Neutrino Oscillations with IceCube DeepCore and PINGU

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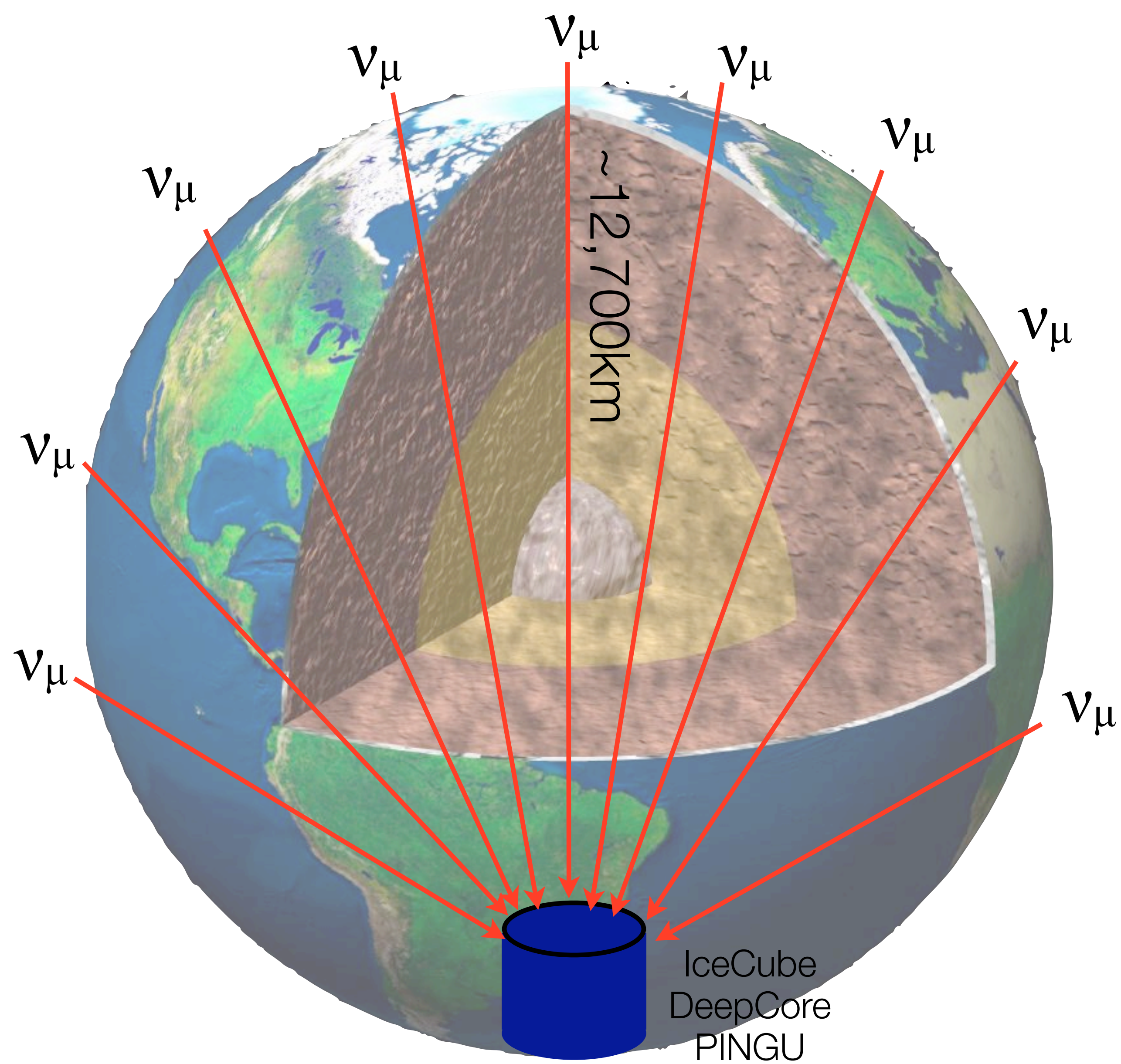
ICECUBE

PRECISION ICECUBE NEXT GENERATION UPGRADE

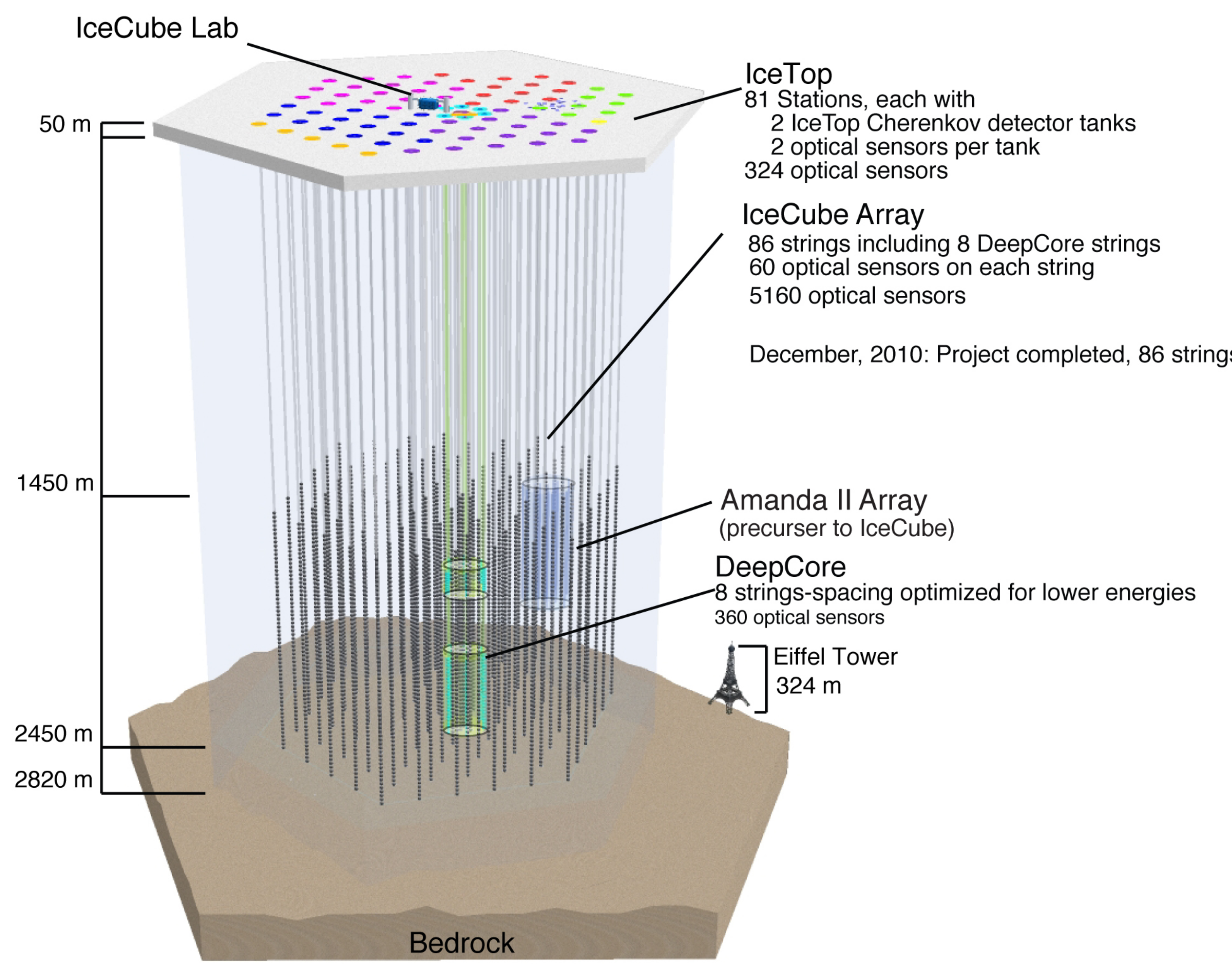
Oscillations of Atmospheric Neutrinos

- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects below ~10-20 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



The IceCube Neutrino Observatory

- Original IceCube design focued on neutrinos with energies above a few hundred GeV
- DeepCore provides reduced volume with threshold ~10 GeV



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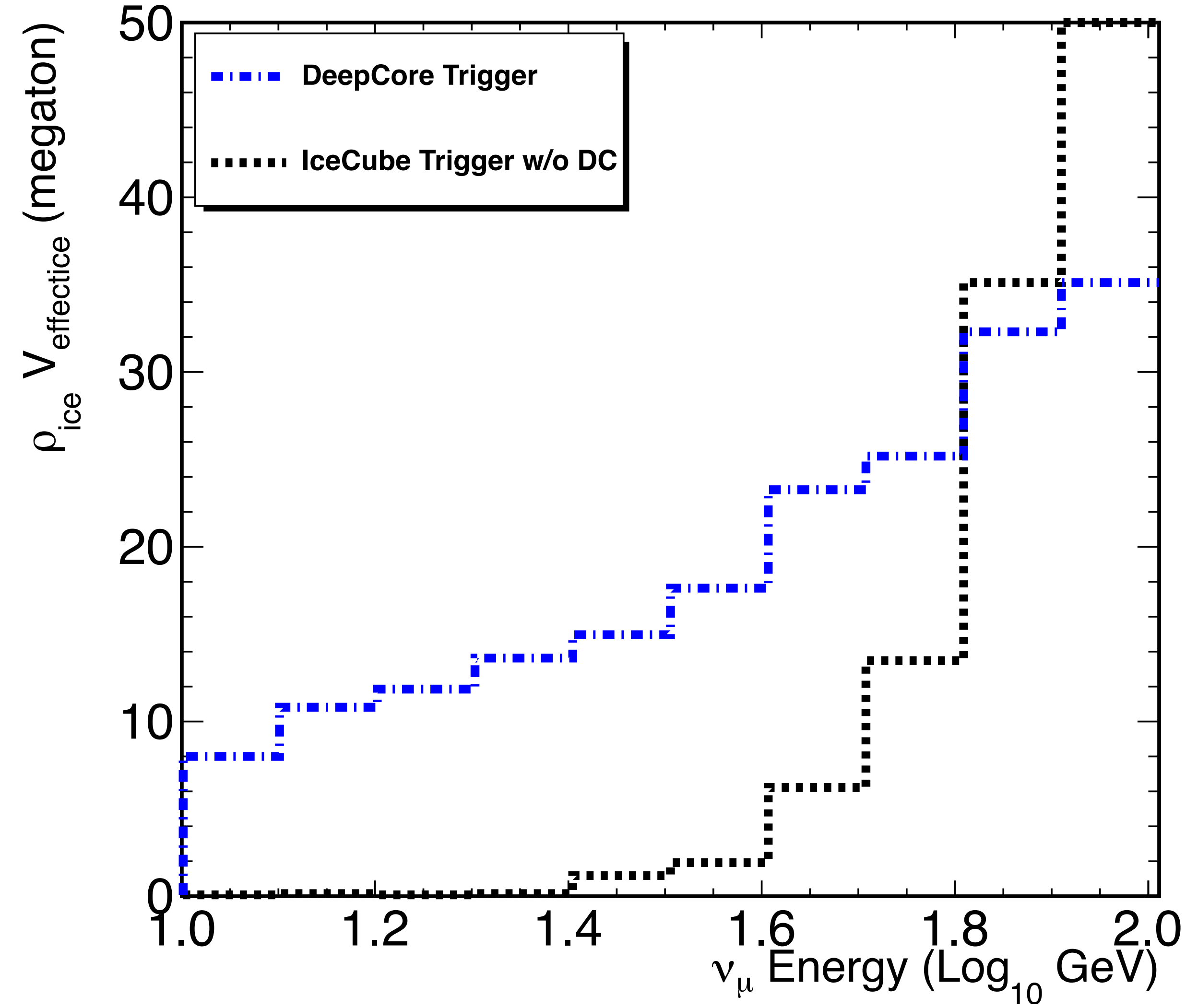
  - Higher efficiency far outweighs reduced geometrical volume
  - Note: comparison at trigger level – analysis efficiencies not included (typically ~10%)



