Neutrino Mass Ordering with IceCube DeepCore

Maria Prado Rodriguez
for the IceCube Collaboration

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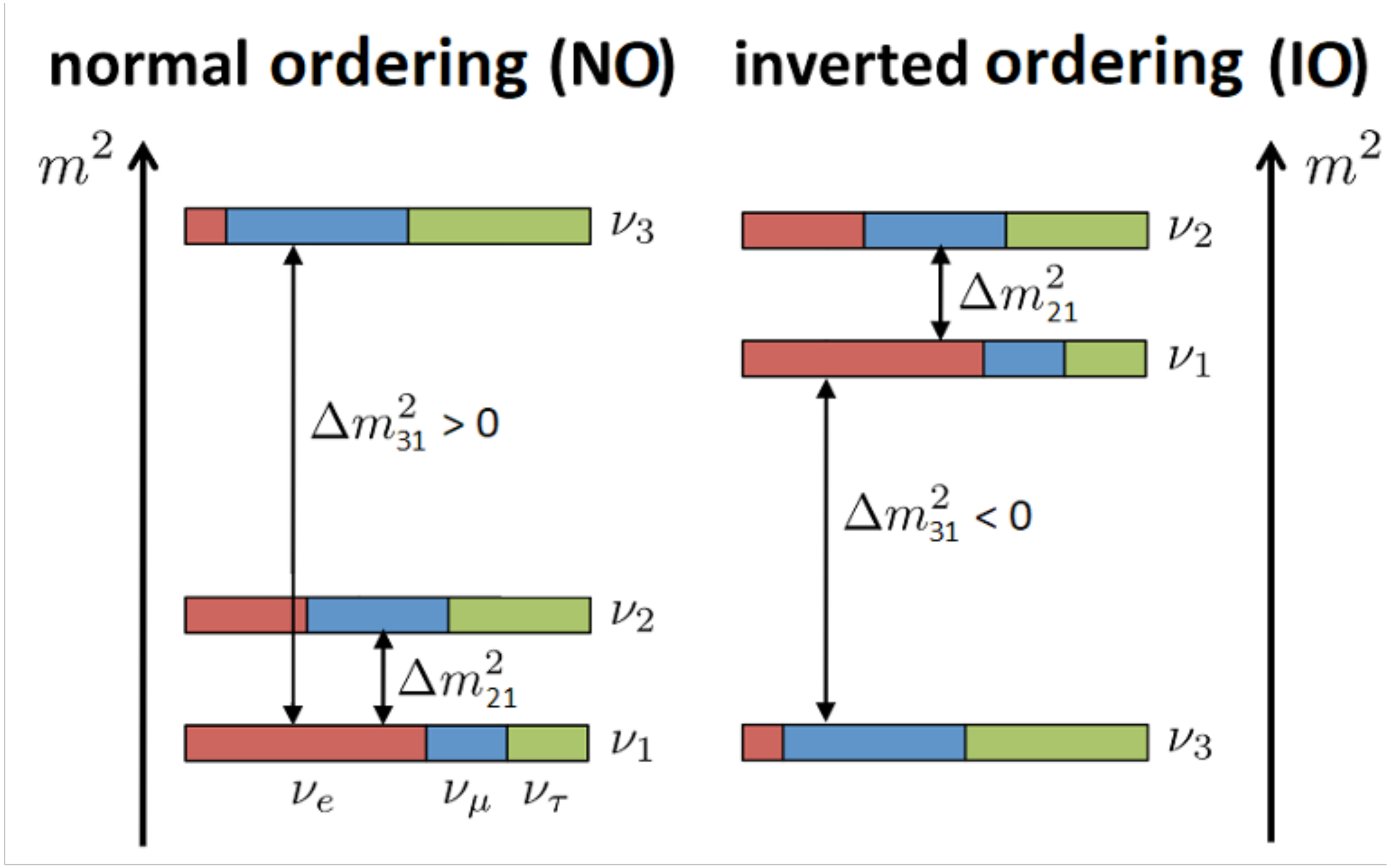
mvprado@icecube.wisc.edu

Neutrino Mass Ordering (NMO)



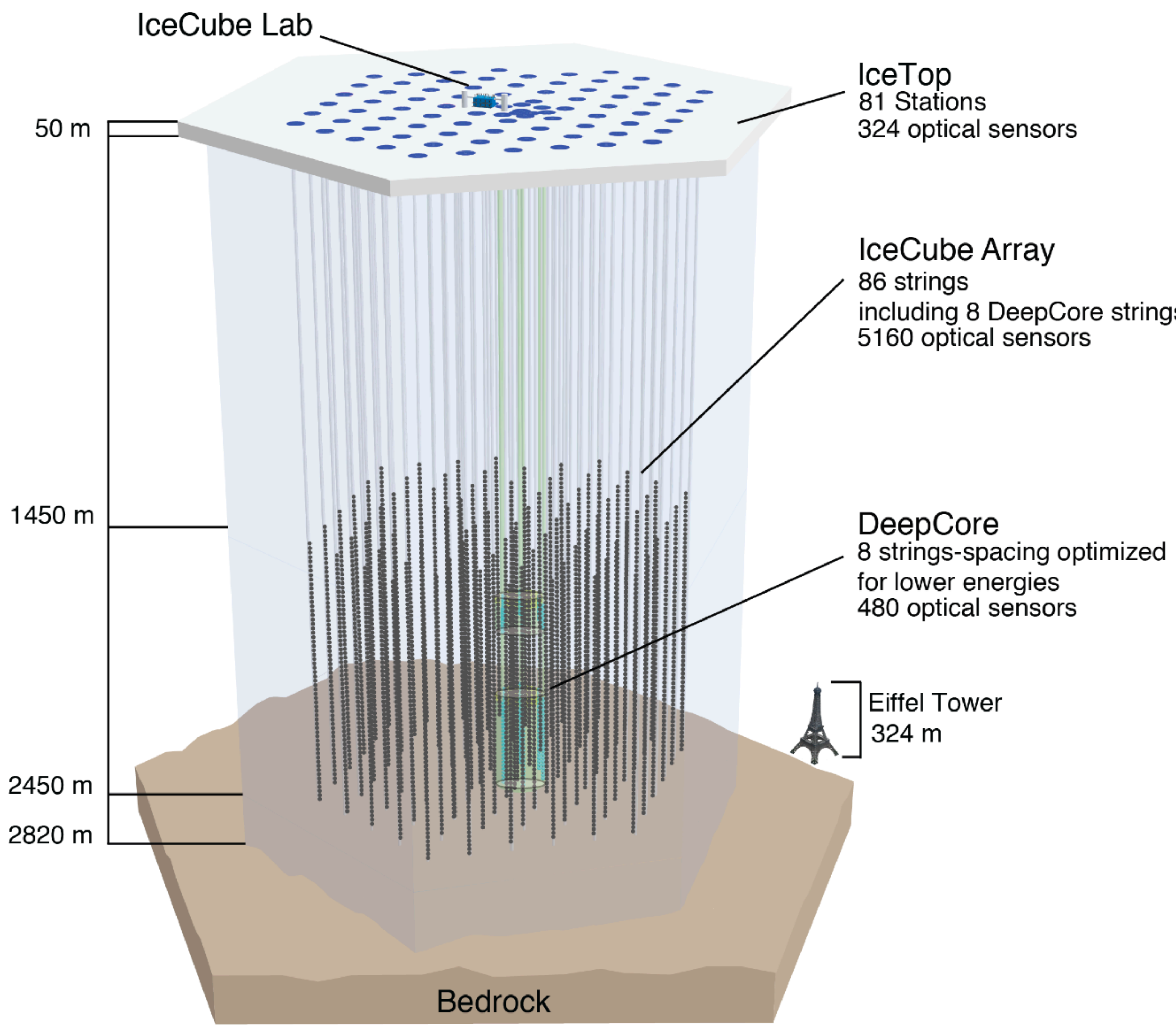
The sign of Δm^2_{31} is not known

We do not know which neutrino is heaviest

We only have a lower bound on the mass of the heaviest neutrino: $\sqrt{2.5 \cdot 10^{-3} \mathrm{eV}^2} \sim 0.05\ \mathrm{eV}$

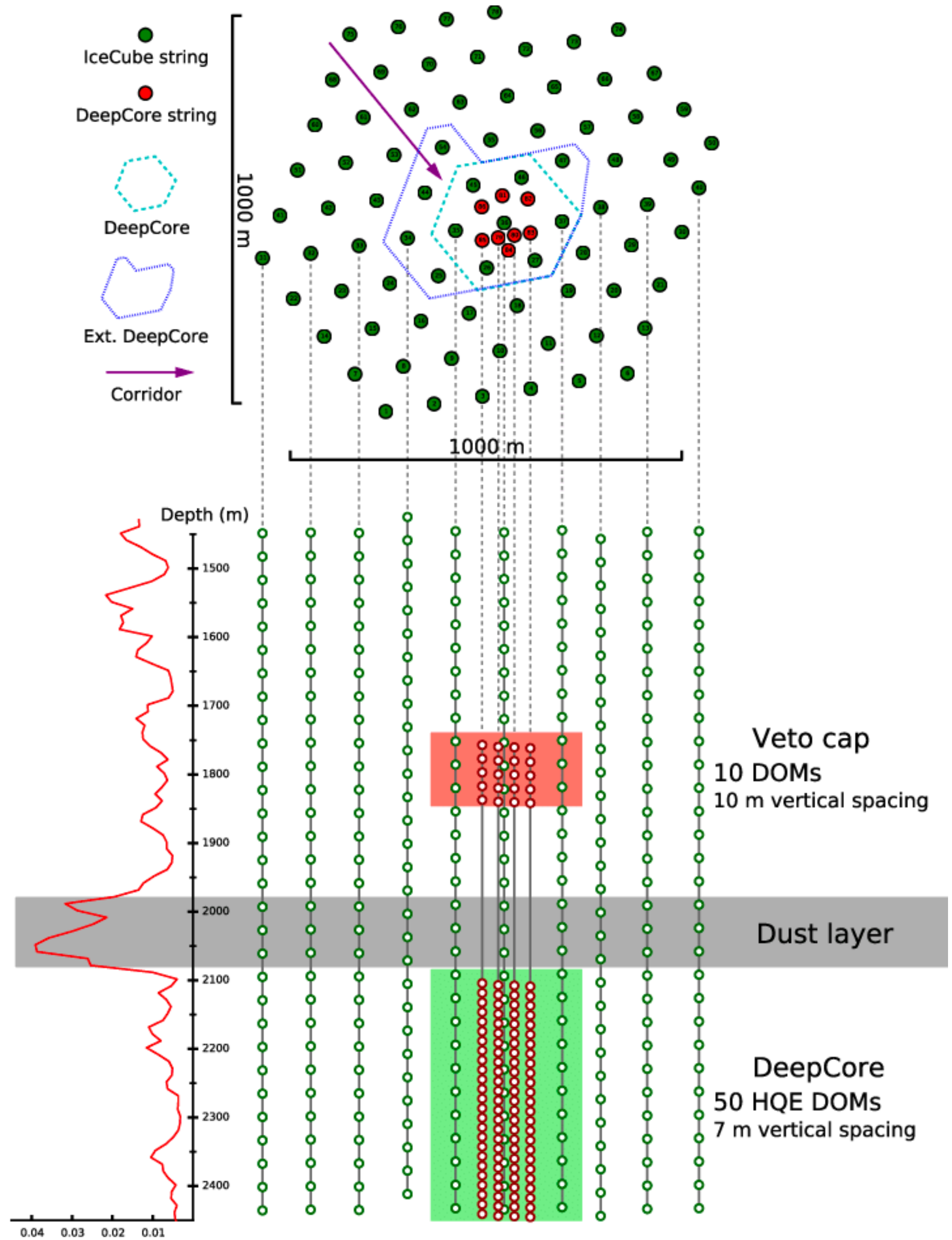
The IceCube Neutrino Observatory

- Ice-Cherenkov neutrino detector at the South Pole
- Optical sensors embedded in Antarctic ice greater than 1.5 kilometers below the surface
- Neutrinos interact via **charged-current** and **neutral-current interactions**



The DeepCore Subarray

- Densely-instrumented region of IceCube (green box/blue hexagon)
- Significantly improves visibility of neutrino events at lower energies (used for neutrino oscillation studies)



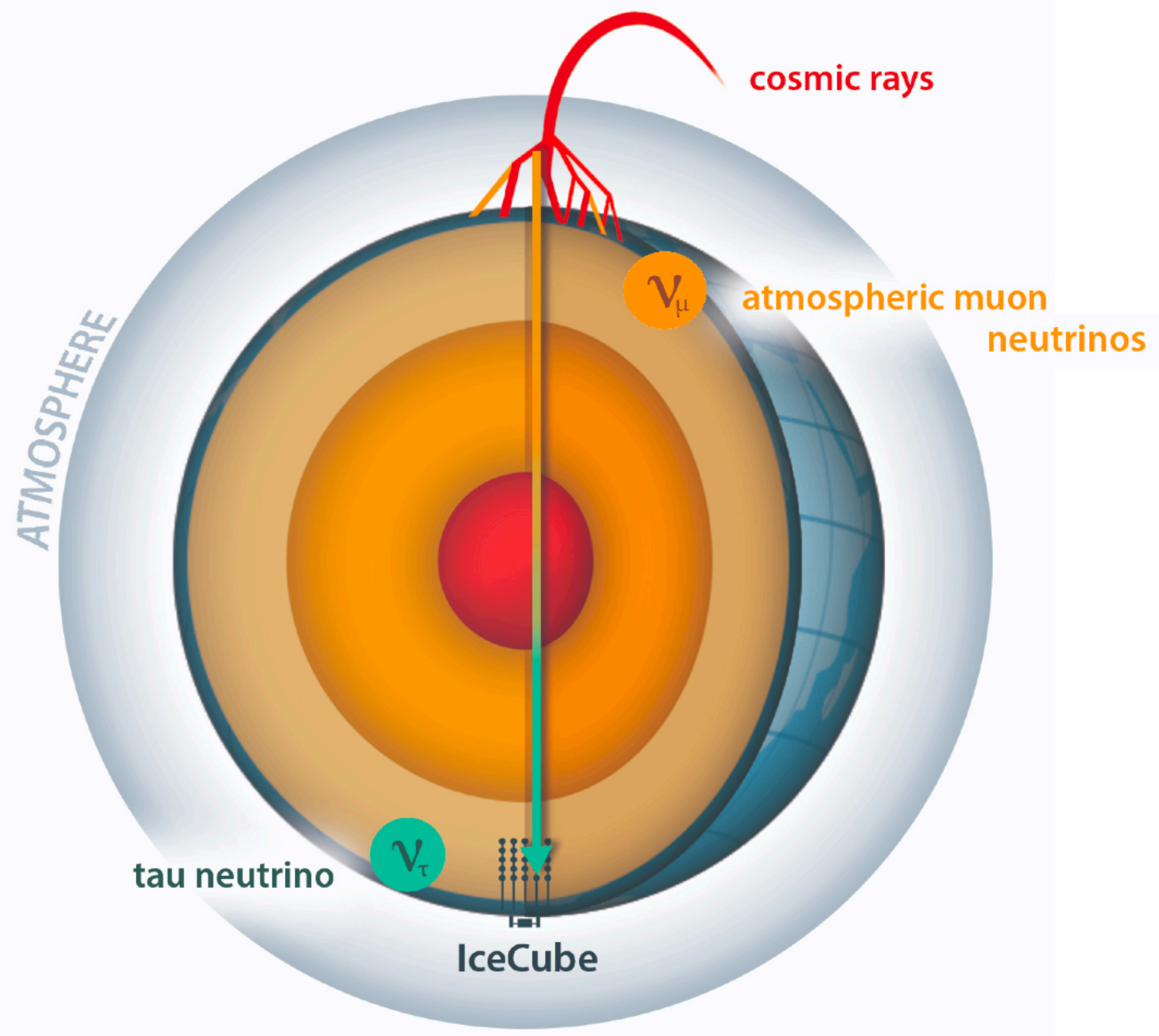
For more, refer back to talk:
Monday 13:50 - Status of IceCube
K. Leonard DeHolton

