Latest neutrino oscillation results and prospect from IceCube

NNN Workshop 2023, Procida

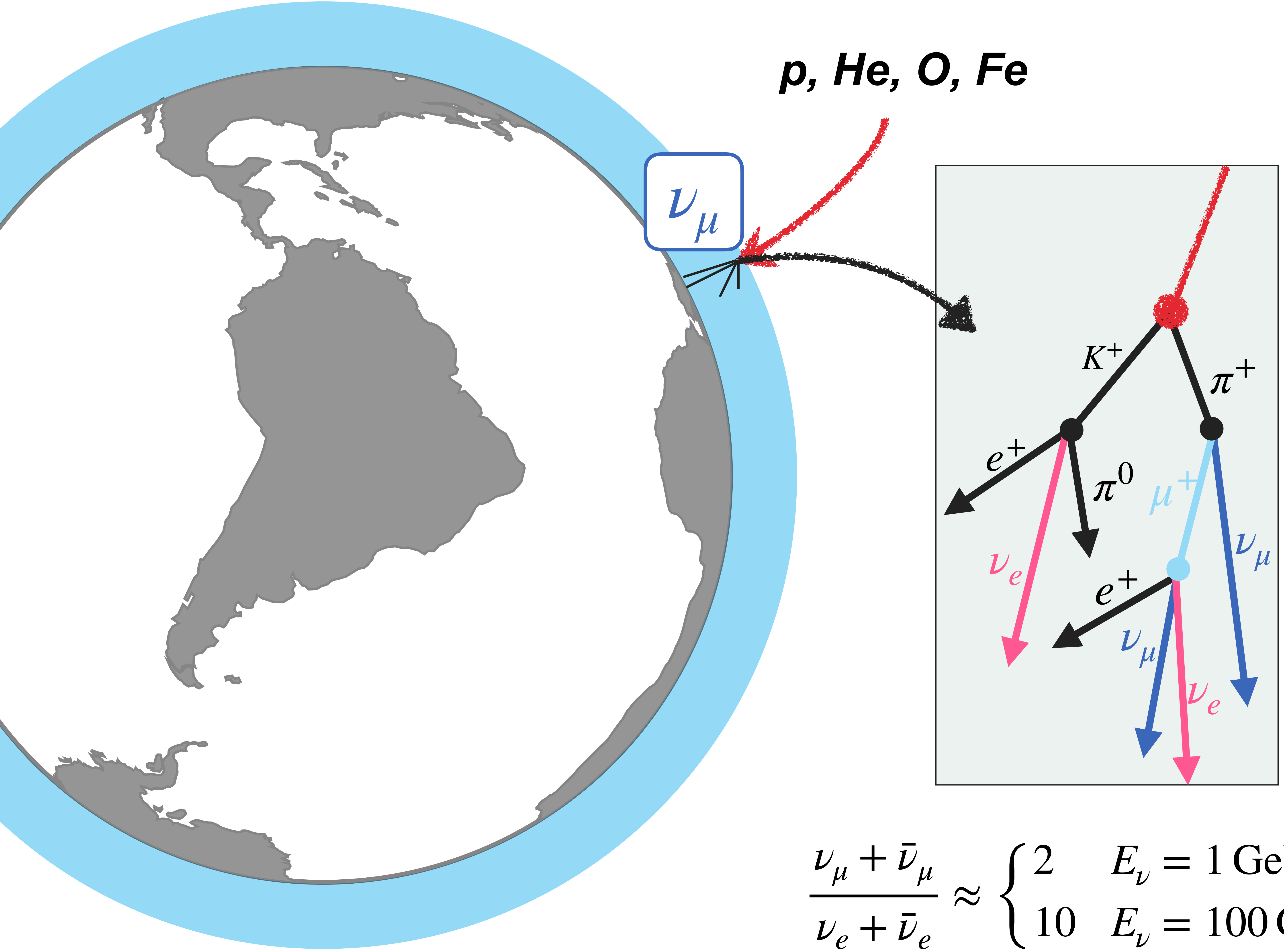
A. Trettin for the IceCube Collaboration, 12.10.2023

ICECUBE

MANCHESTER
1824
The University of Manchester

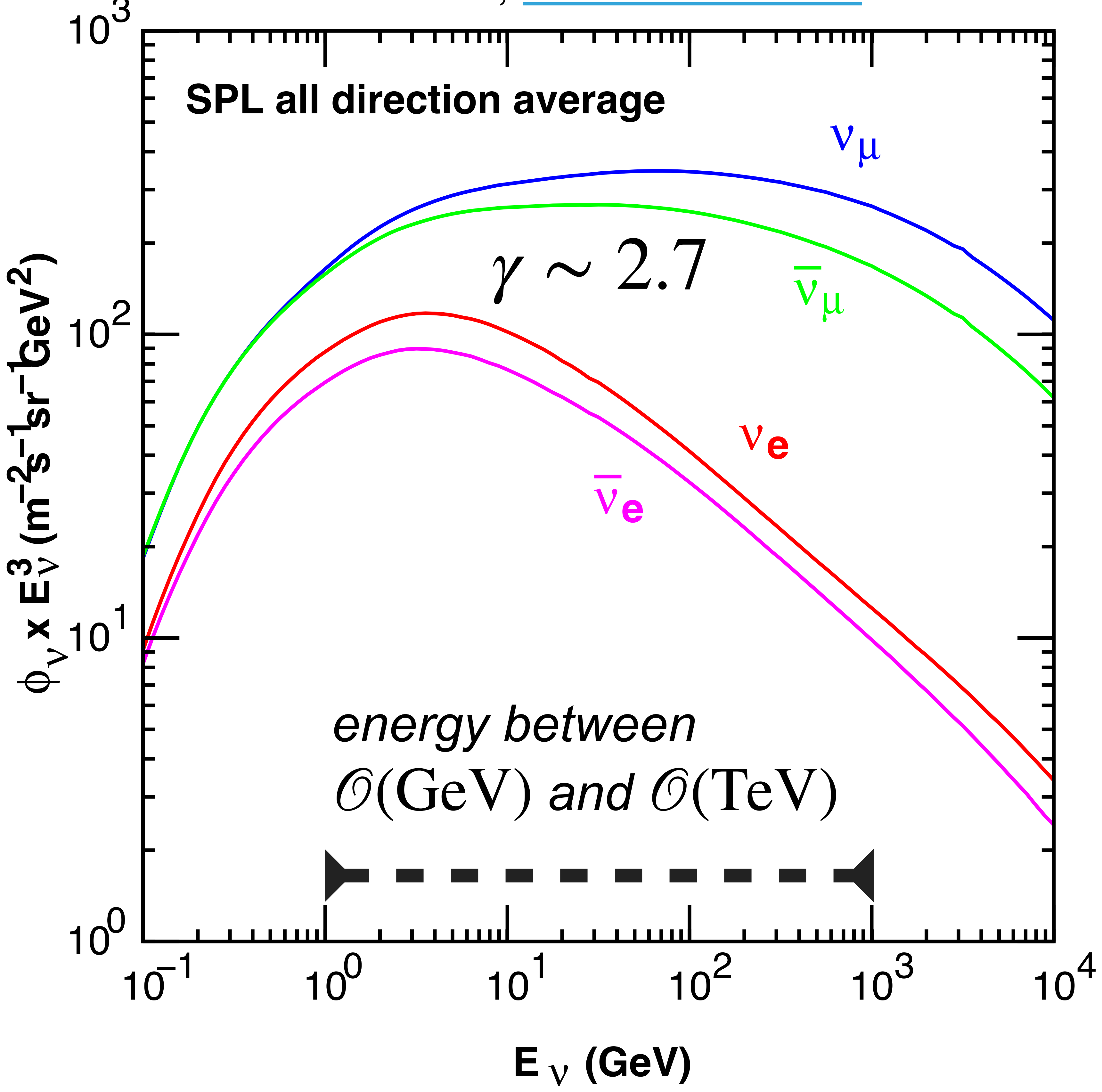
Atmospheric Neutrinos and IceCube

Atmospheric Neutrinos

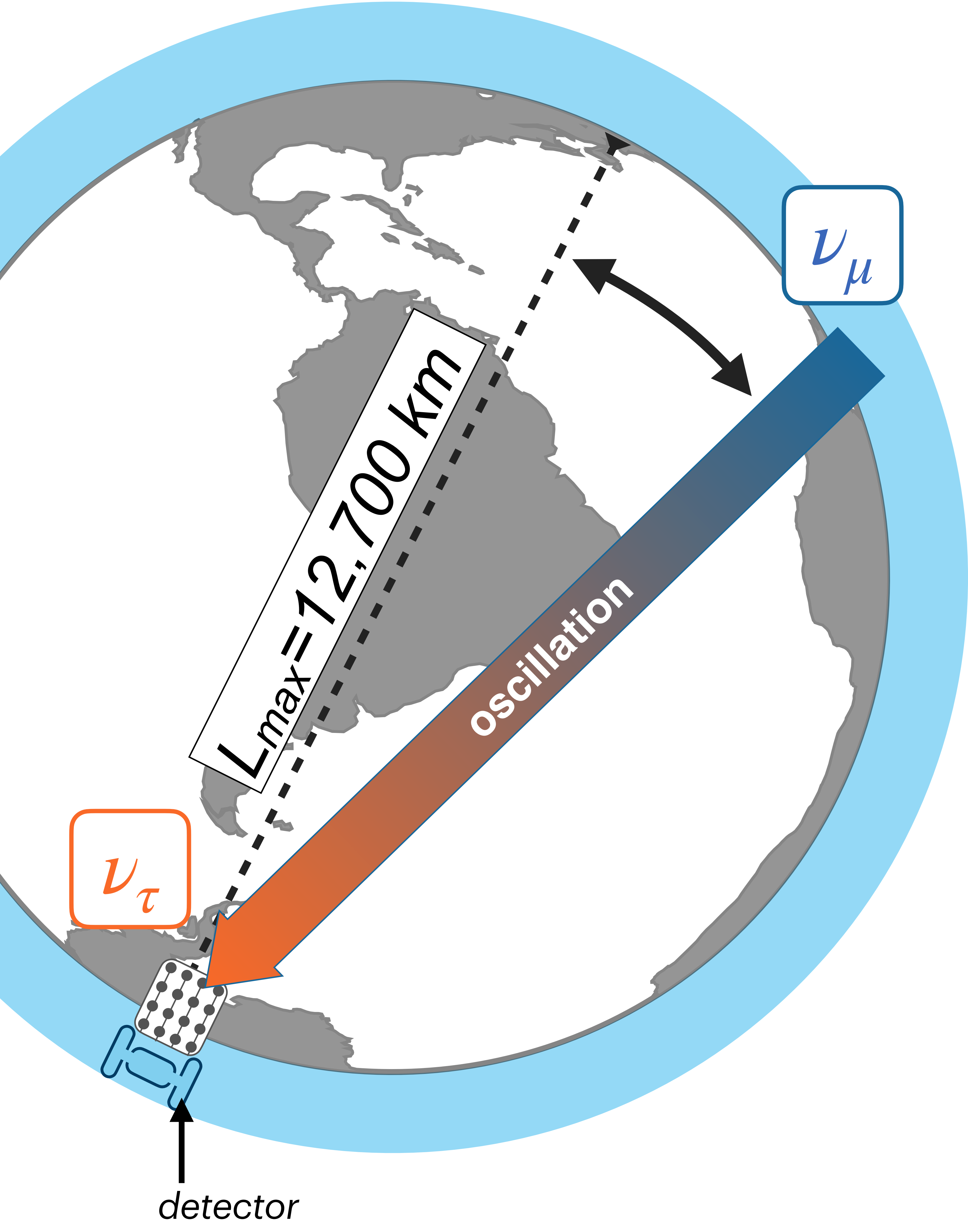


$$\frac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e} \approx \begin{cases} 2 & E_\nu = 1\,\mathrm{GeV} \\ 10 & E_\nu = 100\,\mathrm{GeV} \end{cases}$$

Honda et. al. 2015, arxiv: 1502.03916



Atmospheric Neutrino Oscillations

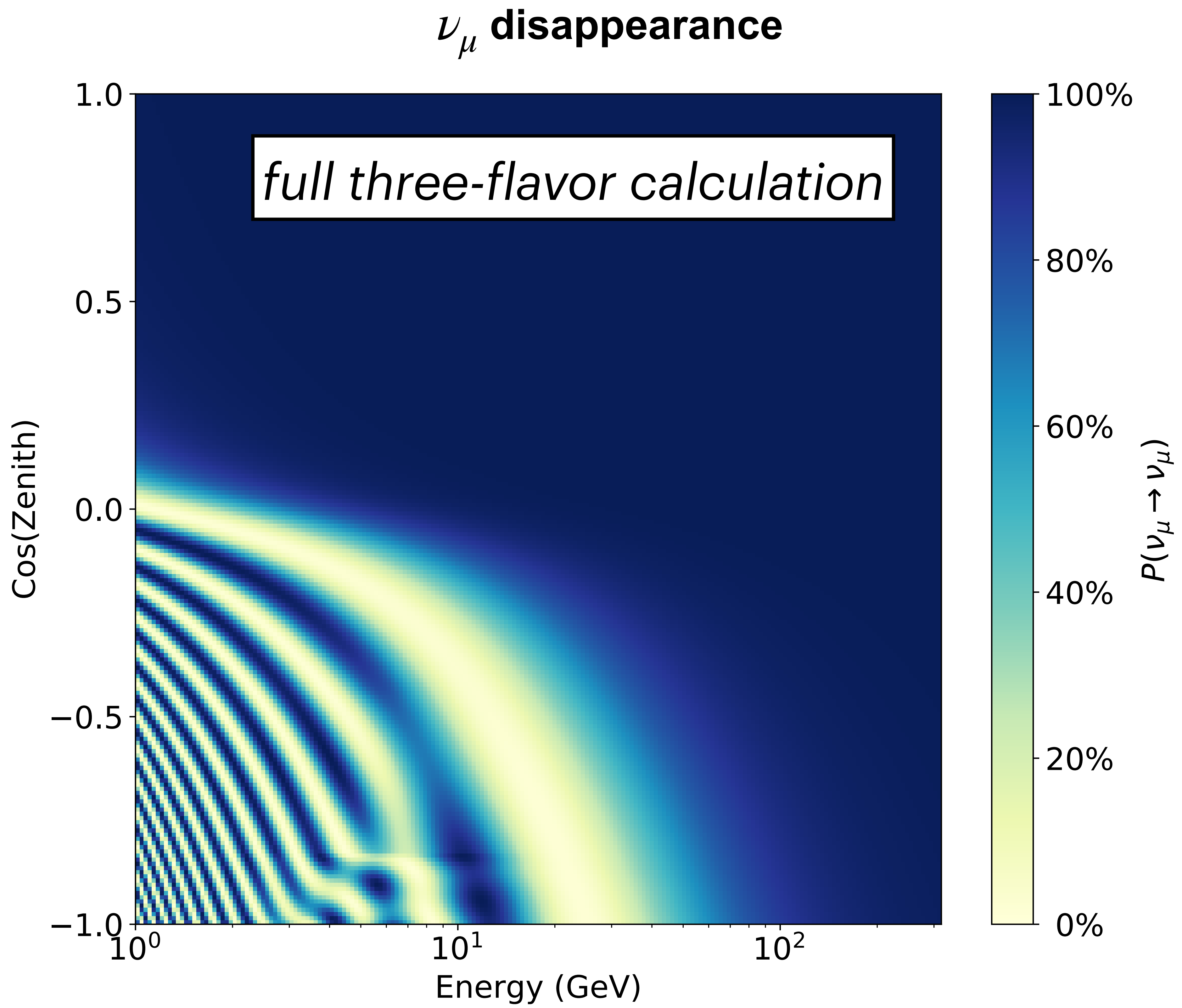


Approximate oscillation probability neglecting Δm^2_{12} and matter effects:

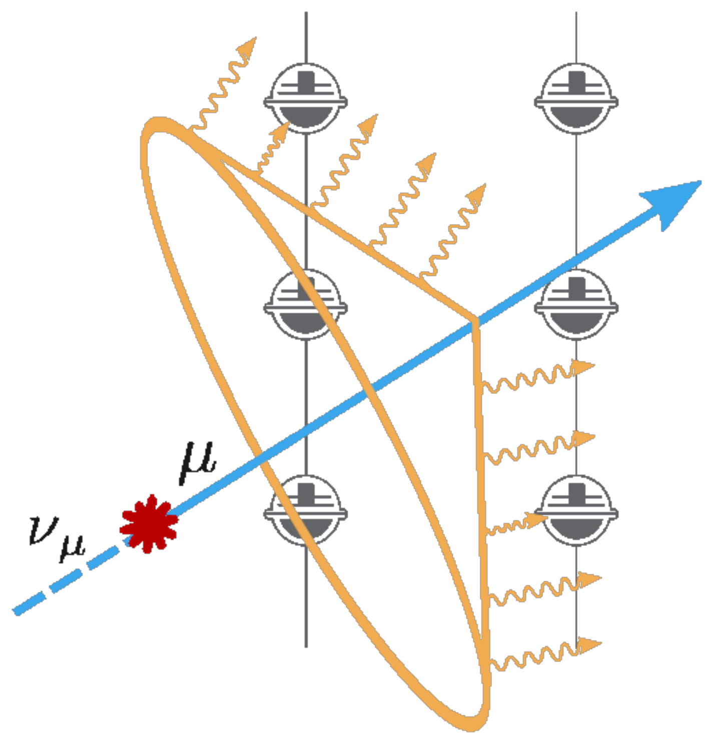
$$\boxed{L = L(\theta_z)}$$

$$\left.\begin{aligned} P(\nu_\mu \to \nu_\mu) &\simeq 1 - 4\,|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)\sin^2\left(\Delta m^2_{31} L/(4E)\right) \\ &\simeq 1 - \sin^2(2\theta_{23})\sin^2\left(\Delta m^2_{31} L/(4E)\right) \end{aligned}\right\} \text{“}\nu_\mu\text{ disappearance”}$$

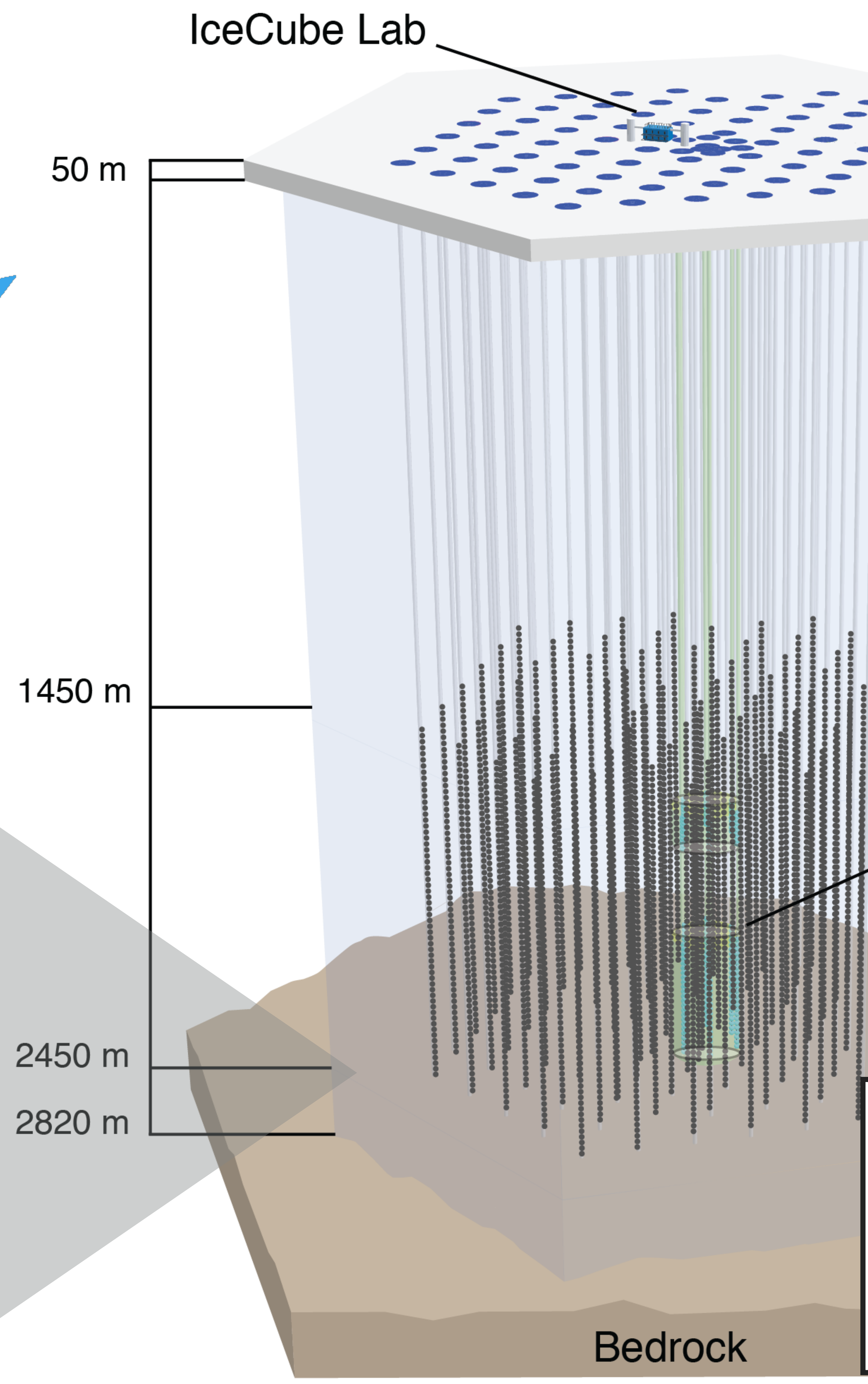
Measure ***energy, zenith angle*** *and compute* ***flavor proxy***



The IceCube Neutrino Observatory



"DOM": Digital Optical Module



IceTop
81 Stations
324 optical sensors

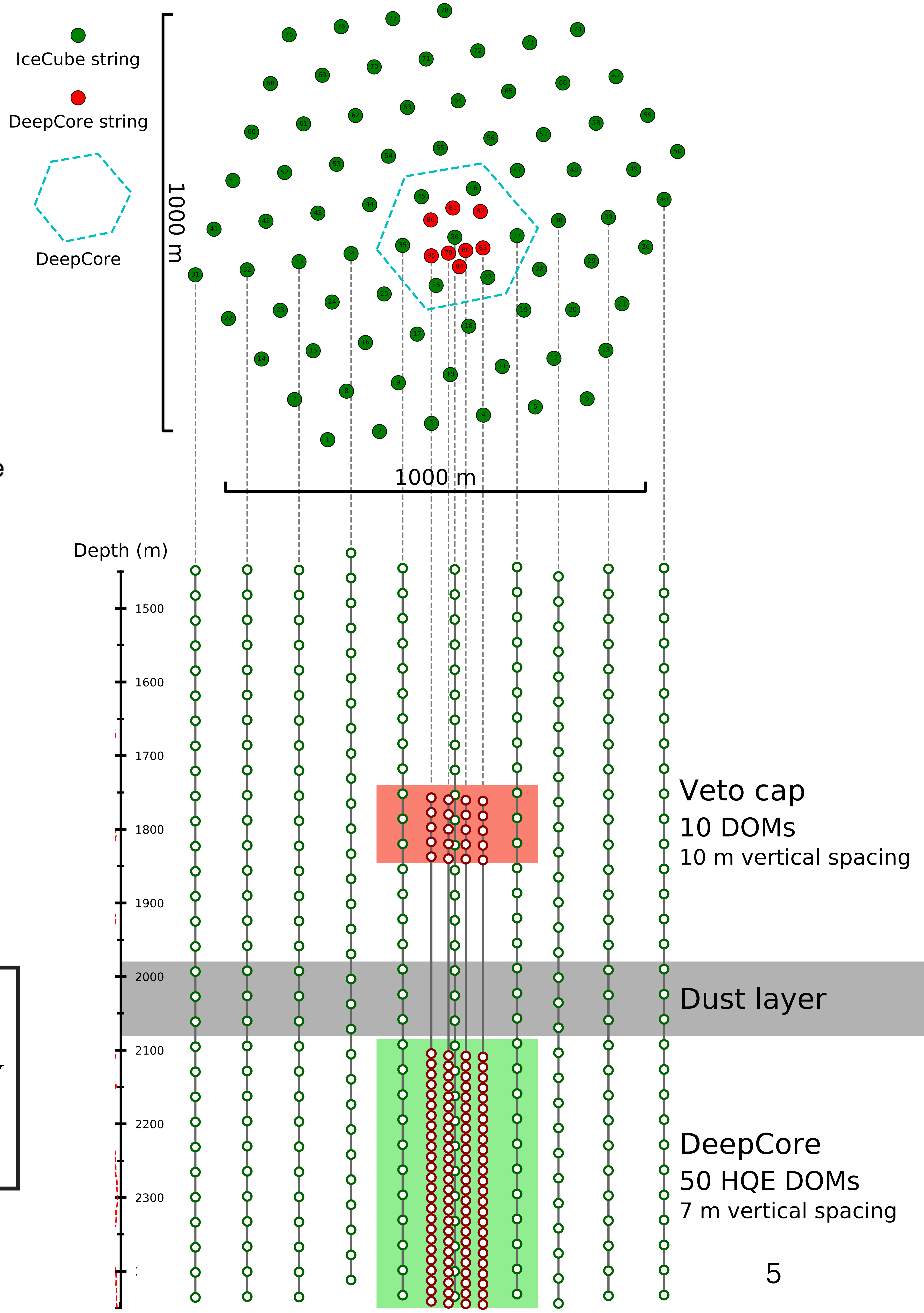
IceCube Array
86 strings
including 8 DeepCore
5160 optical sensors

DeepCore
8 strings-spacing opti
for lower energies
480 optical sensors

Eiffel Tower
324 m

Energy thresholds:

- IceCube: $E \gtrsim 100\,\mathrm{GeV}$
- DeepCore: $E \gtrsim 5\,\mathrm{GeV}$



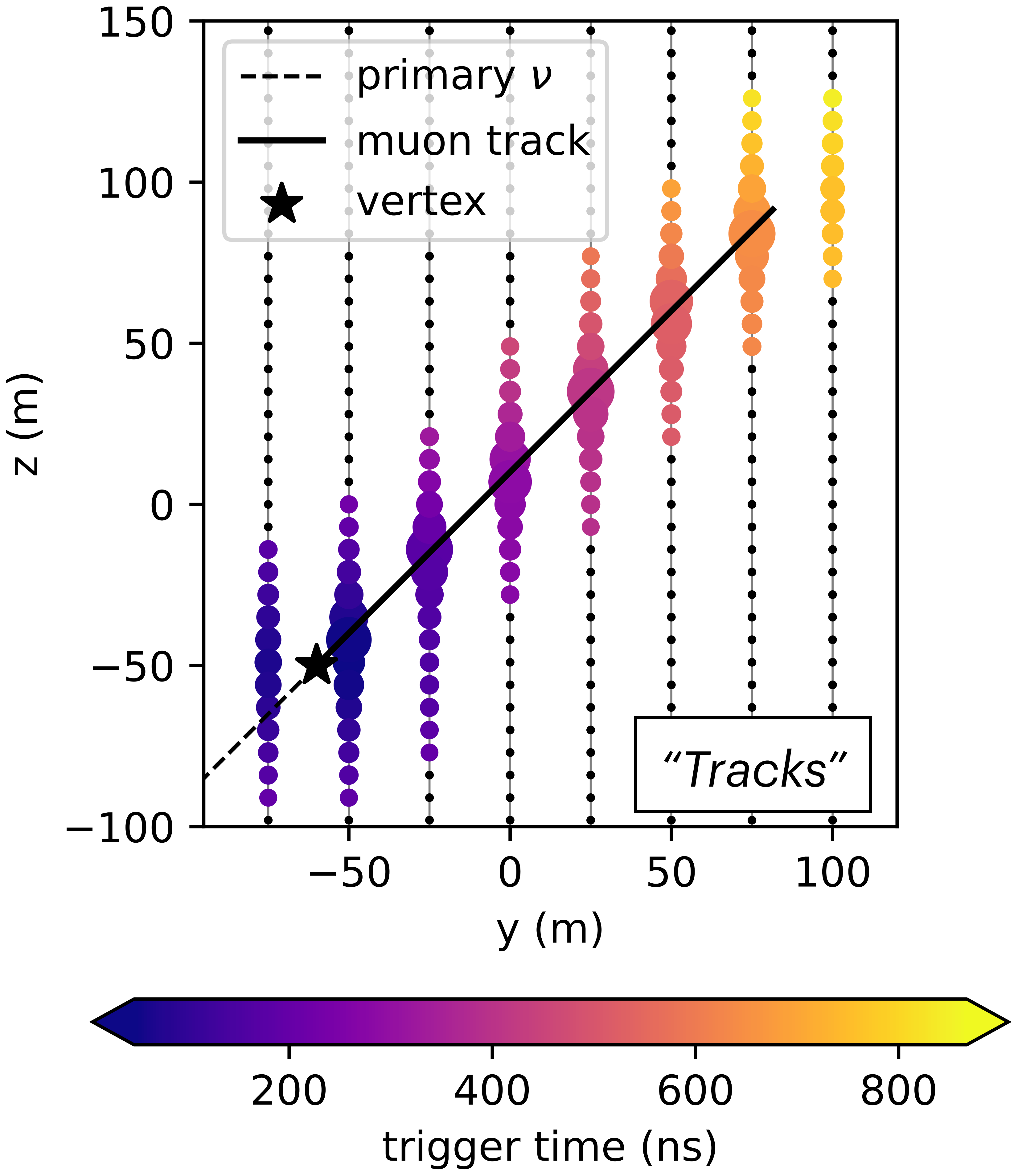
Veto cap
10 DOMs
10 m vertical spacing

Dust layer

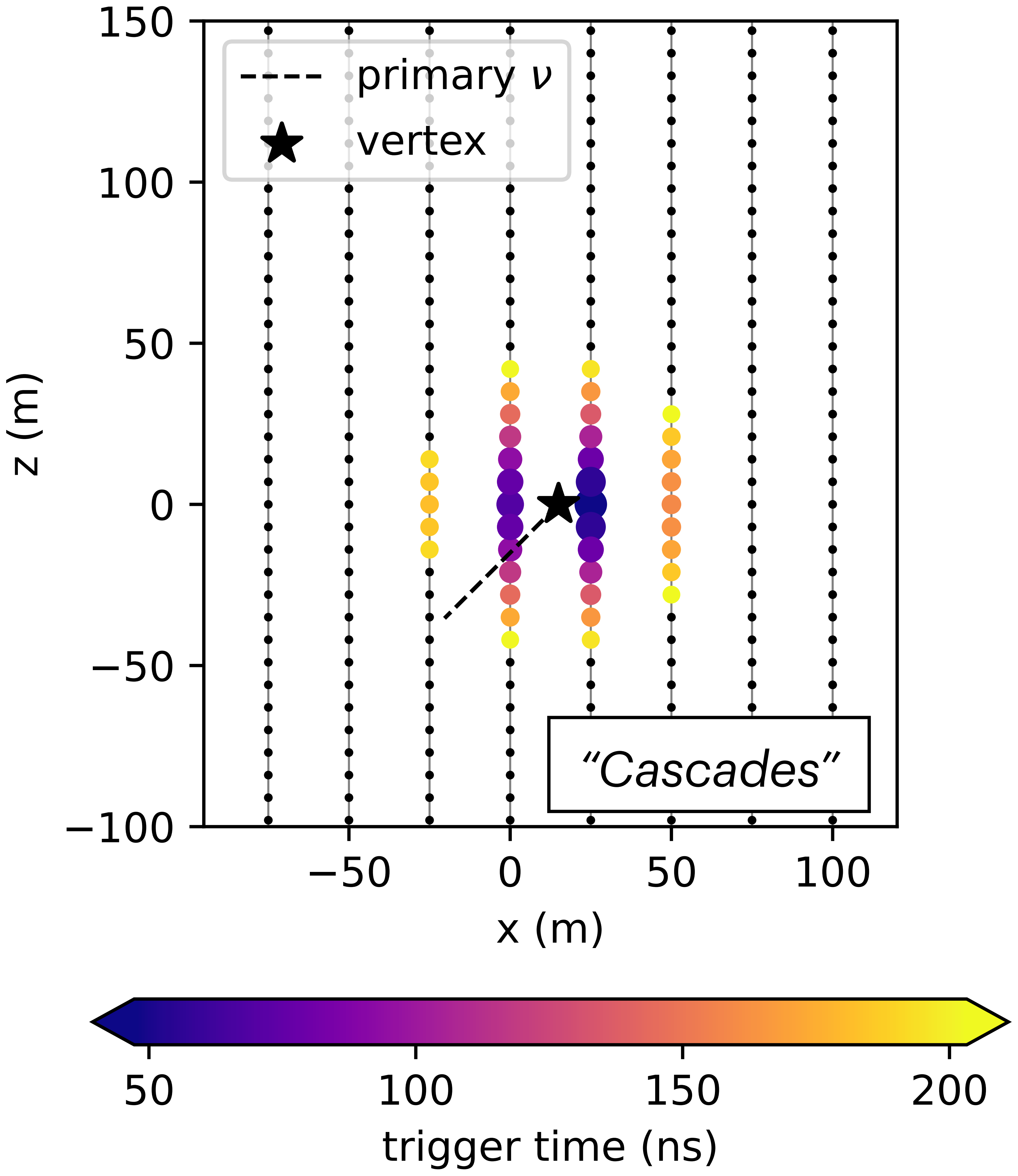
DeepCore
50 HQE DOMs
7 m vertical spacing

