ICECUBE

IceCube-DeepCore-PINGU

IPP AGM/Town Hall Meeting
June 2014

Darren R. Grant

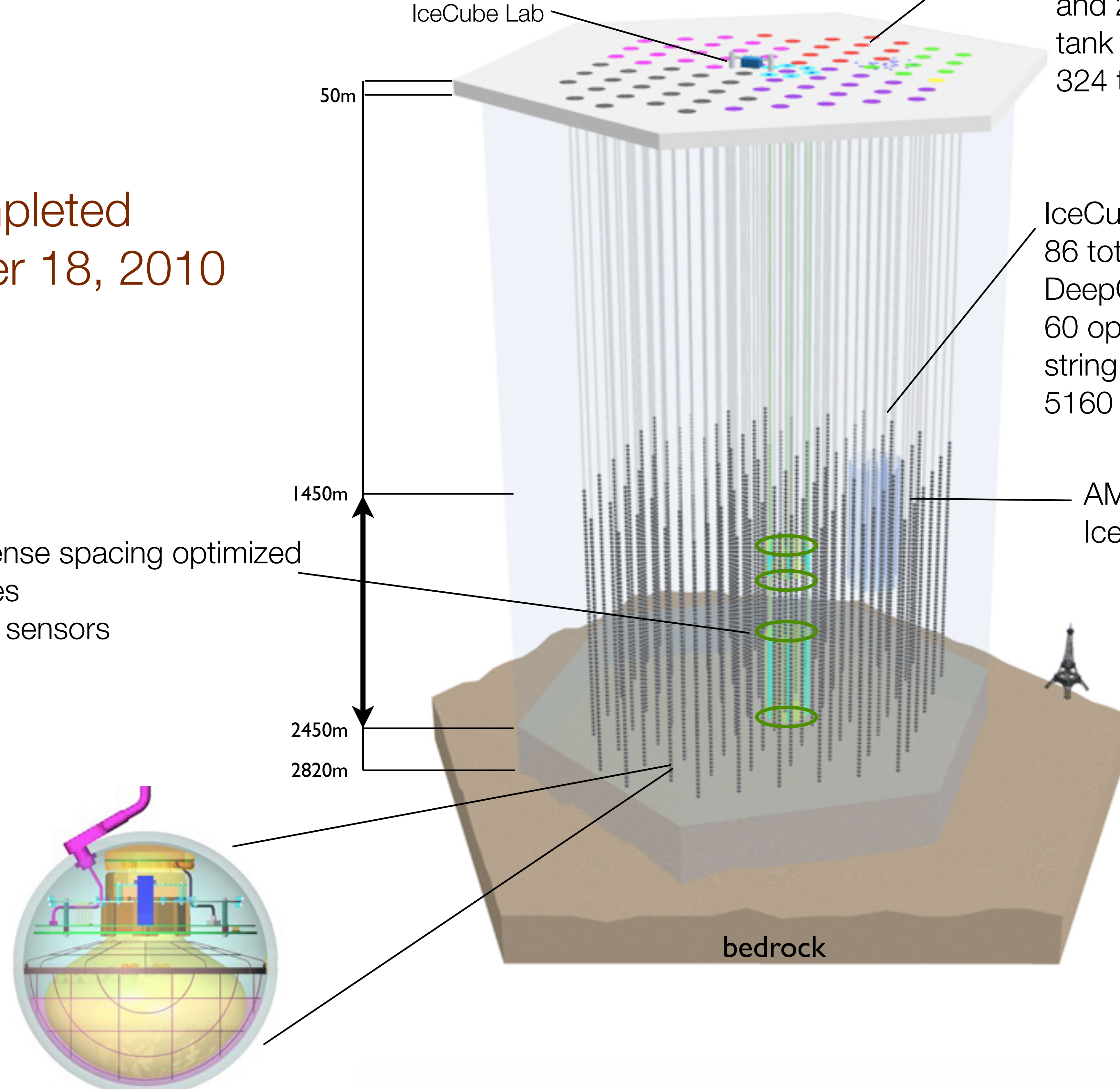
PRECISION ICECUBE NEXT GENERATION UPGRADE

UNIVERSITY OF ALBERTA

UNIVERSITY OF TORONTO

The IceCube Neutrino Observatory

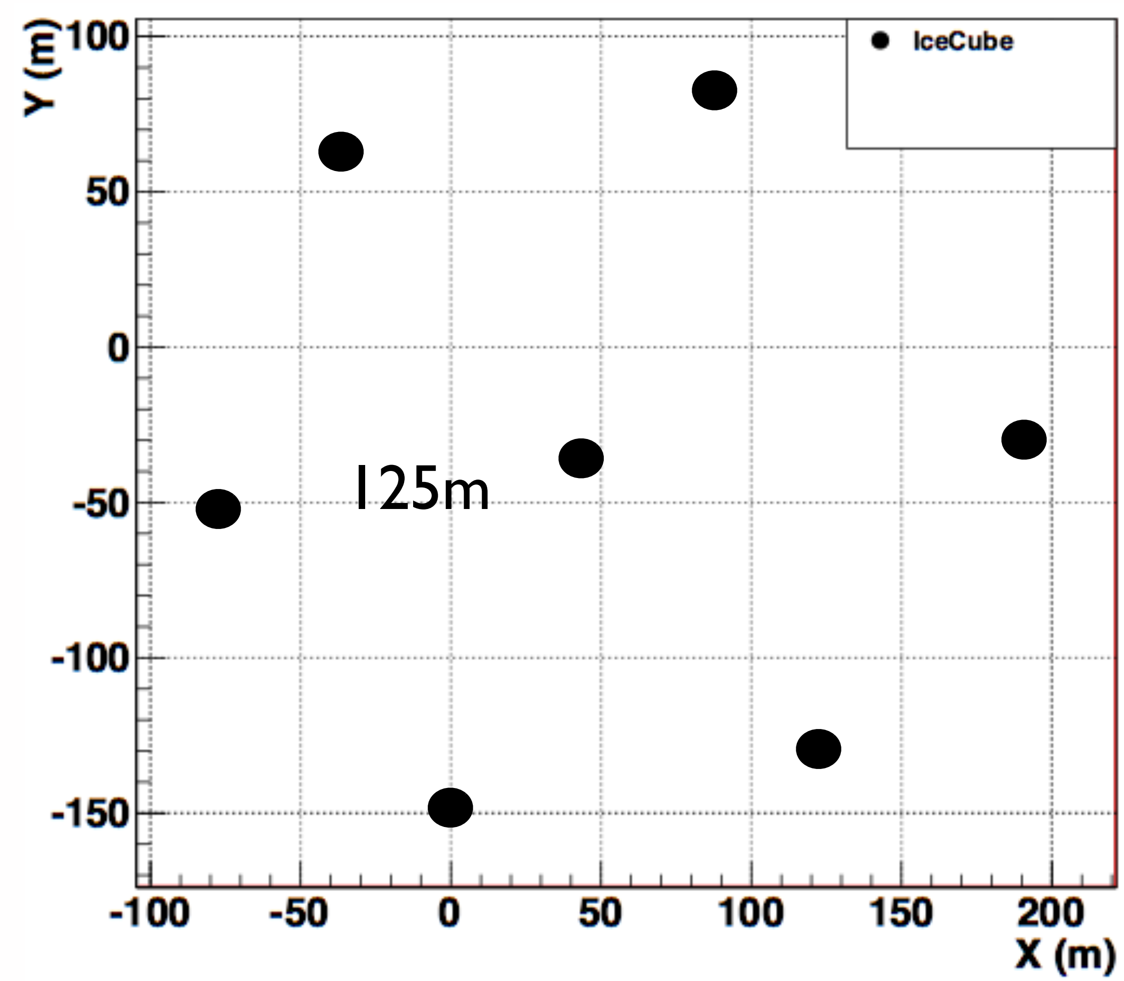
Completed
December 18, 2010

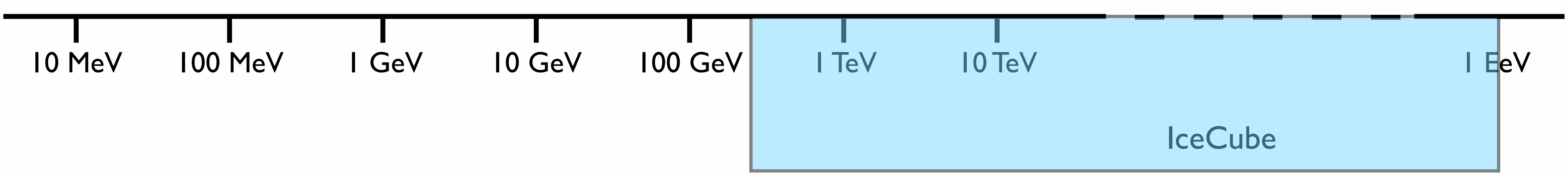


IceCube

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing

IceCube (top centre view)

