Determining the Neutrino Mass Hierarchy with PINGU

PENNSTATE

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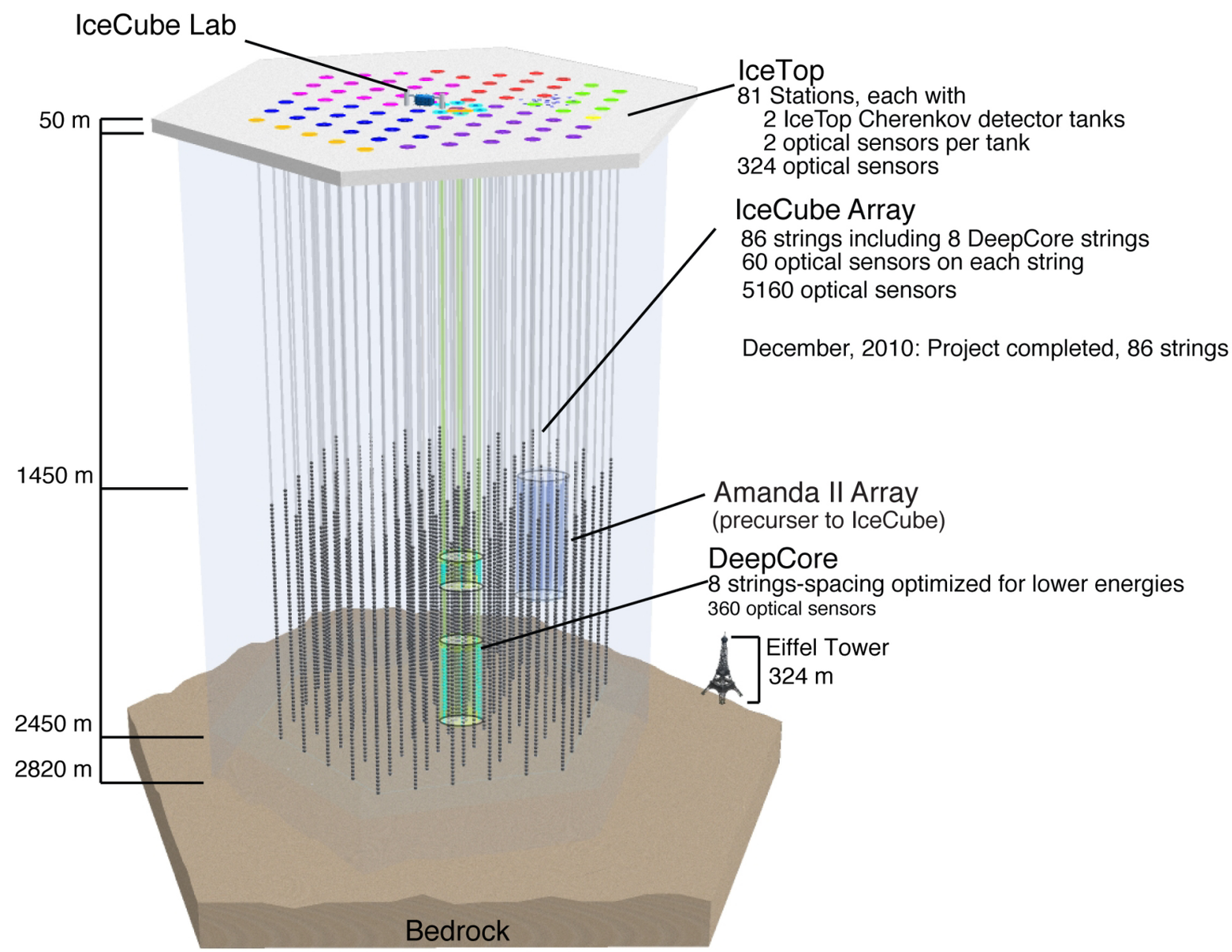
ICECUBE

PRECISION ICECUBE NEXT GENERATION UPGRADE

The IceCube Neutrino Observatory

- World's largest neutrino detector – design focus on neutrinos with energies above a few hundred GeV

- DeepCore provides reduced volume with threshold ~10 GeV



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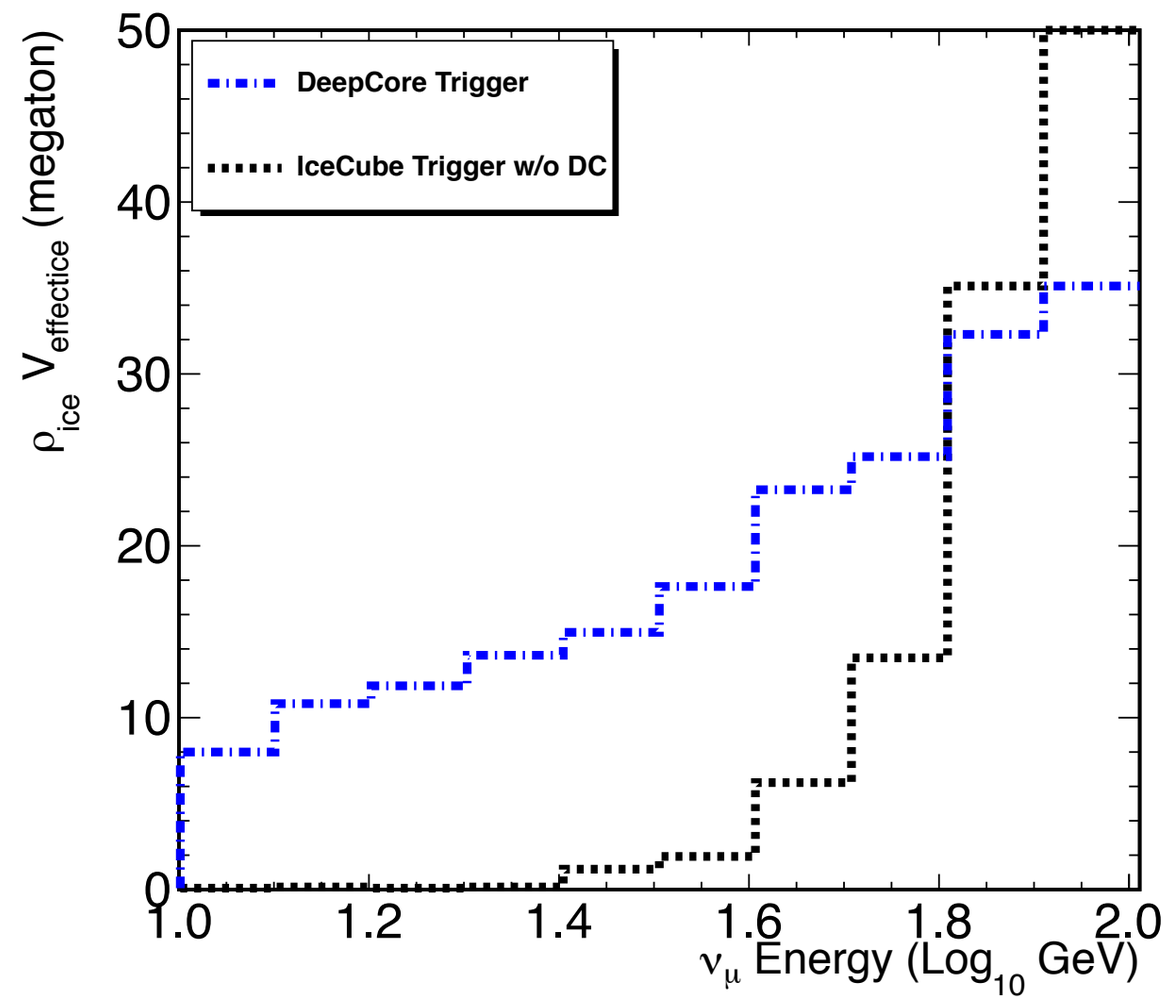
  - Note: comparison at trigger level – analysis efficiencies not included (typically ~10%)



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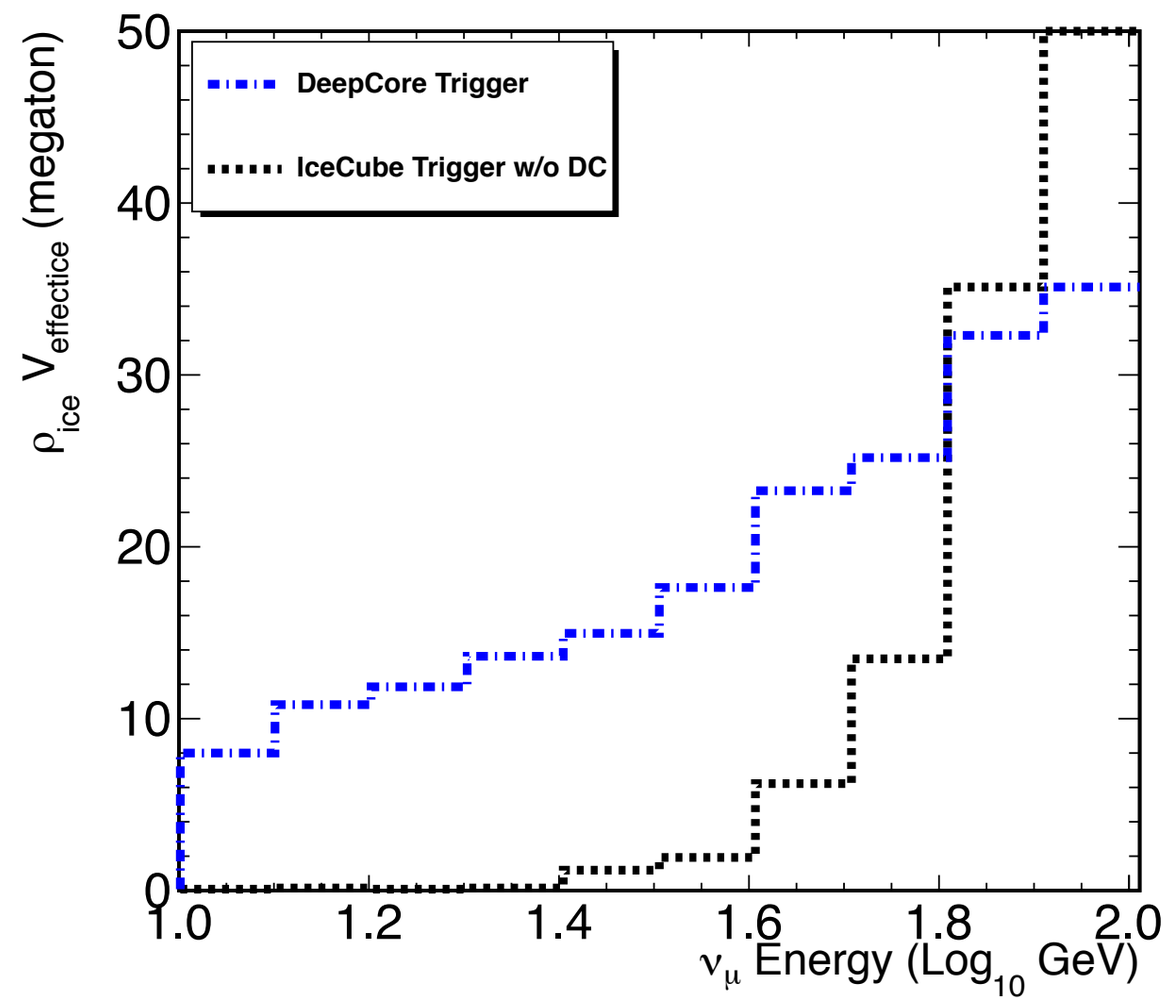
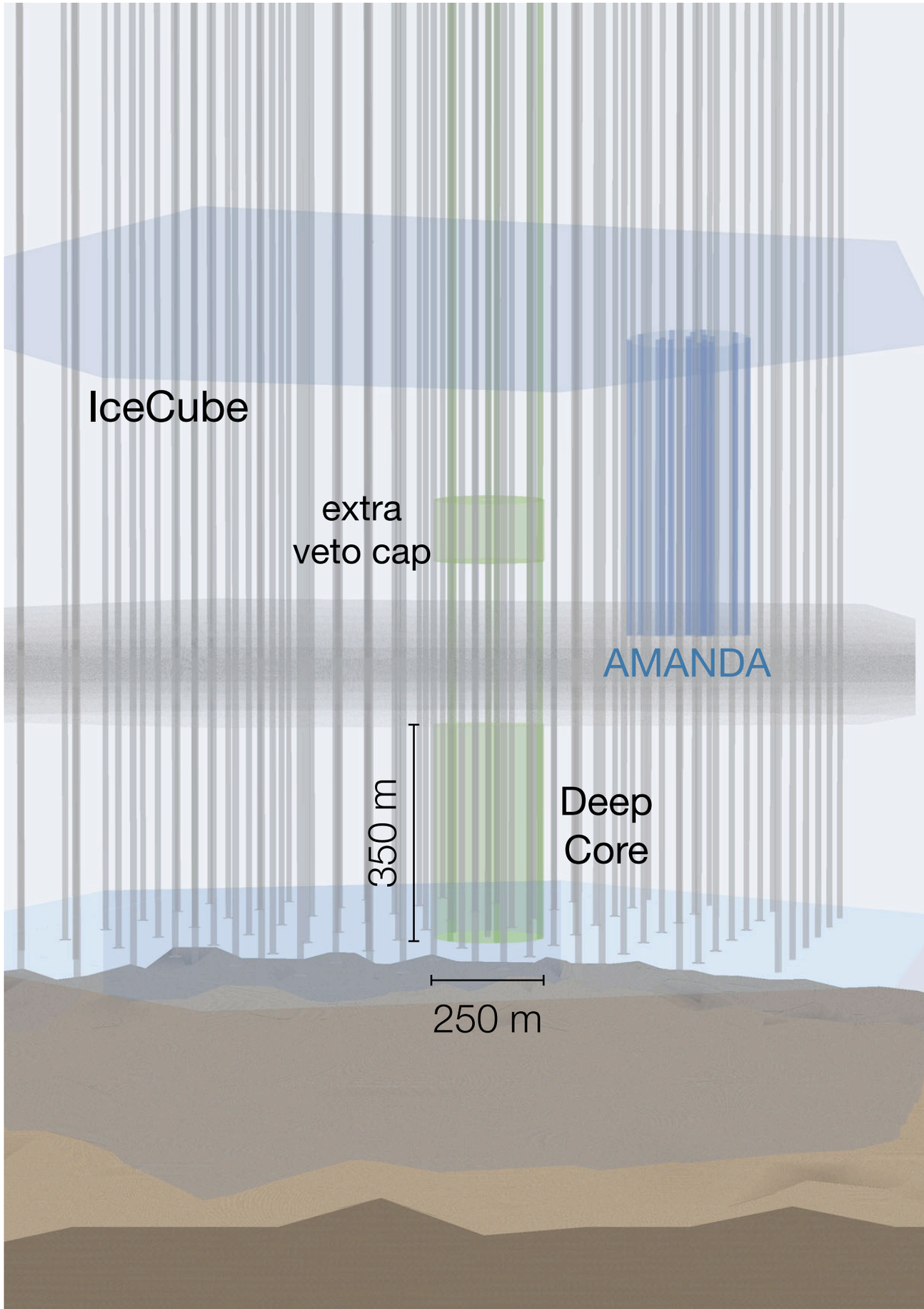


