A simplified framework to explain neutrino oscillations

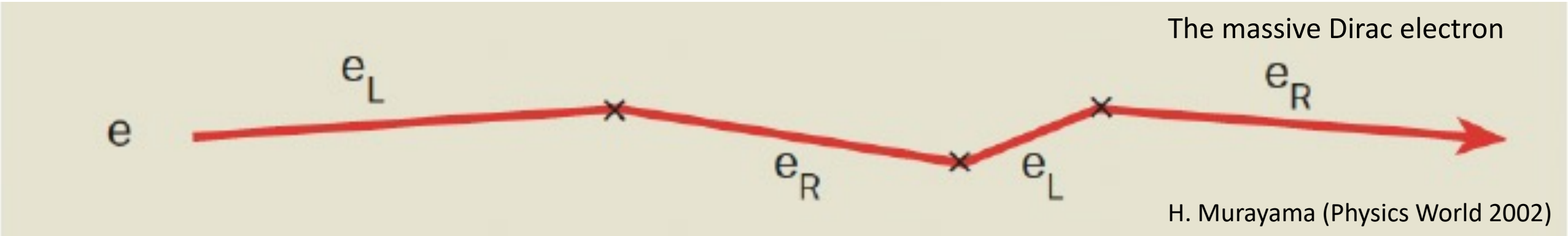
M. Bergevin, Lawrence Livermore National Laboratory

Abstract

Presented here is an alternative interpretation and derivation of neutrino oscillations via a simplified mass model and well-known dynamical system methods. The derivation appears to resolve many well know experimental anomalies such as the short baseline anomaly and the LSND/MiniBoone results without requiring a fourth neutrino. A new measurable quantity defined as the Flavon mass replaces the concept of mixing angles in this model. The model shows agreement with current reactor antineutrino and solar neutrino sectors (with flavon masses $f_{e\mu} = 3.31 \times 10^{-14}$ eV and $f_{e\tau} = 2.49 \times 10^{-11}$ eV). The model has clear predictions that may be easily verified with future medium baseline experiments such as JUNO. Finally, a discussion on possible future experiments to test this model and the status of the work will be presented.

Simplified Diagrams for mass production (Murayama Diagrams)

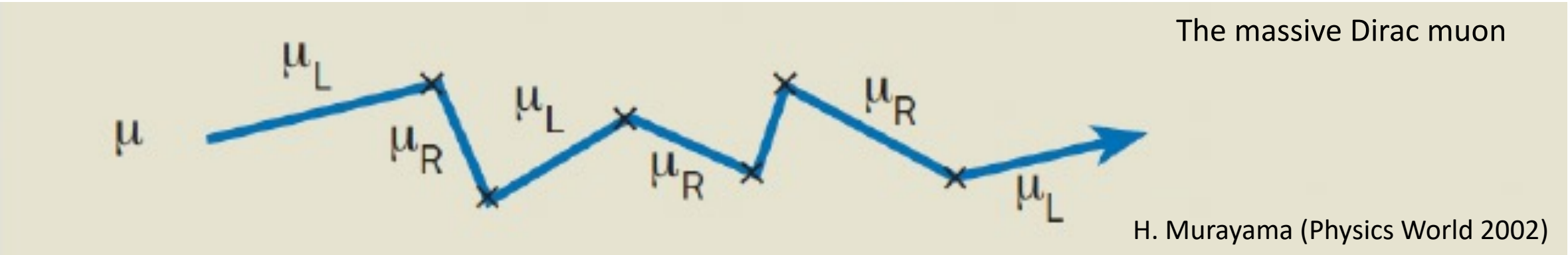
A free Weyl spinor state is assumed to gain mass in discreet Higgs interactions