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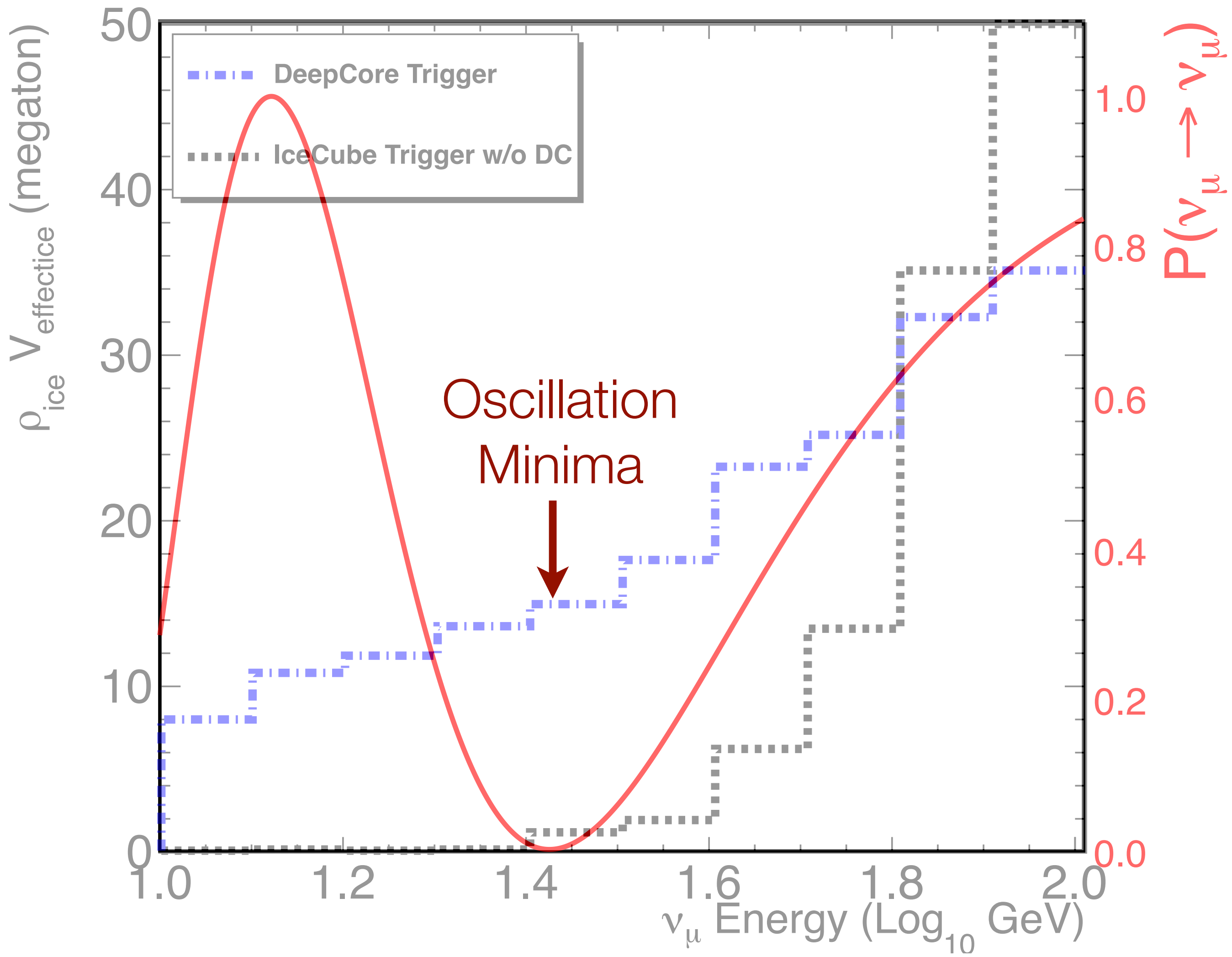
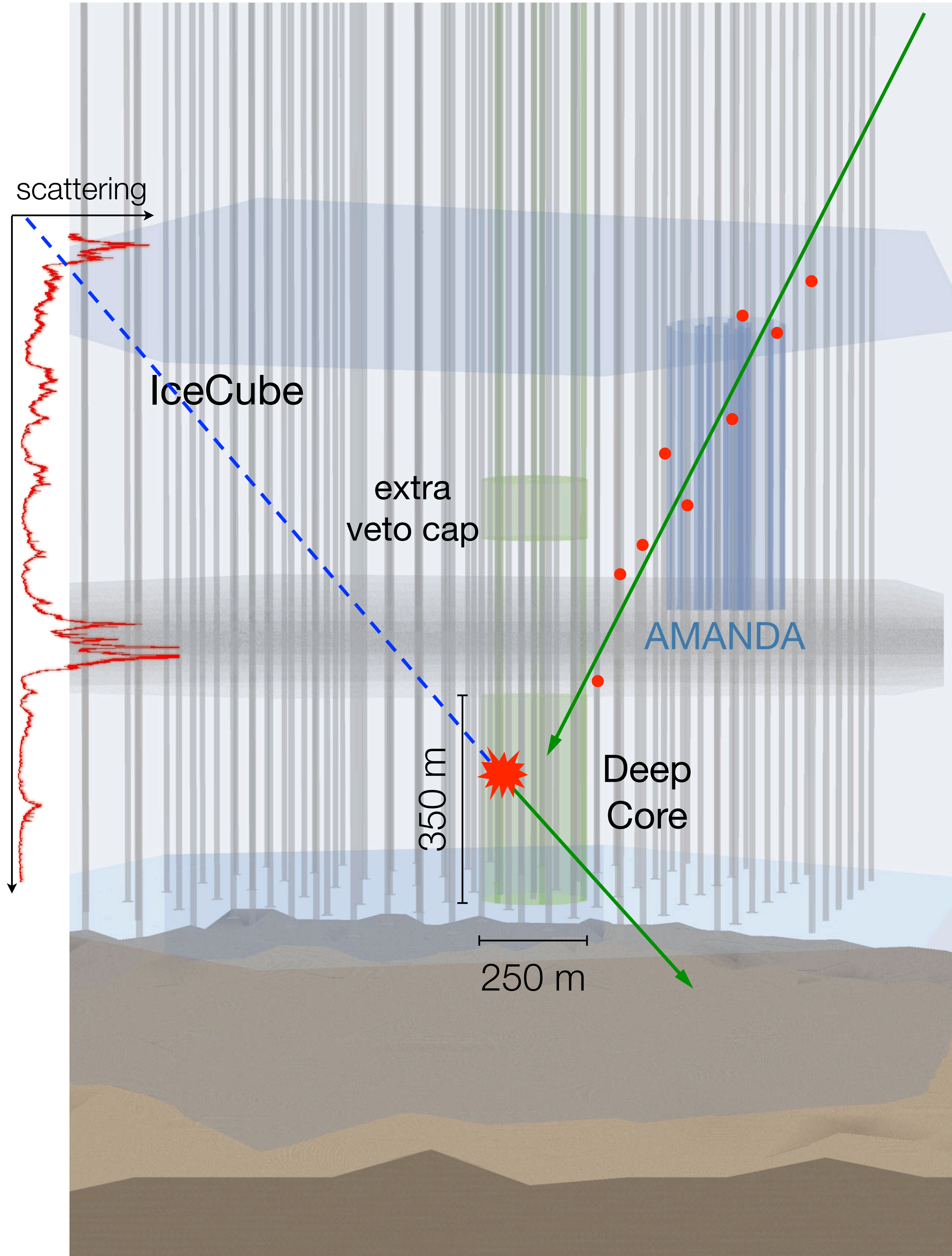


- $\mathcal{O}(10^5)$ atmospheric neutrino triggers per year, $\mathcal{O}(10^4)$ in final data sets

IceCube DeepCore

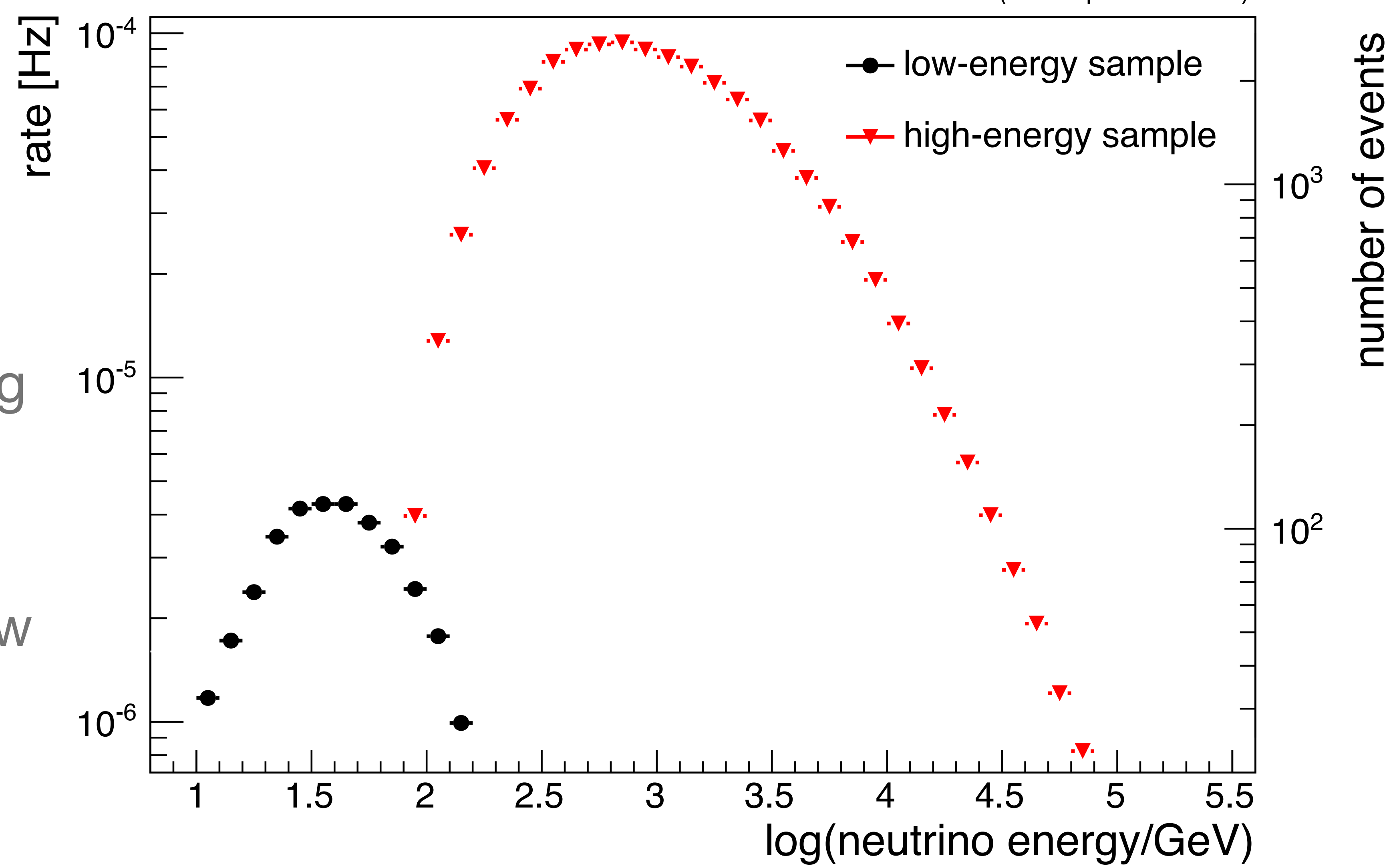
- A more densely instrumented region at the bottom center of IceCube
  - Eight special strings plus 12 nearest standard strings
  - High Q.E. PMTs
  - ~5x higher effective photocathode density
- In the clearest ice, below 2100 m
  - $\lambda_{atten} \approx$ 45-50 m
- IceCube provides an active veto against cosmic ray muon background (around 10^6 times atmospheric neutrino rate)



Muon Disappearance – First Analysis

- Compare zenith-dependent response of standard IceCube muon analysis (high energy) to a modified version for DeepCore
  - Look for oscillation signature in event rate suppression at low energies
  - Detector systematics reduced by comparing HE and LE rates
  - Based on traditional muon analysis, no new techniques designed for DeepCore – lower efficiency accepted

arXiv:1305.3909 (accepted PRL)



Muon Neutrino Disappearance

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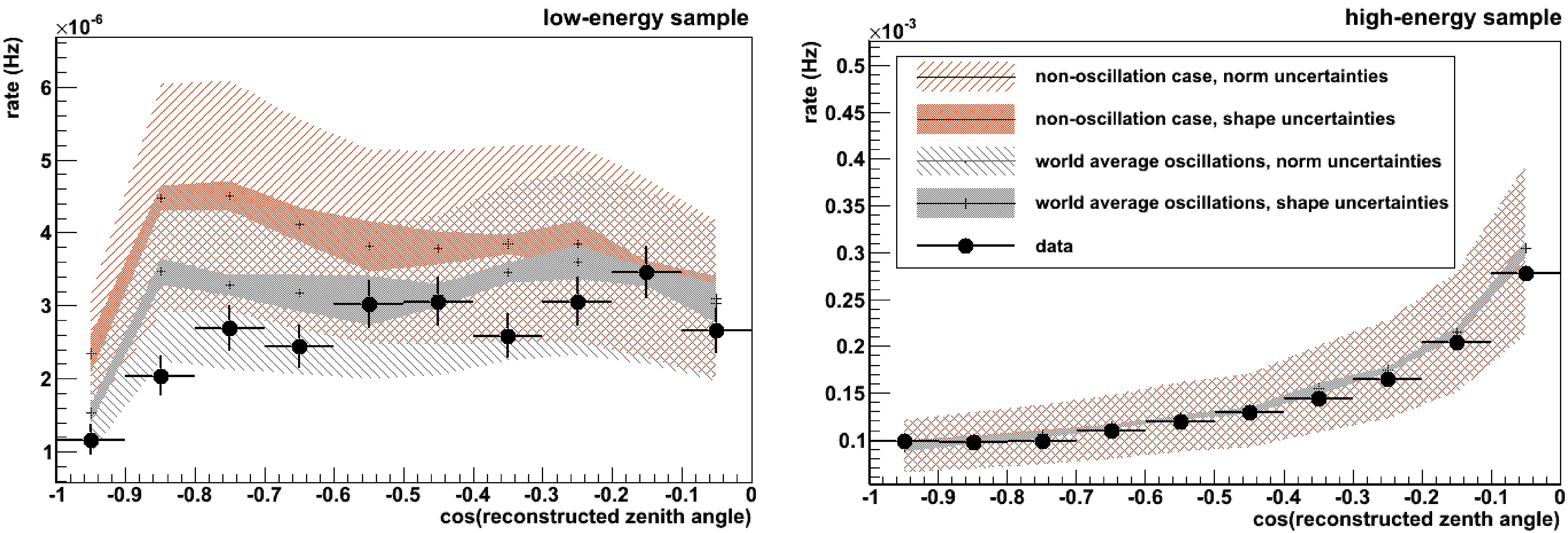
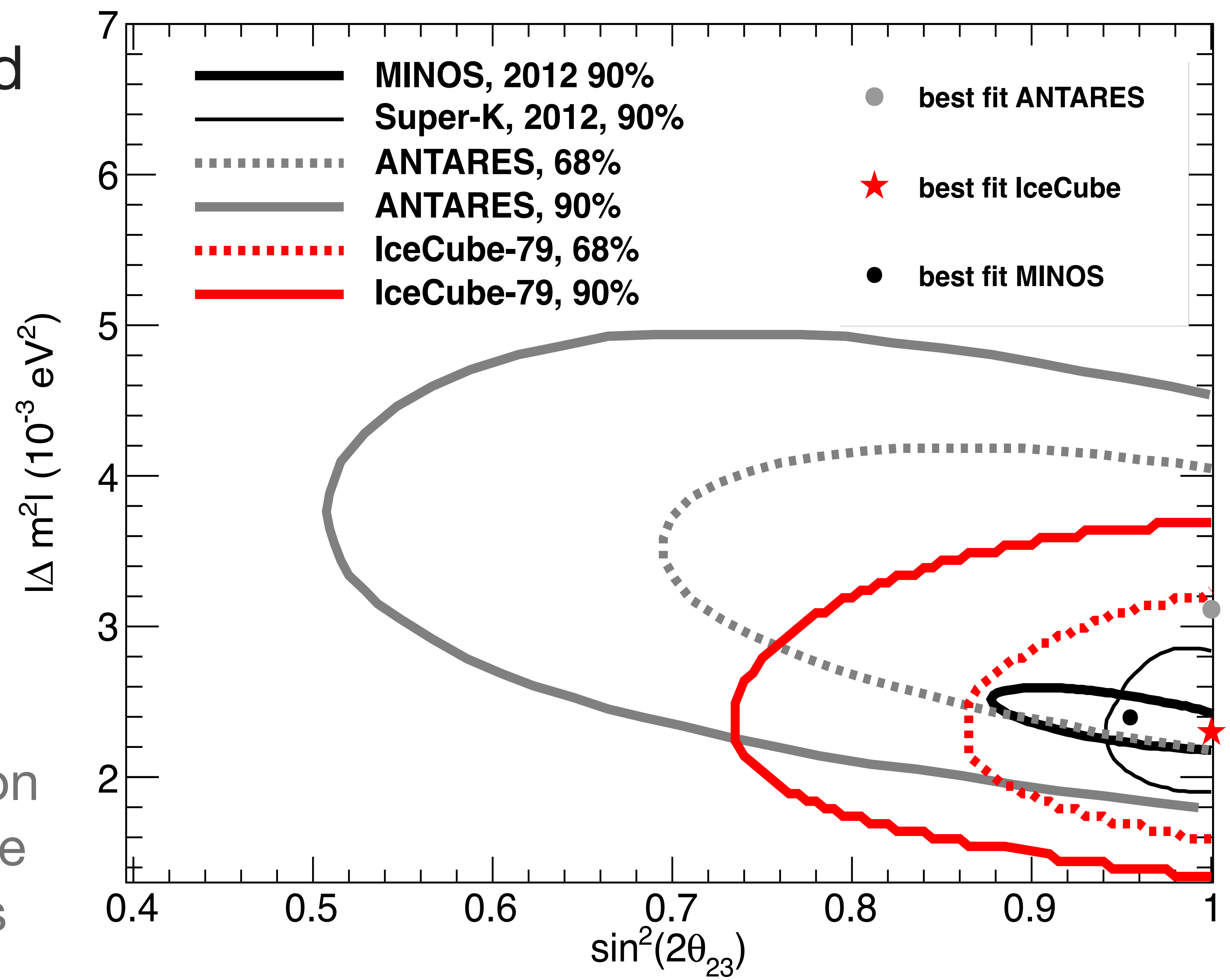


