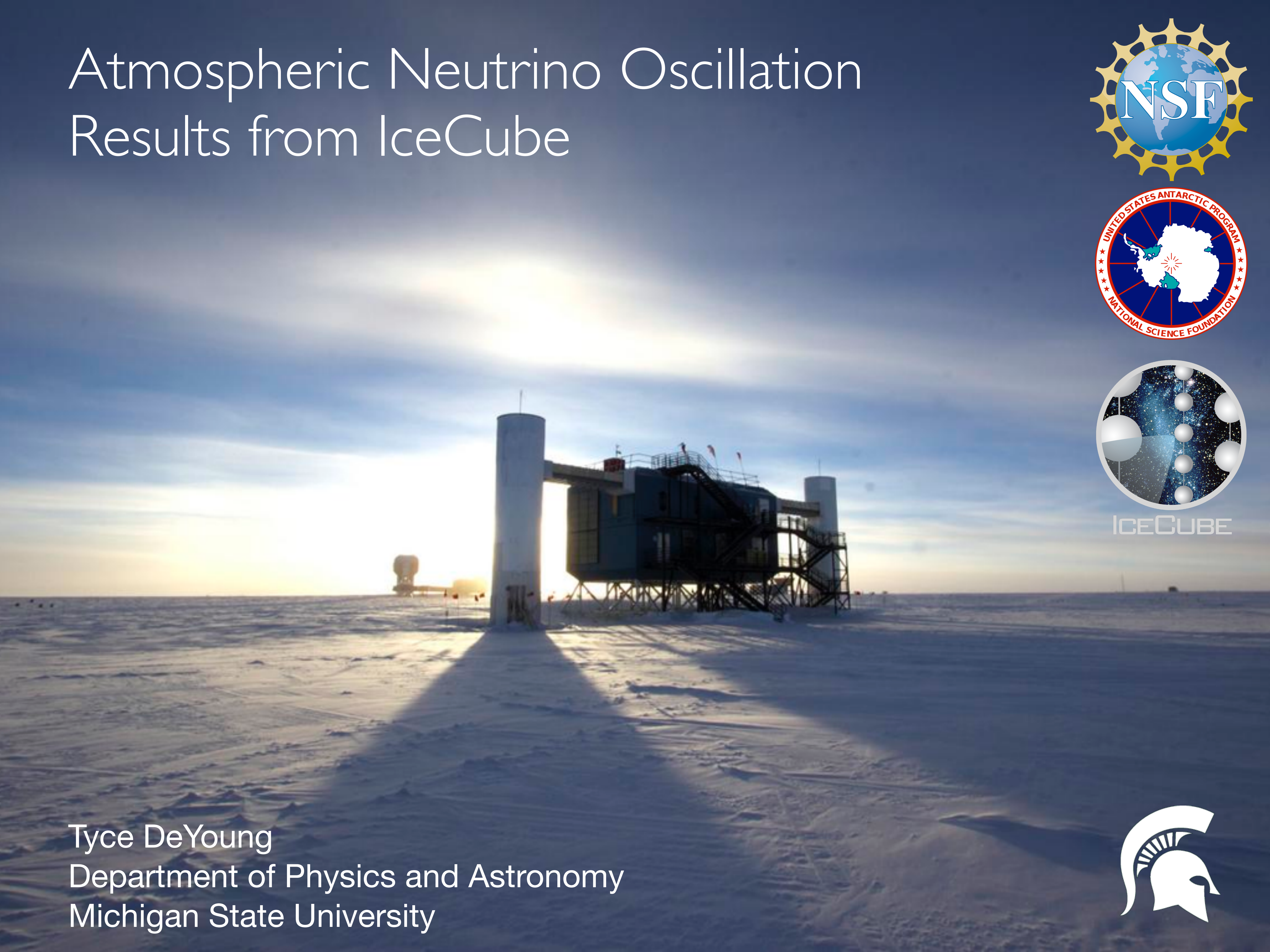
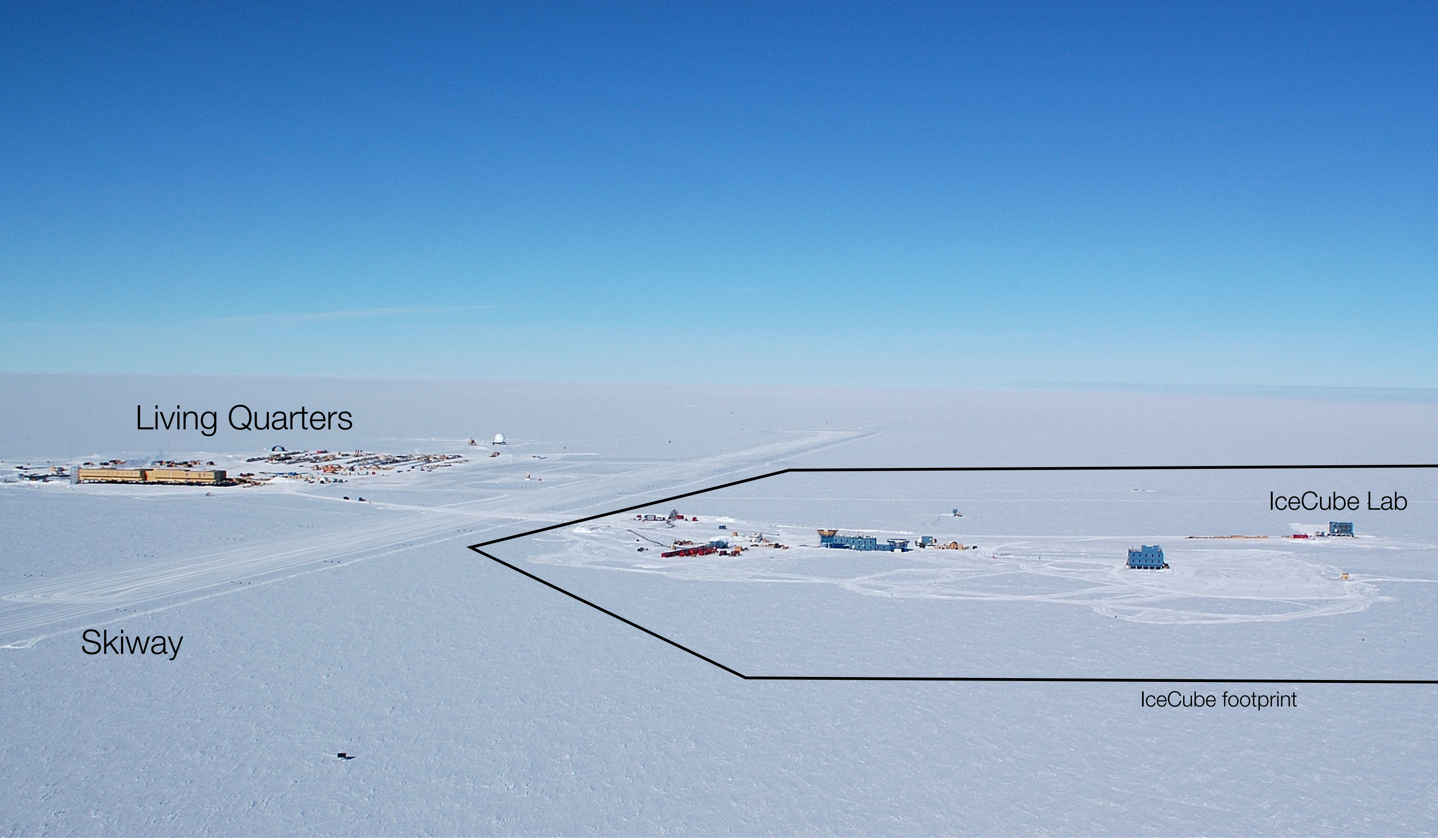


Atmospheric Neutrino Oscillation Results from IceCube

Tyce DeYoung
Department of Physics and Astronomy
Michigan State University

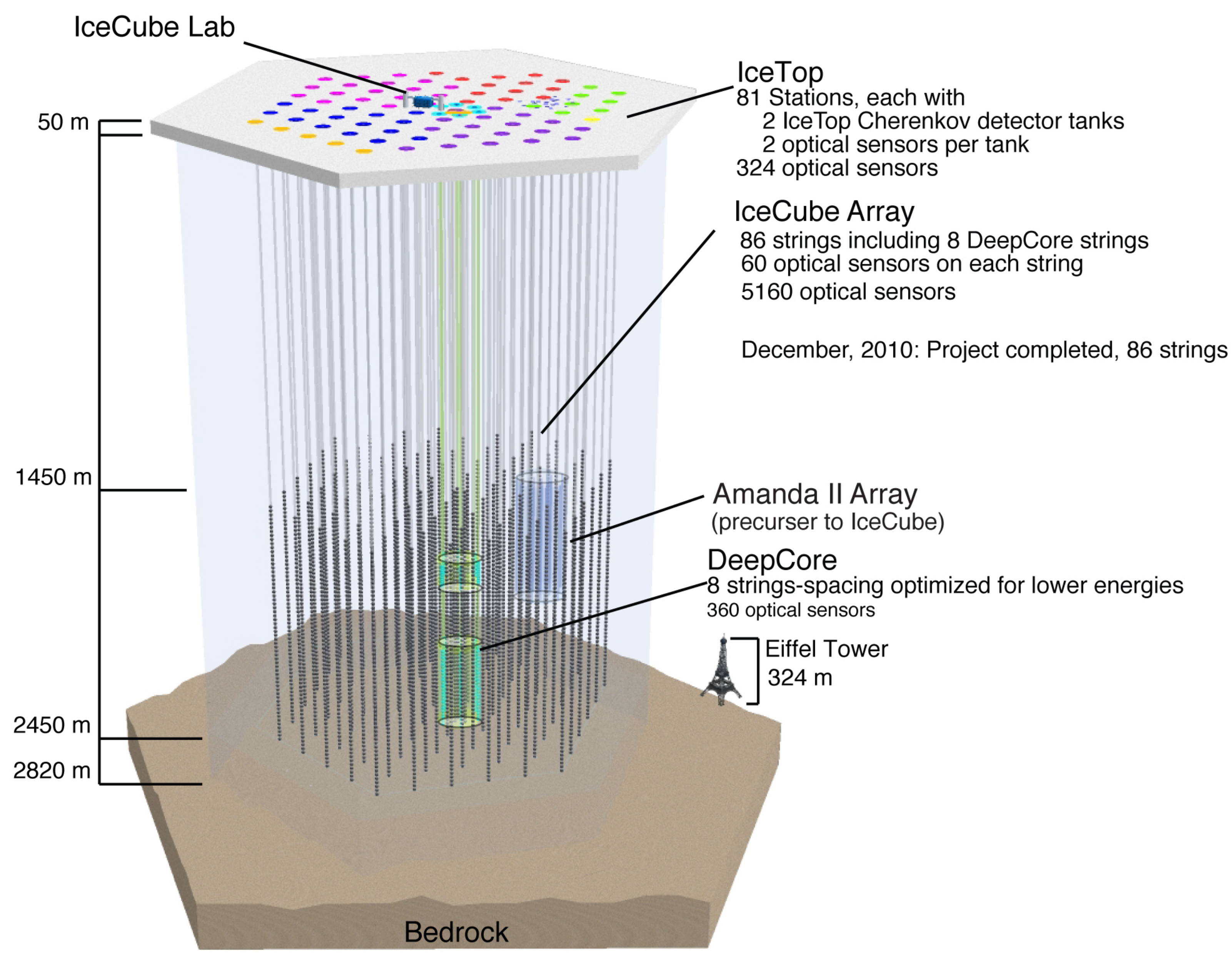


IceCube

One km^3 of extremely transparent polar ice
Buried 1.5 - 2.5 km below the surface of the ice cap
Amundsen-Scott South Pole Station

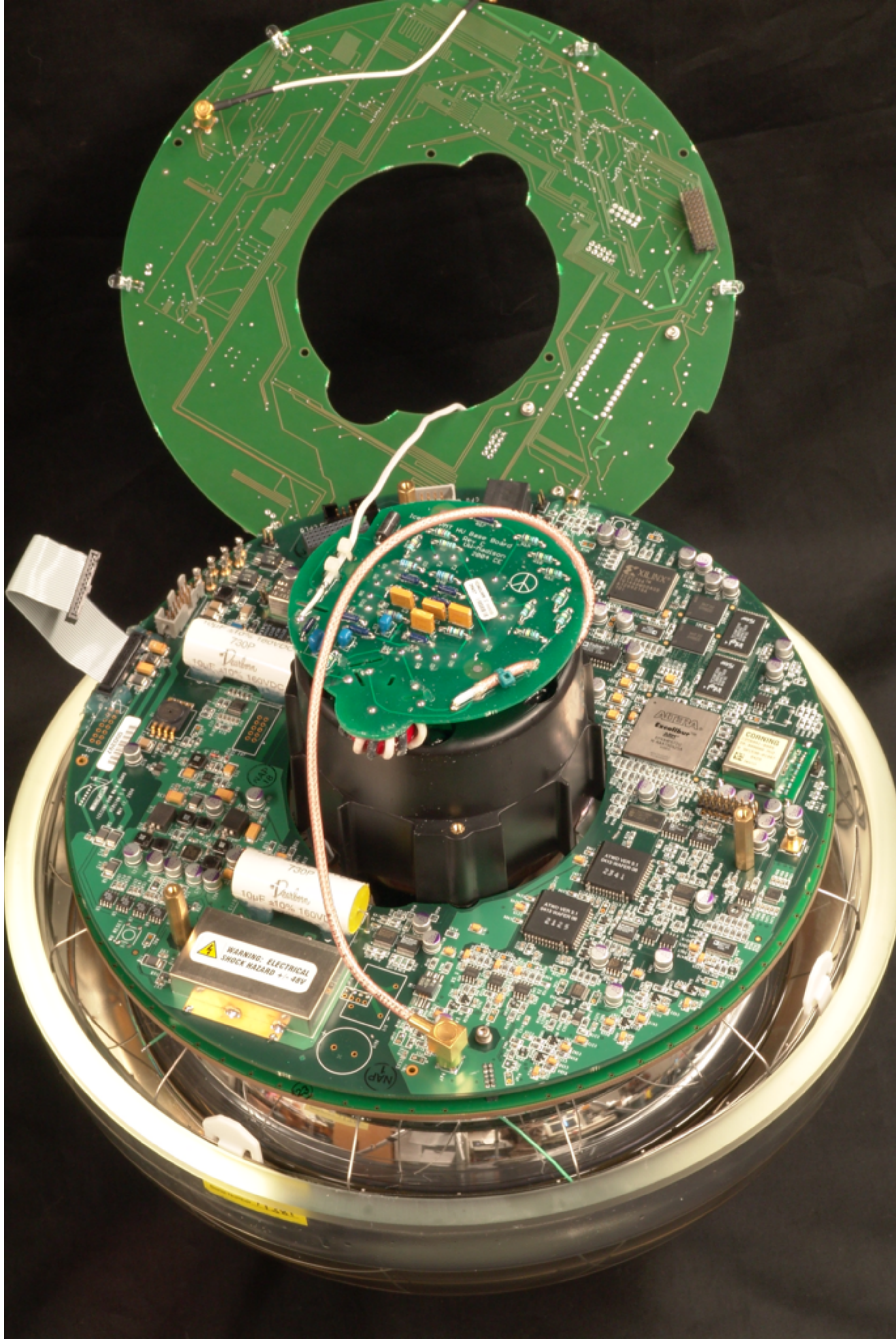
The IceCube Neutrino Observatory

- 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



DOM, Dissected

- Onboard capture of PMT waveforms
  - 300 MS/s for 400 ns with custom ATWD chip (SCA)
  - 40 MS/s for 6.4 μsec with commercial ADC
- Absolute timing < 2 ns (RMS)
- Dynamic range ~1000 p.e./10 ns
- Noise rate ~600 Hz (underlying Poisson rate 260 Hz)
- DOM electronics dead time < 1%
- Survival rate: 98.5%



