Atmospheric neutrino oscillation sensitivities with the IceCube Upgrade

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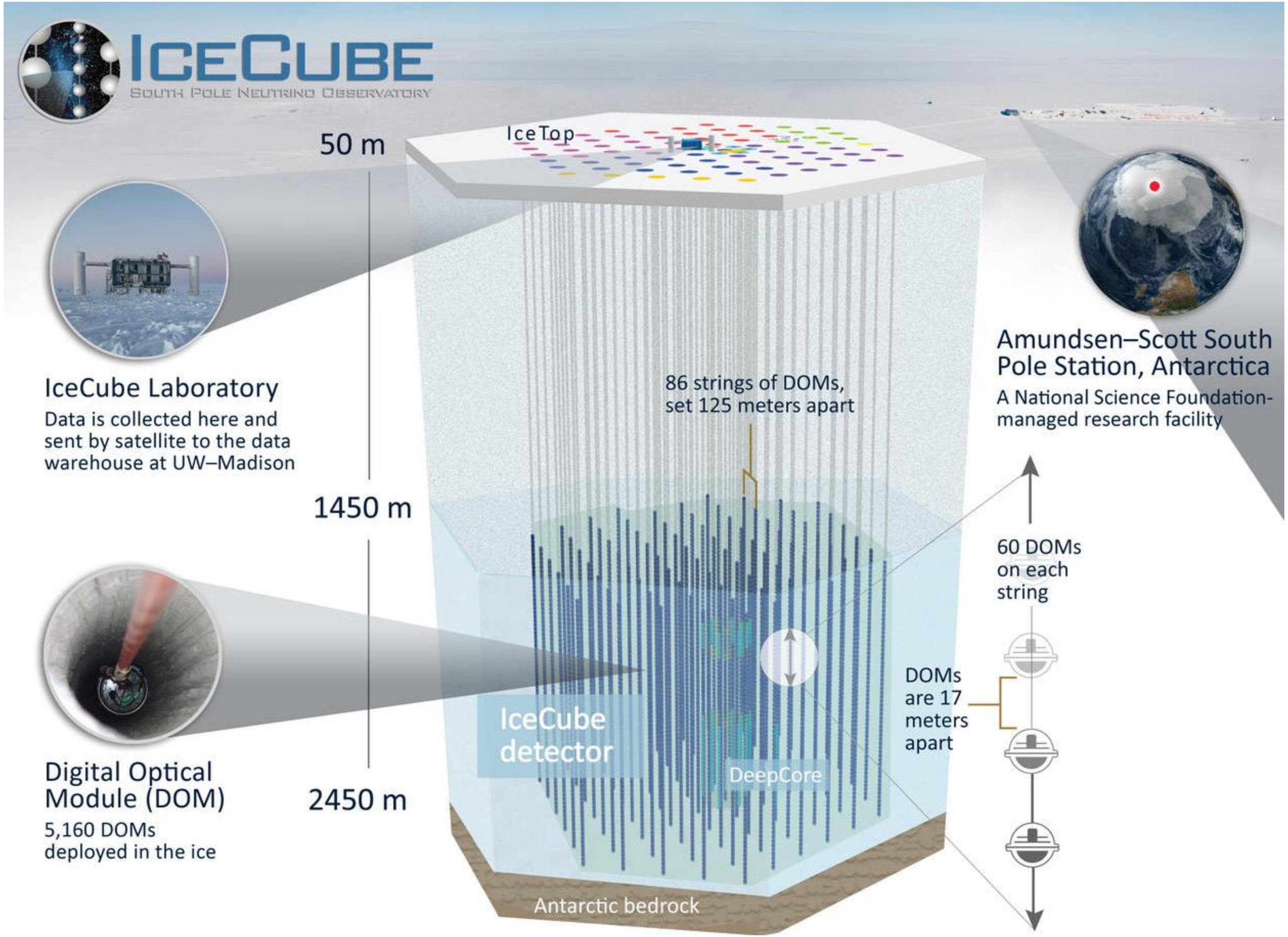
TAUP 2023

ICRC arxiv PoS

PennState


IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

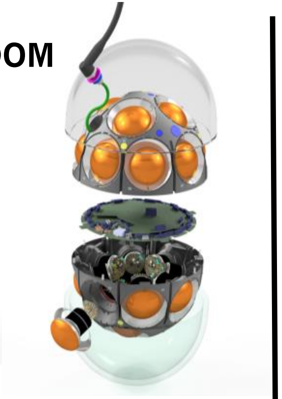
The IceCube Upgrade

The Upgrade

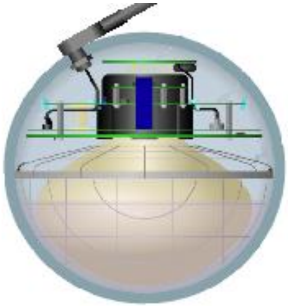
7 new strings hosting new optical sensors

