Particle Physics with IceCube: Selected results

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for the IceCube Collaboration

Flavor Physics and CP Violation

FPCP 2023, Lyon

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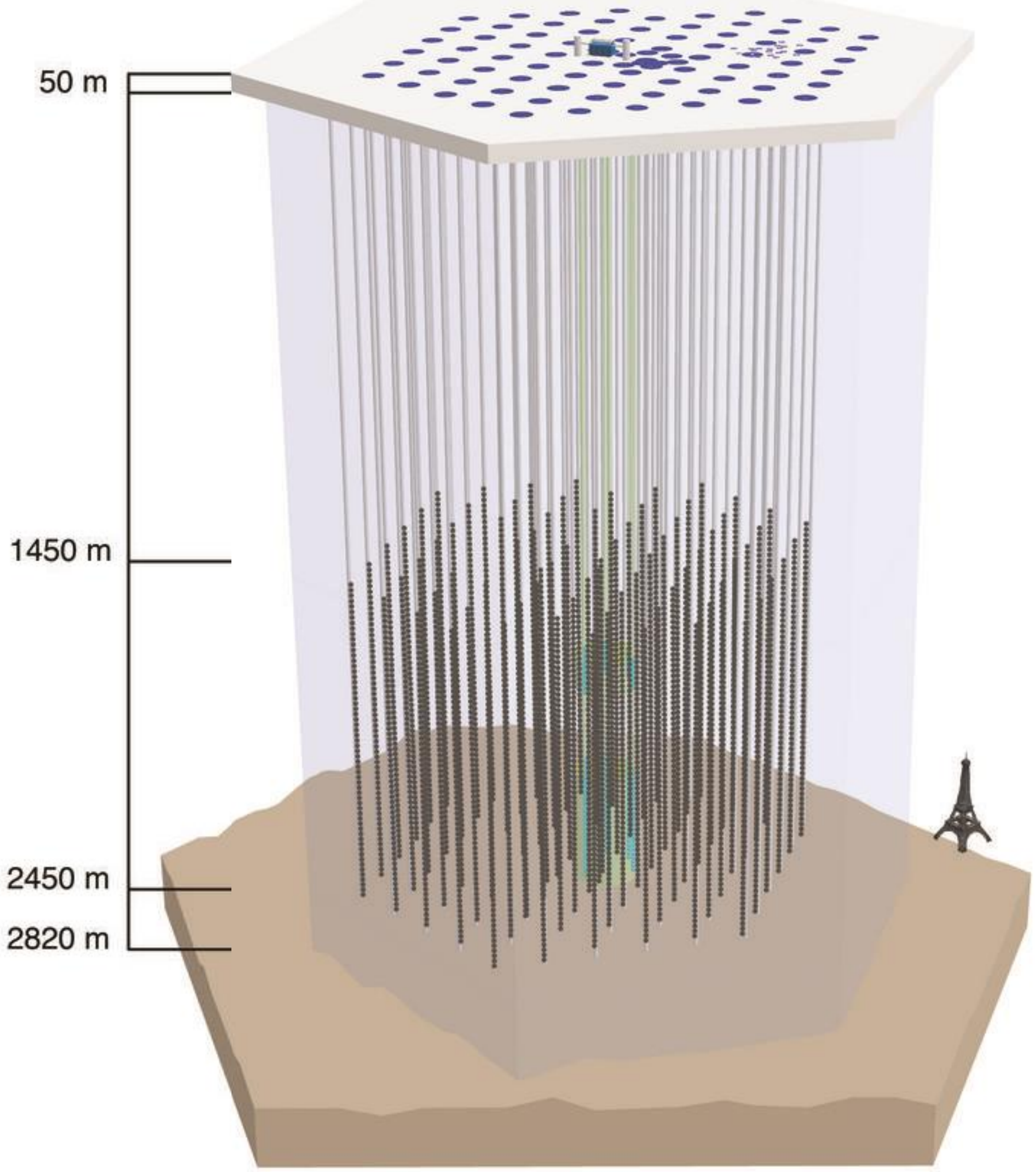
UNIVERSITY OF ALBERTA

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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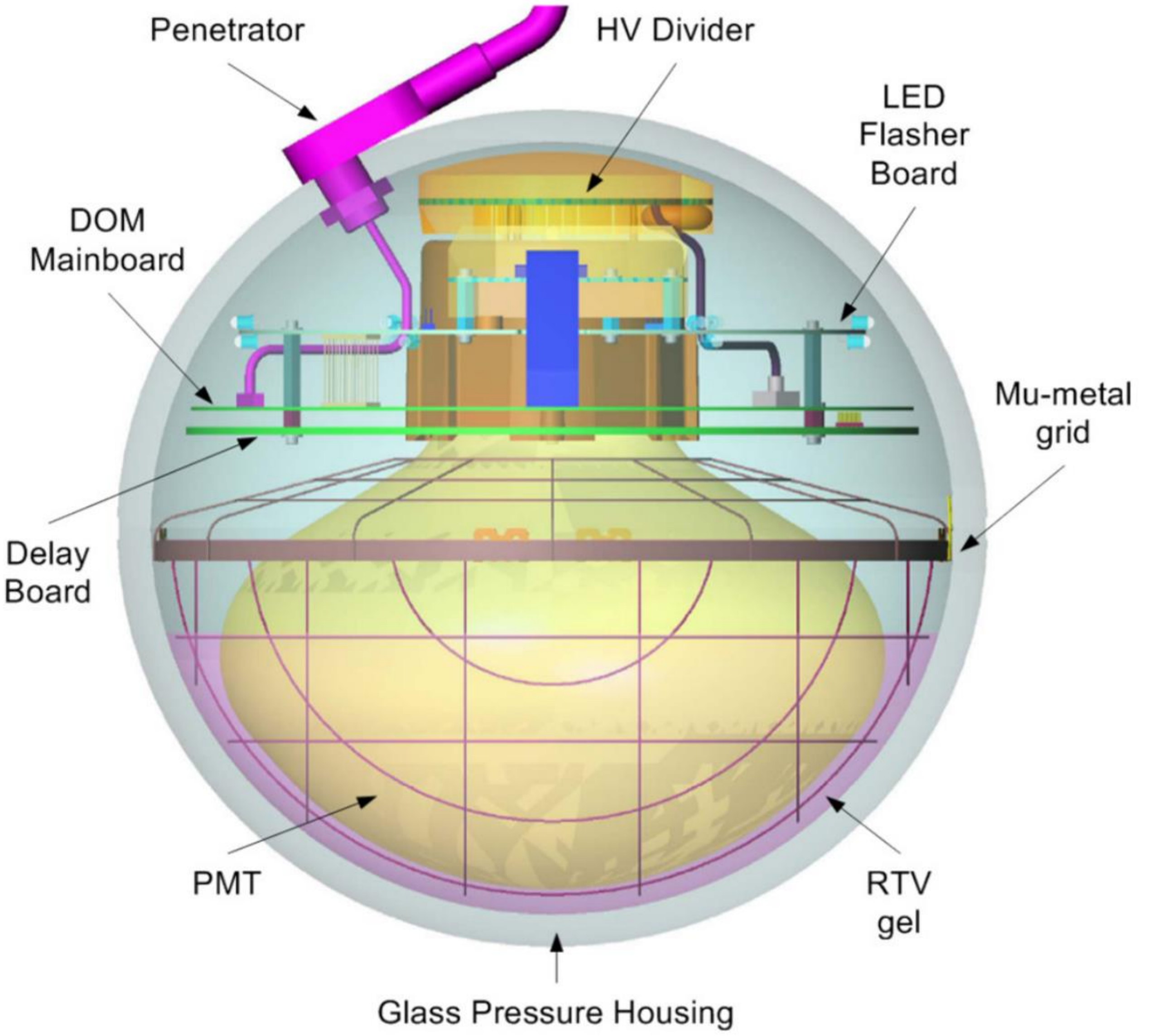

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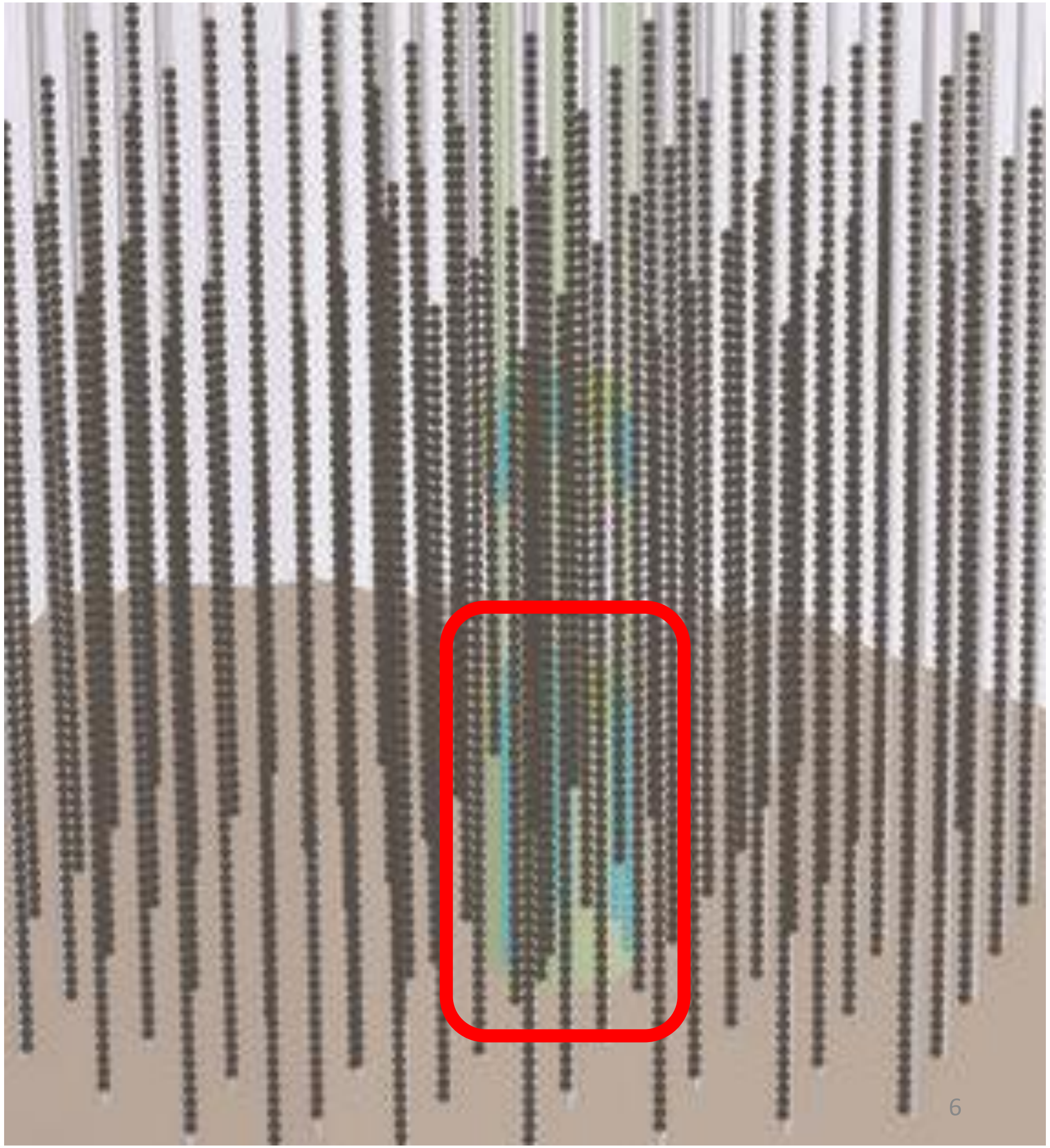
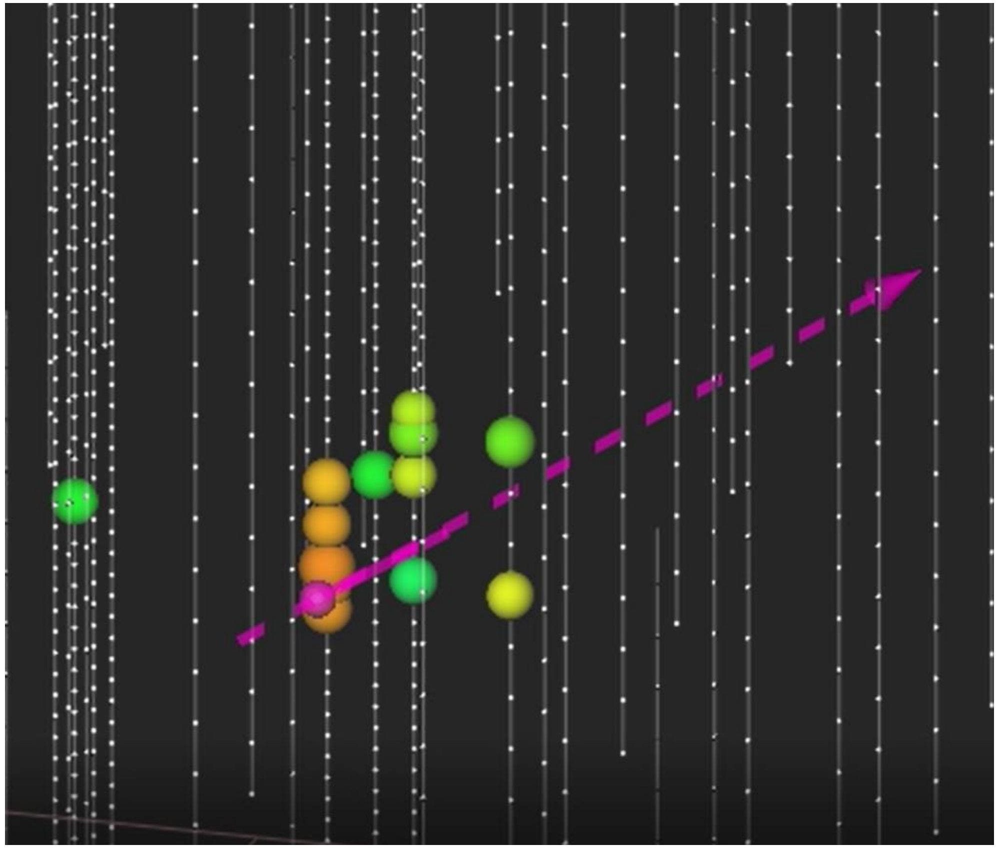
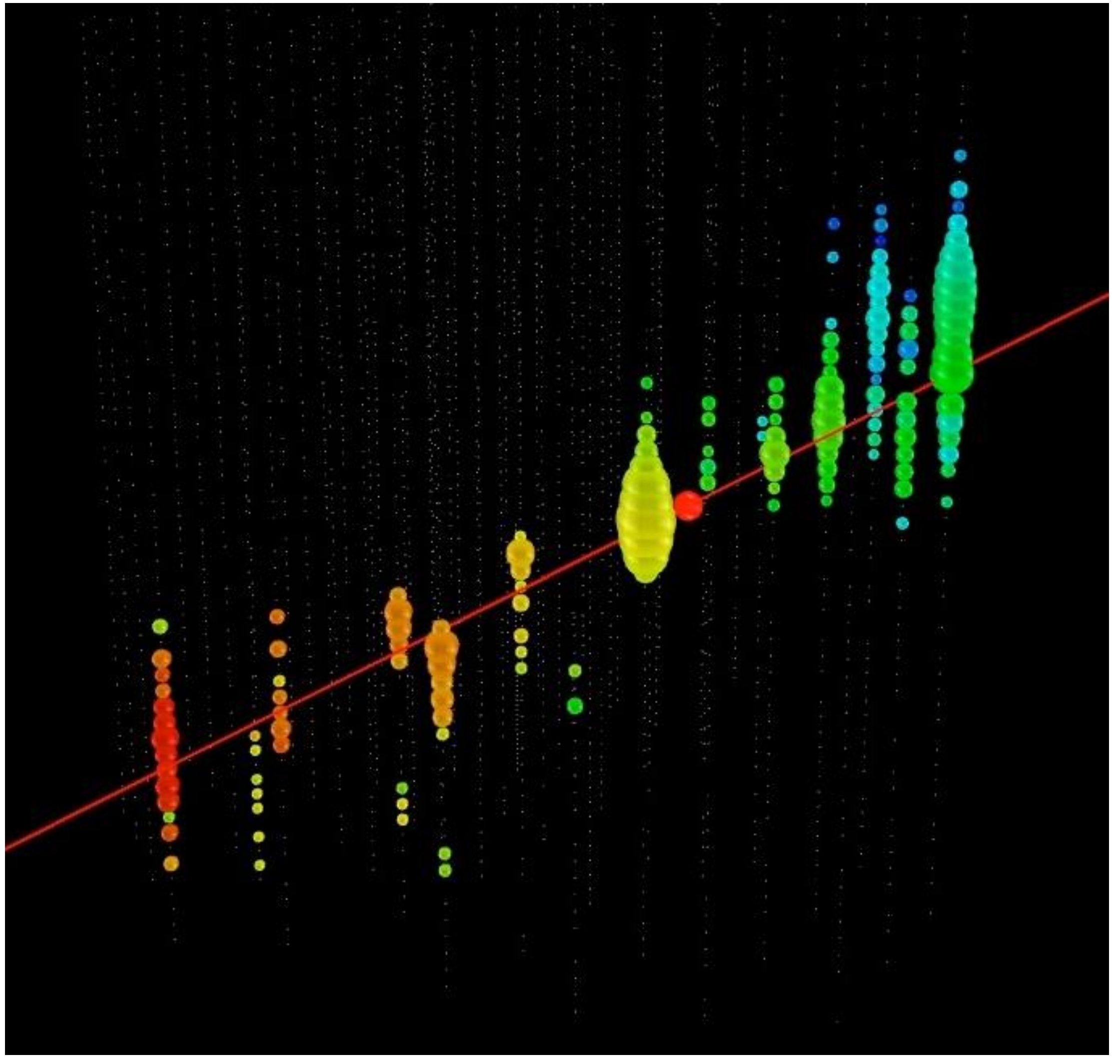
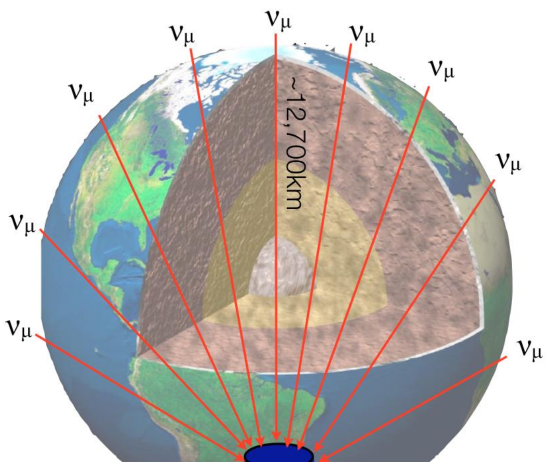


