Atmospheric Neutrinos
with IceCube DeepCore and PINGU

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Neutrinos: Recent Developments and Future Challenges
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The IceCube–PINGU Collaboration

International Funding Agencies

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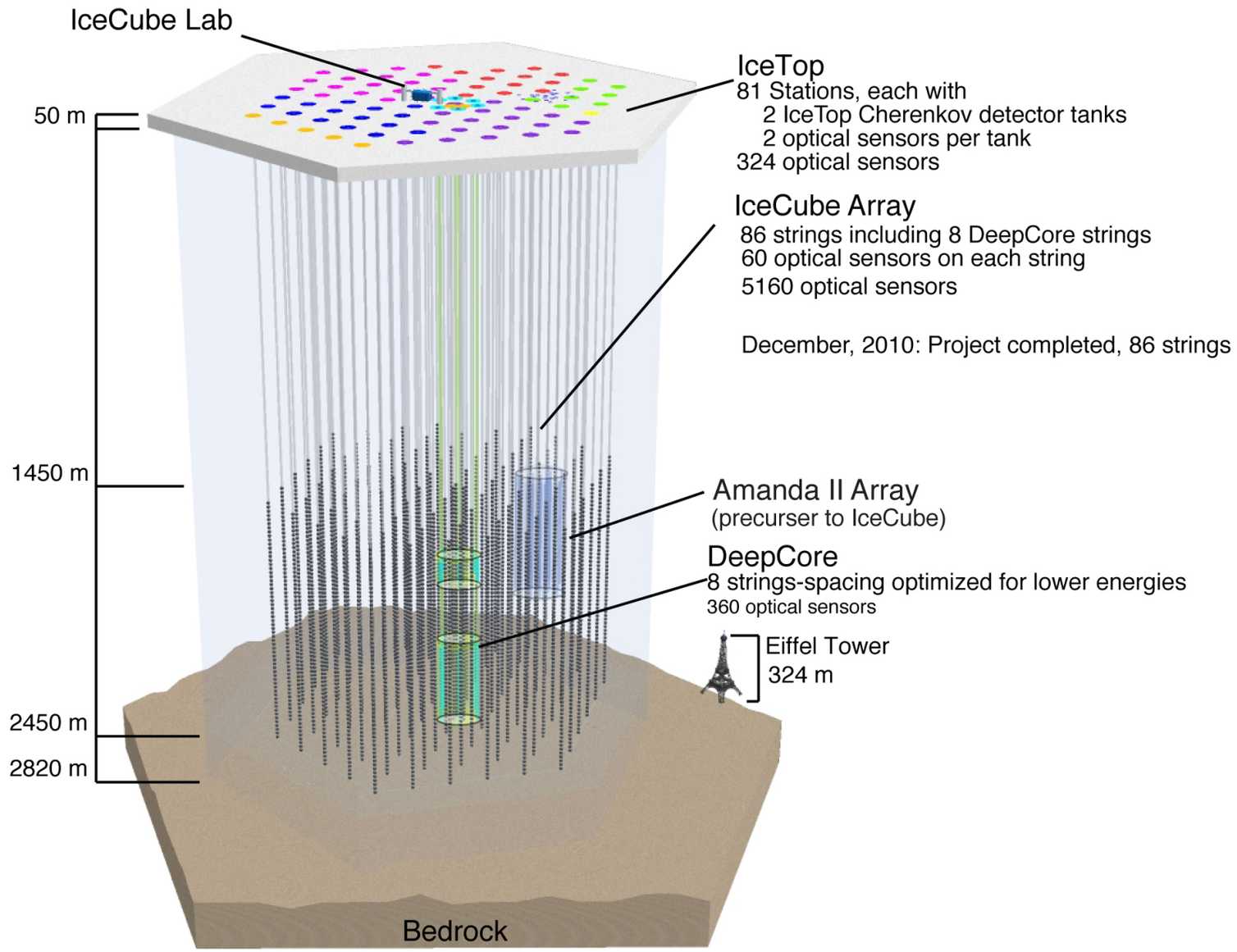
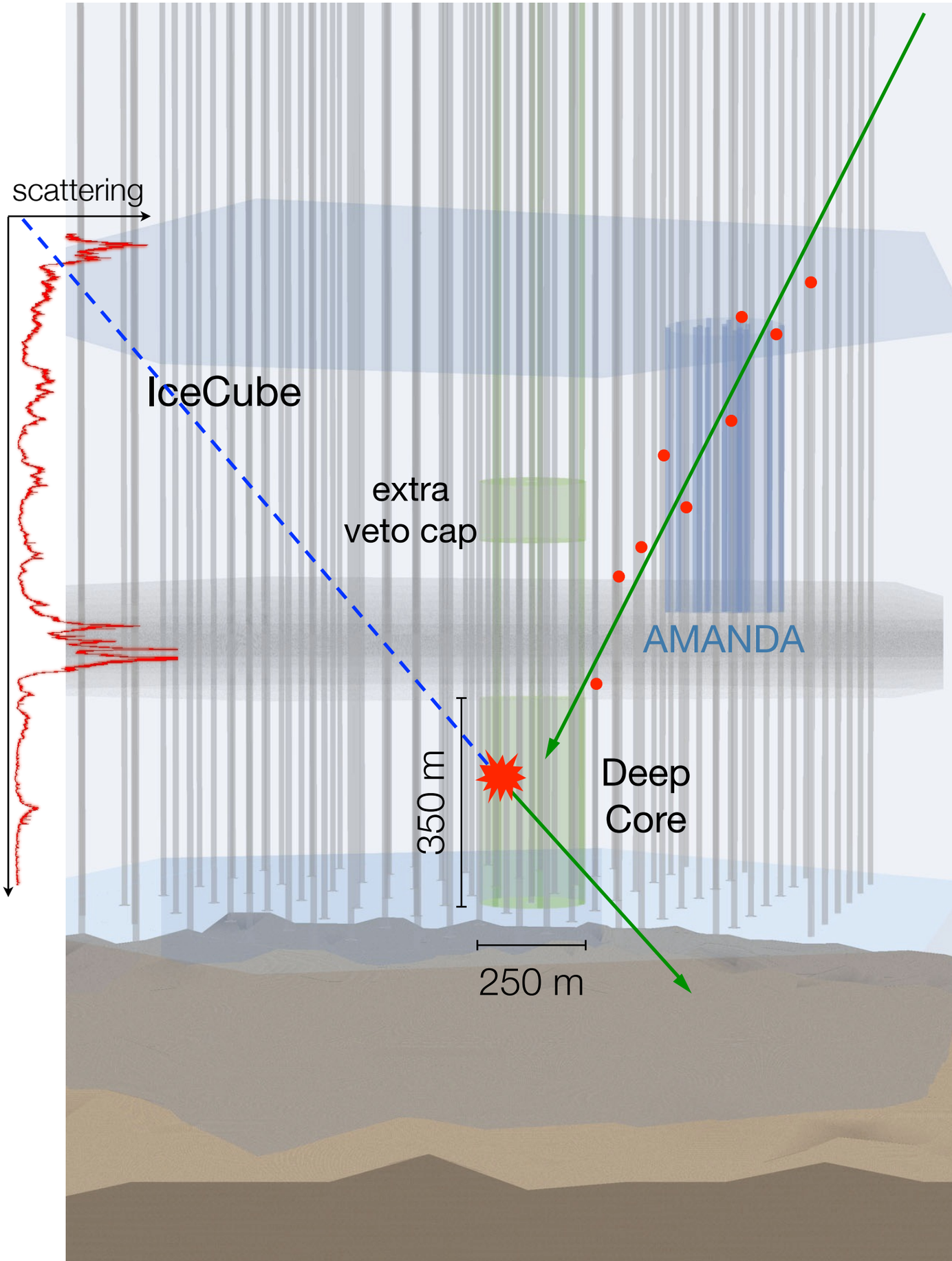
The IceCube Neutrino Observatory

- IceCube focuses on neutrinos with energies above a few hundred GeV
  - 1 km^3 of Antarctic ice as neutrino target and Cherenkov medium
  - 86 strings of 60 DOMs
- DeepCore provides increased sensitivity to neutrinos at energies of 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