D-Egg

mDOM

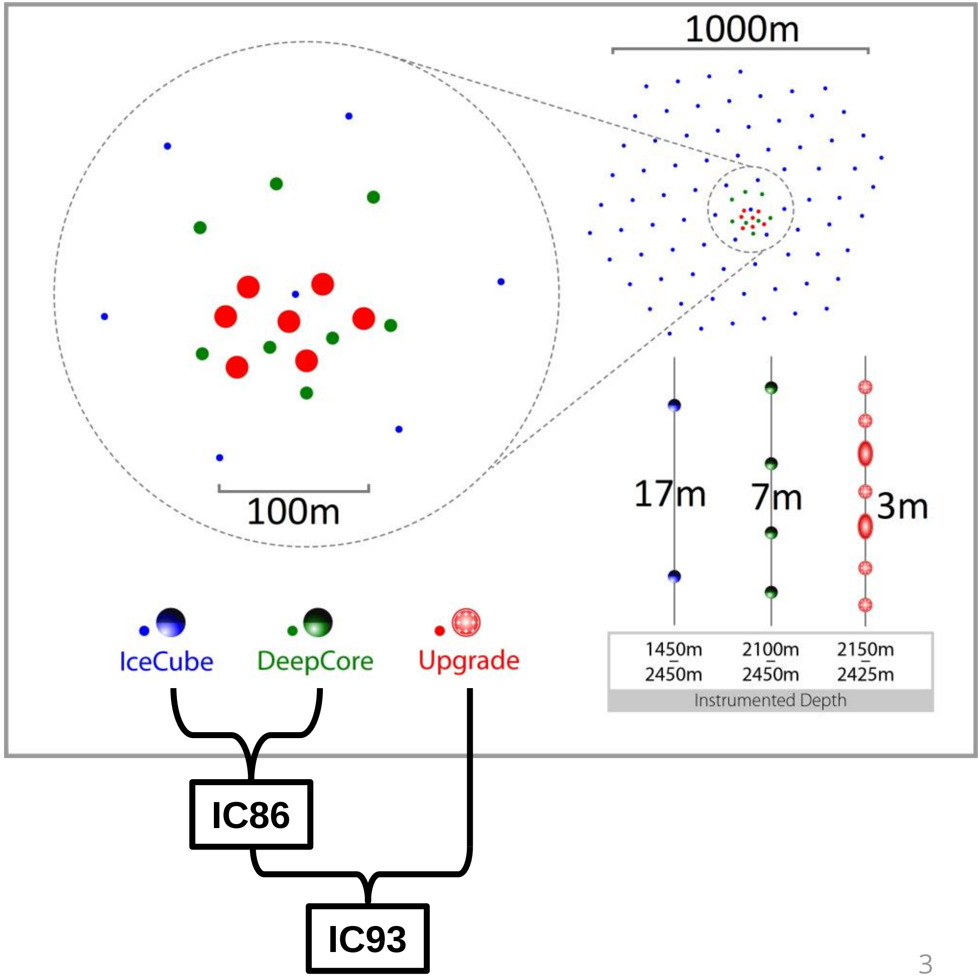


(old) DOM



5-10 times denser spacing

- ➢ detect more light at low energies



Atmospheric neutrinos and oscillations

Atmospheric ν

Cosmic ray interactions in Earth's atmosphere

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

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

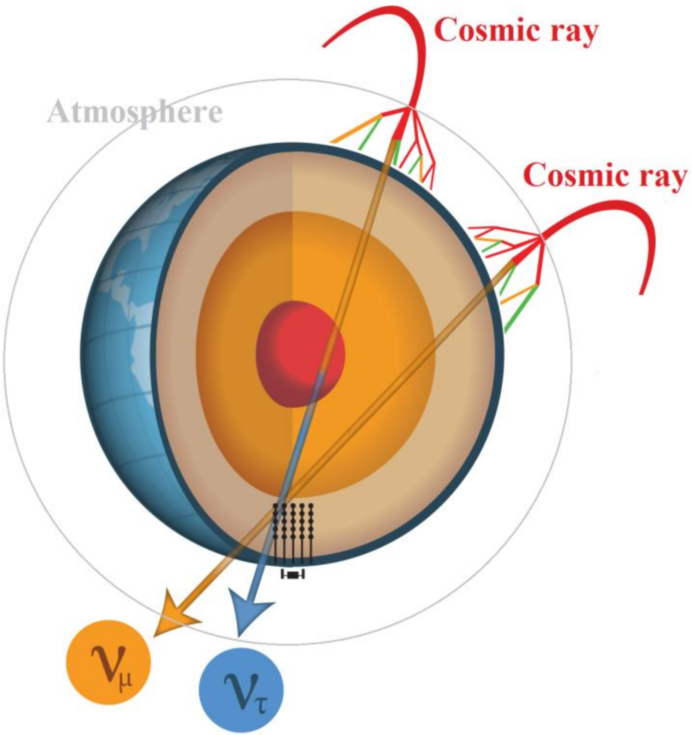
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{\mu} + \overset{(-)}{\nu}_{e}$$

Oscillation probability

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

⇒ Most important neutrino parameters

- $E^{\text{deposited}}$: proxy for neutrino energy E
- cos(zenith): proxy for traveled distance L
- PID: what neutrino flavor did we measure?



Oscillograms

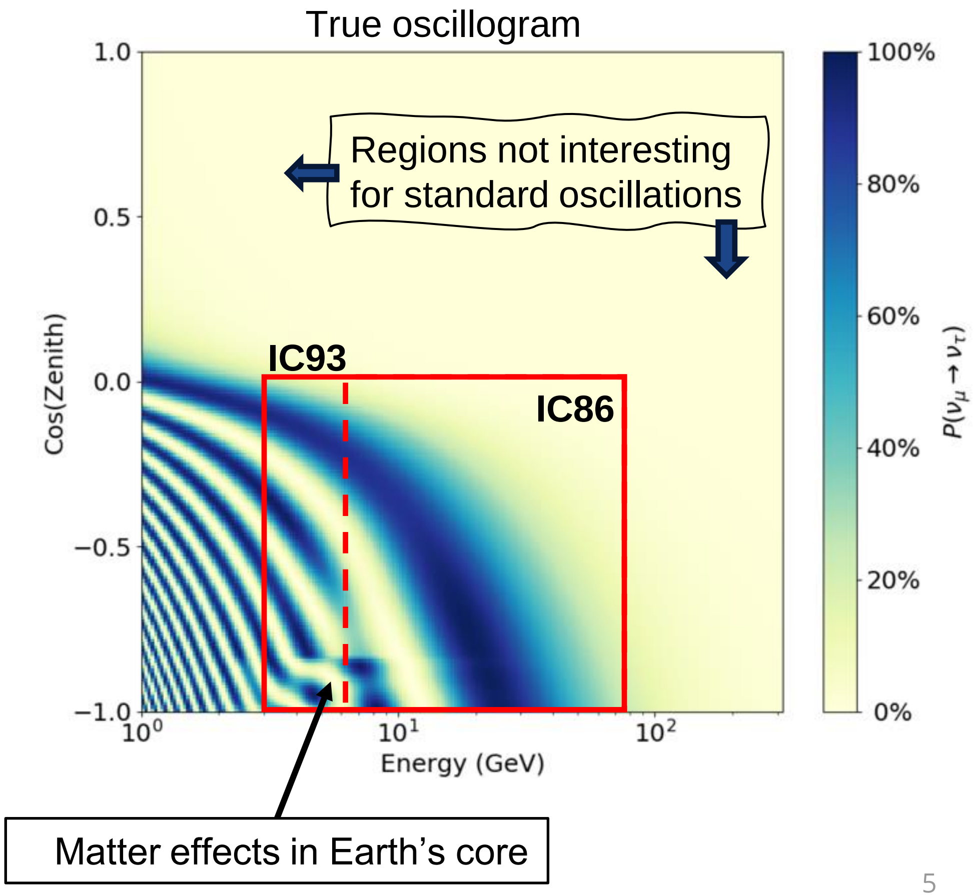
Oscillation probability based on true neutrino parameter values

