Searching for Sterile Neutrinos with IceCube

Rising Stars Symposium in Experimental Particle Physics

September 23rd, 2021

Massachusetts Institute of Technology

Well Established 3ν Mixing Model

Weak Eigenstates

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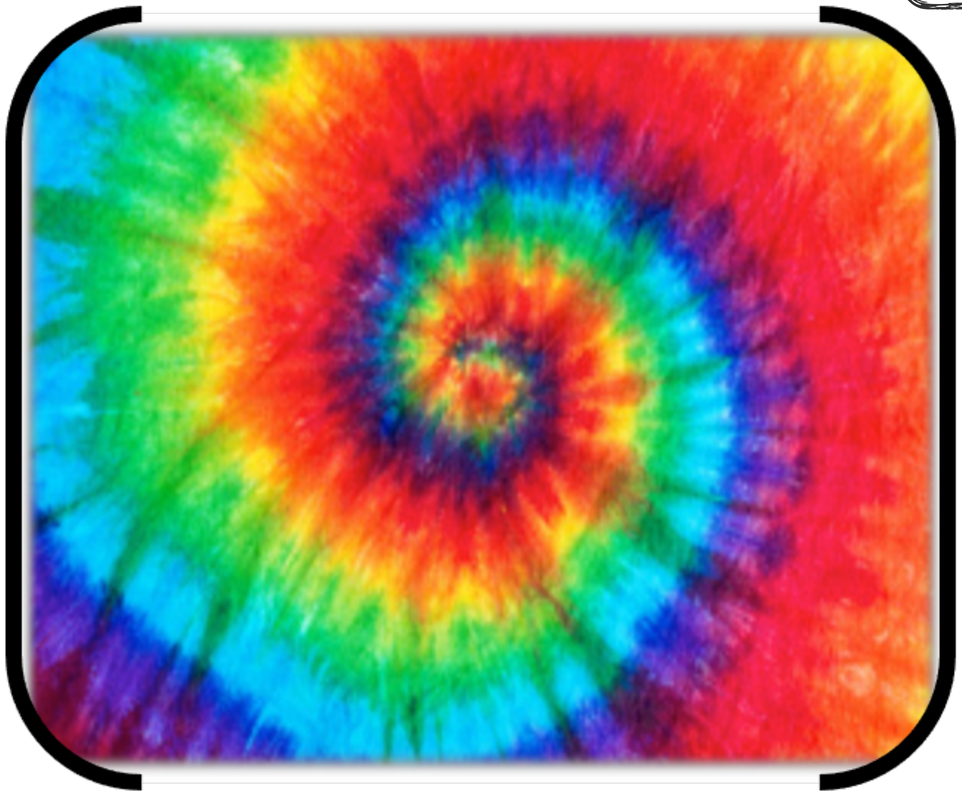
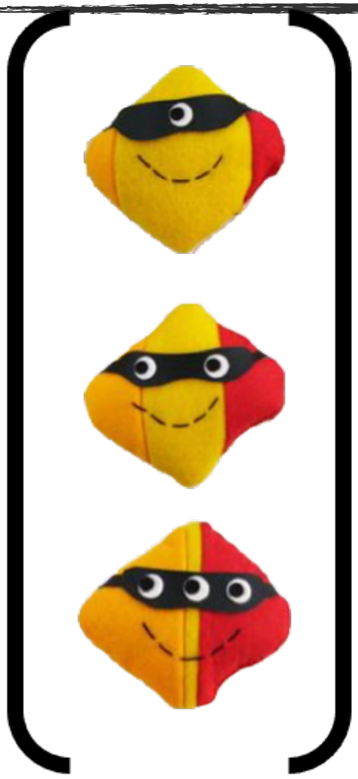


Mixing Matrix



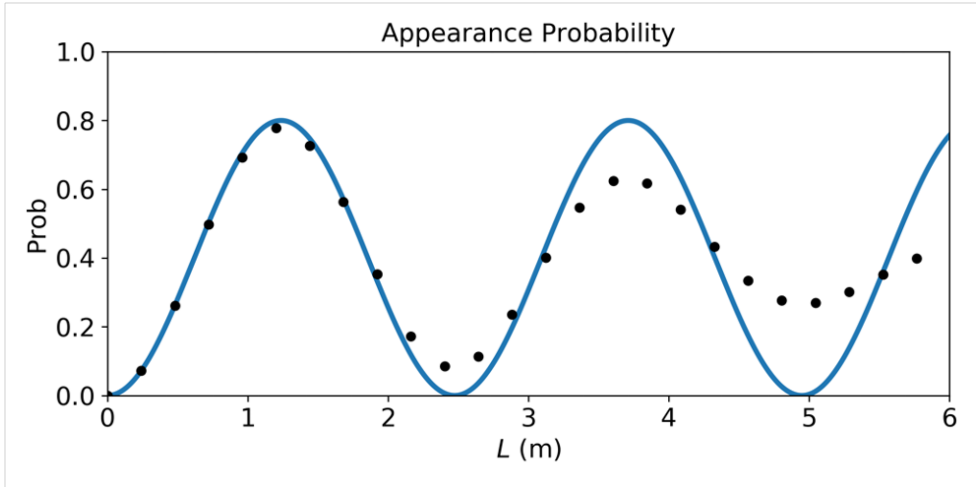
Mass Eigenstates

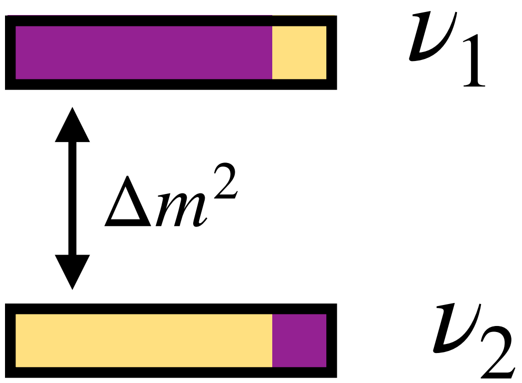
Two Neutrino Oscillation

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\text{eV}^2]L[\text{m}]}{E_\nu[\text{MeV}]}\right)$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E_\nu}\right)$$

$$\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$





$\Delta m^2 = 1$ eV^2

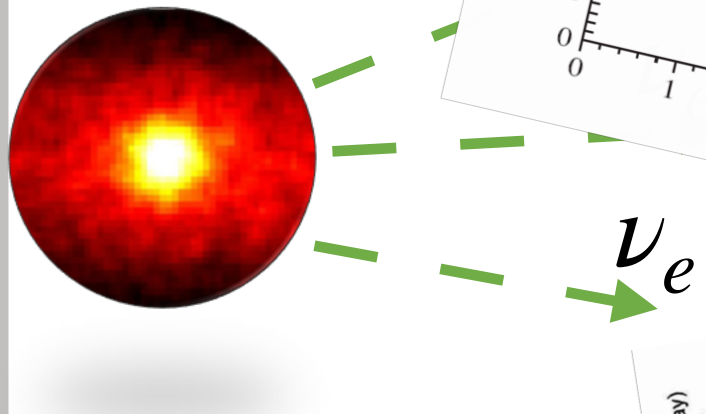
$\sin^2(2\theta) = 0.8$

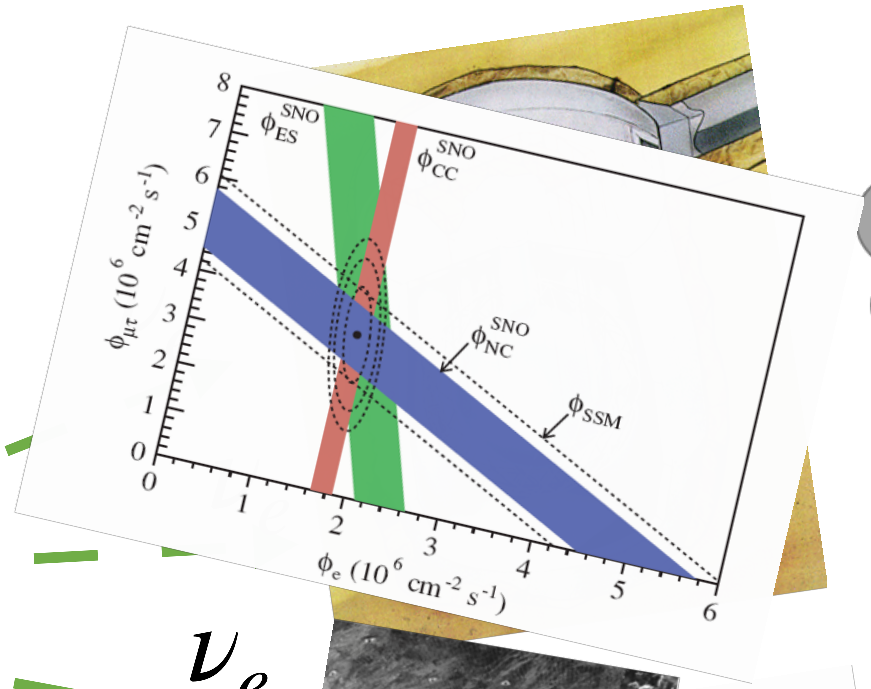
$E_\nu = 1$ MeV

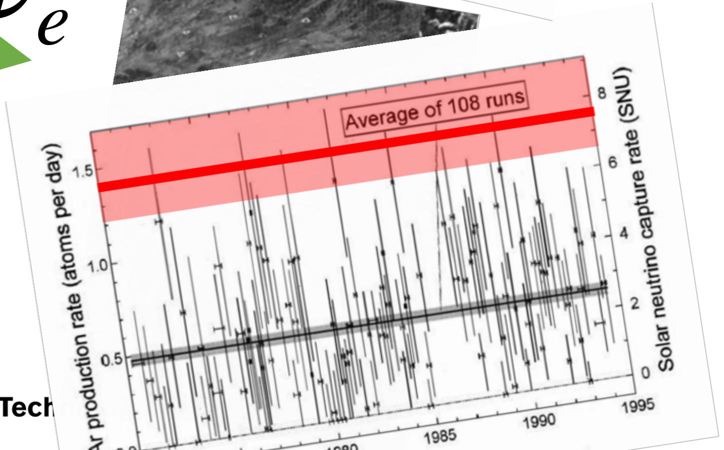
PMNS matrix is commonly written in terms of rotations

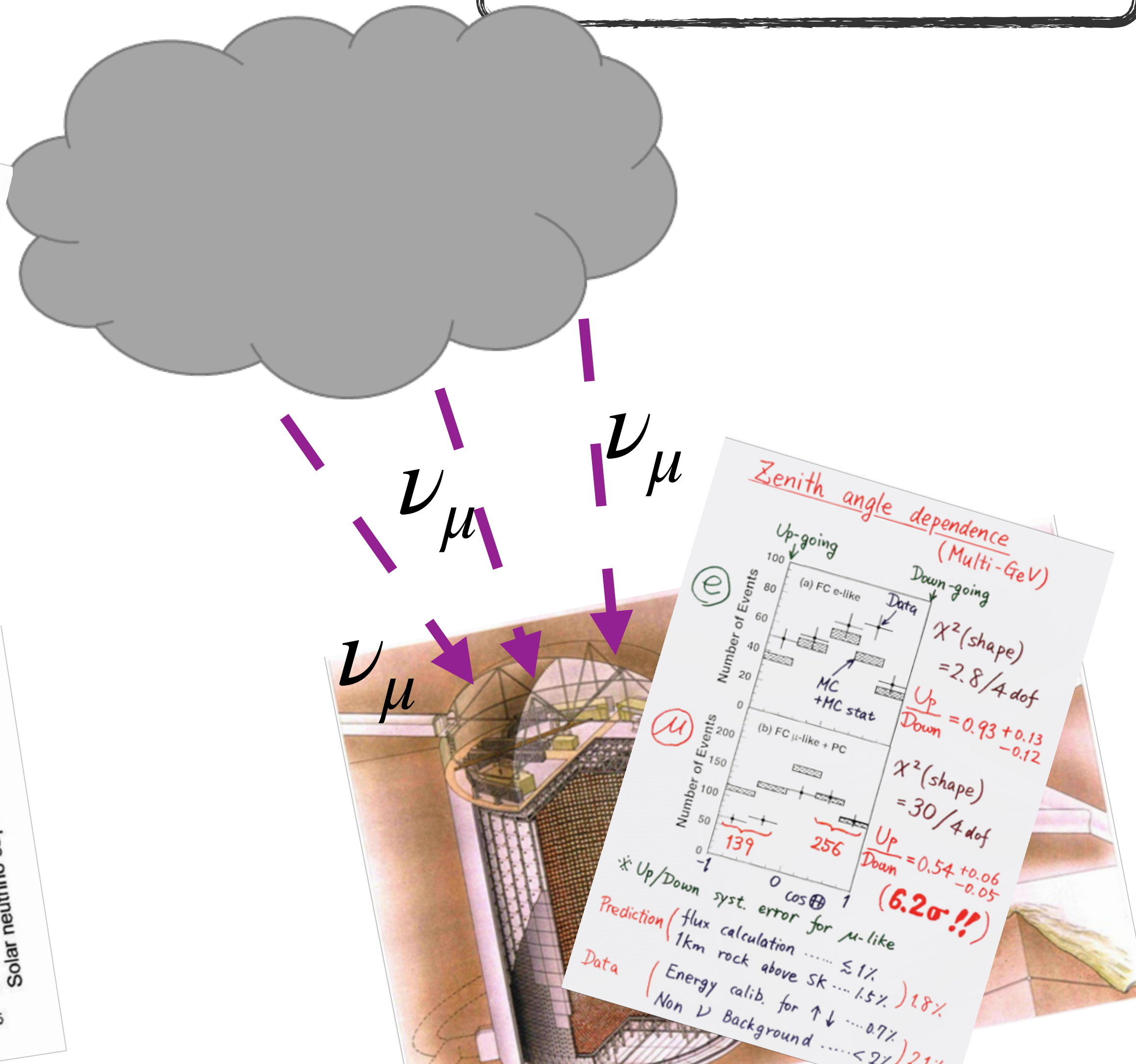
$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Model Resolved Numerous Anomalies



