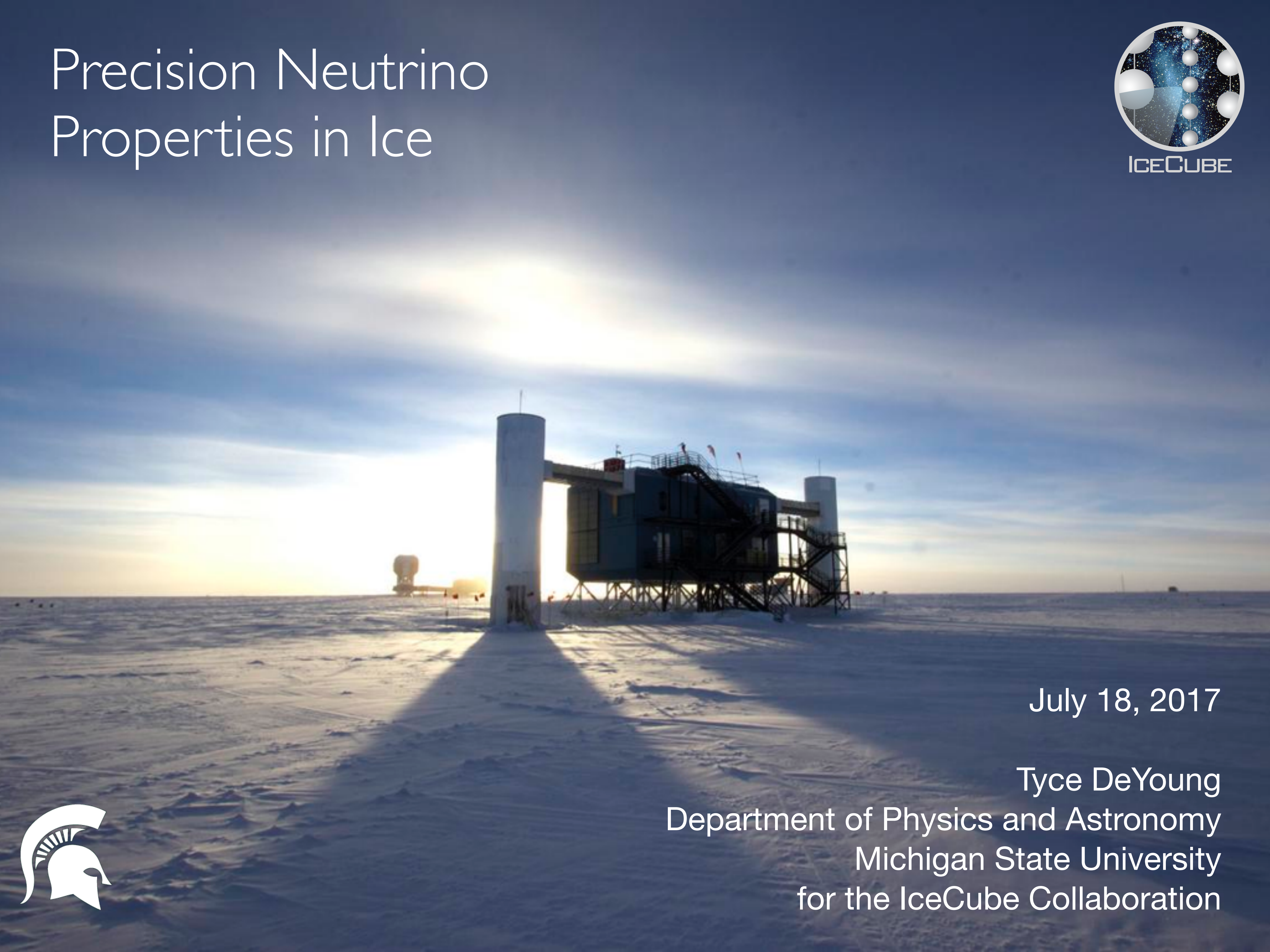


Precision Neutrino Properties in Ice

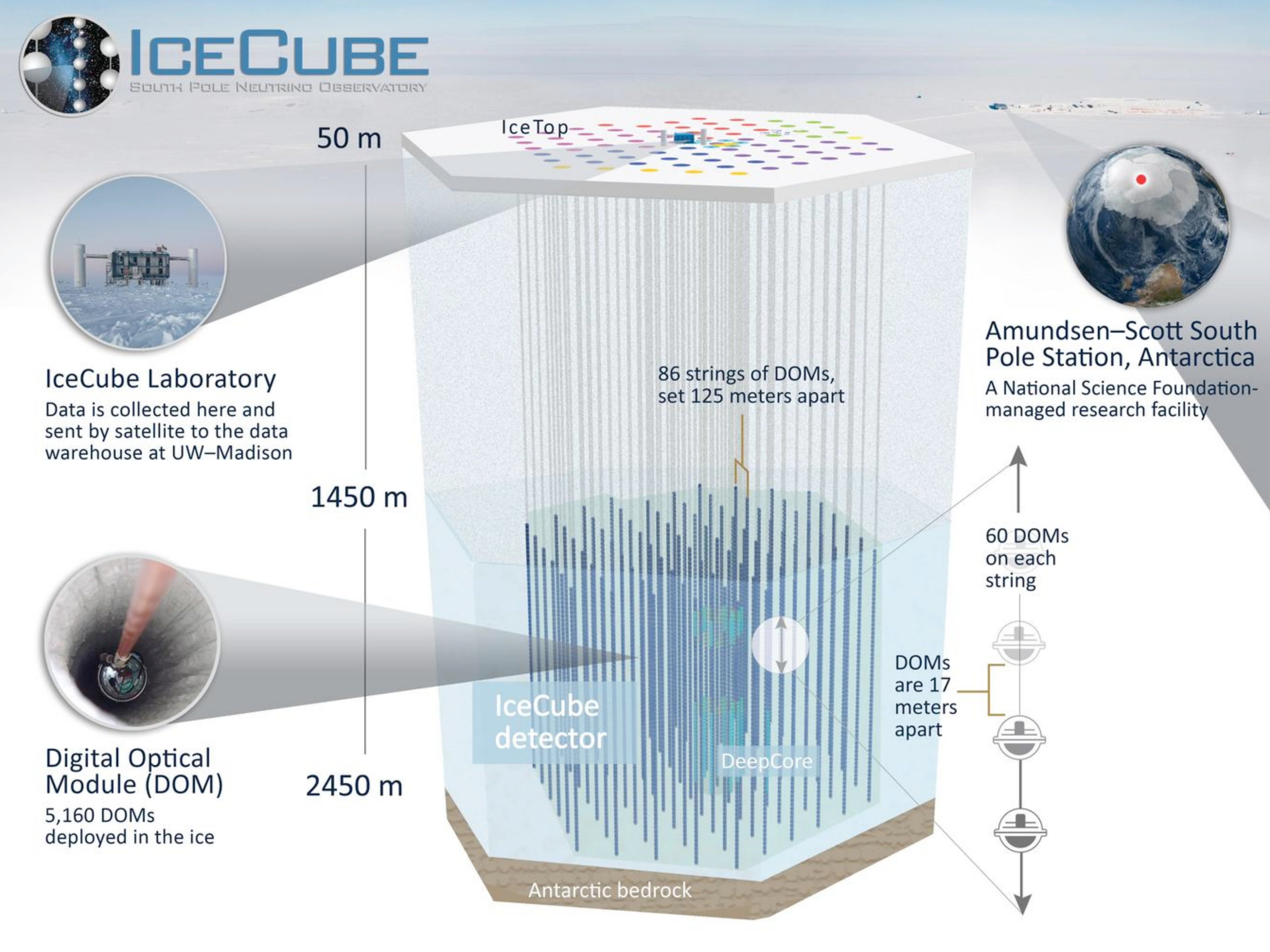
ICECUBE

July 18, 2017

Tyce DeYoung
Department of Physics and Astronomy
Michigan State University
for the IceCube Collaboration

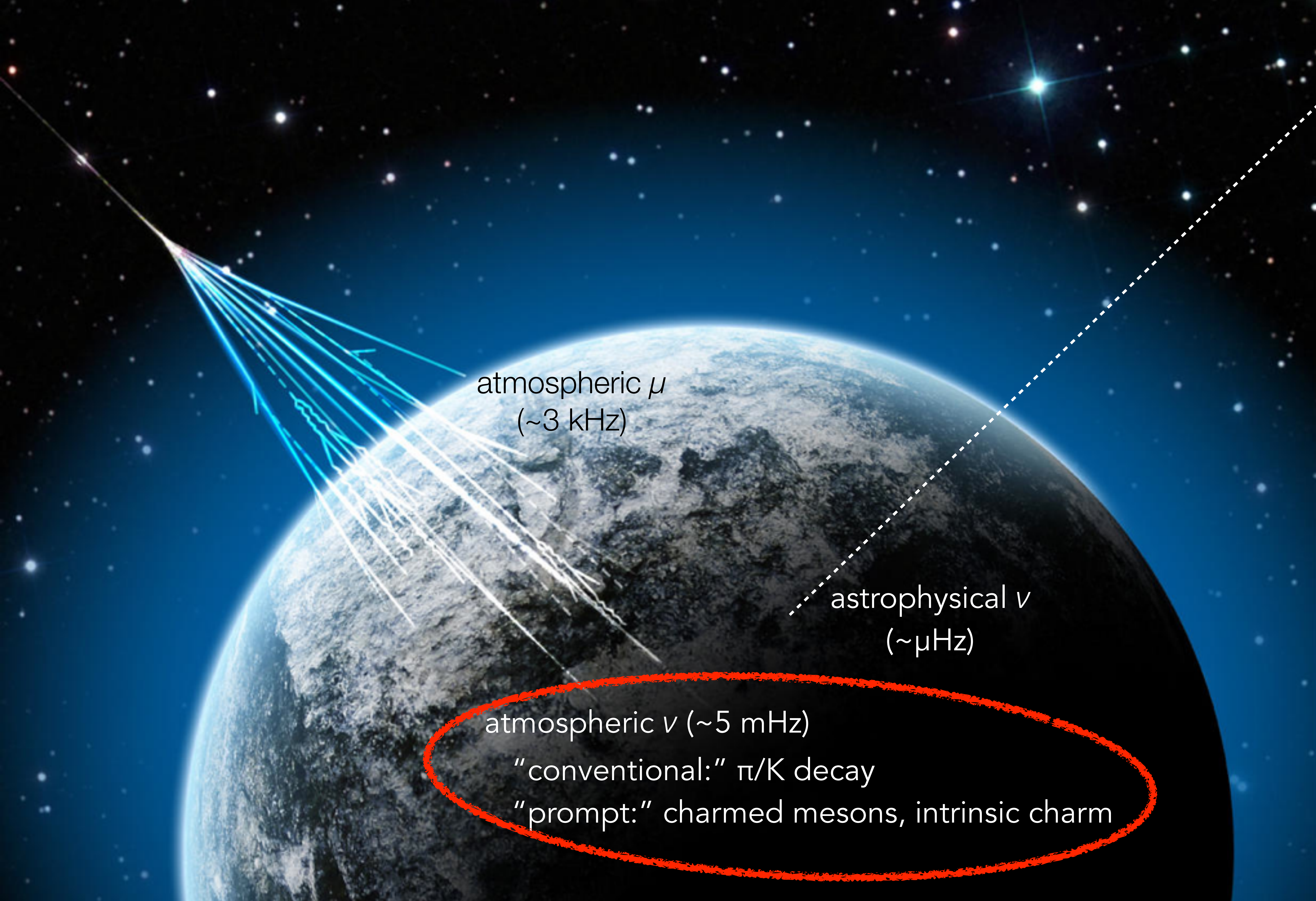
Outline

- Neutrino Physics in Ice
  - Neutrino oscillations with DeepCore
  - Neutrino physics at 10 TeV
- Future Plans: PINGU and IceCube-Gen2 Phase 1