Statistically significant angle-dependent suppression at low energy, high energy sample provides constraint on uncertainties in simultaneous fit

- Shaded bands show range of uncorrelated systematic uncertainties; hatched regions show overall normalization uncertainty

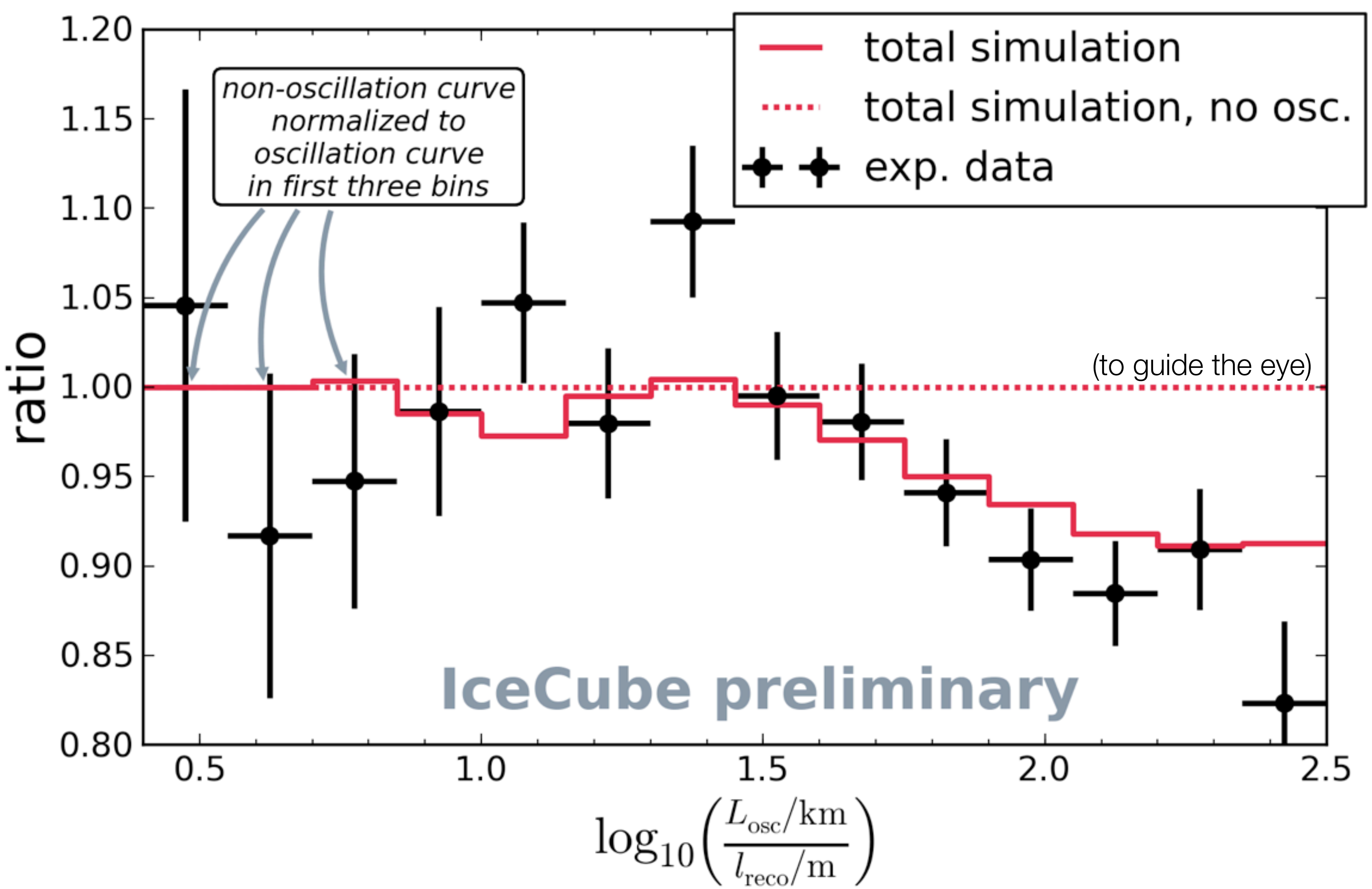
Muon Neutrino Disappearance

- Oscillation parameter allowed regions extracted from zenith distributions
  - Systematics included
- Excellent agreement with world average measurements (with large uncertainties)
  - Potential for significant improvement with inclusion of energy estimators, more advanced reconstructions and event selections



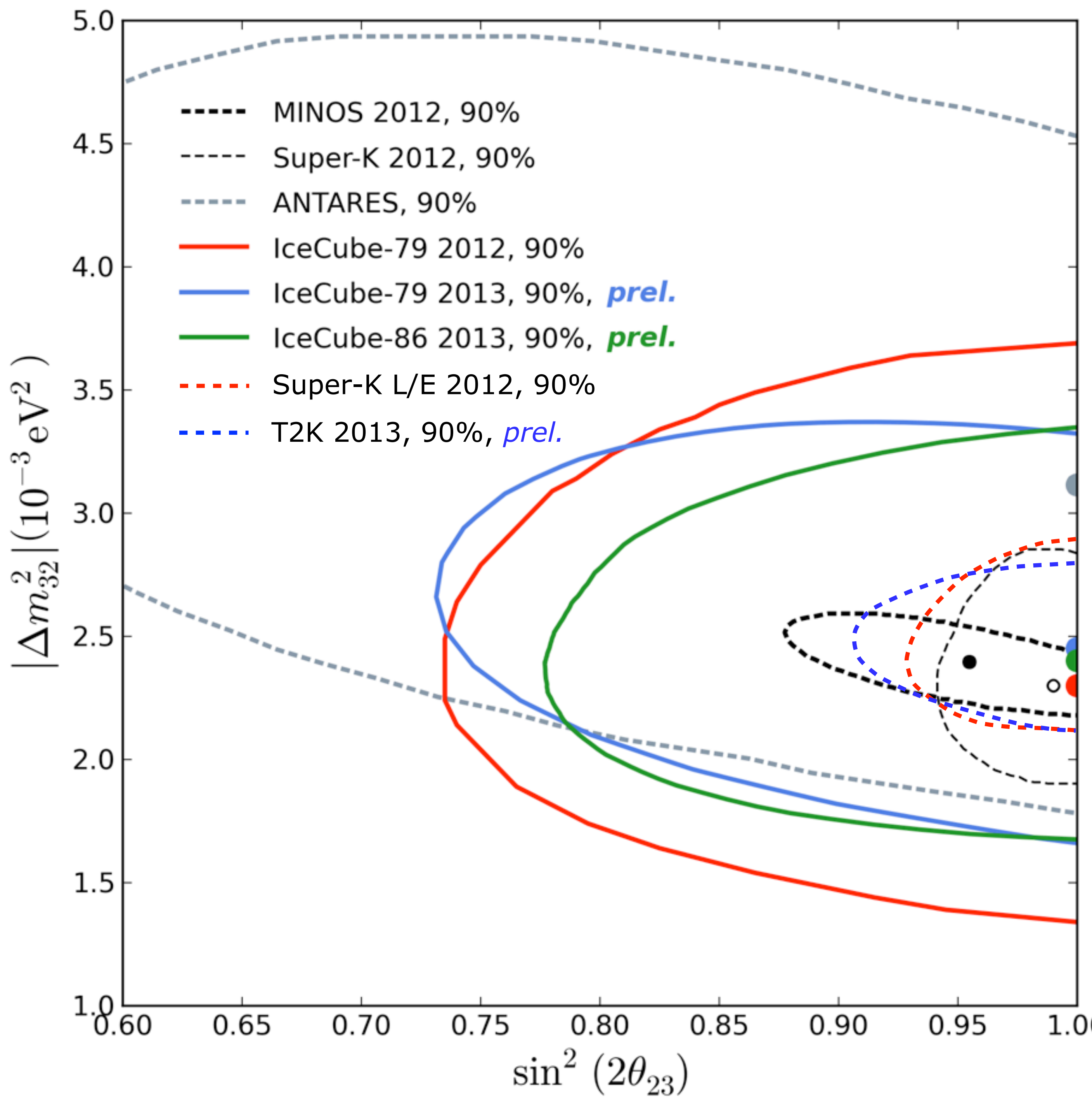
Measuring Flux Modulation due to Oscillations

- Wide range of baselines and energies observed permits marginalization over nuisance parameters
  - Theoretical uncertainties
  - Detector systematics
- Actual analysis is done in 2D, but difficult to visualize
  - Projected here onto reconstructed L/E for illustration



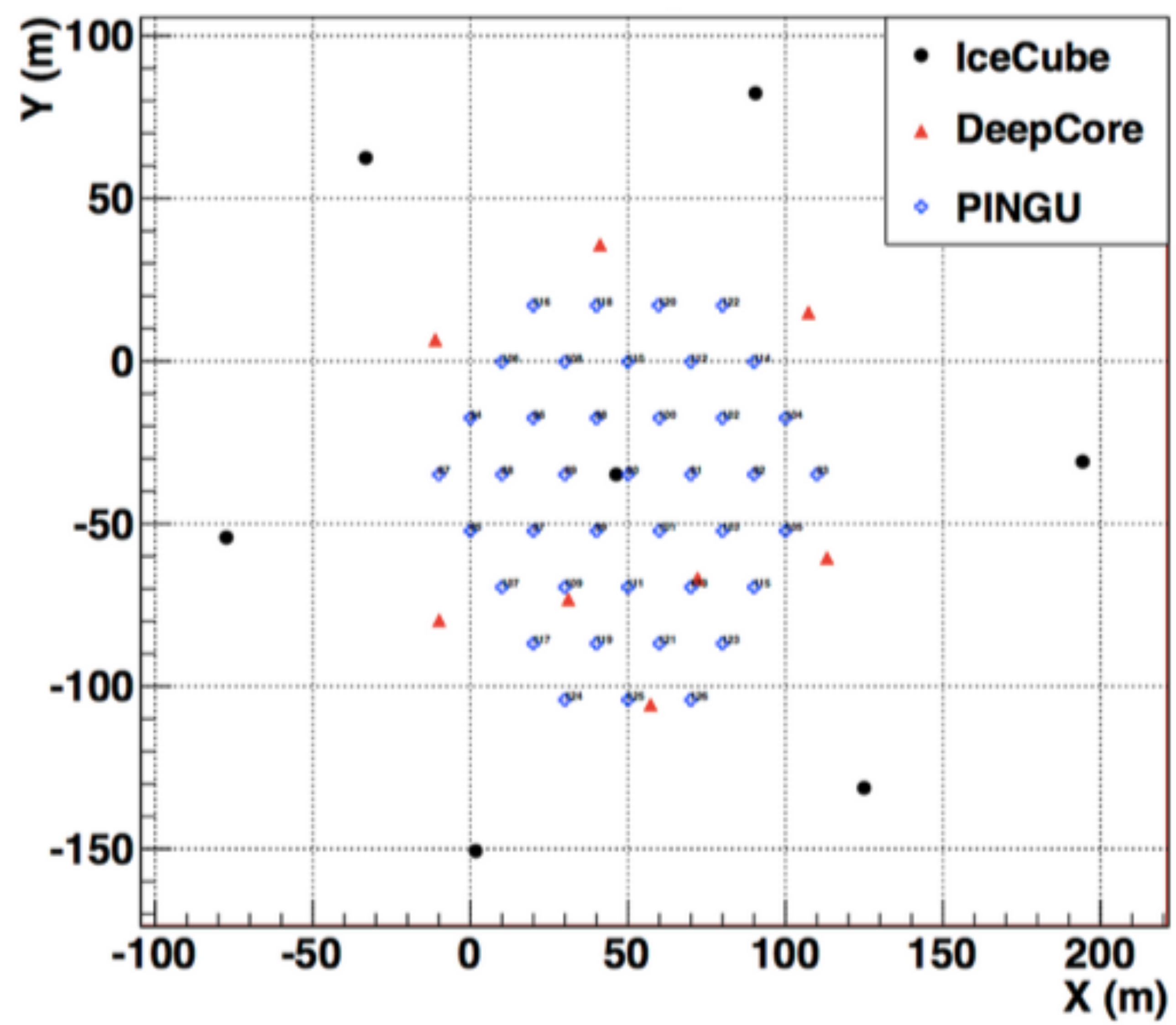
Coming Improvements

- First two-dimensional analyses (energy and angle) coming soon
  - Still based on single year data sets – focus now on technique development
- Multiyear results also in the works
  - Estimated sensitivity for several years is encouraging, even without further improvements on systematics