Neutrino Interactions in IceCube: Idealized

Charged-current ν_μ interactions



Neutral-current interactions + ν_e + ν_τ



DeepCore Event Sample

Trigger and Filter

Reducing background from noise and atm. muons

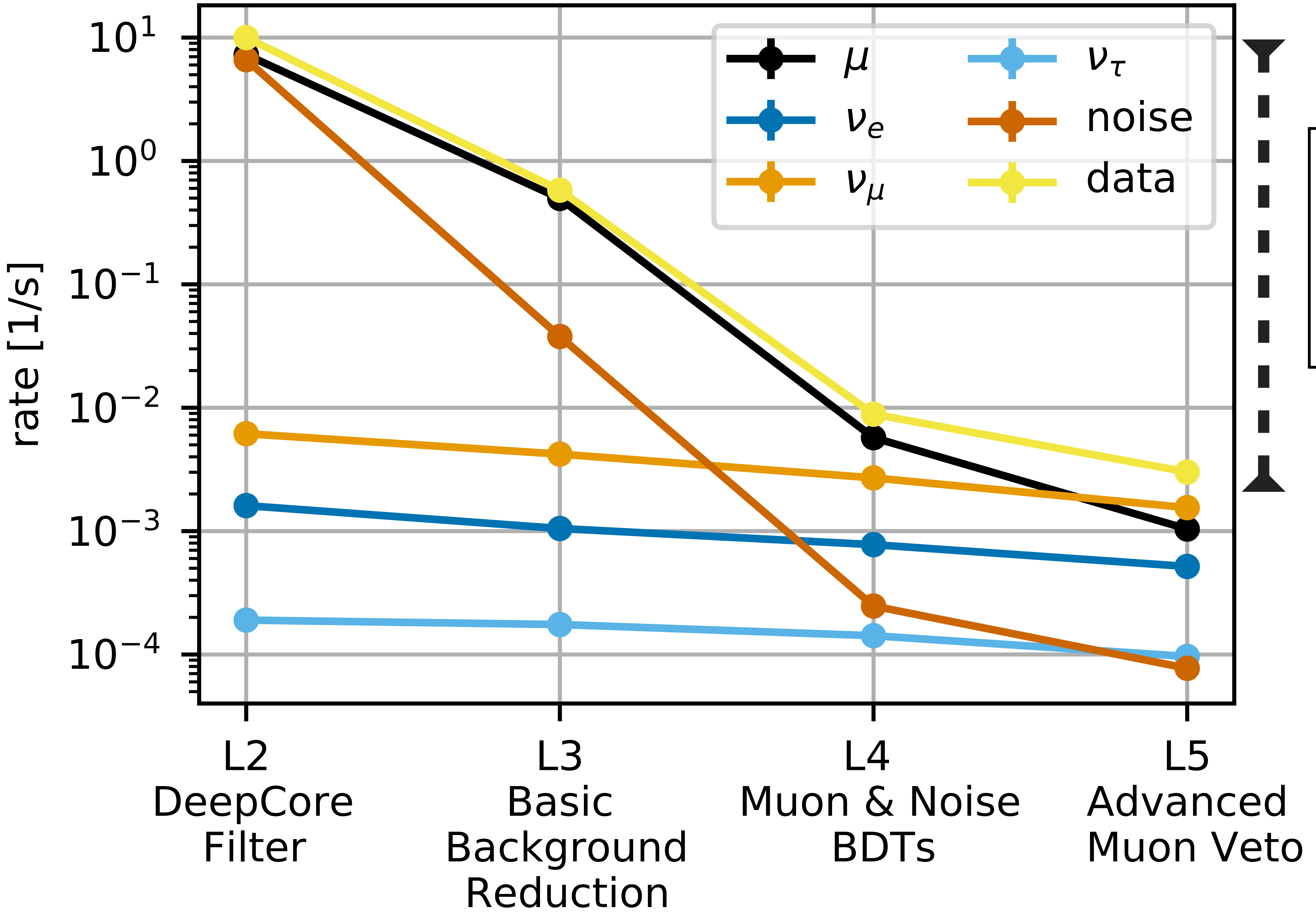
Trigger + online Filter (L2)

Offline Filter (L3 to L5)

Reconstruction + Classification

Final Cuts

Histogram

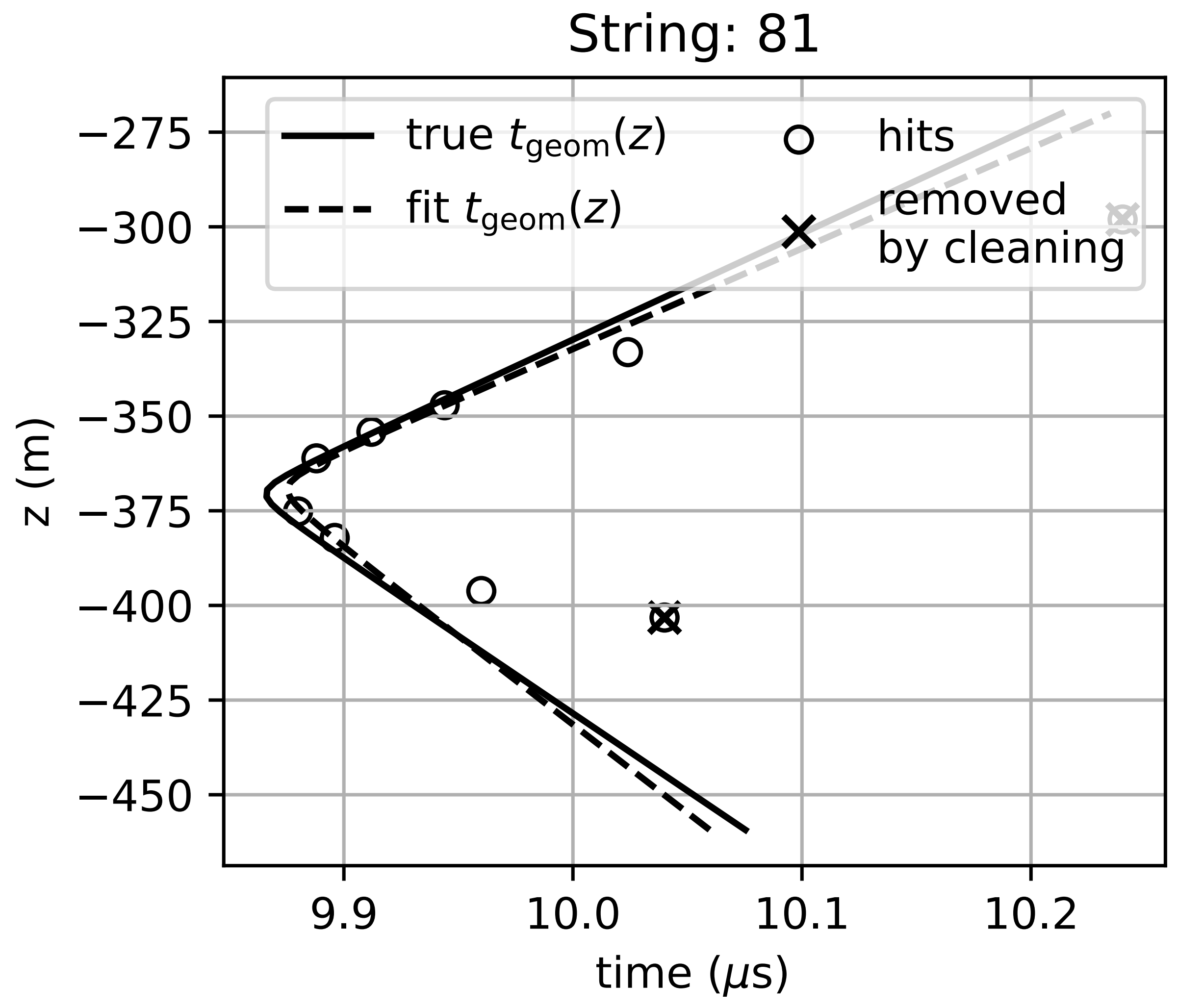


> 3 orders of magnitude background reduction!

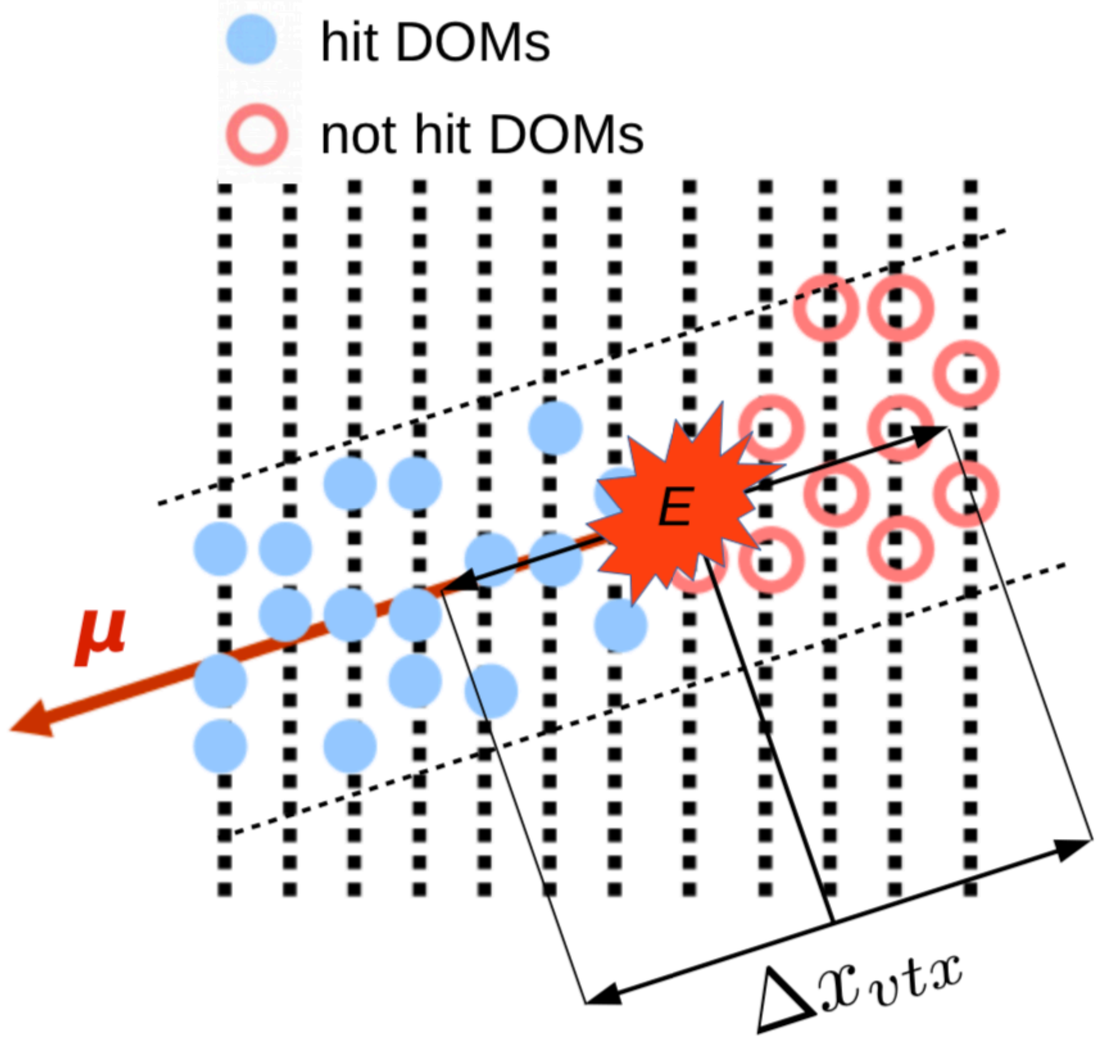
Two Samples

"Golden Events Sample" ← **L5 Filtered Sample** → **CNN Reconstructed Sample**

Geometric Track Fit



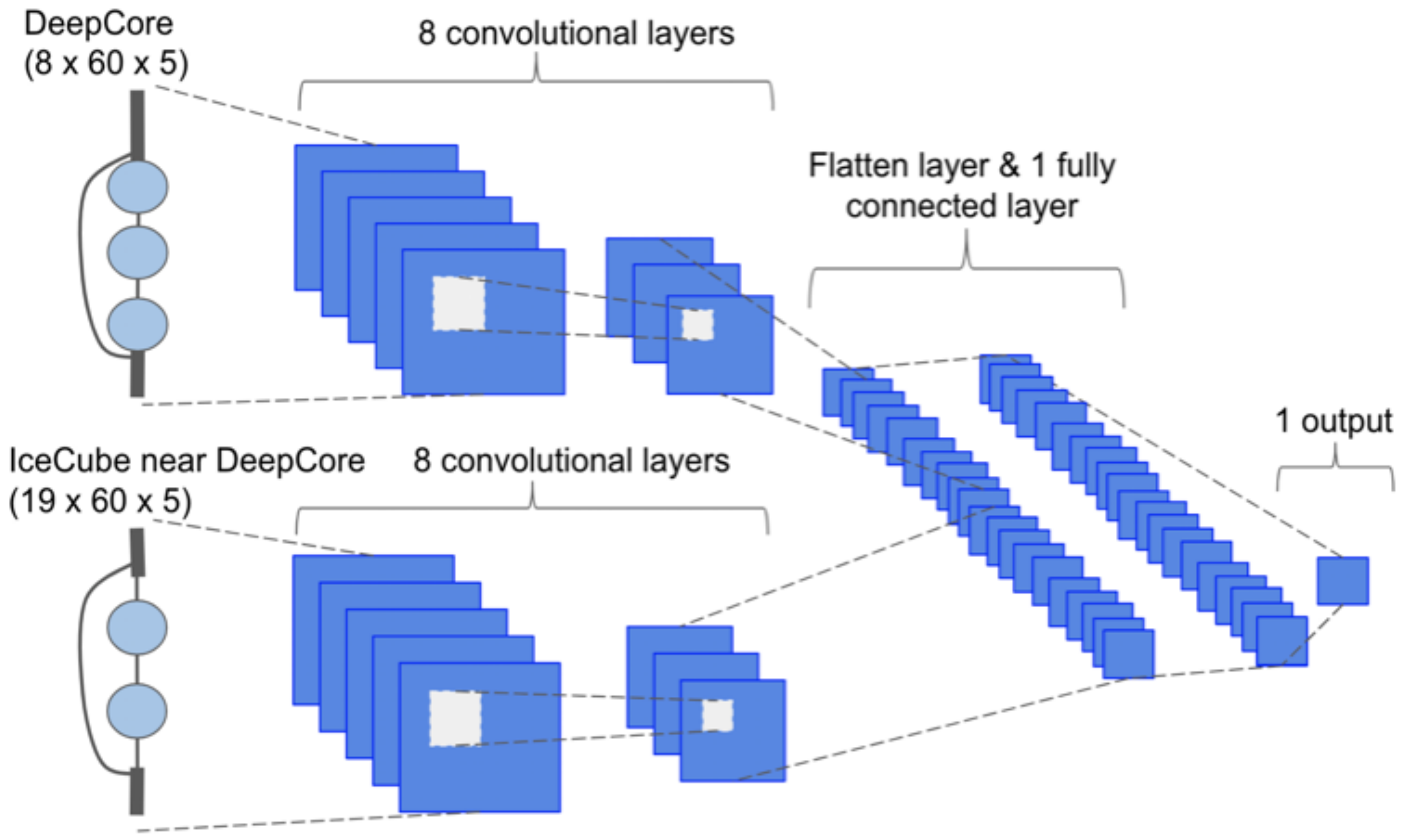
Energy Reconstruction



Reconstruction paper: arXiv:2203.02303

- Reconstructs only very clean track-like events
- Goodness-of-fit variables used in BDT as PID

Convolutional Neural Network



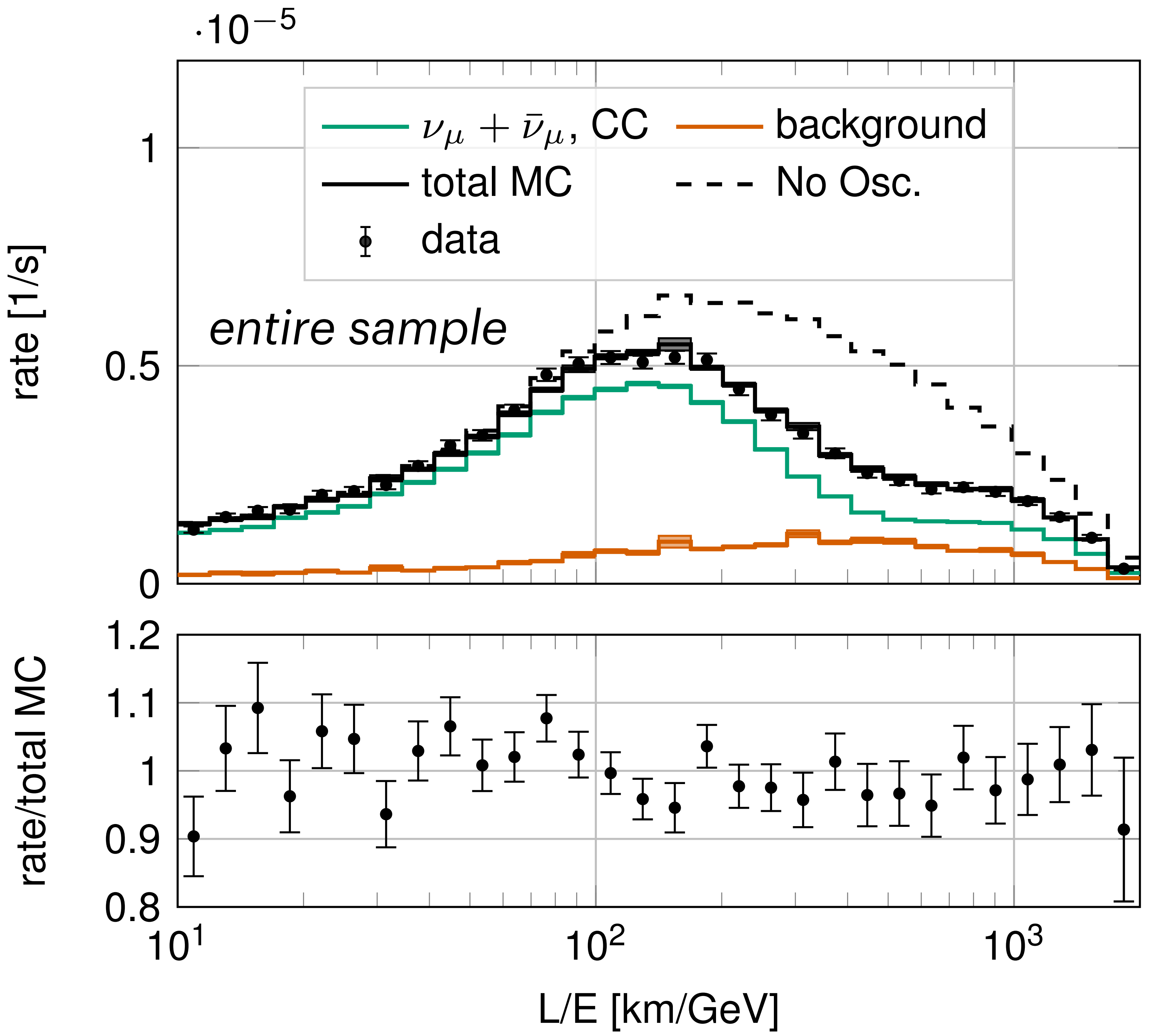
- Machine Learning model trained on simulation
- Zenith, energy, and PID score from one model

Two Samples

"Golden Events Sample"

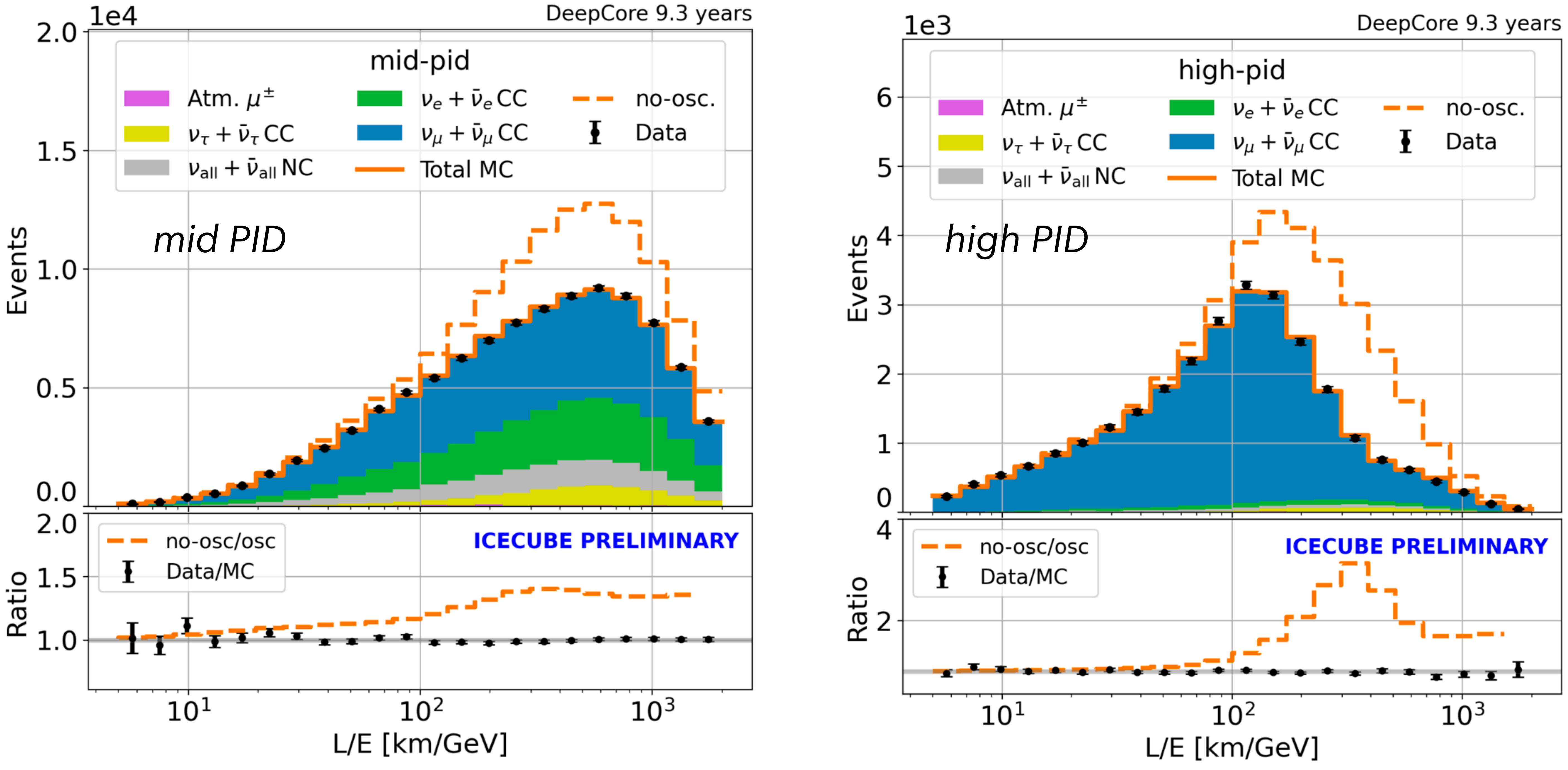
L5 Filtered Sample

CNN Reconstructed Sample



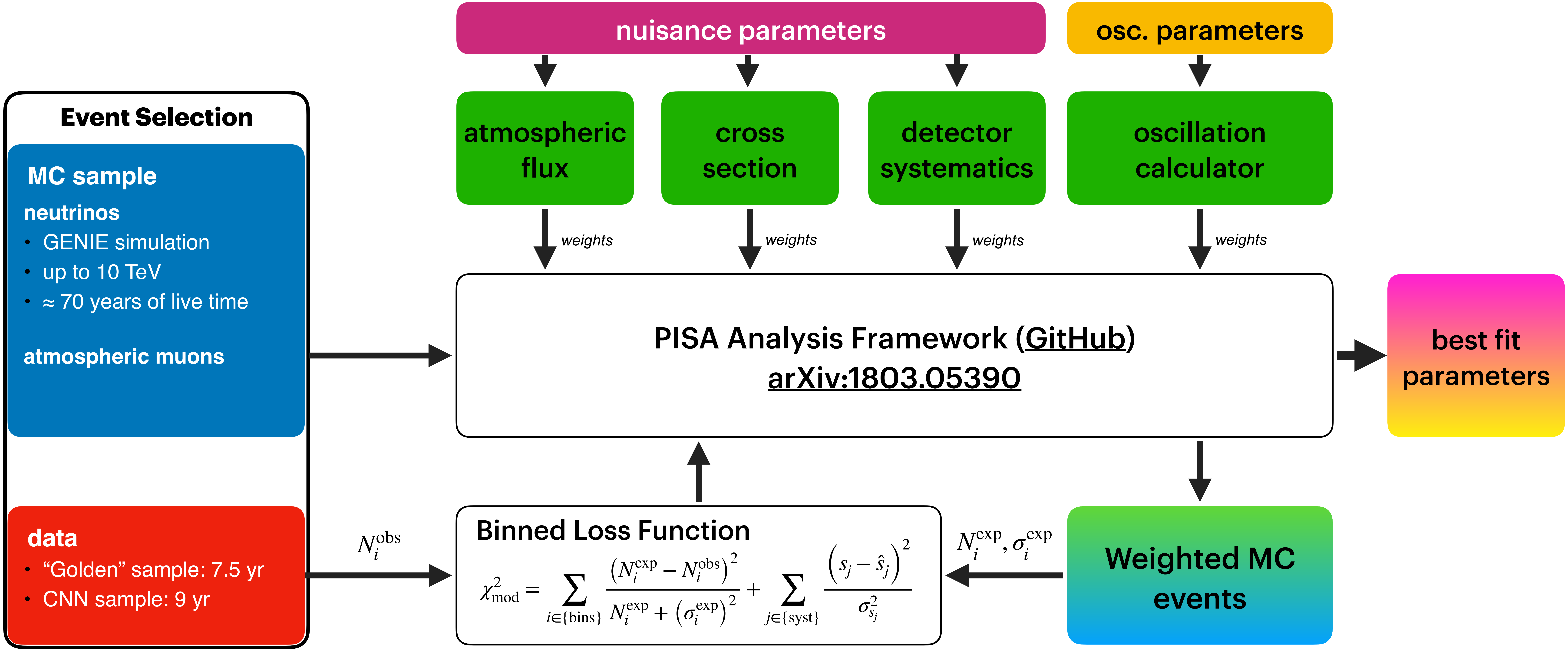
Total: 21 914 observed events
arXiv:2304.12236

≈10x statistics!



