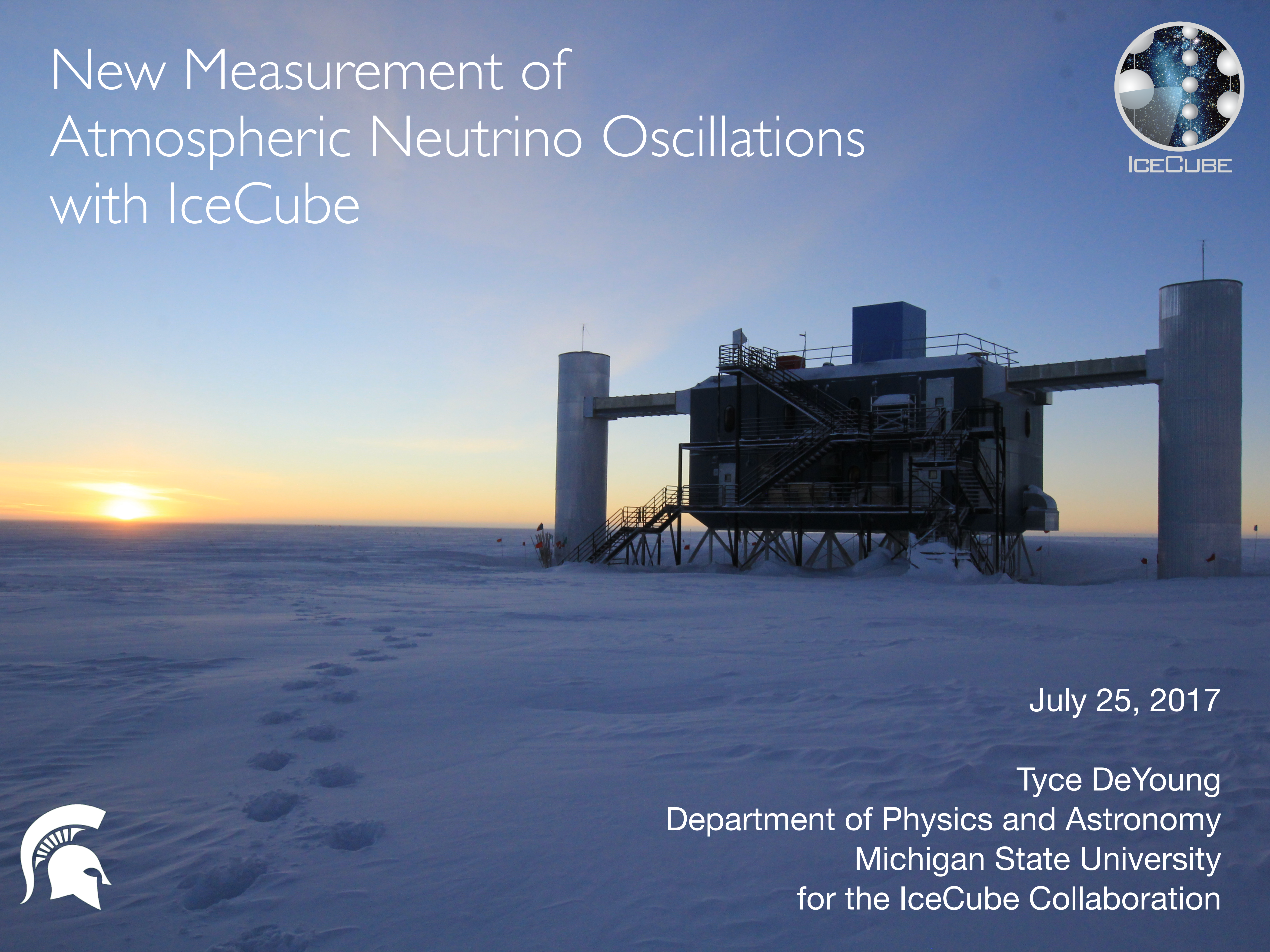
New Measurement of Atmospheric Neutrino Oscillations with IceCube



