

Measurements of neutrino flavor mixing with IceCube

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for the ICE CUBE Collaboration
Rencontres du Vietnam
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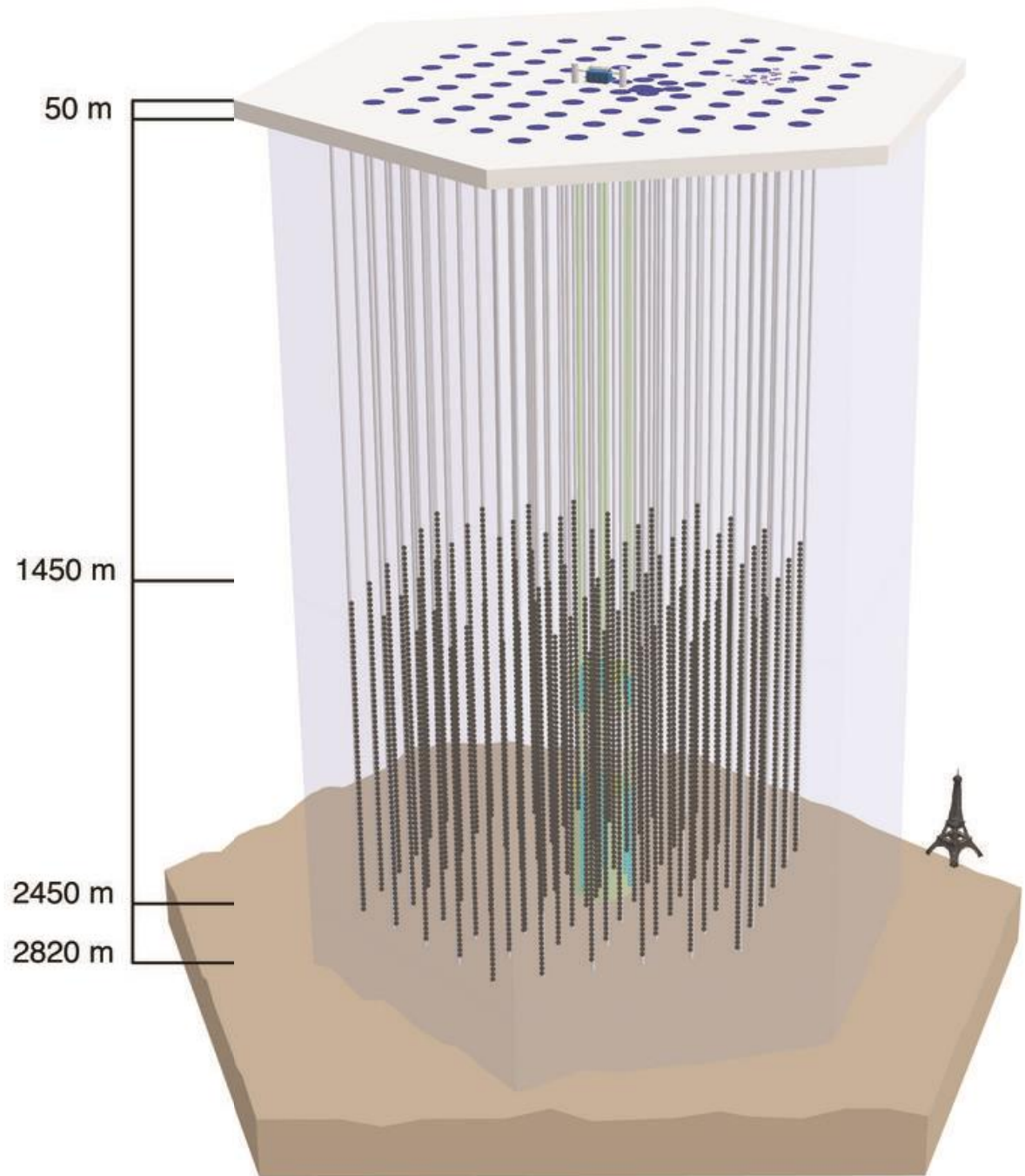
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UNIVERSITY OF
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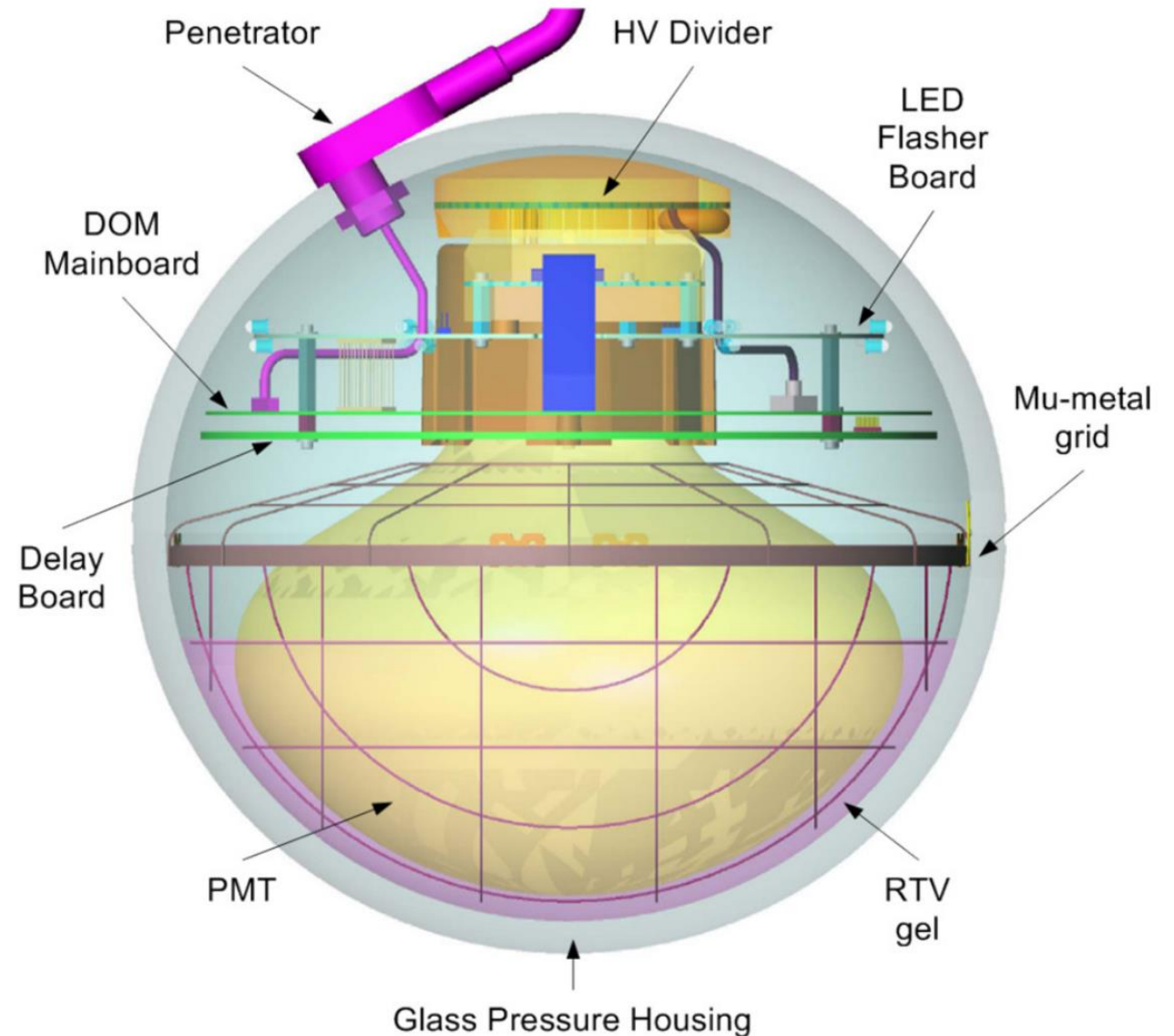
IceCube ν detector

- Ice **Cherenkov** ν detector
- 1.5 – 2.5 km under ice
- 5,160 DOMs
- 86 strings
- Spacing: 17m in z, 125 in x-y
- 1 km³ volume
- LE extension: DeepCore
 - 7m in z
 - 40-70m in x-y



