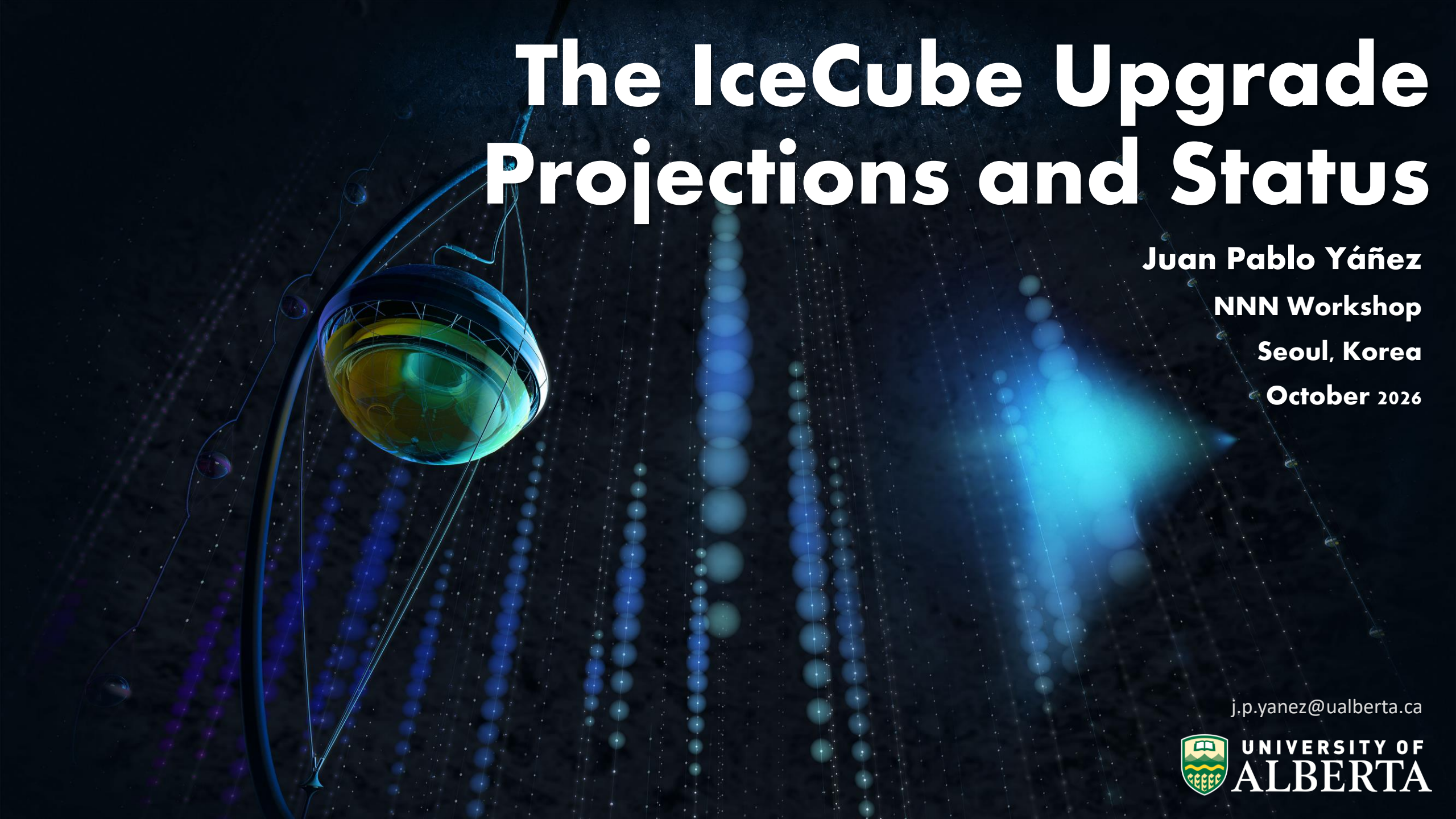


The IceCube Upgrade Projections and Status

Juan Pablo Yáñez

NNN Workshop

Seoul, Korea

October 2026

j.p.yanez@ualberta.ca

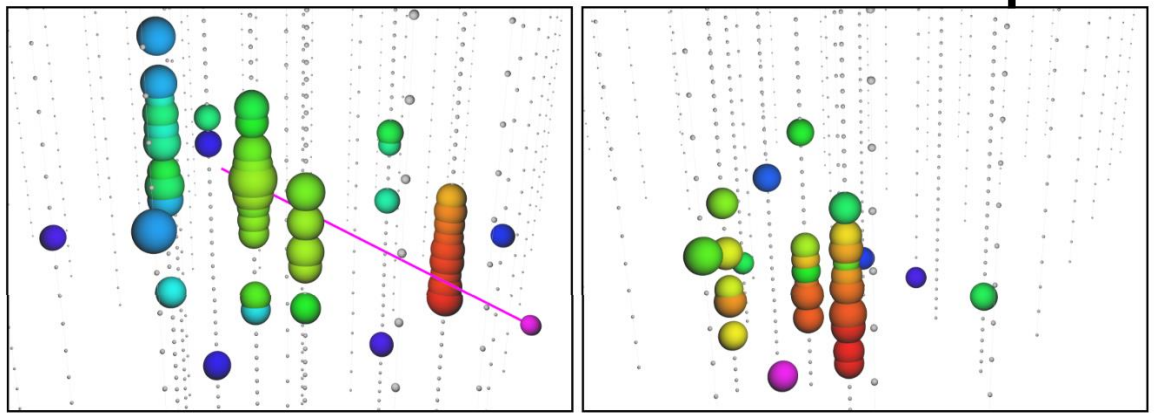
UNIVERSITY OF ALBERTA

IceCube pre-Upgrade

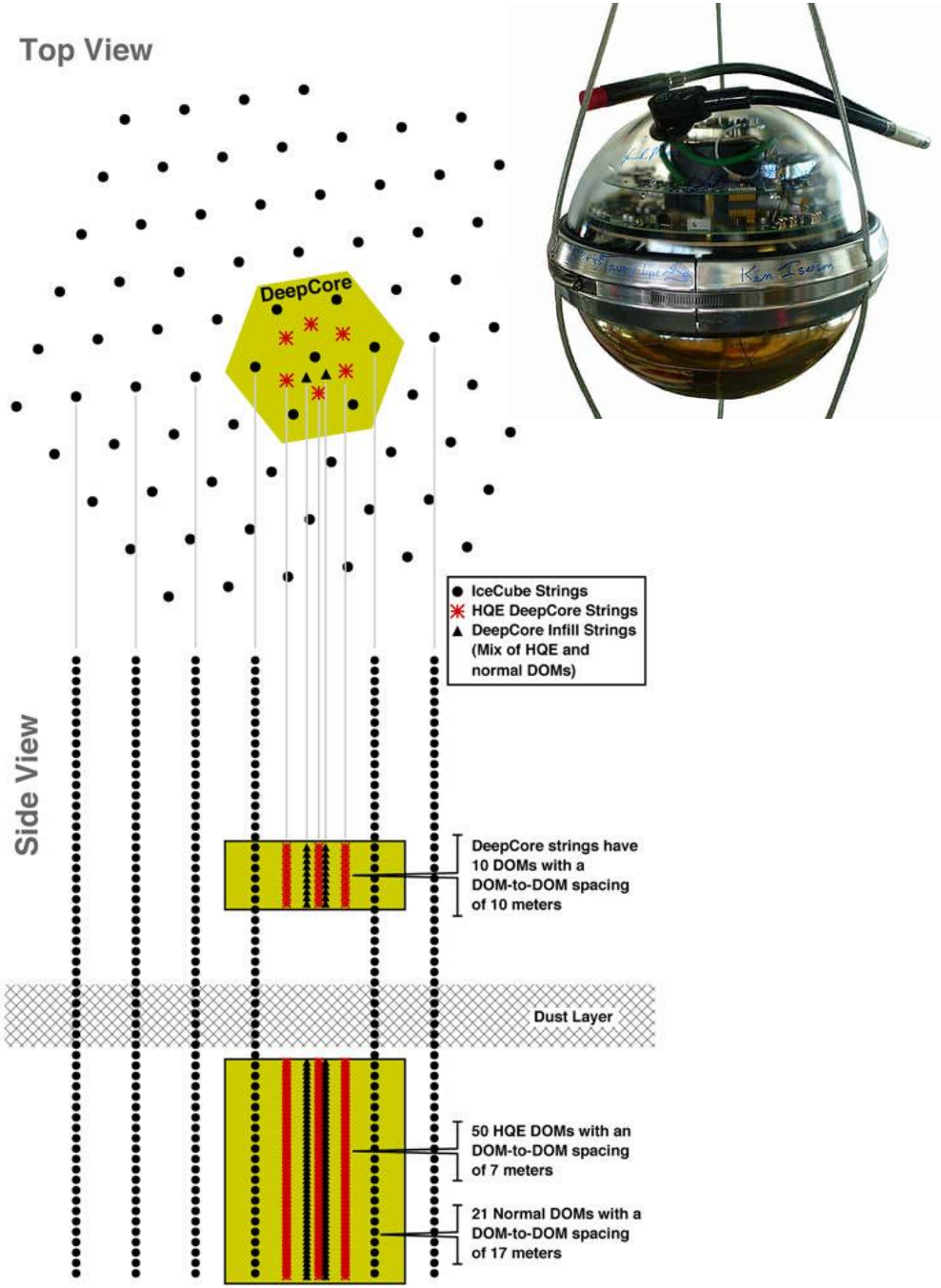
15 years of full detector data

The tens of GeV realm

GeV events in DeepCore

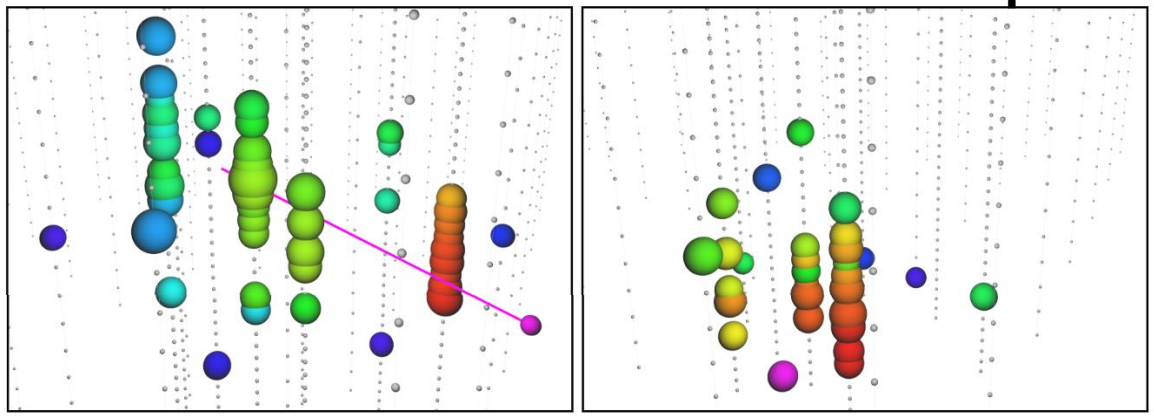


Color indicates time (red=early, blue=late). Sphere size is proportional to number of photons observed.



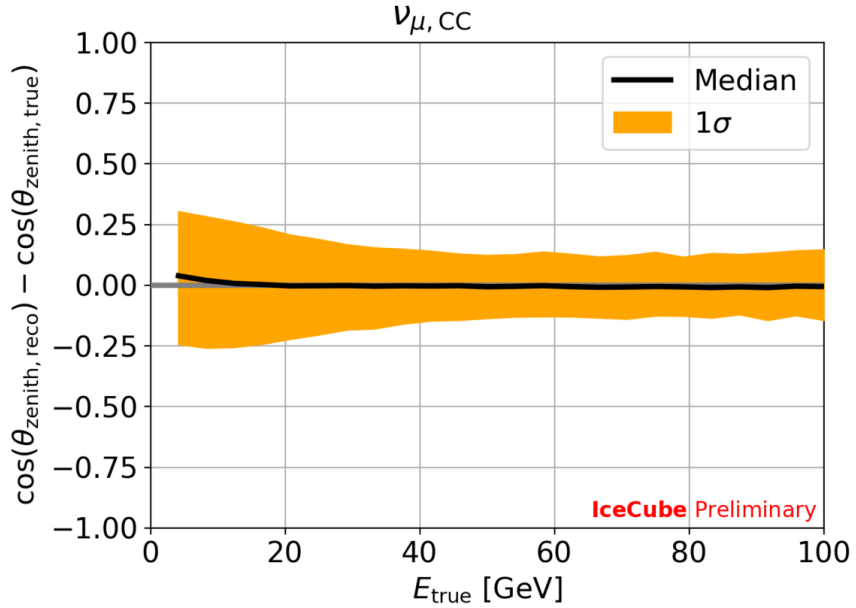
The tens of GeV realm

GeV events in DeepCore

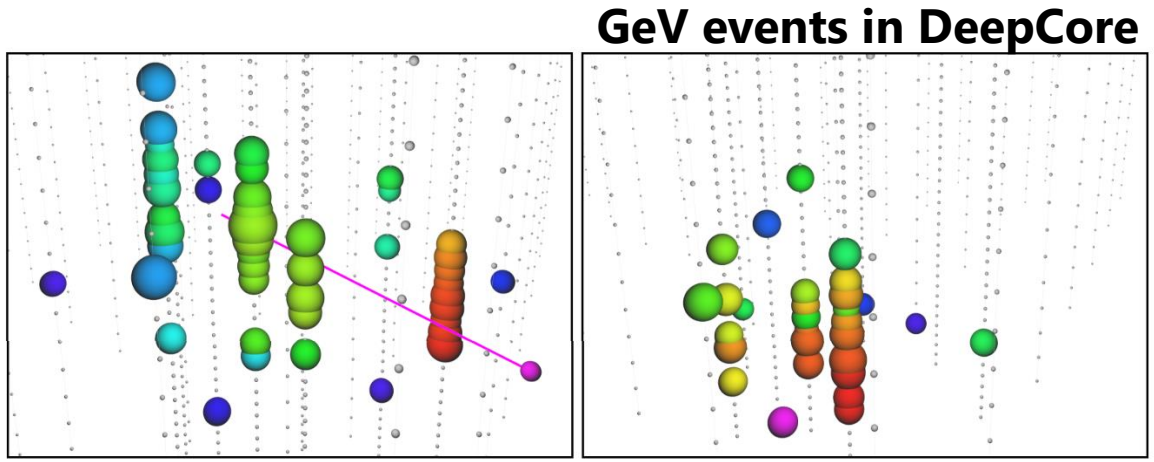


Color indicates time (red=early, blue=late). Sphere size is proportional to number of photons observed.

- Reconstructing flavor, direction and energy with tens of modules
- Data going down to a few GeV, albeit with limited resolution

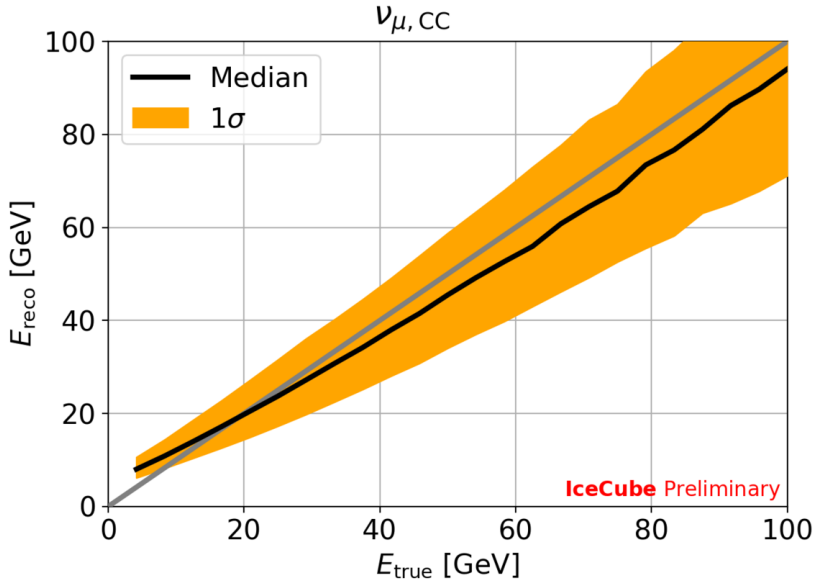


The tens of GeV realm



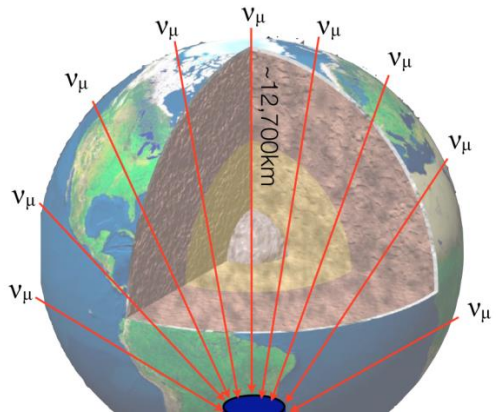
Color indicates time (red=early, blue=late). Sphere size is proportional to number of photons observed.

- Reconstructing flavor, direction and energy with tens of modules
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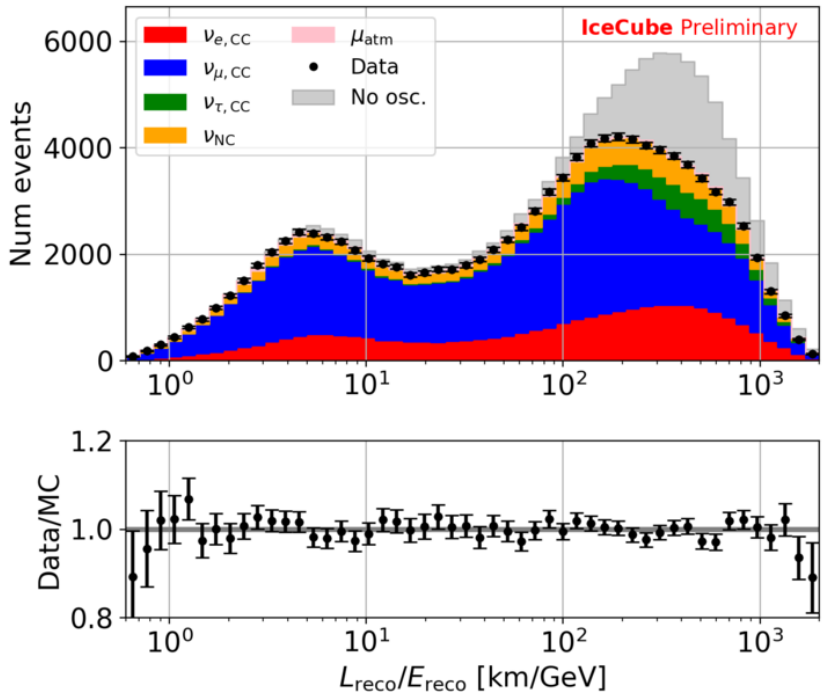


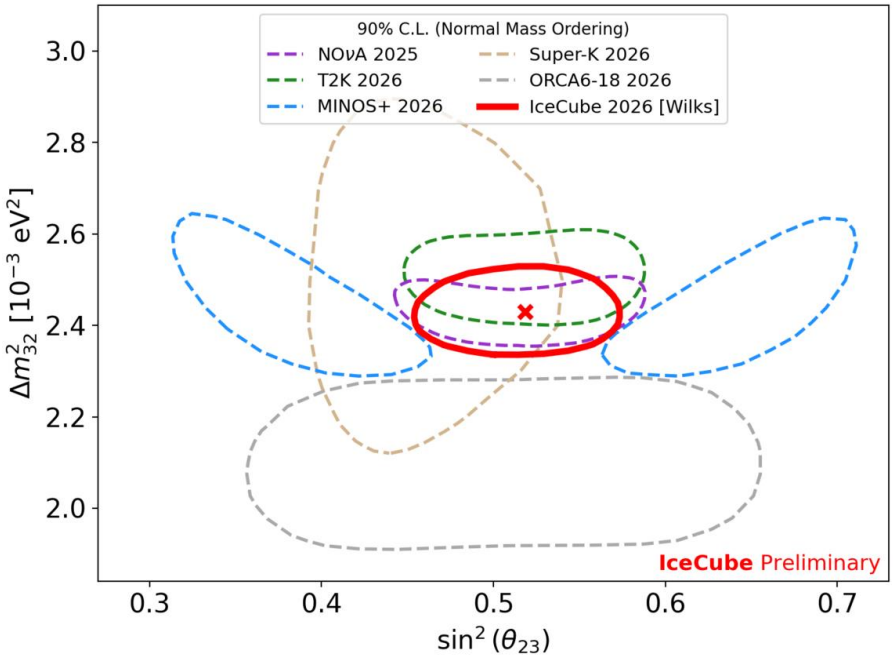
Latest DC results – Oscillations

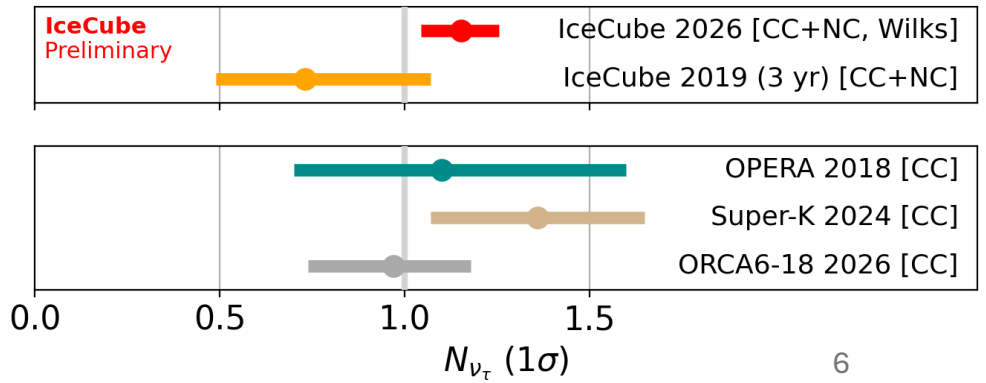
11.1 years of data
108k atmospheric neutrino events



$$P\nu_\mu \to \nu_\mu \simeq 1 - \sin^2 2\theta_{23}\ \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$



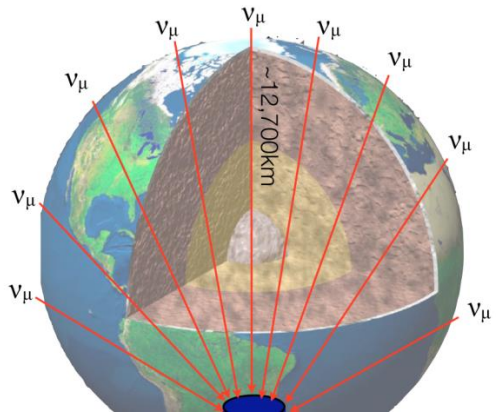




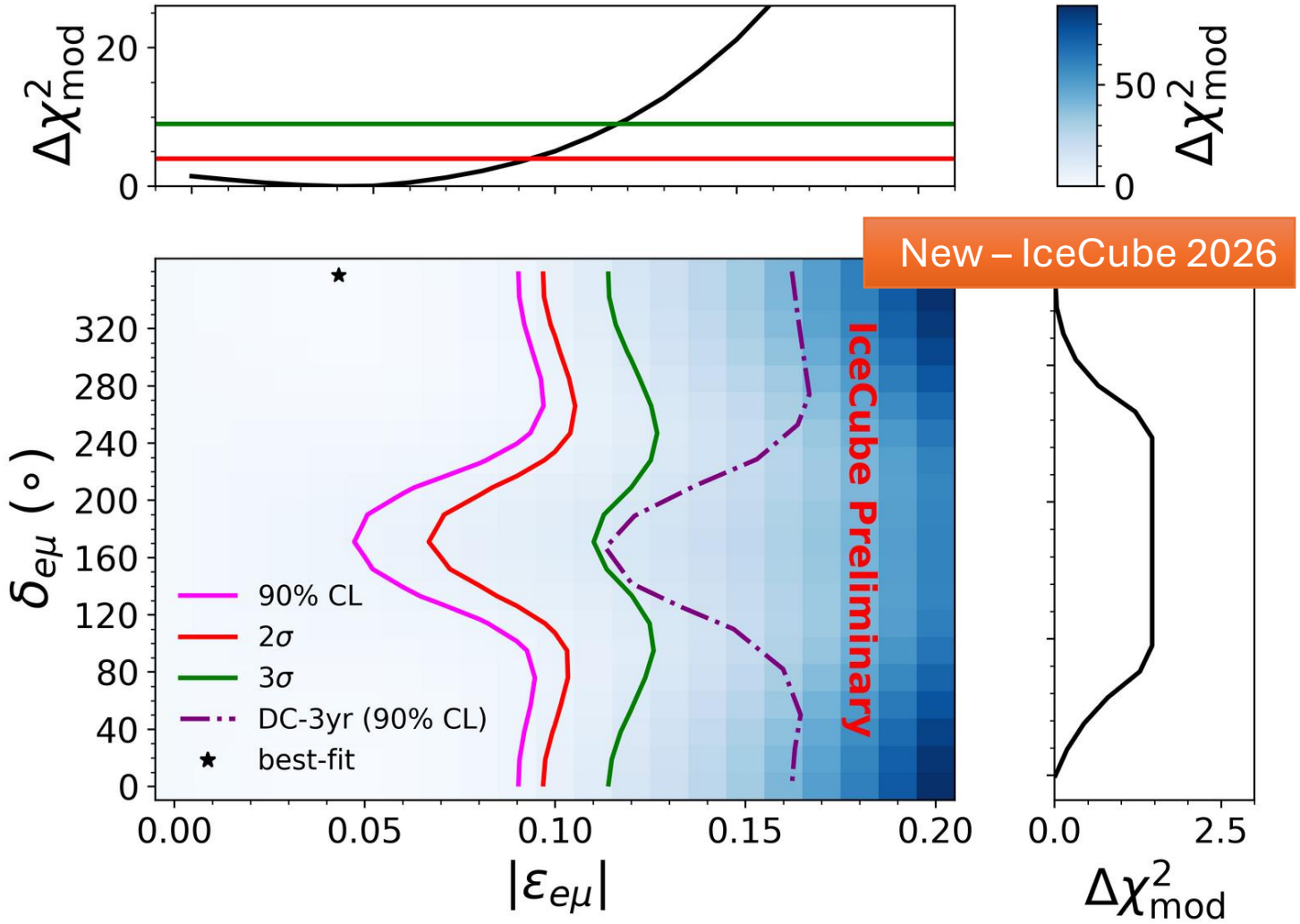
Publication in preparation

Latest DC results – NSI's

11.1 years of data
108k atmospheric neutrino events



$$P\nu_\mu \to \nu_\mu \simeq 1 - \sin^2 2\theta_{23}\ \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