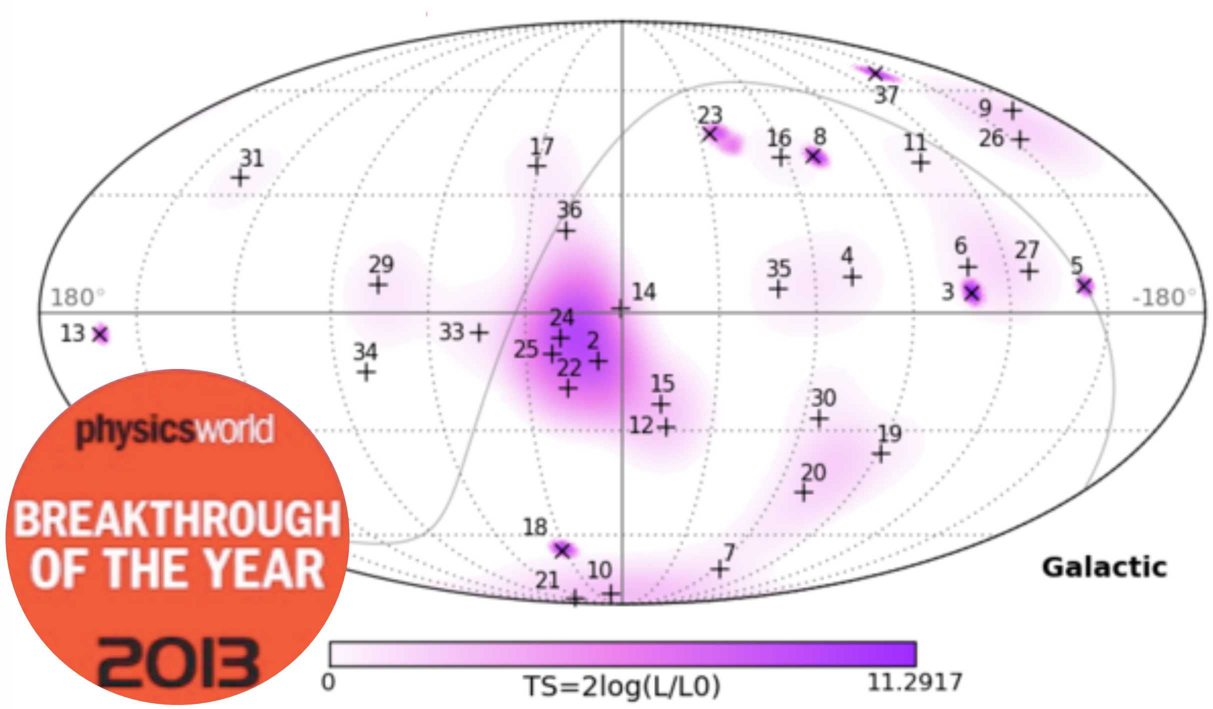


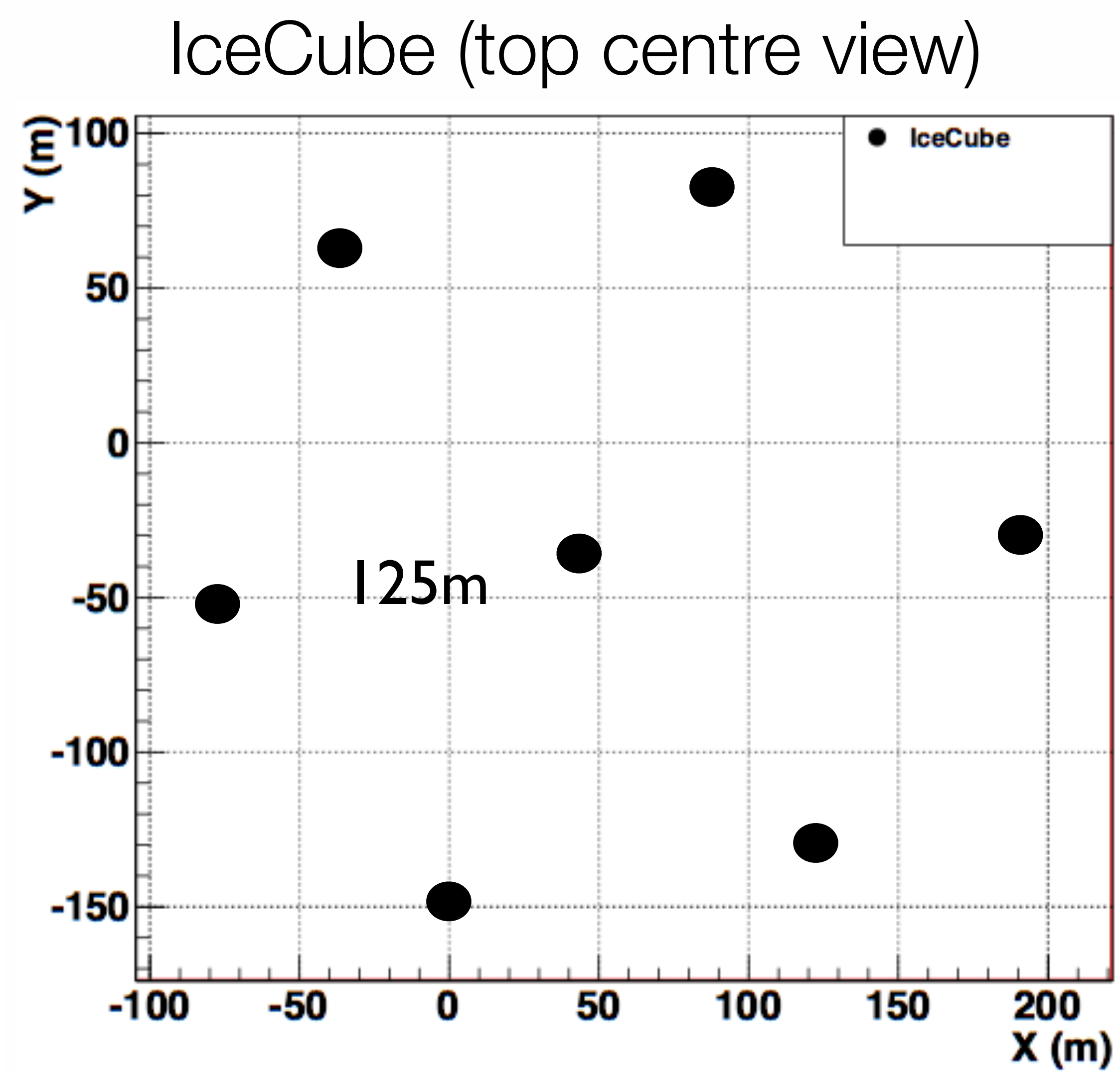


digital optical module - DOM

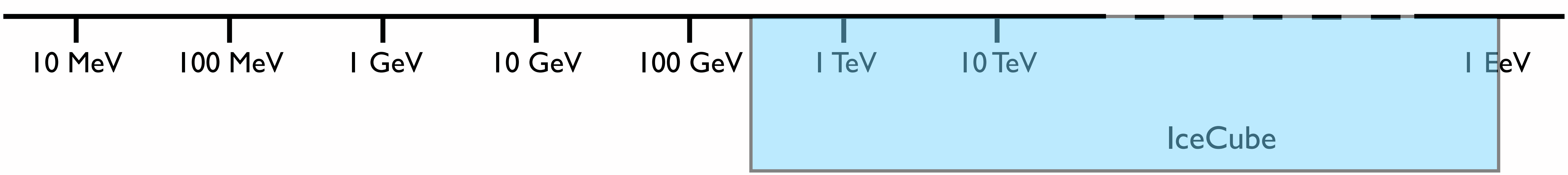
IceCube

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing





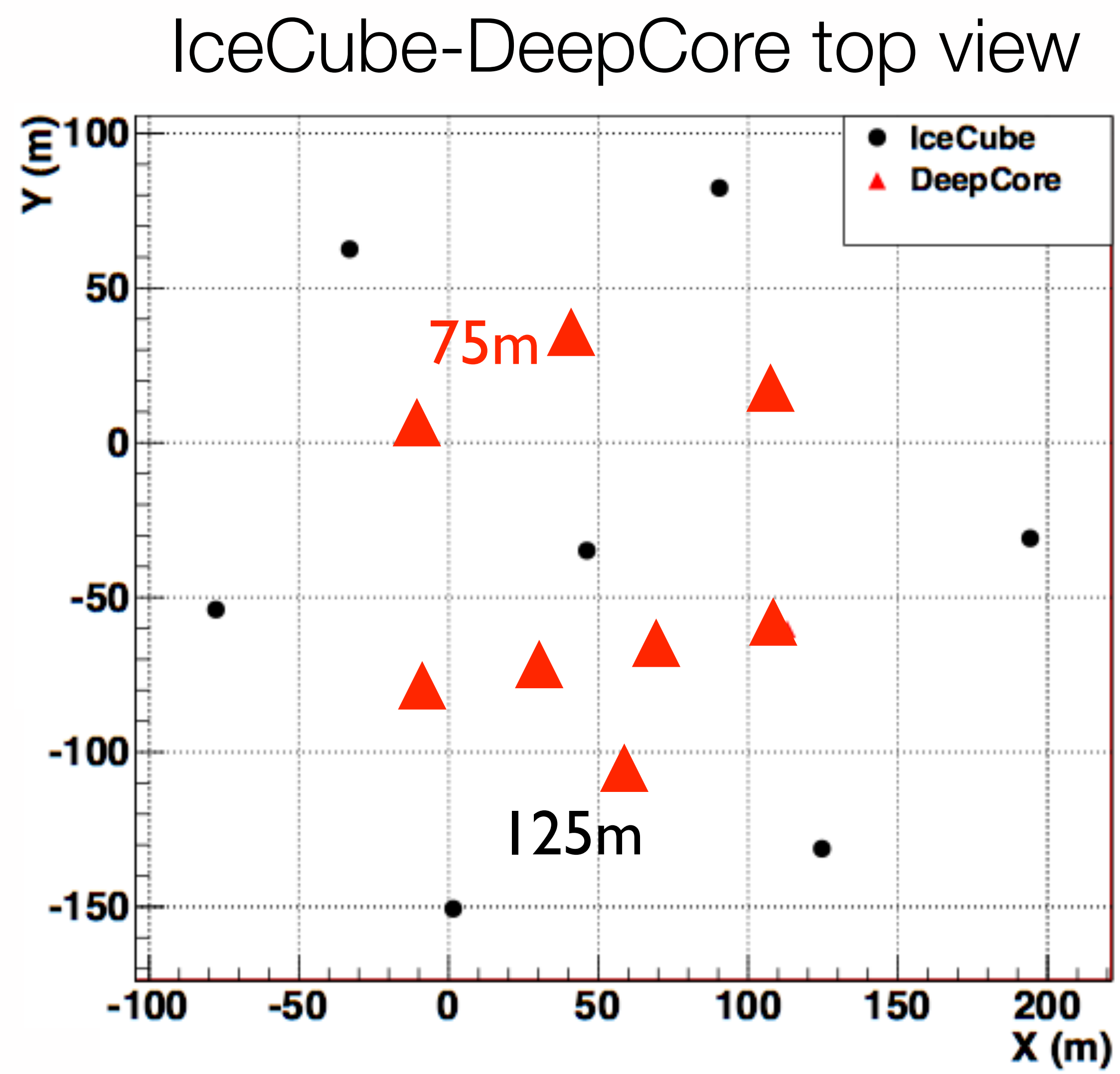
analysis completed on WestGrid's Jasper Cluster

