Atmospheric neutrino oscillations with the IceCube Upgrade

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WIN 25 | June 10th 2025

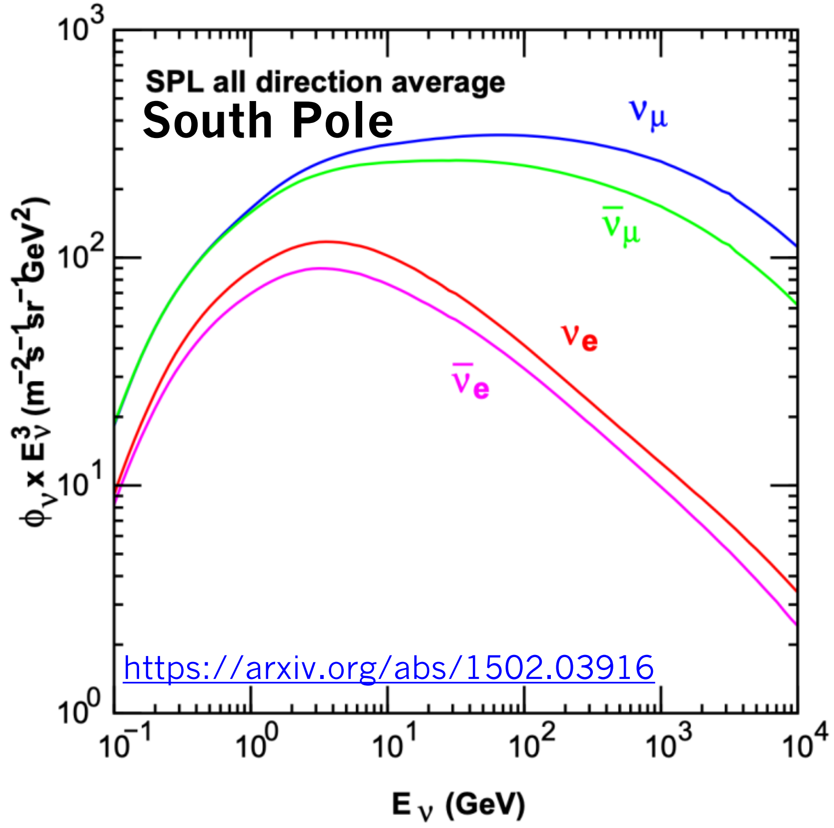
Atmospheric neutrinos

Cosmic rays interact with nucleons in Earth’s atmosphere

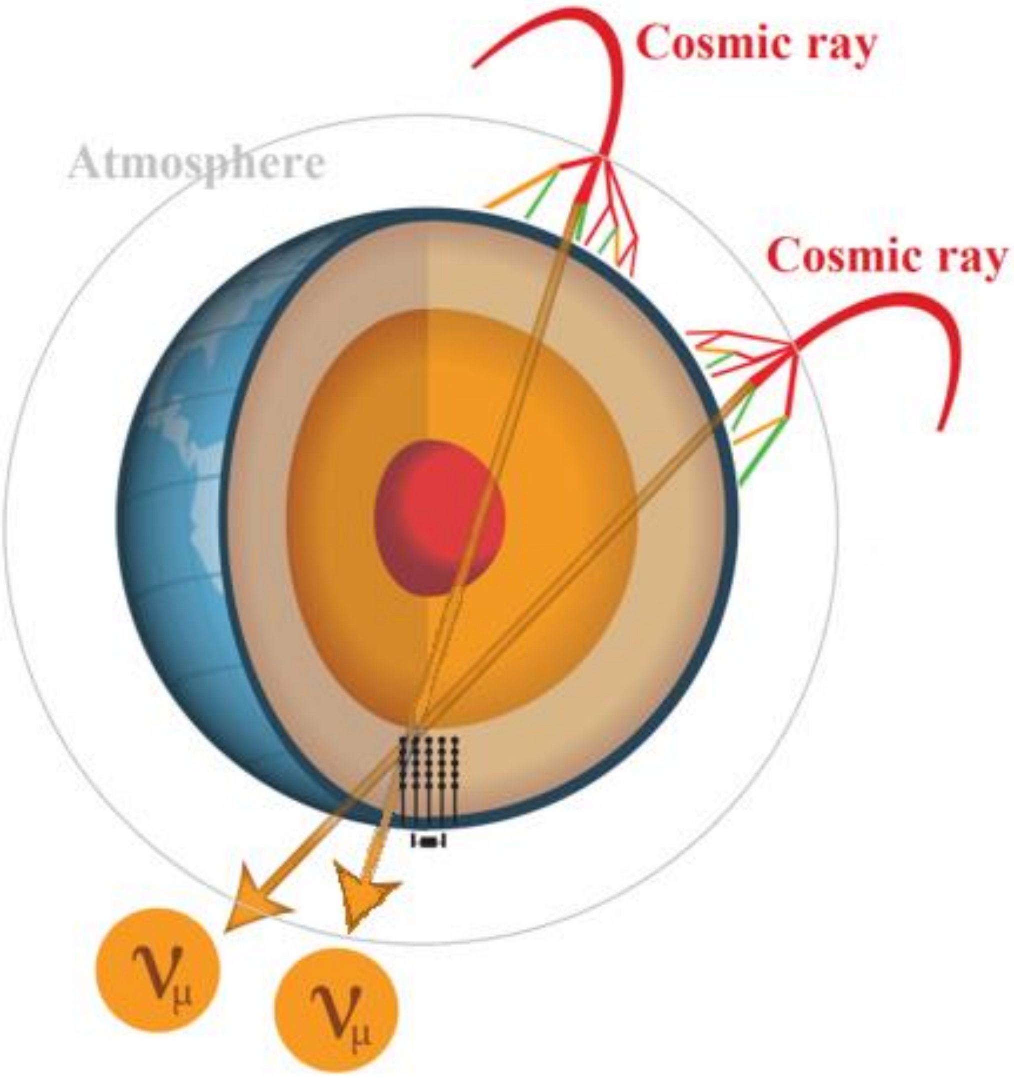
$$p + N \rightarrow \pi^{\pm}/K^{\pm} + X$$

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

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



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

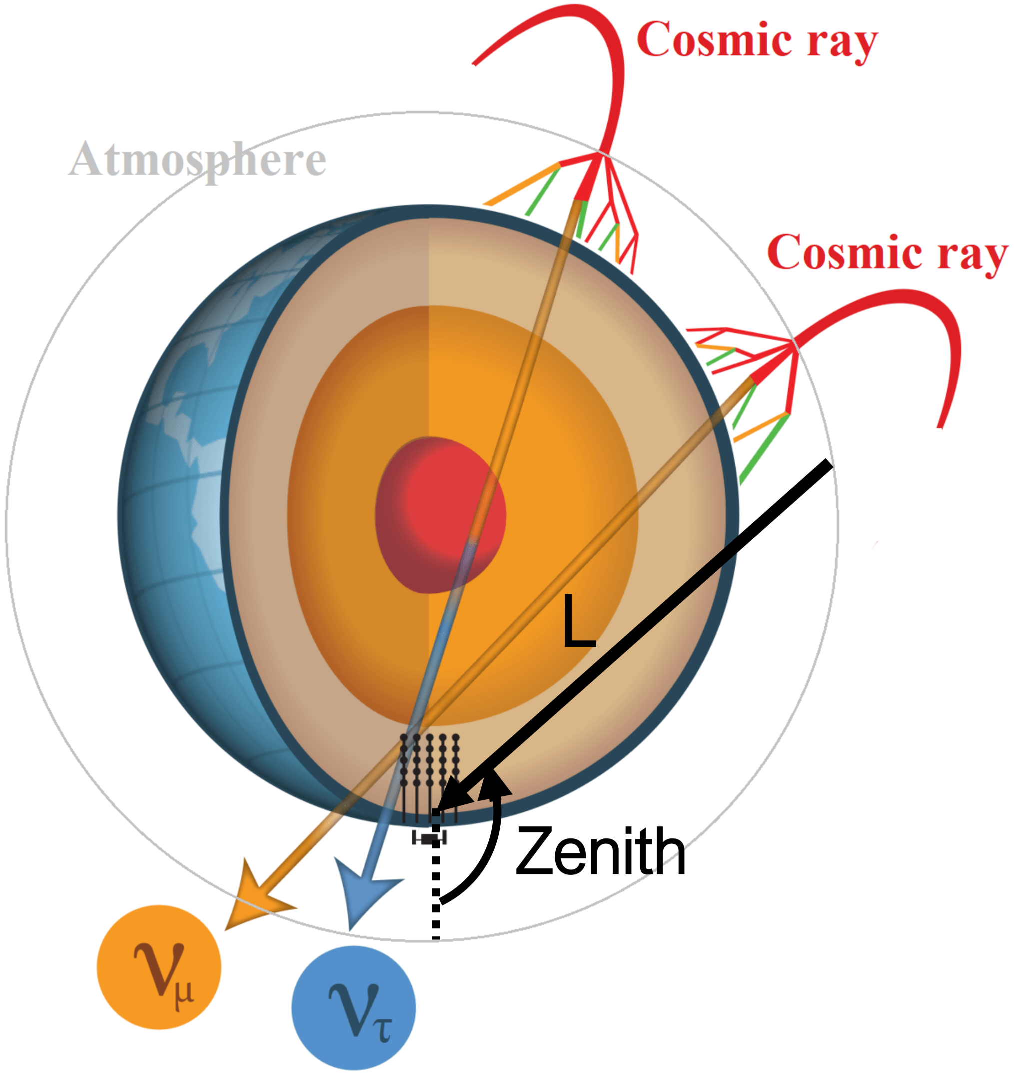
Oscillation probability (simplified)

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

variable

Detector observables

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



Oscillogram

Oscillation probability (simplified)

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

Physics parameters

Mixing angle θ_{mix} (here θ_{23})

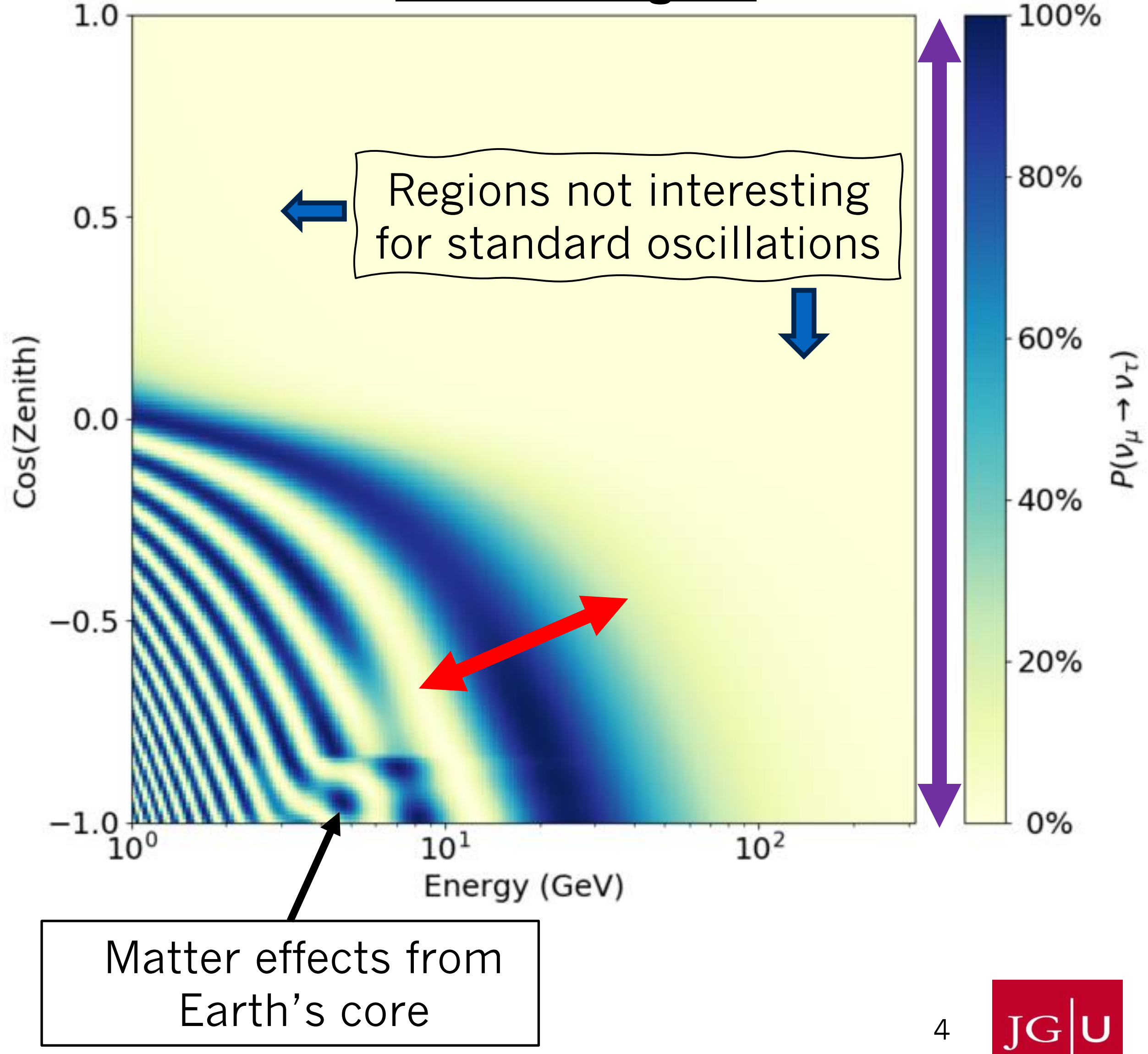
→ amplitude of oscillation

Mass difference Δm^2 (here Δm^2_{32})