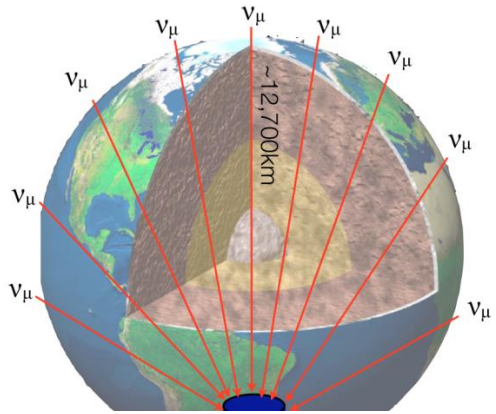


Publication in preparation

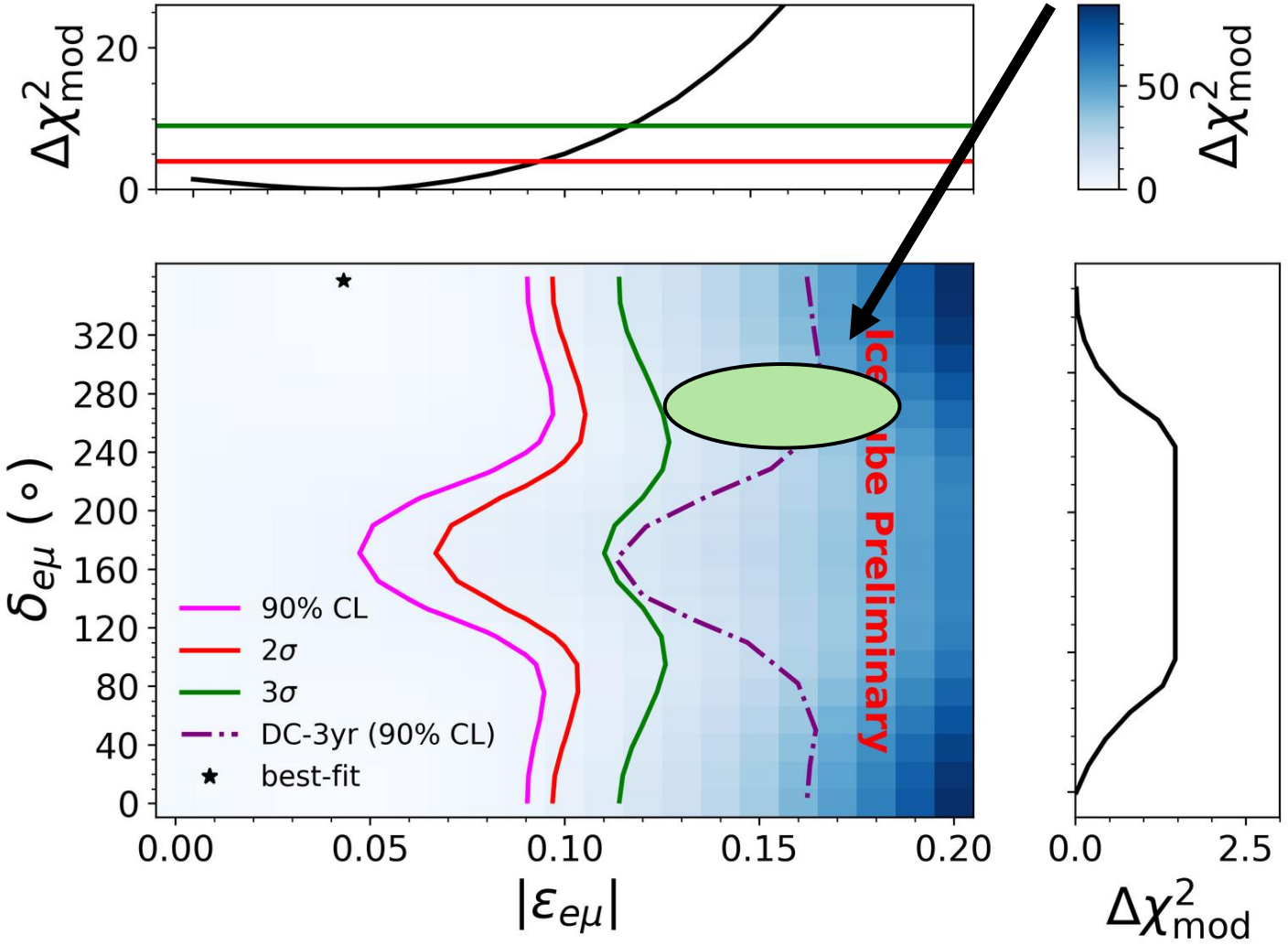
Latest DC results – NSI's

NSI solutions to the T2K/NOvA discrepancy
Chatterjee & Palazzo, PRL **126**, 051801
Denton et al, PRL **126**, 051802

11.1 years of data
108k atmospheric neutrino events



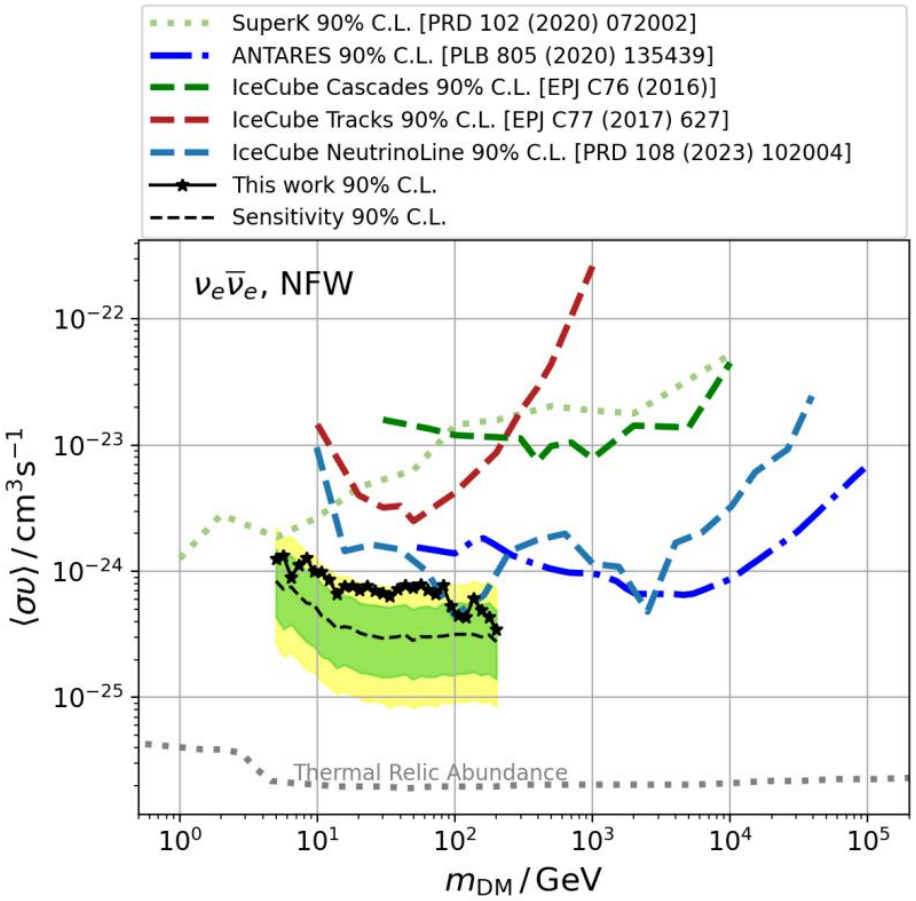
$$P\nu_\mu \to \nu_\mu \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

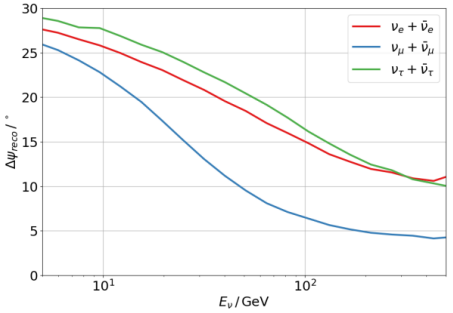


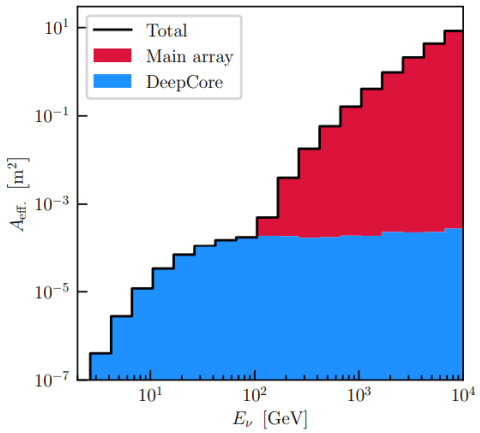
Publication in preparation

Latest DC results – Dark Matter

Galactic Center

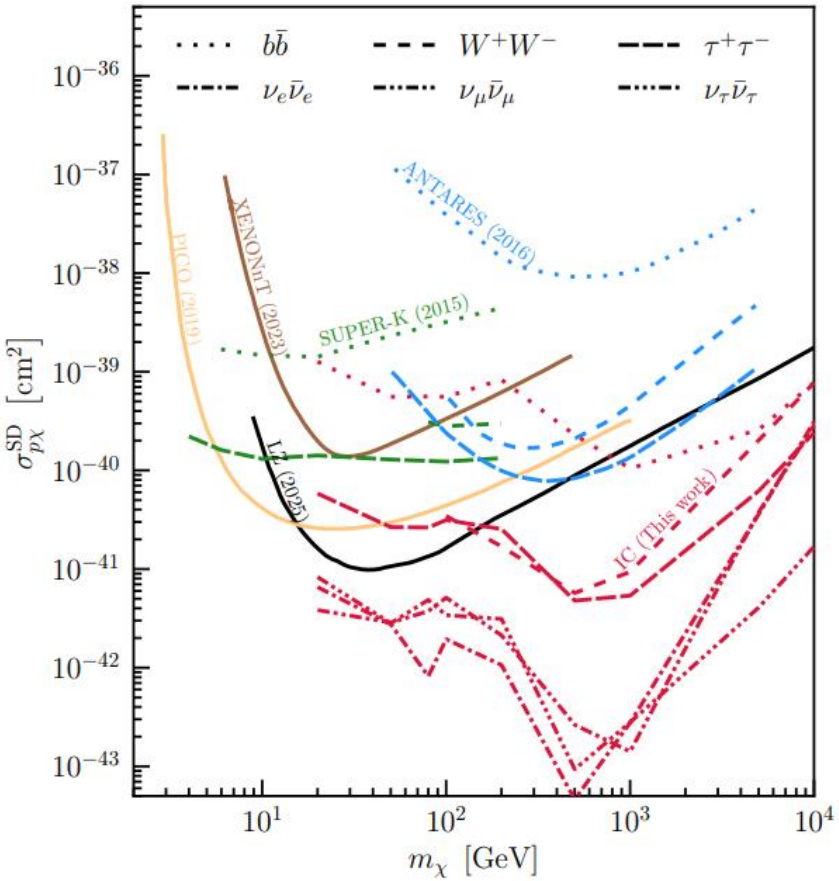






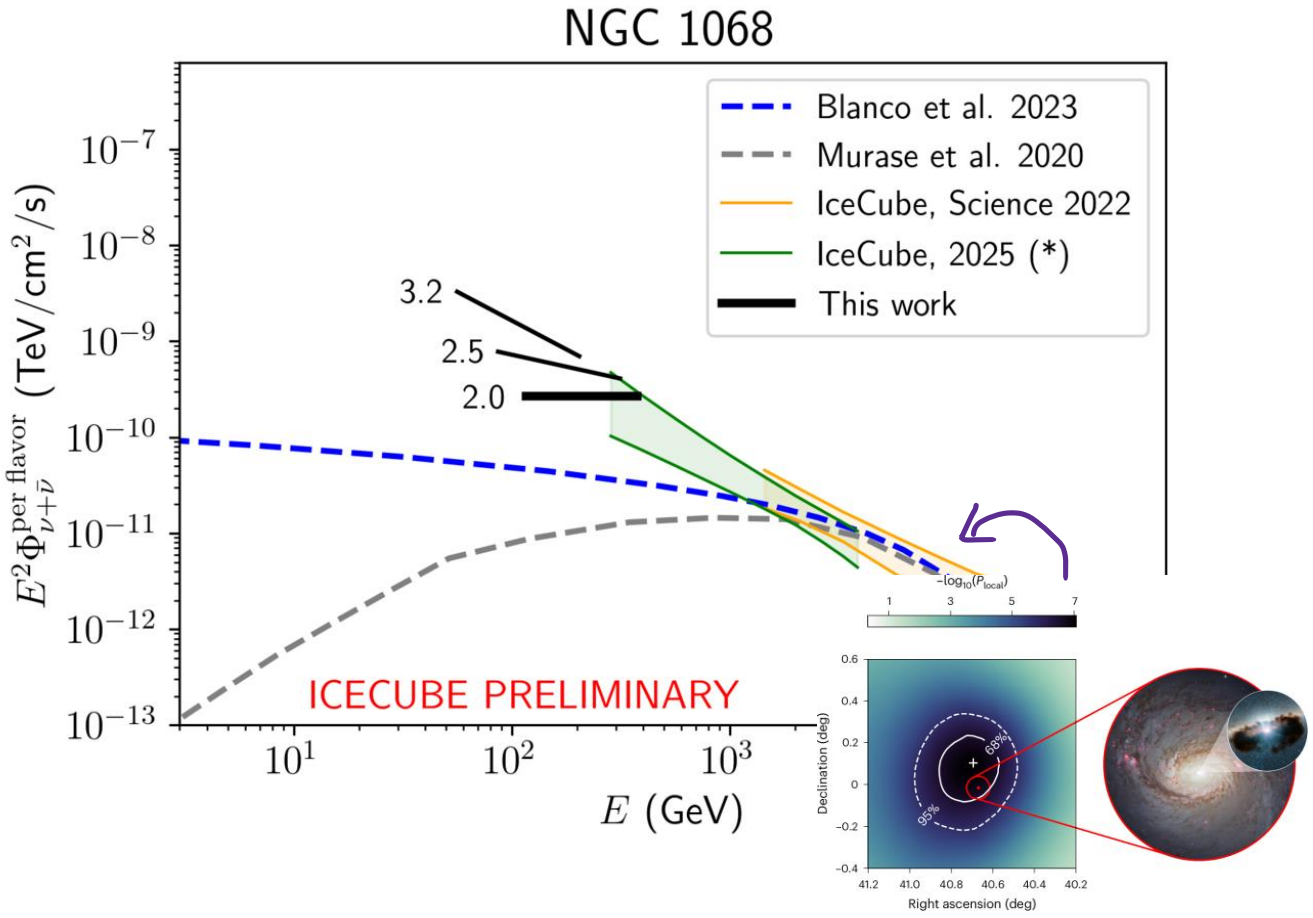
Phys.Rev.D 113 (2026) 12, 122004

The Sun

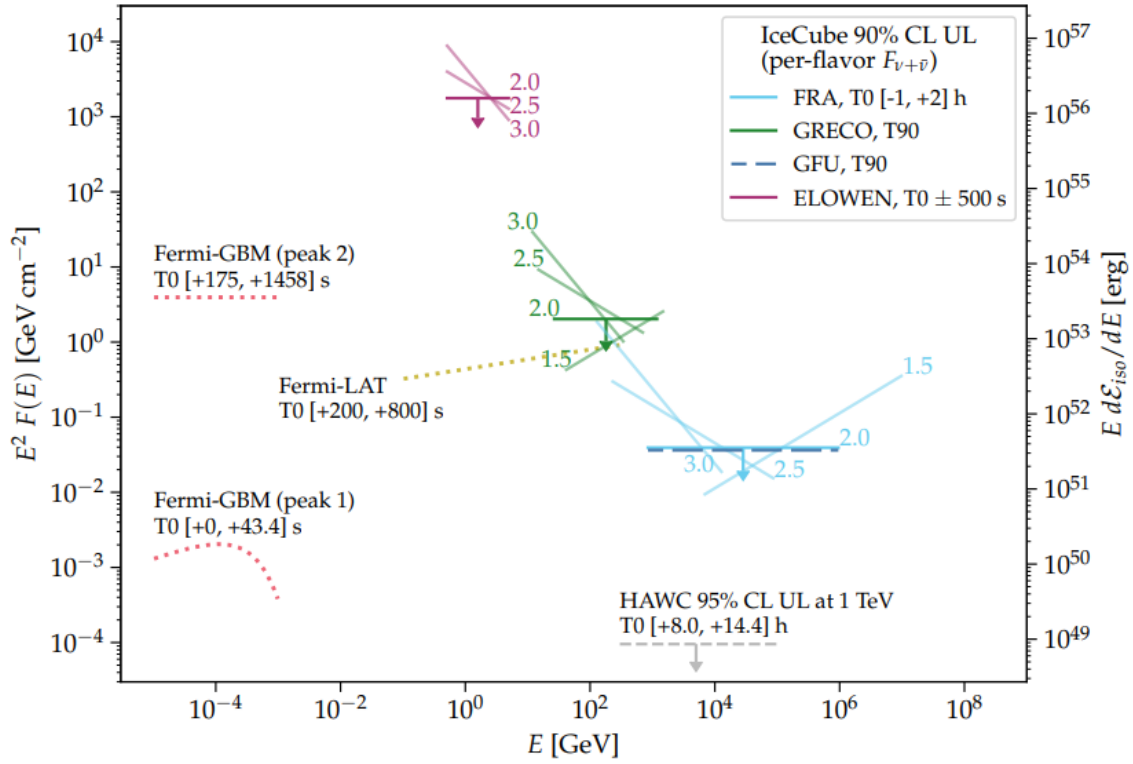


arXiv:2507.08457 **[hep-ex]**

Latest DC results – “Low Energy” Astronomy



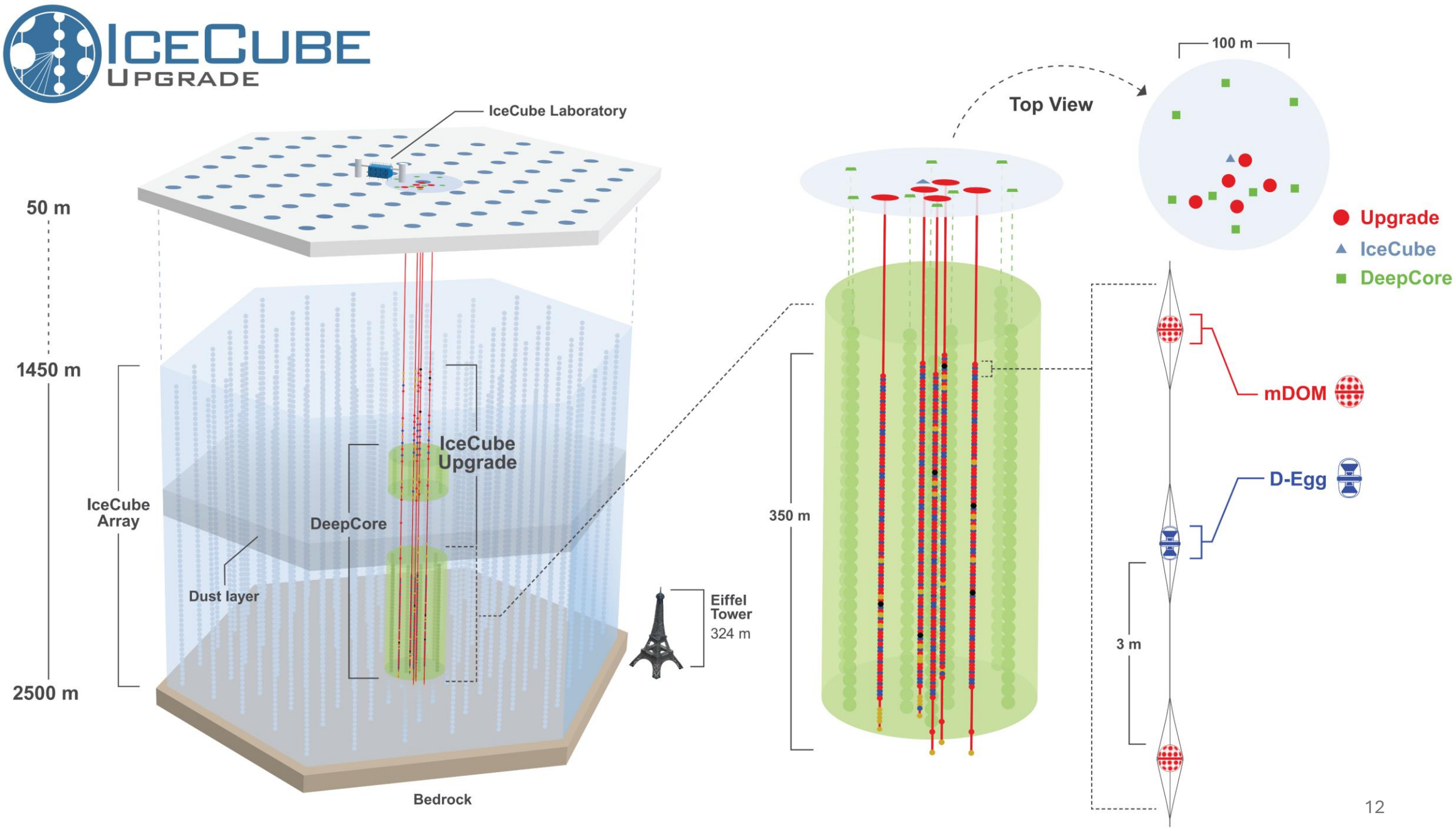
Limits on time-integrated ν flux from GRB 221009A



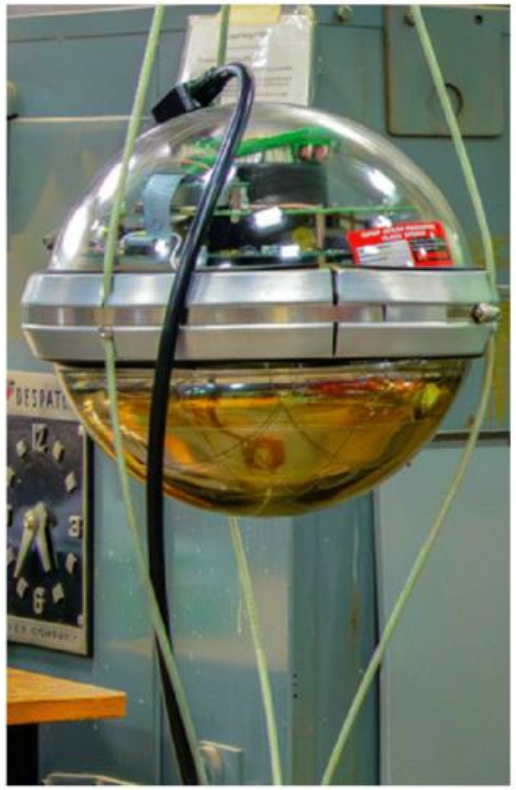
ApJL 946 L26 (2023)

The upgraded IceCube detector

Deployed in 2025/2026 Pole season


IceCube Laboratory
50 m
1450 m
2500 m
IceCube Array
IceCube Upgrade
DeepCore
Dust layer
Bedrock
Eiffel Tower
324 m
Top View
100 m
Upgrade
IceCube
DeepCore
350 m
mDOM
D-Egg
3 m

