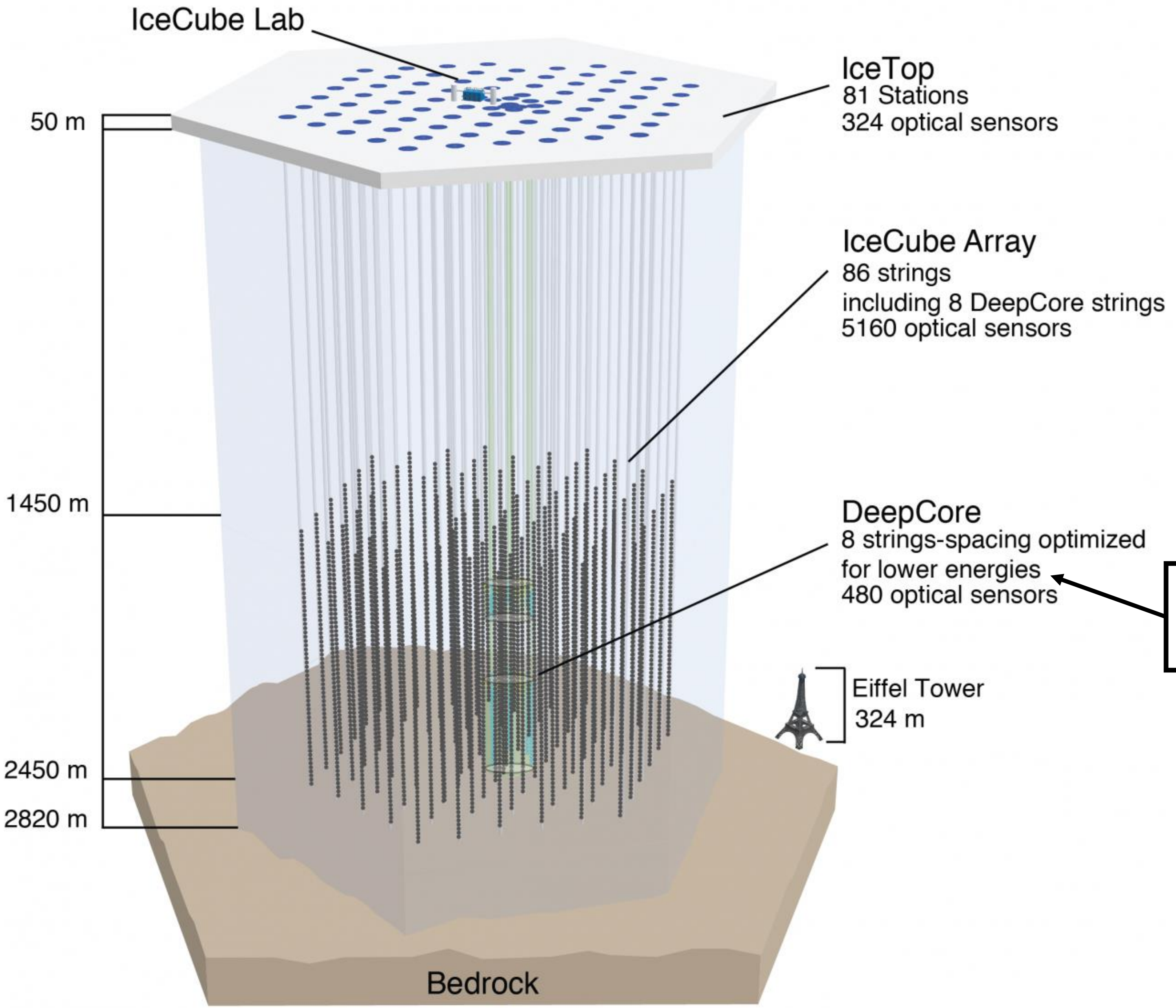
Recent oscillation results with 11 years of IceCube/DeepCore data

Jan Weldert on behalf of the IceCube collaboration
IRN Neutrino meeting | November 3rd 2025

IceCube and DeepCore

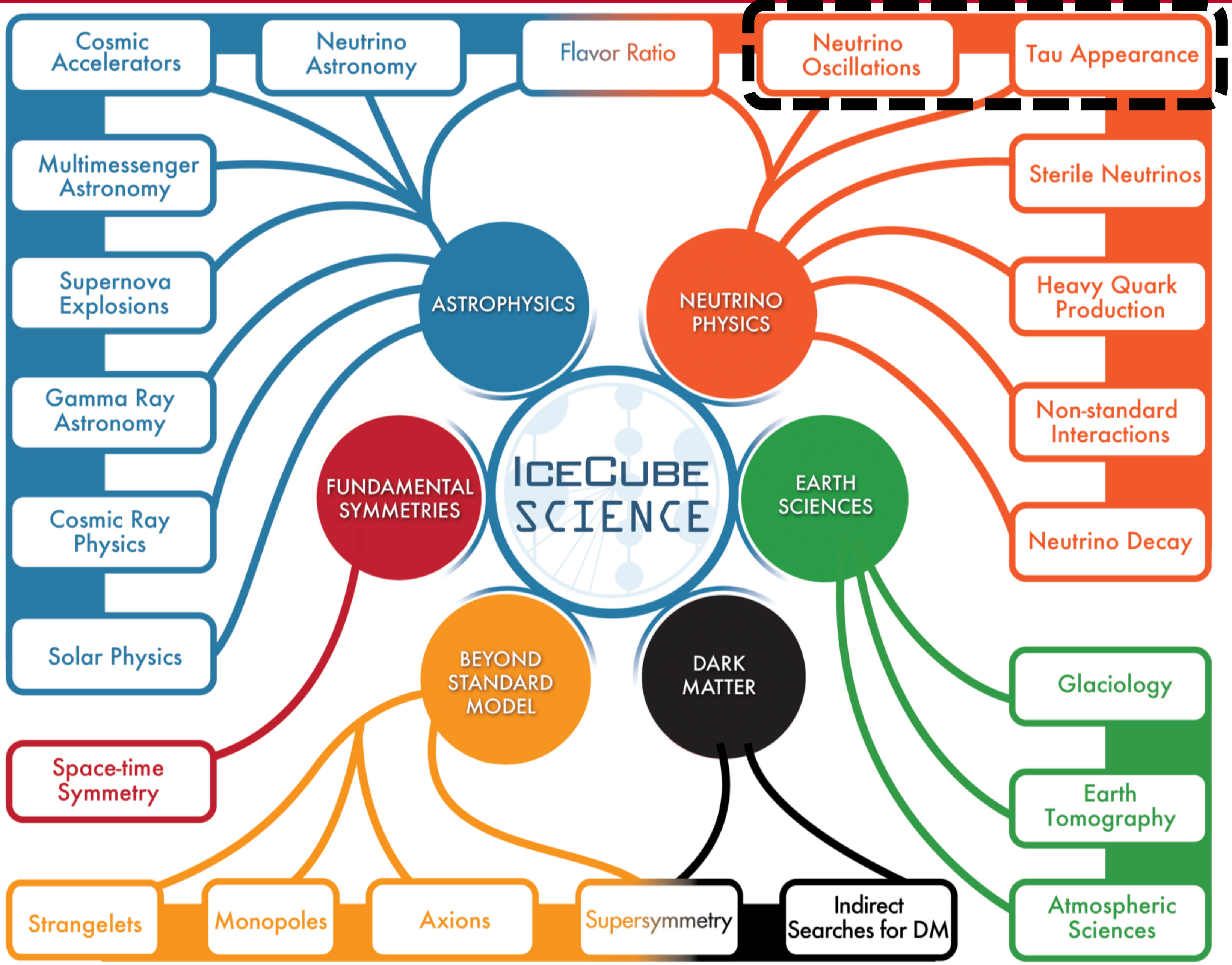


Down to a few GeV

PRISMA+

JG|U

IceCube Science



Focus of todays talk

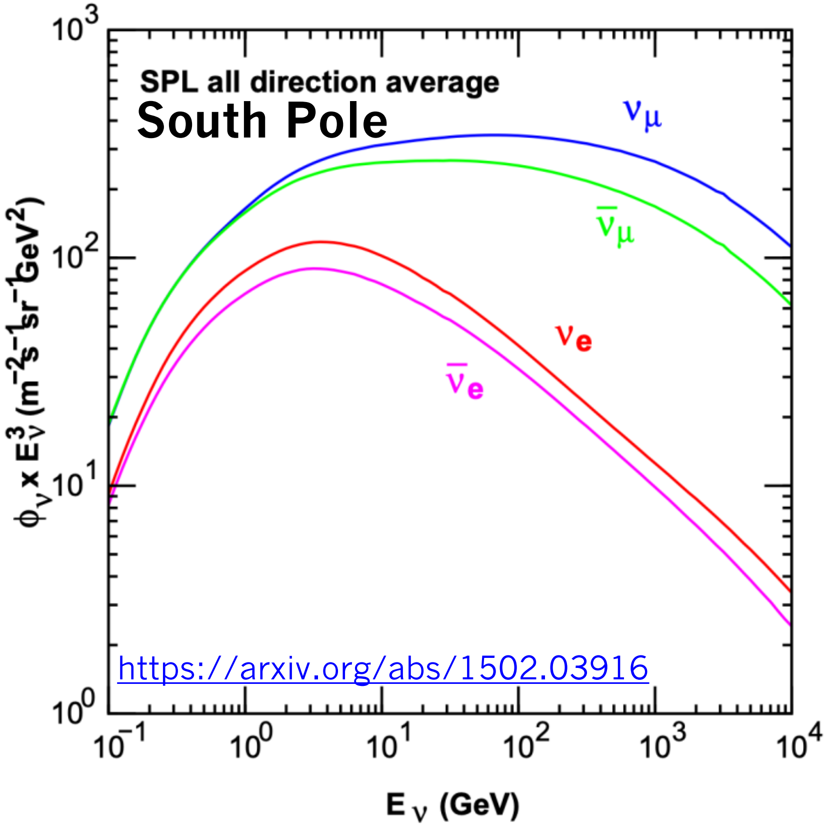
Atmospheric Neutrinos

Cosmic rays interact with nucleons in Earth's atmosphere

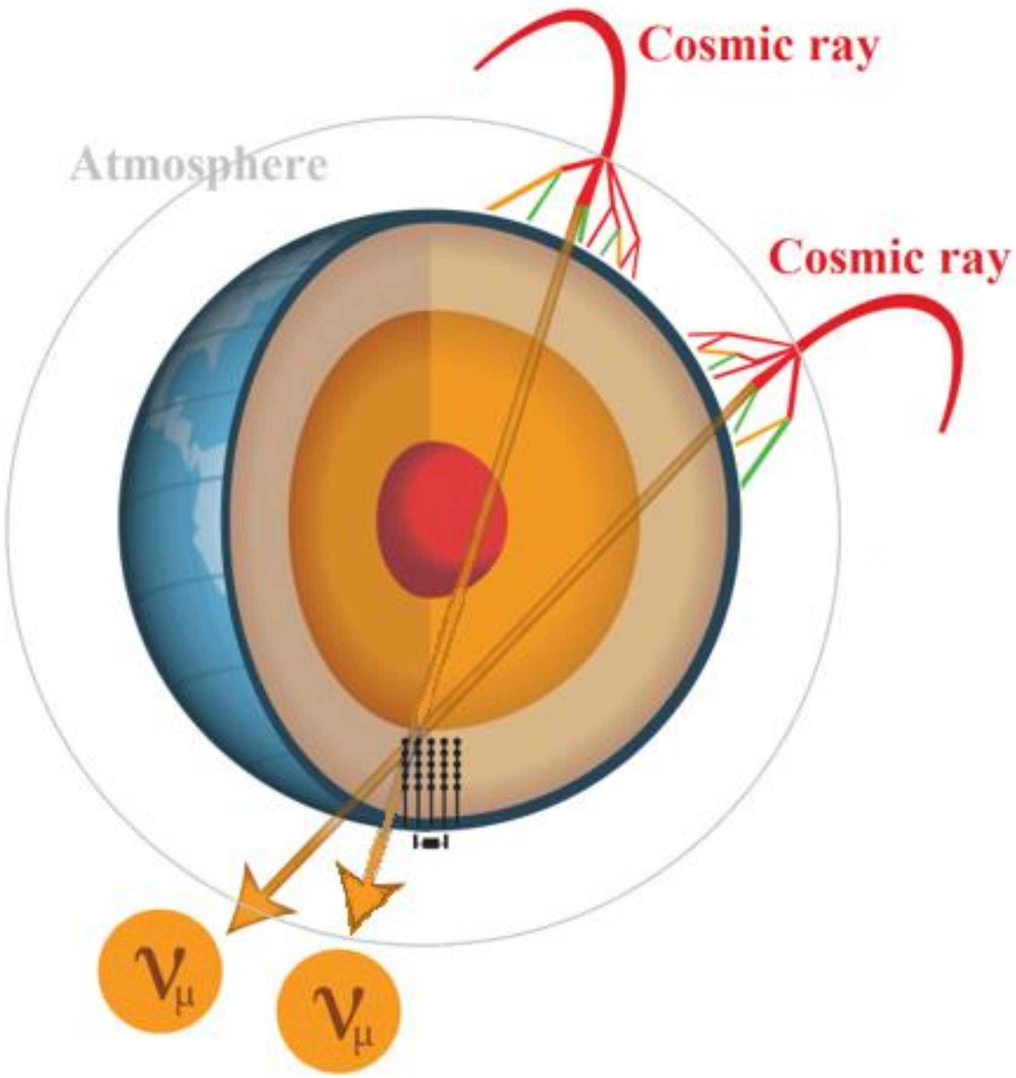
$$p + N \rightarrow \pi^{\pm}/K^{\pm} + X$$

$$\pi^{\pm}/K^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{\mu} + \overset{(-)}{\nu}_{e}$$



https://arxiv.org/abs/1502.03916



Atmospheric Neutrino Oscillations

Neutrino oscillations

flavor (interaction) eigenstates ≠ mass (propagation) eigenstates ⇒ A neutrino created in one flavor might be detected in another flavor

