Neutrino Oscillations with DeepCore and PINGU

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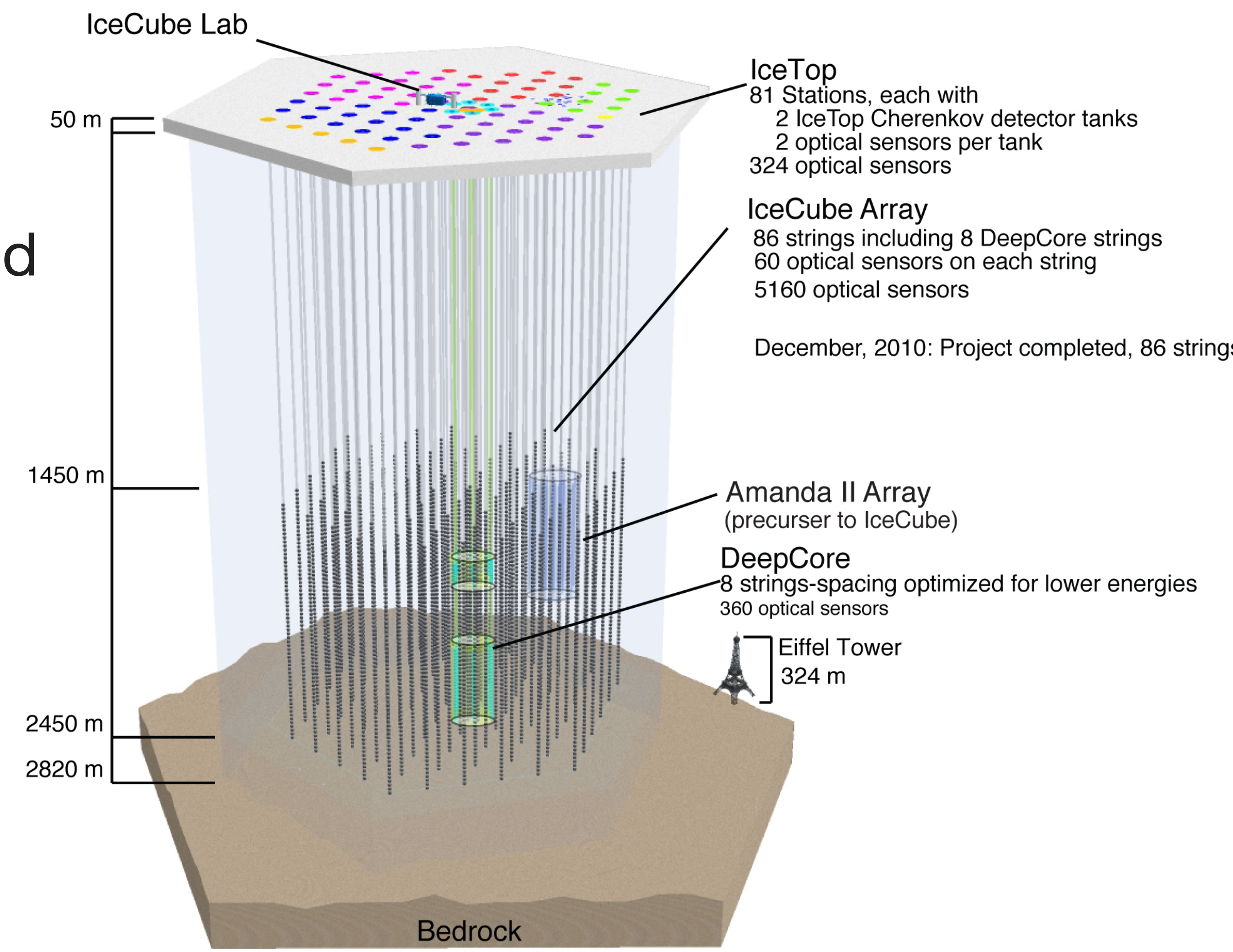
ICECUBE

IceCube DeepCore

- Original IceCube design focused on neutrinos with energies above a few hundred GeV
- DeepCore provides reduced volume with lower energy threshold



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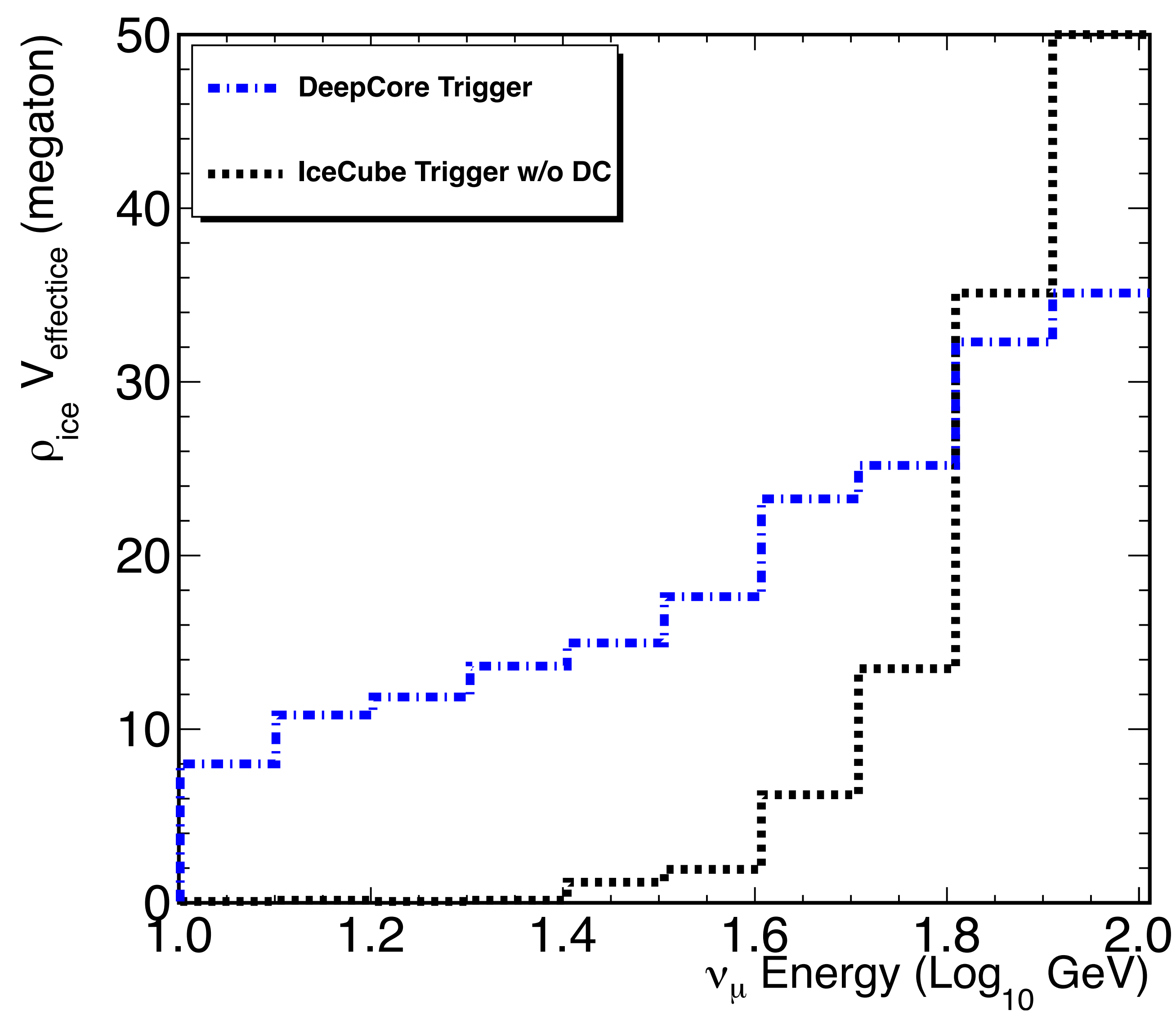
  - Note: comparison at trigger level – analysis efficiencies not included (typically ~10%)