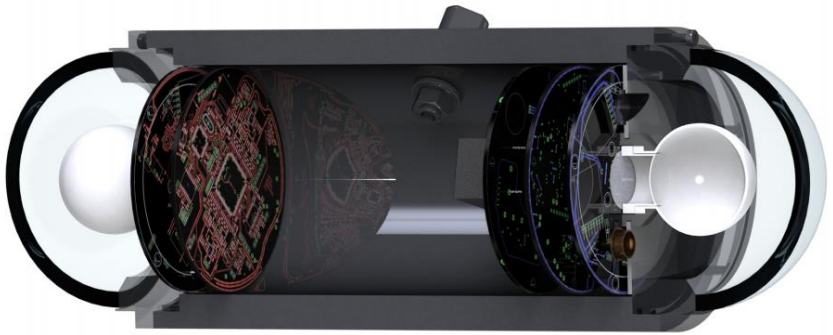
The modules of the Upgrade











Credit: Yuya Makino, IceCube/NSF





IceCube Upgrade drill camp, 2024.
Credit: Michael Rayne/ASC-ARFF

Credit: Yuya Makino, IceCube/NSF

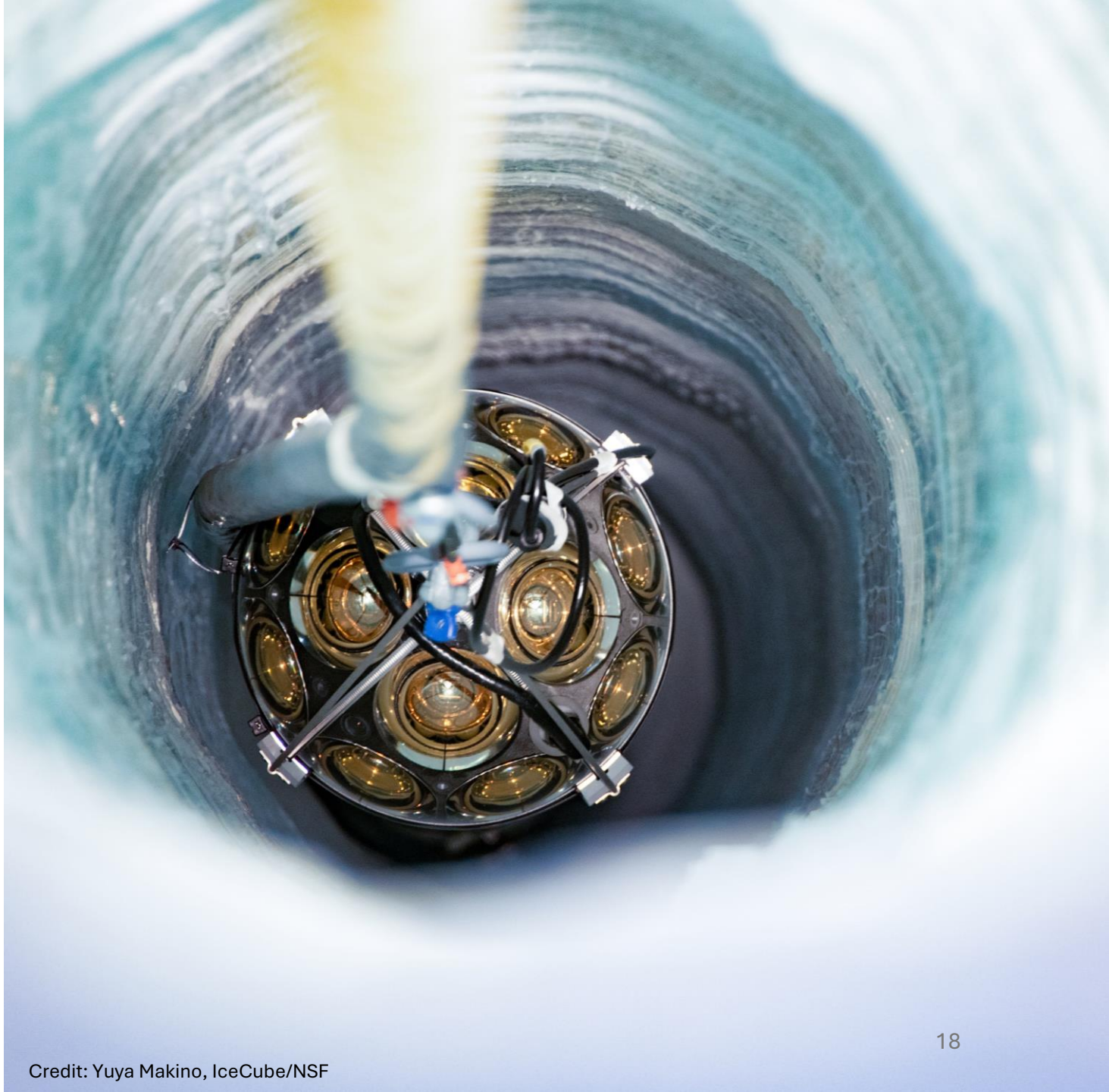


Credit: Kurt Studt, IceCube/NSF


Credit: Yuya Makino, IceCube/NSF

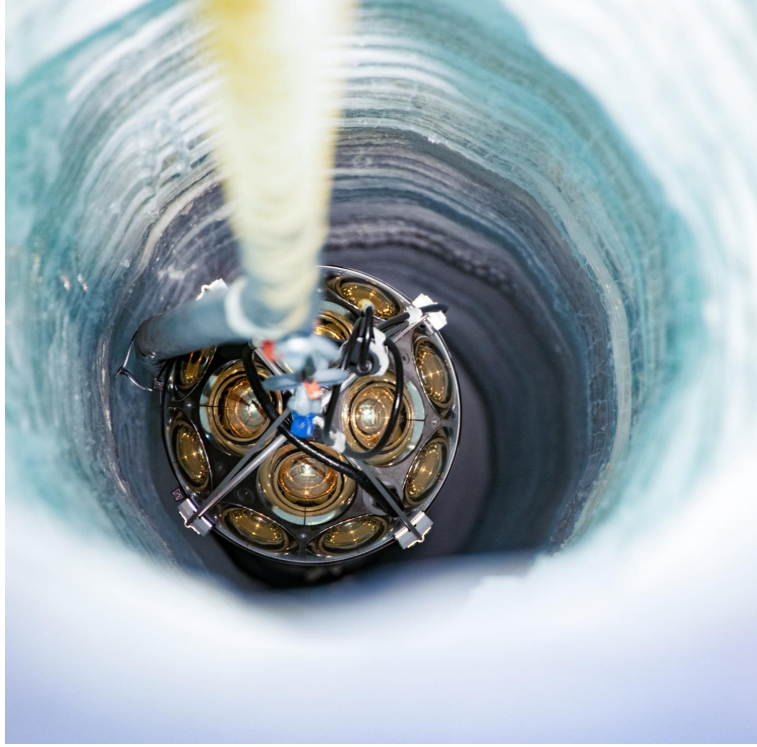


Credit: Aya Ishihara, IceCube/NSF



Credit: Yuya Makino, IceCube/NSF

Summary of deployment



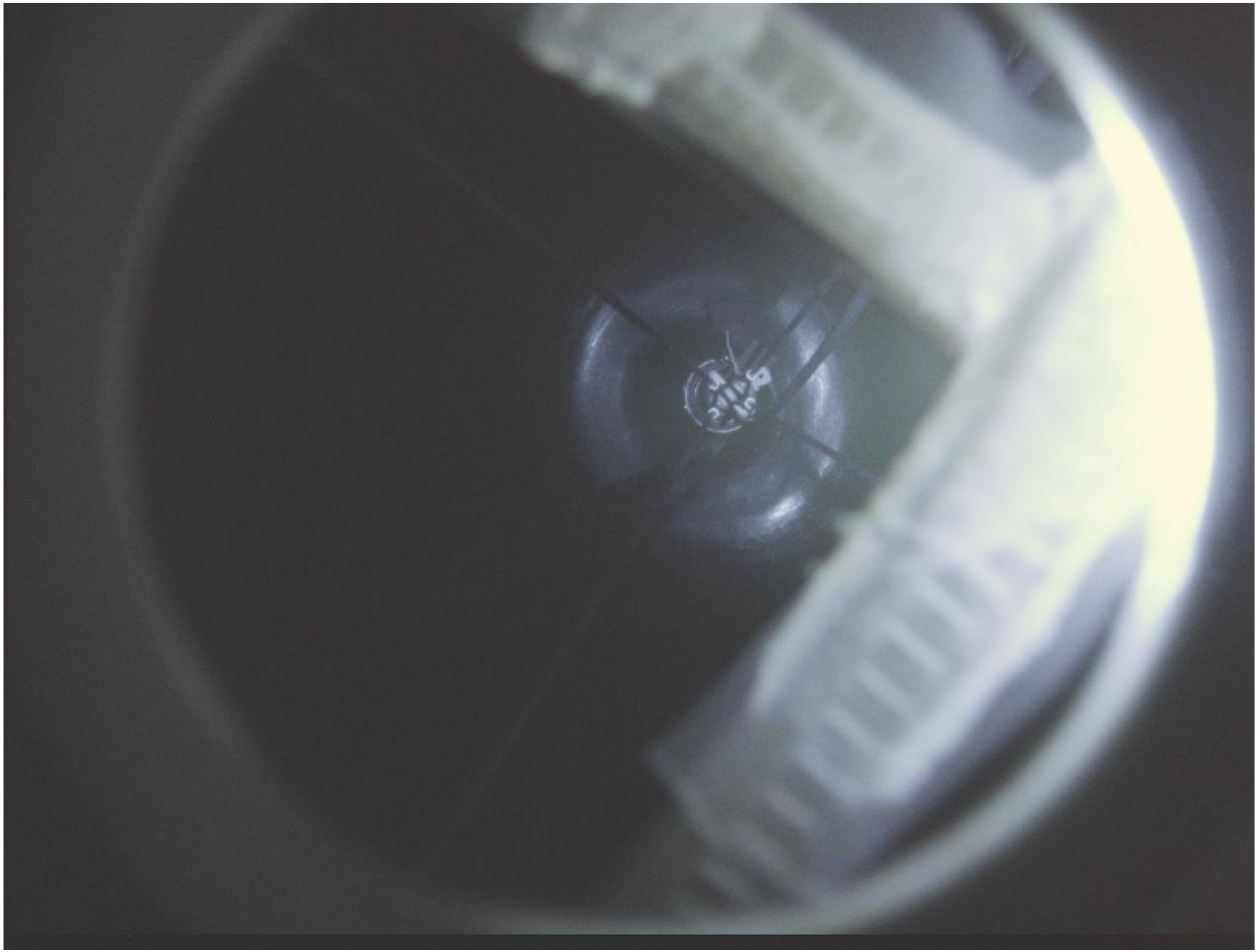
- Drilled 6 of 7 planned holes
  - Issue with drill on hole #6 → hole #7 was not attempted
  - Lost one string during re-freezing
  - Big success after 15 years of no deep drilling at the SP!

- New instrumentation:
  - **505 optical modules** across five strings
    - Majority are multi-PMT modules, other novel designs
  - **64 special / calibration devices**
    - Cameras, collimated beams, isotropic light emitters, acoustic modules, a seismometer

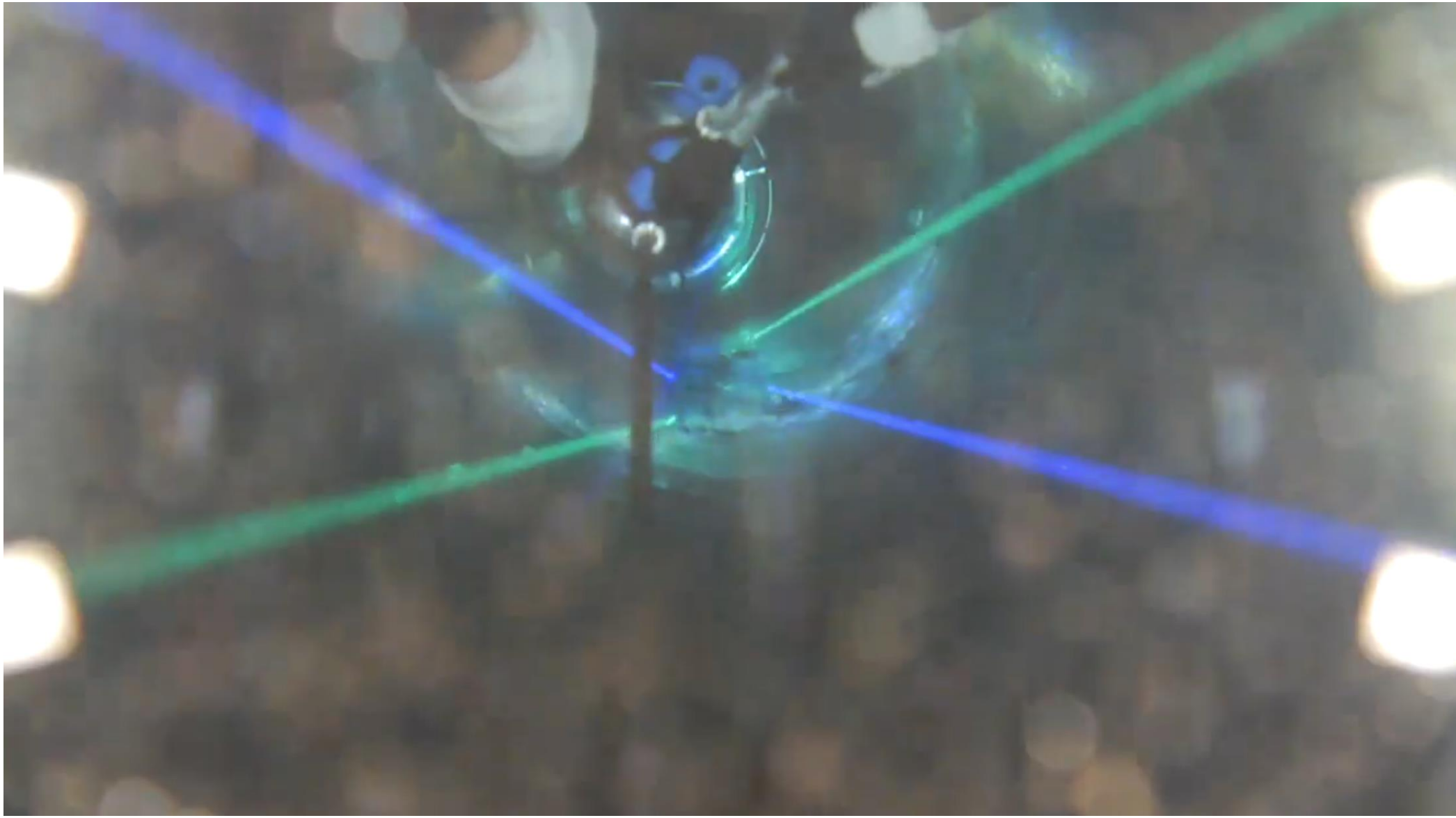
First look at IceCube Upgrade data

All images preliminary

Cameras



Cameras

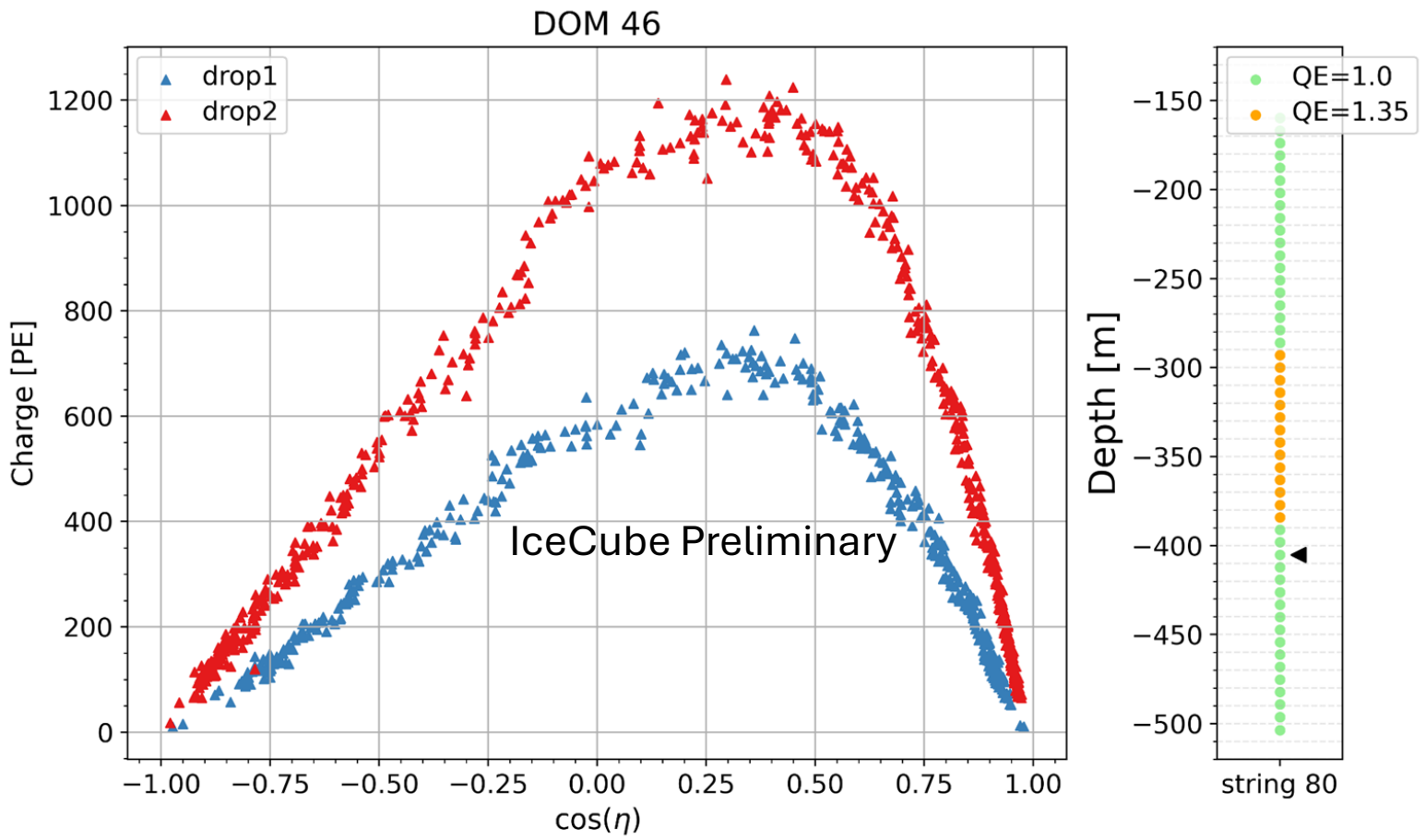


POCAM during drop

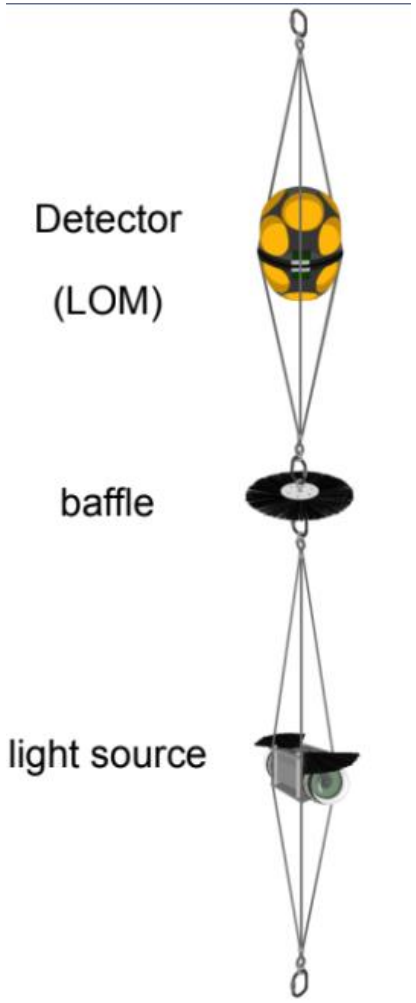
- Illuminating DeepCore
  - String 80 from 2 sides
  - $d = 15m, 20m$
  - $Q_{15m} \simeq 2Q_{20m}$



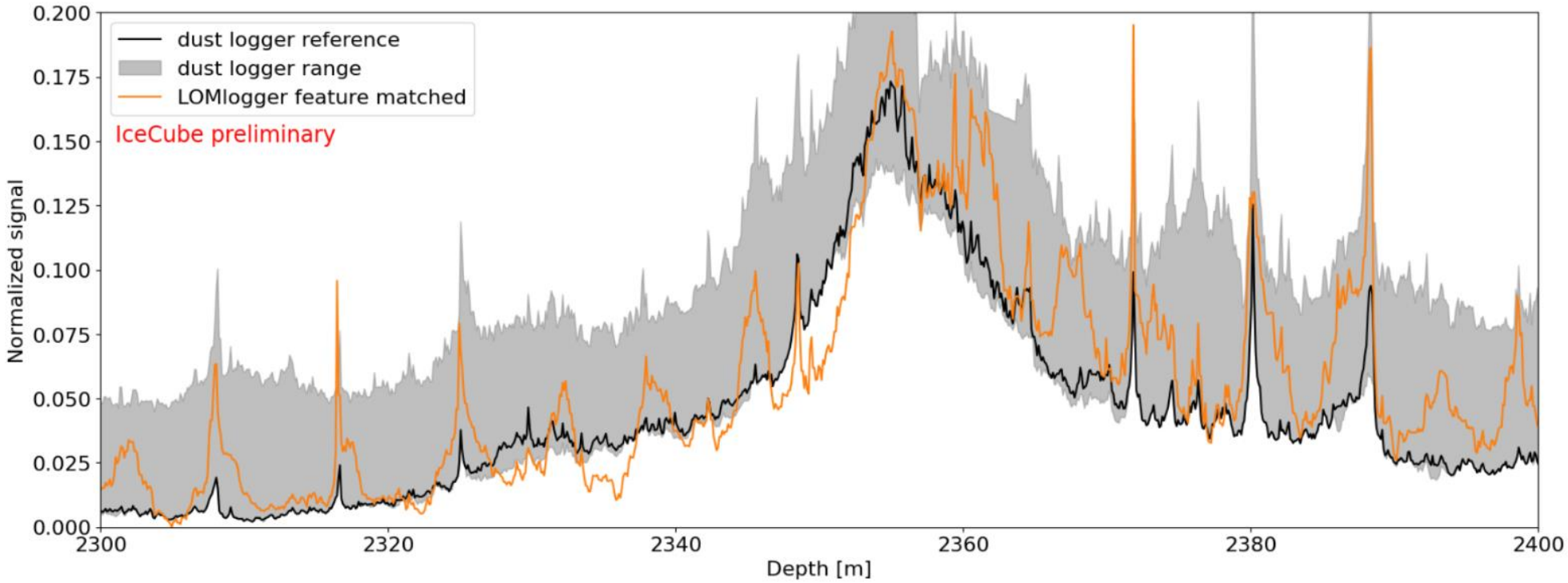
In-situ angular acceptance



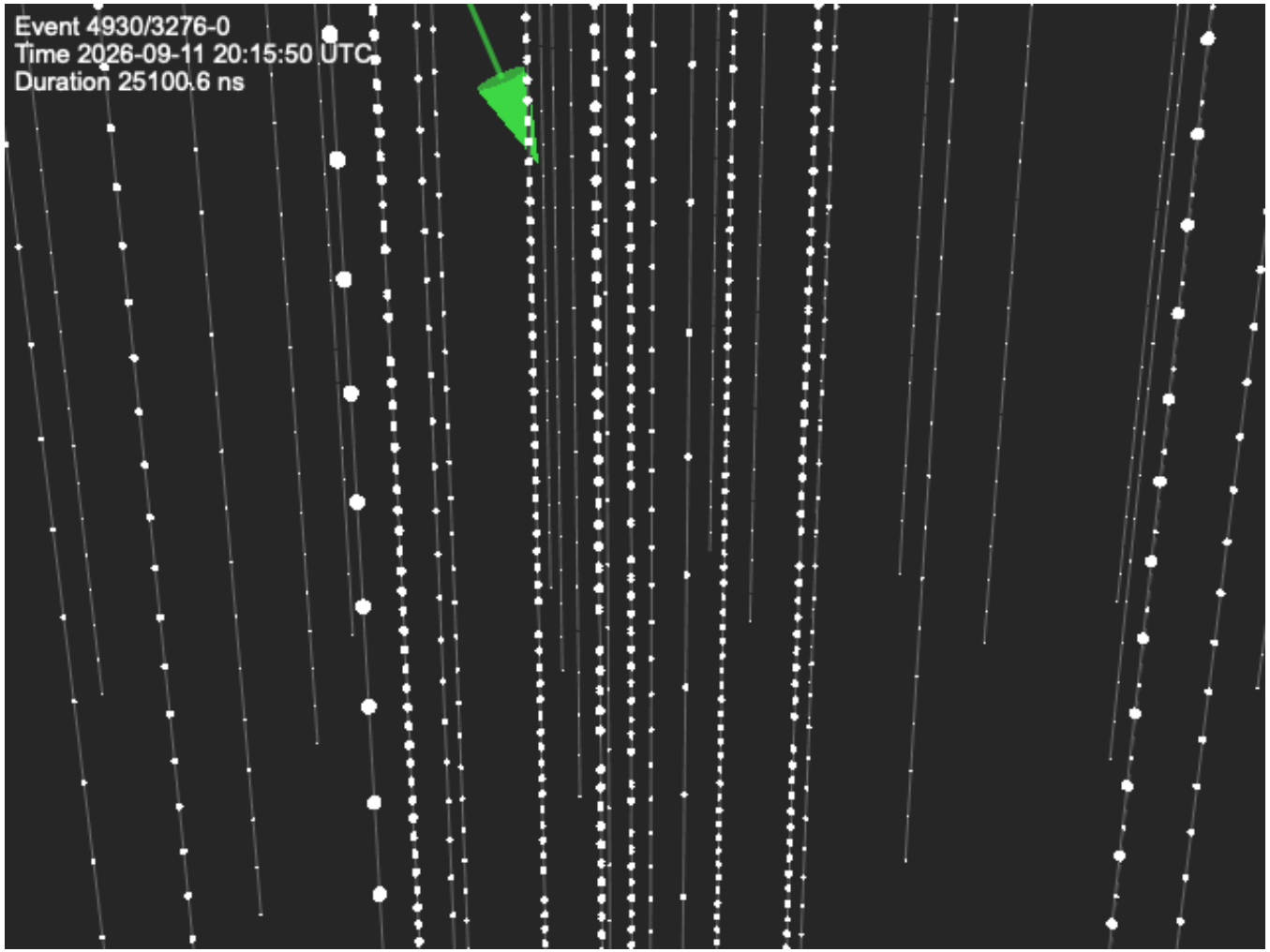
LOMLogger – stratigraphy measurements

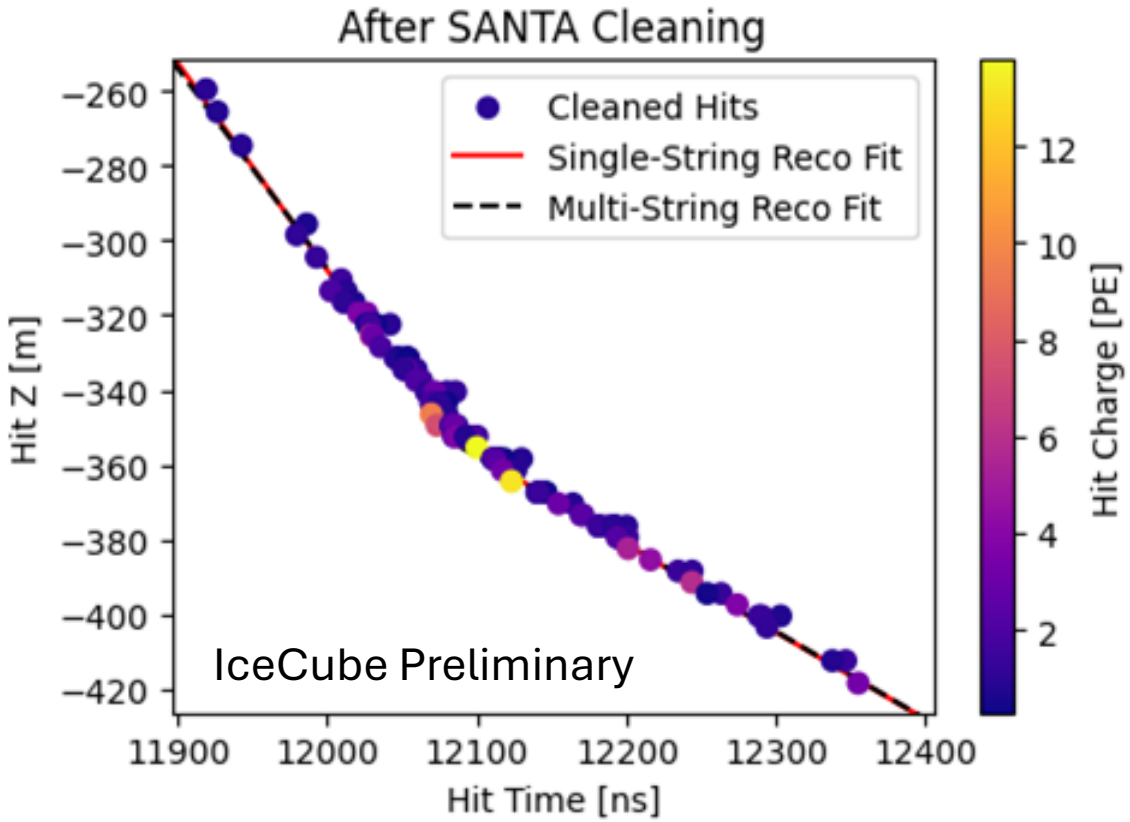


- “Dust logger” ran on different holes in previous years
- LOMLogger dropped in instrumented holes, matching their results for display

