The Neutrino Kaleidoscope: Searches for Non-Standard Neutrino Oscillations at Neutrino Telescopes with a TeV Muon Accelerator Source

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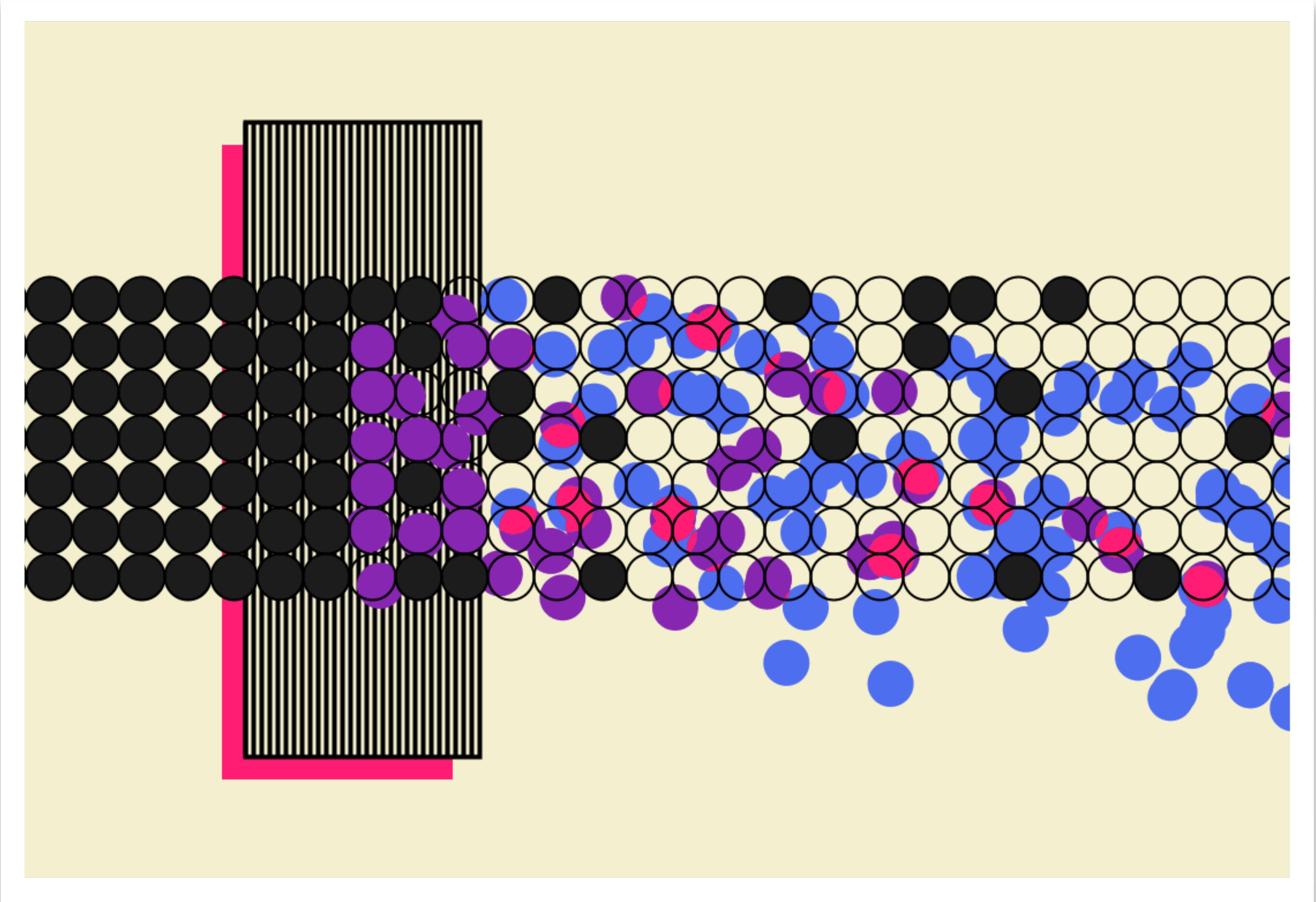

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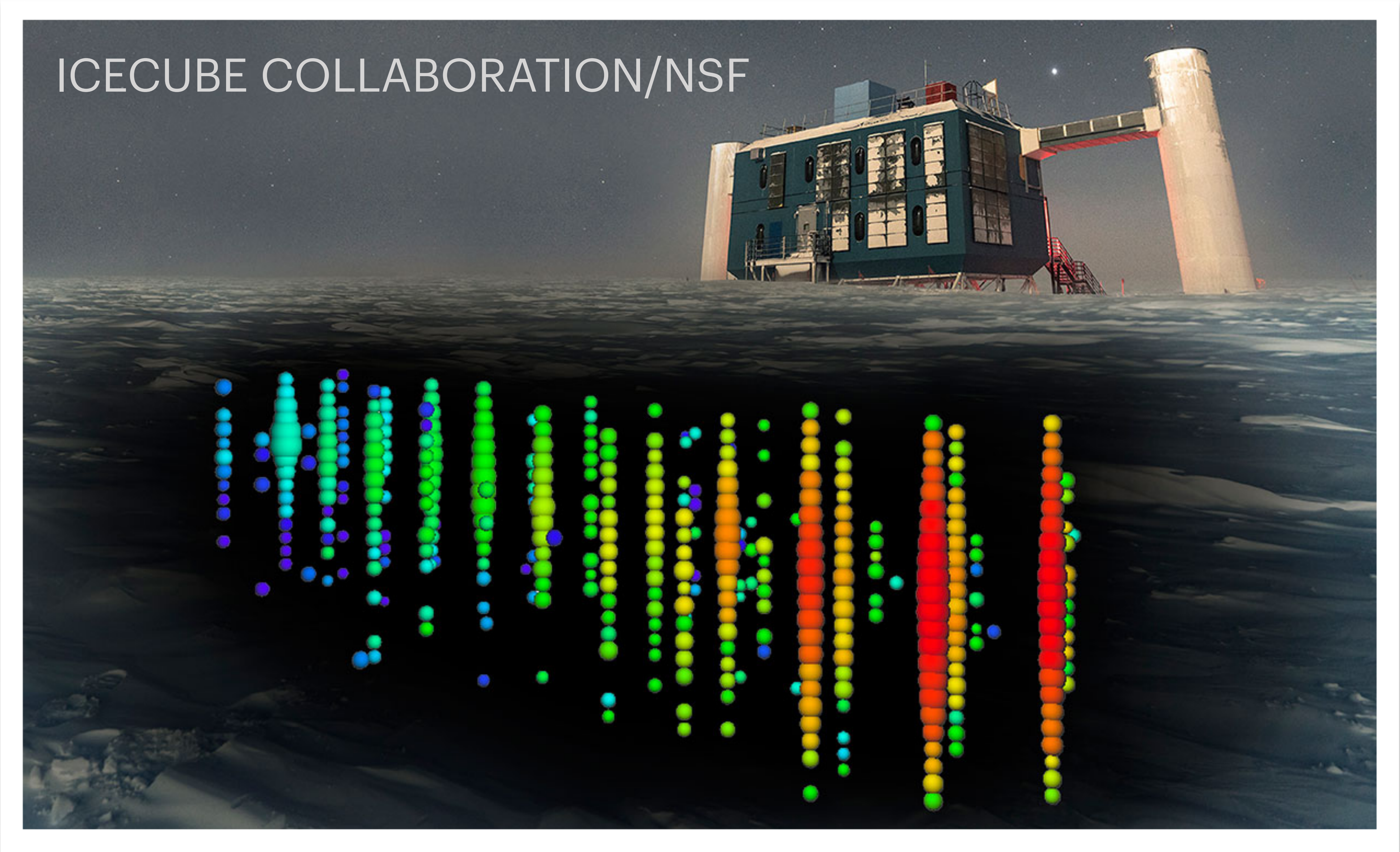
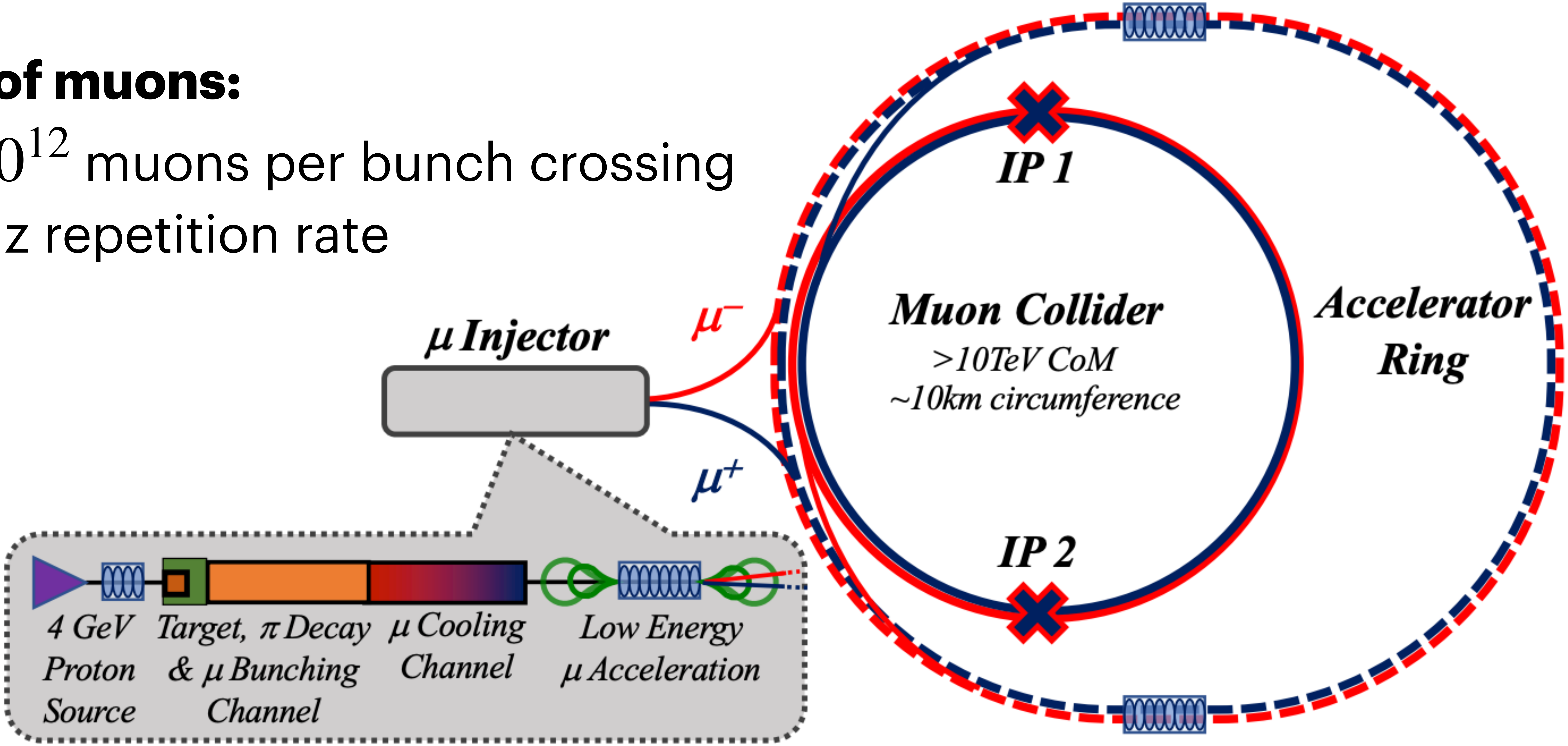


A “Typical” Muon Collider

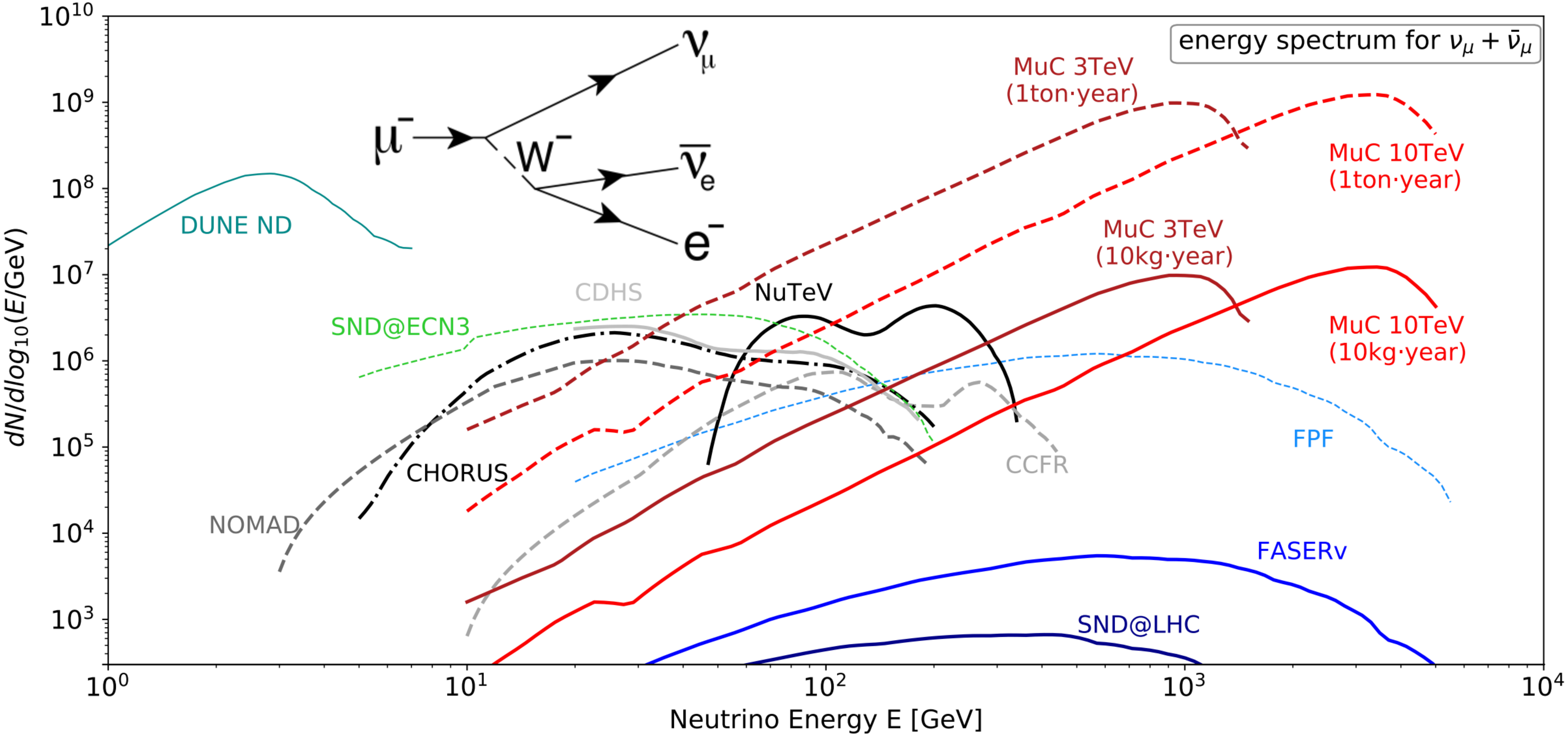
Lots of muons:

2×10^{12} muons per bunch crossing
@ 5 Hz repetition rate



Interim report for the International Muon Collider Collaboration, 2024

Muon Decay → Free Neutrino Beam

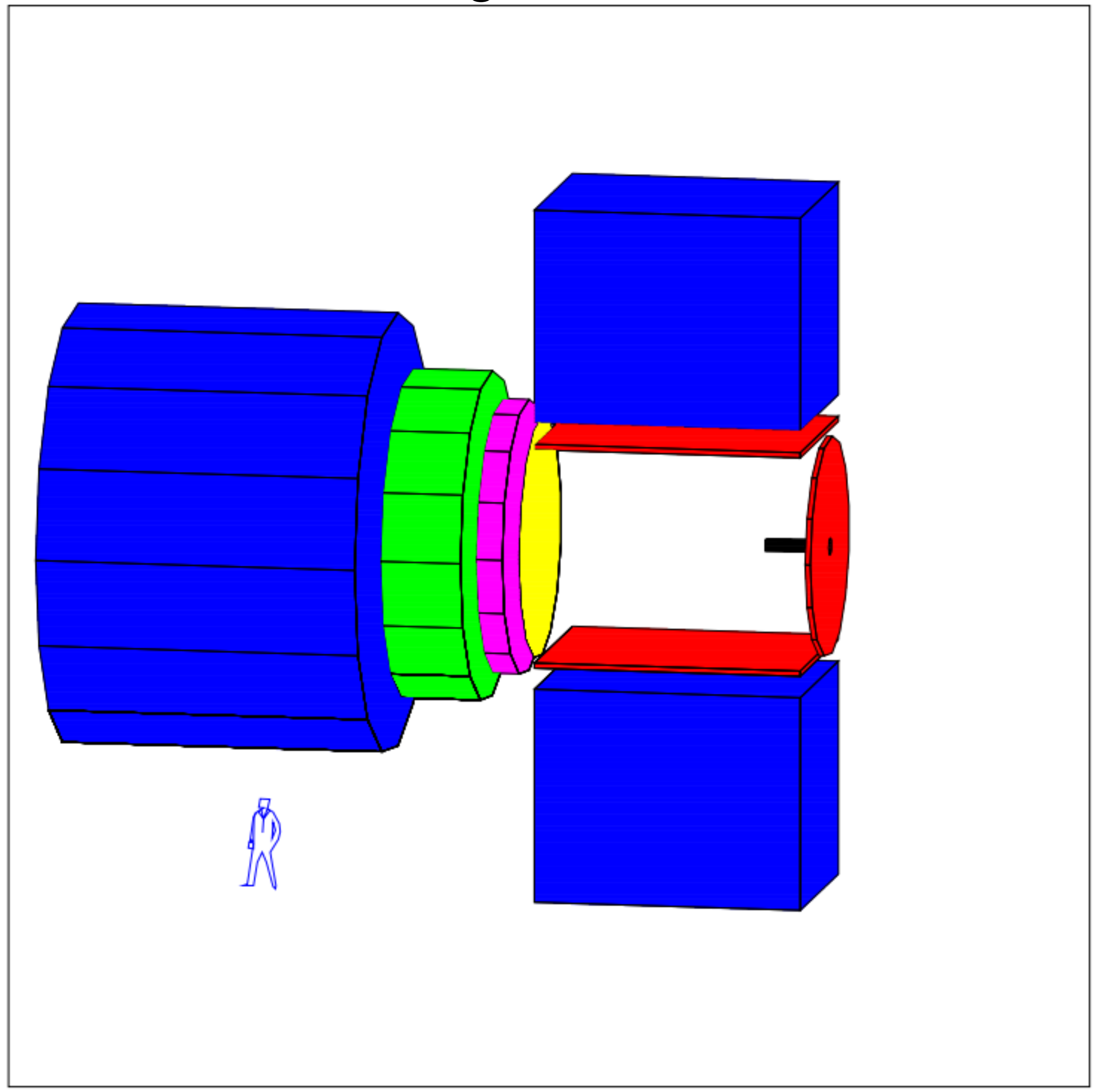


Interim report for the International Muon Collider Collaboration, 2024

Proposed Neutrino Detectors @ a Muon Collider

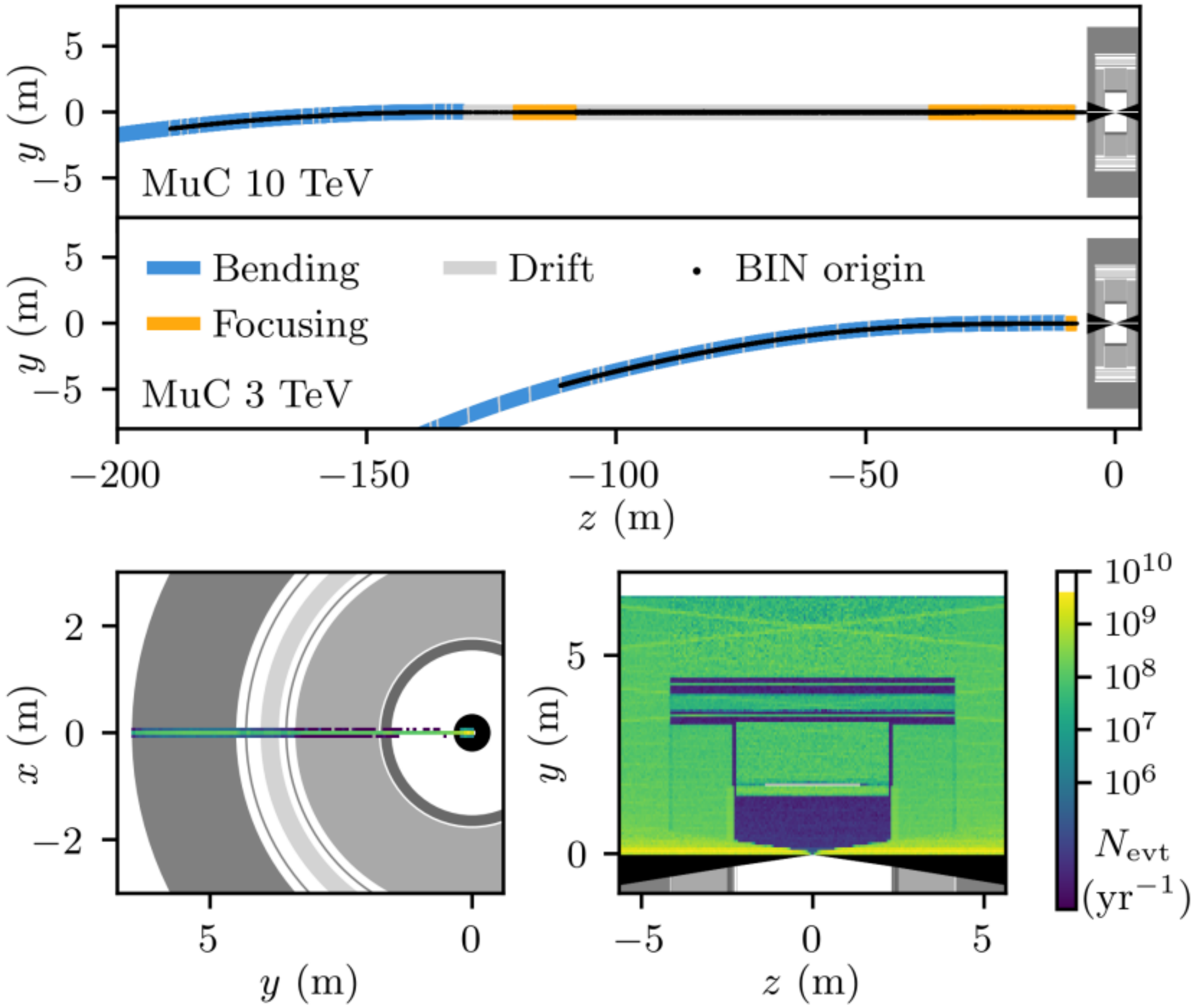
A "general purpose" detector

Bigi+ 2001



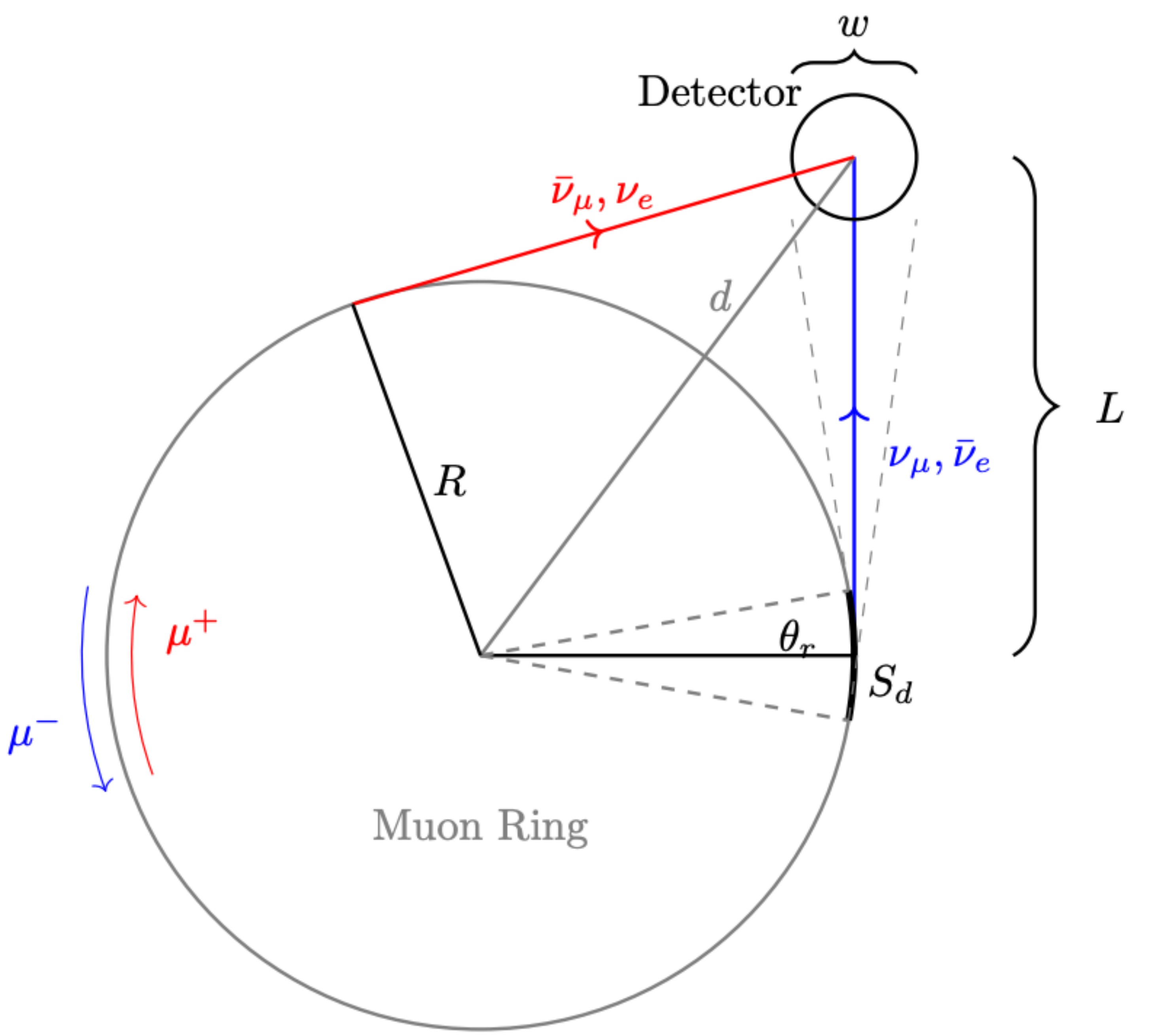
The "neutrino slice" at the interaction point