Total: 150 257 observed events
Proceedings: https://pos.sissa.it/444/1143/pdf

Analysis Setup



Event Selection

MC sample

neutrinos
- GENIE simulation
- up to 10 TeV
- ≈ 70 years of live time

atmospheric muons

data
- "Golden" sample: 7.5 yr
- CNN sample: 9 yr

nuisance parameters

osc. parameters

atmospheric flux

cross section

detector systematics

oscillation calculator

weights

weights

weights

weights

PISA Analysis Framework (GitHub)
arXiv:1803.05390

best fit parameters

N_i^{obs}

Binned Loss Function

$$\chi^2_{\text{mod}} = \sum_{i\in\{\text{bins}\}} \frac{\left(N_i^{\text{exp}} - N_i^{\text{obs}}\right)^2}{N_i^{\text{exp}} + \left(\sigma_i^{\text{exp}}\right)^2} + \sum_{j\in\{\text{syst}\}} \frac{\left(s_j - \hat{s}_j\right)^2}{\sigma_{s_j}^2}$$

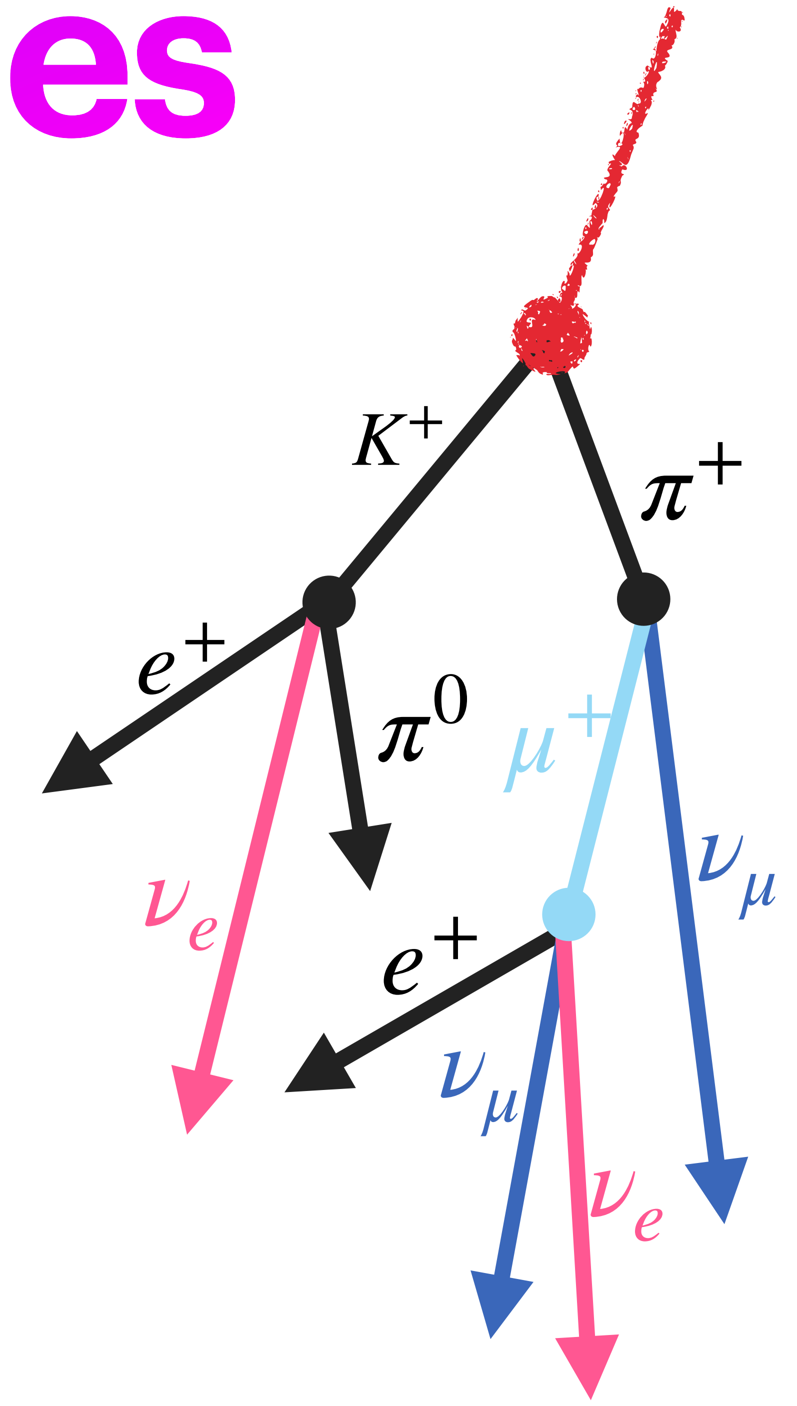
$N_i^{\text{exp}}, \sigma_i^{\text{exp}}$

Weighted MC events

alternatively: Poisson LLH

Systematic Uncertainties

Flux + Cross-section



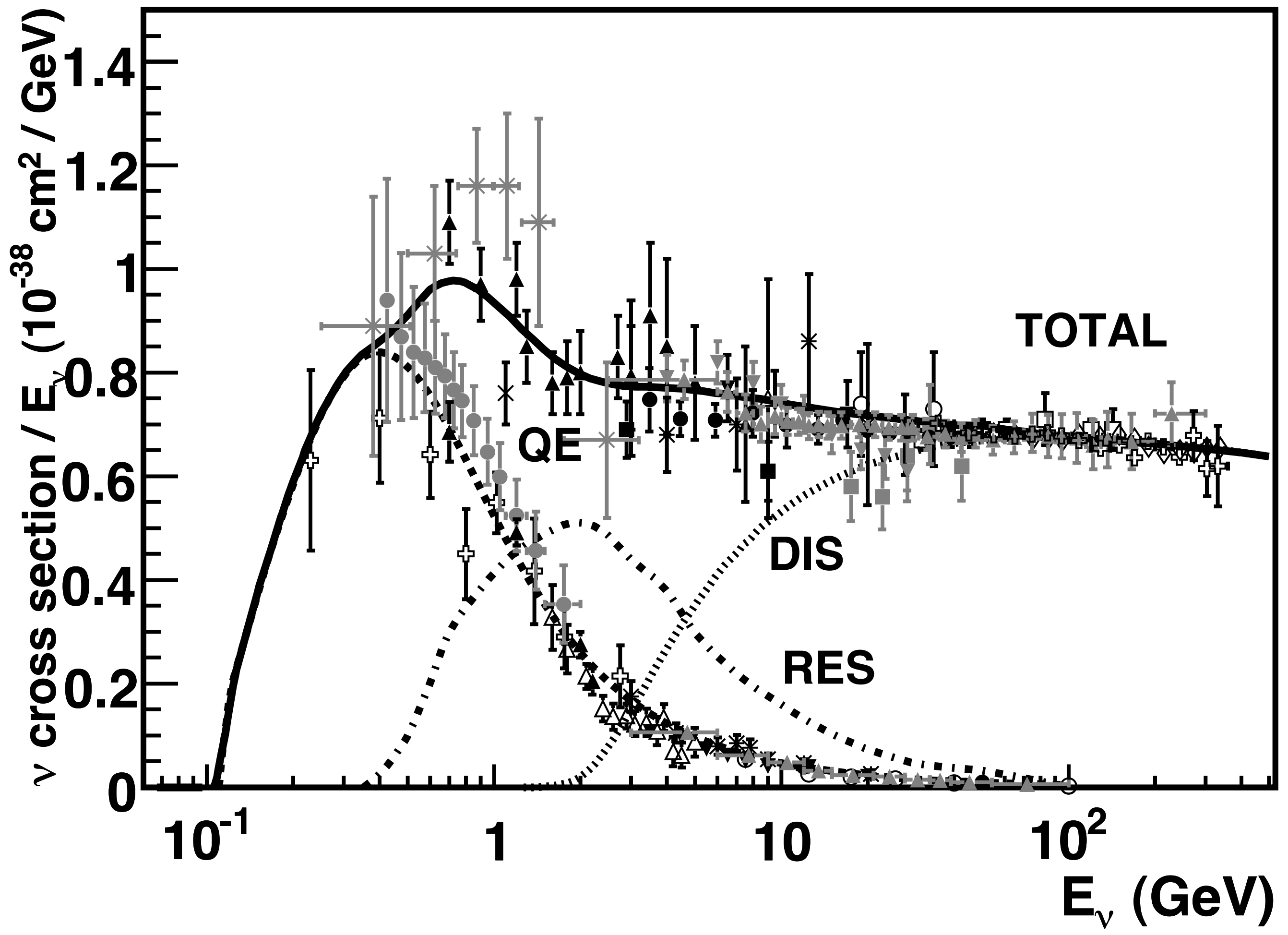
Atmospheric Flux

- Baseline flux by Honda et al. modified by spectral index ($\Delta\gamma$) and meson ($K^\pm$, π^+, π^-) production scale factors

$$\Phi_{\text{sys}} = (\Phi_{\text{nom}} \cdot \Delta\Phi_{\text{nom}}) + \left(b \cdot \frac{\mathrm{d}\Phi_{\text{nom}}}{\mathrm{d}B}\right)$$

Cross-section

- Axial masses for resonant and quasi-elastic scattering (varied in GENIE event generator)
- DIS uncertainty interpolating between GENIE and CSMS cross-sections

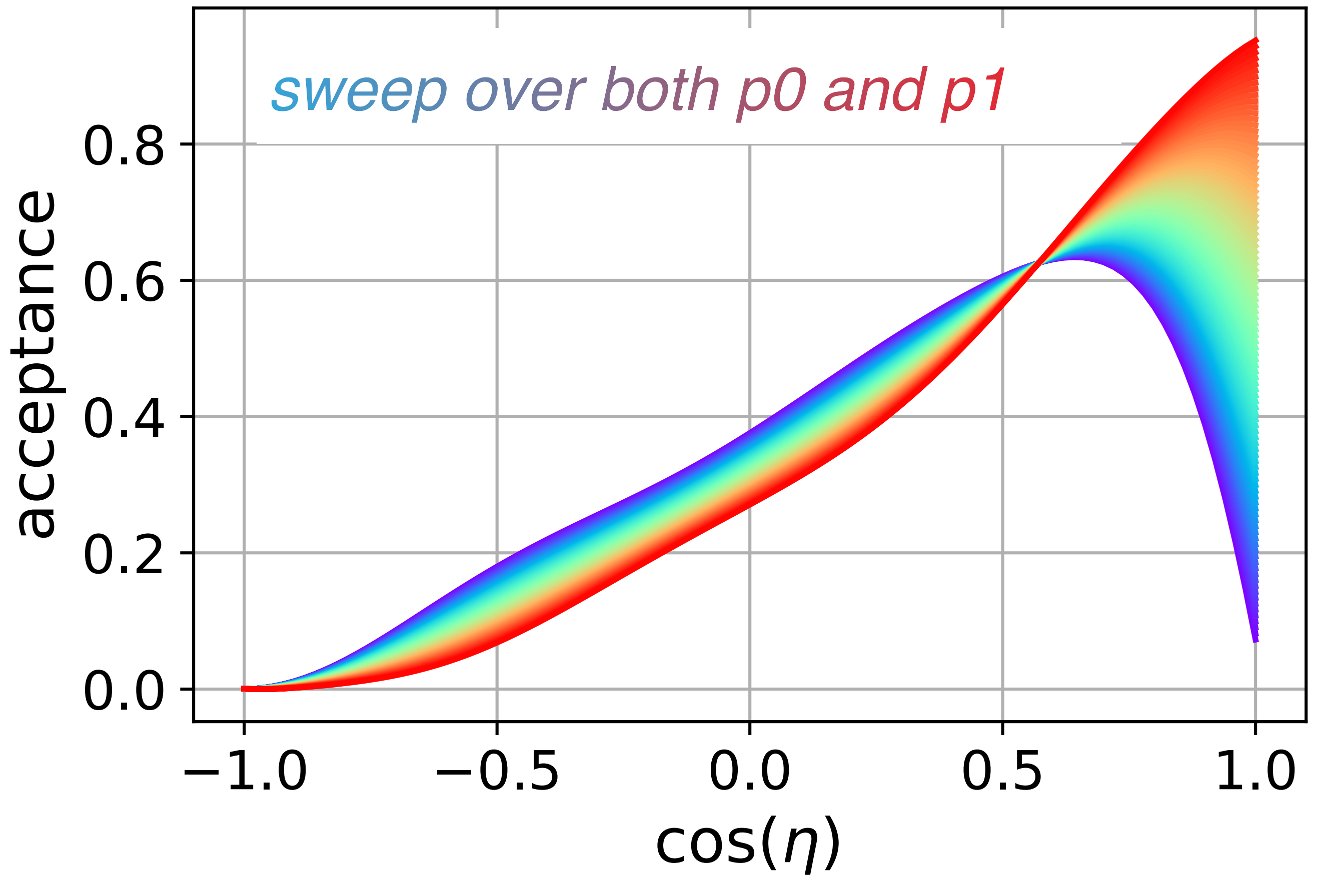


Formaggio et al. (2013)

Detector Properties

DOM Efficiency, Hole Ice, and Bulk Ice Parameters

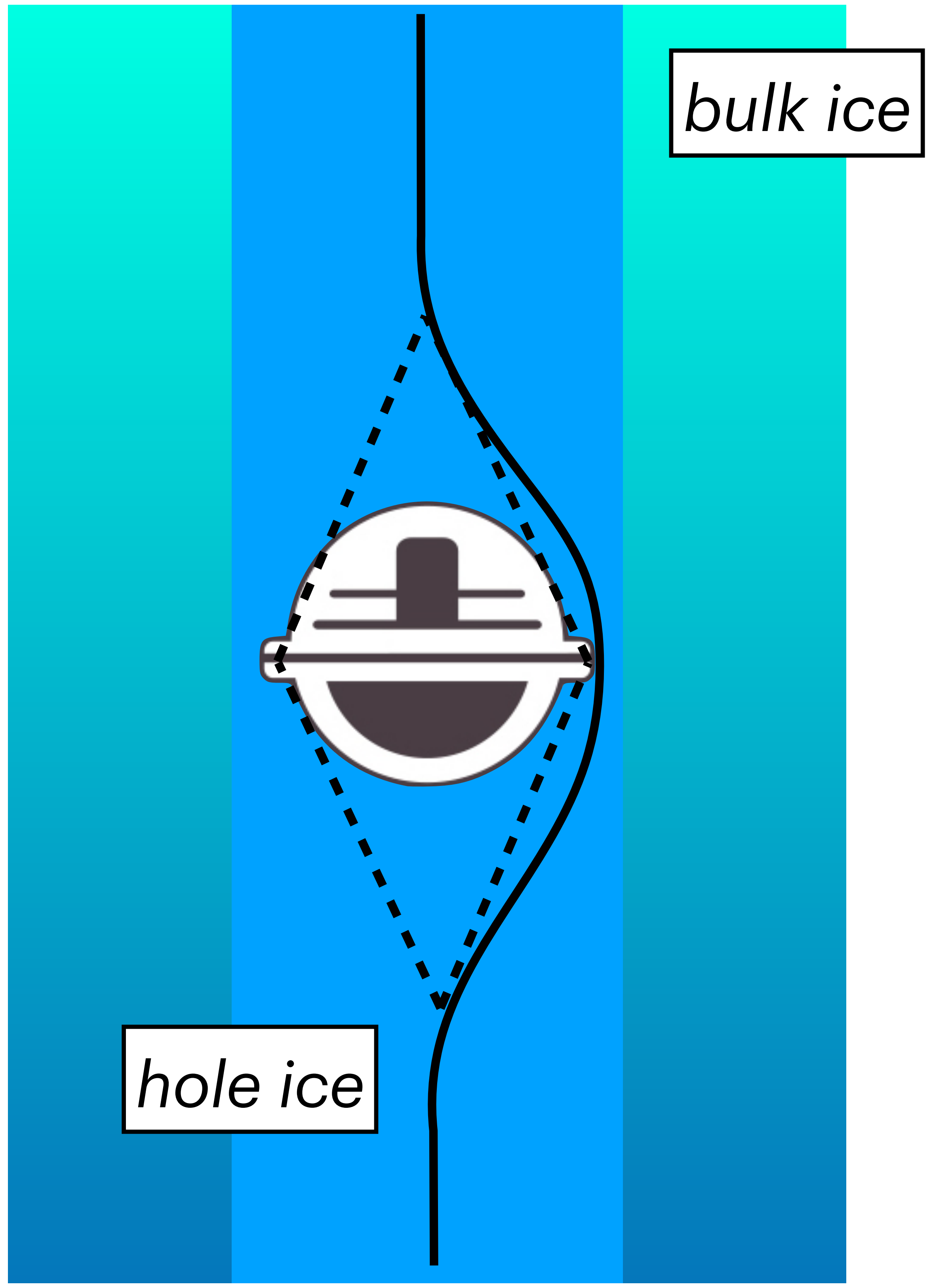
Hole Ice



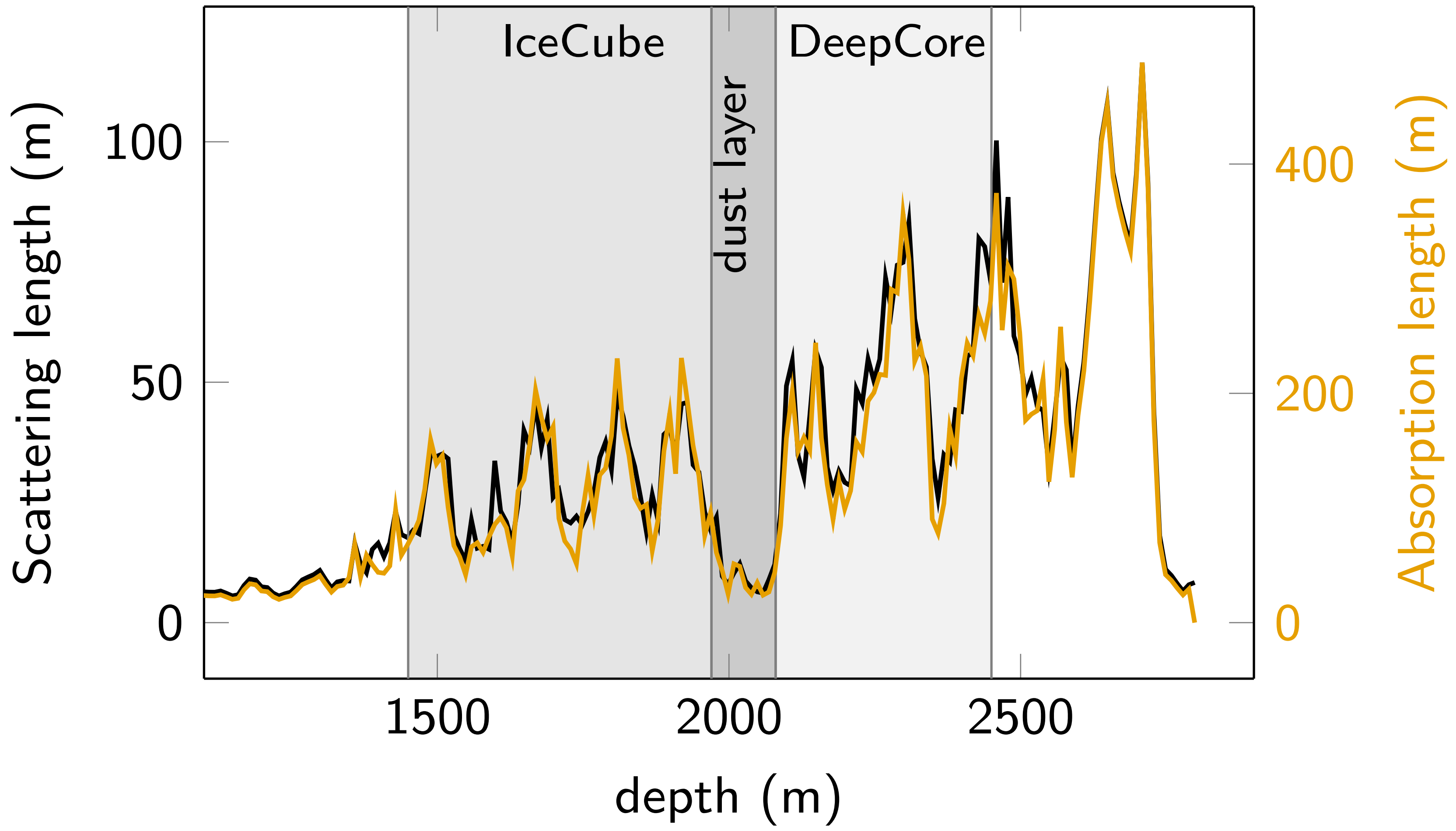
- Two parameters modifying angular acceptance due to hole-ice

DOM Efficiency

- Global scale parameter



Ice Scattering and Absorption

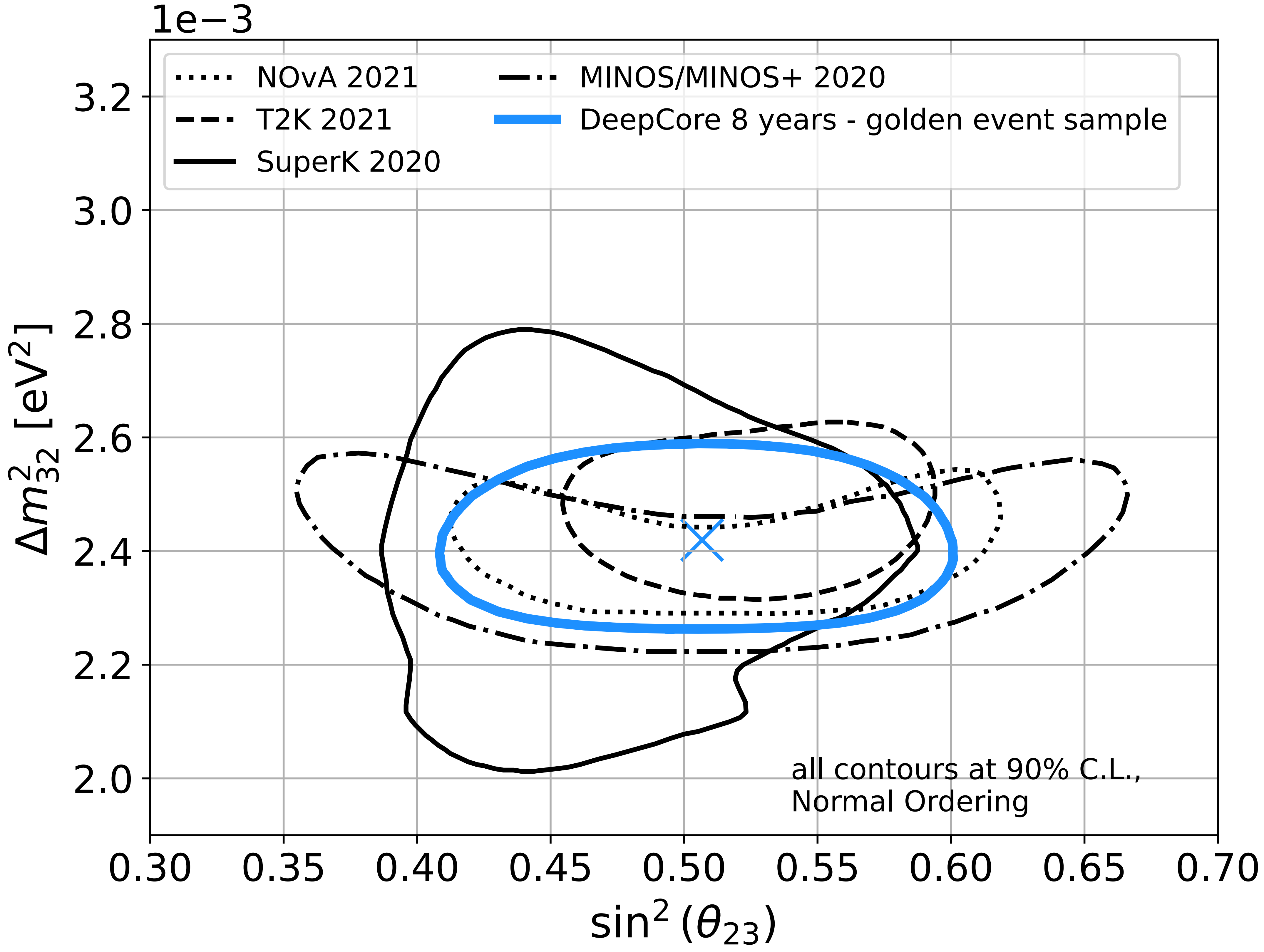


- Global scales on scattering and absorption coefficients

Results of Three-Flavor Measurement

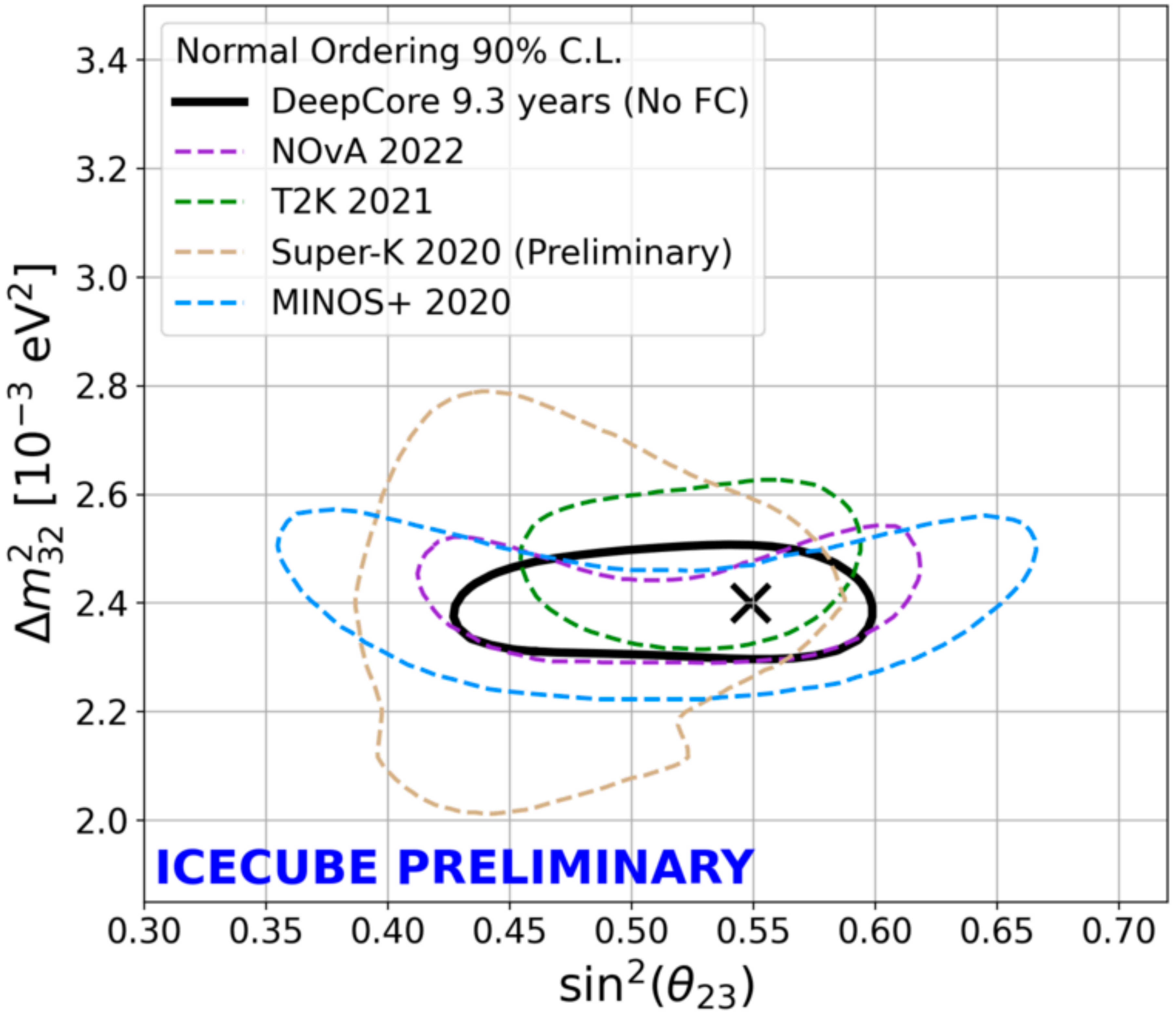
Constraints on atm. mass splitting and mixing angle

Golden Events Sample



arXiv:2304.12236

CNN Reco Sample

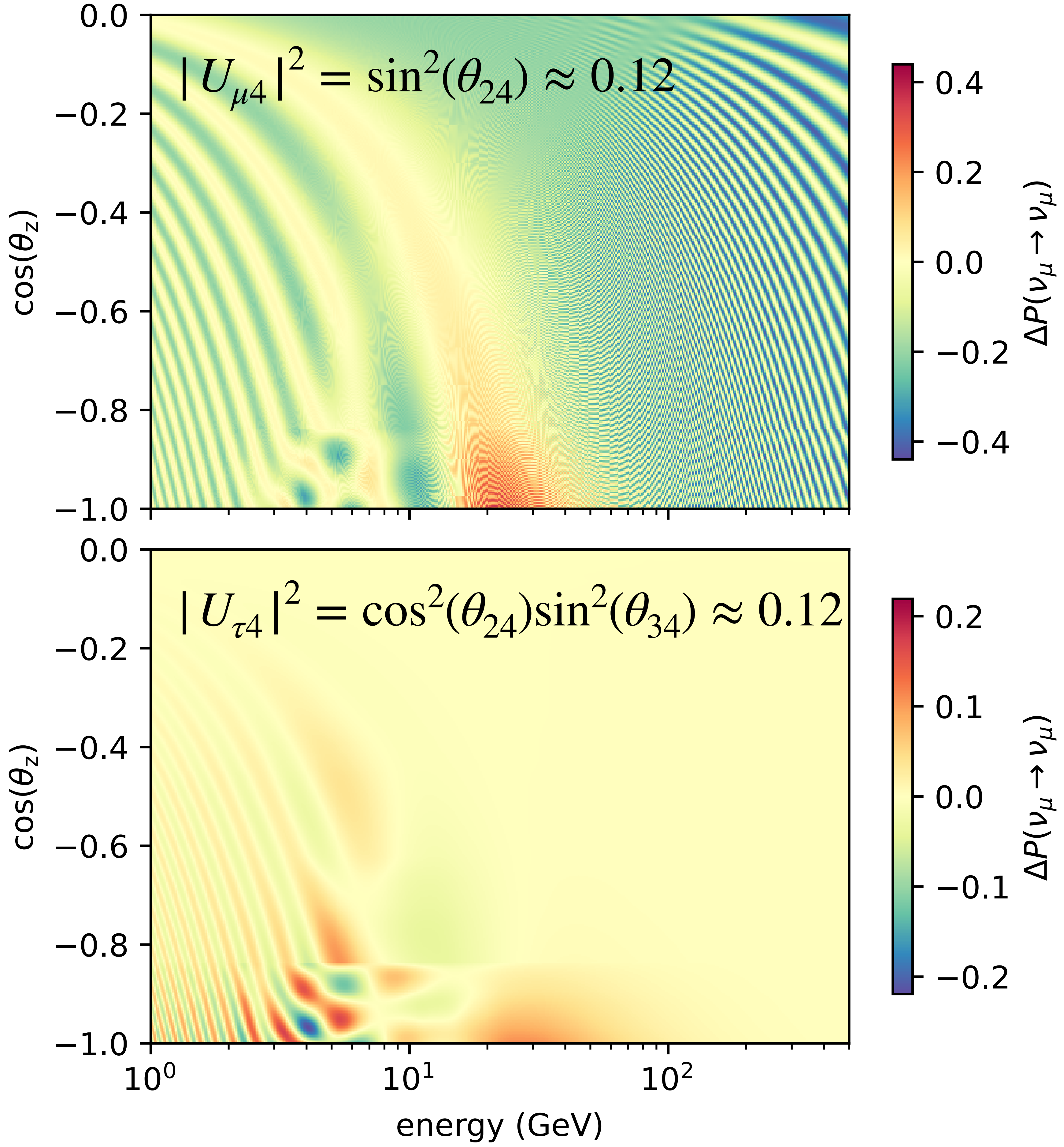


Proceedings: https://pos.sissa.it/444/1143/pdf

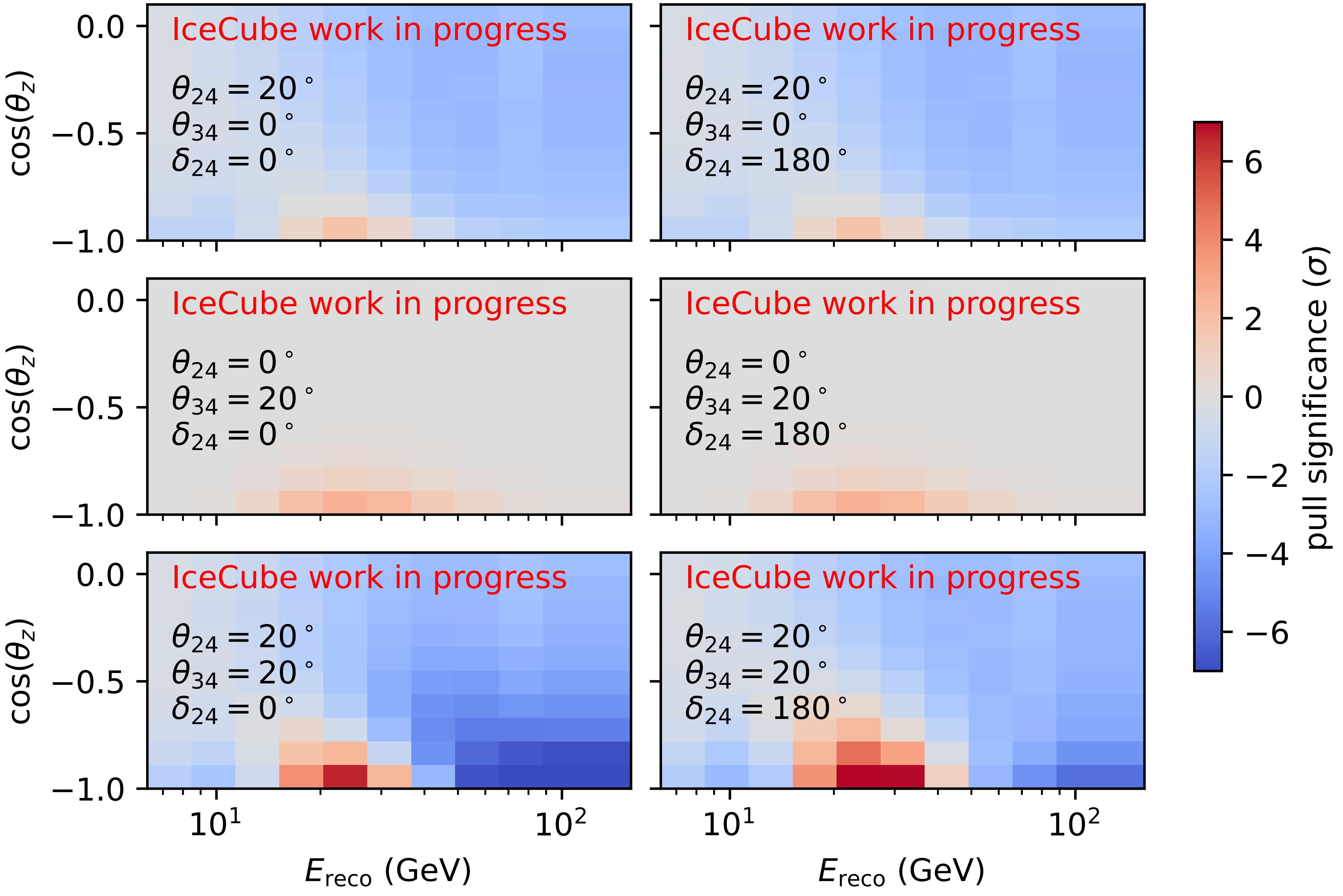
eV-scale Sterile Neutrino Search

Using the Golden Sample

Signal at $\Delta m^2_{41} = 1\ \mathrm{eV}^2$



Signal Significance in Analysis Binning

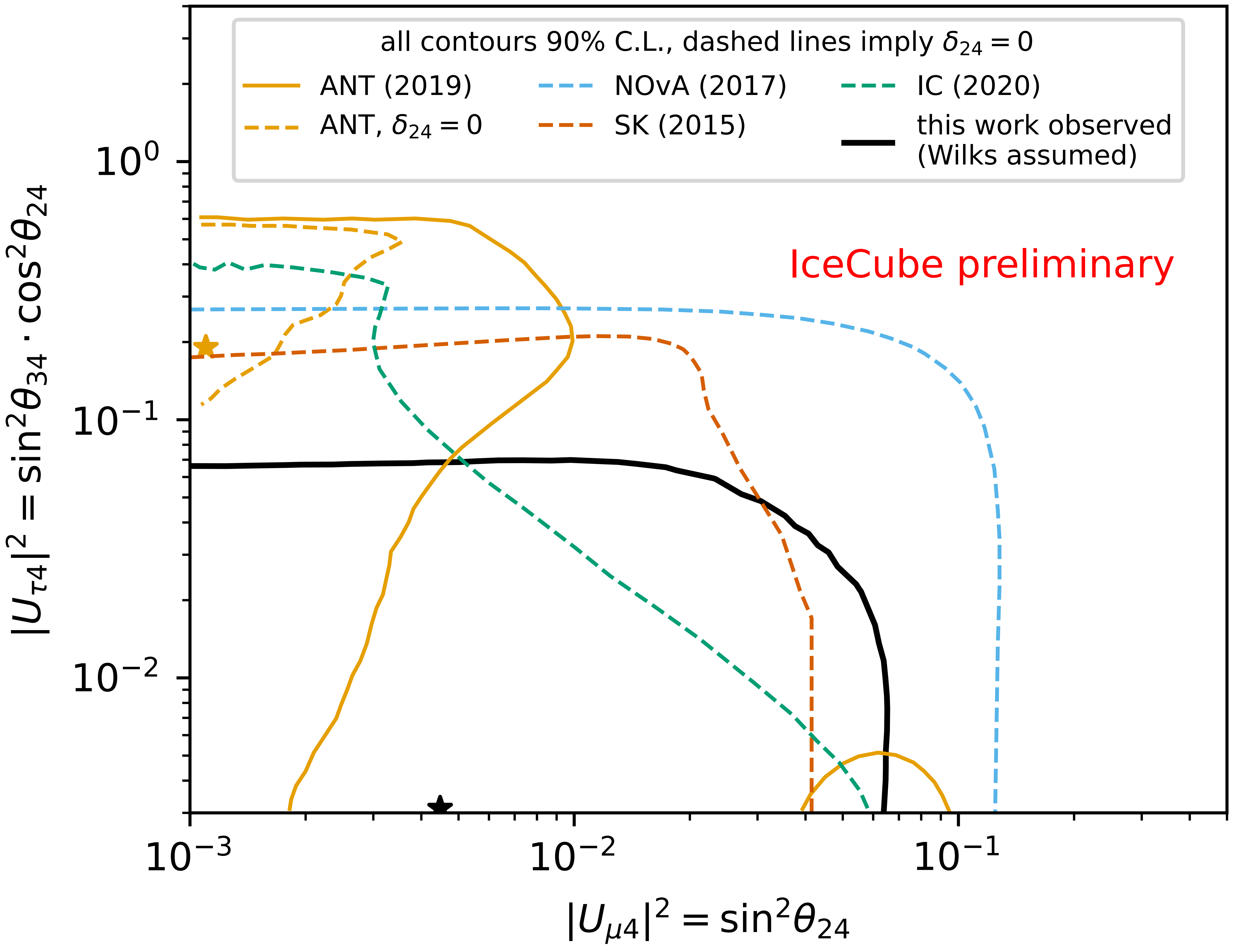


Sterile Search Results

- **No signal of sterile neutrinos observed**
- Marginalized limits (assuming Wilks' theorem with 1 d.o.f.):

