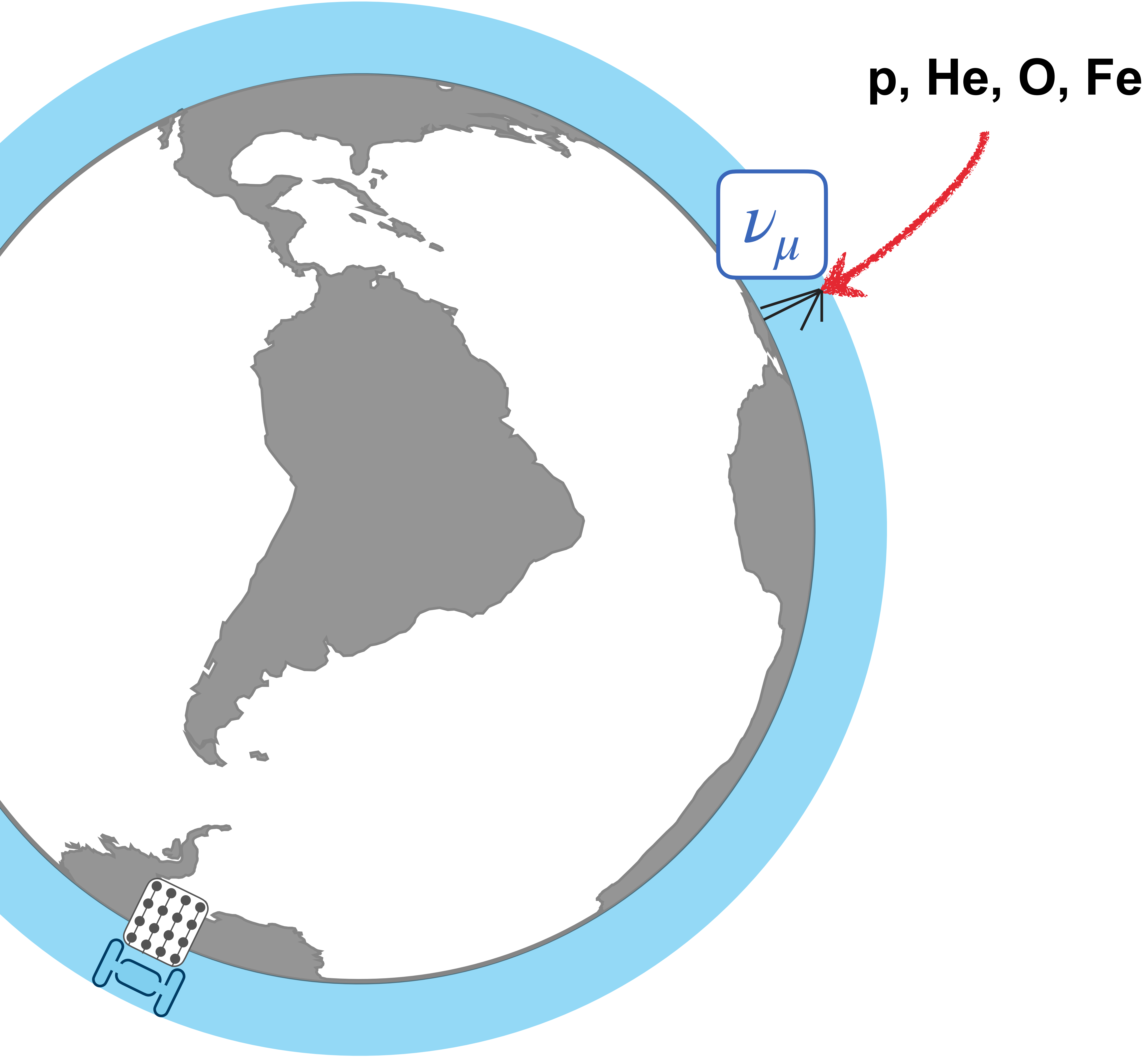
Atmospheric neutrino oscillation measurements and BSM searches with IceCube and KM3NeT

Alexander Trettin on behalf of the IceCube collaboration
PANIC 2021 Conference, Online

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

The Atmosphere as a Natural Beam Target



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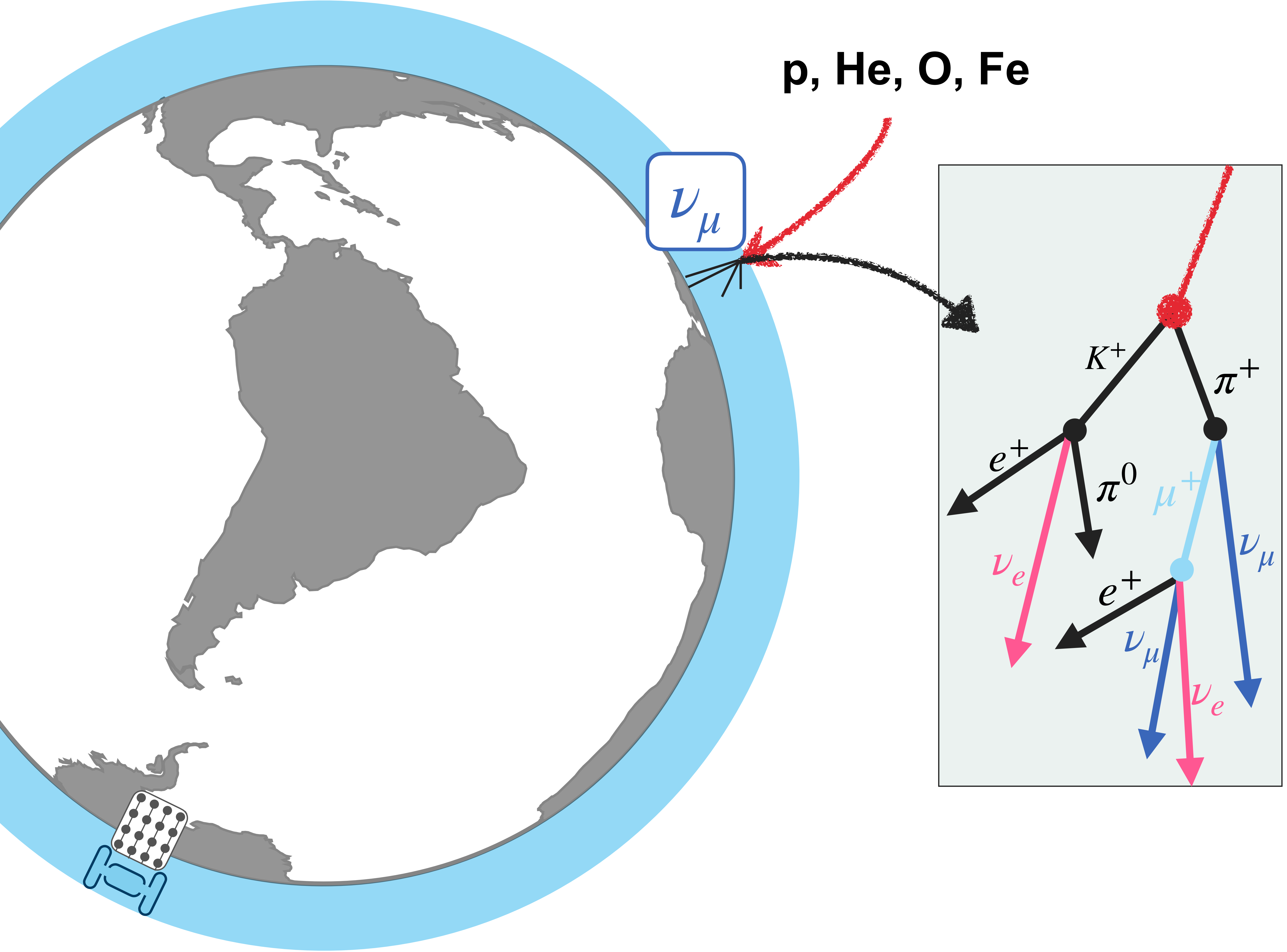

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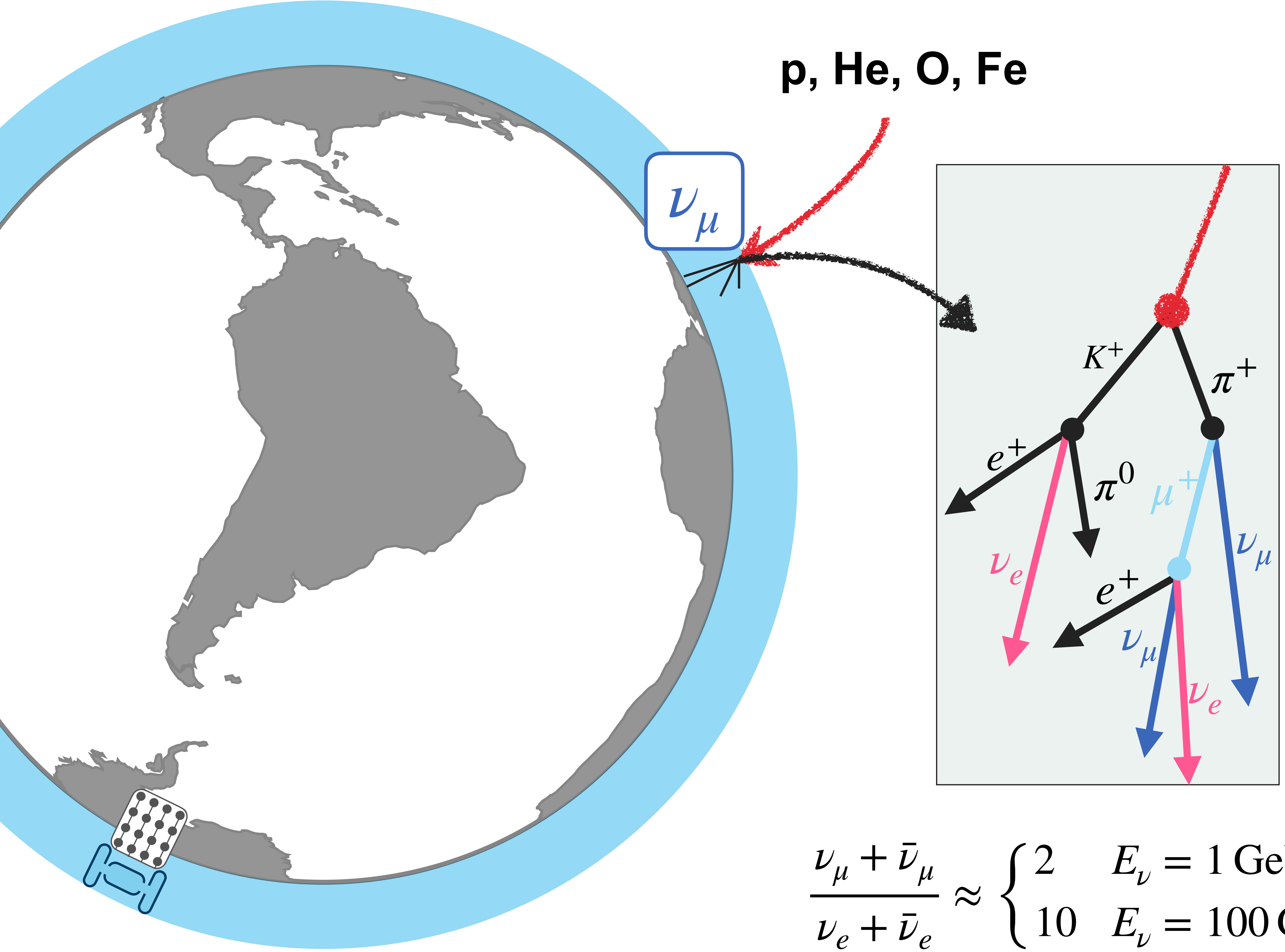

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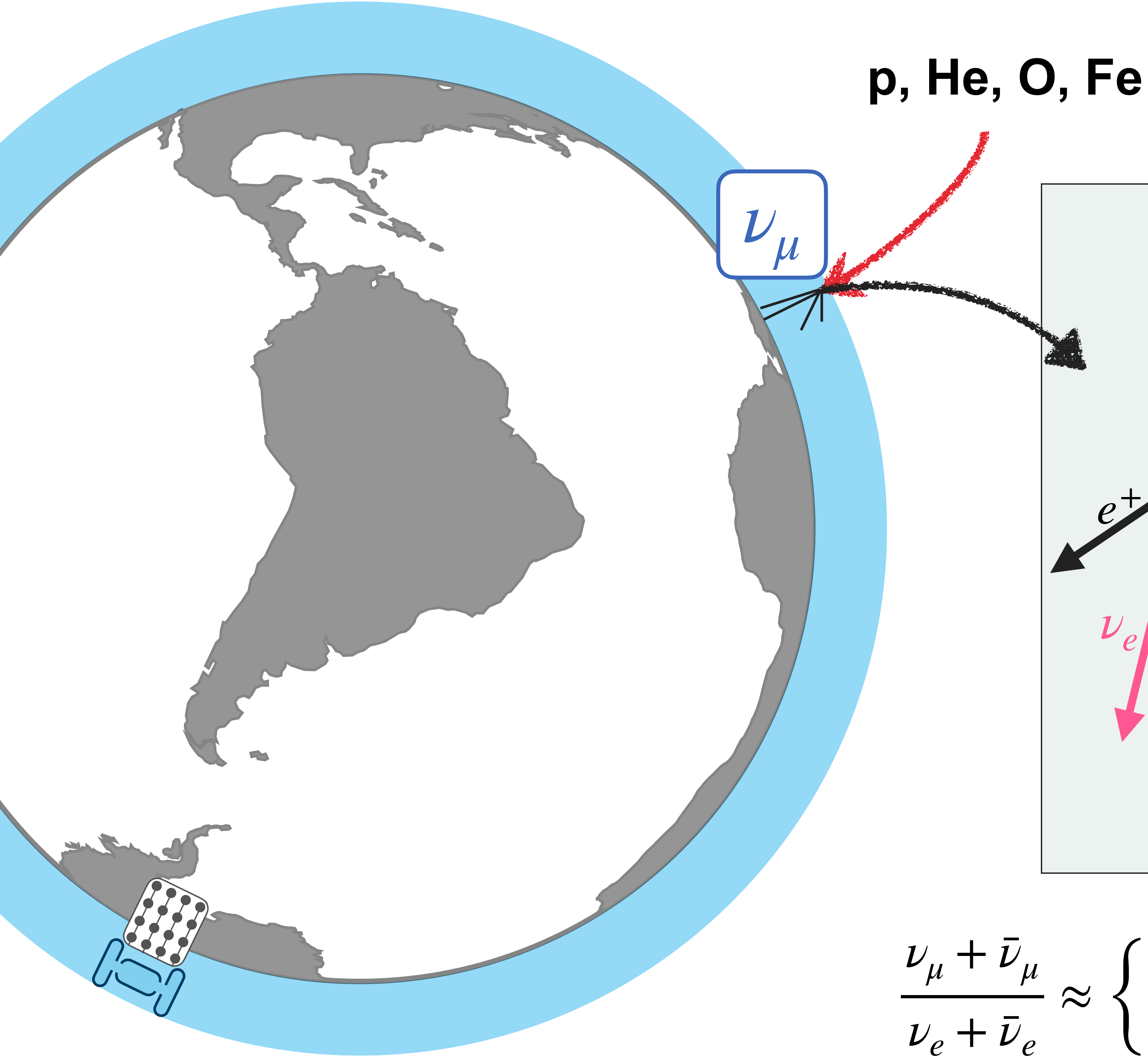

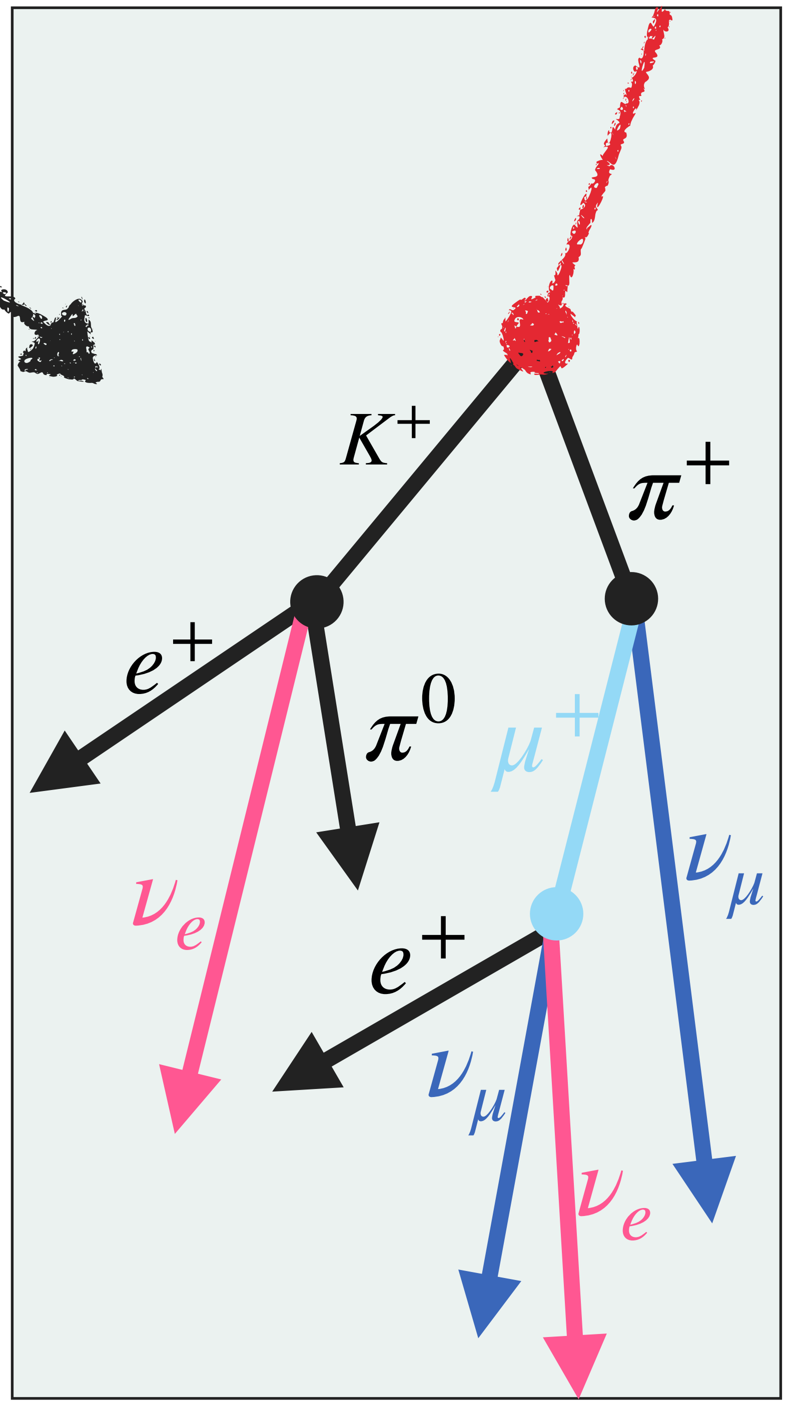

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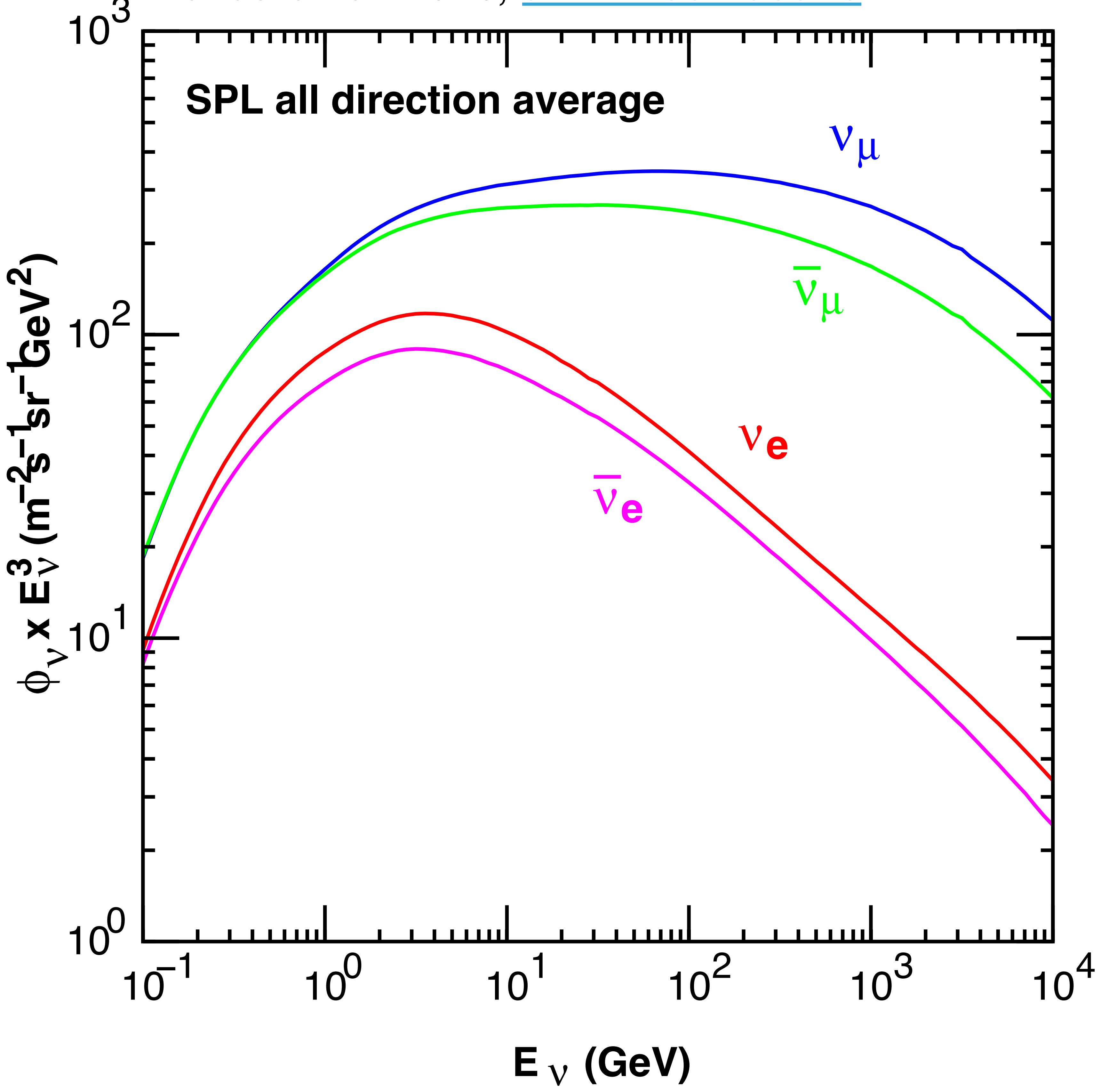
Honda et. al. 2015, arxiv: 1502.03916



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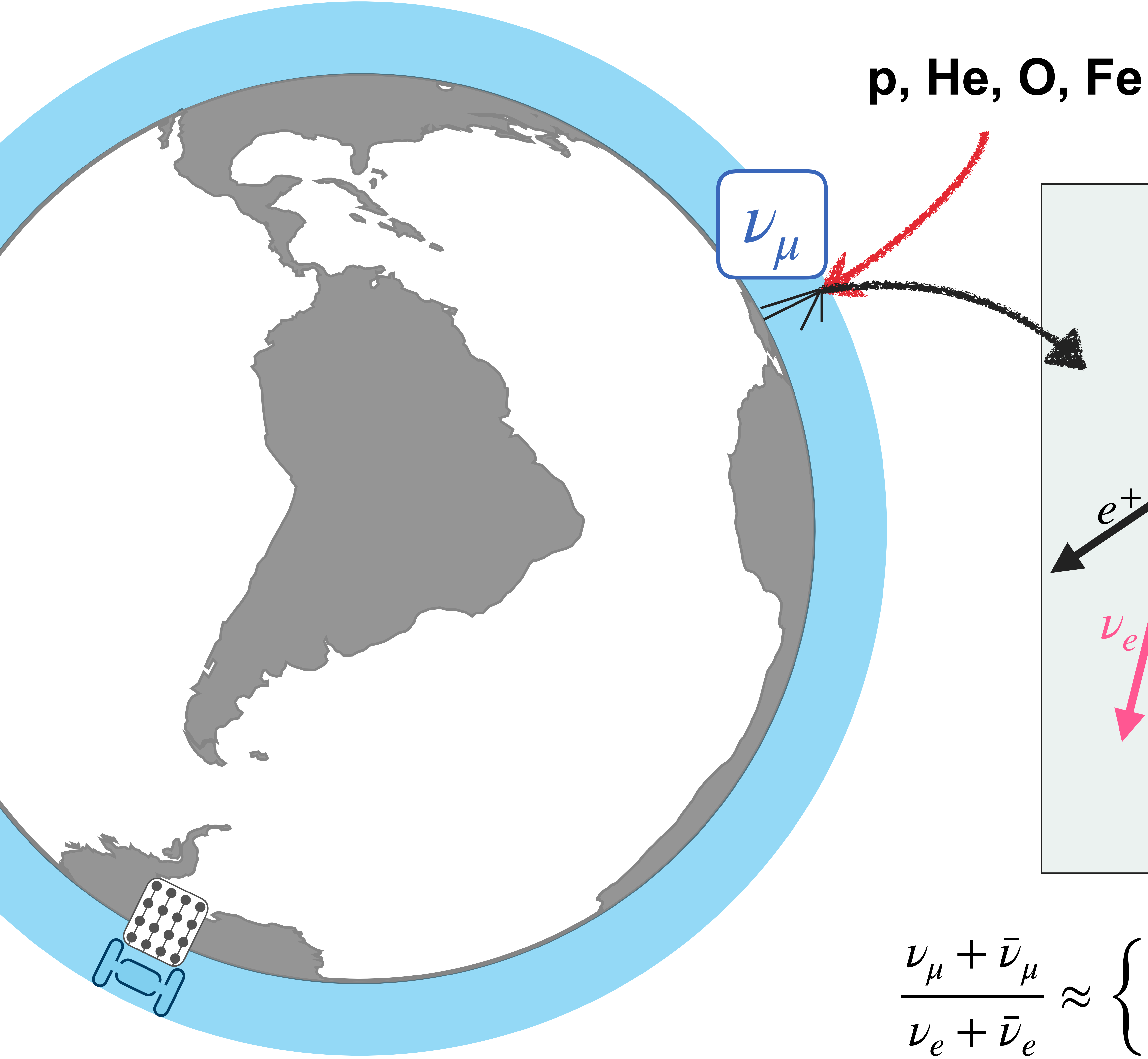

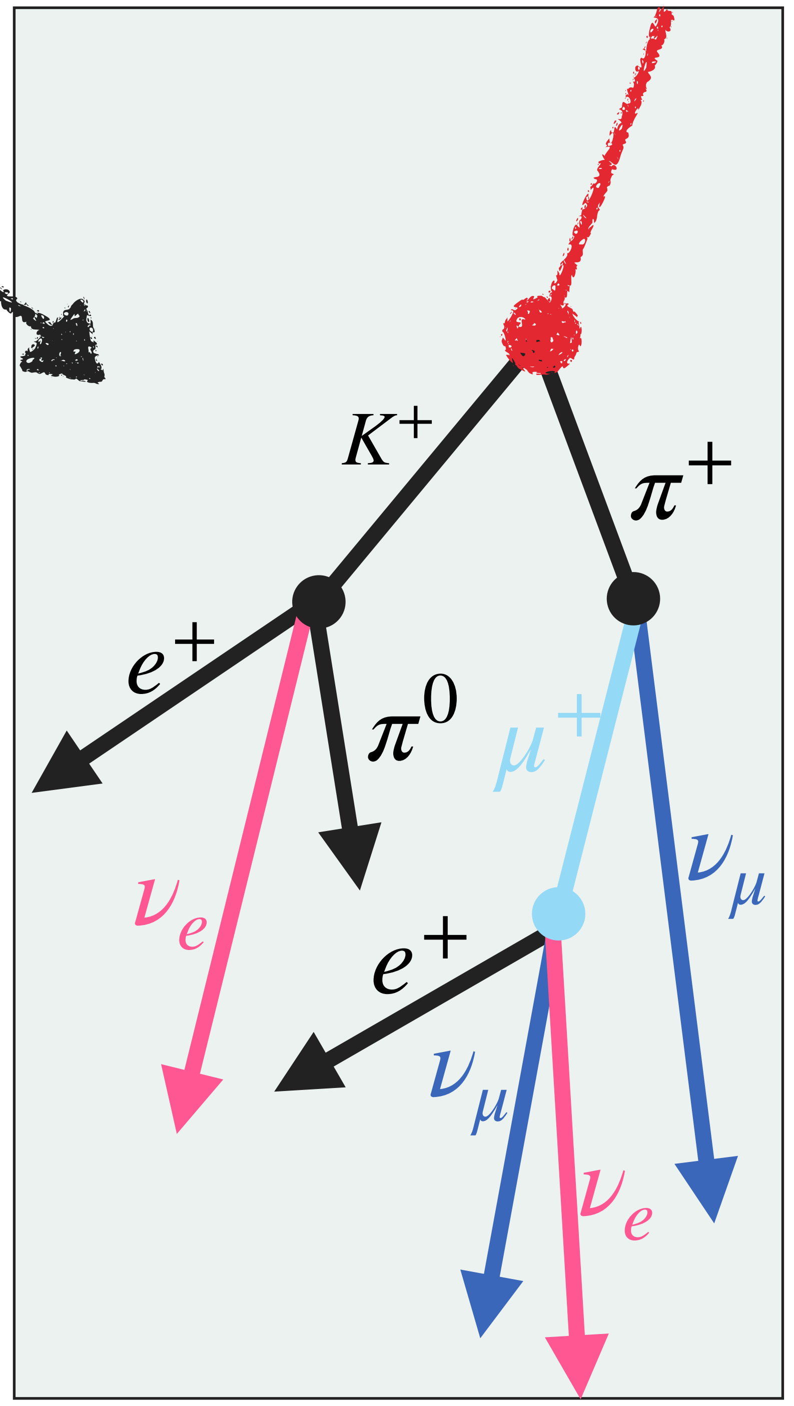

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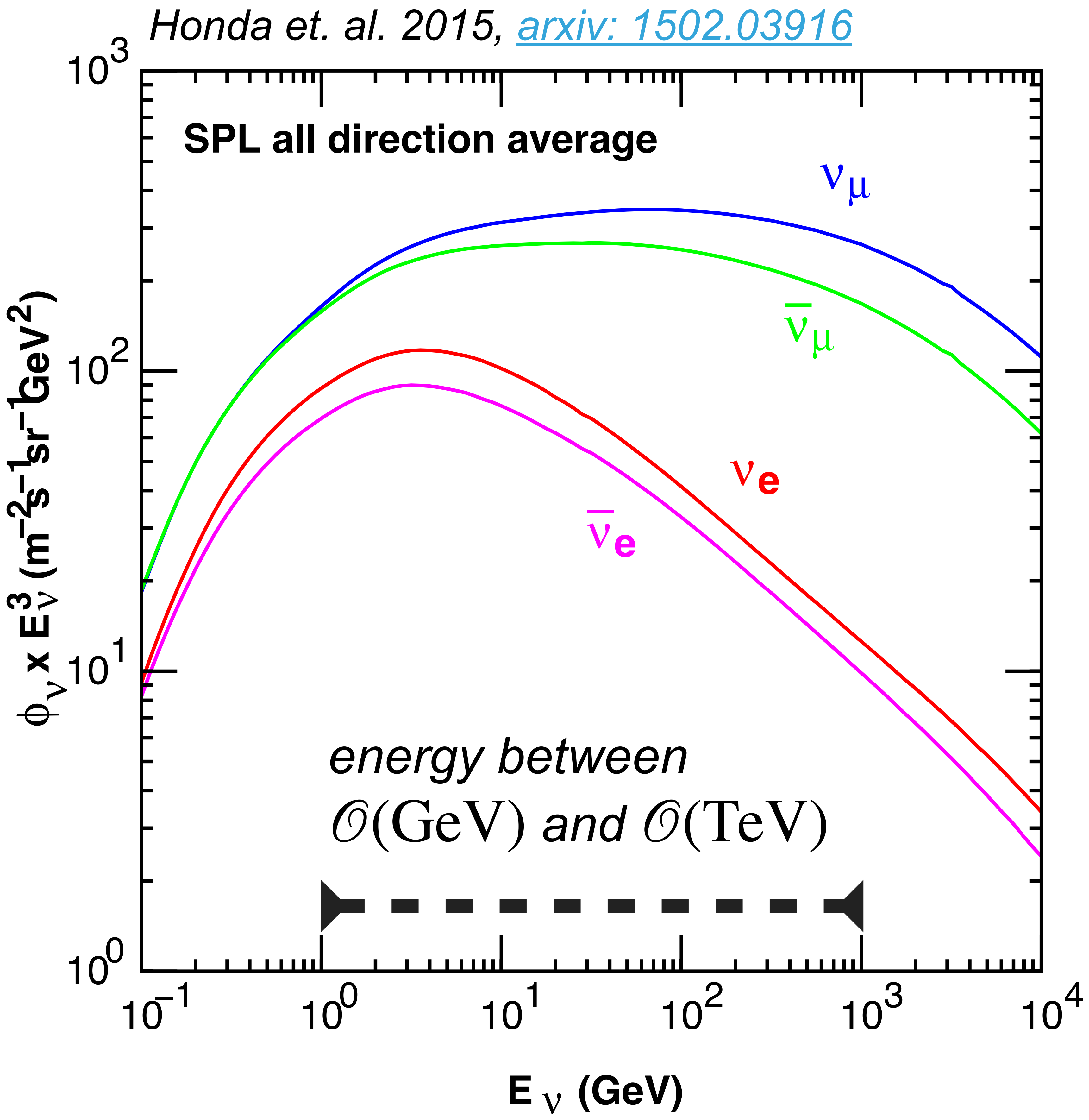

