Measurements of neutrino flavor mixing with IceCube

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for the ICE CUBE Collaboration

Rencontres du Vietnam

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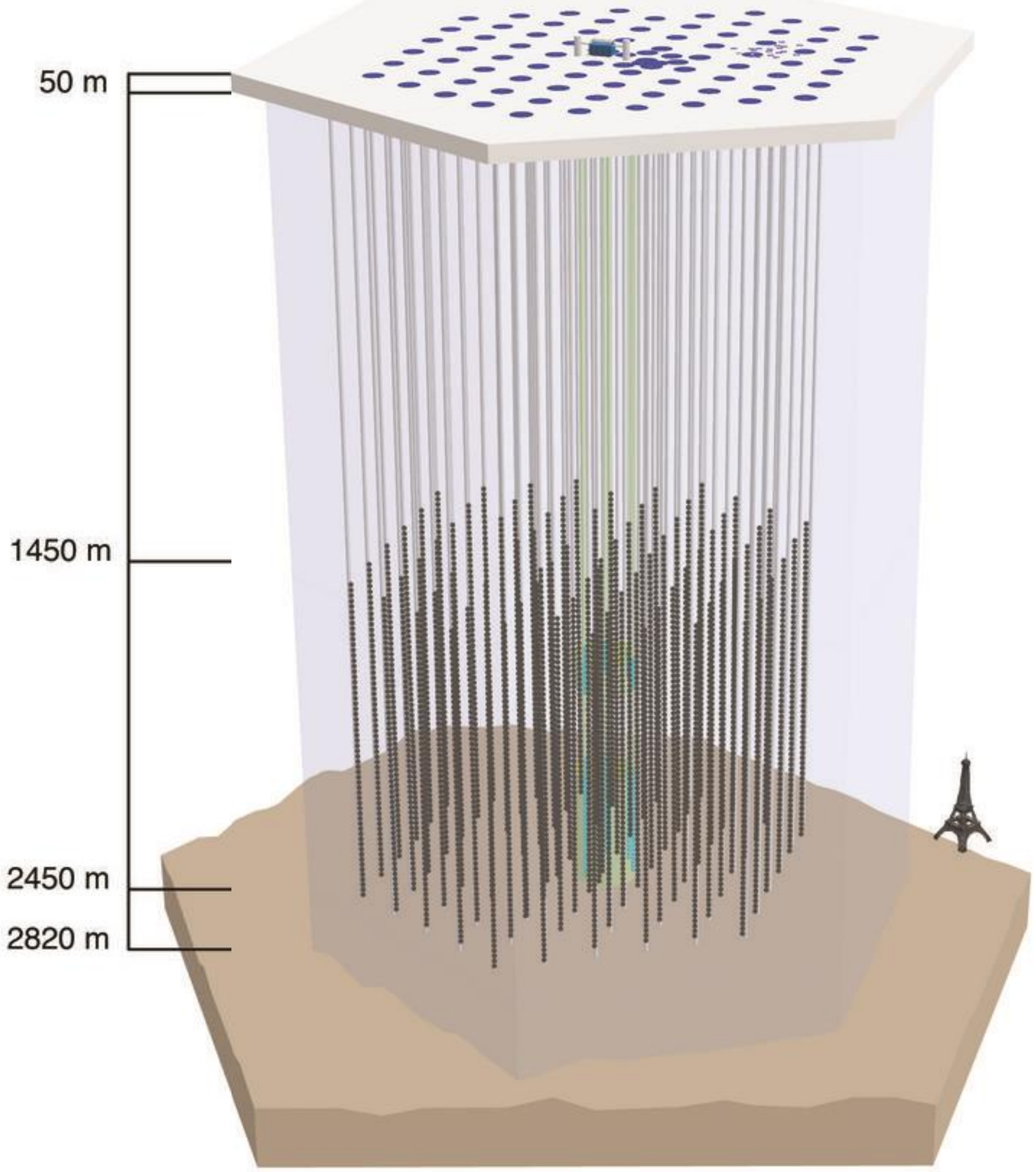
UNIVERSITY OF ALBERTA

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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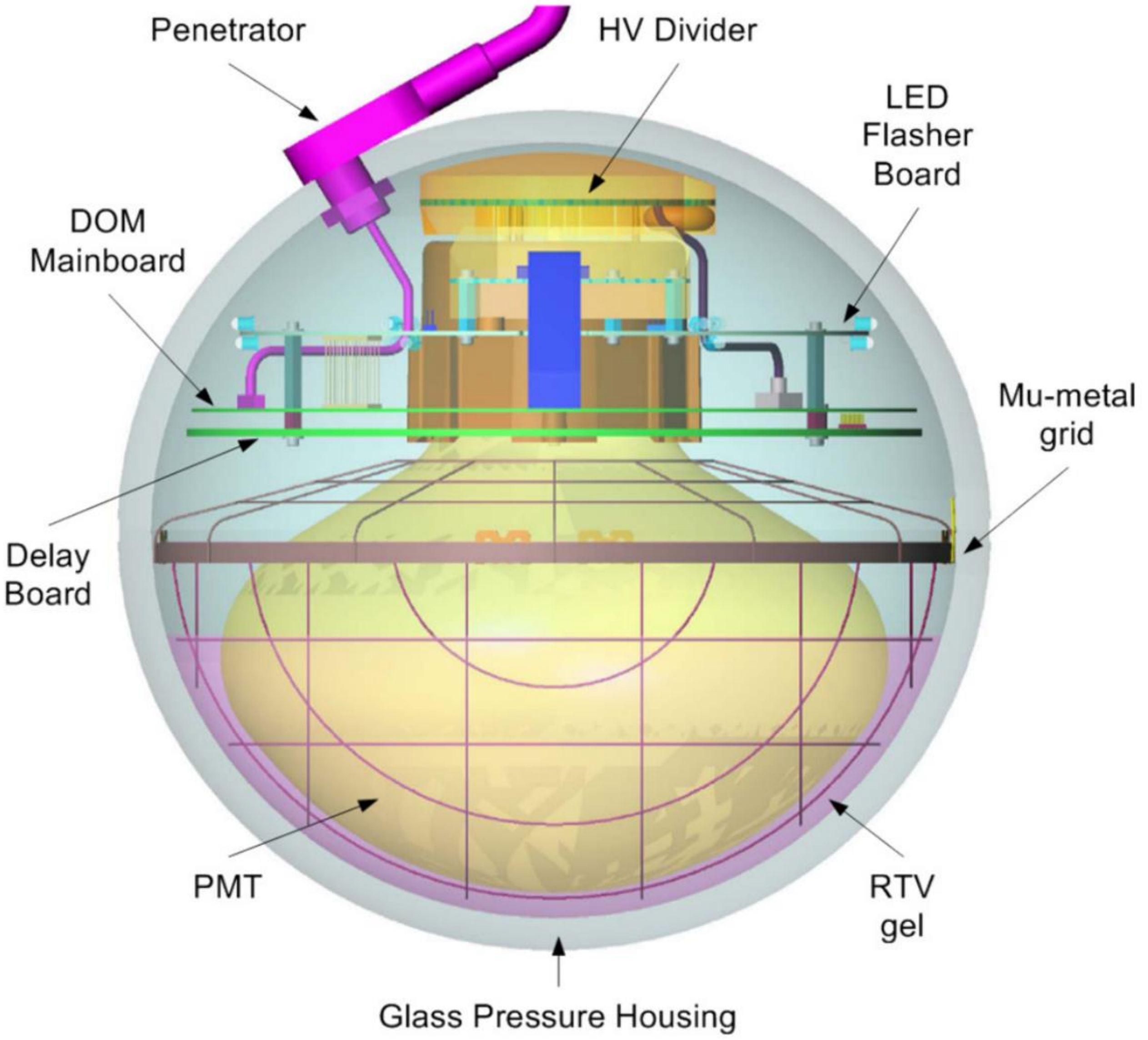