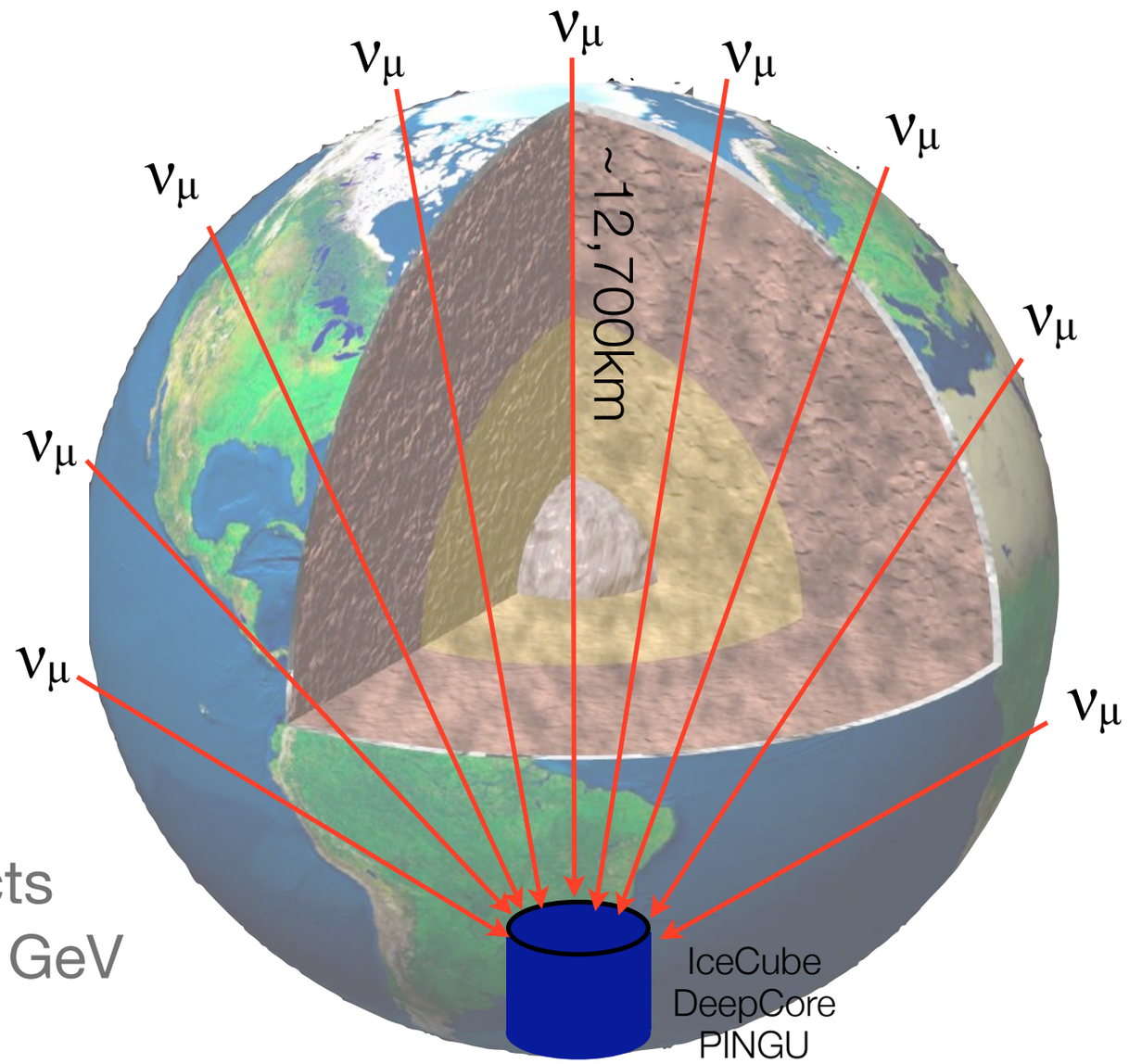


DeepCore Physics

- 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.* C74, 2938 (2014)
- Measurement of atmospheric electron neutrino spectrum
  - First measurement above 50 GeV: *Phys. Rev. Lett*. 110, 151105 (2013)
- Measurements 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

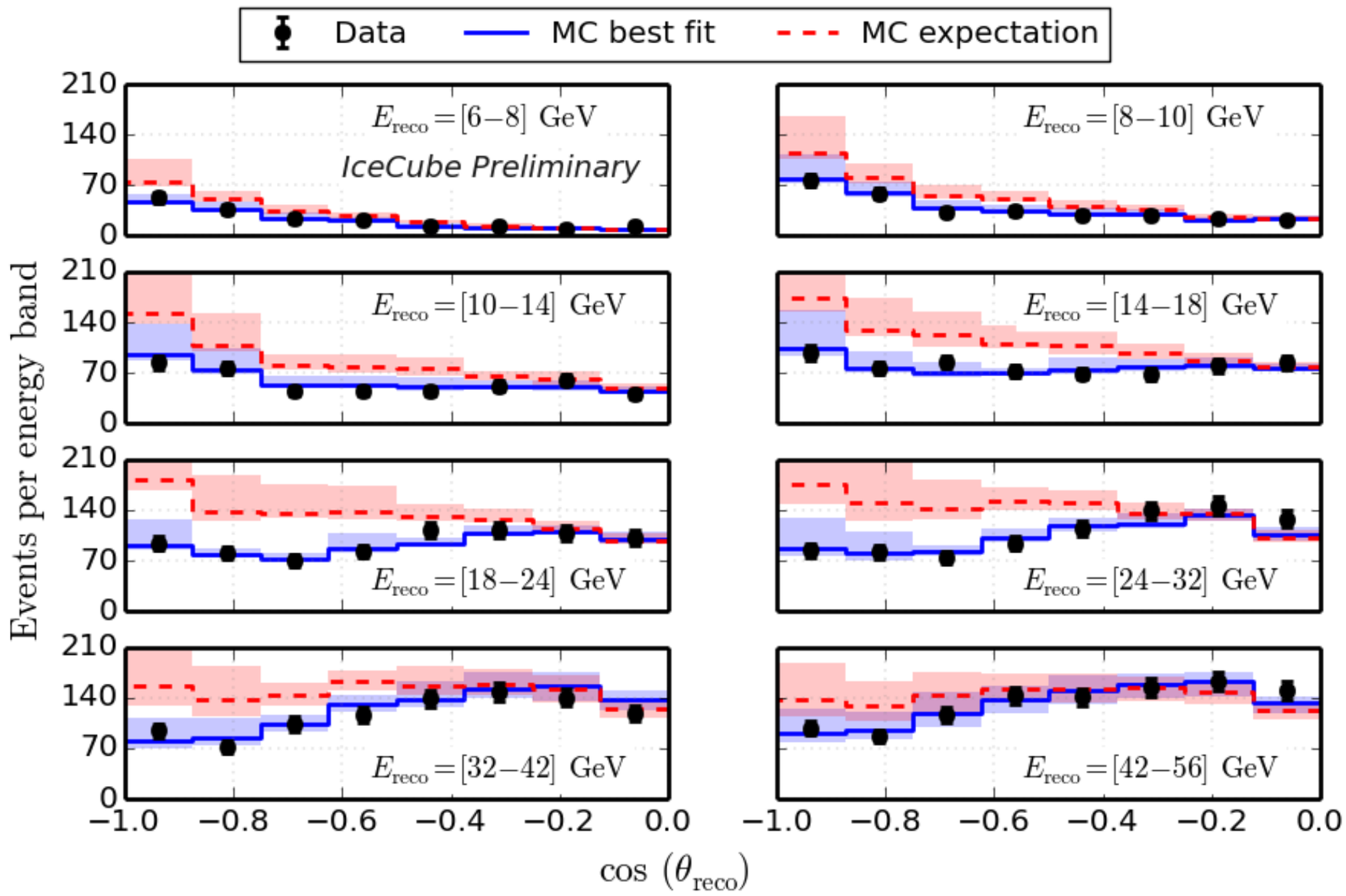
Oscillation Physics with Atmospheric Neutrinos

- 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 $\bar{\nu}$ (MSW etc.) below 10-20 GeV



