The Precision Next Generation IceCube Upgrade (PINGU)

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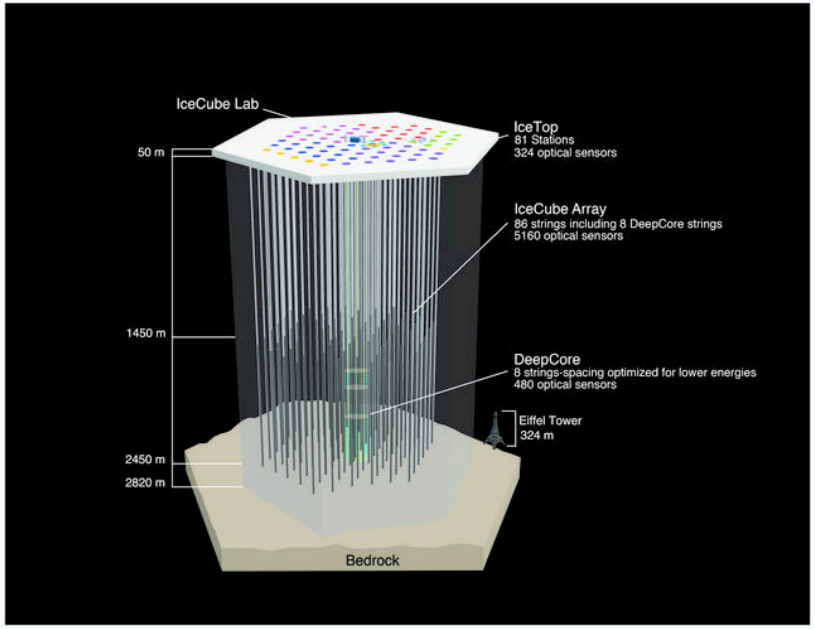
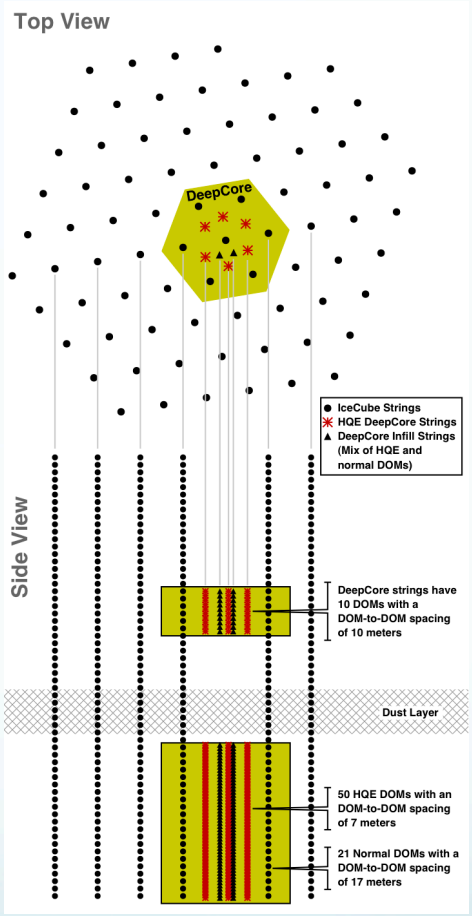
The IceCube Collaboration & PINGU

Collaborating Organizations

Chiba University
Clark Atlanta University
DESY-Zeuthen
Ecole Polytechnique Fédérale de Lausanne
FAU Erlangen-Nürnberg
Georgia Institute of Technology
HU Berlin
JGU Mainz
Lawrence Berkeley National Laboratory
Niels Bohr Institute
Ohio State University
Pennsylvania State University
RU Bochum
RWTH Aachen
Southern University and A&M College
Stockholms universitet
Stony Brook University
Sungkyunkwan University
TU Dortmund
TU München
Universität Bonn
Universität Wuppertal
Université libre de Bruxelles
Université de Mons
Universiteit Gent
University of Adelaide
University of Alabama
University of Alberta
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Canterbury
University of Delaware
University of Geneva
University of Kansas
University of Manchester
University of Maryland
University of Oxford
University of Wisconsin-Madison
University of Wisconsin-River Falls
Uppsala universitet
Vrije Universiteit Brussel

IceCube and DeepCore

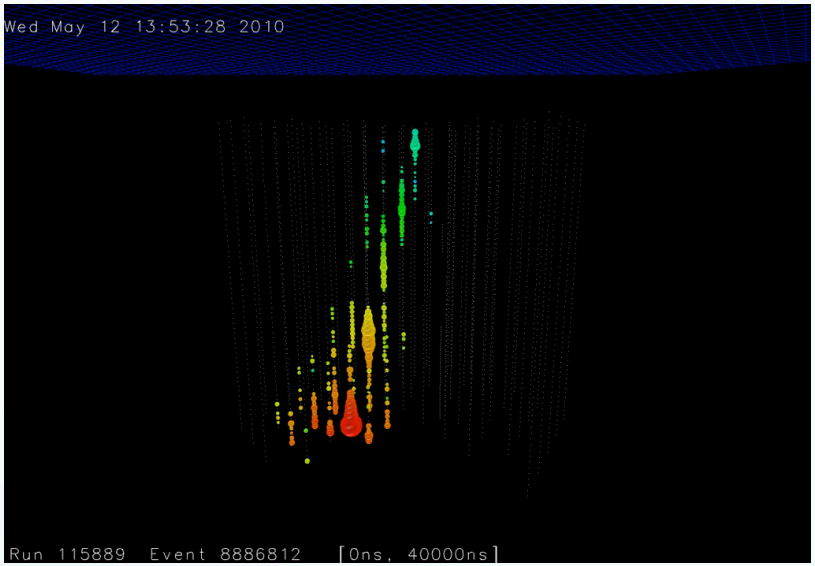




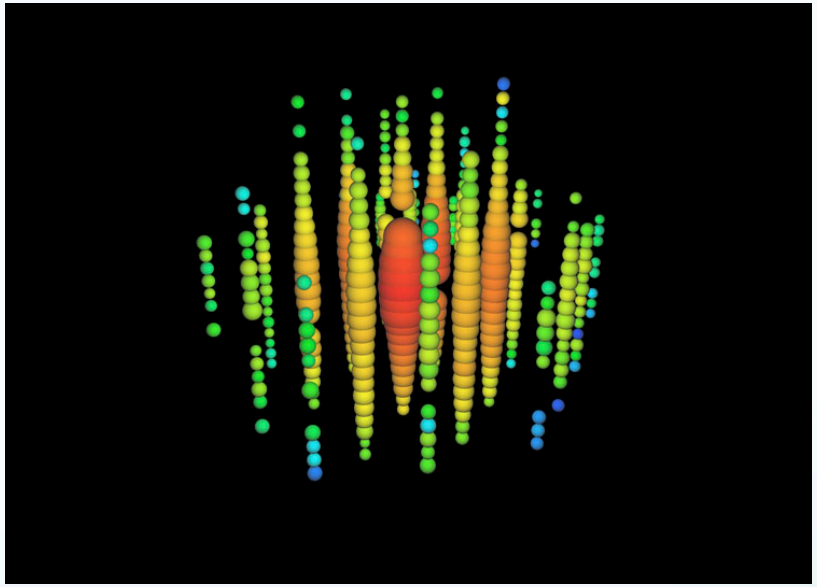
86 strings with 60 Digital Optical Modules (DOMs)
Deployed between 1450 and 2450 m depth
81 IceTop surface stations
Construction complete December 2011

