Neutrino Physics with IceCube and PINGU

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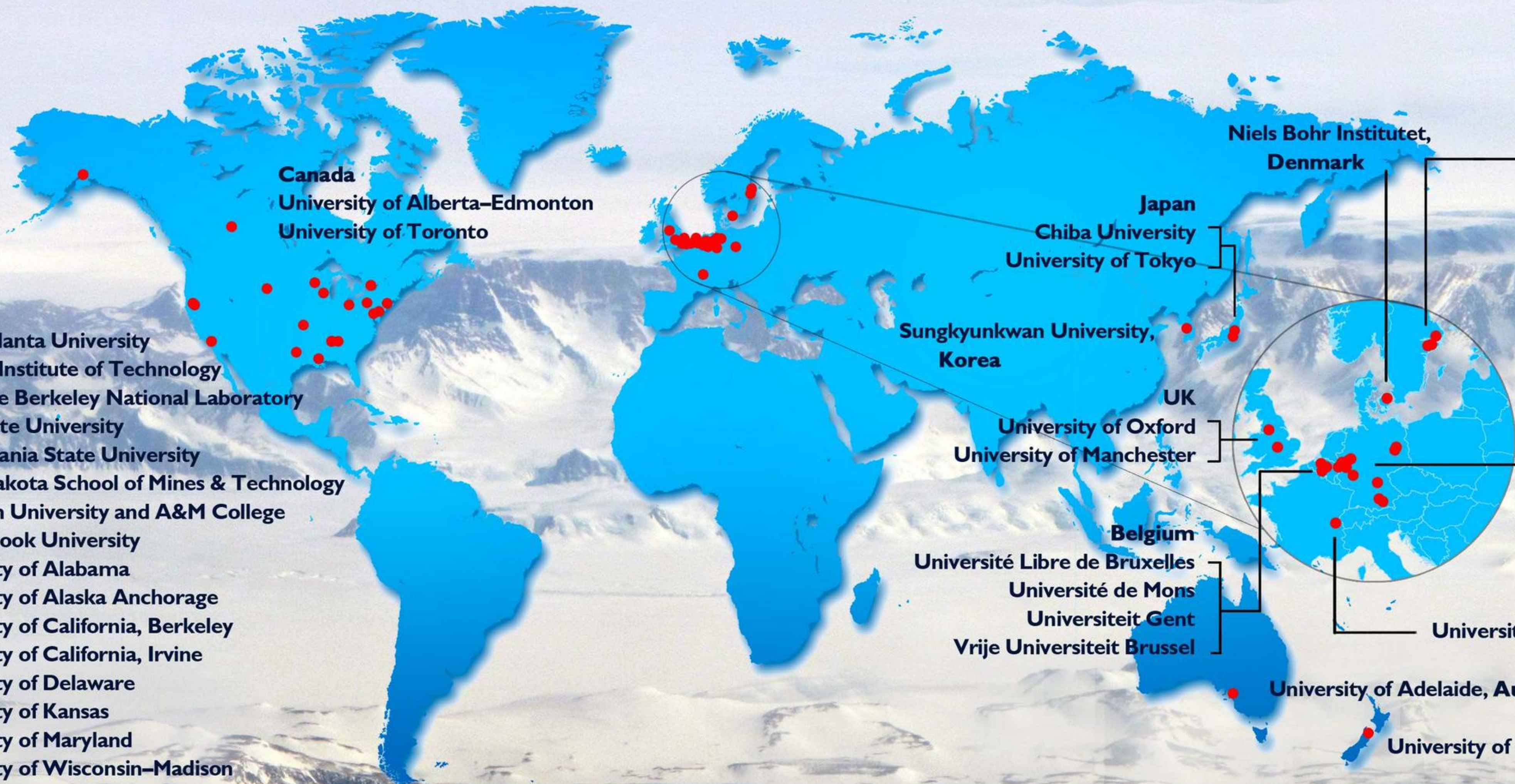
The IceCube–PINGU Collaboration



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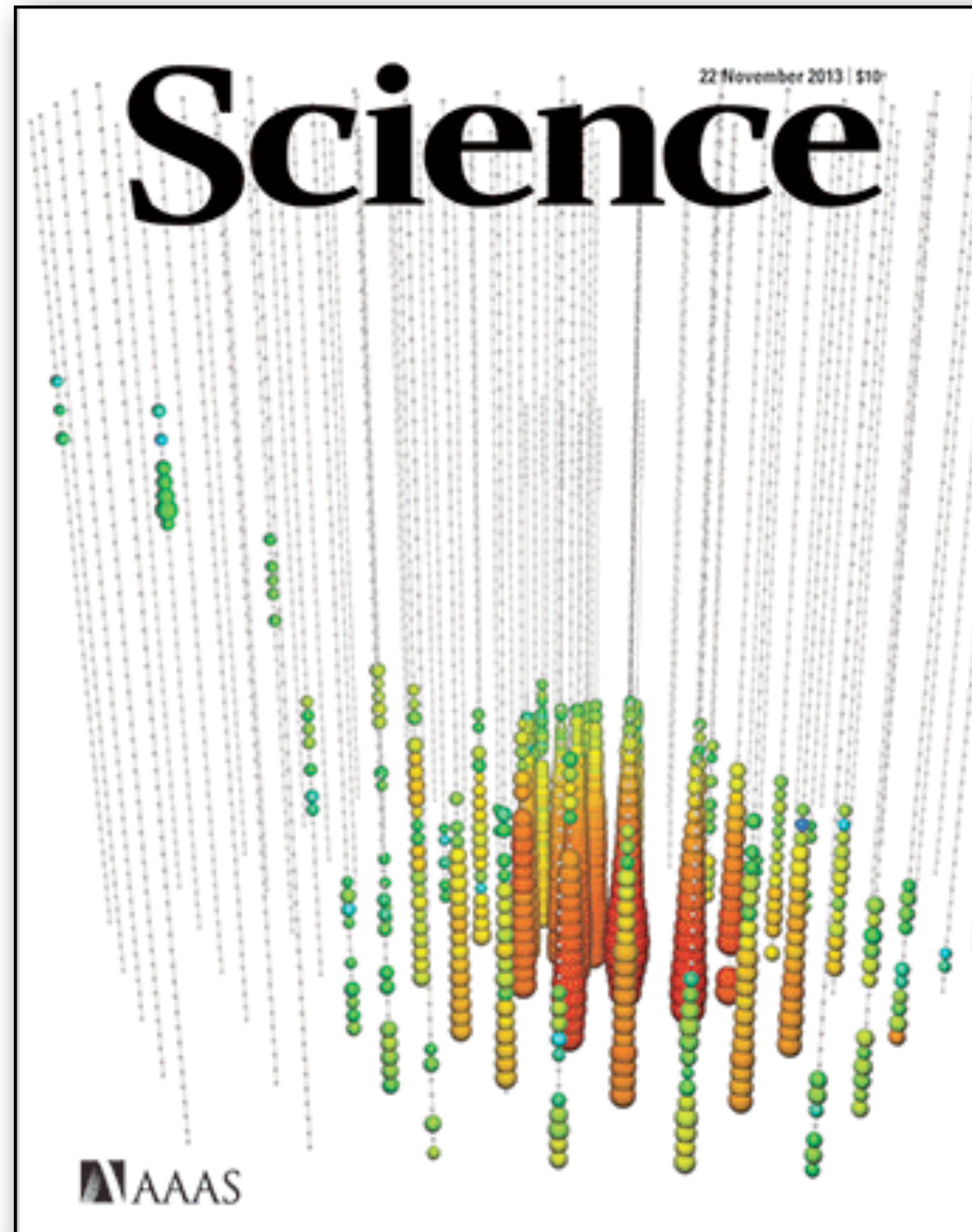
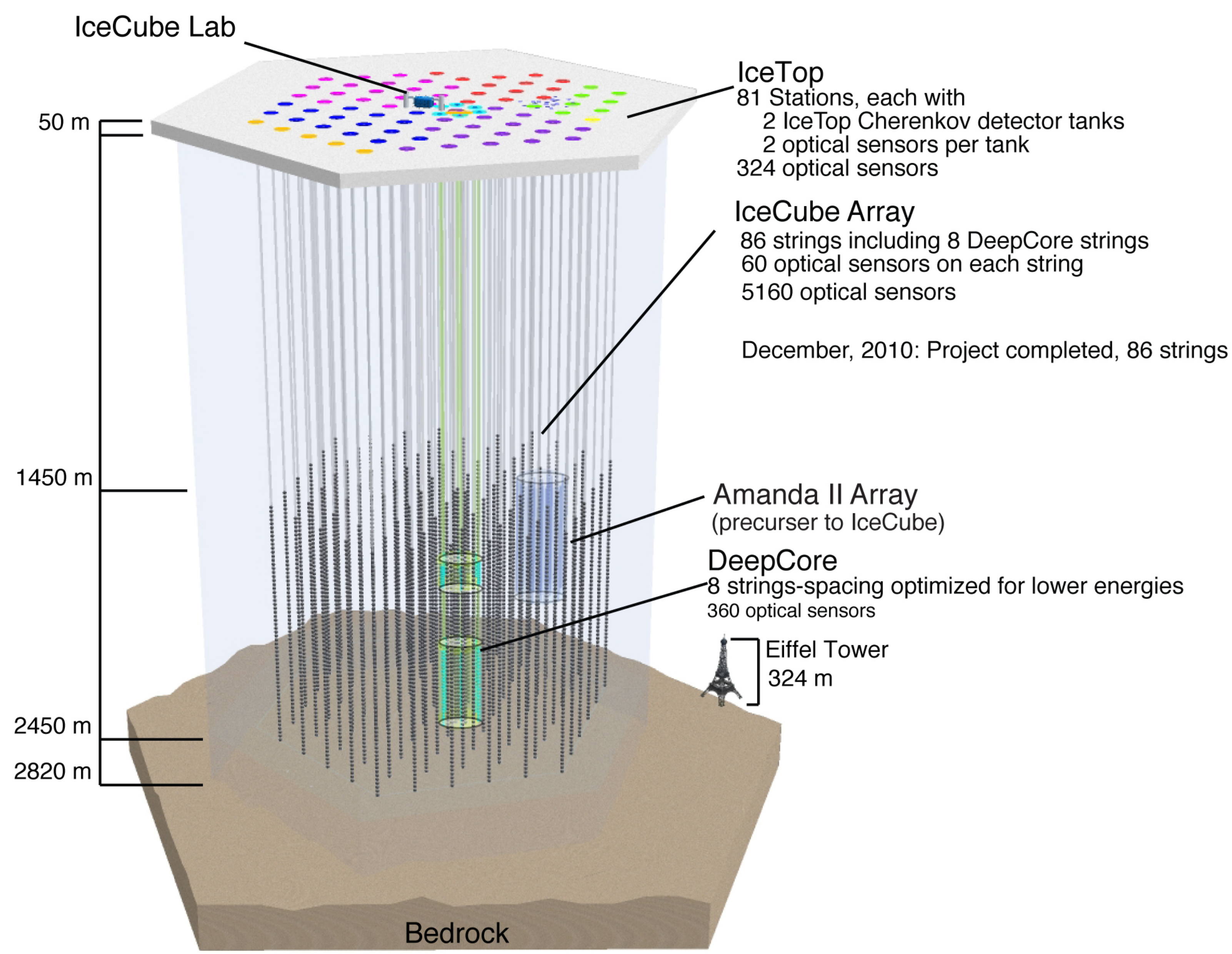
The IceCube Neutrino Observatory

- IceCube focuses on neutrinos with energies above a few hundred GeV
  - 1 km^3 of Antarctic ice as neutrino target and Cherenkov medium