(will be smeared by reconstruction)

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)



Event selection

Background sources

- Atmospheric μ
- PMT noise

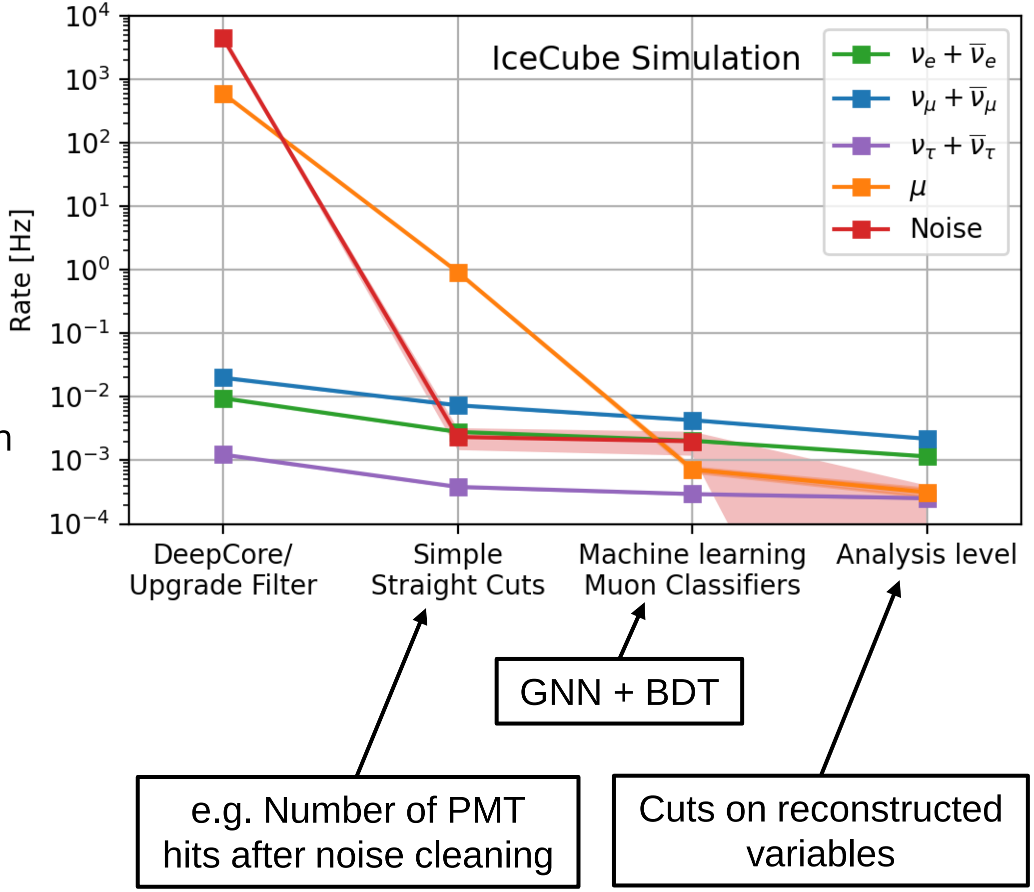
Dominate in our detector

⇒ Need event selection to suppress them

(PMT) noise cleaning by neural network (GNN)

- Removes ~95% of noise hits while keeping ~90% of signal hits

After event selection sample is neutrino dominated



Reconstruction & Classification

Neural network (GNN) based

We use a separate GNN for each variable

PID

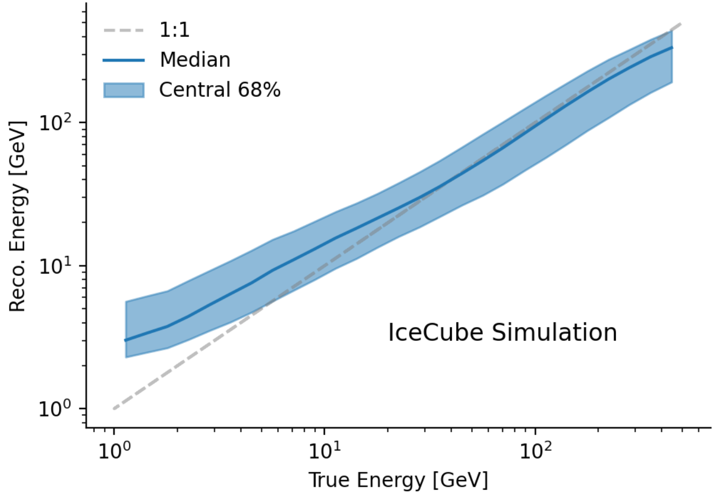
Classifier achieves 0.82 area under the ROC curve giving significant improvement over IC86