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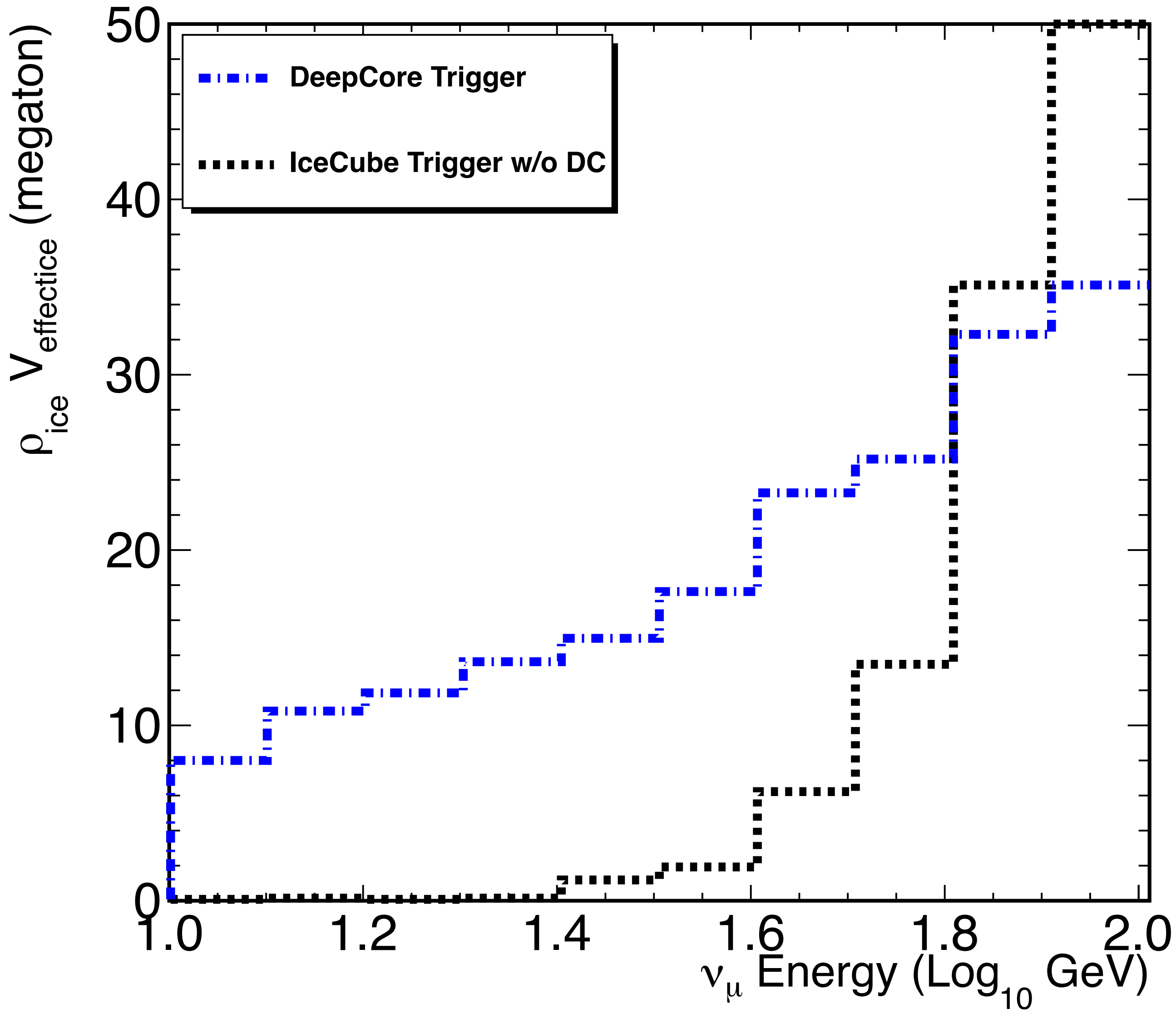
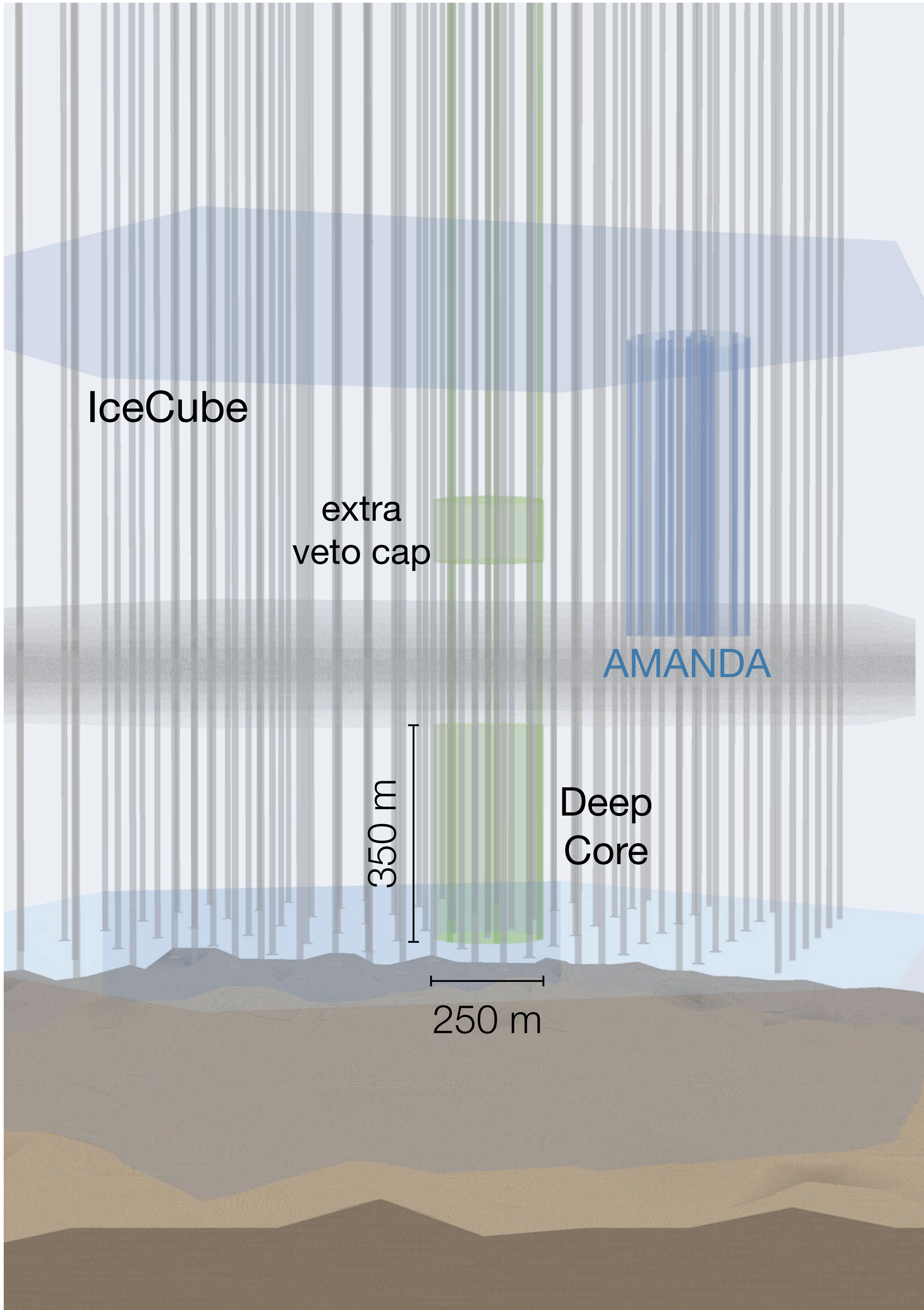
- $\mathcal{O}(10^5)$ atmospheric neutrino triggers per year



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



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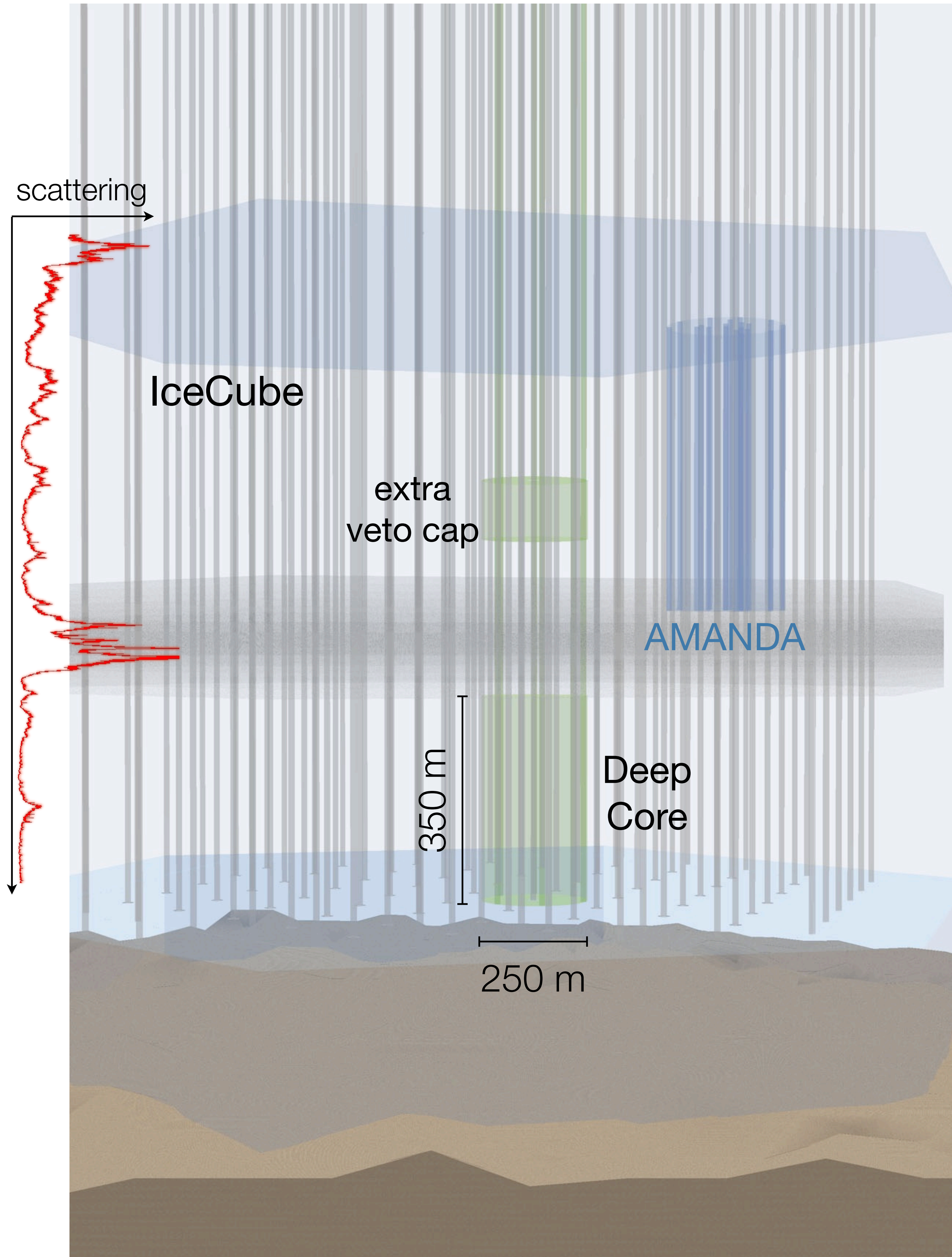