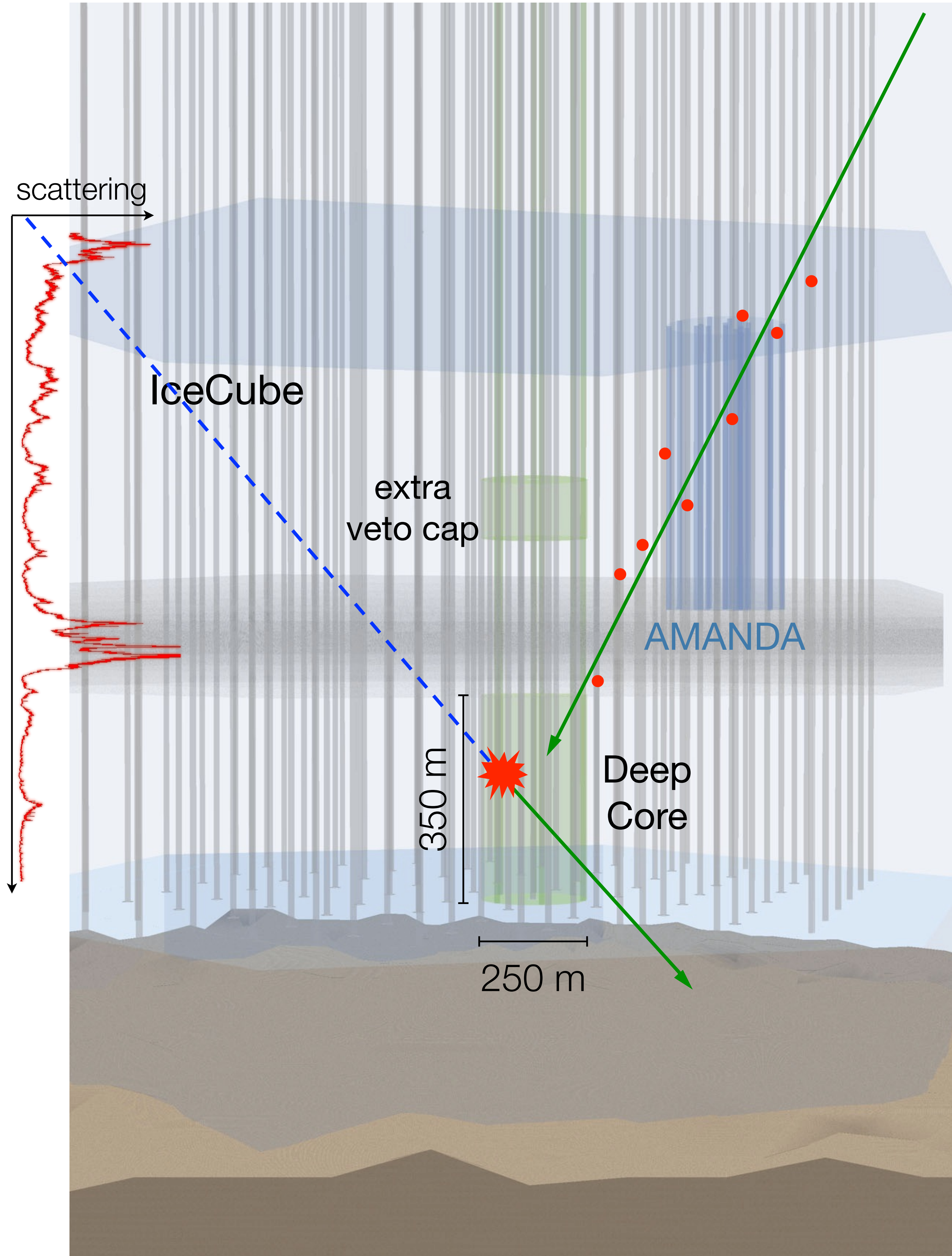
The IceCube Neutrino Observatory

- IceCube focuses on neutrinos with energies above a few hundred GeV
  - 1 km^3 of Antarctic ice as neutrino target and Cherenkov medium
  - 86 strings of 60 DOMs
- DeepCore provides increased effective volume at 10-100 GeV
- Focus on dark matter searches, neutrino oscillations



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
  - String spacing ~70 m, DOM spacing 7 m: ~5x higher effective photocathode density than IceCube
- 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

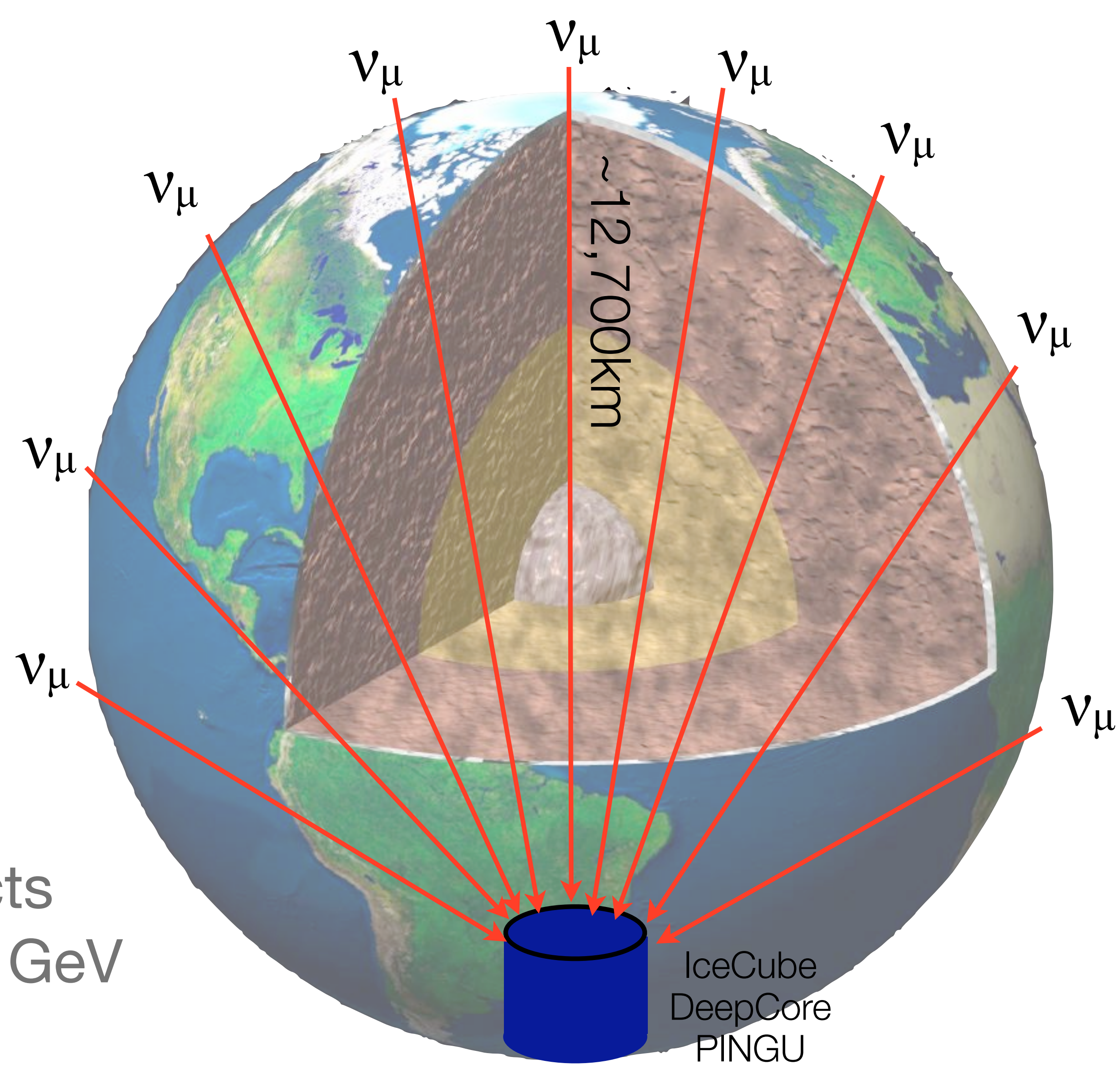


DeepCore Physics

- 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)
  - Dwarf galaxies: *Phys. Rev.* D88, 122001 (2013)
  - Galactic Halo: arXiv:1406.6868, submitted to *Eur. Phys. J. C*
- Direct searches for exotic particles
  - E.g. monopoles: arXiv:1402.3460, *Eur. Phys. J. C* (in press)
- 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 analysis with reduced energy threshold of ~10 GeV greatly improves precision – preliminary results shown at Neutrino 2014

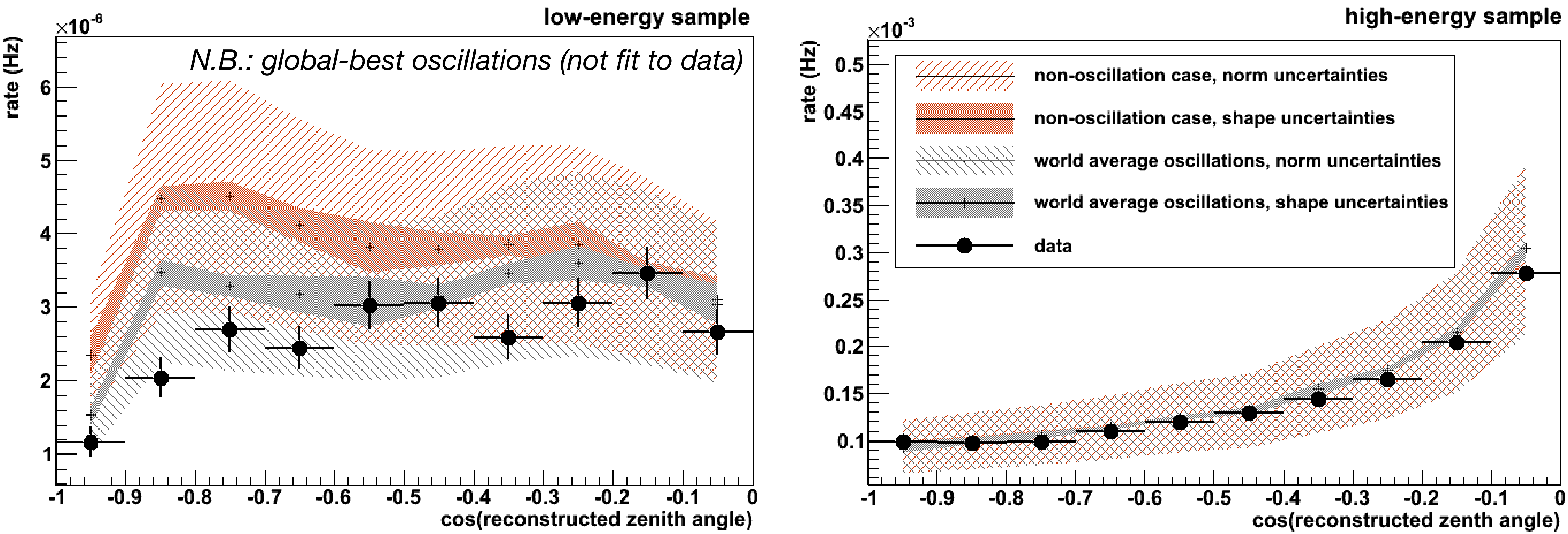
Oscillation Physics with Atmospheric Neutrinos

- Neutrinos available over a wide range of energies and baselines
  - Oscillations produce distinctive pattern in energy-angle space
  - Approach: control systematics using events in "side band" regions – trade statistics for constraints on systematics
- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects on ν or ν̄ (MSW etc.) below 10-20 GeV



Atmospheric Oscillations – First Steps

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

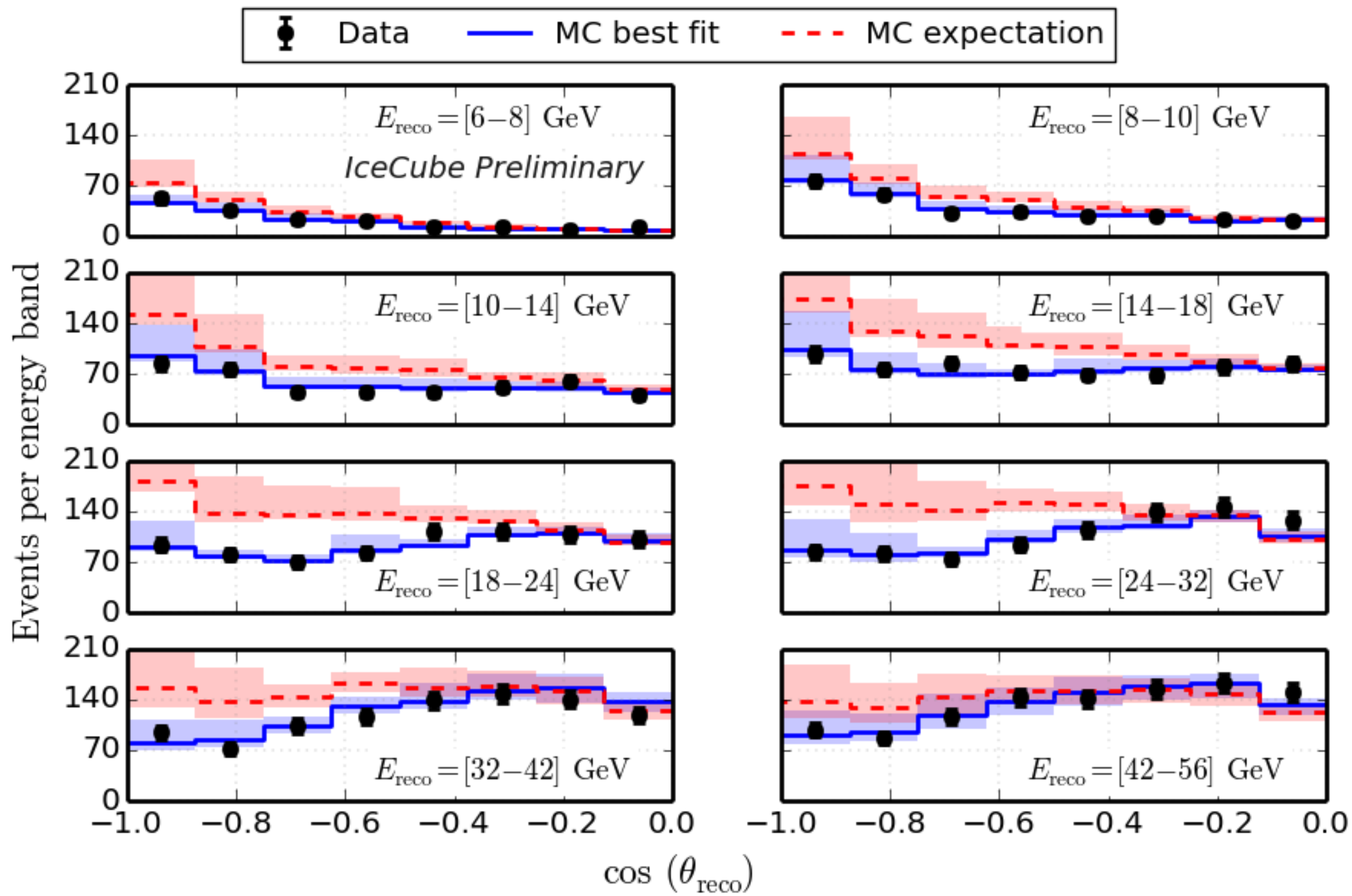


Statistically significant angle-dependent suppression at low energy, high energy sample provides constraint on uncertainties in simultaneous fit