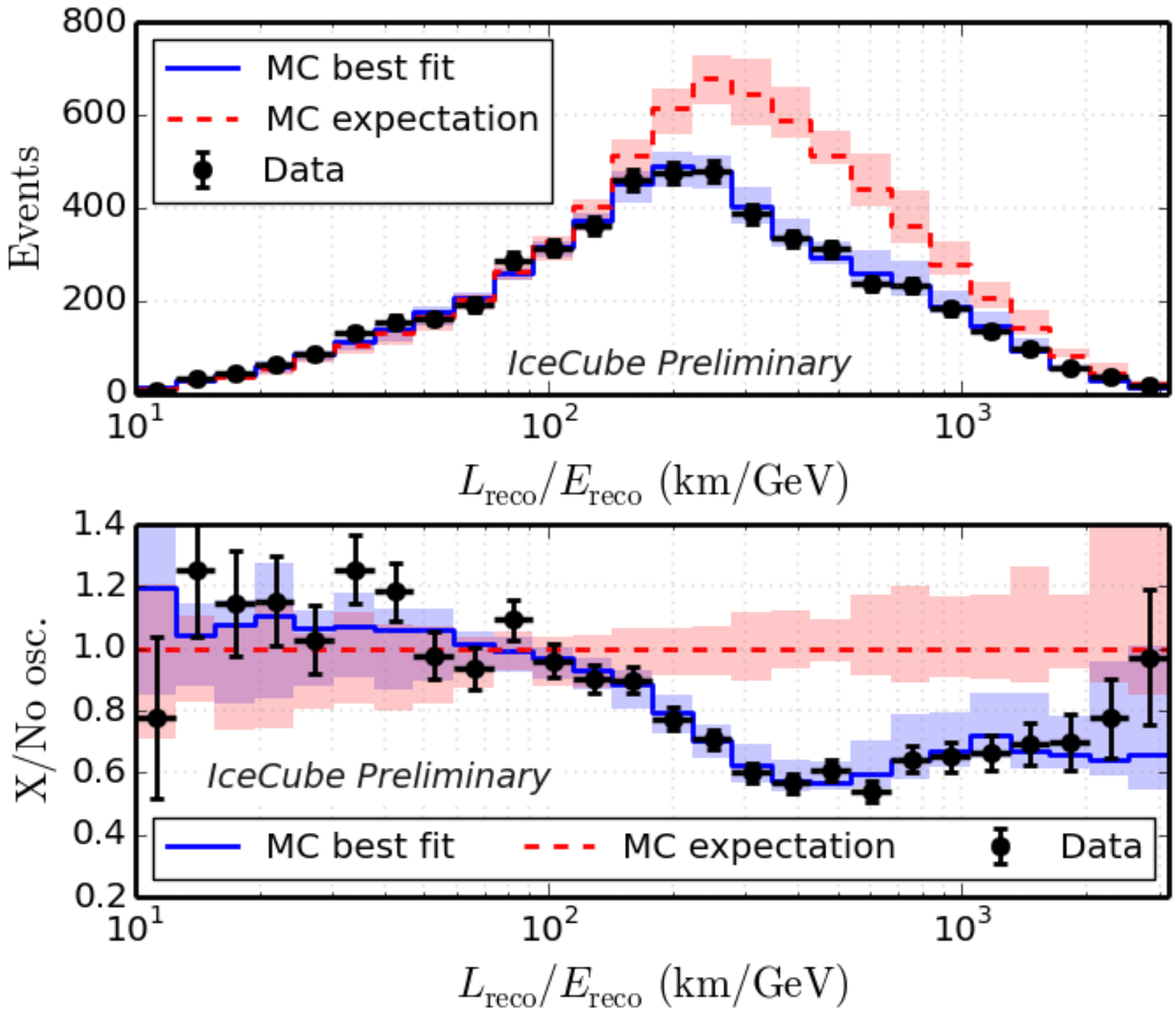
Atmospheric Oscillations – 2nd Generation

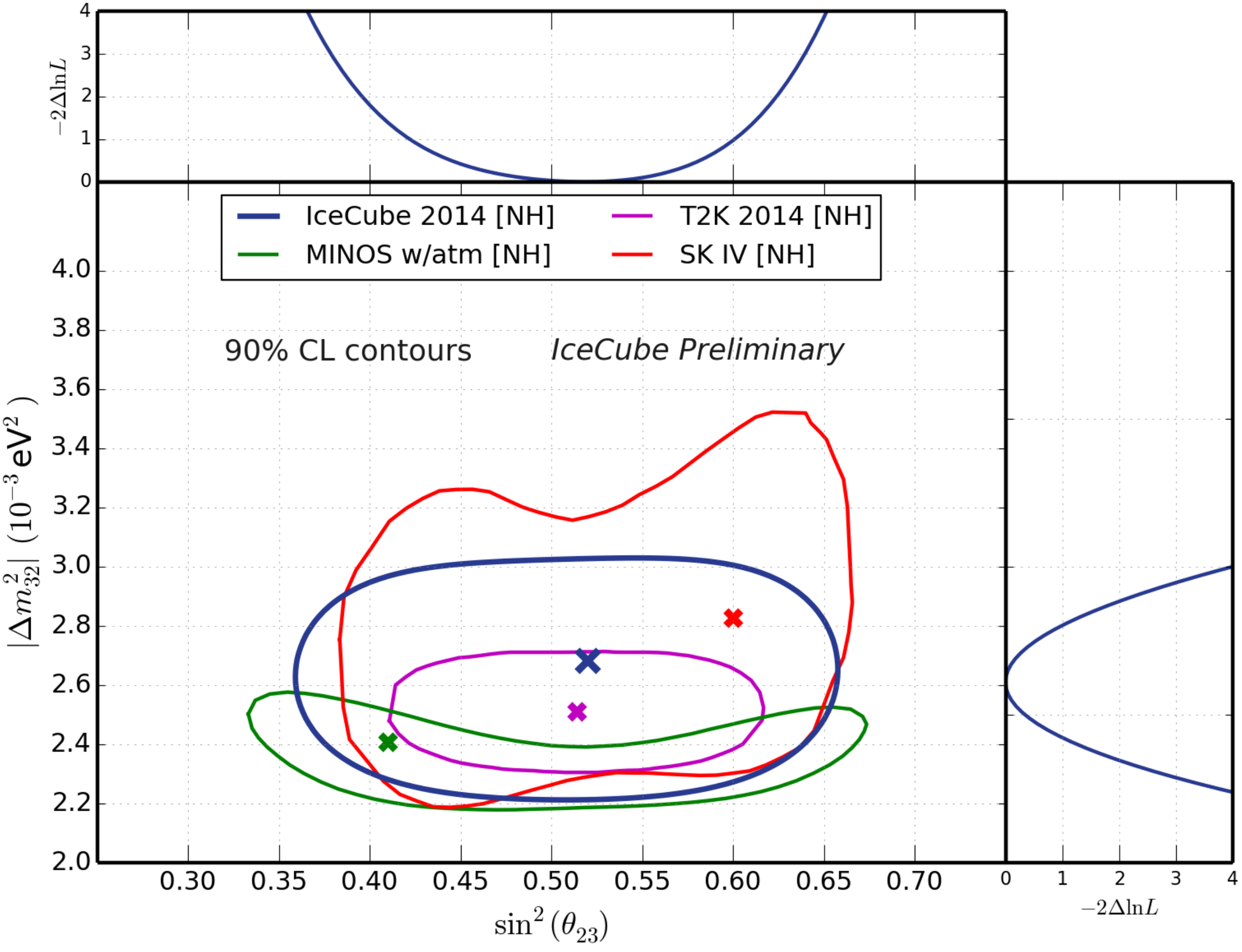
- Three years with improved event selection: 2,500 events per year
- New, specialized low energy event reconstructions, enabling use of multiple energy bins in oscillation energy range
  - Permits tighter constraints on systematics from the data



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 2014 [NH]
T2K 2014 [NH]
MINOS w/atm [NH]
SK IV [NH]
90% CL contours
IceCube Preliminary
$-2\Delta\ln L$
$|\Delta m^2_{32}|$ $(10^{-3}\,\mathrm{eV}^2)$
$\sin^2(\theta_{23})$
$-2\Delta\ln L$

