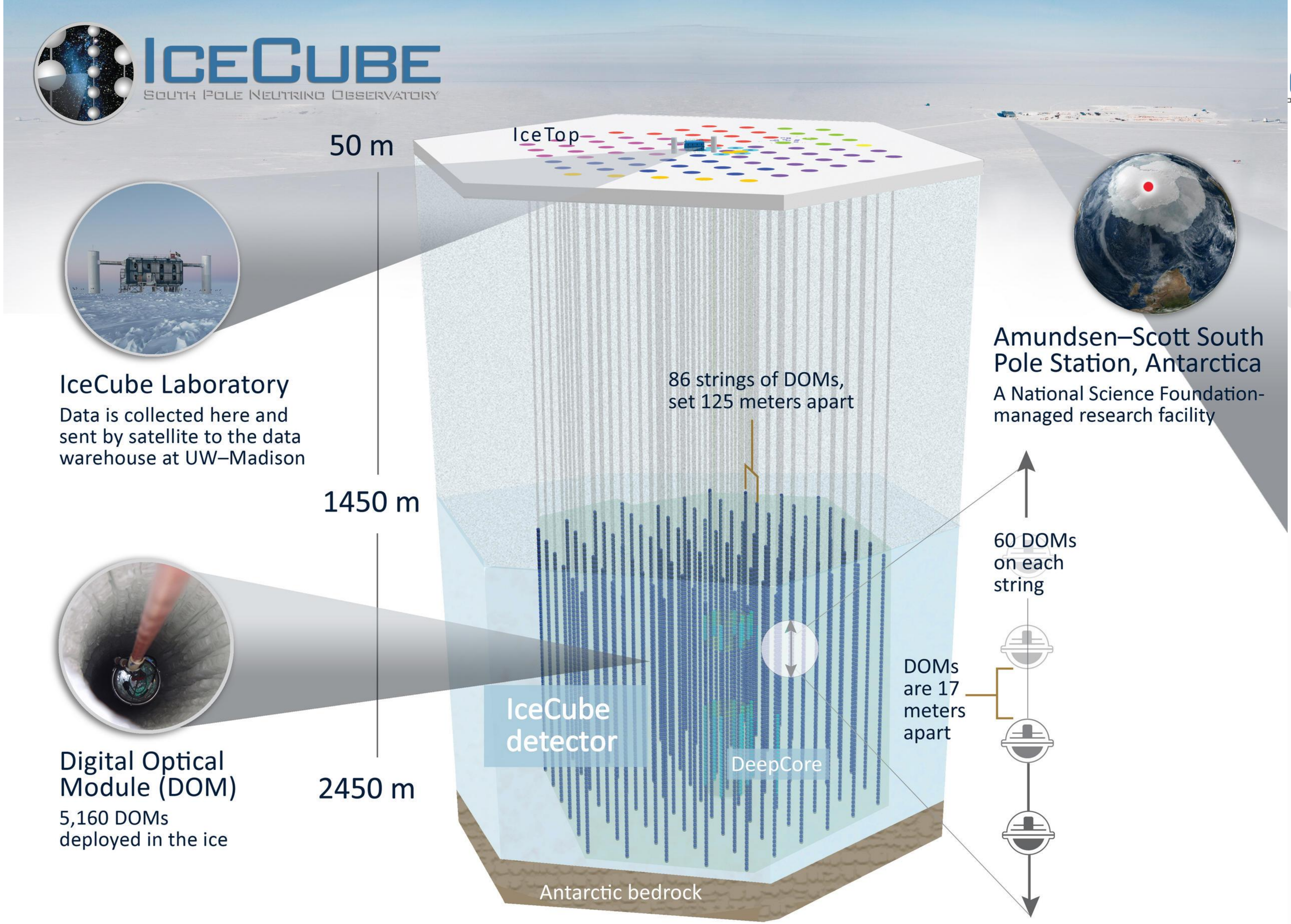
Atmospheric Oscillations with the IceCube Upgrade

Josh Peterson on Behalf of the IceCube Collaboration
NuFact 2024
9/17/2024



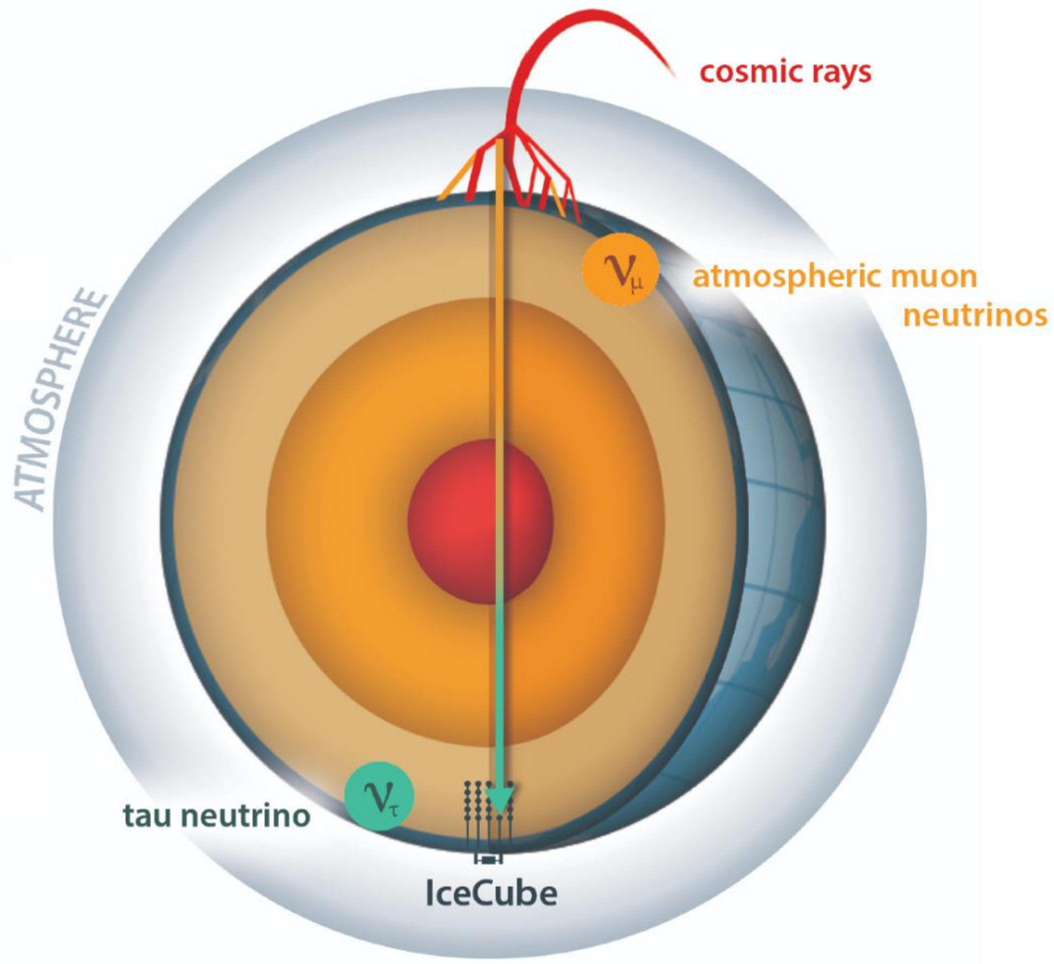
IceCube
South Pole Neutrino Observatory

Oscillations with IceCube

- **Muon neutrinos and electron neutrinos produced in the atmosphere travel through the Earth**

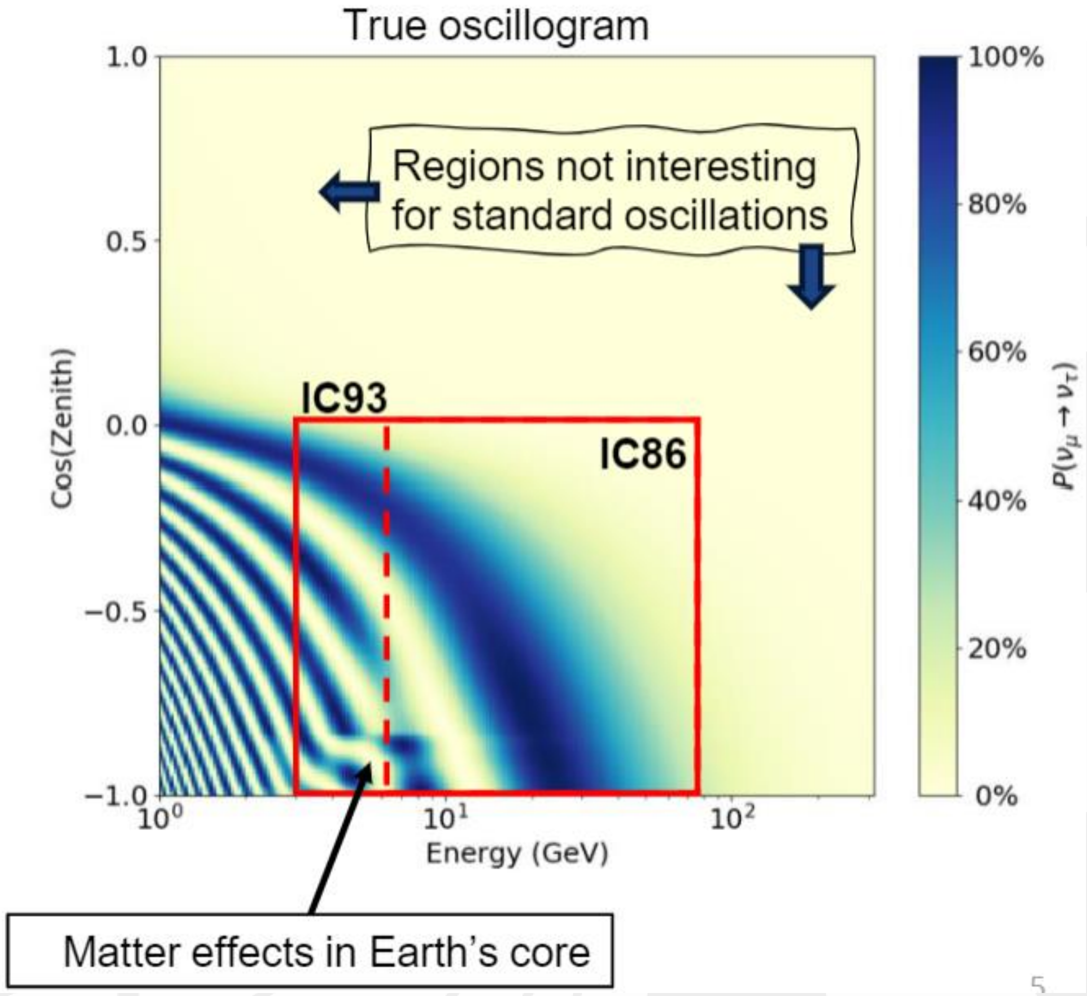
- **During travel, there is a chance that the muon neutrinos may oscillate into tau neutrinos**
  - $P_{\nu_\mu \to \nu_\tau} \approx \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$

- **Muon neutrinos and tau neutrinos produce different event topology, and thus IceCube can measure muon neutrino disappearance**
  - Track like topology for muon neutrinos undergoing charged current interactions
  - Cascade like topology for other flavors and interactions



