Neutrino Oscillations with IceCube DeepCore and PINGU

PENNSTATE

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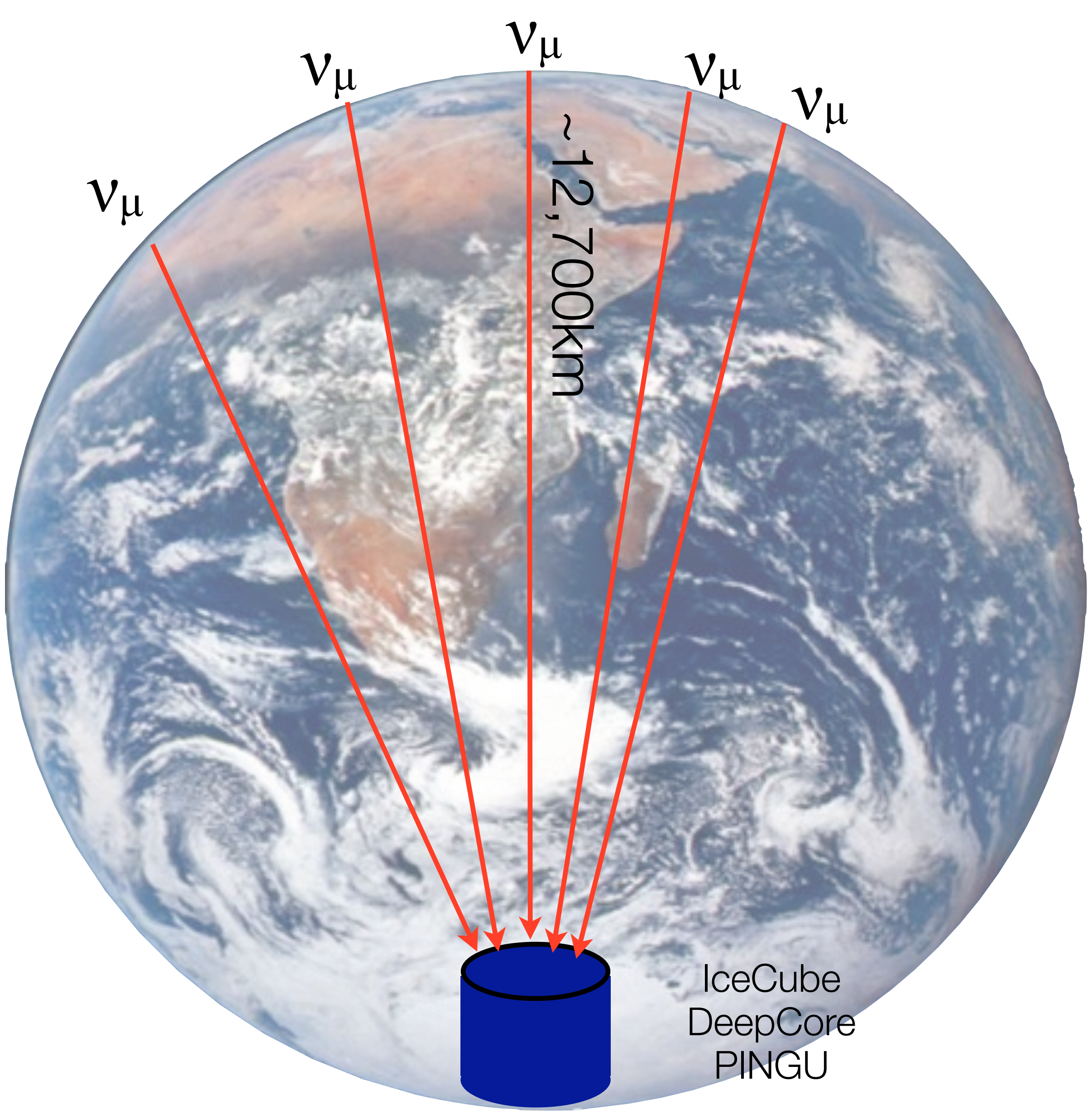
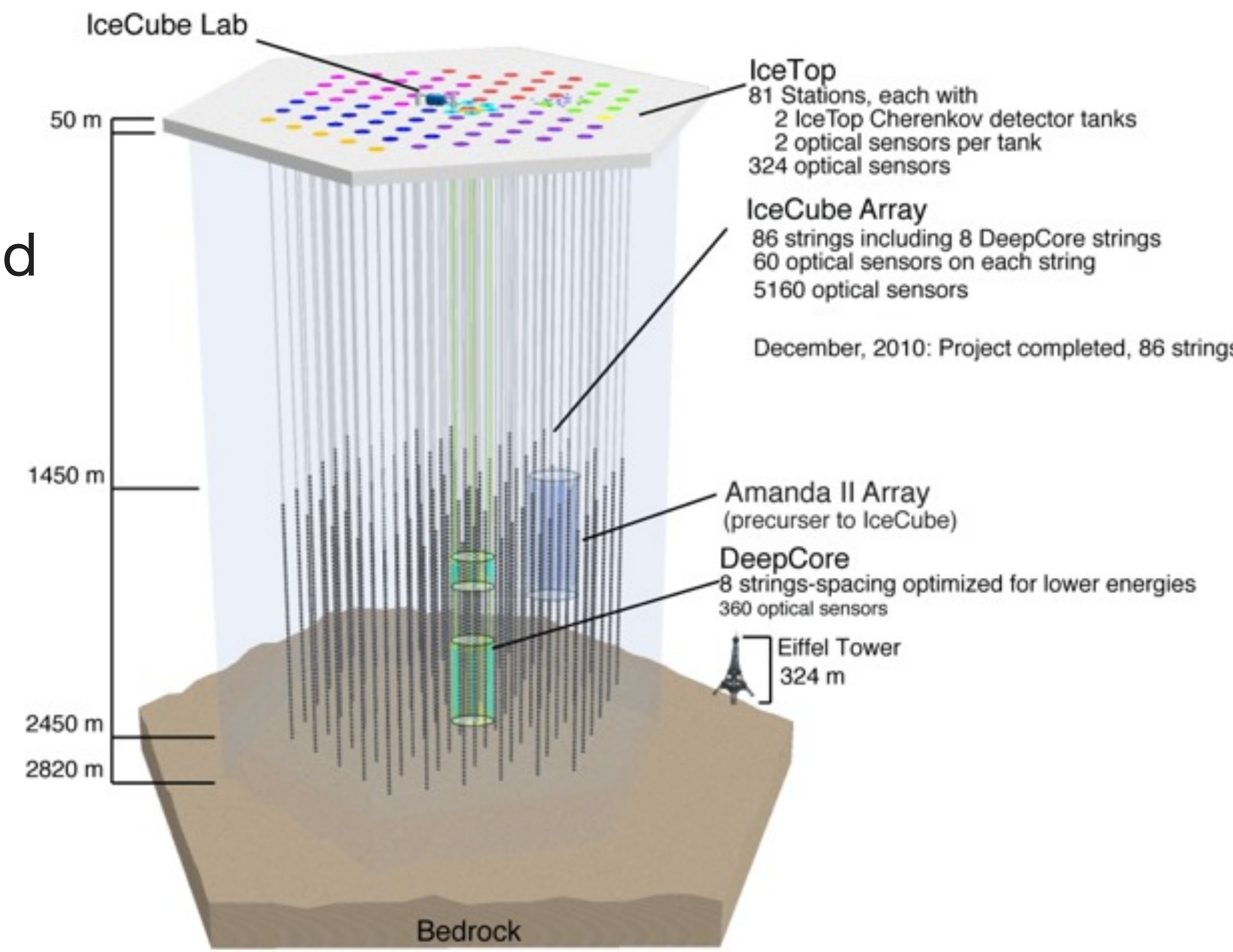
Oscillations with Atmospheric Neutrinos

- Neutrinos oscillating over one Earth radius 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 to mitigate impact of systematics
- Hierarchy-dependent matter effects below ~10-20 GeV



IceCube DeepCore

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

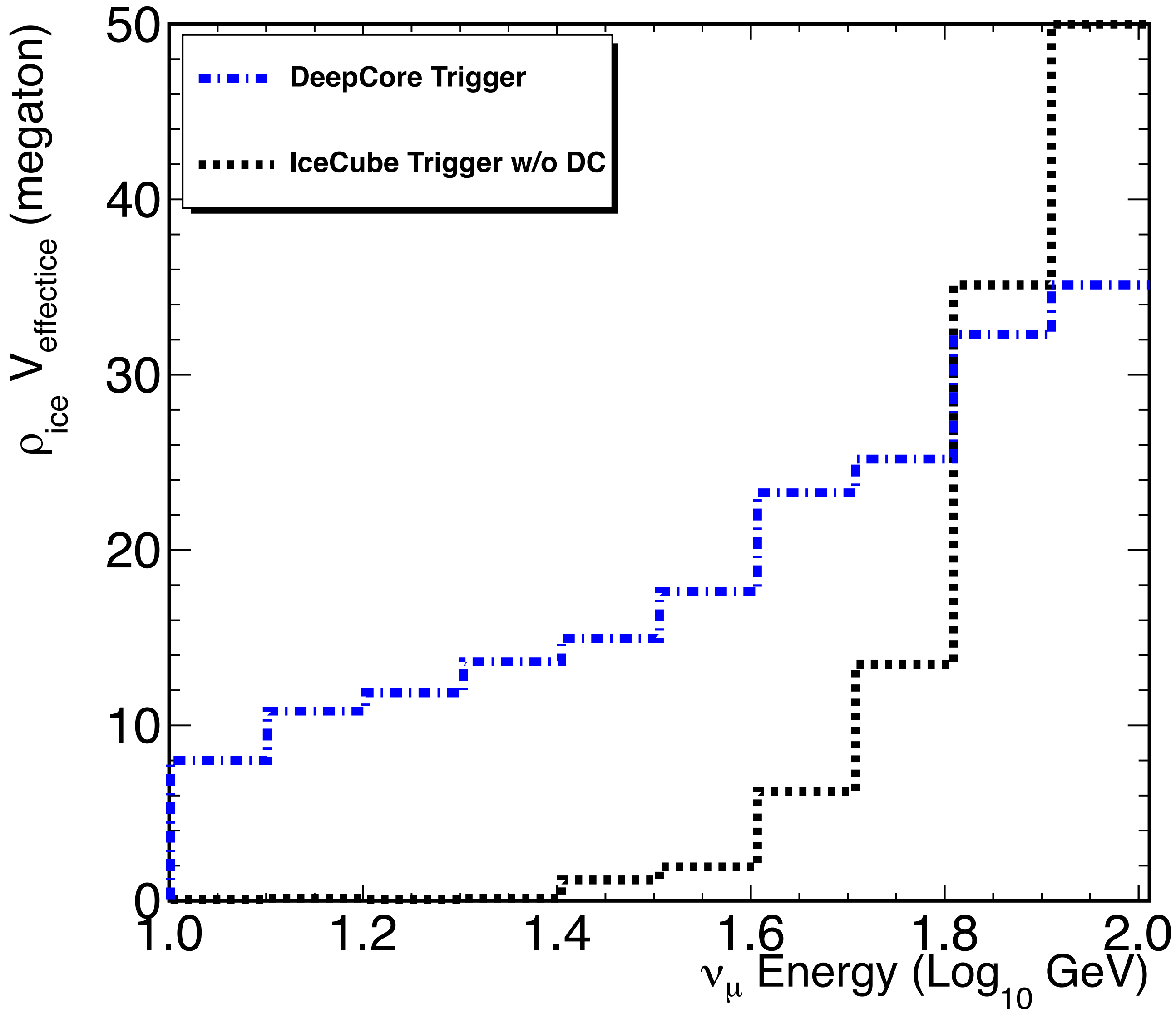


IceCube DeepCore

- Original IceCube design focused on neutrinos with energies above a few hundred GeV