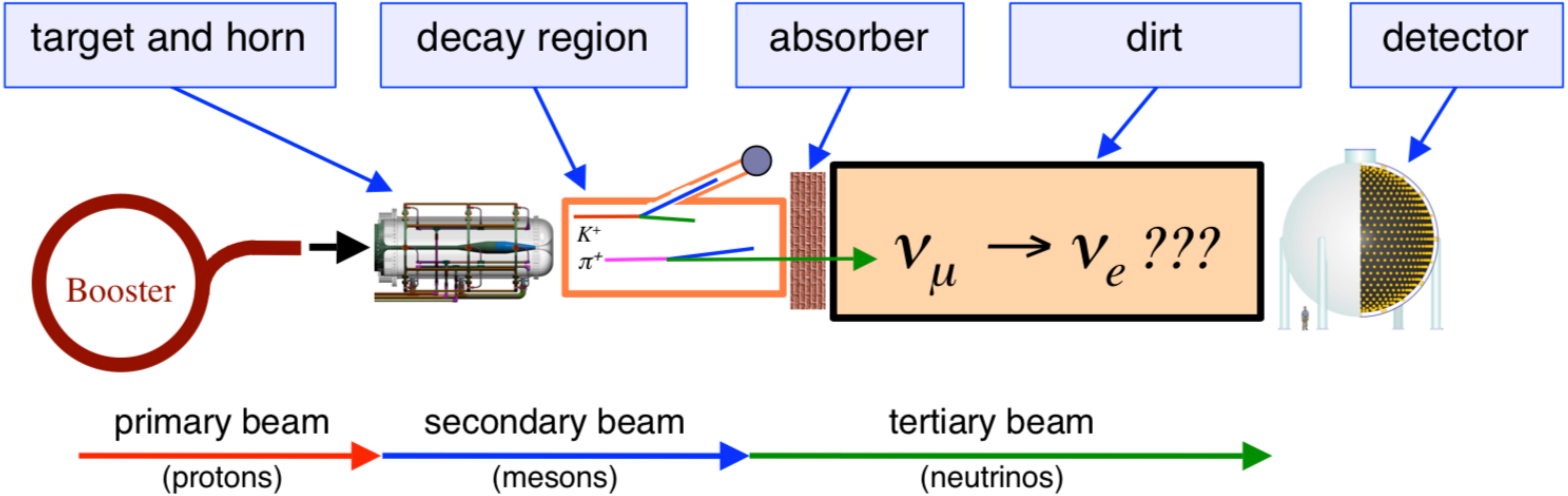






But new anomalies have appeared…

MiniBooNE



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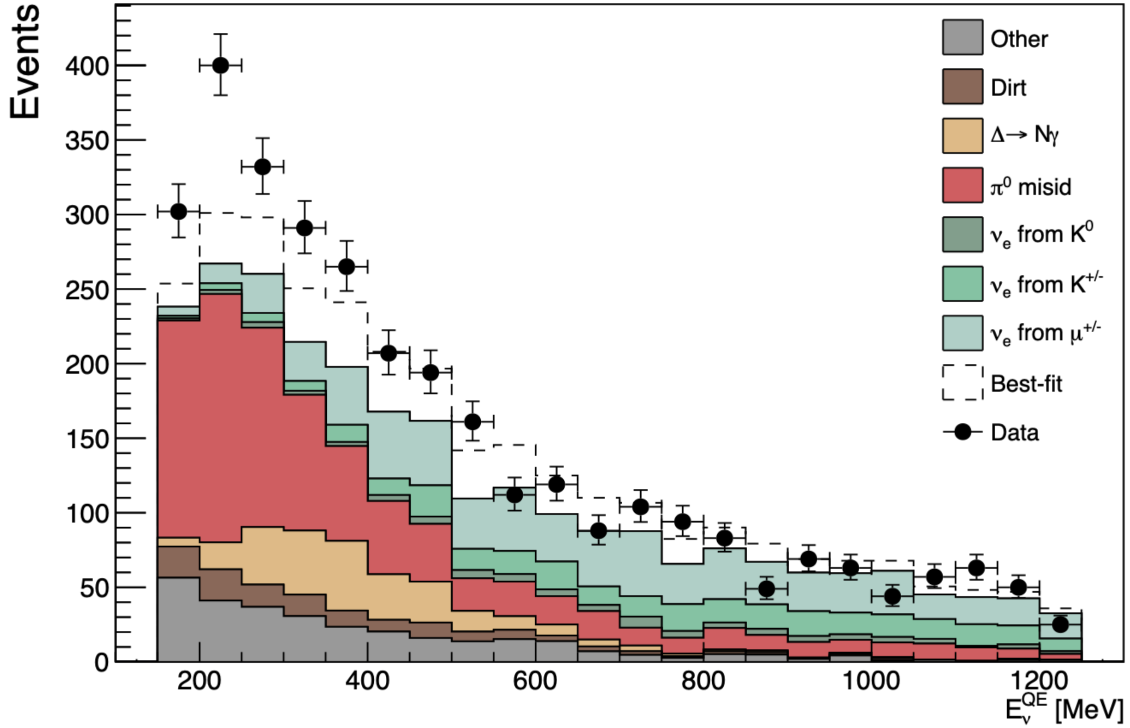
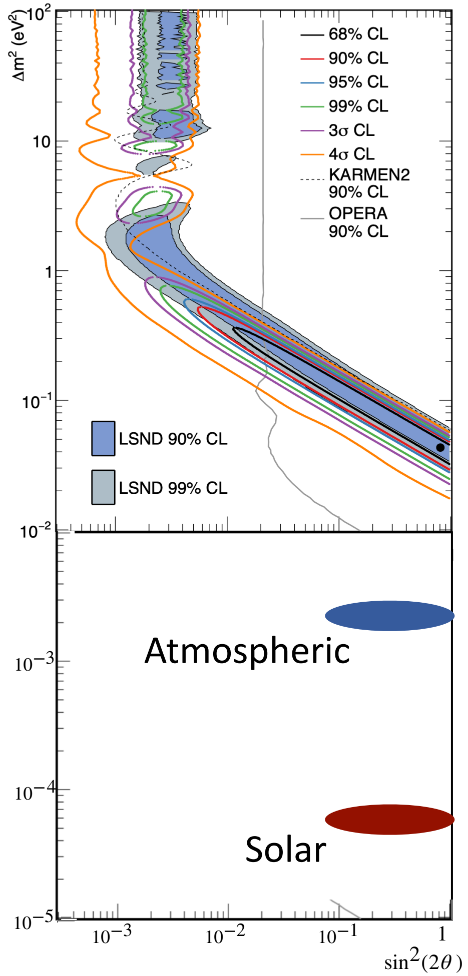
MiniBooNE

With oscillation model, data is inconsistent with SM mass splittings.



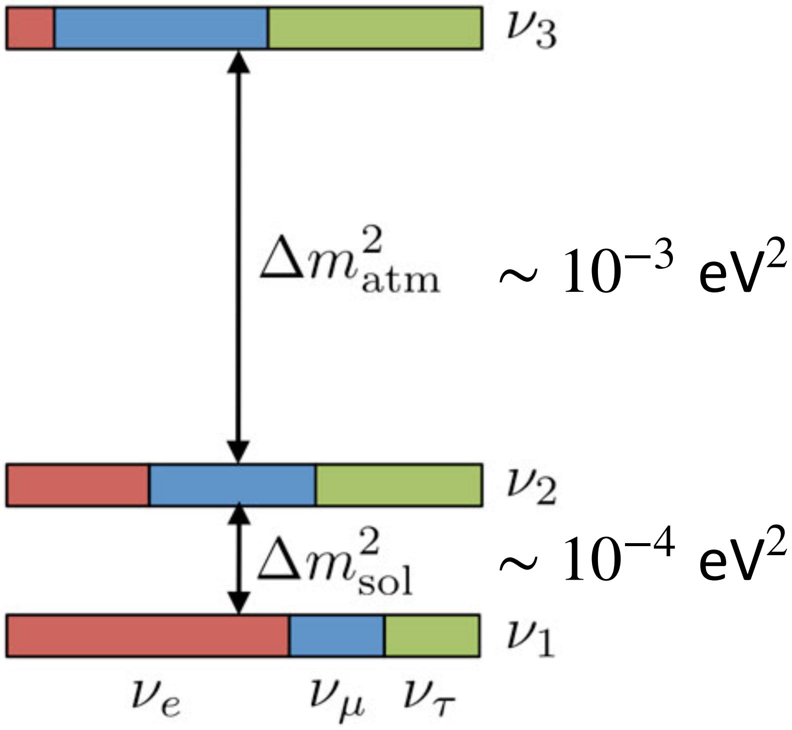


But…

$\Delta m^2 \approx 1$ eV^2 is inconsistent with existing 3ν paradigm.

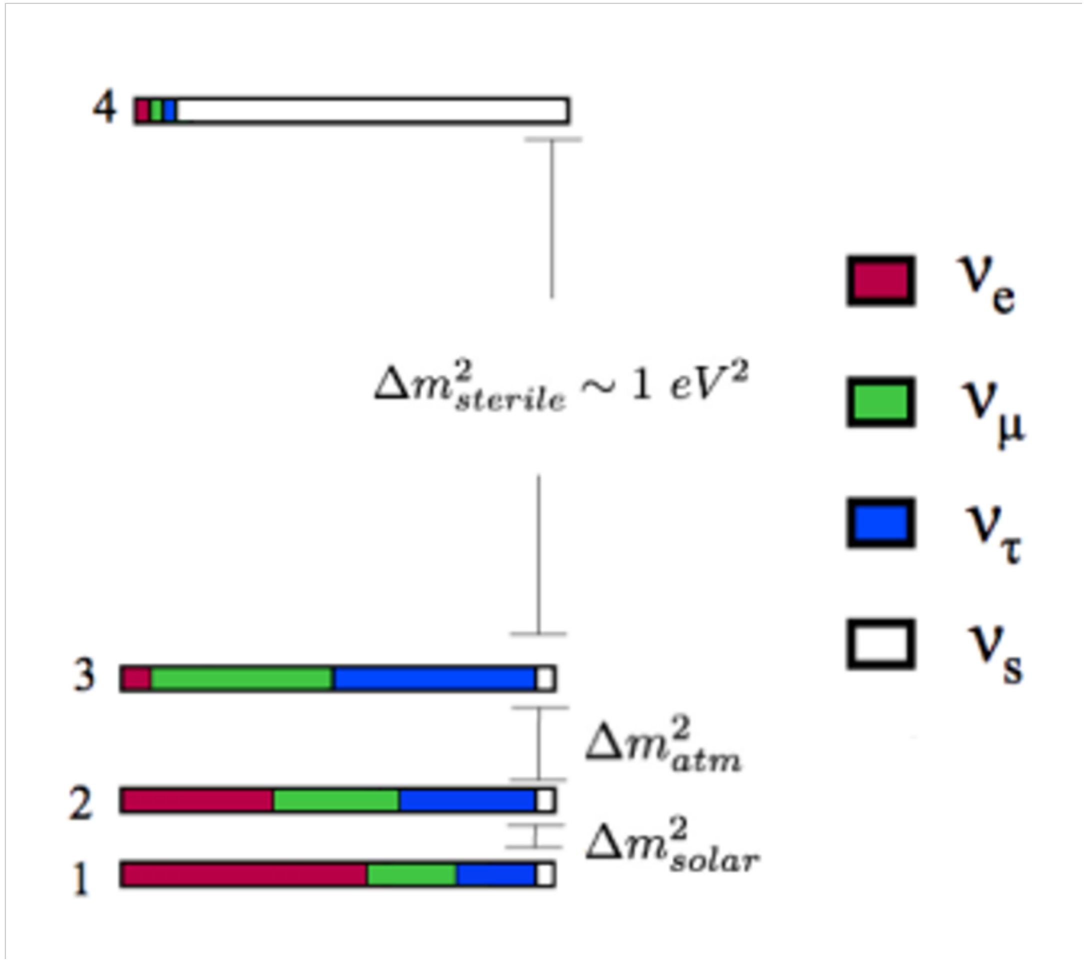
Additional mass state would be required.

If that is the case, the additional neutrino eigenstate cannot interact weakly, thus “sterile.”