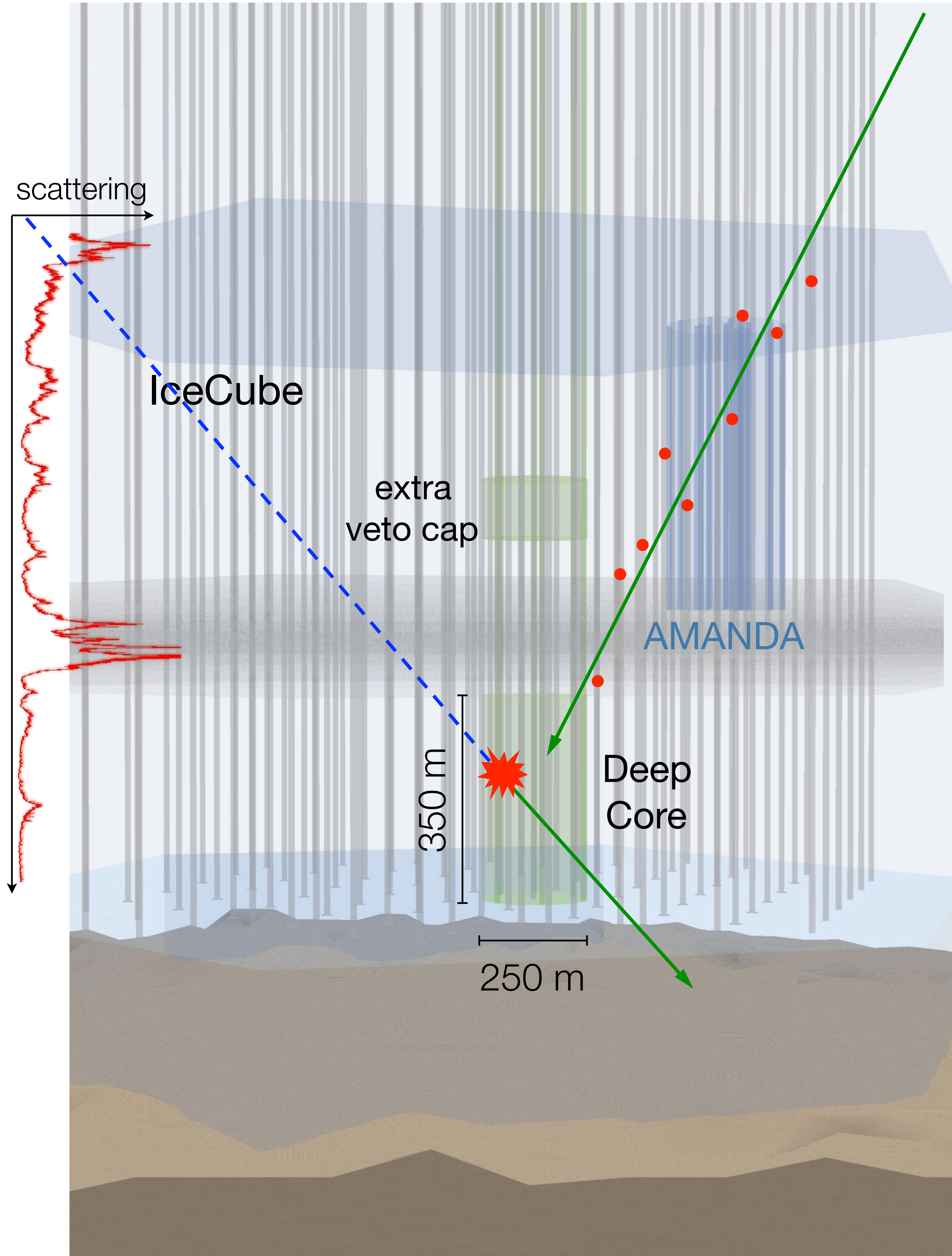
IceCube
South Pole Neutrino Observatory
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

IceCube: Signals and Backgrounds



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



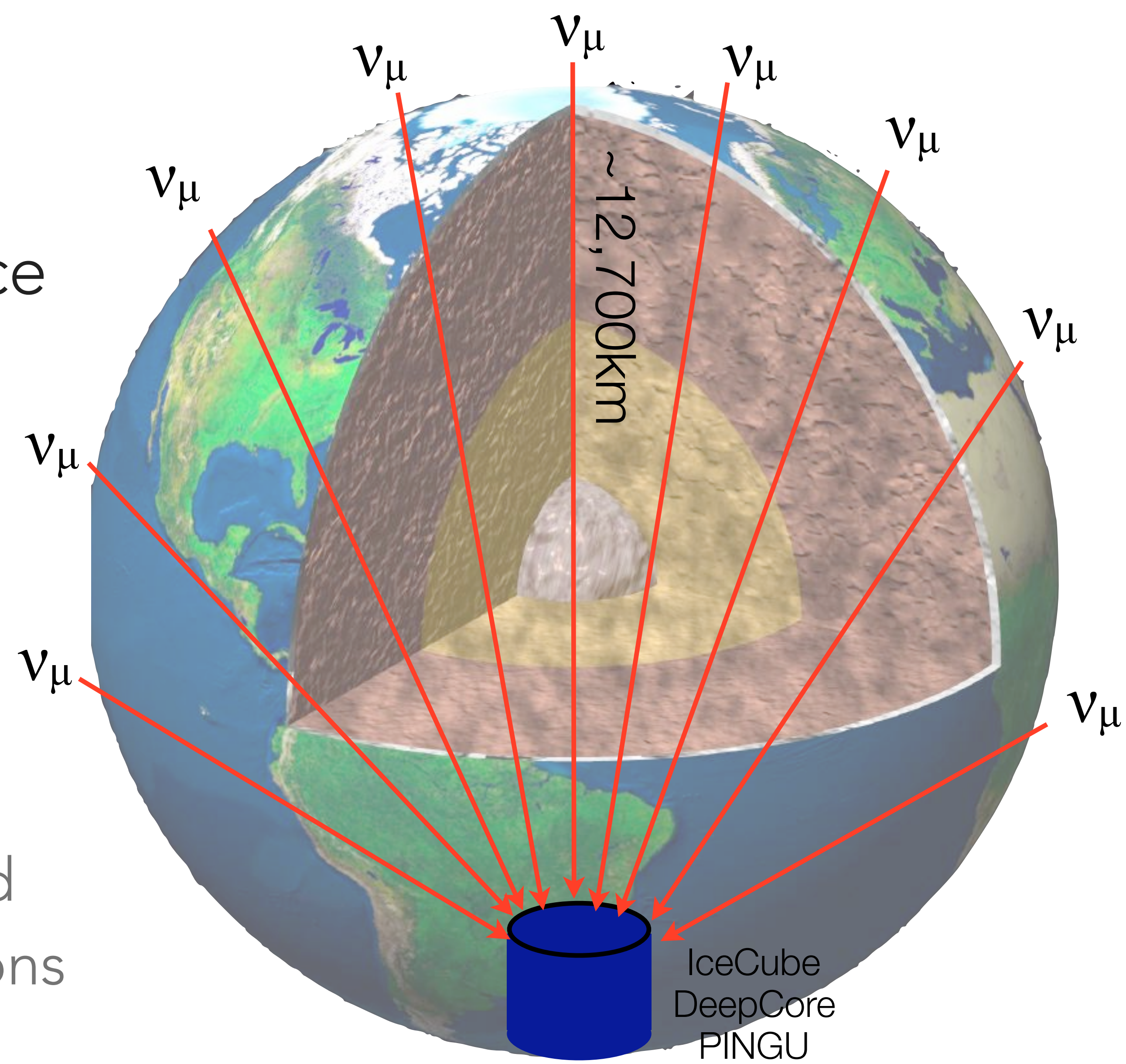
DeepCore Physics: 5-100 GeV

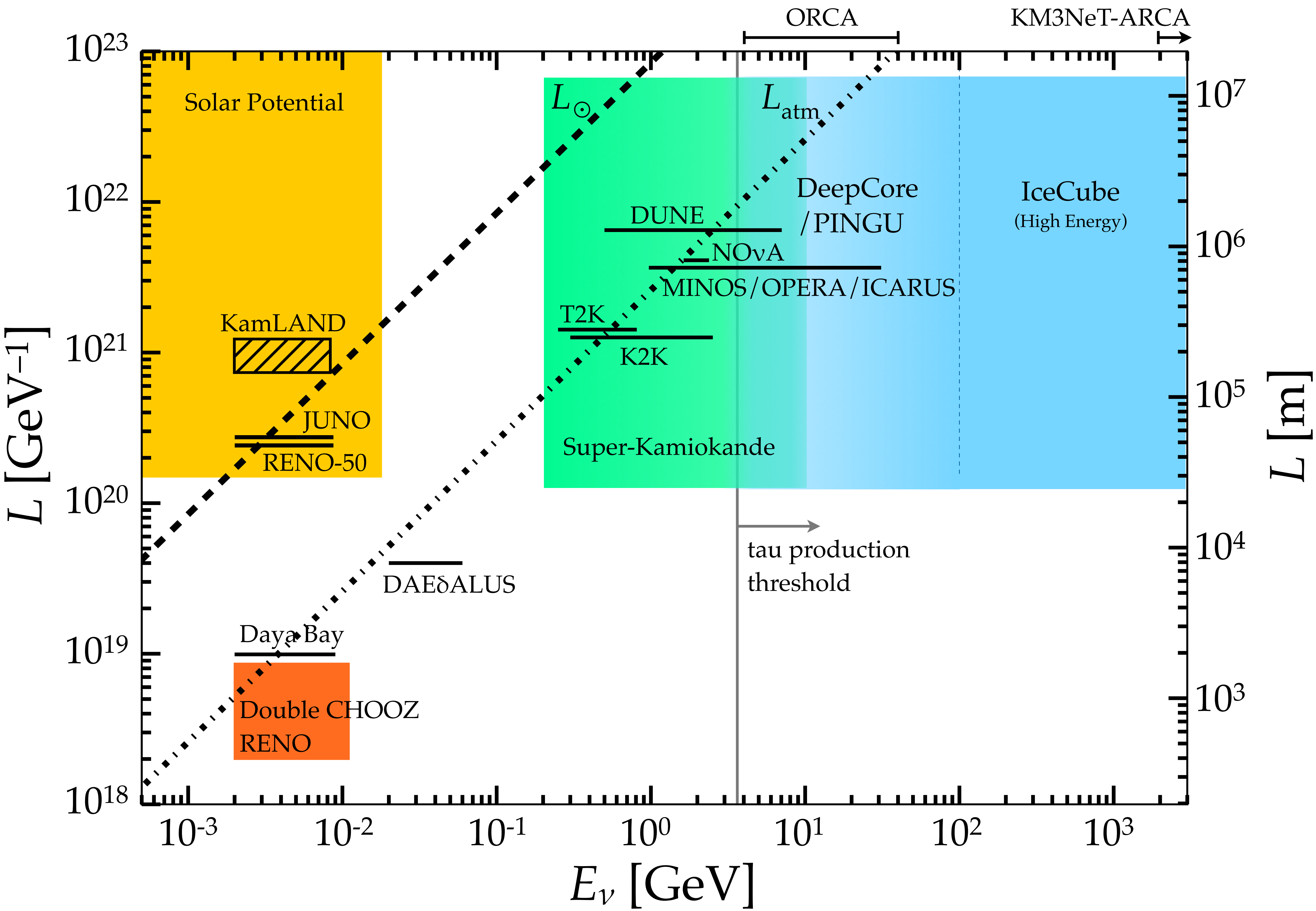
- Searches for dark matter-induced neutrino flux from…
  - …the Sun: *Phys. Rev. Lett.* 110, 131302 (2013), *Eur. Phys. J.* C77, 146 (2017)
  - …the Earth: *Eur. Phys. J.* C77, 82 (2017)
  - …Galactic Center: *Eur. Phys. J.* C75. 492 (2015), *Eur. Phys. J.* C76. 531 (2016), arXiv:1705.08103
  - …Galactic Halo: *Eur. Phys. J.* C75. 20 (2015)
  - …dwarf galaxies: *Phys. Rev.* D88, 122001 (2013)
- Direct searches for exotic particles, e.g. slow monopoles: *Eur. Phys. J.* C74, 2938 (2014)
- Neutrino astronomy: neutrino bursts from, e.g. choked GRBs: *Astrophys. J.* 816, 75 (2016)
- Atmospheric neutrino spectrum: first measurements of ν_e above 50 GeV: *Phys. Rev. Lett.* 110, 151105 (2013), *Phys. Rev.* D91, 122004 (2015)
- … and atmospheric neutrino oscillations

Oscillations with Atmospheric Neutrinos

- Neutrinos available over a wide range of baselines, with energies from a few GeV to 10's of TeV

- Oscillations produce distinctive pattern in 2D energy-angle space
  - Rather than near and far detectors, we have a range of beams and a single detector
  - Multi-MTon volume/high statistics allows deconvolution of systematics (generically depend on angle *or* energy) from oscillations