Beyond IceCube

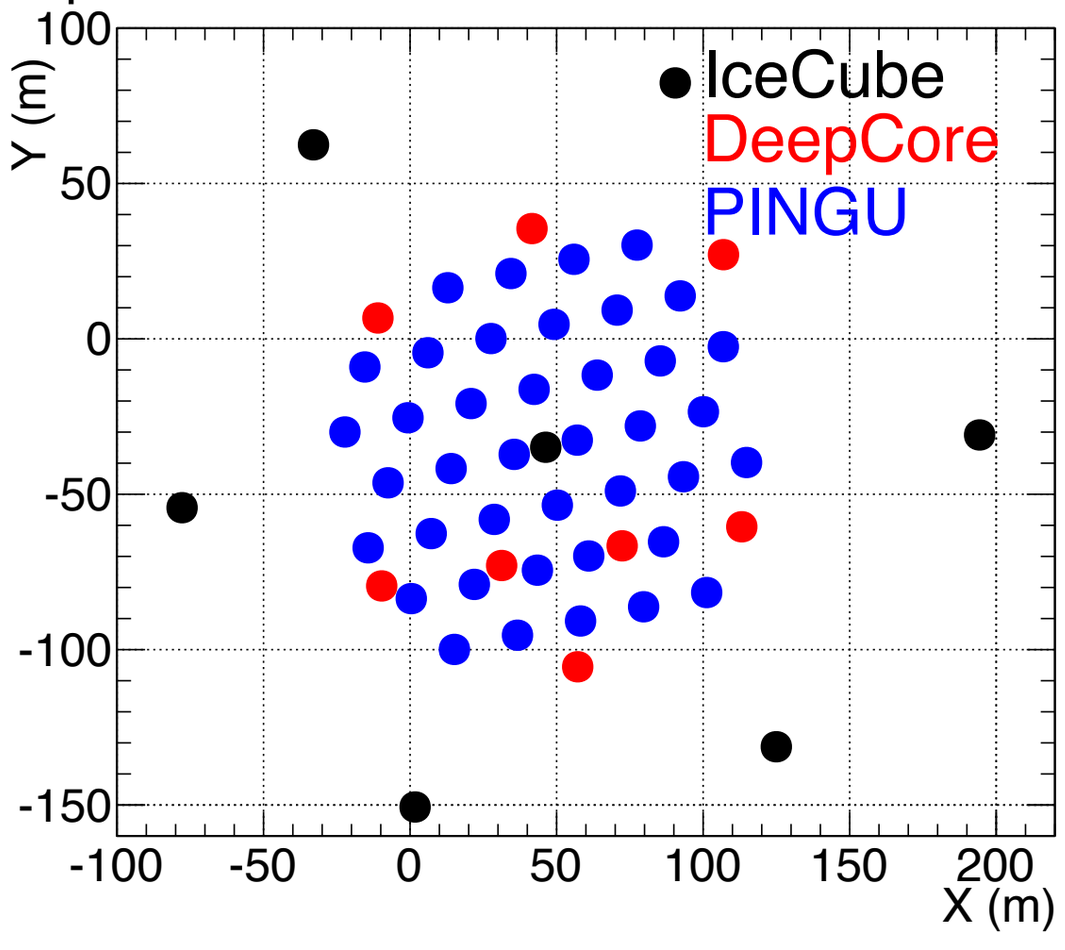
- With its DeepCore extension, IceCube has interesting results in indirect dark matter searches, neutrino oscillation measurements
  - Primary limitation is energy threshold: second oscillation maximum, hierarchy-dependent matter effects, low-mass dark matter just out of reach
- Further augmentation 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 $\ll \lambda_{scatt}$
  - Opportunity to install prototypes for novel types of instrumentation

PINGU

PRECISION ICECUBE NEXT GENERATION UPGRADE

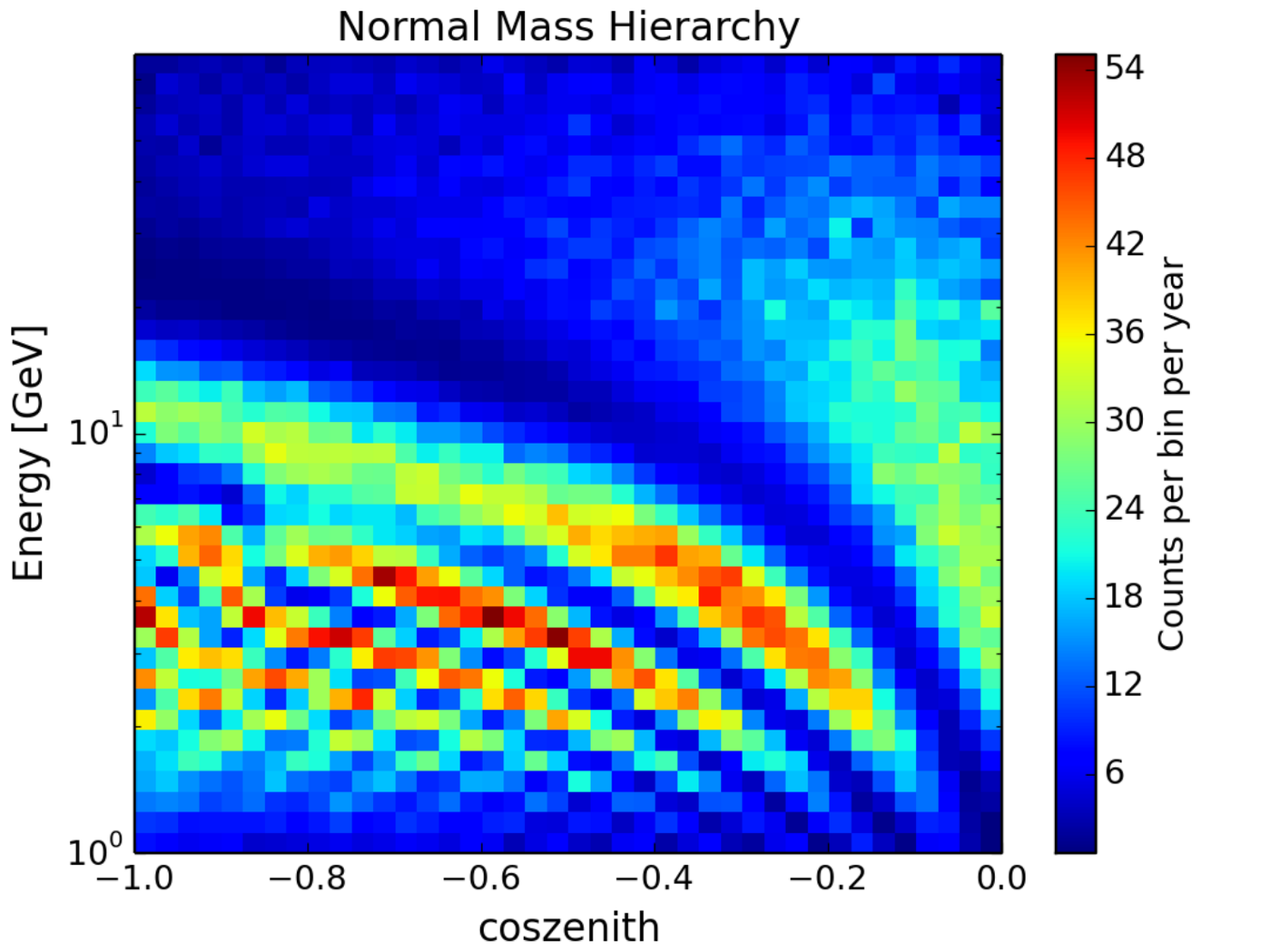
- Baseline detector consists of 40 additional strings of 60 Digital Optical Modules each, deployed in the DeepCore volume
  - Geometry optimization underway – additional DOMs have relatively low incremental cost – final proposal likely 80-96 DOMs/string
  - 20 m string spacing (cf. 125 m for IceCube, 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



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
    - Note: effect of detector resolution not shown here
- 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