- $\mathcal{O}(10^5)$ atmospheric neutrino triggers per year, $\mathcal{O}(10^4)$ in final data sets

Neutrino Physics with IceCube

- Deep Antarctic ice >2100 m below the surface is very pure
  - λ_{atten} ~ 50 m
  - Effective λ_{scatt} ~ 200 m
  - Very good radiopurity: ^{40}K < 0.2 ppm; U, Th at ppb



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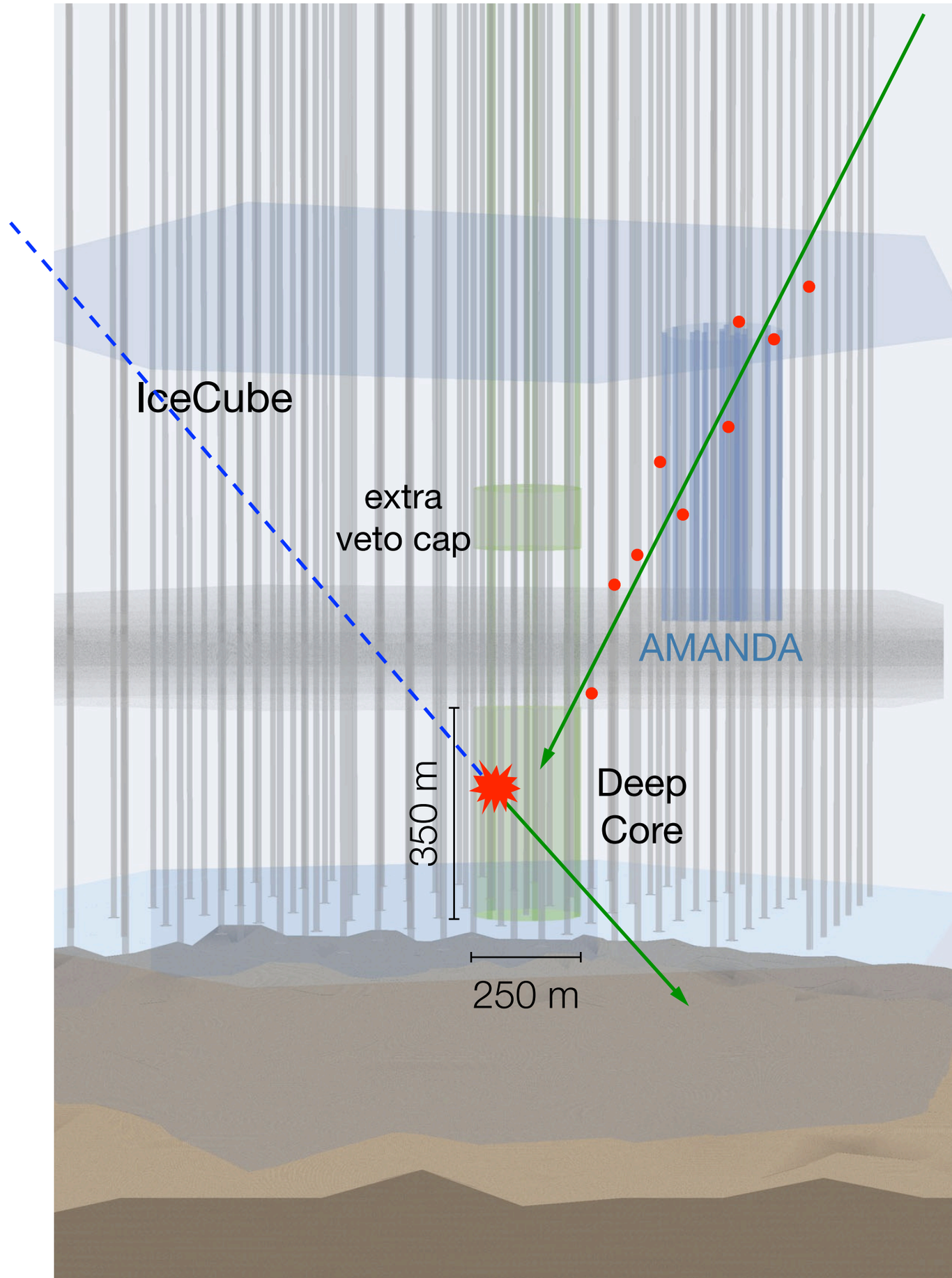

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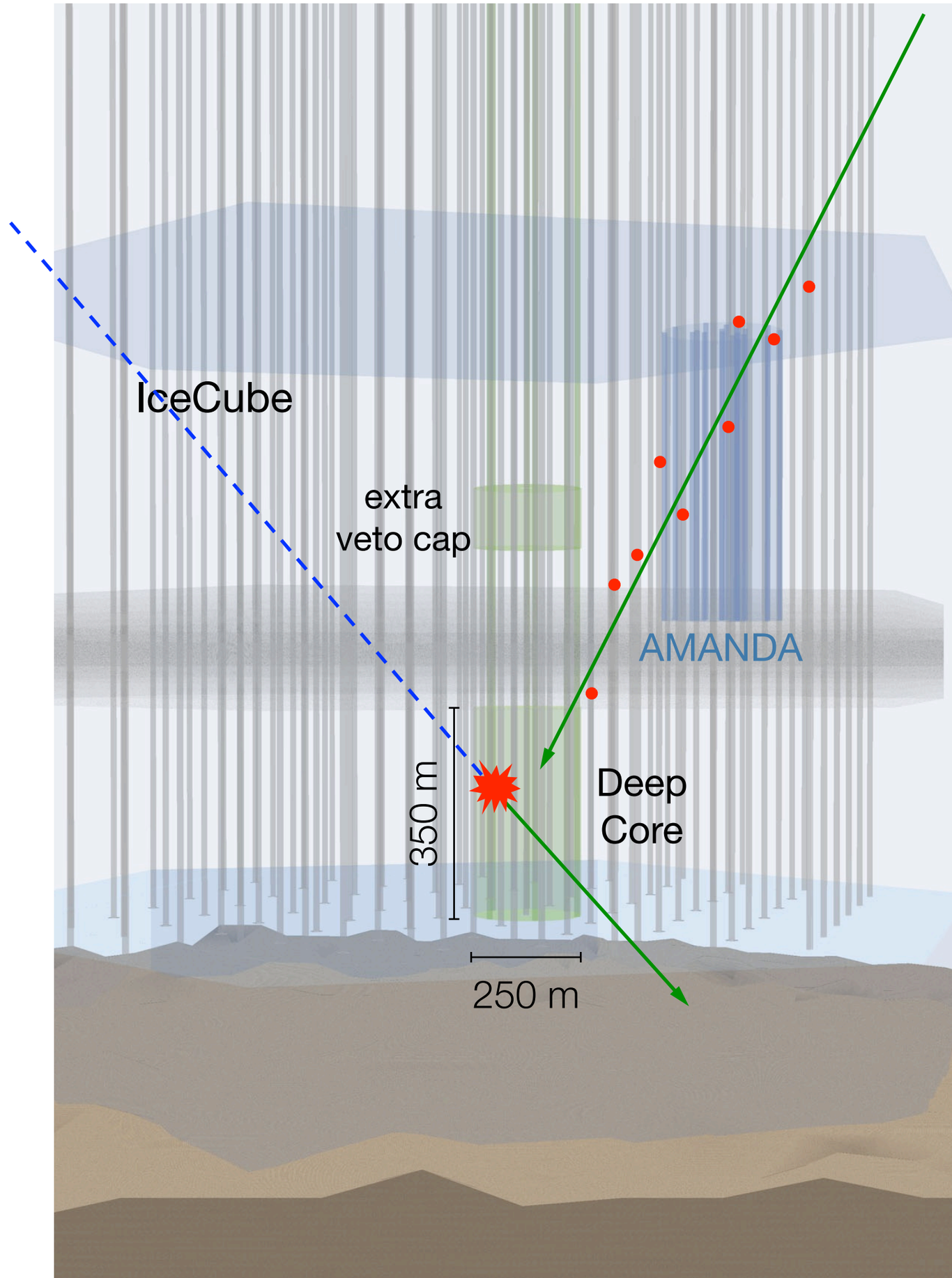
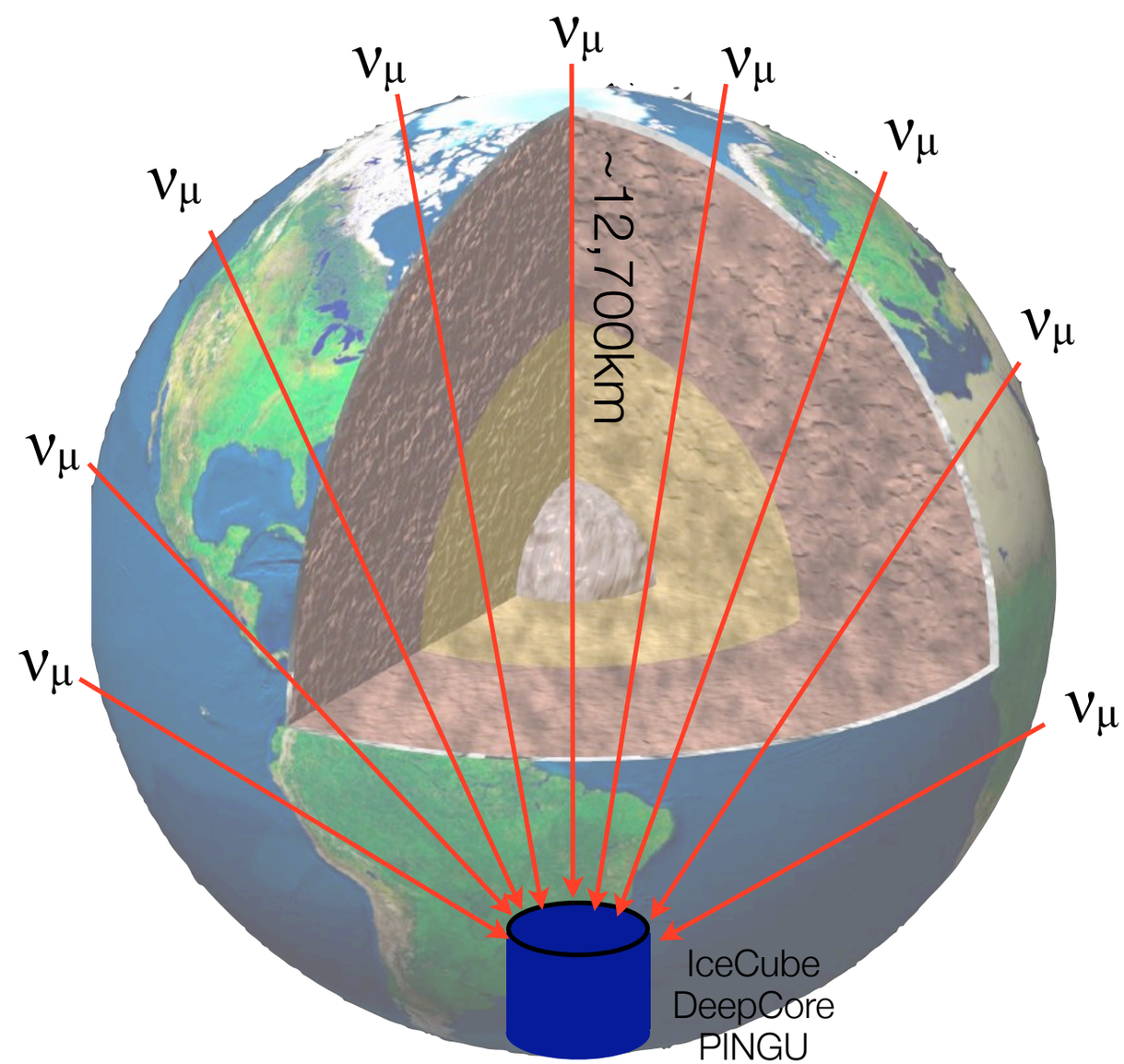
- The Cherenkov medium is the support structure – substantial cost savings