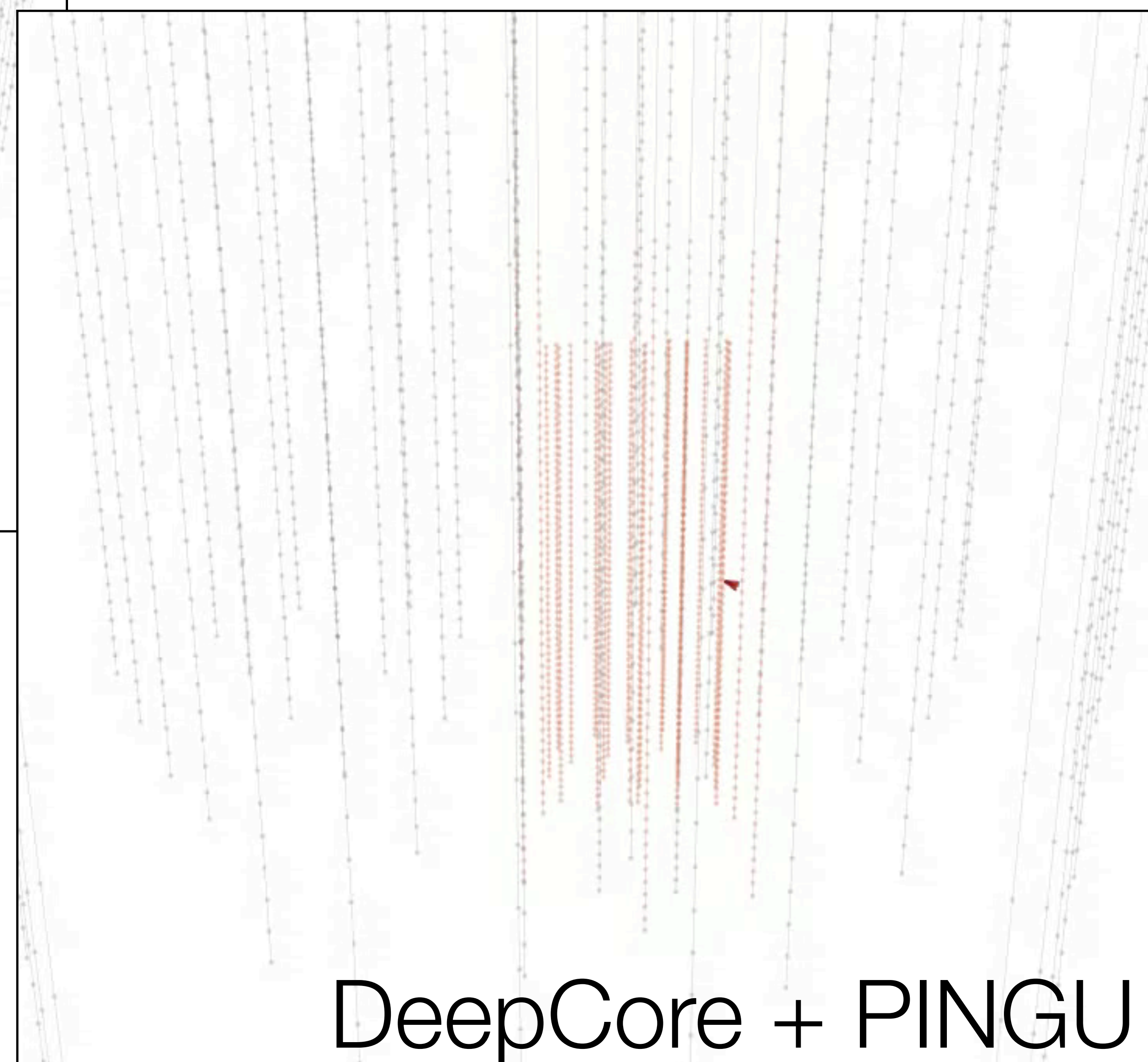


PINGU

- Targeting 40 additional strings of 60-100 Digital Optical Modules each, deployed in the DeepCore volume
  - 20-25 m string spacing (cf. 125 m for IceCube, 73 m for DeepCore)
  - Precise geometry under study
  - Systematics will be better understood with additional in situ calibration devices



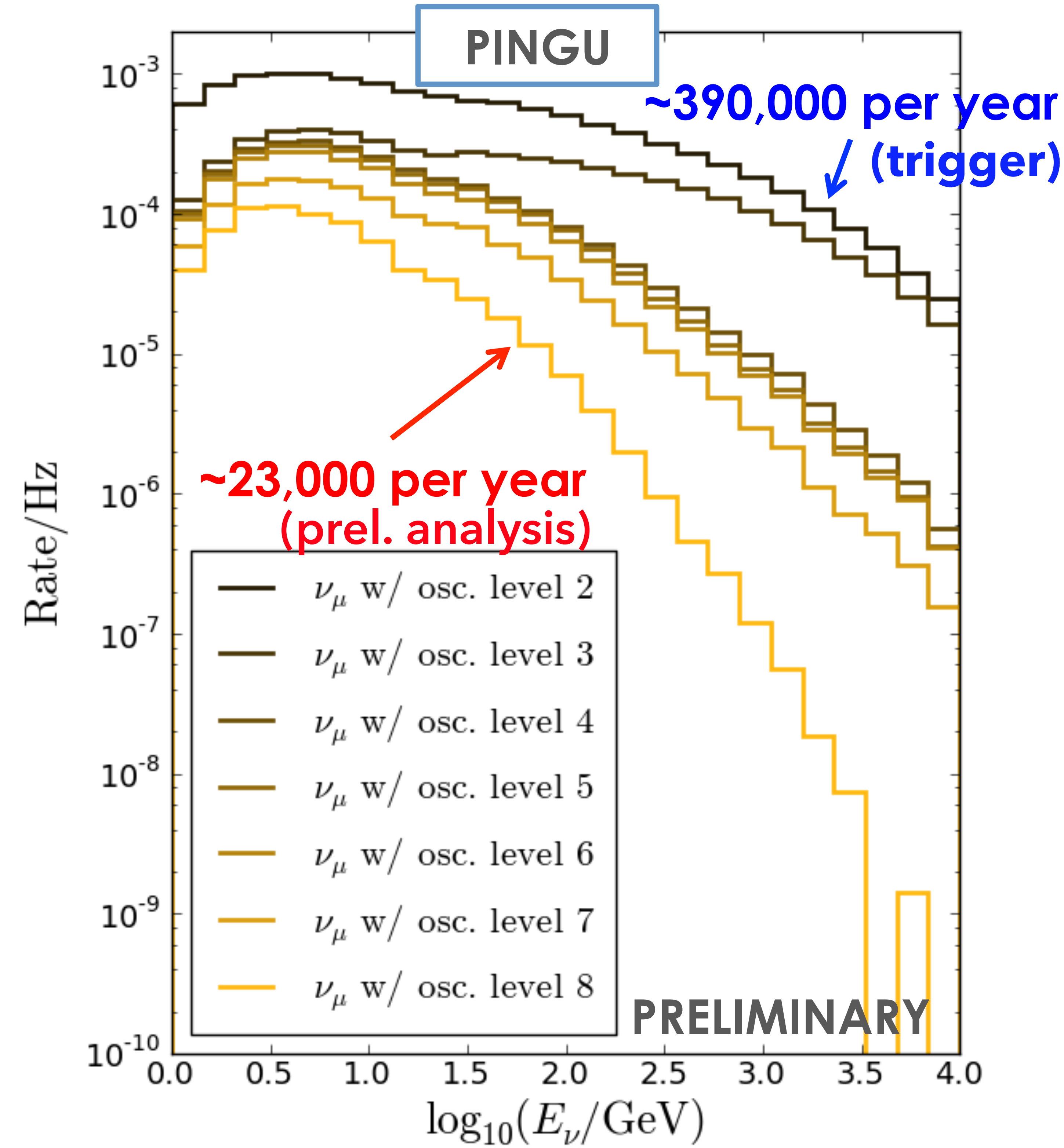
- Cost and technical issues well understood from IceCube experience
  - Start-up costs of $8M – $12M
  - ~$1.25M per string



- 9.28 GeV ν_μ event:
  - 4.9 GeV muon
  - 4.5 GeV cascade
- ~20 vs. ~50 hit DOMs

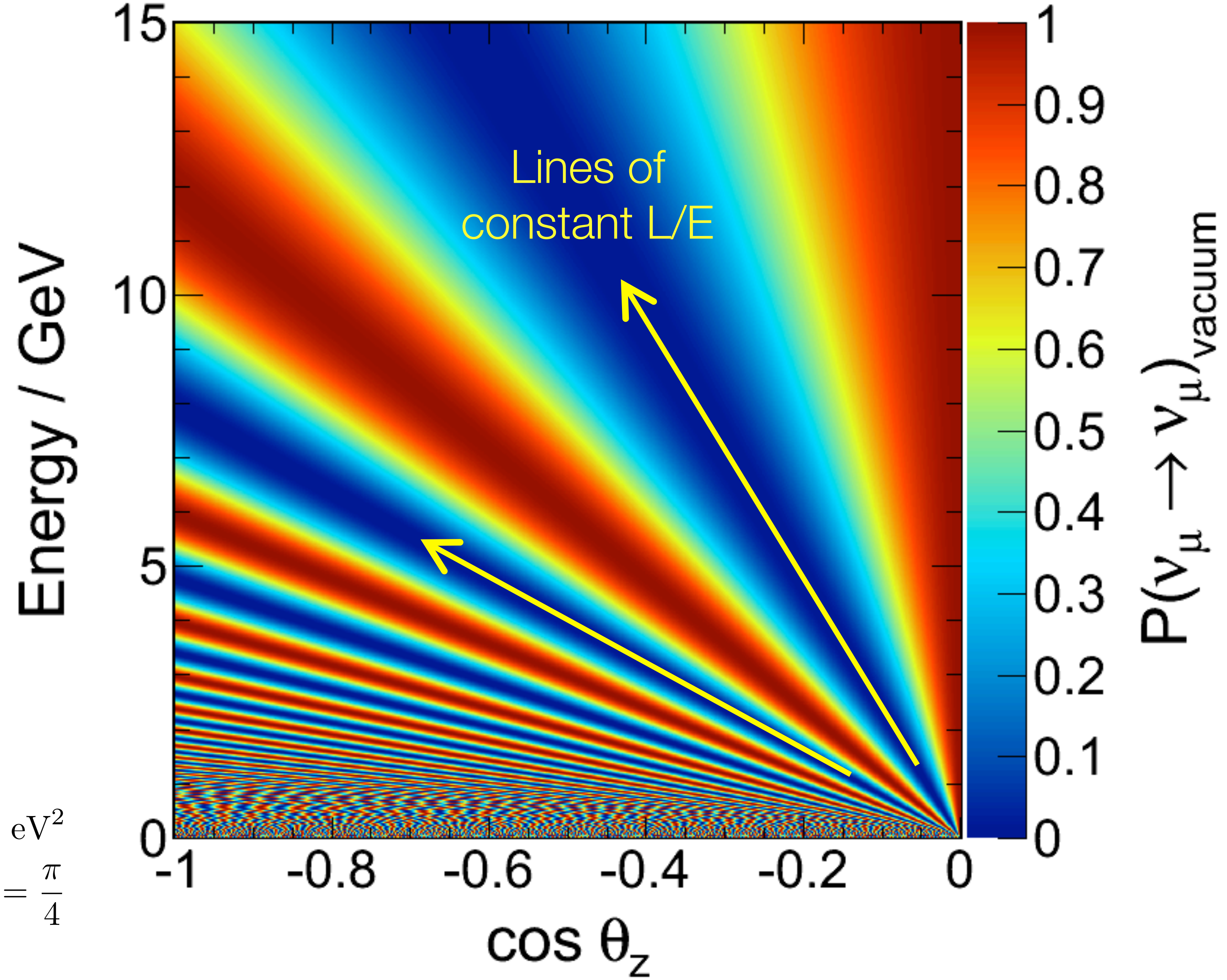
PINGU Energy Range

- A preliminary event selection based on DeepCore analysis
  - 23,000 muon neutrinos per year after oscillations
  - Oscillation signature is the disappearance of 12,000 events per year
- Sufficient to measure neutrino mass hierarchy via matter effects in the 5-20 GeV range without direct $\nu_\mu - \bar{\nu}_\mu$ discrimination
  - Exploit asymmetries in cross sections and kinematics



