Neutrino Mass Ordering using Atmospheric Neutrino Oscillations with IceCube DeepCore

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on behalf of the IceCube Collaboration

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NeuTel 2023 - Venice, Italy
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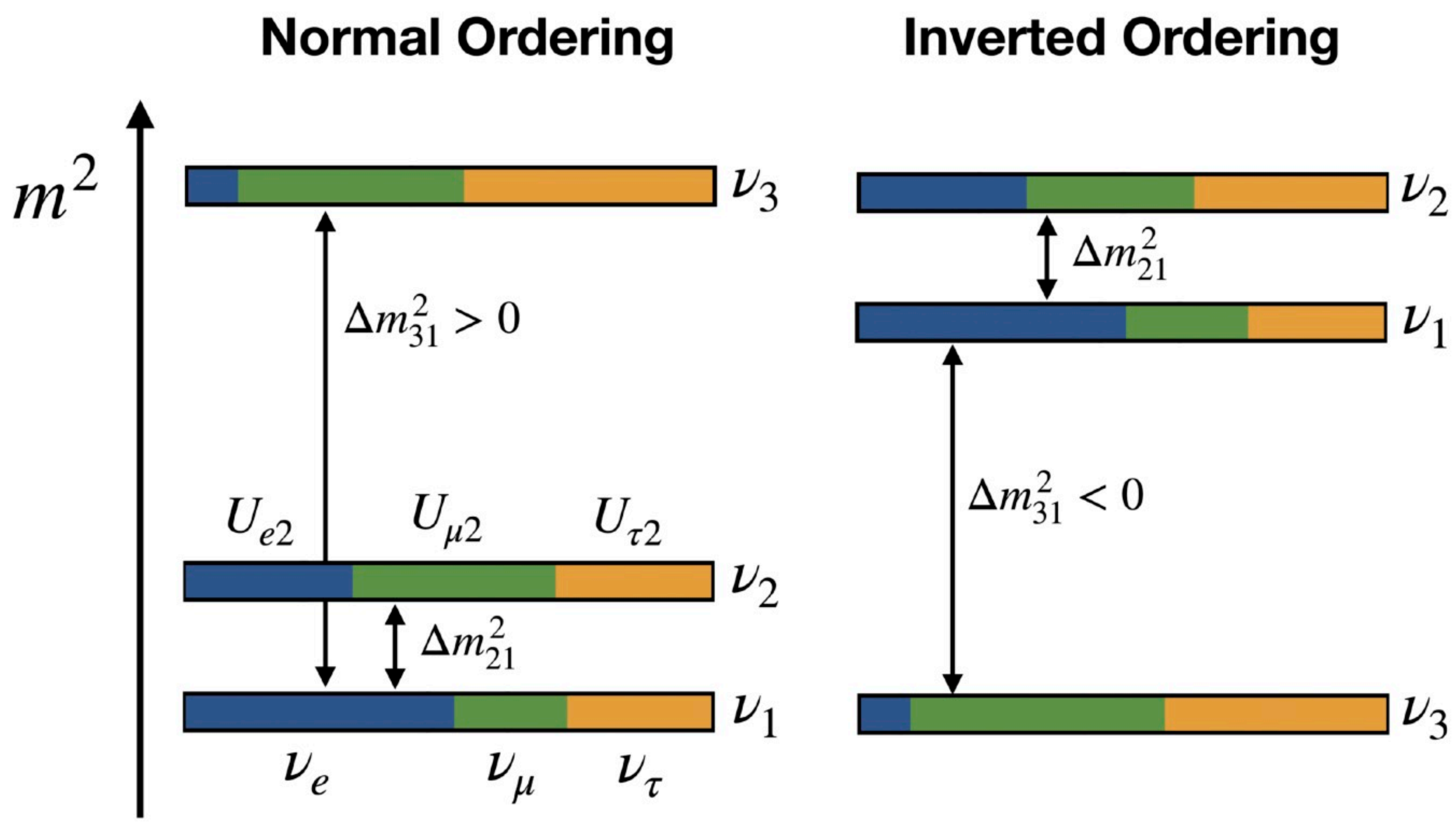
Neutrino Mass Ordering (NMO)

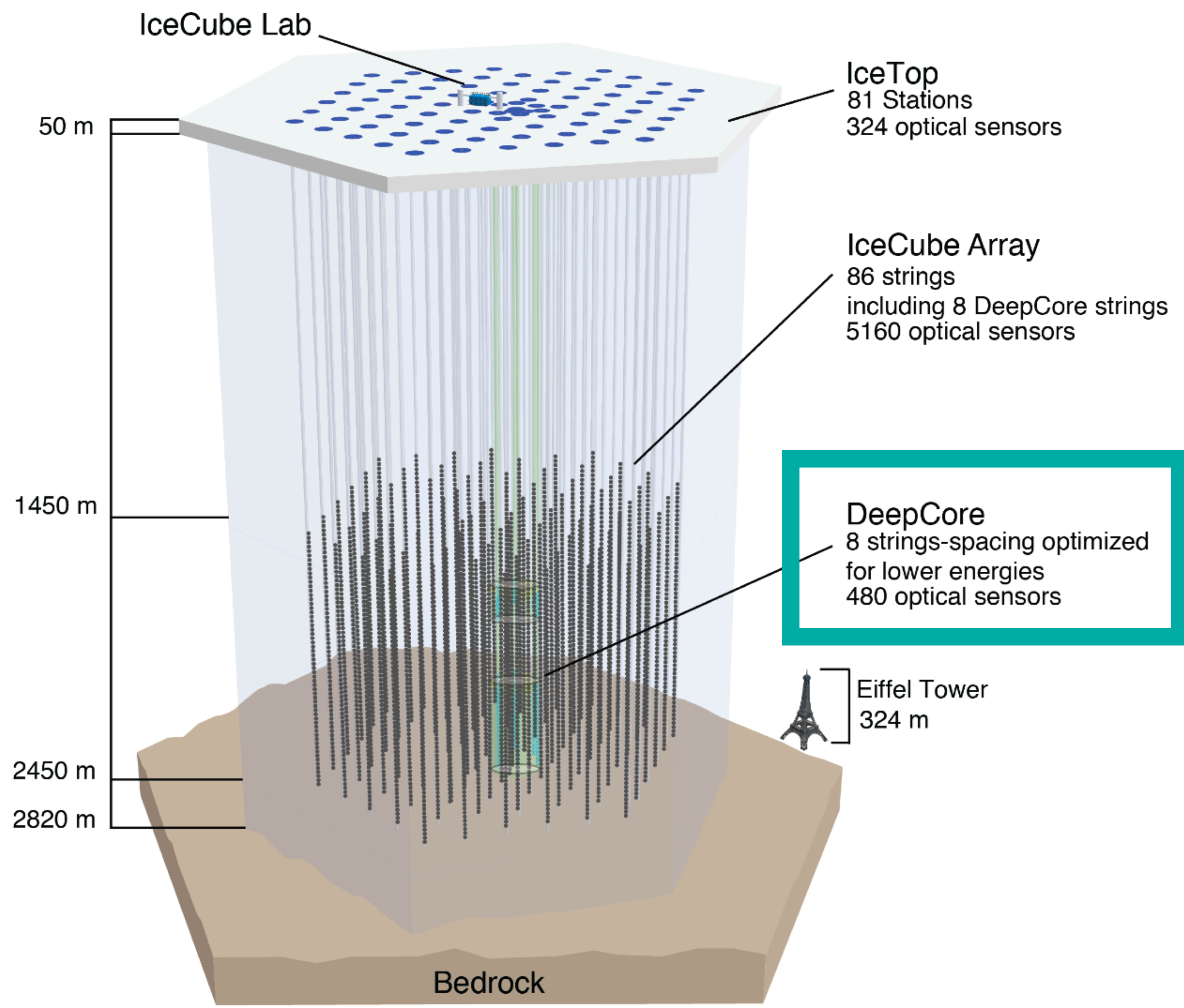


The sign of Δm^2_{31} is not known: We do not know which neutrino is the heaviest

The combined global fit including the Super-K atmospheric data shows a preference for NO over IO by about 2.5σ (NuFit 5.2)

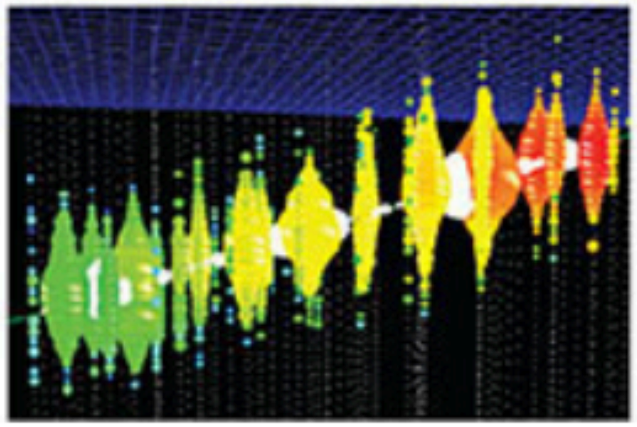
The IceCube Neutrino Observatory

- IceCube transformed 1 cubic km of Antarctic ice into a Cherenkov neutrino detector
- Optical sensors are embedded in the ice greater than 1.5 km below the surface
- DeepCore provides visibility of neutrino events at lower energies (3 GeV - 100 GeV)



Event Signatures in DeepCore

Tracks

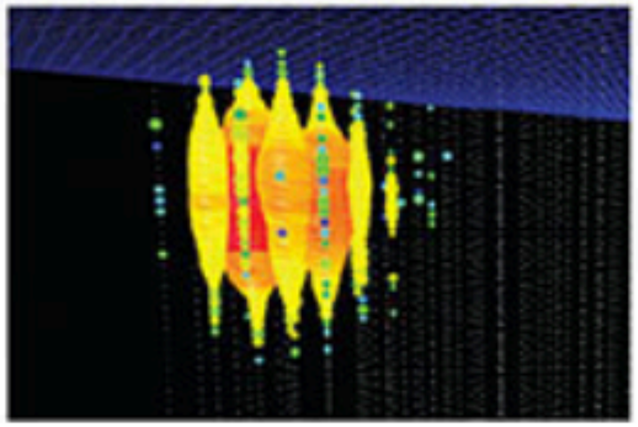


$$\nu_\mu + N \rightarrow \boxed{\mu^- + X}$$

Hadronic shower plus Muon track

Muons travel longer distances than electrons: minimum ionizing particle

Cascades



$$\nu_x + N \rightarrow \nu_x + \boxed{X}$$

Hadronic shower

$$\nu_e + N \rightarrow \boxed{e^- + X}$$

Hadronic shower plus Electromagnetic shower

Electrons scatter

$$\nu_\tau + N \rightarrow \tau^- + \boxed{X}$$
$$\tau^- \rightarrow \nu_\tau + \boxed{X'}$$