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

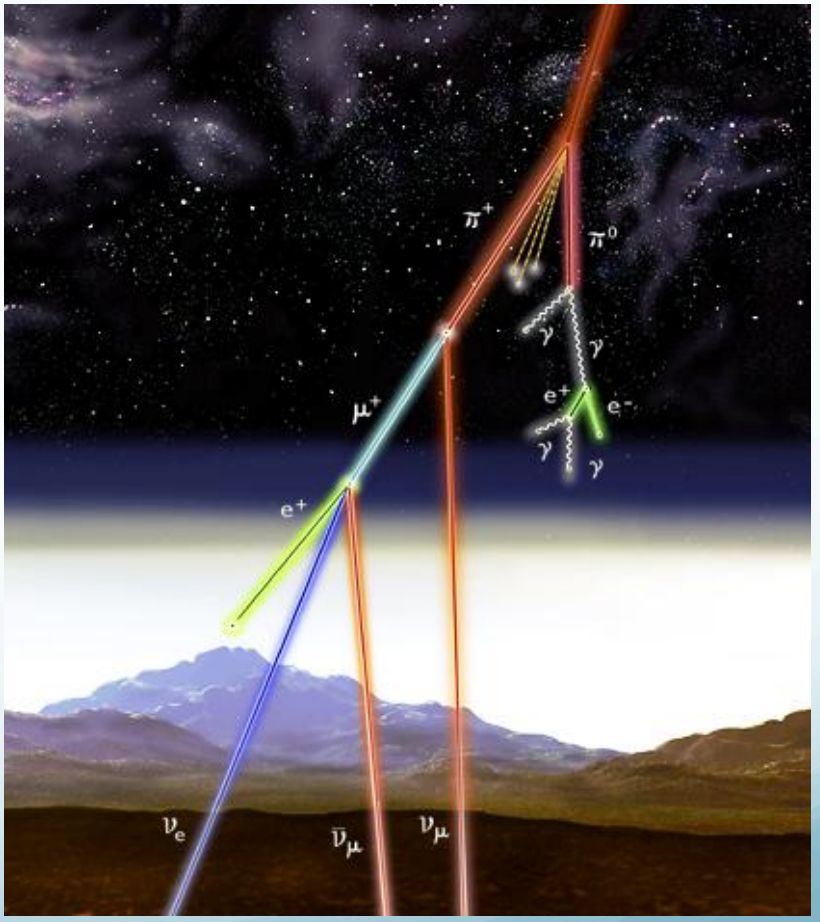


Cascades from charged current electron and tau neutrinos and neutral current interactions of all flavors

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

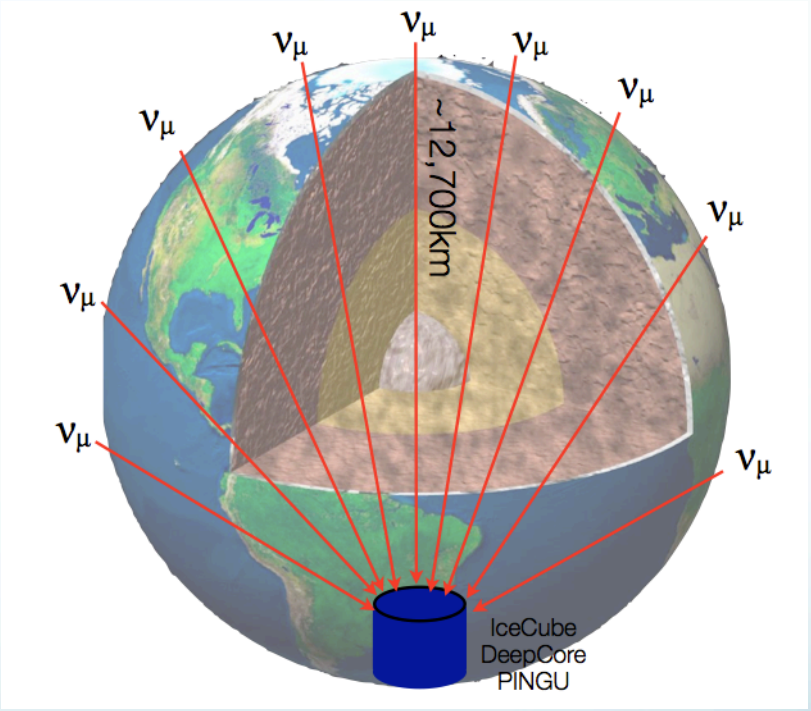
DeepCore Physics

- IceCube designed to detect high energy astrophysical neutrinos
- DeepCore extends IceCube's physics capabilities at low energies
  - Increased sensitivity for indirect dark matter searches
  - Neutrinos physics with cosmic ray-induced atmospheric neutrinos



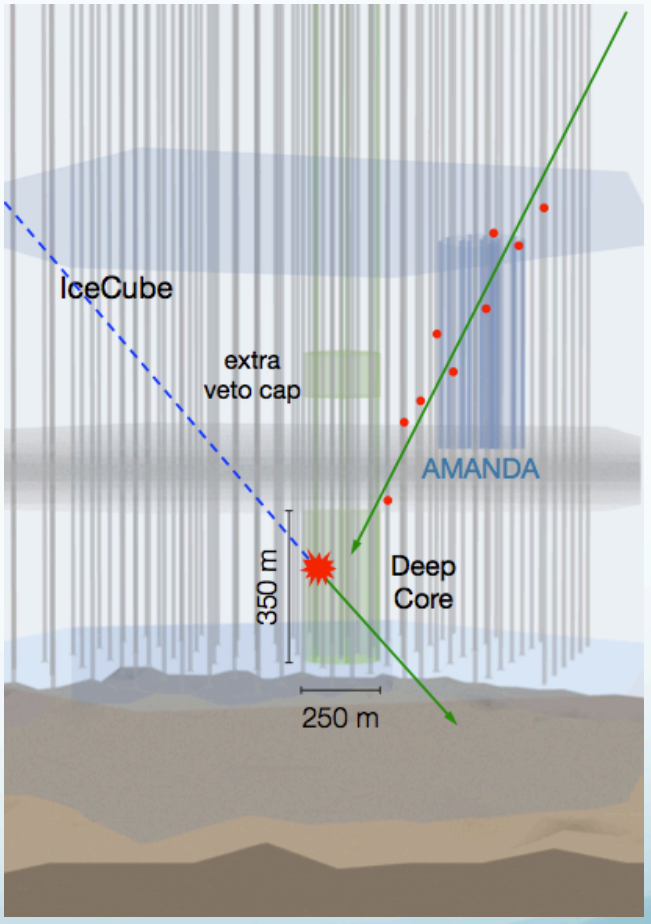
The Beam

- DeepCore uses atmospheric neutrinos from the northern hemisphere
- Range of baselines and energies to control systematics
- Neutrino oscillation in the Earth => MSW effect, strongest effects below ~10 GeV