Neutrino events in IceCube

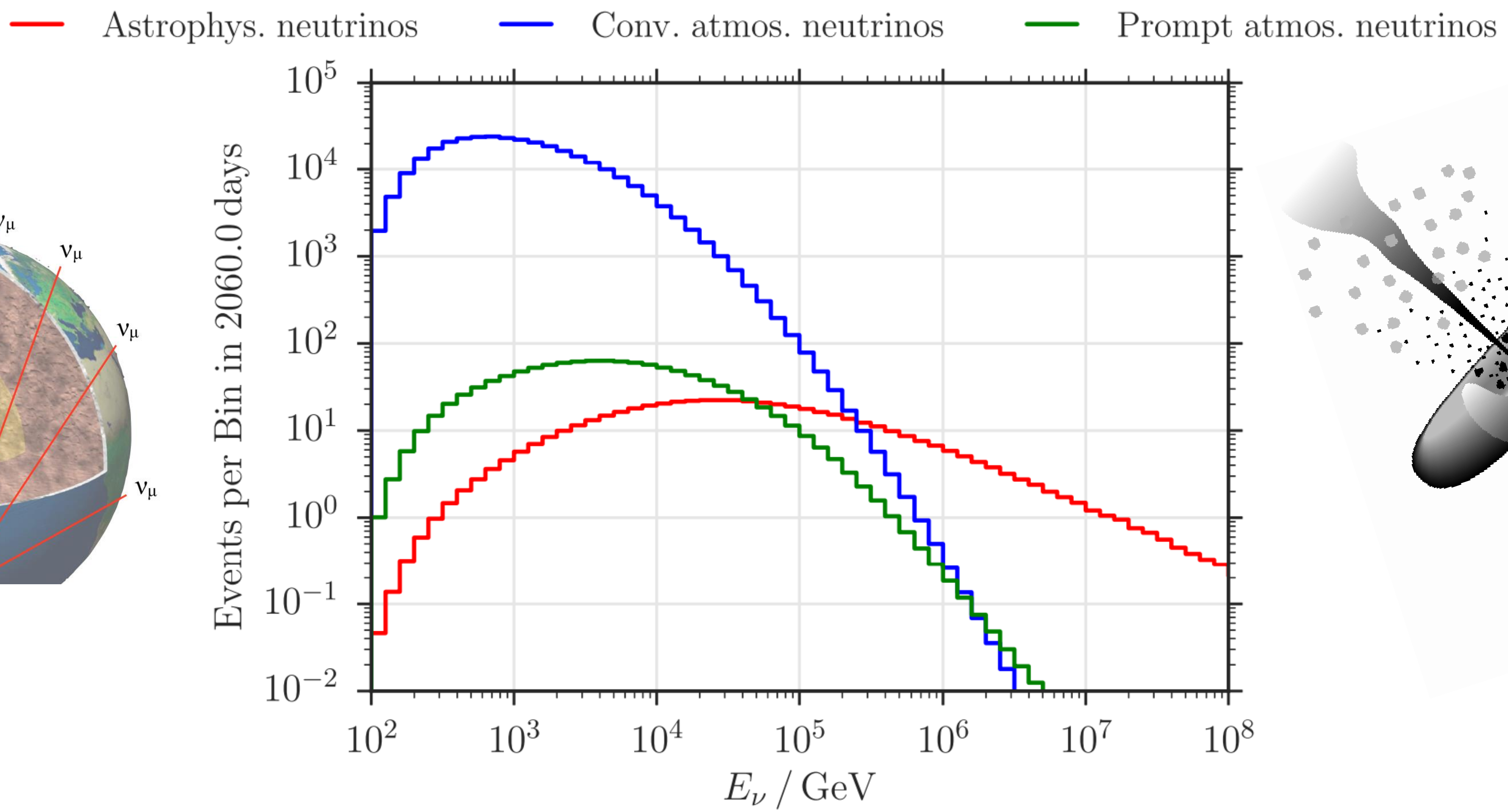


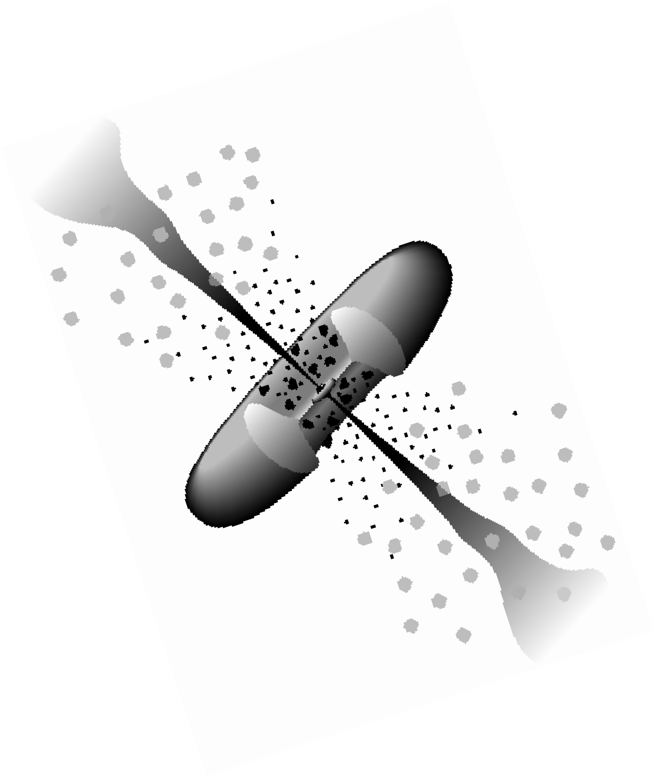


Neutrino sources

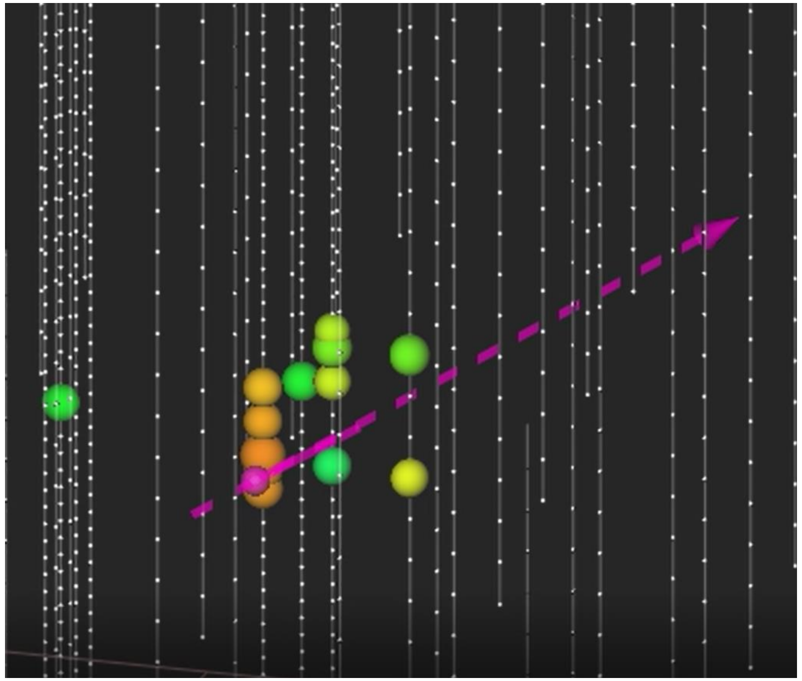


Muon neutrino spectrum





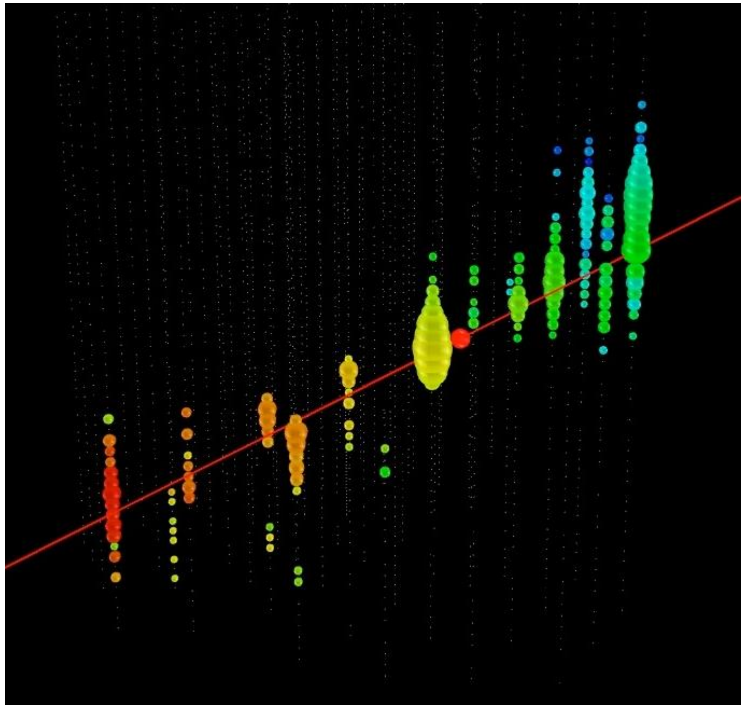
The IceCube regimes



The DeepCore regime

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

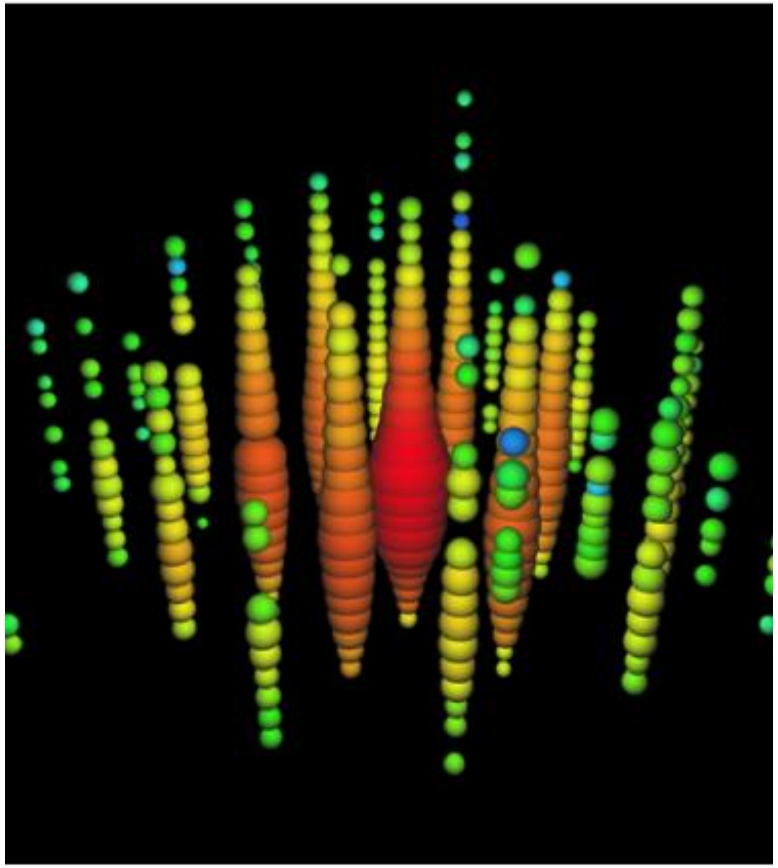
The IceCube regimes



The IceCube track regime

- Bright events, long lever arm = great pointing
- Muons are not contained → energy is a lower limit
- More resilient to systematics
- Can have atmospheric and astrophysical origin

The IceCube regimes



Very high energy cascades

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

Analysis strategy

Detect & reconstruct HE neutrinos, reduce relevant backgrounds

Calibrate the detector using flashers and muons

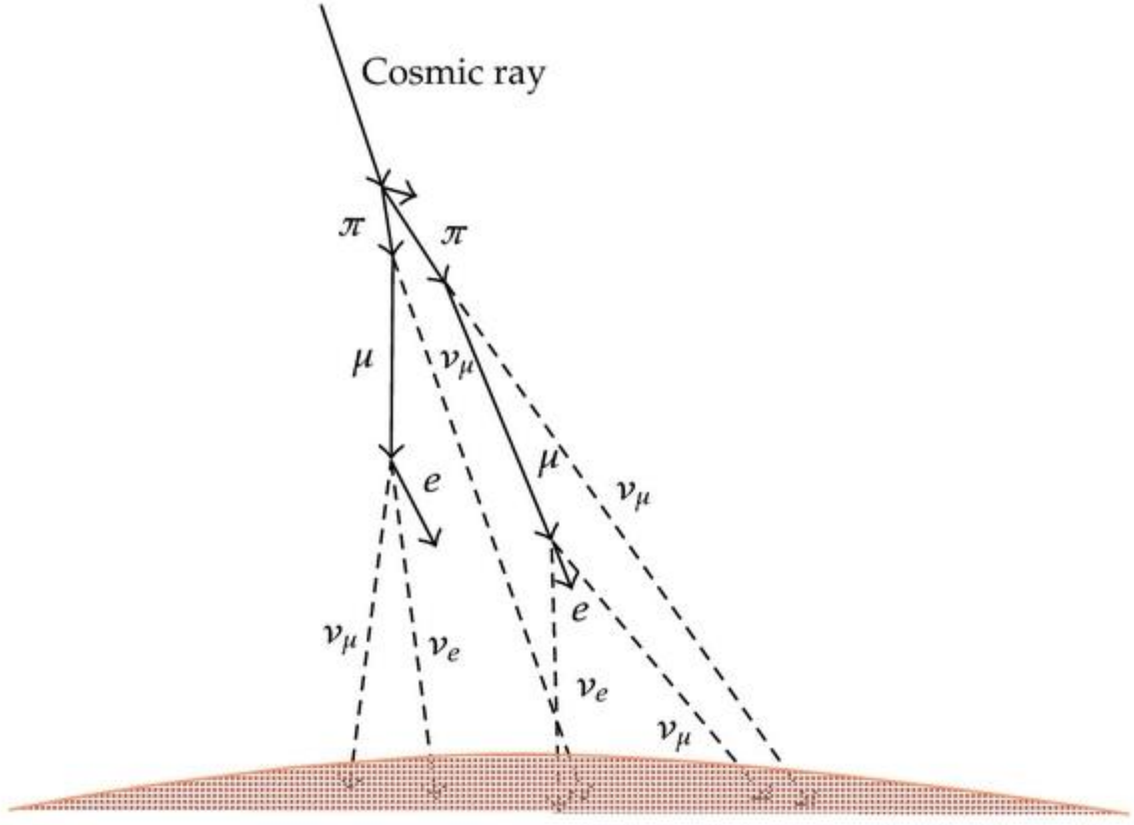
Produce large MC sets with variations to understand detector response to uncertainties

