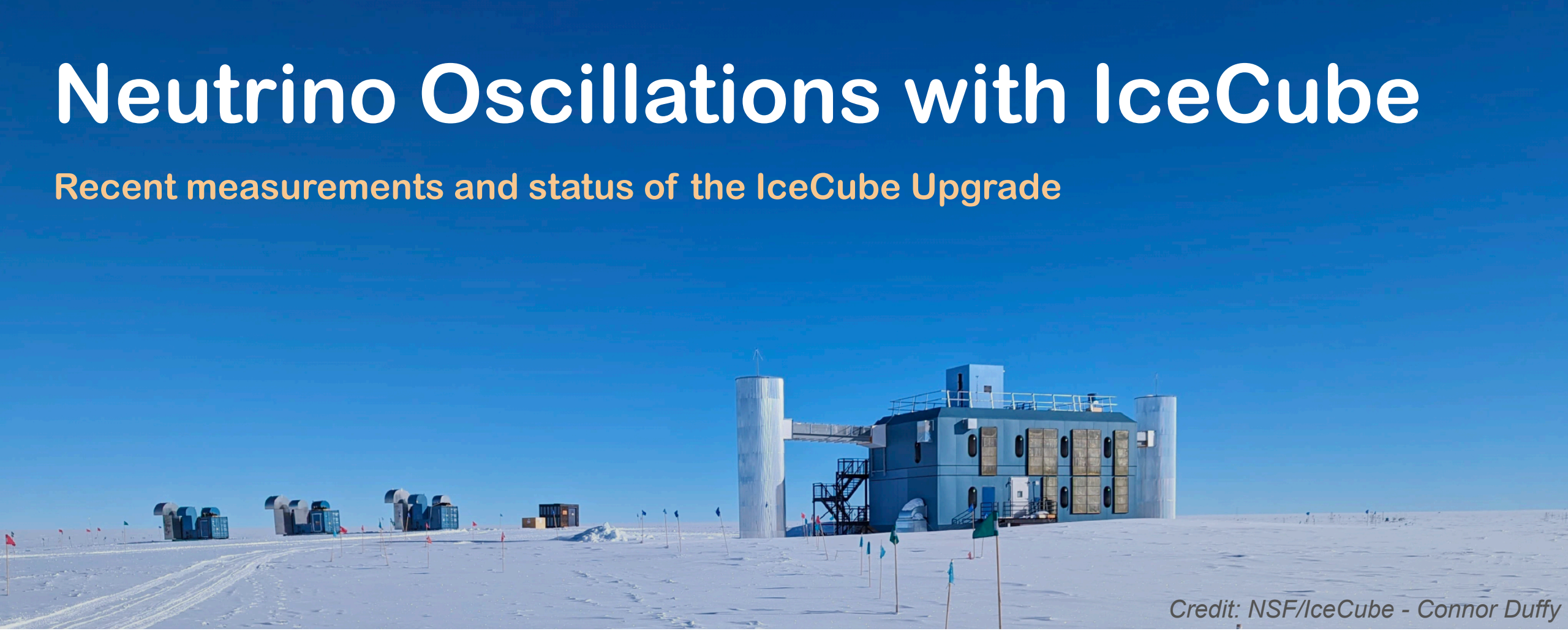
Neutrino Oscillations with IceCube

Recent measurements and status of the IceCube Upgrade



Credit: NSF/IceCube - Connor Duffy

Summer Blot
22.02.2024
Lake Louise Winter Institute 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ICECUBE UPGRADE

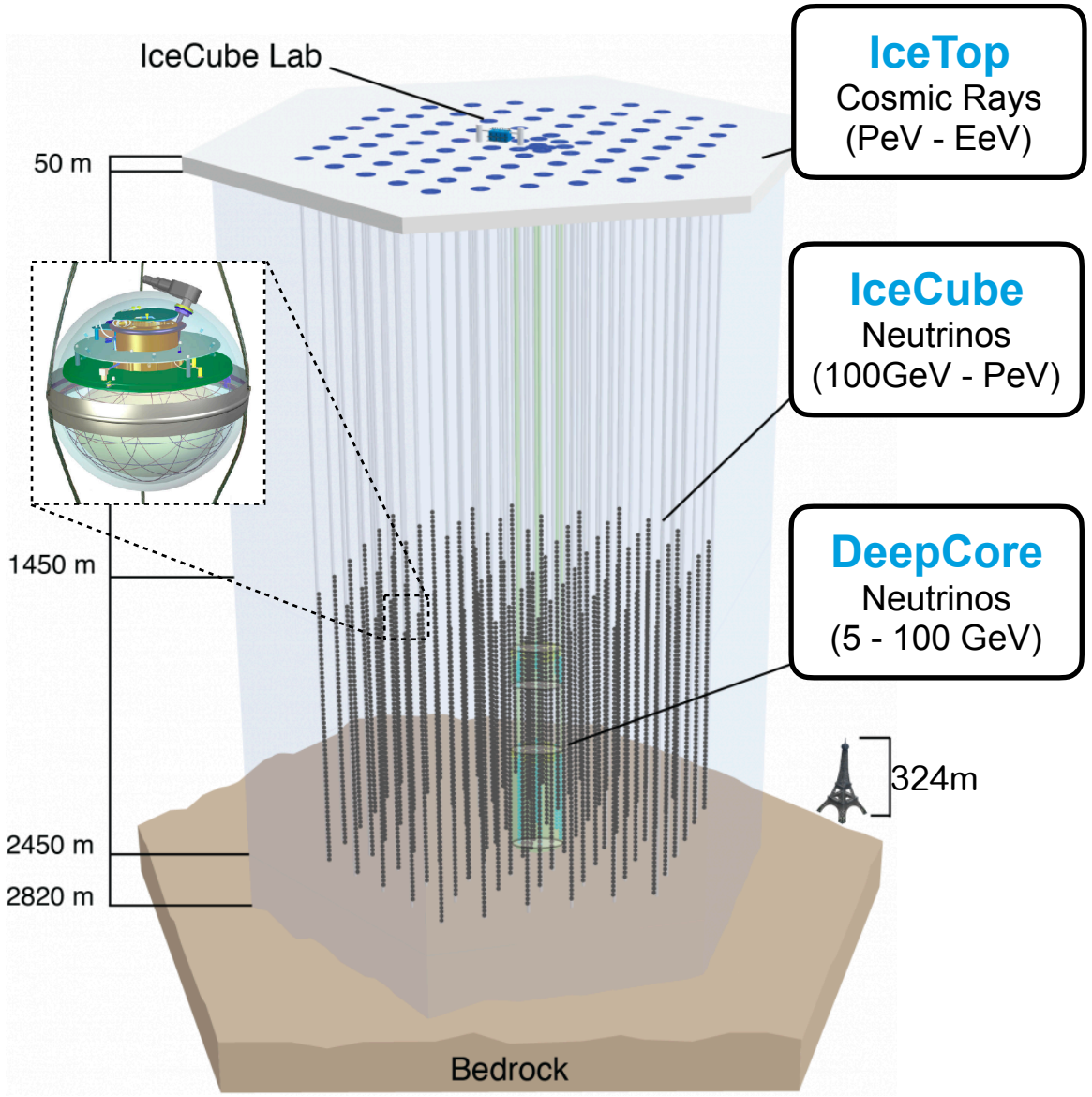
DESY.

The IceCube Neutrino Observatory

- ~1 km^3 Cherenkov detector
- Detect photons with over 5000 Digital Optical Modules (DOMs)
- DOM spacing, PMT quantum efficiency and ice properties are key factors in performance

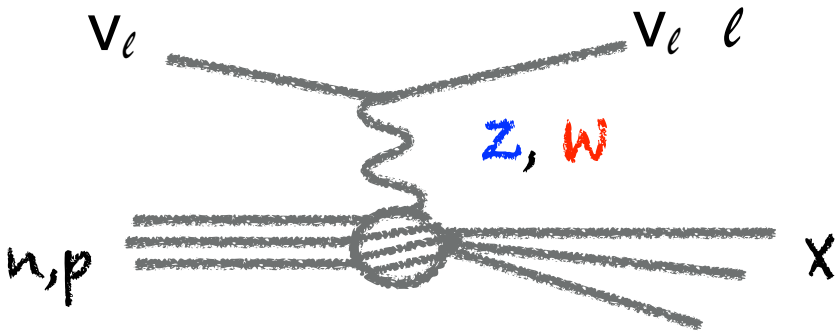
	Spacing [m]		Energy threshold [GeV]
	Horiz.	Vertical	
IceCube	125	17	~100
DeepCore	~50	7	~5

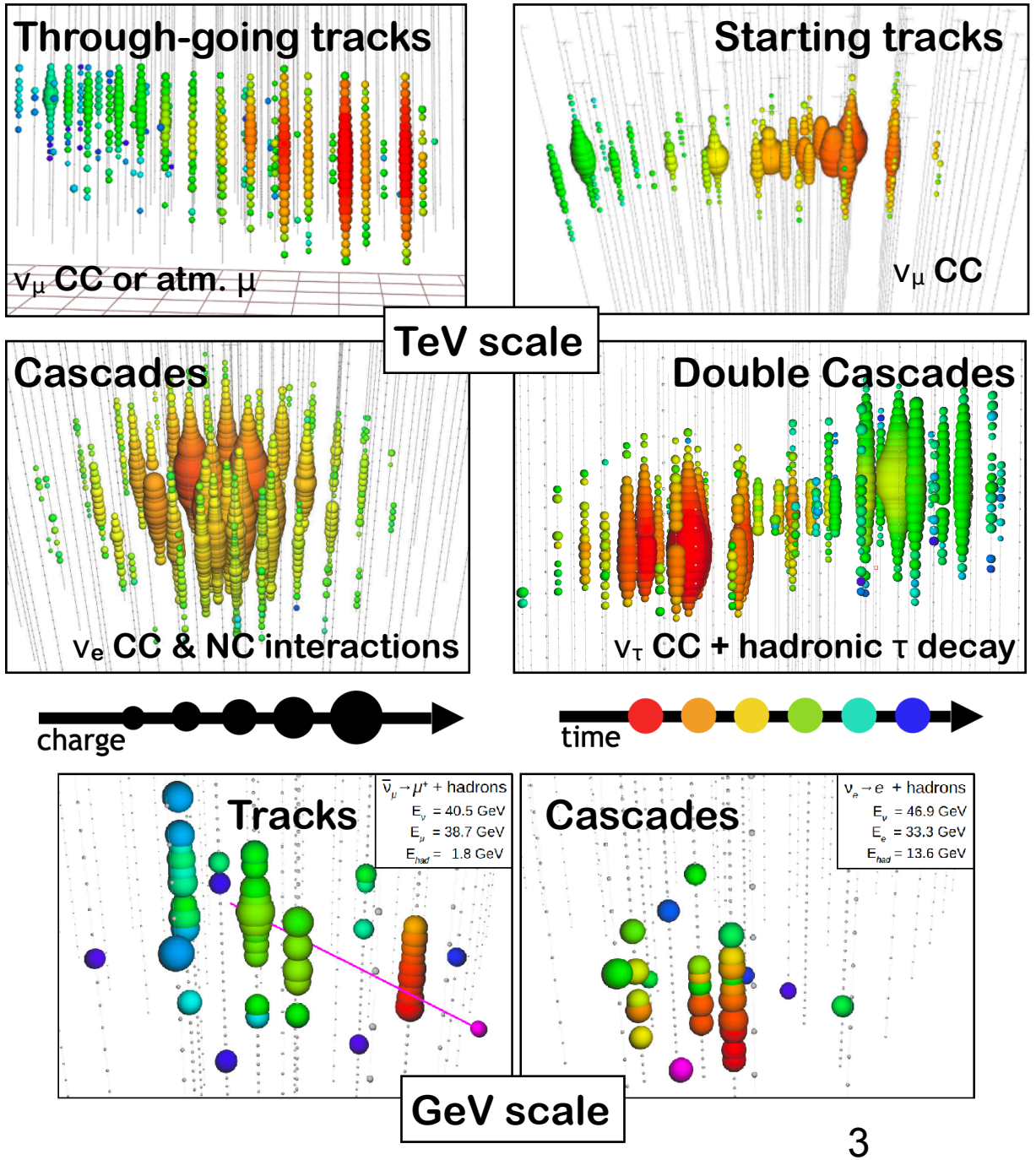
*DeepCore PMTs ~35% higher Q.E.