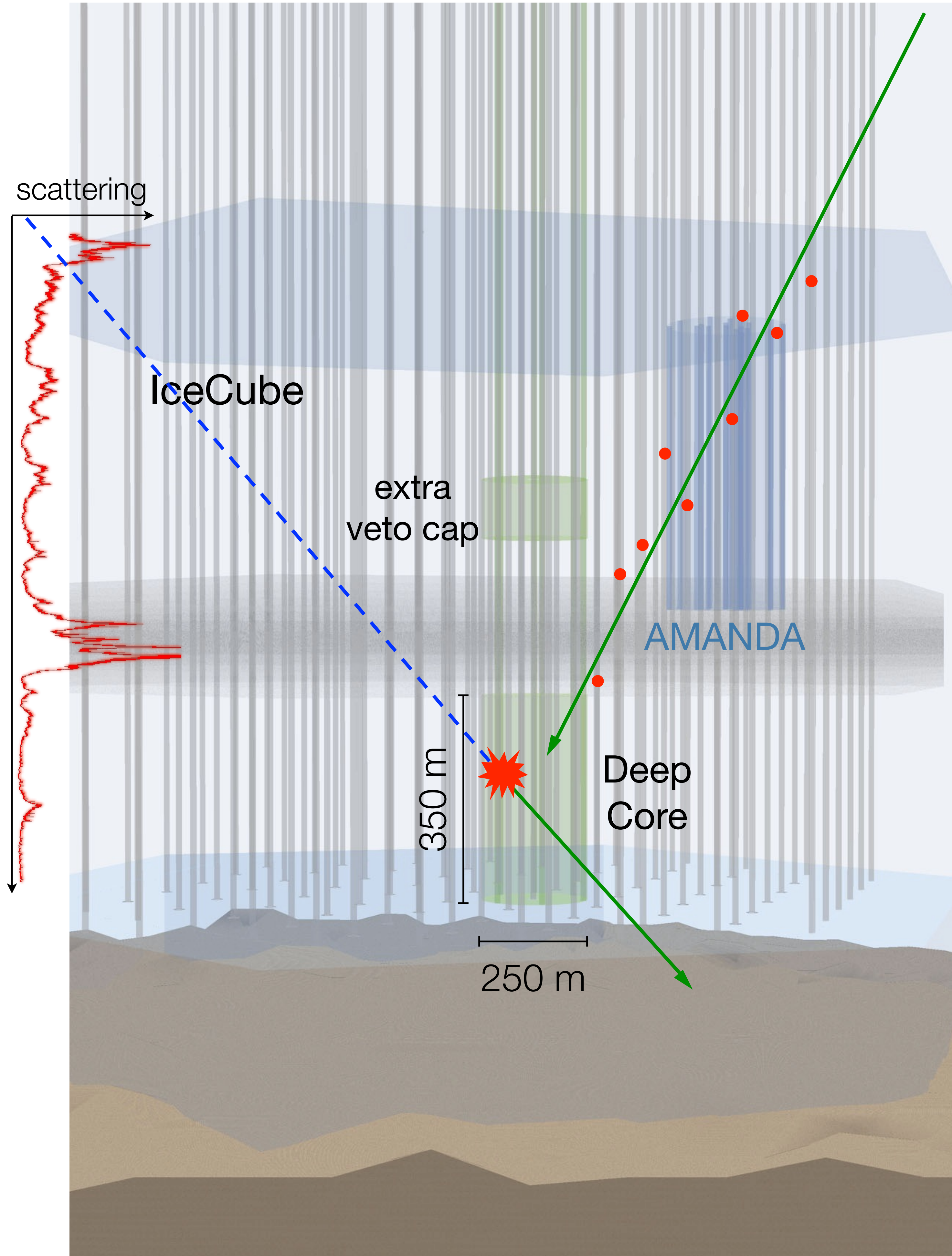

MAX. WEIGHT 550 LBS
DANGER

Digital Optical Module Installation

- Melt a hole in the ice with high-pressure hot water "drill"
  - 65 cm diameter, 2.5 km deep
  - Maximum lateral drift ~1 m
- Attach 60 DOMs to a kevlar-reinforced power and communications cable
  - Run *FINAL* acceptance tests
  - Lower into the hole over the course of about 10 hours
- Wait a few weeks(!) for the hole to refreeze completely

IceCube DeepCore

- A more densely instrumented region at the bottom center of IceCube
  - Eight special strings plus 12 nearest standard strings
  - Hamamatsu 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 and two-dimensional data fit greatly improves precision – arXiv:1410:7227, *Phys. Rev. D* in press

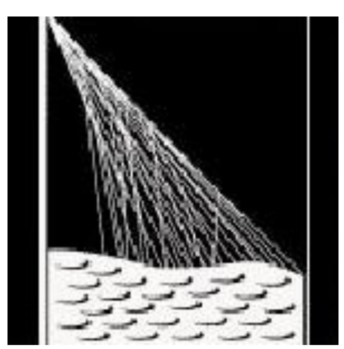
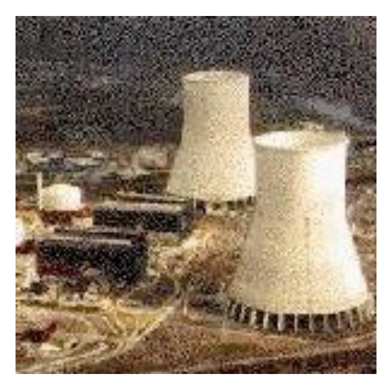
Neutrino Mixing

- Pontecorvo-Maki-Nakagawa-Sakata matrix describes mixing between neutrino flavor eigenstates and mass eigenstates
  - Analogous to CKM matrix for quarks

Potential CP violation ~ θ_{13}

($s_{ij} = \sin\theta_{ij}$ $c_{ij} = \cos\theta_{ij}$)

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

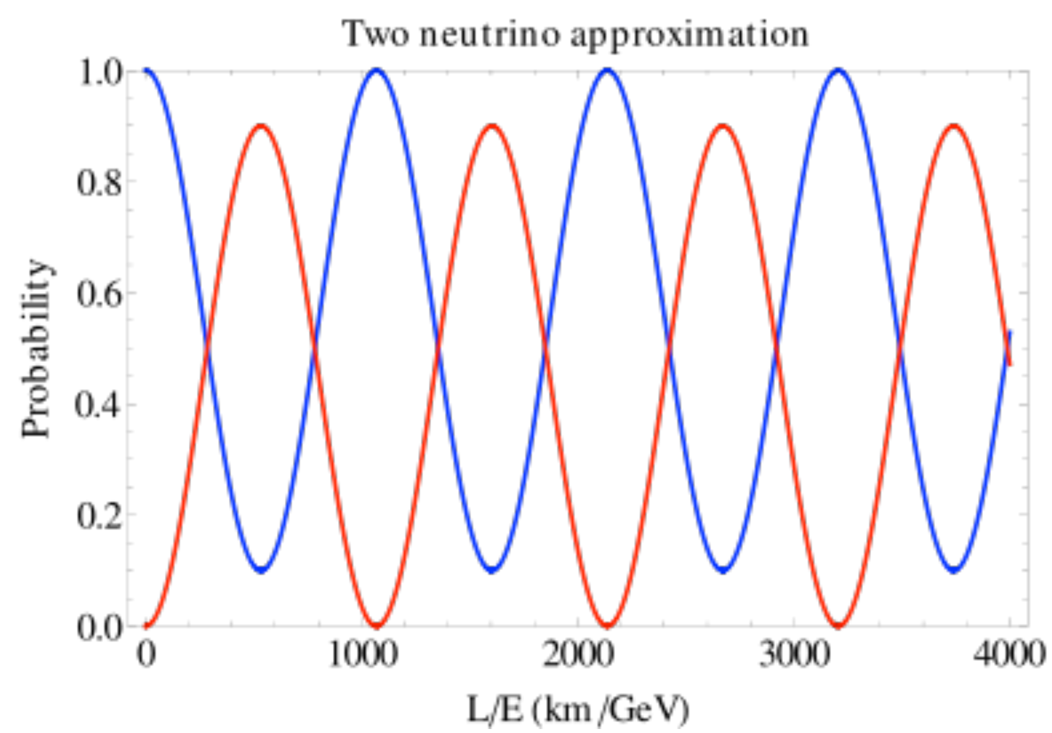
= () x () x ()

atmospheric — reactor/beam — solar

Neutrino Flavor Oscillations

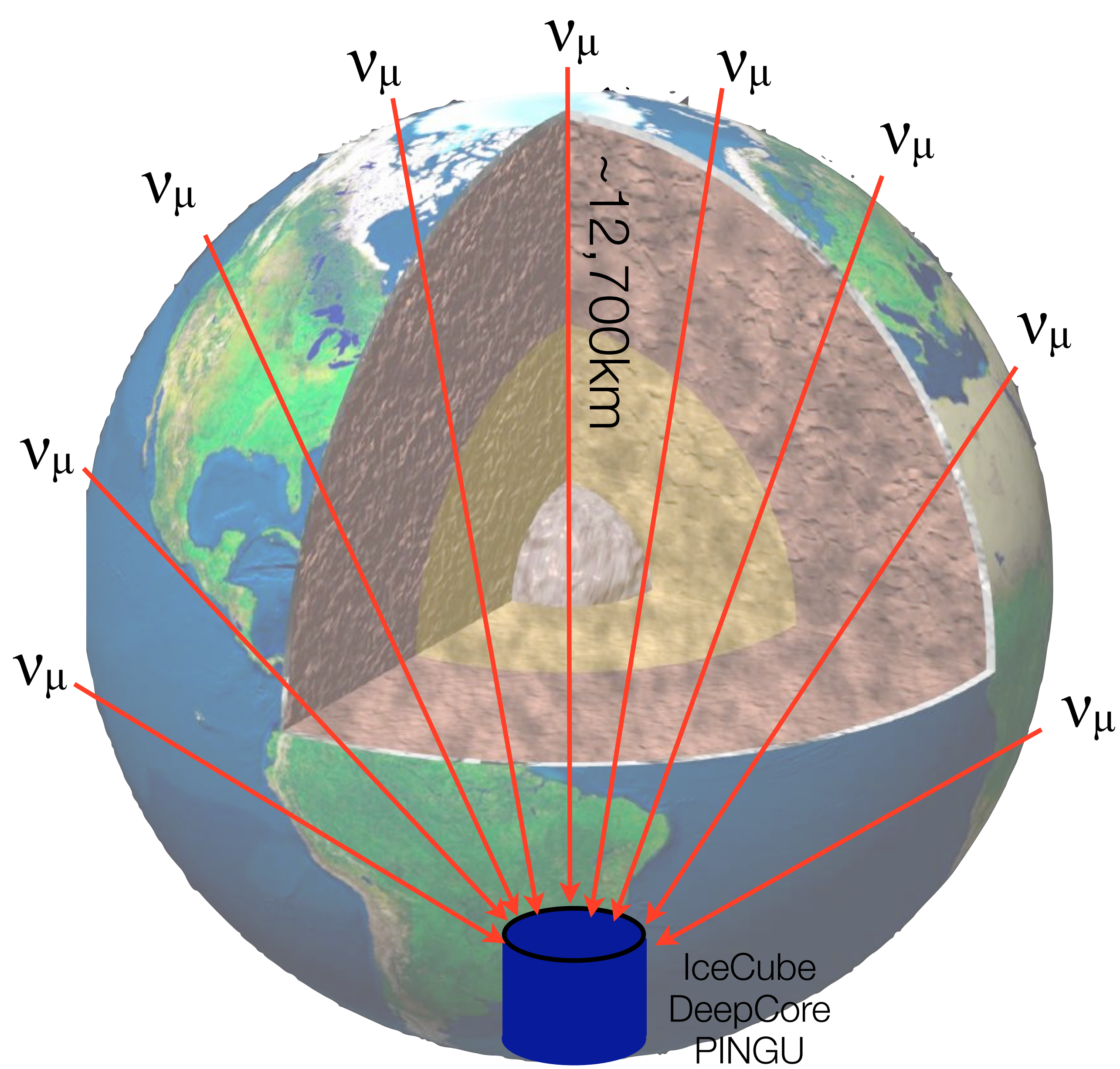
- Neutrinos are produced in flavor eigenstates, but propagation through space depends on the Hamiltonian and thus the mass
  - The three mass components of each flavor eigenstate propagate at different speeds, leading to interference between the flavor components of each mass eigenstate
  - Can calculate the survival probability of each flavor:

$$P_{\alpha\to\alpha} = |\langle\nu_\alpha|\nu_\alpha(t)\rangle|^2 \rightarrow \boxed{\text{Algebra!}} \rightarrow P_{\mu\mu} \approx 1 - \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