Test a hypothesis, establish the significance of observation

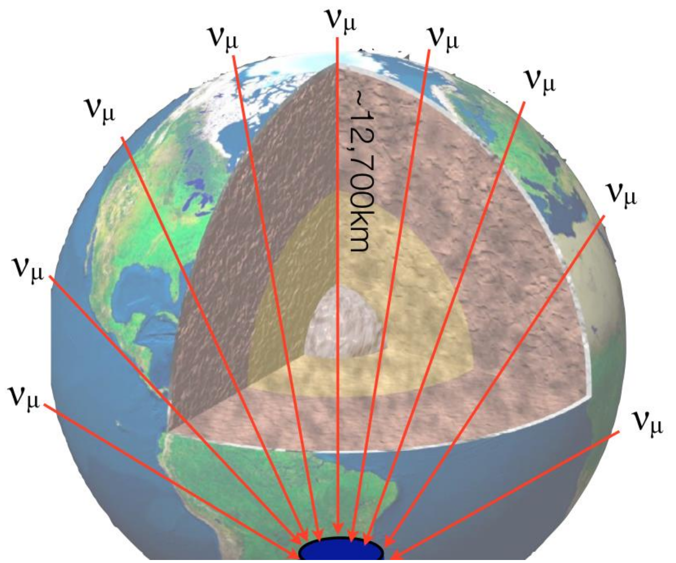
Result

Atmospheric ν

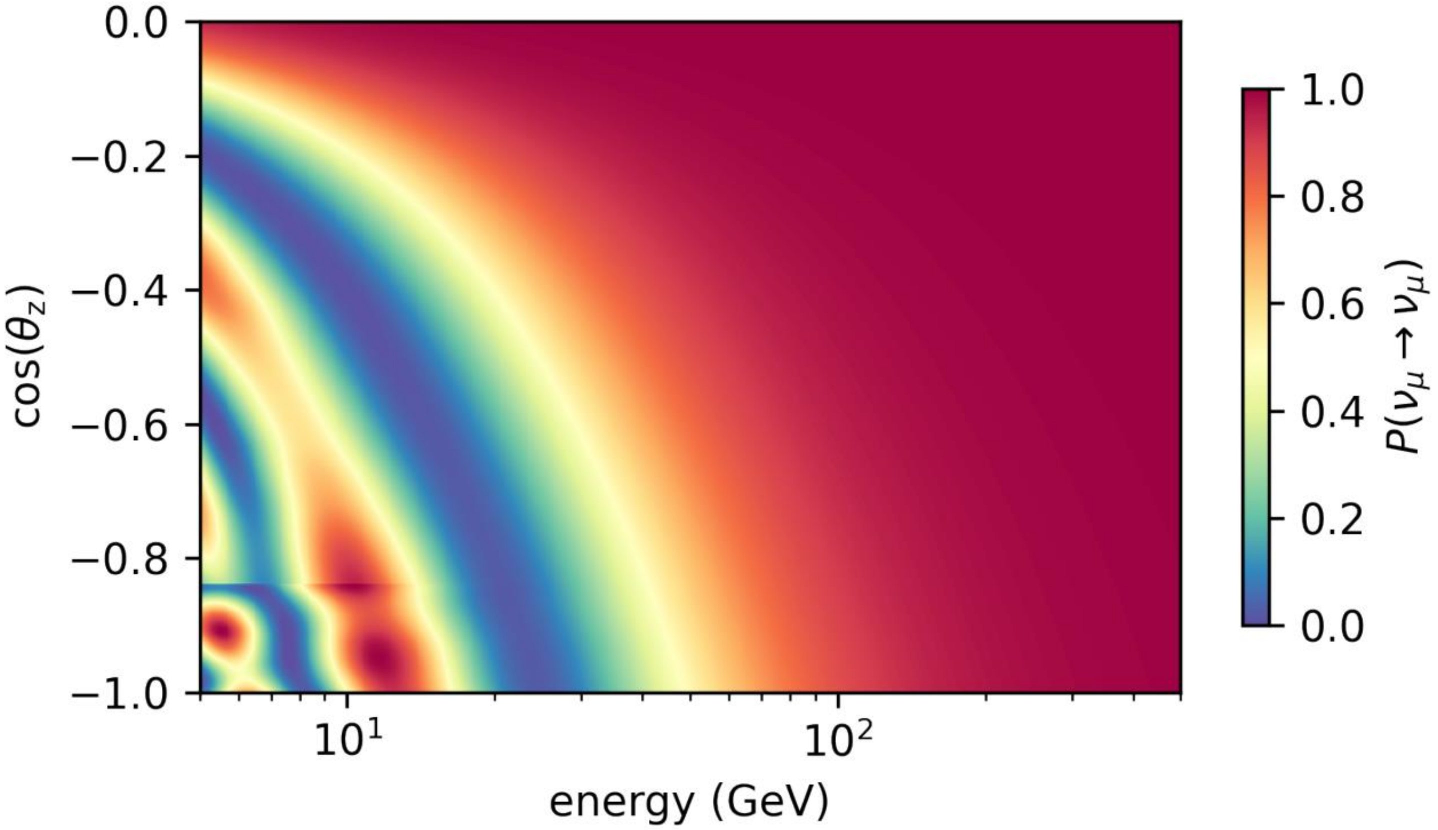
Selected results



Standard oscillations (DC)



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



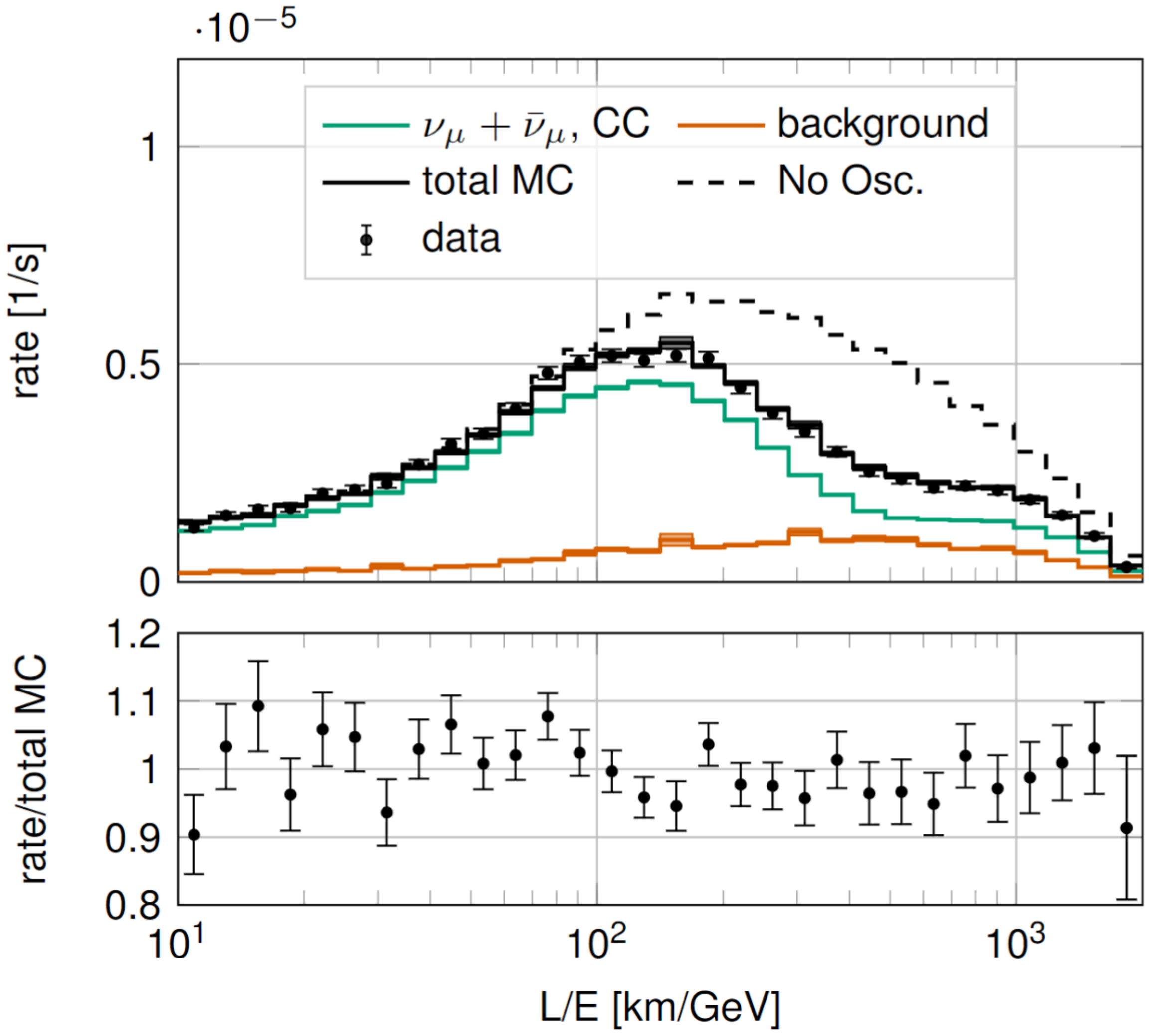
Dominant transition is $\nu_\mu \rightarrow \nu_\tau$ = “tracks” missing, excess of “cascades”

Standard oscillations (DC)

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

- **New sample** incorporating
  - Streamlined event selection, higher efficiency
  - Improved sensor calibration
  - More precise treatment of systematics

- First looked at the **highest quality events**



arXiv:2304.12236 **[hep-ex]**

Standard oscillations (DC)

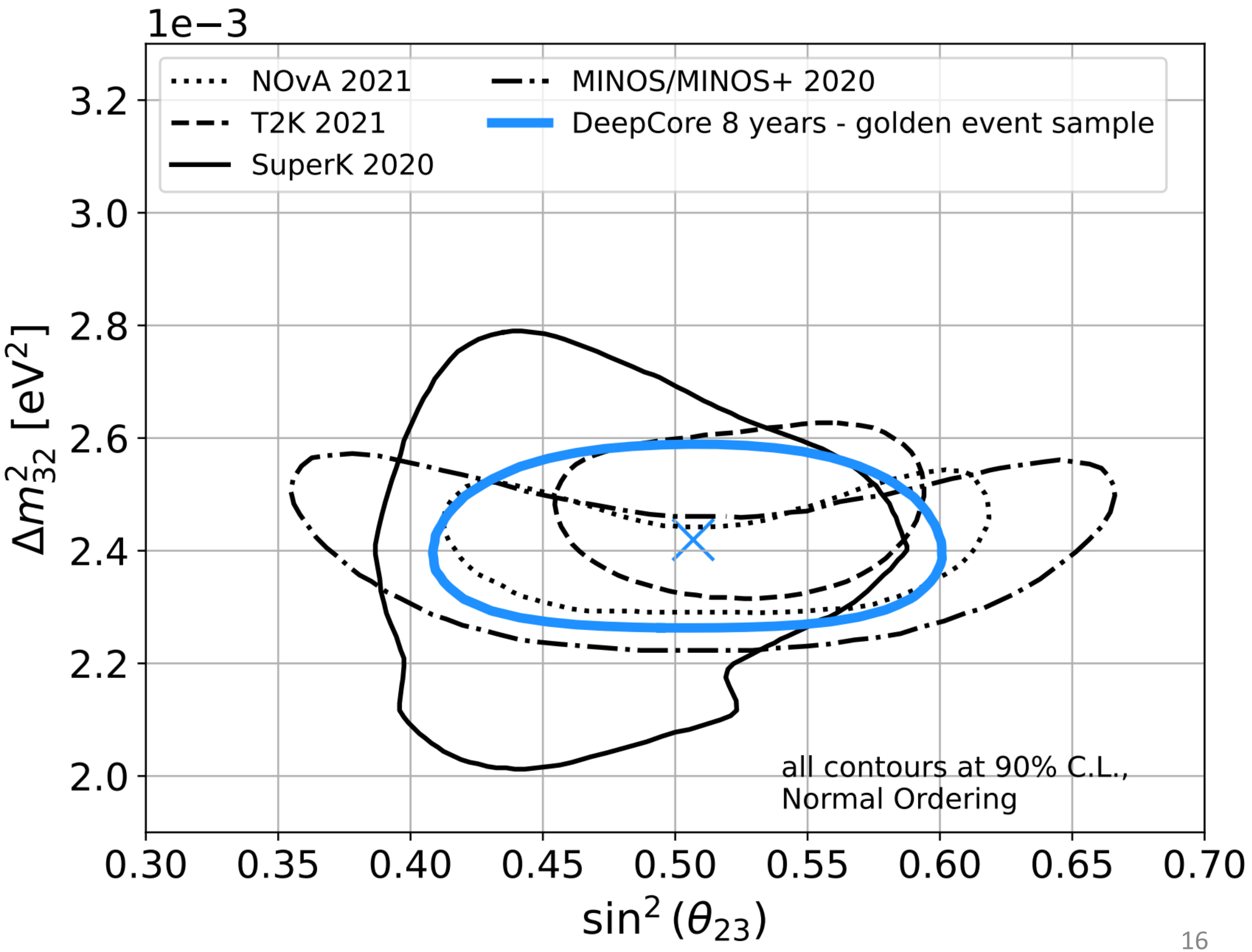
- Best fit values

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

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

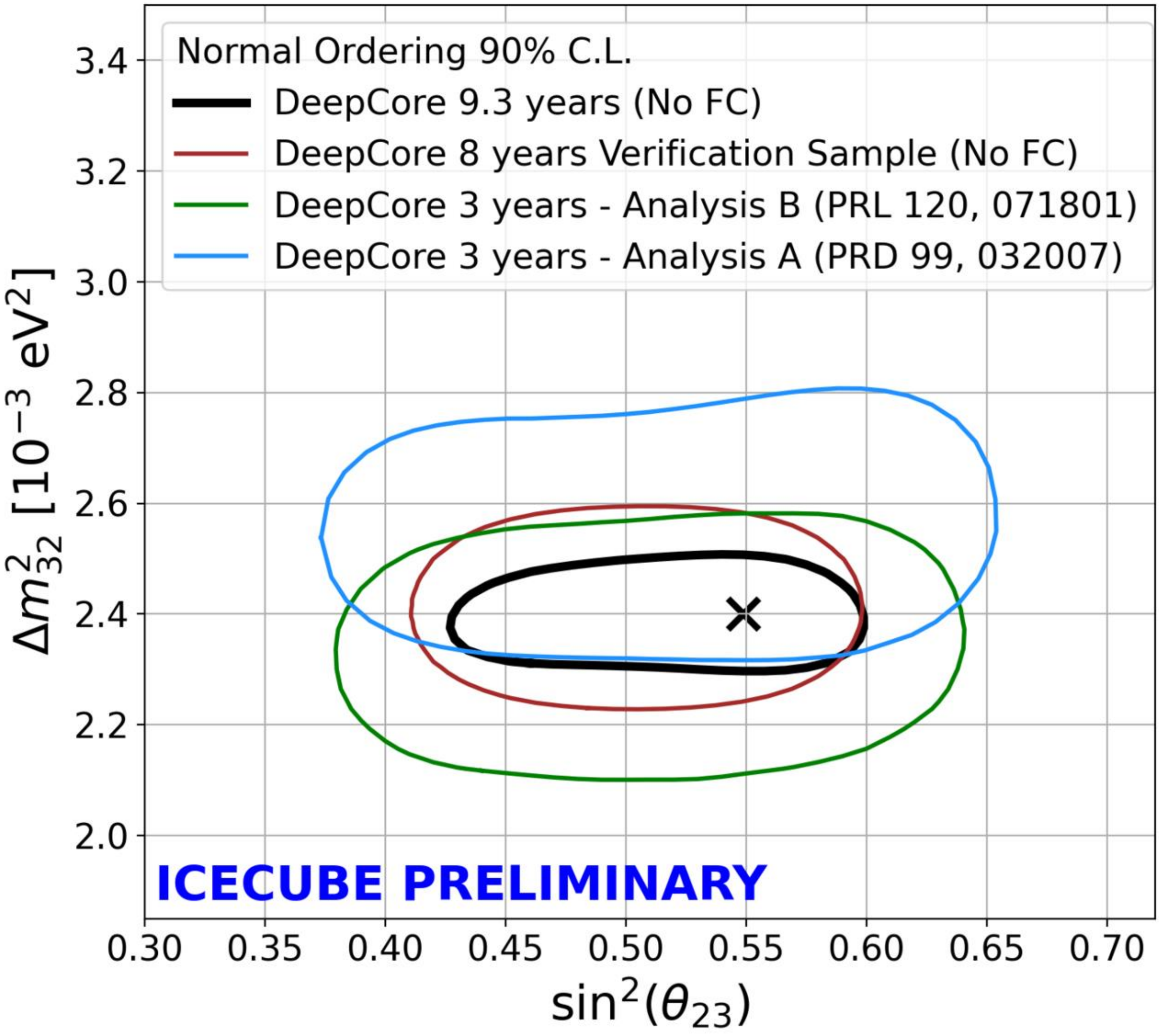
- Excellent **agreement** between data/MC

- Publication submitted to PRD – available in arXiv:2304.12236



Higher statistics ML-based measurement

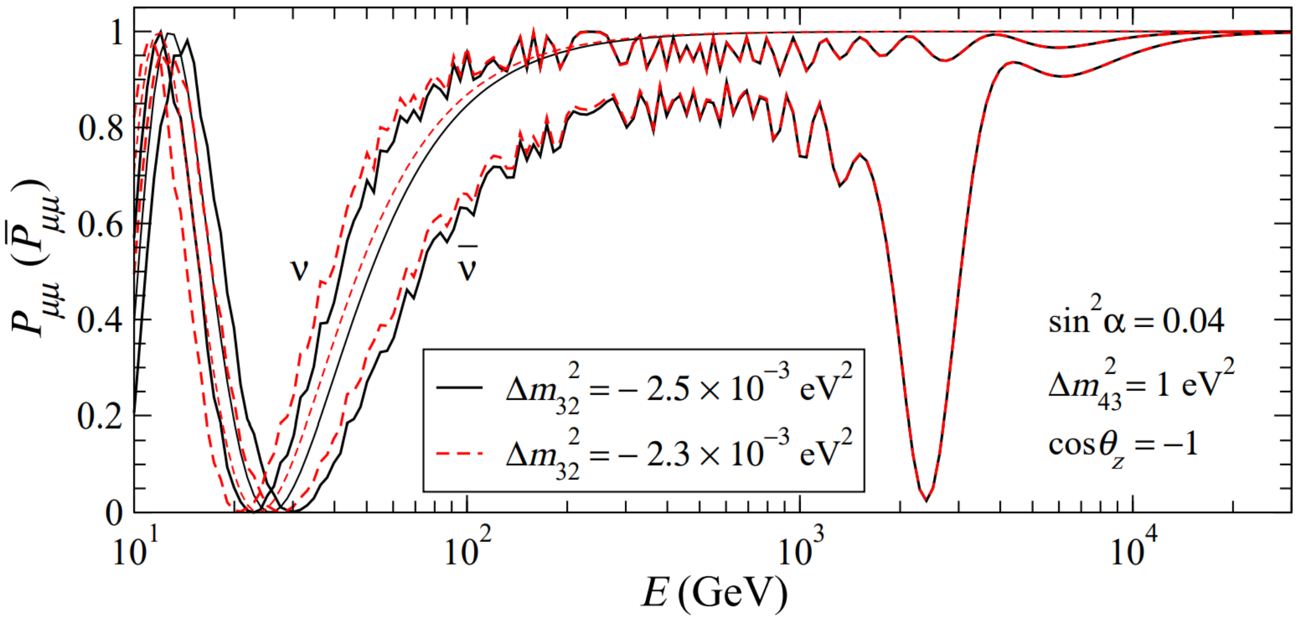
- CNN-based reconstruction and classification
- Can recover events that are hard to handle
- Compatible with “classic” study, with **improved precision**