Neutrino signatures

- DOMs (x,y,z) record photons over time
- Reconstruct energy, direction and particle type (i.e. PID)
- Mostly Deep Inelastic Scattering
- Complexity at vertex washed out by detector sparsity and photon scattering in ice





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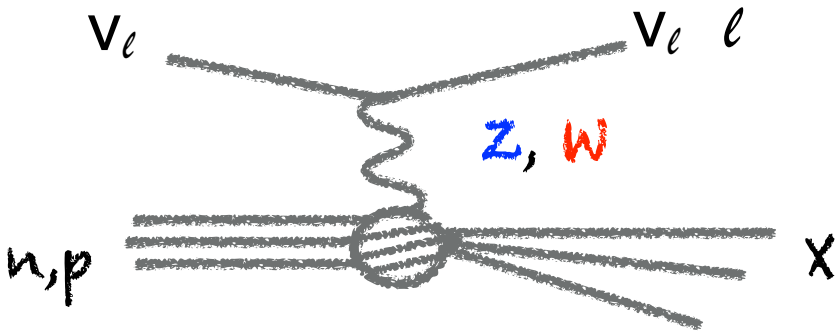
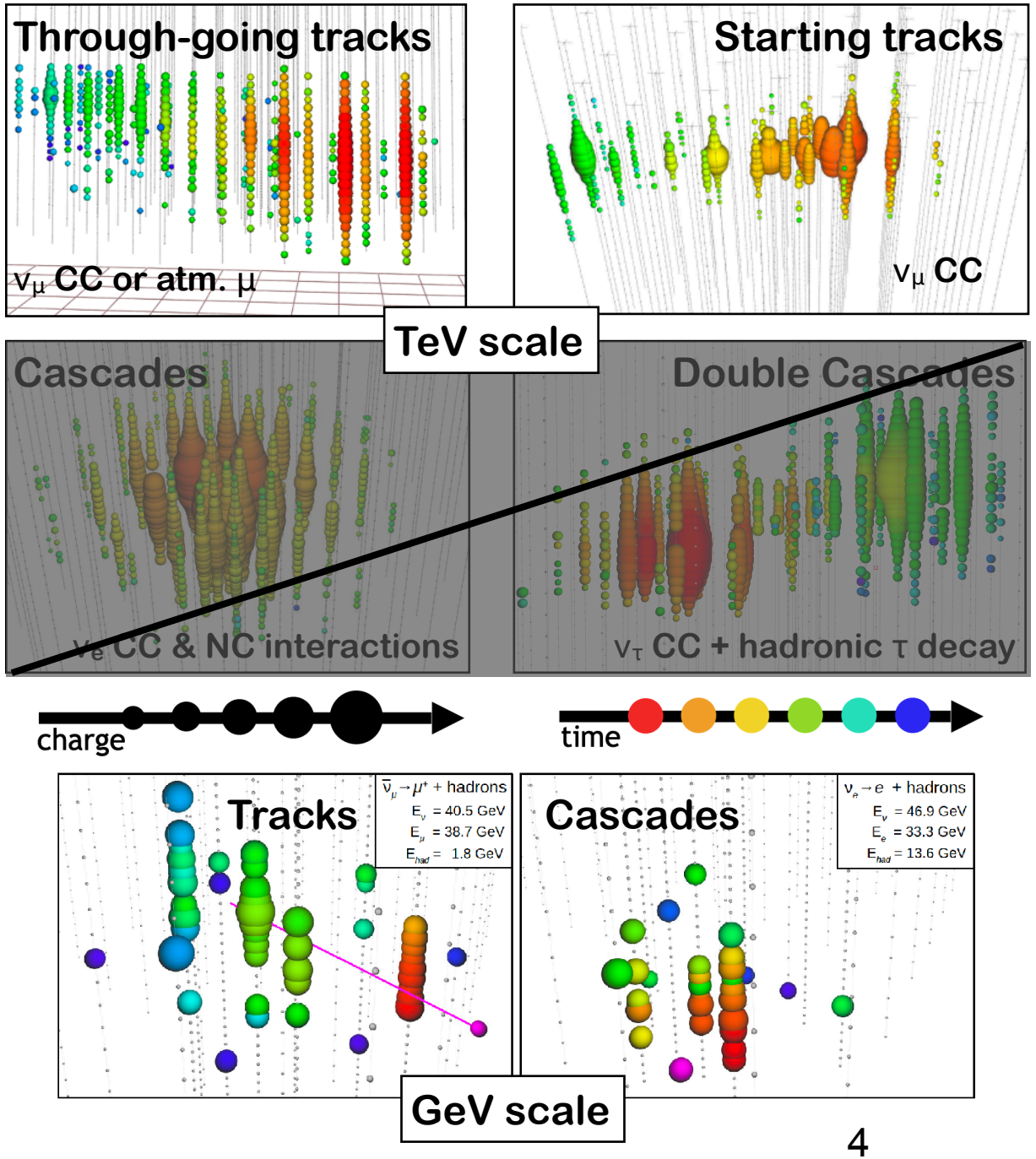
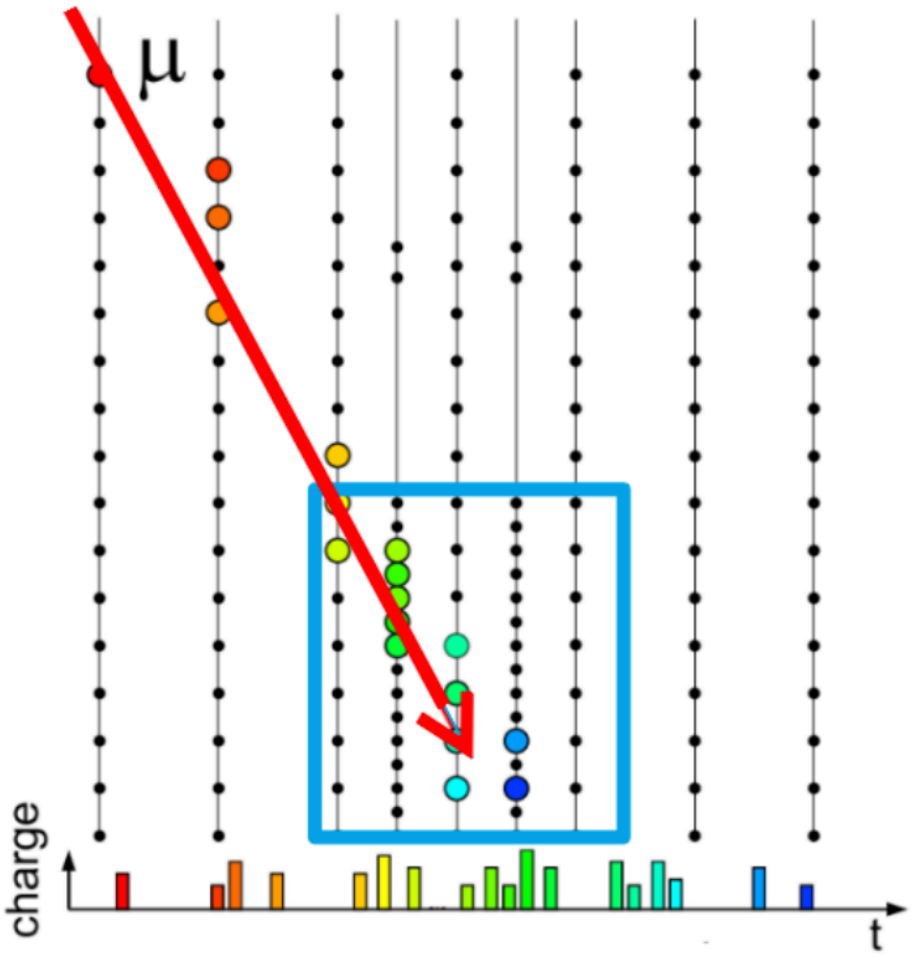




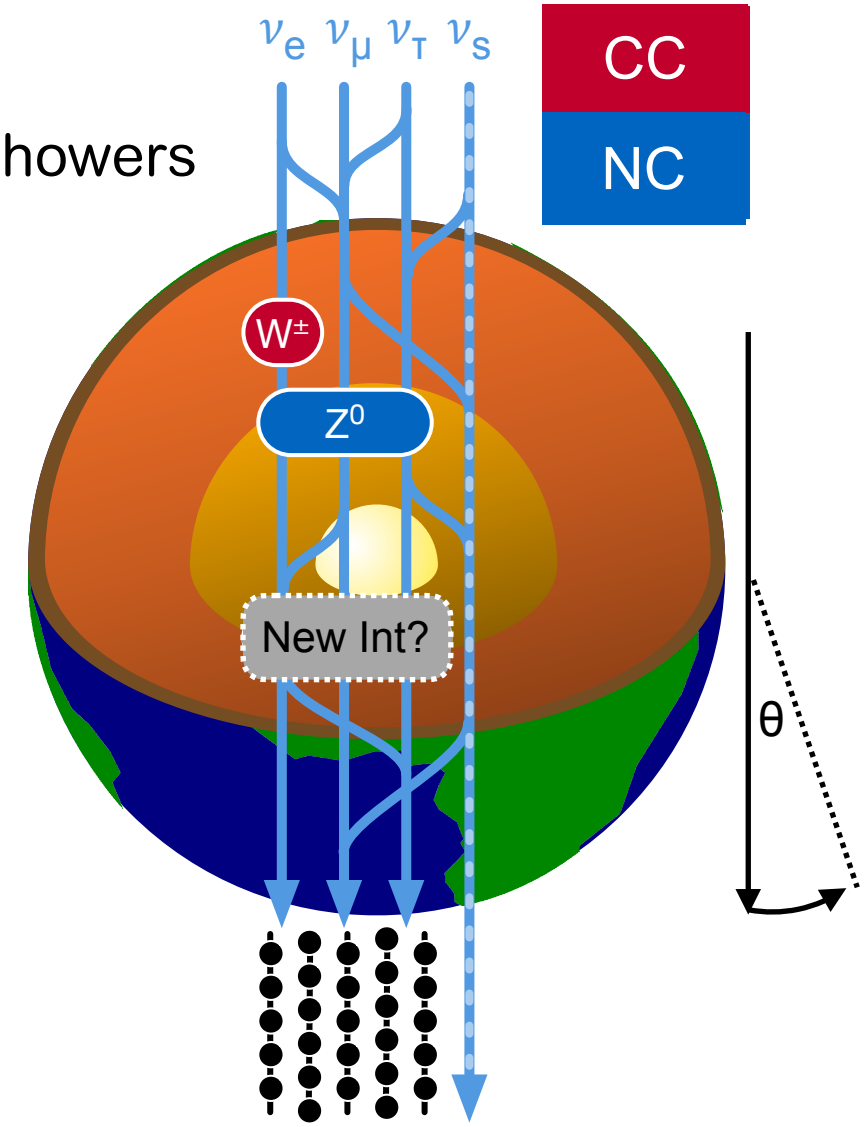
Sources of background

- **Random coincidences** from radioactivity in PMTs/pressure housing
  - Reject with causality-based cleaning algorithms
- **Atmospheric muons** from cosmic ray air showers
  - Mitigate by selecting up-going events: Earth as a shield
  - Special for DeepCore: use IceCube as a veto
- Both types of background are reduced to a negligible level, **leaving hundreds of thousands of neutrinos!**



Atmospheric Neutrino Oscillations

- Natural beam of neutrinos produced by cosmic ray air showers
  - Wide energy band (GeV-TeV)
  - All flavours , neutrino + antineutrino
- Wide range of baselines: ~20 - 12,700 km
- Passage through variable density profile of Earth



Flavour Mass

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

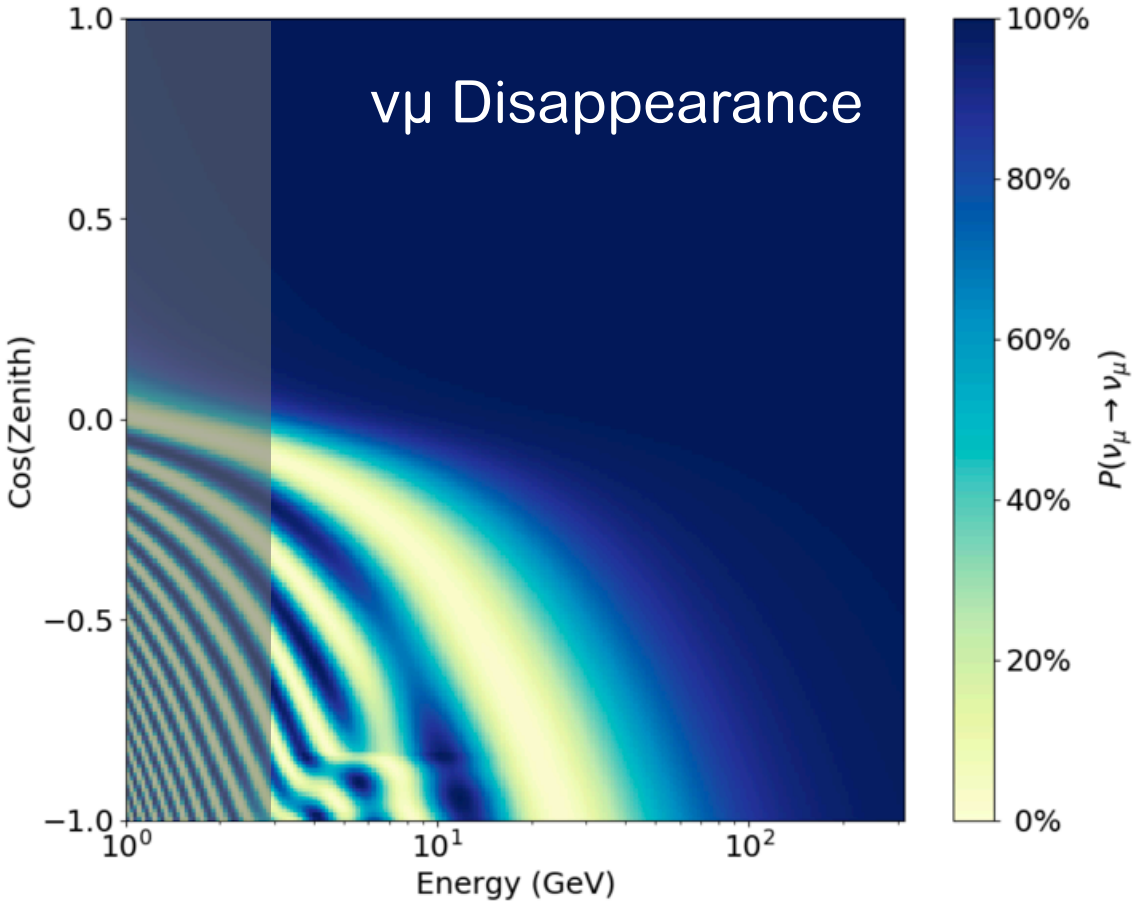
$$\hat{H} = \frac{1}{2E} U\hat{M}^2U^\dagger + \hat{V}_{int}$$

