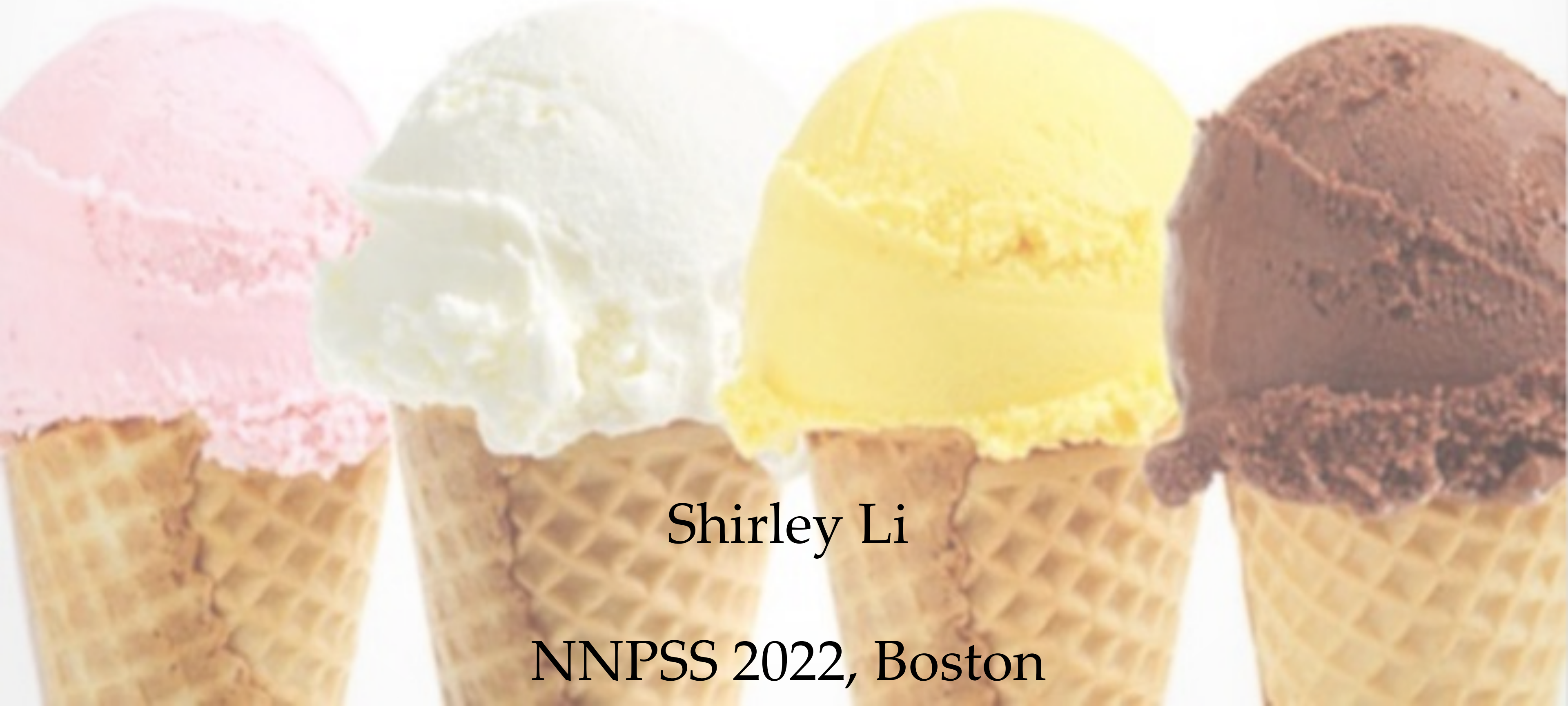
How do neutrinos oscillate?

What we know and do not know about neutrino oscillation



Shirley Li

NNPSS 2022, Boston

Outline

- Standard three-flavor neutrino oscillation
  - Two-level system
  - Matter effect
  - Three-flavor oscillation
- Sterile neutrinos

3-Flavor Neutrino Oscillations

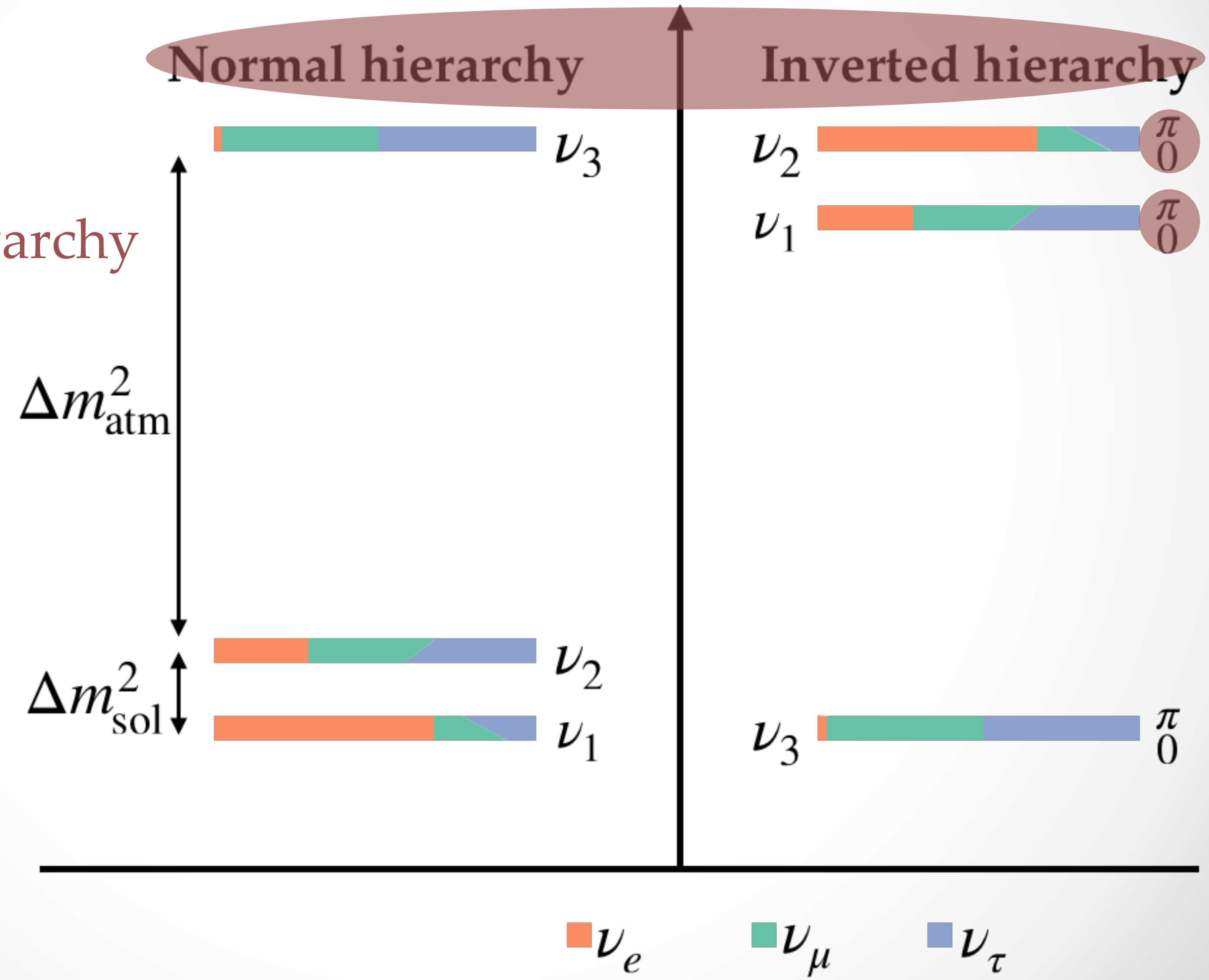
Unknown:

δ_{CP}, mass hierarchy

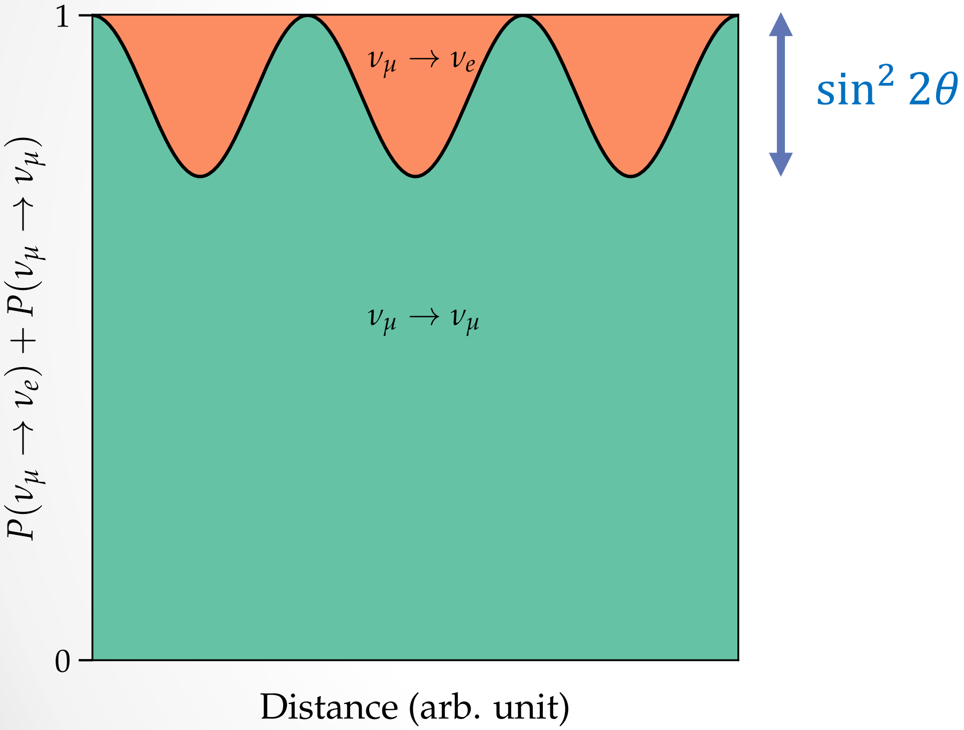
A Few %:

$\theta_{12}, \theta_{13}, \theta_{23},$

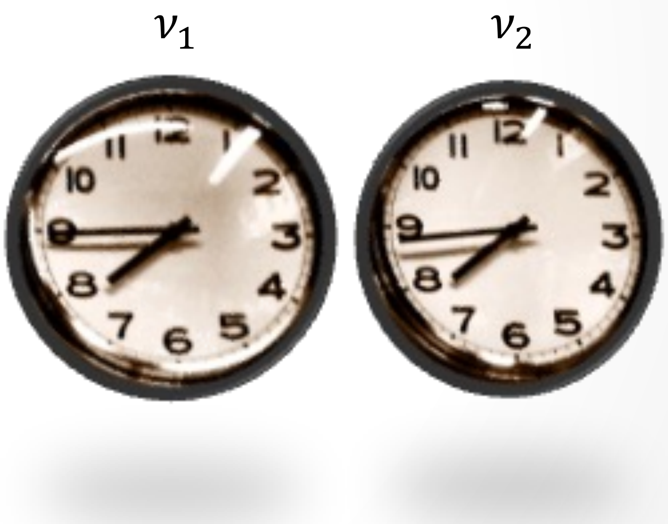
$\Delta m^2_{21}, \Delta m^2_{32}$



Conceptual Idea



Two Out-of-Sync Clocks:



Vacuum Oscillation

Production

$$\nu_\alpha(x) = \sum_{k=1}^{3} U_{\alpha k} \nu_k(x)$$

Flavor Mass

3-Flavor Mixing Parameterized by:

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric

$\mu \to \tau$
500 km/GeV

Reactor/Interference

$\mu \leftrightarrow e$
500 km/GeV

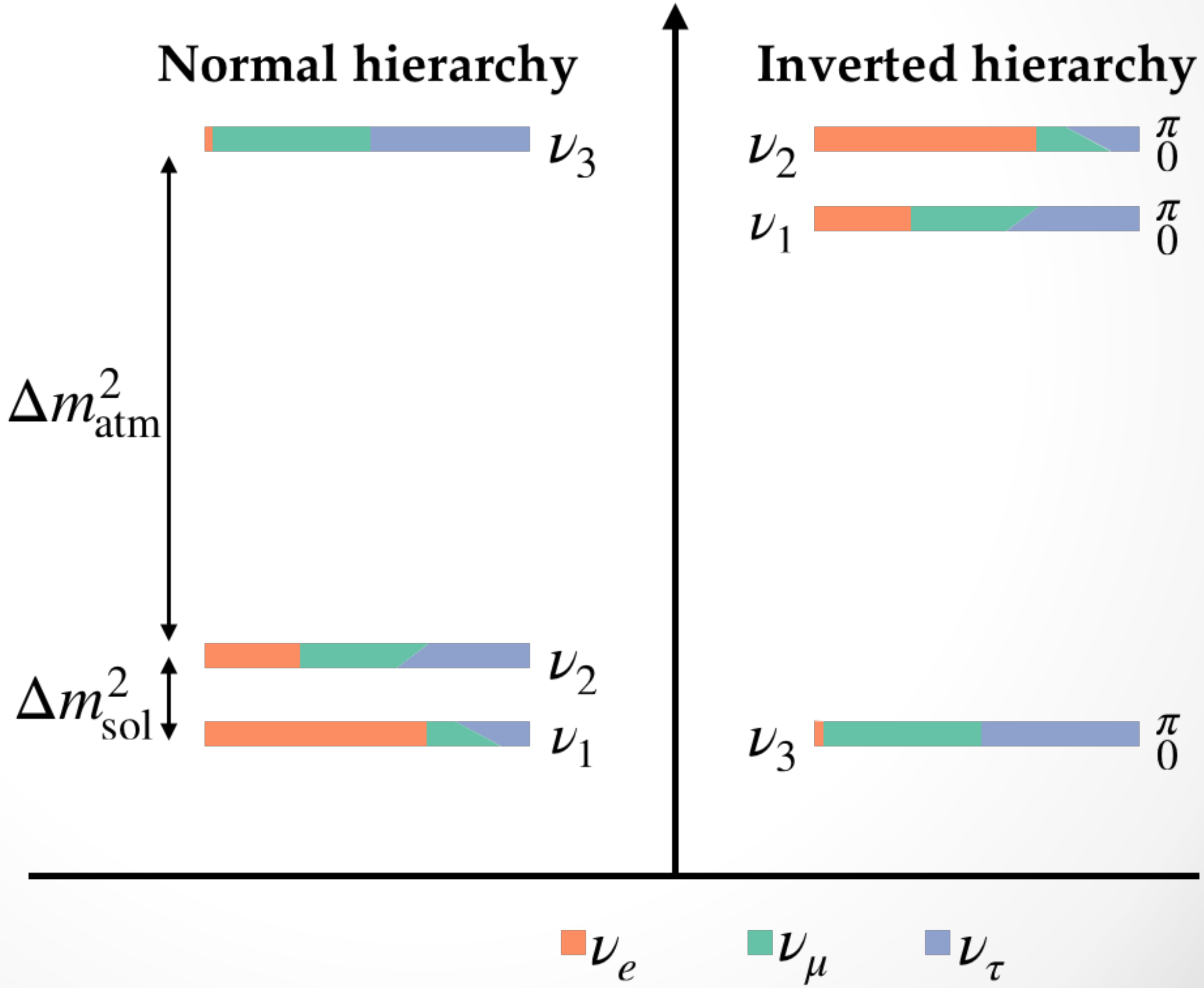
Solar/Reactor

$e \to e$
15000 km/GeV

Vacuum Oscillation

Production

$\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$



Vacuum Oscillation

Propagation

For a two-level system, the Schrodinger equation in the mass basis:

$$i\hbar \frac{\partial}{\partial t}\begin{pmatrix}\varphi_1(t)\\ \varphi_2(t)\end{pmatrix} = H_{mass}\begin{pmatrix}\varphi_1(t)\\ \varphi_2(t)\end{pmatrix} = \begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}\begin{pmatrix}\varphi_1(t)\\ \varphi_2(t)\end{pmatrix}$$

with

$$E_i = \sqrt{p_i^2 + m_i^2} \cong E + \frac{m_i^2}{2E} = E + \frac{m_1^2 + m_2^2}{4E} + \frac{m_i^2 - (m_1^2 + m_2^2)/2}{2E}$$

Dropping identities:

$$H_{mass} = \frac{\delta m^2}{4E}\begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix}, \ \delta m^2 = m_2^2 - m_1^2$$

Vacuum Oscillation

Propagation

In the flavor basis

$$i\hbar \frac{\partial}{\partial t}\begin{pmatrix} \varphi_e(t) \\ \varphi_\mu(t) \end{pmatrix} = H_{\text{flavor}} \begin{pmatrix} \varphi_e(t) \\ \varphi_\mu(t) \end{pmatrix}$$

with

$$H_{\text{flavor}} = U^\dagger \, H_{mass} U = \frac{\delta m^2}{4E}\begin{pmatrix} -cos2\theta & sin2\theta \\ sin2\theta & cos2\theta \end{pmatrix}$$

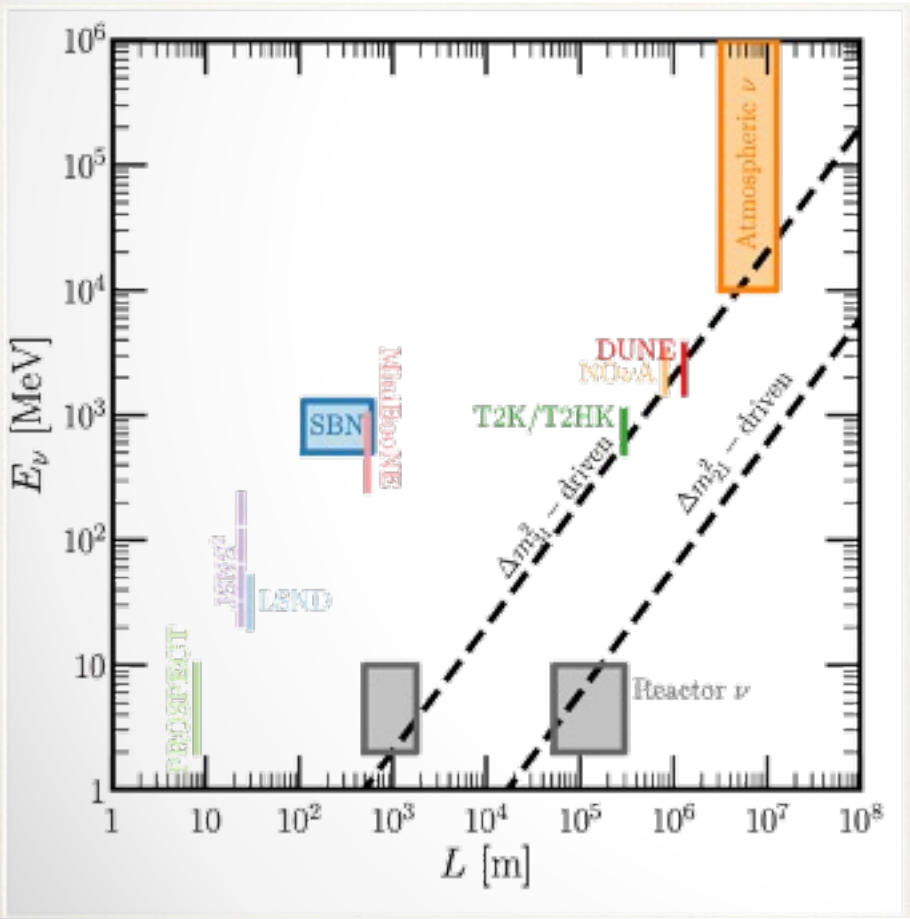
As a result:

$$P(\nu_e \to \nu_e) = |\varphi_e(t)|^2 = 1 - \sin^2 2\theta \sin^2(\frac{\delta m^2 L}{4E})$$

Takeaway Points

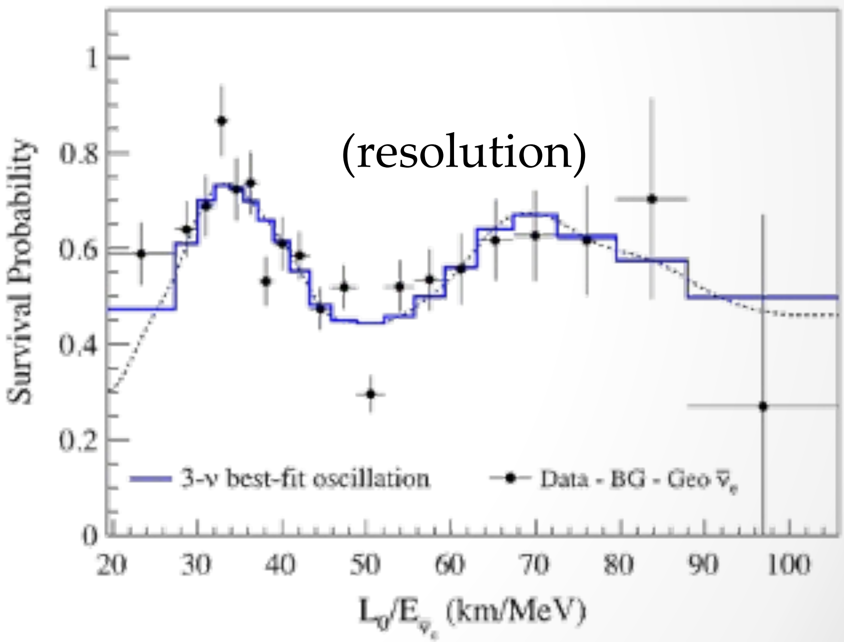
L/E dependence

Figure stole from K. Kelly



KamLAND 2016

(resolution)