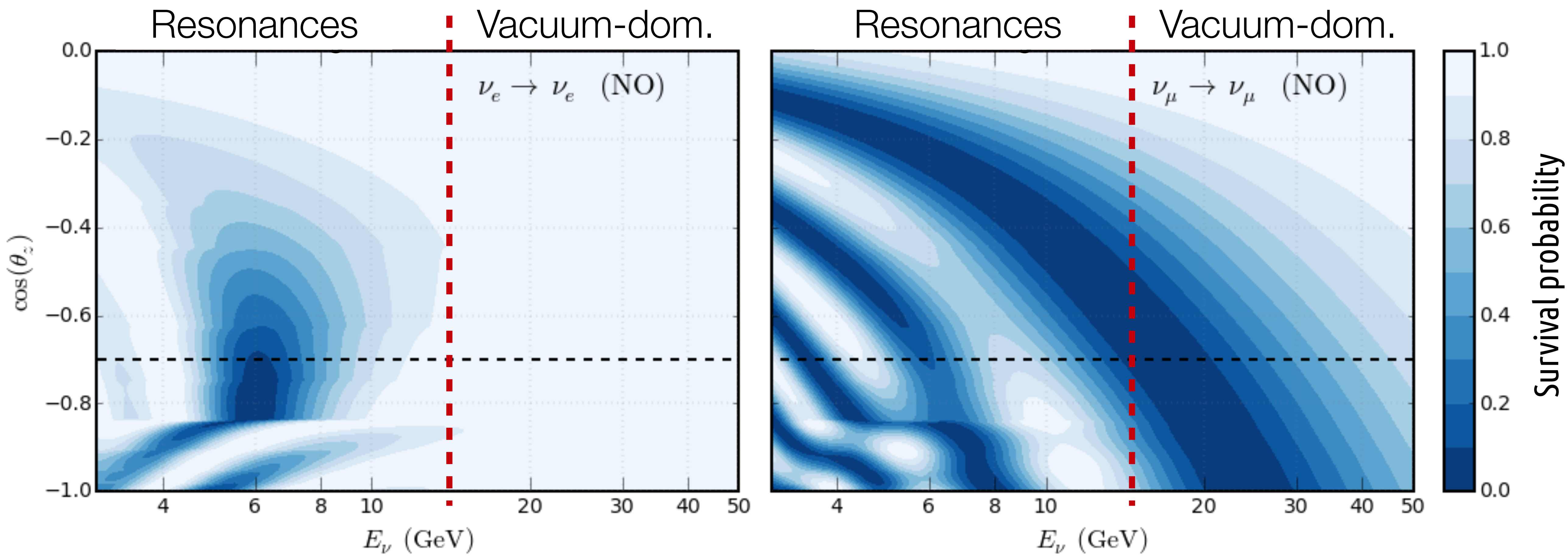




Probing oscillation physics at a range of baselines and energies not accessible to long-baseline or reactor neutrino experiments

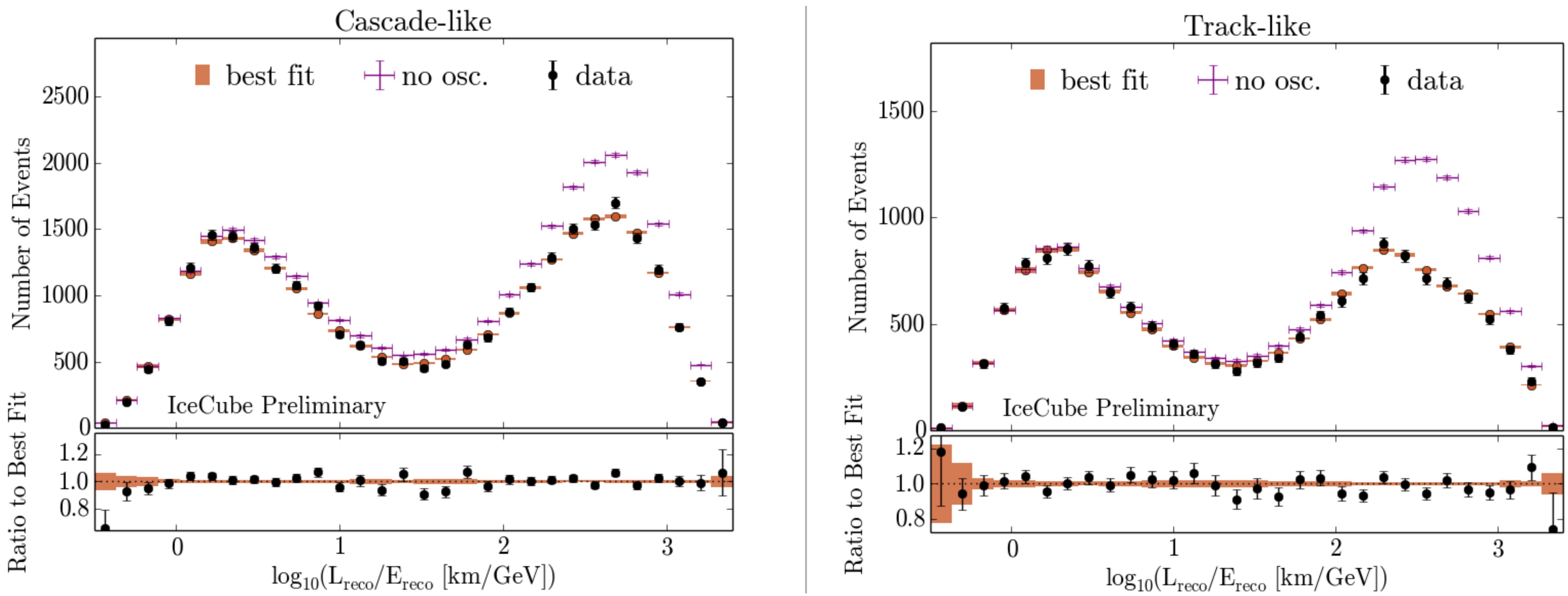
Oscillograms

Yáñez and Kouchner, arXiv:1509.08404



- Measure atmospheric parameters (Δm^2_{atm}, θ_{23}) at high energies
  - Tau neutrino appearance also accessible – test of 3x3 mixing paradigm
- Below ~15 GeV, matter resonances (MSW) depend on mass ordering

Atmospheric Oscillations with DeepCore



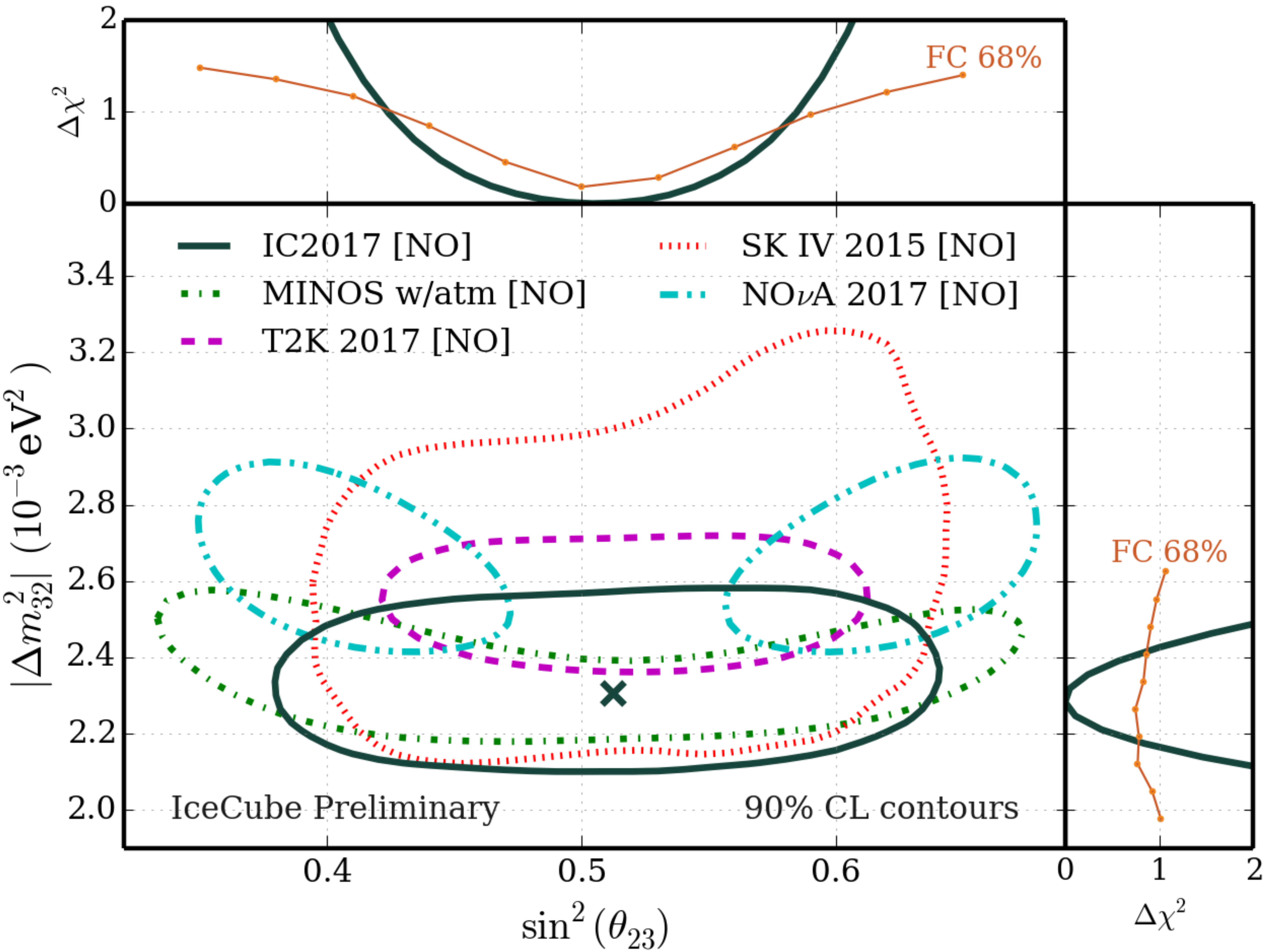
- 41,599 events from 2012-14 data sets, χ^2/n.d.f. = 117 / 119
  - Full analysis is L x E_ν x particle type, projected onto (L/E_ν) for illustration
  - Shaded range shows uncertainty in prediction at best fit (mostly atm. μ)

Nuisance Parameters

Parameters	Priors	Best Fit NO	Best Fit IO
Flux and cross section parameters			
Neutrino event rate [% of nominal]	no prior	85	85
$\Delta\gamma$ (spectral index)	0.00±0.10	-0.02	-0.02
$\nu_e + \bar{\nu}_e$ relative normalization [%]	100±20	125	125
NC relative normalization [%]	100±20	106	106
$\Delta(\nu/\bar{\nu})$ [σ], energy dependent [42]	0.00±1.00	-0.56	-0.59
$\Delta(\nu/\bar{\nu})$ [σ], zenith dependent [42]	0.00±1.00	-0.55	-0.57
M_A (resonance) [GeV]	1.12±0.22	0.92	0.93
Detector parameters			
overall DOM efficiency [%]	100±10	102	102
relative DOM efficiency, lateral [σ]	0.0±1.0	0.2	0.2
relative DOM efficiency, head-on [a.u.]	no prior	-0.72	-0.66
Background			
Atm. μ contamination [% of sample]	no prior	5.5	5.6

- Held fixed due to lack of impact on fit: $\Delta m^2_{21} = 7.53\times10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{13} = 2.17\times10^{-2}$, and $\delta_{CP} = 0°$