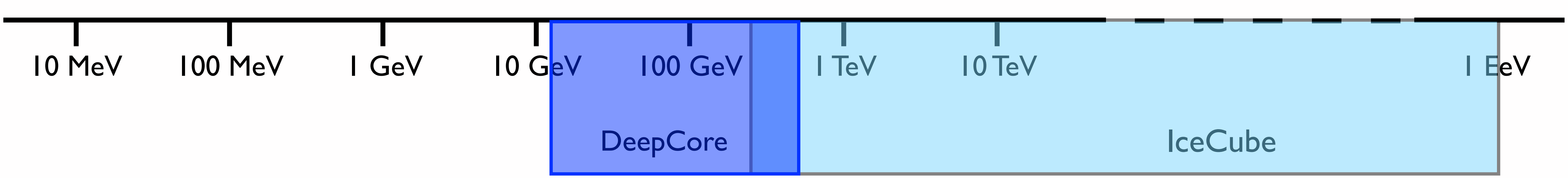


digital optical module - DOM

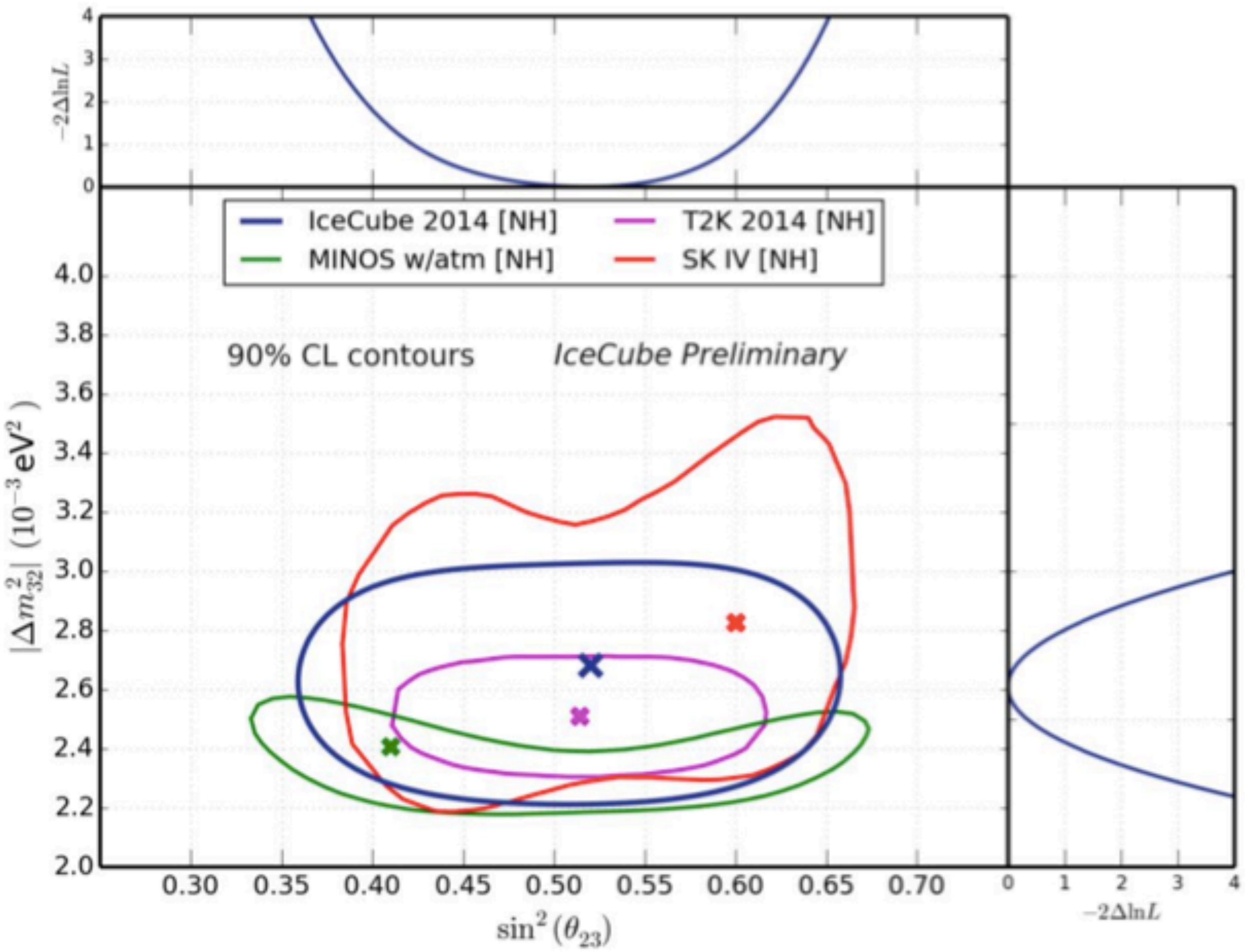
IceCube-DeepCore

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing

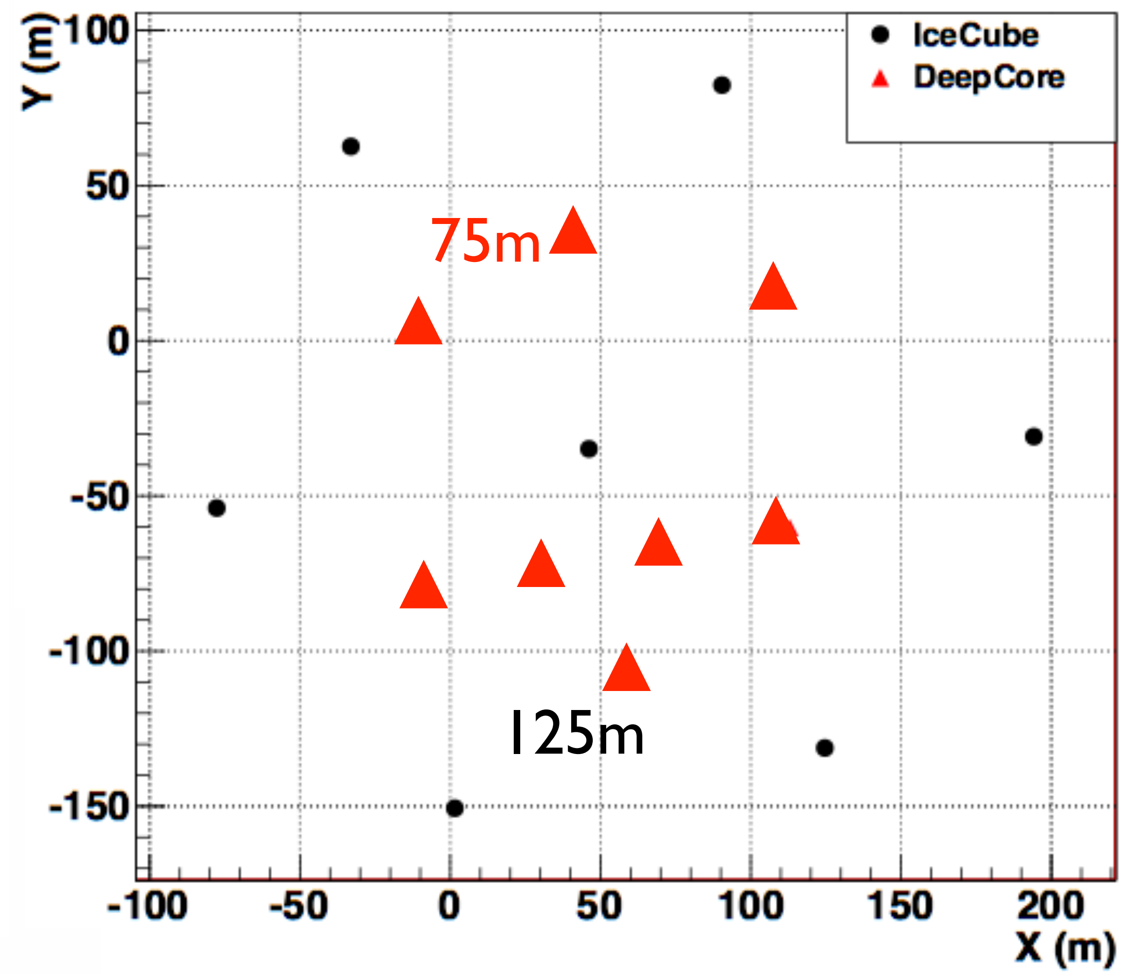




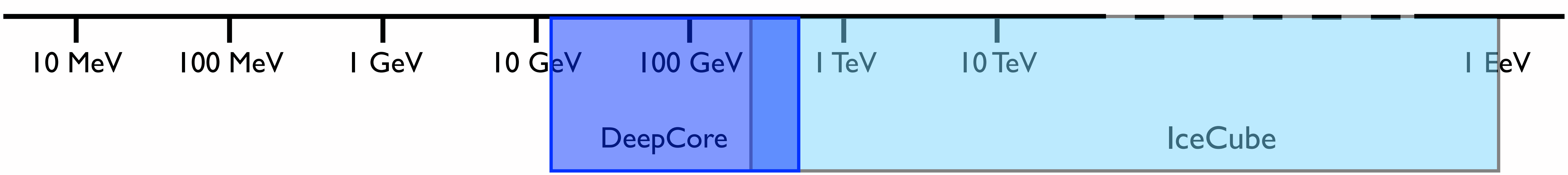
IceCube-DeepCore



IceCube-DeepCore top view



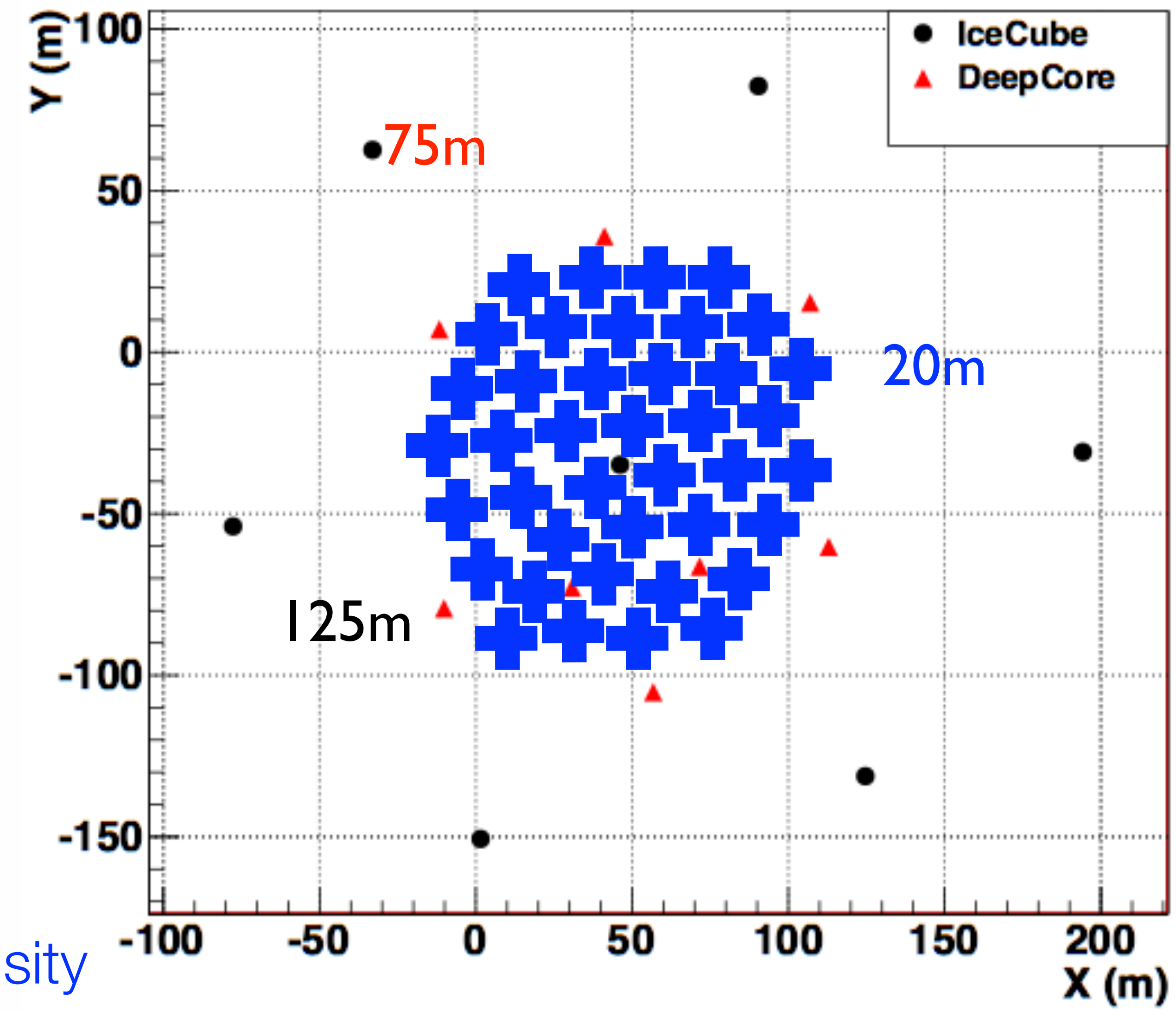
DeepCore low-en working group convened @ U. Alberta; Simulations completed on Compute Canada

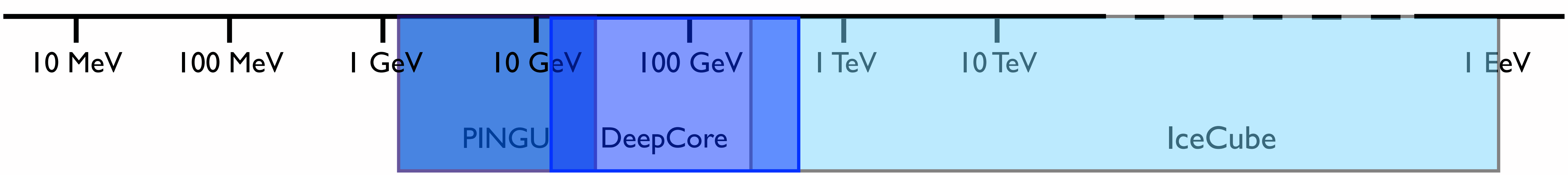


IceCube-DeepCore-PINGU

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing
- Add 40 strings (baseline target)
  - ~20m string spacing
  - 3-5m DOM spacing
  - ~20x higher photocathode density

IceCube-DeepCore-PINGU top view





digital optical module - DOM

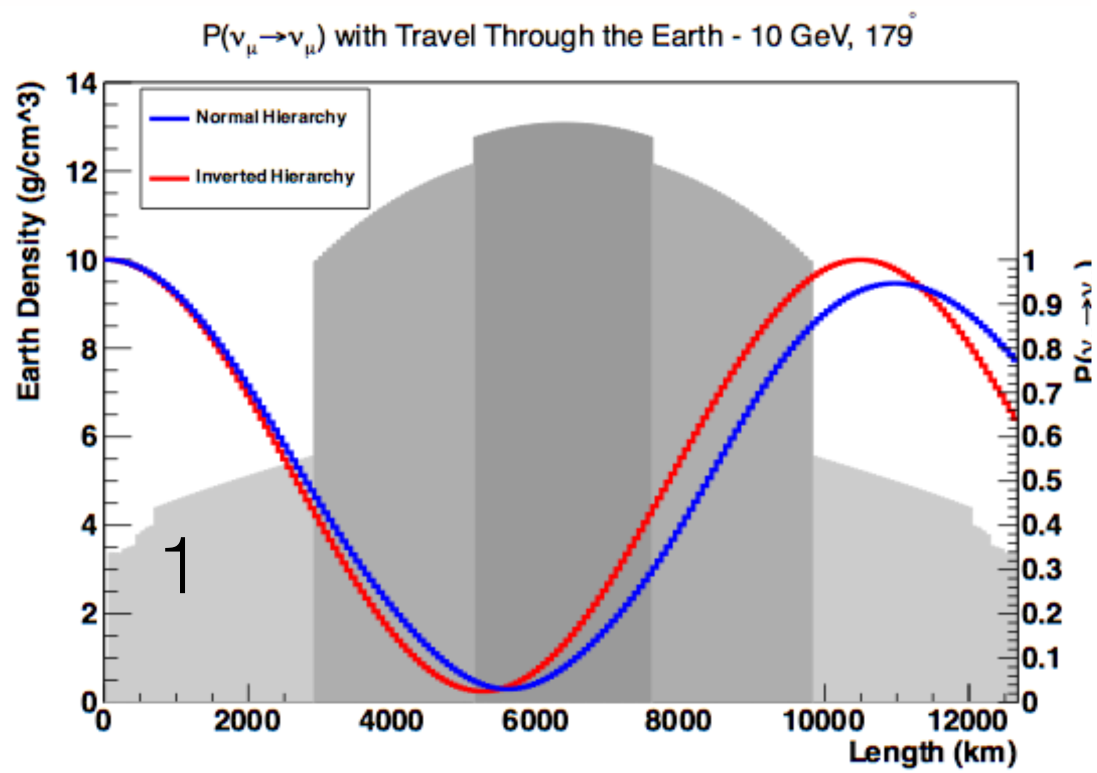
The physics with future atmospheric neutrino detectors

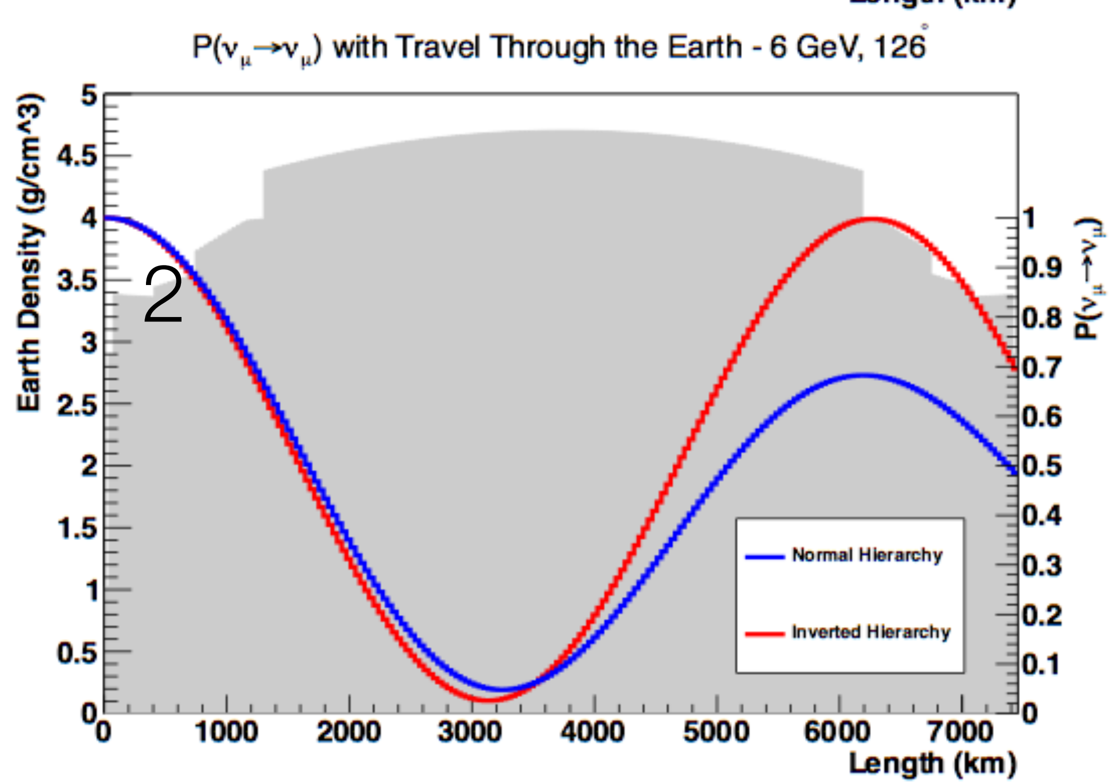
Covered in today's talk

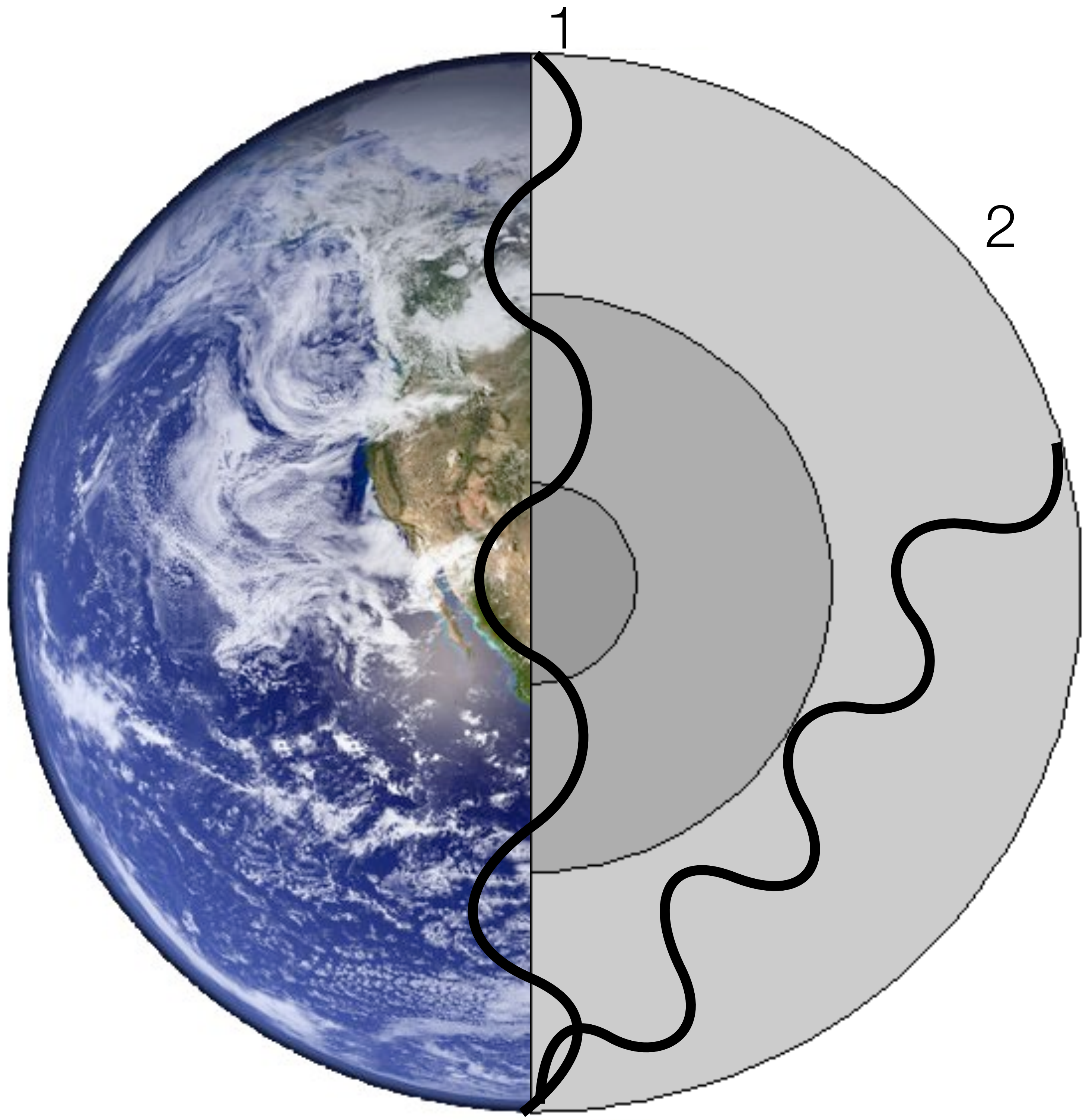
- Gain sensitivity to atmospheric neutrinos in the region below 10 GeV with very high statistics
  - Provide a definitive measurement of the neutrino mass hierarchy (NMH)
  - Will help pin down $(\Delta m_{23})^2$ and test maximal mixing, ν_τ appearance
- Probe lower mass WIMPs
- Gain increased sensitivity to supernovae neutrino bursts, Earth tomography
- Initiate an extensive calibration program to improve systematics knowledge
- Pathfinder technological R&D for the Megaton Ice Cherenkov Array (MICA)