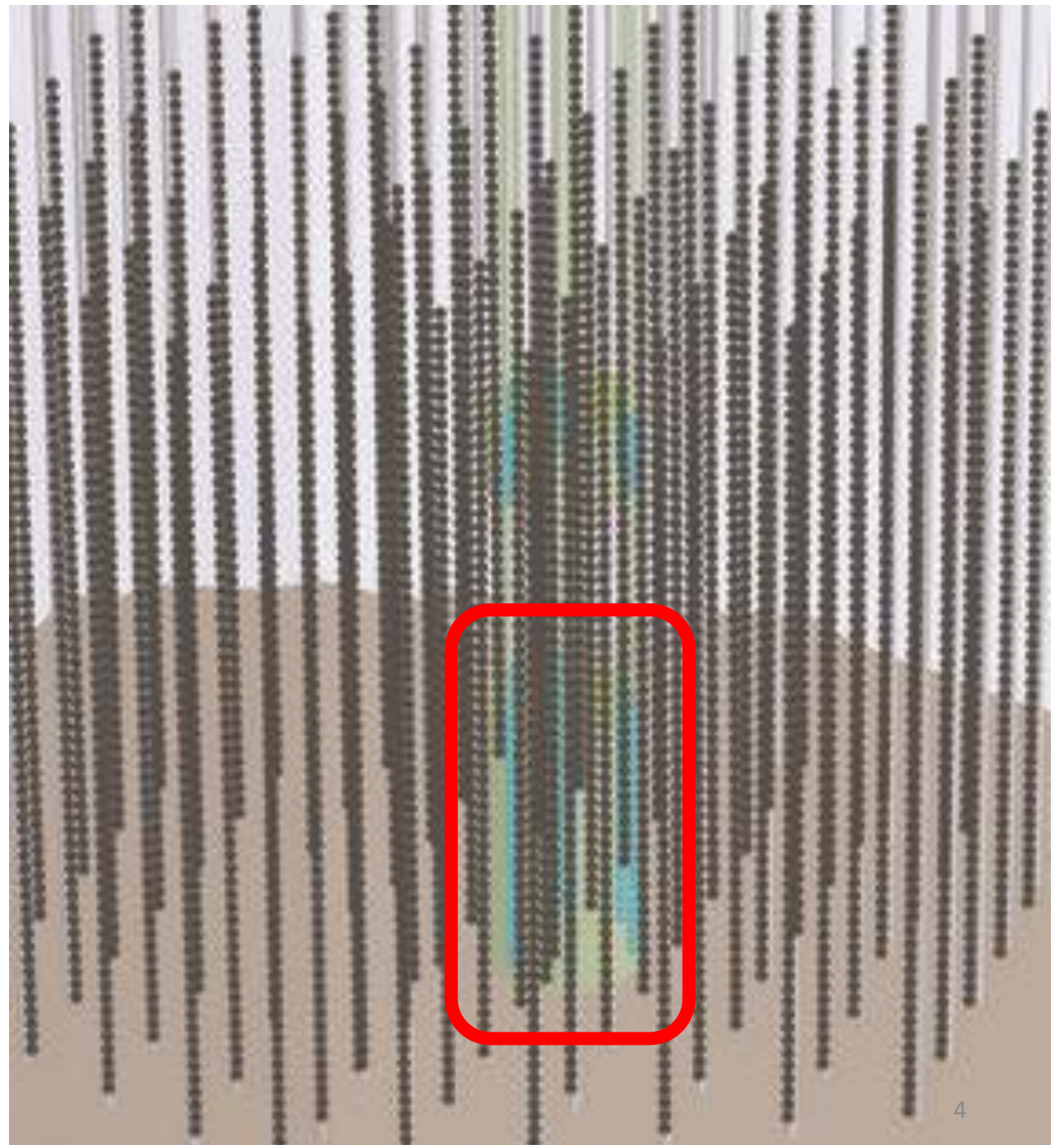
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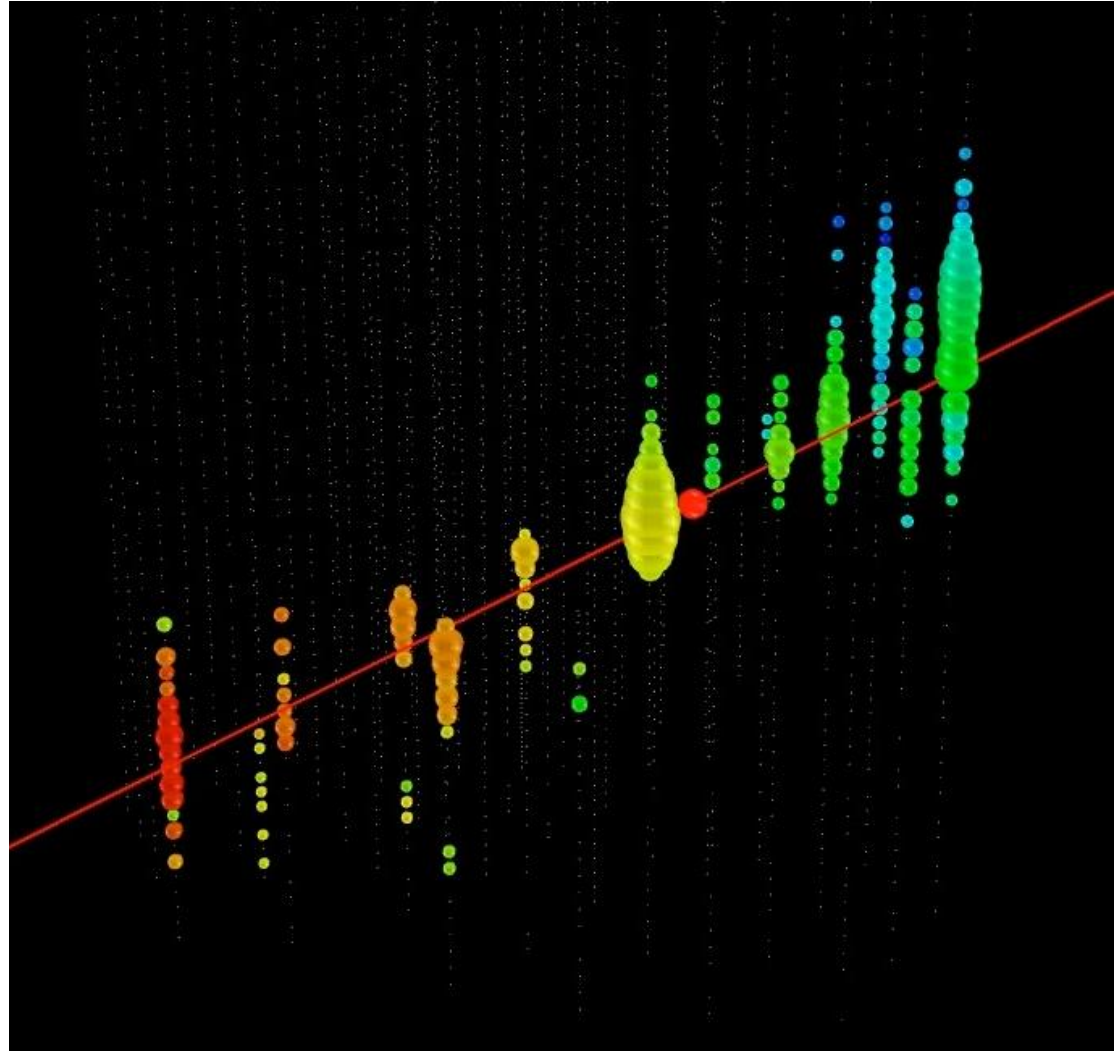
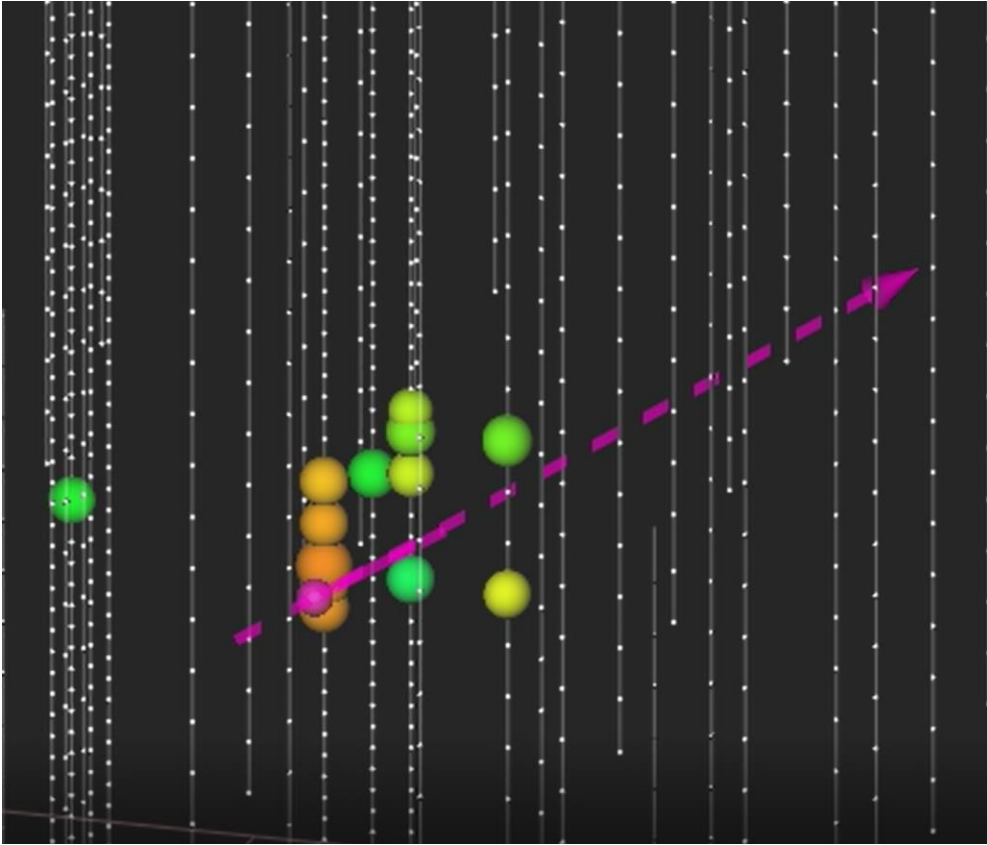


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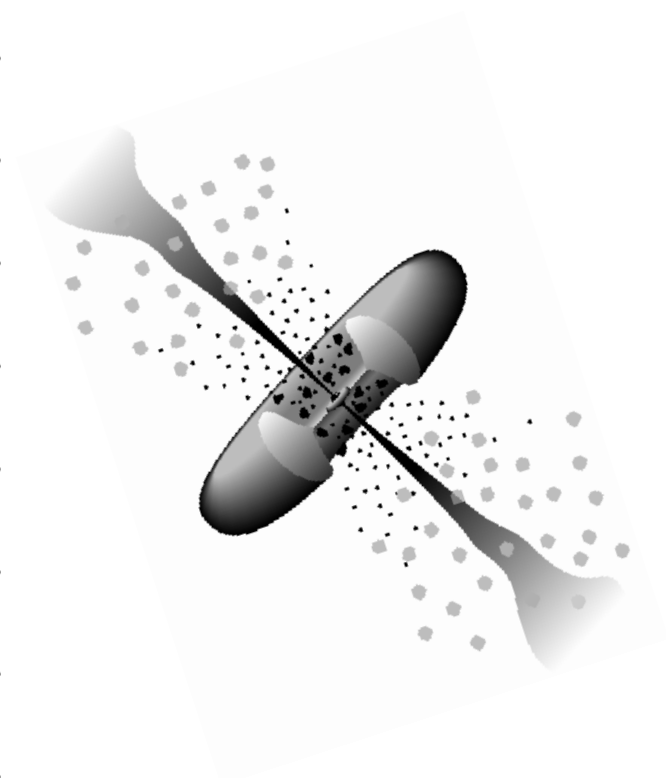
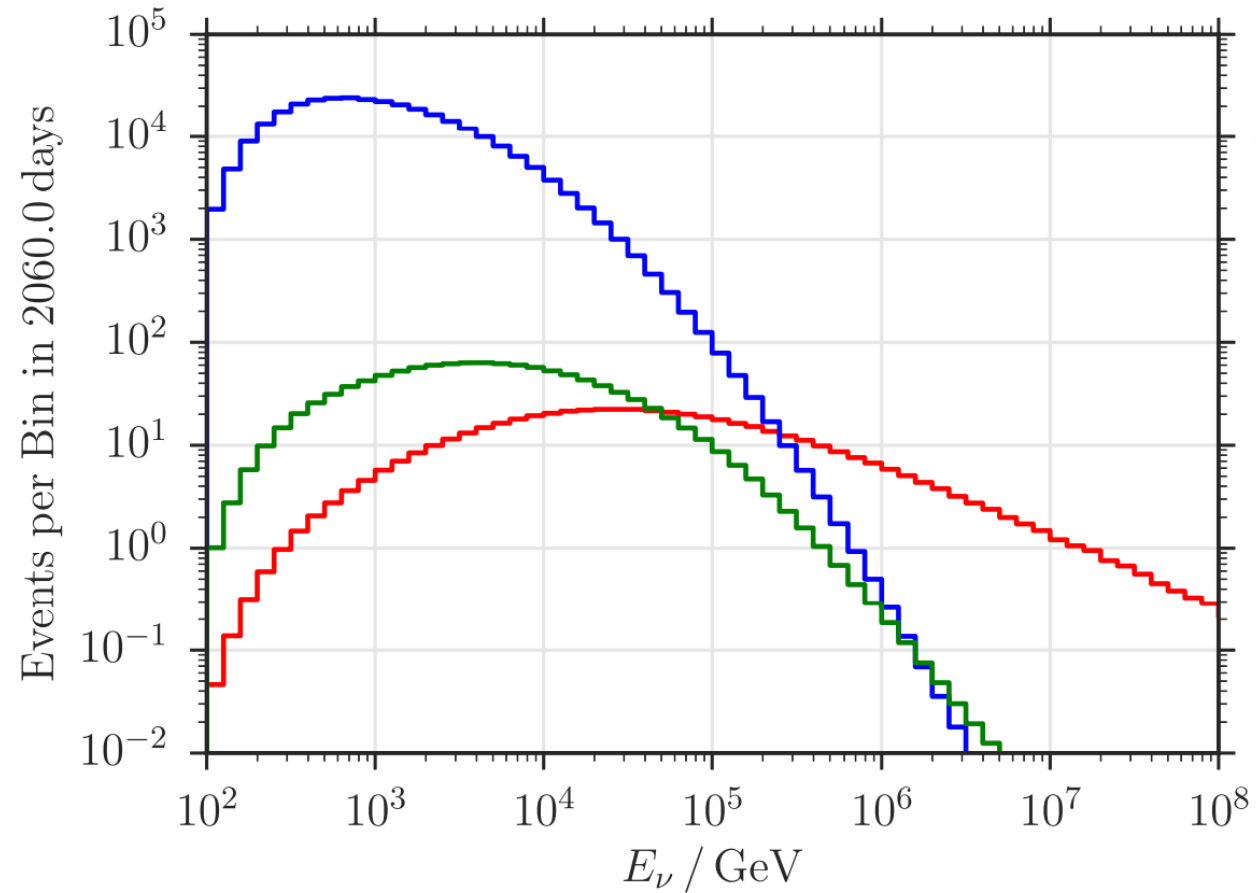
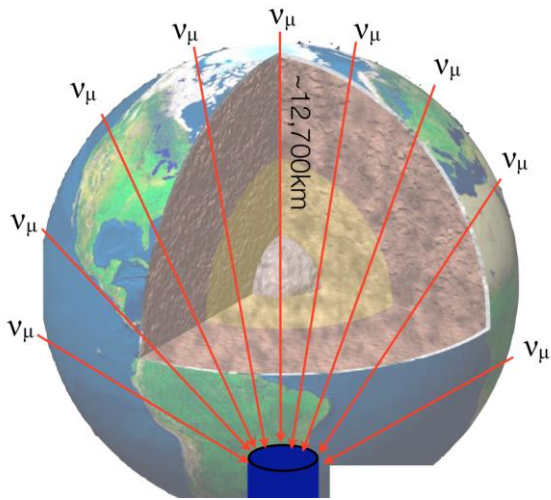


