Neutrino Oscillations and the Neutrino Mass Hierarchy

Tyce DeYoung
Department of Physics
Pennsylvania State University

Neutrinos Beyond IceCube
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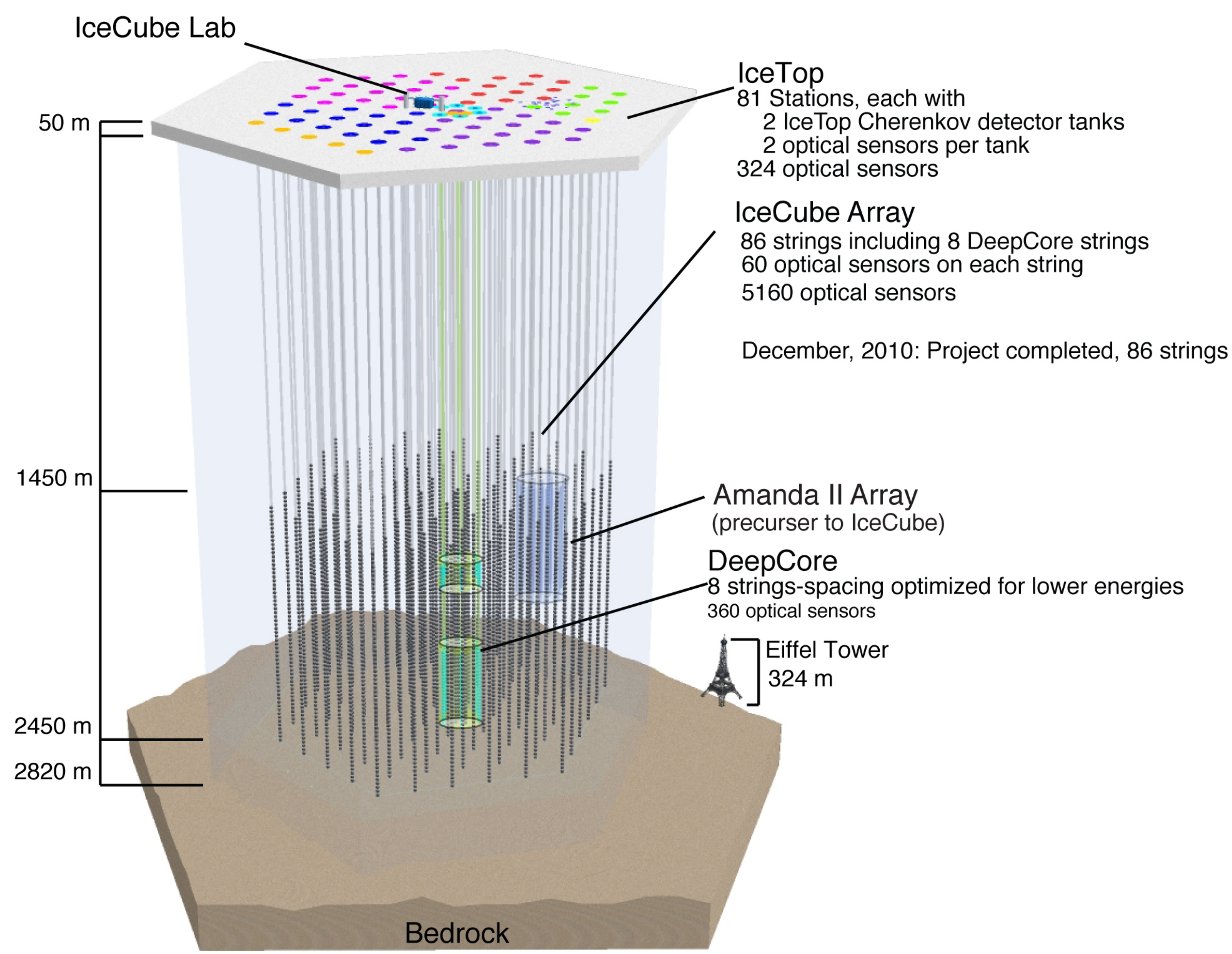
The IceCube Neutrino Observatory

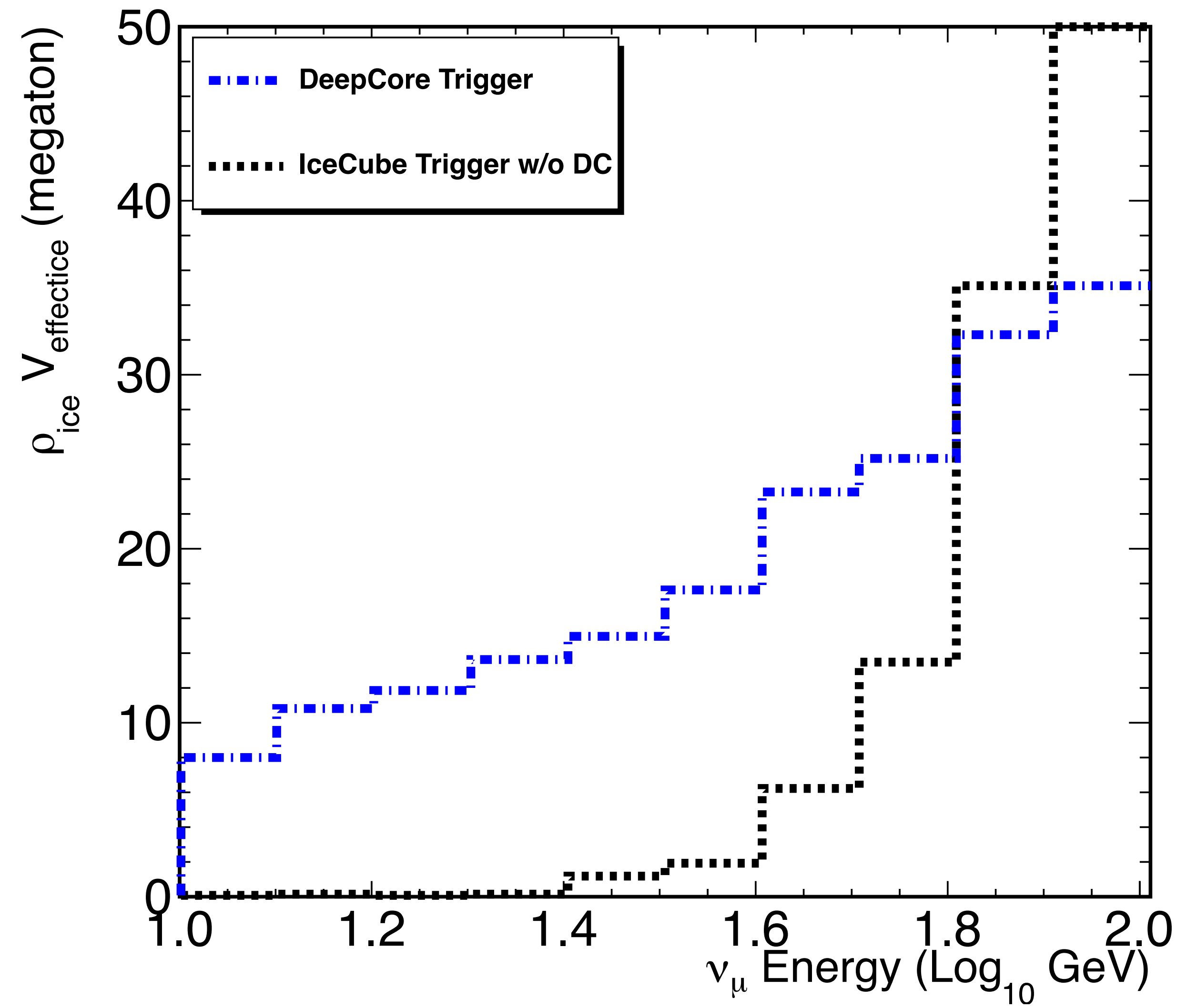
- Original IceCube design focused on neutrinos with energies above a few hundred GeV
- DeepCore provides increased effective volume at 10-100 GeV



The IceCube Neutrino Observatory

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

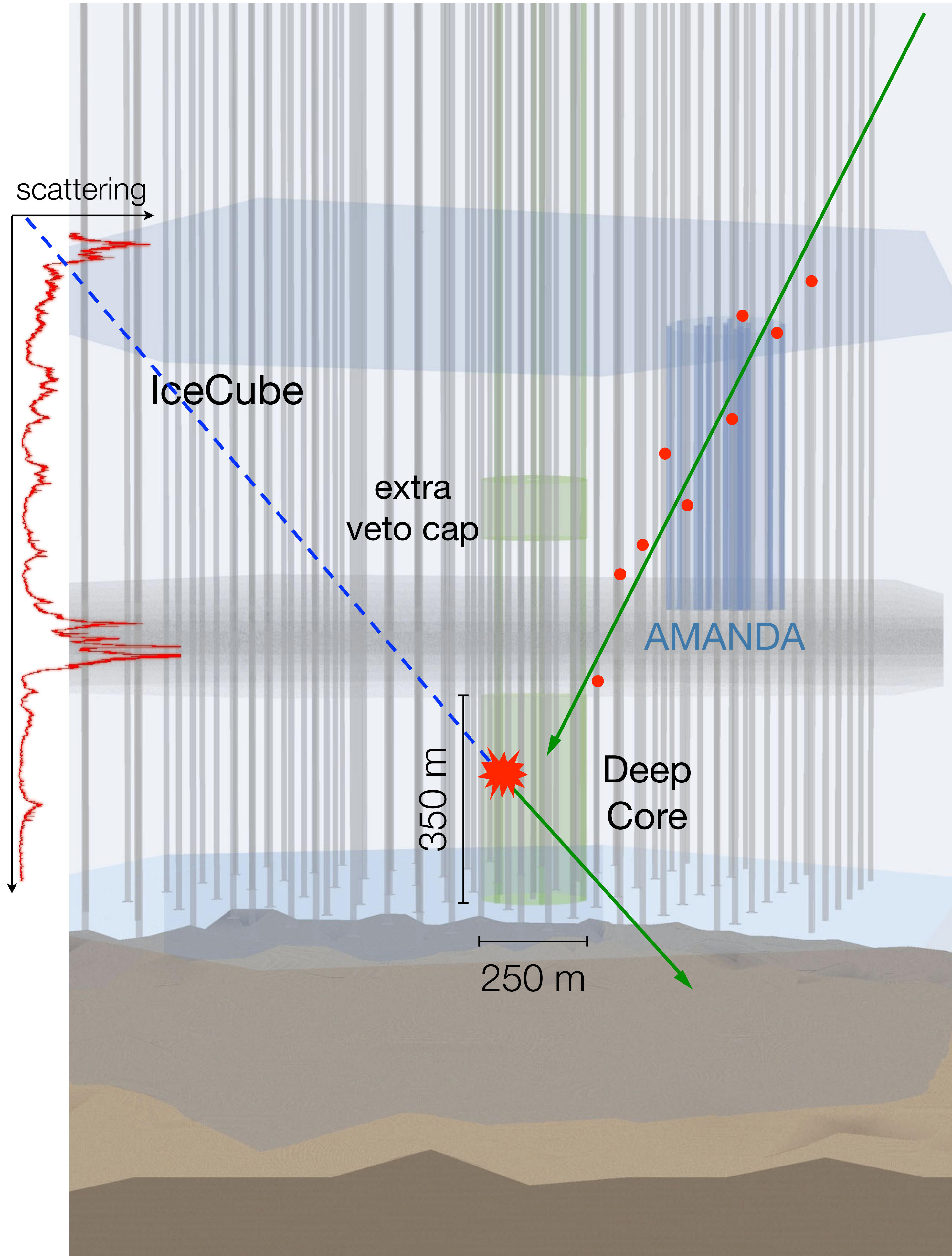
- DeepCore provides increased effective volume at 10-100 GeV
  - Higher efficiency far outweighs reduced geometrical volume
  - Note: comparison at trigger level – analysis efficiencies not included, typically $\mathcal{O}$(10%)