→ frequency of oscillation

Matter disturbs oscillation

True oscillogram



Regions not interesting for standard oscillations

Matter effects from Earth's core

IceCube and DeepCore

Located at the Geographic South Pole

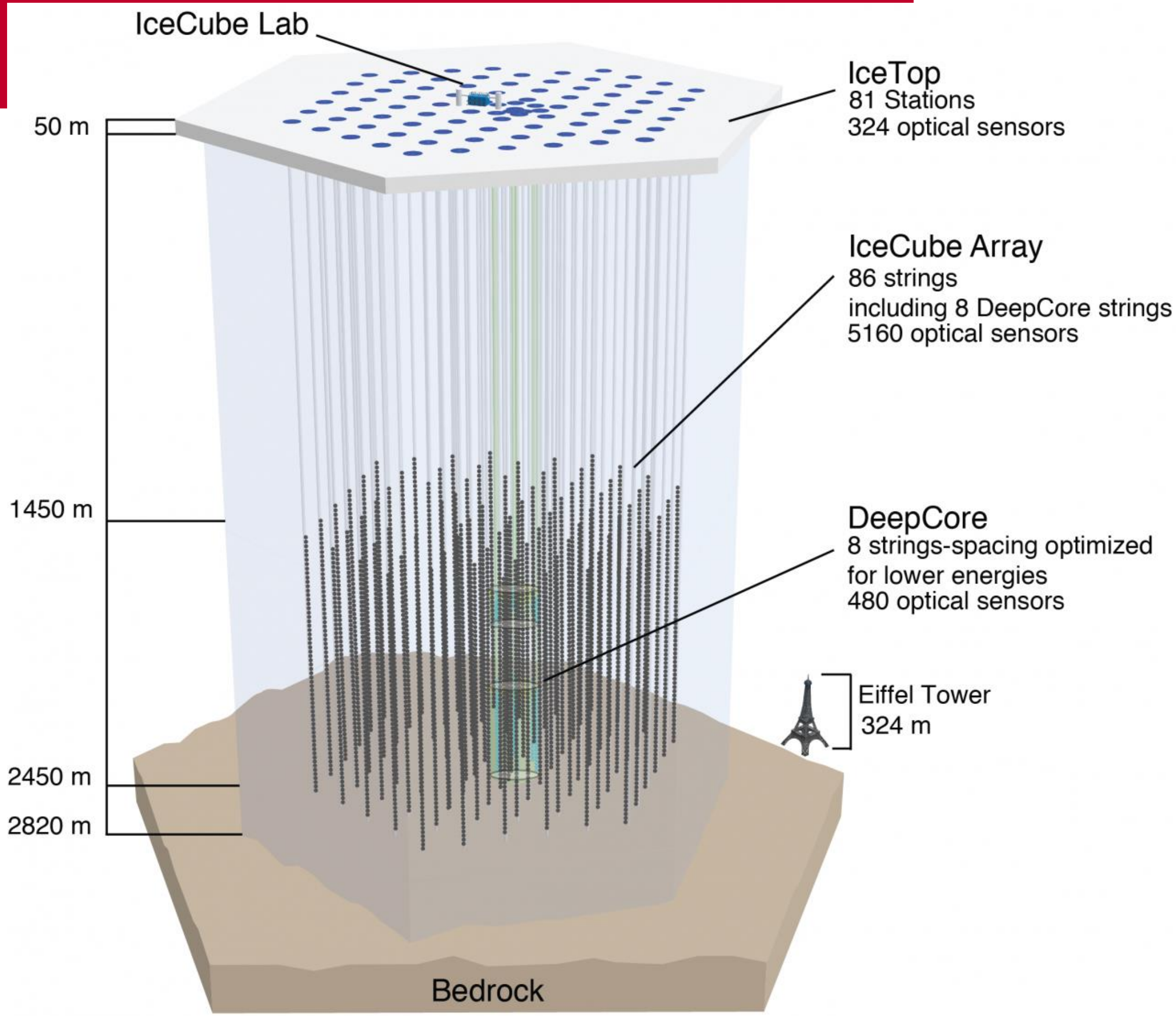
Large arrays of optical sensors (PMTs)

