Oscillation Results From IceCube

Summer Blot

Neutrino Telescopes Conference

Padua, Italy

30 September 2025

ICECUBE UPGRADE

DESY.

Photo credit: NSF / Ilya Bodo

Introduction

- Neutrino flavors states are superposition of non-equal mass states
- Mixing is governed by a **unitary** matrix ***U*** parameterized by:
  - Three mixing angles: $\boldsymbol{\theta_{12}, \theta_{13}, \theta_{23}}$
  - and potential CP-violating phase: $\boldsymbol{\delta_{CP}}$
- Neutrinos accumulate phase differences as they propagate due to mass differences: $\boldsymbol{\Delta m^2_{21}, \Delta m^2_{32}}$
- Leads to neutrino flavor oscillation as a function of L / E

Flavour Mass

$$|\nu_\alpha\rangle = \sum U^*_{\alpha k} |\nu_k\rangle$$

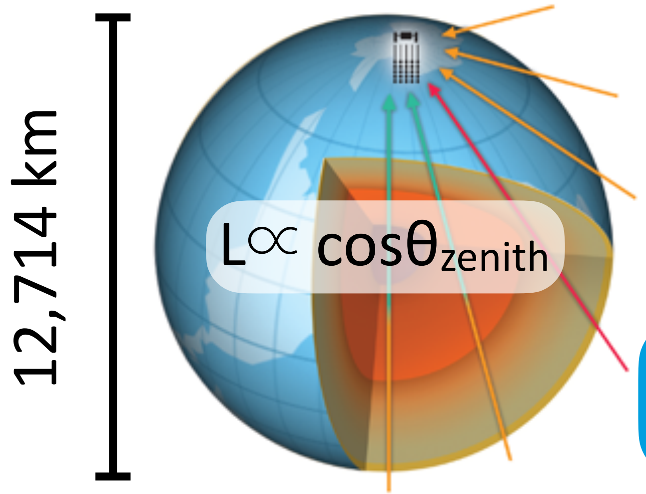
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

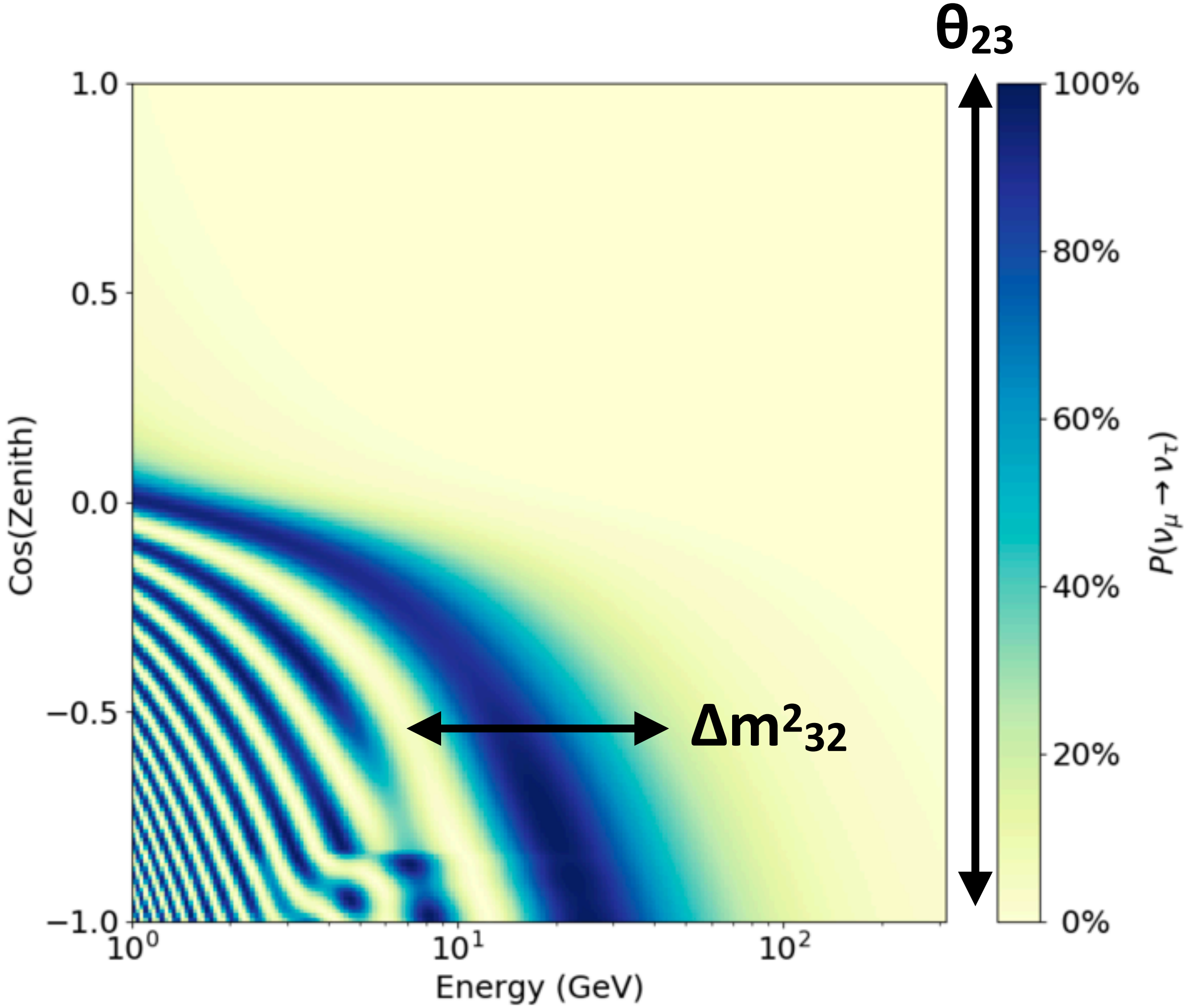
Unitarity implies, e.g.,

$$|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1$$

Atmospheric Neutrino Oscillations

- Cosmic ray air showers produce abundant flux of **ν_μ/anti-ν_μ** and **ν_e/anti-ν_e**
- These atmospheric neutrinos oscillate as they travel through the Earth
- Can measure ν_μ disappearance ($\nu_\mu \to \nu_\mu$) and ν_τ appearance ($\nu_\mu \to \nu_\tau$)
  - Latter explicitly **tests $U_{\tau 3}$ and unitarity**



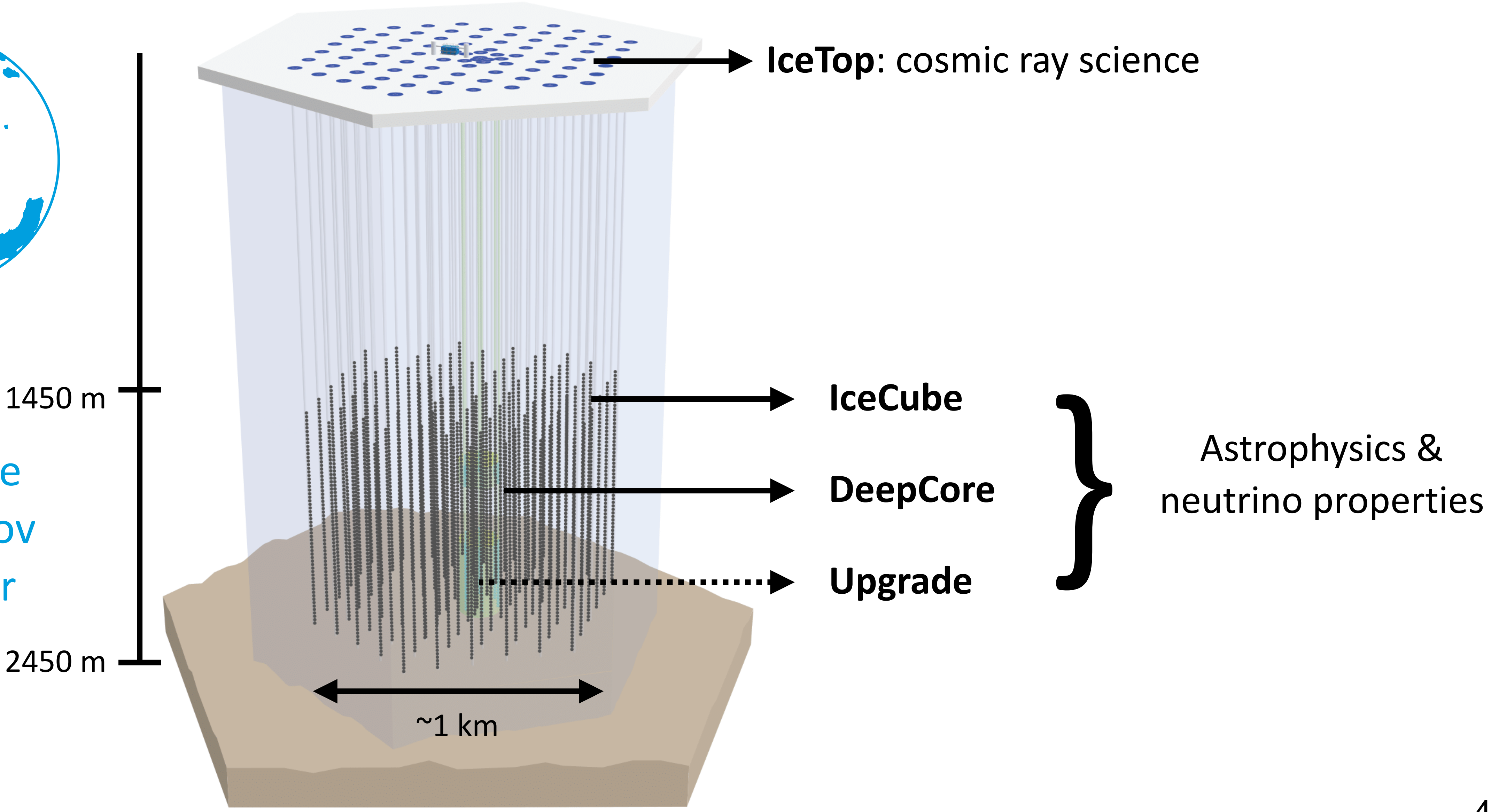


$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta_{23})\sin^2(1.27\,\Delta m^2_{32}\,L / E)$$

DESY.

The IceCube Neutrino Observatory

1 km^3 ice Cherenkov detector

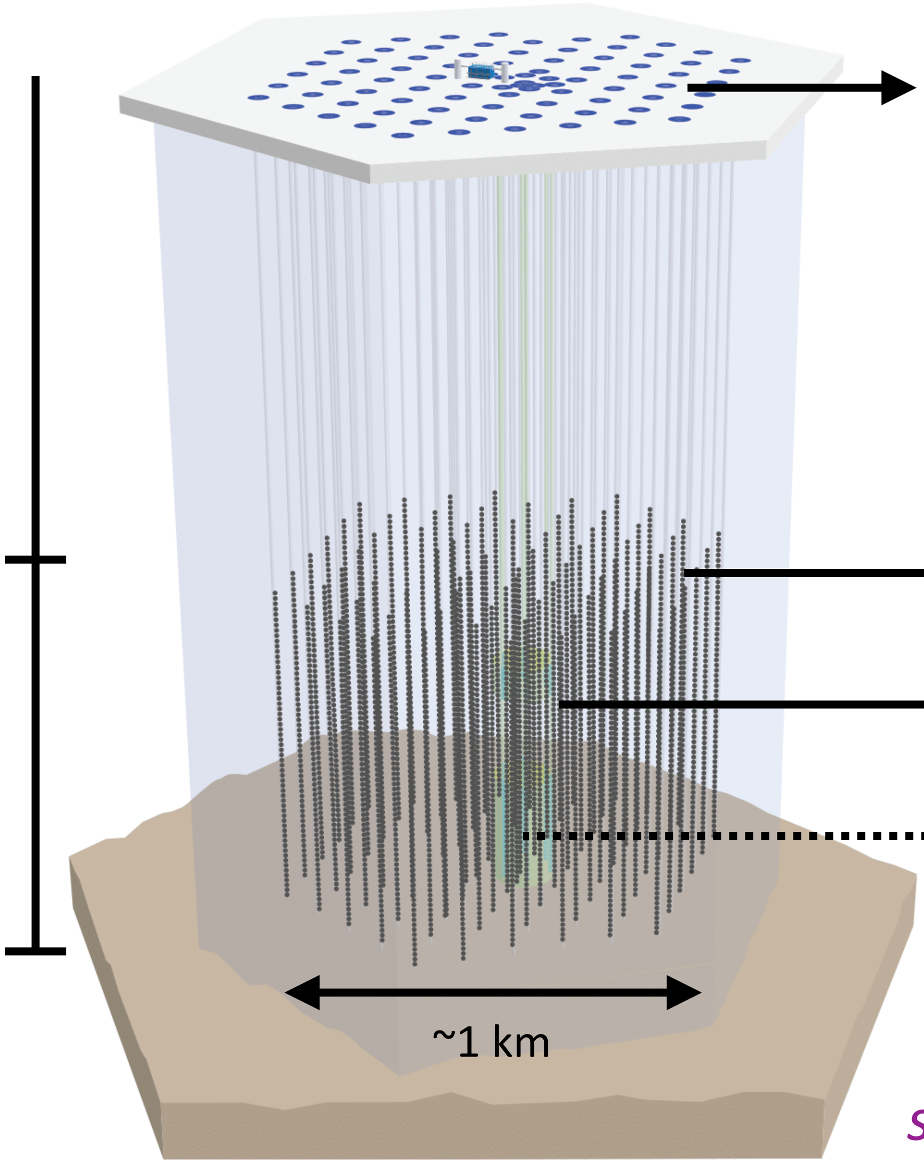


The IceCube Neutrino Observatory

1 km³ ice Cherenkov detector

1450 m

2450 m



IceTop: cosmic ray science

Part 1:
recent results

IceCube

DeepCore

Upgrade

Part 2:
new detector status & prospects

Tomorrow:
Talk by Angela Zegarelli

Astrophysics & **neutrino properties**

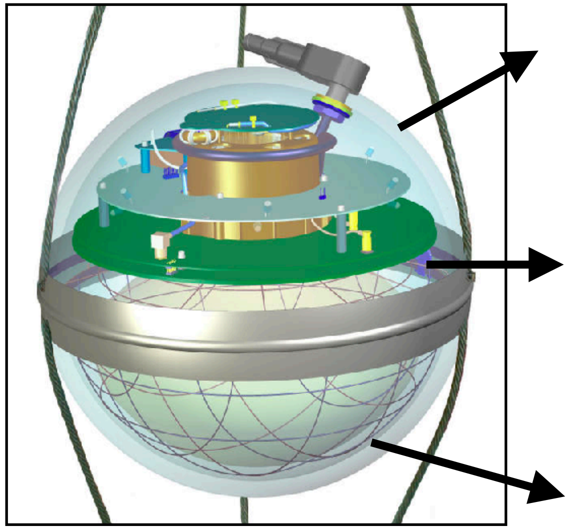
IceCube DeepCore

- 5680 **Digital Optical Modules** (DOMs) embedded 1450-2450 m deep into the ice sheet
- Detect Cherenkov photons from particle interactions
- Spacing, quantum efficiency and ice properties drive **detector performance**

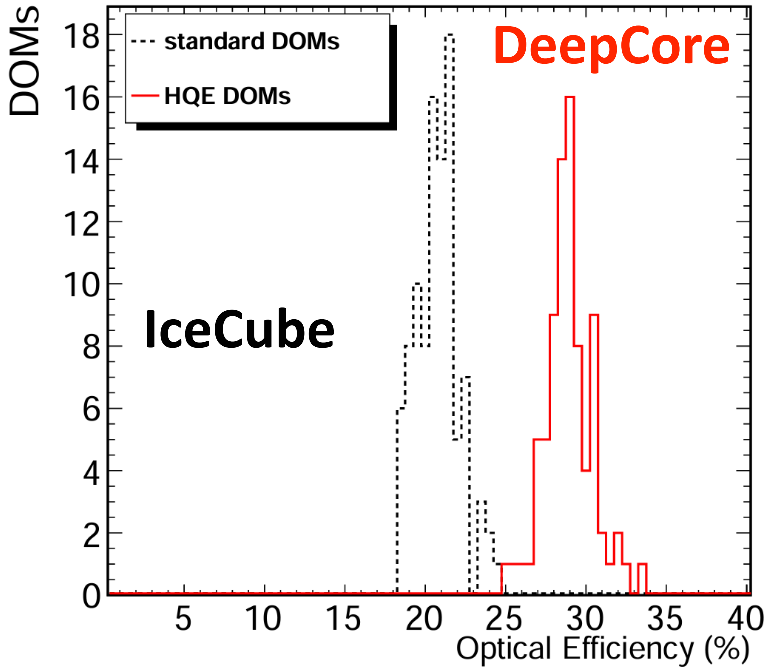
	Spacing [m]		Approximate energy range
	Horiz.	Vertical	
IceCube	125	17	100 GeV – PeV
DeepCore	~50	7	5 – 150 GeV