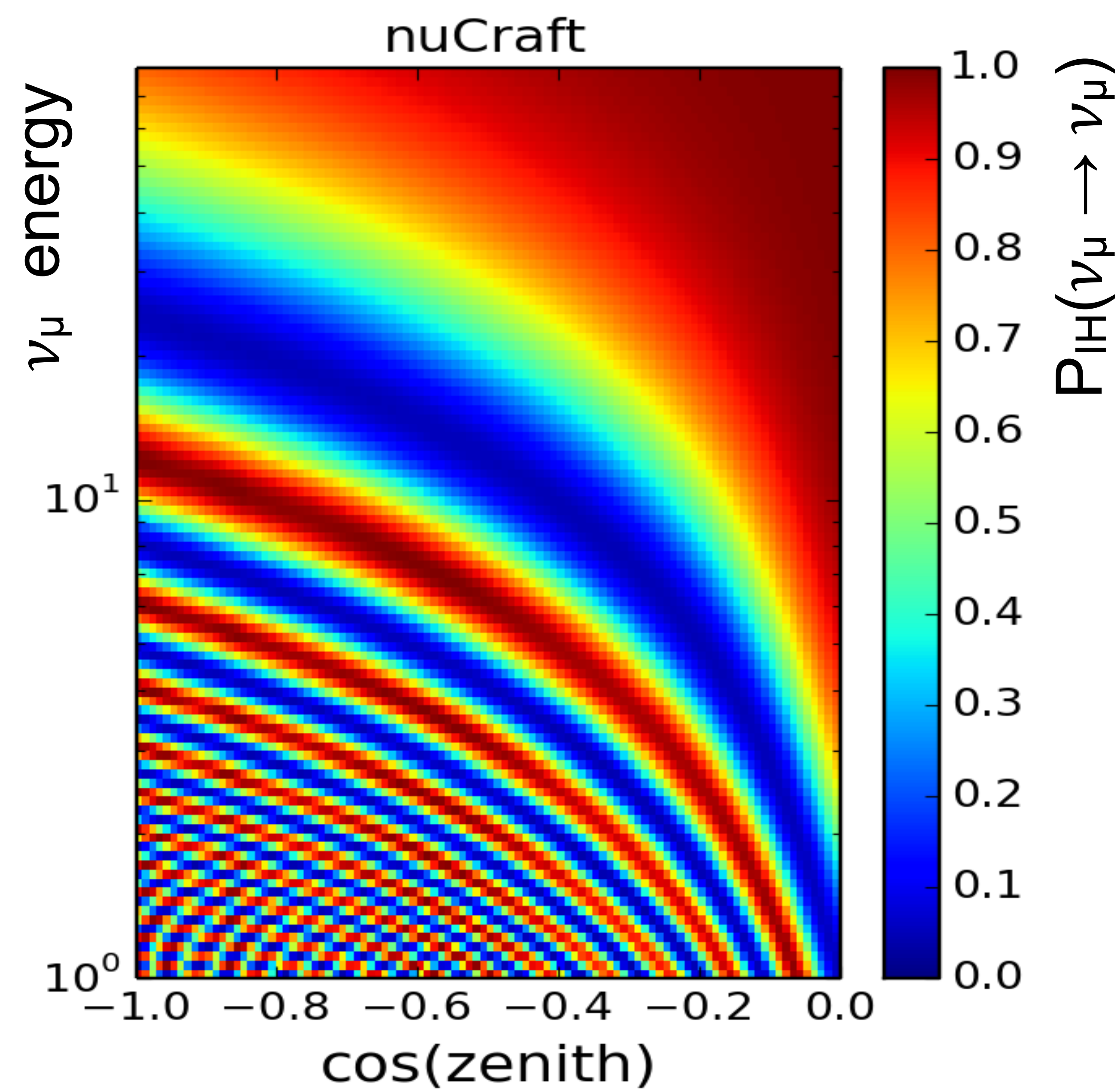
Oscillation Physics with Atmospheric Neutrinos

- Neutrinos available over a wide range of energies and baselines
  - Oscillations produce distinctive pattern in energy-angle space
  - Control systematics using events in “side band” regions – trade statistics for constraints on systematics
  - Effectively, a range of near to far beams rather than near and far detectors
- Need a large detector to provide sufficient statistics for this approach to work



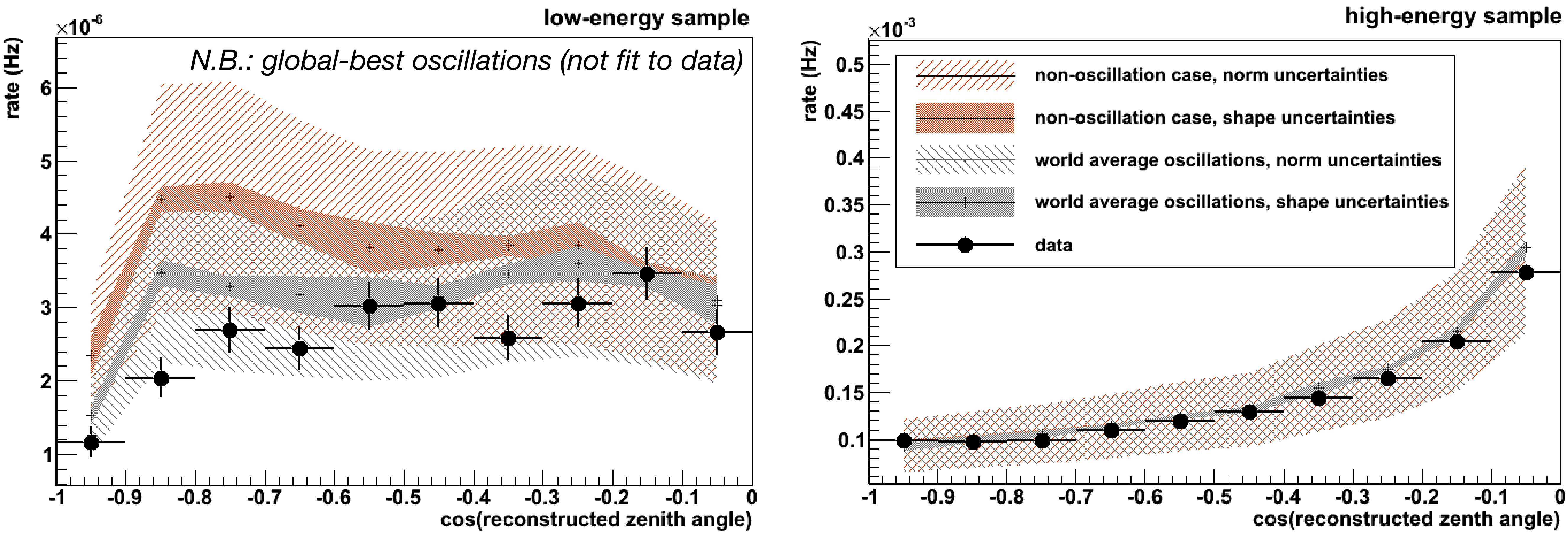
Oscillation Physics with Atmospheric Neutrinos

- Atmospheric ν_μ survival minimum at ~25 GeV for baseline length equal to Earth diameter
- Event rates (trigger level, $E_\nu \gtrsim 10$ GeV):
  - ν_μ ~ 70k / year
  - ν_e ~ 11k / year
- Analysis efficiencies increasing from ~1% in first analysis to ~20% in coming studies



Atmospheric Oscillations – First Steps

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



Two energy slices instead of 2D energy-angle analysis; minor modifications to standard TeV event selection and reconstruction algorithms

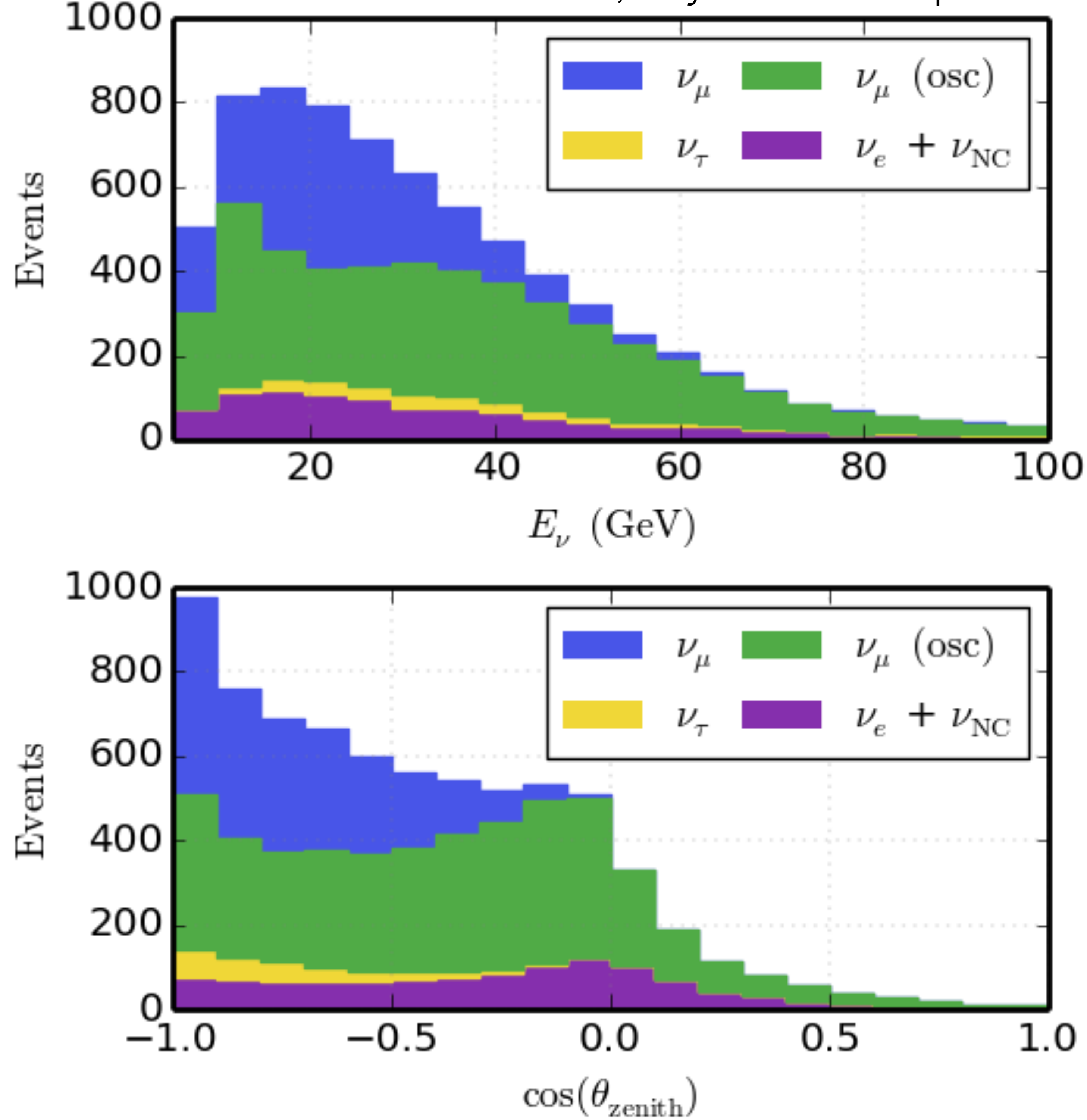
Statistically significant angle-dependent suppression at low energy, high energy sample provides constraint on uncertainties in simultaneous fit

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

Atmospheric Oscillations – 2nd Generation

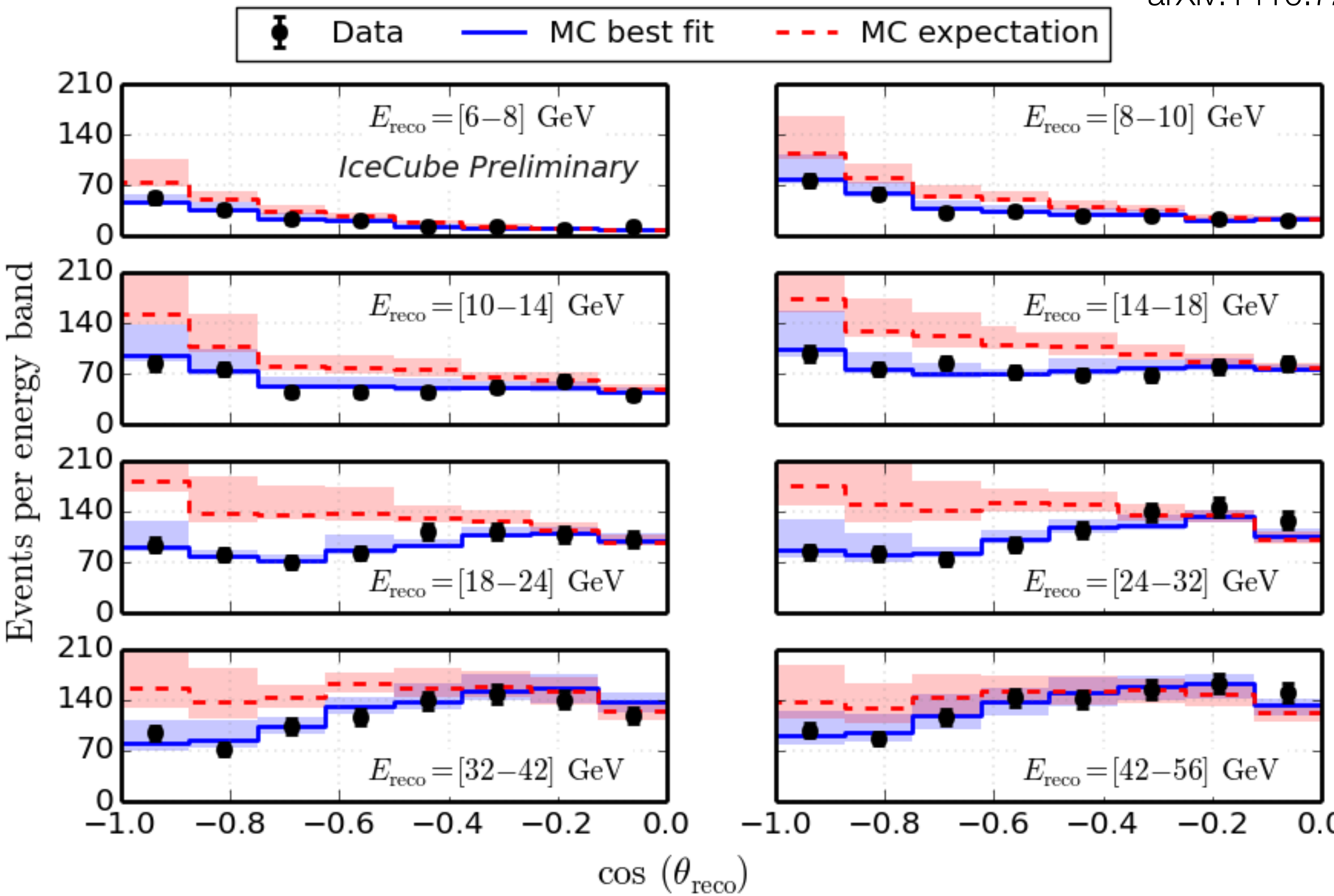
- Three years with improved event selection
  - Increased from ~700 to ~1,500 events per year
- Energy threshold reduced below 10 GeV – see most of first oscillation minimum
- First specialized low-energy reconstructions, enabling use of multiple energy bins in oscillation energy range

arXiv:1410.7227, *Phys. Rev. D* in press



Atmospheric Oscillations – 2nd Generation

arXiv:1410.7227

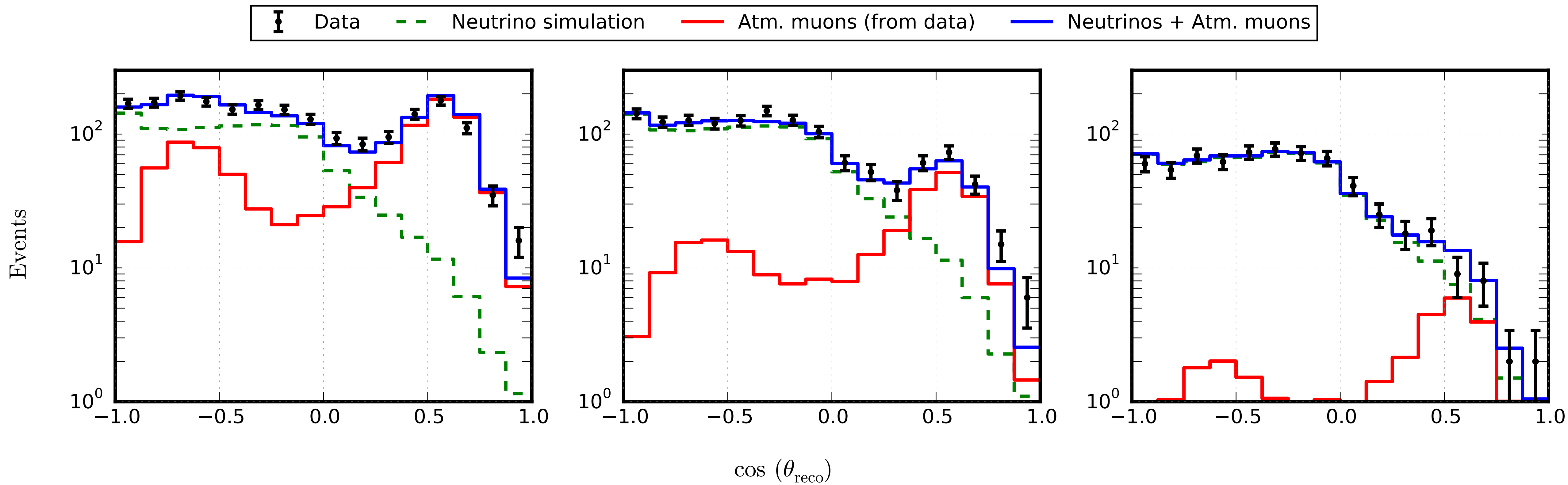


Systematics and Priors

- Priors are implemented as Gaussian weights in global likelihood
  - Fit jointly with parameters of interest (θ_{23} and Δm^2_{atm})
  - Non-analytic parameters treated by bin-wise quadratic interpolation with Gaussian weights
- νN interaction uncertainties subdominant, ~linear above 7 GeV (~97% of sample)
- All posterior values are consistent with expectations

