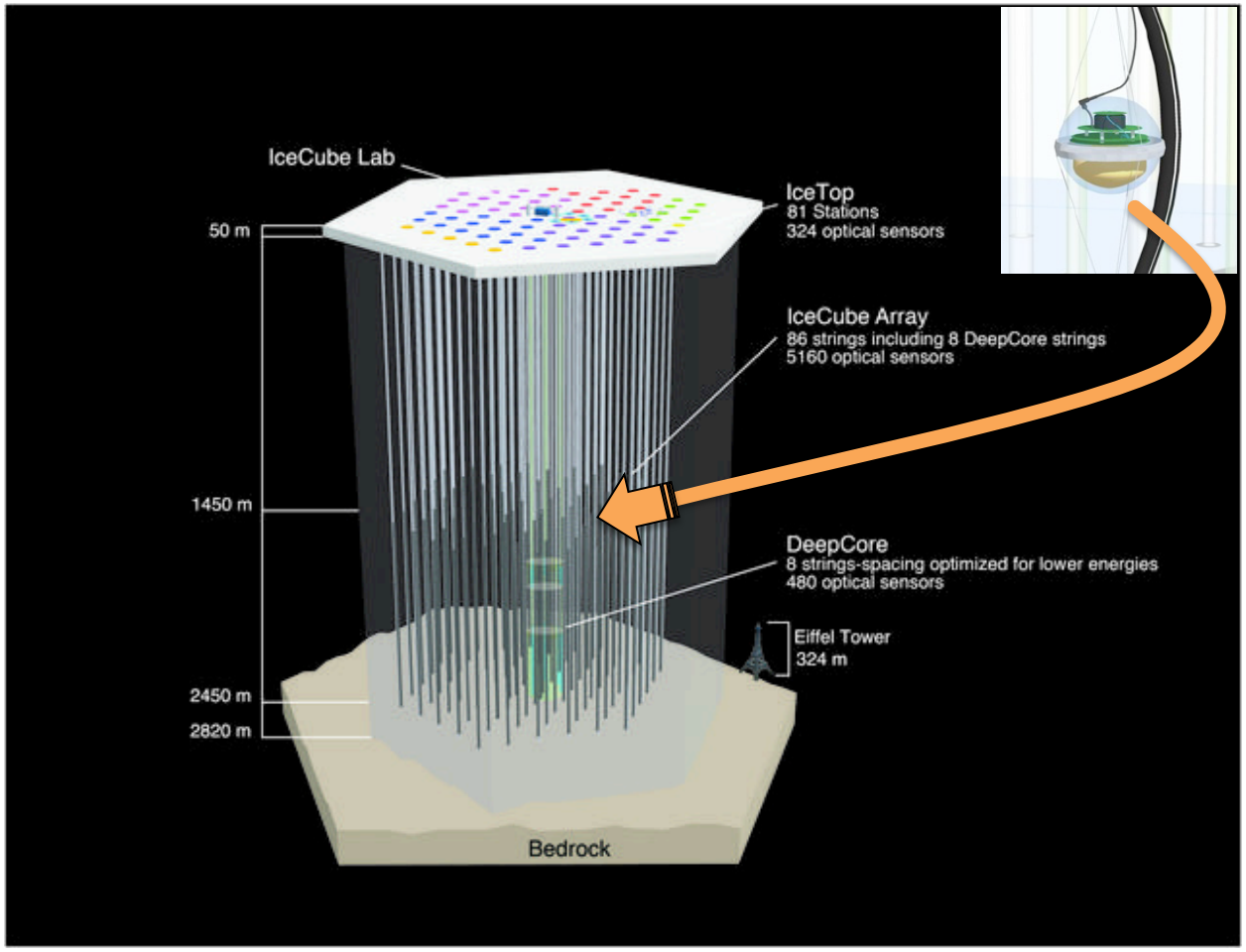
The Precision IceCube Next Generation Upgrade (**PINGU**) is a proposed **low-energy extension to the IceCube Neutrino Observatory**, located at the geographic South Pole. PINGU will **increase IceCube's sensitivity to neutrinos with energies down to a few GeV with a multi-megaton effective volume**. For every year of PINGU detector operation, tens of thousands of atmospheric neutrinos will be collected. This high statistics dataset will allow PINGU to resolve the neutrino mass hierarchy (NMH)

Outline

- The IceCube neutrino observatory
  - From IceCube through DeepCore to PINGU
- PINGU physics program:
  - Gain sensitivity to atmospheric neutrinos in the region below 10 GeV with very high statistics
    - measurement of the
      - **neutrino mass hierarchy (NMH)**
      - $(\Delta m_{23})^2$ and test maximal mixing,
      - ν_τ appearance
      - **indirect dark matter detection**
      - **supernova neutrinos**

The IceCube neutrino observatory



86 strings with 60 Digital Optical Modules (DOMs)
(IceCube + DeepCore)

Optical sensor
10” photomultiplier (PMT)
+ in situ signal digitization
in pressure glass sphere

Deployed between 1450 and 2450 m depth

Instrumented volume: **1 km^3**

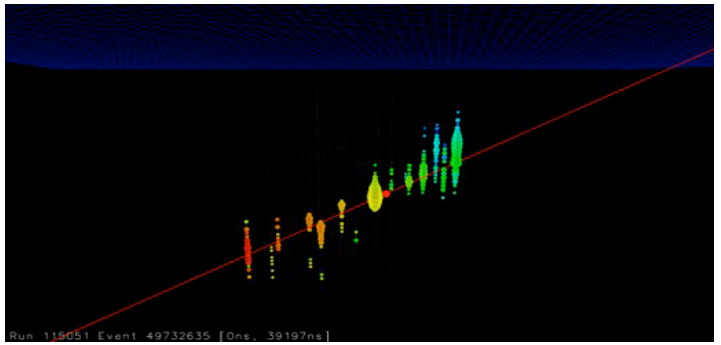
81 IceTop surface stations

Construction complete
December 2010
(data taking since 2005)

The IceCube neutrino observatory

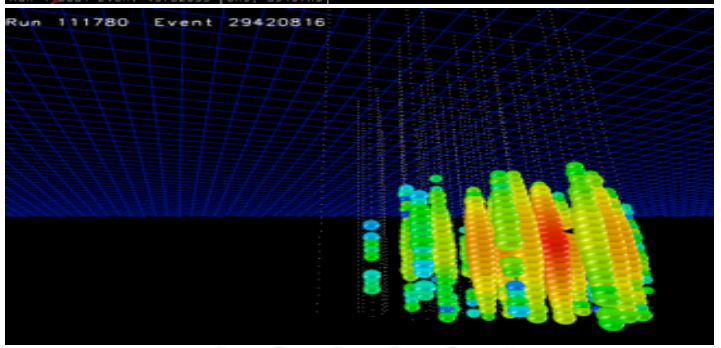
Event Signatures in IceCube

Tracks:
- Source - ν_μ CC interactions
- Good angular resolution (<1°)

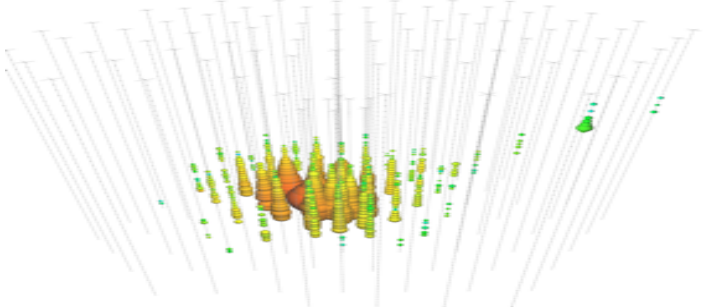


Cascades:
- Source - ν_e, ν_μ, ν_τ NC + ν_e CC interactions
- Good energy resolution (~10% at high energies)

Limited angular resolution (>10°)

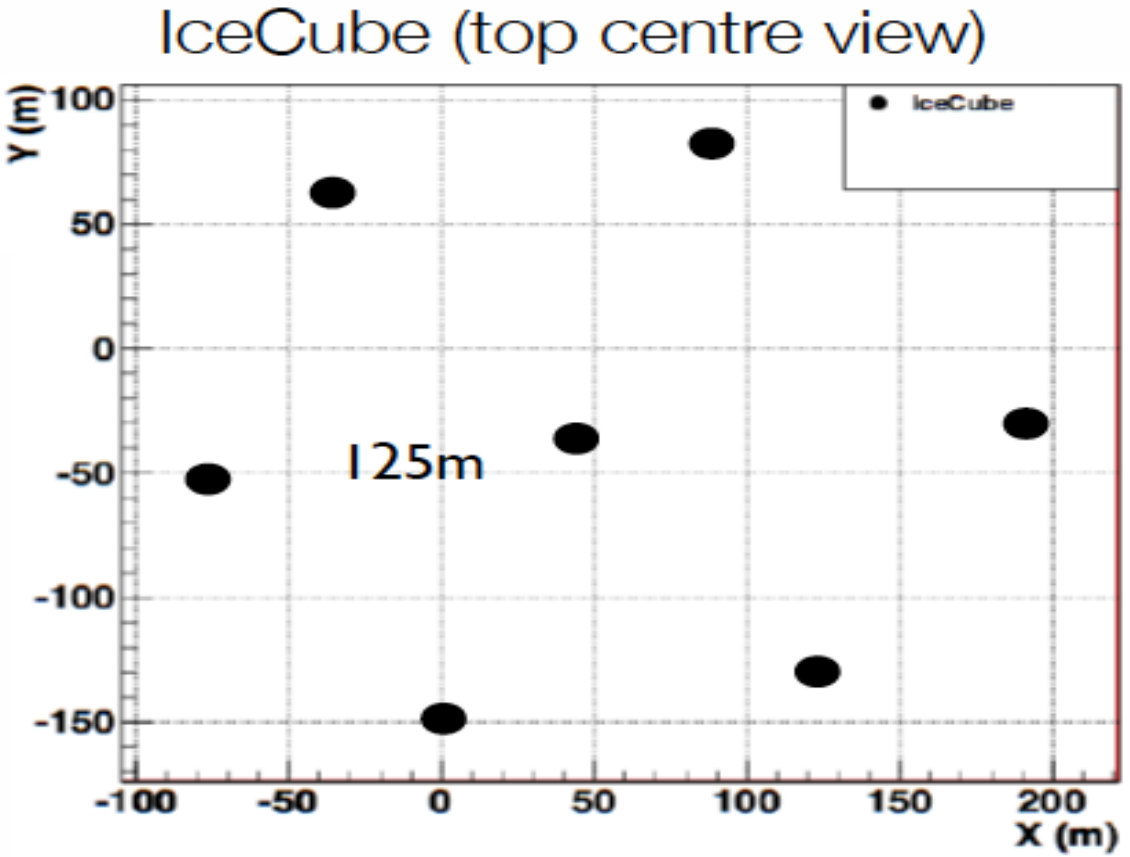


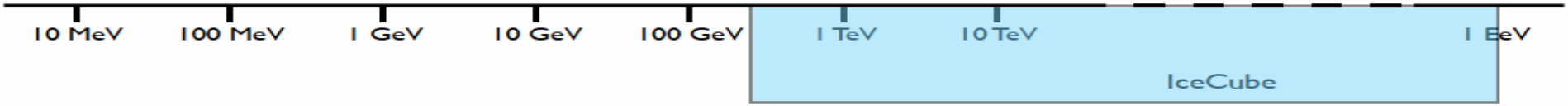
Composites:
- Source - ν_μ CC (ν_τ CC) inside instrumented volume