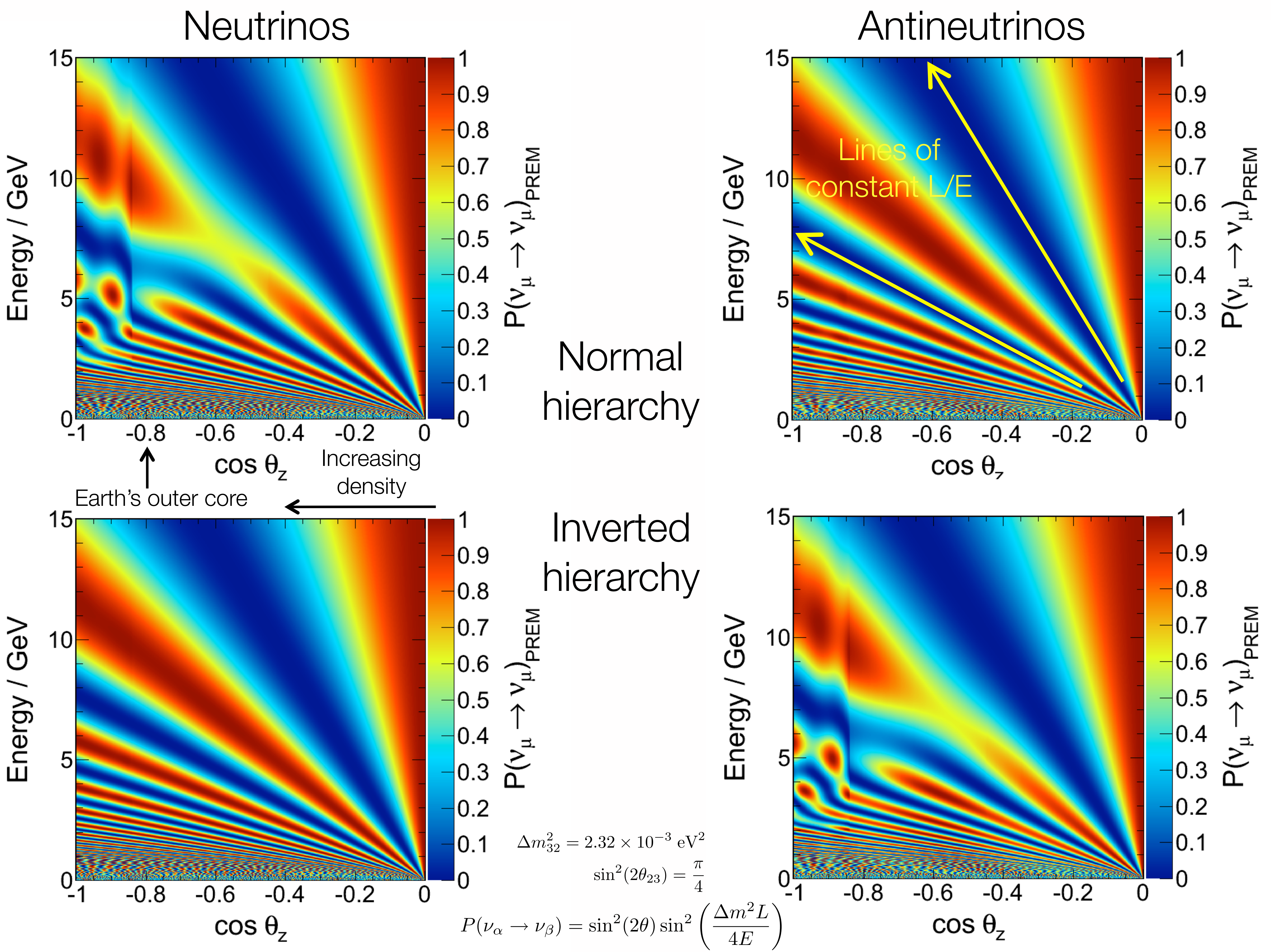
Using atmospheric neutrinos to measure the NMH

Up to 20% differences in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy





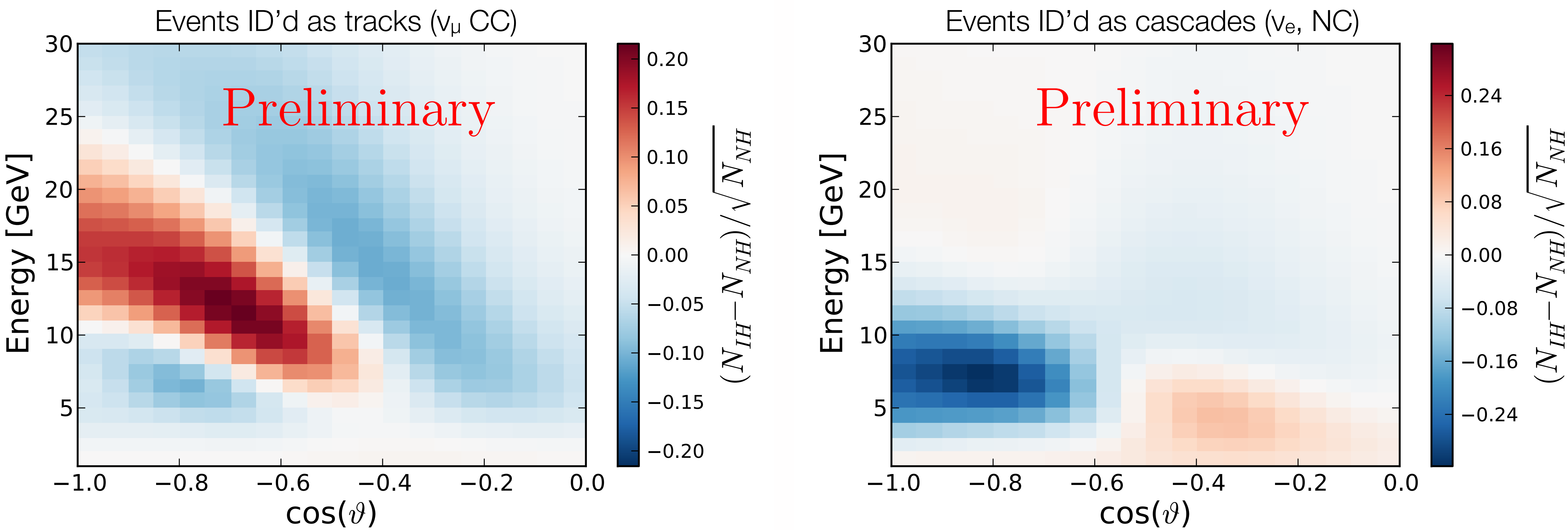




Neutrinos
Antineutrinos
Normal hierarchy
Inverted hierarchy
Energy / GeV
cos θz
P(νμ → νμ)PREM
Lines of constant L/E
Earth's outer core
Increasing density
$\Delta m^2_{32} = 2.32 \times 10^{-3}\ \mathrm{eV}^2$
$\sin^2(2\theta_{23}) = \frac{\pi}{4}$
$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

PINGU and the NMH

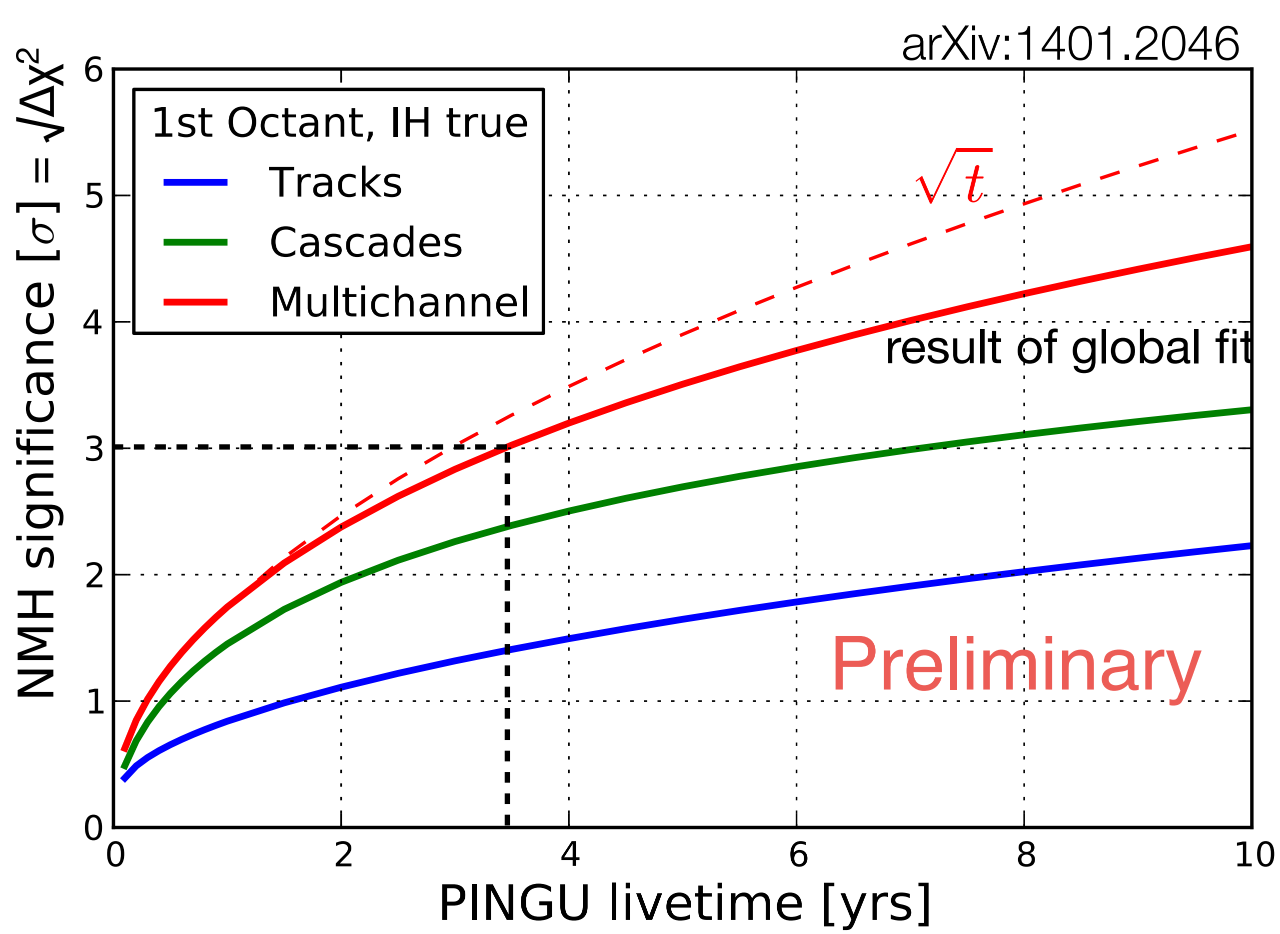
arXiv:1401.2046



- Distinctive (and quite different) hierarchy-dependent signatures are visible in both the track and cascade channels
  - Full MC for detector efficiency, reconstruction, and particle ID included

PINGU and the NMH - predicted sensitivity

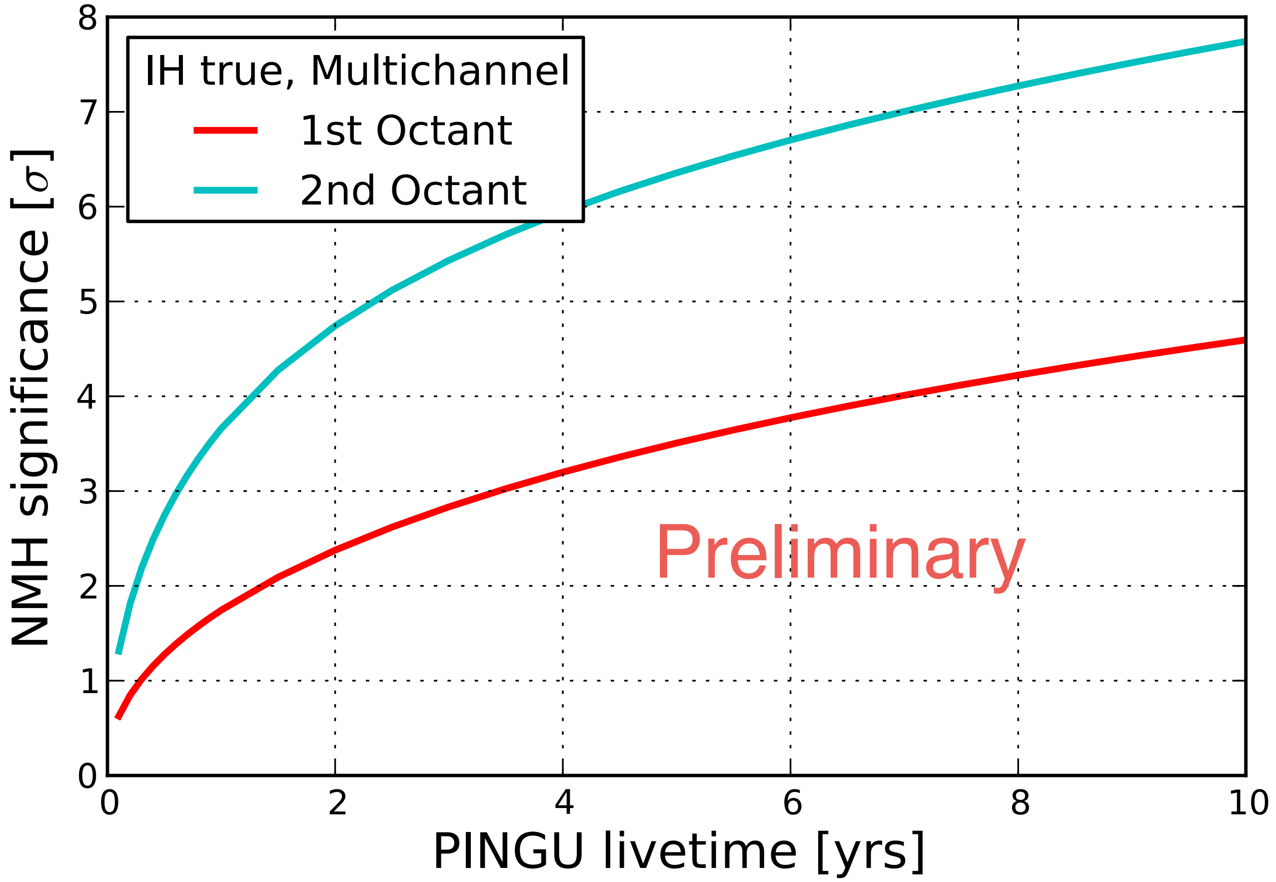
- With baseline geometry, a determination of the mass hierarchy with 3σ significance appears possible with 3.5 years of data
  - Primary estimate uses parametric detector response model based on simulations
  - Vetted against full Monte Carlo studies with more limited statistics and range of systematics
- Optimization of detector geometry & analysis techniques and more detailed treatment of systematics underway