Neutrino Oscillations in Vacuum

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



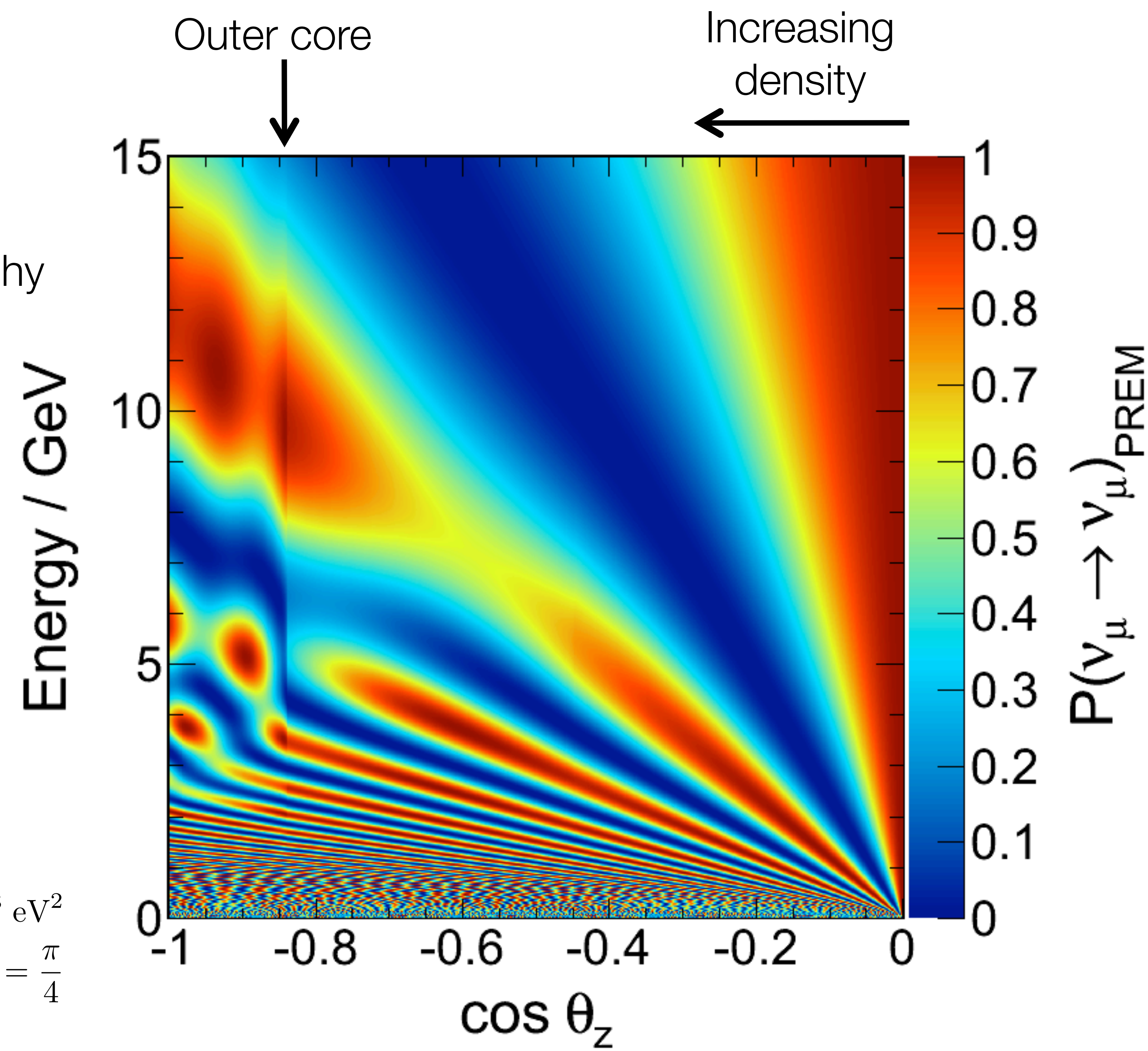
$\Delta m^2_{32} = 2.32 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2(2\theta_{23}) = \frac{\pi}{4}$

Neutrino Oscillations in Matter

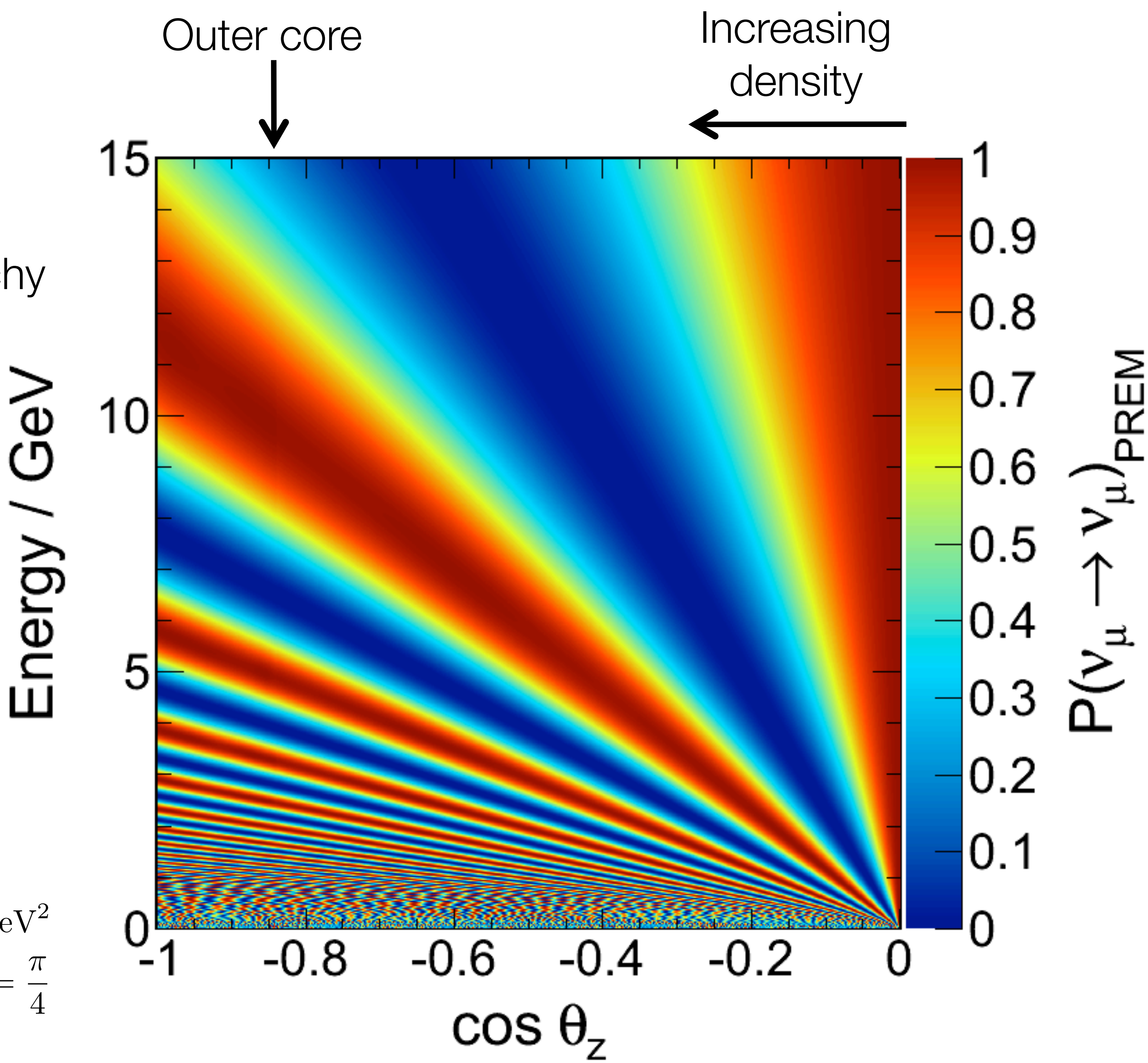
Neutrinos
Normal hierarchy

$$\Delta m^2_{32} = 2.32 \times 10^{-3} \text{ eV}^2$$
$$\sin^2(2\theta_{23}) = \frac{\pi}{4}$$



Neutrino Oscillations in Matter

Neutrinos
Inverted hierarchy



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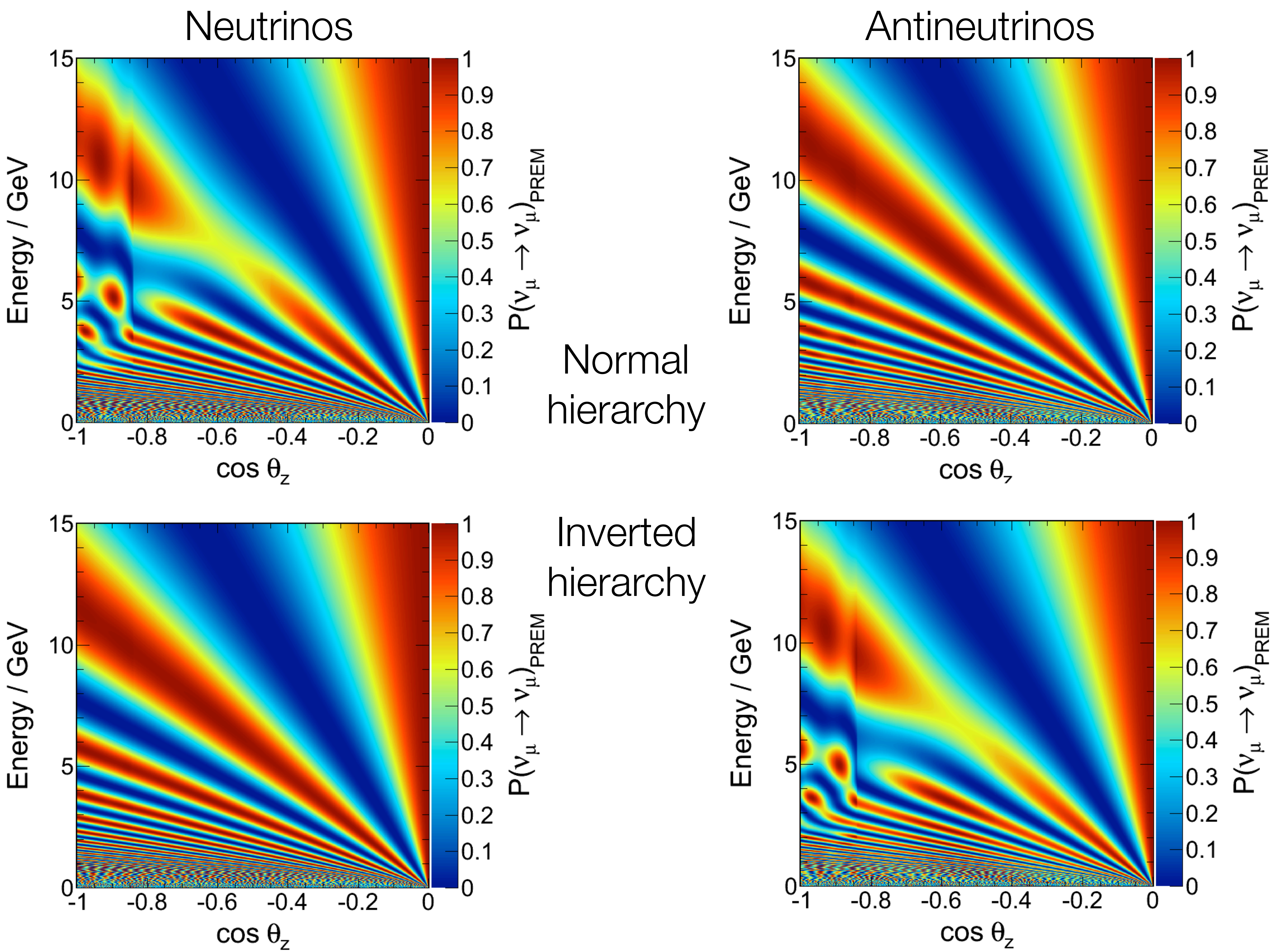


Neutrinos
Antineutrinos
Normal hierarchy
Inverted hierarchy
Energy / GeV
cos θz
P(νμ → νμ)PREM
0
5
10
15
-1
-0.8
-0.6
-0.4
-0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Preliminary Hierarchy Sensitivity Studies