Parameter	Prior width
Atm. μ background norm.	none
Atm. ν_μ flux norm.	none
Atm. ν_e/ν_μ ratio	±20%
Atm. ν spectral index	±0.04
π/K ratio	±10%
$\sin^2(2\theta_{13})$	±.008
DOM efficiency	±10%
Rel. eff. of HQE DOMs	±3%
Bulk ice model	two models
Hole ice scattering	±0.01 cm^{-1}
Cross section model	GENIE vs. Gazizov
DIS cross section	±5%
DIS energy dependence	±0.03
m_A (QE)	+25%/-15%
m_A (resonant)	±20%
Hadronic energy scale	±5%

Modeling Atmospheric Muon Background

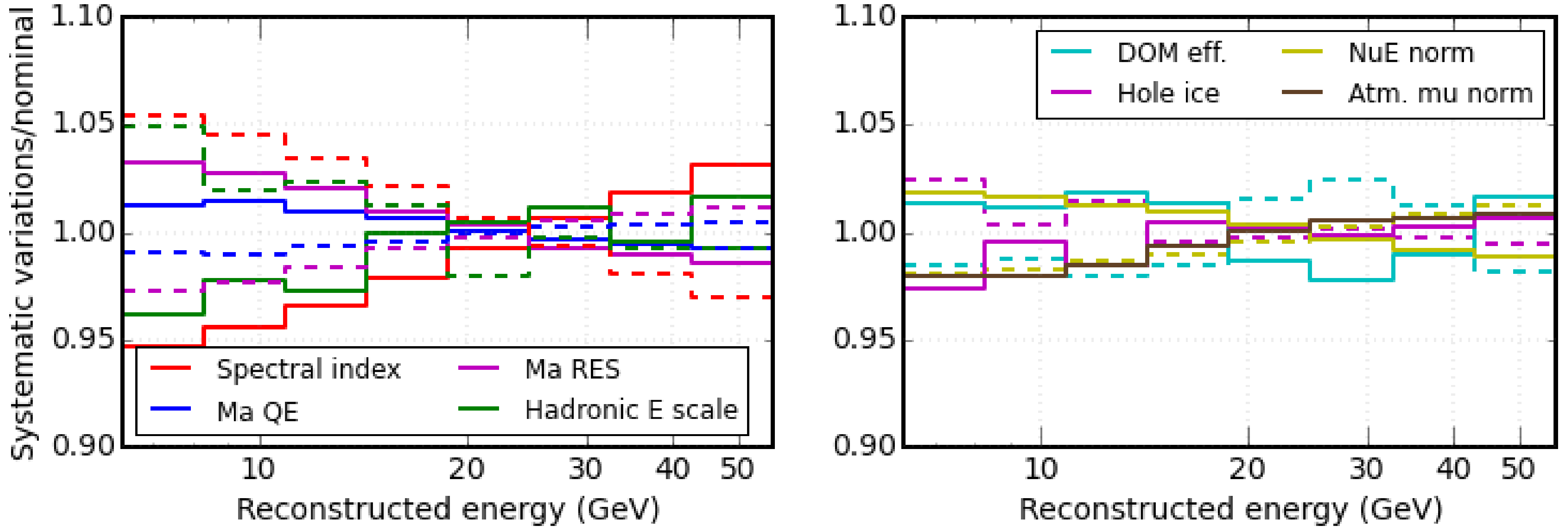


- Computationally infeasible to produce sufficient sample of simulated muons (~10^9 rejection efficiency) – even setting aside accuracy issue

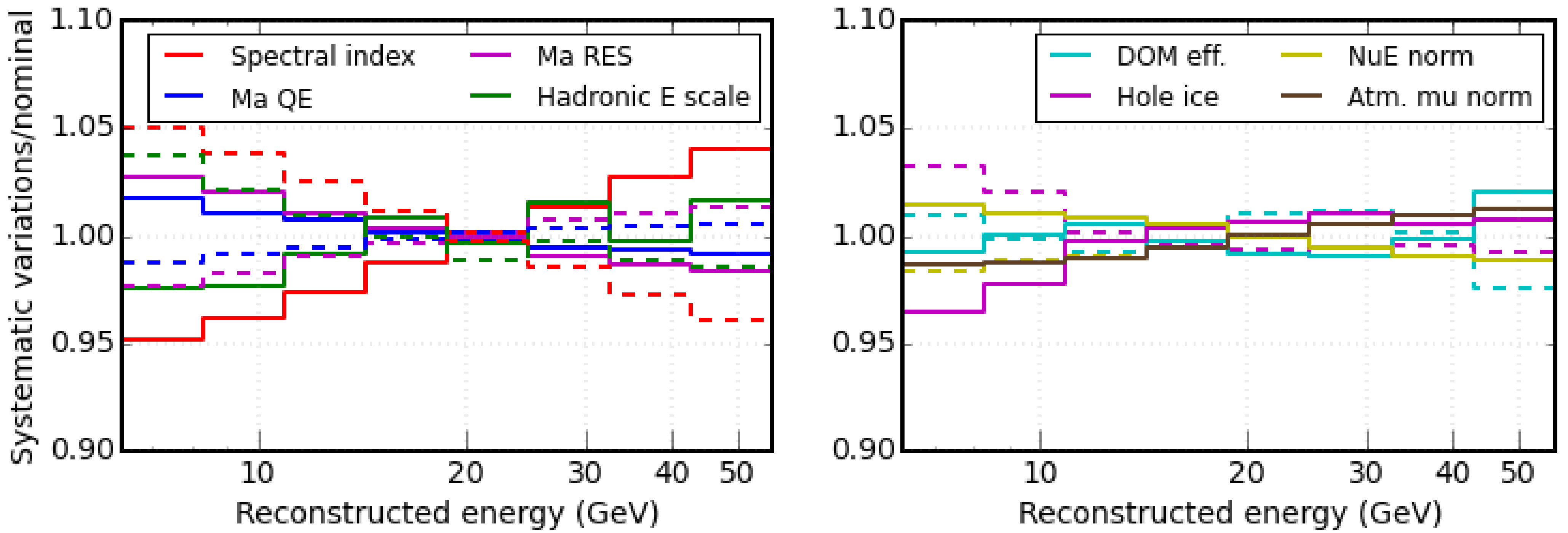
- Instead, invert muon veto – use sample of apparent neutrino events with 1-2 PEs detected in outer layers of IceCube

Interaction vs. Flux Uncertainties

Track-like



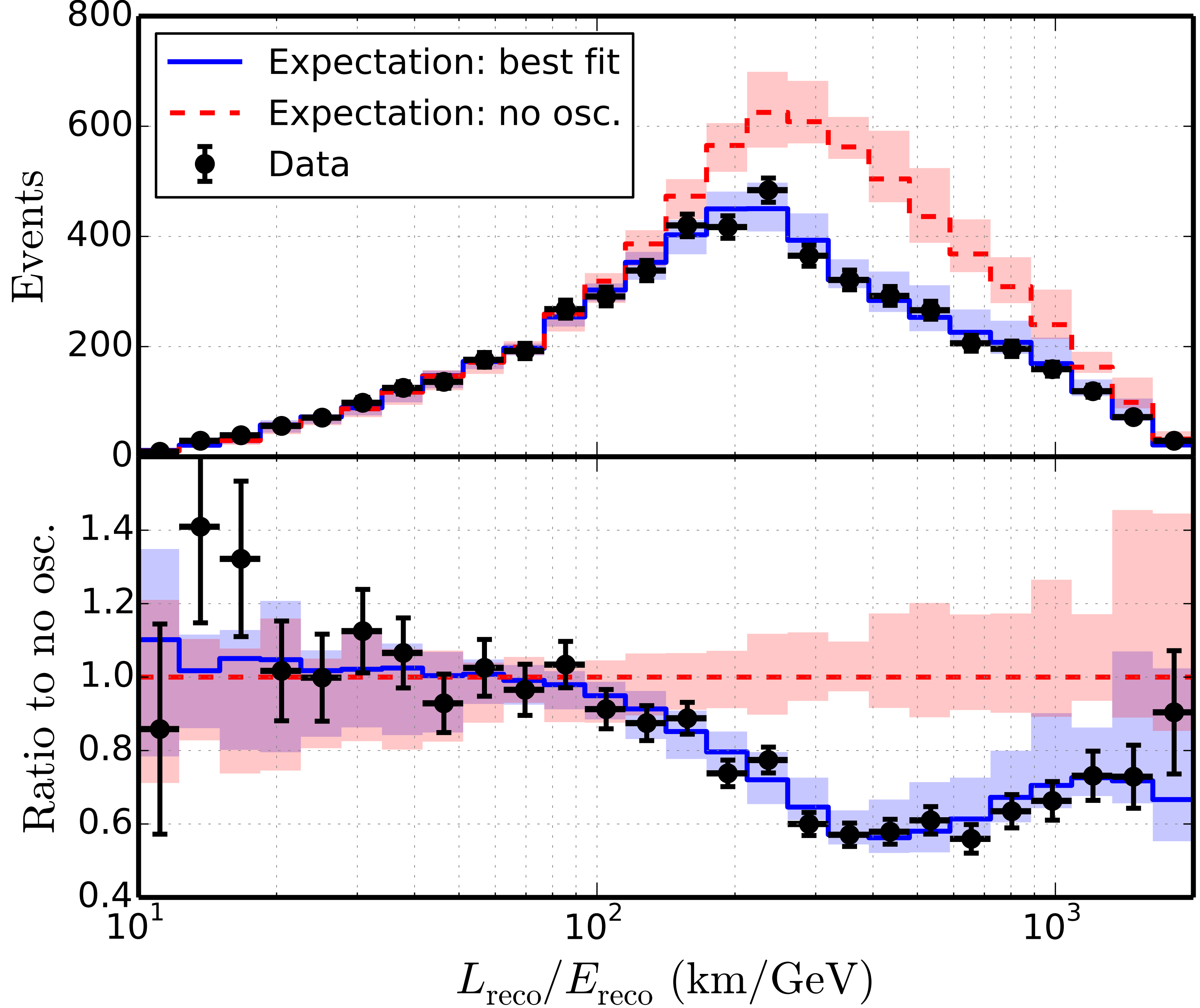
Cascade-like



Atmospheric Oscillations with IceCube

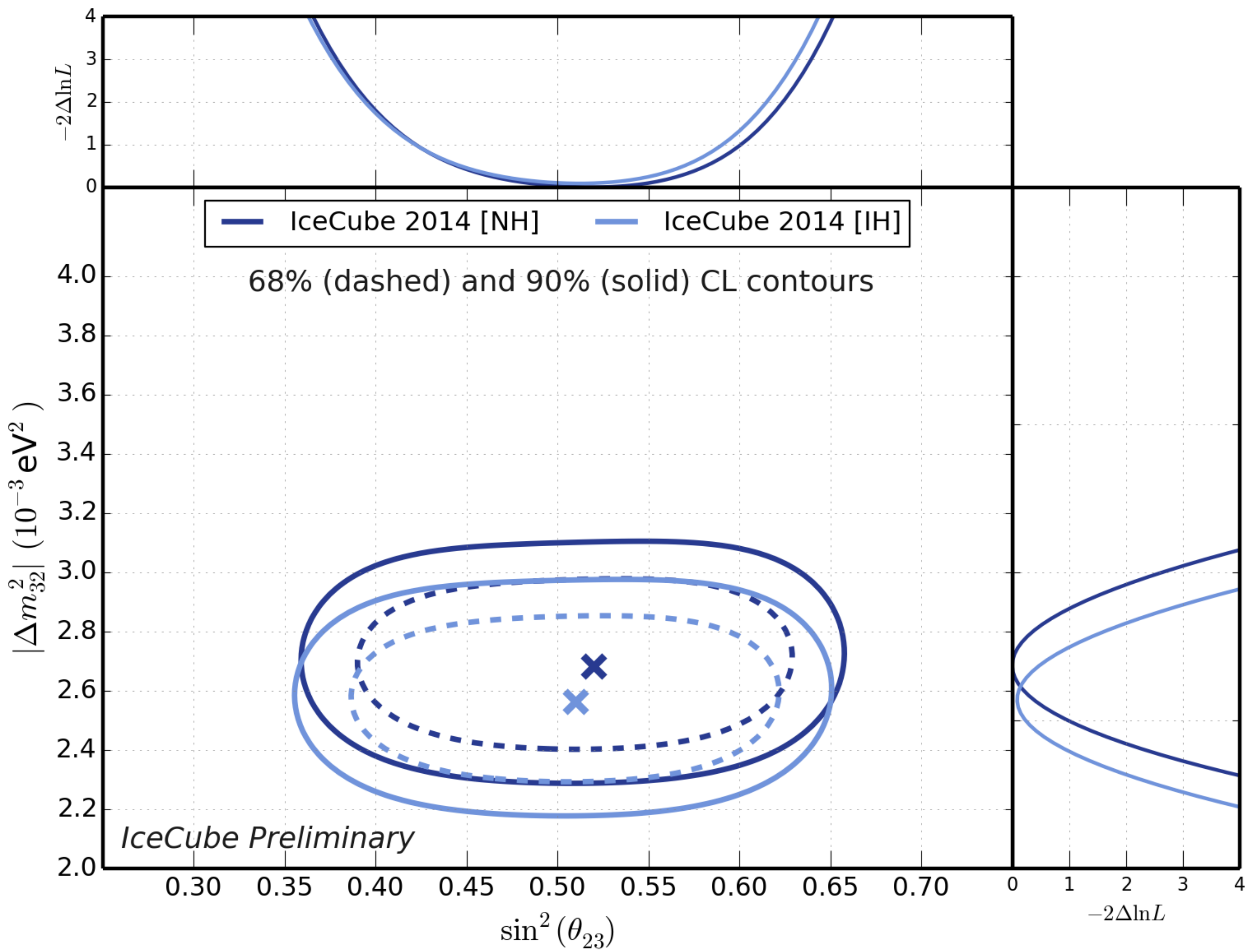
- Projection onto (L/E$_\nu$) for illustration
- Shaded range shows allowed systematics with constraints from current data
    - Systematics-limited; but constraints on systematics are statistics-limited
- Second survival maximum just below DeepCore's energy threshold