IceCube

- Neutrino telescope
- TeV-PeV neutrinos

DeepCore

- IceCube‘s low-energy extension
- GeV neutrinos



Neutrino detection with IceCube

Photon generation

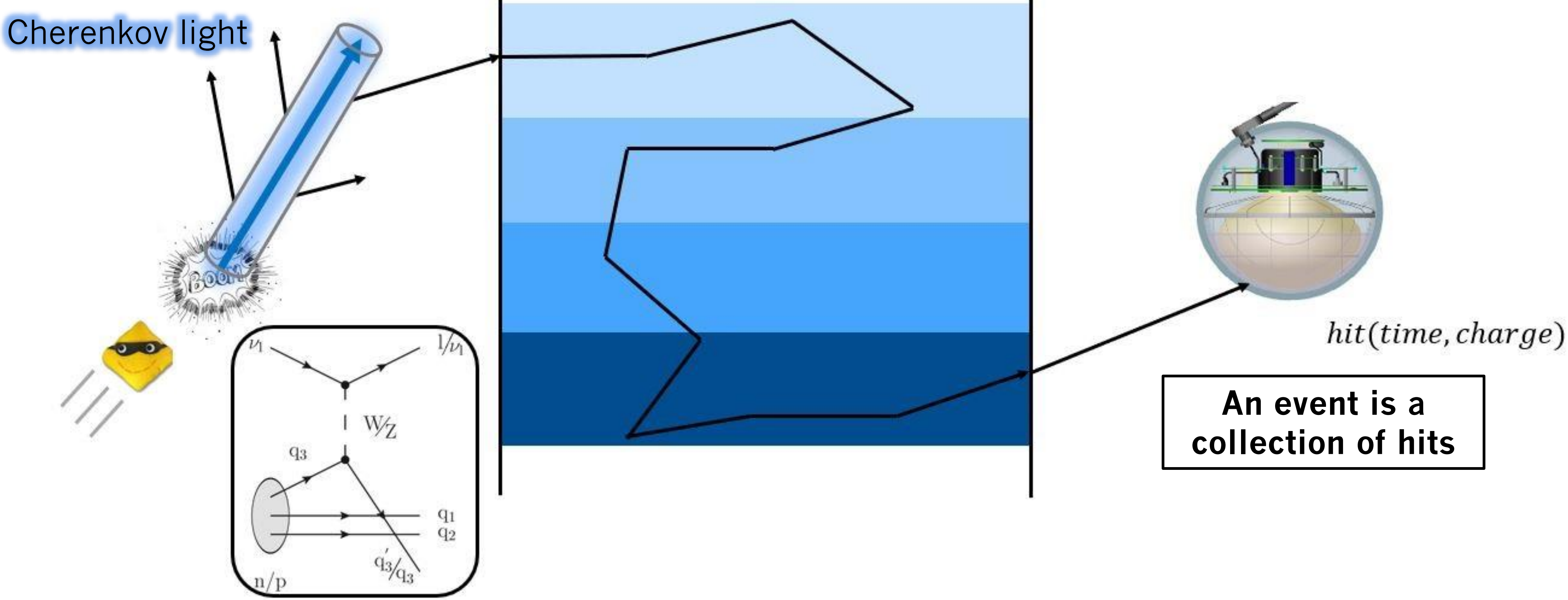
Incomming Neutrino interacts

Photon propagation

Photon scatters through ice

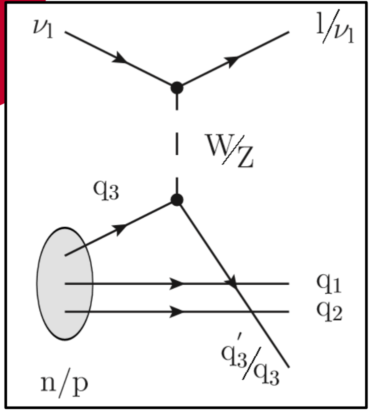
Photon detection

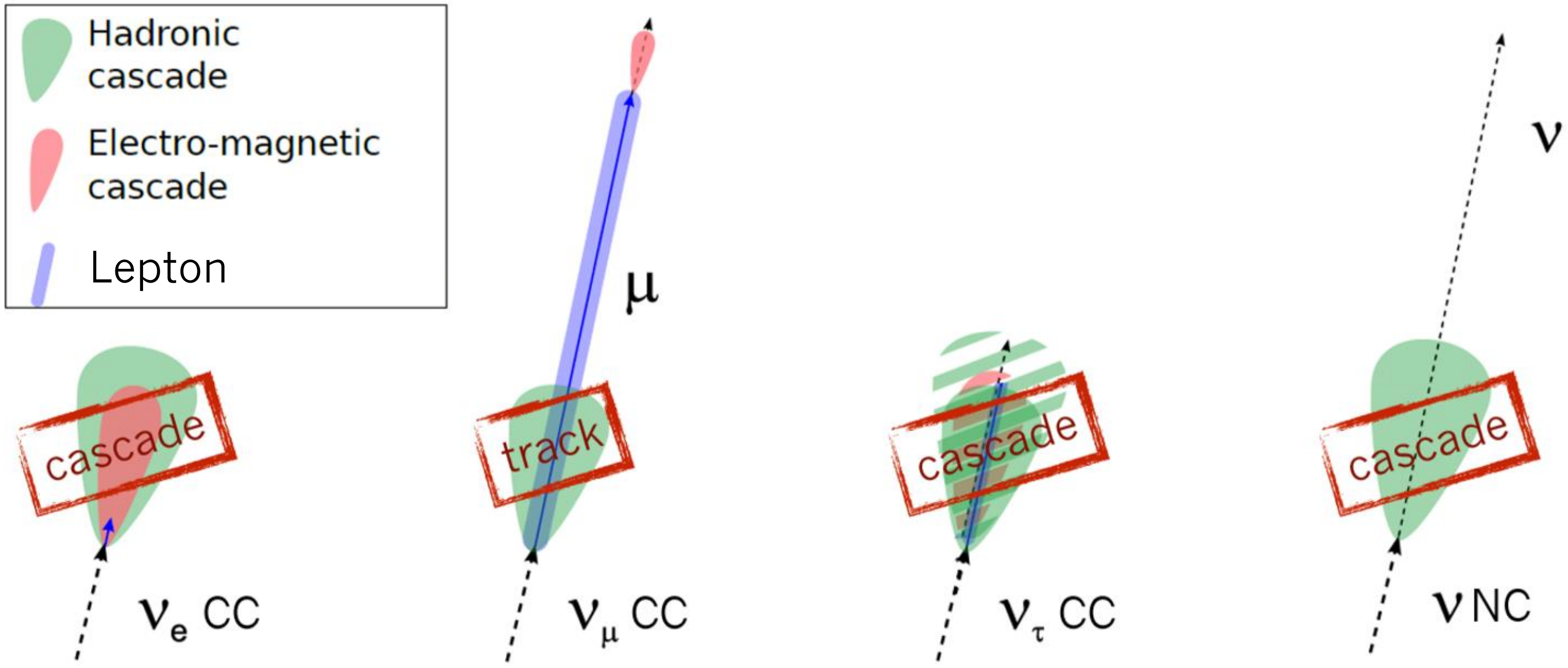
Photon gets detected by PMT



An event is a collection of hits

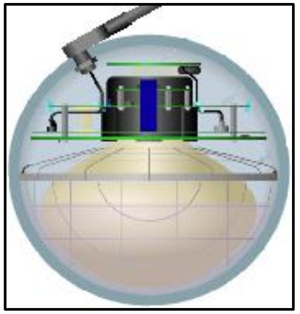
Event topologies



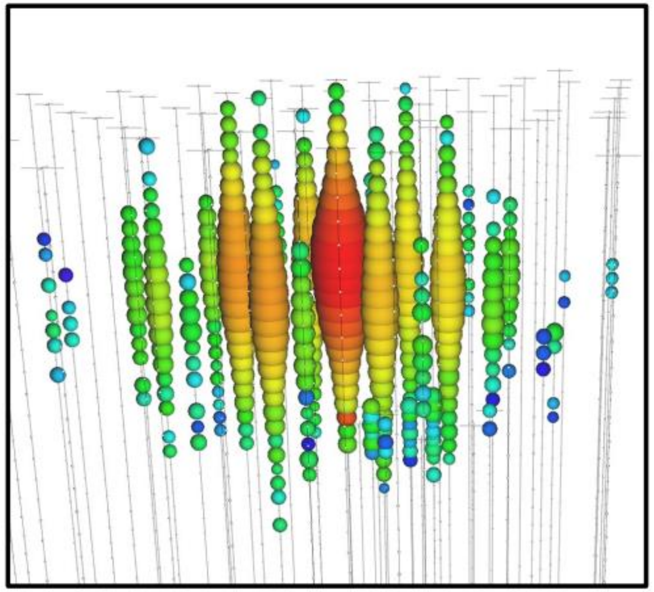


- Unique signature for ν_μ CC
- Used for flavor identification (important for oscillation analysis)

Event topologies IceCube

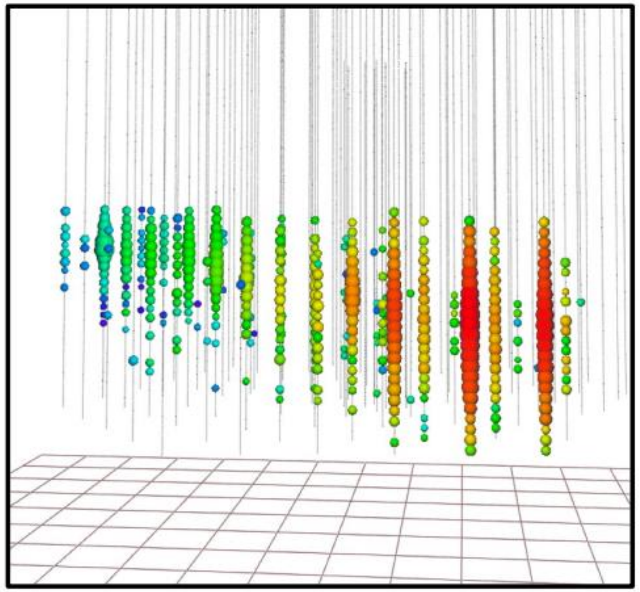


Cascades



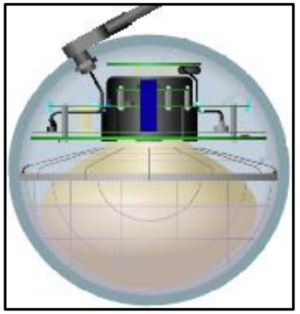
ν_e^{CC}, ν_τ^{CC}, ν^{NC}

Tracks

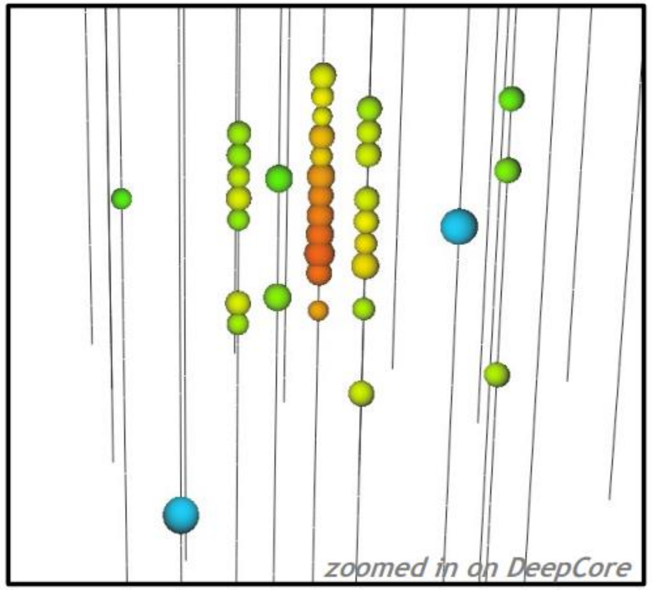


mostly ν_μ^{CC}

Event topologies DeepCore

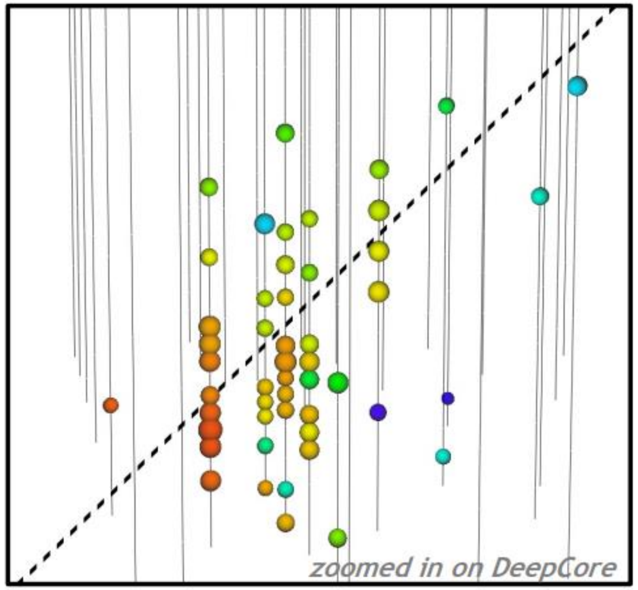


Cascades



$\nu_e^{CC}, \nu_\tau^{CC}, \nu^{NC}$

Tracks



mostly ν_μ^{CC}

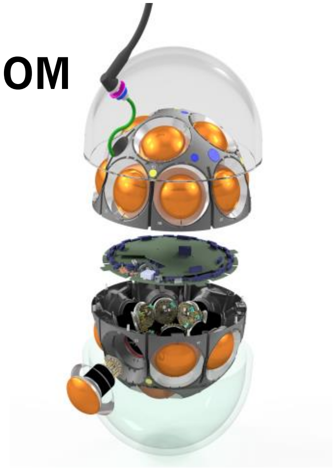
The IceCube Upgrade

The Upgrade

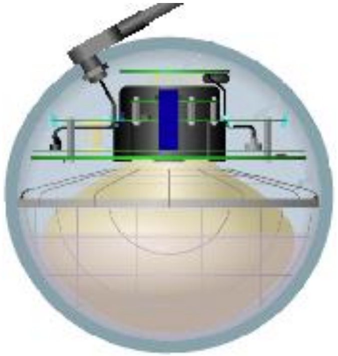
7 new strings hosting new optical sensors