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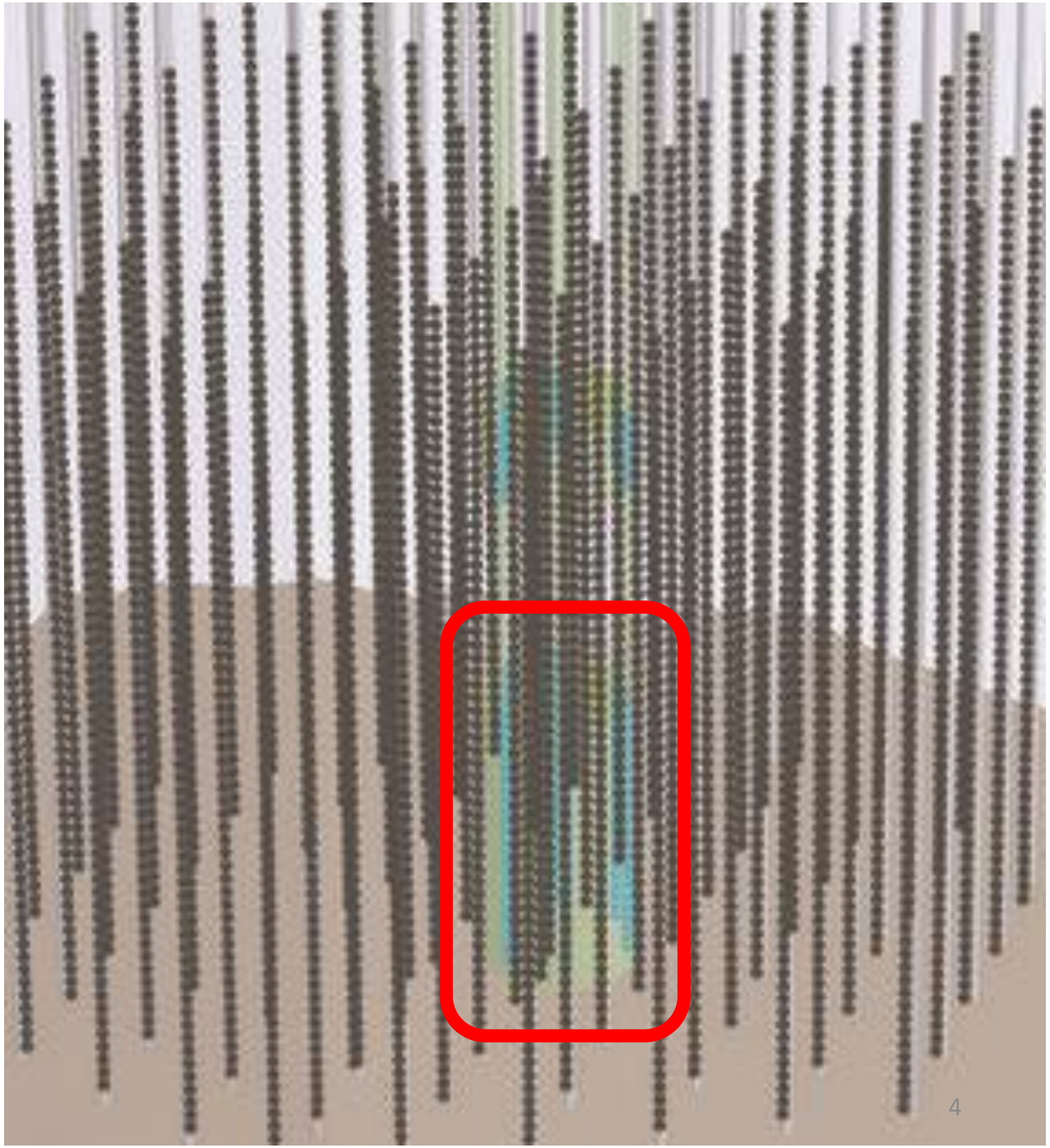
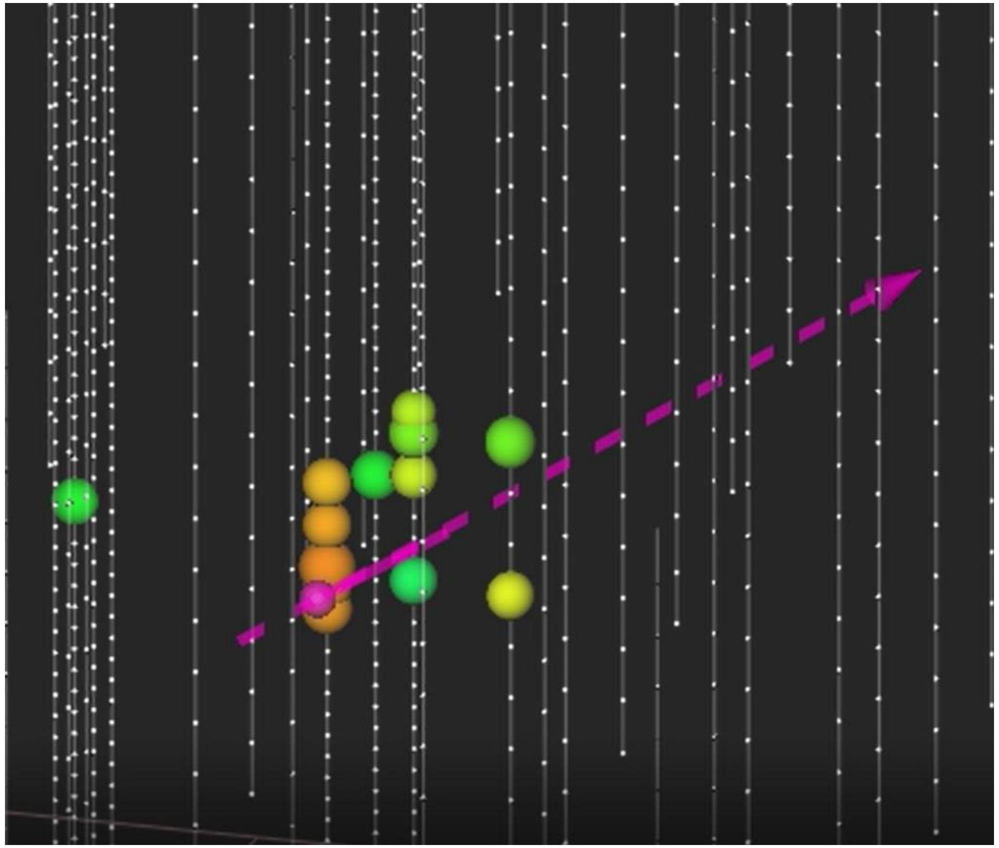
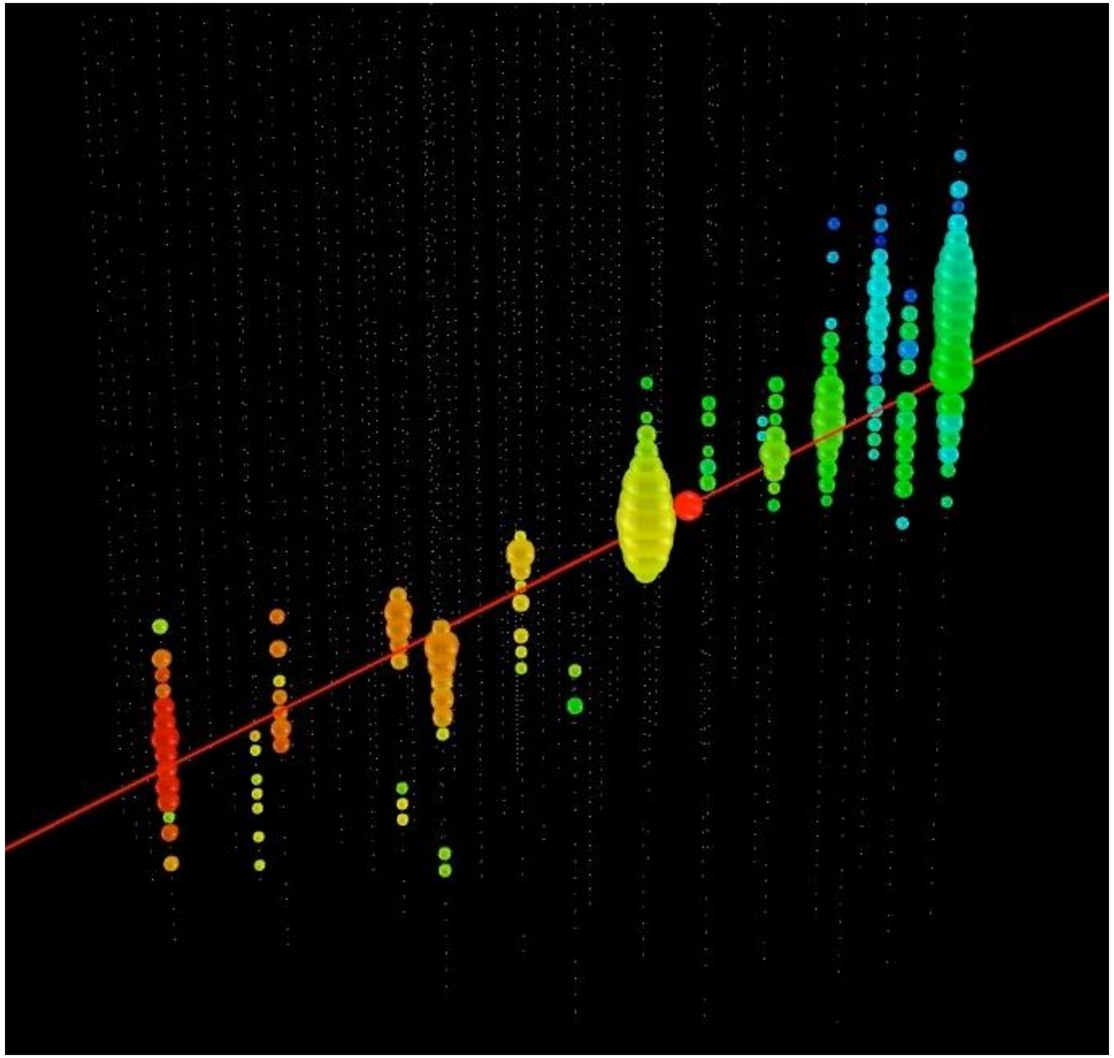
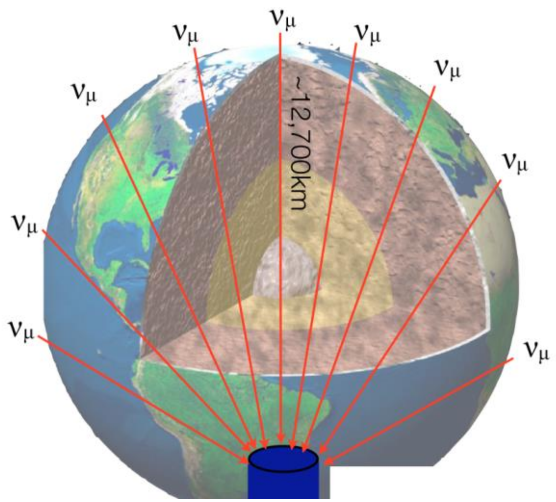