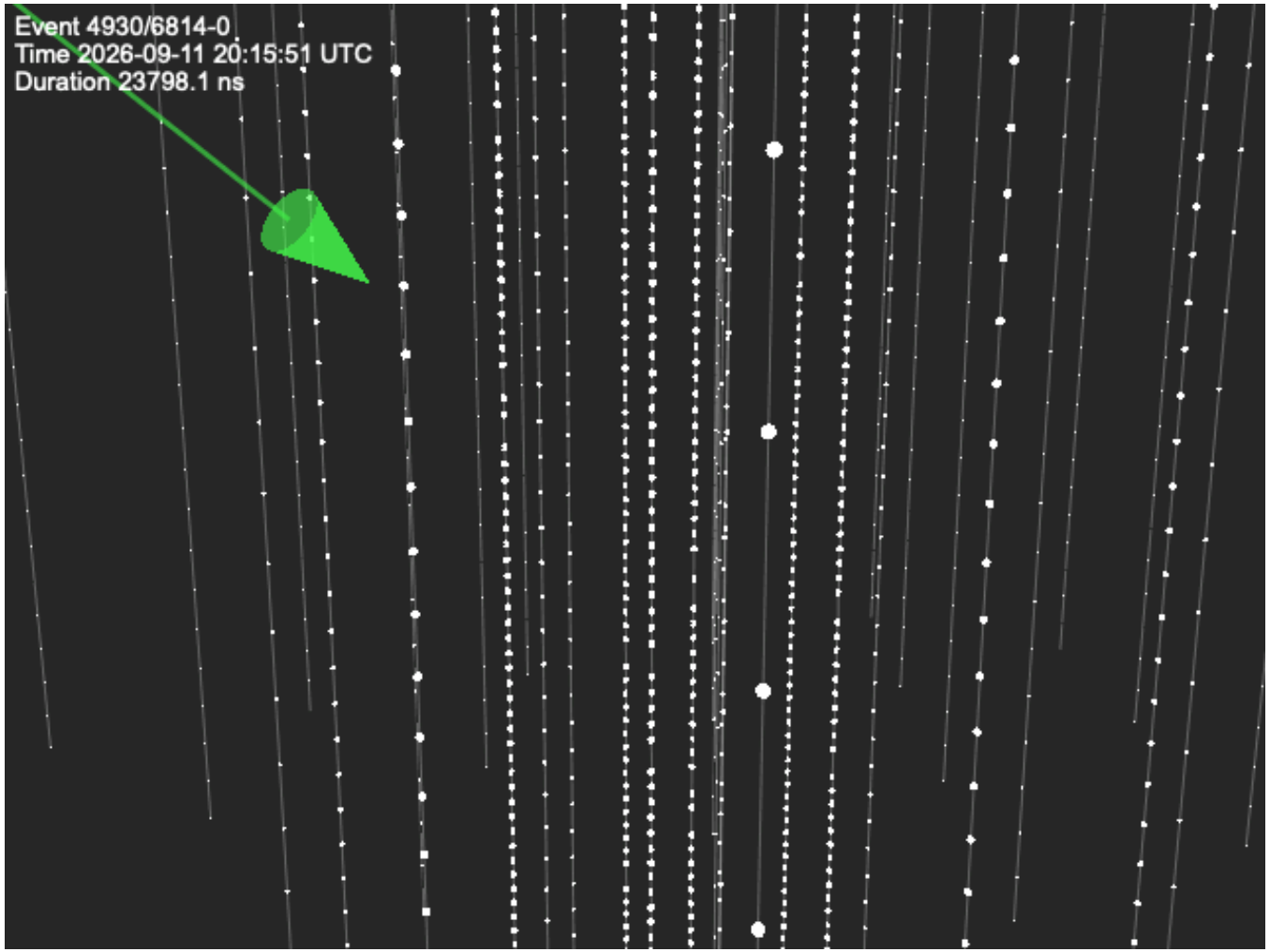


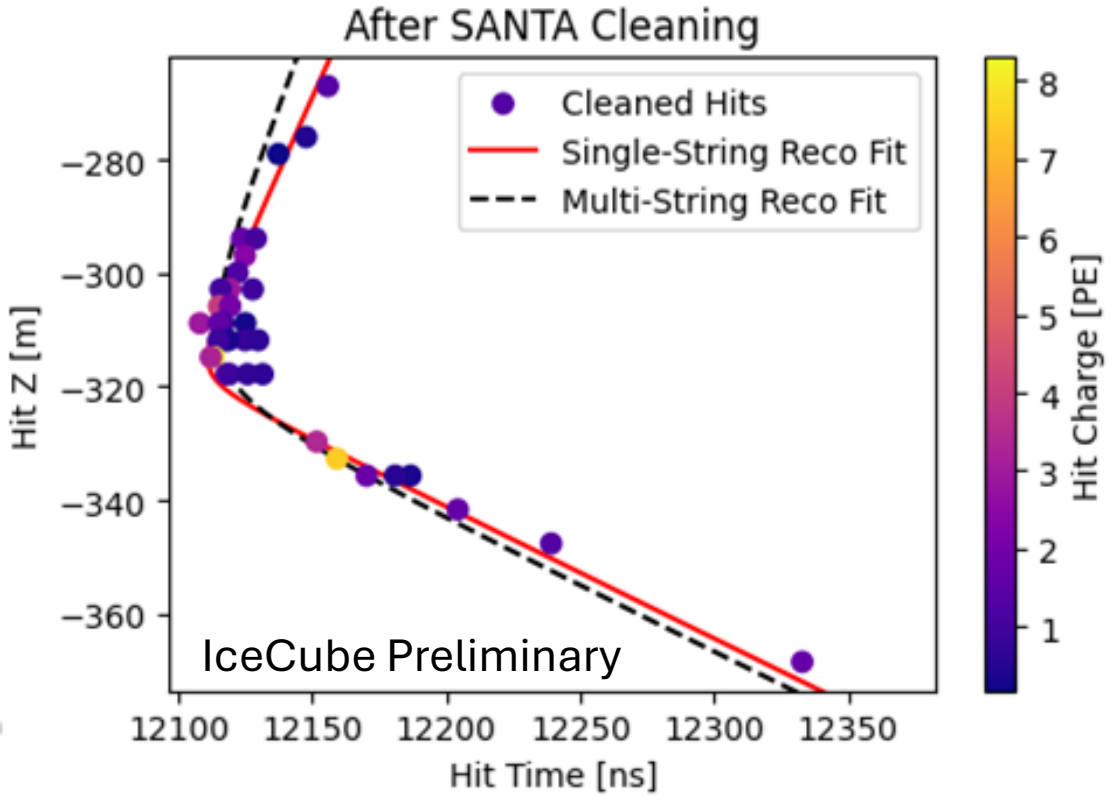
Muons in the upgrade





Muons in the upgrade



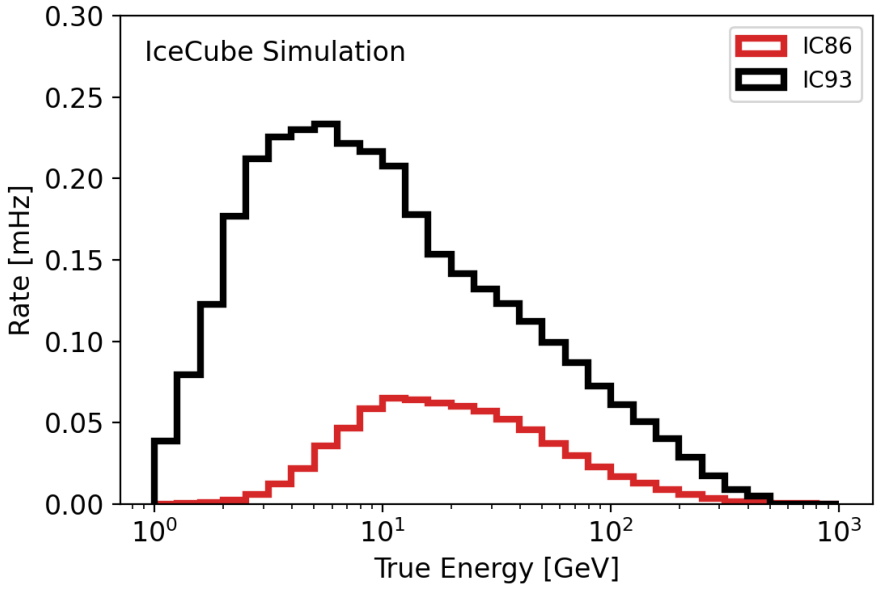


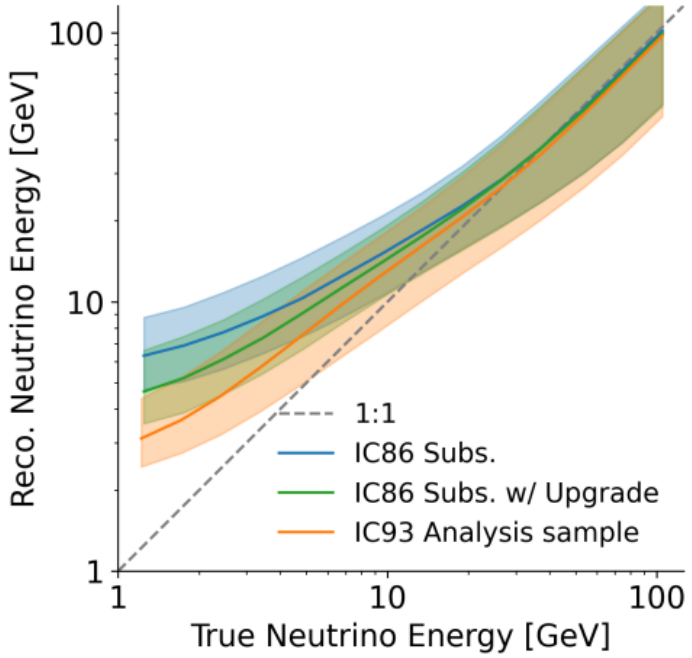
Expected impact of upgrade data

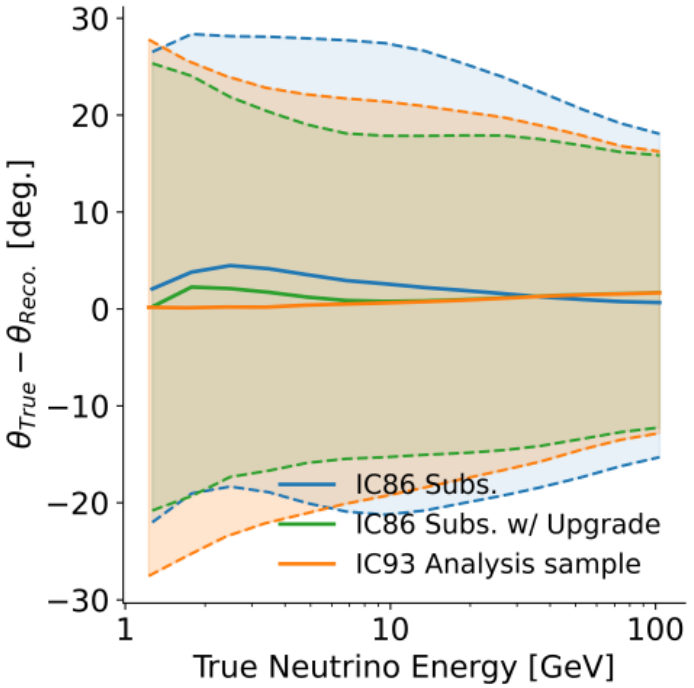
After 3-5 years of operation

Expected response

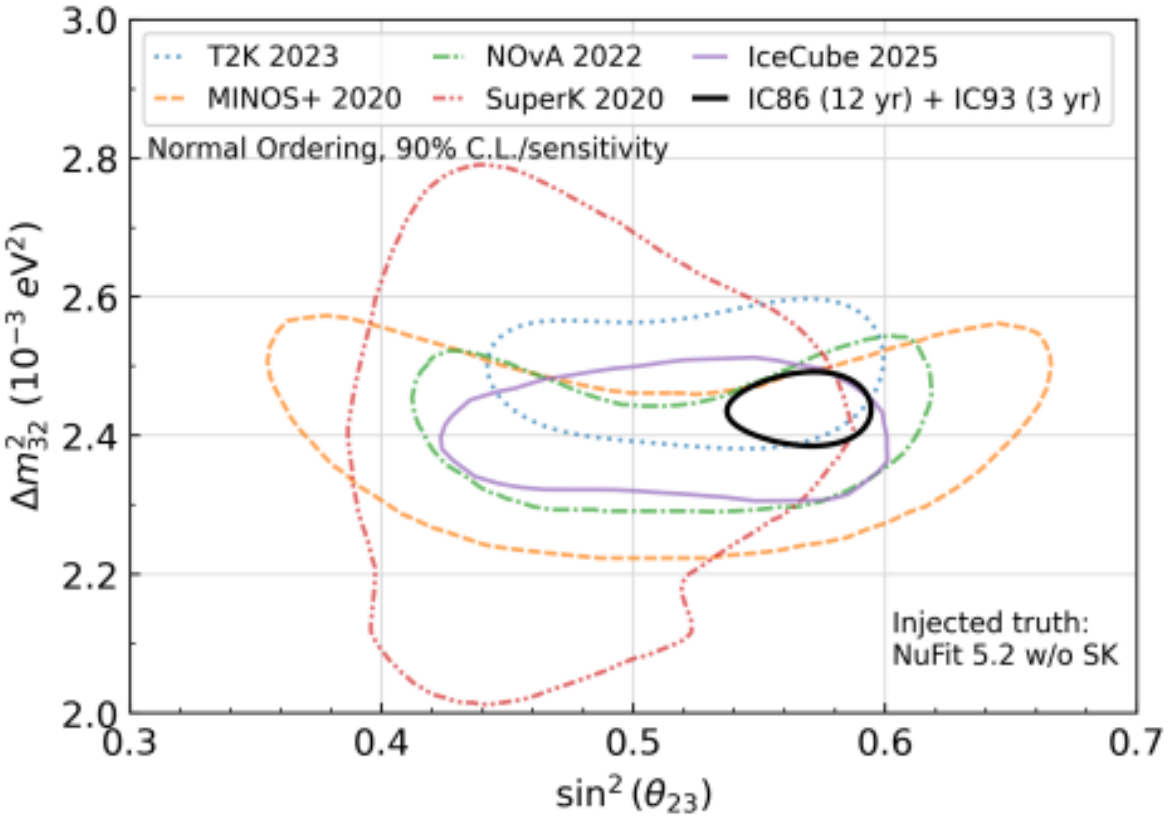
- More low energy events & better reconstructions

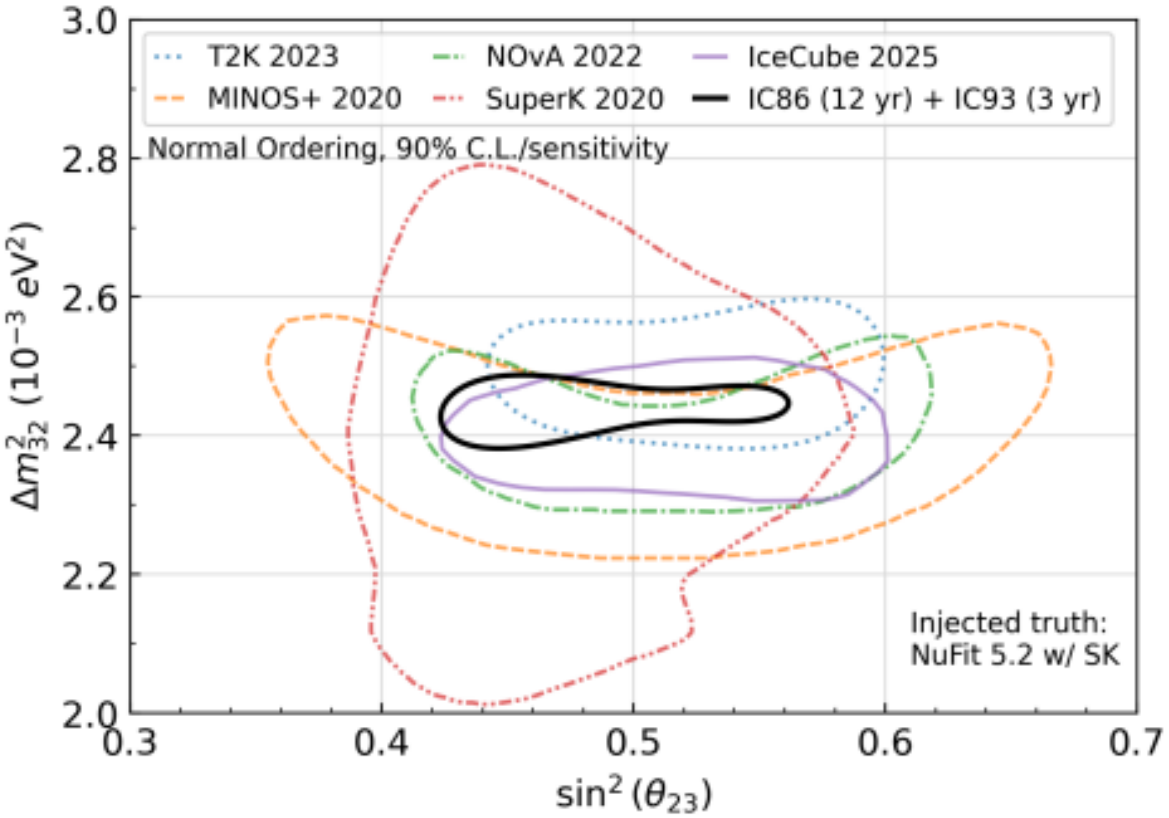






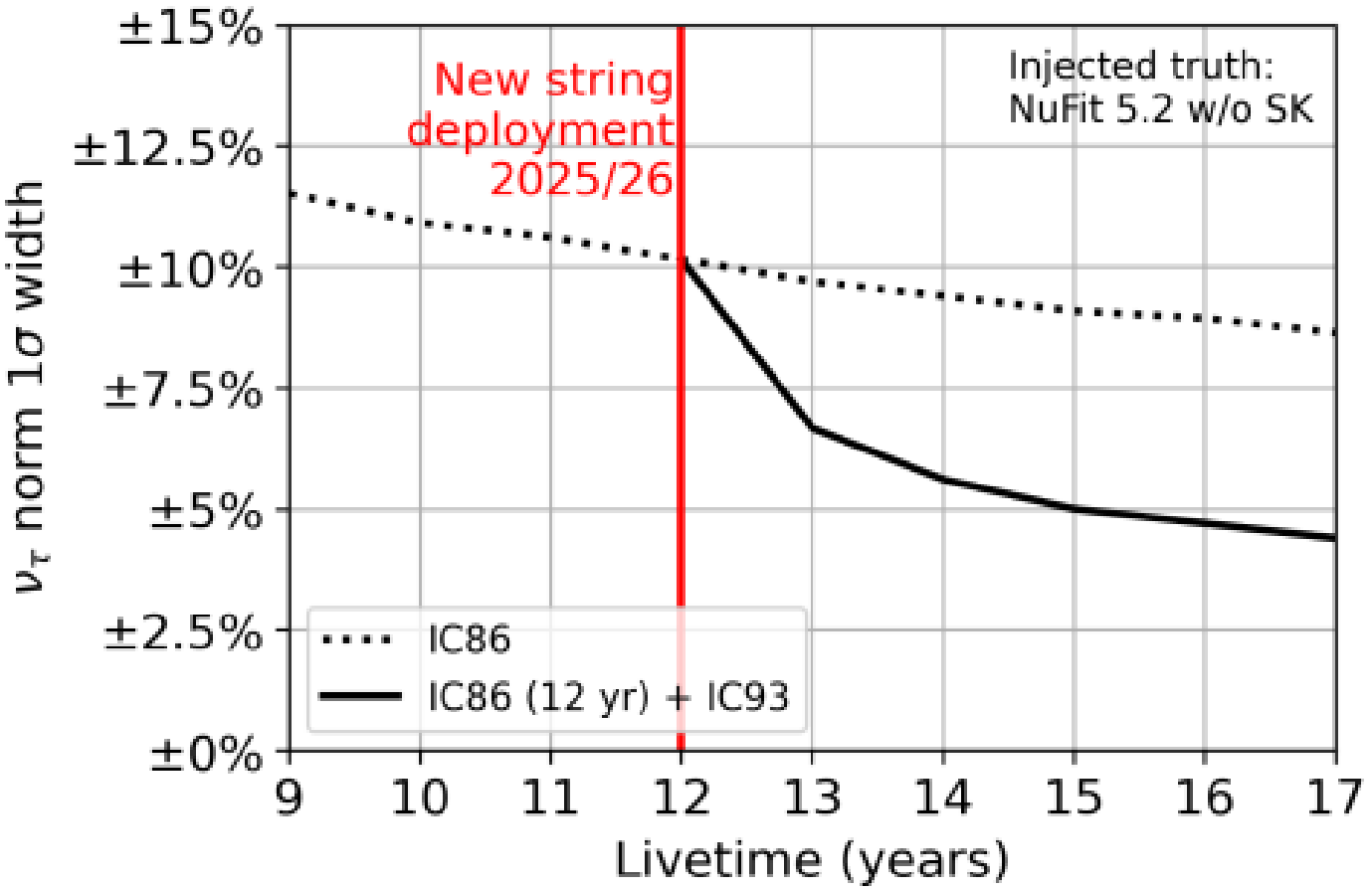
Projections: standard oscillations





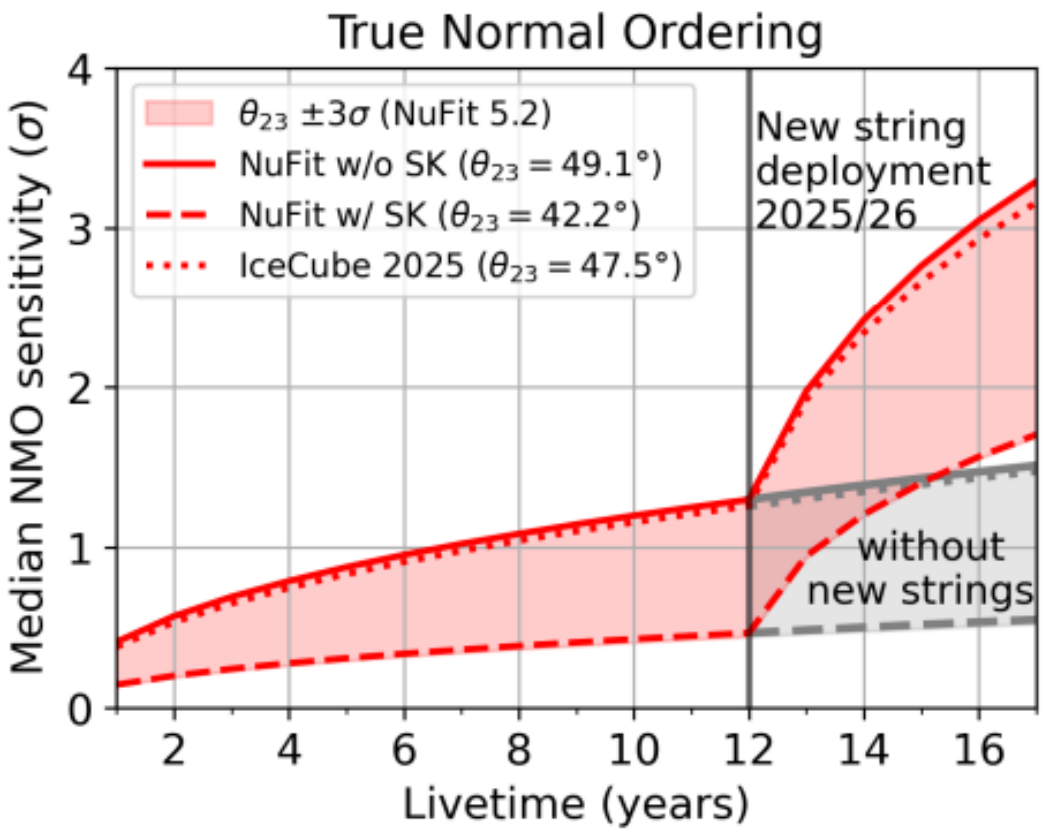
PRD 113 072009 (arXiv:2509.13066)