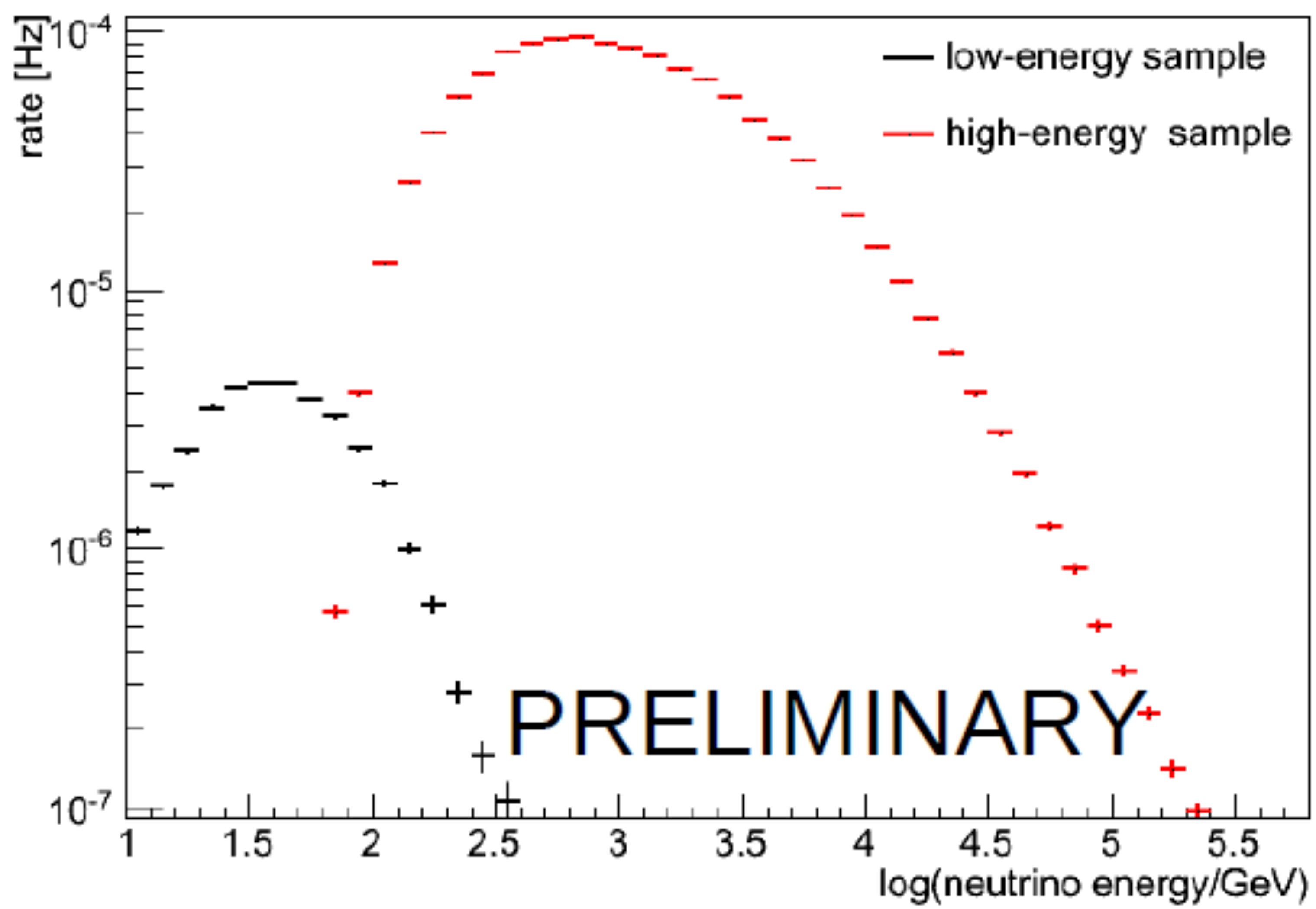
- DeepCore provides reduced volume with lower energy threshold
  - Higher efficiency far outweighs reduced geometrical volume
  - Note: comparison at trigger level – analysis efficiencies not included (typically ~10%)

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

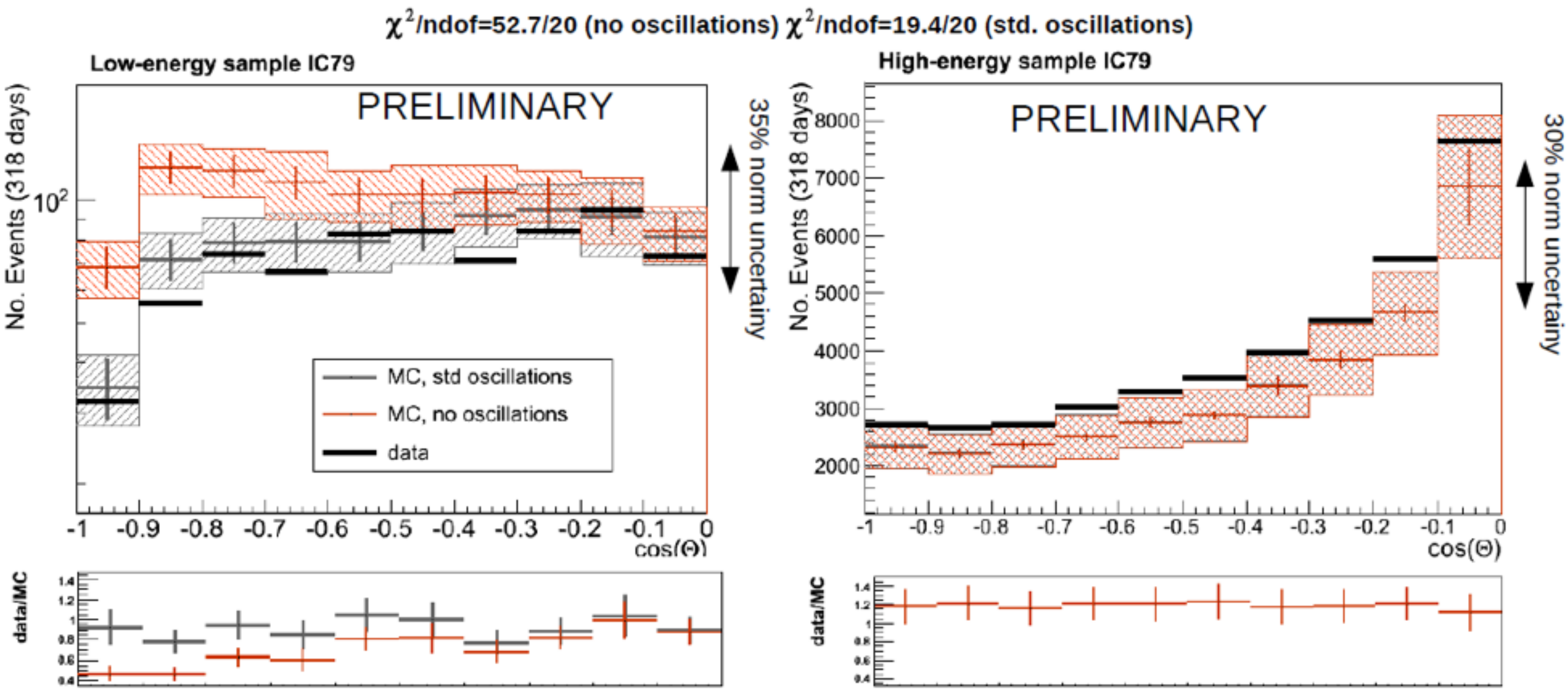


Muon Disappearance in IceCube

- As a first step, compare zenith-dependent response of standard IceCube muon analysis (high energy) to a modified version for DeepCore (low energy)
  - 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 Disappearance in IceCube

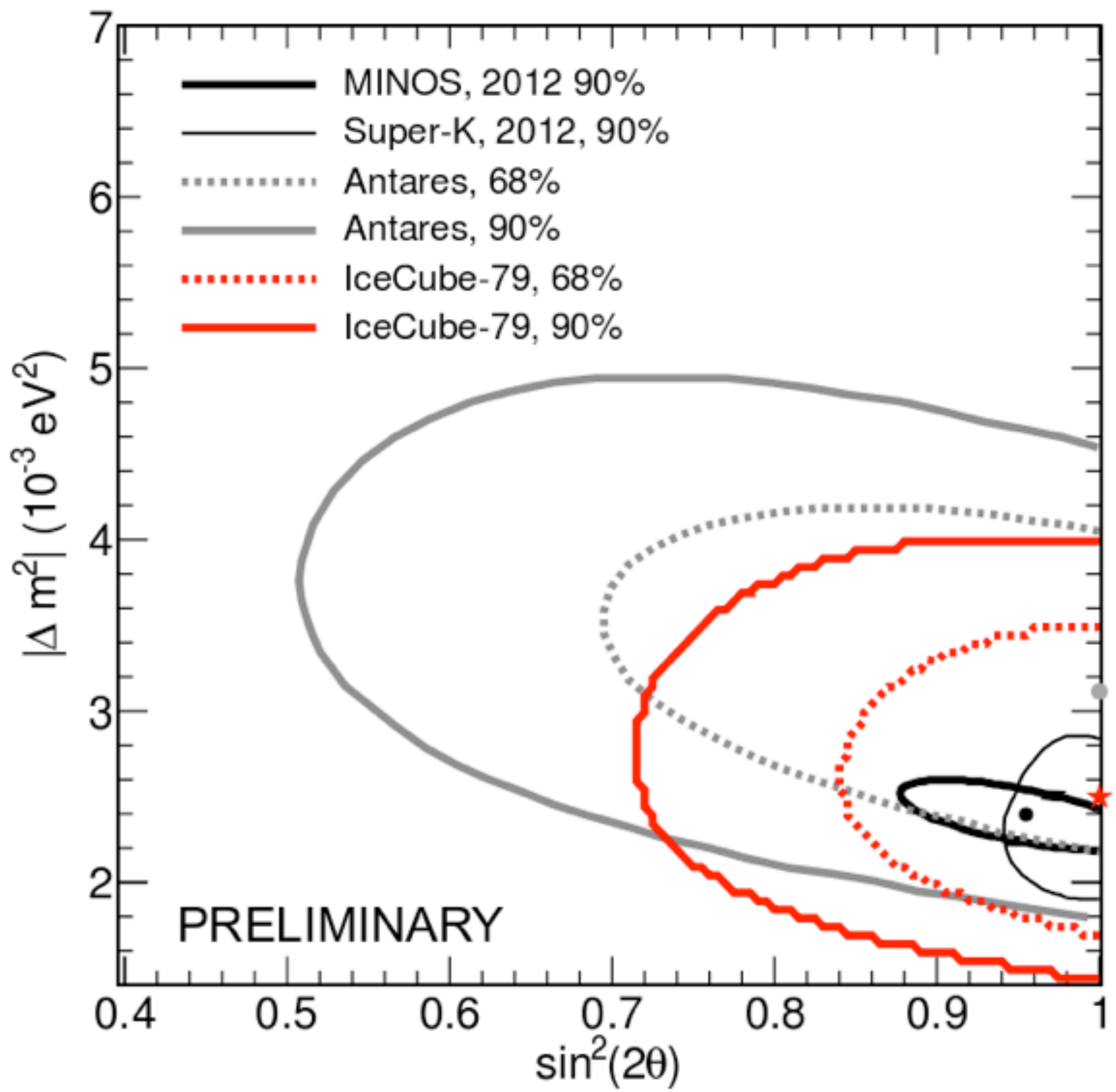


Statistically significant angle-dependent suppression at low energy

- Shaded bands show range of uncorrelated systematic uncertainties; overall normalization uncertainty shown at right