Oscillations with Atmospheric Neutrinos

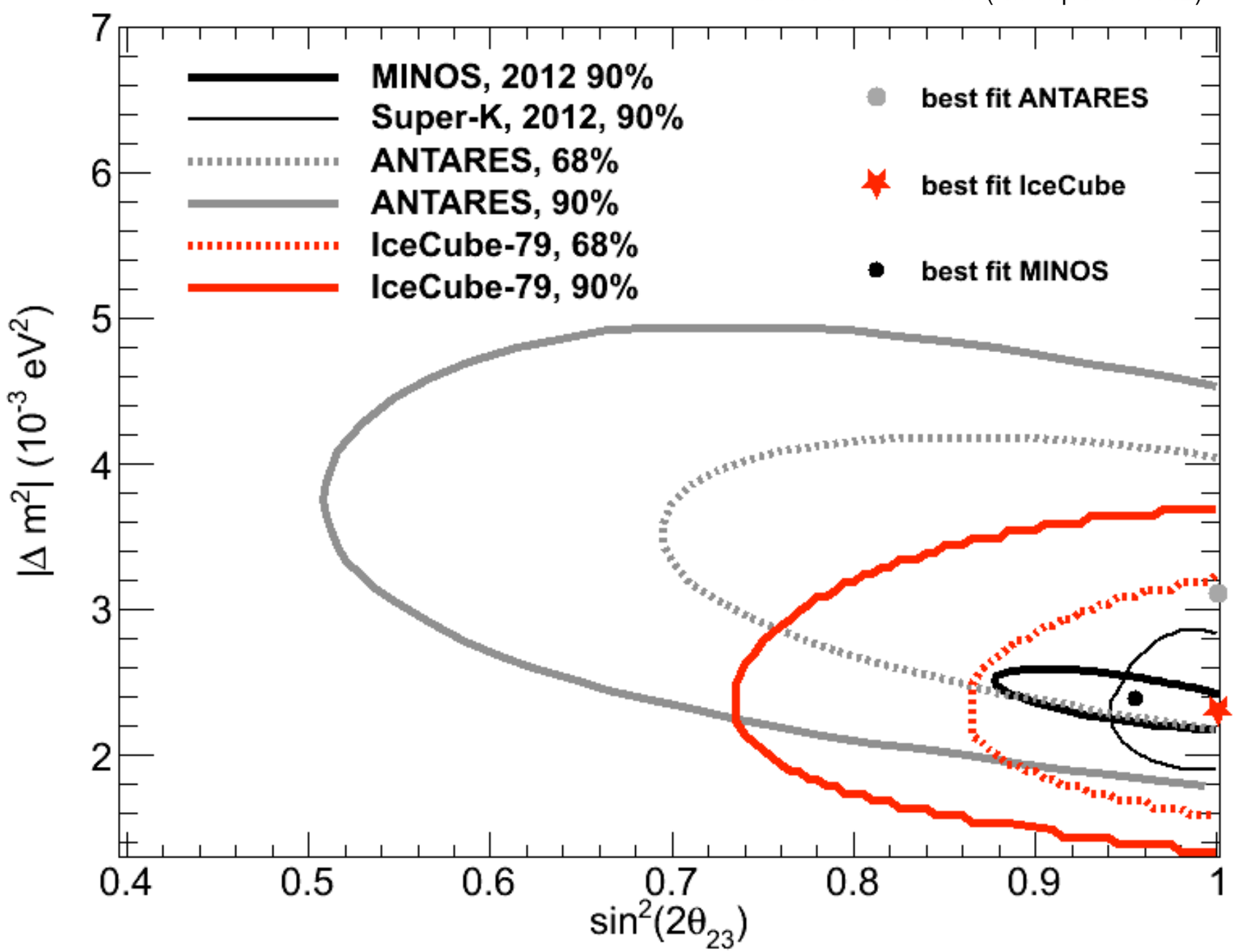
- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects below ~10-20 GeV
- Neutrinos are available over a wide range of energies and baselines
  - Comparison of observations from different baselines and energies is crucial for controlling systematics
  - Essentially, a generalization of the up-down ratio approach



First IceCube Oscillation Measurements

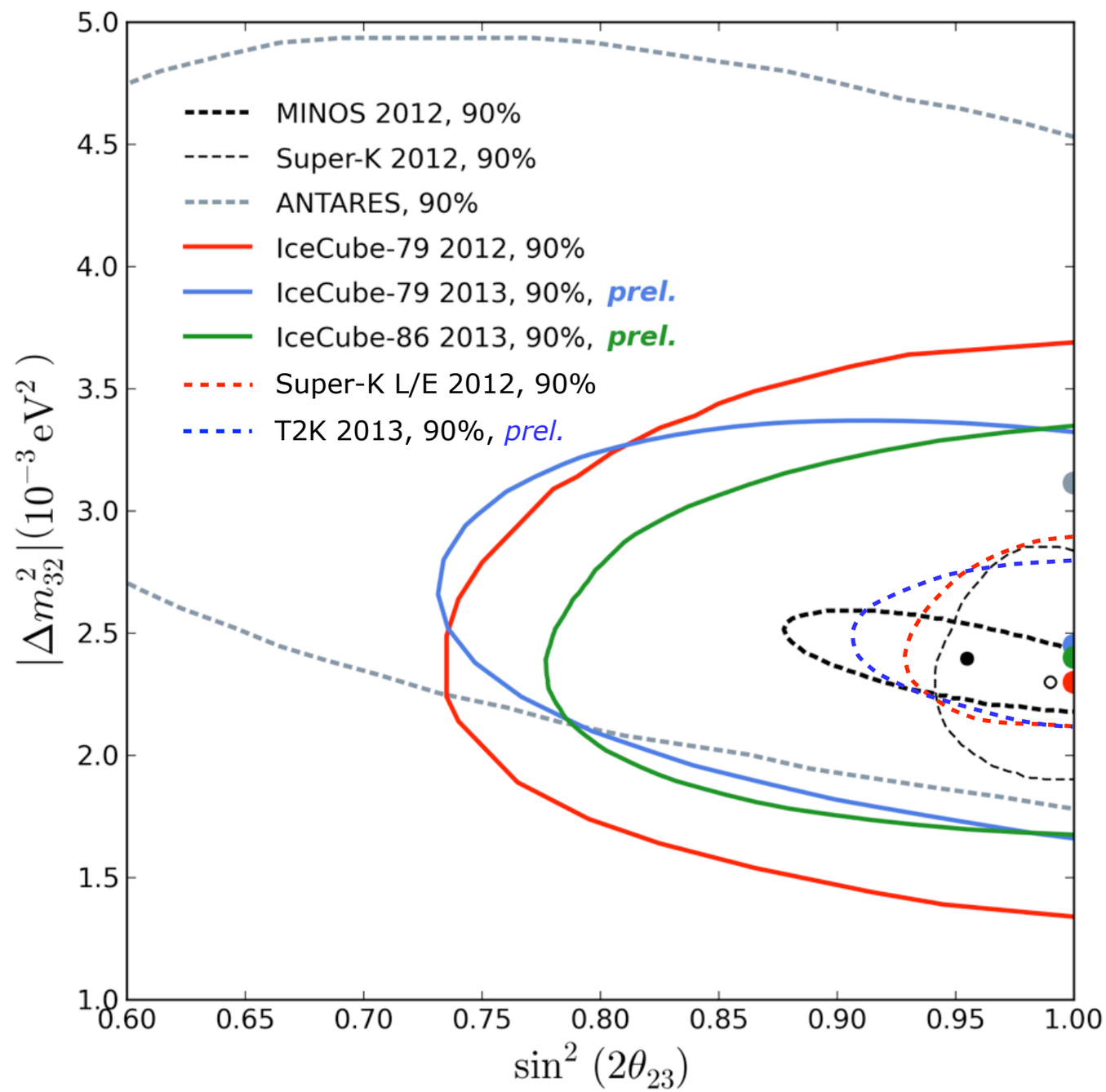
- Based on one year of data with the near-complete IceCube DeepCore detector
- Used a simpler zenith angle comparison analysis (two energy bins)
  - First iteration – prioritized a rapid result

arXiv:1305.3909 (accepted PRL)