PINGU and the NMH - predicted sensitivity

- With baseline geometry, a determination of the mass hierarchy with 3σ significance appears possible with 3.5 years of data
  - Primary estimate uses parametric detector response model based on simulations
  - Vetted against full Monte Carlo studies with more limited statistics and range of systematics
- Optimization of detector geometry & analysis techniques and more detailed treatment of systematics underway

arXiv:1401.2046

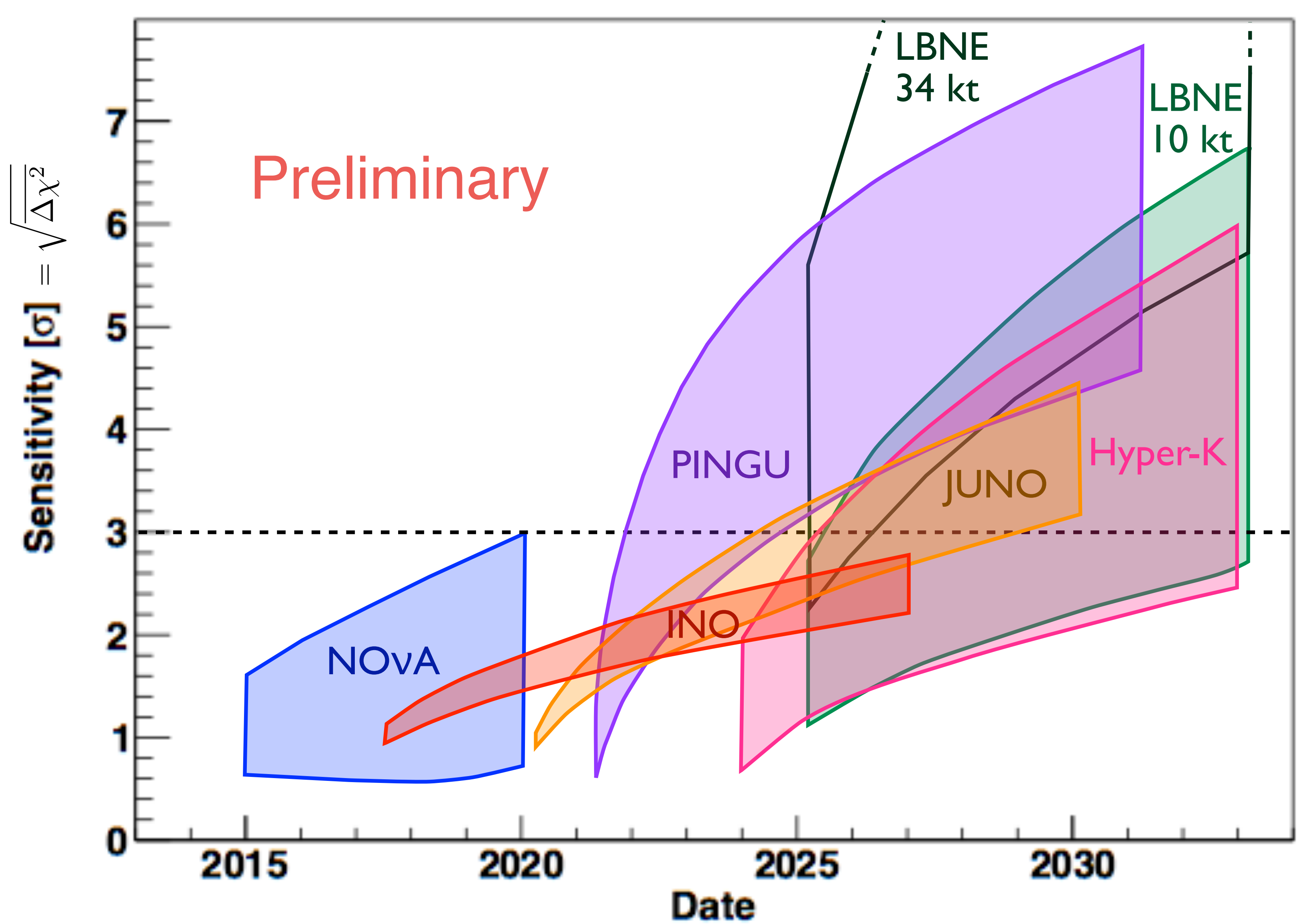


PINGU and the NMH - in broad context

- Several current or planned experiments will have sensitivity to the neutrino mass hierarchy in the next 10-15 years
  - NB: median outcomes shown – large fluctuations possible

after Blennow et al., arXiv:1311.1822

- Widths indicate main uncertainty
  - LBNF/NOvA: δ_{CP}
  - JUNO: σ_E (3.0-3.5%)
  - PINGU/INO: θ_{23} (38.7°–51.3°, 40°–50°)
  - Other projections presented here assume worst-case parameters (1st octant)
- PINGU timeline based on aggressive but feasible schedule



- LBNE from LBNE-doc-8087-v10, Hyper-K from arXiv:1109.3262 (2011), all others from Blennow

Path to PINGU

- Jan 2014 - PINGU Letter of Intent
- May 2014 - P5 decision: "Further development for PINGU is recommended"; Application as IPP project submitted
- Jun 2014 - Submission of CFI IF for PINGU project
- Fall 2014 - US NSF white paper/Early Concept Proposal submitted for review
- Jun 2015 - MREFC (major research equipment and facilities construction) Conceptual Design submission; CFI IF award decision
- Sep 2015 - CDR passed/begin R&RA funding
- Jun 2016 - Preliminary design review
- Jan 2017 - Final design review; start construction remainder CFI IF released
- Dec 2018 - first 8 PINGU strings
- Dec 2019 - next 18 PINGU strings
- Dec 2020 - PINGU complete

IceCube-DeepCore-PINGU and Canada

- The program is (quickly) developing
  - Currently 5 faculty (Alberta, Toronto) @ 2.0 FTE, 1 PDF, 2 PhD students, 4 summer students(~3.5% direct project impact within IceCube)
    - **See talks by Ken Clark, Tania Wood, Sarah Nowicki this week**
  - increasing to 6 faculty @ 3.7 FTE by 2017 (~8% direct impact IceCube; 30% of PINGU)
- Compute Canada resources have permitted key contributions:
  - nearly 1/2 the collaboration's GPU computing
  - ~20% of the collaboration's CPUs
  - generated the full simulation sets for PINGU design studies and DeepCore analyses
  - completed the high energy neutrino search analysis
- Building on established collaboration leadership:
  - Canadian researchers hold positions on the Collaboration, Publications, and Trigger-Filter-Transmission Boards; appointed as convener for the low-energy analysis group; D. Grant appointed co-convener for the PINGU upgrade

IceCube-DeepCore-PINGU and Canada

- Activities primarily supported via NSERC SAP Discovery Grants (renewal NOI to be submitted August 2014)
- CFI IF (in preparation). Full in-kind support secured for calibration and electronics R&D activities (in part at TRIUMF)
  - funding for ~30% of the PINGU optical modules (pending NSF MREFC).

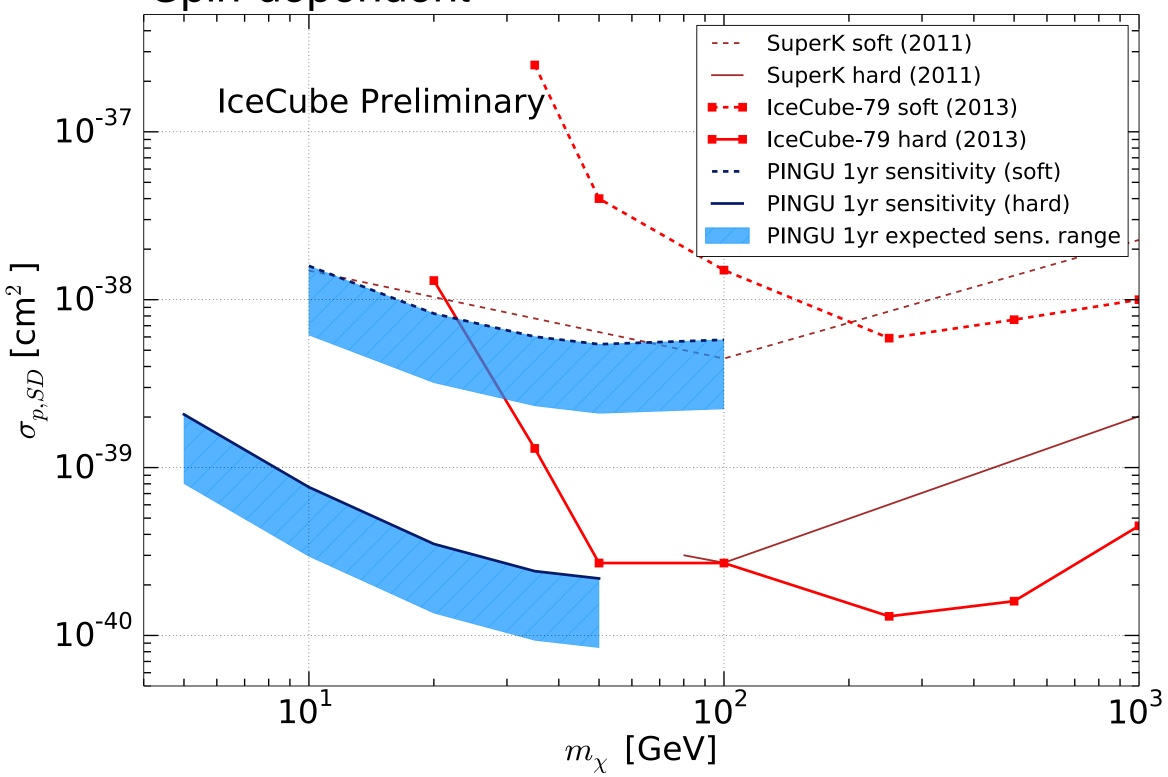
Start date	End date	Source	Value
Apr 2010	Mar 2013	NSERC (SAP Discovery, Individual)	$190,000
Apr 2013	Mar 2014	NSERC (SAP Discovery, Project)	$109,000
Jan 2014	Dec 2014	Compute Canada (RAC)	$975,936
Apr 2014	Mar 2015	NSERC (SAP Discovery, Project)	$180,000
Sep 2015	Dec 2018	CFI IF (in preparation)	$12,200,000

Summary and Outlook

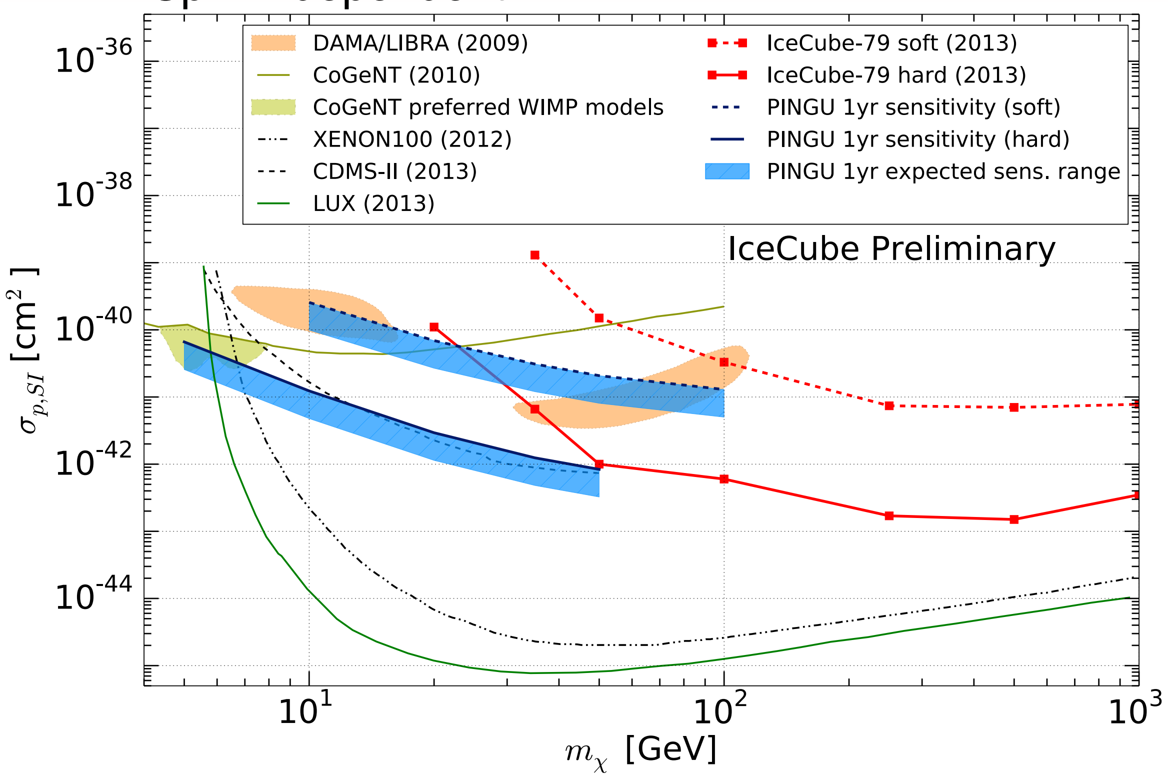
- IceCube and DeepCore paved the way: demonstration of a prolific low-energy neutrino physics in the Antarctic ice with leading sensitivity in the indirect dark matter search and a robust atmospheric neutrino oscillation programs of IceCube. A rich on-going analysis program.
- PINGU is being optimized
  - String and optical module placement has a fairly broad minimum for the NMH sensitivity.
  - 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.
- Beyond the atmospheric neutrino measurements, PINGU will increase the sensitivity to the low-mass indirect WIMP searches, supernova neutrinos, Earth tomography…

PINGU indirect dark matter search

Spin-dependent



Spin-independent



Summary and Outlook

- PINGU advantages include:
  - Use of the similar hardware and deployment techniques as IceCube would significantly reduce project risk
  - Could be quick, dependent on funding (2 years of procurement and fabrication; 2-3 years of deployment)
  - Is a natural part of a Next Generation IceCube Observatory (high energy extension, surface veto array). P5 final draft report "...and we encourage continued work to understand systematics. PINGU could play a very important role as part of a larger upgrade of IceCube, or as a separate upgrade, but more work is required."
  - NSF MREFC, and international partner proposals are now in preparation (still very early days of detector development; interested? come visit us)
- PINGU as a potential stepping stone: acting as a testbed for new photodetectors could lead to a multi-megaton fiducial detector (MICA) reaching a O(10 - 100 MeV) in the ice (supernova neutrinos, very low-mass WIMP searches, (potentially) proton decay).