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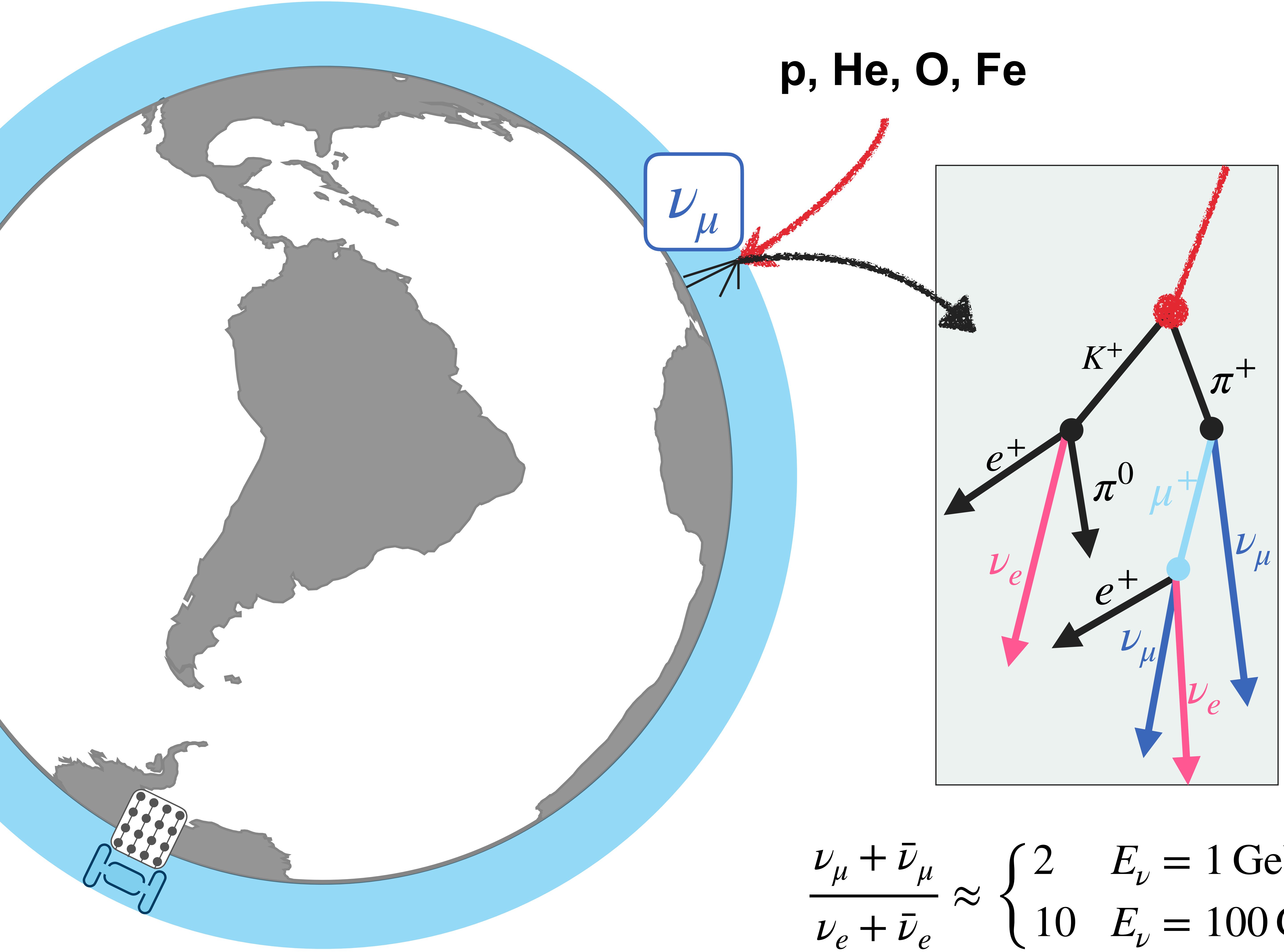

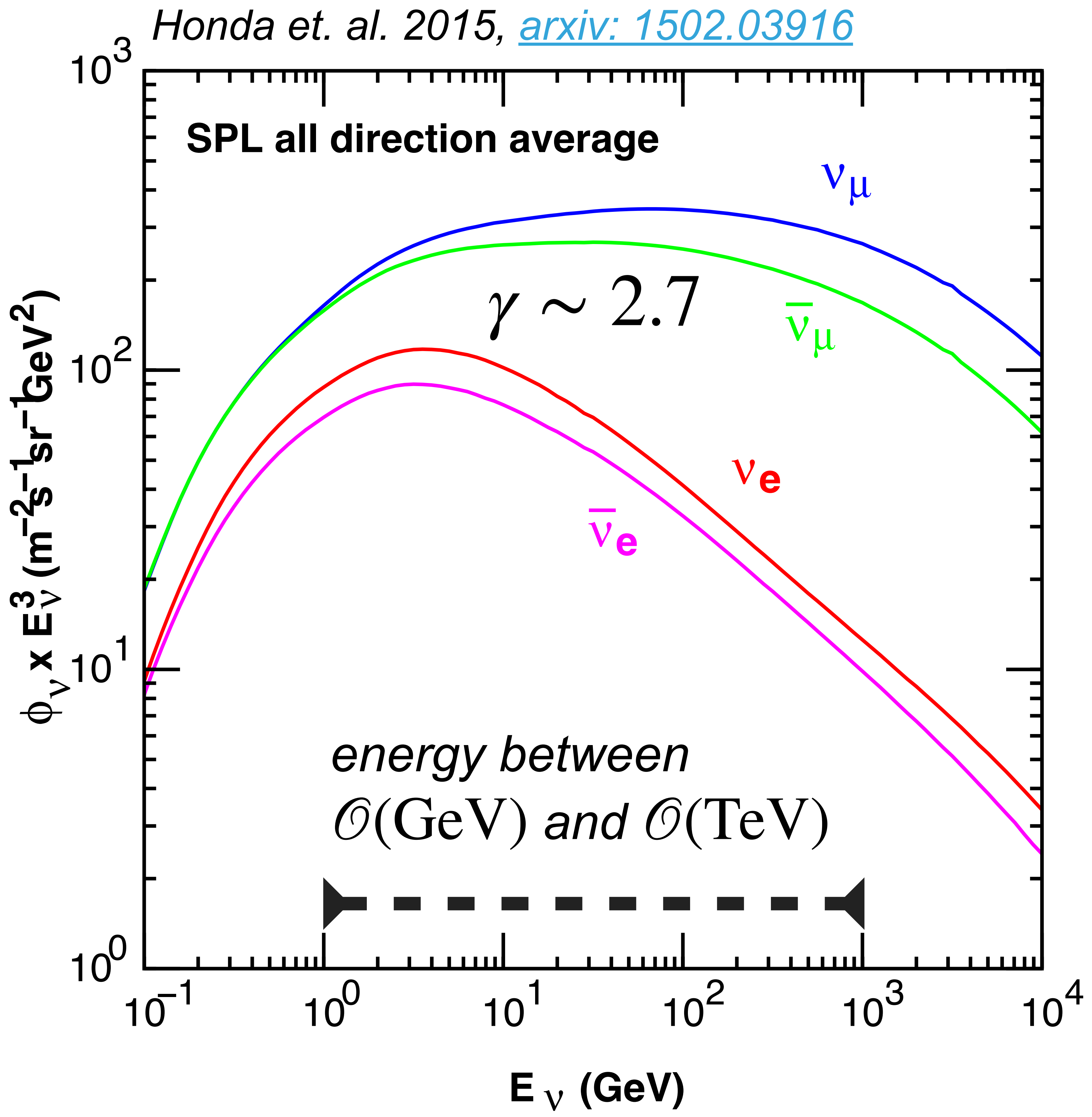

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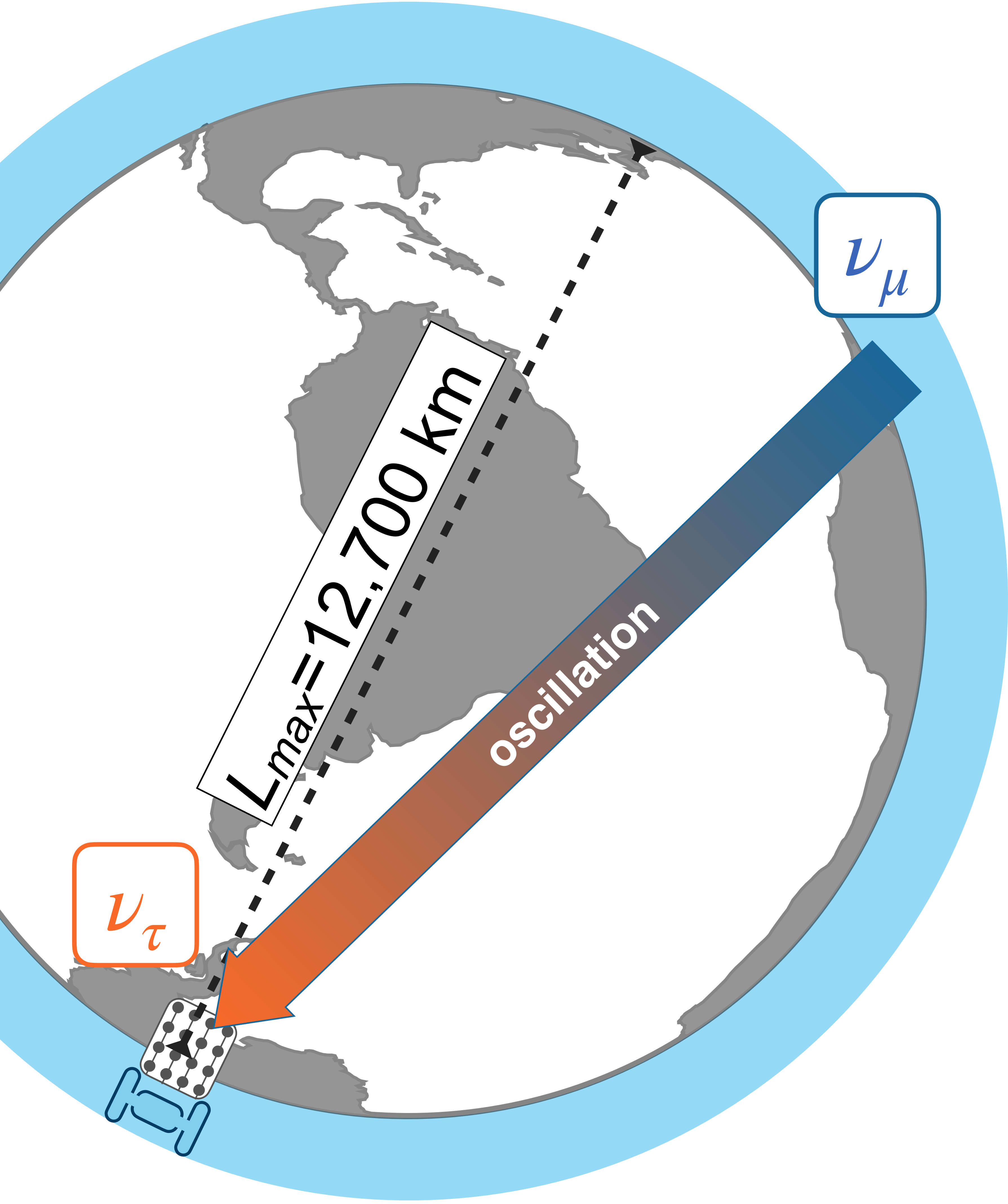
Atmospheric Neutrino Oscillations



neutrino mixing:

flavor eigenstate

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle$$

mass eigenstate

$s_{ij} = \sin\theta_{ij}$

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$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

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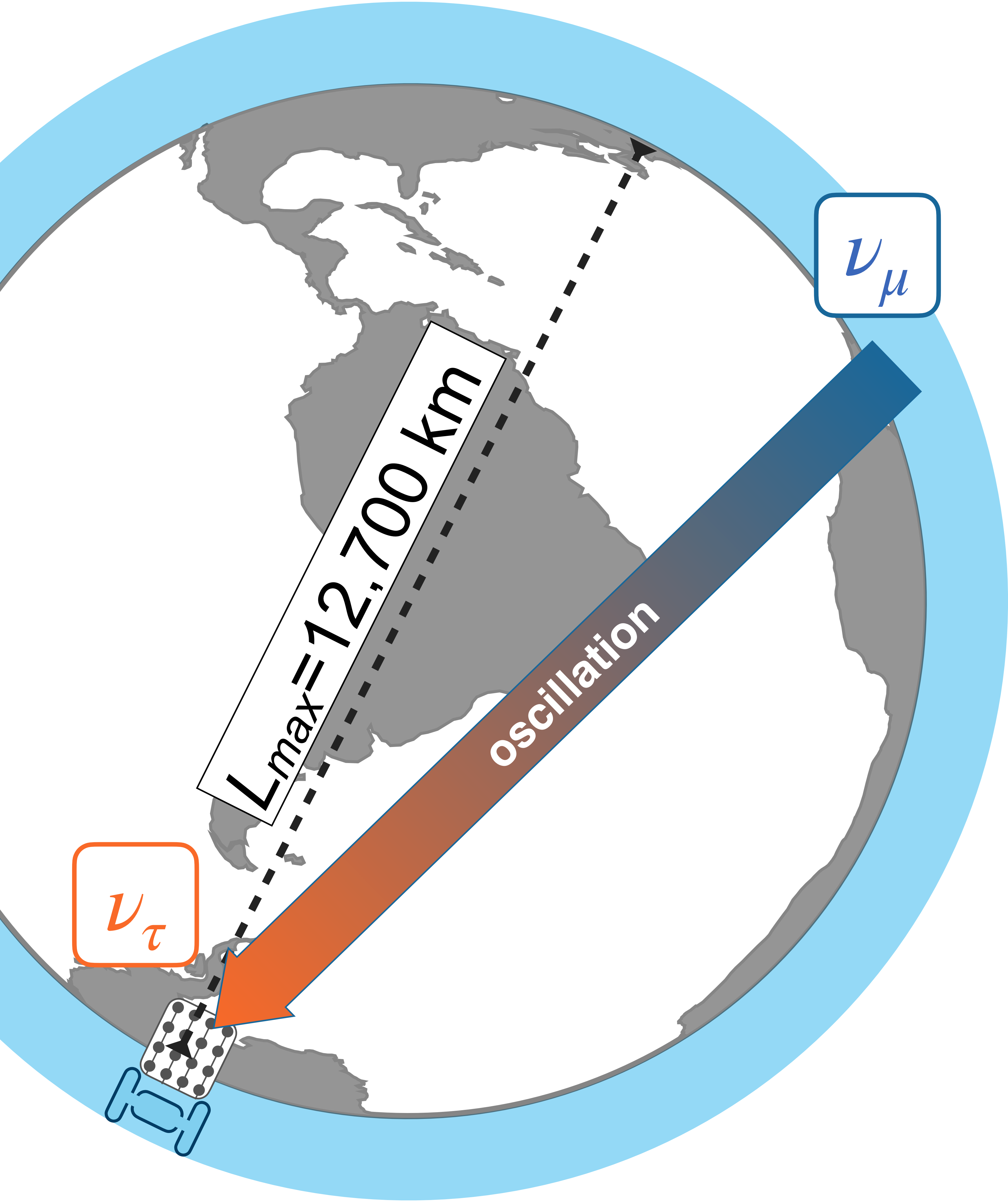

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$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)\sin^2\left(\Delta m^2_{31} L/(4E)\right)$$
$$\simeq 1 - \sin^2(2\theta_{23})\sin^2\left(\Delta m^2_{31} L/(4E)\right)$$

"ν_μ disappearance"

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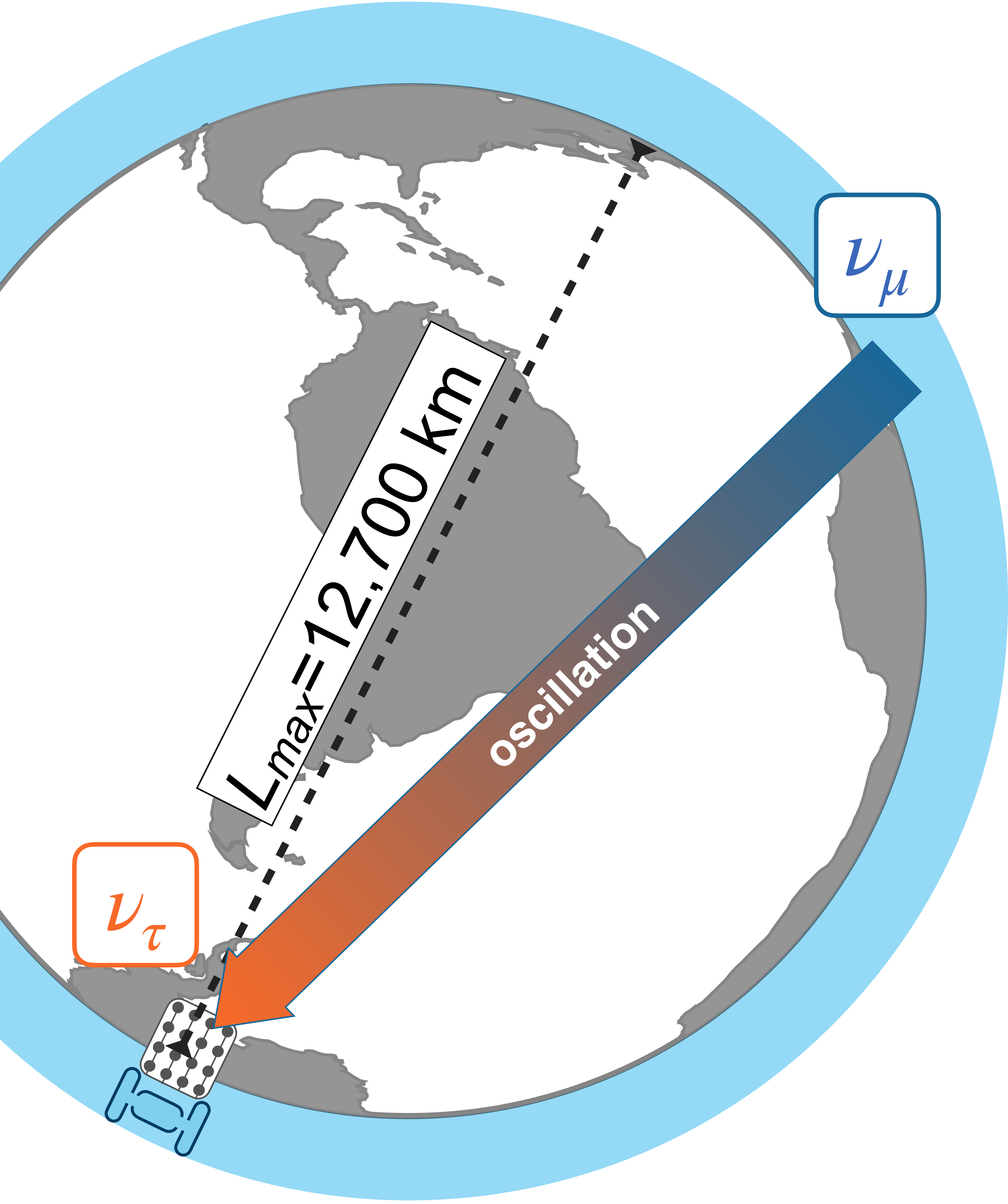

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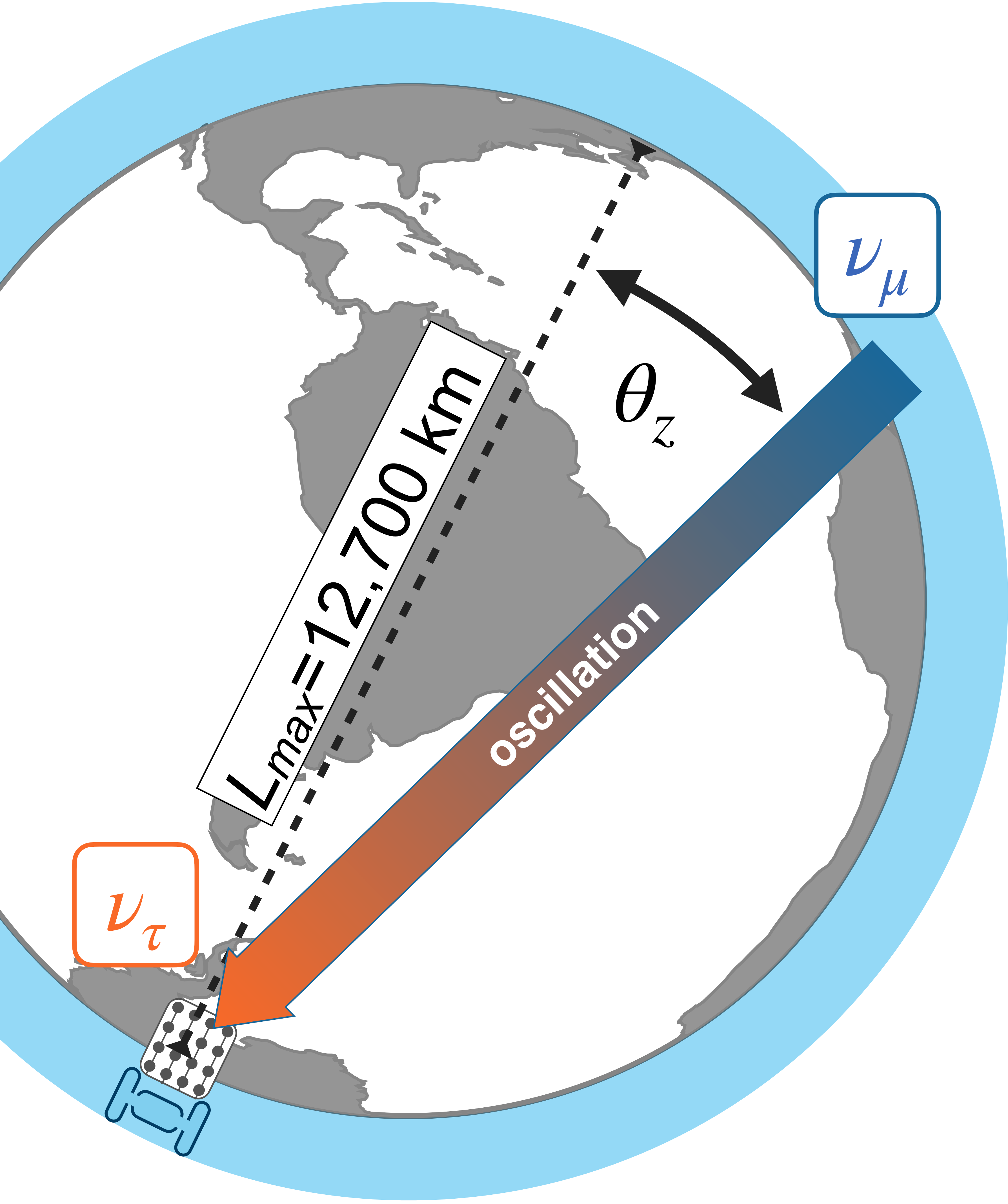

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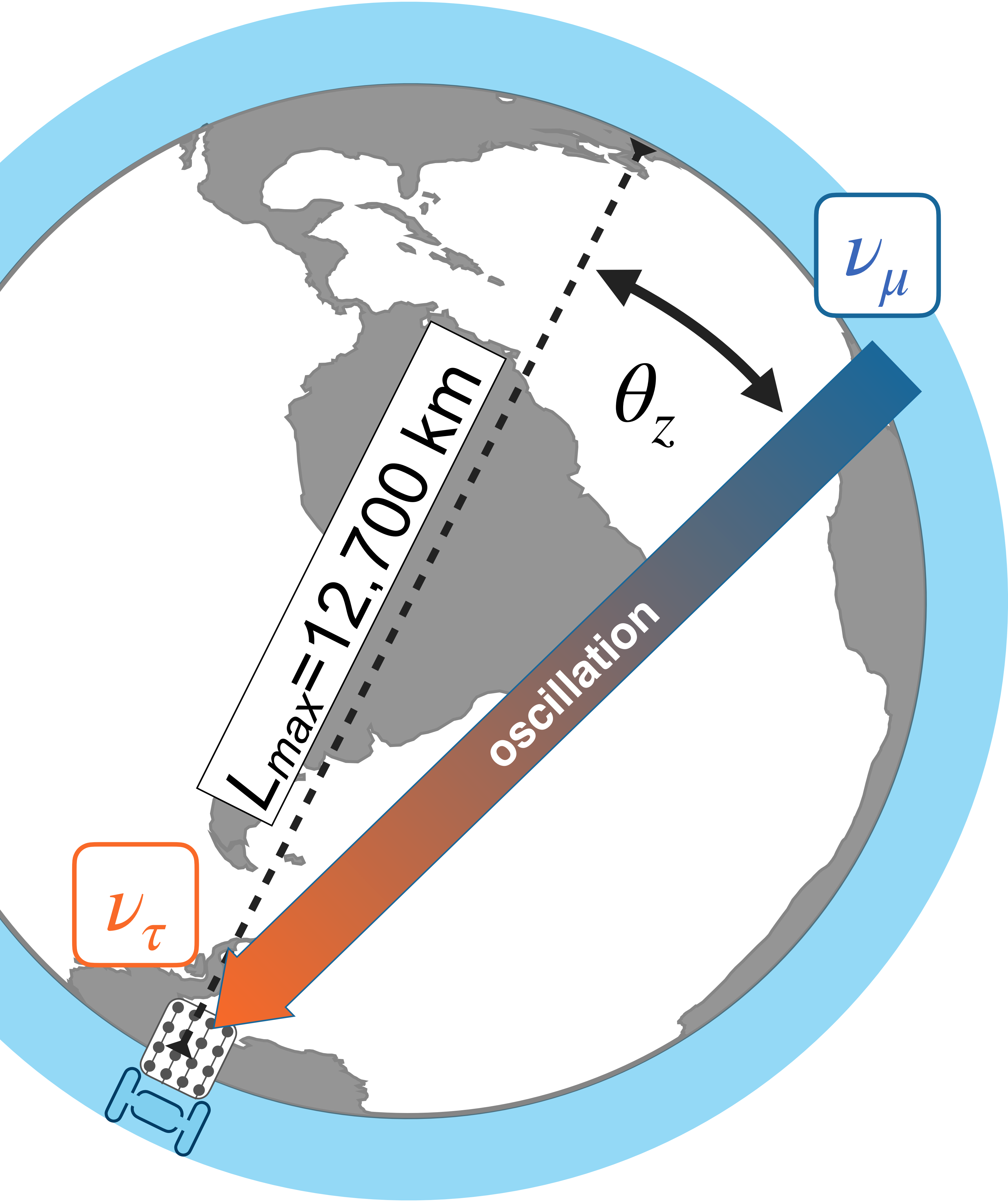