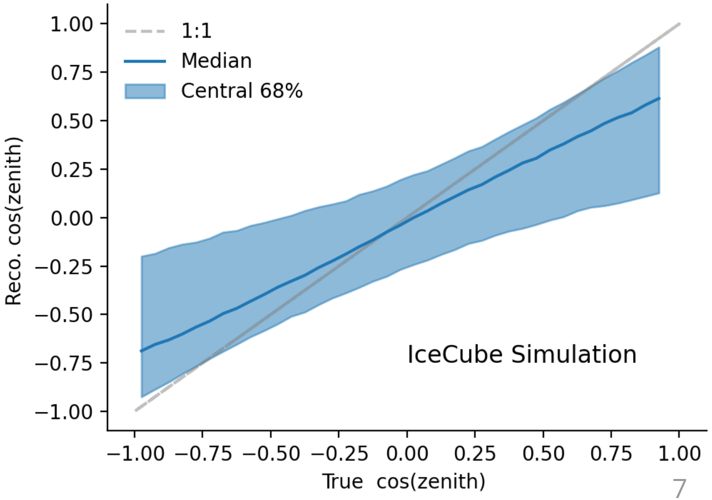
Energy

Similar performance through entire range, bias at lower energies from event selection (and triggering)

Zenith angle

Similar performance through entire range, bias from limited range of possible values [-1,1]





Analysis details

Sensitivities are **Asimov** using a χ^2 metric

Binning

	IC86	IC93
Energy	Log(5,300,12) GeV	Log(3,300,12) GeV
Cos(zen)	Lin(-1,0,10)	Lin(-1,0,10)

On the following slides we compare two scenarios

1. no new strings → 15 yr of IC86
2. new strings → 12 yr of IC86 + 3 yr of IC93

Systematic parameters

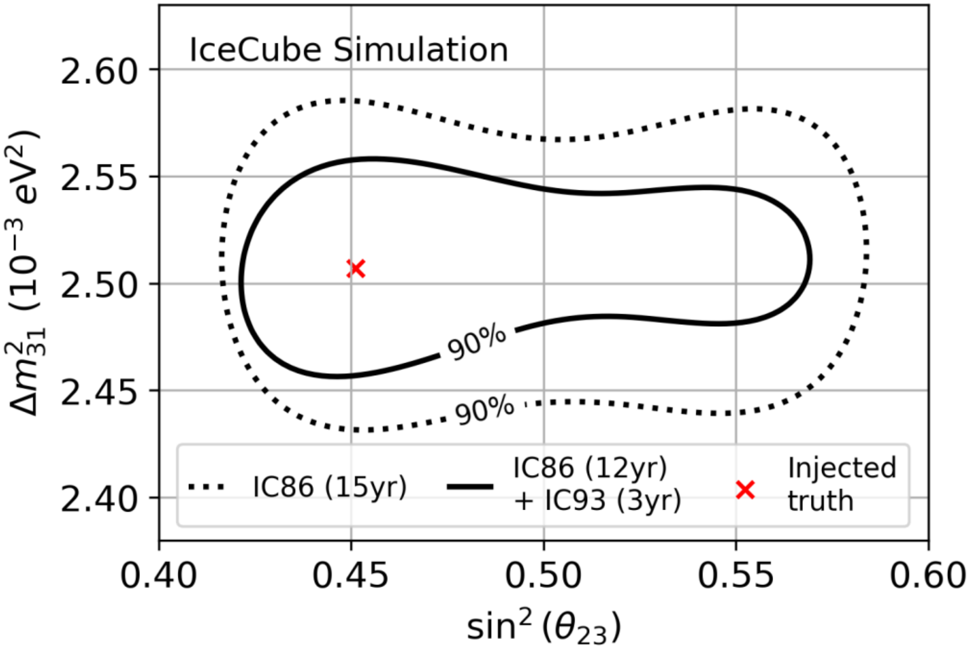
Flux
Spectral index
Uncertainty on Pion and Kaon production
Neutrino and Muon Normalizations
Cross sections
Deep inelastic scattering uncertainty
Axial masses for Resonant CC and Quasi-elastic scattering
Axial masses for Resonant NC and Coherent π scattering
Model uncertainty on tau neutrino cross section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

Atmospheric oscillation parameters

How well can we constrain the atmospheric oscillation parameters Δm^2_{31} and θ_{23}?

90% confidence level after 3 years with the new strings assuming NuFit 5.2

With the new strings IceCube's sensitivity to Δm^2_{31} and θ_{23} increases by about 20-30%



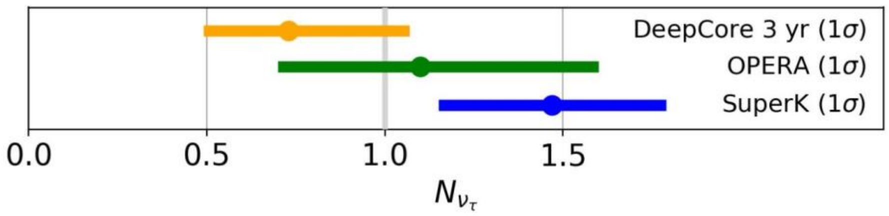
ν_τ normalization

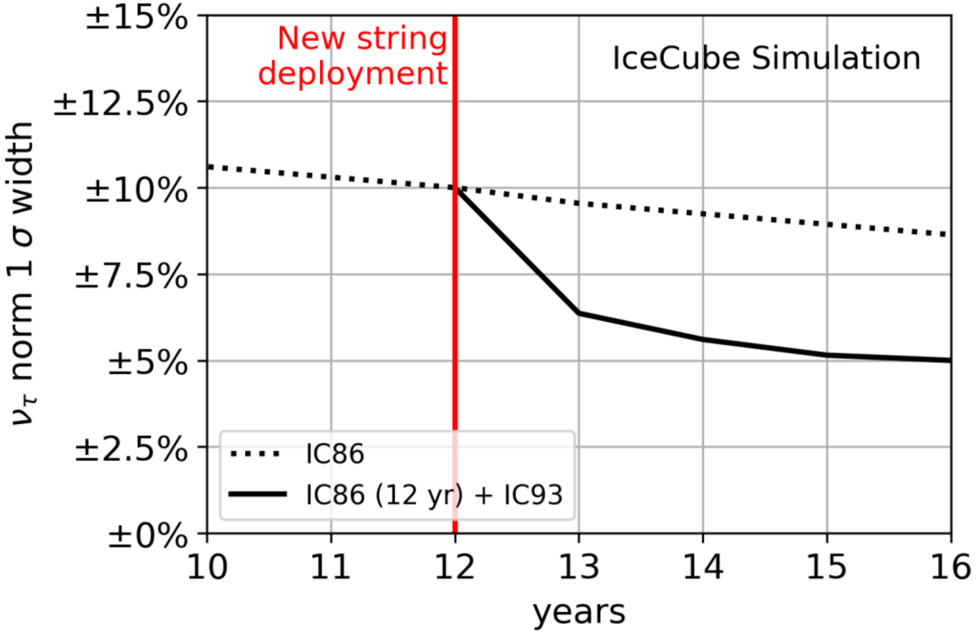
How well can we constrain the number (scale) of detected ν_τ?