IceCube Upgrade Motivation

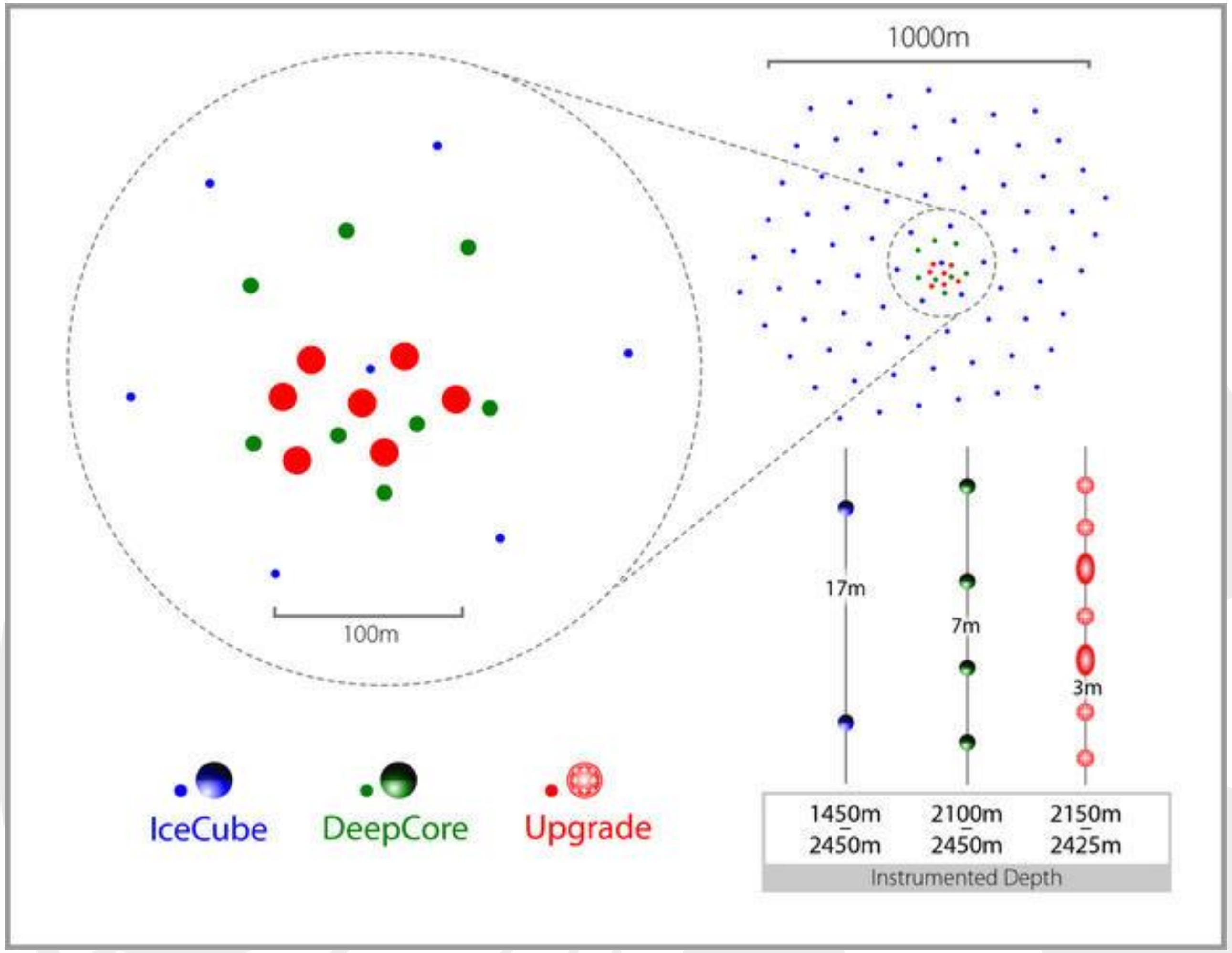
- **Current energy threshold in IceCube DeepCore is about 5 GeV (shown by the dashed line in the plot)**
  - For more information about IceCube Deepcore and current analyses refer to Finn Mayhew's talk
- **Lowering the energy threshold of the IceCube detector would push deeper into a region of parameter space interesting to standard oscillations and matter effects**
- **The best way to probe lower energies more effectively is to more densely instrument the Antarctic Ice**
  - Would also increase number of neutrinos detected



[Jan Weldert's TAUP 2023 Talk]

IceCube Upgrade

- **Install seven new strings densely packed within IceCube DeepCore**
  - Deployment will be in the 2025/2026 Antarctic summer season
- **Each string is roughly five times more densely instrumented than the standard IceCube strings**
- **Utilize digital optical modules (DOMs) that utilize multiple PMTs facing many directions**
- **Also introduce new instruments for better calibration**



arXiv:1908.09441

IceCube Upgrade Hardware

- **mDOM**:
    - 24 3-inch PMTs facing all directions
    - About 400 to be deployed

- **D-Egg**:
    - 2 8-inch PMTs facing down and up
    - 2.8 times higher photon sensitivity than existing DOMs
    - About 280 to be deployed

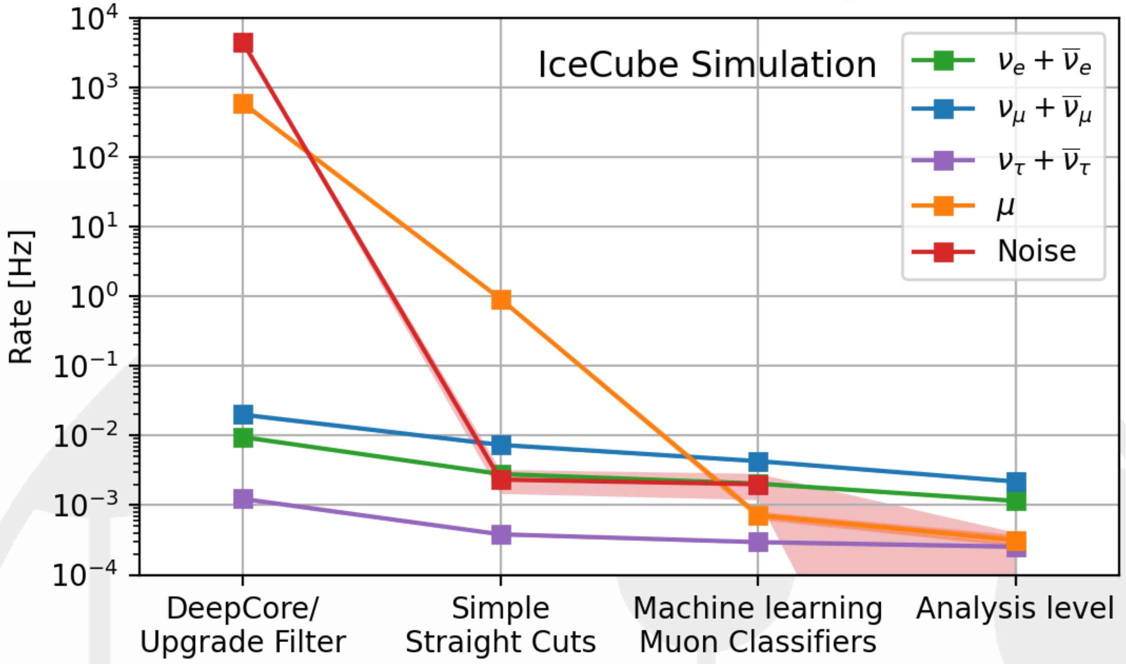
- **Additional optical modules will be implemented for R&D purposes**

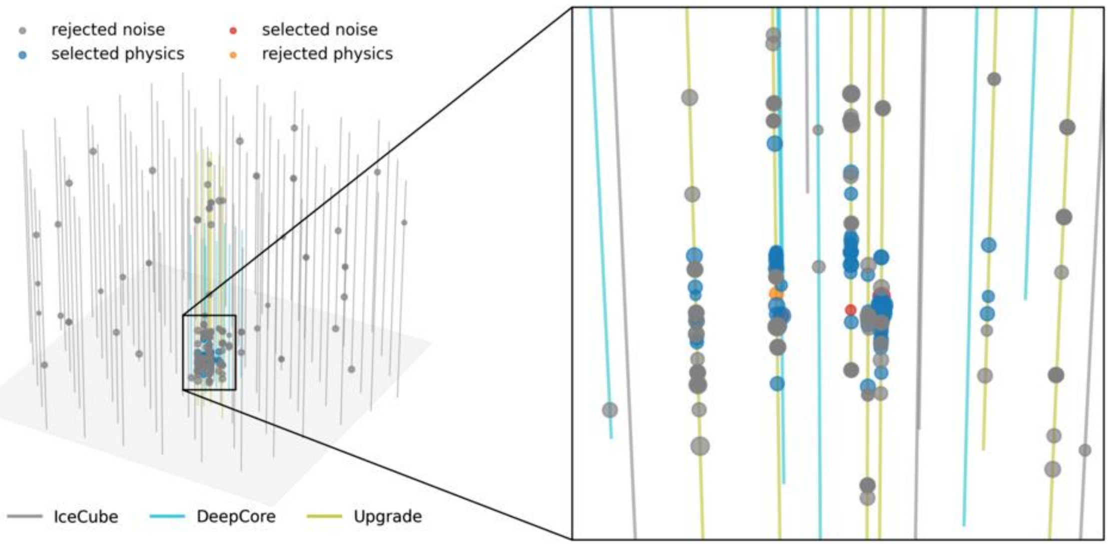
- **A series of calibration devices will also be implemented in order to improve our understanding of the optical properties of the Antarctic ice**

Event Selection

arXiv:2307.15295

- **Background from PMT noise and atmospheric muons dominates what is seen in the detector**
  - Need an event selection to suppress the background
- **With this event selection we have a sample that is neutrino dominated**
- **Graph Neural Network (GNN) based noise selection reduces noise hits by 95% while retaining 90% of physics hits**

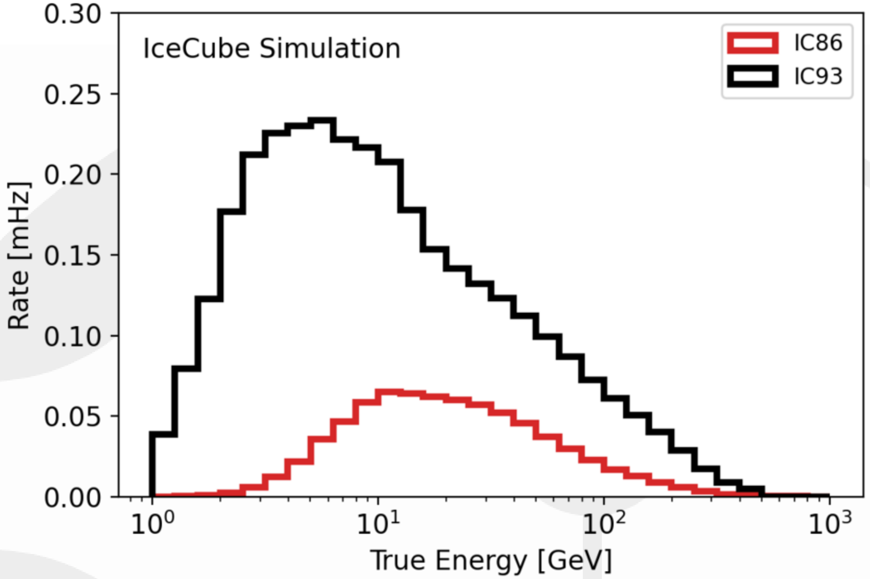


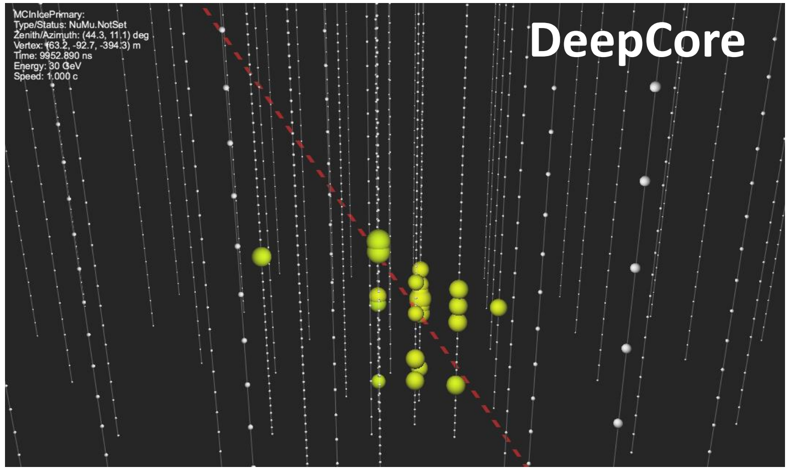


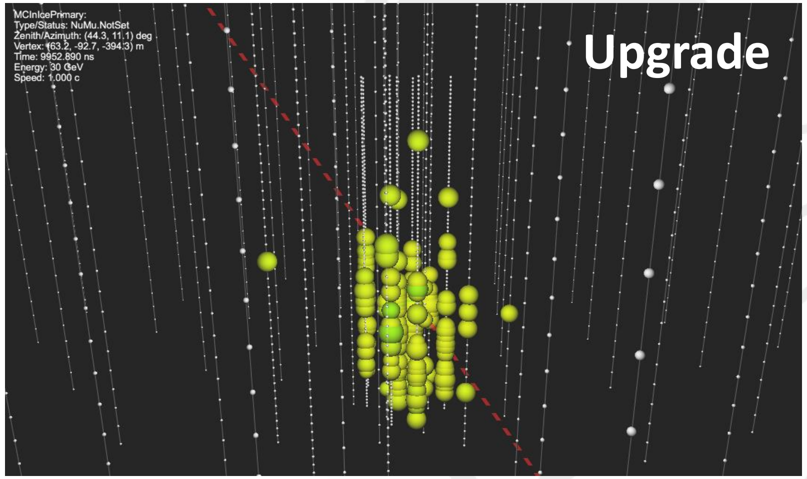
IceCube Upgrade Advantages

arXiv:2307.15295

- **Peak of energy distribution shifts down from about 10 GeV to about 5 GeV**
- **3 to 5 times more neutrino events at the analysis level than with IceCube DeepCore**
  - More events for all energies from 3 GeV to 300 GeV
- **More photon hits per event, which leads to better reconstruction and classification**