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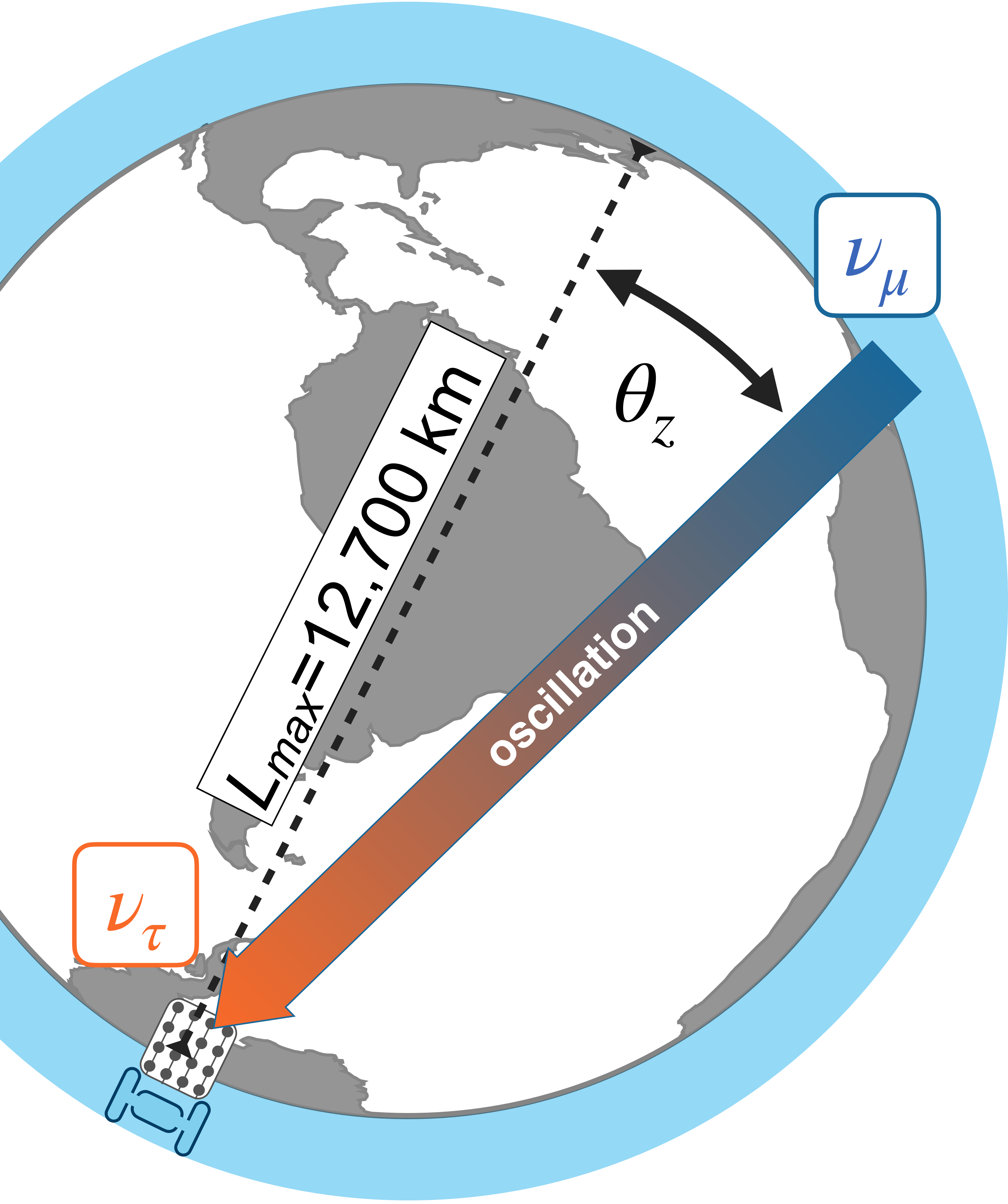

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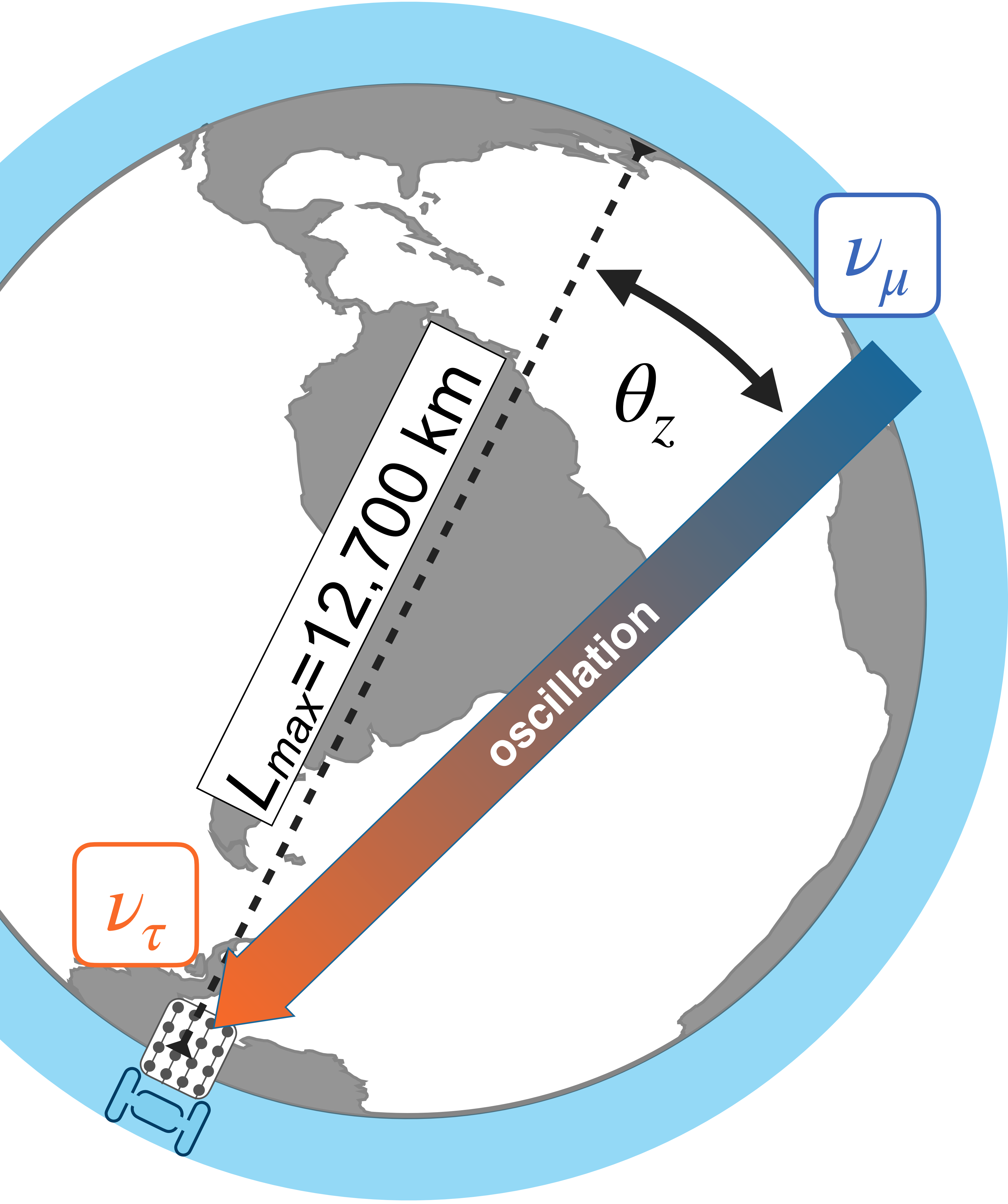

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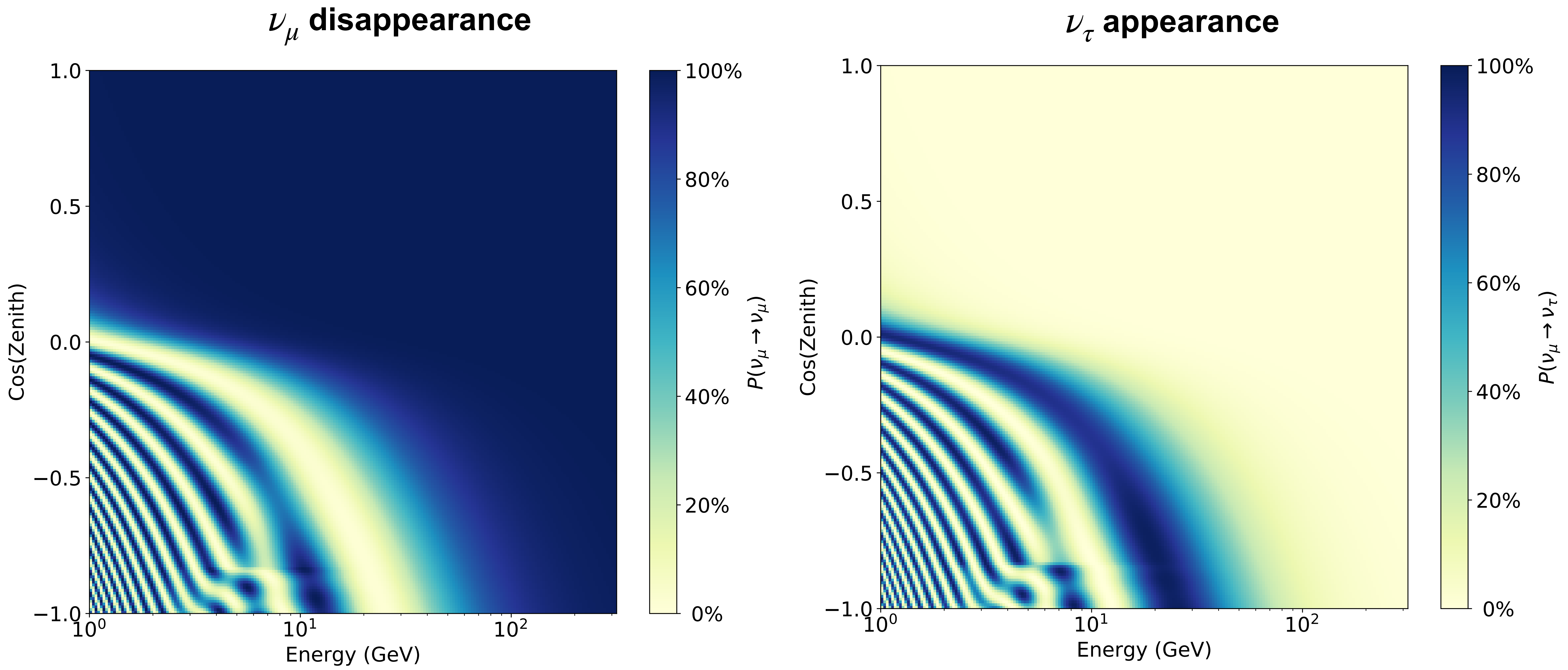

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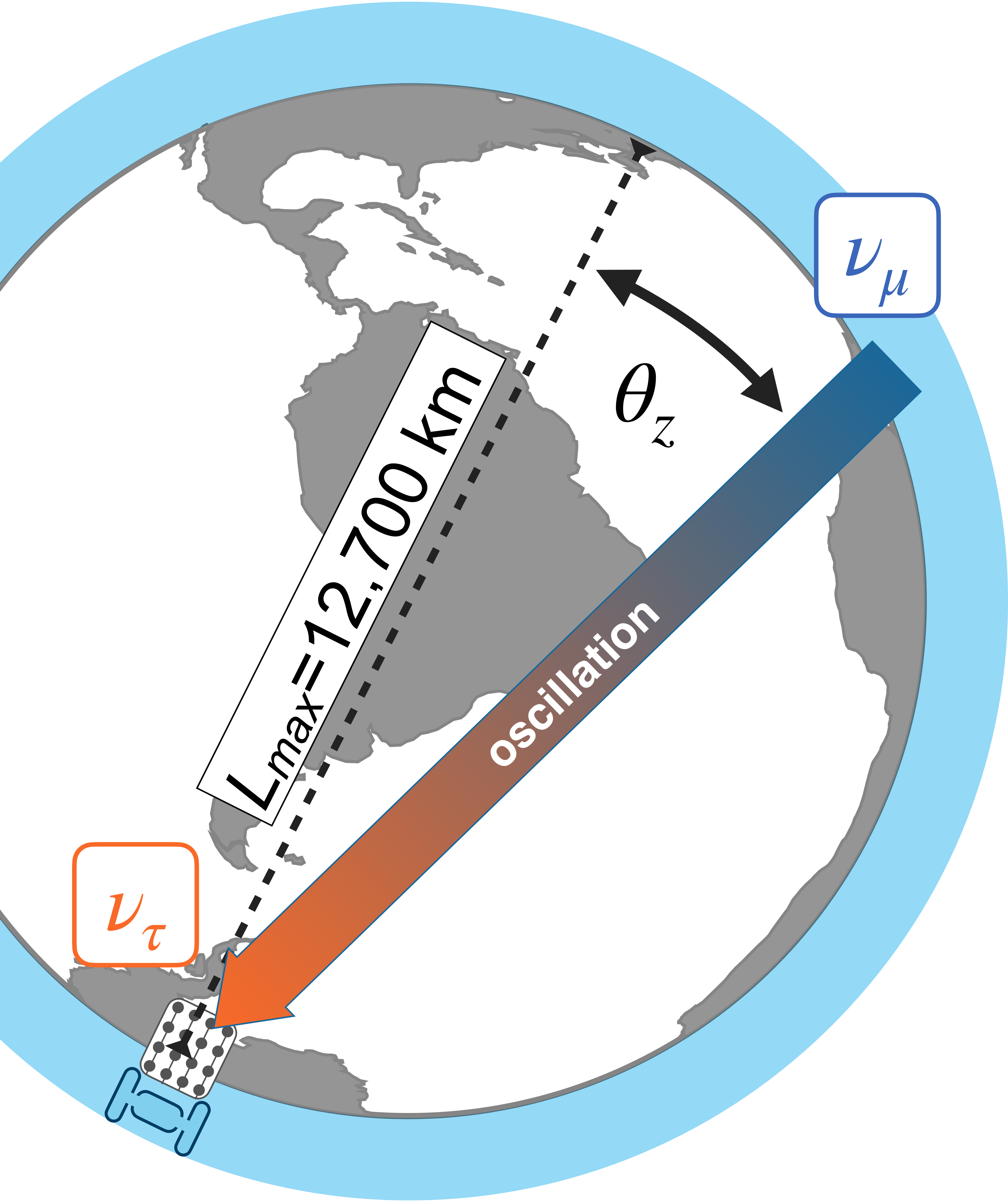

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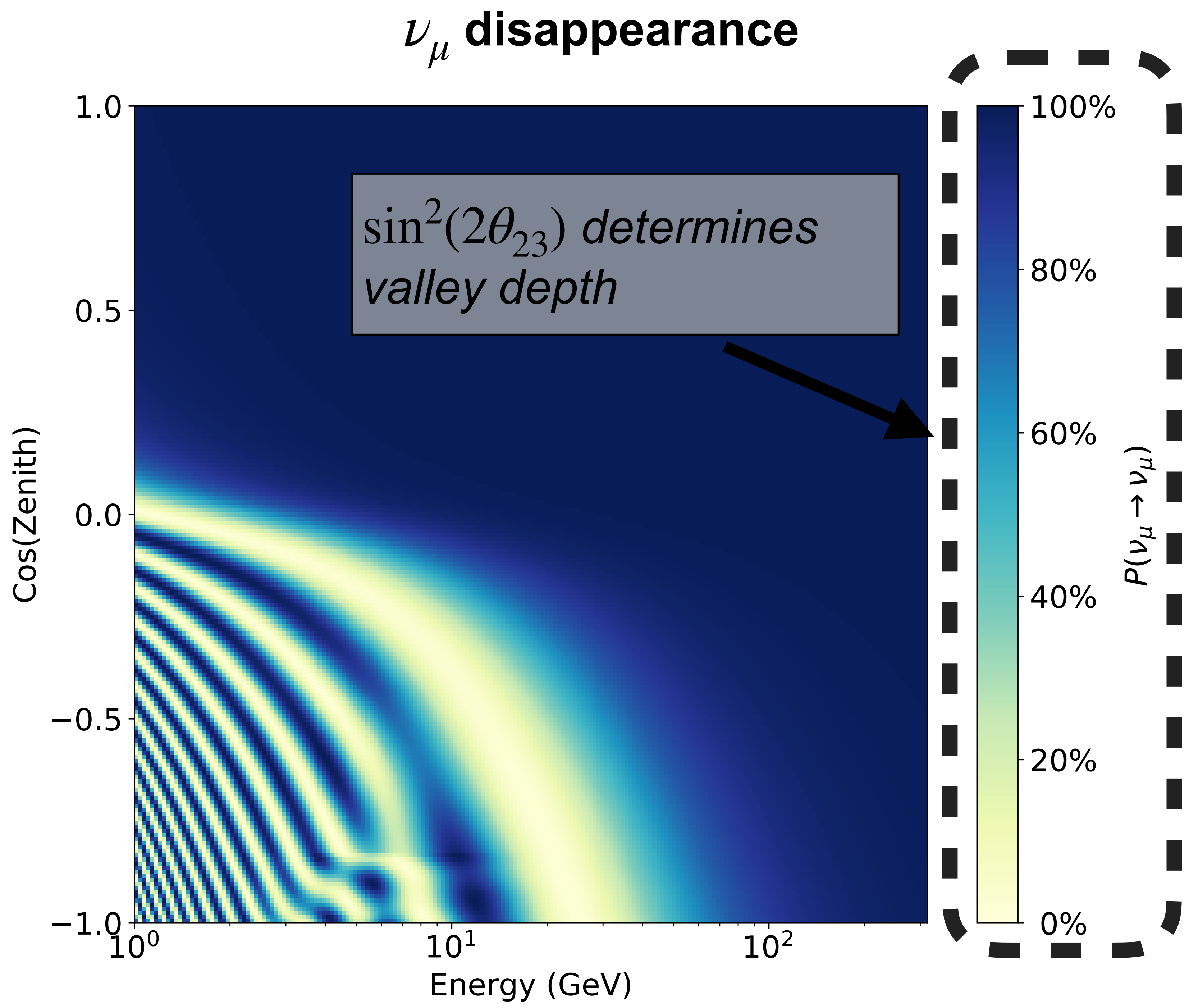

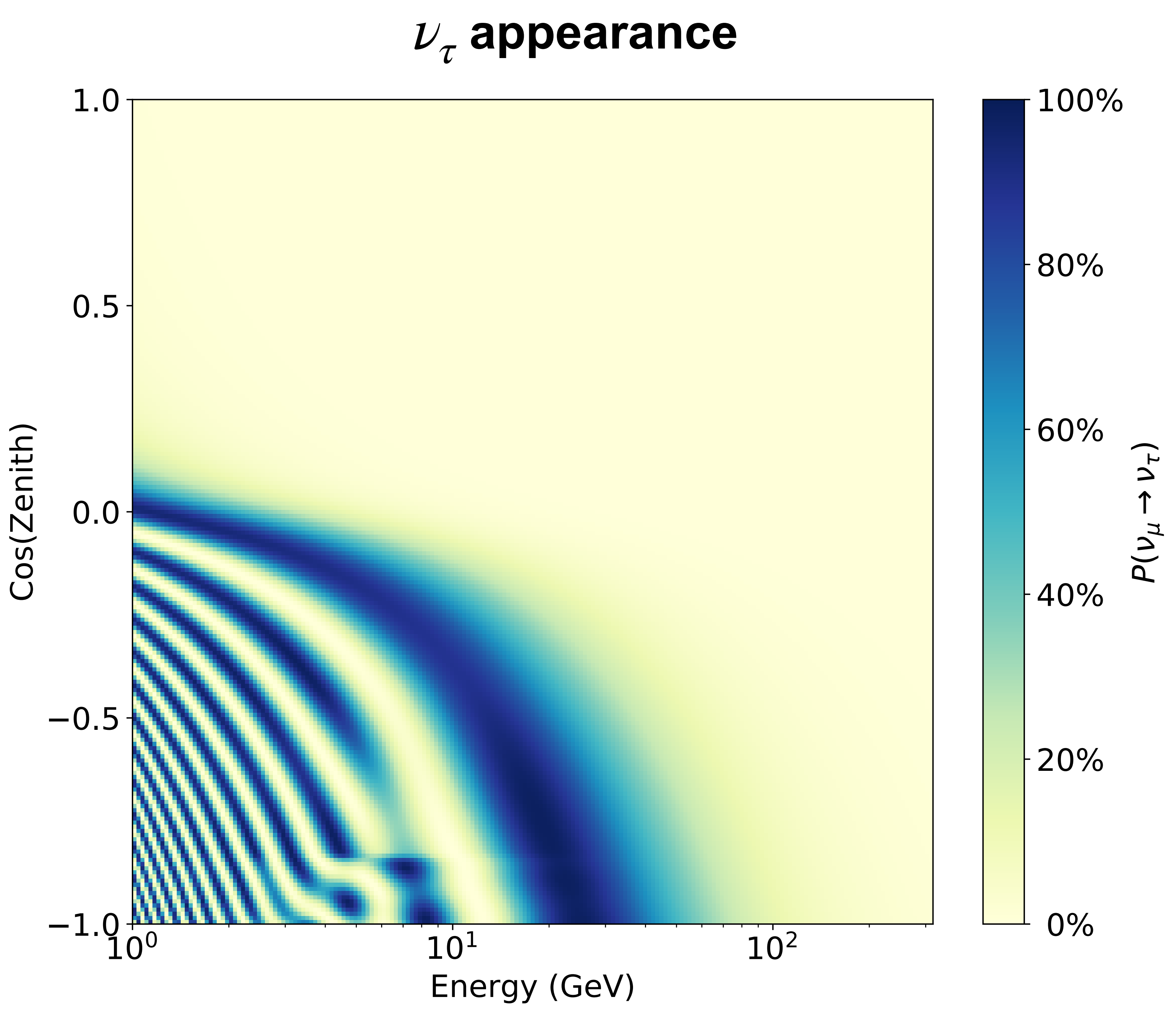

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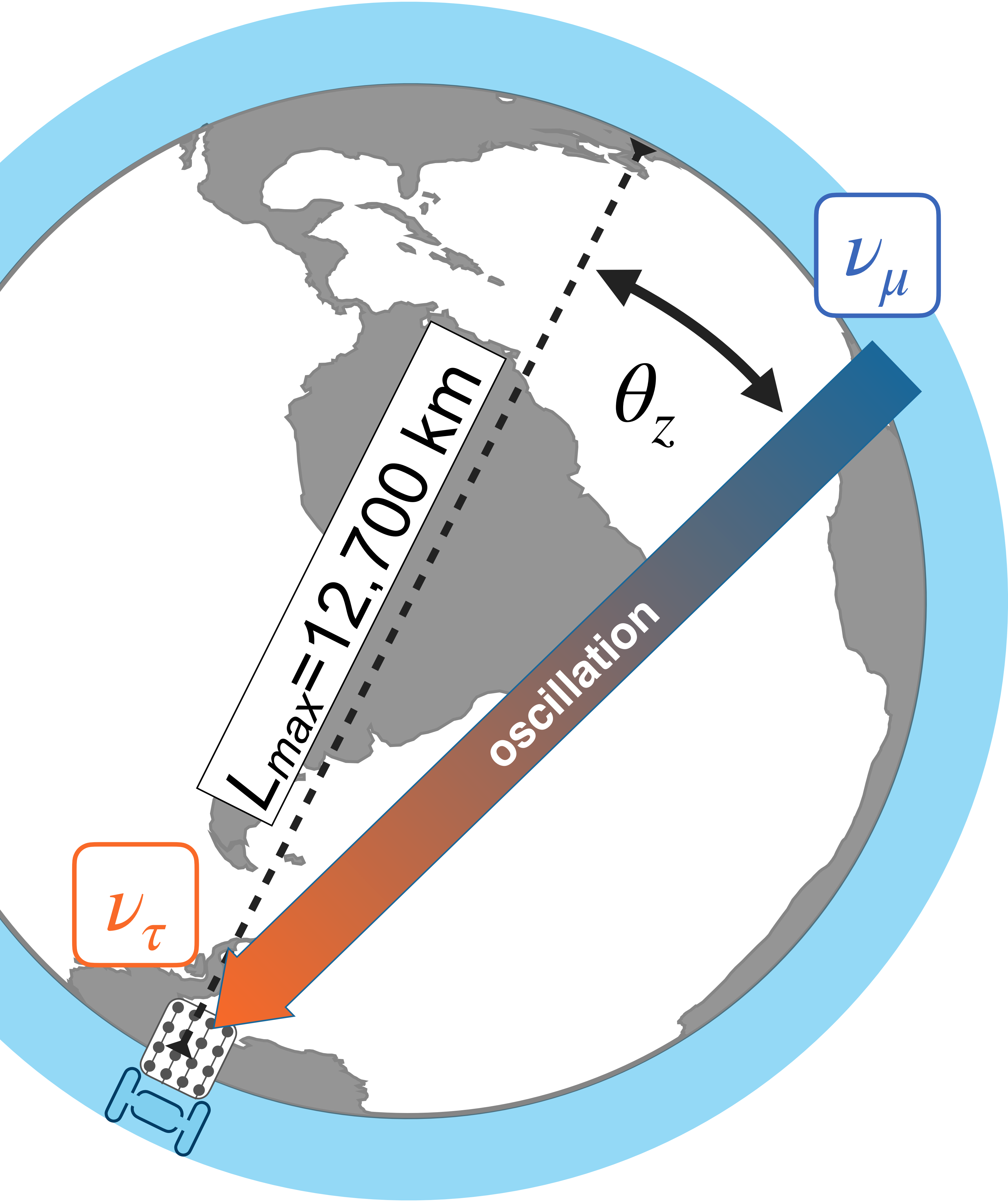

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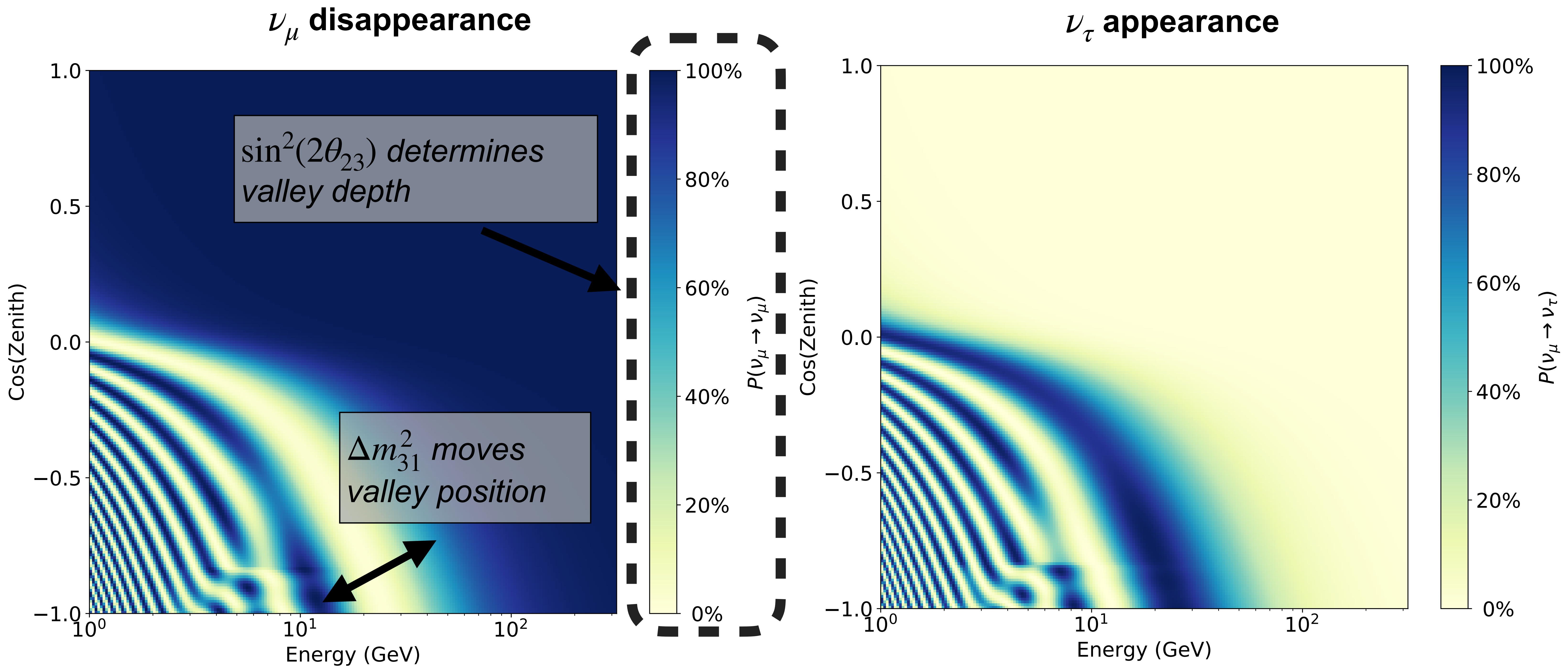