July 25, 2017

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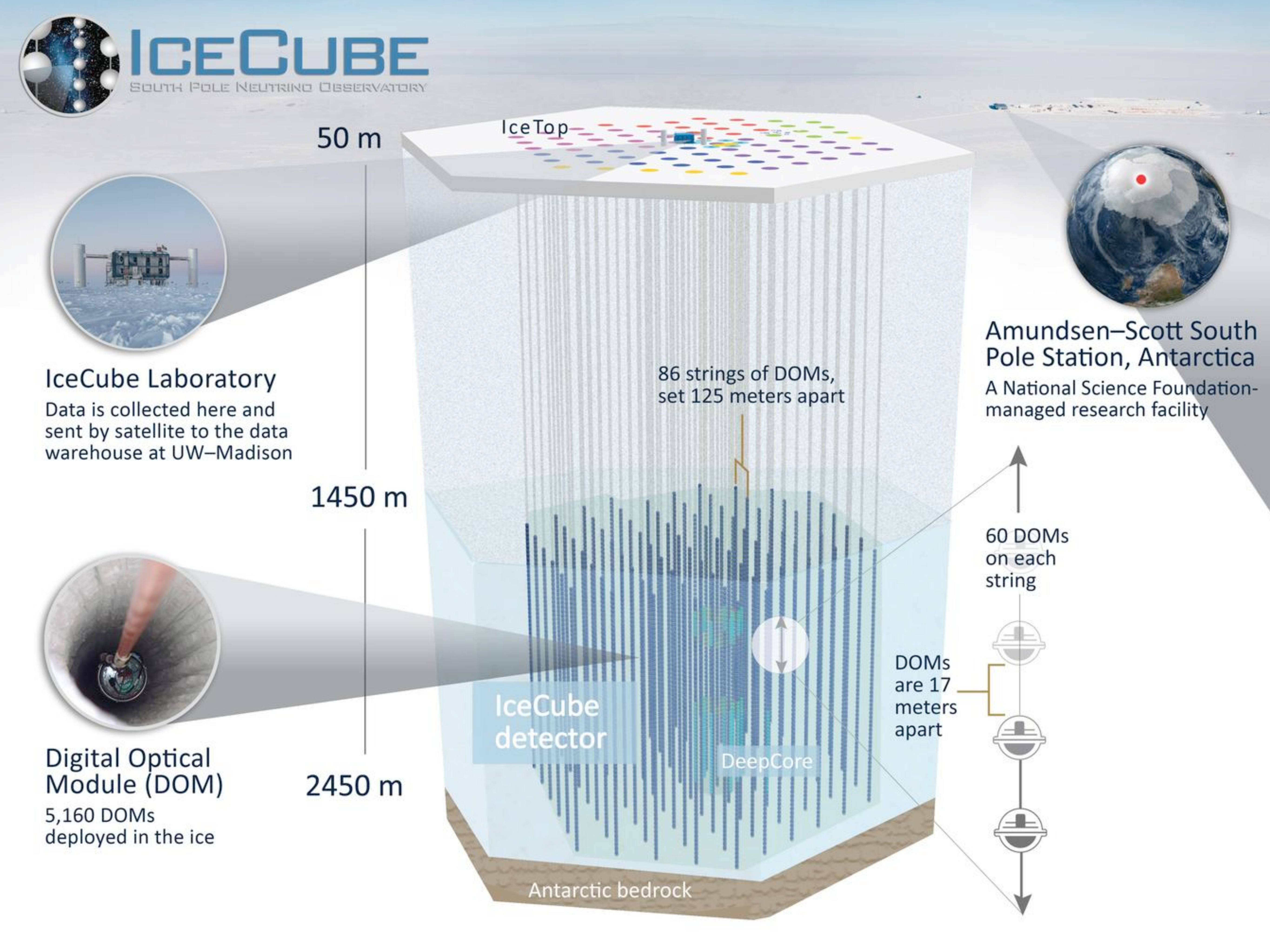
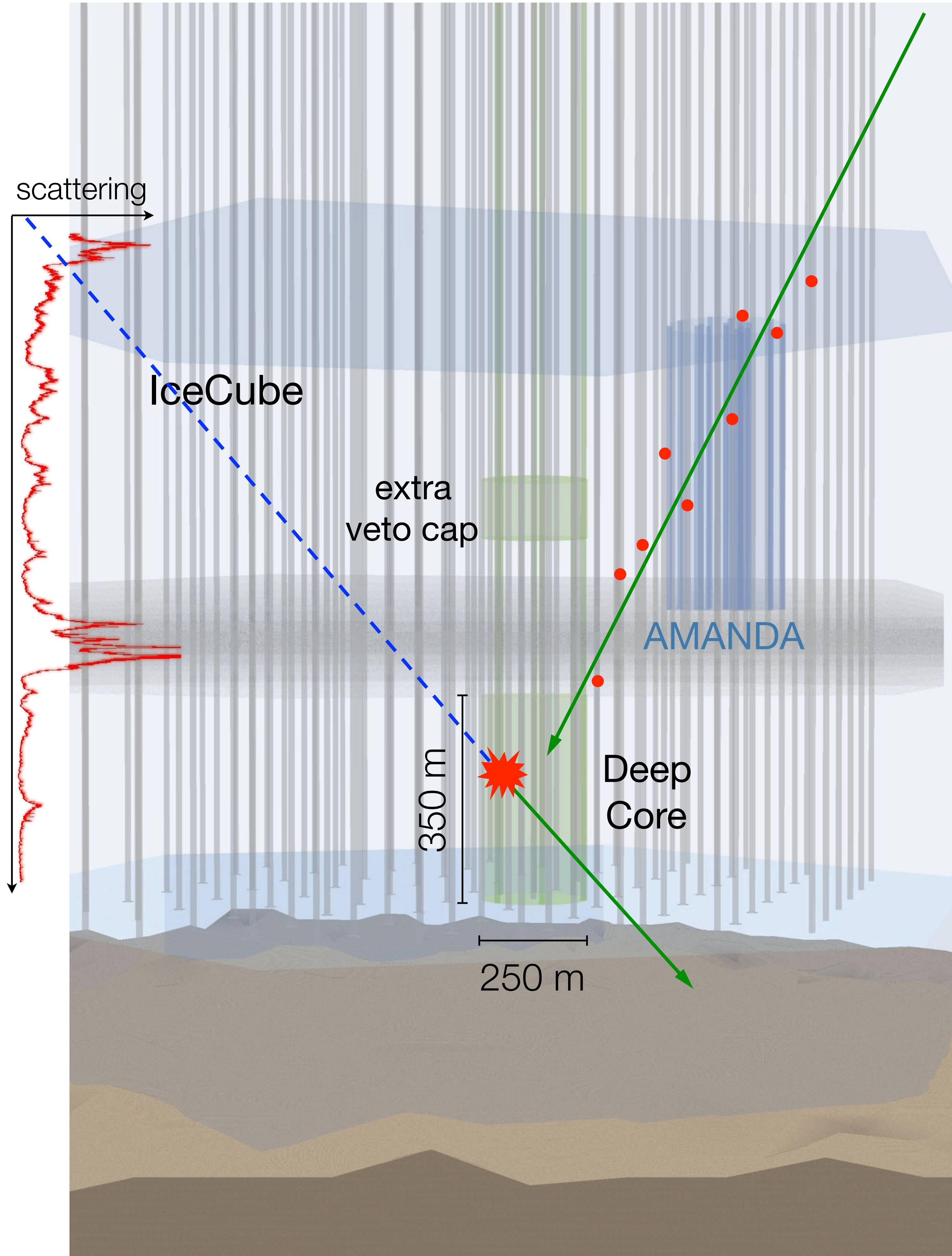

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic 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 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