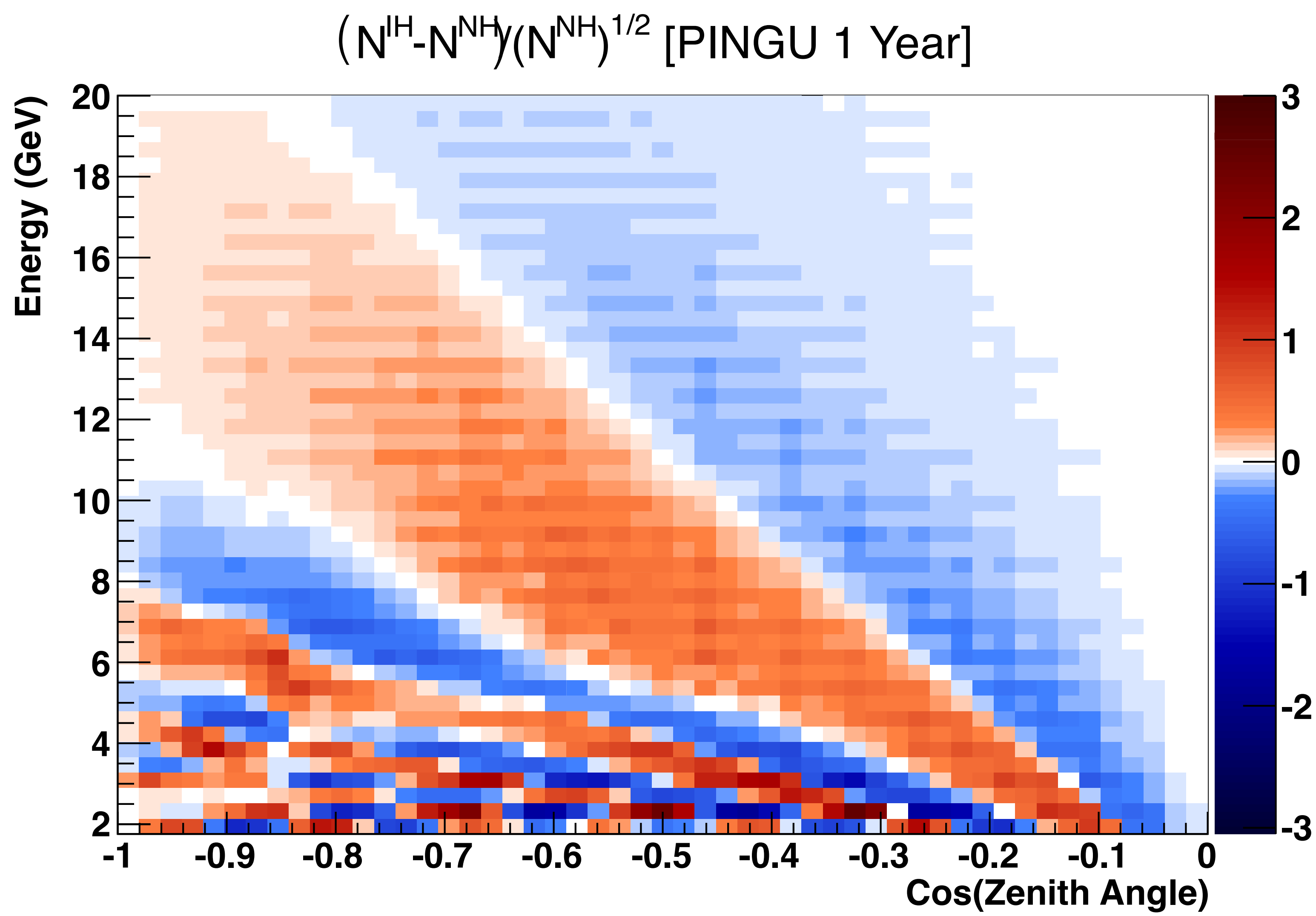
- Measuring a somewhat complicated modulation of a complicated two-dimensional distribution
  - Rather difficult to visualize the data in a simple way
- A useful metric for visualizing the signature is the significance estimate of Akhmedov, Razzaque & Smirnov (arXiv:1205.7071)
  - Binned counting experiment in energy and zenith angle, comparing difference in expected number of events for normal vs. inverted hierarchy due to mass effects

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

$$\begin{aligned} i &= \cos(zenith) \\ j &= energy \end{aligned}$$

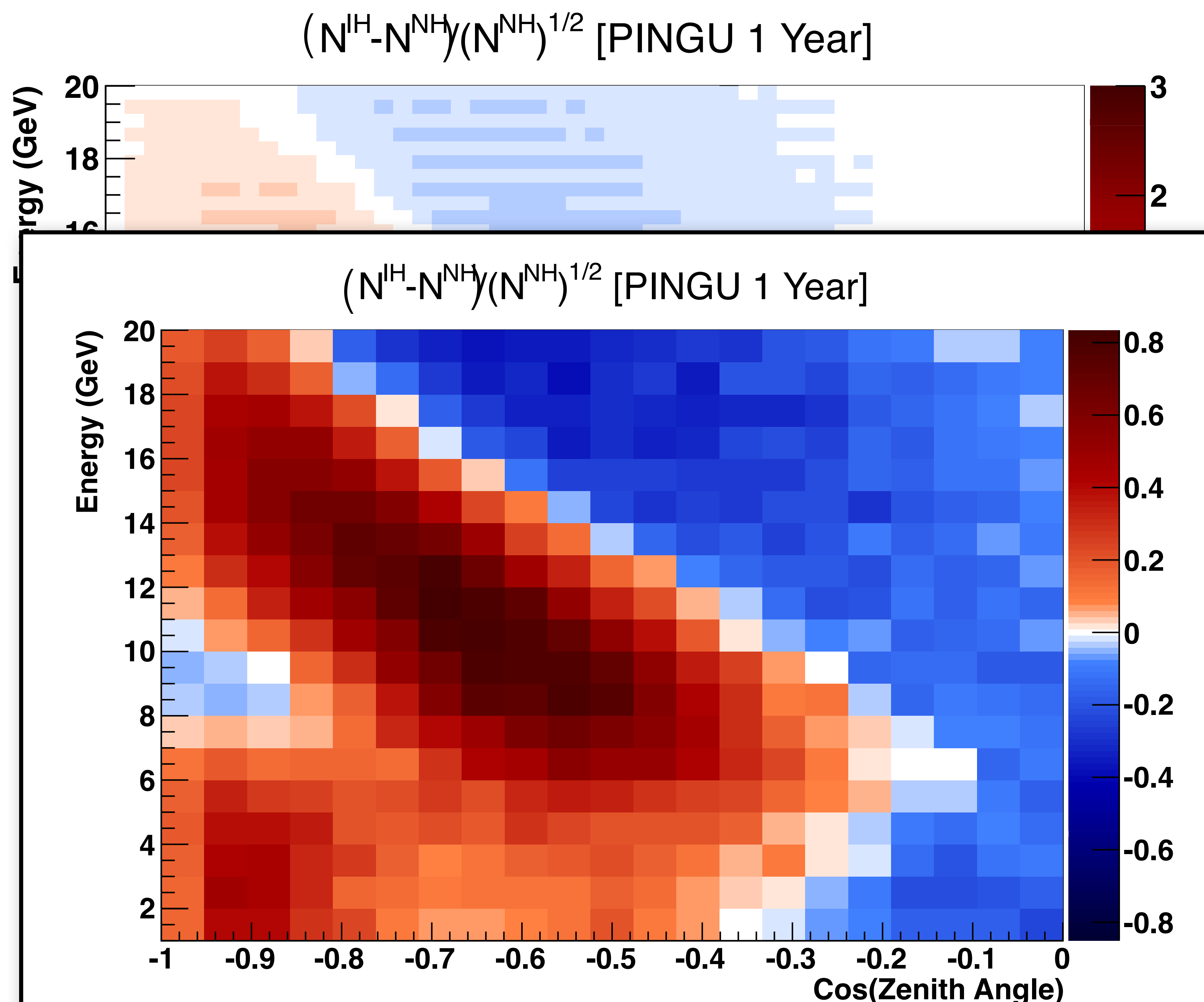
Experimental Signature of the Mass Hierarchy

- Idealized case with no background, perfect flavor ID, 100% signal efficiency



Experimental Signature of the Mass Hierarchy

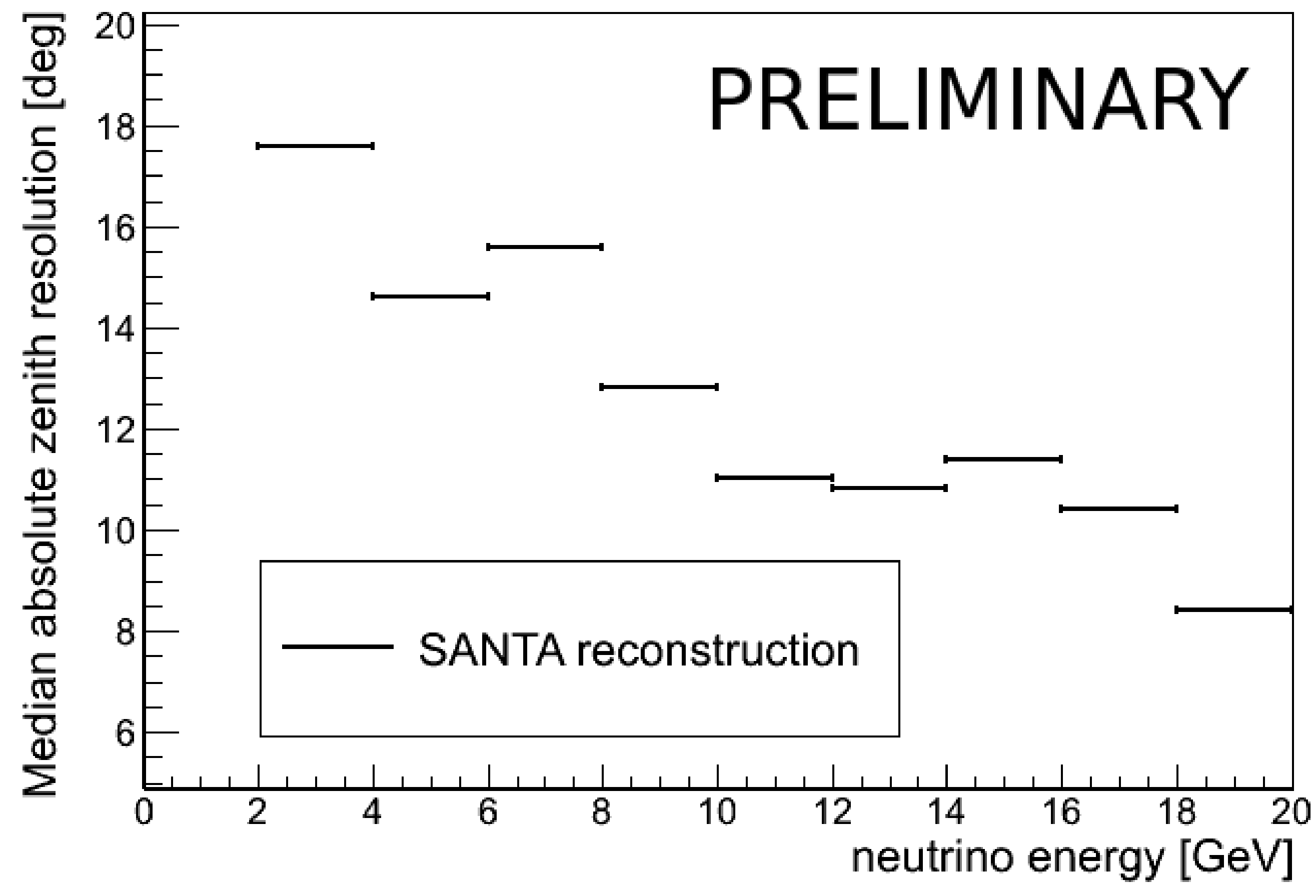
- Idealized case with no background, perfect flavor ID, 100% signal efficiency
  - Different assumed resolutions smear the signature but do not eliminate it
- Hierarchy signature is a distinctive structure in energy-angle plane
  - Key to our approach to controlling systematics

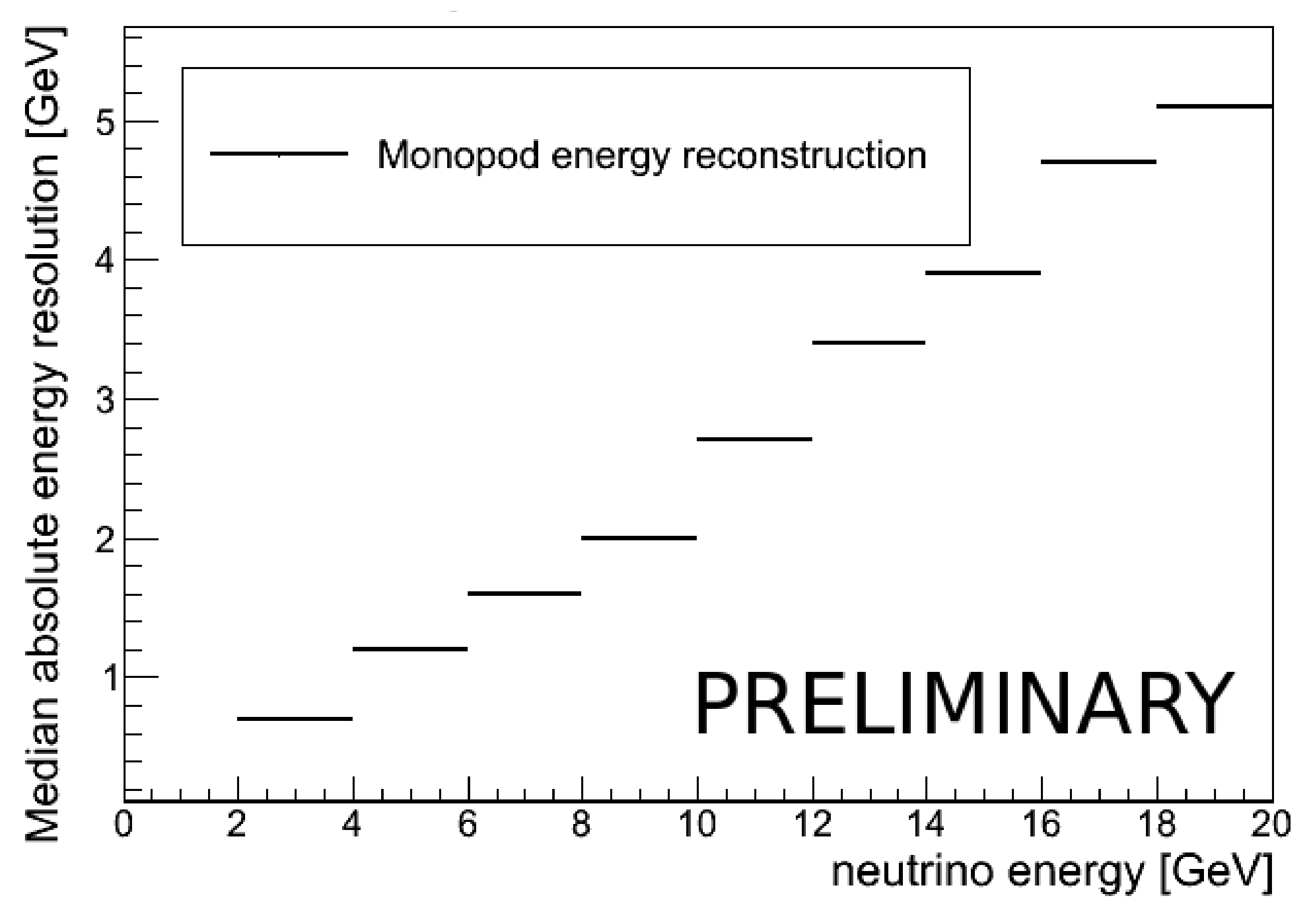


smeared: 3 GeV in ν_μ energy and 11.25° in μ zenith resolution

PINGU Performance and Sensitivity Studies

- Currently using DeepCore algorithms
  - More computationally intensive algorithms can improve resolution
- Systematics studied so far:
  - θ_{23}, θ_{13}, Δm^2_{atm}, δ_{CP} within world average ±2σ ranges
  - Efficiency errors (30%)
  - Atmos. ν spectral index (±0.05)
  - Energy calibration (10% bias)
  - Pointing accuracy (10% bias)
  - Energy resolution (10% error)
  - Angular resolution (10% error)
  - Further studies underway now