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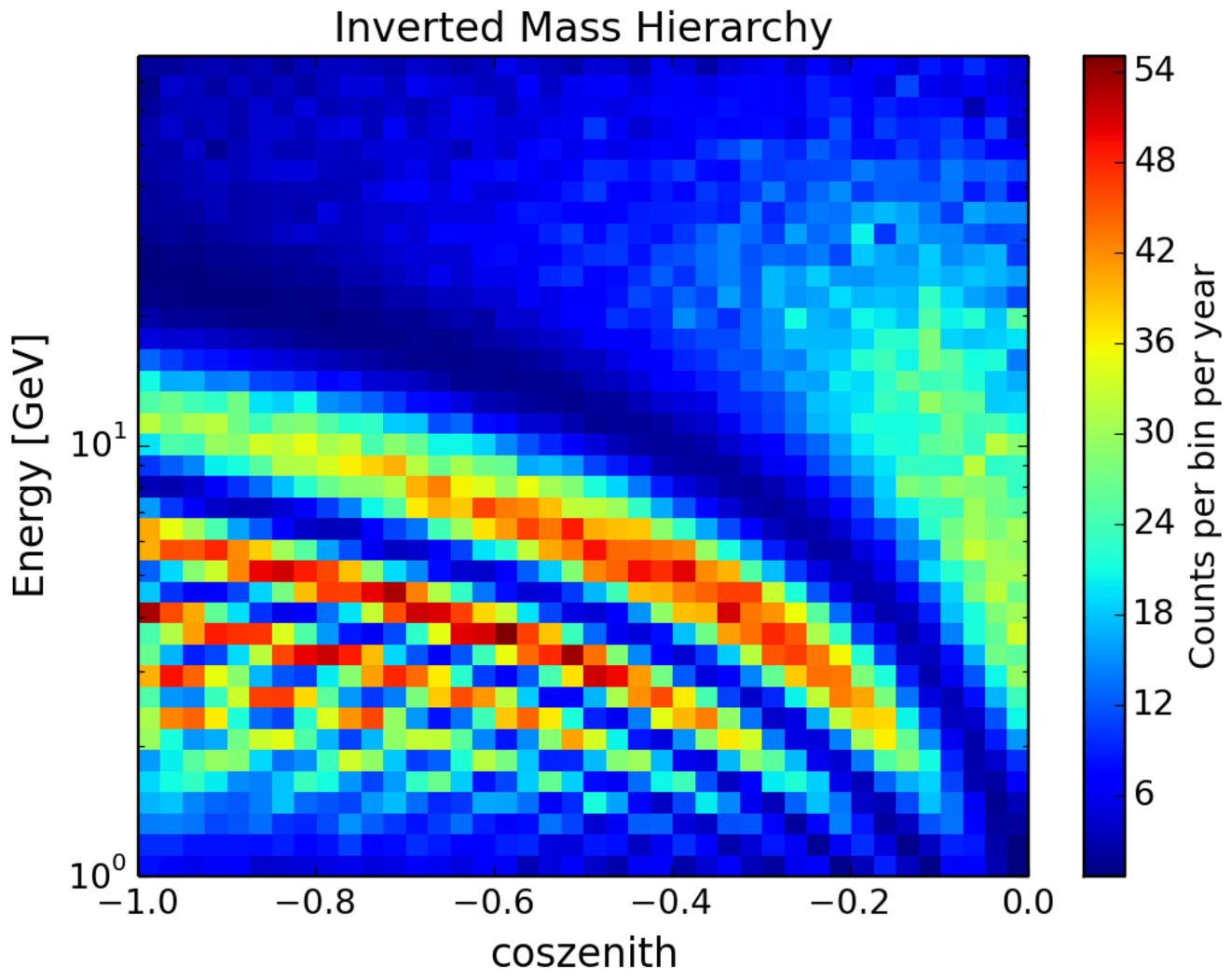
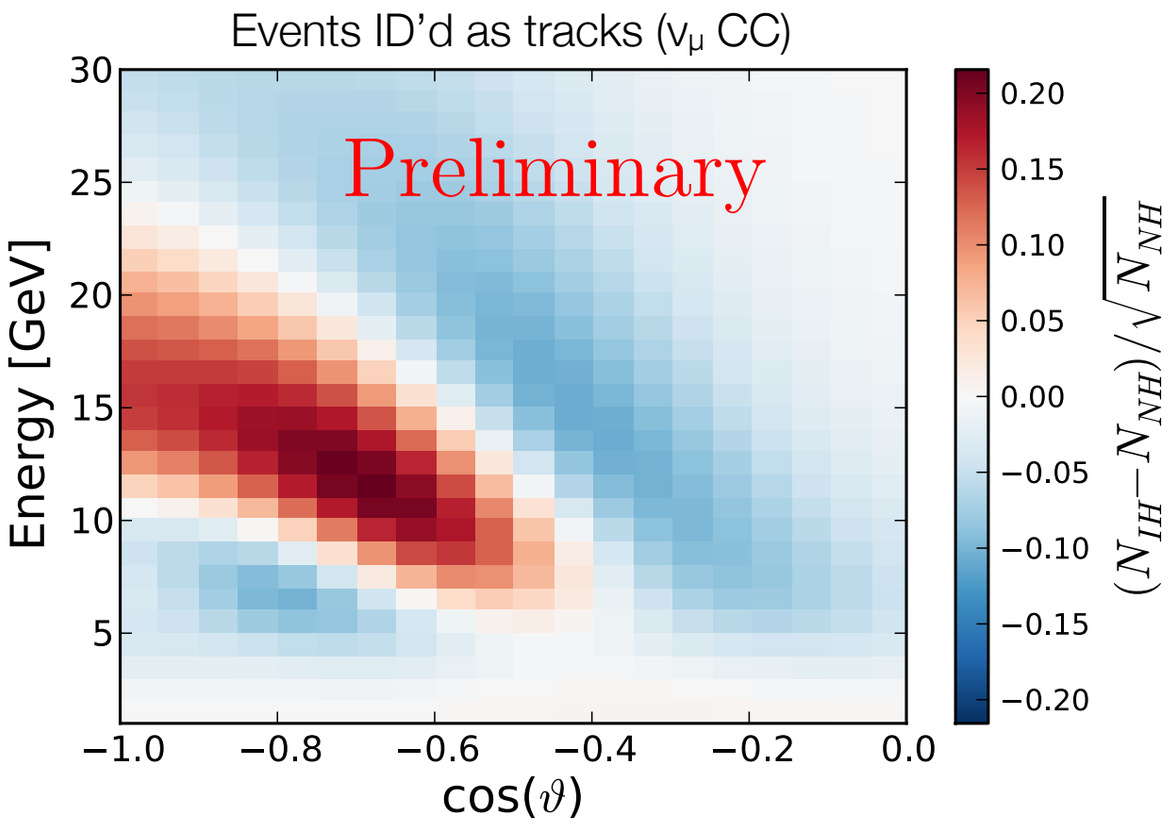
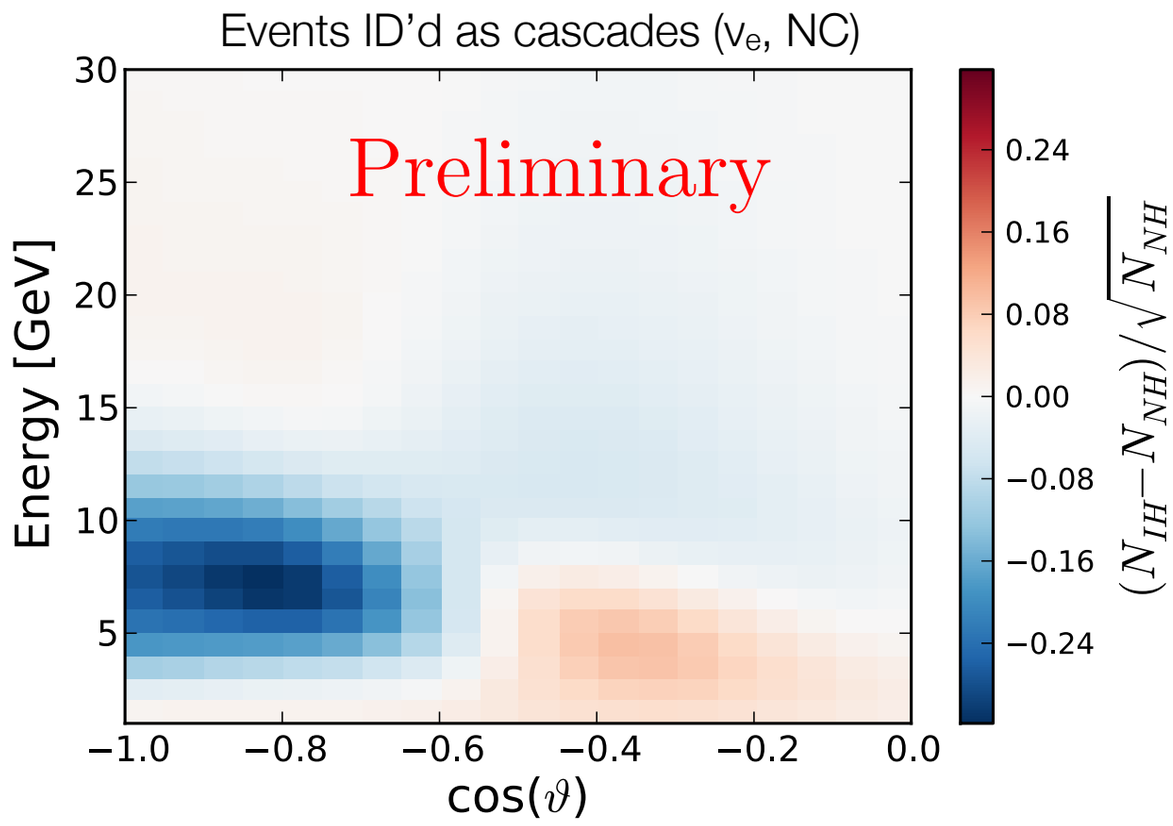