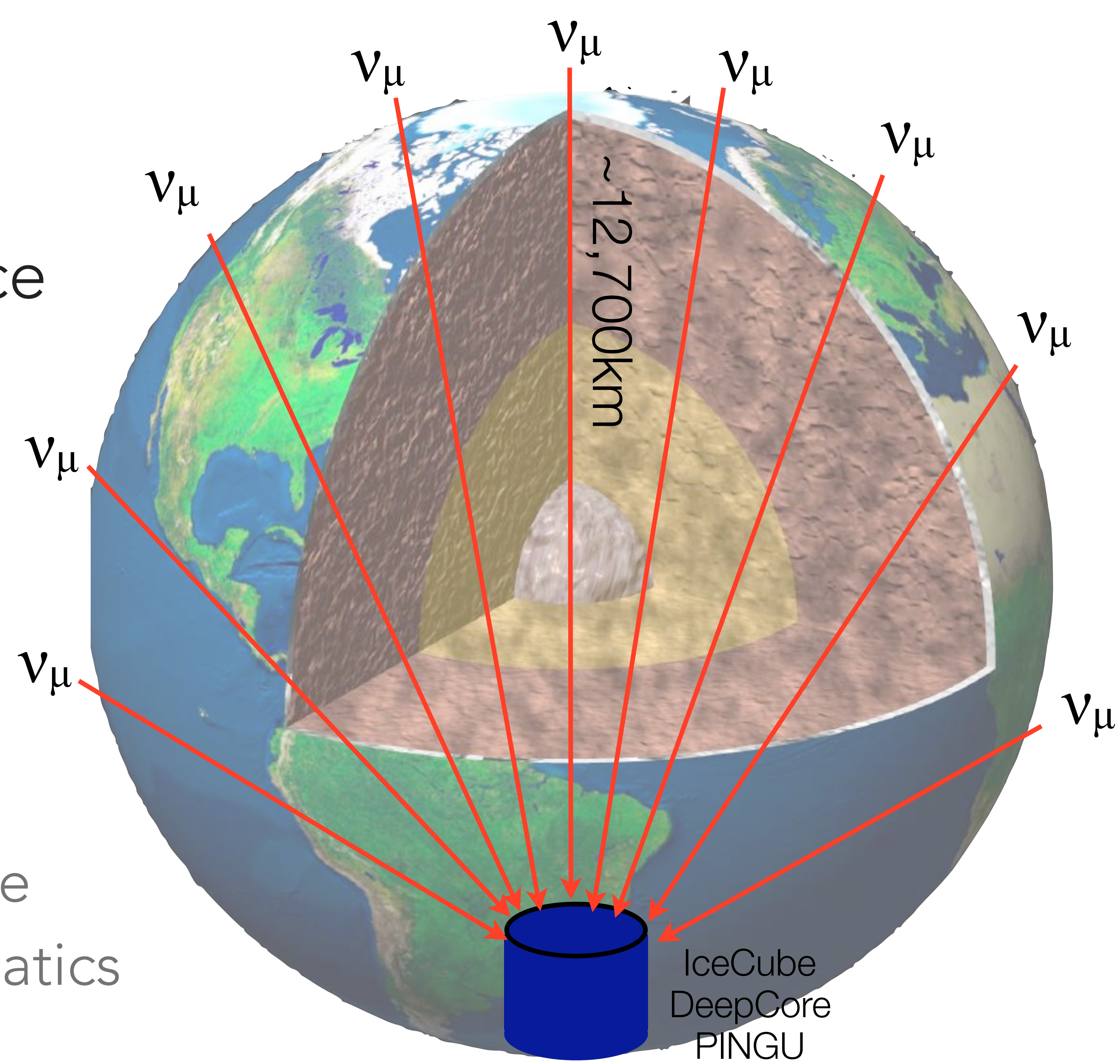
- Searches for dark matter-induced neutrino flux from…
  - …the Sun: *Phys. Rev. Lett.* 110, 131302 (2013), *Eur. Phys. J.* C77, 146 (2017)
  - …the Earth: *Eur. Phys. J.* C77, 82 (2017)
  - …Galactic Center: *Eur. Phys. J.* C75. 492 (2015), *Eur. Phys. J.* C76. 531 (2016), arXiv:1705.08103
  - …Galactic Halo: *Eur. Phys. J.* C75. 20 (2015)
  - …dwarf galaxies: *Phys. Rev.* D88, 122001 (2013)