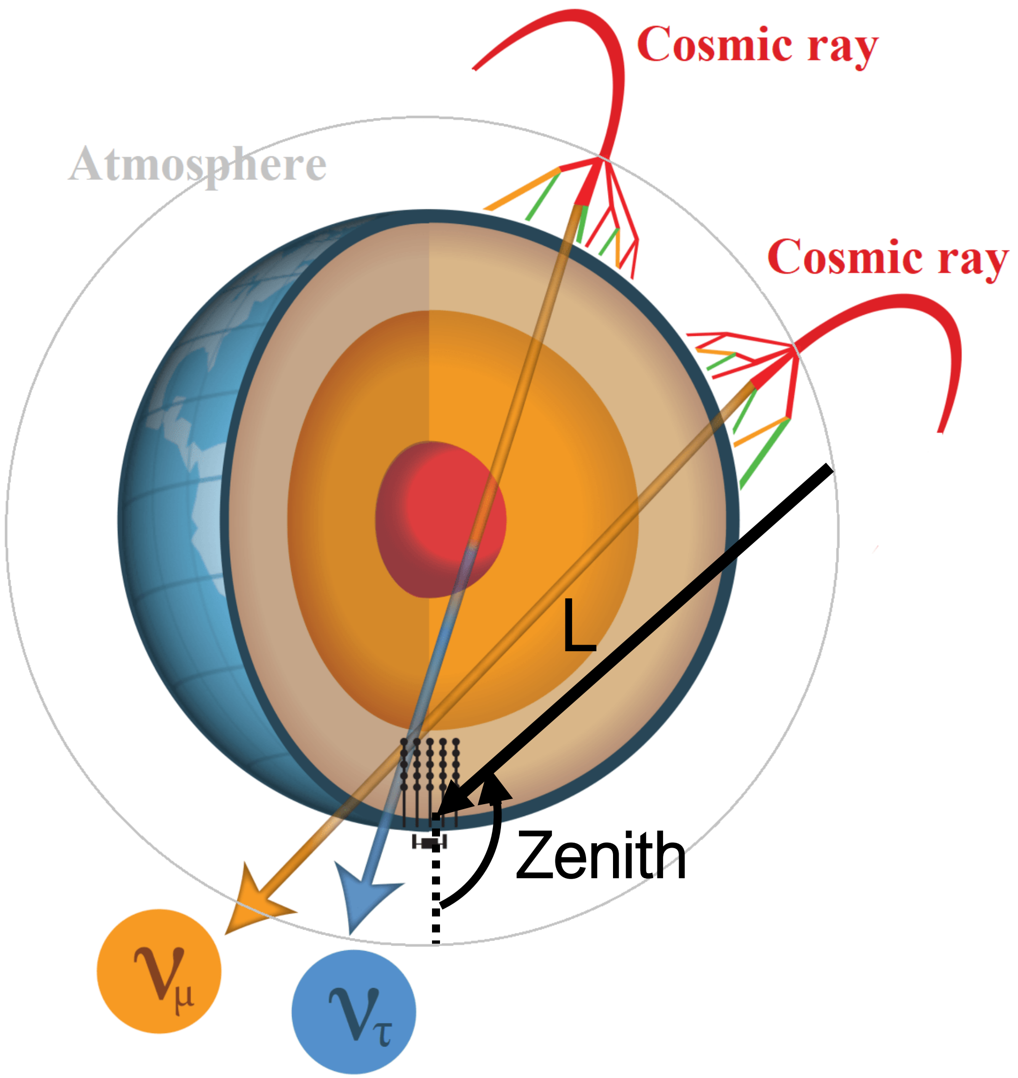
Oscillation probability (simplified)

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta_{\text{mix}})\,\sin^2\!\left(\Delta m^2 \cdot \frac{L}{E}\right)$$

variable

Detector observables

- $E^{\text{deposited}}$: proxy for neutrino energy E
- Cos(Zenith): proxy for traveled distance L



Oscillogram

Oscillation probability (simplified)

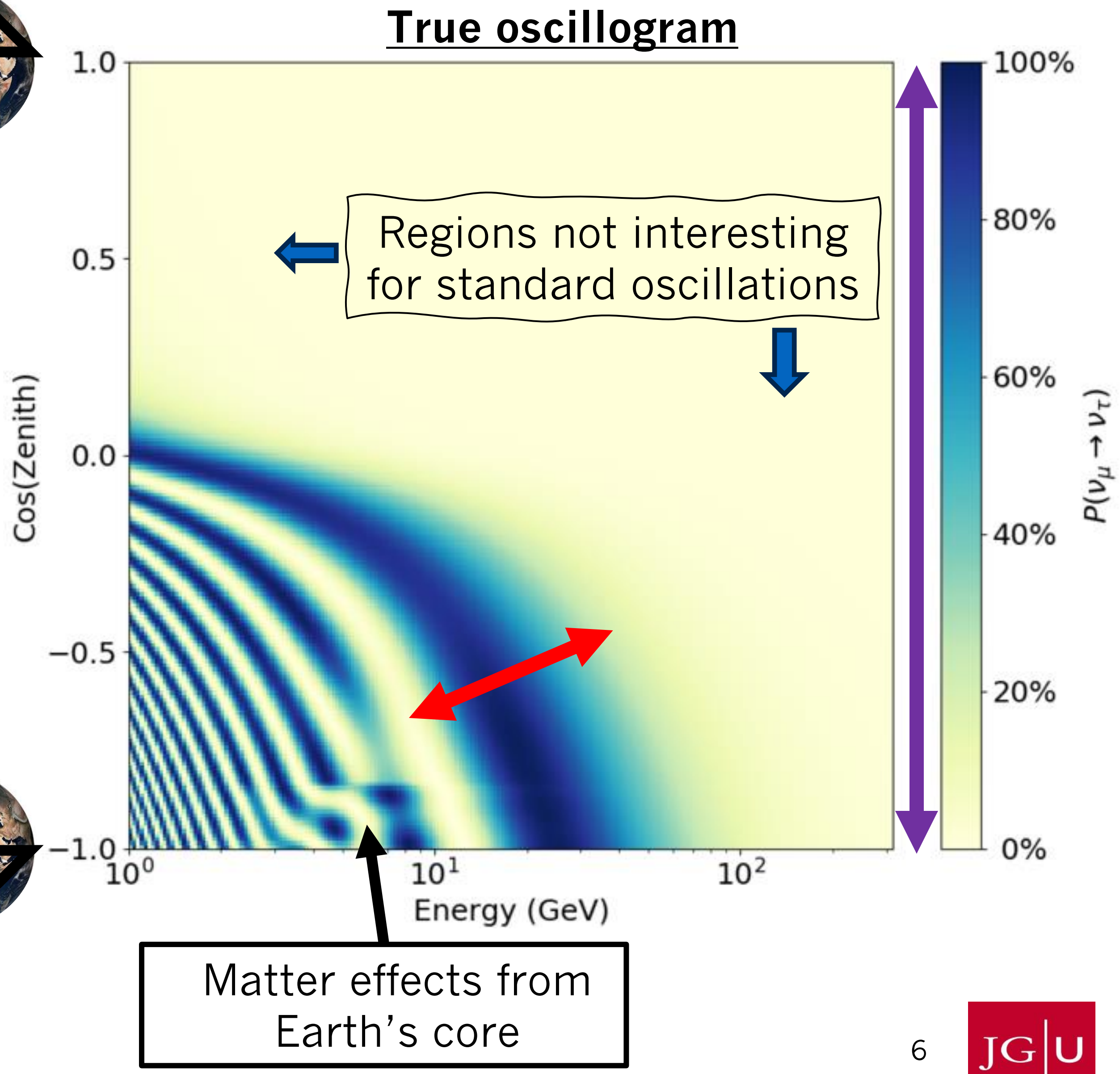
$$P(\nu_\mu \rightarrow \nu_\tau) \approx \sin^2(2\theta_{\text{mix}}) \sin^2(\Delta m^2 \cdot \tfrac{L}{E})$$