D-Egg

mDOM



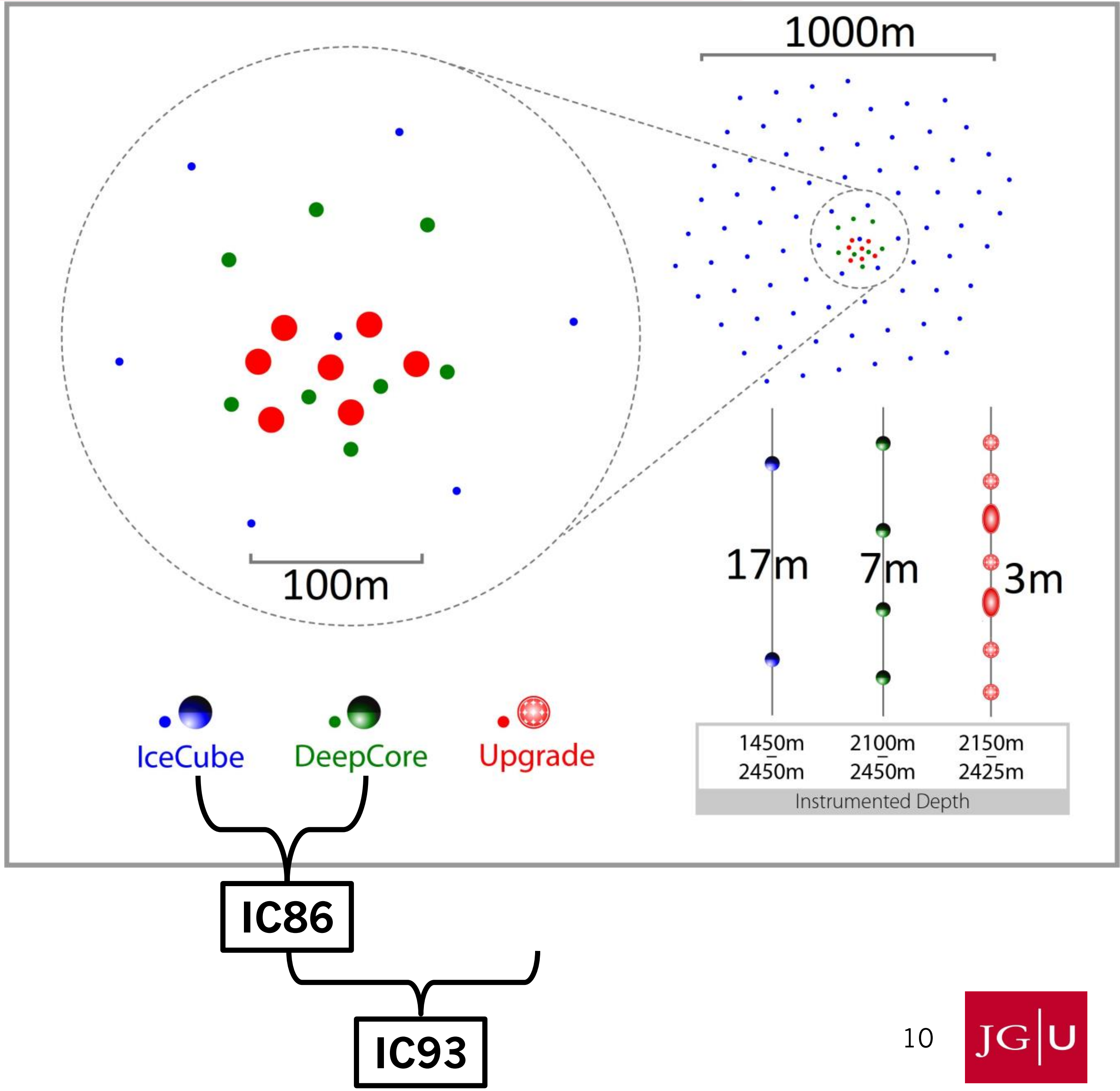
(old) DOM



5–10 times denser spacing

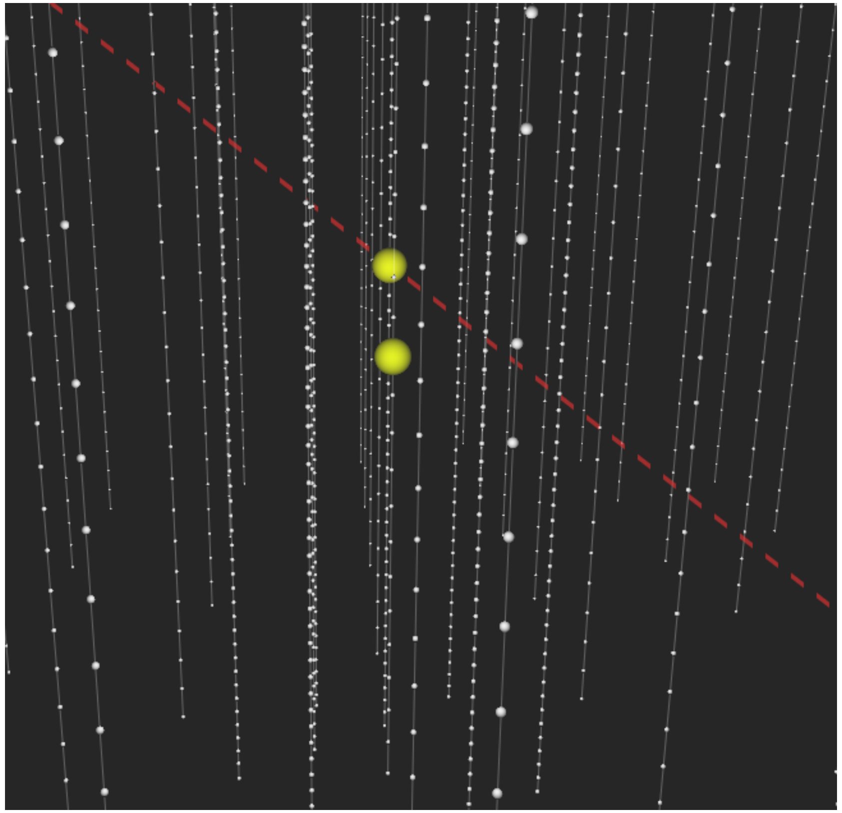
- ➢ detect more light at low energies

Will be deployed next year (!)

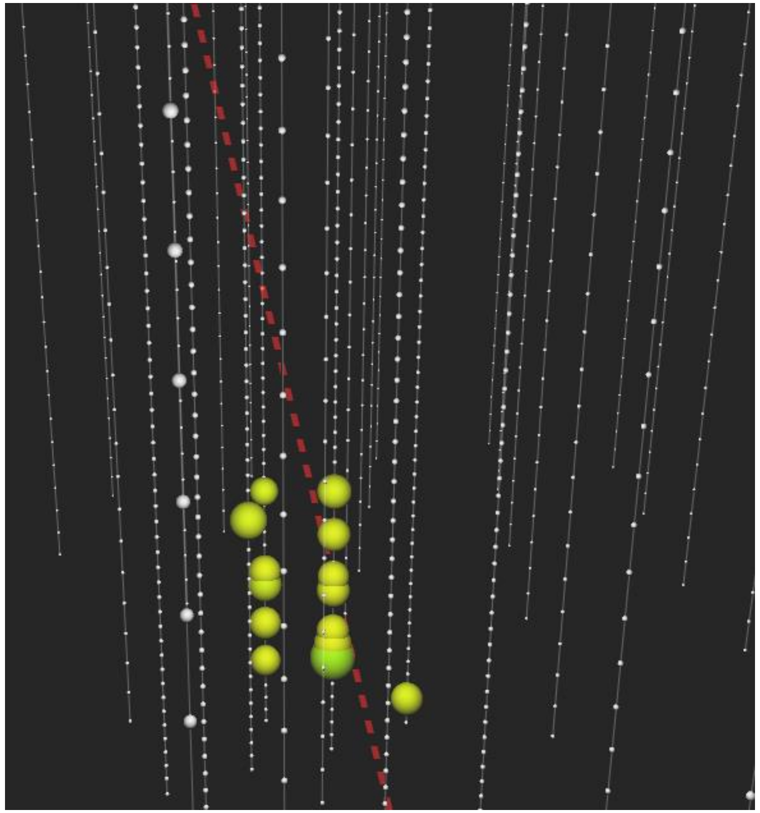


Events in IC86

3.6 GeV ν_μ

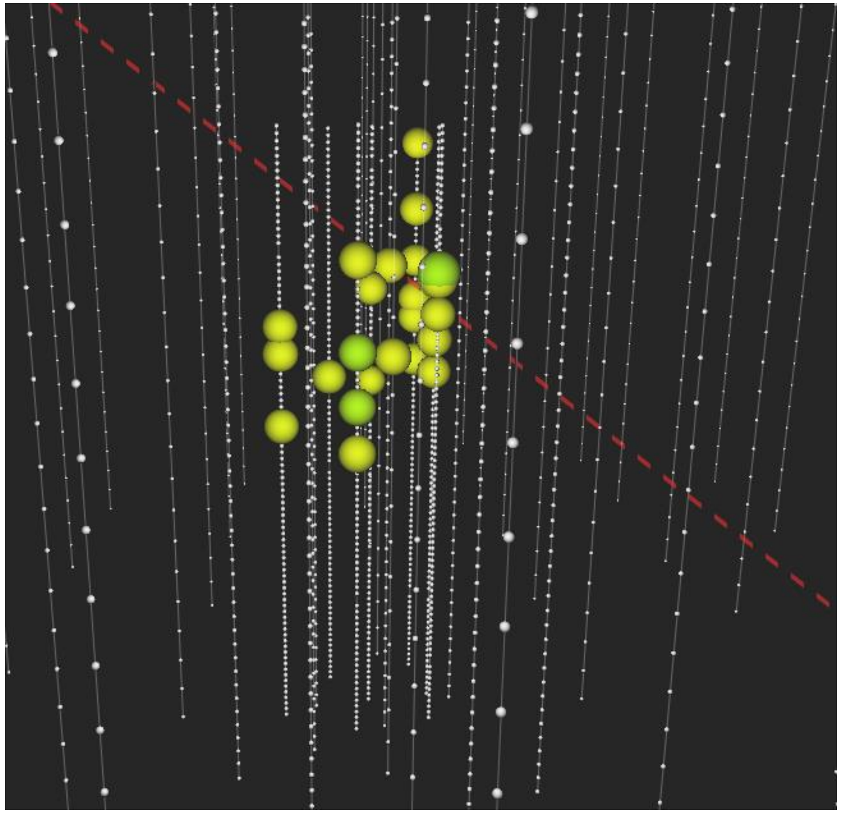


21 GeV $\bar{\nu}_\tau$

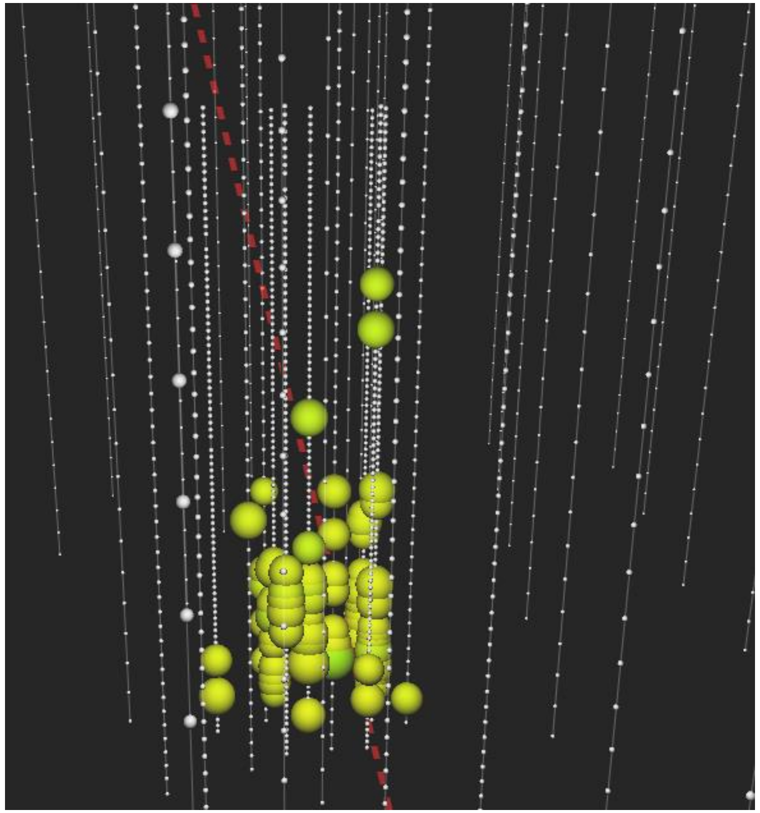


Events in IC93

3.6 GeV ν_μ



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



- More hits with the new strings

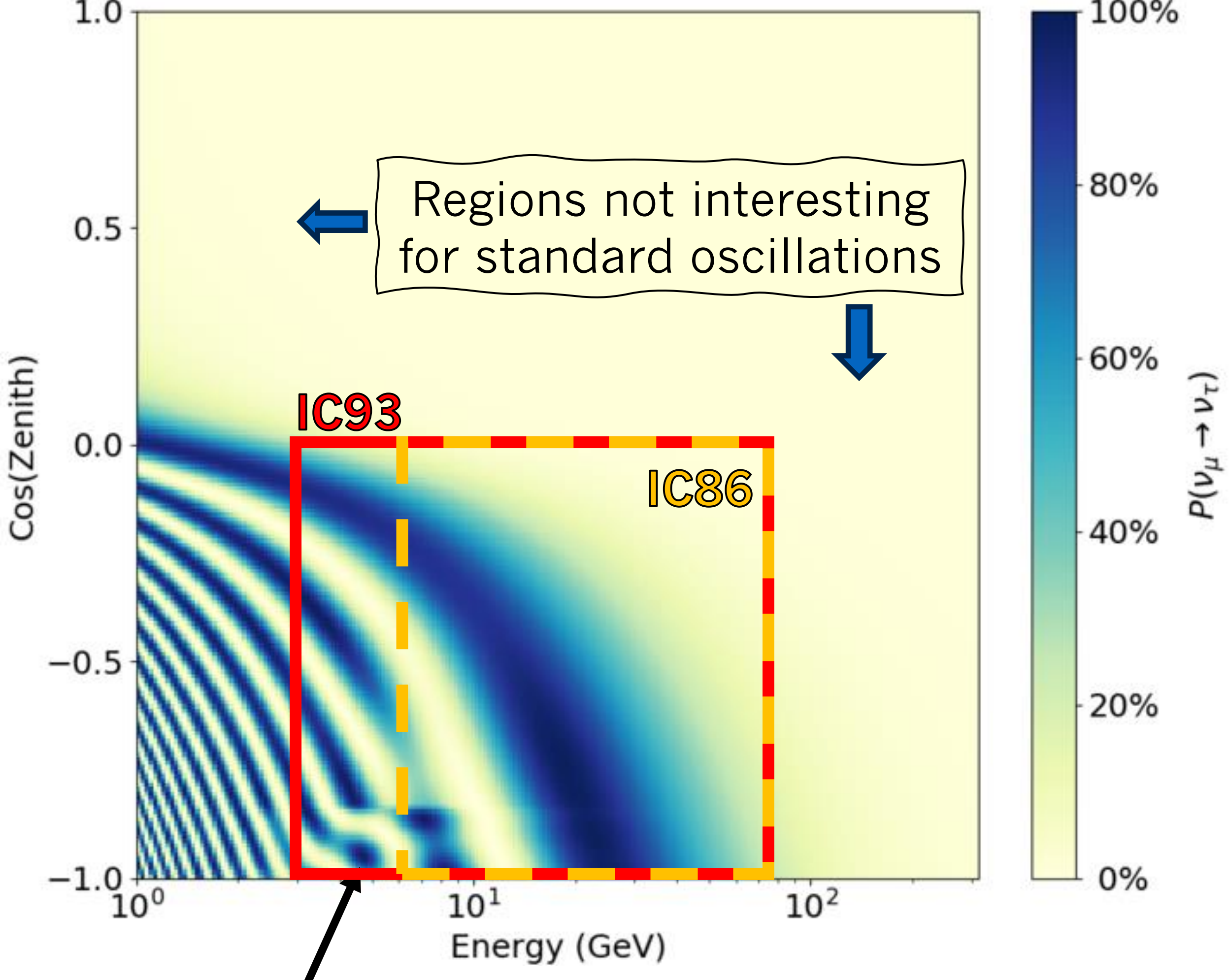
Oscillogram

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 (ν_μ CC vs others)
- better reconstructs observables