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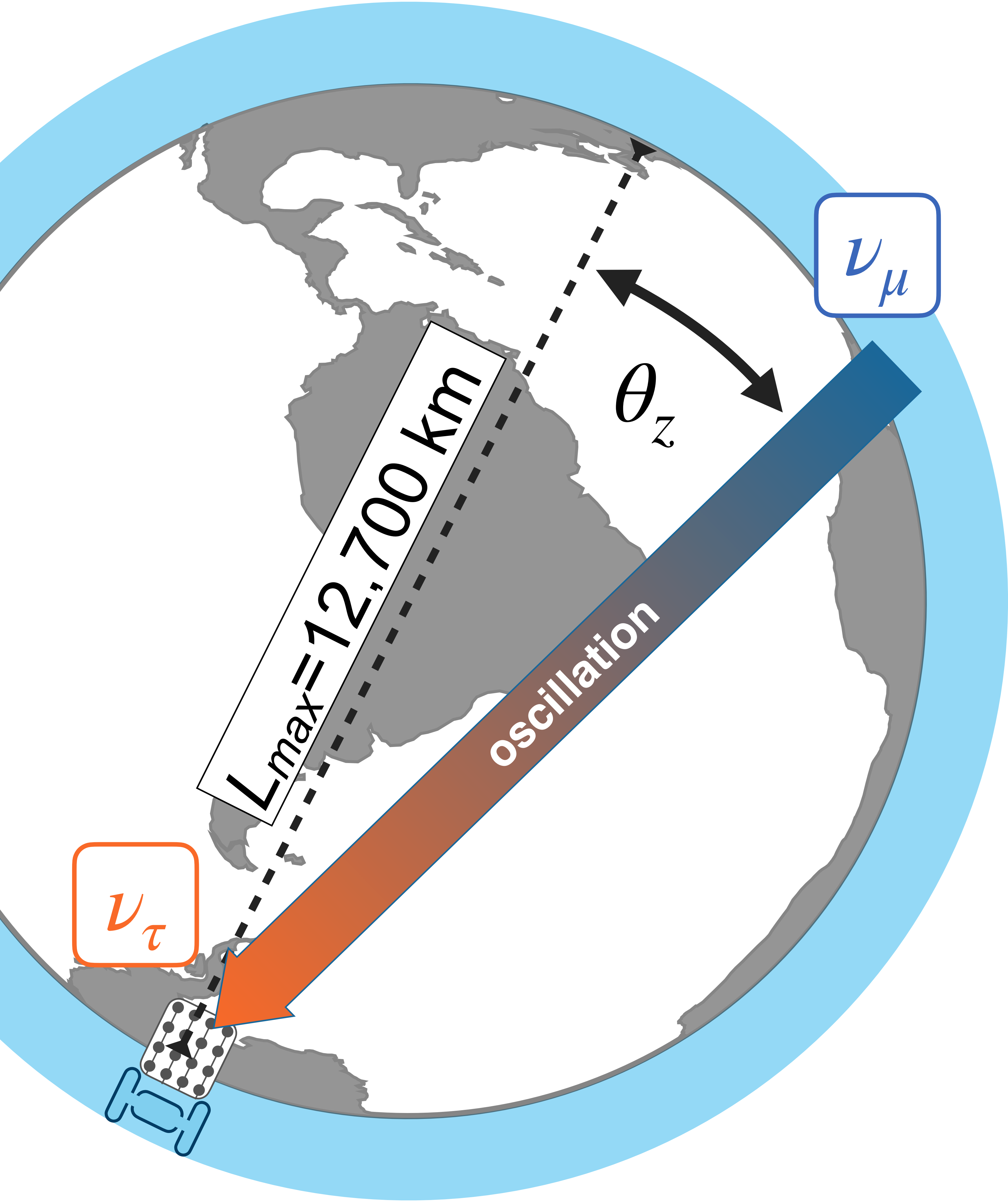
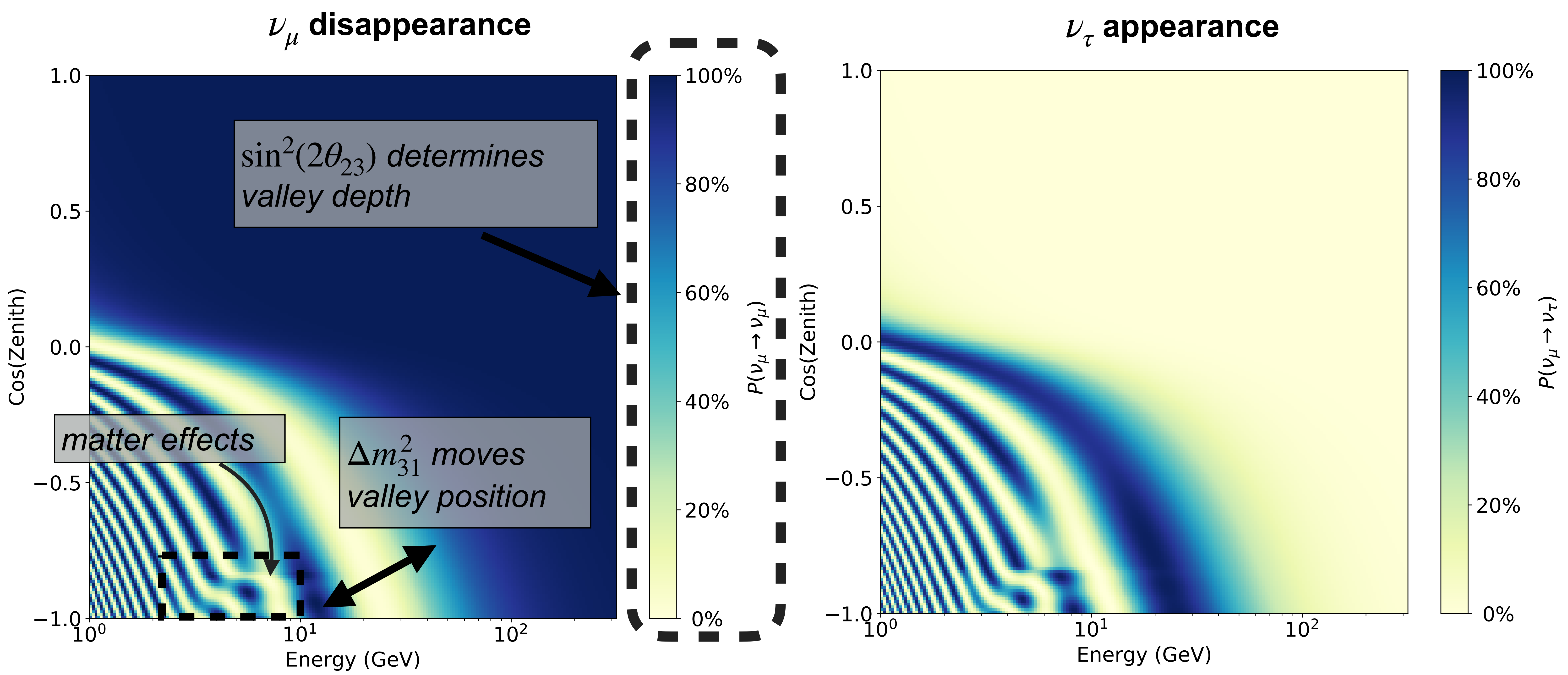
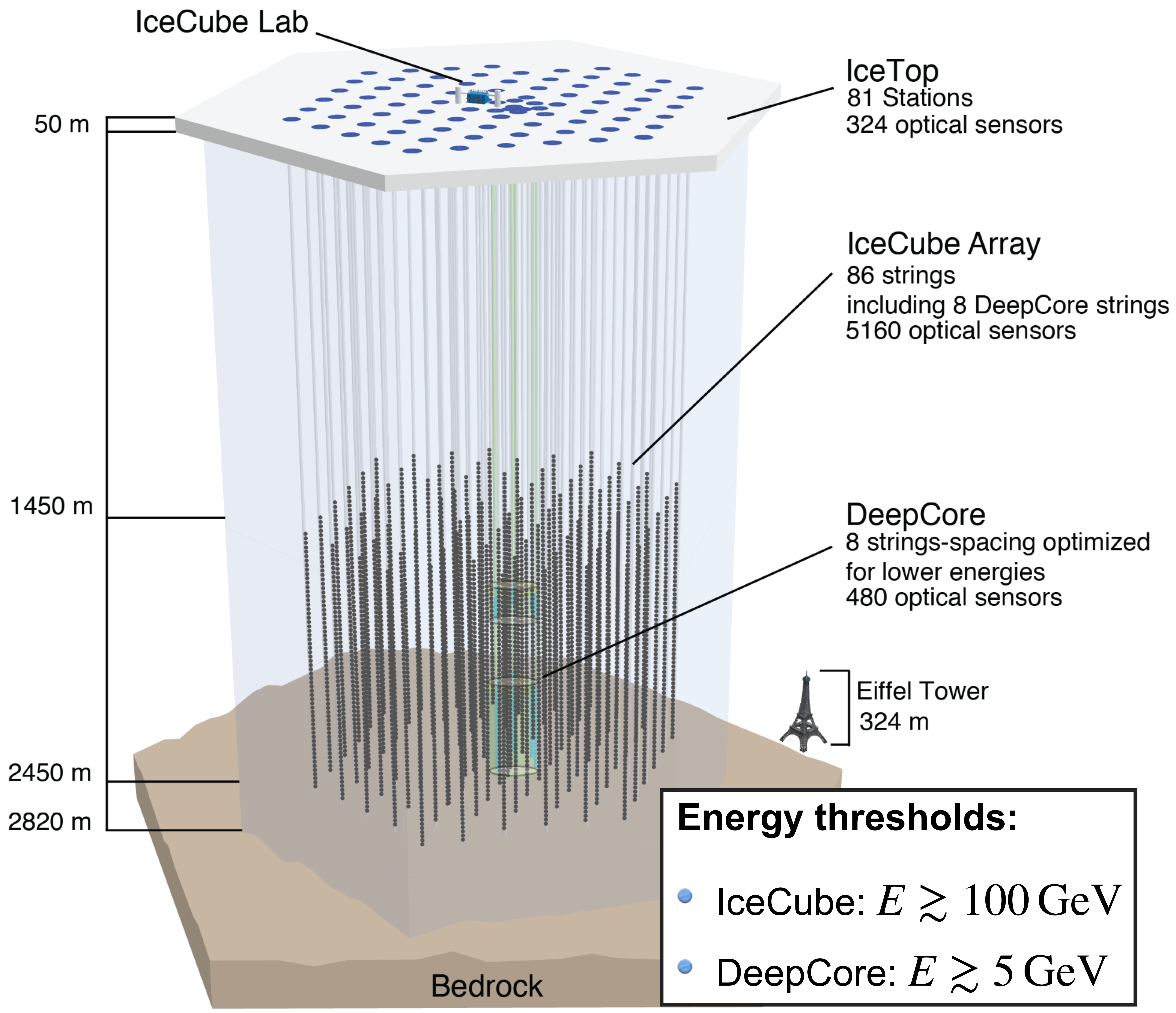


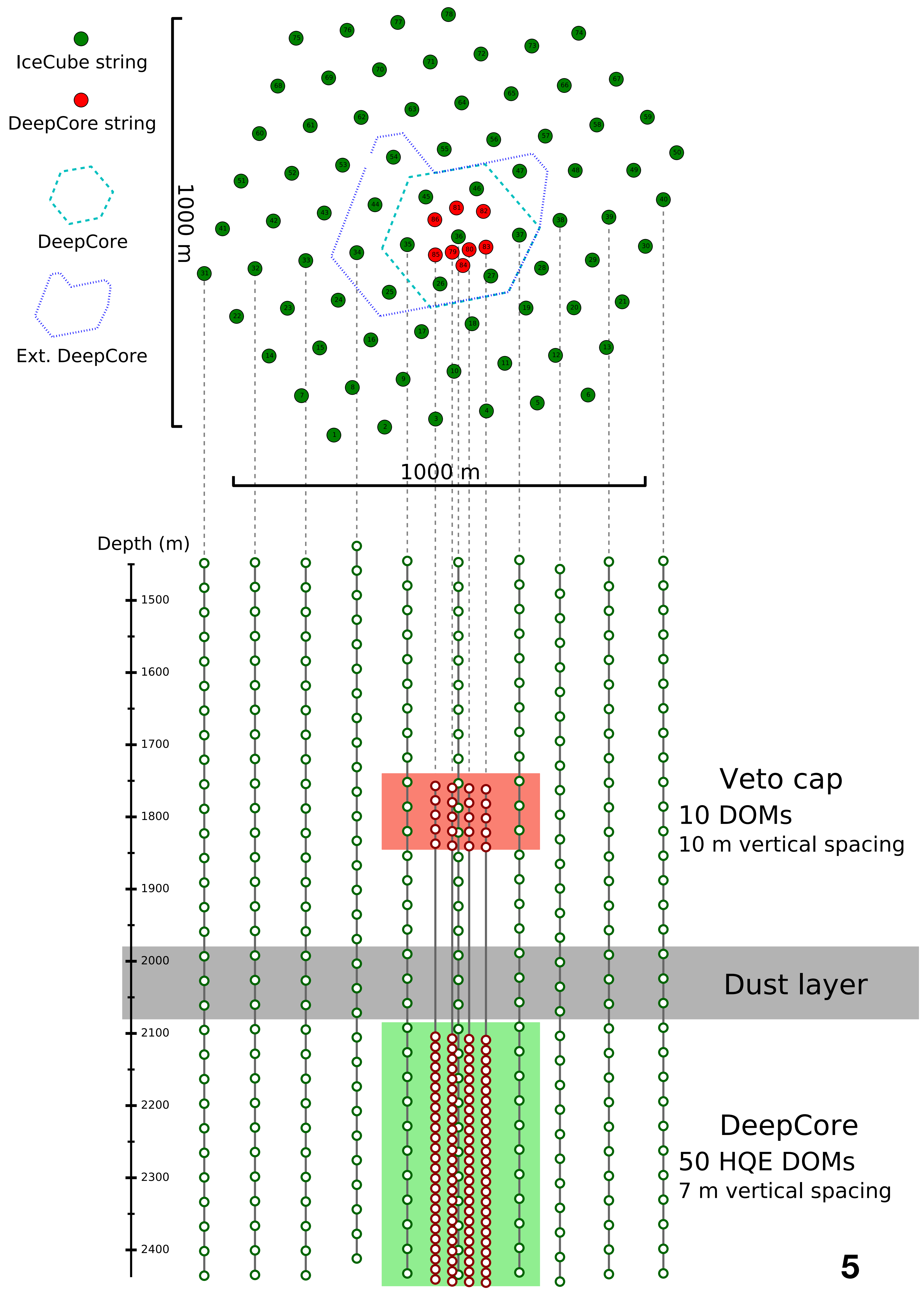


The IceCube Neutrino Observatory



Energy thresholds:

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



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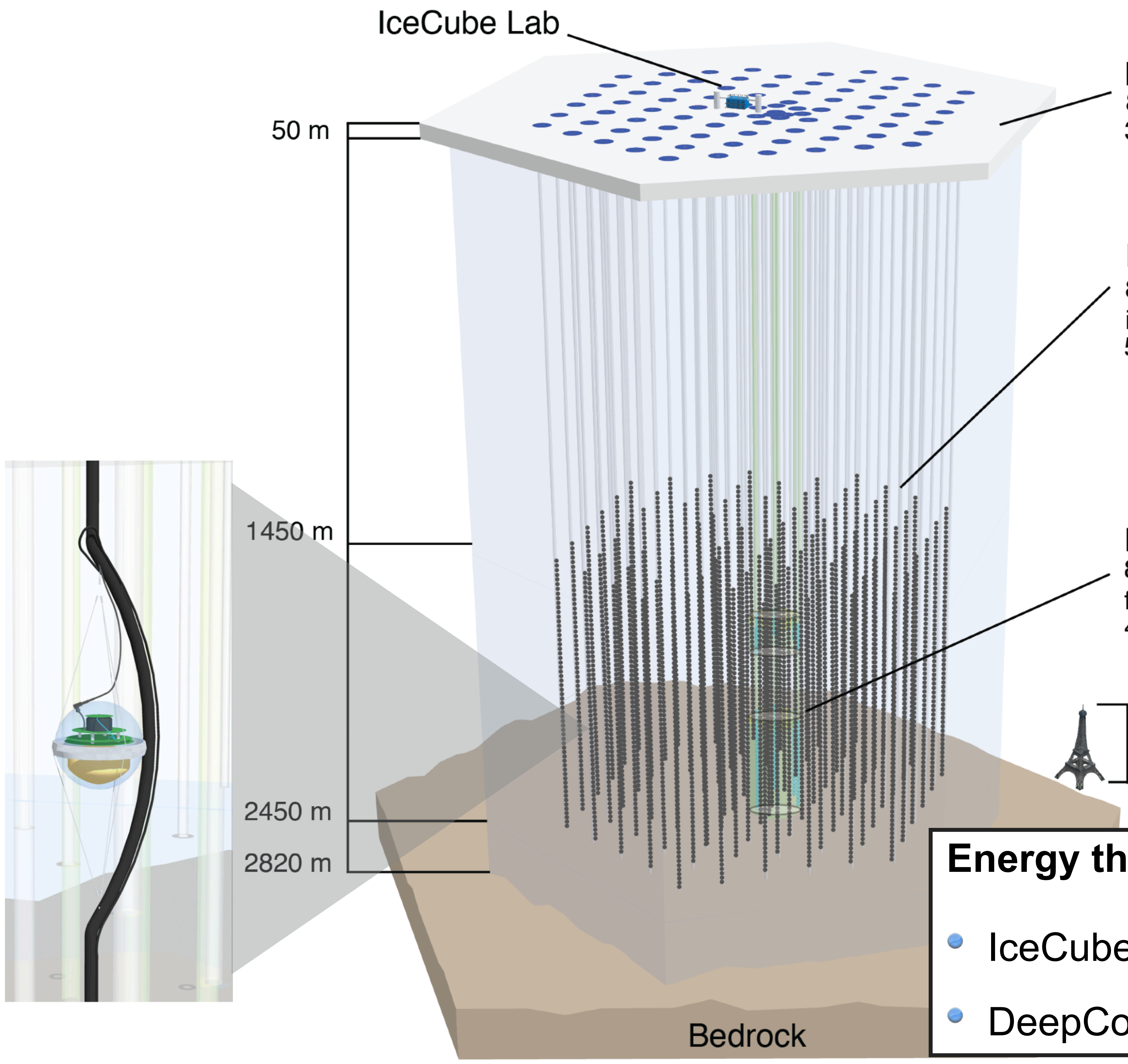

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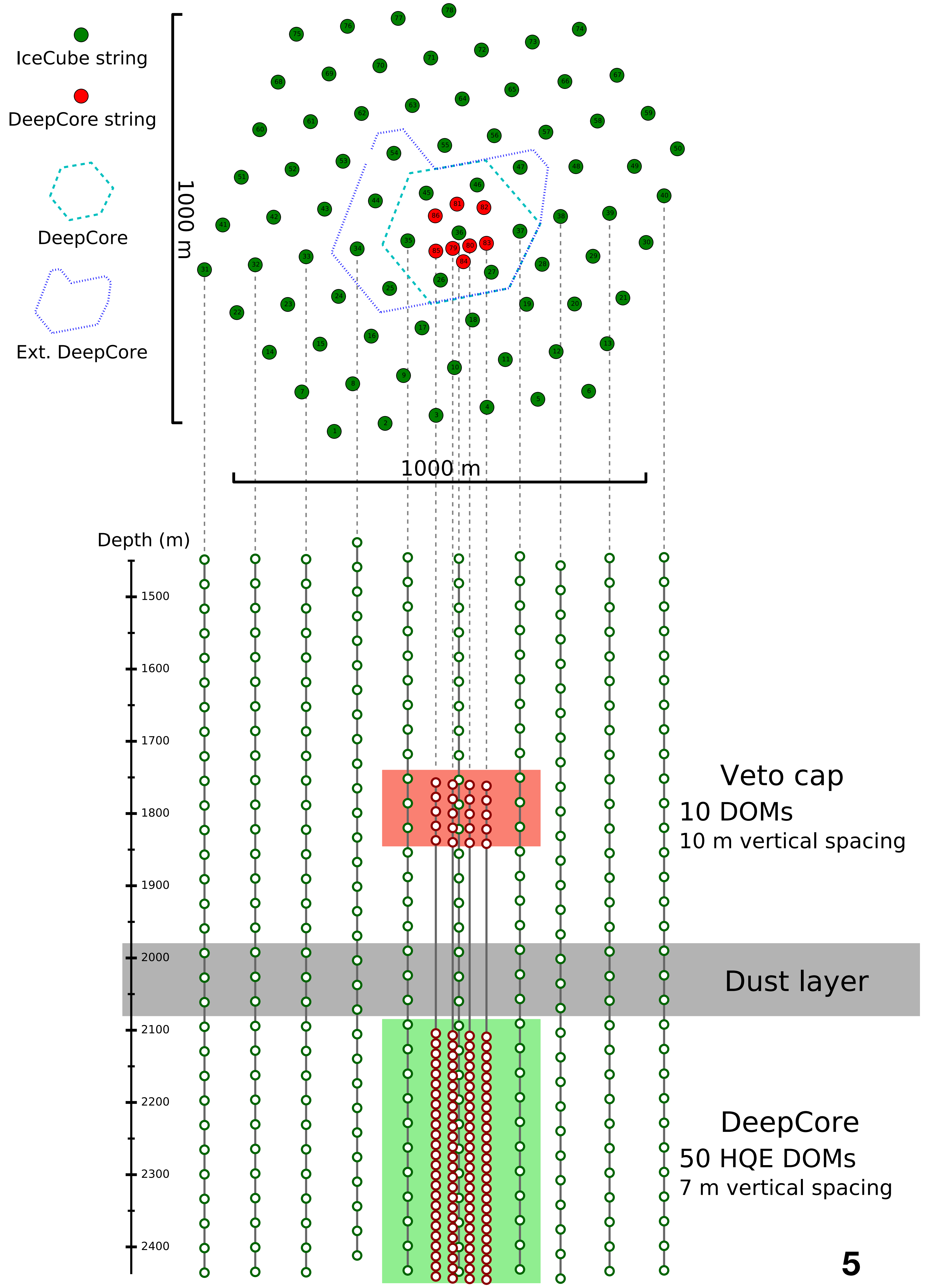
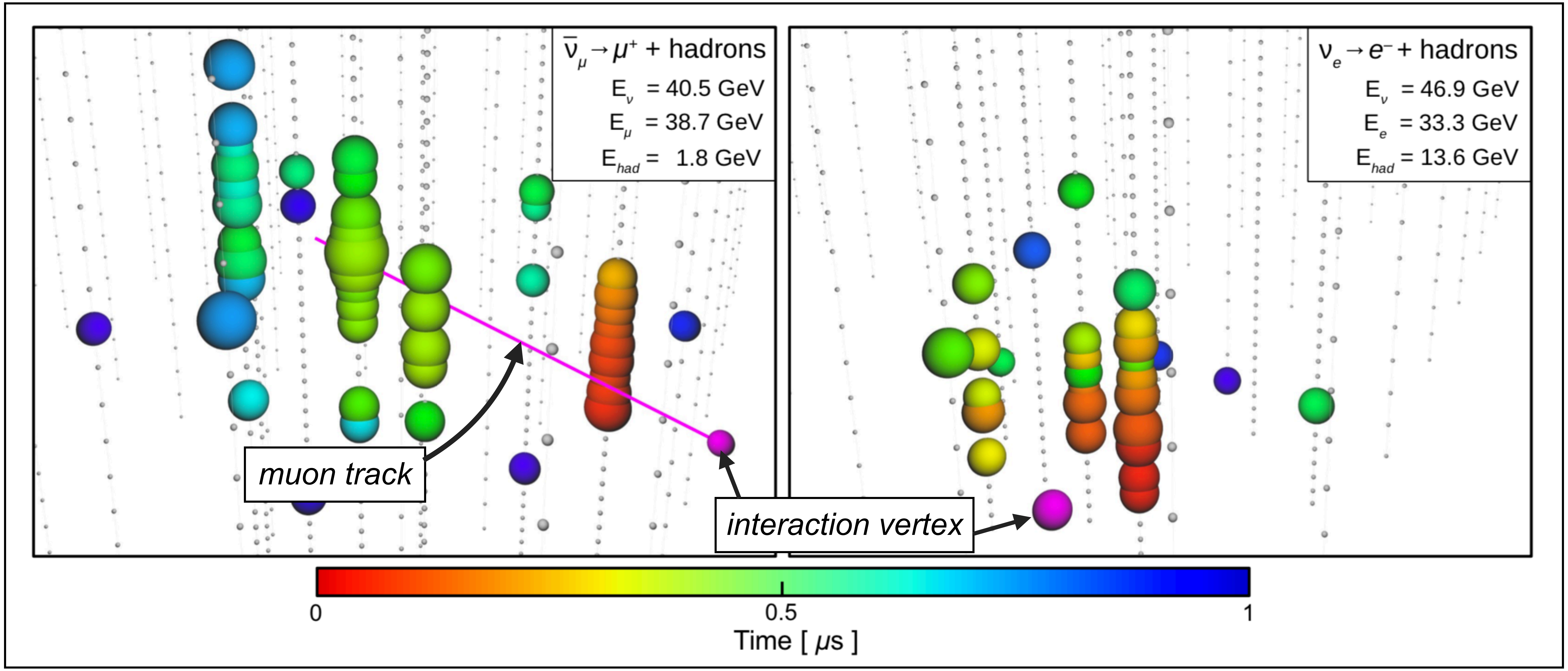


Neutrino Interactions in DeepCore

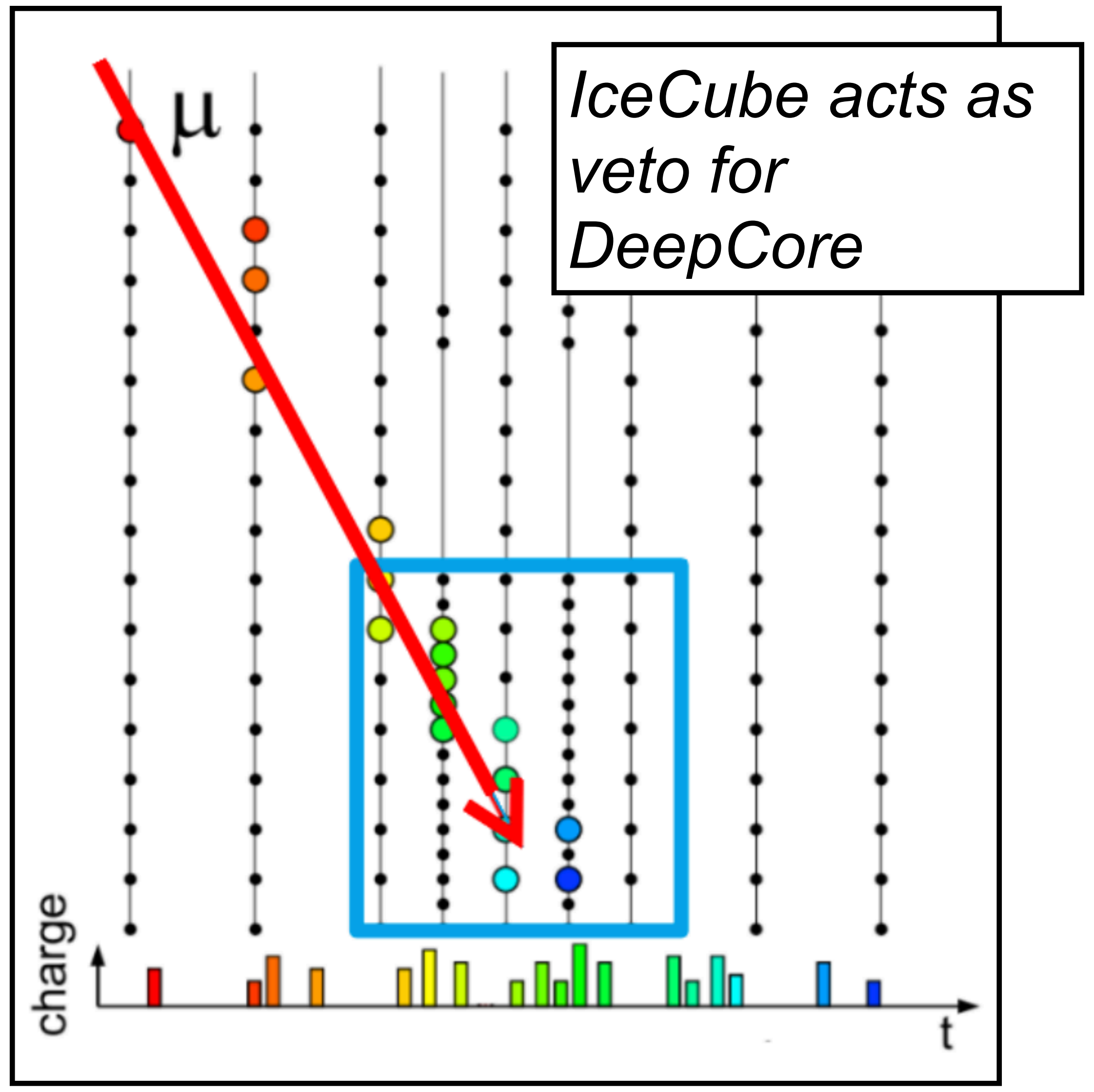
Charged-current ν_μ interactions | **Neutral-current interactions + ν_e + ν_τ**



“tracks” | **“cascades”**

DeepCore Oscillation Analyses in a Nutshell

Selection

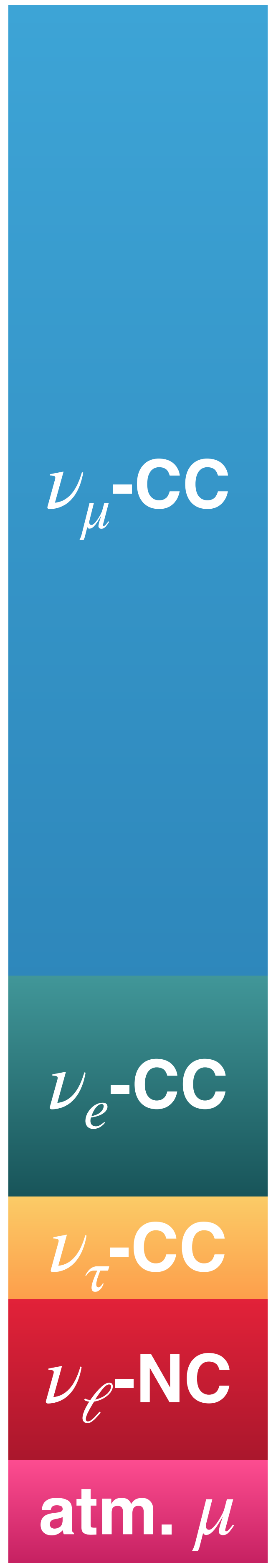


Reconstruction

Resolutions at 20 GeV:

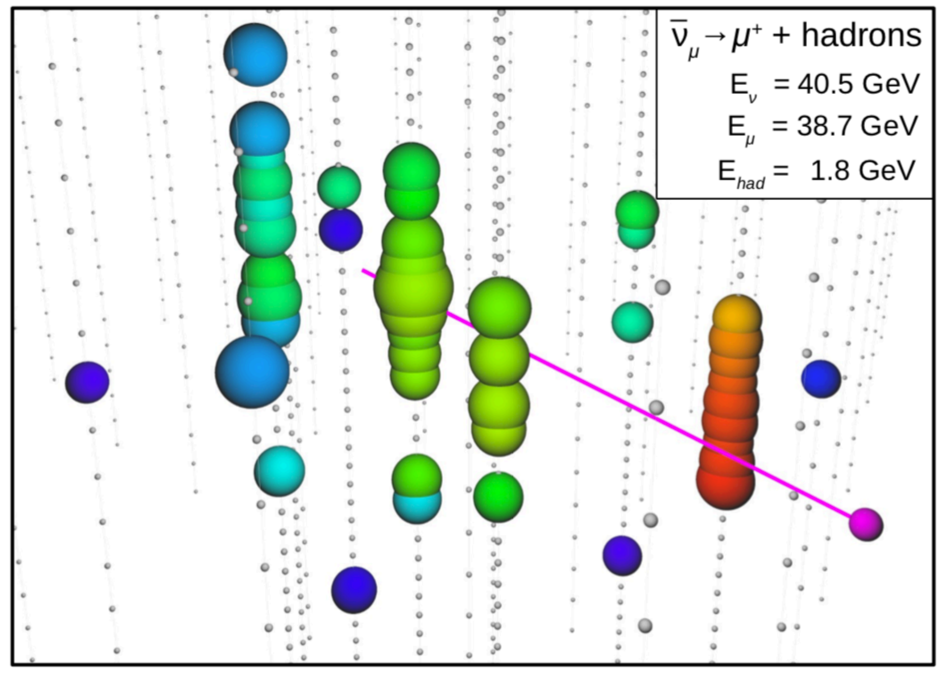
	tracks	cascades
Energy	24 %	29 %
Zenith	10º	16º