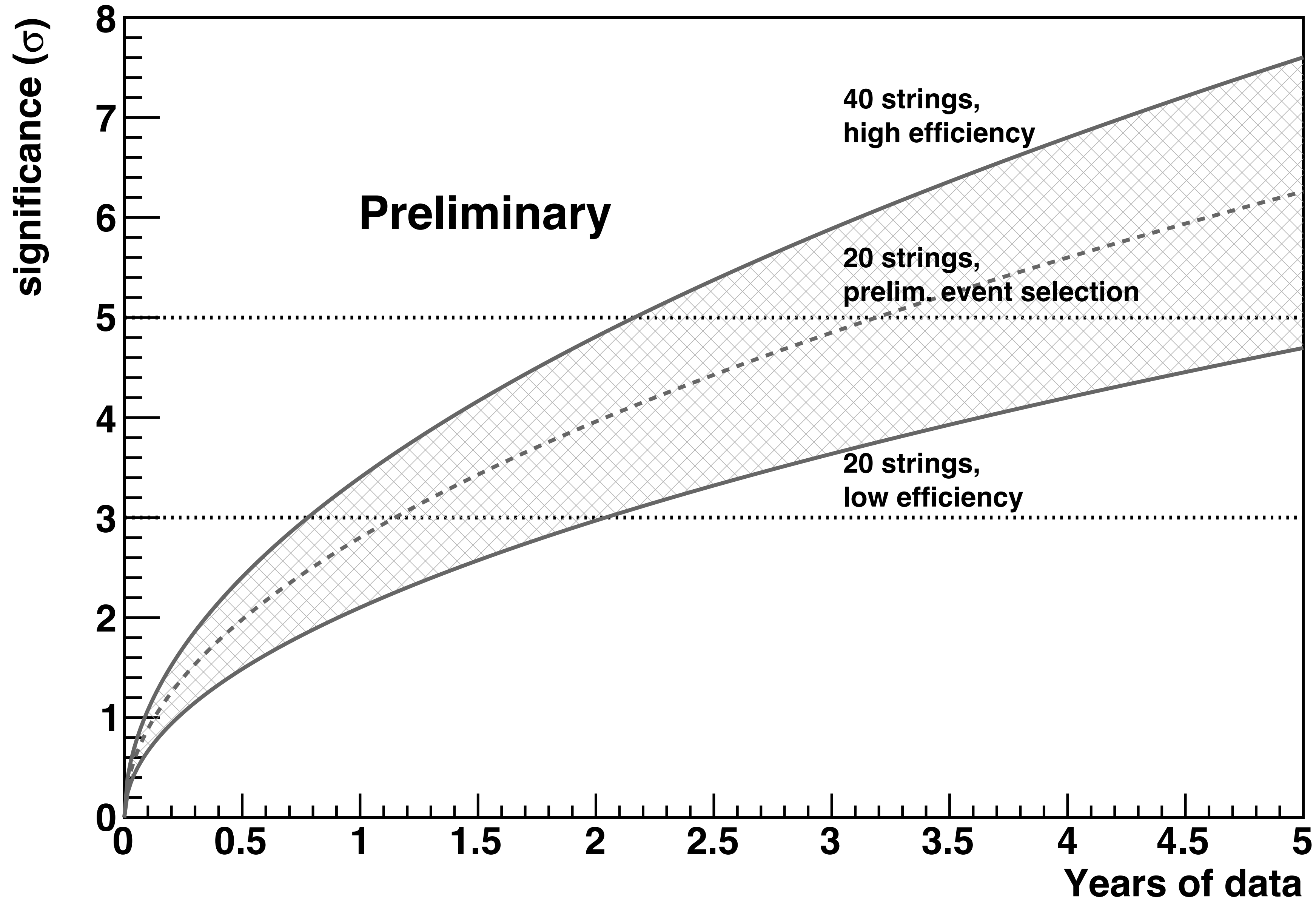




PINGU Hierarchy Sensitivity

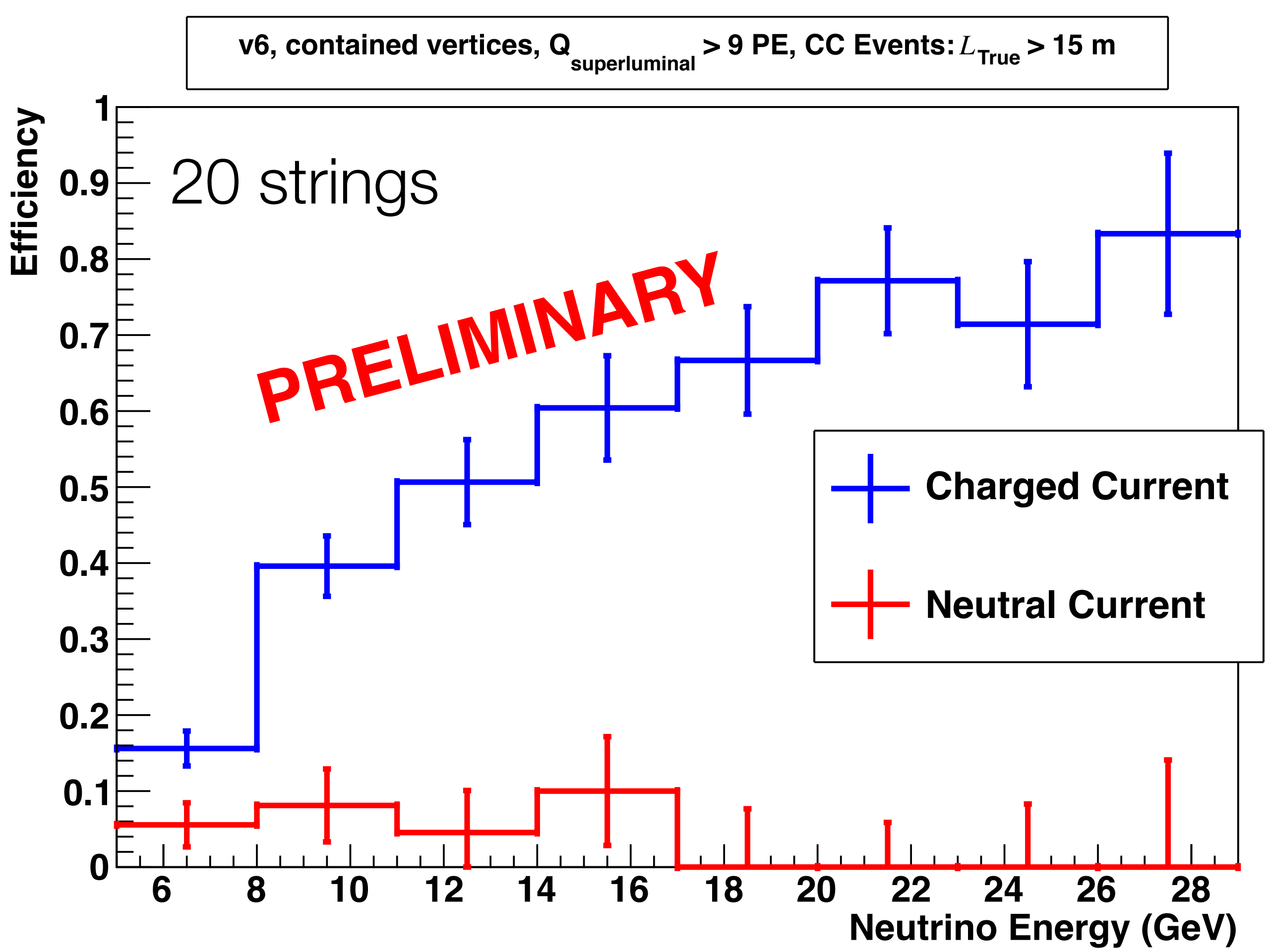
- Sensitivity depends on final detector scope, assumed analysis efficiency, detector resolution, etc.
    - Caveat: not all systematics included in each study
- Even with pessimistic assumptions, 3σ determination expected (median) with 2 years' data
    - 5σ in 2-4 more years
- Working now to refine details and extend systematic studies

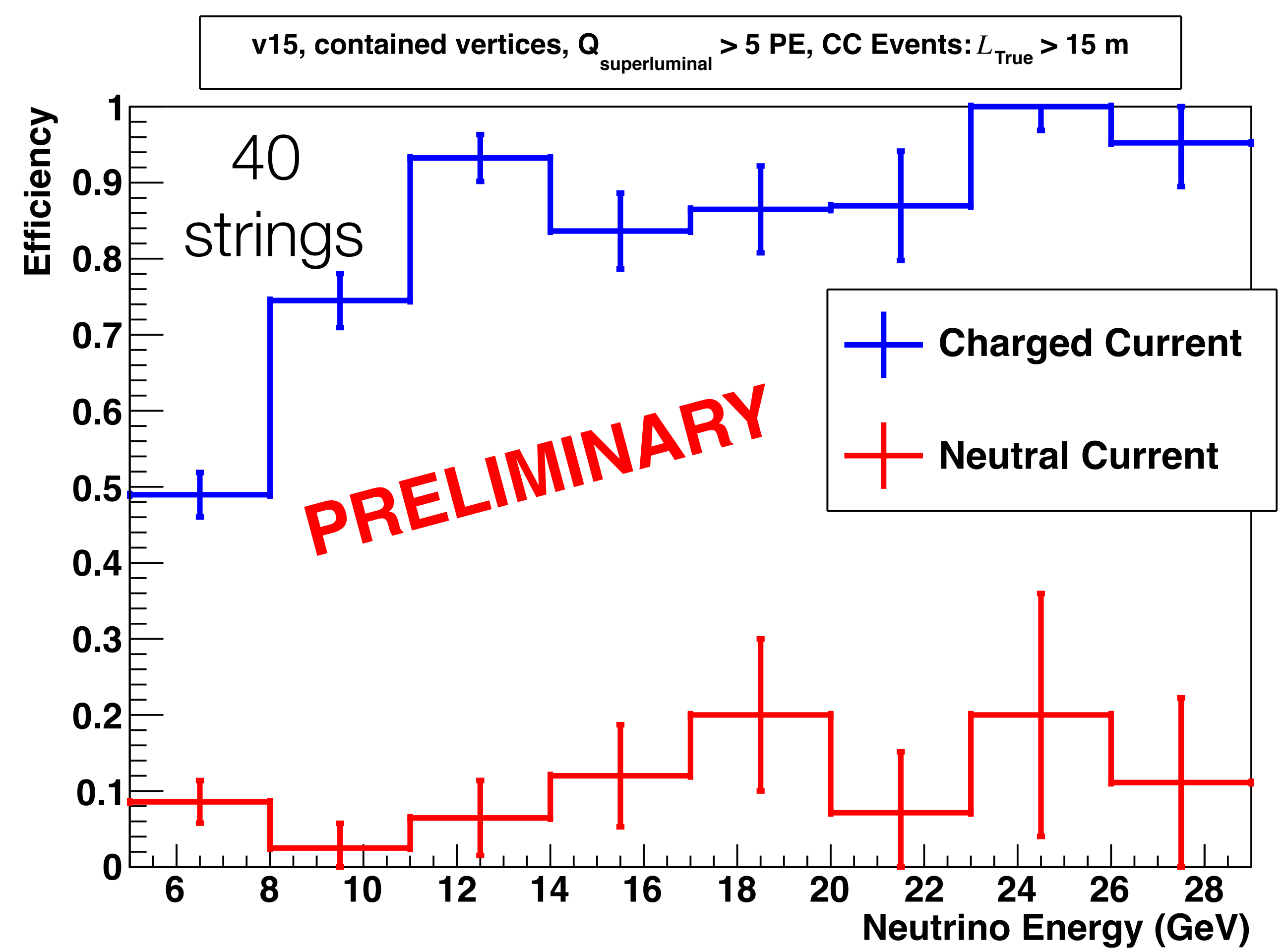
arXiv:1306.5846



First Steps Toward Flavor Identification

- Current sensitivity studies assume no flavor ID – statistical subtraction of backgrounds from ν_x NC, ν_e, ν_τ
- First step: tag ν_μ CC based on presence of track with v > c/n
  - Good efficiency for ν_μ with E_μ > 3 GeV with 40 string geometry