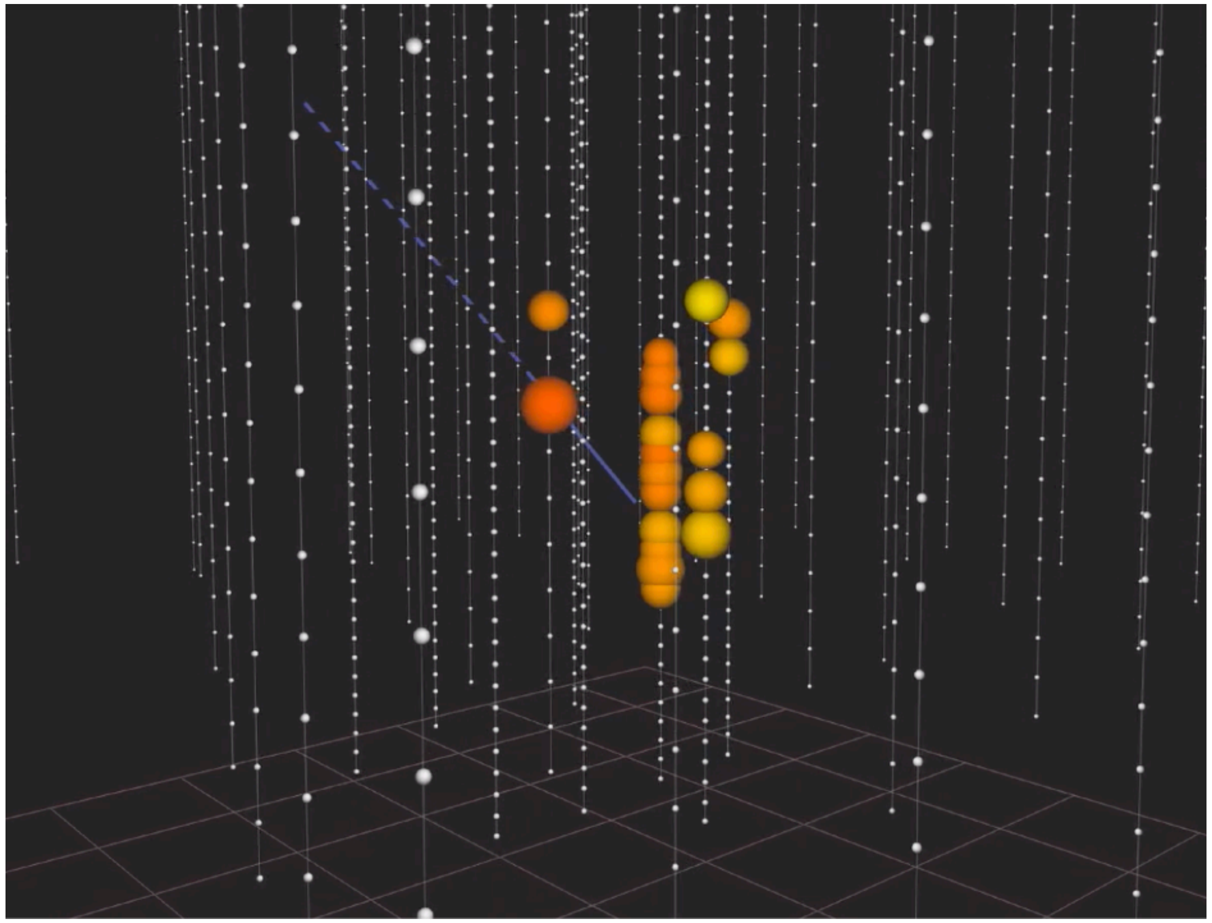
Two Hadronic showers

Taus decay very quickly

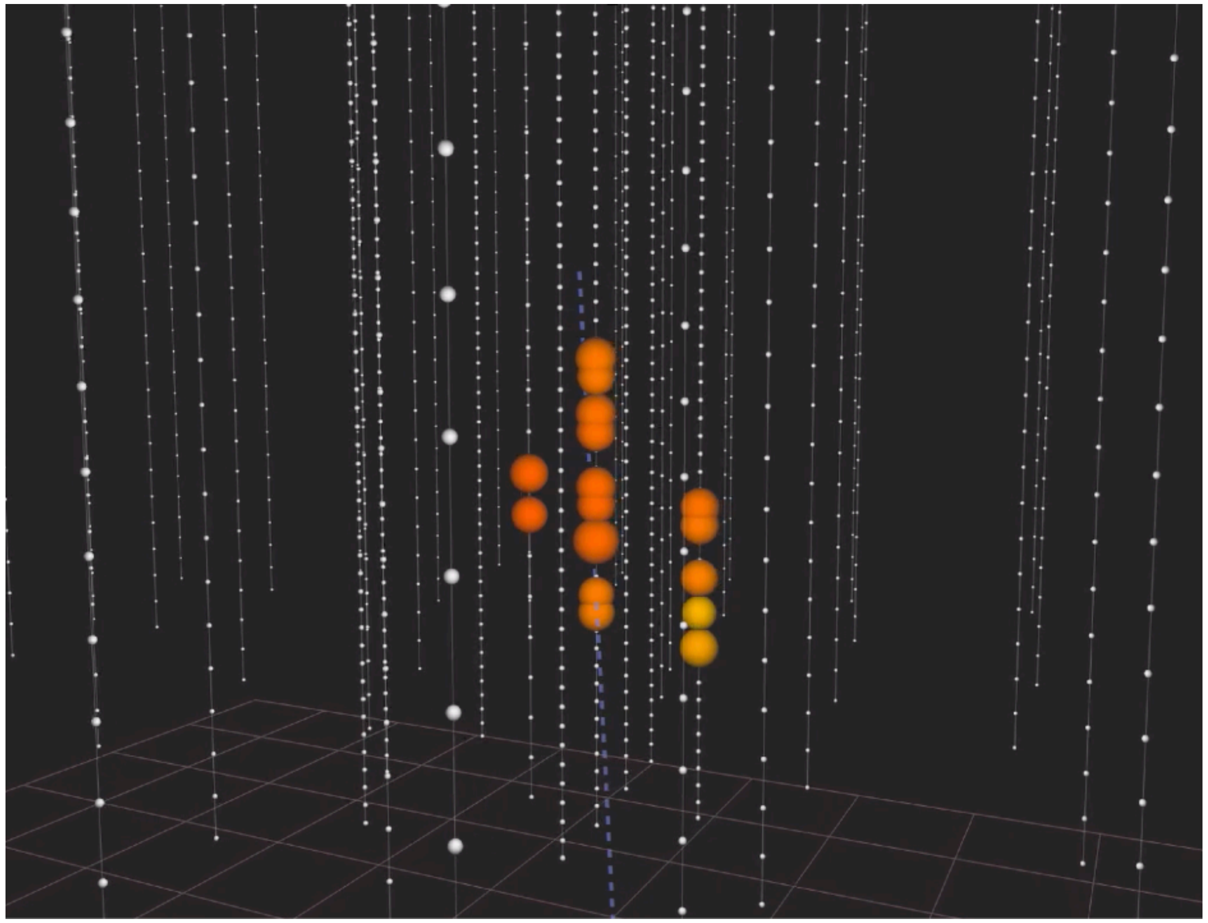
What DeepCore Events Really Look Like

Reconstruction of DeepCore events is a main limiting factor

26 GeV Track



30 GeV Cascade

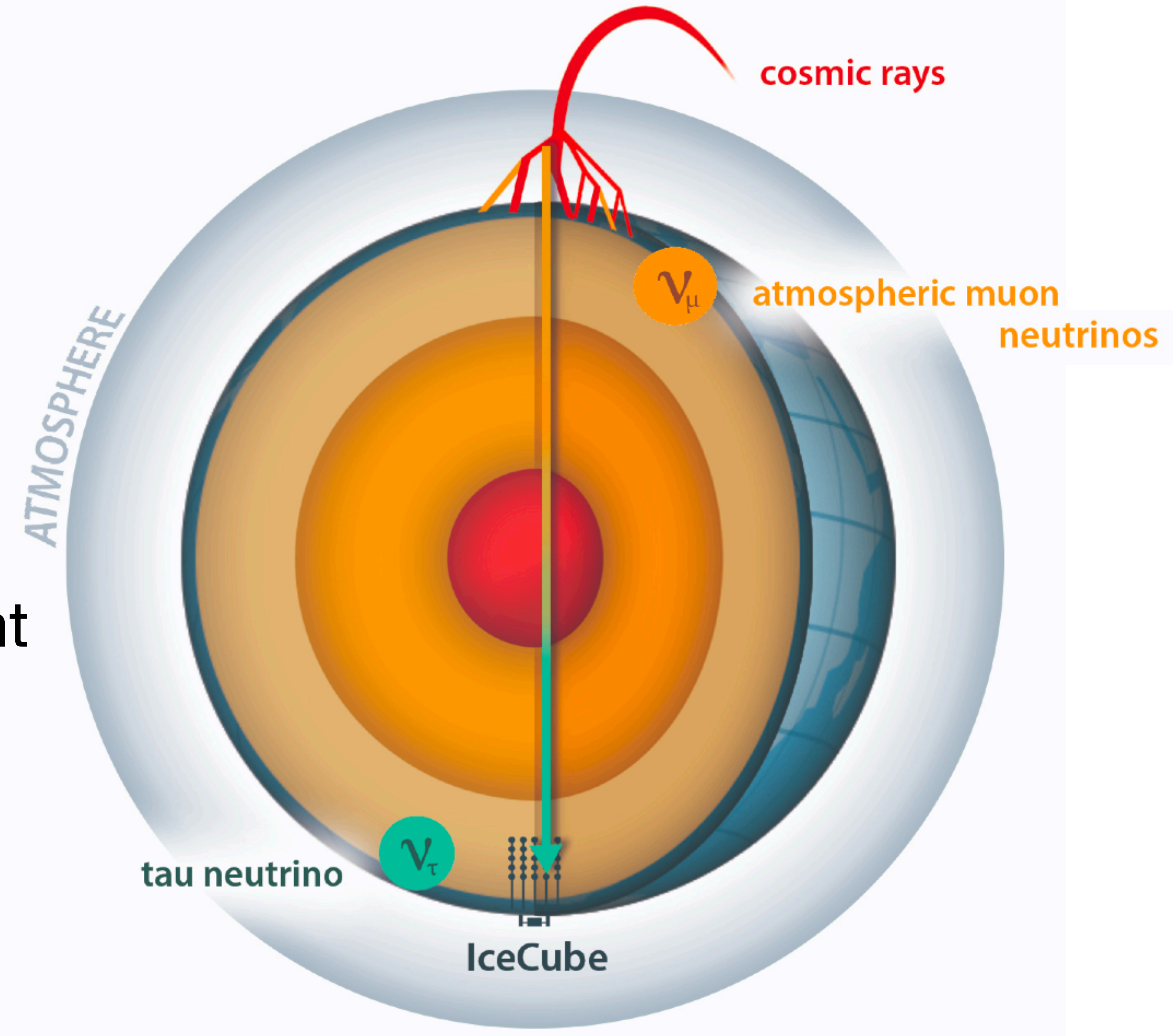


Atmospheric Neutrinos in DeepCore

- Neutrinos from cosmic ray interactions traverse the Earth, oscillating by the time they reach DeepCore

- Electron neutrinos undergo coherent forward scattering with the ambient electrons (**MSW effect**)

- Oscillation probabilities get altered as a result

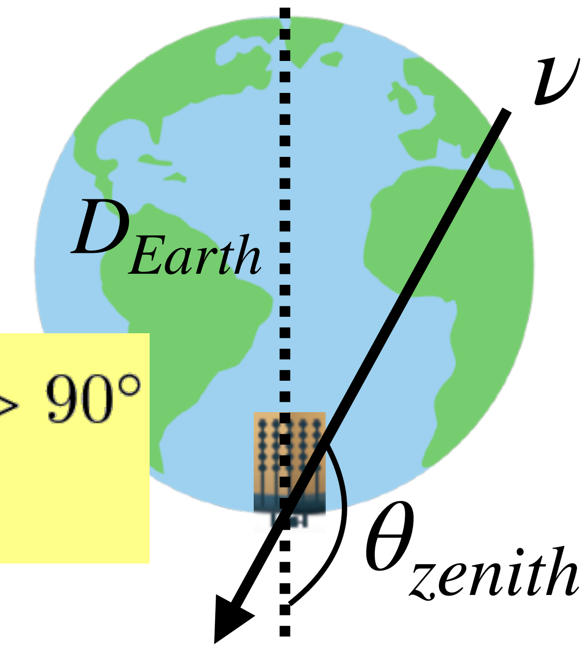


For more, refer back to:
Wed. @ 5:40 PM - Atmospheric neutrino oscillations with IceCube
K. Leonard DeHolton

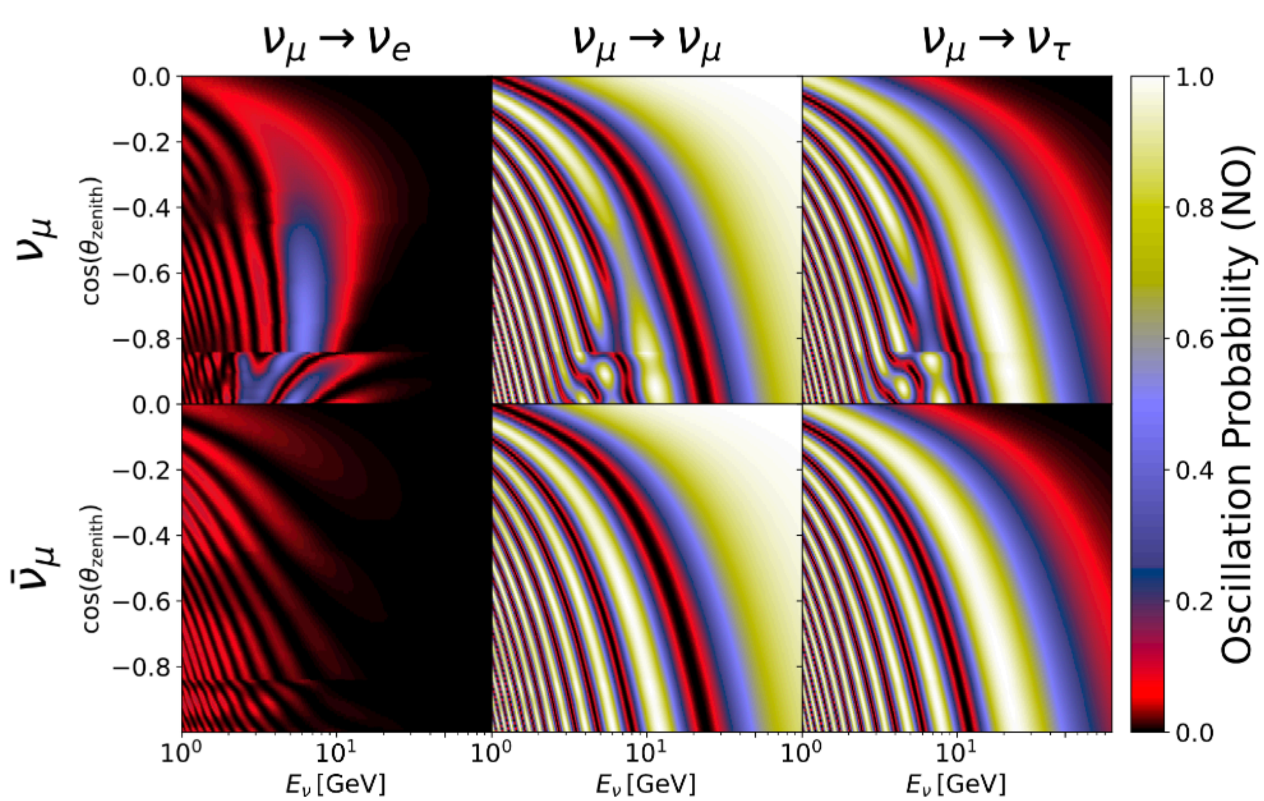
NMO Signal

Matter effects (**MSW effect**) are visible at neutrino energies of about 2.5 GeV to 15 GeV

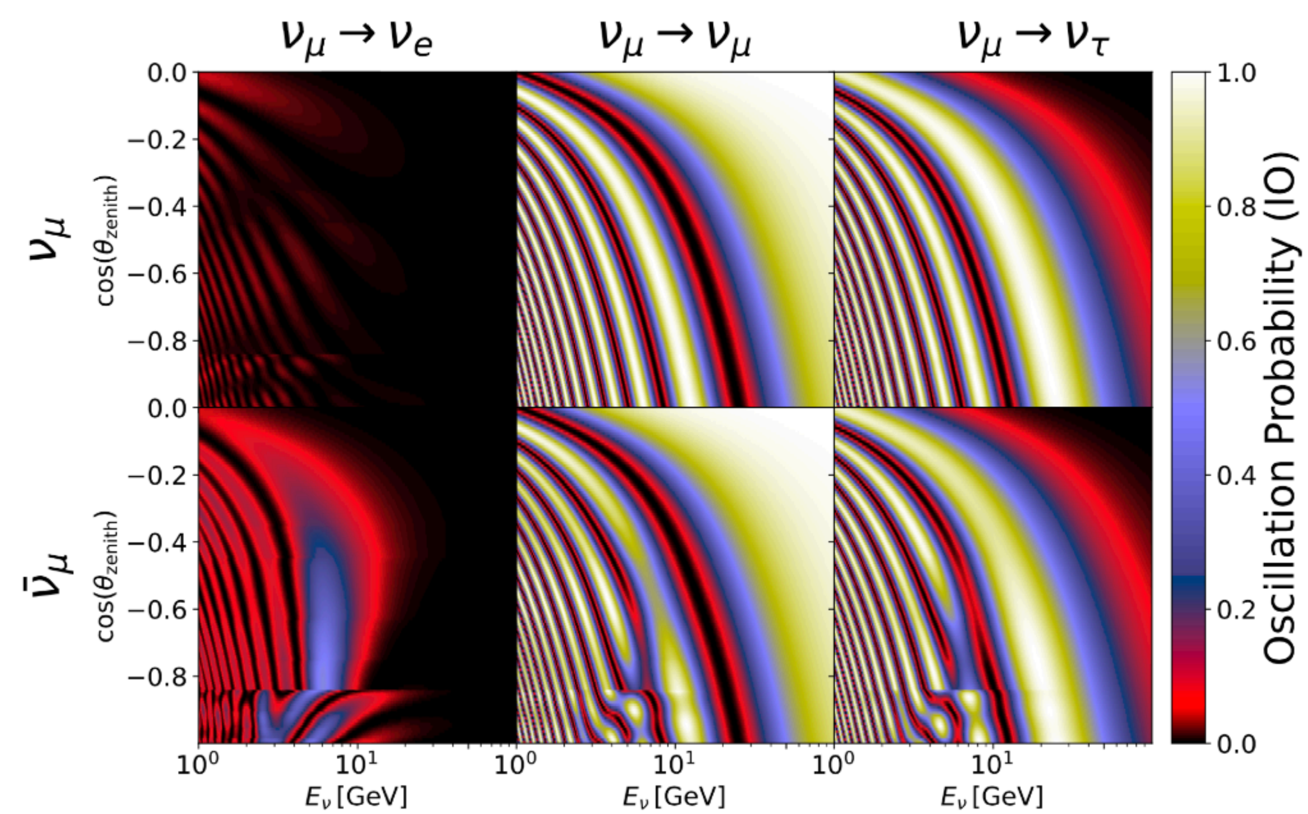
$$L \approx -D_{Earth}\cos(\theta), \quad \theta > 90^\circ$$
$$L \approx 0, \ \text{otherwise}$$



Normal Ordering (NO)

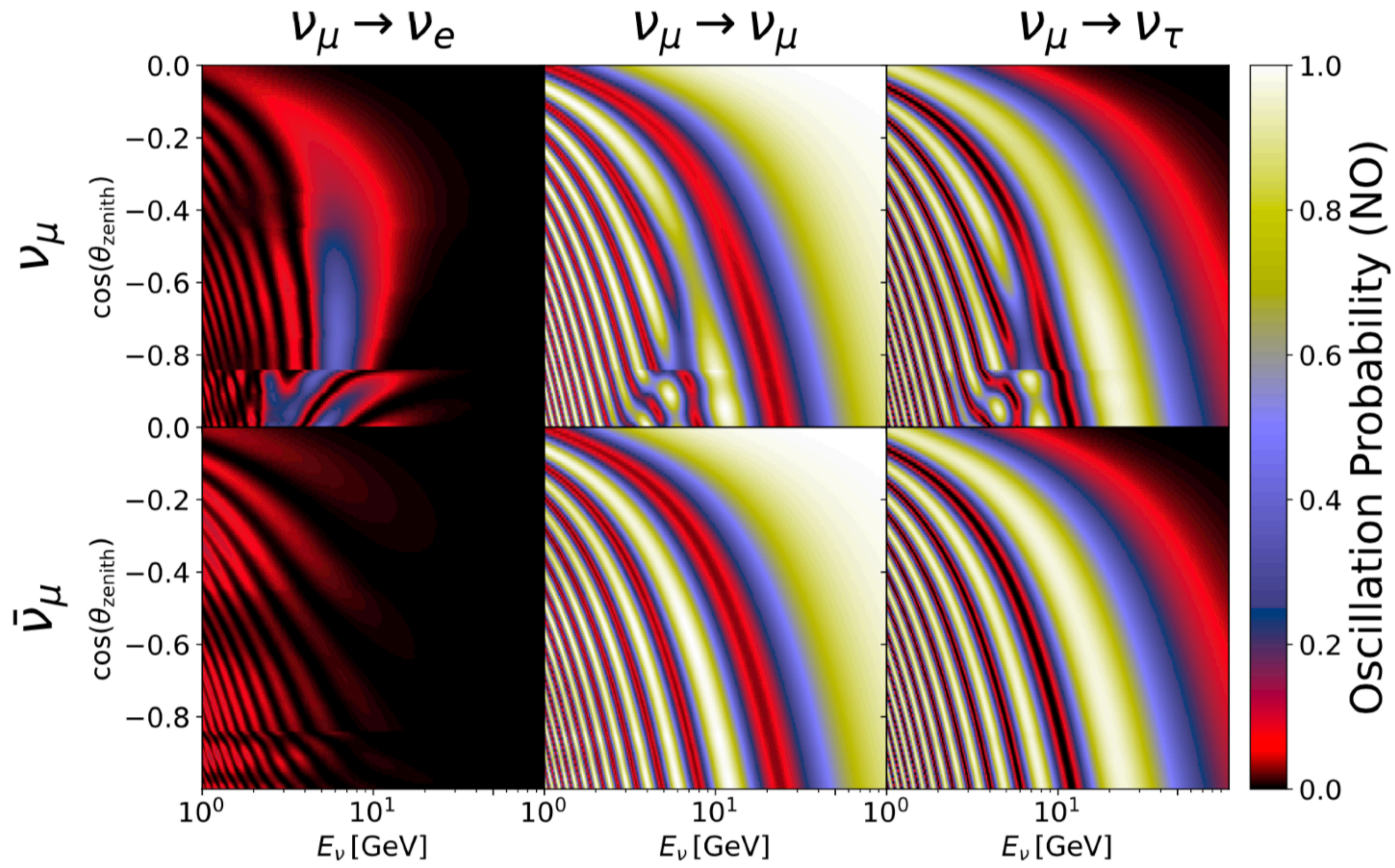


Inverted Ordering (IO)