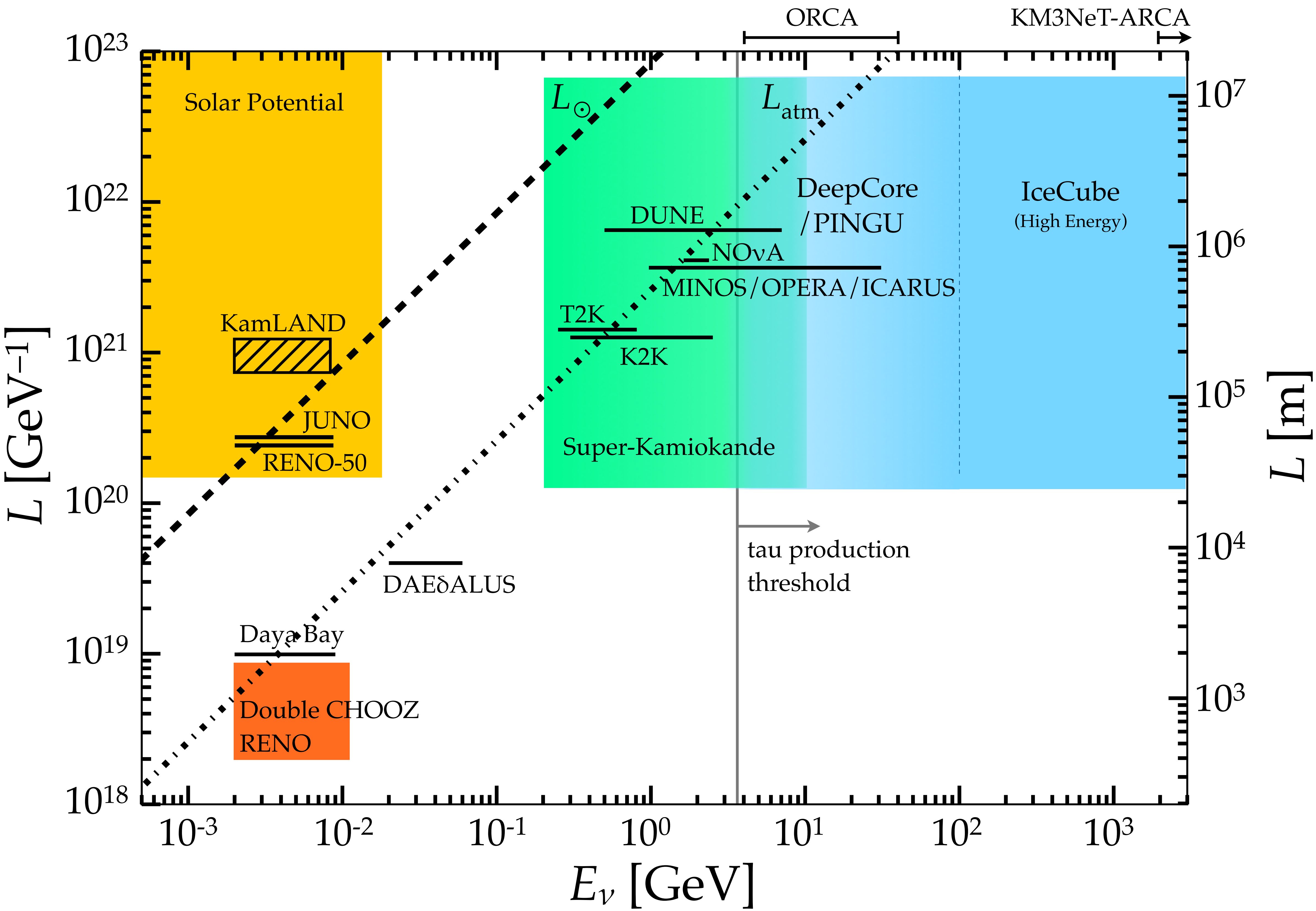
see talk by Morten Medici

- 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 100 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 oscillations (unique dependence on angle *and* energy) from systematics

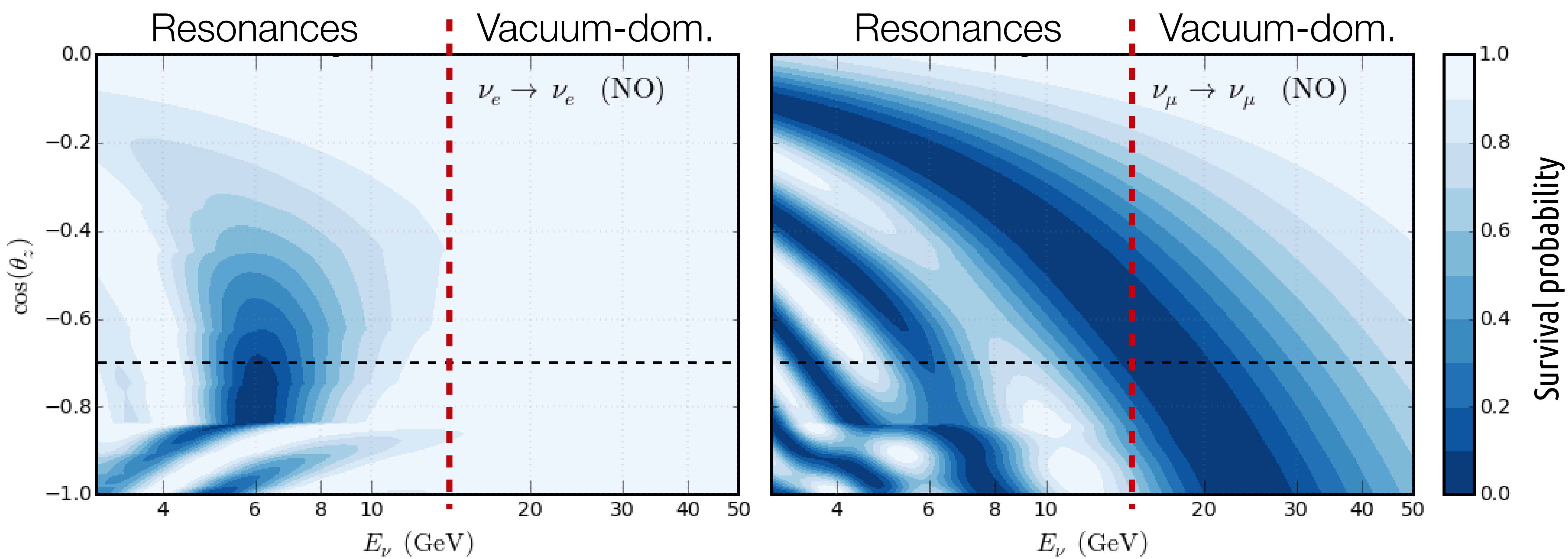




Probing oscillation physics at a range of baselines and energies not accessible to long-baseline or reactor neutrino experiments