- Focus on dark matter searches, neutrino oscillation measurements

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, very low levels of radioactive impurities
- IceCube provides an active veto against cosmic ray muon background

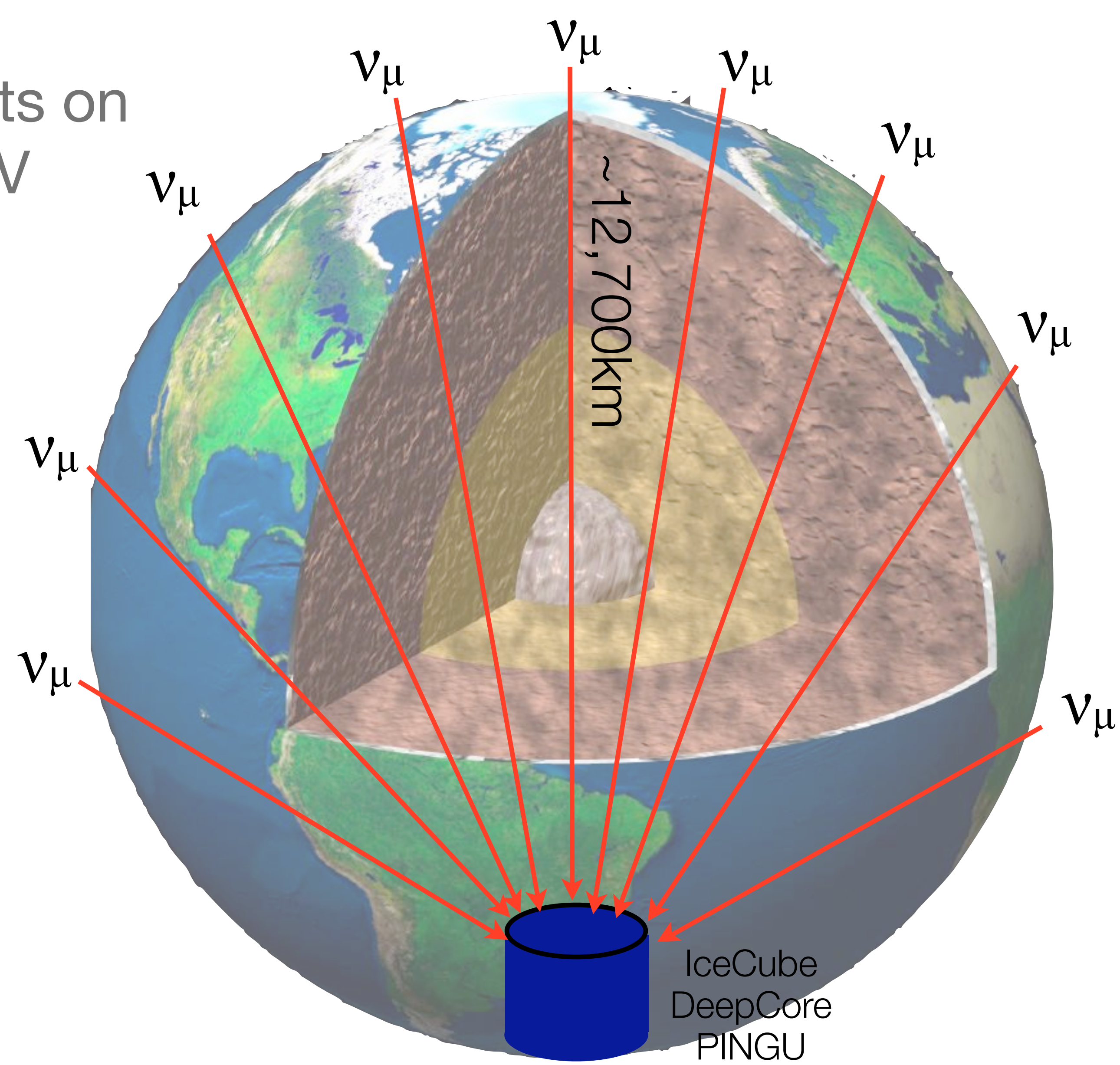


DeepCore Physics

- Dark matter searches
  - Primarily sensitive to WIMP masses above ~50 GeV/c^2 due to energy threshold
  - Solar WIMP annihilation: *Phys. Rev. Lett*. 110, 131302 (2013)
  - Galactic Halo: coming soon
- Direct searches for exotic particles
  - E.g. monopoles: arXiv:1402.3460, submitted to *Eur. Phys. J. C*
- Measurement of atmospheric electron neutrino spectrum
  - First measurement above 50 GeV: *Phys. Rev. Lett*. 110, 151105 (2013)
- Measurement of atmospheric neutrino oscillations
  - First IceCube observation: *Phys Rev. Lett*. 111, 081801 (2013)
  - Improved results coming this summer – new analysis with reduced energy threshold of ~10 GeV will greatly improve precision

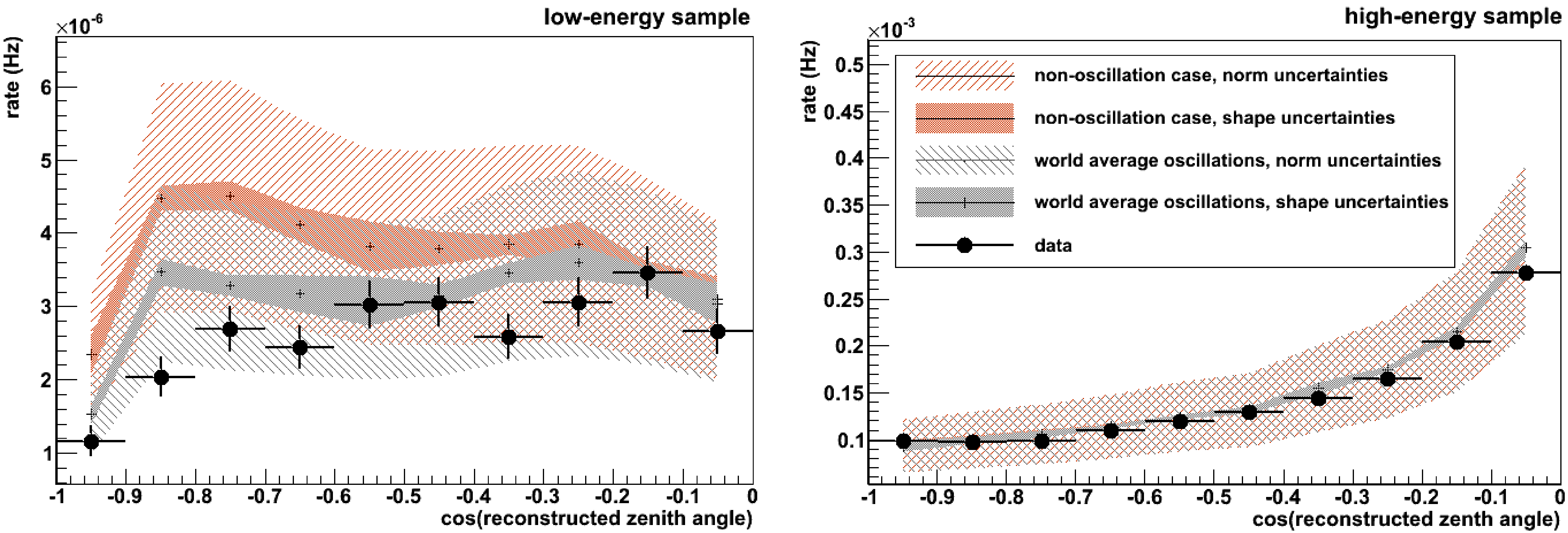
Oscillation Physics with Atmospheric Neutrinos

- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects on ν *or* $\bar{\nu}$ (MSW etc.) below 10-20 GeV
- Neutrinos are available over a wide range of energies and baselines
  - Oscillations produce distinctive patterns in energy-angle space
  - Allows us to control systematics using events in "side band" regions – trade statistics for constraints on systematics



Atmospheric Oscillations – First Analysis

Phys. Rev. Lett. 111, 081801 (2013)