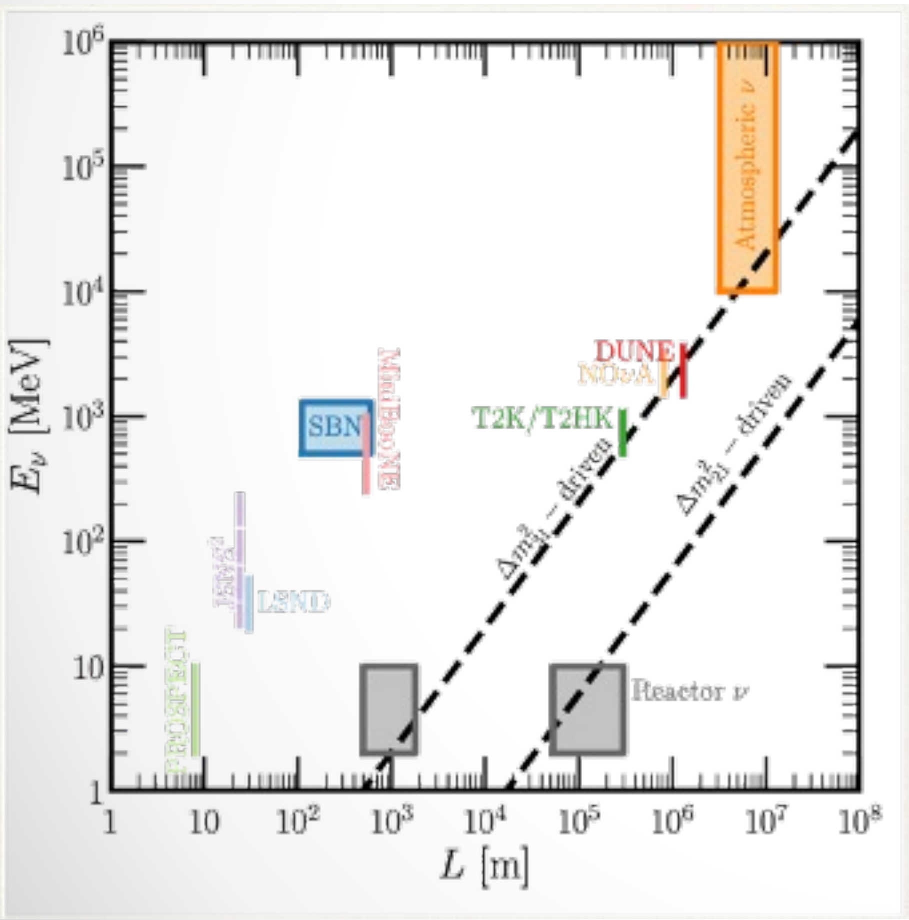


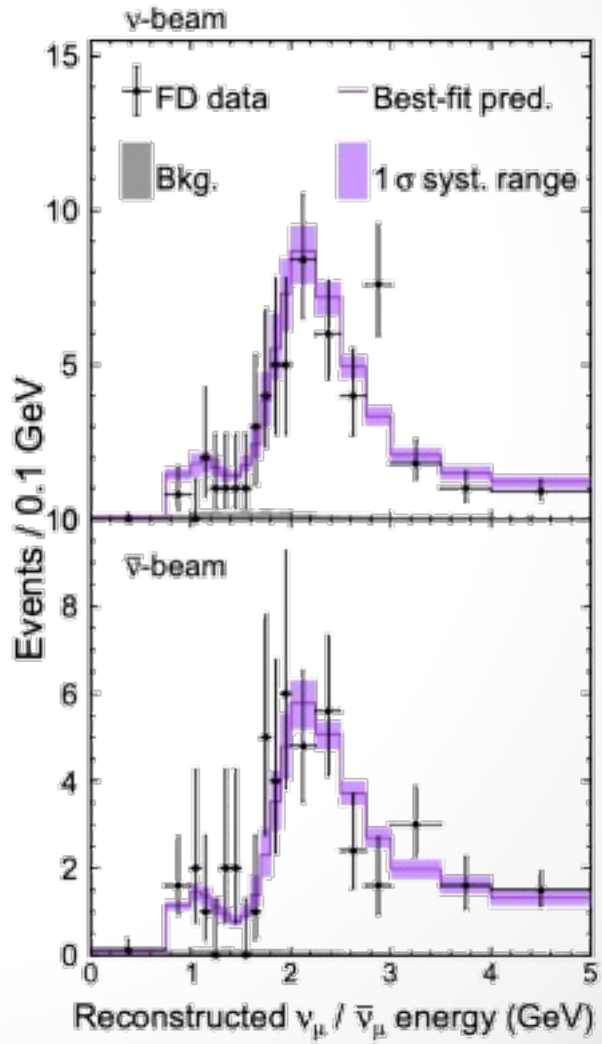
Takeaway Points

L/E dependence

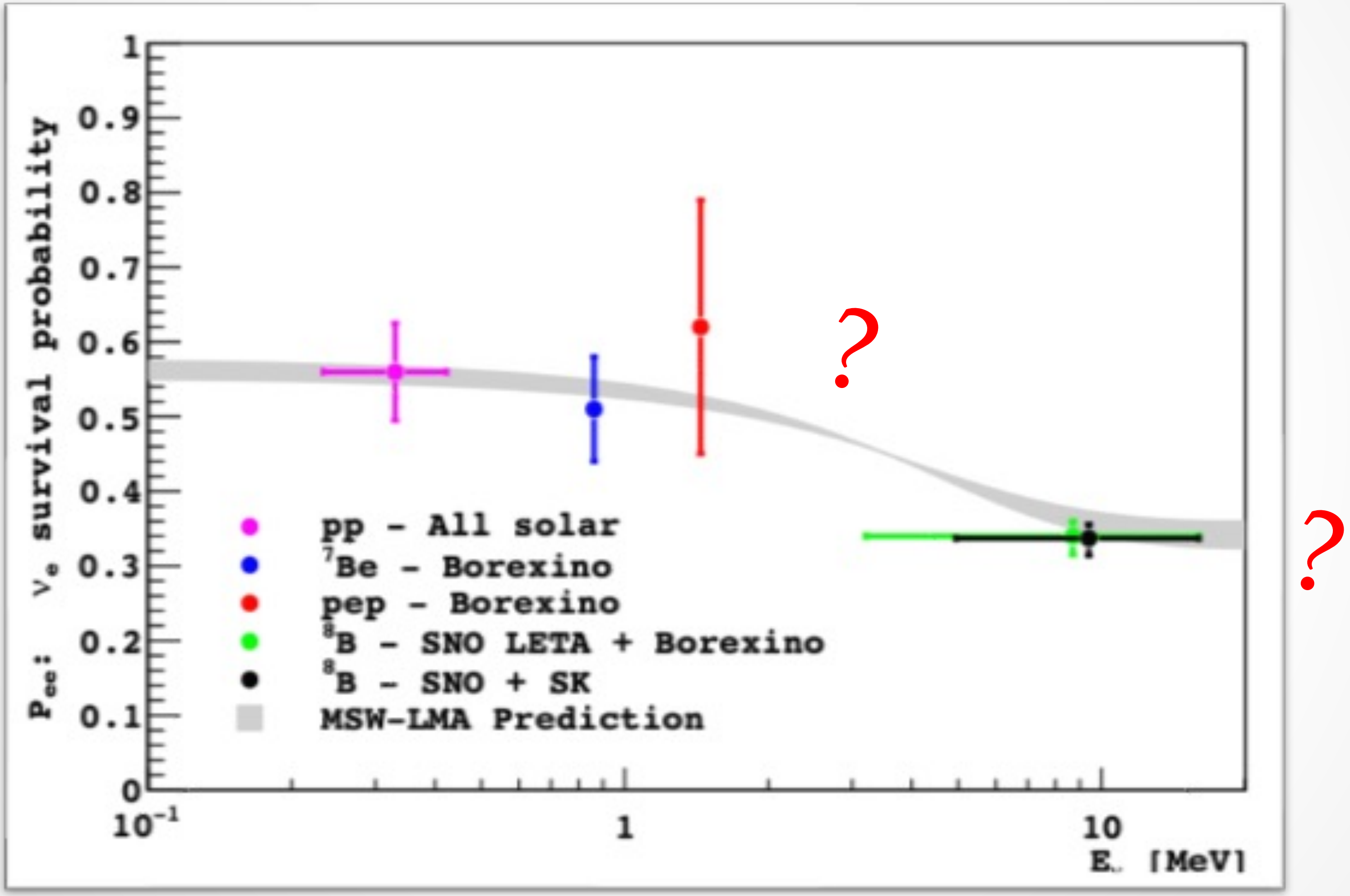
NOvA 2018

Figure stole from K. Kelly





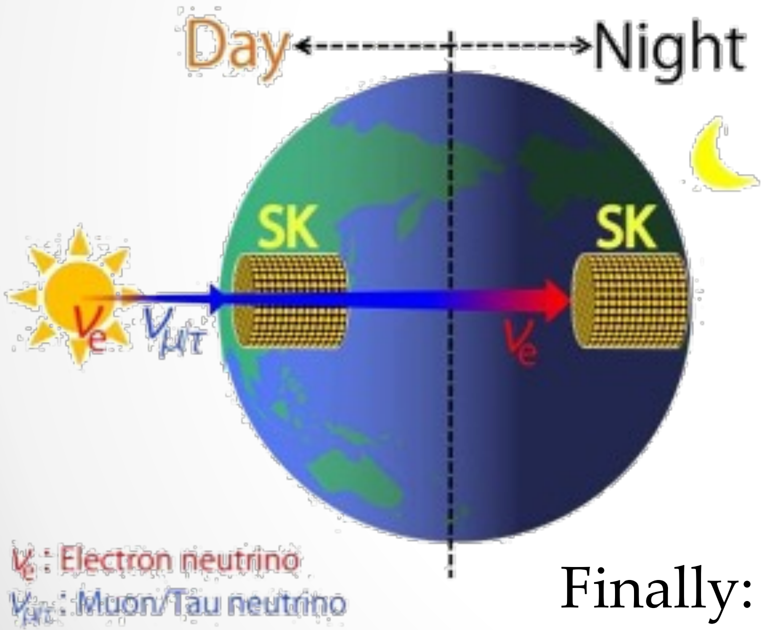
How does this make sense??