Atmospheric Neutrinos in DeepCore

- DeepCore looks at atmospheric neutrinos: energies ranging from 5 GeV to 300 GeV

- Muon neutrinos and electron neutrinos from cosmic ray interactions traverse the Earth and reach DeepCore

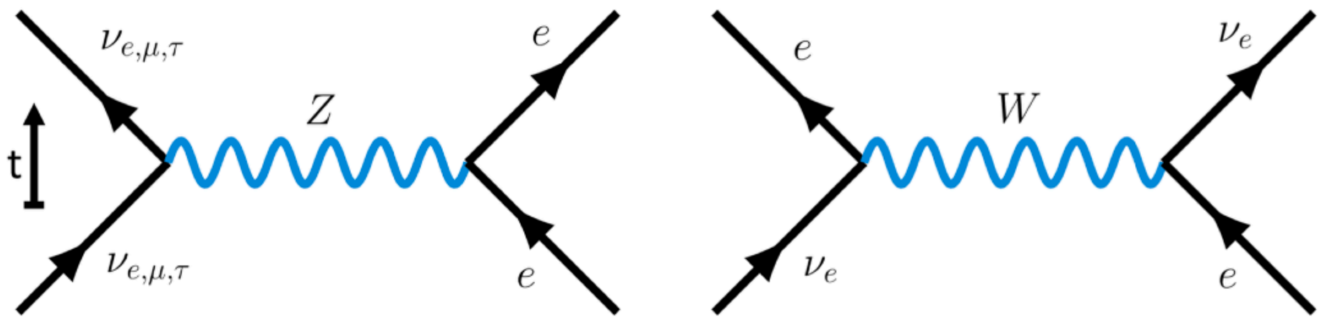
- In the process, Earth matter effects distort naturally occurring neutrino oscillations



NMO with DeepCore

- **DeepCore has opened a new window in the low-energy regime**
- Super-Kamiokande goes up to ~4 GeV and DeepCore takes over from there: multi-GeV range
- DeepCore is analyzing over 9 years of detector data — robust analyses
- DeepCore will play an important role for NMO global fit studies
- DeepCore + JUNO: synergy effects will enhance NMO signal
- DeepCore will allow us to see Earth matter effects

MSW Effect



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

$$\Delta m^2 \to \Delta m_m^2 = C \cdot \Delta m^2$$

$$\sin(2\theta) \to \sin(2\theta_m) = \frac{\sin(2\theta)}{C}$$

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

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

- Neutrinos undergo forward elastic scattering with electrons in matter
- Introduces an effective mixing angle and mass squared difference 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

Effect is maximal when:

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

Neutrinos

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

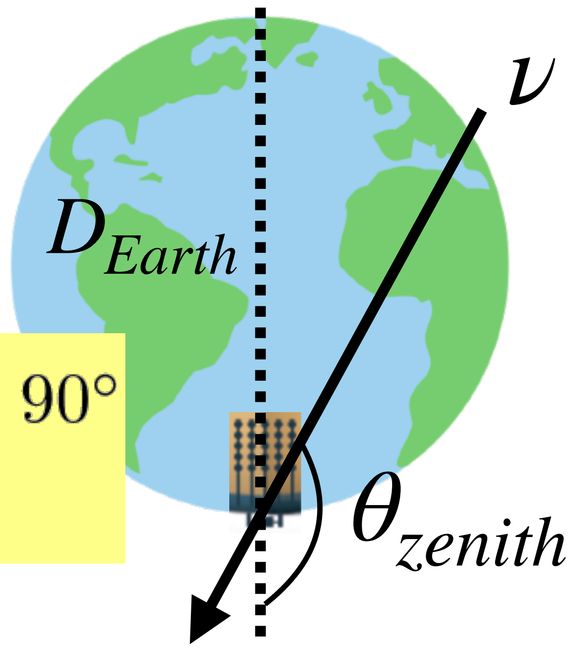
Anti-neutrinos

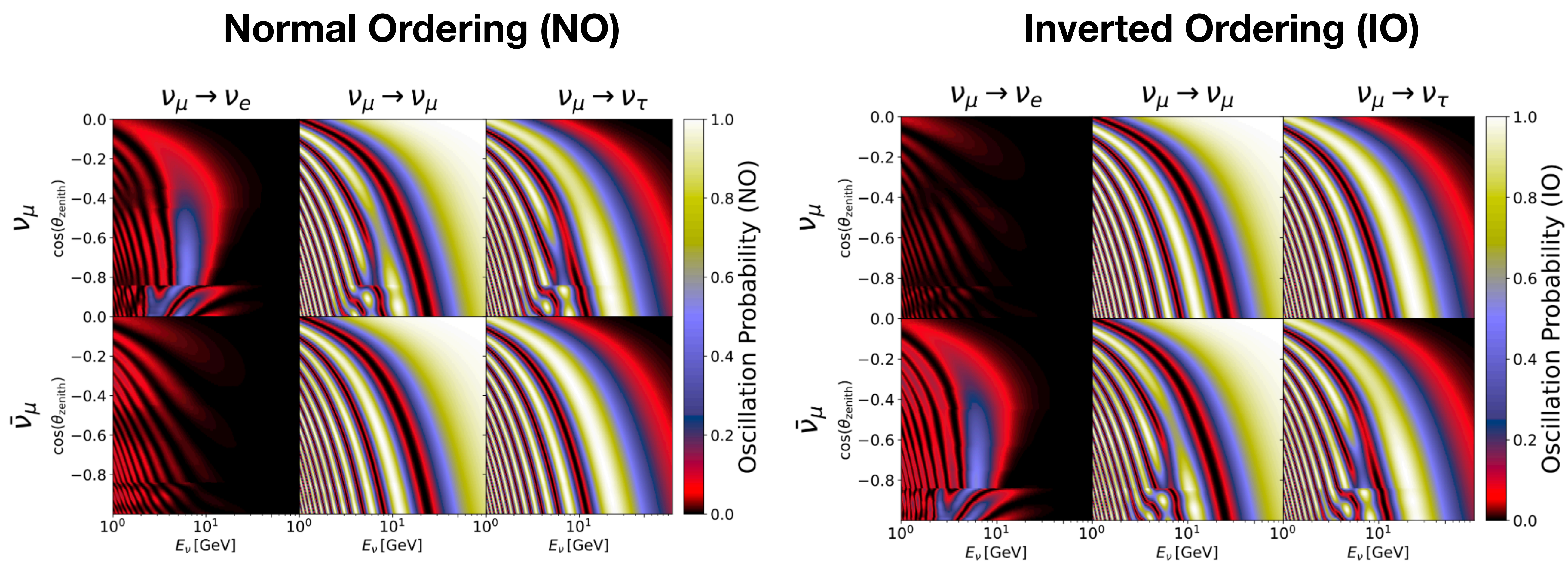
NO true = + Δm^2 **IO true = -**Δm^2

NMO Signal

NMO signal appears due to matter effects for atmospheric neutrinos that traverse the Earth from ~2.5 GeV to 15 GeV

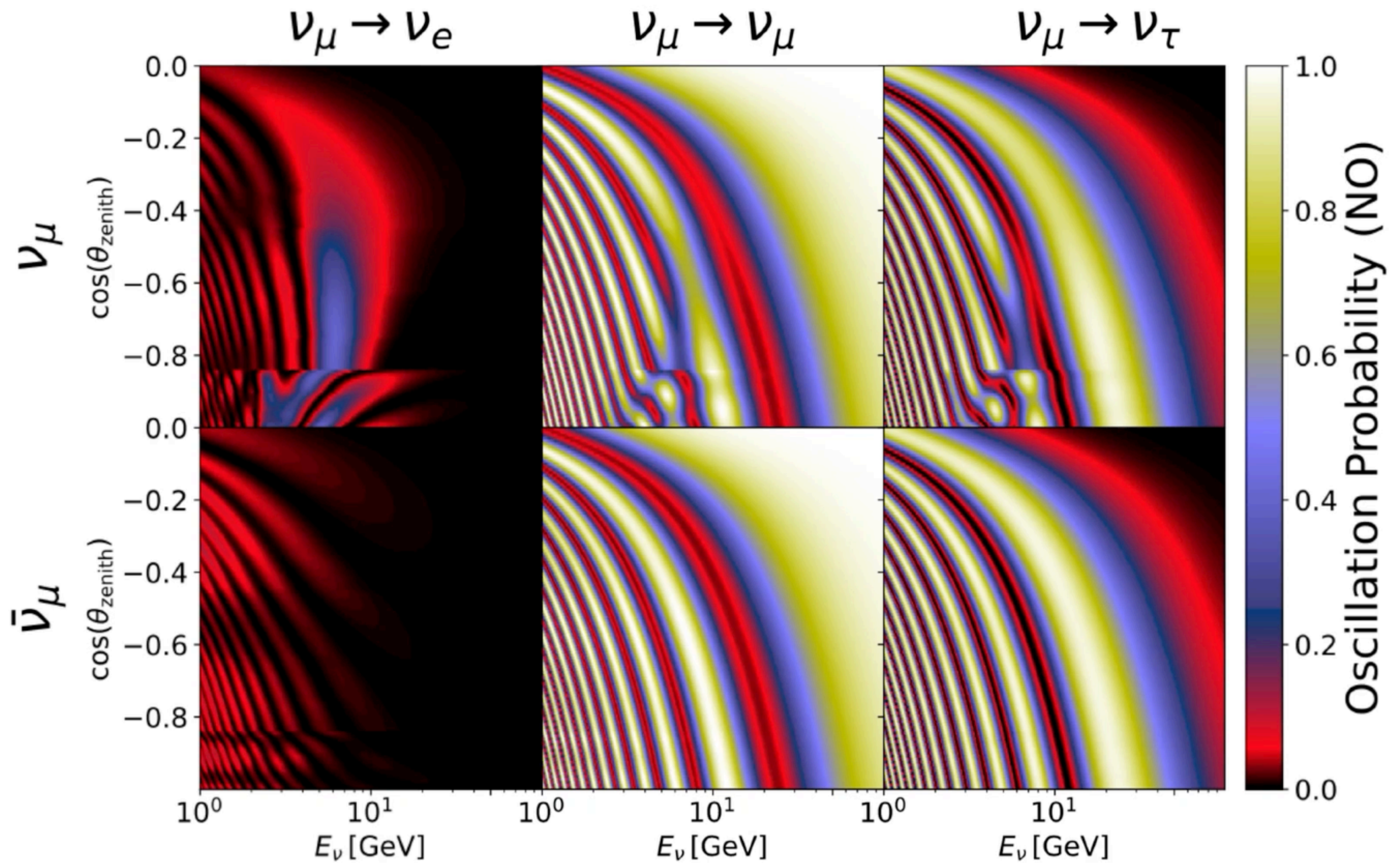
$$L \approx -D_{Earth}\cos(\theta), \quad \theta > 90^\circ$$
$$L \approx 0, \ \text{otherwise}$$





NMO θ_{23} Octant Dependence

$\theta_{23} = 40°$ **vs** $50°$



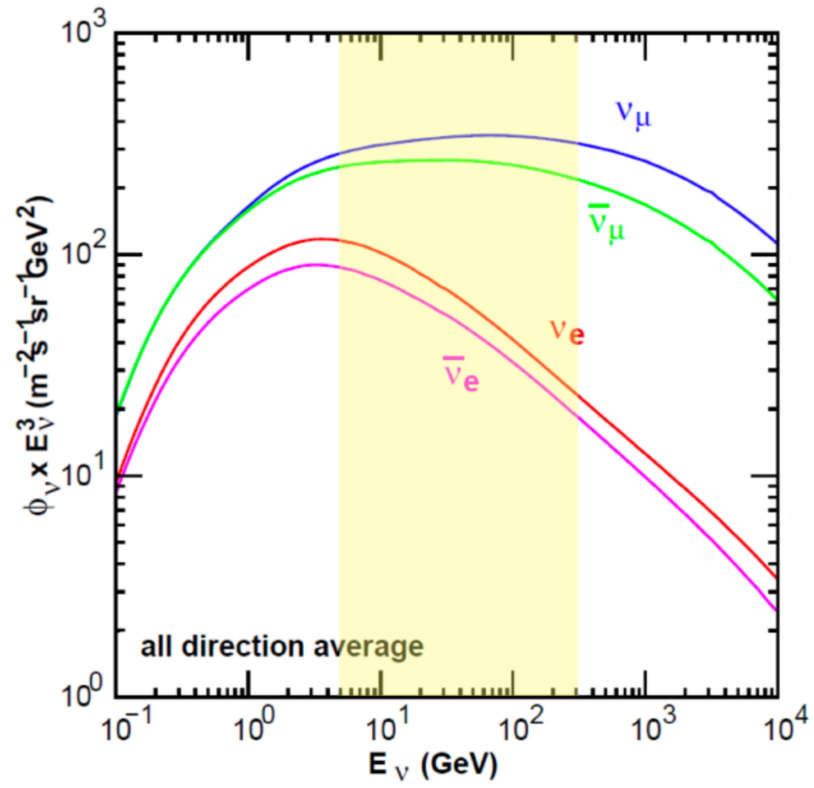
Matter term in the oscillation probabilities gets multiplied by a factor of $\sin^2(\theta_{23})$