Neutrino events in IceCube

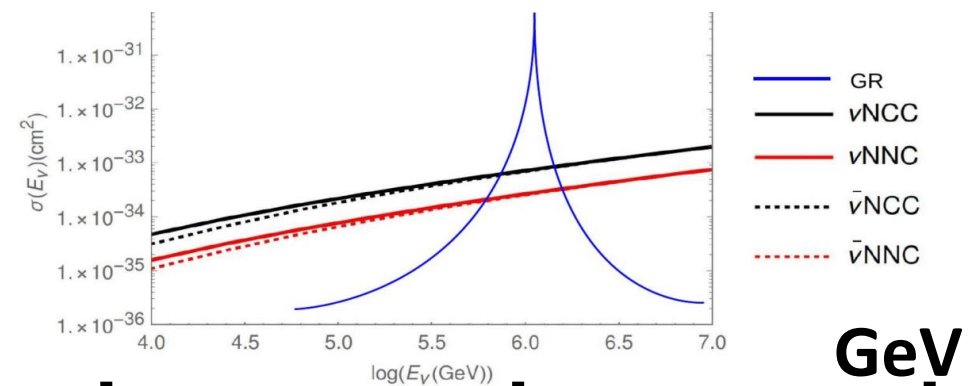
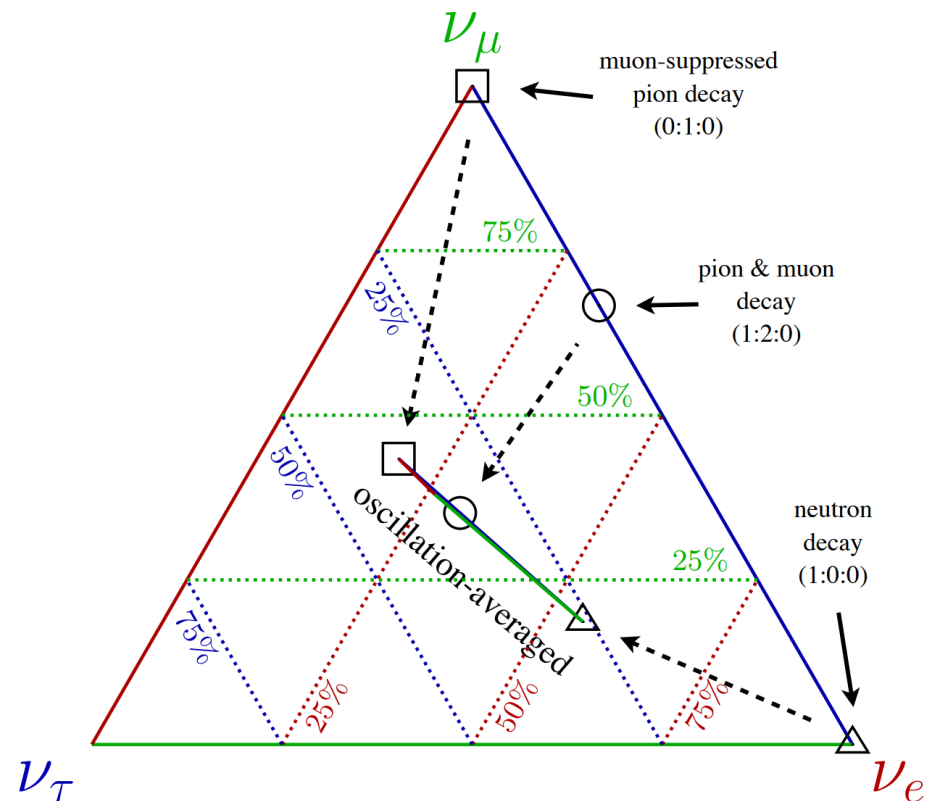
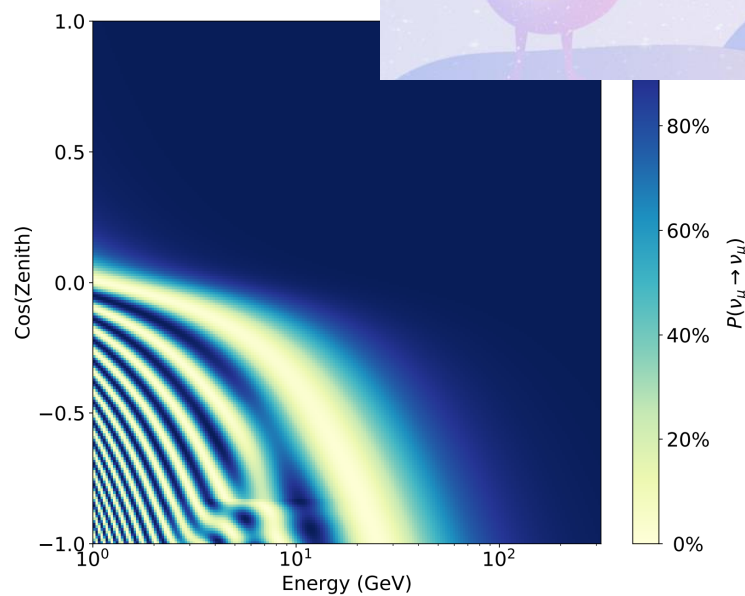
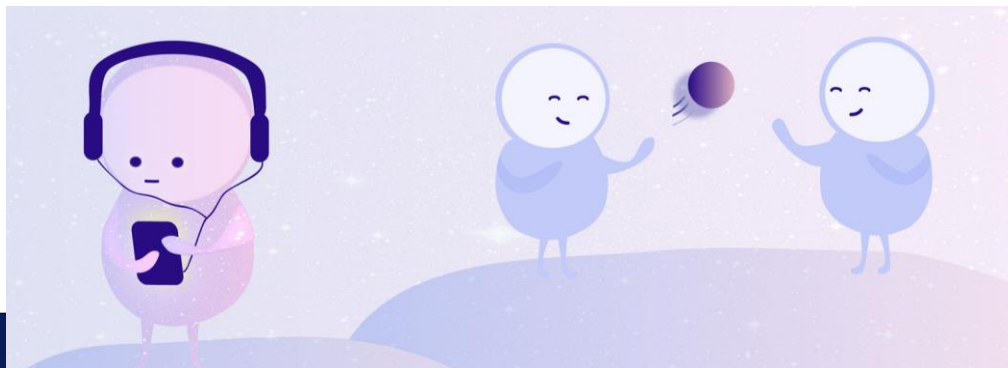


Neutrino sources for mixing studies

— Astrophys. neutrinos — Conv. atmos. neutrinos — Prompt atmos. neutrinos



Flavor mixing E regime



GeV

Flavor mixing E regime

The DeepCore regime

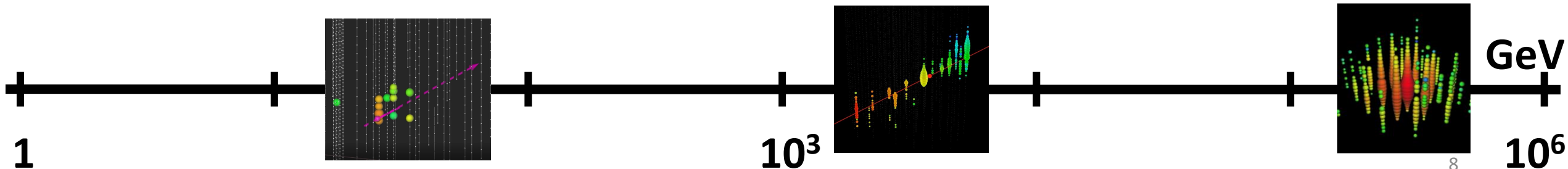
- Aggressive veto techniques to remove atmospheric muons
- Computationally expensive reconstructions
- Good E estimator
- Highly detailed implementation of detector-related systematics

The IceCube track regime

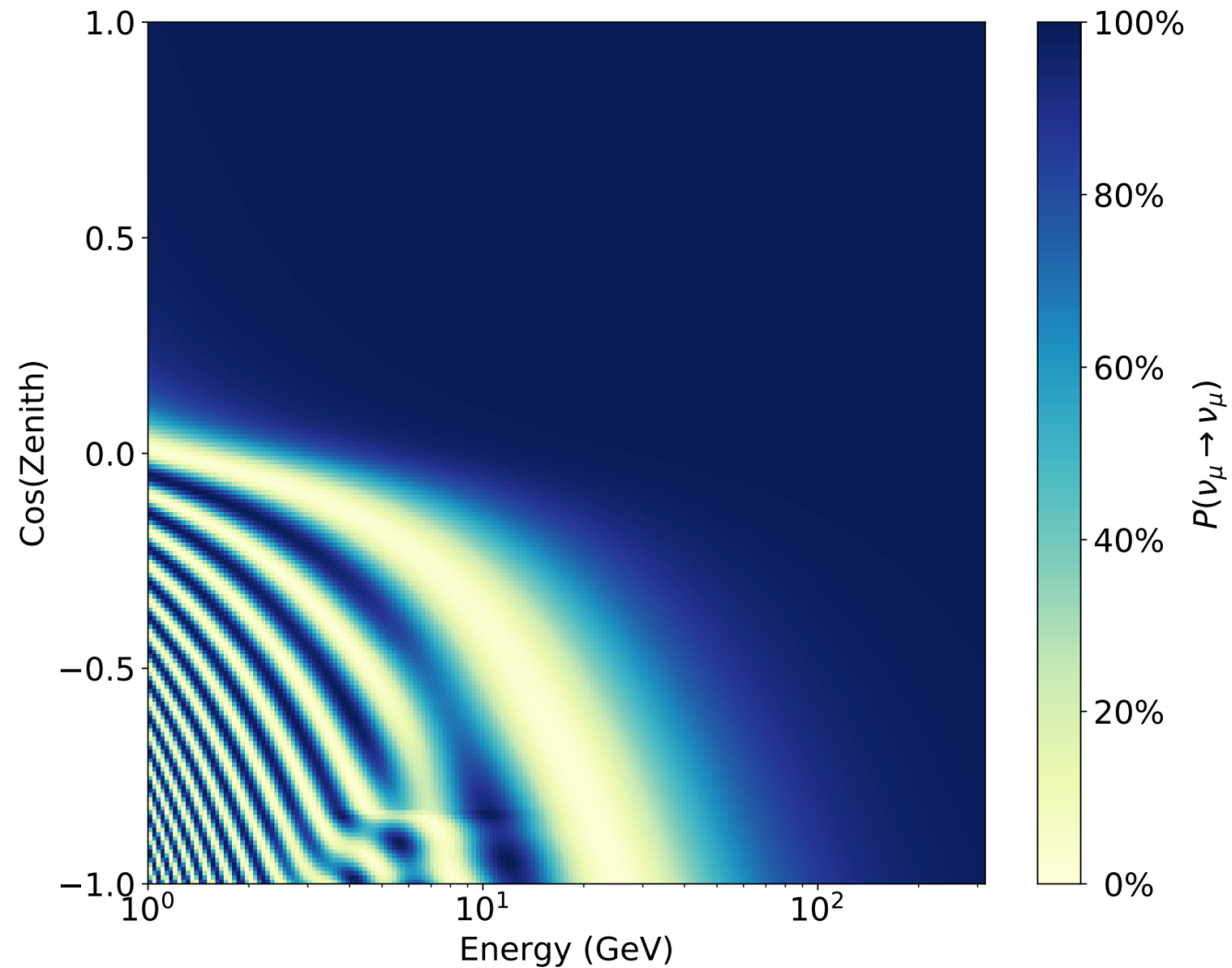
- Bright events, great pointing
- Energy is a lower limit
- More resilient to systematics

Very high energy cascades

- Bright events, contained, good E estimation
- Pointing is not great
- Some susceptibility to systematics
- All-flavor, could ID tau neutrinos



Standard oscillations (DC)