Borexino 2014

Matter Effect

Important for solar & supernova neutrinos, and long-baseline oscillation experiments (e.g. DUNE)



sk.icrr.u-tokyo.ac.jp

$$L \supset -2\sqrt{2}G_F(\bar{\nu}_e\gamma_\mu P_L\nu_e)(\bar{e}\gamma^\mu P_L e)$$

Leads to an effective potential:

$$V = \sqrt{2}G_F n_e$$

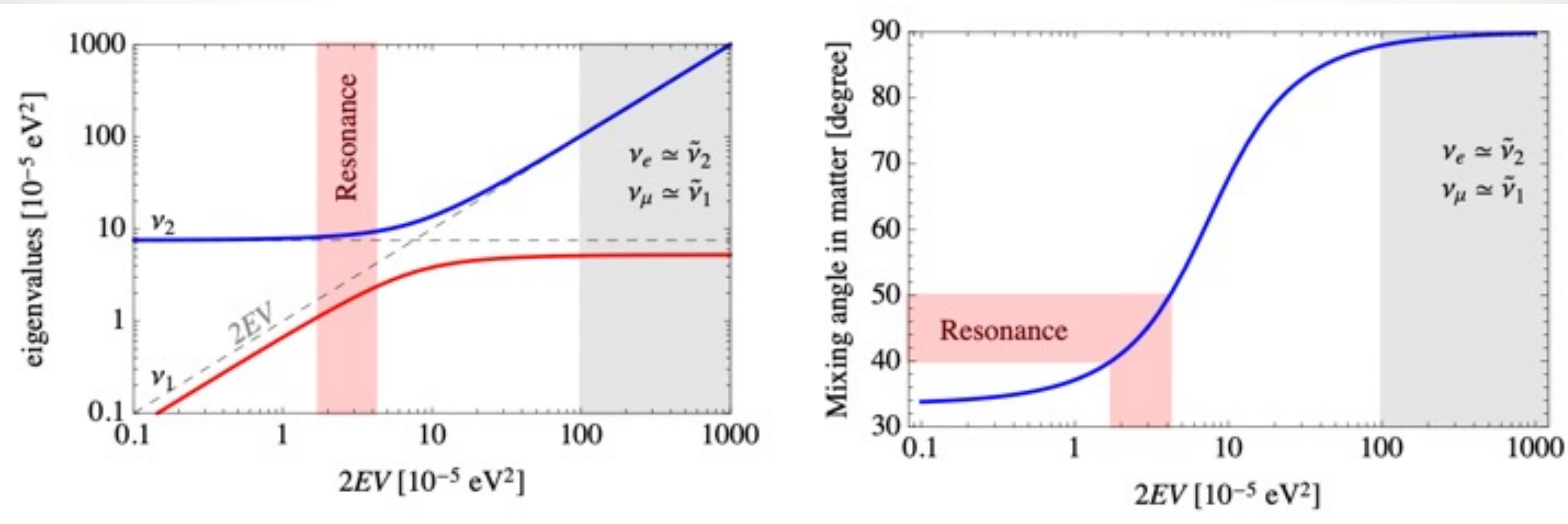
$$H_{\text{matter potential}} = \begin{pmatrix} V & 0 \\ 0 & 0 \end{pmatrix}$$

Finally:

$$H_{\text{flavor}} = \frac{\delta m^2}{4E}\begin{pmatrix} -cos2\theta + \frac{2\sqrt{2}G_F n_e}{\delta m^2/E} & sin2\theta \\ sin2\theta & cos2\theta \end{pmatrix}$$

MSW Effect

Mikheyev–Smirnov–Wolfenstein effect

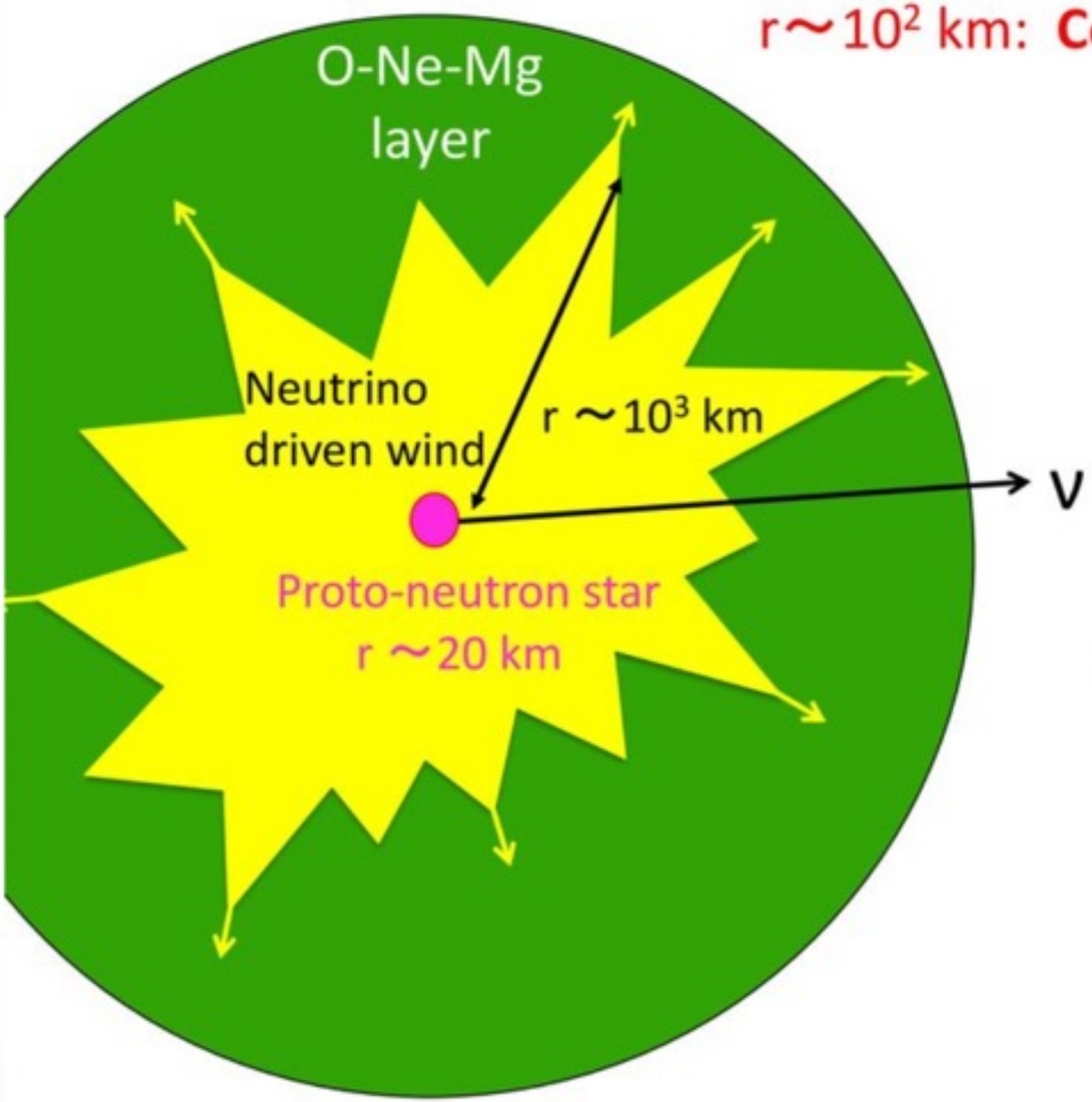


Machado 2022

Crucial for establishing solar neutrino oscillation
& determining the sign of Δm^2_{21}

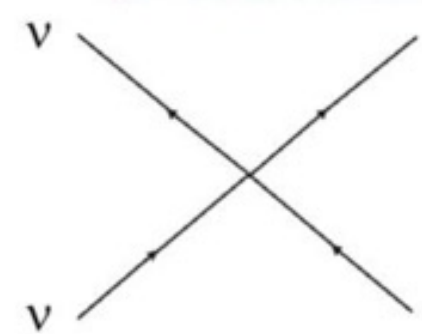
Slide stole from H. Sasaki, 2017

Neutrino oscillations in core-collapse supernovae



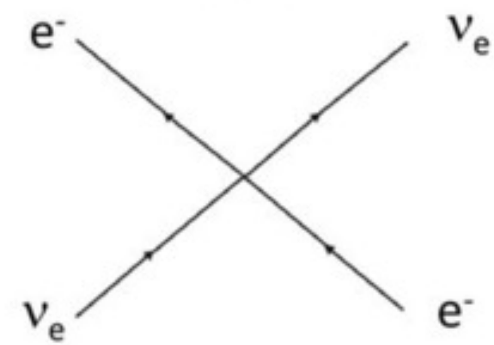
$r \sim 10^2$ km: Collective neutrino oscillations

(ν-ν coherent scatterings)



Duan, et al.,PRD74, 105014, 2006.