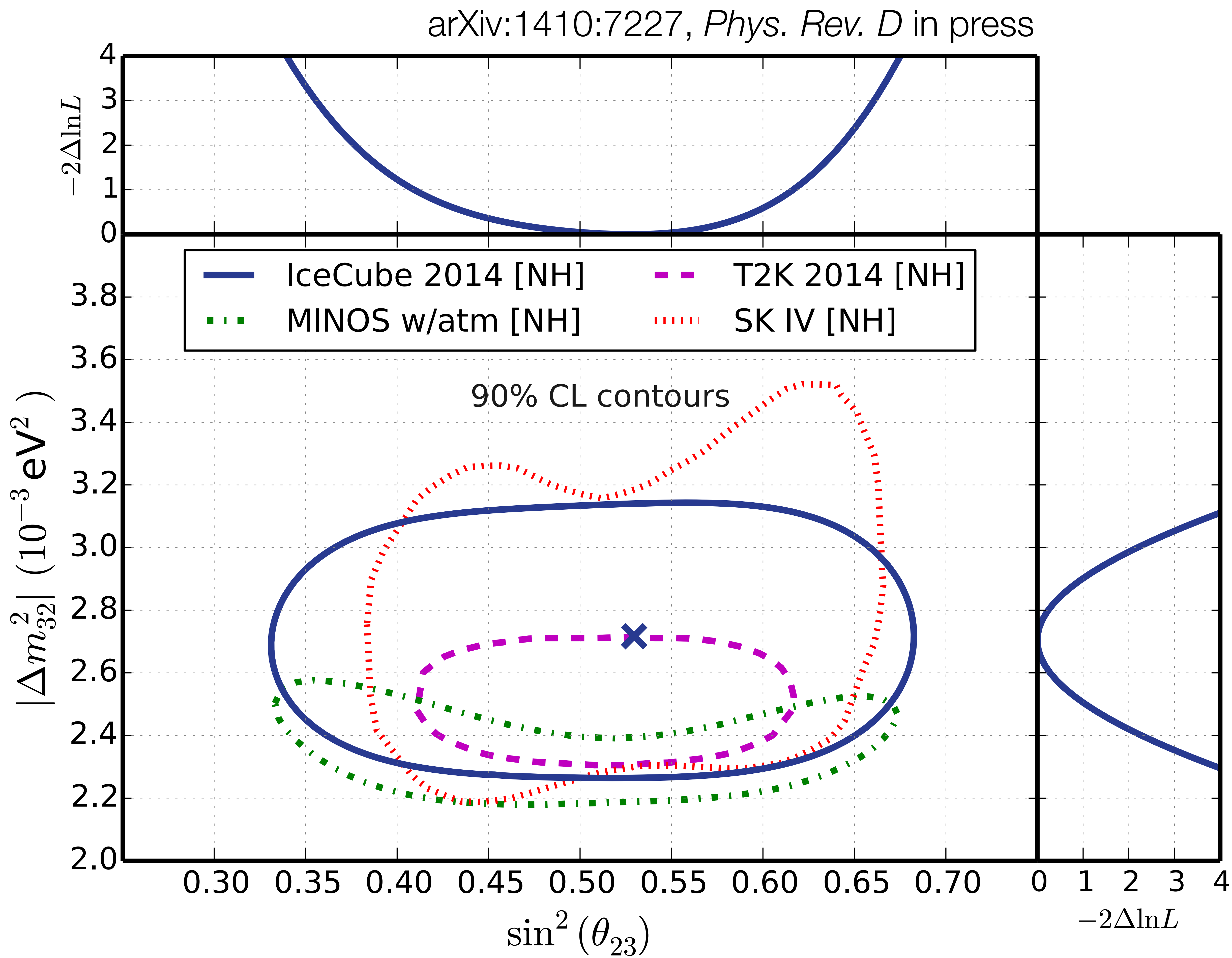
arXiv:1410.7227



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)
  - With IceCube, minimal sensitivity to hierarchy, octant





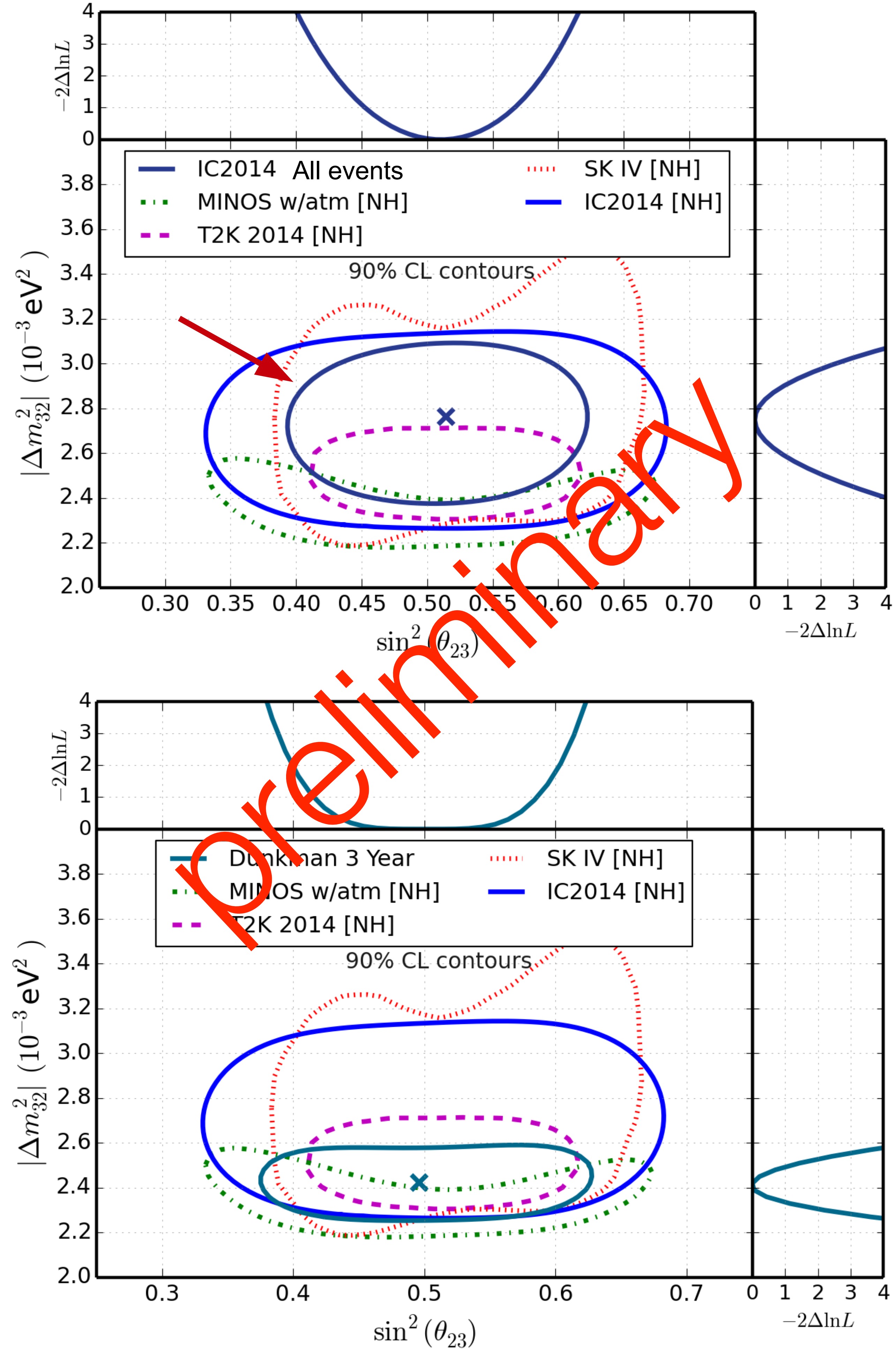
arXiv:1410:7227, Phys. Rev. D in press
IceCube 2014 [NH]
T2K 2014 [NH]
MINOS w/atm [NH]
SK IV [NH]
90% CL contours
$-2\Delta\ln L$
$|\Delta m^2_{32}|$ $(10^{-3}\,\mathrm{eV}^2)$
$\sin^2(\theta_{23})$
$-2\Delta\ln L$

Coming Attractions

- Current PRD analysis: 1,500 events per year (all flavors)
  - O(1%) atmospheric muon background
  - Targeted high quality events, well-reconstructed with simple low-energy algorithm
- Extension of PRD analysis: 5,000 events per year (all flavors)
  - Include events with poorer resolution – don't help map oscillation dip, but provide additional statistics for constraining systematics
- Parallel analysis: 20,000 neutrinos per year
  - New, very computationally intensive maximum-likelihood reconstruction
  - Full-sky analysis for better handle on systematics
  - Larger atmospheric muon background: ~8% upgoing (misreconstructed), ~35% downgoing (evaded veto)

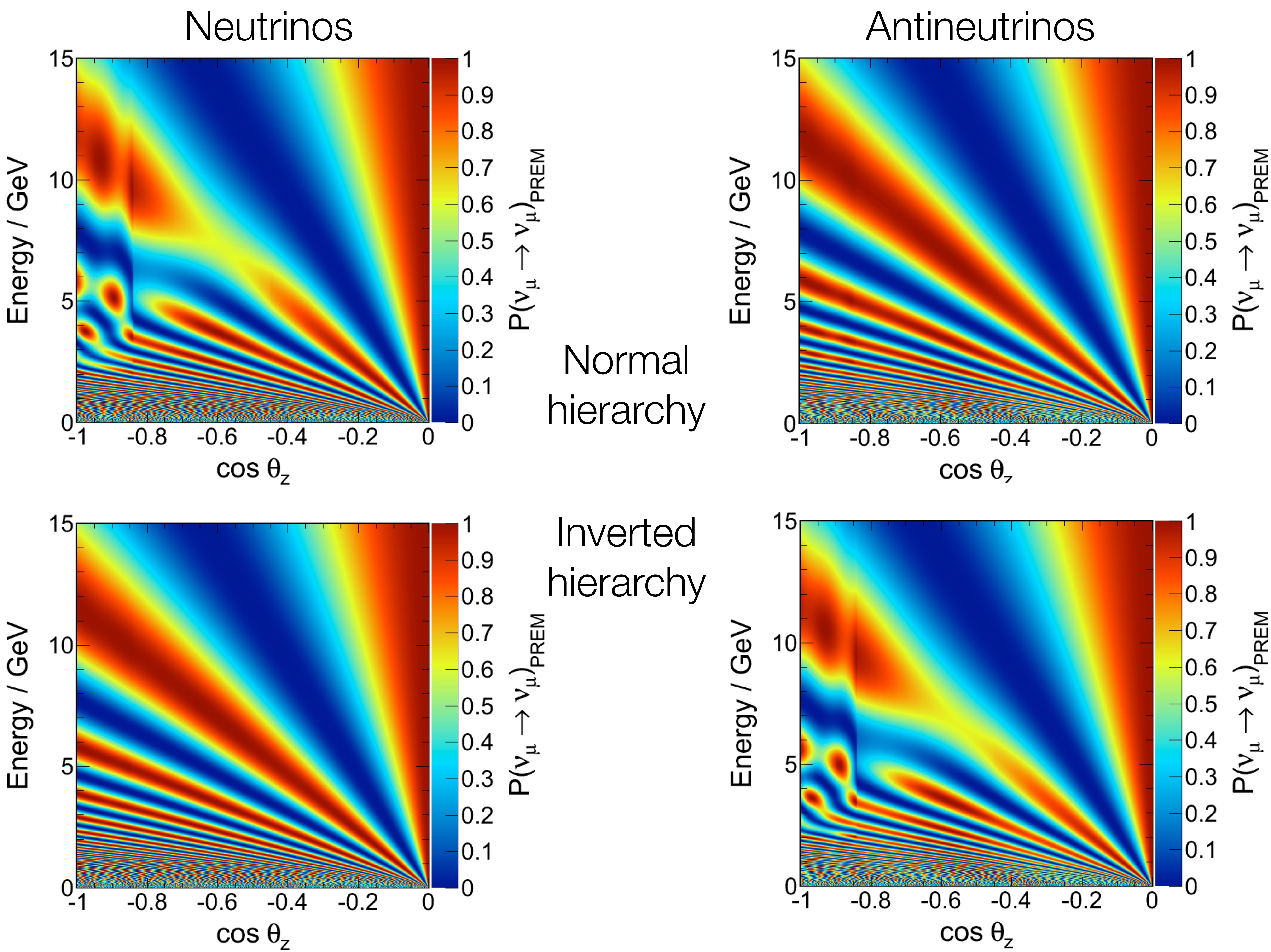
Preliminary Monte Carlo Sensitivities

- Extension: retains high neutrino purity while improving constraints
  - Improvements primarily in measurement of $\sin^2(\theta_{23})$
- Parallel analysis: improved reconstruction and statistics while allowing higher background levels
  - Improvements mainly to measurement of Δm^2_{atm}
- Need to combine these approaches into a single measurement