Best fit: $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$

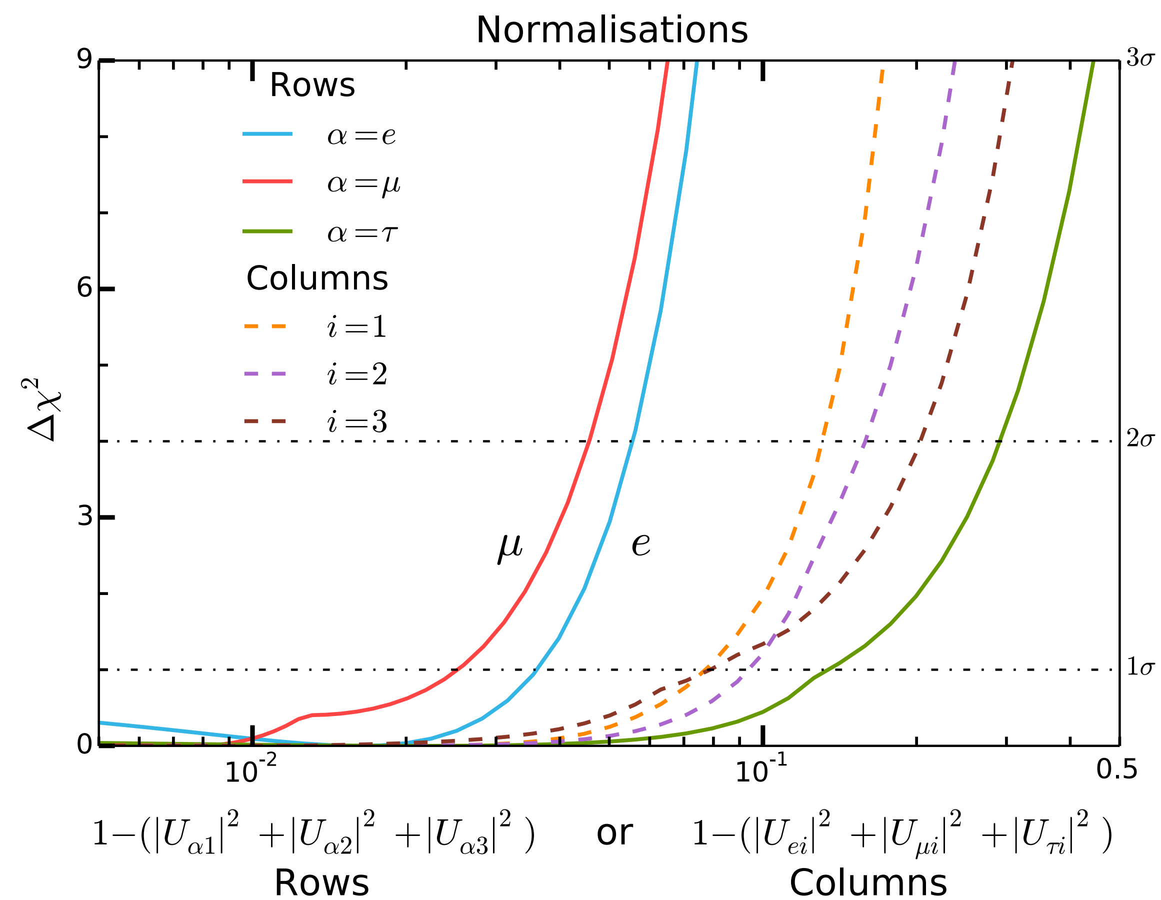


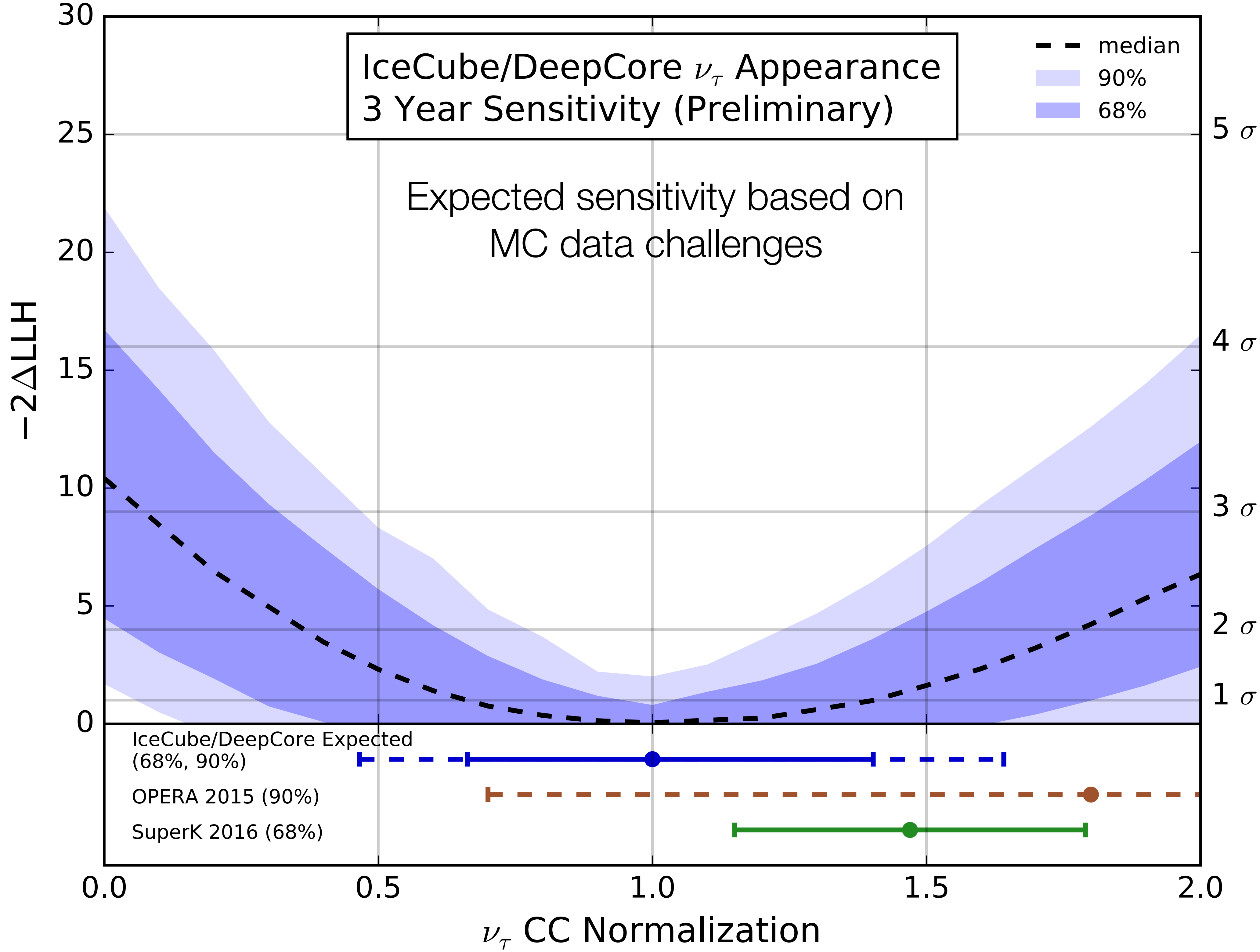
Tau Appearance and PMNS Unitarity

- Direct tests of unitarity of the PMNS mixing matrix are limited by imprecision of tau neutrino appearance data
  - 30% deviations in tau row allowed at 2σ CL by world data
- Tau lepton mass suppresses CC cross section – appearance measurements difficult in long-baseline experiments

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Parke and Ross-Lonergan 2016



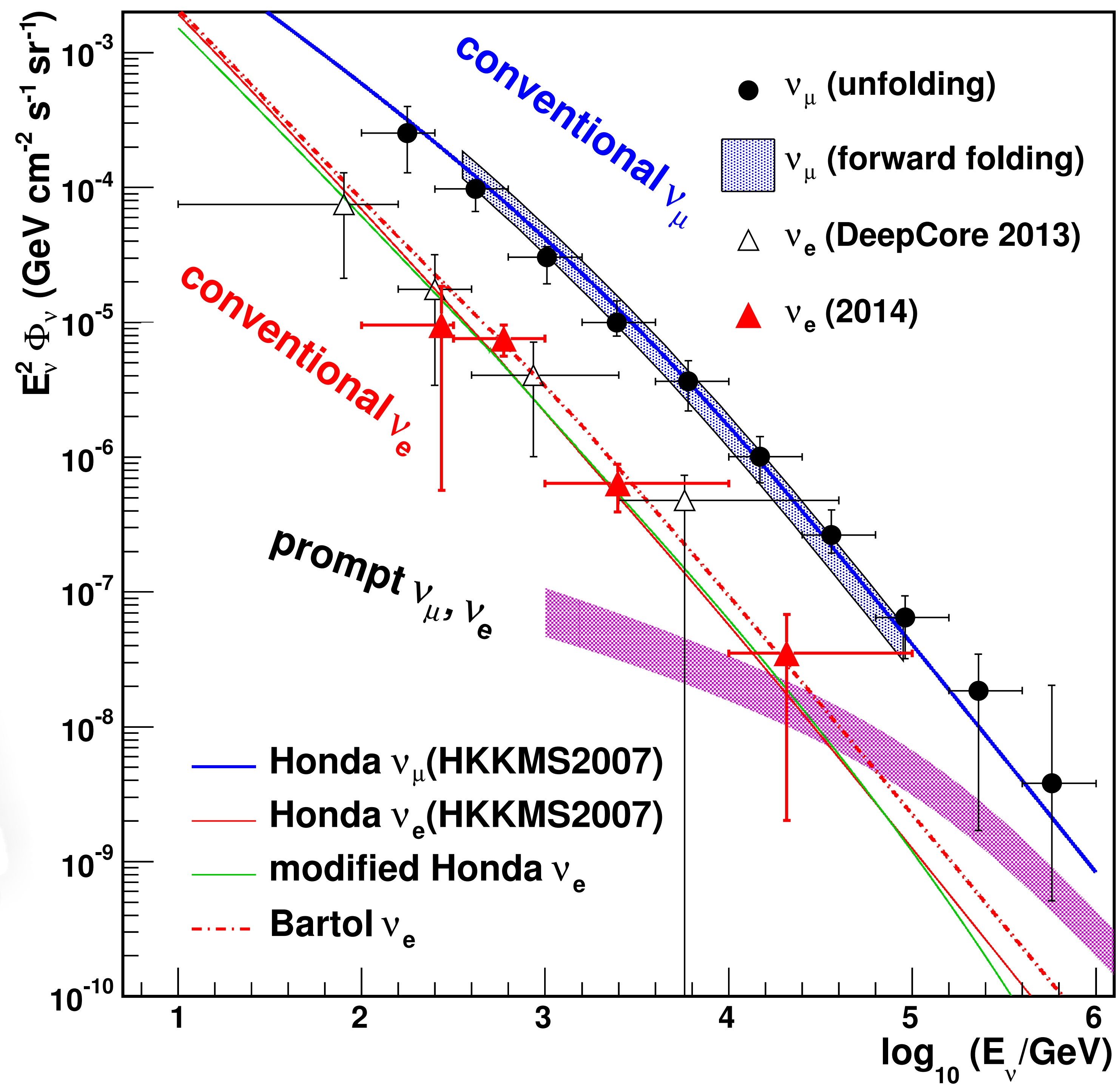


Two parallel analyses underway, results coming soon

Atmospheric Neutrinos at TeV and Above

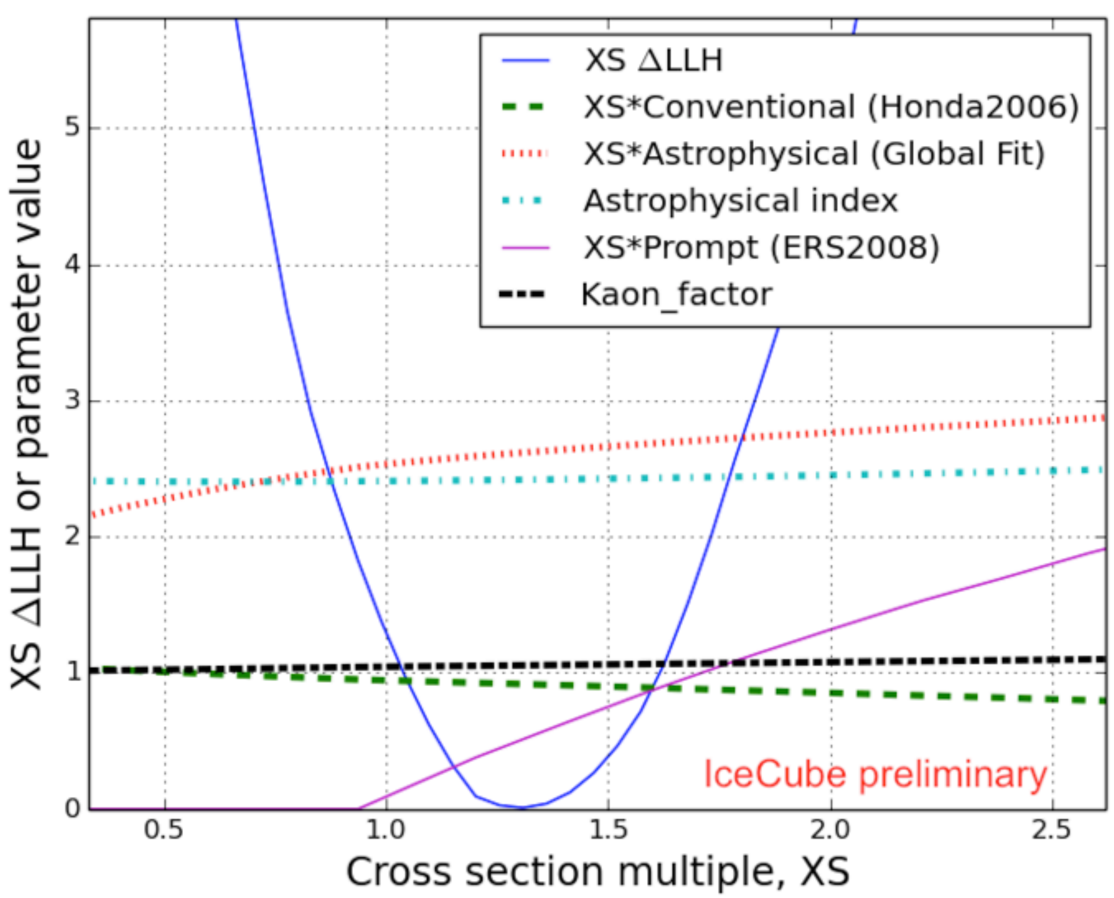
- Unprecedented neutrino data set with energies up to 100 TeV
  - Unique probe of a range of potential new physics