JINST 12 (2017) 03, P03012

DOM



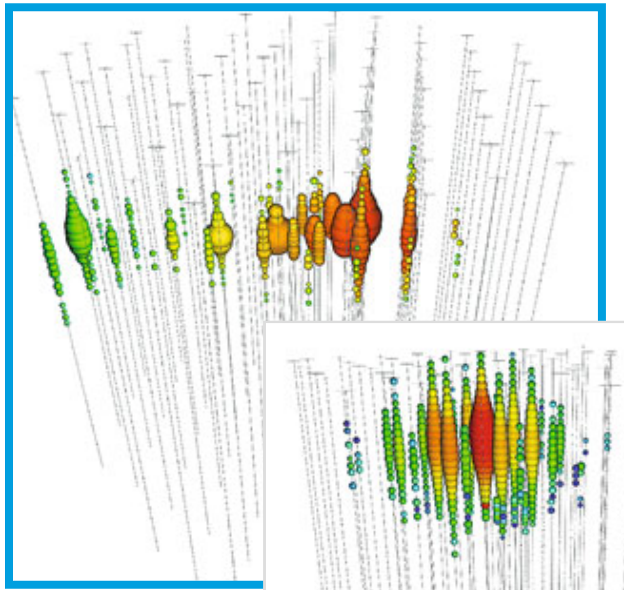
Astropart.Phys. 35 (2012) 615-624



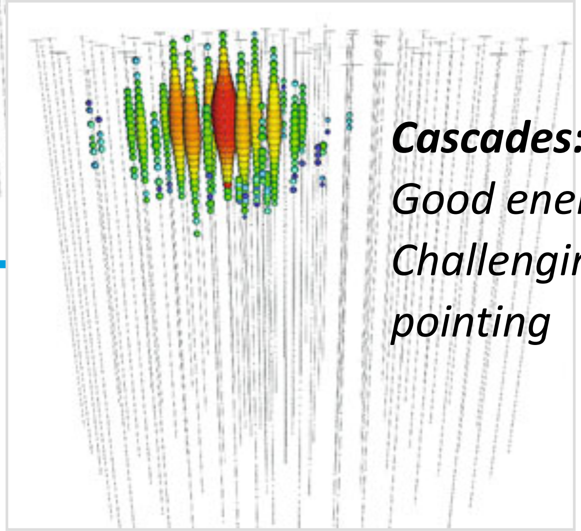
High-Energy neutrino signatures in IceCube

- Most interactions are in **Deep Inelastic Scattering** regime
- Sensitive to **all flavors, neutrino and anti-neutrinos,** but cannot easily distinguish (no ***B***-field)

	NC (Z^0)	CC ($W^\pm$)
ν_e	$\nu_e + N \rightarrow \nu_e + X$	$\nu_e + N \rightarrow e^- + X$
ν_μ	$\nu_\mu + N \rightarrow \nu_\mu + X$	$\nu_\mu + N \rightarrow \mu^- + X$
ν_τ	$\nu_\tau + N \rightarrow \nu_\tau + X$	$\nu_\tau + N \rightarrow \tau^- + X$



Tracks:
Decent energy resolution
Excellent direction/ pointing



Cascades:
Good energy resolution
Challenging direction/ pointing

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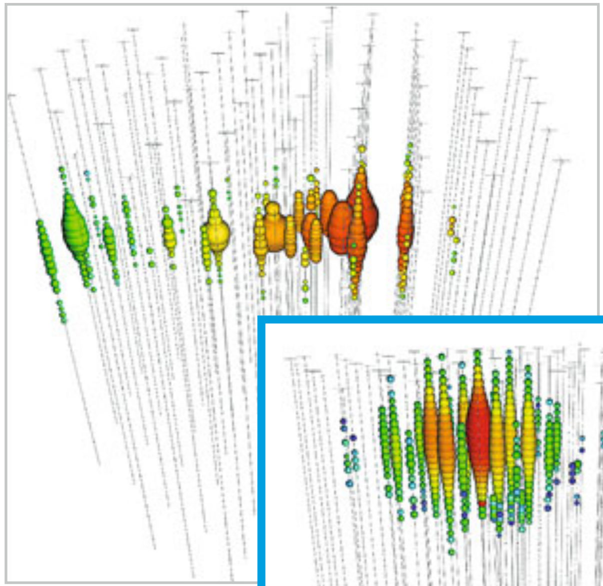

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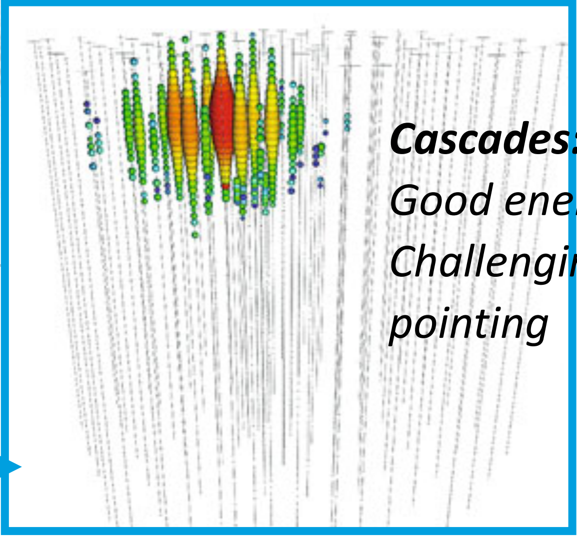

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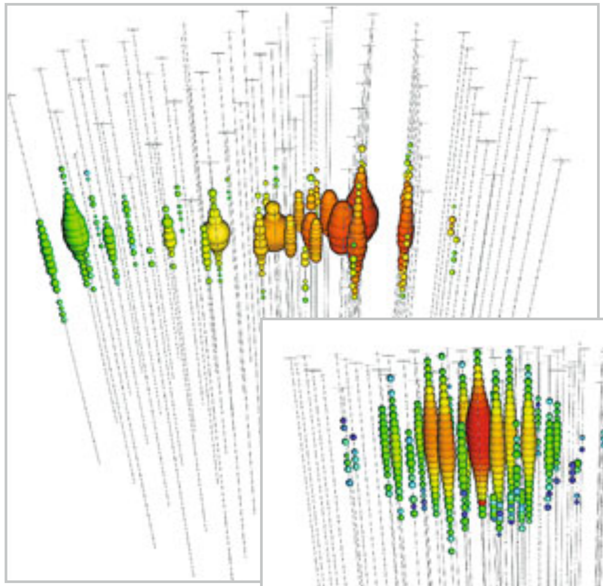

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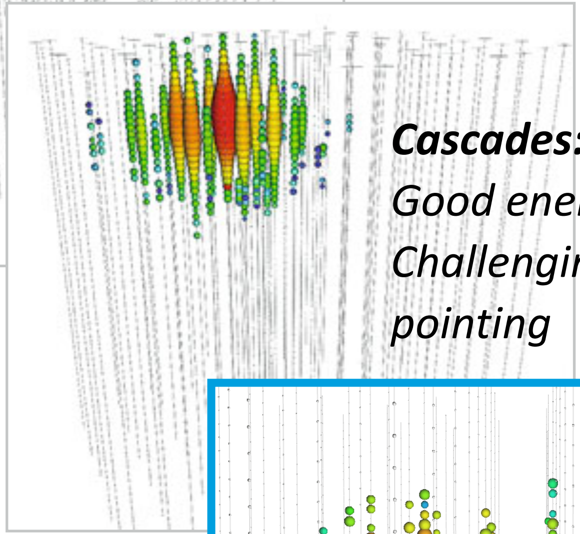

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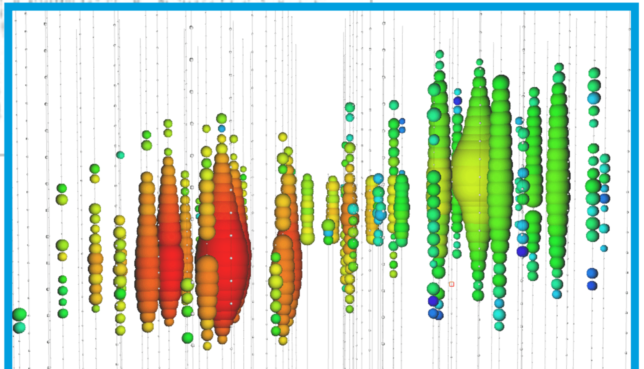

Double Bangs:
Distinct cosmic ν_τ signature

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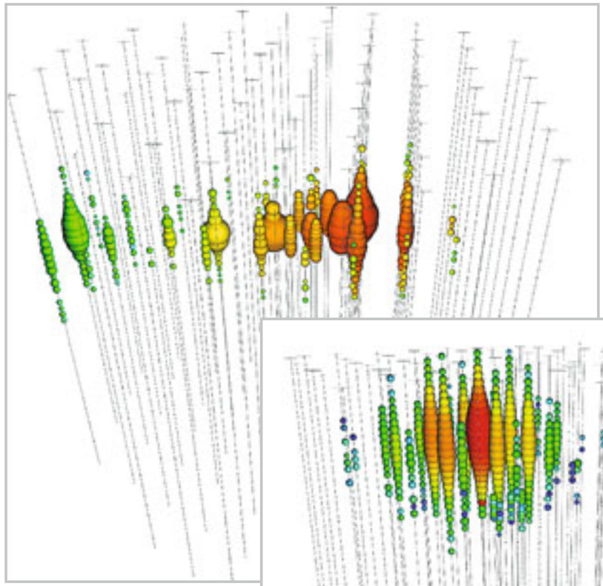

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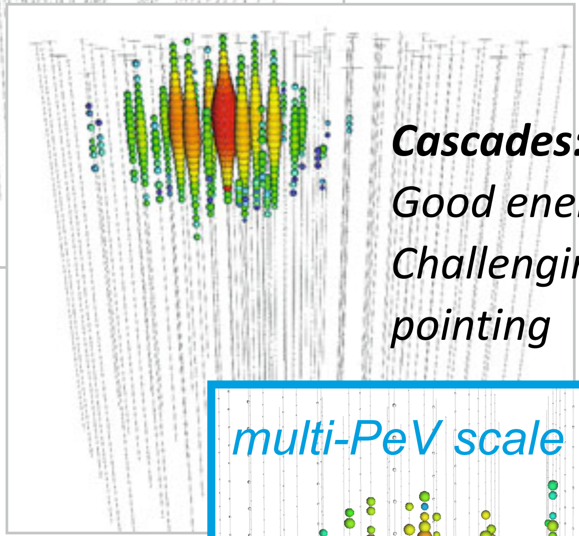

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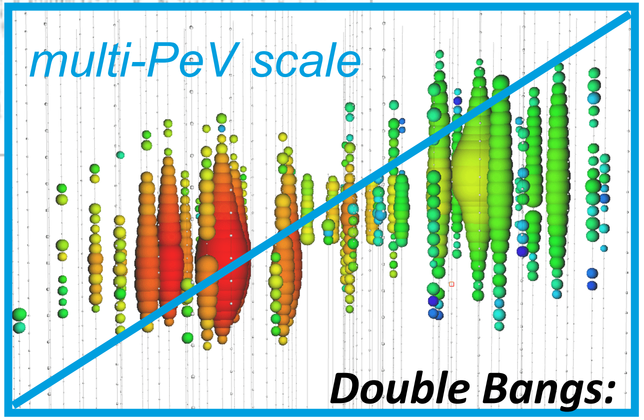

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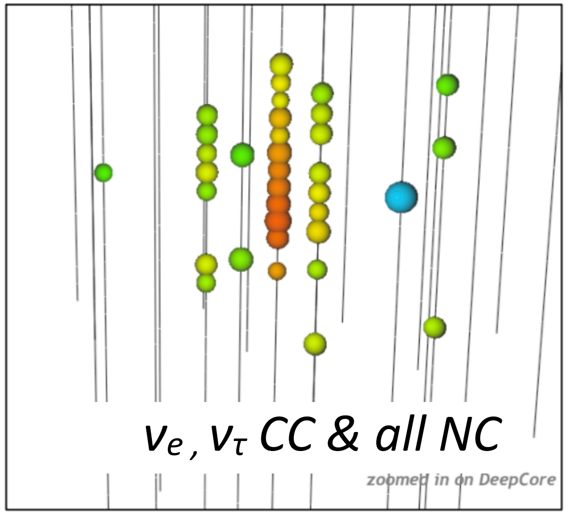
More on IceCube's latest TeV-scale ν_τ measurement:
Phys. Rev. Lett. 132, 151001

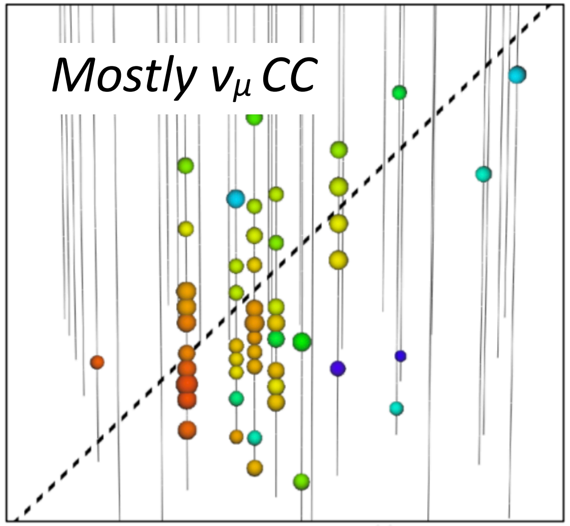
GeV-scale neutrino signatures in DeepCore

- Reconstruction at GeV-scale is **more challenging**
- Apply several approaches:
  - Geometric & likelihood minimization (classical)
    - PRD 108, 012014 (2023), data release HERE
  - Convolutional Neural Networks
    - PRL 134, 091801 (2025), data release HERE
  - NEW **Graph Neural Networks (GNN)**
    - R. Abbasi et al., 2022 JINST 17 P11003

Cascades



Tracks



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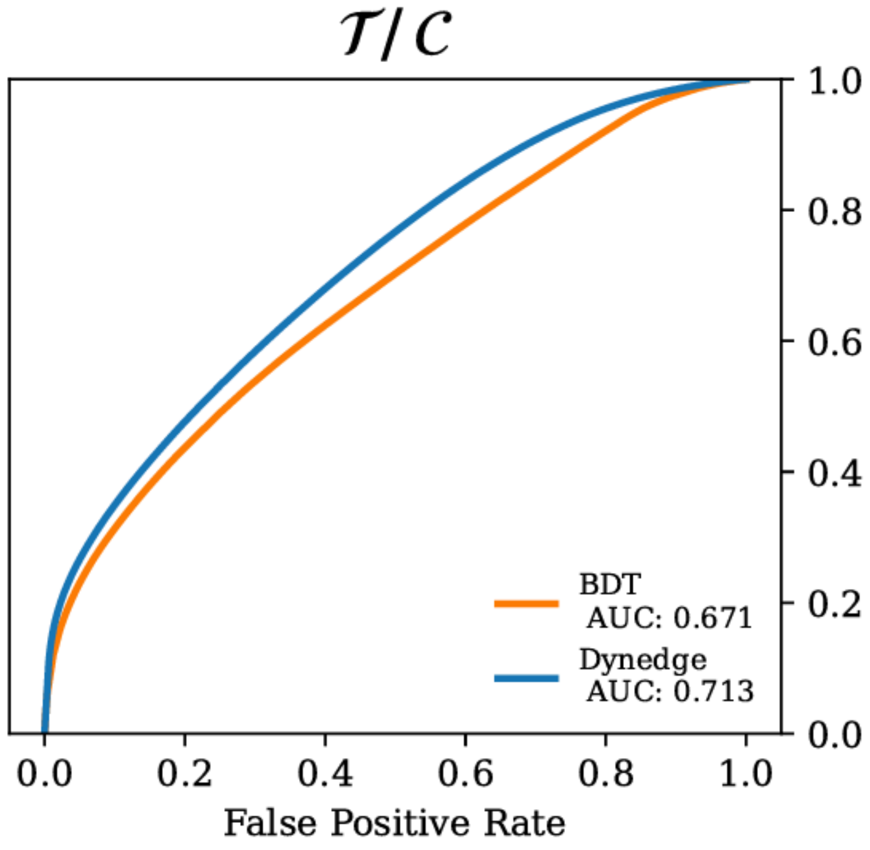
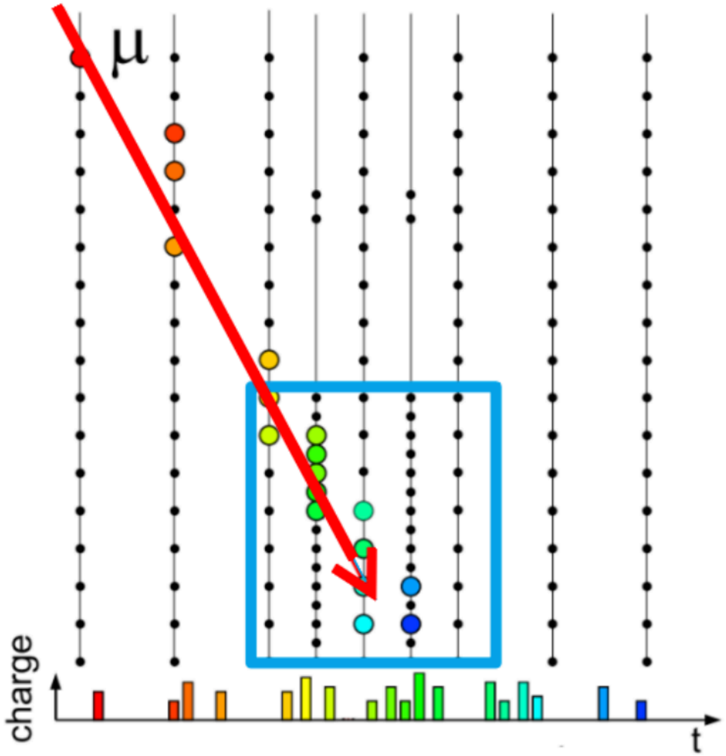
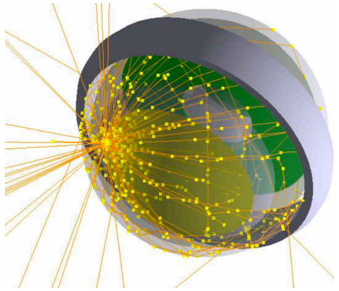