Physics parameters

Mixing angle θ_{mix} (here θ_{23})
→ amplitude of oscillation

Mass difference Δm^2 (here Δm^2_{32})
→ frequency of oscillation

Matter disturbs oscillation



Neutrino Detection with IceCube

Photon generation

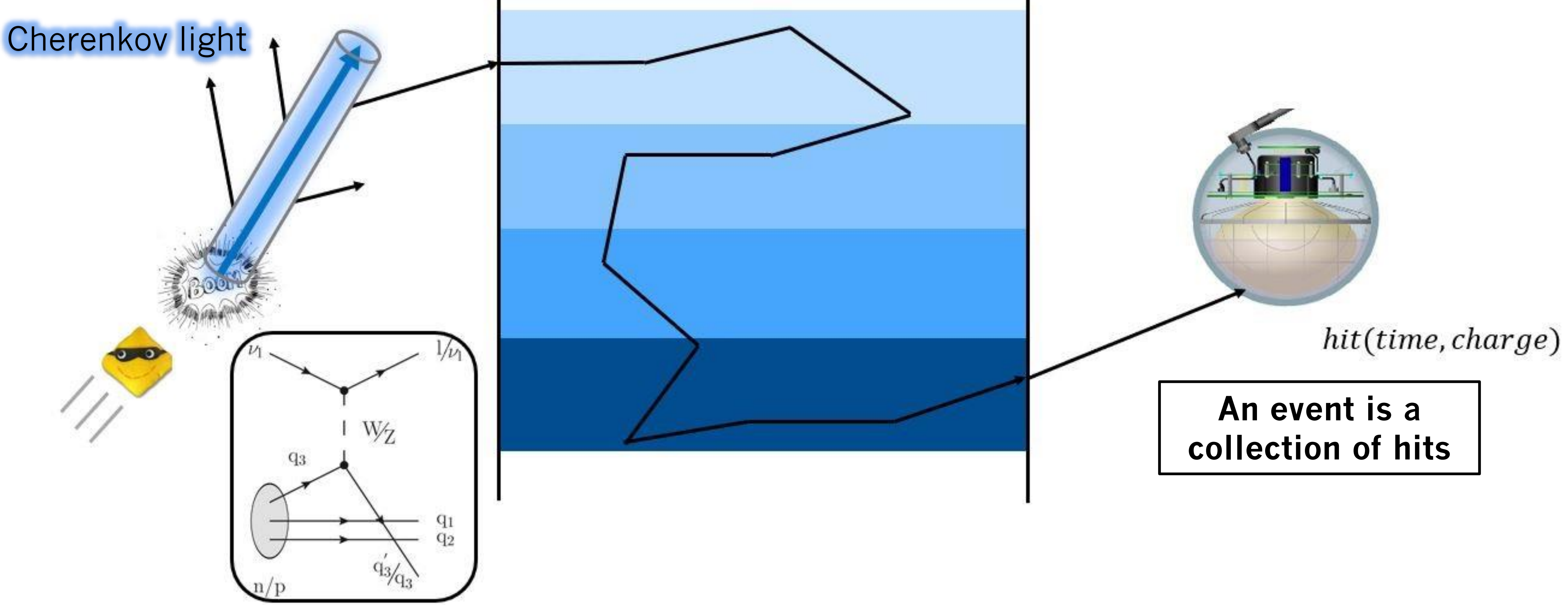
Incomming Neutrino interacts

Photon propagation

Photon scatters through ice

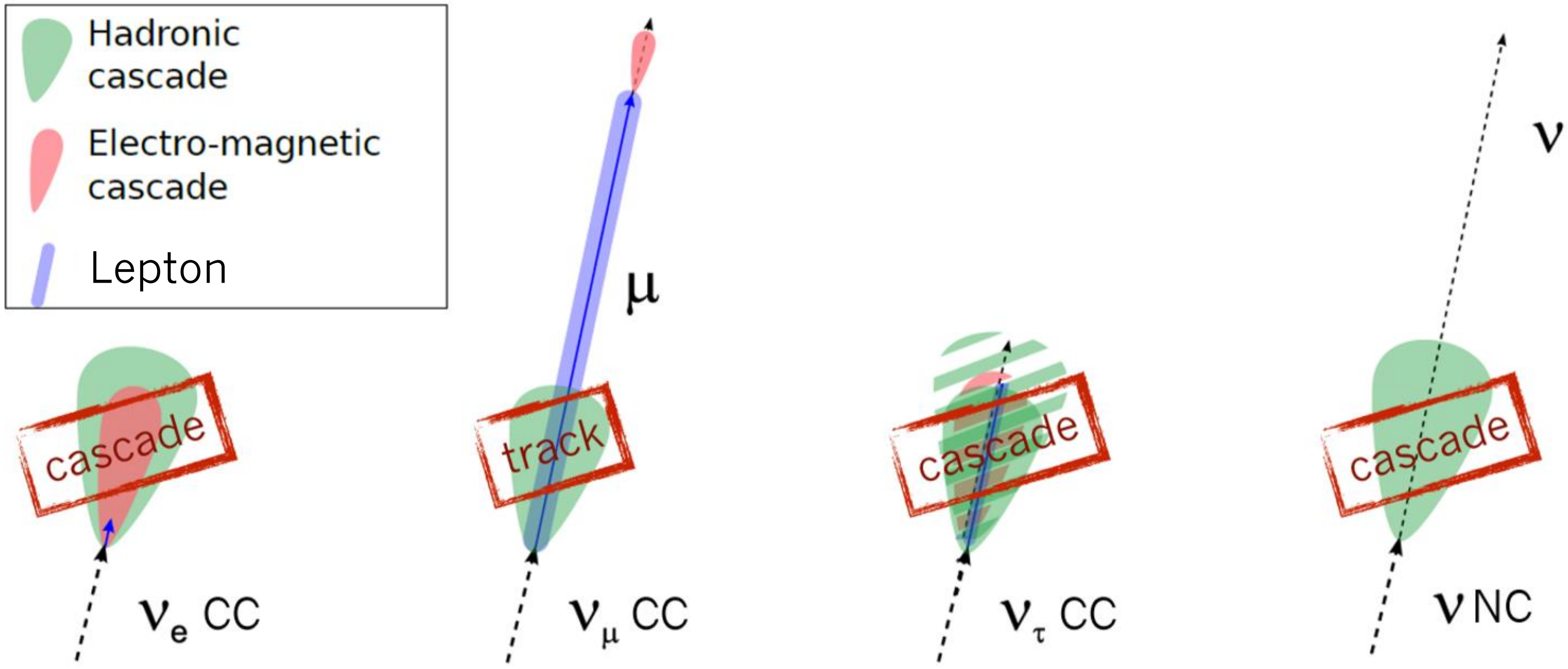
Photon detection

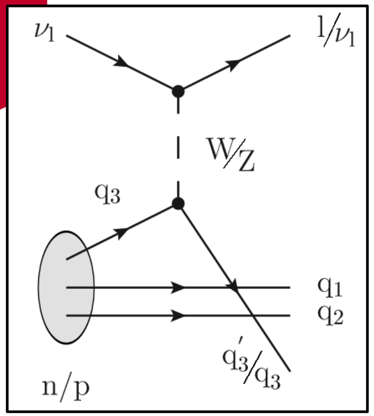
Photon gets detected by PMT



An event is a collection of hits

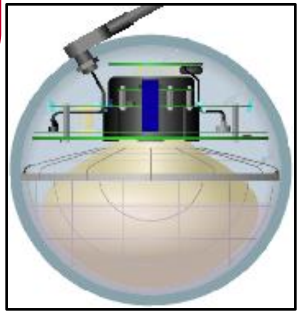
Event Topologies



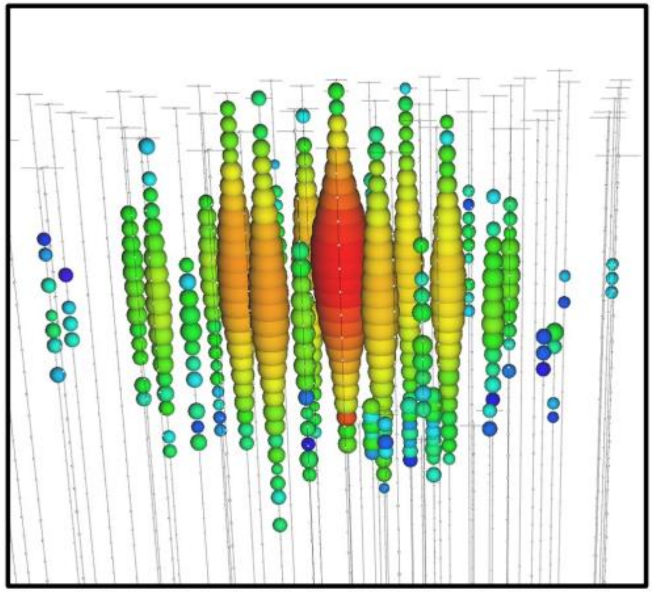


- Unique signature for ν_μ CC
- Used for flavor identification (important for oscillation analysis)

Event Topologies IceCube

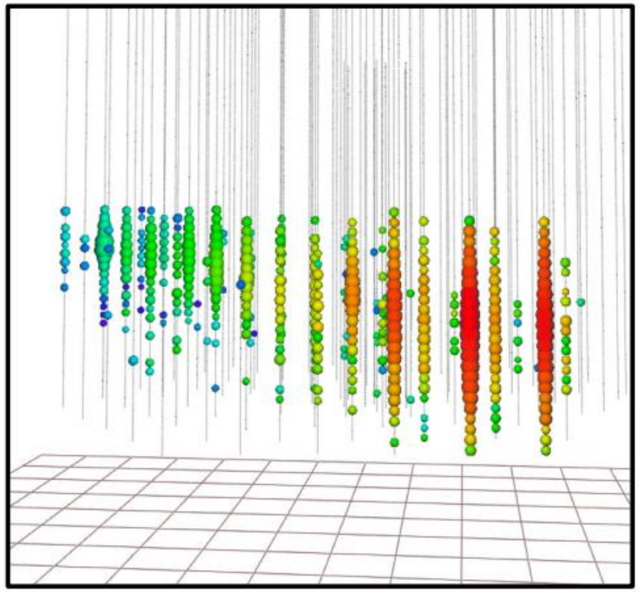


Cascades



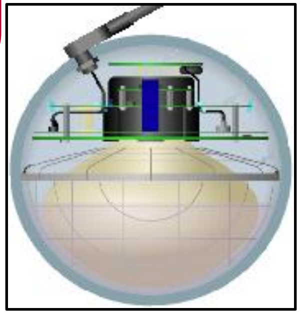
ν_e^{CC}, ν_τ^{CC}, ν^{NC}

Tracks

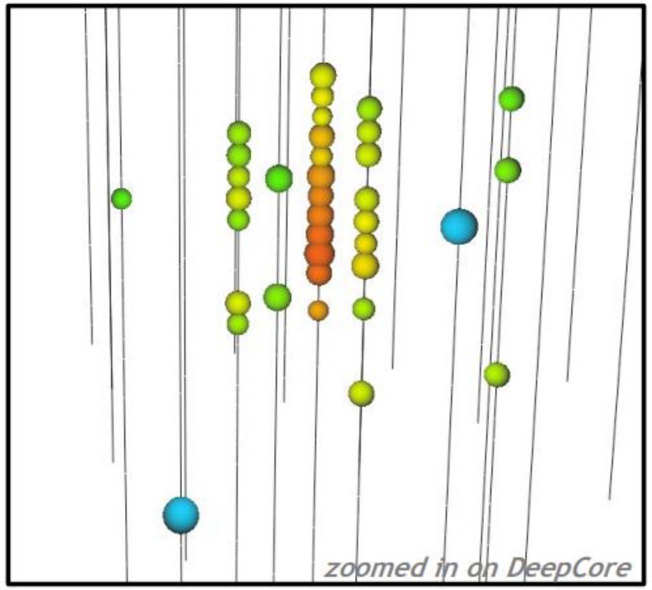


mostly ν_μ^{CC}

Event Topologies DeepCore

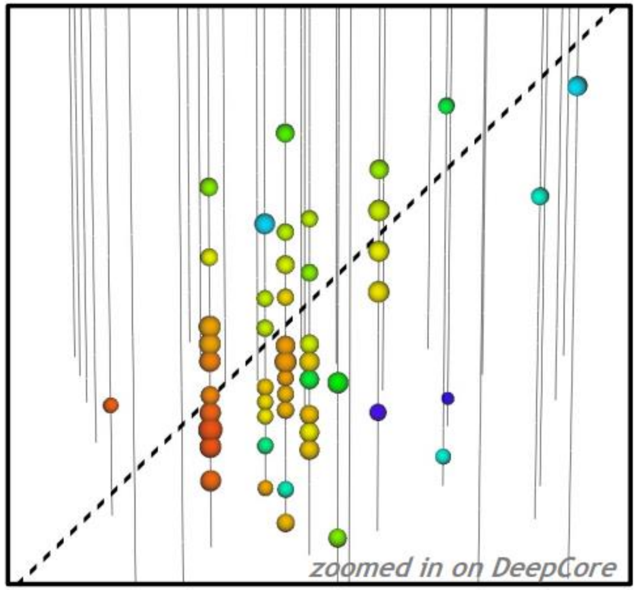


Cascades



ν_e^{CC} , ν_τ^{CC} , ν^{NC}

Tracks



mostly ν_μ^{CC}

Background Sources

Not every event we see is an atmospheric neutrino event

Atmospheric μ's

- Atmospheric muons that don't decay can reach the detector and emit Cherenkov light too
- Rate at DC filter: ~7 Hz
- Can be suppressed by veto regions and BDTs

Pure noise events

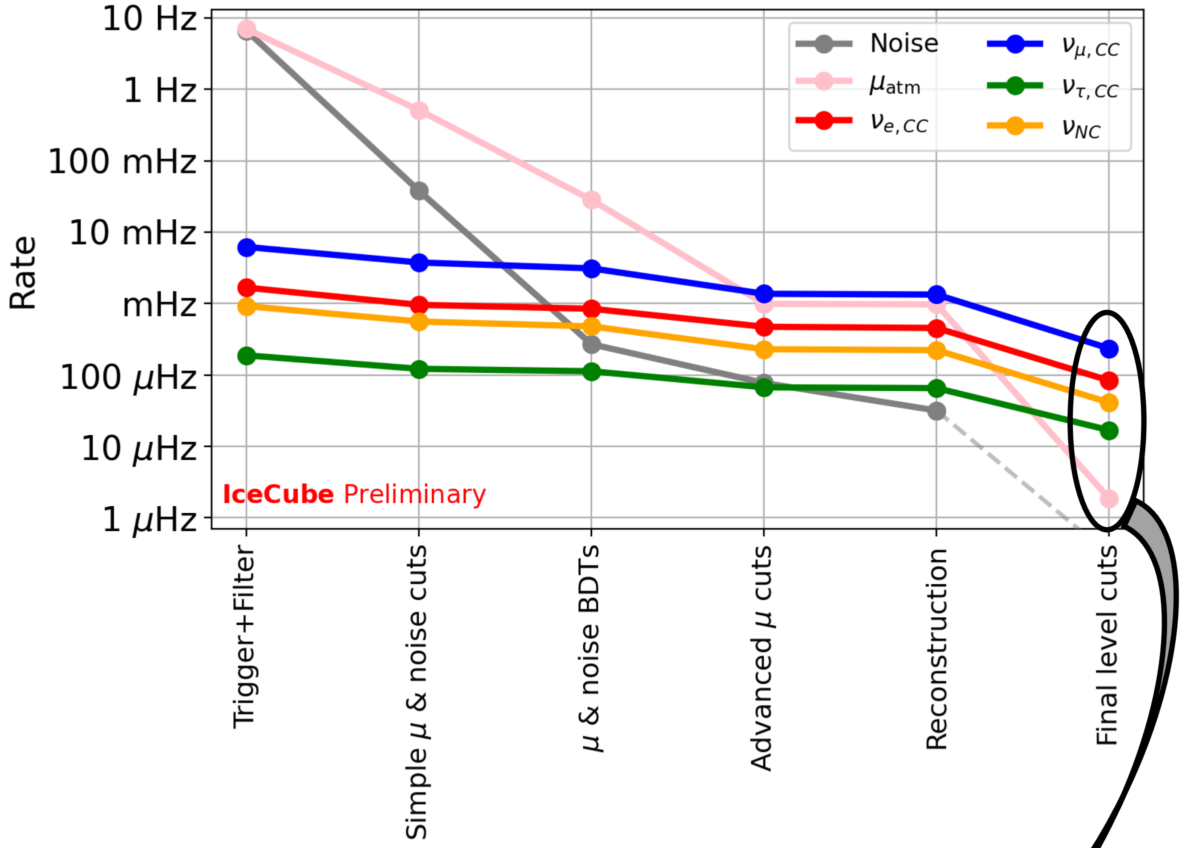
- Coincident occurrence of PMT dark noise or radioactive decays in the DOM glass can trigger the detector
- Rate at DC filter: ~7 Hz
- Can be suppressed by cutting on the number of hit DOMs and BDTs

➢ These backgrounds dominate over neutrinos (~mHz) at filter level

Event Selection

Through multiple selection layers we reach a neutrino dominated sample

1. **Simple cuts** e.g. number of hit modules
2. **BDTs** based on event hit variables
3. **Advanced cuts** e.g. corridor cuts
4. **Reconstruction cut** to remove events that cannot be reconstructed
5. **Analysis cuts** e.g. binning edges



- No noise–only MC survives the final cuts
- The muon contamination is <1%

	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	$108,784 \pm 129$	-

New Atmospheric Neutrino Sample

Contains 11.1 years of IceCube DeepCore data

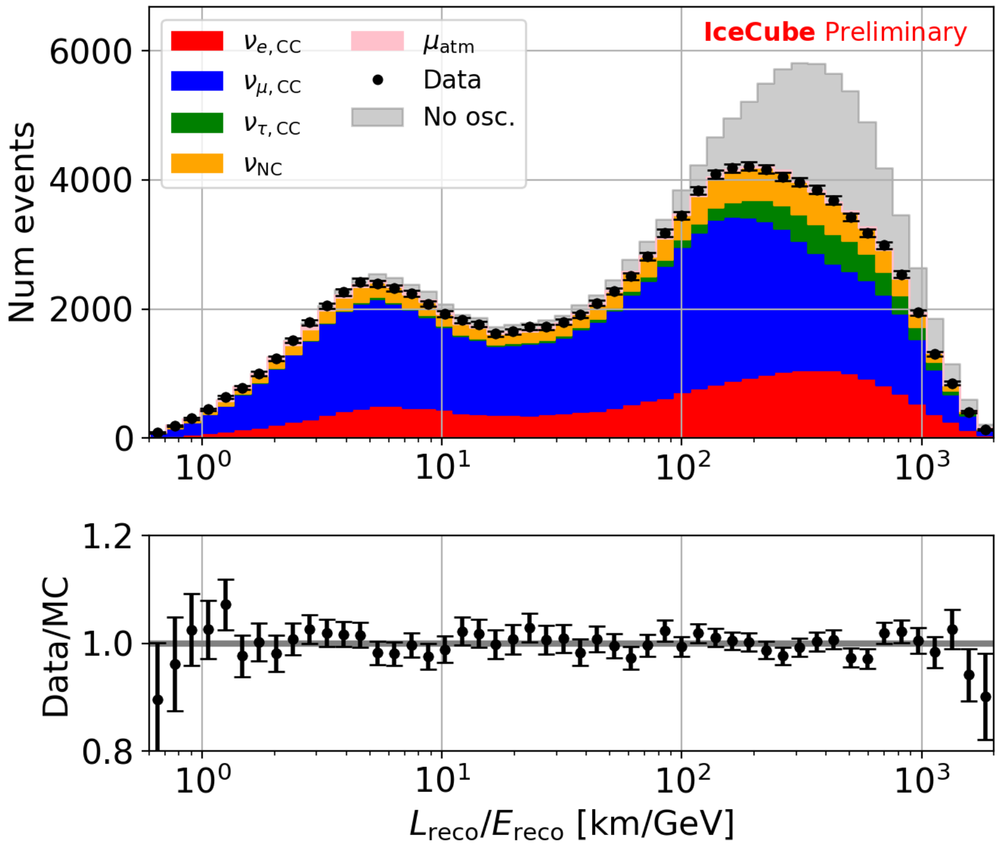
Uses **graph neural networks** for

- reconstruction of neutrino energy
- reconstruction of neutrino zenith angle (traveled distance)
- track–cascade classification

