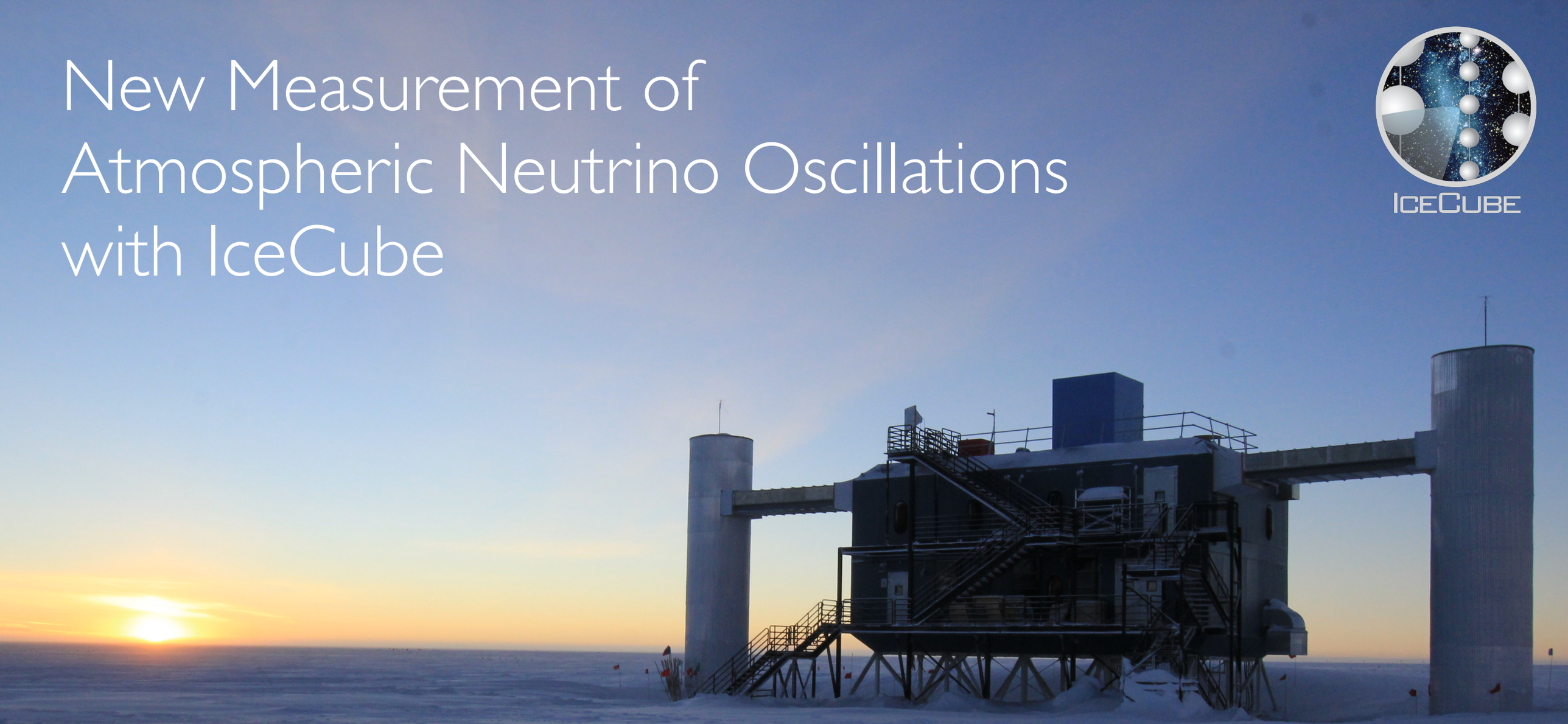
New Measurement of Atmospheric Neutrino Oscillations with IceCube



August 8, 2017

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IceCube

South Pole Neutrino Observatory

50 m

IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison

1450 m

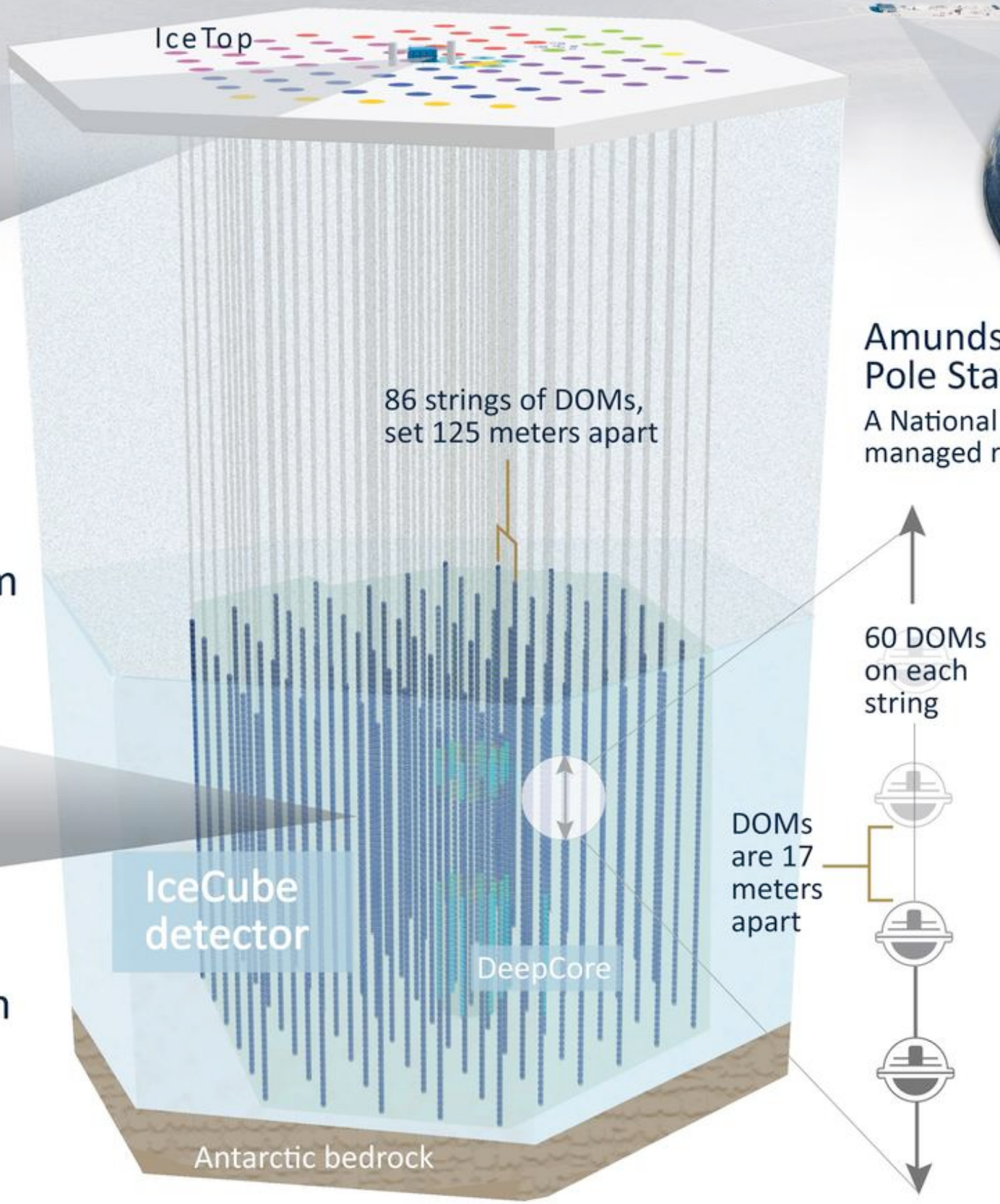
Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