Can be a unitarity test of the PMNS matrix or a test of the ν_τ cross-section

With new strings 1σ uncertainty can be almost reduced by a factor of two

Current results





Neutrino mass ordering

Ordering of the three mass eigenstates

θ_{23} dependence

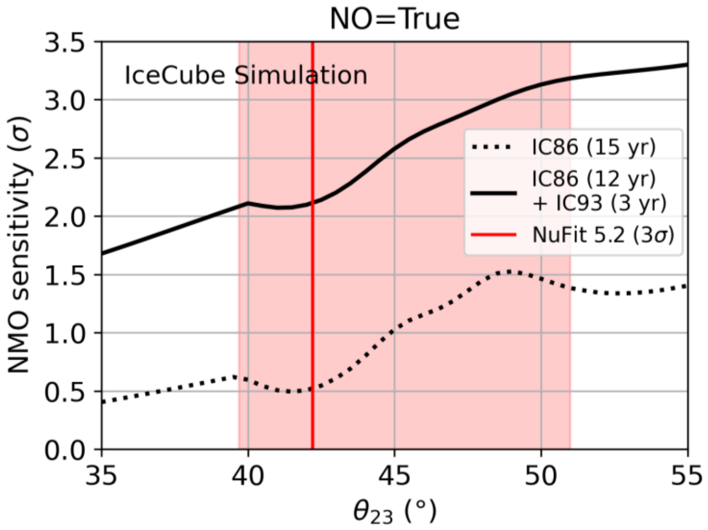
NMO sensitivity strongly depends on true value of θ_{23}

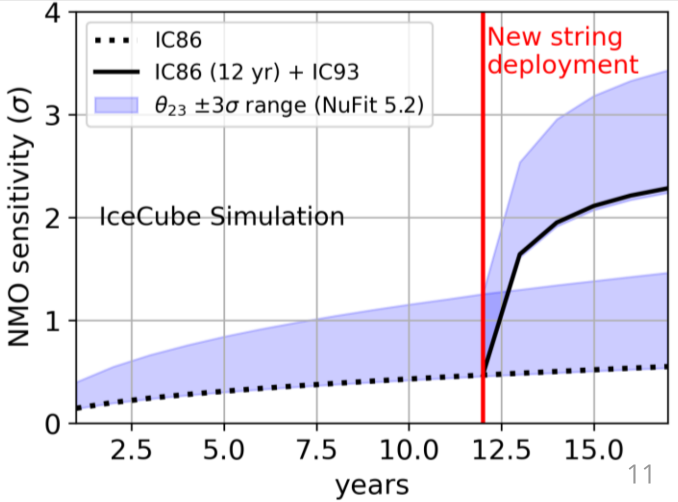
The current NuFit (5.2) value is not very favorable for us

Livetime evolution

New strings significantly enhance NMO sensitivity

- Will reach more than 2σ within a few years
- More than 3σ possible





Summary

The IceCube Upgrade

7 additional strings (IC86 → IC93) improving the performance at GeV energies

First end to end, full Monte Carlo based projected sensitivities presented

The Upgrade will improve the sensitivity to all tested atmospheric neutrino oscillation analyses

- Oscillation parameters: 20-30% improvement
- ν_τ normalization: around 40% improvement
- Neutrino mass ordering: almost 4× boost in sensitivity

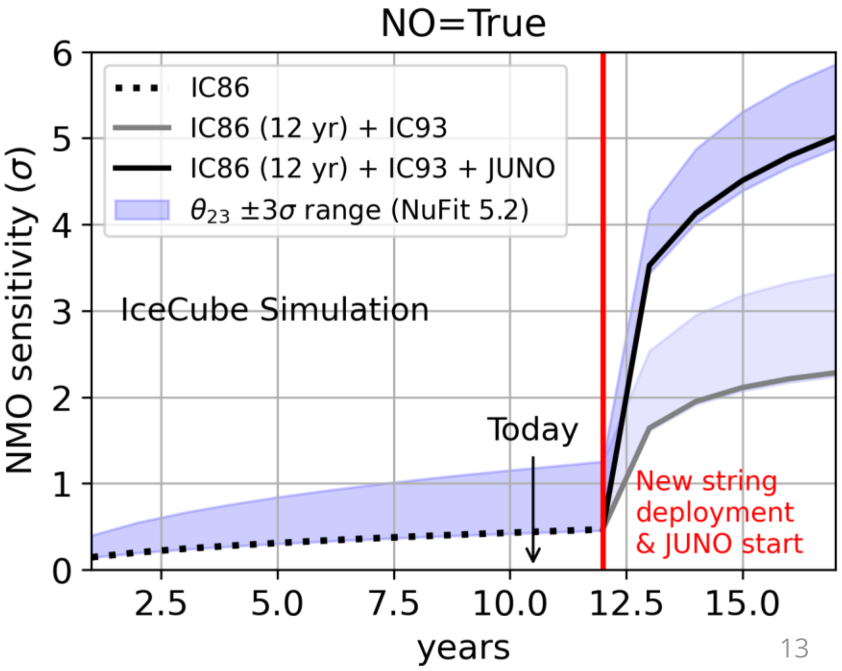
Outlook

These are preliminary sensitivities, improvements are expected due to

- additional deployed calibration devices
- further optimizing triggers and event selection
- optimized analysis choices