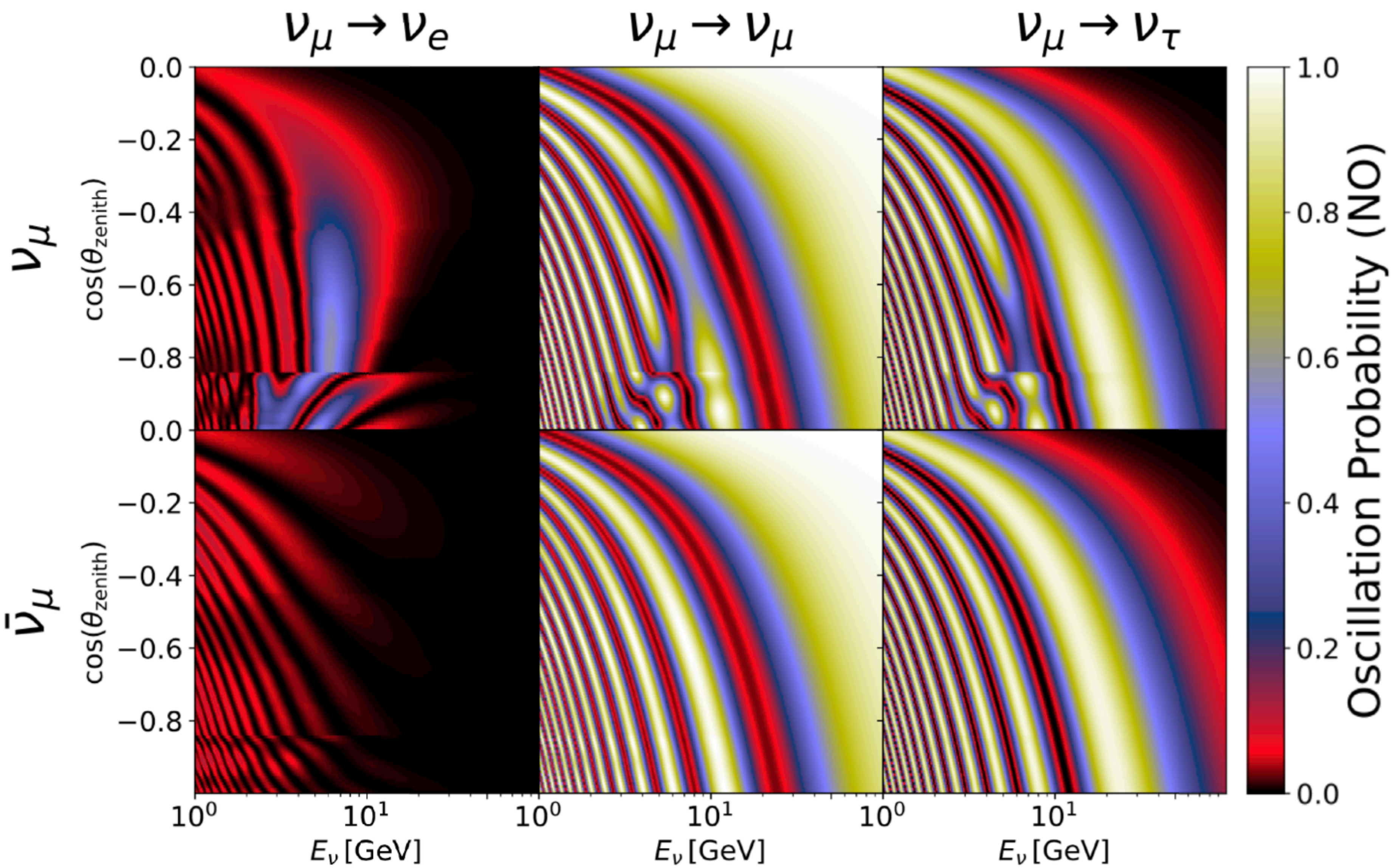
NMO θ_{23} Octant Dependence

$\theta_{23} = 40°$



NMO θ_{23} Octant Dependence

$\theta_{23} = 50^{\circ}$

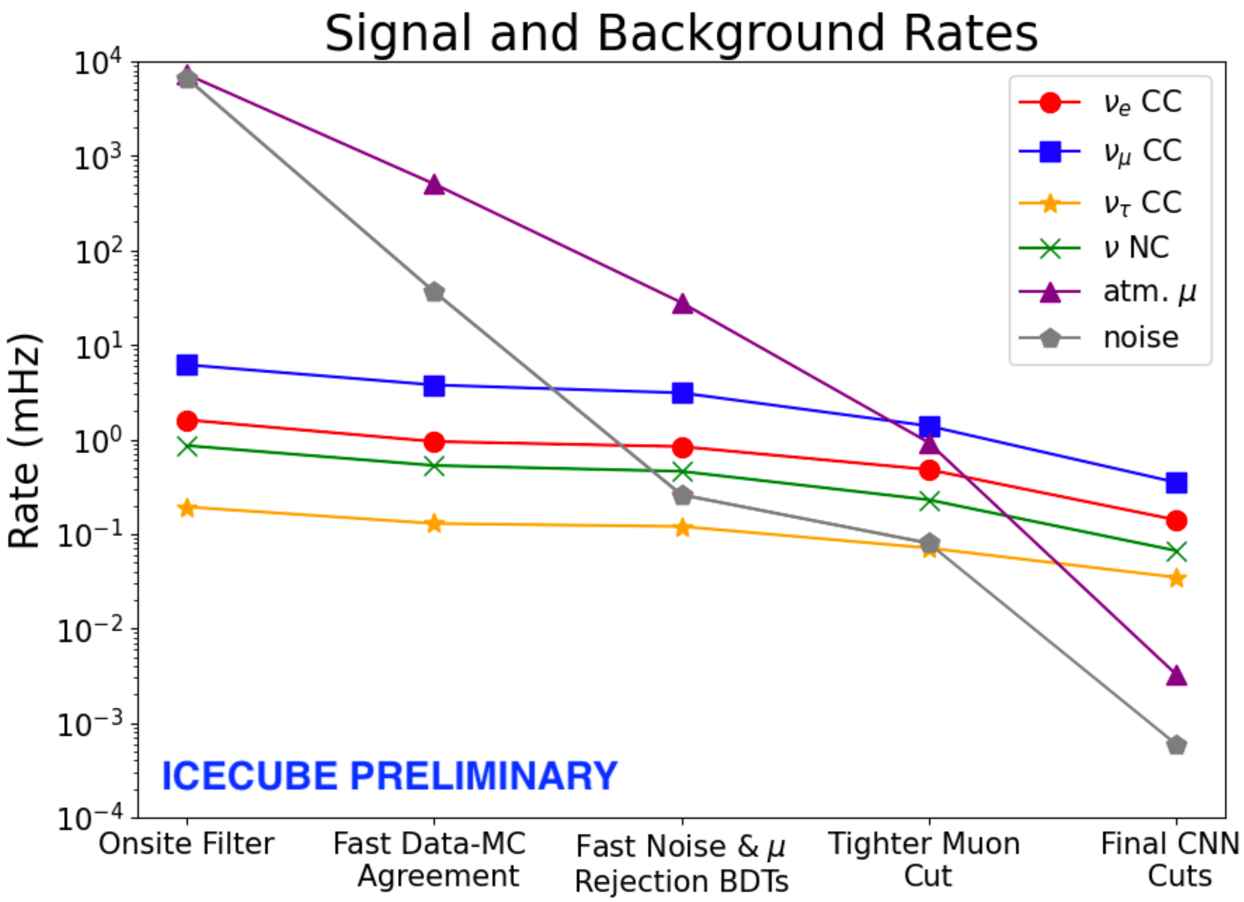


NMO Signal in DeepCore

- DeepCore cannot distinguish between neutrinos and anti-neutrinos
- Flux and cross-section are higher for neutrinos than for anti-neutrinos at DeepCore energies (3 GeV-100 GeV)
- For a combined neutrino/anti-neutrino sample, matter effects are more pronounced for true NO as compared to true IO

9.28-Year Event Sample

- Neutrinos comprise 99.5% of sample
- Convolutional Neural Network (CNN) used for reconstruction of incoming neutrino energy and direction (PoS-ICRC2023-1143)
- CNN for Particle Identification (PID)
- Large number of statistics compared to other neutrino experiments measuring the NMO

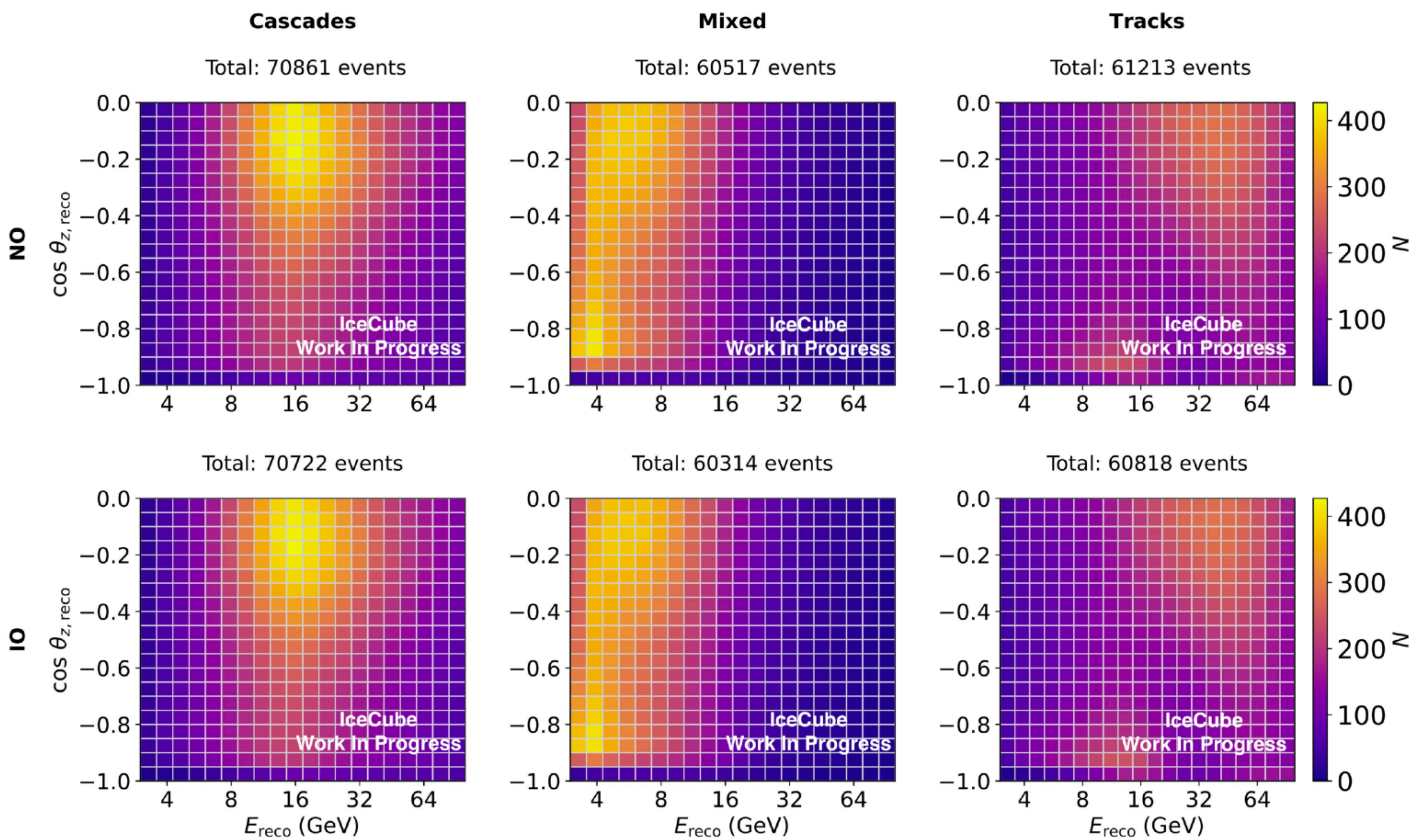


Type	Counts [9.28 years]	Rate [μHz]	% of Sample
All MC	192,605	0.658	-
$\nu_{\rm all} + \bar{\nu}_{\rm all}$ NC	21,412	0.073	11.1
$\nu_e + \bar{\nu}_e$ CC	48,637	0.166	25.3
$\nu_\mu + \bar{\nu}_\mu$ CC	110,645	0.378	57.4
$\nu_\tau + \bar{\nu}_\tau$ CC	10,936	0.037	5.7
muons	973	0.003	0.5

*Values are for Normal Ordering

NMO Analysis Event Distribution

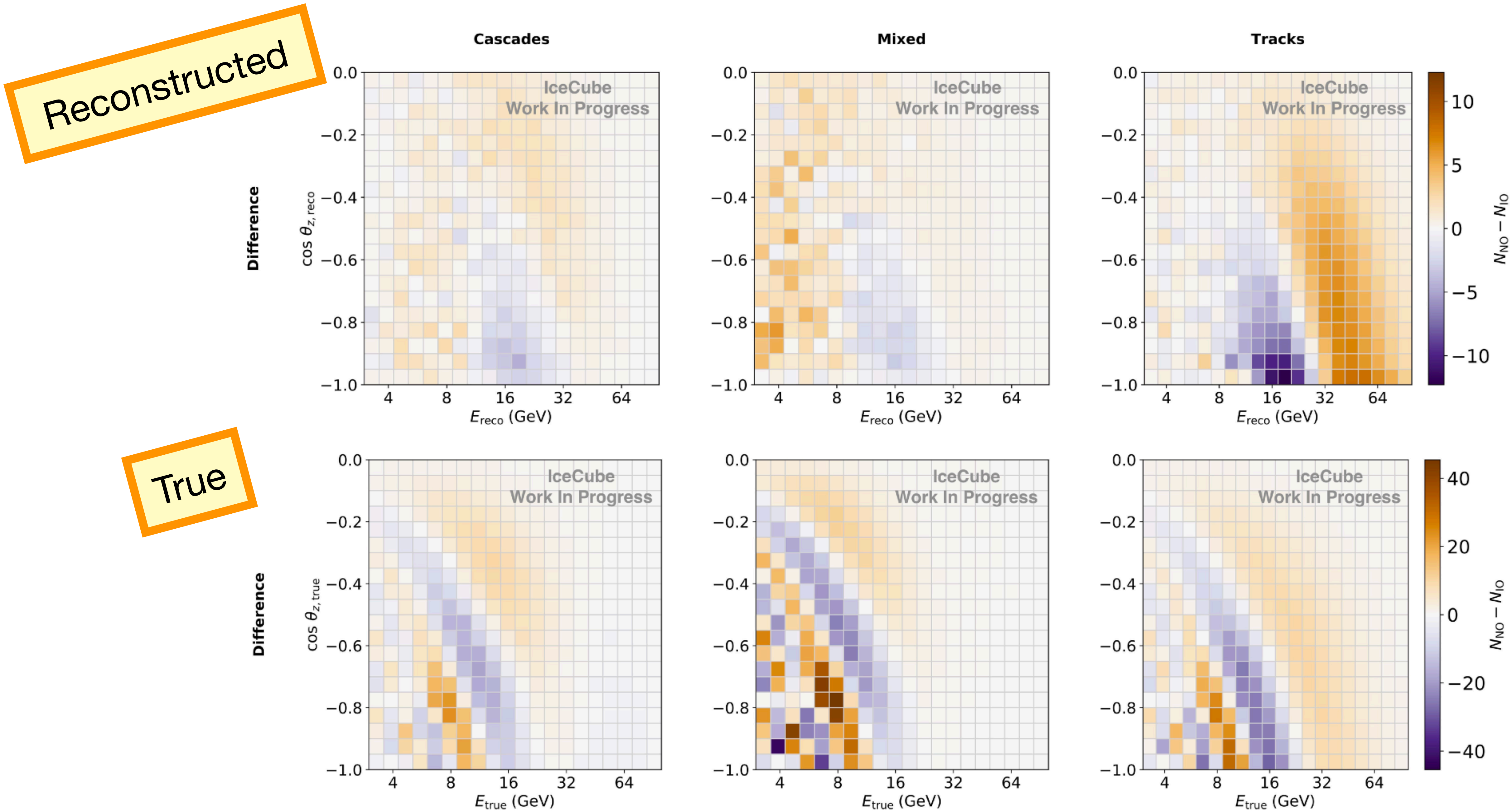
Final level distribution of neutrino and atmospheric muon events using reconstructed quantities



Binning optimization allows for better visibility of oscillation pattern

Effect of Reconstruction

The signal gets significantly smeared out as a result of reconstruction (plots mostly for visual effect as no minimization over oscillation and systematic parameters is performed and no muons are used for simplicity)



Systematic Uncertainties

- **Neutrino flux uncertainties:**
  - Cosmic ray energy spectrum
  - Kaon + Pion production uncertainties (Ex. energy, projectile)
- **Neutrino cross-section uncertainties:**
  - Resonance scattering (mid-energy neutrinos interact at nucleon level)
- **Detector uncertainties:**
  - Ice scattering and absorption
  - Optical efficiency of the photo sensor
  - Birefringence (double refraction of light due to anisotropy of ice)
  - Muon Light Yield (photon propagation in the ice from muons)

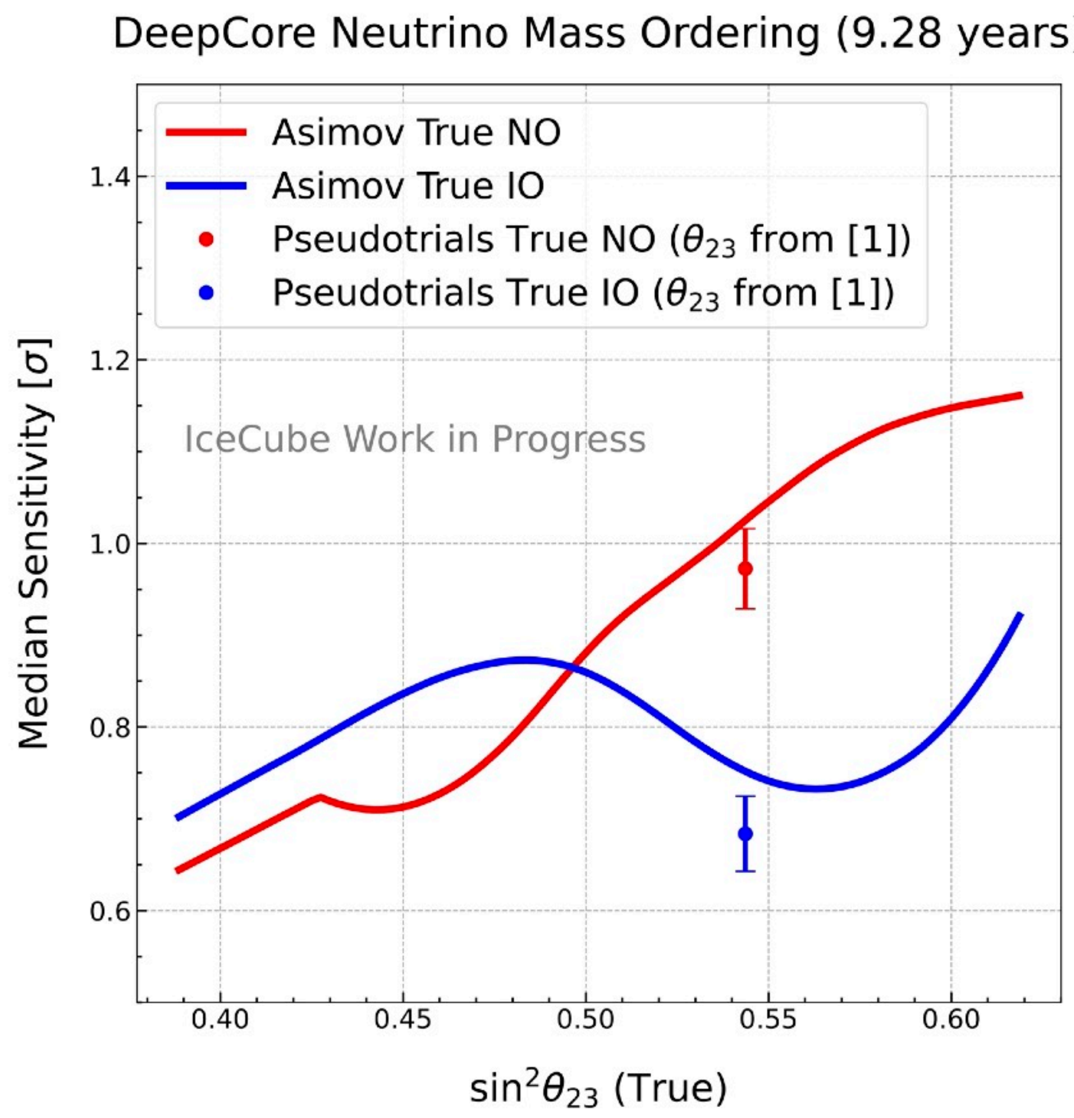
Reference: arXiv:2304.12236

Statistical Uncertainties

- **Limited Monte Carlo (MC) production:**
  - Uncertainty in the value of expected events
  - Found to be negligible for this analysis

- **Limited time of detector data collection:**
  - Performing a frequentist statistical analysis
    - Add statistical fluctuations to the MC data — ***Pseudotrials*** (very computationally expensive)