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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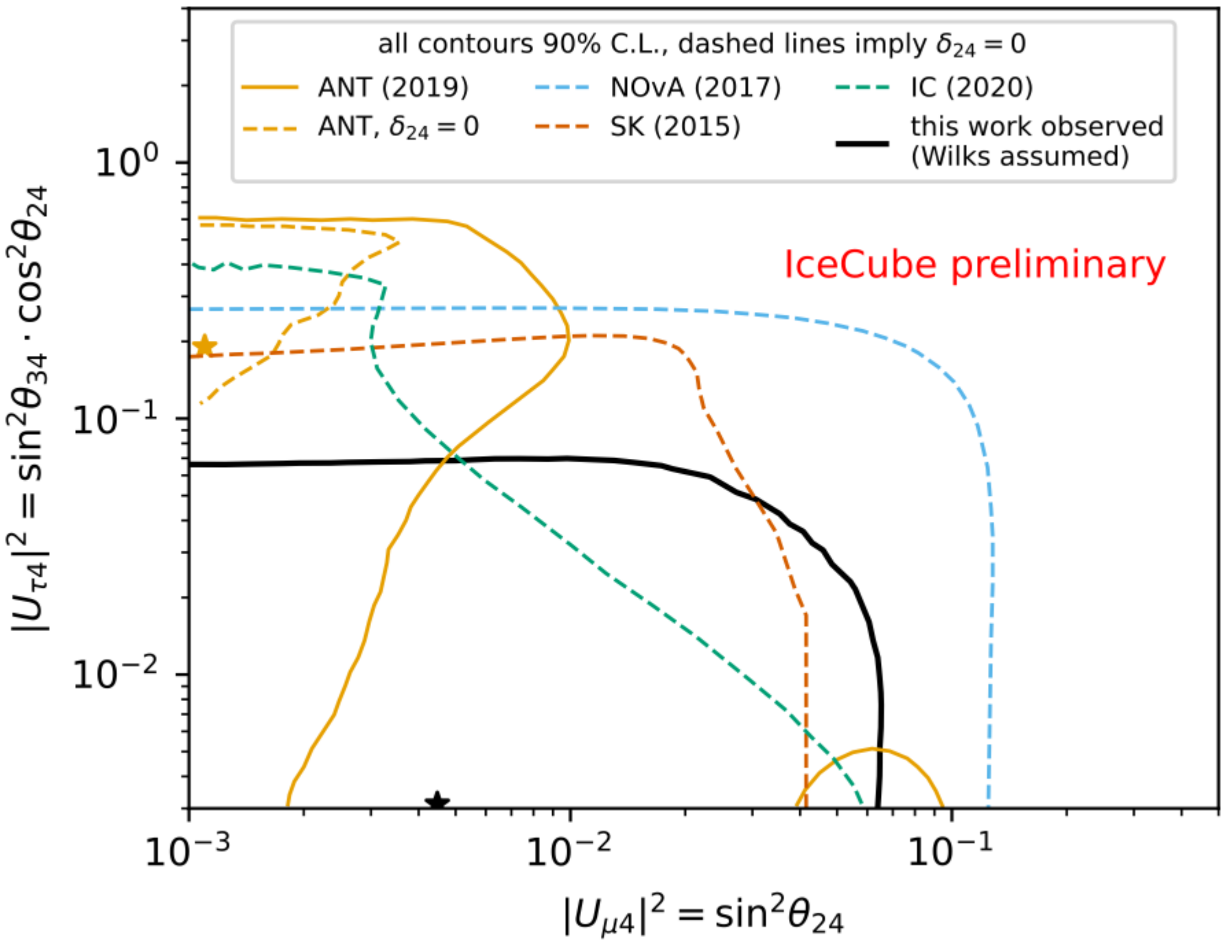
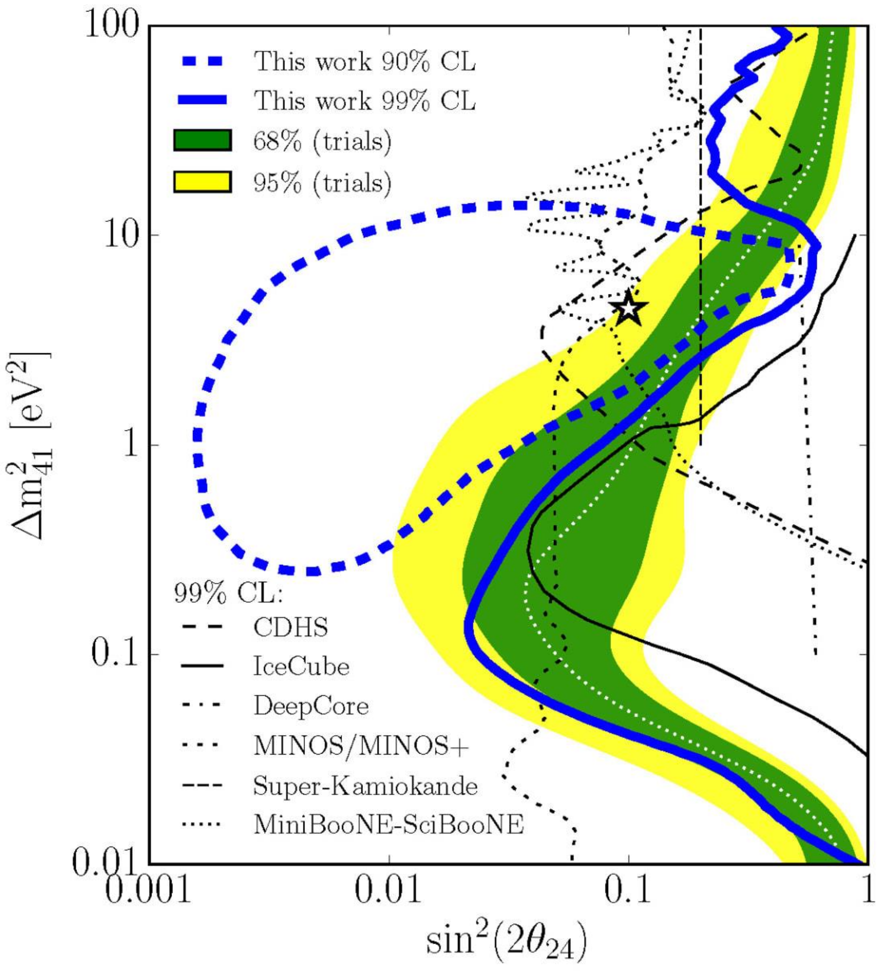




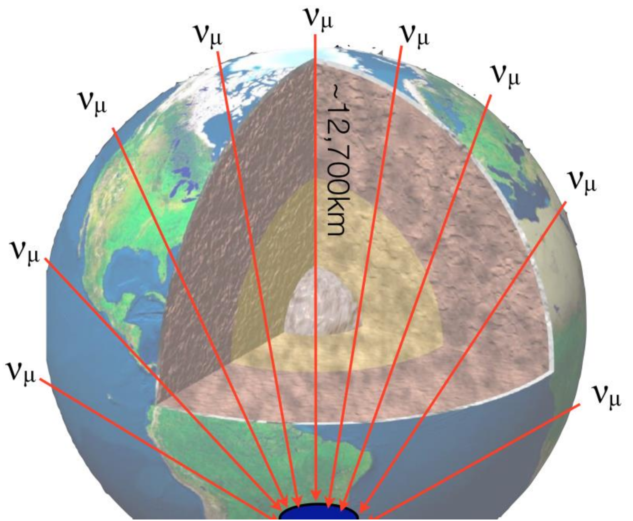
Phys. Rev. Lett. 125, 141801 (2020)

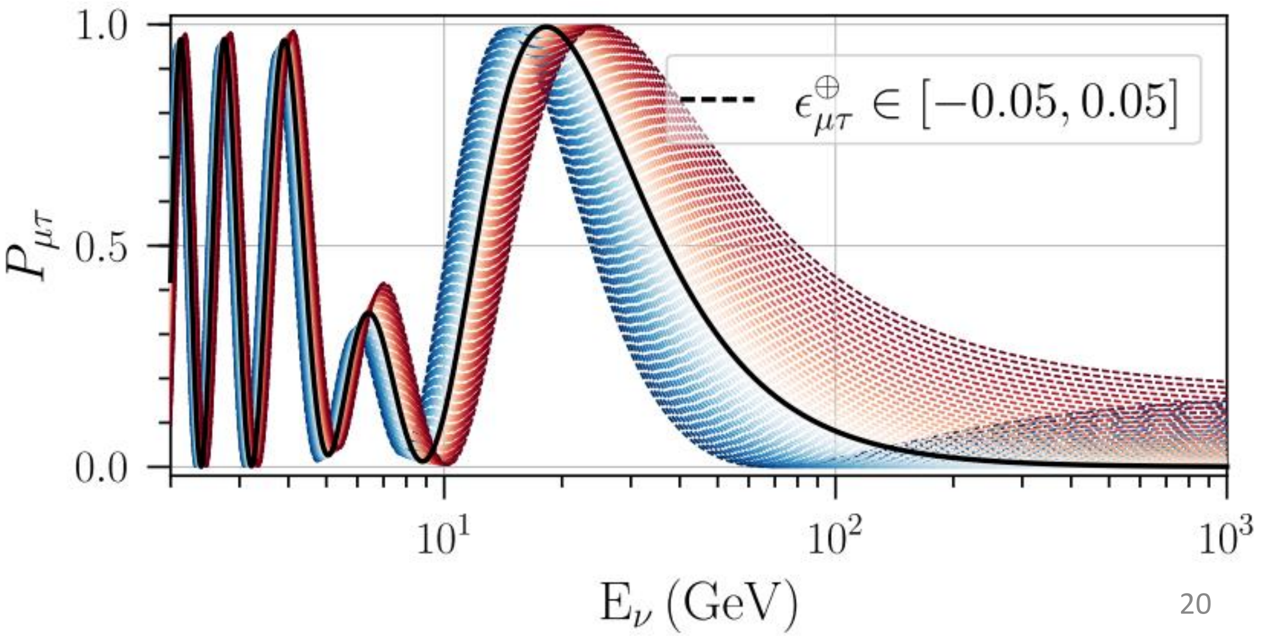
NSI studies (DC & IC)

- Possible new interactions as neutrinos cross matter

$$H_{\mathrm{mat}}(x) = V_{\mathrm{CC}}(x)\begin{pmatrix} 1+\epsilon^{\oplus}_{ee}-\epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau}-\epsilon^{\oplus}_{\mu\mu} \end{pmatrix}$$

- Modulates oscillations, flux





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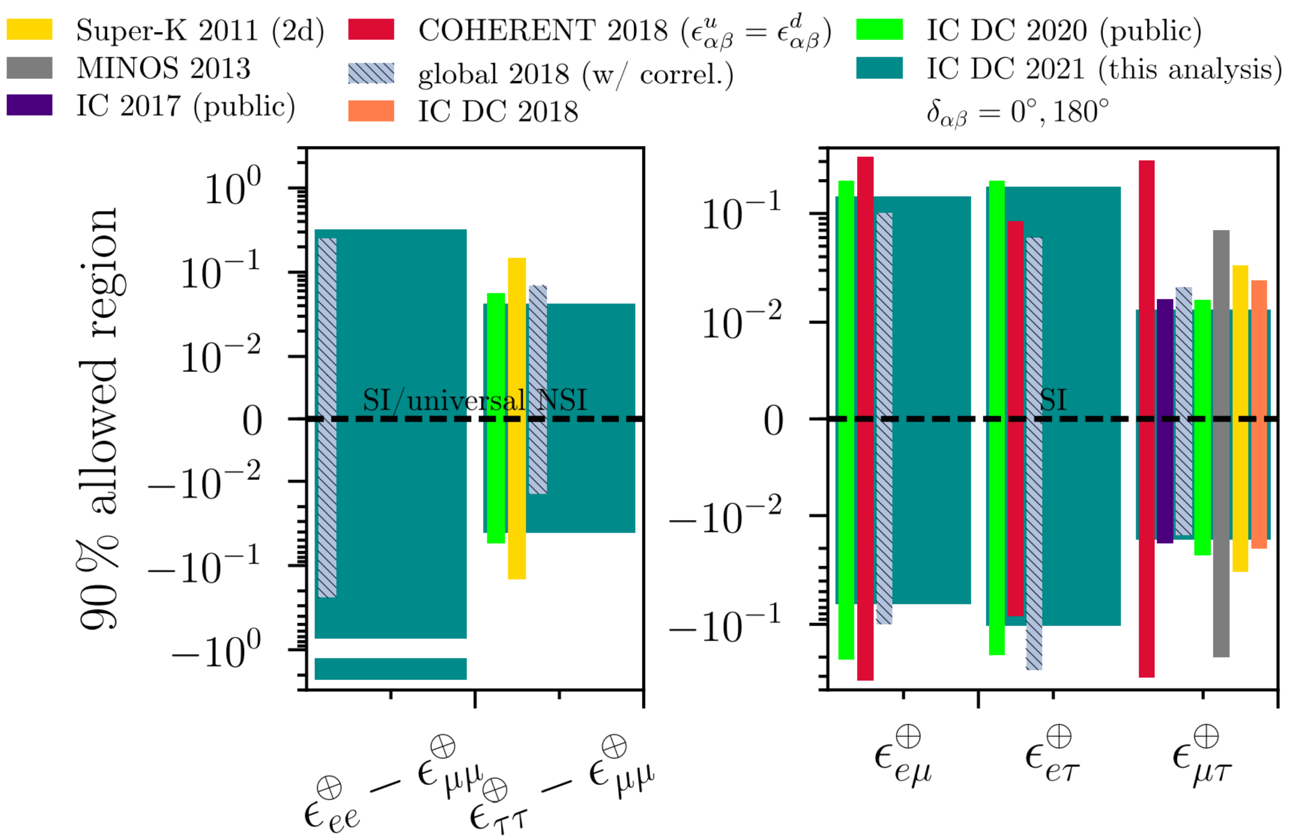
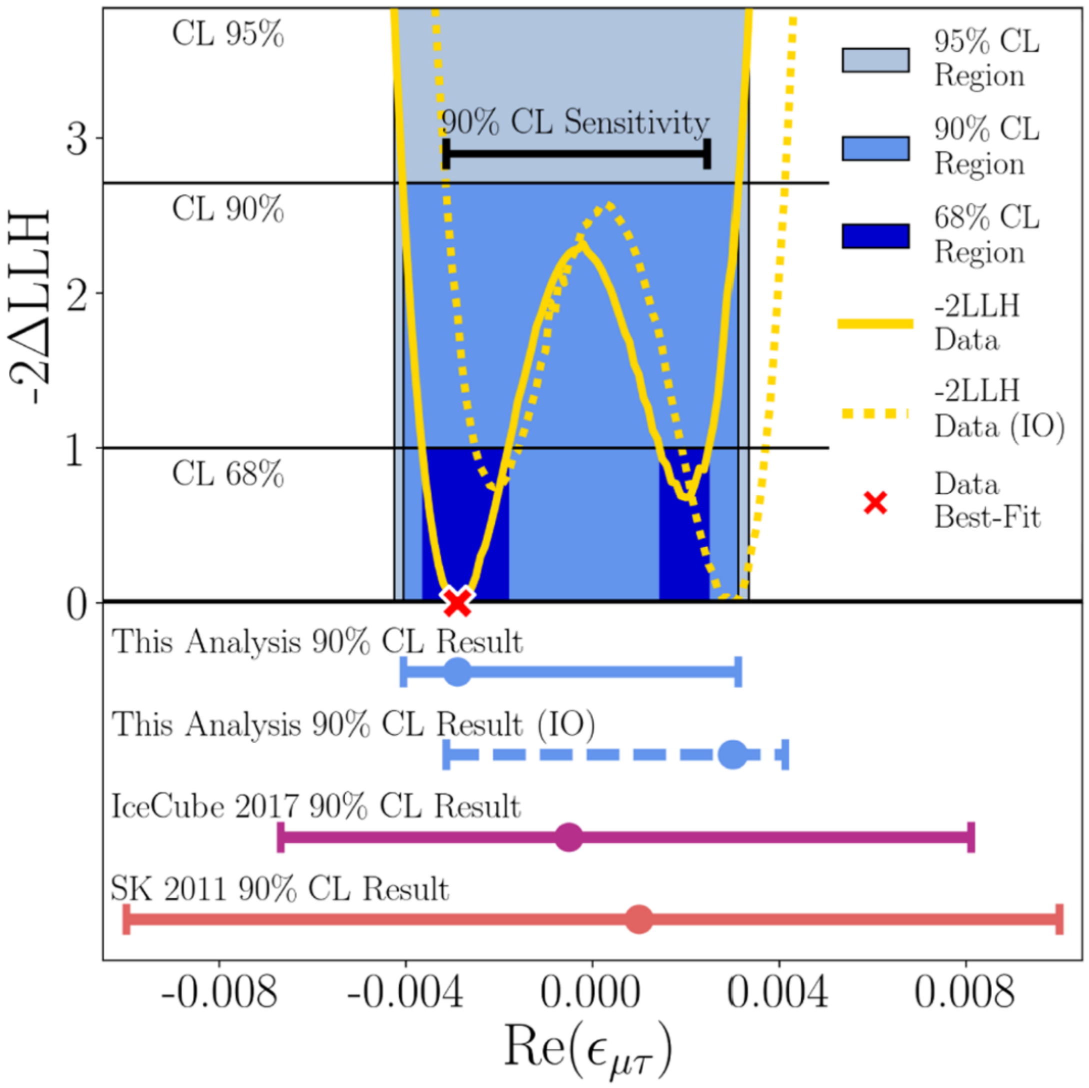