The IceCube neutrino observatory

IceCube
- 78 Strings (60 DOMs per string)
  - 125m string spacing
  - 17m DOM spacing





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•78 Strings (60 DOMs per string)
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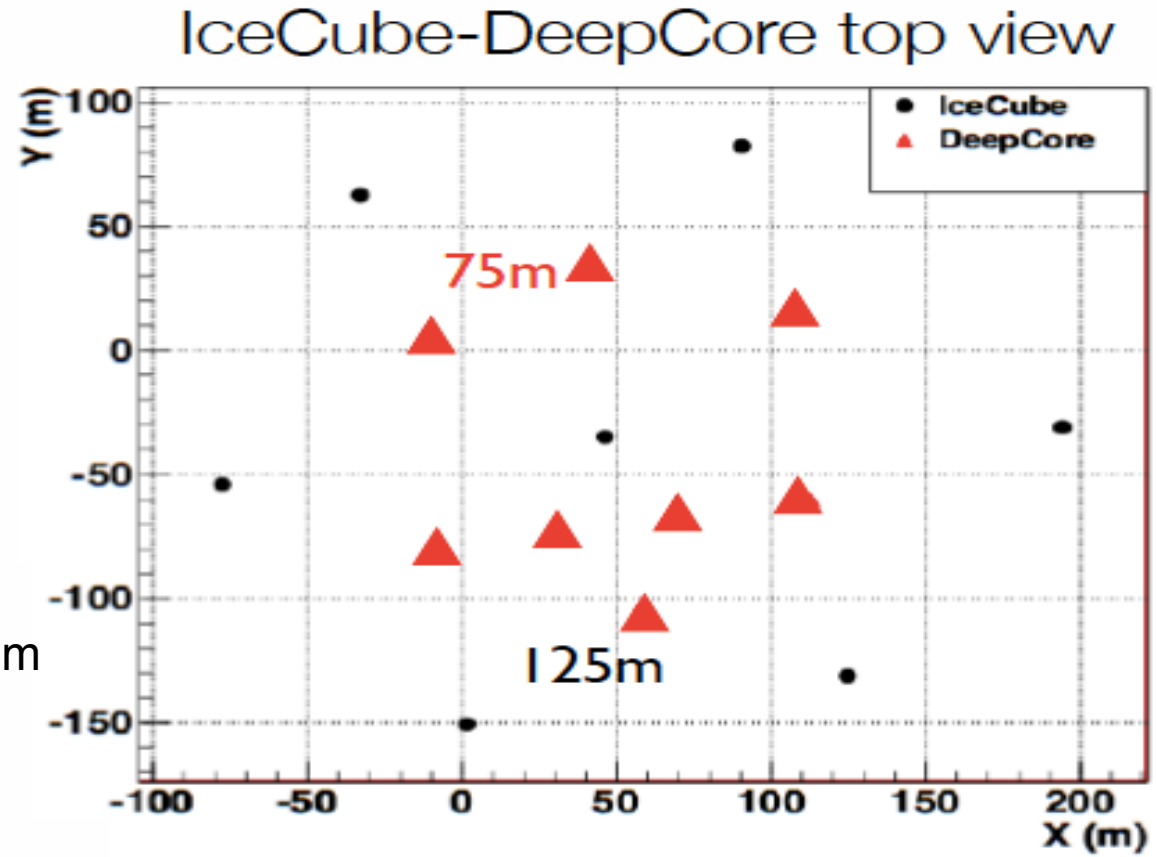
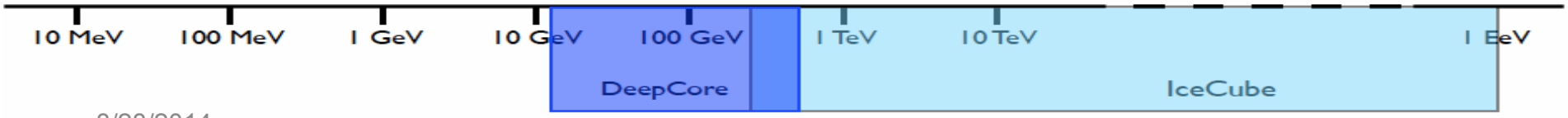
IceCube + **DeepCore**
• 86 Strings (60 DOMs per string)
• Additional 8 strings
  •42-75m string spacing
  •7m DOM spacing
• Possibility to use information from the IceCube strings as a veto





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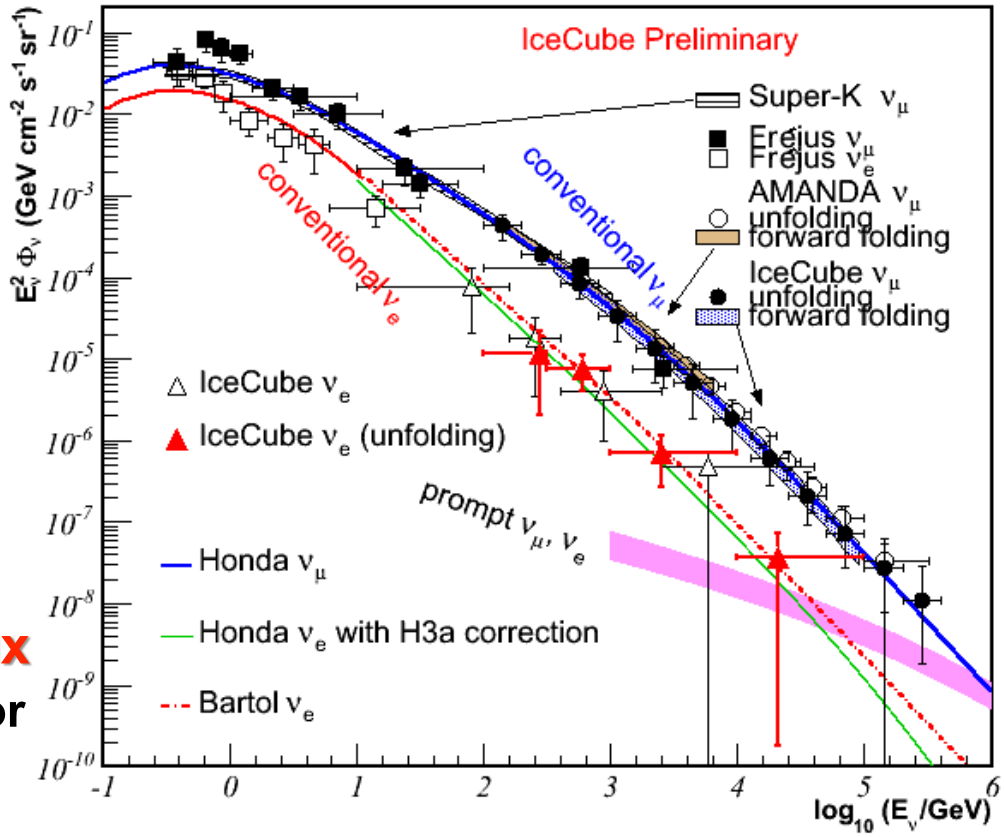
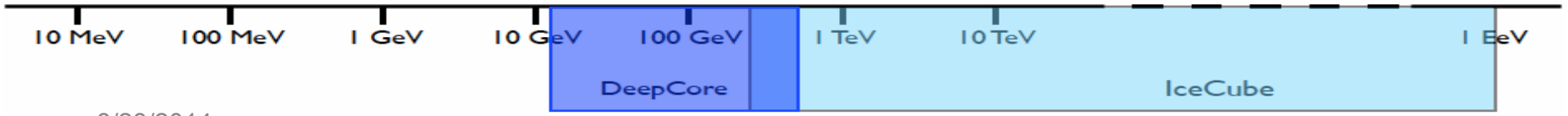
Atmospheric electron neutrino flux measured from 80 GeV to 6 TeV for the first time





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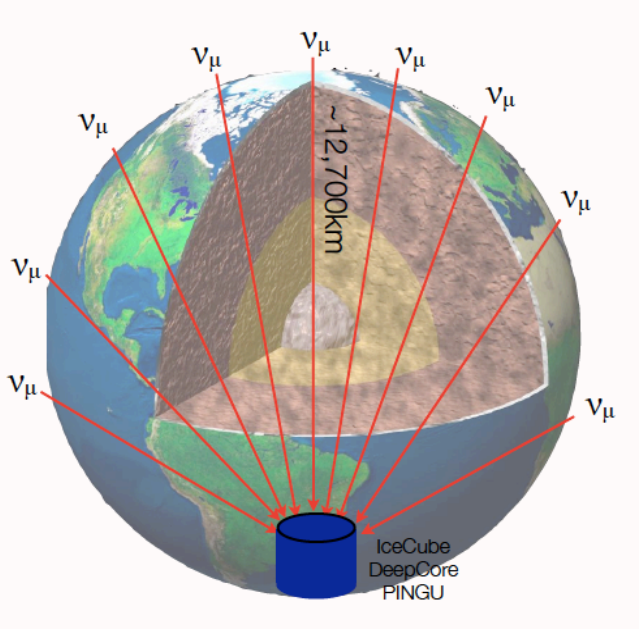
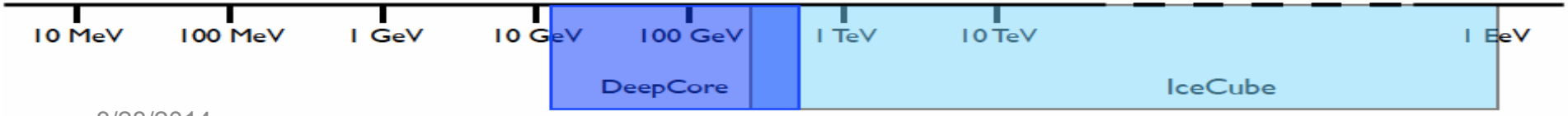
Muon neutrino disappearance measurement



Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV

• Hierarchy-dependent matter effects below ~12 GeV

• Neutrinos are available over a wide range of energies and baselines



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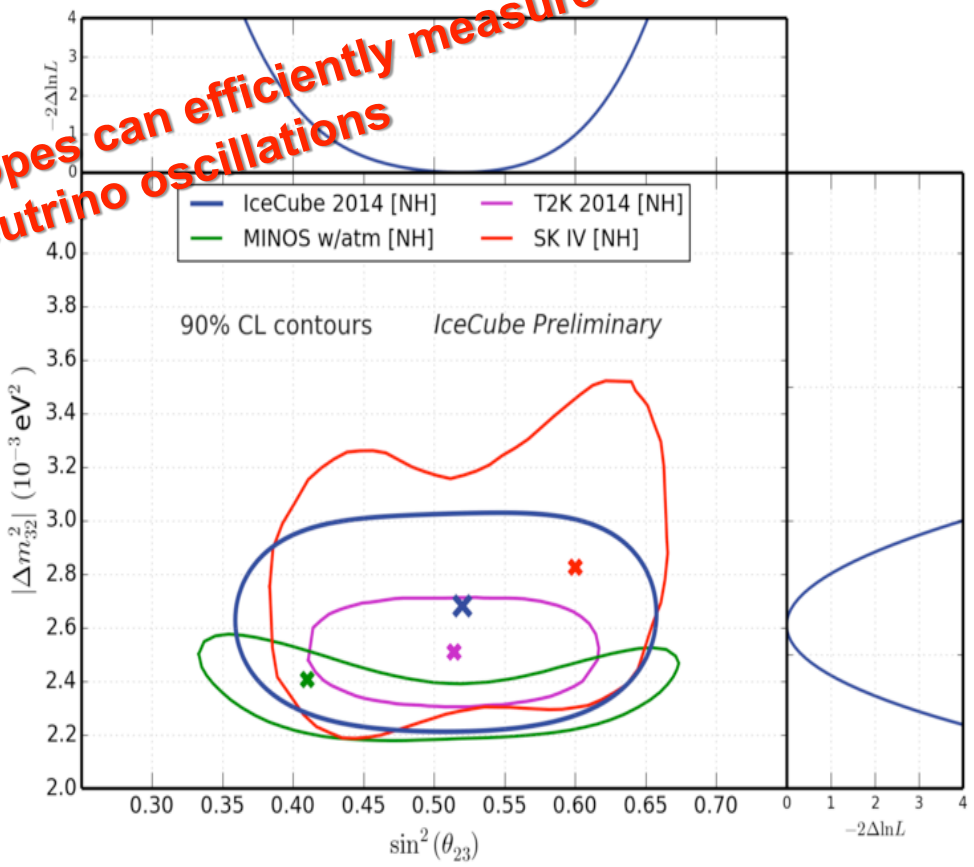
Muon neutrino disappearance measurement

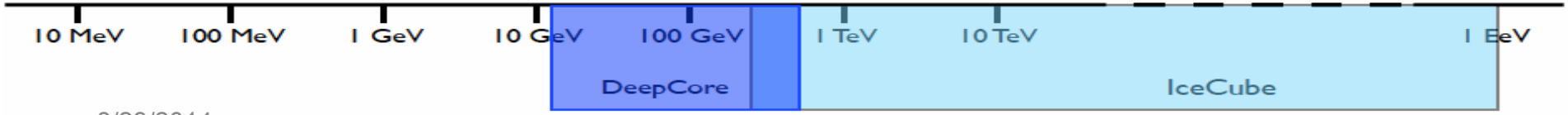
3 years of full IceCube data (5293 events in 953 days)

Competitive with world's best measurements

Results compatible with world average values of θ_{23} and $|\Delta m^2_{23}|$

Neutrino telescopes can efficiently measure atmospheric neutrino oscillations





See IceCube ν_μ oscillation result, **PRL 111, 081801 (2013)** and atm. ν_e detection result, **PRL 110, 151105 (2013).**

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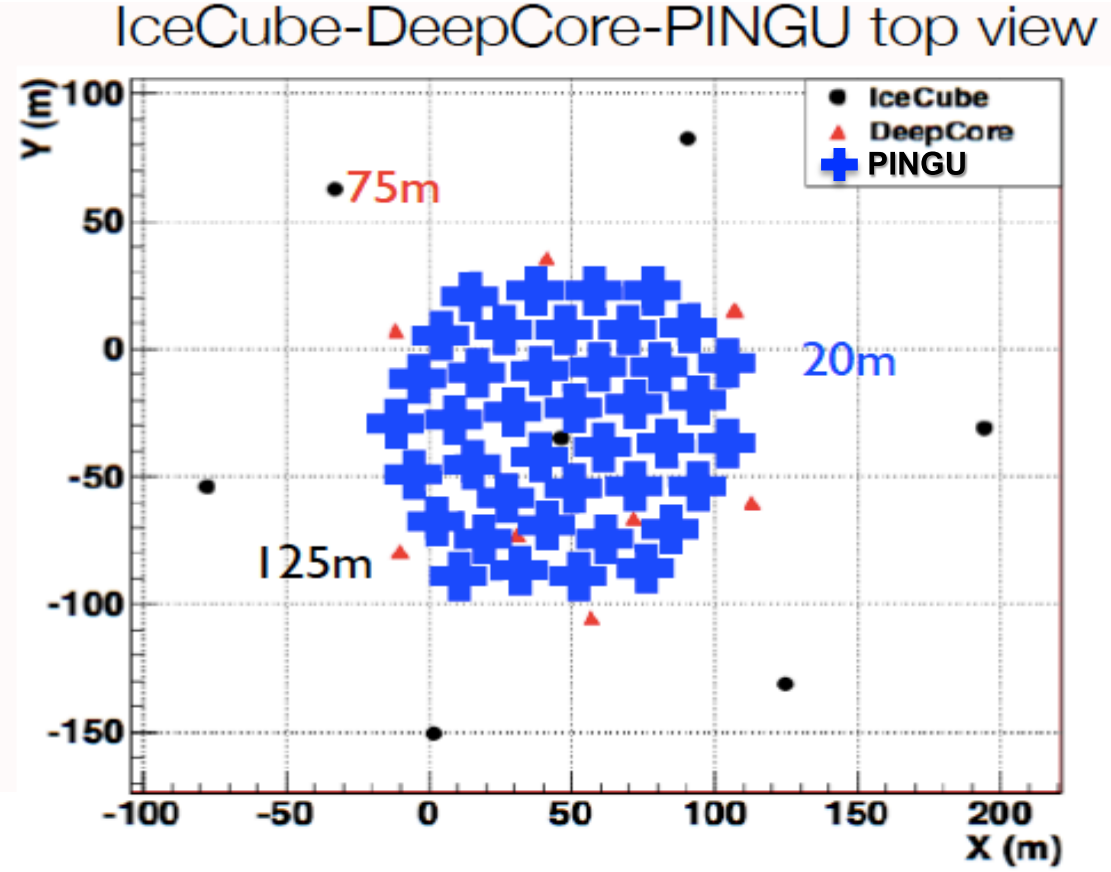
PINGU
• proposed **low-energy extension**
• geometry optimization under study



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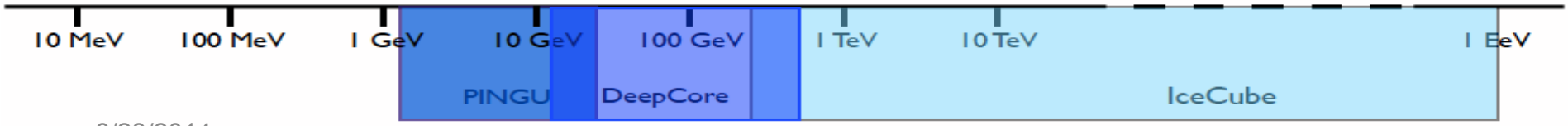
PINGU baseline setup
Add 40 strings with 60 PDOMs* per string
• 20m string spacing
• 5m DOM spacing
• ~15x higher photocathode density

*PINGU Digital Optical Modules = HQE PMT, electronics, pressure vessel, supporting hardware; very similar to IceCube DOM.



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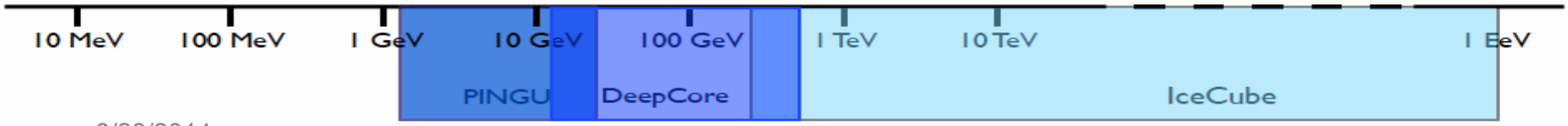
PINGU
• **Relatively modest cost and rapid construction for a NMH measurement**
• IceCube experience shows that drilling 40 strings in 2-3 years is feasible

Improvements to IceCube design:
- **Single digitizer channel**
- **Remove "local coincidence" condition**
- **Feature extraction in ice**

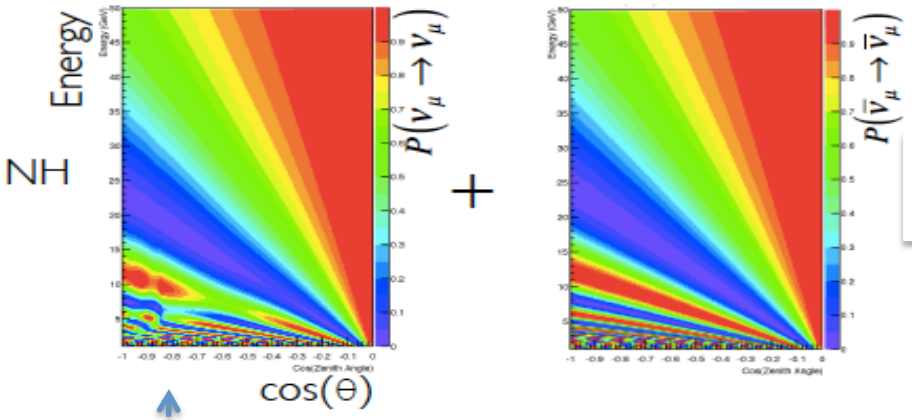
Improve measurement of ice properties and DOM sensitivity with dedicated calibration devices
- **De-gassing of drill water to mitigate bubbles in refrozen hole ice**