Bojorquez-Lopez+ 2024



A "hockey-puck" detector measuring both beams

de Gouvêa+ 2025



Rich physics program: cross sections, QCD, electroweak observables, and more

Introducing the “Neutrino Kaleidoscope”

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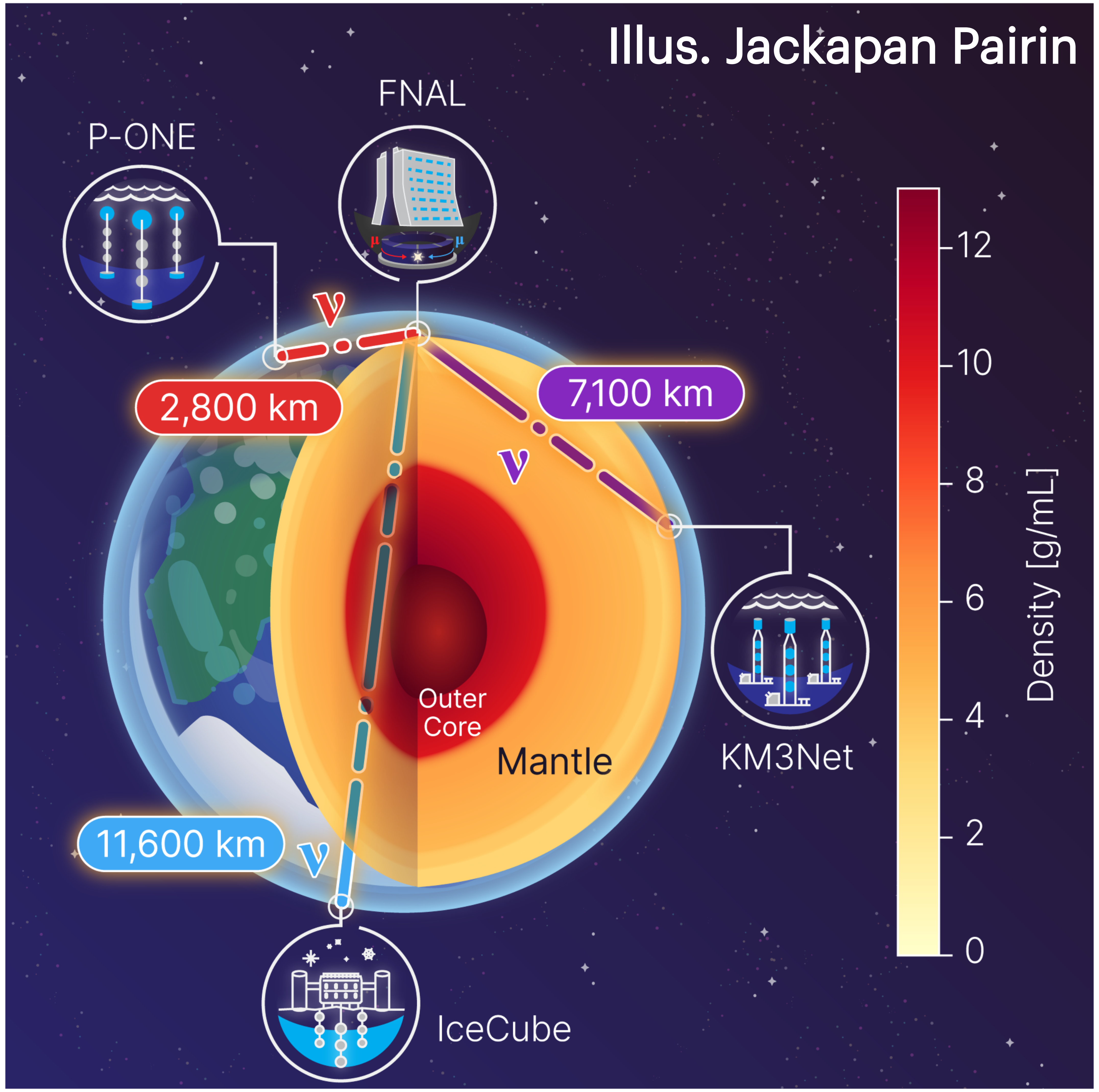
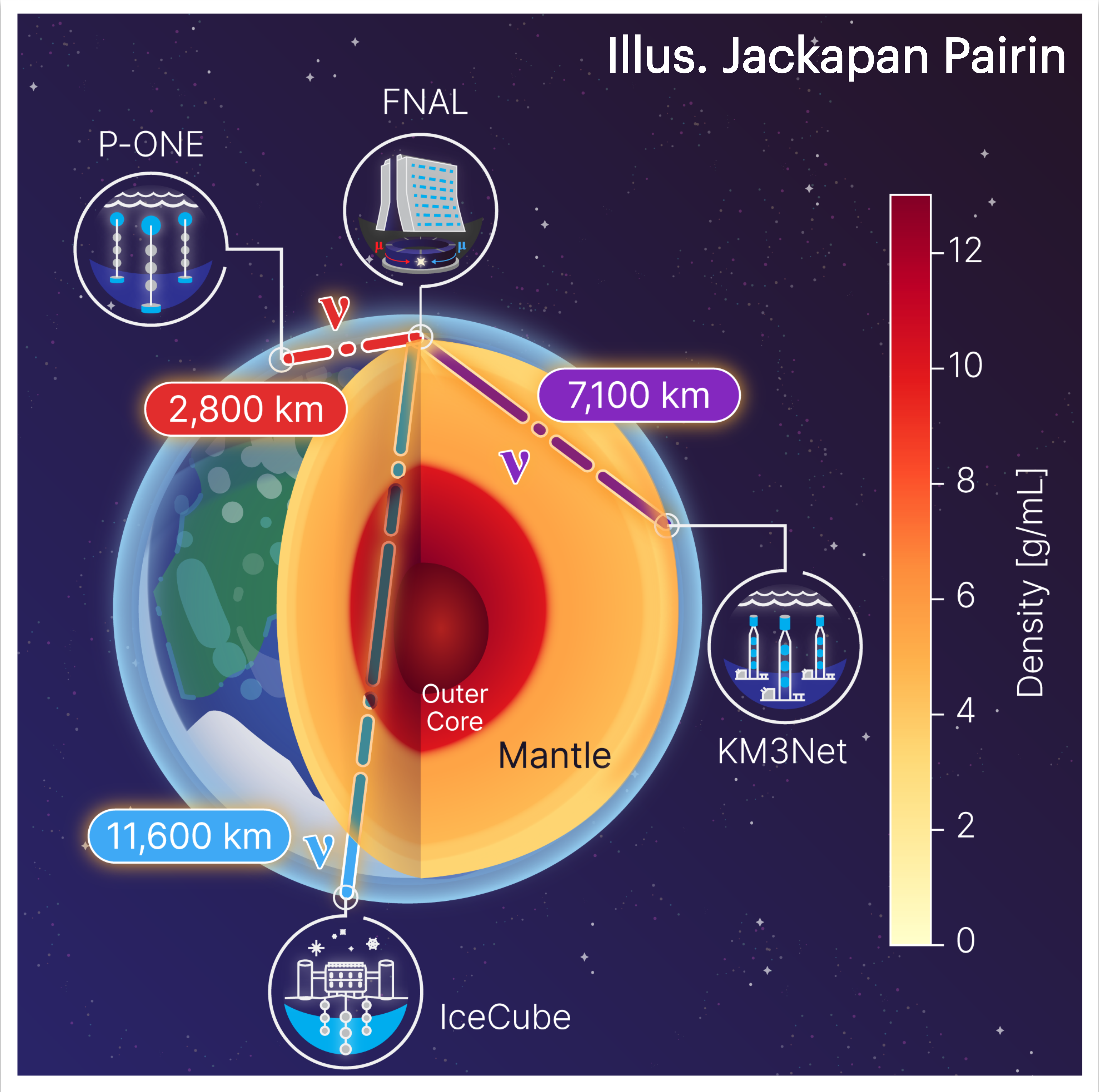
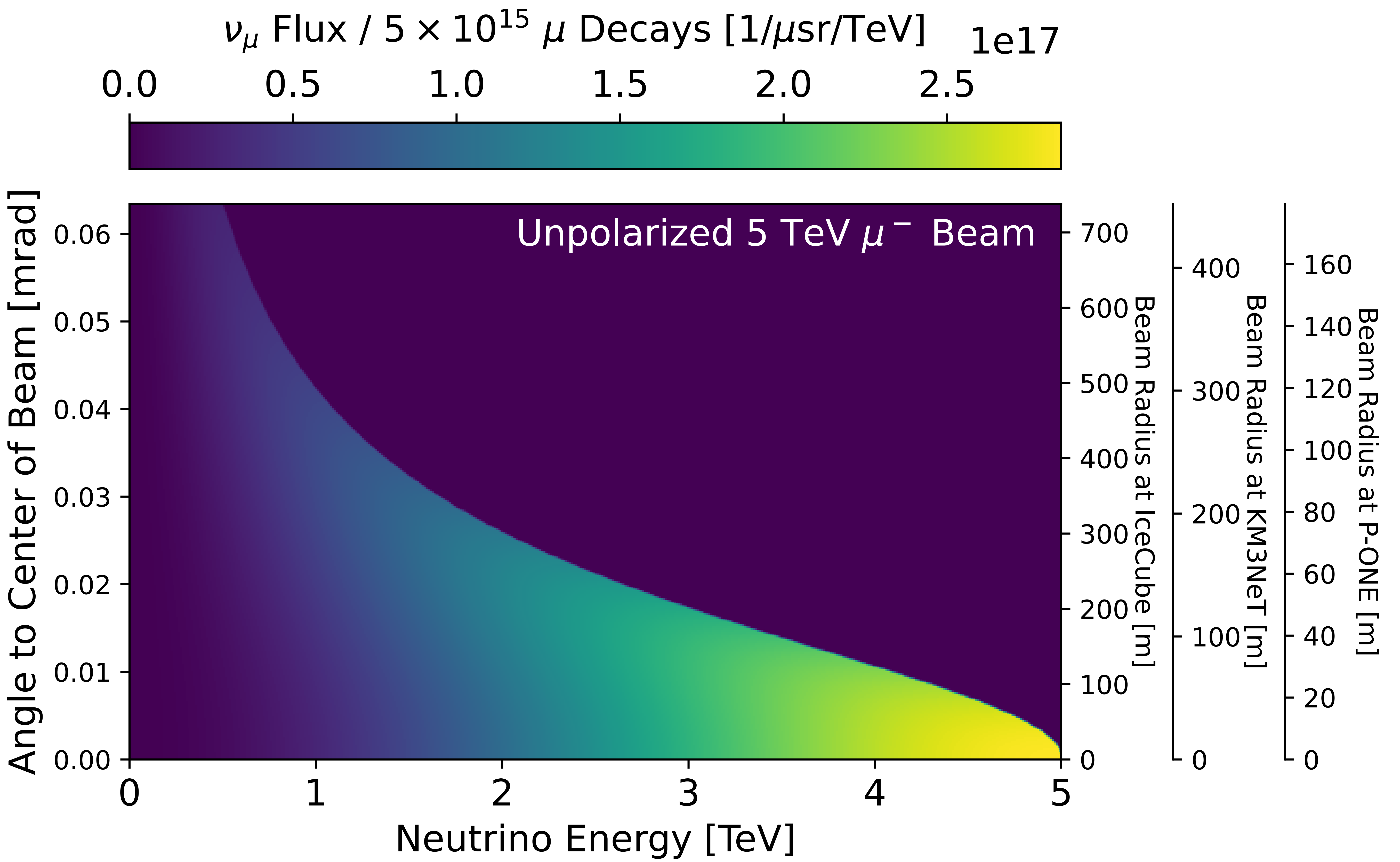


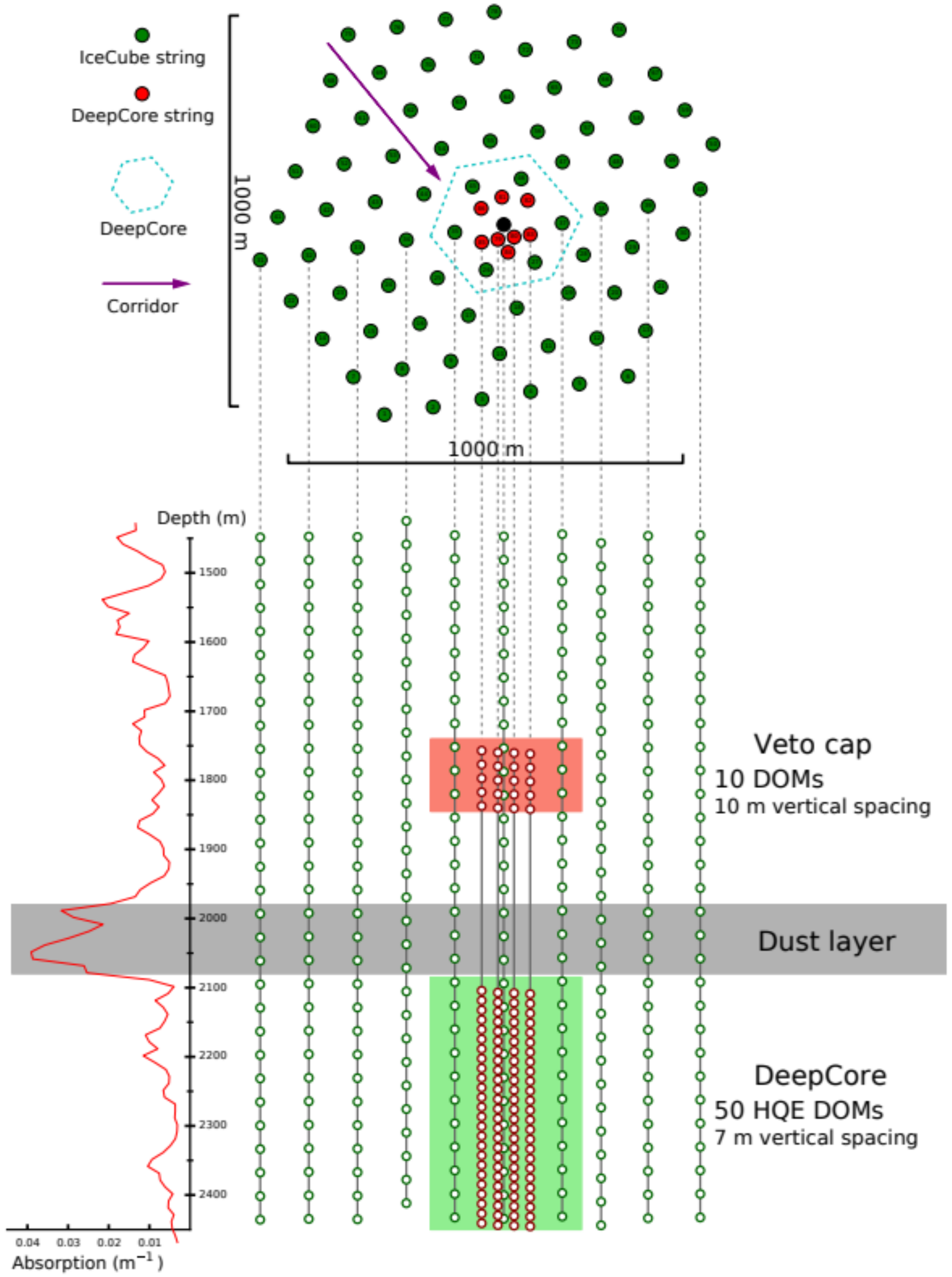
Introducing the "Neutrino Kaleidoscope"

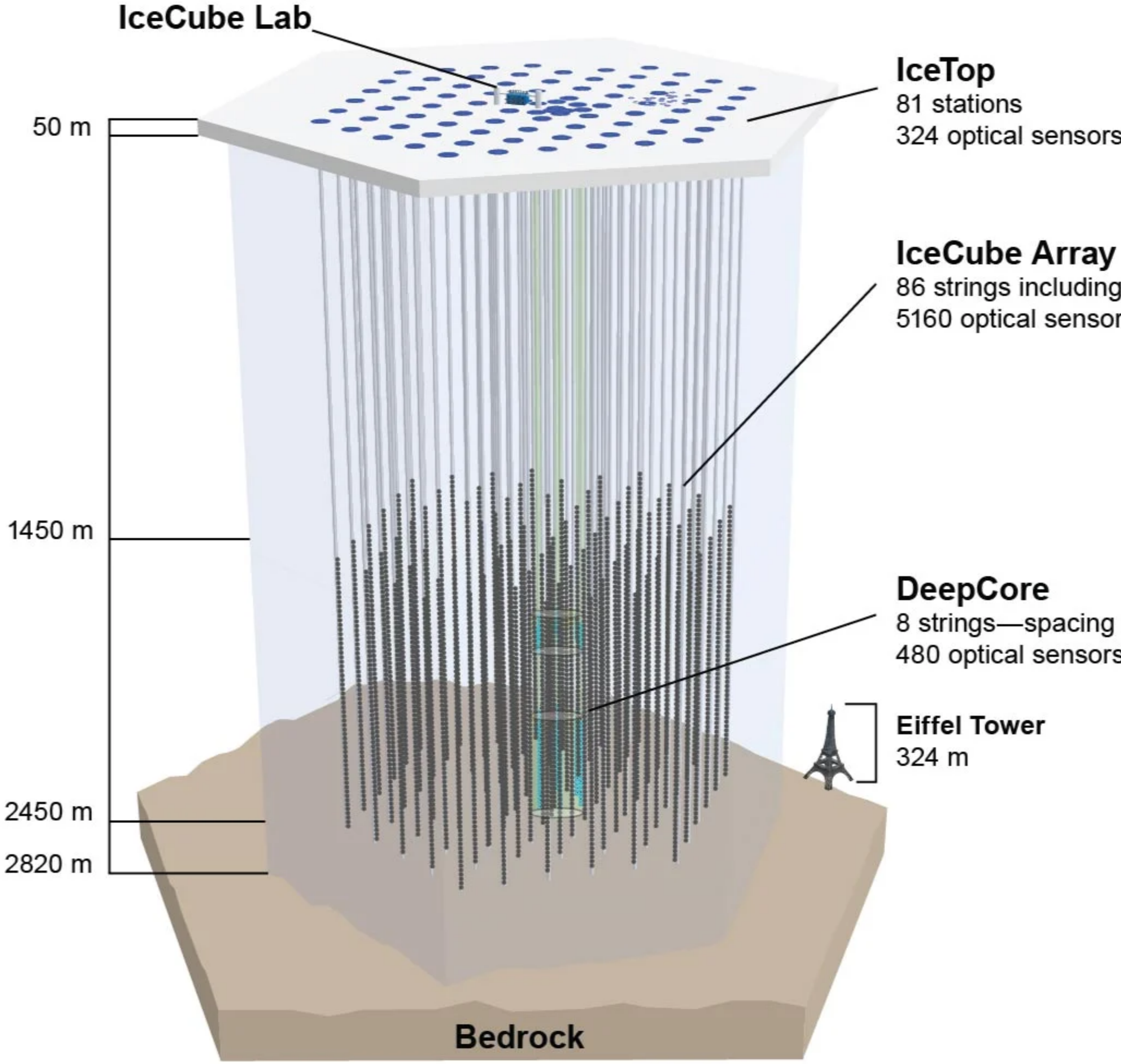


The neutrino beam is collimated to within $\mathcal{O}(100\,\mathrm{m})$ over Earth-diameter distances:
Perfect for Gigaton-scale neutrino telescopes!