Example: Track vs Cascade classification with GNN

Backgrounds & mitigation strategies

- **Muons** are also produced in cosmic ray air showers
  - Characterize with CORSIKA and MuonGun
  - Use Earth as a shield
  - For DeepCore: use IceCube as veto
  - Machine learning to clean up the rest
- Accidental coincidence of **radioactive decays**
  - Remove with causality-based hit cleaning algorithms
  - Characterize with random/unbiased trigger windows and lab measurements

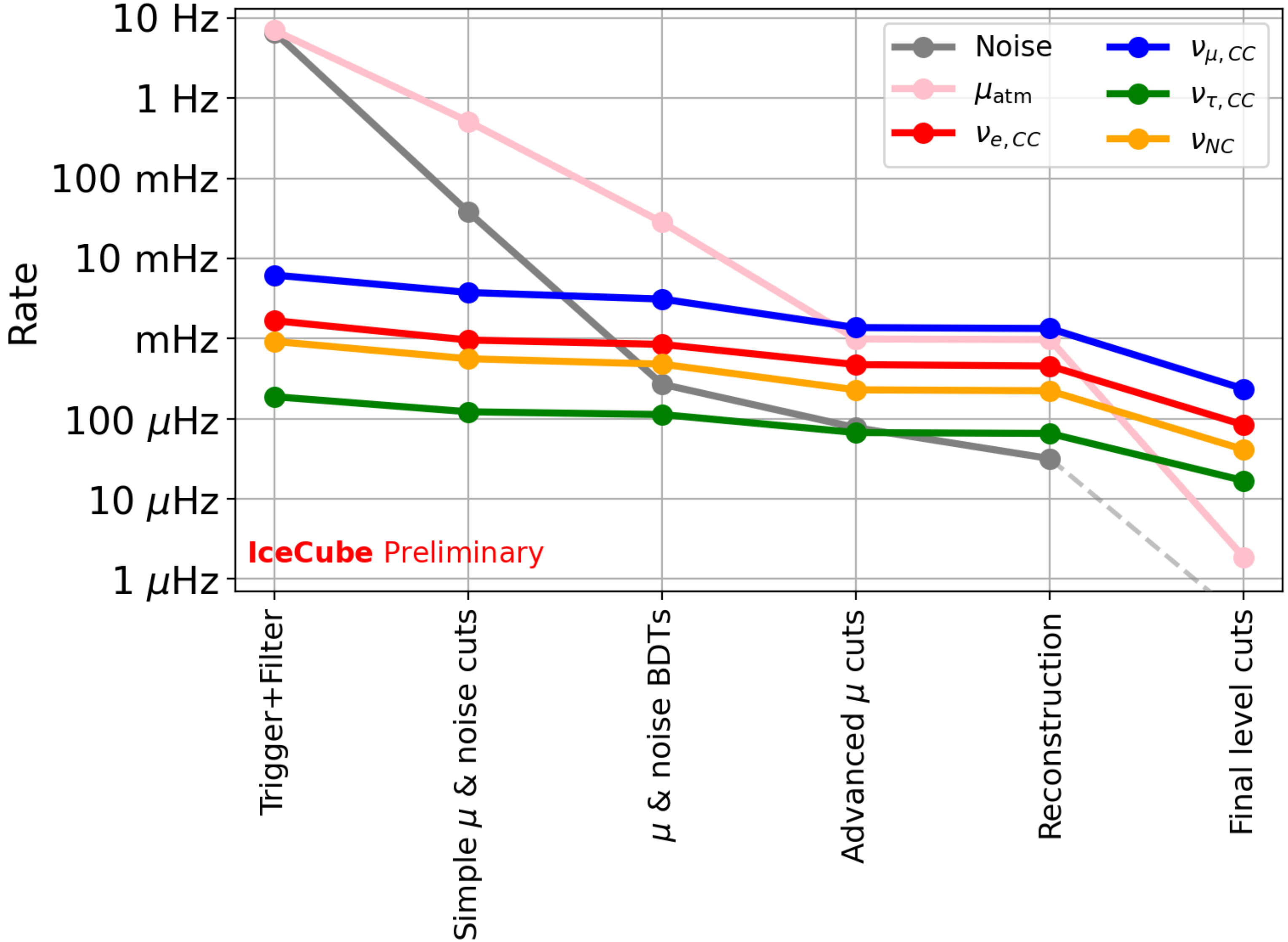




Poster at Neutrino 2018
M. Unland

Atmospheric Neutrino Event selection

- Muon rate reduced by more than **10^{-5}**
- Accidental rate (i.e. "noise") at final level is **negligible**
- **Retain 5%** of triggered atmospheric neutrinos

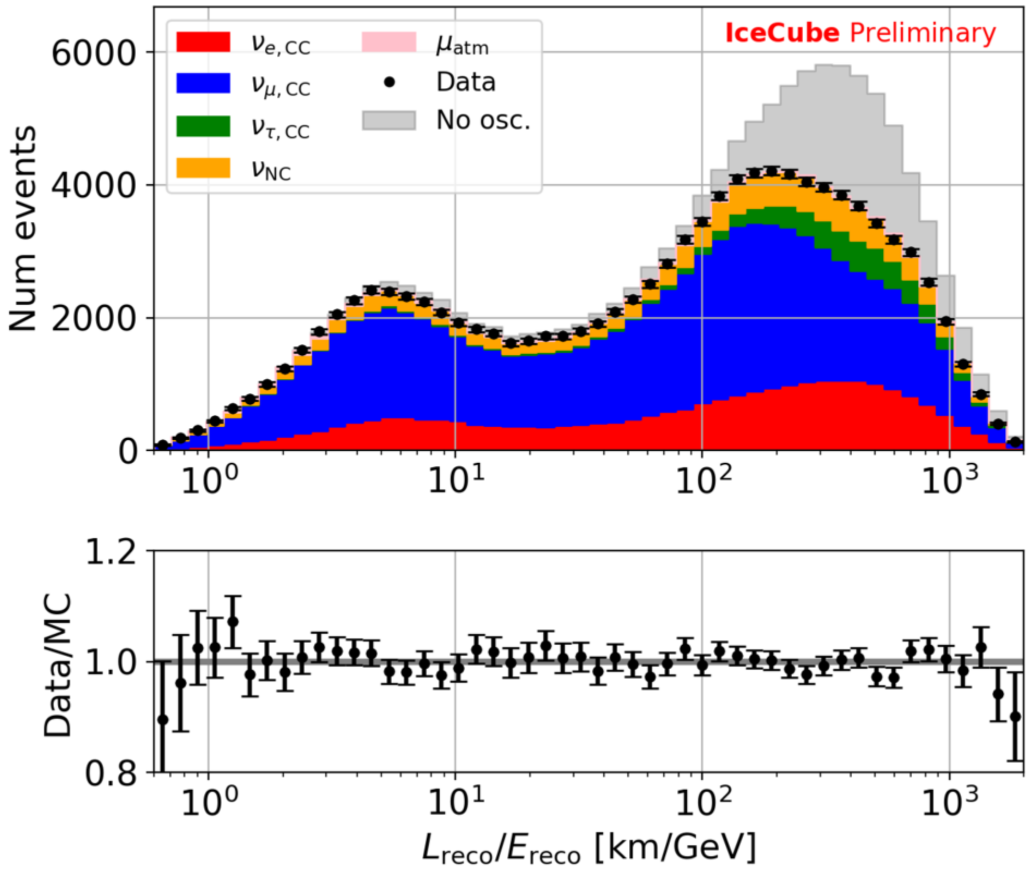


DESY.

New atmospheric neutrino oscillations results

- **New analysis of 11.1 years** of IceCube DeepCore data
- Uses **GNN reconstruction** for neutrino energy, zenith angle and flavor identification
- Investigate both **ν_μ disappearance** ($\nu_\mu \rightarrow \nu_\mu$) and **$\nu_\tau$ appearance** ($\nu_\mu \rightarrow \nu_\tau$) channels
- Incorporates **state-of-the-art** PMT noise filtering and modeling of systematic uncertainties

108,784 ± 129 events (total)
0.7% atm. μ contamination

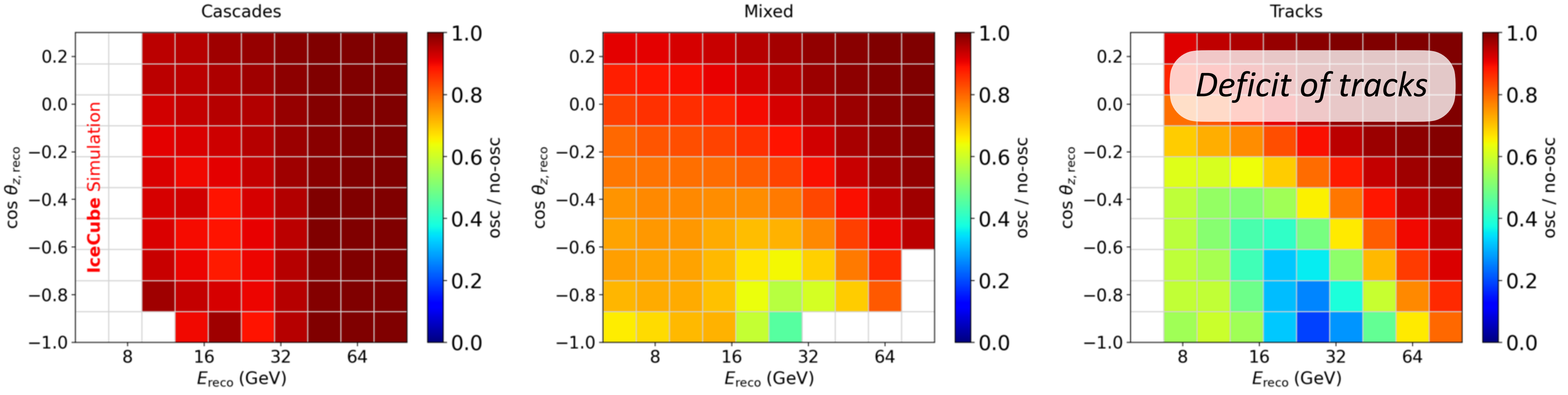


Analysis signals

ν_μ disappearance ($\nu_\mu \rightarrow \nu_\mu$)

Vary θ_{23} and Δm^2_{32}

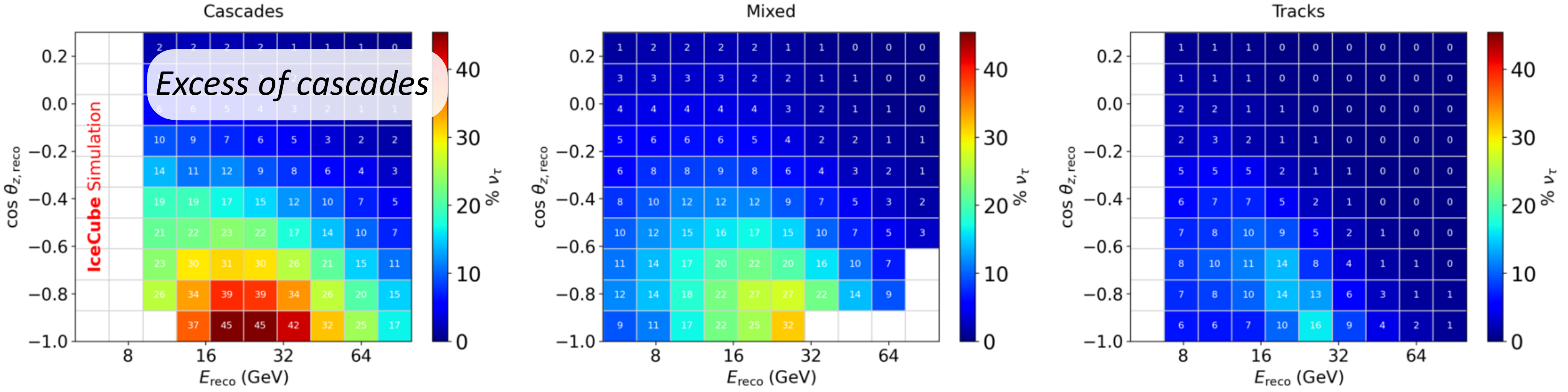
Maintain PMNS unitarity



ν_τ appearance ($\nu_\mu \rightarrow \nu_\tau$)

Vary θ_{23} and Δm^2_{32}

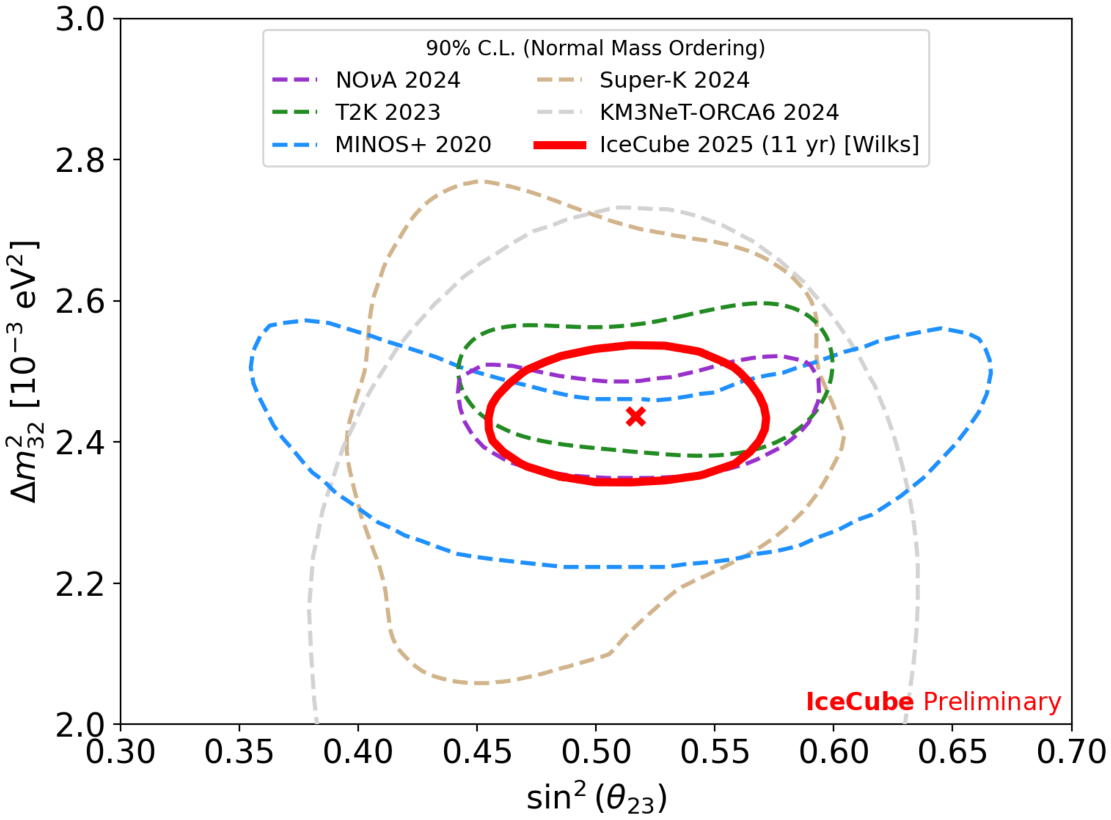
+ vary ν_τ normalization



ν_μ disappearance ($\nu_\mu \rightarrow \nu_\mu$)

New!