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

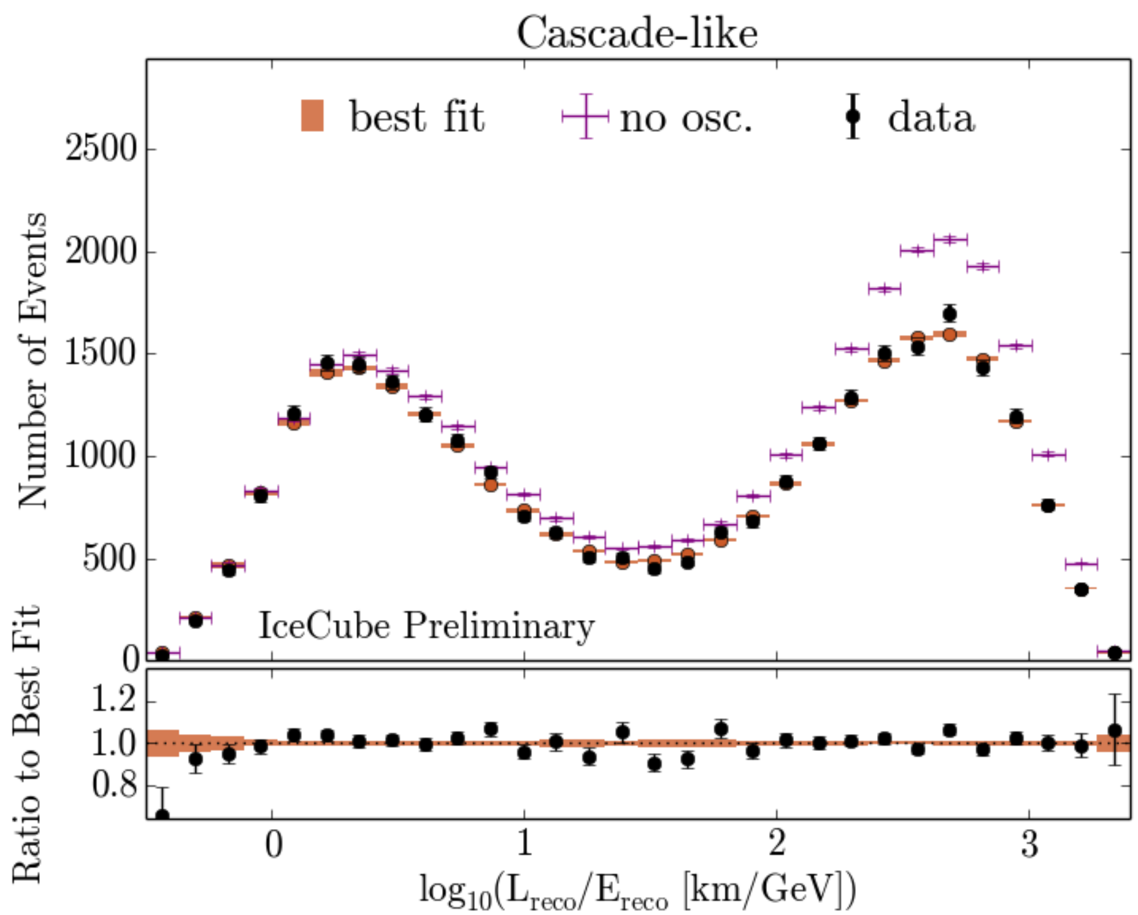
see talk by Michael Larson

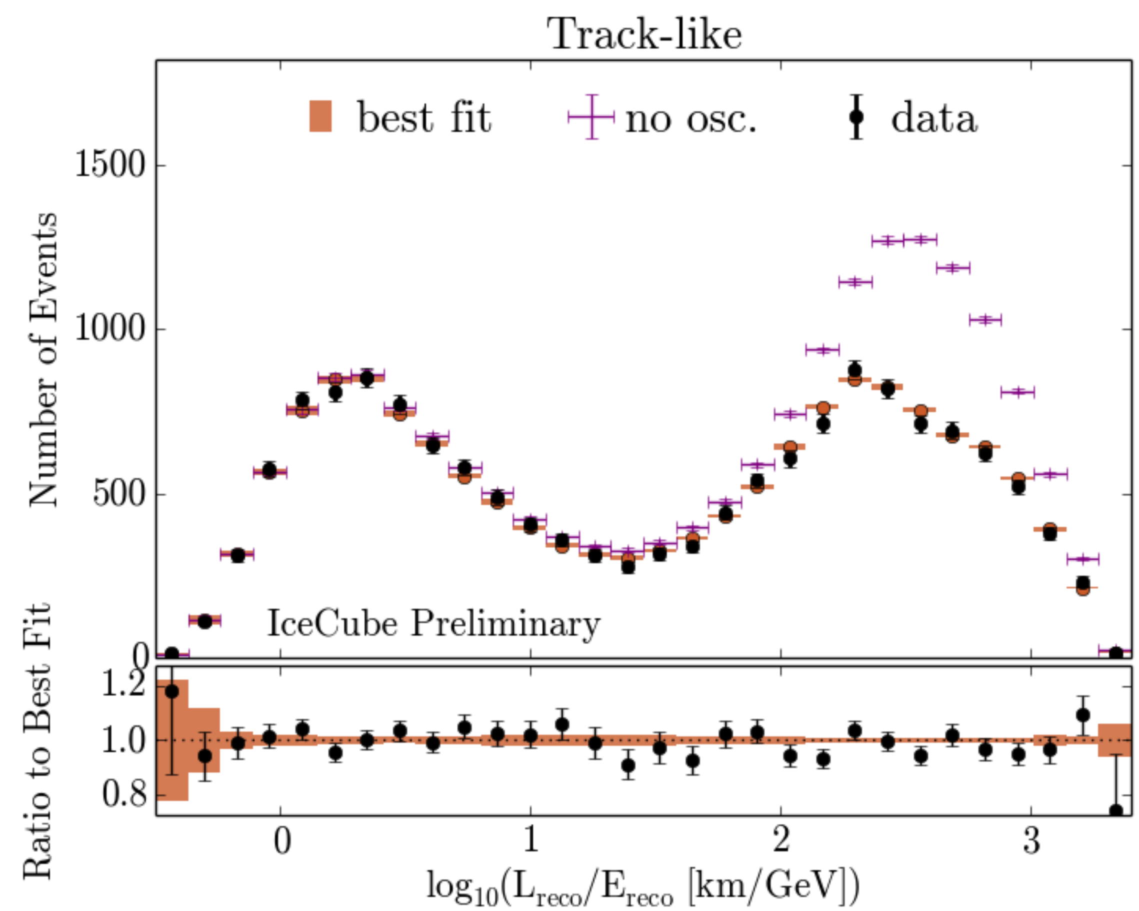
- Below 10-15 GeV, matter resonances depending on mass ordering