Shows good data–MC agreement

Two analyses have been performed on new sample

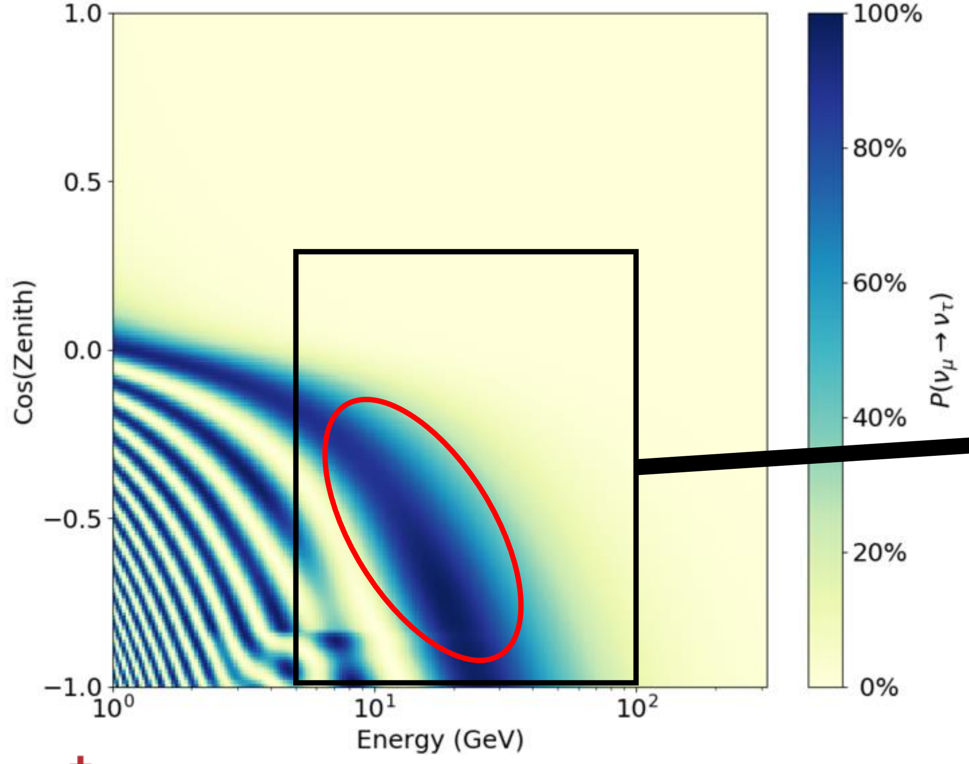
- atmospheric oscillation parameters θ_{23} and Δm^2_{32}
- ν_τ appearance



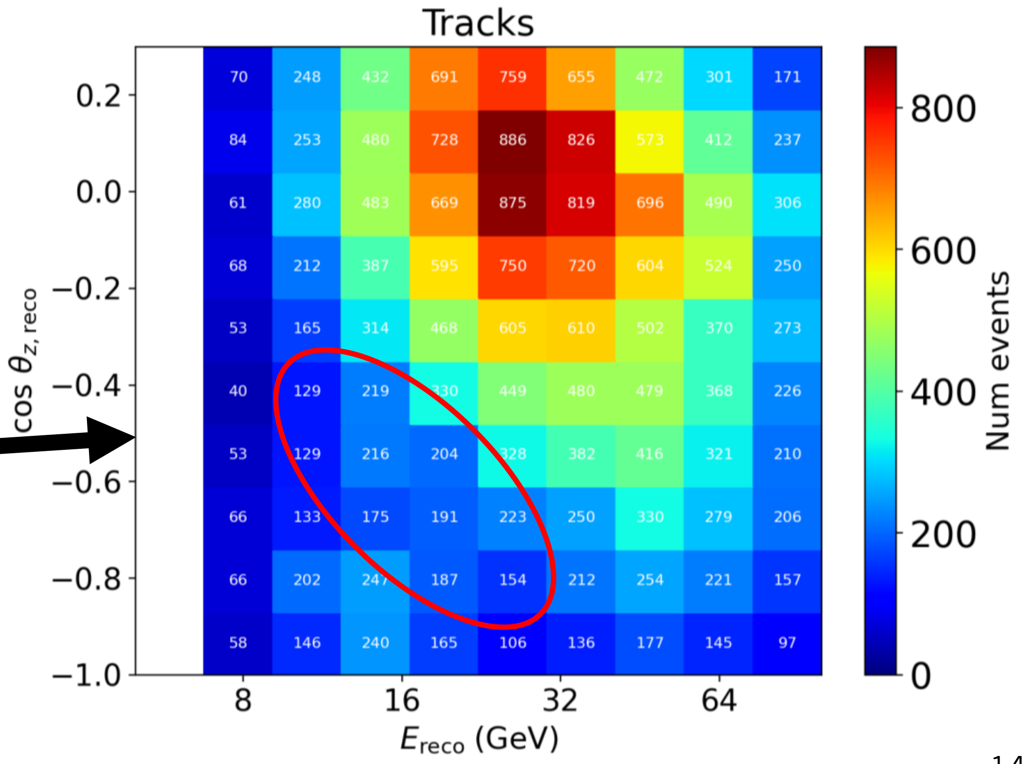
What do we actually see from the Oscillogram

- With DeepCore we can only resolve a small part of the oscillogram
- Measurement also includes flux spectrum, energy dependent cross–section, ...
- **But** in tracks (high purity ν_μ sample) you can see ν_μ disappearance by eye

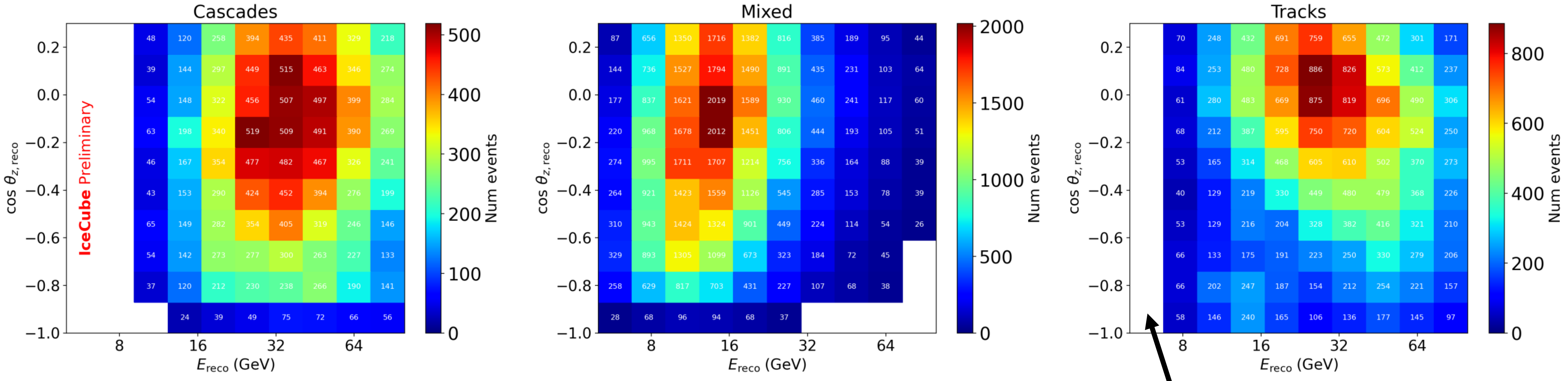
True oscillogram



Measurement



Analysis Binning



Reconstructed energy

10 logarithmic bins between 5 and 100 GeV

Reconstructed cosine zenith angle

10 linear bins between –0.1 and 0.3

Event type classification (track vs cascade)

3 non–uniform bins covering scores between 0 and 1 → also use cascade–like events in analysis

White bins are masked because of low statistics

Systematics Uncertainties

Many sources of systematic uncertainty were studied

- only include the most impactful

Flux

Spectral index of atmospheric neutrino flux

Barr modifications of MCEq

Cross–section

Quasi elastic and resonance axial mass; re–weight from GENIE

Difference in DIS between GENIE and CSMS

Neutrino normalization

Detector

Overall optical module efficiency scale

Ice properties

Background

Atmospheric muon normalization

Flux $\Delta\gamma$
Flux π^+ G
Flux π^+ H
Flux π^+ I
Flux K^+ W
Flux K^+ Y
$M_{A,QE}$
$M_{A,res}$
$\mathrm{DIS}_{\mathrm{tot}}$
$\mathrm{DIS}_{\mathrm{diff}}$
N_ν
DOM efficiency
Hole ice, p_0
Hole ice, p_1
Dust absorption
Ice absorption
Ice scattering
N_μ

Improvements to Previous DeepCore Results

More livetime

- 11 years, 2 more than last result

Better noise cleaning, more robust reconstruction

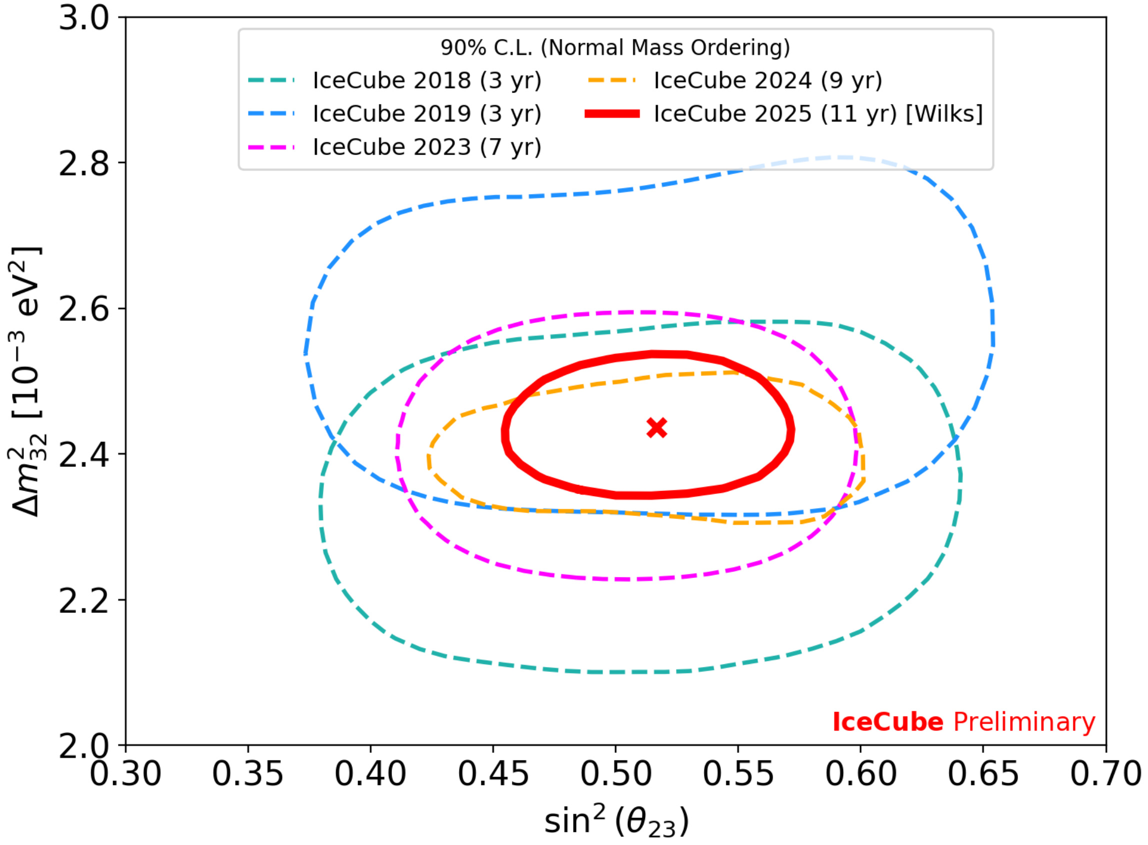
- More PMT effects (e.g. afterpulses) removed
- Reconstruction only uses best modeled quantities

Additional ice systematic and improved ice model

- Intrinsic ice (in contrast to dust) absorption
- Include birefringence ice structure in simulation

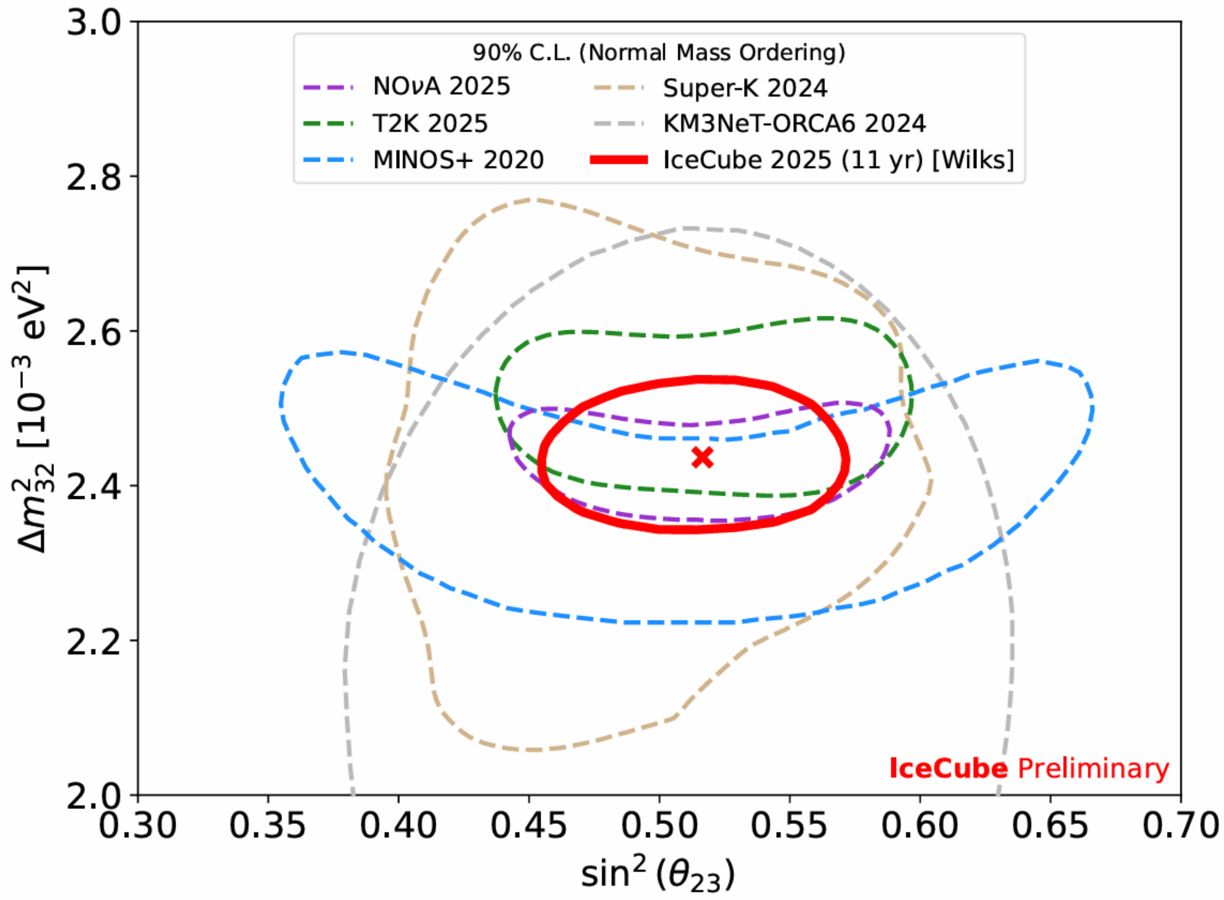
Improved muon and tau simulation

- Include β–dependence in μ light yield calculation
- Include polarization and resonances in τ decay