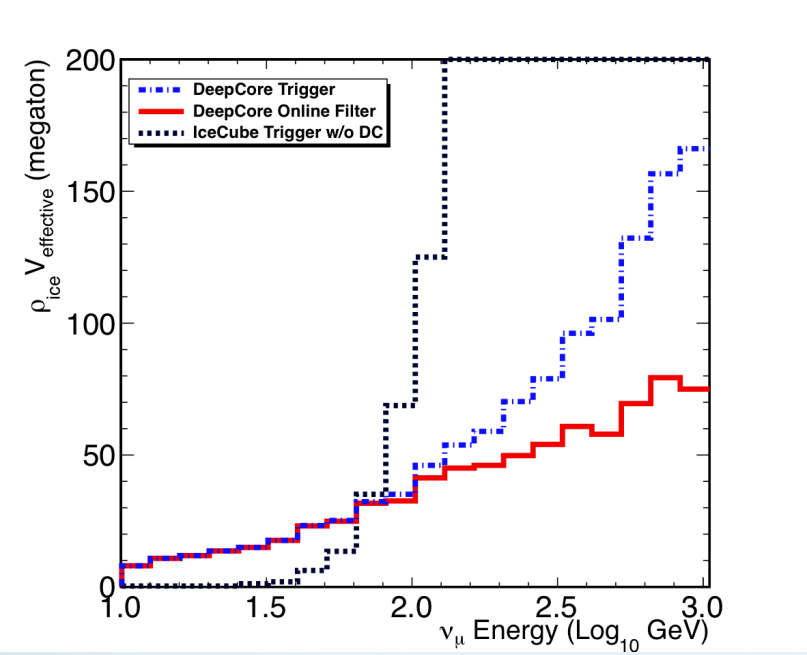


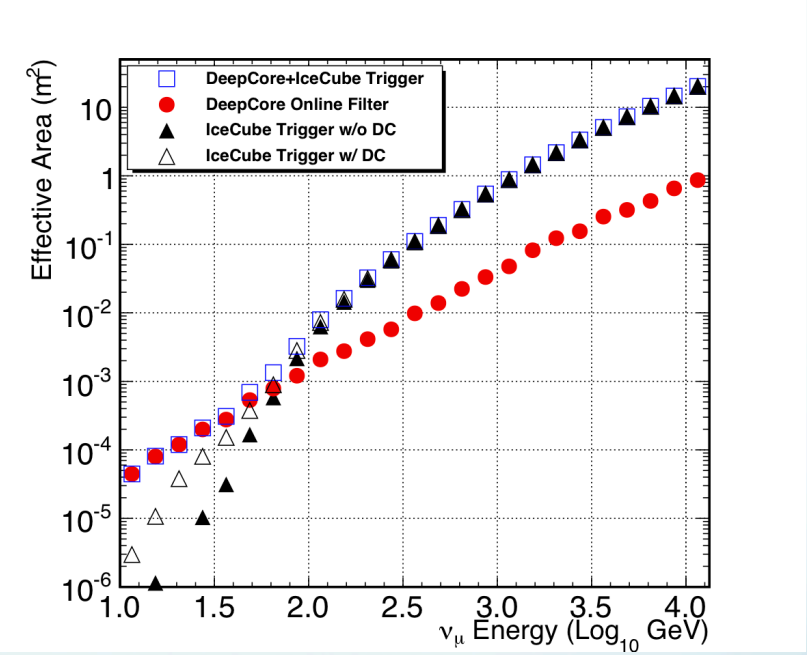
IceCube as a Veto

- **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**



DeepCore Sensitivity to Atmospheric Neutrinos

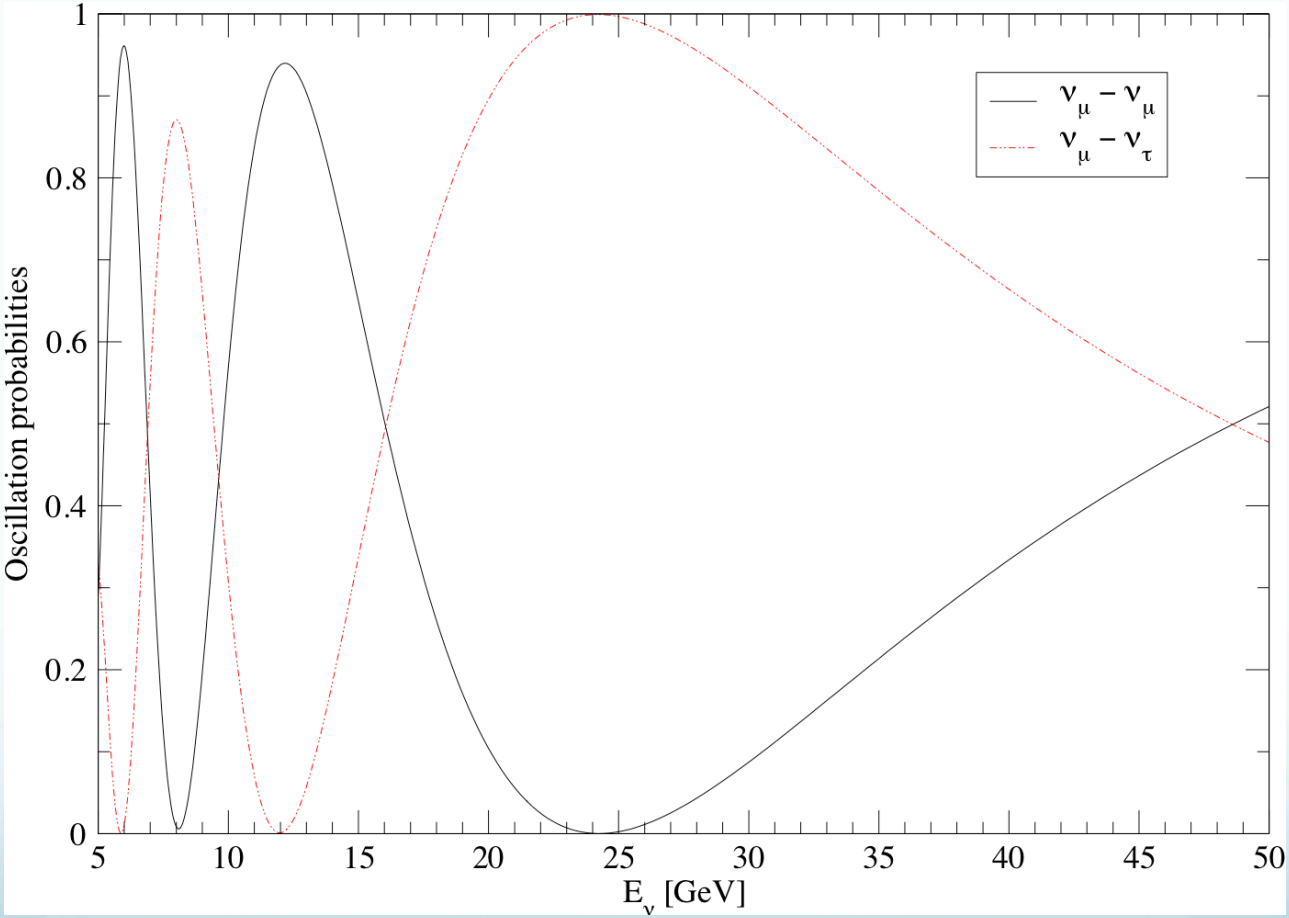




Effective target mass and area for muon neutrinos in IceCube/DeepCore

Astroparticle Physics, Volume 35, Issue 10, May 2012, Pages 615-624

Neutrino Oscillations in DeepCore

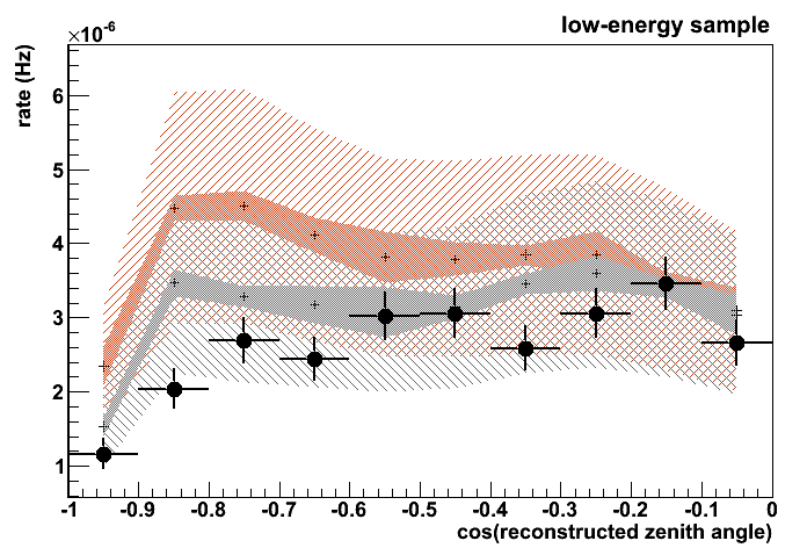


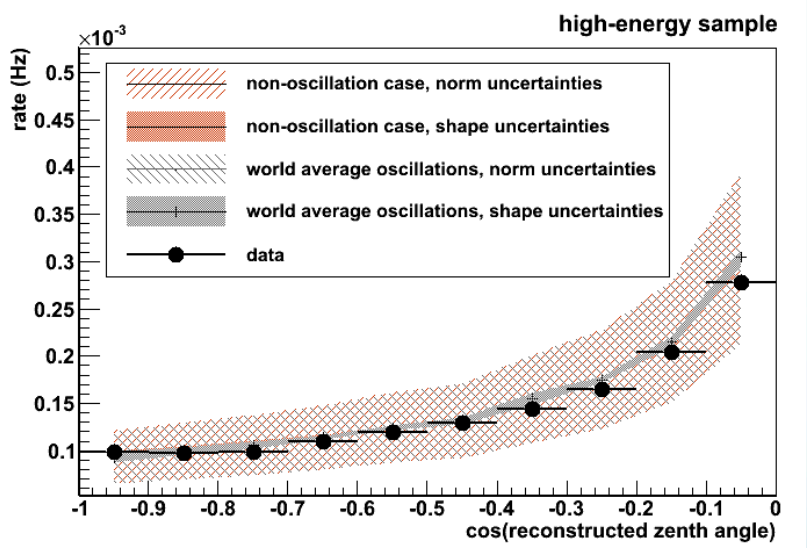
Mena, Mocioiu and Razzaque, Phys.Rev.D78:093003 ,2008

Muon neutrino survival probability is at 25 GeV with baseline of 1 Earth diameter

Neutrino Oscillations in DeepCore (2010-11 data)