Event Sample

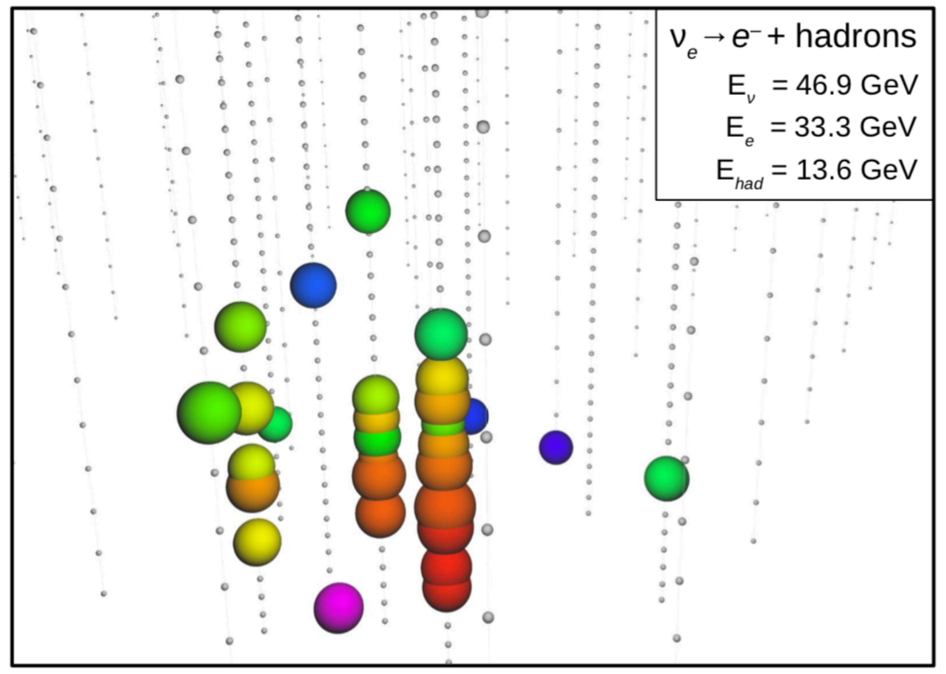


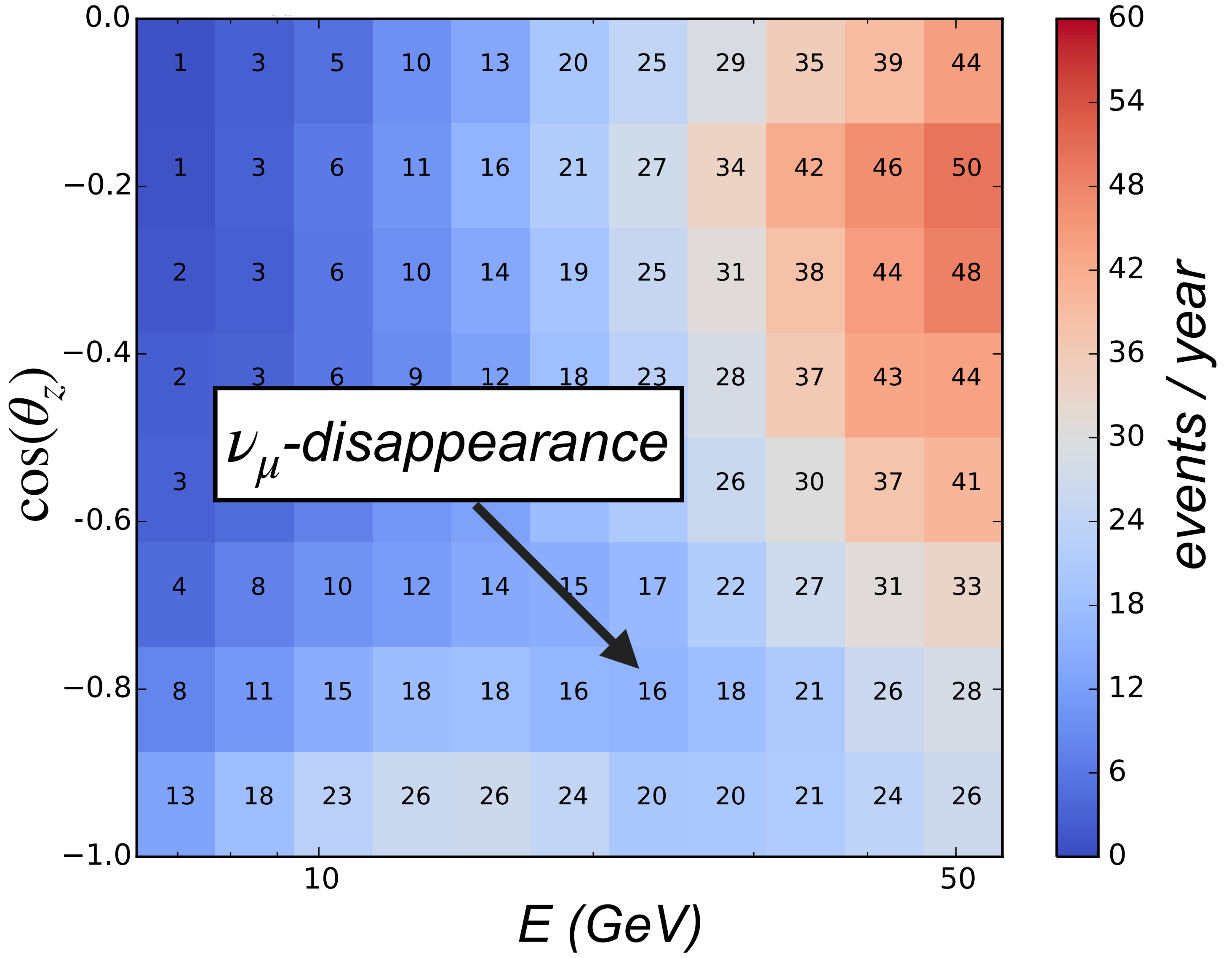
Classification

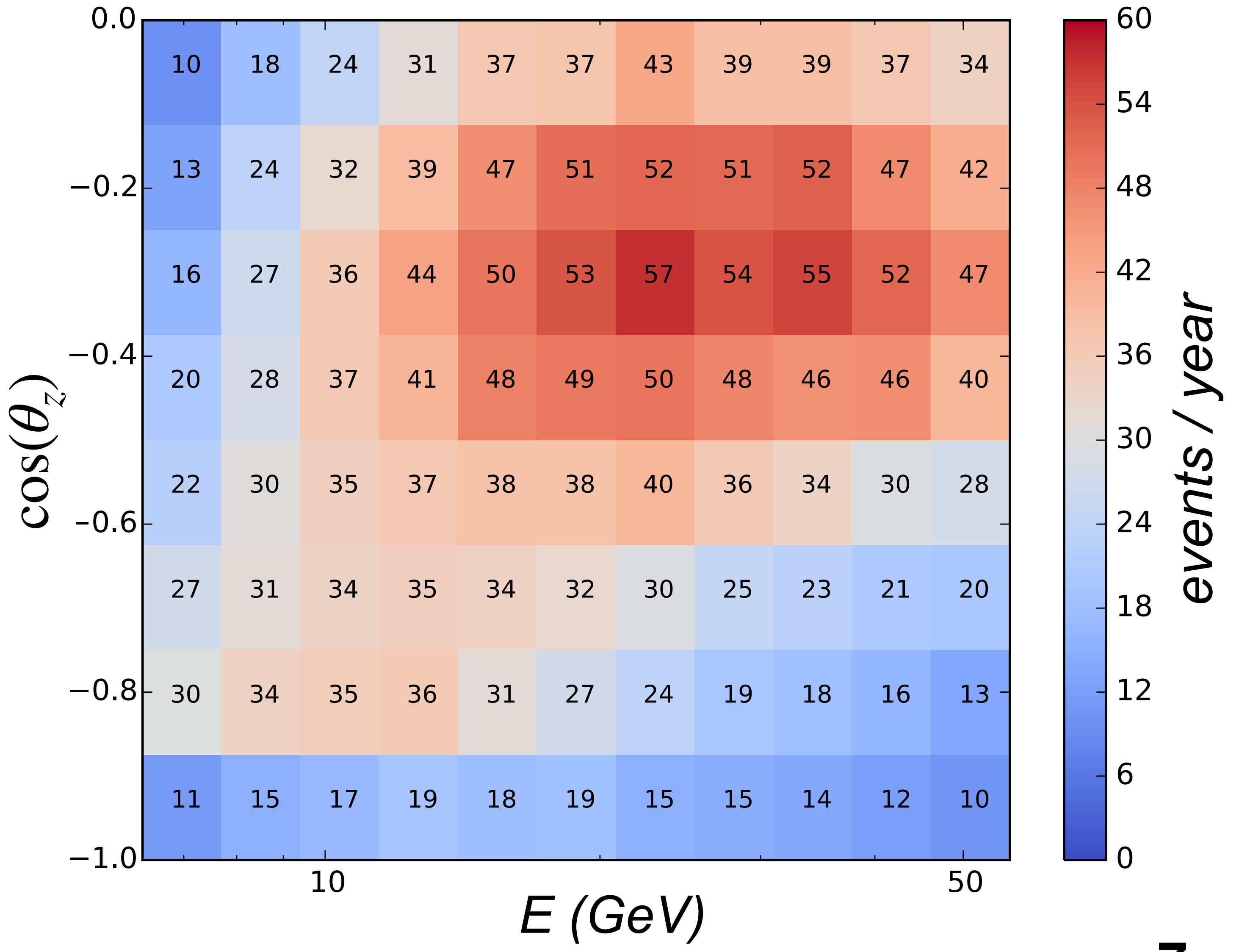
“track-like”



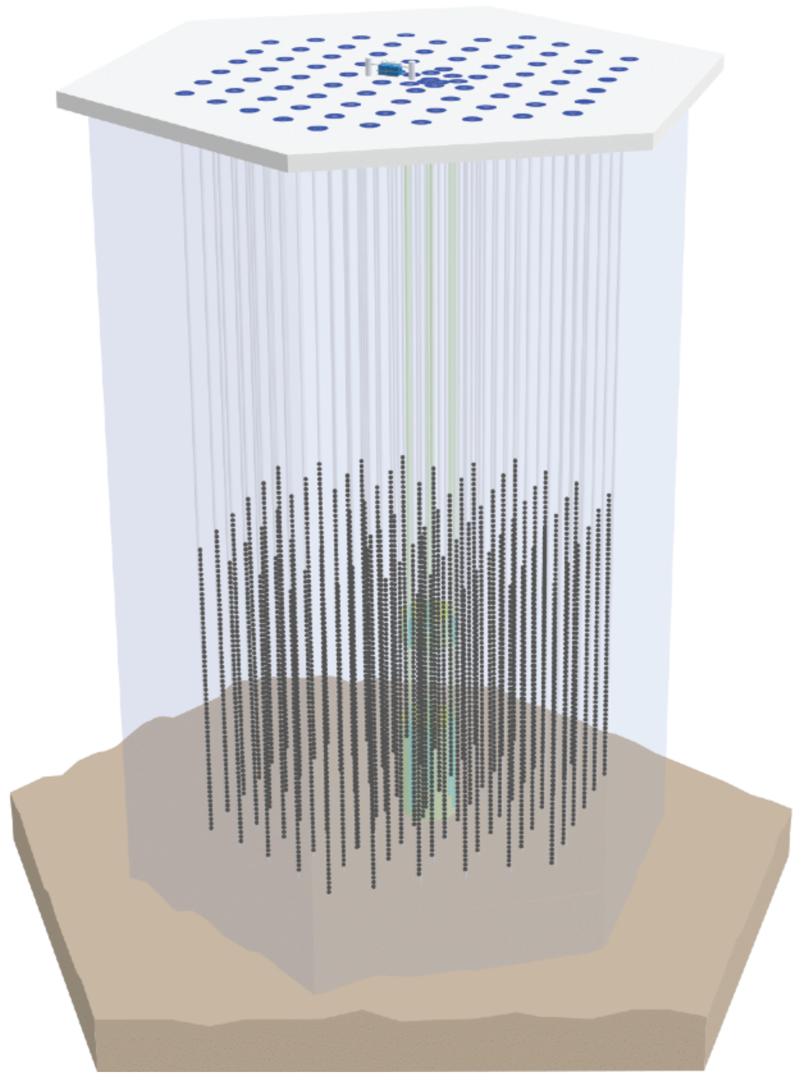
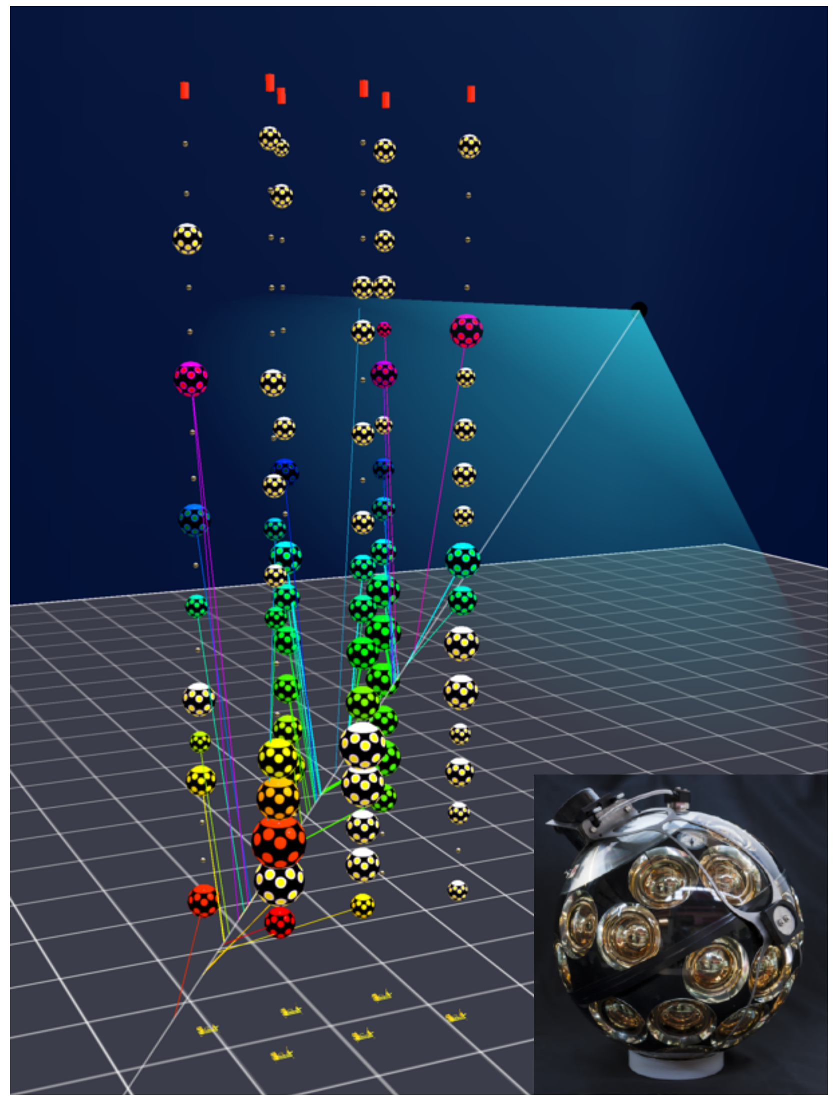
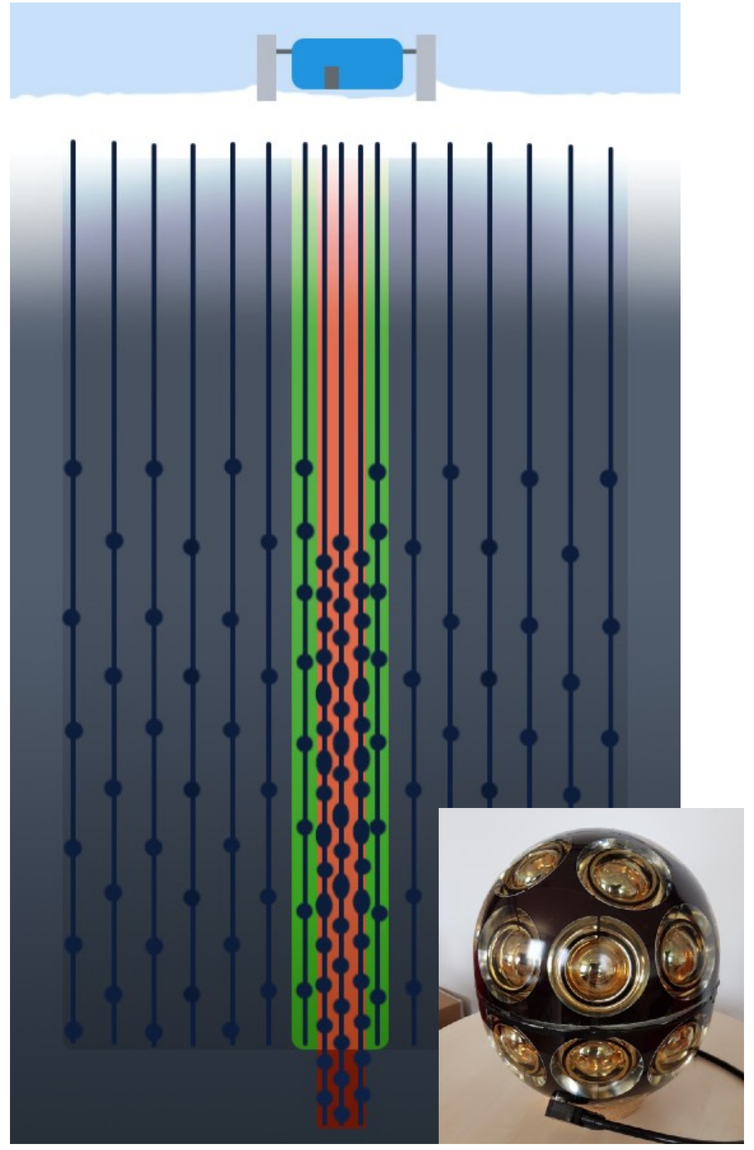
“cascade-like”





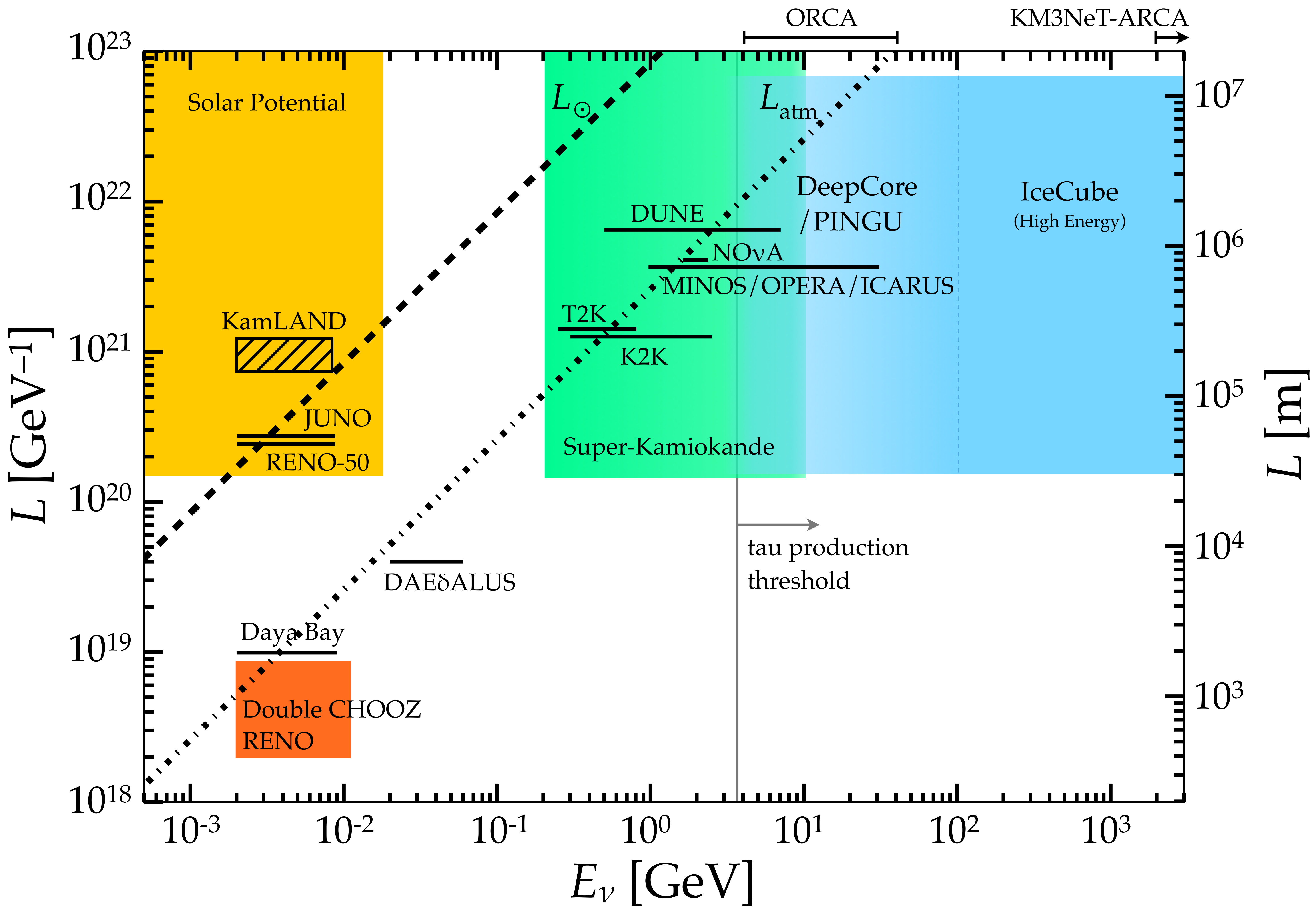


IceCube and KM3NeT: Present and Future

	IceCube DeepCore	KM3NeT/ORCA	IceCube Upgrade
deployment years	2009 — 2011	2019 —	2022 —
detector mass	**~20 MT (DeepCore)**	~7 MT	~2 MT
veto volume	**1 km³ (IceCube)**	shared with fiducial	**1 km³ (IceCube)**
medium	ice: **-absorption**, +scattering	water: +absorption, **-scattering**	ice: **-absorption**, +scattering
string / sensor spacing	20-50 m / 7 m	**20 m** / 9 m	**20 m / 3 m**
no. sensors / PMTs per sensor	400 / 1	**2070 / 31**	700 / 24
energy threshold	5 GeV	3 GeV	**1 GeV**

Neutrino Experiments in the Global Context



Abundant Physics Opportunities

Experimental Setup

Physics

Atmospheric Neutrinos:

- energy: GeV - TeV, ɣ ~ 2.7
- baseline: variable, up to 12,700 km
- composition: mostly $\nu_\mu/\bar{\nu}_\mu$, some $\nu_e/\bar{\nu}_e$

Detector Capabilities:

- method: Cherenkov effect
- energy threshold: $\gtrsim 5\,\mathrm{GeV}$
- ν-flavor separation: $\nu_\mu/\bar{\nu}_\mu$-CC vs. rest

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Physics

Muon Neutrino Disappearance: $P(\nu_\mu \rightarrow \nu_\mu)$

- value of θ_{23}, Δm^2_{32}

Abundant Physics Opportunities

Experimental Setup

Atmospheric Neutrinos:

- energy: GeV - TeV, ɣ ~ 2.7
- baseline: variable, up to 12,700 km
- composition: mostly $\nu_\mu/\bar{\nu}_\mu$, some $\nu_e/\bar{\nu}_e$

Detector Capabilities:

- method: Cherenkov effect
- energy threshold: $\gtrsim 5\,\mathrm{GeV}$
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Through Matter Effects:

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- Non-Standard Interactions (NSI)

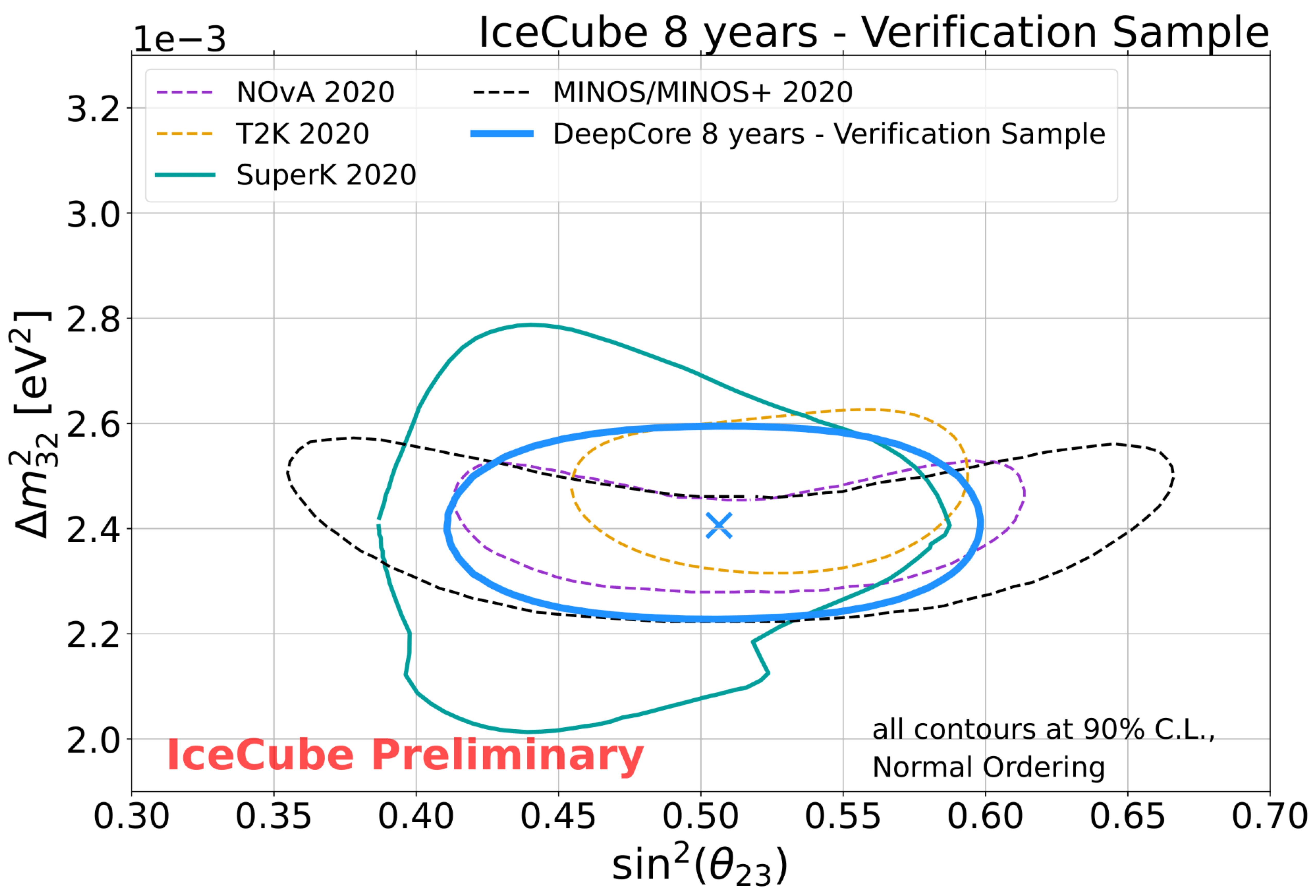
Other:

- additional mass eigenstates (sterile neutrinos)
- decoherence (space-time quantum effects)

Analysis Results & Future Sensitivities

Latest 3-flavor Measurement at IceCube

- new sample of atmospheric neutrinos with 8 years of live time and improved calibration
- sub-sample of highly pure, well reconstructed ν_μ events: “Verification Sample” (~23000 events)
- recently unblinded result (normal ordering assumed)
  - $\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$
  - $\Delta m^2_{32} = 2.41^{+0.084}_{-0.084} \times 10^{-3}\,\mathrm{eV}^2$



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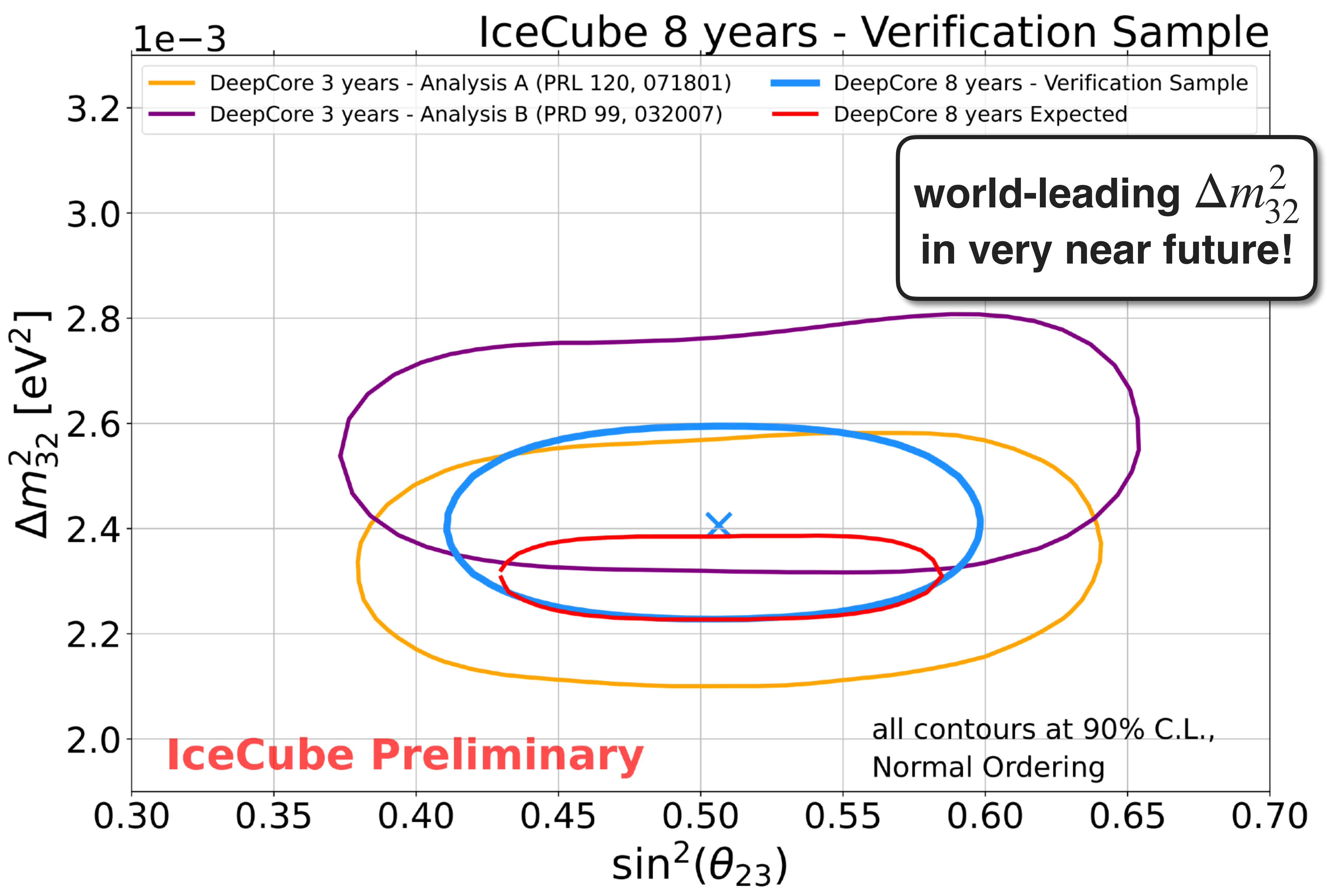