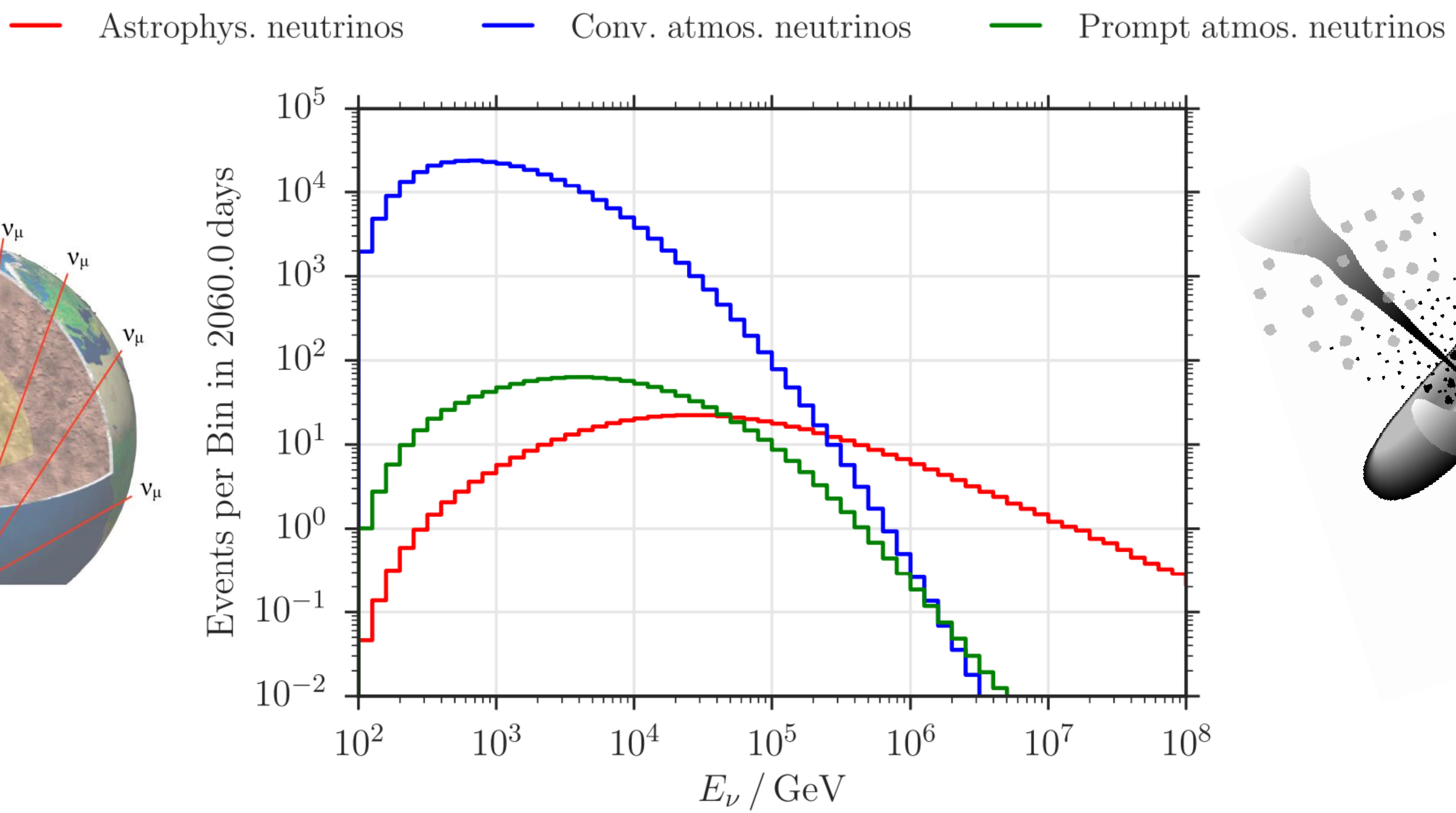
Neutrino events in IceCube

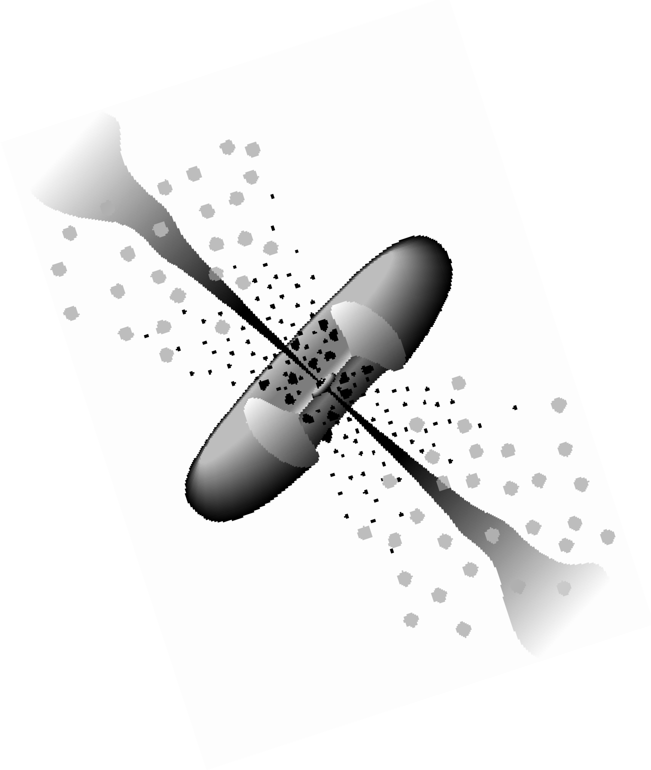




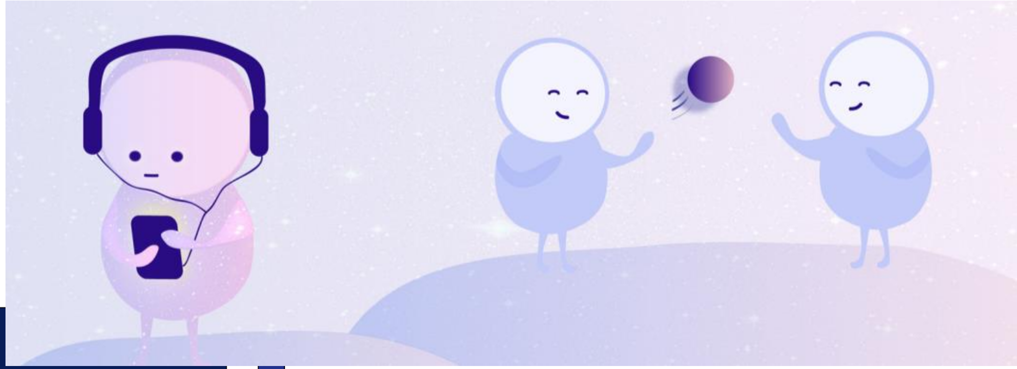
Neutrino sources for mixing studies

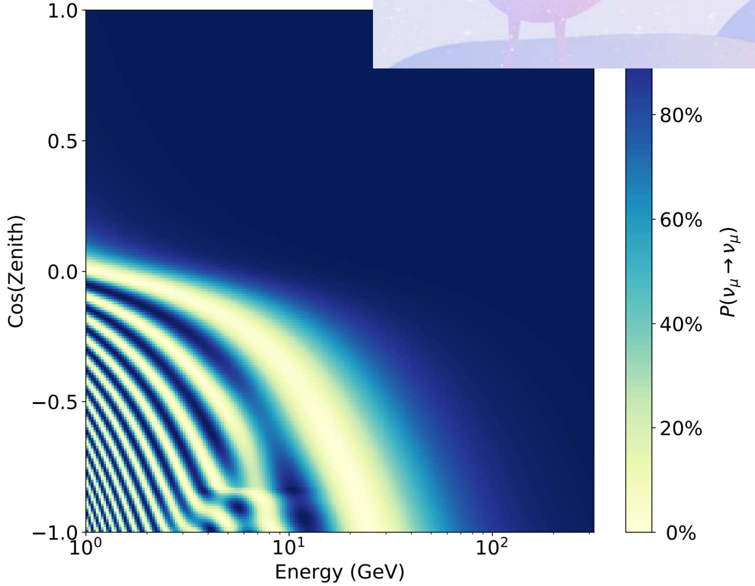


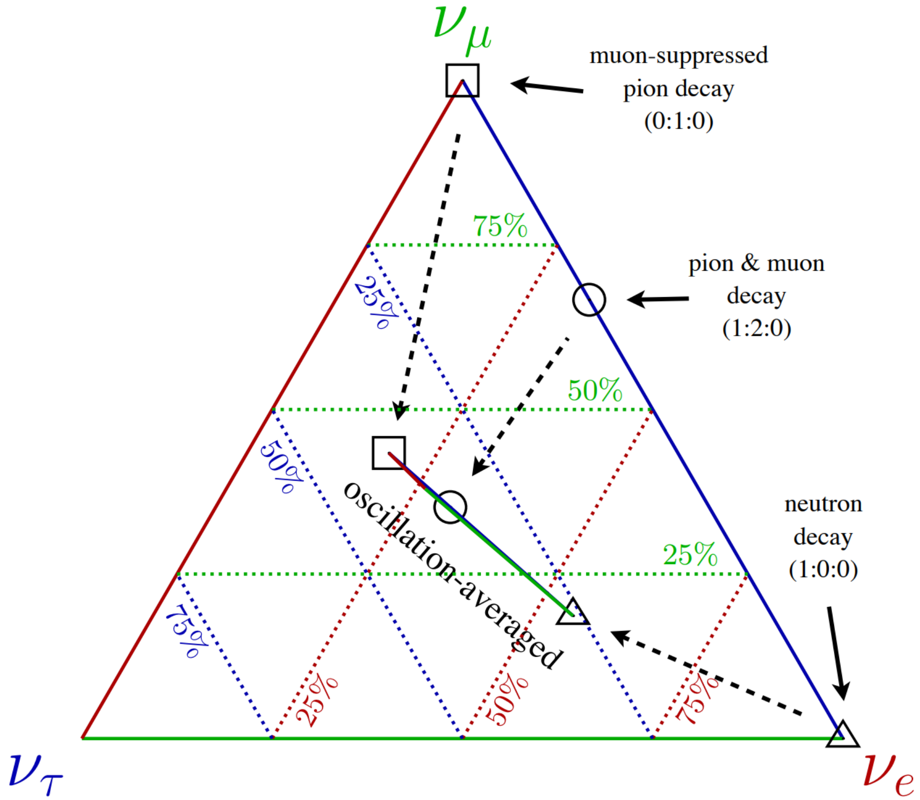


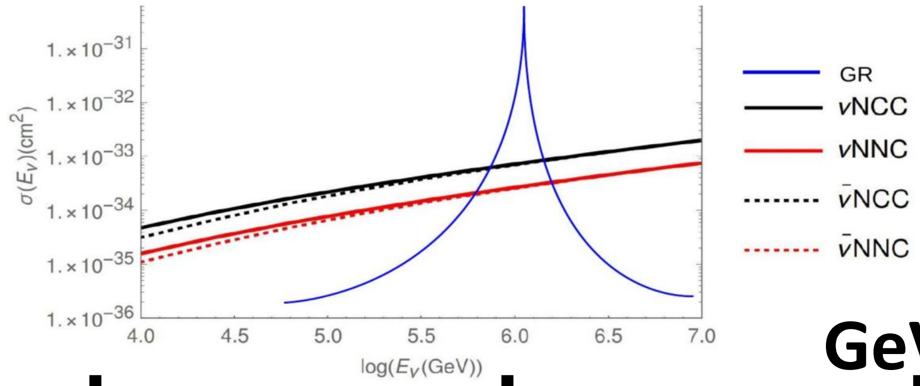


Flavor mixing E regime









GeV

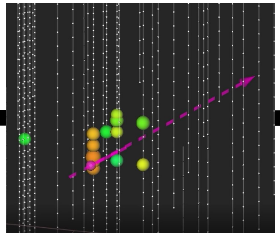
1 **10^3** **10^6**

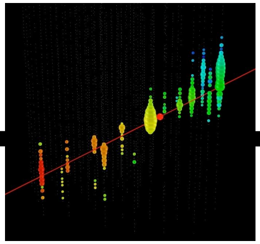
Flavor mixing *E* regime

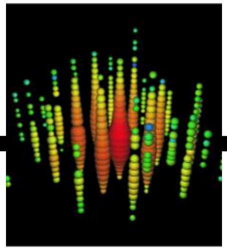
The DeepCore regime
- Aggressive veto techniques to remove atmospheric muons
- Computationally expensive reconstructions
- Good E estimator
- Highly detailed implementation of detector-related systematics

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



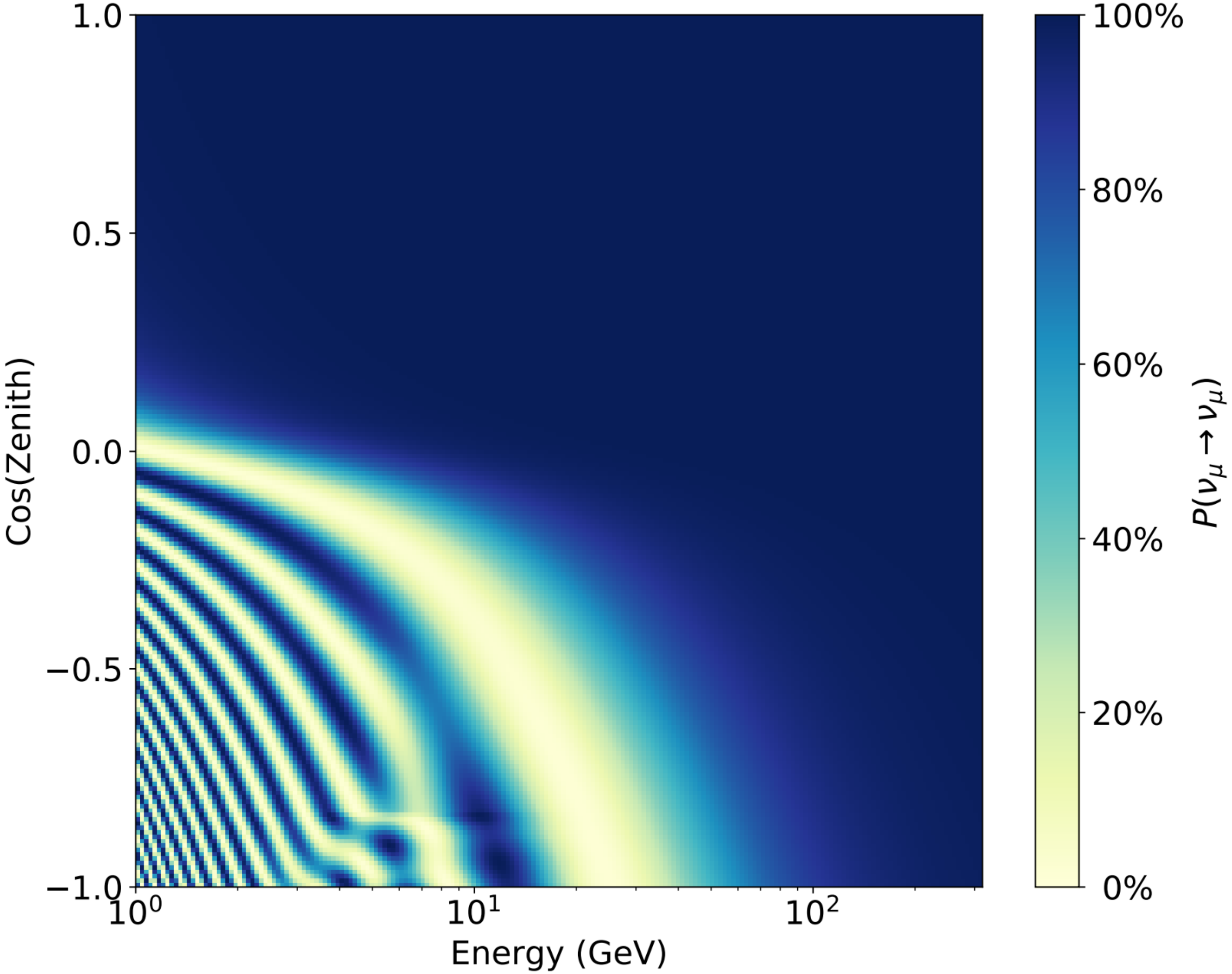




GeV

1 10^3 10^6

Standard oscillations (DC)