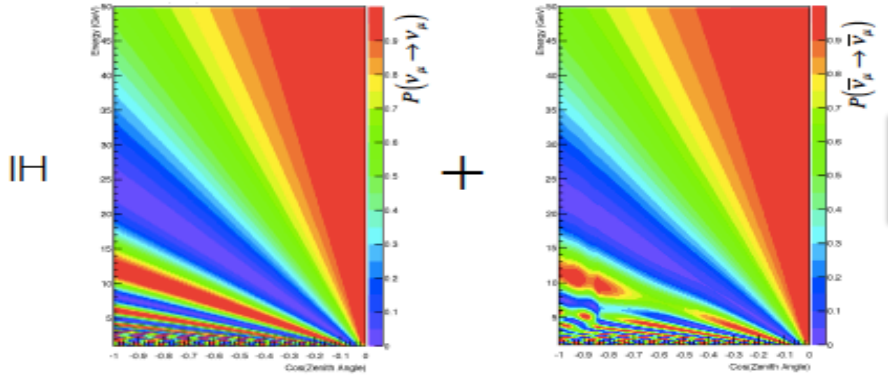
PINGU physics program

The NMH Signature in PINGU

Upgoing (denser) ν_μ **Horizontal (less dense)** anti$-\nu_\mu$



Earth's outer core



= [pattern A]

= [pattern B]

Feasible?
Pattern A = Pattern B

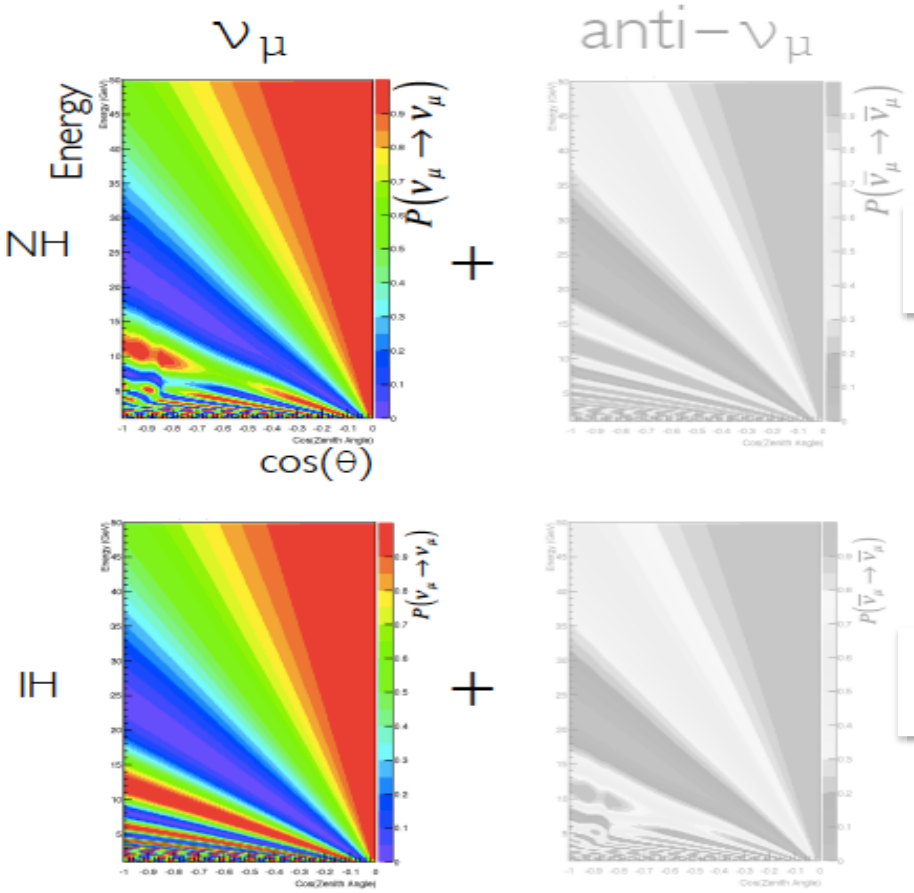
MSW and Parametric Oscillations:
- L. Wolfenstein Phys. Rev. D17 (1978)
- S. Mikheyev and A. Y. Smirnov Prog. Part. Nucl. Phys. 23 (1989)
- E. K Akhmedov, et al., Nucl. Phys. B542 (1999)

PINGU Signature:
- O. Mena, I. Mocioiu, and S. Razzaque, Phys. Rev. D 78 (2008)
- E. K. Akhmedov, S. Razzaque, and A. Y. Smirnov, JHEP 1302 (2013)
- PINGU LoI arXiv:1401.2046

$$\Delta m^2_{32} = 2.32 \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\theta_{23}) = \frac{\pi}{4}$$
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

PINGU physics program

The NMH Signature in PINGU



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$$\sigma(\nu) \sim 2\,\sigma(\bar{\nu})$$
$$\varphi(\nu_{atm}) > \varphi(\bar{\nu}_{atm})$$
$$A \neq B \quad !!!$$

Also true for ν_e

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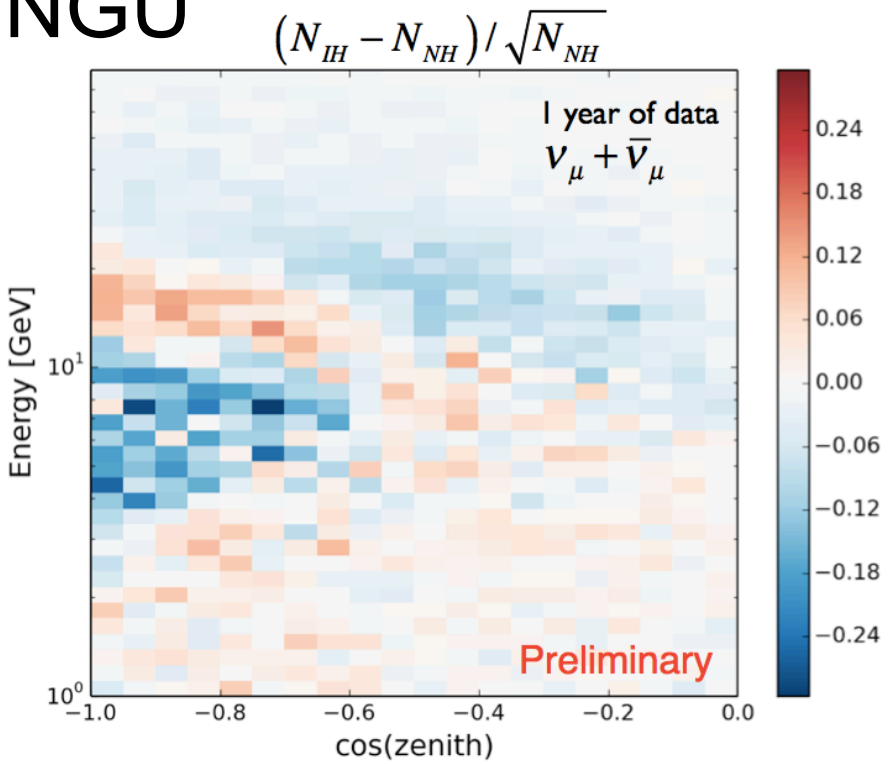
PINGU physics program

The NMH Signature in PINGU

The signature of the hierarchy can be noticed by looking at the pattern of expected excesses and deficits in the E vs. cos(θz) plane

Distinguishability metric (Akhmedov *et al.*, JHEP 2013(02) pp. 1-39) used to show NMH pattern in PINGU data



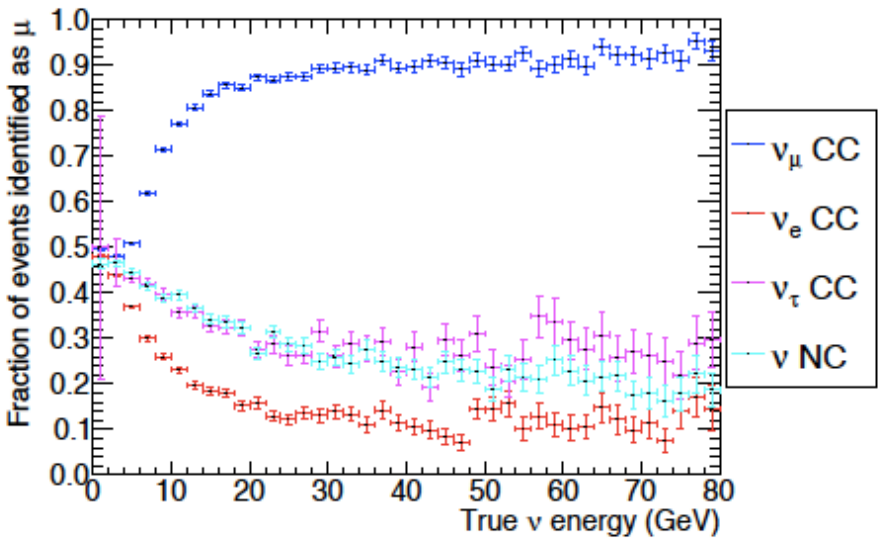
reconstructions included but not yet particle ID