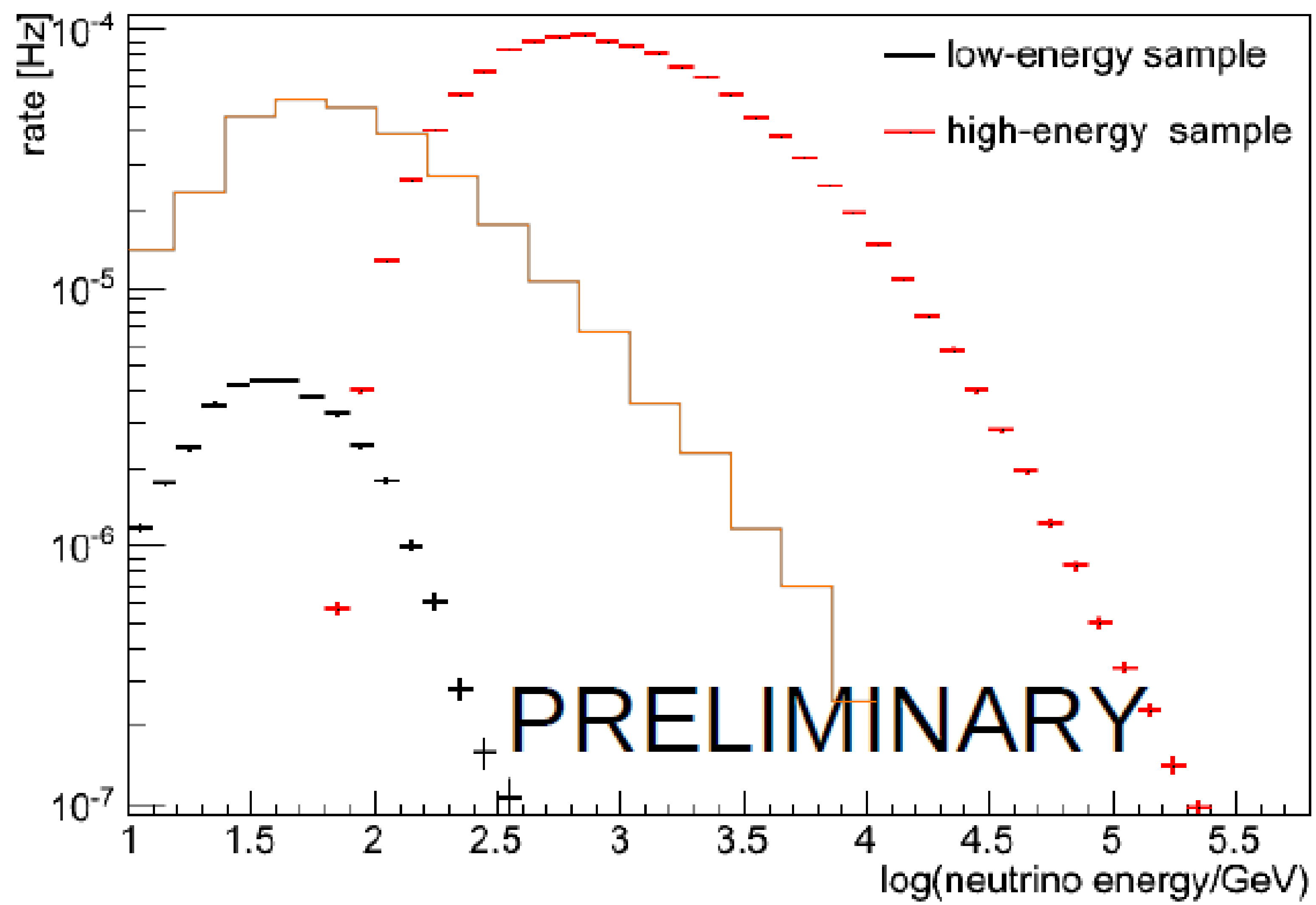
Muon Disappearance in IceCube

- Oscillation parameter allowed regions extracted from zenith distributions
  - Systematics included in contours via χ^2 covariance (“pulls”)
- Preliminary results in agreement with world average measurements (with large uncertainties)



Ongoing Improvements

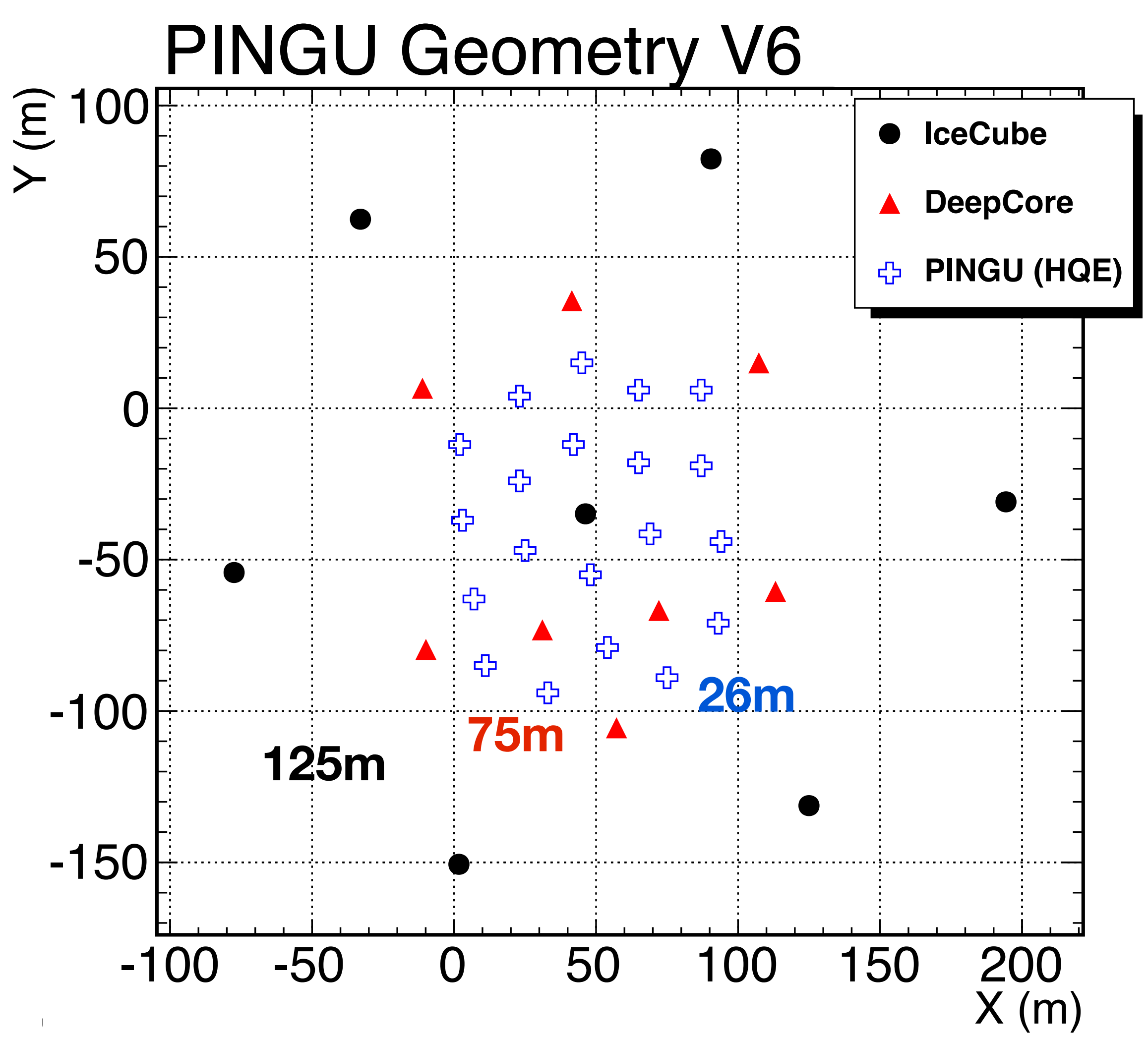
- Parallel analysis of first year of data from DeepCore
  - Introduce specialized data analysis and background rejection techniques for DeepCore
  - Low energy event yield improved by almost an order of magnitude

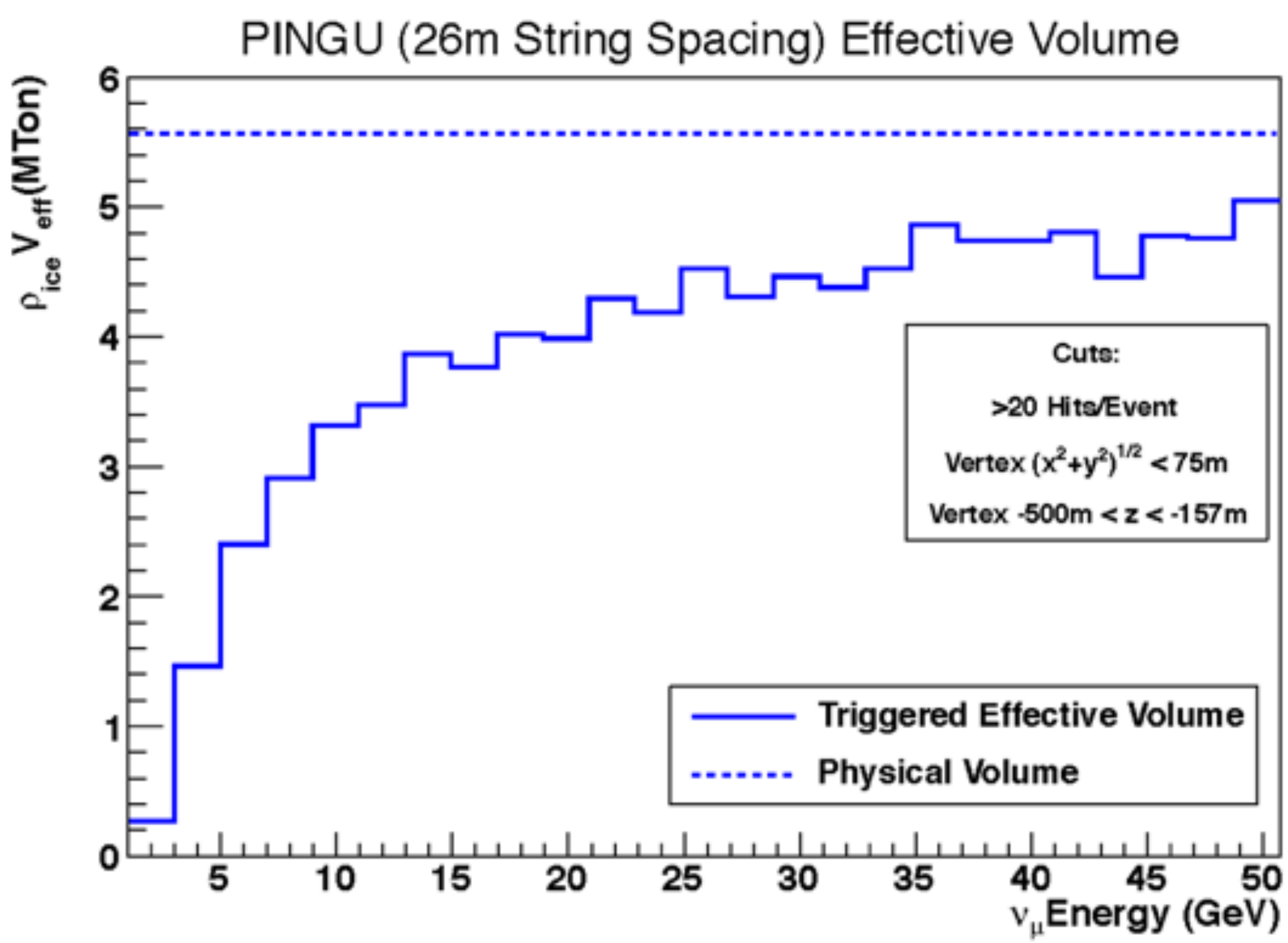


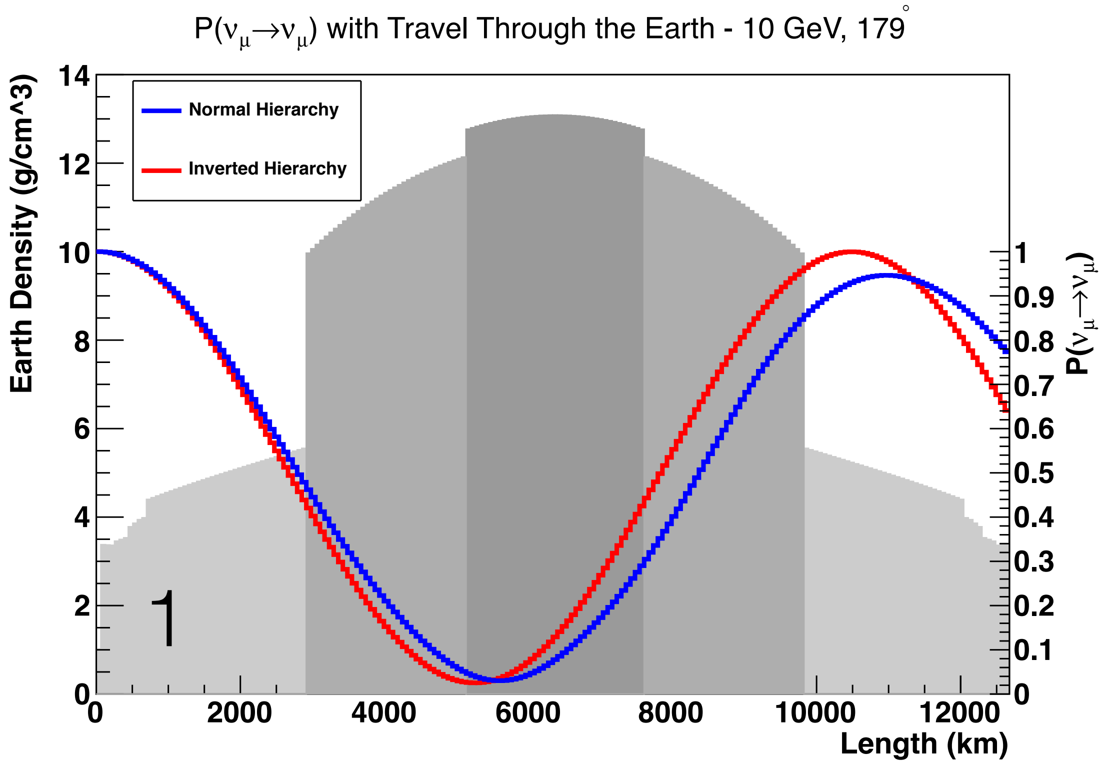
- Also including an energy estimator based on track length of contained neutrino-induced muons, 2 more DeepCore strings
  - Potentially substantial improvements in precision, depending on impact of systematics