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

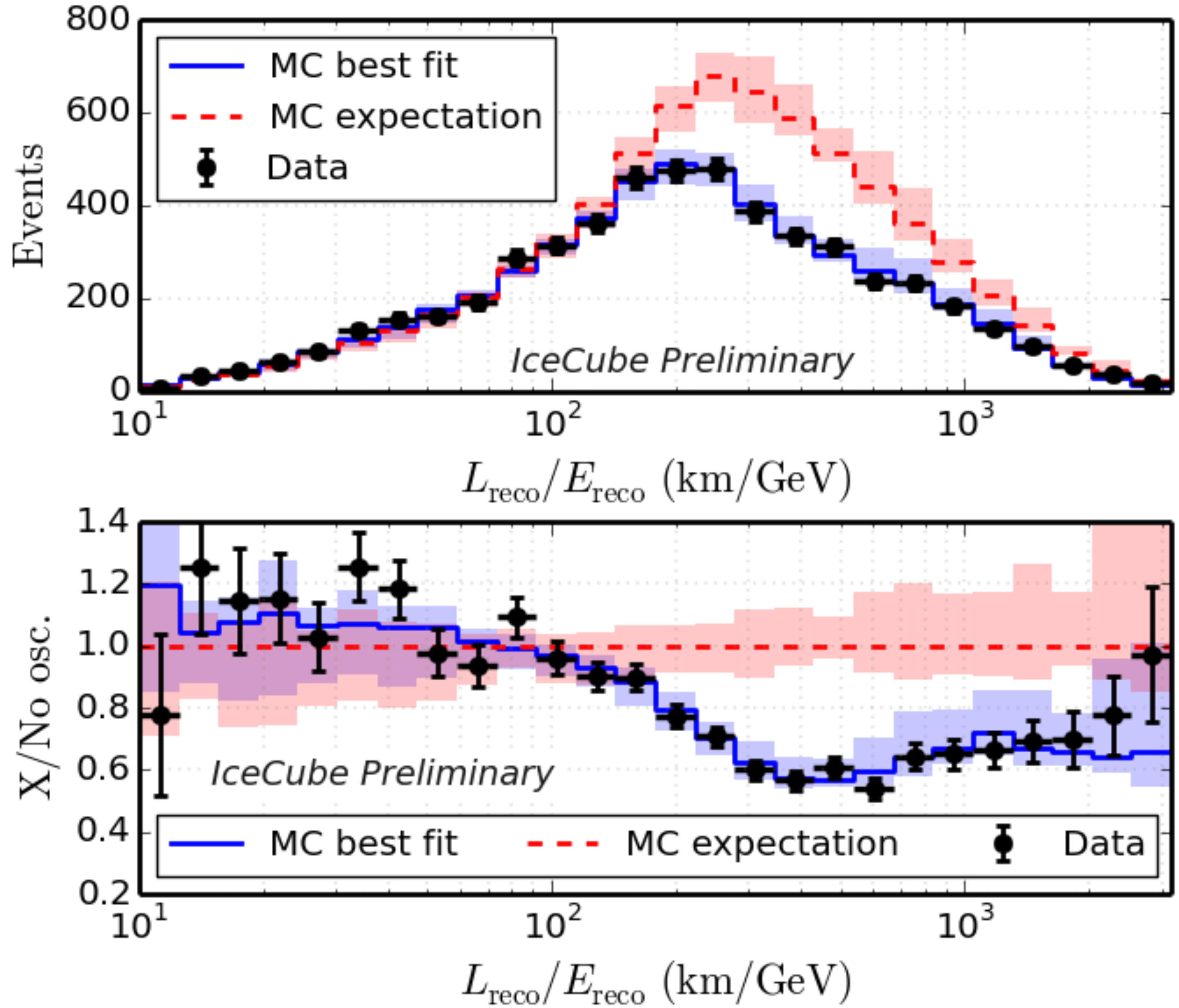
Atmospheric Oscillations – 2nd Generation

- Three years with improved event selection: 2,500 events per year
- Much better reconstructions, enabling use of multiple energy bins in oscillation energy range
  - Permits tighter constraints on systematics from the data



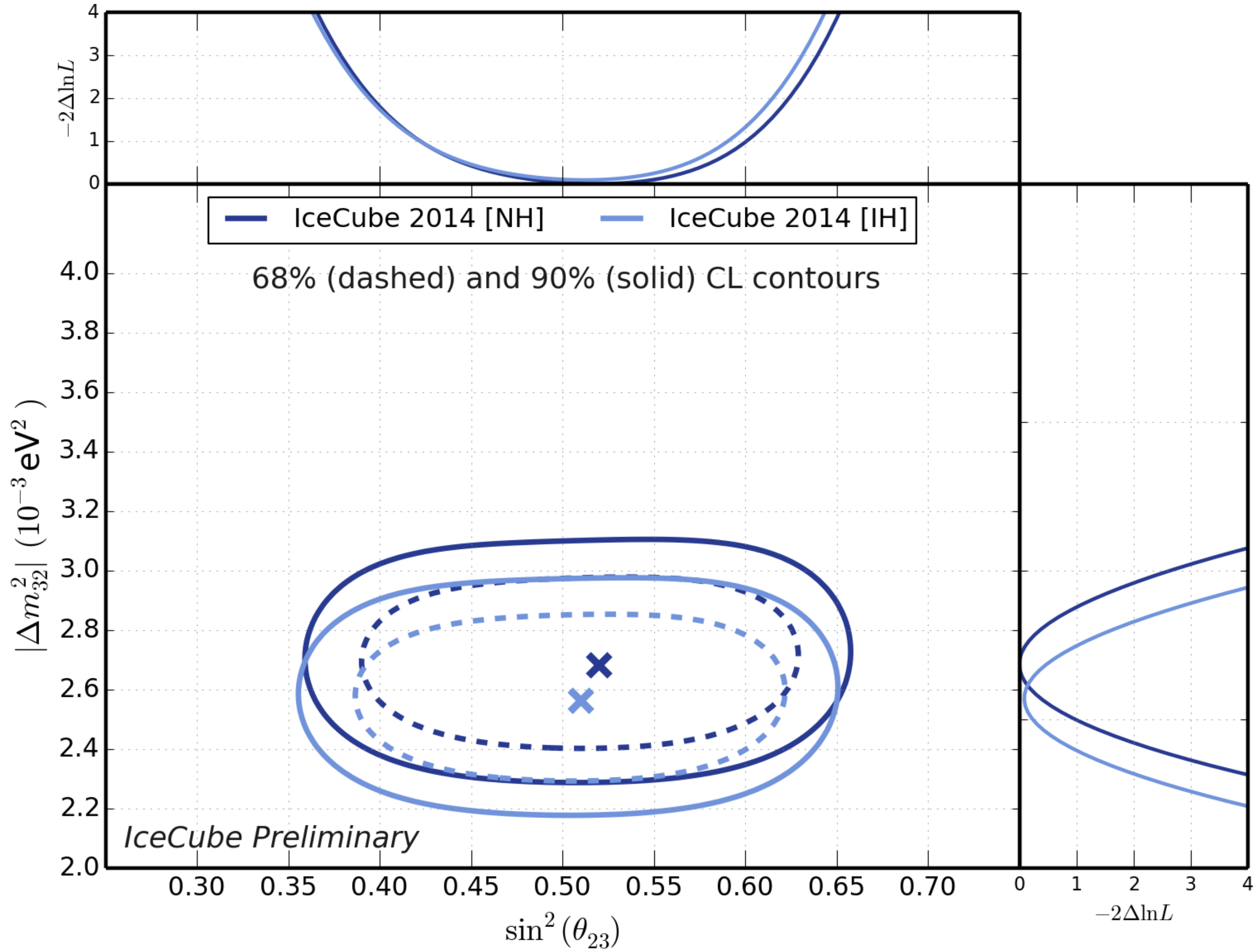
Atmospheric Oscillations – 2nd Generation

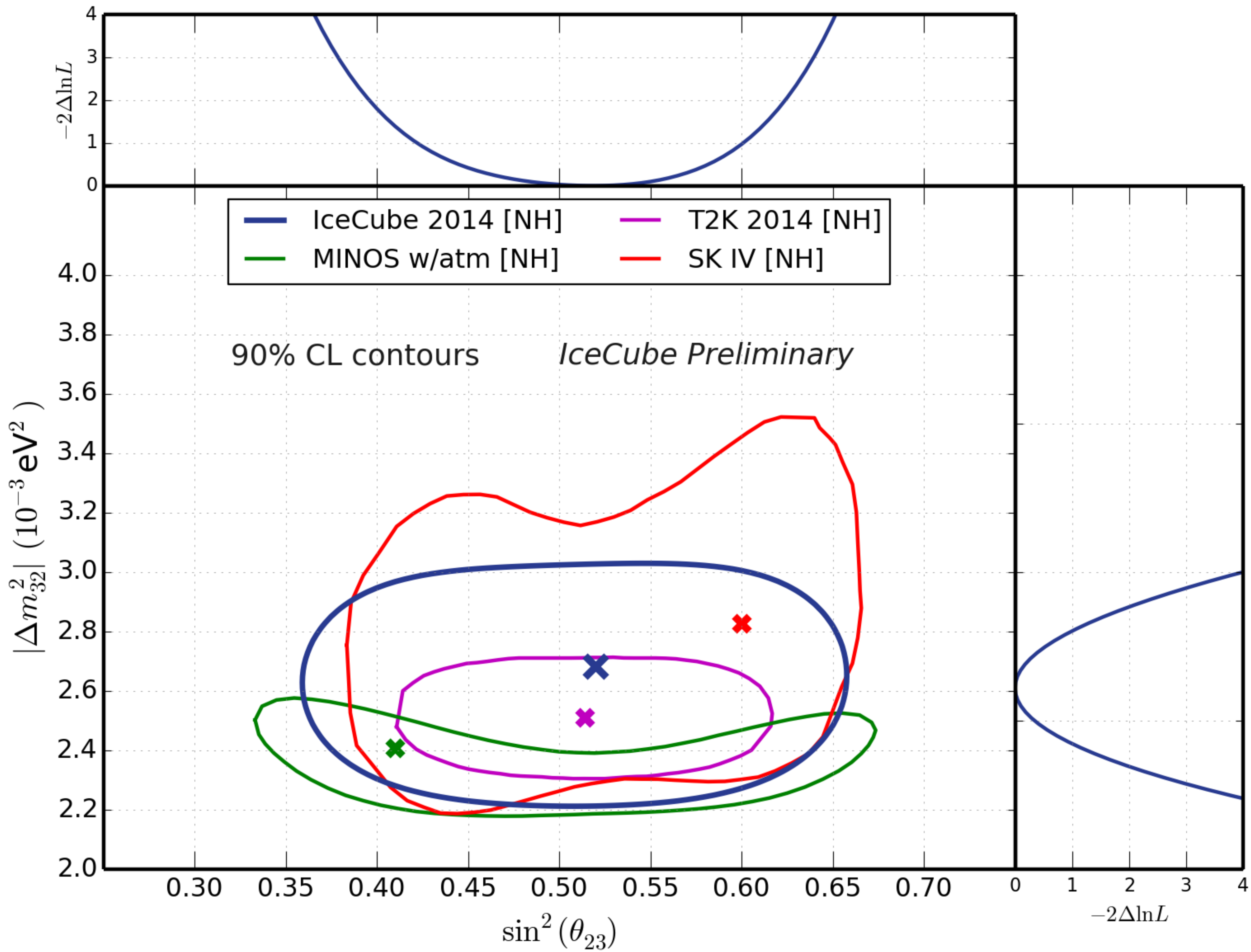
- Project data onto reconstructed (L/E_ν) for illustration
  - Actual analysis is performed in 2D
- Shaded range shows allowed systematics
- Second survival maximum just below DeepCore's energy threshold



IceCube Muon Disappearance Measurement

- Contours determined by profile likelihood of Δm^2_{32}, $\sin^2(\theta_{23})$
  - Other oscillation parameters fixed at Fogli et al. (arXiv:1205.5254)
  - Detector systematics incorporated as nuisance parameters with Gaussian constraints





IceCube 2014 [NH]
T2K 2014 [NH]
MINOS w/atm [NH]
SK IV [NH]
90% CL contours
IceCube Preliminary
$-2\Delta\ln L$
$|\Delta m^2_{32}|$ (10^{-3}eV^2)
$\sin^2(\theta_{23})$
$-2\Delta\ln L$
0
1
2
3
4
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70