$r \sim 10^3$ km: MSW effect



L. Wolfenstein,PRD17, 2369, 1978.

3-Flavor Neutrino Oscillations

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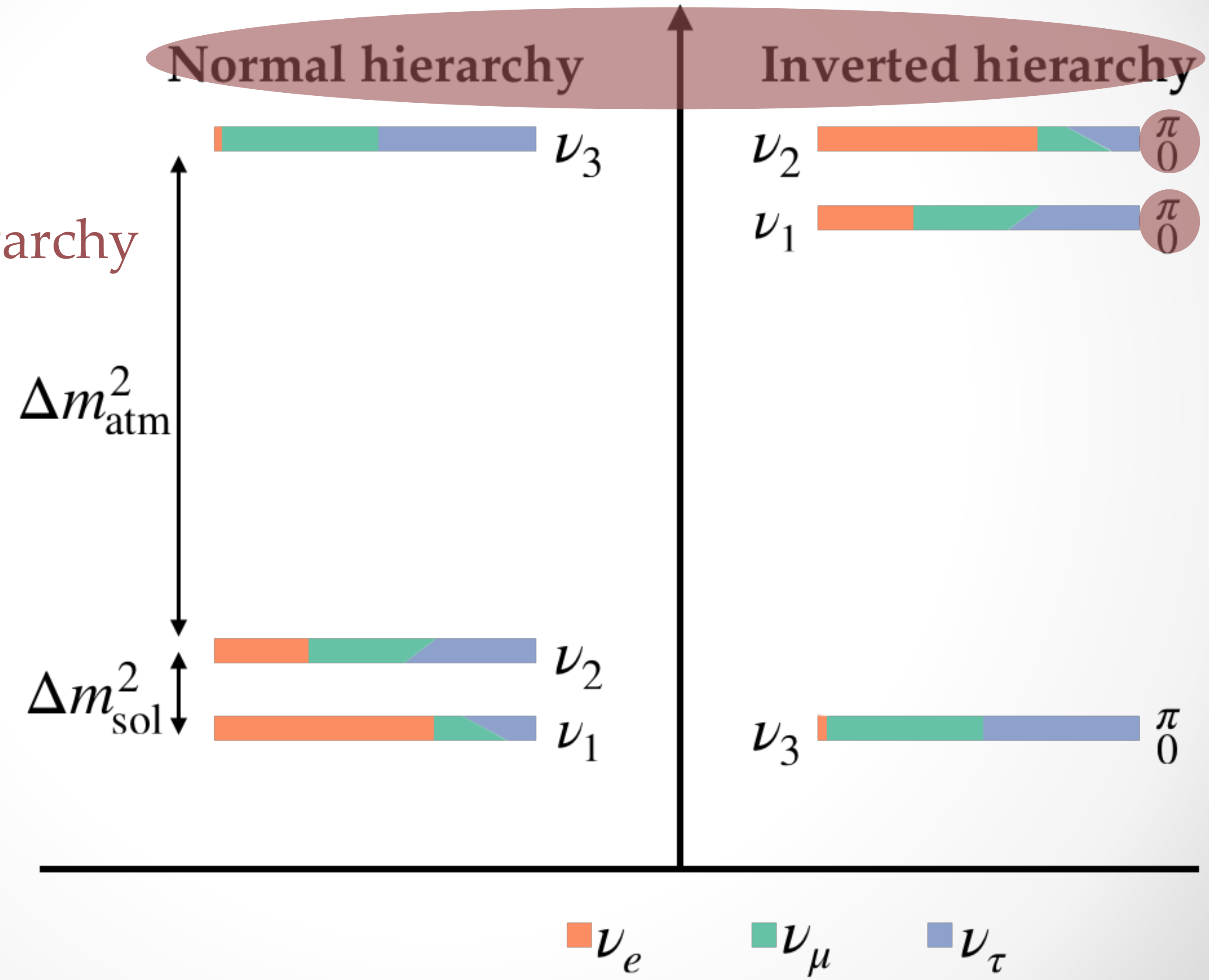


3-Flavor Neutrino Oscillations

Unknown

δ_{CP}, MH

A Few %:

$\theta_{12}, \theta_{13}, \theta$

$\Delta m^2_{21}, \Delta m$

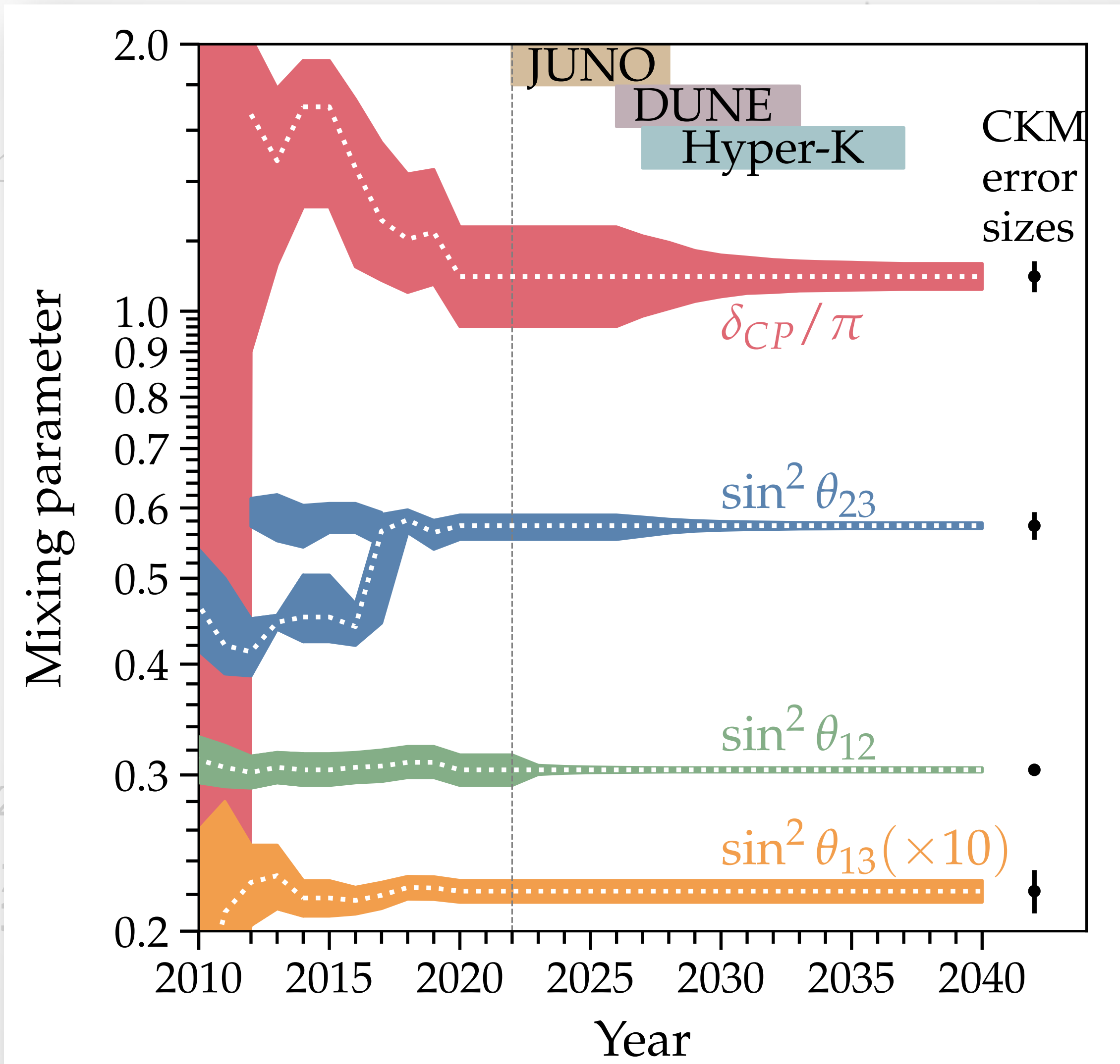
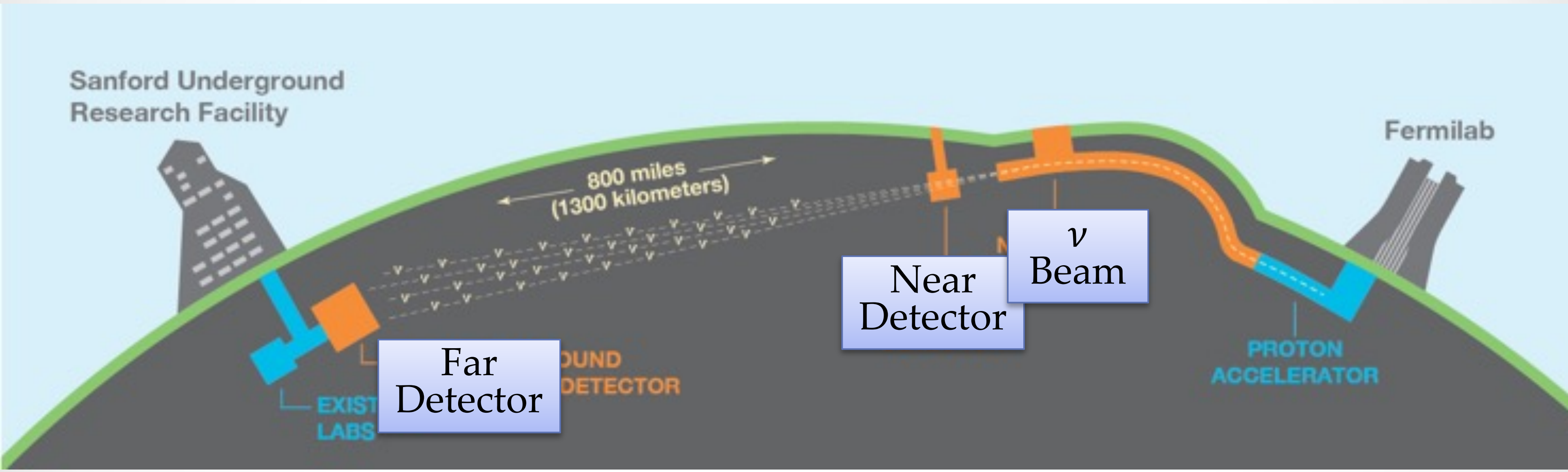


Figure modified from Song et al., 20

Long-Baseline Accelerator Experiments

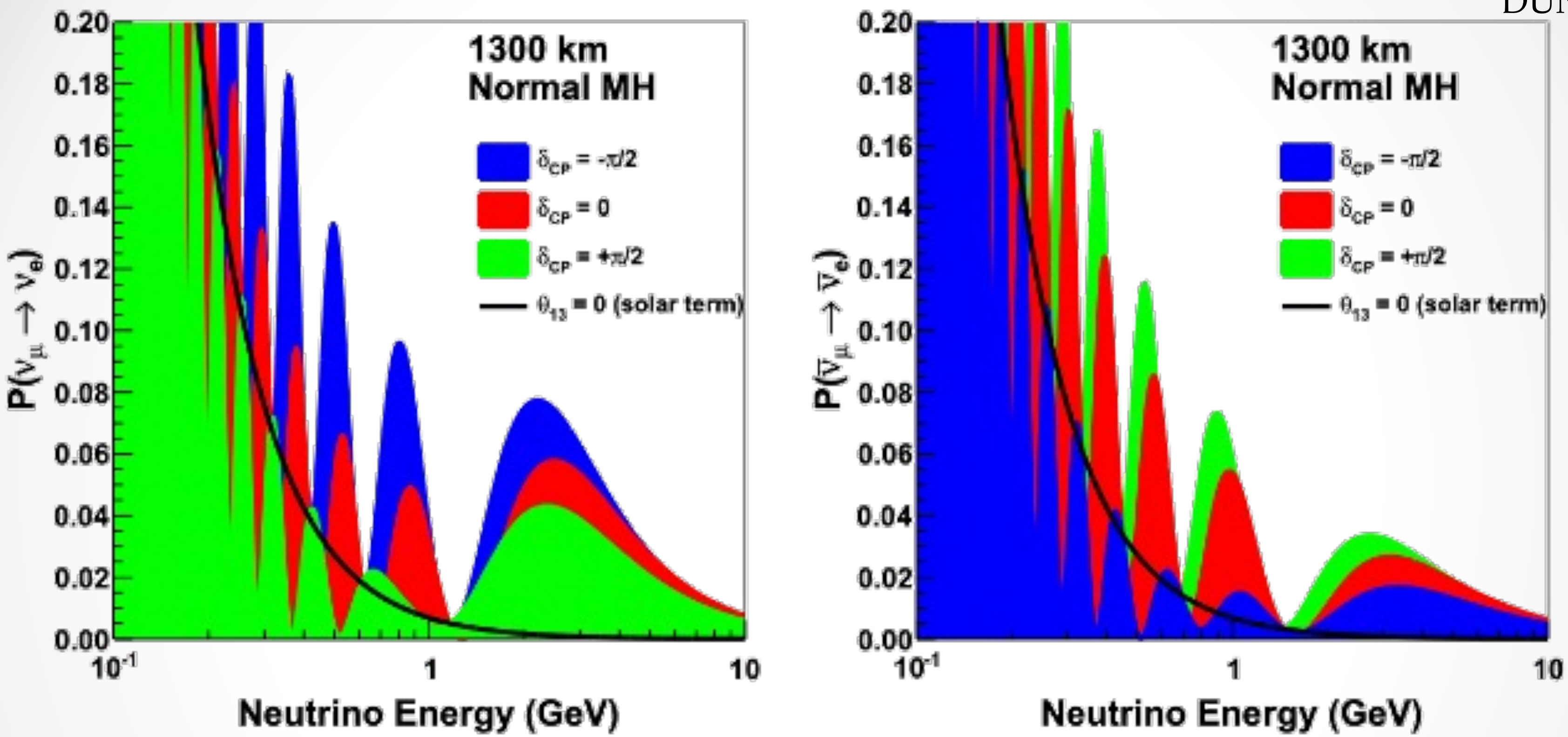
$$0.5\text{—}5\ \text{GeV}\ \nu_\mu \xrightarrow{\sim 1000\ \text{km}} \nu_e$$