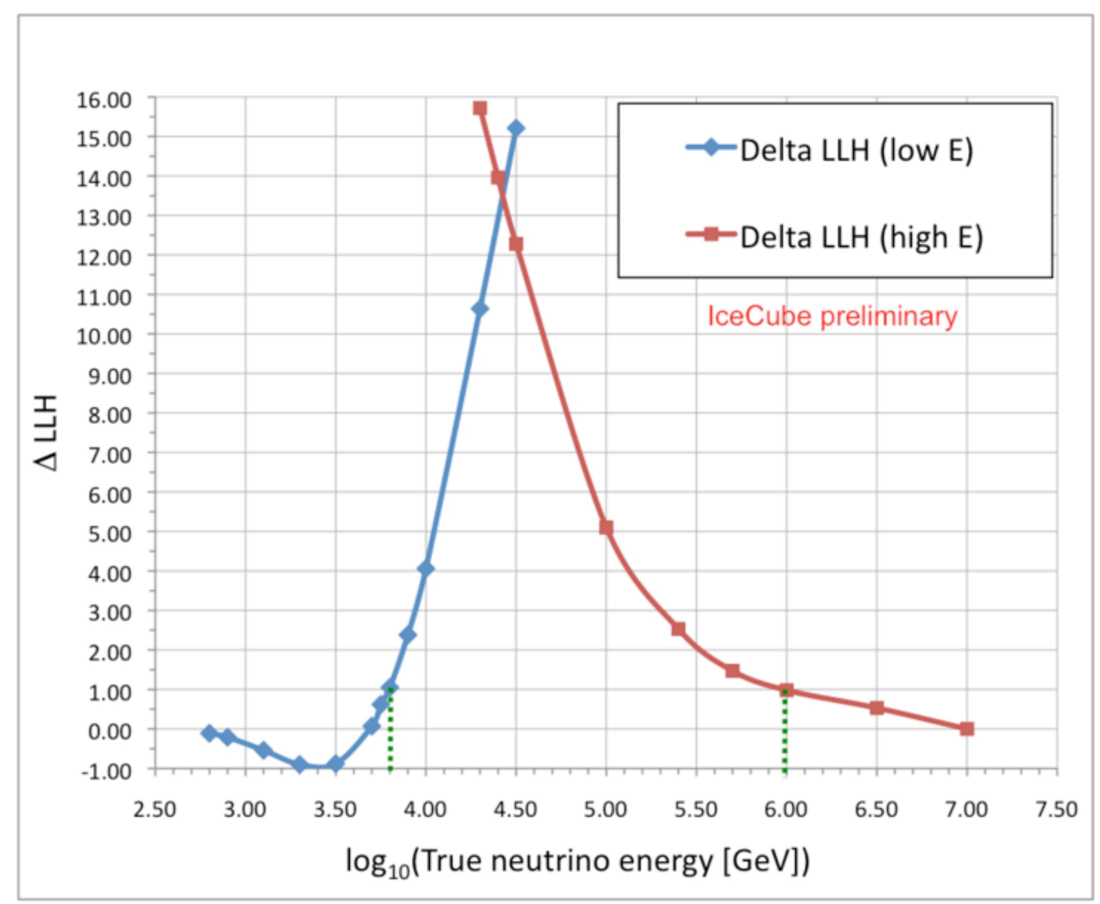
e.g. sterile neutrinos: talk by Carlos Argüelles tomorrow



TeV Neutrino Cross Section

- Measure neutrino absorption in the Earth, knowing matter density
    - Observe 1.30 $^{+0.30}_{-0.26}$ (stat) $^{+0.32}_{-0.40}$ (syst) x Standard Model prediction (from Cooper-Sarkar *et al.*, JHEP Aug. 2011) from 6.3 TeV to 980 TeV
    - Prompt and astrophysical fluxes are important systematics…

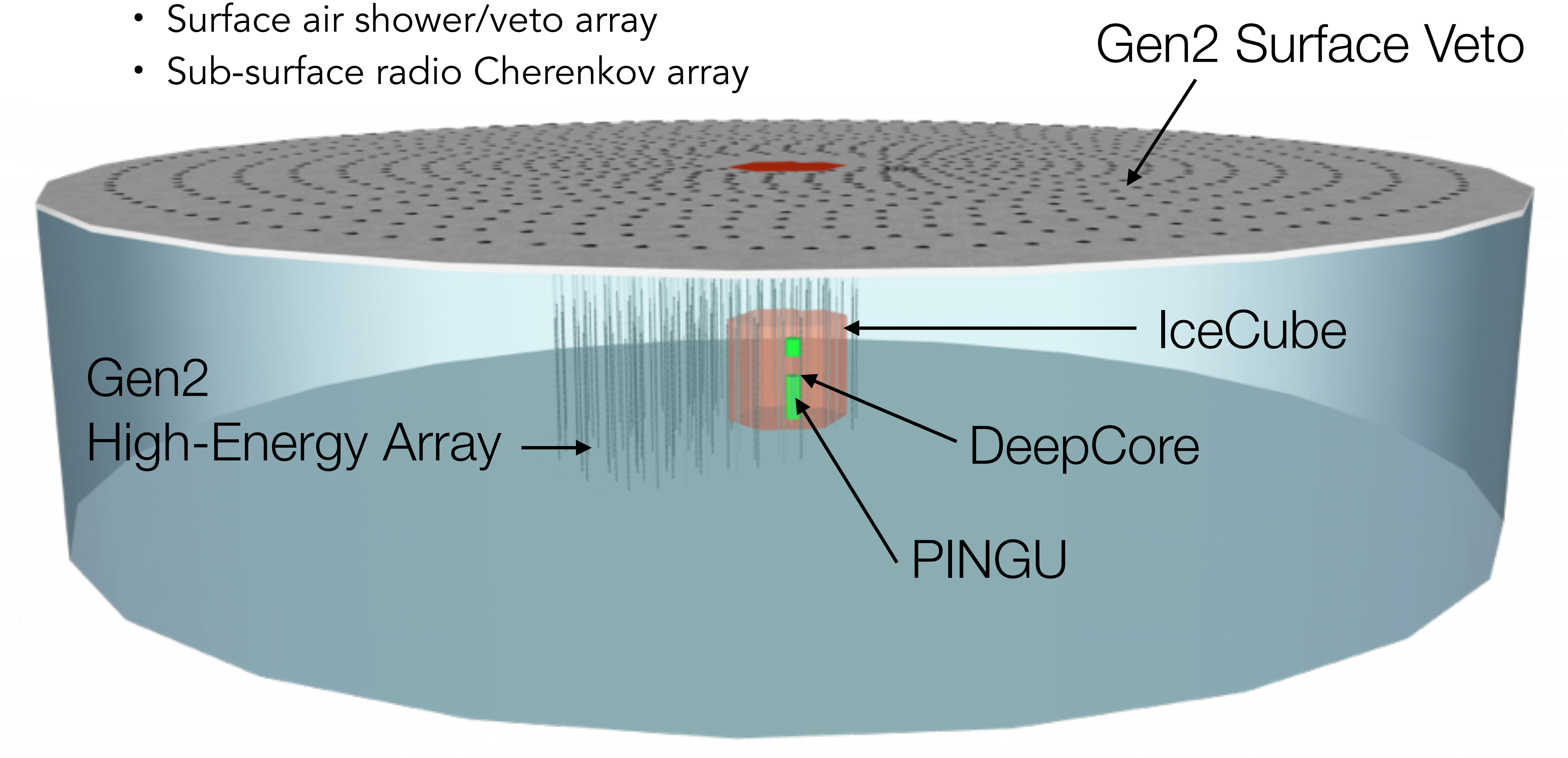




IceCube Gen2

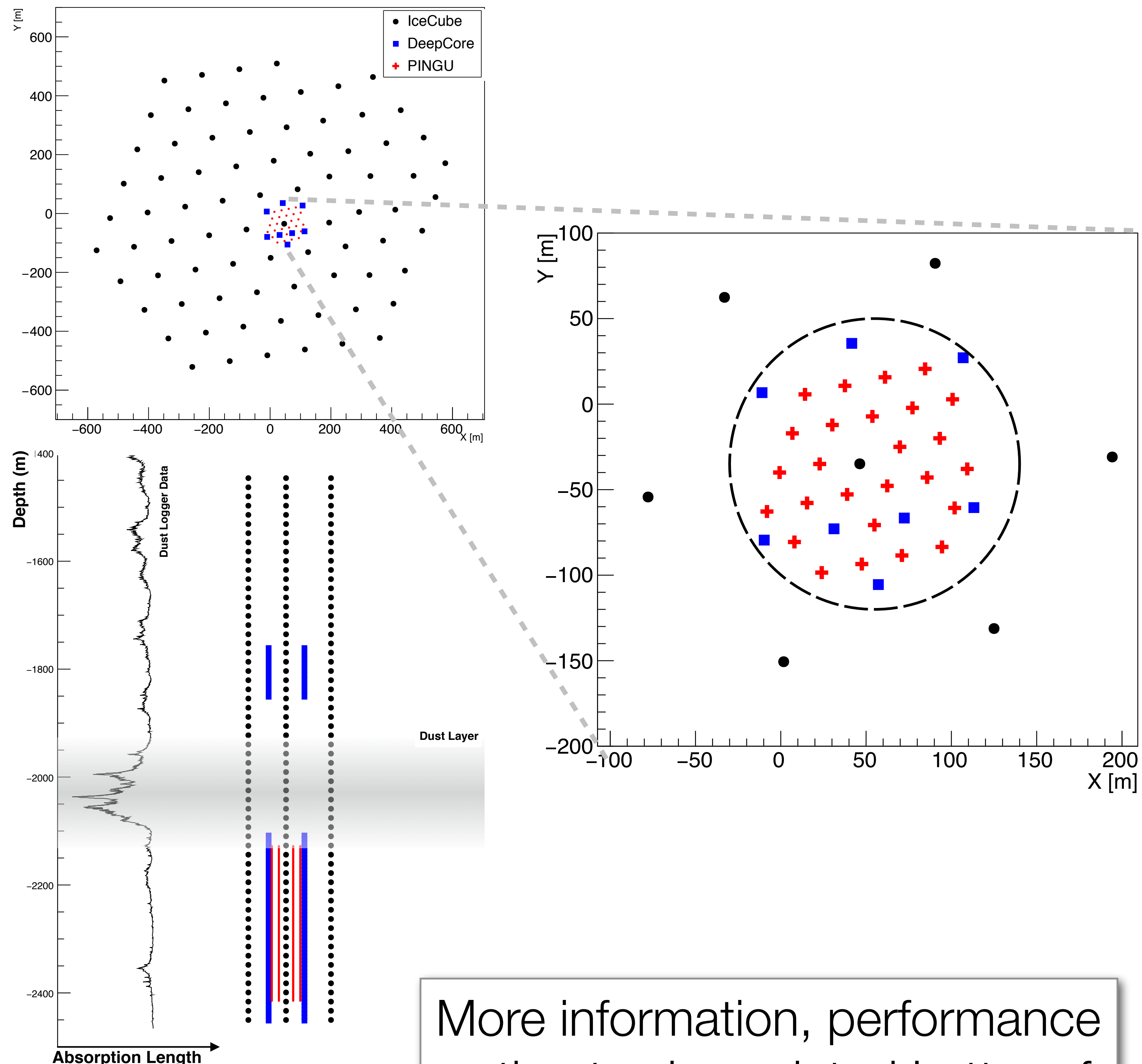
Envisioned neutrino facility addressing a wide range of scientific topics spanning GeV-EeV energies

- Gen2 high energy array
- PINGU low energy extension
- Surface air shower/veto array
- Sub-surface radio Cherenkov array