Neutrino Sample

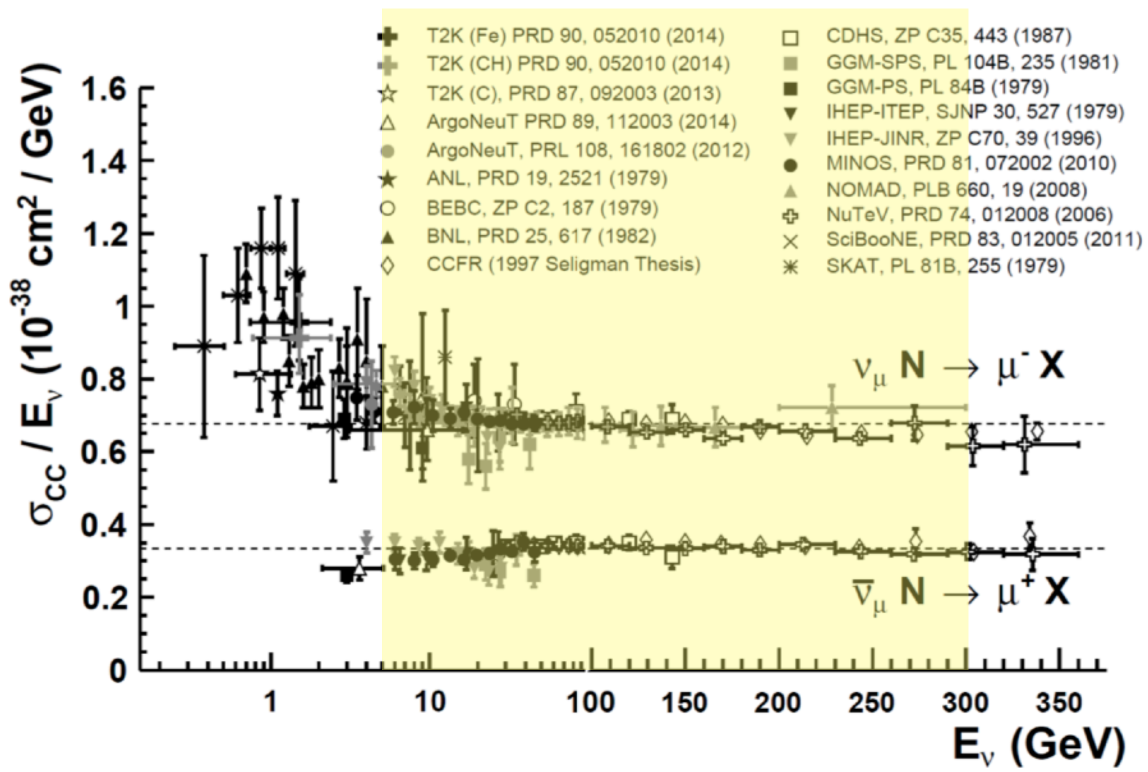
- Neutrino flux at DeepCore energies (5 GeV-300 GeV) is higher than anti-neutrino flux
- Total neutrino cross section at DeepCore energies for neutrino-nucleon scattering is about two times greater for neutrinos vs anti-neutrinos

DOI: 10.18154/RWTH-2018-231554

Flux



Cross Section

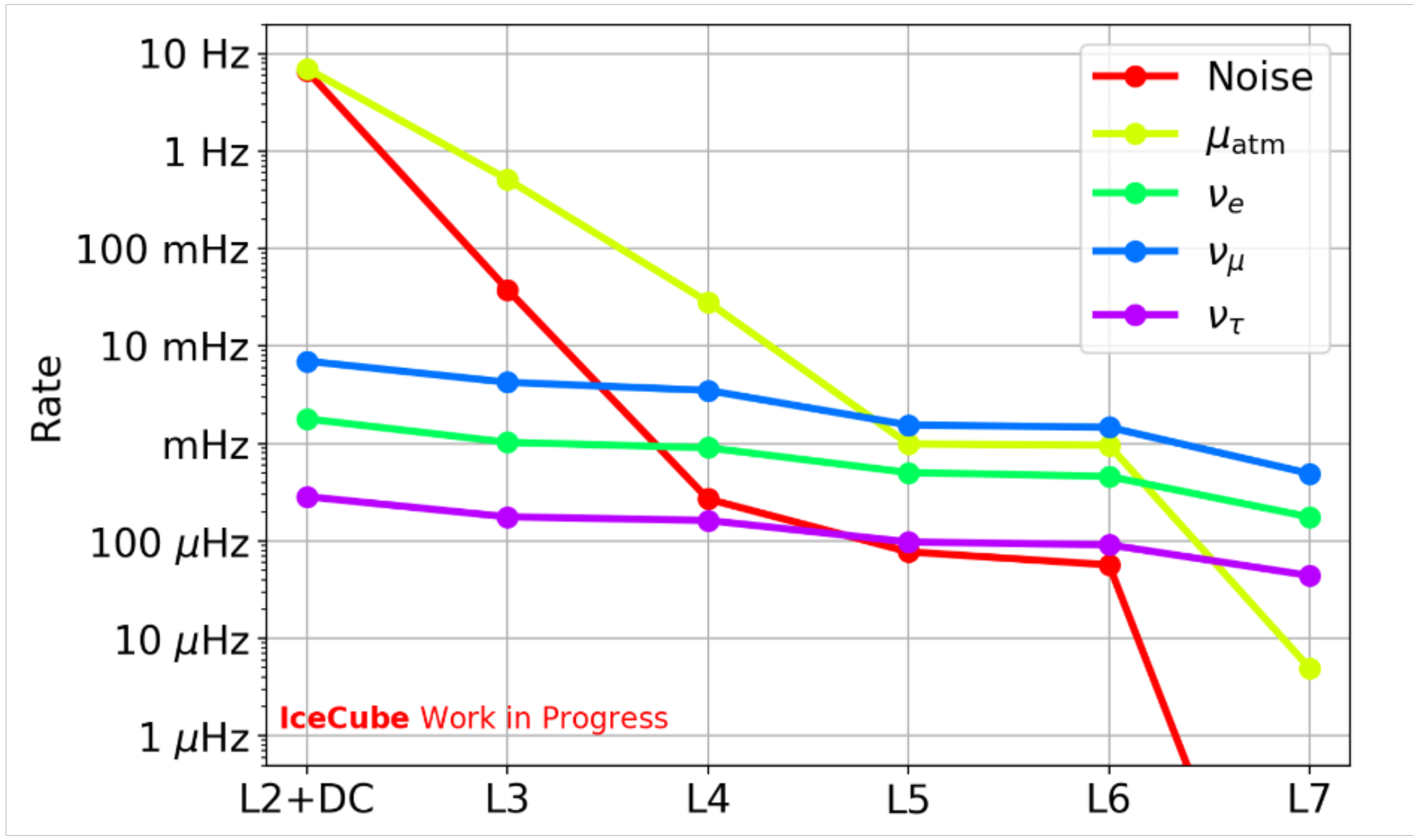


NMO Signal in DeepCore

- Higher sample of neutrinos than anti-neutrinos
- DeepCore is not able to distinguish between neutrinos and anti-neutrinos
- For a combined neutrino/anti-neutrino sample, matter effects are more pronounced for a true NO than for a true IO

9-Year Event Sample

- 99% neutrino purity (6+ orders of magnitude suppression in background)
- BDT classifiers used for background rejection (atmospheric muon and noise)
- More background reduction: fiducial volume containment cuts, cuts on muons that pass the veto region undetected
- More efficient reconstruction method (arXiv:2203.02303v1)
- Improved particle identification method: BDT classifier

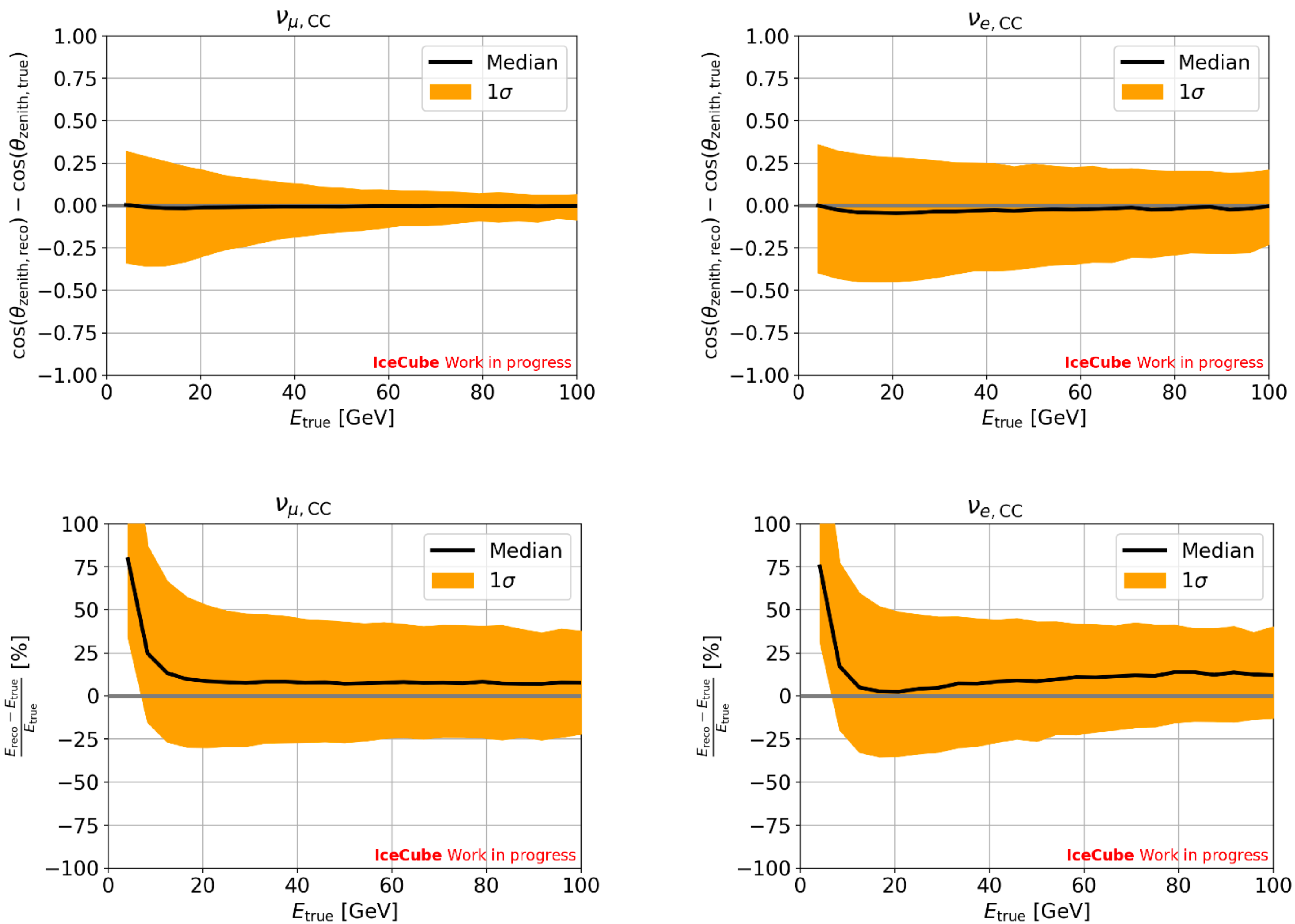


	Rate [mHz]	Num events [9.3 yr]	% of sample
$\nu_{e,\mathrm{CC}}$	0.162	47541 ± 73	23.0
$\nu_{\mu,\mathrm{CC}}$	0.432	126411 ± 126	61.1
$\nu_{\tau,\mathrm{CC}}$	0.032	9510 ± 21	4.6
ν_{NC}	0.075	21966 ± 50	10.6
μ_{atm}	0.005	1463 ± 87	0.7
Total	0.707	206894 ± 179	-