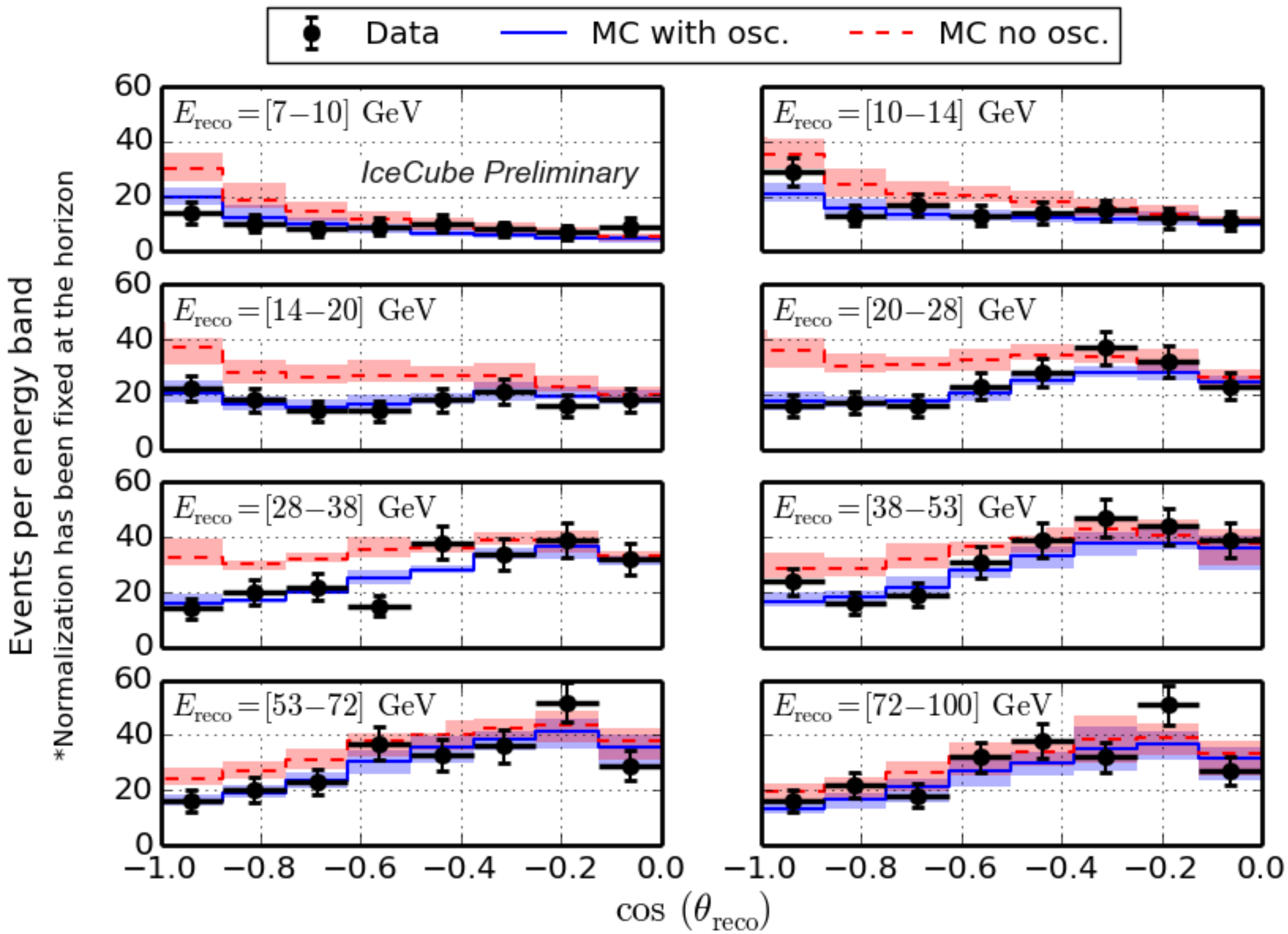


Statistically significant angle-dependent suppression at low energy, high energy sample provides constraint on uncertainties in simultaneous fit

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

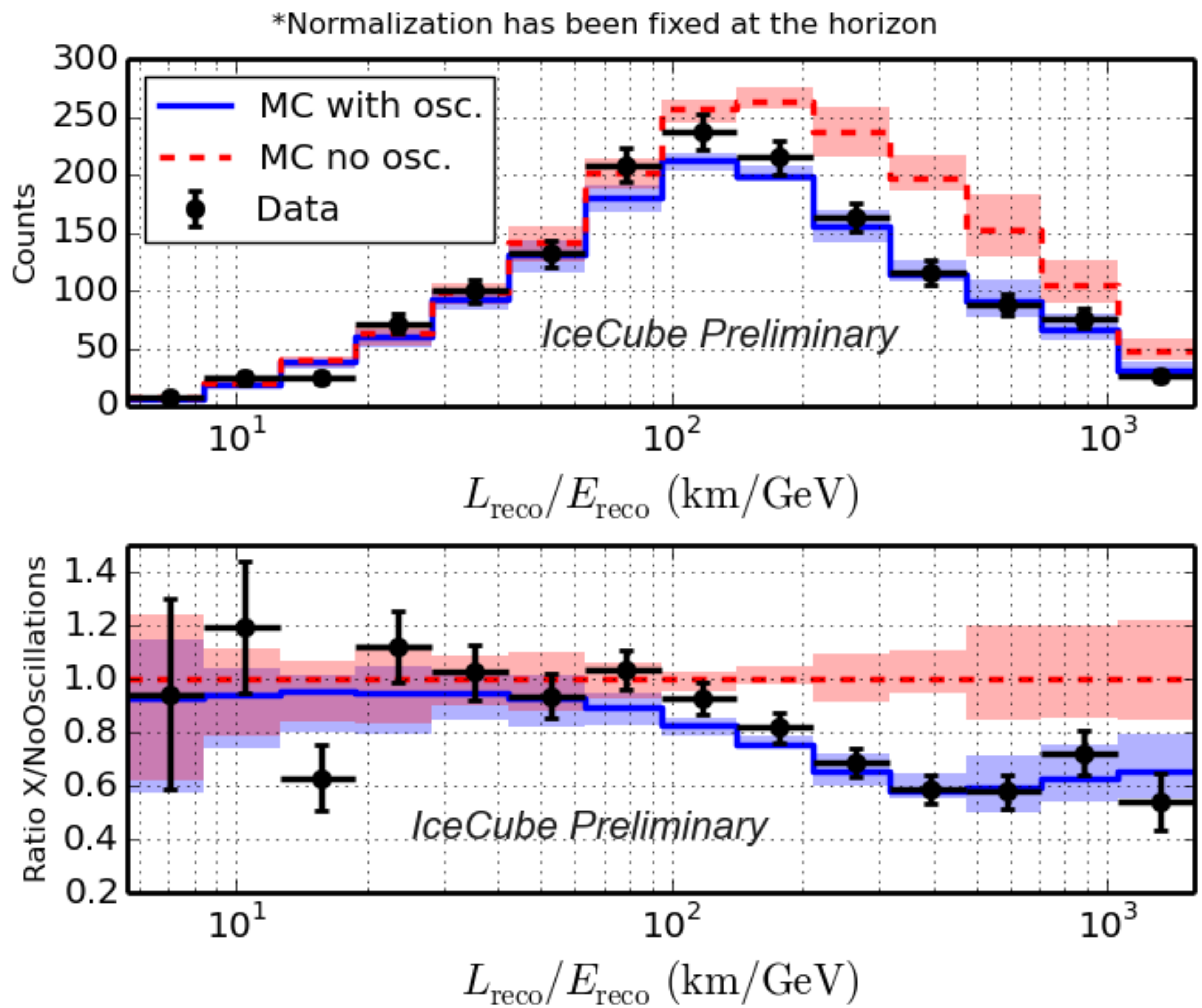
Atmospheric Oscillations – 2nd Generation

- Improved event selection – 2,500 events per year
- Significantly better reconstructions, enabling use of multiple energy bins in oscillation energy range
  - Permits tighter constraints on systematics from the data



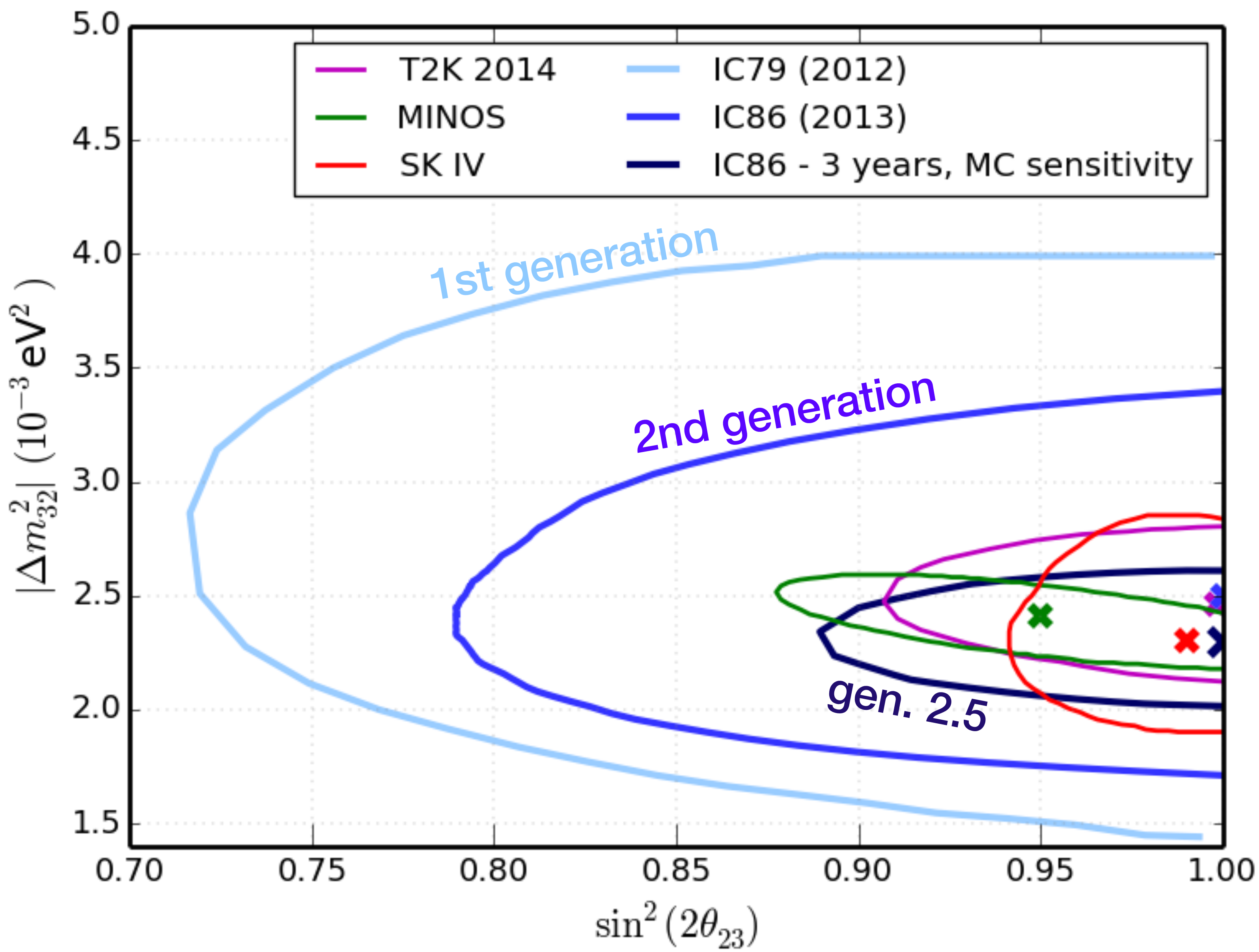
Atmospheric Oscillations – 2nd Generation

- Project data onto reconstructed (L/E$_\nu$) for illustration
  - Actual analysis is performed in 2D
- Second muon survival maximum just below DeepCore's energy threshold – accessible with PINGU



Atmospheric Oscillations – 2nd Generation

- Expected contours from current analysis are becoming competitive with world's leading measurements
  - Data to be "unblinded" before Neutrino 2014
  - Here: injecting maximal mixing to illustrate sensitivity
- 3rd generation of event selections and reconstructions in the pipeline – we will soon do even better!