see talk by Martin Leuermann

Atmospheric Oscillations with DeepCore

arXiv:1707.07081





- 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

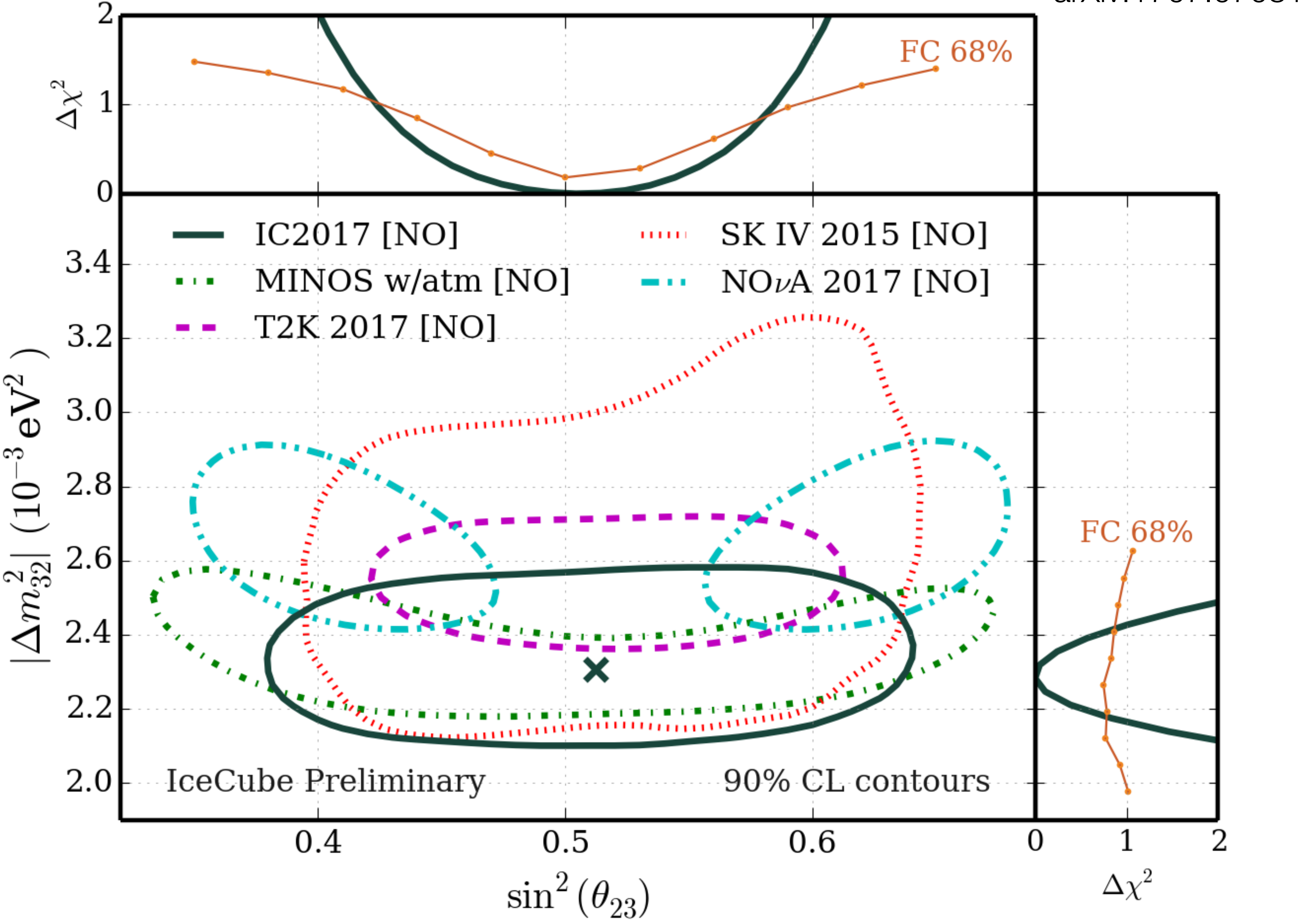
arXiv:1707.07081

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

arXiv:1707.07081



Outlook

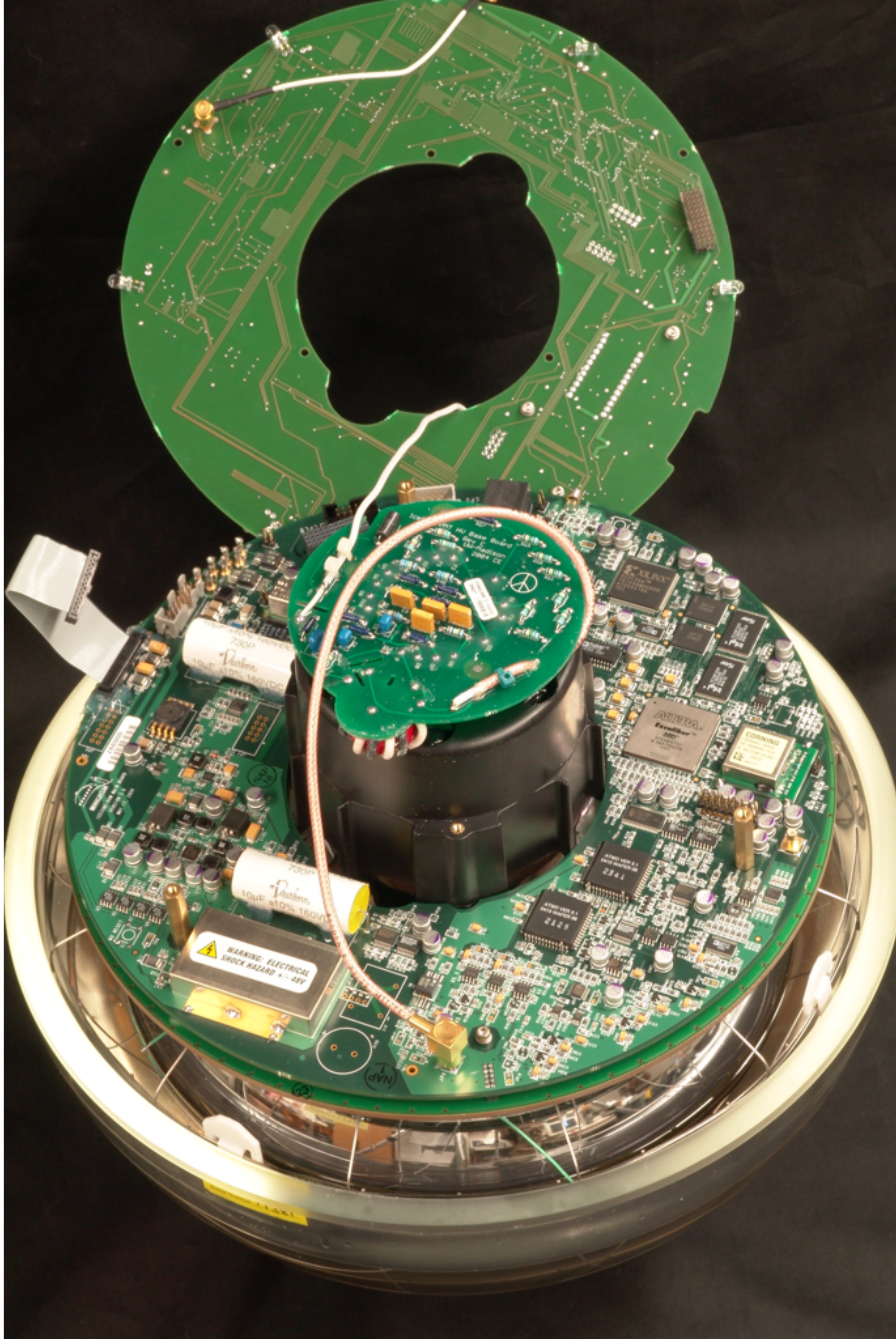