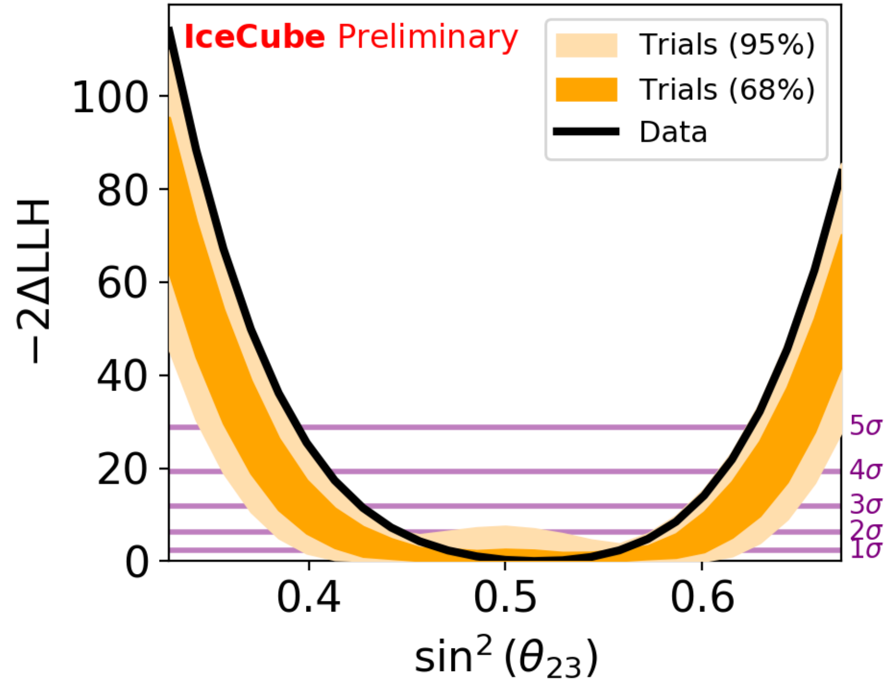
Atmospheric Oscillation Parameters

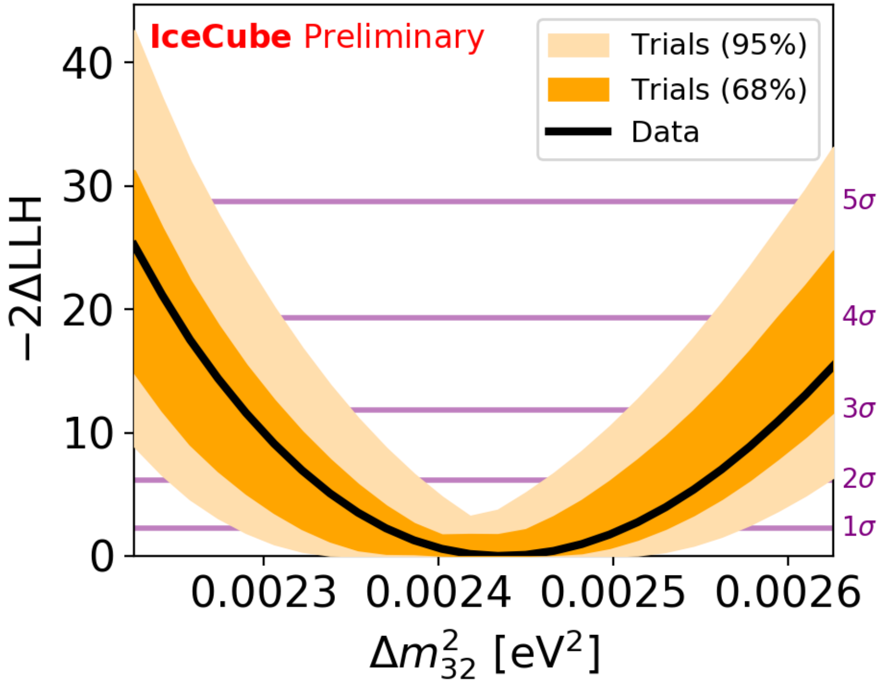
- Perform simultaneous fit of θ_{23} and Δm^2_{32}
- Best fit θ_{23} is in upper octant, consistent with maximal mixing
- Normal mass ordering is preferred
- Excellent agreement between simulation and data, with p–value = 37.1 %
- Result is independent of δ_{CP}, with minimal influence of cross–section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



Best fit point: $\sin^2(\theta_{23}) = 0.516$
$\Delta m^2_{32} = 2.44 \cdot 10^{-3}$ eV²

Atmospheric Oscillation Parameters – 1D Profiles





$\sin^2(\theta_{23}) = 0.516^{+0.028}_{-0.030}$

$\Delta m^2_{32} = 2.44^{+0.047}_{-0.045} \cdot 10^{-3}$ eV²

Comparing to pseudodata trials

- $\sin^2(\theta_{23})$ constraint strong but within statistical fluctuations
- Δm^2_{32} constraint approximately average

ν_τ Appearance

How well can we constrain the number (scale) of detected ν_τ?

Do we see more or less ν_τ than we would expect from ν_μ disappearance?

This analysis simply fits an additional **ν_τ normalization parameter** N_{ν_τ}

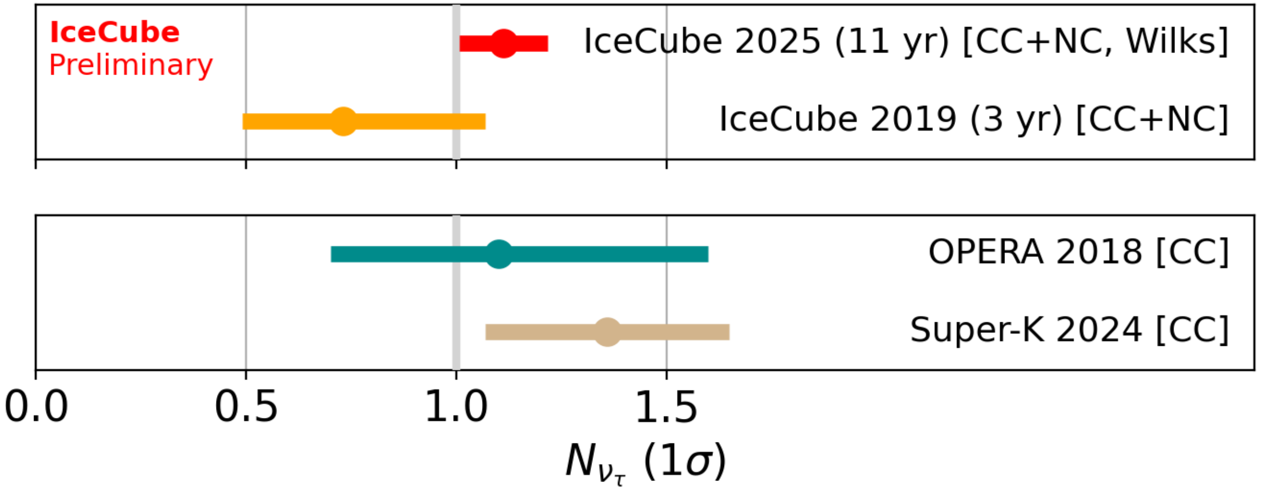
- scales the weight of all (CC+NC) ν_τ events in the sample

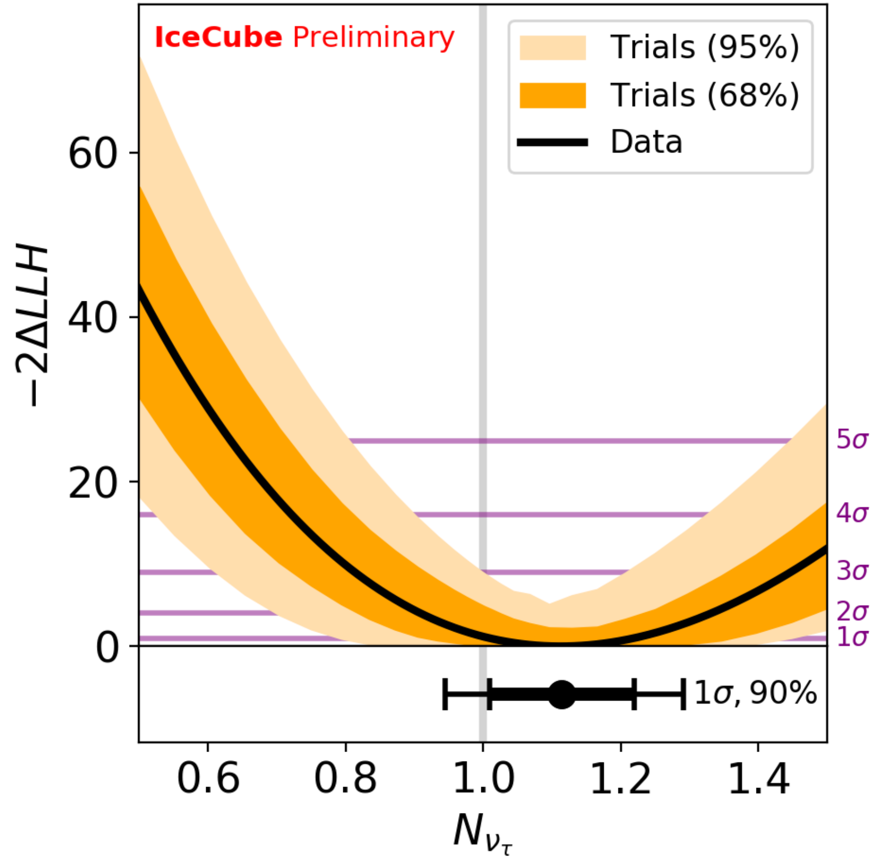
No direct physics meaning but can be:

- a unitarity test of the neutrino mixing matrix (e.g., sterile neutrinos, neutrino decay)
- a test of the ν_τ cross–section (scale)

ν_τ Appearance

- Best–fit value: $1.11^{+0.11}_{-0.10}$
- Consistent with standard expectation at ~1σ
- Goodness of fit p–value = 39.4 %





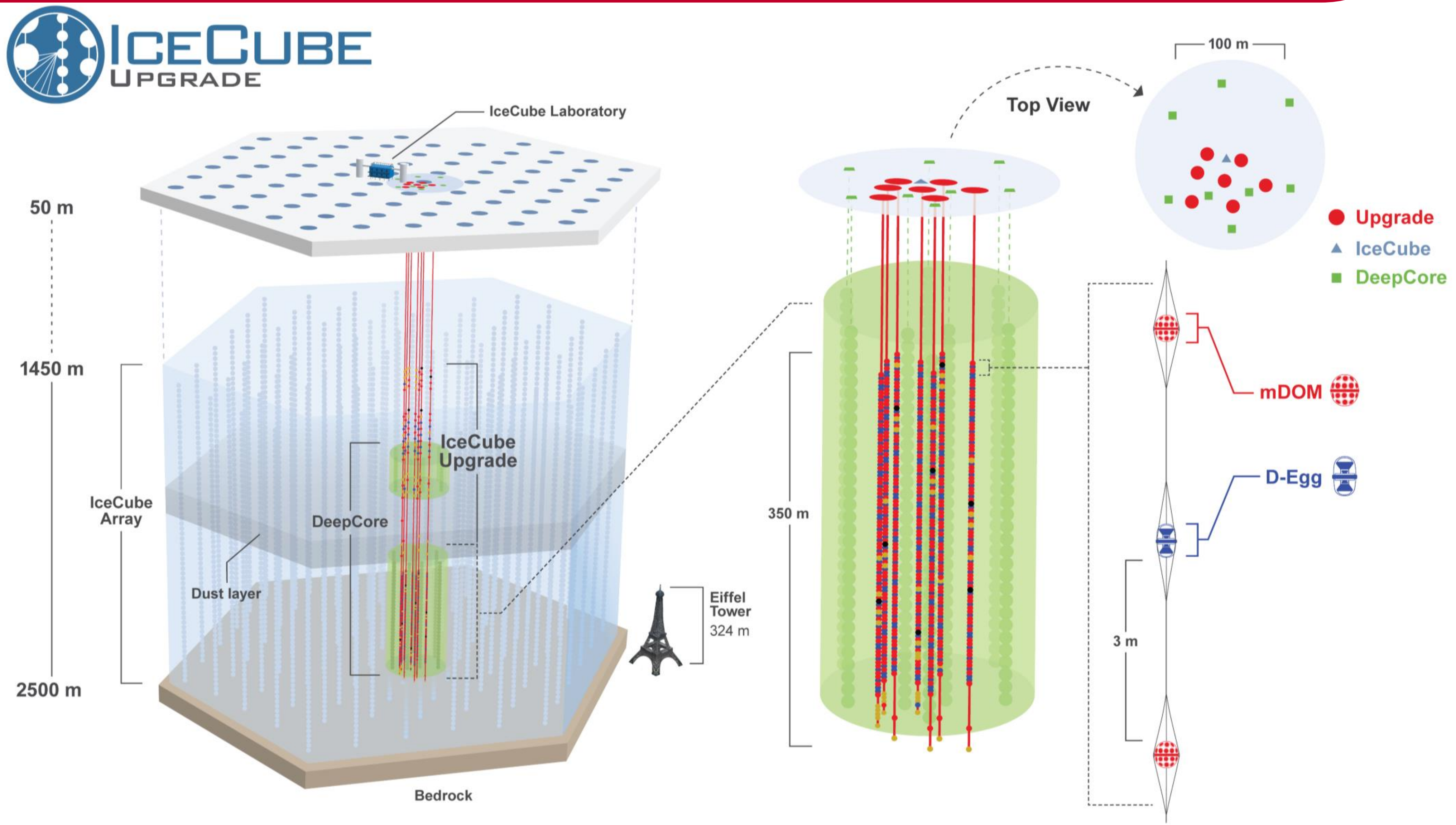
PRiSMA+ JG|U

Interim Conclusion – DeepCore

- New 11–year DeepCore atmospheric neutrino sample is ready
- Shows good data–MC agreement
- Atmospheric oscillation parameter results consistent with global constraints
- Measured ν_τ normalization consistent with standard expectations
- Other studies are ongoing

Looks good so far, but what will the future bring?