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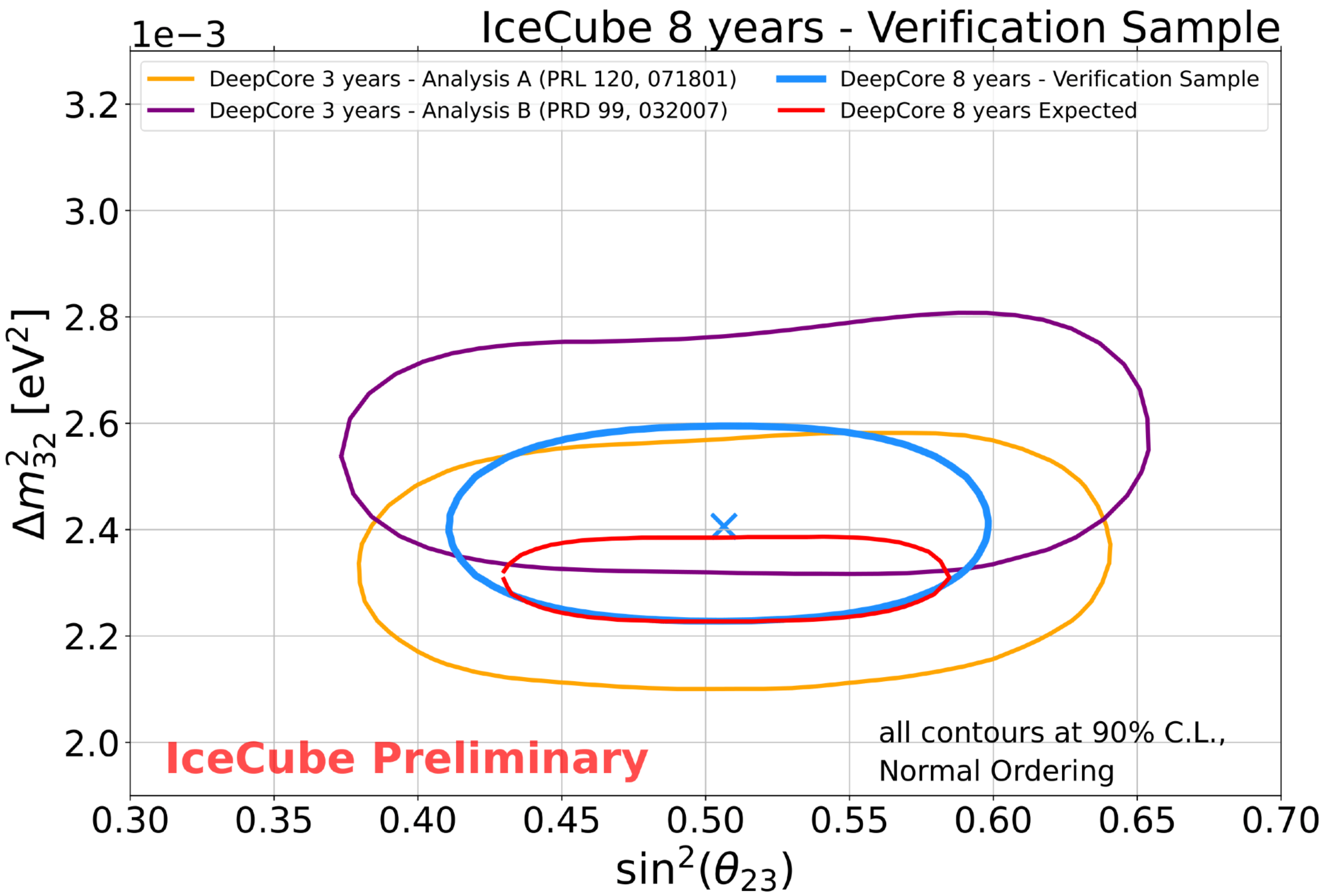
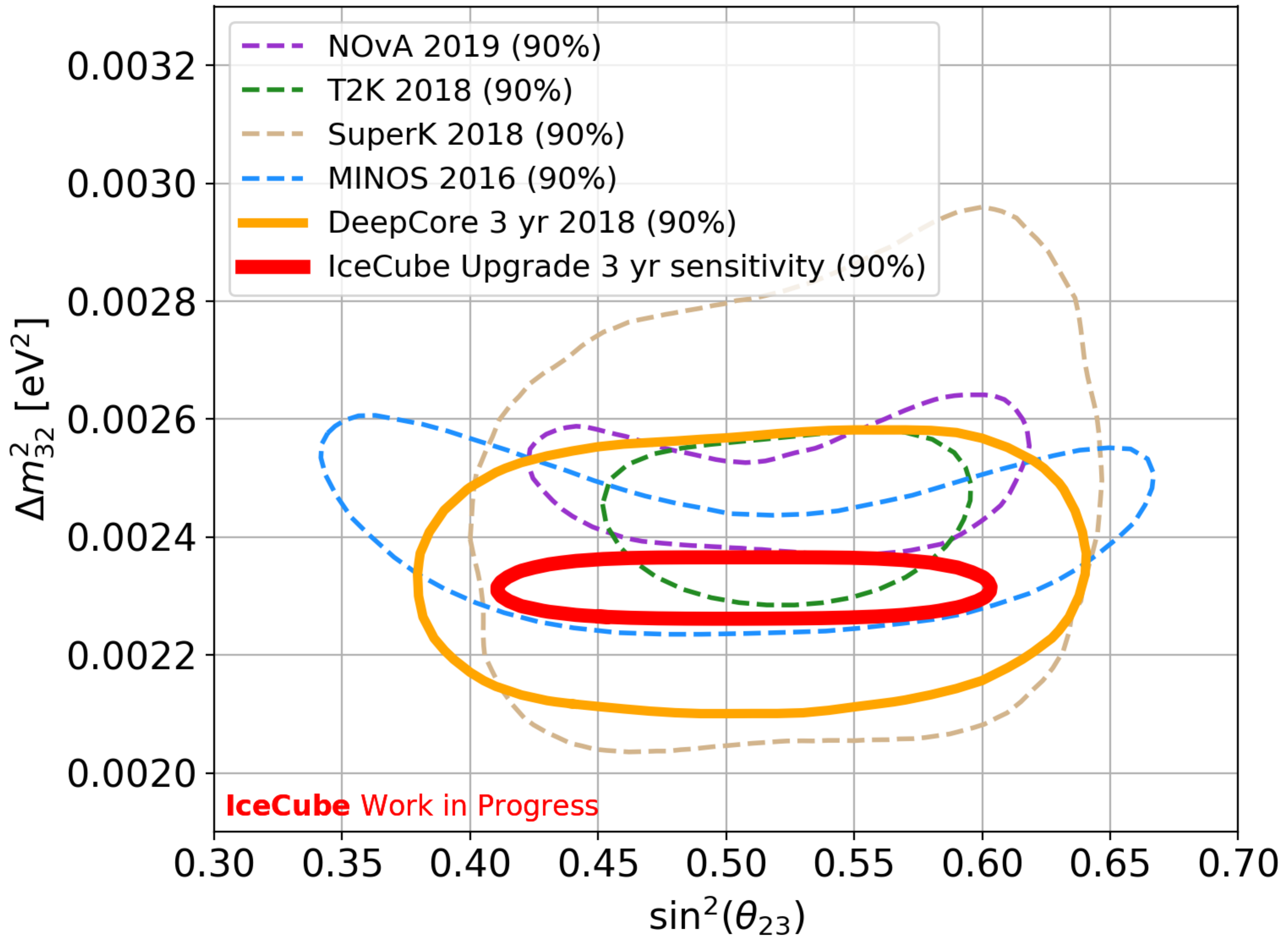
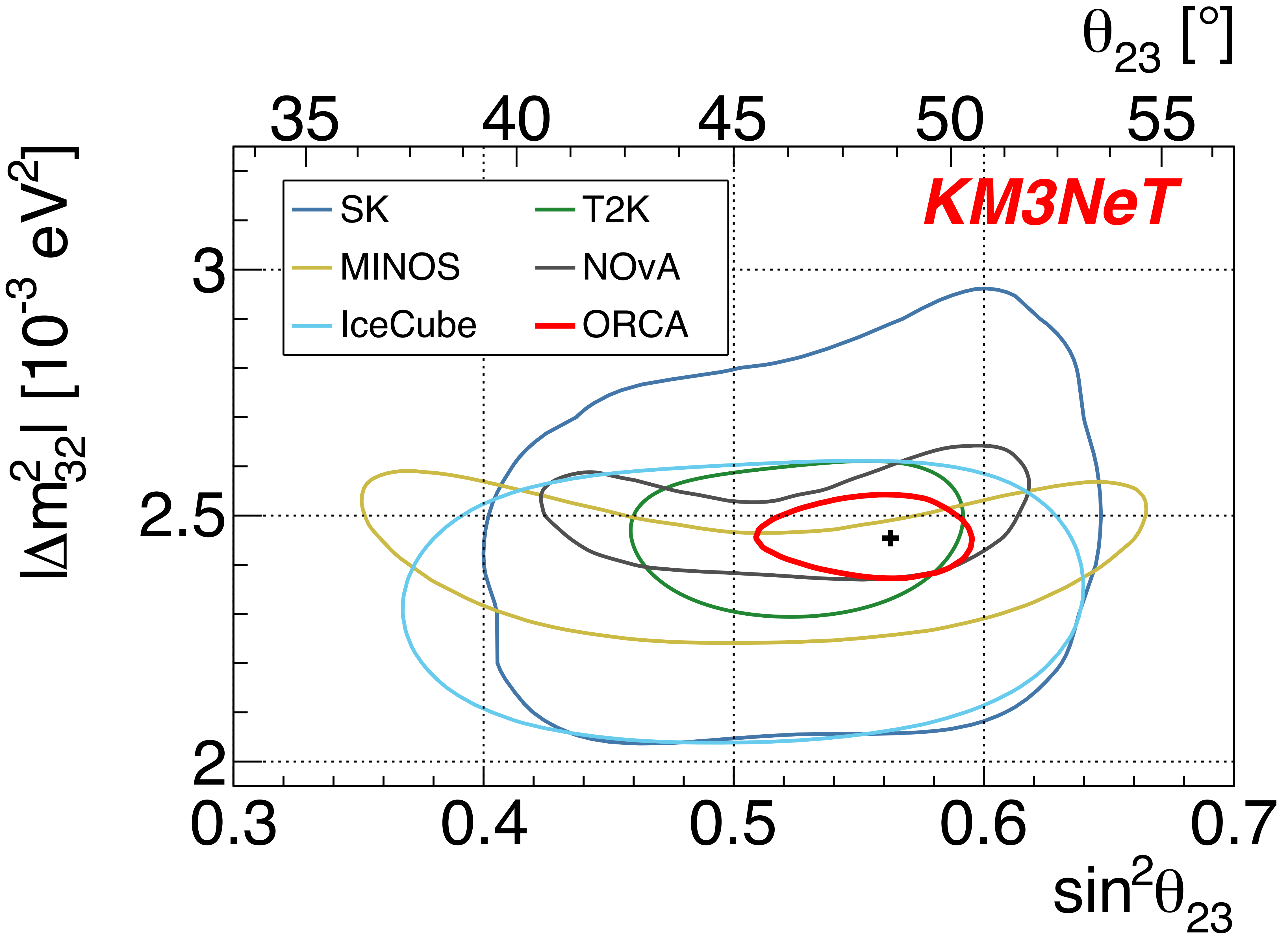
- honorable mention: first ORCA measurement with 6 (of 115) strings!



Expectations in Future Detectors

Hot on the heels of accelerator experiments!





Expected 3 year sensitivity with IceCube Upgrade, https://pos.sissa.it/358/1031

expected 3 year, 90% sensitivity, KM3NeT Collaboration, arxiv: 2103.09885

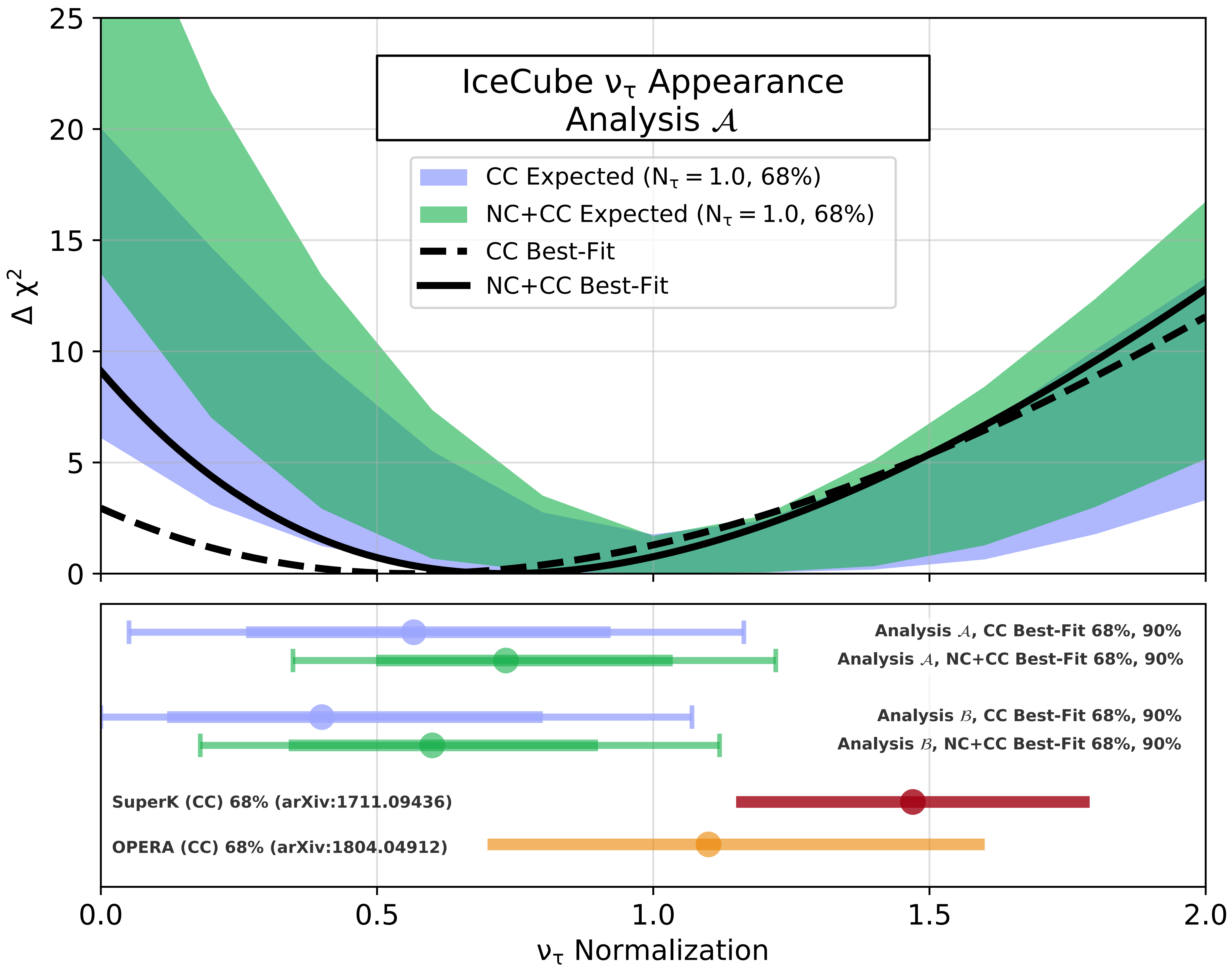
Testing Unitarity with Tau-Appearance

- three-flavour oscillations imply unitary mixing matrix: neutrinos can't disappear into or appear out of nothing!
- unitarity implies rows and columns are normed:

$$\underbrace{|U_{e3}|^2 + |U_{\mu 3}|^2}_{} + |U_{\tau 3}|^2 = 1$$

experimentally established to sum to 0.5

- standard oscillation analysis with free floating ν_τ normalization
- results compatible with standard 3-ν oscillation (at 90% C.L.)



DeepCore result with 3 years of data, arxiv:1901.05366

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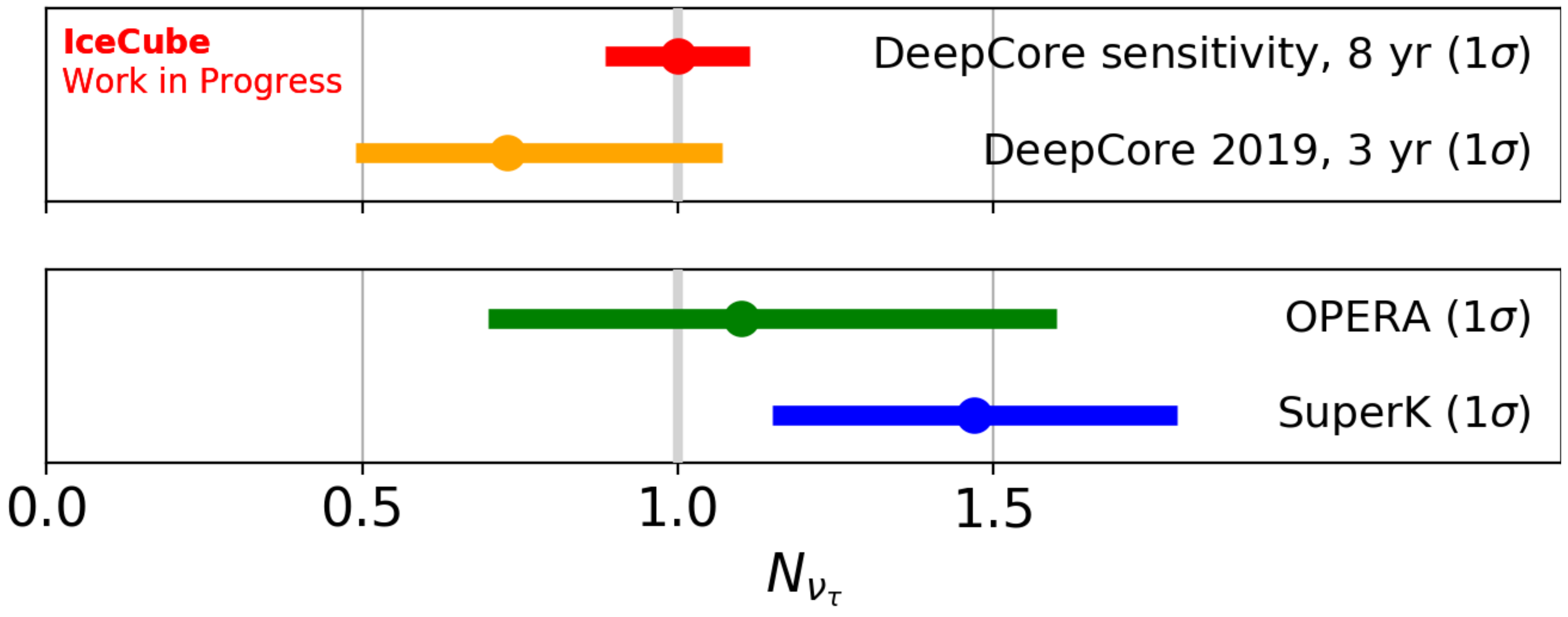

Expected sensitivity with 8 years of DeepCore

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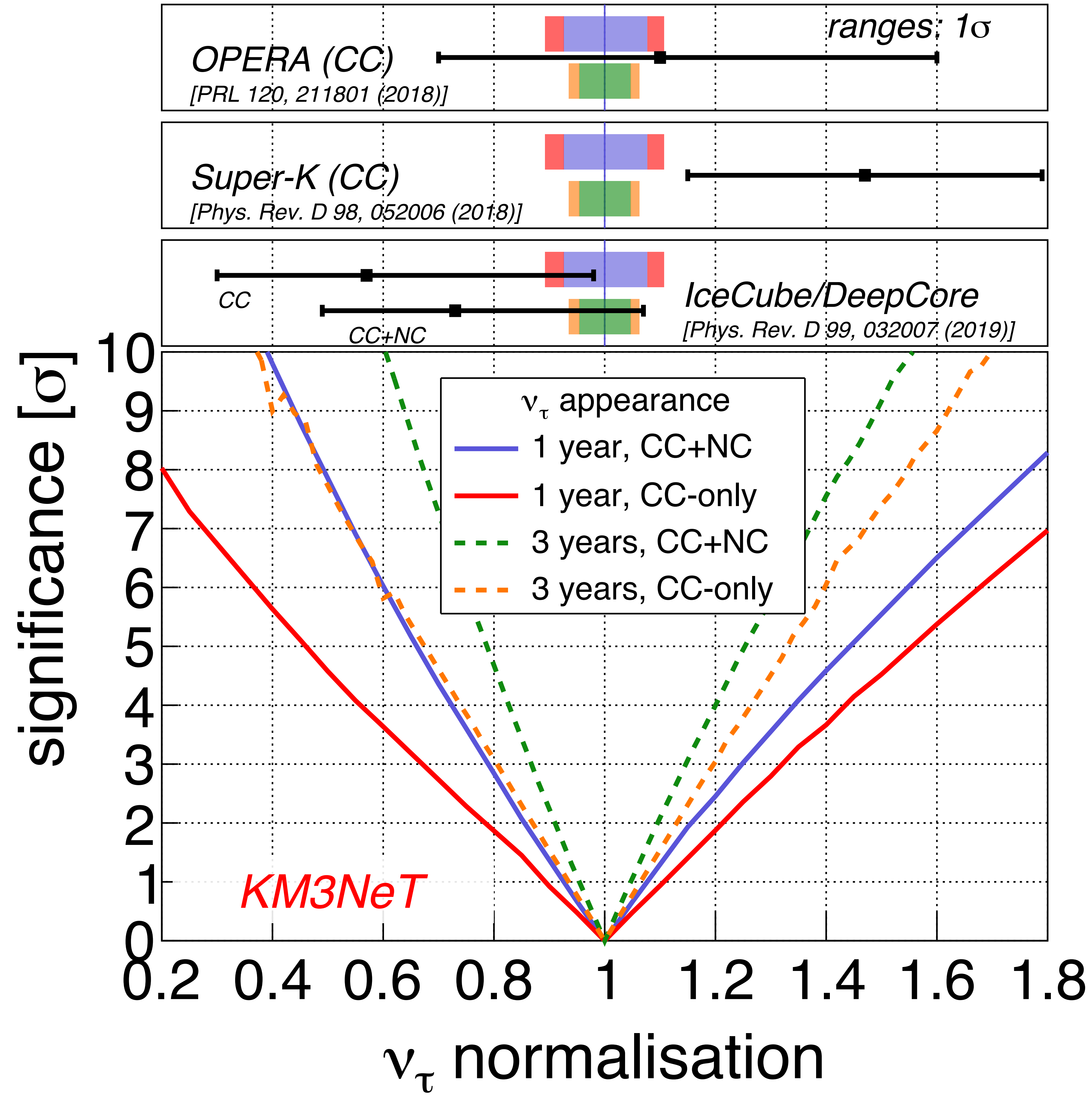


KM3NeT Collaboration, [arxiv: 2103.09885]

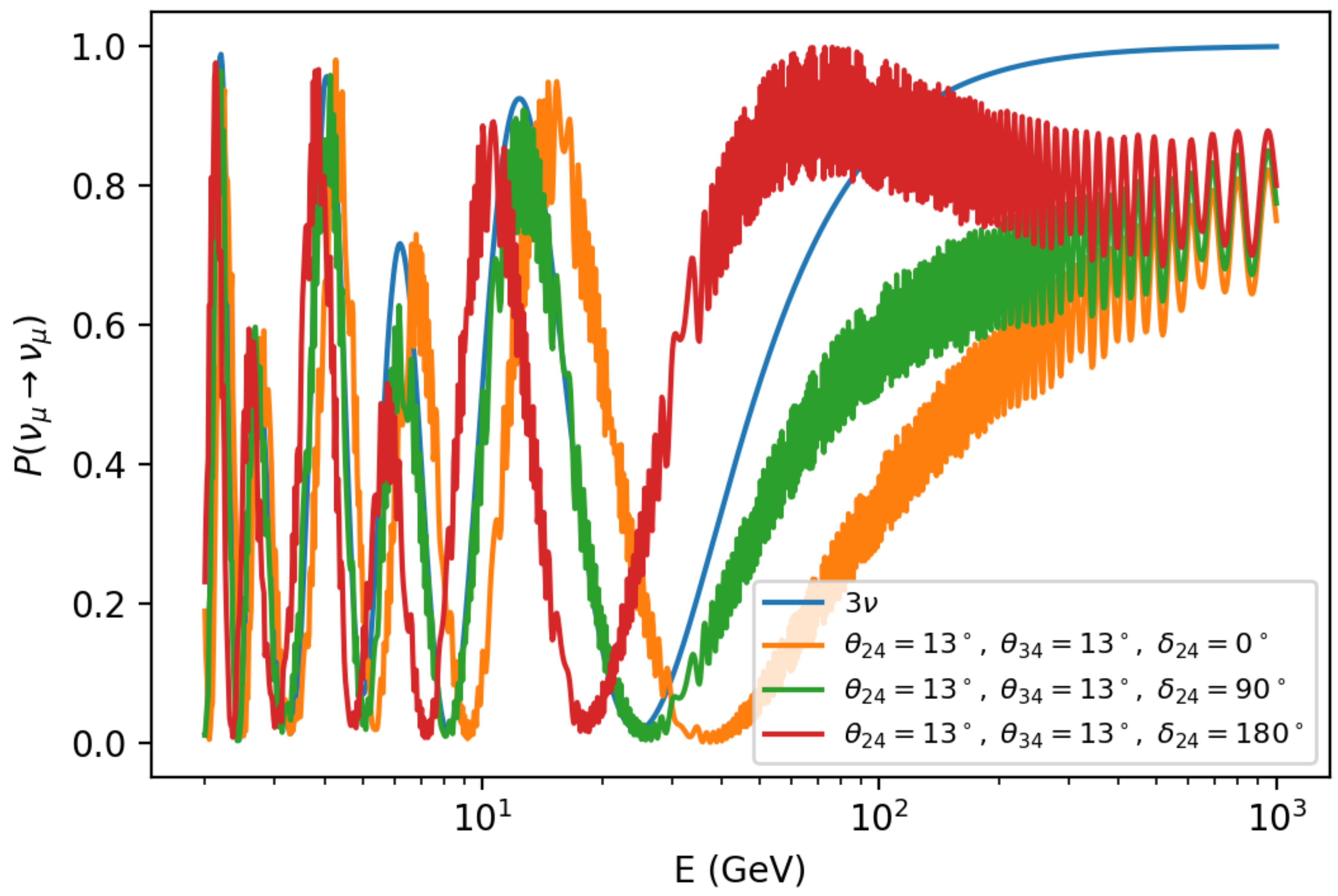
What physics could hide in non-unitarity?

- one possible explanation: sterile neutrinos!

- no weak interaction, invisible to detector!
- mass splitting $\Delta m_{41}^2 \approx \mathcal{O}(1\,\mathrm{eV}^2)$ hinted by anomalies in other experiments
- additional flavor state ν_s and additional mass state ν_4

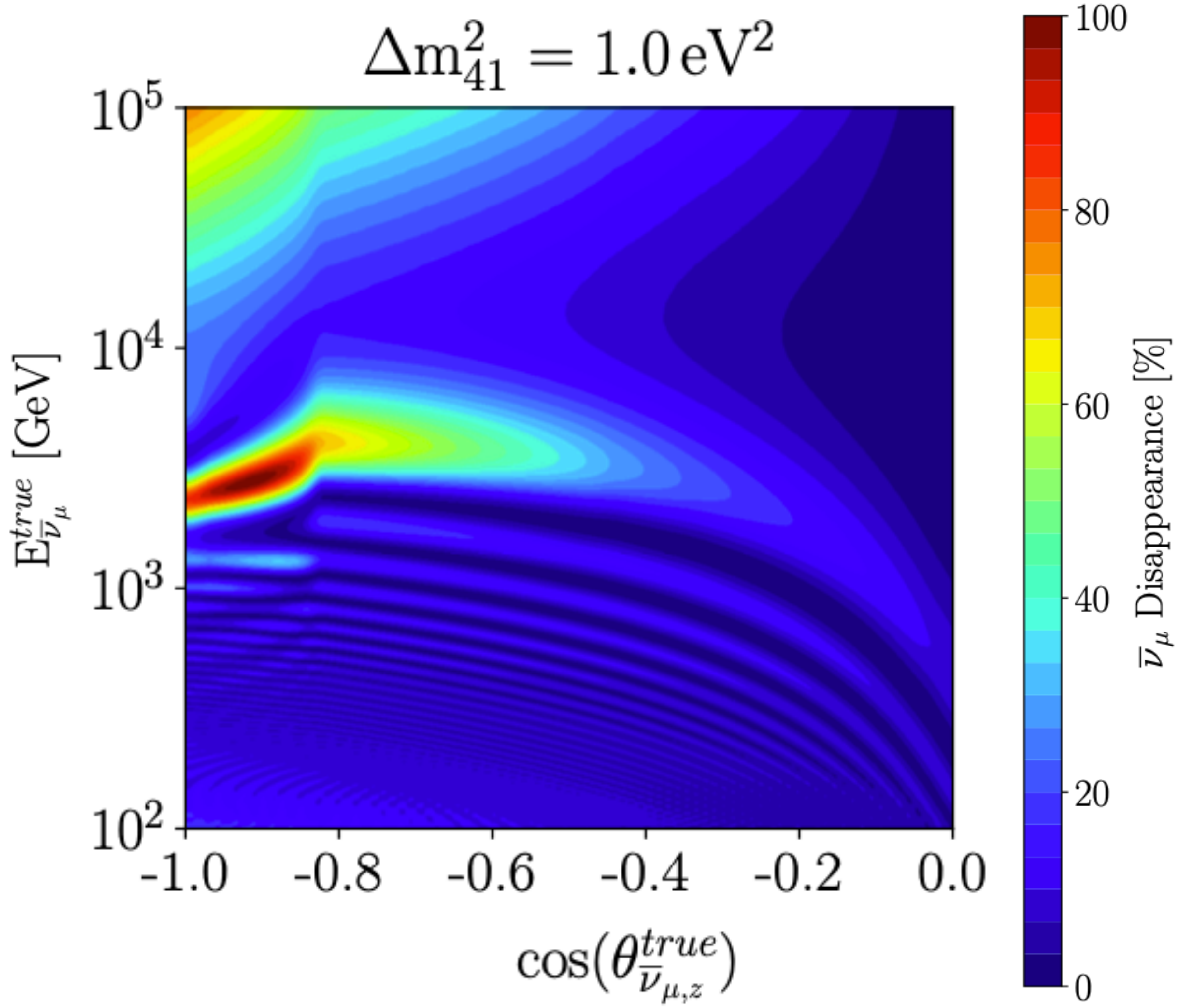
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} = R_{34}(\theta_{34})\tilde{R}_{24}(\theta_{24},\delta_{24})\tilde{R}_{14}(\theta_{14},\delta_{14})R_{23}(\theta_{23})\tilde{R}_{13}(\theta_{13},\delta_{13})R_{12}(\theta_{12})$$