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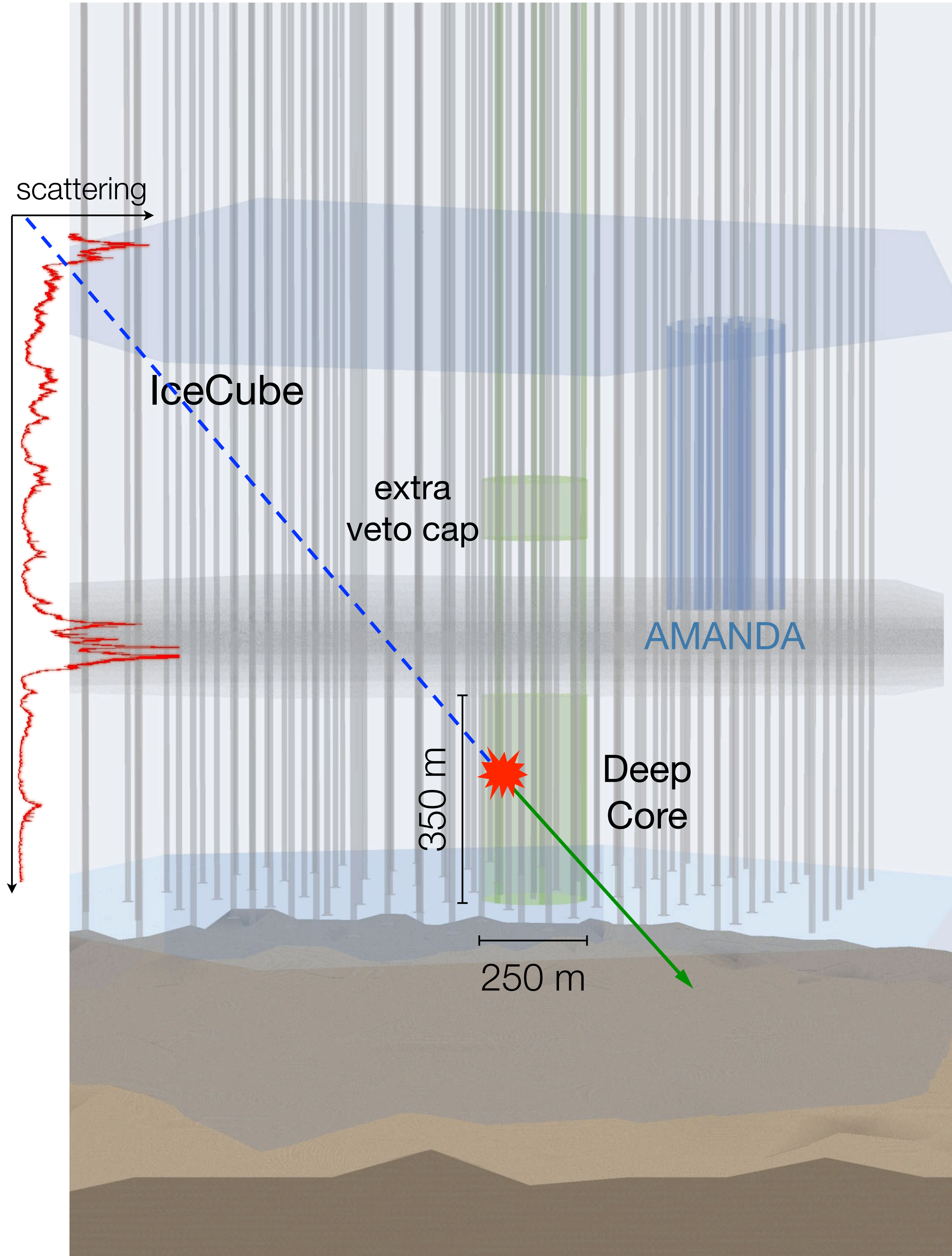

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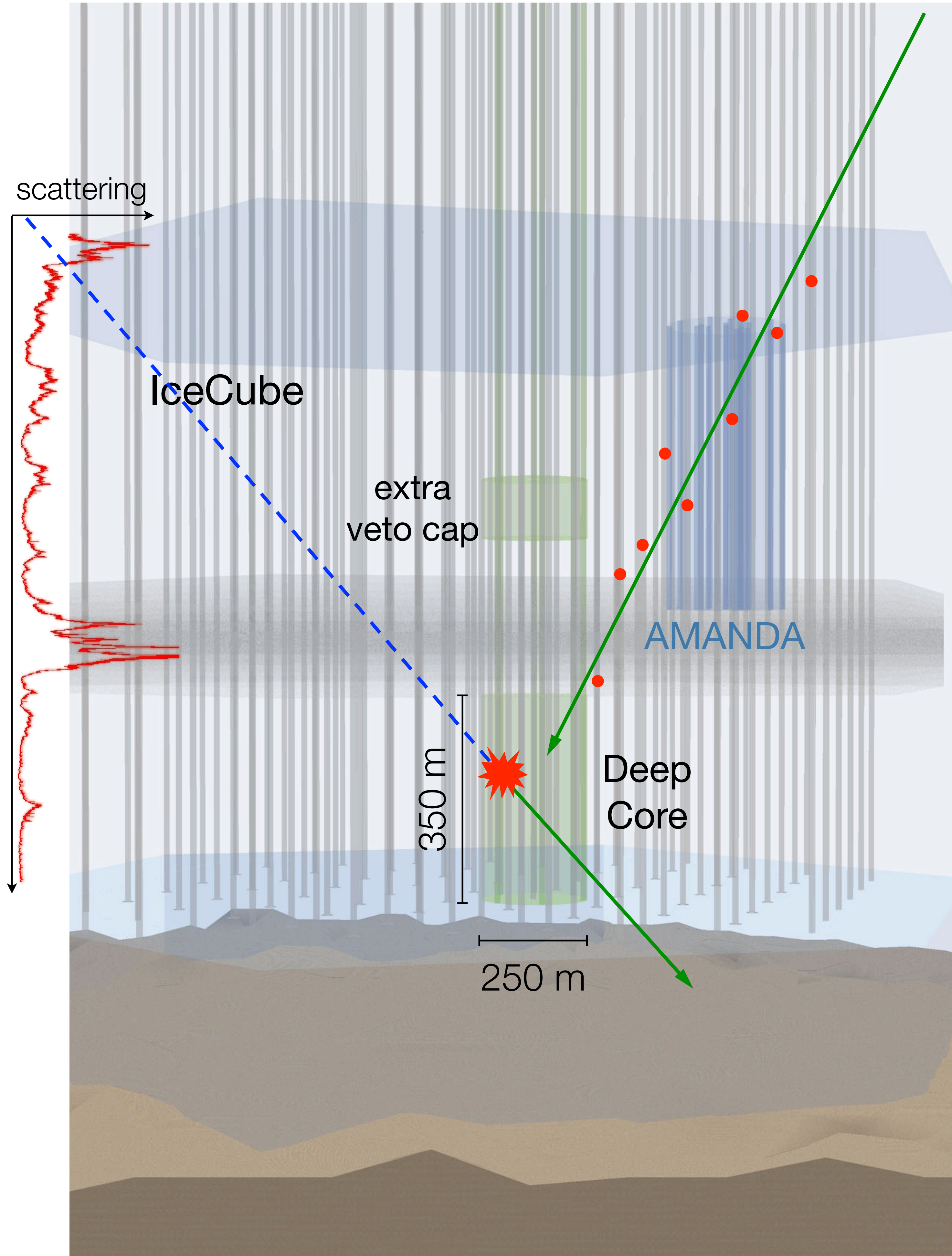
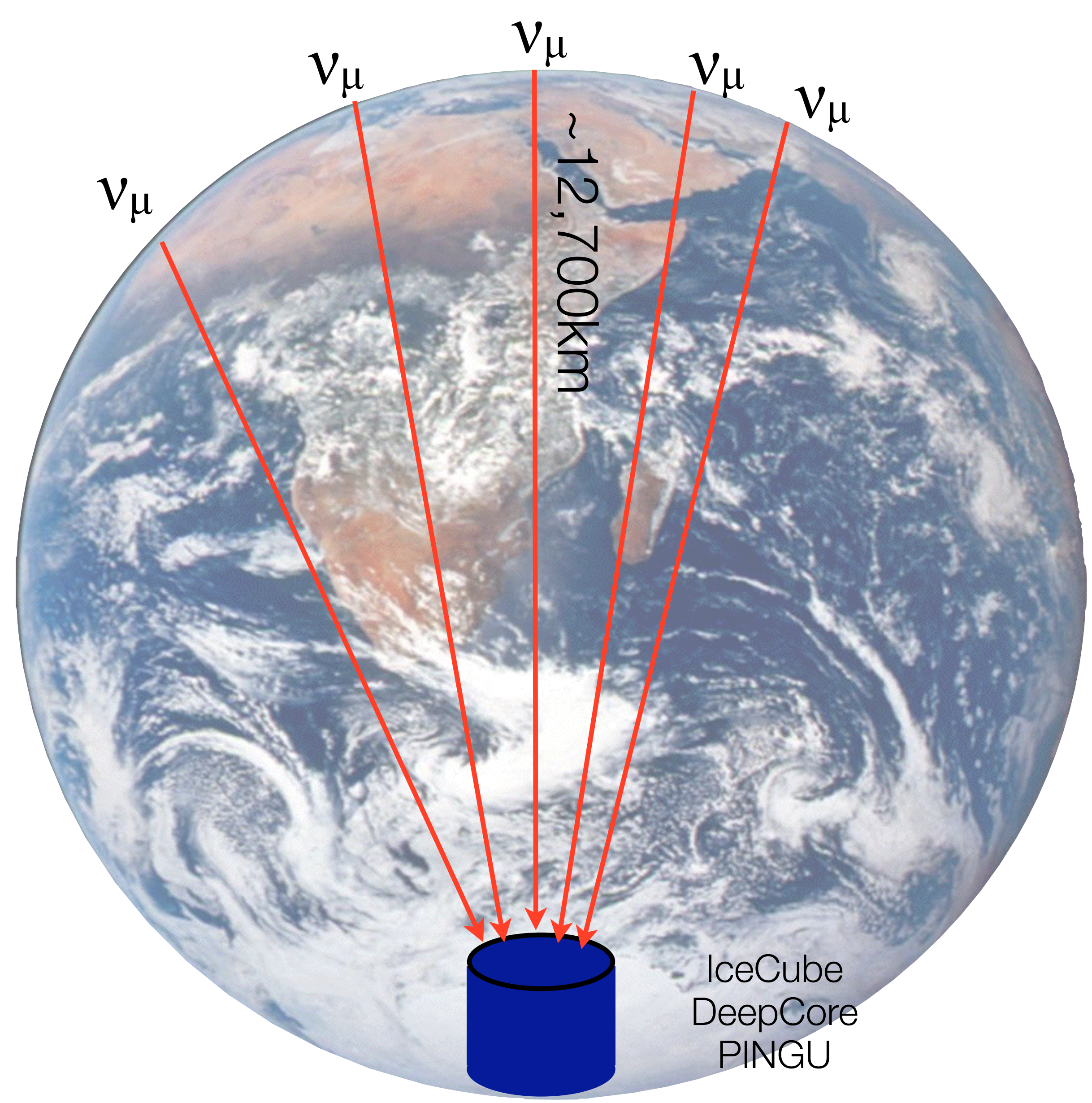