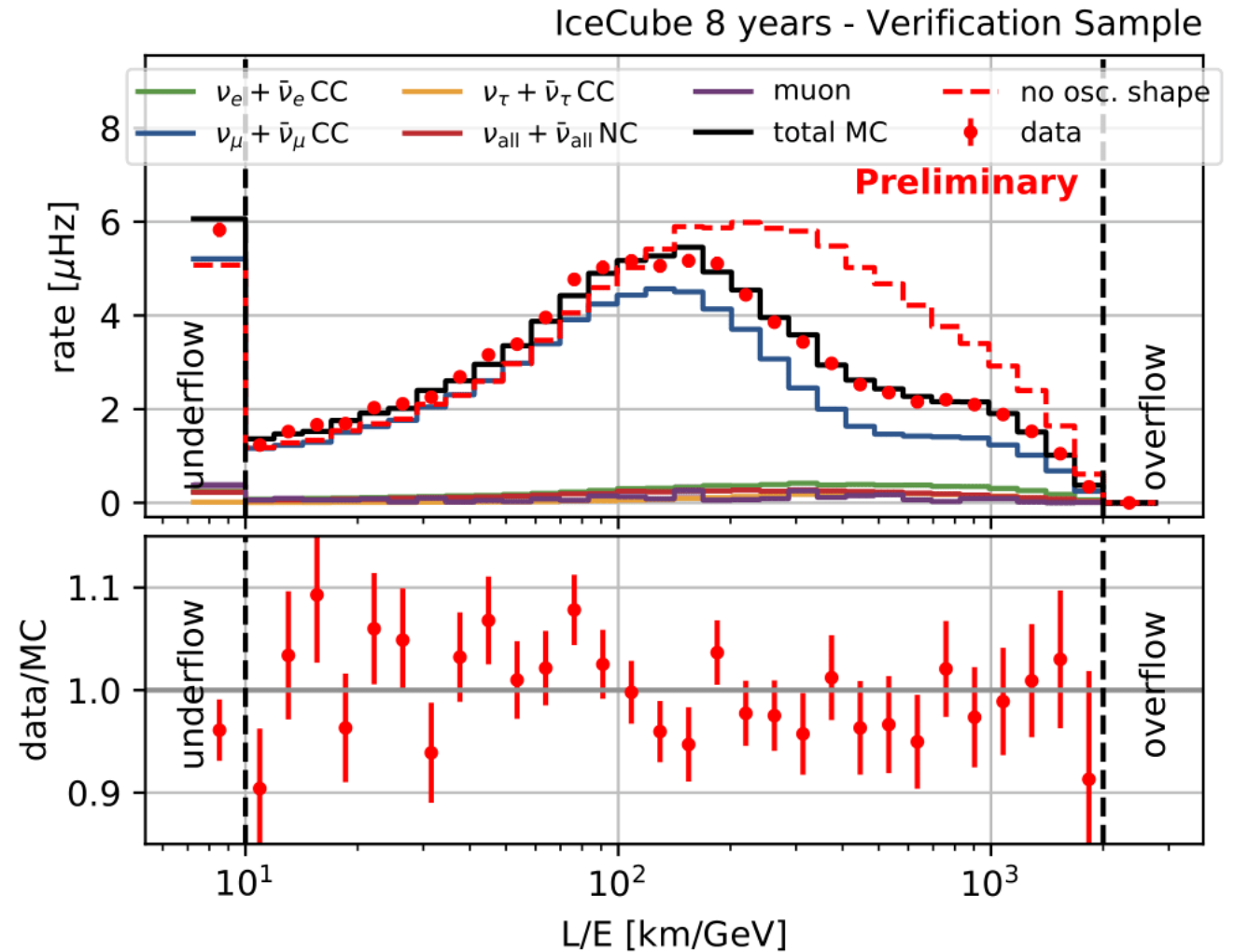


$$P\nu_\alpha \rightarrow \nu_\beta \simeq \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2}{4E} L \right)$$

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Standard oscillations (DC)

- New sample incorporating
 - Streamlined event selection, higher efficiency
 - Improved sensor calibration
 - More precise treatment of systematics
- First looked at the highest quality events



Standard oscillations (DC)

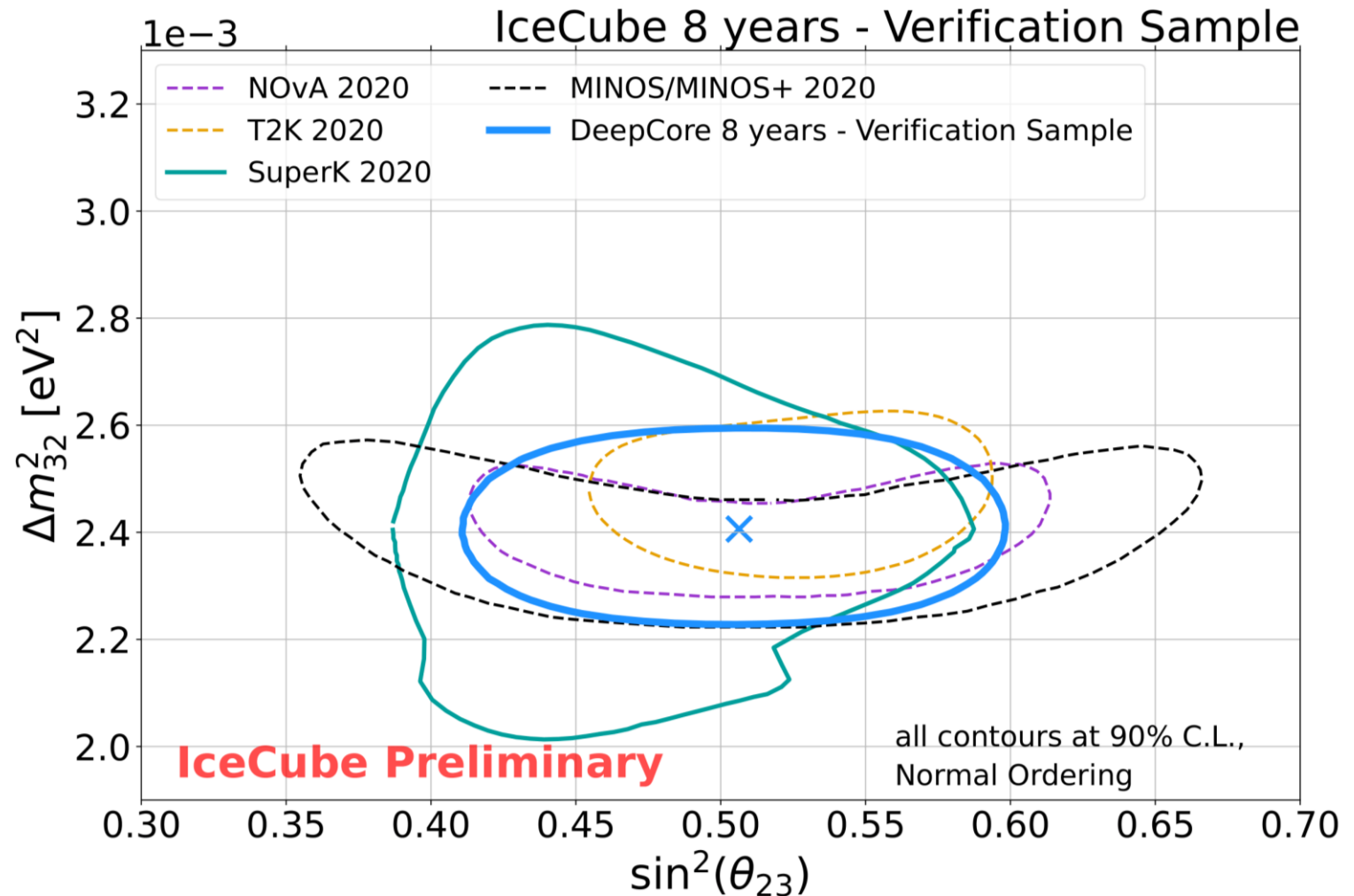
- Best fit values

$$\sin^2 \theta_{23} = 0.505^{+0.051}_{-0.050}$$

$$\Delta m_{32}^2 = 2.41 \pm 0.084 \times 10^{-3} \text{ eV}^2$$

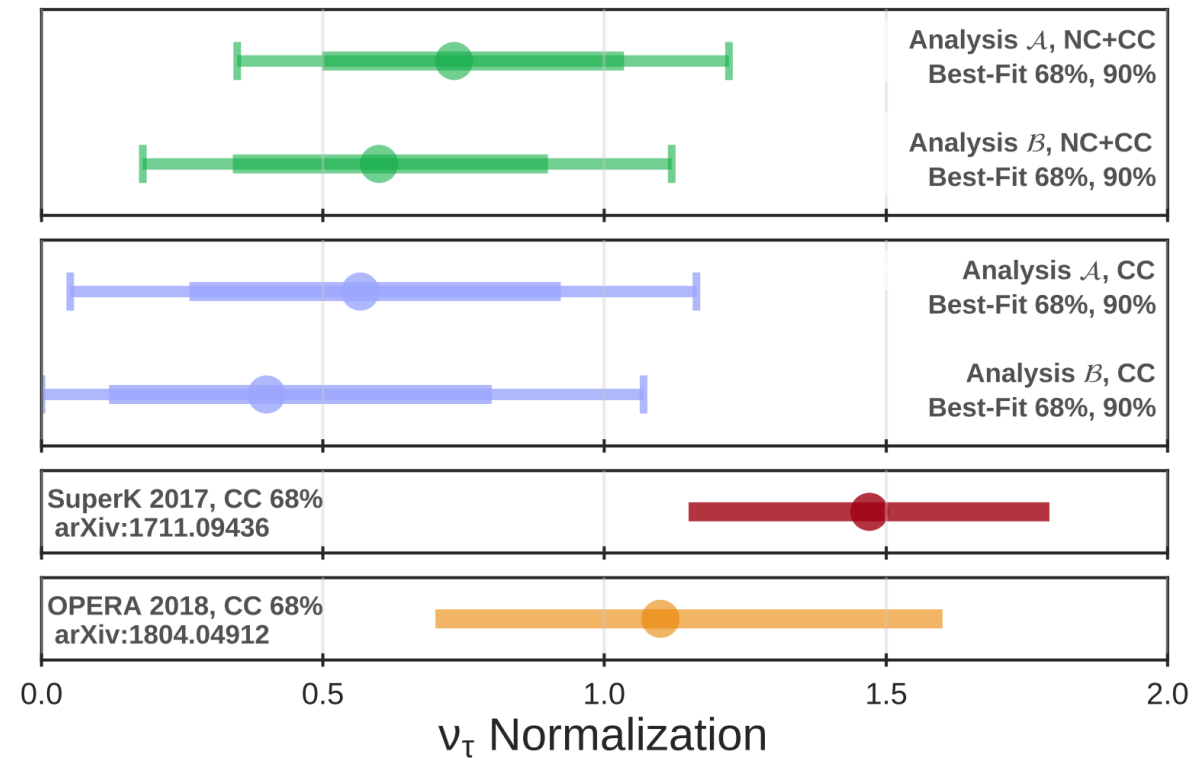
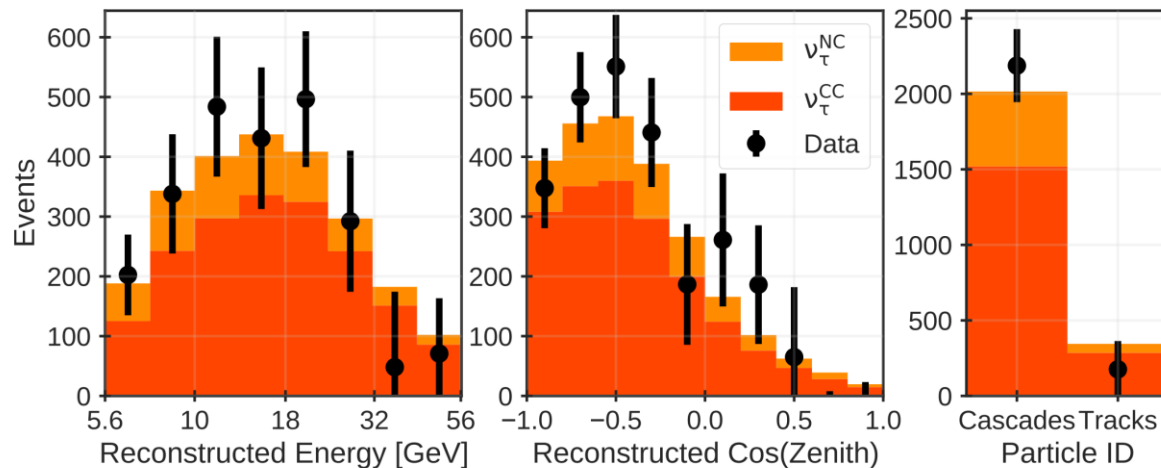
- Excellent agreement between data/MC

- Publication in preparation



Standard oscillations (DC) – tau appearance

- Older sample, new analysis still in progress

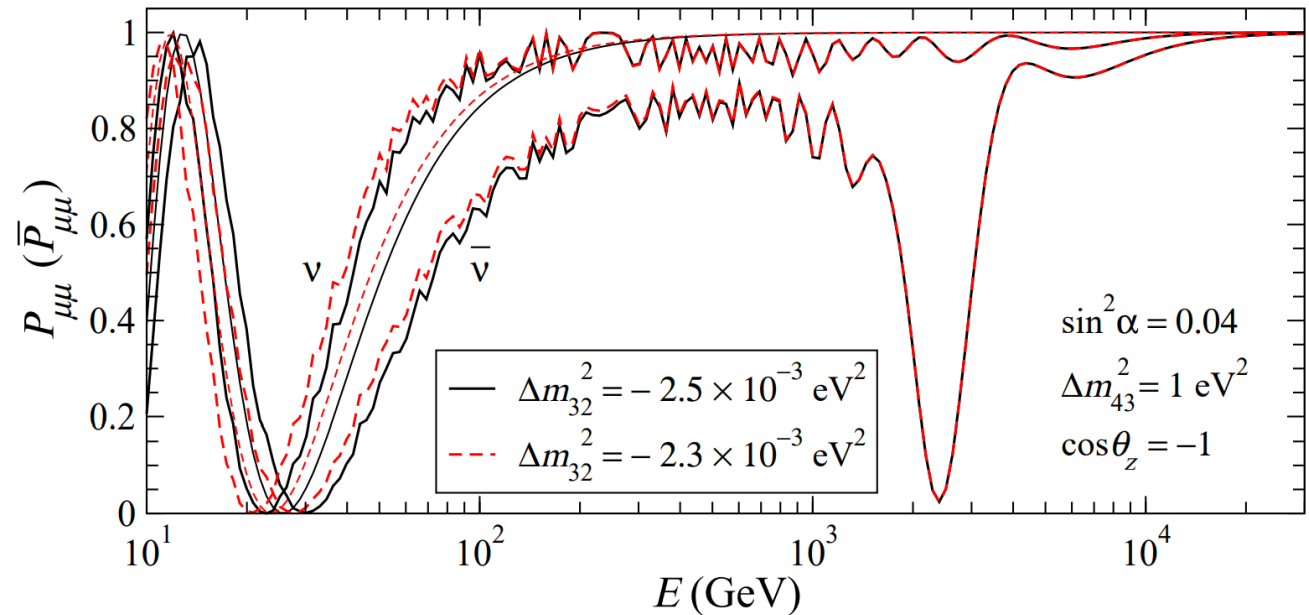


Phys. Rev. D 99, 032007 (2019)