True oscillogram



Regions not interesting for standard oscillations

Matter effects from Earth's core

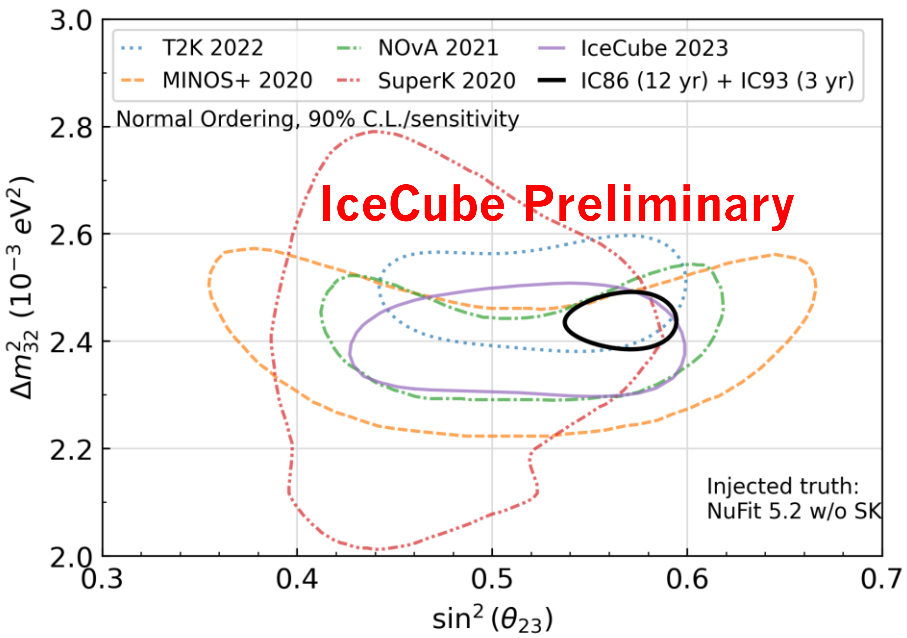
Atmospheric oscillation parameters

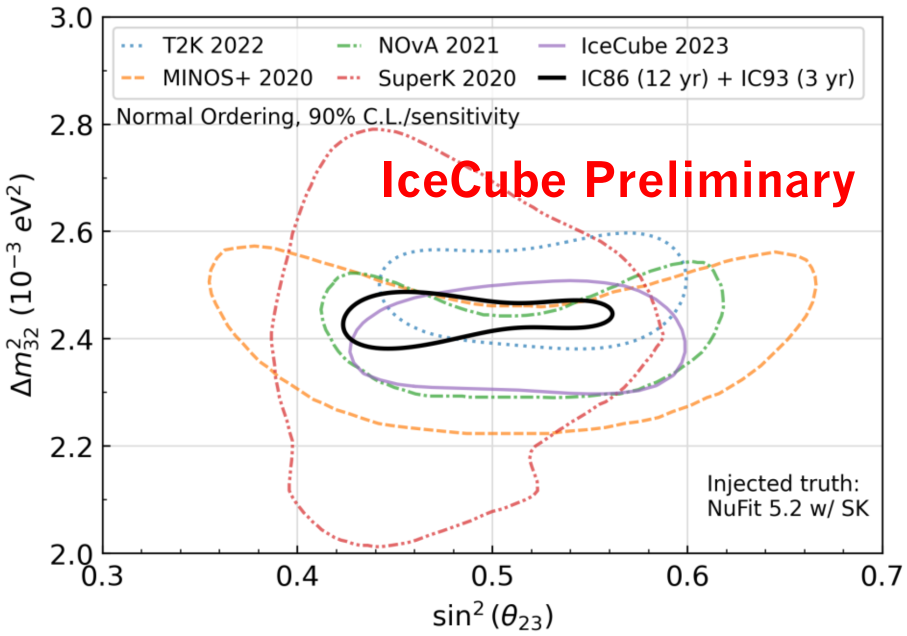
How well can we determine mixing angle θ_{23} and mass difference Δm^2_{32}?

Compare to current **results** from other detectors

- T2K: beam experiment
- NOvA: beam experiment
- MINOS+: beam experiment
- SuperK: atmospheric neutrino experiment

➢ Will be among the most precise measurements

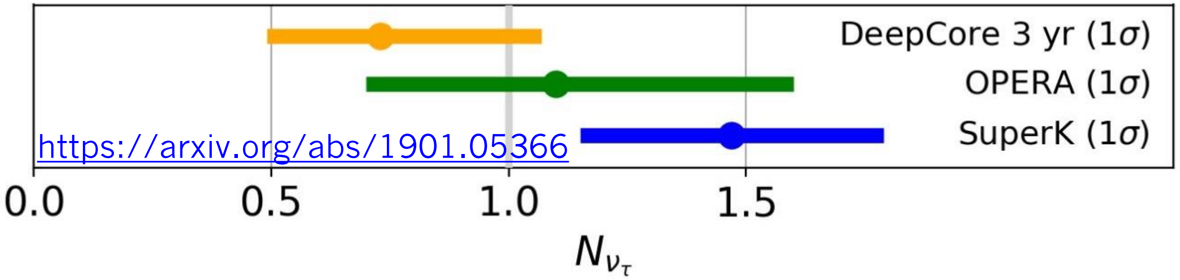




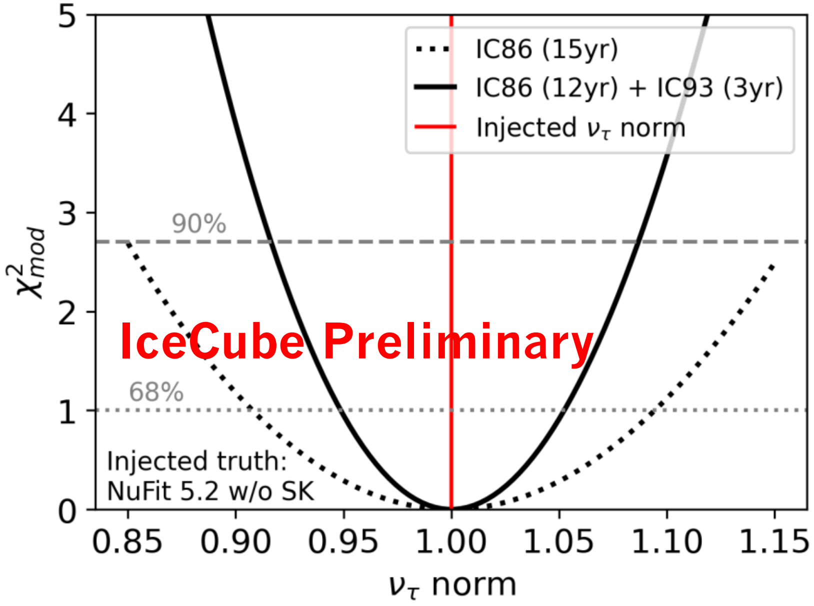
ν_τ normalization

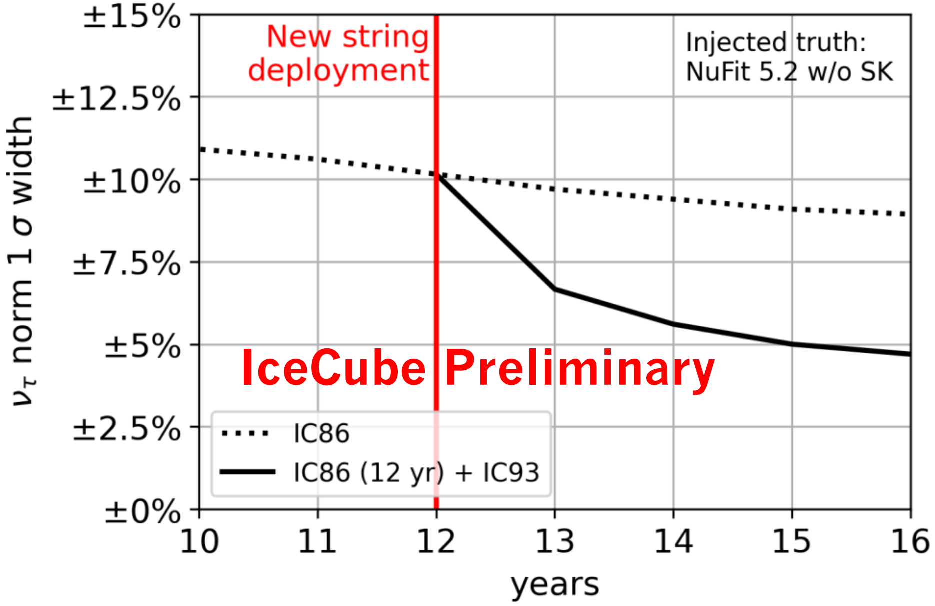
How well can we constrain the number (scale) of detected ν_τ?

Current results:



Lower plot shows sensitivity evolution over time





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

Neutrino Mass Ordering

How well can we determine the NMO?

Strongly depends on true value of θ_{23}

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

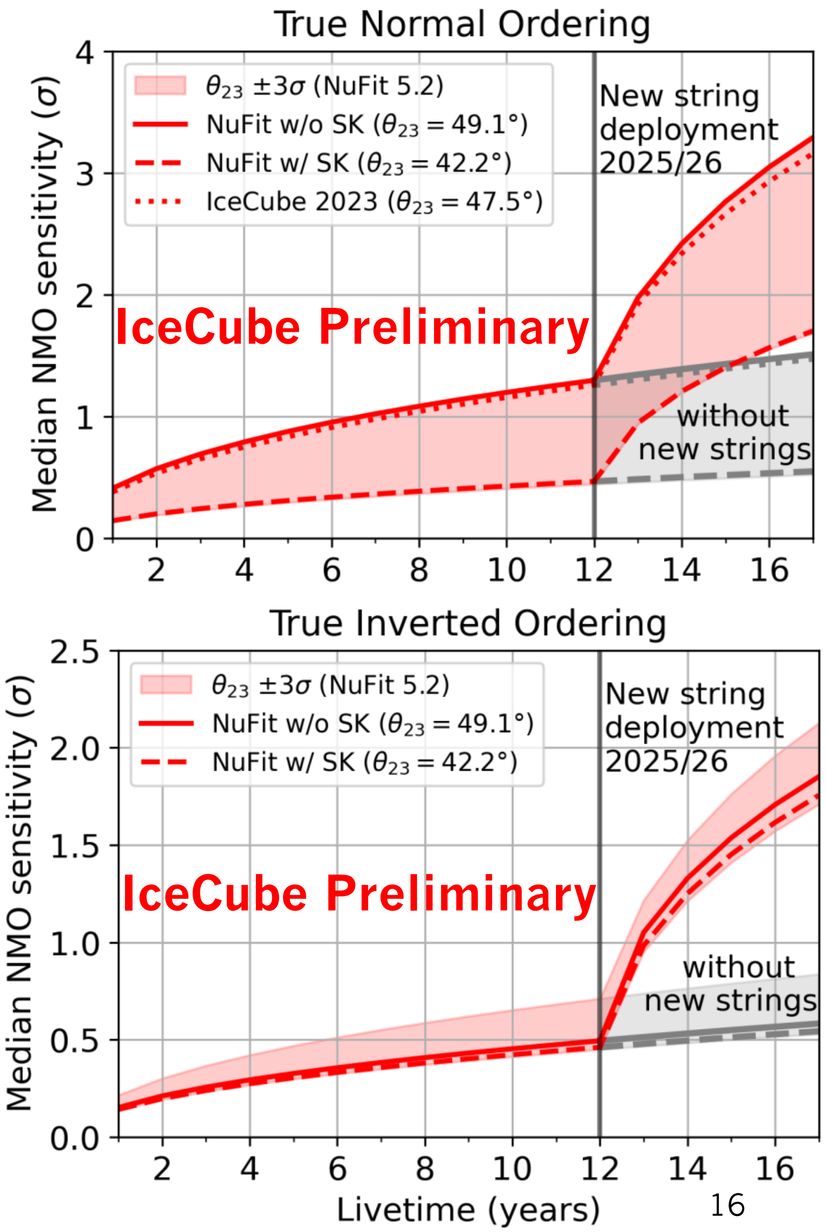
Current global preference (NuFIT 6.0, September 2024)