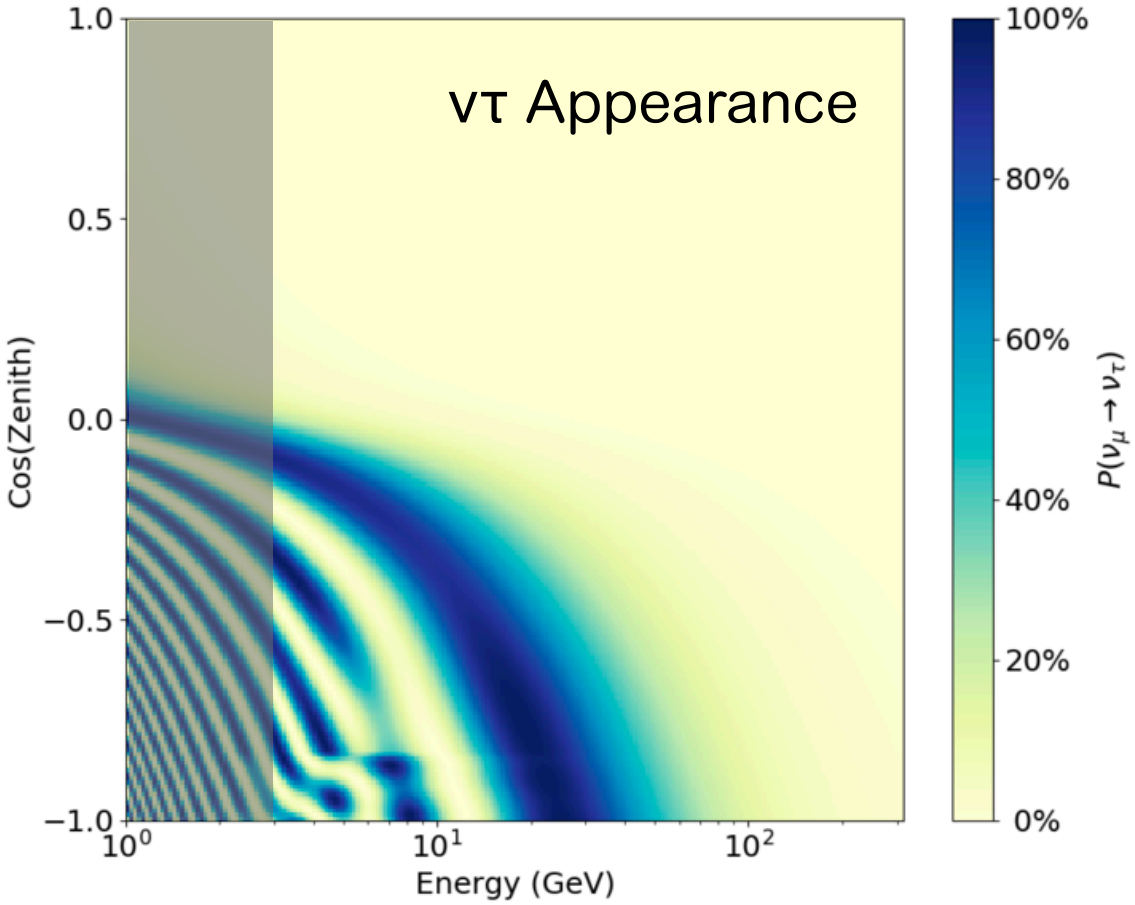
U_{PMNS} parameterised by…
- Three mixing angles: θ_{12}, θ_{13}, θ_{23}
- δCP

Two mass splittings…
- $\Delta m^2_{21} \sim 10^{-5}$ eV^2
- $\Delta m^2_{32} \sim 10^{-3}$ eV^2

IceCube DeepCore primarily sensitive to θ_{23} and Δm^2_{32}

Standard Atmospheric Neutrino Oscillations (3x3 mixing)

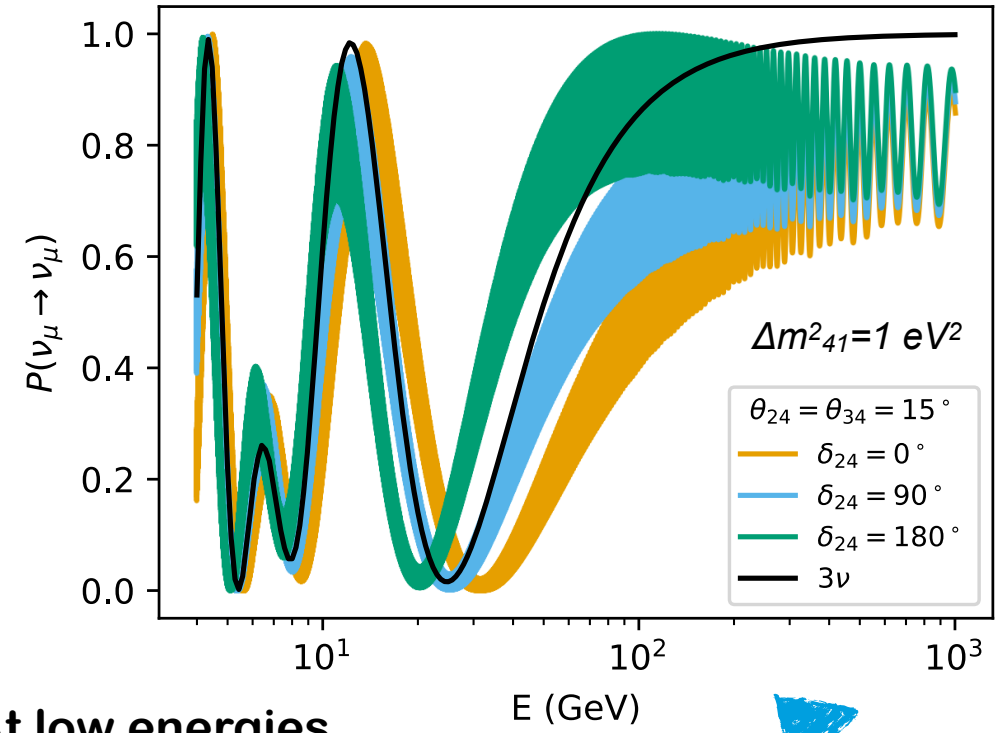




*Normal ordering assumed

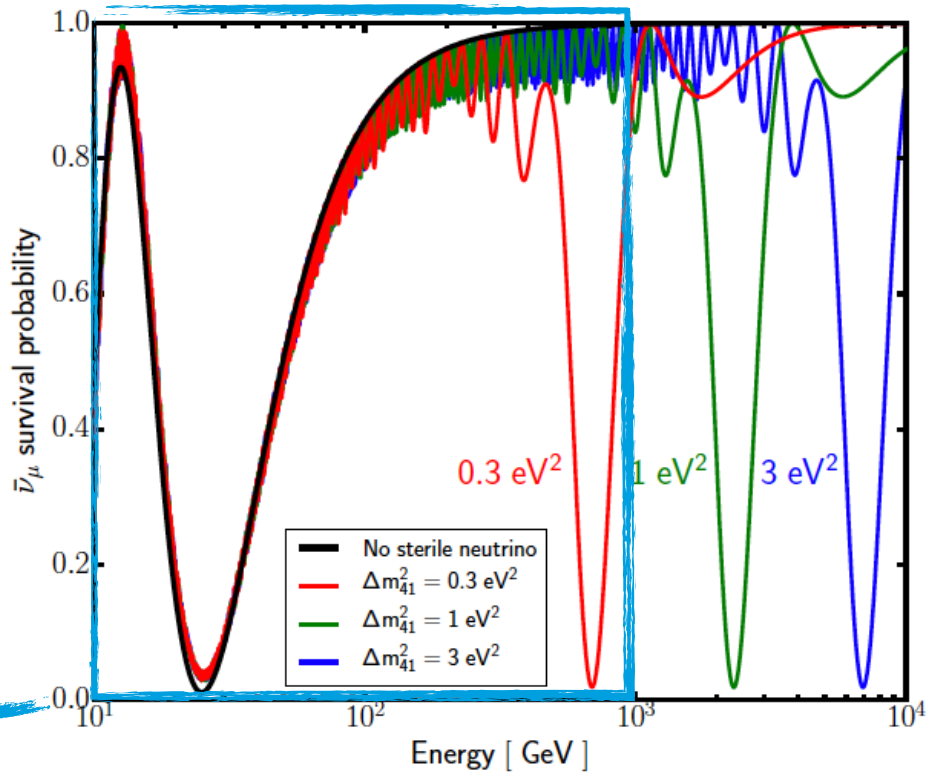
Oscillations + 1 light sterile neutrino (4x4 mixing)

Extended 4x4 mixing matrix introduces new parameters



At high energies

- MSW-like resonance effect
- Sensitive to Δm^2_{41},θ_{24} (θ_{34})



At low energies

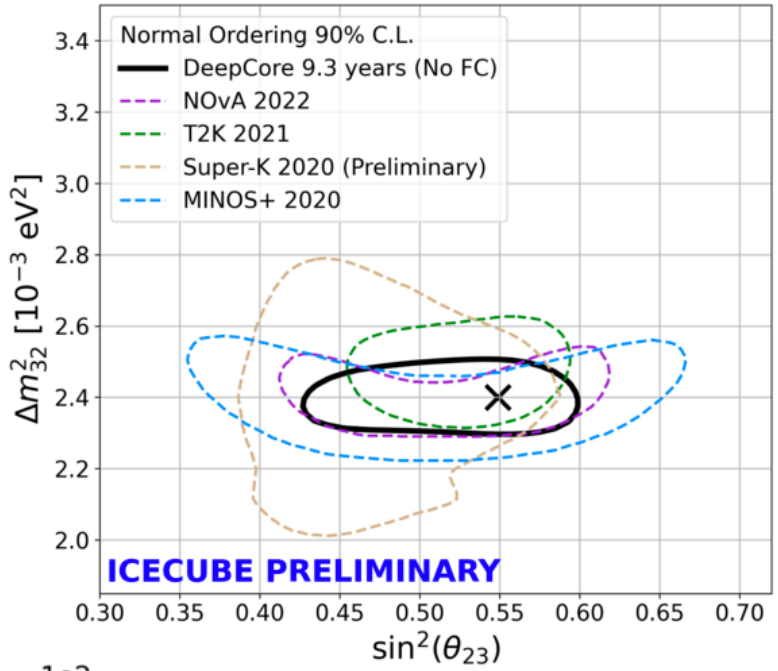
- Cannot resolve rapid oscillations
  - Independent of $\Delta m^2_{41} \gtrsim 1\text{eV}^2$
- Sensitive to θ_{24},θ_{34},δ_{24}

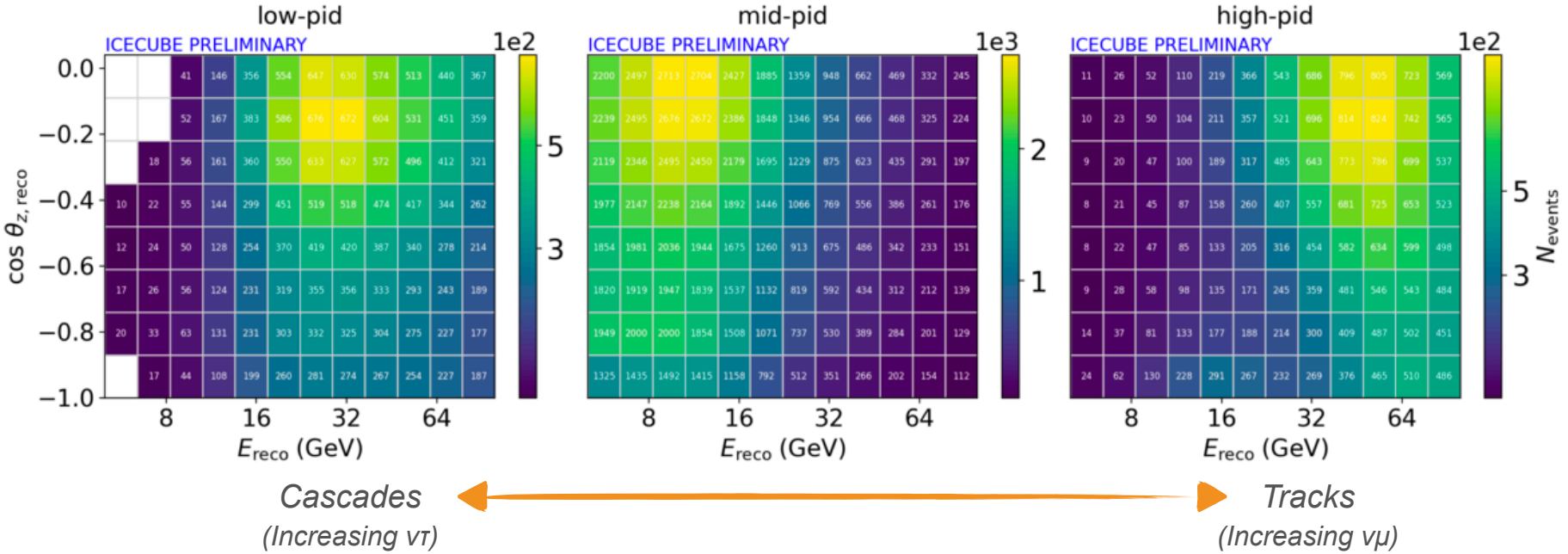
Strongest effects for core-crossing neutrinos