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

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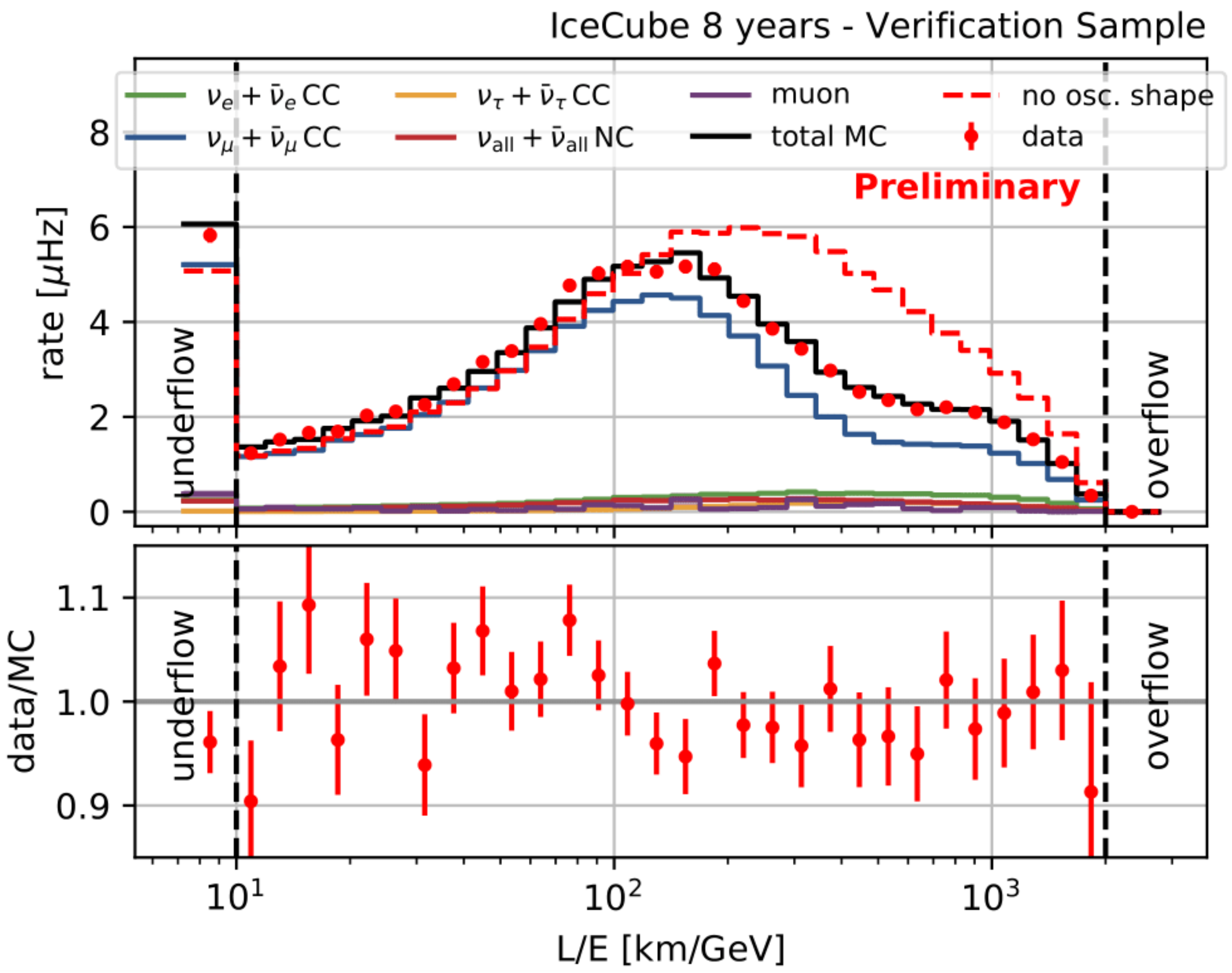
Standard oscillations (DC)

- 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)