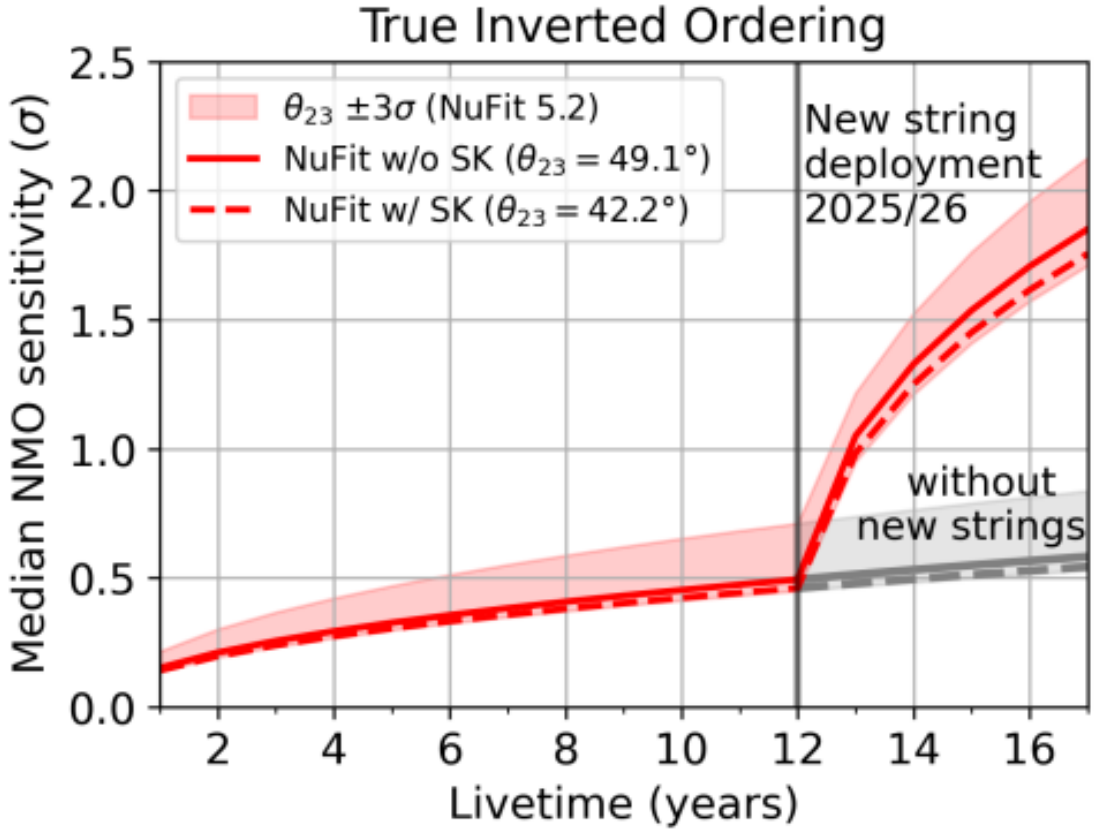
Projections: ν_τ appearance



PRD 113 072009 (arXiv:2509.13066)

Projections: Neutrino Mass Ordering

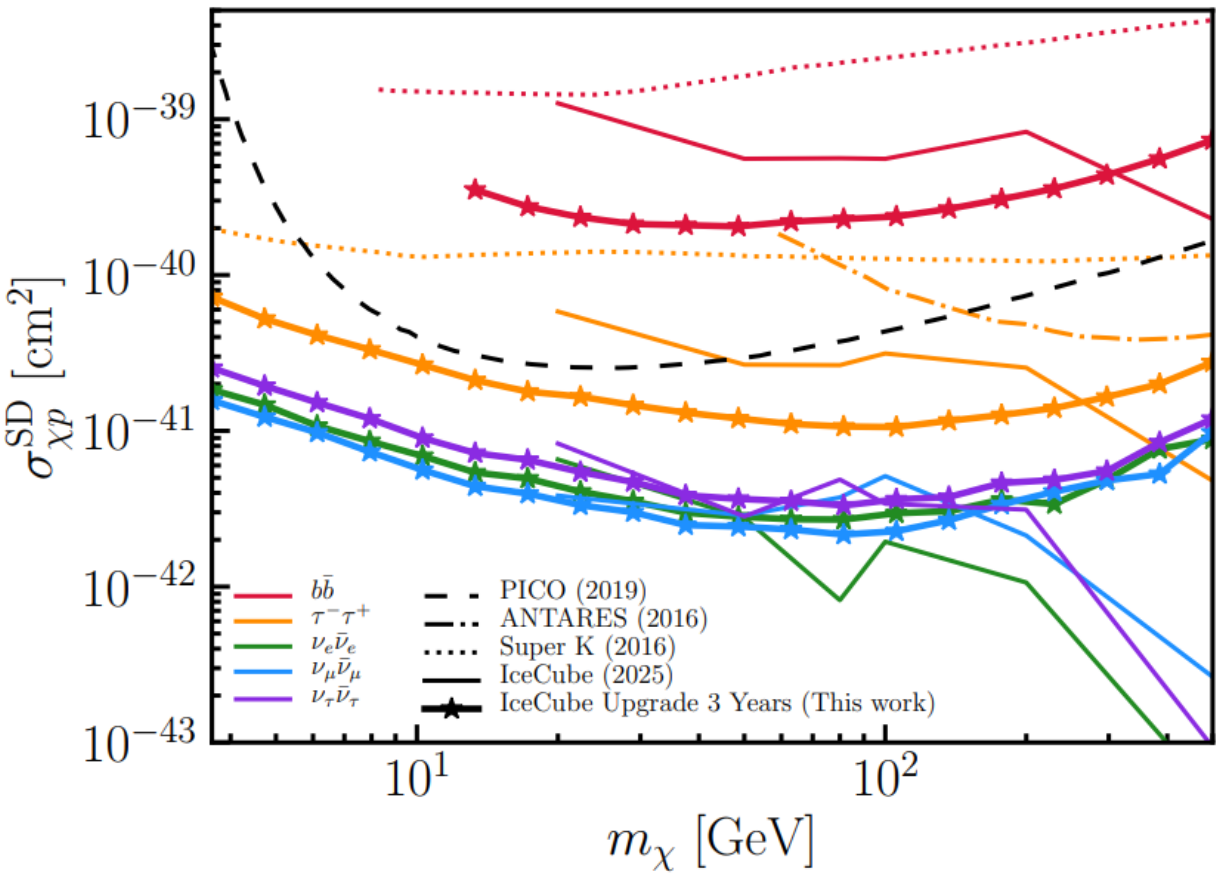




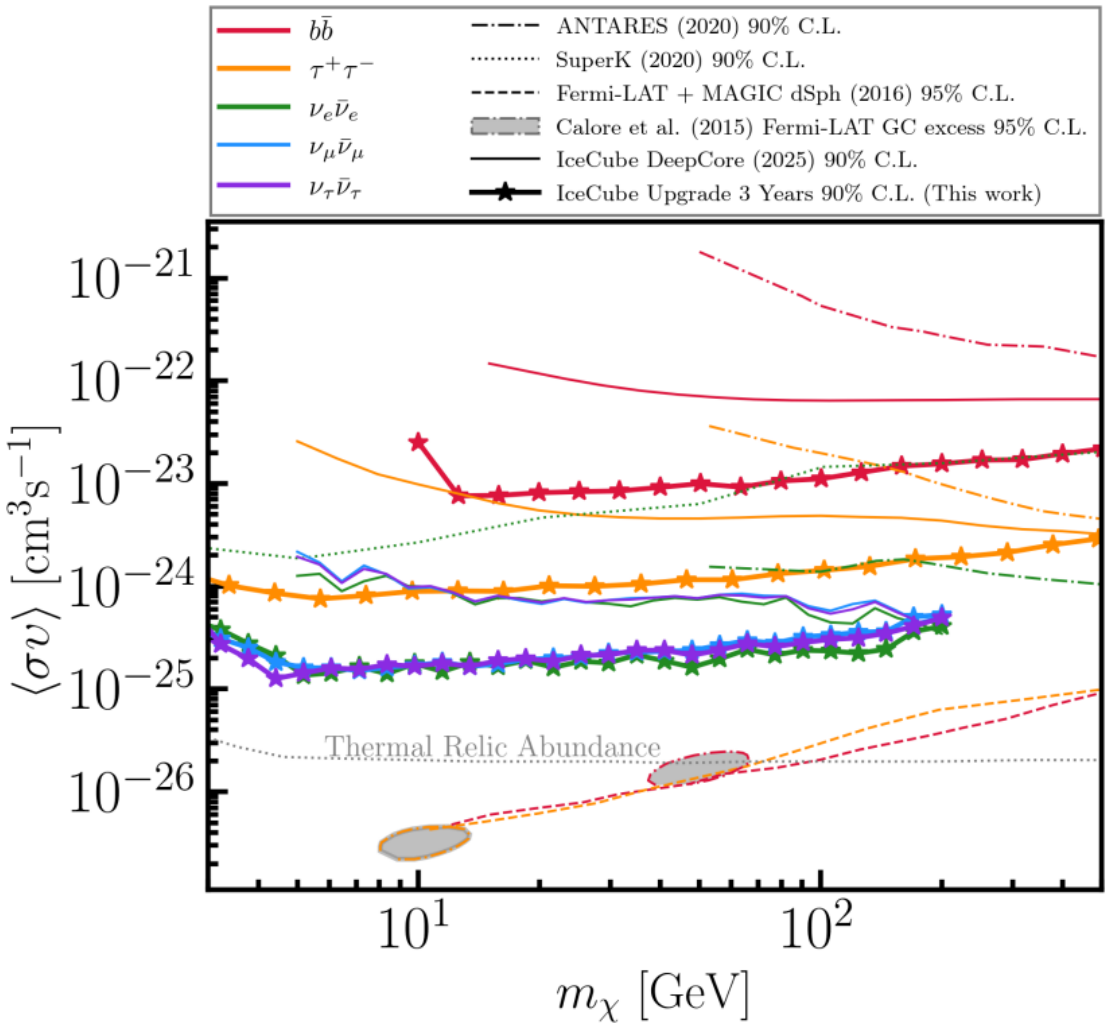
PRD 113 072009 (arXiv:2509.13066)

Projections: Dark Matter

The Sun



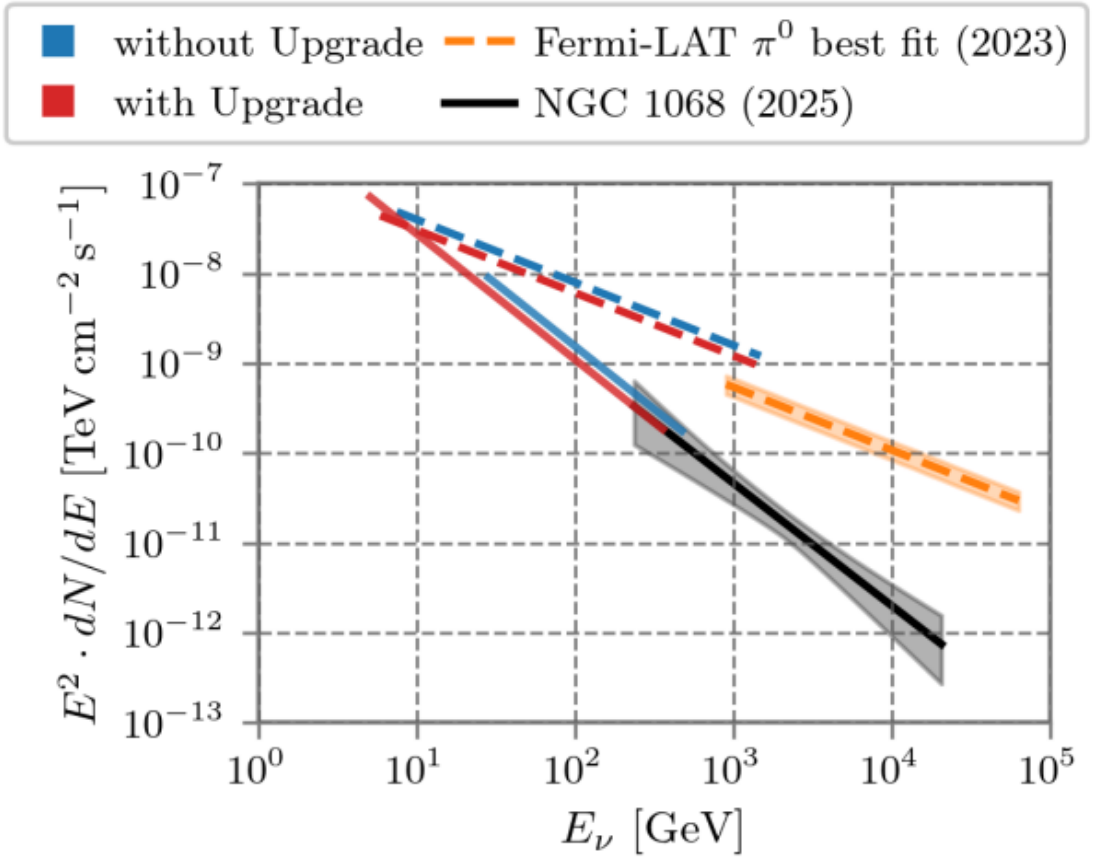
Galactic Center



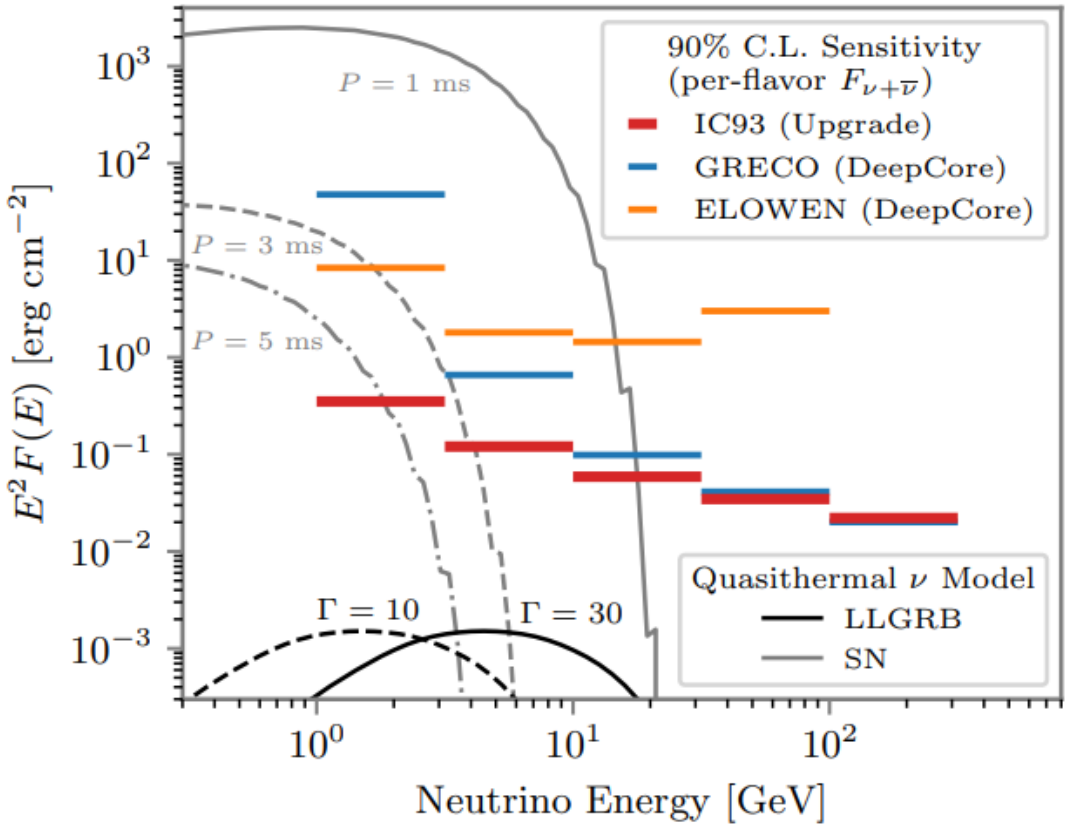
arXiv:2605.06600 **[hep-ex]**

Projections: Neutrino Sources

NGC 1068 & Galactic Plane – steady sources



Sensitivity to transients T=1000s

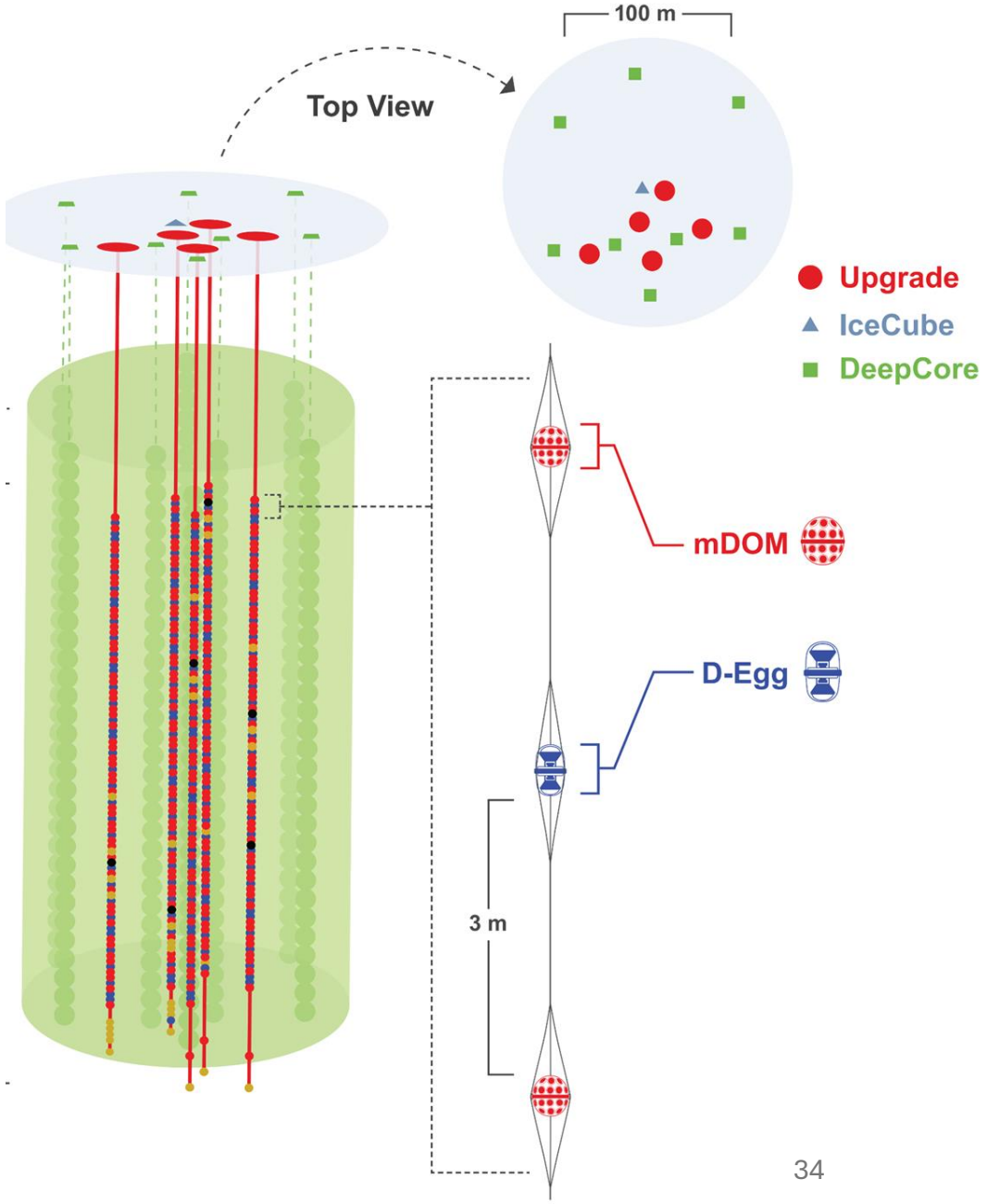


arXiv:2608.28395 **[astro-ph.HE]**

Summary & Outlook

- IceCube has received an **upgrade**
  - 5 strings
  - **505 new sensors**
  - 64 special / calibration devices
  - Integration with IceCube DAQ ongoing

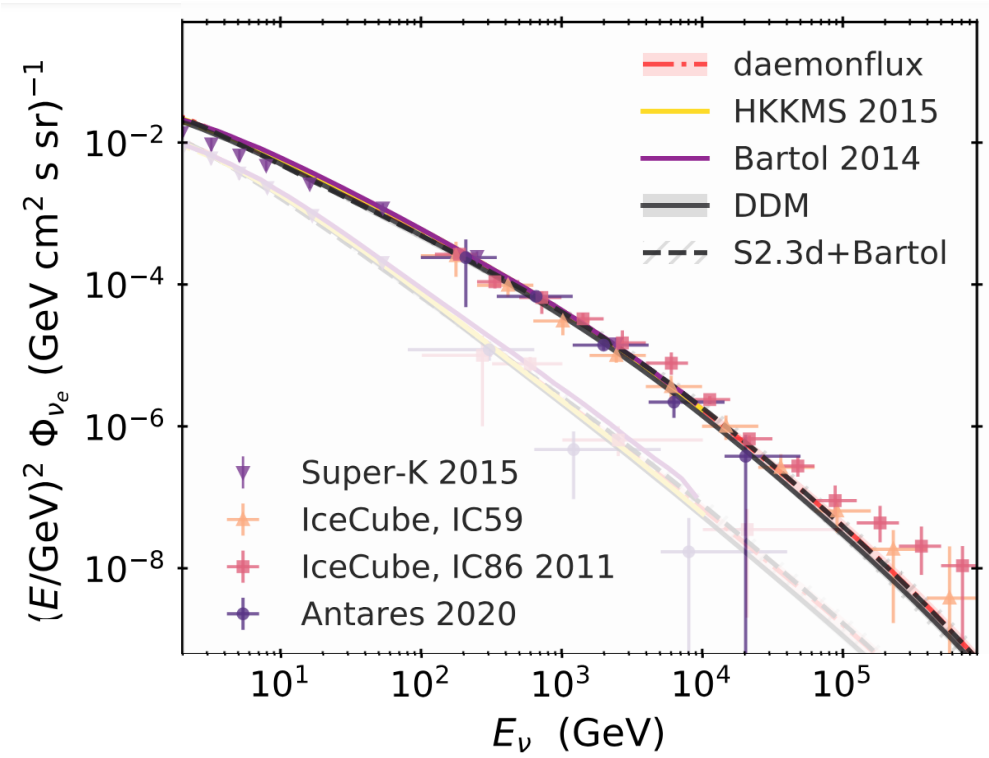
- **Publications** on physics potential
  - Neutrino oscillations: PRD 113 072009 (arXiv:2509.13066)
  - Dark matter: arXiv:2605.06600
  - Neutrino astronomy: arXiv:2608.28395




TWR1

Additional material

Atmospheric ν studies



- Most flux from decay of $\pi^{\pm}$ and $K^{\pm}$
  - Beam of ν_e, ν_μ (+ antineutrinos)
- Event information: energy *E* & direction *L*
  - Well suited to measure ν oscillations