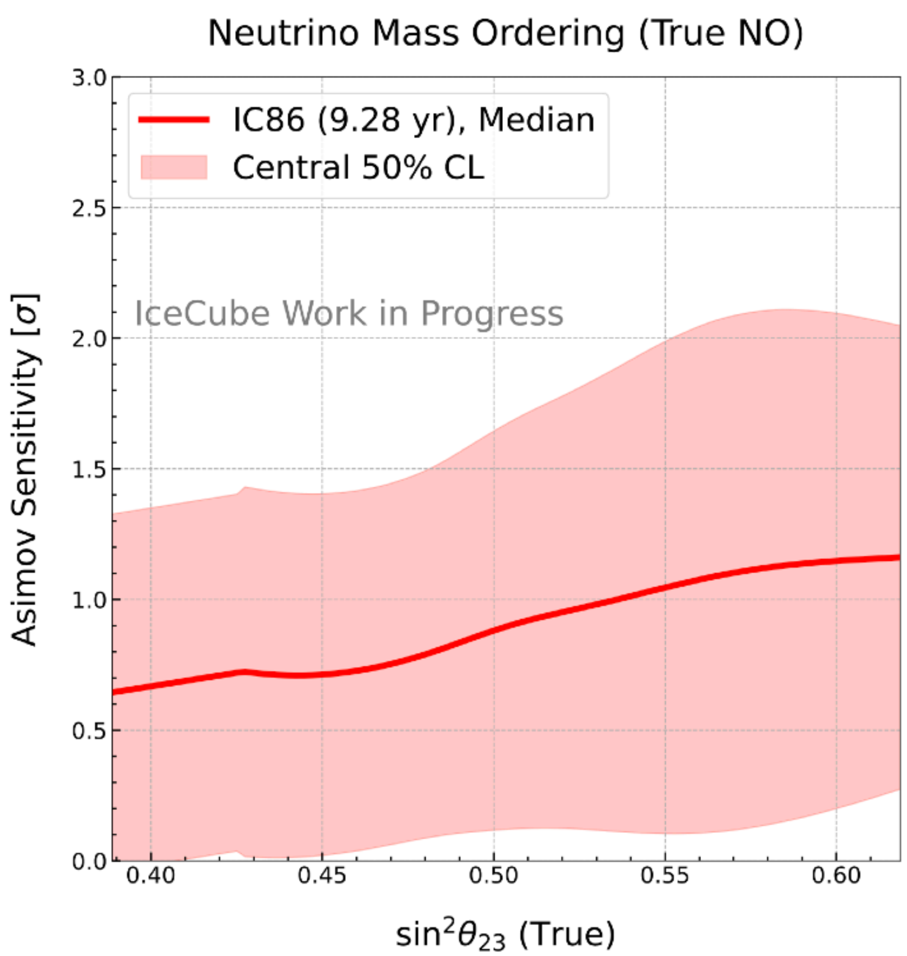
9.28-Year DeepCore NMO Sensitivity

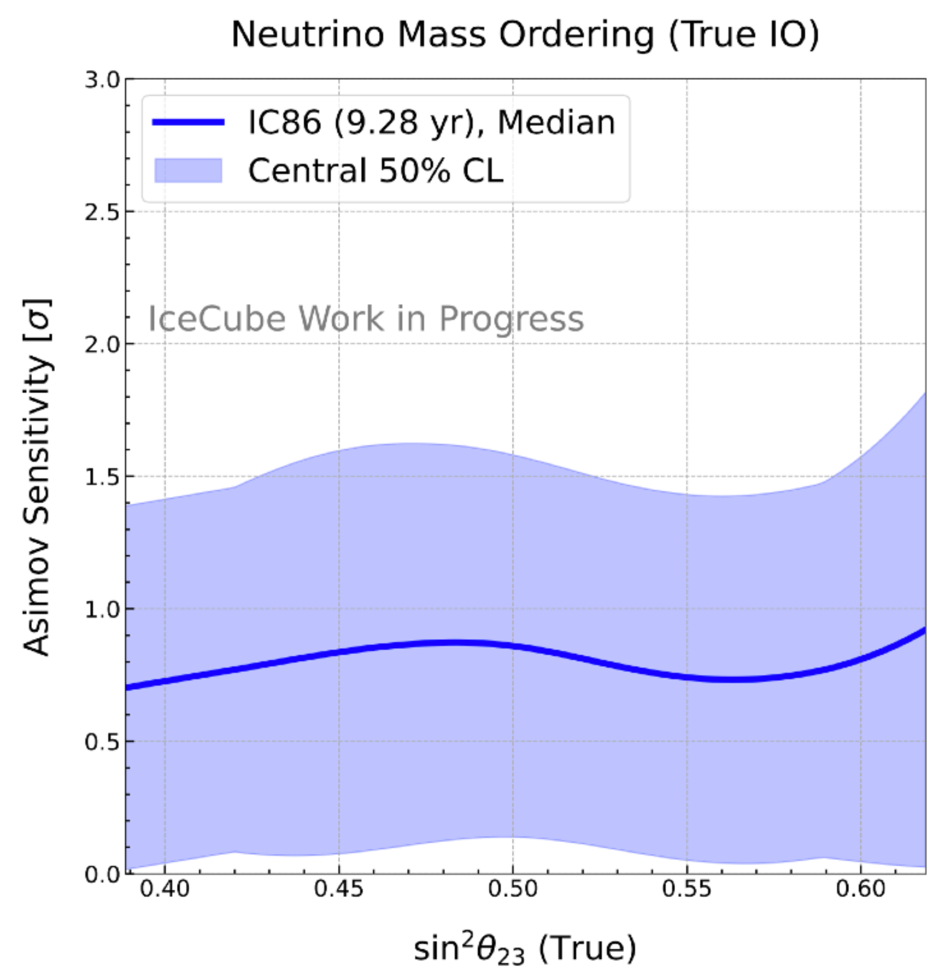


[1] Talk at ICRC 2023

- Asimov — Good approximation method of the statistically fluctuated median (arXiv:1311.1822v2); significantly less computationally expensive
- 1000 pseudotrials performed at the DeepCore best fit θ_{23} value

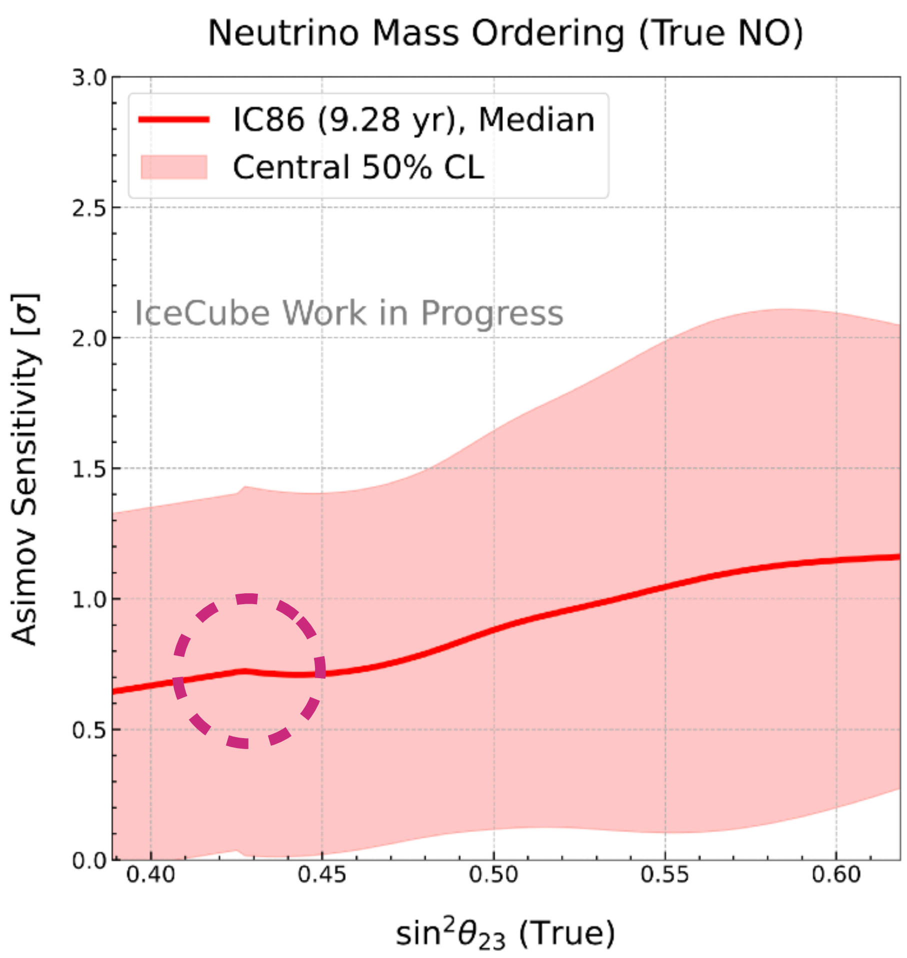
9.28-Year DeepCore NMO Sensitivity

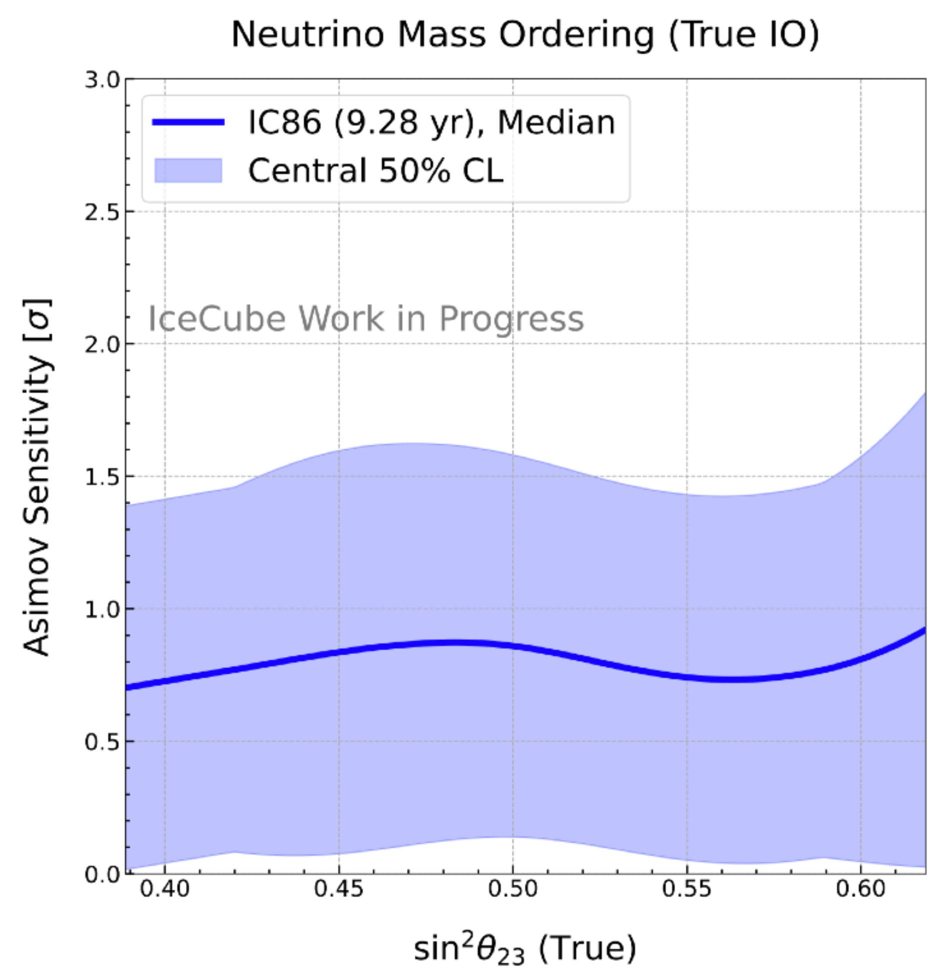




Central 50% C.L. bands represent case where observed value is not at the median

9.28-Year DeepCore NMO Sensitivity

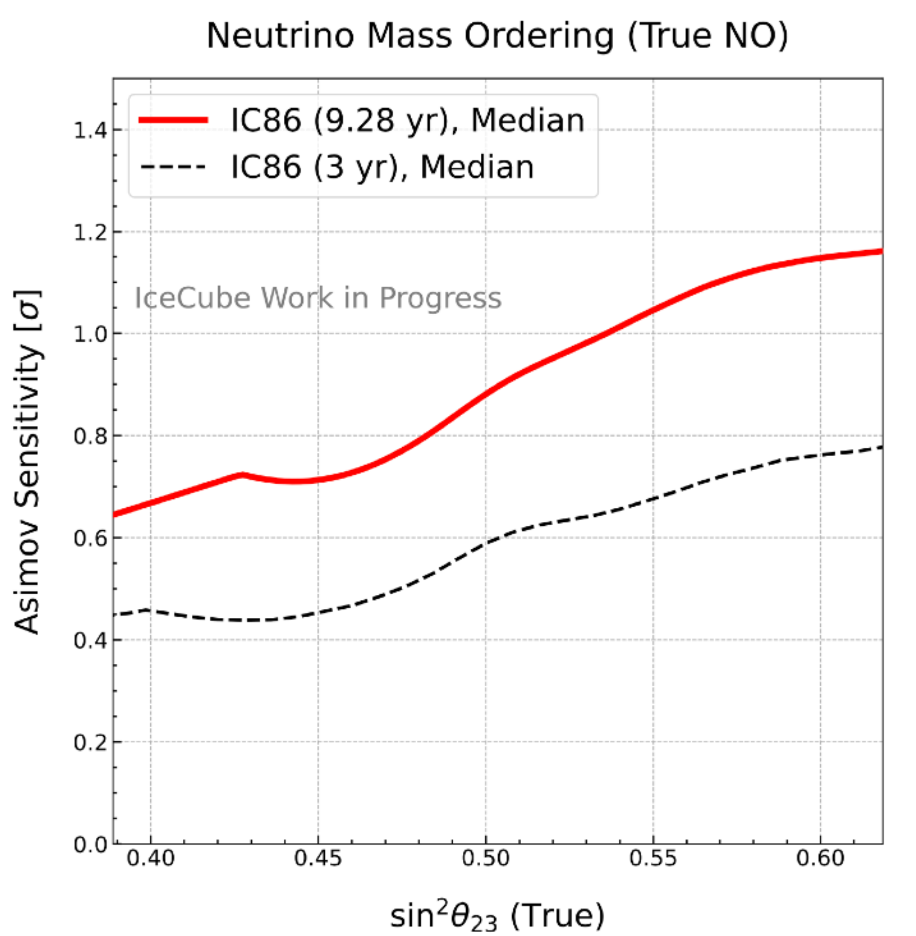


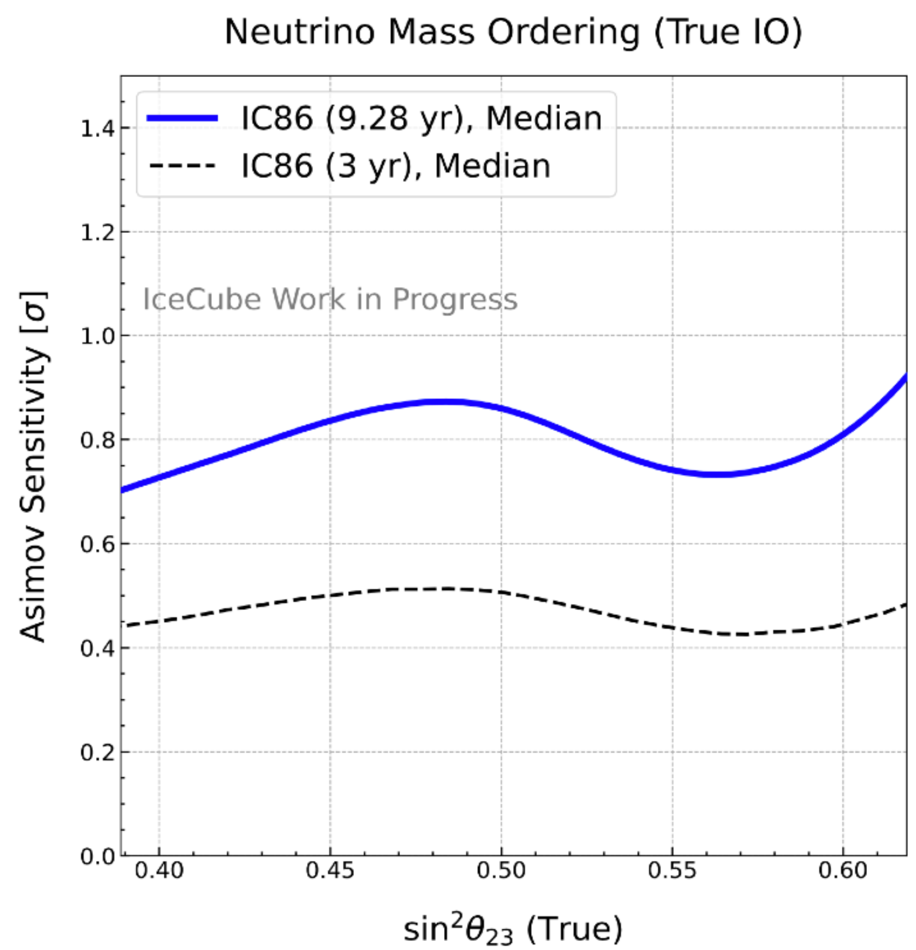


Central 50% C.L. bands represent case where observed value is not at the median

Kink in lower octant of True NO is due to discontinuity in the phase space of best-fit θ_{23} when fitting a theory with a different ordering than the ordering of the data **(θ_{23}-Octant-Mass-Ordering Degeneracy link)**