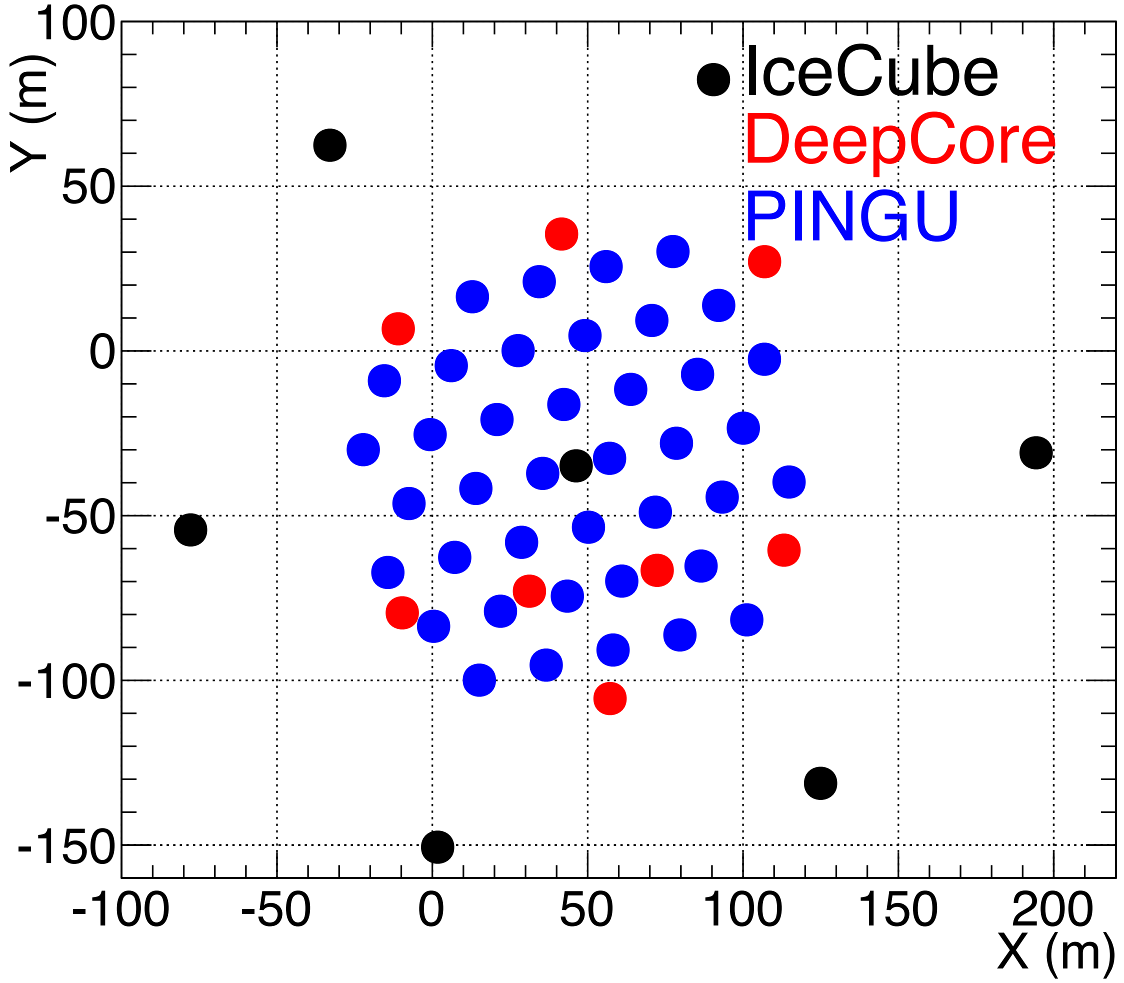
Beyond IceCube

- With its DeepCore extension, IceCube has interesting results 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 broader range of physics, including determination of the neutrino mass hierarchy
  - Follow IceCube design closely: quick to deploy, low technical risk, 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

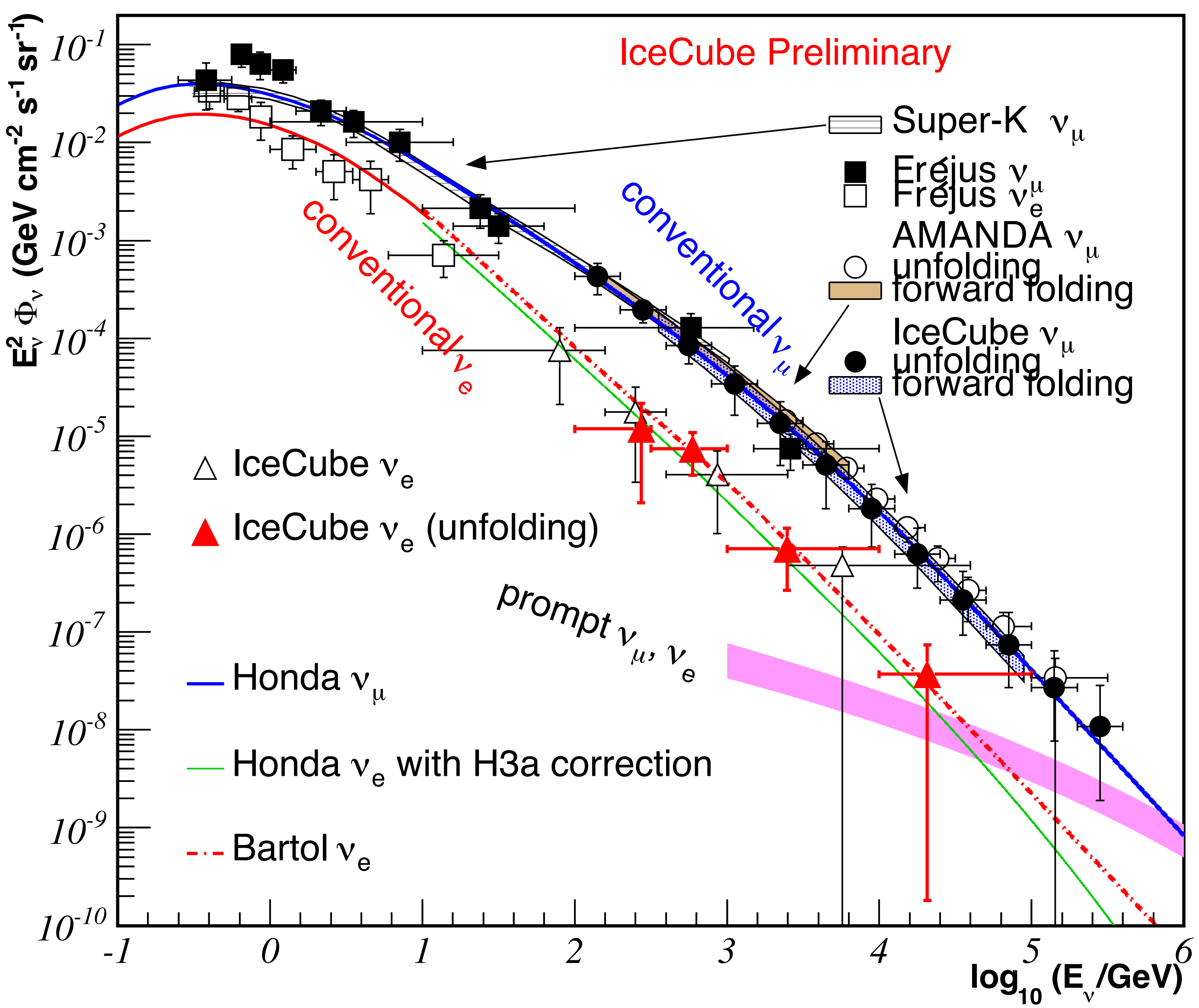
- Baseline 40 additional strings of 60 Digital Optical Modules each, deployed inside the DeepCore volume
  - 20 m string spacing (cf. 125 m for IceCube, 72 m for DeepCore)
  - ~15x higher photocathode density
  - Precise geometry under study – significantly improved performance possible with some additional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

Top view of the PINGU new candidate detector



Atmospheric Neutrinos in PINGU

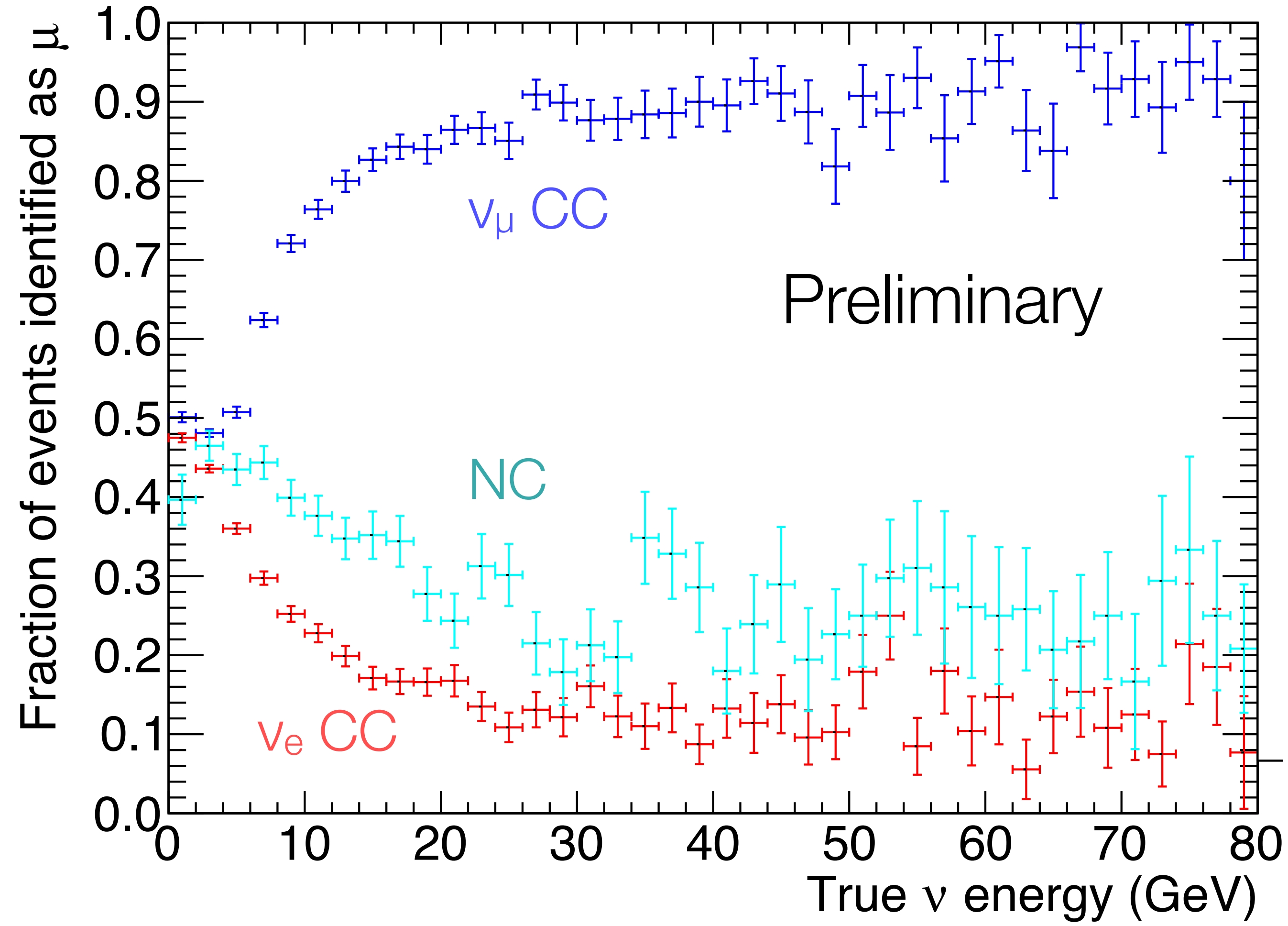
- Broad range of neutrino energies above a threshold of a few GeV