2450 m

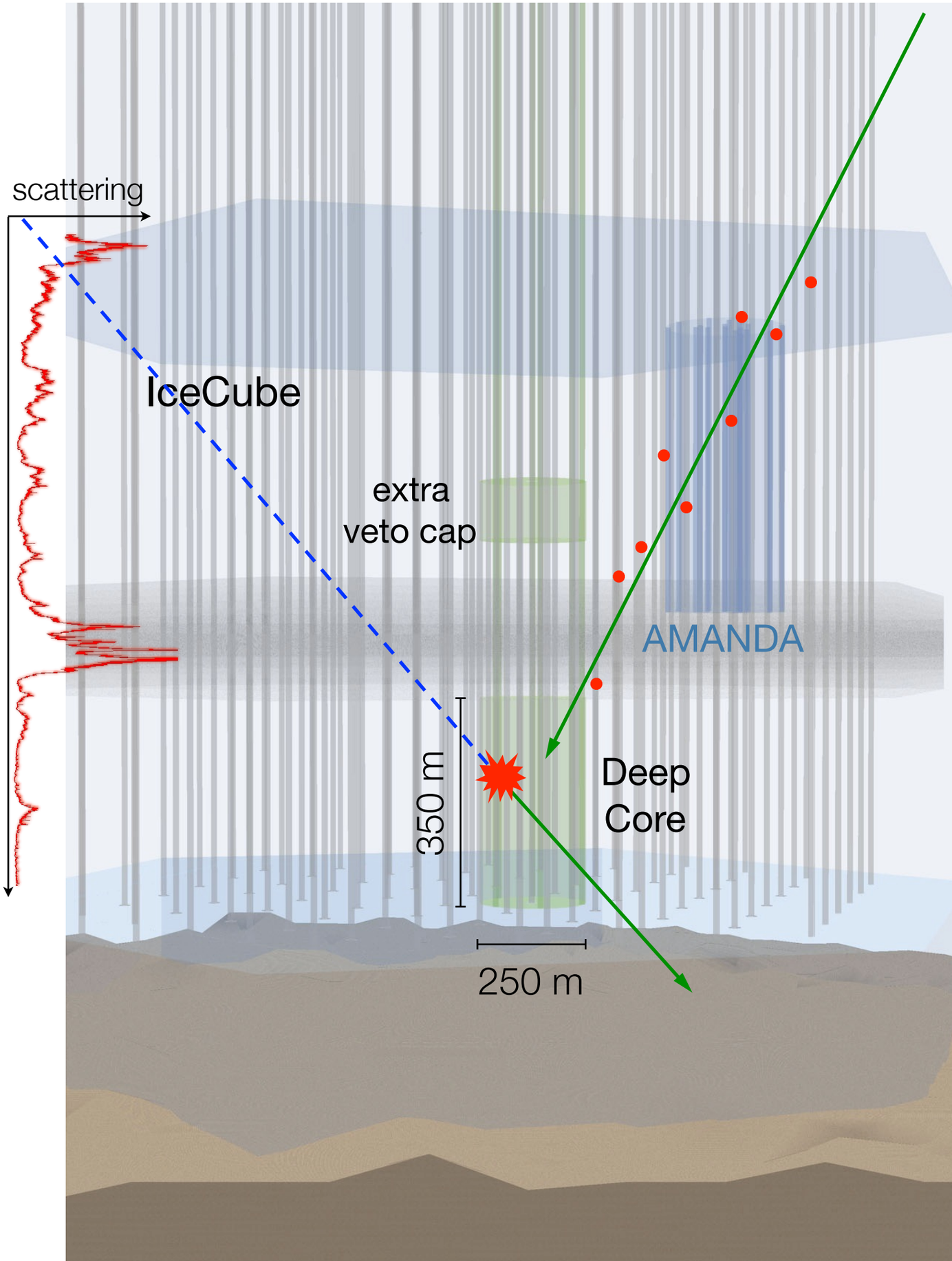
Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility



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



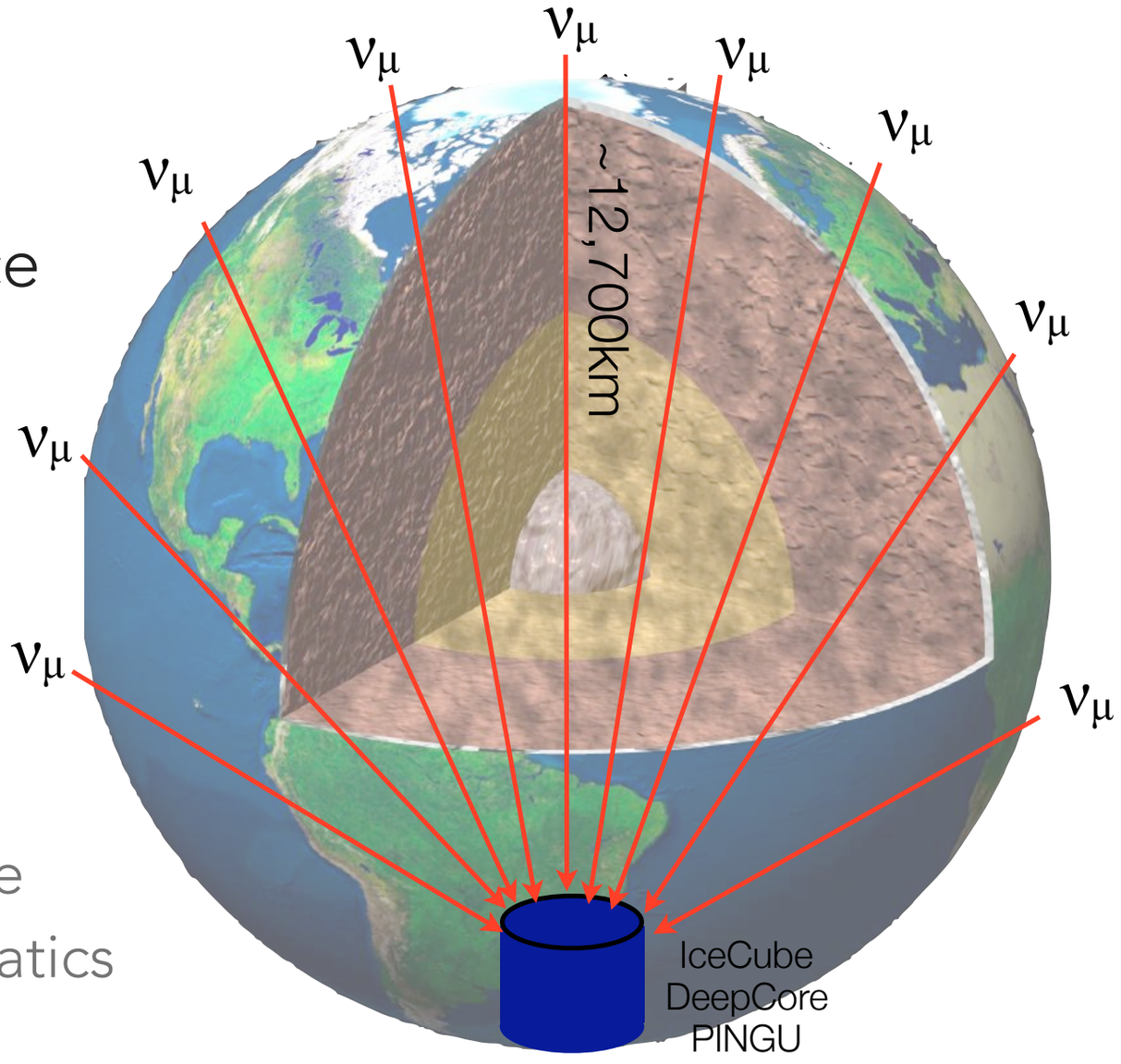
DeepCore Physics: 5-100 GeV

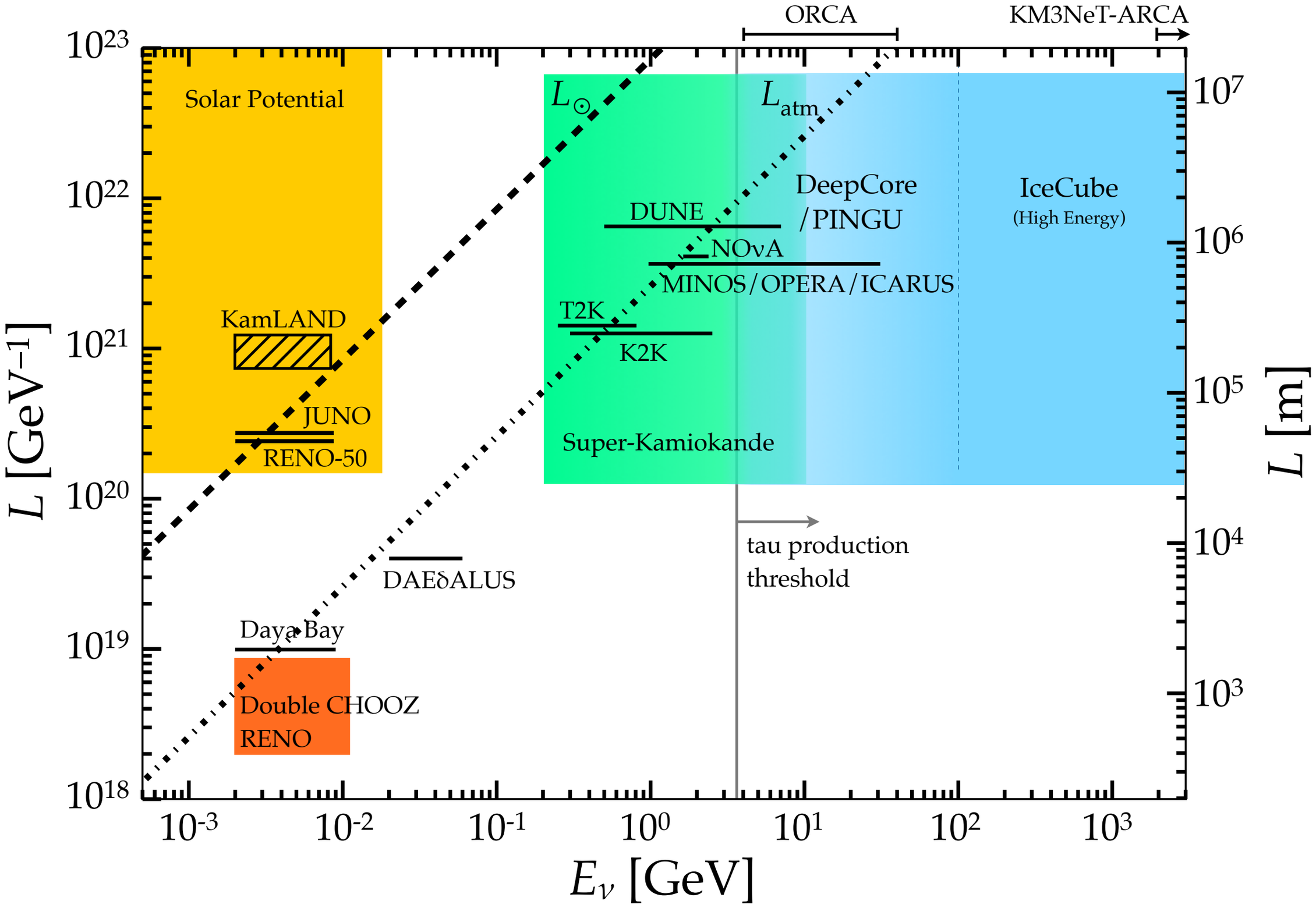
- Searches for dark matter-induced neutrino flux from…
  - …the Sun: *Phys. Rev. Lett.* 110, 131302 (2013), *Eur. Phys. J.* C77, 146 (2017)
  - …the Earth: *Eur. Phys. J.* C77, 82 (2017)
  - …Galactic Center: *Eur. Phys. J.* C75. 492 (2015), *Eur. Phys. J.* C76. 531 (2016), arXiv:1705.08103
  - …Galactic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