Signature in DeepCore is deficit of muon neutrino CC tracks



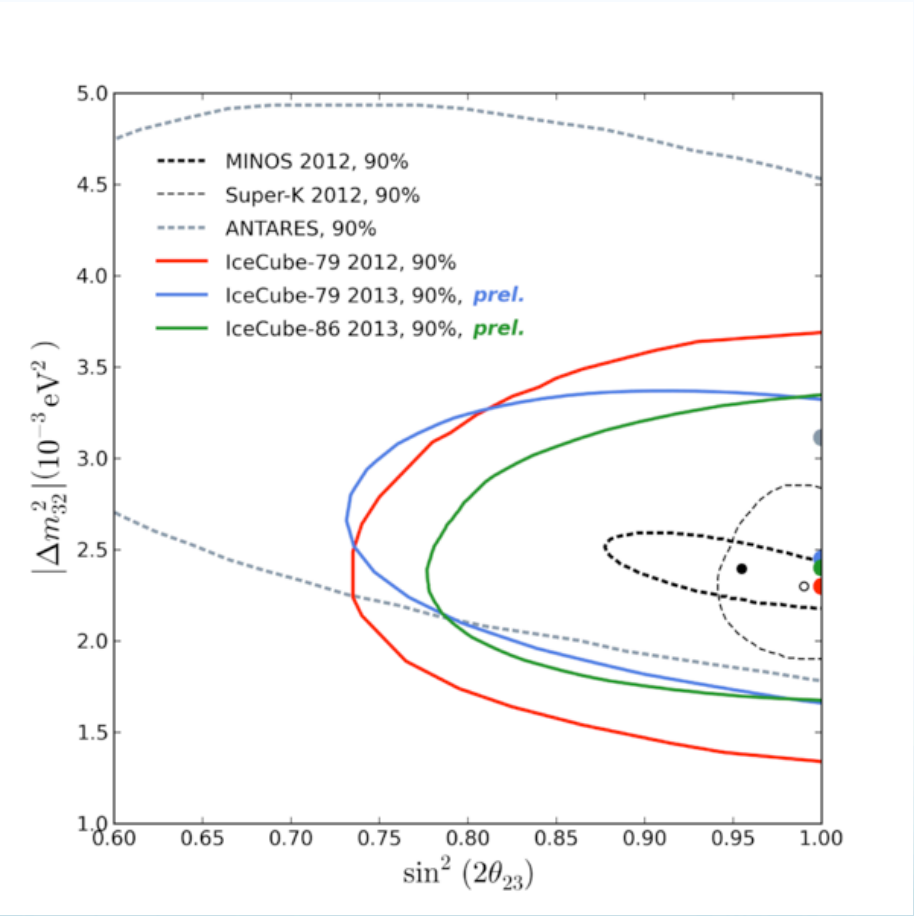


Comparison of low energy neutrino sample (20-100 GeV) to standard oscillation parameters and no-oscillation case

Comparison of high energy neutrino sample (100 GeV-10 TeV) to standard oscillation parameters and no-oscillation case

arXiv:1305.3909, accepted by PRL

Neutrino Oscillations in DeepCore

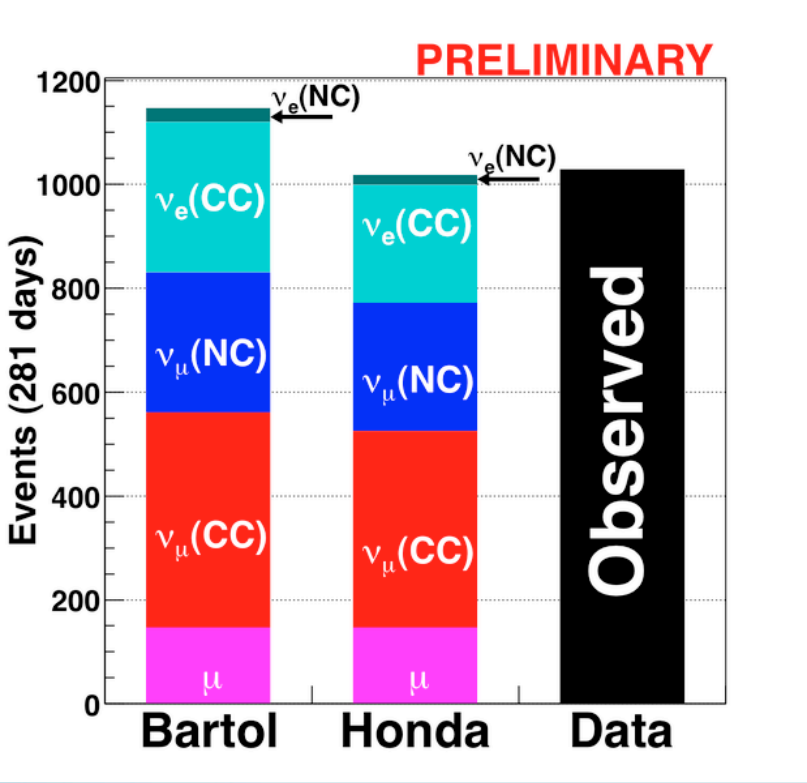


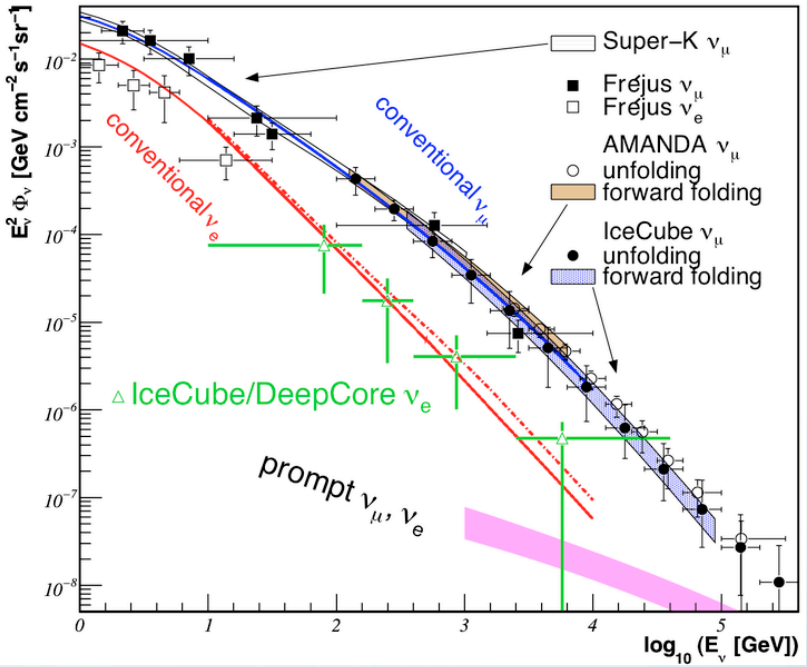
Oscillation analyses from IC79 (2010-11) and IC86 (2011-12)