DUNE 15



The Measurements

DUNE 2015



$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

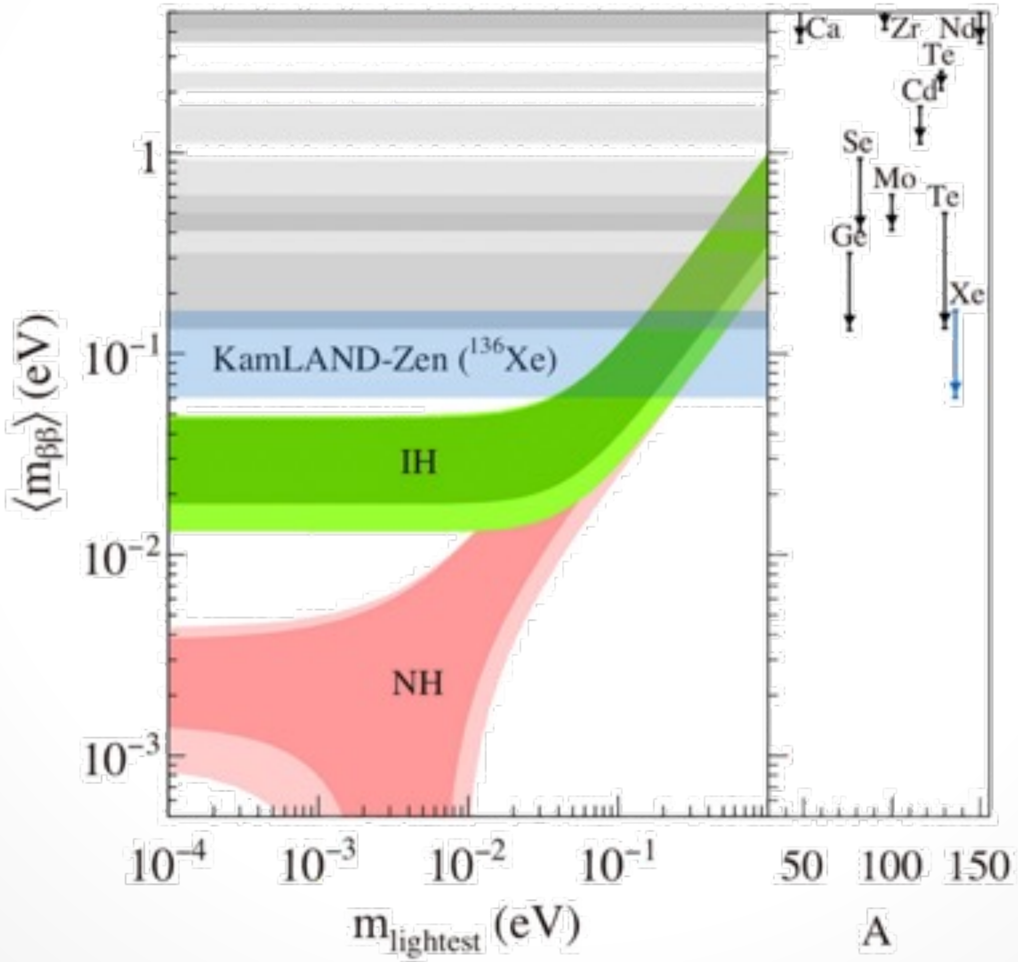
Why oscillation?

What we do not know about neutrino oscillation

Inputs for Other Physics

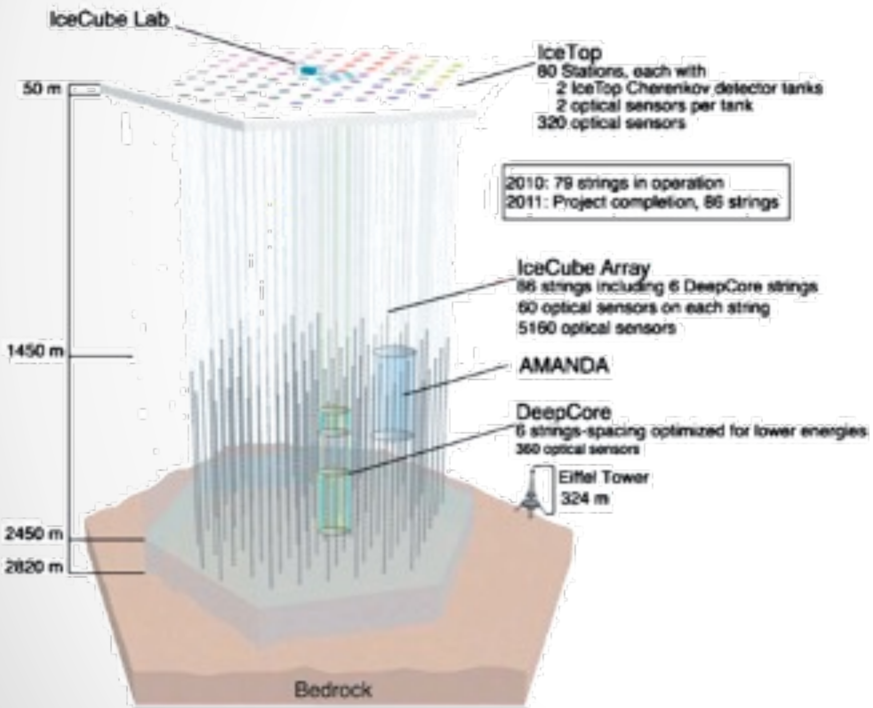
KamLAND 2016

$0\nu\beta\beta$ decay

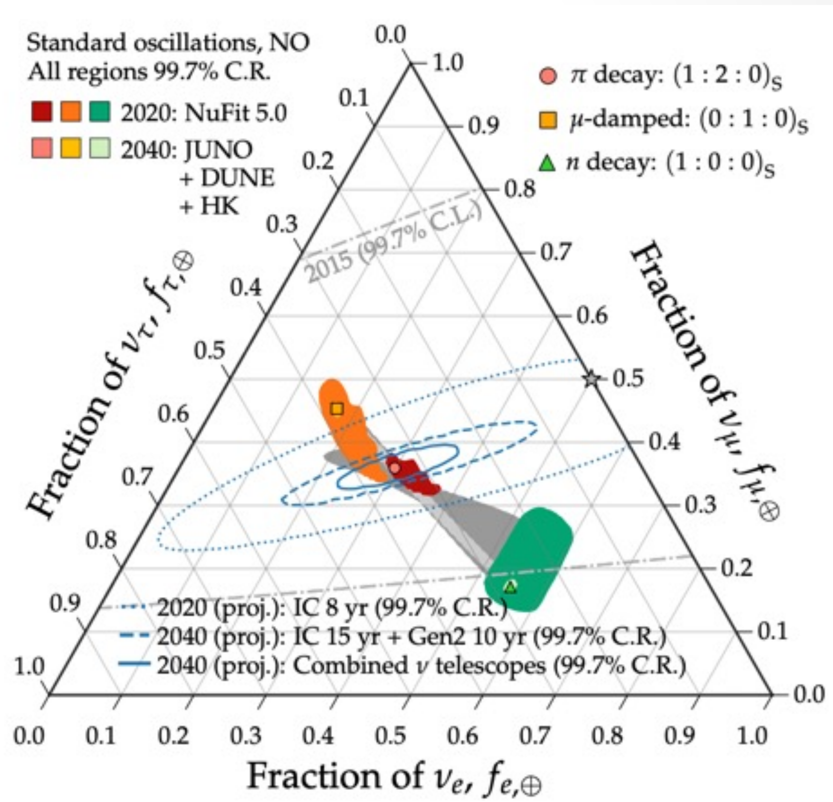


Inputs for Other Physics

Astrophysical neutrino sources



Song et al., 2020



Testing Oscillation Paradigm

A unitary 3*3 mixing matrix isn't the whole story…

Neutrinos have masses

Weinberg operator:

$$L \supset c_\nu \frac{LHLH}{\Lambda} + \text{h.c.}$$

New Physics at Scale Λ =>
New States =>

$$(3\times3)\, U_{\alpha k} \rightarrow (n\times n)\, \mathcal{U}_{\alpha k}$$

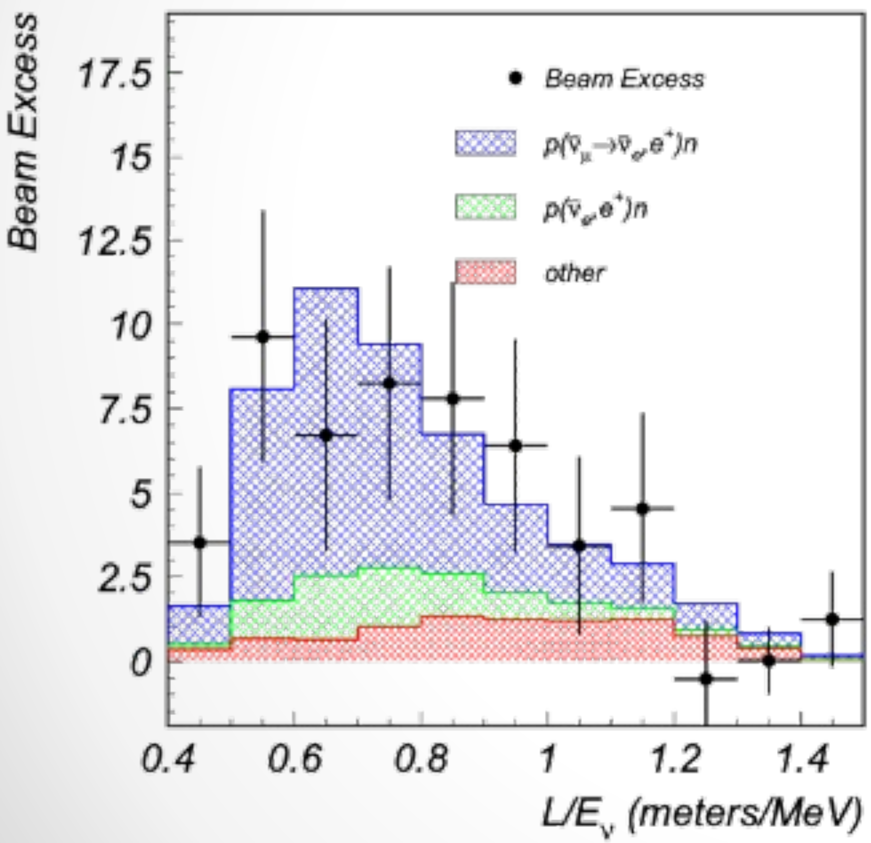
$$U_{\text{PMNS}}^{\text{Extended}} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}}^{U_{\text{PMNS}}^{3\text{x}3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \end{matrix} & \begin{matrix} \ddots & \vdots \end{matrix} \\ \begin{matrix} U_{s_n1} & U_{s_n2} & U_{s_n3} \end{matrix} & \begin{matrix} \cdots & U_{s_nn} \end{matrix} \end{pmatrix}$$

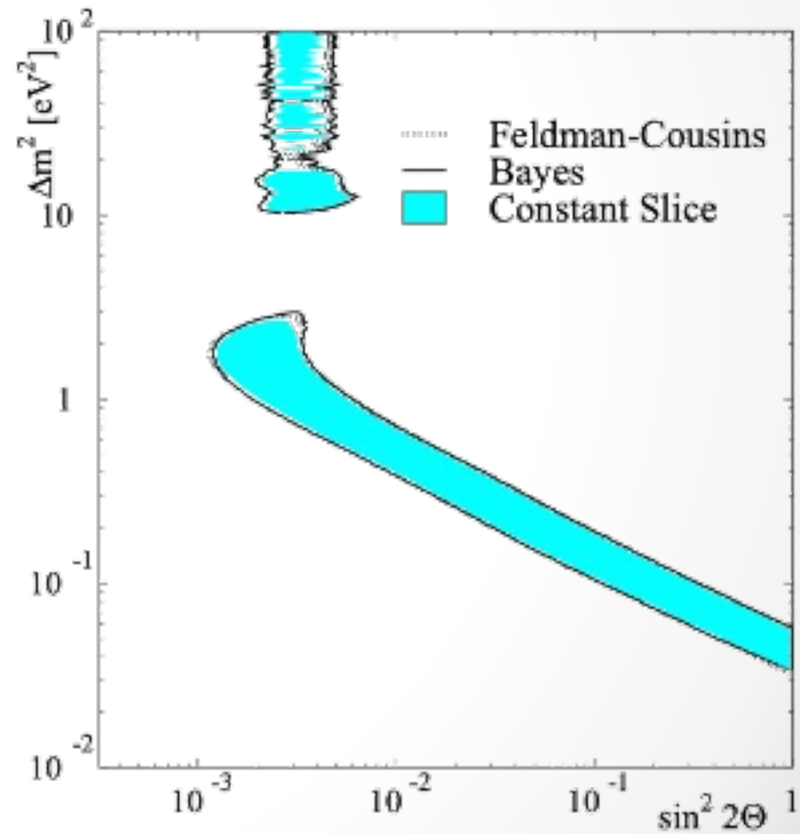
Sterile neutrinos?

Short-Baseline Anomaly

LSND (Liquid Scintillator Neutrino Detector)