Yu, Micallef, ICRC2023

Recent measurement of Δm^2_{32} & θ_{23}

- Uses Convolutional Neural Network reconstructions
- Atm. muon contamination < 1% !
- Likelihood fit includes nuisance parameters for systematics: detector calibration, flux and cross-section





$$\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$$

$$\Delta m^2_{32} = (2.40^{+0.05}_{-0.04}) \times 10^{-3}\ \mathrm{eV}^2$$

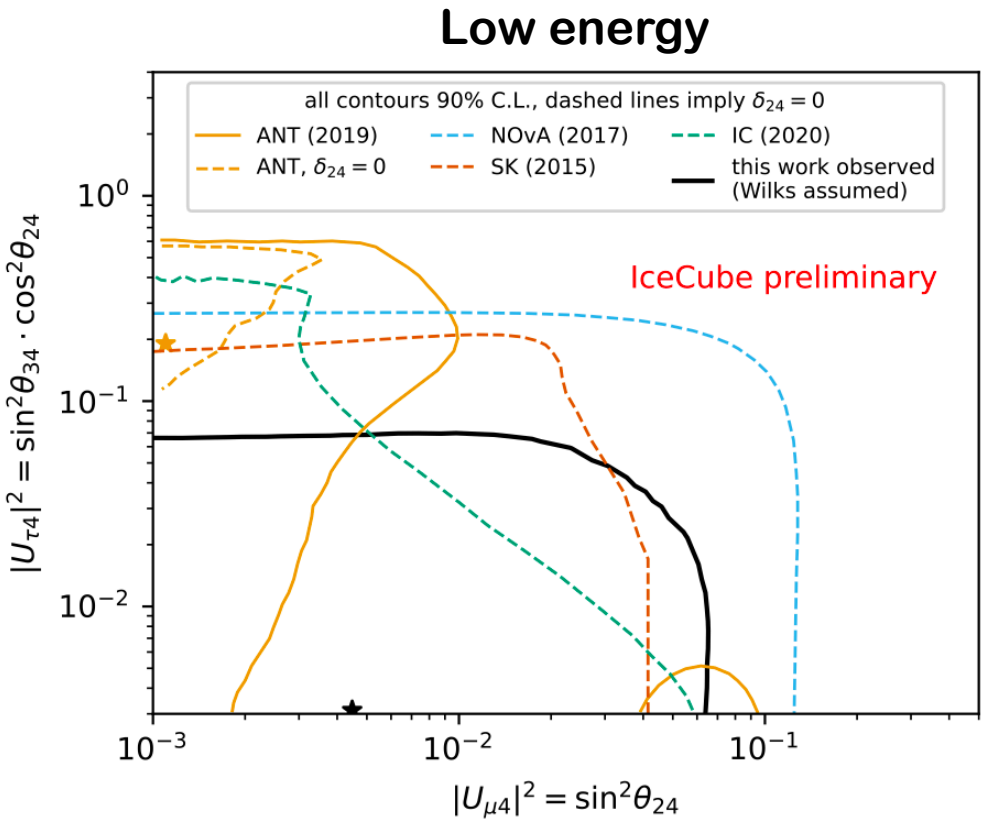
1σ errors include stat.+ syst. and F.C. corrections for accurate coverage

Searches for sterile neutrinos

- Two separate analyses that focus on different energy regimes
- Difference in signals and influence of systematics

Low energy: 5-150 GeV

- Fit compatible with null hypothesis
- $|U_{\mu 4}|^2 < 0.053$, $|U_{\tau 4}|^2 < 0.057$ @90%CL



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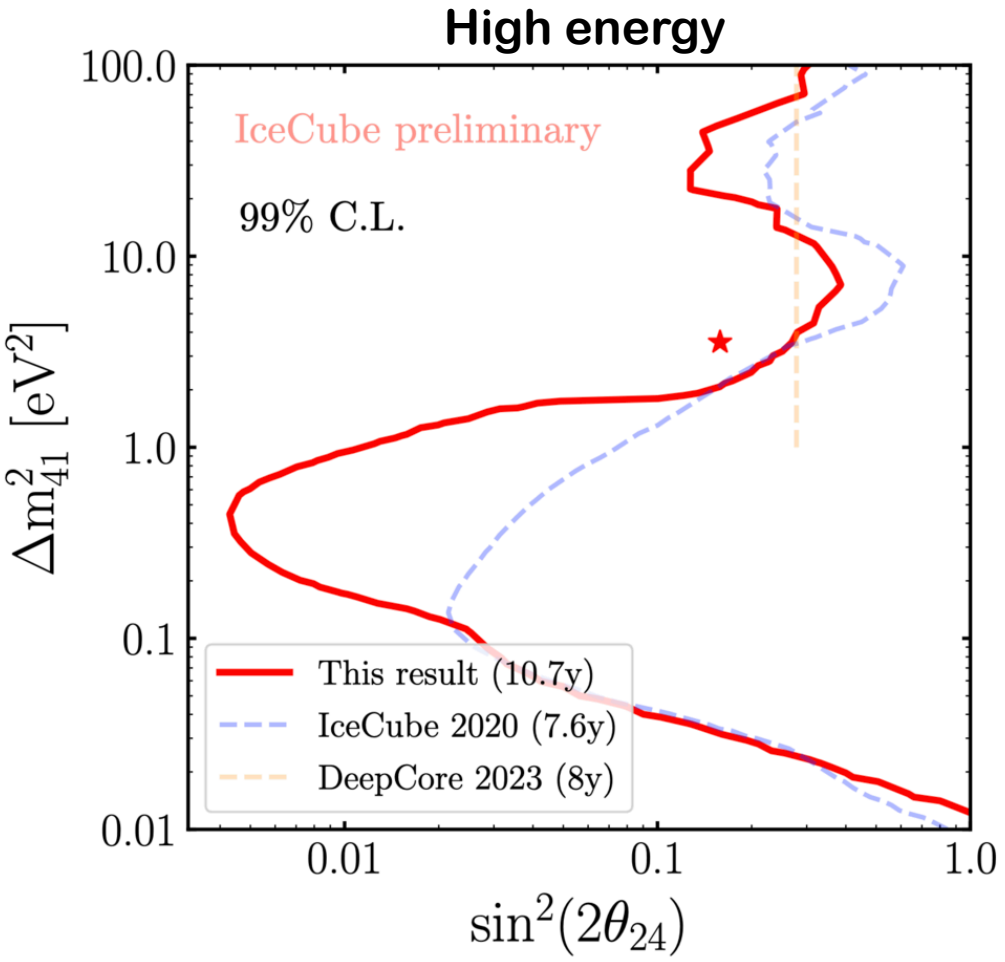
High energy: 500 GeV-10 TeV

- Best fit $\Delta m^2_{41} = 3.5\ eV^2$, $\sin^2(2\theta_{24}) = 0.16$
- Also compatible with null hypothesis (p-value of best fit compared to null <3σ)



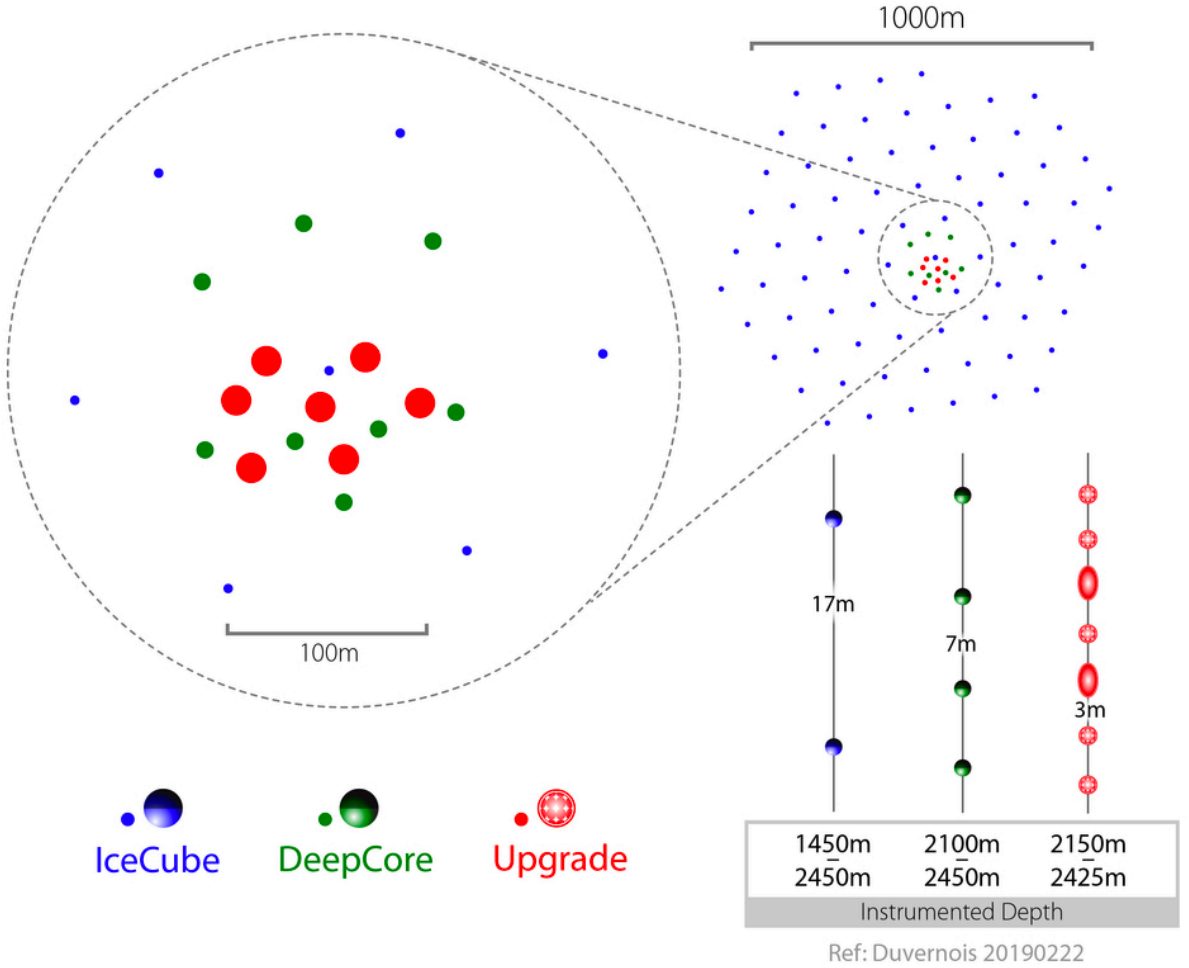
More details on high-energy result: A. Garcia, TeVPA2023

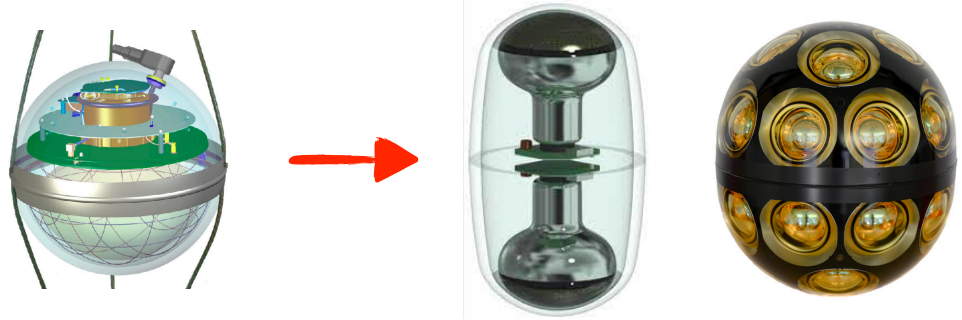
The IceCube Upgrade

- Installation: **Dec 2025 - Jan 2026**
- Precision oscillation measurements
- Improved detector calibrations
- R&D for future IceCube-Gen2

Key Features

- >800 new modules, multi-PMT designs
- Assortment of new calibration devices
- x2 reduced inter-module spacing
- Explore deep ice down to 2600 m