Searches for sterile neutrinos (DC & IC)

- More elements in the neutrino mixing matrix
 - Modulate standard oscillations
 - Can create large oscillations for small mixing angle due to matter effects

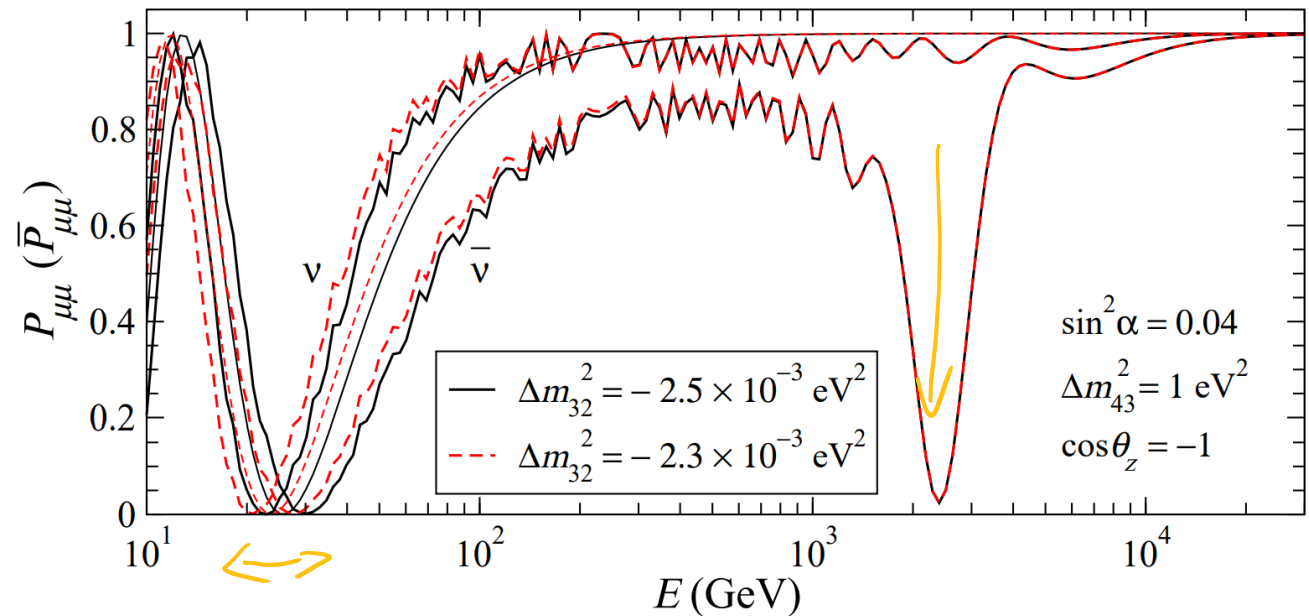
$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}.$$



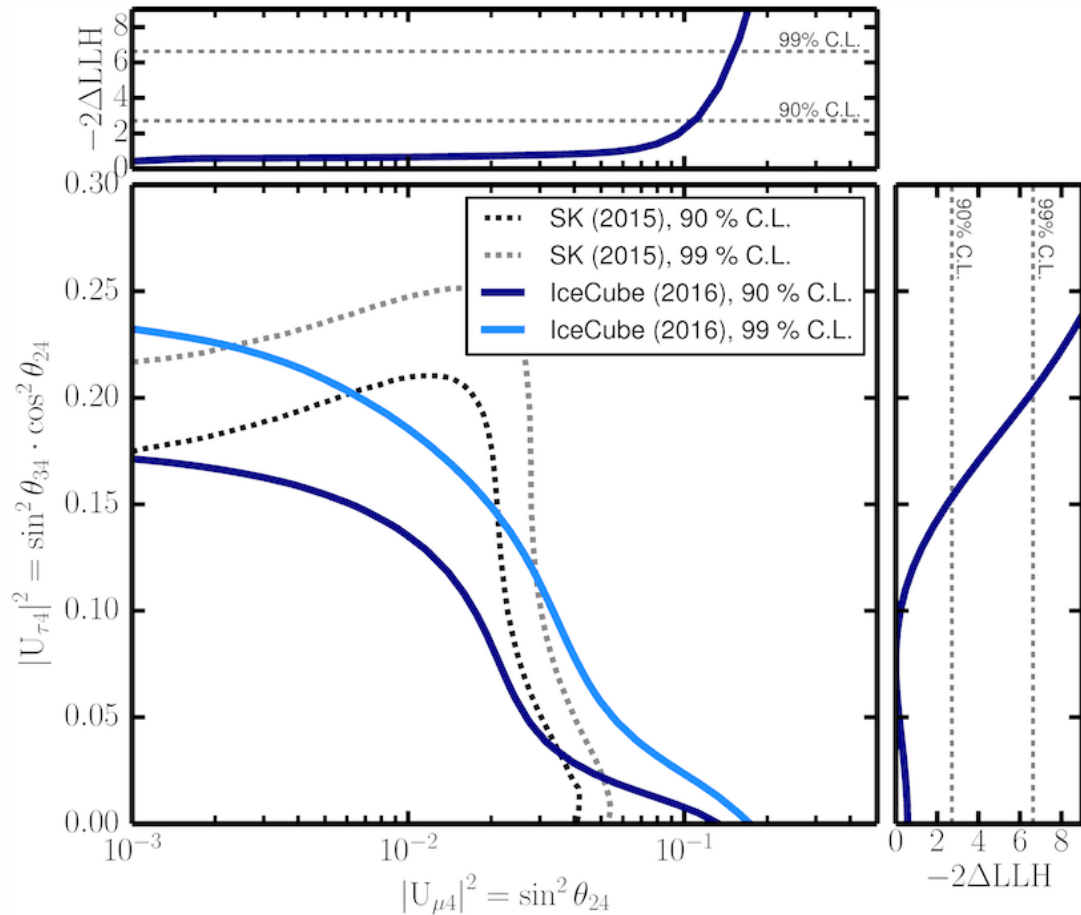
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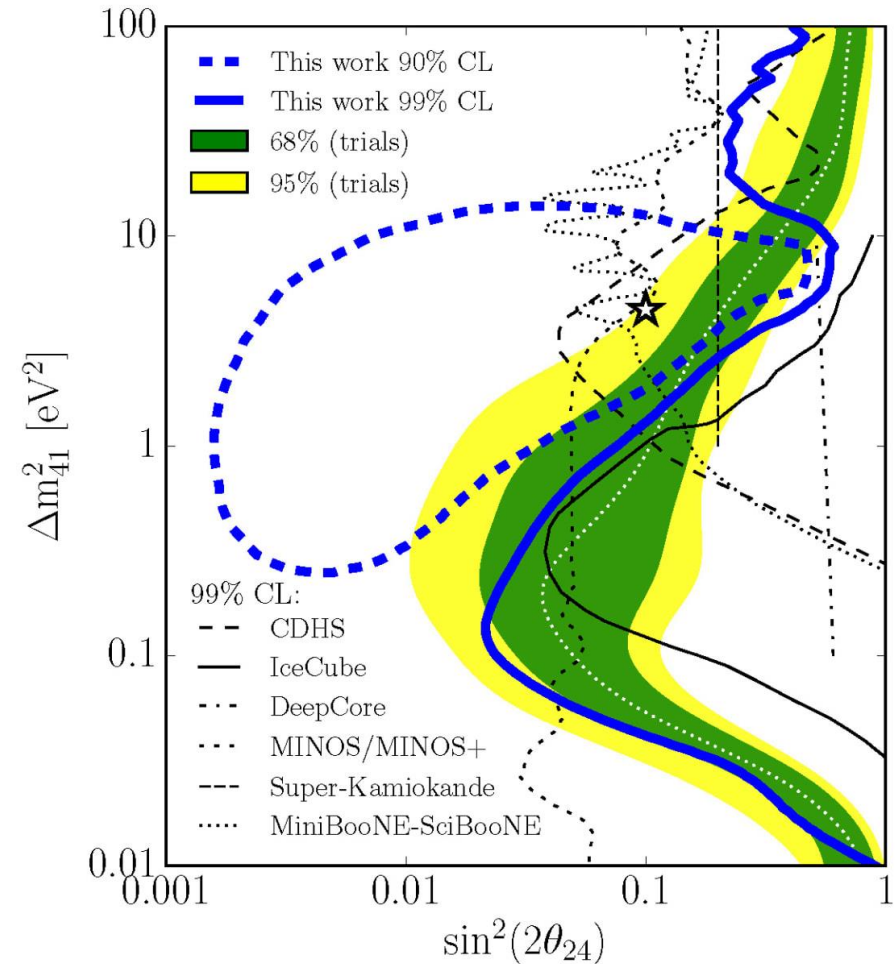
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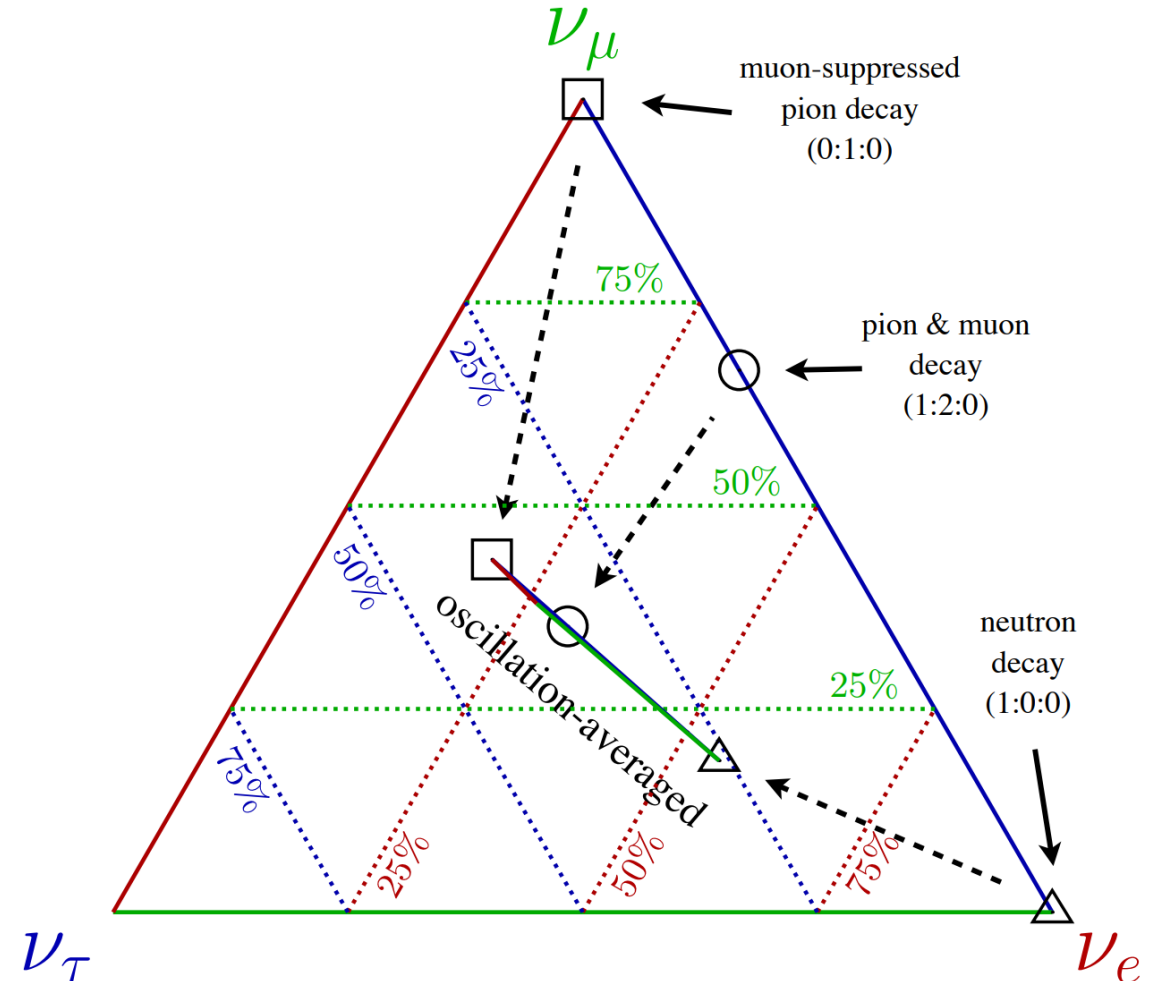
Phys. Rev. D 95, 112002 (2017)