3 new mixing angles, 2 new CP phases

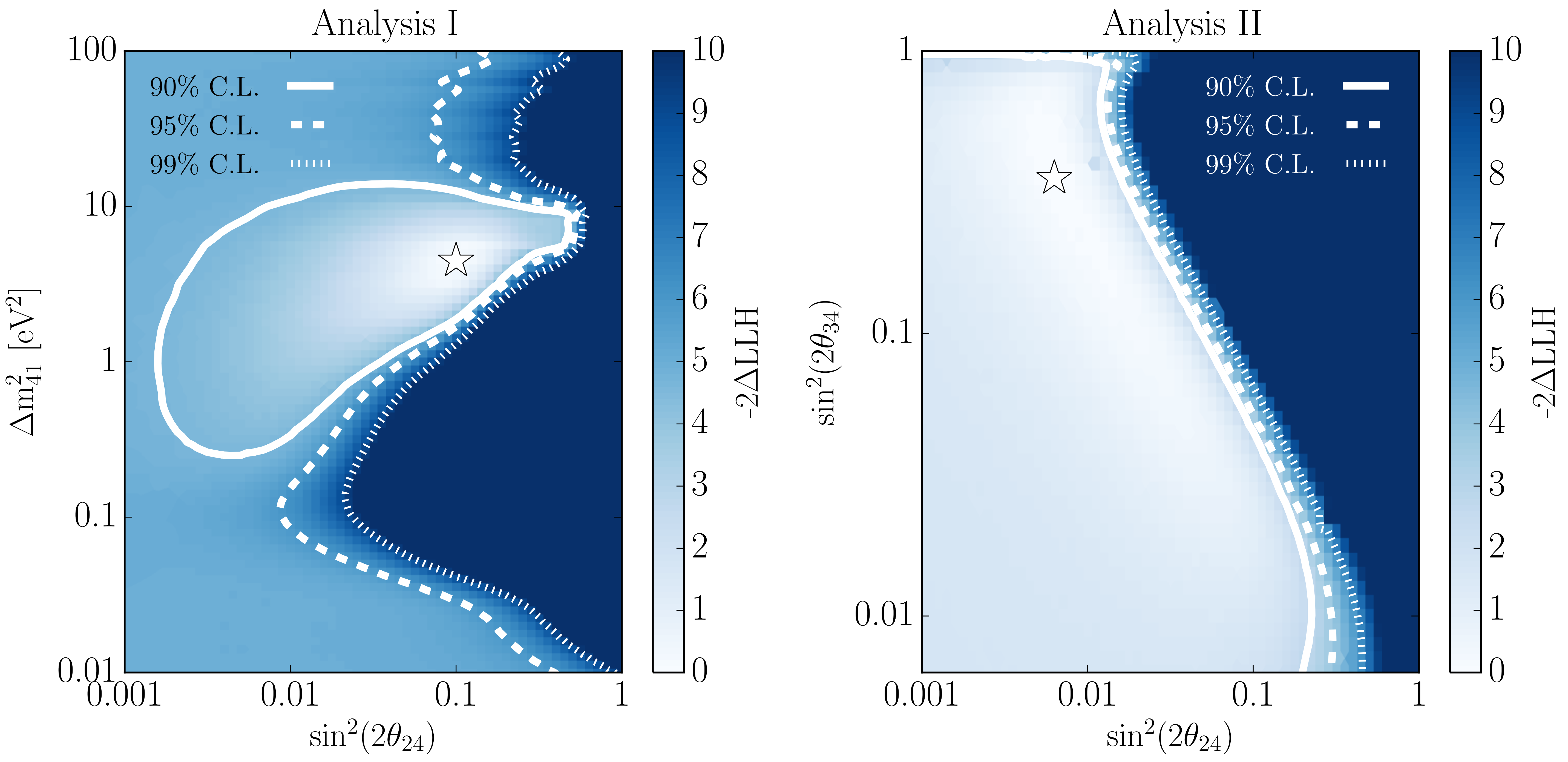


Sterile neutrinos at high and low energies

"High" energies: 500 GeV - 10 TeV



IceCube Collaboration, 2020, arXiv:2005.12943

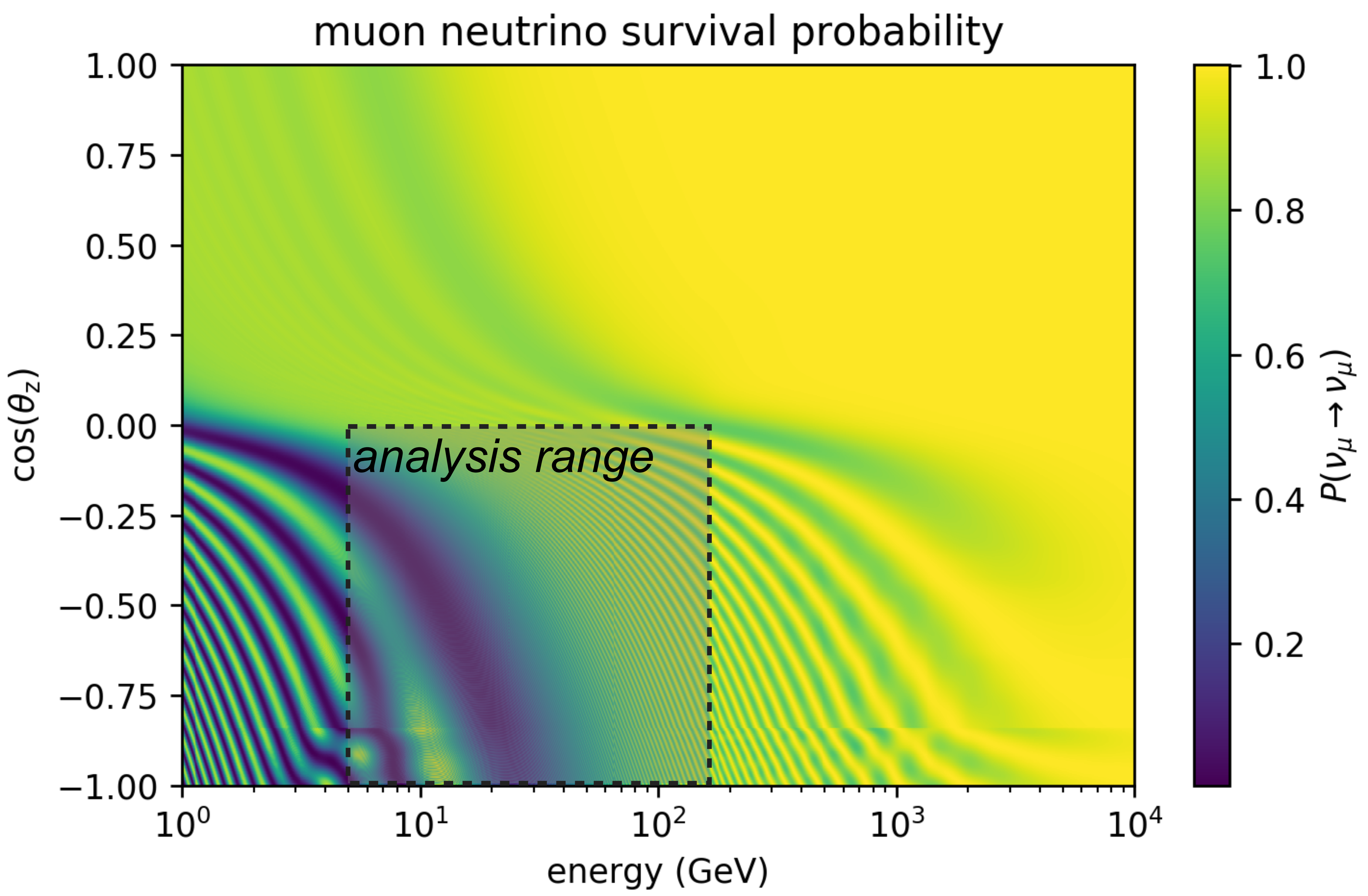


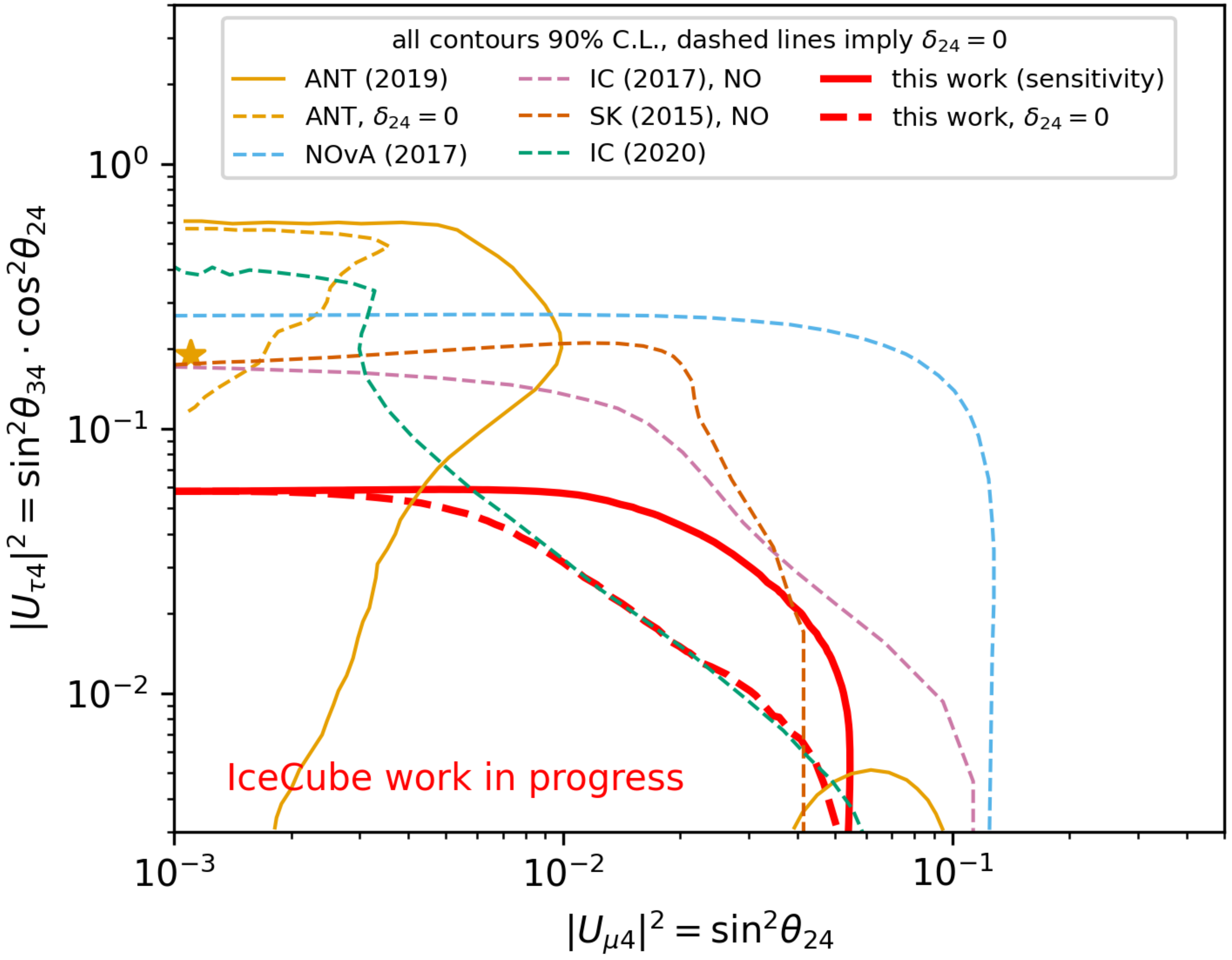
> Earth's core greatly enhances oscillation probability into eV-scale sterile antineutrinos (MSW resonance condition)

> sterile neutrino signature: deficit of $\bar{\nu}_\mu$ between 1 and 10 TeV

Sterile neutrinos at high and low energies

“Low” energies: 5 - 150 GeV





Projected sensitivity of sterile search with 8 years of DeepCore data

- very fast, unresolvable oscillations + distortion
- IceCube: World-leading limits on $|U_{\tau 4}|^2$ and $|U_{\mu 4}|^2$!

Non-Standard Interactions (NSI)

> ν interaction via new heavy mediator

> NC forward scattering of all flavors → effective potential

in flavor basis

$$H_{\mathrm{mat}} = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1 + \overbrace{(\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu})}^{\epsilon_{\oplus}} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & (\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu}) \end{pmatrix}$$

flavor-changing interactions

breaking of lepton-universality

> mostly model independent

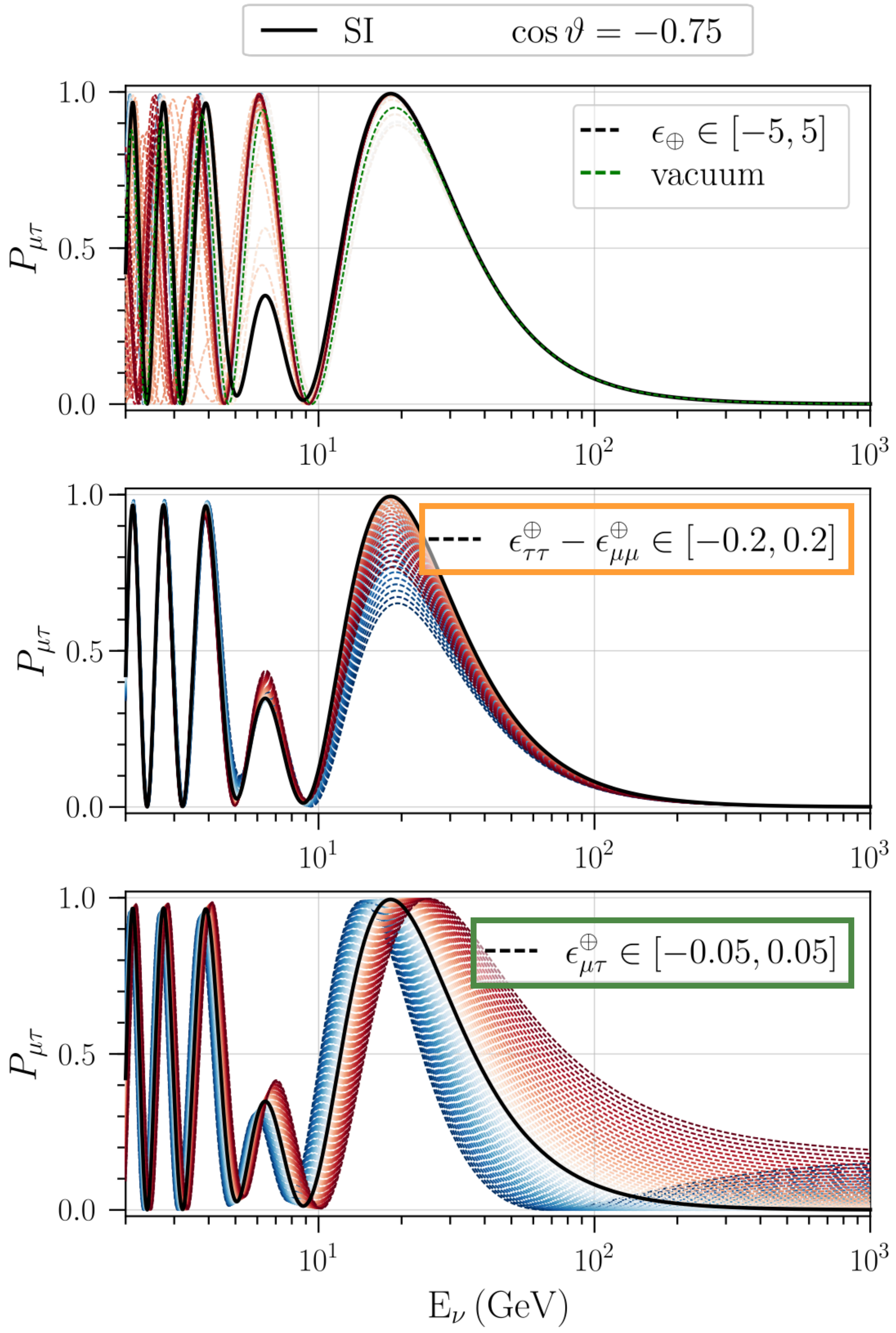
> possible explanation for known tensions between NOνA and T2K[1]

> atmospheric neutrinos:

  > highest sensitivity to $\epsilon^{\oplus}_{\mu\tau}$ at energies > 100 GeV

  > sensitivity to $\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu}$ (and other parameters) at energies < 100 GeV

IceCube Collaboration, 2021, arXiv:2106.07755



[1]Chatterjee & Palazzo, 2020, arXiv:2008.04161

Latest DeepCore NSI Result

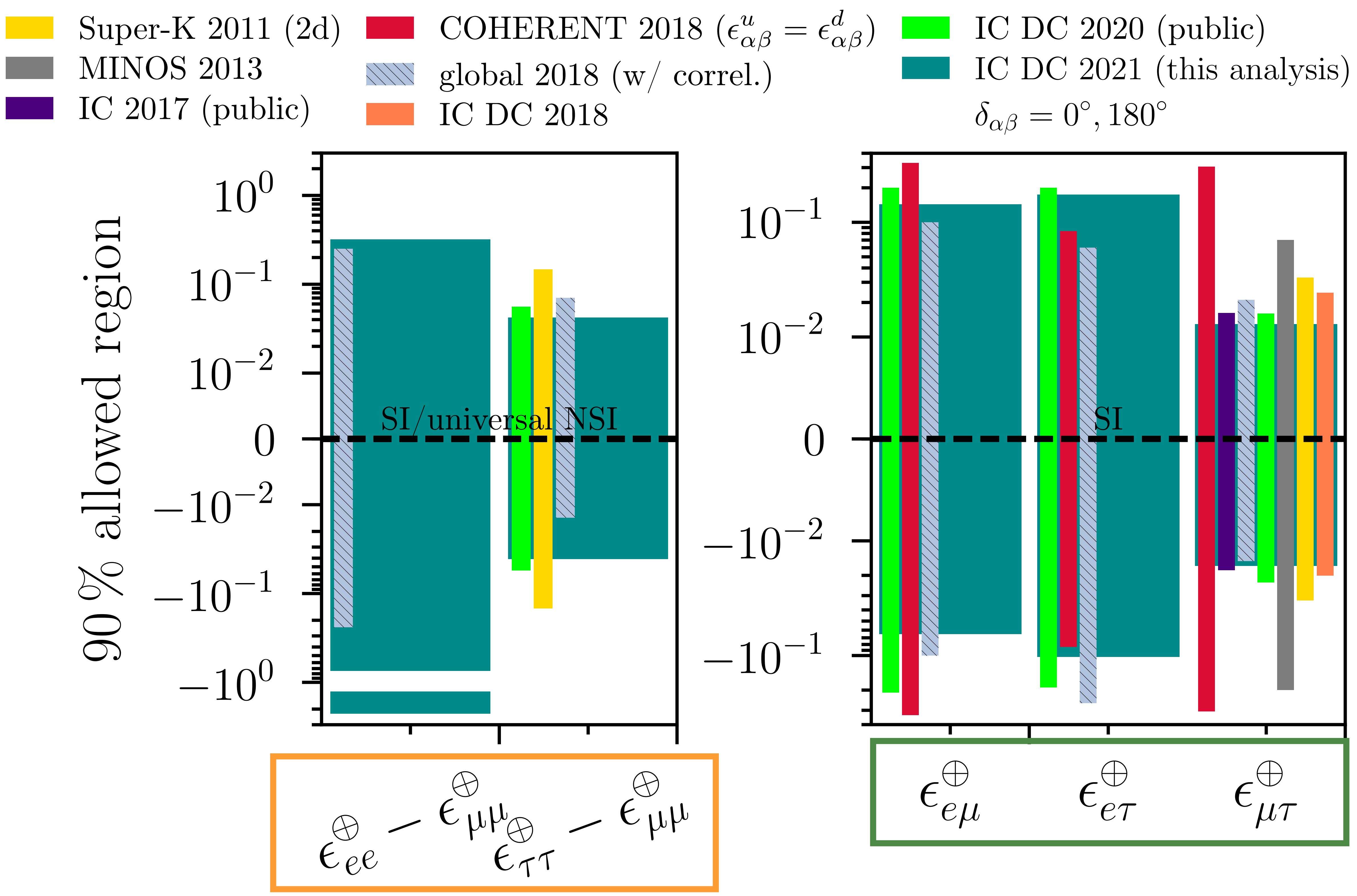
- 3 years of data
- energy range: 5.6 - 100 GeV

flavor-changing interactions

$$\begin{pmatrix} 1 + (\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}) & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & (\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu}) \end{pmatrix}$$

breaking of lepton-universality

- first analysis to constrain all NSI parameters simultaneously

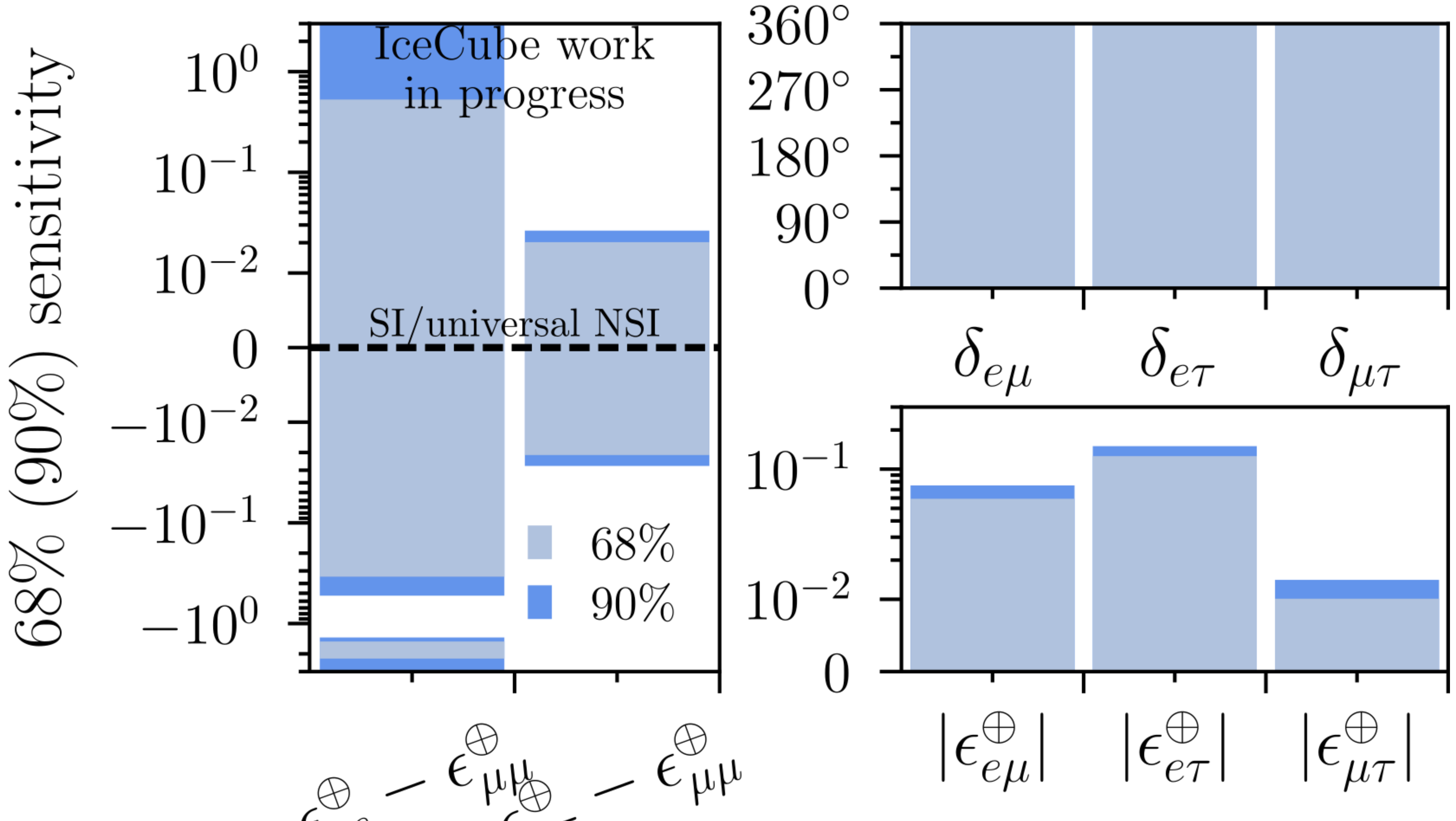


IceCube Collaboration, 2021, arXiv:2106.07755

- assumption: all $\epsilon^{\oplus}_{\alpha\beta}$ are real ($\delta_{\alpha\beta} = 0°, 180°$)

Upcoming IceCube NSI Analyses

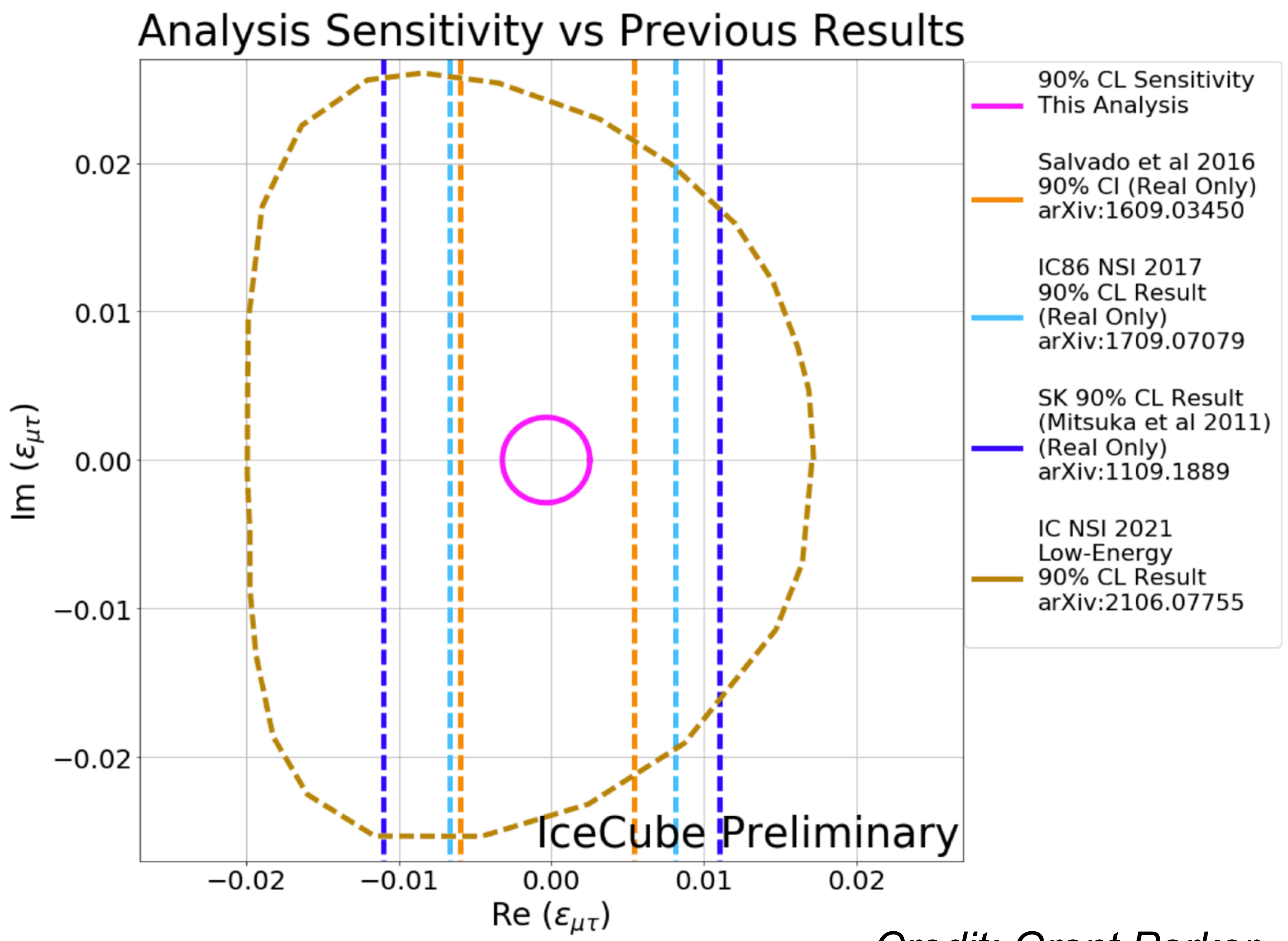
“Low” Energies: 5 - 150 GeV



Credit: Elisa Lohfink

- expected sensitivity: $|\epsilon^{\oplus}_{\mu\tau}| < 1.4 \times 10^{-2}$
- ORCA 3 yrs: $-1.7 \times 10^{-3} < \epsilon^{\oplus}_{\mu\tau} < 1.7 \times 10^{-3}$

“High” Energies: 500 GeV - 10 TeV



Credit: Grant Parker

- same sample as the [high-energy sterile search]
- fit real and imaginary part of $\epsilon^{\oplus}_{\mu\tau}$

Summary & Outlook

- IceCube and KM3NeT are extremely versatile instruments
- atmospheric neutrinos allow precision measurements of $P(\nu_\mu \rightarrow \nu_\mu)$
- matter + long baseline allow probing of several phenomena beyond the Standard Model
- DeepCore keeps leading the field of atmospheric oscillation measurements, closing in on accelerator sensitivity
- construction of ORCA and IceCube Upgrade to greatly increase sensitivity to GeV-scale oscillation phenomena