Reconstructed energy ΔE/E ~ 0.27 at E_{true} = 5 GeV

Reconstructed zenith angle σ_θ~13° at E_{true} = 5 GeV

Particle ID in PINGU

Preliminary



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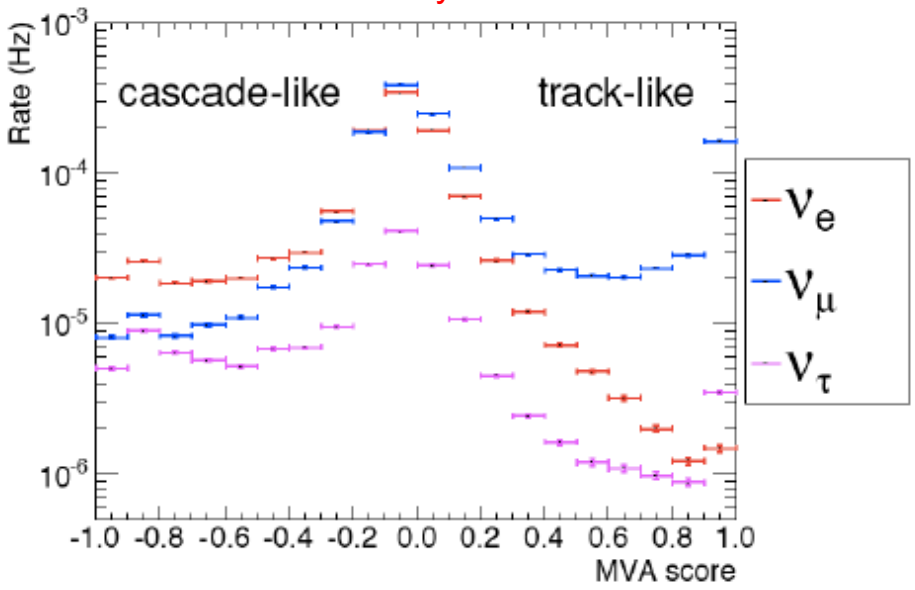
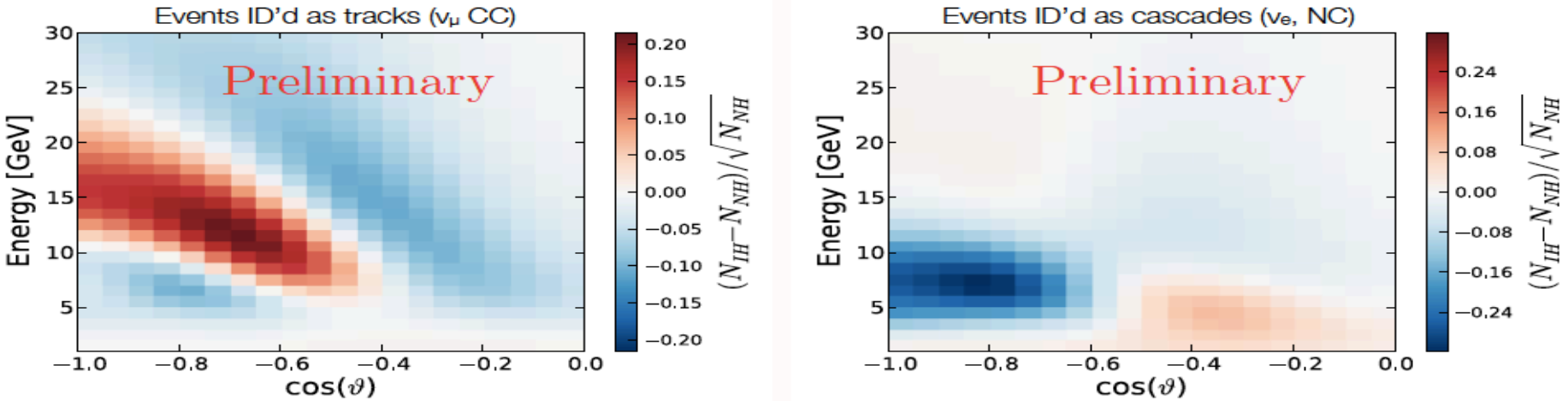


PINGU physics program

The NMH in PINGU

arXiv:1401.2046



Full MC for **<u>detector efficiency, reconstruction, and particle ID included</u>**

In both channels (track and cascade) the hierarchy-dependent signatures are visible

Use energy-zenith angle histograms to calculate PINGU's sensitivity to the NMH
Calculate sensitivity with three methods:

1. **Fisher information matrix**
2. **Asimov approach**
3. **Log likelihood ratio**

Methods agree with each other

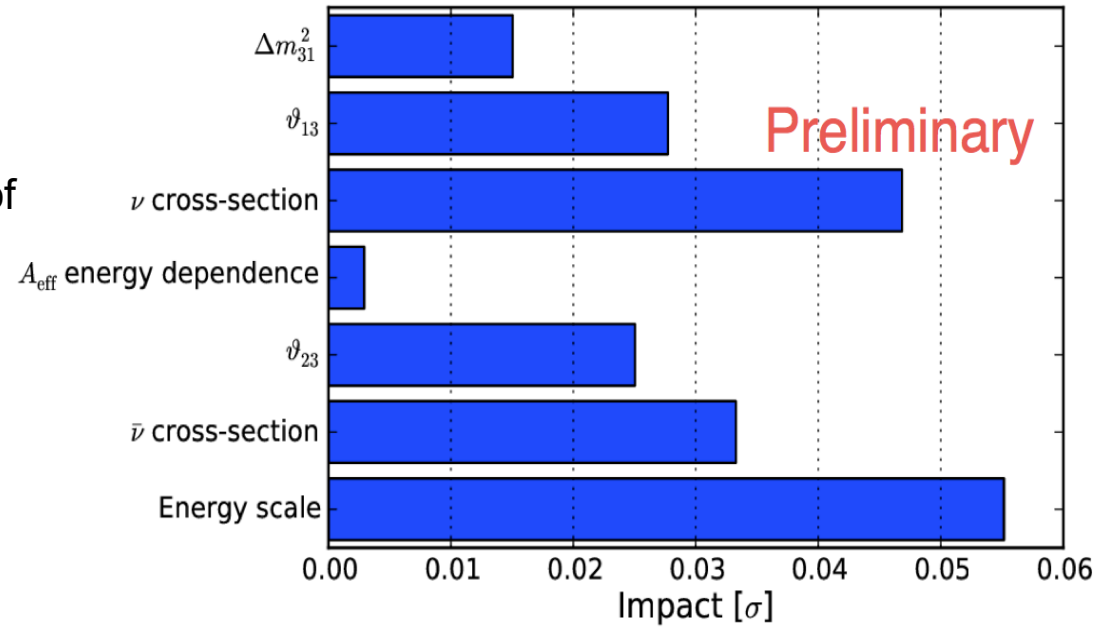
PINGU physics program

PINGU NMH systematics

- **Energy scale** - E_{reco}/E_{true} (5%)
- **ν cross-section** – cross section/flux normalization (changed by ±15%)
- **Δm^2_{31}, ϑ13, ϑ13** – current knowledge of oscillation parameters (varied by ± 1σ)
- **Aeff** – Affective area degenerate with the spectral index of atmospheric flux

Additional systematics currently being incorporated:

- **Particle ID** performance
- **Cross-section details**
- **Ice Model**



Impact = significance between the case with all systematics applied vs. all but one systematic applied.

Large impact from the **Energy Scale and cross-section normalization**

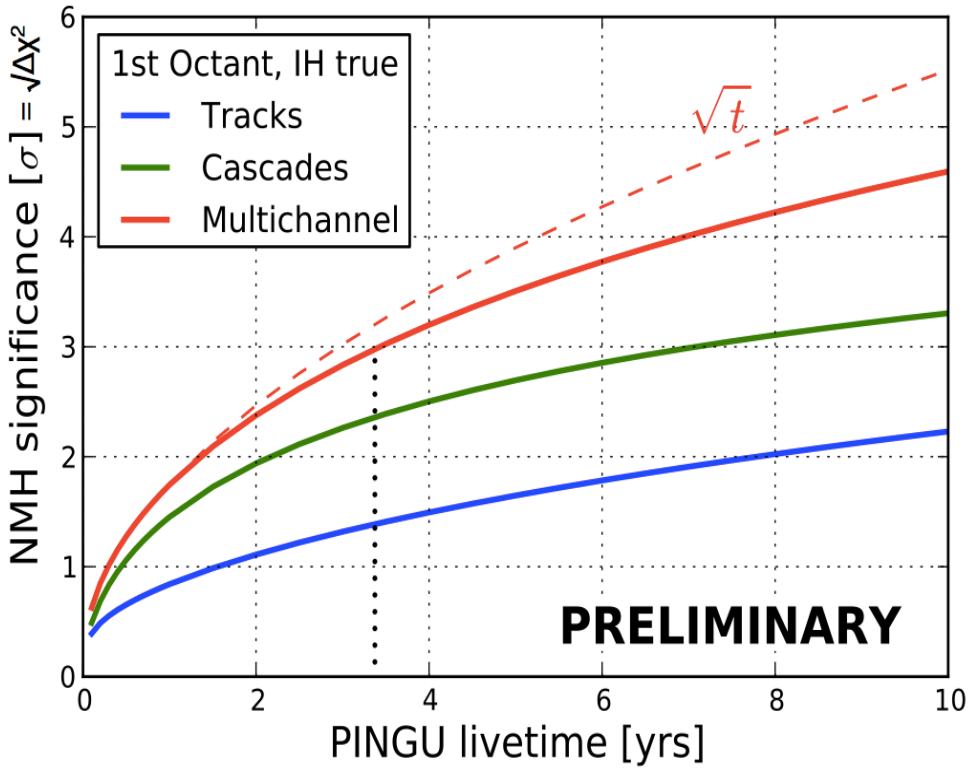
Minimal effect from δ_{CP}

NMH

Significance (calculated using parametric model of detector response)

- **Includes systematics and particle ID**

The most conservative scenario
IH, 1st Octant



•With <u>inverted hierarchy (1st octant)</u>, reach 3σ in 3.5 years (not including data collected during construction)

The earliest anticipated starting date for full-detector PINGU running is early **2020**

NMH

Effect of octant on significance

Significance (calculated using parametric model of detector response)