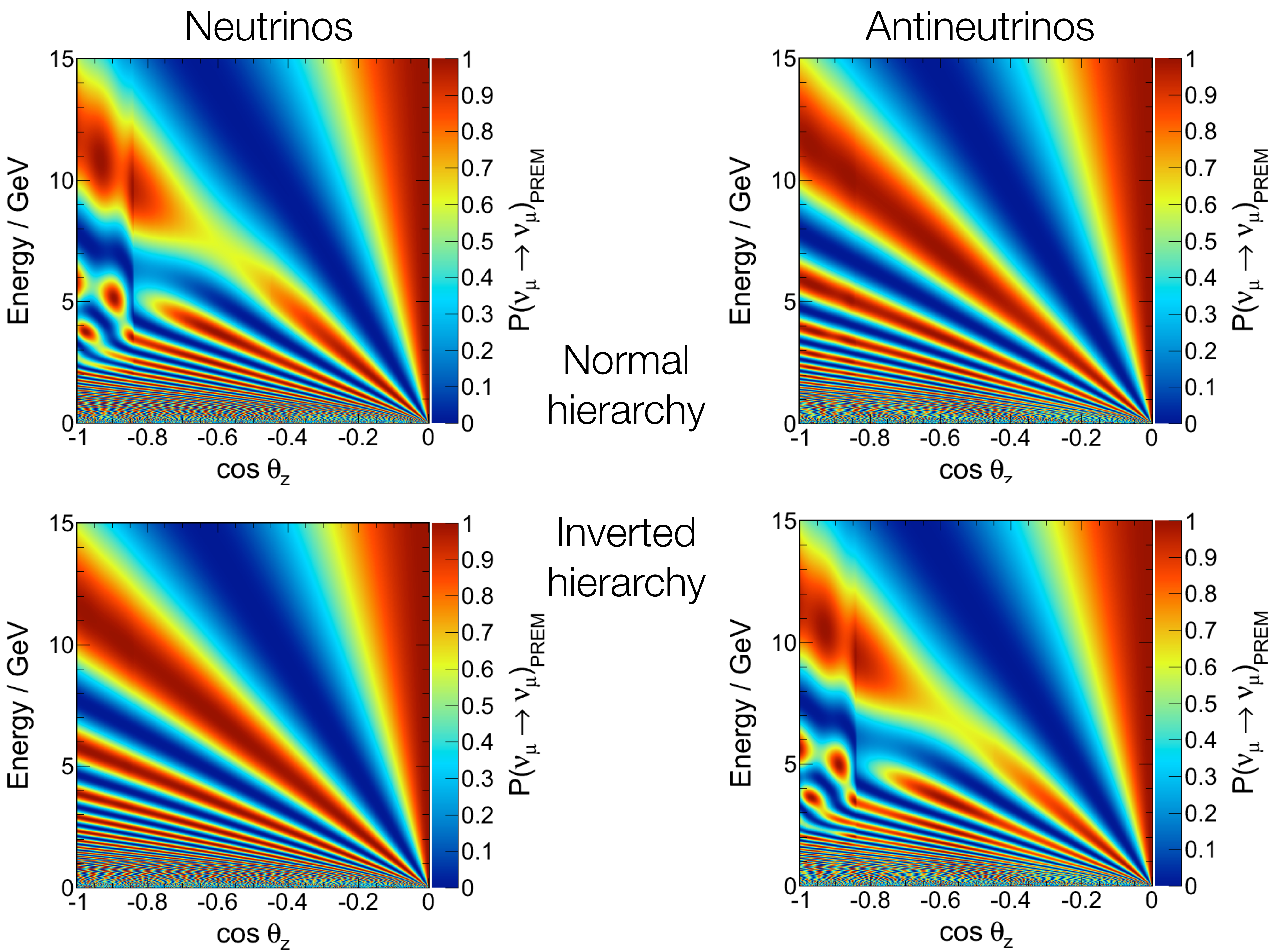


Events/yr	Trigger	Analysis
ν	52k	26k
ν	86k	35k
ν	6.4k	2.7k
ν	17k	7.9k

Signatures of the Neutrino Mass Hierarchy

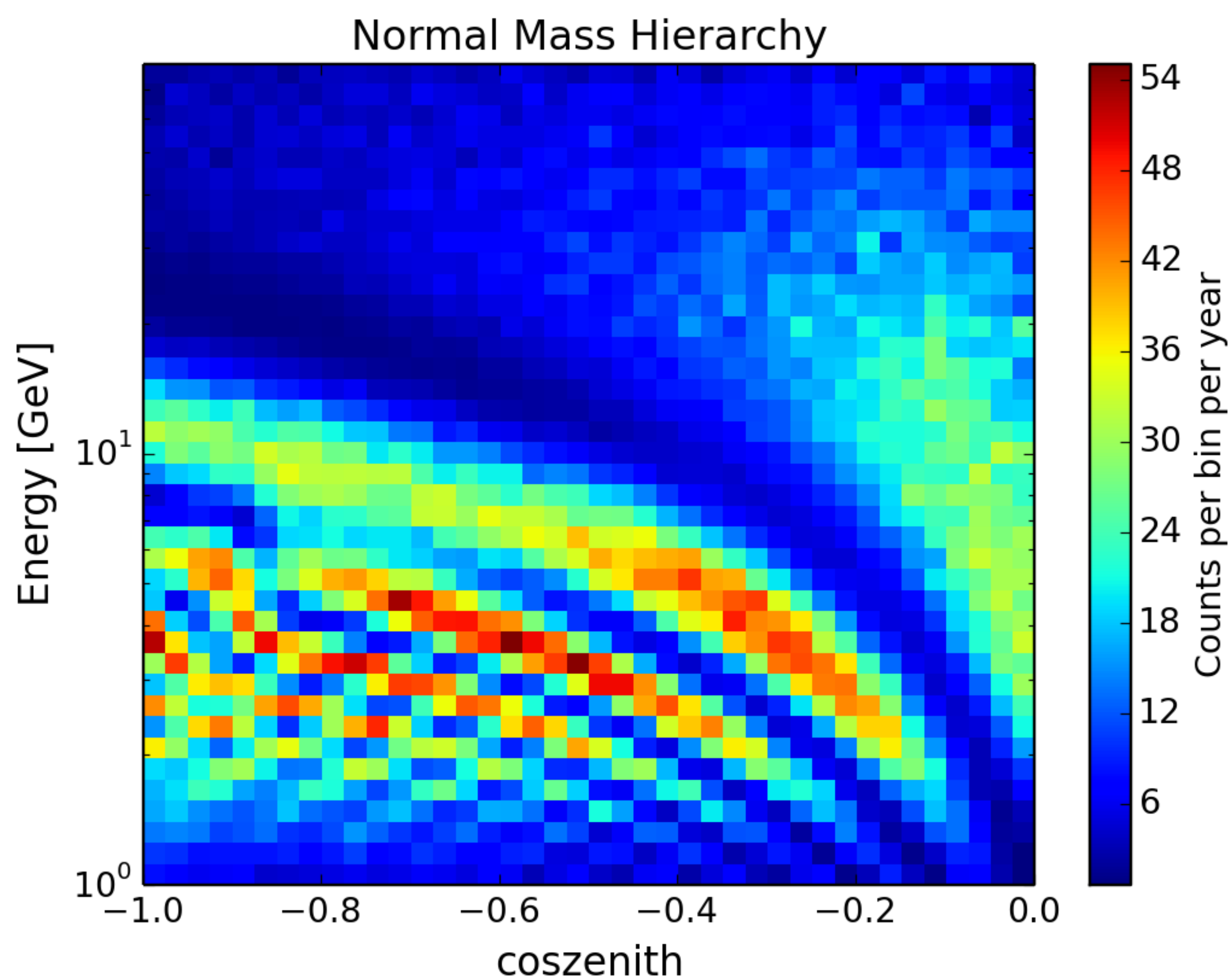
- Matter effects alter oscillation probabilities for neutrinos or antineutrinos traversing the Earth
  - Maximum effects seen for specific energies and baselines (= zenith angles) due to the Earth's density profile
  - Neutrino oscillation probabilities affected if hierarchy is normal, antineutrinos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

Muon Neutrino + Antineutrino Rates (True)

- Cannot distinguish ν from ν̄ directly – rely instead on differences in fluxes, cross sections (and kinematics)
- Differences clearly visible in expected atm. muon (ν + ν̄) rate even with 1 year's data
  - Note: detector resolutions *not* included
  - Artificially fine binning used for illustration



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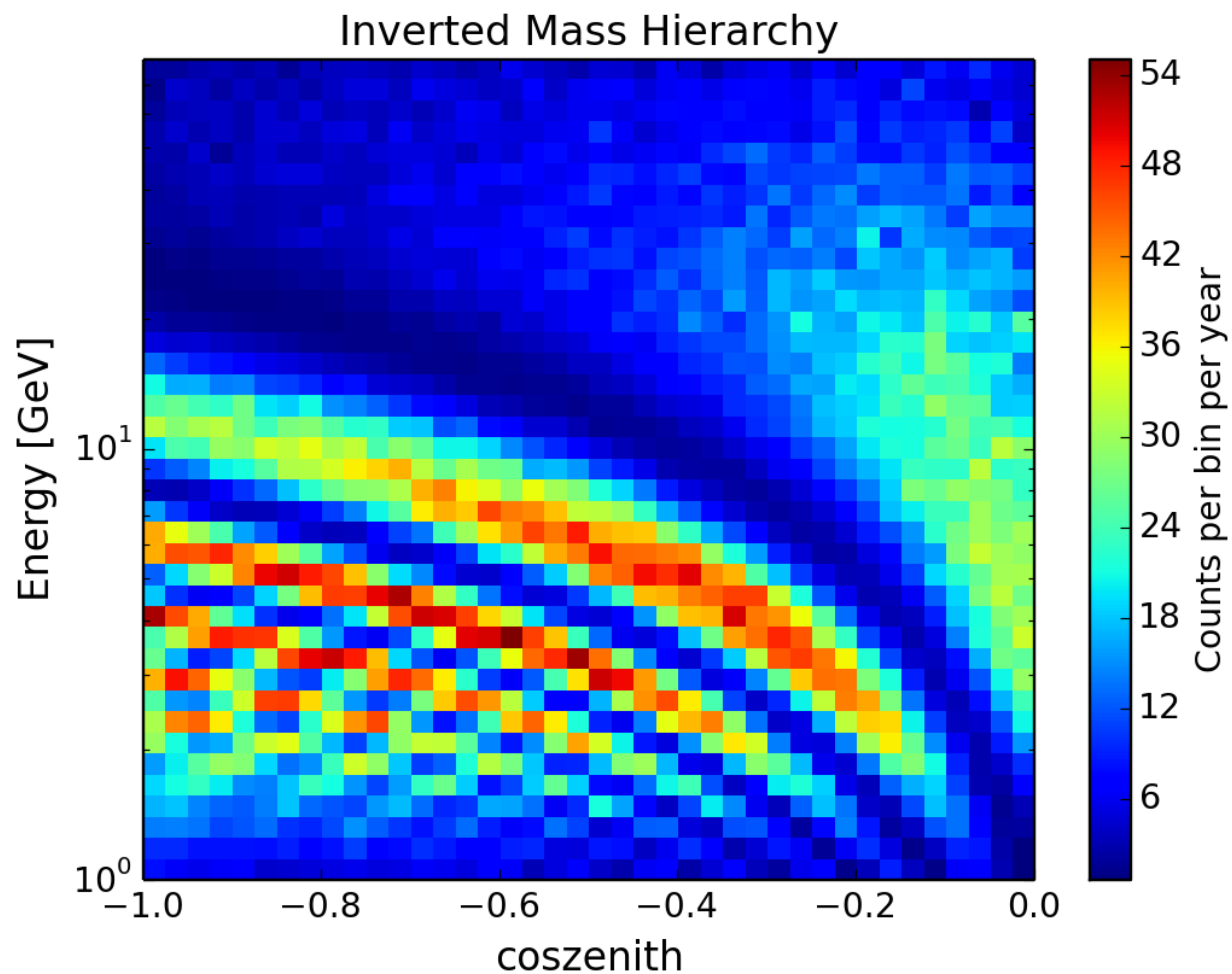
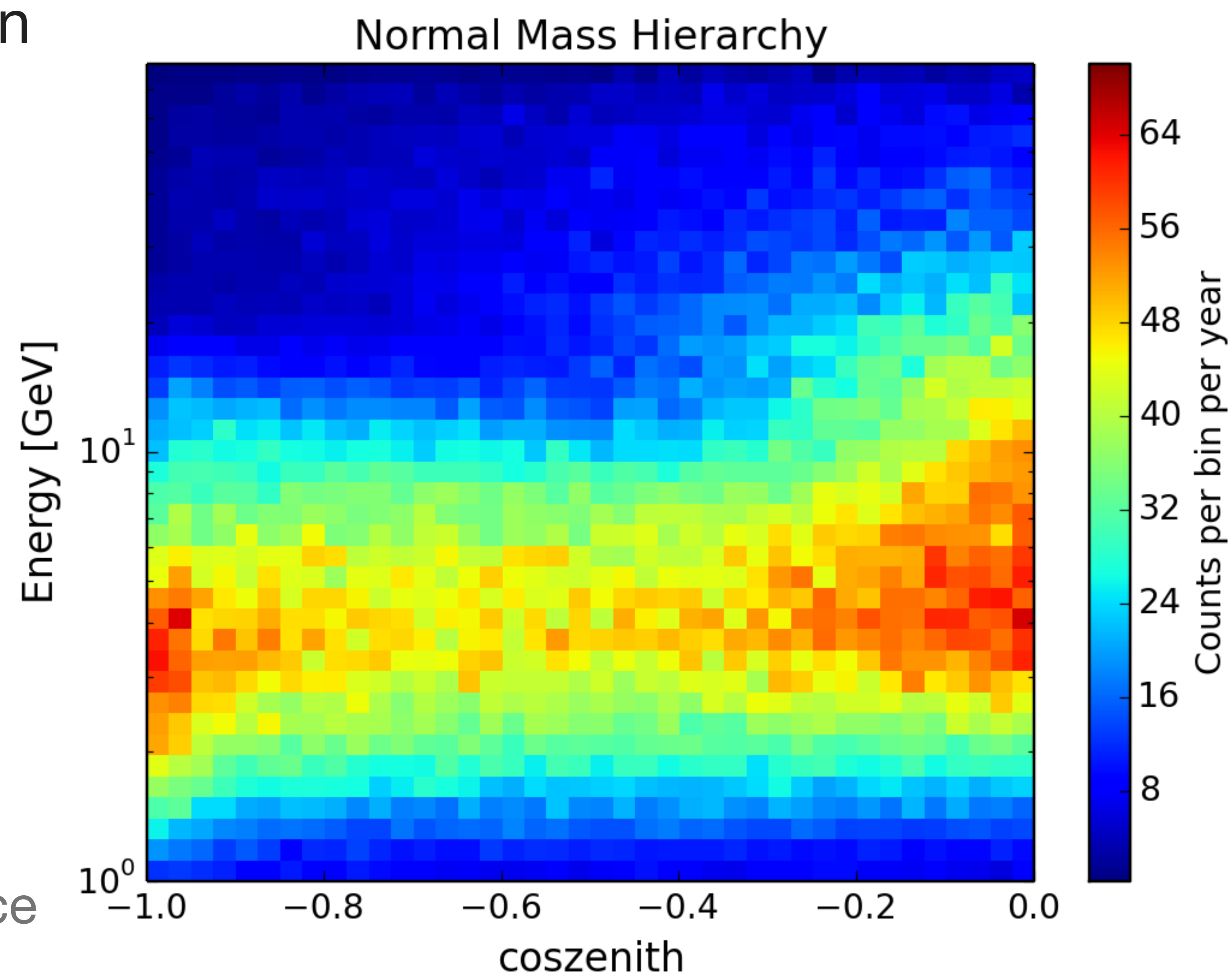


Observed Muon Neutrino + Antineutrino Rates

- Apply detector resolution via full MC simulation and reconstructions
- Signature is barely distinguishable by eye with a single year of muon neutrino data
    - Distortion of a rapidly varying pattern – need to subtract out the baseline variation to see the small difference