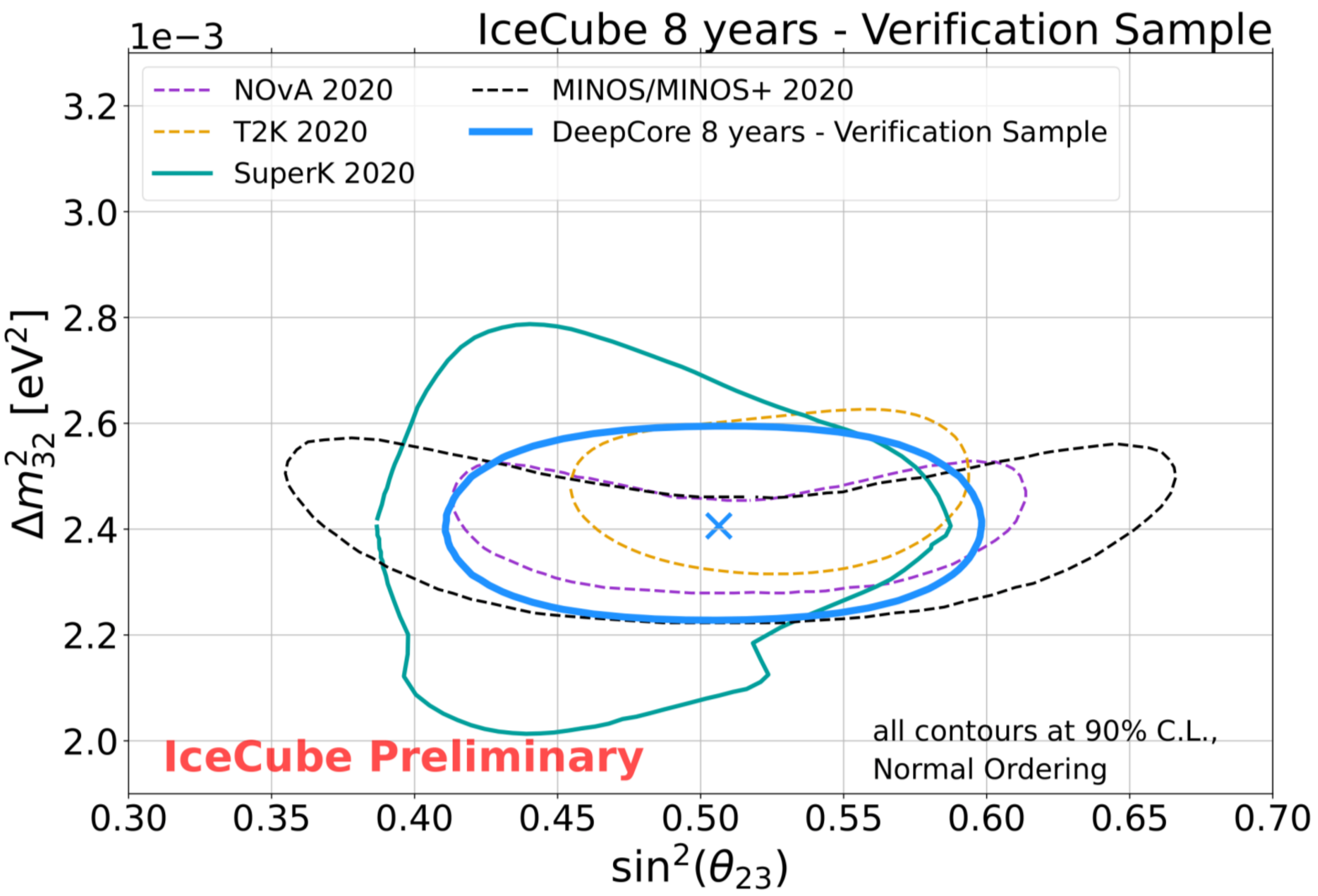
- Best fit values

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

  $\Delta m^2_{32} = 2.41 \pm 0.084 \times 10^{-3}$ eV²

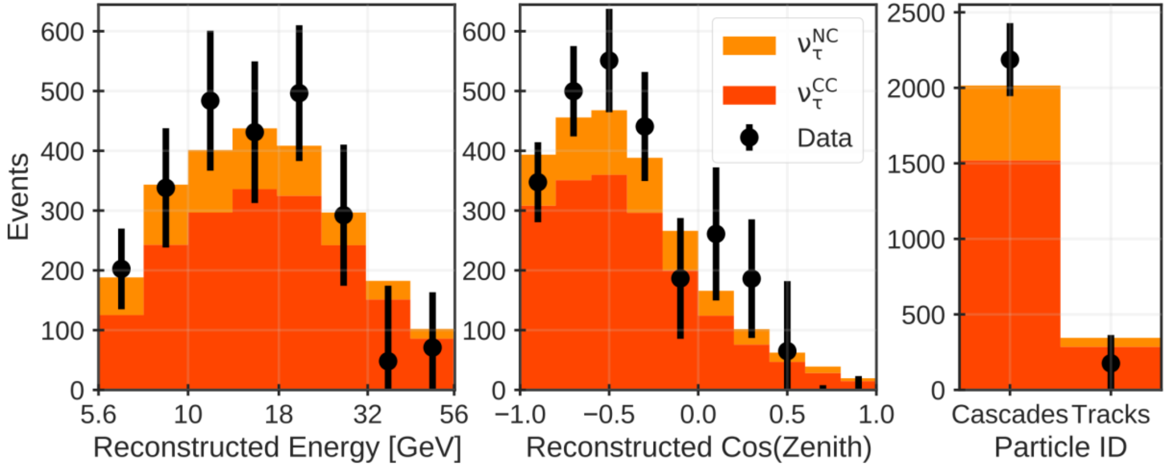
- Excellent agreement between data/MC

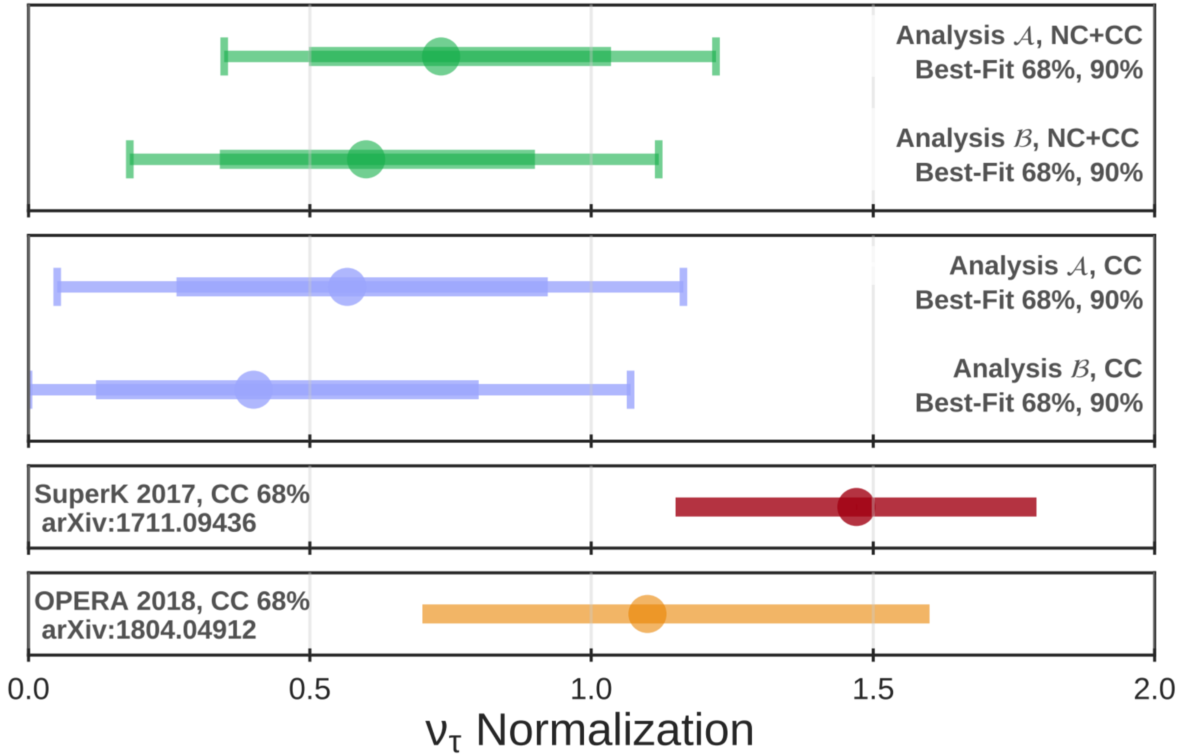
- Publication in preparation



Standard oscillations (DC) – tau appearance

- Older sample, new analysis still in progress



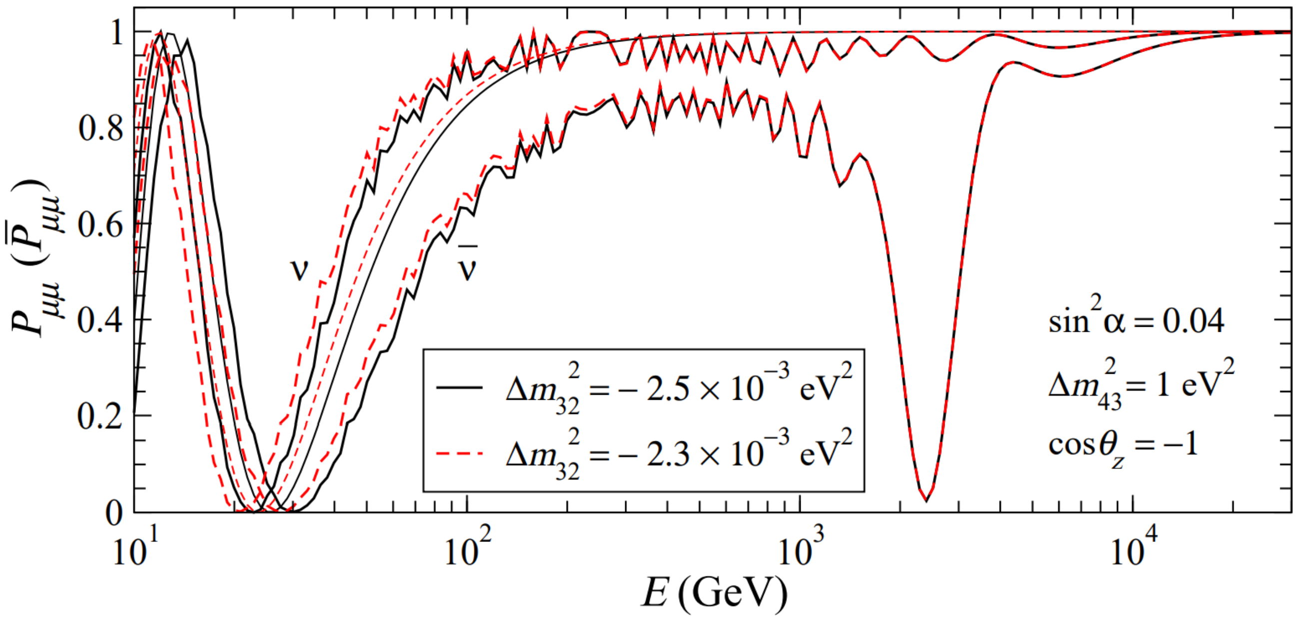


Phys. Rev. D 99, 032007 (2019)

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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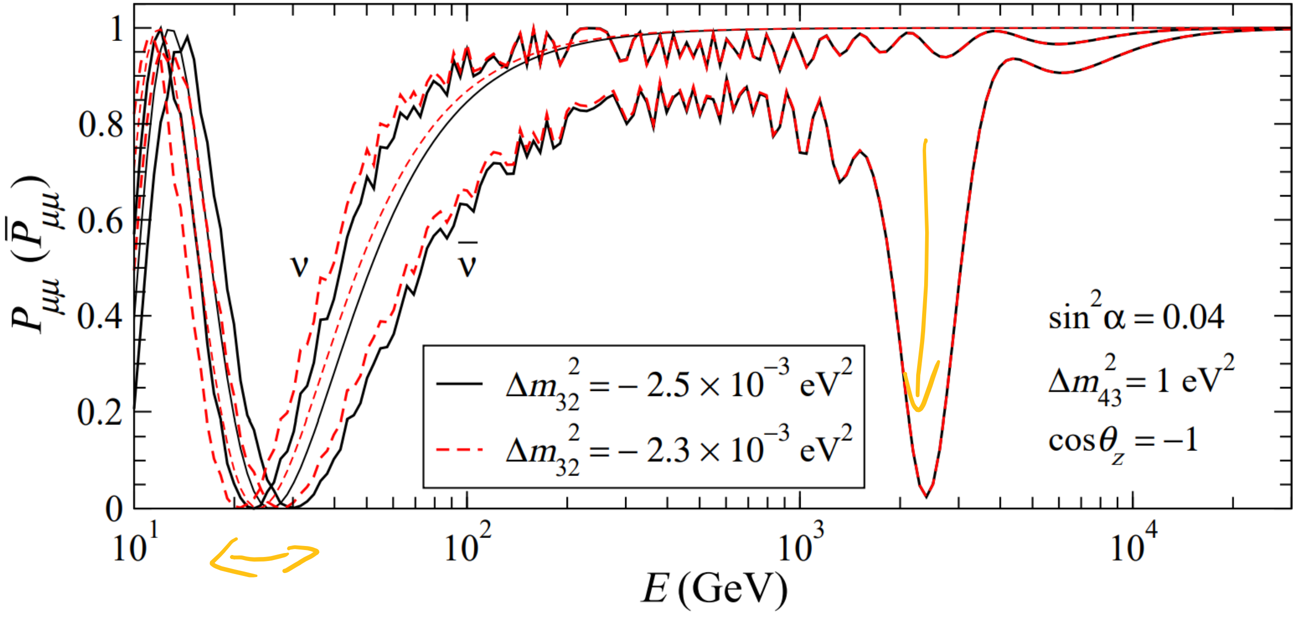

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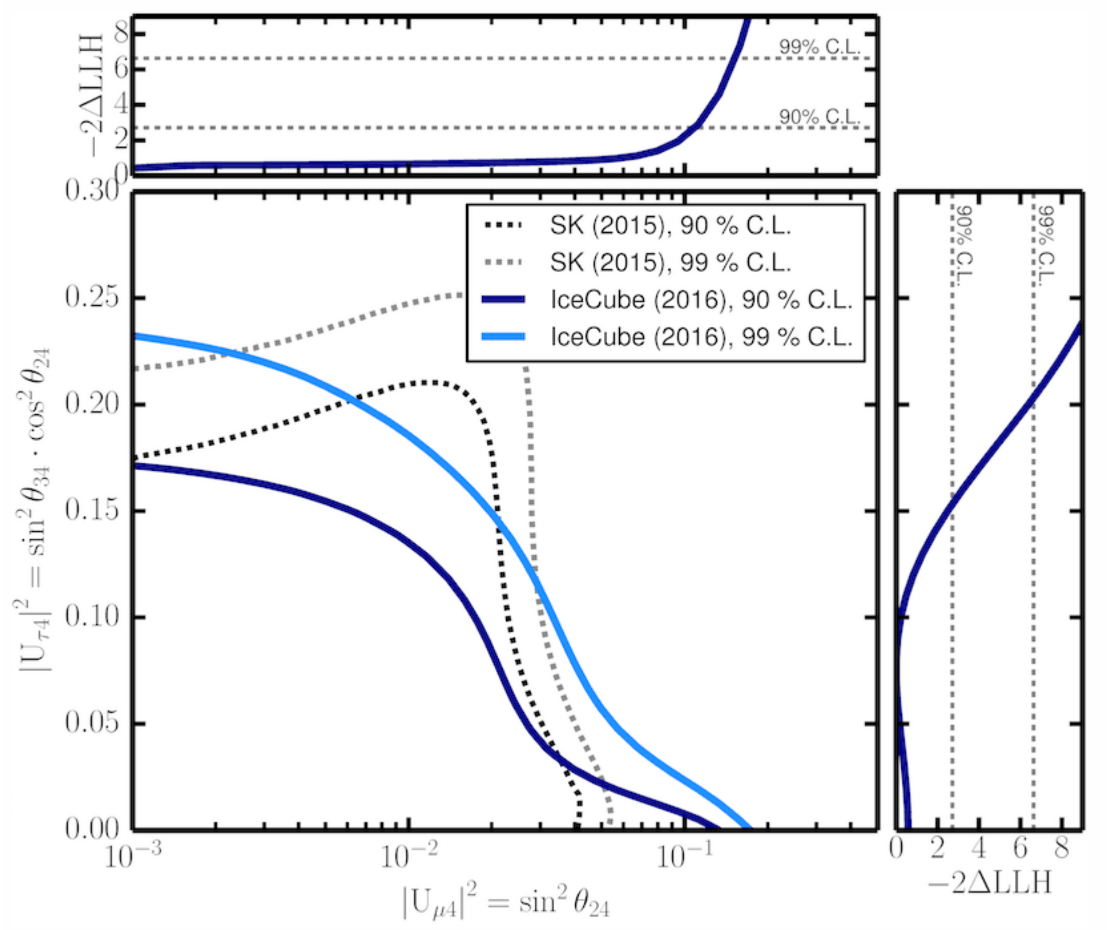
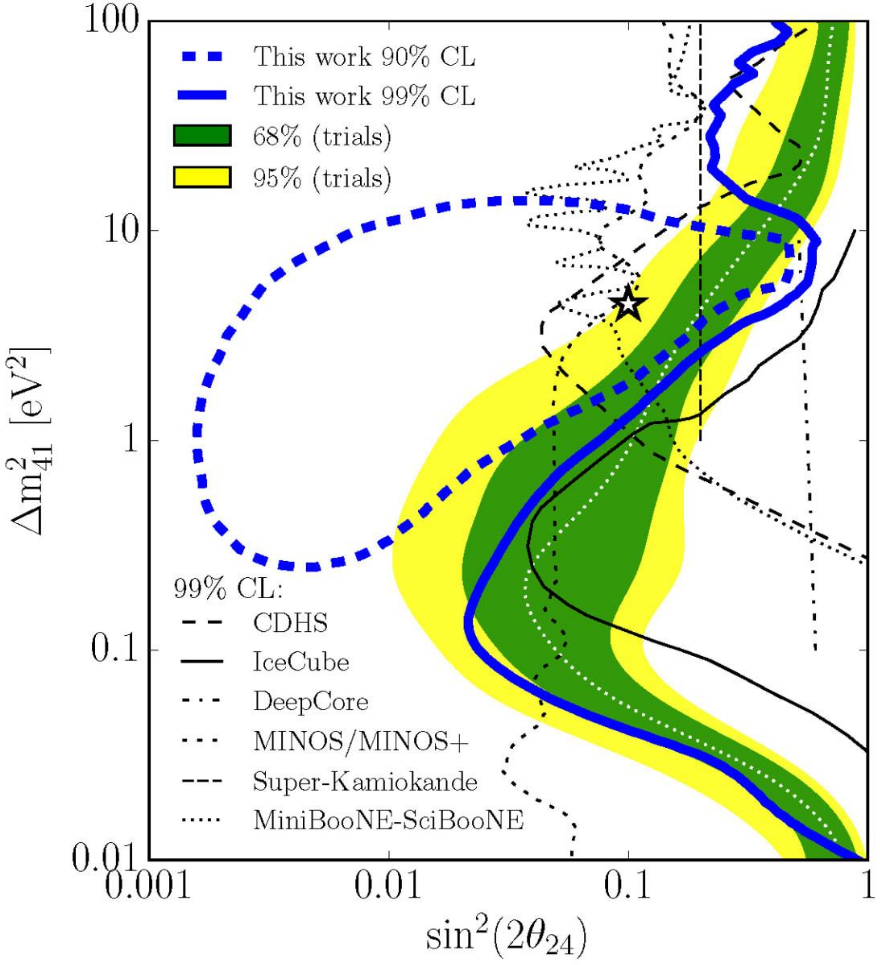