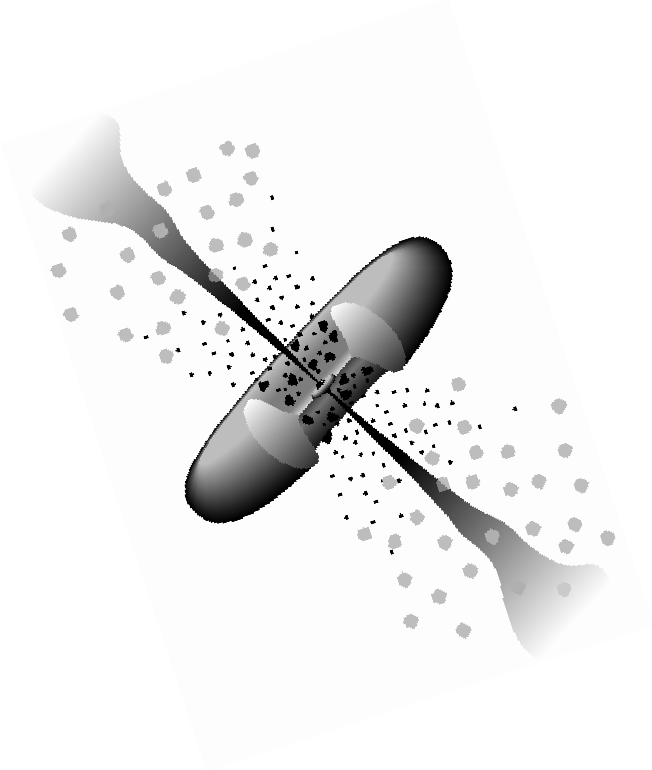
Phys. Rev. D104 (2021) 072006



Phys. Rev. Lett. 129, 011804 (2022)

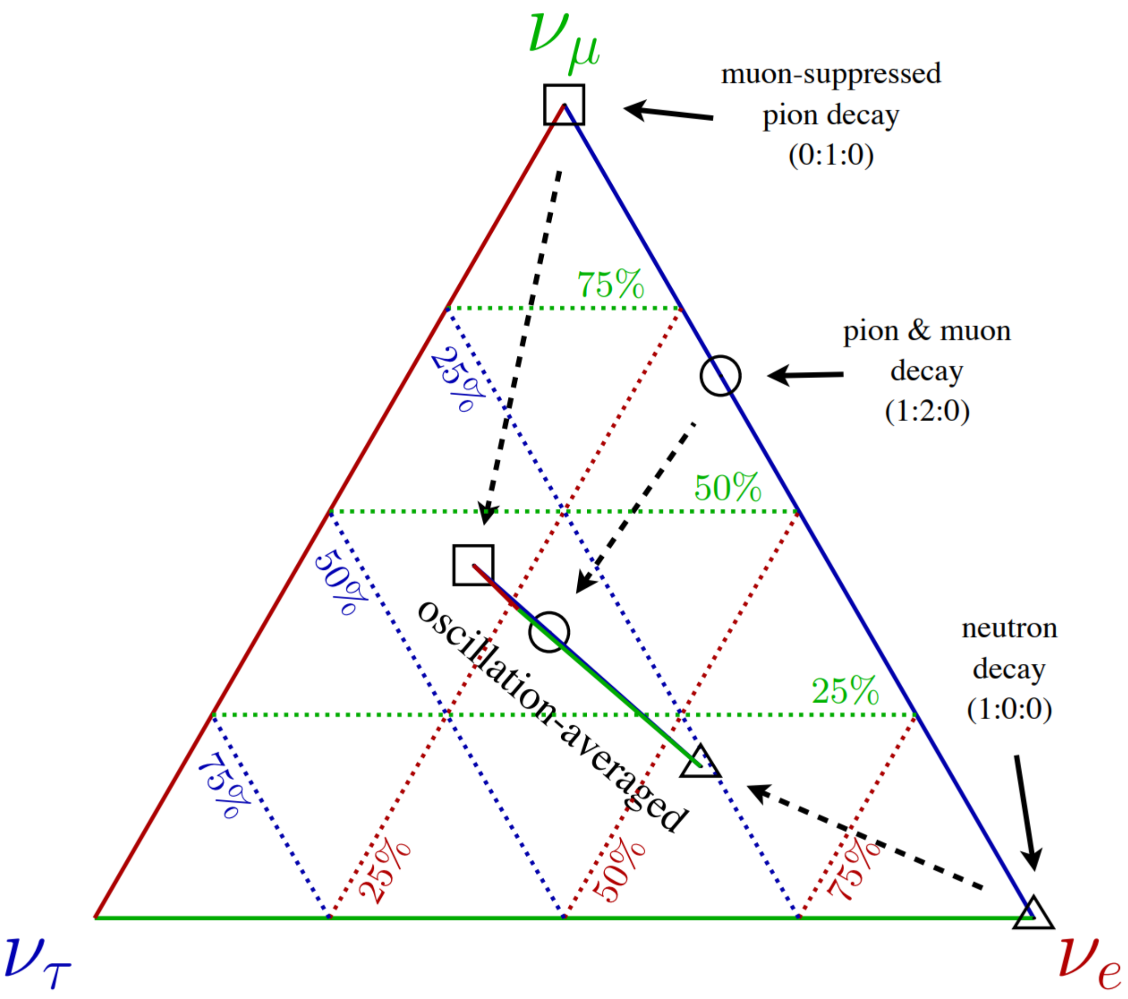
Astrophysical ν

Selected results

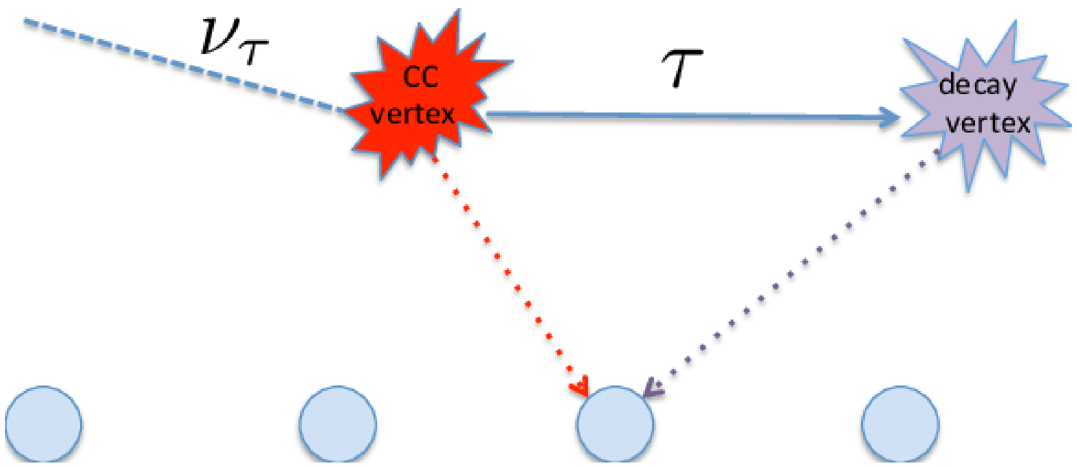


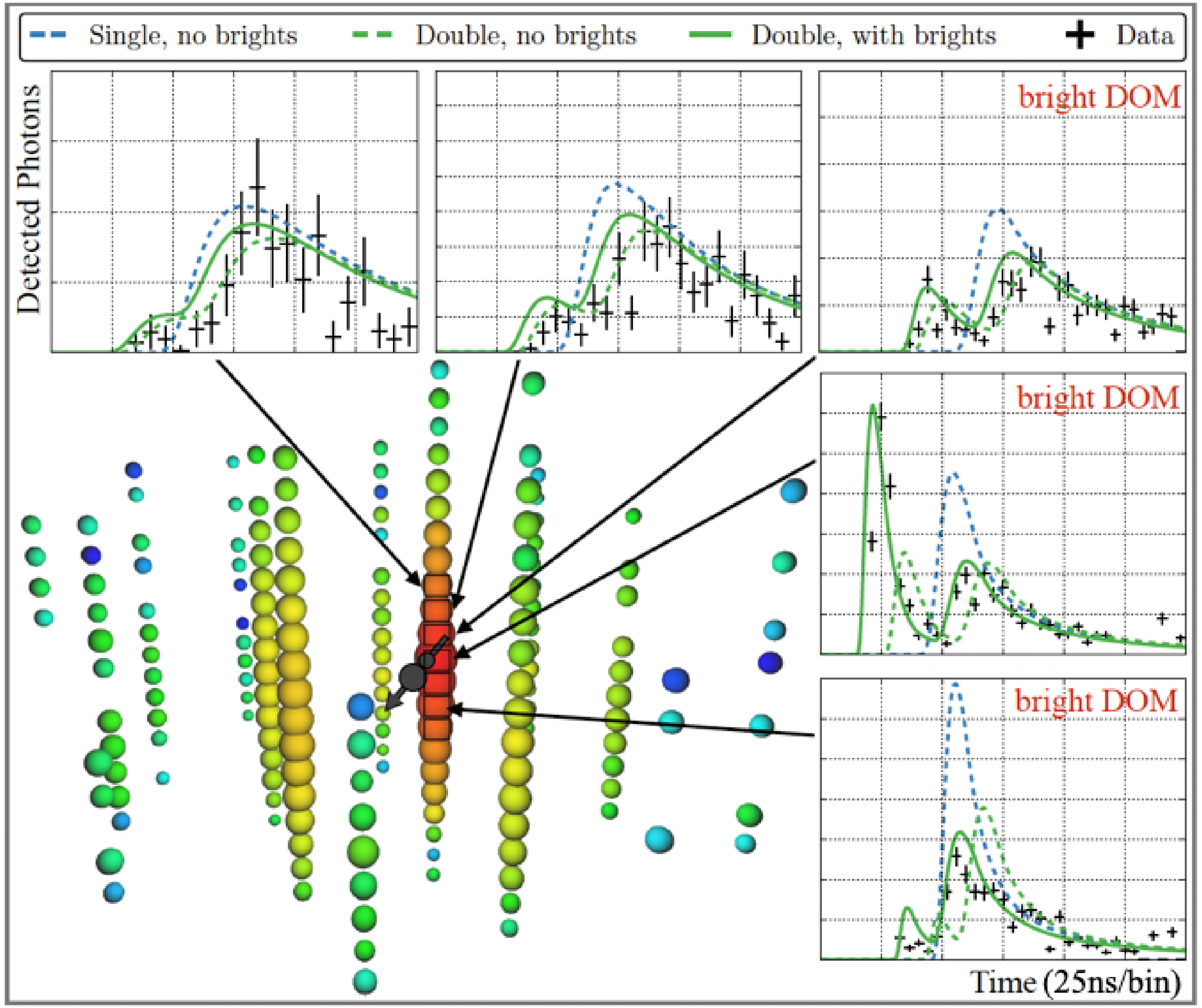
Astrophysical neutrino flavor (HE cascades)

- IceCube has been observing a diffuse flux of astrophysical HE neutrinos since 2013
- Nominal expectation is that they come from light meson decays near some accelerator
  - Similar physics to atmospheric neutrino production
  - **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 ν_τ observations (HE cascades)

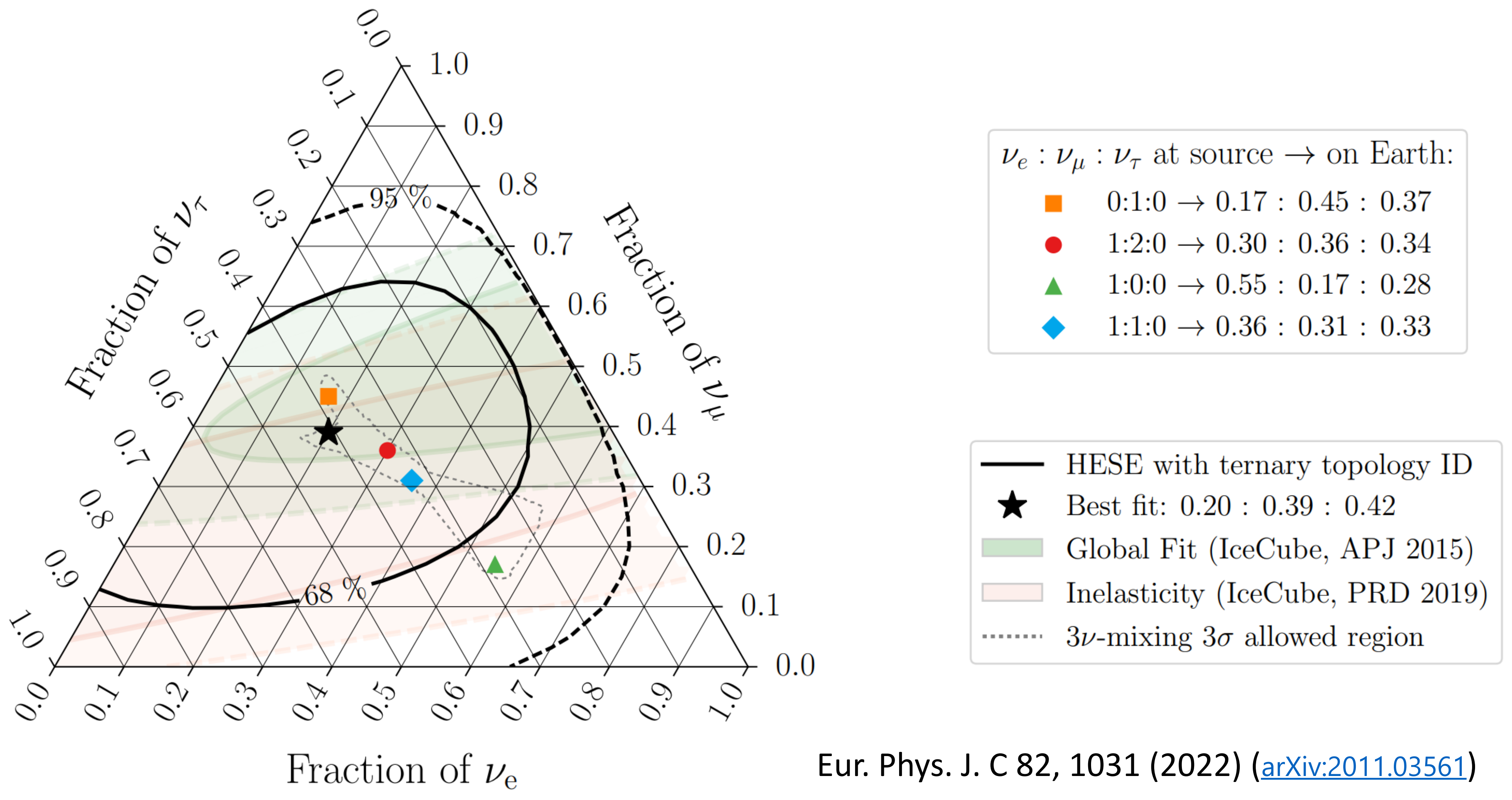




- **Two** candidates observed in a "**classic**" search looking for "double waveforms"
- Rejection of no-ν_τ hypothesis at 2.8σ

Eur. Phys. J. C 82, 1031 (2022) (arXiv:2011.03561)

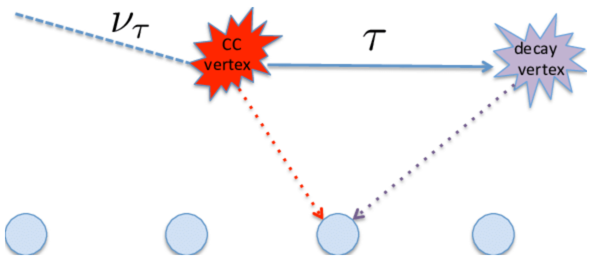
Astrophysical ν_τ observations (HE cascades)