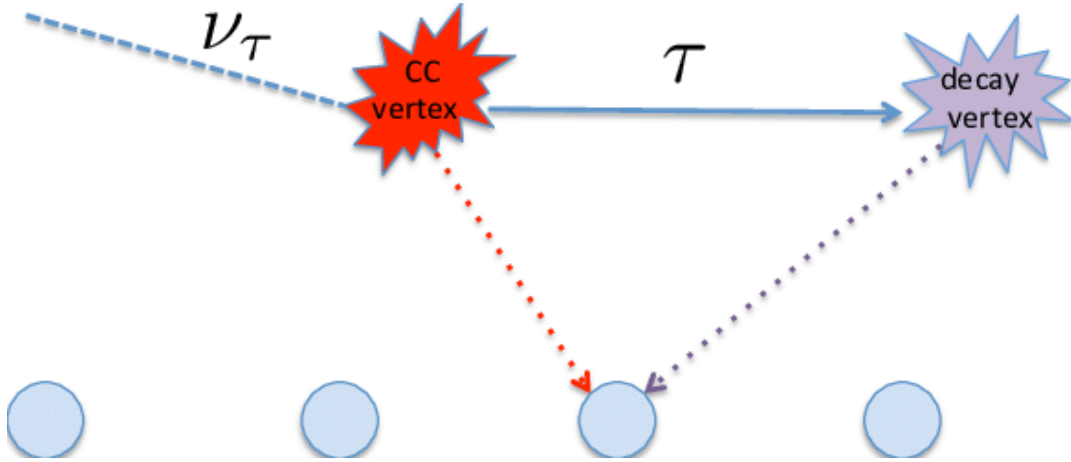
Phys. Rev. Lett. 125, 141801 (2020)

Astrophysical tau observations (HE cascades)

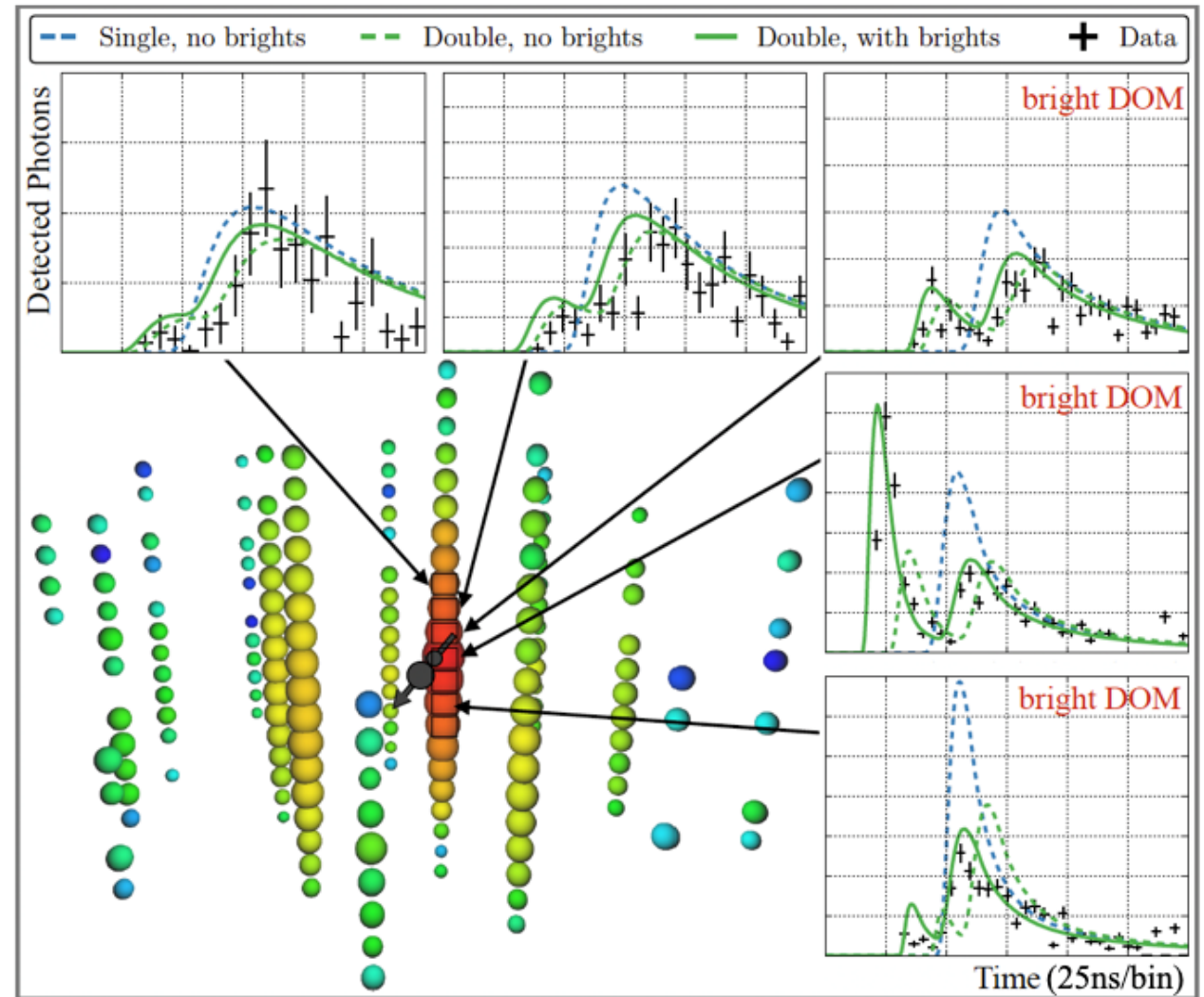
- Astrophysical neutrinos expected to come from light meson decays
 - No tau neutrino component
- But neutrino mixing will scramble the flavors by the time they get to Earth
 - Tau neutrinos expected
 - Observed flavor ratio at Earth expected in a narrow region



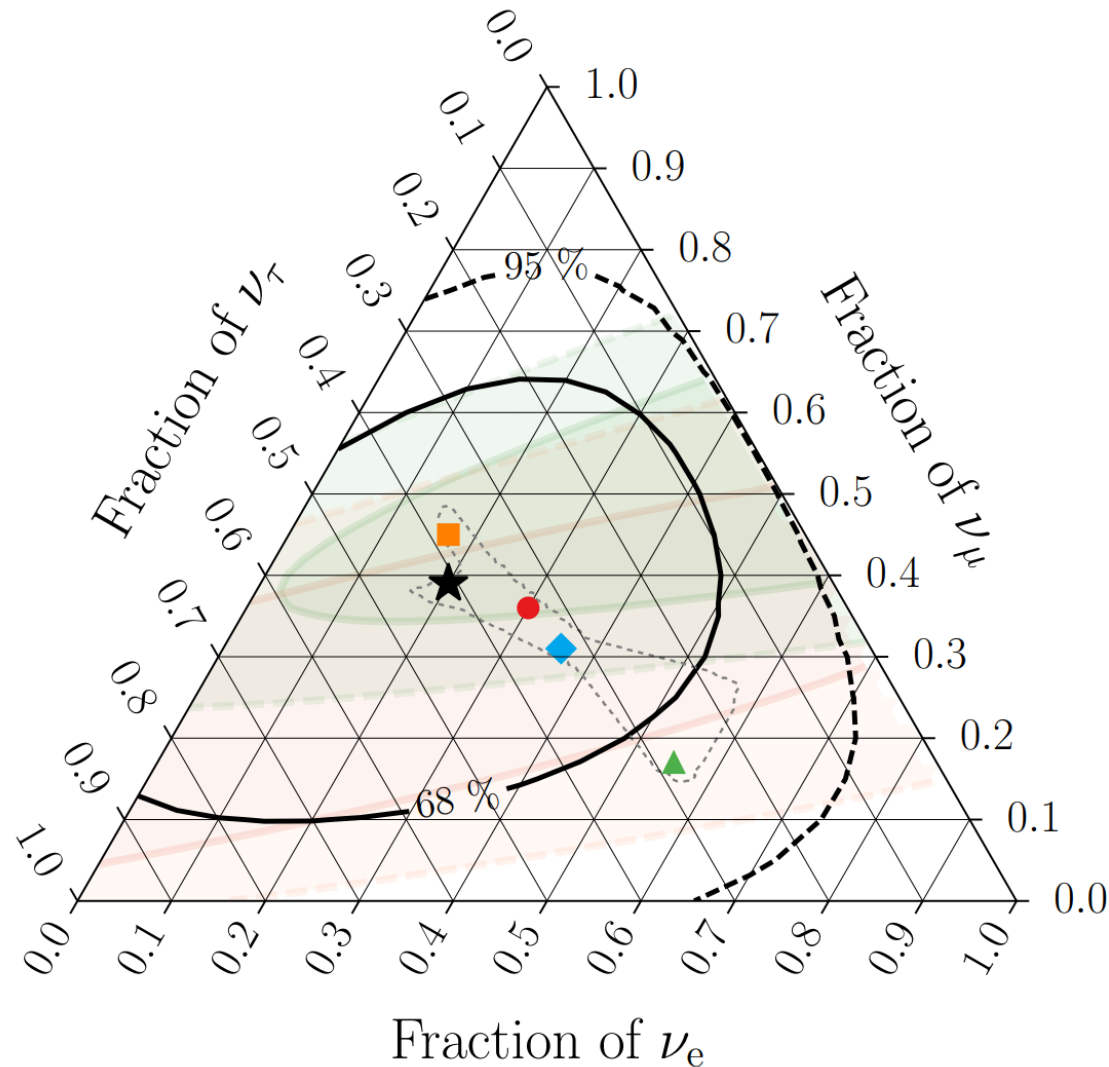
Astrophysical tau observations (HE cascades)



- Two events observed in 1 search (here)
 - [arXiv:2011.03561](https://arxiv.org/abs/2011.03561) [hep-ex]
- New ML-based approaches developed
 - Expect 5 ν_τ events on 0.5 background
 - Could reject no-tau hypothesis at 5sigma
 - Results coming soon



Astrophysical tau observations (HE cascades)