Reconstruction Resolution

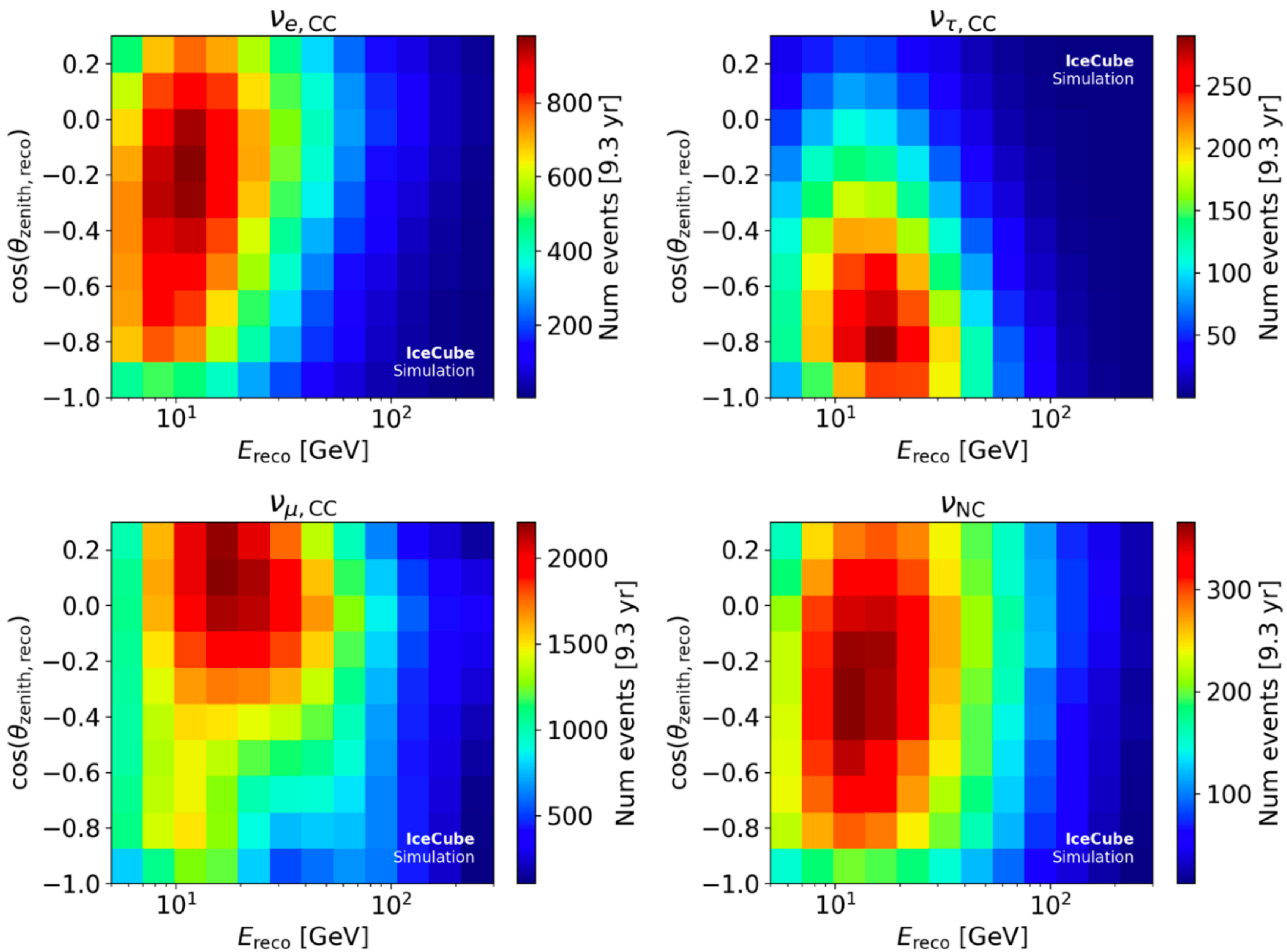
Angular resolution

Energy resolution



Sample Event Distribution

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



Systematic Uncertainties

- **Cosmic ray neutrino flux uncertainties:** Honda flux model (PhysRevD.92.023004) as baseline flux model with MCEq scheme for more model flexibility (EPJWebofConf.99.08001) — Barr parametrization (PhysRevD.74.094009) systematic parameters for Pion and Kaon production uncertainties

- **Neutrino cross-section uncertainties:** Deep Inelastic Scattering (DIS) cross section systematic parameter for CSMS (JHEP08(2011)042) ↔

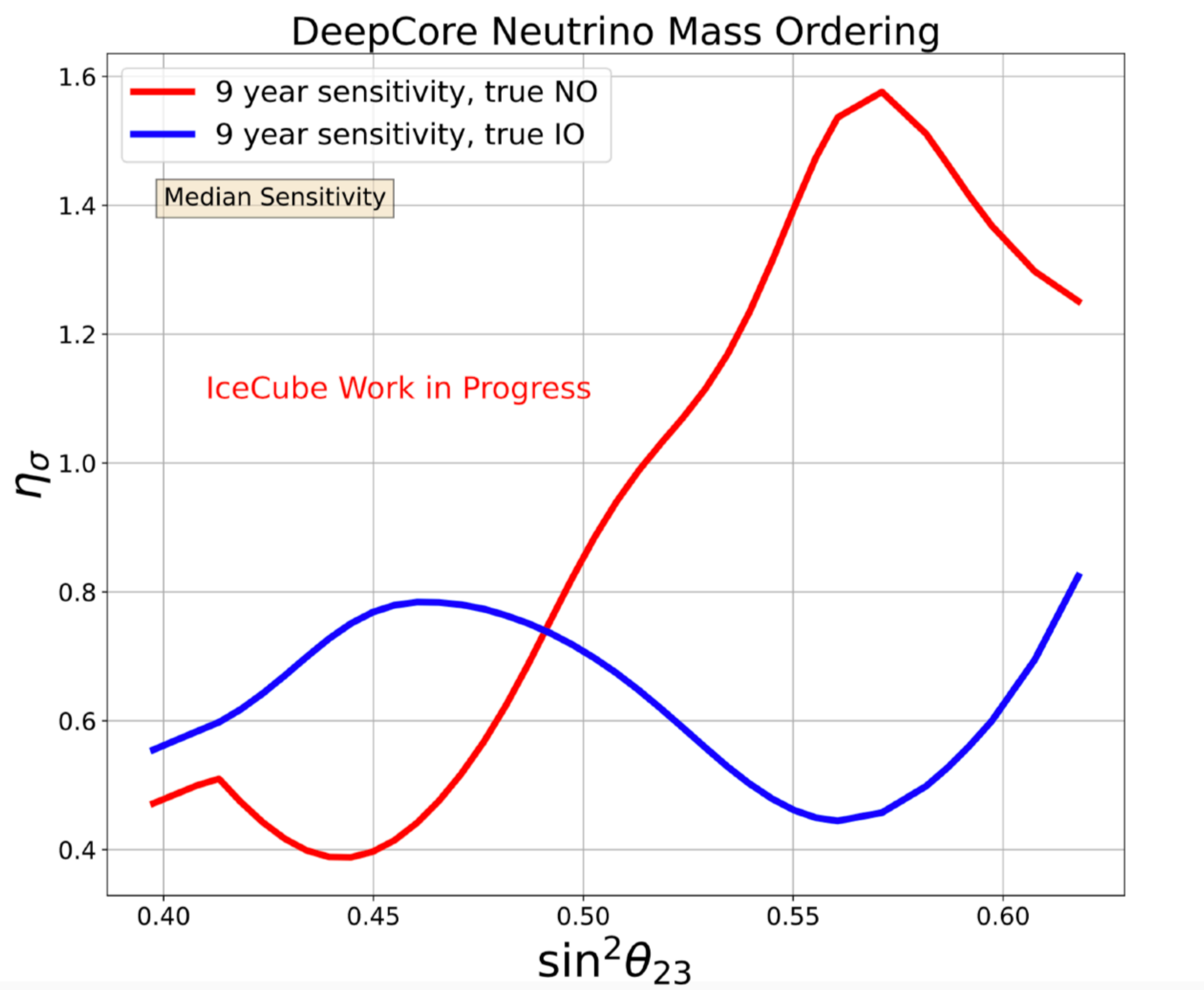
  GENIE (arXiv:1510.05494) transformation as well as systematic parameters for the axial mass of Resonance (RES) and quasi-elastic (QE) interactions

- **Detector uncertainties:** Includes ice scattering and absorption properties systematics as well as the optical efficiency of the PMT

9-Year NMO Sensitivity

Key observations:

- Upper octant is most favorable for resolving the ordering provided NO is true
- Lower octant is most favorable for resolving the ordering provided IO is true

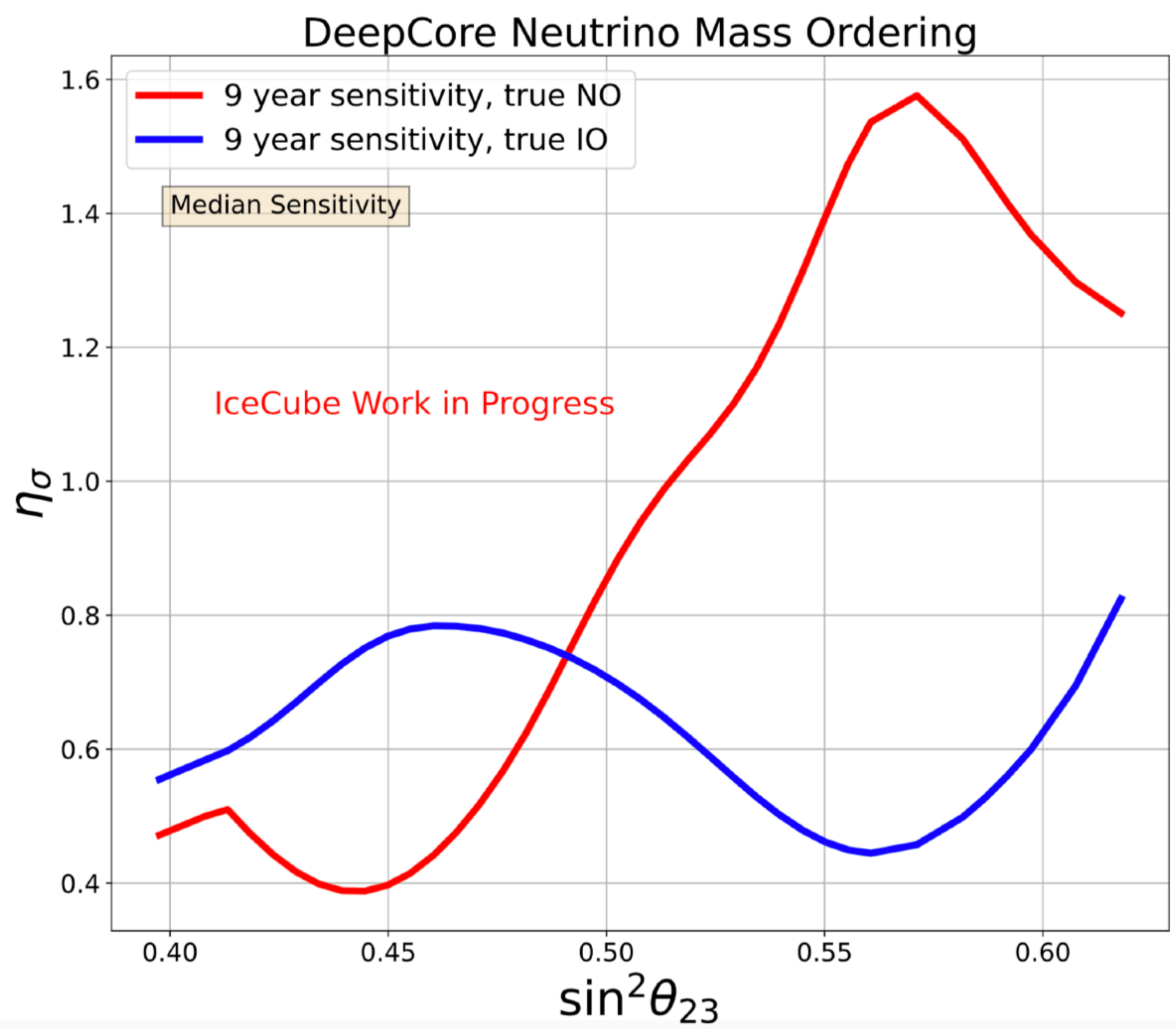


9-Year NMO Sensitivity

Next Step:

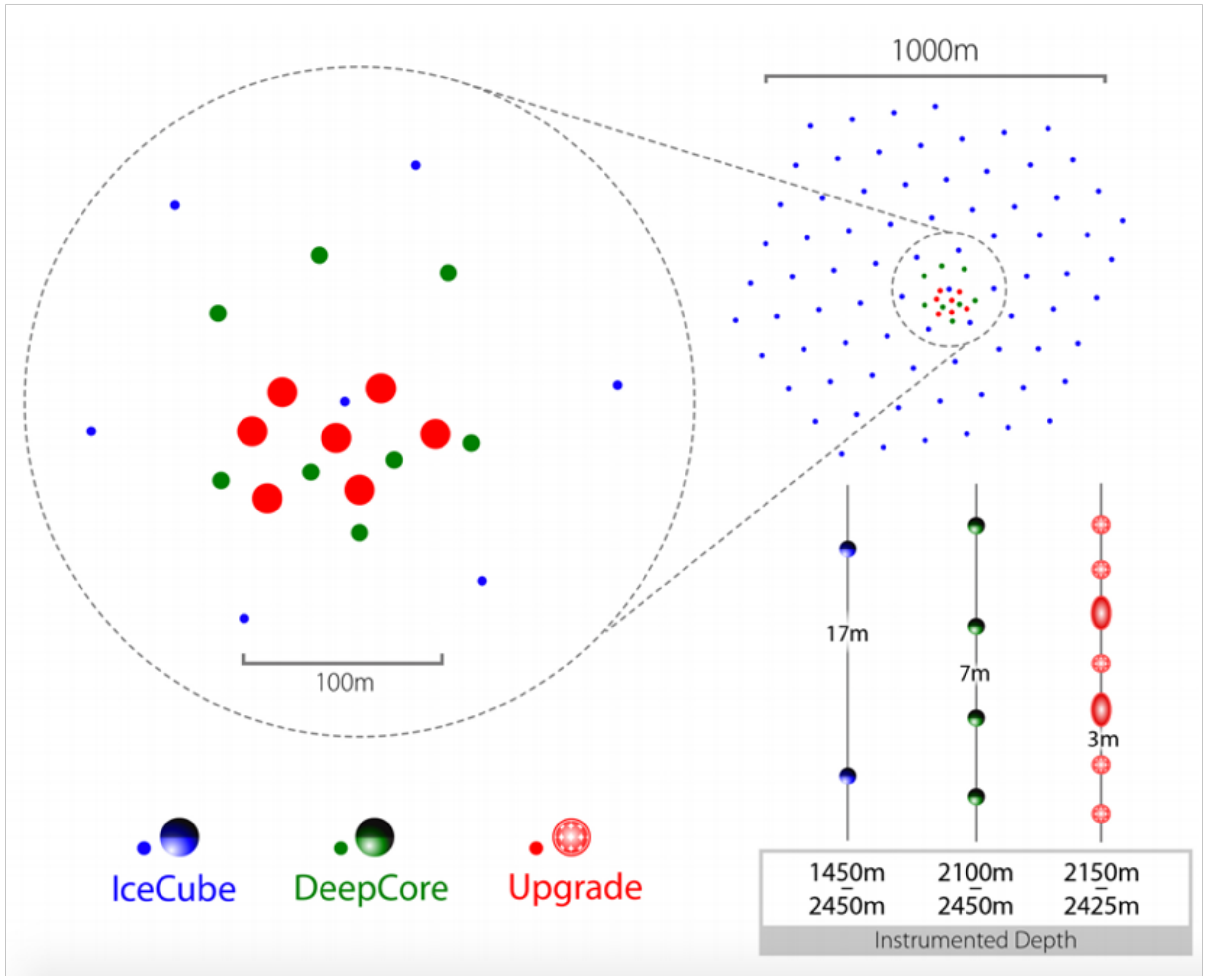
Plan to analyze further the impact of

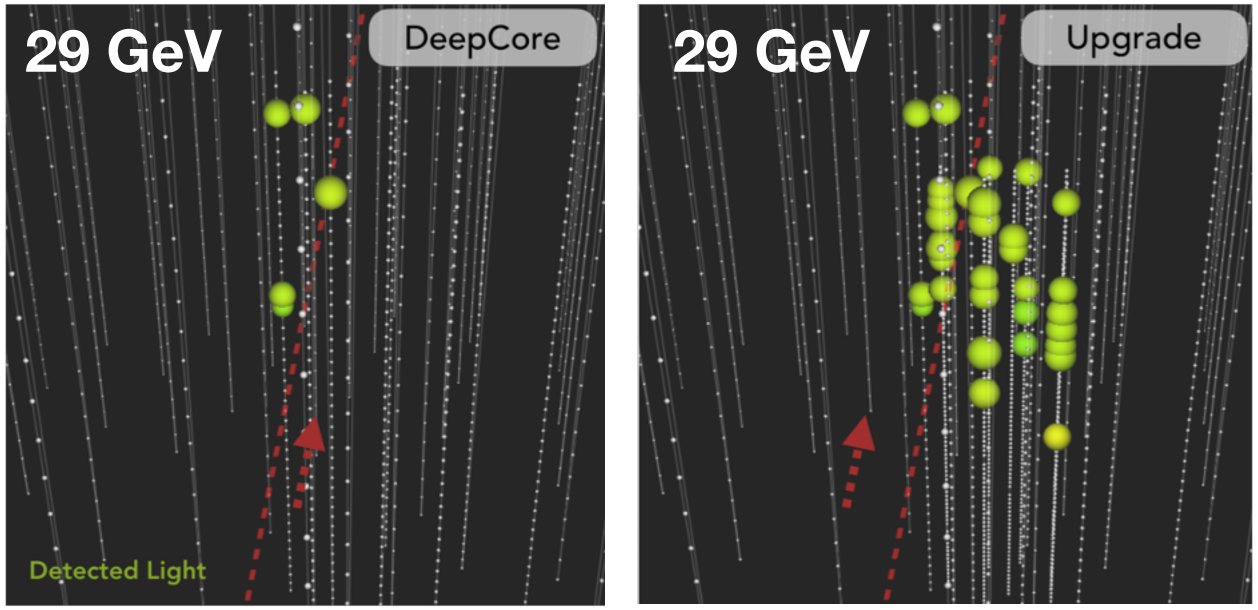
- Binning
- Systematic uncertainties
- Priors on oscillation parameters
- Particle Identification
- Reducing the energy threshold



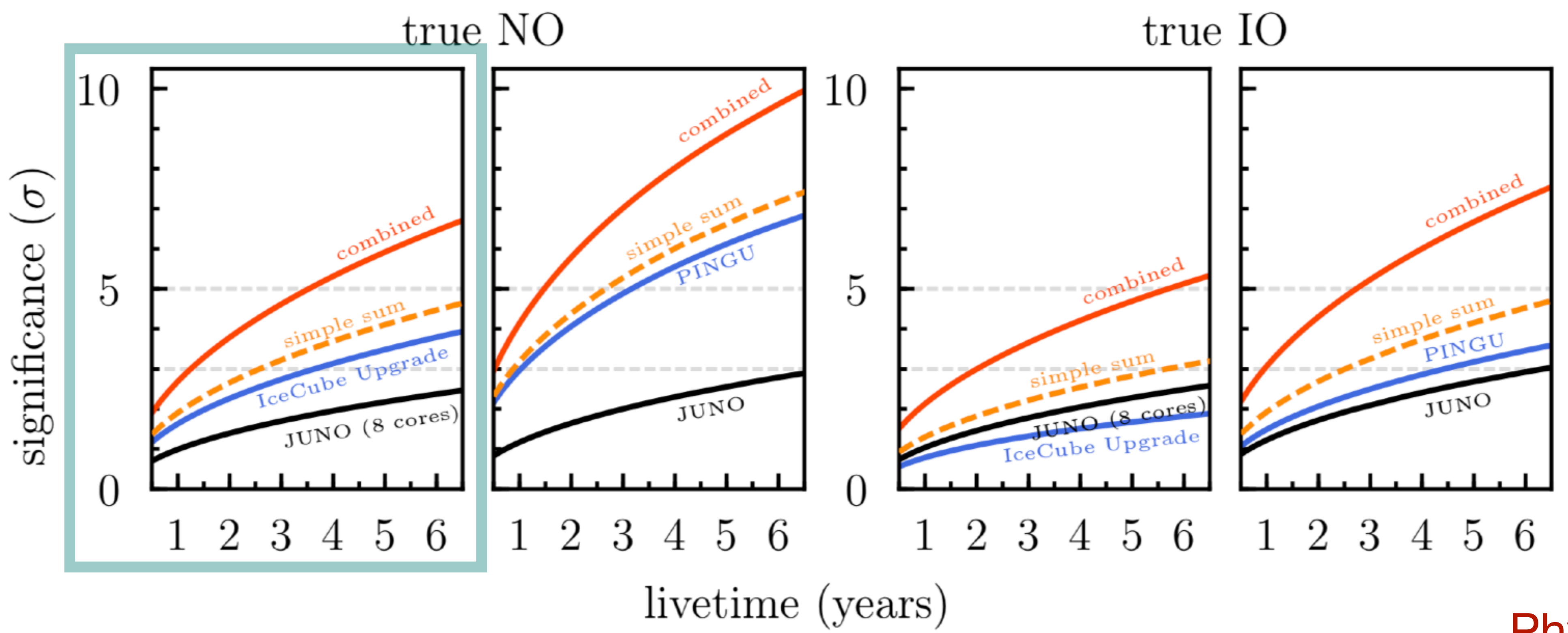
The IceCube Upgrade

- Seven more strings will be added with smaller optical sensor spacing
- Will help us reach lower energy events (1-10 GeV) as well as improve the current analysis
- Will be more sensitive to NMO signal region (~2.5 -15 GeV)





NMO with the Upgrade + JUNO



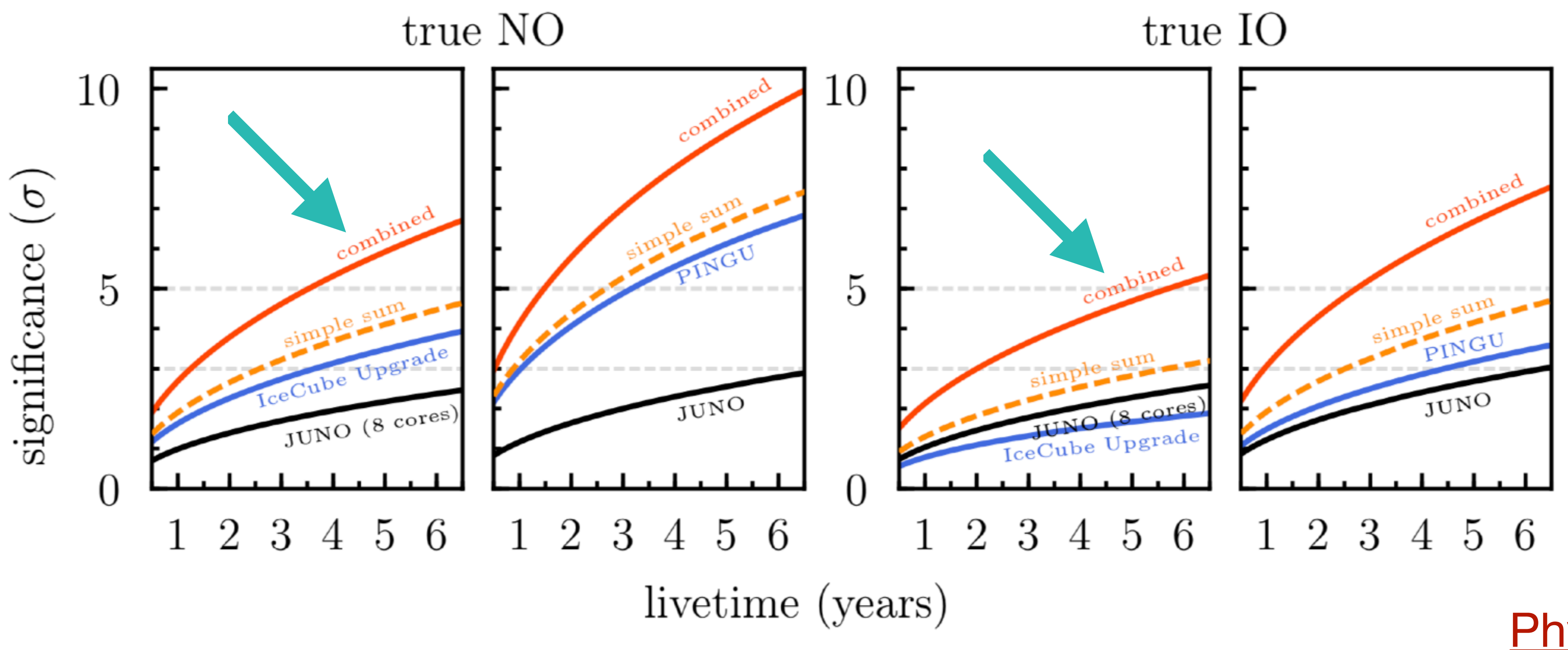
NO: $\theta_{23} = 49.6°$

IO: $\theta_{23} = 49.8°$

PhysRevD.101.032006

- 3σ projected NO sensitivity after four years of data-taking of **Upgrade only**

NMO with the Upgrade + JUNO



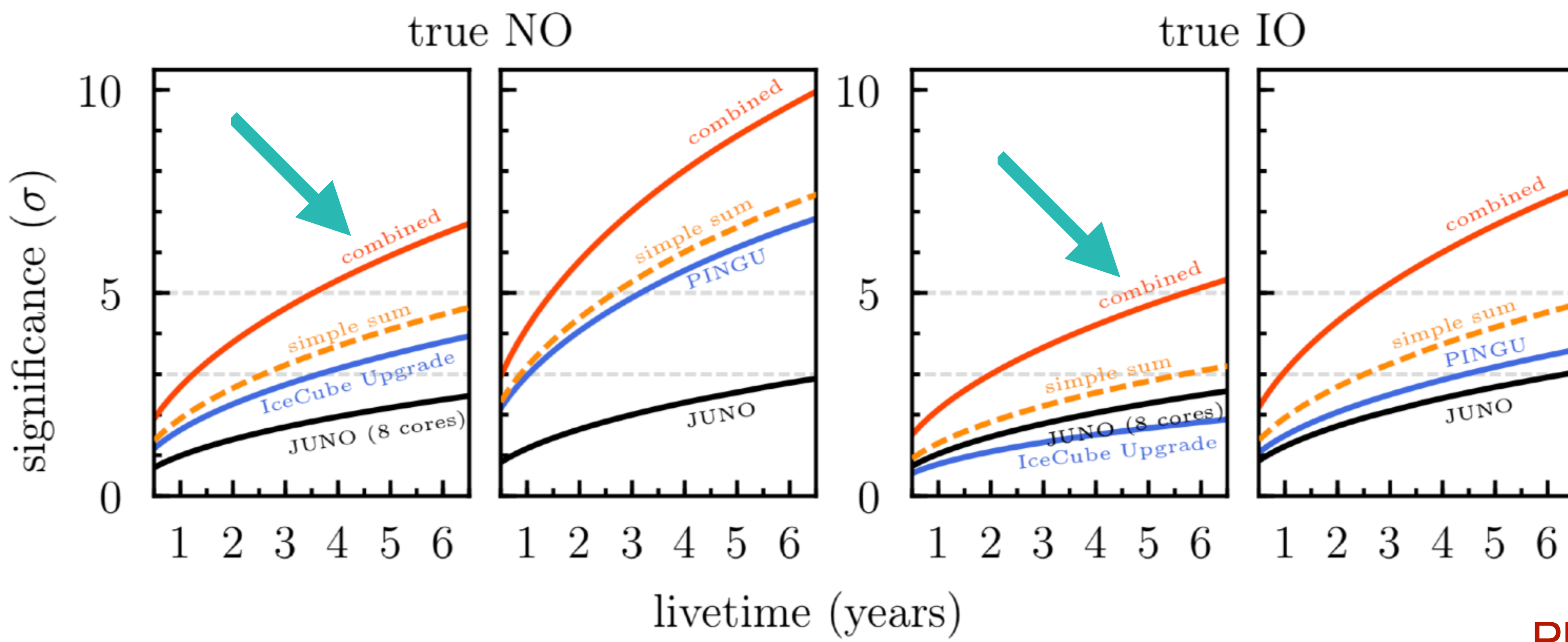
NO: $\theta_{23} = 49.6^{\circ}$

IO: $\theta_{23} = 49.8^{\circ}$

PhysRevD.101.032006

- 3σ projected NO sensitivity after four years of data-taking of **Upgrade only**
- **JUNO+Upgrade combined sensitivity**: same oscillation parameters in the fit for both experiments

NMO with the Upgrade + JUNO



NO: $\theta_{23} = 49.6^{\circ}$

IO: $\theta_{23} = 49.8^{\circ}$

PhysRevD.101.032006

- 3σ projected NO sensitivity after four years of data-taking of **Upgrade only**
- **JUNO+Upgrade combined sensitivity:** same oscillation parameters in the fit for both experiments
- Synergy effect observed for JUNO+Upgrade combined sensitivity when fitting opposite orderings: IO to NO data and NO to IO data

DeepCore NMO Outlook

- The future looks bright for the NMO!
- DeepCore: Over 200k atmospheric neutrino events in 9.3 years
- DeepCore + JUNO NMO: DeepCore already has data — JUNO is coming soon
- Synergy effects between DeepCore + JUNO could give us promising NMO results soon
- The IceCube Upgrade is fully funded and will be deployed soon (2025-2026)
- With ~3.5 years of both Upgrade + JUNO data, synergy effects could enhance NMO signal up to 5σ for a **true NO** (PhysRevD.101.032006)
- With ~6 years of both Upgrade + JUNO data, synergy effects could enhance NMO signal up to 5σ for a **true IO** (PhysRevD.101.032006)