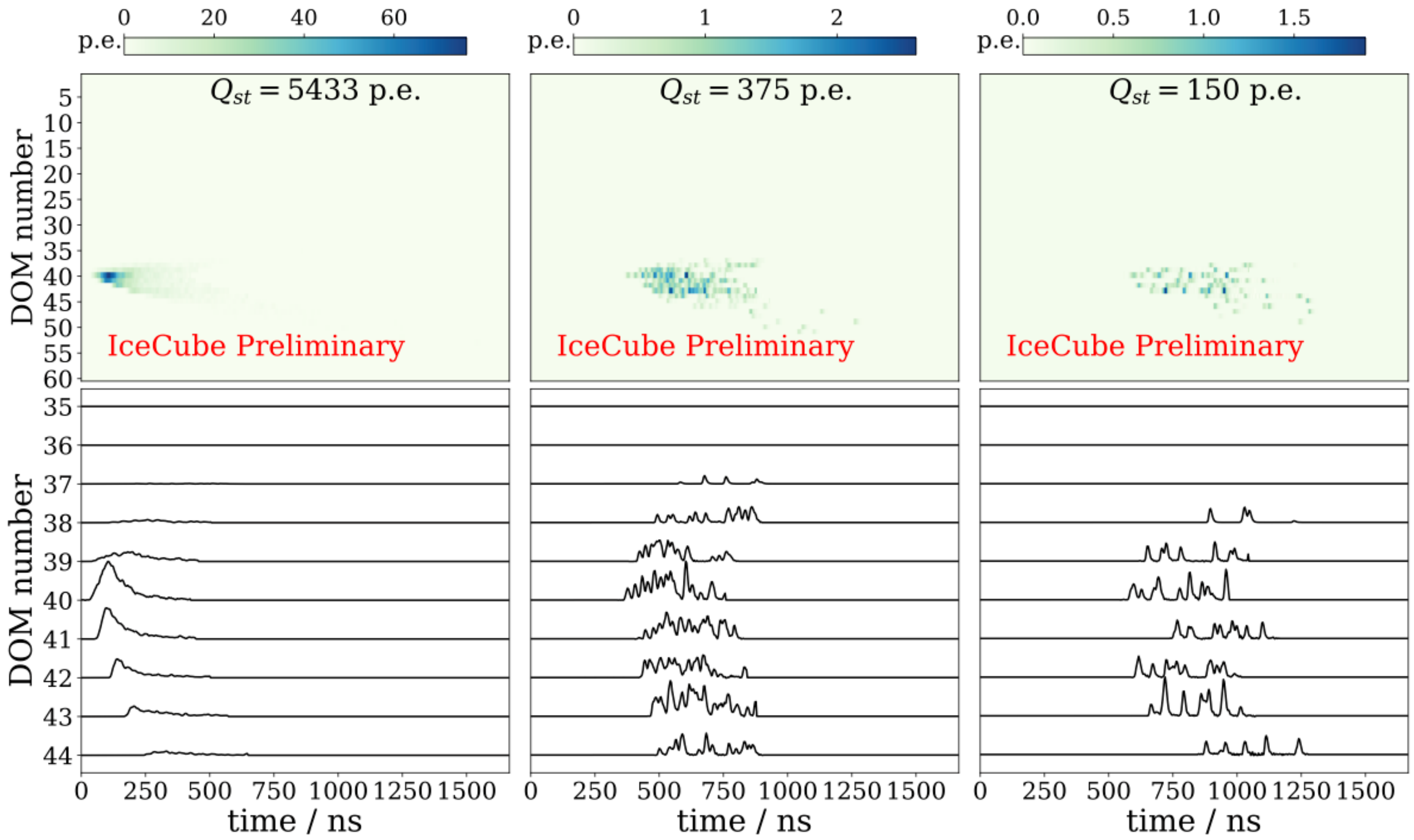


Eur. Phys. J. C 82, 1031 (2022) (arXiv:2011.03561)

New approach for astro-ν_τ observations

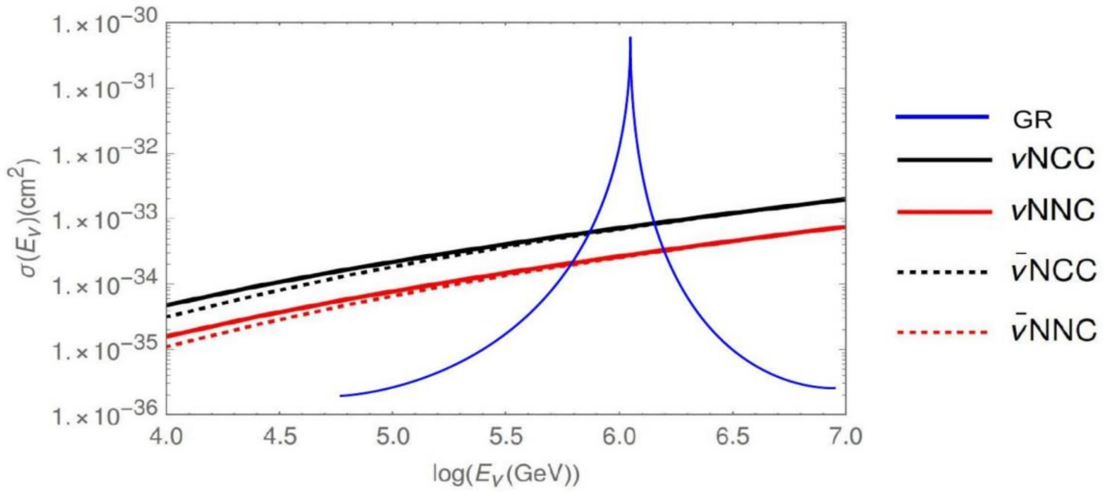
- **ML-based** search
- Gains sensitivity by combining information of multiple DOMs, on multiple strings
- Observed **7** $\boldsymbol{\nu_\tau}$ candidates on **0.5** expected background
- Post-unblinding checks have been performed and are under final collaboration review

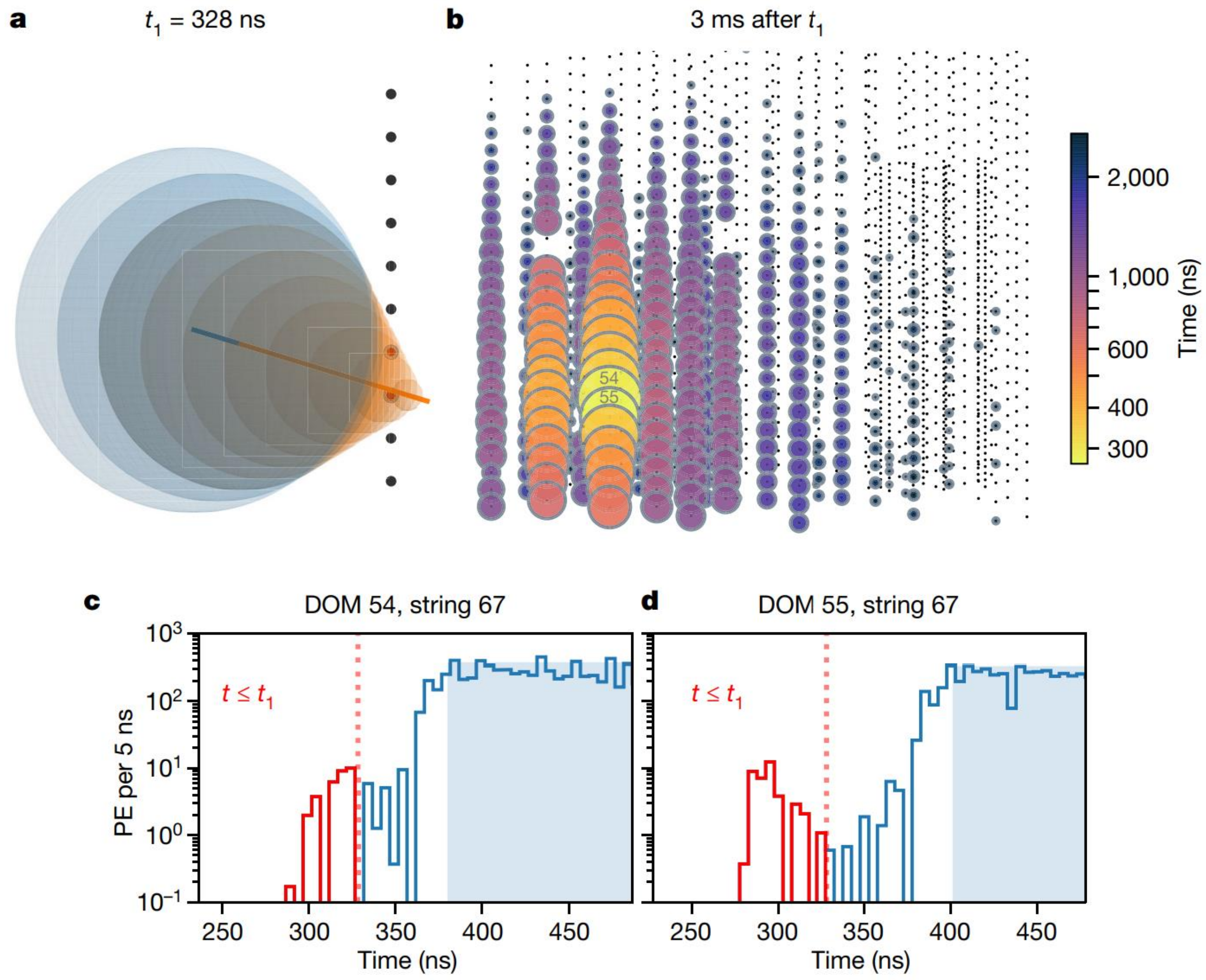




W-production by $\overline{\nu_e} - e^-$

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





Nature **volume 591**, pages220–224 (2021)

Summary & Outlook

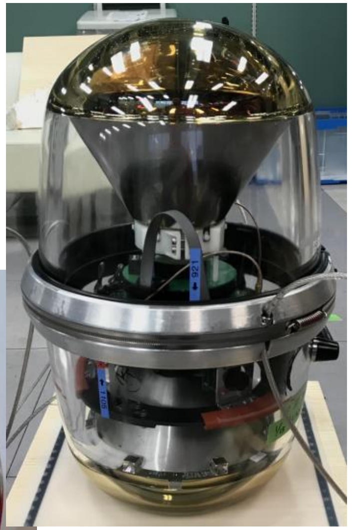
- IceCube keeps on measuring atmospheric & astrophysical neutrinos
  - Discovered a diffuse HE nu flux, now well established
  - First flaring and steady sources of HE neutrinos identified

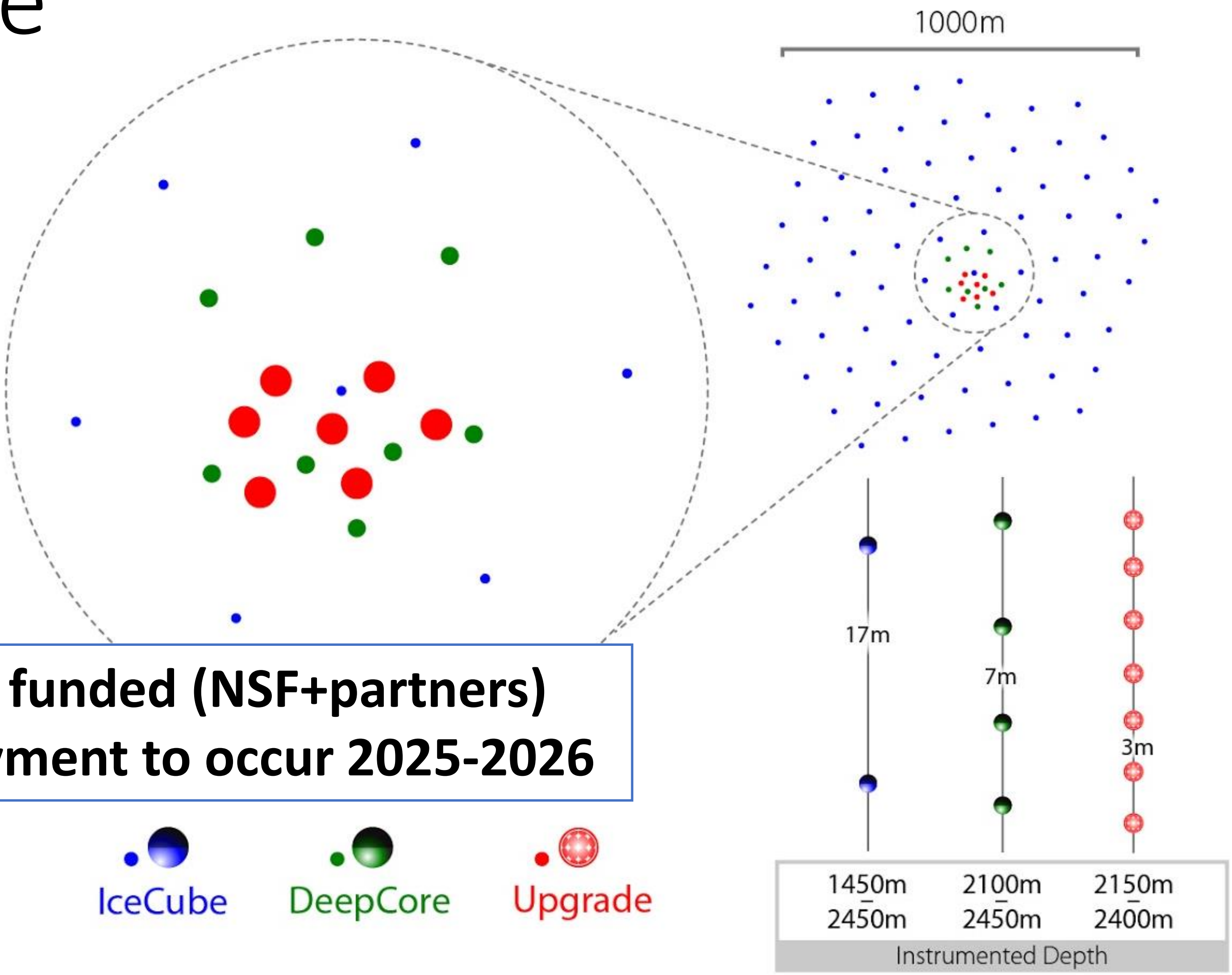
- Unique particle physics research with these neutrinos
  - Most precise atm. nu oscillations measurement
  - Flavor composition of diffuse flux
  - *Glashow resonance, sterile neutrino searches, non-standard interactions

- More instrumentation for more discoveries coming

The future of IceCube

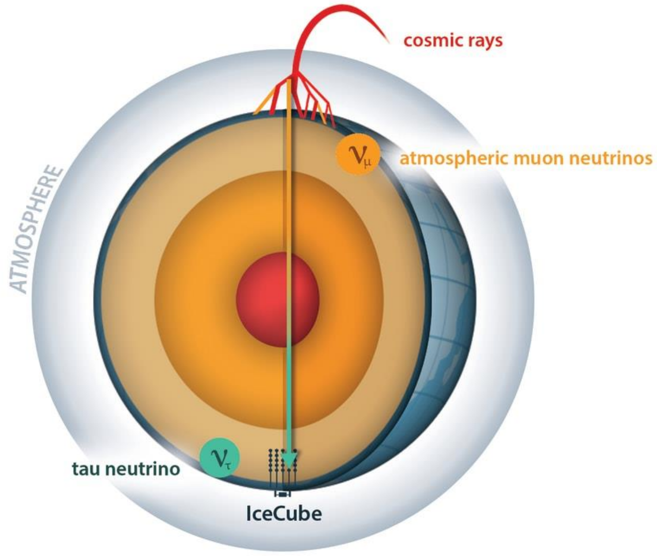
- The IceCube upgrade
  - Recalibration of all data
  - Lower E threshold for DC