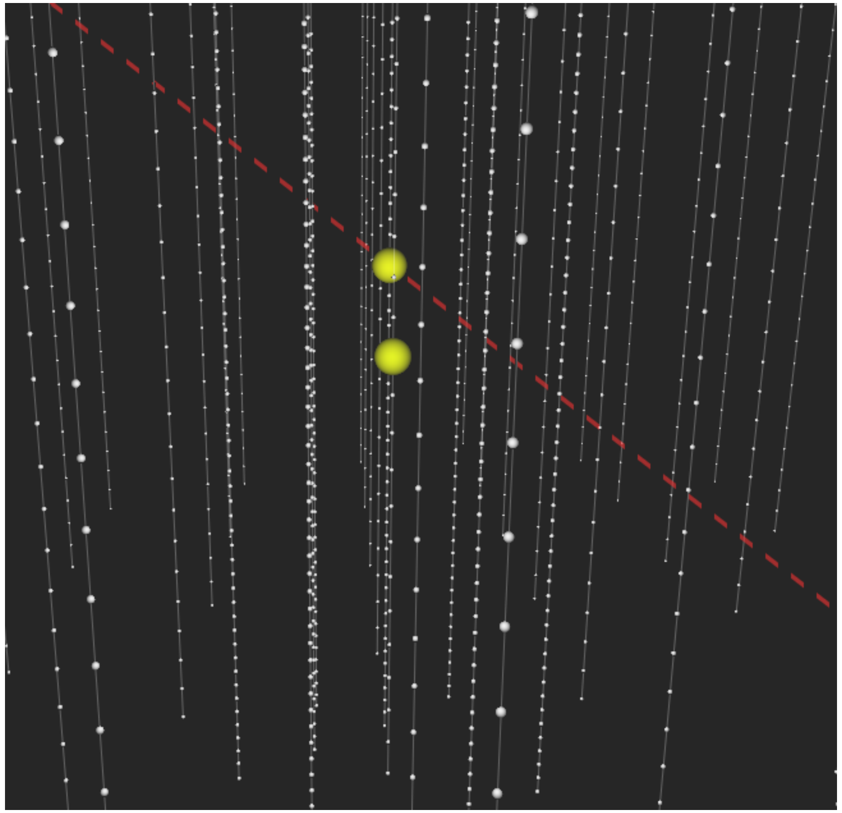
The IceCube Upgrade (IC93)



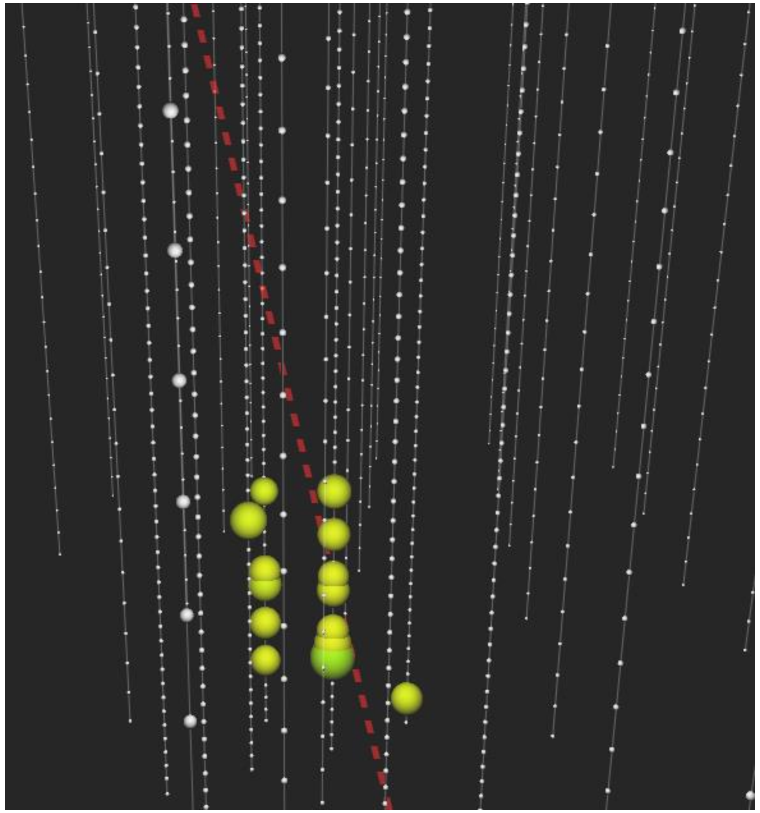
Deployment starts end of this year!

Events in IC86

3.6 GeV ν_μ

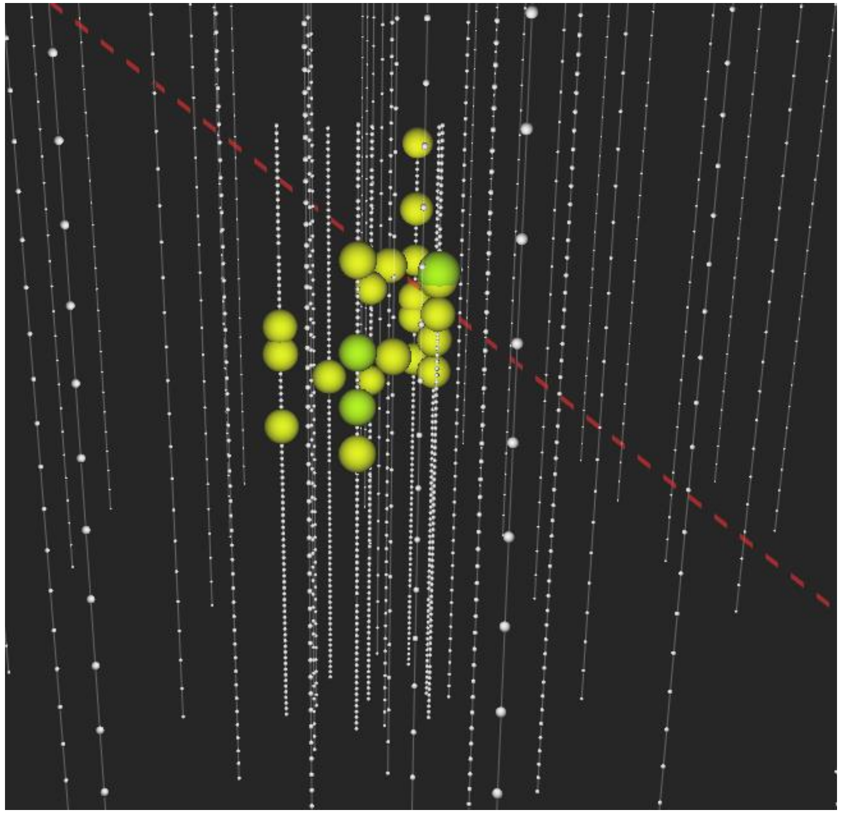


21 GeV $\bar{\nu}_\tau$

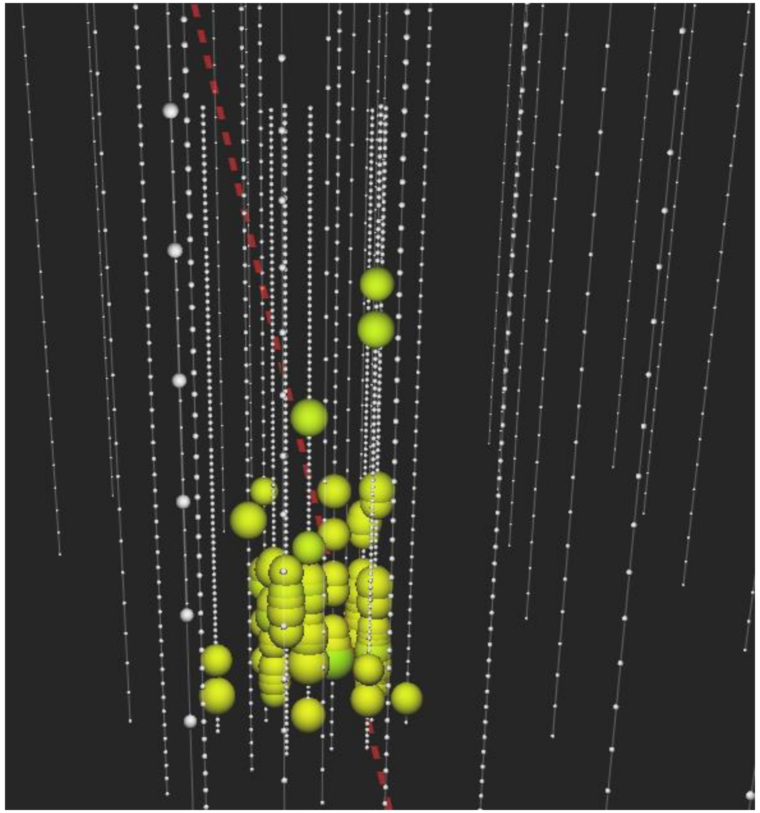


Events in IC93

3.6 GeV ν_μ



21 GeV $\bar{\nu}_\tau$



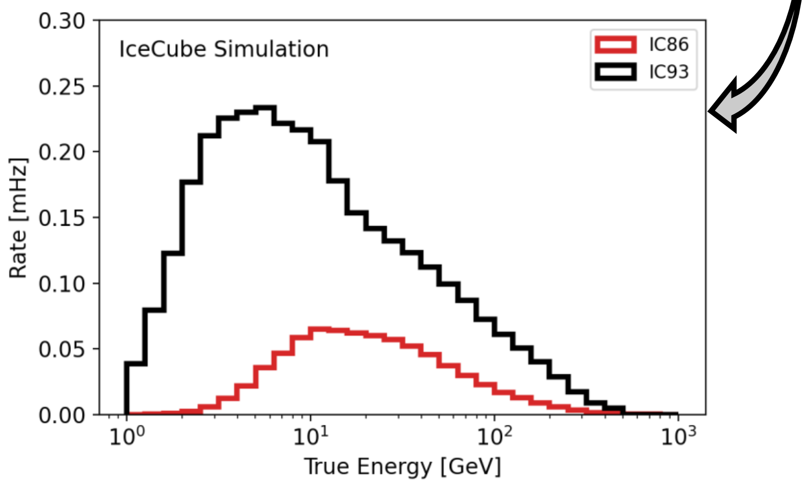
- More hits with the new strings

Improvements with the Upgrade

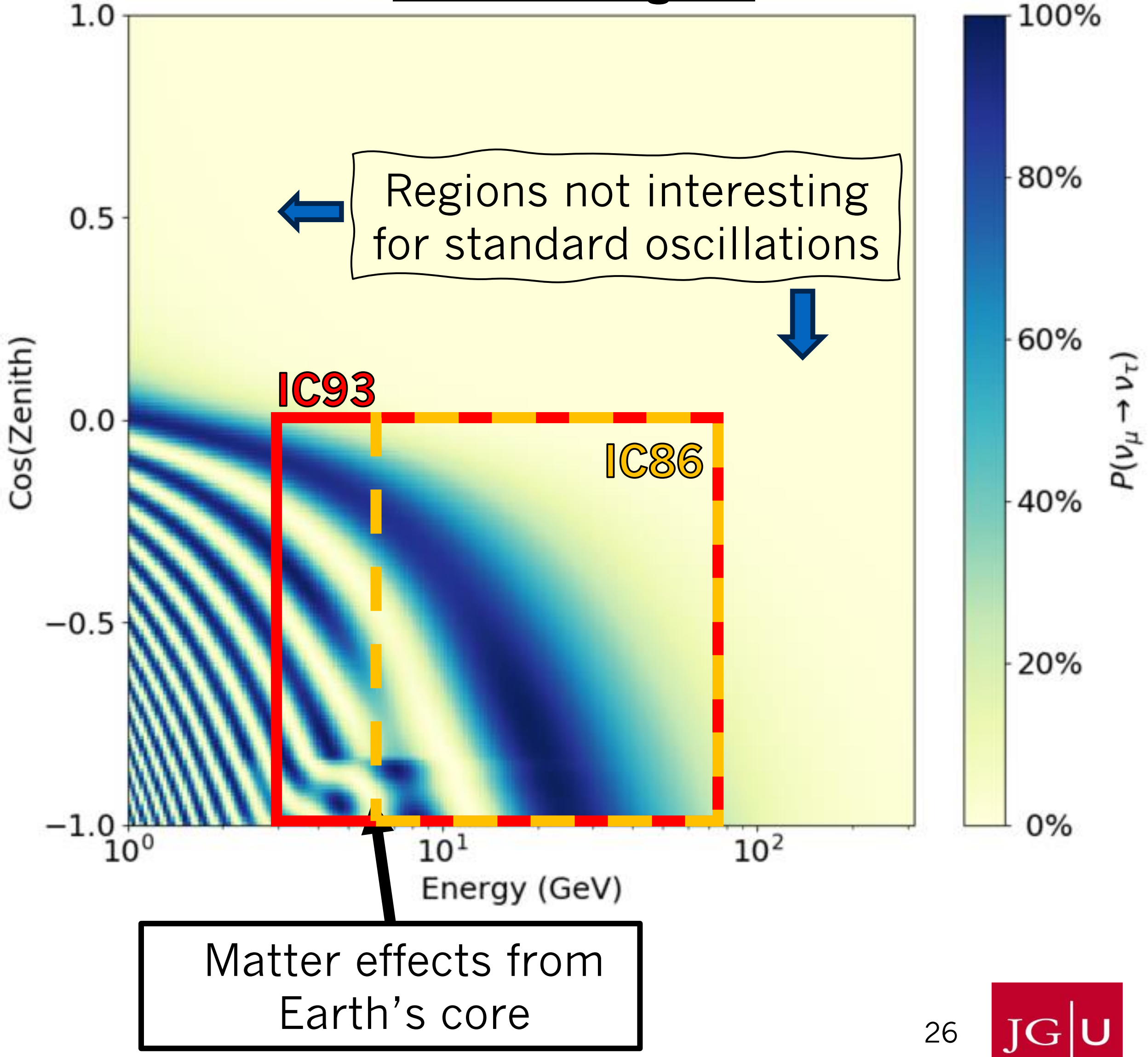
Energy threshold of detector due to limited number of detected photons