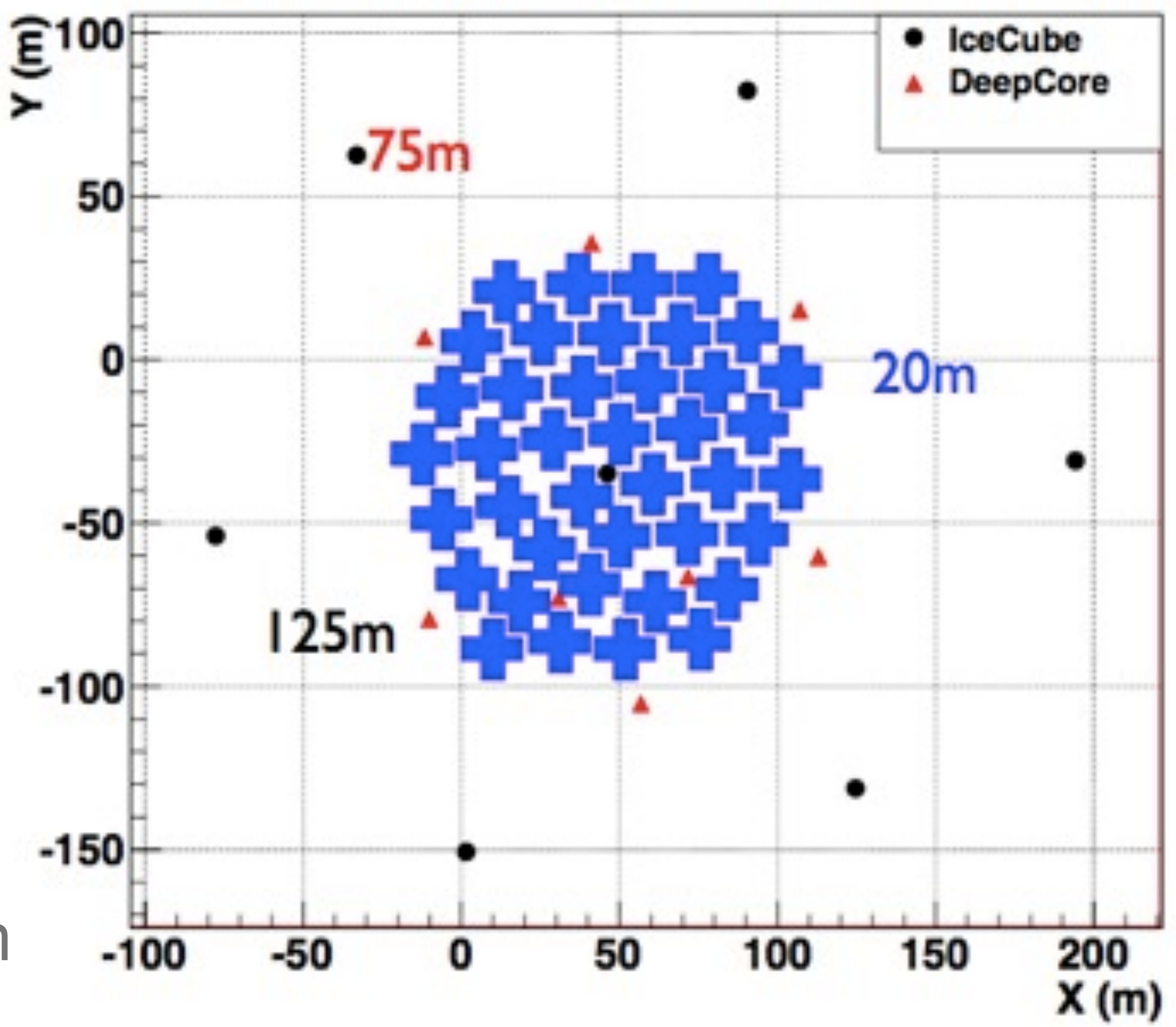
Neutrinos Beyond IceCube: Particle Physics

- With its DeepCore extension, IceCube is competitive in indirect dark matter searches, neutrino oscillation measurements
  - Primary limitation is energy threshold: second oscillation maximum, hierarchy-dependent matter effects, low-mass dark matter just out of reach
- A further augmentation of IceCube DeepCore would provide an energy threshold low enough to enable a broad range of physics, including determination of the neutrino mass hierarchy
  - Follow IceCube design closely: quick to deploy, low technical risk, relatively moderate cost
- Also provide platform for more precise understanding of the ice
  - Improved in situ calibration light sources, and emitter-detector baselines $\ll \lambda_{scatt}$
  - Would provide a benefit for both high energies and low energy physics

PINGU

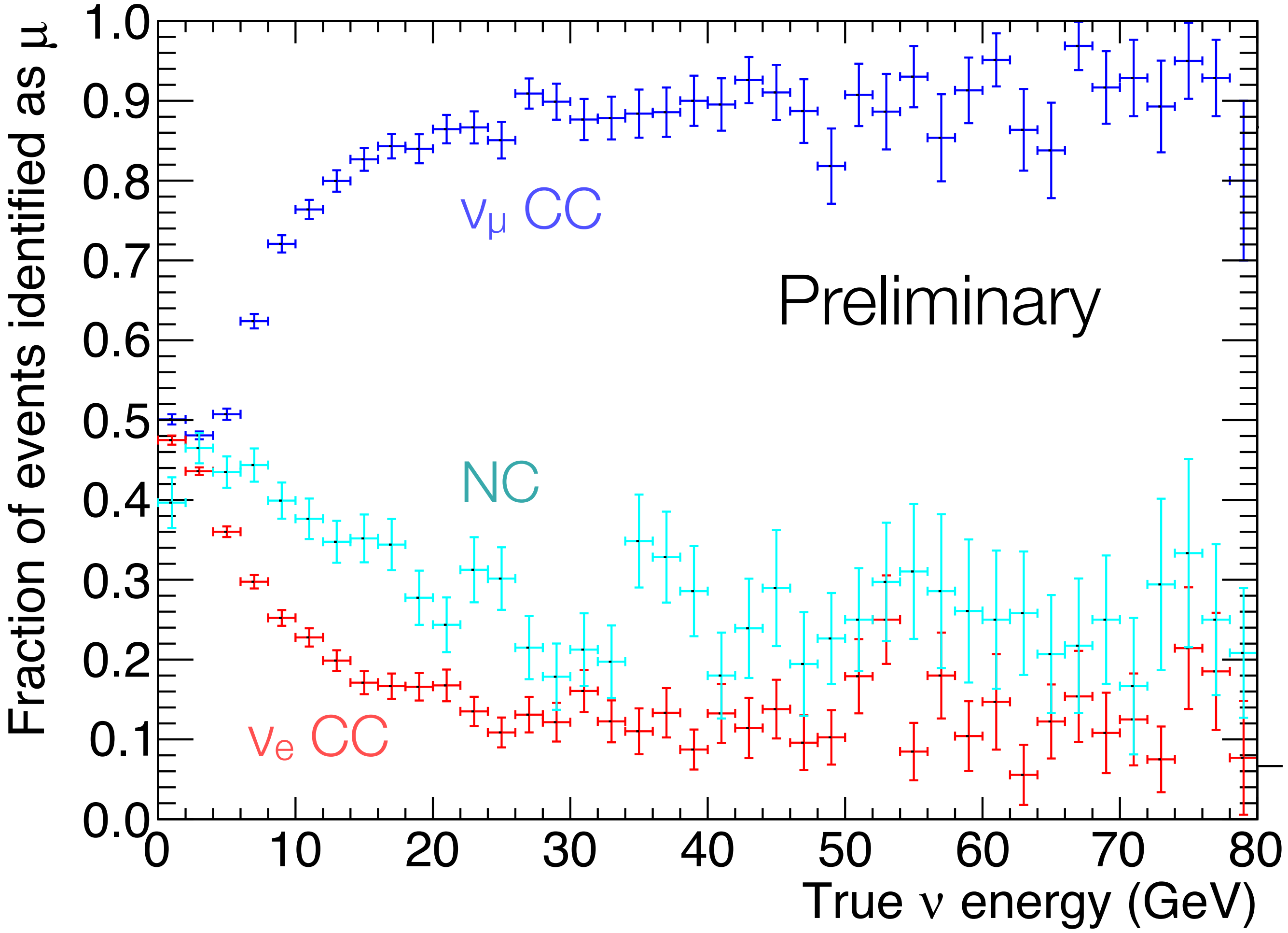
- Baseline 40 additional strings of 60 Digital Optical Modules each, deployed inside the DeepCore volume
  - 20 m string spacing (cf. 125 m for IceCube, 72 m for DeepCore)
  - ~15x higher photocathode density
  - Precise geometry under study – significantly improved performance possible with some additional instrumentation
- Use the same updated IceCube DOMs, electronics, drill as for a high-energy extension
  - Also take opportunity to install R&D prototypes for novel instrumentation