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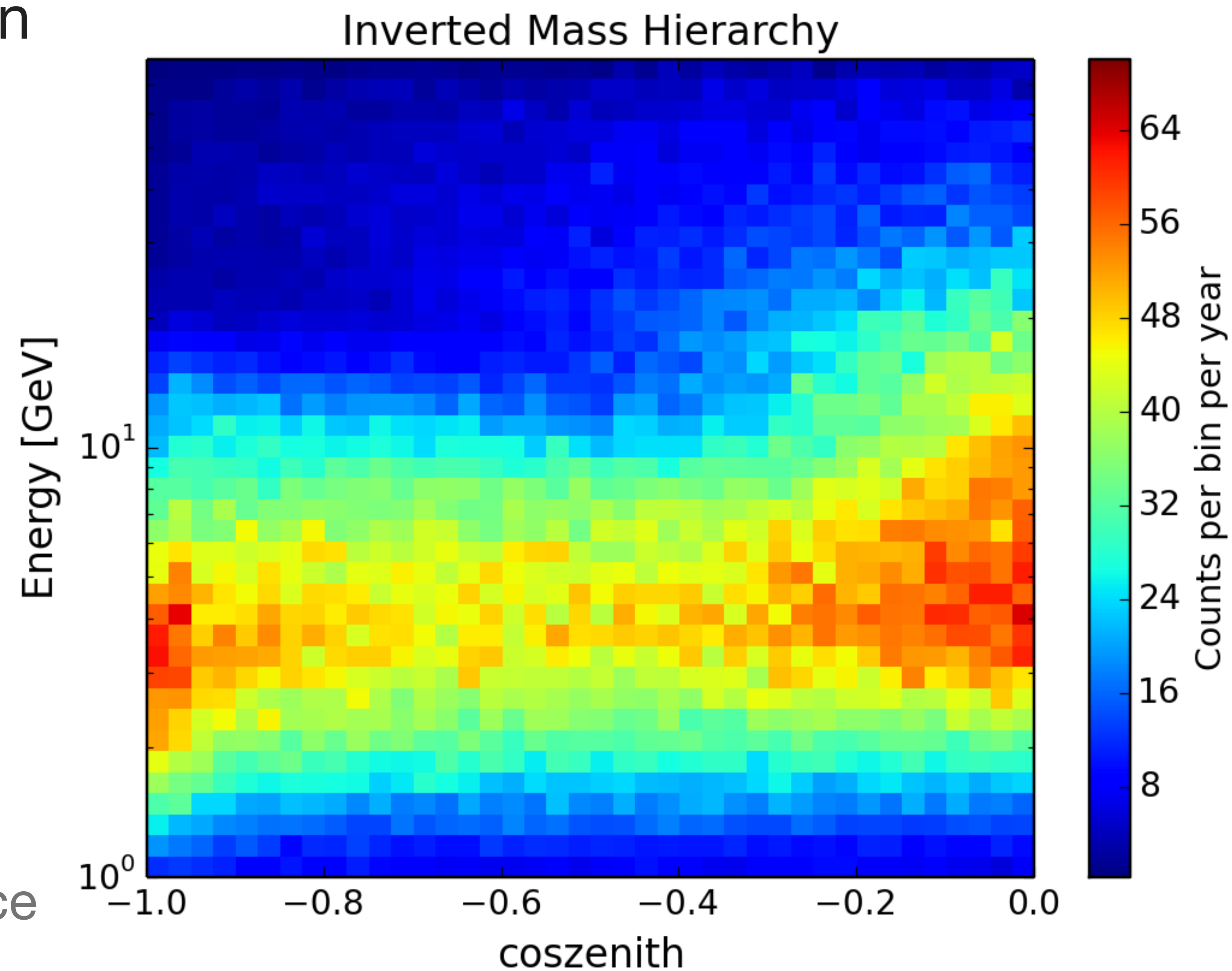
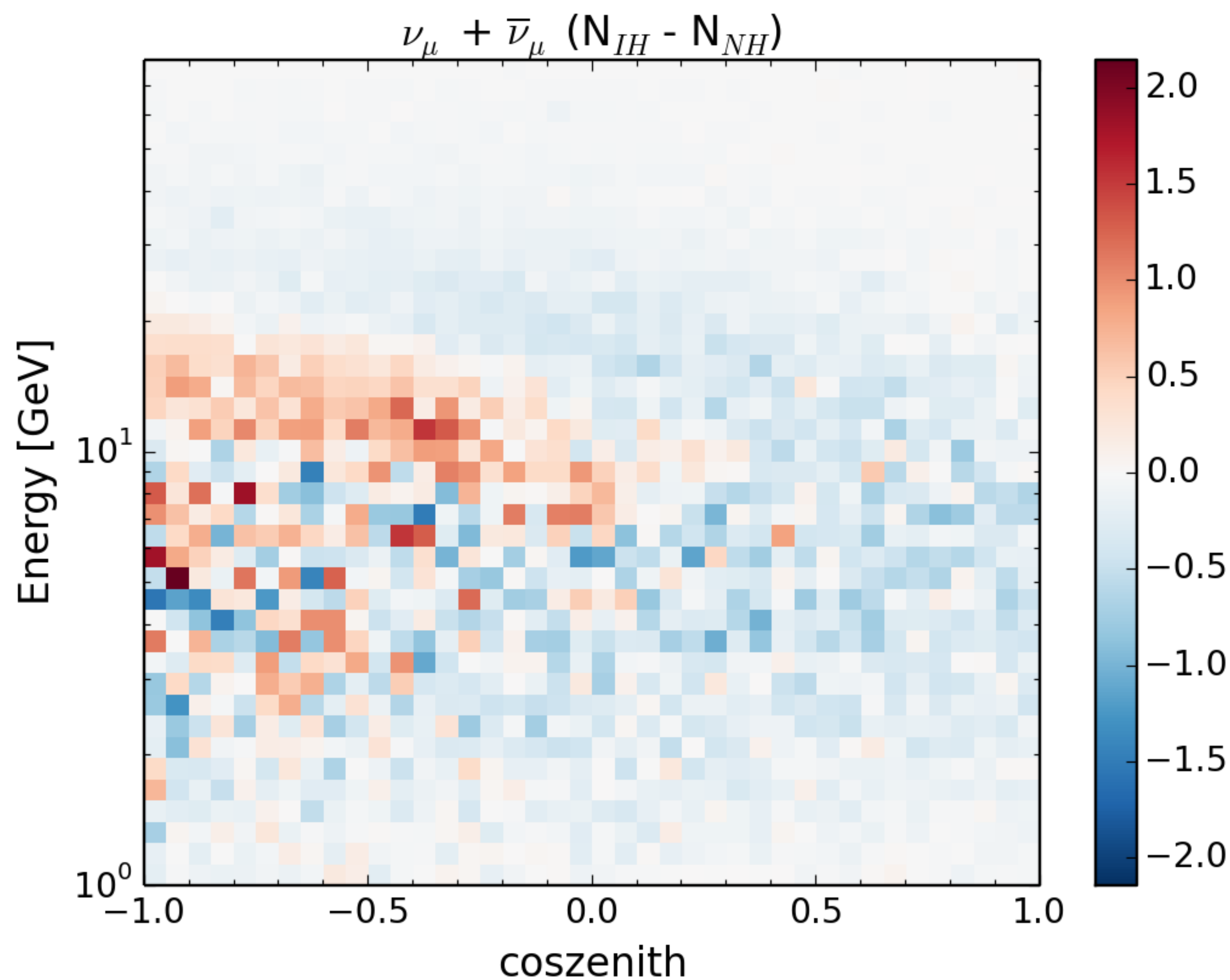


Hierarchy Signature: $\nu_\mu + \overline{\nu}_\mu$ Rate Differences

- 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



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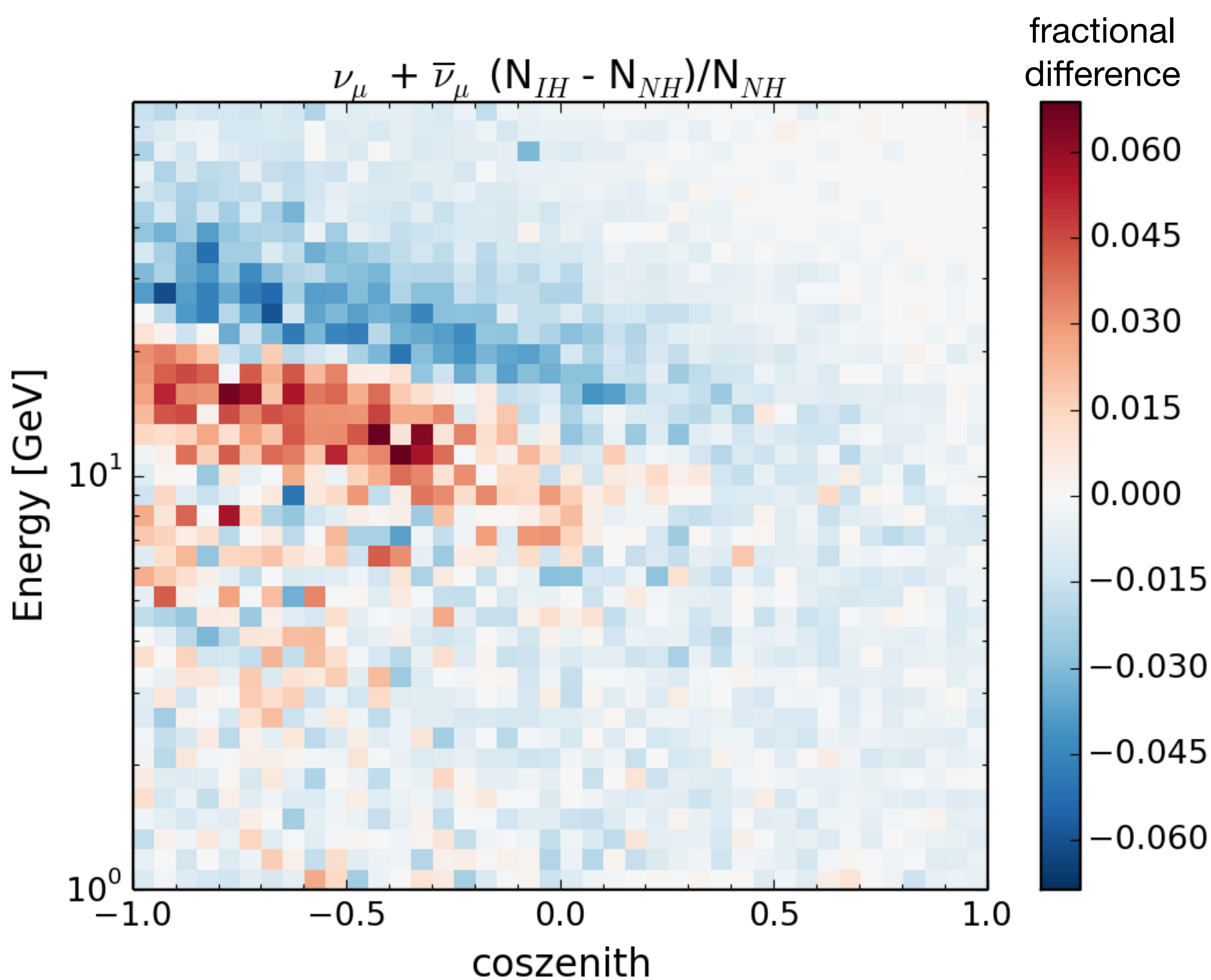
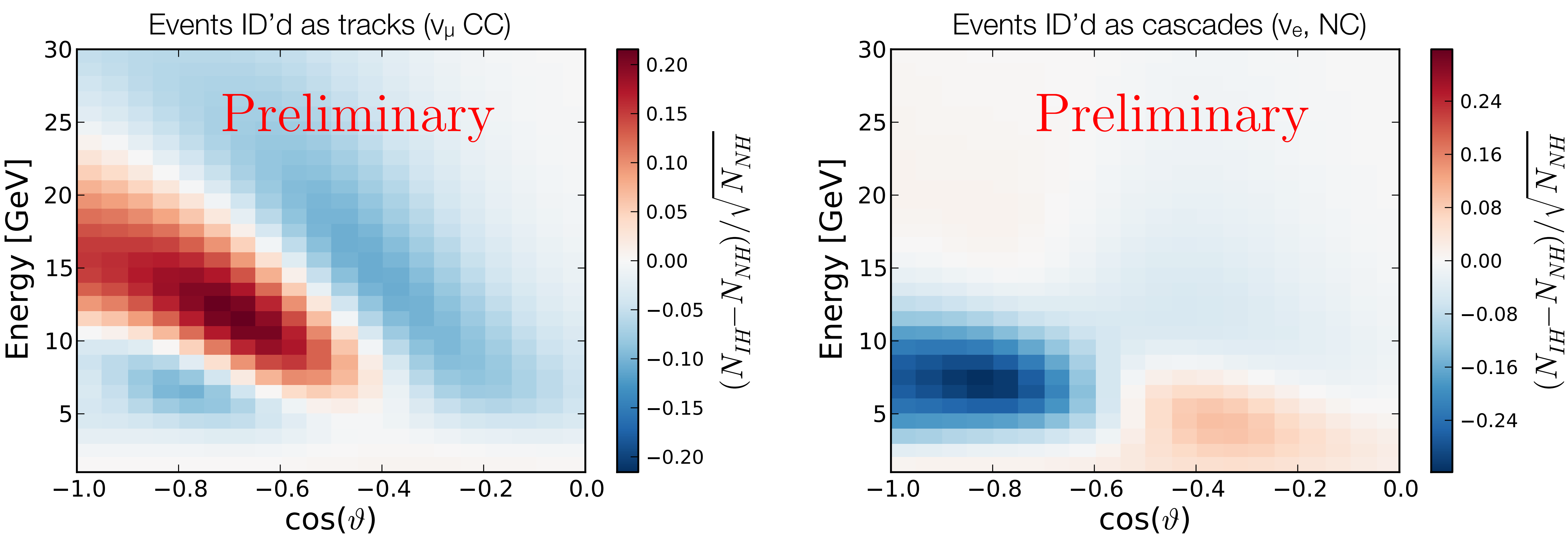