Multiple reconstruction techniques

Significance contours from DeepCore neutrino oscillation analyses

Cascades in DeepCore

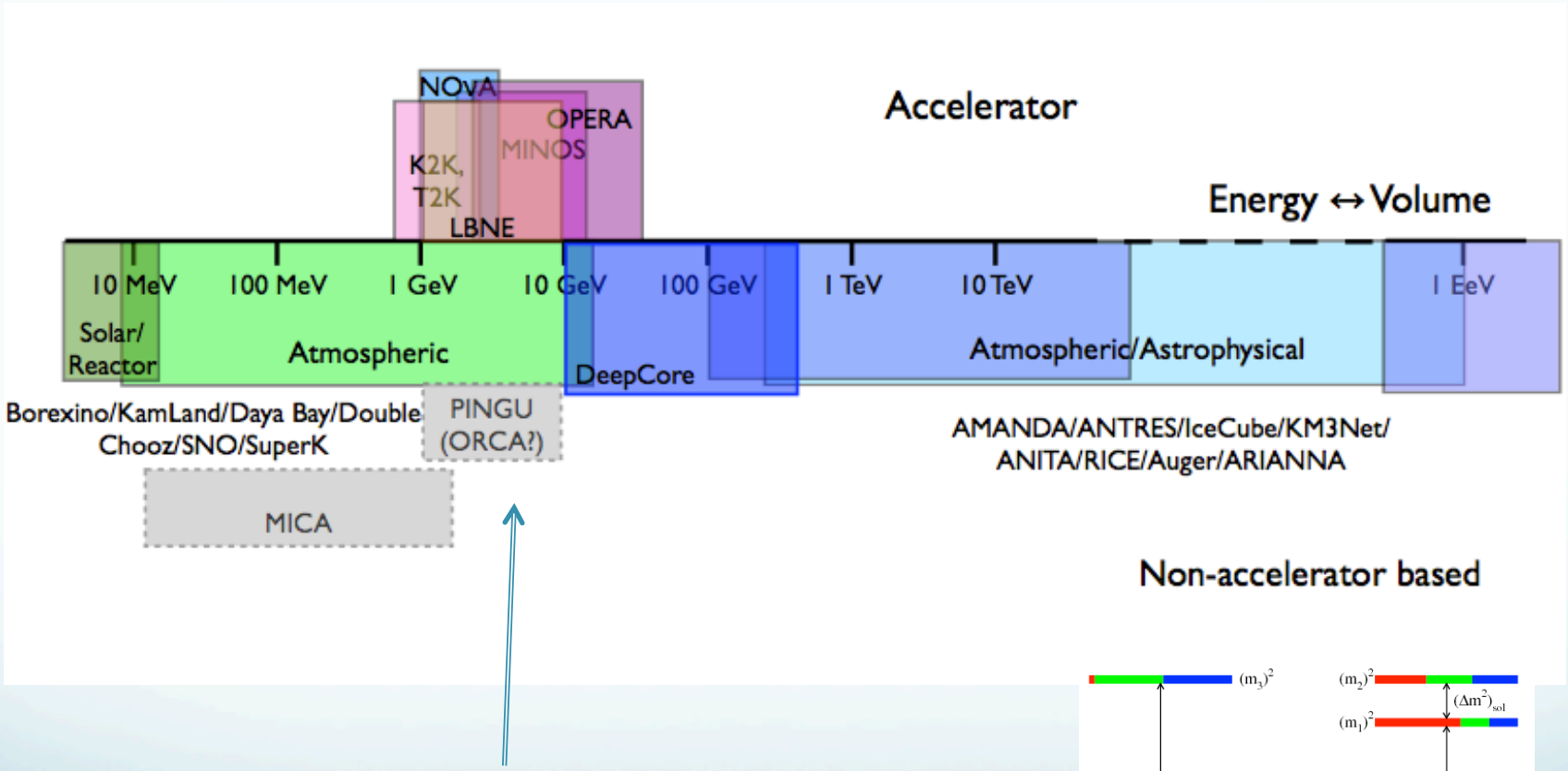




IceCube veto allowed DeepCore to measure atmospheric electron neutrino flux from 80 GeV to 6 TeV for the first time

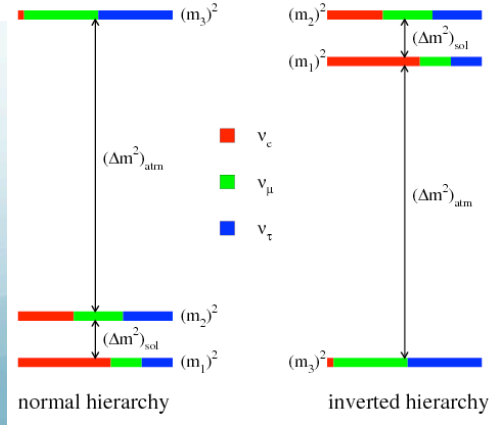
Phys. Rev. Lett. 110 (2013) 151105

The Next Generation of Neutrino Experiments



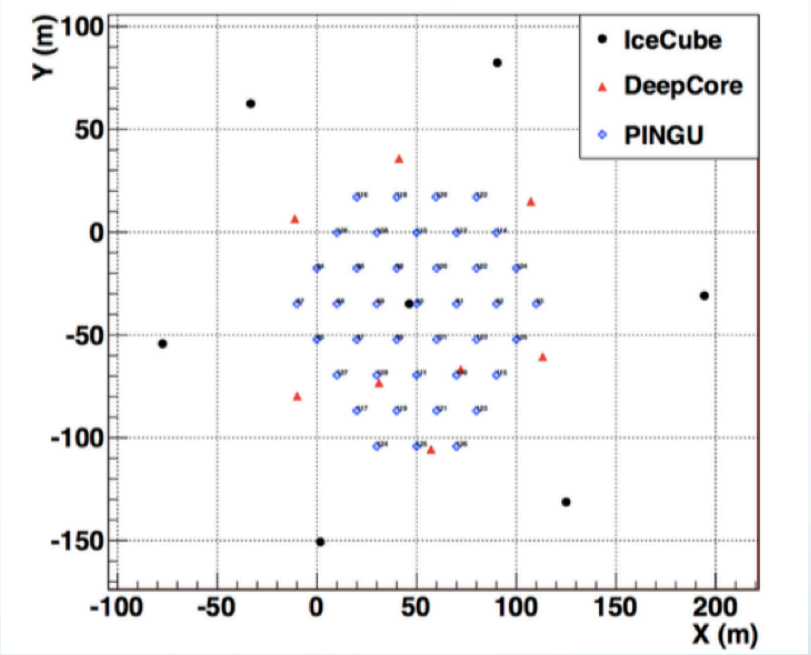
Some outstanding questions in neutrino physics:

Are neutrinos their own antiparticles?
Is the neutrino mass hierarchy normal or inverted?
CP violation in neutrino oscillation?



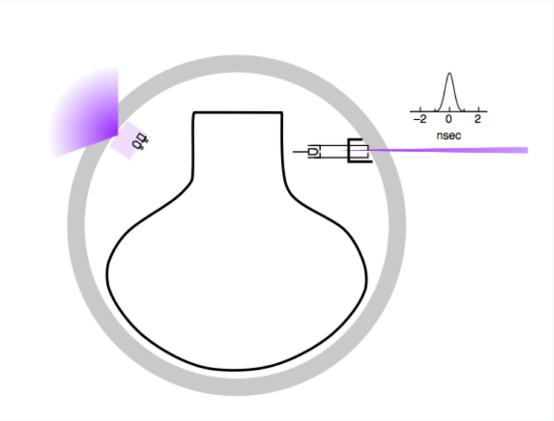
PINGU

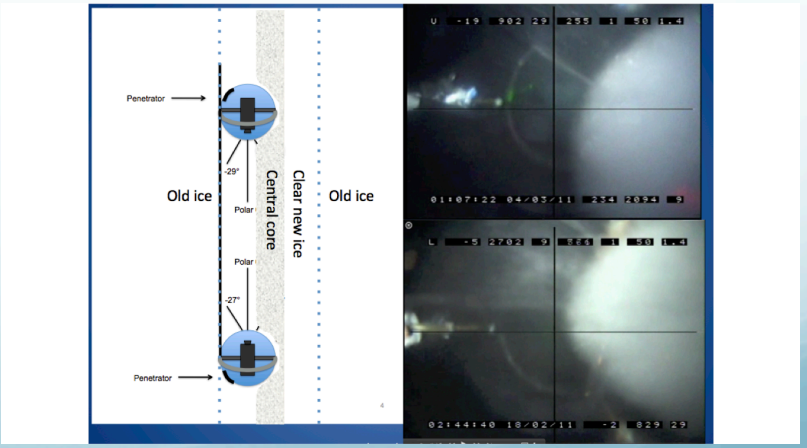
- Proposed infill extension of IceCube/DeepCore
- 40 strings with 60-100 DOMs per string
- 25 m string-to-string spacing, ~3x less than DeepCore
- Cost ~ $1.25 million per string, $10 million drilling setup
- IceCube experience shows that drilling 40 strings in 2-3 years is feasible