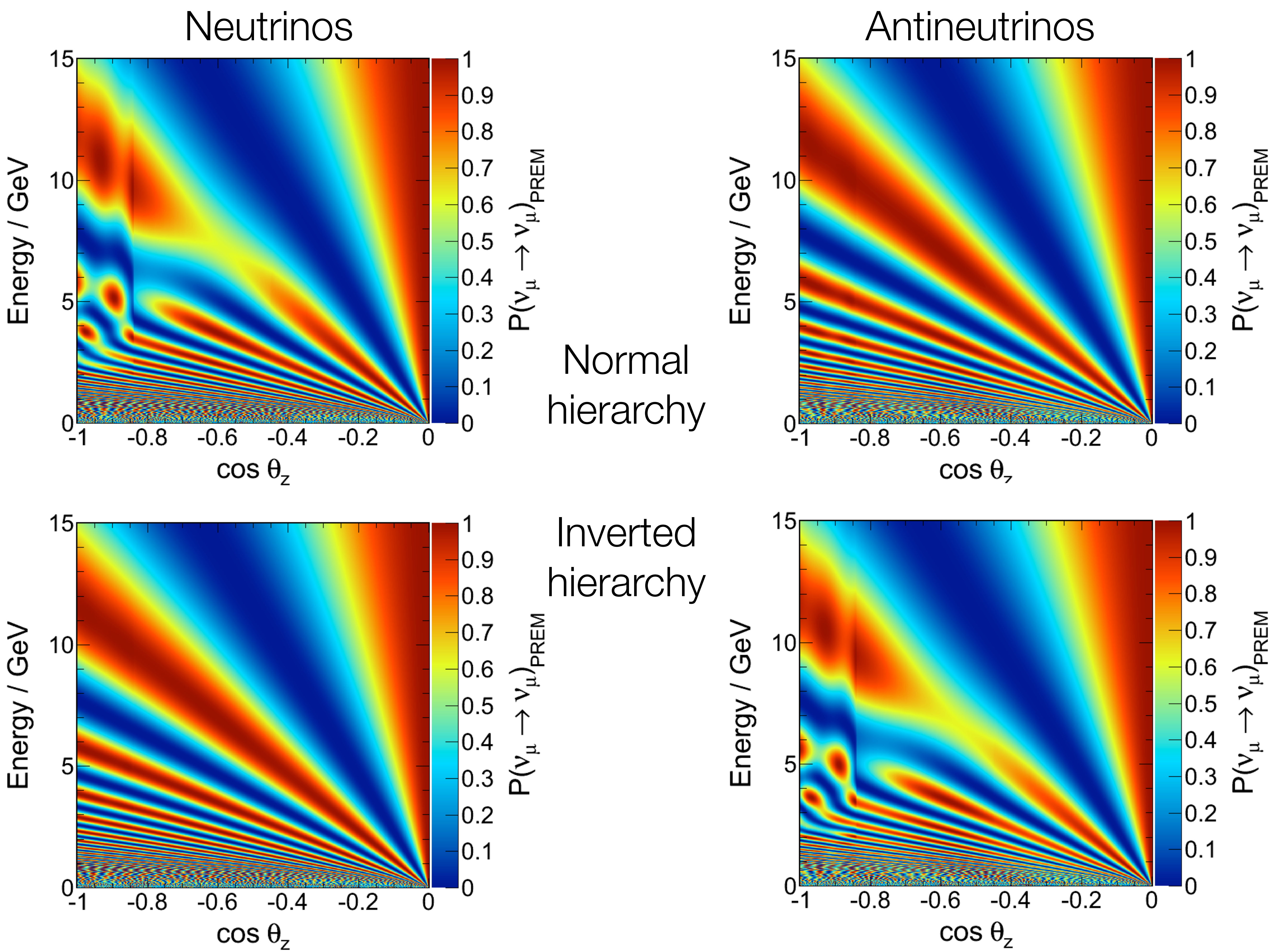
IceCube-DeepCore-PINGU top view



Signatures of the Neutrino Mass Hierarchy

- Matter effects alter oscillation probabilities for neutrinos or antineutrinos traversing the Earth
  - Maximum effects seen for specific energies and baselines (= zenith angles) due to the Earth's density profile
  - Neutrino oscillation probabilities affected if hierarchy is normal, antineutrinos if inverted
  - Rates of all flavors are affected
- At higher energies, 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



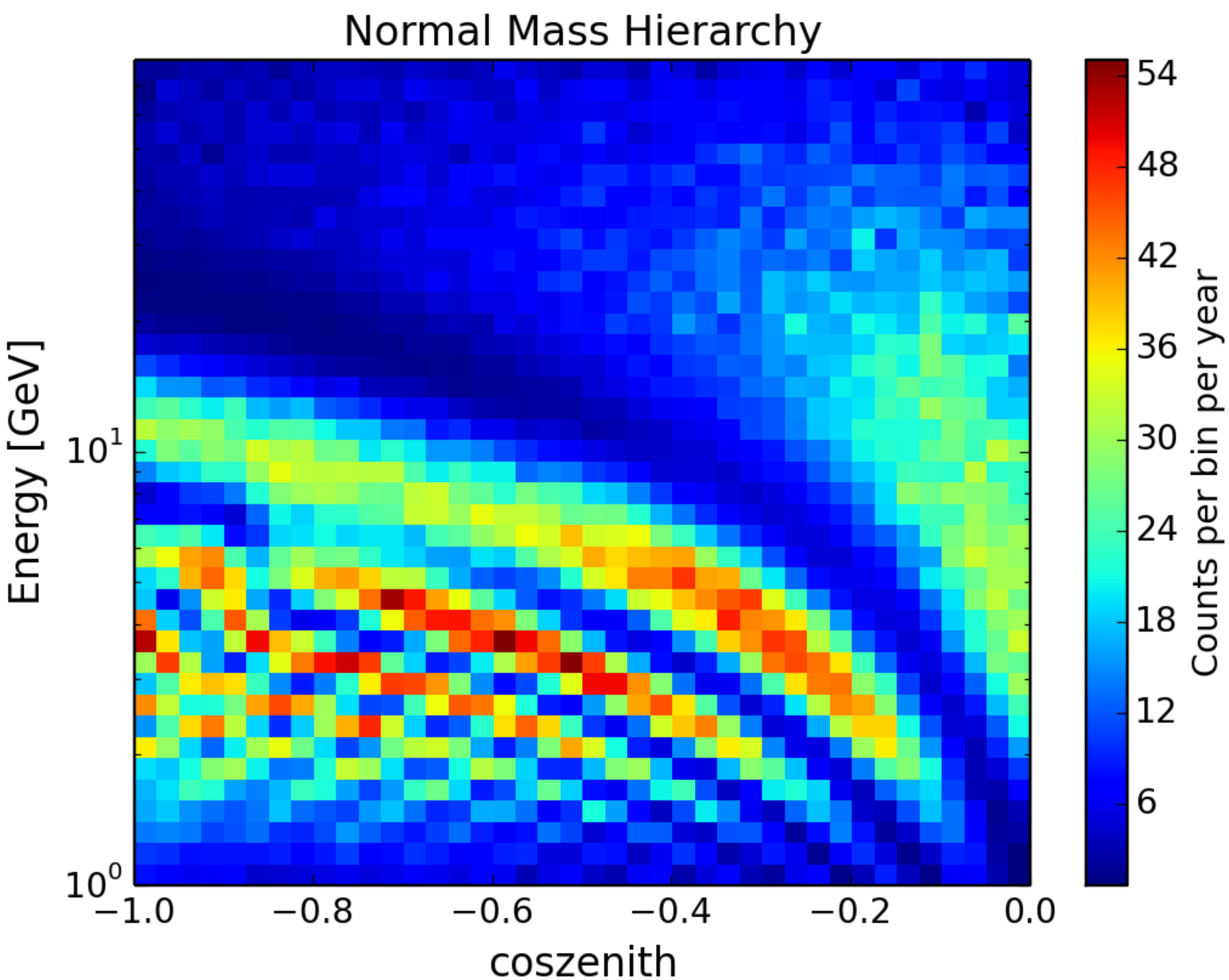


Neutrinos
Antineutrinos
Normal hierarchy
Inverted hierarchy
Energy / GeV
cos θ_z
$P(\nu_\mu \rightarrow \nu_\mu)_{PREM}$
15
10
5
0
-1
-0.8
-0.6
-0.4
-0.2
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Muon Neutrino + Antineutrino Rates (True)

- Cannot distinguish ν from ν̄ directly – rely instead on differences in fluxes, cross section (and kinematics)

- Differences clearly visible in expected atm. muon (ν + ν̄) rate even with 1 year's data
  - Note: detector resolutions *not* yet included



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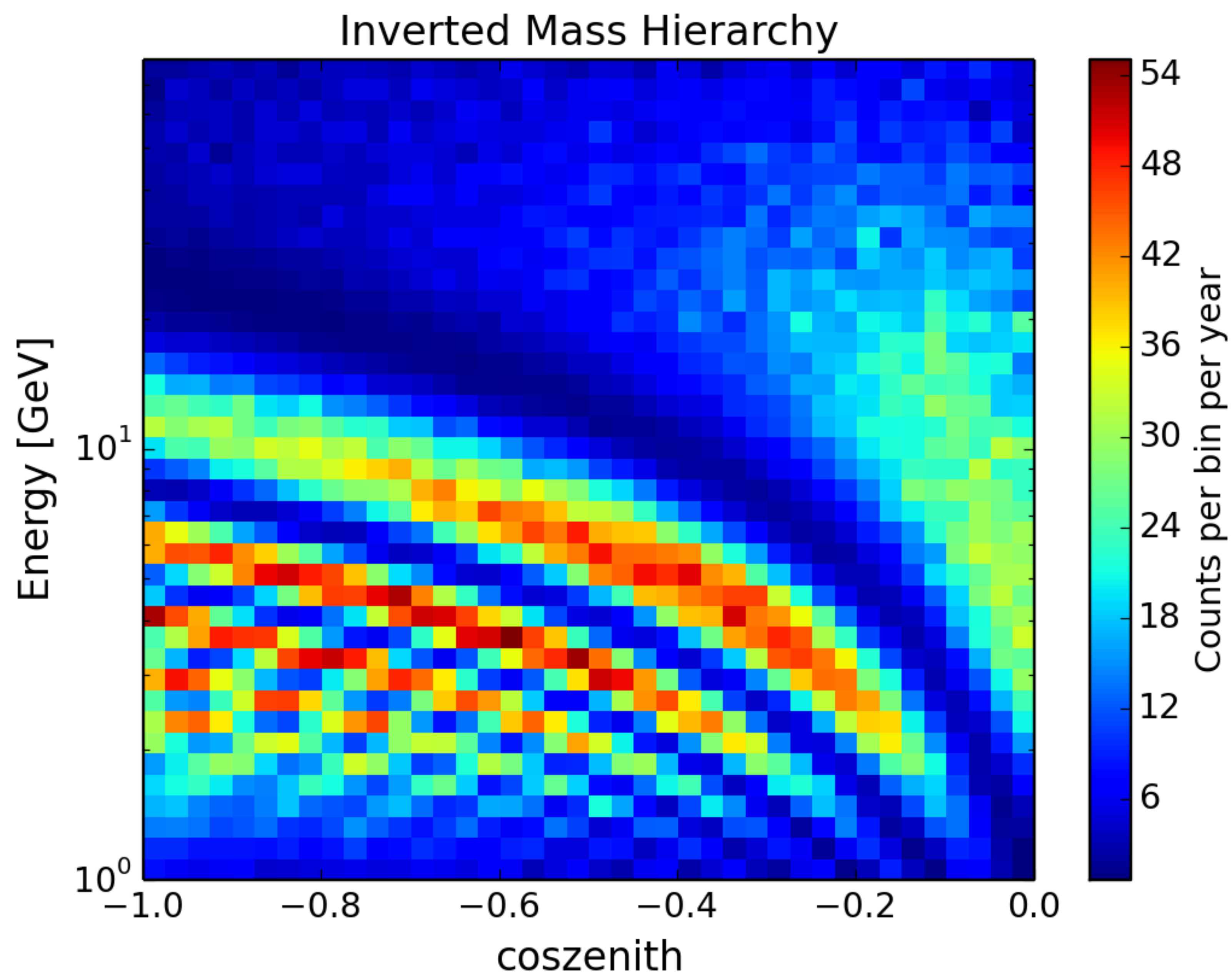
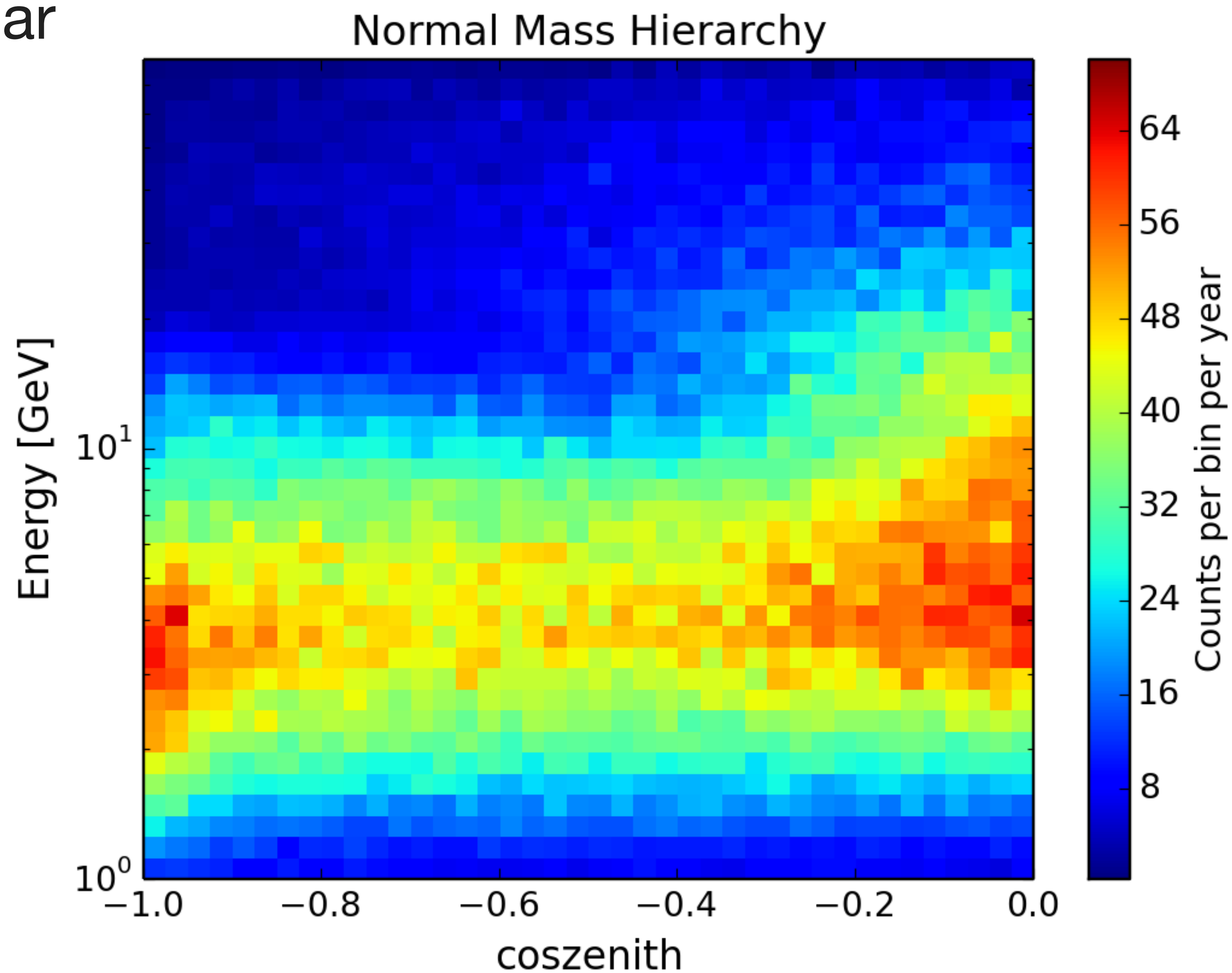