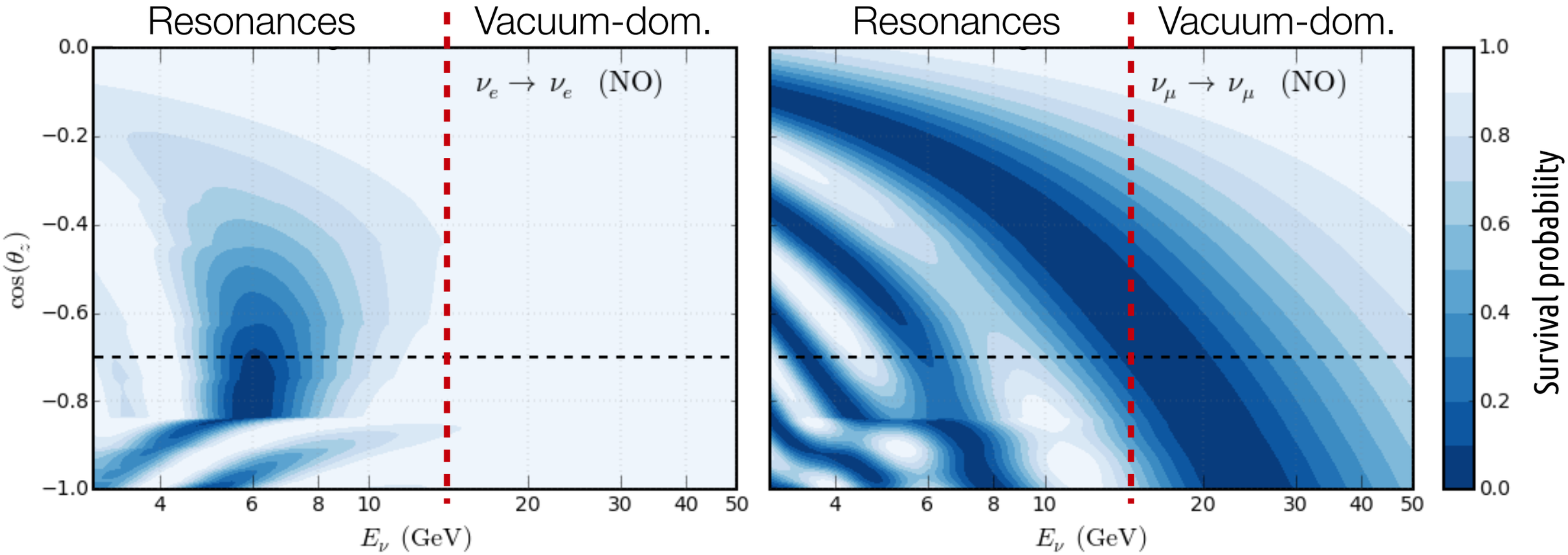




Probing oscillation physics at a range of baselines and energies not accessible to long-baseline or reactor neutrino experiments

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

Analysis Improvements

IceCube 2014

- *Phys Rev* D91, 072004 (2015)
- Focused on "golden" ν_μ CC events
  – clear muon tracks with several un-scattered photons
- Used only up-going events to reduce backgrounds
- Residual atmospheric muon background estimated from data