- **Includes systematics and particle ID**

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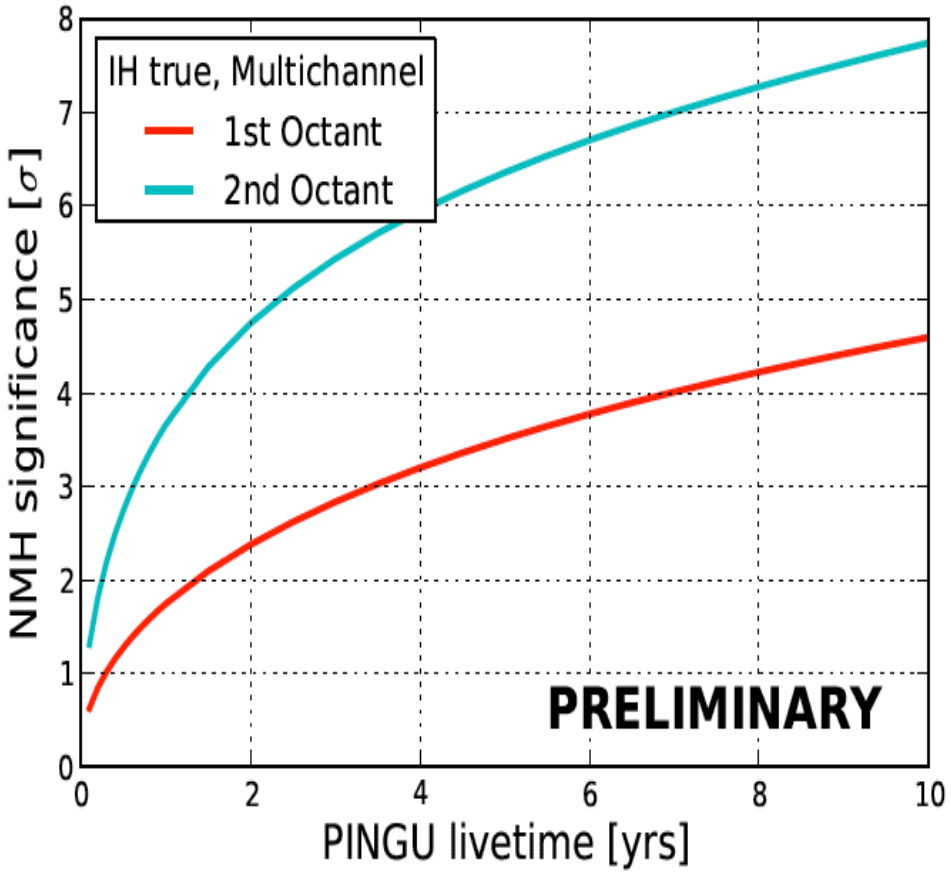
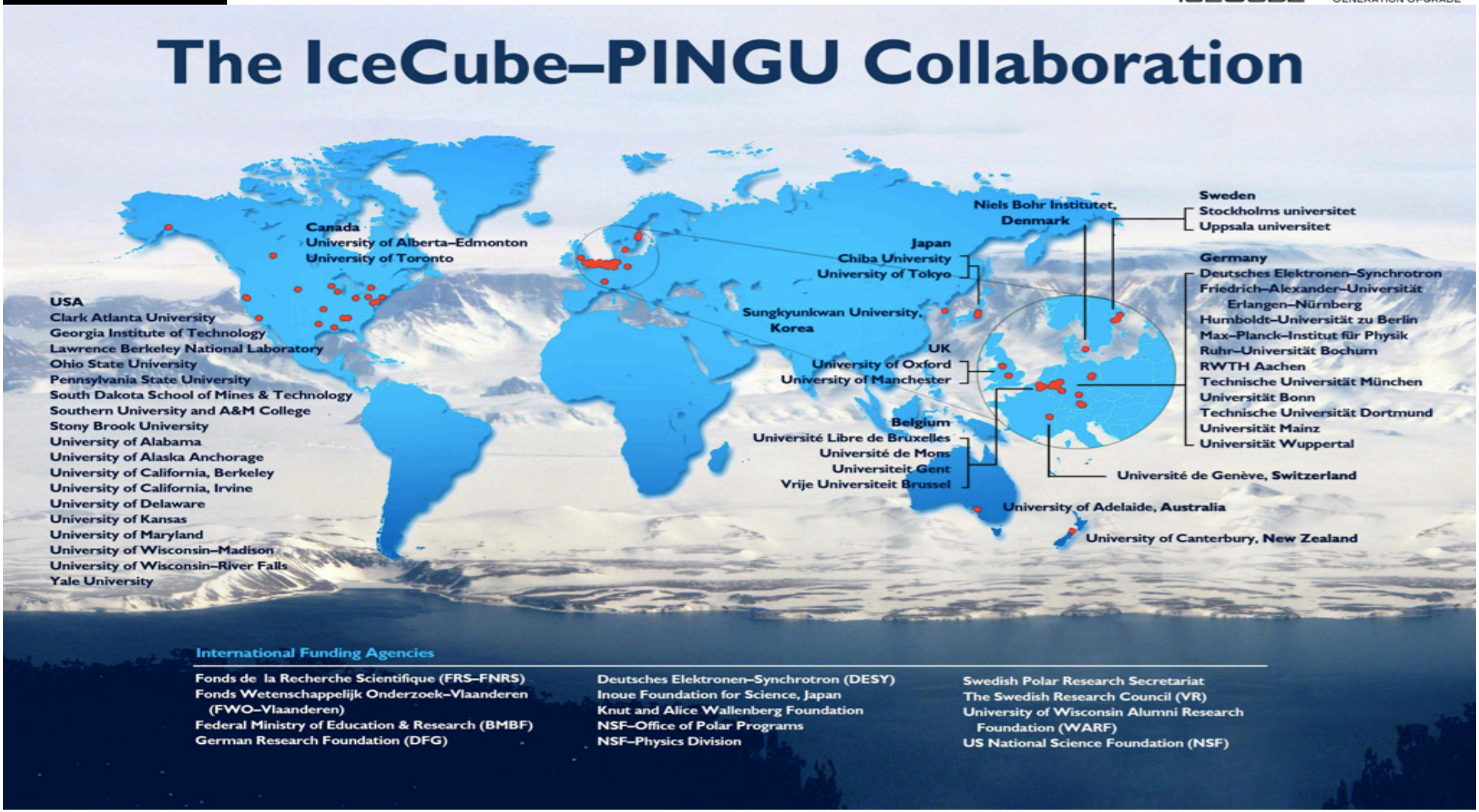


Summary

- IceCube covers a wide range of topics in astrophysical and particle 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
  - Prepare the way for further IceCube extensions

- **Letter of intent on the archive (arXiv:1401.2046)**
  - **LoI update this fall**


The IceCube–PINGU Collaboration
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University of Alberta–Edmonton
University of Toronto
USA
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
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Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
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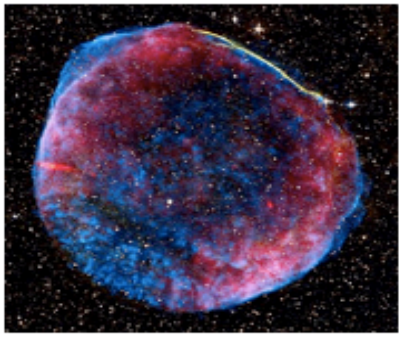
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

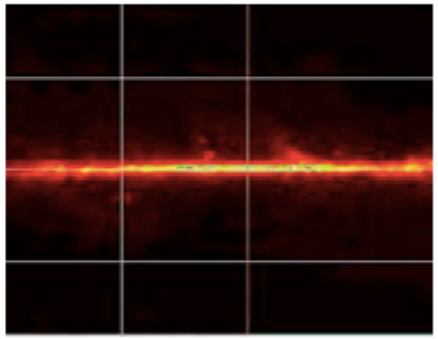
BACKUP SLIDE

Physics with IceCube

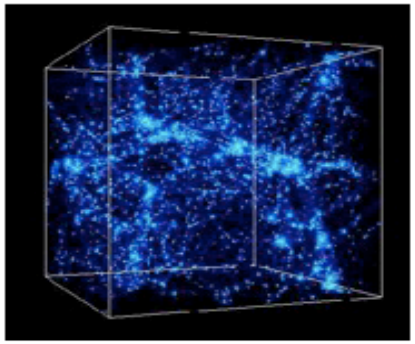
Cosmic accelerators



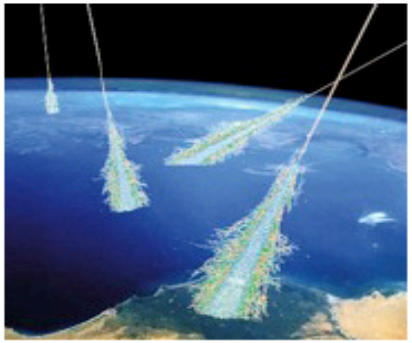
Diffuse fluxes



Dark Matter & Exotic Physics

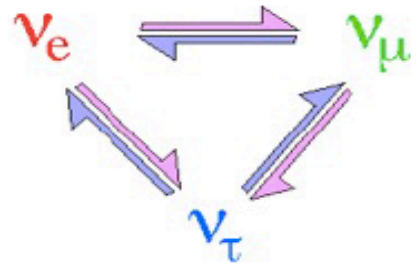


Cosmic rays



Supernovae

Neutrino Properties & Particle Physics



Physics with IceCube

Cosmic accelerators

- Point-like sources (SNRs, Binaries ...)
- Extended sources
- Transients (GRBs, AGN flares ...)

Diffuse fluxes

- All-sky fluxes (e.g. cosmogenic)
- Galactic plane
- Extended structures (e.g. Fermi-Bubbles)

Dark Matter & Exotic Physics

- Indirect DM search (Sun, Galactic halo)
- Magnetic monopoles, Q-balls
- Lorentz invariance violation

Cosmic rays

- Spectrum around "knee" (10^{15}–10^{17} eV)
- Composition
- Anisotropy

Supernovae

- Galactic/LMC SNe
- Phases
- Neutrino hierarchy

Neutrino Properties & Particle Physics

- Neutrino oscillations
- Charm in showers
- K/π ratio in showers
- Cross sections at very high energies