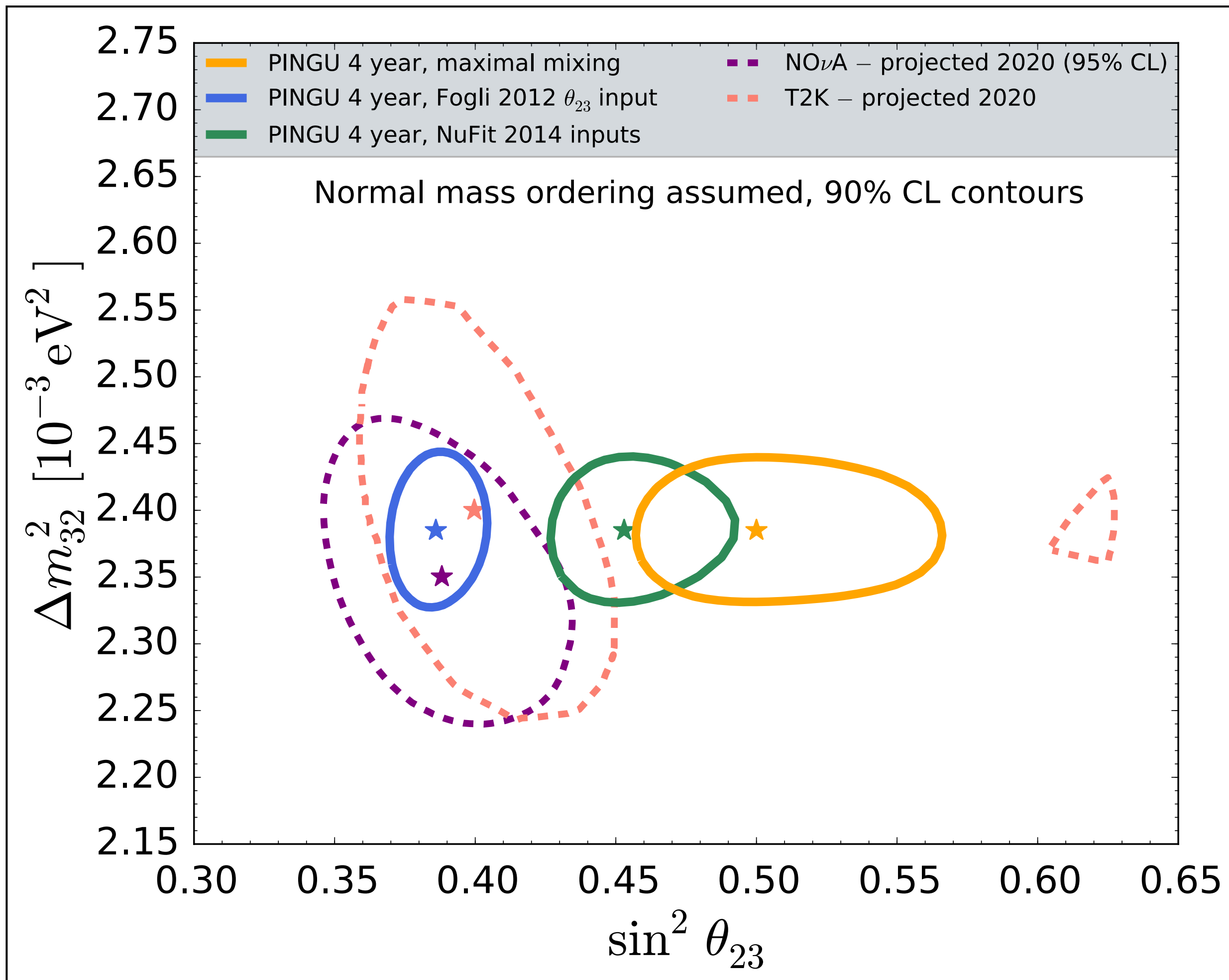
PINGU

- 26 additional, very densely instrumented strings embedded in DeepCore
    - Additional calibration devices to better control detector systematics
- 6 MTon fiducial volume with few GeV energy threshold

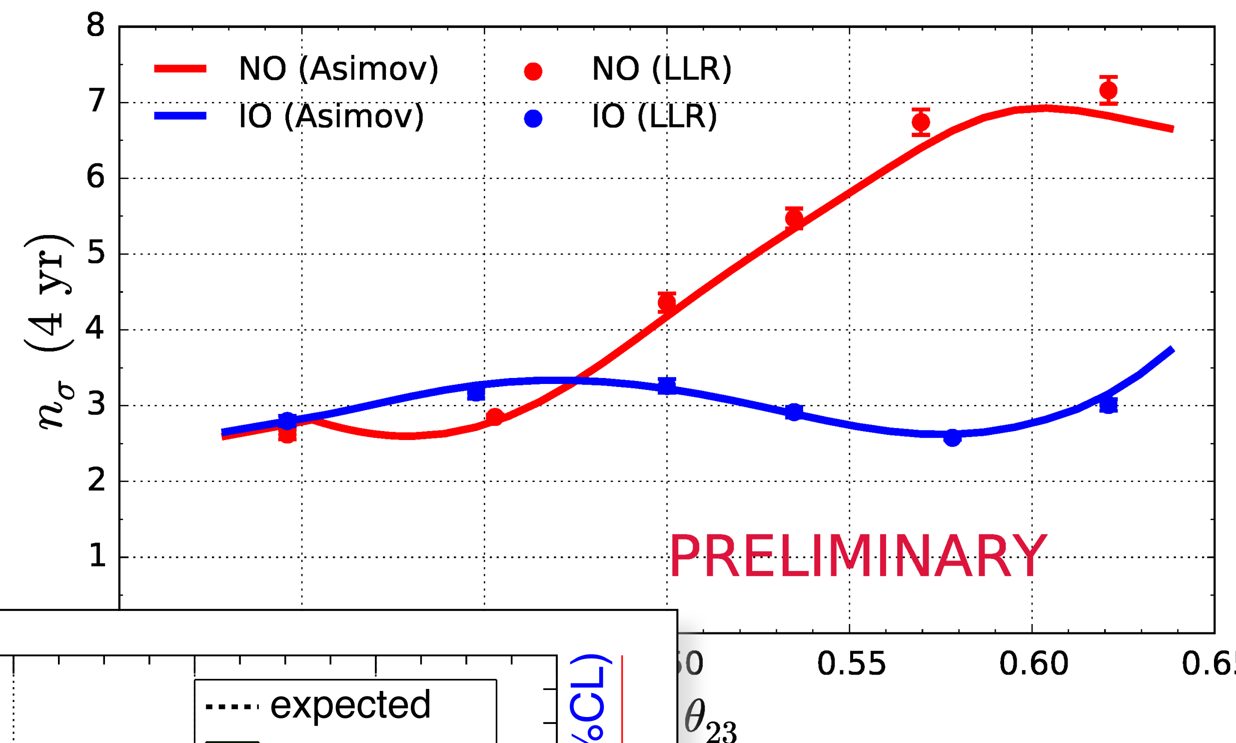


More information, performance estimates in updated Letter of Intent, arXiv:1607.02671

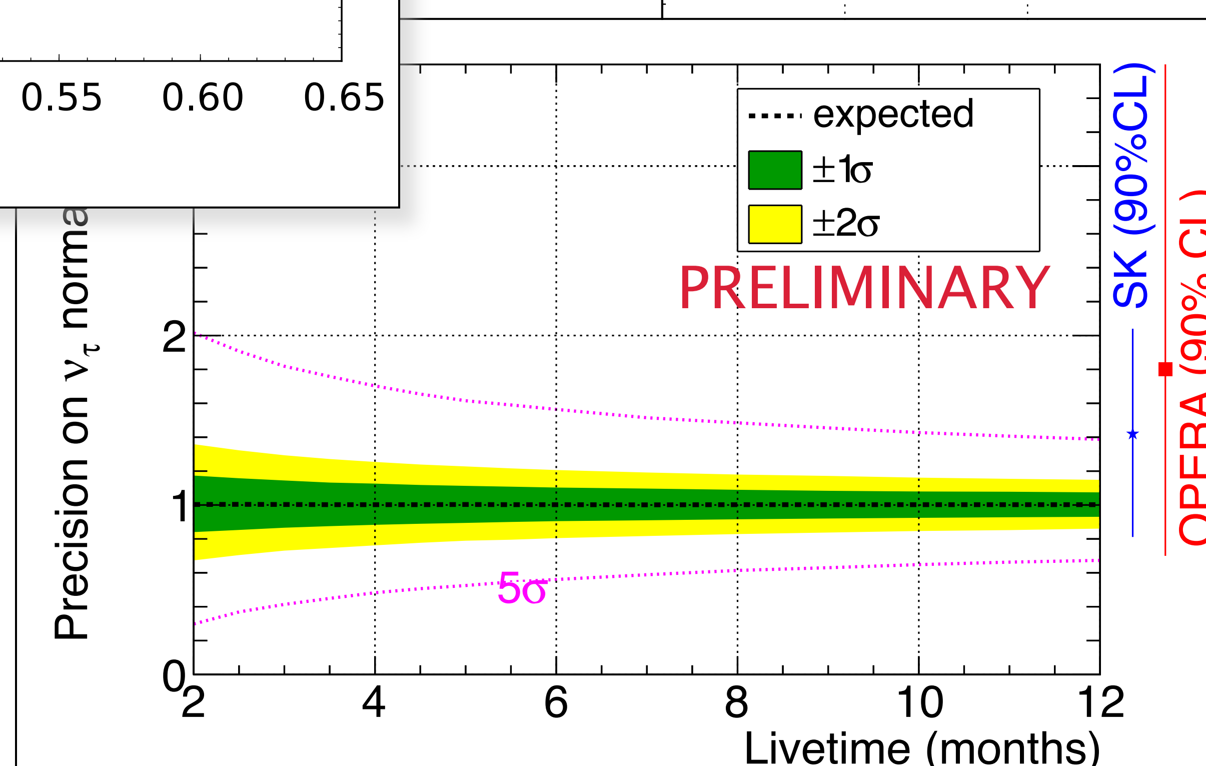
Neutrino Physics with PINGU



Determination of the neutrino mass ordering



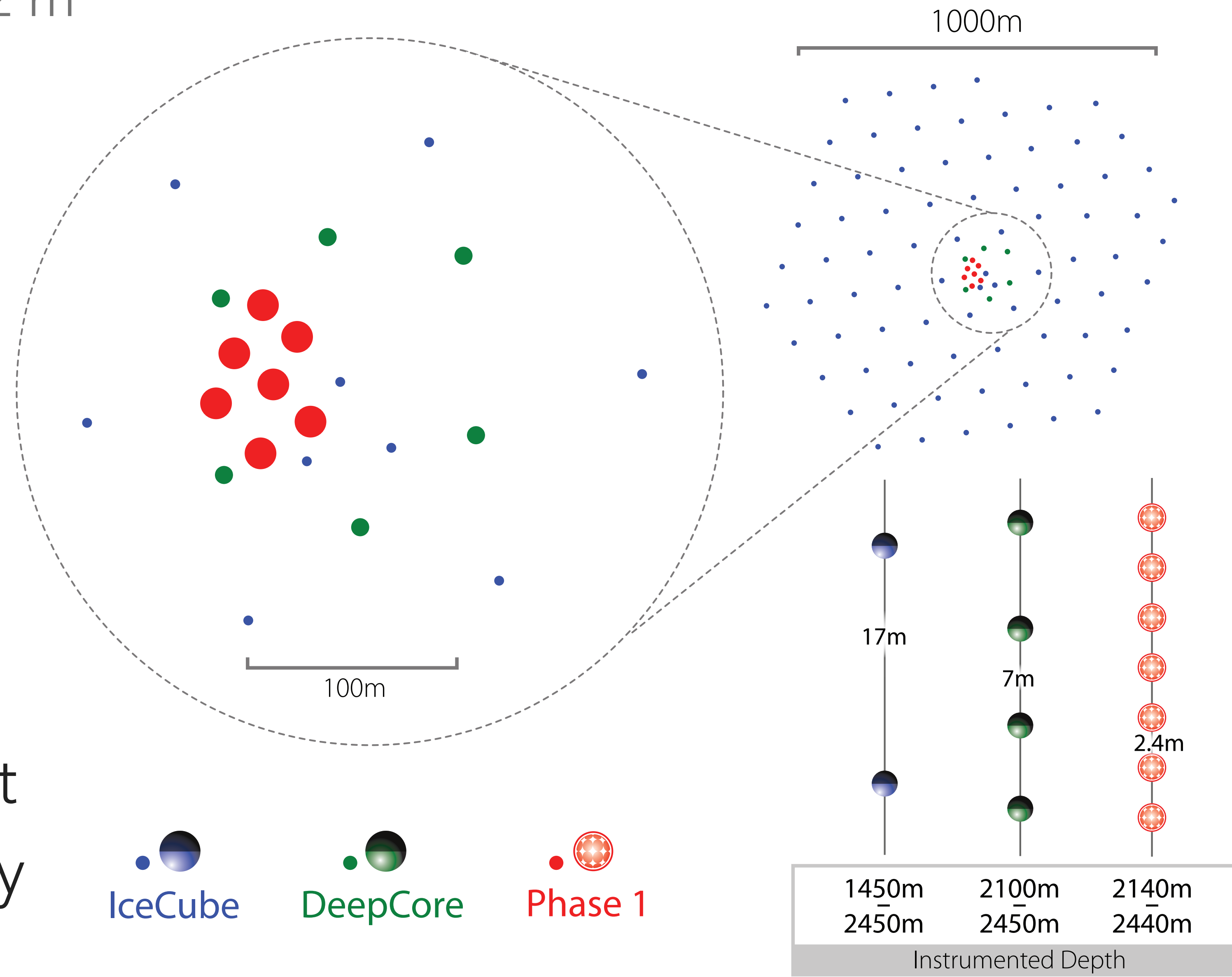
Measurement of mixing parameters with different method/energy range – Excellent sensitivity to octant of θ_{23}