Hierarchy Signature: Statistical Significance

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)
  - Parametrized rates and detector resolutions and efficiencies used to eliminate statistical fluctuations

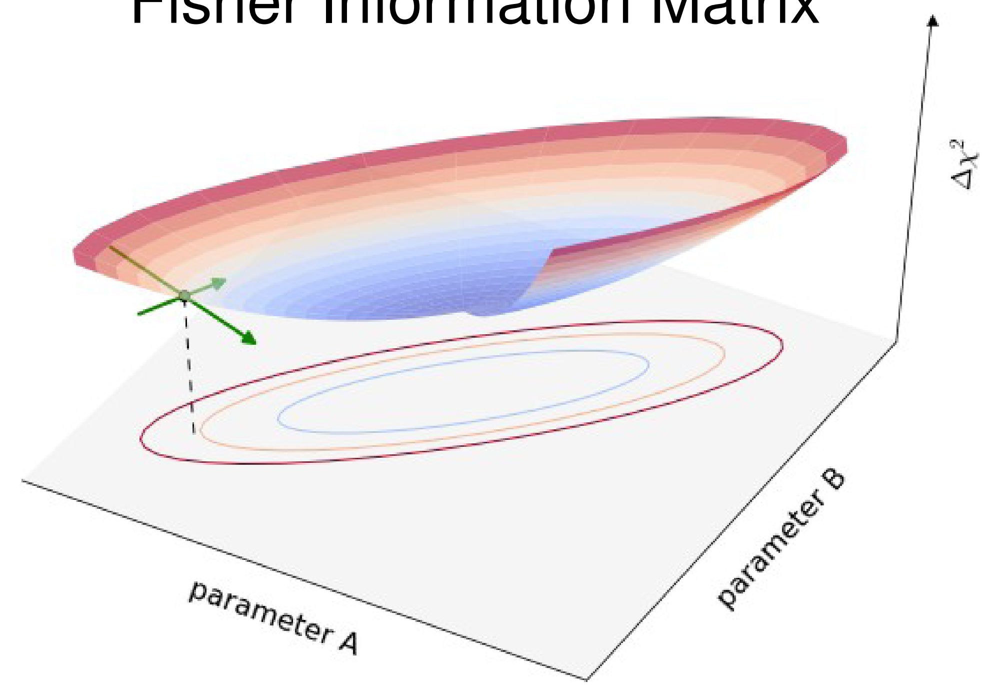
Estimating Sensitivity to the Mass Hierarchy

- Fisher Information Matrix method uses parametrized detector response based on full simulation, uses gradients in likelihood space to determine width of parabolic minimum

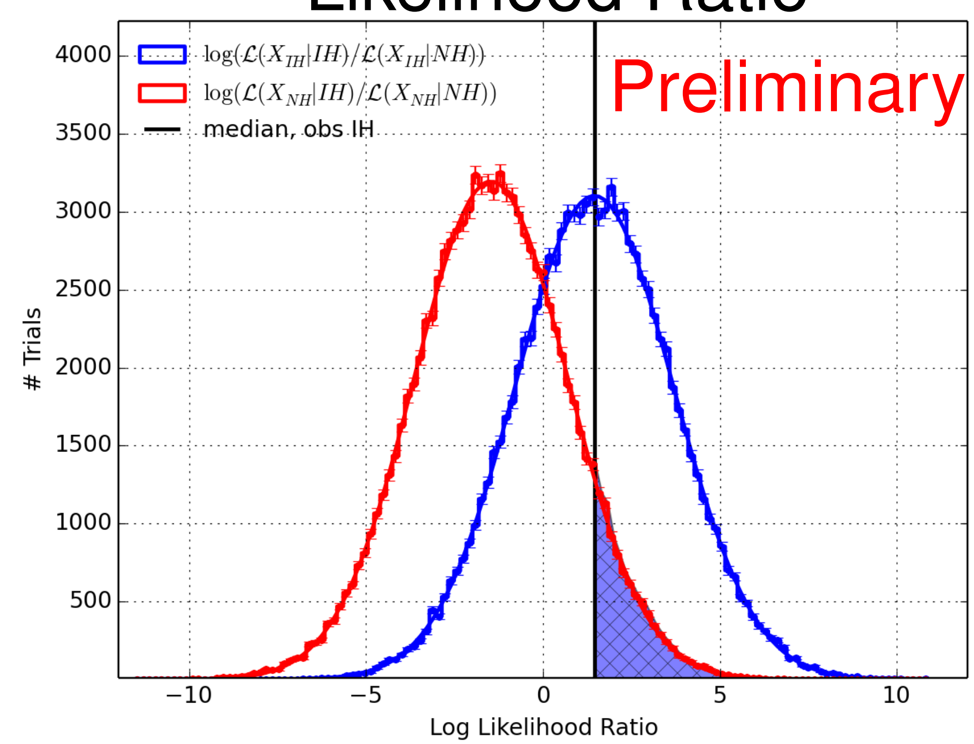
- Full Monte Carlo method uses likelihood ratio analysis of pseudo-data sets: slower, includes fewer systematics but does not pre-suppose distributions are Gaussian

- For common set of systematics and high statistics, the methods agree

Fisher Information Matrix

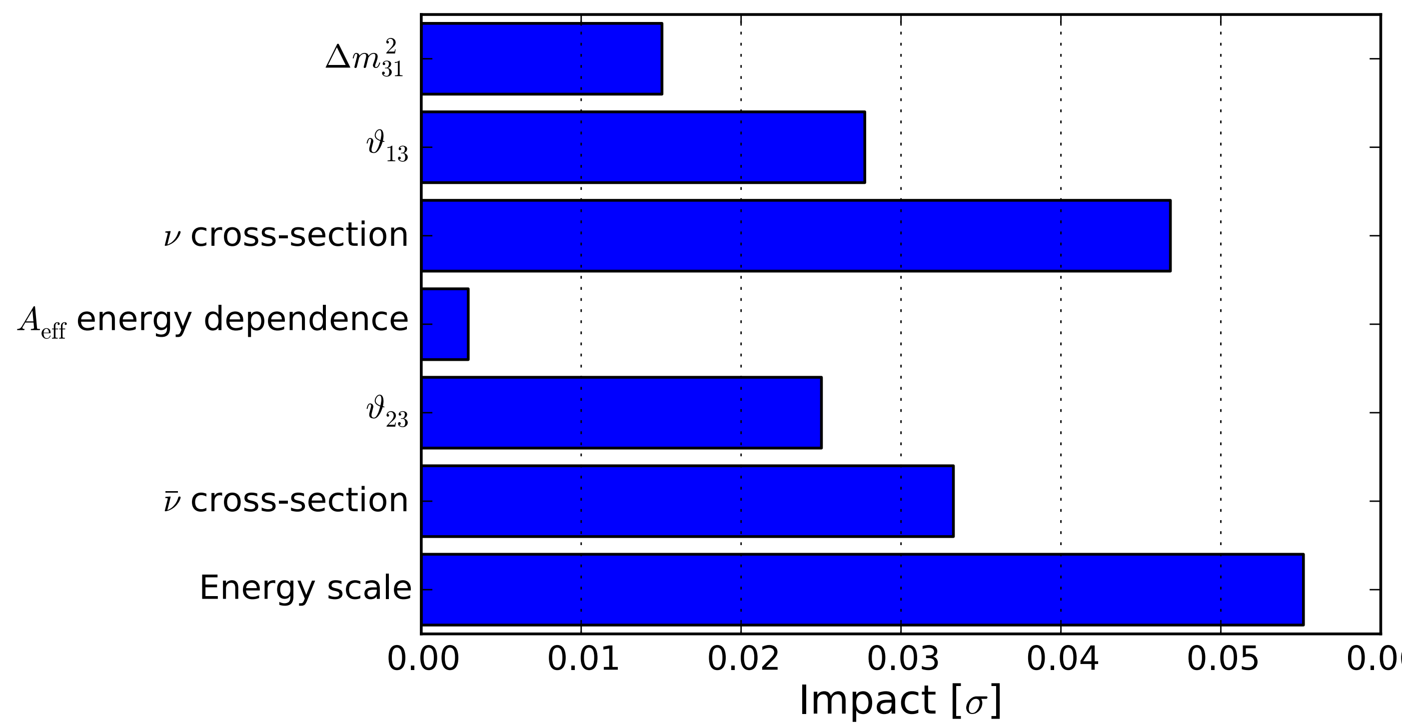


Likelihood Ratio



Systematics

- Dominant systematics are uncertainties in neutrino and antineutrino cross sections, possible energy scale errors
- Currently working on more detailed modeling of uncertainties from cross sections (using GENIE), ice optical properties
- CP-violating phase δ has little impact (as expected)

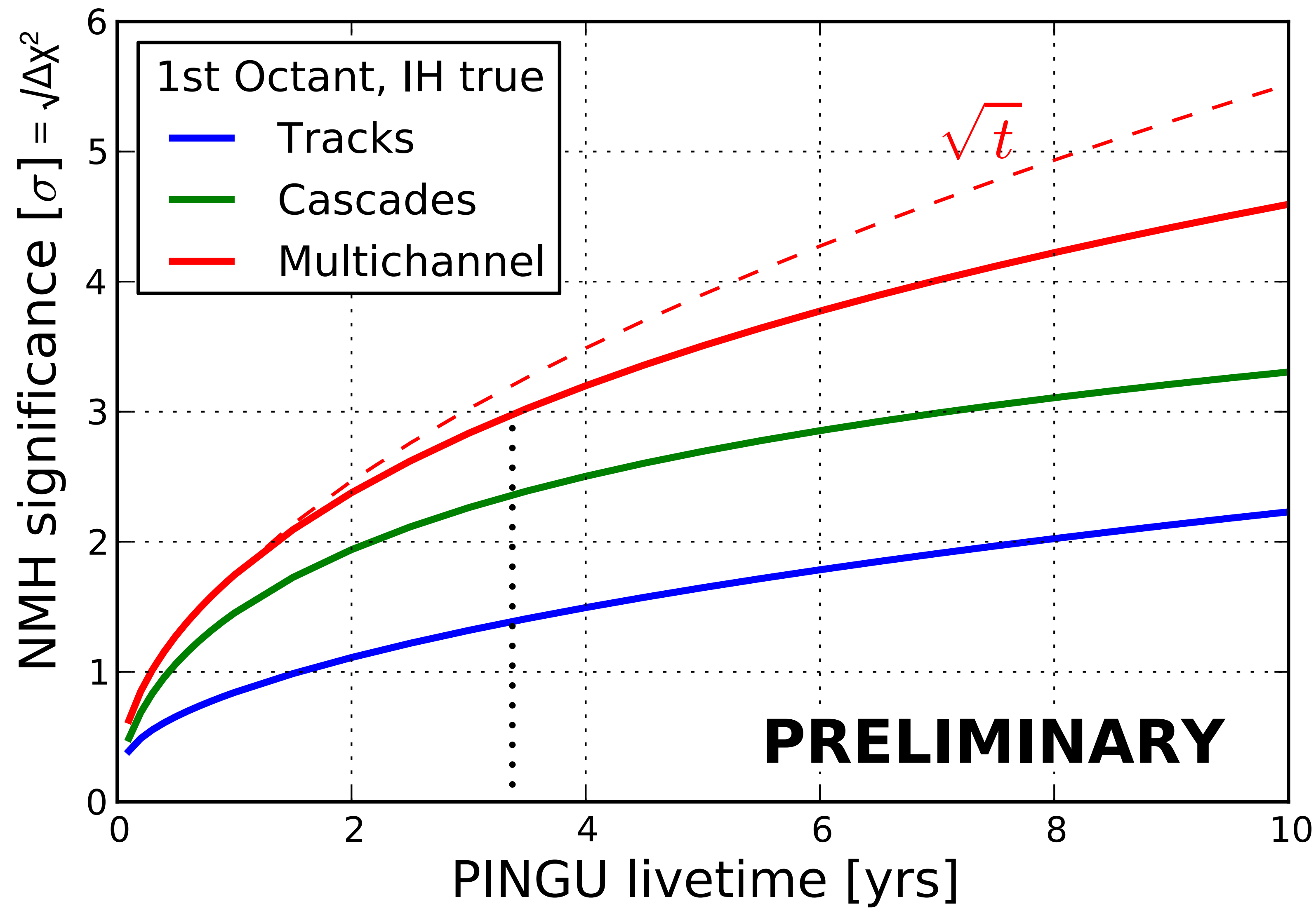


Impact: change to NMH significance if systematic error is assumed perfectly determined by other data