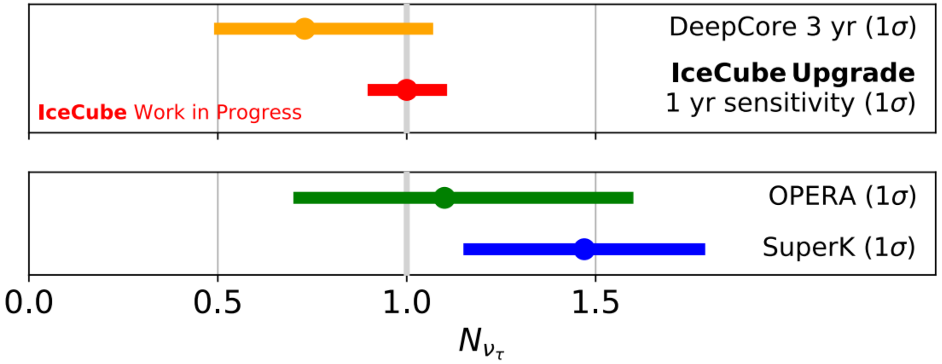




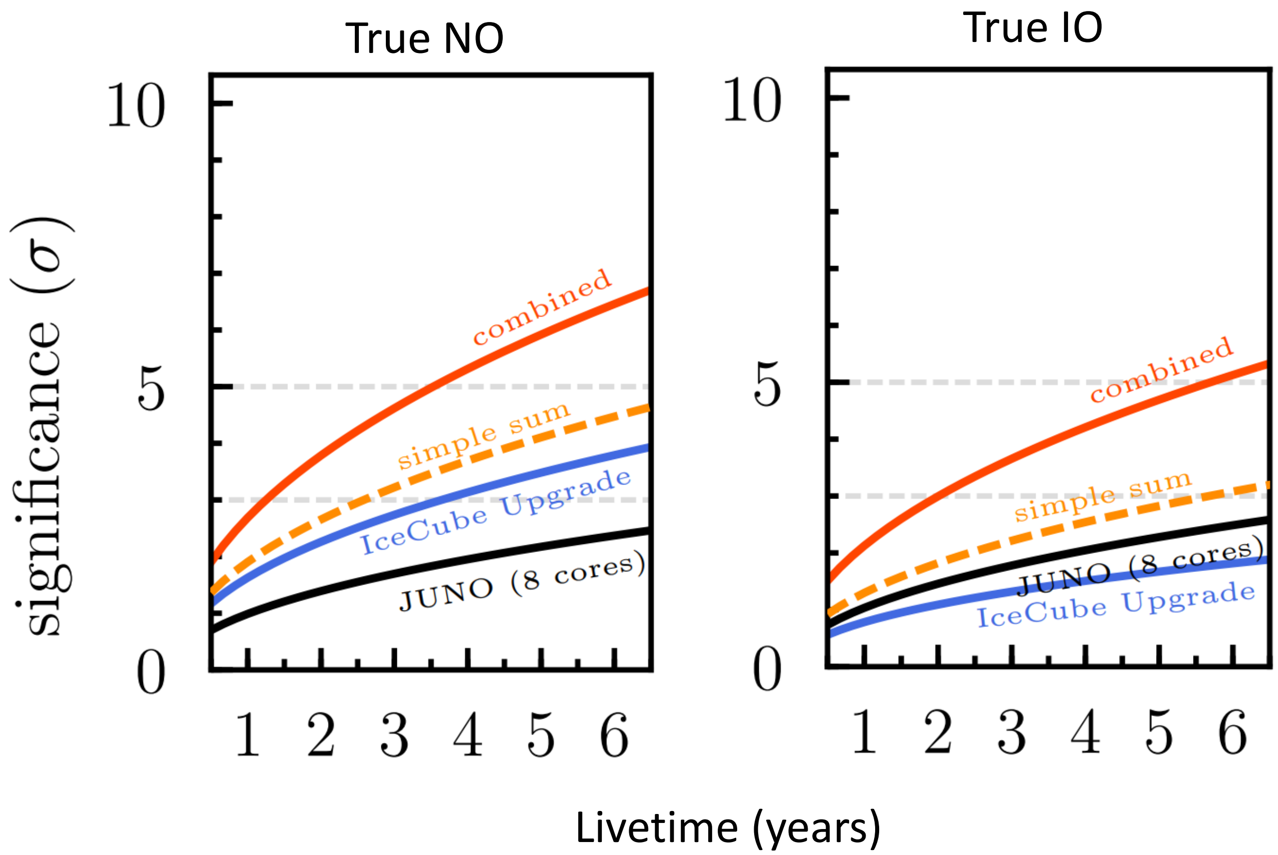
Fully funded (NSF+partners)
Deployment to occur 2025-2026

IceCube Upgrade impact



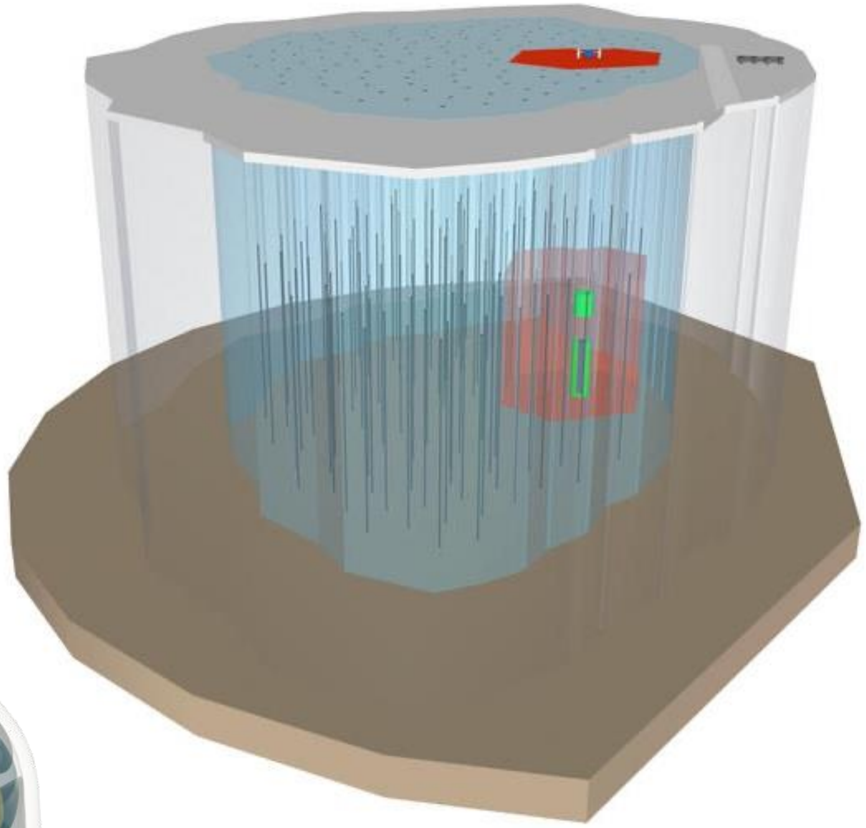


Phys. Rev. D 101, 032006 (2020)



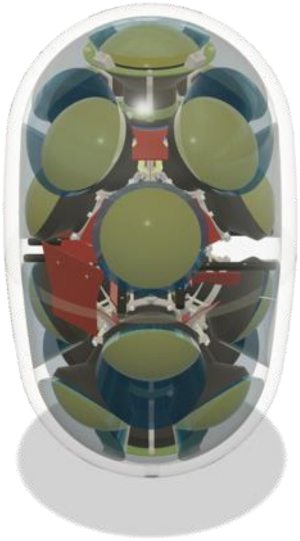
IceCube-Gen2: optical

- ~10x the contained volume of IceCube
- 5x the effective area
- 2x the angular resolution (on tracks)



D-Egg

mDOM



Gen2 DOM

Features new pixelated module, based on development work in the IceCube Upgrade

Thank you for your attention, on behalf of

THE ICECUBE COLLABORATION

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UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

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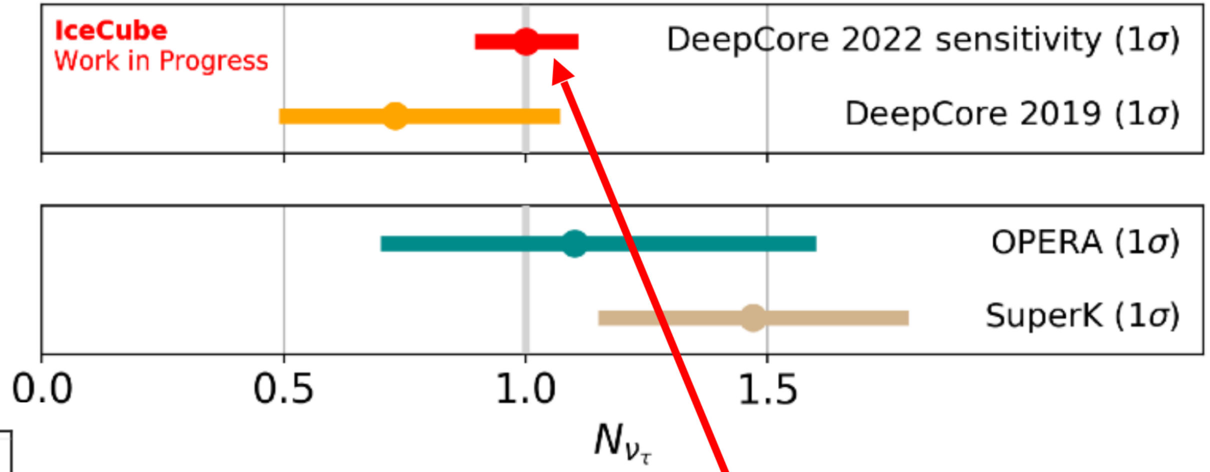
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

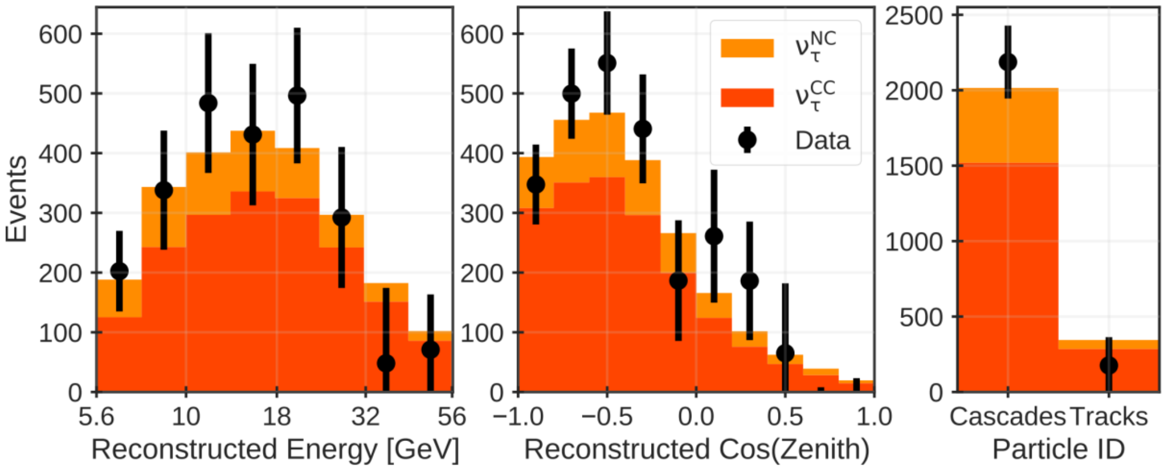
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

Backup

Standard oscillations (DC) to ν_τ

- Results from older sample
- Analysis with new sample will come next





Phys. Rev. D 99, 032007 (2019)

Expecting world-leading 11% precision

~9,700 $\nu_{\tau,CC}$ events expected

Signal is statistical excess of upgoing cascades with suppressed cross section

Tests PMNS unitarity and $\nu_{\tau,CC}$ cross section

Systematics

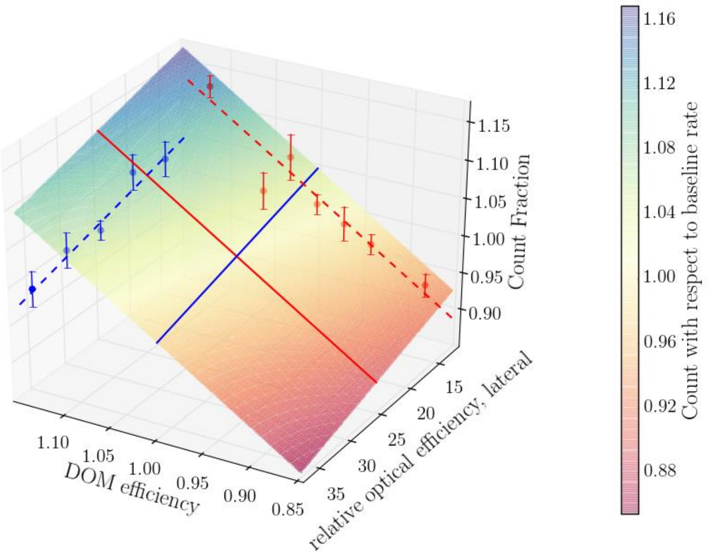
Tested, but subdominant:

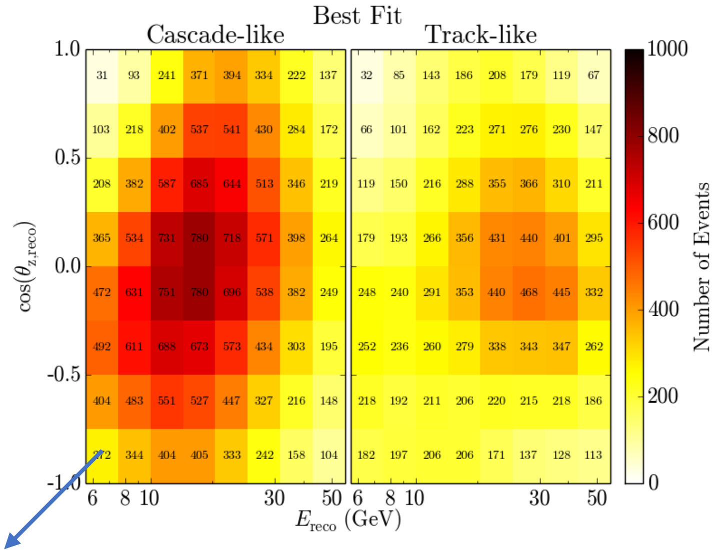
- DIS x-sec NuTeV corrections
- X-sec higher twist parameters
- X-sec valence quark correction
- Hadronization multiplicity
- Optical acceptance models

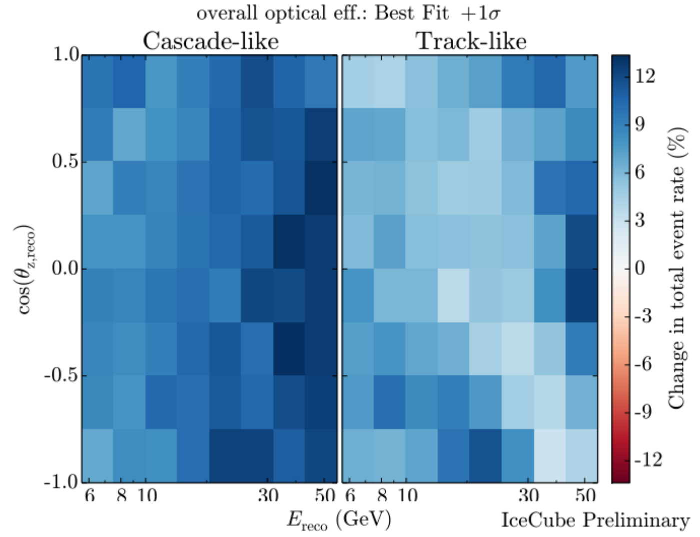
		Analysis $\mathcal{A}$	
Parameter	Prior	(CC + NC)	Best fit (CC)
Neutrino flux and cross section:			
ν_e/ν_μ Ratio	1.0 ± 0.05	1.03	1.03
ν_e Up/Hor. Flux ratio (σ)	0.0 ± 1.0	−0.19	−0.18
$\nu/\bar{\nu}$ Ratio (σ)	0.0 ± 1.0	−0.42	−0.33
$\Delta\gamma_\nu$ (Spectral index)	0.0 ± 0.1	0.03	0.03
Effective Livetime (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