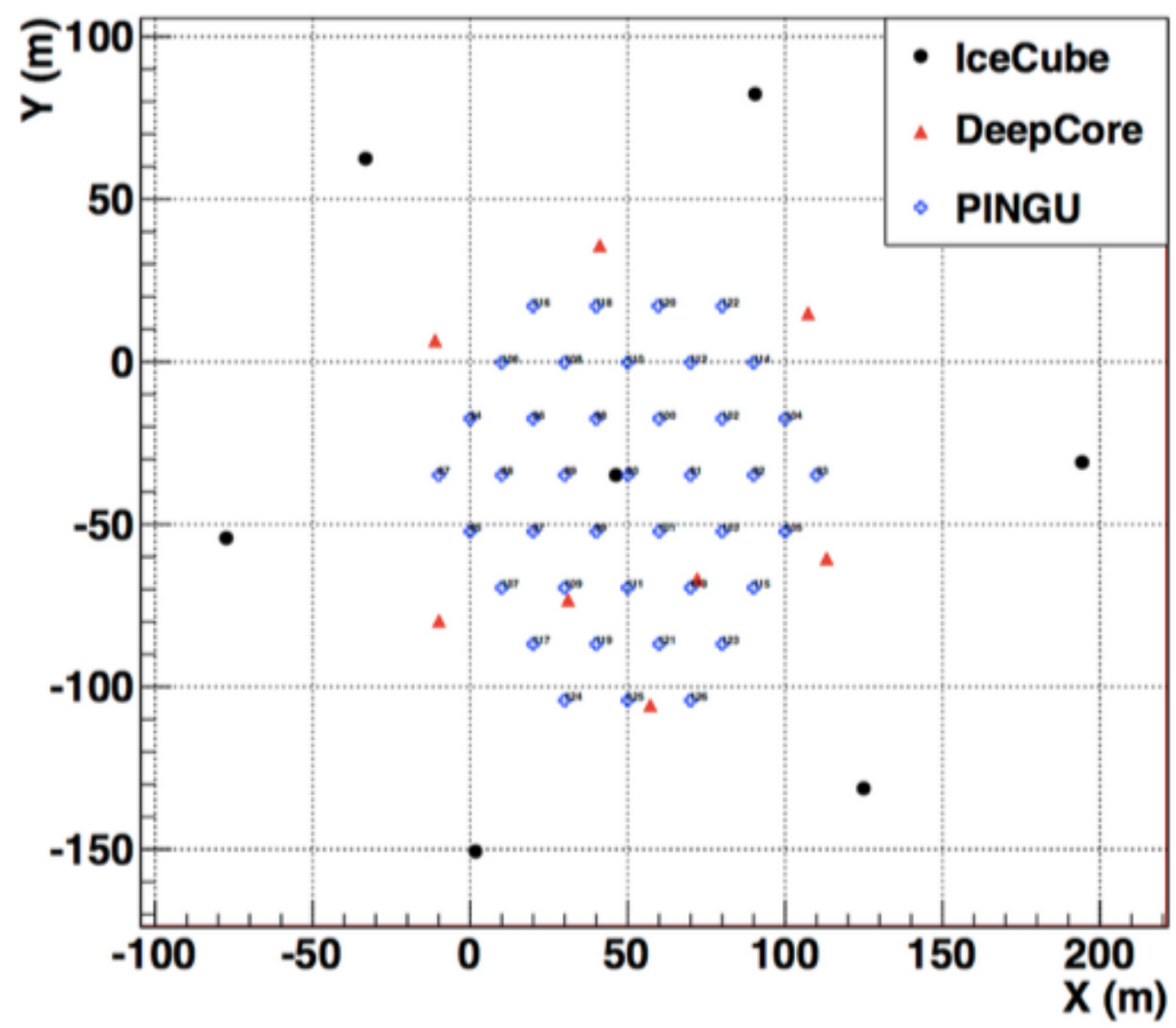
Coming Improvements

- 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



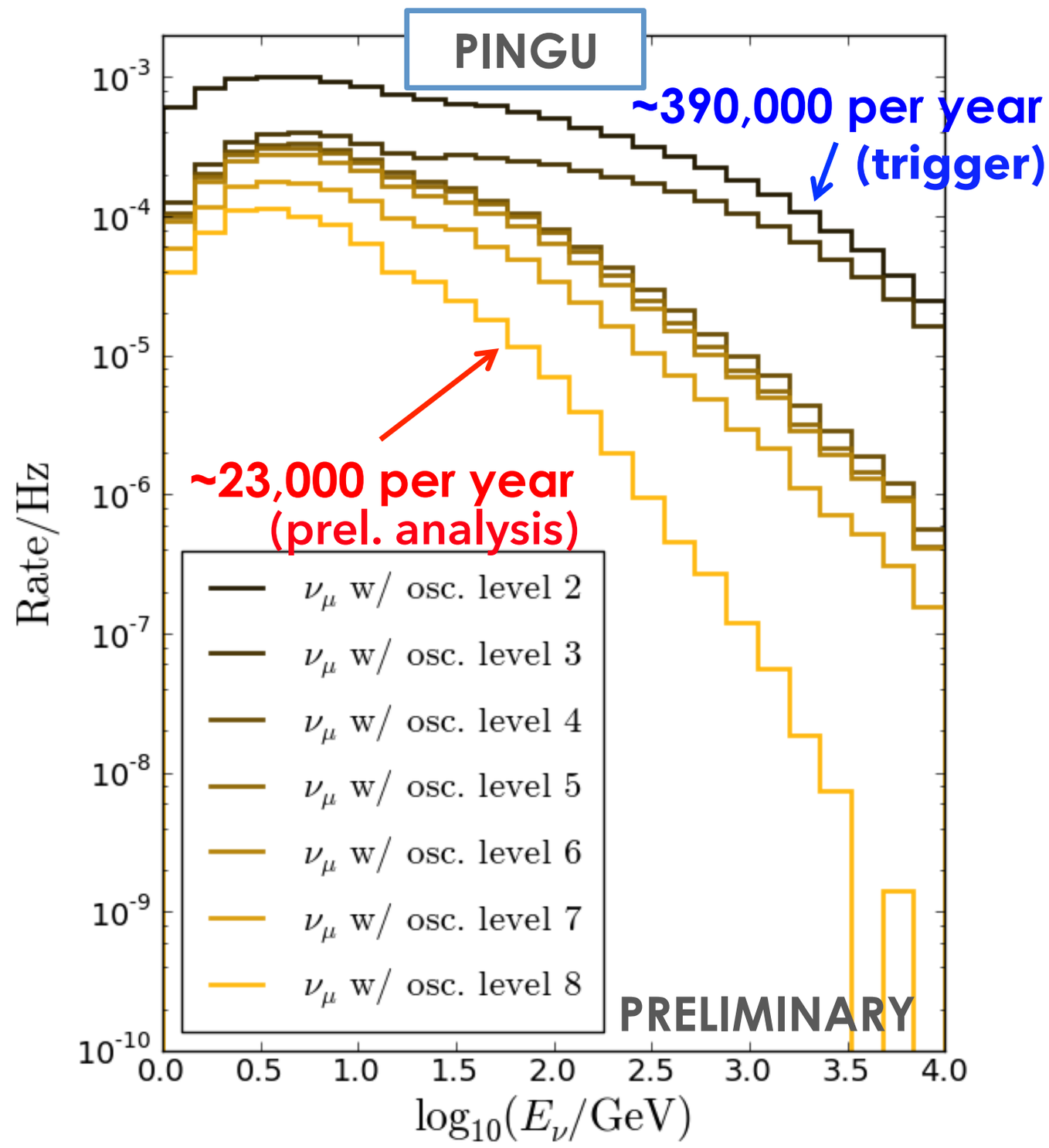
PINGU

- 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



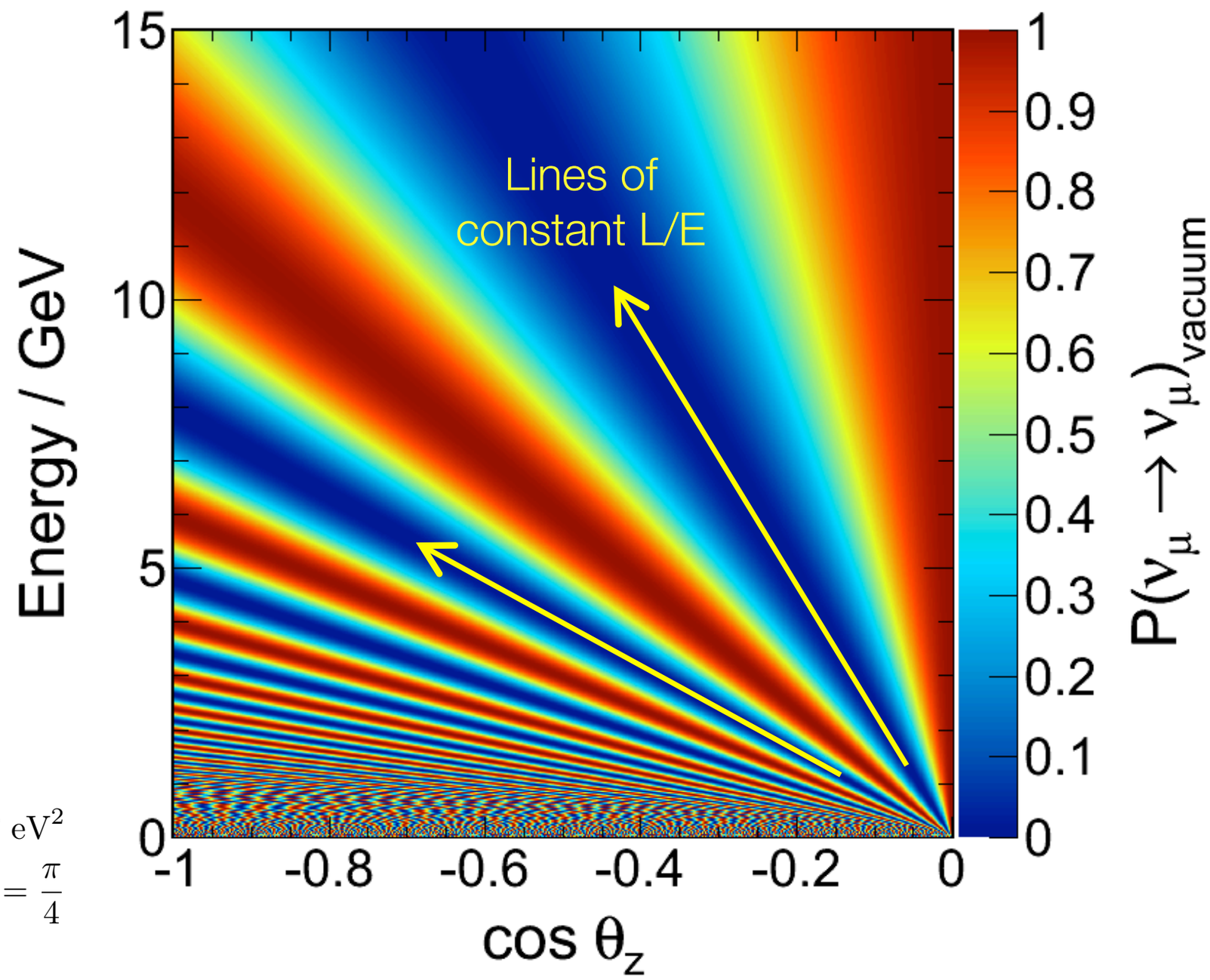
PINGU Energy Range

- 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

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

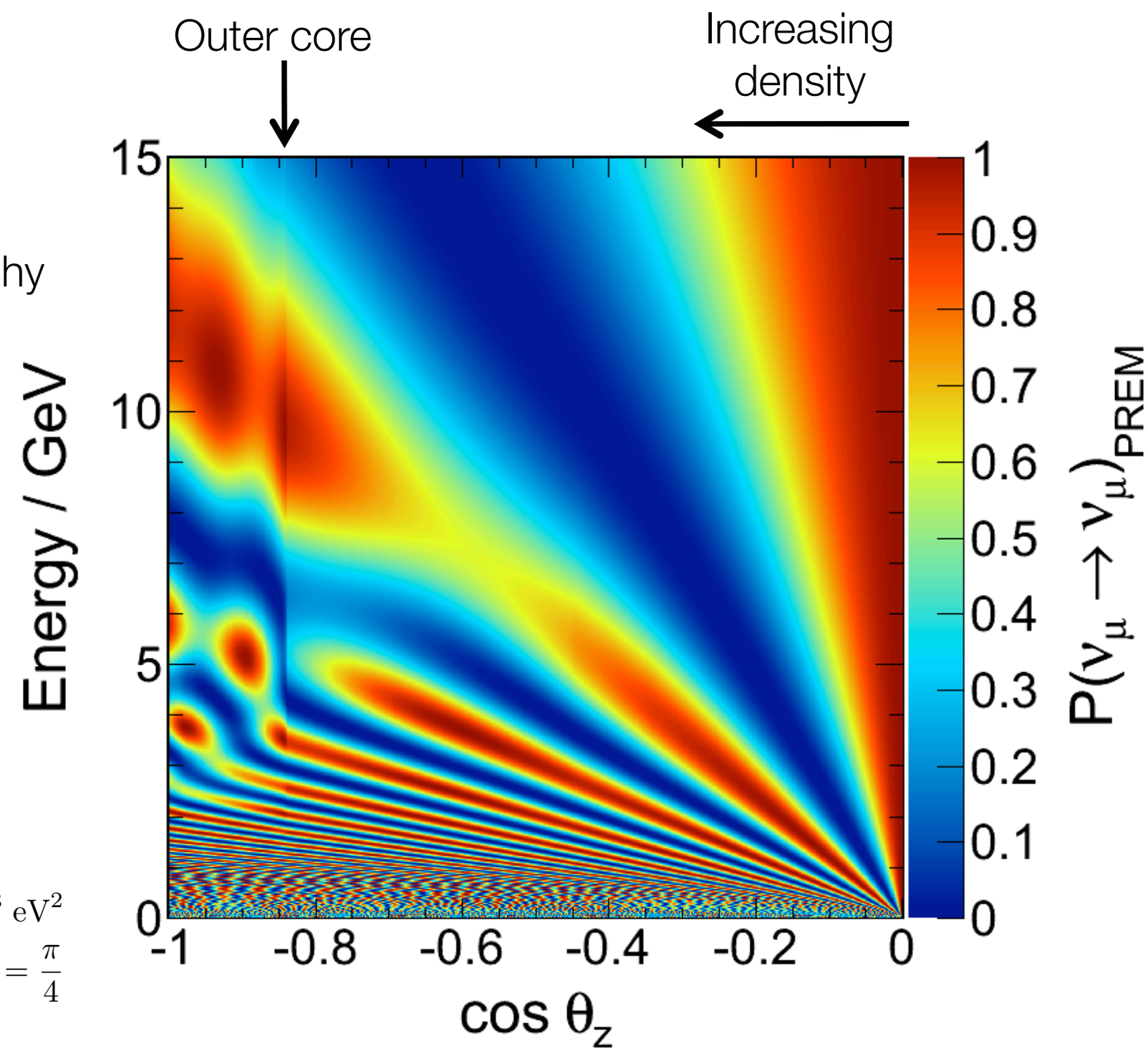


$$\Delta m^2_{32} = 2.32 \times 10^{-3}\ \mathrm{eV}^2$$

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

Neutrino Oscillations in Matter

Neutrinos
Normal hierarchy



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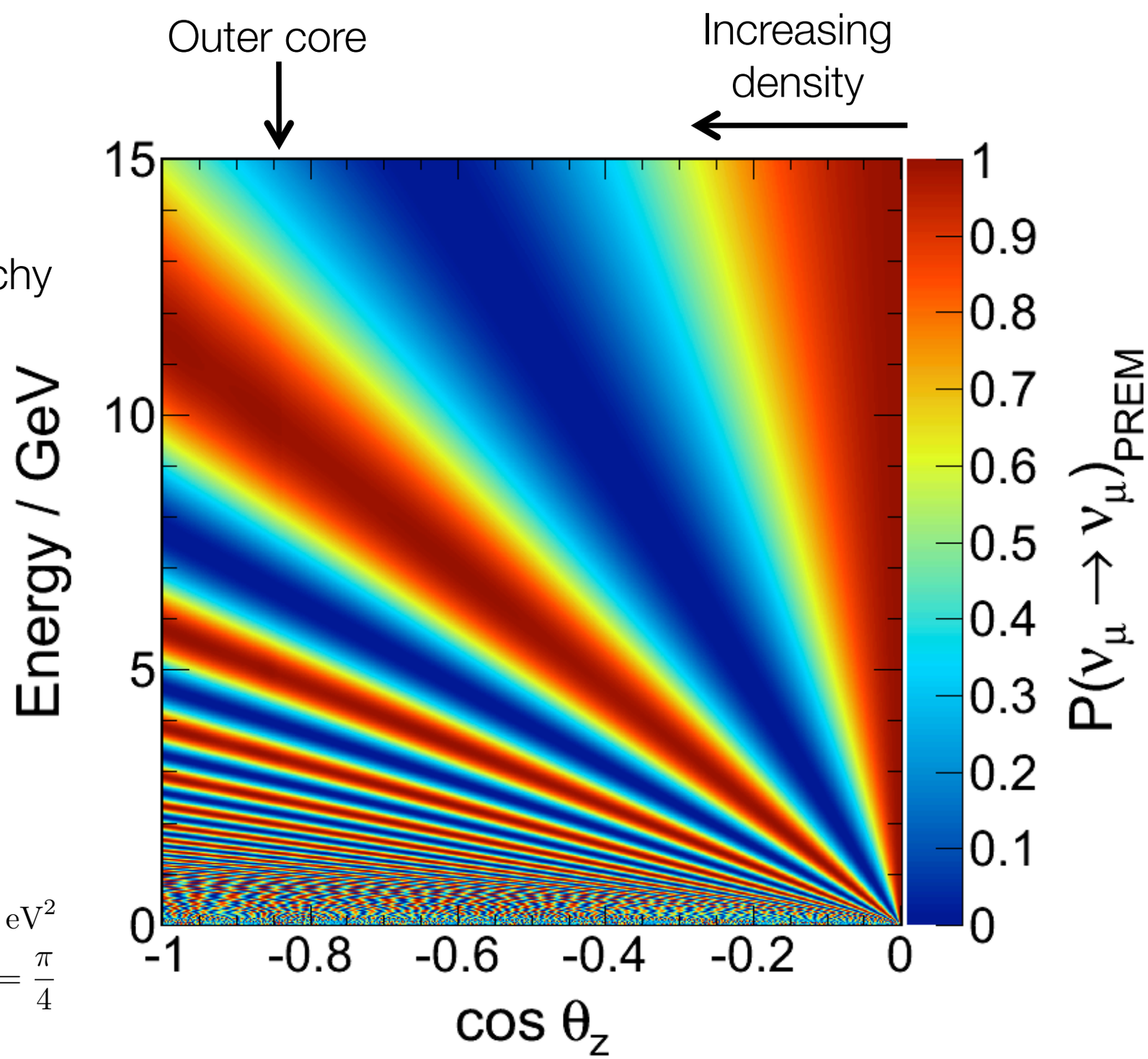
Neutrino Oscillations in Matter