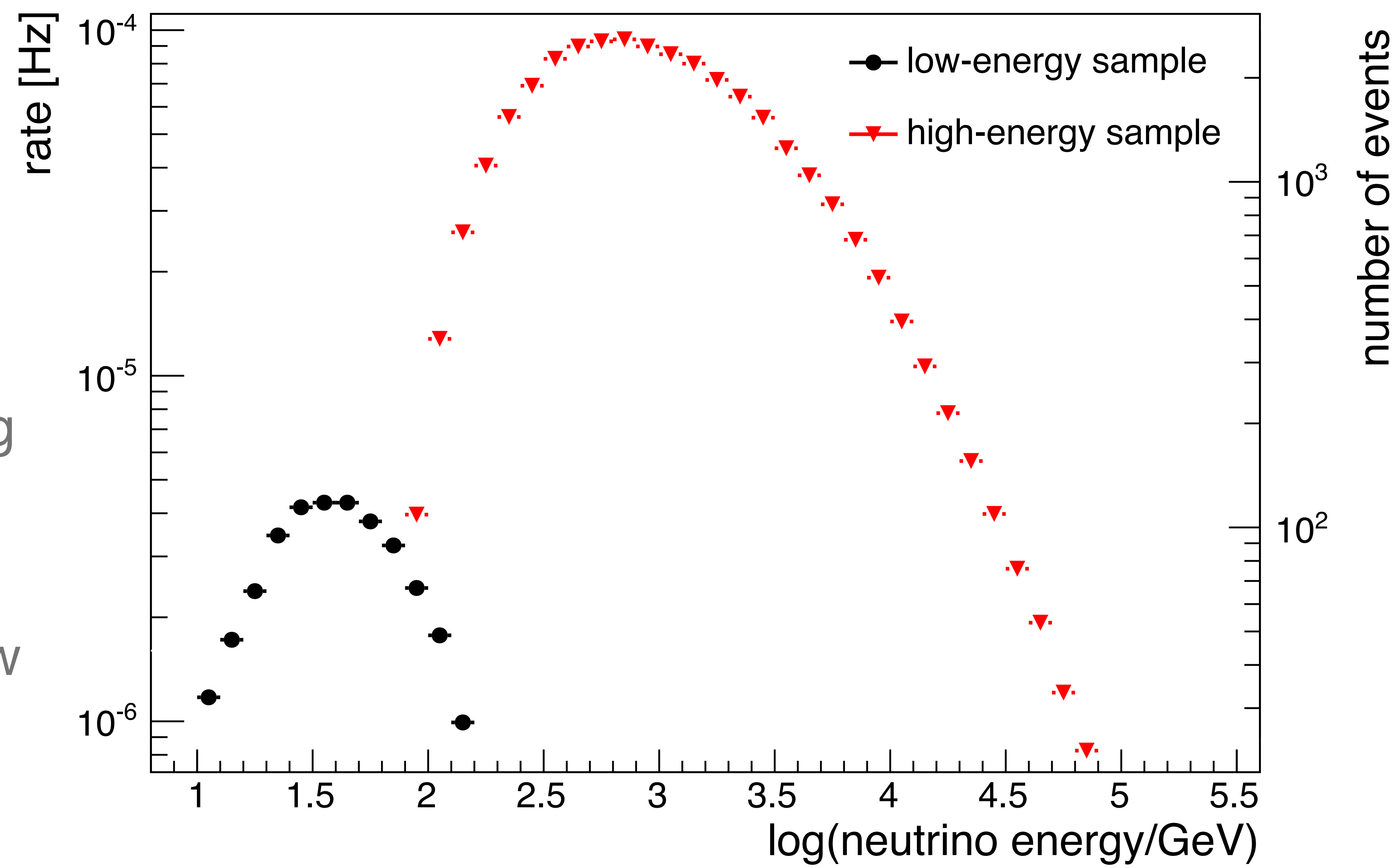
Oscillations with Atmospheric Neutrinos

- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Corresponding maximum in ν_τ appearance probability
- Neutrinos from all terrestrial baselines are available for free
  - Compare observations from different baselines and energies to mitigate impact of systematics
- Hierarchy-dependent matter effects below ~10-20 GeV