Credit: JUNO Collaboration / JGU-Mainz

3+1 Model



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

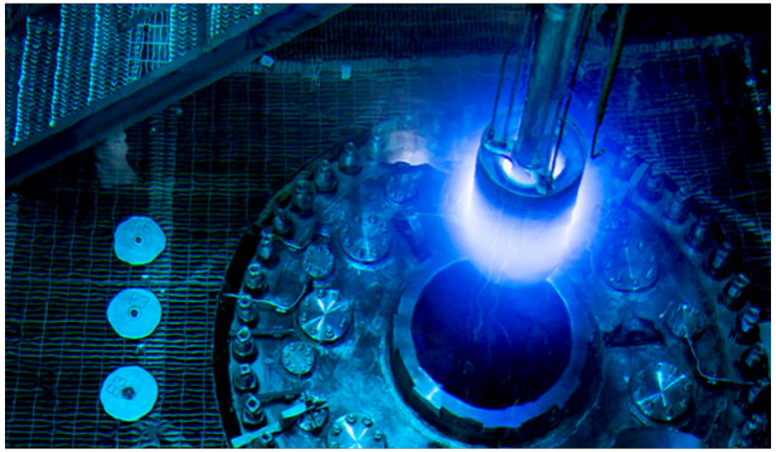
What we've seen before

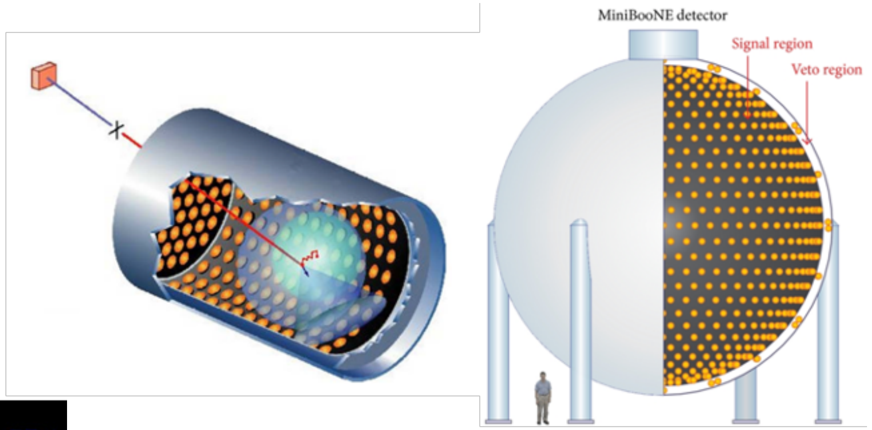
New measurable parameters

$$\Delta m^2_{\text{sterile}} \gg \Delta m^2_{\text{atm}} > \Delta m^2_{\text{solar}}$$

Other experiments have seen sterile neutrino-like signatures

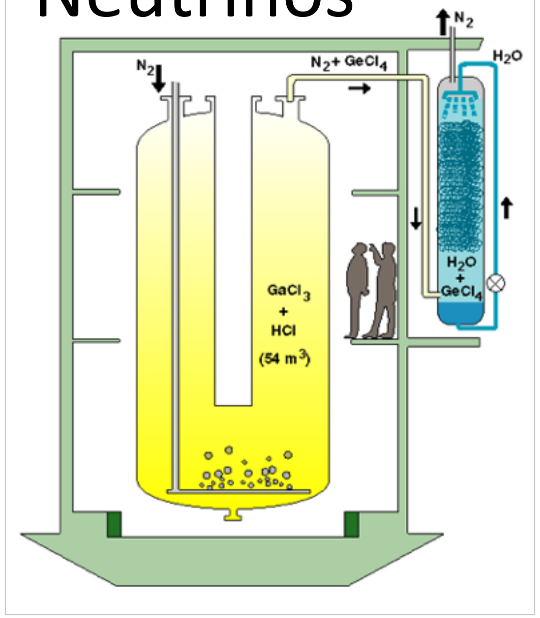
Reactor Neutrinos





Accelerator Neutrinos

Radioactive Source Neutrinos



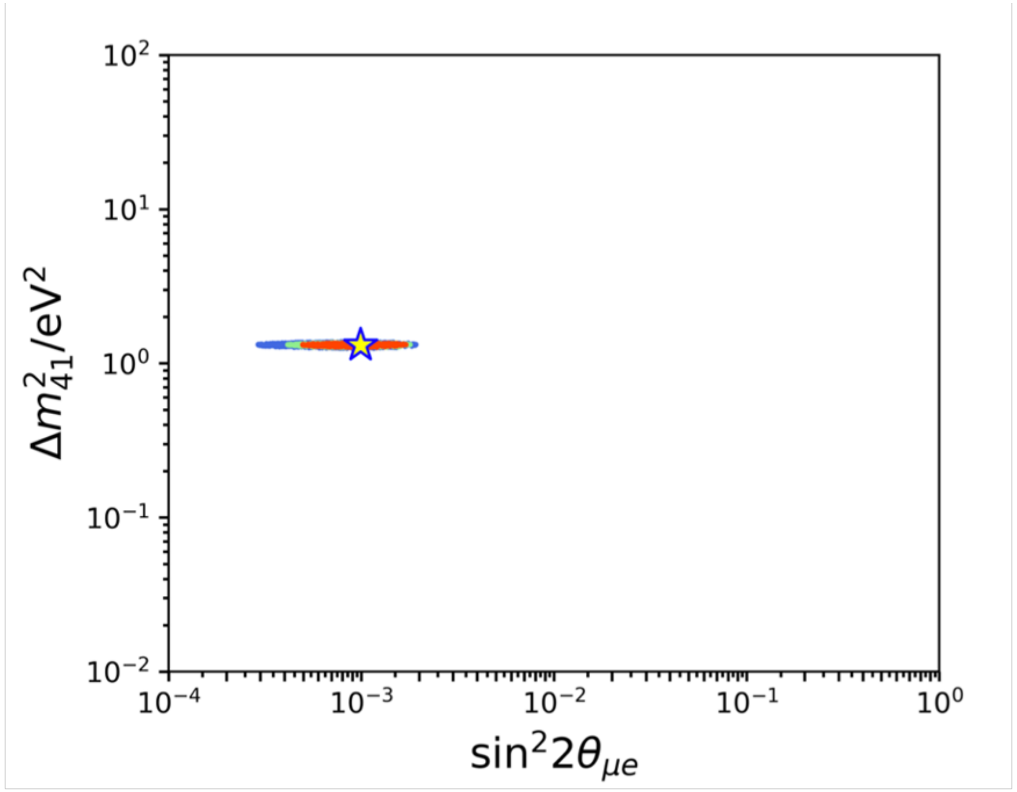
3+1 Global Fits

$$\Delta m^2_{41} = 1.32 \text{ eV}^2$$
$$|U_{e4}| = 0.12$$
$$|U_{\mu 4}| = 0.14$$

$$\sin^2(2\theta_{\mu e}) = 1.05 \times 10^{-3}$$

$$\chi^2_{\text{BF}} = 458 \text{ (506 dof)}$$
$$\chi^2_{\text{Null}} = 493 \text{ (509 dof)}$$

$$\Delta\chi^2_{\text{Null - BF}} = 35 \text{ (3)}$$



$$4|U_{e4}|^2|U_{\mu 4}|^2$$

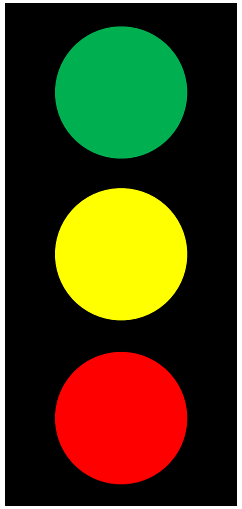
But this is not a solved puzzle

A minimal sterile neutrino model requires each of the following

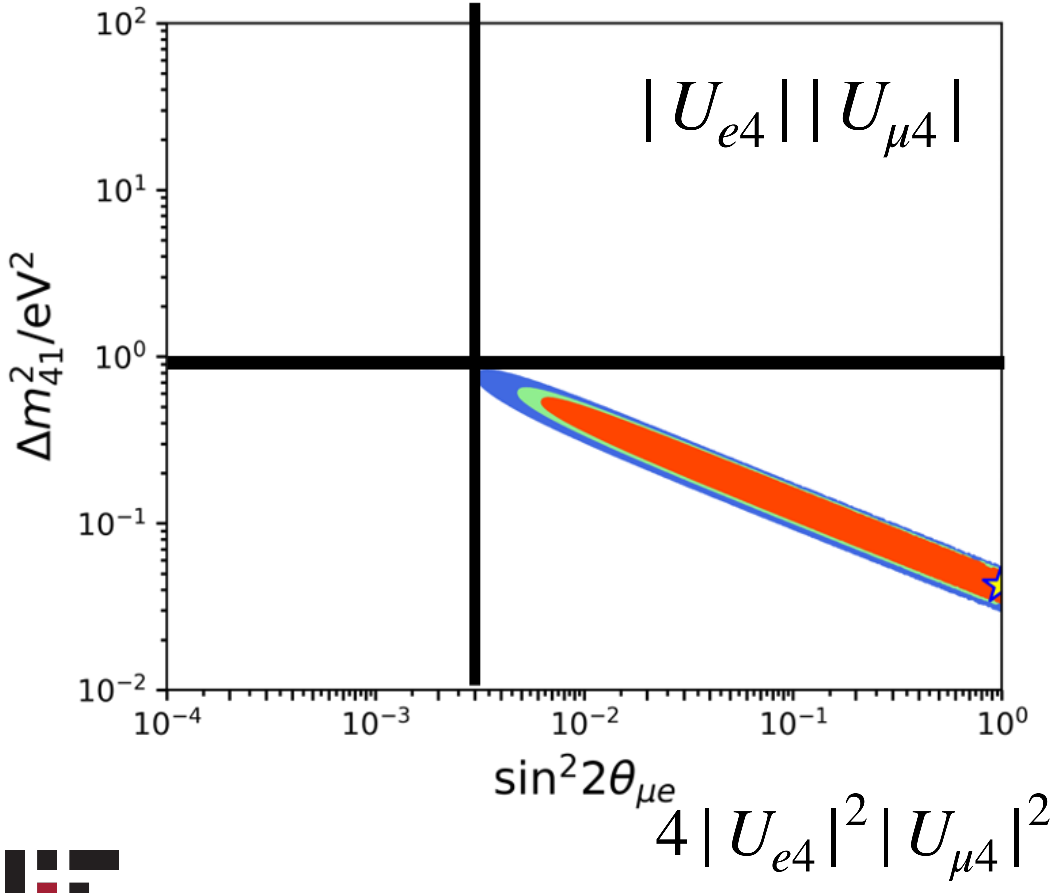
$\nu_\mu \rightarrow \nu_e$ appearance

$\nu_e \rightarrow \nu_e$ disappearance

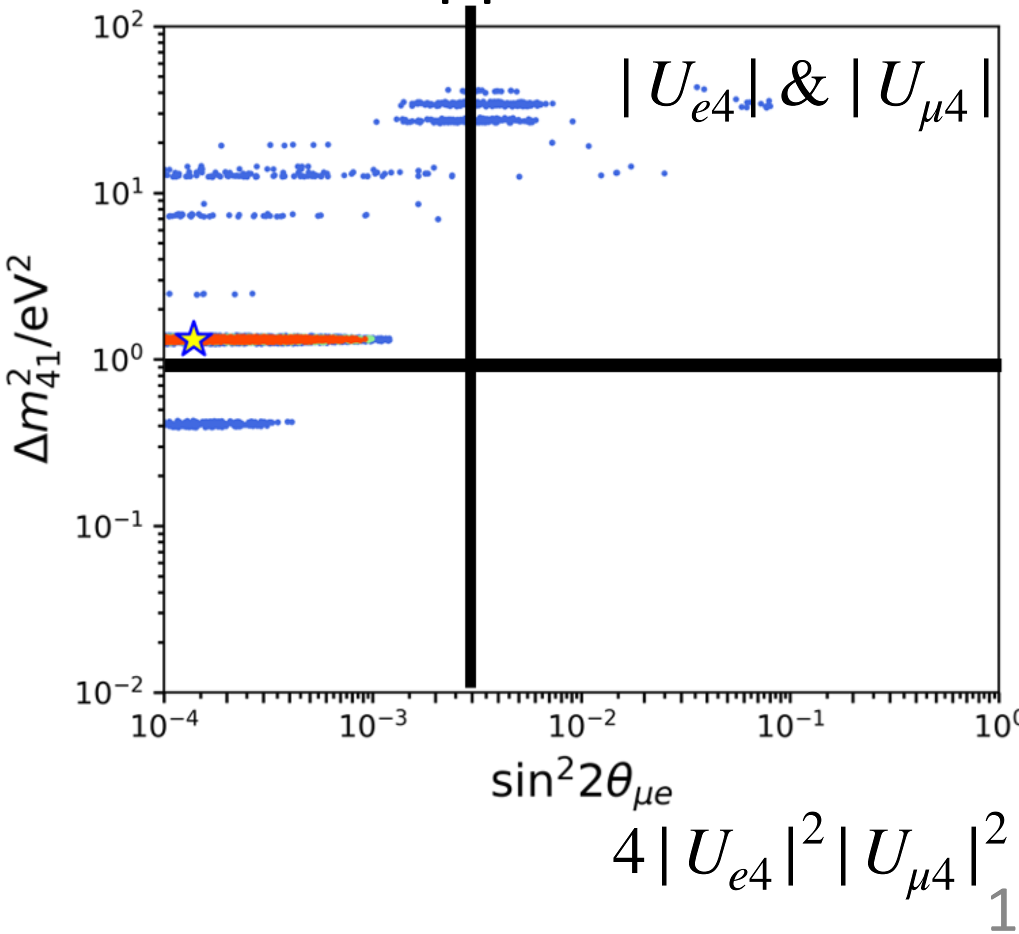
$\nu_\mu \rightarrow \nu_\mu$ disappearance