- In addition to multimessenger astrophysics, IceCube's copious background of atmospheric neutrinos enables investigation of a range of neutrino physics

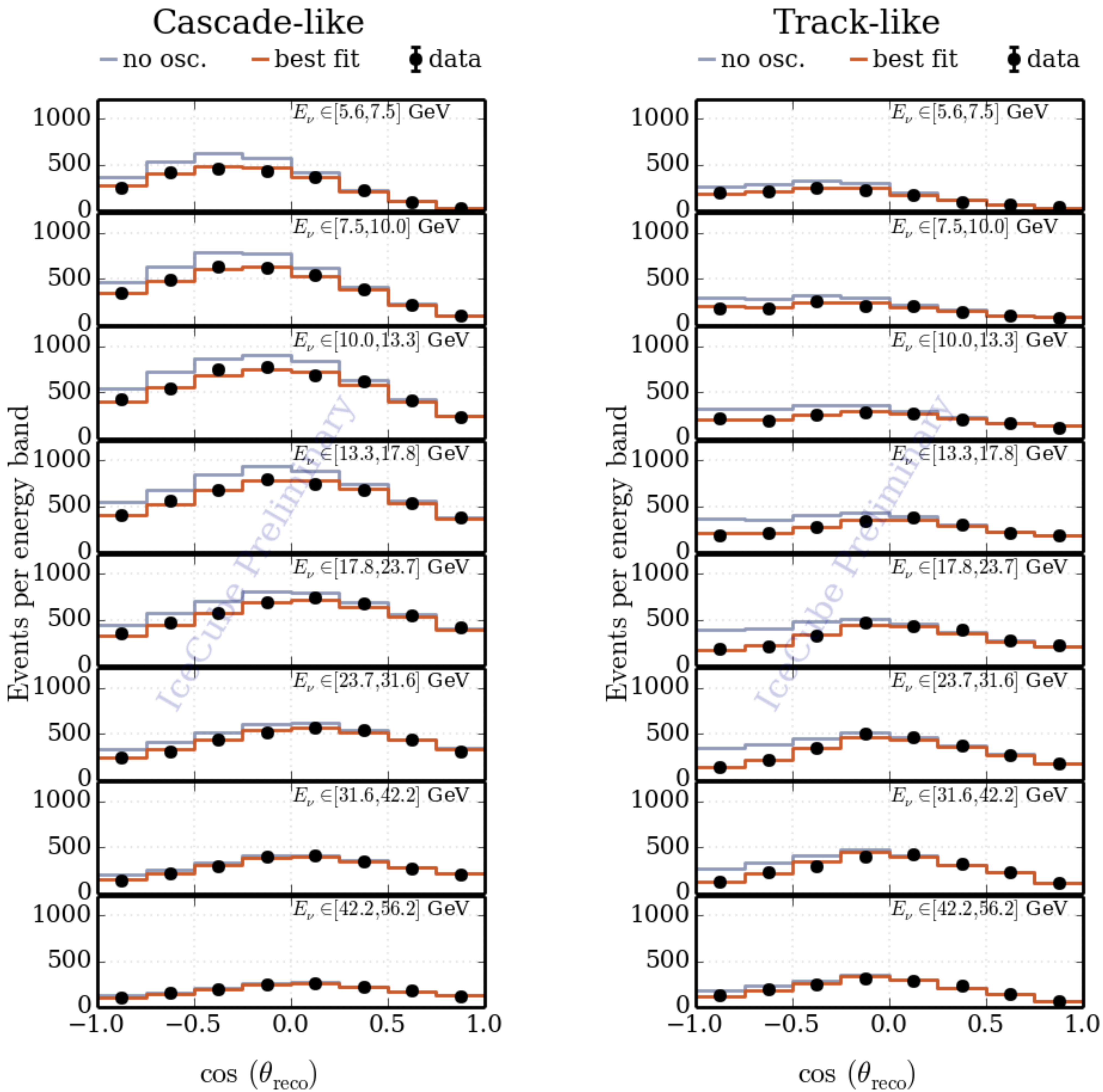
- Observations in a unique energy range
  - Different systematics than long-baseline experiments
  - Sensitivity to possible new physics in the neutrino sector