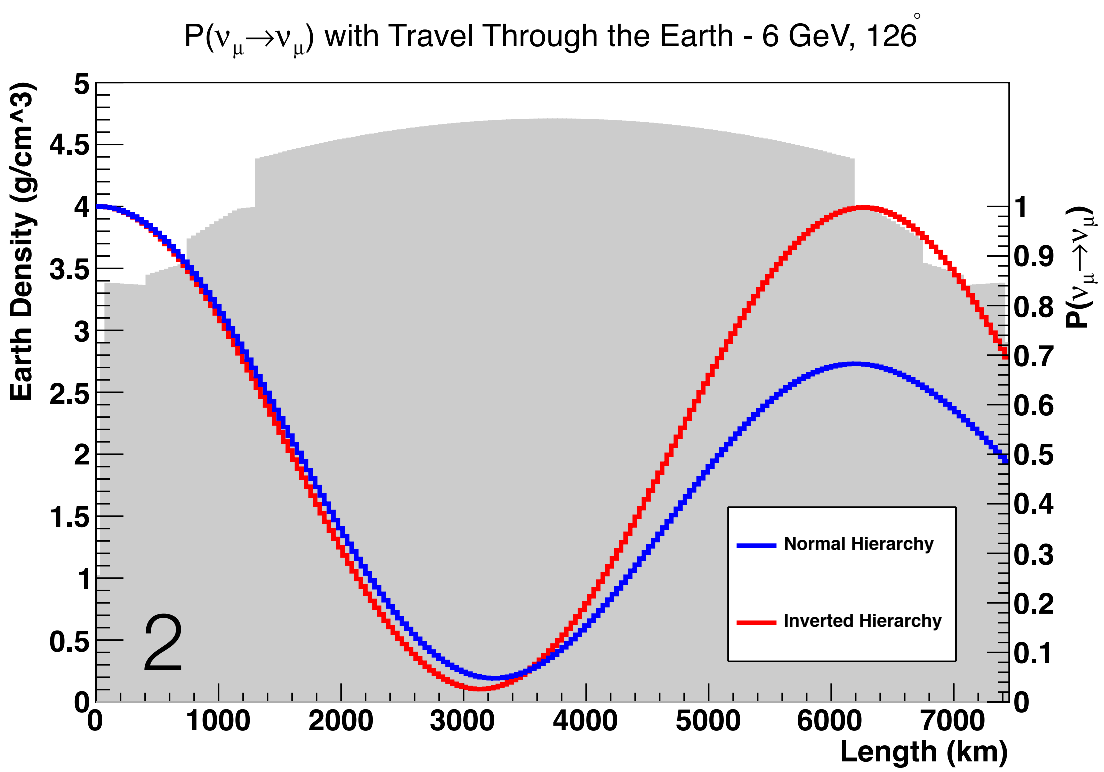
PINGU

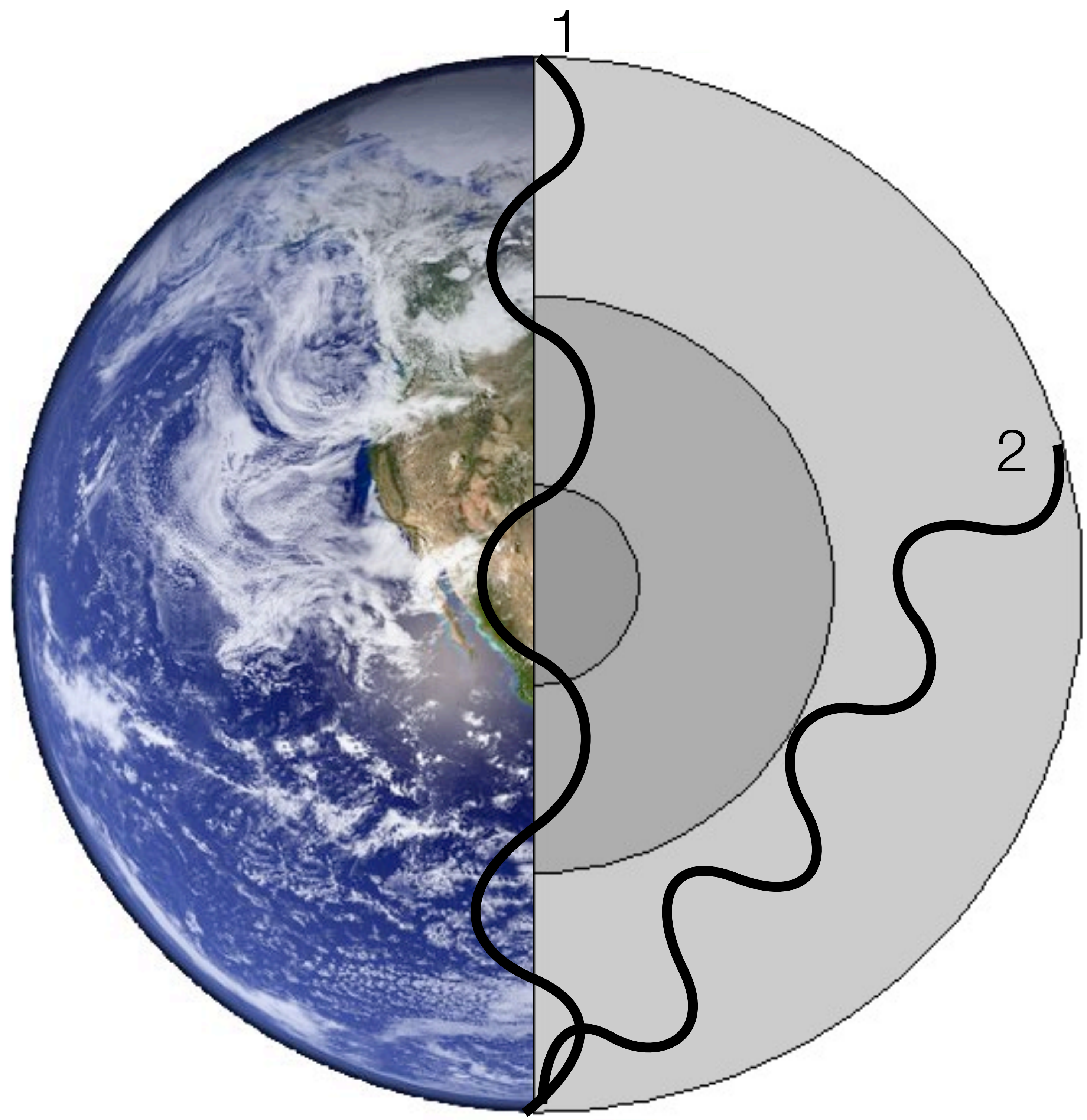
- Studying potential of an even denser infill array – PINGU
  - Possibility of exploiting neutrino/anti-neutrino asymmetries and matter oscillation effects to measure neutrino mass hierarchy, given the large θ_{13}
  - Feasibility studies now underway – one of several candidate geometries











Matter Effects & Hierarchy

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

Preliminary Hierarchy Sensitivity Studies

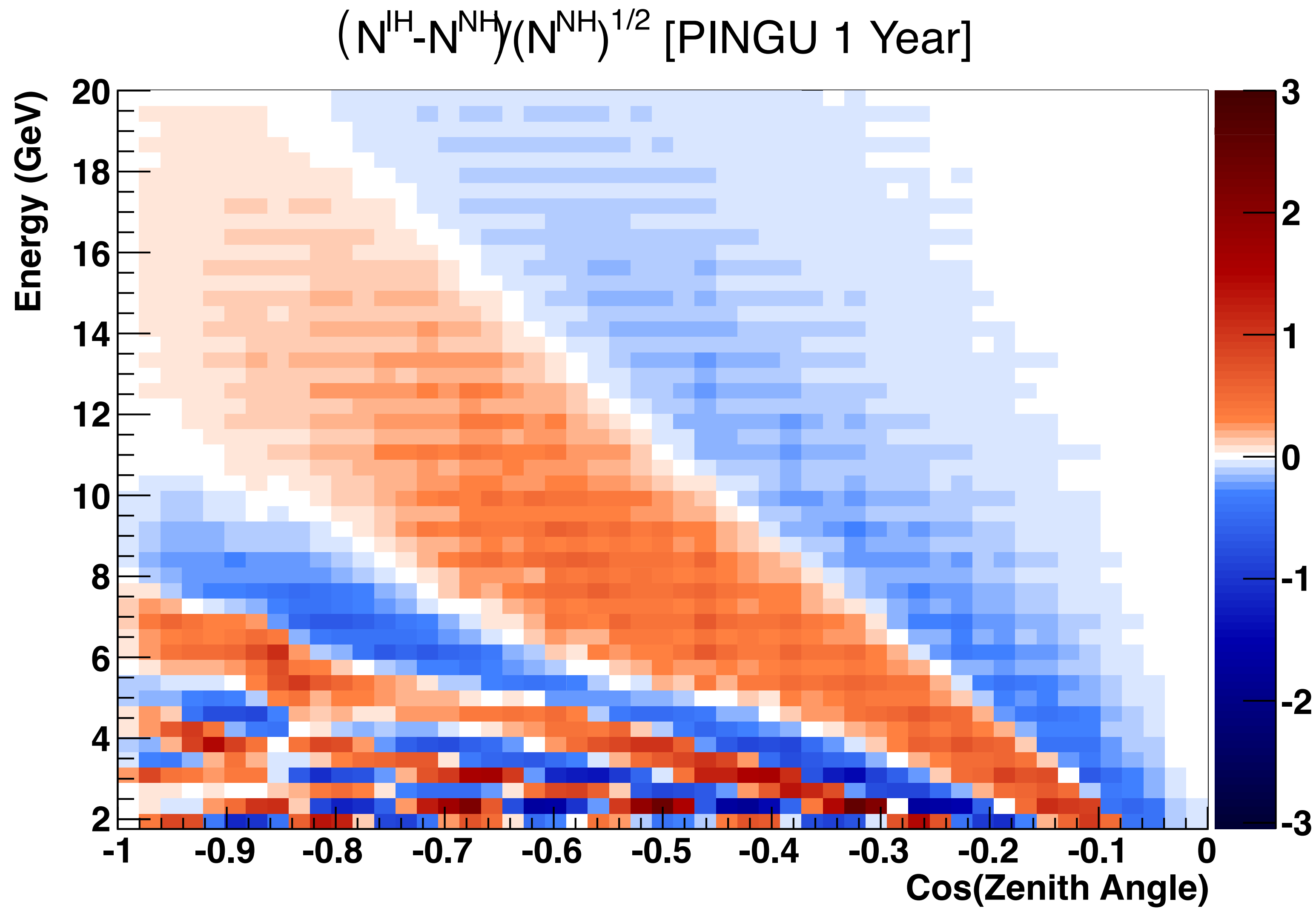
- Idealized case w/ perfect event ID, 100% event selection efficiency, no quality cuts and no background
  - Need to scale down by some assumed analysis efficiency, plus background contamination
  - Evaluation of angular and energy resolution is ongoing
- As a preliminary metric, use the significance estimate of Akhmedov, Razzaque & Smirnov (arXiv:1205.7071) to evaluate potential
  - Binned counting experiment in energy and zenith angle, comparing difference in expected number of events for normal vs. inverted hierarchy due to mass effects