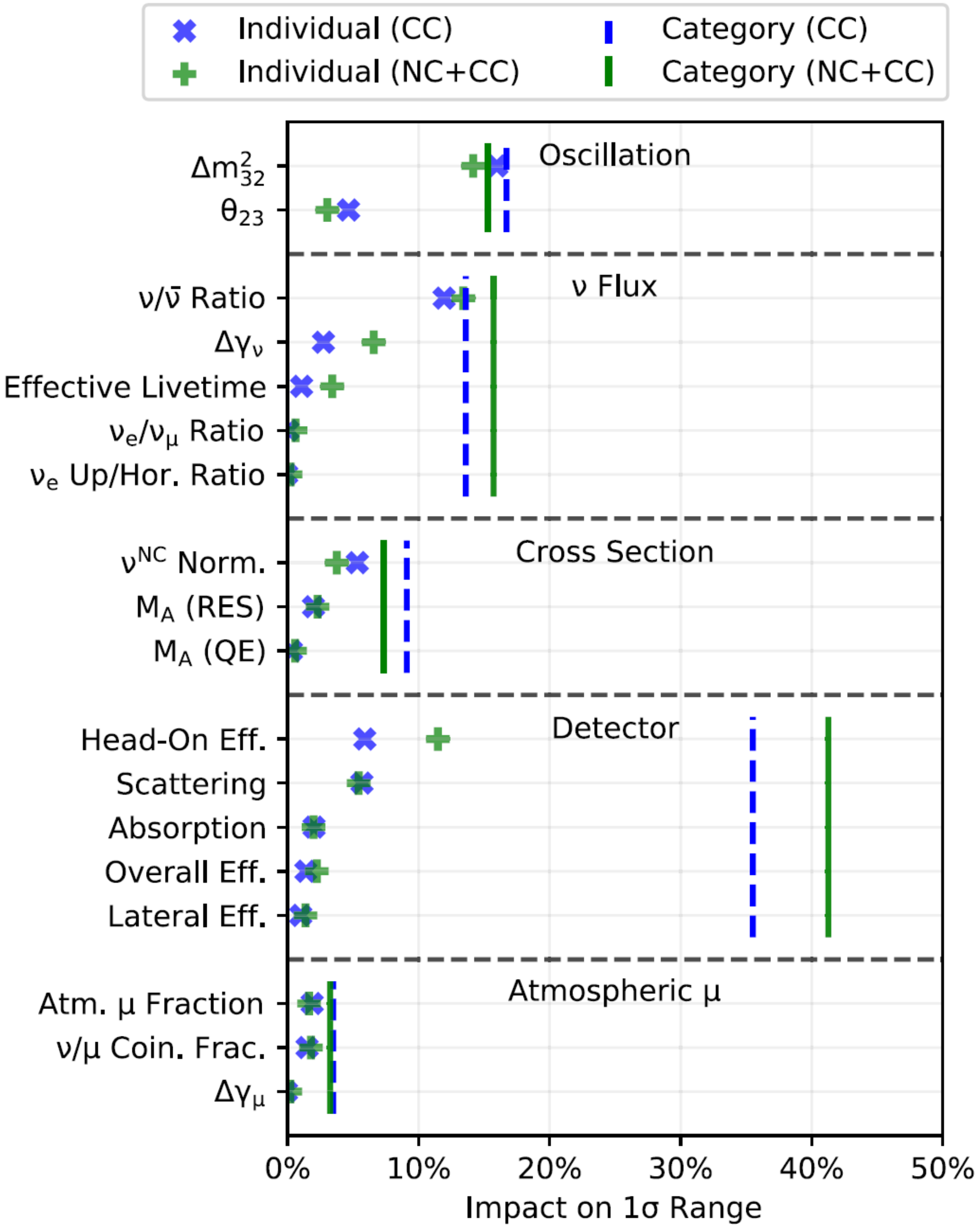
Systematic uncertainties

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

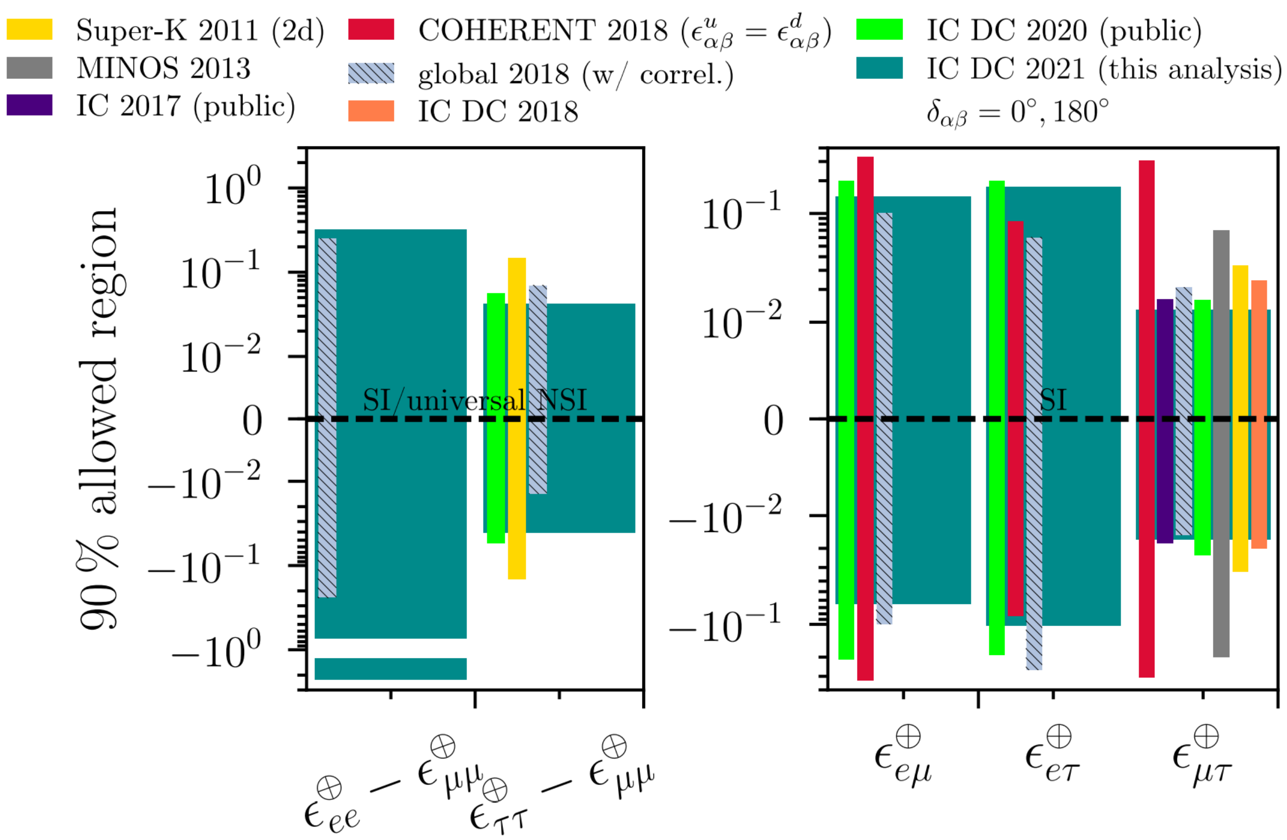




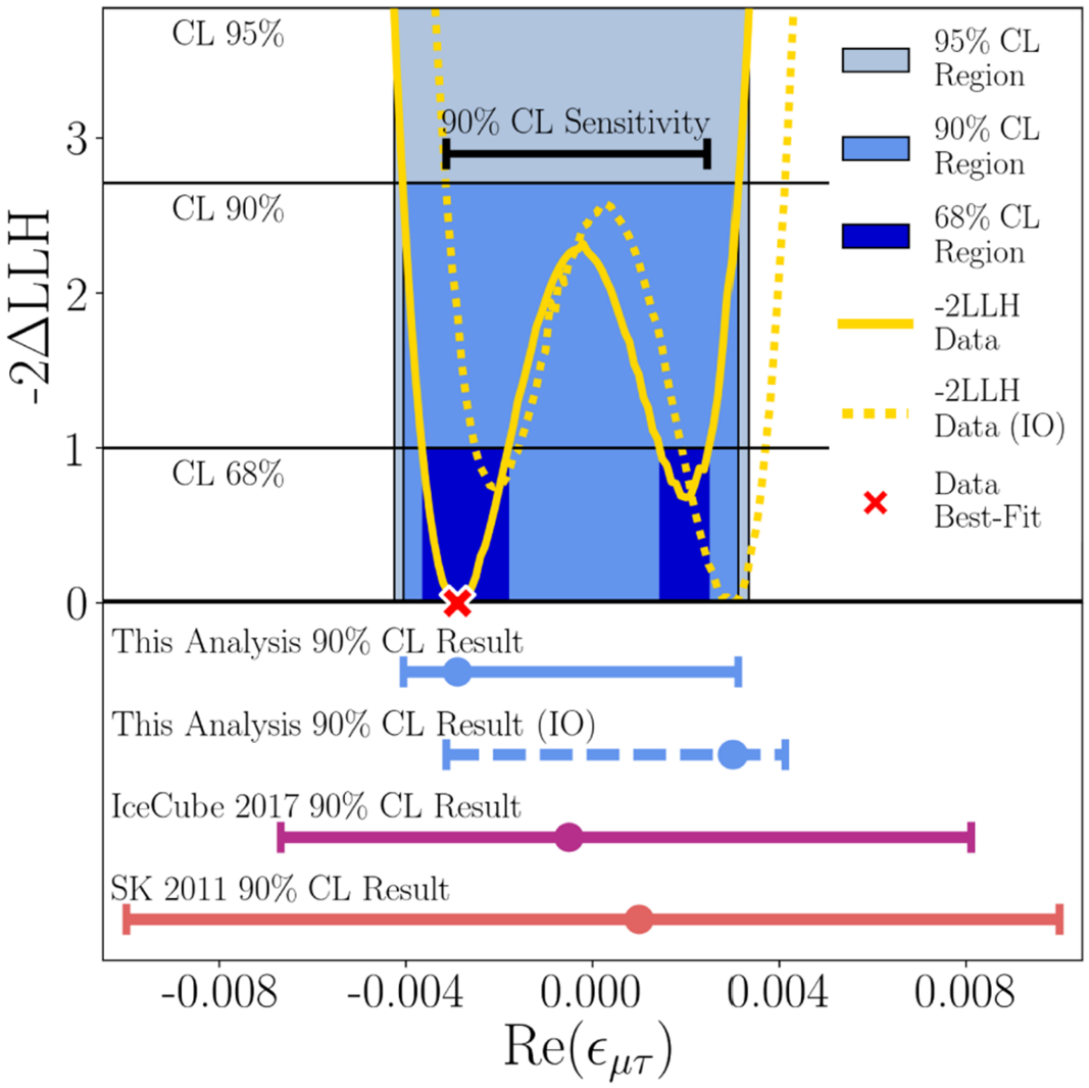



Individual (CC)
Individual (NC+CC)
Category (CC)
Category (NC+CC)
Oscillation
Δm^2_{32}
θ_{23}
ν Flux
ν/ν̄ Ratio
$\Delta\gamma_\nu$
Effective Livetime
ν_e/ν_μ Ratio
ν_e Up/Hor. Ratio
Cross Section
ν^{NC} Norm.
M_A (RES)
M_A (QE)
Detector
Head-On Eff.
Scattering
Absorption
Overall Eff.
Lateral Eff.
Atmospheric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

NSI studies (DC & IC)



Phys. Rev. D104 (2021) 072006



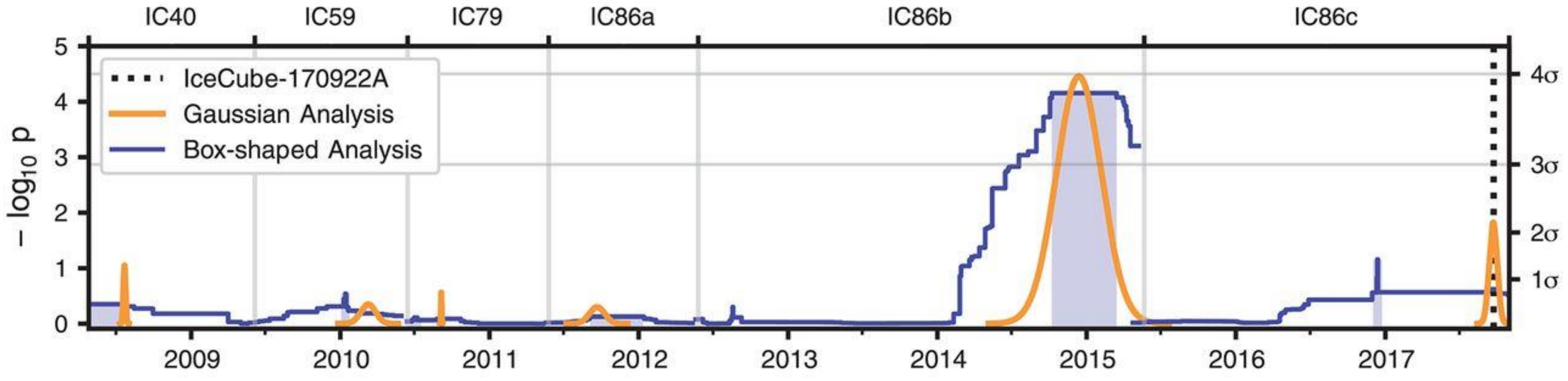
Phys. Rev. Lett. 129, 011804 (2022)

A summary on astrophysical results

- TXS 0506+056
- NGC 1068
- The Galactic Plane

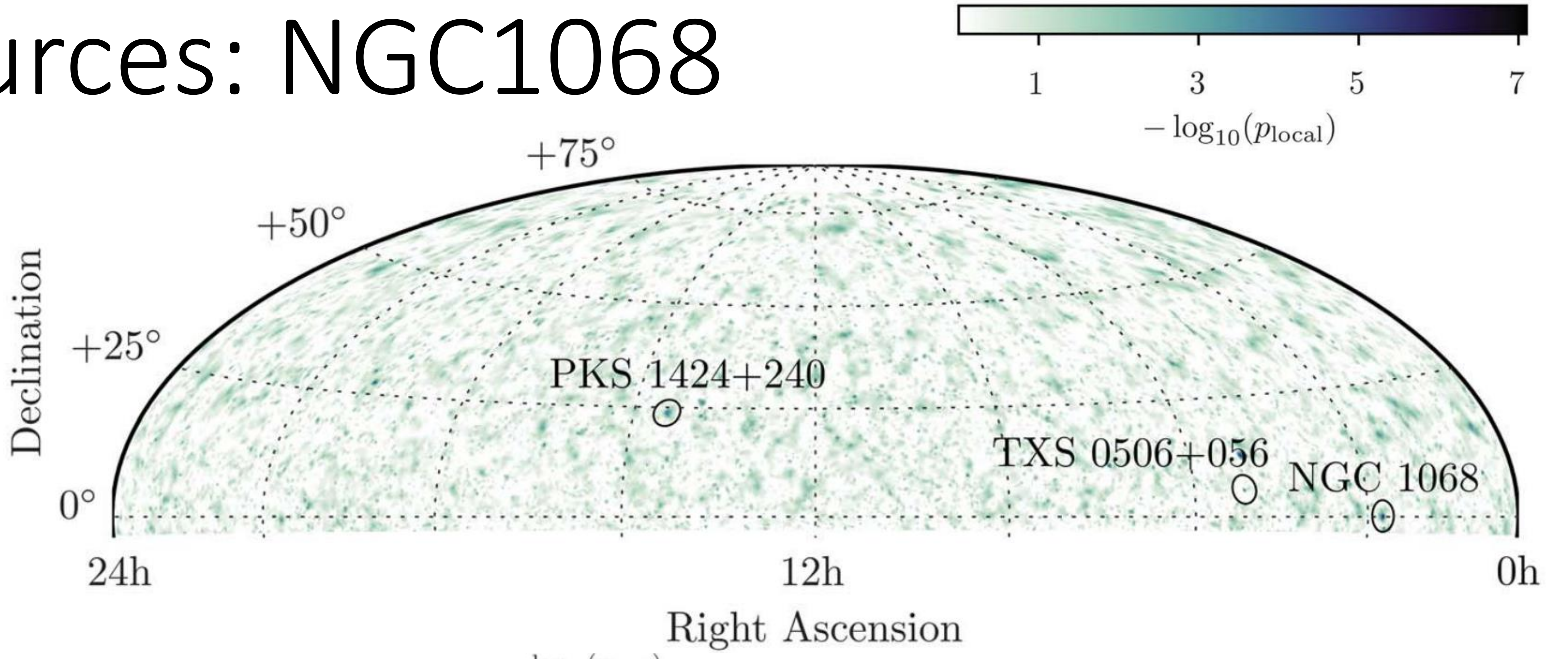
Astrophysical sources: TXS 0506+056

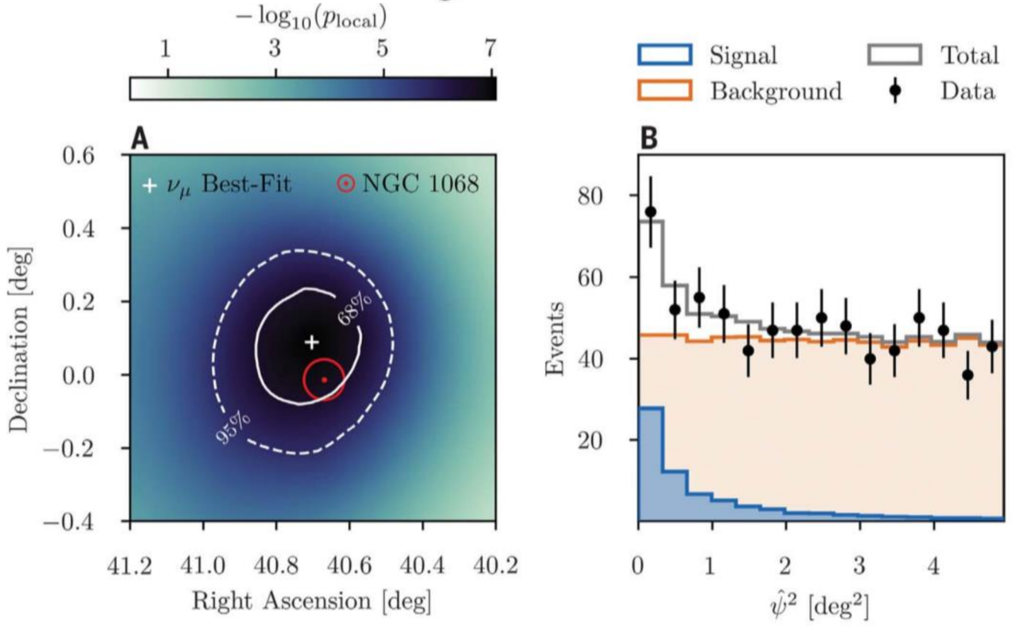
- Flaring
  - 3.5 σ evidence for a neutrino flare in late 2014 – early 2015 (long before IceCube-170922A)
  - 158-day duration (box)
  - 110-day duration (Gaussian)
- 13 excess neutrinos above atmospheric background
  IceCube. Science (2018)
  - At this time TXS 0506+056 was not flaring in γ-rays



Astrophysical sources: NGC1068

- Look for an excess of neutrinos from a likely direction in the sky
- Found that NGC 1068 has an excess of 79^{+22}_{-20} neutrinos at TeV energies
- Global significance of 4.2σ





The IceCube regimes

The IceCube mid-energy cascade regime

- Patterns are hard to distinguish
- Really hard to work with
- Atmospheric neutrino background can be suppressed