NMO combining datasets

Phys. Rev. D **101**, 032006

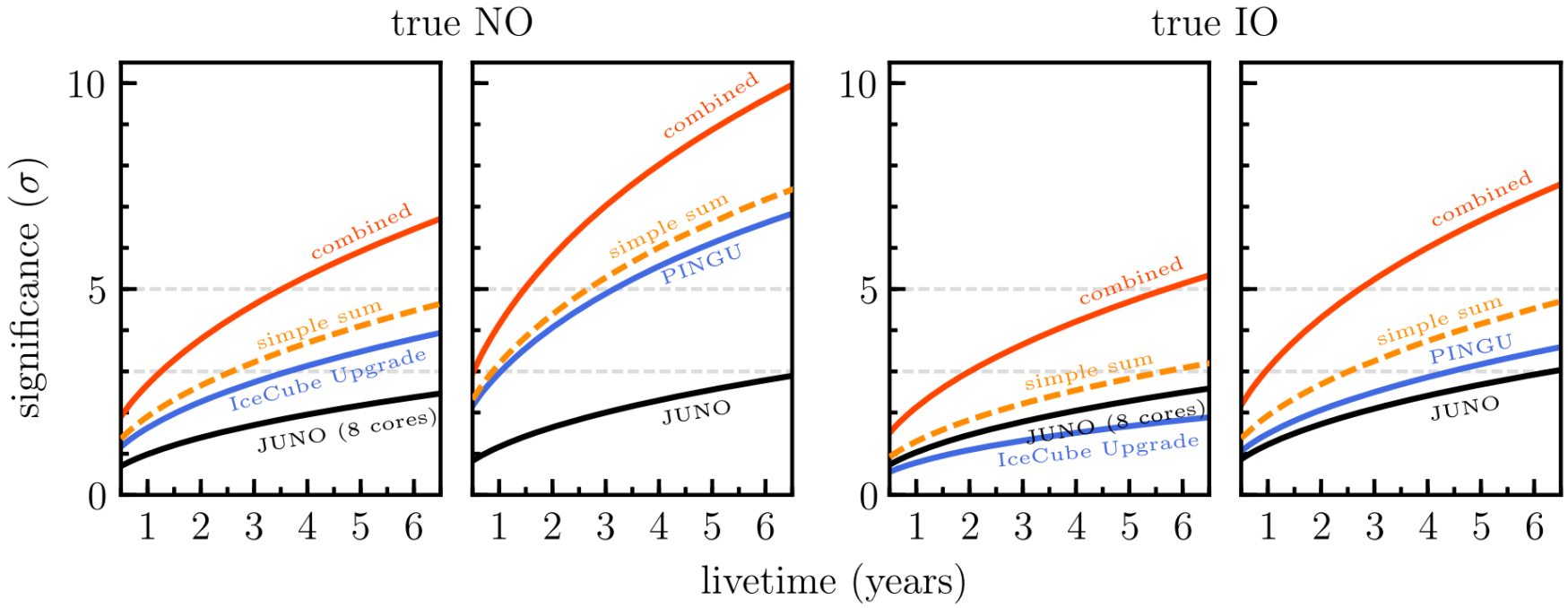


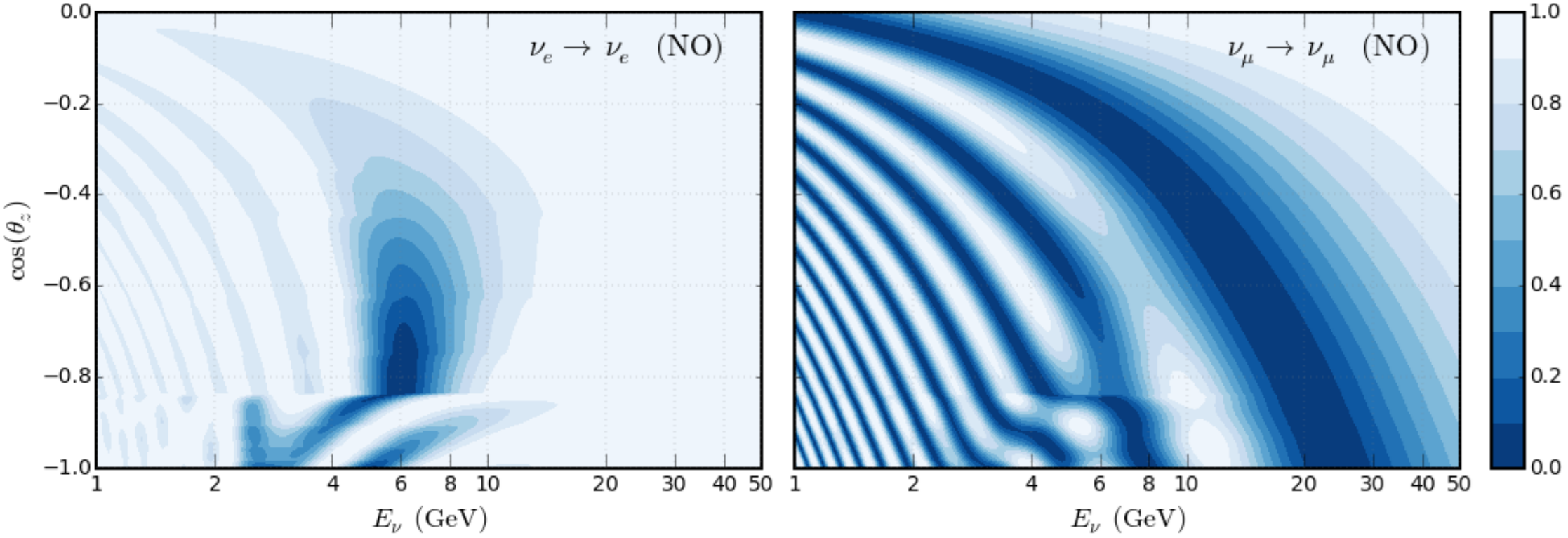
FIG. 6. Livetime evolution of the NMO sensitivity of each considered pair of experiments: stand-alone, the simple (quadratic) sum, and the combination. Results for the nominal JUNO configuration and PINGU are shown side-by-side with the 8-core JUNO configuration (labeled as "JUNO (8 cores)") and the IceCube Upgrade. The two panels on the left assume true NO, while the two panels on the right assume true IO.

Atmospheric ν studies: oscillations

- Well suited for measuring flavor transitions from oscillations

$$P\nu_\mu \to \nu_\mu \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

arXiv:1509.08404 [hep-ex]



Atmospheric ν studies: oscillations

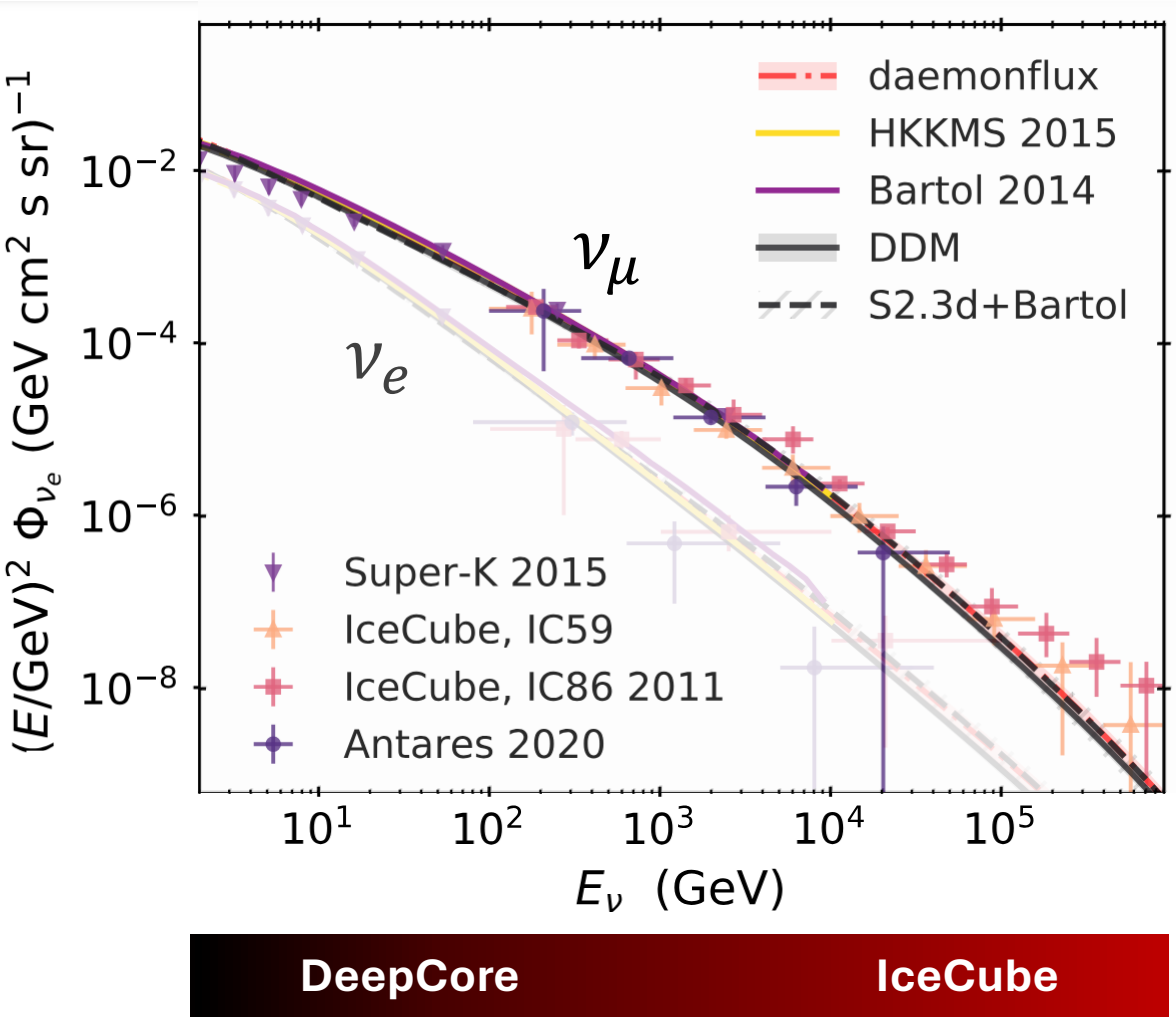
- Well suited for measuring flavor transitions from oscillations

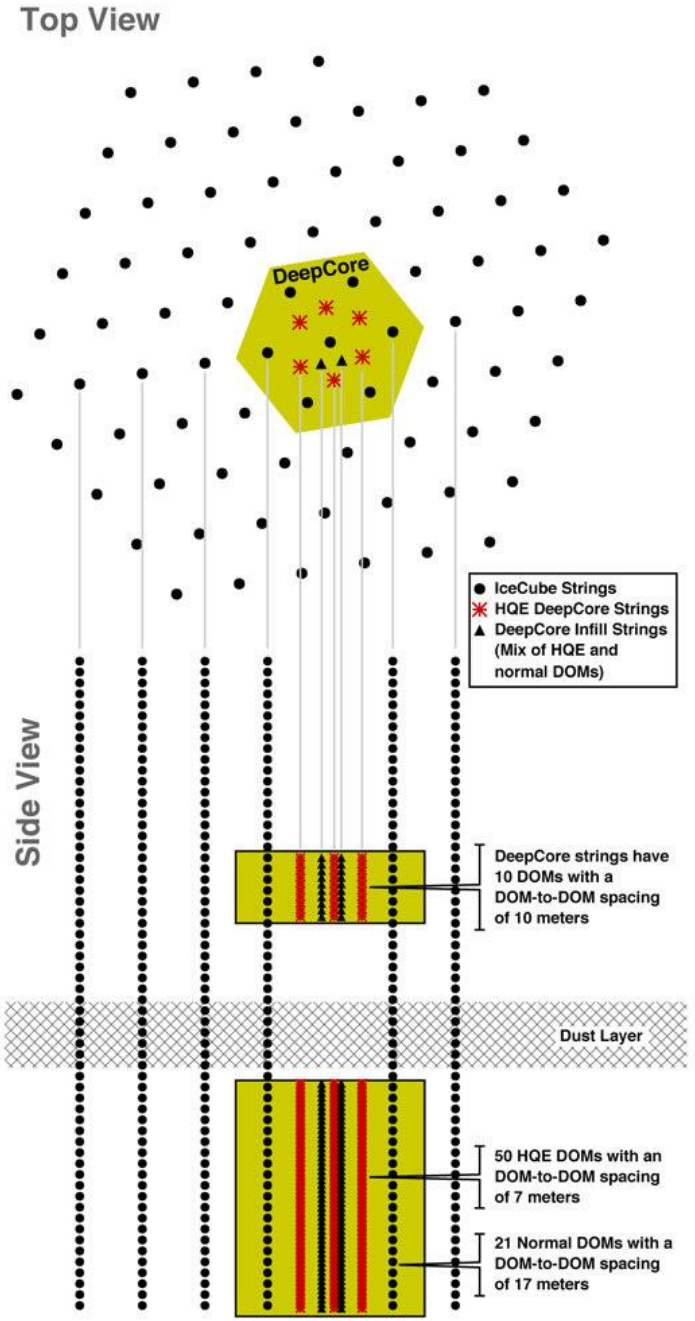
$$P\nu_\mu \rightarrow \nu_\mu \simeq 1 - \sin^2 2\theta_{23} \ \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

- Can measure appearance channel simultaneously

- Deviations from 3-flavor mixing are sensitive to BSM models
  - Sterile neutrinos, non-standard interactions, ν decoherence

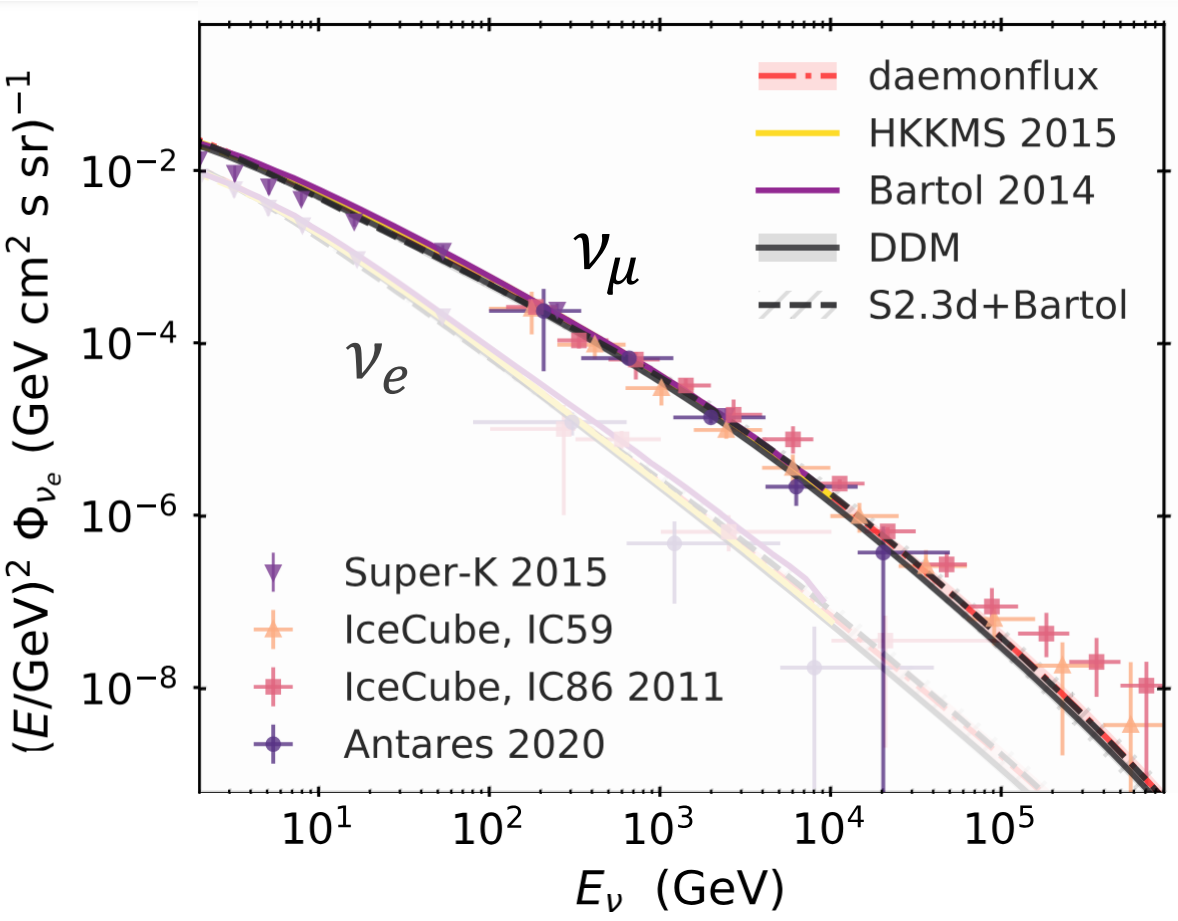
Atmospheric neutrino data





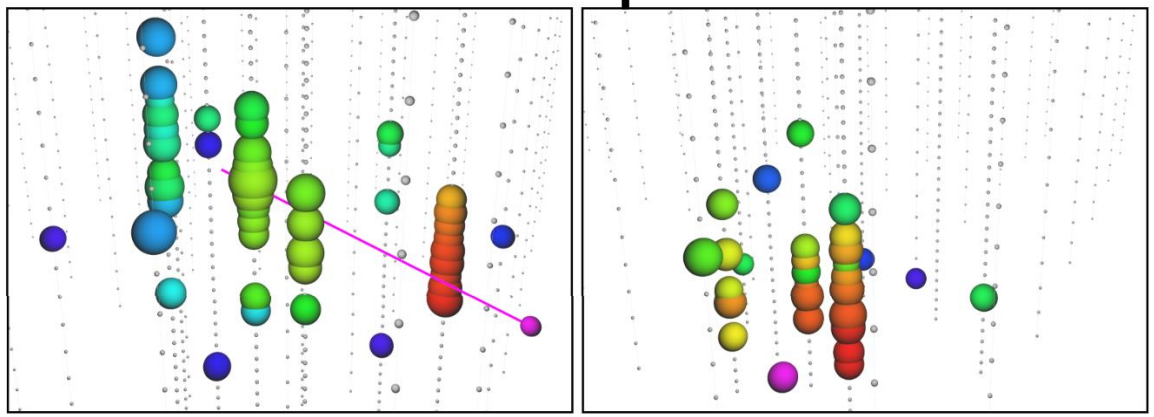
Color indicates time (red=early, blue=late). Sphere size is proportional to number of photons observed.

Atmospheric neutrino data



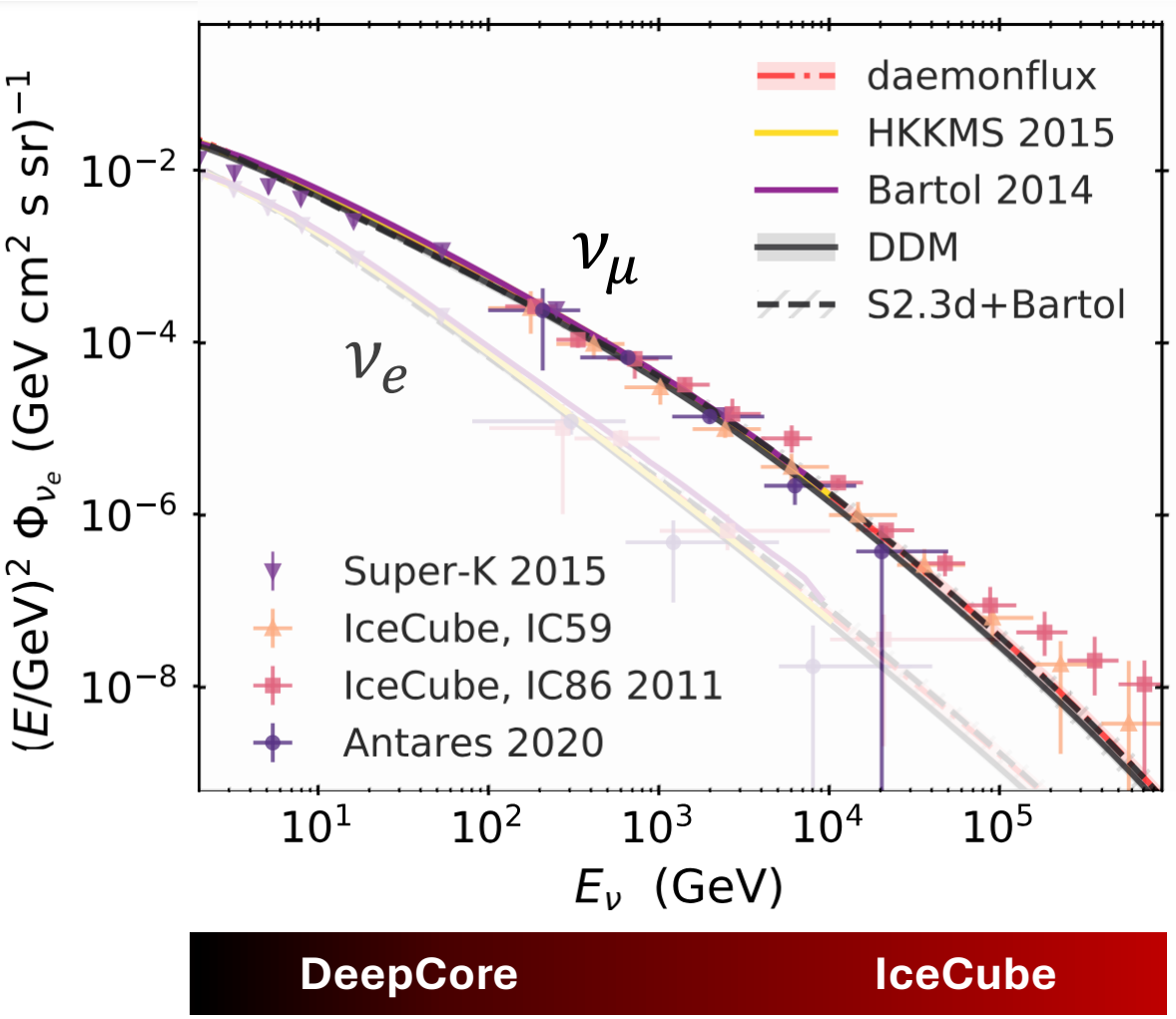
DeepCore **IceCube**

GeV events in DeepCore for ν oscillations

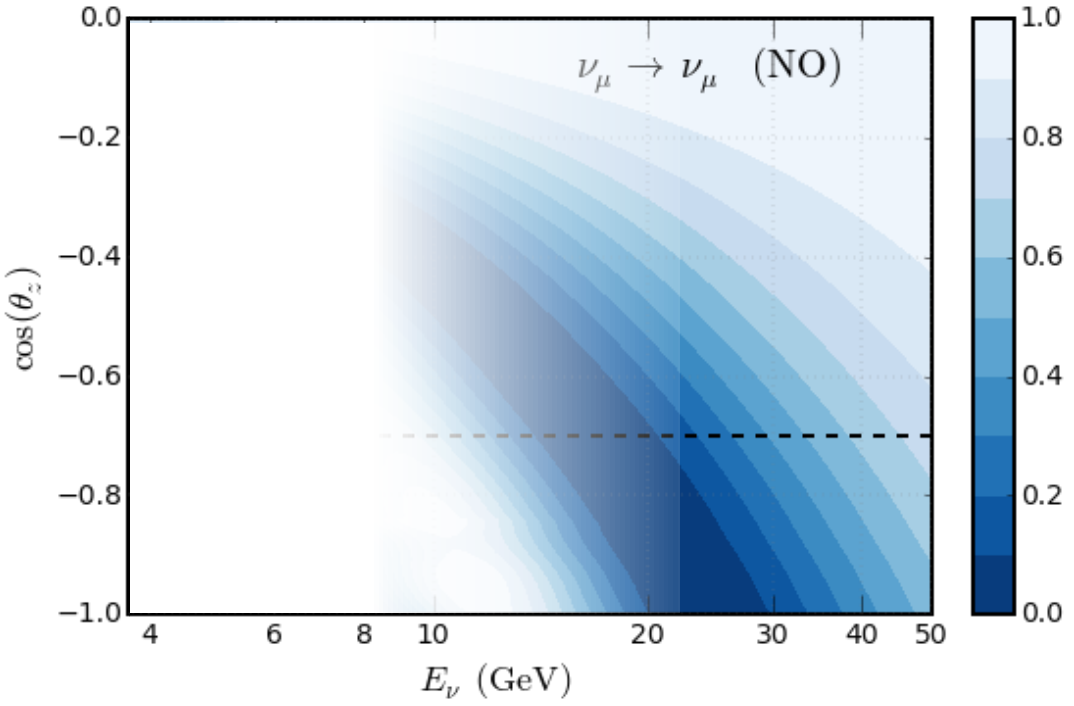


Color indicates time (red=early, blue=late). Sphere size is proportional to number of photons observed.