  $|U_{\mu4}|^2 < 0.0534\ (90\,\%\ \mathrm{C.L.}),\ 0.0752\ (99\,\%\ \mathrm{C.L.})$

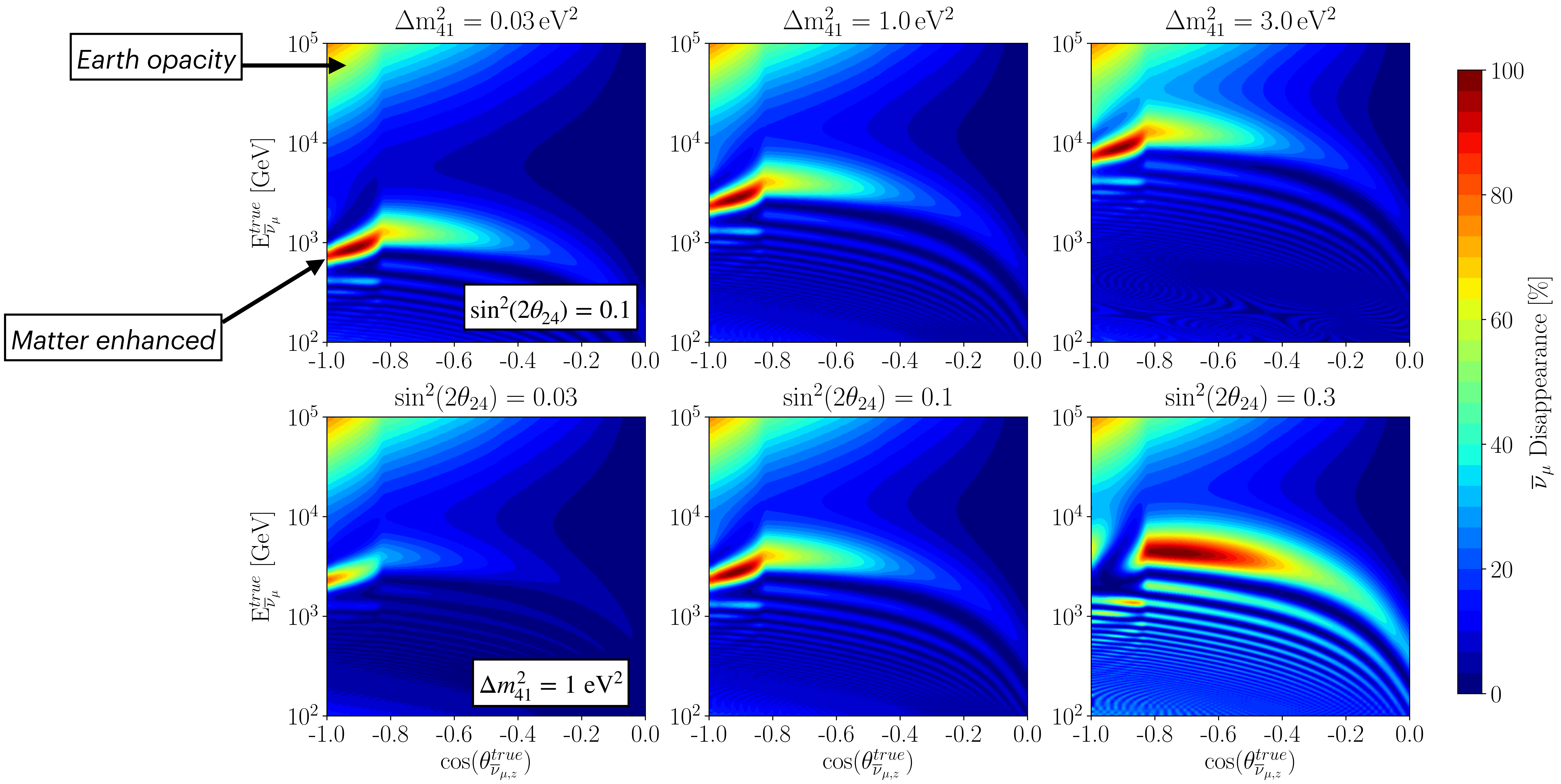
  $|U_{\tau4}|^2 < 0.0574\ (90\,\%\ \mathrm{C.L.}),\ 0.0818\ (99\,\%\ \mathrm{C.L.})$
- Feldman-Cousins spot-checks suggest these are conservative limits
- NMO approx. degenerate with sign of $\cos(\delta_{24})$
  → result is effectively marginalized over NMO
- Constraint on $|U_{\tau4}|^2$ *stronger than global unitarity constraint* (Hu et al. 2021)



Measurements using TeV-scale Atmospheric Neutrinos

Matter-Enhanced Sterile Neutrino Search

Exploiting the MSW effect and Parametric Resonance



Earth opacity

Matter enhanced

$\Delta m^2_{41} = 0.03\,\mathrm{eV}^2$

$\Delta m^2_{41} = 1.0\,\mathrm{eV}^2$

$\Delta m^2_{41} = 3.0\,\mathrm{eV}^2$

$\sin^2(2\theta_{24}) = 0.1$

$\sin^2(2\theta_{24}) = 0.03$

$\sin^2(2\theta_{24}) = 0.1$

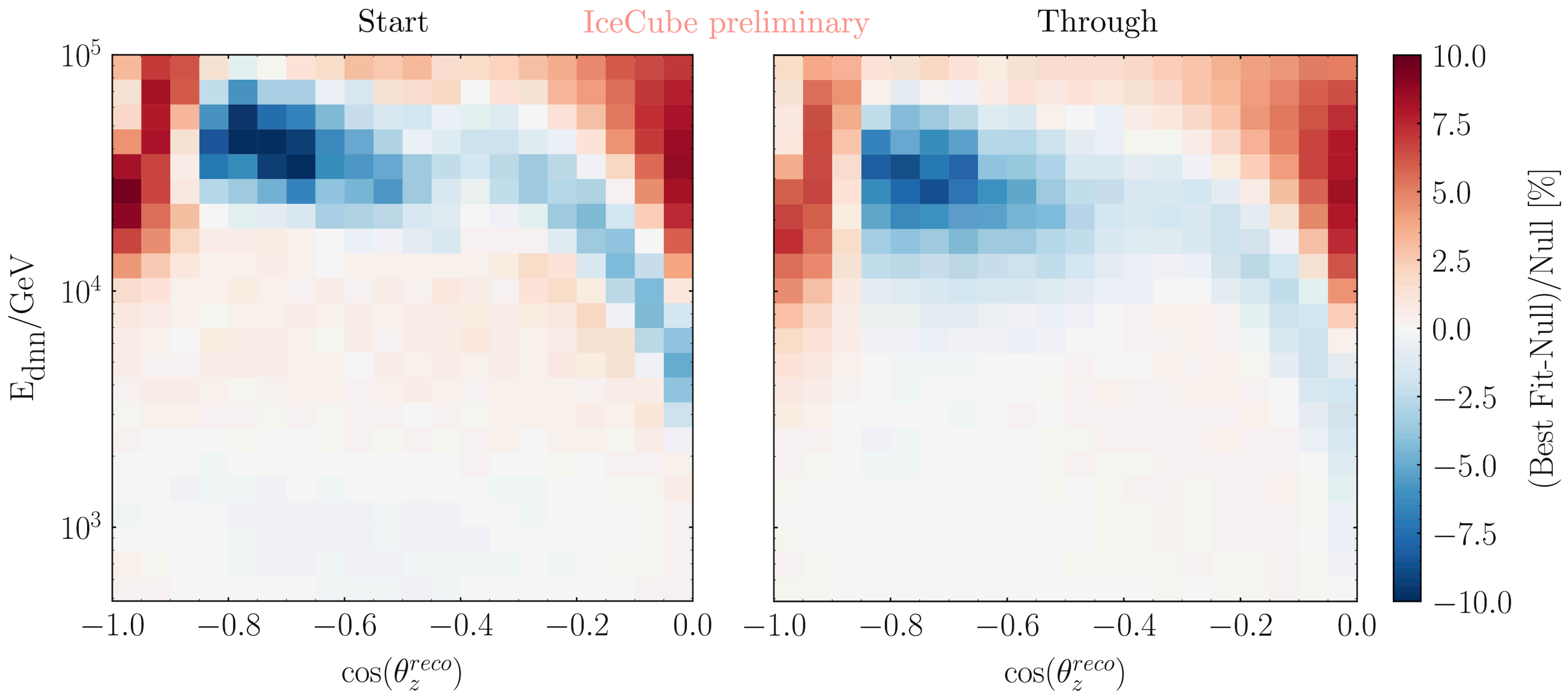
$\sin^2(2\theta_{24}) = 0.3$

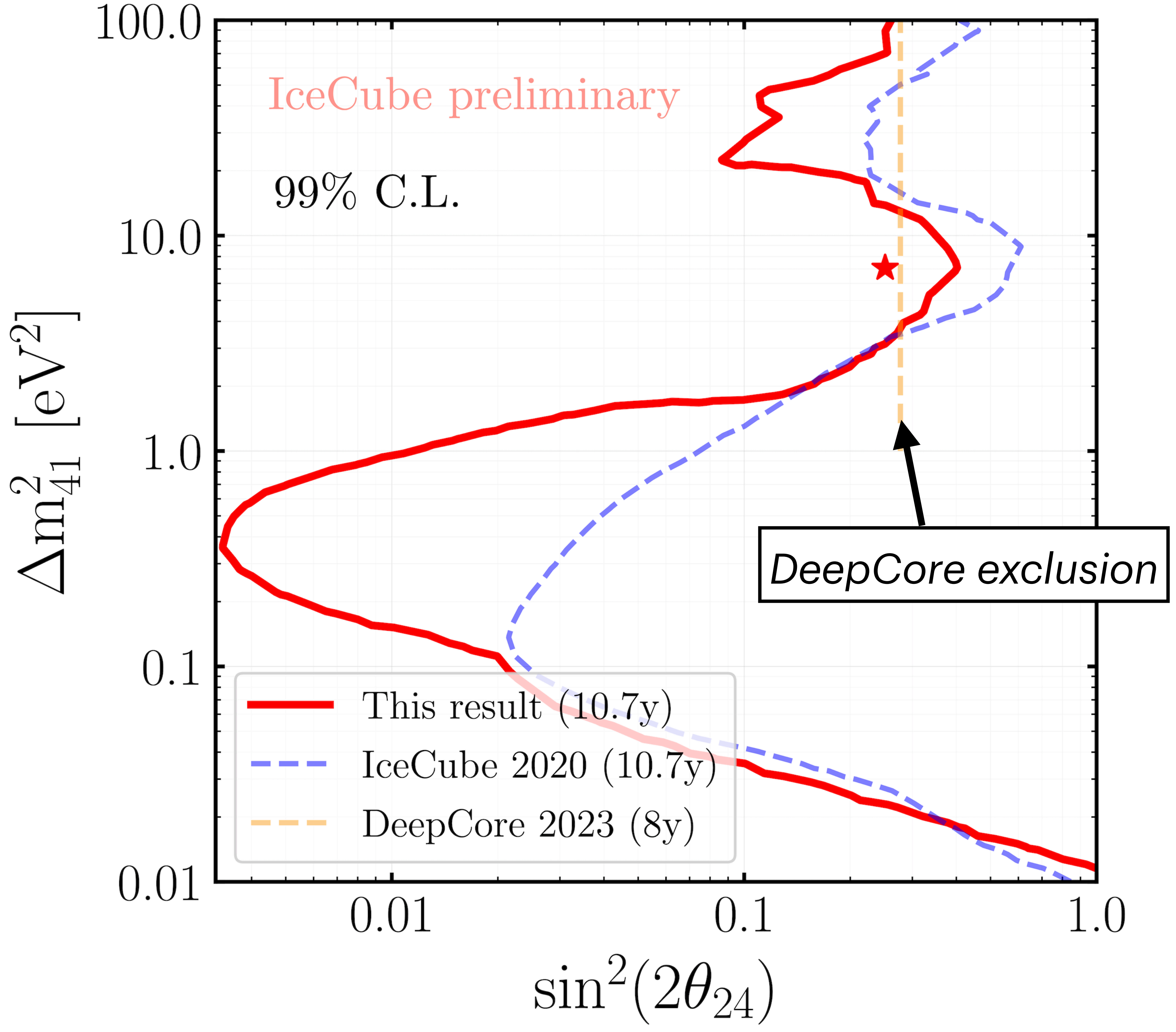
$\Delta m^2_{41} = 1\ \mathrm{eV}^2$

Matter Enhanced Sterile Search: Results

Improved over the 2020 result

- Updated selection and energy estimate with ML tools
- Atmospheric flux treatment DAEMONFLUX (PRD107, 123037)
- Result compatible with previous analysis



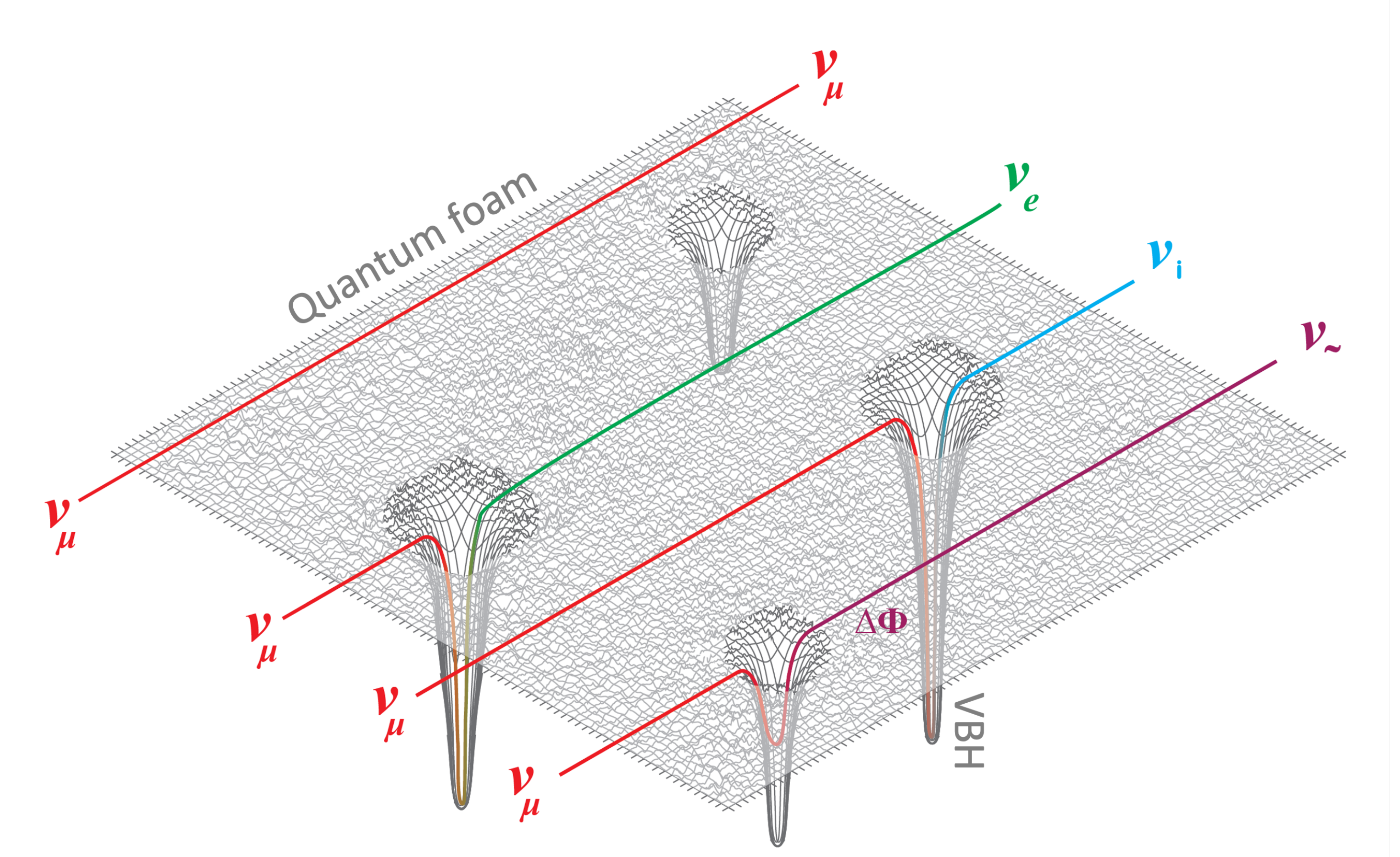


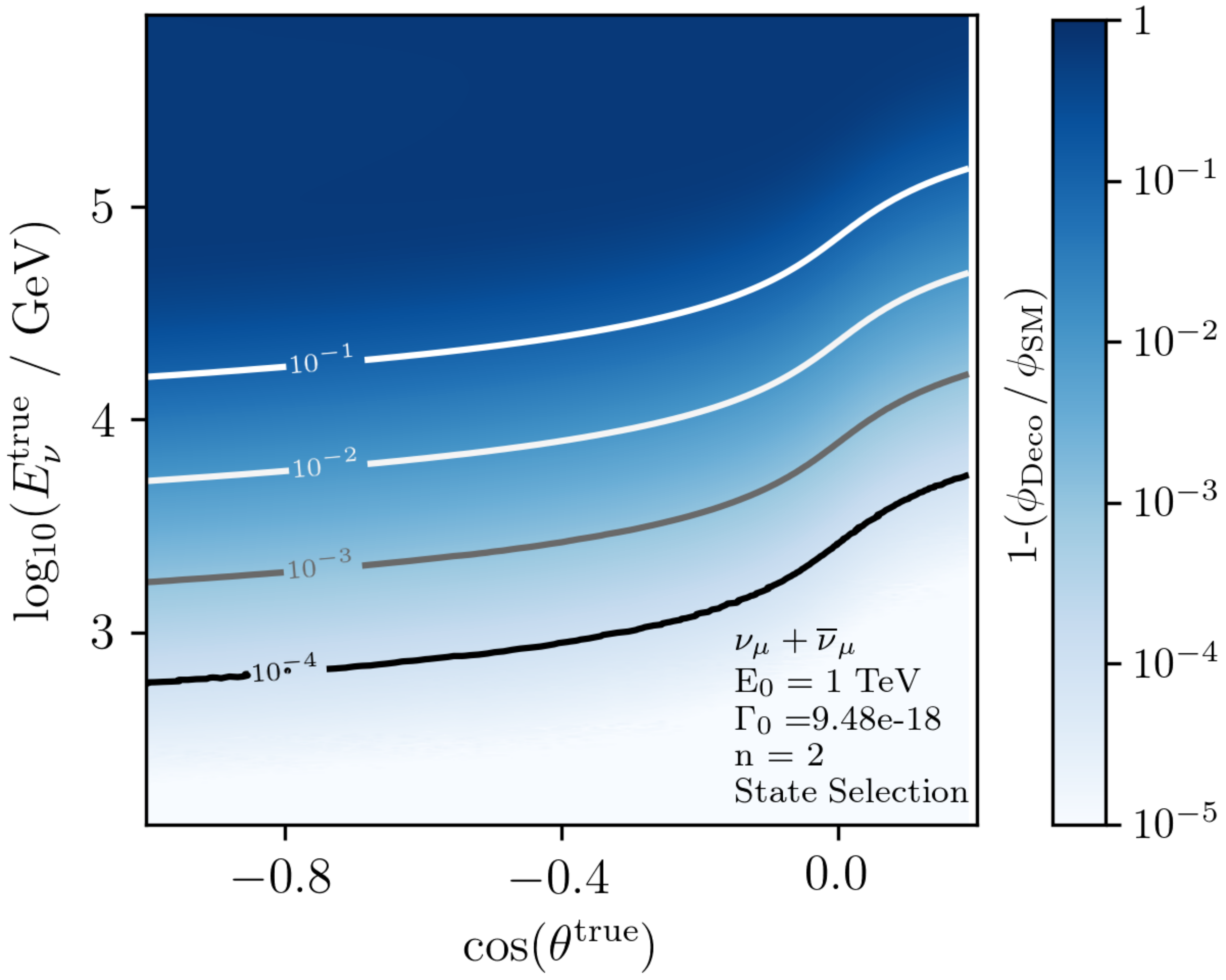
Search for Decoherence Effects

Testing Quantum Gravity with Atmospheric Neutrinos

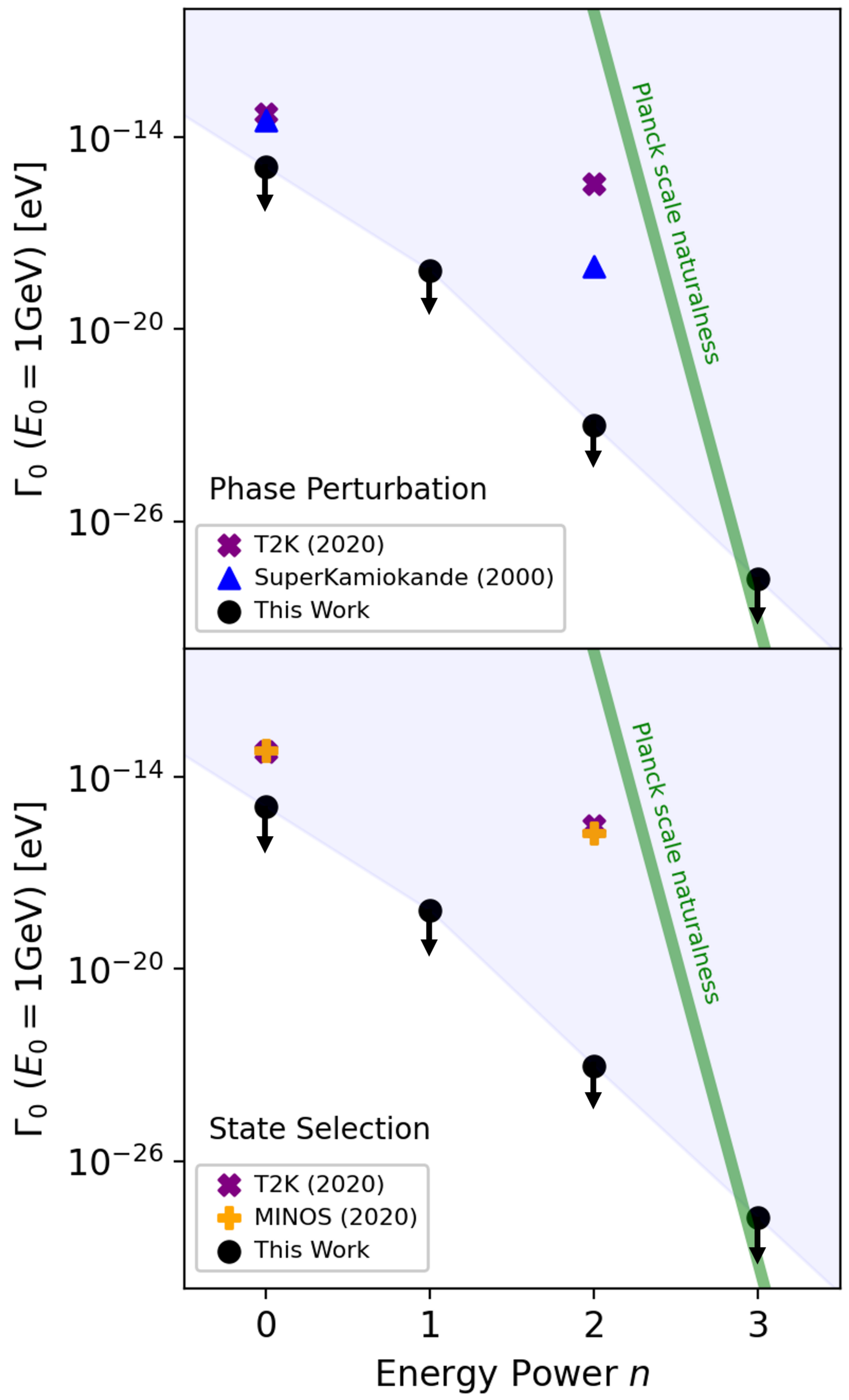
Interactions with virtual black holes lead to dampening with decoherence strength:

$$\Gamma(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{E_0} \right)^n$$





Muon neutrino oscillogram under the state selection model. *arXiv:2308.00105*



➡ World's strongest constraints on decoherence effect for all $n \le 3$

Summary of Results

- Developed a **new DeepCore sample** with improved neutrino purity and more live time than any previous DeepCore analysis
- **Sterile neutrino search with DeepCore** in the 3+1 paradigm assuming mass splitting $> 1\ \mathrm{eV}^2$ using a "golden sample" of very track-like events
  - Strongest limit on $|U_{\tau 4}|^2$ to date, competitive limit on $|U_{\mu 4}|^2$
- **Three-flavor result** using new ML reconstruction
  - Most precise Δm^2_{32} and θ_{23} measurement with atmospheric neutrinos to date
- **Improved matter-enhanced sterile neutrino search** using TeV-scale atmospheric neutrinos giving improved exclusion over 2020
- **Search for decoherence effects** producing world-leading exclusion for quantum-gravity induced decoherence parameter

And now, a look into the future...