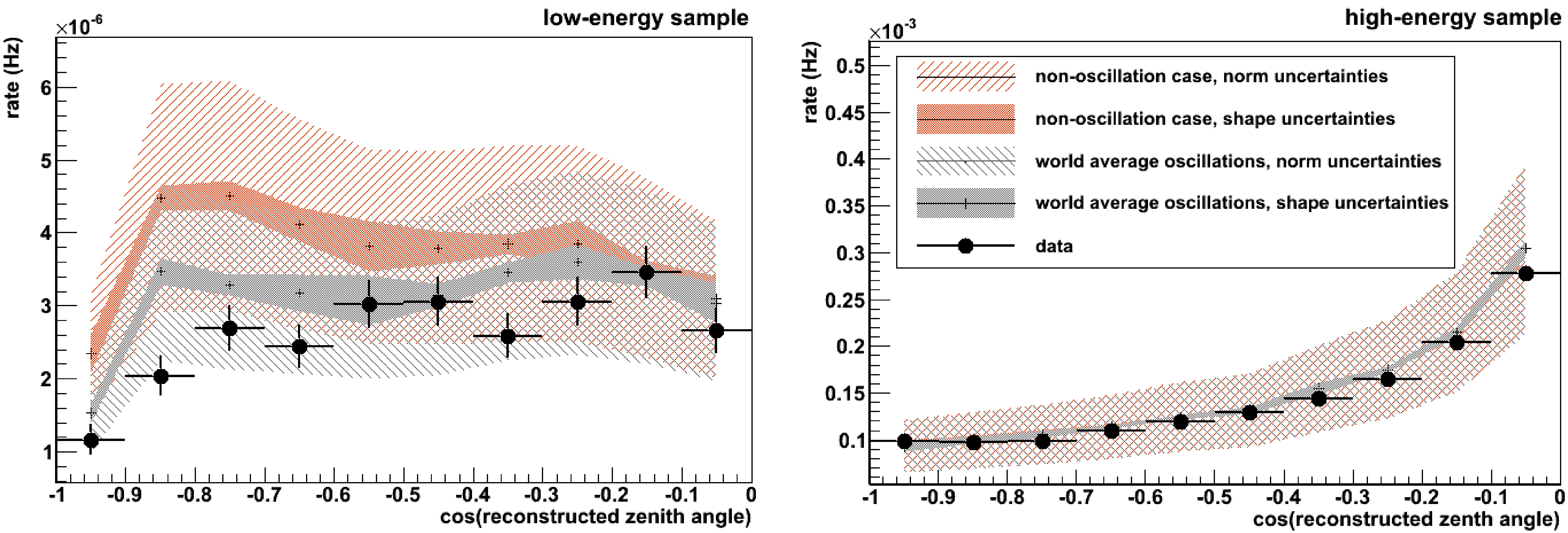


Muon Disappearance

- As a first step, 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



Muon Neutrino Disappearance

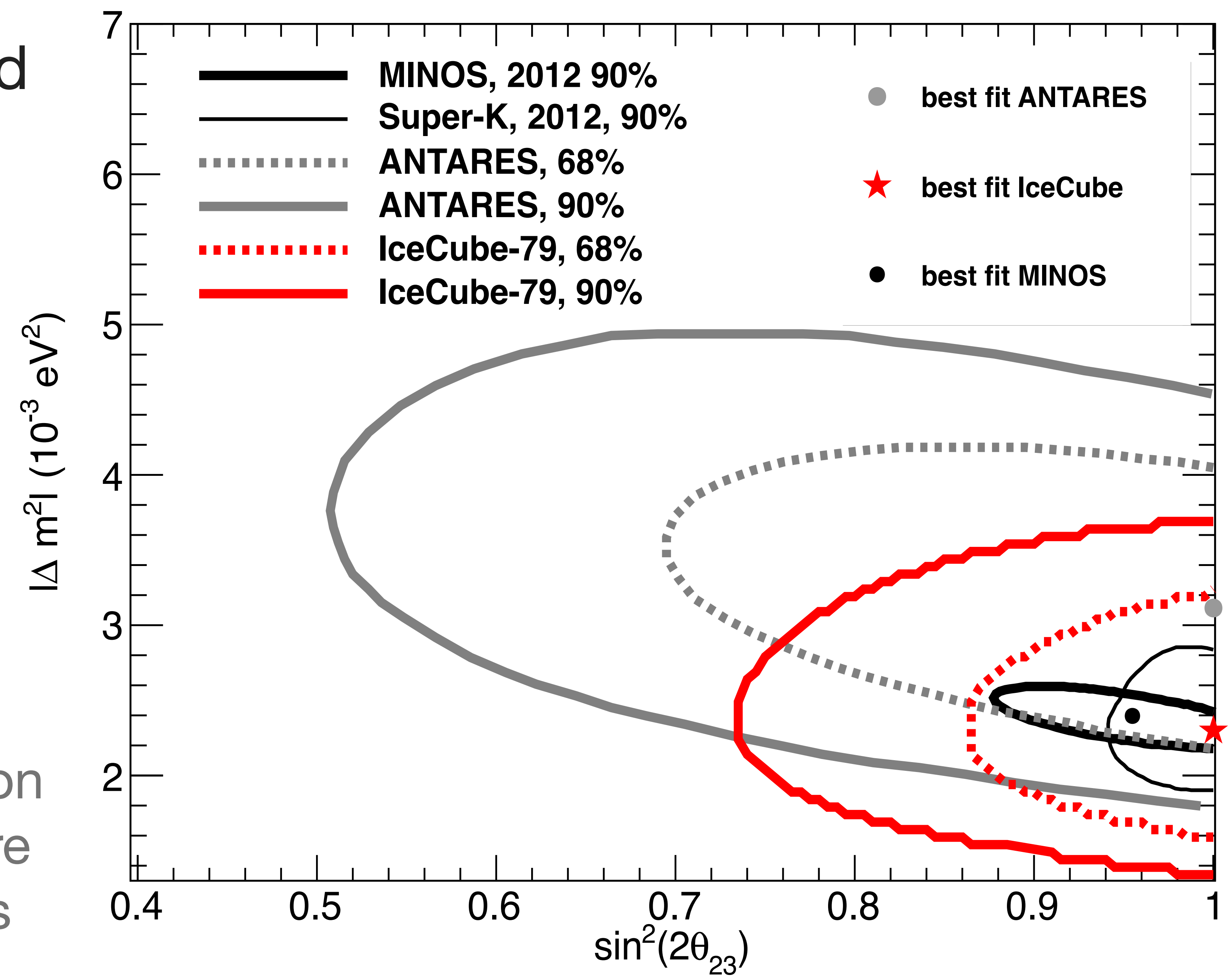


Statistically significant angle-dependent suppression at low energy, high energy sample provides constraint on uncertainties in simultaneous fit

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

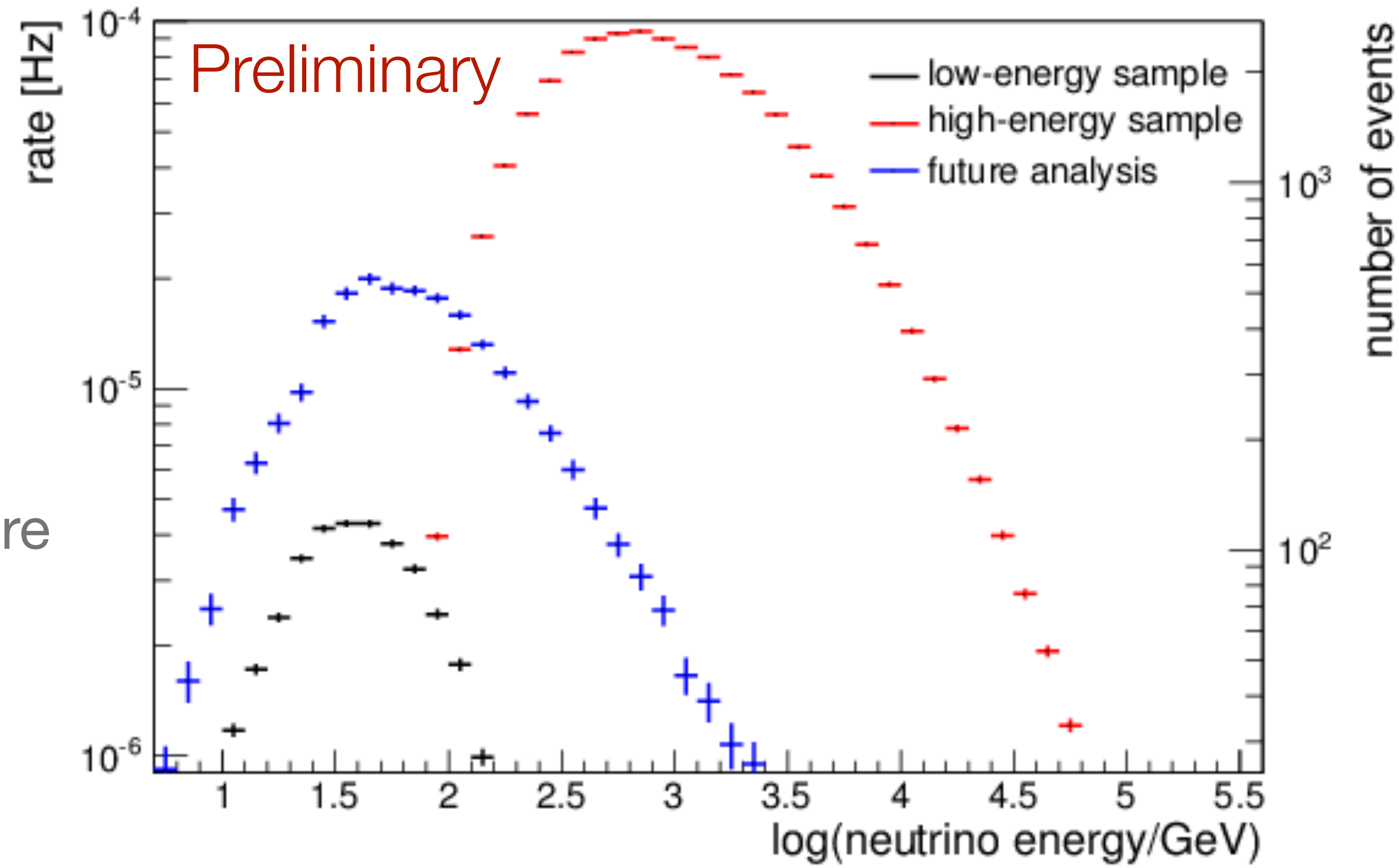
Muon Neutrino Disappearance

- 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



Ongoing Improvements

- Parallel analysis of first year of data from DeepCore
  - Introduce specialized data analysis and background rejection techniques for DeepCore
  - Low energy event yield improved by almost an order of magnitude