IceCube: an Example Neutrino Telescope

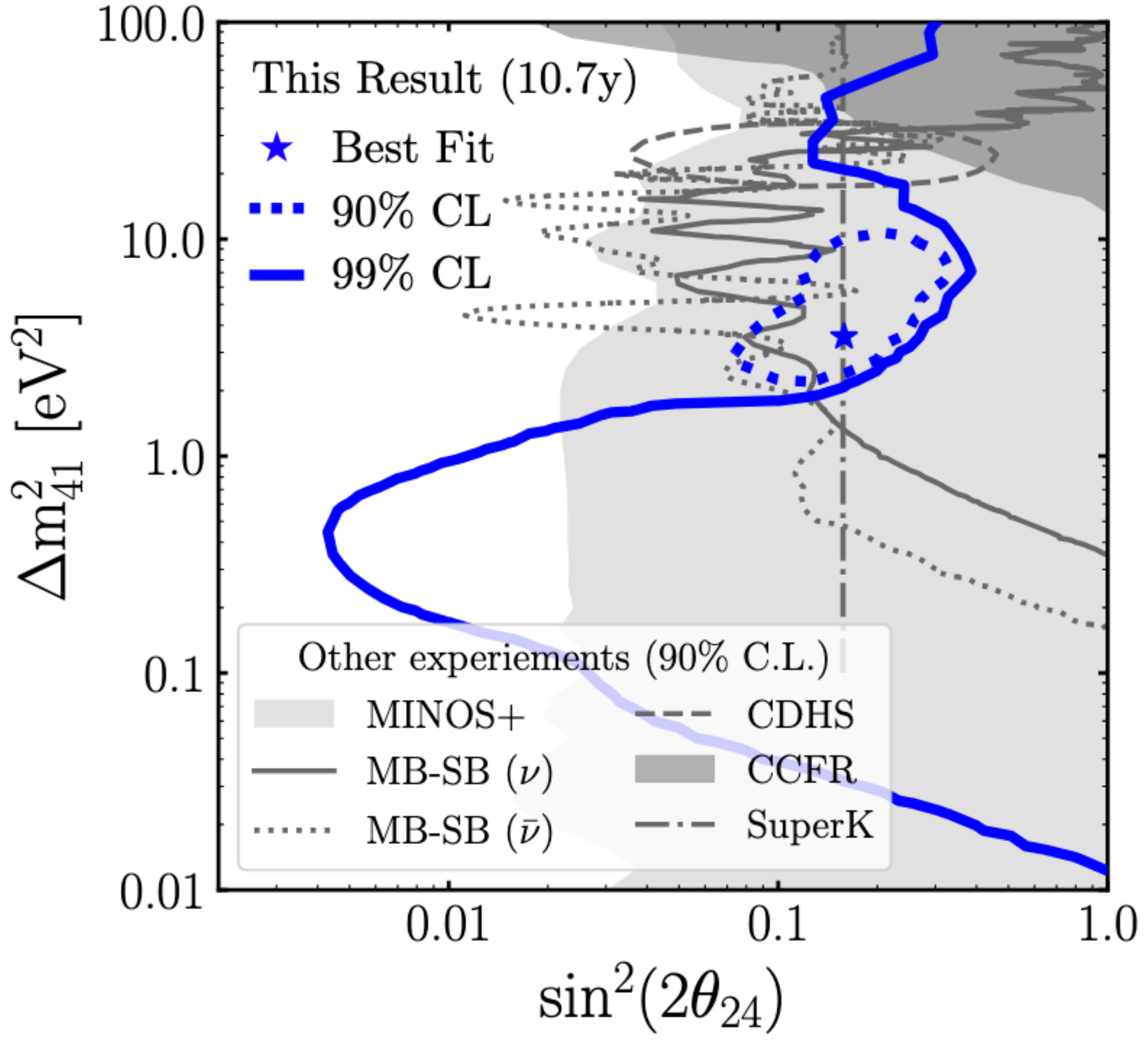




Quanta 2023

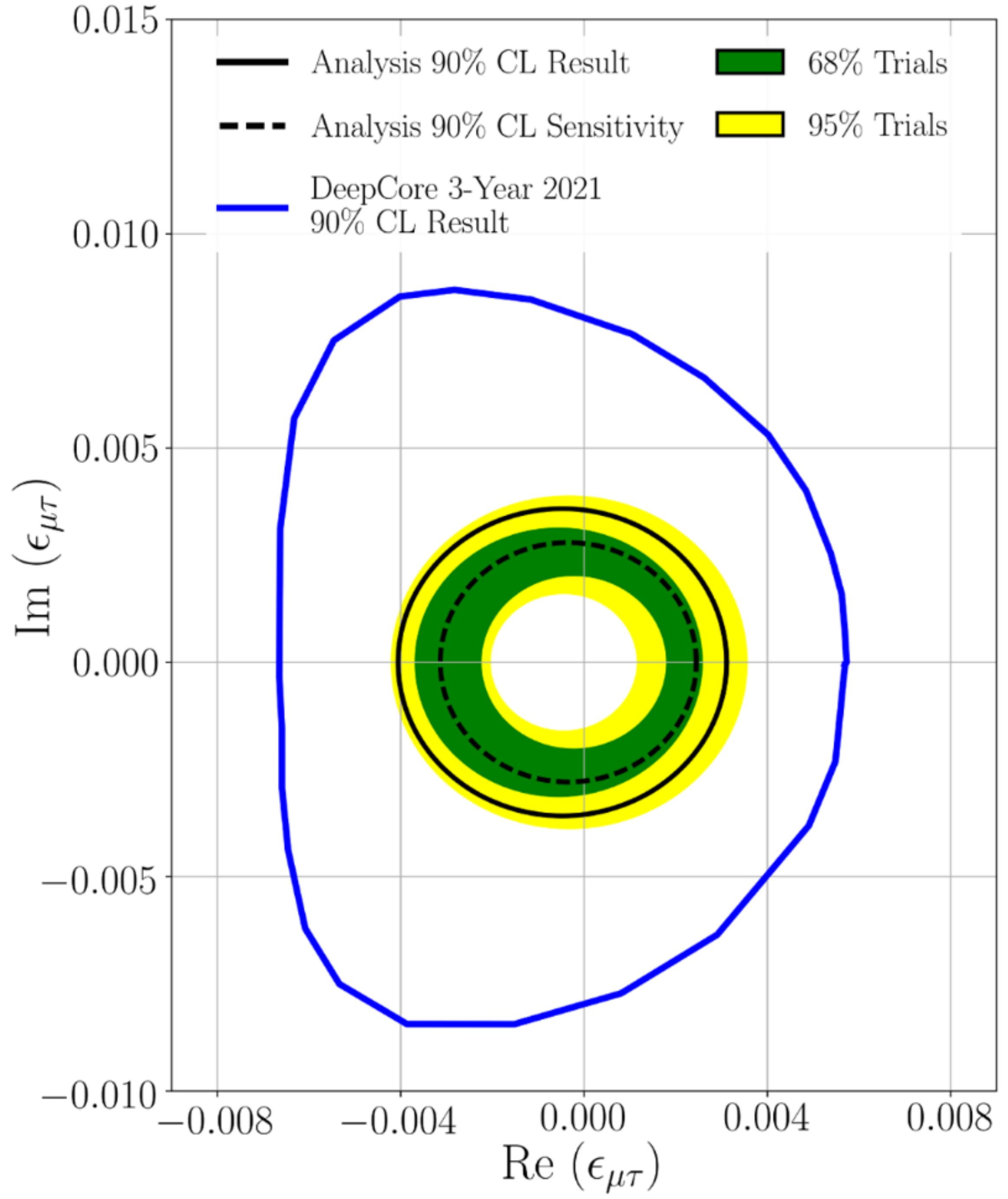
Neutrino Telescopes Search for **Non-Standard** Neutrino Oscillations with TeV Atmospheric Neutrinos

eV-Scale Sterile Neutrinos



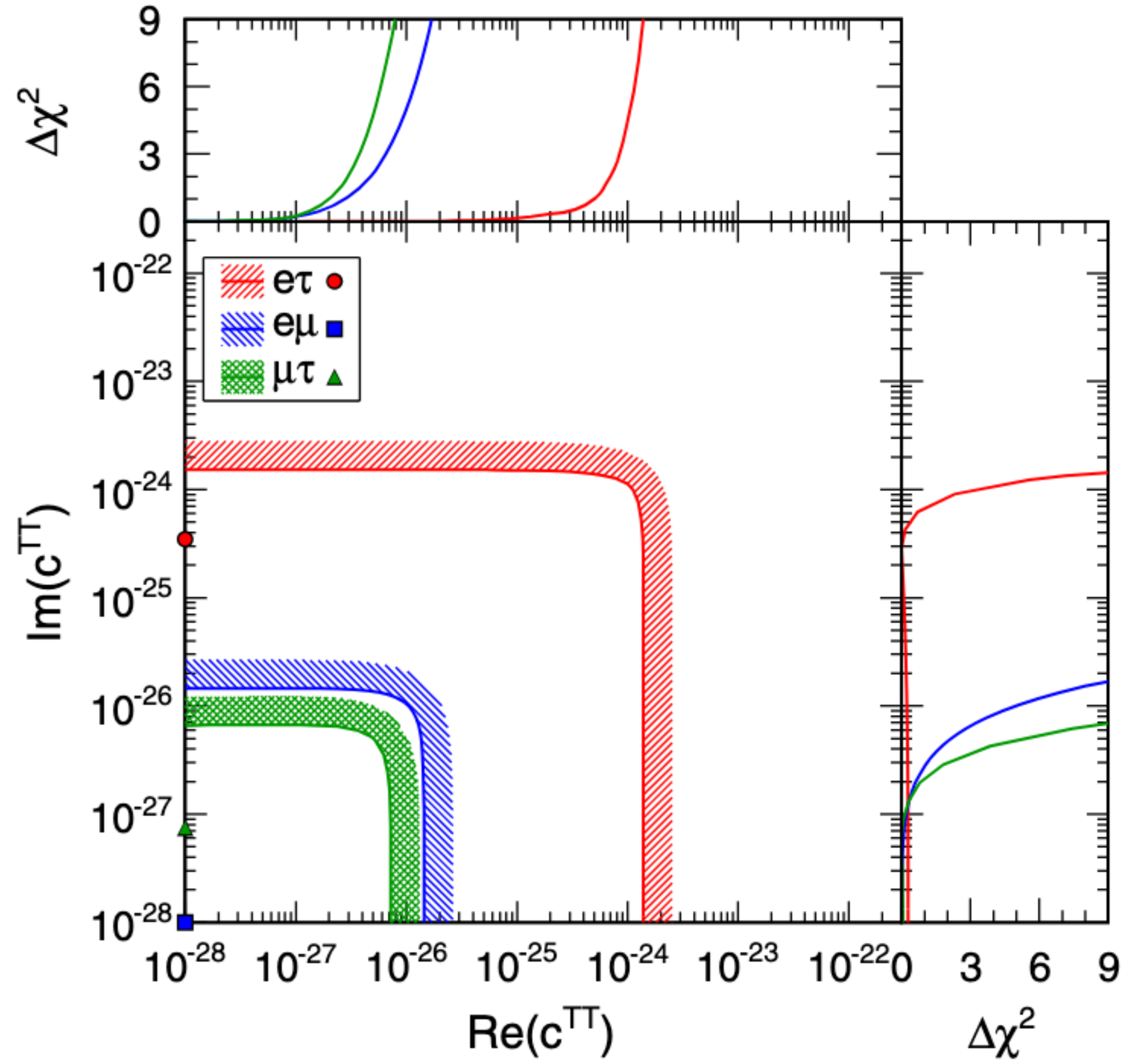
Phys. Rev. Lett. 133, 201804 (2024)

Neutrino-Matter Potential



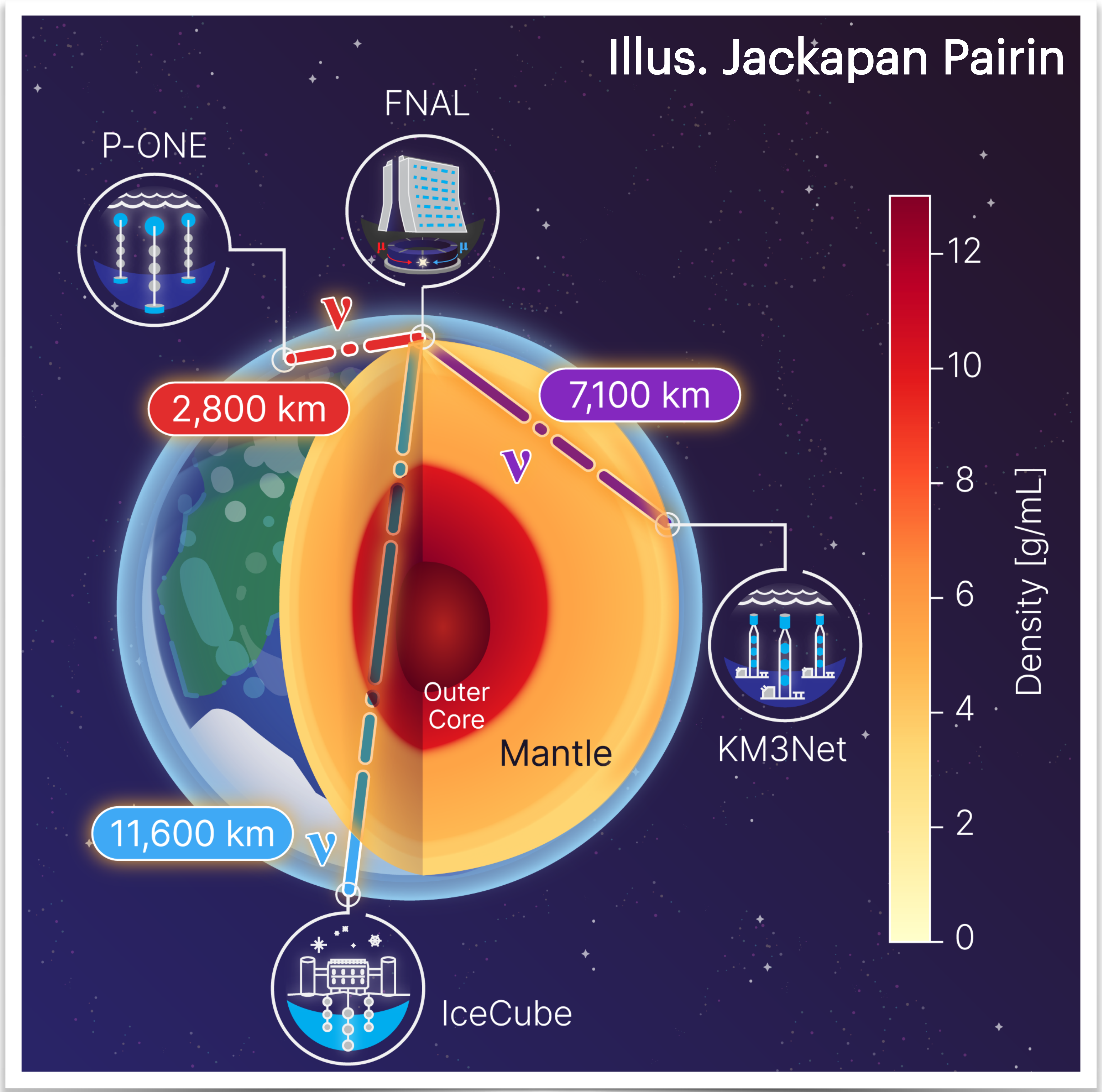
Phys. Rev. Lett. 129 (2022) 1, 011804

Lorentz Invariance Violation



Phys. Rev. D 91, 052003 (2015)

A Beam for Neutrino Telescopes



<u>Two Options for Pointing</u>

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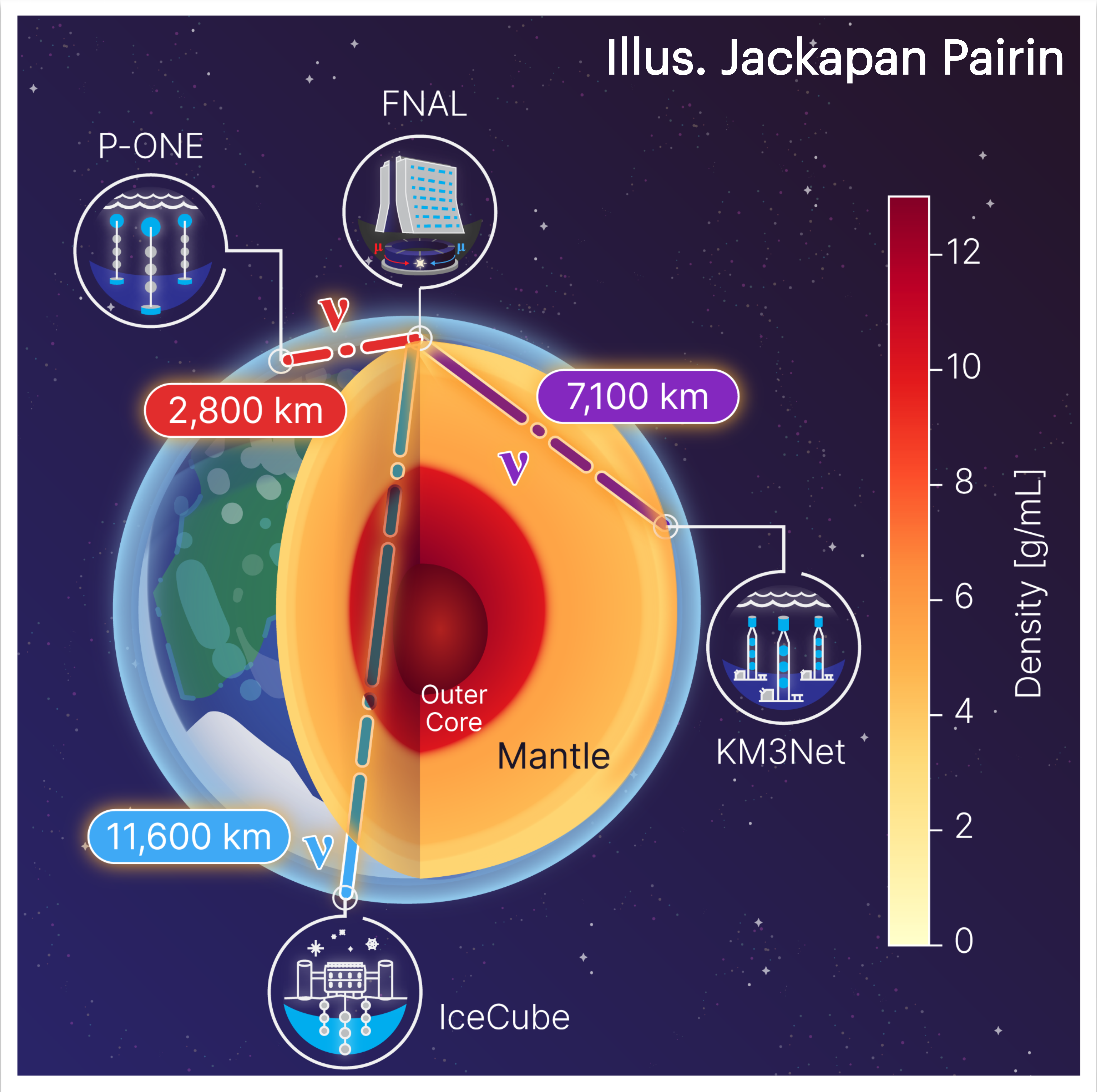

<u>Two Options for Pointing</u>

1: Point a straight section of the beamline at a telescope

- Typical 30 cm section results in 5×10^{14} muon decays per year
- 100 m straight section near the interaction point results in 8×10^{18} muon decays per year, though larger angular spread
- Likely only possible for FNAL → P-ONE

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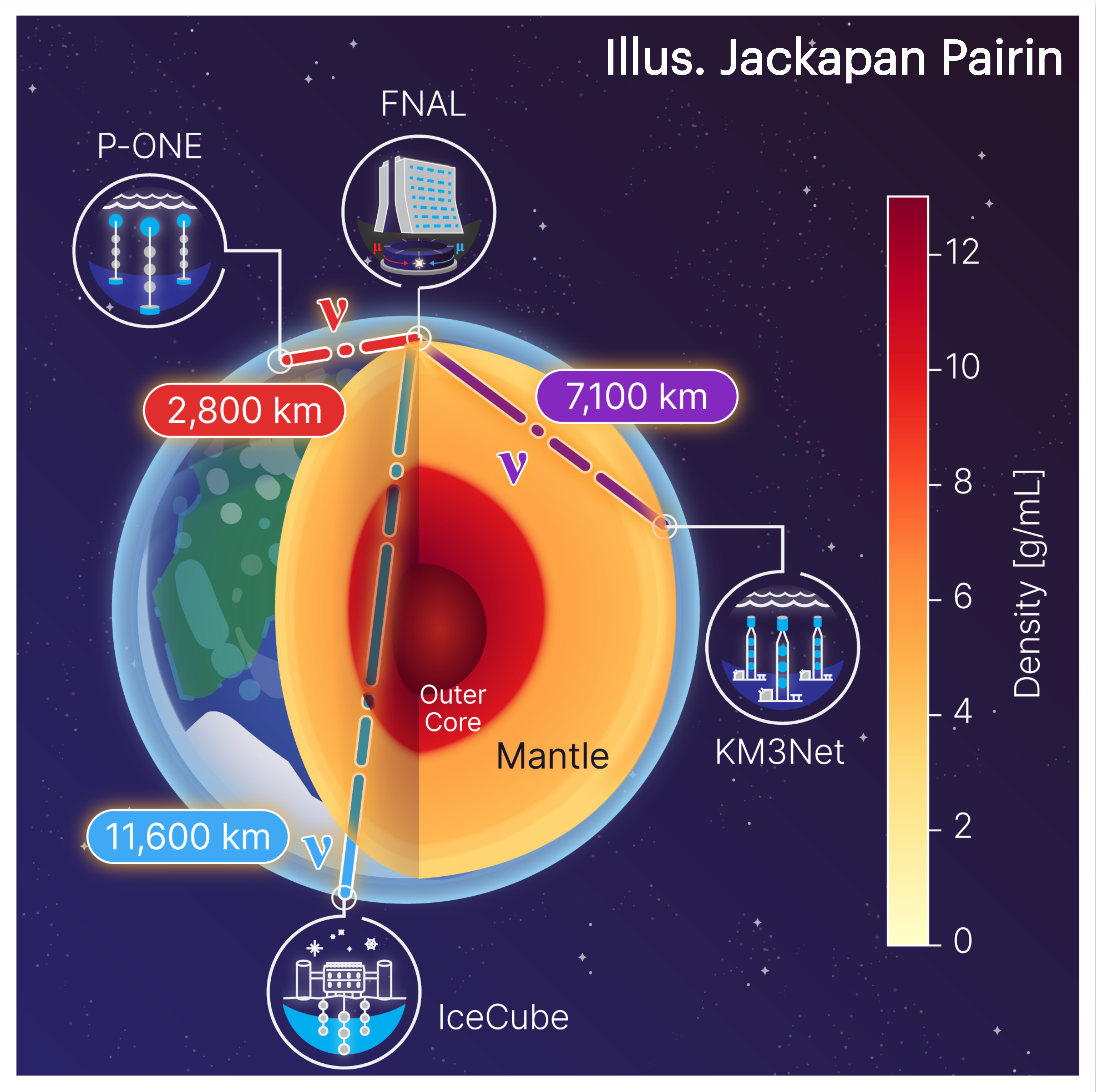

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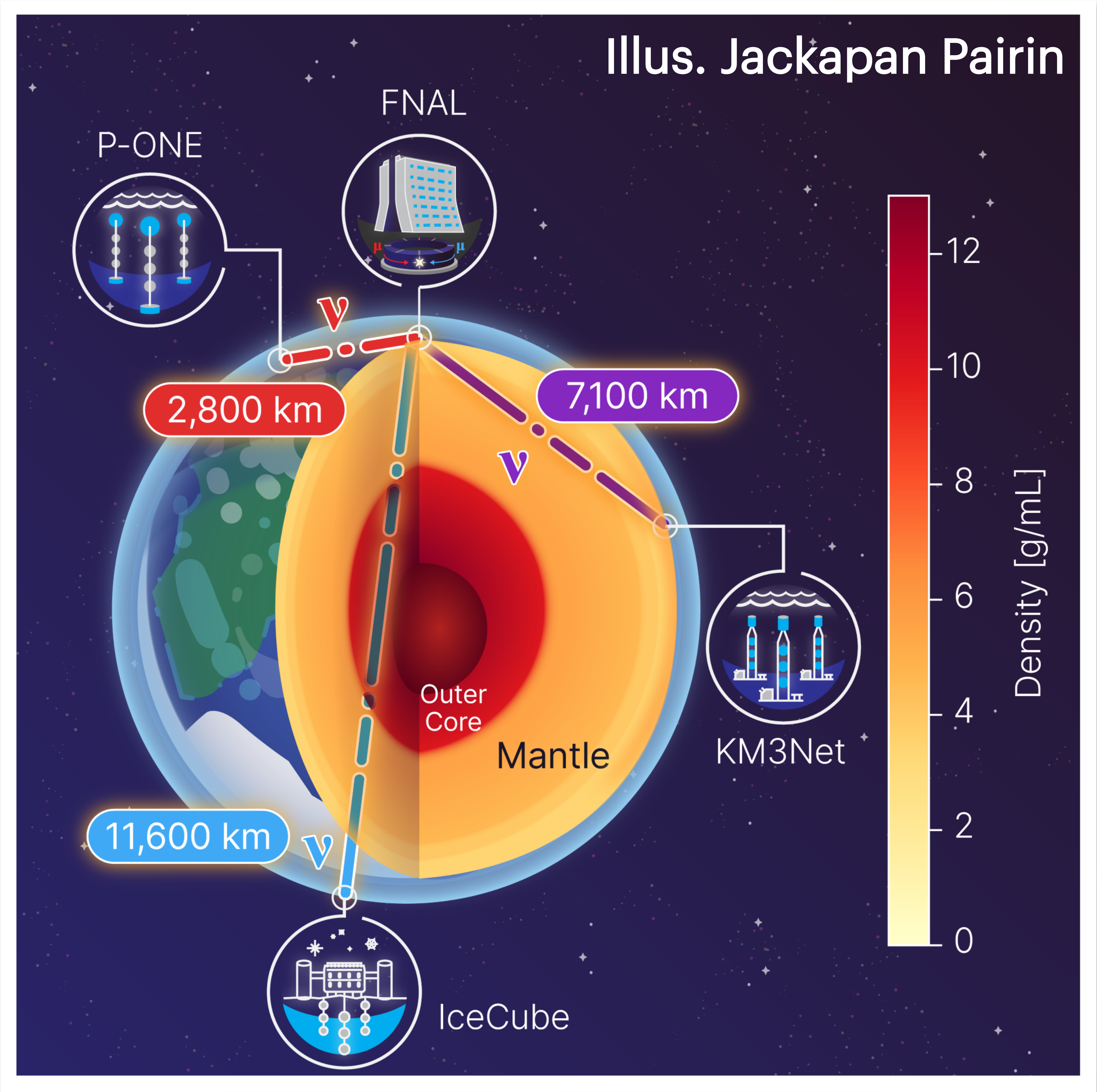