IceCube Upgrade

2 MT of Dense Instrumentation for Low Energy Measurements

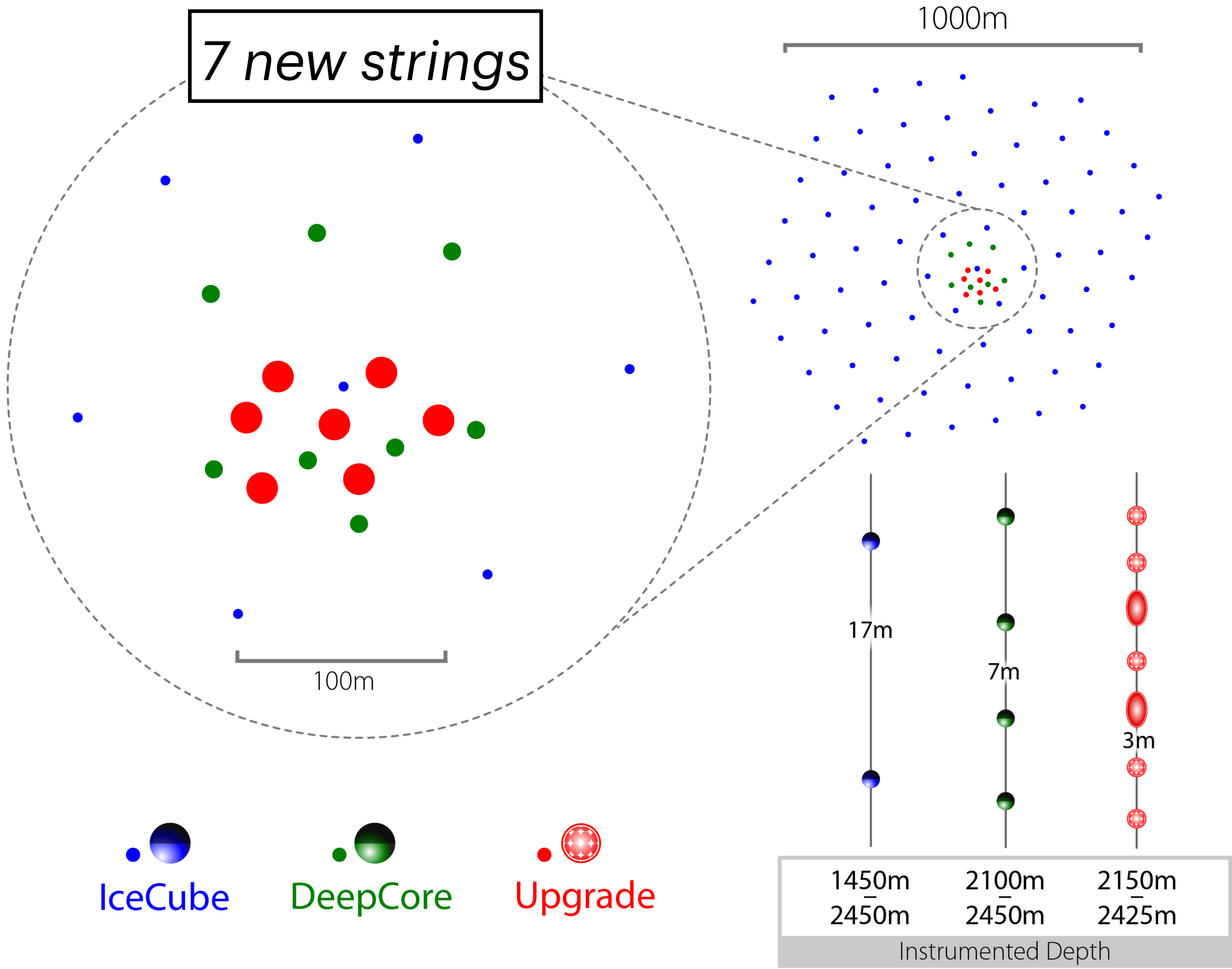
mDOM

D-Egg

2 new module types

Credit: S. Niedworok

Credit: M. Shimizu

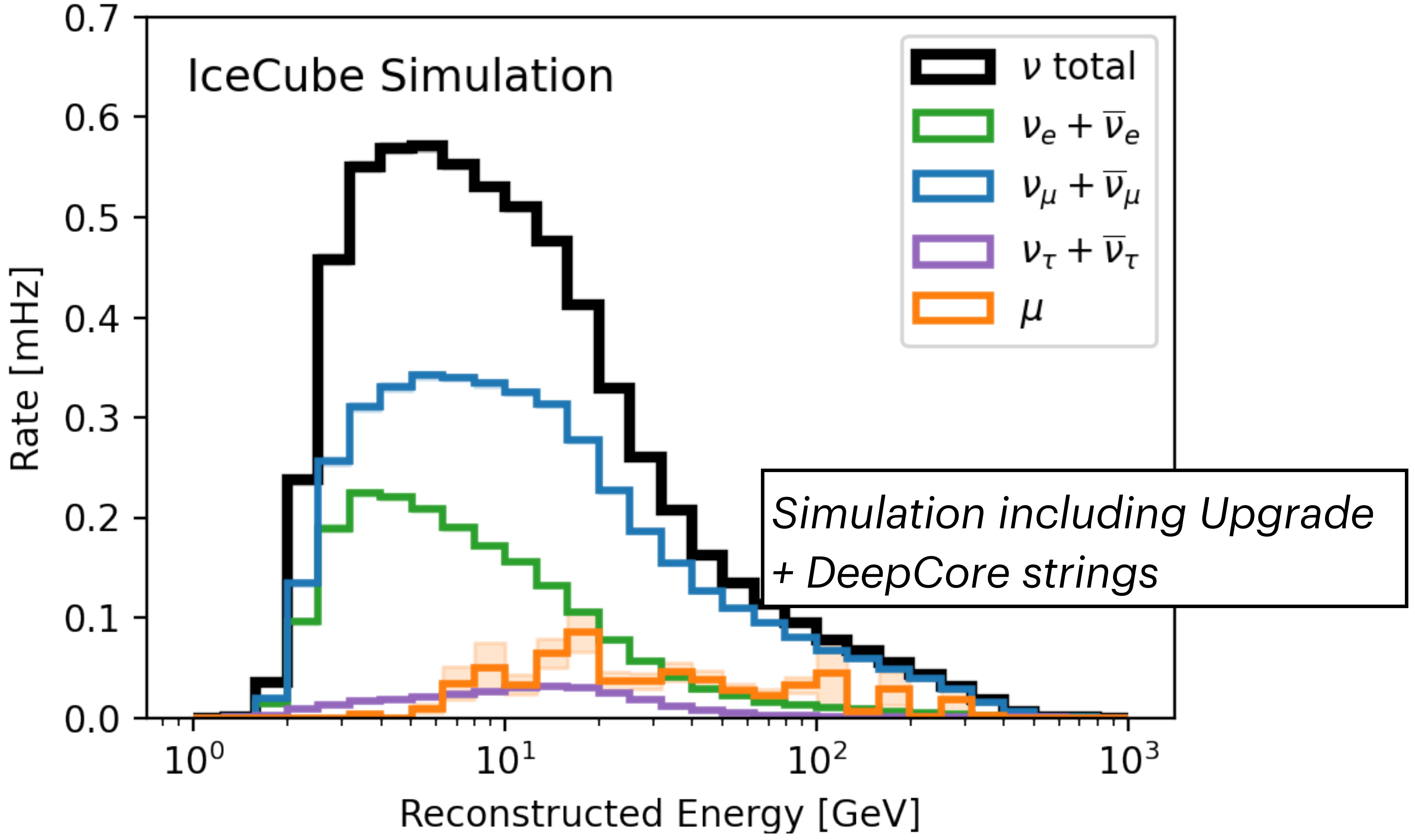


Aya Ishihara, The IceCube Upgrade — Design and Science goals, (arXiv:1908.09441)

IceCube Upgrade

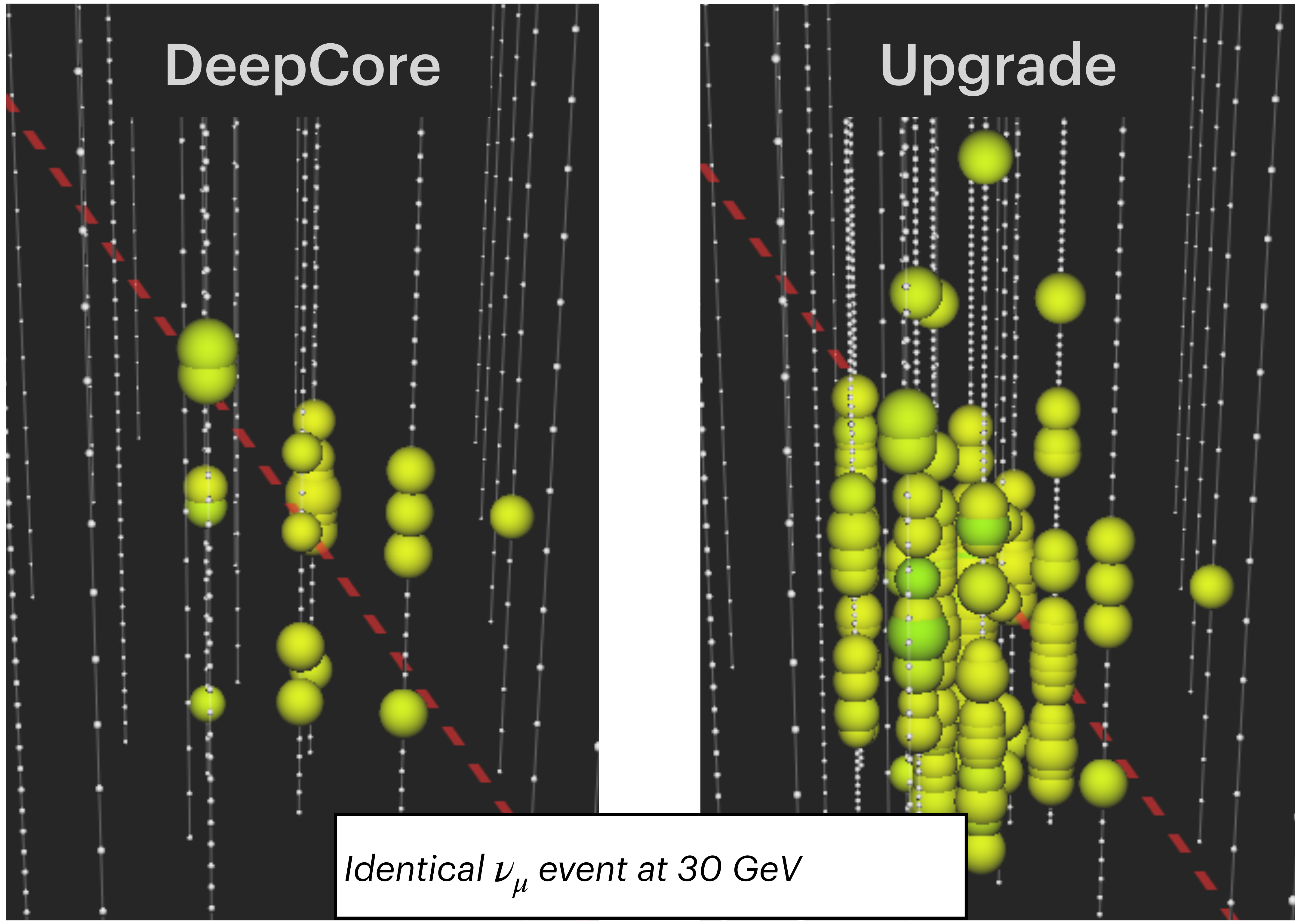
Expected Performance

- **Denser instrumentation** for energy threshold ~ 1 GeV
- **Higher event rate** about 4x DeepCore



Simulation including Upgrade + DeepCore strings

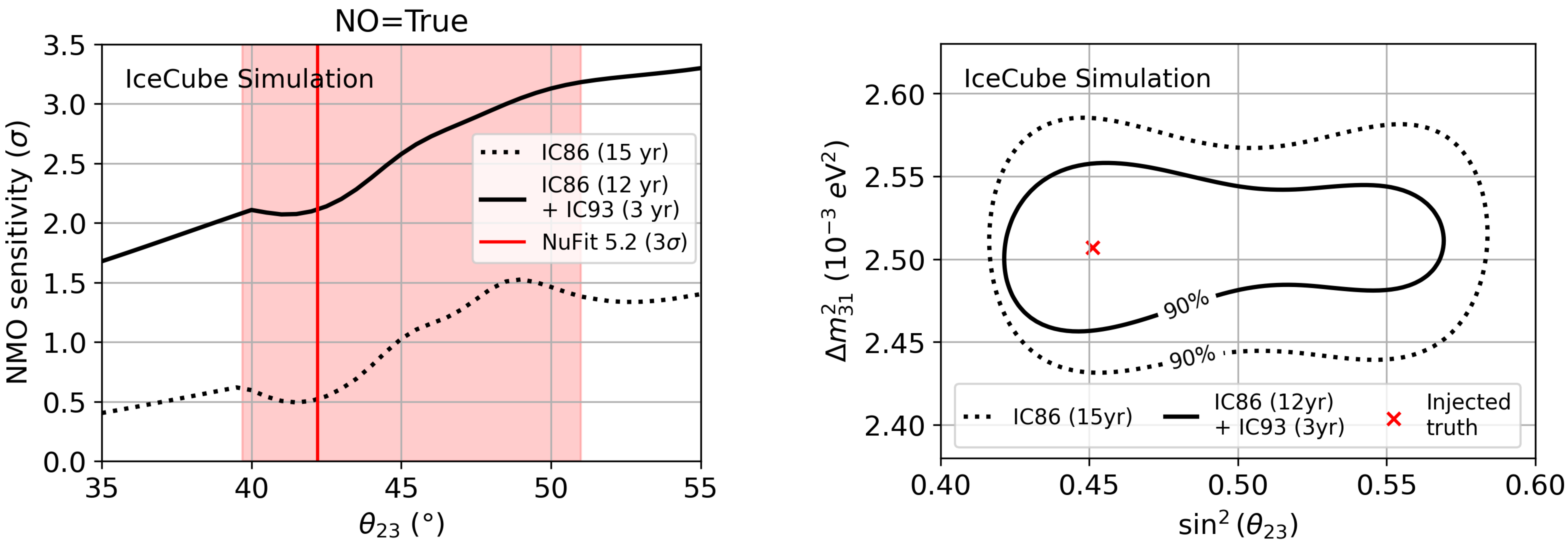
arXiv:2307.15295



Identical ν_μ event at 30 GeV

IceCube Upgrade

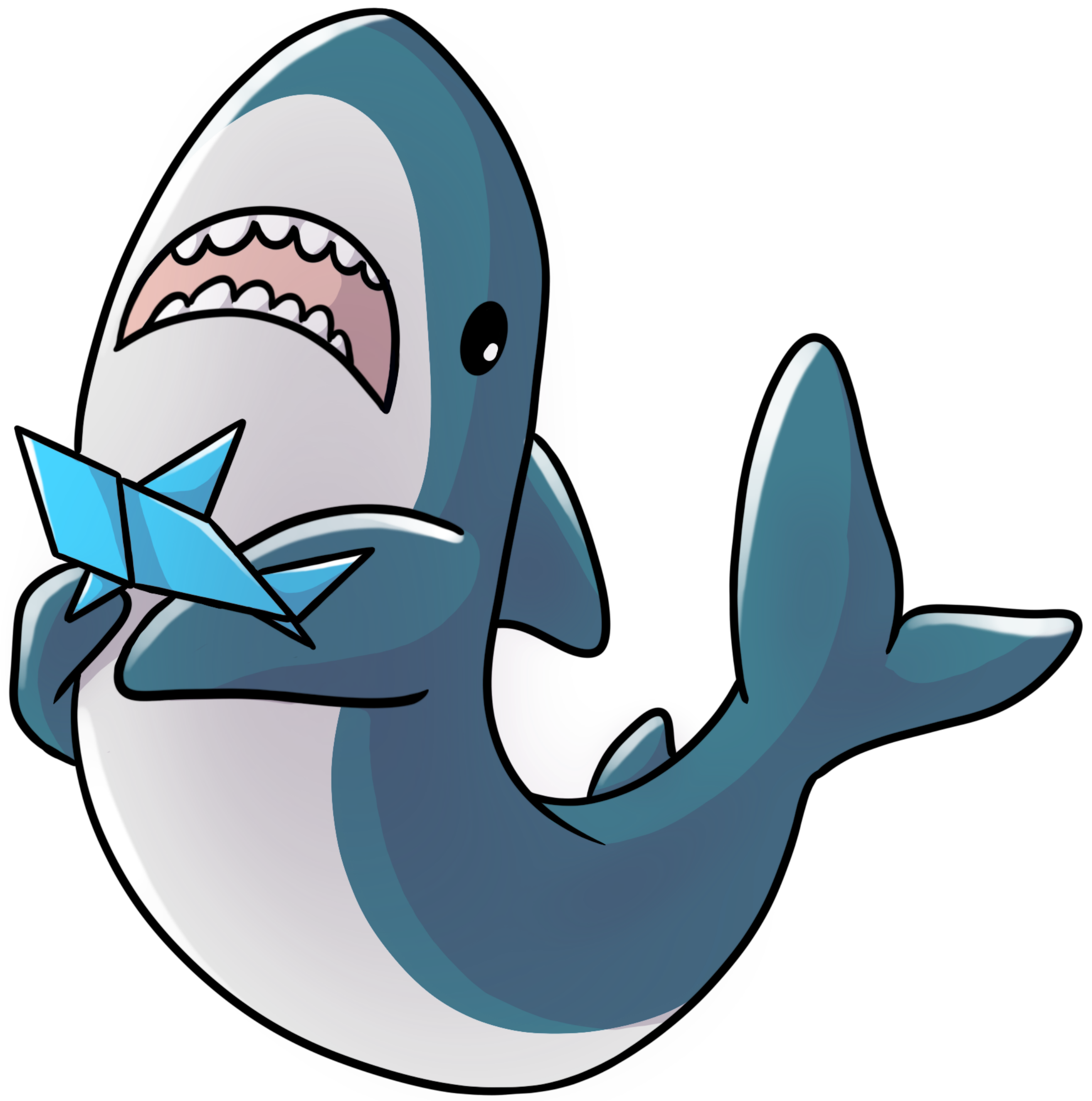
Expected Oscillation Sensitivity Improvements



Upgrade sensitivity study: arXiv:2307.15295

The future is exciting!

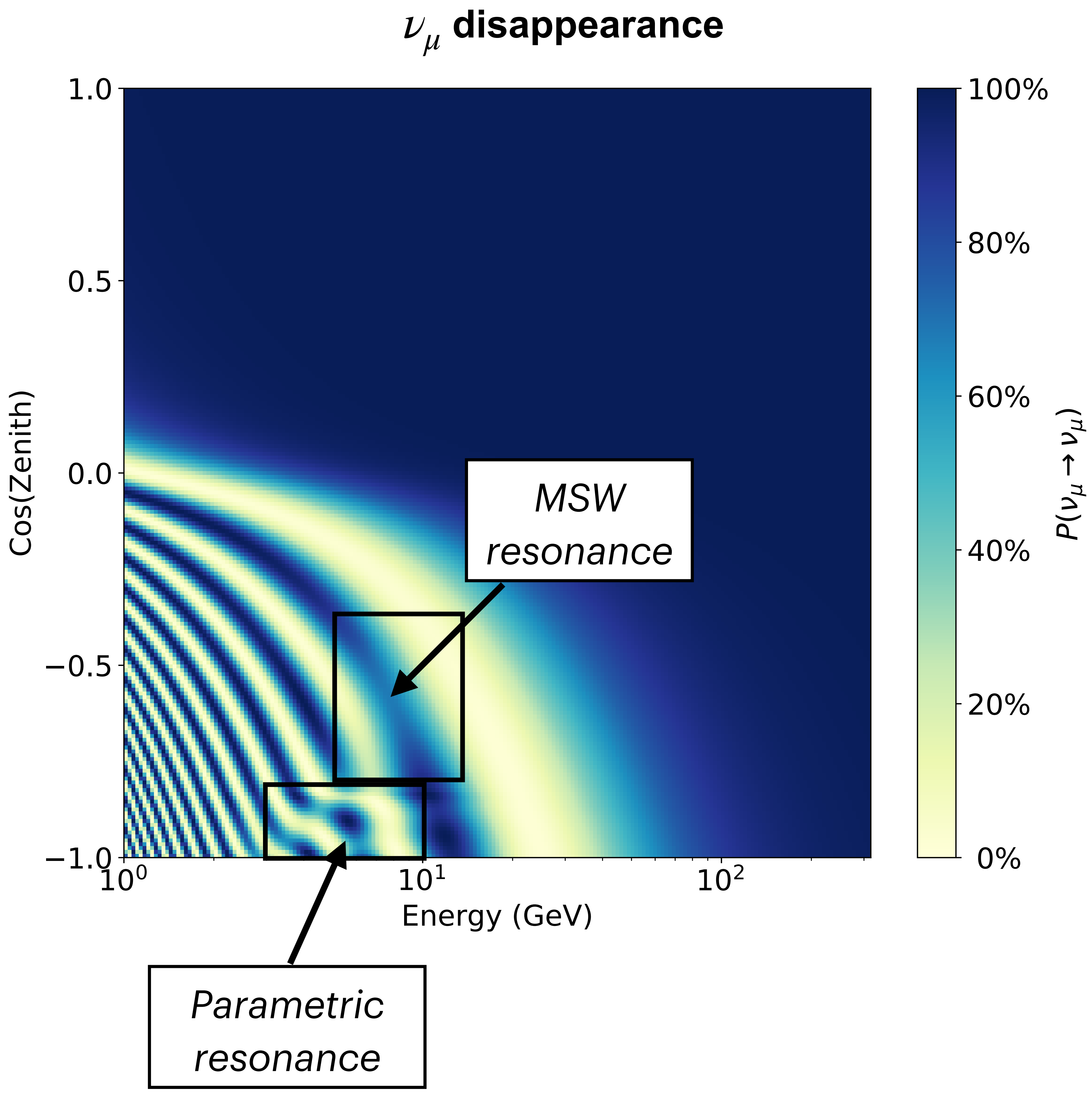
Thank you!



Backup

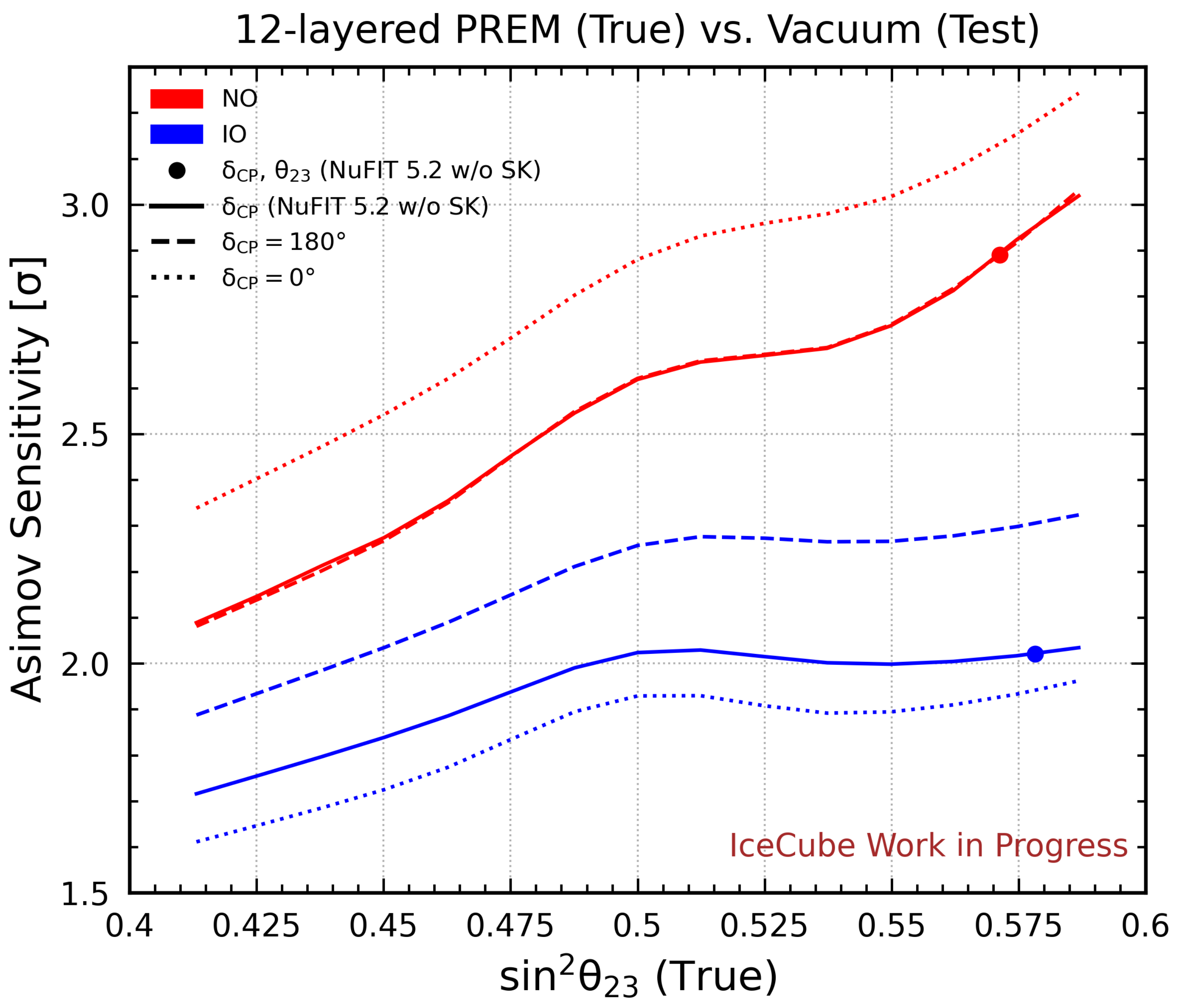
Neutrino Tomography of the Earth

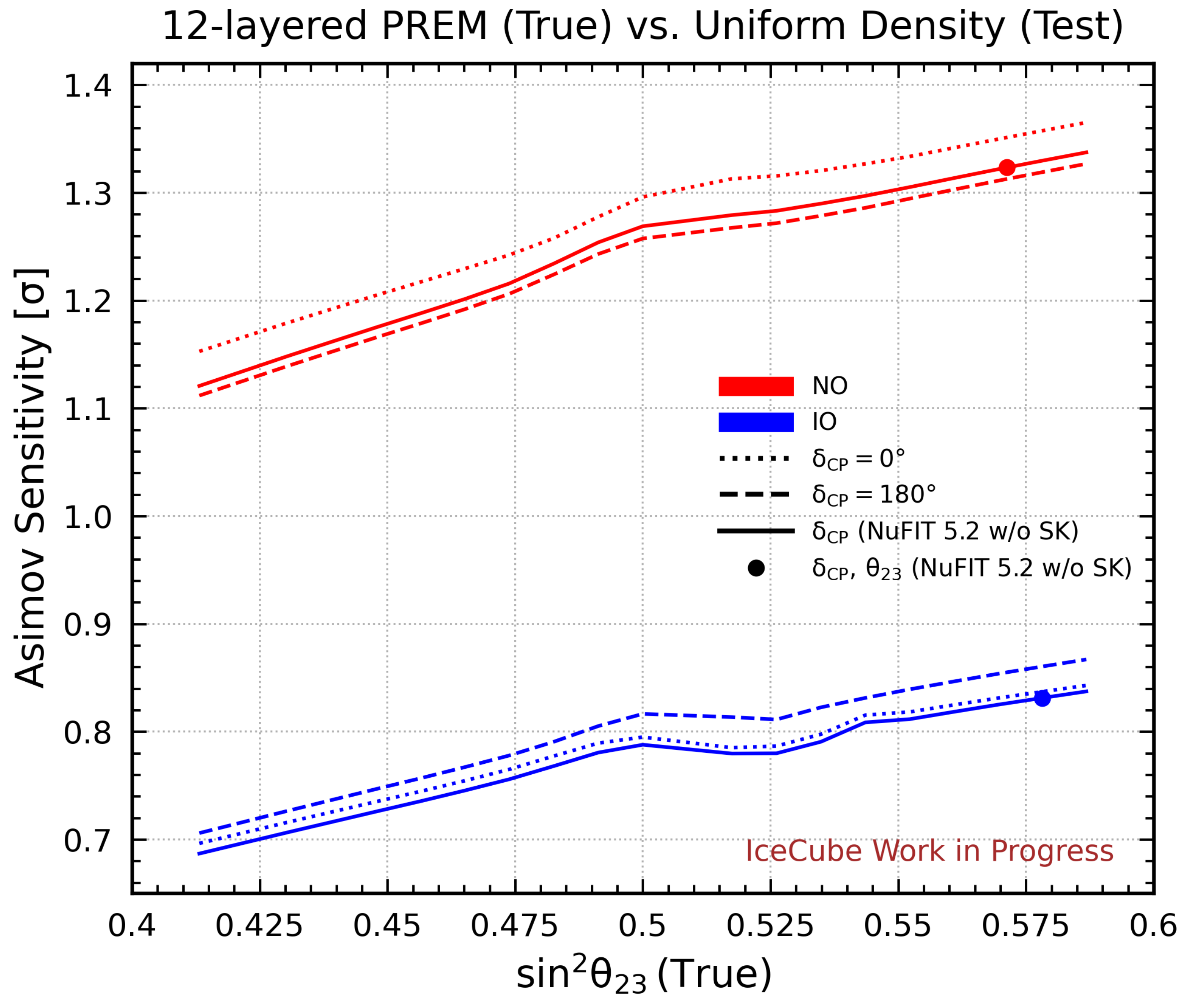
Recent Sensitivity Study using the FLERCNN Sample


ν_μ **disappearance**

MSW resonance

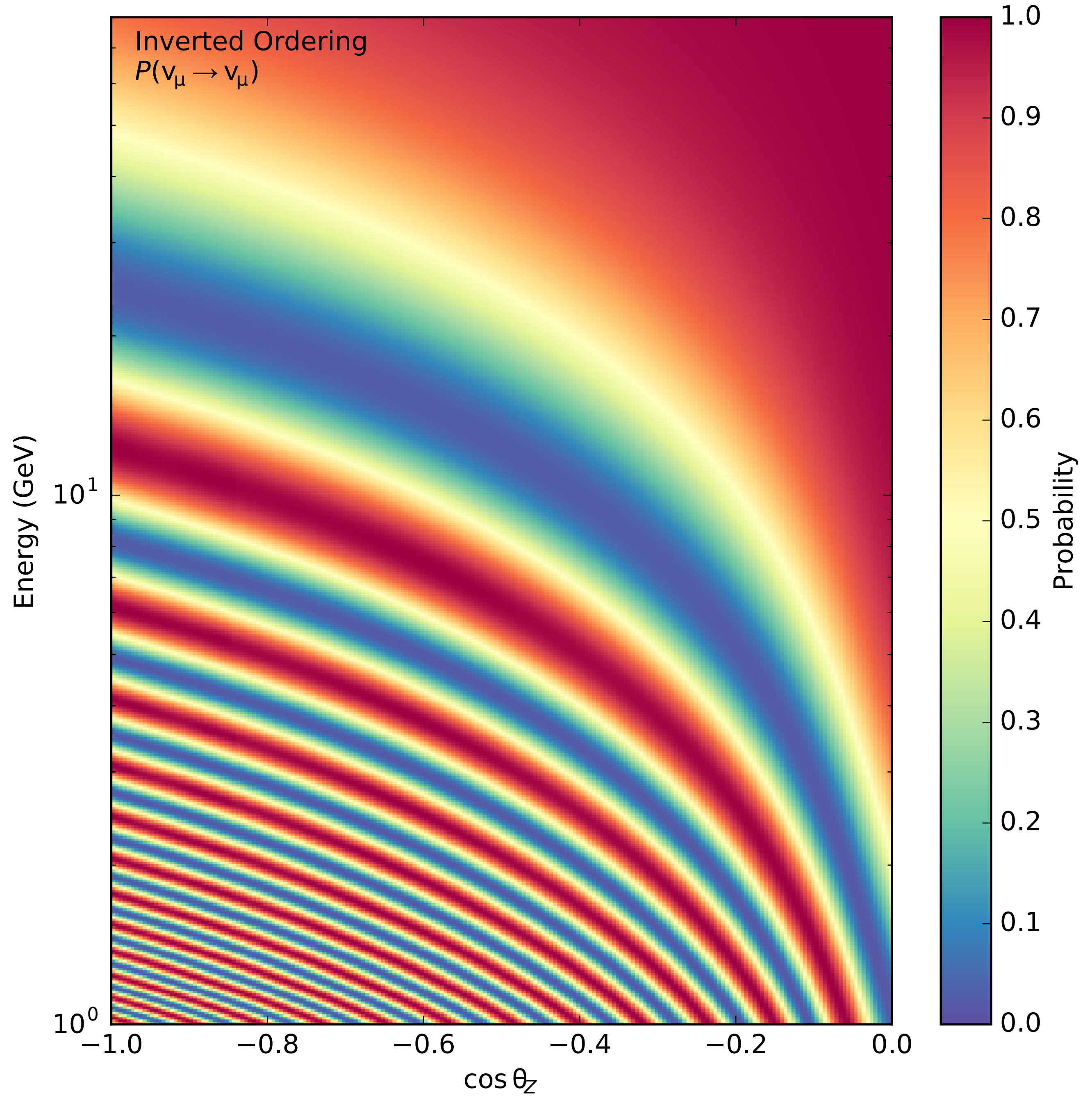
Parametric resonance

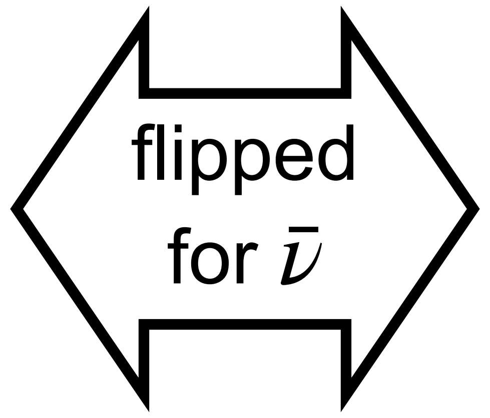

12-layered PREM (True) vs. Vacuum (Test)