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

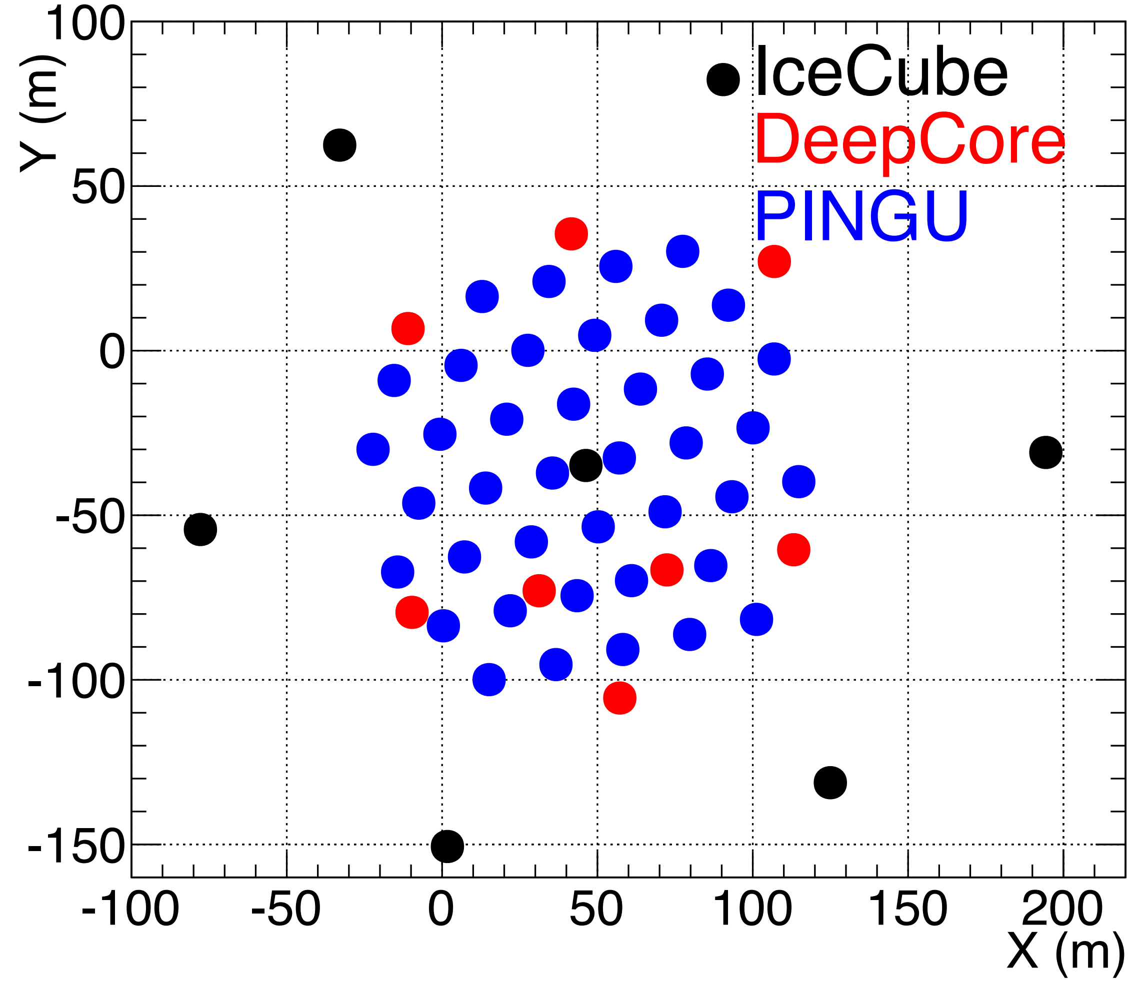

Neutrinos
Antineutrinos
Normal hierarchy
Inverted hierarchy
Energy / GeV
cos θz
P(νμ → νμ)PREM
15
10
5
0
-1
-0.8
-0.6
-0.4
-0.2
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

PINGU

Precision IceCube Next Generation Upgrade

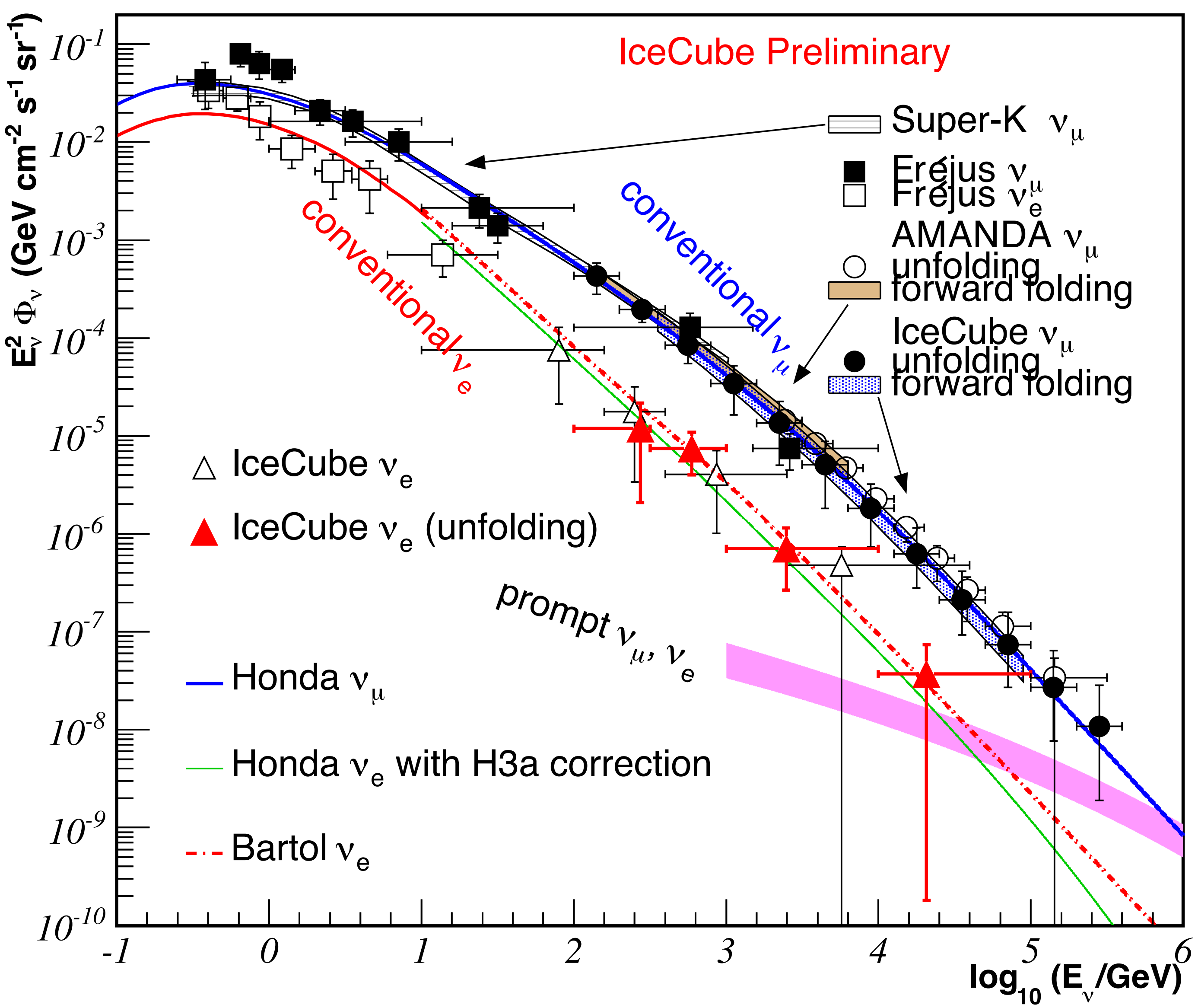
- Baseline detector consists of 40 additional strings of 60 Digital Optical Modules each, deployed inside the DeepCore volume
  - Geometry optimization underway – additional DOMs have relatively low incremental cost – final proposal likely 80-96 DOMs/string
  - 20-22 m string spacing (cf. 125 m for IceCube, 72 m for DeepCore)
  - ~25x higher photocathode density
  - Additional in situ calibration devices will better control detector systematics (not included in projected performance)
- Engineering issues and cost of deploying instrumentation are well understood from IceCube experience
  - Can install ≥20 strings per season once underway

Top view of the PINGU new candidate detector



Atmospheric Neutrinos in PINGU

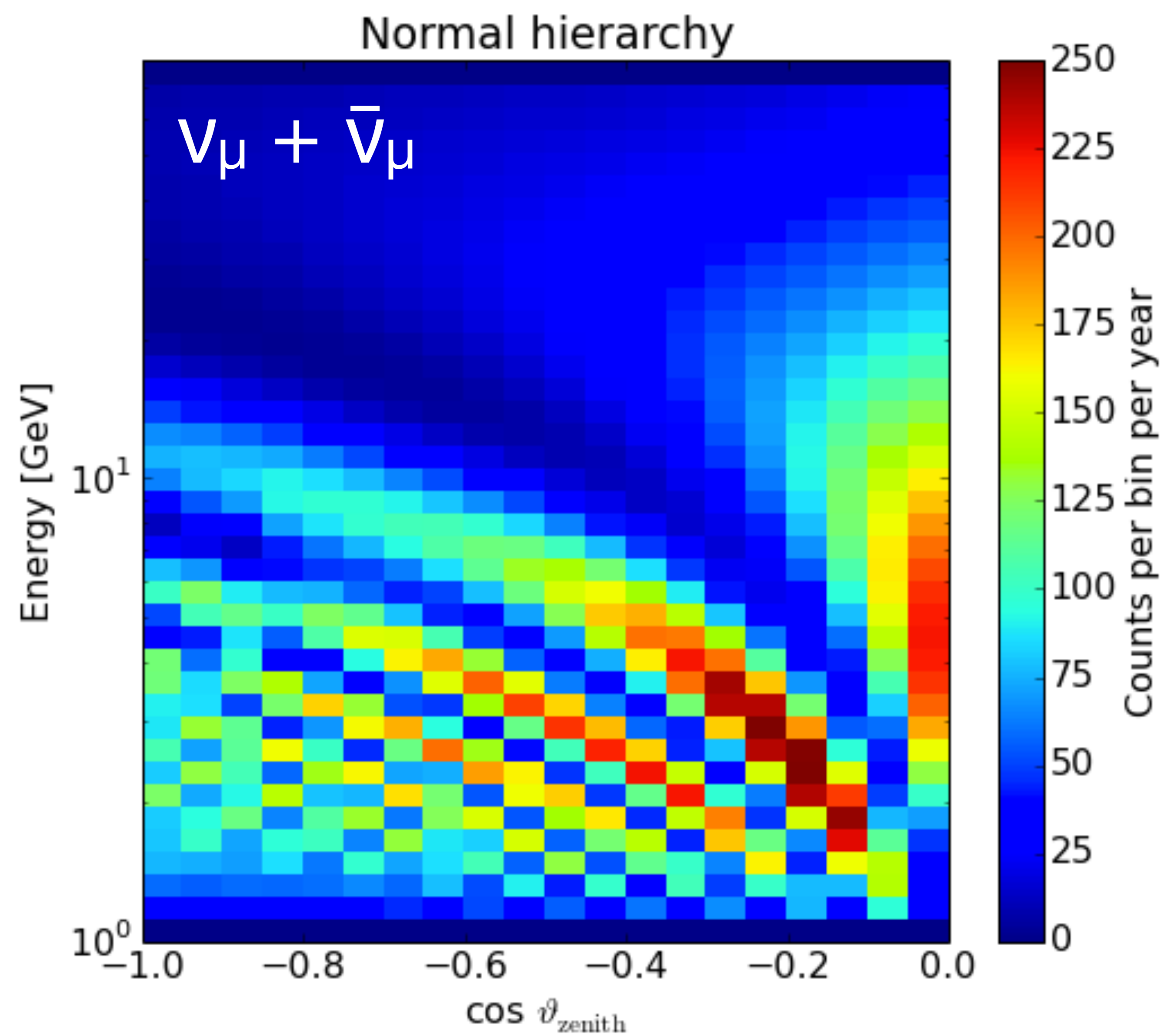
- Broad range of neutrino energies above a threshold of a few GeV



Contained events/yr	Trigger	Analysis
ν_e CC	52k	38k
ν_μ CC	86k	50k
ν_τ CC	6.4k	2.6k
ν_x NC	17k	7.9k

Signature of the Neutrino Mass Hierarchy

- Matter effects alter oscillation probabilities for neutrinos or antineutrinos traversing the Earth
  - Neutrino oscillation probabilities affected if hierarchy is normal, antineutrinos if inverted
  - Maximal effects at specific E_ν and baselines (= zenith angles) due to the Earth's density profile
  - Rates of all flavors are affected
  - Note: effect of detector resolution not shown here
- Distinct signatures observable in both tracks (ν_μ CC) and cascades (ν_e and ν_τ CC, ν_x NC)



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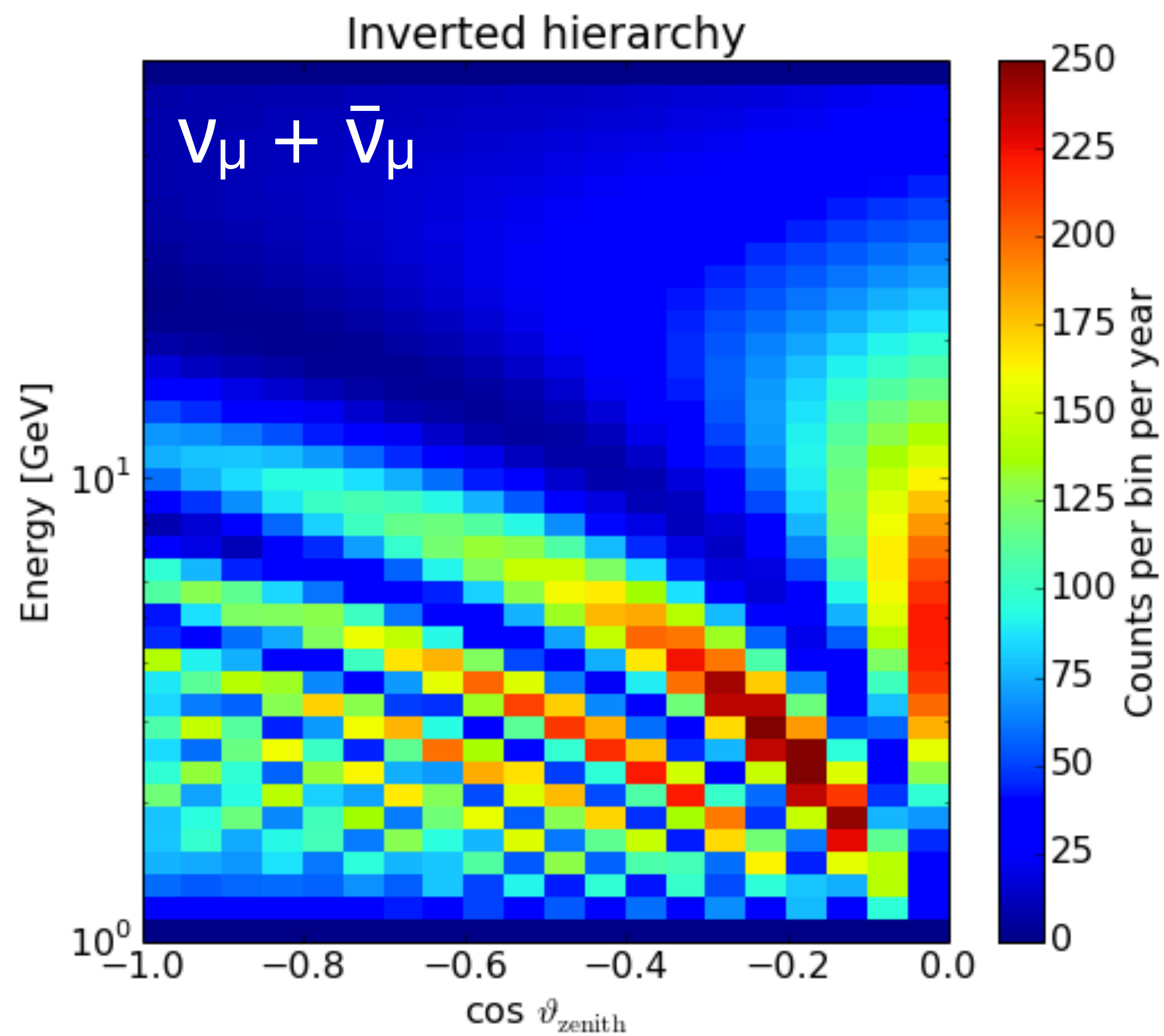