- New measurement of atmospheric oscillations has precision similar to NOvA, T2K, MINOS; prefers maximal mixing
  - Follow-on analyses using this data set, and a variant with even higher statistics, are underway

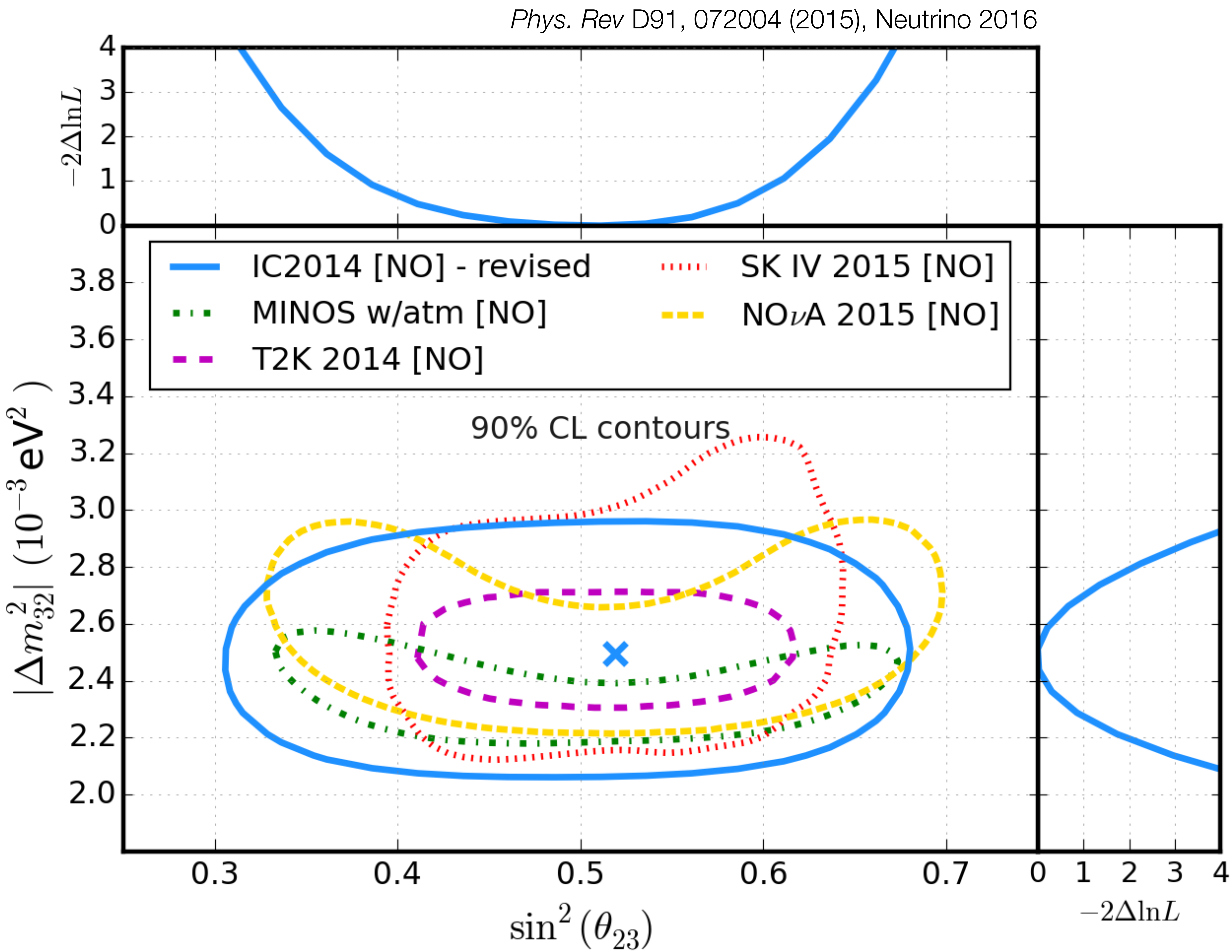
Digital Optical Module

- Onboard capture of PMT waveforms
  - 300 MS/s for 400 ns with custom ATWD chip
  - 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%





Cascade-like
Track-like
no osc.
best fit
data
$E_\nu \in [5.6, 7.5]$ GeV
$E_\nu \in [7.5, 10.0]$ GeV
$E_\nu \in [10.0, 13.3]$ GeV
$E_\nu \in [13.3, 17.8]$ GeV
$E_\nu \in [17.8, 23.7]$ GeV
$E_\nu \in [23.7, 31.6]$ GeV
$E_\nu \in [31.6, 42.2]$ GeV
$E_\nu \in [42.2, 56.2]$ GeV
Events per energy band
$\cos(\theta_{\mathrm{reco}})$
IceCube Preliminary



Phys. Rev D91, 072004 (2015), Neutrino 2016
IC2014 [NO] - revised
SK IV 2015 [NO]
MINOS w/atm [NO]
NOνA 2015 [NO]
T2K 2014 [NO]
90% CL contours
$|\Delta m^2_{32}|\ (10^{-3}\,\mathrm{eV}^2)$
$\sin^2(\theta_{23})$
$-2\Delta\ln L$