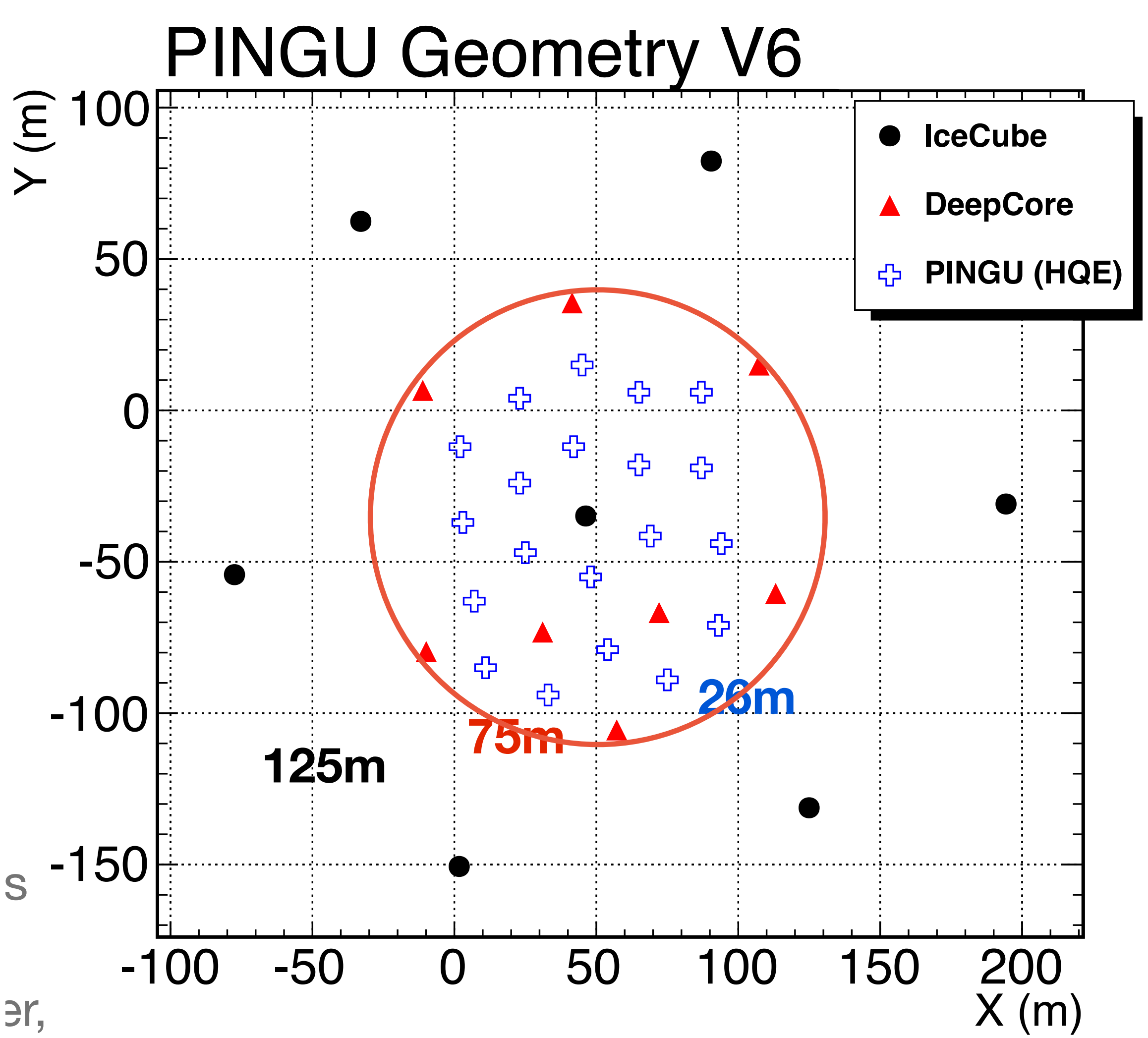
- Also including an energy estimator based on track length of contained neutrino-induced muons, 2 more DeepCore strings
  - Potentially substantial improvements in precision, depending on impact of systematics

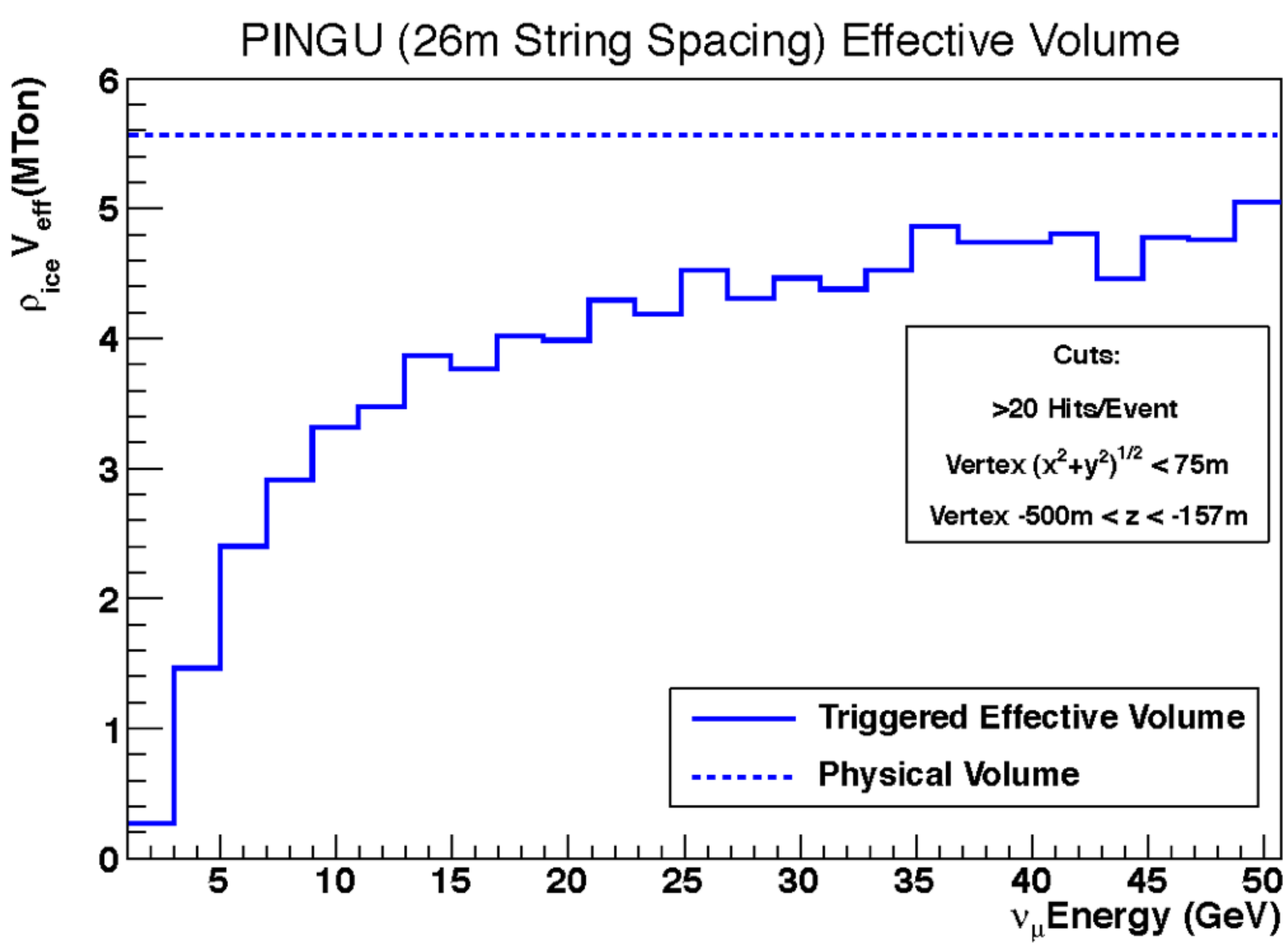
Future Directions

- Preliminary estimates of sensitivity suggest competitive measurements of oscillation parameters will be possible soon
  - Final precision will depend on improvements in energy and angular resolution, understanding of systematics – progress ongoing!
- Also studying possibility of extending low energy reach of IceCube with an even denser infill array – PINGU
  - Possibility of exploiting neutrino/anti-neutrino asymmetries and matter oscillation effects to measure neutrino mass hierarchy, given the large value of θ_{13}
  - Studies of feasibility and performance requirements now underway