For the NMO a huge boost in sensitivity can be achieved by combining IC93 with the medium baseline experiment JUNO

➢ 5σ within a few years of joint operation realistic



Thank you for your attention

Neutrino detection

Photon generation

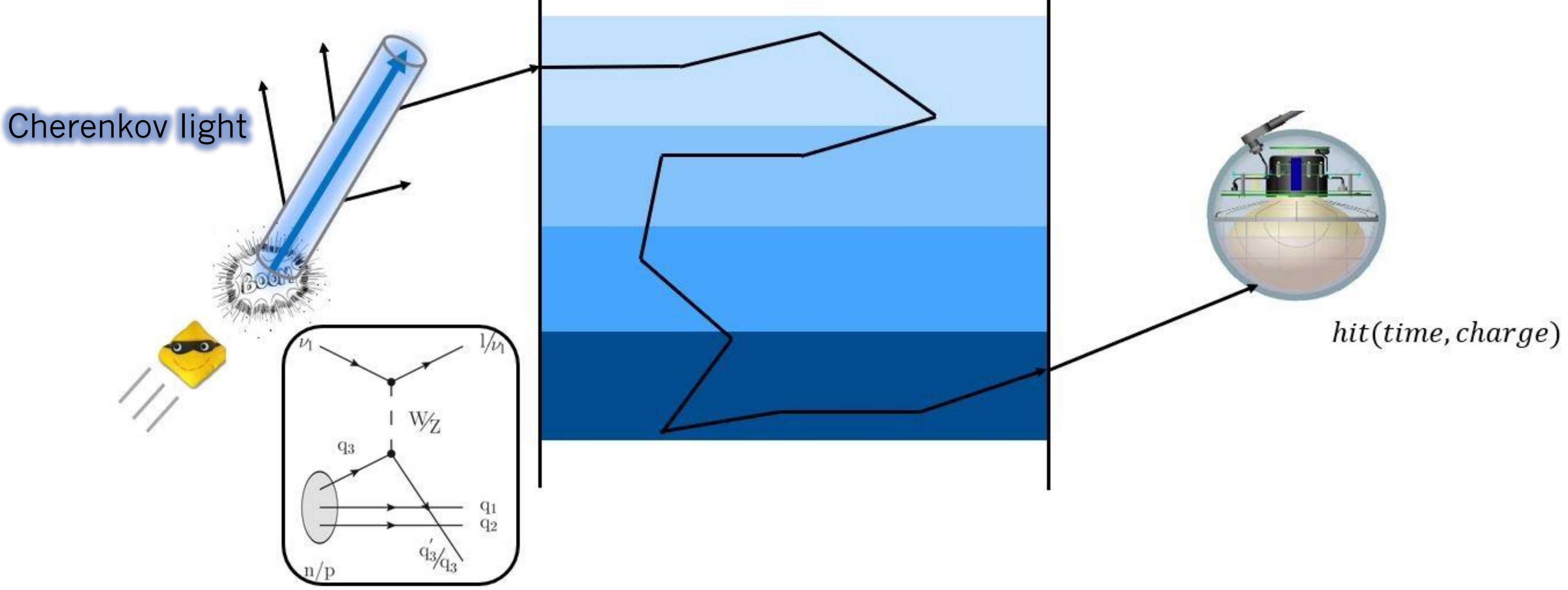
Incomming Neutrino interacts

Photon propagation

Photon scatters through ice

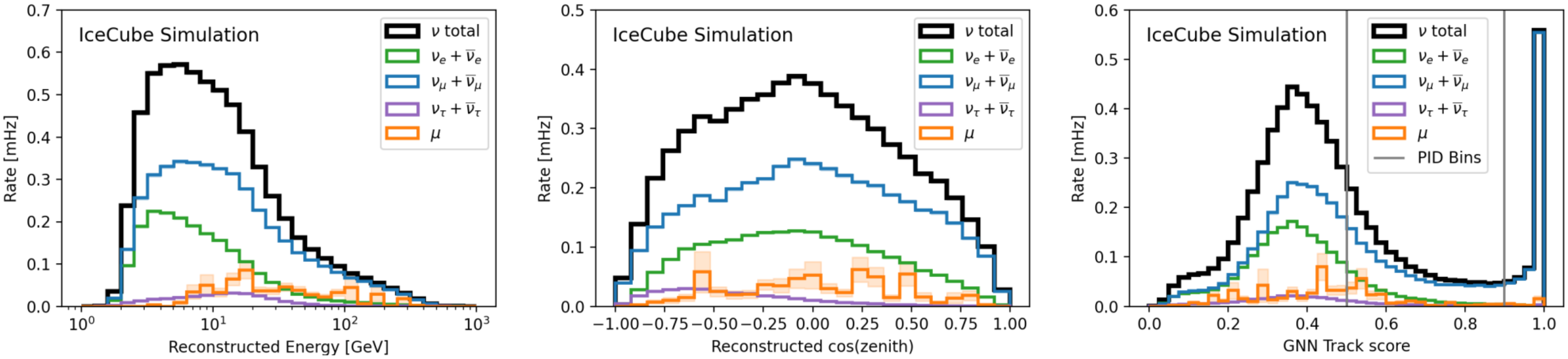
Photon detection

Photon gets detected by PMT



Event sample – analysis level

Final level parameter distribution for the most important analysis variables

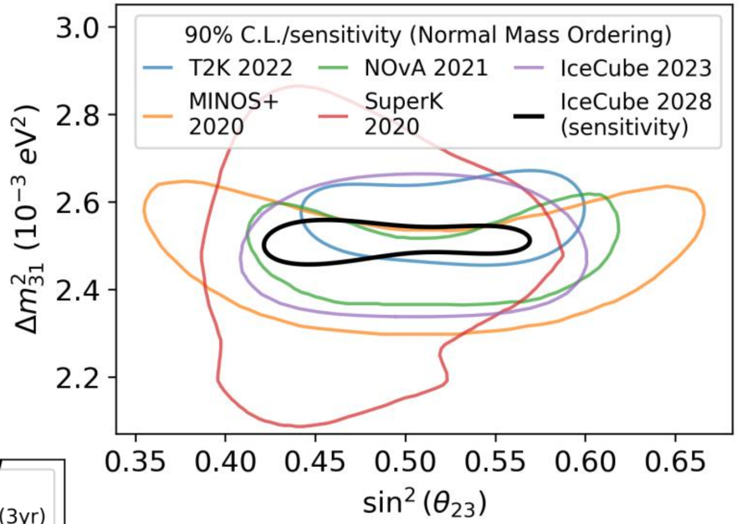


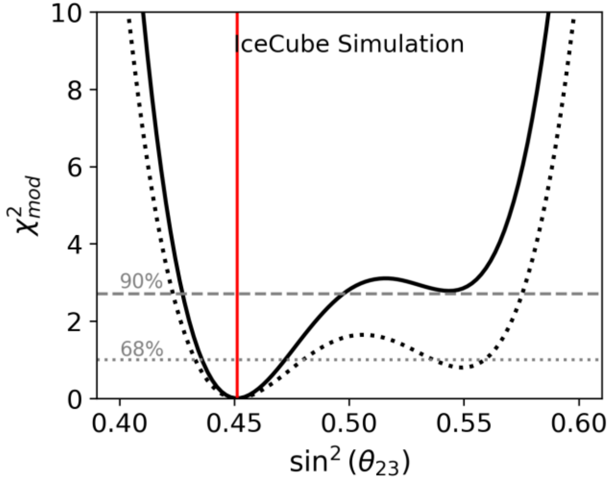
Free parameters

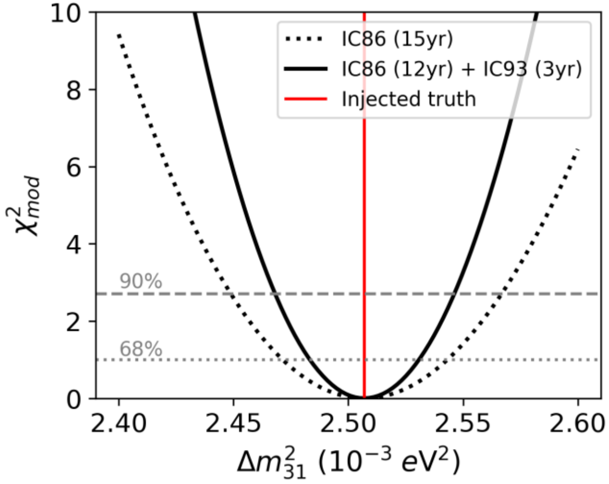
Description	Parameter(s)	Atm. osc.	ν_τ	NMO
Flux				
Spectral index	γ	x	x	x
	d_π	-	-	x
Uncertainty on Pion and Kaon production (Barr et al. [16])	$g_\pi, h_\pi, i_\pi, w_K, z_K$	x	x	x
	y_K	x	x	-
Neutrino and Muon Normalizations	A_{eff}, μ_{atm}	x	x	x
Cross sections				