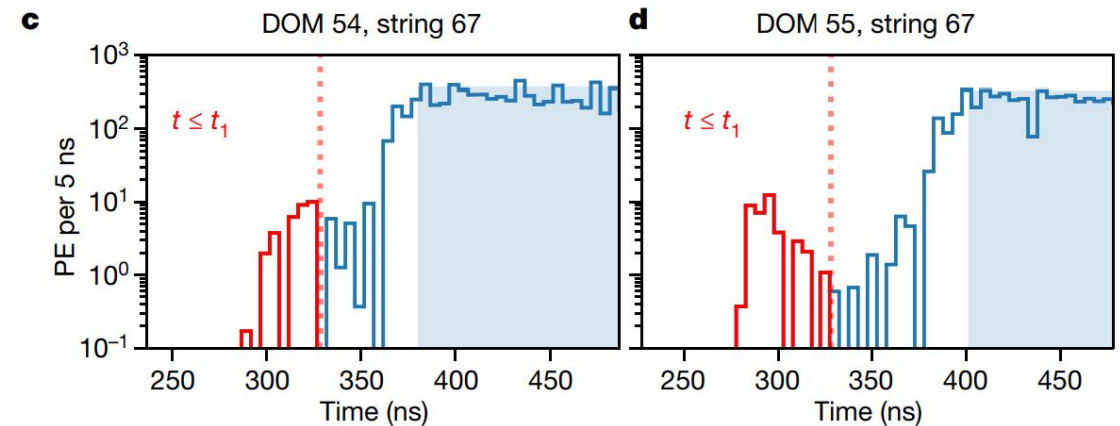
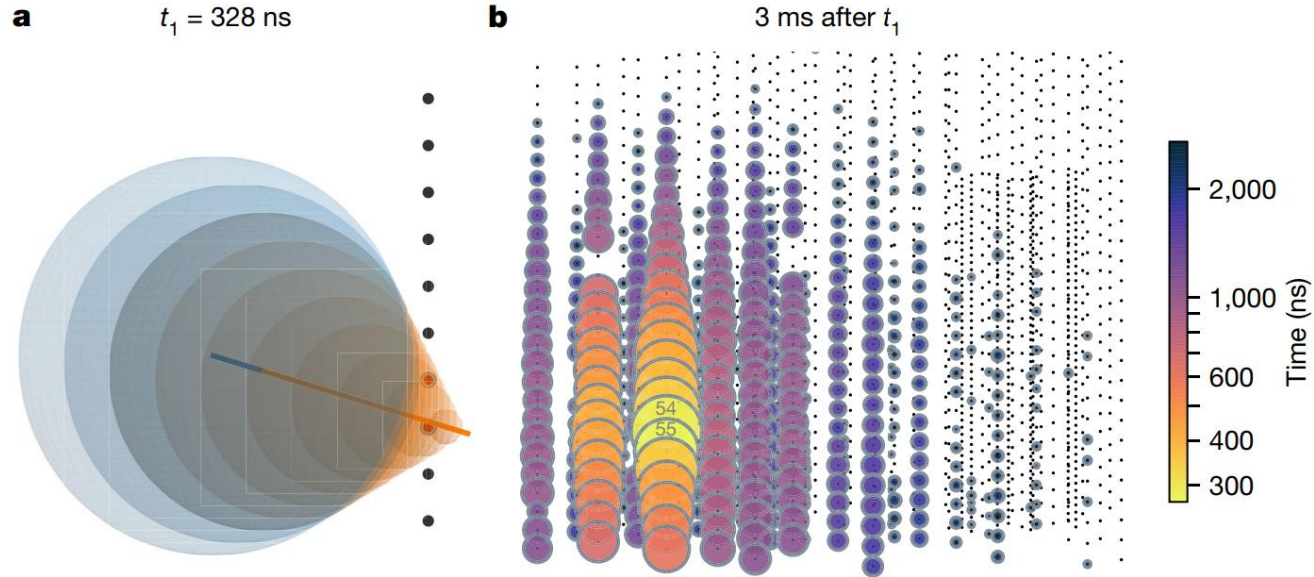
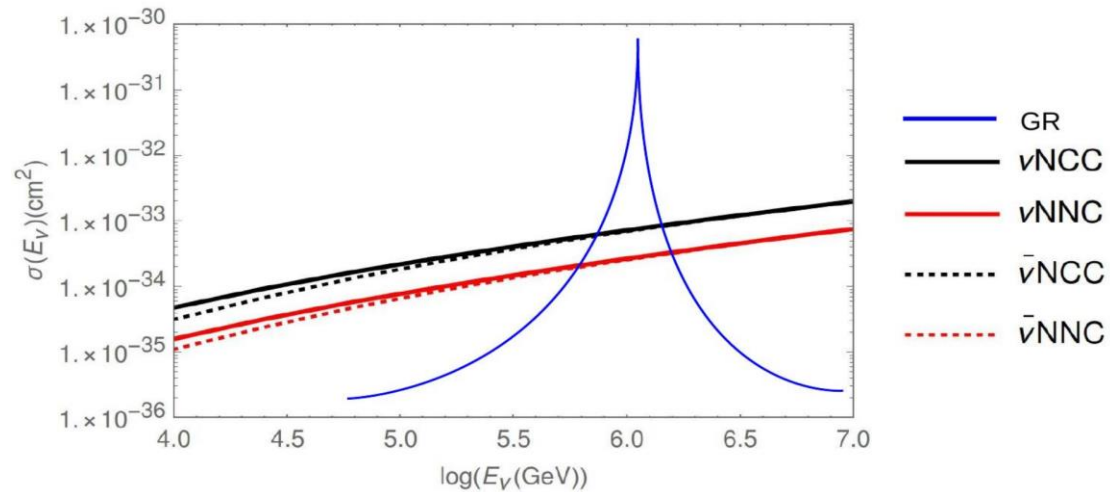
$\nu_e : \nu_\mu : \nu_\tau$ at source \rightarrow on Earth:

- $0:1:0 \rightarrow 0.17 : 0.45 : 0.37$
- $1:2:0 \rightarrow 0.30 : 0.36 : 0.34$
- ▲ $1:0:0 \rightarrow 0.55 : 0.17 : 0.28$
- ◆ $1:1:0 \rightarrow 0.36 : 0.31 : 0.33$

- HESE with ternary topology ID
- ★ Best fit: $0.20 : 0.39 : 0.42$
- Global Fit (IceCube, APJ 2015)
- Inelasticity (IceCube, PRD 2019)
- 3ν -mixing 3σ allowed region

W-production by $\bar{\nu}_e - e^-$

- Process: $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$
- Cross section enhancement at 6.32 PeV
- One event observed
 - Rejects no resonance at about 2.5sigma



Summary and Outlook (i)

- IceCube has measured neutrino mixing from GeV to PeV energies
 - Precision measurement of atmospheric oscillations
 - Searches for other flavors (steriles, U_{PMNS} non-unitarity) so far negative
 - First evidence of astrophysical tau neutrinos found
 - First Glashow resonance event found
- Data analysis is still on-going – over 10 years of stable data!
 - Inclusive version of low-energy sample being finalized, boost of 5x stats
 - All DC-suite of studies will improve significantly
 - New cascades+tracks HE sample being put together
 - ML efforts in astrophysical ν_τ well underway

Summary and Outlook (ii)

- The IceCube upgrade
 - Recalibration of all data
 - Lower E threshold for DC

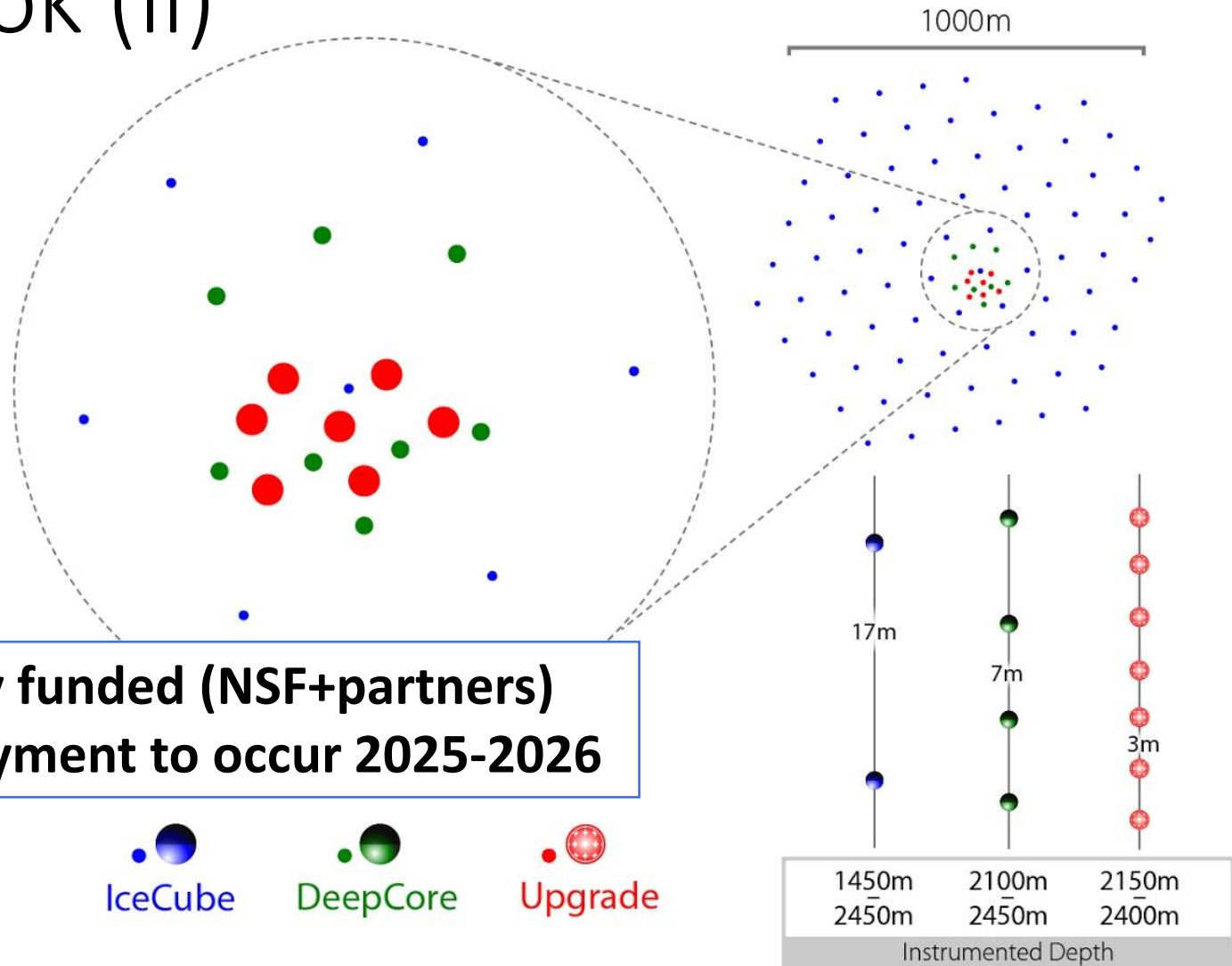


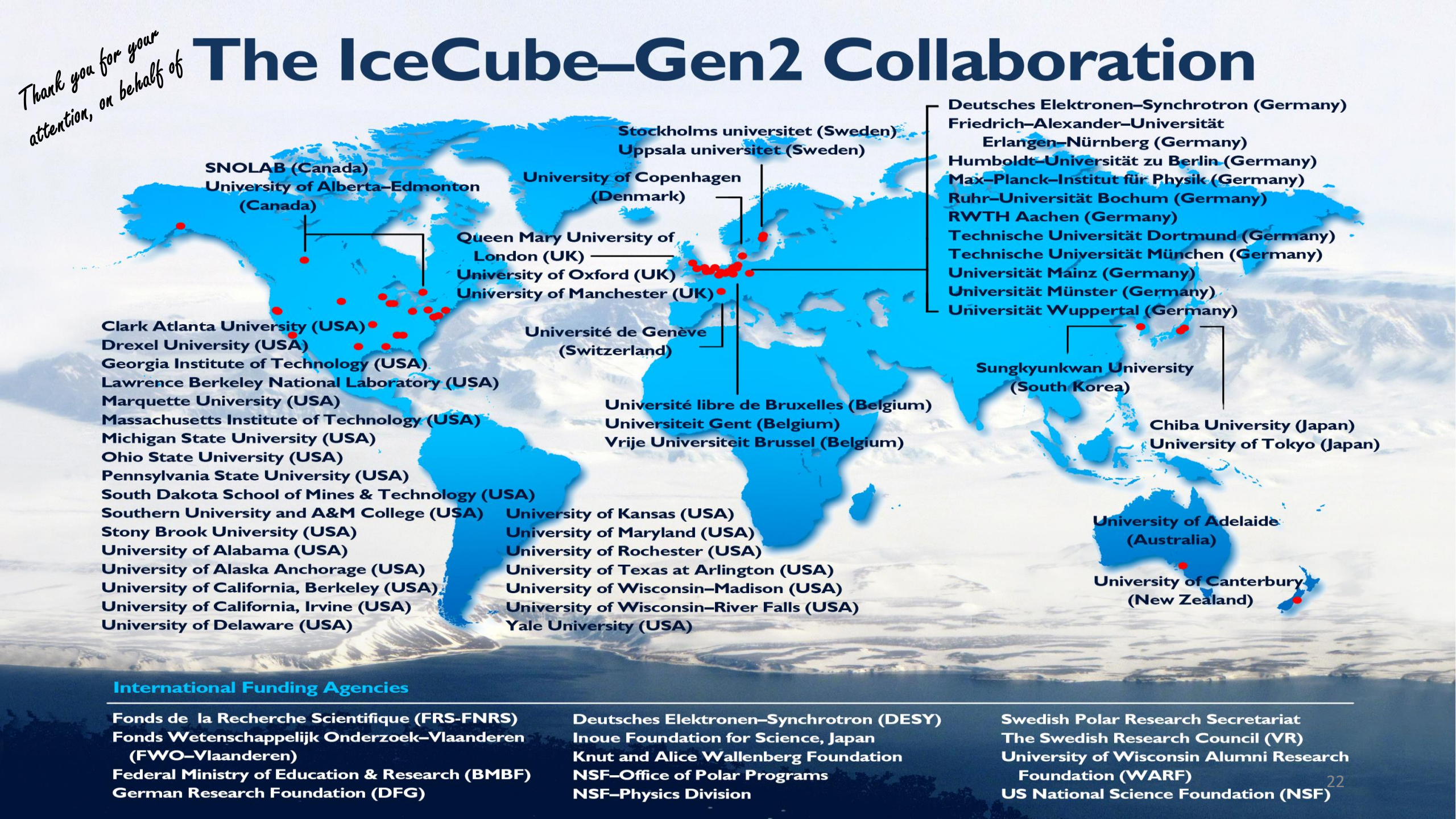
**Fully funded (NSF+partners)
Deployment to occur 2025-2026**