Phys. Rev. D 95, 112002 (2017)

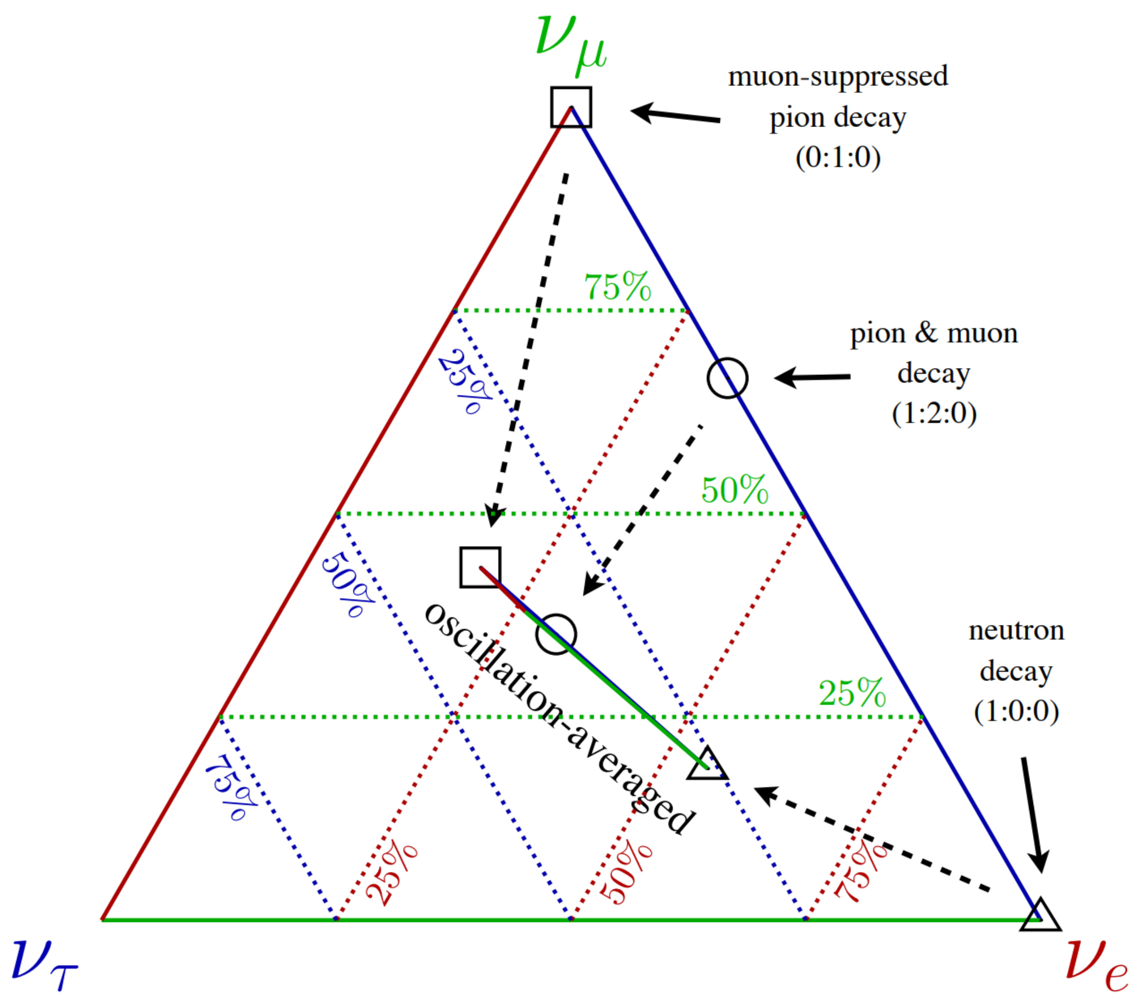


Phys. Rev. Lett. 125, 141801 (2020)

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



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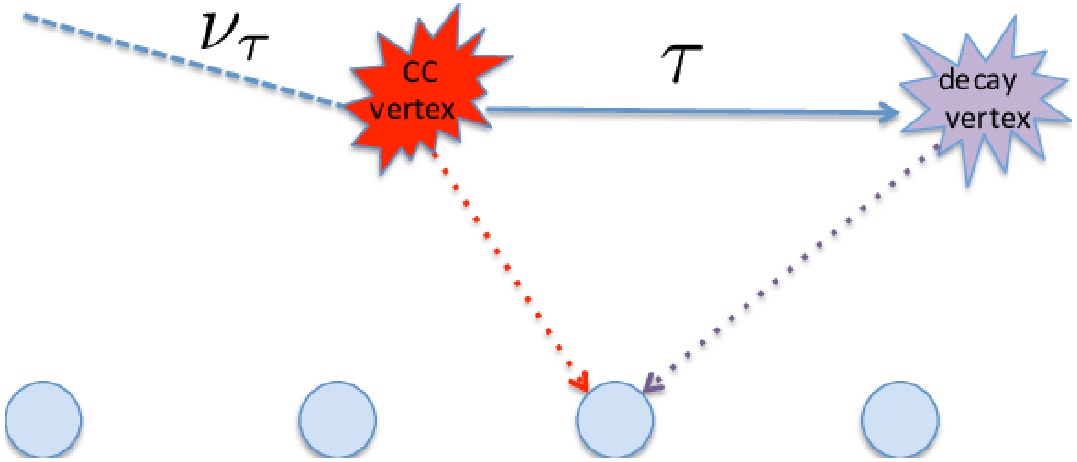
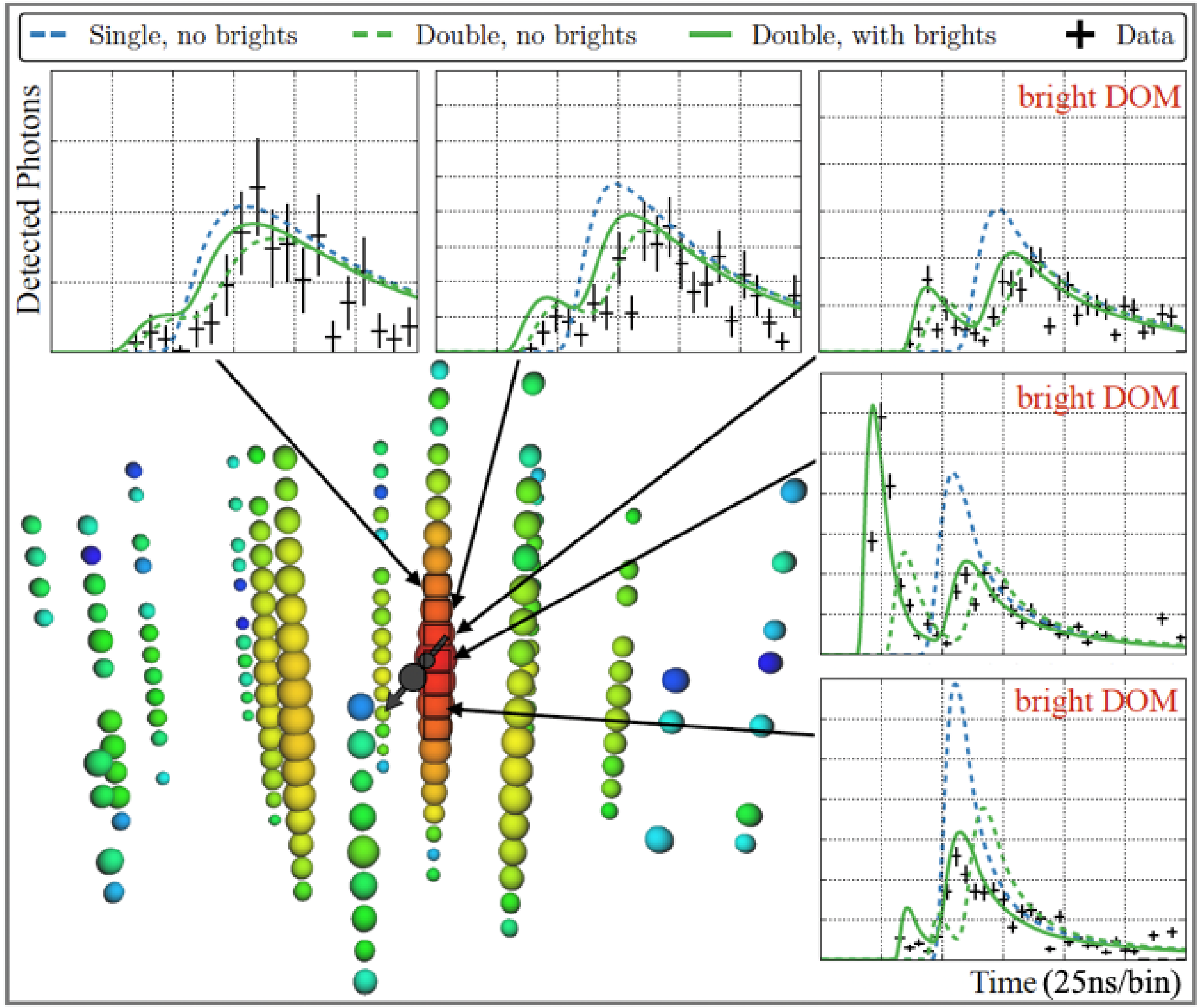
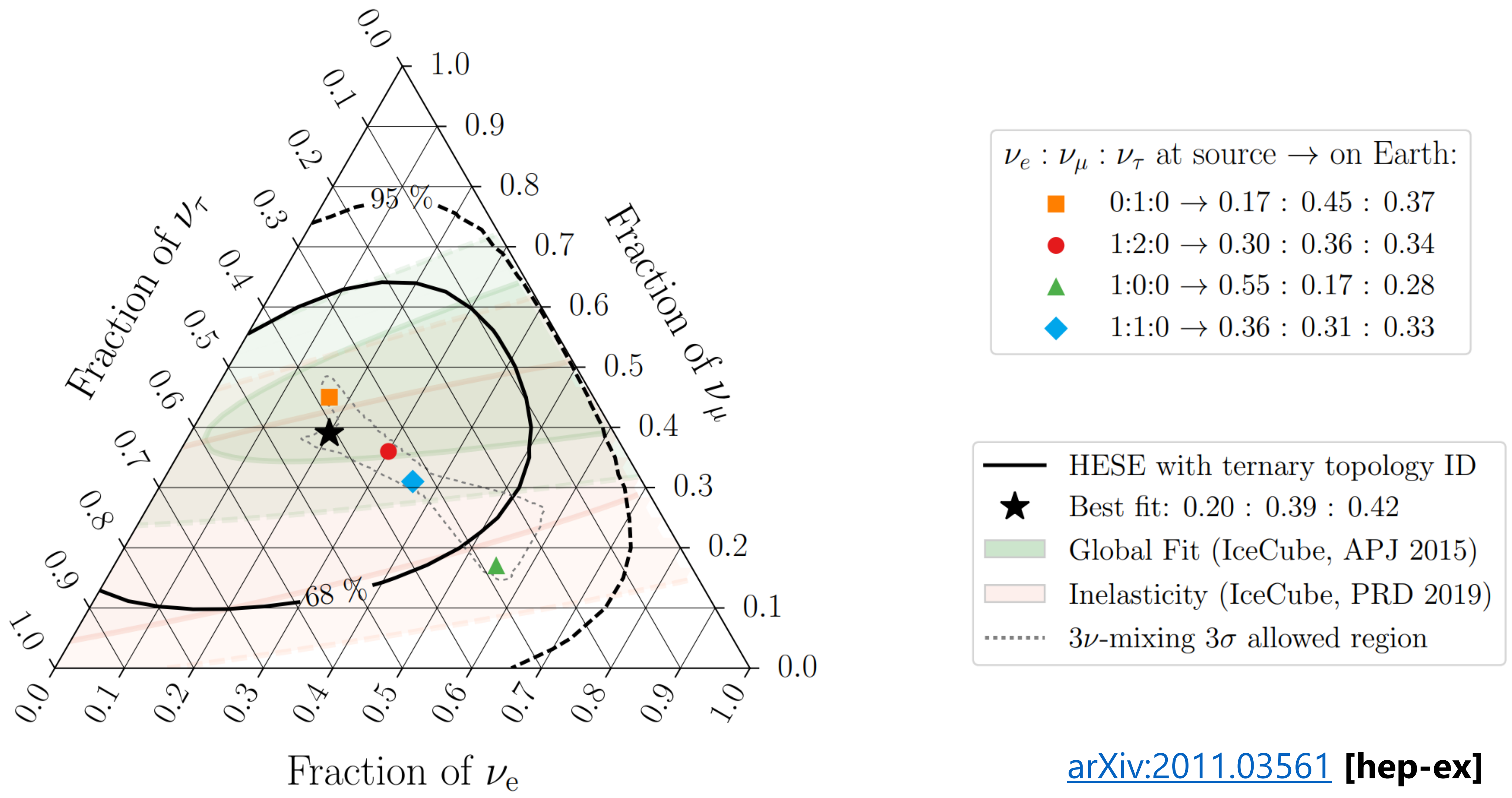