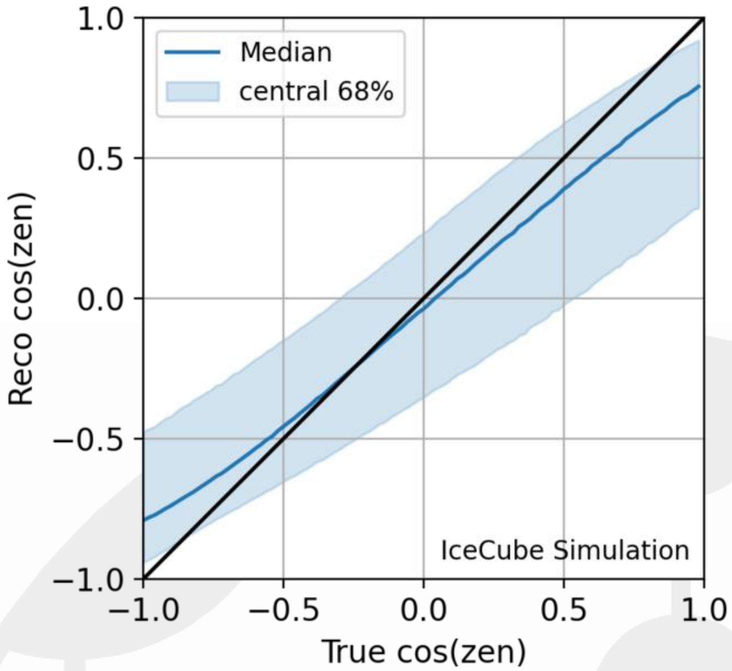


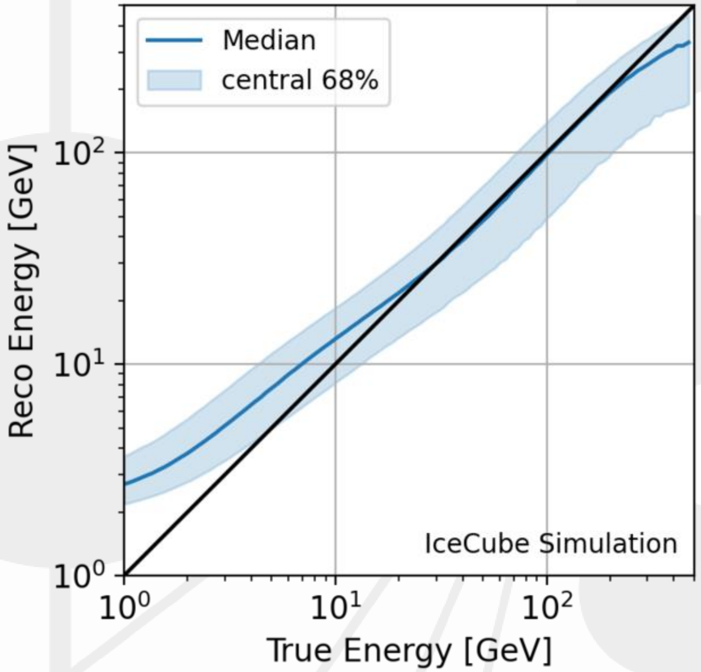


Flavor	IC86	IC93
$\nu_\mu + \overline{\nu_\mu}$	0.76 mHz	4.3 mHz
$\nu_e + \overline{\nu_e}$	0.25 mHz	2.0 mHz
$\nu_\tau + \overline{\nu_\tau}$	0.05 mHz	0.3 mHz

Reconstruction and Classification

- **Train a GNN for each observable**
- **Event Topology (PID)**
  - Achieves an area under the ROC curve of 0.82, which is a significant improvement from IceCube DeepCore
- **Energy**
  - Uniform performance over energy range of interest
- **Cos(Zenith Angle)**
  - Uniform performance over all zenith angles





Sensitivity Analysis

- **The sensitivities that will be shown are Asimov sensitivities unless specified otherwise**
- **There are two detector configurations considered:**
  - IC86: The current IceCube detector with DeepCore
  - IC93: IceCube with the IceCube Upgrade
- **There are two scenarios considered:**
  - 15 years of IC86
  - 12 years of IC86 with 3 years of IC93

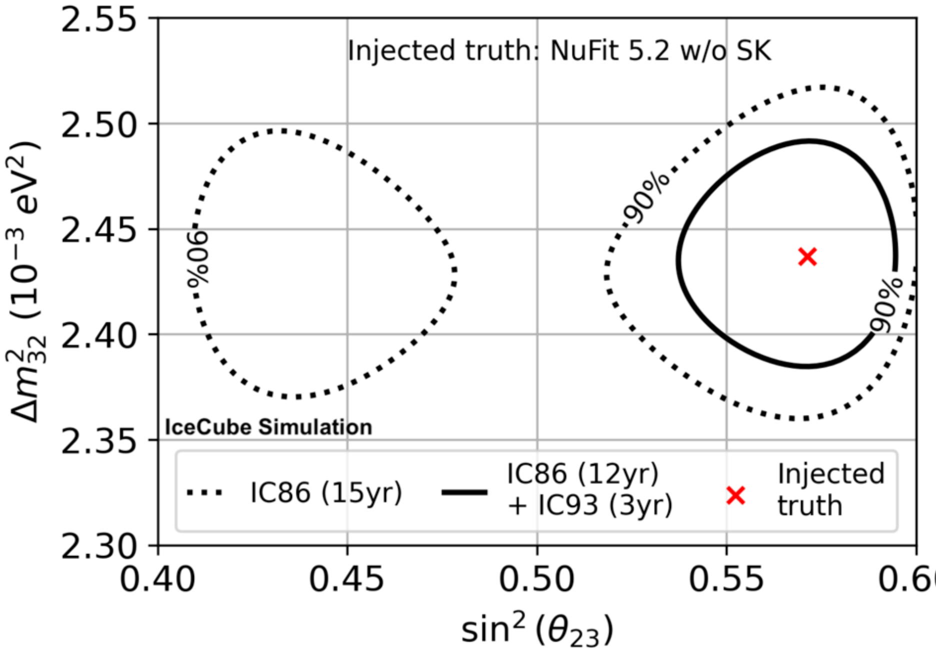
	IC86	IC93
Energy	12 Log bins from 5 GeV to 300 GeV	12 Log bins from 3 GeV to 300 GeV
Cos(Zenith)	10 Linear bins from -1.0 to 0.0	10 Linear bins from -1.0 to 0.0

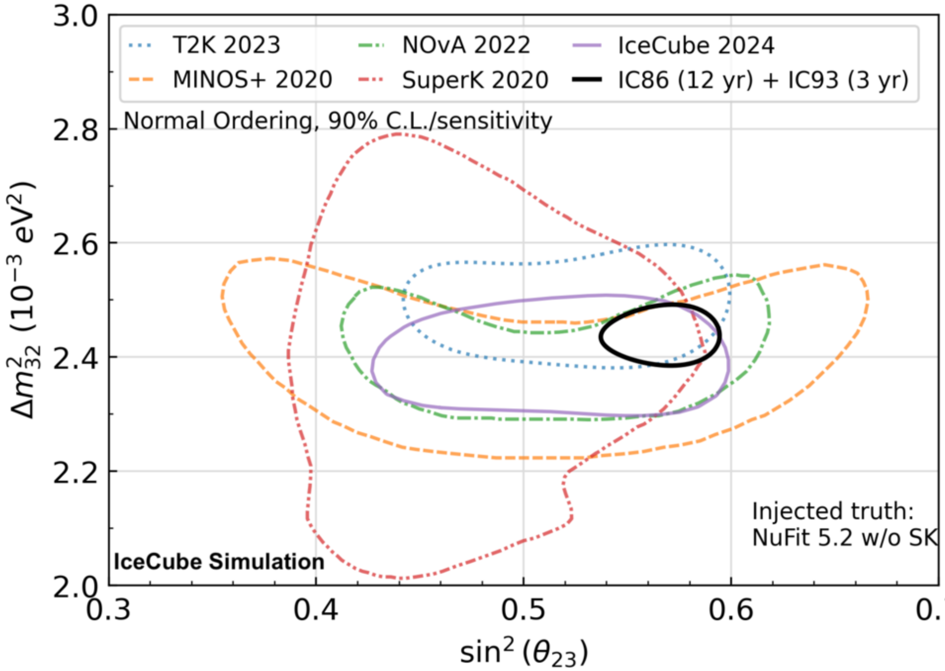
Systematic parameters

Flux
Spectral index
Uncertainty on Pion and Kaon production
Neutrino and Muon Normalizations
Cross sections
Deep inelastic scattering uncertainty
Axial masses for Resonant CC and Quasi-elastic scattering
Axial masses for Resonant NC and Coherent π scattering
Model uncertainty on tau neutrino cross section
Detector
Bulk ice properties scattering and absorption
Optical module efficiencies
Angular acceptance (IC86 configuration only)

ν_μ Disappearance

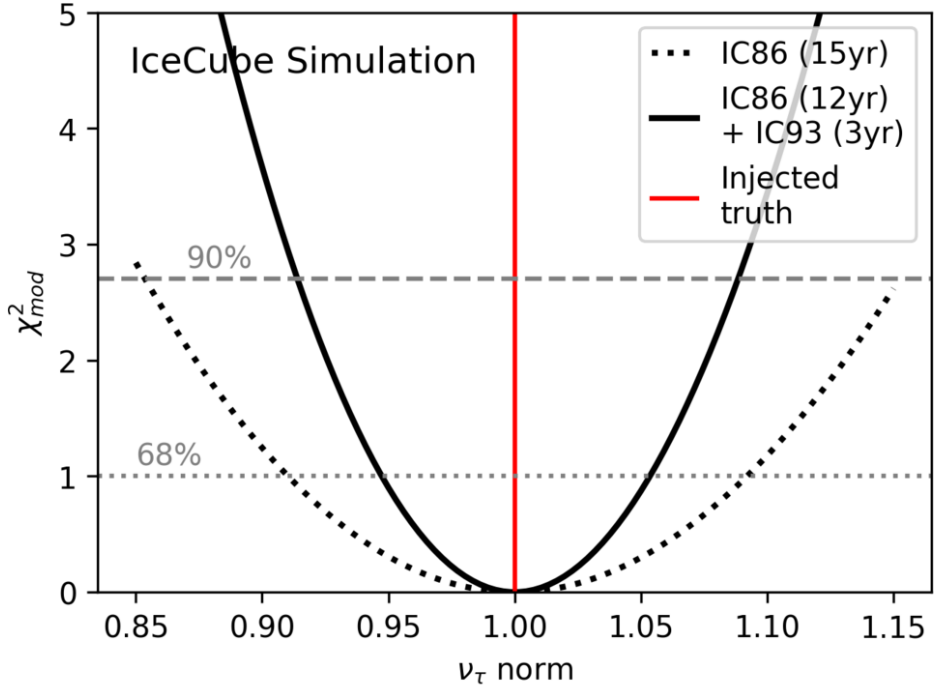
- **Measure the oscillation parameters θ_{23} and $|\Delta m^2_{32}|$**
- **90% confidence level region shrinks by 55% to 70% with IceCube Upgrade**
- **IC93 could exclude maximal mixing from 90% contour and determine the octant of θ_{23} depending on the true value of θ_{23}**
- **The constraints to the atmospheric oscillation parameters from IC93 will be among the world's most precise**