~2.5σ for NO with SuperK and IC24

<1σ for IO without SuperK and with IC19

New strings strongly increase NMO sensitivity

- 1.8σ – 3.3σ after 5 years if NO is true
- 1.7σ – 2.1σ after 5 years if IO is true
- Matter effects on ν oscillations will be established at 5σ



Neutrino Mass Ordering

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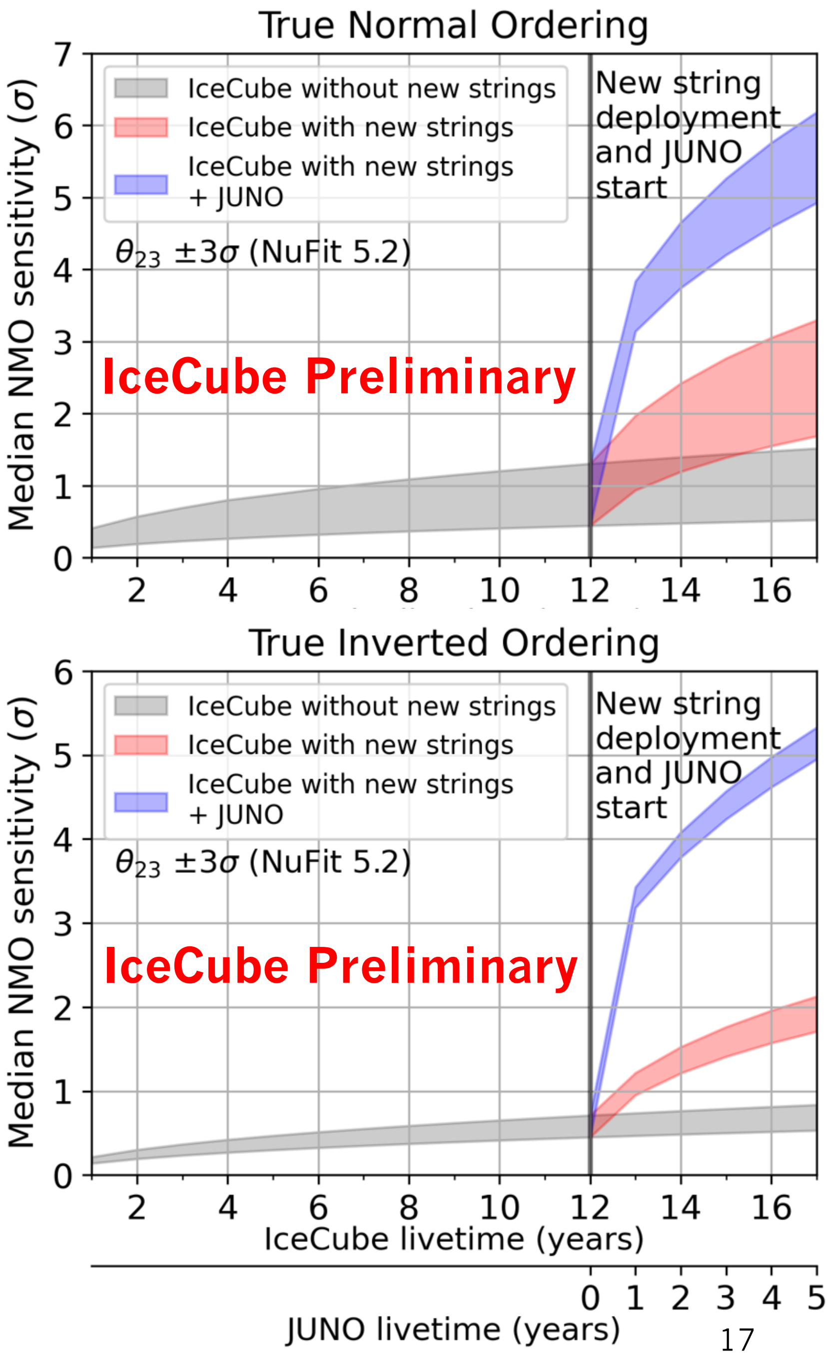
Combined fit with reactor experiment JUNO further boosts NMO sensitivity

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

⇦ for either ordering



Conclusion

The IceCube Upgrade, deployed in 2025/26, will significantly enhance our GeV capabilities

Atmospheric oscillation parameters

- will be among most precise measurements

ν_τ normalization

- <5% precision for 1σ range

Neutrino mass ordering

- 1.7σ – 3.3σ after 5 years

A combined JUNO–IceCube–KM3NeT analysis will determine the NMO at 5σ within ~5 years independent of the true ordering or true value of θ_{23}

Thank you for your attention!

Backup

Background rejection

Background sources

- Atmospheric μ
- Pure noise triggers

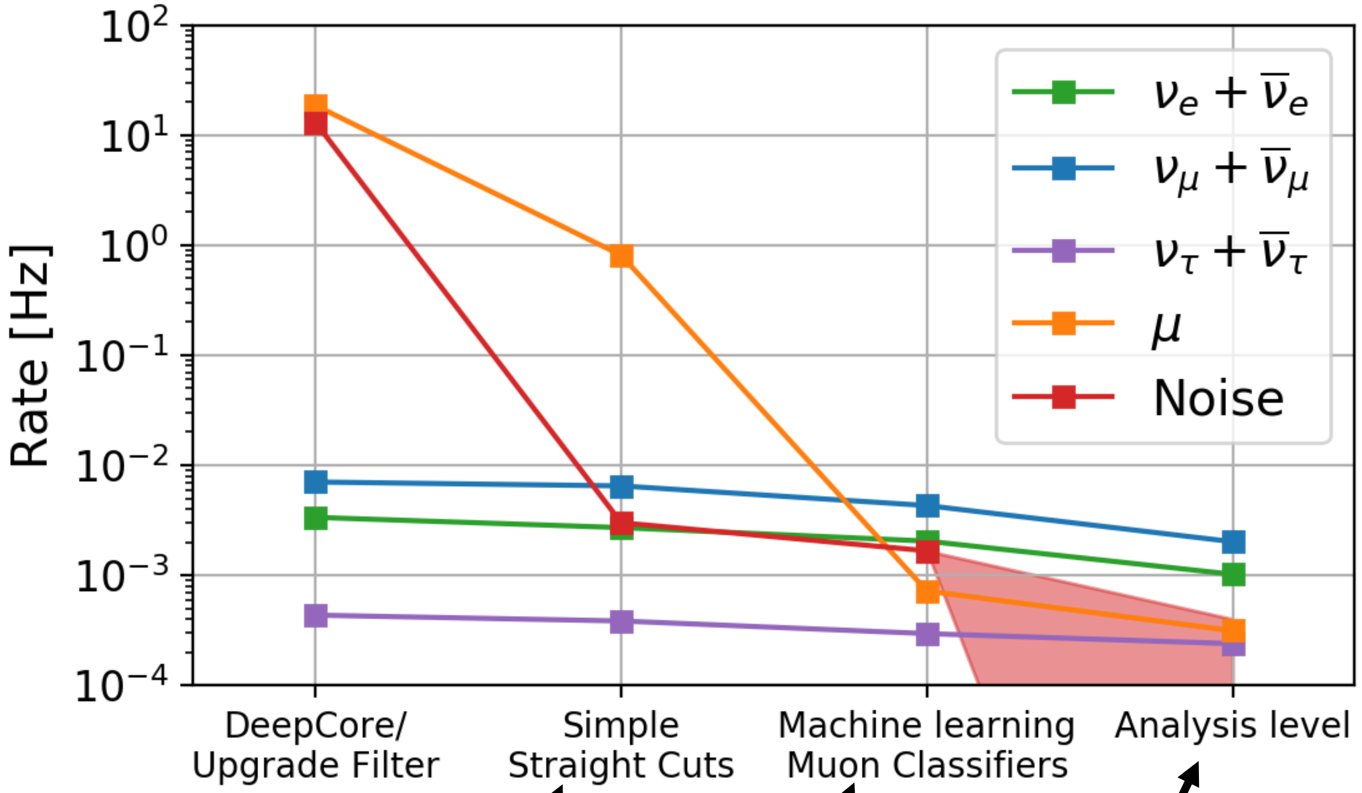
Noise

- PMT dark noise and radioactive decays in module glass housing
- removed by neural network (GNN)