The IceCube–PINGU Collaboration

International Funding Agencies

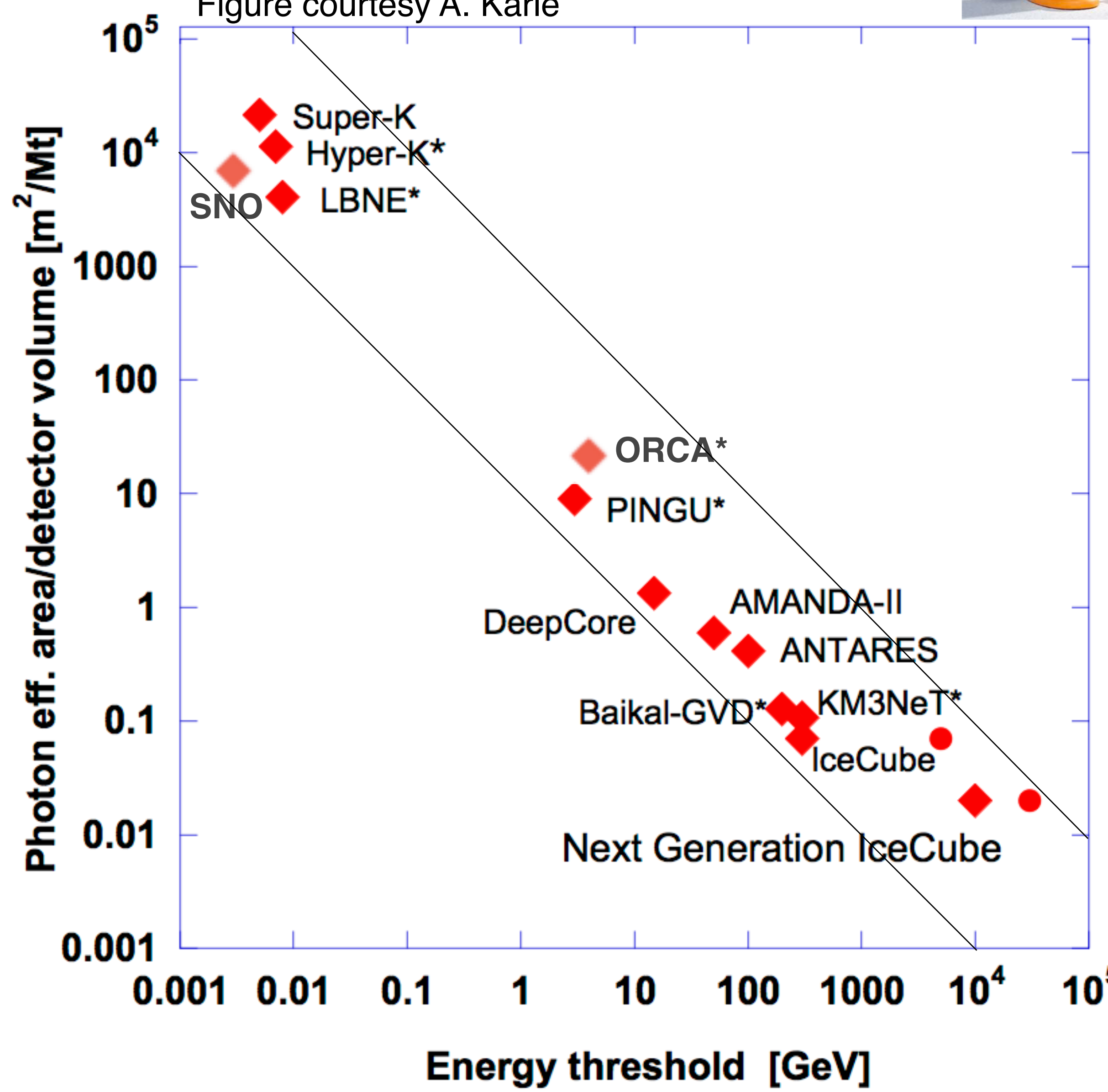
Fonds de la Recherche Scientifique (FRS–FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
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)

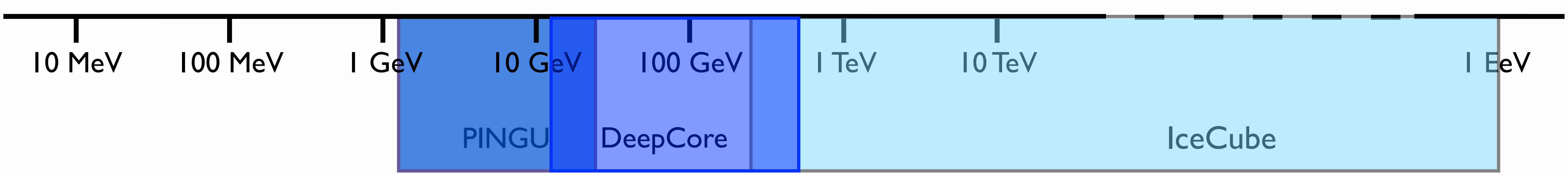
Backup slides

IceCube-DeepCore-PINGU

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing
- Add 40 strings (baseline target)
  - ~20m string spacing
  - 3-5m DOM spacing
  - ~20x higher photocathode density

Figure courtesy A. Karle

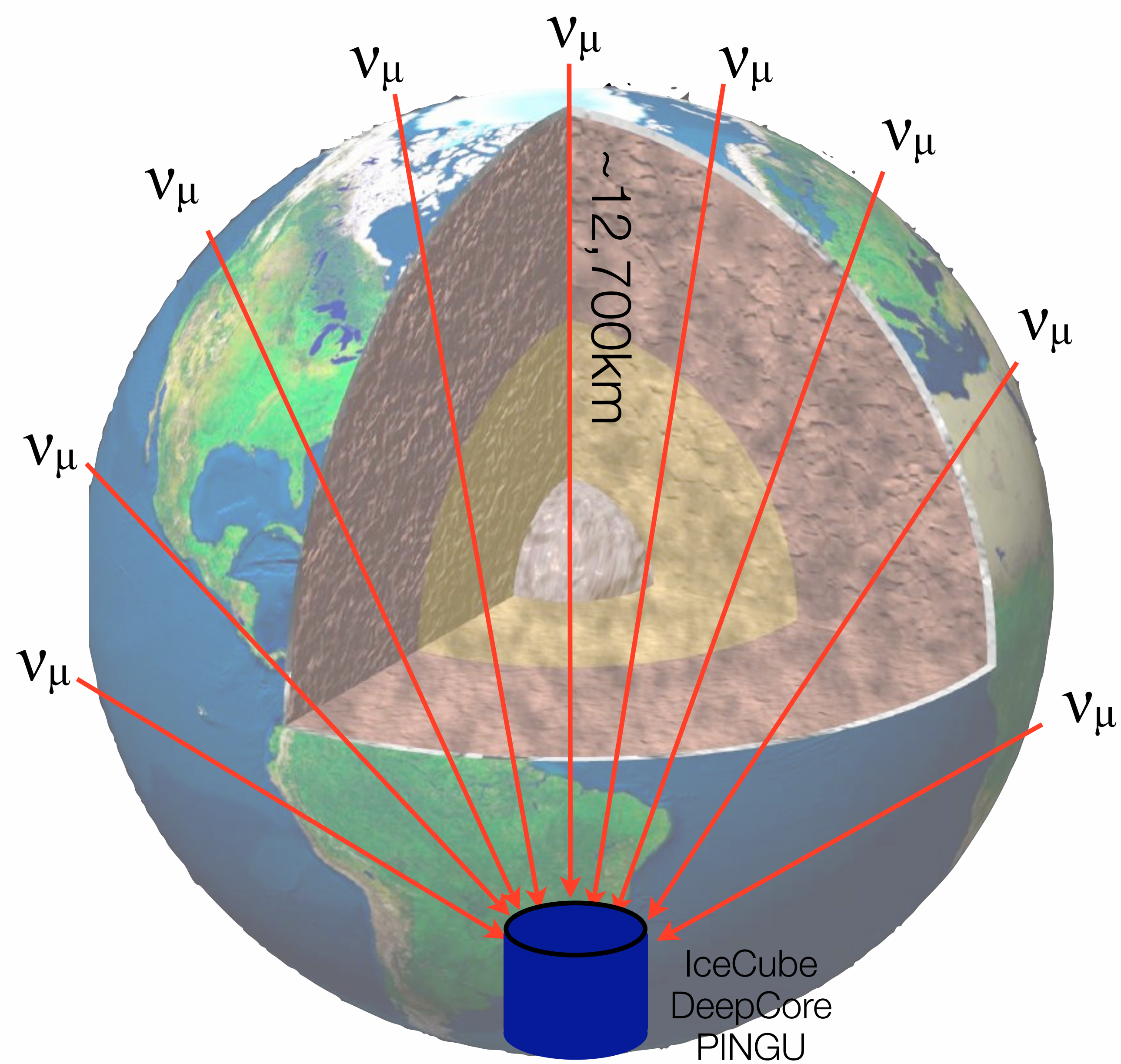




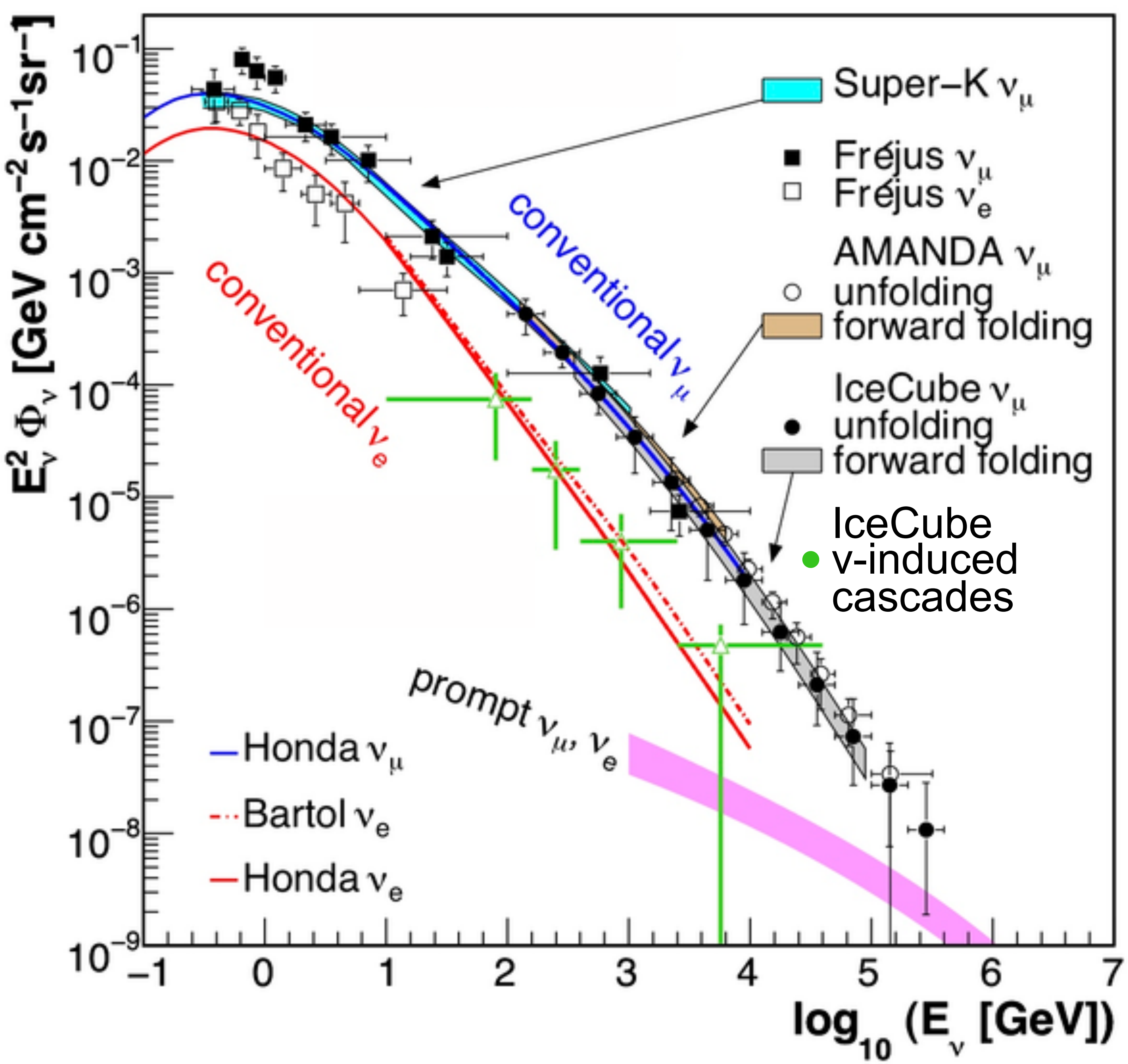
digital optical module - DOM

Oscillations with Atmospheric Neutrinos

- 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
  - Comparison of observations from different baselines and energies is crucial for controlling systematics
  - Essentially, a generalization of the up-down ratio approach