Observed Muon Neutrino + Antineutrino Rates

- Including detector angular and energy resolutions, signature is barely distinguishable by eye with only a single year of muon neutrino data
  - Distortion of a complicated pattern
  - Detector resolution determined by full MC simulation using IceCube tools modified for low energy events



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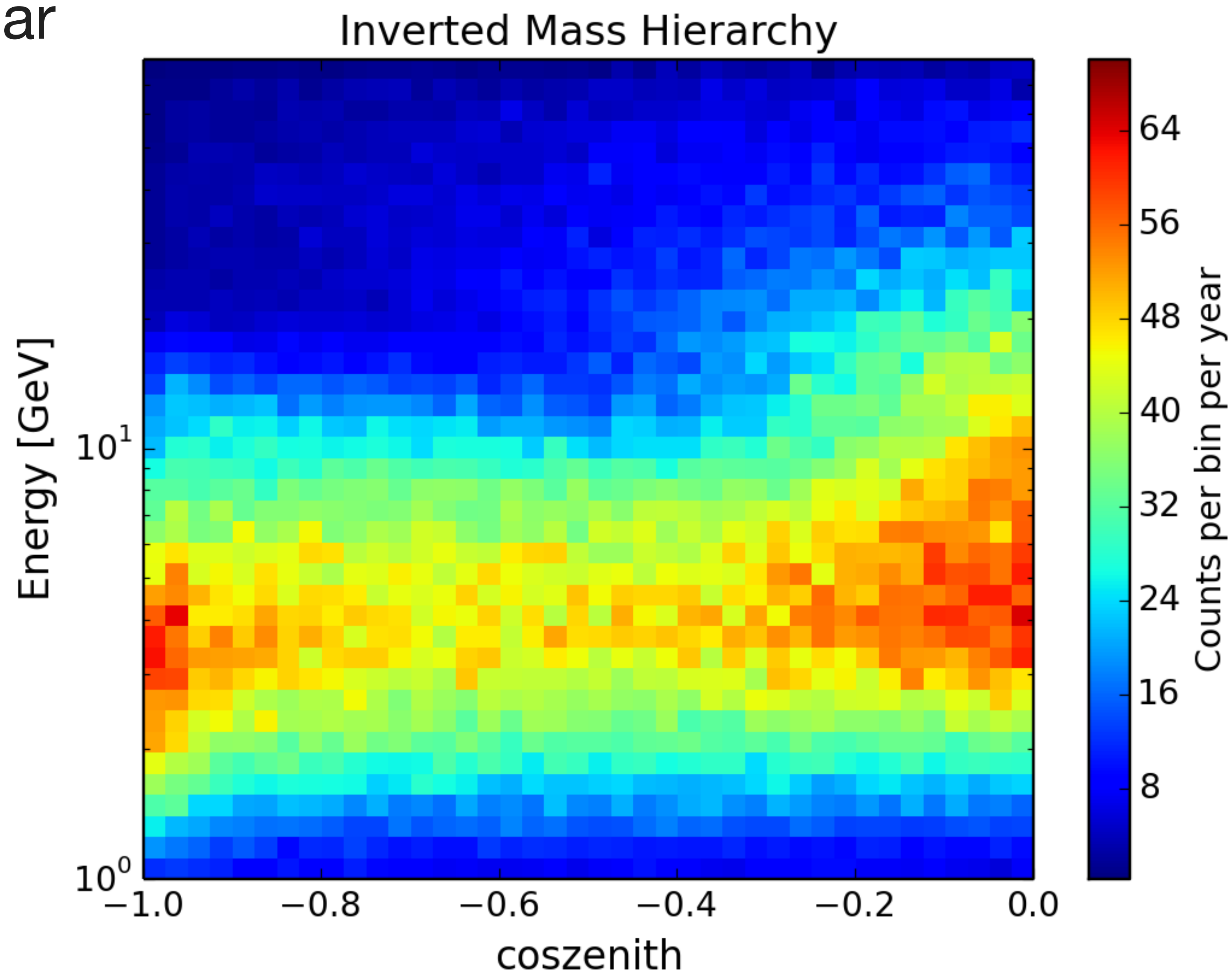
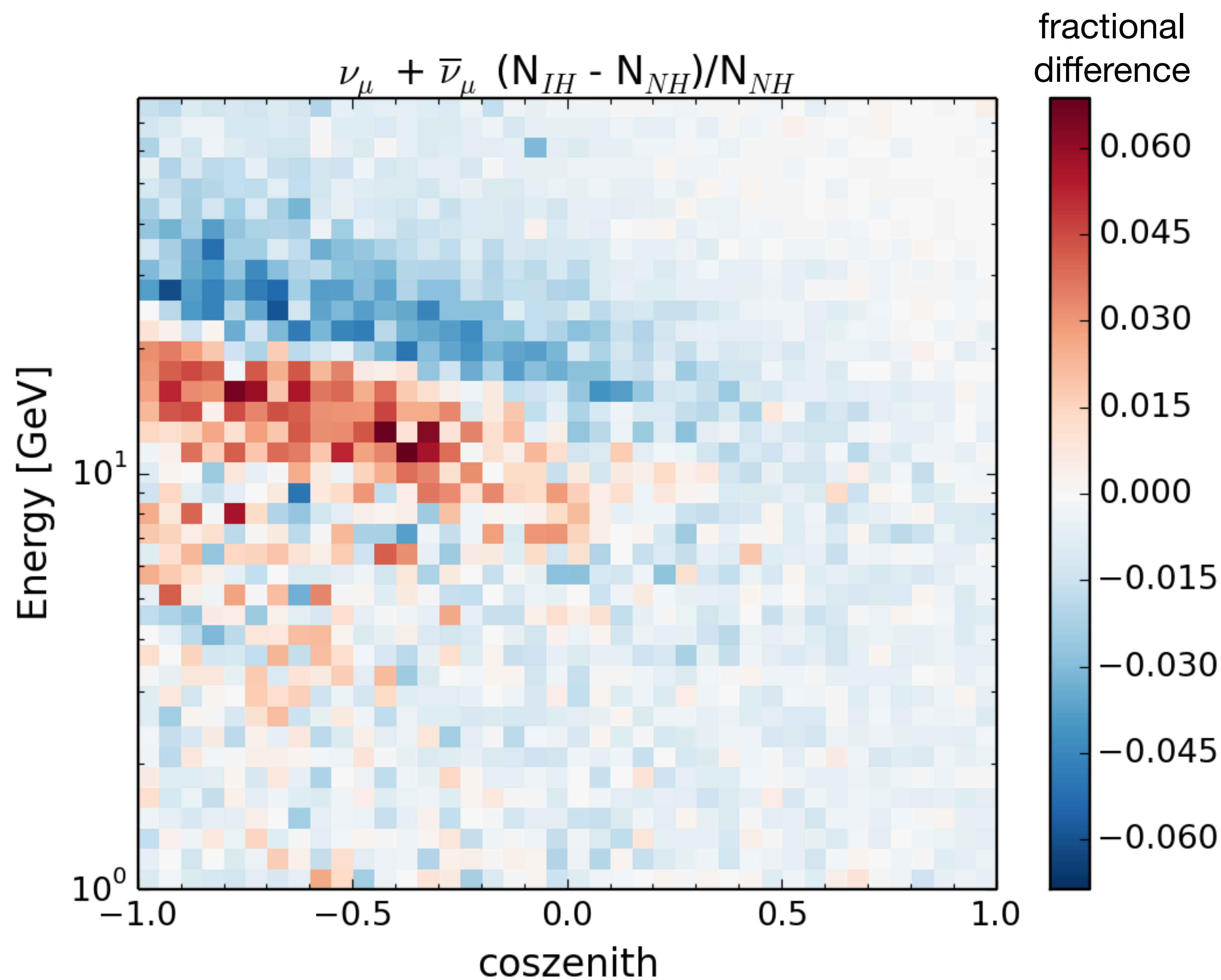