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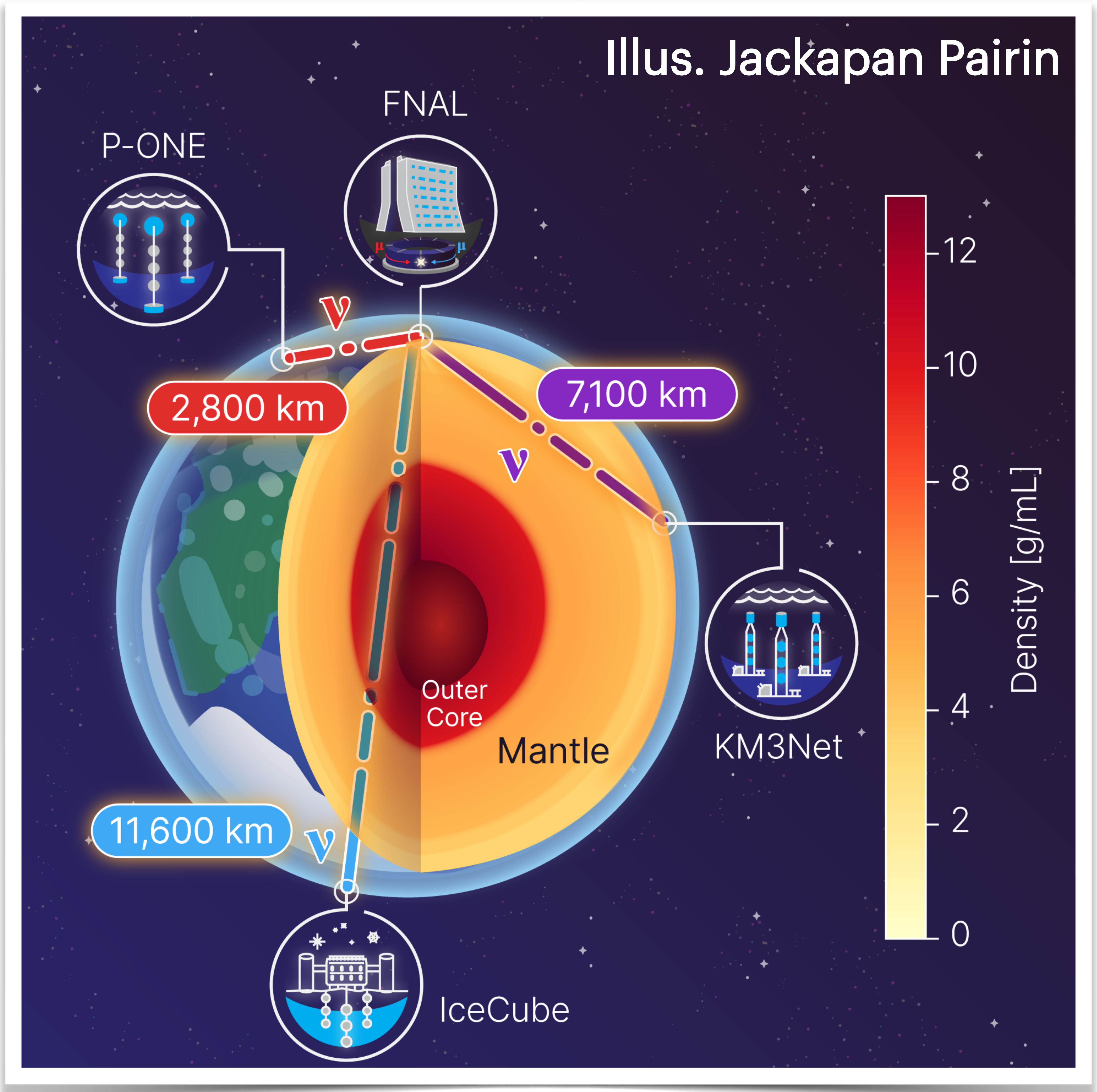

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Between these cases, we expect approximately $10^8 - 10^{11}$ neutrino interactions per year

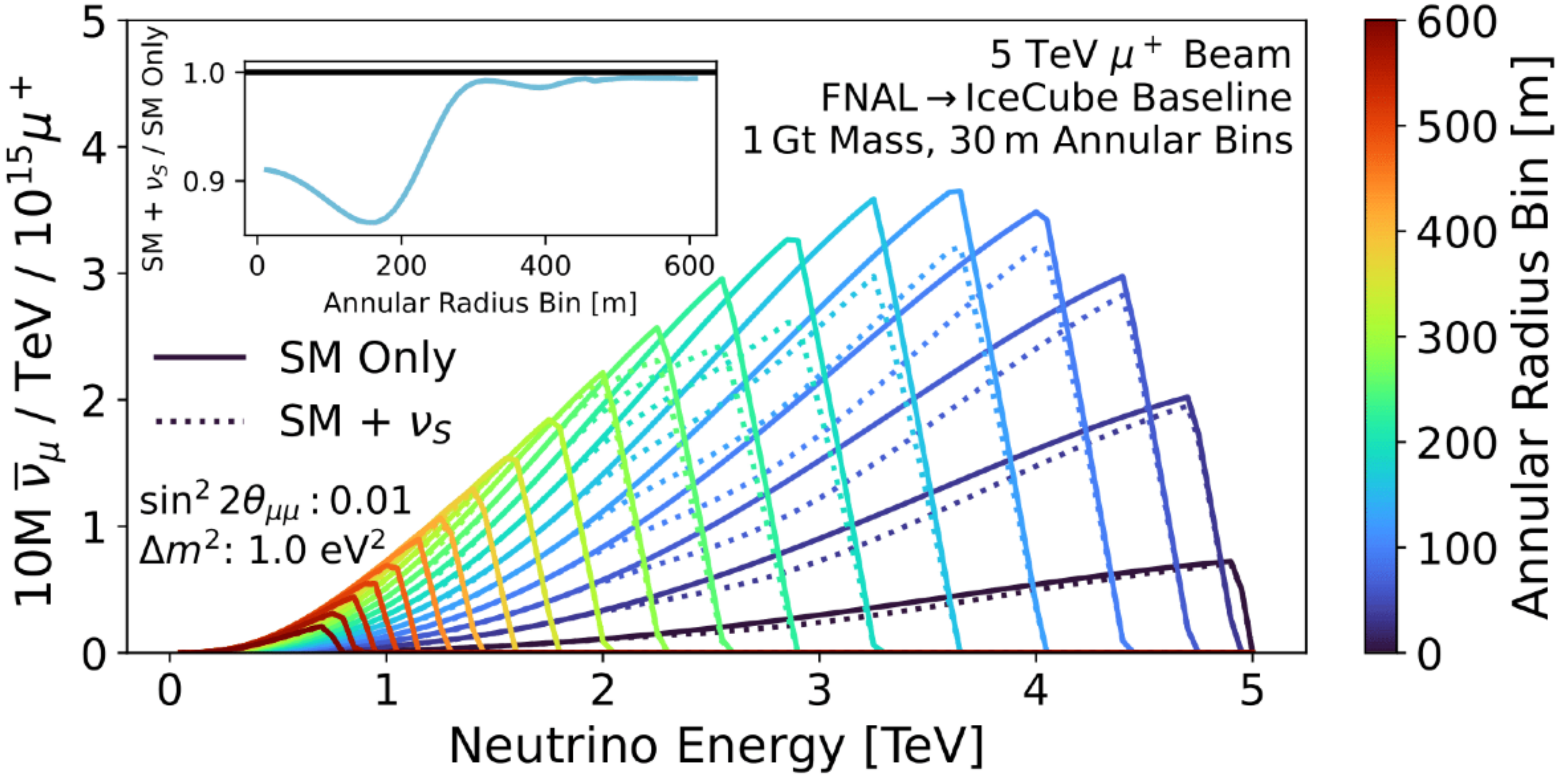
ν Kaleidoscopes for Sterile Neutrinos

An eV-scale right-handed neutrino (aka a sterile neutrino) would induce non-standard matter effects as neutrinos propagate through the Earth

$$i\frac{d}{dx}\begin{pmatrix}\nu_\alpha \\ \nu_S\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m_{41}^2}{4E}\cos 2\theta_{\alpha\alpha} \pm_\alpha G_F N_e/\sqrt{2} & \frac{\Delta m_{41}^2}{4E}\sin 2\theta_{\alpha\alpha} \\ \frac{\Delta m_{41}^2}{4E}\sin 2\theta_{\alpha\alpha} & \frac{\Delta m_{41}^2}{4E}\cos 2\theta_{\alpha\alpha} \end{pmatrix}\begin{pmatrix}\nu_\alpha \\ \nu_S\end{pmatrix}$$

$$\pm_\alpha = \begin{cases} +1 & \alpha \in \{e, \bar{\mu}\} \\ -1 & \alpha \in \{\bar{e}, \mu\} \end{cases}$$

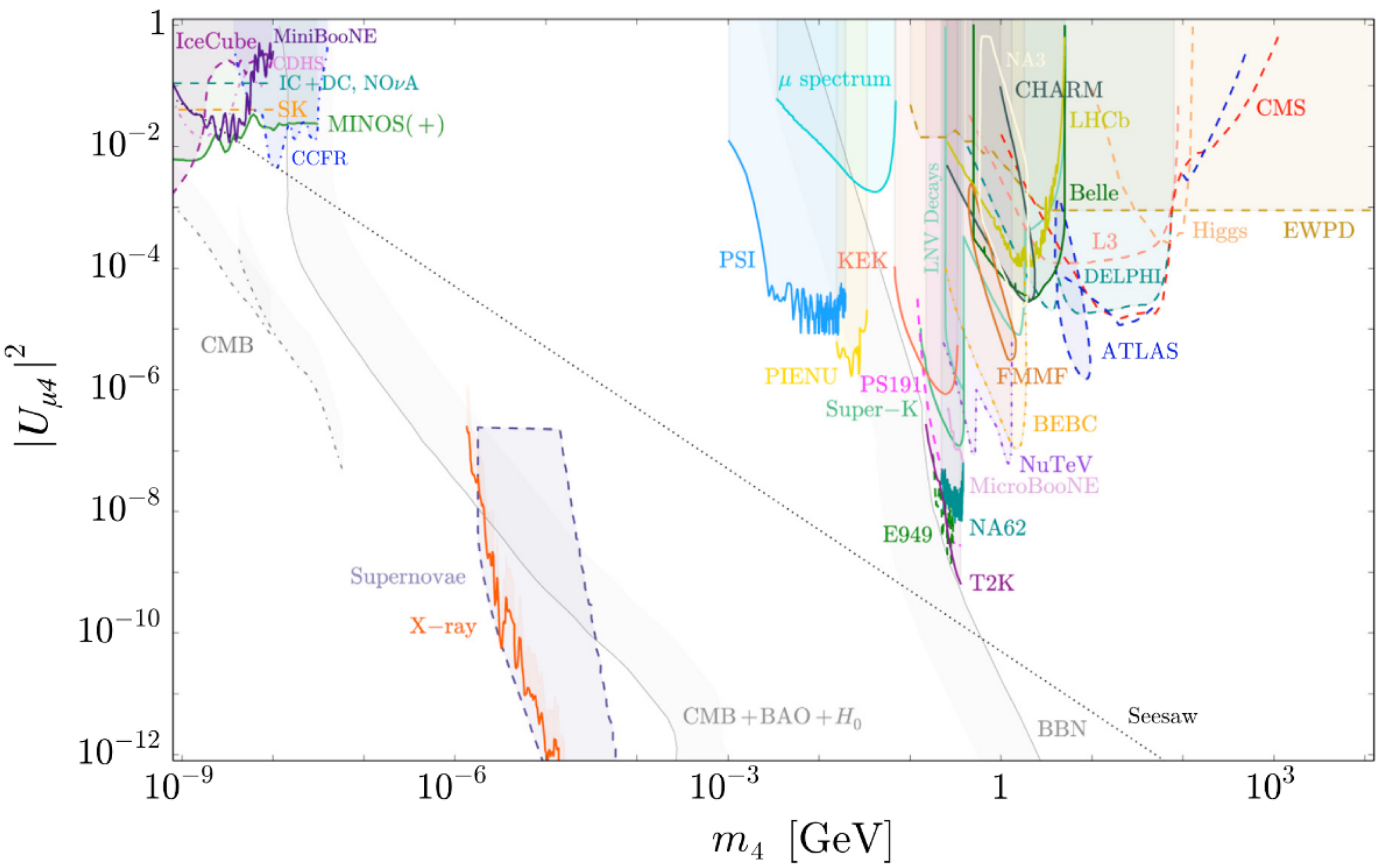
This would lead to a distortion in the energy **and** radial distributions in a ν kaleidoscope



Why Look for Sterile Neutrinos?

The mass of neutrinos means that right handed neutrinos exist at some mass scale

A search at the eV-scale may also be motivated if the current generation of "short-baseline" neutrino experiments result in discovery

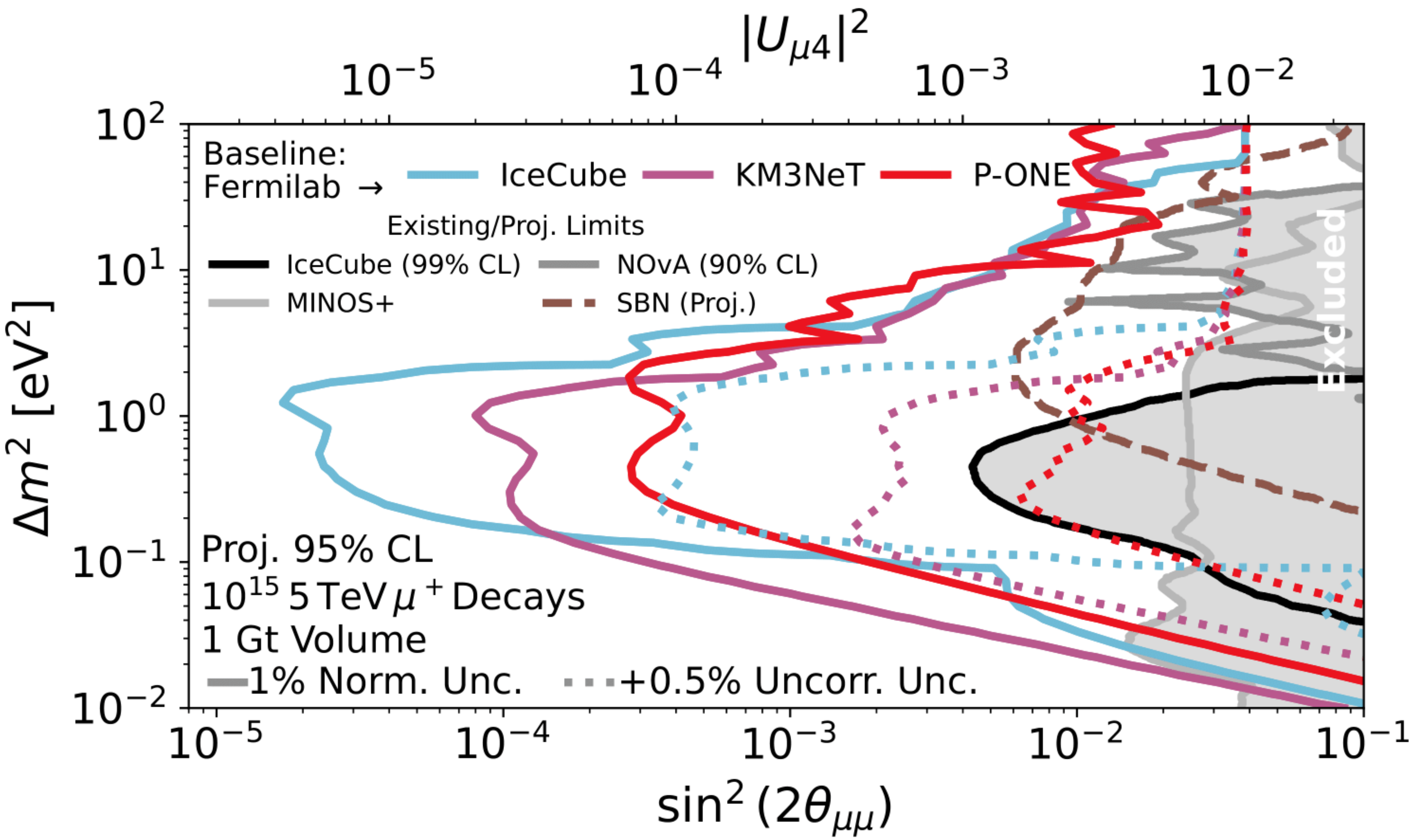


ν Kaleidoscopes Sensitivity to Sterile Neutrinos

We consider muon neutrino disappearance via a sterile neutrino with a "tracks" dataset at each telescope

The sensitivity is computed with the annular radius of the neutrino interaction vertex

The reach goes up to three orders of magnitude beyond existing searches!



What about active neutrino oscillations?

Oscillations the $\mu - \tau$ sector are governed by:

$$i\frac{d}{dx}\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix} = \left[\frac{\Delta m^2_{31}}{4E}\begin{pmatrix}-\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23}\end{pmatrix} + \begin{pmatrix}V_{\mu\mu} & V_{\mu\tau} \\ V^*_{\mu\tau} & V_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix},$$

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In the short baseline regime, $\frac{\Delta m^2_{31}}{4E}L, VL << 1,$

$$P_{\nu_\mu \to \nu_\tau} = L^2 \left| \frac{\Delta m^2_{31}}{4E}\sin 2\theta_{23} + V_{\mu\tau} \right|^2 + \mathcal{O}(L^4)\,.$$

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We can look for new physics that produces non-standard oscillations via a nonzero $V_{\mu\tau}$

Oscillations from Quantum Gravity

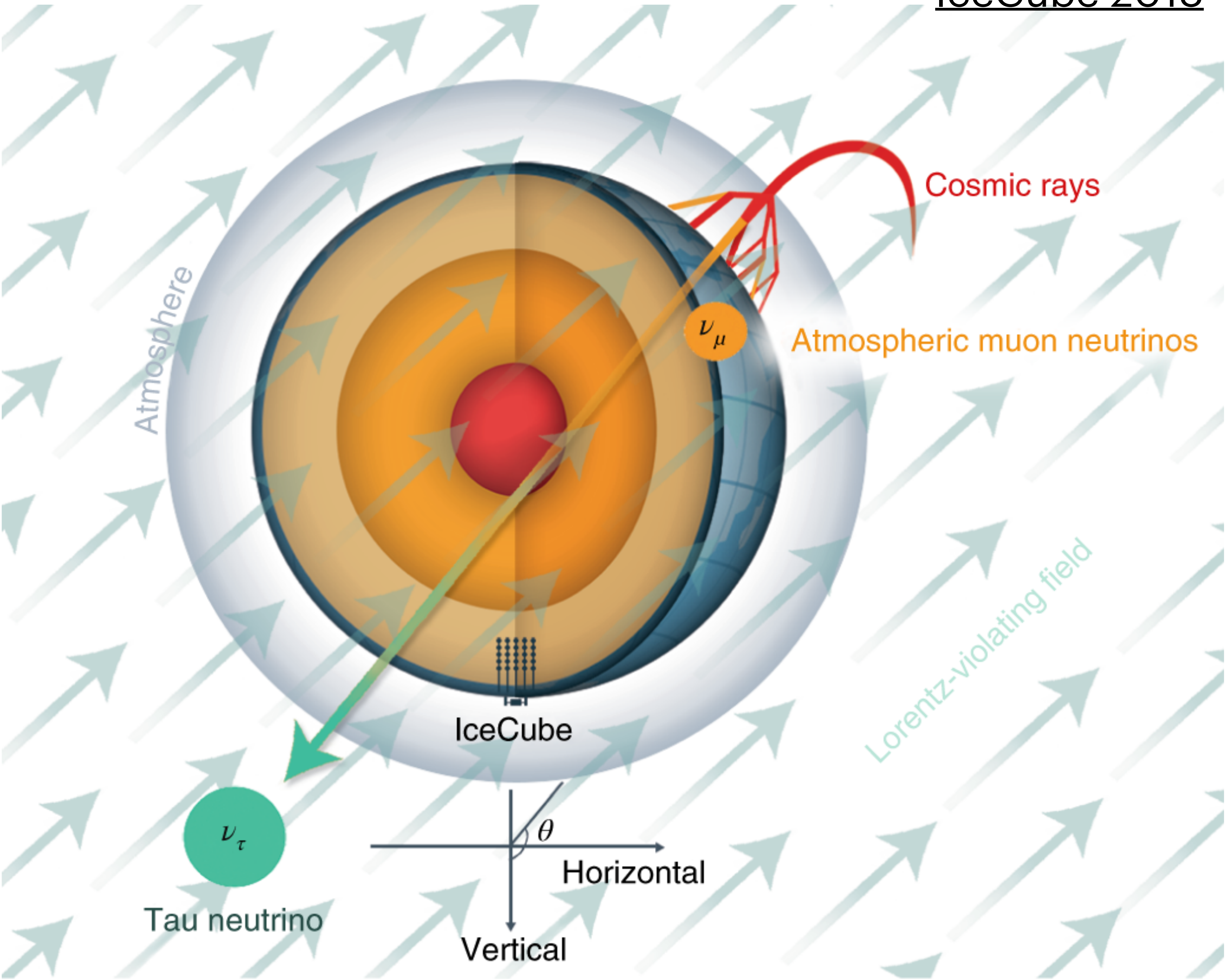
Quantum gravity theories predict Planck-suppressed Lorentz violation [Addazi+ 2021]

Leads to frame-dependent neutrino oscillations described by the Standard Model Extension [Kostelecký+ 2003]

$$V_{\mu\tau} = \frac{1}{E}[(a_L)^{\mu}_{\mu\tau} p_\mu - (c_L)^{\mu\nu}_{\mu\tau} p_\mu p_\nu]$$

$$P_{\nu_\mu \to \nu_\tau} \approx L^2 \left| \frac{\Delta m^2_{31}}{4E} \sin 2\theta_{23} + V_{\mu\tau} \right|^2$$