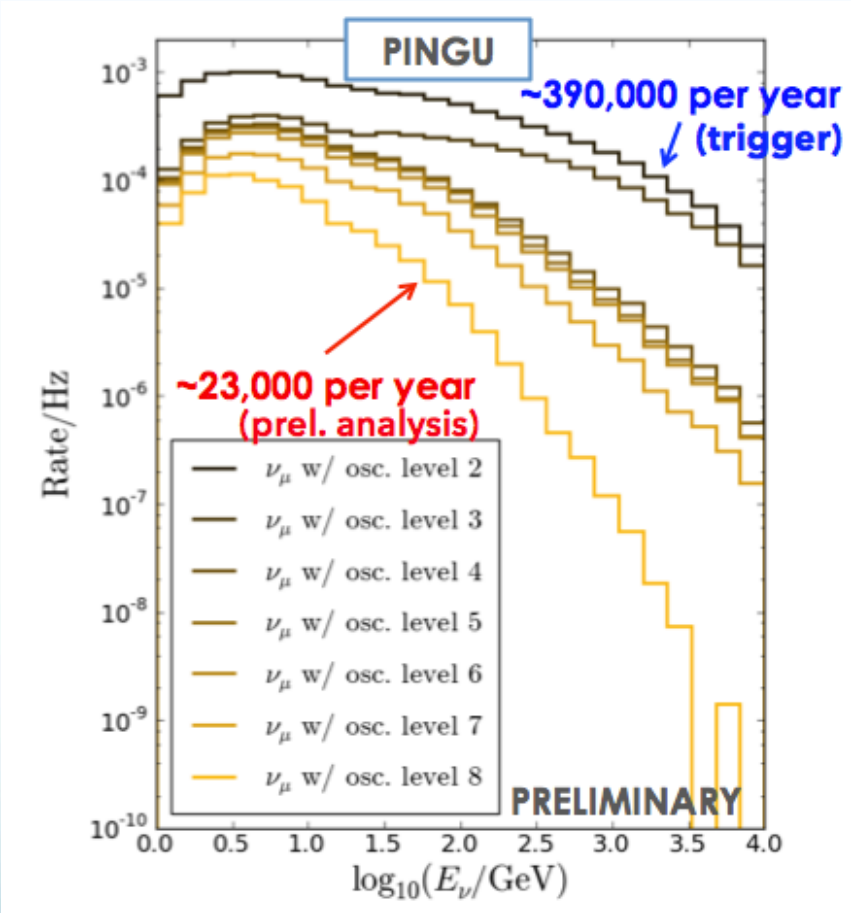
PINGU Design

- **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**

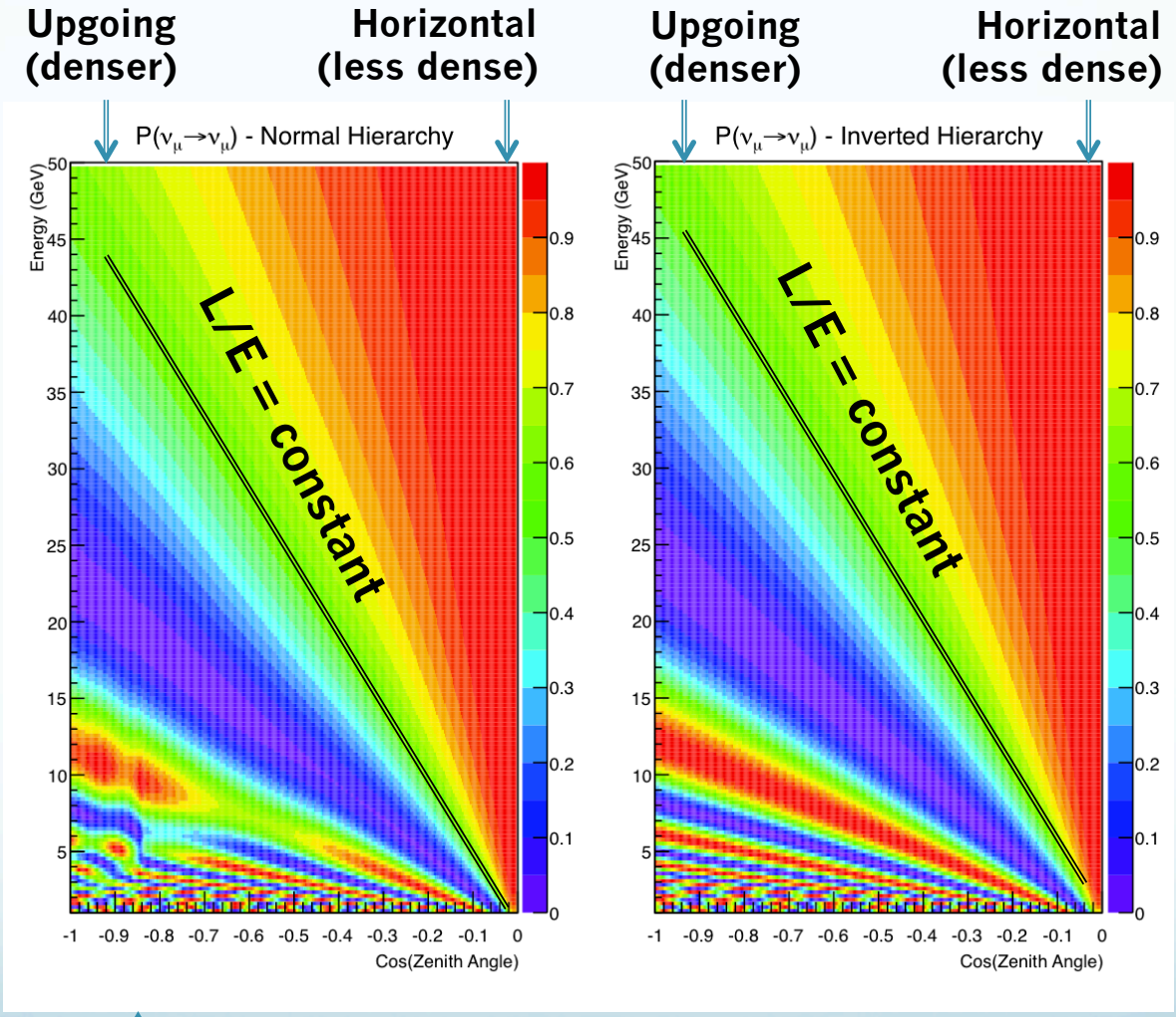




Neutrino rates in PINGU



Mass hierarchy



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

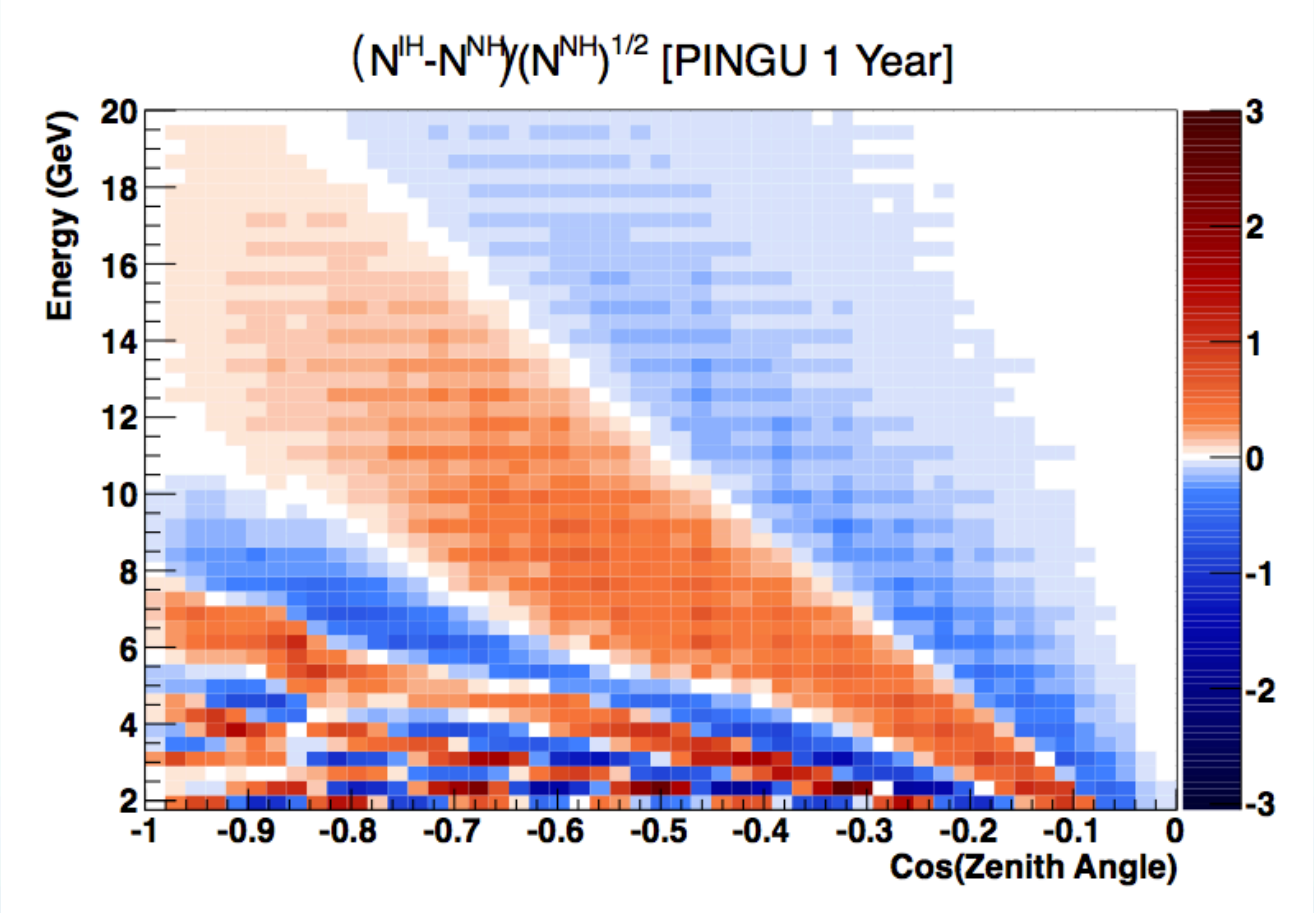
Distinguishability Metric

$$S_{tot} = \sqrt{\Sigma_{ij} \frac{\left(N_{ij}^{IH} - N_{ij}^{NH}\right)^2}{N_{ij}^{NH}}}$$

$$N_{i,j}^{NH} = P\left(\nu_\mu\right)_{i,j}^{NH} \Phi\left(\nu_\mu\right)_{i,j}^{NH} \sigma\left(\nu_\mu\right)_{i,j}^{NH} V_{i,j}^{eff} + P\left(\bar{\nu}_\mu\right)_{i,j}^{NH} \Phi\left(\bar{\nu}_\mu\right)_{i,j}^{NH} \sigma\left(\bar{\nu}_\mu\right)_{i,j}^{NH} V_{i,j}^{eff}$$