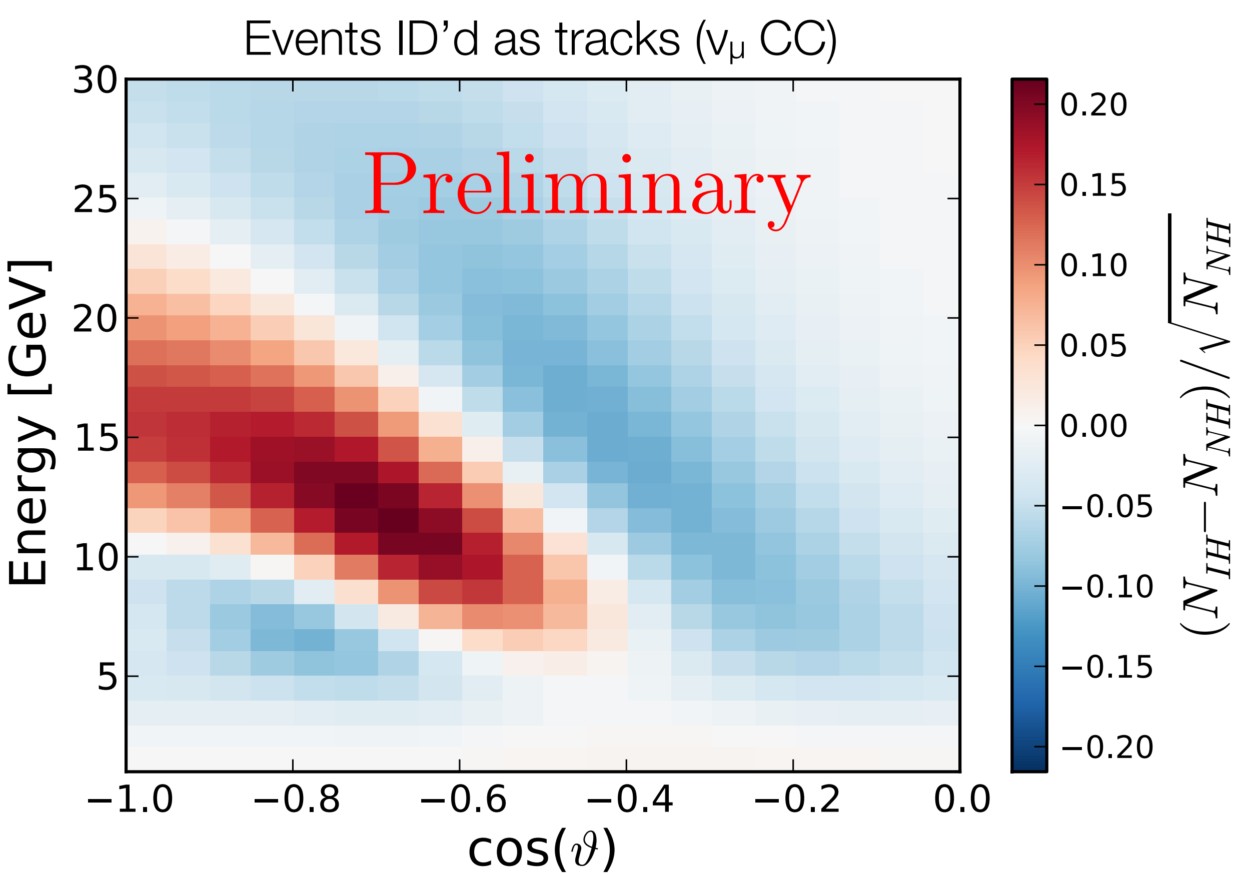
Hierarchy Signature: $\nu_\mu + \overline{\nu}_\mu$ Rate Differences

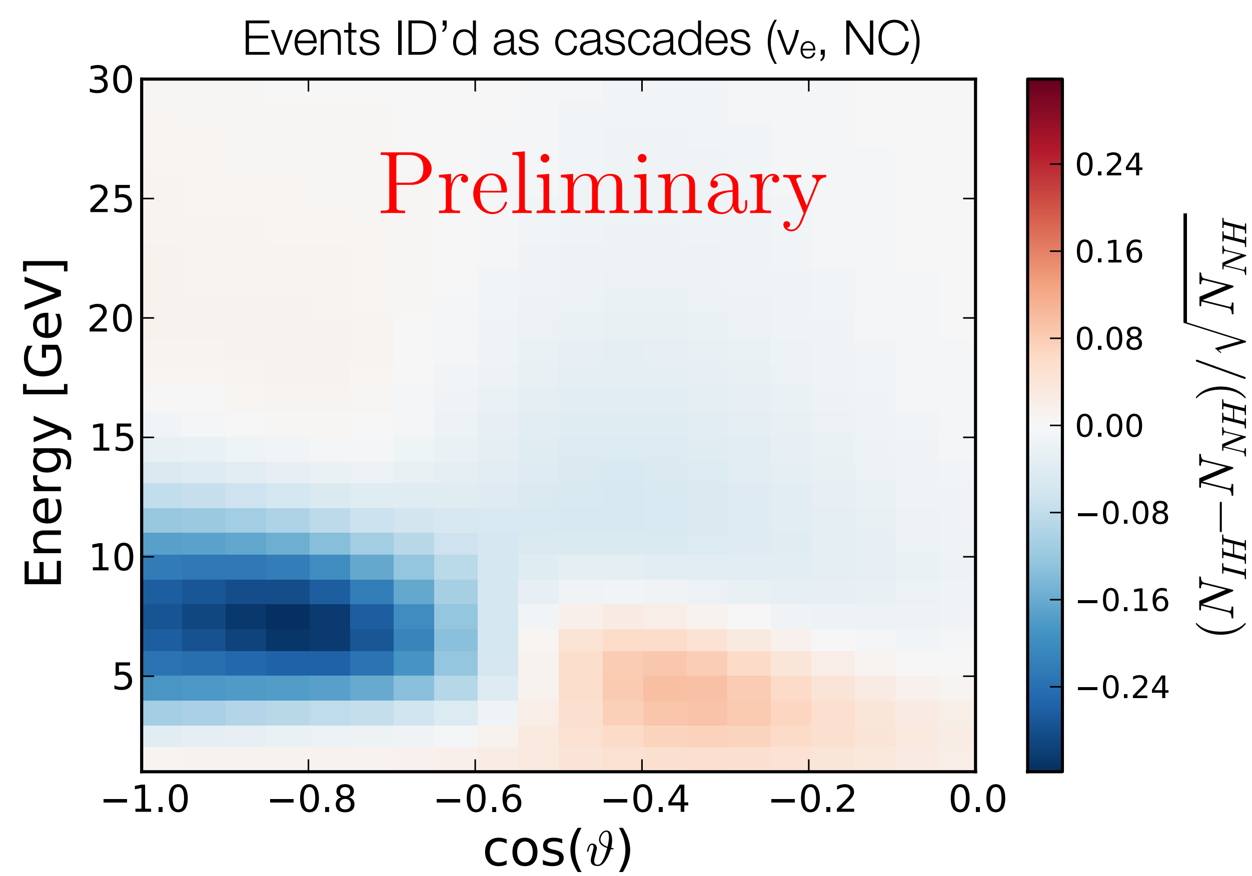
- The signature of the hierarchy is more visible by looking at the pattern of expected excesses and deficits in the E vs. cos(θ) plane
  - Structure of the pattern gives some protection against systematics
  - Note: reconstructions included in these plots, but not particle ID



Experimental Signatures of the Mass Hierarchy

arXiv:1401.2046



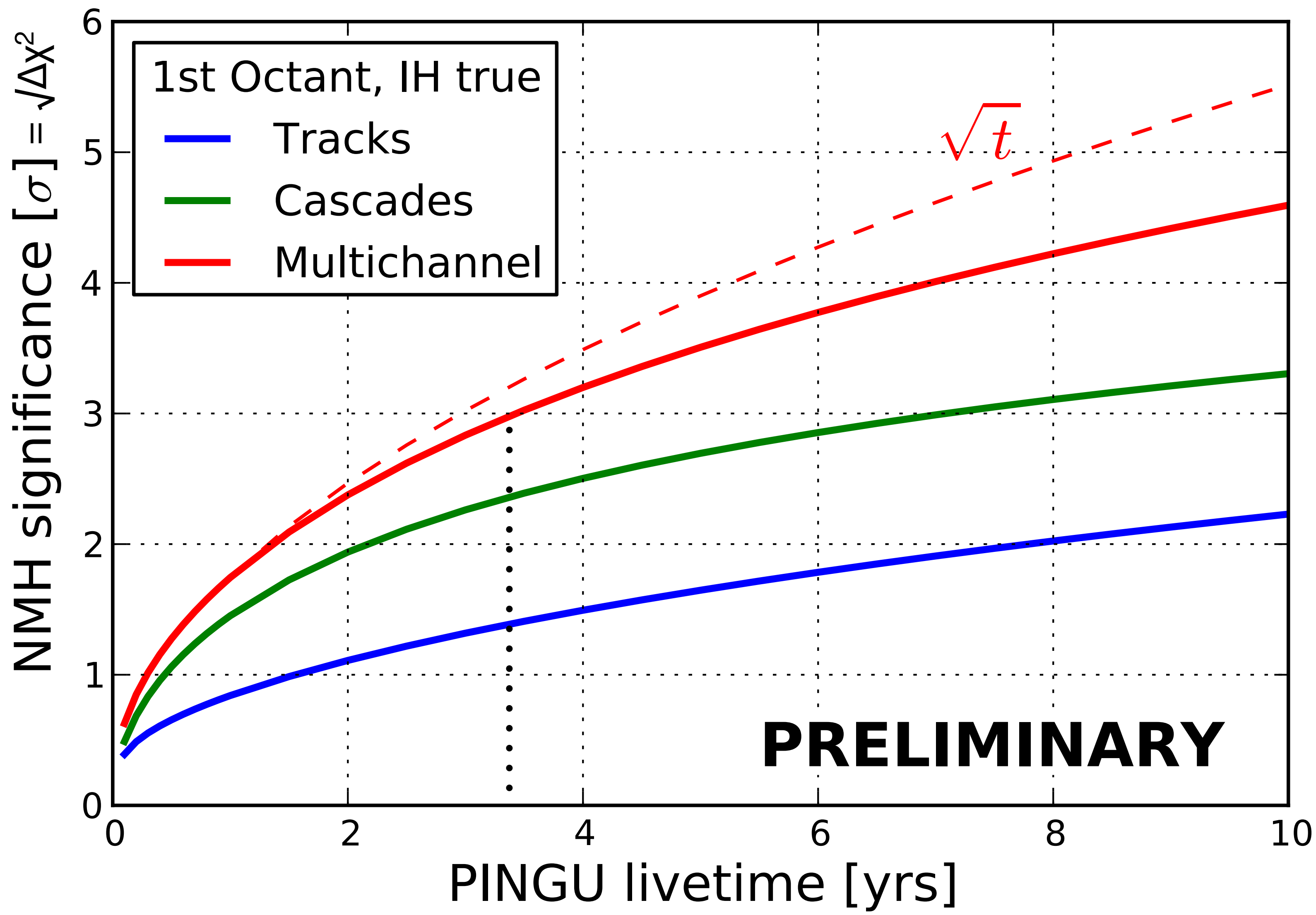


- Distinctive (and quite different) hierarchy-dependent signatures are visible in both the track and cascade channels
  - Quantity shown is an illustration of statistical significance per bin (as per Akhmedov et al. arXiv:1205.7071)
  - Full MC for detector efficiency, reconstruction, and particle ID included