IceCube 2018



Lorentz Violation in Practice

We look for oscillations at the sidereal frequency: $\omega_\oplus = 2\pi/(23\text{ h }56\text{ min})$

$$V_{\mu\tau} = (C)_{\mu\tau} + (A_s)_{\mu\tau}\sin\omega_\oplus T_\oplus + (A_c)_{\mu\tau}\cos\omega_\oplus T_\oplus + (B_s)_{\mu\tau}\sin 2\omega_\oplus T_\oplus + (B_c)_{\mu\tau}\cos 2\omega_\oplus T_\oplus,$$

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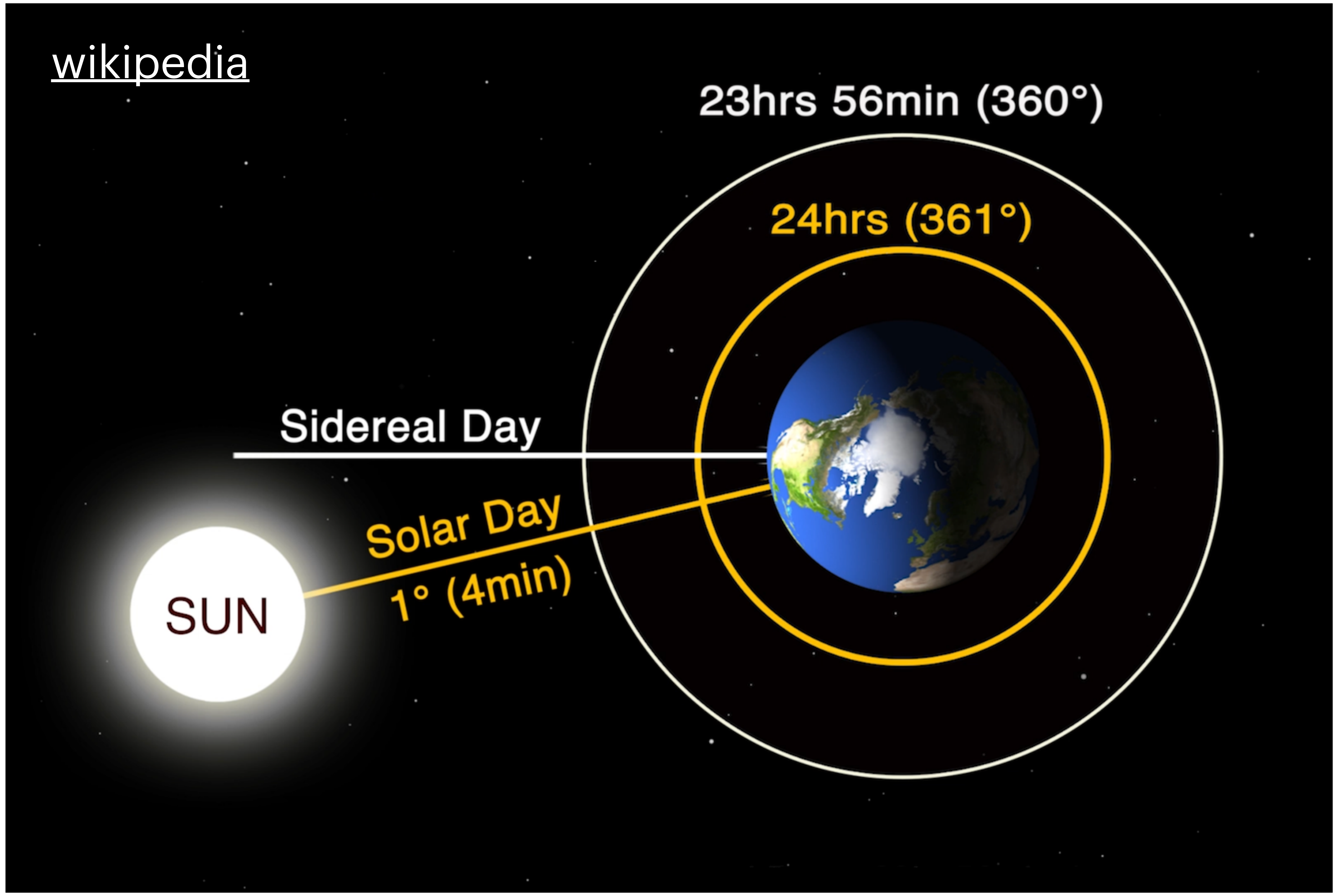

$\{C, A_s, A_c, B_s, B_c\}$ are experiment-dependent linear combinations of a^μ_L, $c^{\mu\nu}_L$

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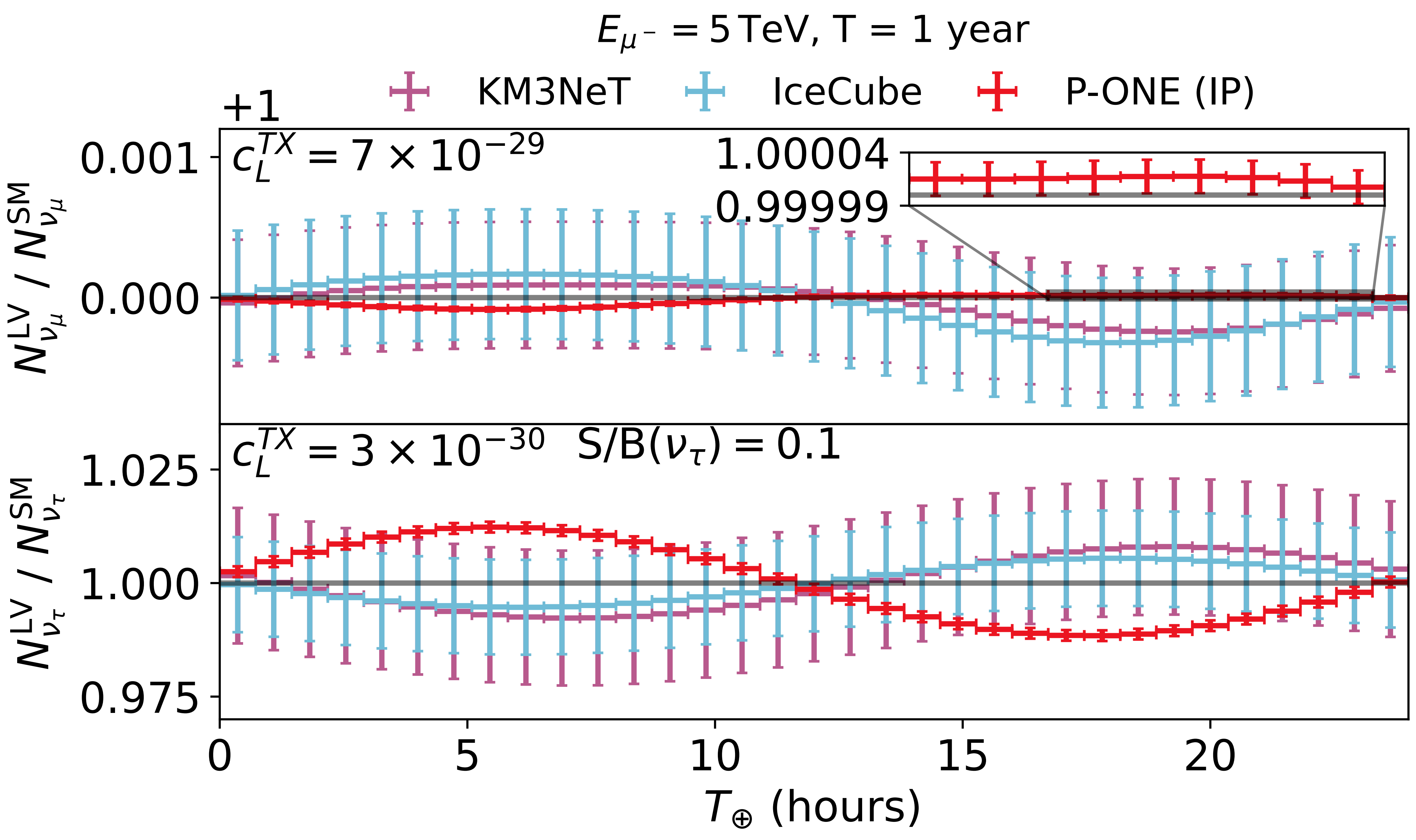
$$V_{\mu\tau} = \frac{1}{E}[(a_L)^{\mu}_{\mu\tau}p_{\mu} - (c_L)^{\mu\nu}_{\mu\tau}p_{\mu}p_{\nu}]$$

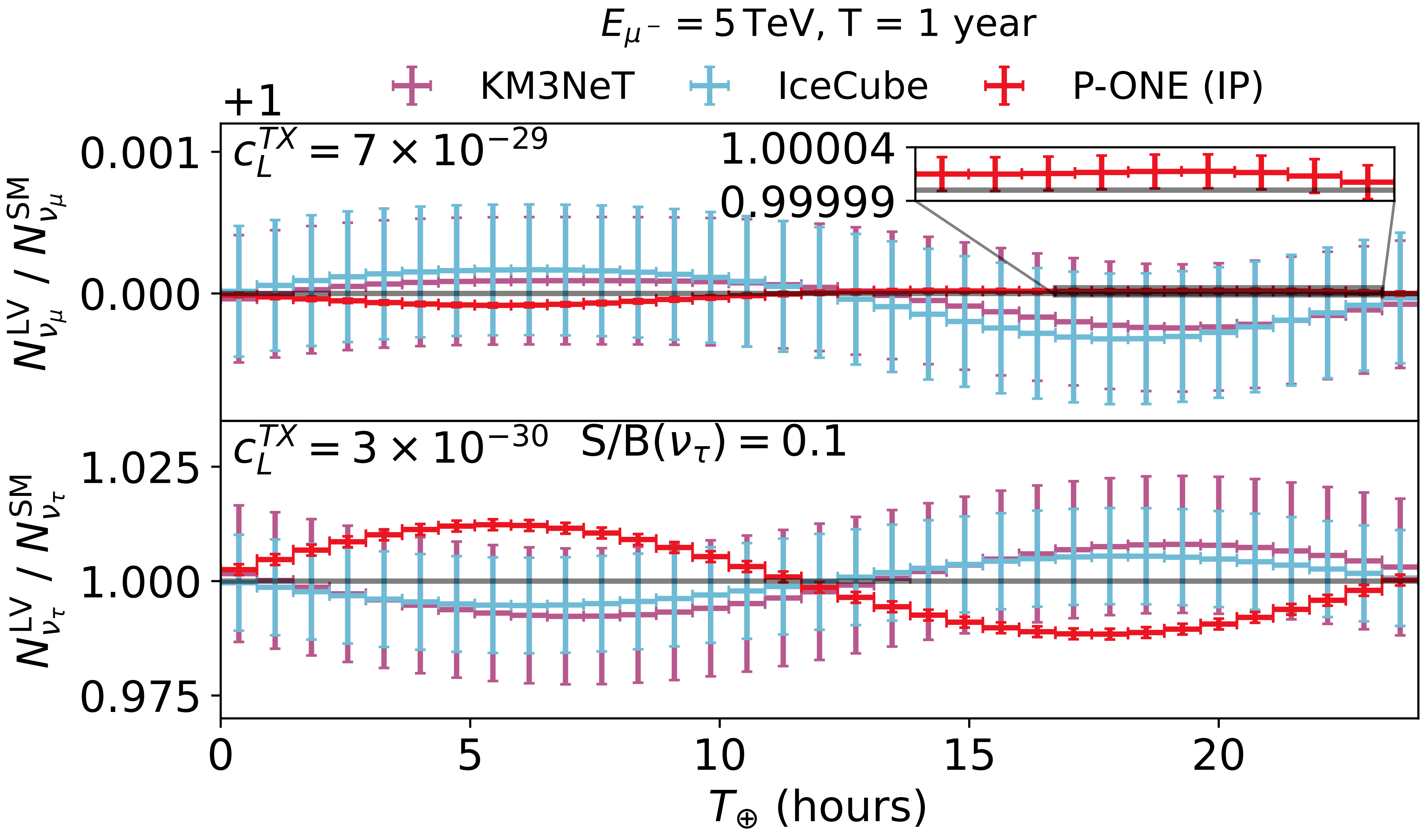
$$P_{\nu_\mu\to\nu_\tau} \approx L^2\left|\frac{\Delta m^2_{31}}{4E}\sin 2\theta_{23} + V_{\mu\tau}\right|^2$$

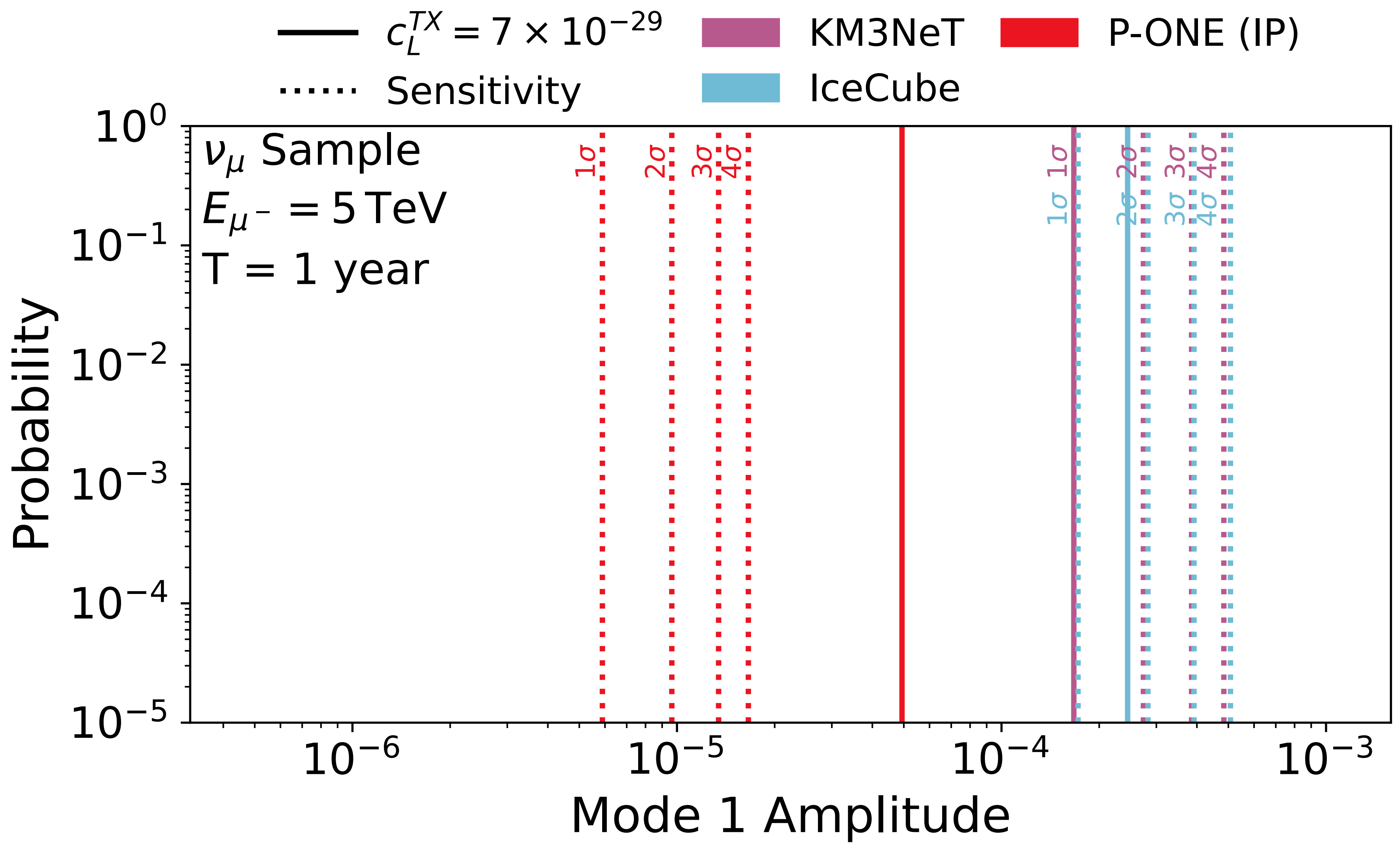
Easy case: ν_μ oscillations in a "tracks" sample

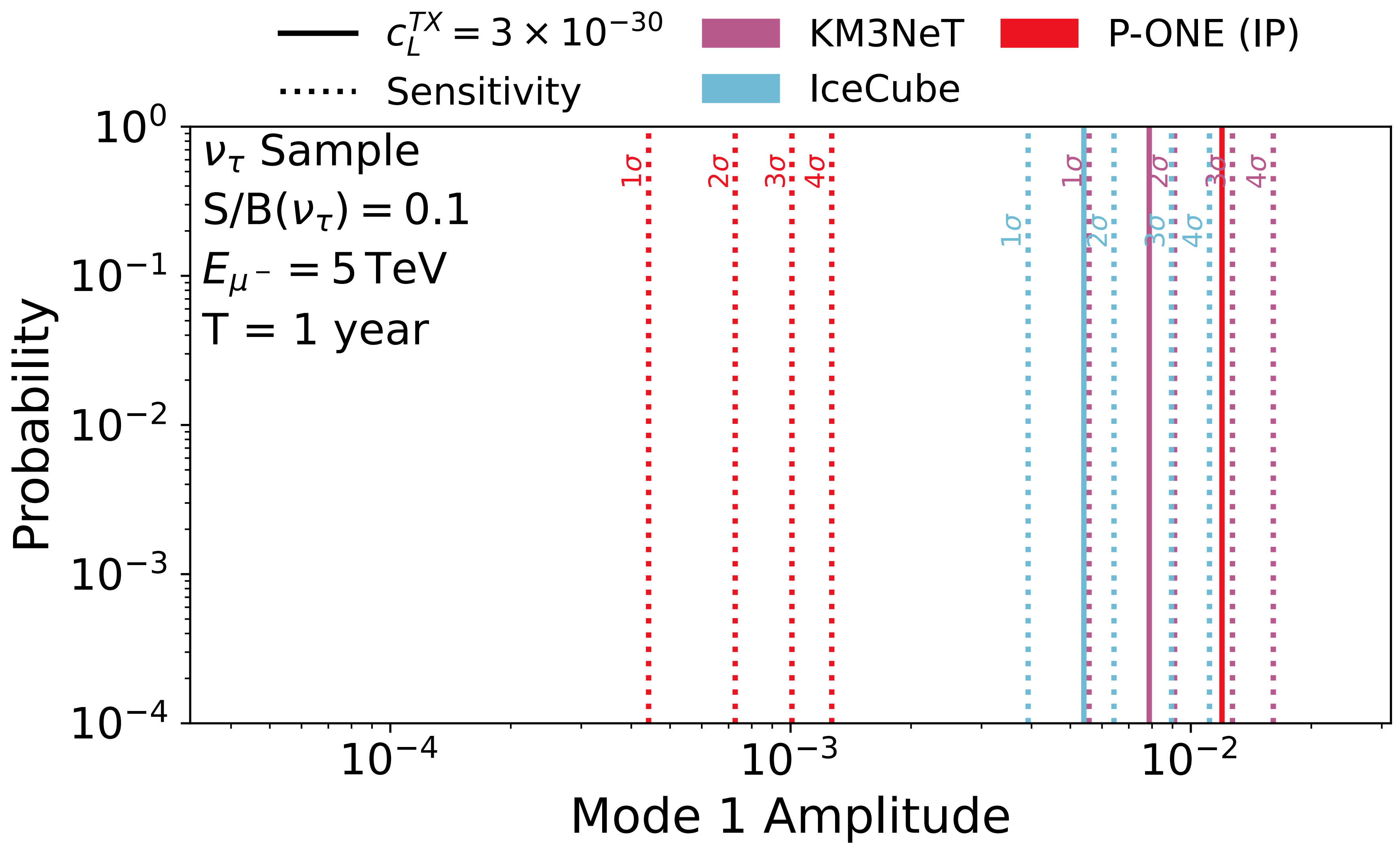


Challenge case: ν_τ oscillations in a ν_τ-enhanced sample with a signal-to-background ratio of 10%