Neutrinos
Inverted hierarchy



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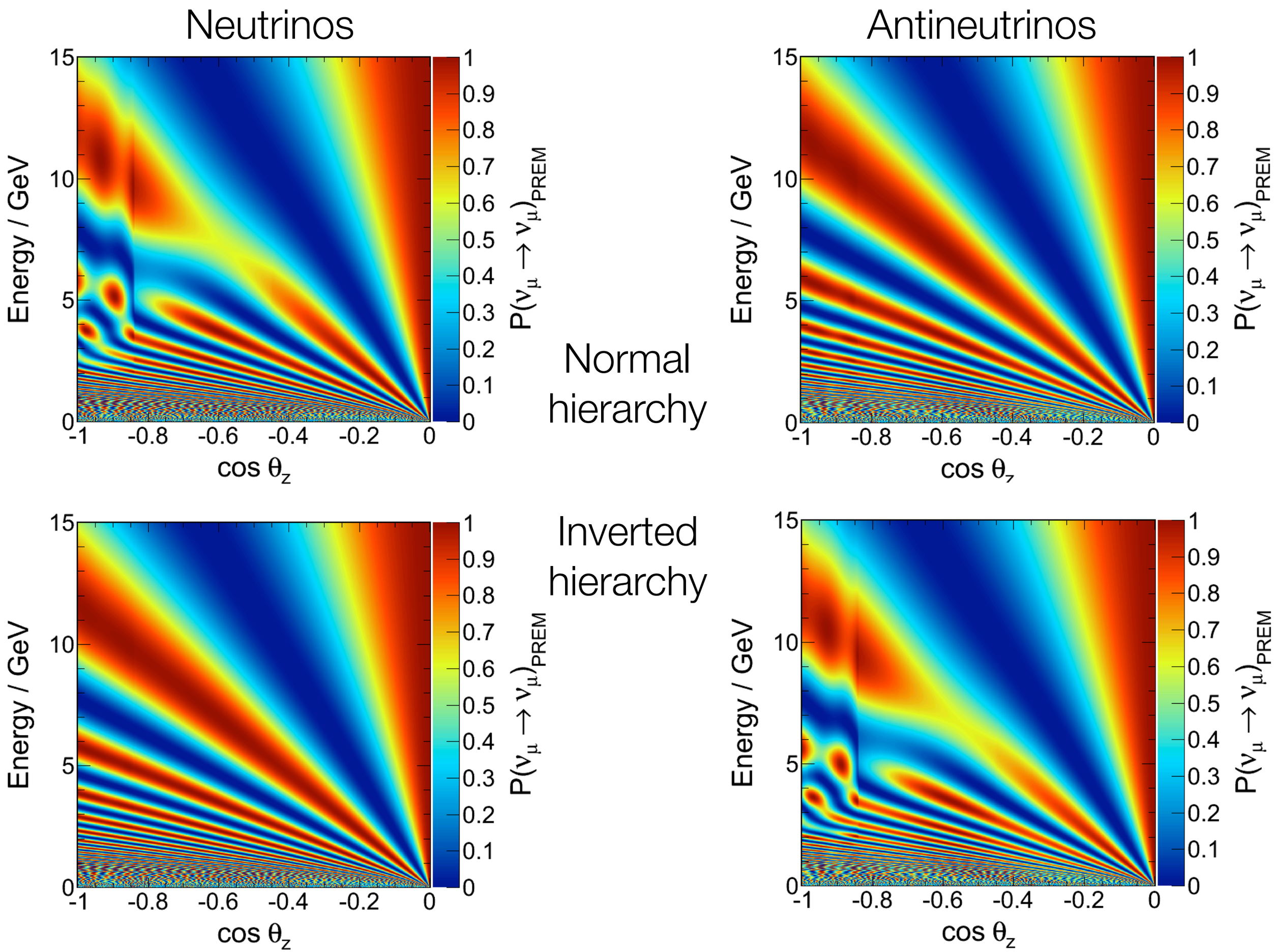
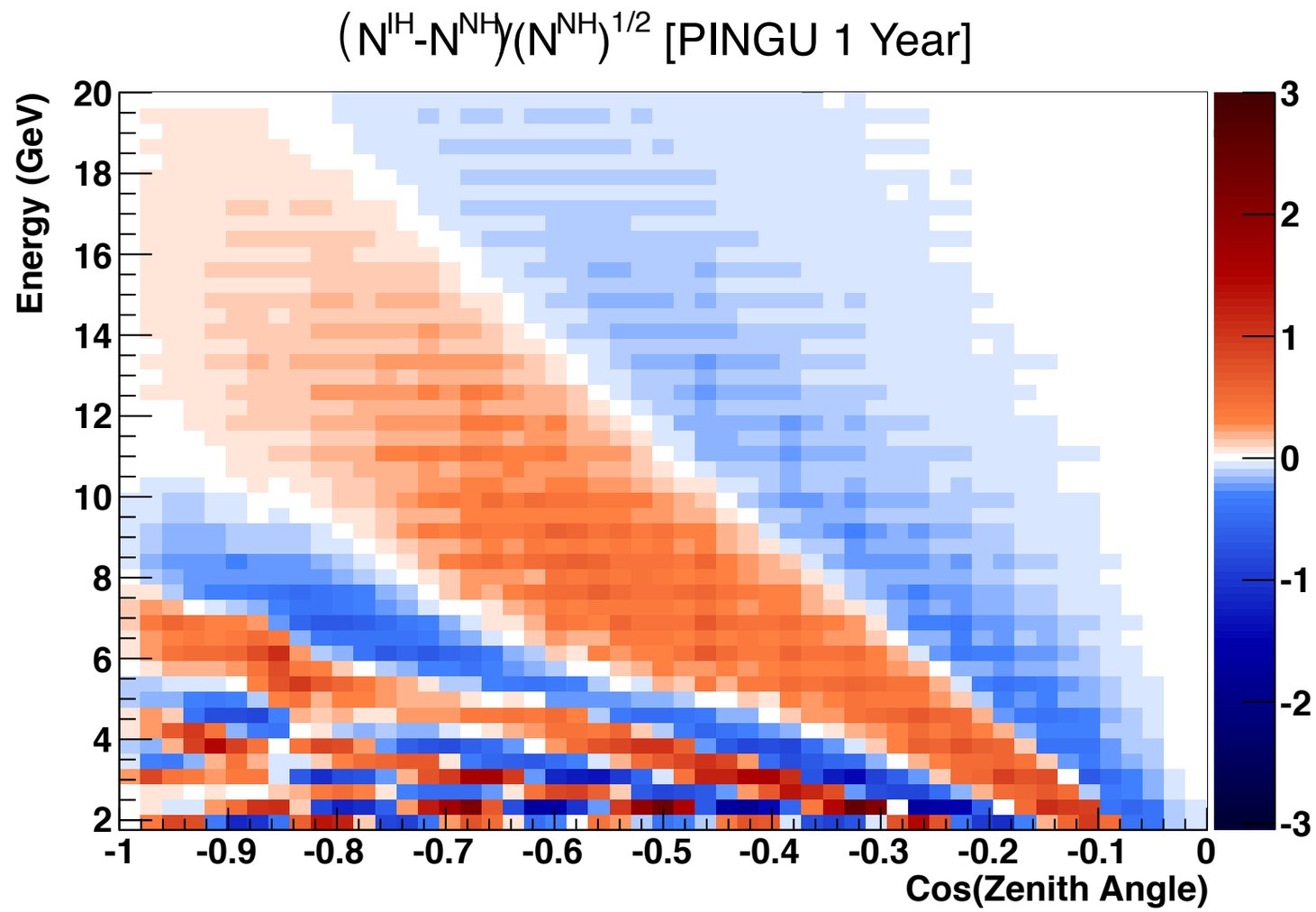

Neutrinos
Antineutrinos
Normal hierarchy
Inverted hierarchy
Energy / GeV
cos θz
P(νμ → νμ)PREM
15
10
5
0
-1
-0.8
-0.6
-0.4
-0.2
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Experimental Signature of the Mass Hierarchy

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



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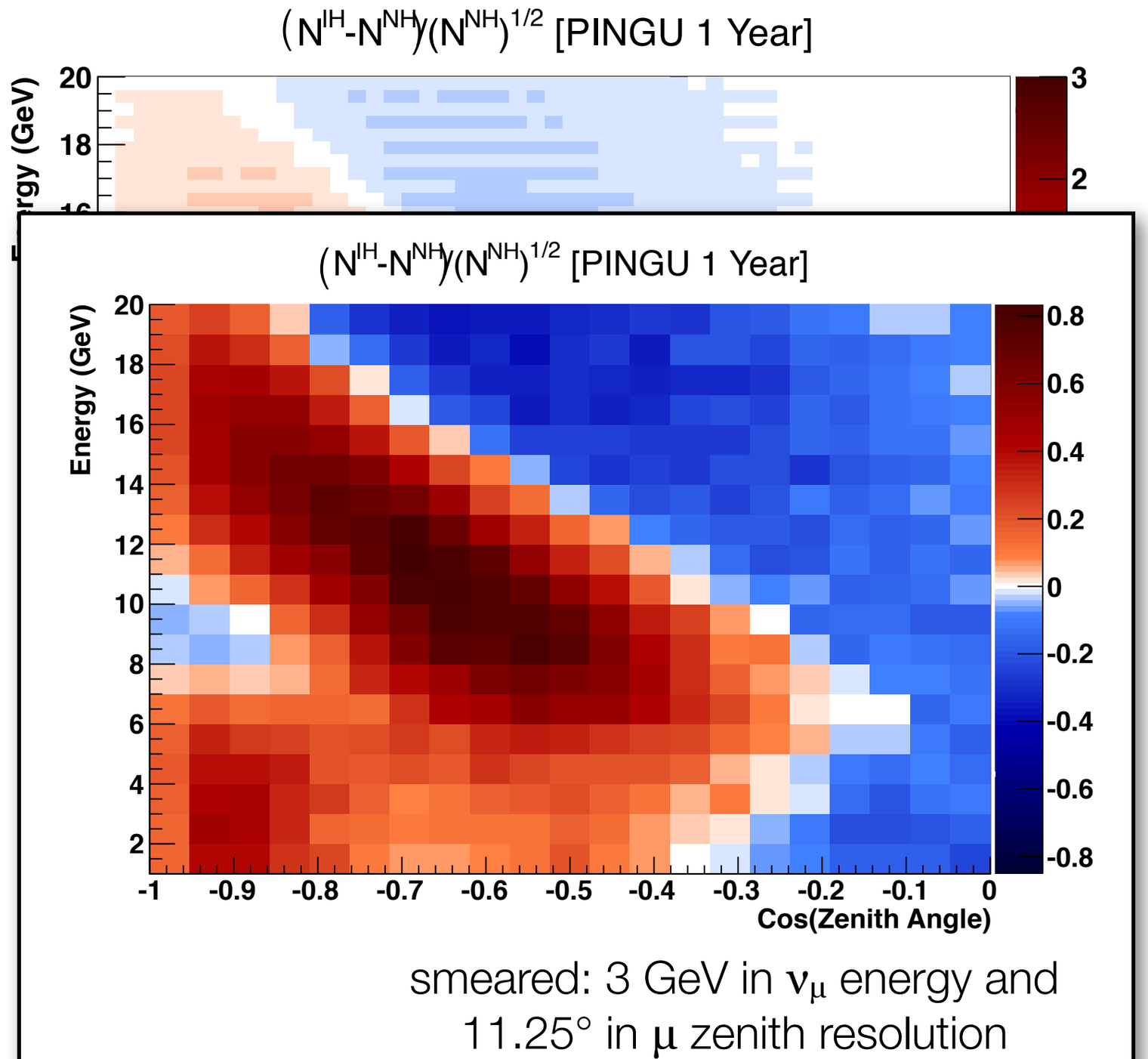
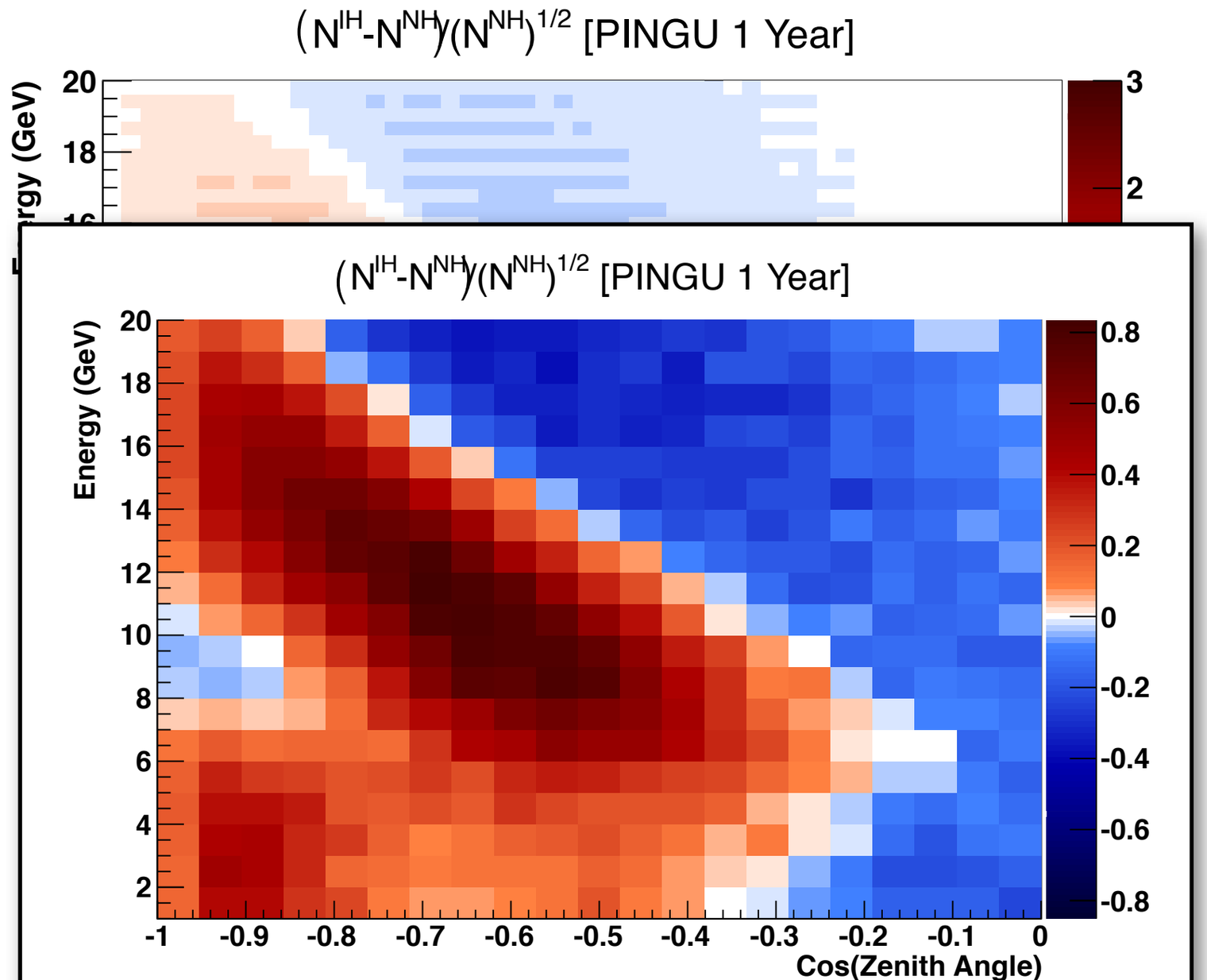