Appearance



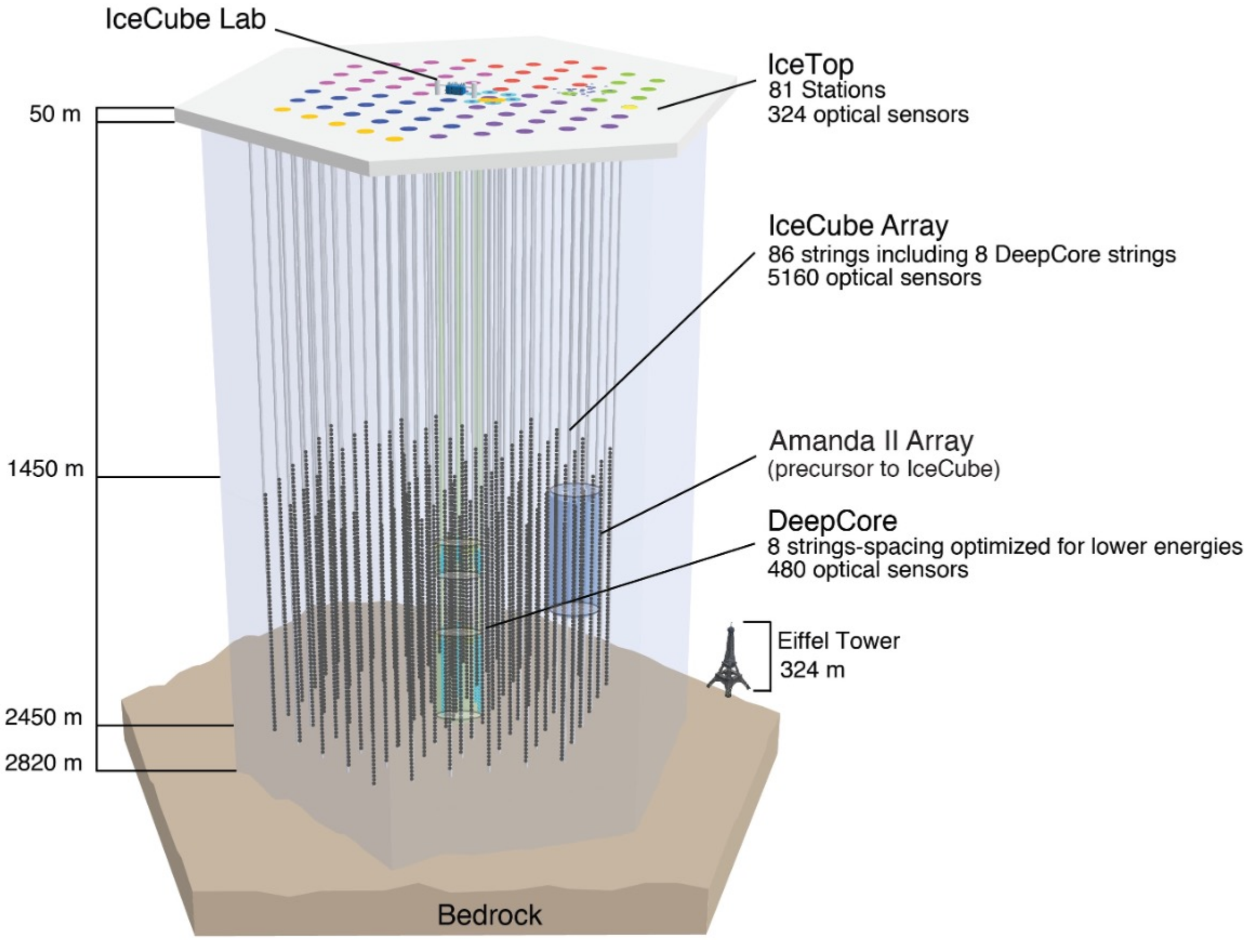
Disappearance

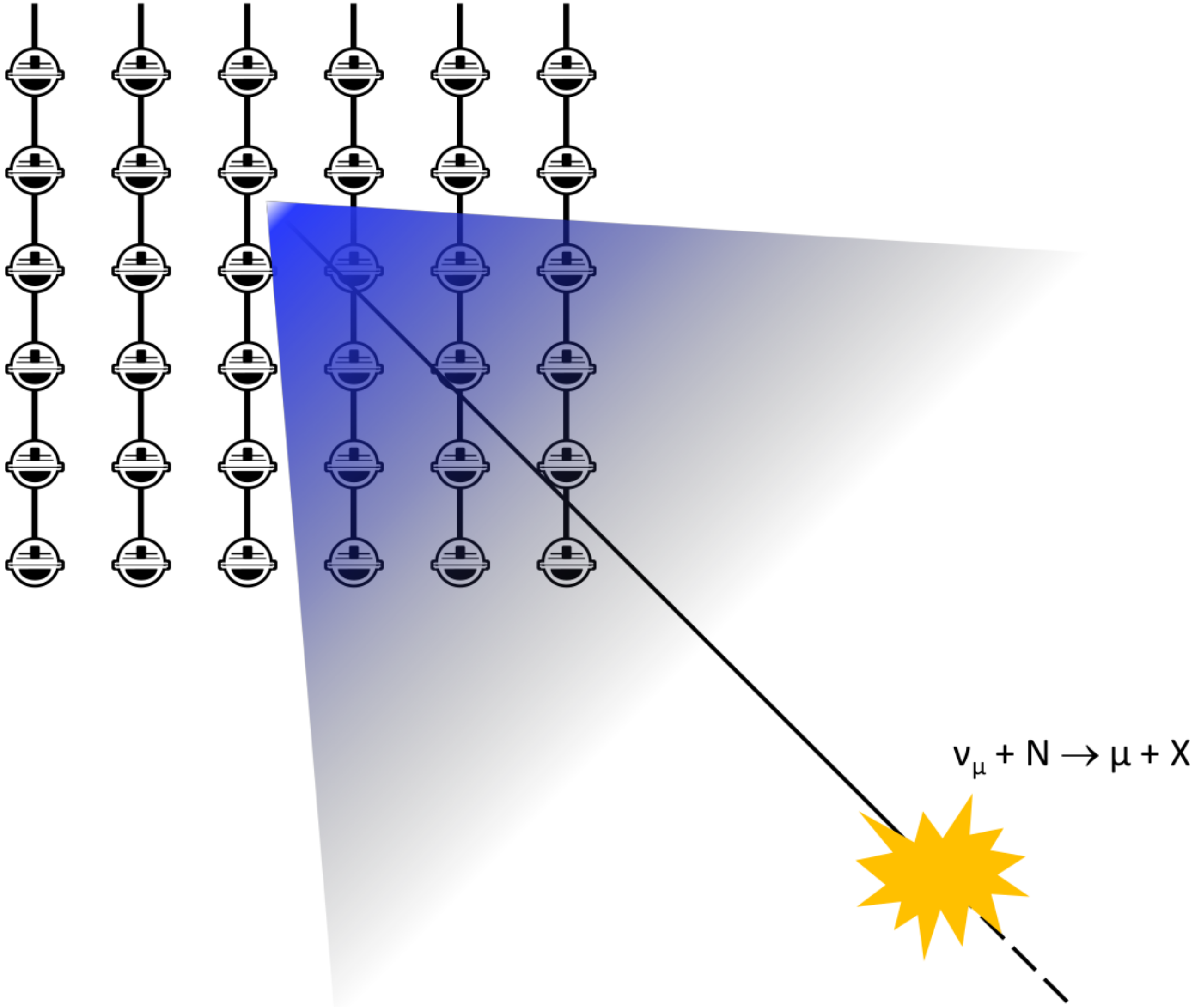


IceCube

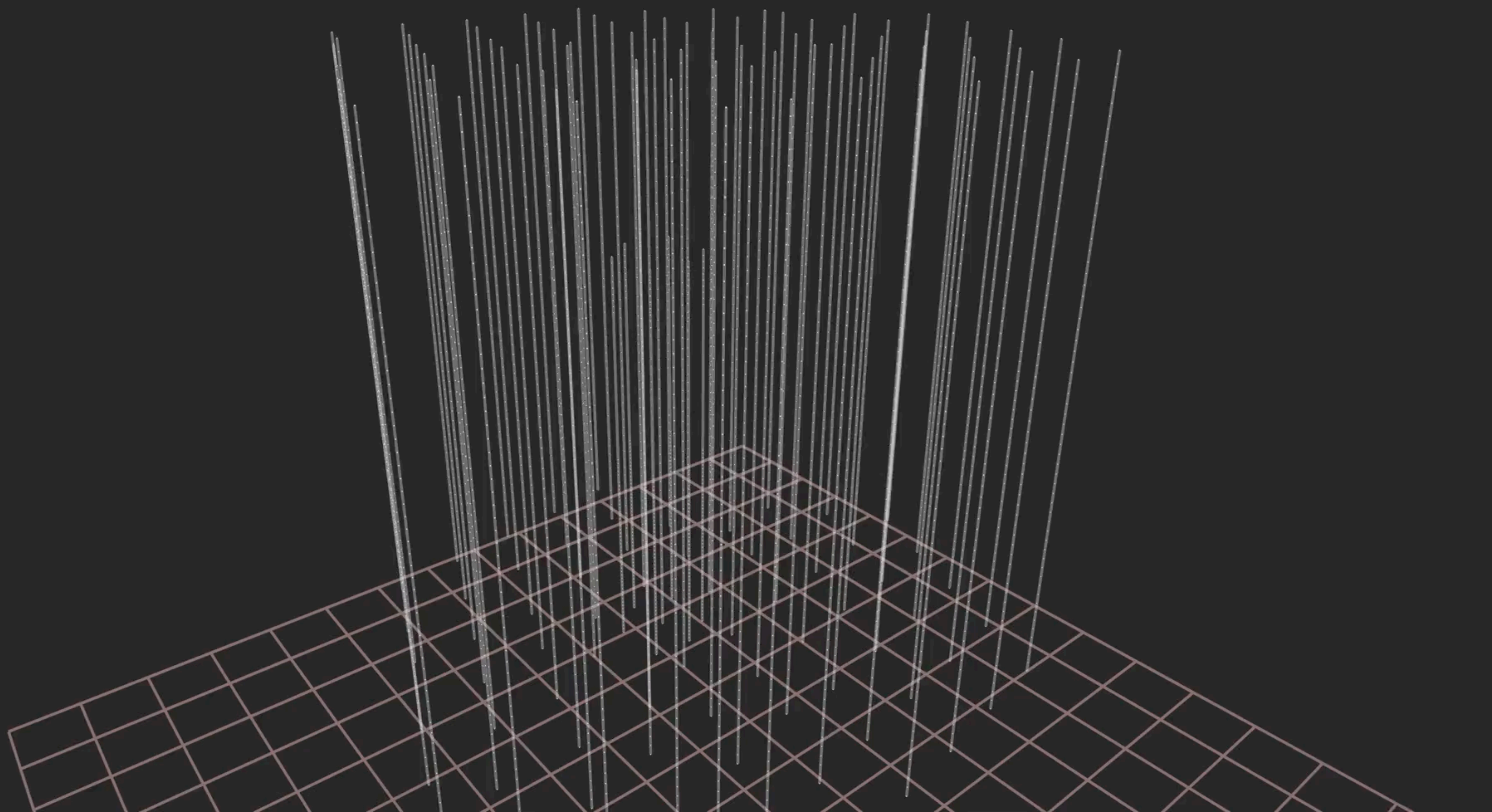
IceCube

- ~1 Gigaton detector in the Antarctic ice.
- 5160 optical sensors, called DOMs
- 86 strings, 60 DOMs on each strings




$\nu_\mu + N \rightarrow \mu + X$

Fri, 12 Nov 2010 13:14:20 UTC
t = 9700 ns




Time
https://fwlibraryfoundation.org/kuan-wei/

Matter Enhanced Oscillations With Steriles (MEOWS)

Use the large atmospheric muon neutrino flux to conduct a novel study of sterile neutrinos oscillations utilizing the matter effects due to the Earth.