Lorentz Violation in Practice

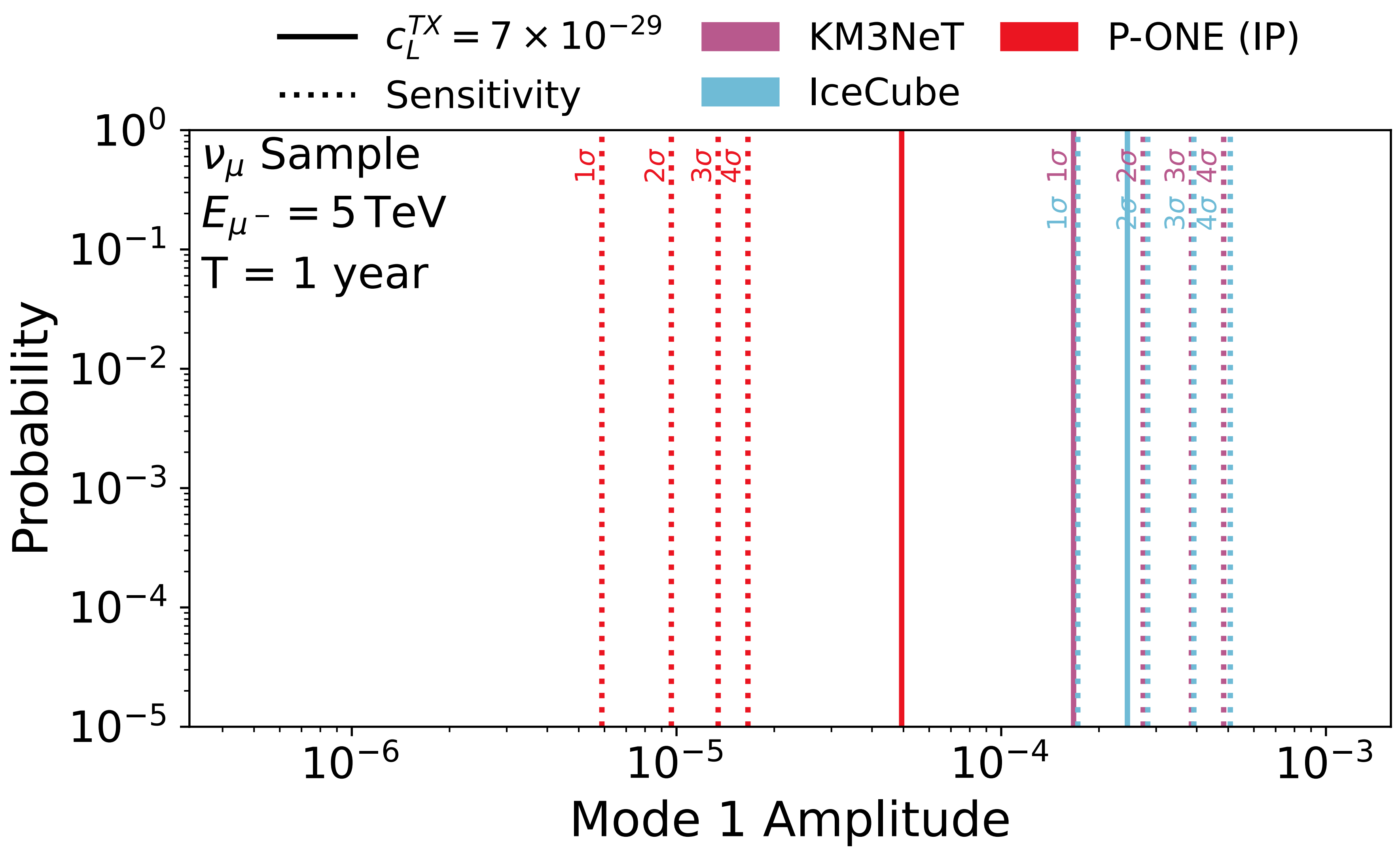


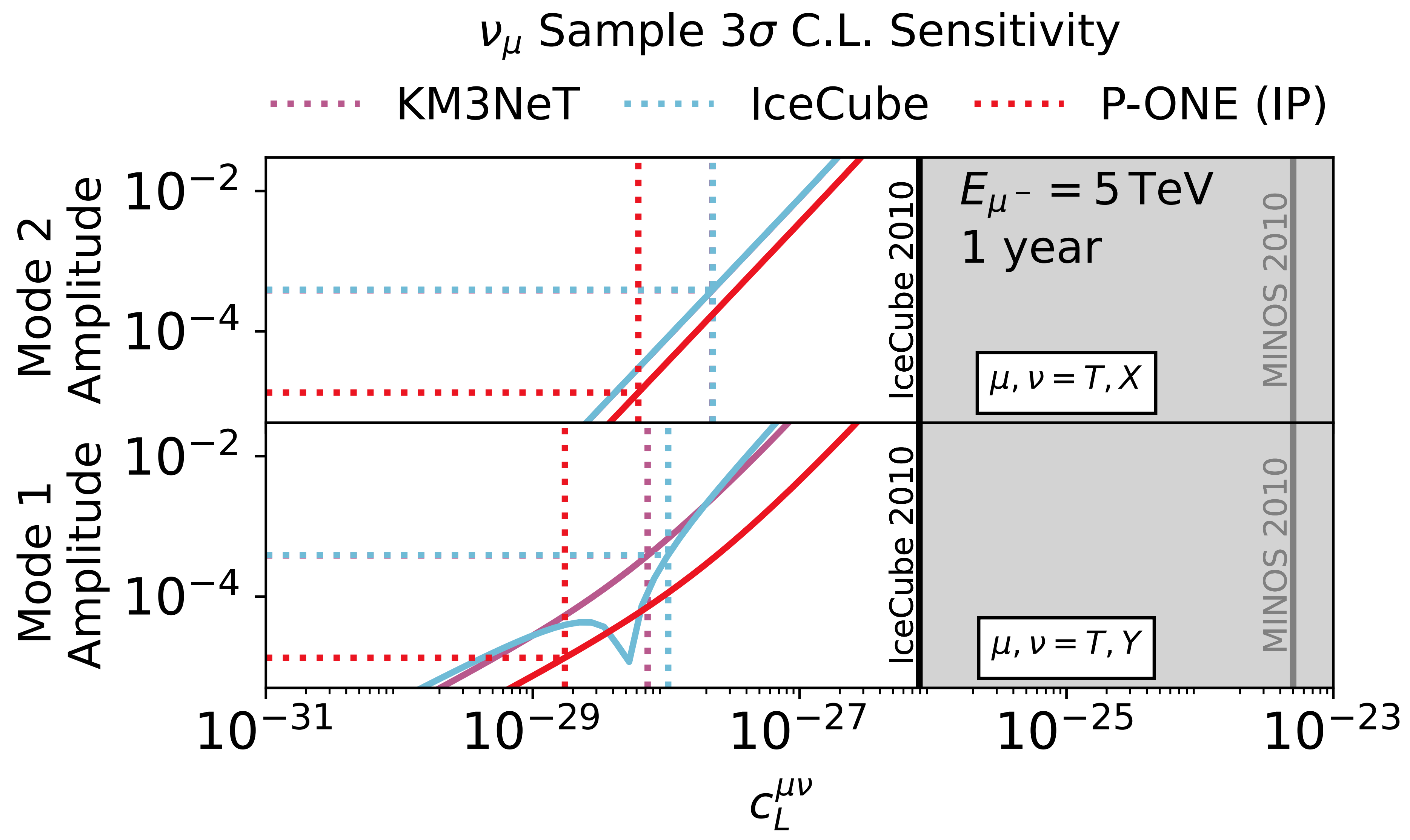


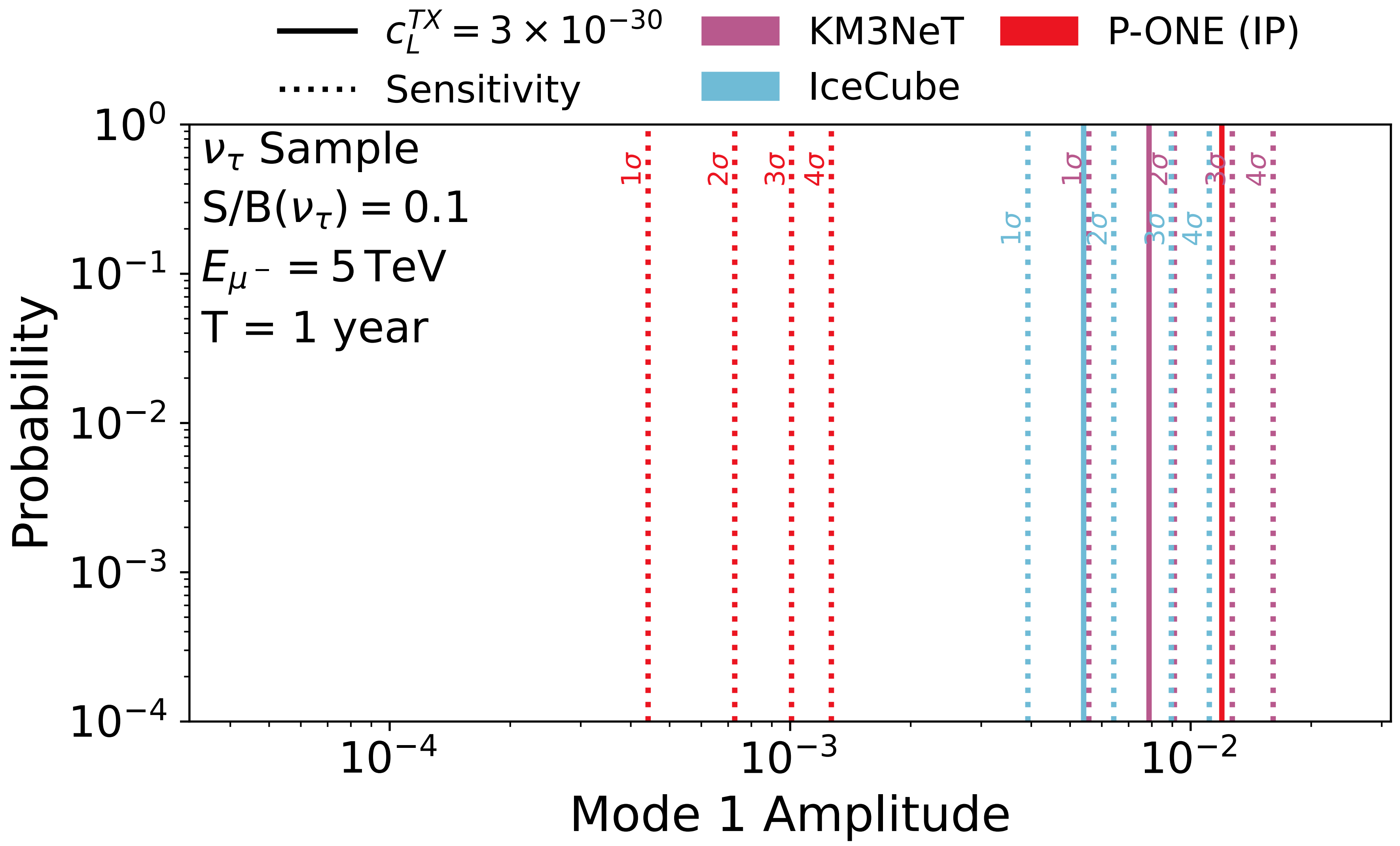


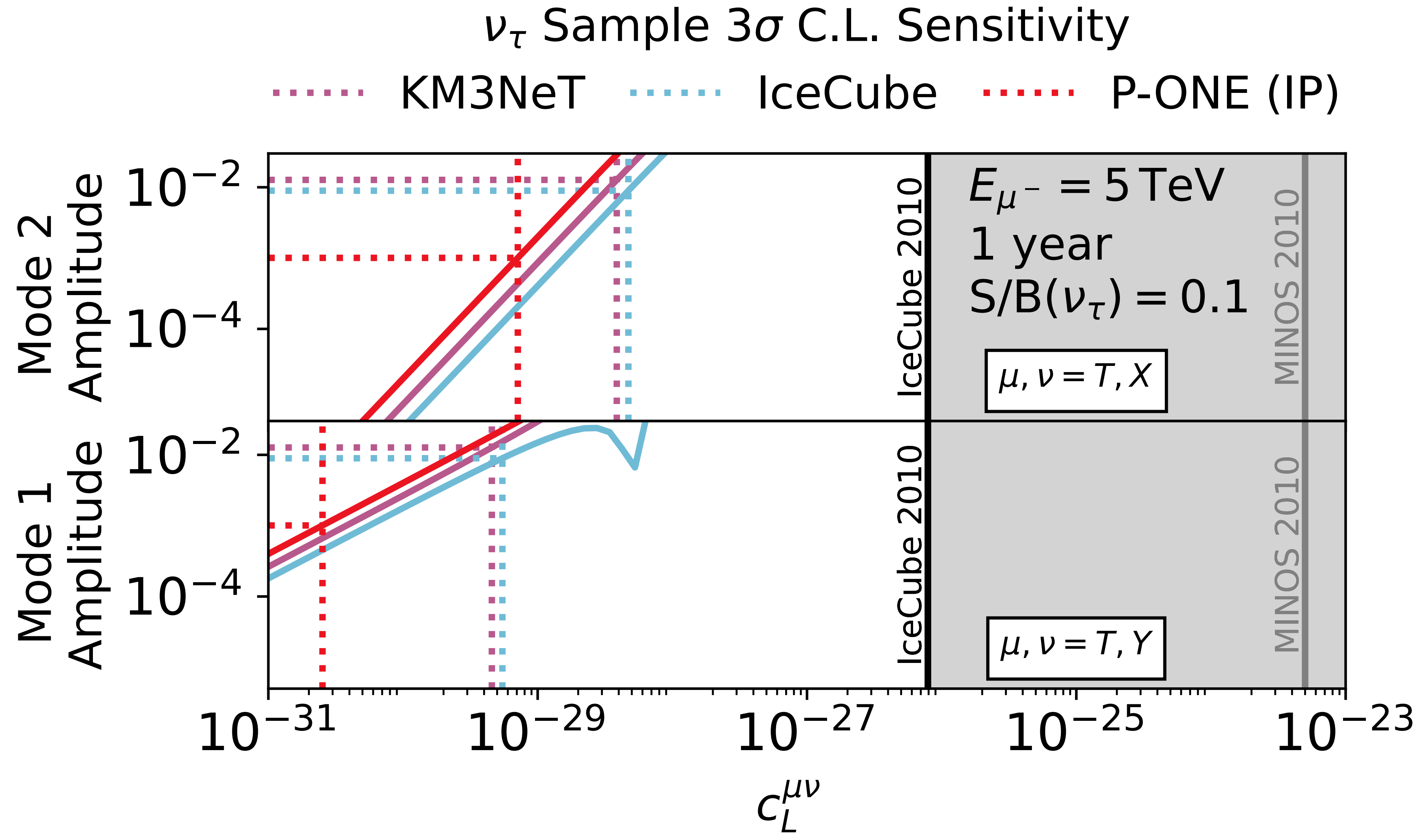
We perform a Fourier analysis on harmonics of the sidereal frequency

Lorentz Violation in Practice









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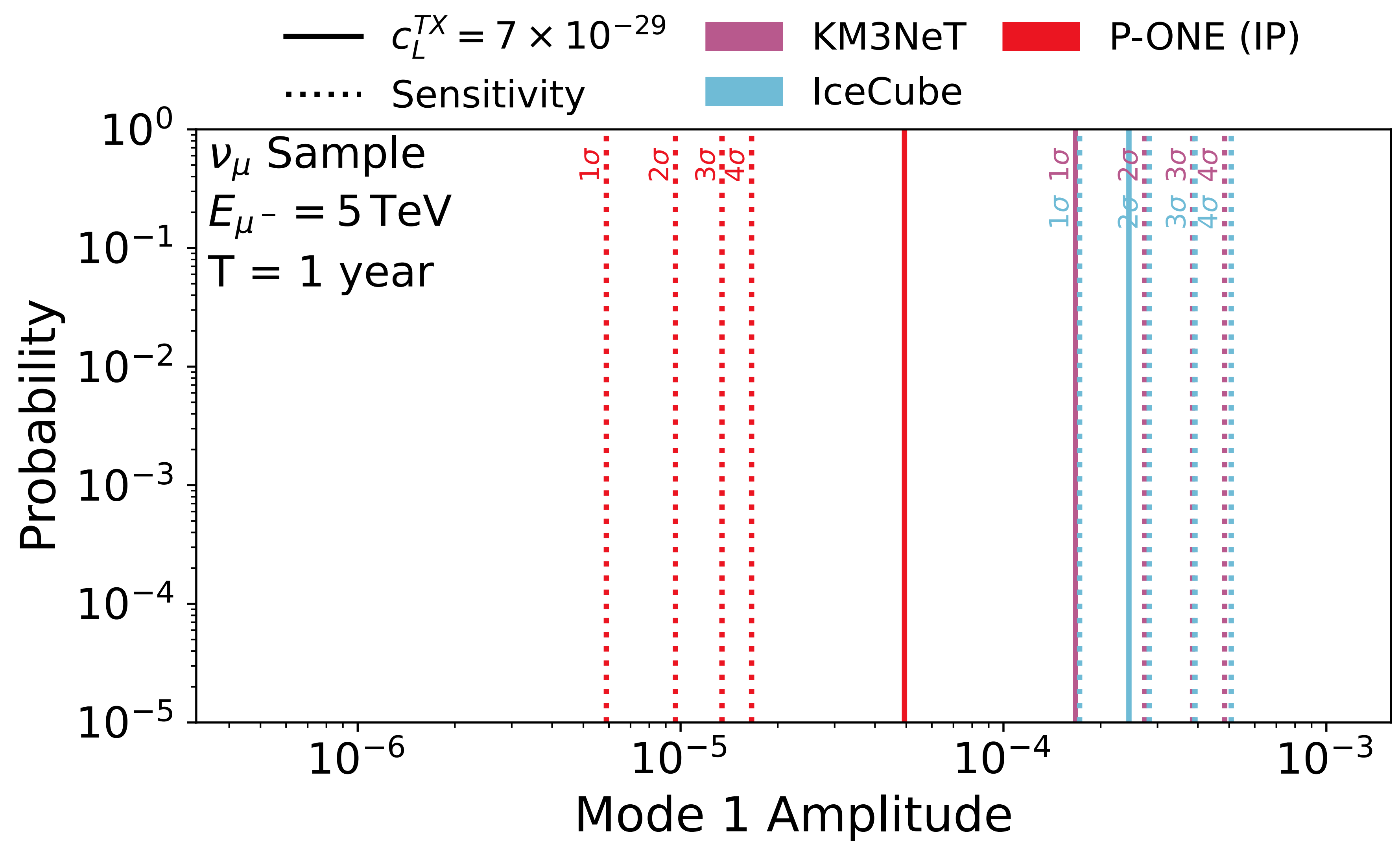
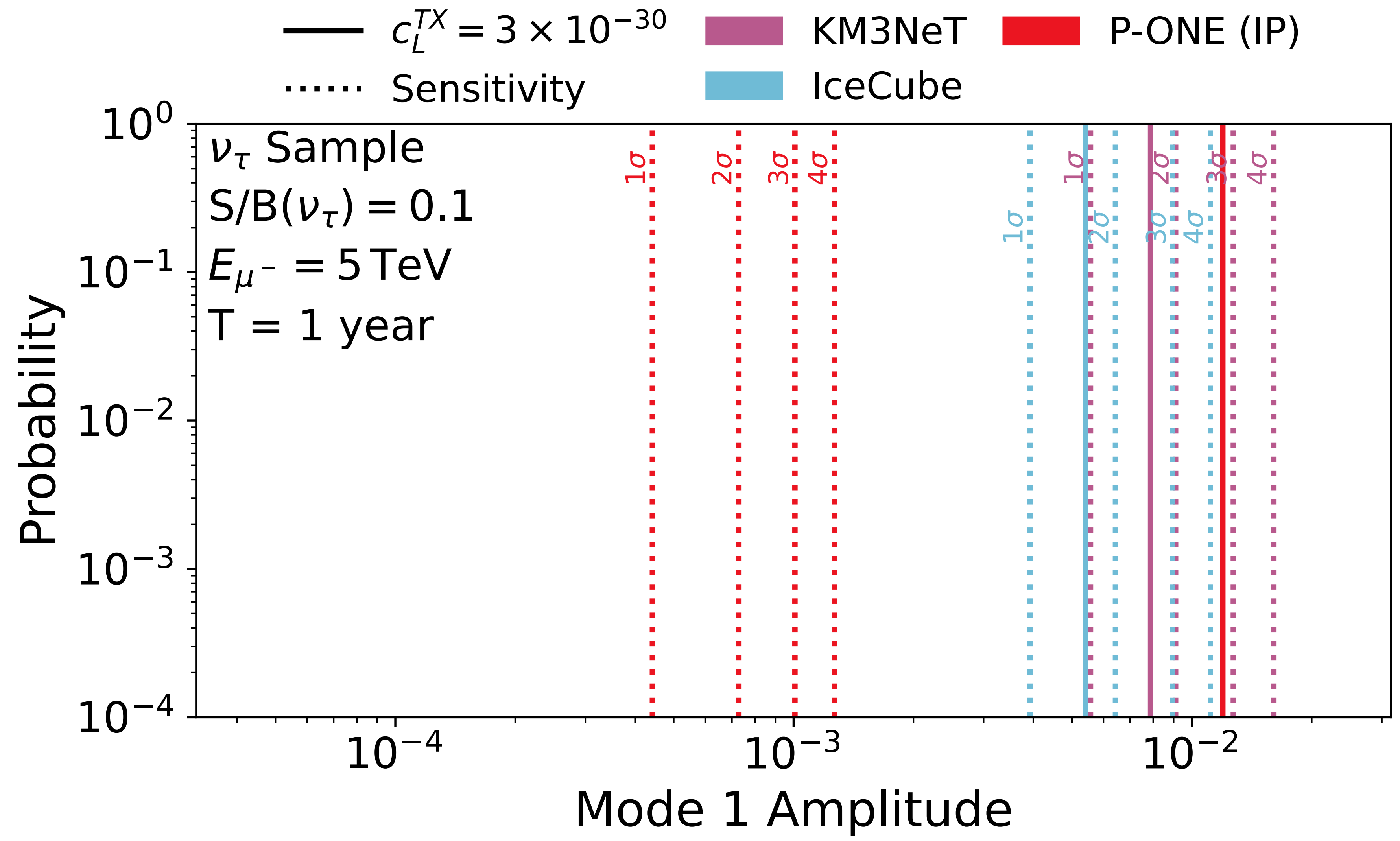
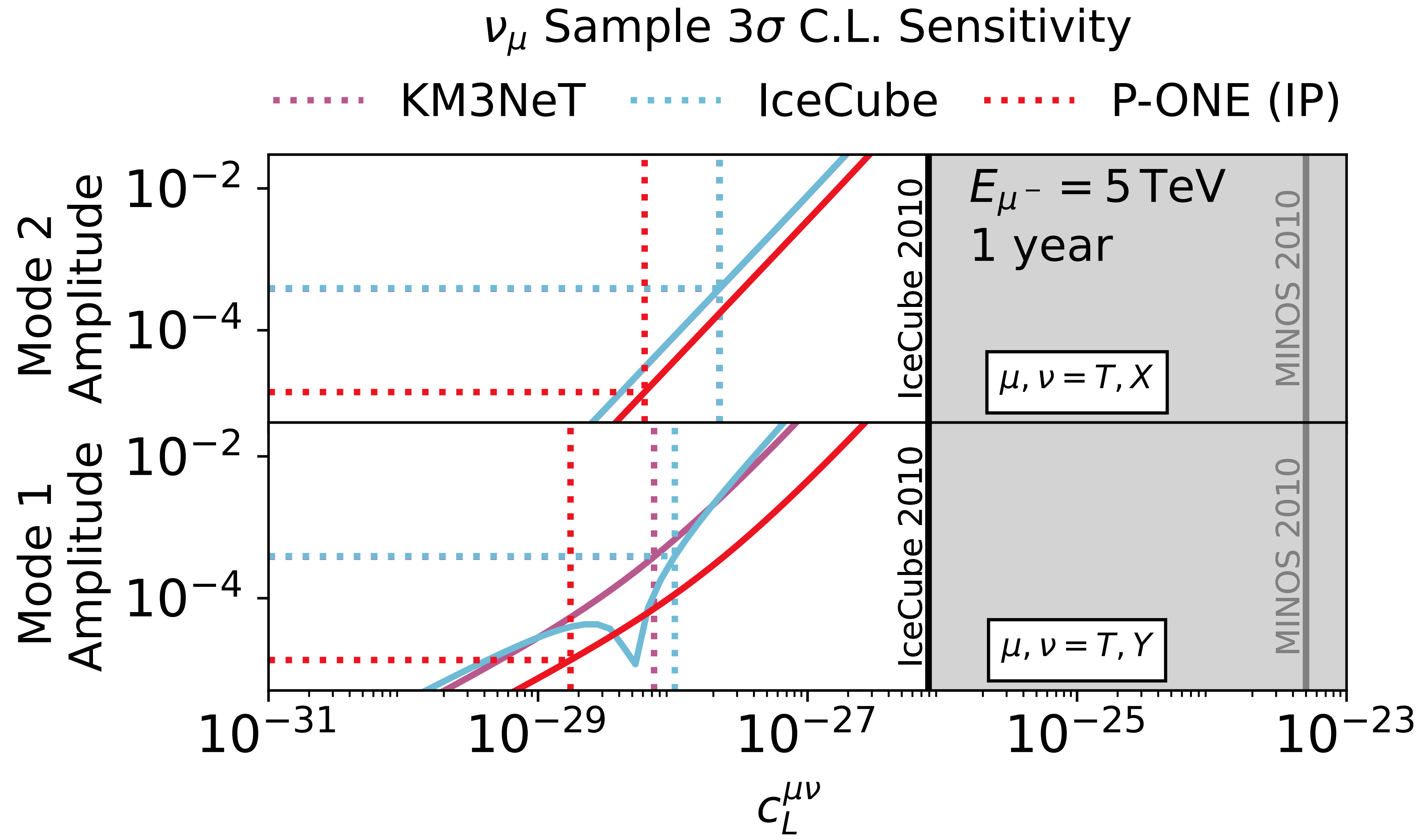
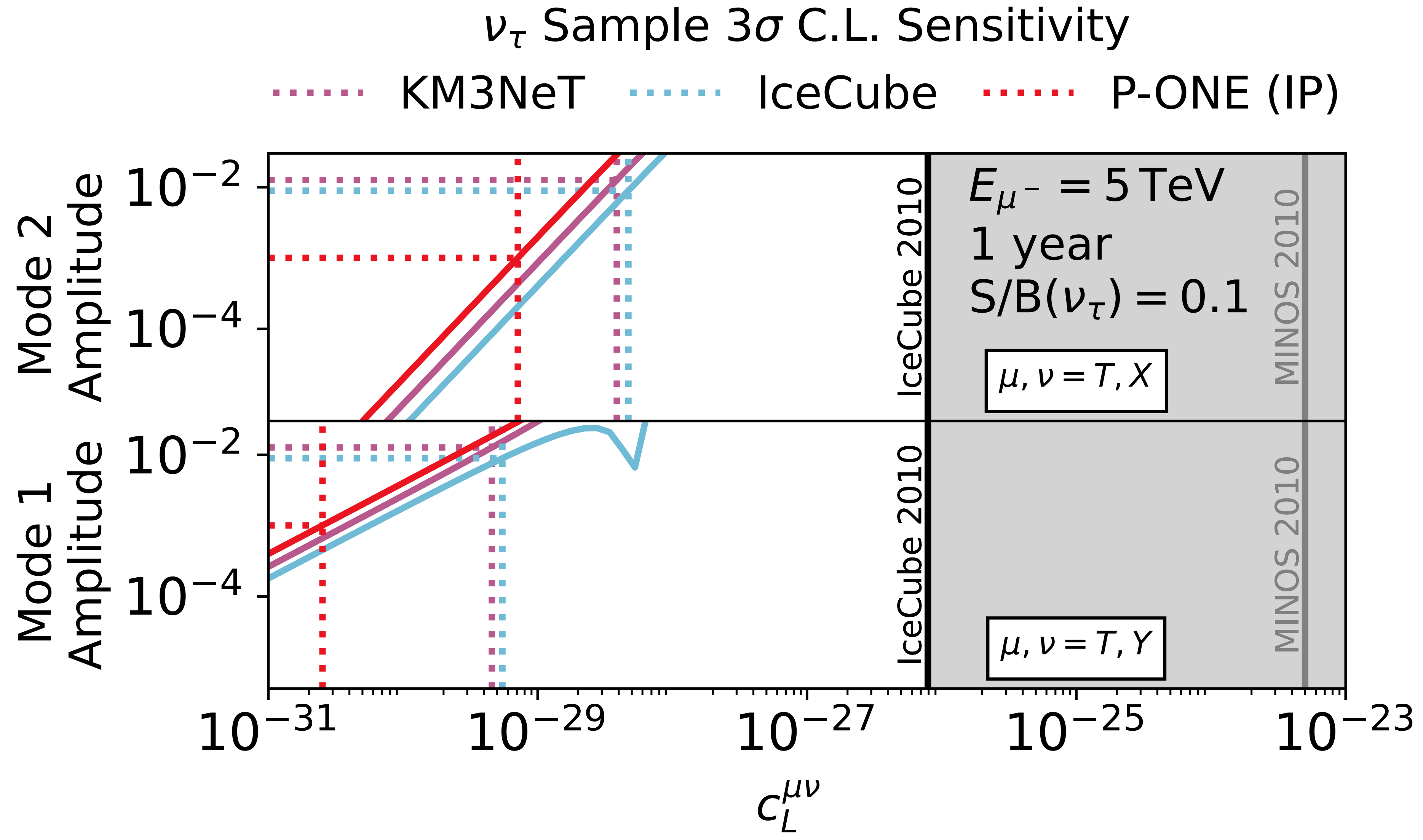




ν kaleidoscopes can improve upon existing constraints by multiple orders of magnitude!