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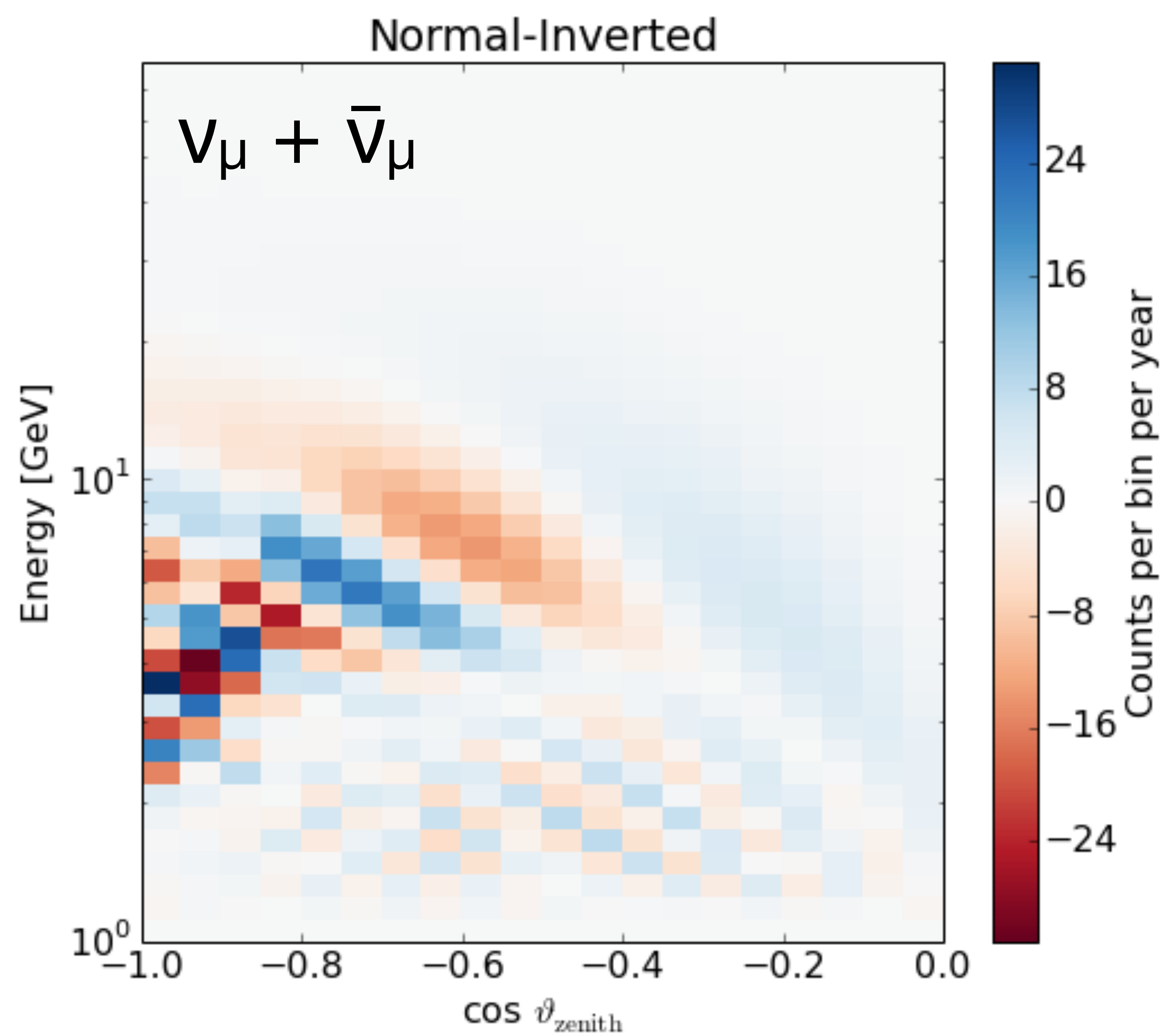

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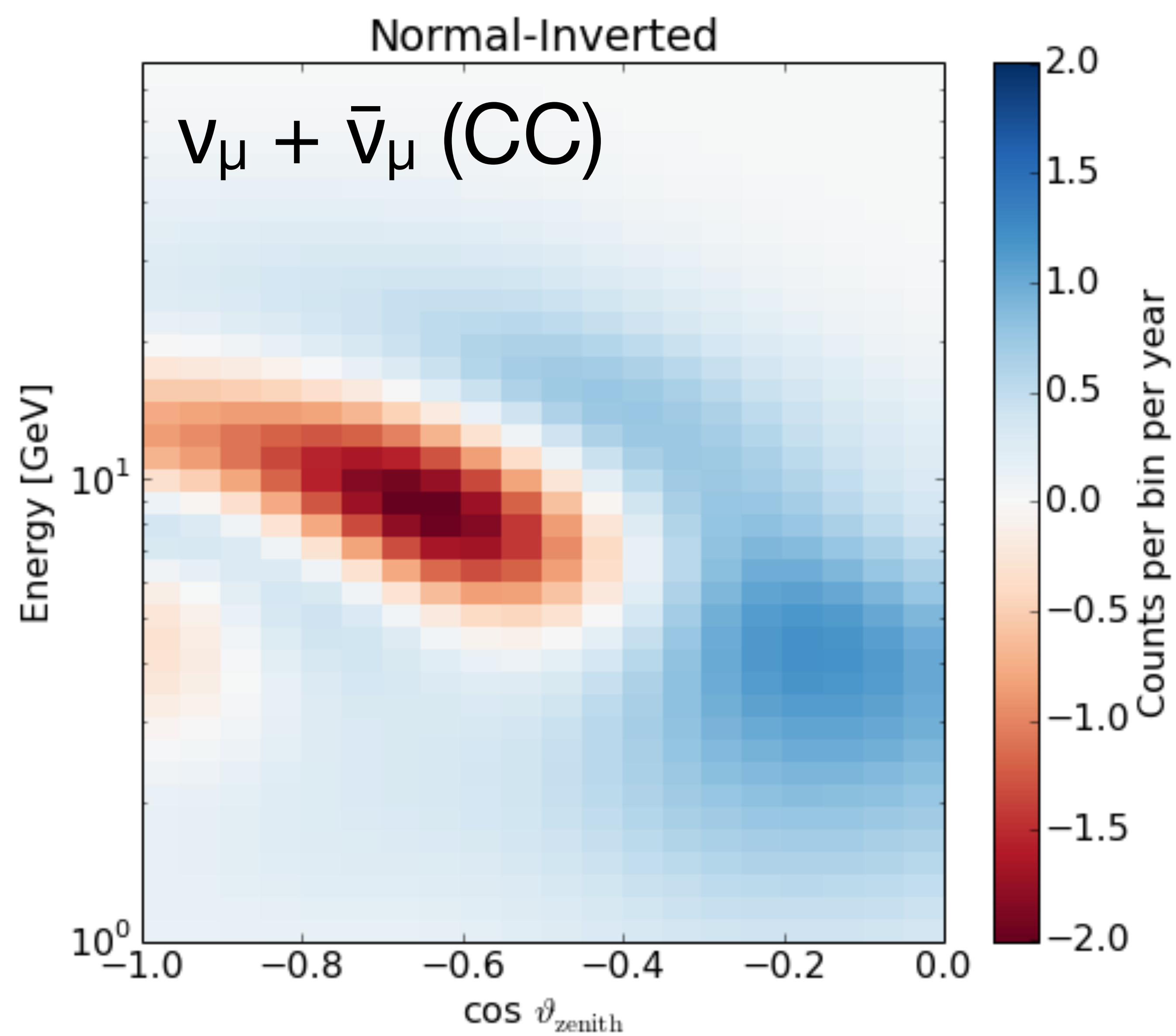
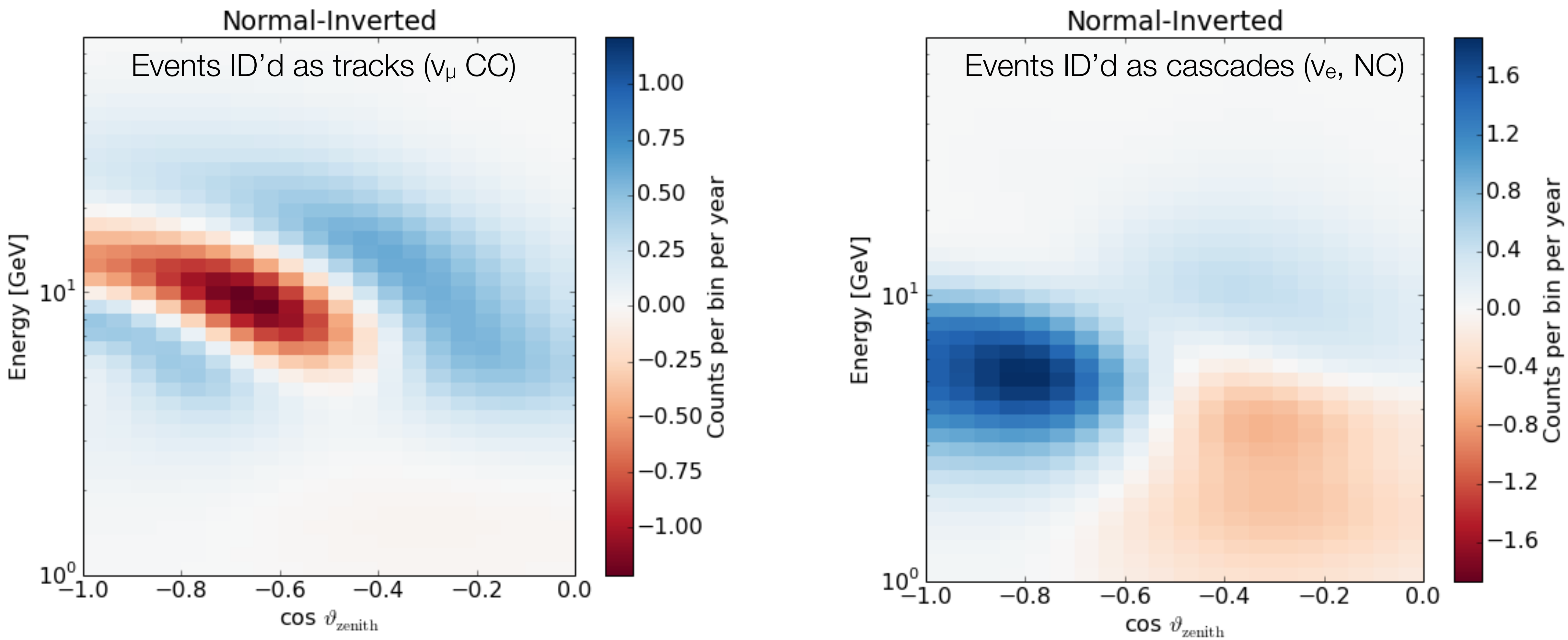


- Distinct signatures observable in both tracks (ν_μ CC) and cascades (ν_e and ν_τ CC, ν_x NC)

Hierarchy Signature



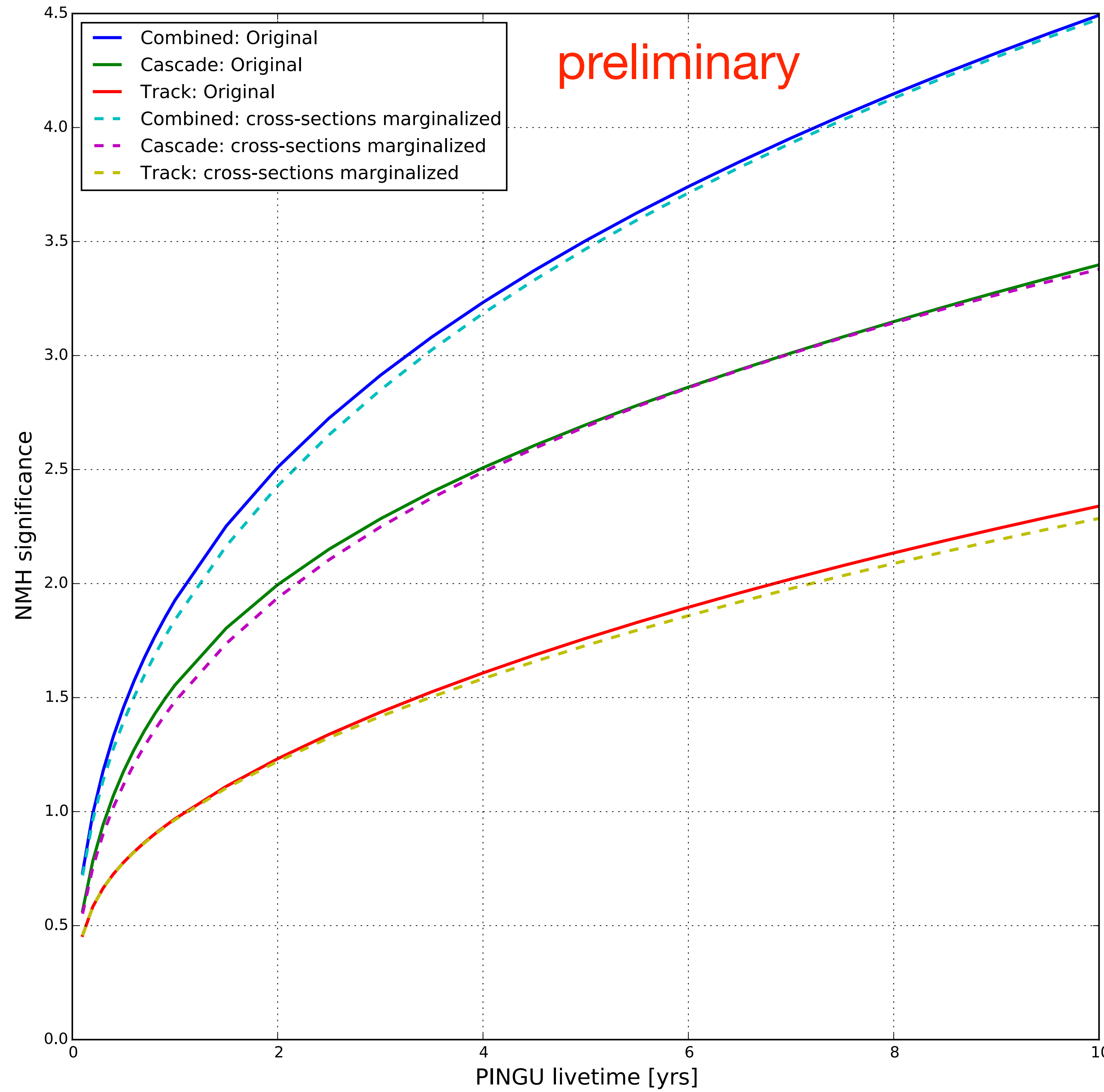
- With full detector response included, distinctive (and quite different) hierarchy-dependent signatures are still visible in both the track and cascade channels
  - Particle ID based on tagging ν_μ CC tracks – 90% purity above ~10 GeV
  - Lack of low-energy tracks due to decreasing ability to distinguish track from vertex cascade at lower energies