Precision measurement of ν_τ appearance – probe unitarity of PMNS matrix

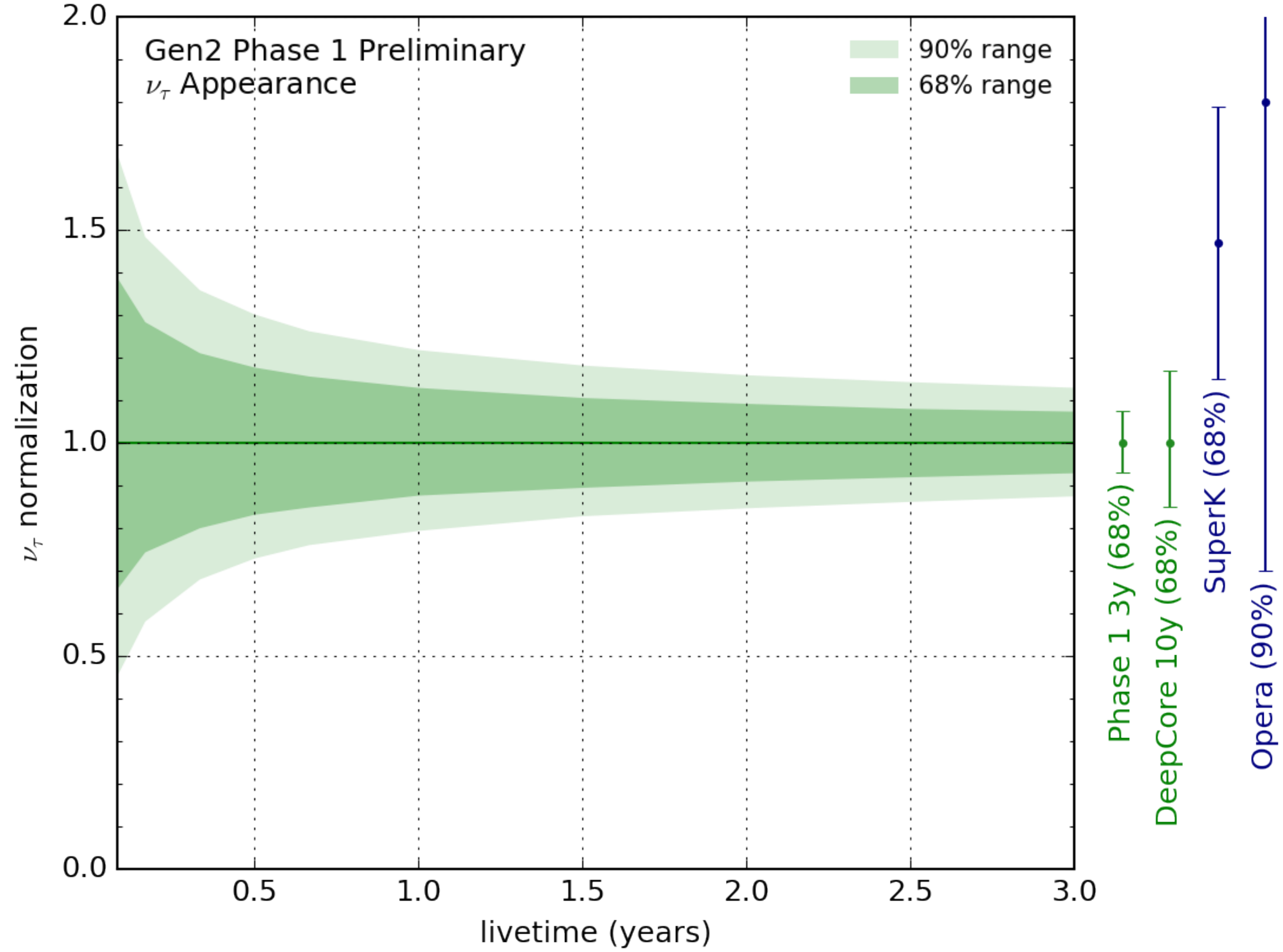
First Step: IceCube-Gen2 Phase 1

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices, incorporating lessons learned from a decade of IceCube calibration efforts
- Improve scientific capabilities of IceCube at both high and low energy



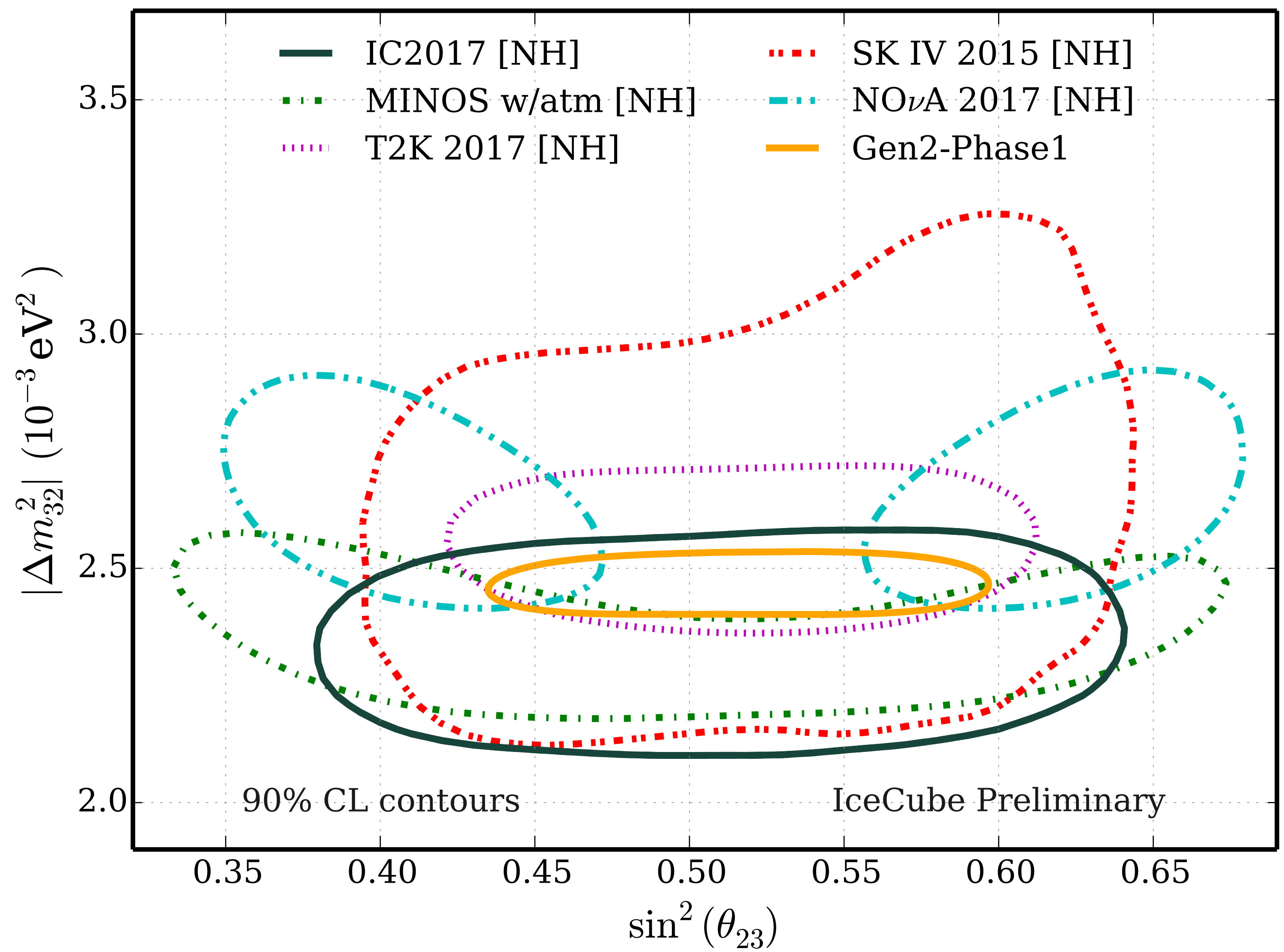
Tau Neutrino Appearance

- DeepCore will already make the world's most precise measurements of tau neutrino appearance
- IceCube-Gen2 Phase 1 required to achieve better than 10% precision on ν_τ appearance



Atmospheric Oscillation Parameters

- Currently unclear whether $\sin^2\theta_{23}$ is maximal
  - 3rd mass state made up of equal parts ν_μ, ν_τ
  - Evidence of new symmetry?
- IceCube, T2K consistent with maximal mixing, NOvA disfavors at 2.6σ



- Phase 1 will enable IceCube measurements with precision competitive with projected final T2K/NOvA results

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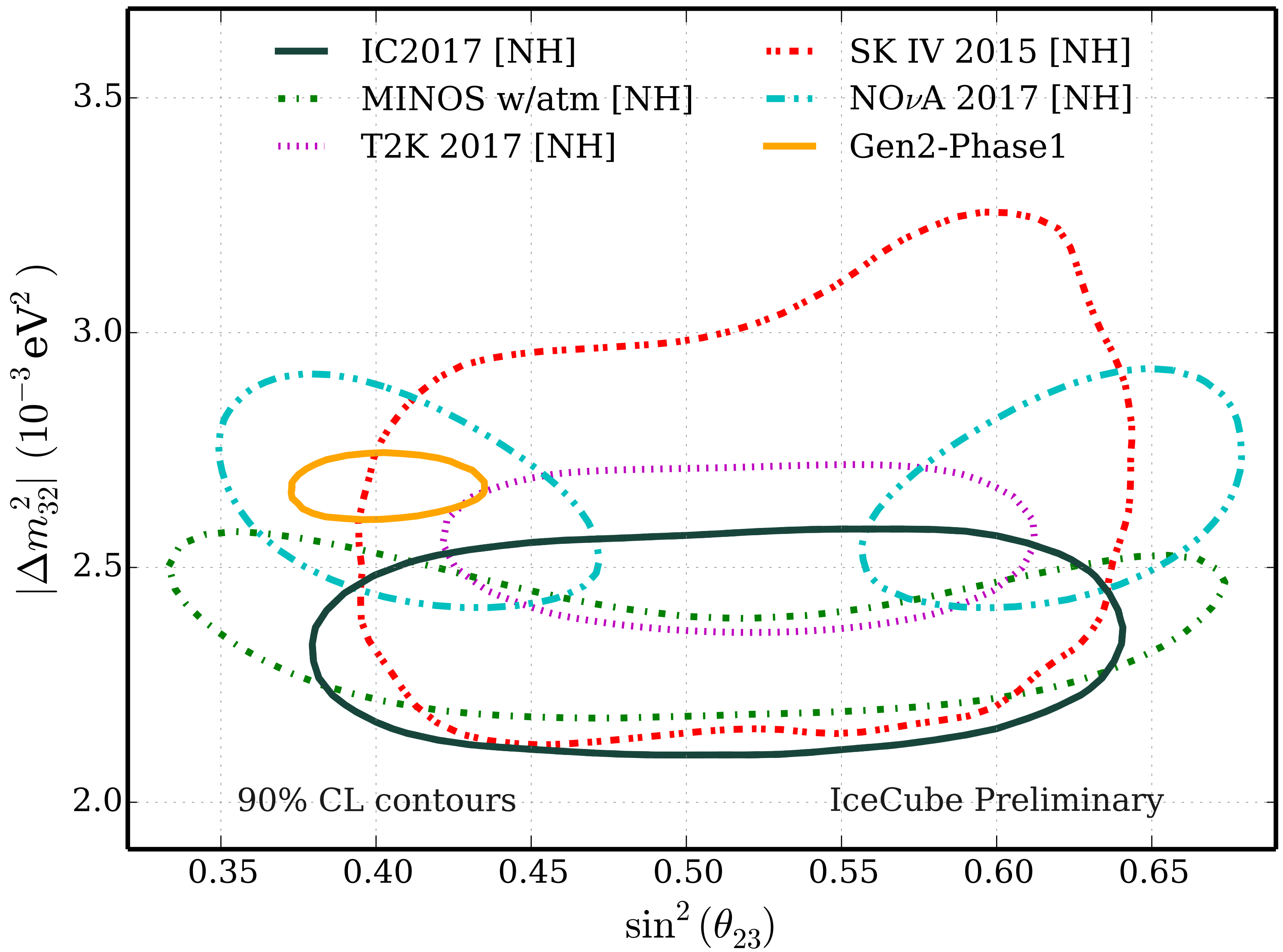