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

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

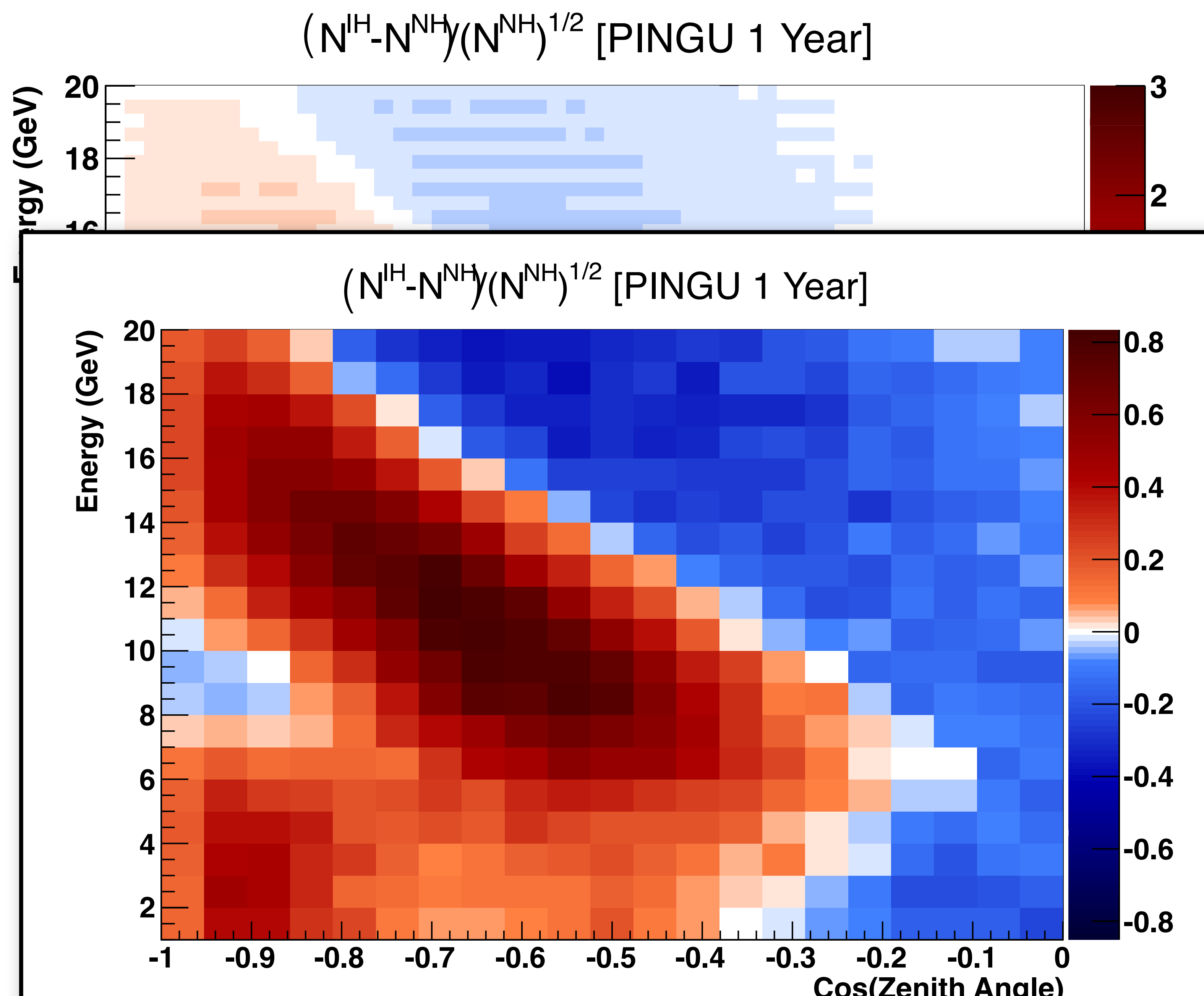
Signature of the Mass Hierarchy

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



Signature of the Mass Hierarchy

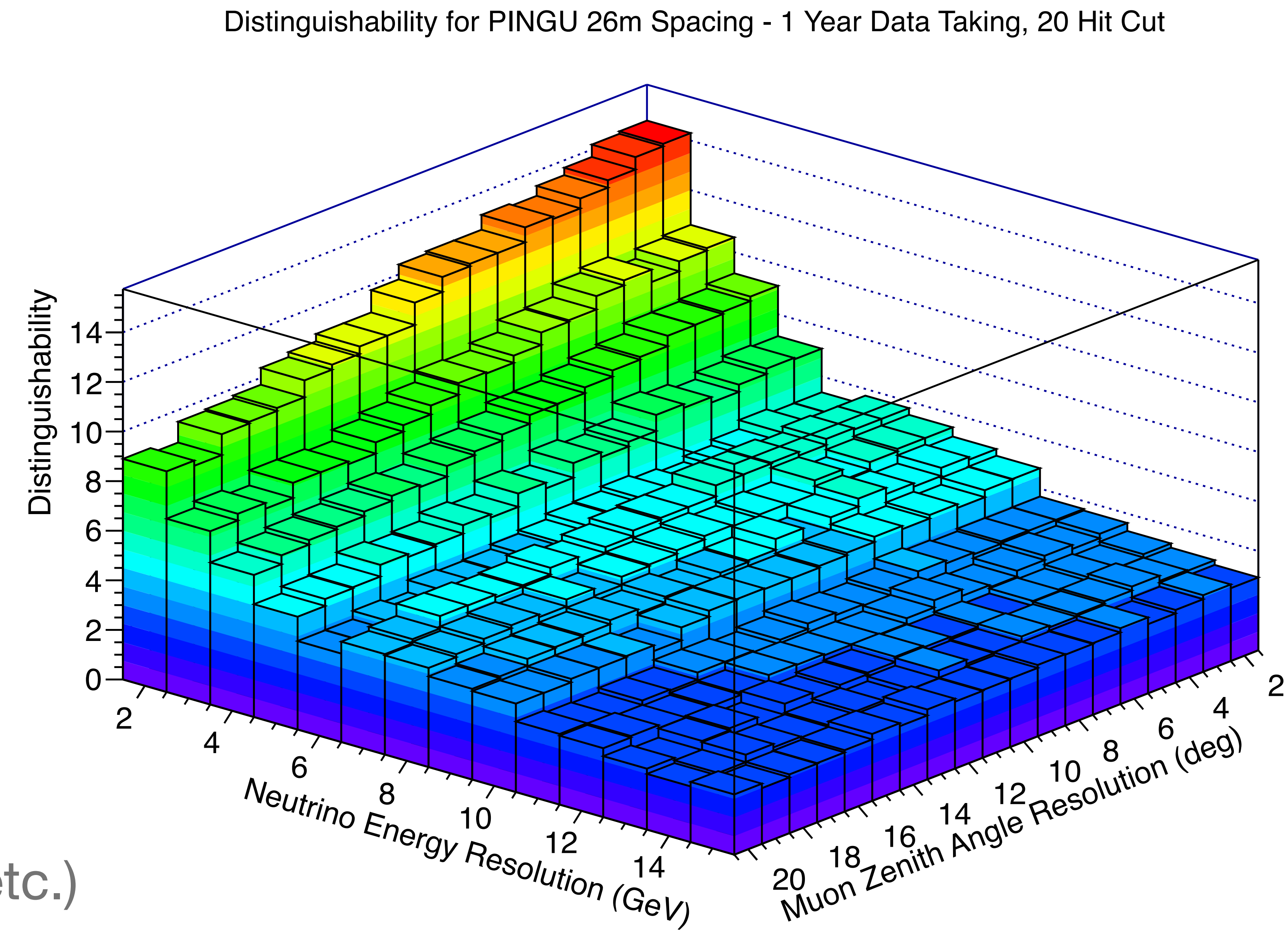
- Idealized case with no background, perfect flavor ID, 100% signal efficiency
- Different assumed resolutions smear the signature but do not eliminate it
  - NB: angular resolution is for muon – kinematic effects are included
  - Expected efficiencies and resolutions under investigation now



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

Sensitivity vs. Performance

- Require 20 DOMs hit in PINGU, and evaluate expected significance after (1 year x 100% efficiency) as a function of assumed energy and muon angular resolution
  - Required performance parameters will drive detector design
  - Need to fold in systematics and physics degeneracies (e.g. Δm_{31}^2)
  - More sophisticated resolution models will also be evaluated (e.g. energy/inelasticity dependence, biases, etc.)



Other Neutrino Measurements

- δ_{CP} has little to no effect on our measurements
  - Hierarchy determination via ν_μ disappearance – 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
  - Potentially observable in DeepCore/PINGU as a distortion of cascade energy (and angular?) spectrum
  - Oscillation effects scale as L/E_ν, so longer baselines move effect to higher energy with reduced kinematic suppression of tau neutrino cross section
  - PINGU gives far better energy resolution and ν_μ tagging than DeepCore
- More precise measurement of atmospheric (2-3) oscillations

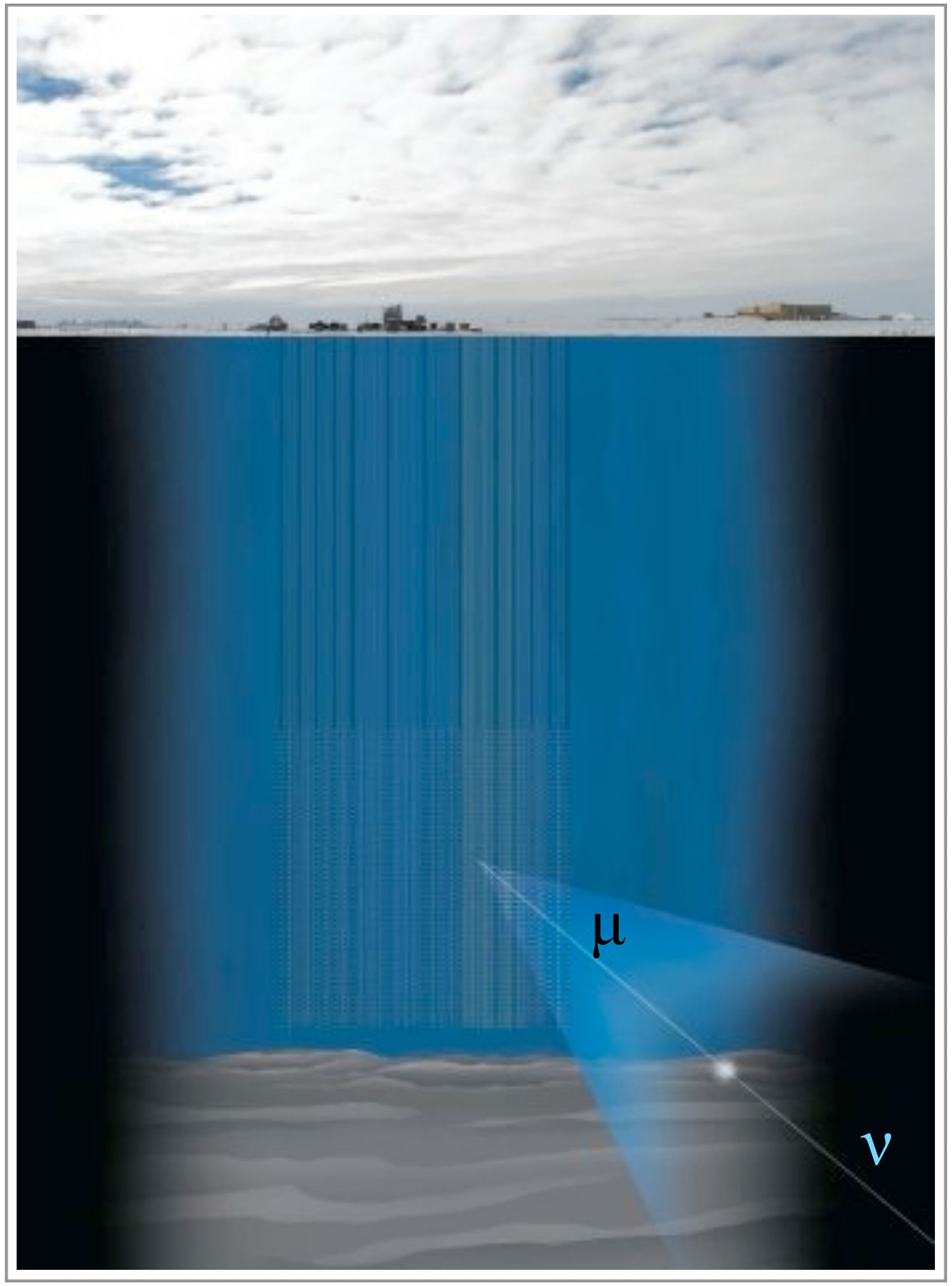
Advantages of PINGU

- Well-established detector and construction technology
- Relatively low cost: ~$10M design/startup plus ~$1.25M per string
- 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 DeepCore energies – e.g. tau appearance
  - Opportunity for R&D toward other future ice/water Cherenkov detectors
- Working toward a LoI now