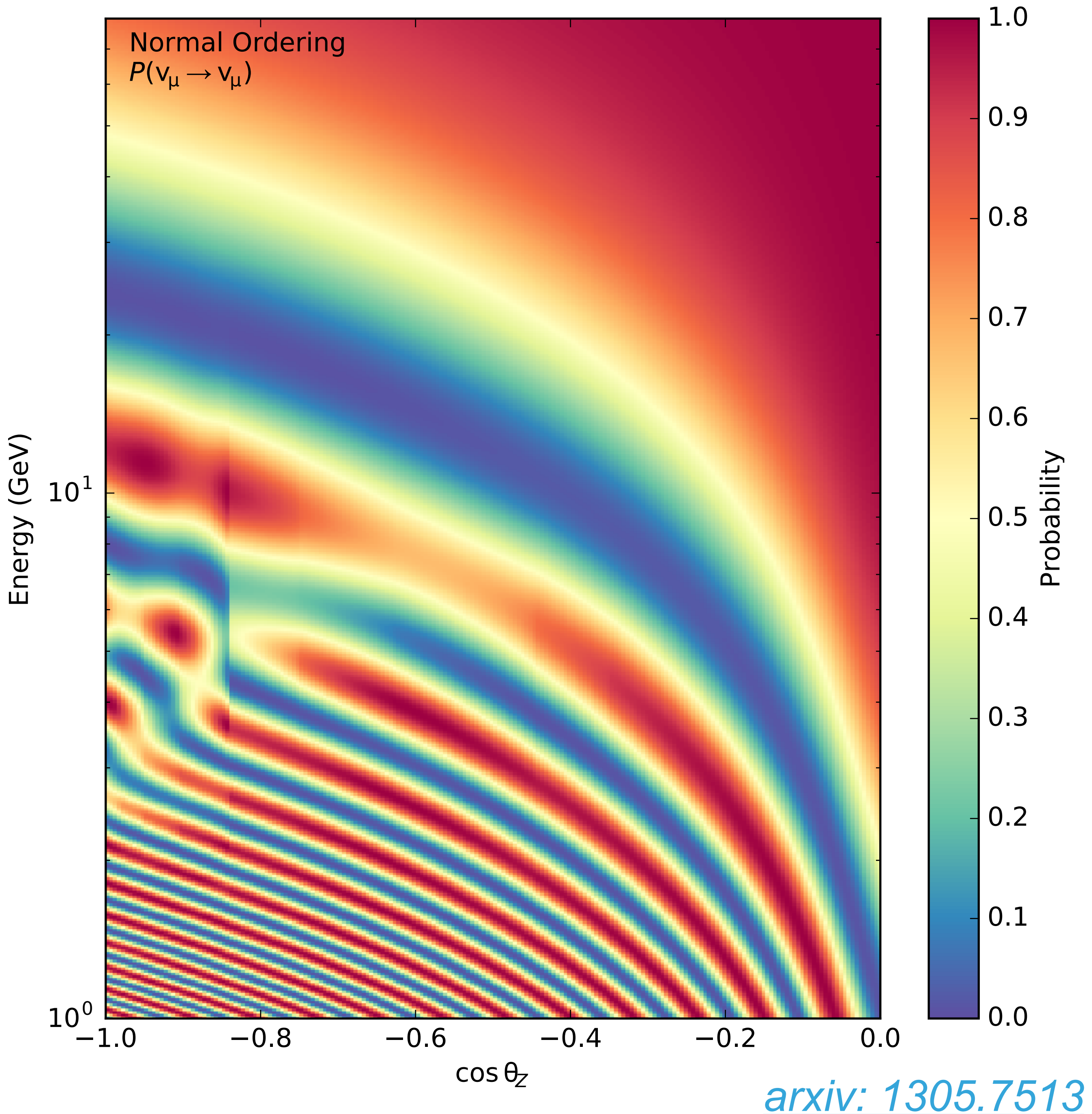

12-layered PREM (True) vs. Uniform Density (Test)

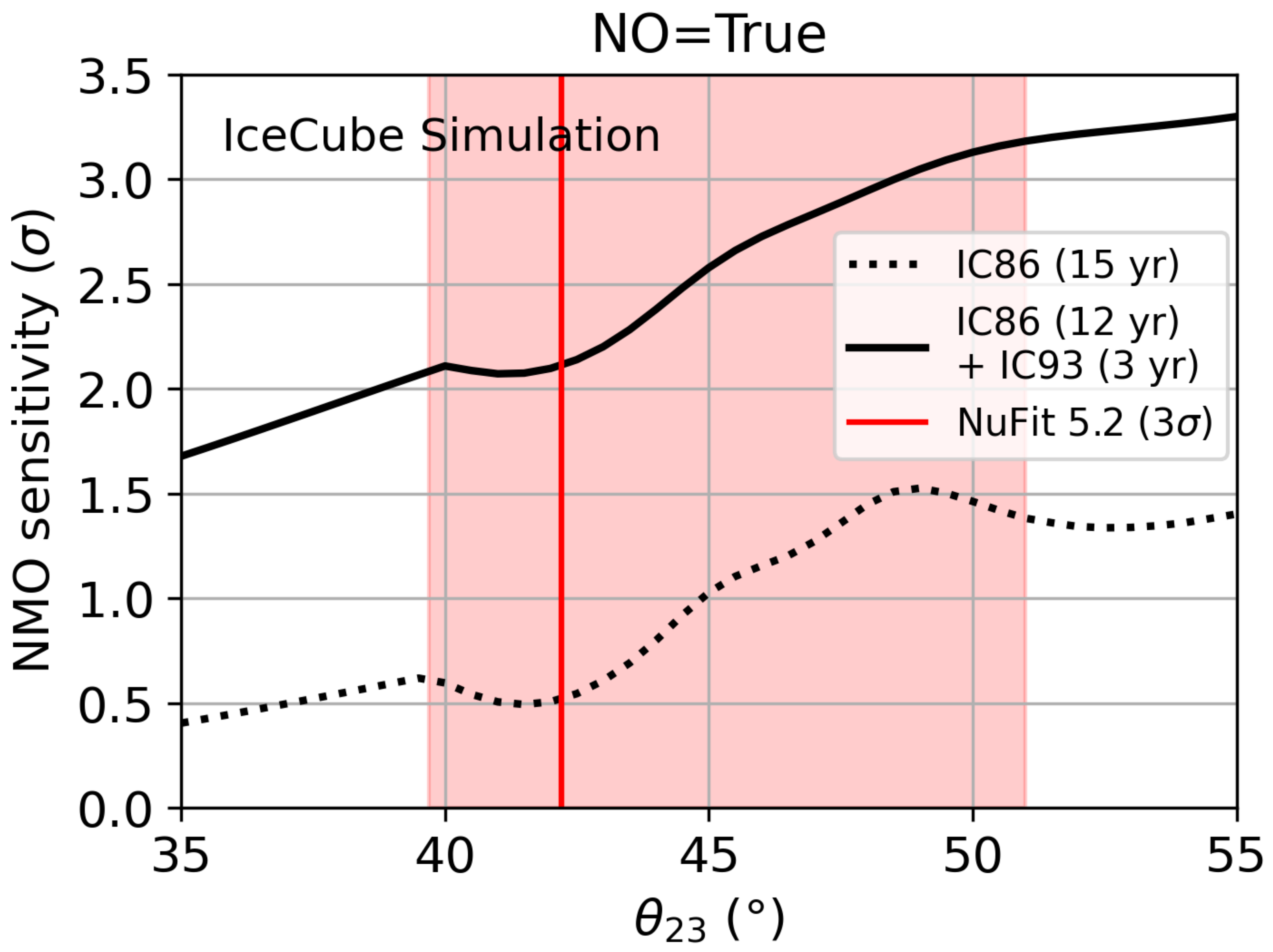
Earth Density Profile	**Layer Boundaries [km]**	**Layer Density [g/cm³]**	**Electron Number Density Y_e**
PREM	12 Layers	12 Densities	0.5
Uniform Density	1 Layer	5.53	0.5

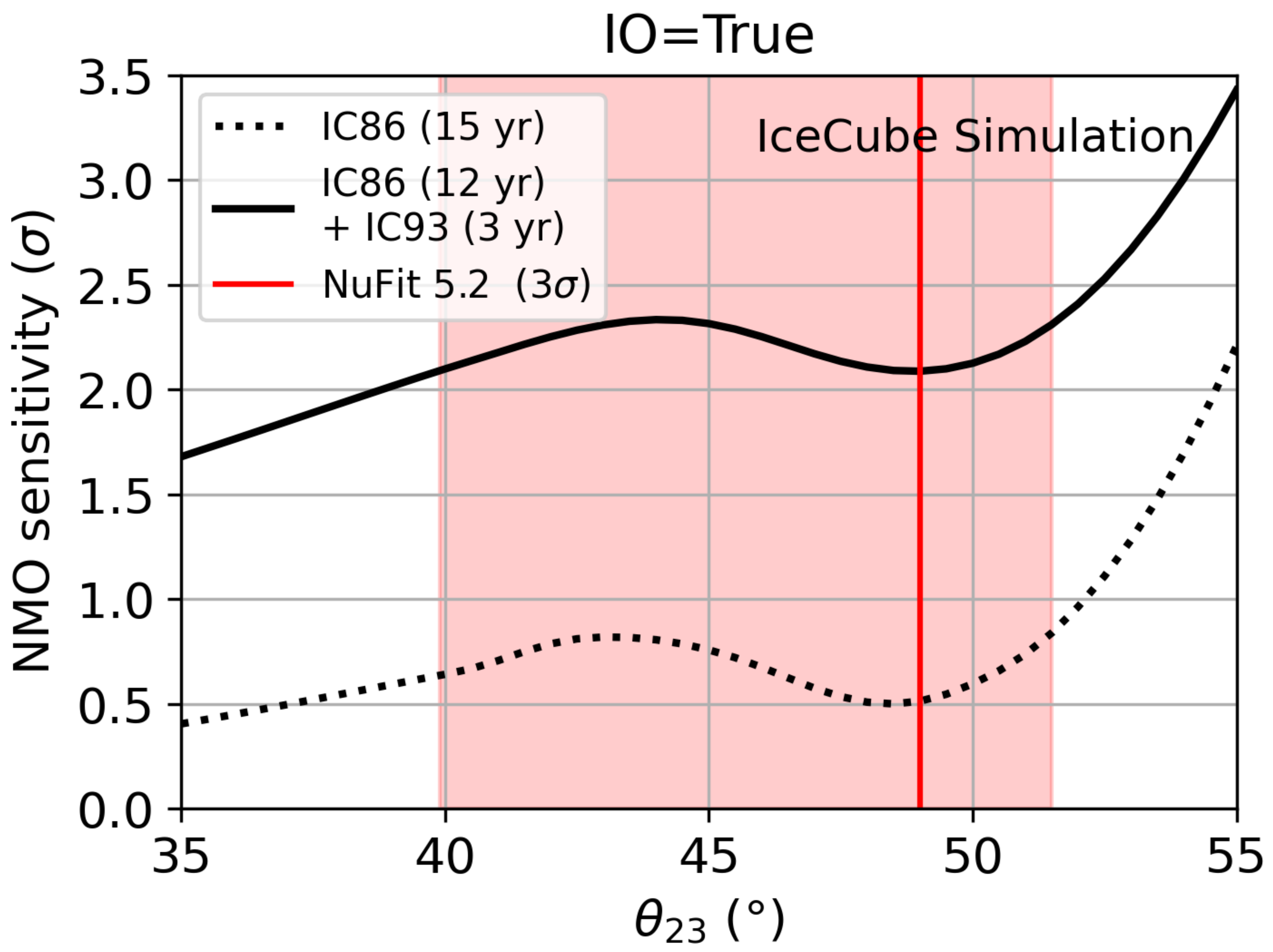
Neutrino Mass Ordering (NMO)



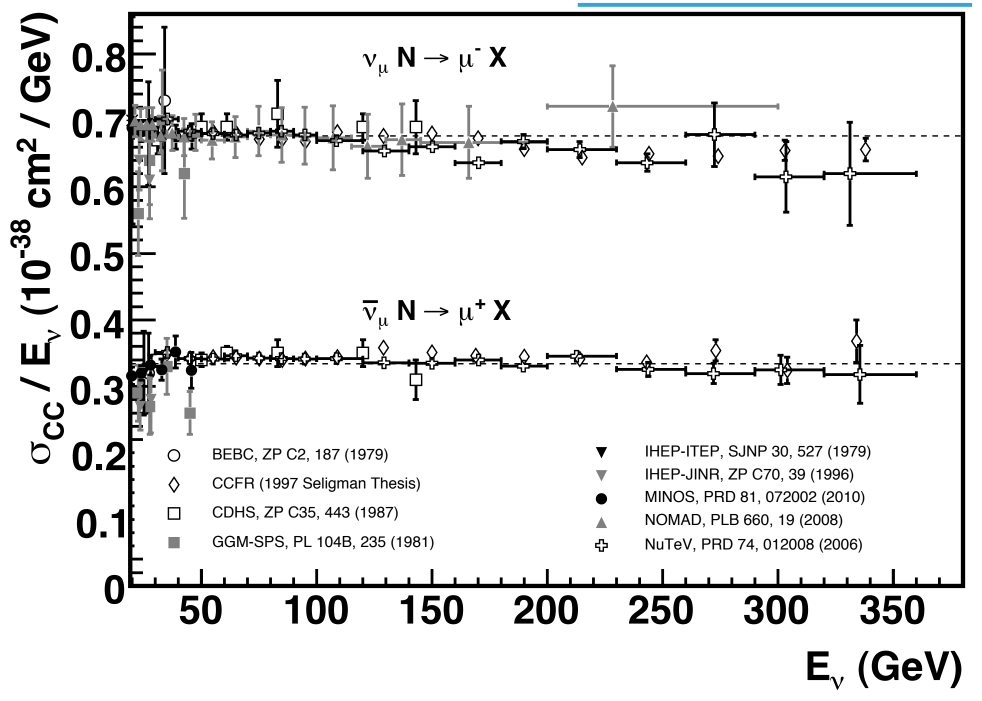

flipped for $\bar{\nu}$







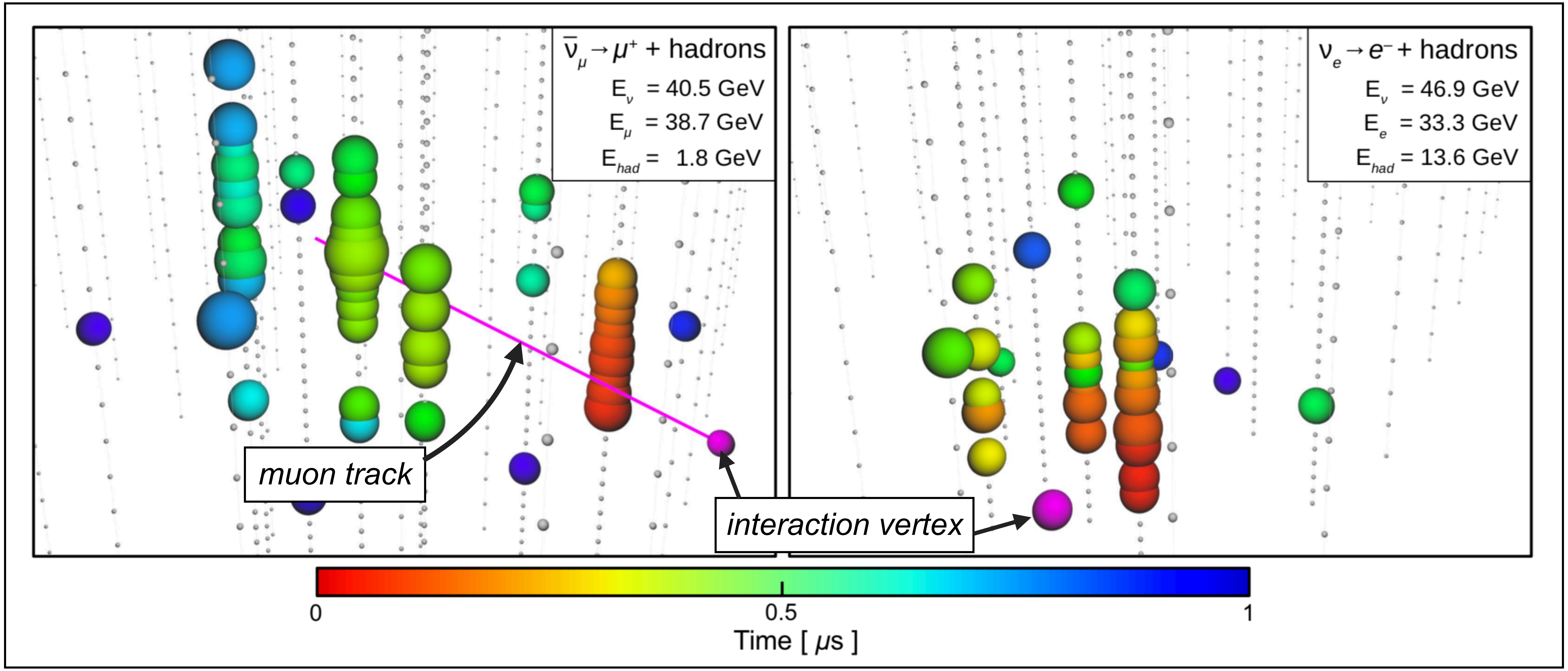
arxiv: 1305.7513



- matter-induced distortions for ν in NO, $\bar{\nu}$ in IO
- ν, $\bar{\nu}$ indistinguishable to detector
  - ➡ effect on rates due to different cross-sections

Neutrino Interactions in DeepCore: Realistic

Charged-current ν_μ interactions **Neutral-current interactions + ν_e + ν_τ**



"tracks" ***"cascades"***

Event Selection

Trigger + Online Filter

Trigger + online Filter (L2)

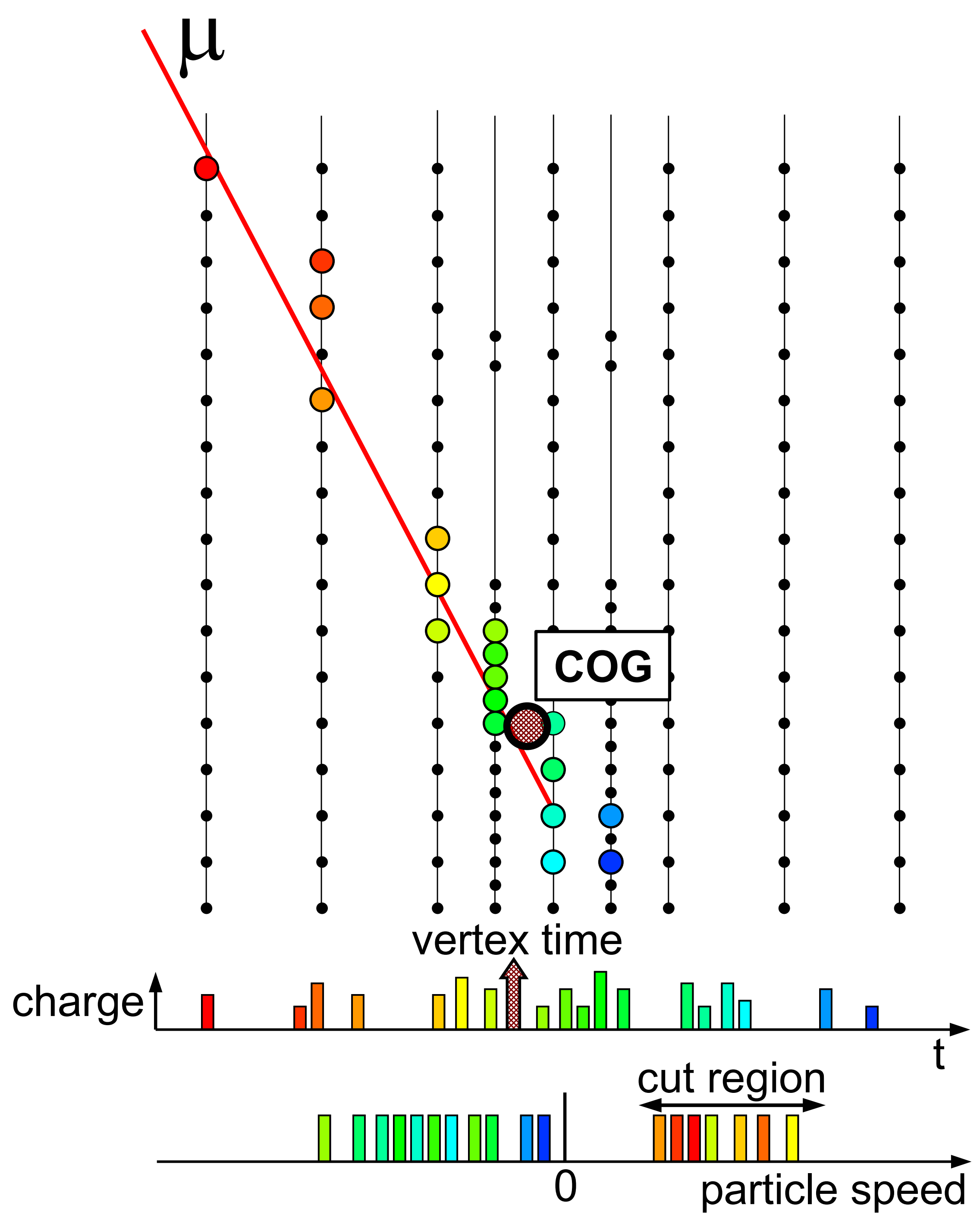
Offline Filter (L3 to L5)

Reconstruction + Classification

Final Cuts

Histogram

- Trigger: at least three DOMs fulfill “hard local coincidence” (HLC) within DeepCore fiducial volume
- Online filter: veto event when hits outside DeepCore compatible with muon hypothesis
- Events passing filter sent North via Satellite 📡



Offline Filter

Reducing background from noise and atm. muons

Trigger + online Filter (L2)

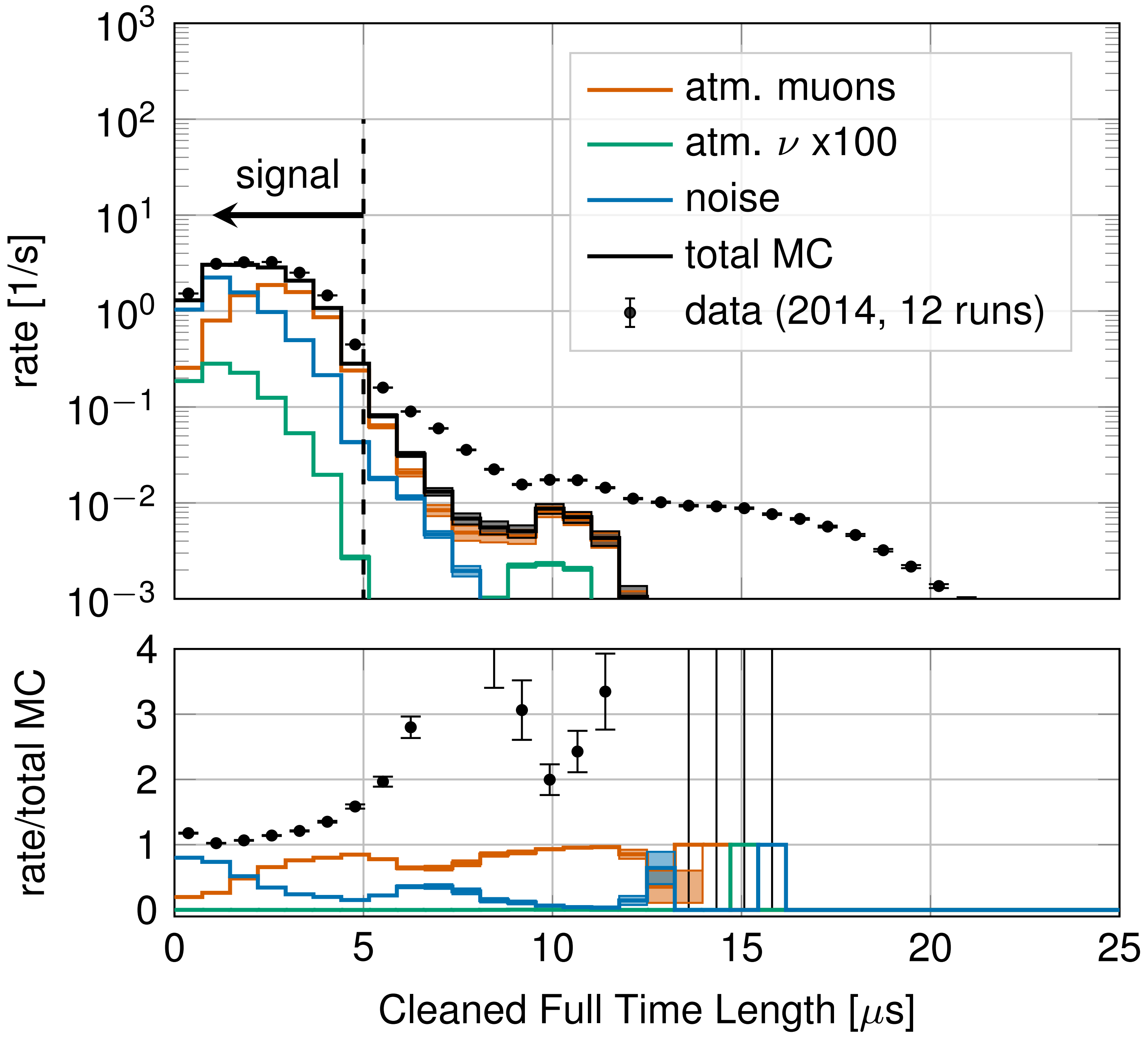
Offline Filter (L3 to L5)

Reconstruction + Classification

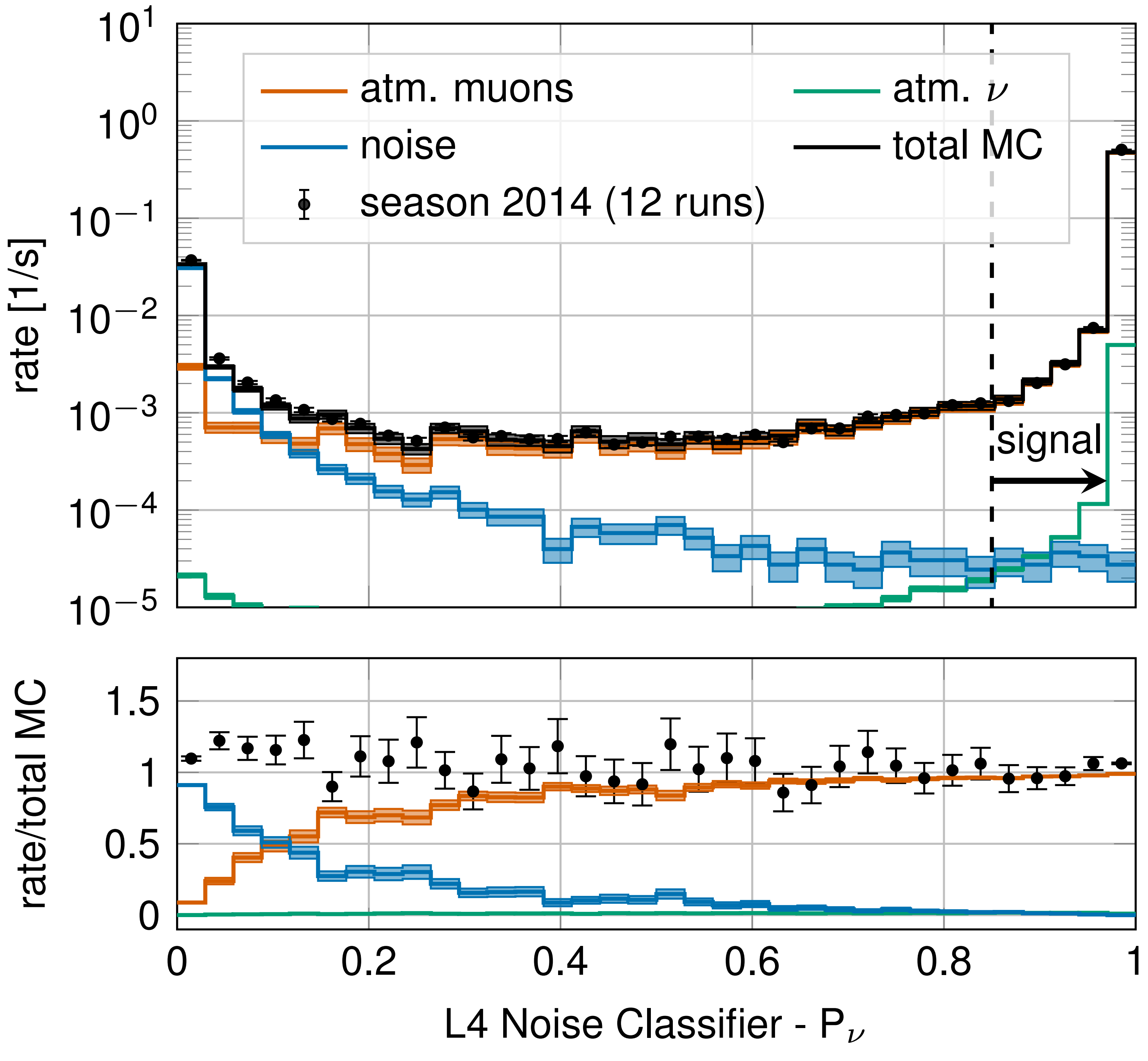
Final Cuts

Histogram

Event Duration (L3)



Noise BDT (L4)



Offline Filter

Reducing background from noise and atm. muons

Trigger + online Filter (L2)

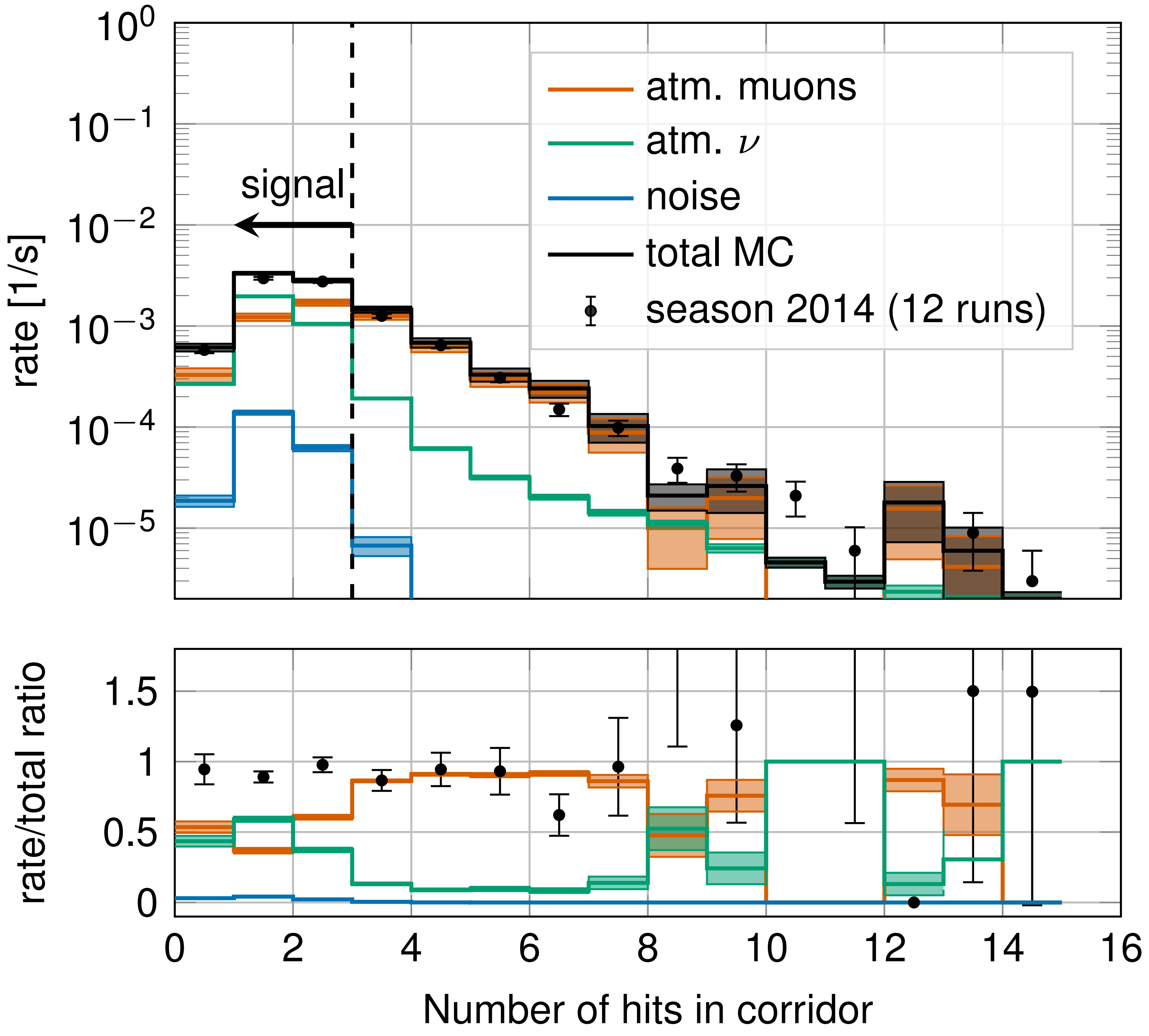
Offline Filter (L3 to L5)