Other Neutrino Measurements

- δ_{CP} has no effect on our hierarchy measurement
  - Hierarchy determination via ν_μ disappearance, not appearance – resolve degeneracy for other experiments
- High-statistics measurement of ν_τ appearance
  - In the standard oscillation scenario, the disappearing ν_μ are converted to ν_τ – confirmation of tau appearance at expected rate is an interesting test
  - Oscillation effects scale as L/E_ν, so longer baselines move effect to higher energy with reduced kinematic suppression of tau neutrino cross section
- Improved measurement of atmospheric oscillation parameters
- Over-constraint of parameters in the standard oscillation paradigm is essential for testing non-standard scenarios (e.g. A. Friedland)

Advantages of PINGU

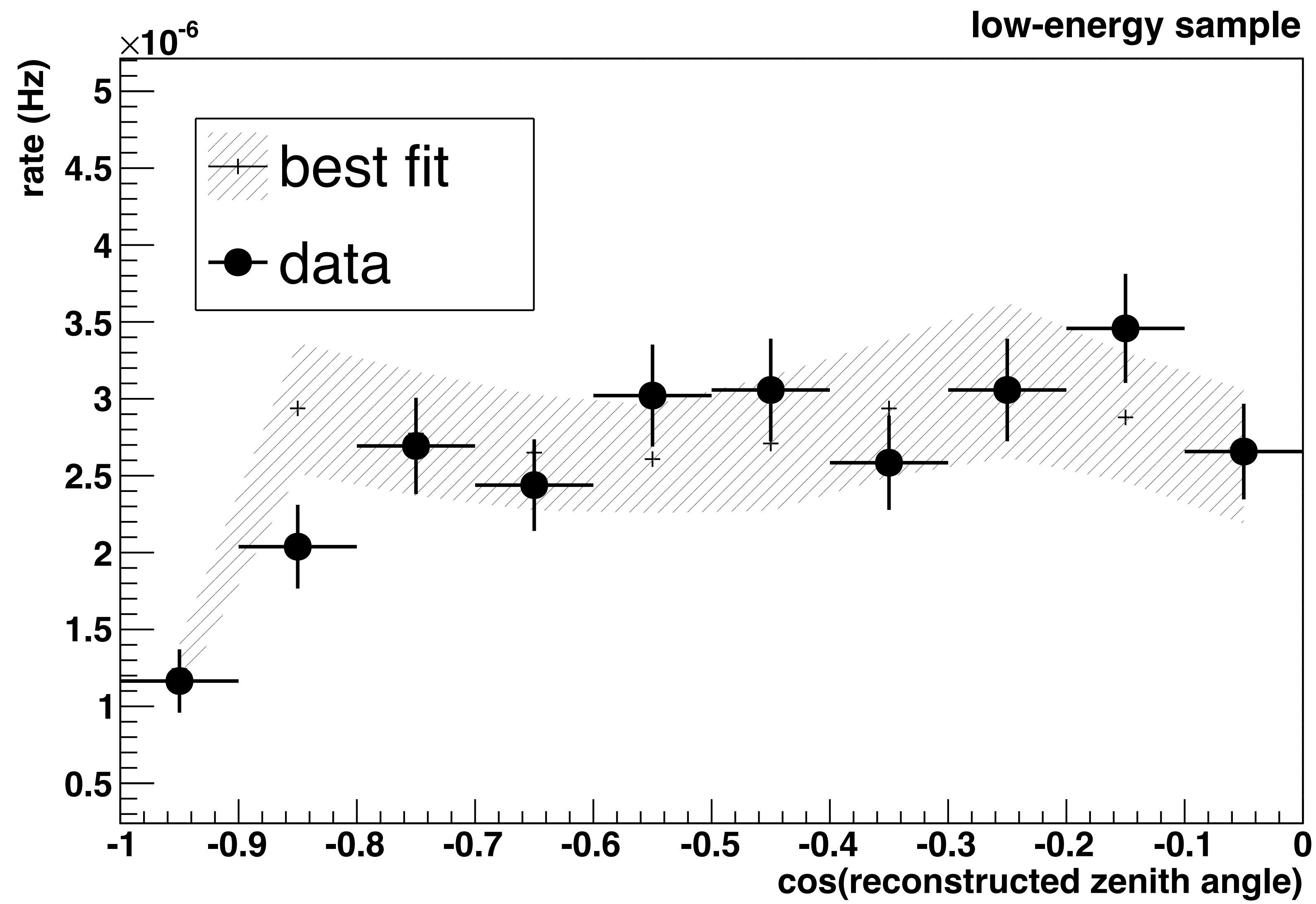
- Relatively cheap
  - Start up costs of \$8-12M, plus ~\$1.25M per string, split between the US and foreign partners
  - Well understood technology and techniques – low risk
- Relatively quick
  - Could begin deployment in the 2016/17 austral summer season, completion in 2-3 years (depending on scope)
  - 3σ determination of the hierarchy by 2020, 5σ in 2-4 more years
- Targeted measurement would resolve degeneracies
  - Allow LBNE to focus on CP violation
- Working now on a detailed Letter of Intent and full proposal

Backup Slides

Best-fit Oscillations

- Statistical significance of observation established with respect to world average oscillation parameters

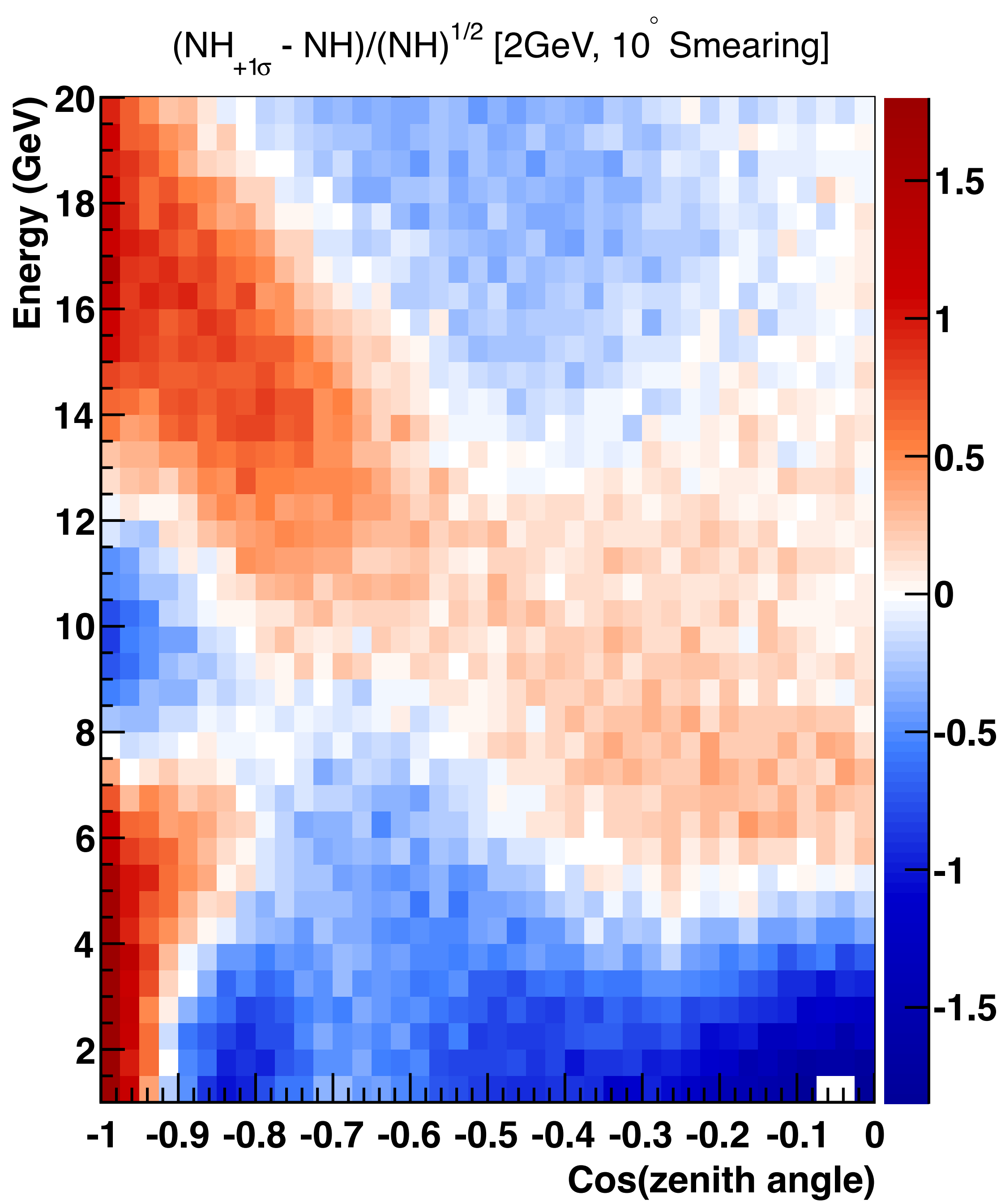
- As a second step, we fit Δm^2_{23} and $\sin^2(2\theta_{23})$ by χ^2 minimization, with nuisance parameters fit simultaneously

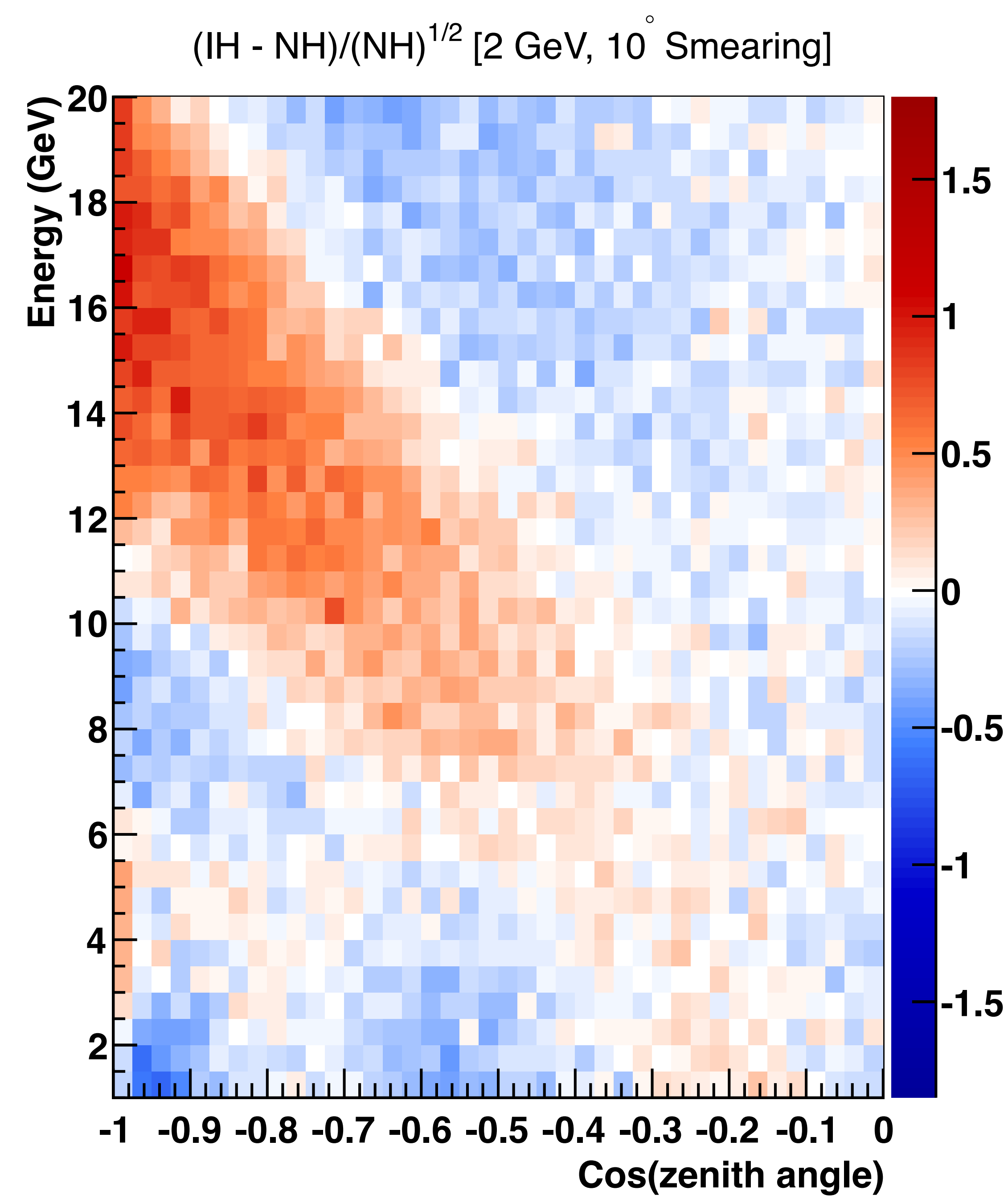


  - $\Delta m^2_{23} = 2.3 \times 10^{-3}\ \text{eV}^2$, $\sin^2(2\theta_{23}) = 1.0$
  - $\chi^2 = 15.7$ for 18 degrees of freedom

Theoretical Uncertainties

- E.g., uncertainty in Δm_{31}^2 is partially degenerate with the hierarchy





PINGU

- One of several candidate geometries under investigation
  - Exploring requirements for mass hierarchy measurement – additional strings may be added if better angular and energy resolution is needed
  - Systematics can be addressed with additional in situ calibration devices