LSND 2001

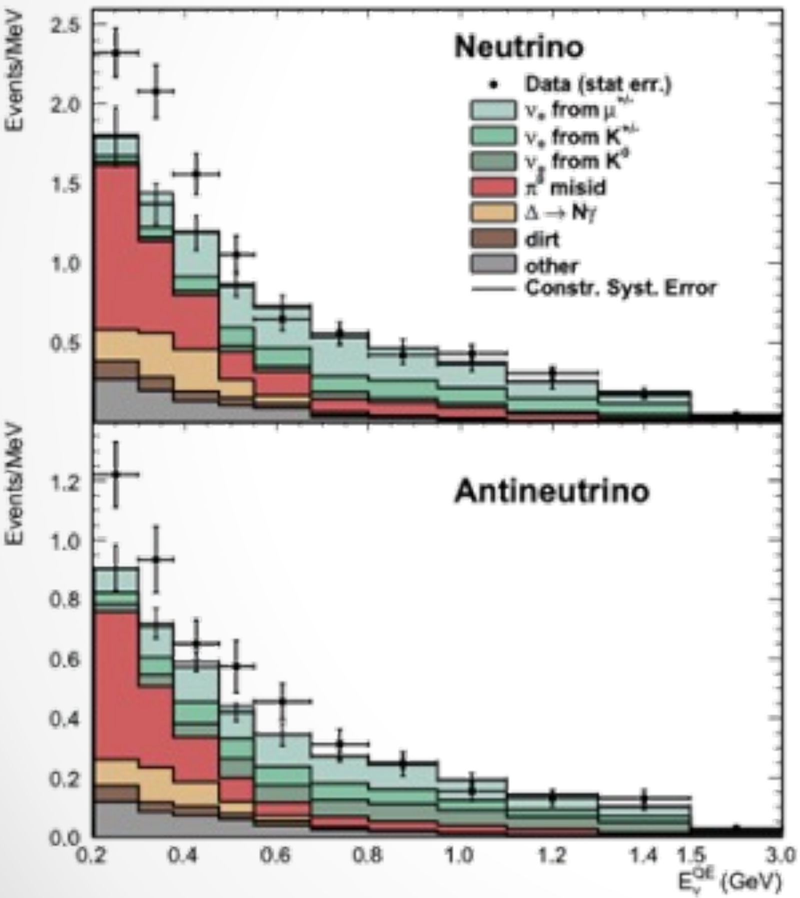


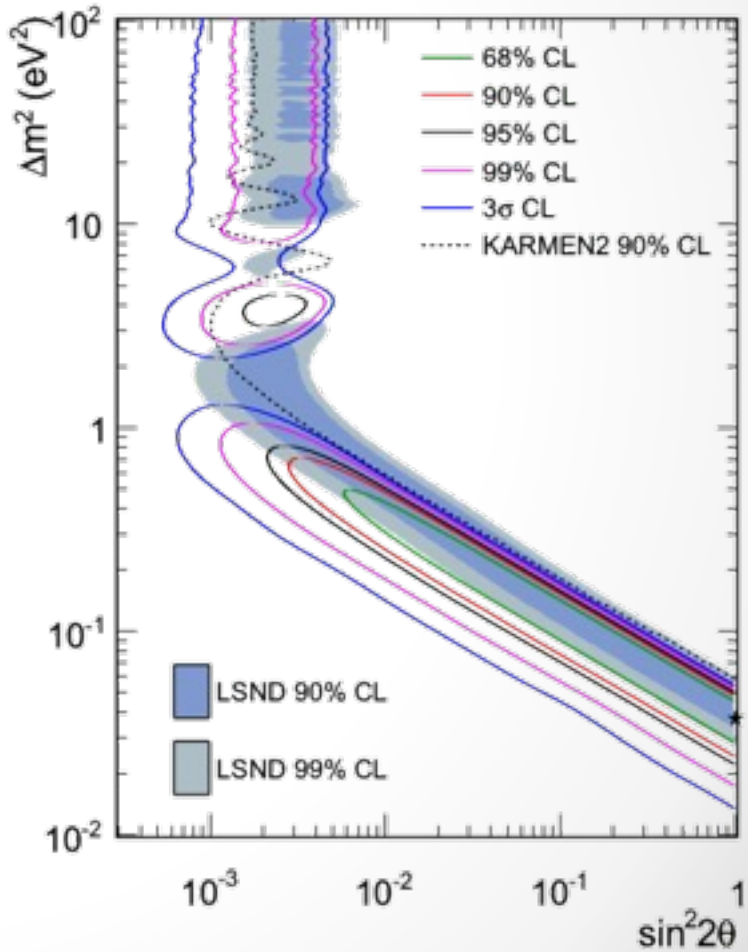


Short-Baseline Anomaly

MiniBooNE

MiniBooNE 2012



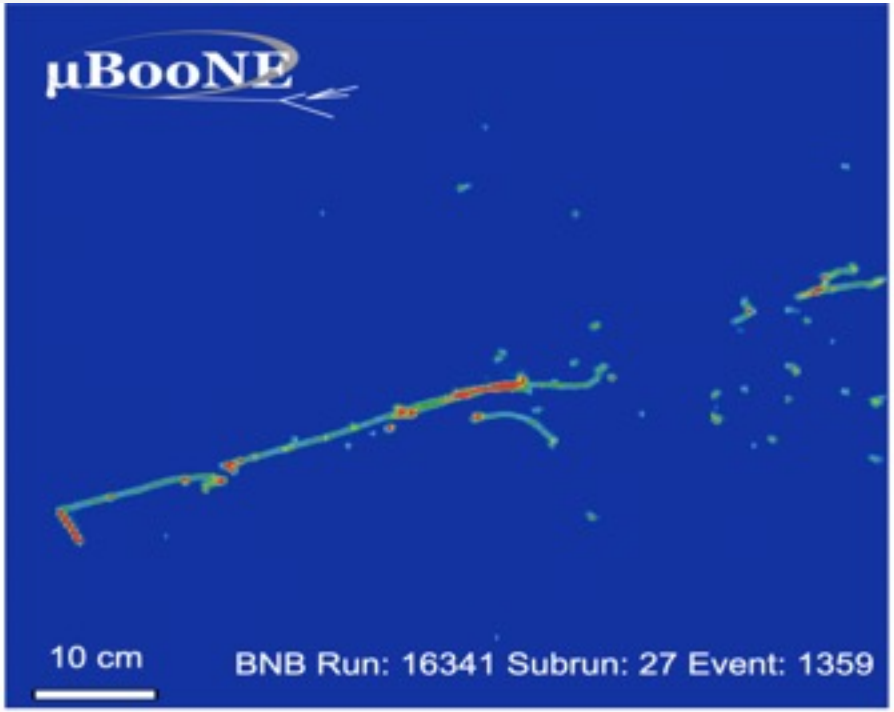


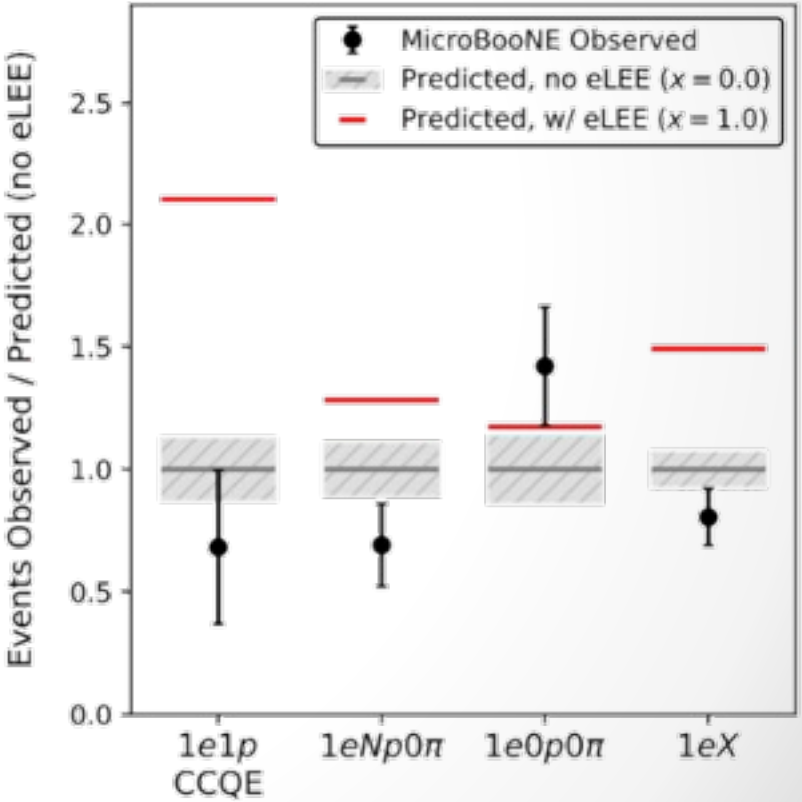
Short-Baseline Anomaly

MicroBooNE 2021

MicroBooNE

Liquid argon TPC



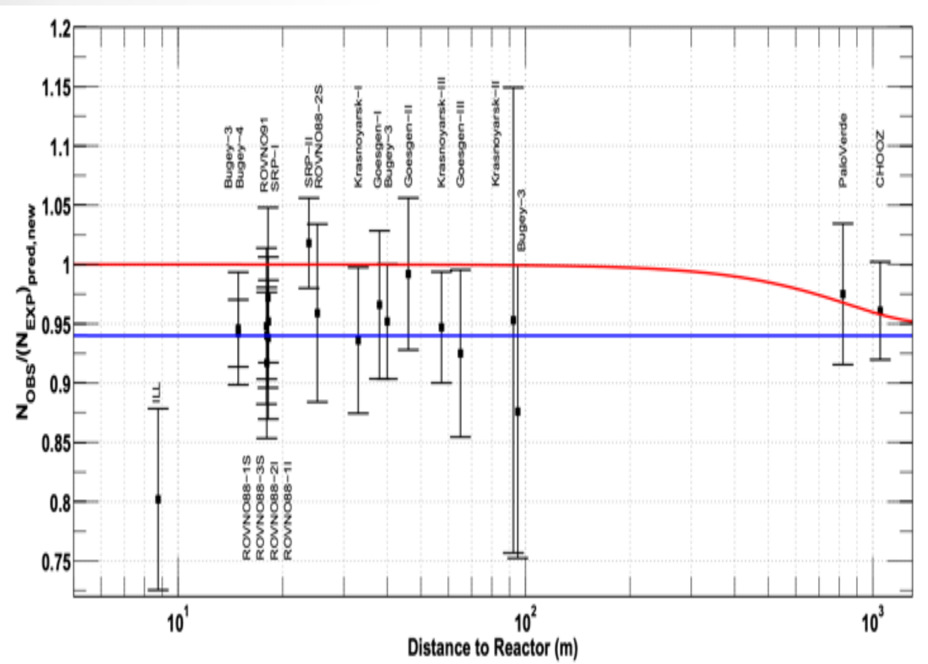


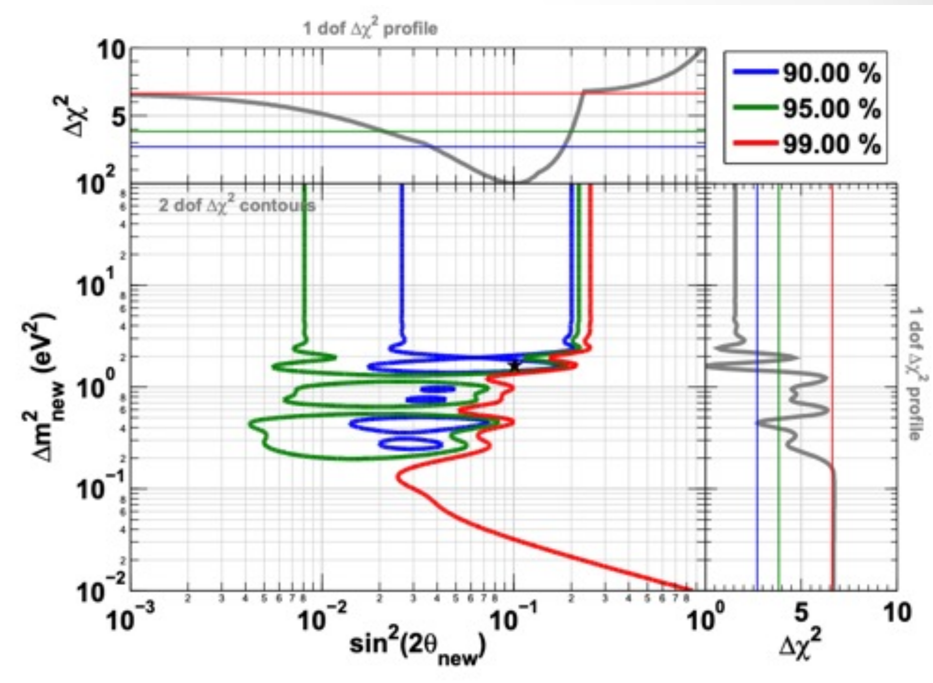
The jury is still out

Reactor Anomaly

From a combination of experiments

Mention et al., 2011



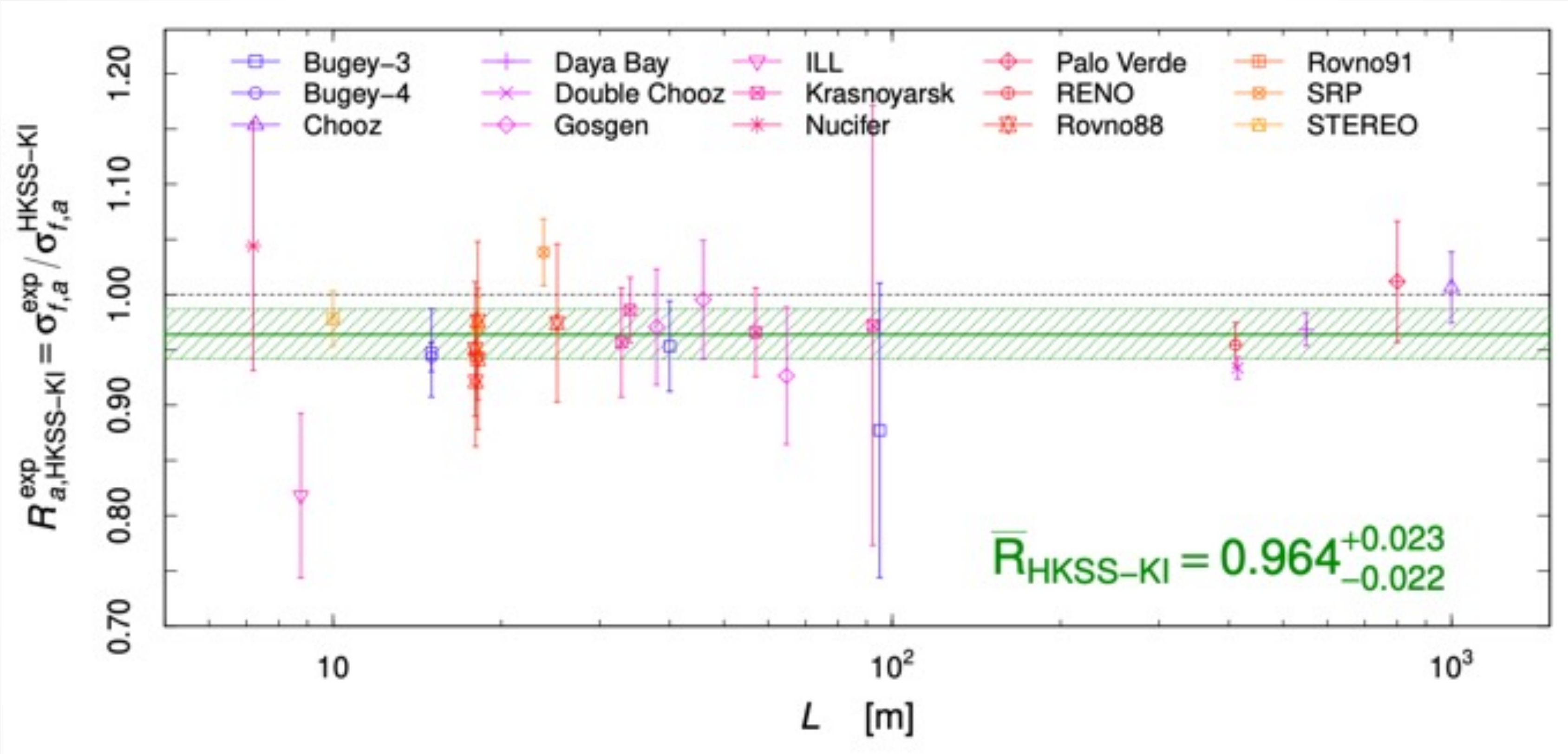


Similar region as the short-baseline anomaly hints at

Reactor Anomaly

The key is evaluation of reactor neutrino fluxes

Giunti et al., 2022



The jury is still out

Conclusions

- Standard three-flavor neutrino oscillation
  - Two-level system
  - Matter effect
  - Three-flavor oscillation
- Sterile neutrinos
  - Neutrino-nucleus cross sections
  - Reactor flux evaluations
  - Experimental capabilities