Backup Slides

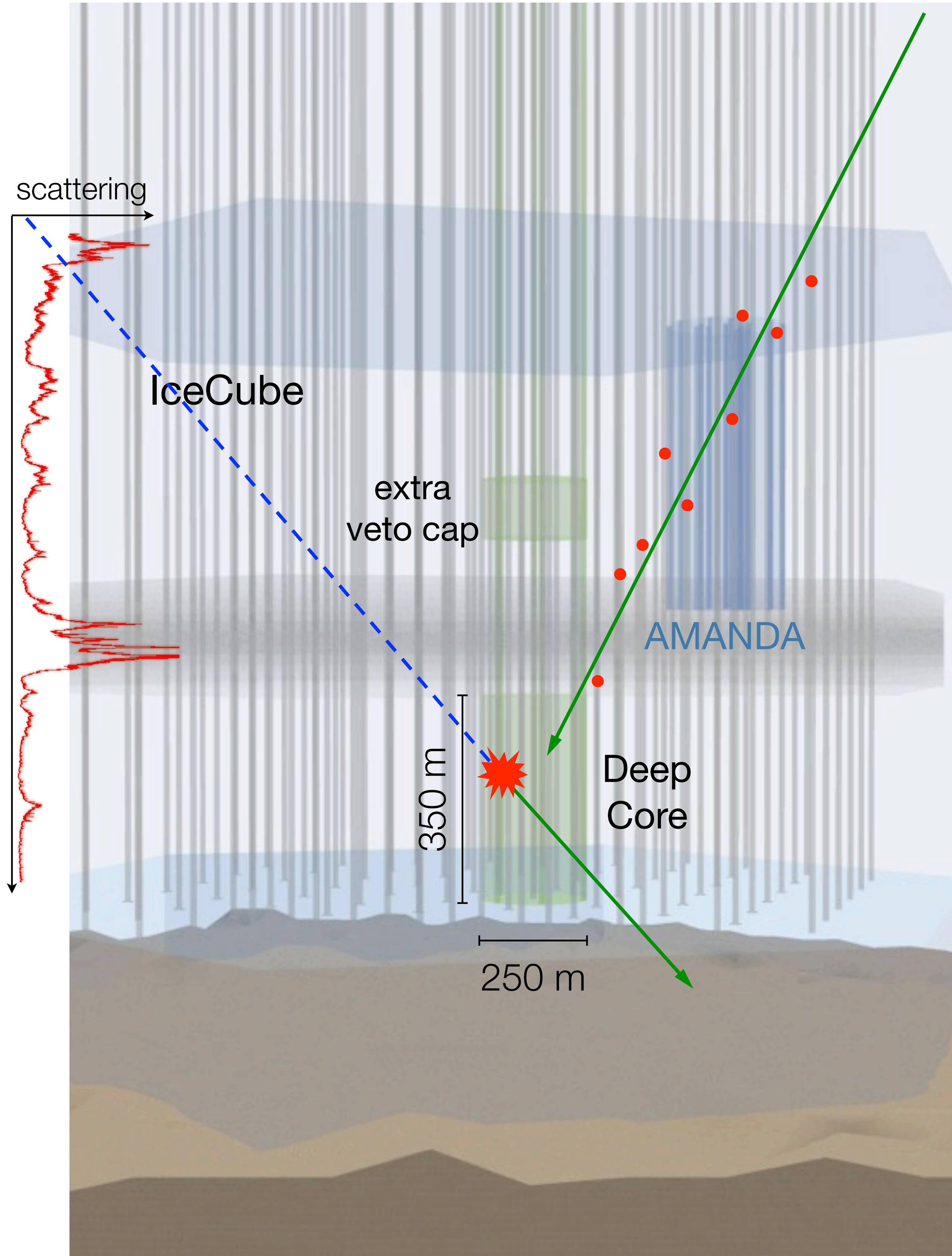
IceCube: a High Energy Neutrino Telescope

- Use transparent Antarctic ice as both target and Cherenkov medium
- Neutrinos interact in or near the detector
  - Cherenkov radiation detected by 3D array of optical sensors (OMs)
  - Long straight muon tracks from ν_μ CC
    - $\mathcal{O}$(5 m/GeV) at low energy
  - $\mathcal{O}$(few m) cascades from ν_e CC, low energy ν_τ CC, and ν_x NC



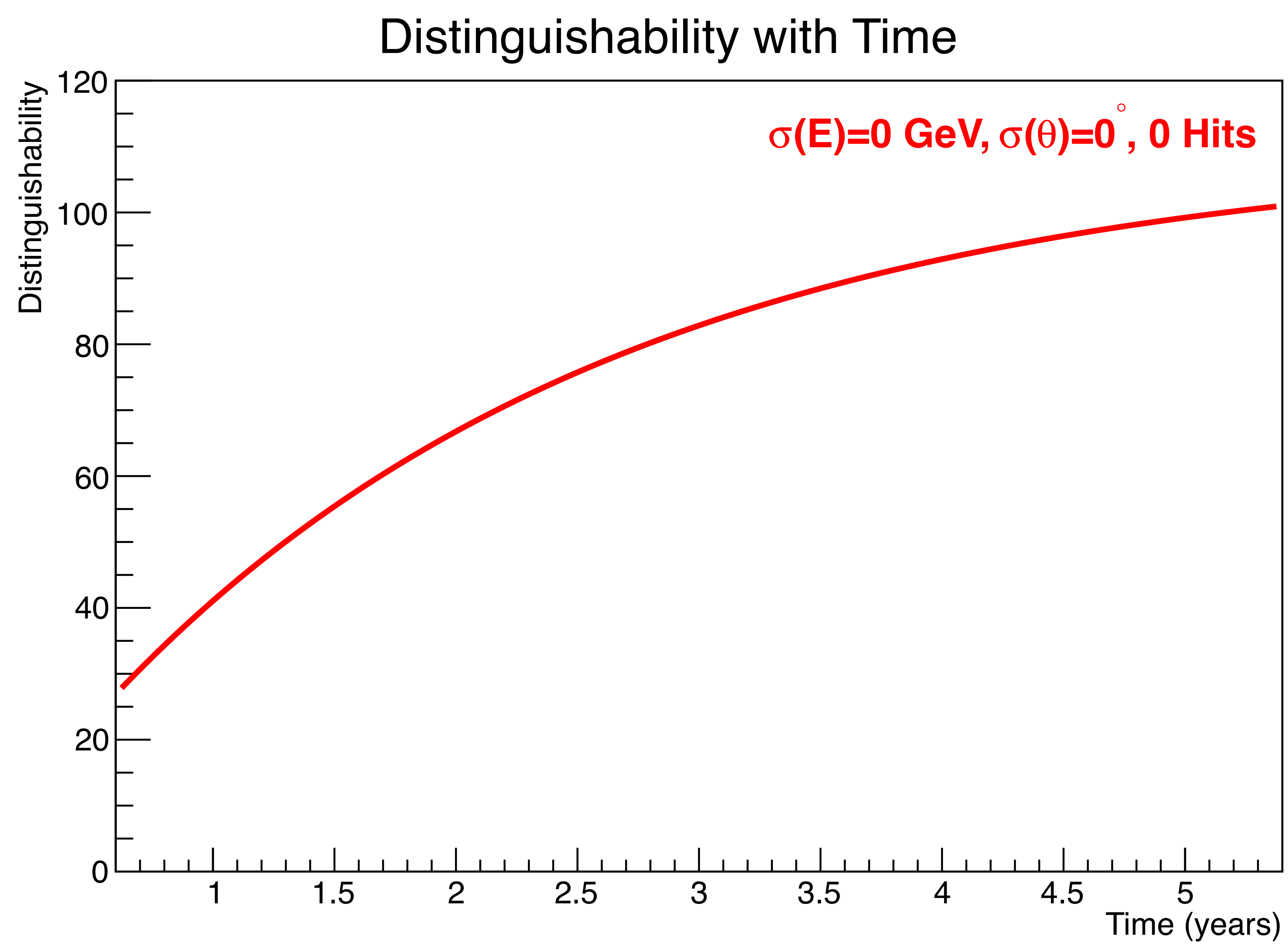
IceCube DeepCore

- A more densely instrumented region at the bottom center of IceCube
    - Eight special strings plus 12 nearest standard strings
    - Hamamatsu super-bialkali PMTs
    - ~5x higher effective photocathode density
- In the clearest ice, below 2100 m
    - λ_{atten} up to 45-50 m
- IceCube provides an active veto against cosmic ray μ background (around 10^6 times atmospheric neutrino rate at 1.9 k.m.w.e.)