PINGU Hierarchy Sensitivity

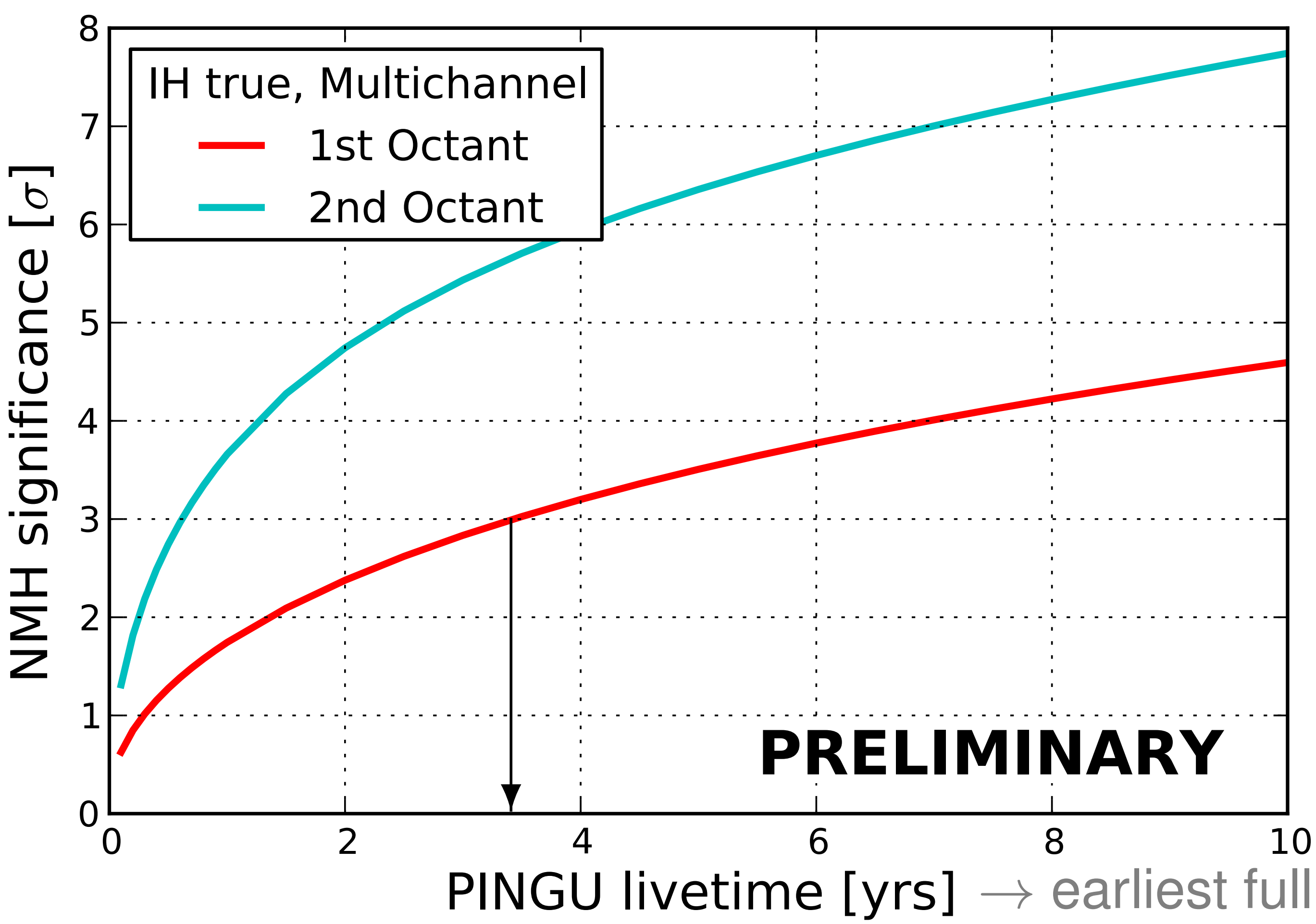
- With baseline geometry, a determination of the mass hierarchy with 3σ significance appears possible with 3.5 years of data (first octant)
    - Combine track and cascade channels to obtain final significance
    - Based on Fisher matrix result vetted against full MC studies
- Optimization of detector geometry & analysis techniques and more detailed treatment of systematics underway

arXiv:1401.2046



Impact of True Oscillation Parameters

- Baseline sensitivity assume worst case (atmospheric mixing angle in the first octant) – maximal or second octant much better
  - Expected progress in measurements of cross sections, θ_{13} will also help



$\rightarrow$ earliest full detector starting date anticipated: 2020

True oscillation parameters
θ_{12} = 33.6°
θ_{23} = 38.7°, 51.3°
θ_{13} = 8.93°
Δm^2_{21} = $7.54 \cdot 10^{-5}$ eV^2/c^4
Δm^2_{31} = $-2.38 \cdot 10^{-3}$ eV^2/c^4
δ_{CP} = 0

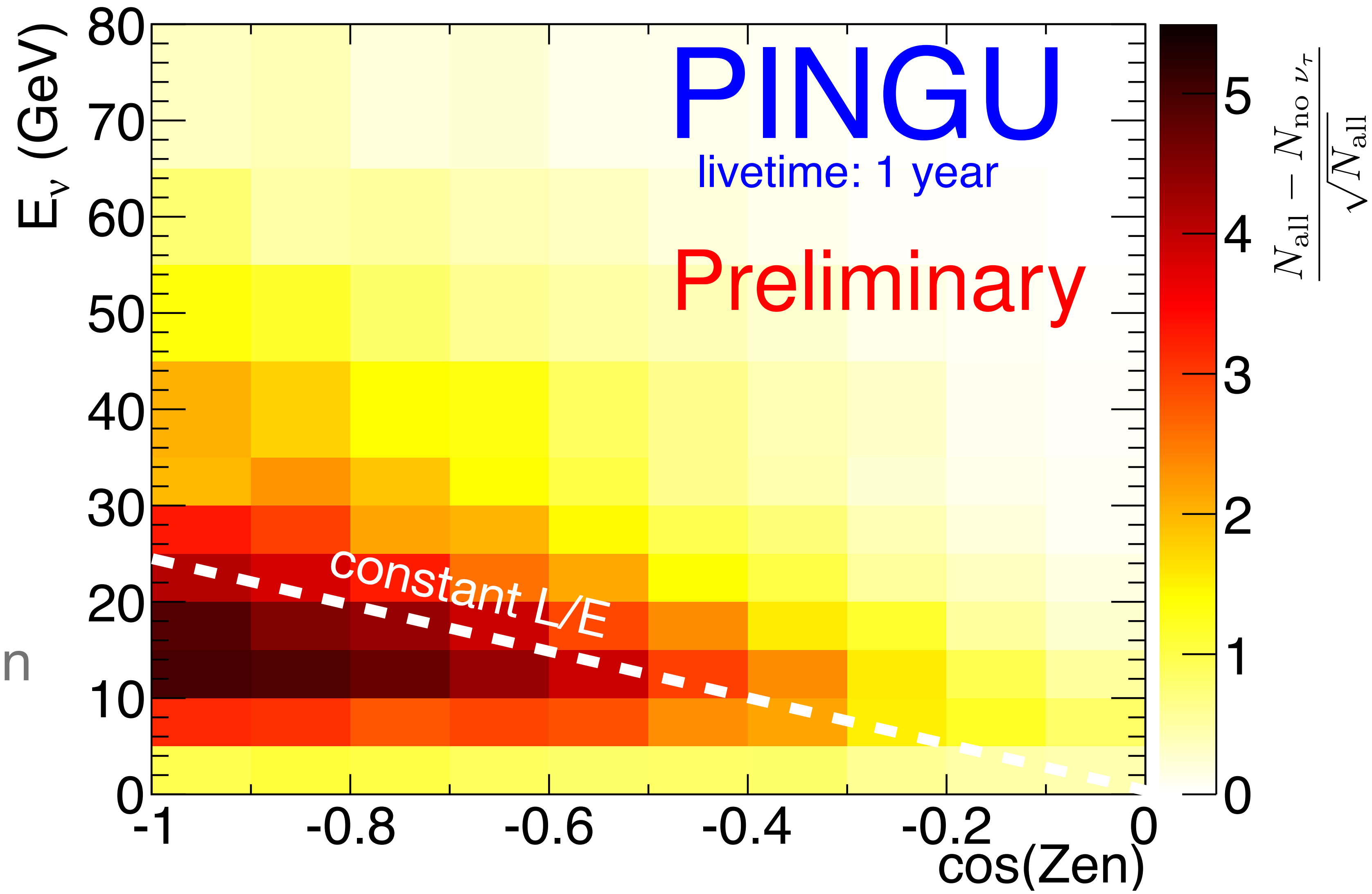
[based on Fogli et al., Phys.Rev. D86 (2012) 013012]

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

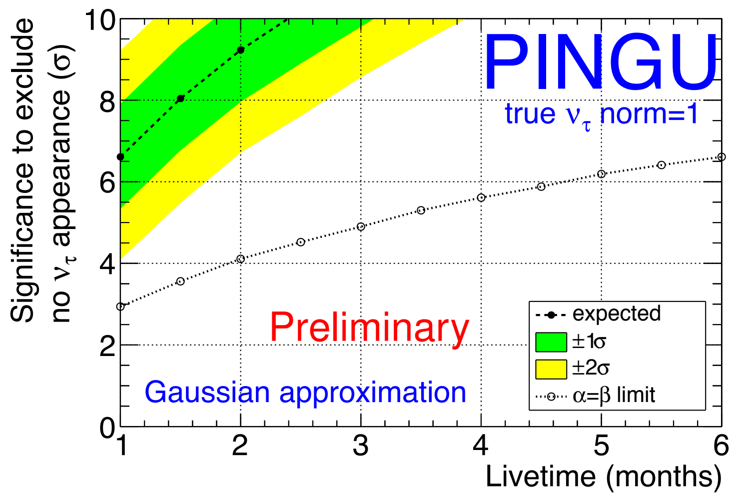
Tau Appearance with PINGU

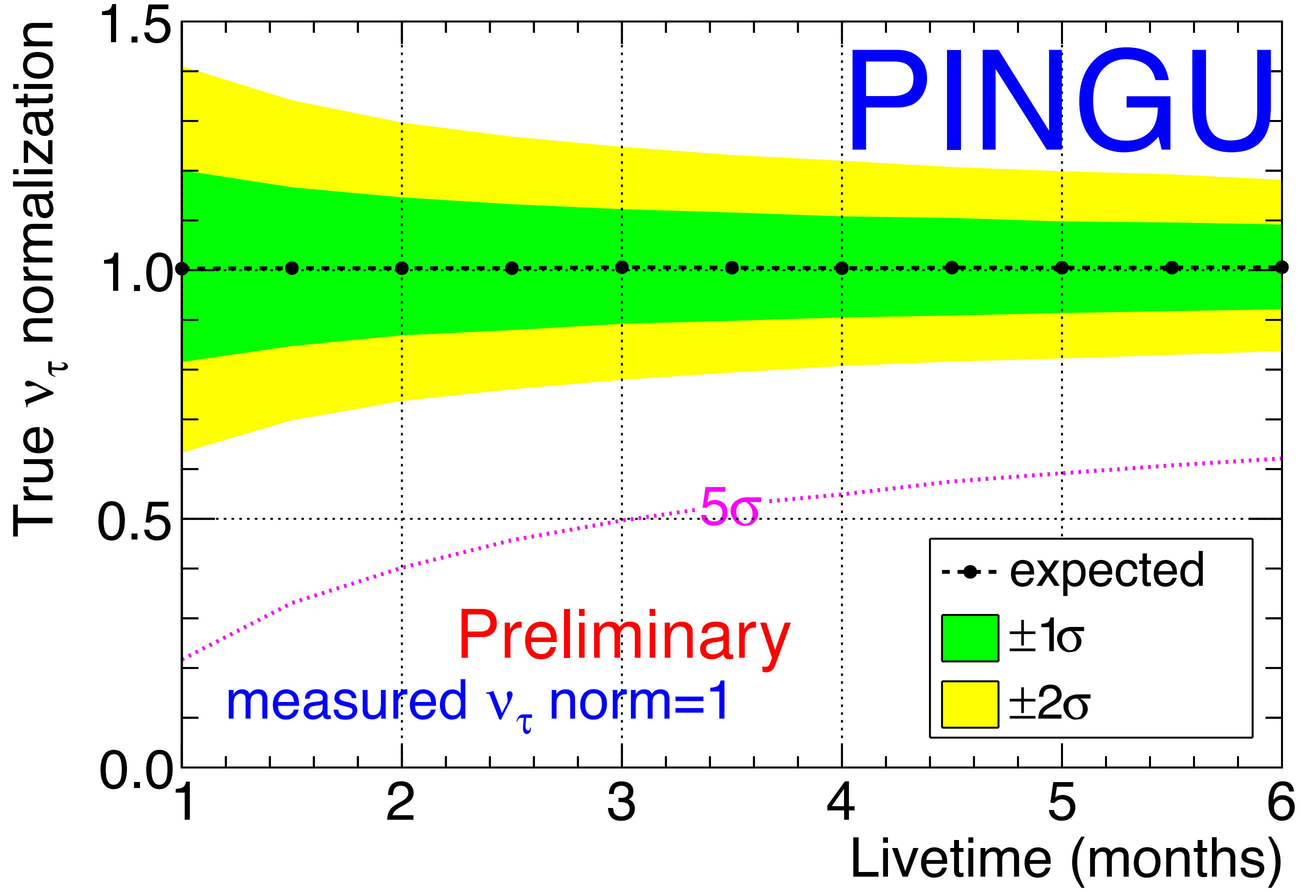
- Higher energy range of PINGU vs. OPERA, Super-K substantially improves appearance rate
  - Reduced kinematic suppression due to tau lepton mass
- Tau appearance visible as distortion of cascade energy-angle distribution
  - Preliminary studies suggest 5σ observation of ν_τ possible with around 1 month of PINGU data



Tau Appearance with PINGU

- Similar set of systematics, assumptions as used in hierarchy study
- Interesting test of the unitarity of the neutrino mixing matrix
  - 10% precision on the ν_τ appearance rate within 1 year





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 a range of higher energies/longer baselines, with high statistics
- 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
- I've focused today on neutrino physics, but also interesting potential in searches for dark matter and other exotica

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 muon veto~~ world-class neutrino observatory 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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