- Perform simultaneous fit of θ_{23} and Δm^2_{32}
- Best fit θ_{23} is in **upper octant**, consistent with maximal mixing
- **Normal mass ordering** is preferred
  - Dedicated NMO analysis ongoing
- Excellent agreement between simulation and data, with **p-value = 37.1 %**
- Result is **independent of δ_{CP}**, with minimal influence of cross-section systematics



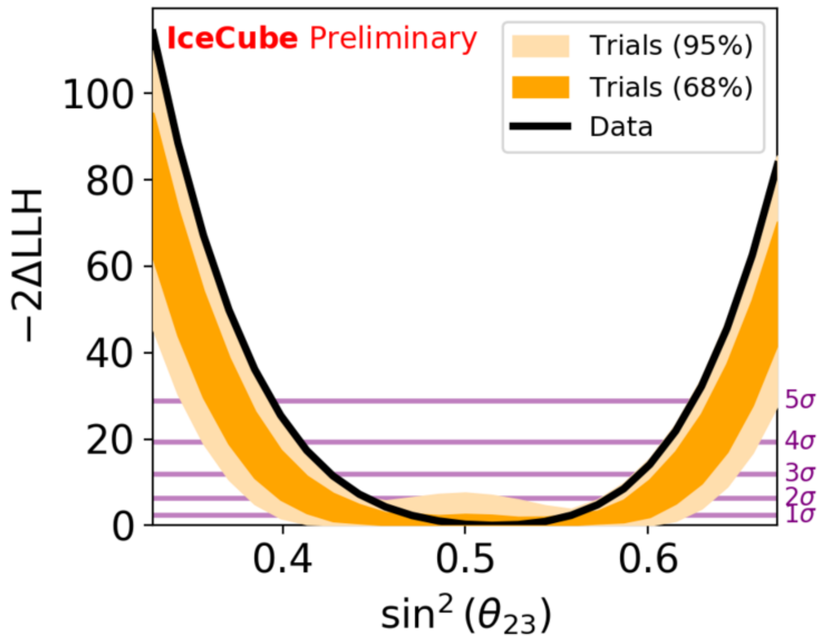
Best fit point: $\sin^2\theta_{23} = 0.516$

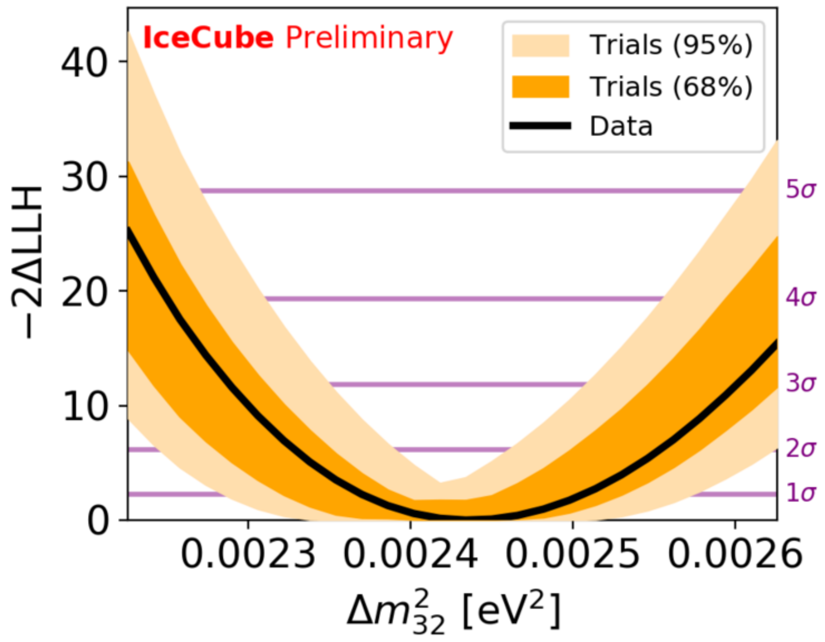
$\Delta m^2_{32} = 2.44 \times 10^{-3}$

DESY.

ν_μ disappearance ($\nu_\mu \rightarrow \nu_\mu$)

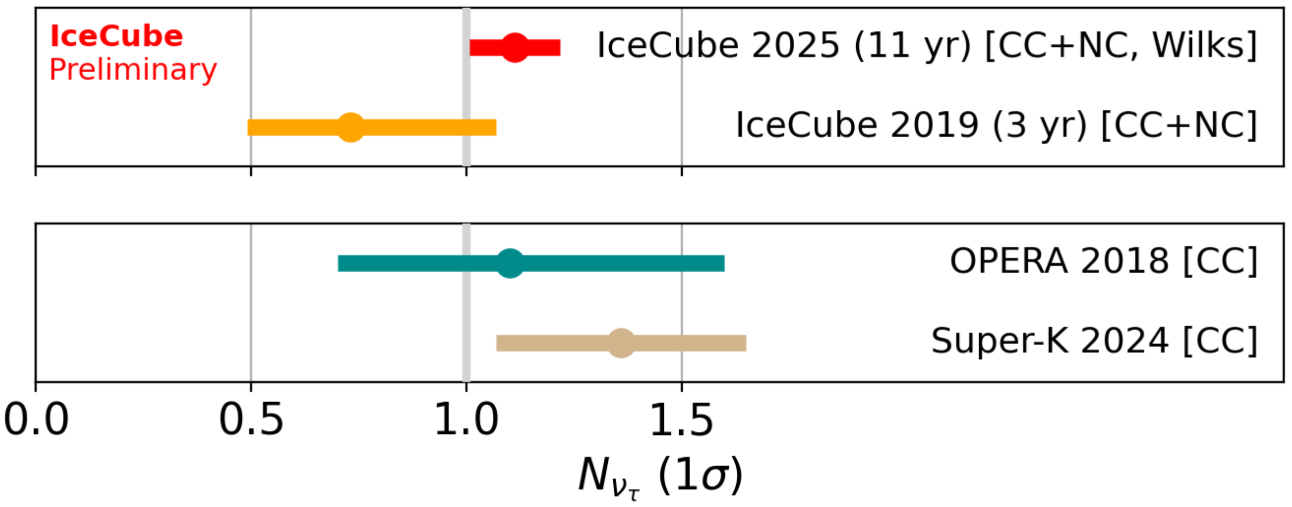
- **Compare measurement to expectation** from Monte Carlo pseudo experiments
- Mass splitting aligns well with expectation
- Mixing angle is within 95% of trials, but **more constraining than median expectation**
  - Consistent with previous results
  - Continue to investigate potential causes
- Final uncertainties will be calculated with Feldman-Cousins corrections, **caution extracting too much from these plots!**

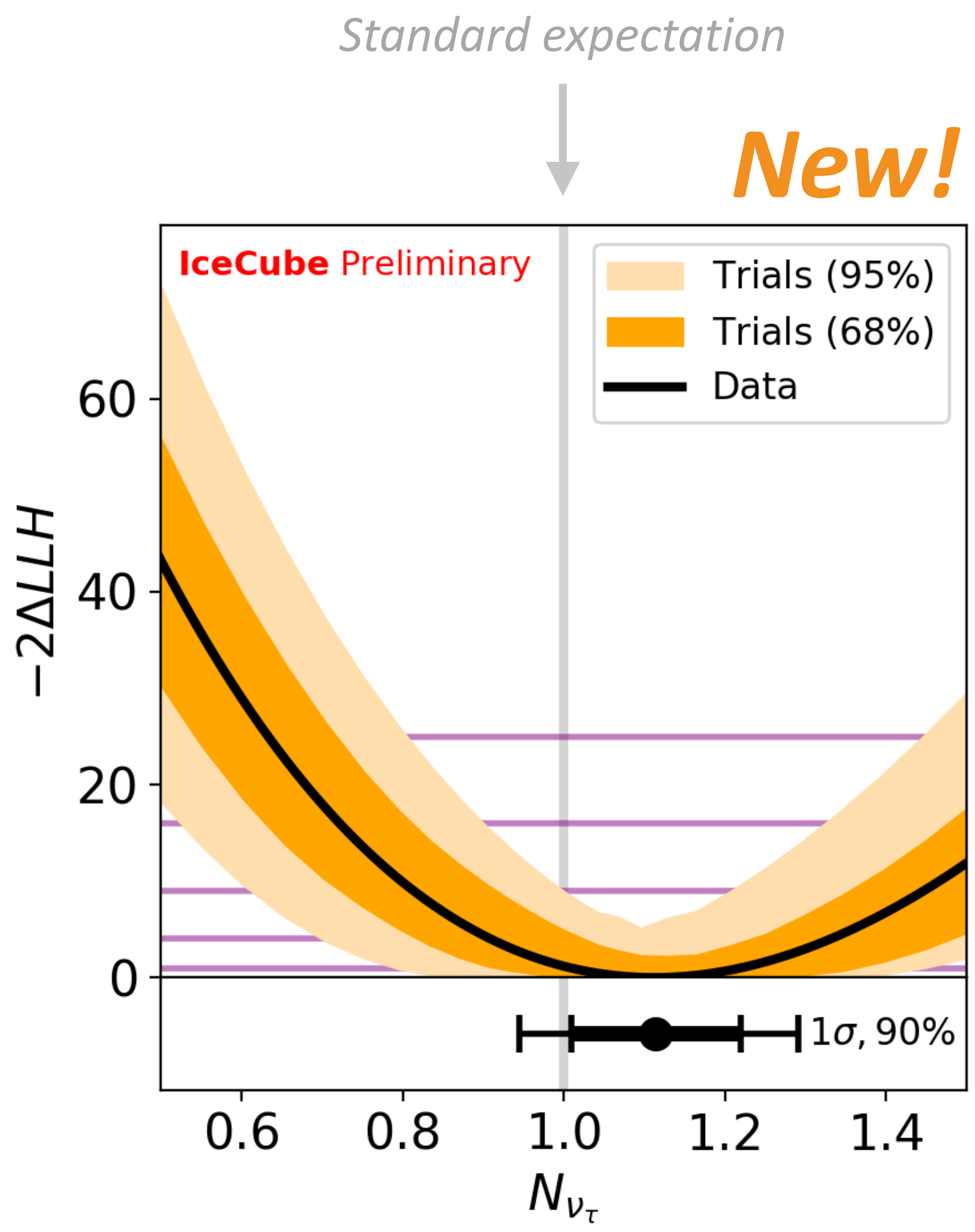




ν_τ appearance ($\nu_\mu \to \nu_\tau$)

- Additionally fit ν_τ normalization to test PMNS unitarity and cross-section
- Best-fit: $1.11\ ^{+0.11}/_{-0.10}$ **consistent with standard expectation** at 1σ
- Goodness of fit **p-value = 39.4%**

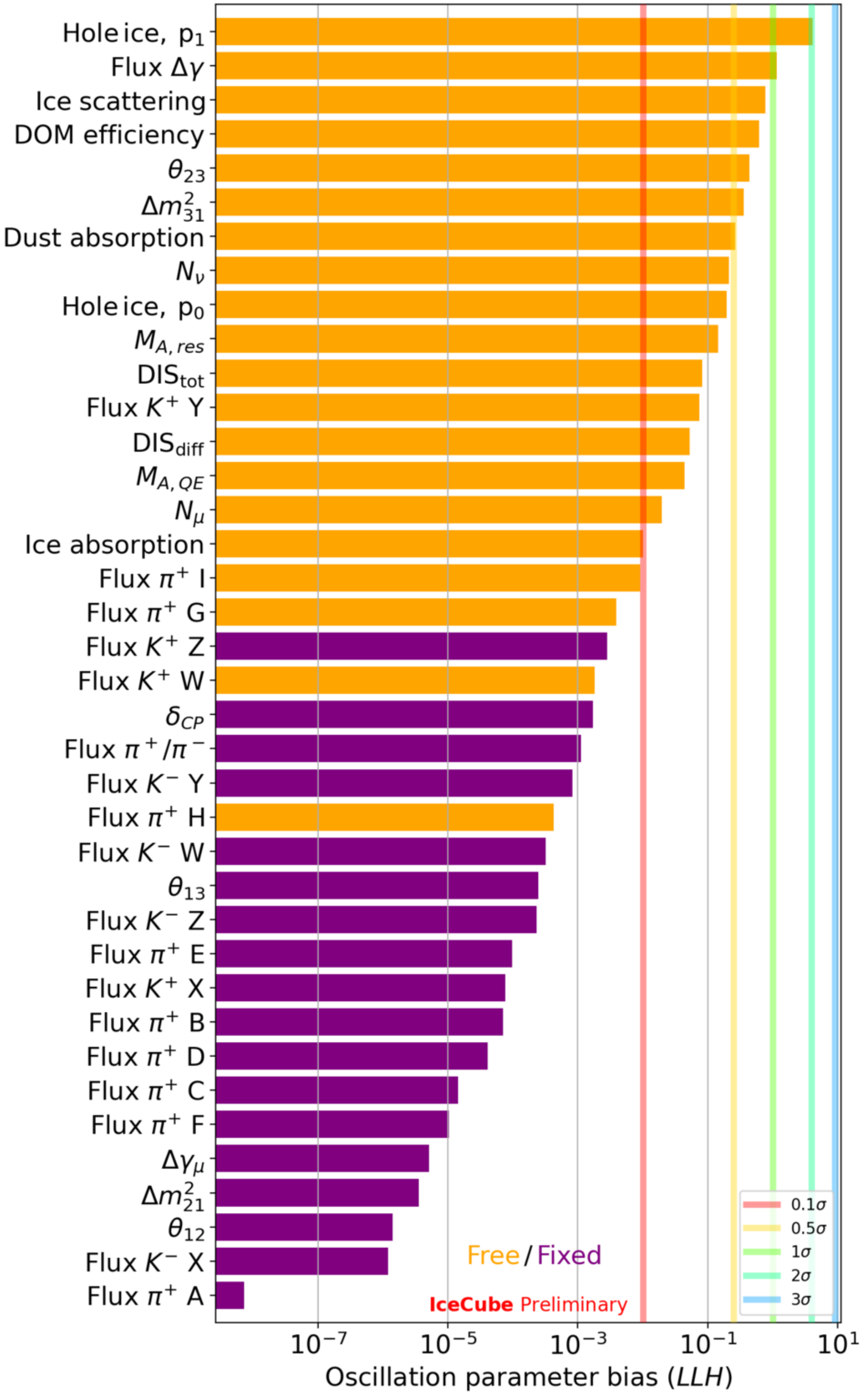




DESY.