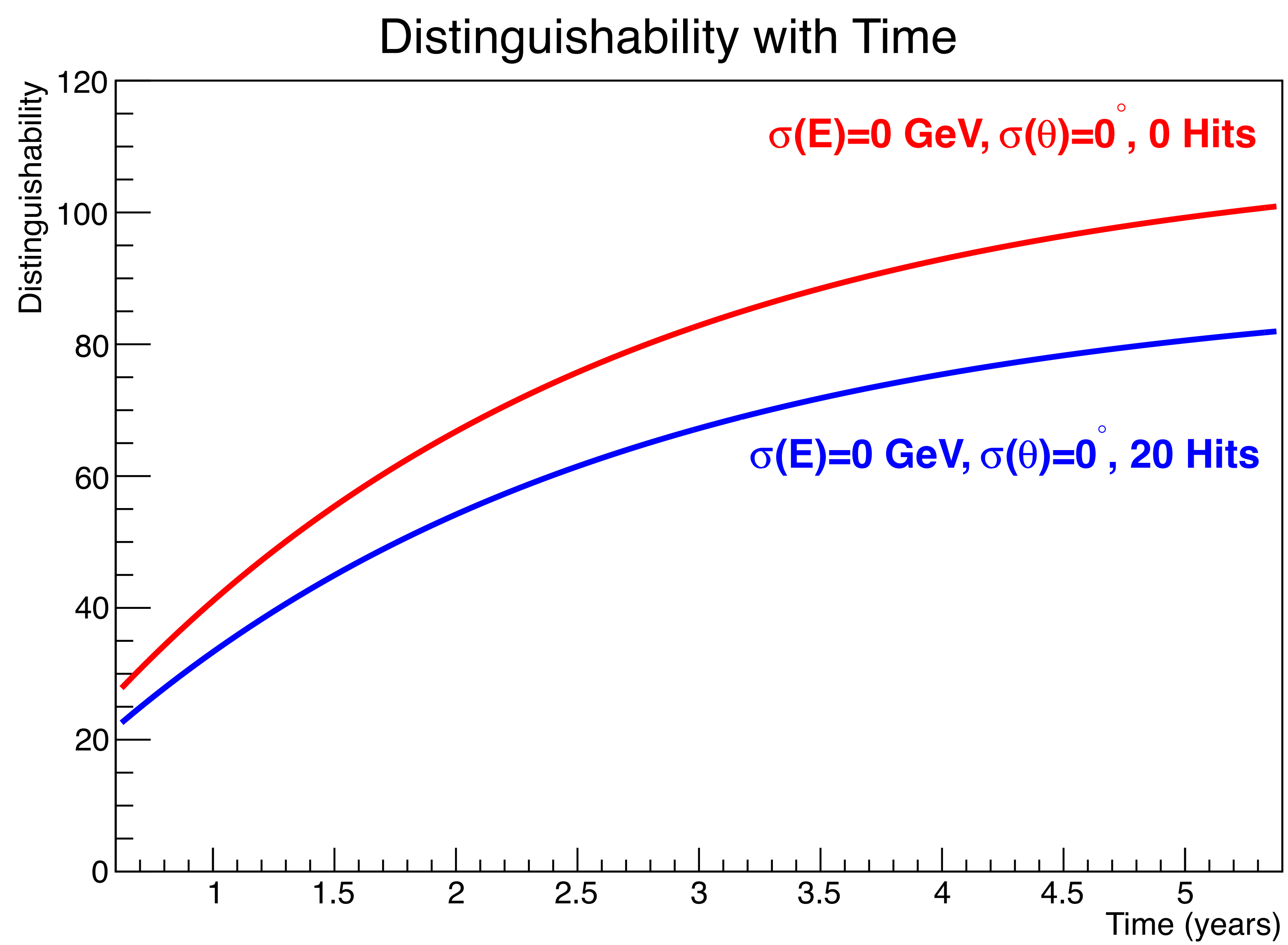
Sensitivity to Mass Hierarchy

- Start with perfect resolution and 100% efficiency



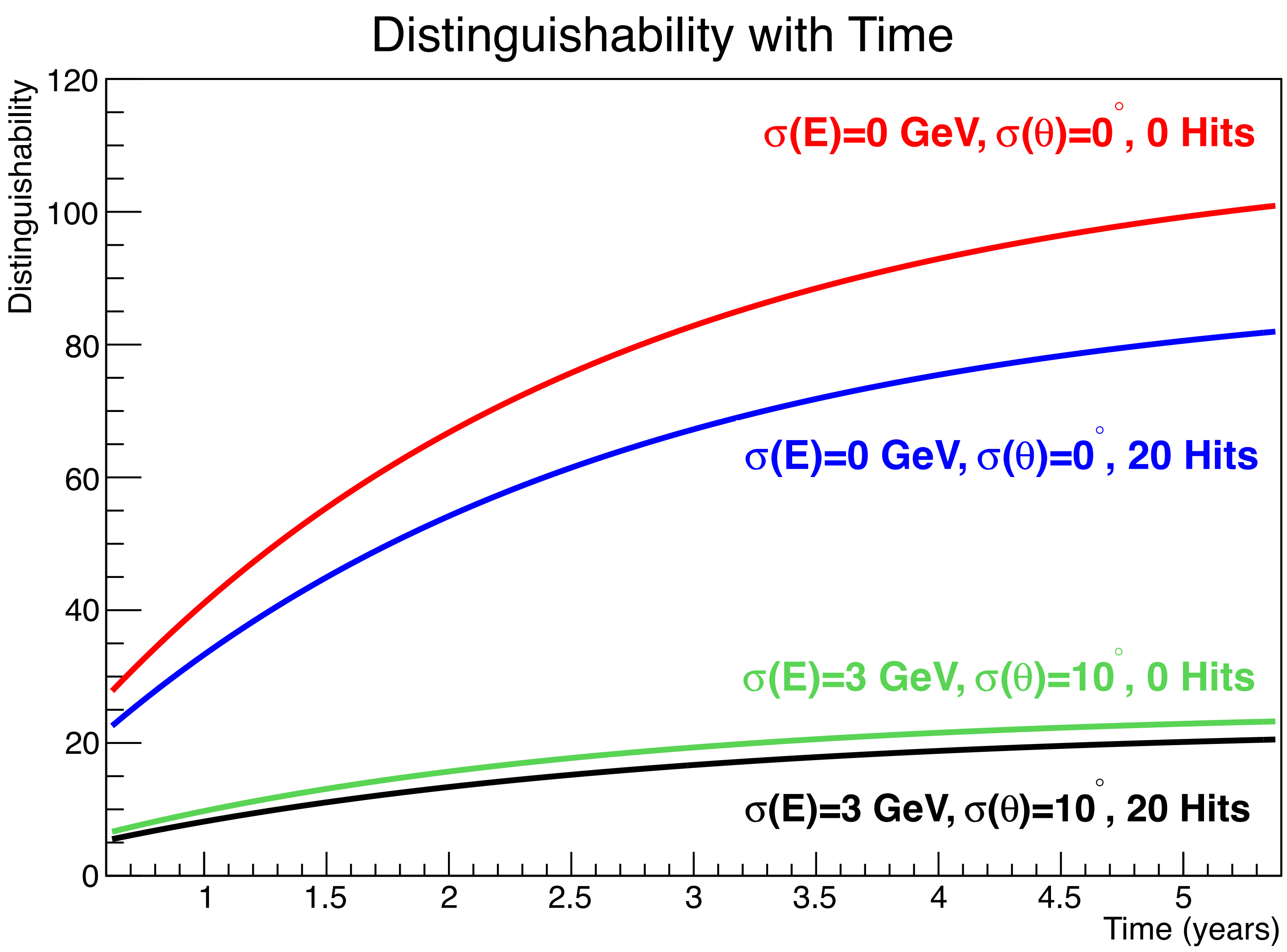
Sensitivity to Mass Hierarchy

- Start with perfect resolution and 100% efficiency
- Apply a 20 DOMs "reconstructibility" cut to mimic analysis efficiency



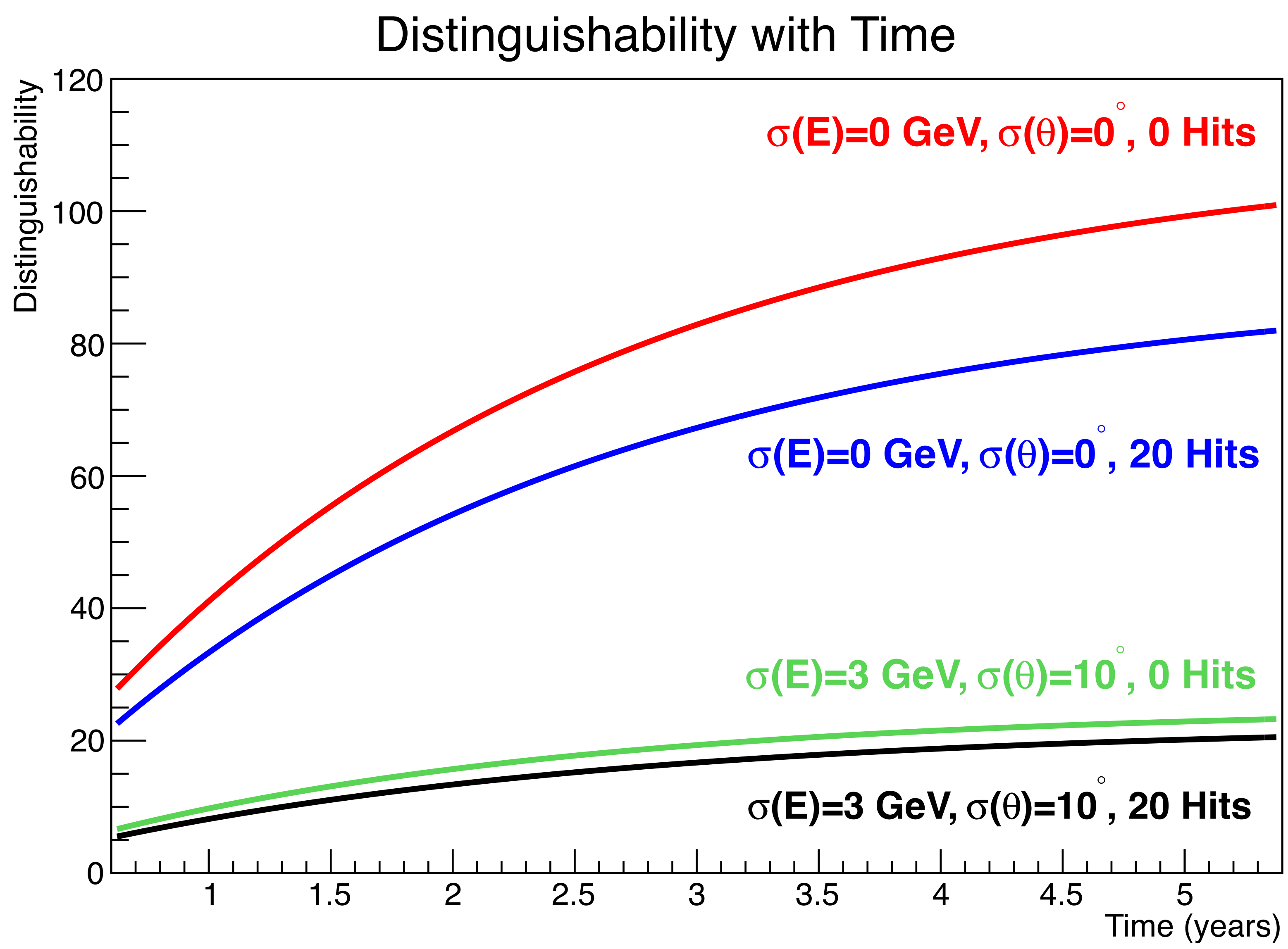
Sensitivity to Mass Hierarchy

- Start with perfect resolution and 100% efficiency
- Apply a 20 DOMs "reconstructibility" cut to mimic analysis efficiency
- Apply an assumed detector energy resolution