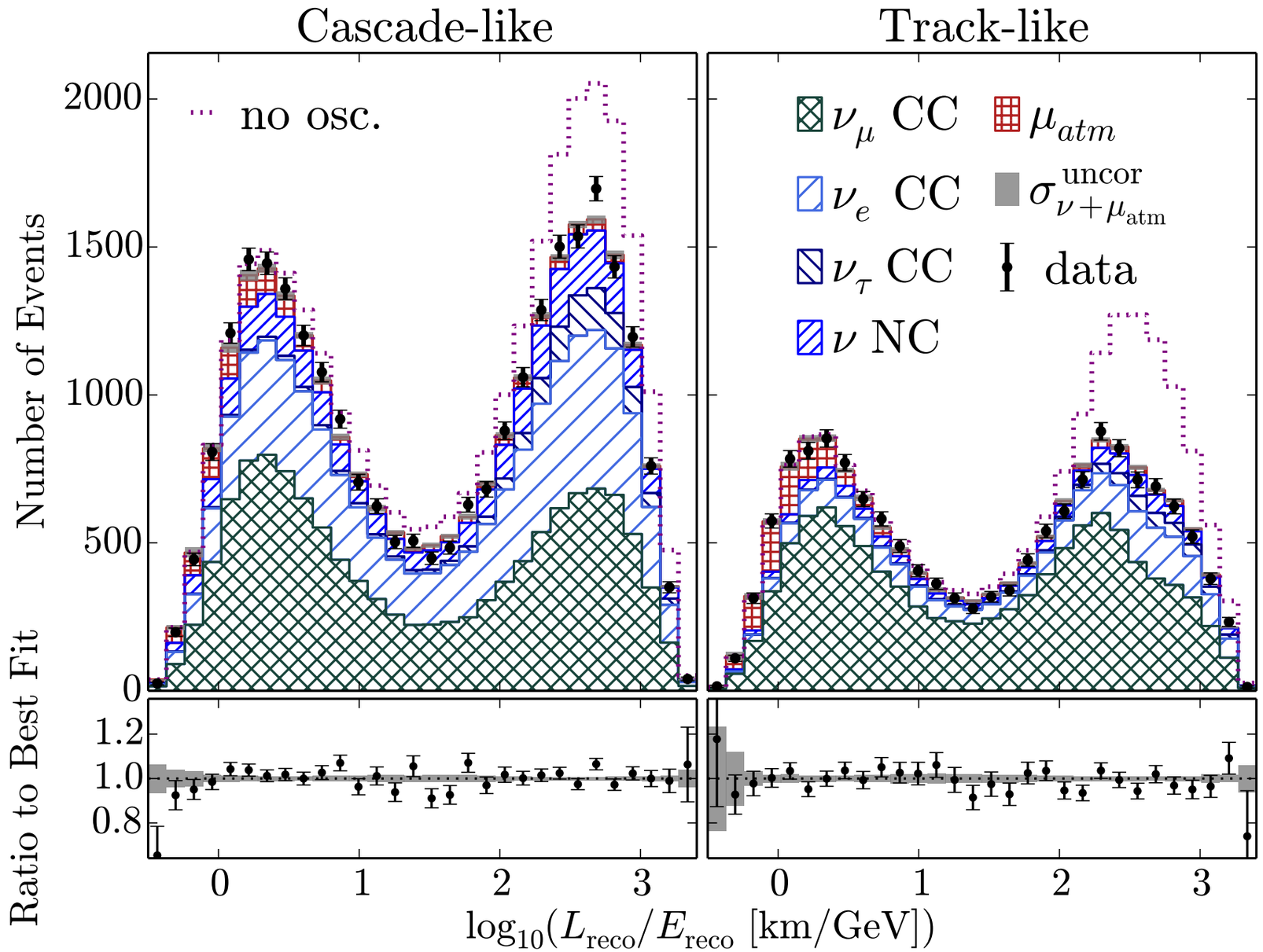
IceCube 2017

- arXiv:1707.07081
- Order of magnitude increase in statistics
- Full likelihood reconstruction provides similar mean energy, angular resolution despite inclusion of lower-quality events
- Incorporates non-ν_μ CC ("cascade") events and down-going events to constrain systematics
- Residual atmospheric muon background estimated from data
- Fitter accounts for statistical uncertainty in expectation