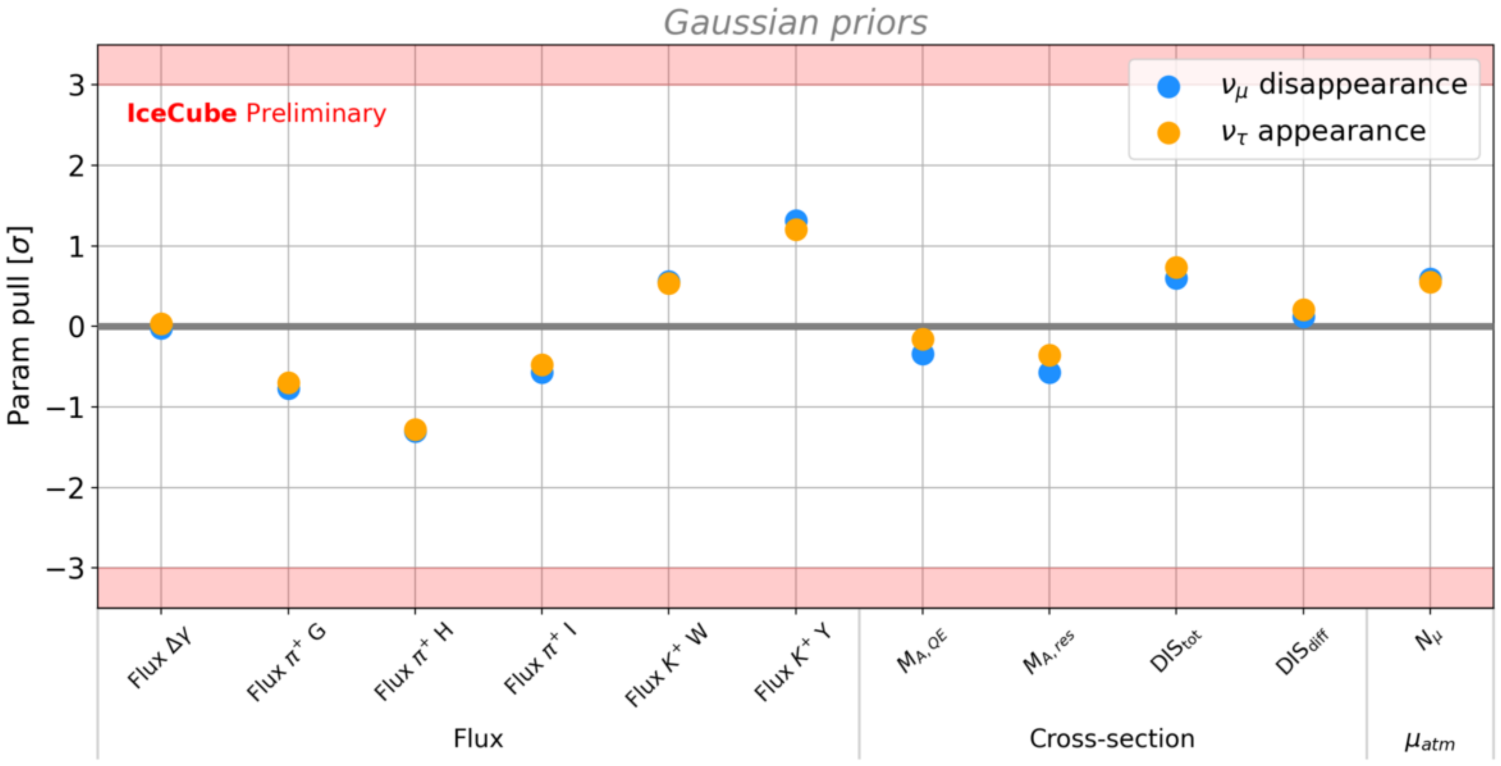
Systematics uncertainties

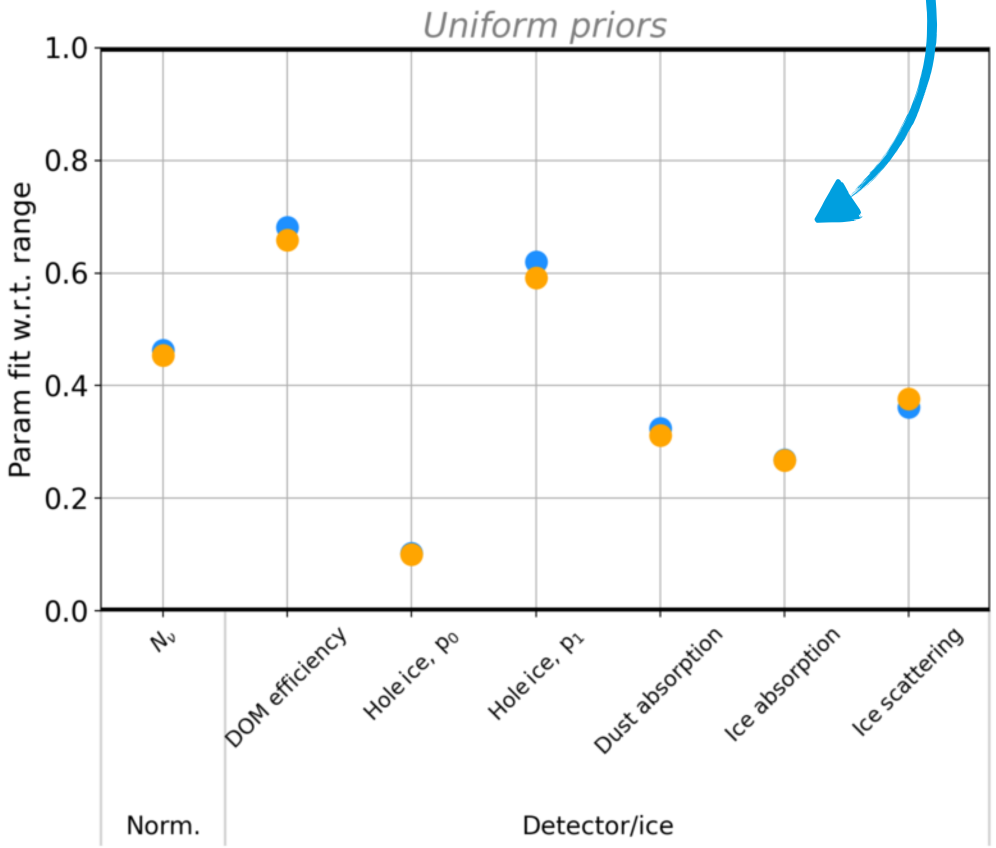
- Many sources of systematic uncertainty were studied
  - **Detector calibration**, atmospheric flux, muon rate, cross section, and other oscillation parameters
- Include only impactful systematics as nuisance parameters in the fit with priors where applicable
- **No significant pulls** with respect to priors were observed



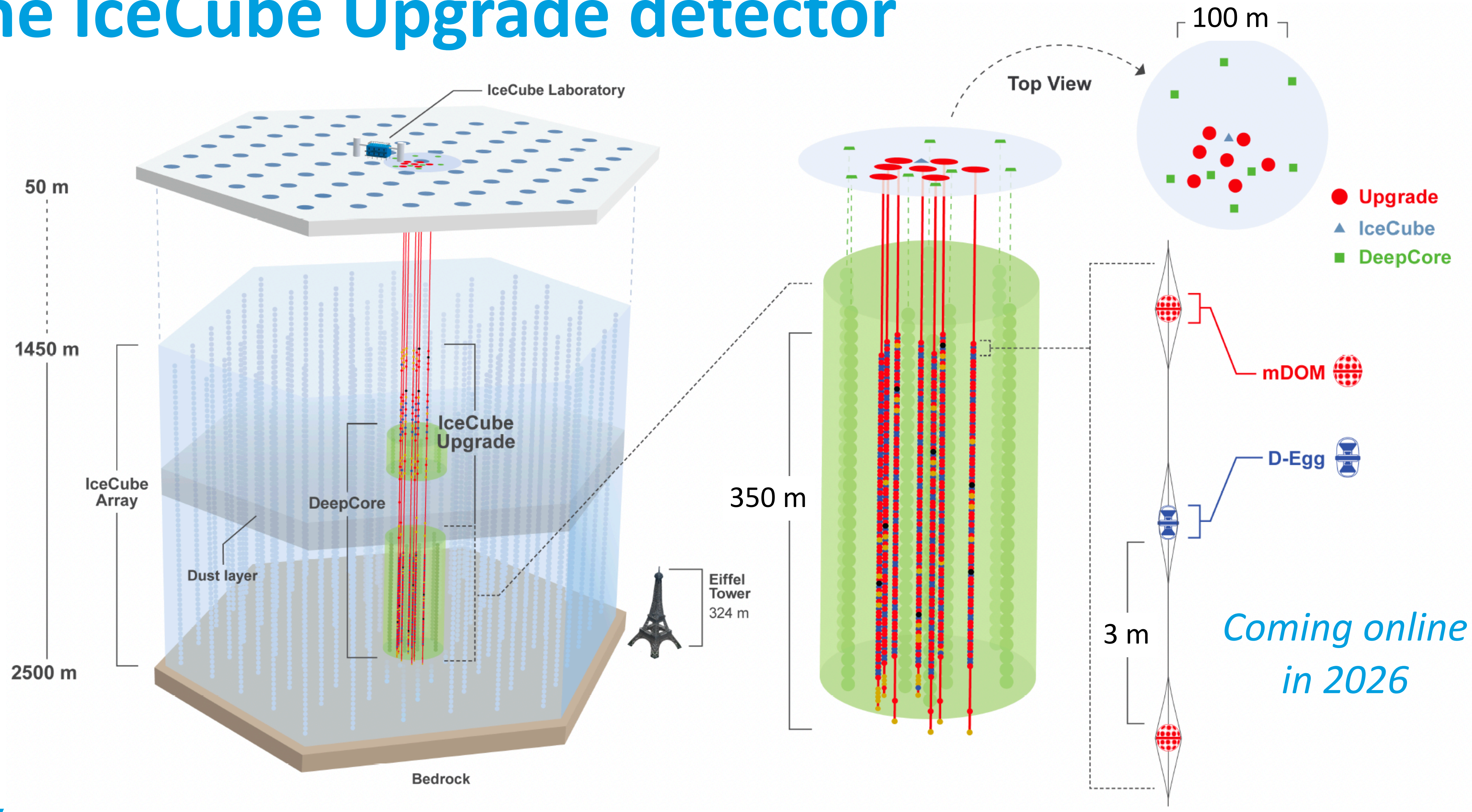
Nuisance Parameter Pulls

Detector & ice calibration contribute largest source of uncertainty, **no priors**!