Reaching Double Planck Suppression

$$V_{\mu\tau} \sim a_{\mu\tau}^{(3)} - c_{\mu\tau}^{(4)} \cdot p + a_{\mu\tau}^{(5)} \cdot p^2 - c_{\mu\tau}^{(6)} \cdot p^3 + \ldots$$

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We have been investigating these

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Many quantum gravity theories predict higher-dimension operators at the Planck scale [Kostelecký+ 2011]

$$a^{(5)} \sim E_P^{-1} \qquad c^{(6)} \sim E_P^{-2} \qquad E_P = 1.22 \times 10^{19}\ \text{GeV}$$

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Configuration	KM3NeT	IceCube	P-ONE (IP)
ν_μ sample, $E_\mu = 5$ TeV	$2.8 \times 10^3/E_P^2$	$1.2 \times 10^3/E_P^2$	$5.3 \times 10^2/E_P^2$
ν_τ-enriched sample, $E_\mu = 5$ TeV	$26/E_P^2$	$17/E_P^2$	$2.1/E_P^2$
ν_μ sample, $E_\mu = 50$ TeV	$11/E_P^2$	$5.3/E_P^2$	$1.9/E_P^2$

Sensitivity to $c^{(6)}$ in units of E_P^{-2}

Reaching Double Planck Suppression

$$V_{\mu\tau} \sim a^{(3)}_{\mu\tau} - c^{(4)}_{\mu\tau} \cdot p + a^{(5)}_{\mu\tau} \cdot p^2 - c^{(6)}_{\mu\tau} \cdot p^3 + \dots$$

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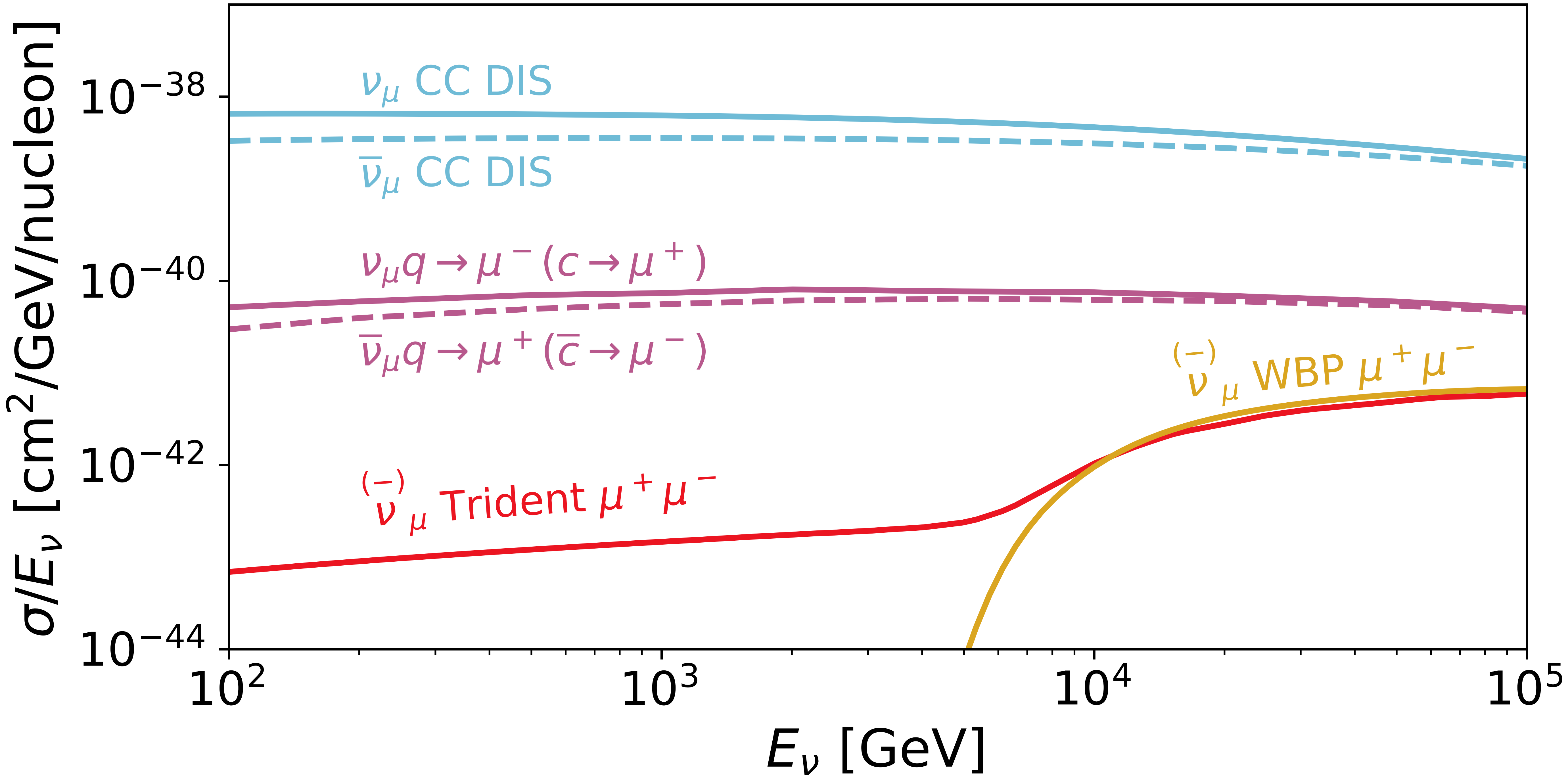
Sensitivity to $c^{(6)}$ in units of E_P^{-2}

First terrestrial access to double-Planck-suppressed Lorentz violation!

Bonus Events: Unprecedented Rates of Rare Neutrino Interactions Producing $\mu^+\mu^-$ Pairs

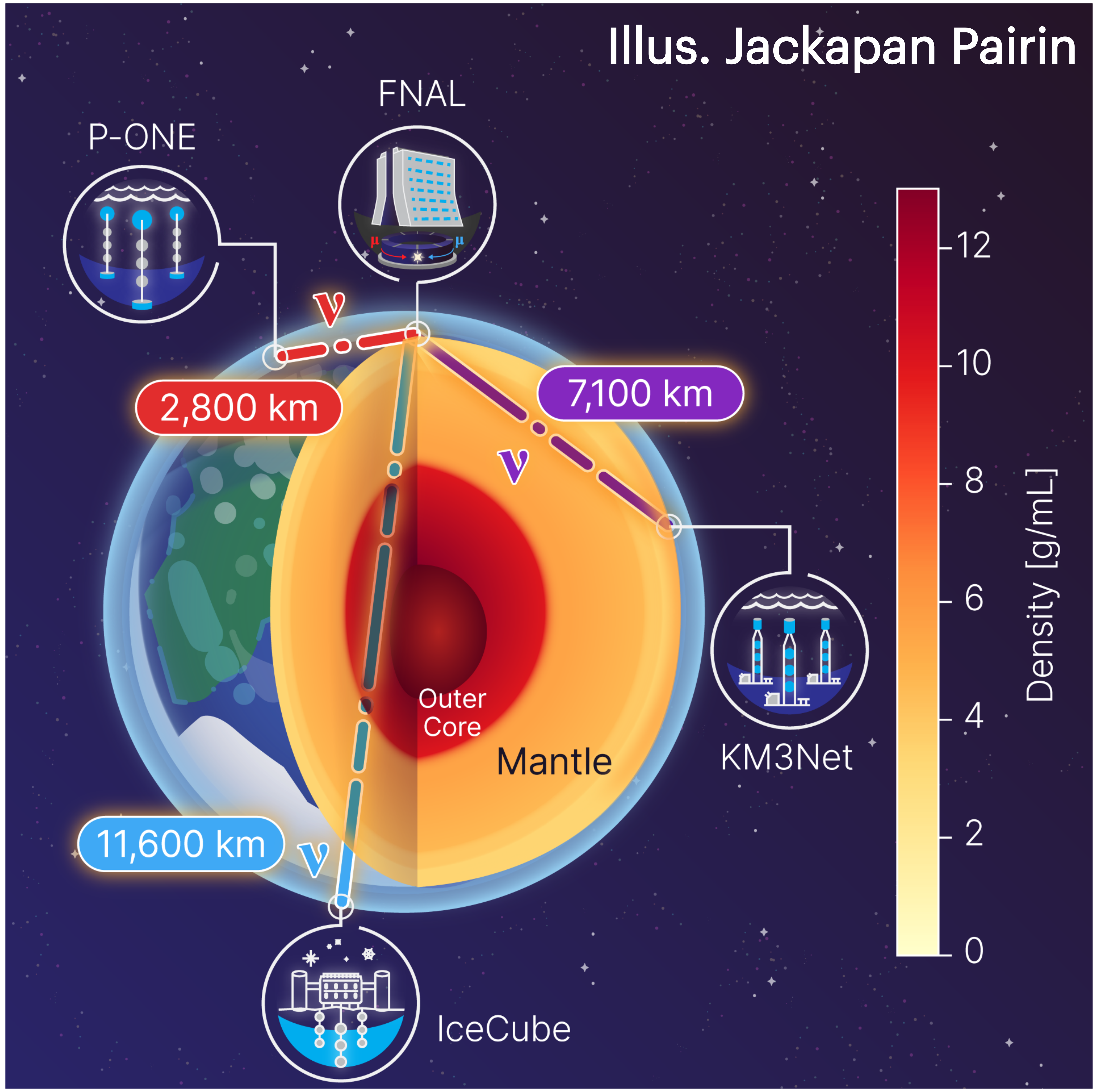


Events per year:

Process	KM3NeT	IceCube	P-ONE (IP)
ν_μ CC DIS	1.7×10^8	1.6×10^8	1.3×10^{11}
$\nu_\mu q \to \mu^-(c \to \mu^+)$	2.2×10^6	2.1×10^6	1.8×10^9
ν_μ Trident $\mu^+\mu^-$	5.2×10^3	5×10^3	4.2×10^6
ν_μ WBP $\mu^+\mu^-$	3.6	3.6	2.8×10^3

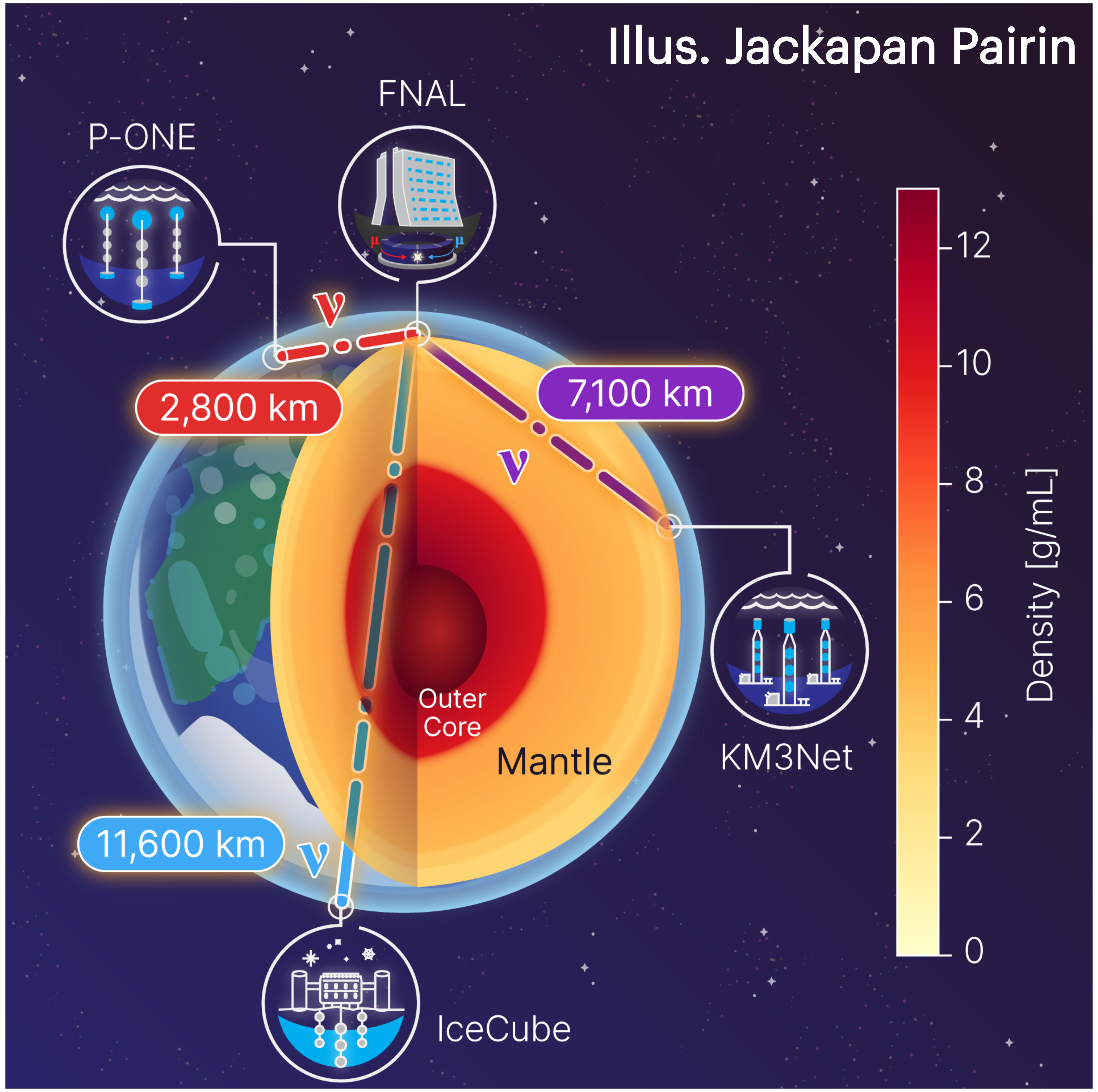
See Zhou+ 2021 and S. Sarkar Thesis (2023) for discussions on tagging dimuons in IceCube

In Sum


Illus. Jackapan Pairin
FNAL
P-ONE
2,800 km
7,100 km
11,600 km
Outer
Core
Mantle
KM3Net
IceCube
12
10
8
6
4
2
0
Density [g/mL]

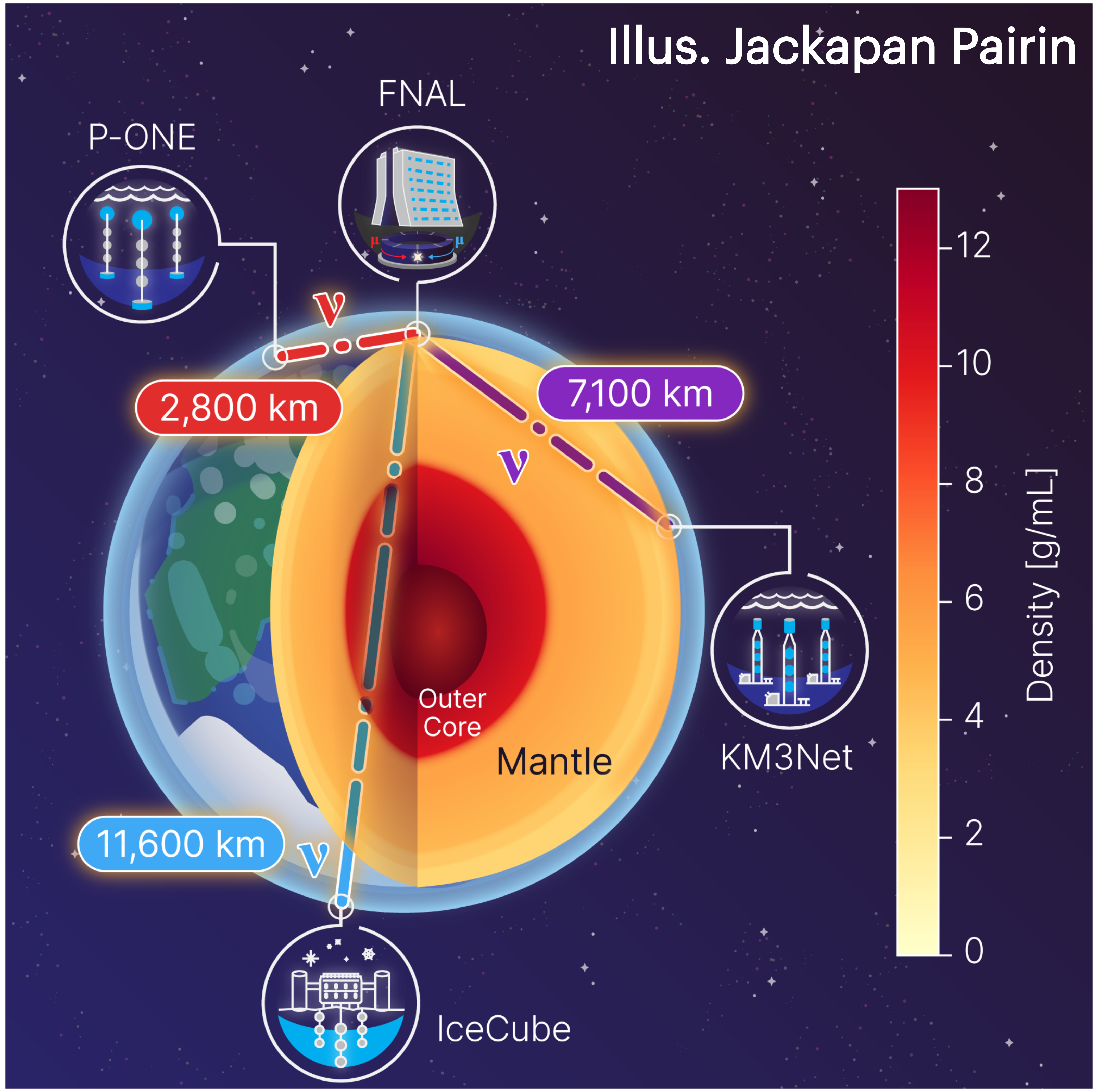
In Sum

- Neutrino kaleidoscopes offer a unique opportunity for a high-intensity, high-energy, & long-baseline neutrino experiment



In Sum

- Neutrino kaleidoscopes offer a unique opportunity for a high-intensity, high-energy, & long-baseline neutrino experiment
- Physics capabilities include:



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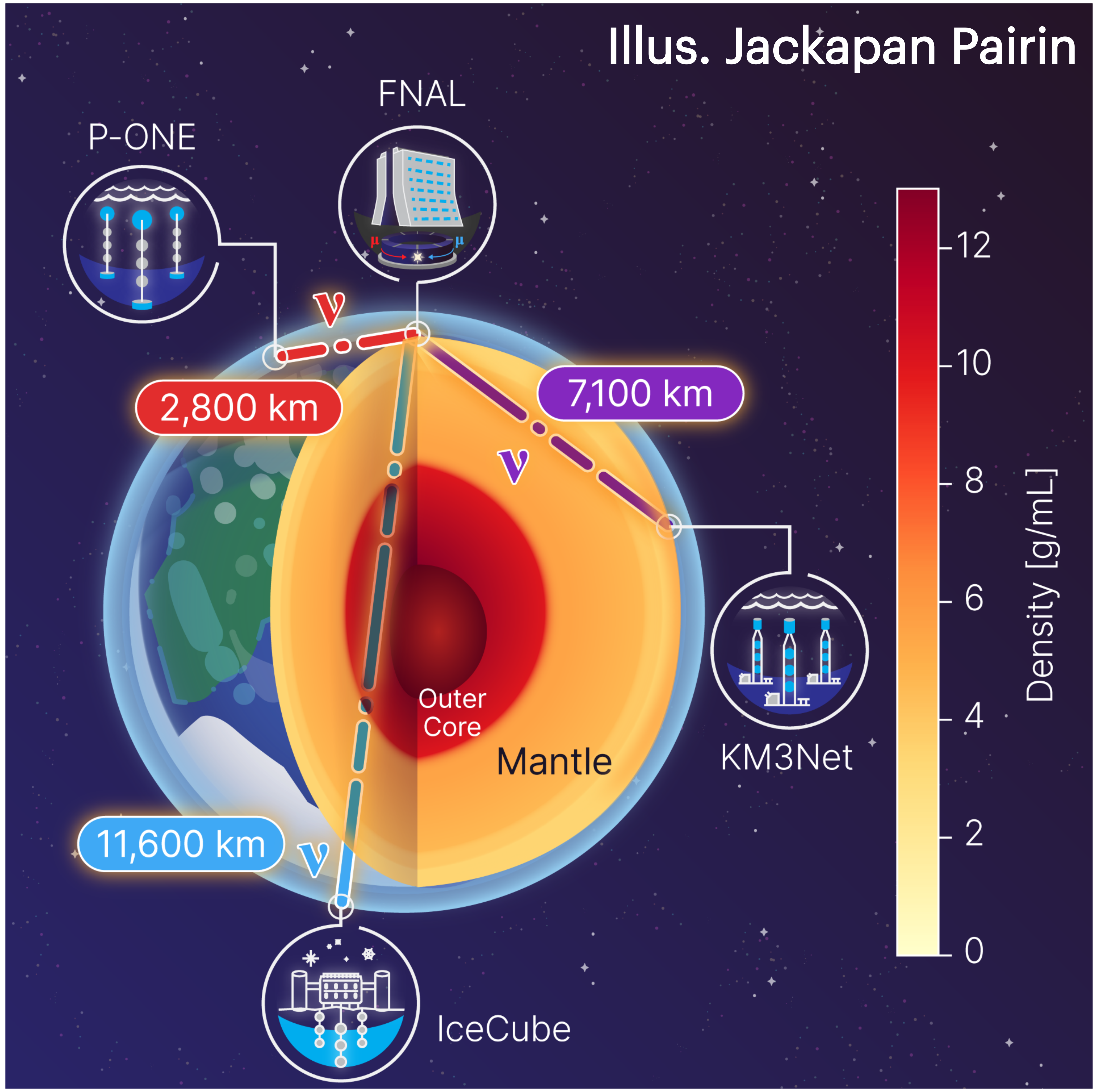
  1. Strong sensitivity to eV-scale sterile neutrinos