Hierarchy Signature: Statistical Significance

arXiv:1401.2046

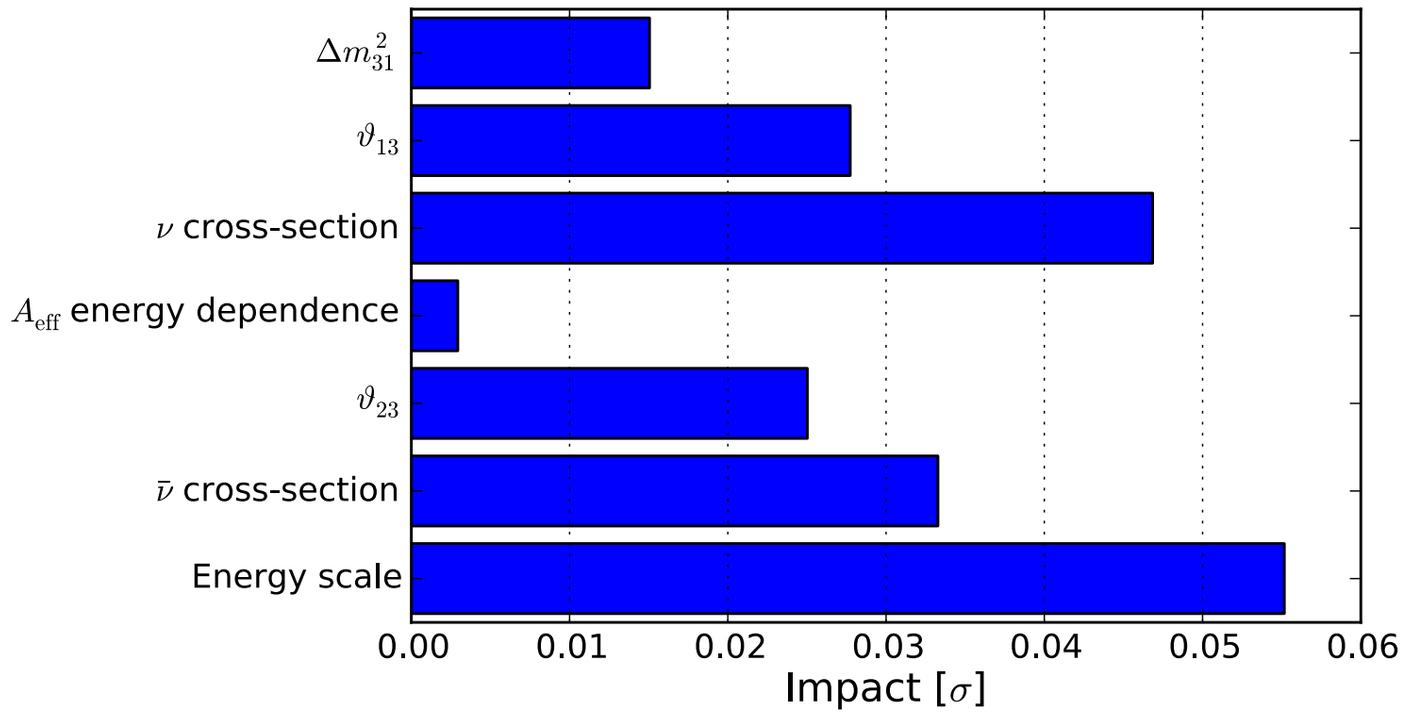




- With full detector response included, distinctive (and quite different) hierarchy-dependent signatures are still visible in both the track and cascade channels
  - Quantity shown is an illustration of statistical significance per bin (as per Akhmedov et al. arXiv:1205.7071)
  - Parametrized rates and detector resolutions and efficiencies used to eliminate statistical fluctuations

Leading Systematics

- Dominant systematics are uncertainties in neutrino and antineutrino cross sections (equivalently, fluxes), possible energy scale errors
  - Currently working on more detailed modeling of uncertainties from cross sections (using GENIE), ice optical properties



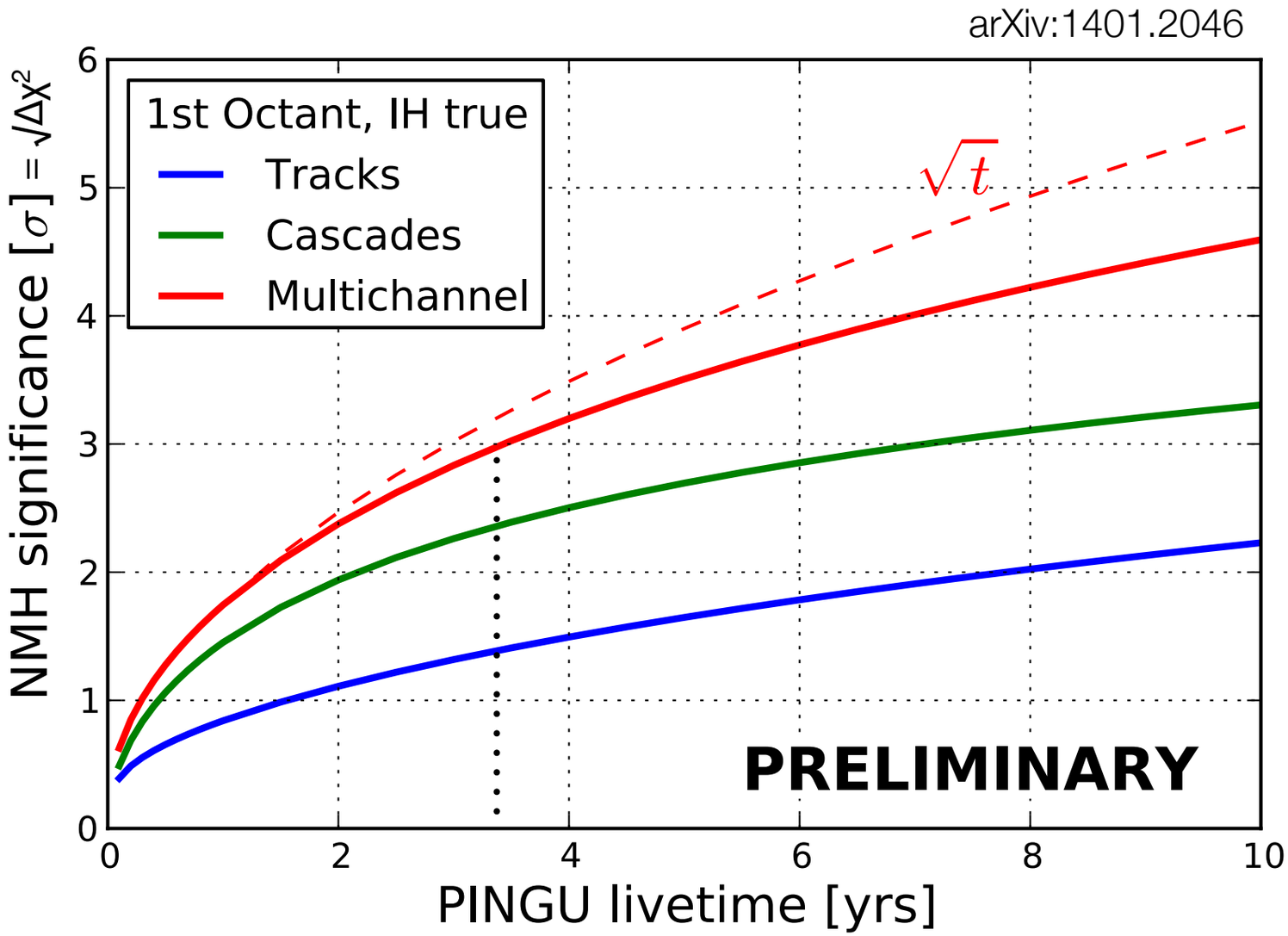
Impact: change to NMH significance if systematic error is assumed perfectly determined by other data

- CP-violating phase δ has little impact (as expected)

- Conservatively assume current knowledge of systematics – some will be better understood by the time PINGU is operational

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: worst case)
  - Combine track and cascade channels to obtain final significance
  - Maximal mixing or the second octant improve expected significance
- Based on full Monte Carlo simulations of detector performance
  - Optimization of detector geometry & analysis techniques and more detailed treatment of systematics underway