Atmospheric neutrino data

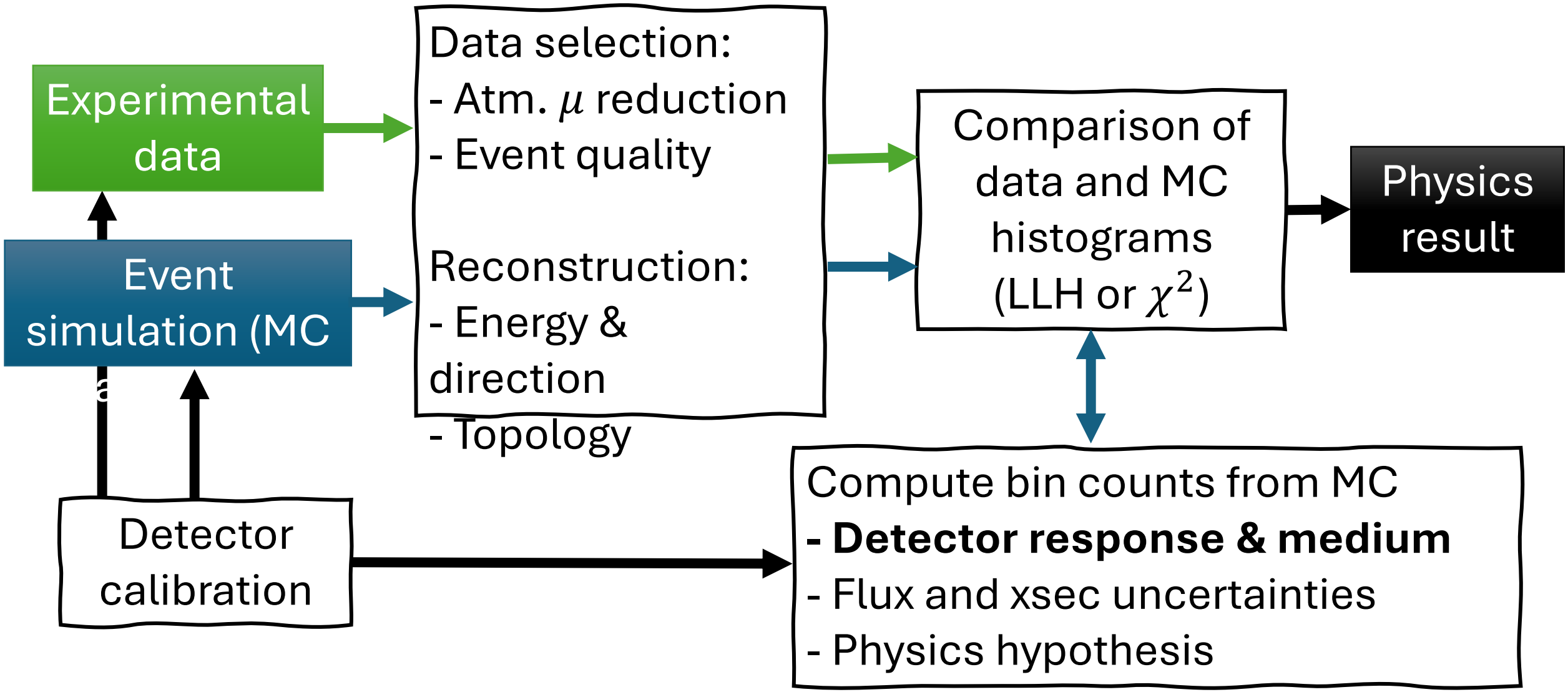


$$P\nu_\mu \to \nu_\mu \simeq 1 - \sin^2 2\theta_{23}\ \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$



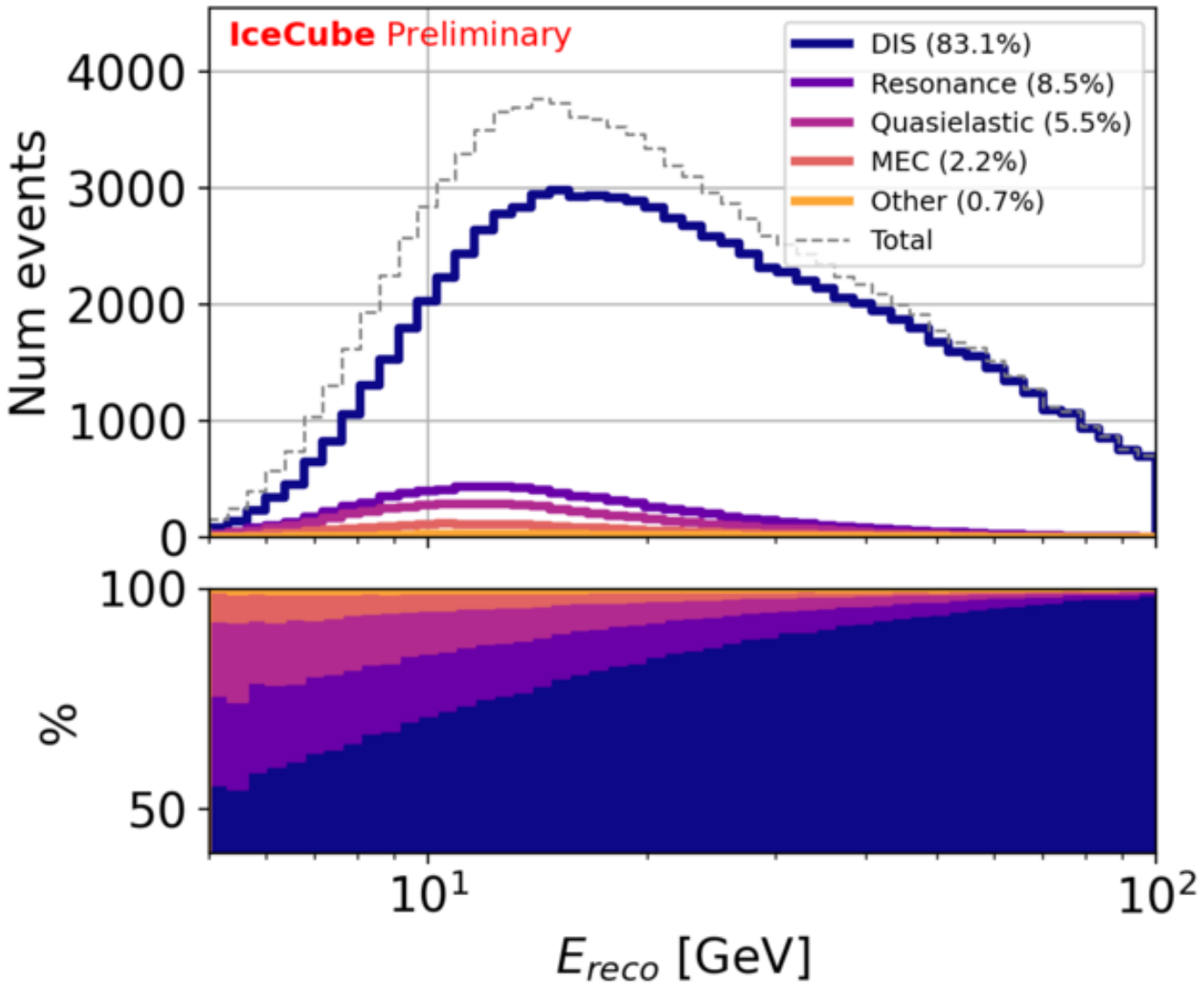
Color indicates time (red=early, blue=late). Sphere size is proportional to number of photons observed.

Analysis **strategy** for oscillations



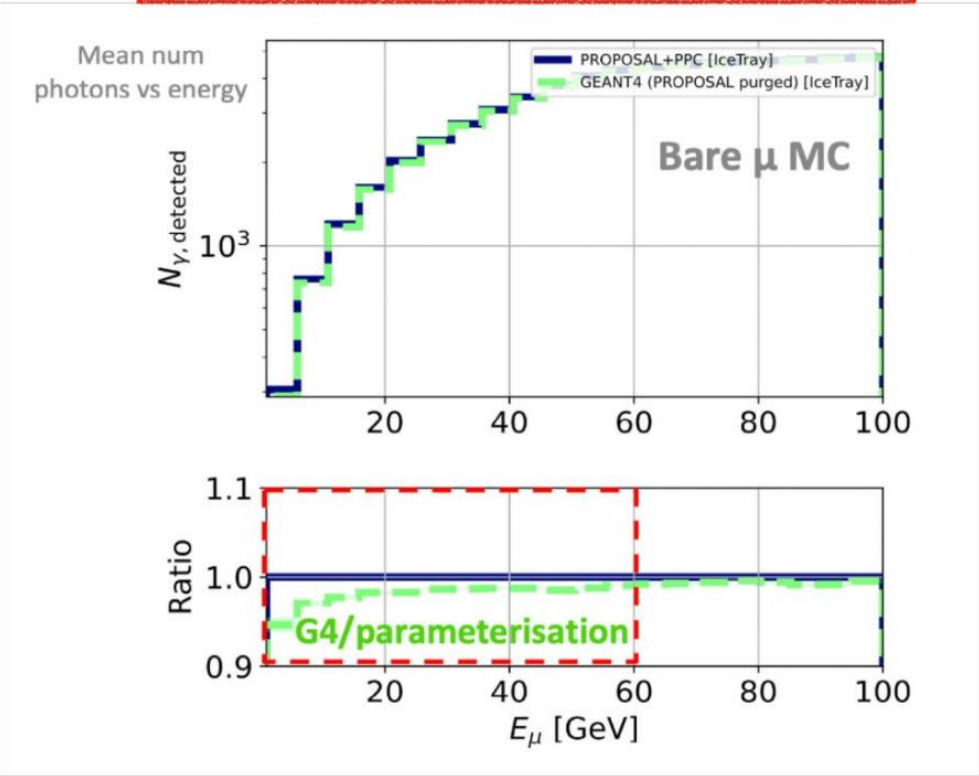
Interaction types

- DeepCore

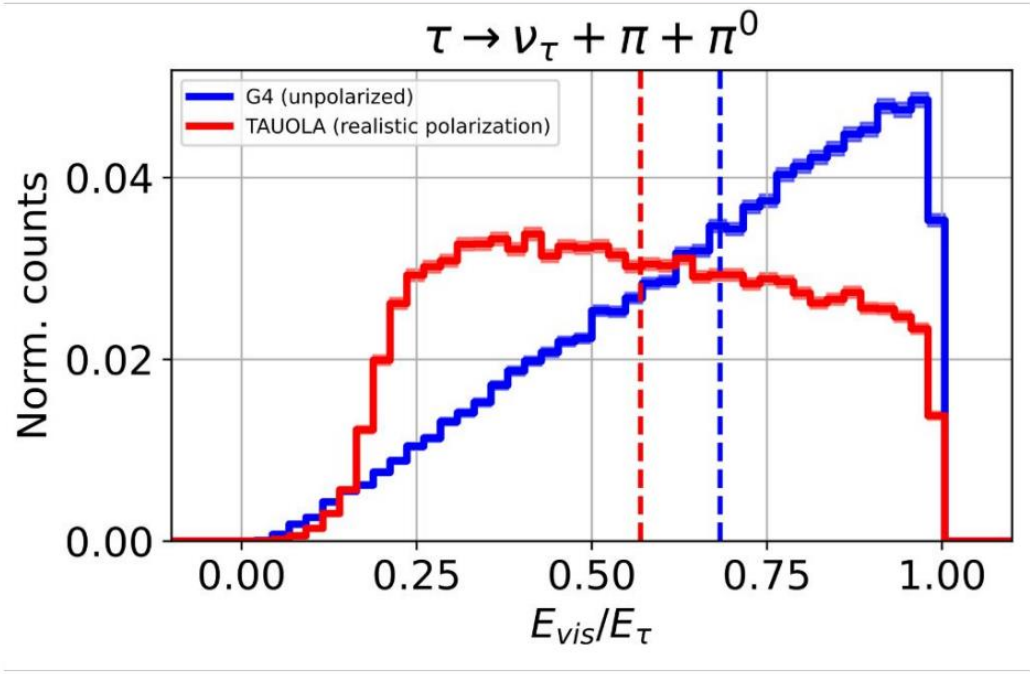


Improvements: simulation

Corrected μ light yield using GEANT4



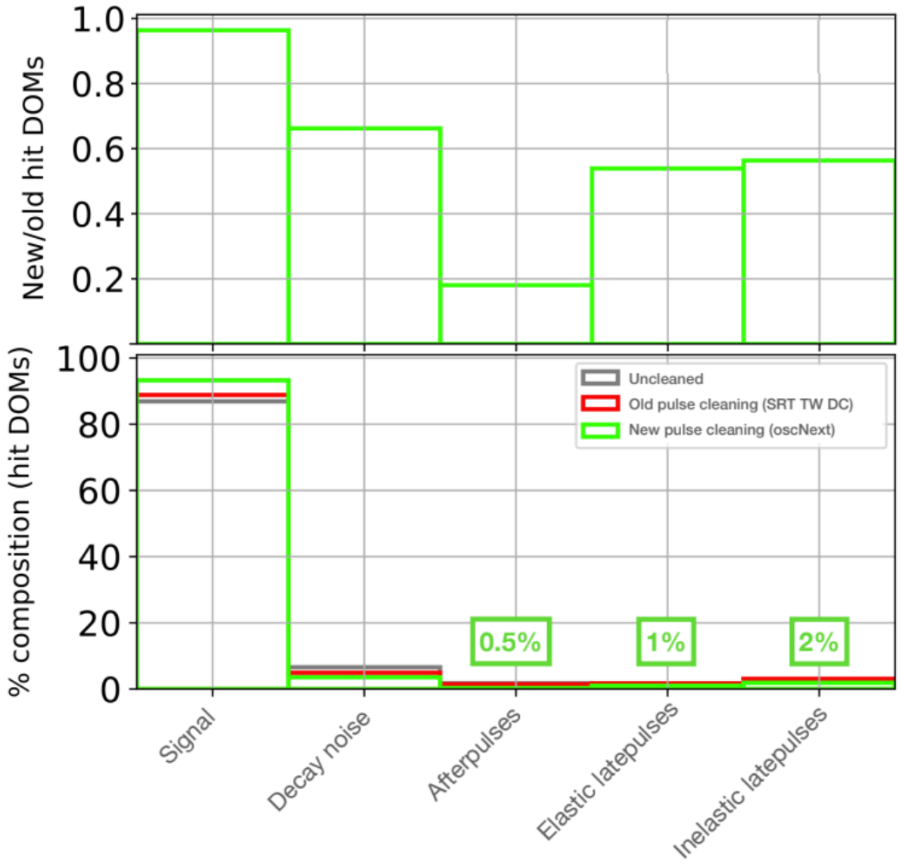
Polarisation & resonances included in τ decays using TAUOLA



$\Longrightarrow$ **$\nu_{\mu,CC}$ and $\nu_{\tau,CC}$ events both dimmer than older MC**

Improvements: analysis

- Revamped noise cleaning
  - Using hit/no-hit only
  - Relying on leading edge time
  - Narrow signal time window
  - Optimized old algorithms
- DynEdge reco (GNN)
  - Faster processing
  - Slightly better resolution
- Tighter quality cuts
  - Containment, nhit, μ rejection



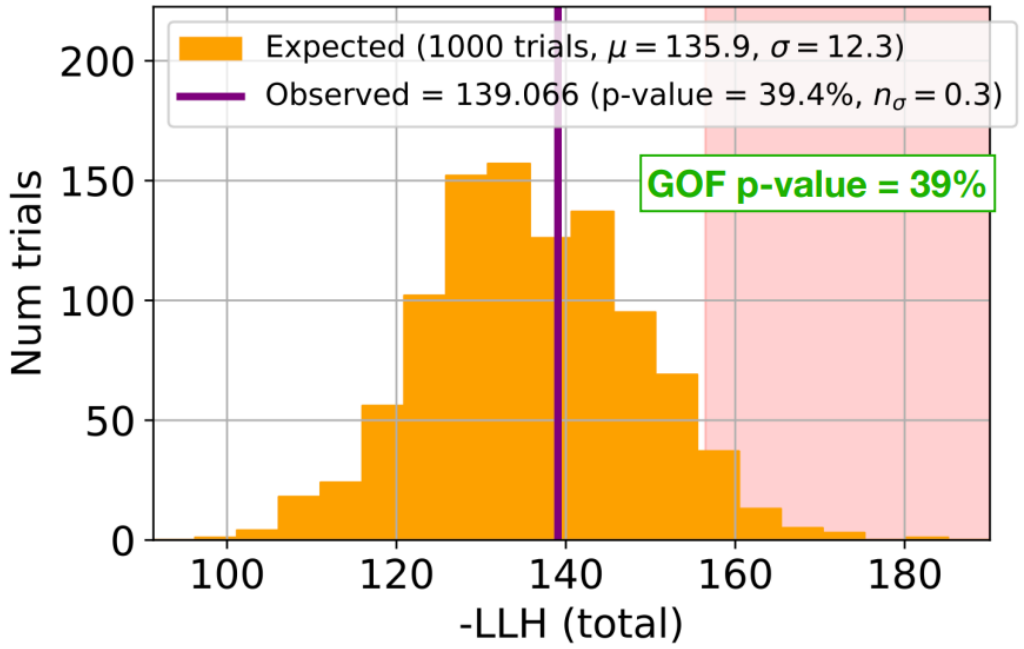
Backgrounds reduced by:

35% (decay noise)

45% (late pulses)

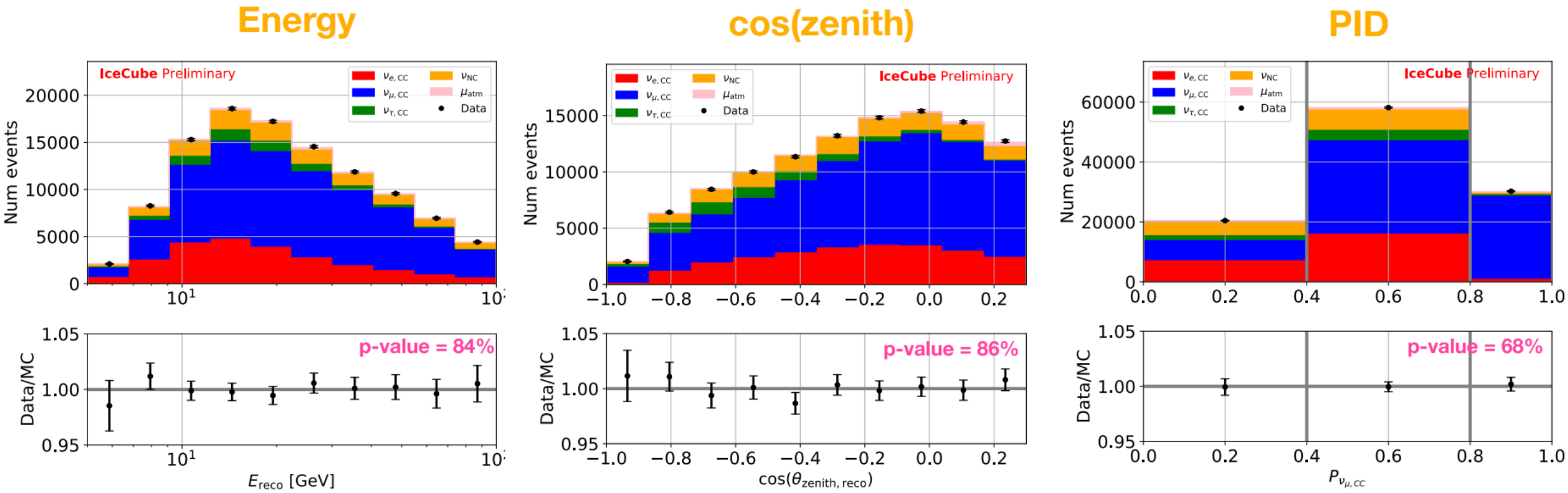
80% (afterpulses)

Results



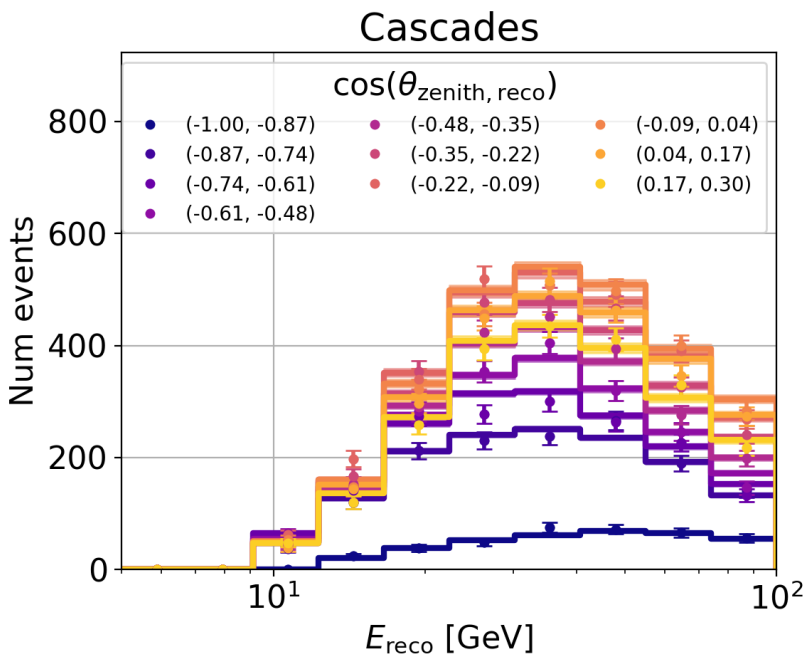
Param	Nominal	Fit	Prior [σ]	Range
Flux $\Delta\gamma$	0	-0.00178	0.1	-0.5, 0.5
Flux π^+ G	0	-0.231	0.3	-1.5, 1.5
Flux π^+ H	0	-0.195	0.15	-0.75, 0.75
Flux π^+ I	0	-0.0694	0.122	-0.61, 0.61
Flux K^+ W	0	0.223	0.4	-2, 2
Flux K^+ Y	0	0.395	0.3	-1.5, 1.5
$\sin^2(\theta_{23})$	0.544	0.516	-	0.117, 0.883
Δm^2_{32} [eV^2]	0.0024	0.00244	-	0.00143, 0.00343
$M_{A,QE}$	0	-0.336	1	-2, 2
$M_{A,res}$	0	-0.568	1	-2, 2
$\mathrm{DIS_{tot}}$	0	0.602	1	-3, 3
$\mathrm{DIS_{diff}}$	0	0.127	1	-3, 3
N_ν	1	0.98	-	0.1, 2
DOM efficiency	1	1.04	-	0.9, 1.1
Hole ice, $\mathrm{p_0}$	0.1	-0.218	-	-0.3, 0.5
Hole ice, $\mathrm{p_1}$	-0.05	-0.0321	-	-0.125, 0.025
Dust absorption	1	0.97	-	0.913, 1.09
Ice absorption	1	0.87	-	0.72, 1.28
Ice scattering	1.05	1.03	-	0.963, 1.14
N_μ	1	1.24	0.4	0.1, 3