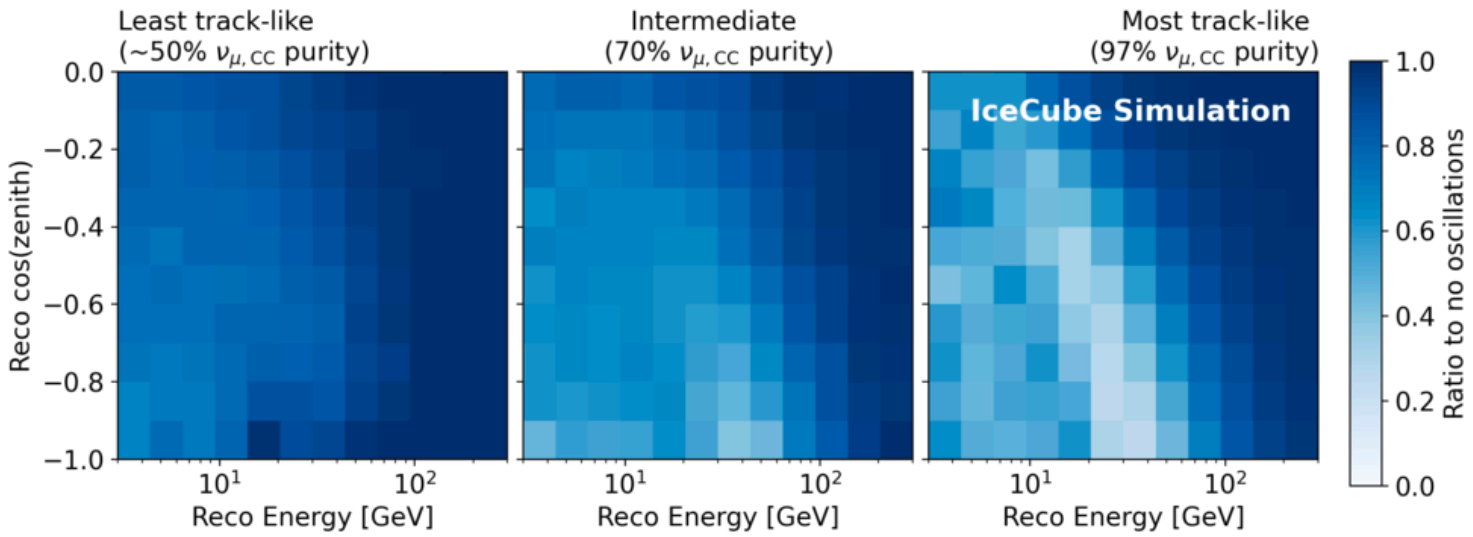
Expected Performance with Upgrade

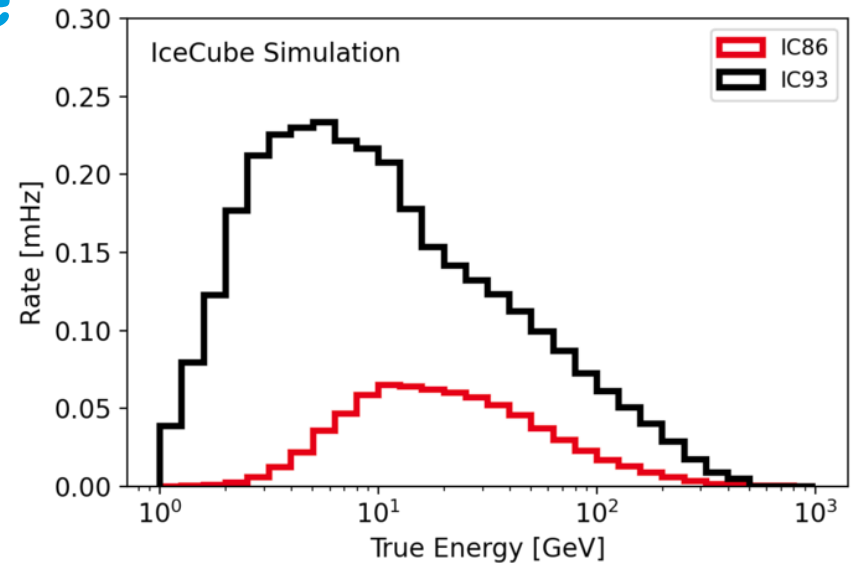
Better detection efficiency at GeV scale

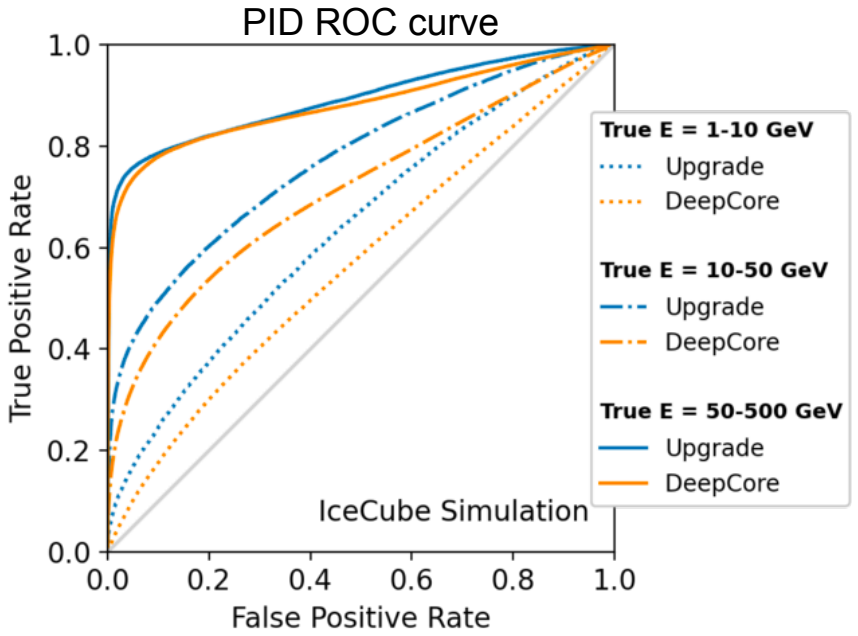
- Expect ~300k neutrinos with 3 years of Upgrade
- Around 10k of these will be ντ CC

Improved resolutions

- Factor 2-4 improved energy & zenith reconstruction
- Significant improvement in track vs cascade separation





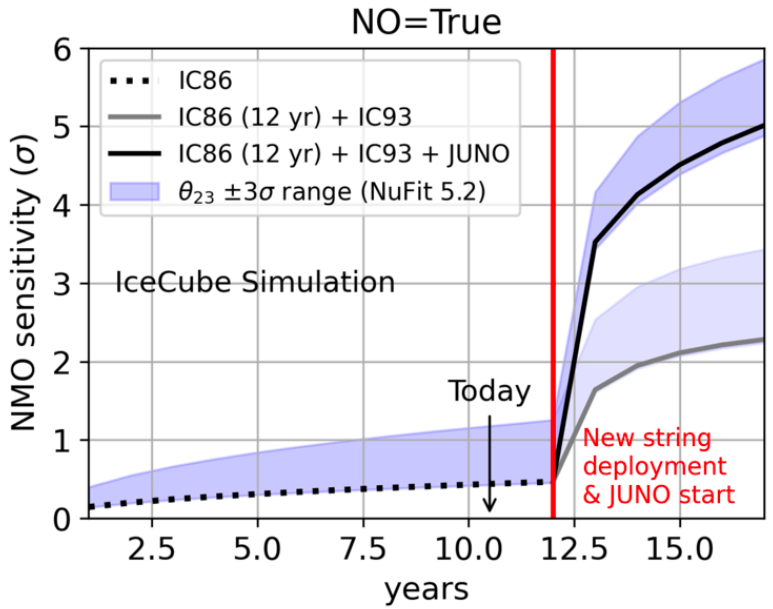


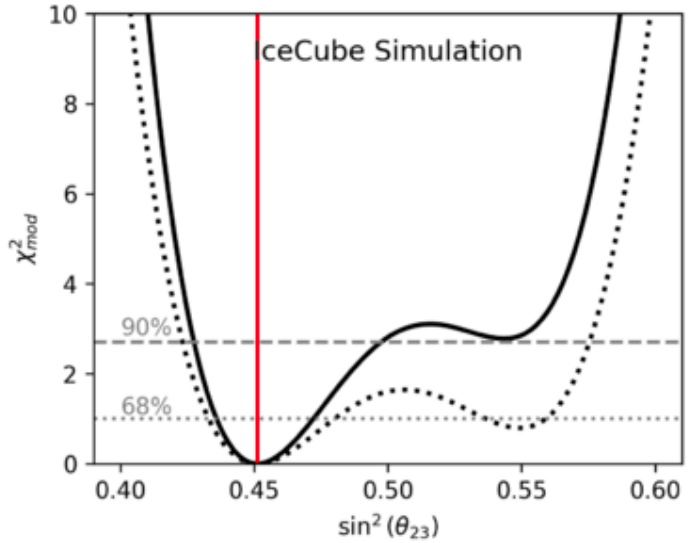
Expected sensitivity after 3 years

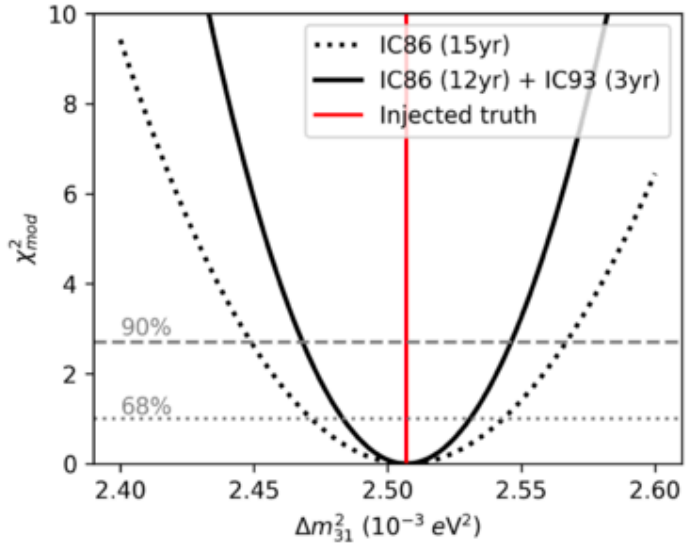
Eller et al., ICRC2023

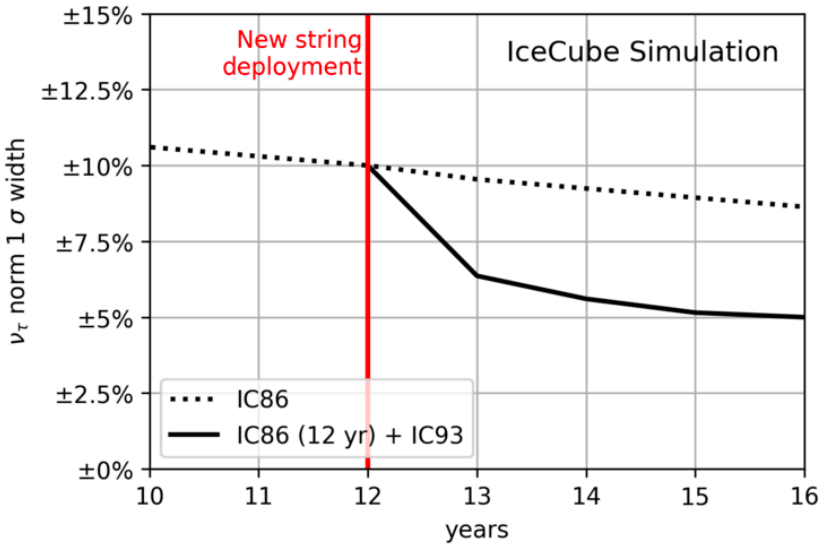
- Improved sensitivity to θ_{23} including octant and atmospheric mass splitting Δm^2_{32}
- 5% uncertainty on $\nu\tau$ normalisation - combination of PMNS unitarity and $\nu\tau$ cross-section
- Neutrino mass ordering determination at 2-3σ (5σ with JUNO)

+ much more!

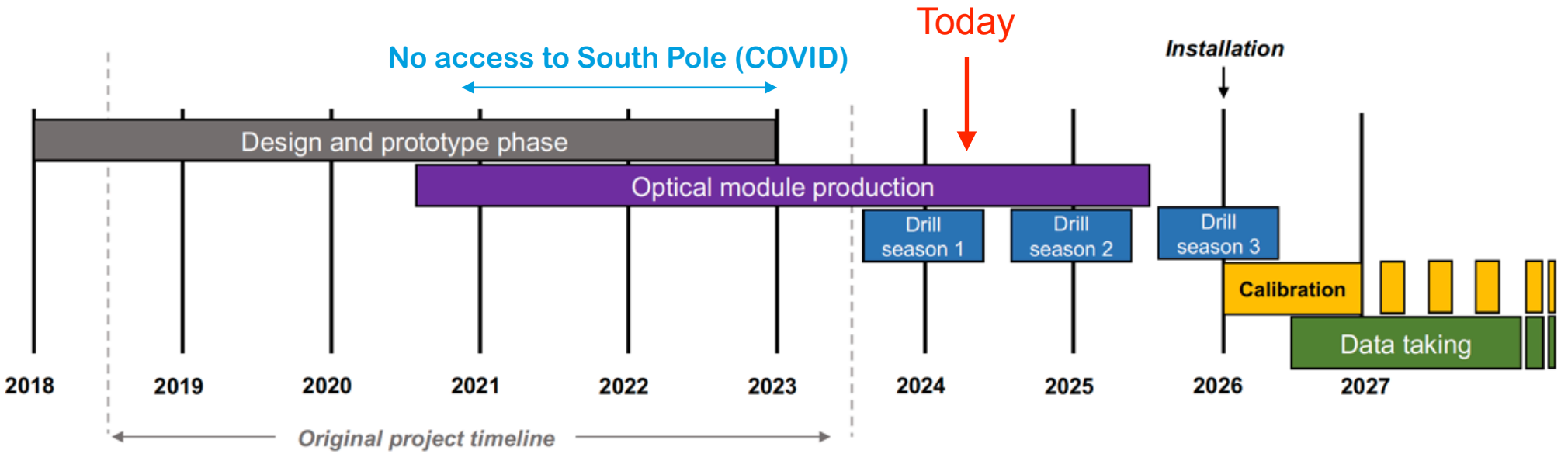






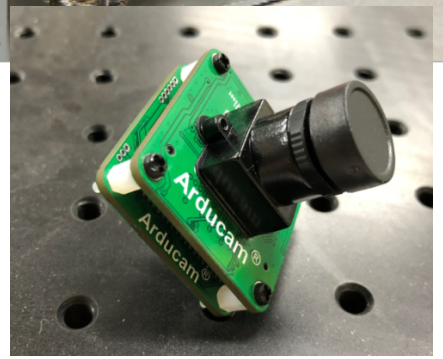


IceCube Upgrade Timeline



First drill season just completed - very successful!