Experimental Signature of the Mass Hierarchy

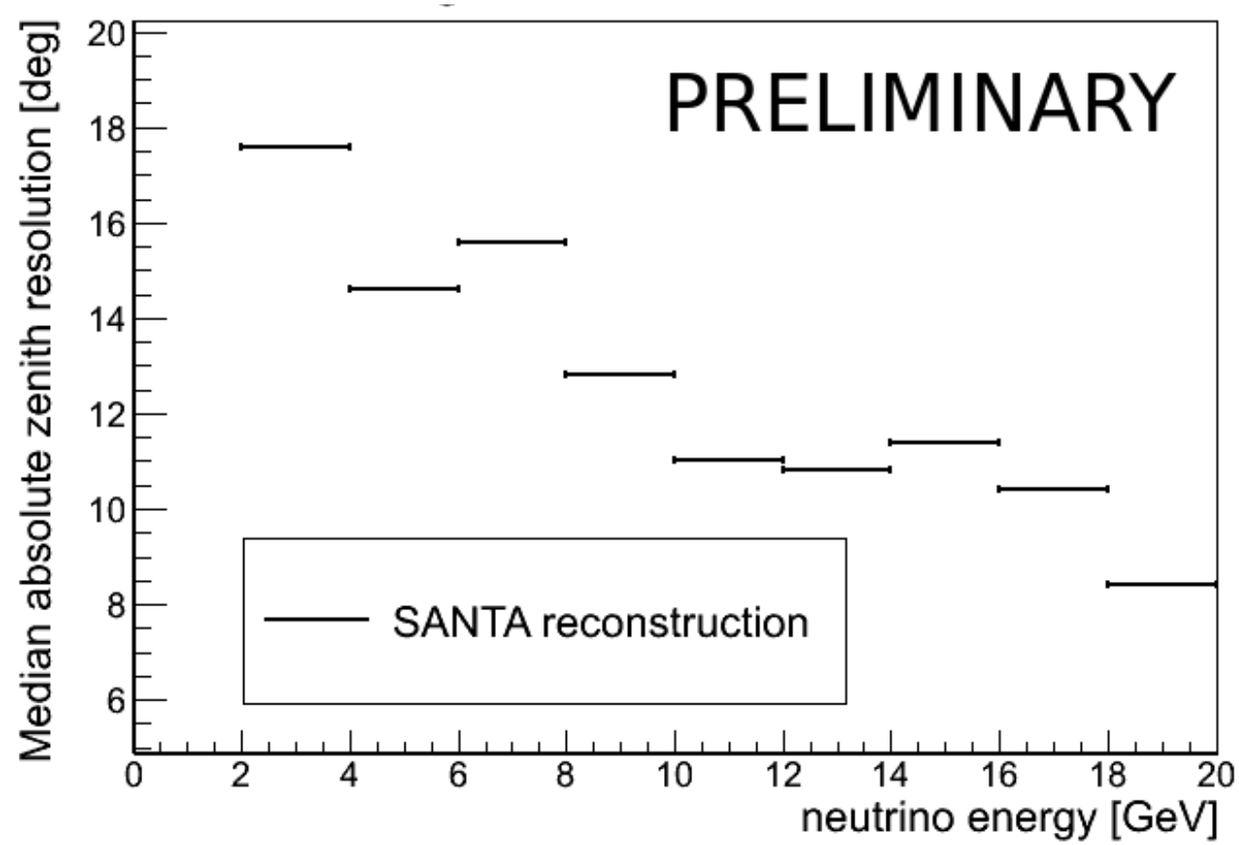
- Idealized case with no background, perfect flavor ID, 100% signal efficiency
  - Different assumed resolutions smear the signature but do not eliminate it
- Hierarchy signature is a distinctive structure in energy-angle plane
  - Key to our approach to controlling systematics

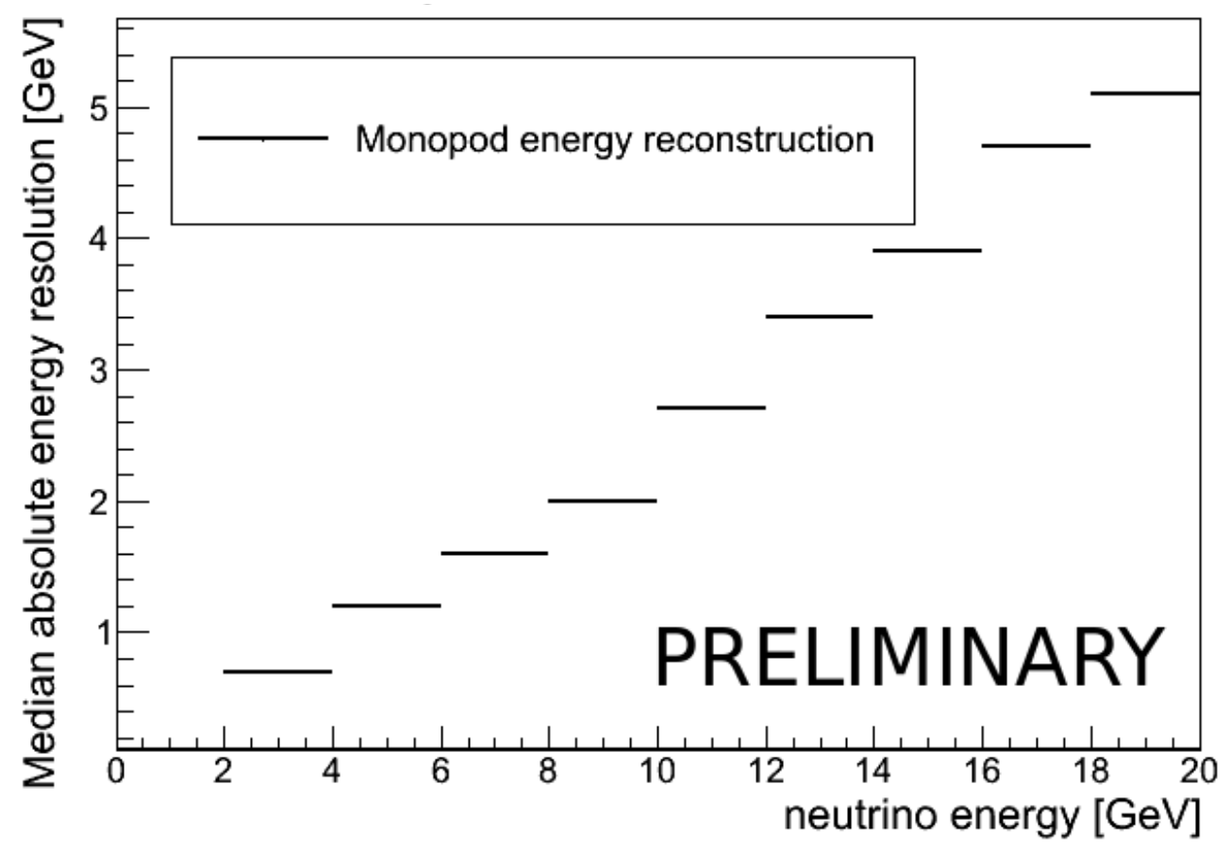


smeared: 3 GeV in ν_μ energy and 11.25° in μ zenith resolution

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

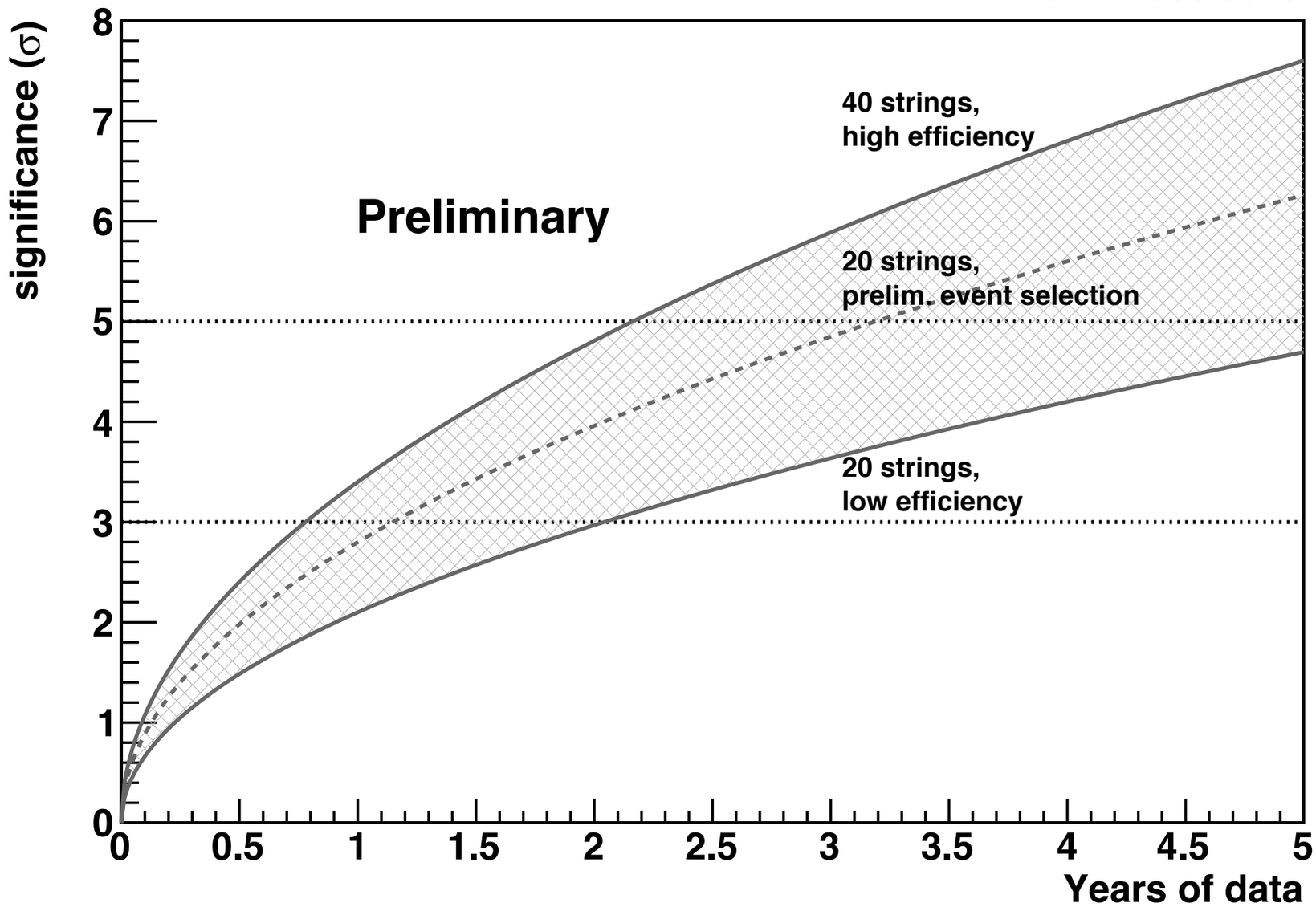




PINGU Hierarchy Sensitivity

- Sensitivity depends on final detector scope, assumed analysis efficiency, detector resolution, etc.
  - Caveat: not all systematics included in each study