Deep inelastic scattering uncertainty [17]	DIS_{CSMS}	x	x	-
Axial masses for Resonant CC and Quasi-elastic scattering	$M^{CC}_{A,res}, M_{A,QE}$	x	x	x
Axial masses for Resonant NC and Coherent π scattering	$M^{NC}_{A,res}, M_{A,coh}$	-	-	x
Model uncertainty on tau neutrino cross section [18]	ν_τ xsec	-	-	x
Detector				
Bulk ice properties scattering and absorption	scat., abs.	x	x	x
Optical module efficiencies (IceCube and Upgrade modules)	$\text{OM}_{\text{eff,ICDC}}, \text{OM}_{\text{eff,ICU}}$	x	x	x
Angular acceptance (IC86 configuration only)	p_0, p_1	x	x	x
Oscillations				
Mixing Angles	θ_{13}	-	-	x
	θ_{23}	M	x	x
Mass splitting	Δm^2_{31}	M	x	x
Unitarity breaking parameter	ν_τ norm	-	M	-
Neutrino Mass Ordering	NMO	NO	NO	M

Atmospheric oscillation parameters

Comparison to current sensitivities

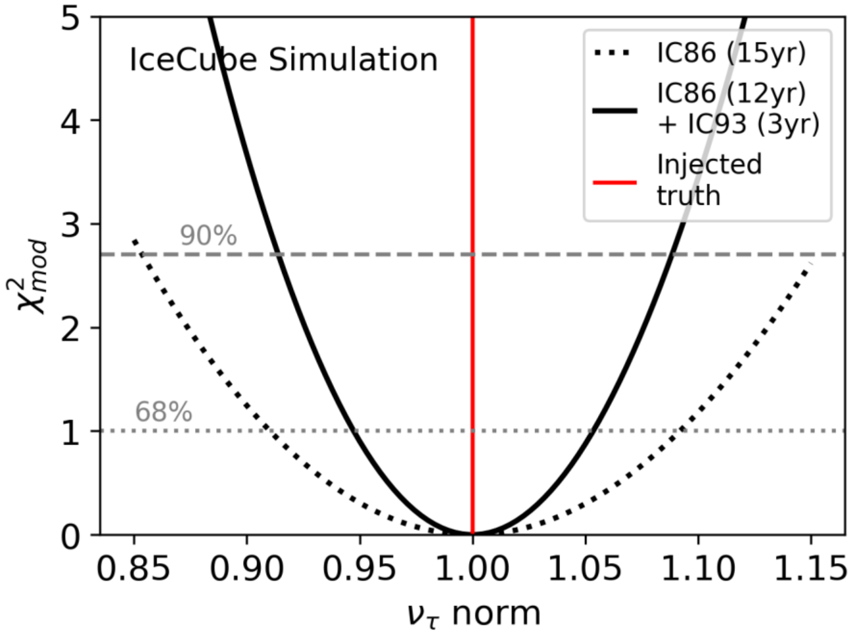






1D projections

ν_τ normalization



Sensitivity 3 years after planned deployment

Neutrino mass ordering (NMO)