Comparison To Previous DeepCore NMO Analysis

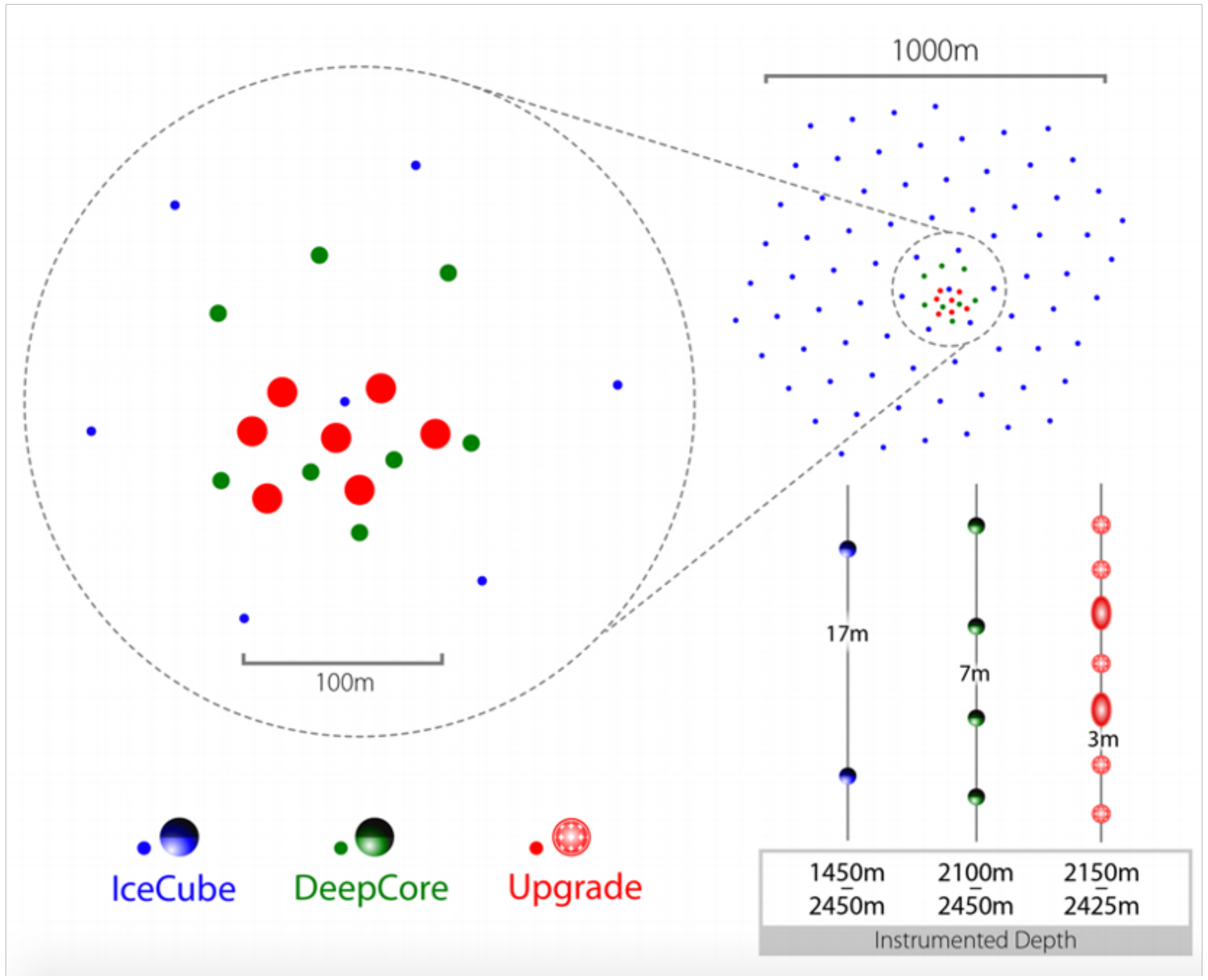


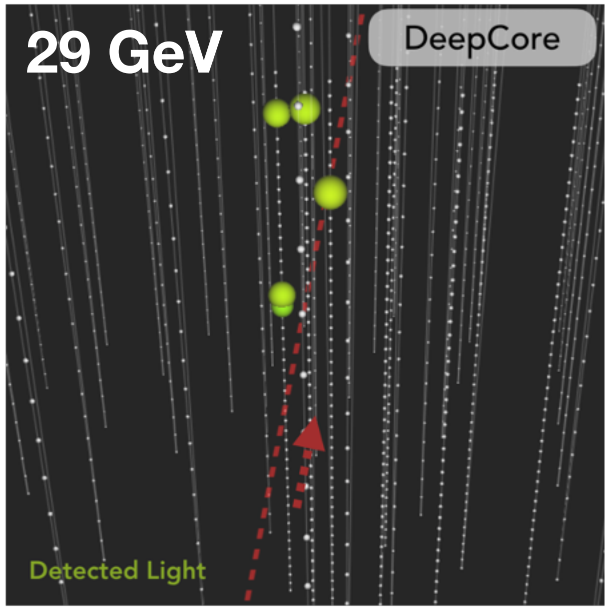


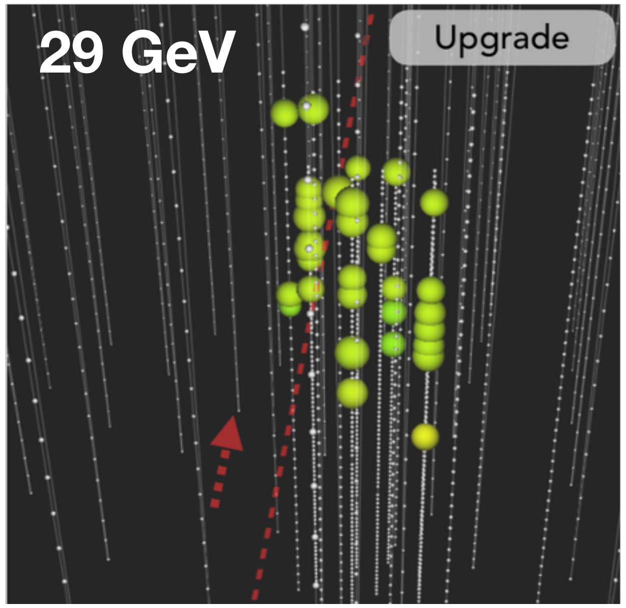
Previous DeepCore NMO analysis

- Each analysis was performed using different data filtering, reconstruction, systematic uncertainty treatment, PID, binning, etc.
- Reconstruction capability and PID are still main limiting factors despite the increase in detector livetime

The IceCube Upgrade



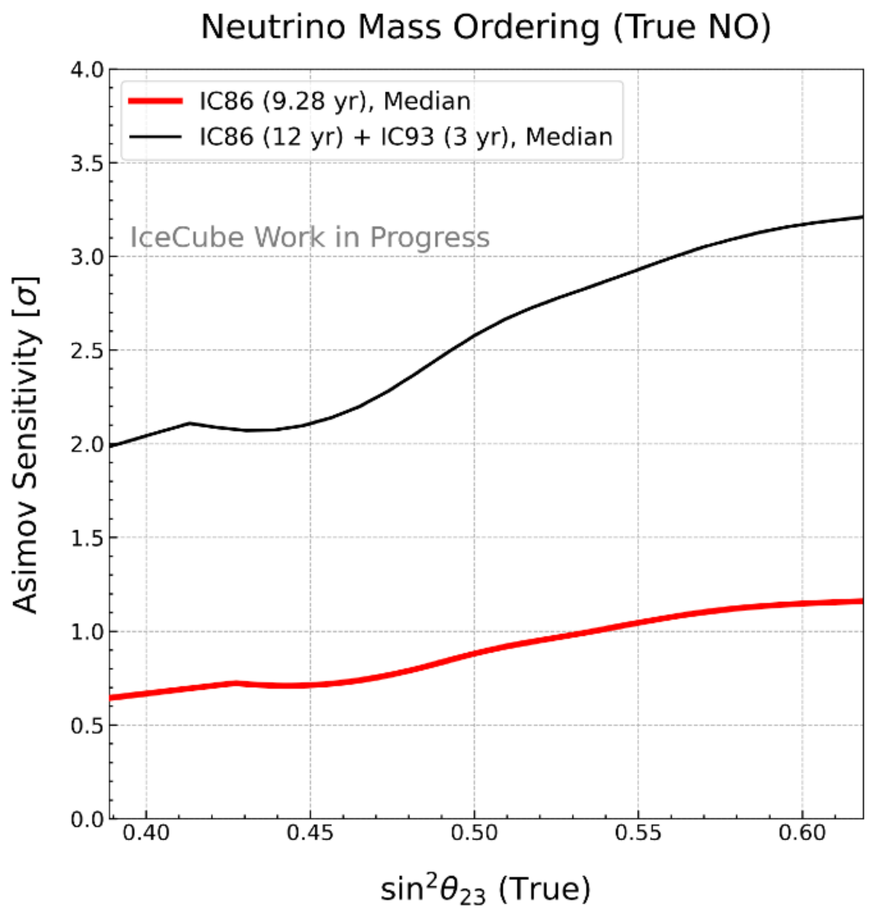


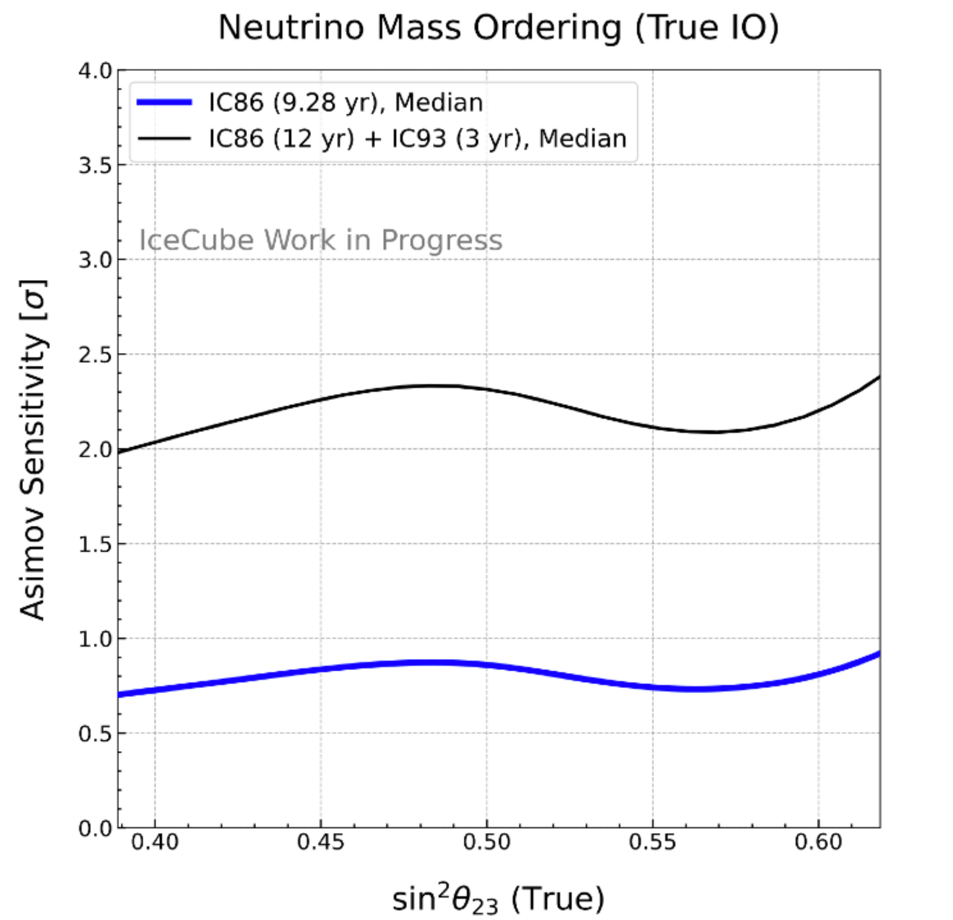


Seven more strings will be added with smaller optical sensor spacing:
Extend energy range down to 1 GeV

Fully funded — to be deployed in 2025/2026

DeepCore vs Upgrade NMO Sensitivity

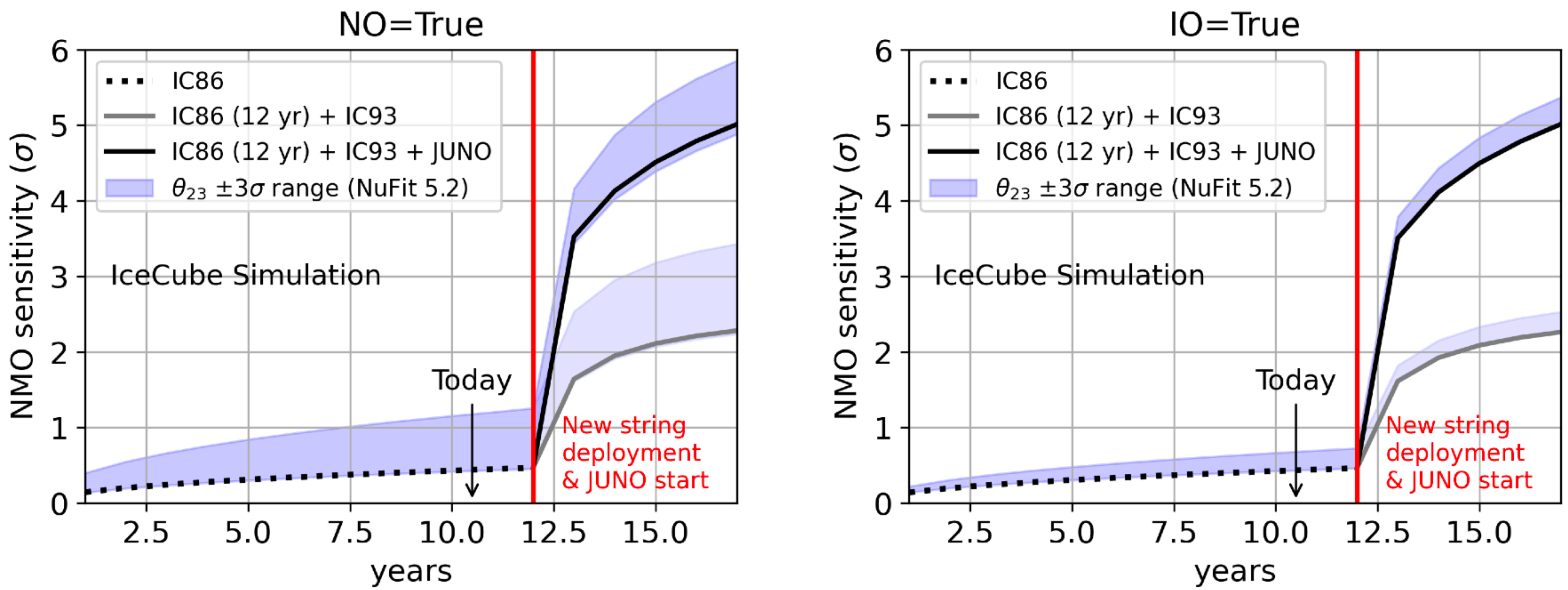




Upgrade sensitivities not yet optimized (PoS-ICRC2023-1036)

- Can really see the effects of improving the event quality with the Upgrade: Much better reconstruction capability and PID
- Projected 2.6σ NO sensitivity after **12 years of DeepCore + 3 years of the Upgrade** at maximal mixing of θ23 (2.3σ for IO)

New Upgrade + JUNO Projections



* JUNO assumptions from here (but only use 8 cores)

** *Upgrade sensitivities not yet optimized* (PoS-ICRC2023-1036)

- **JUNO + Upgrade combined sensitivity:** Synergistic effects seen due to joint fit of the oscillation parameters
- With 5 years of both Upgrade + JUNO data, synergistic effects could enhance NMO signal up to 5σ for both **true NO and true IO**
- Note: Sensitivities in these plots are not optimized

DeepCore NMO Outlook

- Exciting outlook for NMO in coming years!
- DeepCore: Almost 200k atmospheric neutrino events in 9.28 years
- DeepCore faces limitations due to event quality but the IceCube Upgrade will improve this
- DeepCore + Upgrade combined sample will have the luxury of high statistics AND improved event quality
- With 5 years of both Upgrade + JUNO data, synergistic effects could enhance NMO signal up to 5σ for both **true NO and true IO**

Thank you


Università degli Studi di Padova
INFN
PADOVA
Dipartimento di Fisica e Astronomia Galileo Galilei

Backup Slides

Current Status of Oscillation Parameters

NuFIT 5.1 (2021)

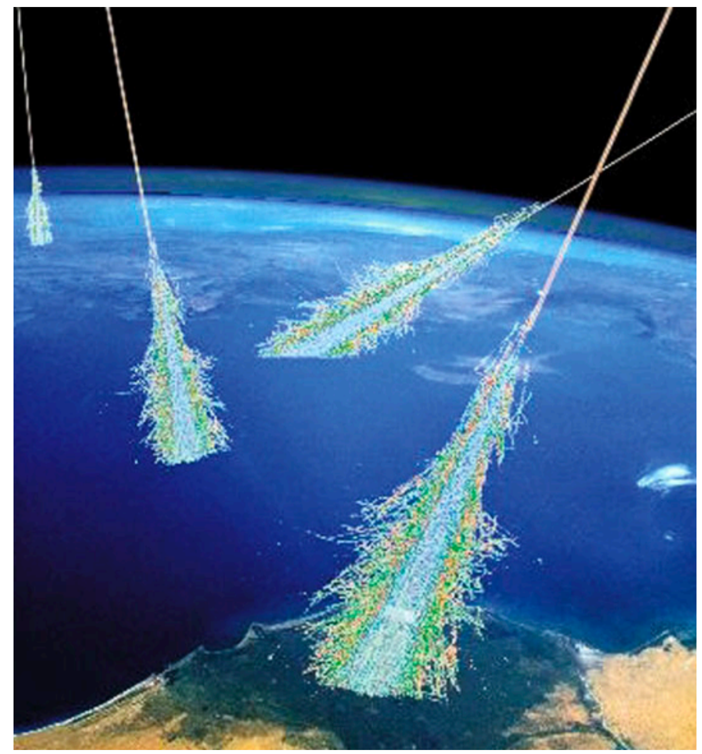
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{\mathrm{CP}}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

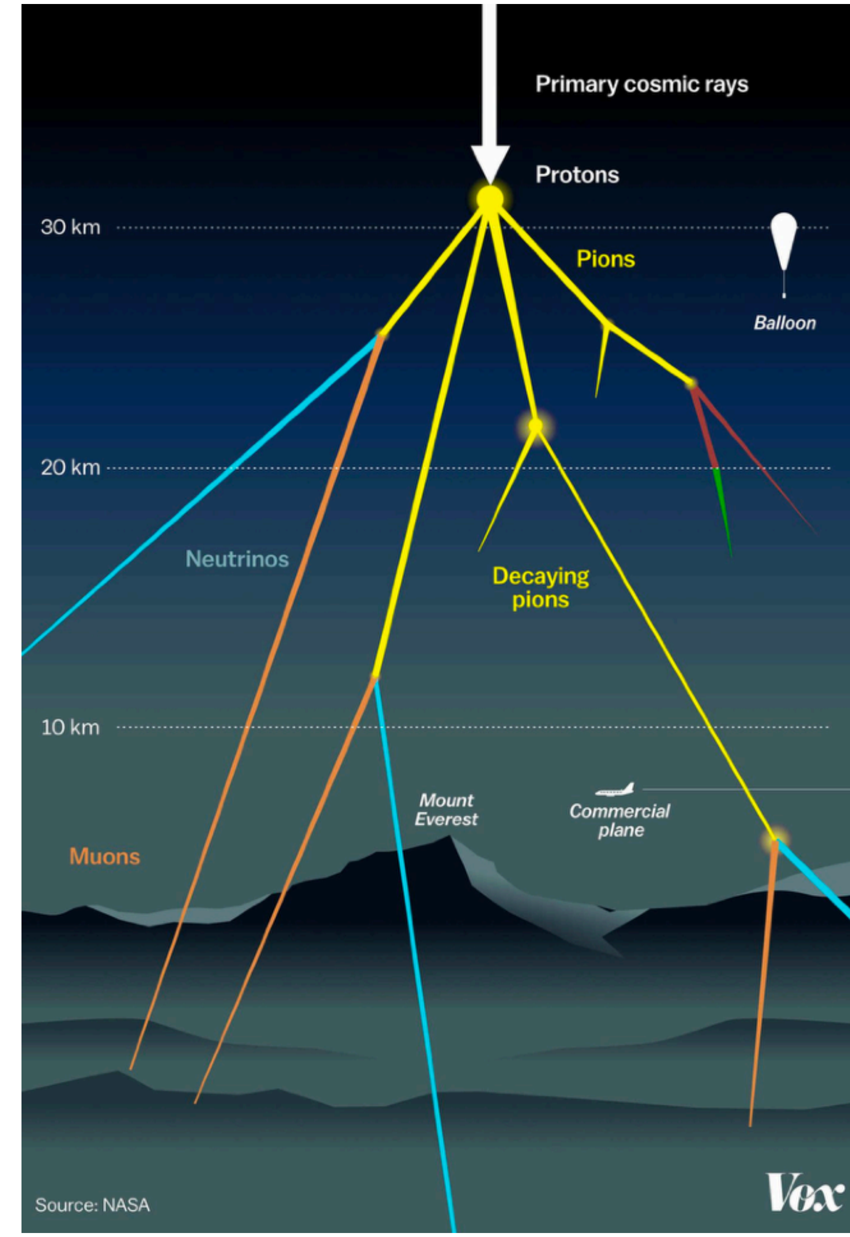
The combined global fit shows preference for NO over IO by about 2.6σ