arXiv:1306.5846



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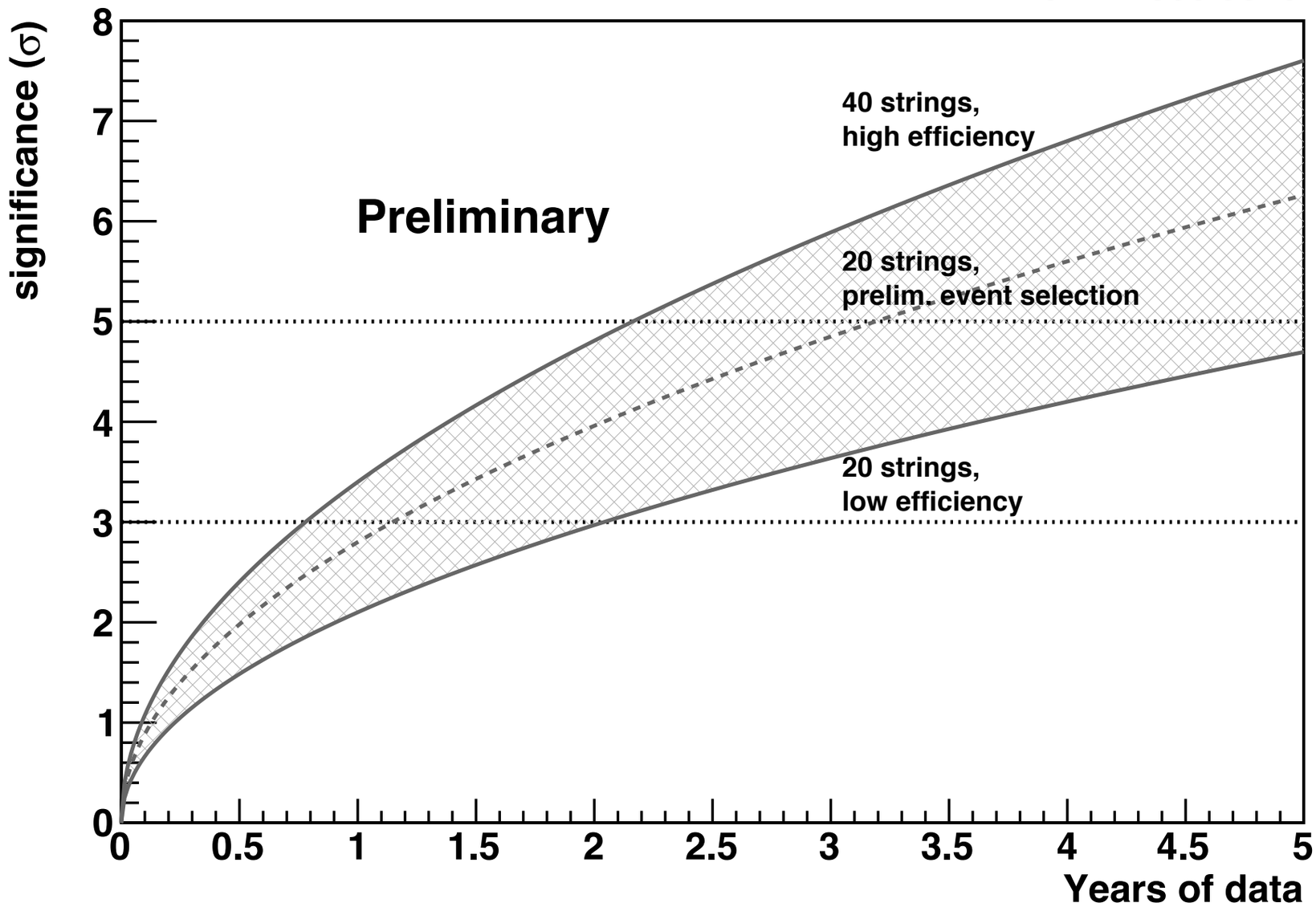

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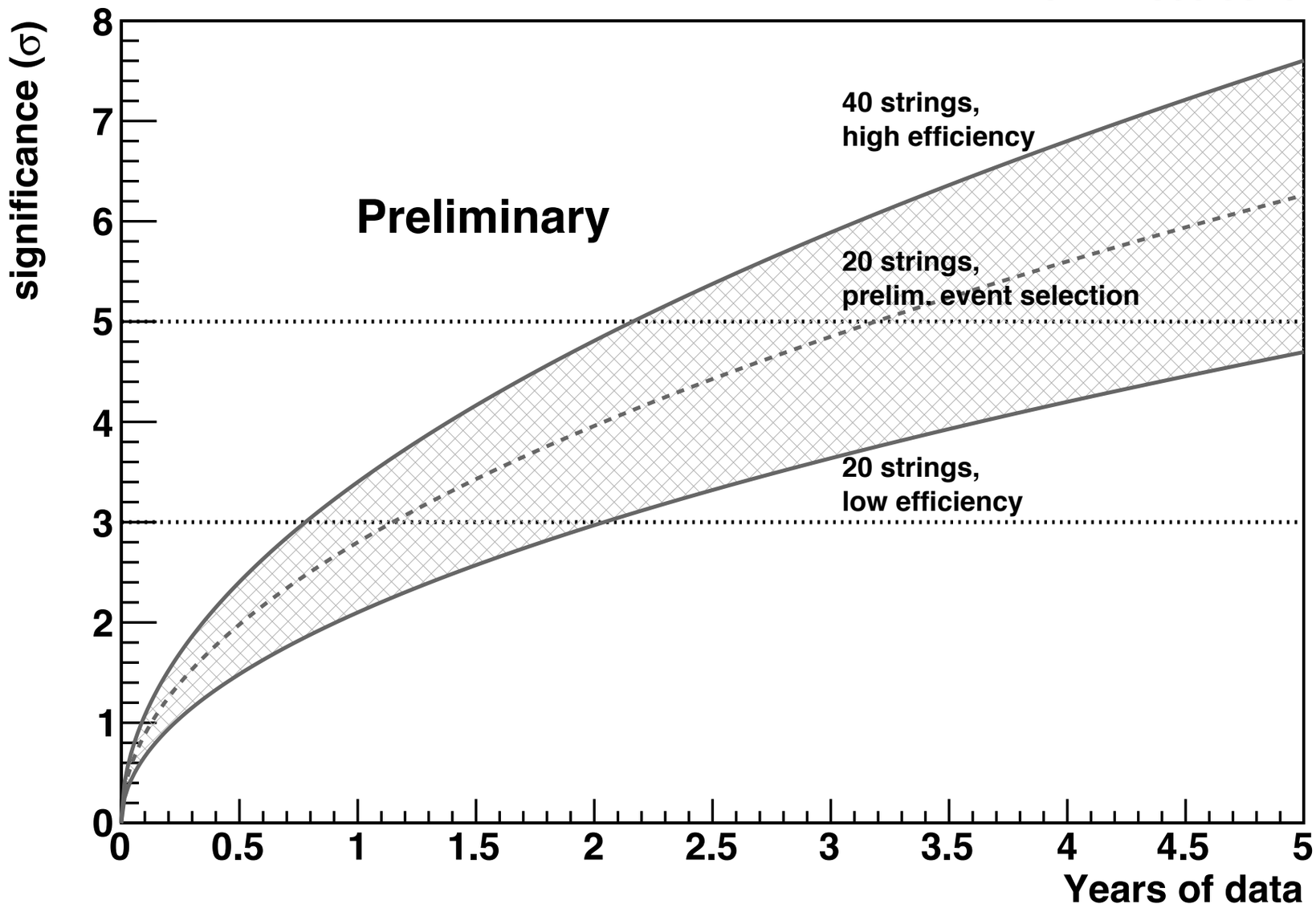


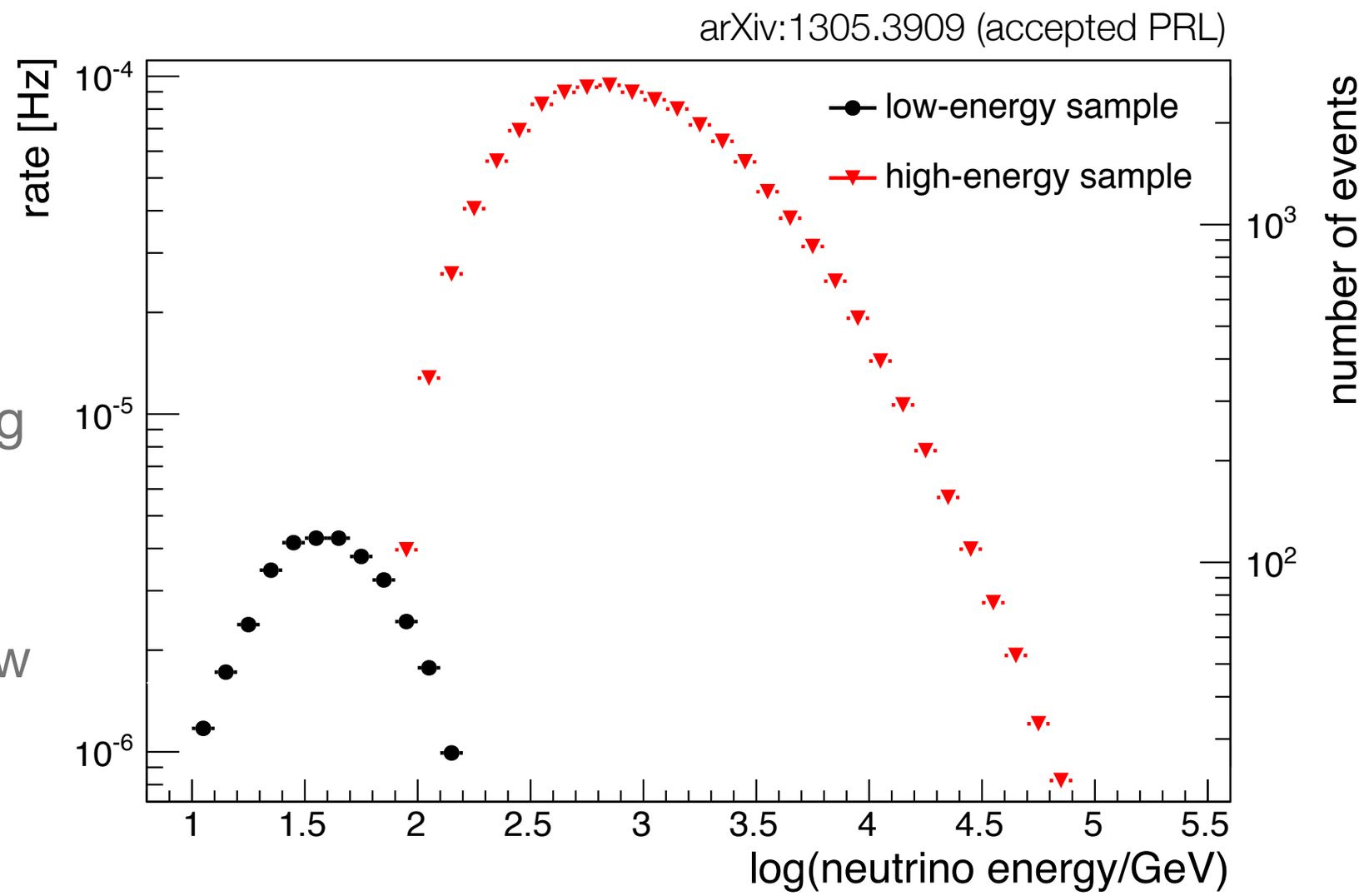
Advantages of PINGU

- 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

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



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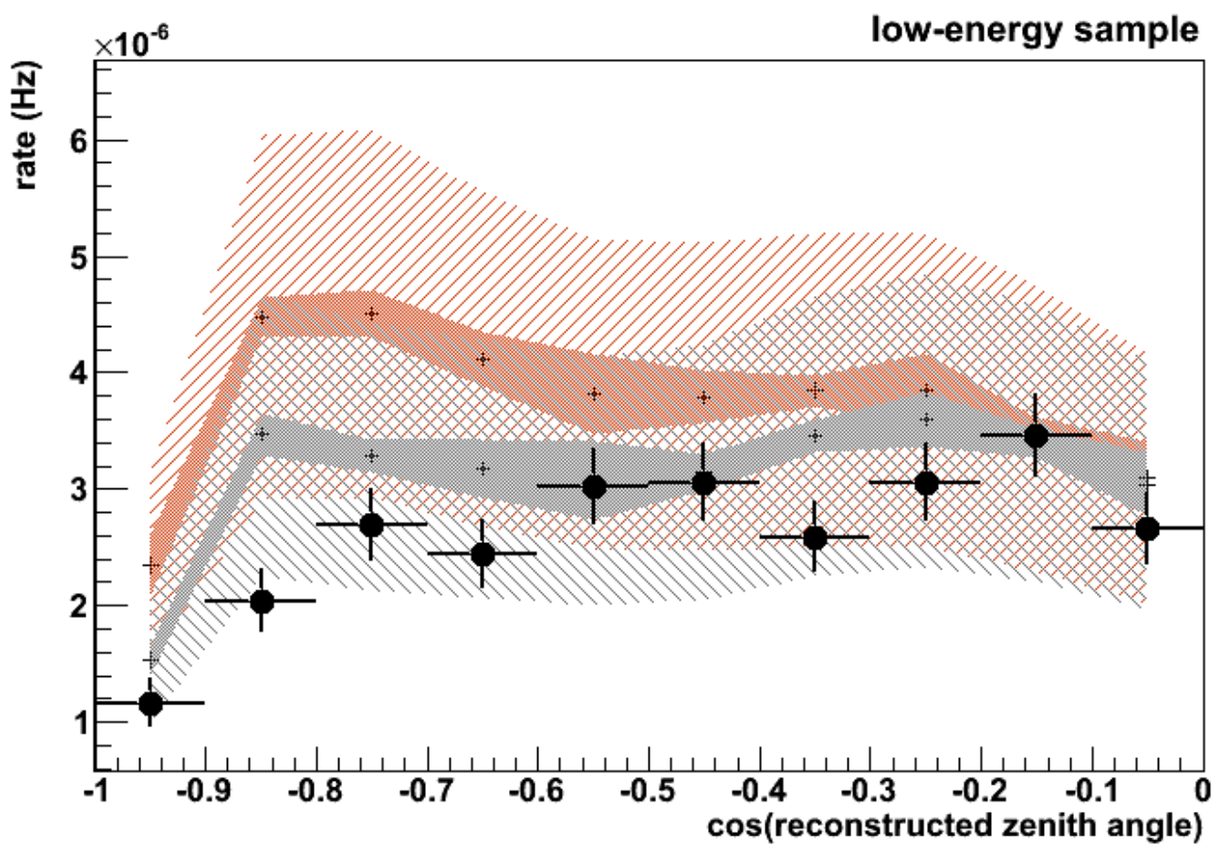
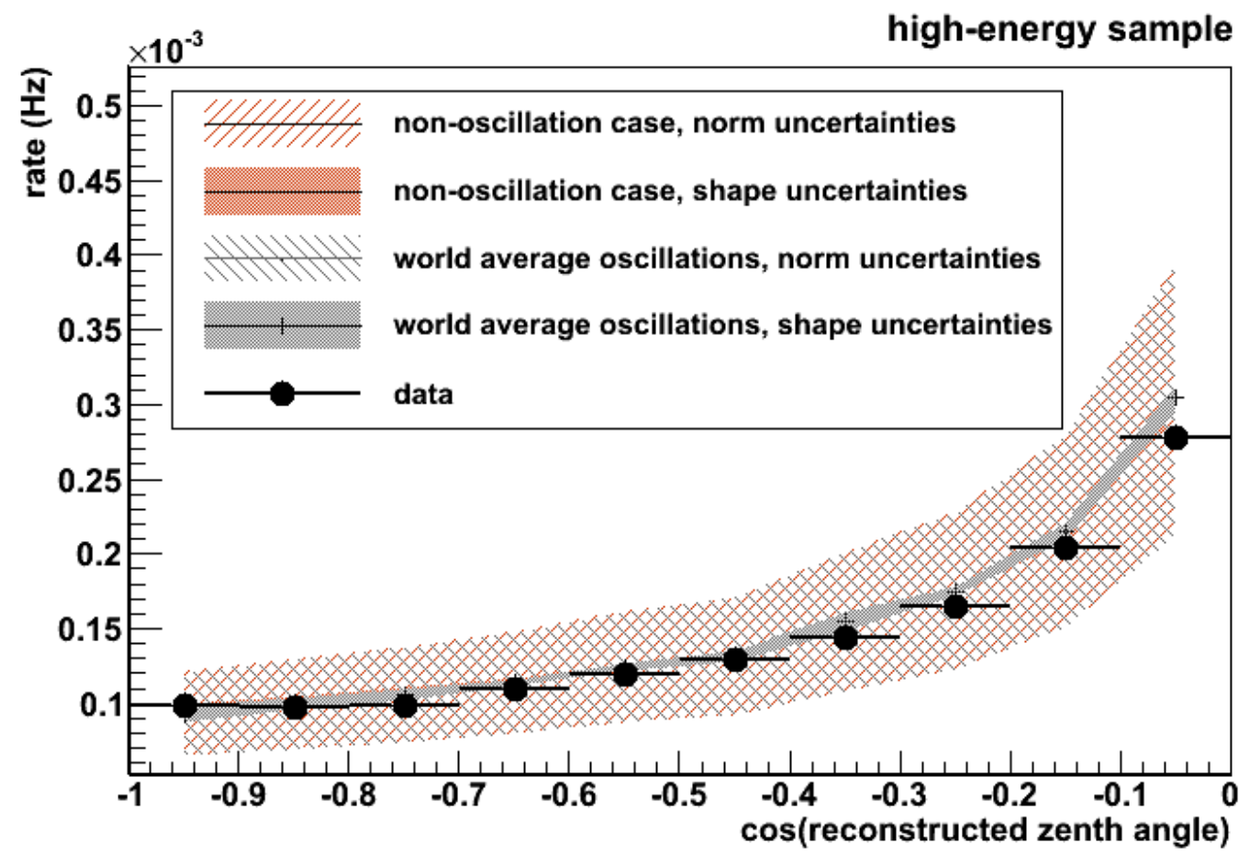