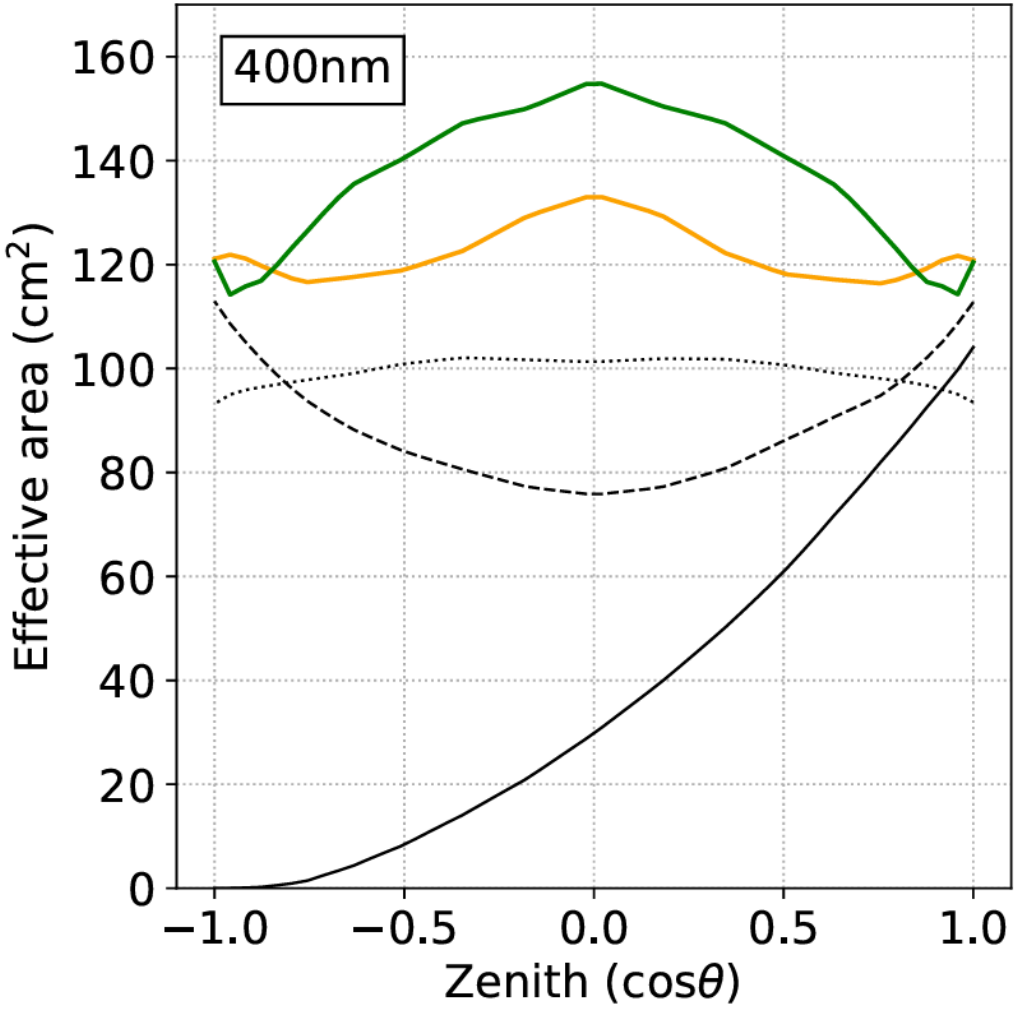
IceCube Upgrade sensor production

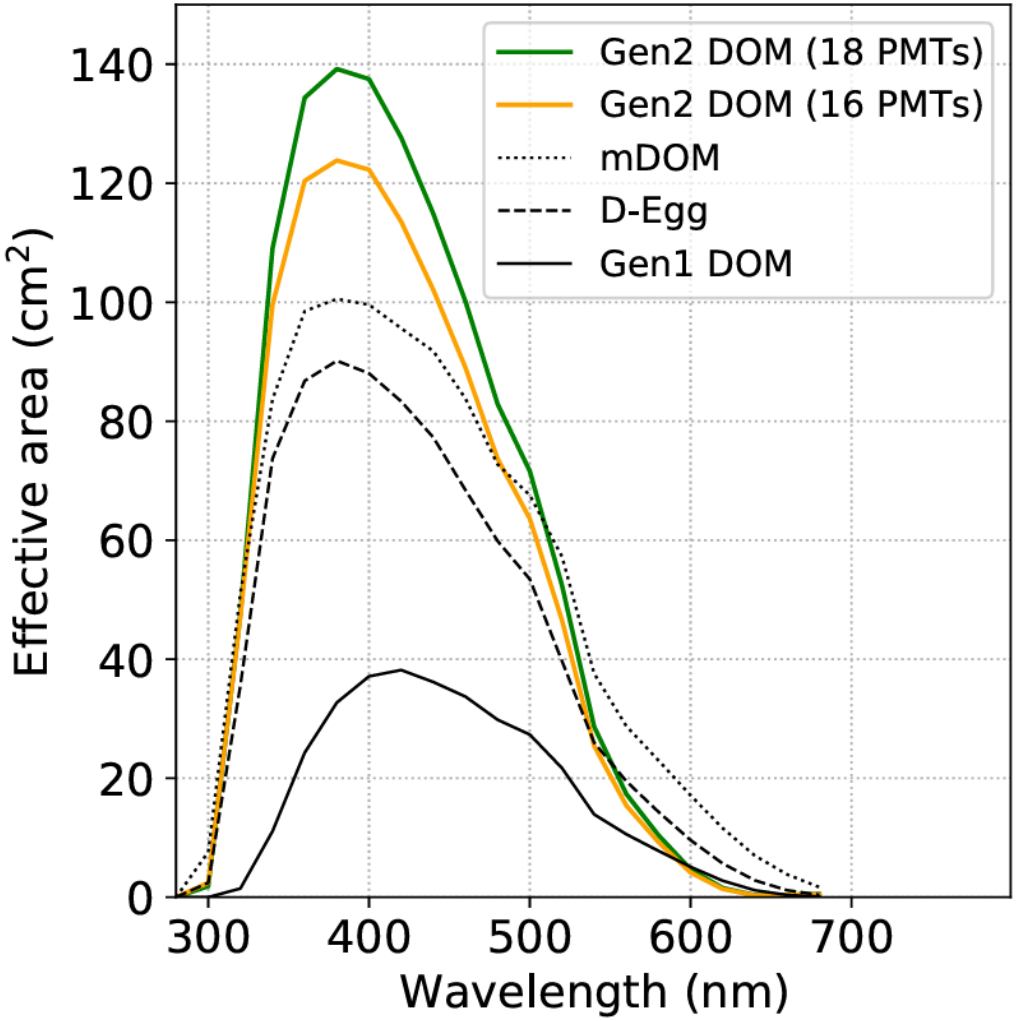


Sensor production and characterisation running smoothly

Exciting prospects with new calibration devices and multi-PMT sensors!