PINGU Hierarchy 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

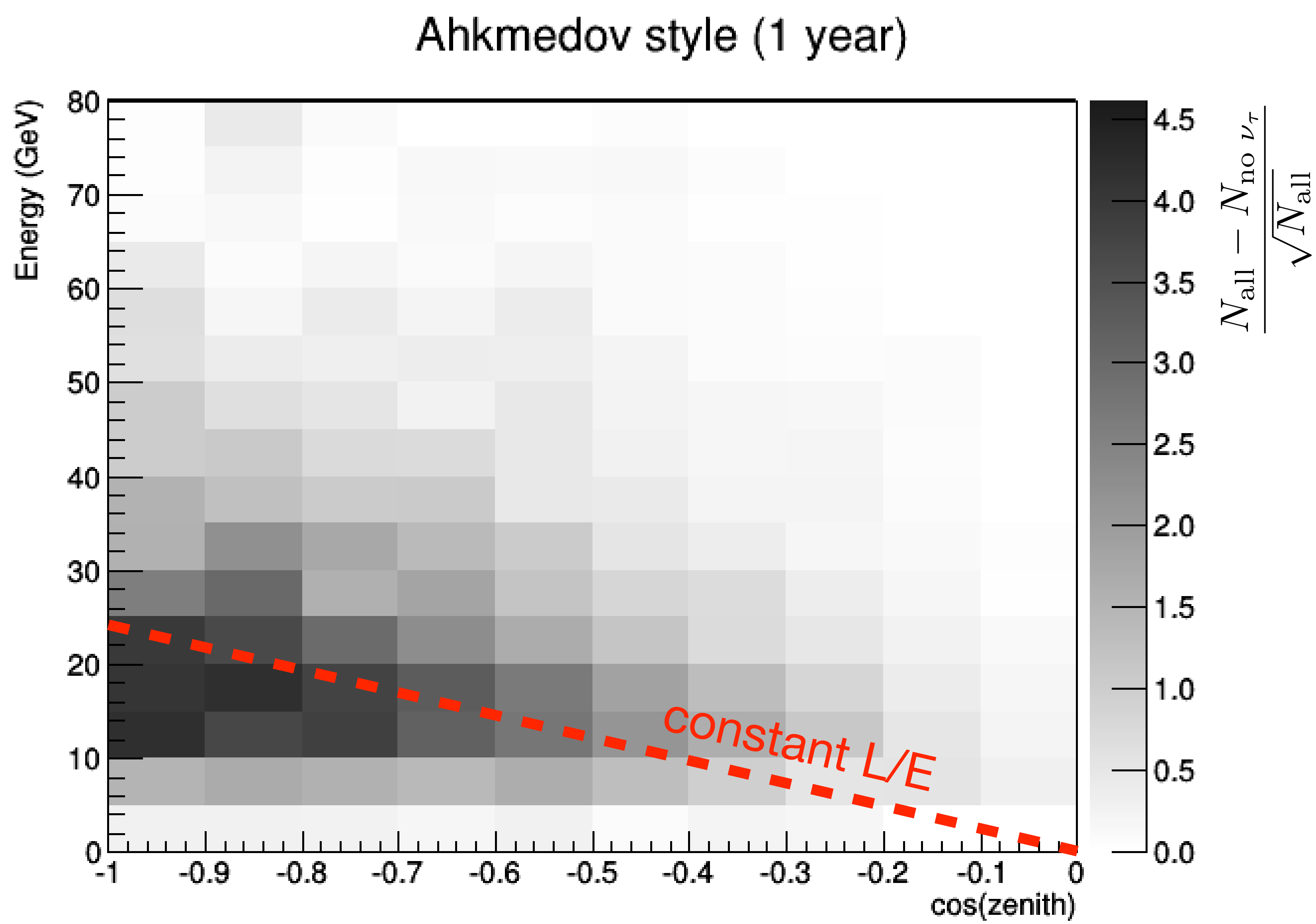


Other Scientific Goals of PINGU

- World-class measurements of atmospheric oscillation parameters
  - DeepCore already becoming competitive with current generation of experiments, and further improvements coming soon
  - PINGU would provide access to multiple oscillation maxima – preliminary estimates of measurement precision are extremely encouraging
- 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 of unitarity of 3x3 mixing matrix
- Search for dark matter with masses below 10 GeV
  - Indirect search for solar annihilations a uniquely background-free channel

Tau Appearance Measurement

- Higher energy range of PINGU vs. OPERA, Super-K substantially improves appearance rate
  - Reduced kinematic suppression due to tau lepton mass
- Tau appearance visible as distortion of cascade energy-angle distribution
  - Preliminary studies suggest 5σ observation of ν_τ possible with less than a year of PINGU data

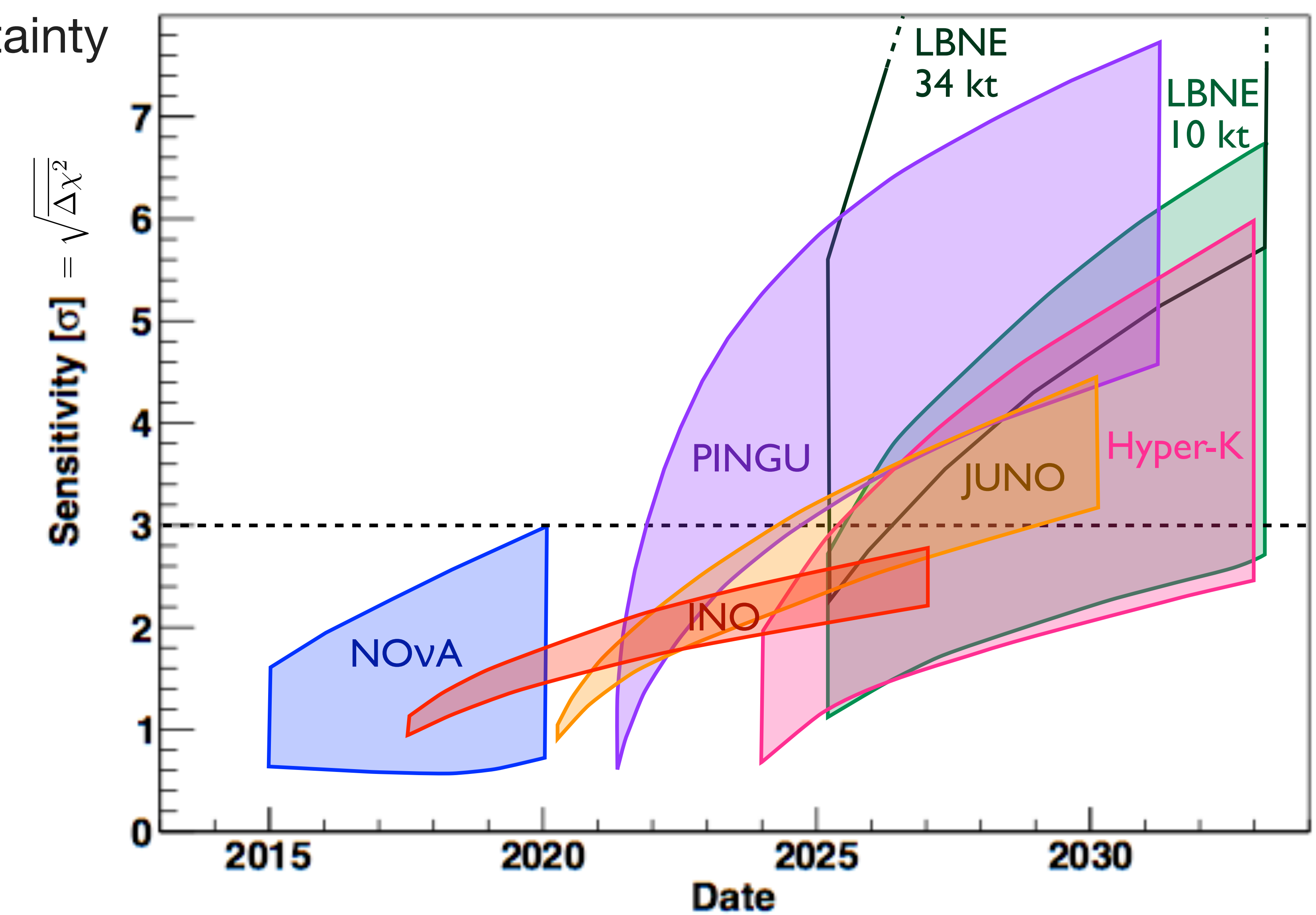


PINGU in Context

- 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
  - LBNE/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, all others from Blennow



PINGU in Context

- The neutrino sector is the least well understood part of the Standard Model – rapid progress in measurement, potential for new physics
- PINGU has a unique place in the world-wide neutrino program
  - Measurements at higher energies/longer baselines, with high statistics
- δ_{CP} has minimal effect on our hierarchy measurement
  - Helps to resolve degeneracy of CP violation and hierarchy in long baseline experiments (e.g., T2K + NOvA)
- Opportunity to discover new physics is greatly enhanced by PINGU's statistical reach and complementarity with other experiments
  - Over-constraint of parameters in the standard oscillation paradigm is necessary for searching for new physics in the neutrino sector – multiple measurements using different techniques are essential

PINGU and Next-Generation IceCube

- PINGU would be a natural part of a Next Generation IceCube Observatory
  - Marginal cost of PINGU is relatively modest in MREFC scenario
- PINGU would use the same hardware and techniques as in-ice extensions of IceCube to high energies
  - Common design gives flexibility to optimize based on progress of the field
- PINGU is a potential leader of a very competitive community measurement. Rapid development of PINGU (as a first phase or a standalone project) would pave the way for high energy expansion of IceCube – engineering, drill equipment, etc.
  - Considerable interest in PINGU from non-US partners who were not involved in IceCube, but substantial US contribution clearly required

Final Thoughts

- The South Pole ice cap is a unique site for underground physics, as well as for neutrino astronomy
  - Excellent optical Cherenkov medium, very low levels of radioactive impurities
  - Substantial overburden, with a ~~highly efficient active muon veto~~ neutrino observatory facility already in place
  - Polar ice cap functions as both Cherenkov radiator and support structure: cost is driven by instrumentation, not installation – *independent of scale*
- PINGU will establish IceCube and the South Pole as a world-class facility for fundamental physics, as well as astrophysics
  - Beginning to evaluate potential capabilities to search for proton decay, observe extragalactic supernova neutrinos
  - Next Generation IceCube will provide opportunities for detector R&D with potential for breakthrough reductions in cost

The IceCube–PINGU Collaboration

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Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
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University of California, Irvine
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