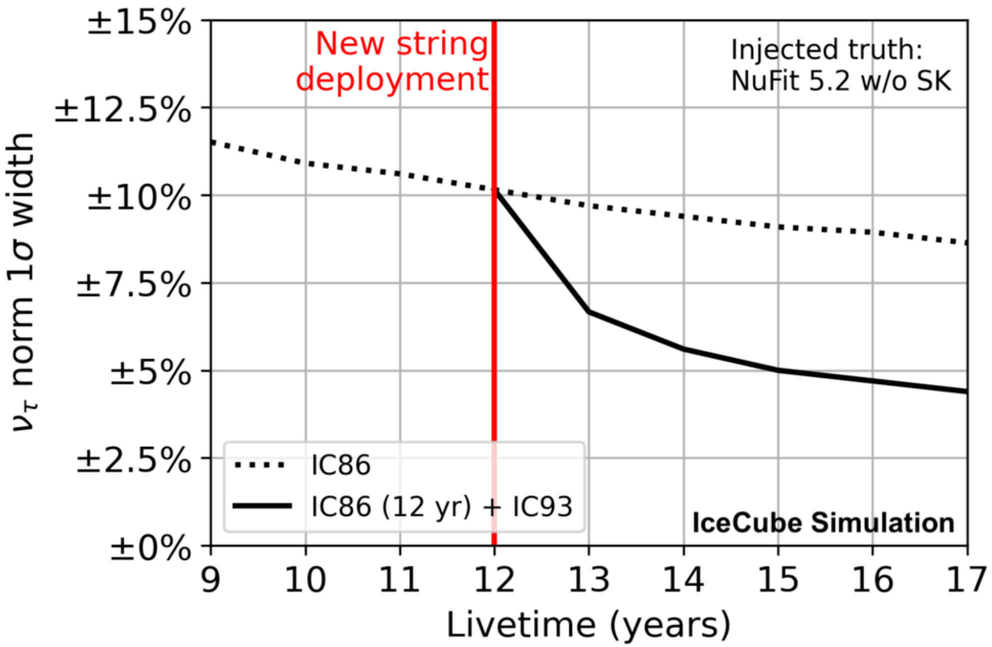




ν_τ Appearance

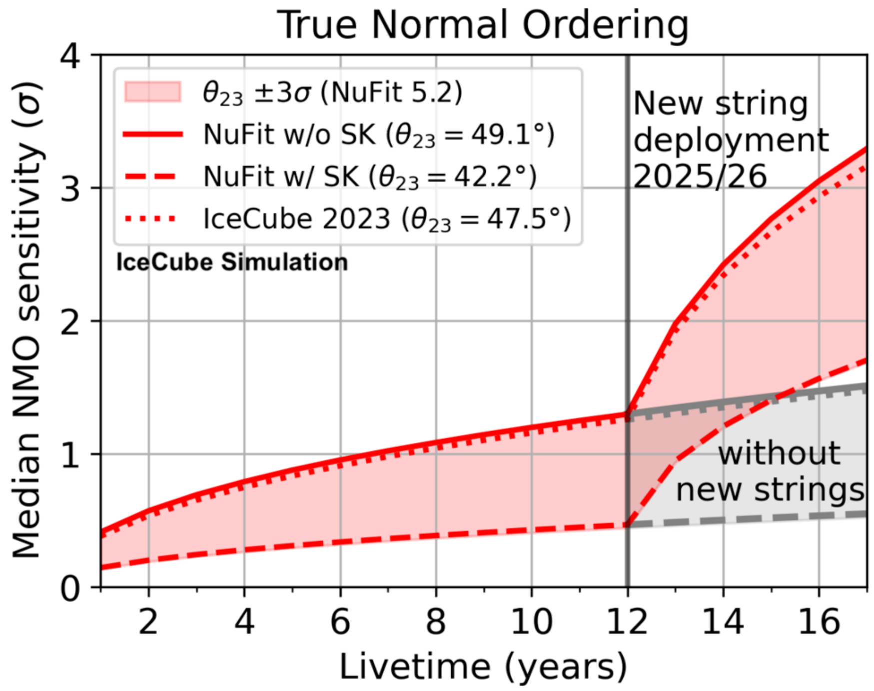
- **Constrain the number of detected tau neutrinos in our data sample**
  - Tau neutrinos would only be in the sample due to oscillations, not present in the atmospheric neutrino flux
  - Number of tau neutrinos is treated as a normalization factor multiplied by the expected number of tau neutrinos
- **With the IceCube Upgrade the 1σ uncertainty of the tau neutrino normalization can be reduced by a factor of two**

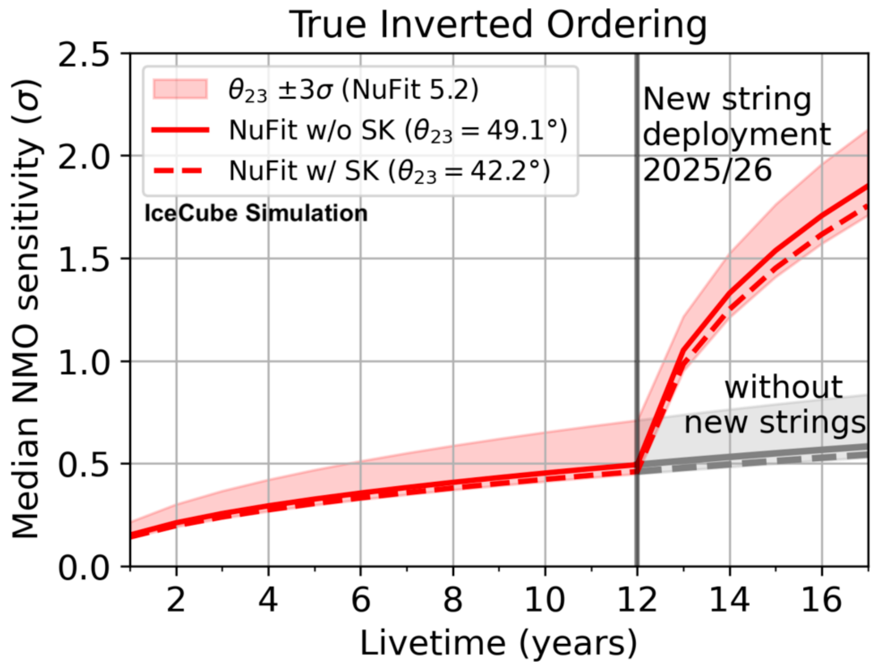




Neutrino Mass Ordering

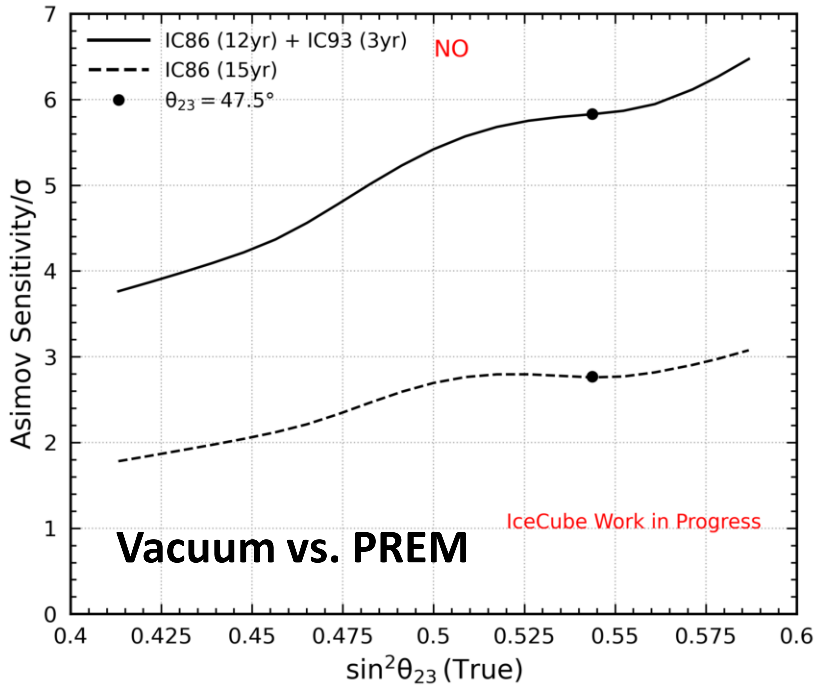
- **Determine whether the normal mass ordering or the inverted mass ordering is preferred**
    - Look for low energy matter effects and determine if they are coming from neutrinos or antineutrinos
- **The IceCube Upgrade will improve the sensitivity to more than 2σ within a few years**
- **A sensitivity of 3σ is possible with IC93 for the normal ordering depending on the true value of θ_{23}**
- **Further improvements expected when combining IC93 with reactor experiments like JUNO**

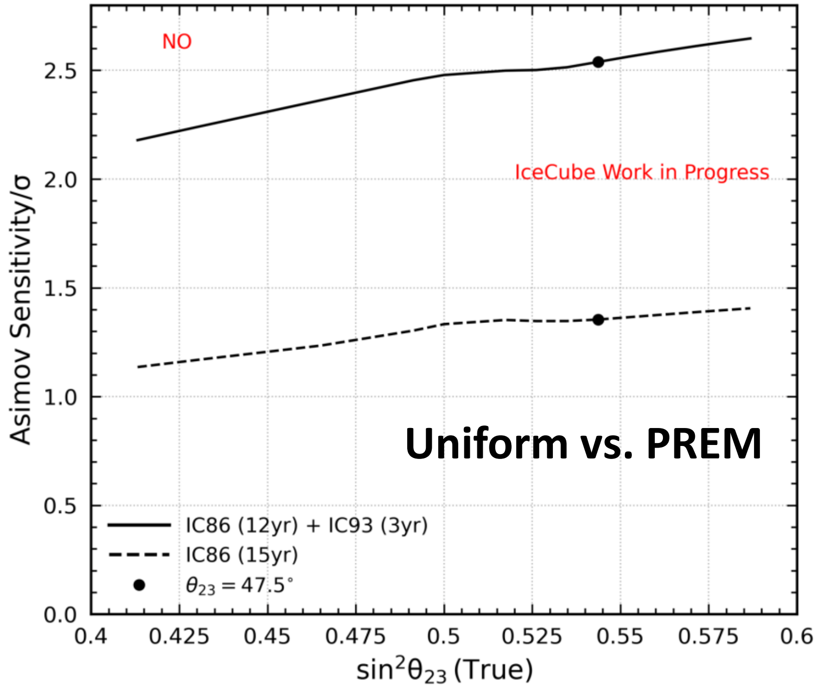




Probing Earth's Structure

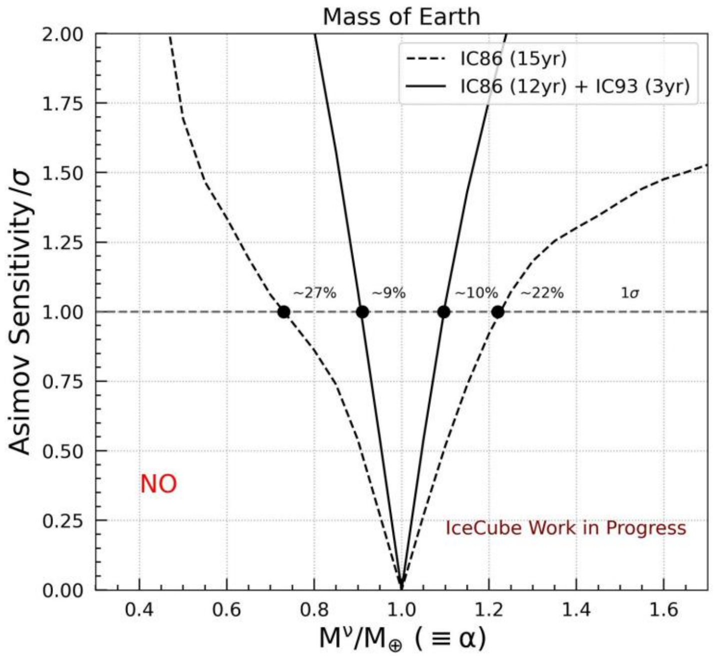
- **Verify the existence of matter effects in our neutrino data by comparing a 12 layer PREM Earth model to vacuum**
  - Could find a preference for matter effects at a 4 to 5σ level with IC93 depending on the value of θ_{23}
- **Verify Earth's layered structure by comparing a 12 layer PREM Earth model to a uniform Earth density profile**
  - Could verify a preference for layered Earth at a 2.5σ level with IC93
- **Both analyses show significantly improved results with IC93**