IceCube Upgrade sensor performance

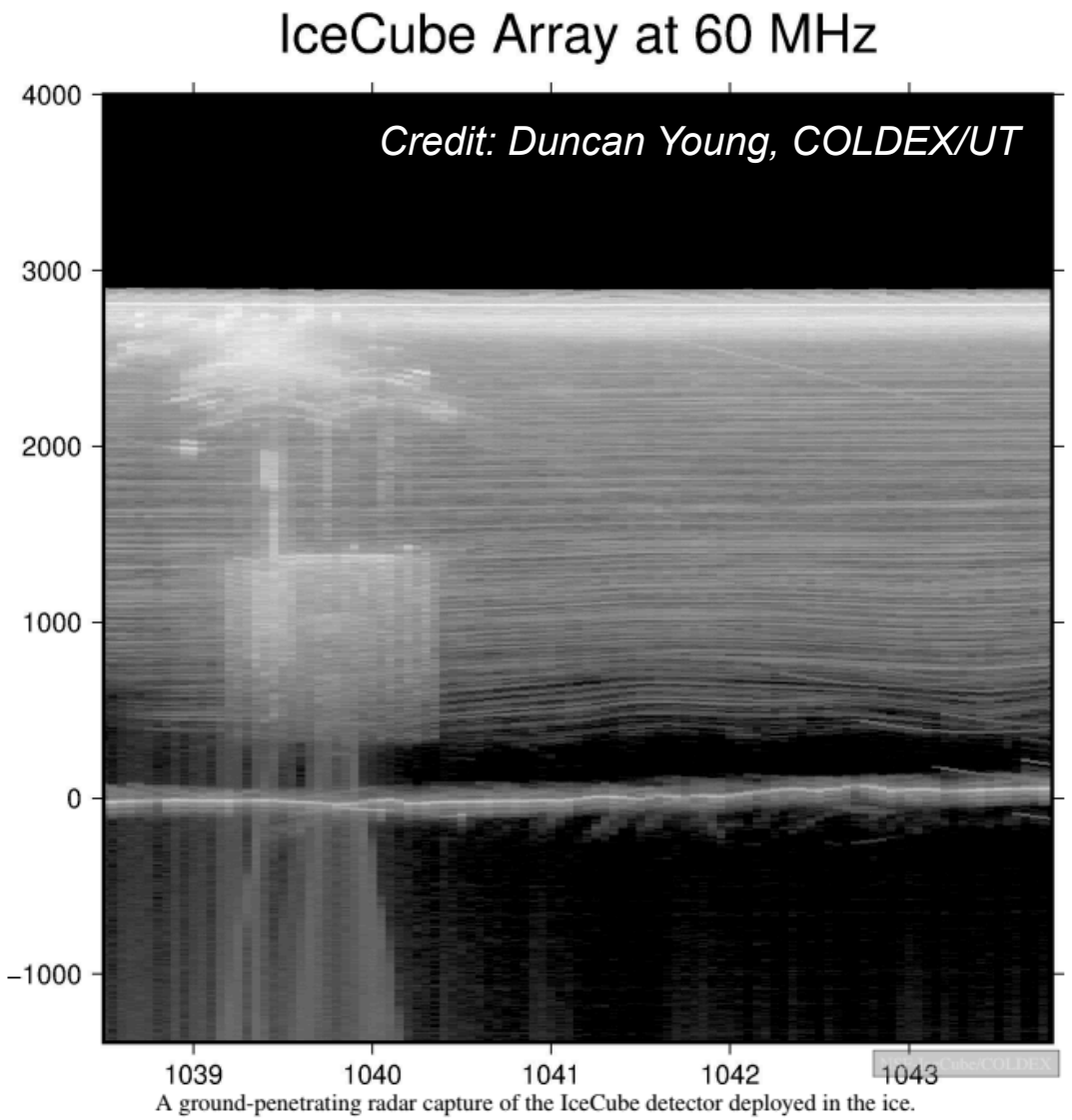




IceCube Gen2 TDR

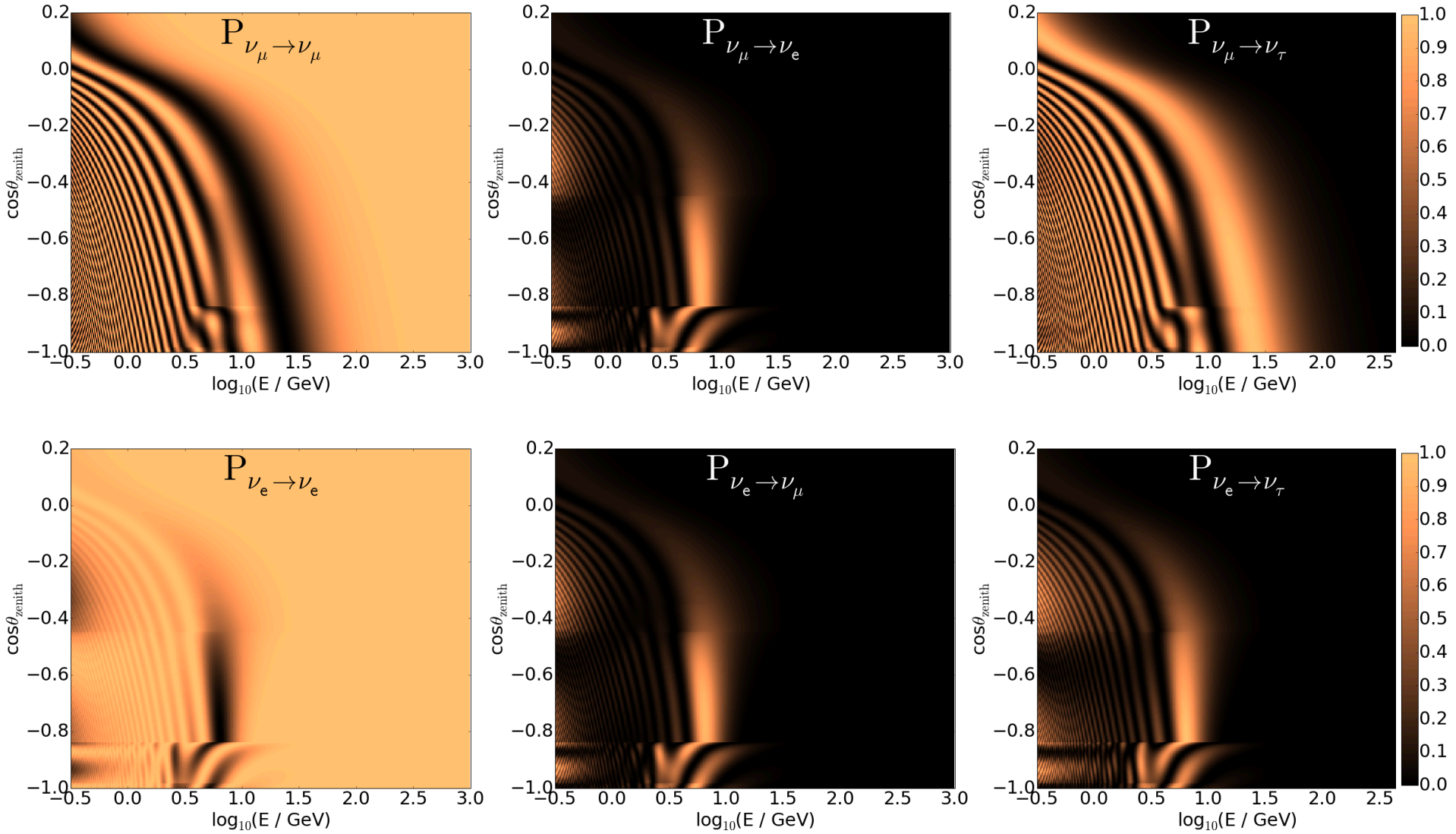
Conclusions

- Atmospheric neutrinos are an excellent probe of neutrino oscillations
  - Standard oscillation results are comparable to accelerators, but with **higher energies** and **longest baselines**
  - **New** sterile neutrino searches through muon neutrino disappearance **consistent with null hypothesis**
- Ramping up for installation of the IceCube Upgrade in 2025/26, enabling even more great science!