Analysis Improvements Underway

- Increased #DOMs/string to match baseline Gen2 High Energy design (marginal cost of DOMs is relatively small)
- Inclusion of additional detector-related effects on event reconstruction – appears minimal
  - Uncertainties in optical properties of South Pole ice (e.g. anisotropic scattering)
  - Injecting DOM-by-DOM calibration errors for sensitivity to Cherenkov photons, in addition to possible systematic errors in energy scale calibration (already included)
- Correcting Monte Carlo error in non-Poissonian noise levels in simulated PINGU DOMs
- Treatment of ν-N interaction uncertainties via GENIE instead of ad hoc scaling
- Detailed modeling of atmospheric flux uncertainties (per Barr et al. astro-ph/0611266) rather than simpler scaling of flux level and spectral index
- Validating treatment of atmospheric muon background
- Incorporating full suite of systematic uncertainties into likelihood-based significance estimates from ensemble of pseudo-data sets
- Updating priors on new and existing uncertainties

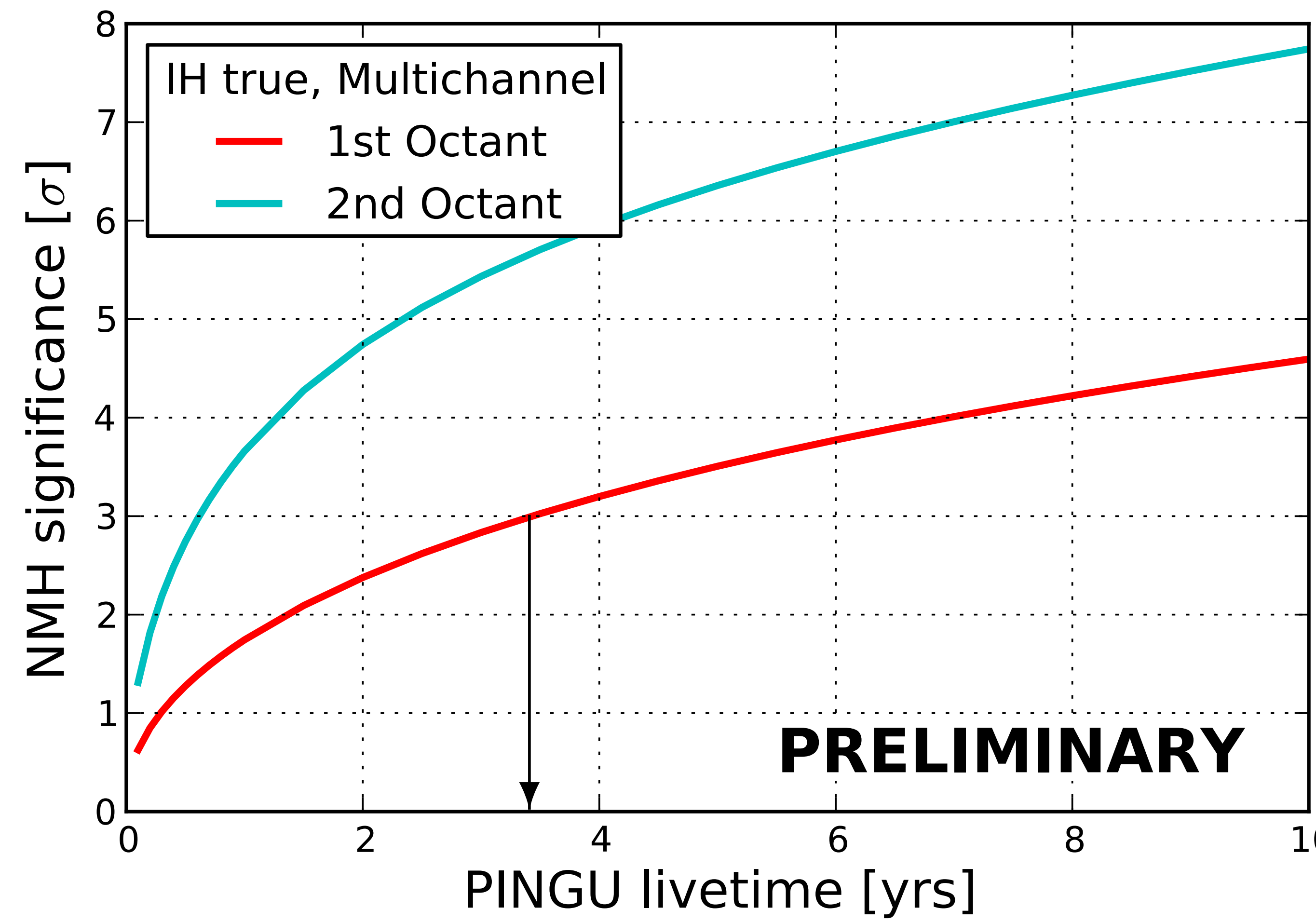
Neutrino Interaction Uncertainties

- Biggest effects so far: uncertainties in Bodek-Yang higher twist parameters, axial mass term for hadron resonance production
  - Ad hoc scalings still included, and covariance not accounted for – likely over-counting…
- Small additional effect compared to existing systematics



Other Oscillation Parameters

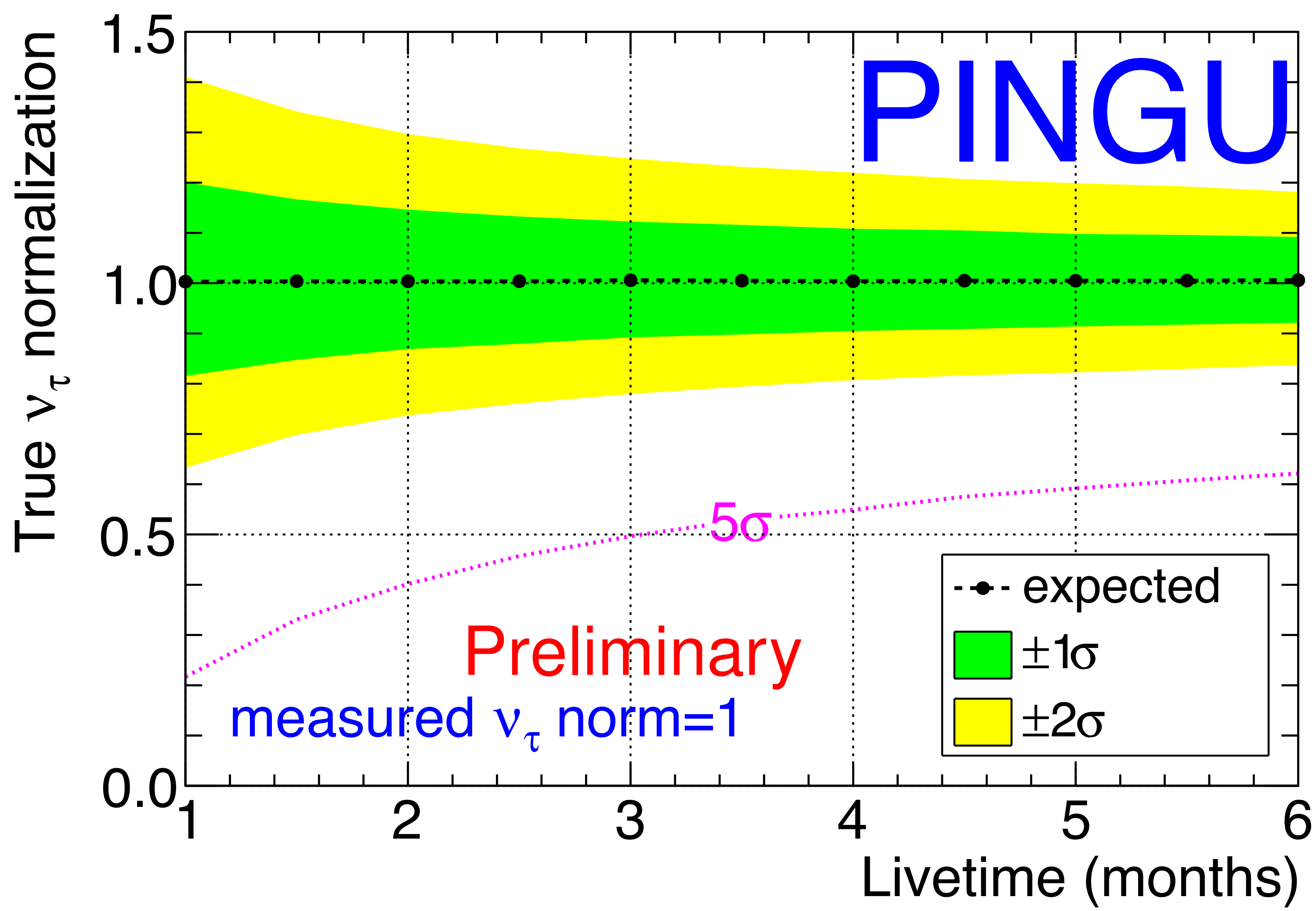
- PINGU not sensitive to δ_{CP} – complementarity with NOvA, T2K
- Sensitivity to the mass ordering strongly dependent on θ_{23} octant
  - Worst-case first octant solution assumed in performance studies
  - Implies considerable ability to measure octant (not yet evaluated explicitly)



- Precision for θ_{23} and Δm^2_{atm} being evaluated, appears comparable to NOvA or T2K 2020 expectations

Tau Neutrino Appearance

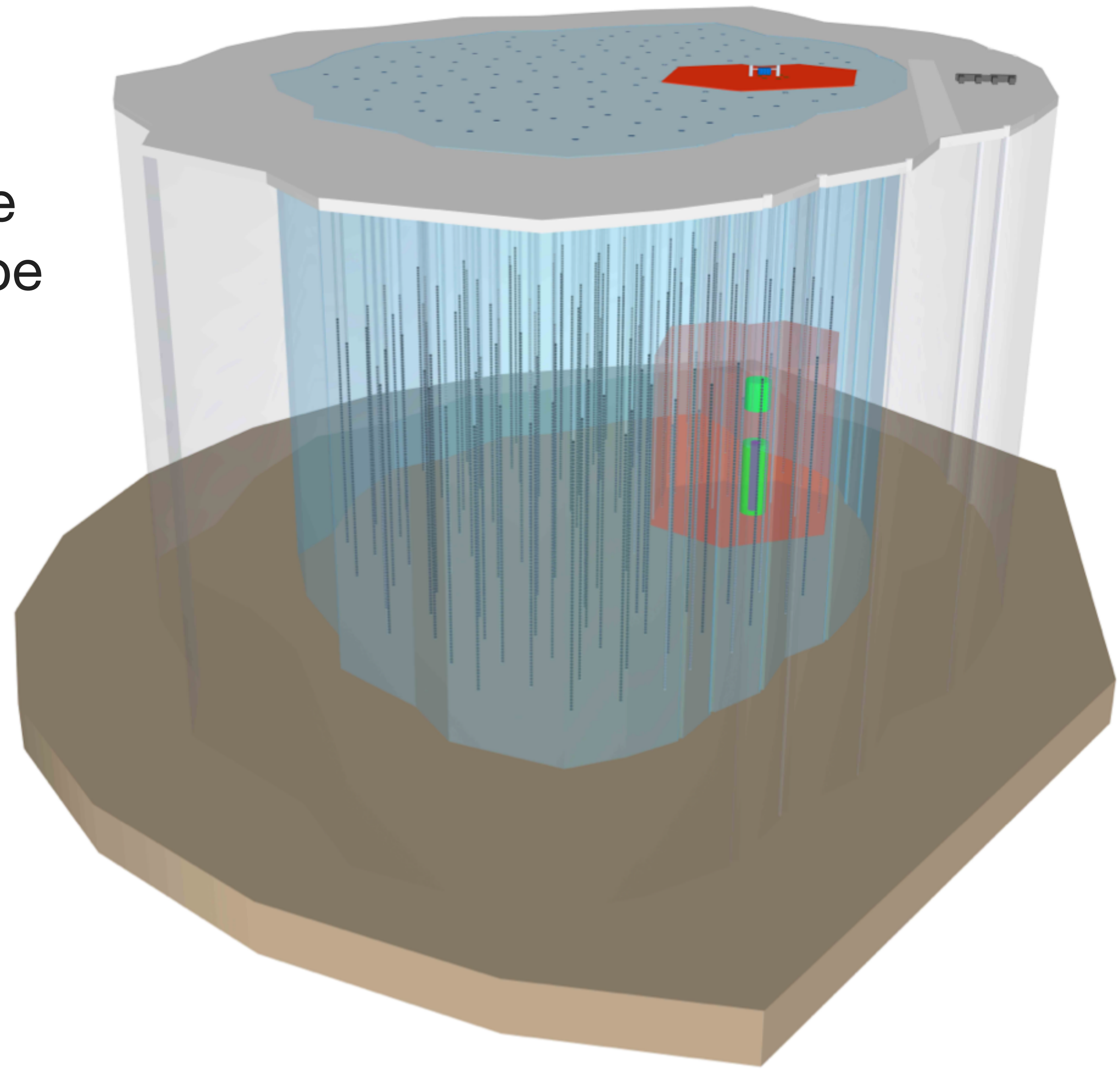
- Energy range of PINGU allows uniquely high tau neutrino rates
  - Measure ν_τ appearance as characteristic distortion of cascade angular/energy distribution



- Interesting test of unitarity of 3x3 neutrino mixing
  - Direct probe of $U_{\tau 3}$
  - 10% precision on ν_τ appearance rate within a year

IceCube-Gen2

- Planning underway for a multipurpose facility leveraging the experience and investment in IceCube
  - White paper describing our vision of this detector at arXiv:1412.5106
- PINGU will be one component of IceCube-Gen2



Cost and Schedule

- Primary US funding source for IceCube-Gen2 would be NSF
  - MREFC-scale facility, total cost comparable to original IceCube
  - Many items common to PINGU and other elements (drill, engineering, etc.)
  - Marginal cost of PINGU within larger IceCube-Gen2 is $88M, with expected non-US contributions of $25M
- Gen2 conceptual design document and PINGU performance update this year
- In a technically limited timeline, PINGU completion possible by January 2021 or 2022

Cost for PINGU Component	
Hardware	$48M
Logistics	$23M
Contingency	$16M
Expected non-US contributions	$25M
Total US Cost	$63M

(elements do not sum to total due to rounding)

Conclusions

- 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 complementarity with other experiments
- PINGU will be a natural part of the IceCube-Gen2 Observatory
  - Closely based on IceCube technology – low technical and cost risk
  - PINGU will use the same hardware as high energy extensions of IceCube – common design gives flexibility to optimize based on progress of the field
- Focus today is on neutrino physics, but also interesting potential in searches for low mass dark matter and other exotica