Cosmic Rays

- Cosmic rays: Highly energetic protons and nuclei that crash into our atmosphere

- Pions are the dominant source of atmospheric neutrino production

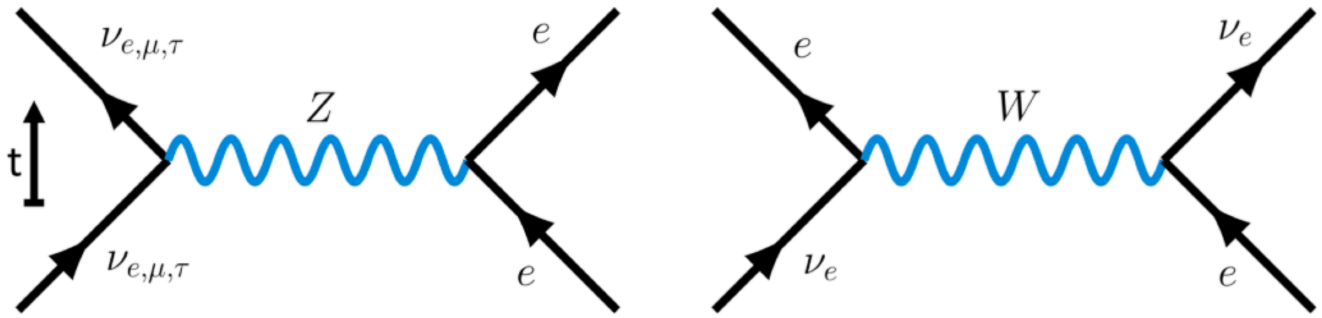




$$p^+ + N \rightarrow \pi^+ + X$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \bar{\nu_\mu} + \nu_e$$

Pion production from cosmic rays

Mikheyev **S**mirnov **W**olfenstein (**MSW**) Effect



(a) Neutral Current (NC) (b) Charged Current (CC)

$$\boxed{\begin{aligned} \Delta m^2 &\rightarrow \Delta m_m^2 = C \cdot \Delta m^2 \\ \sin(2\theta) &\rightarrow \sin(2\theta_m) = \frac{\sin(2\theta)}{C} \end{aligned}}$$

with $C = \sqrt{(\cos(2\theta) - A)^2 + \sin^2(2\theta)}$

$$A = \pm \frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m^2}$$

- Neutrinos undergo coherent forward scattering with electrons in matter
- Introduces an effective mixing angle and mass splitting in the oscillation probabilities
- Example: MSW effect in a two-flavor oscillation case with constant electron density (N_e)
- Neutrinos (+) / Anti-neutrinos (-)
- Resonance occurs for neutrinos if NO is true or anti-neutrinos if IO is true

MSW effect is maximal when:

$$\sin(2\theta_m) = 1$$

Neutrinos

$$E_\nu = \pm \frac{\Delta m^2}{2\sqrt{2}G_F N_e} \cos(2\theta)$$

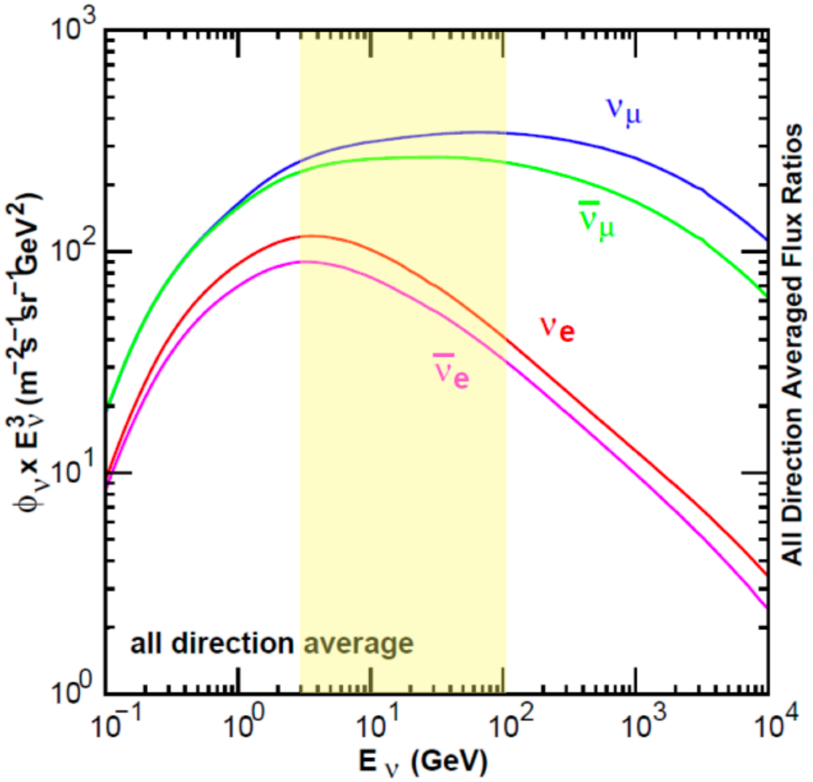
Anti-neutrinos

NO true = + Δm^2 **IO true = -**Δm^2

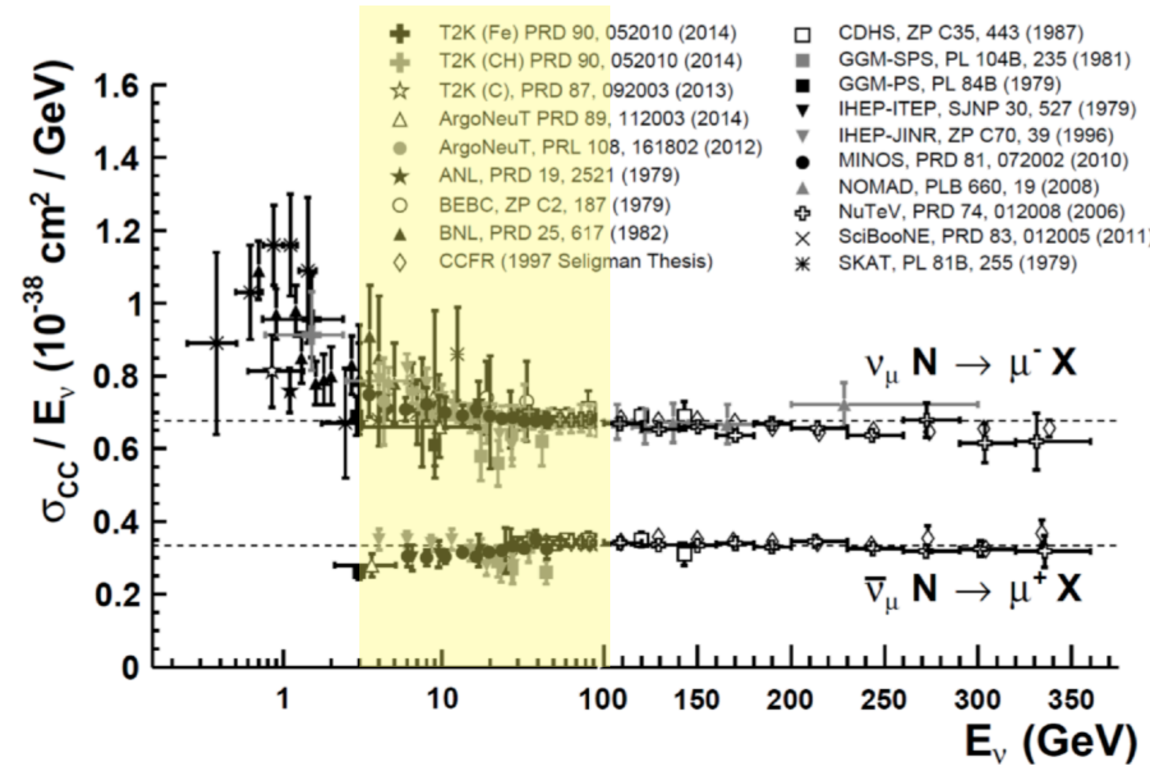
Neutrinos & Anti-Neutrinos in DeepCore

- Neutrino flux at DeepCore energies (3 GeV-100 GeV) is higher than anti-neutrino flux
- Neutrino cross section at DeepCore energies is about two times greater for neutrinos than anti-neutrinos

Flux



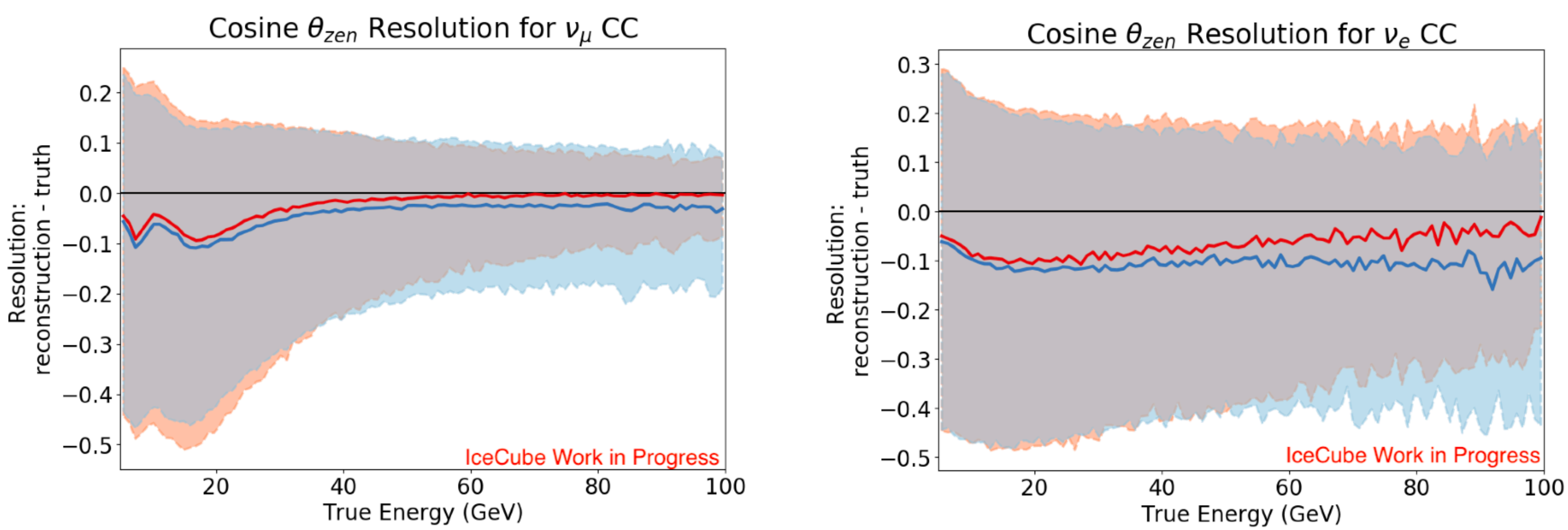
Cross Section



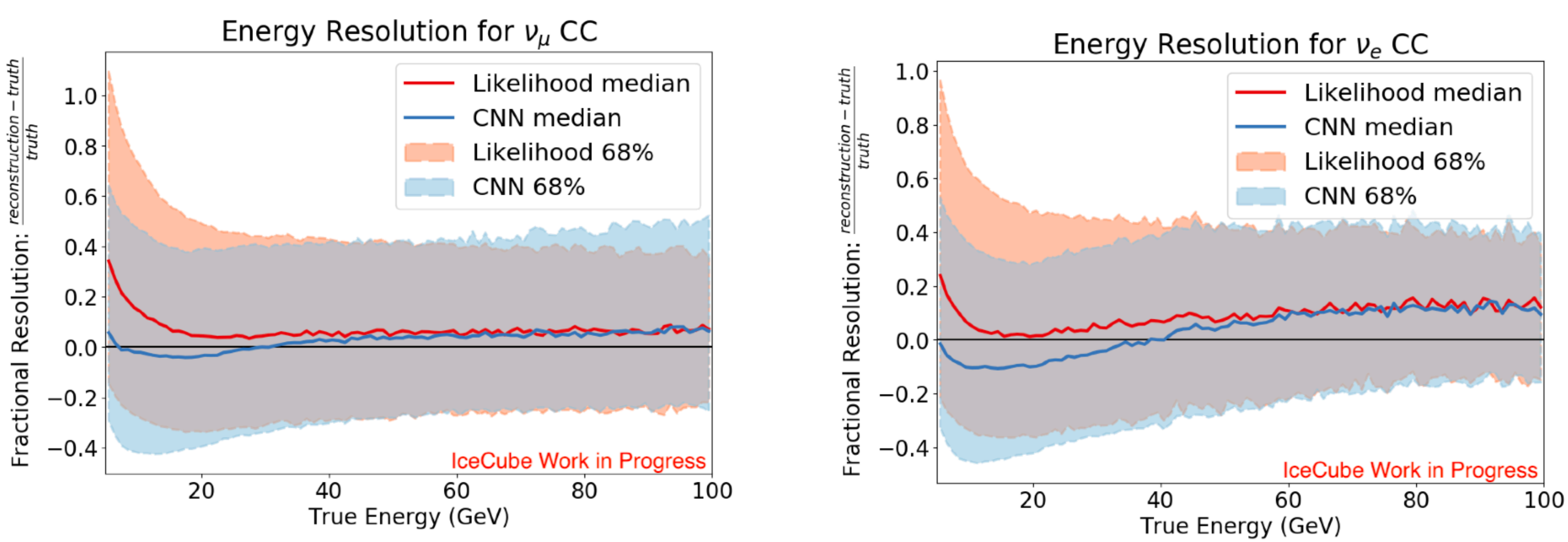
DOI: 10.18154/RWTH-2018-231554

Reconstruction Resolution

Angular resolution



Energy resolution

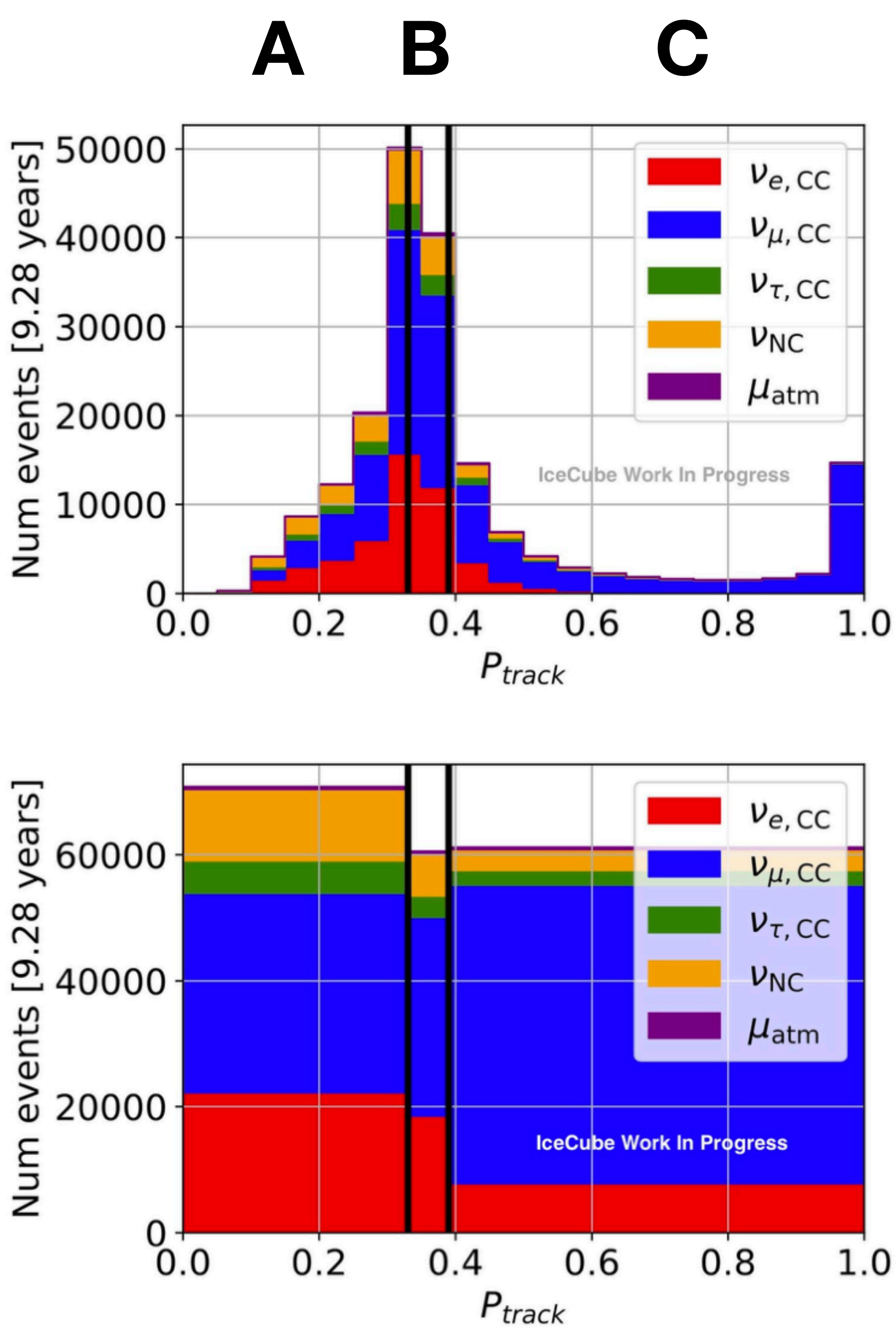


DeepCore Particle Identification (PID)

A CNN classifier is used to classify events as either:

> **A.** Cascades
> **B.** Low purity tracks (“Mixed”)
> **C.** High purity tracks

- Classification prevents further dilution of the signal between event signatures
- Tracks at very low energies do not travel far and can be confused as cascades
- **Boundaries goal:** Optimal classification of events while maintaining large number of events in each bin for statistical stability