Background dominates at trigger/filter level

⇒ Need event selection

After event selection sample is neutrino dominated

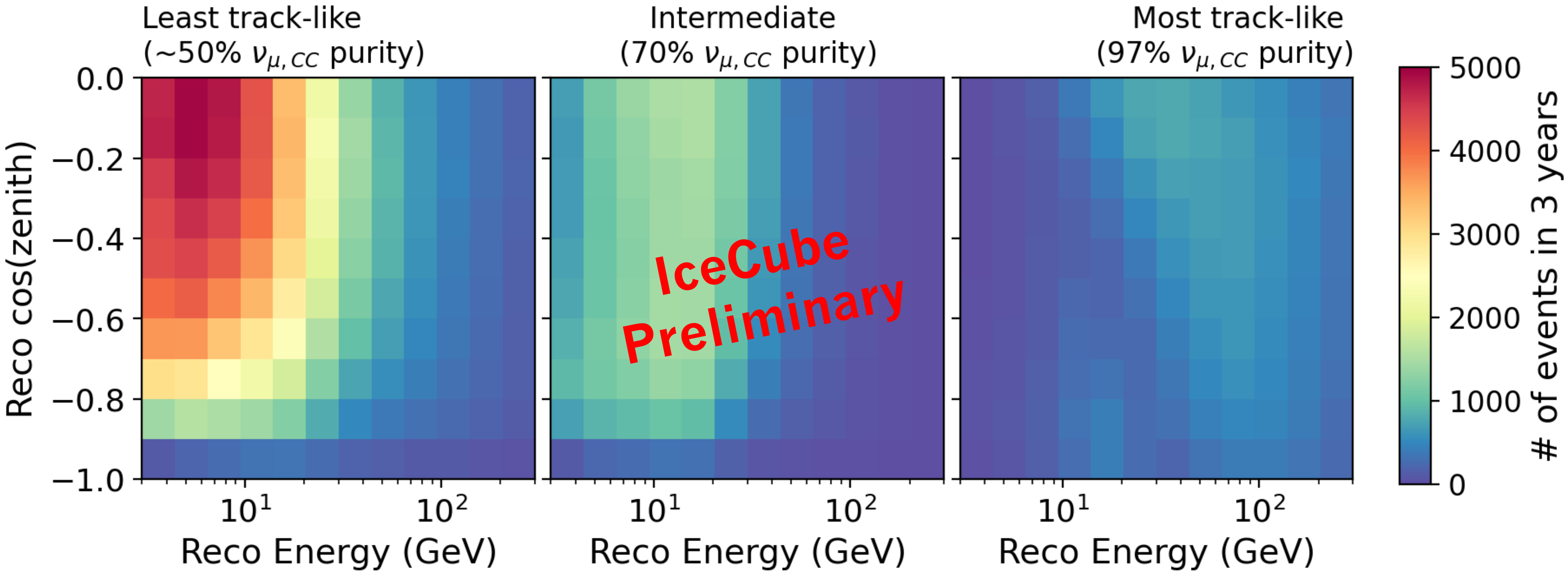


GNN + BDT

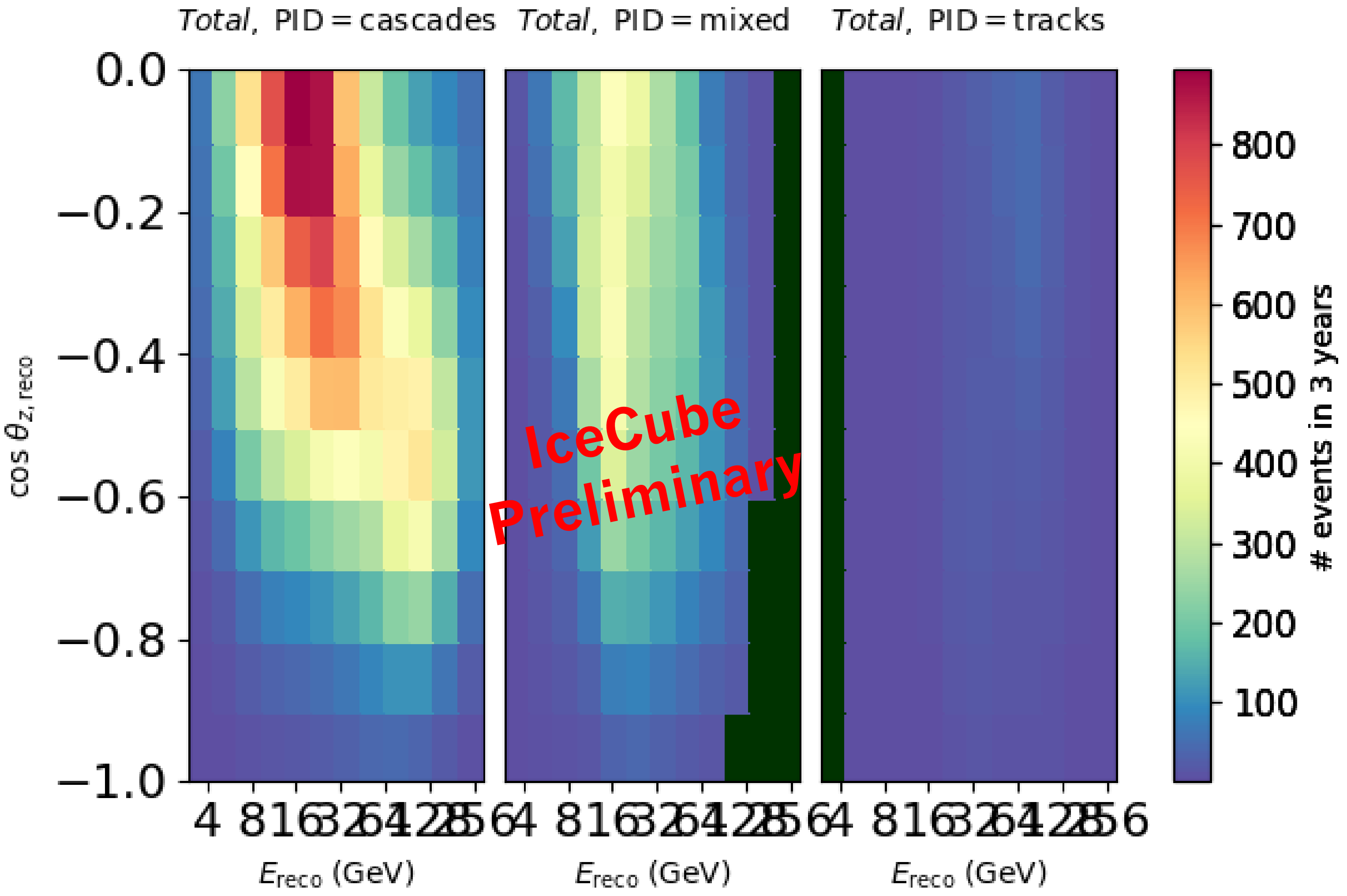
e.g. Number of PMT hits after noise removal

Cuts on reconstructed variables

Event histograms for IC93 analysis



Muon map


Total, PID = cascades
Total, PID = mixed
Total, PID = tracks
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
cos $\theta_{z,\mathrm{reco}}$
4 8 16 32 64 128 256
E_{reco} (GeV)
800
700
600
500
400
300
200
100
events in 3 years
IceCube Preliminary

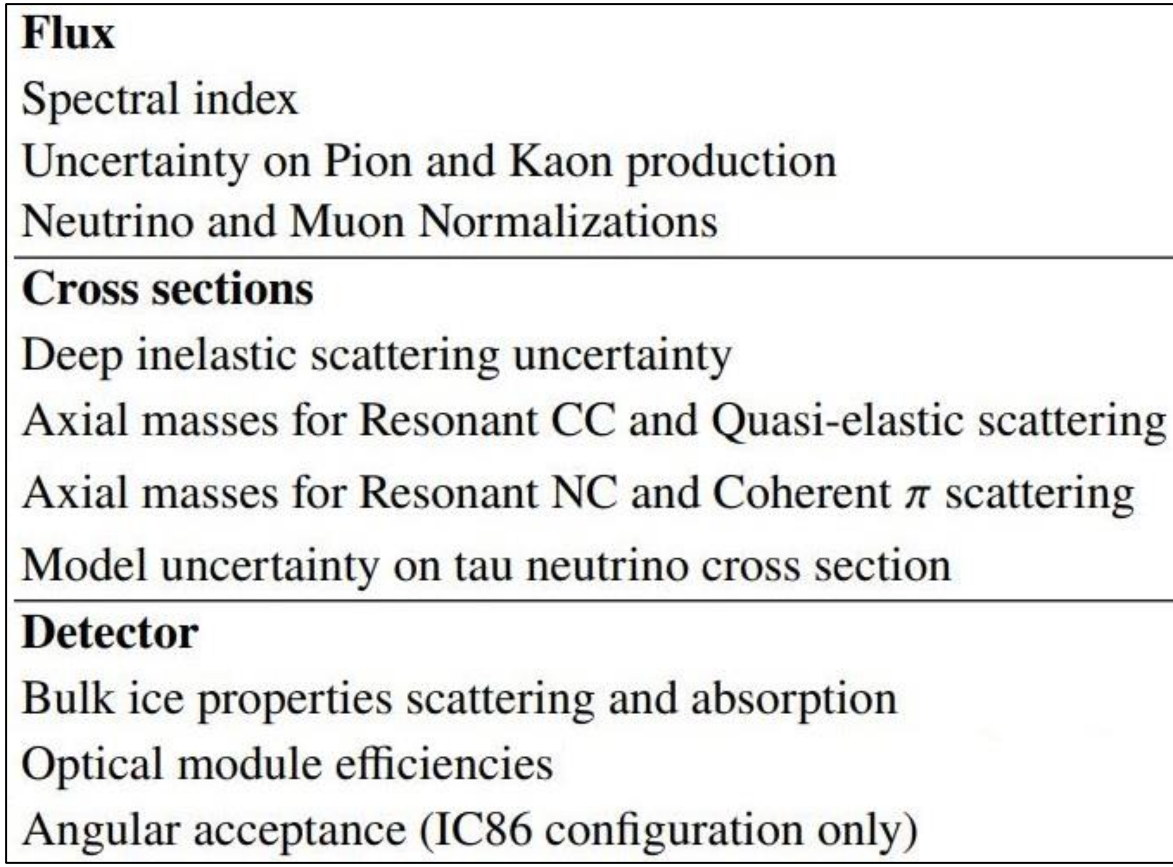
Analysis details

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)

Systematic parameters

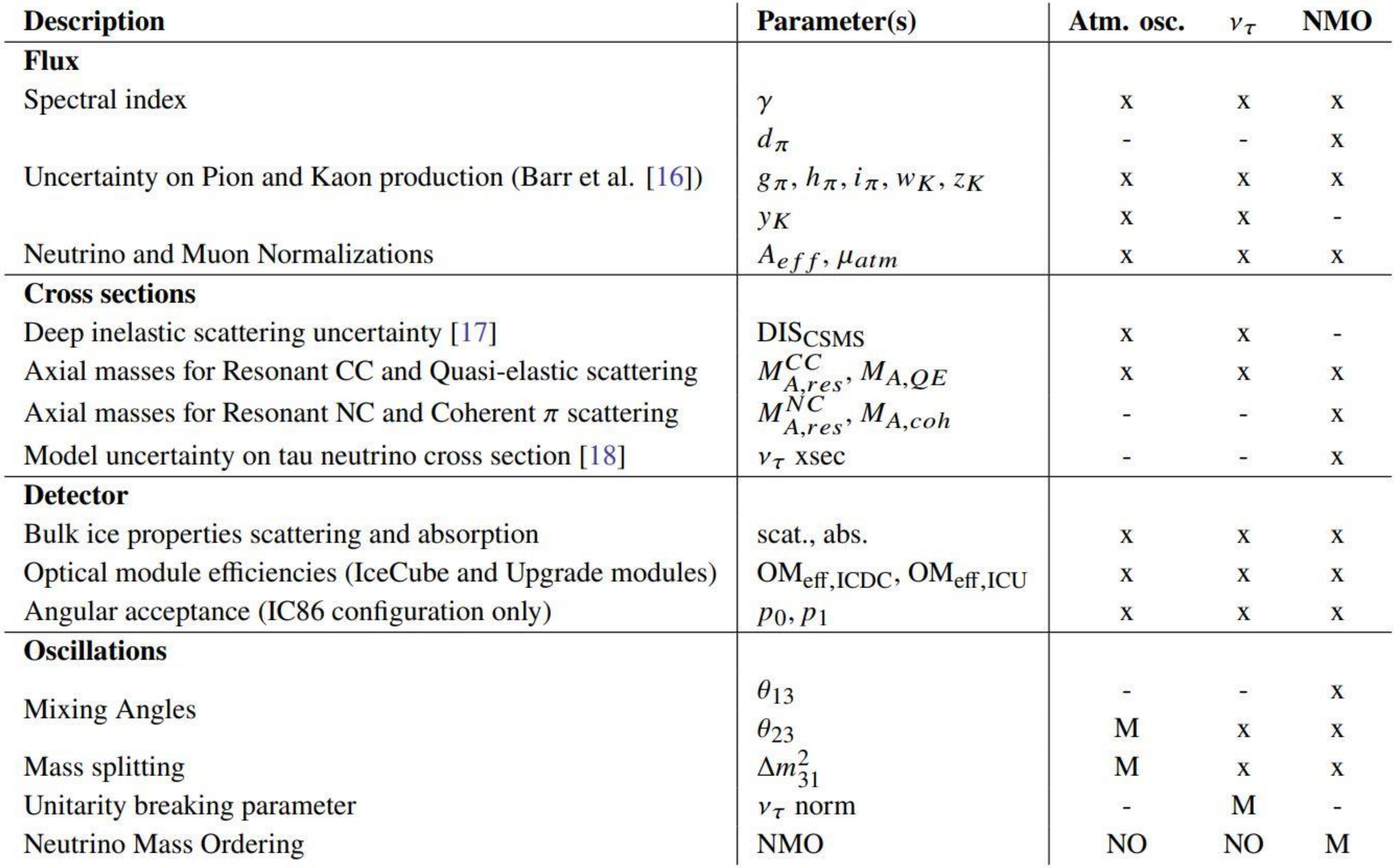


Flux
Spectral index
Uncertainty on Pion and Kaon production
Neutrino and Muon Normalizations

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)

Free parameters



Description	**Parameter(s)**	**Atm. osc.**	ν_τ	**NMO**
Flux				
Spectral index	γ	x	x	x
Uncertainty on Pion and Kaon production (Barr et al. [16])	d_π	-	-	x
	$g_\pi, h_\pi, i_\pi, w_K, z_K$	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]	$\mathrm{DIS}_{\mathrm{CSMS}}$	x	x	-
Axial masses for Resonant CC and Quasi-elastic scattering	$M_{A,res}^{CC}, M_{A,QE}$	x	x	x
Axial masses for Resonant NC and Coherent π scattering	$M_{A,res}^{NC}, M_{A,coh}$	-	-	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)	$\mathrm{OM}_{\mathrm{eff,ICDC}}, \mathrm{OM}_{\mathrm{eff,ICU}}$	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_{31}^2	M	x	x
Unitarity breaking parameter	ν_τ norm	-	M	-
Neutrino Mass Ordering	NMO	NO	NO	M

Atmospheric oscillation parameters

How well can we determine mixing angle θ_{23} and mass difference Δm^2_{32}?