Summary

- Nine-year DeepCore event sample: More than triple the data as compared to previous DeepCore studies (PhysRevD.99.032007) with improved signal to background ratio

- Nine-year NMO sensitivity: Upper octant of θ_{23} is the most favorable region for resolving the ordering provided NO is true

- We plan to analyze further the impact of all the analysis components to improve the NMO signal

- The IceCube Upgrade will see neutrino events as low as 1 GeV

- The IceCube Upgrade alone has a projected NMO sensitivity of 3σ for the NO after 4 years of data taking

- DeepCore + Upgrade + JUNO: synergy effects with JUNO will enhance NMO signal with a very exciting outlook

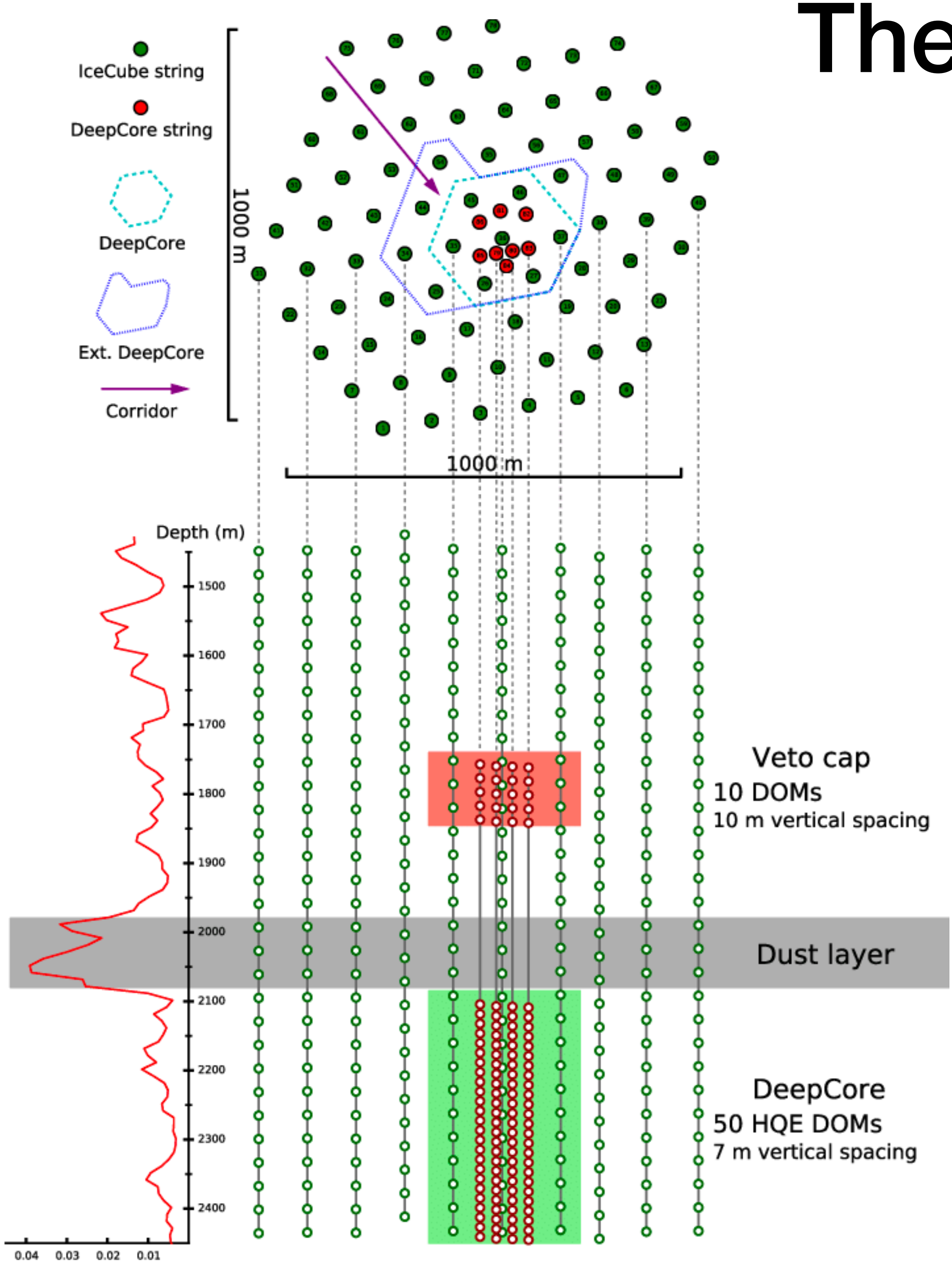
Thank you

Backup Slides

NMO Motivation

- Neutrinos have a non-zero mass, now what?
- The neutrino mass ordering becomes one of the building blocks of several neutrino physics models:
    - Neutrinoless double beta decay — enhanced signal for true IO
    - Sterile neutrino studies
    - Non-standard interaction studies

The DeepCore Subarray



	IceCube	DeepCore
Number of strings	78 IceCube strings	8 DeepCore strings
Vertical distance between DOMs	17 meters	7 meters
Horizontal distance between DOMS	110-150 meters	40-90 meters
Total DOMs per string	60	60

Analytical expression for these channels in the approximations of one mass scale dominance (OMSD), i.e. $\alpha = \Delta m^2_{21}/\Delta m^2_{31} = 0$. (E.K.Akhmedov et.al., hep-ph/0402175)

In the approximation where s13 <<1,

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \Delta - \sin^2 2\theta_{13} s^2_{23} \frac{\sin^2(\hat{A}-1)\Delta}{(\hat{A}-1)^2} - \frac{2}{(\hat{A}-1)} s^2_{13} \sin^2 2\theta_{23} \left(\sin\Delta \cos A\Delta \frac{\sin(\hat{A}-1)\Delta}{\hat{A}-1} - \frac{\hat{A}}{2}\Delta \sin 2\Delta \right) \quad (1)$$

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{13} s^2_{23} \frac{\sin^2(\hat{A}-1)\Delta}{(\hat{A}-1)^2} \quad (2)$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} s^2_{23} \frac{\sin^2(\hat{A}-1)\Delta}{(\hat{A}-1)^2} \quad (3)$$

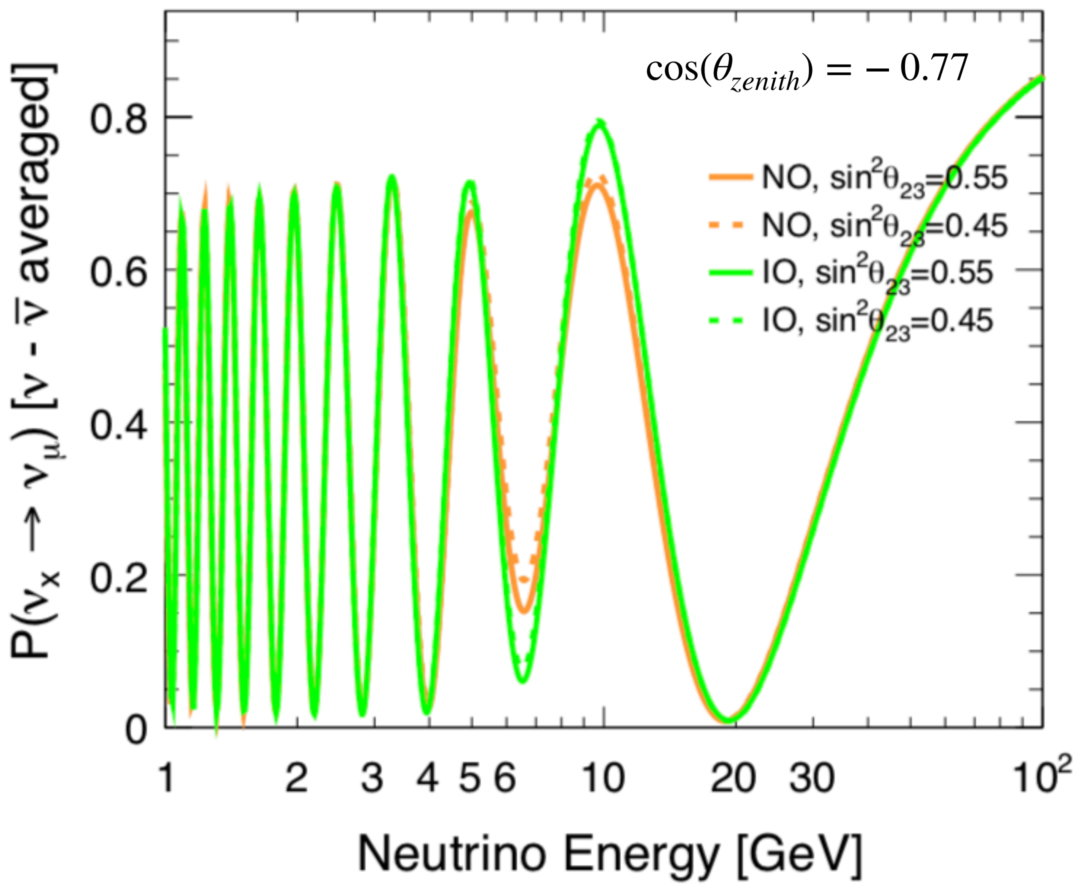
$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13} \frac{\sin^2(\hat{A}-1)\Delta}{(\hat{A}-1)^2} \quad (4)$$

where $\Delta \equiv \Delta m^2_{31} L/4E$ and $\hat{A} \equiv A/\Delta m^2_{31}$. The Wolfenstein matter term, $A = 2\sqrt{2} G_F N_e E = 7.6 \times 10^{-5} \times \rho(g/cm^3) \times E(\mathrm{GeV})$,

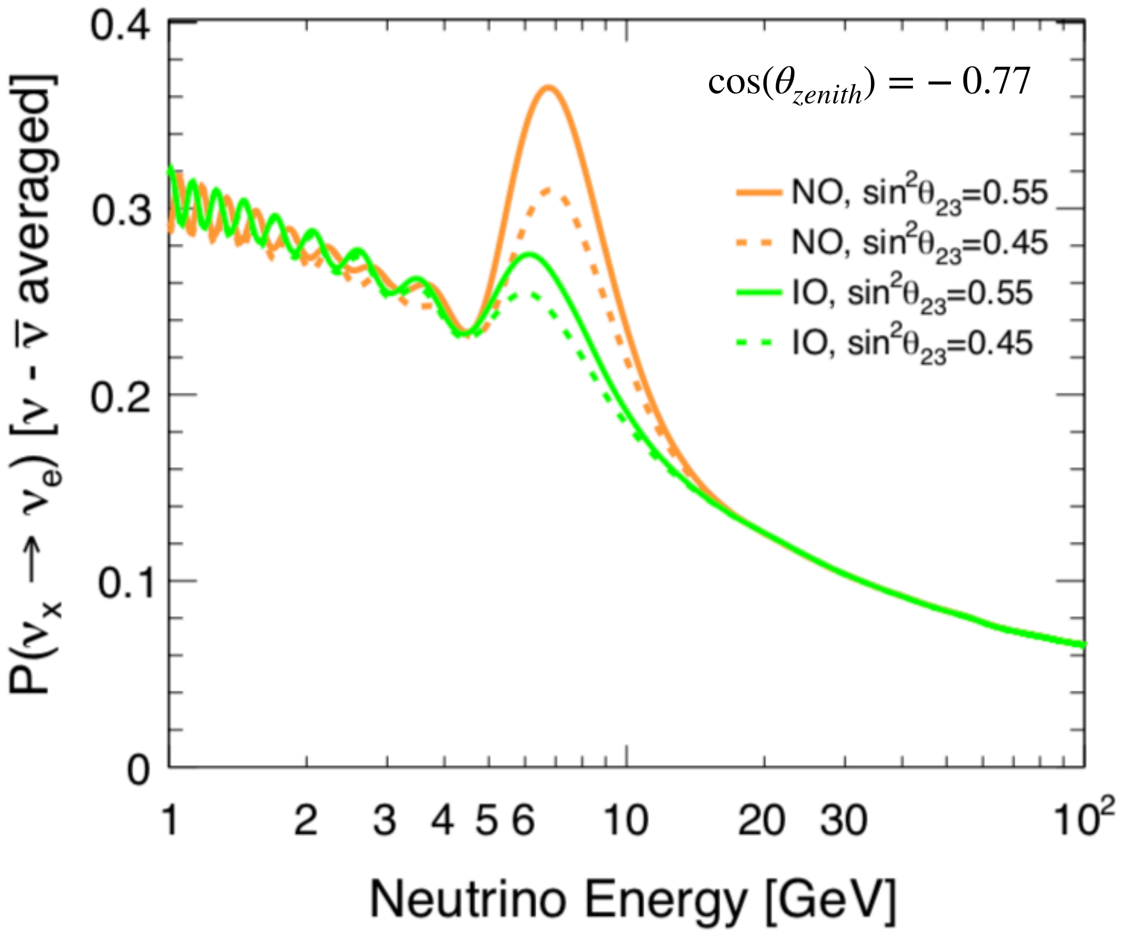
Oscillation Probabilities

Full three-flavor oscillation probability in presence of matter effects with combined neutrino/antineutrino weighted average

Tracks



Cascades



If we put all information of flux and cross-section together, we can define final probability for track-like channels ($P(\nu_x \to \nu_\mu)$) and cascade-like channels ($P(\nu_x \to \nu_e)$) as following:

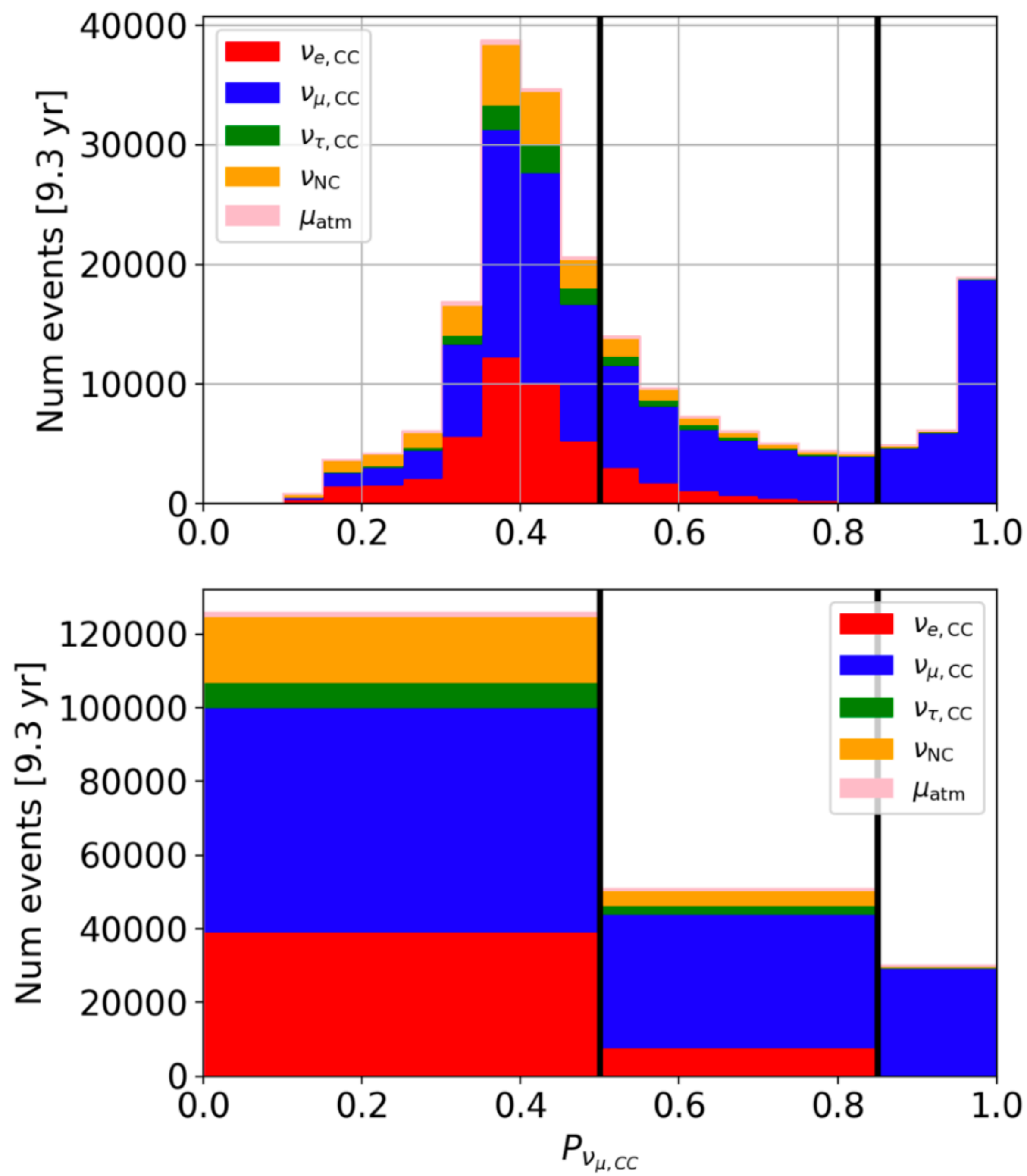
$$P(\nu_x \to \nu_\mu) = \frac{P(\nu_\mu \to \nu_\mu) + \frac{1}{x_1}P(\nu_e \to \nu_\mu) + \frac{1}{y_1 z_1}P(\bar{\nu}_\mu \to \bar{\nu}_\mu) + \frac{1}{x_2 y_2 z_2}P(\bar{\nu}_e \to \bar{\nu}_\mu)}{\left(1 + \frac{1}{x_1} + \frac{1}{y_1 z_1} + \frac{1}{x_2 y_2 z_2}\right)} \tag{5}$$

$$P(\nu_x \to \nu_e) = \frac{P(\nu_\mu \to \nu_e) + \frac{1}{x_1}P(\nu_e \to \nu_e) + \frac{1}{y_1 z_1}P(\bar{\nu}_\mu \to \bar{\nu}_e) + \frac{1}{x_2 y_2 z_2}P(\bar{\nu}_e \to \bar{\nu}_e)}{\left(1 + \frac{1}{x_1} + \frac{1}{y_1 z_1} + \frac{1}{x_2 y_2 z_2}\right)} \tag{6}$$

where,
x_1 is flux ratio of ν_μ/ν_e, y_1 is flux ratio of $\nu_\mu/\bar{\nu}_\mu$ z_1 is cross-section ratio of $\nu_\mu/\bar{\nu}_\mu$
x_2 is flux ratio of $\bar{\nu}_\mu/\bar{\nu}_e$, y_2 is flux ratio of $\nu_e/\bar{\nu}_e$ z_2 is cross-section ratio of $\nu_e/\bar{\nu}_e$

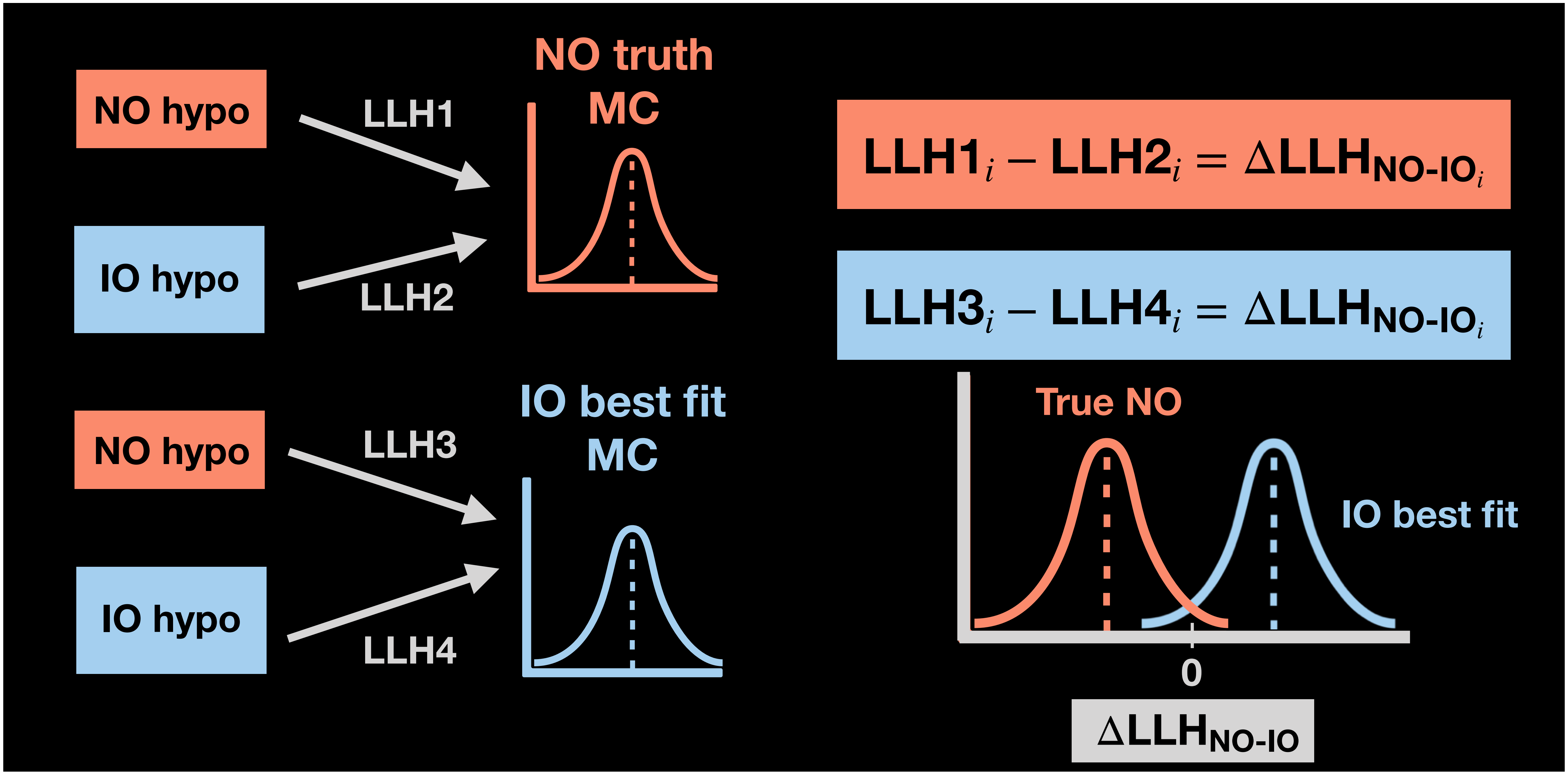
Note: All factors (x_1, y_1, z_1 etc.) are function of energy.

DeepCore PID: BDT



NMO Analysis

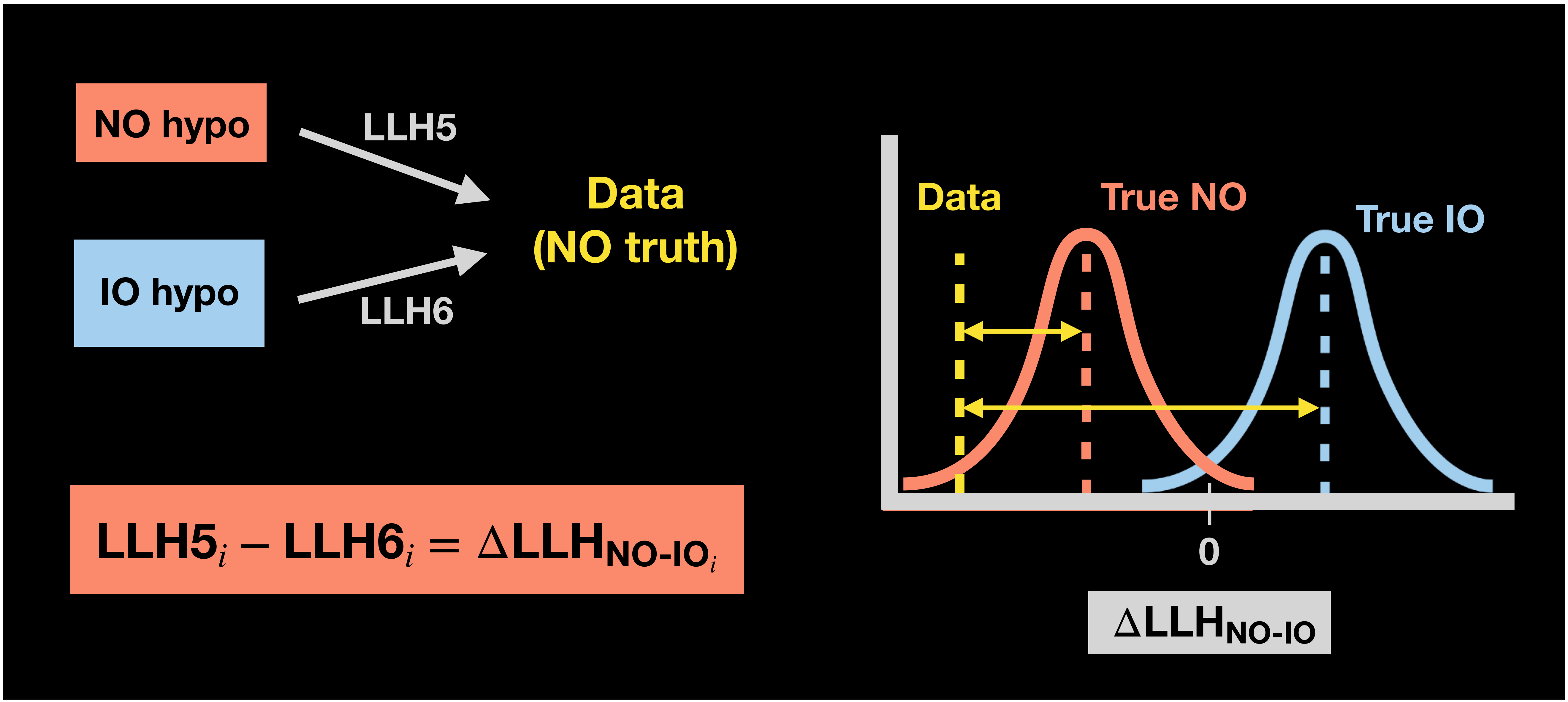
Example using MC data: Assume NO (True Ordering)



Goal: Be able to reject even the best fit case of the wrong ordering

NMO Analysis

Example using real data: Assume NO (True Ordering)