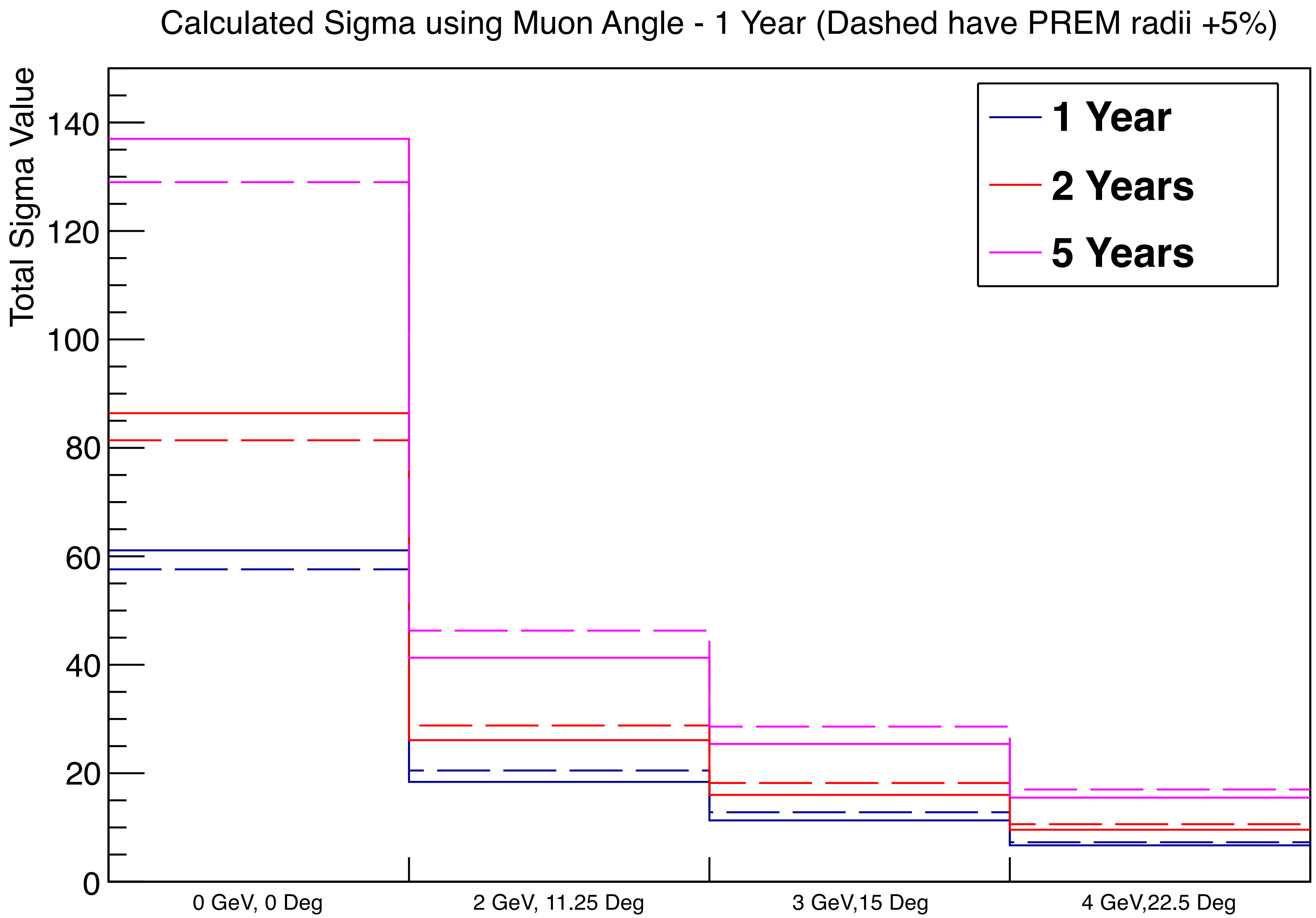
Sensitivity to Mass Hierarchy

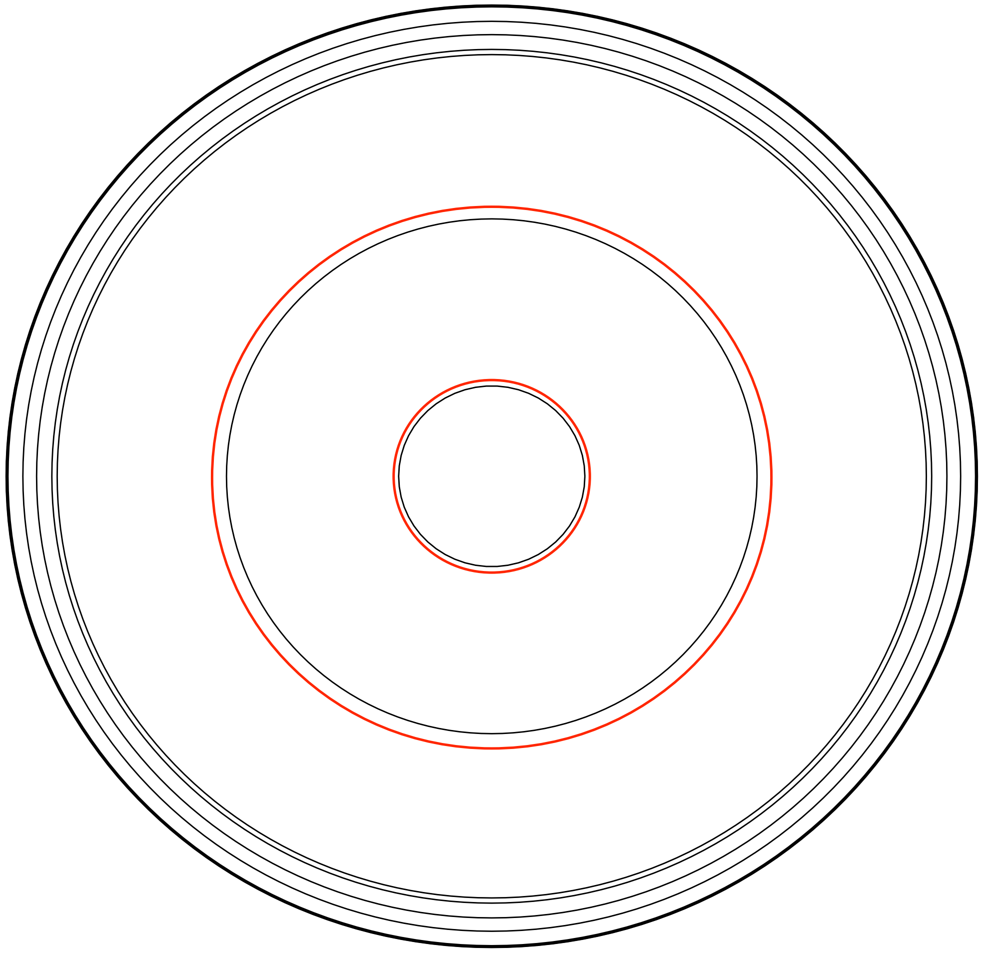
- Start with perfect resolution and 100% efficiency
- Apply a 20 DOMs "reconstructibility" cut to mimic analysis efficiency
- Apply an assumed detector energy resolution
- Repeat for various assumed resolutions



PREM Uncertainties

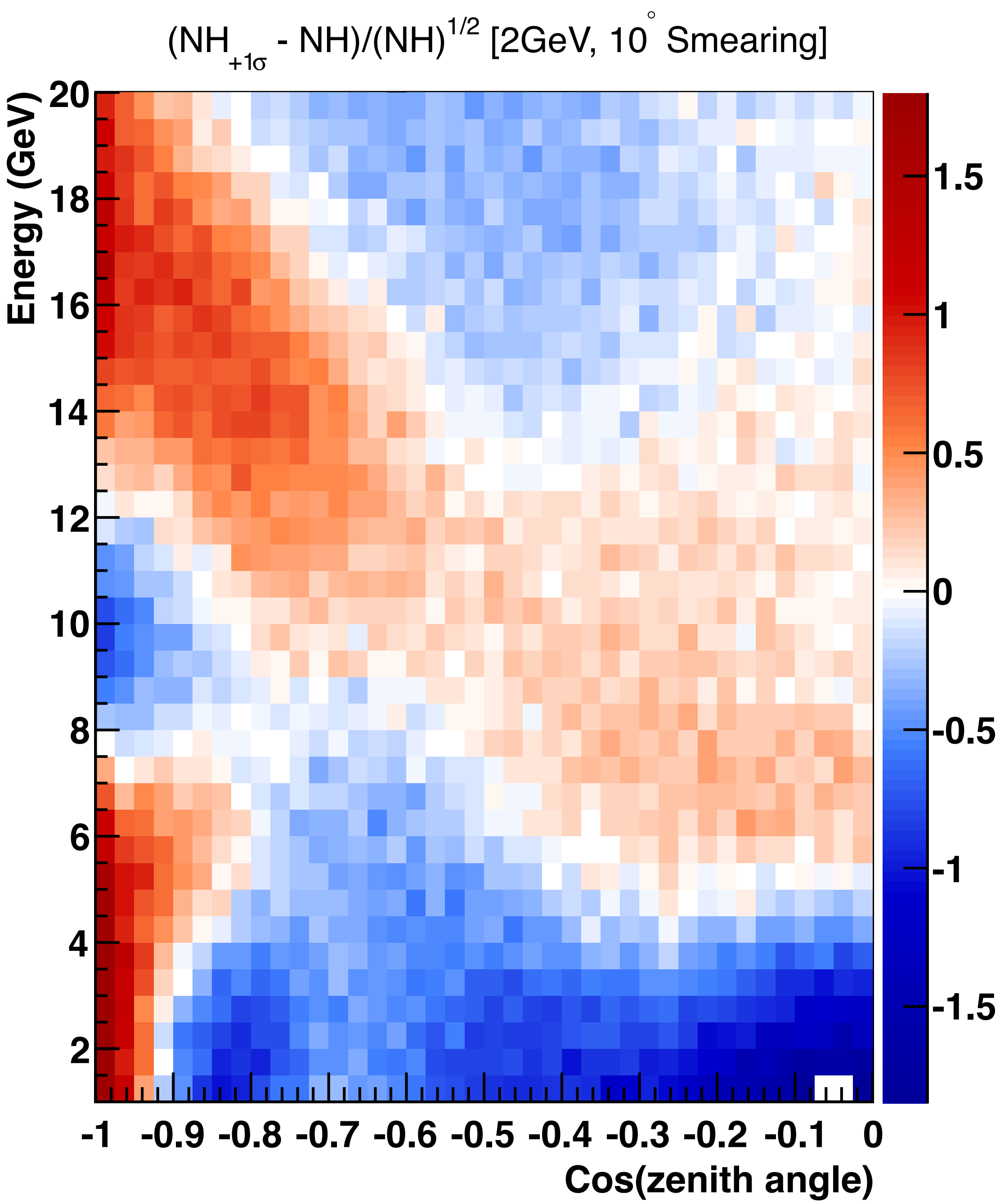
- Varied PREM layer radii by ±5%, probably about a 5x overestimate
- Distinguishability largely unaffected by model uncertainties

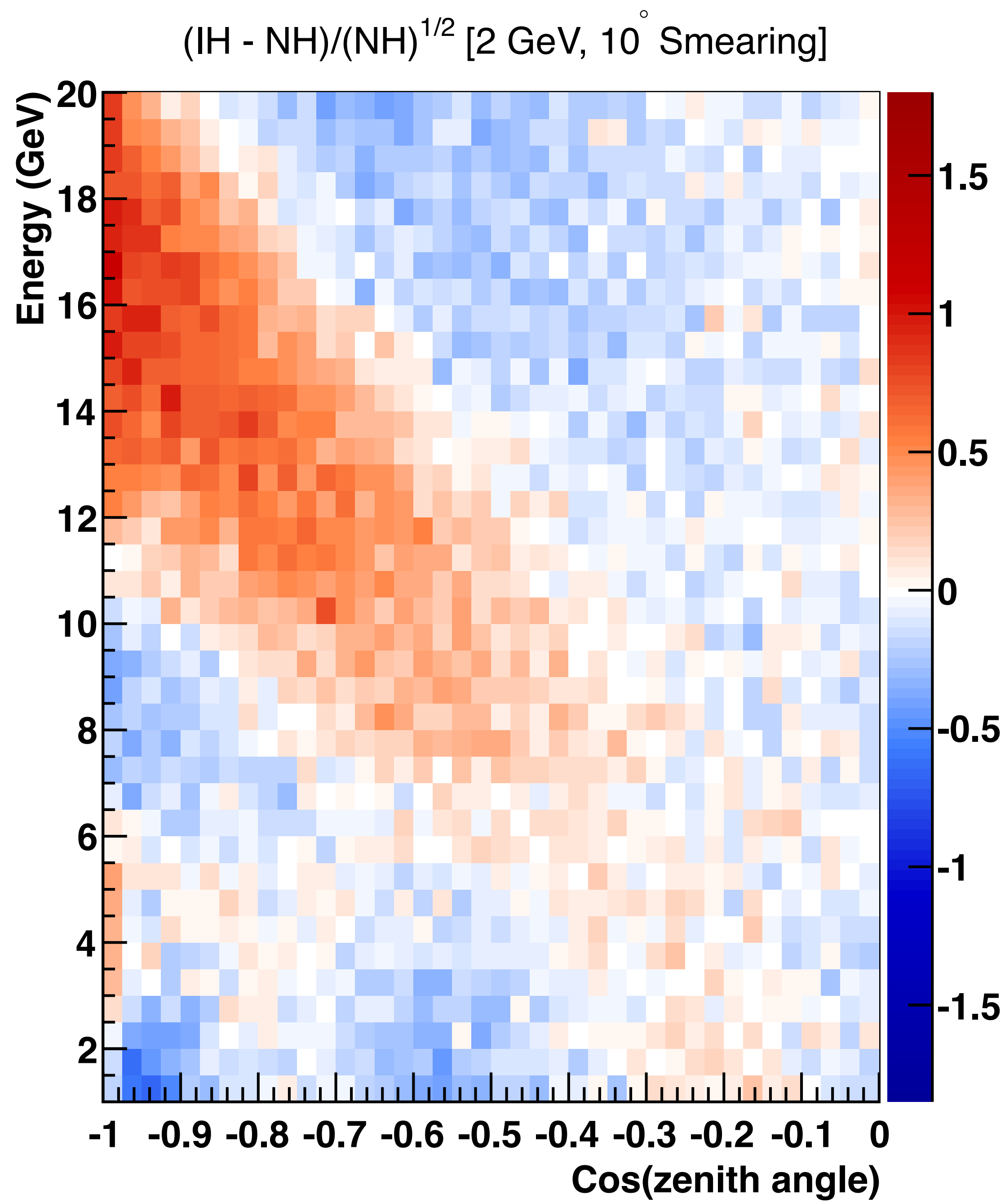




Theoretical Uncertainties

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





θ_{23} Maximal?

Fernandez-Martinez, Giordano, Mena, and Mocioiu, *Phys. Rev.* D82, 093011 (2010).

- External feasibility study of a $\sin(\theta_{23})$ measurement in a DeepCore/PINGU-like detector
  - 10 years of exposure, various threshold and resolution assumptions up to σ_E = 5 GeV, $\sigma_{\cos(\theta)}$ = 0.25
  - Requirements not dissimilar to those for hierarchy

Observable energies of 5 to 50 GeV
10 energy bins, 4 angular bins
vs.
1st energy bin, 1 angular bin +
9 energy bins, 4 angular bins
vs.
Exclude first 2 energy bins:
8 energy bins, 4 angular bins