Upgrade (IC93)

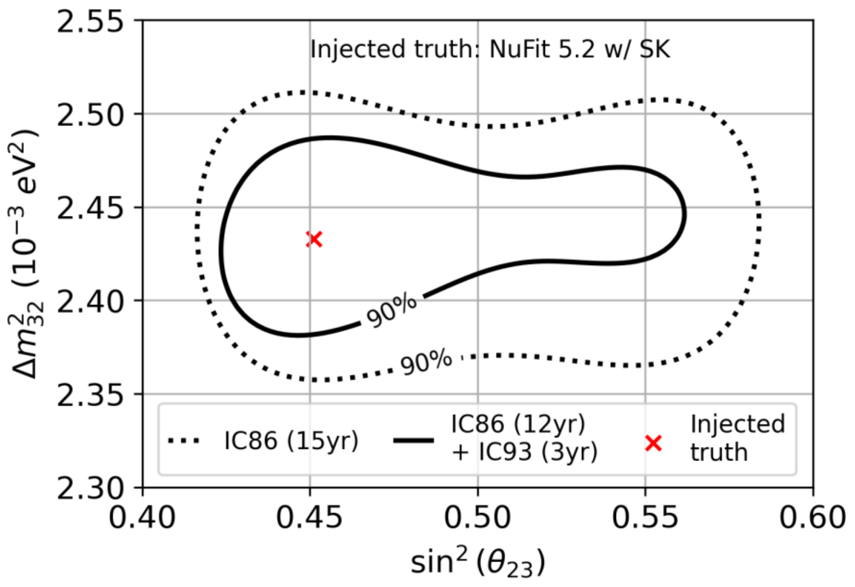
- gives access to more of the interesting region
- detects more neutrinos (at all energies)
- better identifies tracks vs cascades
- better reconstructs observables



True oscillogram



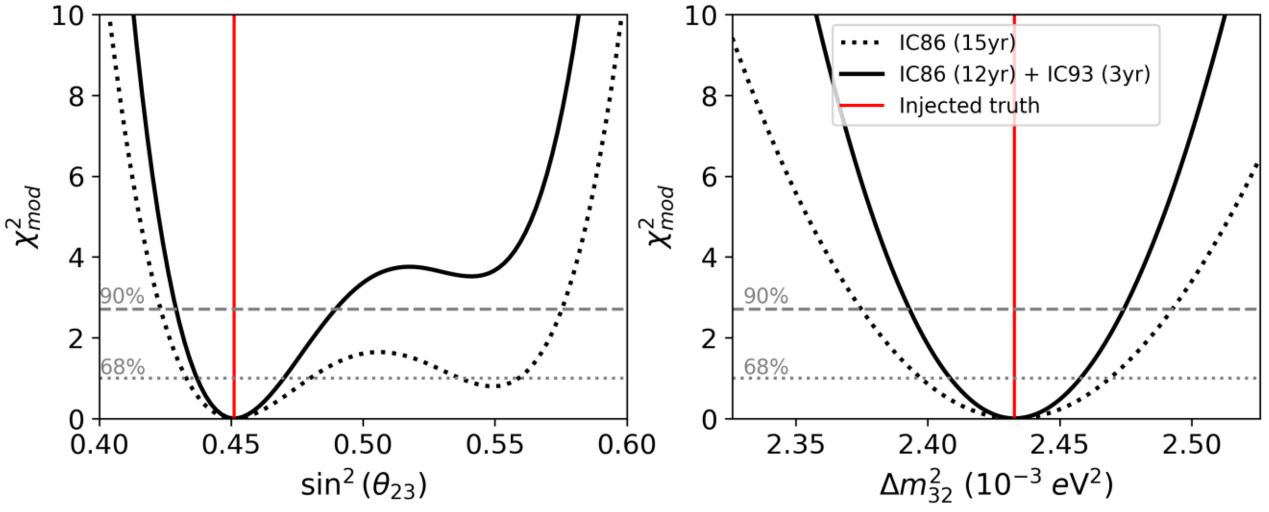
How much will the Upgrade improve our results?



Compare two scenarios, 3 years after planned deployment

1. Continue running IC86 w/o new strings (·····)
2. Install new strings (—)

- With the new strings the area enclosed by the 2D 90% contour is nearly reduced by half
- Better sensitivity to both mixing parameters



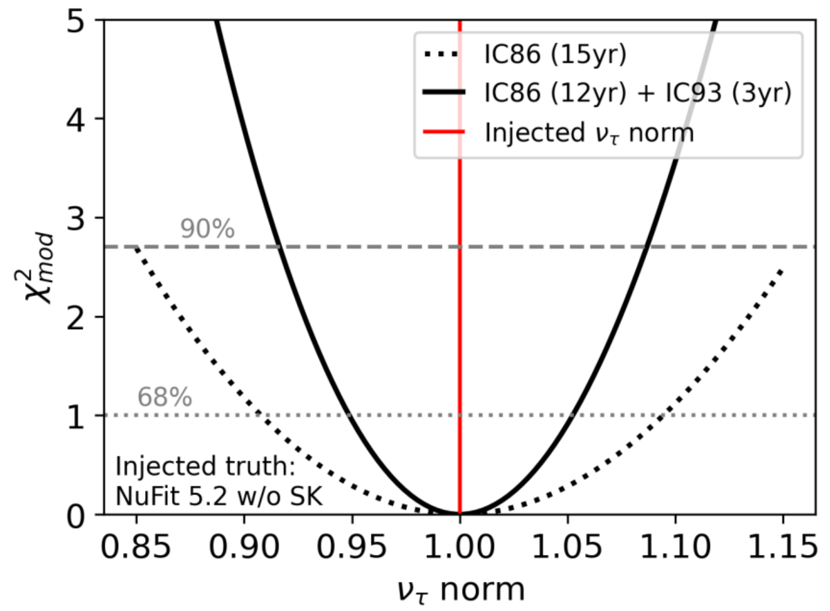
More details in pre–print: [arXiv.2509.13066]

ν_τ Appearance

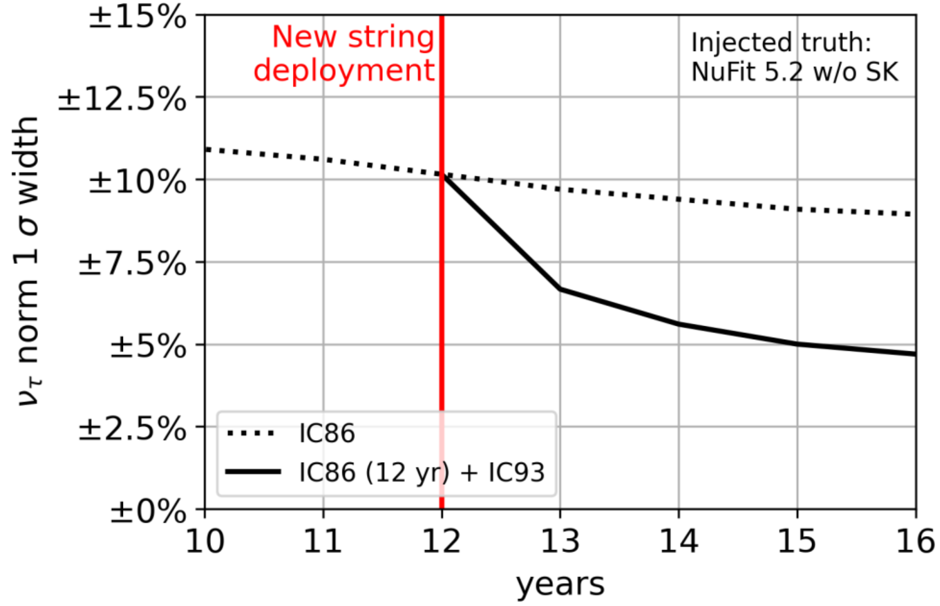
How much will the Upgrade improve our results?

Compare two scenarios, 3 years after planned deployment

1. Continue running IC86 w/o new strings (·····)
2. Install new strings (—)



- Can constrain ν_τ norm much better than DC only
- With new strings 1σ uncertainty can be almost reduced by a factor of two

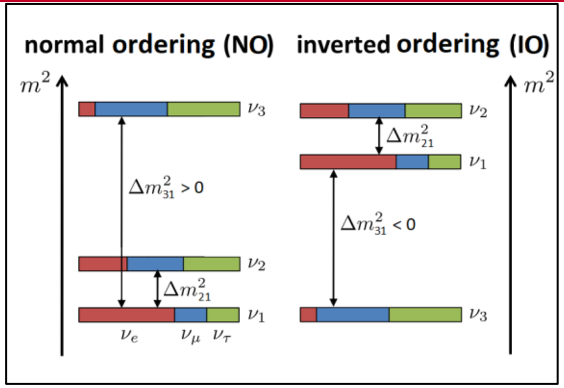


More details in pre–print: [arXiv.2509.13066](https://arxiv.org/abs/2509.13066)

PRiSMA+

JG|U

Neutrino Mass Ordering



How well can we determine the NMO?

Strongly depends on true θ_{23} value

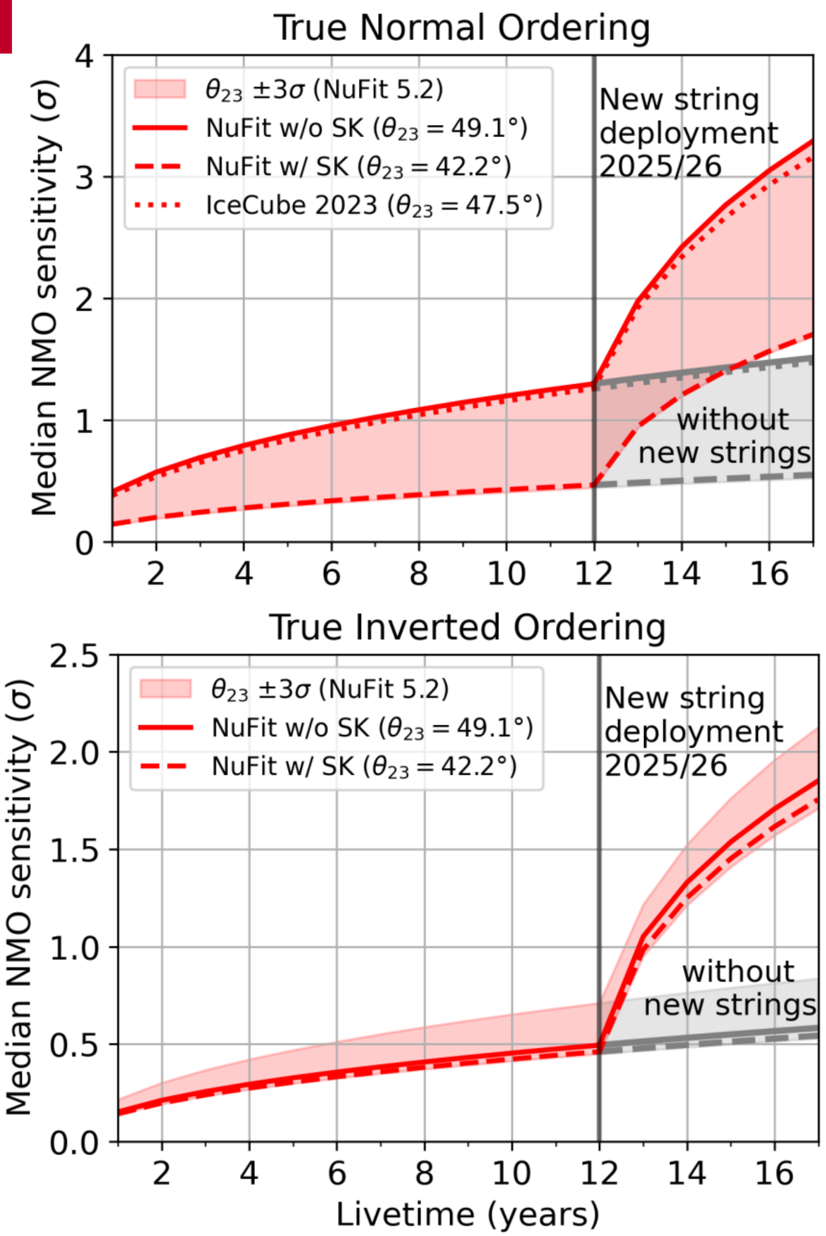
⇒ show NMO sensitivities for a range of θ_{23} values

New strings strongly increase IceCube's NMO sensitivity

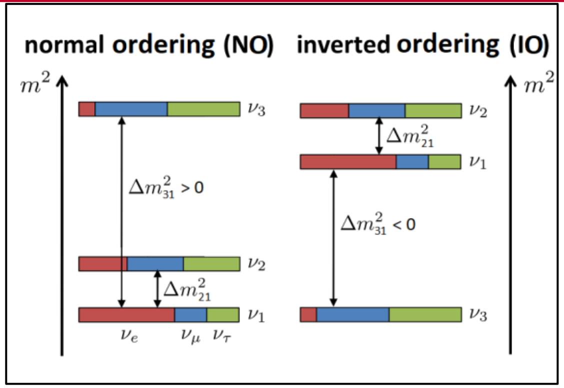
- 1.8σ – 3.3σ after 5 years if NO is true
- 1.7σ – 2.1σ after 5 years if IO is true

Current global preference (NuFIT 6.0, September 2024):

- ~2.5σ for NO with SuperK and IC24 data
- <1σ for IO without SuperK and with IC19 data



Neutrino Mass Ordering



How well can we determine the NMO?