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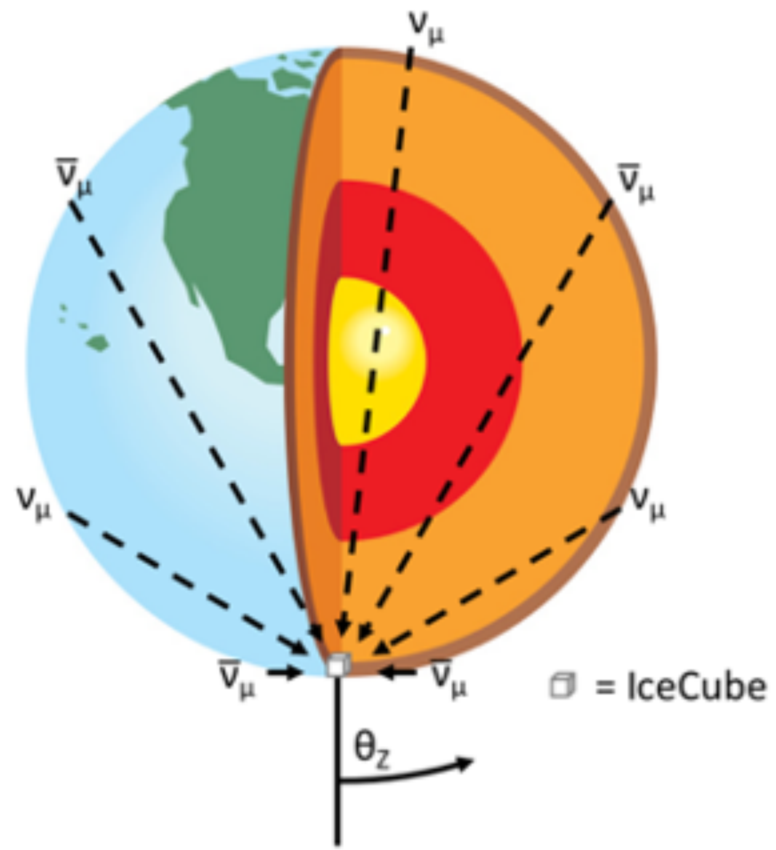
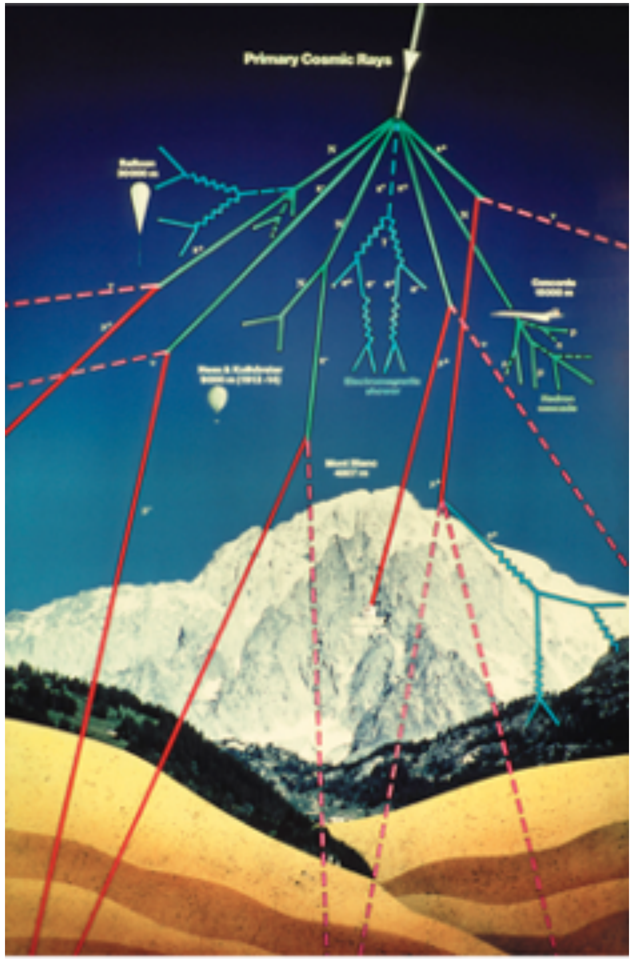
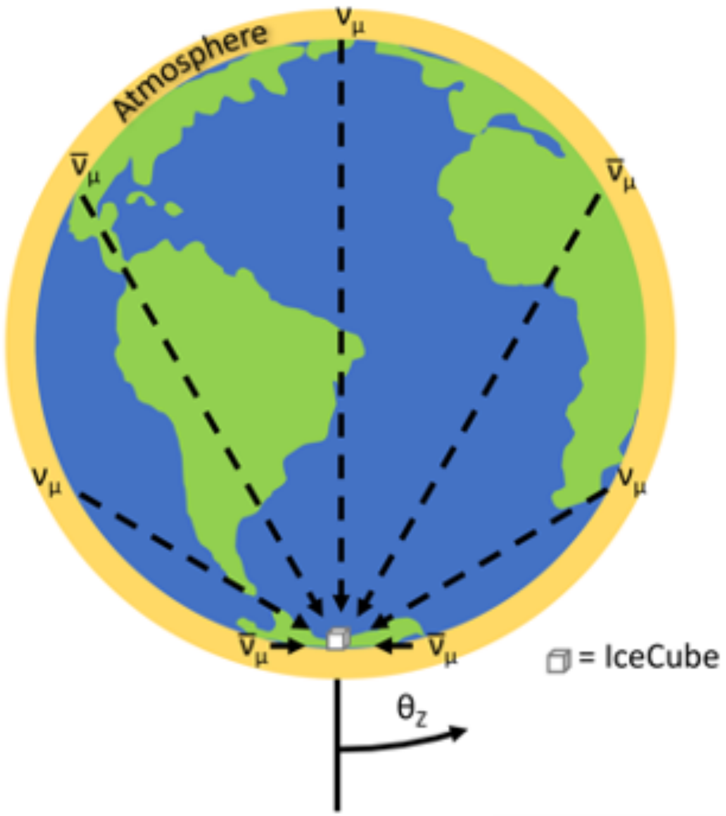
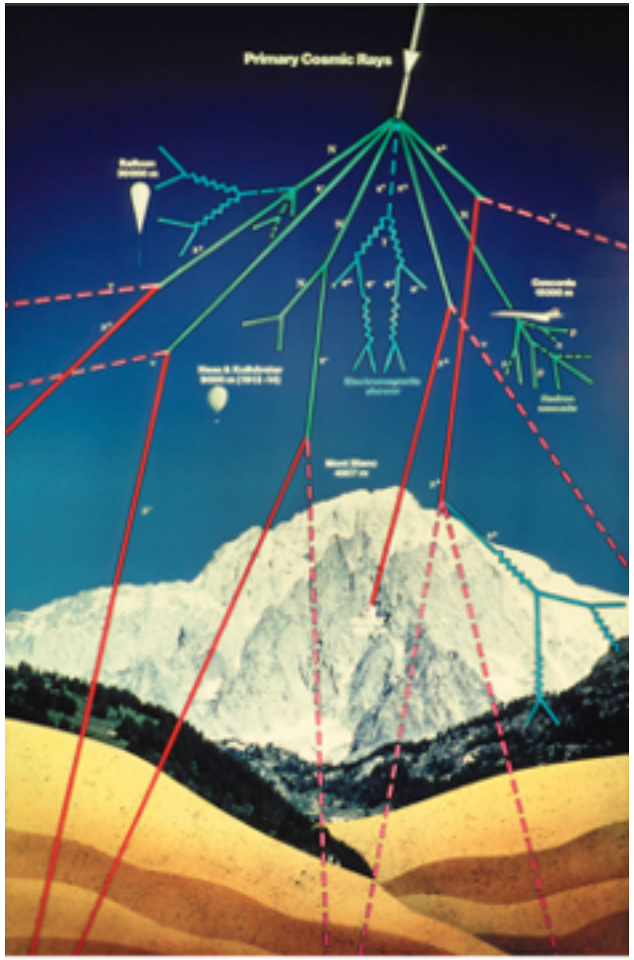


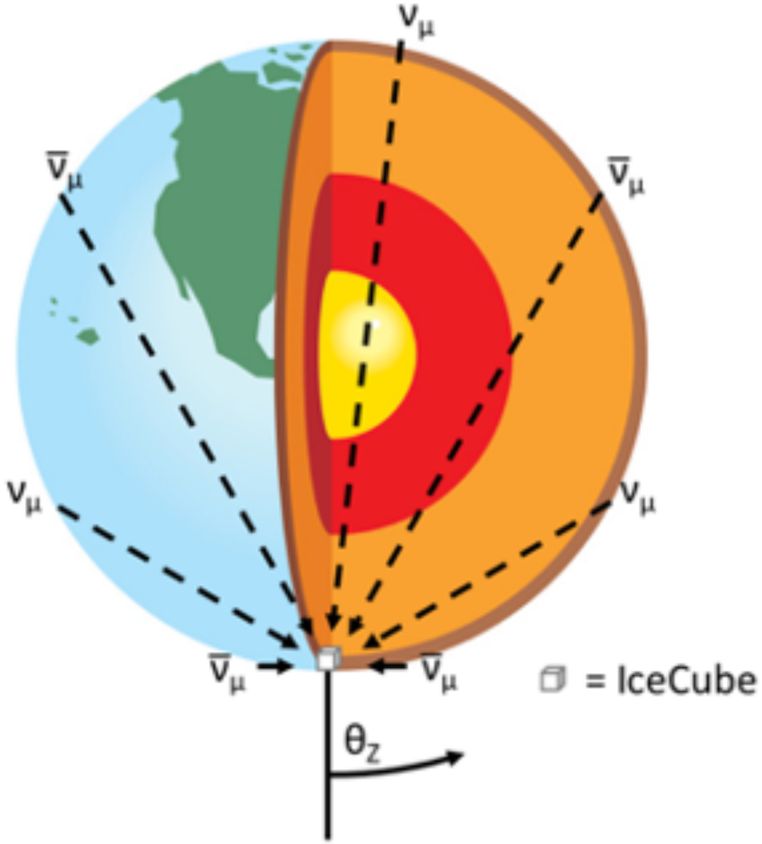
Atmospheric Neutrinos





Atmospheric Neutrinos





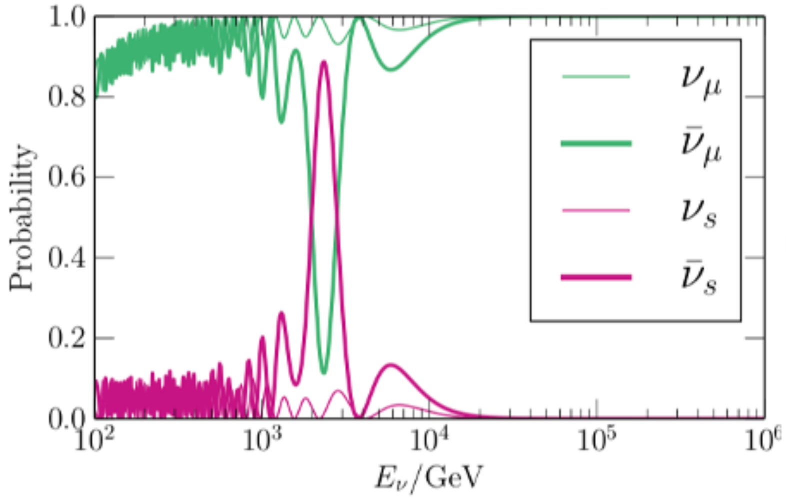
Matter Enhanced Oscillations

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2(2\theta_M)\cdot\sin^2\left(1.27\Delta m_M^2 \frac{L}{E_\nu}\right)$$

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}\ ,\ \tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A}{\Delta m^2 \cos 2\theta}}$$

$$A = \mp\sqrt{2}E_\nu G_F N_N$$

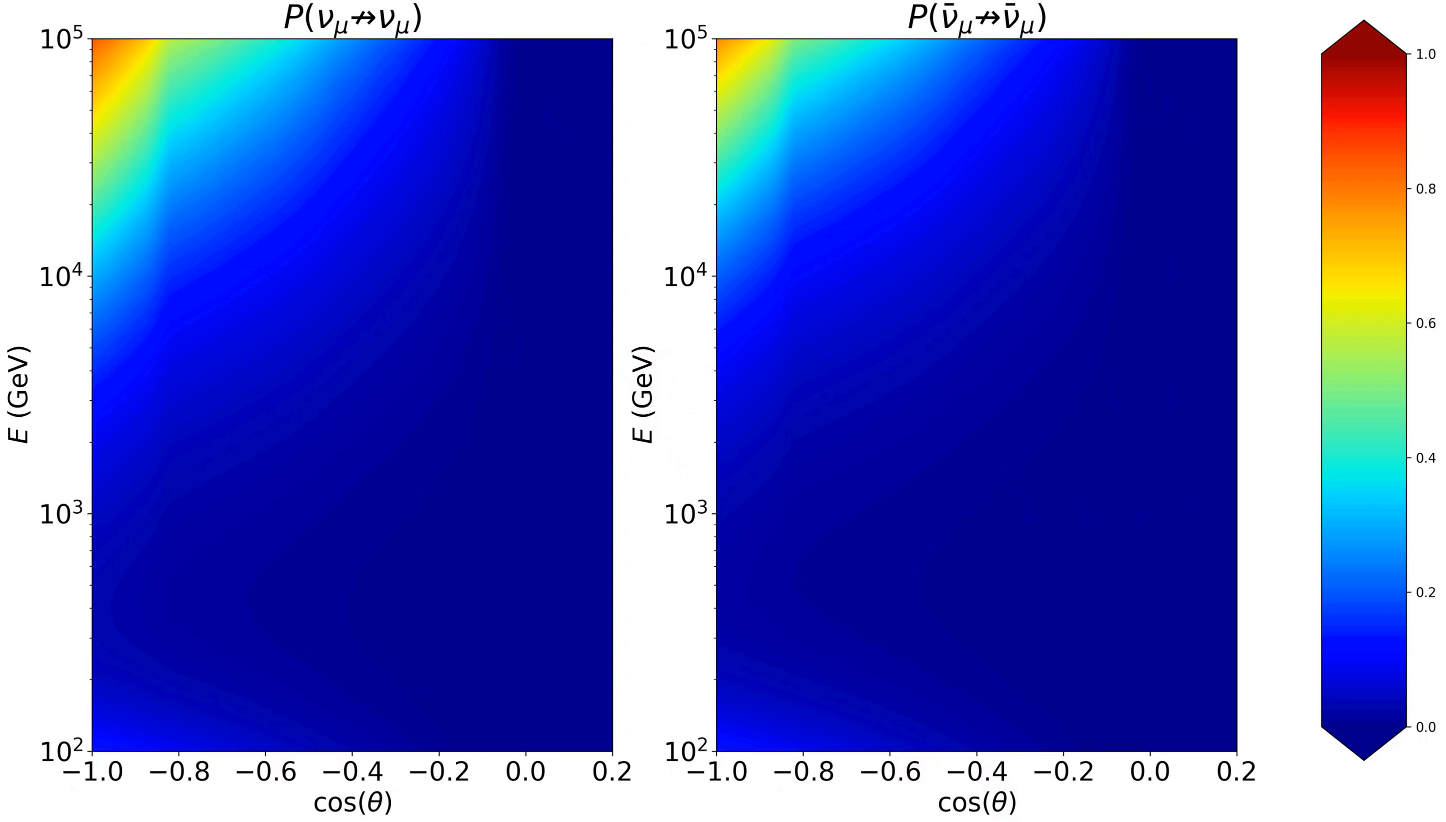
$$E_\nu^{res} = \mp\frac{\cos 2\theta \cdot \Delta m^2}{\sqrt{2}G_F N} \approx \mp\frac{\cos 2\theta\cdot\Delta m^2}{0.038(\rho[g/cm^3])}$$