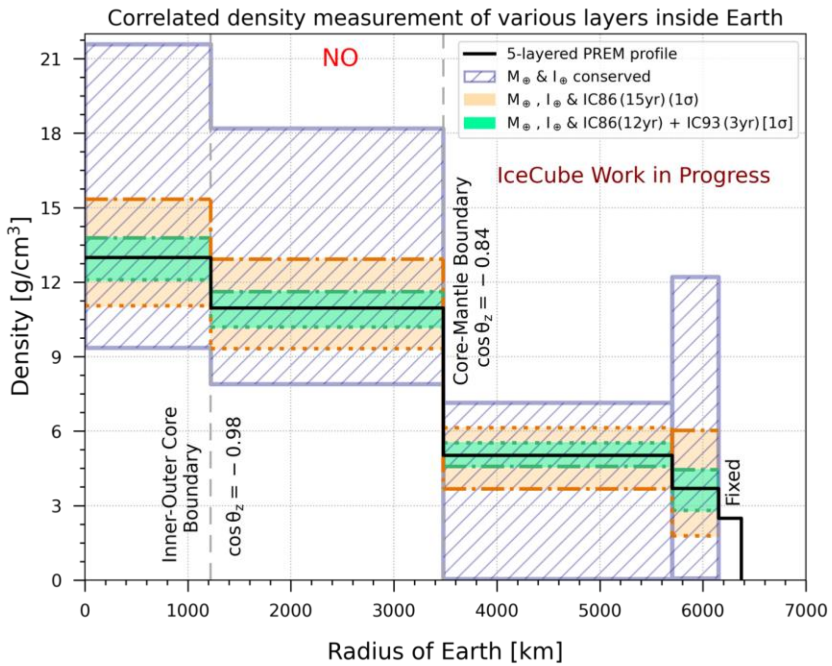




Probing Earth's Structure

- **Use matter effects to measure the mass of the Earth**
  - IC93 could measure the mass of Earth with a 1σ precision of 9 to 10%
  - About a factor of 2 increase in precision in the measurement of Earth's mass with IC86
- **Use neutrino data to constrain the allowed densities of Earth's layers (while conserving Earth's total mass and moment of inertia)**
  - Significant improvement on constraints for all layer densities when using IC93





Summary

- **Next year we will deploy the IceCube Upgrade**
- **The IceCube Upgrade includes seven more densely instrumented strings, improved digital optical modules, and calibration instruments**
- **Upgrade analyses will incorporate improved event selection, reconstruction, and classification techniques**
- **Expect significant improvements to the following measurements:**
    - **Oscillation parameters θ_{23} and $|\Delta m^2_{32}|$**
    - **ν_τ normalization**
    - **Neutrino mass ordering**
    - **Distinguishing Earth's structure from vacuum and uniform density**
    - **Earth's mass and the mass of Earth's core**

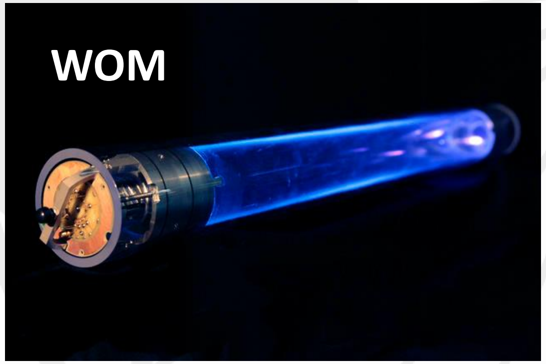
Backup Slides

IceCube Upgrade DOMs

- **mDOM**:
  - 24 3-inch PMTs facing all directions
  - About 400 to be deployed

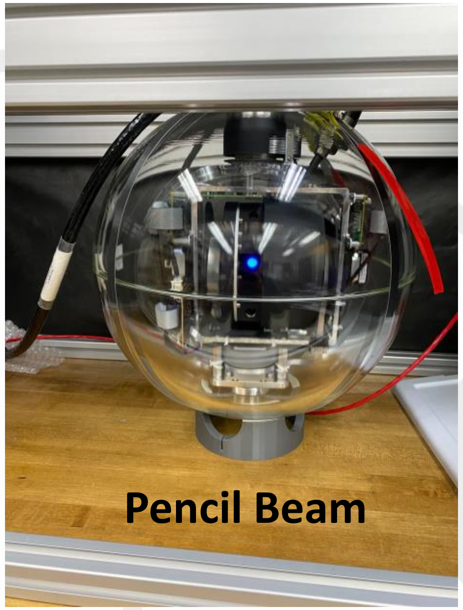
- **D-Egg**:
  - 2 8-inch PMTs facing down and up
  - 2.8 times higher photon sensitivity than existing DOMs
  - About 280 to be deployed

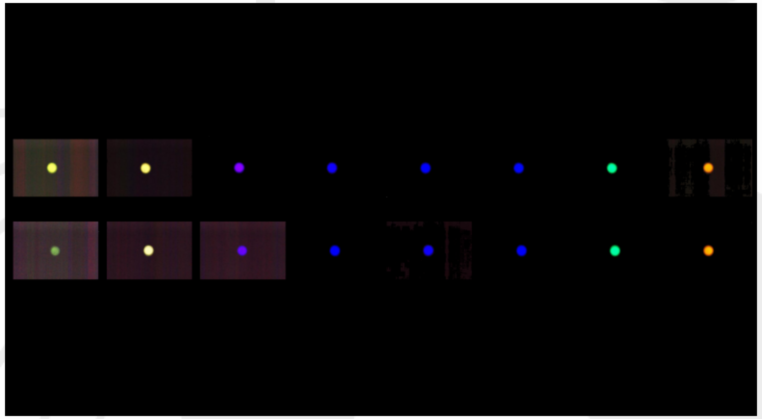
- **DOMs to be deployed in small numbers for testing purposes:**
  - pDOM: Same design as current IceCube DeepCore DOMs
  - LOM: prototype for IceCube Gen2
  - WOM: module that uses wavelength shifting paint
  - FOM: fiber optic module



IceCube Upgrade Calibration Instruments

- **Instruments for studying the optical properties of the Antarctic ice:**
  - Precision Optical Calibration Module: Can emit isotropic nanosecond-long pulses of light
  - Pencil Beam: Can emit beams of light (smaller than one degree) with 8 wavelengths in any direction with a precision of 0.1 degree
- **Other instruments to be included consist of acoustic modules, radio pulsers, Swedish Camera devices, and a seismometer**



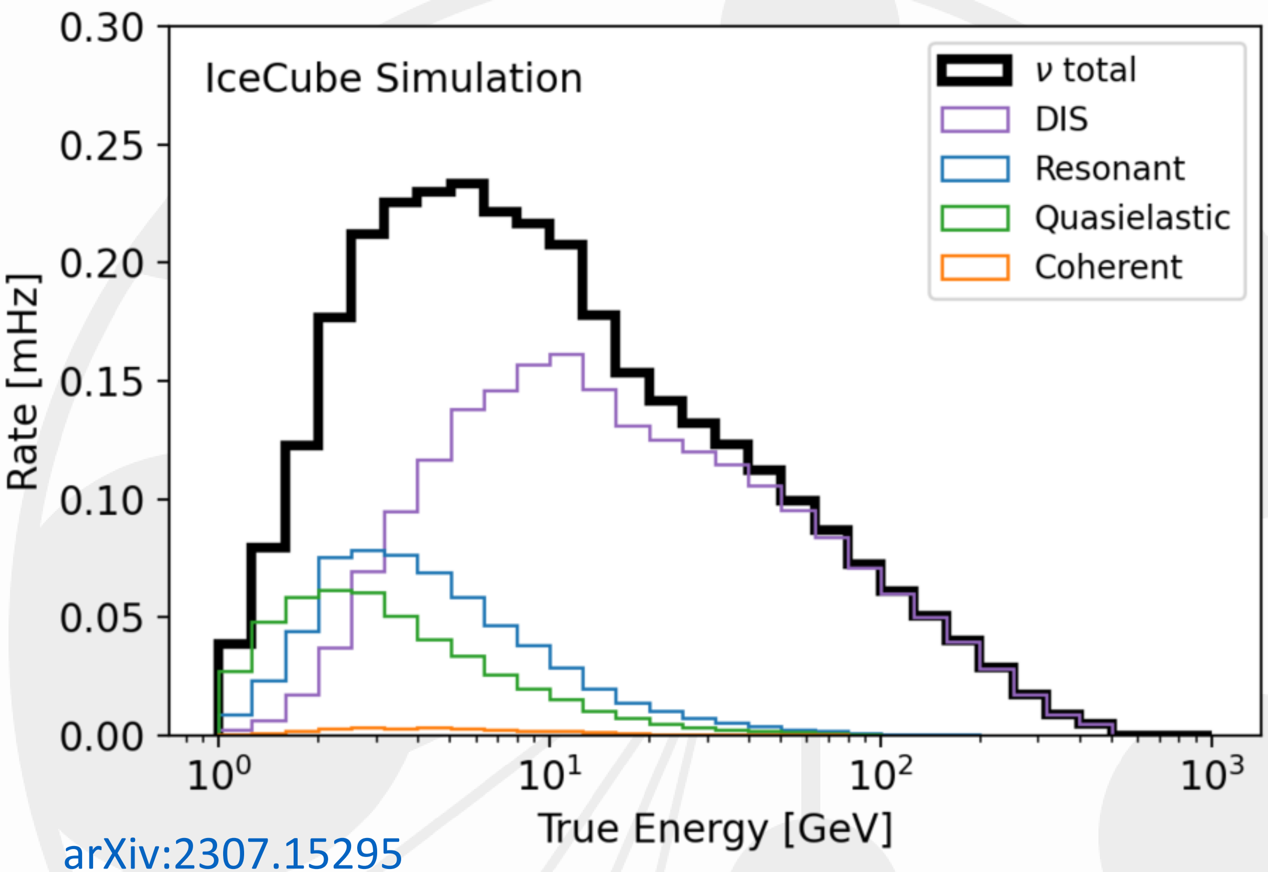


Systematics

Parameter	Nominal	Prior	AOP	ν_τ	NMO
Detector:					
DOM eff. IC86	1.0	± 0.1	free		
DOM eff. ICU	1.0	± 0.05	free		
Ice absorption	1.0	± 0.05	free		
Ice scattering	1.0	± 0.1	free		
Relative eff. p_0	0.10	[-0.6, 0.5]	free		
Relative eff. p_1	-0.05	[-0.15, 0.05]	free		
Flux:					
$\Delta\gamma_\nu$	0.0	± 0.1	free		
$\Delta\pi^\pm$ yields D	0.0	± 0.3	fixed		free
$\Delta\pi^\pm$ yields G	0.0	± 0.3	free		
$\Delta\pi^\pm$ yields H	0.0	± 0.15	free		
$\Delta\pi^\pm$ yields I	0.0	± 0.61	free		
ΔK^+ yields W	0.0	± 0.4	free		
ΔK^+ yields Y	0.0	± 0.3	free		fixed
ΔK^+ yields Z	0.0	± 0.122	fixed		free
Cross-section:					
M_A^{CCQE} (in σ)	0.0	± 1.0	free		
M_A^{CCRES} (in σ)	0.0	± 1.0	free		
M_A^{NCRES} (in σ)	0.0	± 1.0	free		
M_A^{coh} (in σ)	0.0	± 1.0	fixed		free
DIS CSMS	0.0	± 1.0	free		fixed
ν_τ x-sec scale	0.0	[-1.0, +1.0]	fixed		free
Normalisation:					
A_{eff} scale	1.0	[0.1, 2.0]	free		
Atm. muons:					
Atm. μ scale	1.0	[0.1, 3.]	free		
Oscillations:					
θ_{13}	NuFit5.2	0.11	fixed		free
θ_{23}	NuFit5.2	None	free*	free	free
Δm^2_{31}	NuFit5.2	None	free*	free	free
ν_τ normalization	1.0	None	fixed	free*	fixed
mass ordering	NO	n/a	fixed		free*