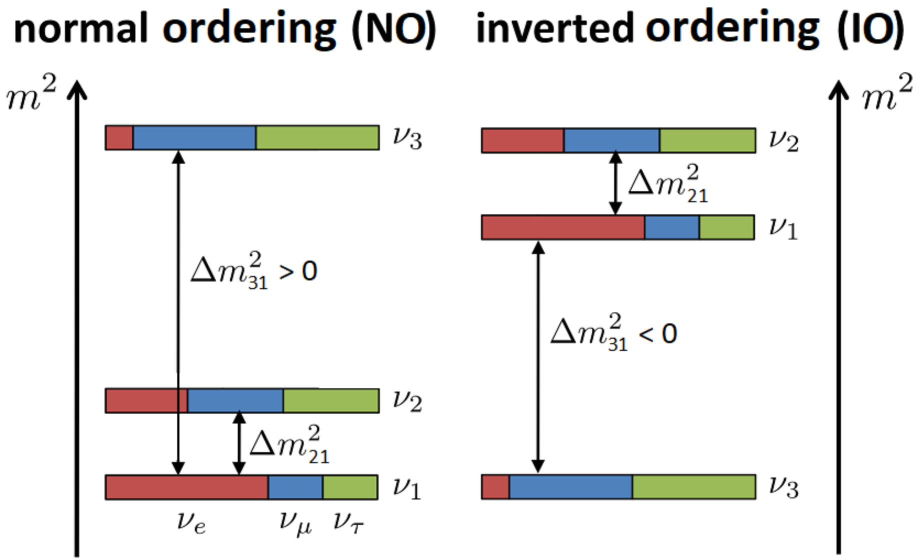
Ordering of the neutrino mass eigenstates

ν-oscillation (vacuum, leading-term)

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2(2\theta)\sin^2\left(\Delta m^2 \frac{L}{E}\right)$$

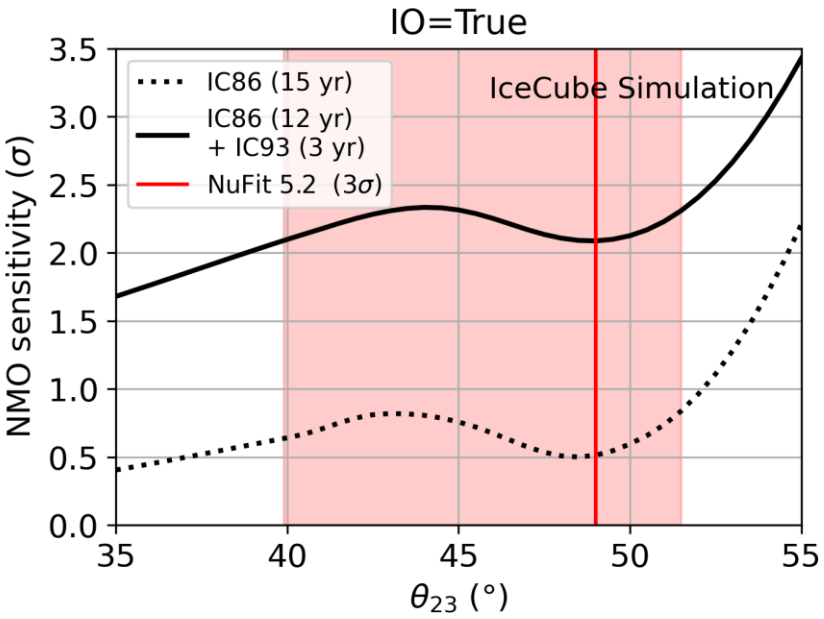
$$\Rightarrow P \propto \sin^2(x) = \sin^2(|x|)$$

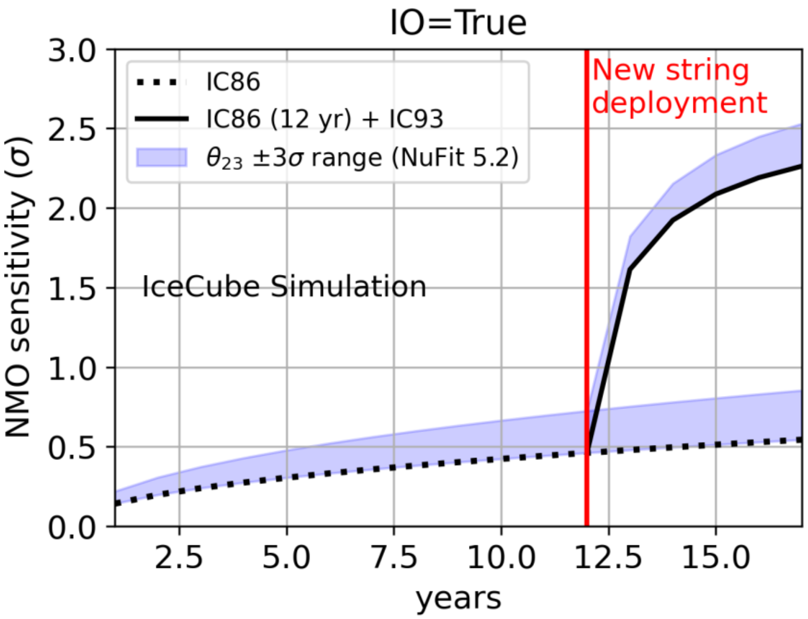
(vacuum) oscillations not sensitive to sign of Δm^2



- Use matter effects (seen on slide 5) to distinguish orderings

NMO sensitivities for true inverted ordering





NMO sensitivities with JUNO for true inverted ordering