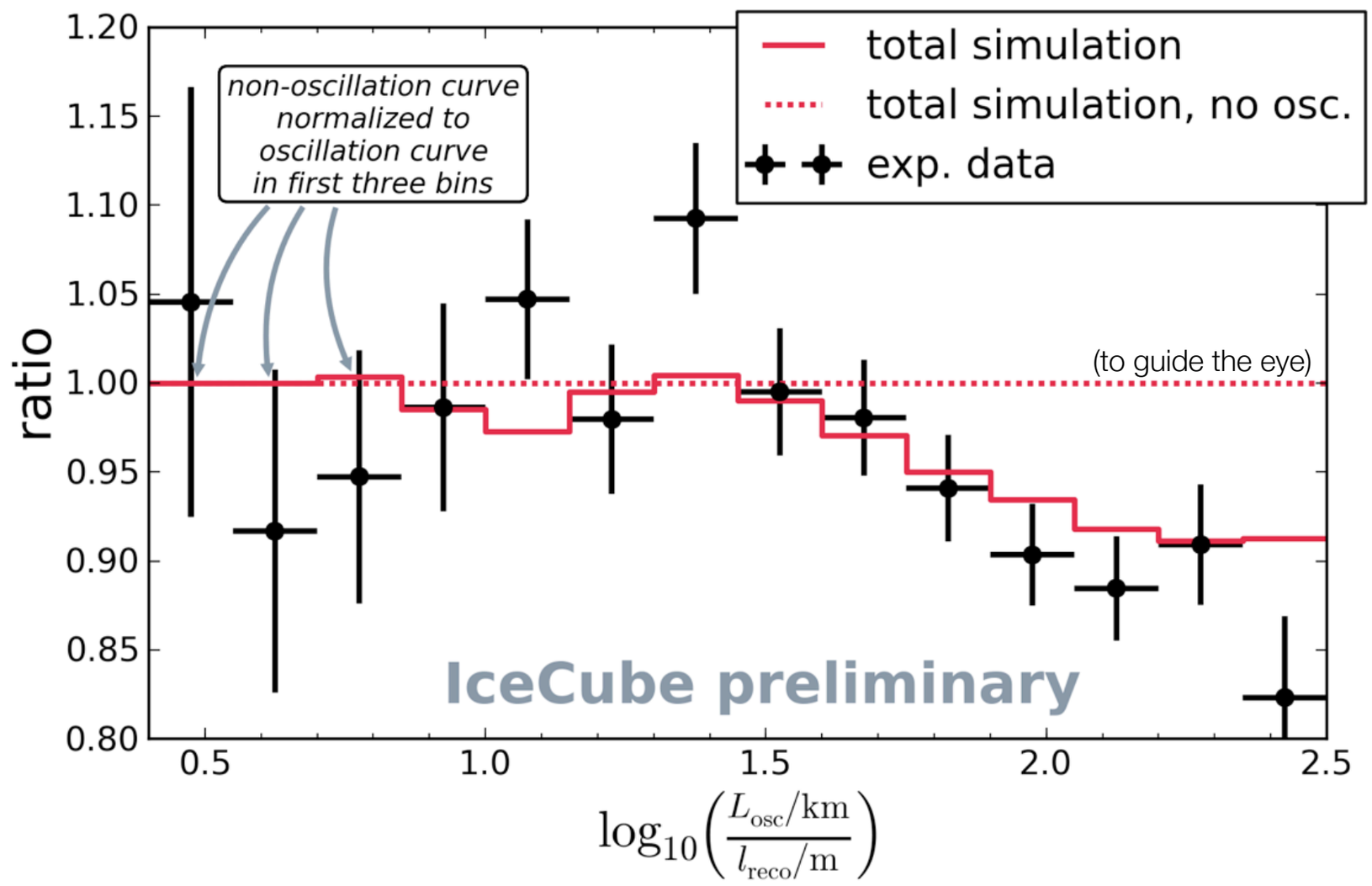


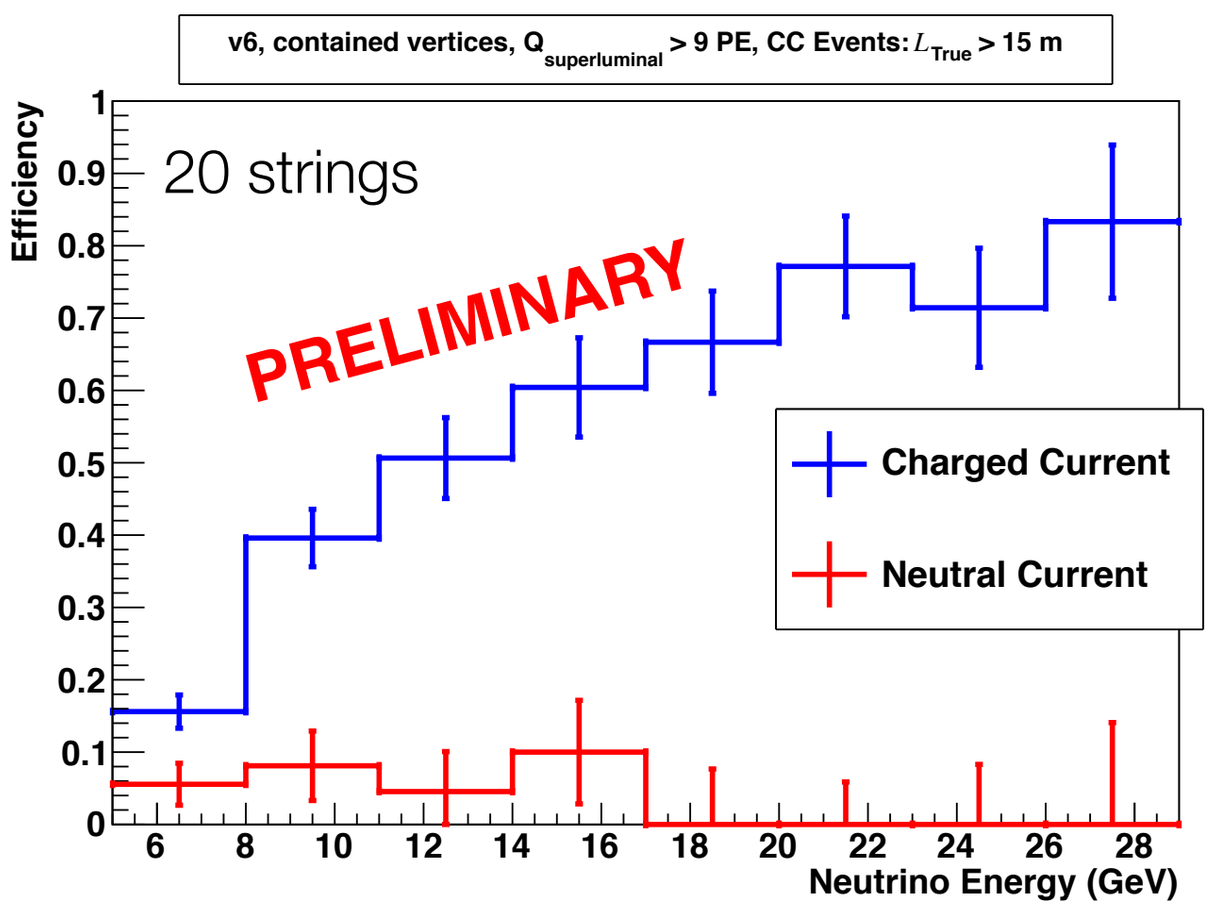
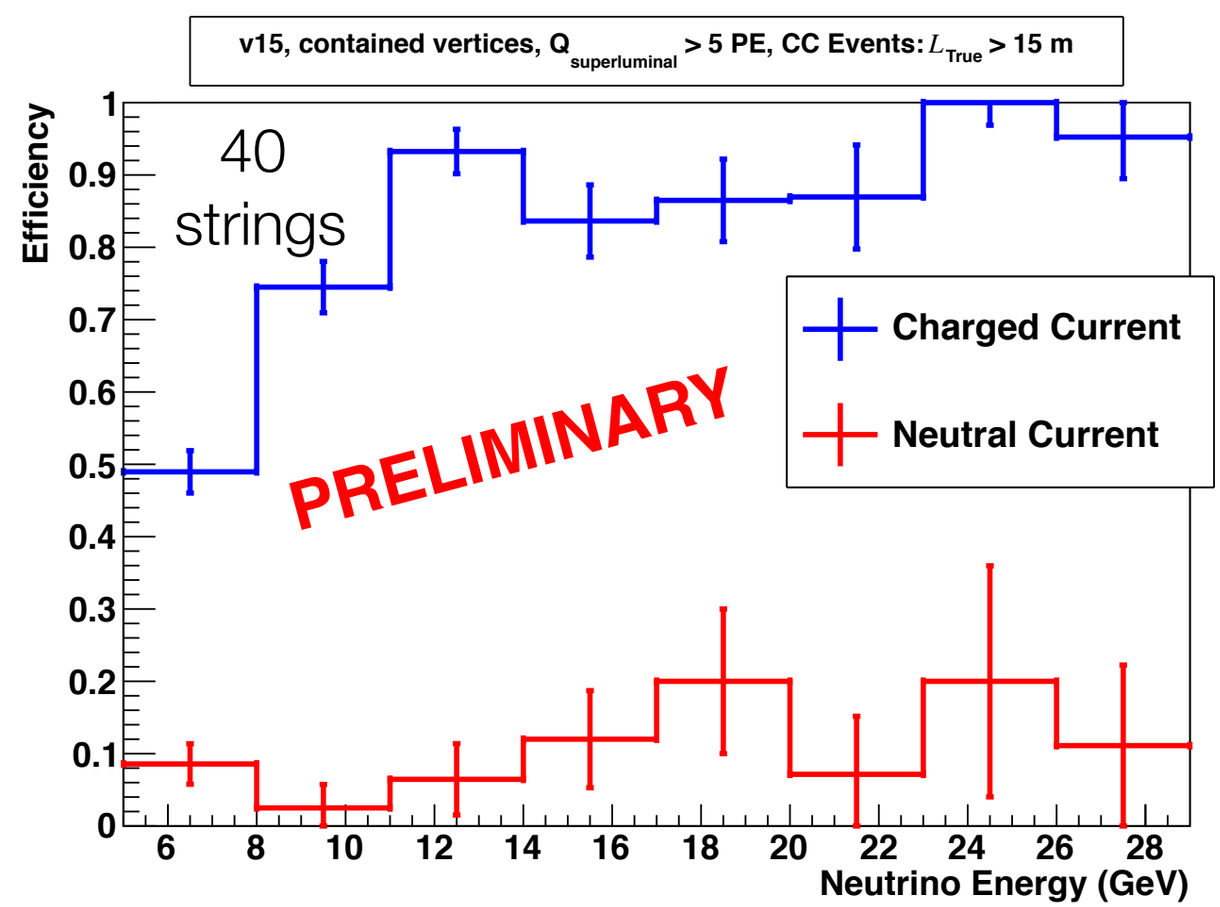
Statistically significant angle-dependent suppression at low energy, high energy sample provides constraint on uncertainties in simultaneous fit

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

Measuring 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



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