Strongly depends on true θ_{23} value

⇒ show NMO sensitivities for a range of θ_{23} values

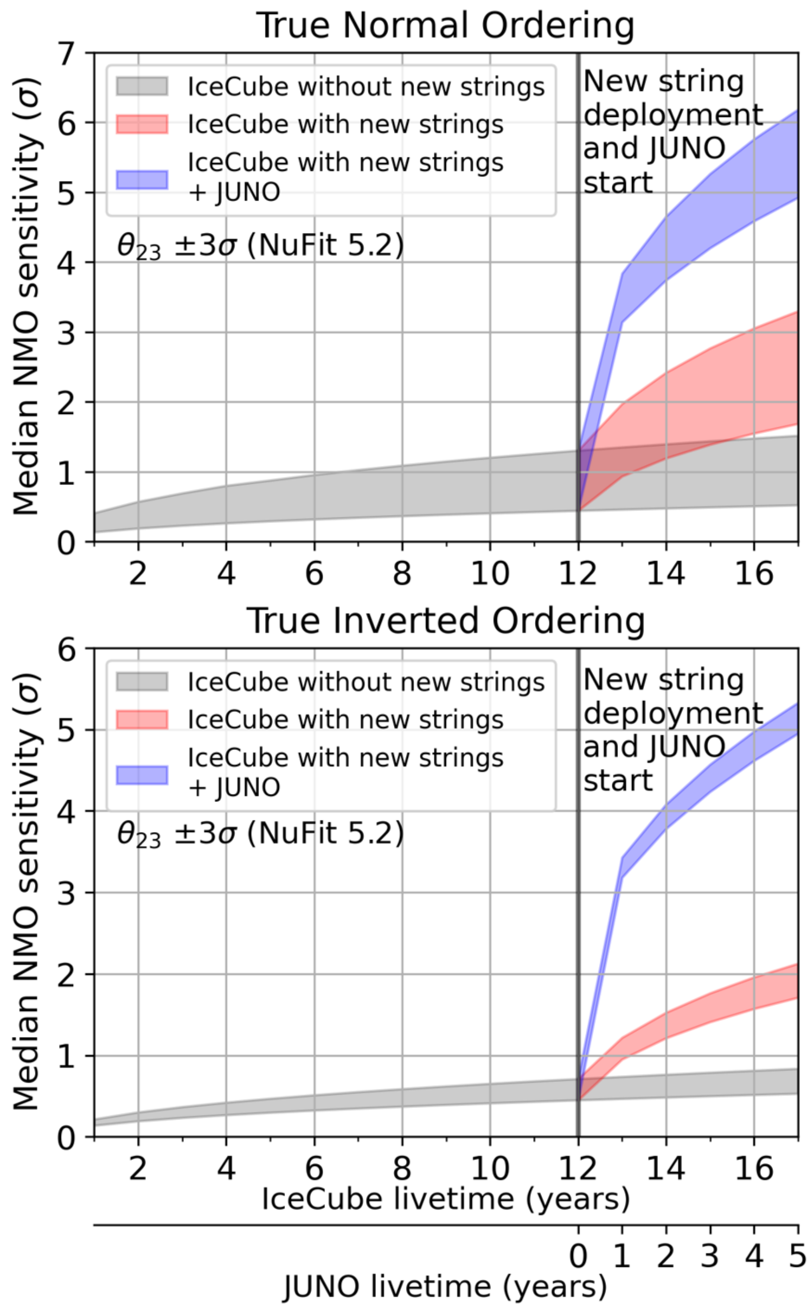
Combined fit with reactor experiment JUNO further boosts sensitivity

- 3σ with 1 year of data (each)
- 5σ after 5 years of data (each)

for either ordering

Current global preference (NuFIT 6.0, September 2024):

- ~2.5σ for NO with SuperK and IC24 data
- <1σ for IO without SuperK and with IC19 data



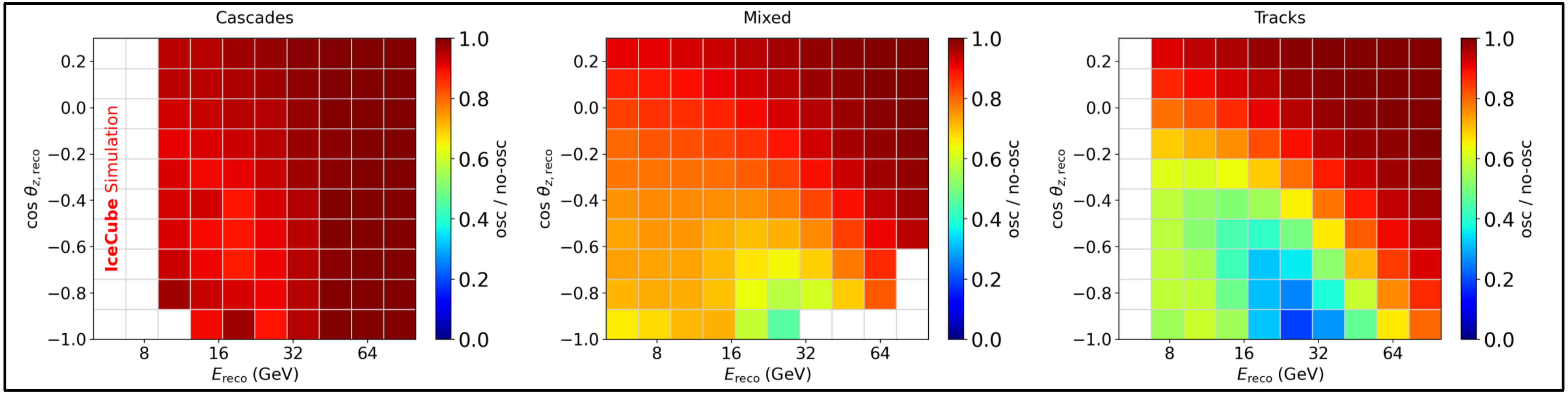
Conclusion

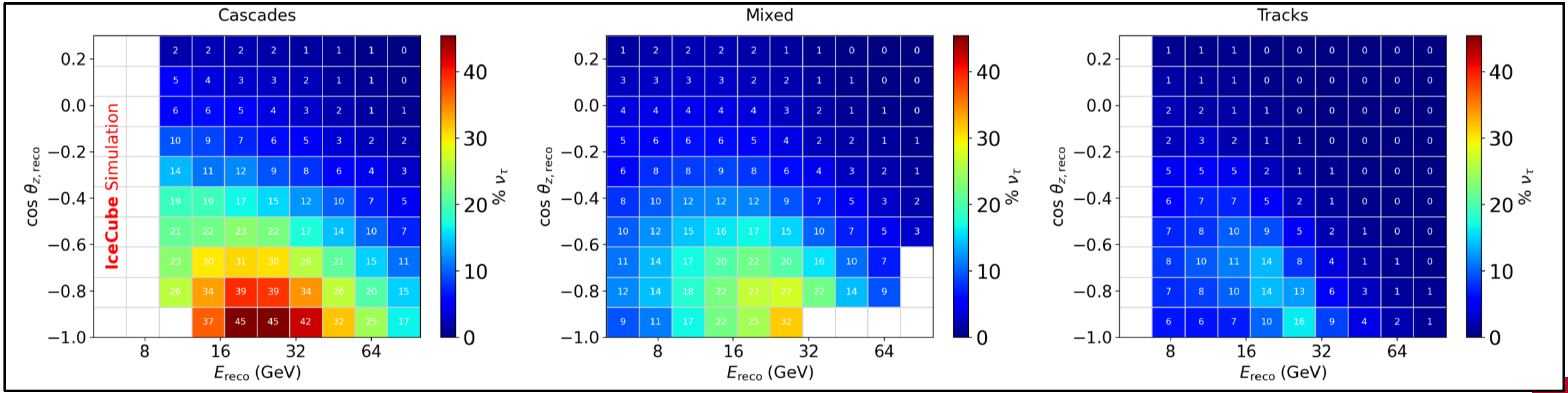
- New atmospheric oscillation results from IceCube DeepCore are consistent with global constraints
- Measured ν_τ normalization consistent with standard expectation/PMNS unitarity
- IceCube Upgrade installation in 2025/26 will yield more data and higher precision studies
- NMO will strongly benefit from Upgrade → 5σ possible in combined fit

Thank you for your attention!

Backup

Signals

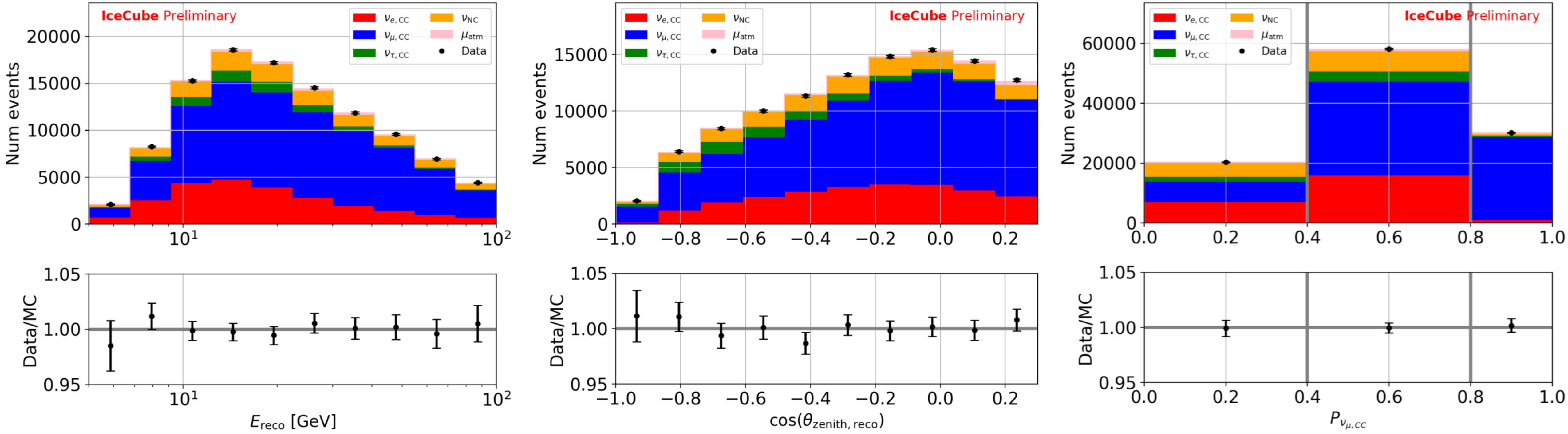




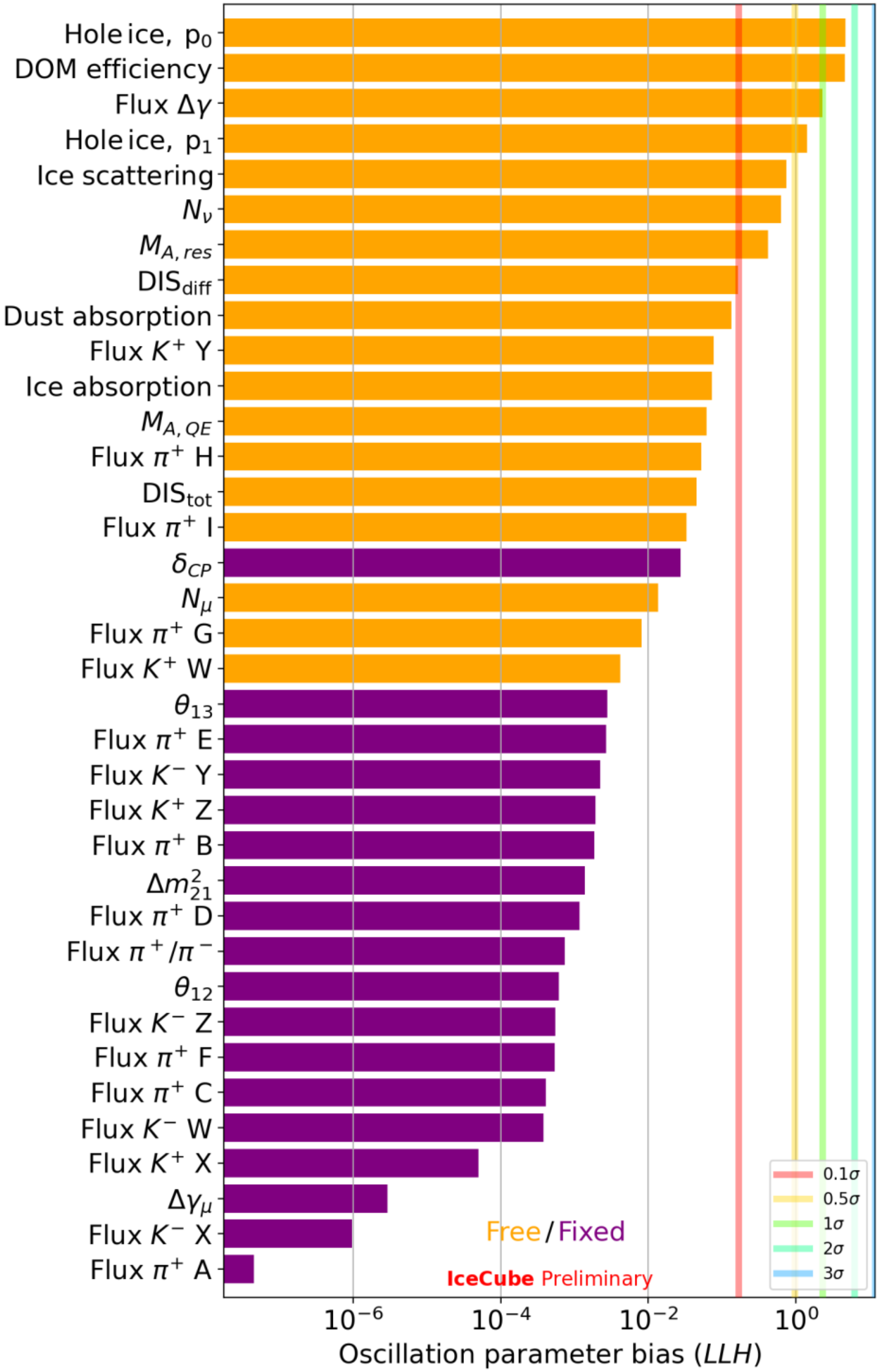
PRISMA+

JG|U

Data–MC Agreement 1D



Systematics Uncertainties



Nuisance Parameter Pulls