The IceCube Upgrade detector



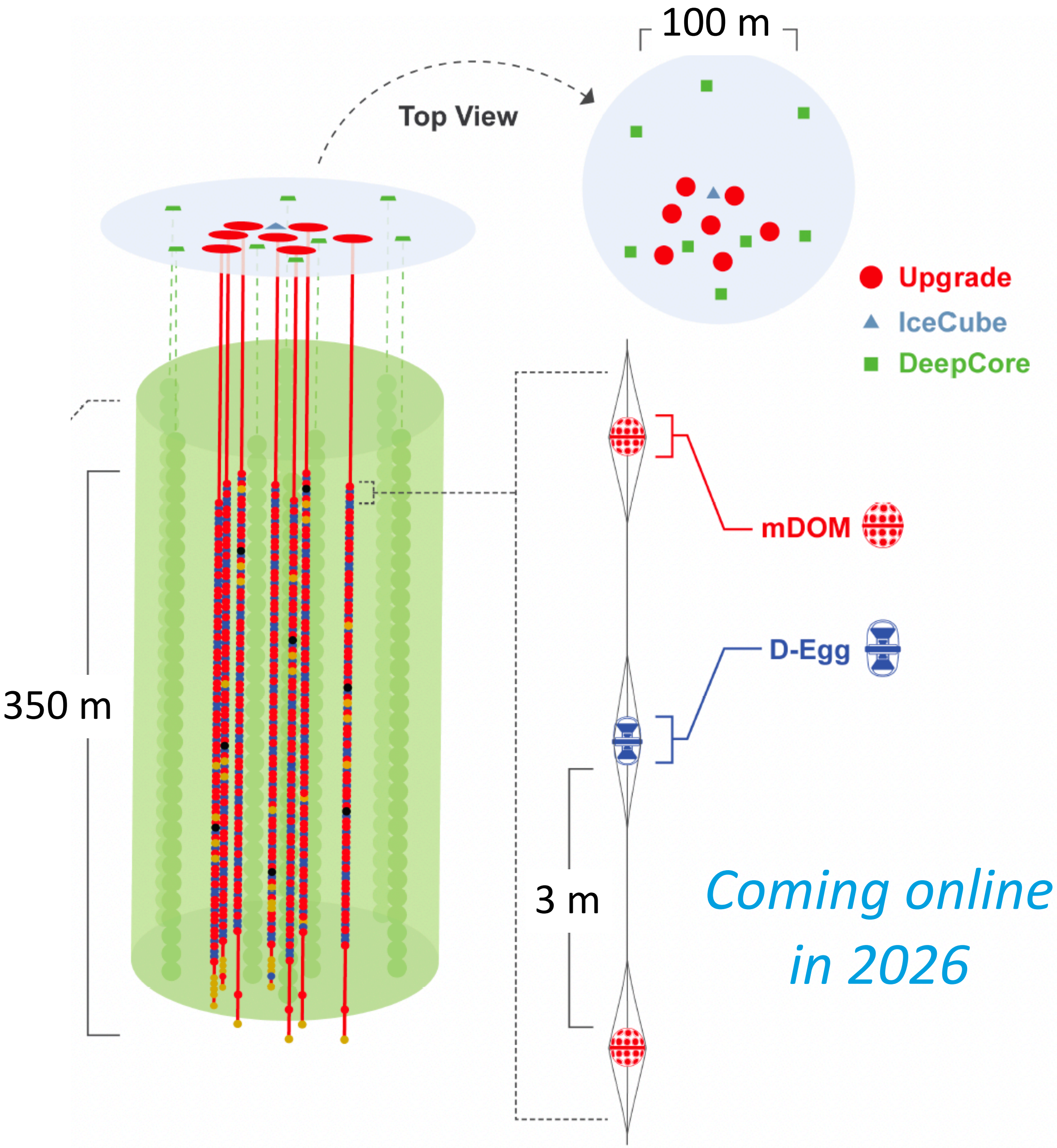
Coming online in 2026

New Optical Modules

~400 mDOMs | ~300 DEggs

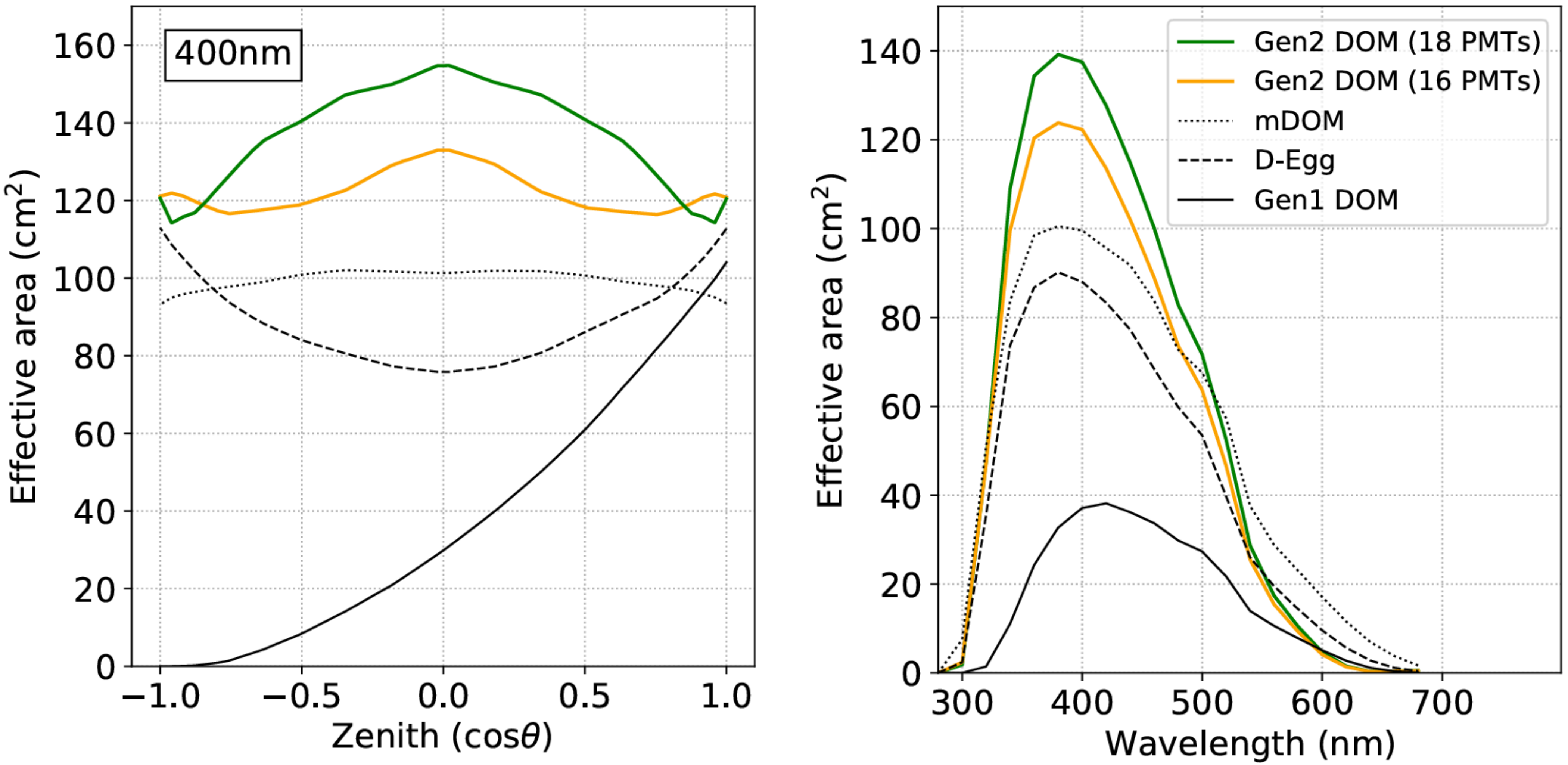
24 x 3" PMTs | 2 x 8" PMTs

+ Increased photocathode area
+ Improved angular acceptance



Coming online in 2026

Next Generation Optical Sensor Performance

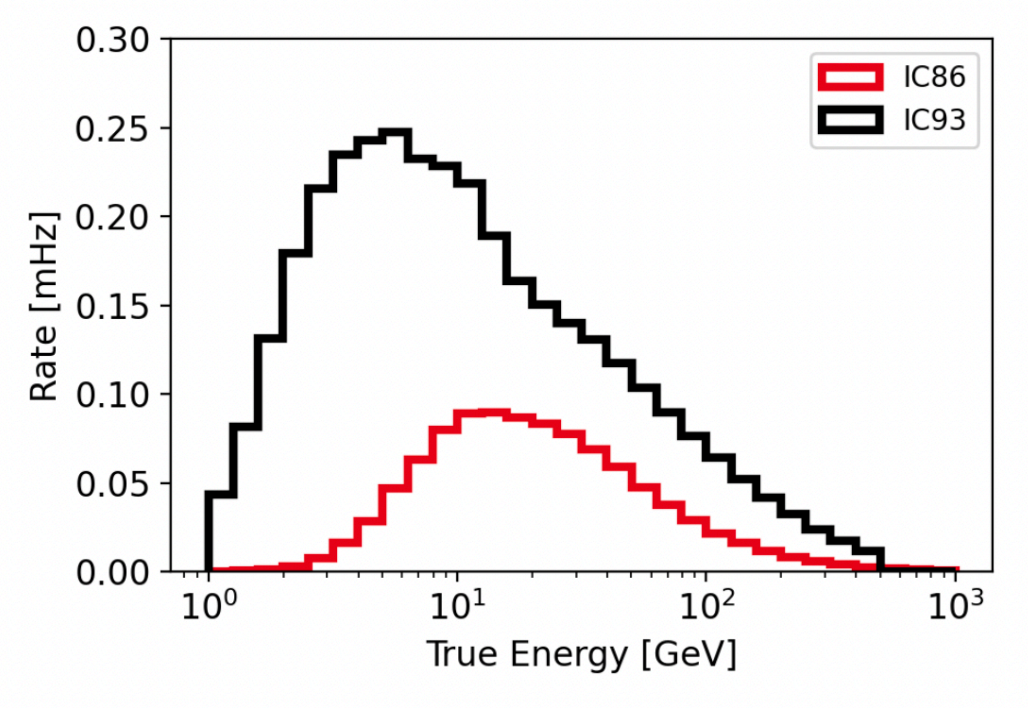


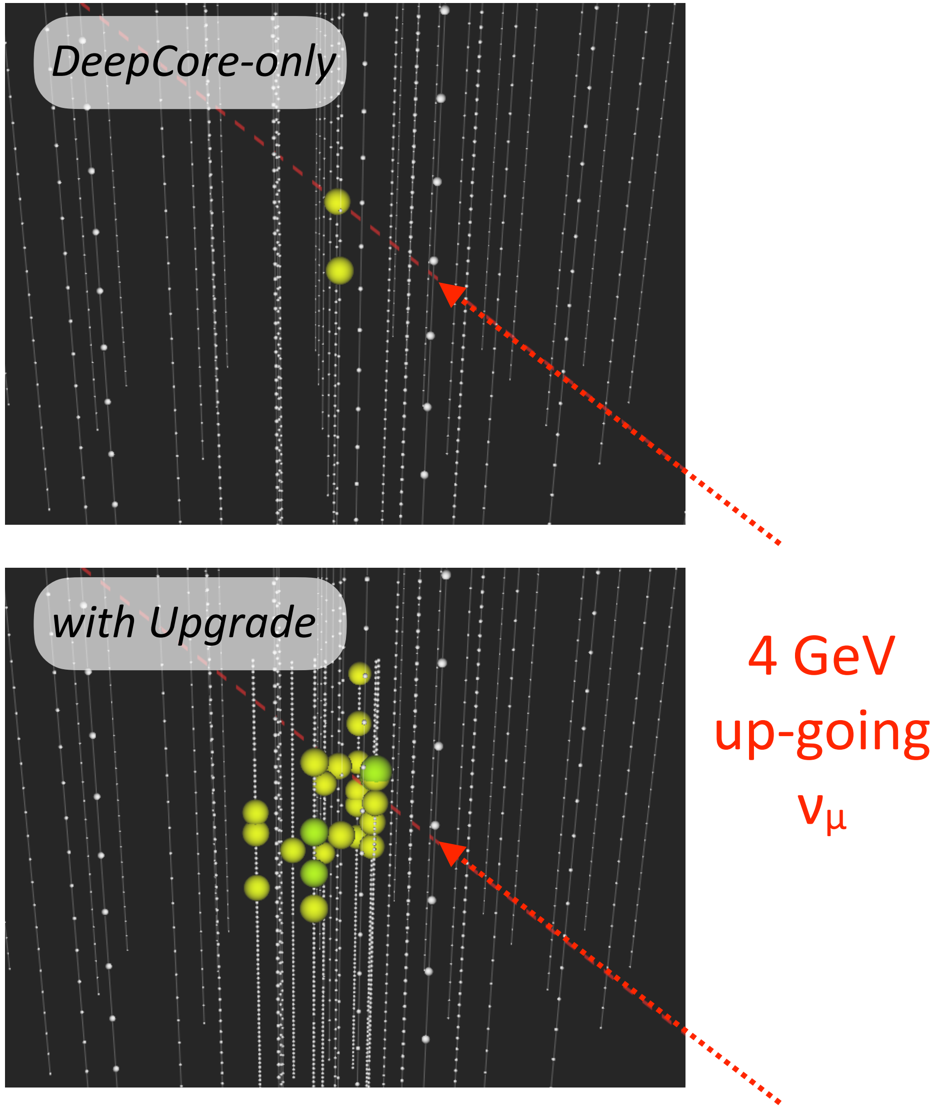
IceCube Gen2 TDR

DESY.

Improved ν detection

- Increased sensor density in **2 Mton core**
- Lowers energy threshold down to **~1 GeV**
- Increased efficiency and improved resolution at GeV-scale

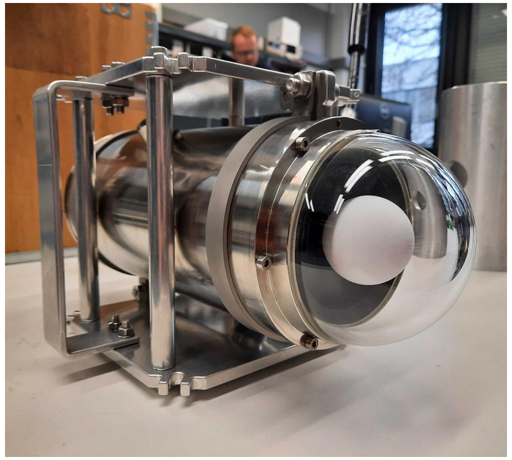


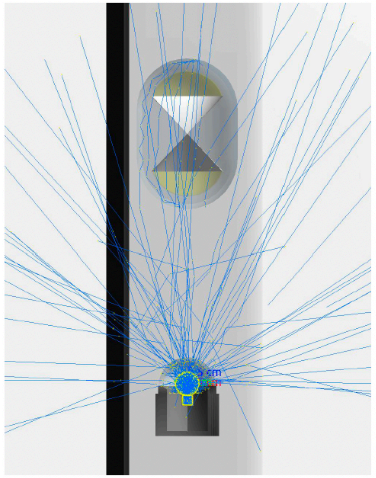


Detector calibration

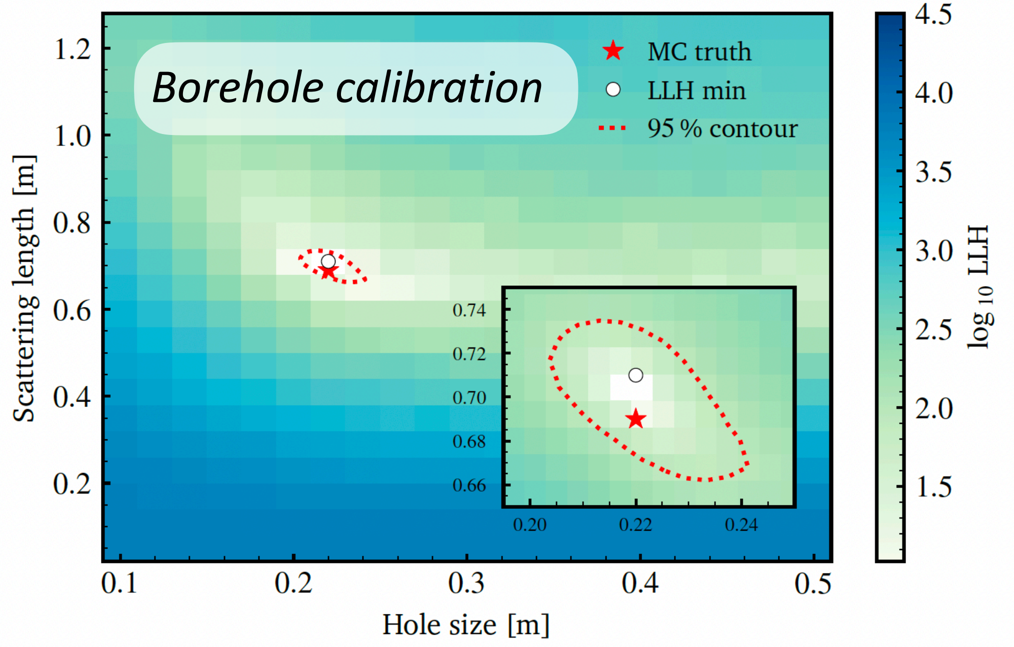
- Several **new calibration devices** will be installed with unique capabilities:
  - Acoustic sensors
  - Multi-wavelength, pulsed light sources — both highly collimated and isotropic emission
  - CMOS and video cameras
- **Reduce crucial systematic uncertainties** related to detector instrumentation and ice

Precision Optical Calibration Module (POCAM)



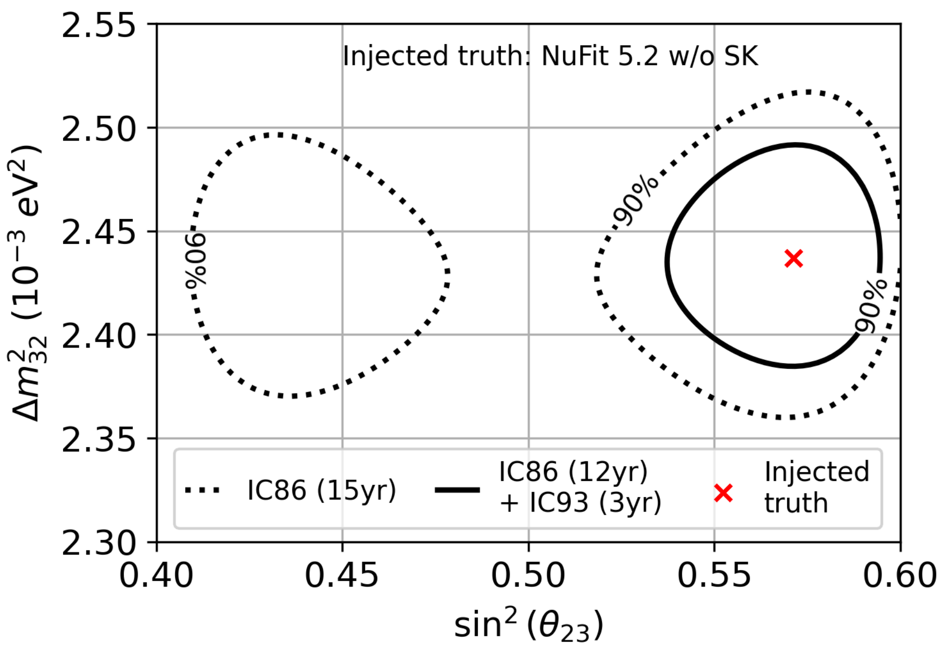


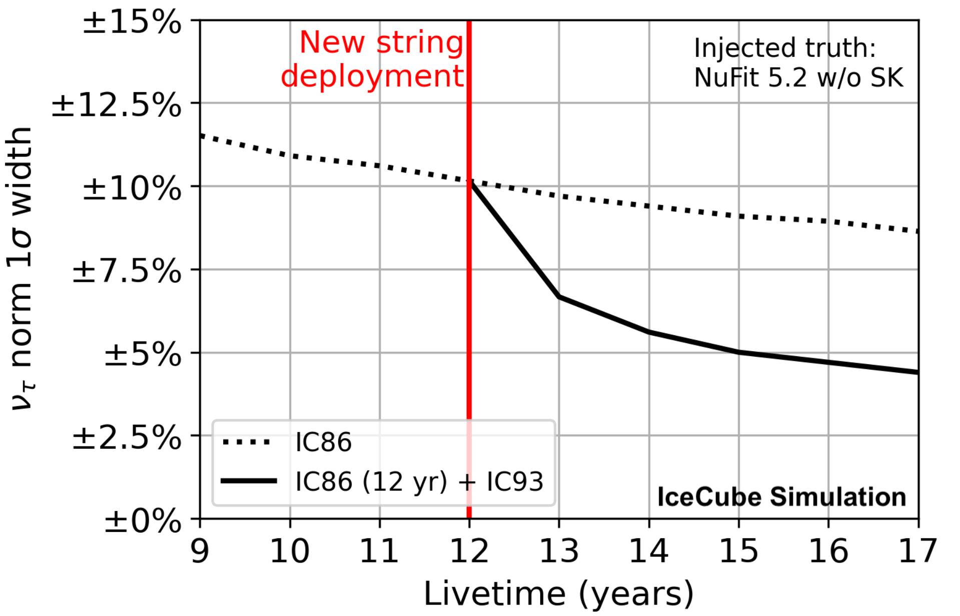
F. Henningson, PhD thesis TUM (2021)



More precise probe of atmospheric neutrino mixing

- Sensitivities estimated using simulated events with realistic filtering and systematics
- Analyzing up-going neutrinos ($\cos\theta < 0$) with energies from 3-300 GeV
- **Improved sensitivity** to θ_{23} and Δm^2_{32}
- Expect ~**5% precision on ν_τ normalization** with 3 years of livetime
- **More details in pre-print:** arXiv.2509.13066

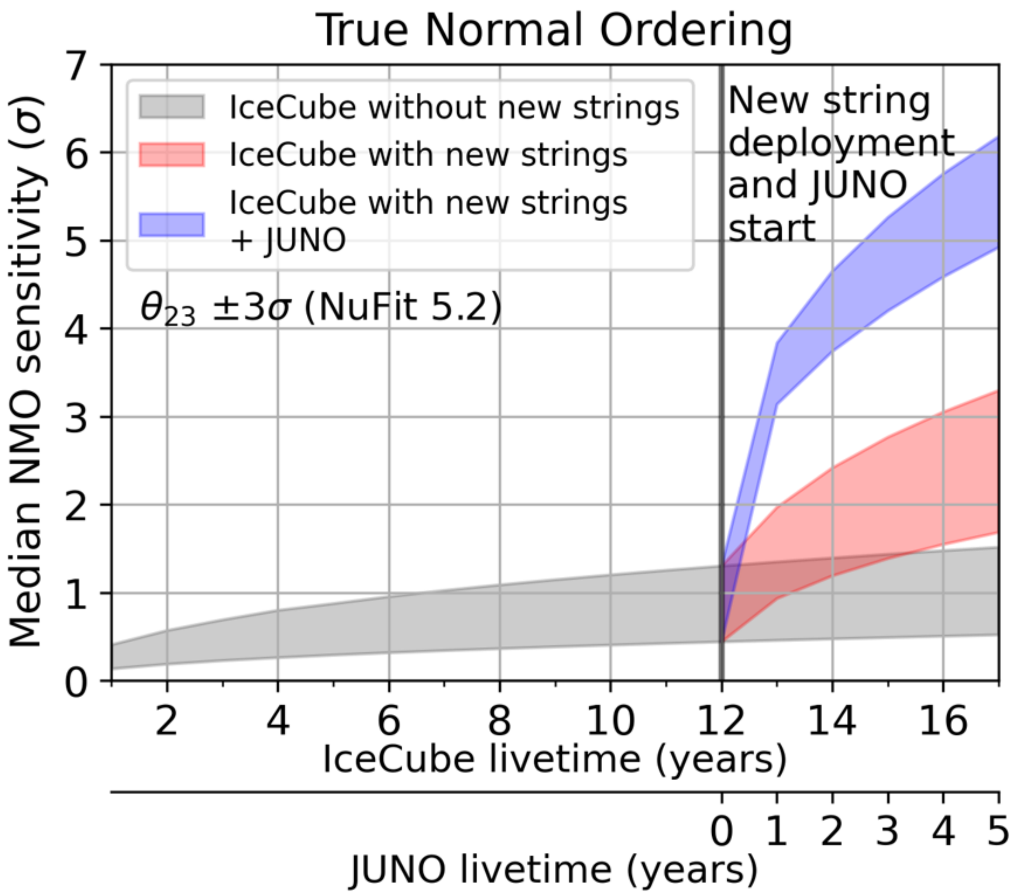




DESY.

Neutrino mass ordering

- **Resonance effects in the Earth** enhance ν_e (anti-ν_e) appearance for normal (inverted) mass ordering
- Dominant effect seen in low energy (<5 GeV), core-crossing events
- Sensitivity with IceCube Upgrade:
  - **3σ rejection of wrong mass ordering** after 4 years in optimistic scenario
  - Even faster if combined with JUNO (see e.g. Phys. Rev. D 101, 032006)



Test your own models/analyses with the *IceCube Upgrade MC data release*

DESY.