PINGU's Atmospheric ν Signal

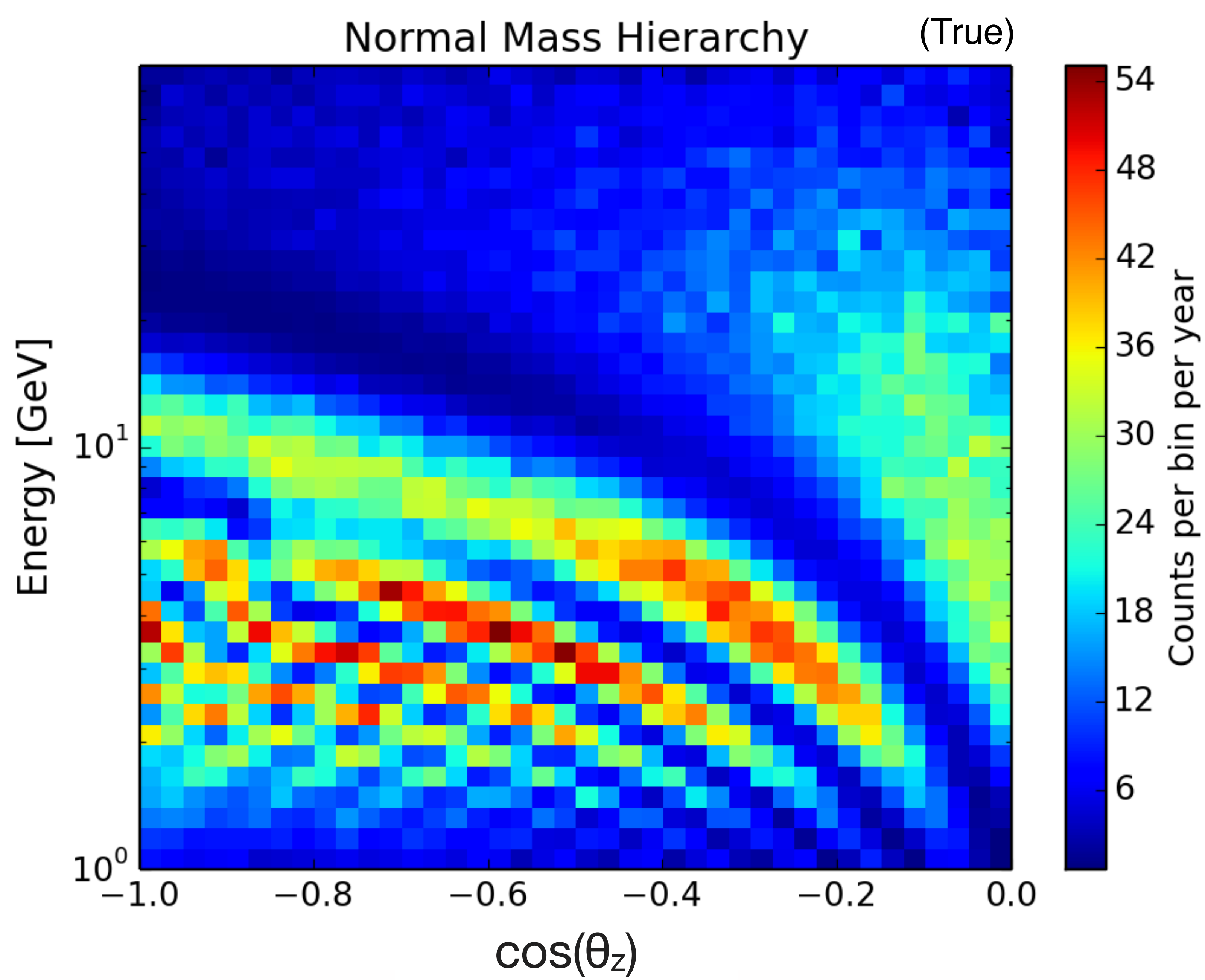


N(Events) Expected in PINGU per Year		
	Trigger Detector	Pass Baseline Analysis
ν_e CC	52k	26k
ν_μ CC	86k	35k
ν_τ CC	6.4k	2.7k
ν_x NC	17k	7.9k

1 GeV < E < 80 GeV

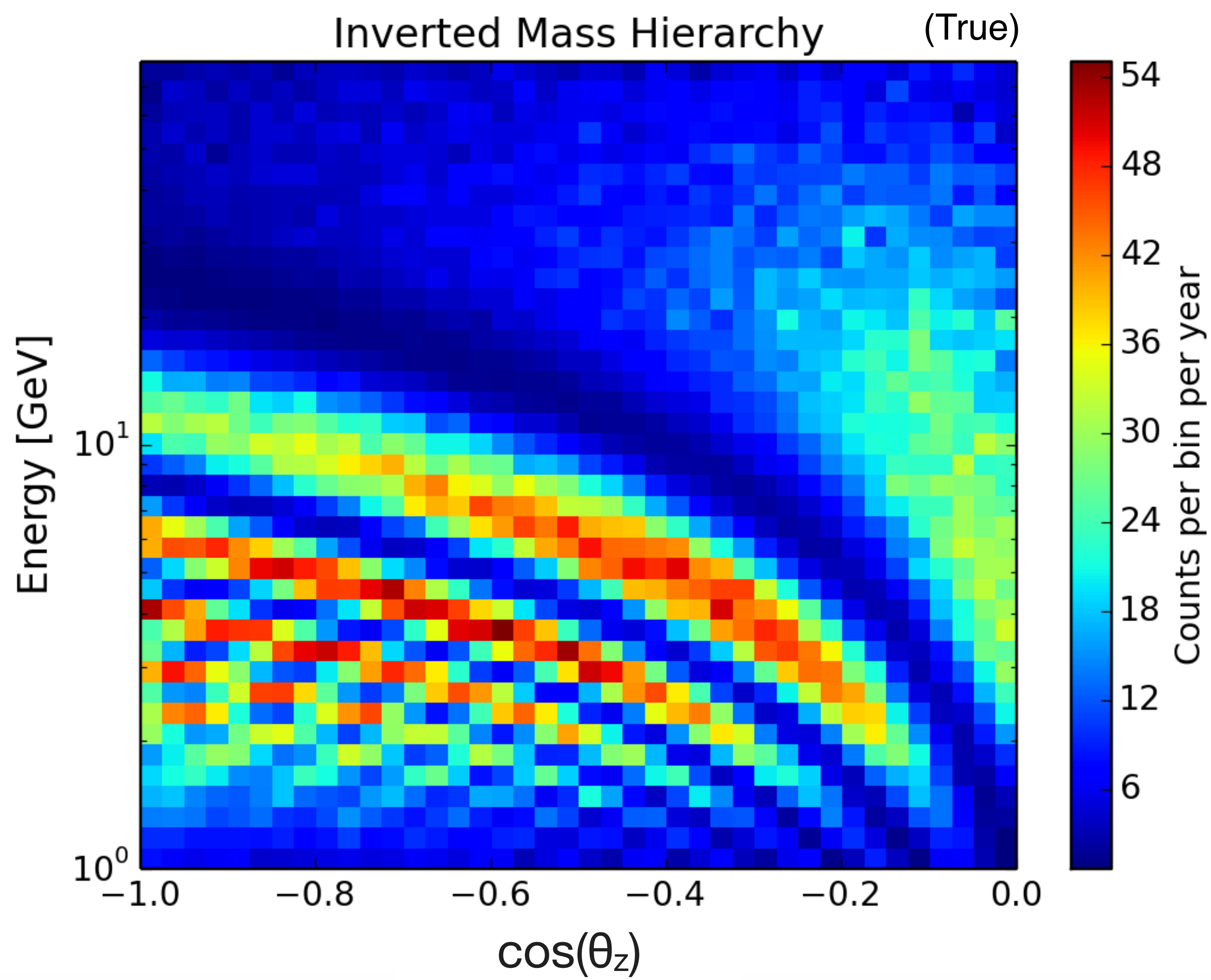
PINGU and the NMH

- Cannot distinguish ν from $\bar{\nu}$ directly – rely instead on differences in fluxes, cross sections (and kinematics)
- Differences clearly visible in expected atm. muon ($\nu + \bar{\nu}$) rate even with 1 year's data
    - Note: detector resolutions not yet included here



PINGU and the NMH

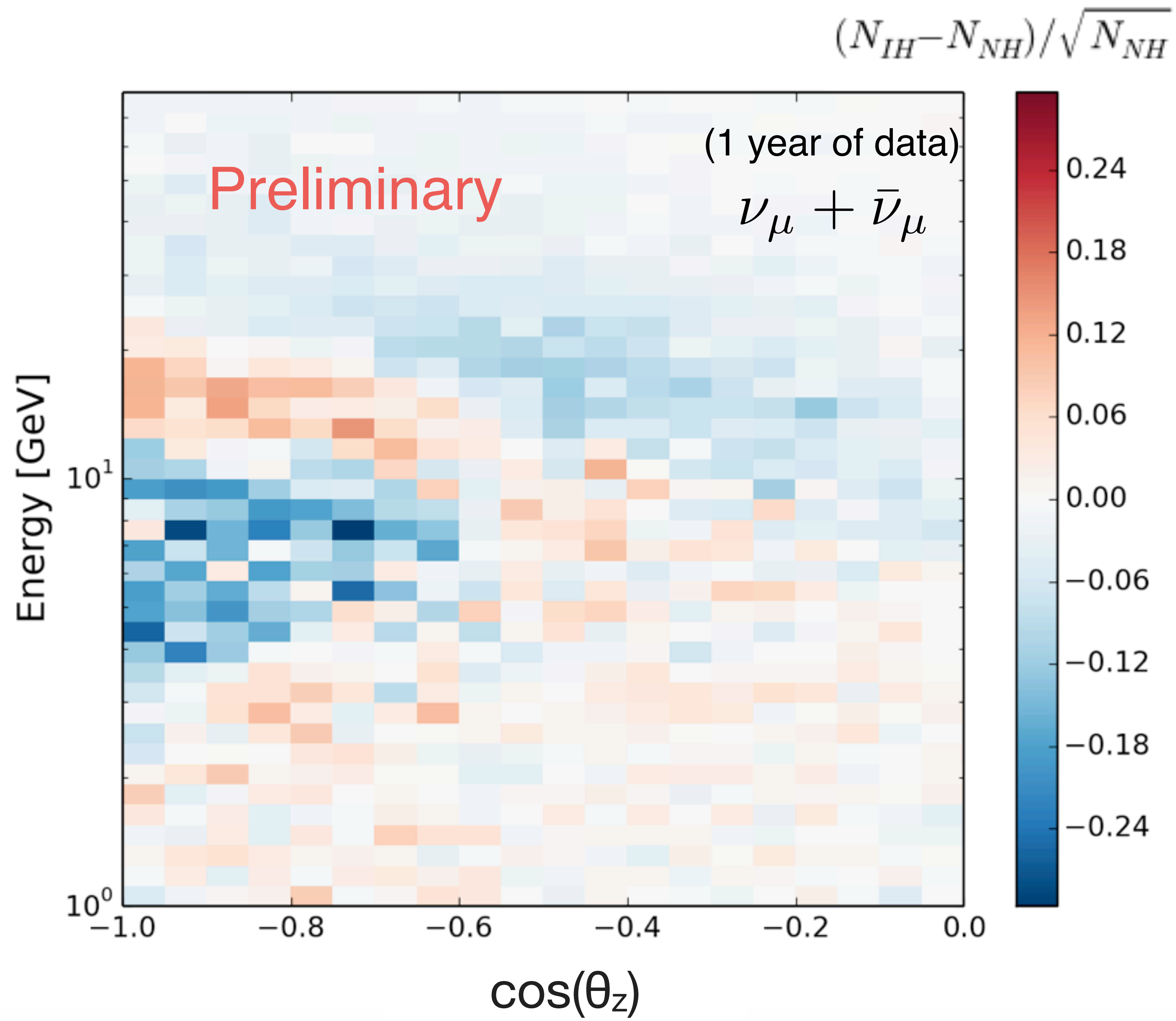
- Cannot distinguish ν from $\bar{\nu}$ directly – rely instead on differences in fluxes, cross sections (and kinematics)
- Differences clearly visible in expected atm. muon ($\nu + \bar{\nu}$) rate even with 1 year's data
  - Note: detector resolutions not yet included here



PINGU and the NMH

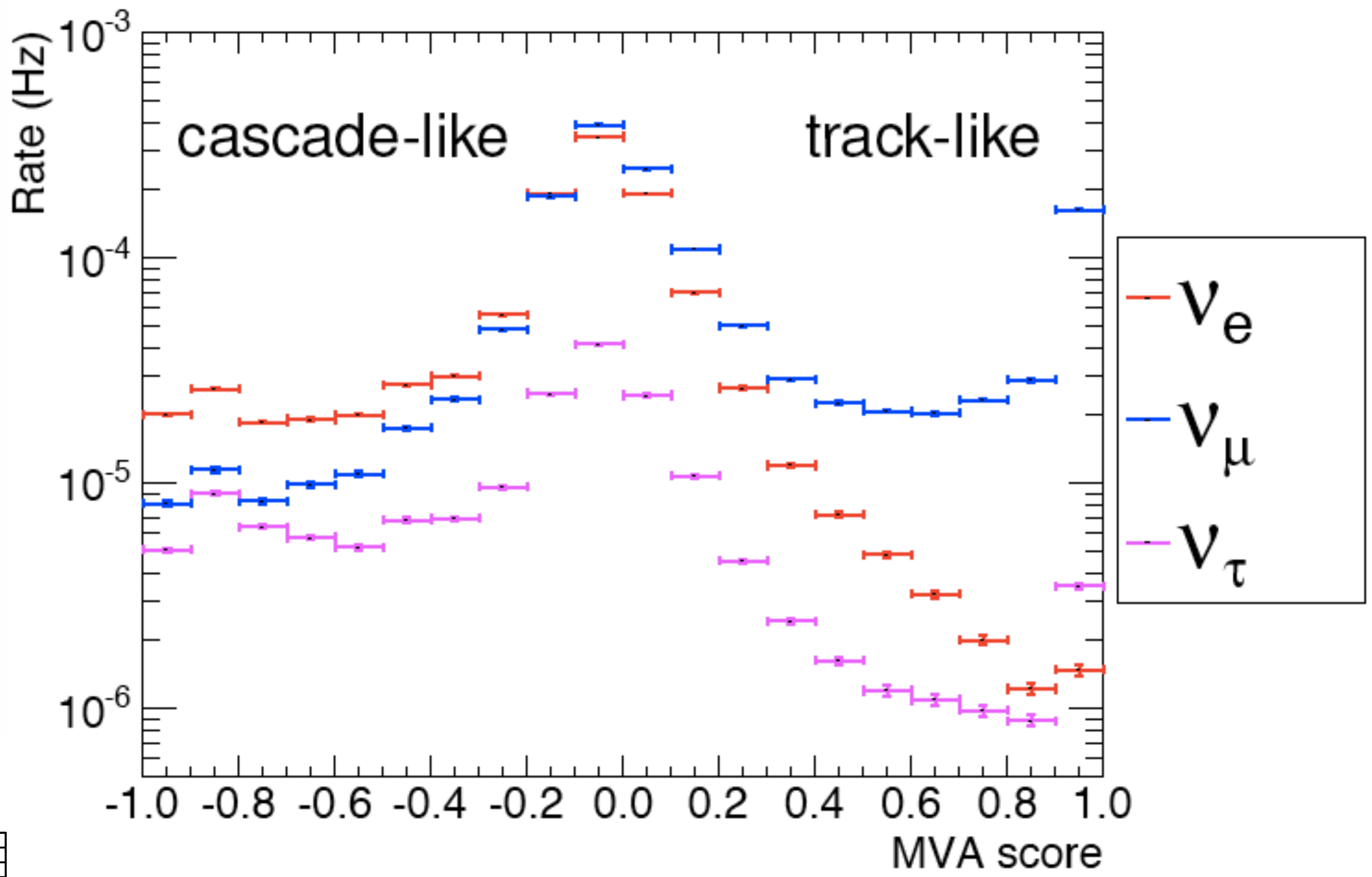
- Once detector resolutions are included the signature of the hierarchy is apparent by looking at the pattern of expected excesses and deficits in the E vs. cos(θ_z) plane
  - Structure of the pattern gives some protection against systematics
  - Note: reconstructions included in these plots, but not yet particle ID