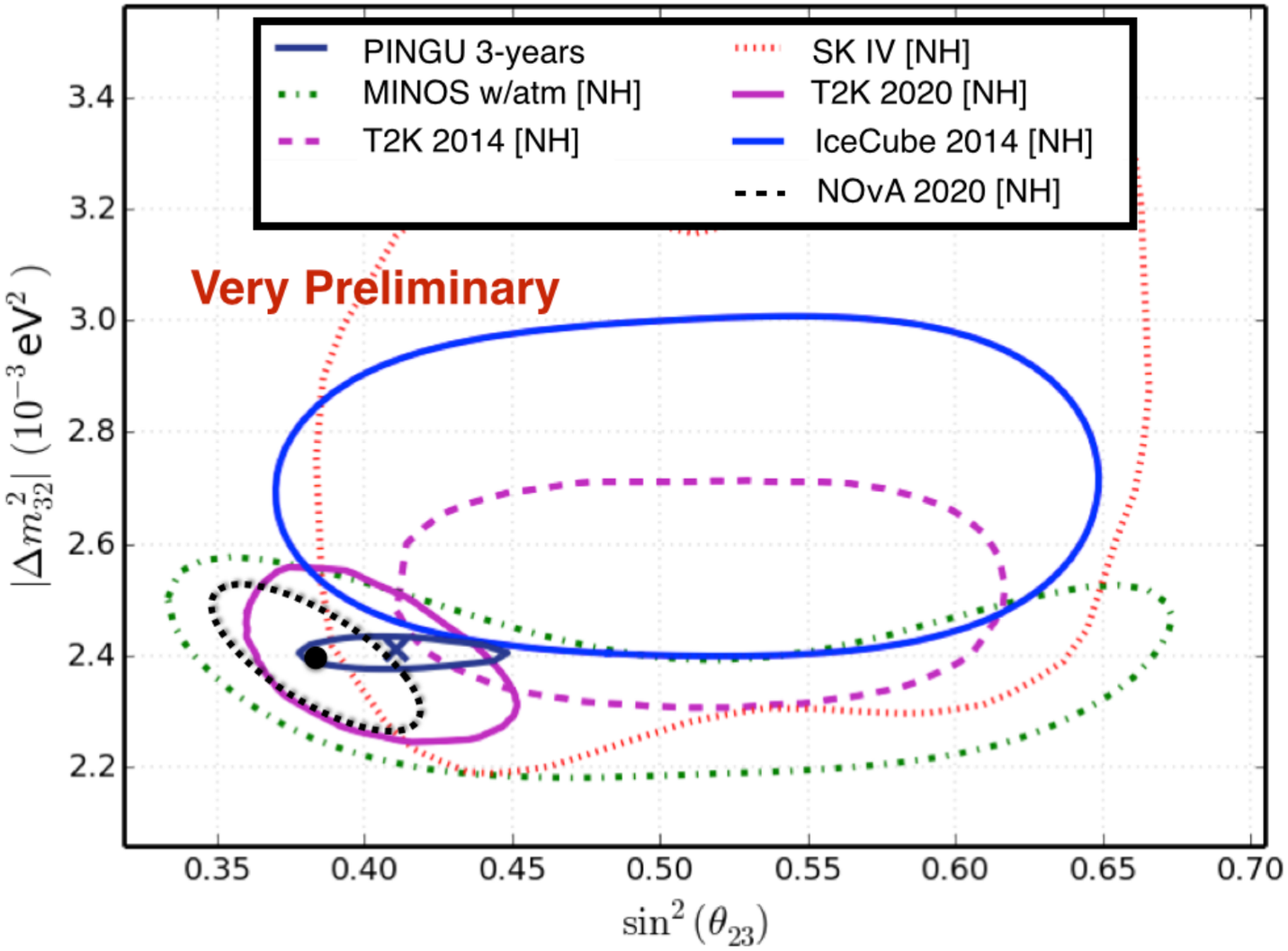


Other Scientific Goals of PINGU

- 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

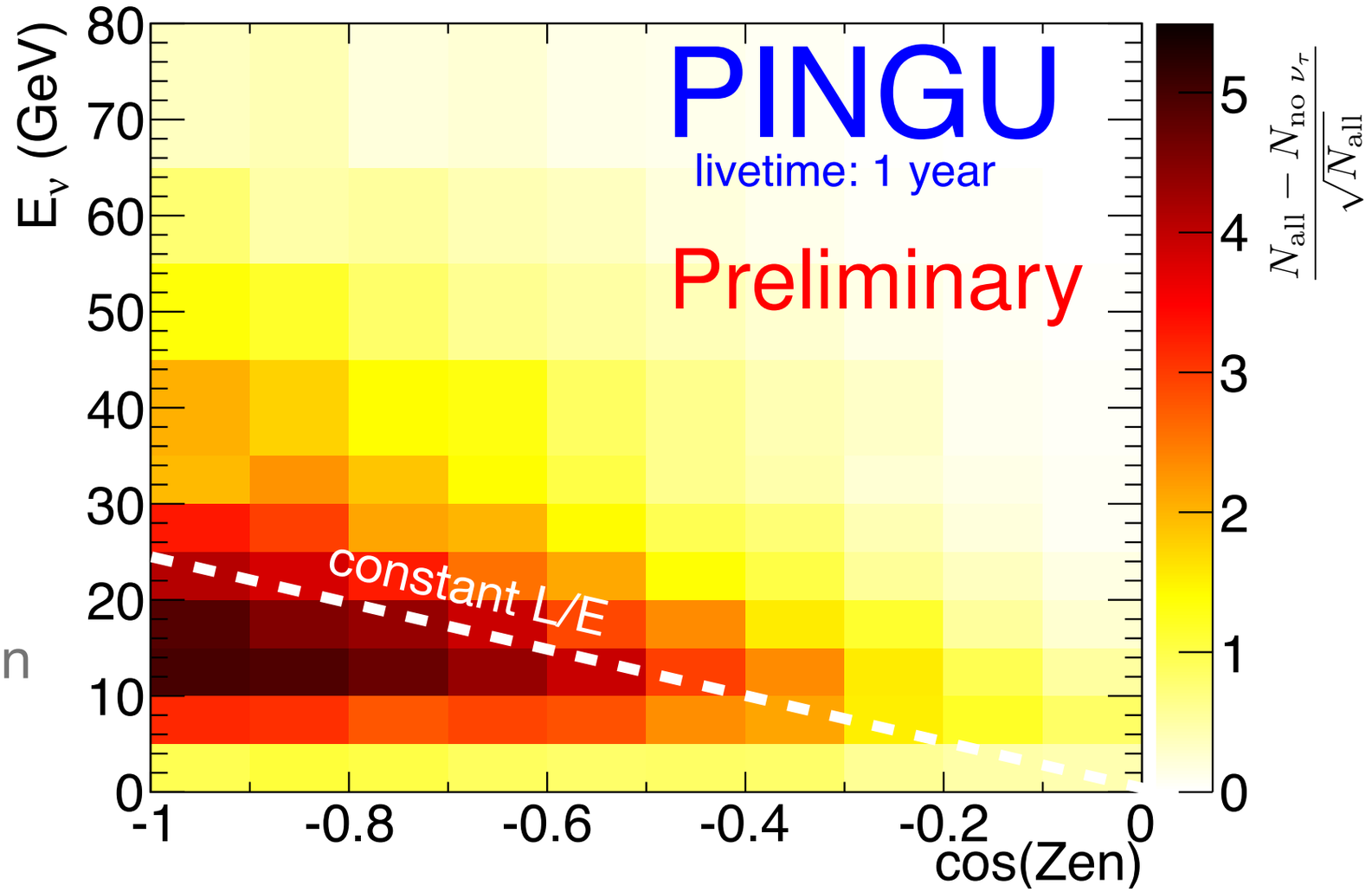
Oscillation Parameters

- *Preliminary* estimates of PINGU precision of oscillation parameters
  - Assumed current global fit preferred values
- Warning: not all systematic effects included yet, probably over-optimistic (Δm^2 in particular)
  - Work in progress – intended only to give a first indication of relative improvement over DeepCore alone