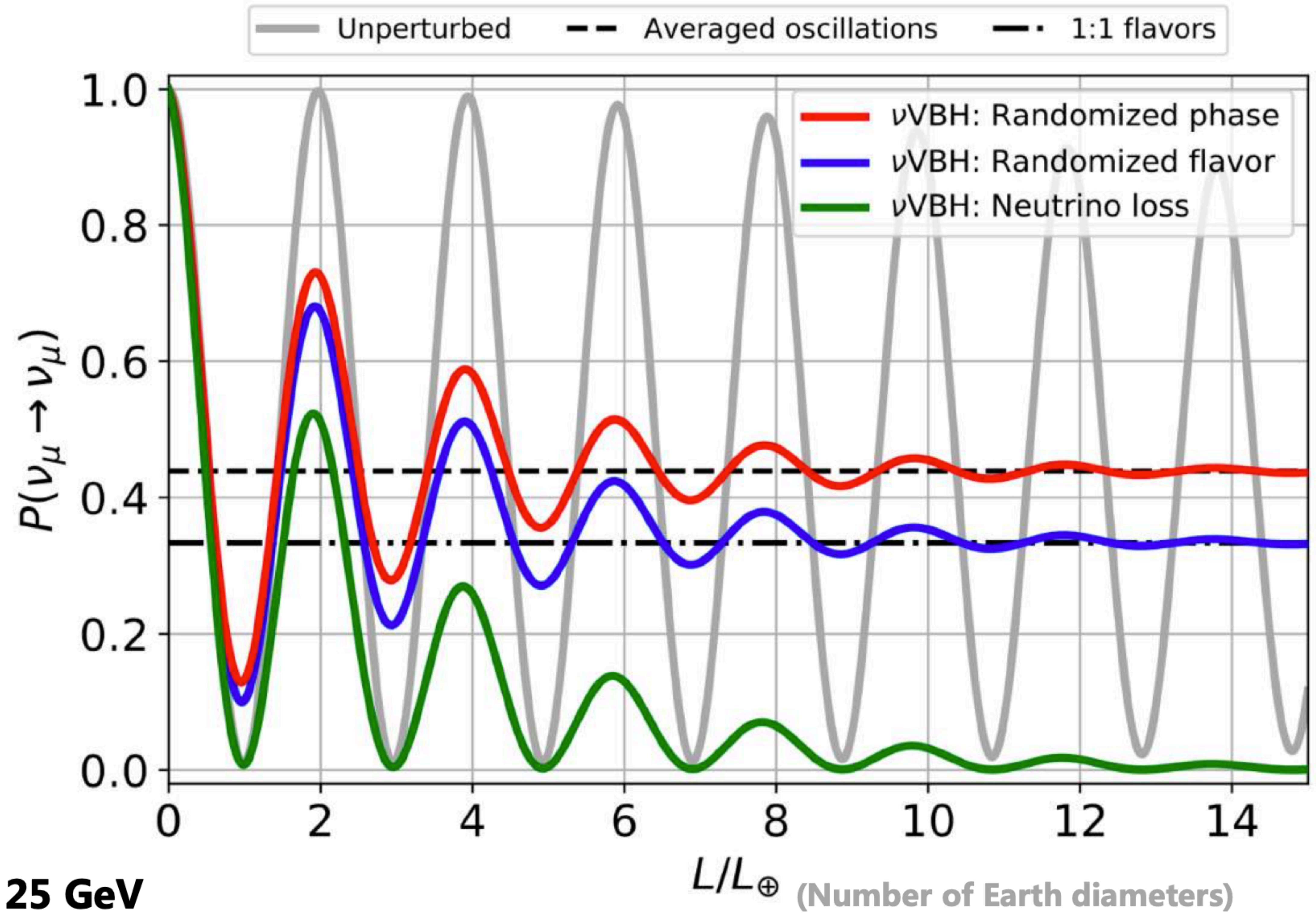
Backup

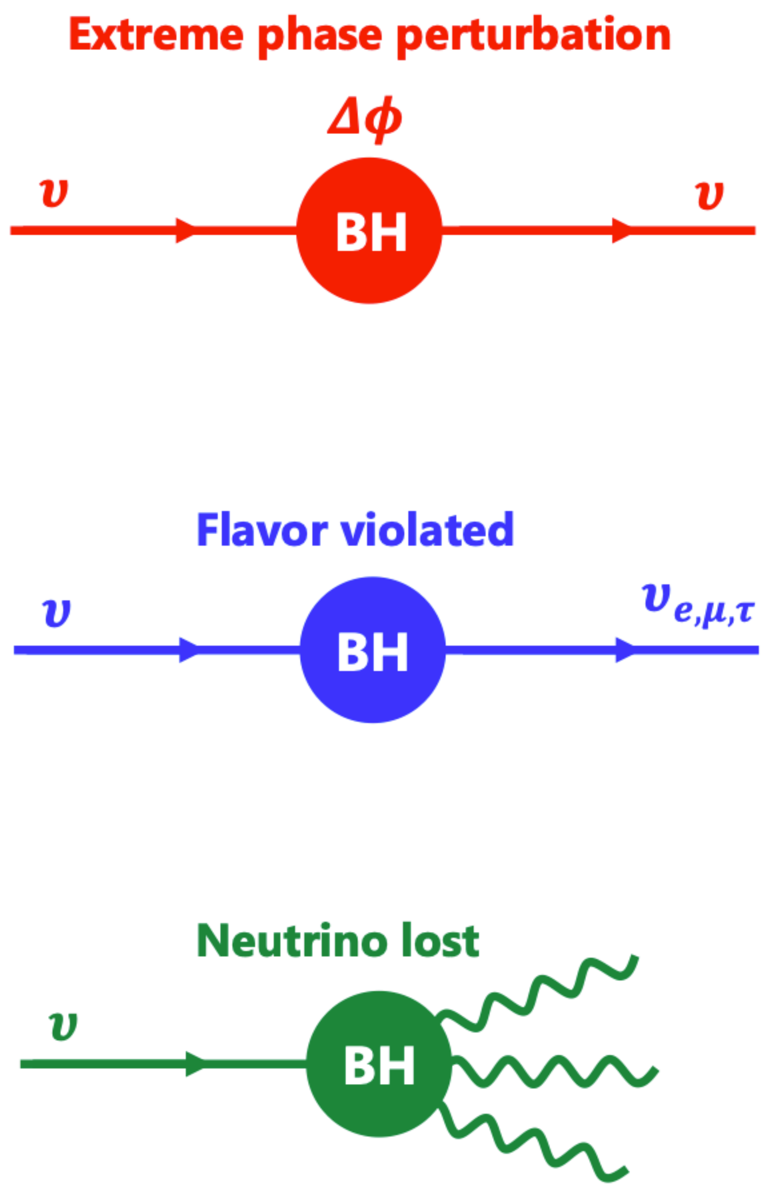
Neutrino Decoherence due to Virtual Black Holes

standard oscillations *decoherence* *decoherence length*

state density evolution: $\dot{\rho} = -i[H,\rho] - \mathscr{D}[\rho] \longrightarrow \frac{1}{\Gamma} \equiv L_{\mathrm{coh}}$

magnitude of elements of $\mathscr{D}$

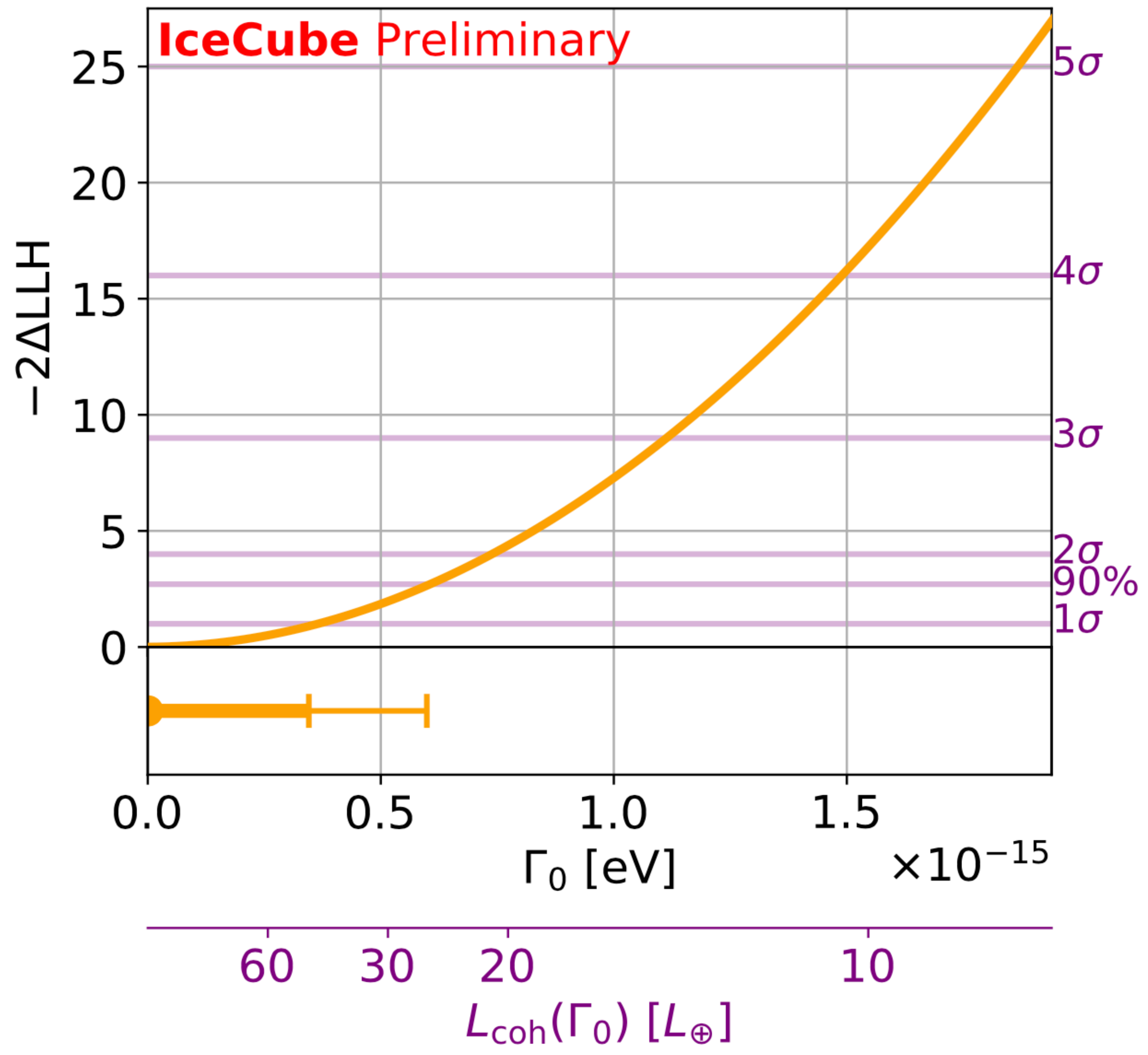




E = 25 GeV

Credit: Tom Stuttard

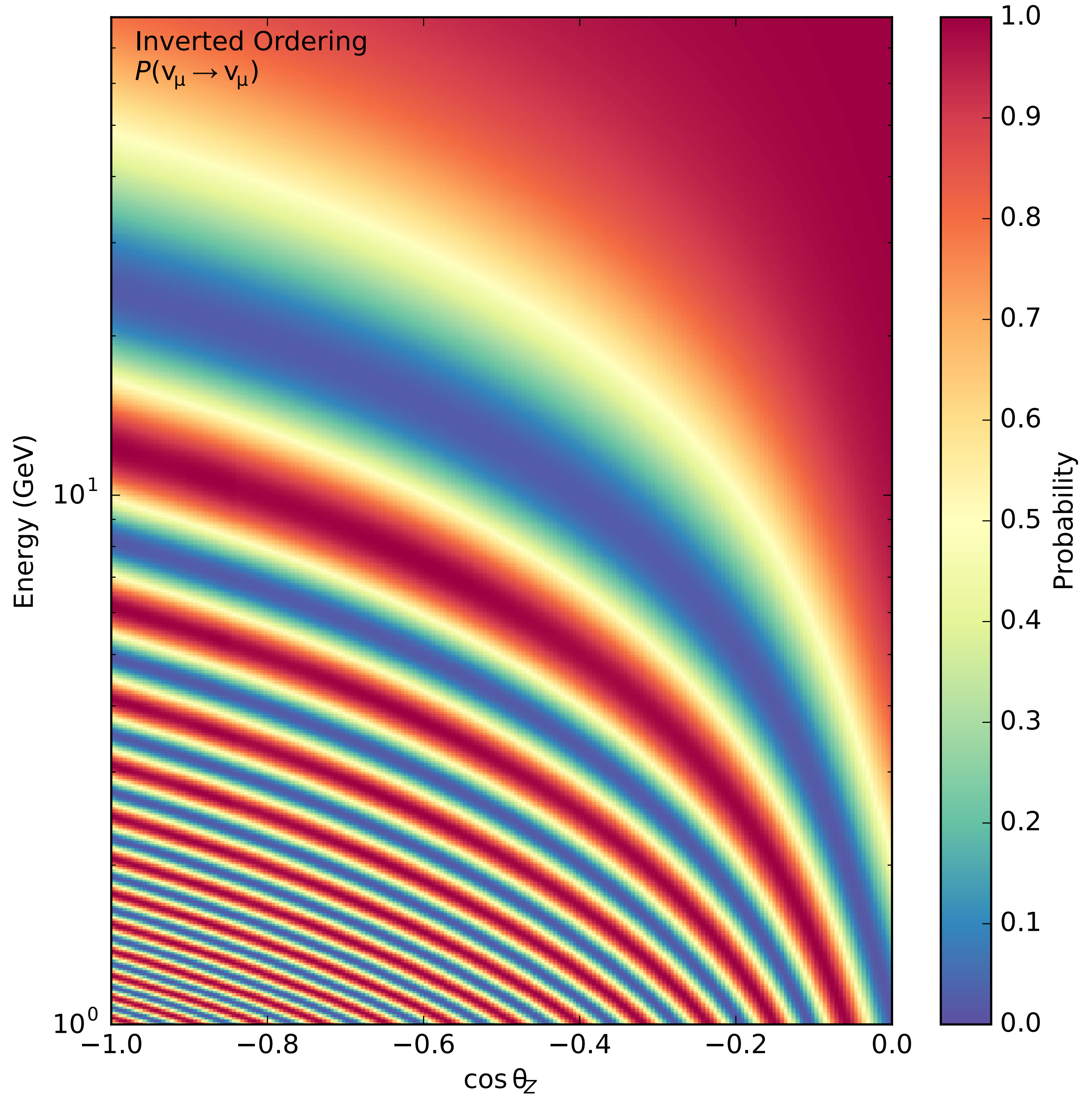
Sensitivity with 8 years of DeepCore

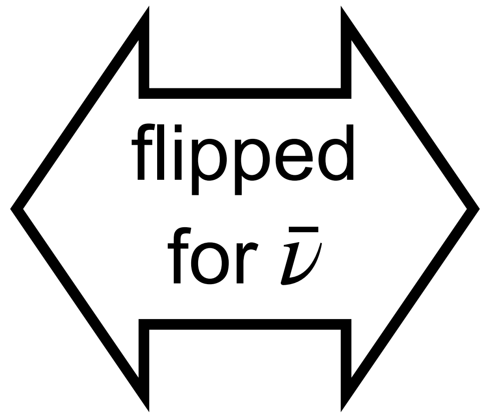


Stuttard & Jensen, 2020, arxiv:2007.00068

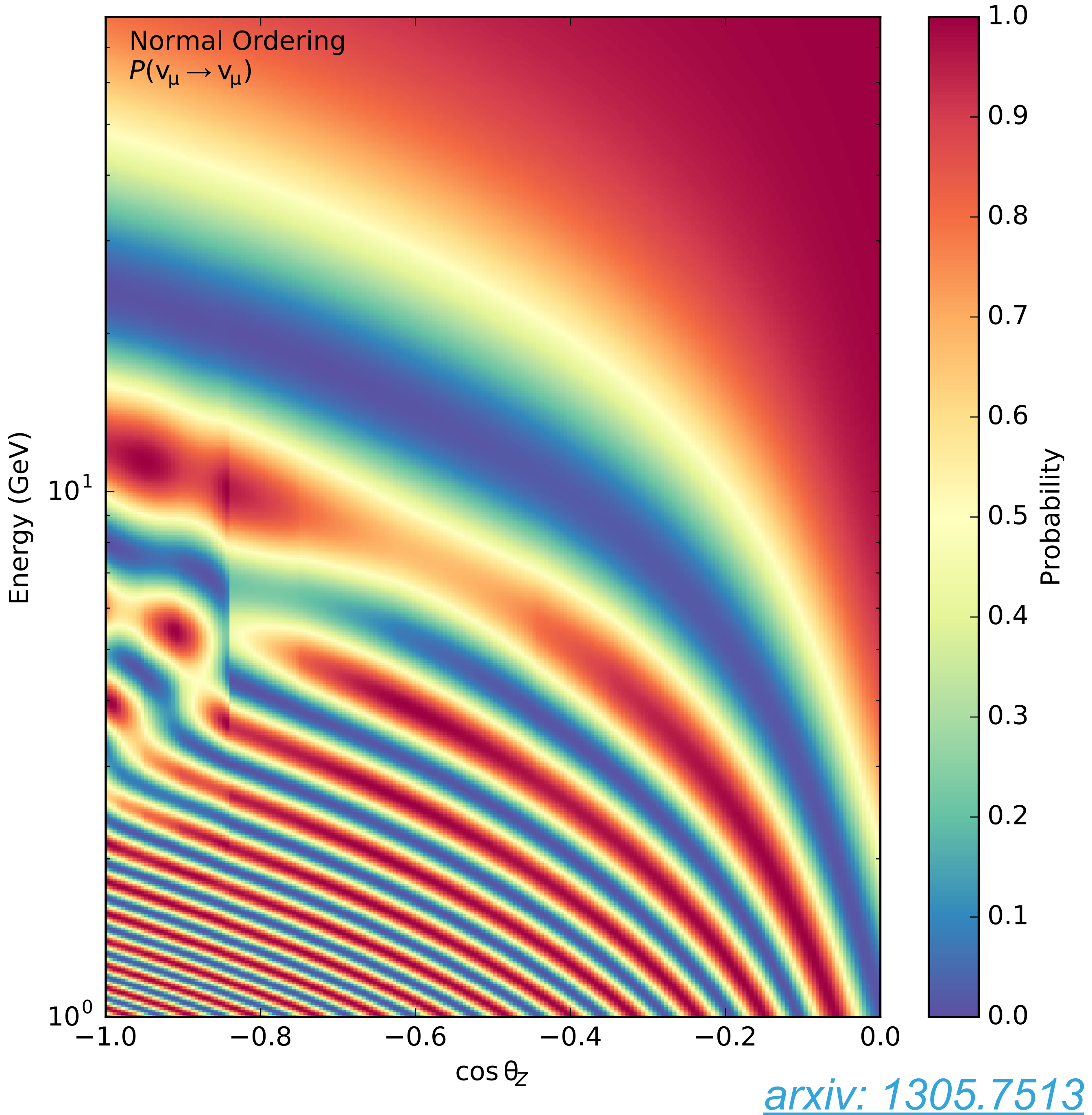
Neutrino Mass Ordering (NMO)

$P(\nu_\mu \to \nu_\mu)$, **inverted ordering**



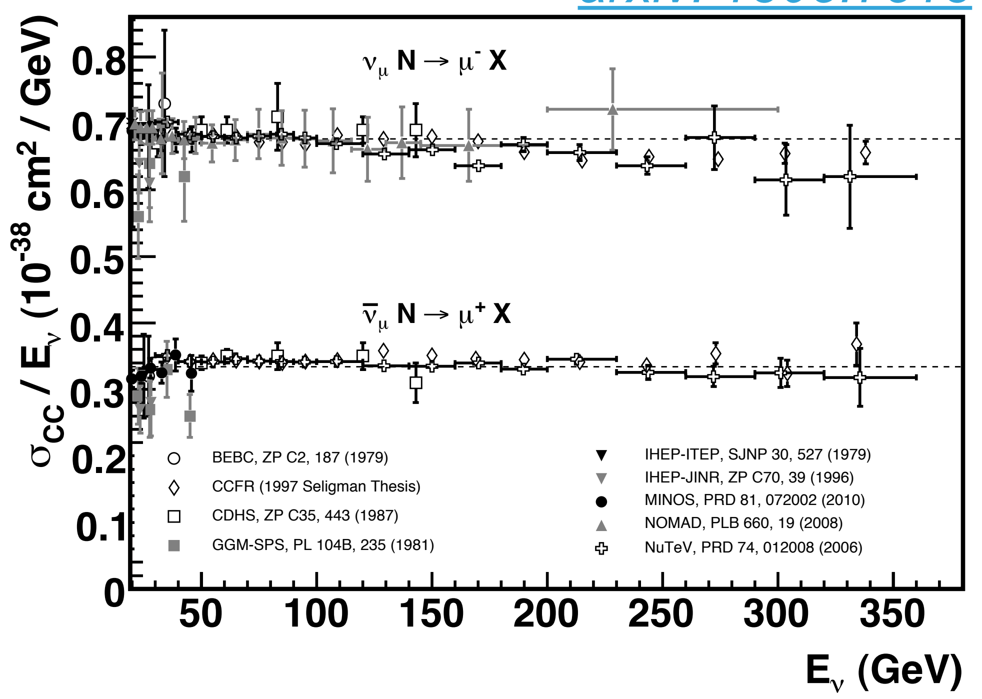


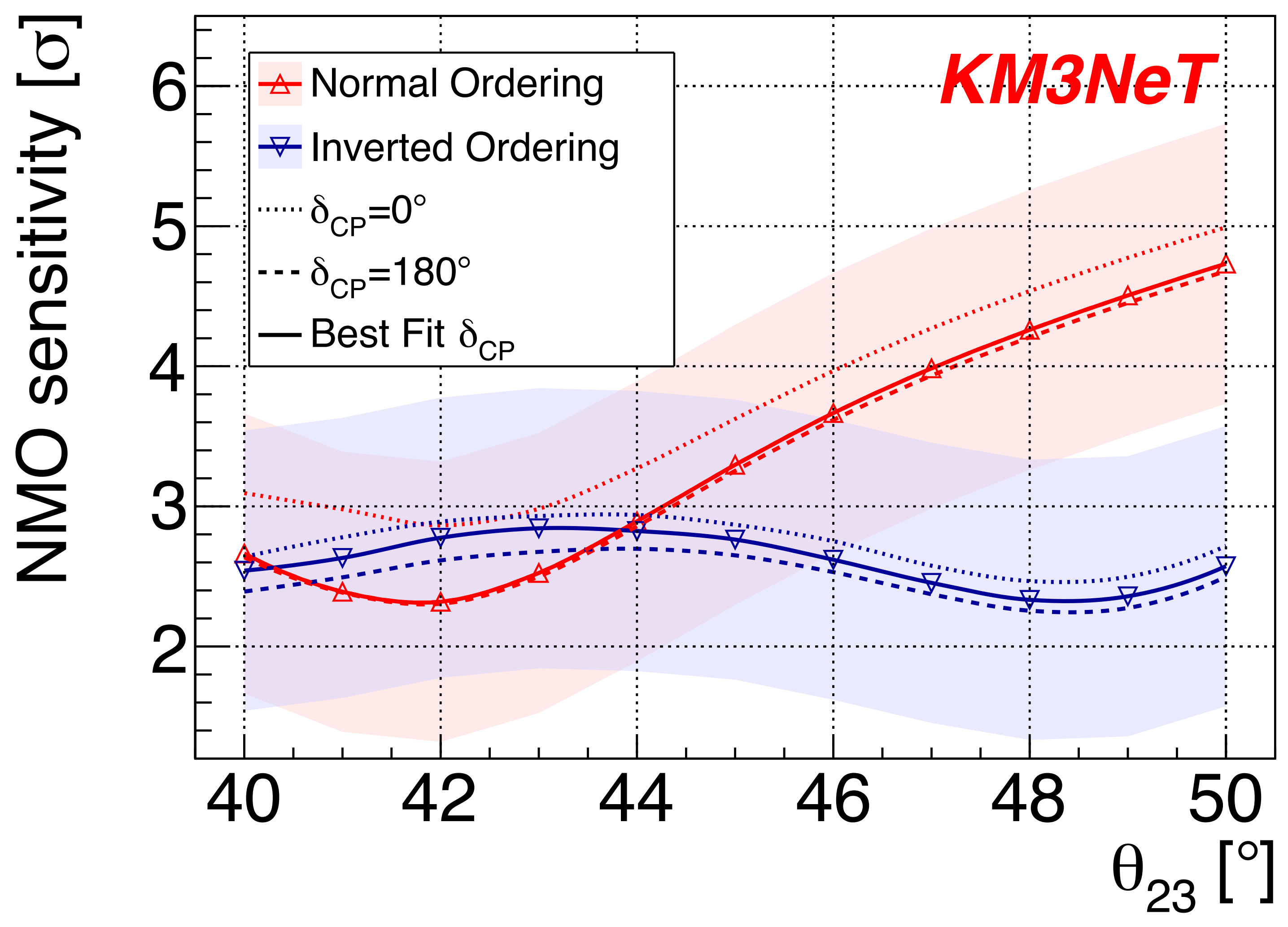
$P(\nu_\mu \to \nu_\mu)$, **normal ordering**

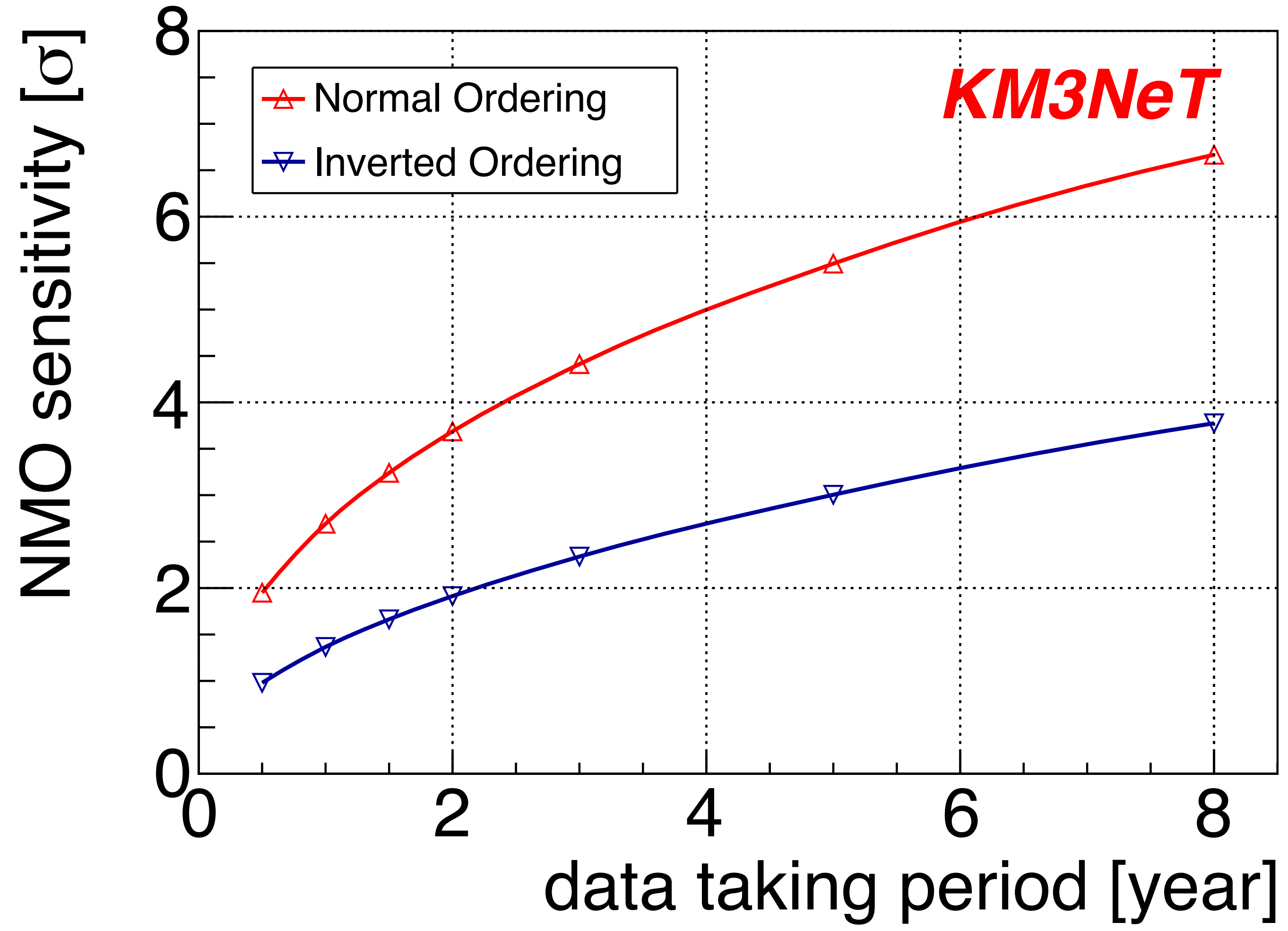


- matter-induced distortions for ν in NO, $\bar{\nu}$ in IO
- $\nu, \bar{\nu}$ indistinguishable to detector
  - ➡ effect on rates due to different cross-sections

arxiv: 1305.7513

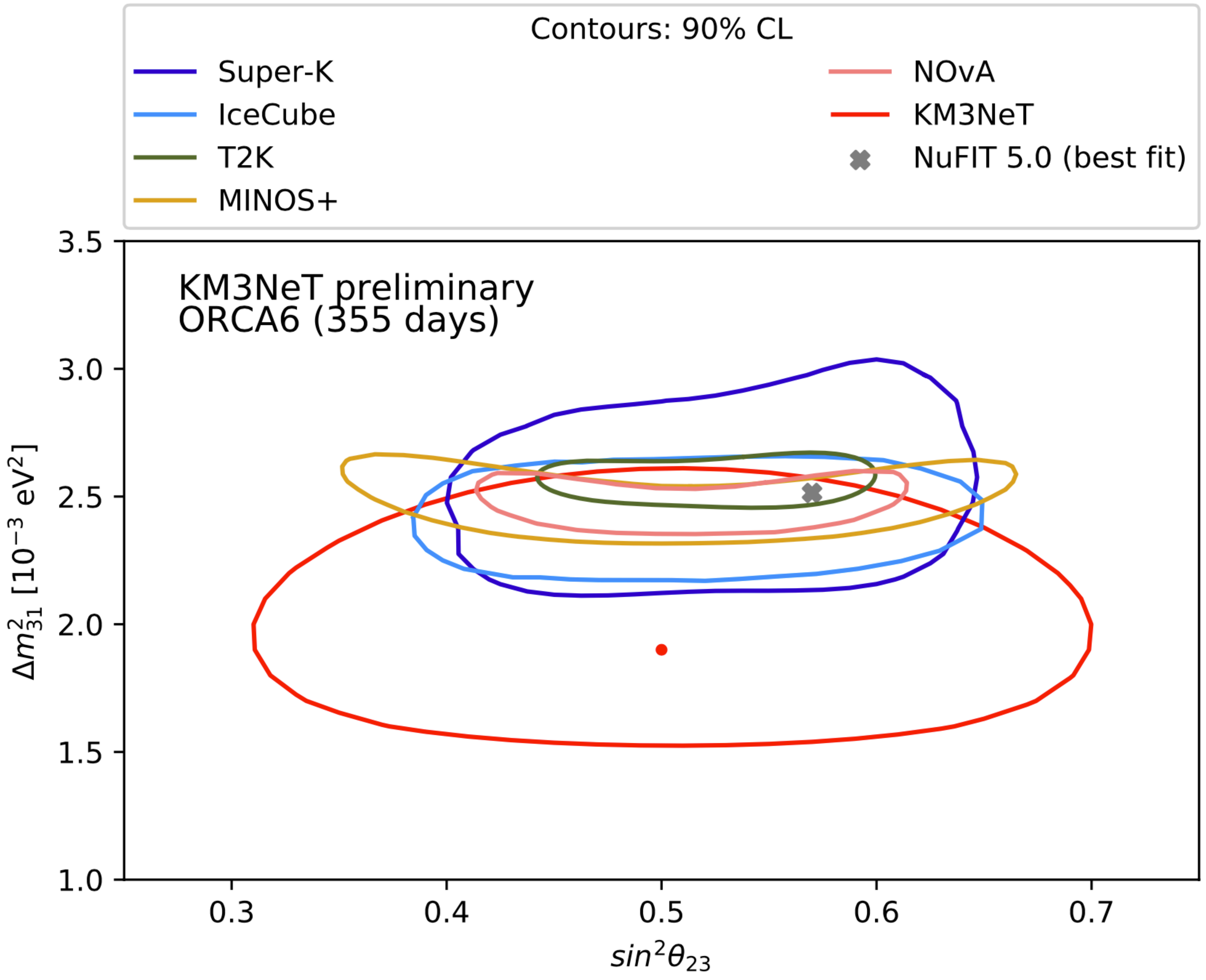






KM3NeT Collaboration, arxiv: 2103.09885

ORCA 6-String Oscillation Measurement



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