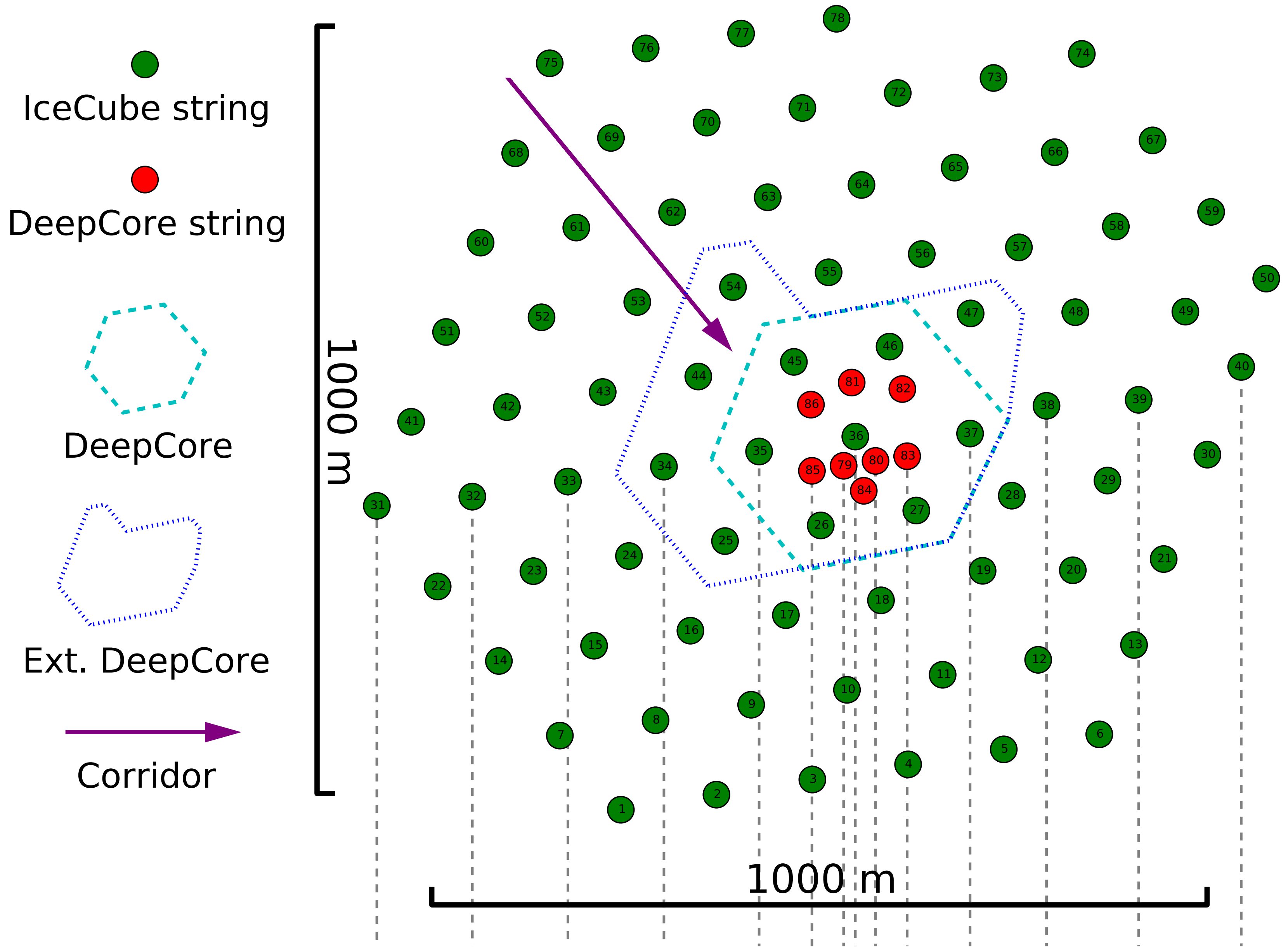
Reconstruction + Classification

Final Cuts

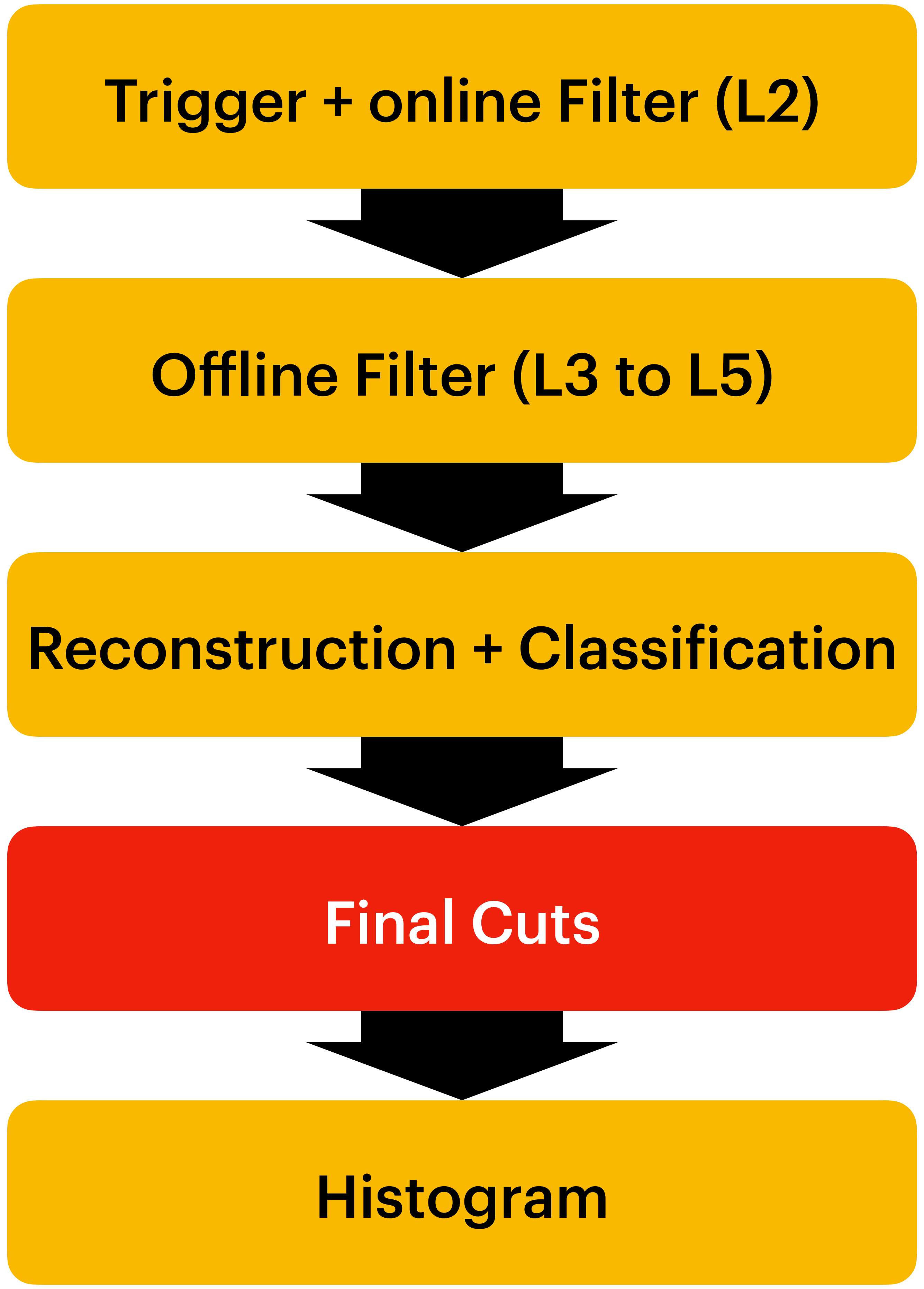
Histogram

Corridor Cut (L5)





Final Sample Cuts



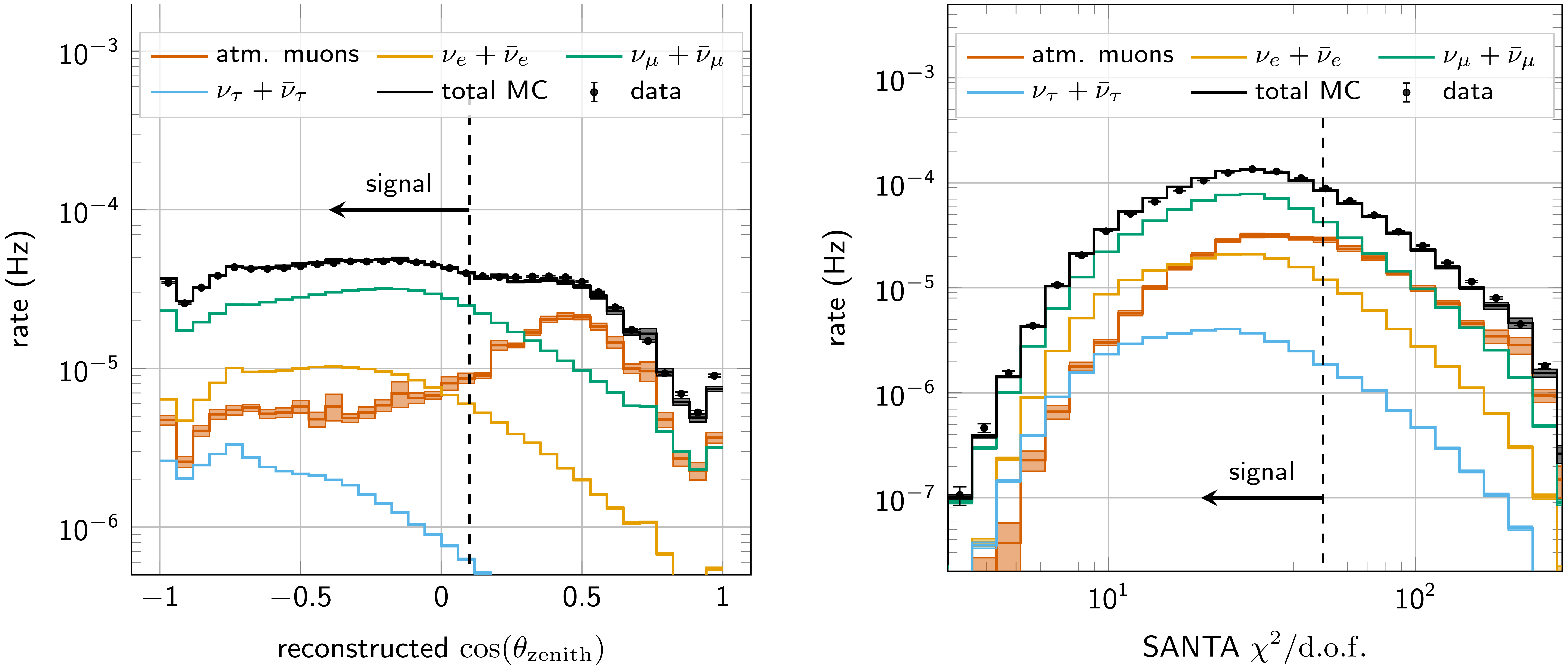
Trigger + online Filter (L2)

Offline Filter (L3 to L5)

Reconstruction + Classification

Final Cuts

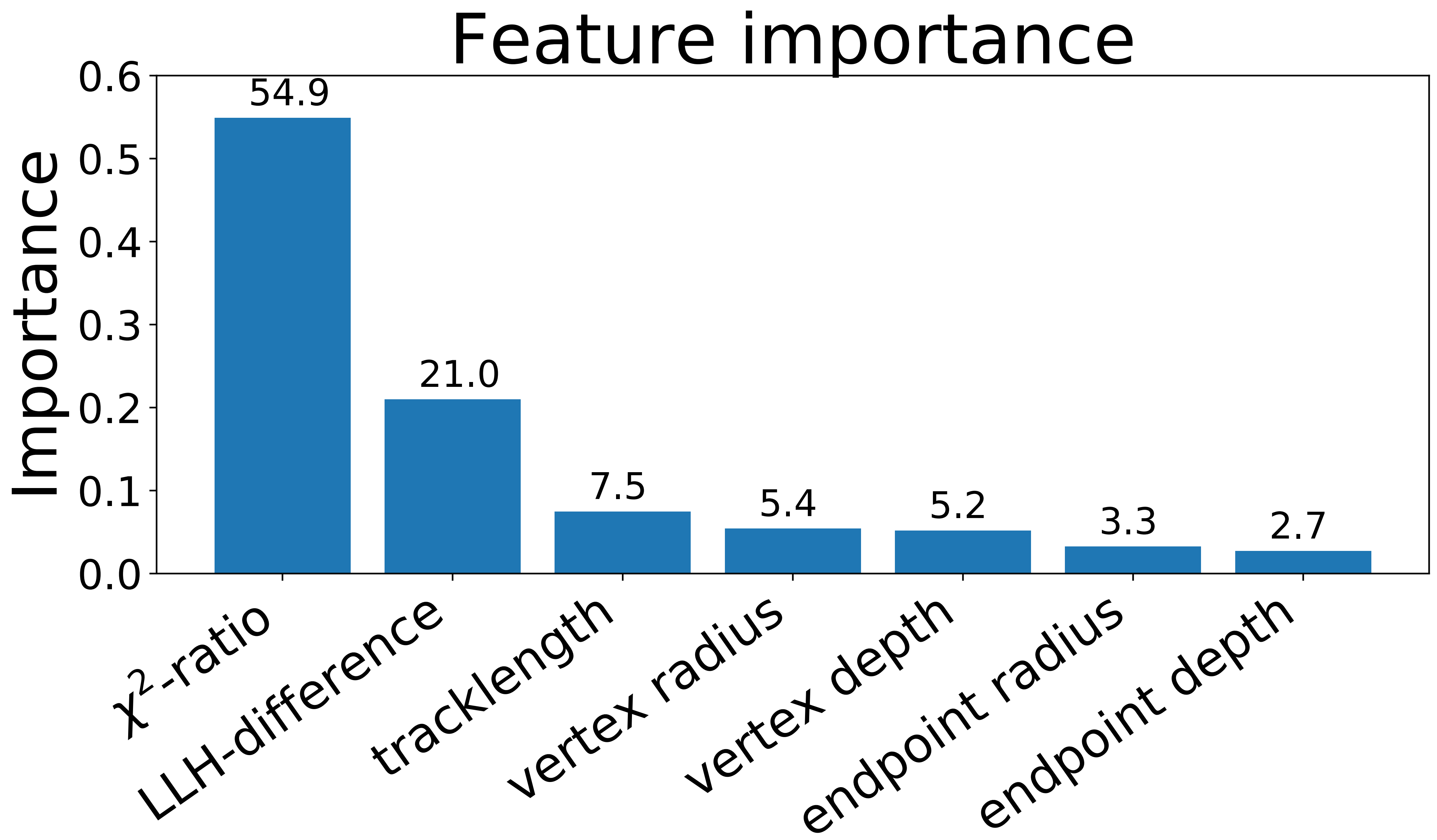
Histogram

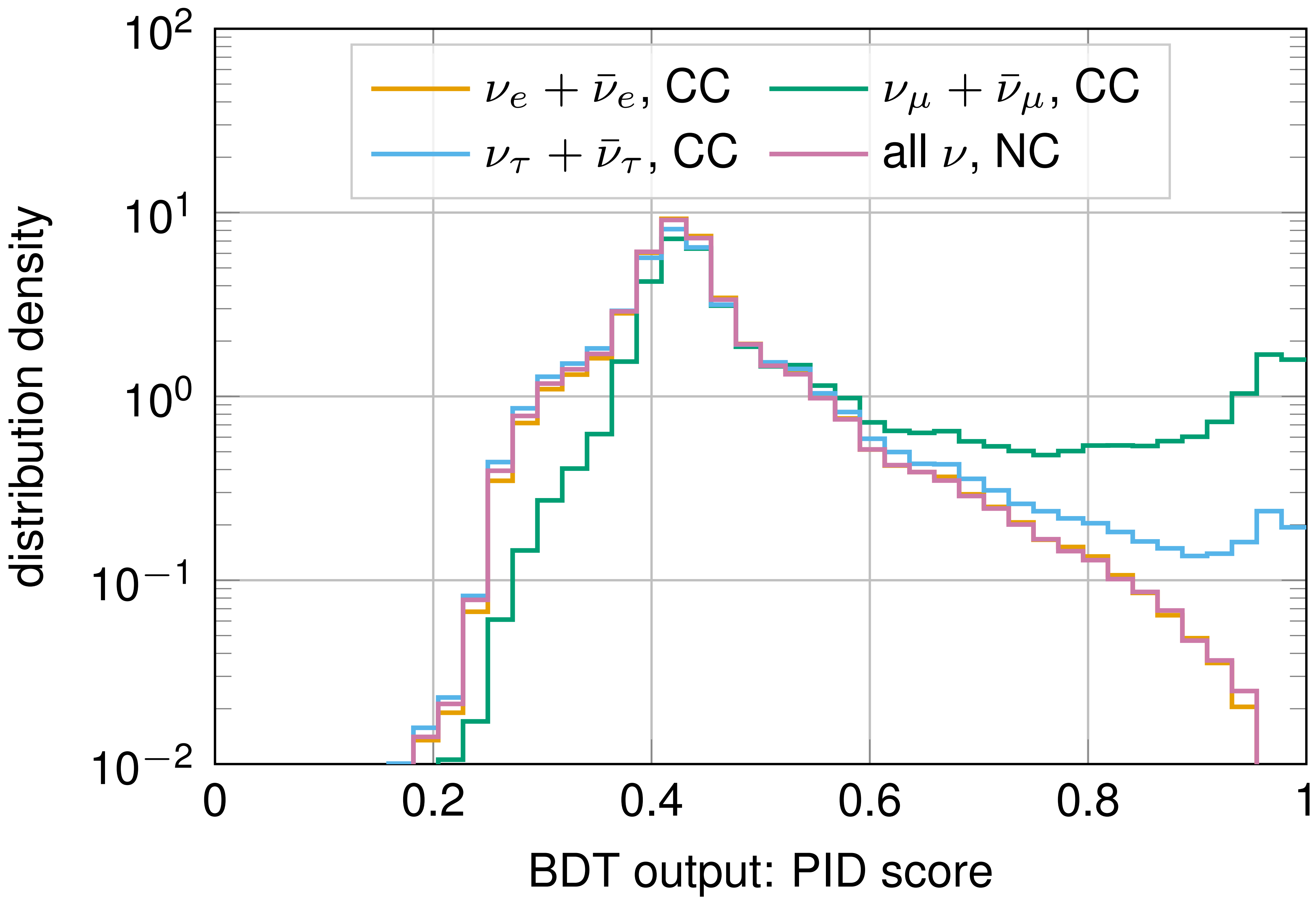


- Track-like (PID > 0.55), well-reconstructed (reco. χ^2 cut) events from below or only slightly above the horizon ($\cos(\theta_z) < 0.1$)
- Background (atm. muon) reduced to ~2% !

Event PID BDT

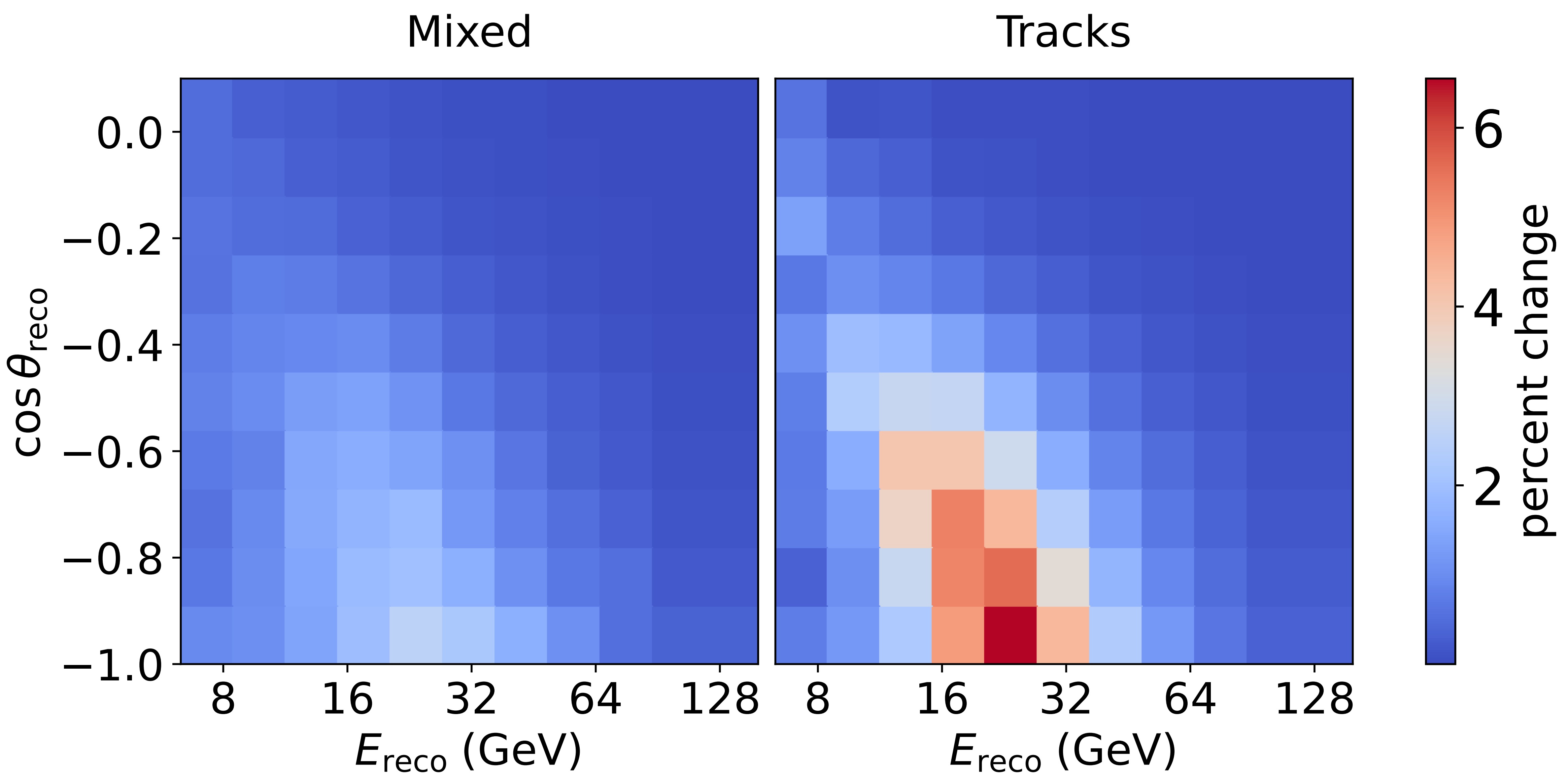
Golden Event Sample

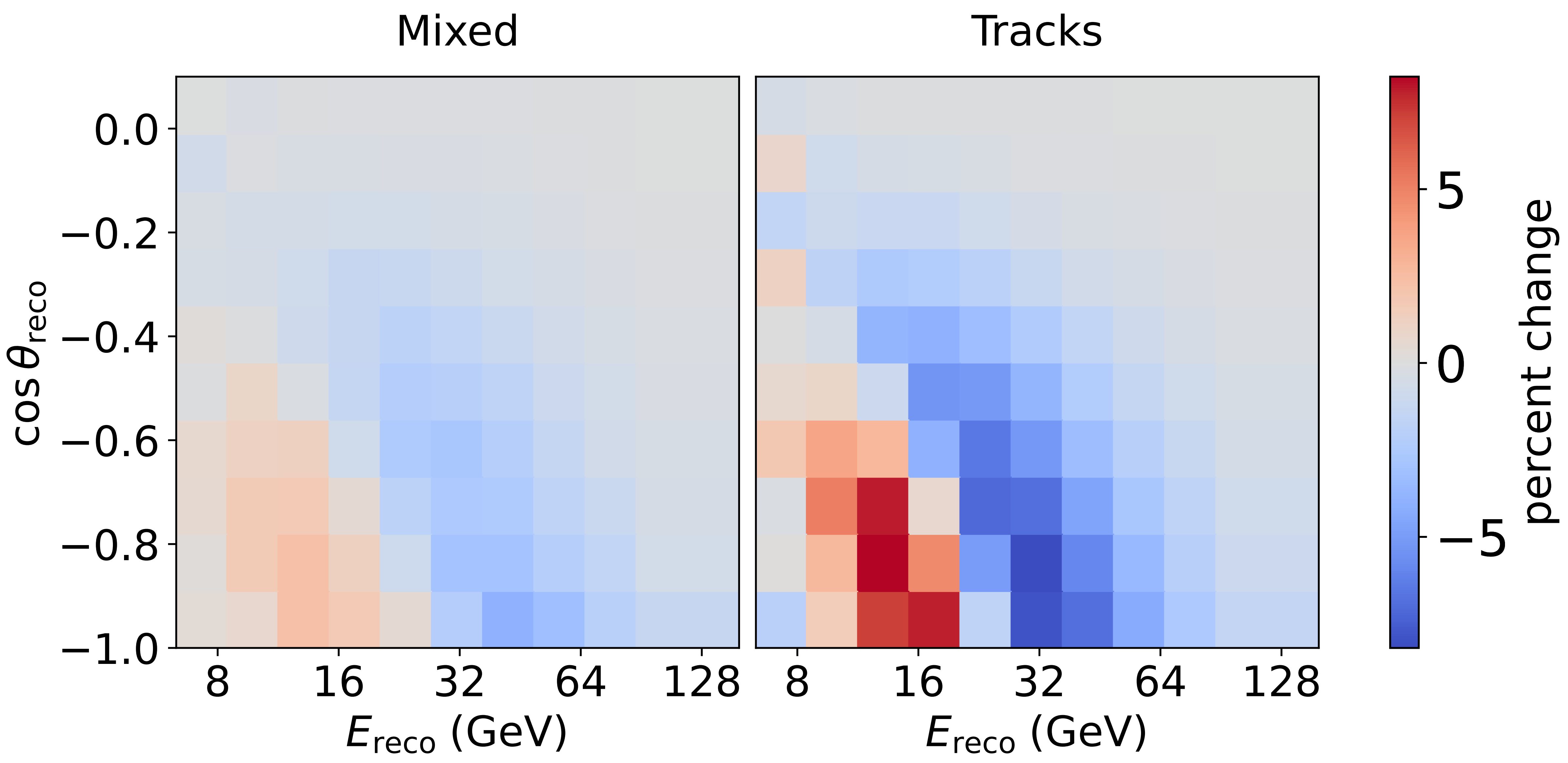




Oscillation Signal

Standard three-flavor atmospheric neutrino oscillations



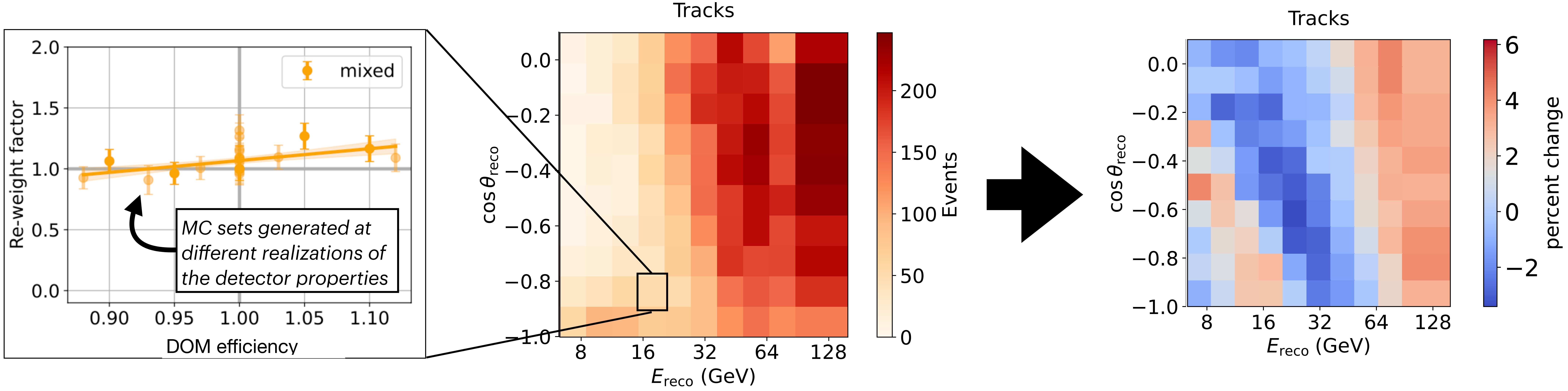


- ➡ Baseline θ_{23} close to maximal → less disappearance when increased

- ➡ Increasing Δm^2_{23} moves osc. minimum up

Detector Systematics Implementation

Bin-wise gradients



MC sets generated at different realizations of the detector properties

Effect of increasing DOM eff. by +10%

- Linear fit in each bin to estimate re-weighting factor
- Effect of DOM efficiency strongly depends on assumed Δm^2_{32}
- Solution: Fit over grid in Δm^2_{32}, piecewise-linear interpolate all gradients

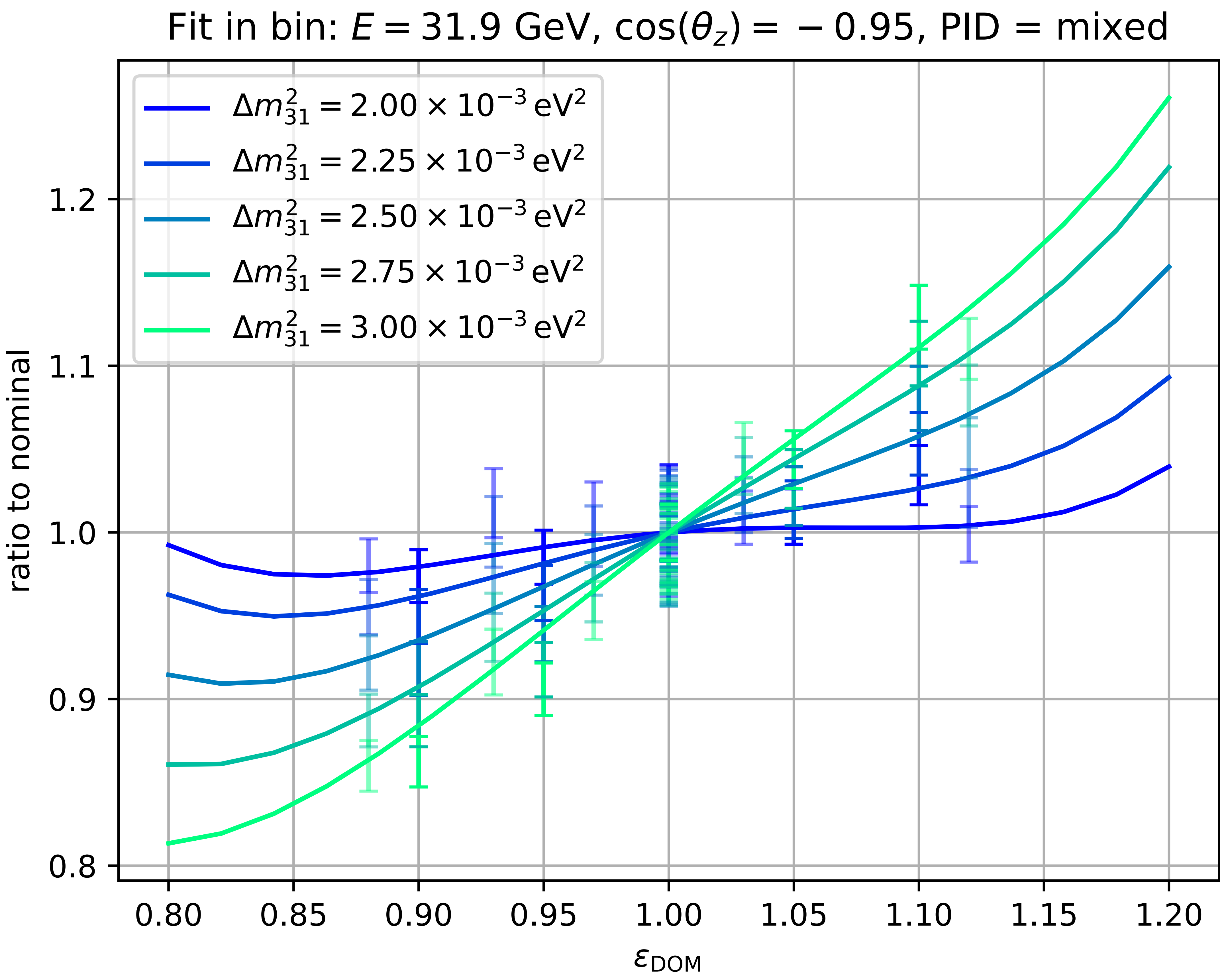
Treatment of Detector Systematics

Why a different treatment is needed

- In three-flavor analysis: **bin-wise** gradients
- Detector response depends on assumed oscillation parameters

➡ need to decouple detector response from oscillations, flux, etc.