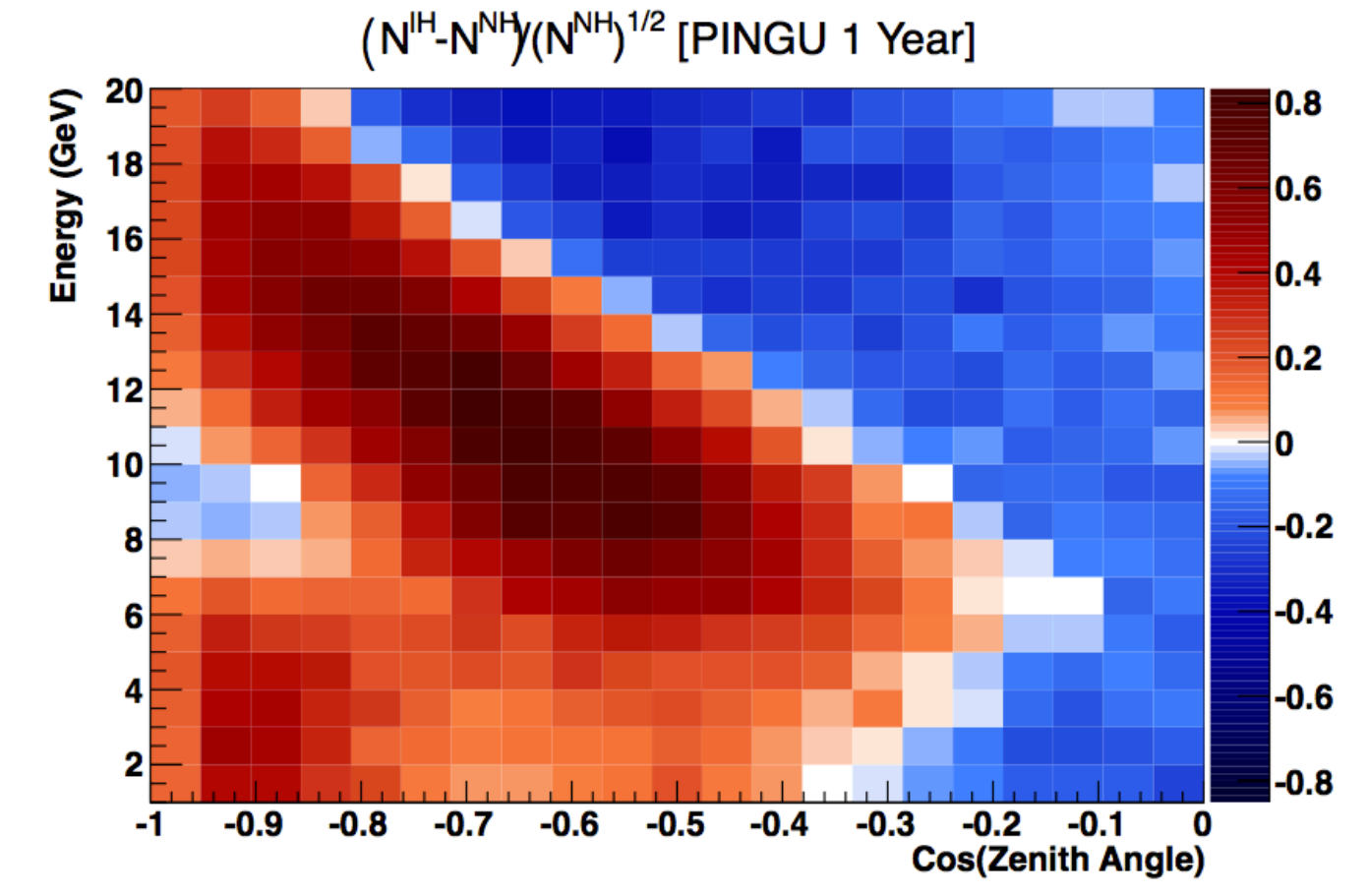
Although PINGU cannot distinguish between neutrinos and antineutrinos, differences in cross sections and kinematics allow PINGU to measure the mass hierarchy

Signature of MH in PINGU



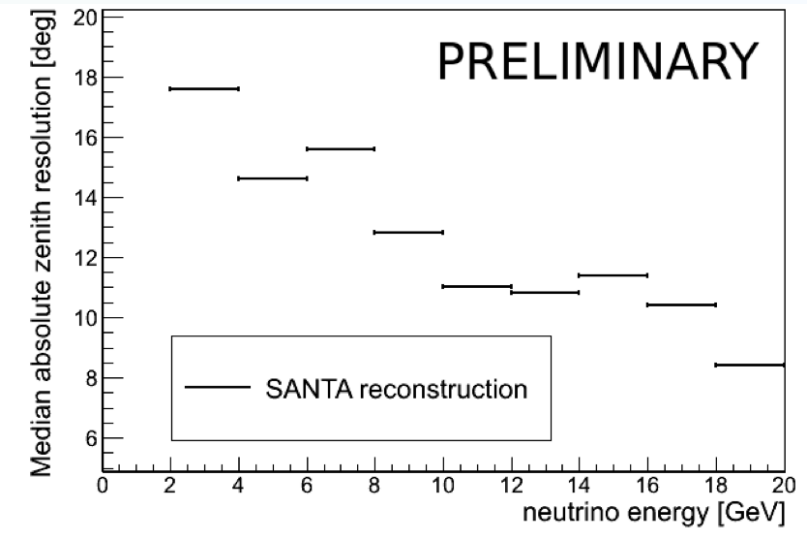
Ideal case: no background contamination
Perfect flavor ID: no confusion between low-energy muon neutrino CC tracks and NC/electron CC/tau CC cascades
100% signal efficiency