Sensitivity to NMH in Upcoming Neutrino Experiments

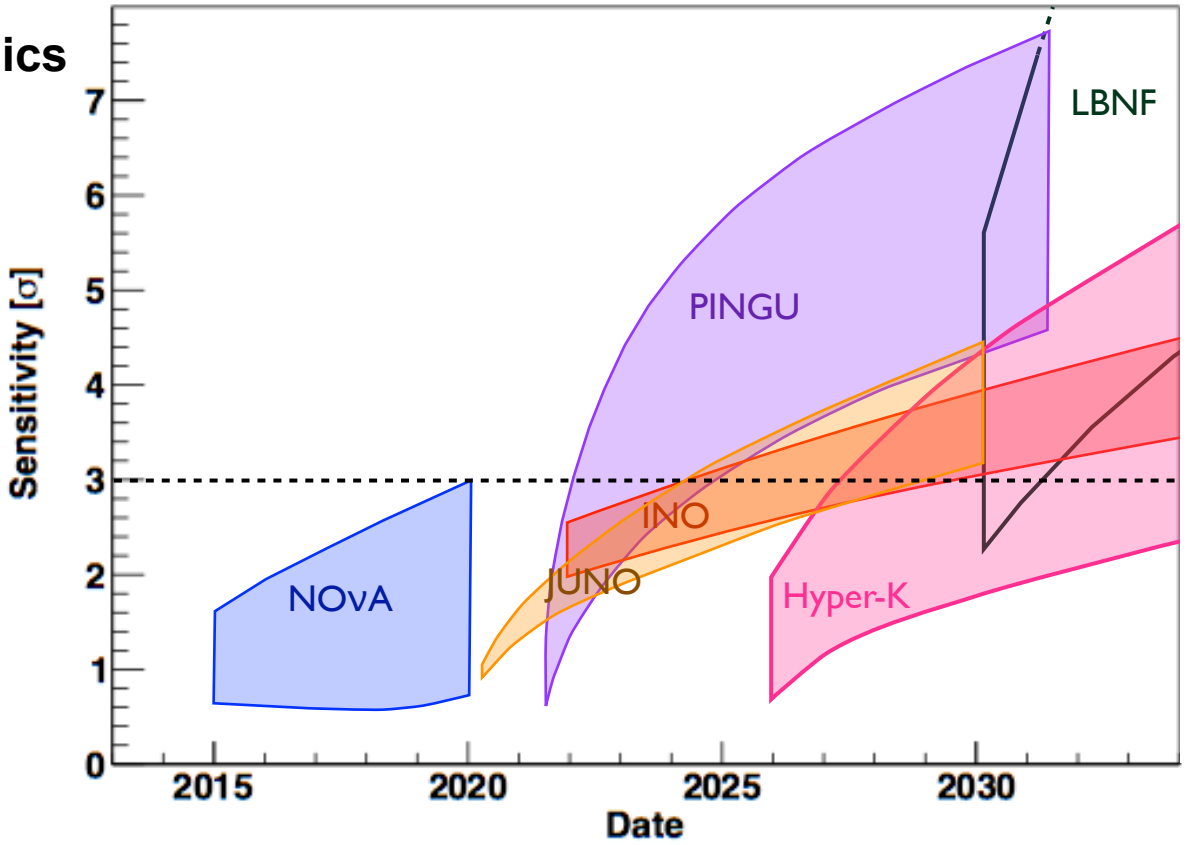
Widths indicate main physics uncertainty

PINGU/INO/HyperK: θ_{23} (38.7º–51.3º, 40º–50º)

LBNE/NOvA: δ_{CP}

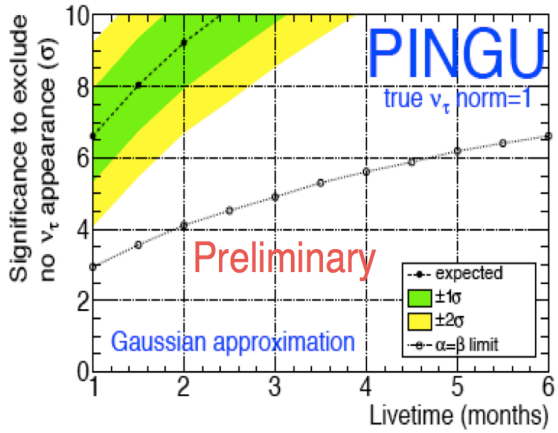
JUNO: σ_E

worst-case parameters (1st octant)

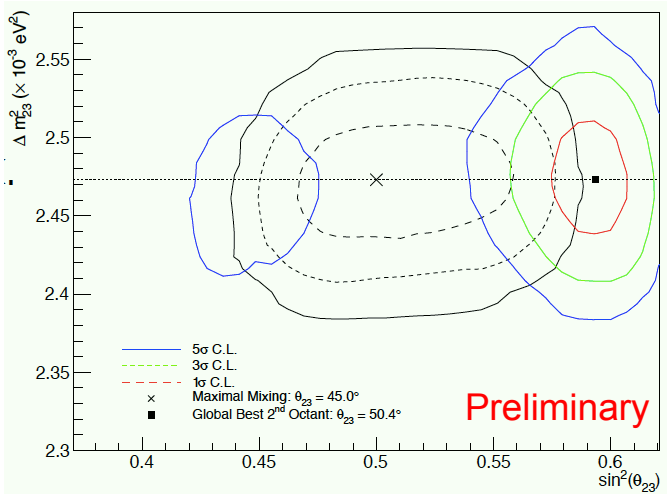


Blennow et al., arxiv:1311.1822, LBNE-doc-8087-v10, Hyper-K from arXiv:1109.3262 (2011), Hyper-K start date is 2025 (ICHEP14), INO from arXiv:1406.3689v1.

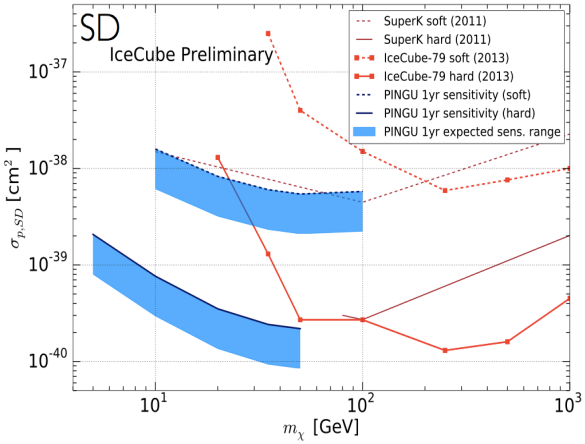
More PINGU Science Goals



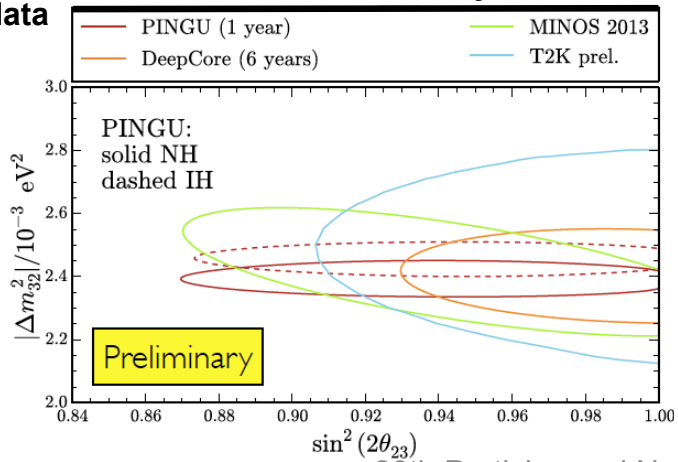
Tau neutrino appearance: 5σ exclusion of no tau neutrino appearance in one month of PINGU data



5σ exclusion of no maximal mixing after 5 years



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



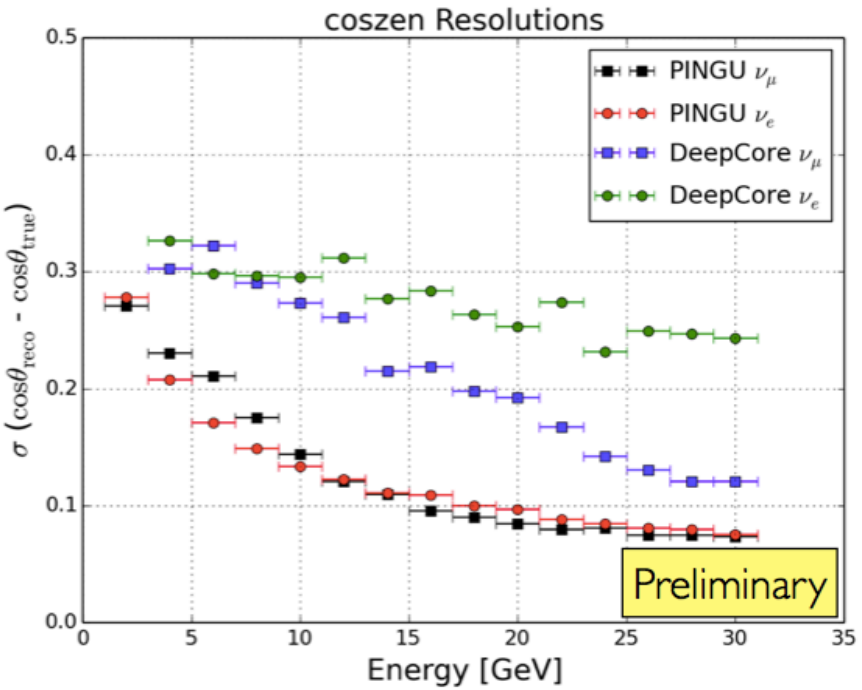
ν_μ disappearance
Result based on old reconstruction (expected to improve)