Atmospheric Oscillations with DeepCore

arXiv:1707.07081

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



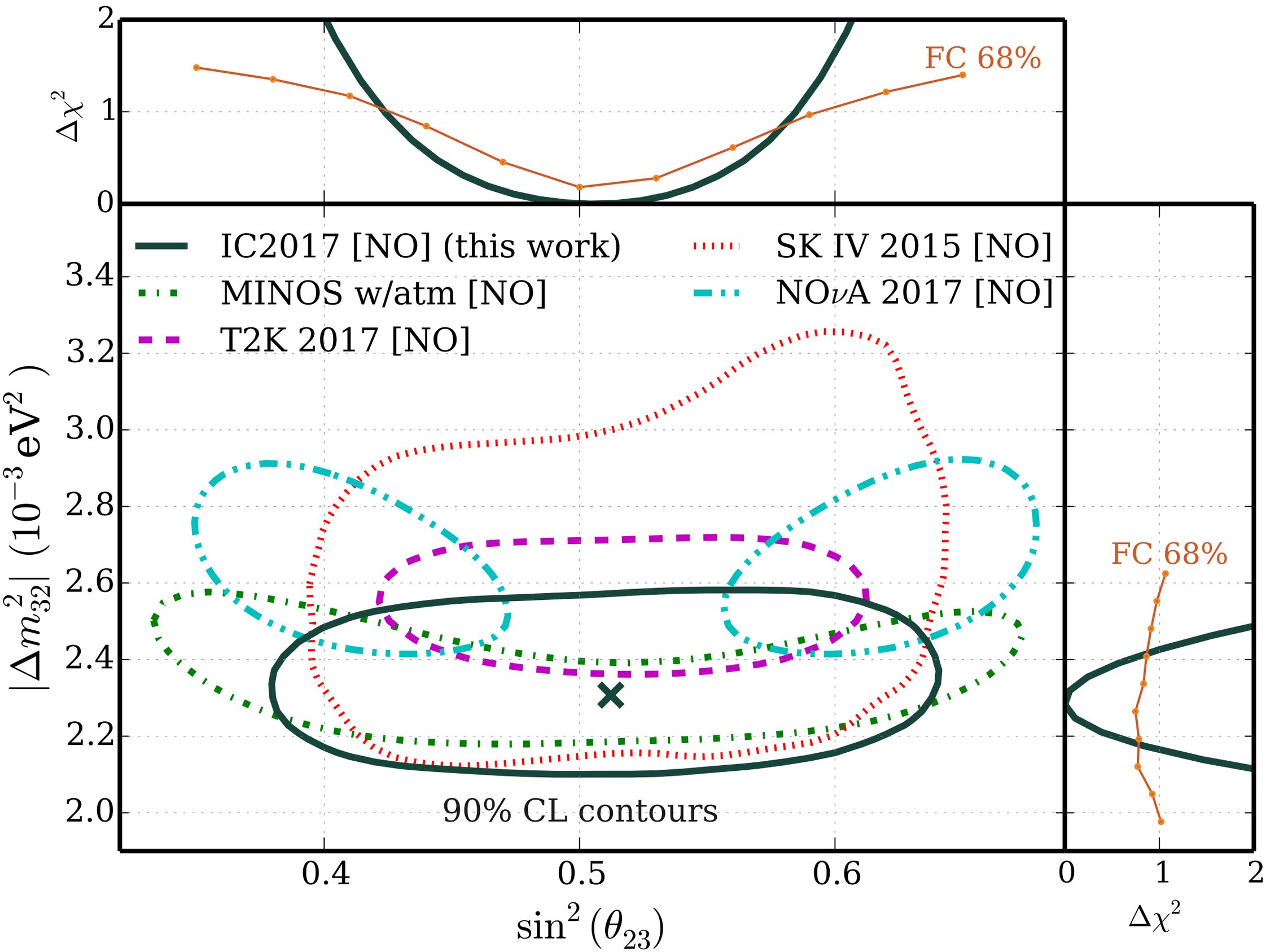
Nuisance Parameters

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, $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{13} = 2.17 \times 10^{-2}$, and $\delta_{CP} = 0°$

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



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

THE ICECUBE COLLABORATION

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DENMARK
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ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
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University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

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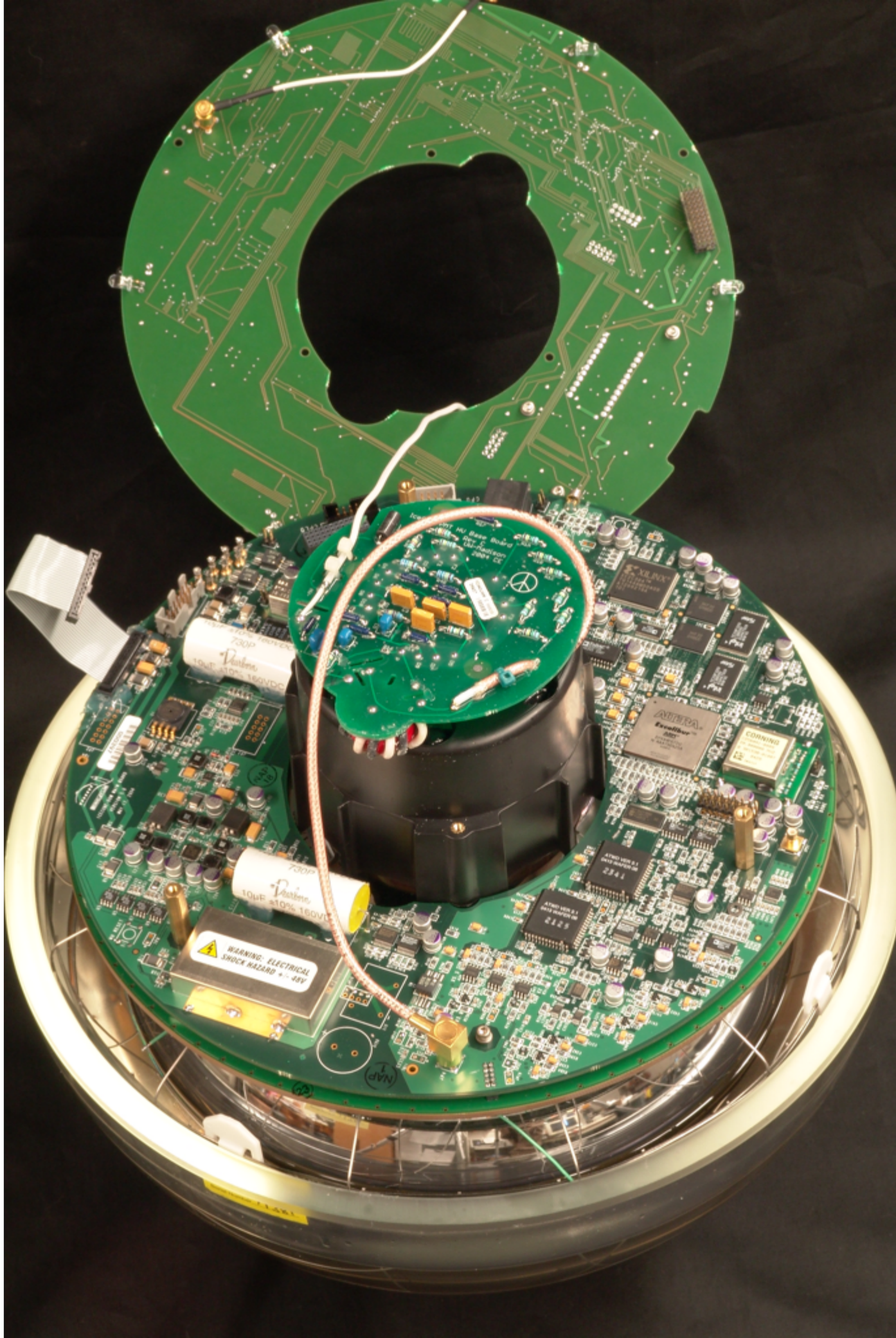
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube
South Pole Neutrino Observatory