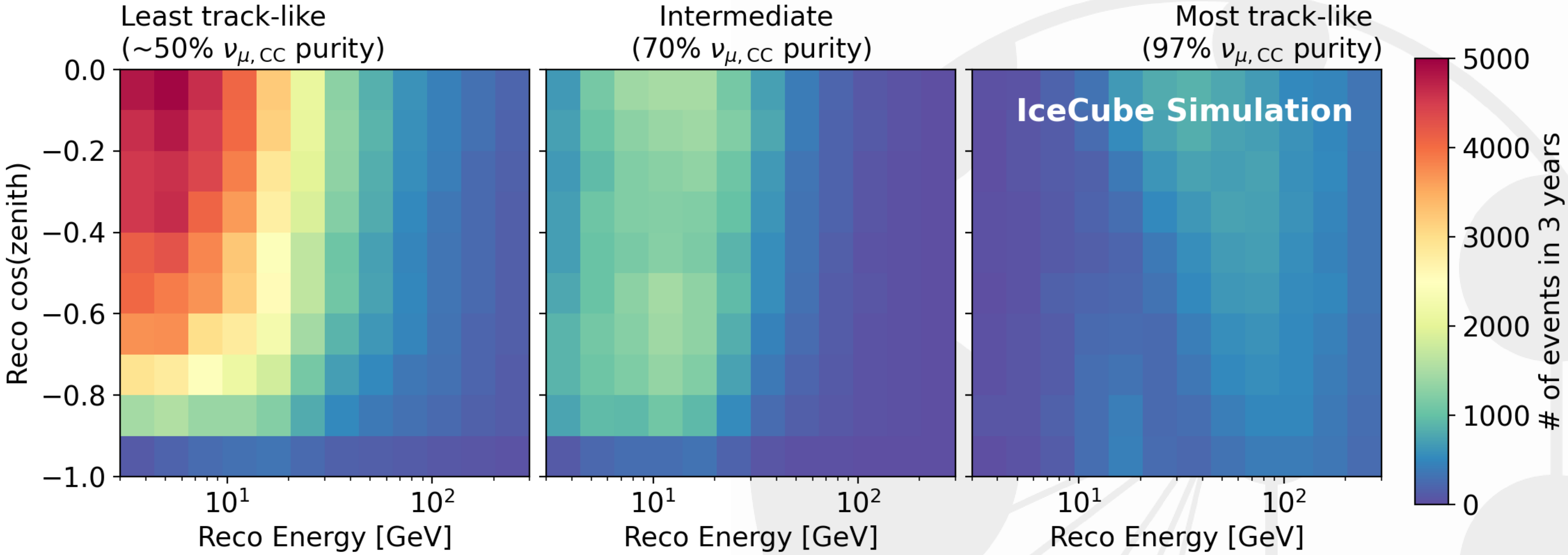
Possible New Systematics

- **Detector systematics due to the new module types and improved ice models**
- **Cross section systematics due to different types of interactions at low energies**
- **Flux uncertainties for lower energy production**
  - Systematics from improved flux models
- **Additional oscillation parameters may become non-negligable**



arXiv:2307.15295

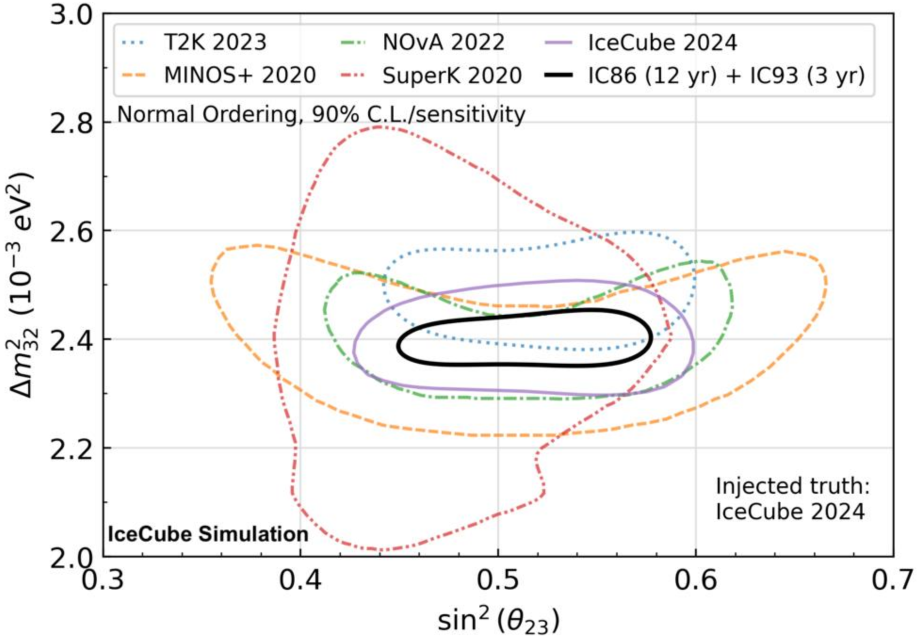
Analyses Bin Counts

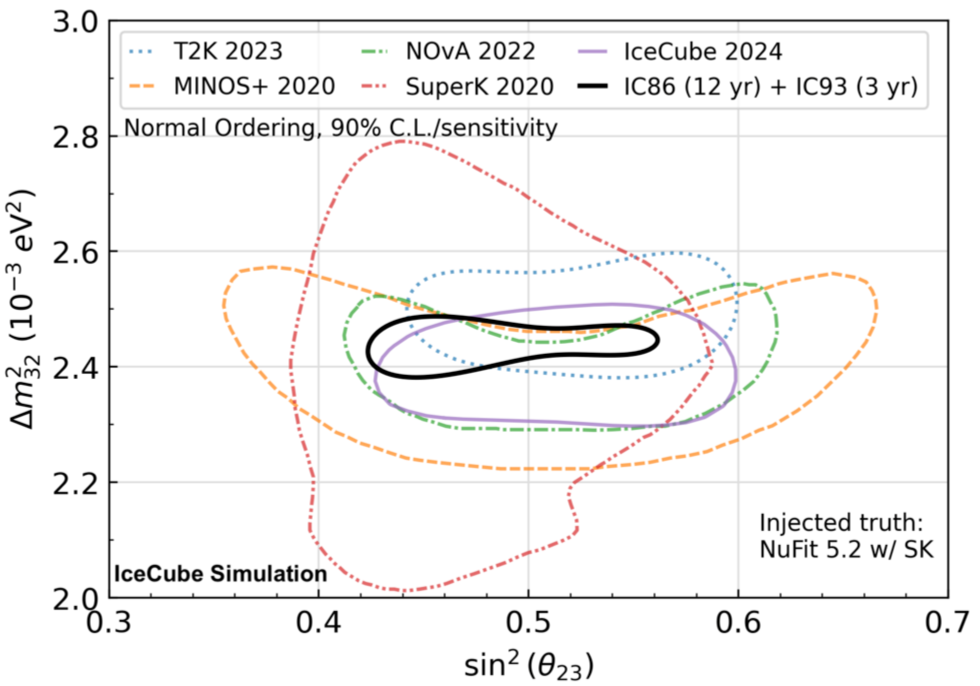


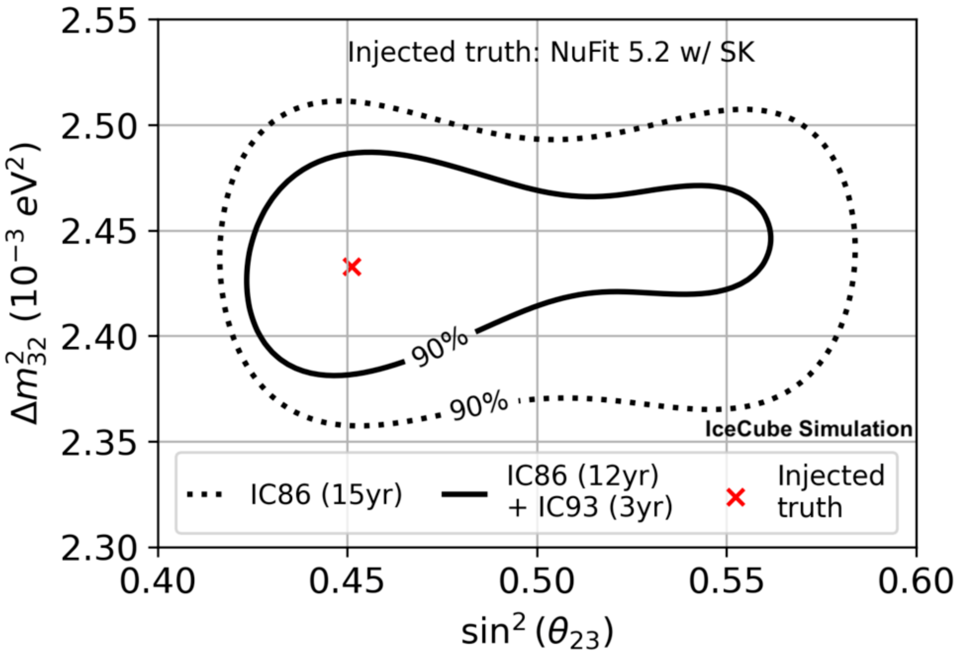
arXiv:2307.15295

ν_μ Disappearance

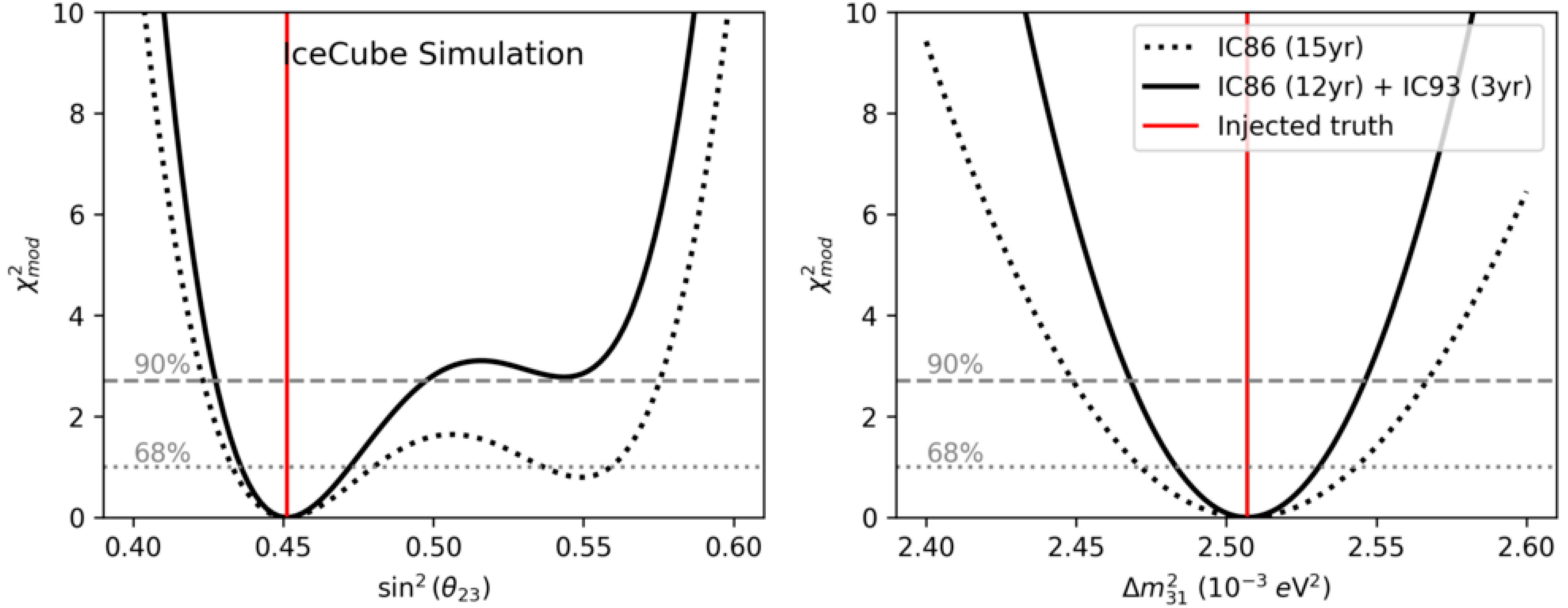
- **Similar levels of improvement are shown for different values of θ_{23} with the IceCube Upgrade**
- **Cannot exclude maximal mixing from 90% contour with NuFit 5.2 w/ SK best fit and the latest IceCube muon neutrino disappearance analysis**