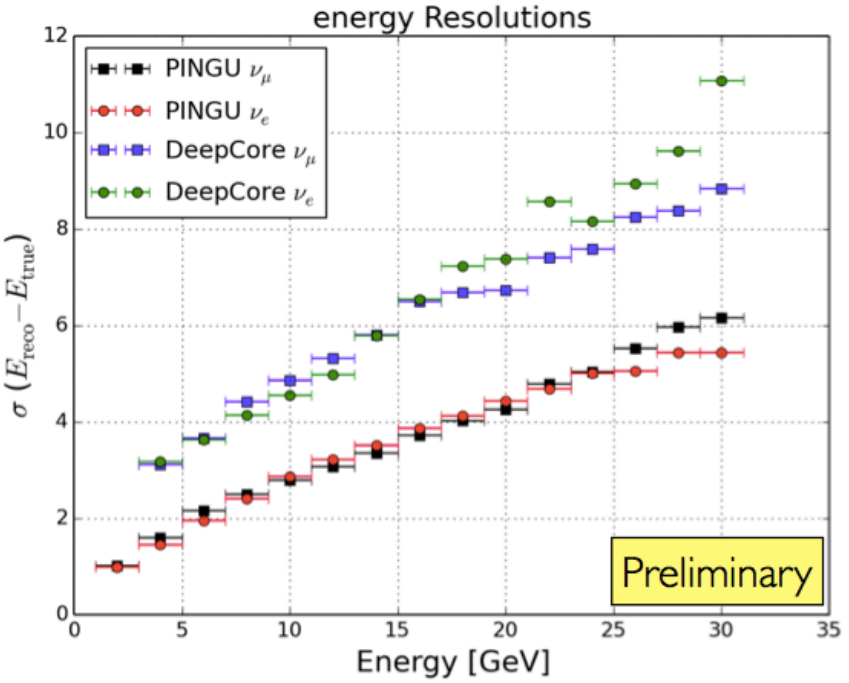
Highly competitive after 1 year

PINGU costs

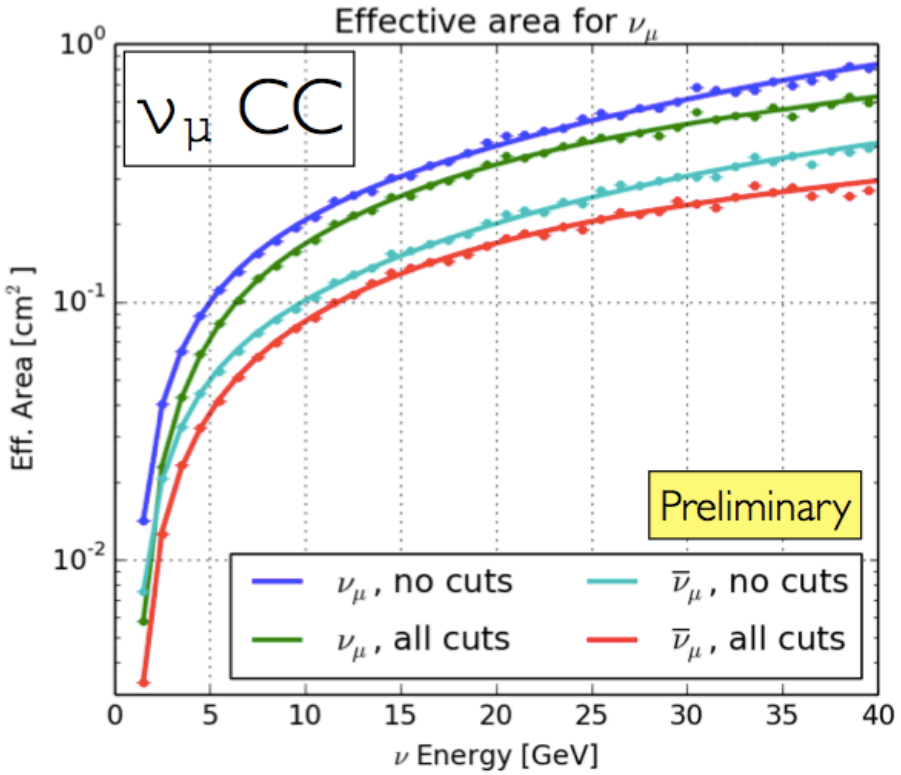
- Standalone PINGU
  - US cost $60m: $21m startup, $1.61m per string
  - Assume $25m non-US contribution
- PINGU as part of a facility at Pole
  - US cost $40m: $7m startup, $1.44m per string
  - Assume $25m non-US contribution
- **Additional detectors (increasing from 60 to 96 modules per string) improves 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**
- **MREFC proposal in preparation, CFI proposal submitted and under review, other countries in the process of applying for funding**

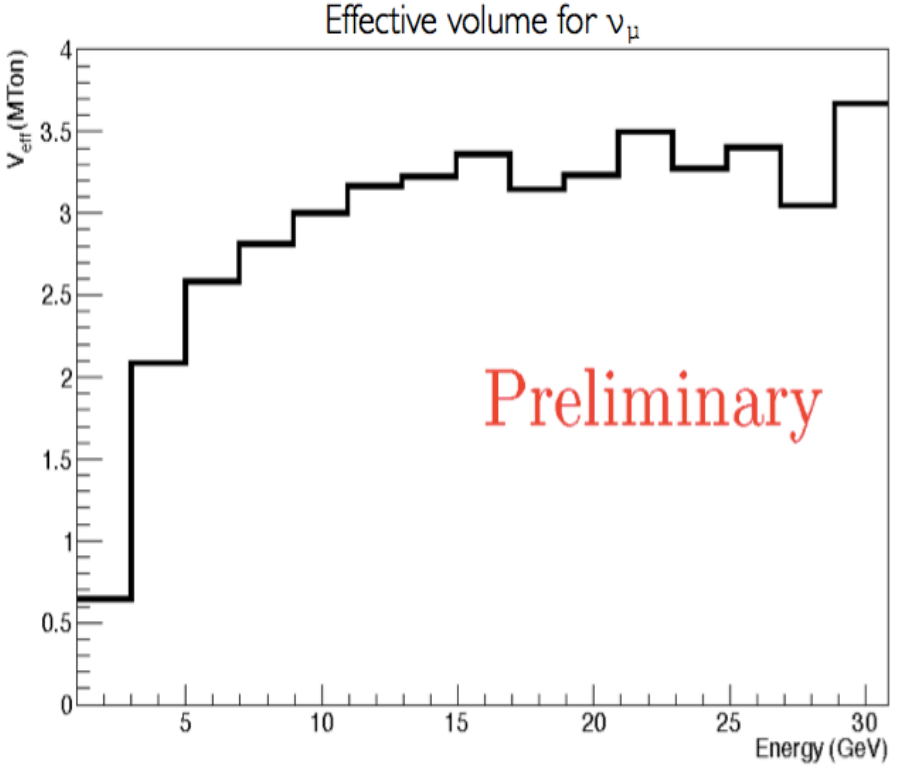
Energy and Zenith Angle Resolution



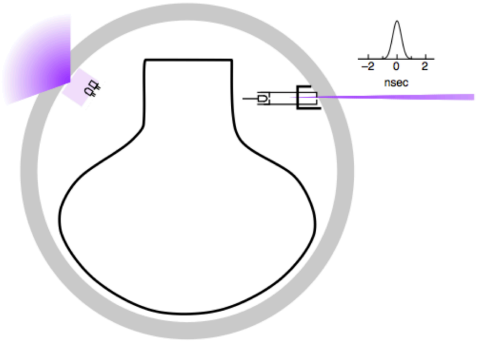


Effective areas

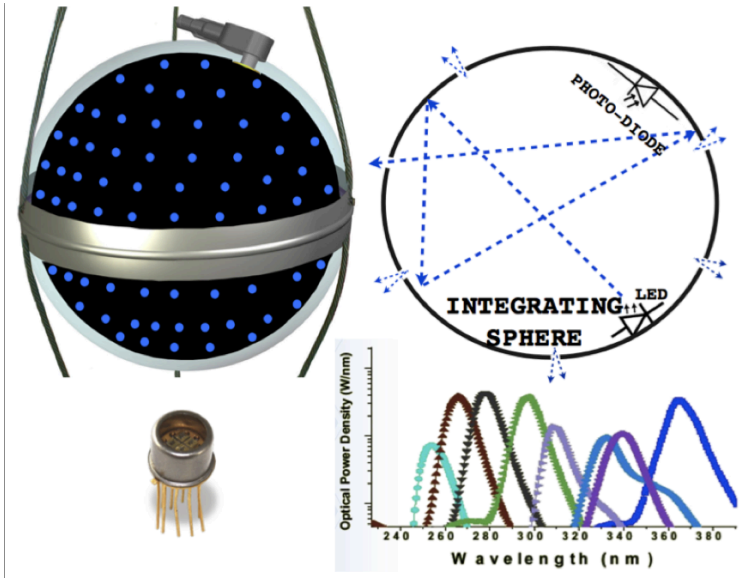




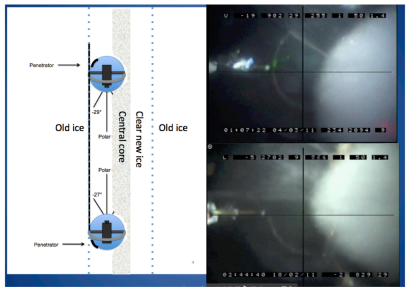
Calibration Devices



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

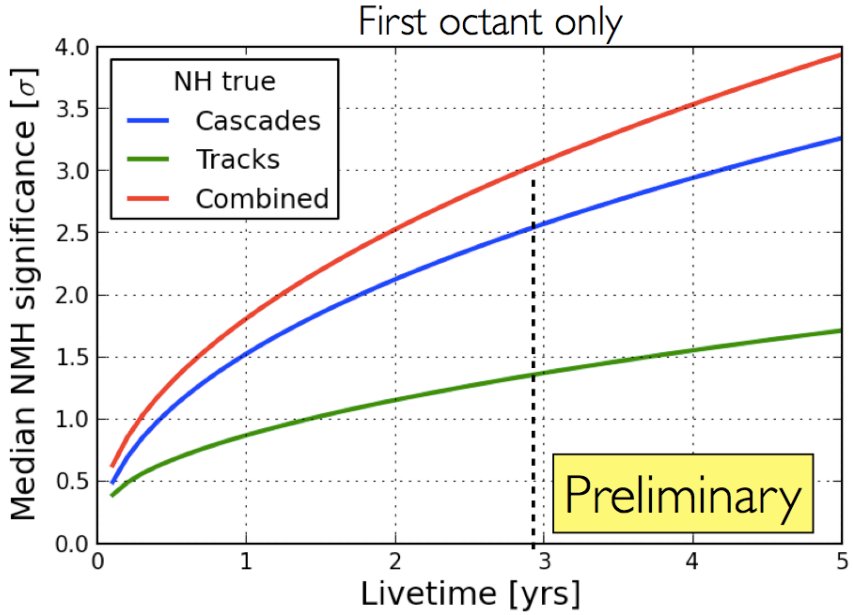


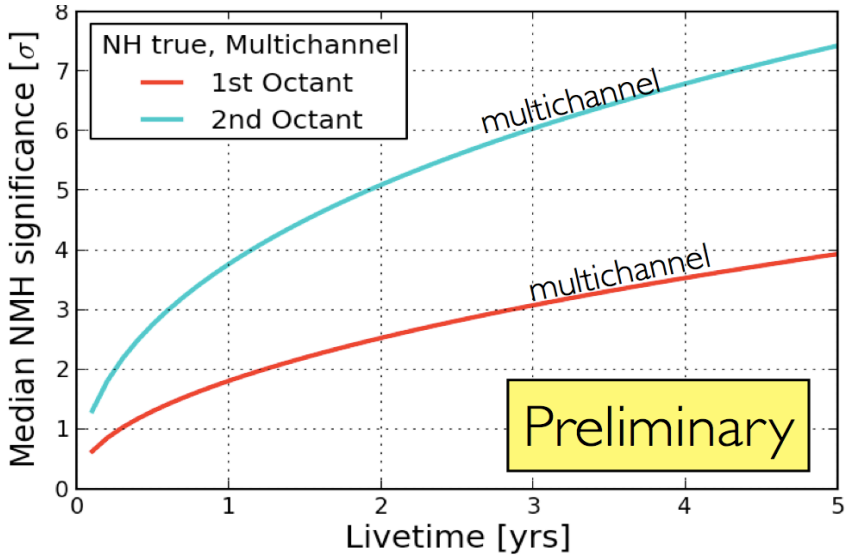
Under development: Precision Optical Calibration Module: diffuse multiwavelength source



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

NMH Significance vs. time





Significance vs. time assuming normal hierarchy, first octant - **less conservative than assuming inverted hierarchy**
3σ in 3 years

Effect of octant on significance

Livetime during construction not included