➡ new statistical method to get **event-wise** gradients that decouple detector response from flux and oscillation



nuSQuIDS in one slide

- formulate problem in interaction (Dirac) picture

$$H_s(t) = H_0 + H_1(t)$$

- operators evolve with H_0 (exactly solvable part)

$$\bar{O}_I(t) = e^{iH_0 t} O_S e^{-iH_0 t}$$

- state densities evolve with $H_1(t)$

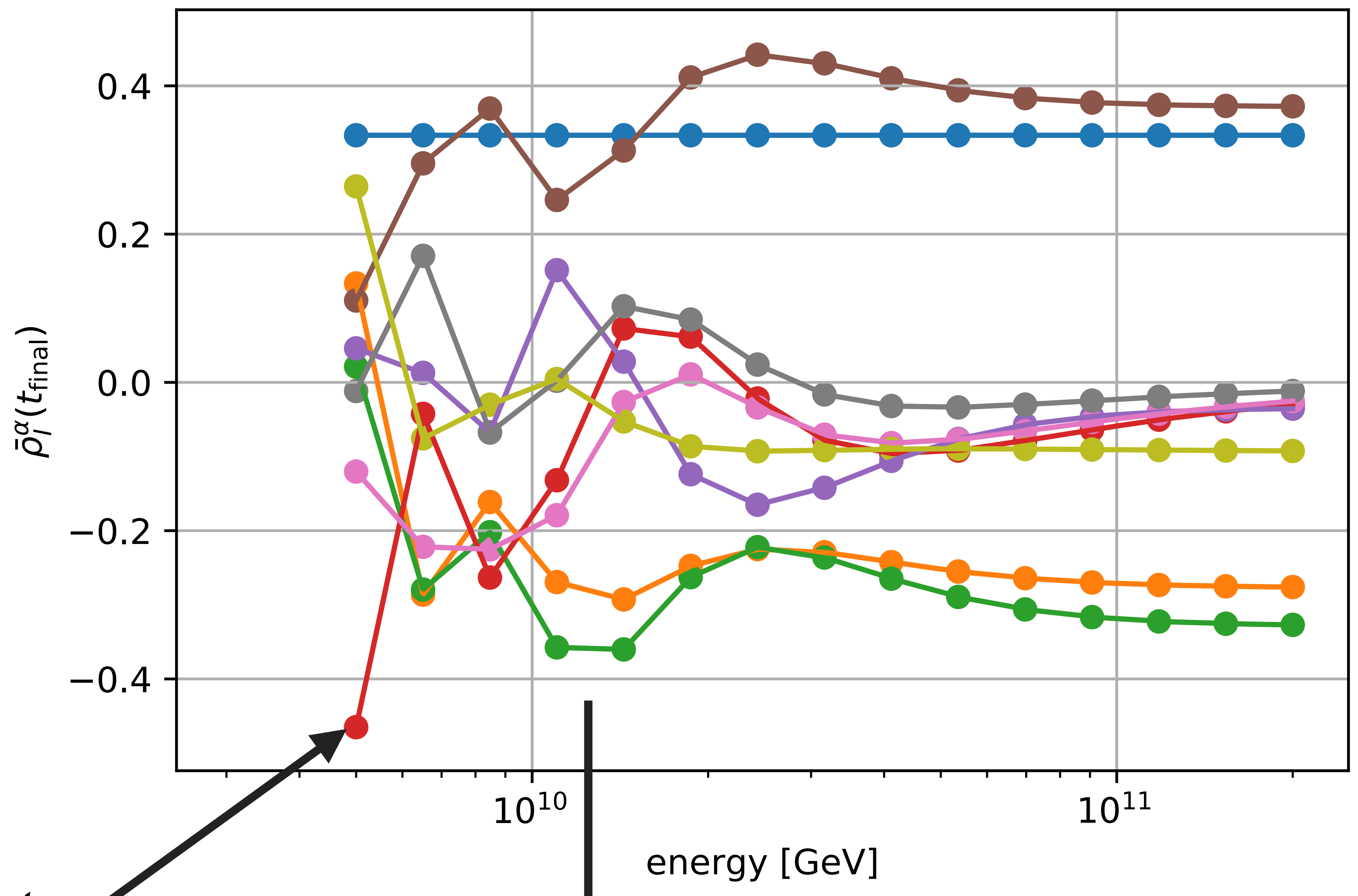
$$\partial_t \bar{\rho}_I(t) = -i[\bar{H}_{1,I}(t), \bar{\rho}_I(t)]$$

- probability to arrive in flavor state i :

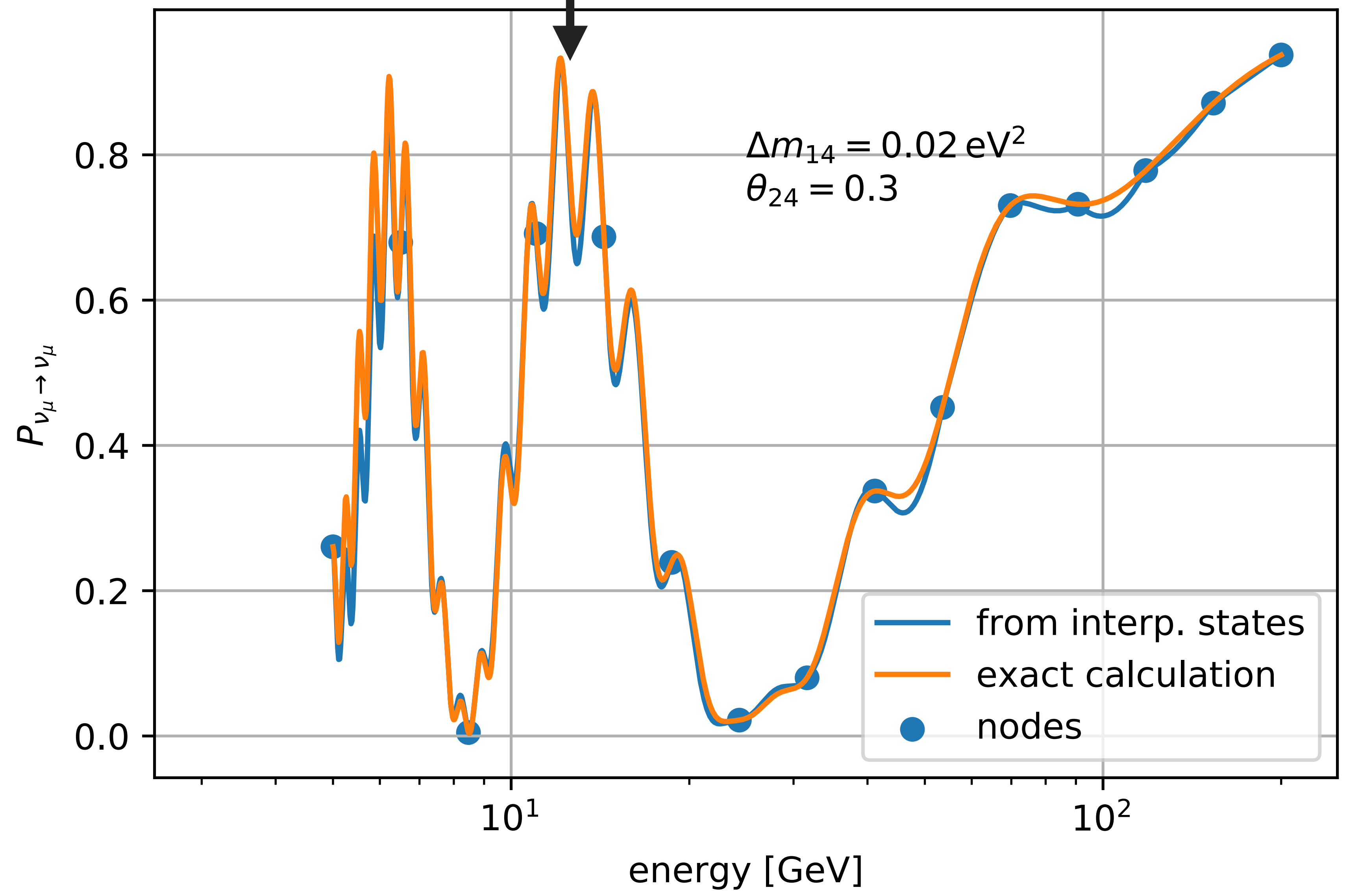
$$p_i(t) = \mathrm{Tr}(\underbrace{\bar{\Pi}^{(i)}(t)}\,\bar{\rho}_I(t))$$

projection operator on flavor state i evolved with H_0

solve numerically at each node

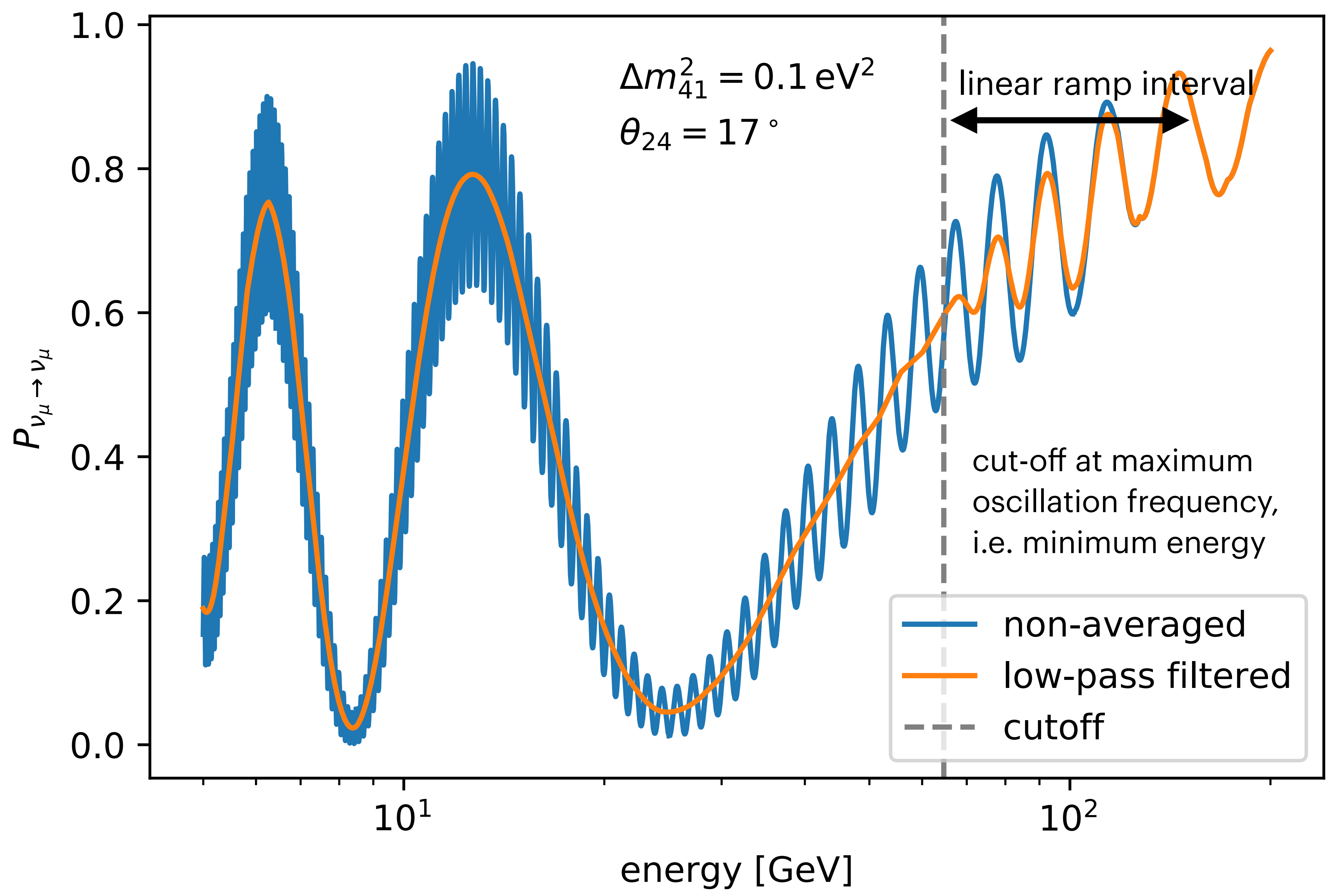


calculate $p_i(t)$ from interpolated $\bar{\rho}_I(t_{\mathrm{final}})$ between nodes



Two Kinds of Low-Pass Filtering

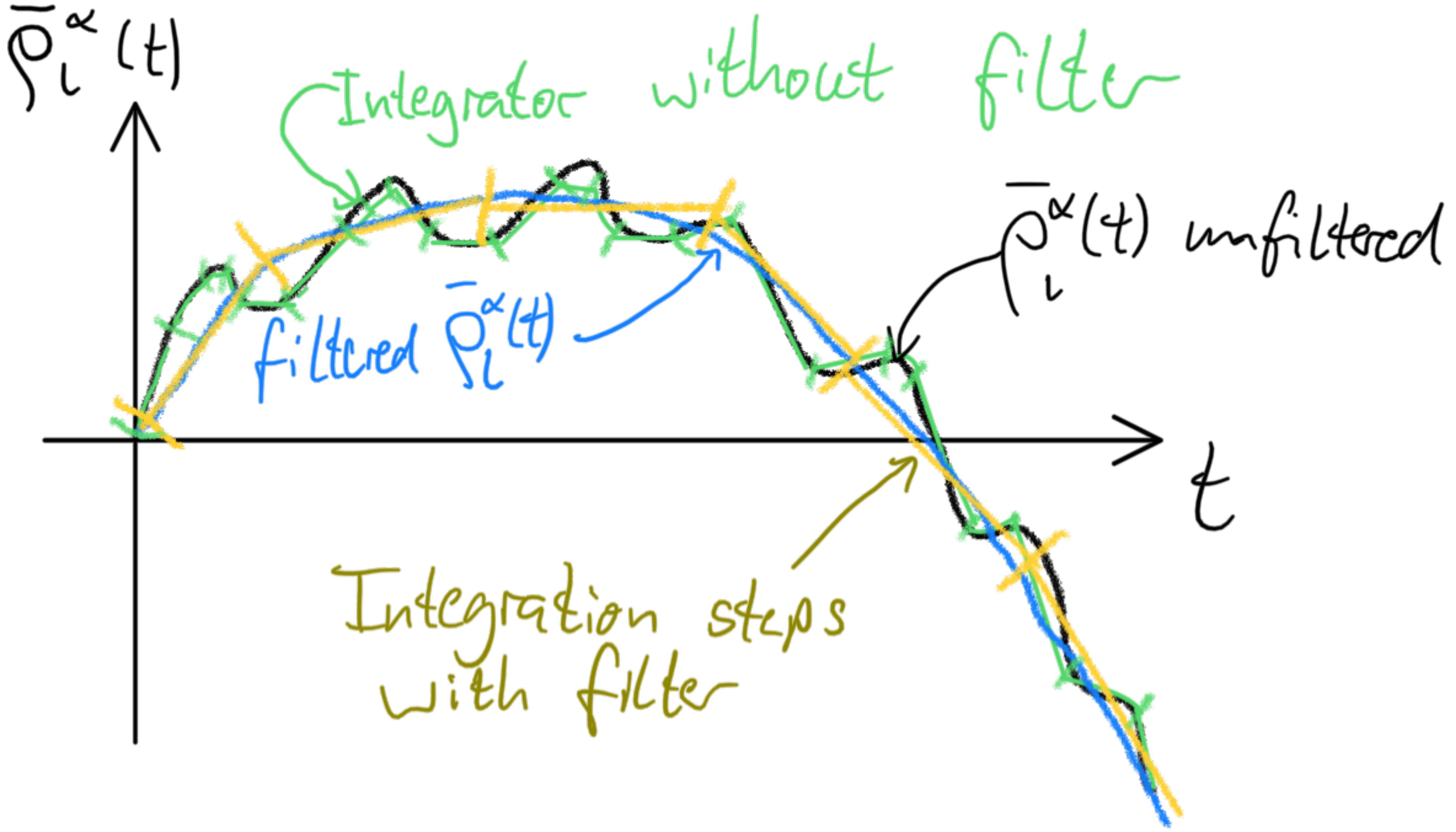
Applied to Trace Operation



Survival probability of a directly up-going muon neutrino in the presence of 0.1 eV² sterile neutrinos with low-pass filtering applied to the trace operation.

- Replace very fast oscillations by their average amplitude
- Allows calculation on grid

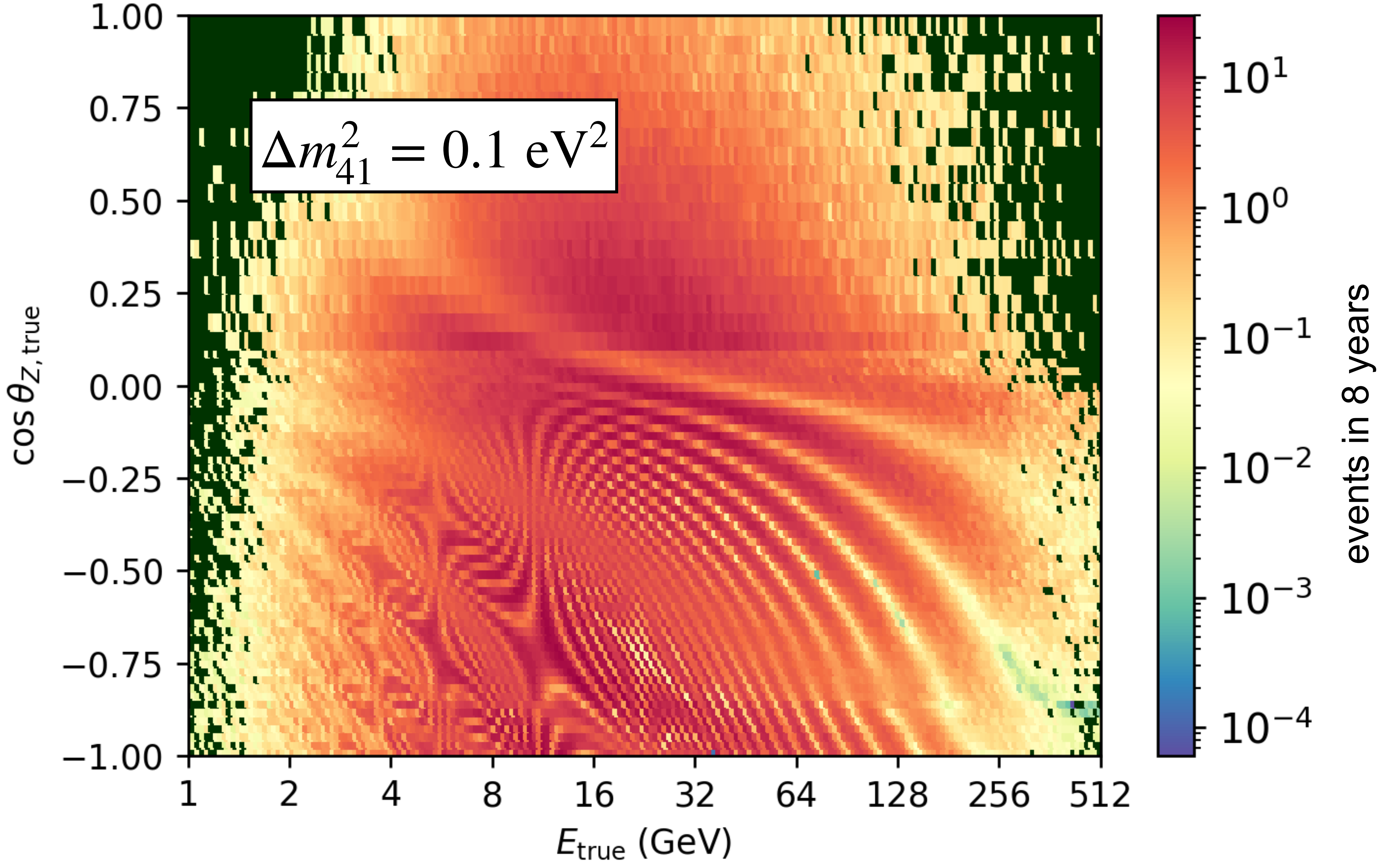
Applied to numerical integration



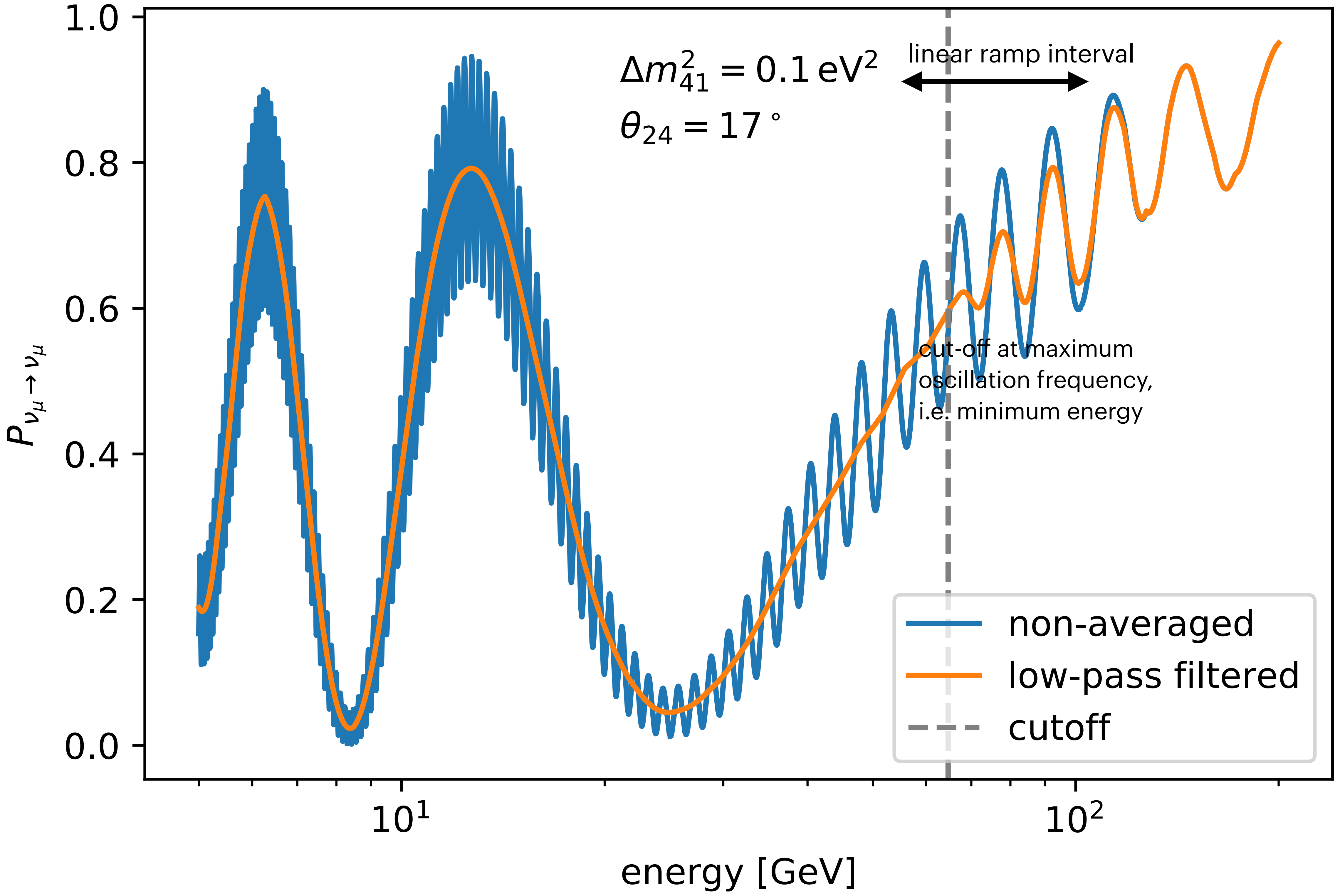
- Filter RHS of time evolution equation
- Greatly speeds up numerical integration

Low-Pass Filtering

Artifacts due to fast oscillations



Fast Oscillation Filtering

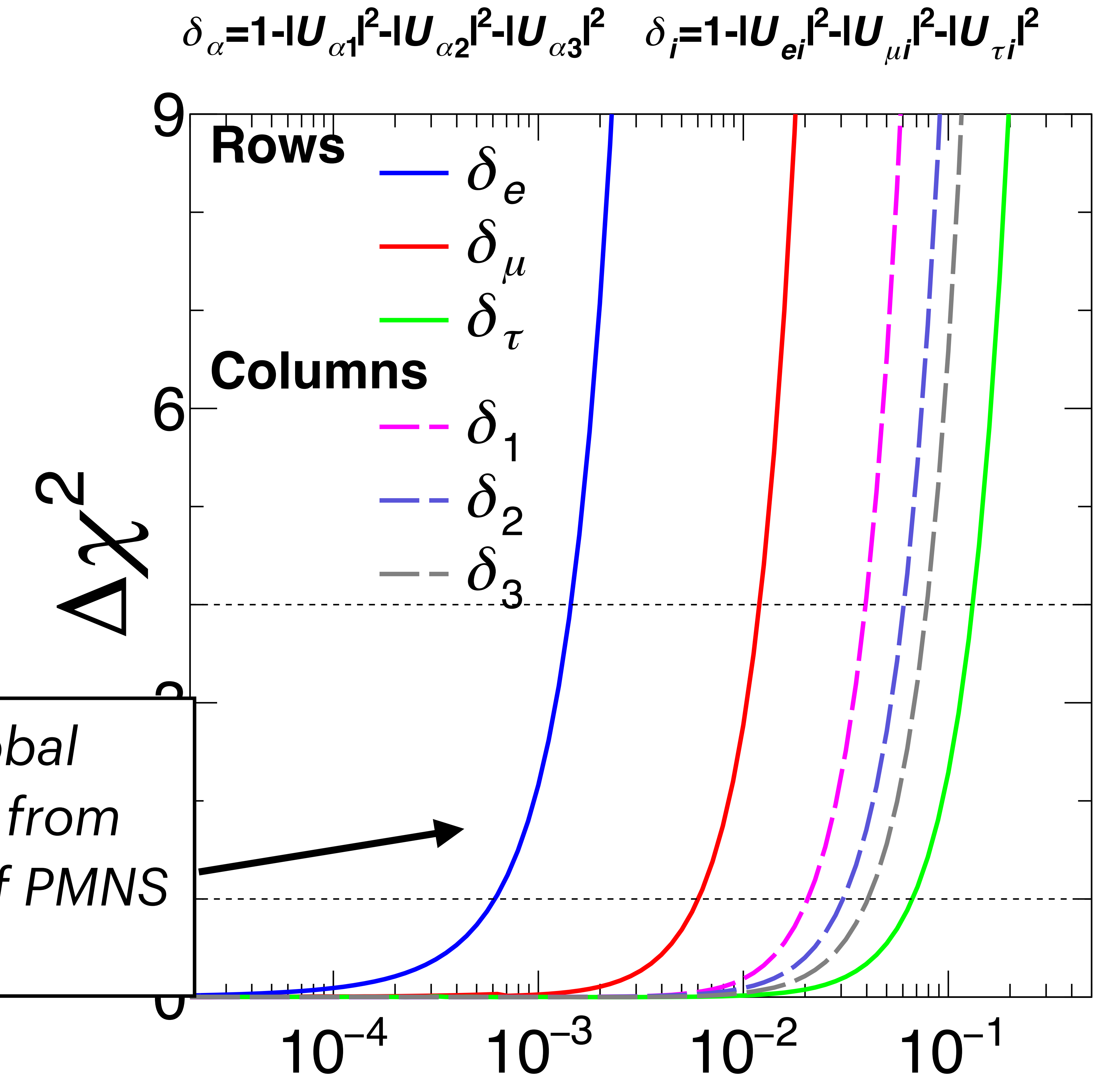


linear ramp interval

cut-off at maximum oscillation frequency, i.e. minimum energy

Why set $|U_{e4}| = 0$?

Already strongly constrained



Strong global constraint from unitarity of PMNS matrix

Constraints from unitarity of PMNS matrix. Hu et al. (2021)

Expecting no leading-order effect in $\nu_\mu \to \nu_\mu$ channel

Meloni, Tang & Winter (2010)

$$U = R_{34}(\theta_{34}, 0)R_{24}(\theta_{24}, 0)R_{14}(\theta_{14}, 0)R_{23}(\theta_{23}, \delta_3) \times R_{13}(\theta_{13}, \delta_2)R_{12}(\theta_{12}, \delta_1).$$

Analytical expression assuming $\Delta m^2_{41} \gg \Delta m^2_{31}$ and long baseline (measuring Δm^2_{31}, Δm^2_{41} averaged out):

$$\mathcal{P}_{ee} = 1 - 2s^2_{14} - 4s^2_{13}\Delta^2_{31}\frac{\sin^2(\Delta_{31}-\Delta_e)}{(\Delta_{31}-\Delta_e)^2},$$

$$\Delta_{ij} \equiv \Delta m^2_{ij}L/(4E)$$

$$\mathcal{P}_{\mu\mu} = \cos^2(\Delta_{31})(1-2s^2_{24}) + 8\hat{s}^2_{23}\sin^2(\Delta_{31}) + c^2_{12}\Delta_{12}\sin(2\Delta_{31}) + \quad (13)$$

$$2s_{24}s_{34}\cos\delta_3\Delta_n\sin(2\Delta_{31}) - 2s^2_{13}\Delta_{31}\cos(\Delta_{31}) \times \frac{(\Delta_{31}-\Delta_e)\Delta_e\sin(\Delta_{31}) - \Delta_{31}\sin(\Delta_{31}-\Delta_e)\sin(\Delta_e)}{(\Delta_{31}-\Delta_e)^2}, \quad (14)$$

Approximate Vacuum Oscillation Equations

Long Baseline 3+1 Model

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}[U_{\alpha i}U_{\beta i}^* U_{\alpha j}^* U_{\beta j}]\sin^2(\Delta_{ij}) + 2\sum_{i<j} \mathrm{Im}[U_{\alpha i}U_{\beta i}^* U_{\alpha j}^* U_{\beta j}]\sin(2\Delta_{ij})$$

Simplifying Assumptions:

- $\Delta_{41} = \Delta_{42} = \Delta_{43} \gg \Delta_{32}$
- Δ_{32} is measureable
- $\Delta_{21} = 0$ (neglect solar mass splitting)
- $\sin^2(\Delta_{41}) = 1/2$ (replace rapid oscillation by average)

Oscillation Channels

$$P_{\mu\mu} = 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) - 4|U_{\mu 3}|^2(1 - (|U_{\mu 3}|^2 + |U_{\mu 4}|^2))\sin^2\Delta_{32}$$

$$\begin{aligned} P_{\mu\tau} = {} & 2|U_{\mu 4}|^2|U_{\tau 4}|^2 \\ & -4\sin\left[\Delta_{32}\right]\left(\cos\left[\Delta_{32}\right]\mathrm{Im}\left[U_{\tau 3}U_{\mu 3}^*\left(U_{\mu 1}U_{\tau 1}^* + U_{\mu 2}U_{\tau 2}^*\right)\right] + \mathrm{Re}\left[U_{\tau 3}U_{\mu 3}^*\left(U_{\mu 1}U_{\tau 1}^* + U_{\mu 2}U_{\tau 2}^*\right)\right]\sin\left[\Delta_{32}\right]\right) \end{aligned}$$

Matter Enhanced Sterile Search: Observed Events