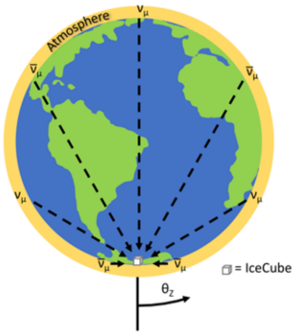


Plotted for:

- ❖ Δm^2_{41} = 1 eV^2, $\sin^2 2\theta_{24}$ = 0.1

$\Delta m^2 = 1\ \text{eV}^2, \theta_{24} = 0^\circ, \theta_{34} = 0^\circ$





For animation please see keynote

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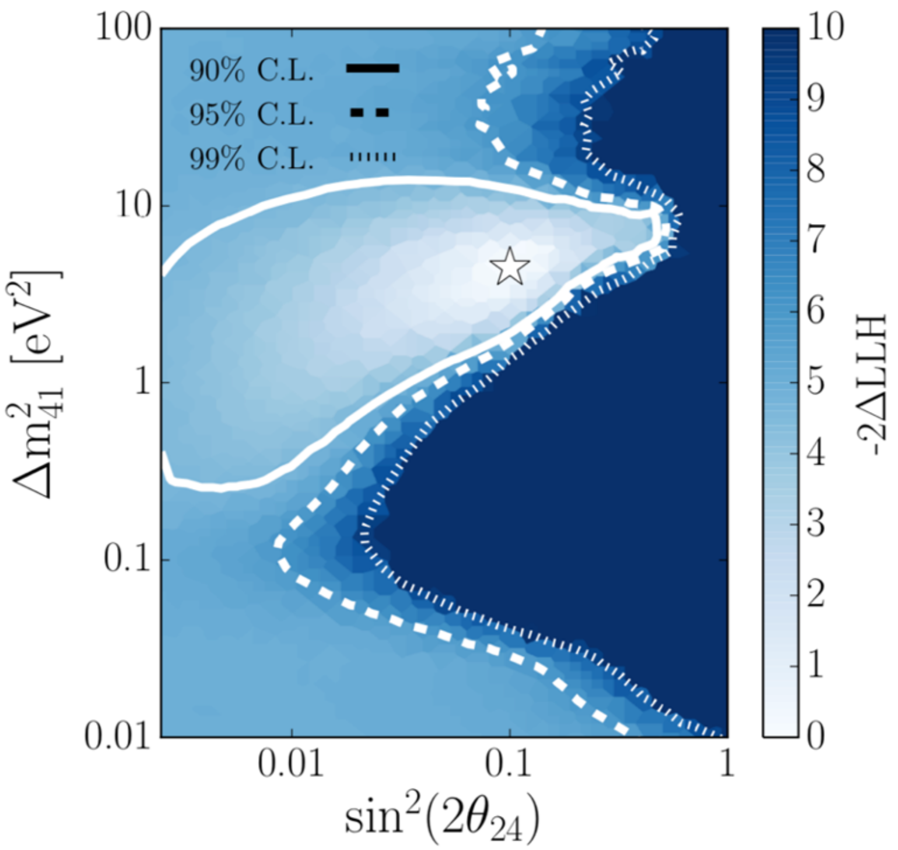
MEOWS - 8 year search



2ΔLLH from Null = 4.97 (8.0%)

305,891 muon neutrino candidates analyzed

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

$$\Delta m^2_{41} = 4.5 \text{ eV}^2$$

Existing analysis fits to two sterile points

$$\Delta m^2_{41} \ \& \ \theta_{24}$$

But sterile neutrino introduces *six* new parameters

$$\Delta m^2_{41}, \theta_{14}, \theta_{24}, \theta_{34}, \delta_{14}, \delta_{24}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$|U_{e4}|^2 = 0$$

$$|U_{\mu 4}|^2 = \sin^2\theta_{24}$$

$$|U_{\tau 4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}$$

What we've seen before

New measurable parameters

Existing analysis fits to two sterile points

Δm^2_{41} & θ_{24} $|U_{\mu 4}|^2 = \sin^2\theta_{24}$

But sterile neutrino introduces *six* new parameters

$\Delta m^2_{41}, \theta_{14}, \theta_{24}, \theta_{34}, \delta_{14}, \delta_{24}$

In the analysis

$\theta_{14} = 0$ & $\delta_{14} = 0$ ← Negligible $|U_{e4}|^2 = 0$

Existing analysis fits to two sterile points

$$\Delta m_{41}^2 \;\&\; \theta_{24}$$

But sterile neutrino introduces *six* new parameters

$$\Delta m_{41}^2, \theta_{14}, \theta_{24}, \theta_{34}, \delta_{14}, \delta_{24}$$

In the analysis

$\theta_{14} = 0 \;\&\; \delta_{14} = 0$ ← Negligible

$\theta_{34} = 0 \;\&\; \delta_{34} = 0$ ← ?

$$|U_{\tau 4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}$$

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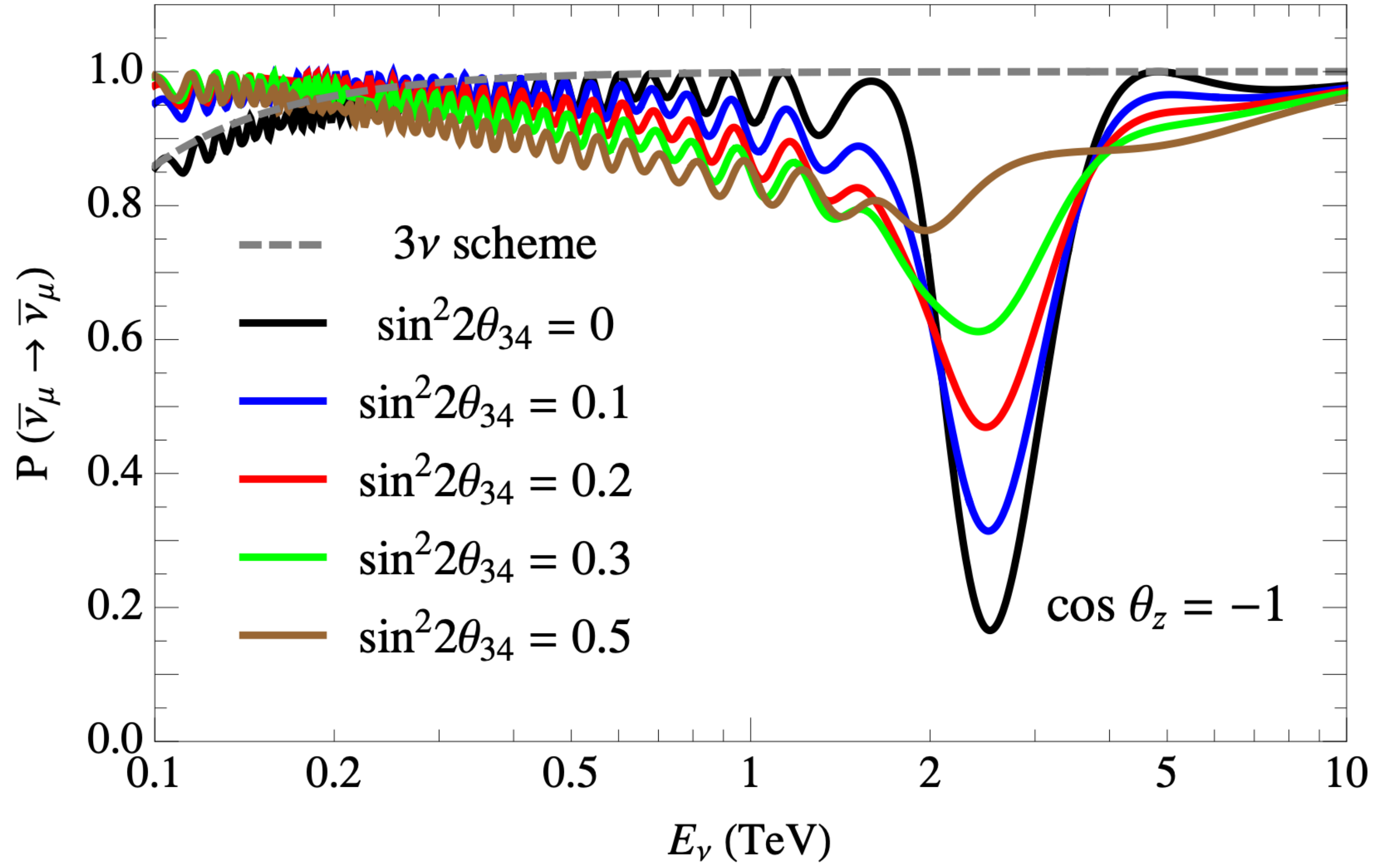
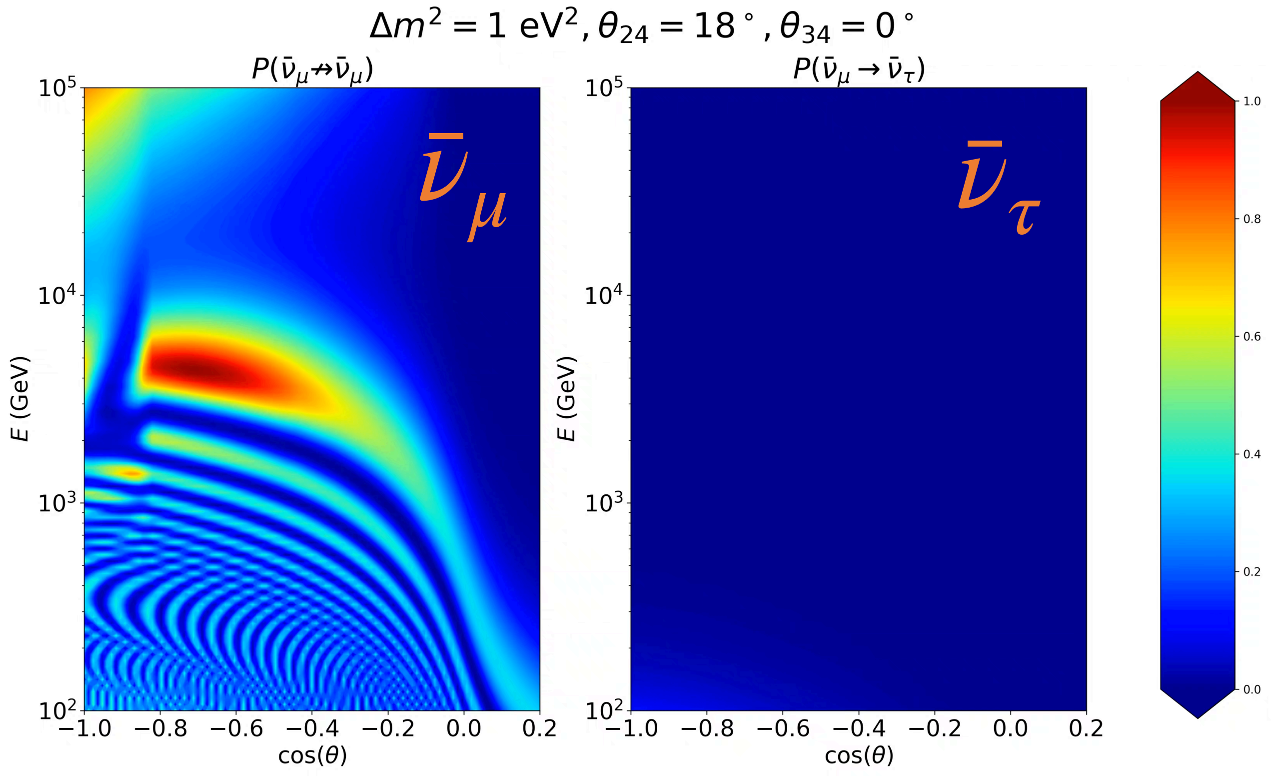
What about θ_{34}?



Increasing θ_{34} increases the strength of the effect. Therefore, $\theta_{34} = 0$ is the conservative estimate, providing an upper bound to θ_{24}.



For animation please see keynote

Allowing $\theta_{34} \neq 0$ produces a non-negligible effect.

Also, introduces significant $\bar{\nu}_\tau$ appearance.

θ_{34} is the least bounded of the sterile mixing parameters.

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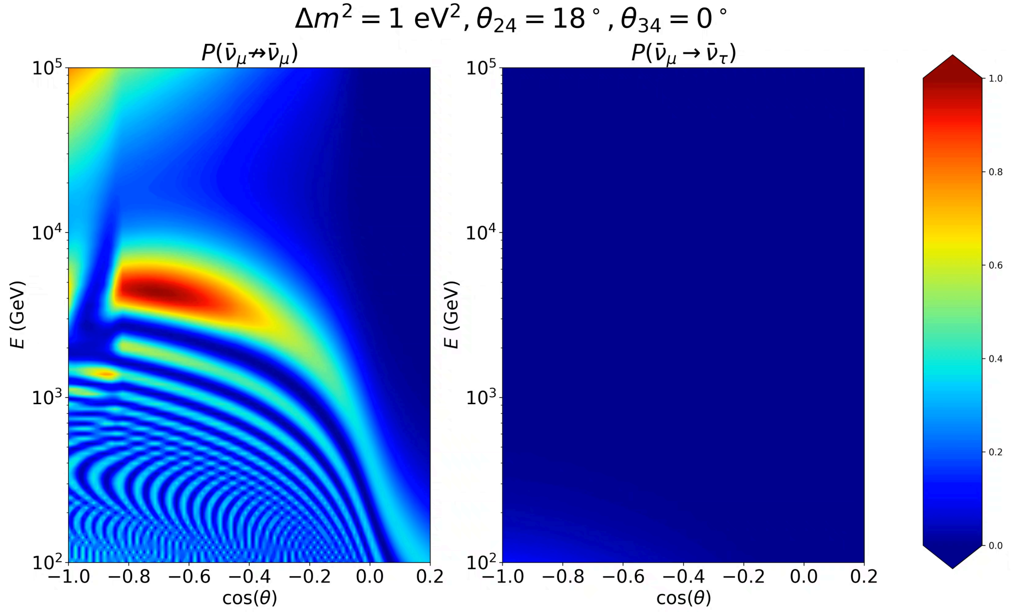
Expanding MEOWS with θ_{34}

Current work is to add this additional parameter to the existing MEOWS analysis.