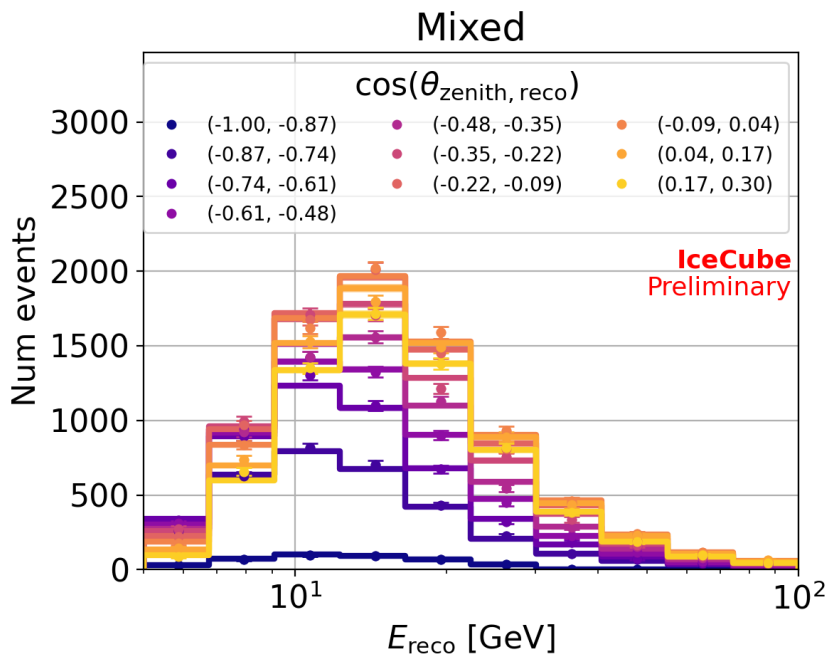
Data/MC agreement post-fit in 1D

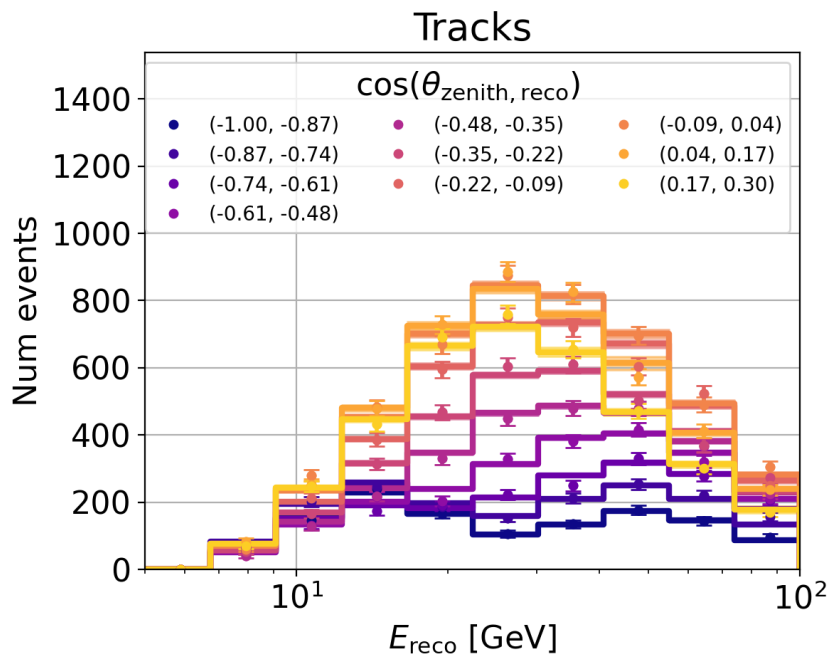


Excellent post-fit data-MC agreement

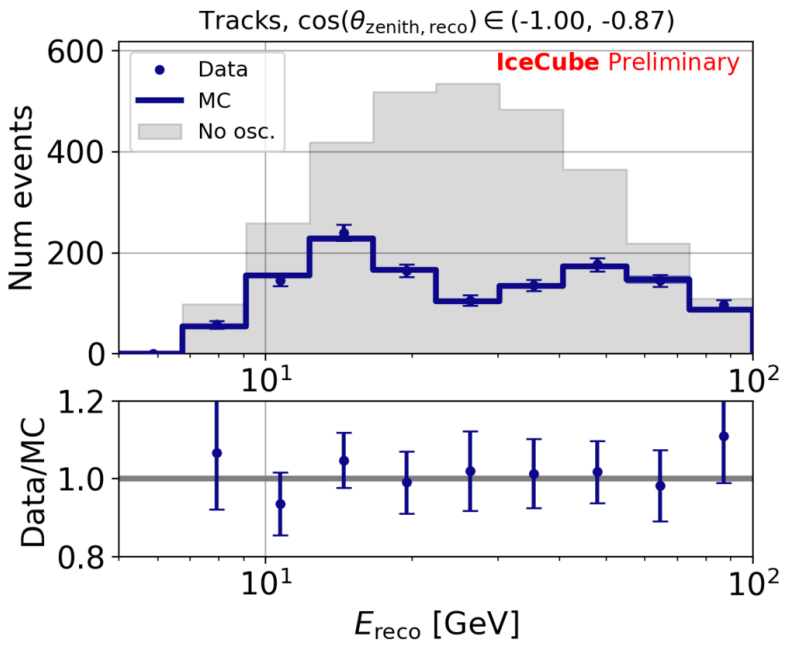
Data/MC in full space

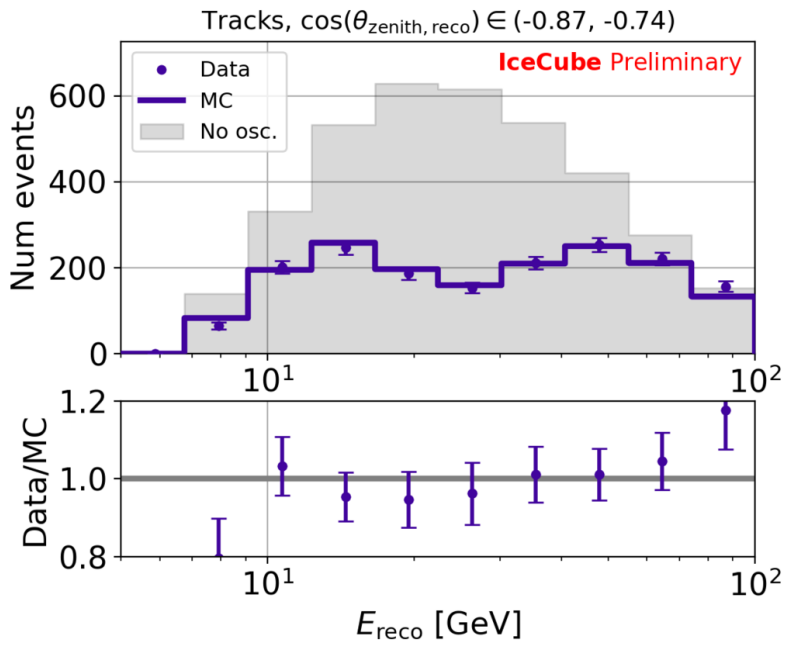


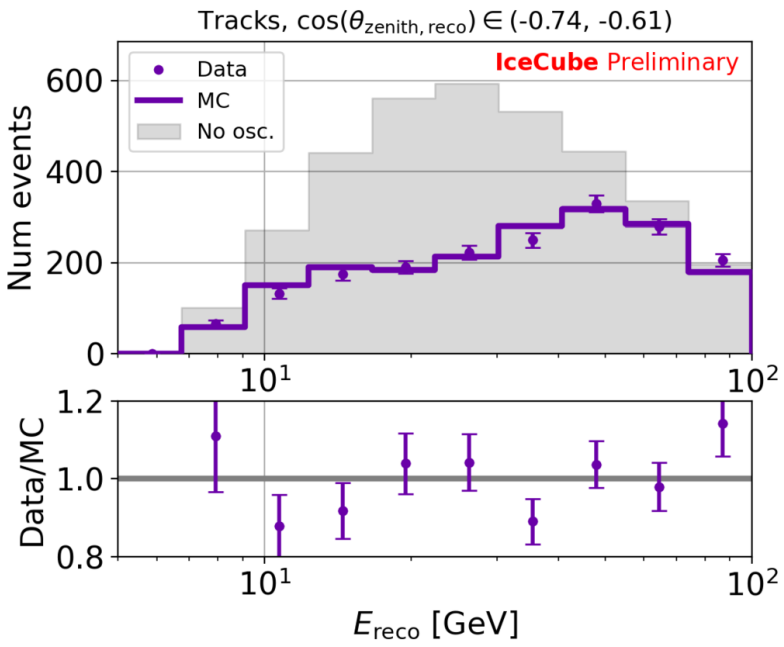




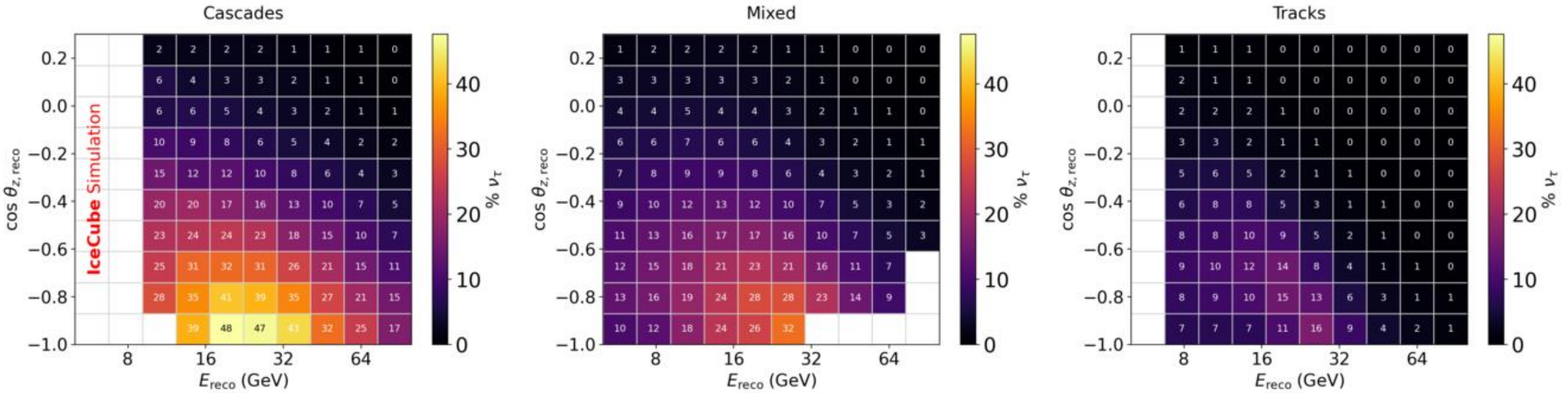
Zoom in: regions with highest signal strength



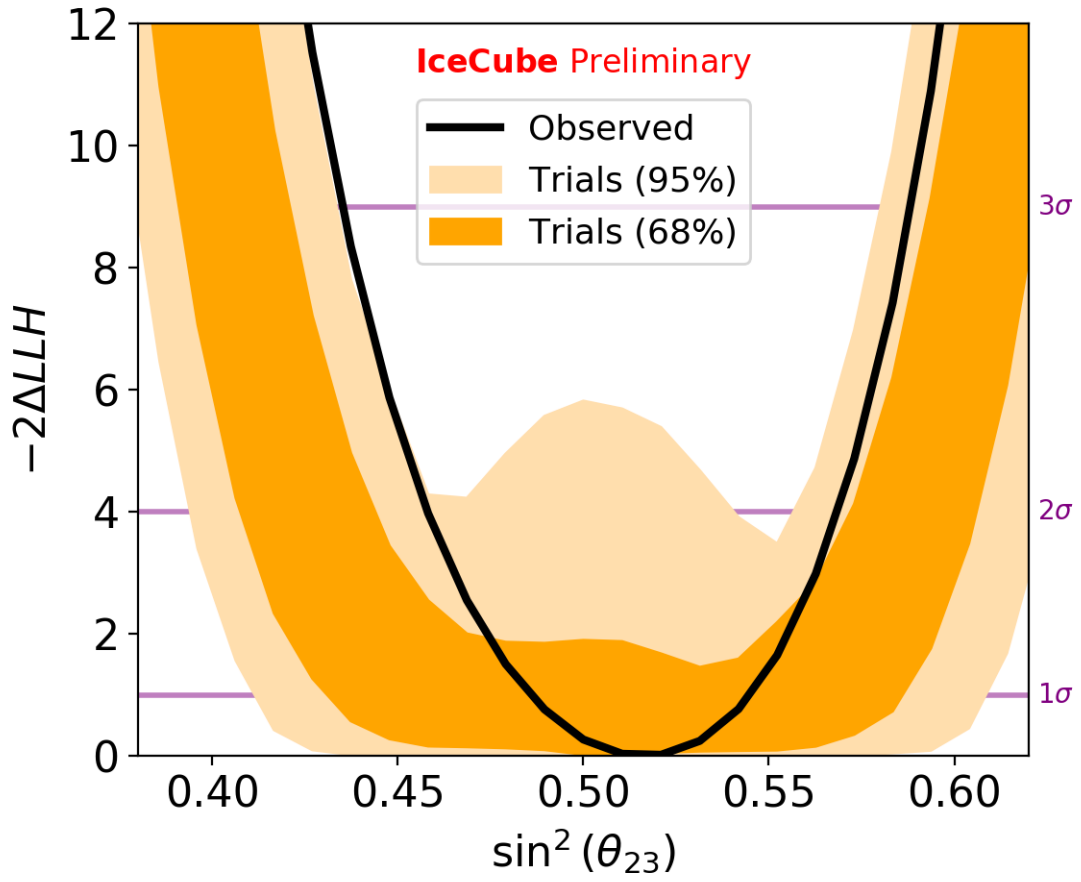


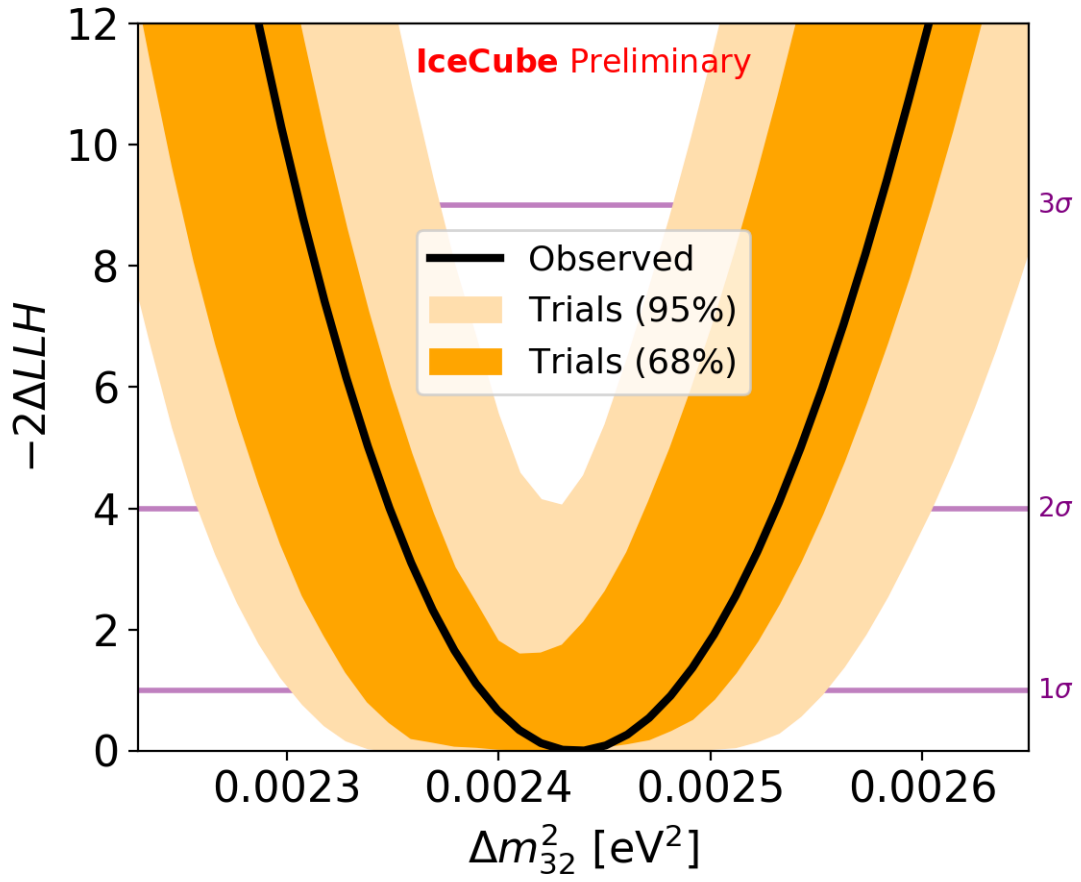


NuTau signal

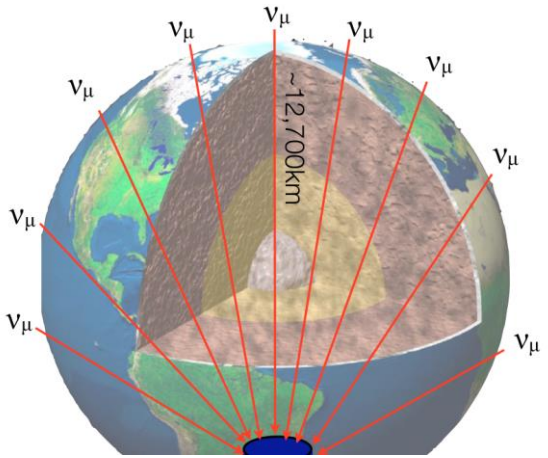


Likelihood profiles

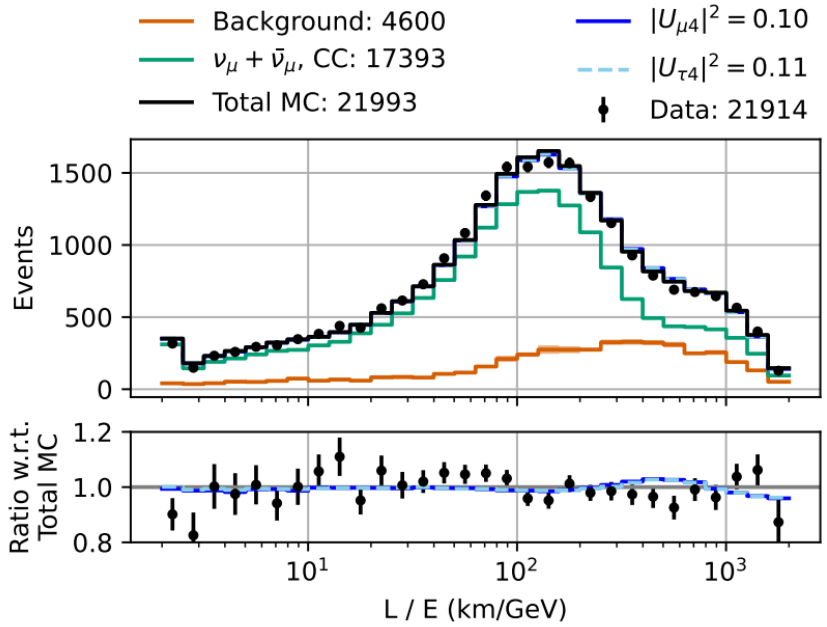


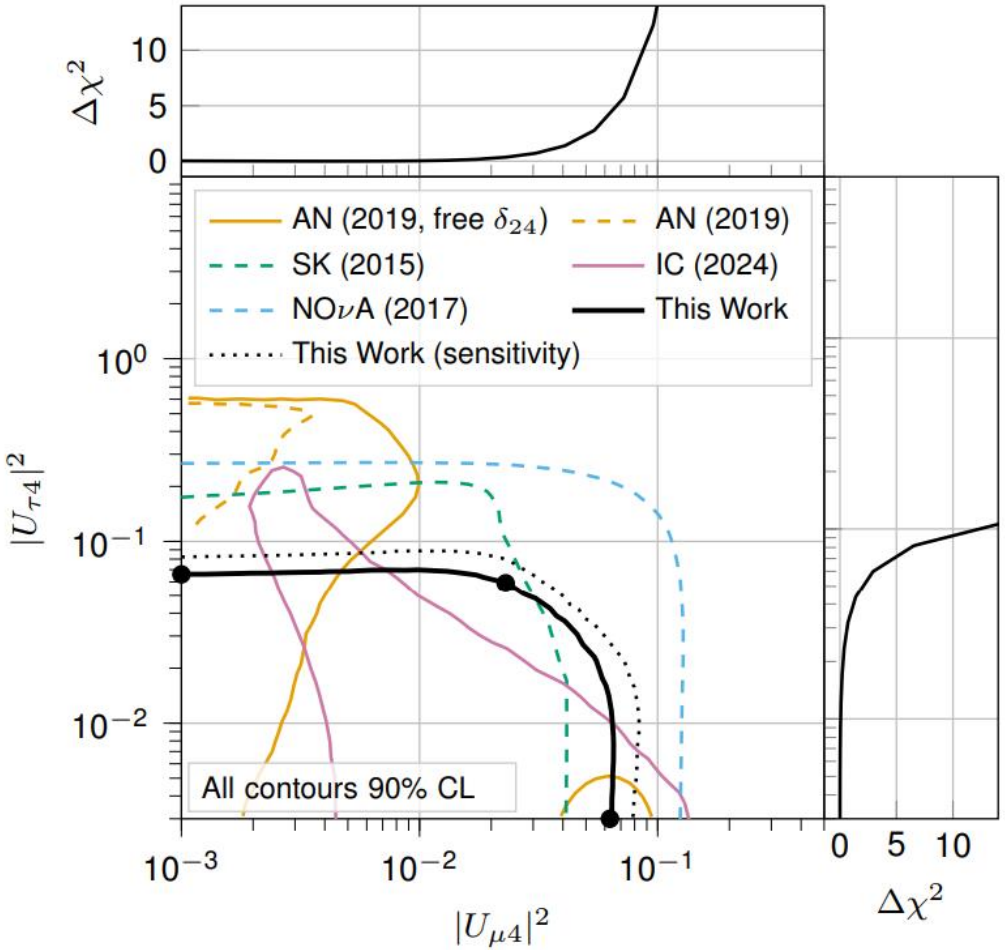


Latest DC results – sterile states



$$U^{3+1}_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$





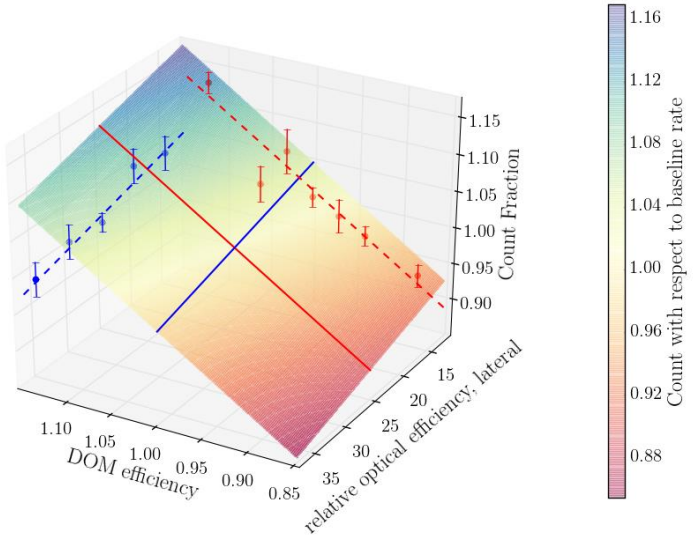
arXiv:2407.01314 **[hep-ex]**

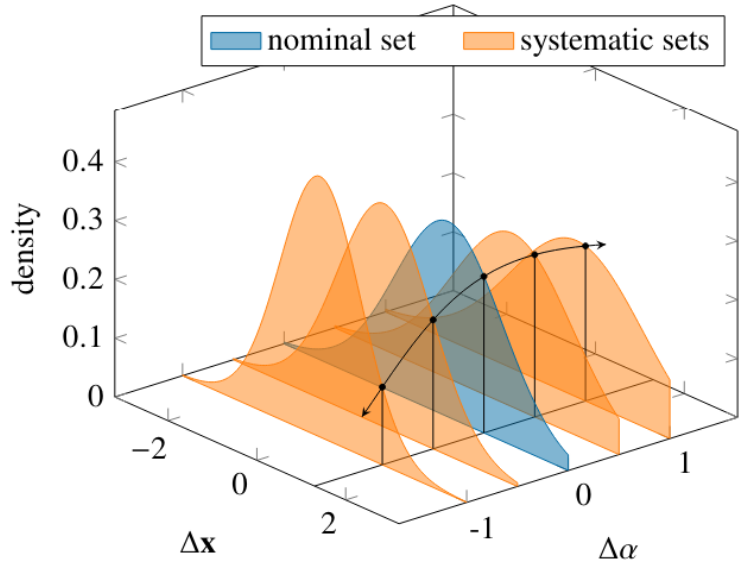
Parameterizing **calibration** information

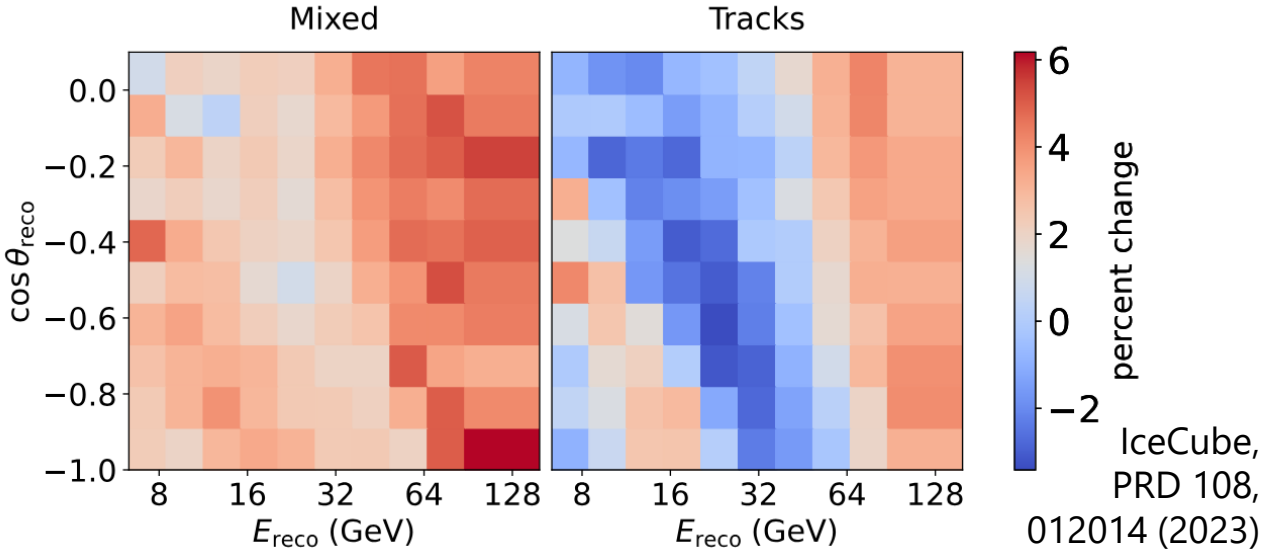
Fischer, Naab, Trettin
arXiv:2305.02257

- Detector-related systematics dominate uncertainty
  - Multiple strategies to account for their impact
- MC production
  - MC at multiple parameter combinations
  - MC with smoothly varying parameters
- Parameterization
  - Gradients obtained from binned MC expectation
  - Event-wise weights from PDFs obtained with ML
- Latest addition:
  - Birefringence in the ice crystals

IceCube, The Cryosphere 18 (2024) 1, 75-102





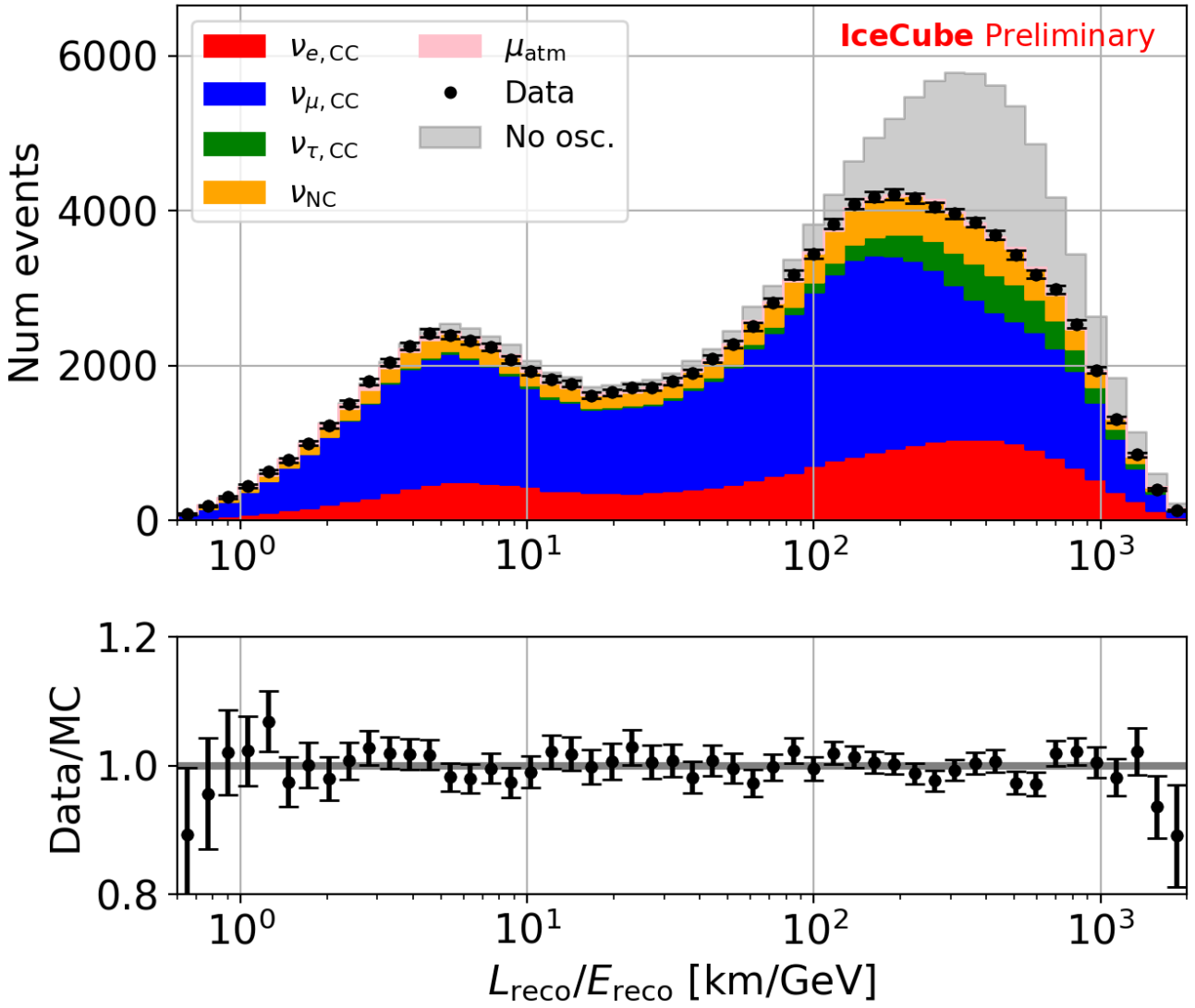


IceCube, PRD 108, 012014 (2023)

Projections in L/E space

$$P\nu_\mu \rightarrow \nu_\mu \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

- All final-level data shown
- Strong ν_μ deficit
- Small ν_τ appearance
- Full analysis done in a 3D-space of $E, \cos\theta, PID$



The signature of ν oscillations

$$P\nu_\mu \rightarrow \nu_\mu \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

- Latest oscillation analysis, publication in preparation