IceCube


DeepCore


Upgrade





*Thank you for your
attention, on behalf of*

The IceCube–Gen2 Collaboration

- SNOLAB (Canada)
- University of Alberta–Edmonton (Canada)
- Clark Atlanta University (USA)
- Drexel University (USA)
- Georgia Institute of Technology (USA)
- Lawrence Berkeley National Laboratory (USA)
- Marquette University (USA)
- Massachusetts Institute of Technology (USA)
- Michigan State University (USA)
- Ohio State University (USA)
- Pennsylvania State University (USA)
- South Dakota School of Mines & Technology (USA)
- Southern University and A&M College (USA)
- Stony Brook University (USA)
- University of Alabama (USA)
- University of Alaska Anchorage (USA)
- University of California, Berkeley (USA)
- University of California, Irvine (USA)
- University of Delaware (USA)
- University of Copenhagen (Denmark)
- Queen Mary University of London (UK)
- University of Oxford (UK)
- University of Manchester (UK)
- University of Kansas (USA)
- University of Maryland (USA)
- University of Rochester (USA)
- University of Texas at Arlington (USA)
- University of Wisconsin–Madison (USA)
- University of Wisconsin–River Falls (USA)
- Yale University (USA)
- Stockholms universitet (Sweden)
- Uppsala universitet (Sweden)
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- Friedrich–Alexander–Universität Erlangen–Nürnberg (Germany)
- Humboldt–Universität zu Berlin (Germany)
- Max–Planck–Institut für Physik (Germany)
- Ruhr–Universität Bochum (Germany)
- RWTH Aachen (Germany)
- Technische Universität Dortmund (Germany)
- Technische Universität München (Germany)
- Universität Mainz (Germany)
- Universität Münster (Germany)
- Universität Wuppertal (Germany)
- Université de Genève (Switzerland)
- Université libre de Bruxelles (Belgium)
- Universiteit Gent (Belgium)
- Vrije Universiteit Brussel (Belgium)
- Sungkyunkwan University (South Korea)
- Chiba University (Japan)
- University of Tokyo (Japan)
- University of Adelaide (Australia)
- University of Canterbury (New Zealand)

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)

Systematics

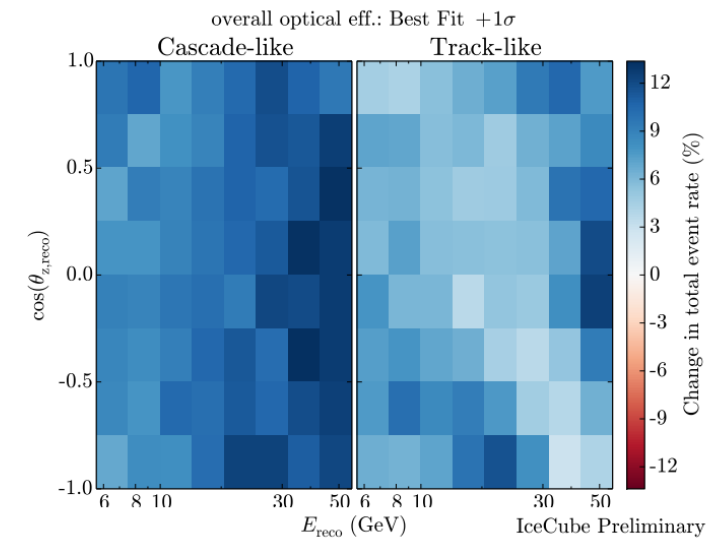
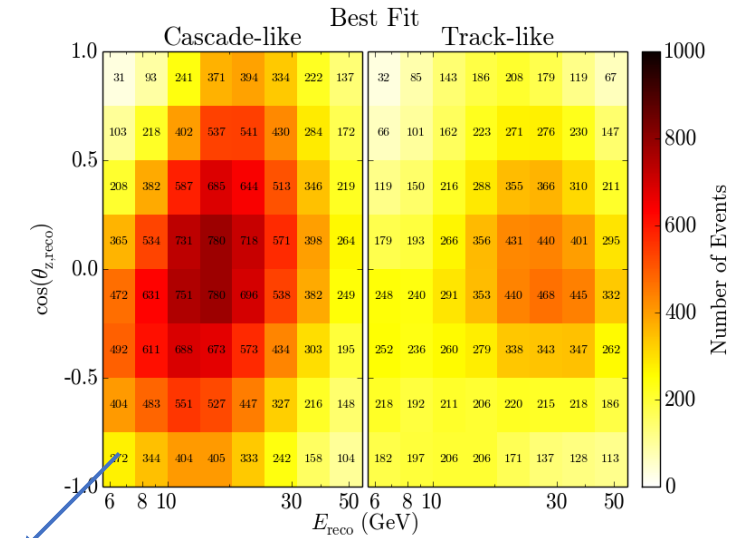
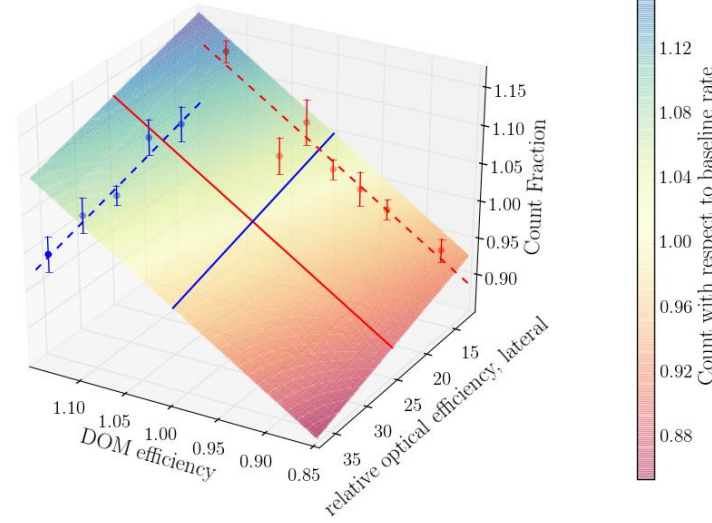
Tested, but subdominant:

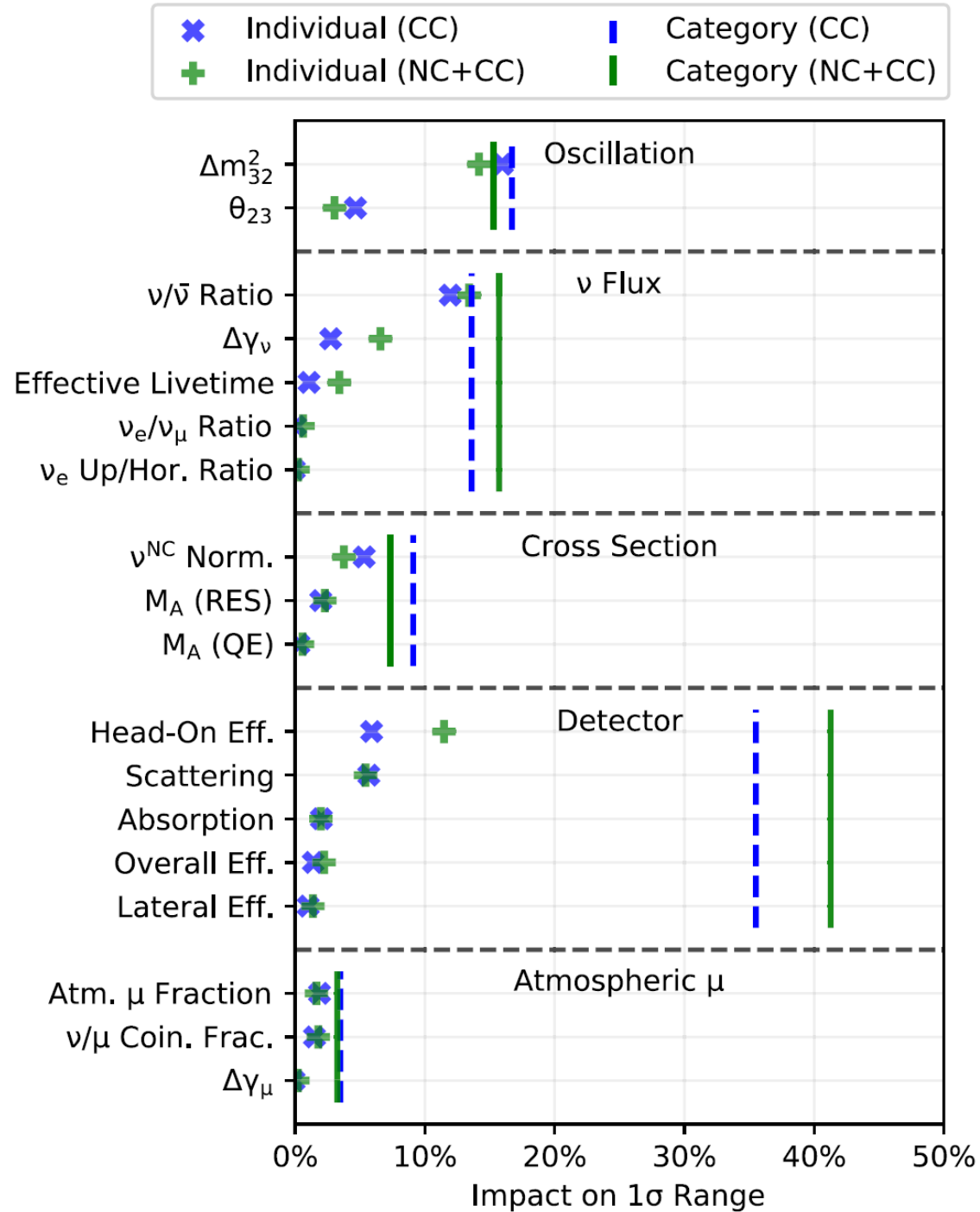
- DIS x-sec NuTeV corrections
- X-sec higher twist parameters
- X-sec valence quark correction
- Hadronization multiplicity
- Optical acceptance models

Parameter	Prior	Analysis \mathcal{A}	
		(CC + NC)	Best fit (CC)
<i>Neutrino flux and cross section:</i>			
ν_e/ν_μ Ratio	1.0 ± 0.05	1.03	1.03
ν_e Up/Hor. Flux ratio (σ)	0.0 ± 1.0	−0.19	−0.18
$\nu/\bar{\nu}$ Ratio (σ)	0.0 ± 1.0	−0.42	−0.33
$\Delta\gamma_\nu$ (Spectral index)	0.0 ± 0.1	0.03	0.03
Effective Livetime (years)	...	2.21	2.24
M_A^{CCQE} (Quasielastic) (GeV)	$0.99^{+0.248}_{-0.149}$	1.05	1.05
M_A^{res} (Resonance) (GeV)	1.12 ± 0.22	1.00	0.99
NC Normalization	1.0 ± 0.2	1.05	1.06
<i>Oscillation:</i>			
θ_{13} (°)	8.5 ± 0.21
θ_{23} (°)	...	49.8	50.2
Δm_{32}^2 (10^{-3} eV ²)	...	2.53	2.56
<i>Detector:</i>			
Optical Eff., Overall (%)	100 ± 10	98.4	98.4
Optical Eff., Lateral (σ)	0.0 ± 1.0	0.49	0.48
Optical Eff., Head-on (a.u.)	...	−0.63	−0.64
Local ice model
Bulk ice, scattering (%)	100.0 ± 10	103.0	102.8
Bulk ice, absorption (%)	100.0 ± 10	101.5	101.7
<i>Atmospheric muons:</i>			
Atm. μ fraction (%)	...	8.1	8.0
$\Delta\gamma_\mu$ (μ Spectral index, σ)	0.0 ± 1.0	0.15	0.15
Coincident $\nu + \mu$ fraction	$0.0 + 0.1$	0.01	0.01
<i>Measurement:</i>			
ν_τ Normalization	...	0.73	0.57

Systematic uncertainties

- Continuous modification of expectation at each bin
- Include:
 - Cross section
 - Neutrino flux
 - Detection optical efficiency
 - Relative angular acceptance
 - Background expectation





oscNext verification – total charge