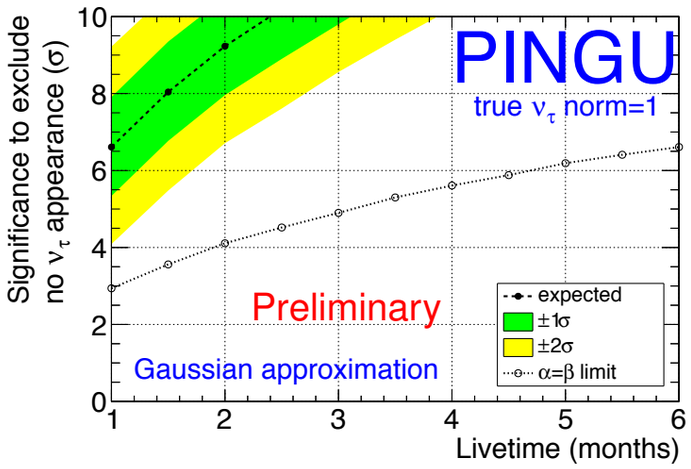
Tau Appearance with PINGU

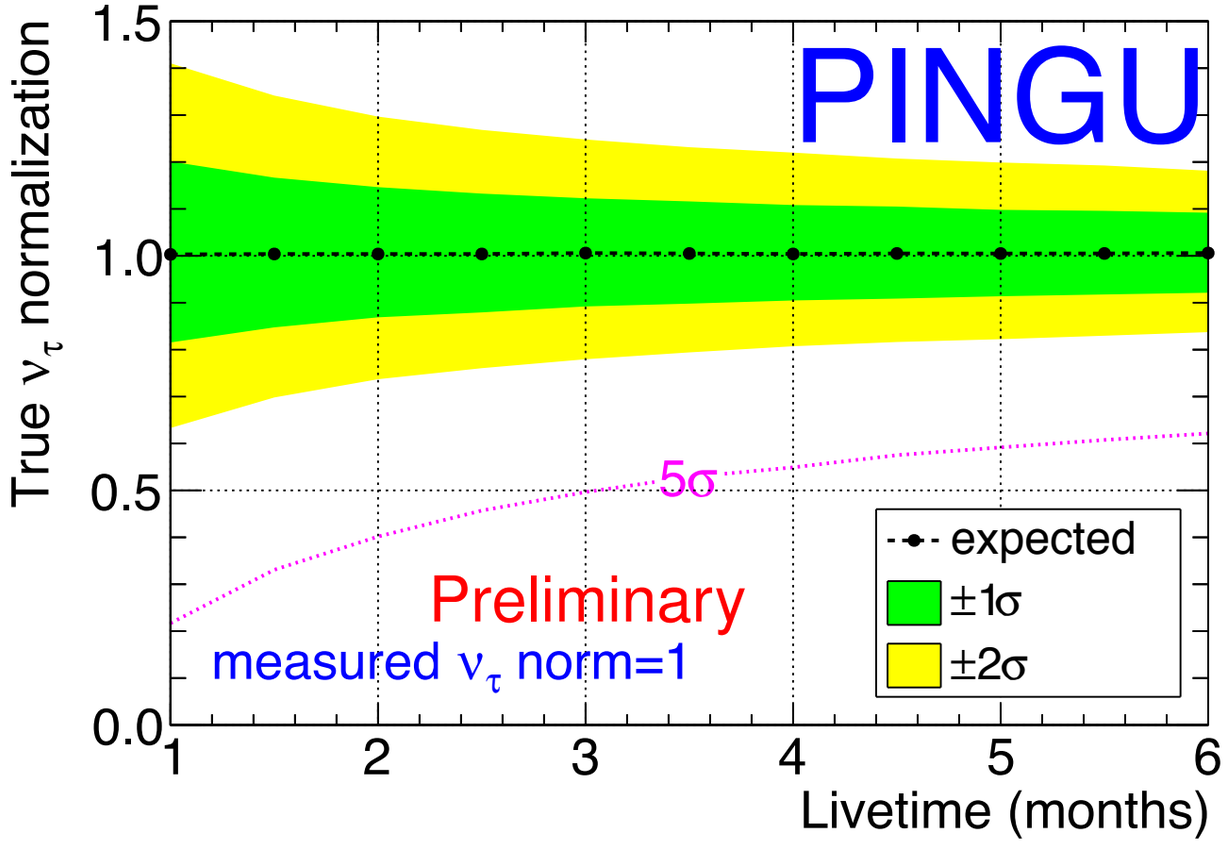
- Higher energy range of PINGU vs. OPERA, Super-K substantially improves appearance rate
  - Reduced kinematic suppression due to tau lepton mass
- Tau appearance visible as distortion of cascade energy-angle distribution
  - Preliminary studies suggest 5σ observation of ν_τ possible with around 1 month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

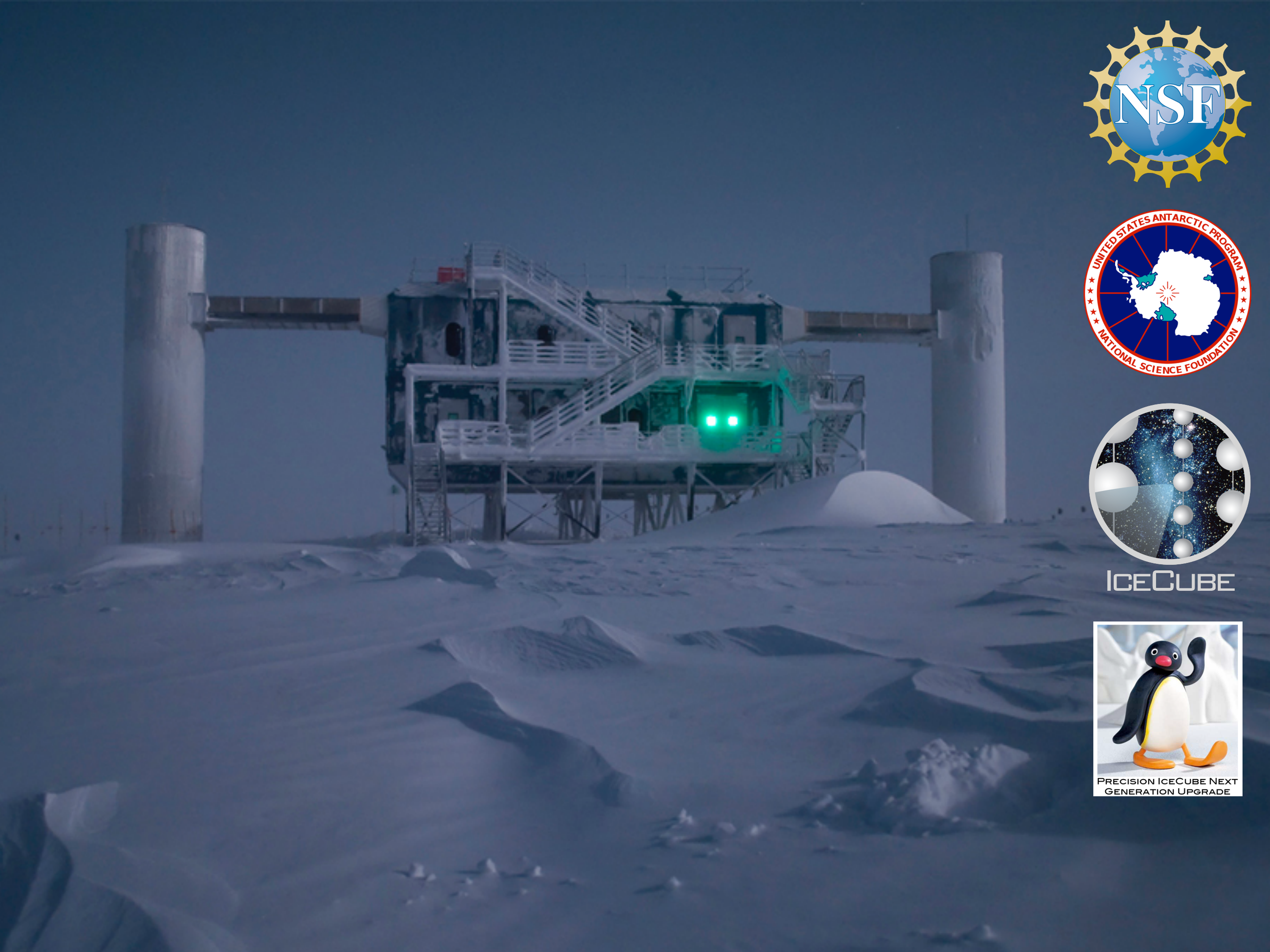
- Opportunity to discover new physics is greatly enhanced by PINGU's statistical reach and complementarity with other experiments
  - Over-constraint of parameters in the standard oscillation paradigm is necessary for searching for new physics in the neutrino sector – multiple measurements using different techniques are essential

PINGU and IceCube-GenTwo

- An expanded IceCube-based facility is being proposed for the South Pole following the discovery of high energy astrophysical neutrinos
  - PINGU for GeV-scale physics (neutrino oscillations, dark matter, SNe)
  - A high energy expansion for 100 TeV – PeV scale neutrinos
  - Opportunities for related projects: ARA, DM-Ice, etc.
- Design will closely follow that of IceCube
  - Similar photodetectors with upgraded electronics
  - Reduces R&D cost and technical, schedule and budget risk
- Estimated PINGU share of facility cost: $55M US + $25M non-US
  - PINGU to be deployed first, as early as late 2018 – early 2021 in a favorable funding scenario
  - Statistically significant determination of the hierarchy possible by 2024 or 2025

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 beyond PINGU to search for proton decay, observe extragalactic supernova neutrinos
  - IceCube-GenTwo will provide opportunities for detector R&D with potential for breakthrough reductions in cost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