- Two events observed in 1 search (here)
  - arXiv:2011.03561 **[hep-ex]**
- New ML-based approaches developed
  - Expect 5 ν_τ events on 0.5 background
  - Could reject no-tau hypothesis at 5sigma
  - Results coming soon

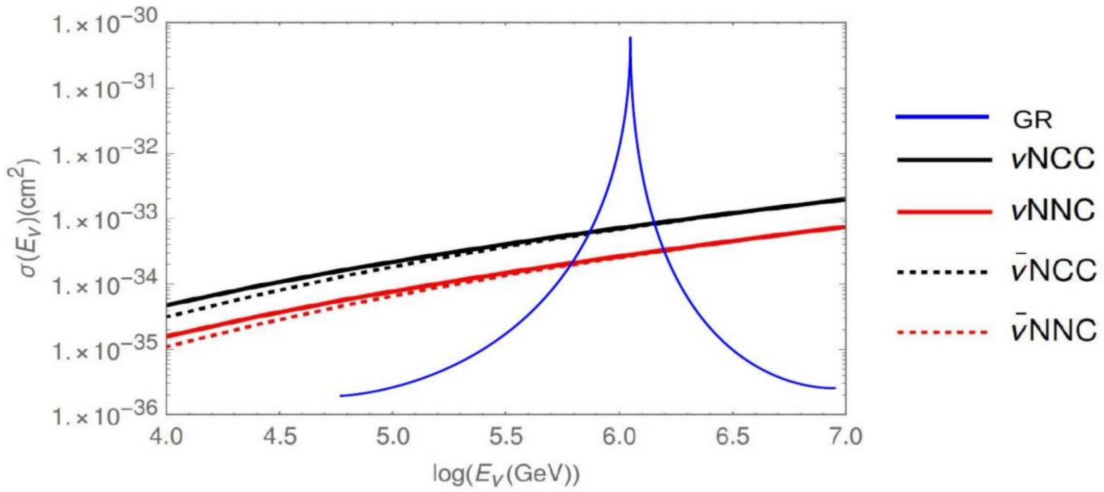
Astrophysical tau observations (HE cascades)