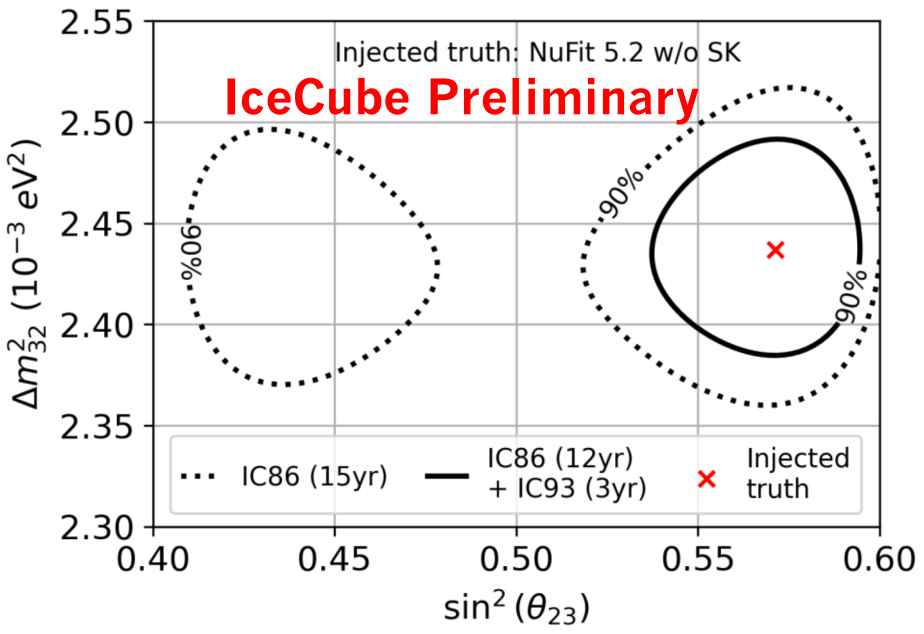
Compare two scenarios, with 3 years of data

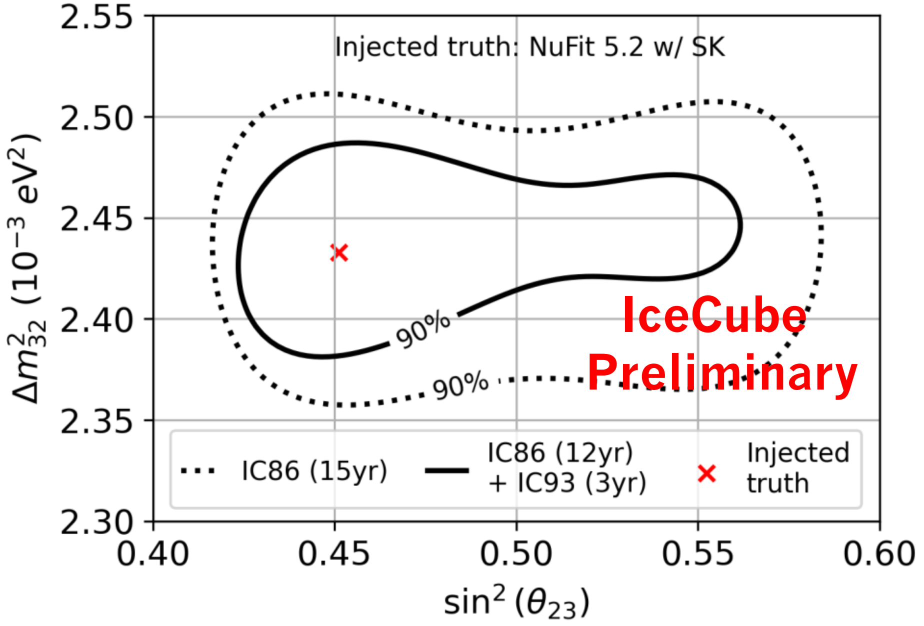
- Continue running IC86 w/o new strings (····)
- Install new strings (—)

Nufit 5.2 global fit result as injected truth

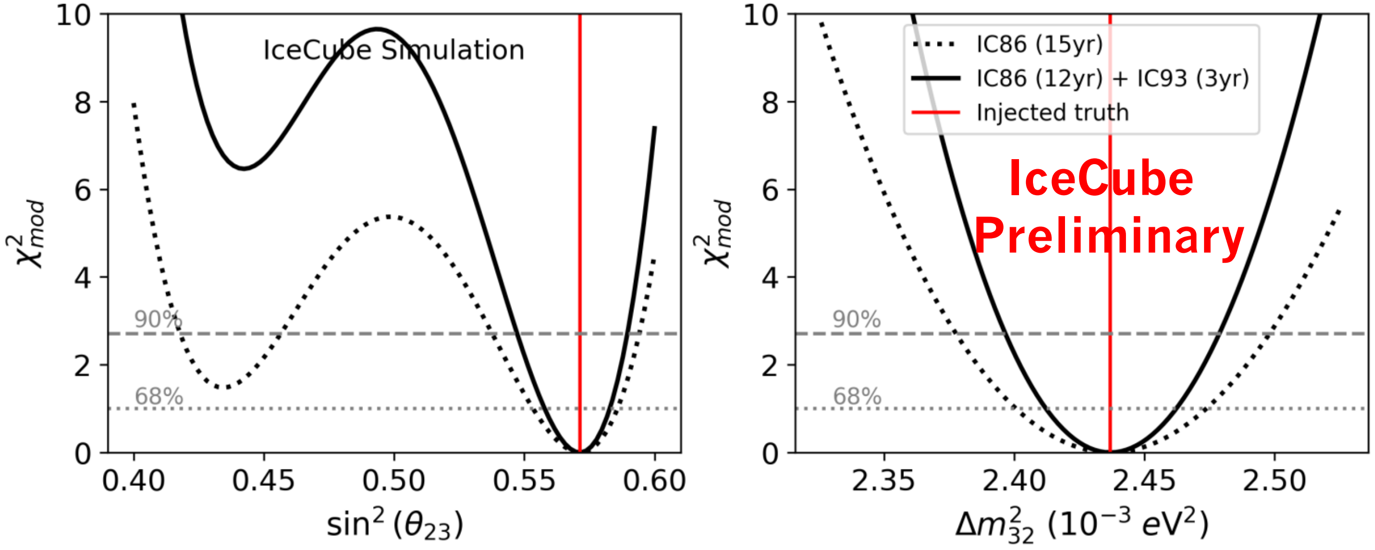
there are two available, one **w/o** and one **w/** SuperK

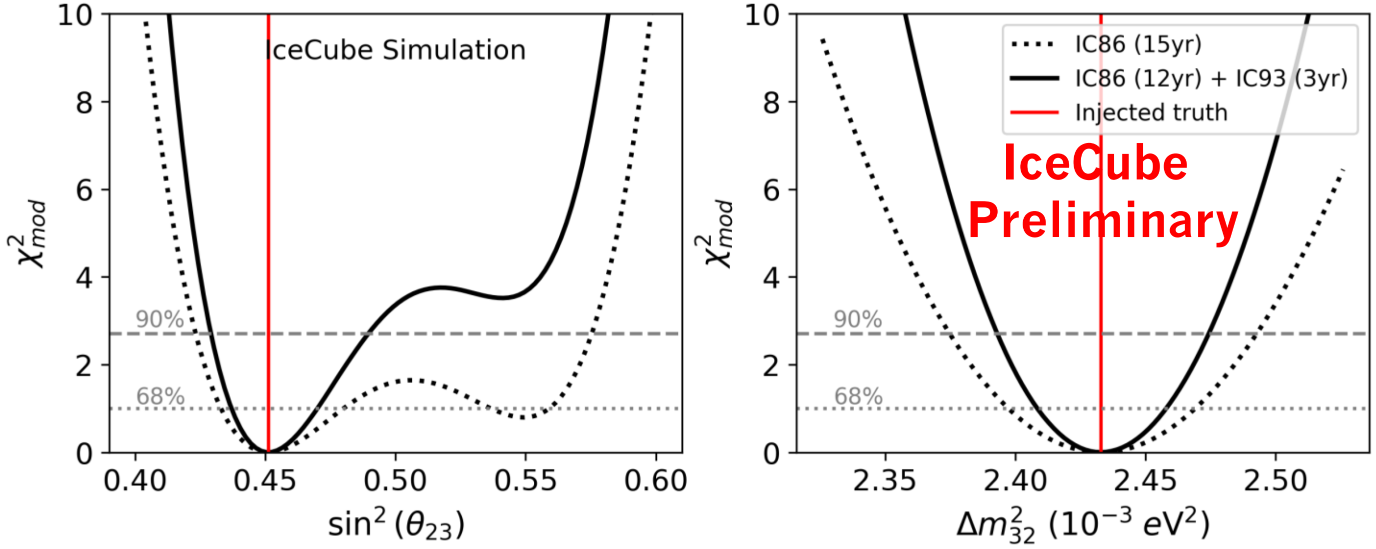
- ➢ Measure θ_{23} and Δm^2_{32} with increased precision
- ➢ Depending on true value of θ_{23}, could determine octant or reject maximal mixing





Atmospheric oscillation parameters 1D





ν_τ normalization

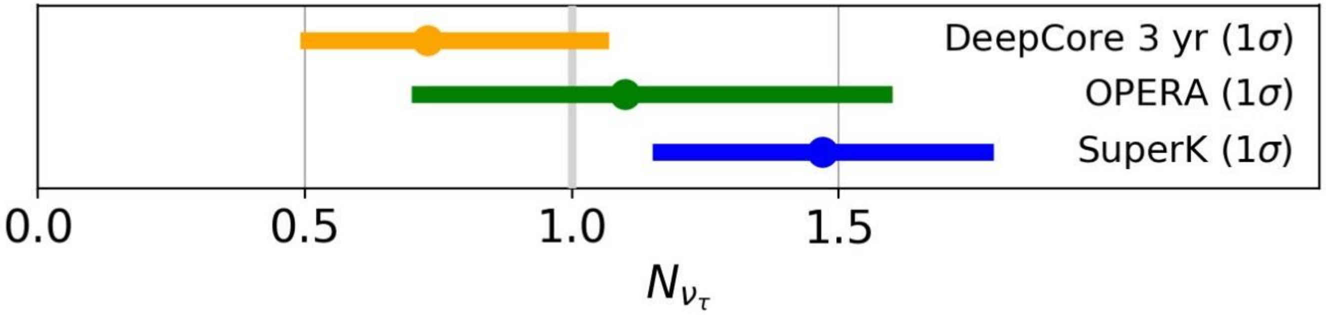
How well can we constrain the number (scale) of detected ν_τ?

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

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)

Current results:



Neutrino mass ordering (NMO)

Ordering of the (three) neutrino mass eigenstates

ν-oscillations (vacuum, leading-term)

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

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

⇒ difficult to determine the sign of Δm^2

$m_1 < m_2$ known from solar neutrino oscillations

normal ordering (NO) **inverted ordering (IO)**