Computational challenges of adding an additional dimension.

Improving $\tau \rightarrow \mu + \ldots$ decay simulation



For animation please see keynote

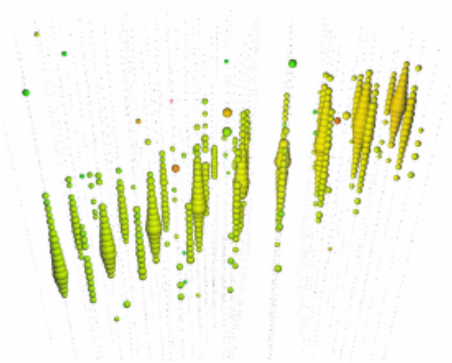
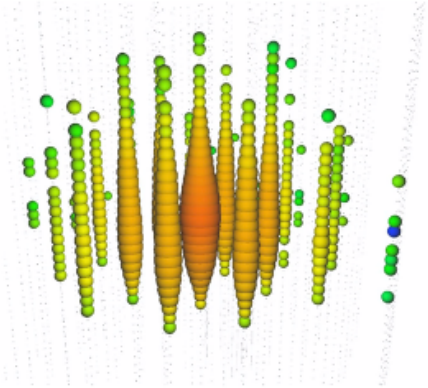
Future for MEOWS?

We have a long term goal to include Cascade signatures into the MEOWS analysis. This opens up additional channels:

$\nu_\mu \rightarrow \nu_e$ & $\nu_\mu \rightarrow \nu_\tau$ (CC)

$\nu_\mu \rightarrow \nu_\alpha$ (NC)

With better energy resolution compared to muon track events.

Tracks	Cascades
	
ν_μ Charged Current	ν_e Charged Current ν Neutral Current

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Future of Sterile Neutrinos?

Experiments like MicroBooNE and SBN will either support or kill (or somewhere in between?) the sterile hypothesis.

If the hypothesis survives these tests, a few indirect approaches can be taken:

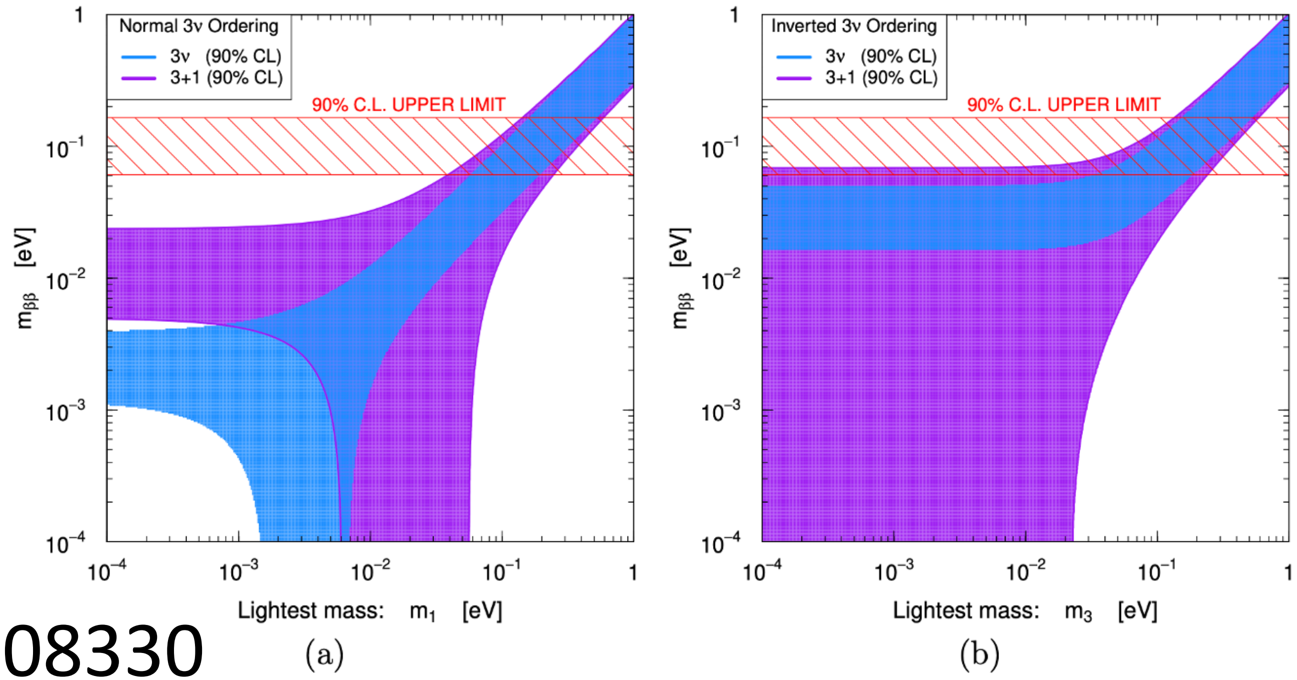
- $0\nu\beta\beta$ experiments
- Lepton unitarity constraints

$0\nu\beta\beta$ decay experiments

$$|m_{\beta\beta}| = \left|\mu_1 + \mu_2 e^{i\alpha_2} + \mu_3 e^{i\alpha_3} + \mu_4 e^{i\alpha_4}\right|$$

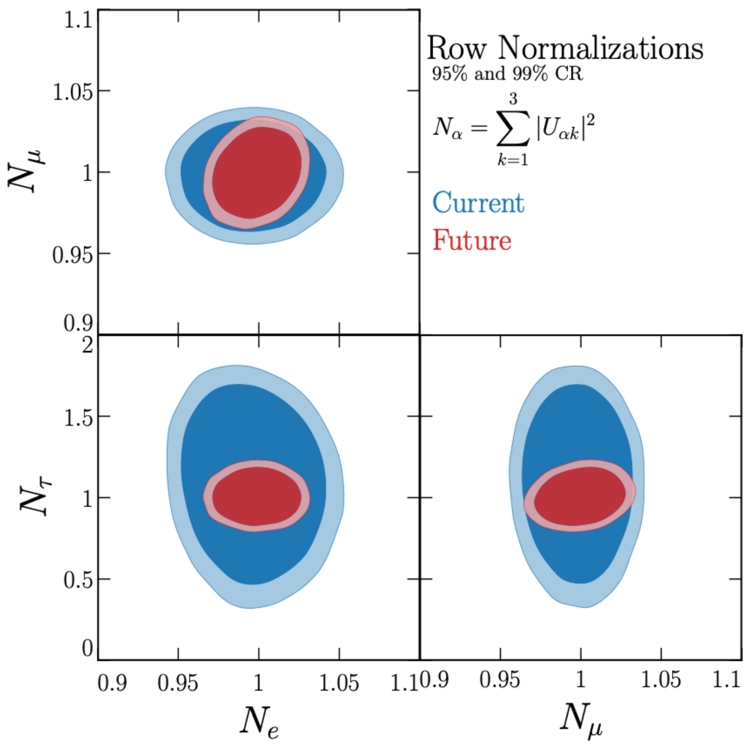
Normal

Inverted



arXiv:1901.08330

Testing Unitarity

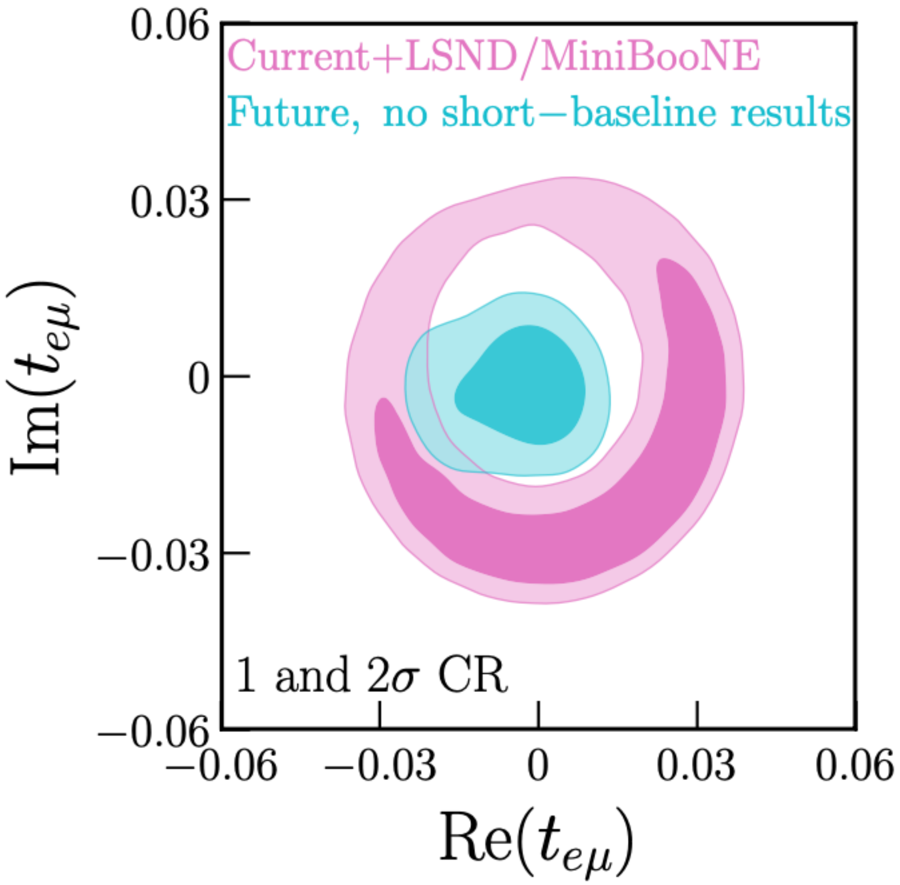


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$\text{Improvement Factor}: \begin{pmatrix} 3.0 & 3.6 & 1.0 \\ 6.4 & 2.9 & 2.0 \\ 1.9 & 2.8 & 3.2 \end{pmatrix}$$

arXiv:2008.01088

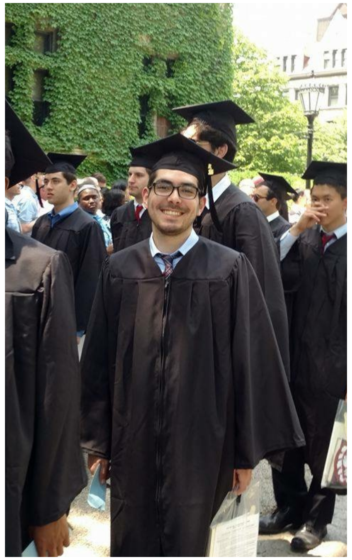
$$N_\alpha \equiv |U_{\alpha1}|^2 + |U_{\alpha2}|^2 + |U_{\alpha3}|^2 = 1 \quad (\alpha = e,\ \mu,\ \tau),$$



$$t_{\alpha\beta} \equiv U^*_{\alpha 1}U_{\beta 1} + U^*_{\alpha 2}U_{\beta 2} + U^*_{\alpha 3}U_{\beta 3} = 0 \quad (\alpha \neq \beta; \quad \alpha,\ \beta = e,\ \mu,\ \tau).$$

Thank you!

Thank you!



Thank you!