Breaking the Octant Degeneracy

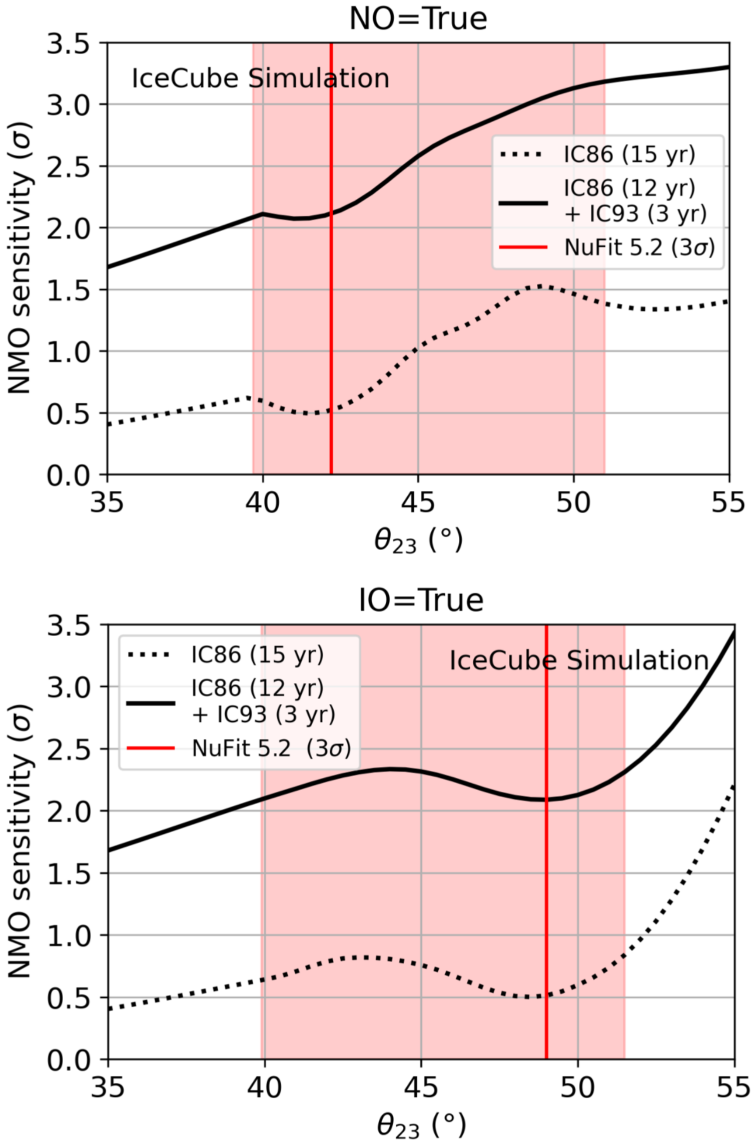


- **We can see from the $\sin^2(\theta_{23})$ sensitivity that one octant is preferred over the other, and that maximal mixing is disfavored**
  - This behavior is likely caused by matter effects, since they proportional to $\sin^2(\theta_{23})$

Upgrade NMO θ_{23} Dependance

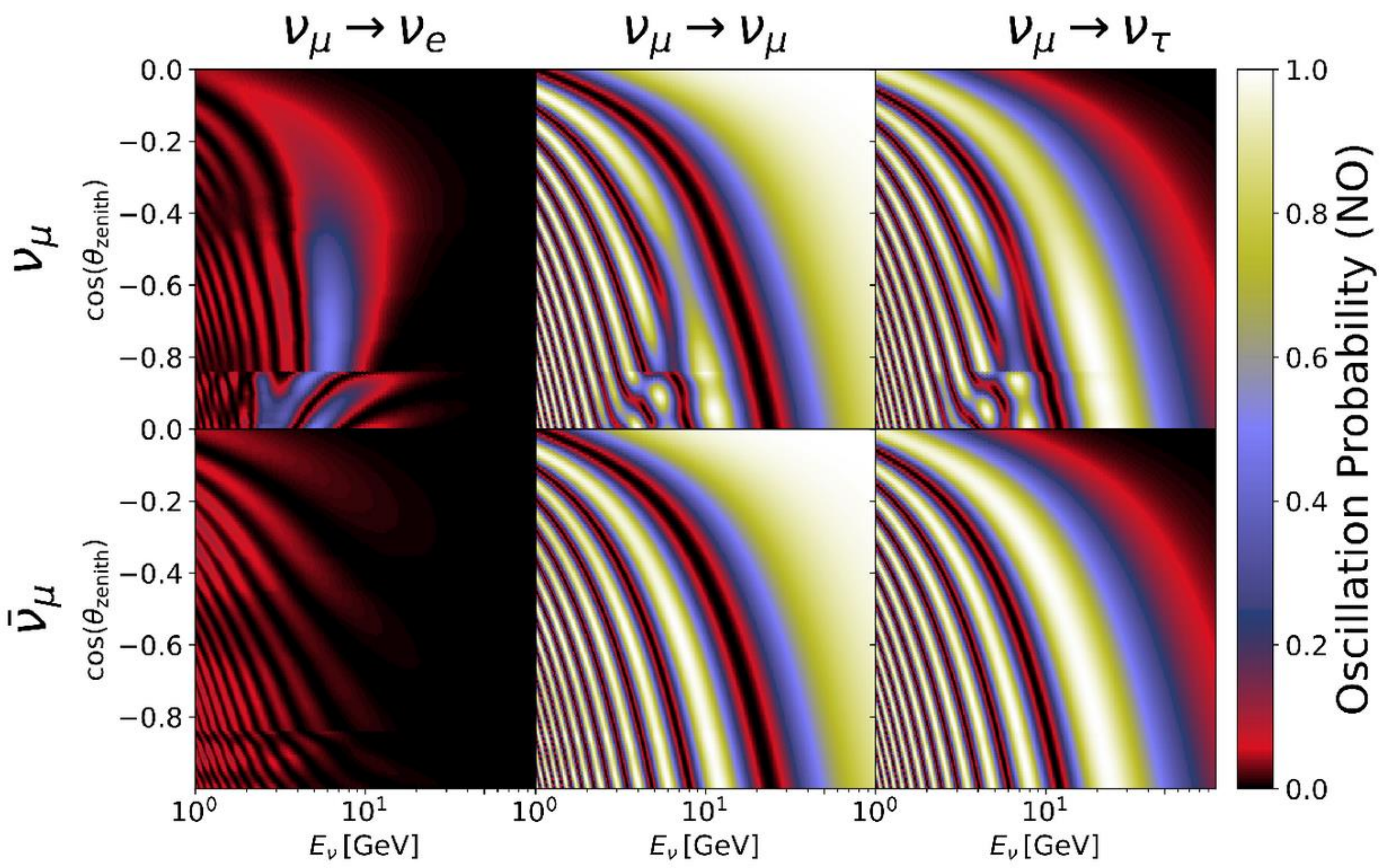
- **The bands shown in slide 14 correspond to the values of θ_{23} in the shaded region of the plots shown here**

- **The true value of θ_{23} has a significant impact on the achievable sensitivity to the NMO**



NMO with IceCube DeepCore

- **Matter effects will only manifest in the neutrino or antineutrino channel depending on which mass hierarchy is true**
- **The atmospheric flux contains more neutrinos than antineutrinos**
    - Important since IceCube cannot distinguish neutrinos from antineutrinos
- **Measure the intensity of the matter effect signal to determine if the matter effects are from the neutrino or antineutrino channel**
- **For latest results see Finn's talk**



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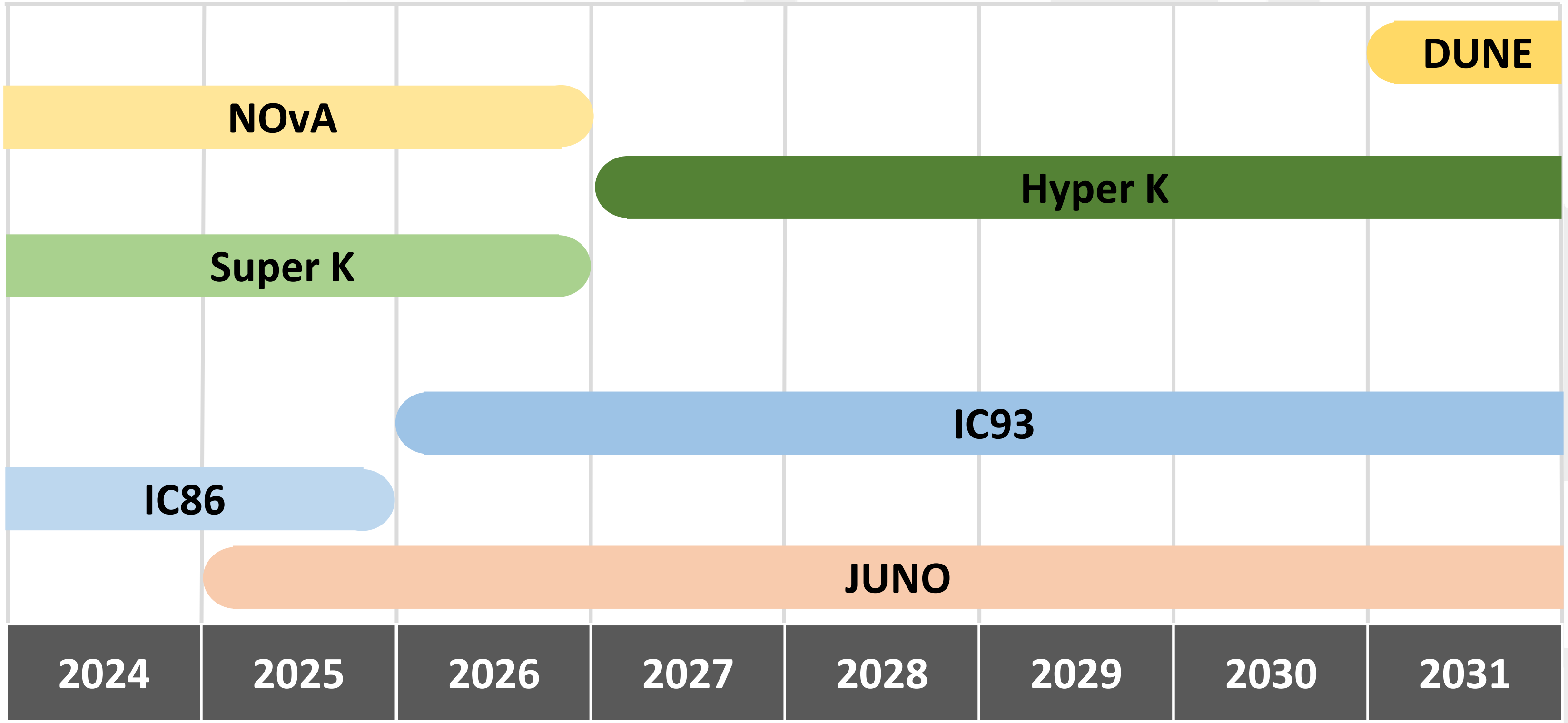
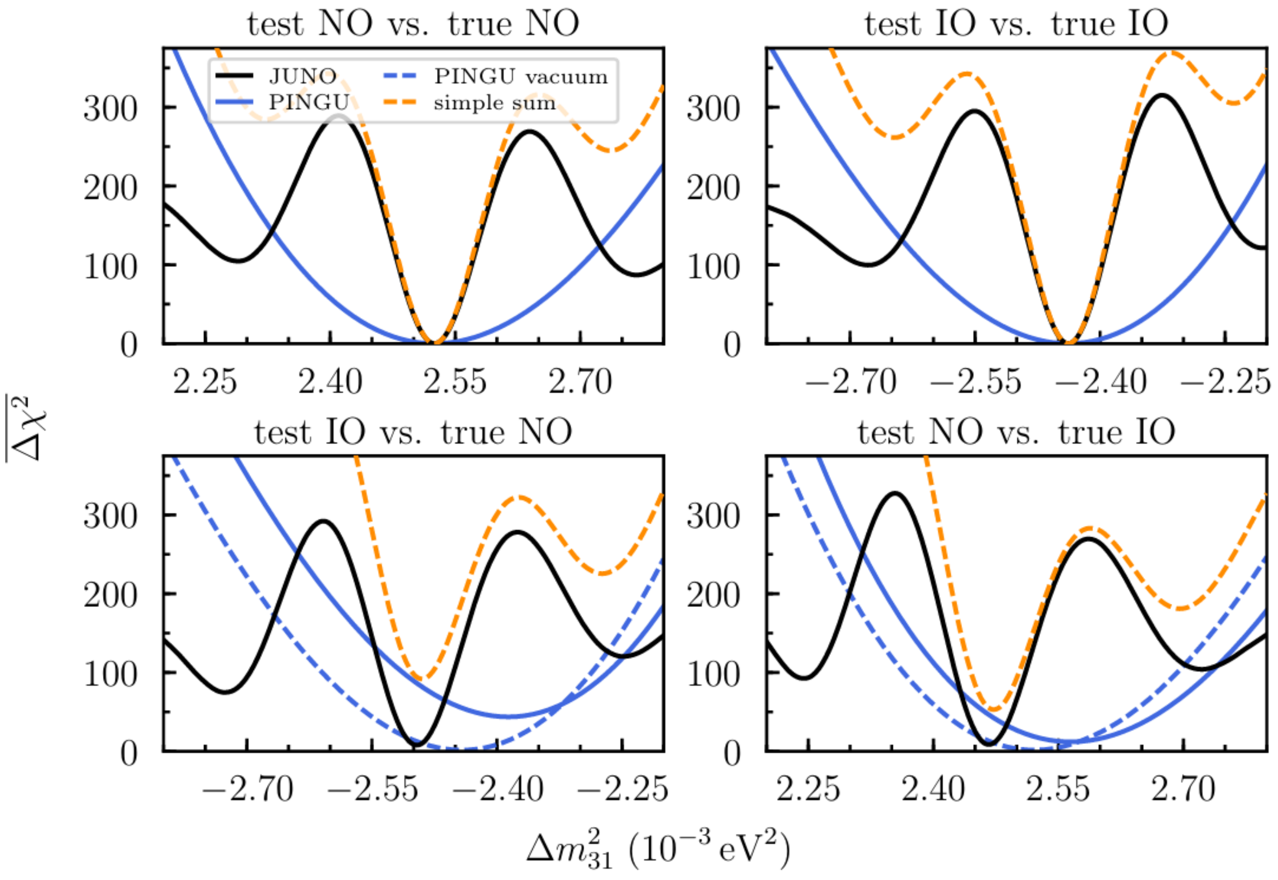
Experiment Timeline