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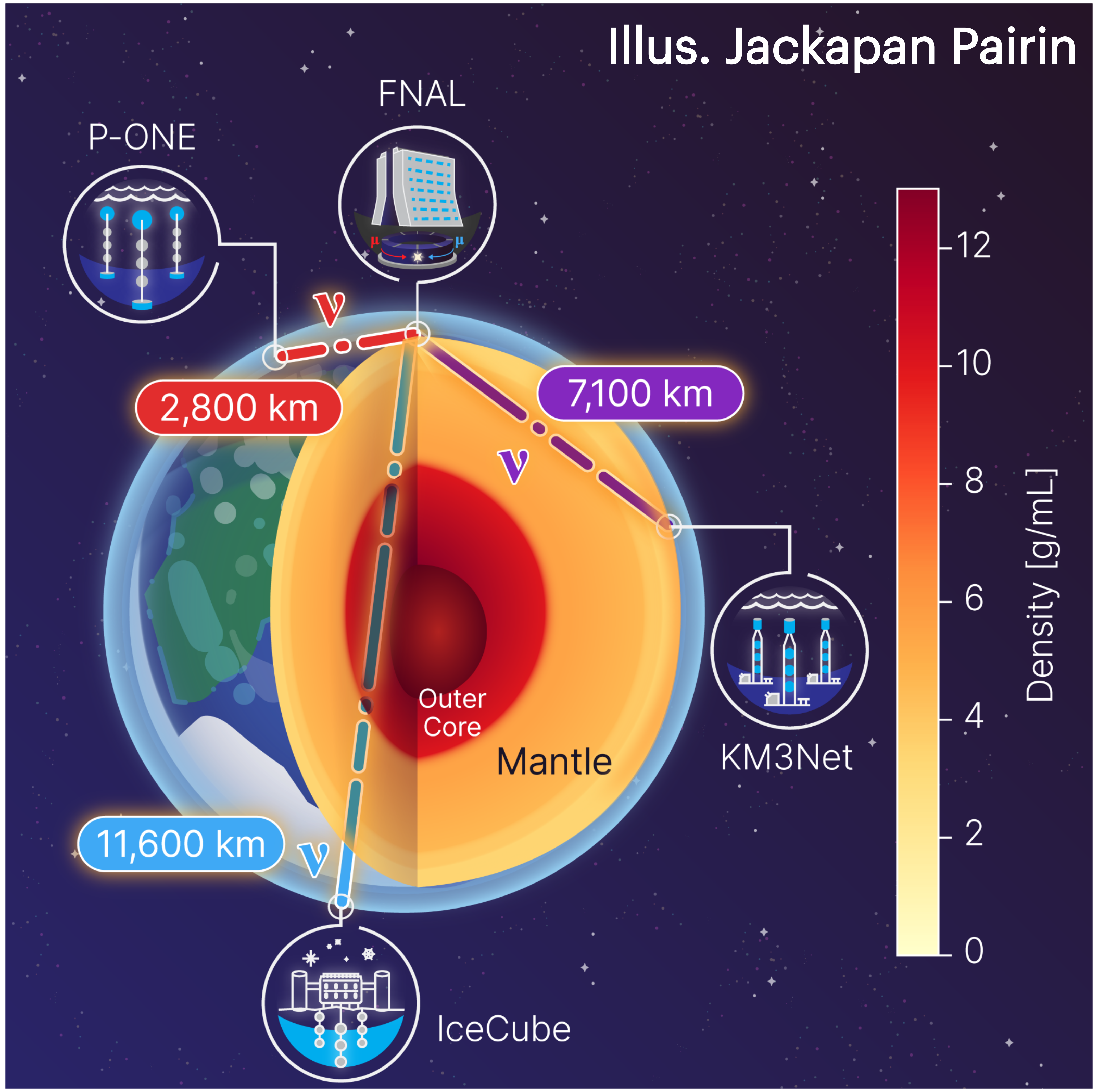
  2. Neutrino oscillations from double Planck-suppressed Lorentz variation



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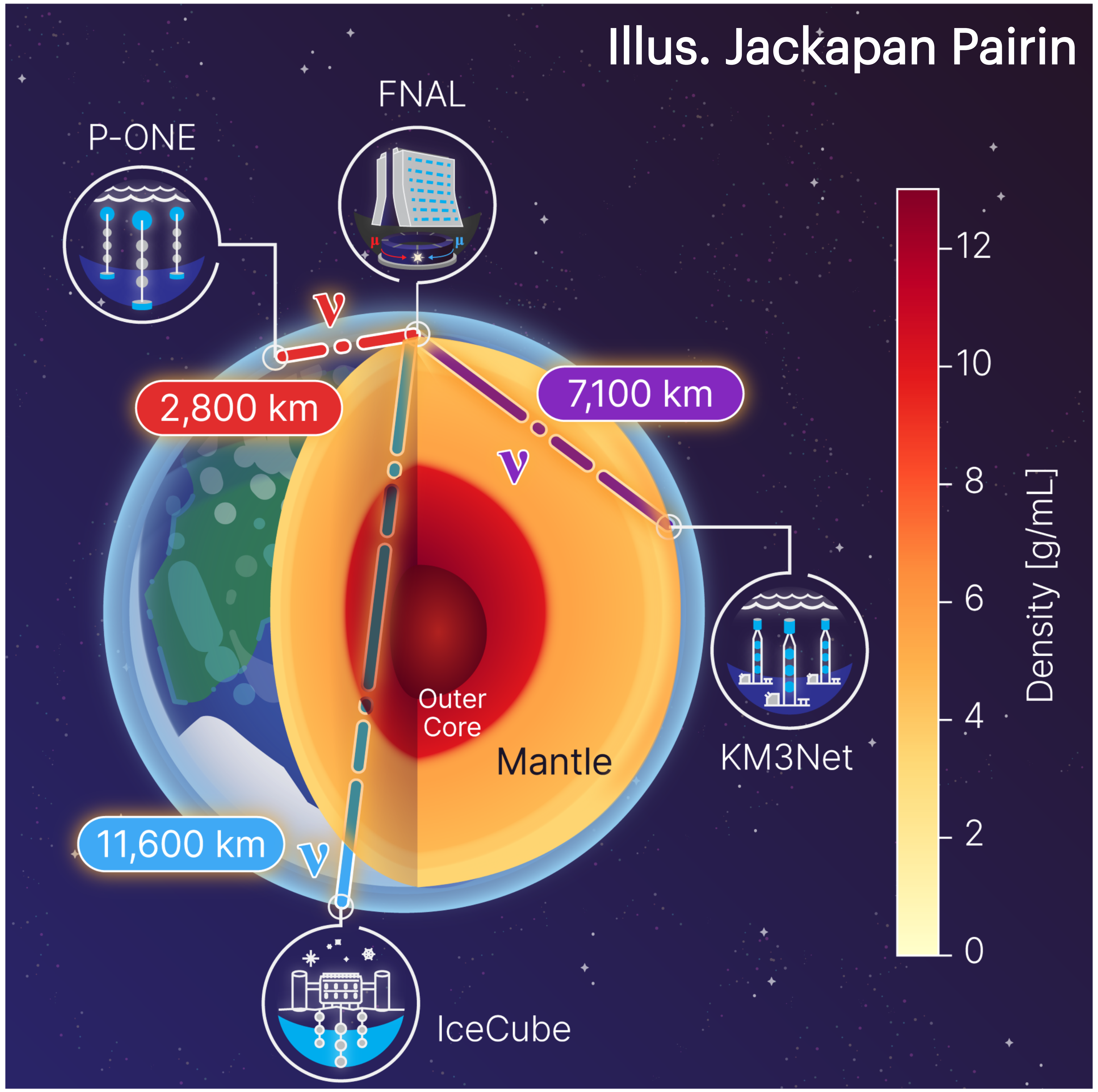

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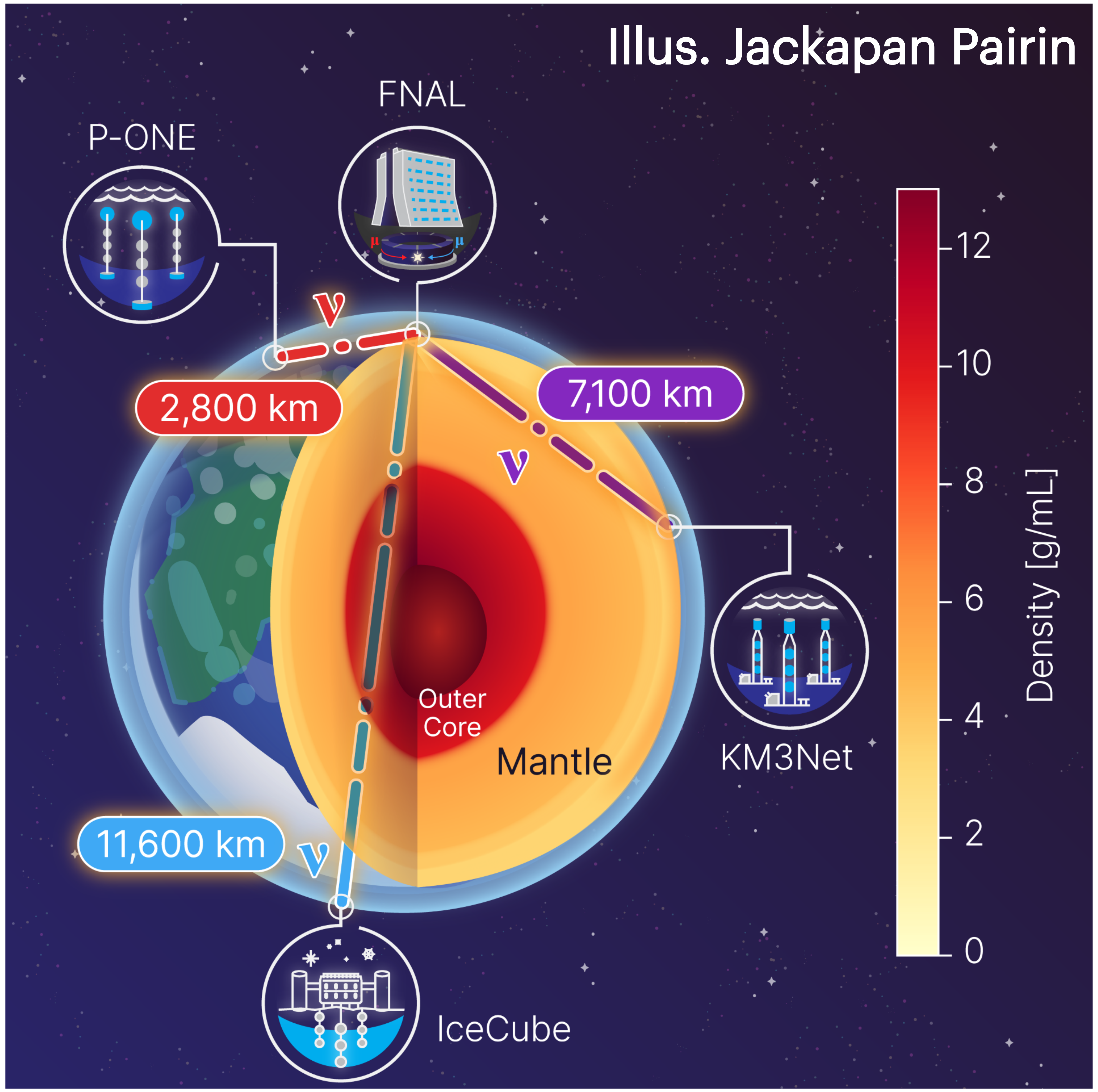
  4. Probing matter potentials from non-standard interactions



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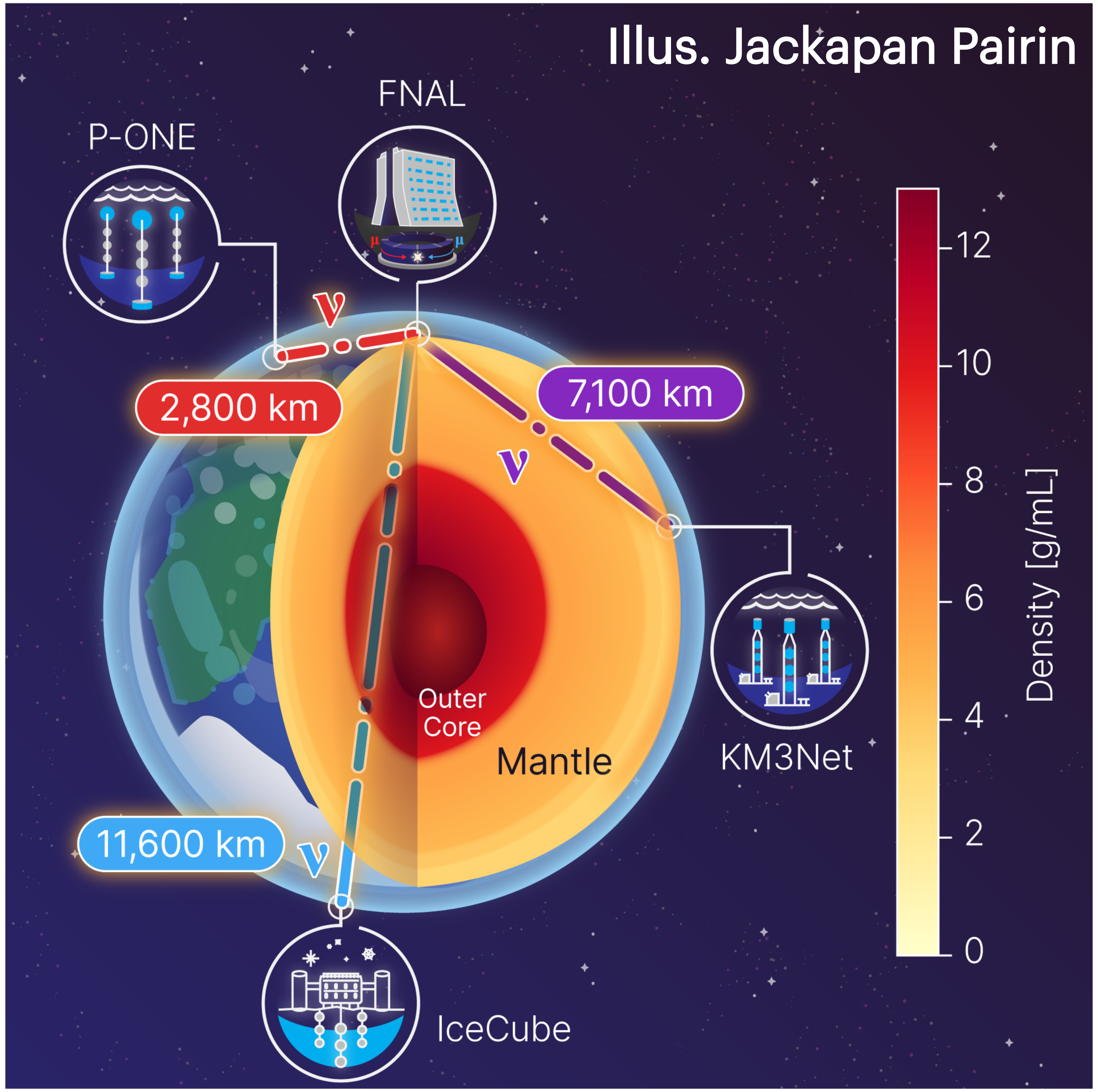
  2. Neutrino oscillations from double Planck-suppressed Lorentz variation
  3. Rare $\mu^+\mu^-$ neutrino interactions
  4. Probing matter potentials from non-standard interactions
  5. More…?



Thank you!

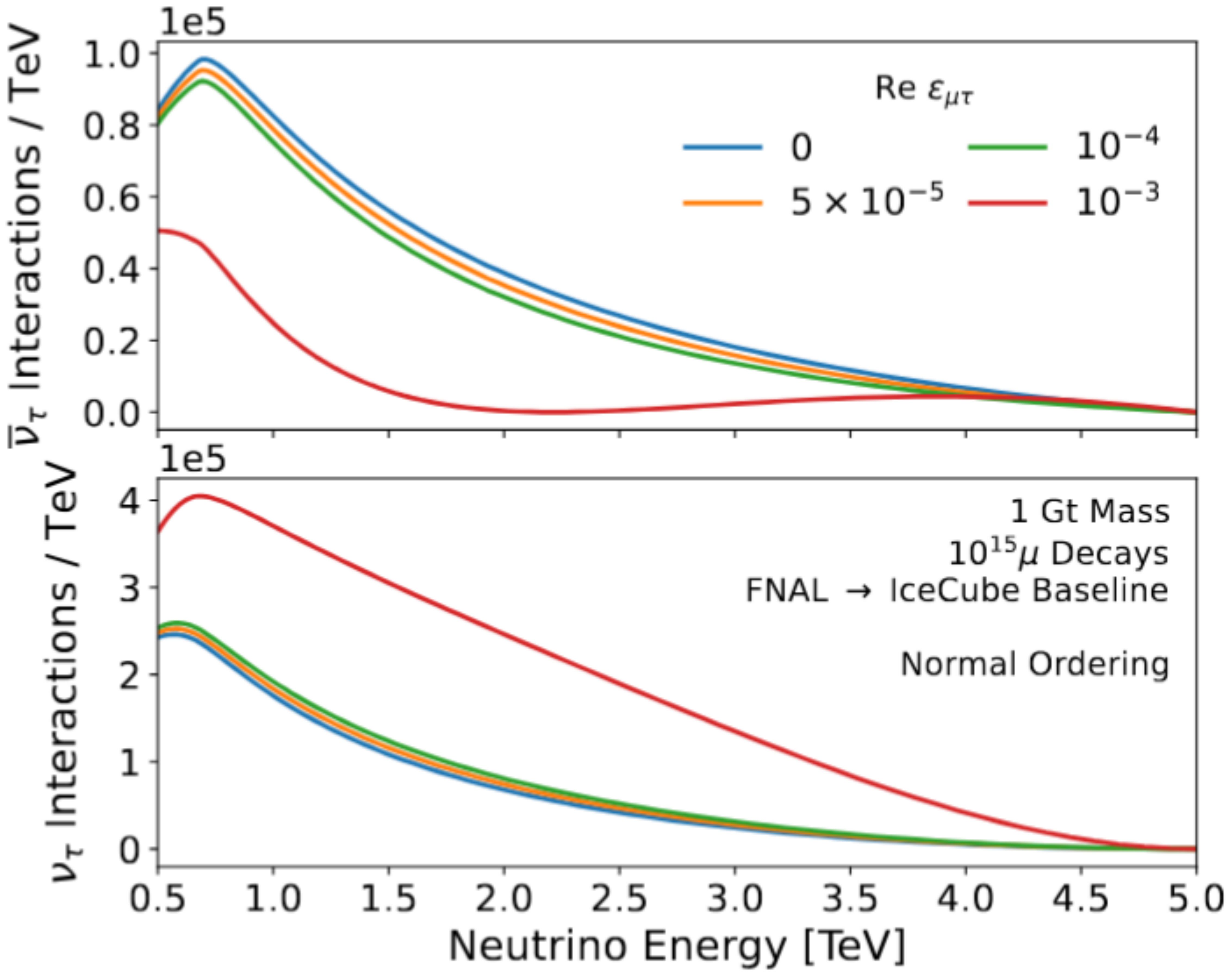
And again, here is our pre-pre-print 🙂

Backup Slides

Bonus Oscillations: Neutrino Matter Potential

- A small muon-tau (*off diagonal*) matter potential term would have a large impact on the tau neutrino interaction rate

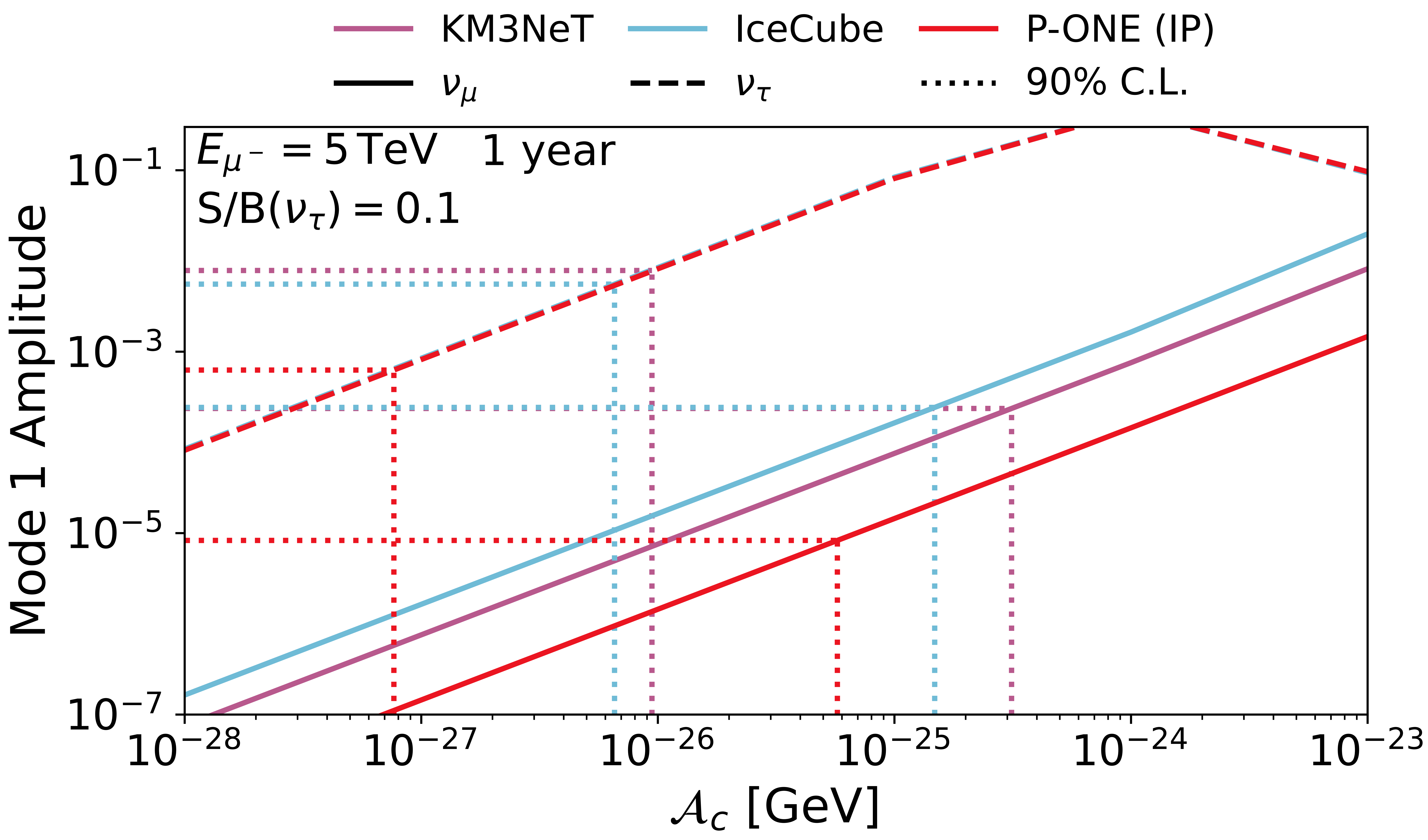
- The effect would be different in direction for tau and anti-tau neutrinos (for a real potential)



Can the Angular Dispersion be Made Small Enough?

- Transverse Normalized Emittance 25 um*rad
- At 5 TeV, geometric emittance: 0.5 nm*rad

- Beam spot size in **ring:** ~5 mm
- Beam angular dispersion in beam: ~0.1 urad


KM3NeT
IceCube
P-ONE (IP)
ν_μ
ν_τ
90% C.L.
$E_{\mu^-} = 5\,\mathrm{TeV}$ 1 year
$\mathrm{S/B}(\nu_\tau) = 0.1$
Mode 1 Amplitude
$\mathcal{A}_c$ [GeV]
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-28}
10^{-27}
10^{-26}
10^{-25}
10^{-24}
10^{-23}