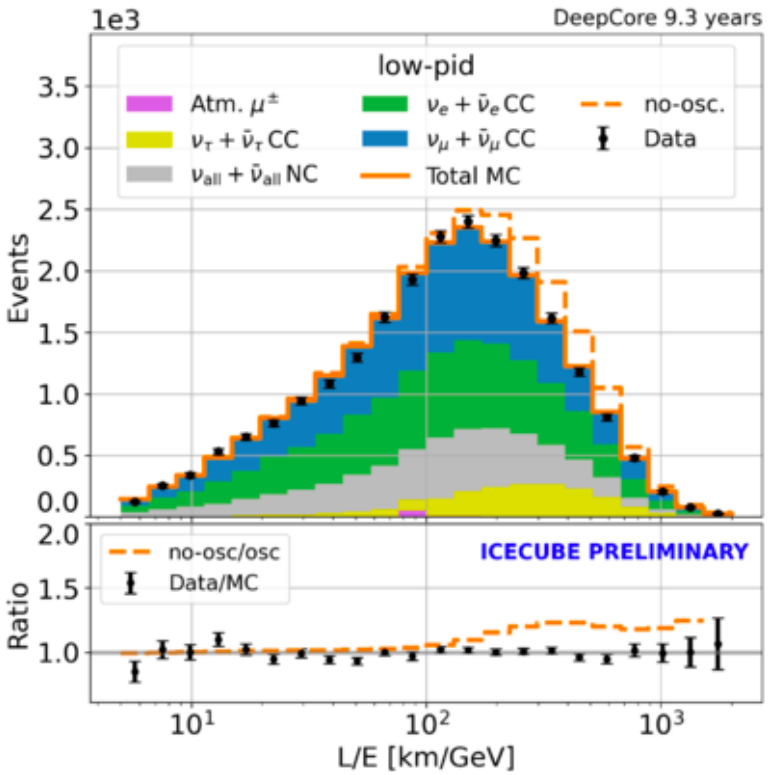


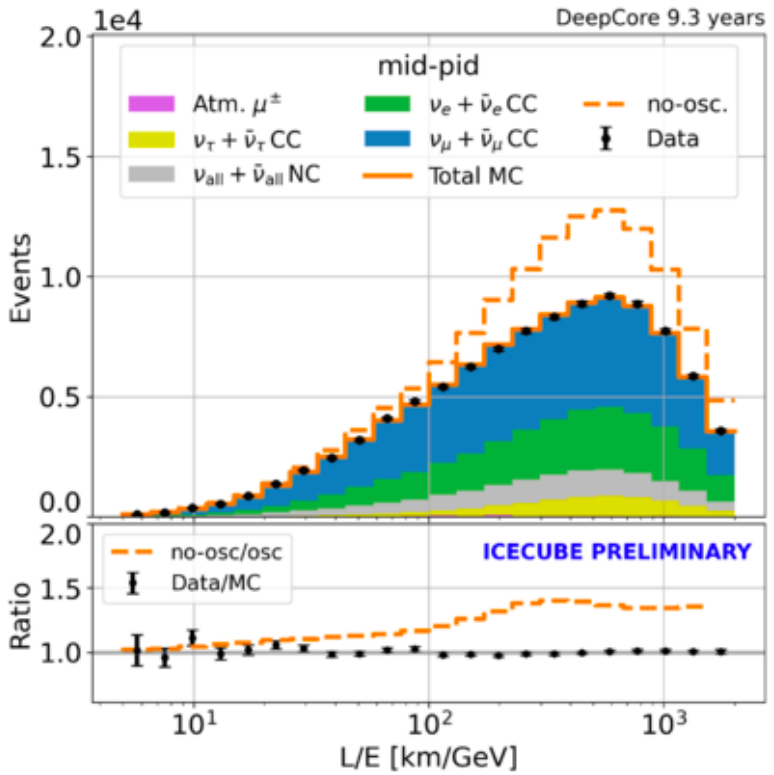
Backup

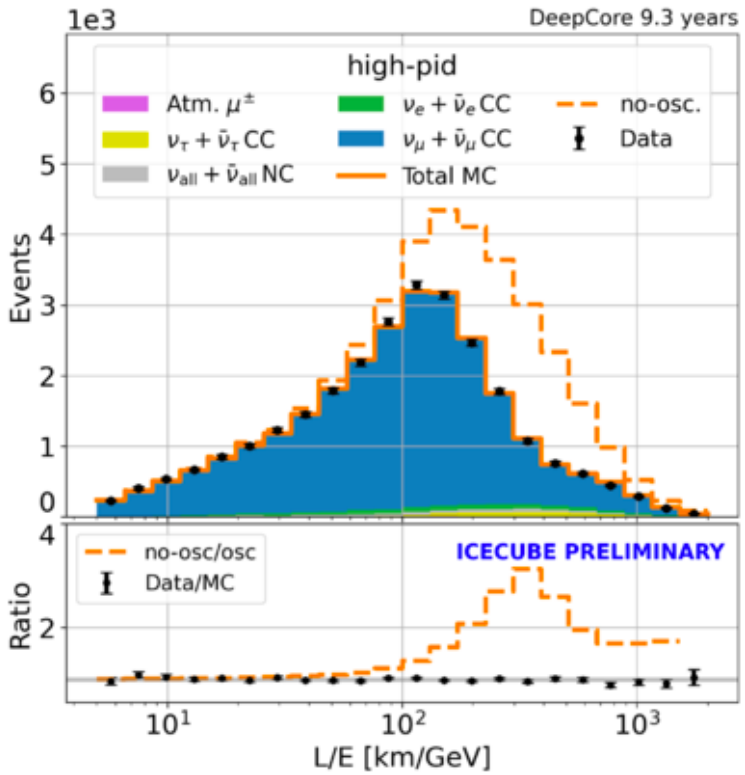
Atmospheric Neutrino Oscillations



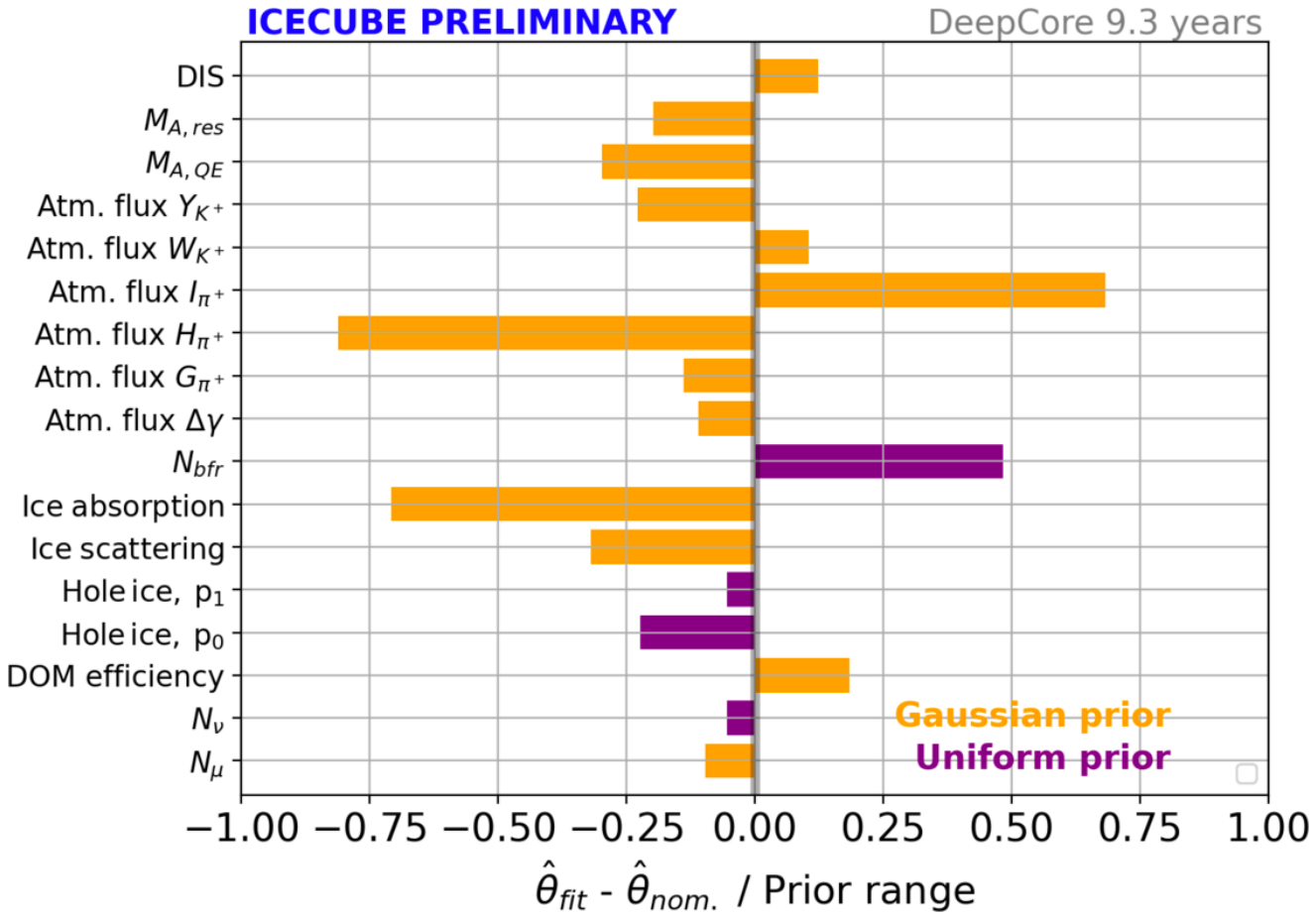
CNN reconstructed GeV sample



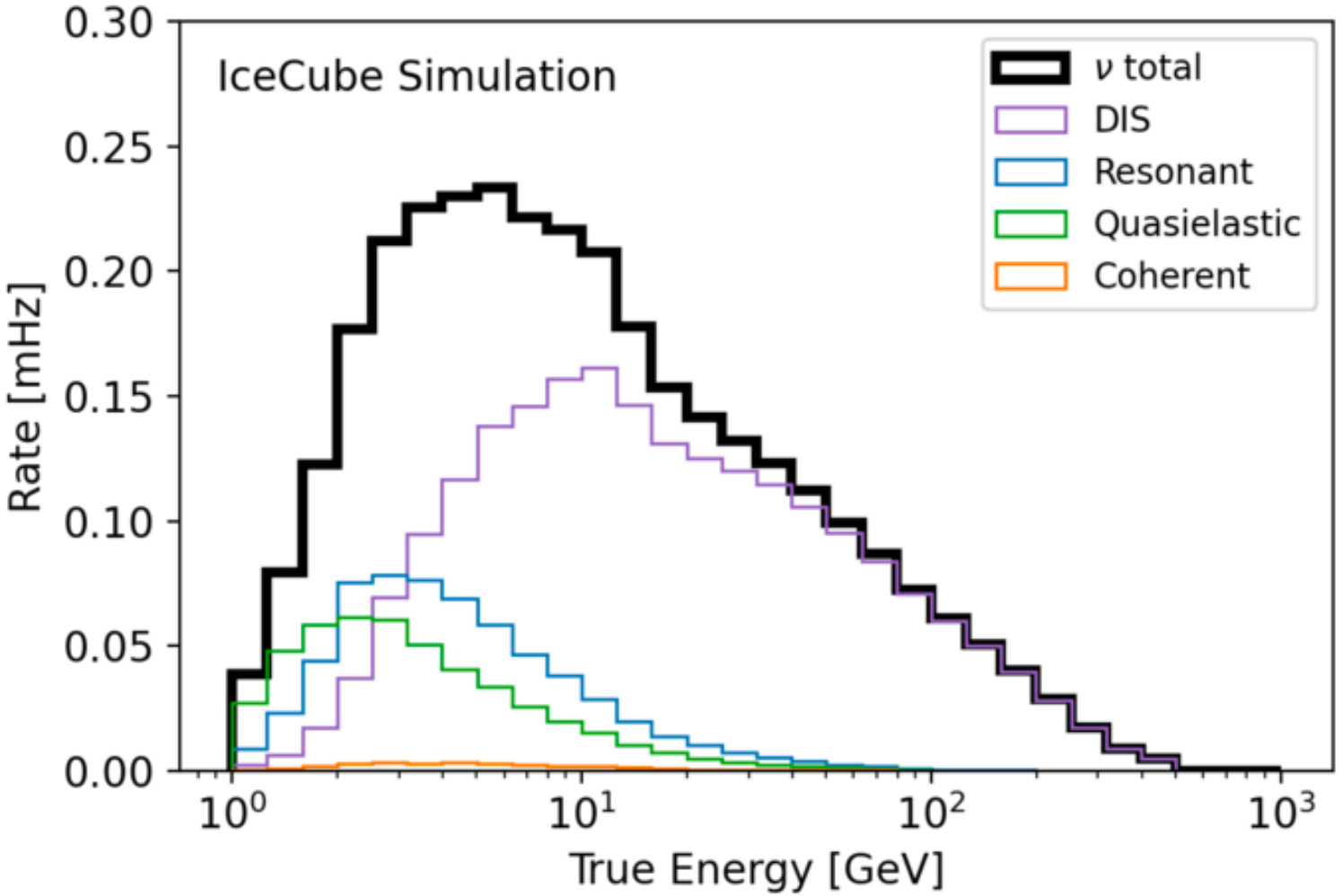




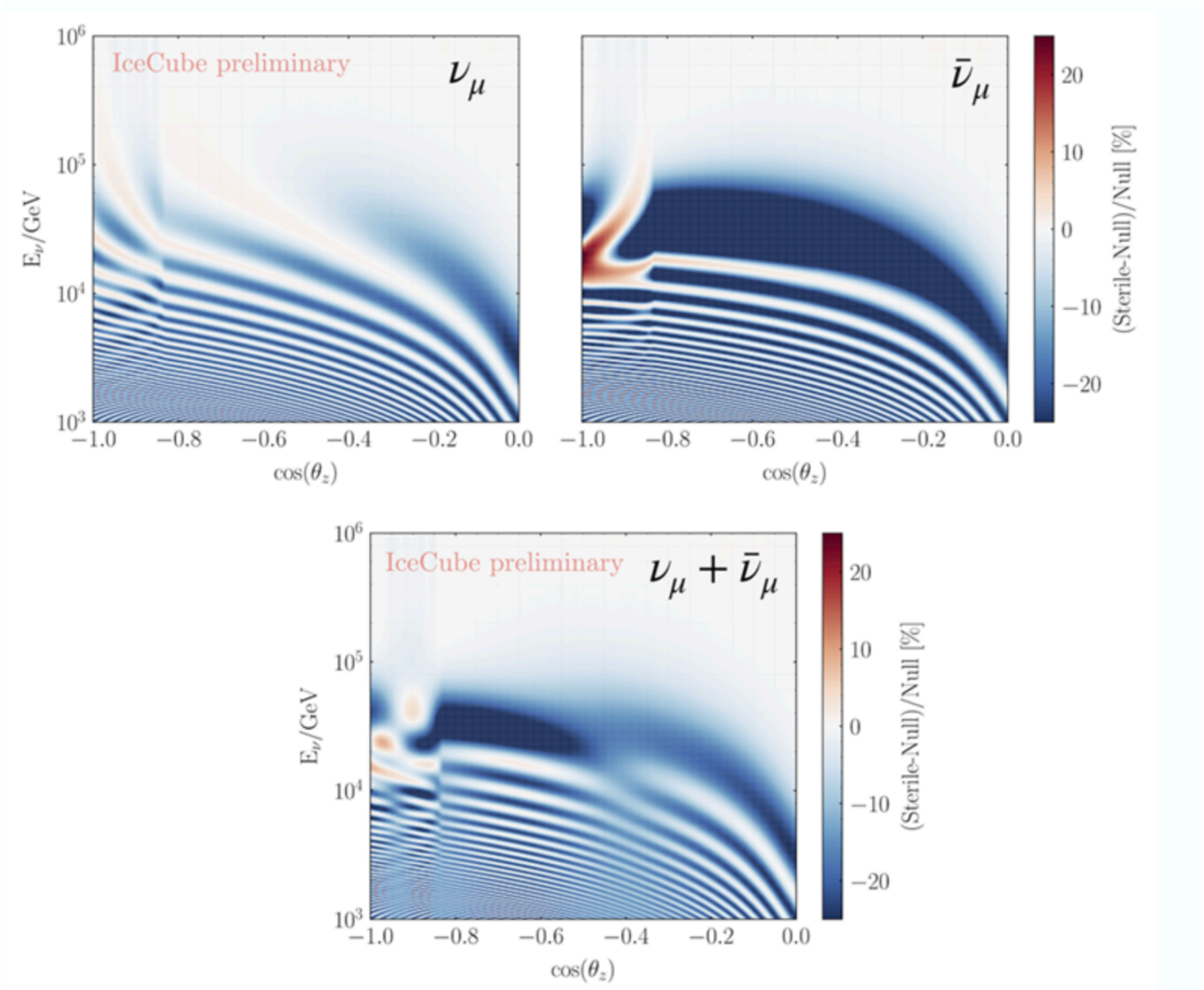
Systematic uncertainties: standard oscillations



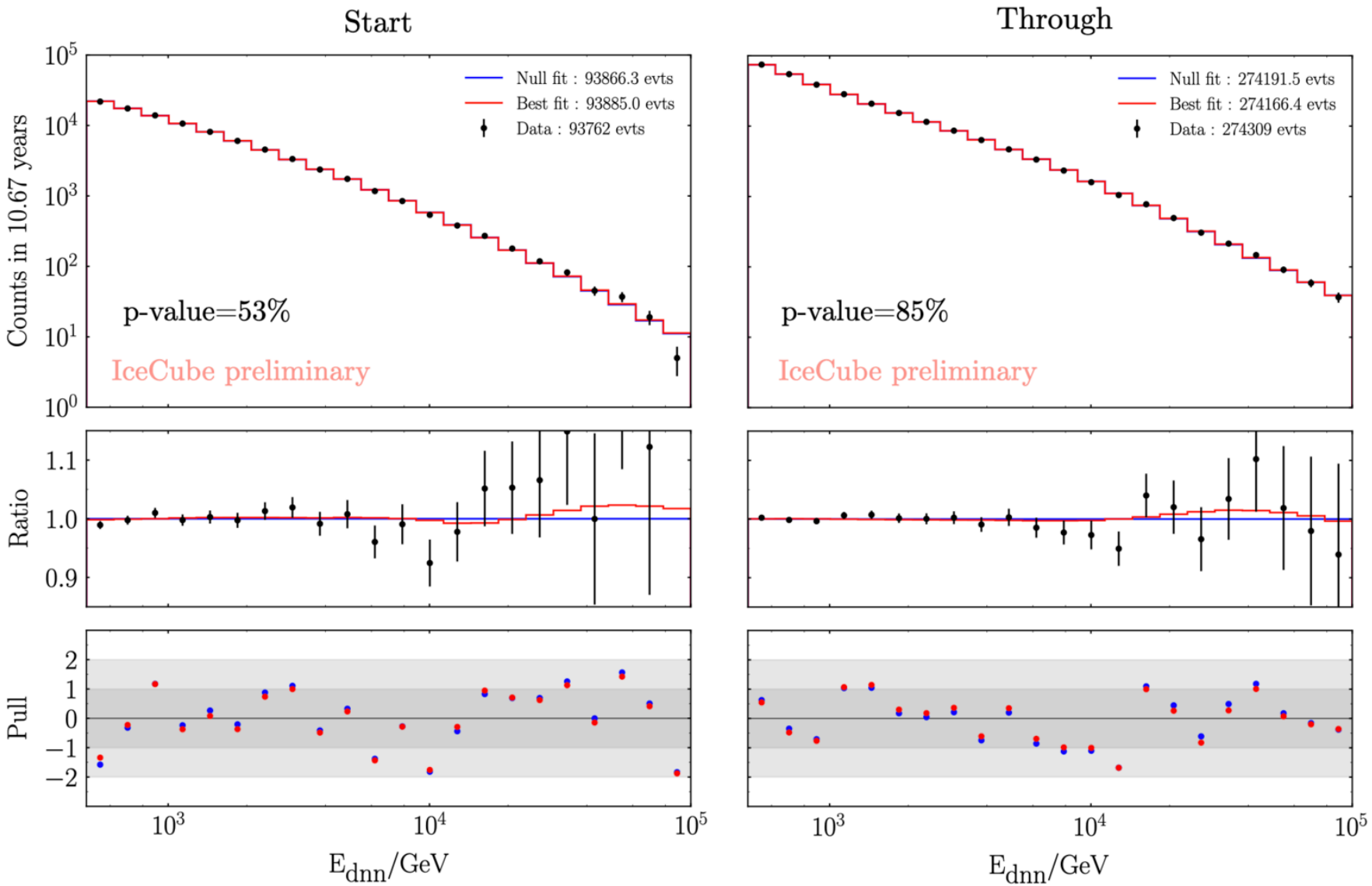
IceCube Upgrade: Event rate by cross-section



High energy sterile neutrino oscillograms



Systematic uncertainties: high energy sterile search



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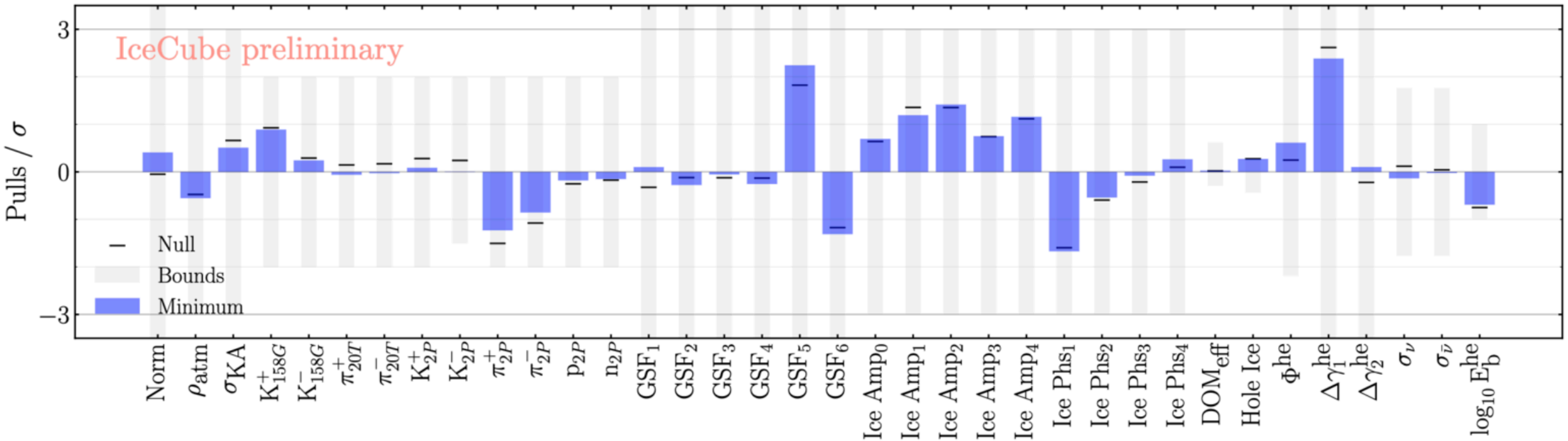

Ice Stratigraphy