Summary & Outlook

- **New atmospheric oscillation results** from IceCube DeepCore are consistent with global constraints

- **Measured ν_τ normalization** consistent with standard expectation/PMNS unitarity

- **IceCube Upgrade installation in 2025/26** will yield more data and higher precision studies

Preparations from last field season at South Pole

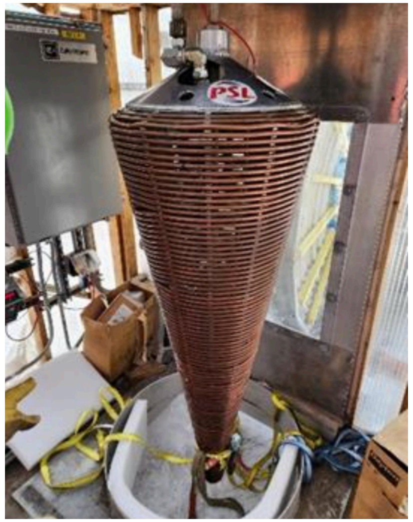


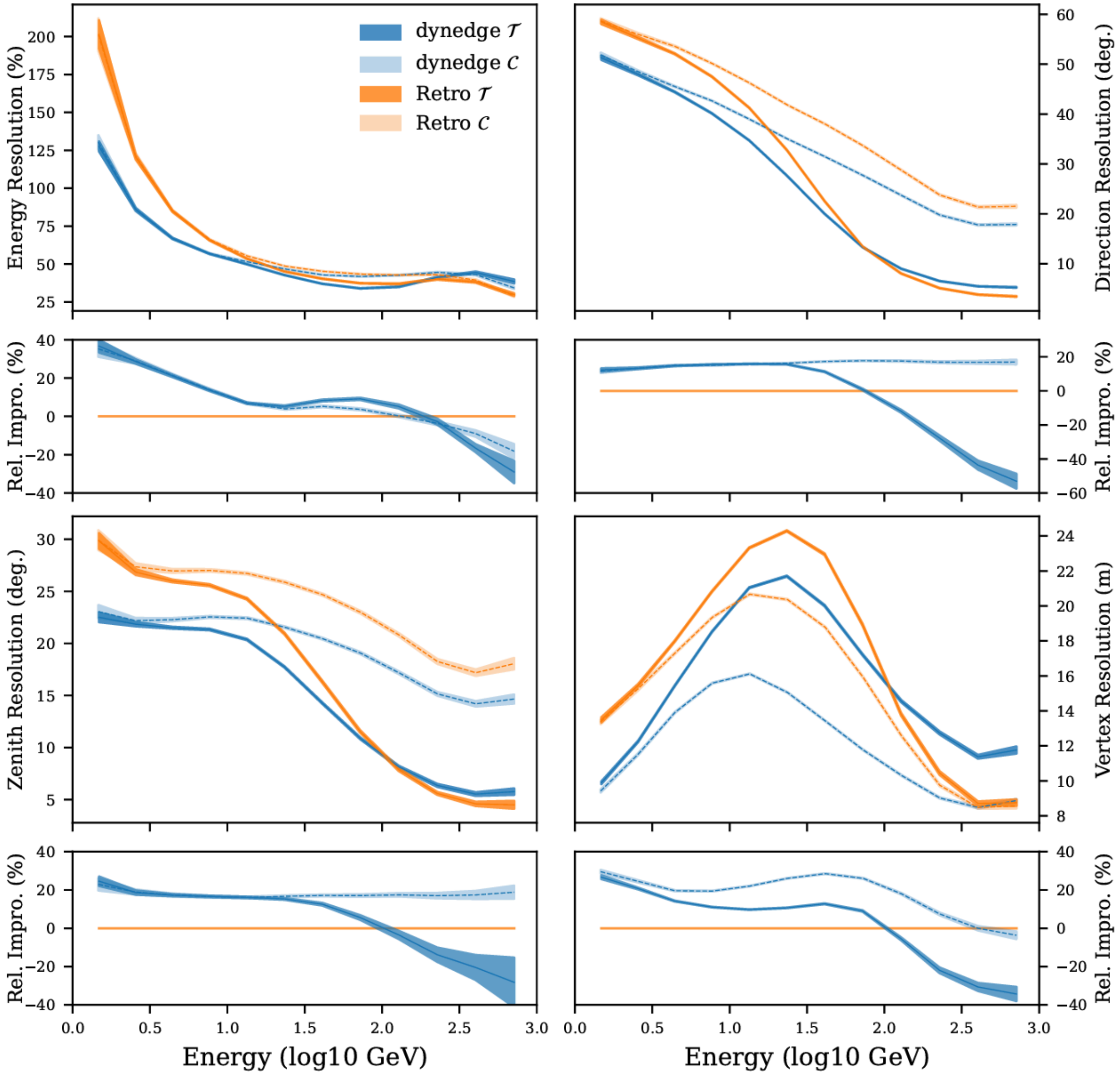
Photo Credit: NSF / IceCube

Backups

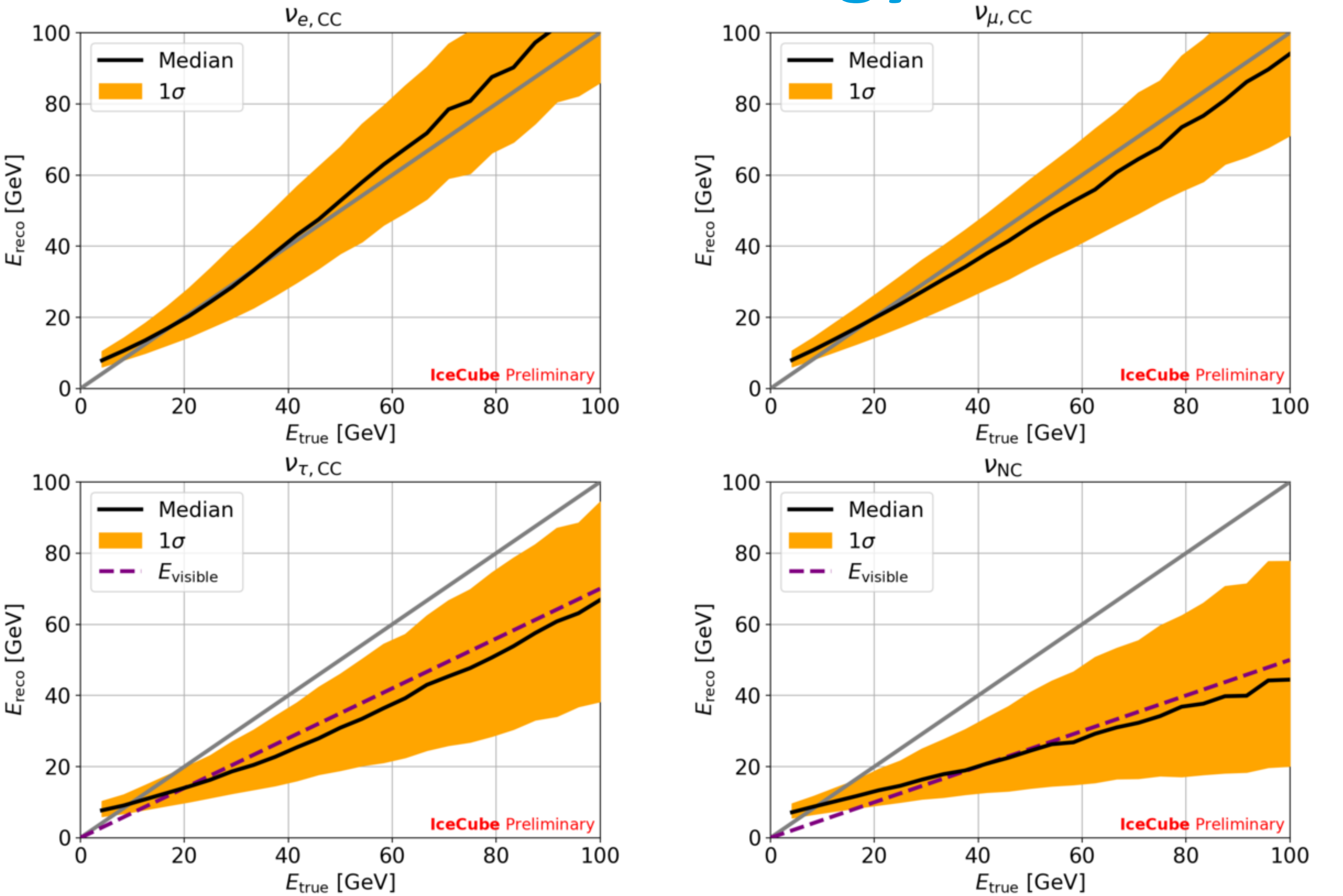
Graph Neural Network Performance

T = tracks
C = cascades

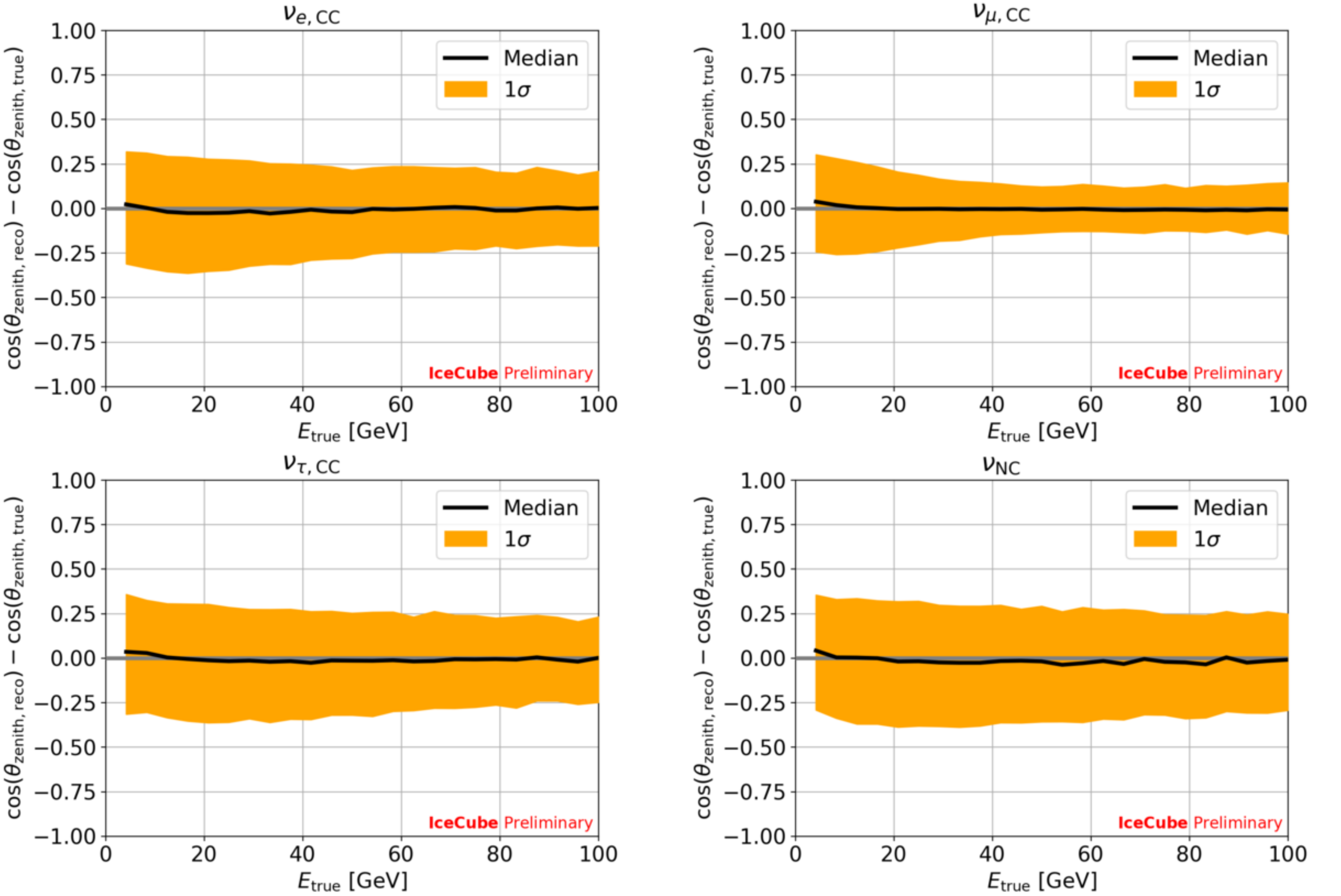
- GNN outperforms classical likelihood approach (i.e. Retro)
- Improved energy, zenith resolution, especially at lower energies
- Runtime performance:
    - ~5kHz on GPU
    - 37 Hz on single CPU core



Graph Neural Network - Energy resolution



Graph Neural Network - Zenith resolution

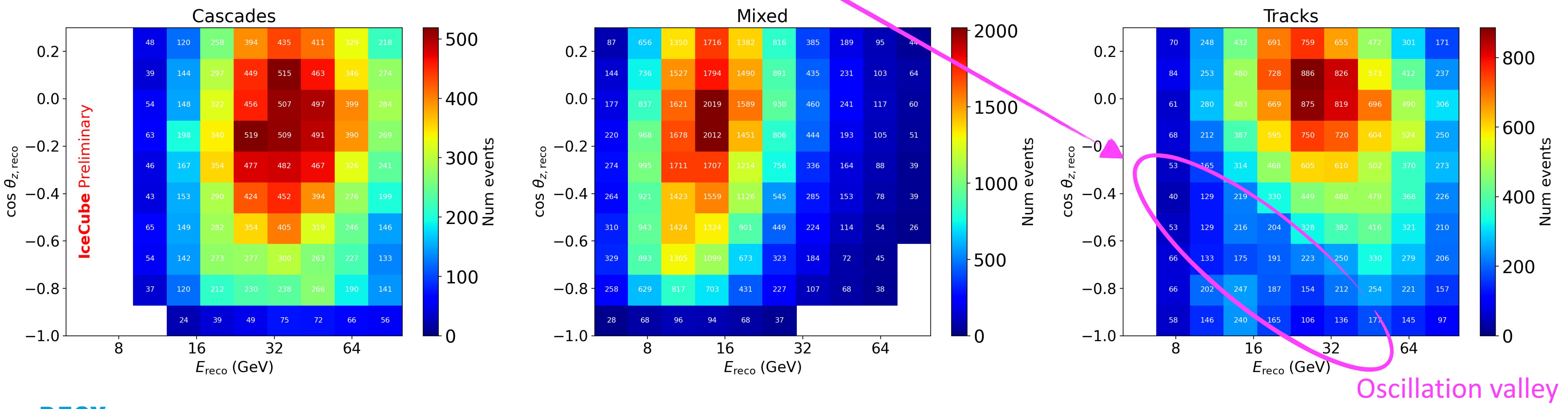


DESY.

New atmospheric neutrino mixing analysis

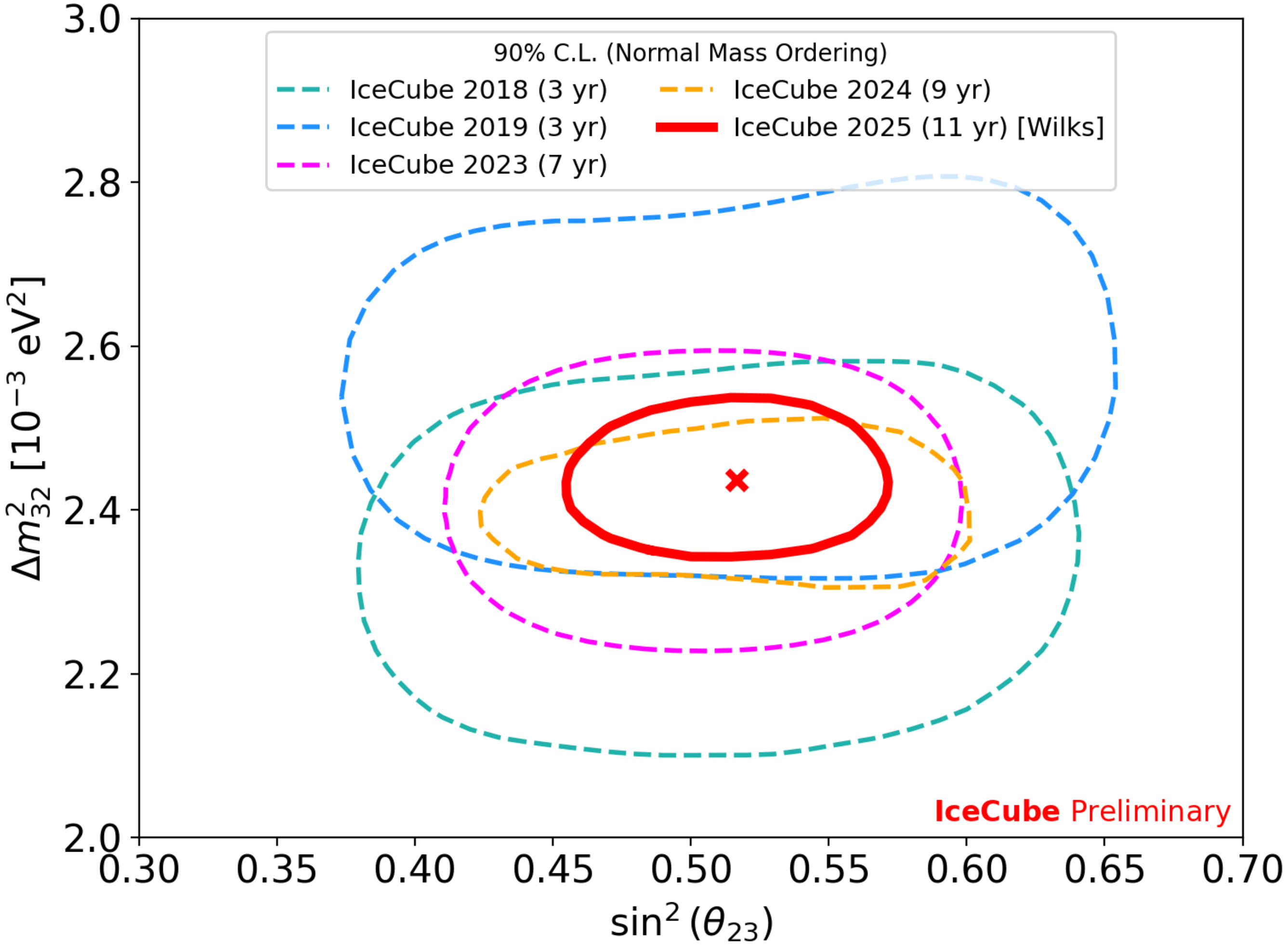
- Over 100k neutrinos in final sample
- >5k charged current ν_τ!
- Oscillation valley visible by eye in track-like sample from **detector data**