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





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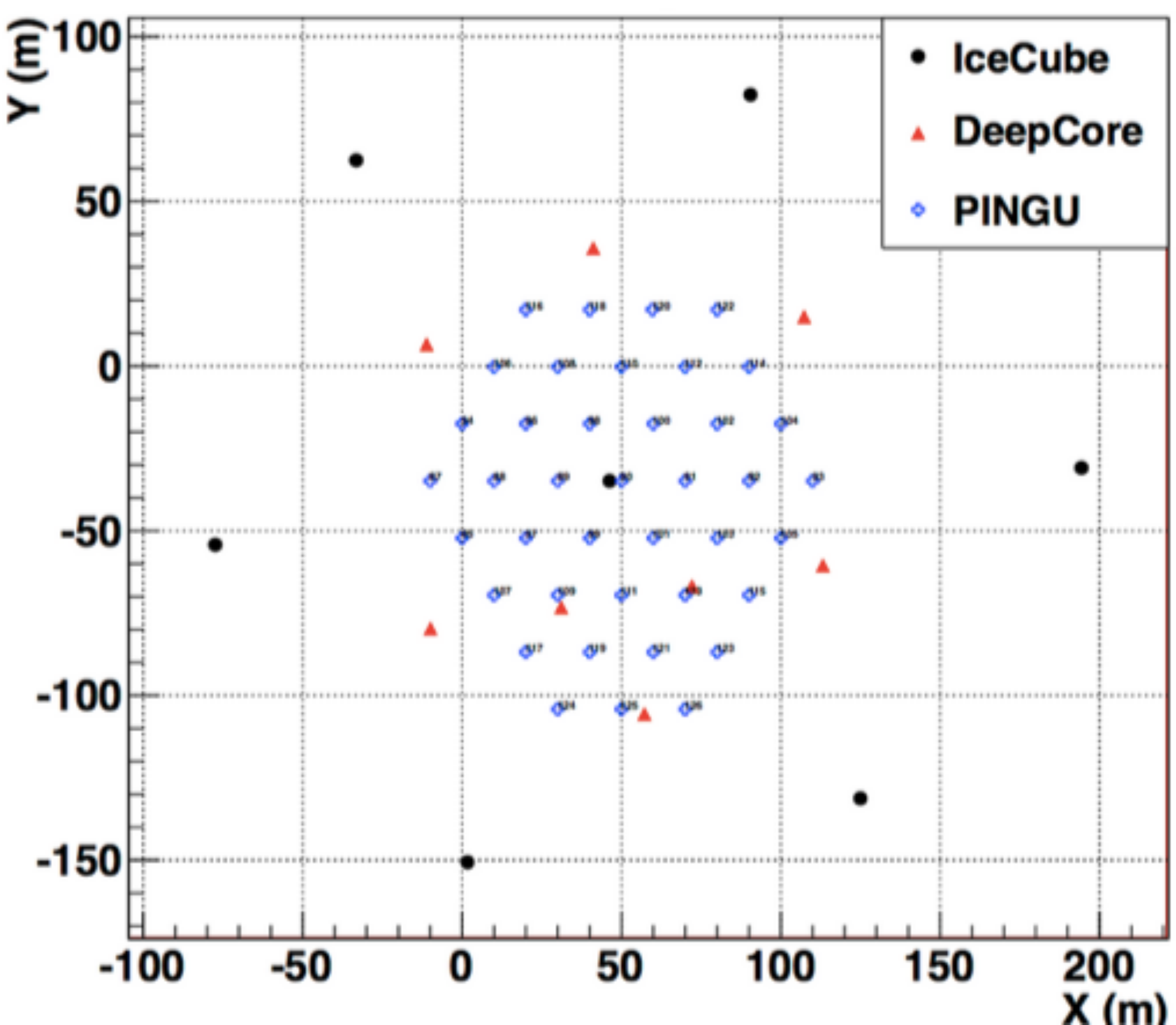
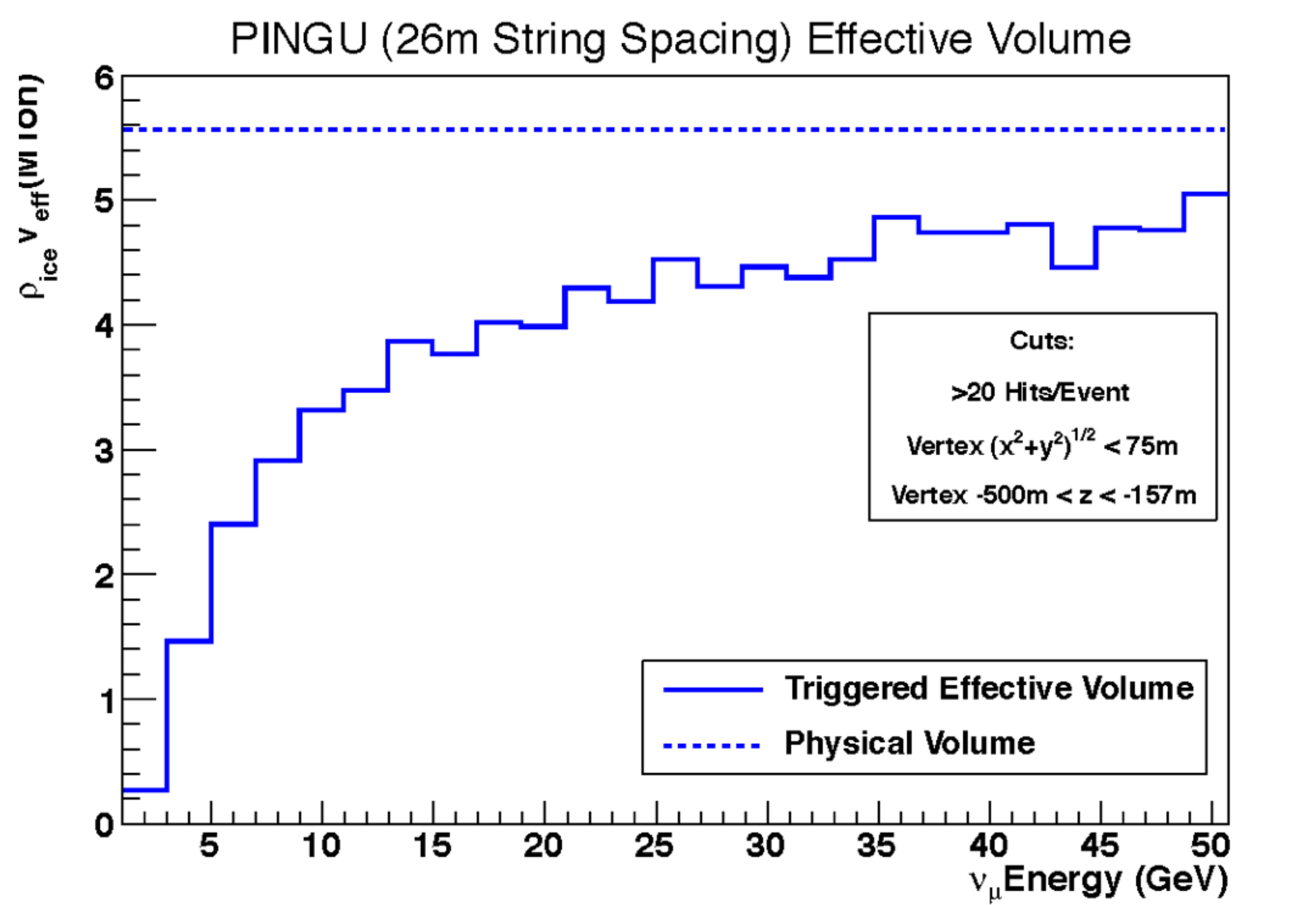
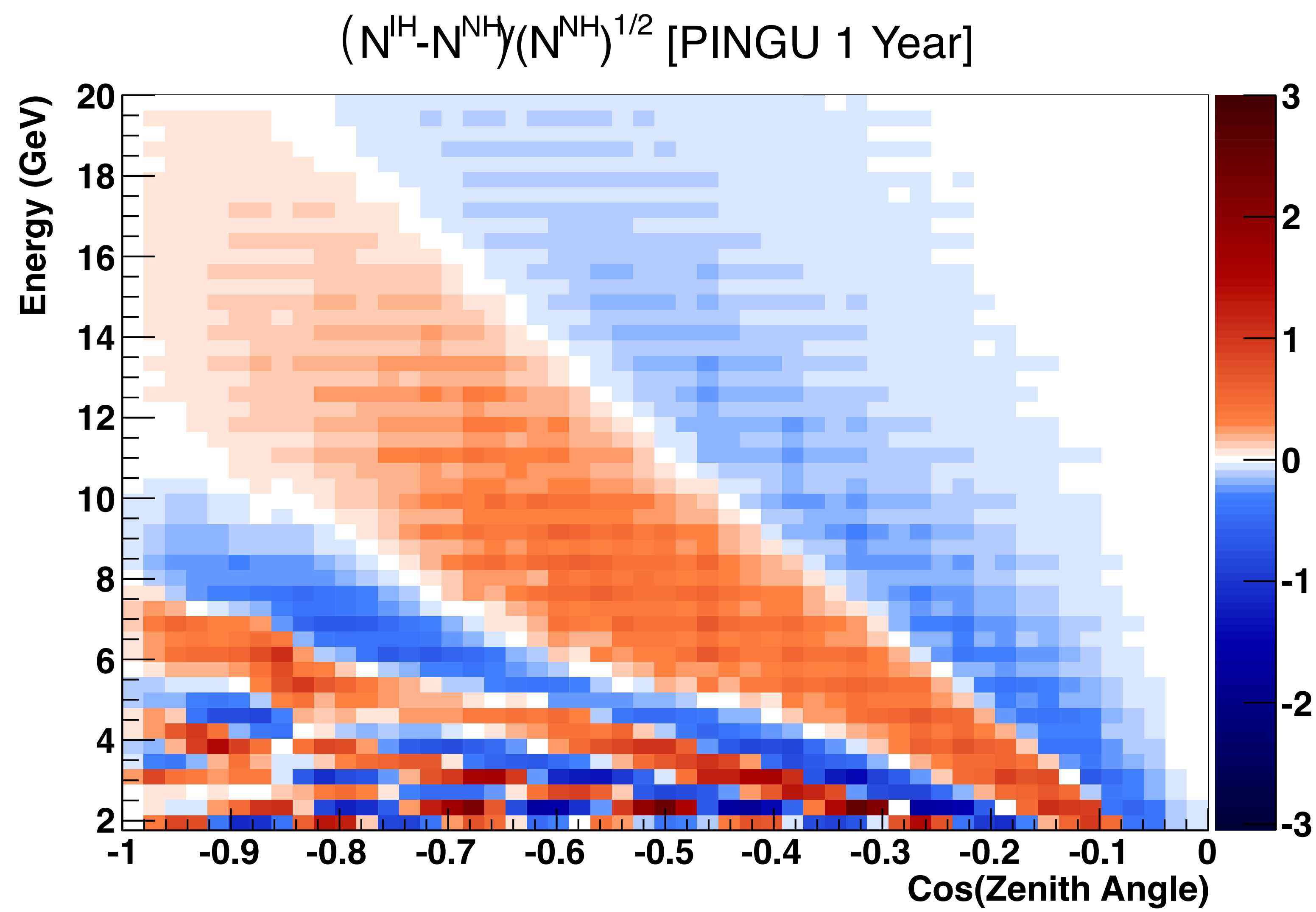