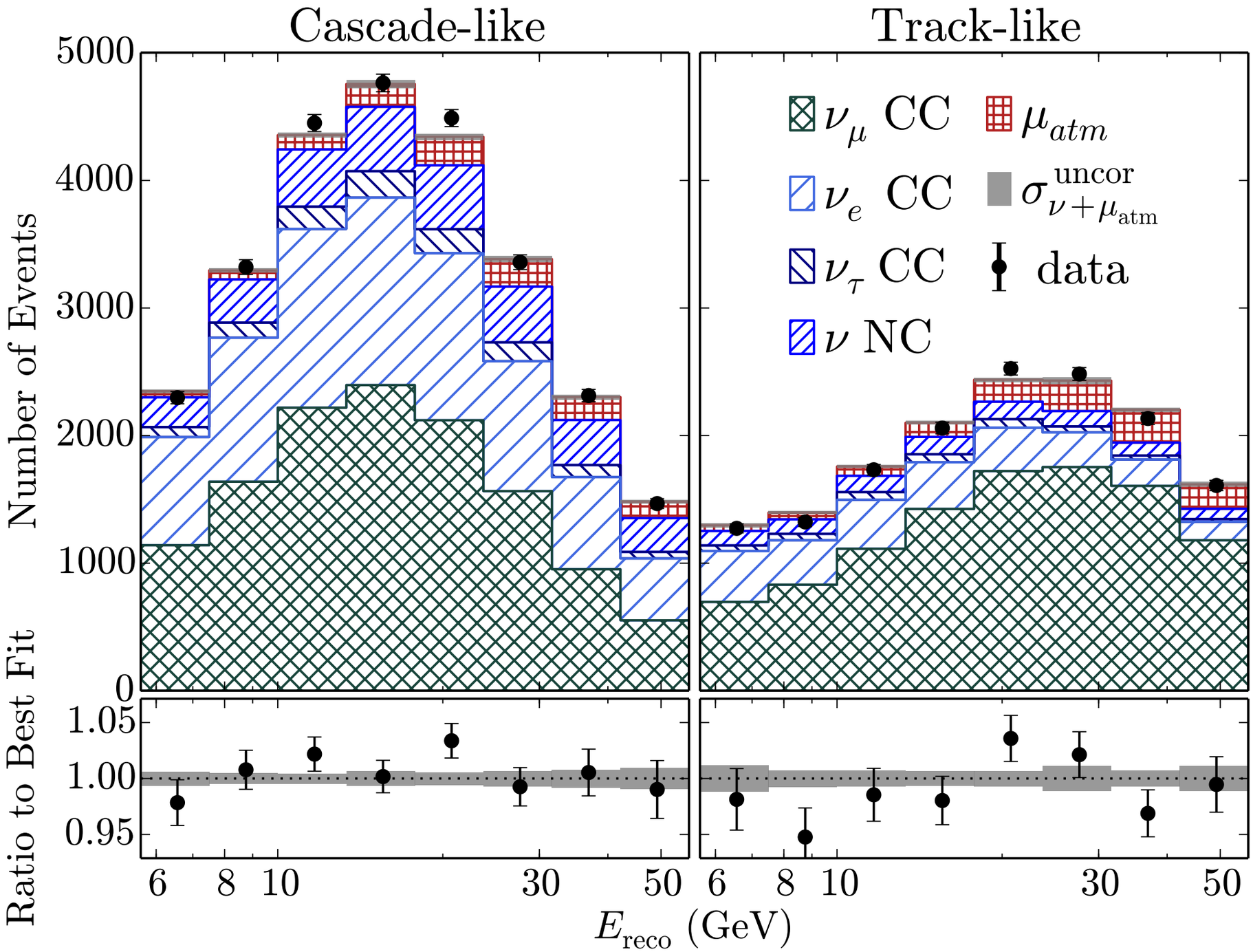
icecube.wisc.edu

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%

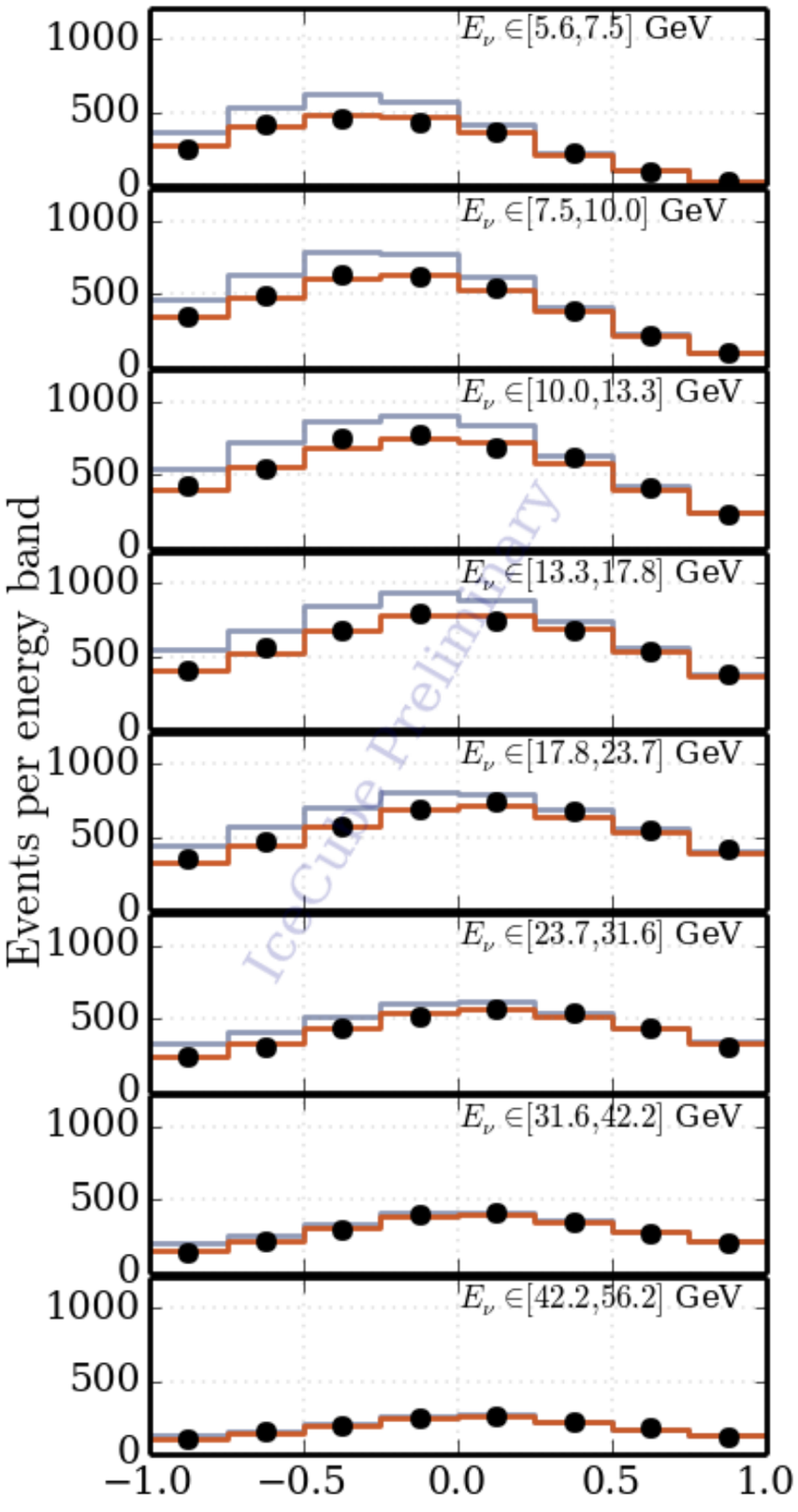


Reconstructed Energy