- **The IceCube Upgrade will become operational at a time when other oscillation experiments will not be running**
- **The JUNO experiment will start collecting data shortly before the IceCube Upgrade becomes operational**



NMO with Upgrade and JUNO

- **There is an inherent discrepancy in measurements of $|\Delta m^2_{31}|$ from muon neutrino disappearance and electron neutrino disappearance experiments when assuming the wrong mass ordering**
- **Any pair of experiments with sufficient precision can take advantage of this discrepancy**
  - IceCube Upgrade and JUNO are two such experiments
- **Note: The plots shown here utilize PINGU (a proposed low energy extension to IceCube) but the same physics holds true for the IceCube Upgrade**



arXiv:1911.06745

IC Upgrade and JUNO Simulation

- **The best way to take advantage of the discrepancy in measurements of $|\Delta m^2_{31}|$ is to perform a joint fit with both JUNO and IceCube Upgrade**

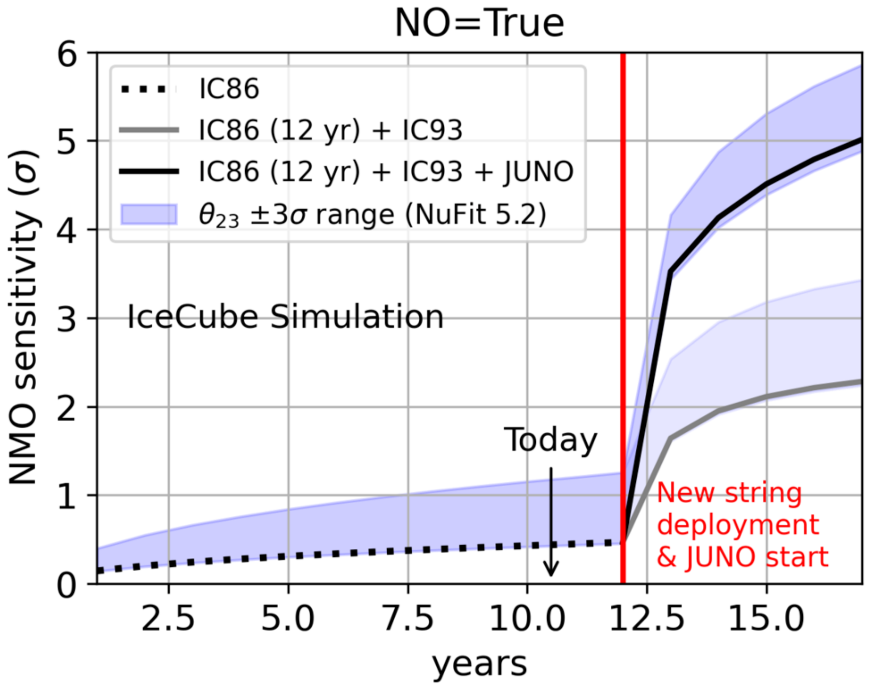
- **The joint fit is done by adding the metric values of the two detectors, similar to what is done in a global fit**

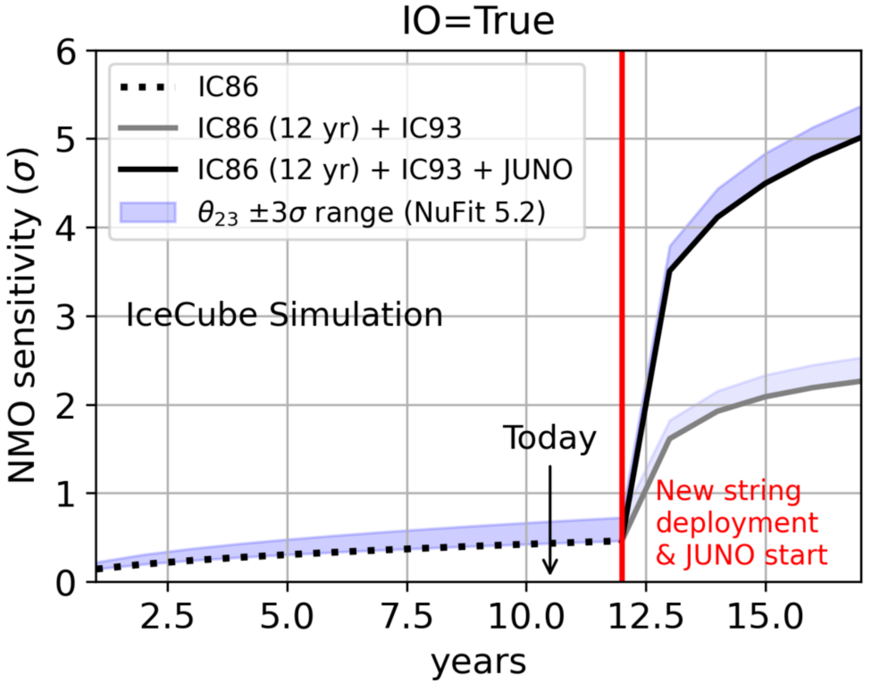
- **Assumptions about JUNO used in simulation from** arXiv:1507.05613

    - Utilizes an 8-core JUNO configuration

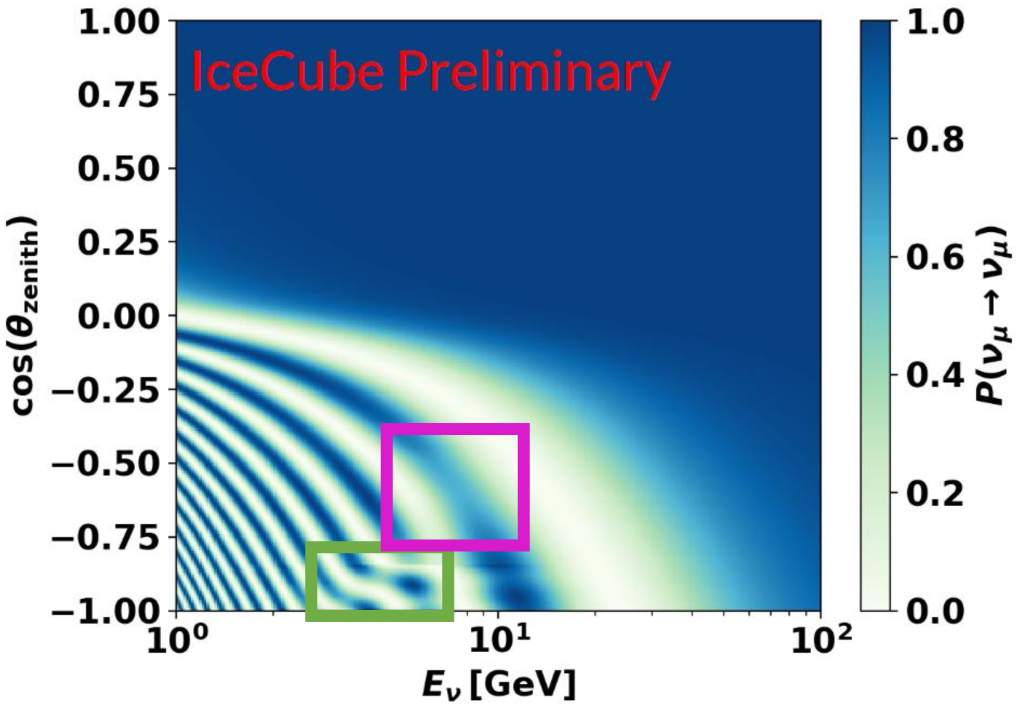
Upgrade and JUNO

- **With just IC93, we can expect to achieve a sensitivity of 2 to 3σ in a few years**
  - Depends on the true mass hierarchy and the true value of θ_{23}
- **With a joint fit a sensitivity of 5σ could be possible with 3 to 7 years of data**
  - For both mass orderings we see a significant improvement when combining the IceCube Upgrade with JUNO





Matter Effects



- **Earth's matter is full of electrons, which introduces the following potential to the Hamiltonian in the flavor basis:**

$$H_m = H_{vac} + V_{CC}\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}$$

$$V_{CC} = \pm\sqrt{2}G_F N_e = \pm 7.6 \times 10^{-14} \times Y_e \left[\frac{\rho}{g/cm^3}\right] eV$$

- **Matter effects are only applied to neutrinos or antineutrinos depending on the mass ordering**
- **MSW resonance: effective mixing angle is maximized**
- **Parametric resonance: for periodic density profiles the oscillation phase is modified, producing large flavor transitions**
- **Can be leveraged for studies on neutrino mass ordering, Earth's interior structure, breaking the octant degeneracy of θ_{23}, and studies of physics beyond the Standard Model**

Matter Induced ν_e Appearance

- **Studies that require matter effects (NMO, probing the structure of the Earth) optimize their analyses for regions affected by matter effects**

- $P_{\mu e} \approx 4 s_{13}^2 s_{23}^2 \frac{\sin^2(A-1)\Delta}{(A-1)^2}$, asymmetric about $\theta_{23} = 45^\circ$
- $A = \pm \frac{2E}{\Delta m_{31}^2} (7.56 \times 10^{-14} eV) \left(\frac{\rho(x)}{g/cm^3}\right) Y_e(x)$

- **Resonant enhancement of electron neutrino appearance occurs at energies such that $A \approx 1$**
  - This matter induced oscillation channel manifests below 20 GeV
  - Note it can only be one if the signs of the potential (neutrinos = +, antineutrinos = -) and Δm_{31}^2 multiply to 1