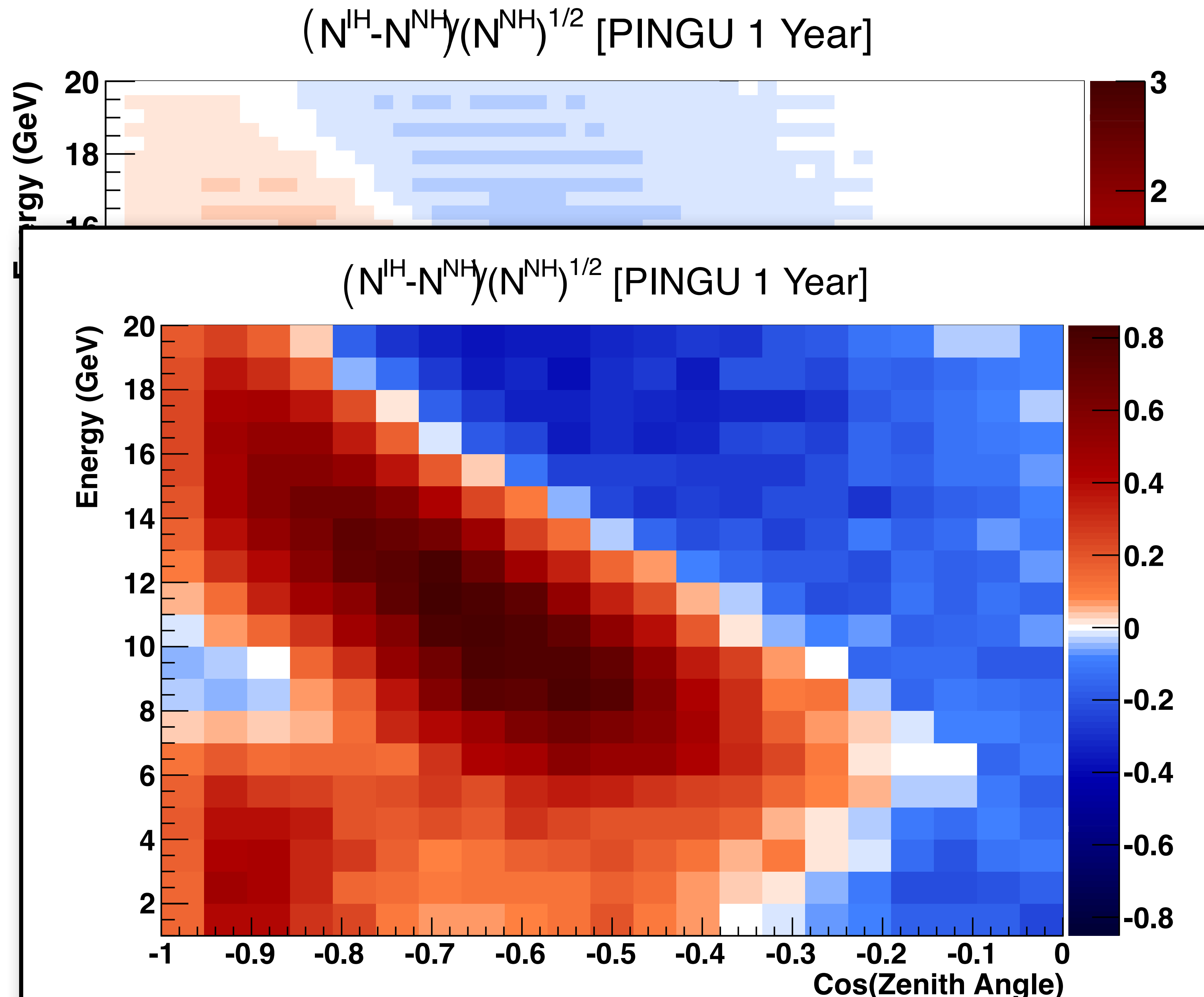
Signature of the Mass Hierarchy

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



Signature of the Mass Hierarchy

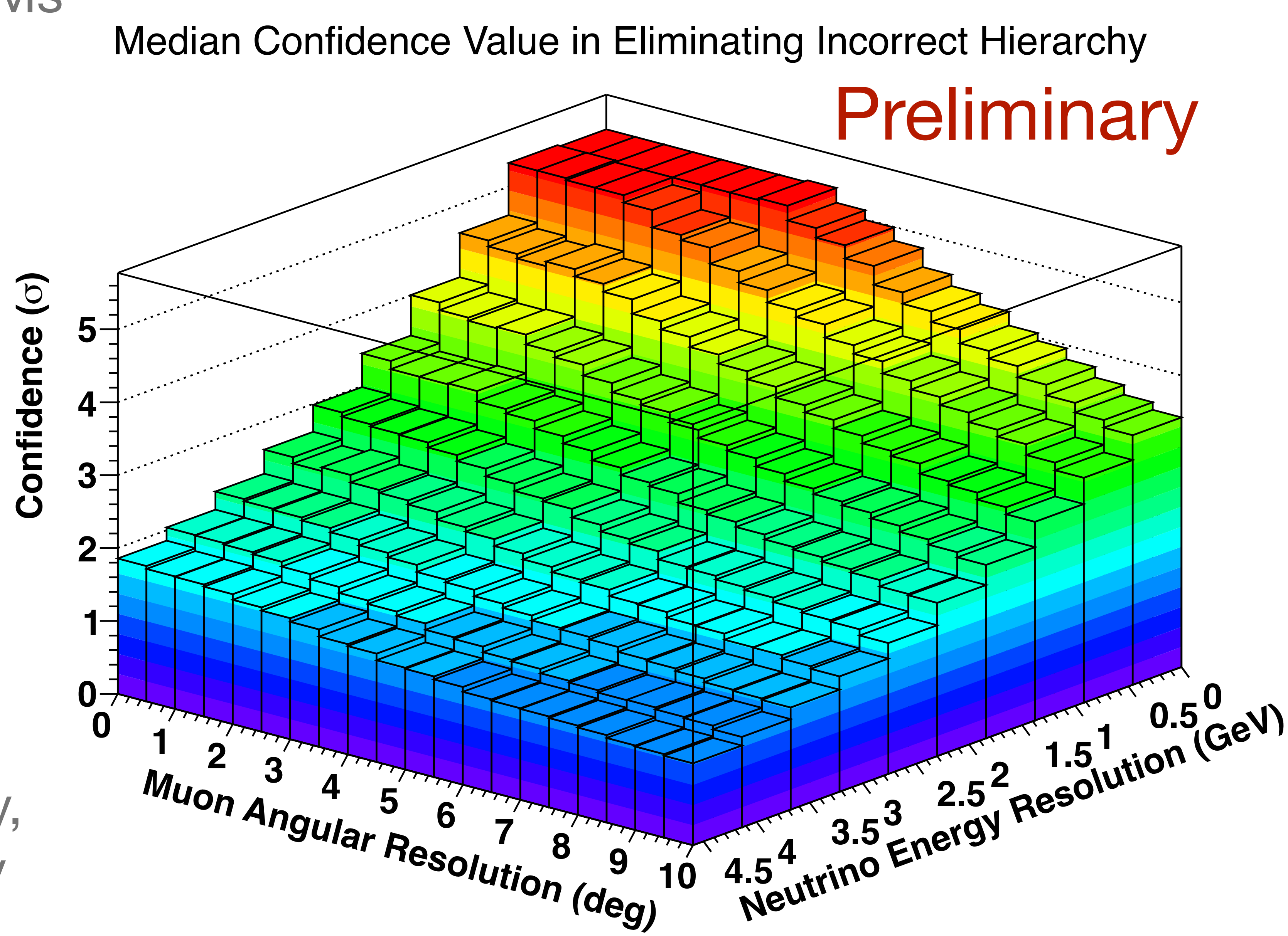
- Idealized case with no background, perfect flavor ID, 100% signal efficiency
- Different assumed resolutions smear the signature but do not eliminate it
  - NB: angular resolution is for muon – kinematic effects *are* included
  - Expected efficiencies and resolutions under investigation now



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

Sensitivity vs. Performance

- Numerically evaluate confidence of hierarchy determination after 1 year as a function of assumed energy and muon angular resolution
  - For now, require 20 DOMs hit in PINGU as a proxy for analysis efficiency
  - Need to fold in systematics and physics degeneracies (e.g. Δm_{31}^2)
  - Details of analysis technique still being tuned for power, robustness
  - Sensitivity to maximality, octant, etc. under study



Advantages of PINGU

- Well-established detector and construction technology
- Relatively low cost: ~$10M design/startup plus ~$1.25M per string (depending on number of sensors, cost of fuel, etc.)
- Rapid schedule: deployment could be complete by 2017-18, depending on final scope
    - Quick accumulation of statistics once complete
- Provides a platform for more detailed calibration systems to reduce detector systematics
    - Enhance physics at PINGU energies – e.g. hierarchy, ν_τ appearance
    - Opportunity for R&D toward other future ice/water Cherenkov detectors
- Working toward a Letter of Intent now