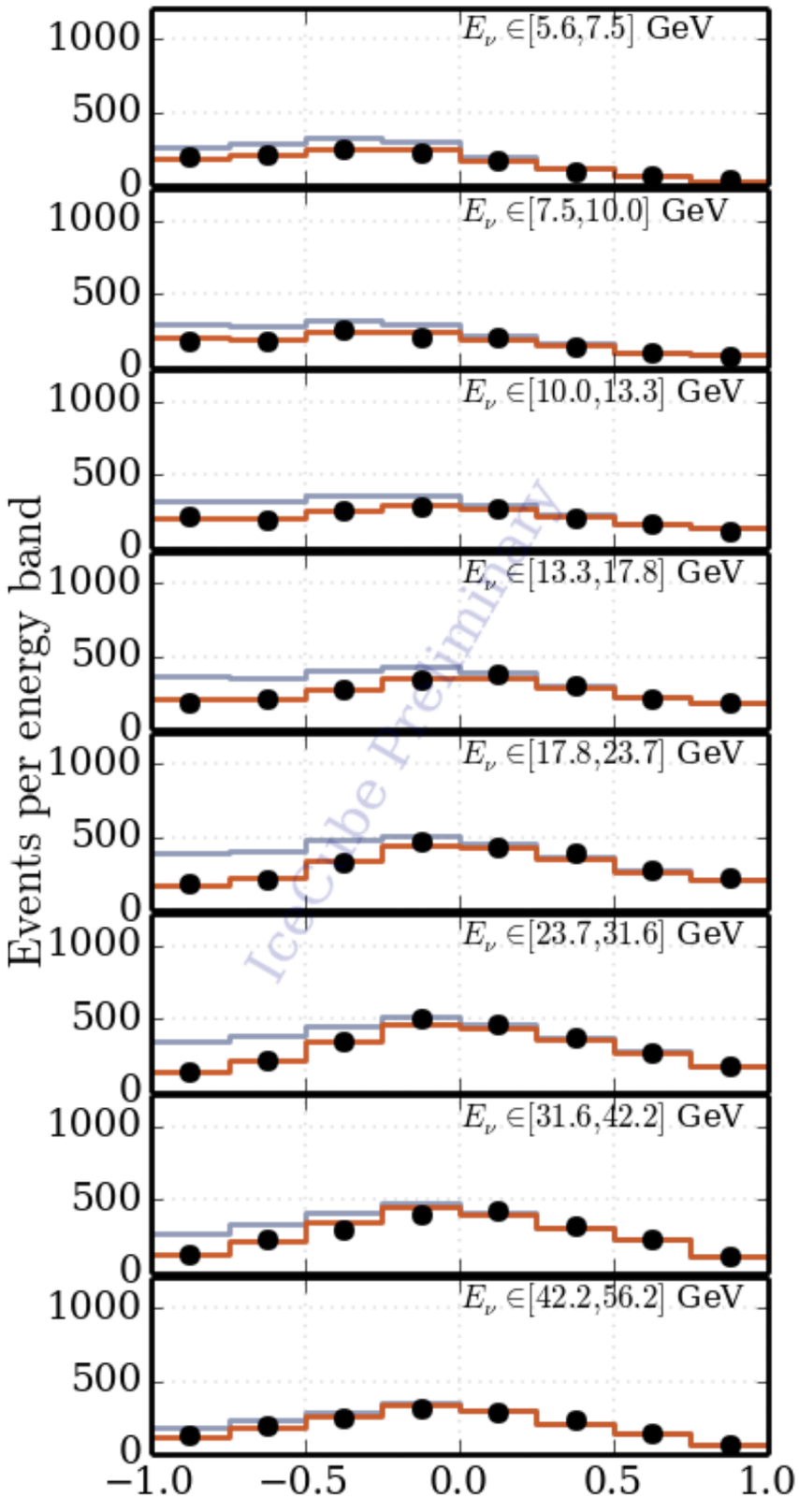
Cascade-like

no osc. — best fit — data



Track-like

no osc. — best fit — data



Phys. Rev D91, 072004 (2015), Neutrino 2016