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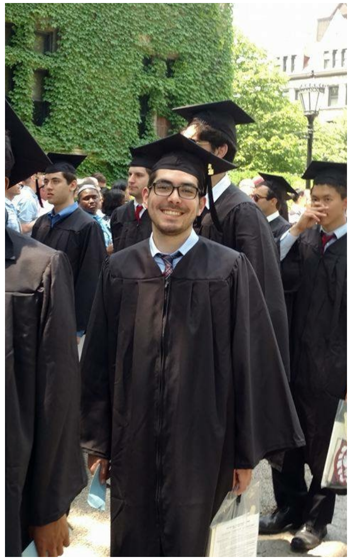
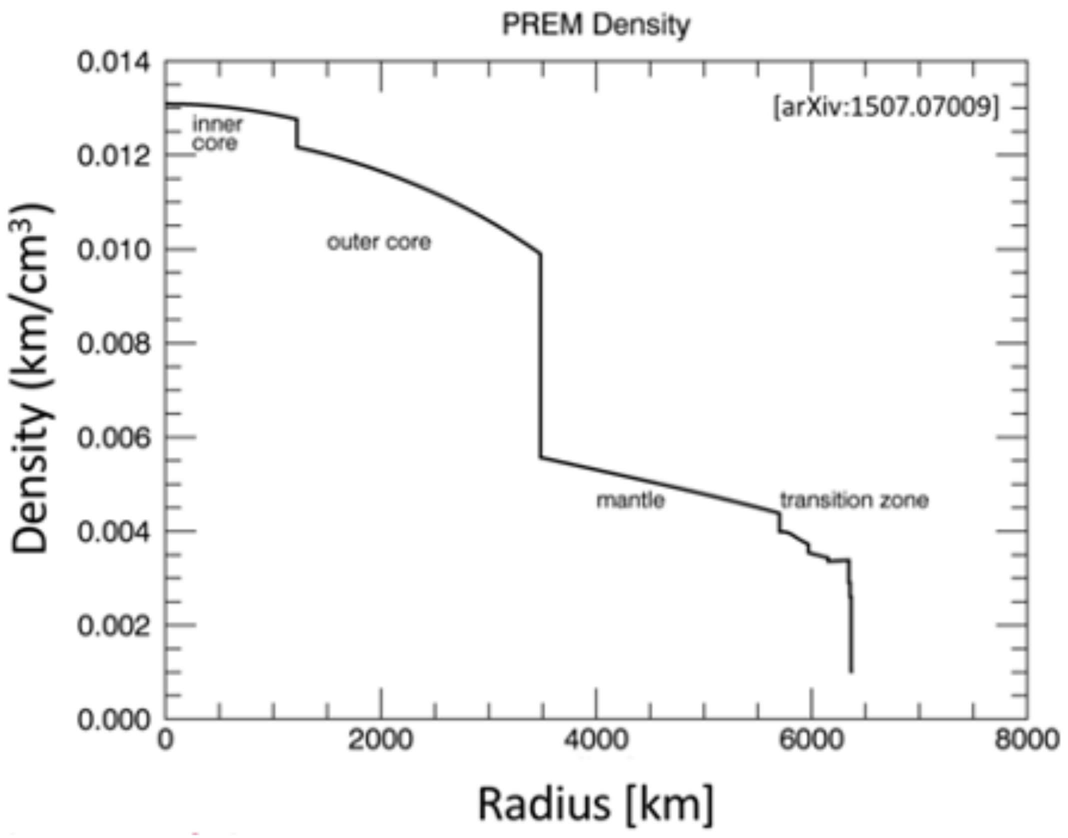



PREM Density
[arXiv:1507.07009]
inner core
outer core
mantle
transition zone
Density (km/cm³)
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
2000
4000
6000
8000
Radius [km]

Matter Enhanced Oscillations

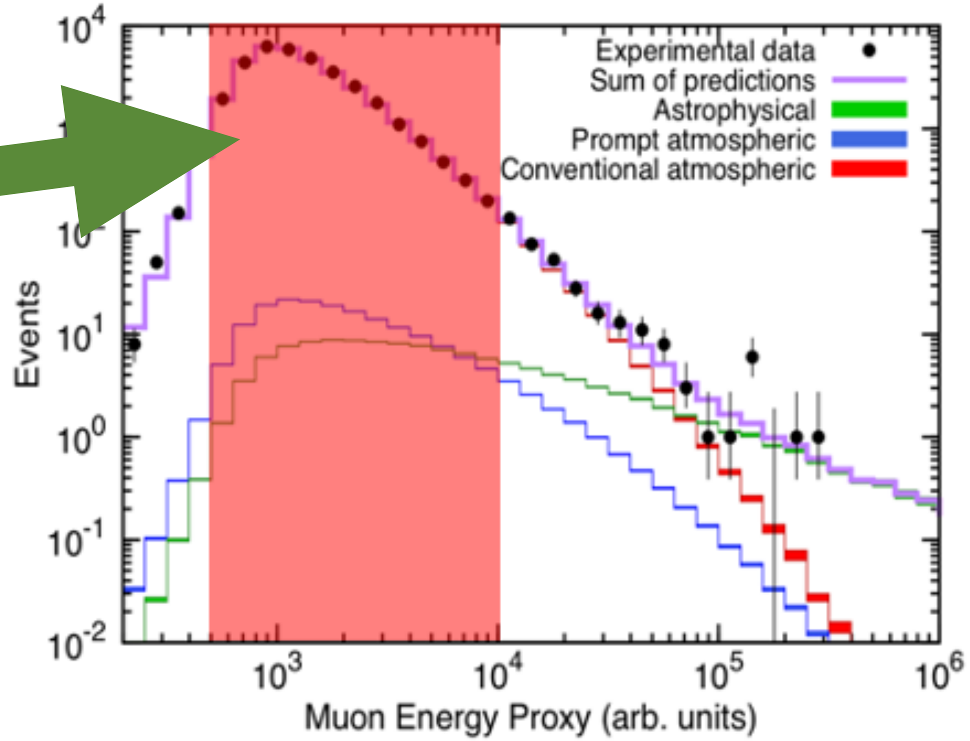
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \frac{1}{2\mathrm{E}}U\begin{pmatrix}0 & 0 & 0 & 0\\ 0 & \Delta\mathrm{m}^2_{21} & 0 & 0\\ 0 & 0 & \Delta\mathrm{m}^2_{31} & 0\\ 0 & 0 & 0 & \Delta\mathrm{m}^2_{41}\end{pmatrix}U^\dagger\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} + \sqrt{2}\mathrm{G}_F\begin{pmatrix}n_e(x) & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & -\mathrm{n}_n/2\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

Muon rate from Northern Hemisphere

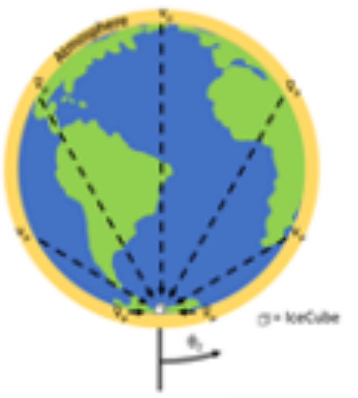
$$E_\nu^{res} = \mp \frac{\cos 2\theta \cdot \Delta m^2}{\sqrt{2} G_F N} \approx \mp \frac{\cos 2\theta \cdot \Delta m^2}{0.038(\rho[g/cm^3])}$$

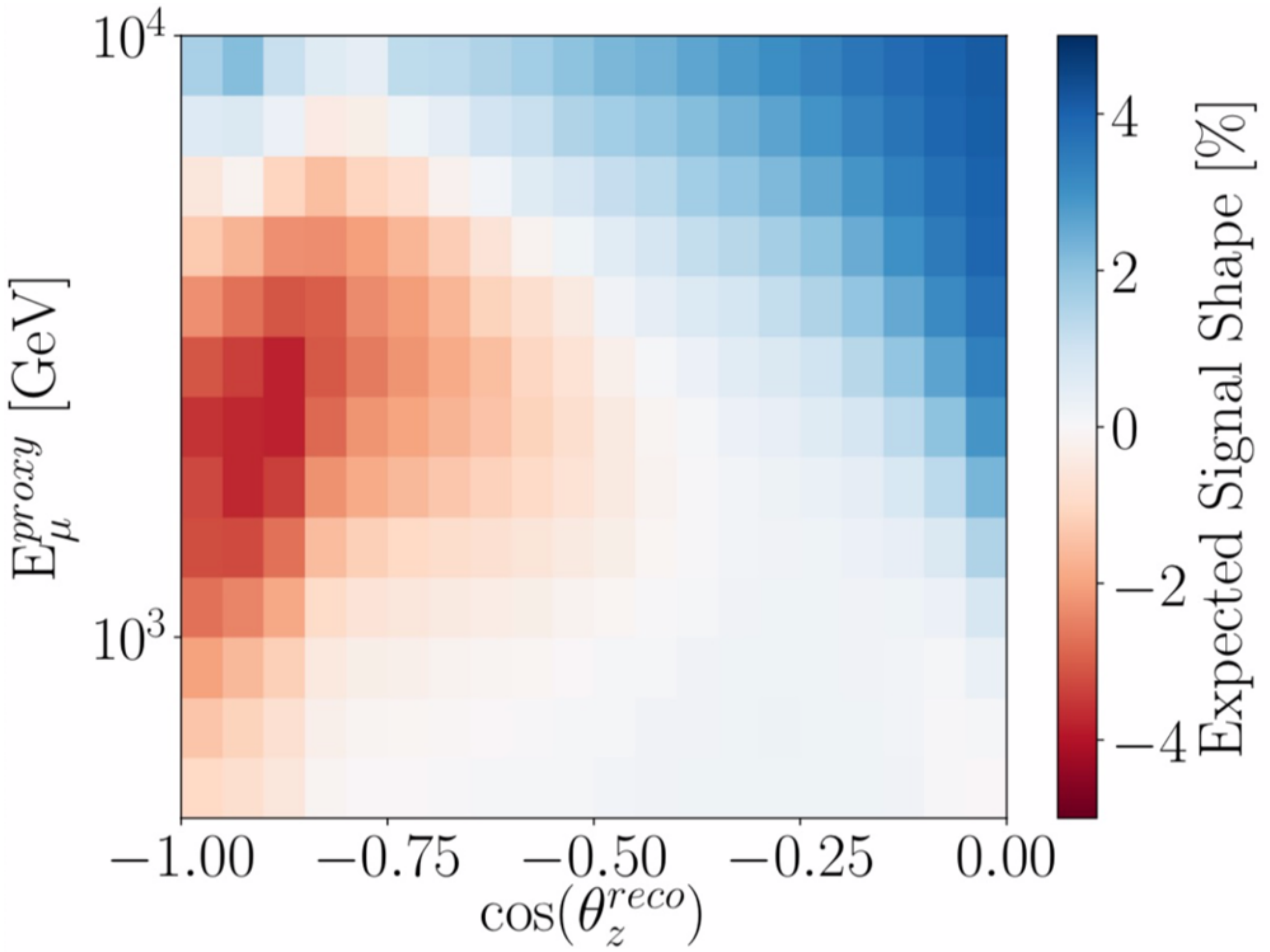
At core density, and Global Best Fits, expected here:

Current MEOWS energy range is 500 GeV – 10 TeV

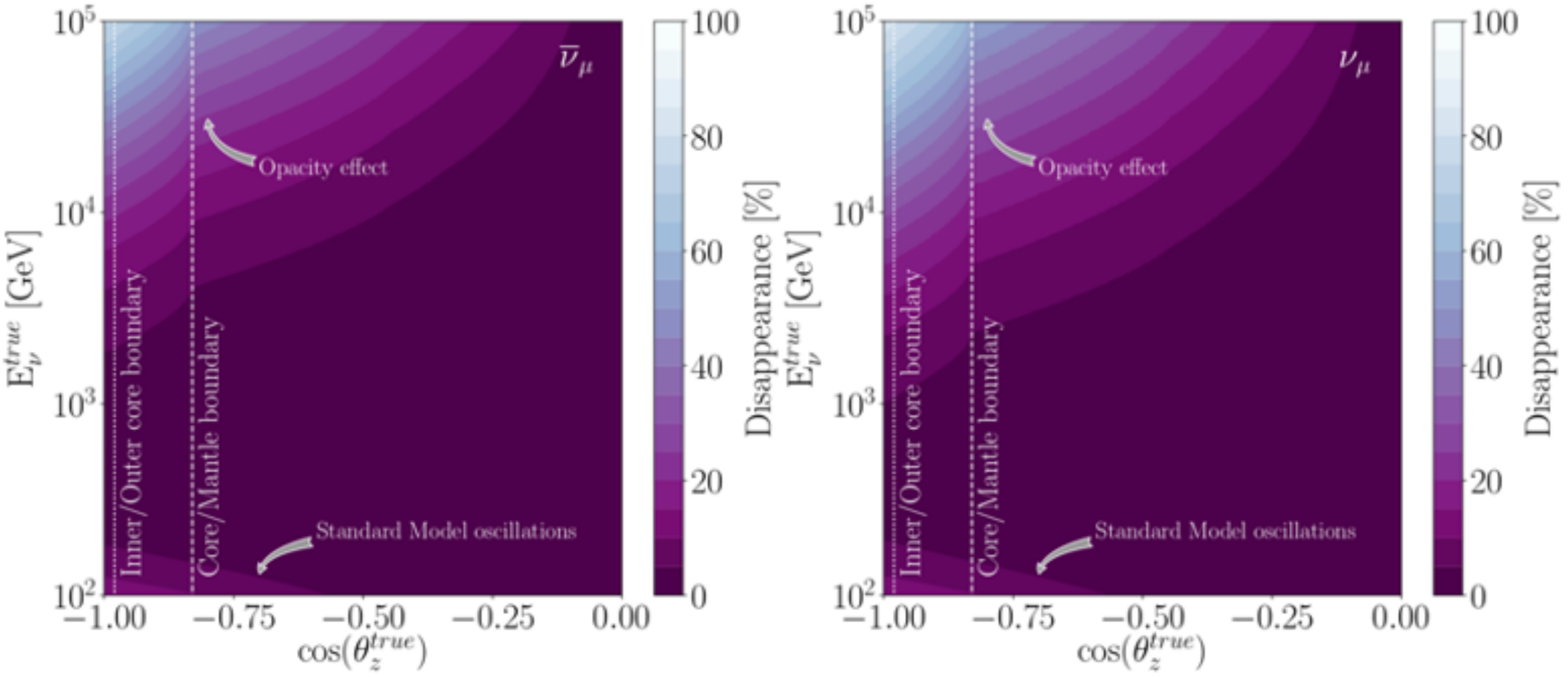


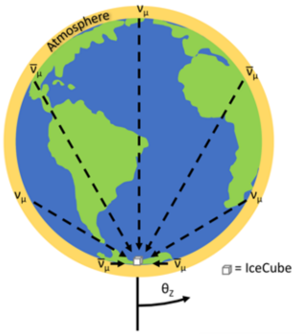
Expected Observation





No sterile neutrino





With Sterile Neutrino