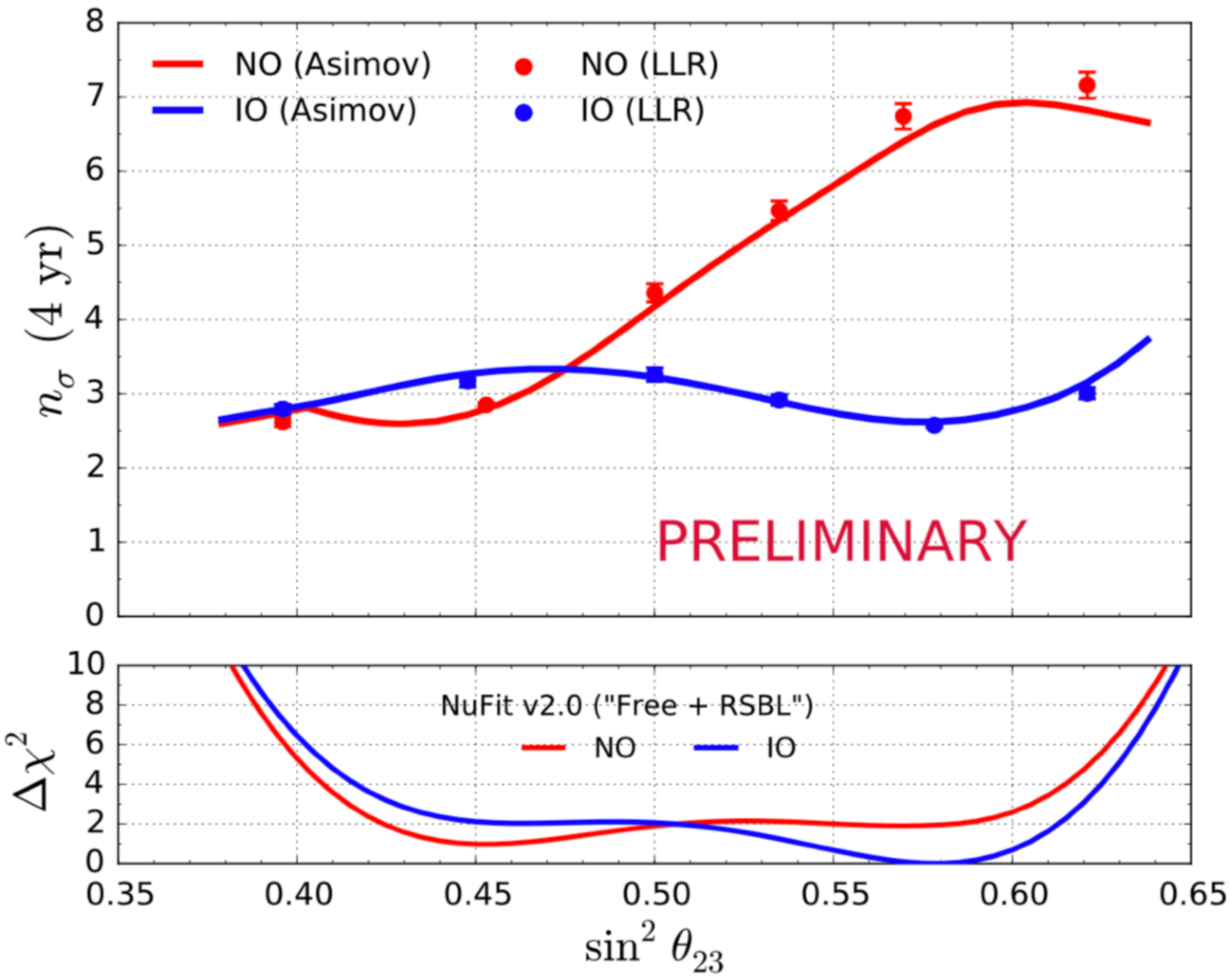


NMO Sensitivity Equation Used

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

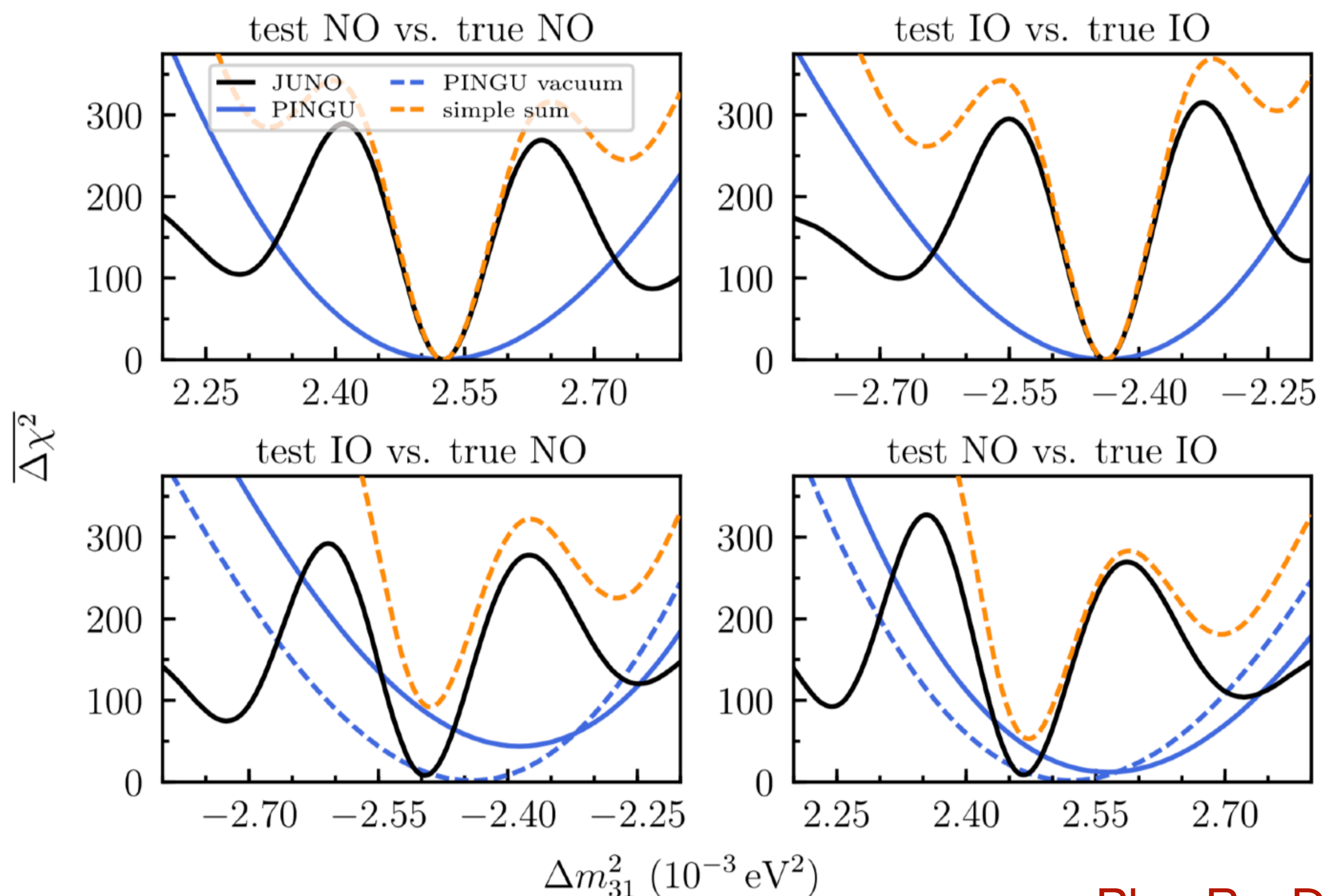
How many standard deviations away from the median of the wrong best-fit ordering is the observed value?

PINGU NMO Sensitivity



arXiv:1401.2046

IceCube + JUNO Synergy Effect



Livetime of 6 years

PhysRevD.101.032006

Synergy effect coming from fitting NO to IO data (and vice versa)

IceCube + JUNO Synergy Effect

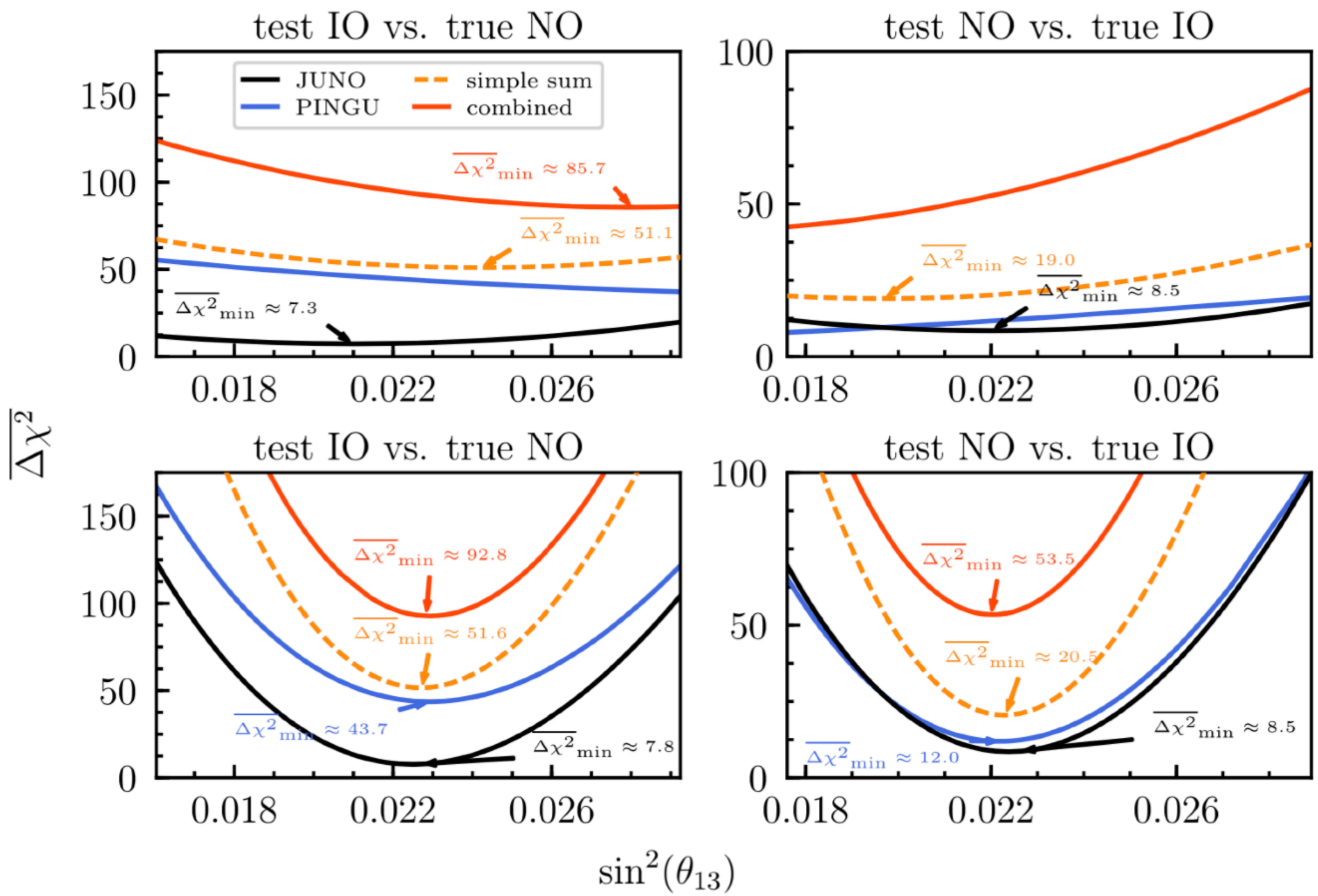


FIG. 5. θ_{13} synergy effect after 6 years of livetime of both experiments, without (top) and with (bottom) a prior on the parameter, assuming true NO on the left and true IO on the right. In each case, the wrong ordering is fit to the true one. In contrast to Fig. 4, here we show the full combined fit (solid red) in addition to the "simple sum" (dashed orange).

PhysRevD.101.032006

Oscillation & Nuisance Parameters

Stage	Param	Fixed/Free	Nominal	Prior	Range
mceq_barr	$\Delta\gamma_\nu$	Free	0	gaussian, $\sigma = \pm 0.1$	[-0.5, 0.5]
mceq_barr	energy pivot [GeV]	Fixed	24.1	-	-
mceq_barr	Barr, π^+/π^-	Fixed	0	-	-
mceq_barr	Barr, a_π^+	Fixed	0	-	-
mceq_barr	Barr, b_π^+	Fixed	0	-	-
mceq_barr	Barr, c_π^+	Fixed	0	-	-
mceq_barr	Barr, d_π^+	Fixed	0	-	-
mceq_barr	Barr, e_π^+	Fixed	0	-	-
mceq_barr	Barr, f_π^+	Fixed	0	-	-
mceq_barr	Barr, g_π^+	Free	0	gaussian, $\sigma = \pm 0.3$	[-1.5, 1.5]
mceq_barr	Barr, h_π^+	Free	0	gaussian, $\sigma = \pm 0.15$	[-0.75, 0.75]
mceq_barr	Barr, i_π^+	Free	0	gaussian, $\sigma = \pm 0.122$	[-0.61, 0.61]
mceq_barr	Barr, w_K^+	Free	0	gaussian, $\sigma = \pm 0.4$	[-2, 2]
mceq_barr	Barr, x_K^+	Fixed	0	-	-
mceq_barr	Barr, y_K^+	Free	0	gaussian, $\sigma = \pm 0.3$	[-1.5, 1.5]
mceq_barr	Barr, z_K^+	Fixed	0	-	-
mceq_barr	Barr, w_K^-	Fixed	0	-	-
mceq_barr	Barr, x_K^-	Fixed	0	-	-
mceq_barr	Barr, y_K^-	Fixed	0	-	-
mceq_barr	Barr, z_K^-	Fixed	0	-	-
prob3	earth model	Fixed	osc/PREM_12layer.dat	-	-
prob3	YeI	Fixed	0.466	-	-
prob3	YeM	Fixed	0.496	-	-
prob3	YeO	Fixed	0.466	-	-
prob3	detector depth [km]	Fixed	2	-	-
prob3	prop height [km]	Fixed	20	-	-
prob3	θ_{12} [deg]	Fixed	33.8	-	-
prob3	θ_{13} [deg]	Fixed	8.61	-	-
prob3	θ_{23} [deg]	Free	45.4	uniform	[0, 90]
prob3	δ_{CP} [deg]	Fixed	0	-	-
prob3	Δm^2_{21} [eV^2]	Fixed	7.39e-05	-	-
prob3	Δm^2_{31} [eV^2]	Free	0.00248	uniform	[0.001, 0.005]
genie_sys	$M_{A,QE}$	Free	0	gaussian, $\sigma = \pm 1$	[-2, 2]
genie_sys	$M_{A,res}$	Free	0	gaussian, $\sigma = \pm 1$	[-2, 2]
dis_sys	DIS	Free	0	gaussian, $\sigma = \pm 1$	[-3, 3]
aeff	livetime [common_year]	Fixed	9.28	-	-
aeff	N_ν	Free	1	uniform	[0.1, 2]
aeff	N_{ν_τ}	Fixed	1	-	-
aeff	$N_{\nu,NC}$	Fixed	1	-	-
atm_muons	$\Delta\gamma_\mu$	Fixed	0	-	-
weight	N_μ	Free	1	uniform	[0.1, 3]
hypersurfaces	DOM Efficiency	Free	1	gaussian, $\sigma = \pm 0.1$	[0.8, 1.2]
hypersurfaces	Hole ice, p_0	Free	0.102	uniform	[-0.6, 0.5]
hypersurfaces	Hole ice, p_1	Free	-0.0493	uniform	[-0.15, 0.05]
hypersurfaces	Ice absorption	Free	1	gaussian, $\sigma = \pm 0.05$	[0.9, 1.1]
hypersurfaces	Ice scattering	Free	1.05	gaussian, $\sigma = \pm 0.1$	[0.85, 1.25]

These two are free in NMO analysis (arrows pointing to Barr, w_K^- and Barr, y_K^-)

Other Useful References

[1] Agarwalla, S.K., Prakash, S. & Sankar, S.U. Resolving the octant of θ_{23} with T2K and NOνA. *J. High Energ. Phys.* **2013,** 131 (2013). https://doi.org/10.1007/JHEP07(2013)131

[2] IceCube Collaboration, (2019), arXiv:1908.09441v1