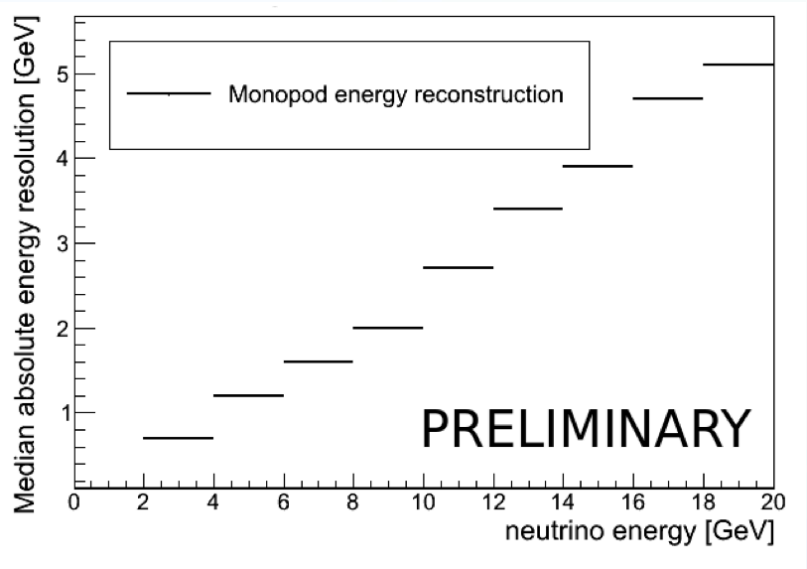
Signature of MH in PINGU



Energy resolution of 3 GeV
Angular resolution of 11.25°

Energy and Direction Resolution Systematics

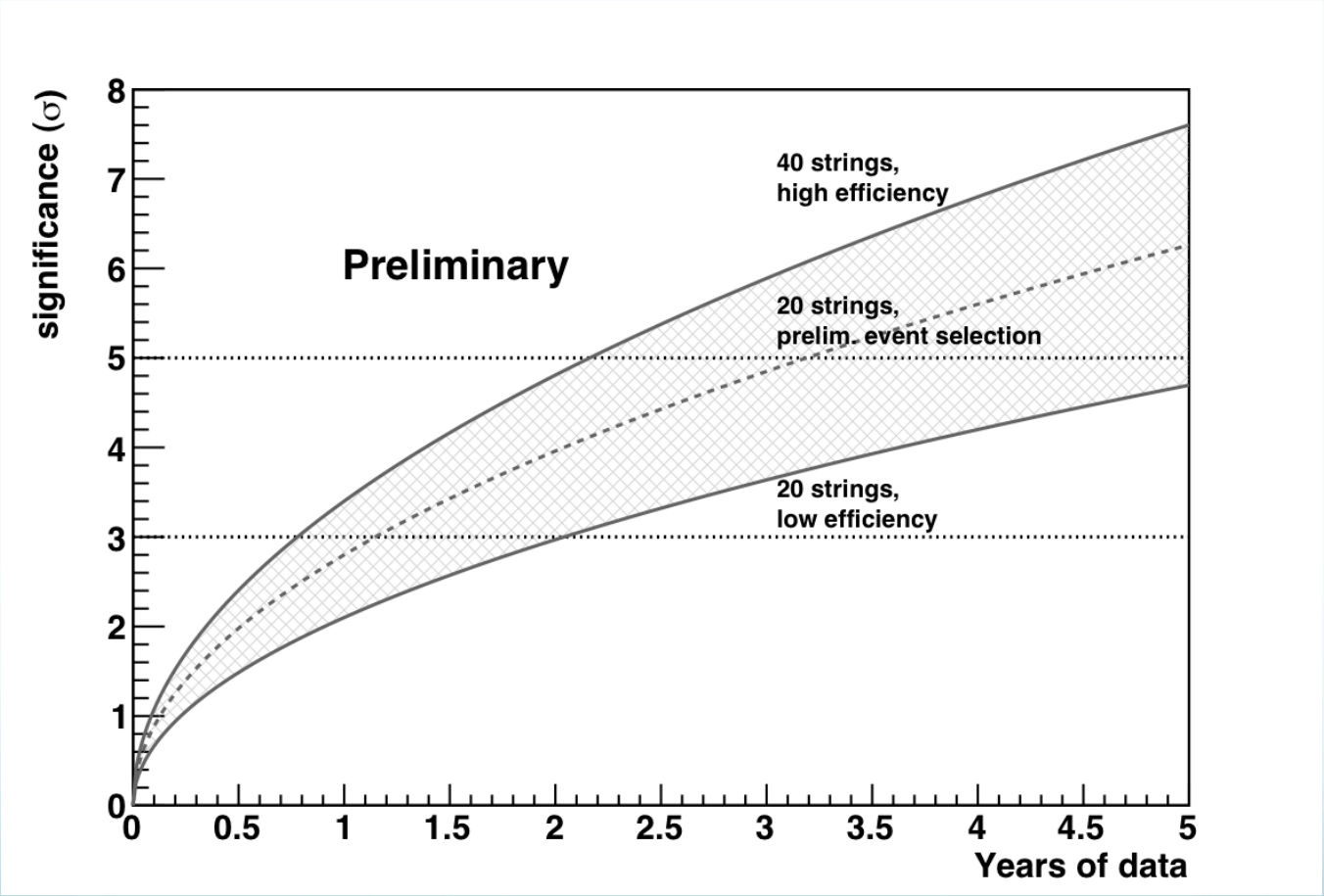




Reconstruction using algorithms developed for DeepCore
Systematics studied:

- **$\pm 2\sigma$ of world average values for θ_{23}, θ_{13}, Δm^2_{atm}, δ_{cp}**
- **10% shift and 10% error on angular resolution**
- **10% shift and 10% error on energy resolution**
- **30% efficiency error**
- **±0.05% on atmospheric neutrino spectral index**
- **More studies underway**

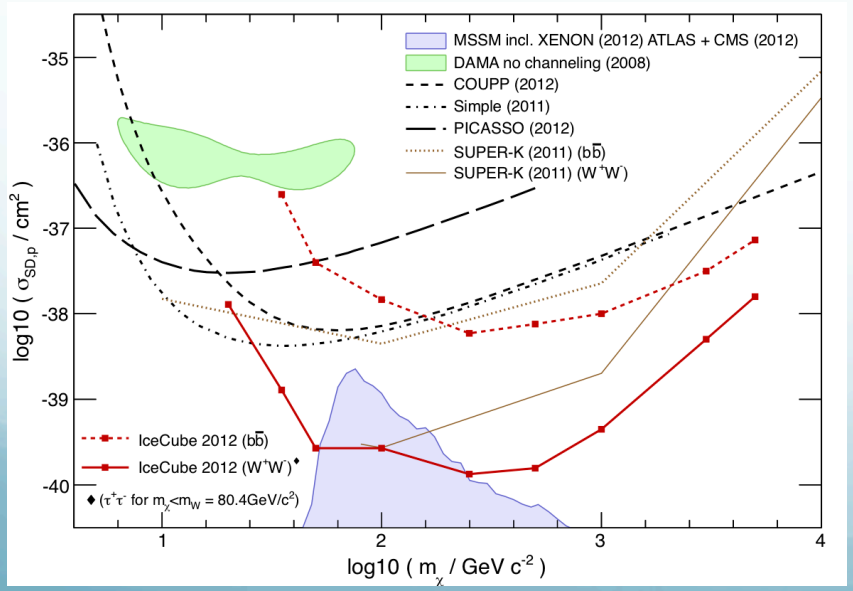
PINGU Sensitivity to MH

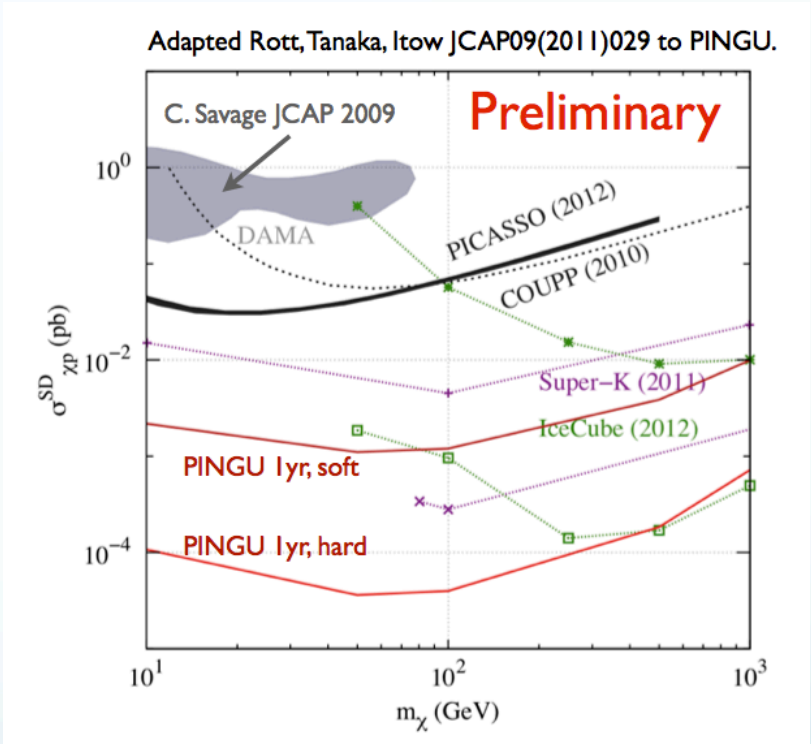


Even in pessimistic case, 3σ measurement in 2 years
More detailed systematics studies underway

More PINGU Physics

- **Improved sensitivity to indirect dark matter**
- **Supernova neutrinos**
- **Tau neutrino appearance – excess of cascades**





Sensitivity to spin-dependent cross section of WIMP annihilation in the Sun

Phys. Rev. Lett. 110, 131302 (2013)

PINGU Status

- Letter of intent in prep, proposal to follow
- Detailed studies of systematic errors under way
- Improved low-energy reconstruction algorithms being applied to simulated PINGU events
- If funded, plan deployment 2016-2019, results by 2021
- Future plans: Cherenkov ring imaging detector in ice (MICA)… proton decay is still an open issue

Summary

- IceCube and DeepCore are already publishing physics results with atmospheric neutrinos
- The extensive experience gained with IceCube PINGU construction and analysis plans
- PINGU can be deployed with relatively low cost and short construction time
- PINGU could determine the neutrino mass hierarchy at 3σ within 2 years of detector completion
- Letter of intent and full proposal underway