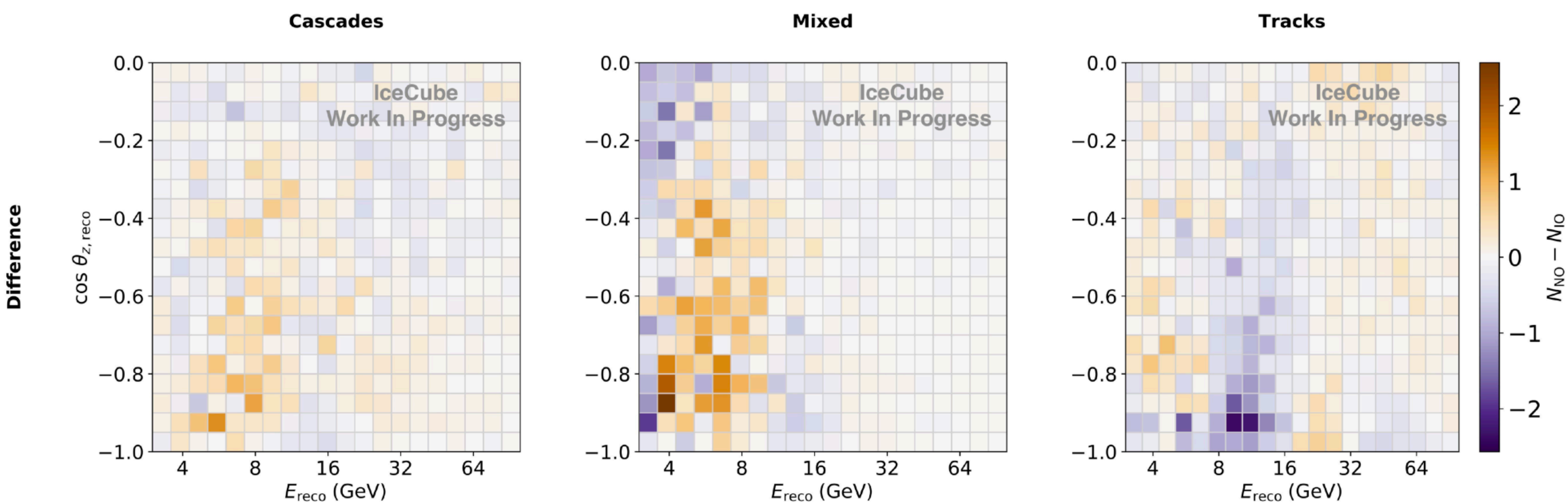


Uncertainties

- Account for uncertainties as free parameters in the simulation
- Include uncertainties for **flux + cross-section + oscillations + detector response**
- Re-weigh events according to variations of any given free parameter value

The Power of Binning Optimization

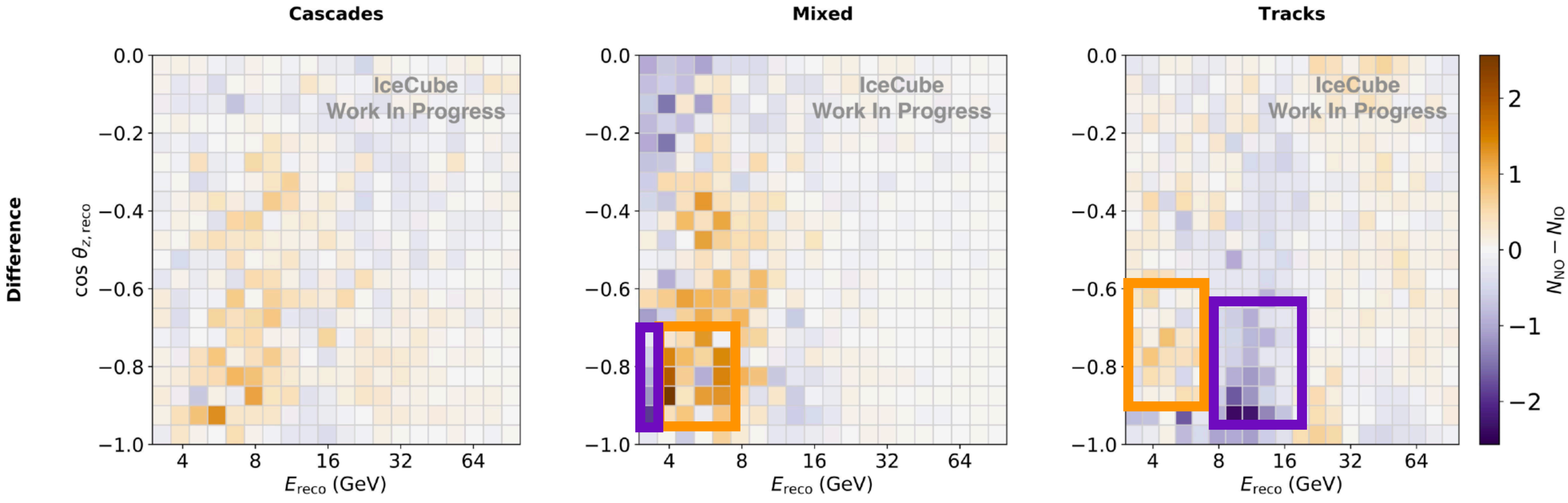
Event difference between NO and IO after LLH minimization (for a true NO)



The Power of Binning Optimization

Can visually see power of binning: With larger bins, some bins would merge and average out

…inimization (for a true NO)



NMO Analysis: MC

Assume NO is the true ordering

Nominal NO truth

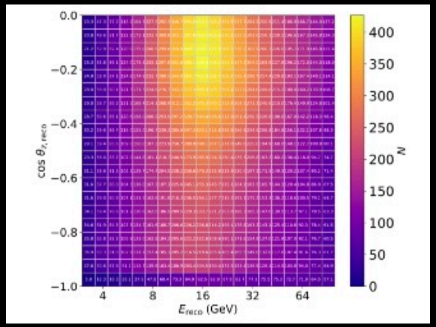
+ statistical fluctuations (1000 trials)

NO theory

IO theory

$\mathbf{LLH1}_i$

$\mathbf{LLH2}_i$



NMO Analysis: MC

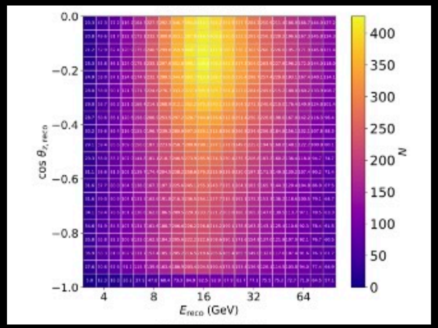
Assume NO is the true ordering

Nominal NO truth

+ statistical fluctuations (1000 trials)

NO theory → $LLH1_i$

IO theory → $LLH2_i$

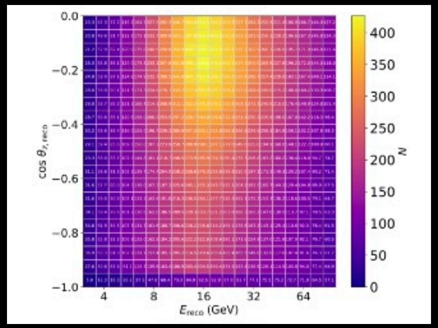


IO best fit to the truth

+ statistical fluctuations (1000 trials)

NO theory → $LLH3_i$

IO theory → $LLH4_i$

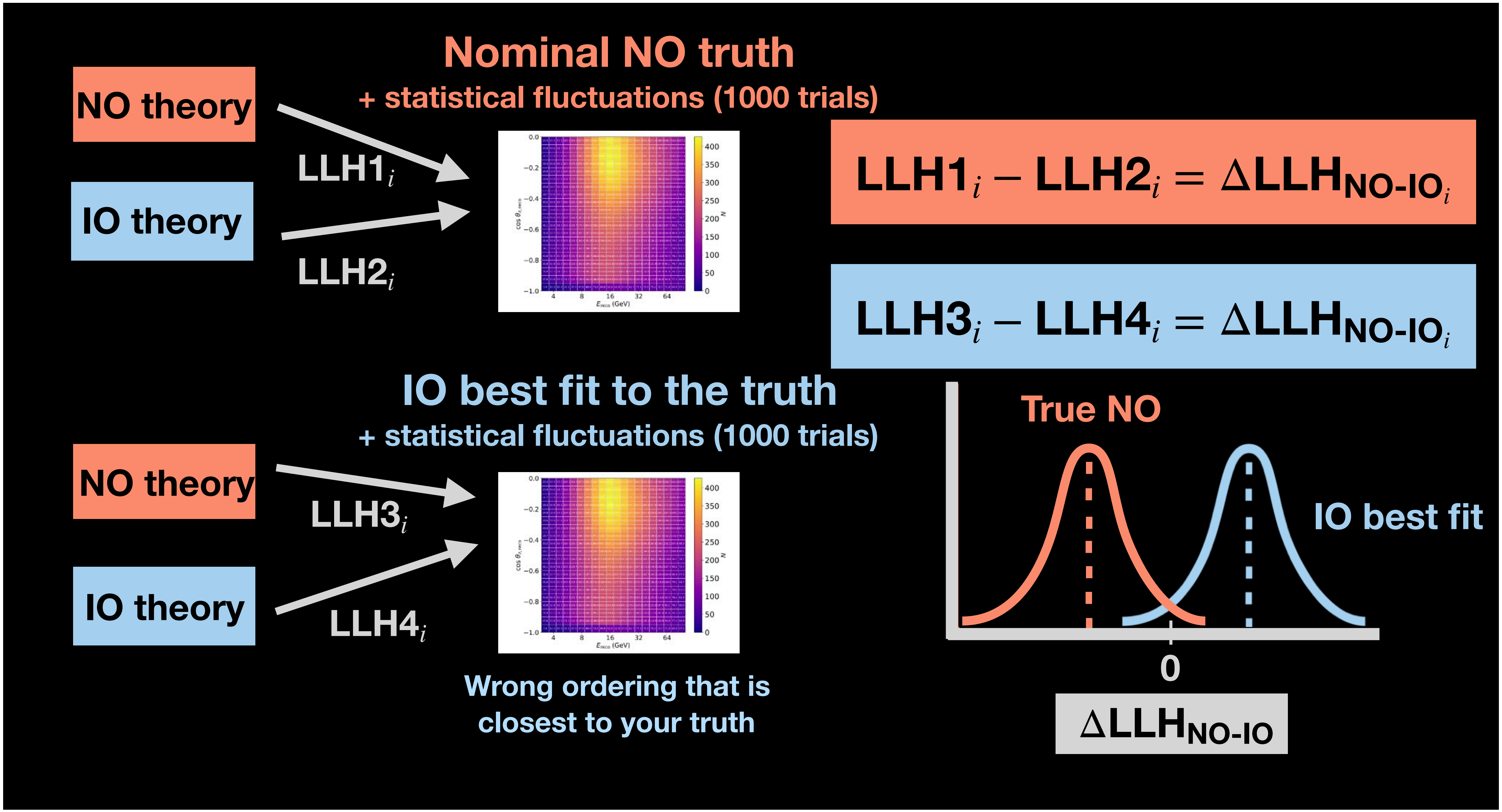


Wrong ordering that is closest to your truth

Four LLH distributions

NMO Analysis: MC

Assume NO is the true ordering



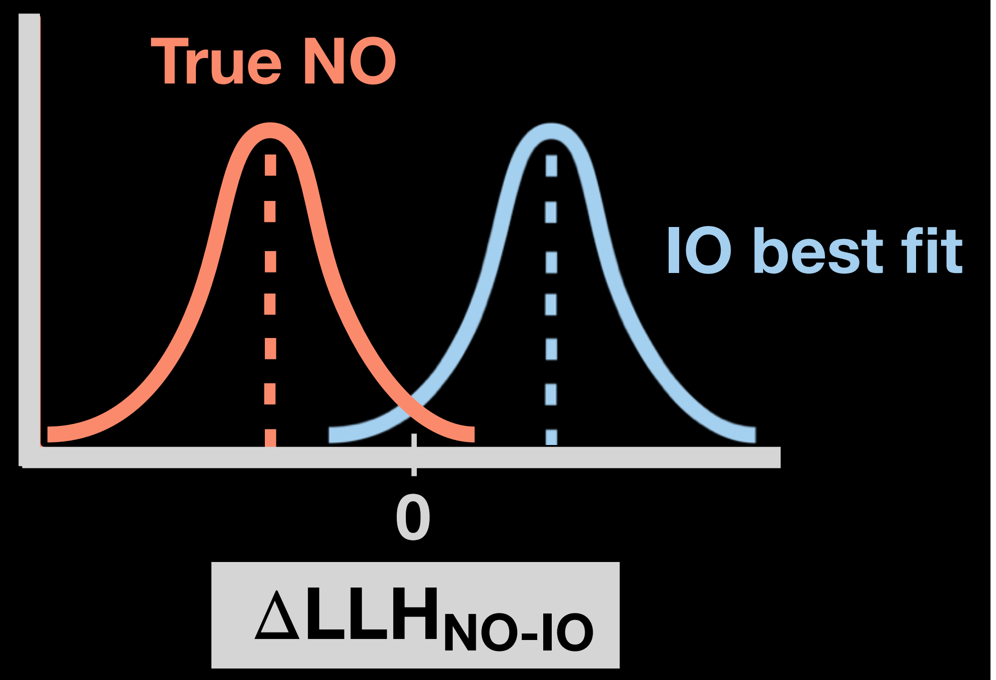
NMO Analysis: MC

Assume NO is the true ordering

Two dLLH distributions

$$\text{LLH1}_i - \text{LLH2}_i = \Delta\text{LLH}_{\text{NO-IO}_i}$$

$$\text{LLH3}_i - \text{LLH4}_i = \Delta\text{LLH}_{\text{NO-IO}_i}$$



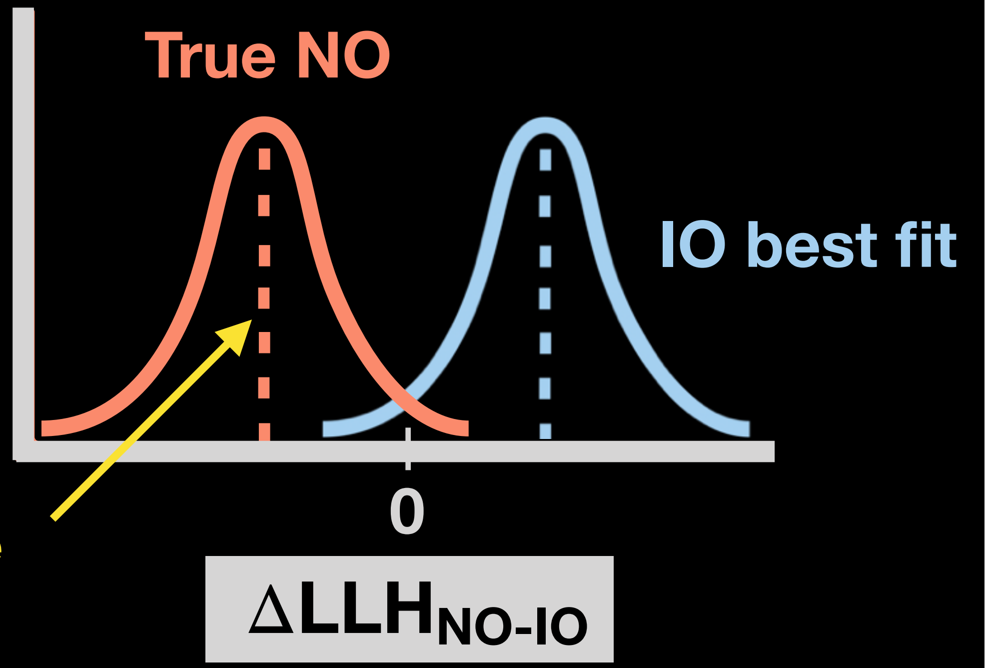
NMO Analysis: MC

Assume NO is the true ordering

How far away from the observed value is the median value of the wrong ordering?

$\textbf{LLH1}_i - \textbf{LLH2}_i = \Delta\textbf{LLH}_{\textbf{NO-IO}_i}$

$\textbf{LLH3}_i - \textbf{LLH4}_i = \Delta\textbf{LLH}_{\textbf{NO-IO}_i}$



Treat this as the observed value

NMO Analysis: MC

Assume NO is the true ordering

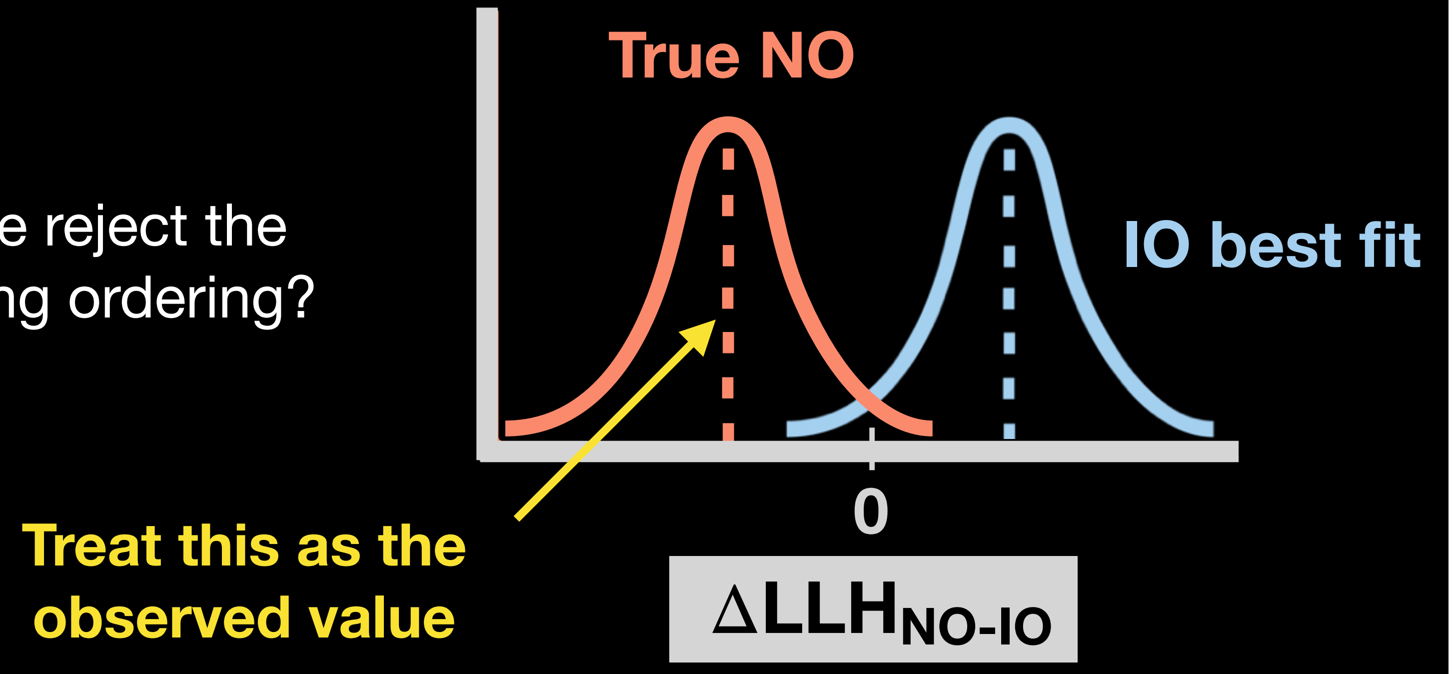
How far away from the observed value is the median value of the wrong ordering?

$$\mathbf{LLH1}_i - \mathbf{LLH2}_i = \Delta\mathbf{LLH}_{\mathbf{NO\text{-}IO}_i}$$

$$\mathbf{LLH3}_i - \mathbf{LLH4}_i = \Delta\mathbf{LLH}_{\mathbf{NO\text{-}IO}_i}$$