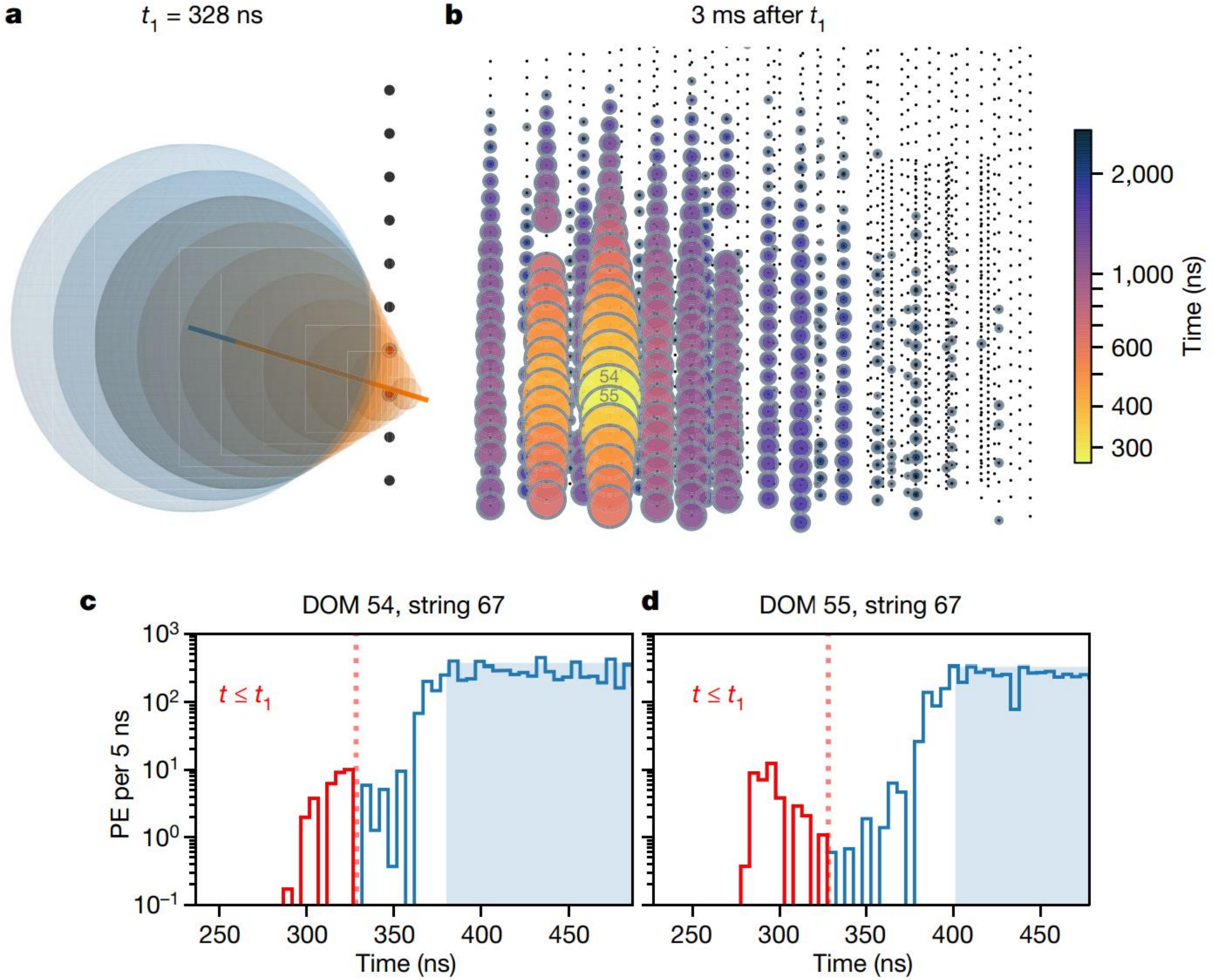


arXiv:2011.03561 **[hep-ex]**

W-production by $\overline{\nu_e} - e^-$

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





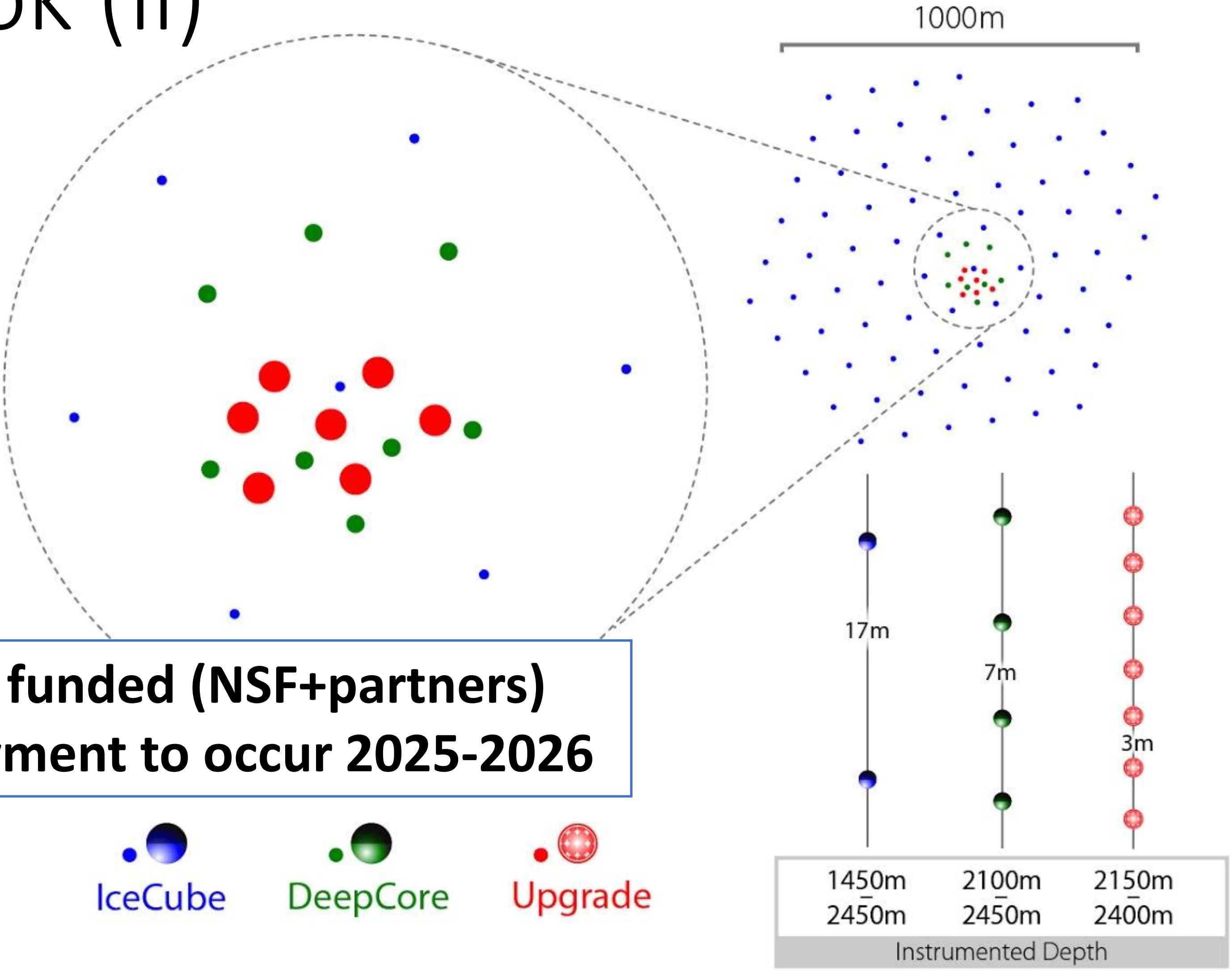
Summary and Outlook (i)

- 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

Thank you for your attention, on behalf of

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)
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Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
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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

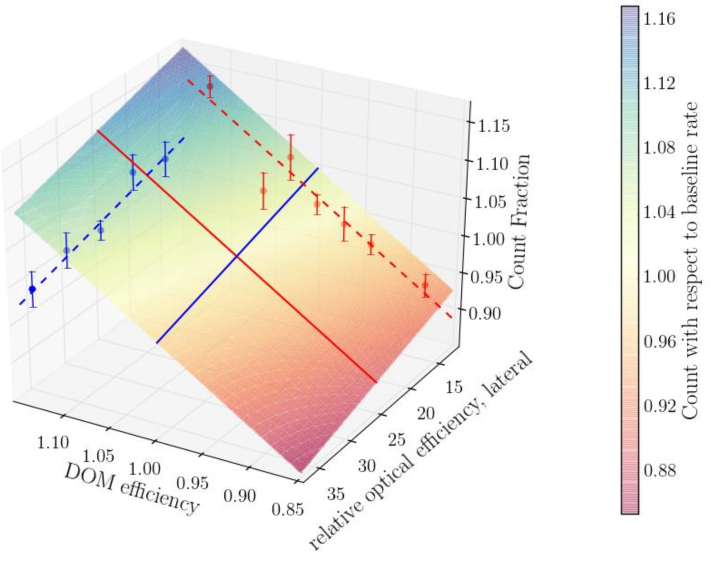
Tested, but subdominant:

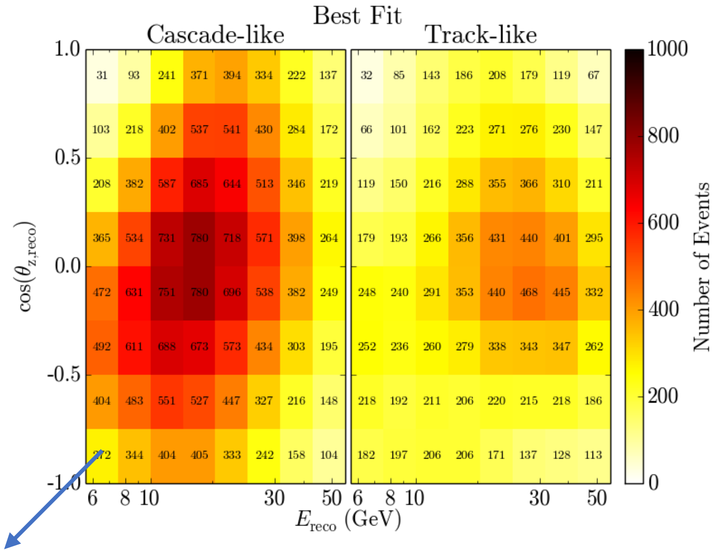
- DIS x-sec NuTeV corrections
- X-sec higher twist parameters
- X-sec valence quark correction
- Hadronization multiplicity
- Optical acceptance models

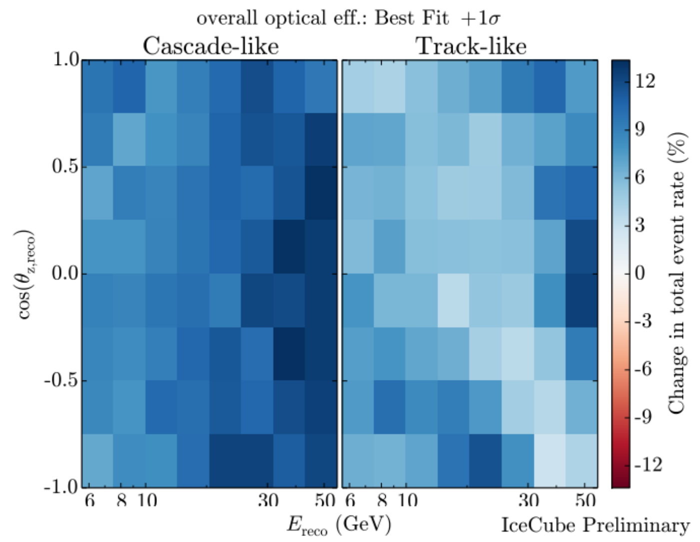
		Analysis $\mathcal{A}$	
Parameter	Prior	(CC + NC)	Best fit (CC)
Neutrino flux and cross section:			
ν_e/ν_μ Ratio	1.0 ± 0.05	1.03	1.03
ν_e Up/Hor. Flux ratio (σ)	0.0 ± 1.0	−0.19	−0.18
$\nu/\bar{\nu}$ Ratio (σ)	0.0 ± 1.0	−0.42	−0.33
$\Delta\gamma_\nu$ (Spectral index)	0.0 ± 0.1	0.03	0.03
Effective Livetime (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
Oscillation:			
θ_{13} (°)	8.5 ± 0.21	⋯	⋯
θ_{23} (°)	⋯	49.8	50.2
Δm^2_{32} (10^{-3} eV^2)	⋯	2.53	2.56
Detector:			
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
Atmospheric muons:			
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
Measurement:			
ν_τ Normalization	⋯	0.73	0.57

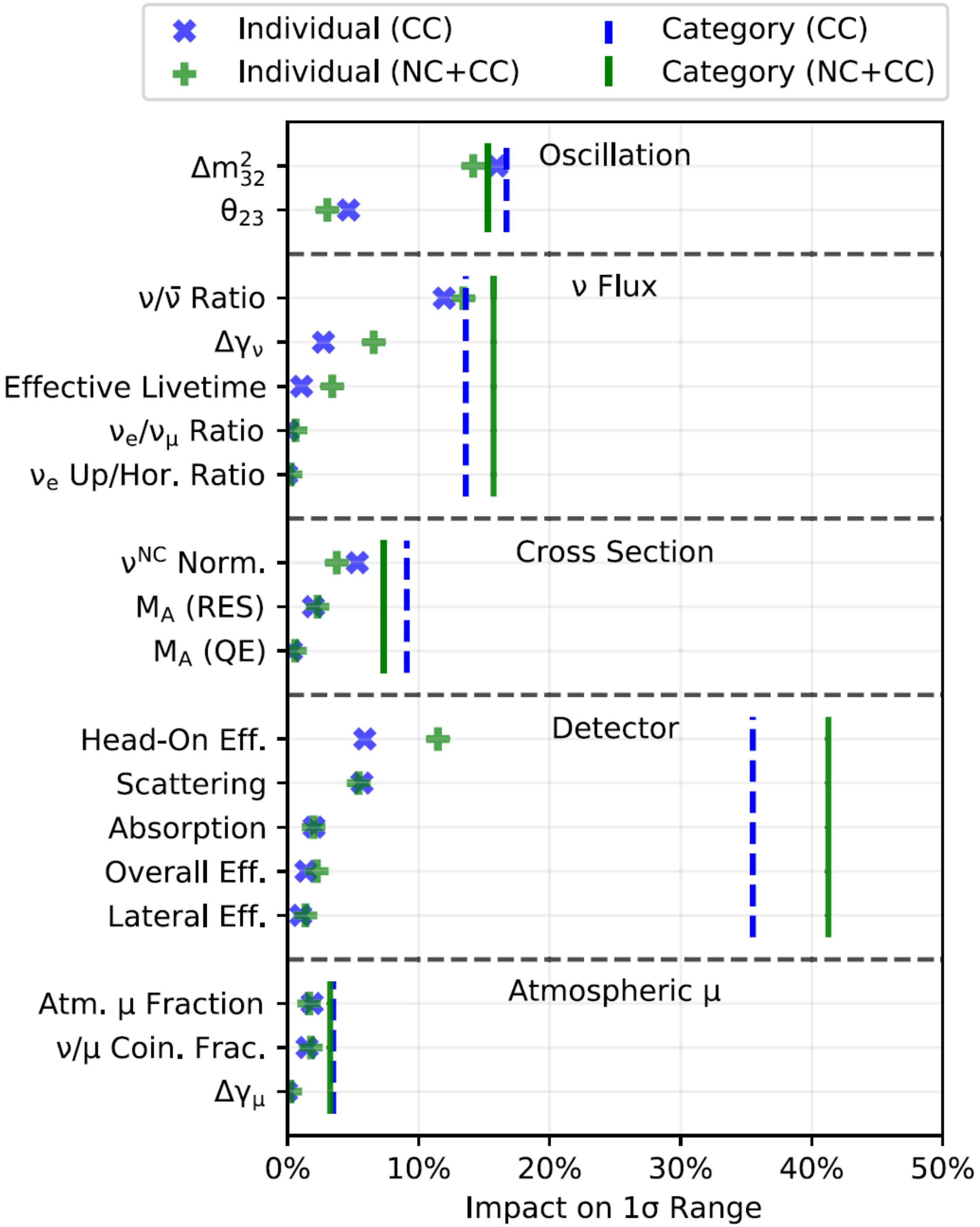
Systematic uncertainties

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








Individual (CC)
Individual (NC+CC)
Category (CC)
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Oscillation
Δm^2_{32}
θ_{23}
ν Flux
$\nu/\bar{\nu}$ Ratio
$\Delta\gamma_\nu$
Effective Livetime
ν_e/ν_μ Ratio
ν_e Up/Hor. Ratio
Cross Section
ν^{NC} Norm.
M_A (RES)
M_A (QE)
Detector
Head-On Eff.
Scattering
Absorption
Overall Eff.
Lateral Eff.
Atmospheric μ
Atm. μ Fraction
ν/μ Coin. Frac.
$\Delta\gamma_\mu$
0%
10%
20%
30%
40%
50%
Impact on 1σ Range

oscNext verification – total charge