	Rate [μHz]	Num events [11.1 yr]	% of sample
$\nu_{e,\mathrm{CC}}$	71	$24,822 \pm 56$	22.8
$\nu_{\mu,\mathrm{CC}}$	187	$65,665 \pm 97$	60.4
$\nu_{\tau,\mathrm{CC}}$	16	$5,629 \pm 21$	5.2
ν_{NC}	34	$11,912 \pm 39$	11.0
μ_{atm}	2	754 ± 46	0.7
Total	311	$108,784 \pm 129$	-



ν_μ disappearance ($\nu_\mu \rightarrow \nu_\mu$)

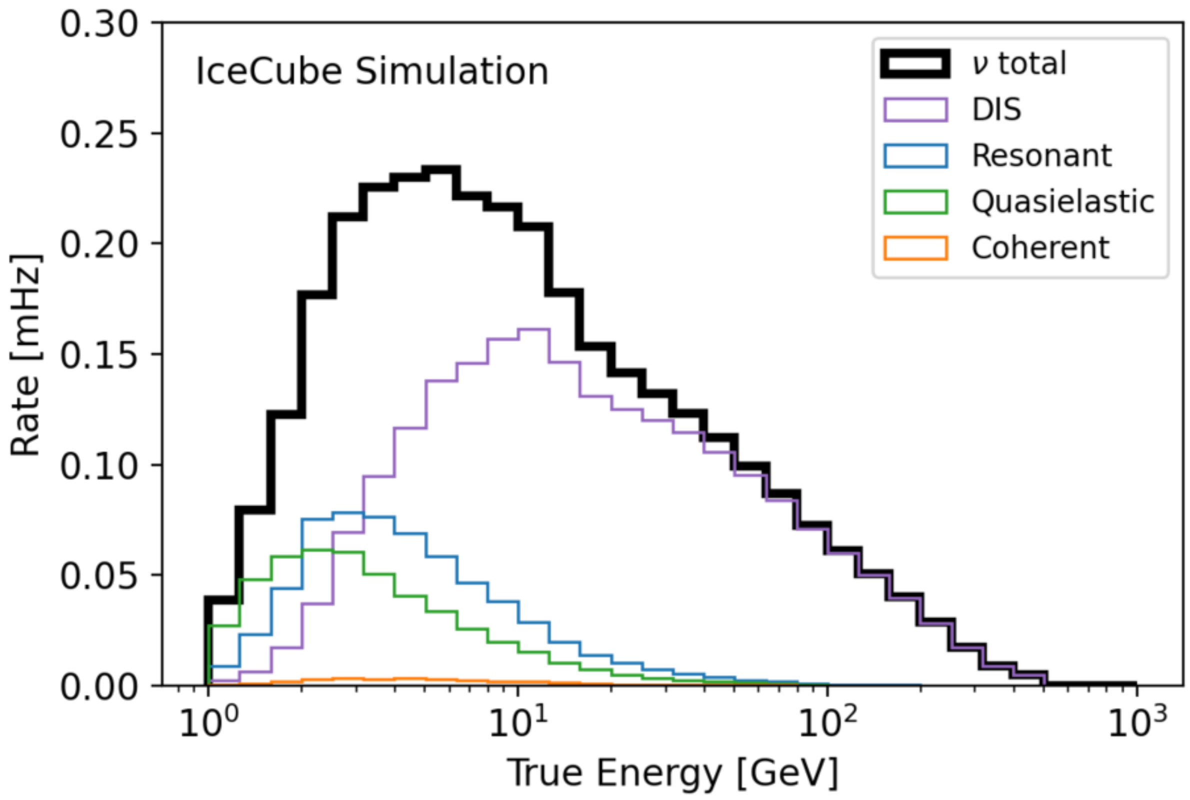
- New result is **consistent** with previous IceCube DeepCore analyses
- **Somewhat expected** due to overlap between samples and similar systemic treatments
- Still, very **different approaches to reconstruction and background rejection** lead to similar results



DESY.

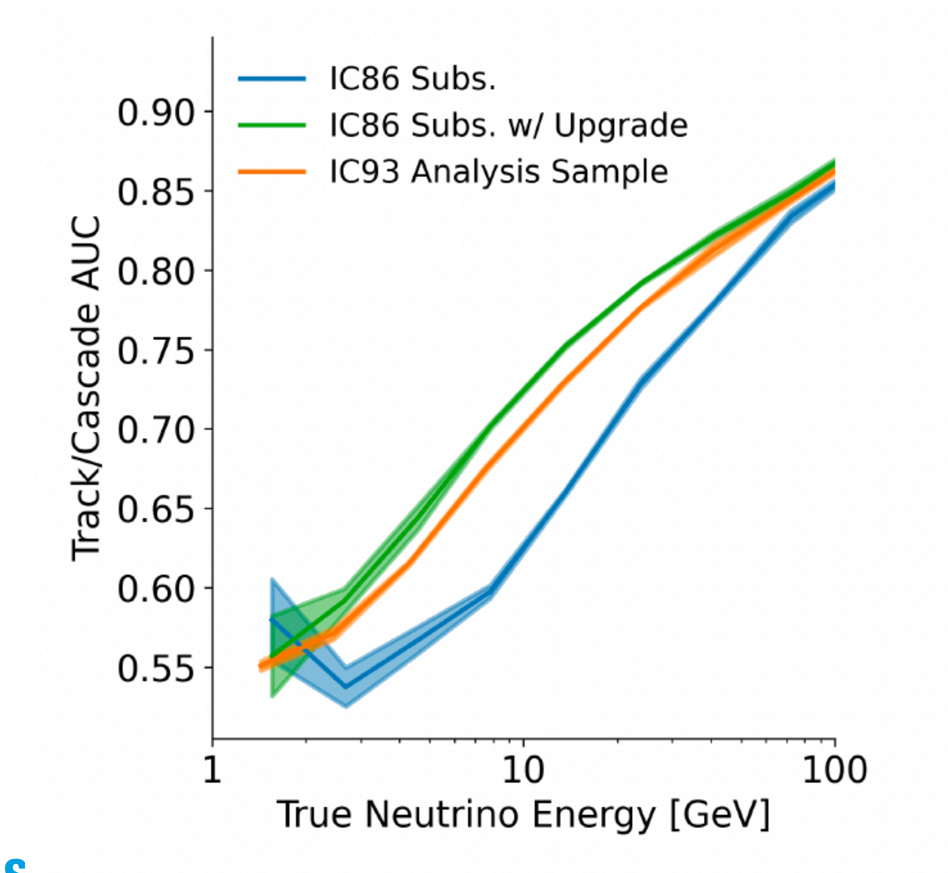
Breakdown of event rate with ICUpgrade

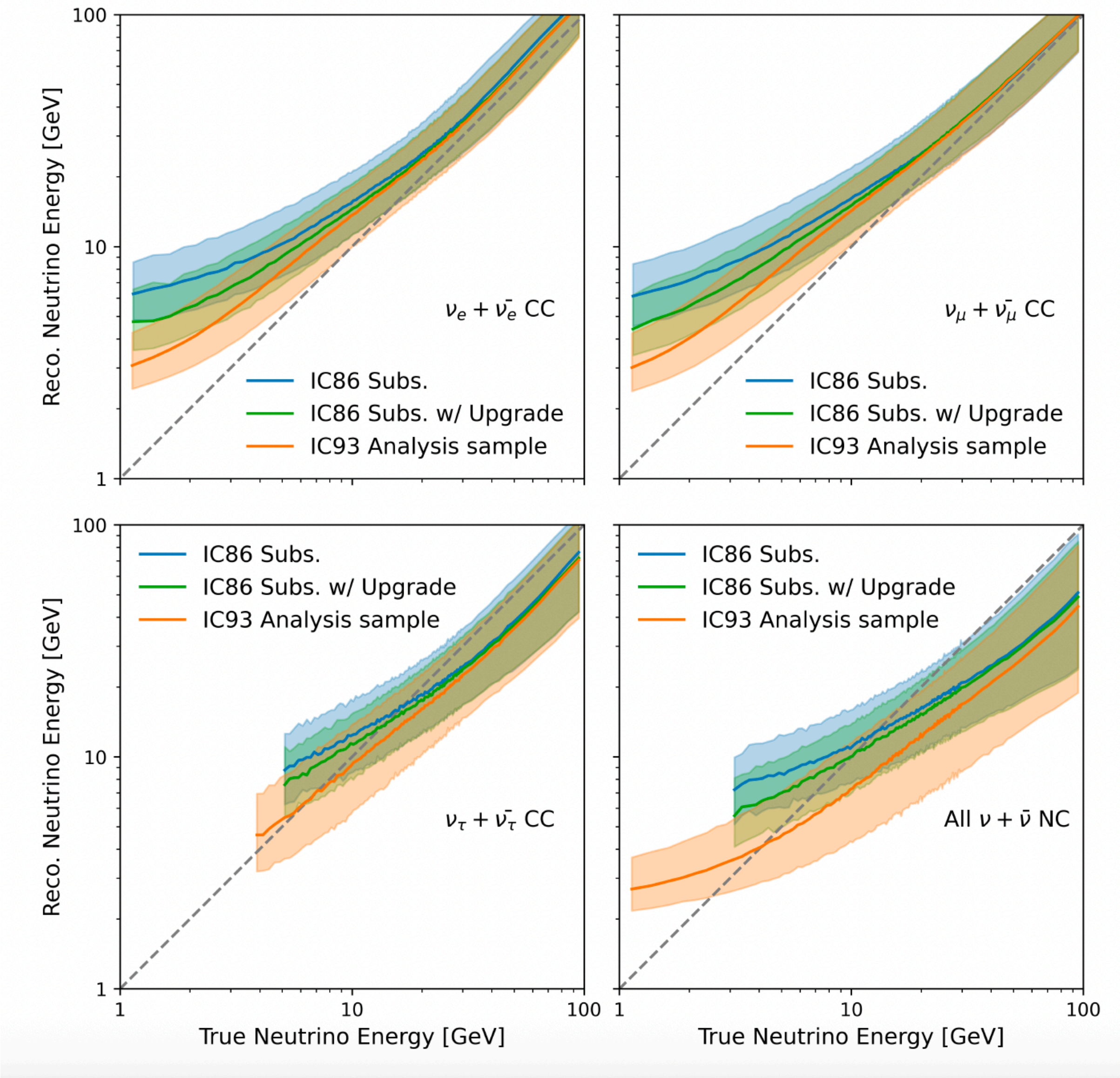
- Increased effective area at lower energies compared to DeepCore
- Deep inelastic scattering events remain the dominant contribution
- Larger relative contributions from resonant, quasi elastic and coherent scattering
- Investigating potential for new systematic uncertainties using GENIE



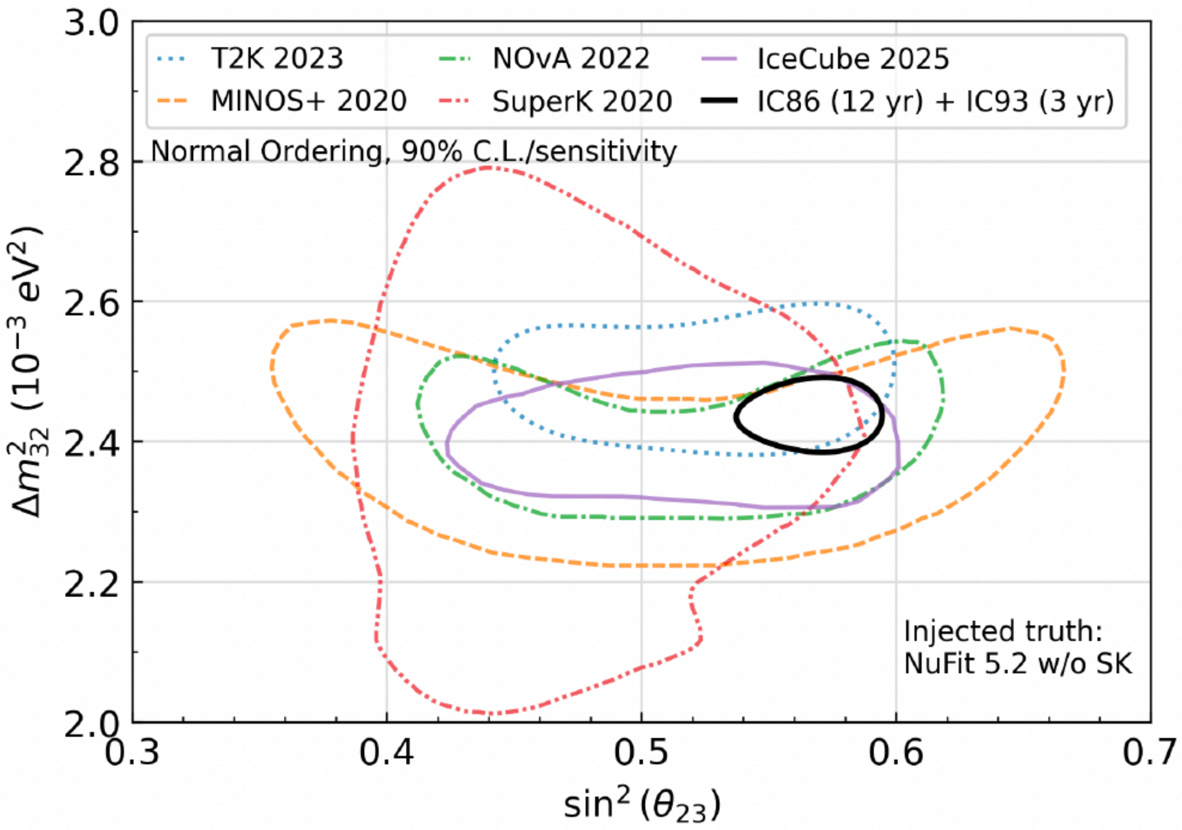
Reconstruction performance with IC93

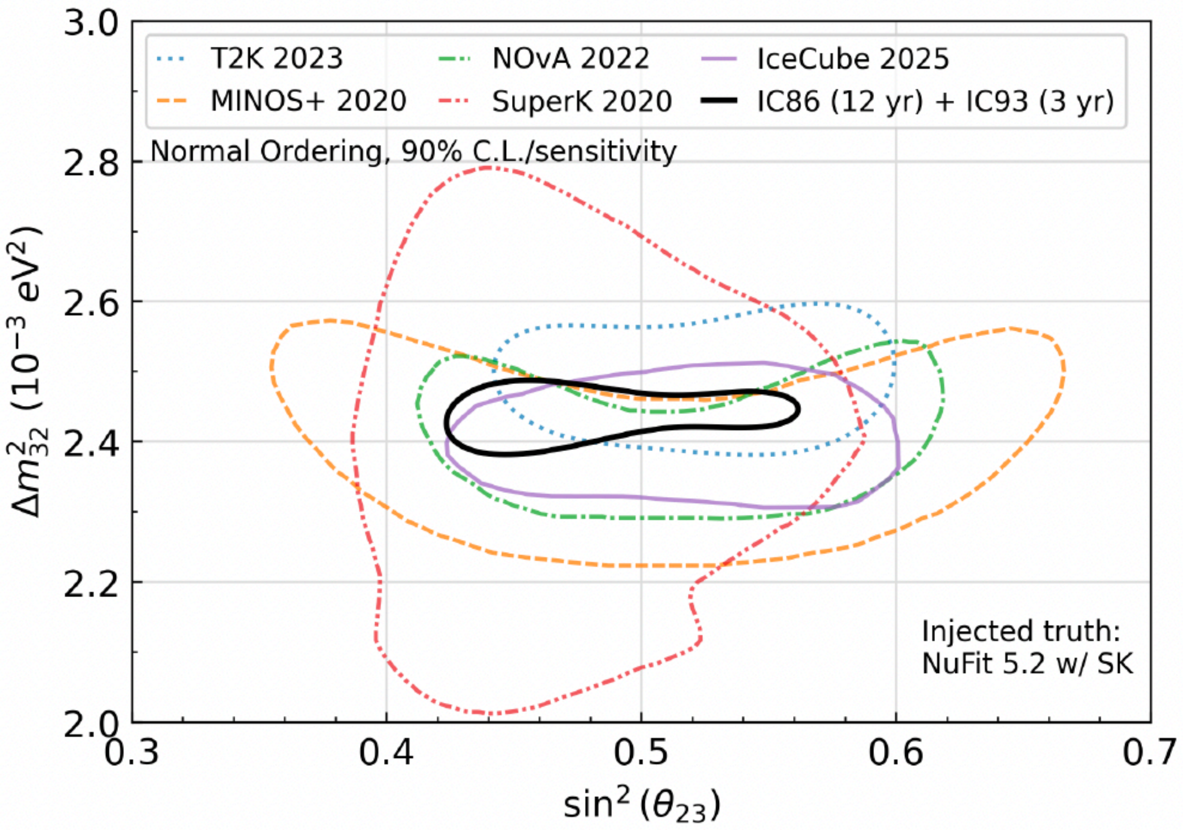
- Improved reconstruction, particularly at low energies





ICUpgrade: atmospheric neutrino mixing





DESY.

NMO Sensitivity with IceCube Upgrade