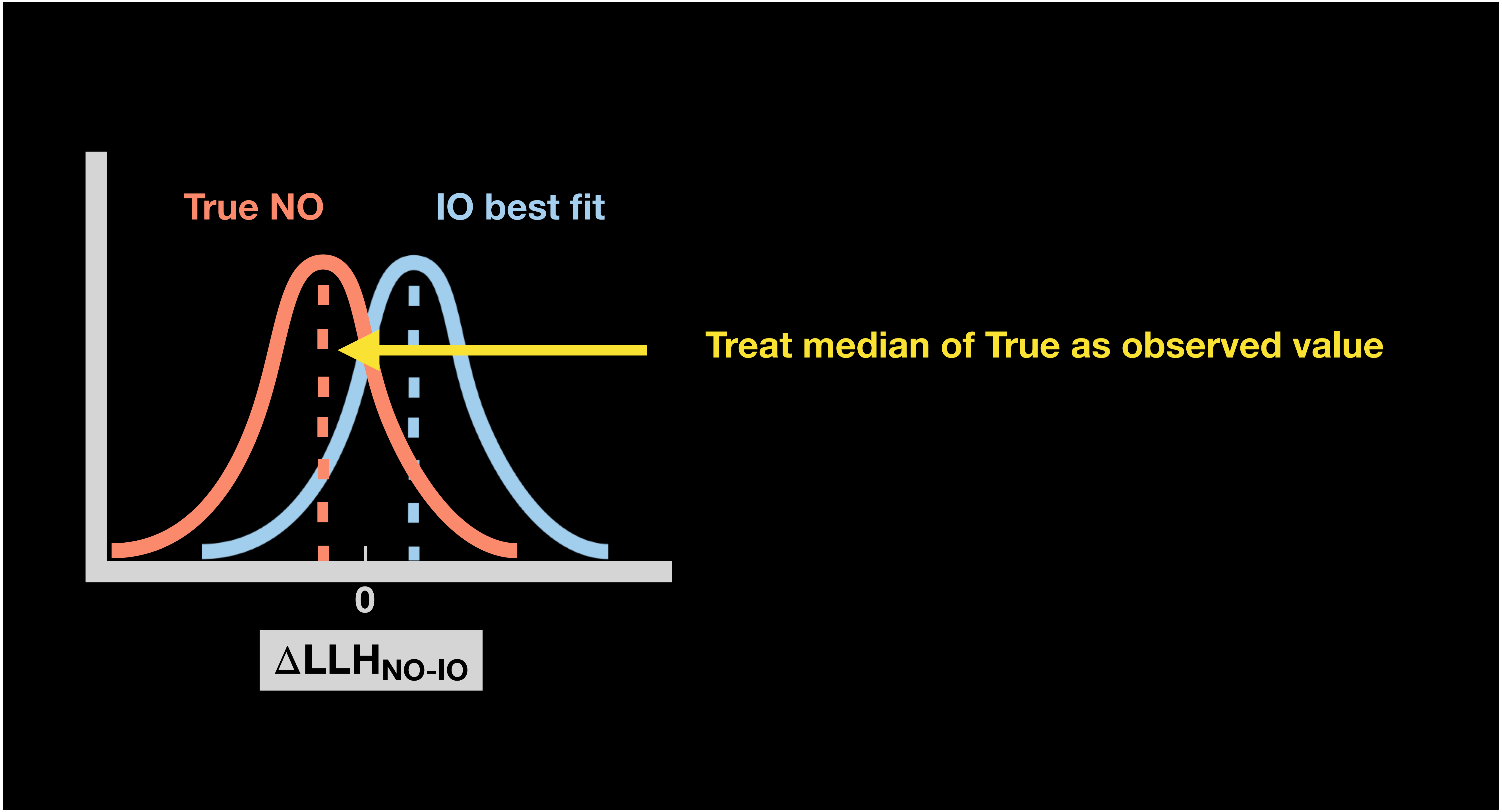
NMO Median Sensitivity:

Given our observed value, how well can we reject the median of even the closest case of the wrong ordering?



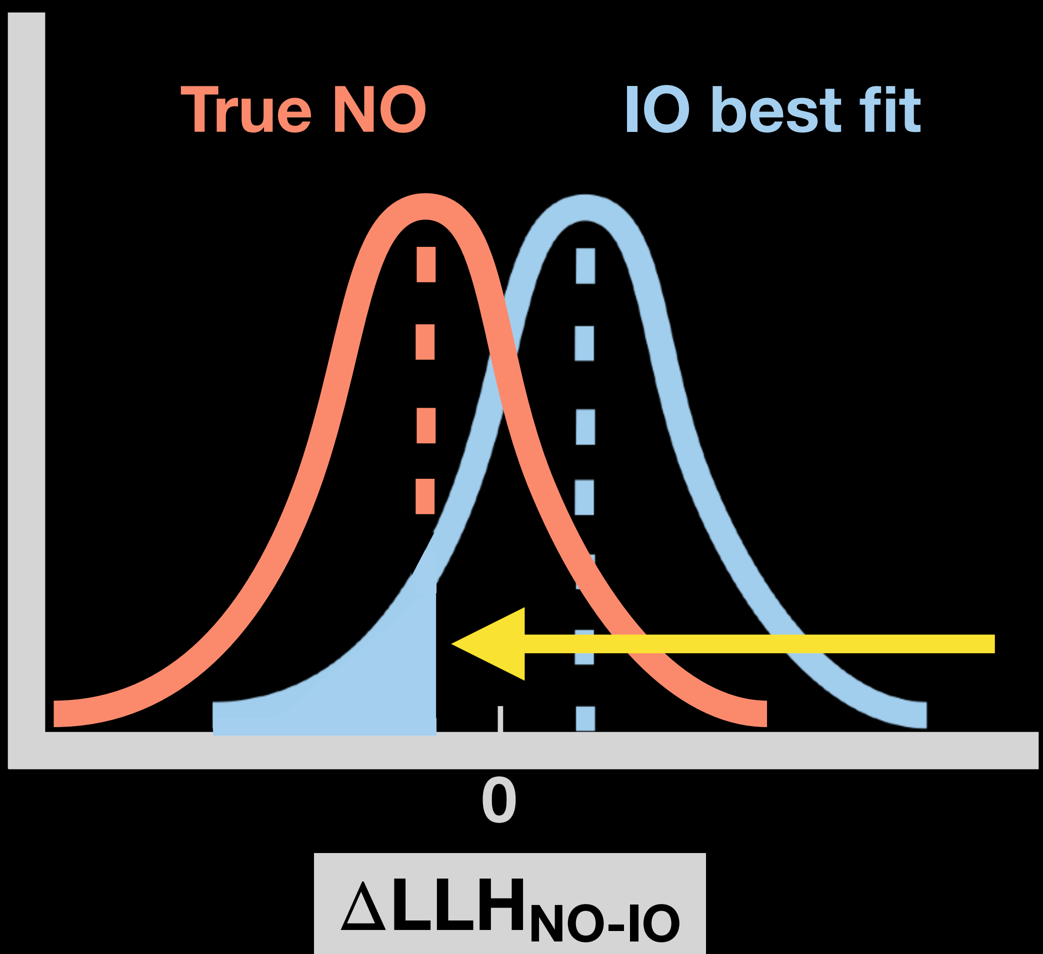
NMO Analysis: MC

Assume NO is the true ordering



NMO Analysis: MC

Assume NO is the true ordering

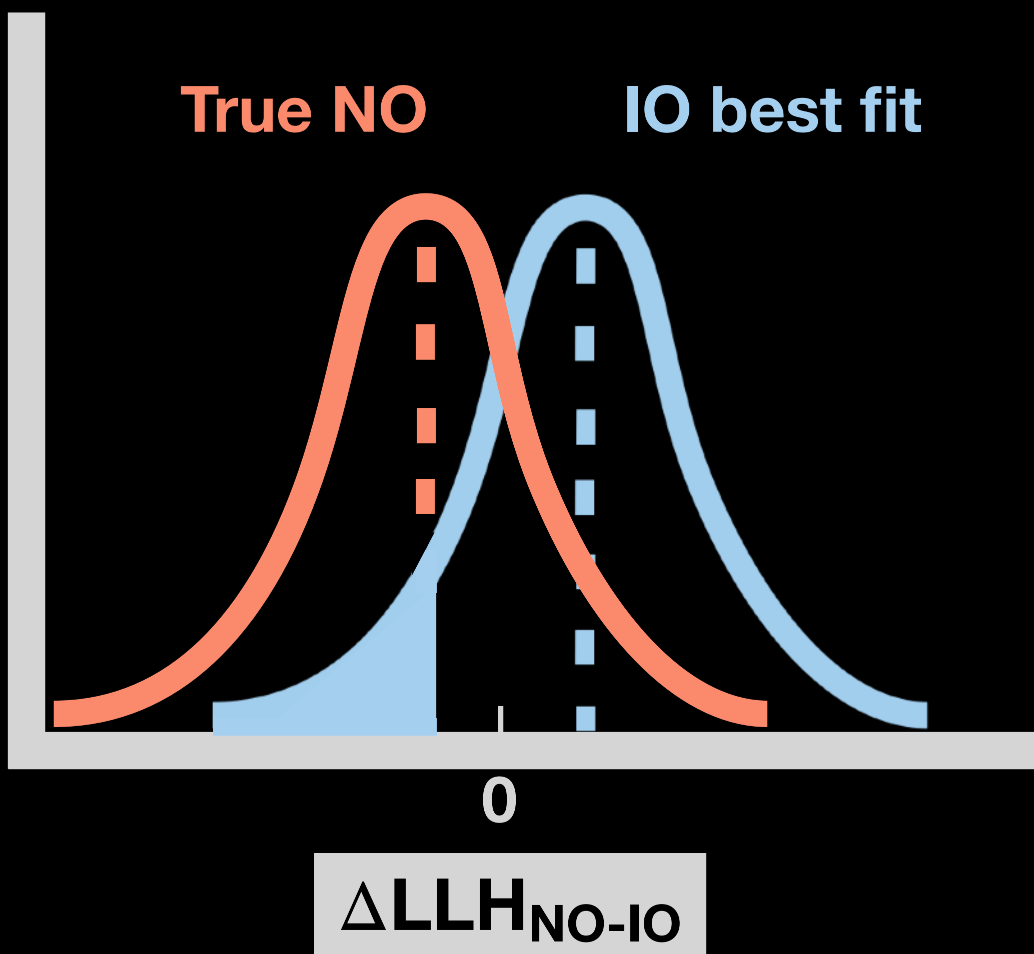


P-value: The probability of obtaining results at least as extreme as the observed results

NMO Analysis: MC

Assume NO is the true ordering

Reference here



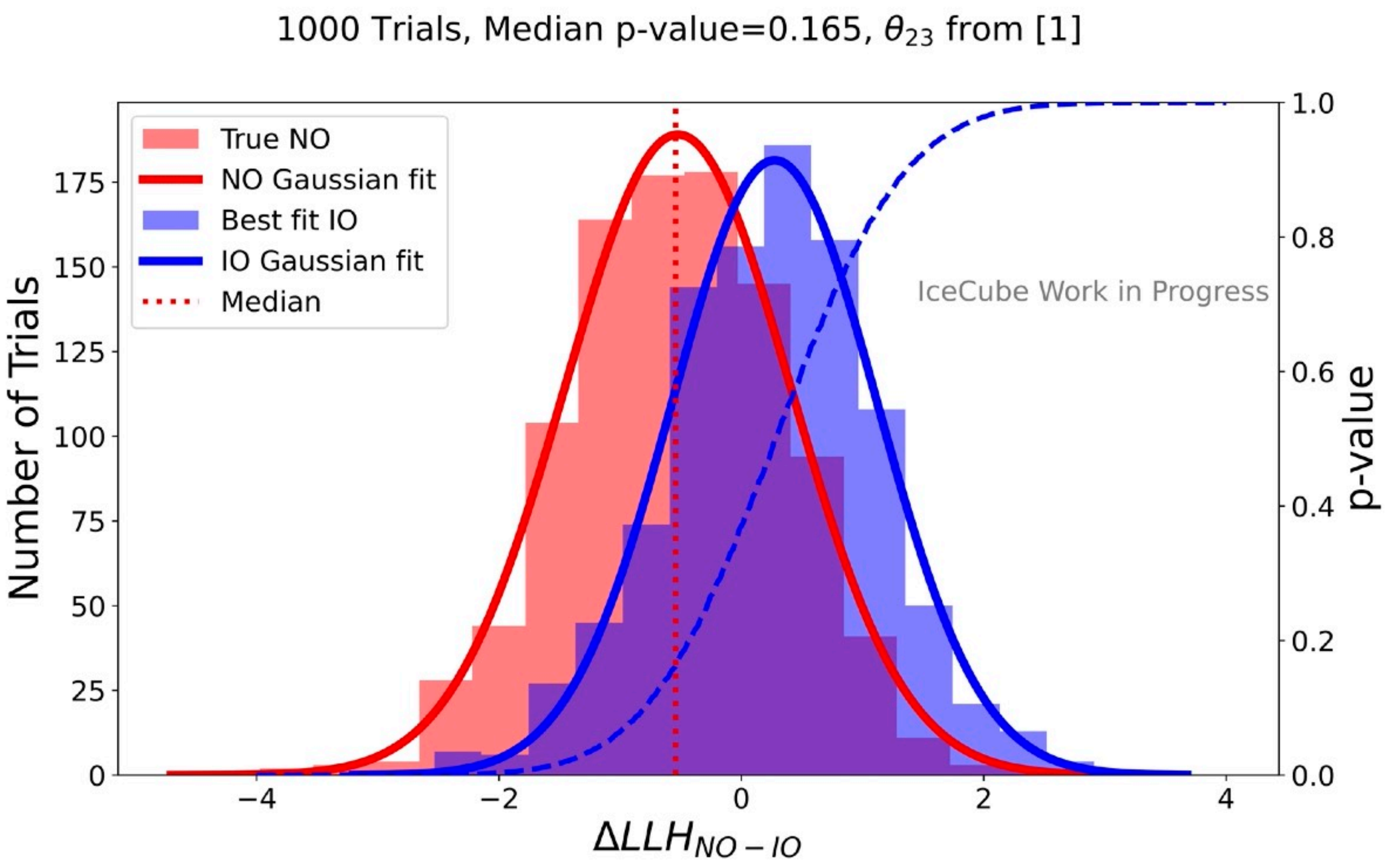
One-Sided Median Sensitivity

$$\eta_\sigma = \sqrt{2}\,\mathbf{erfc}^{-1}(2\mathbf{p})$$

Pseudotrials DeepCore Best Fit θ23

- 1000 trials
- **P-value:** 0.168
- **Median sensitivity:** 0.962σ

True NO

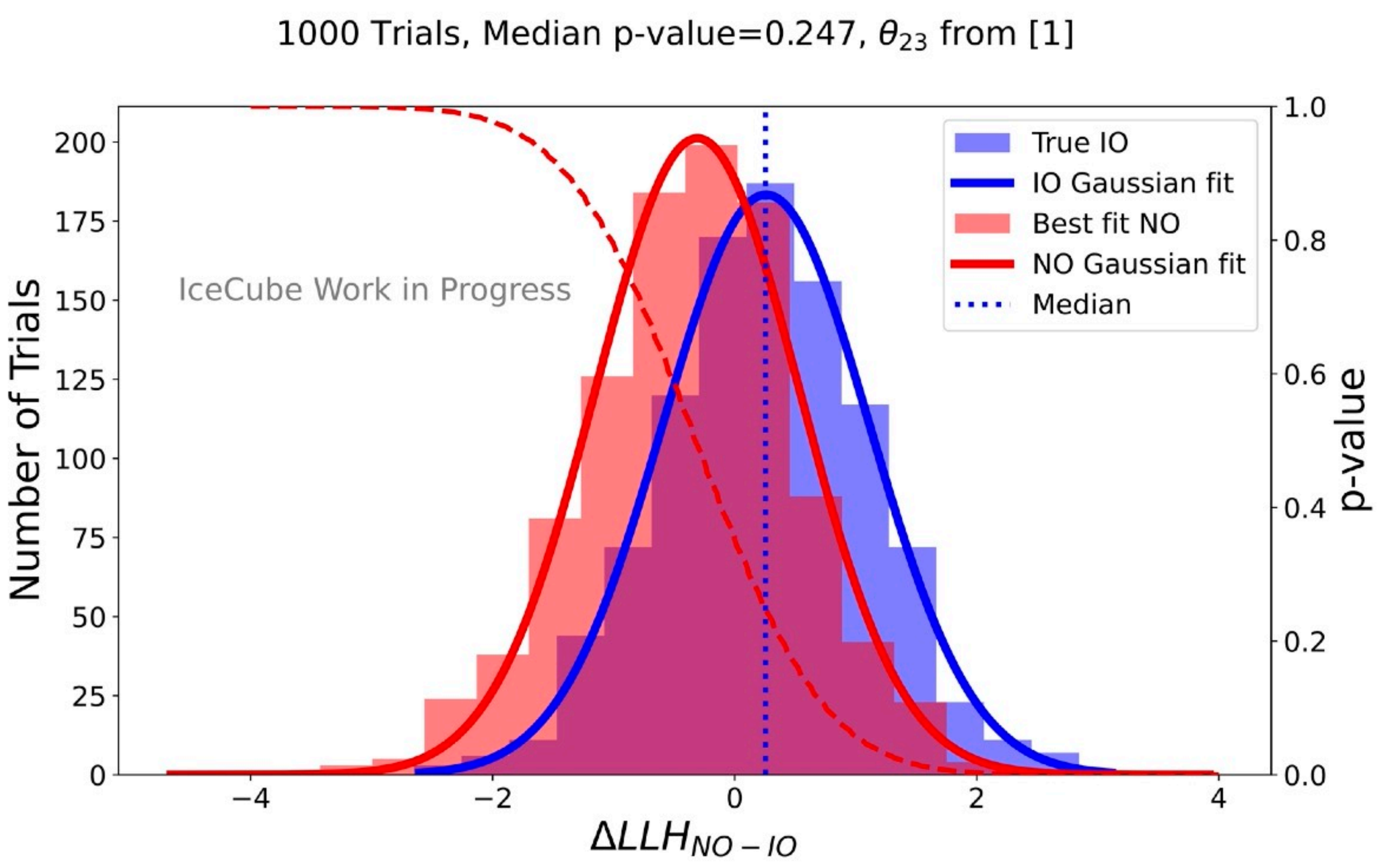


[1] Talk at [Lake Louise Winter Institute 2023]

Pseudotrials DeepCore Best Fit θ23

- 1000 trials
- **P-value:** 0.247
- **Median sensitivity:** 0.684σ

True IO



[1] Talk at [Lake Louise Winter Institute 2023]

NMO Asimov Sensitivity

How many standard deviations away from the median of the wrong ordering is the observed value?

$$\eta_\sigma = \frac{\overline{\Delta\textbf{LLH}}_{\textbf{NO-IO}}(\textbf{observed}) - \overline{\Delta\textbf{LLH}}_{\textbf{NO-IO}}(\textbf{wrong best fit})}{\sigma_{\Delta\textbf{LLH}_{\textbf{NO-IO}}(\textbf{wrong best fit})}}$$

NMO Analysis

If using real data