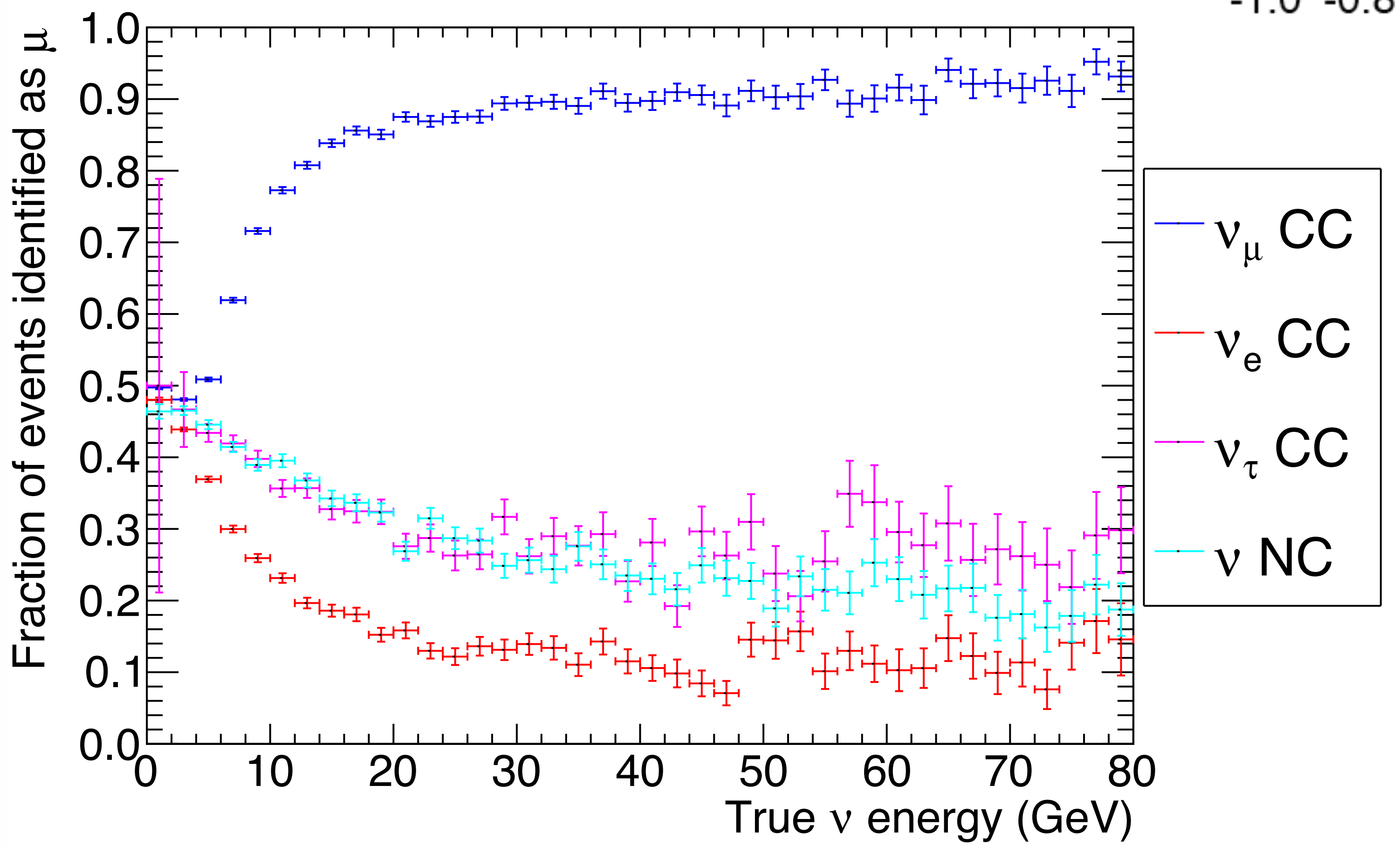
following JHEP, 2013(02):, pp. 1-39



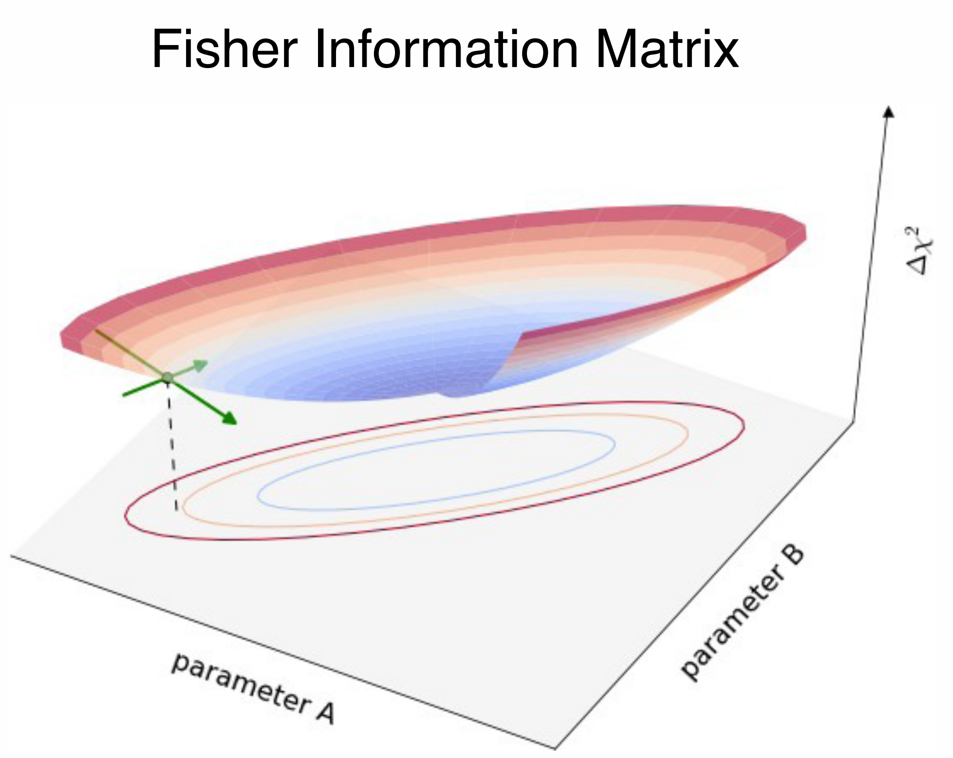
PINGU Particle ID

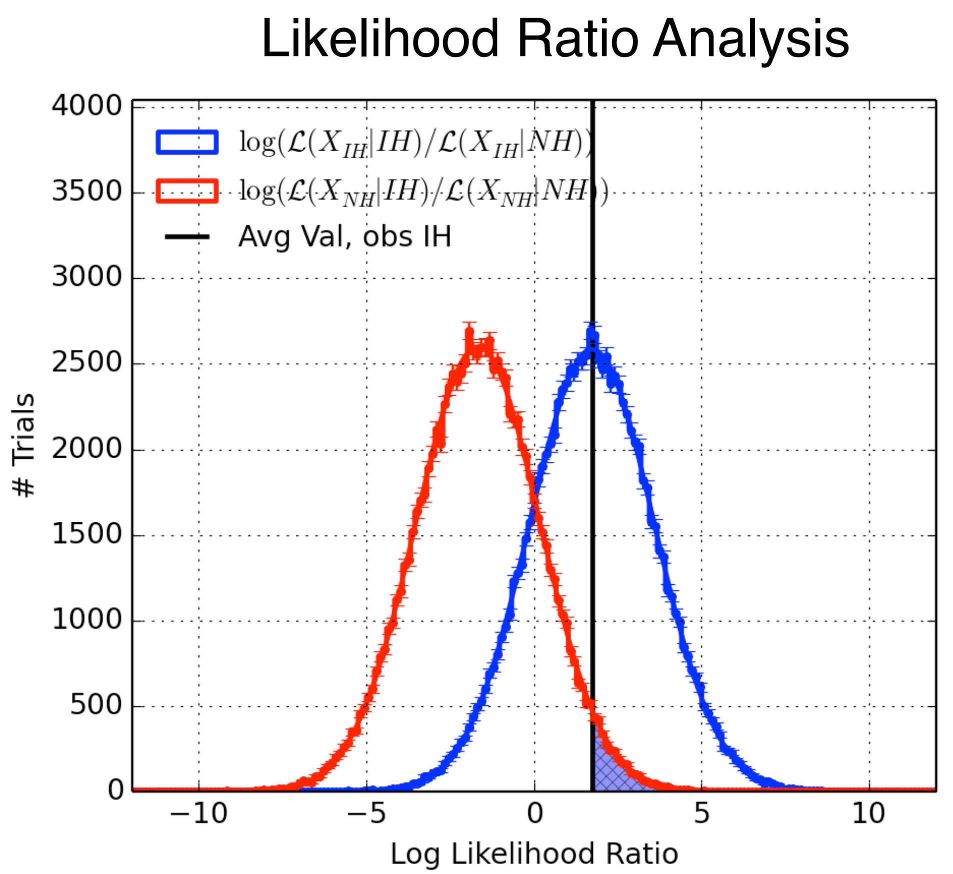
- ν_μ CC events distinguishable by the presence of a muon track
  - Distinct signatures observable in both track (ν_μ CC) and cascade (ν_e and ν_τ CC, ν_x NC) channels





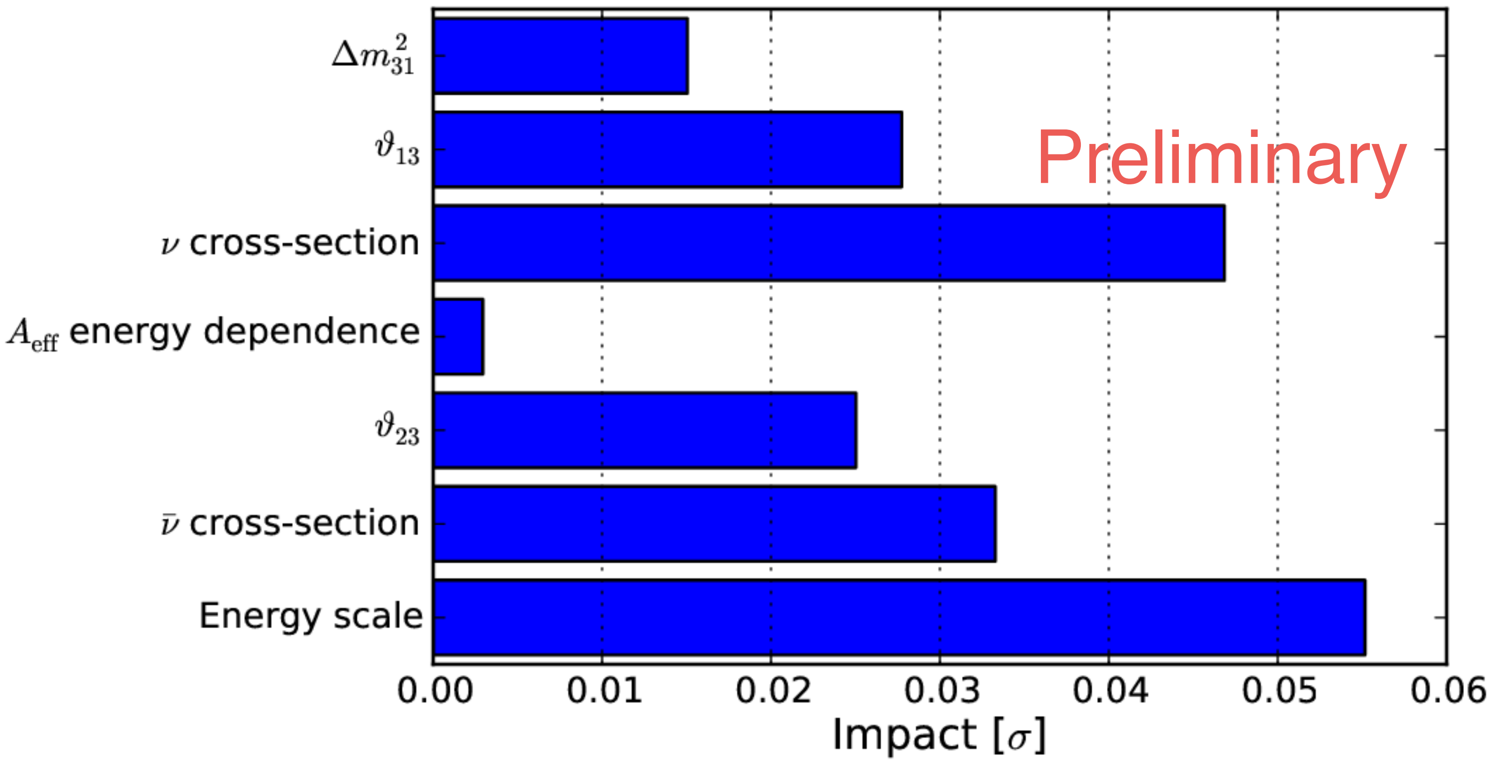
PINGU and the NMH - extracting the sensitivity





- Estimations from the full simulation operating on event histograms in Energy and cos(zenith)
  - Fast evaluation using the Fisher Information Matrix (FIM) where the gradients at each point fully describe the parabolic minimum (invert and obtain the full covariance matrix for the experiment
  - Full analysis from pseudo data sets applied as templates; LLR provides degree of agreement between pseudo set and one hierarchy vs. the other.
  - The Likelihood distributions are fit well by Gaussians; the two methods agree

PINGU and the NMH - applying the systematics



Parameter	Description
Δm^2_{31}, ϑ_{23}, ϑ_{13}	Oscillation parameters
ν / $\bar{\nu}$ cross-section	Cross-section/flux normalization (fully degenerate)
A_{eff} energy dependence	Degenerate with spectral index of atmospheric flux
Energy scale	E_{reco}/E_{true}

- Strongest impact from the Energy Scale and cross-section normalization, δ_{CP} has a minimal effect.
- Additional systematics currently being incorporated:
  - Particle ID performance
  - Cross-section details
  - Ice Model

PINGU Digital Optical Module (PDOM)