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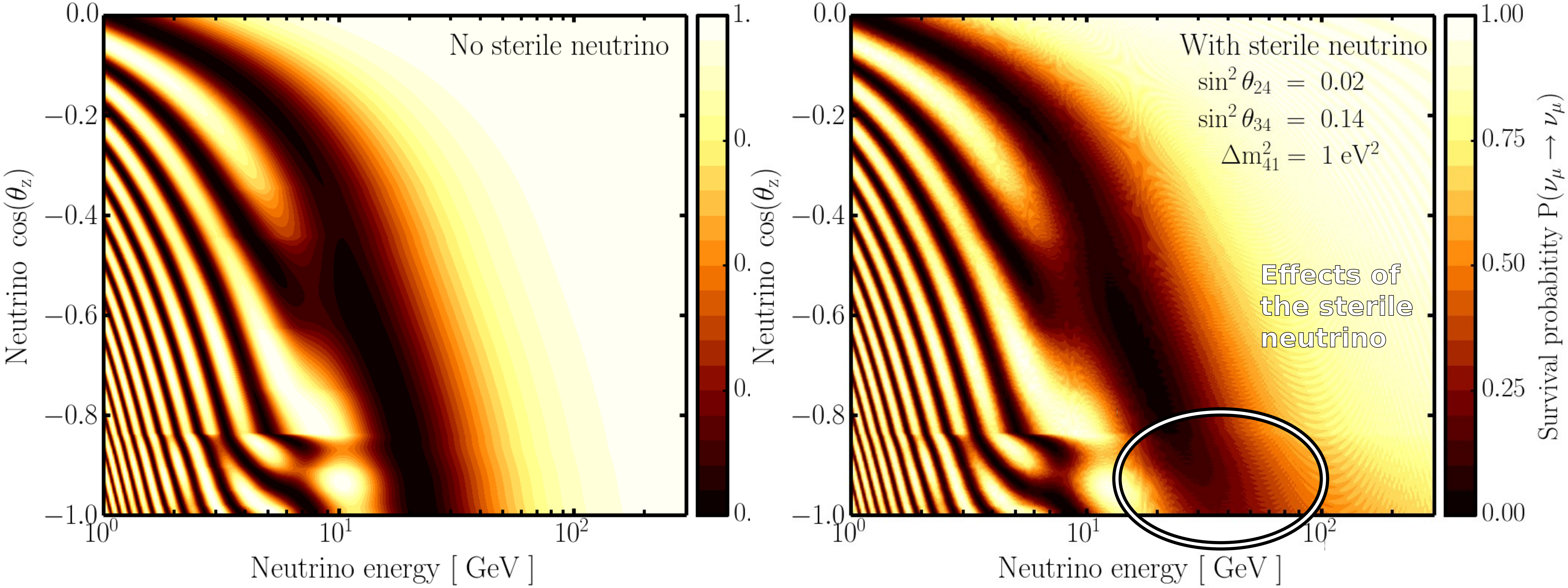
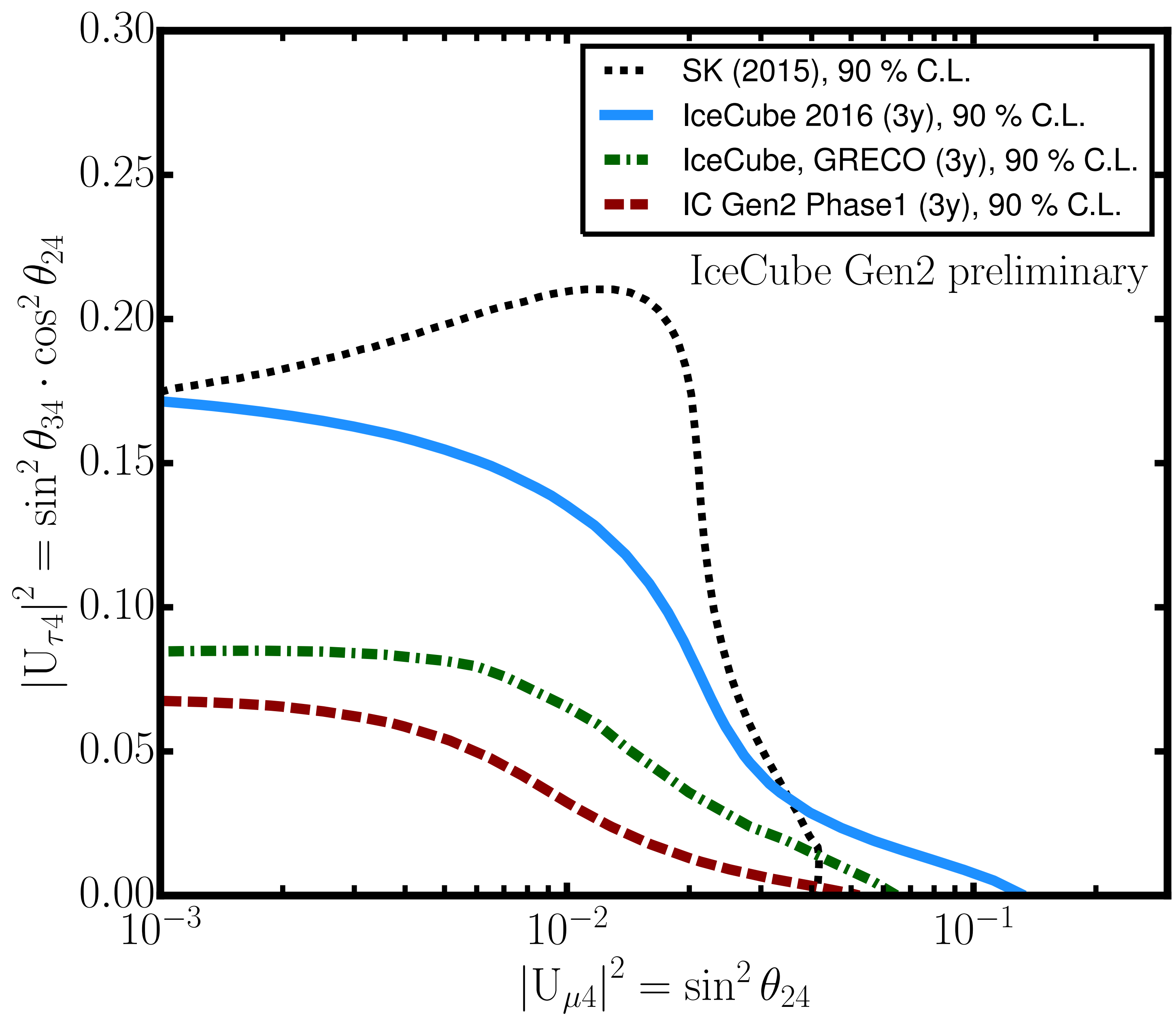
Sterile Neutrinos



Sterile Neutrinos

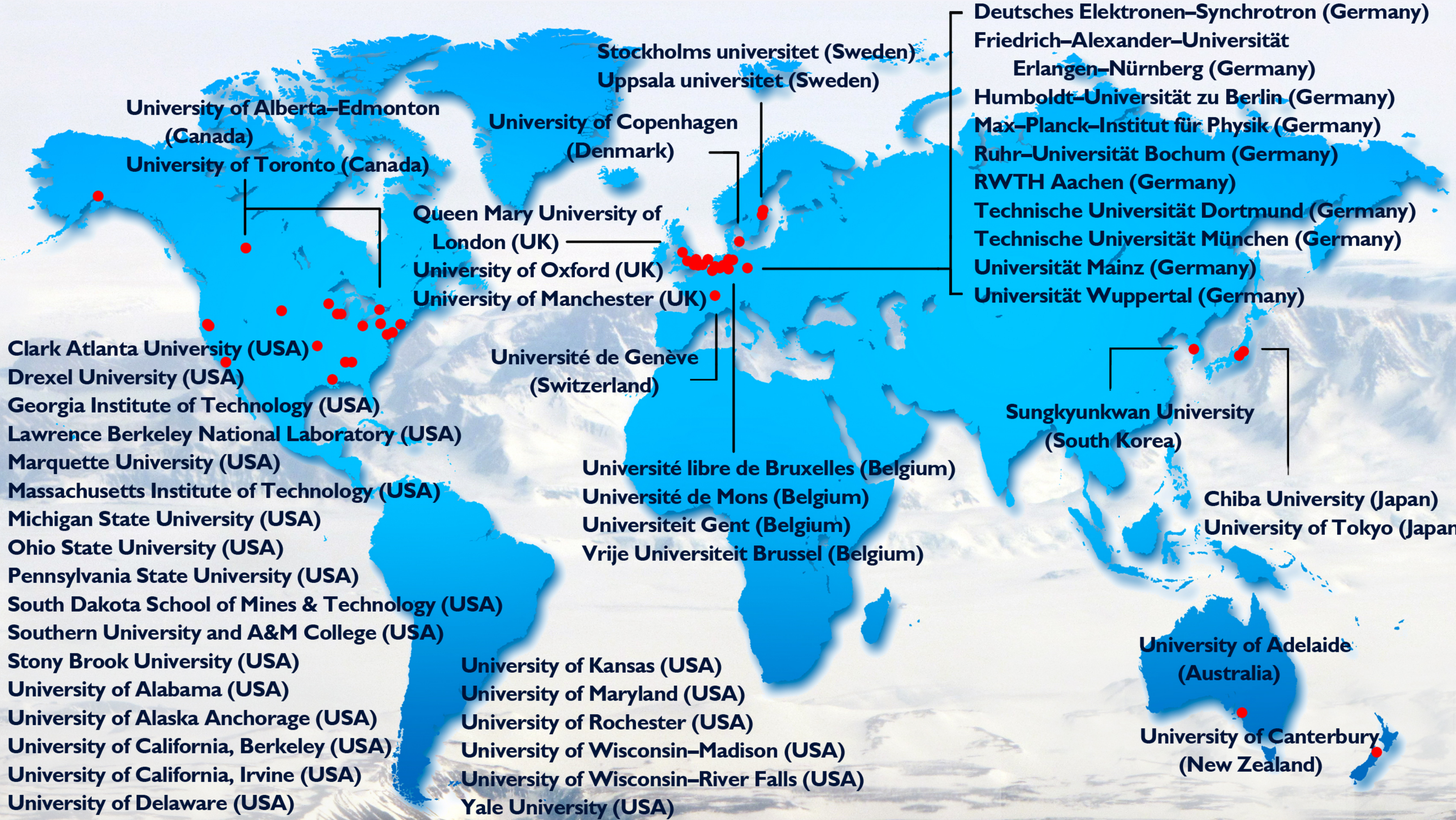
- Higher precision event reconstructions increase sensitivity considerably, even though the effect is mainly at E_ν > 20 GeV
- Phase 1 should produce similar improvements in searches for non-standard neutrino interactions (NSI) — under investigation



Summary and Outlook

- The IceCube Neutrino Observatory is a groundbreaking contributor to a new era of multimessenger astrophysics
- IceCube's copious background of atmospheric neutrinos also enables investigation of a range of neutrino and BSM physics
  - Neutrino oscillations, sterile neutrinos, UHE neutrino interactions, dark matter, Lorentz violation, monopoles, etc.
- Planning is underway for IceCube-Gen2: accelerate progress toward understanding astrophysical neutrinos, plus a rich neutrino physics program with PINGU
  - First step: Phase 1, substantially increase IceCube reach for both high energy neutrino astronomy and low energy neutrino physics

The IceCube-Gen2 Collaboration



International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)