The massive Dirac electron

H. Murayama (Physics World 2002)

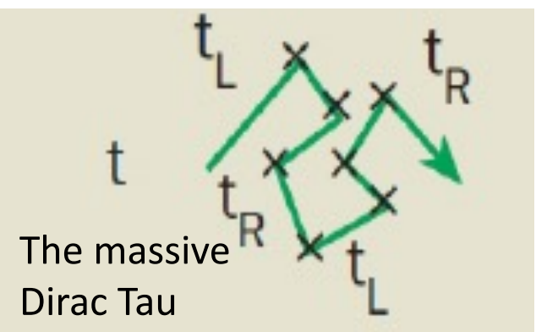
Flavor mass is equivalent to the frequency of these discreet interactions



The massive Dirac muon

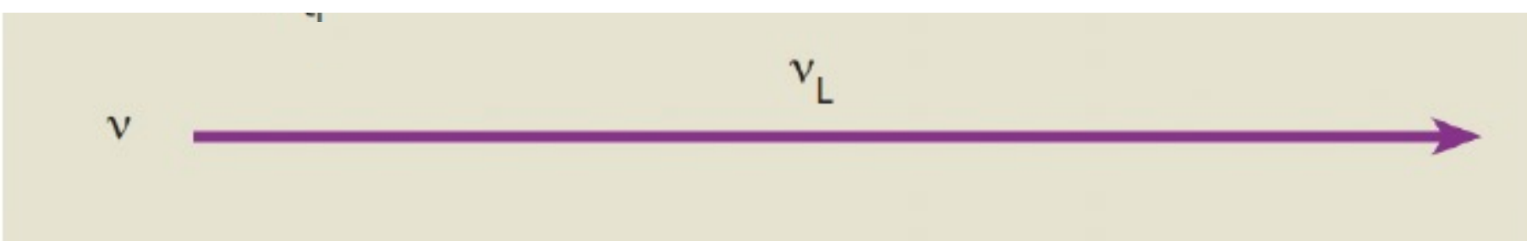
H. Murayama (Physics World 2002)

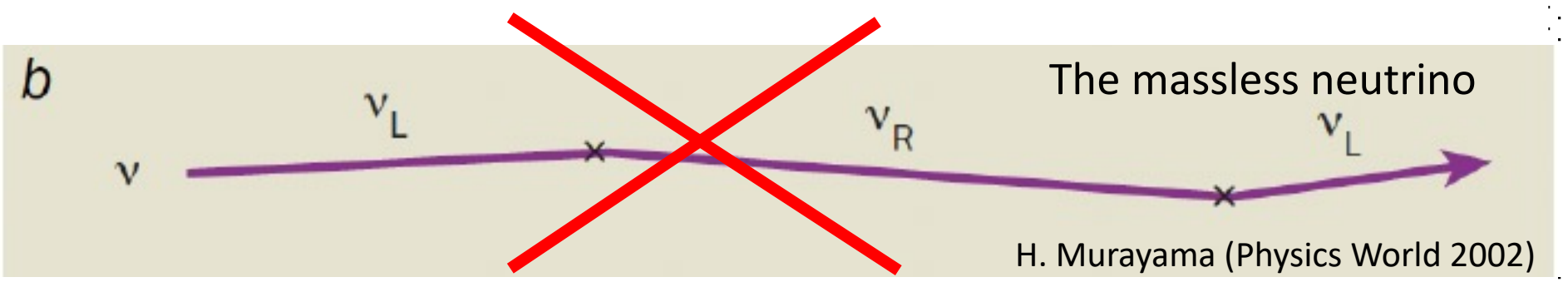
The transformation of the free Weyl spinor from a left- to right-handed states are akin to successive spin flips. More frequent spin flips lead to higher mass.



The massive Dirac Tau

A standard neutrino should not have mass due to the absence of right-handed neutrinos





The massless neutrino

H. Murayama (Physics World 2002)

Neutrino mass is possible if a right-handed neutrino is much heavier than the left-handed neutrino.

H. Murayama (Physics World 2002)

The massive Majorana neutrino

Energy states of the system

$$\mathbf{H}_{FD} = \begin{cases} \begin{pmatrix} -\vec{\sigma}\cdot\vec{p} & m \\ m & \vec{\sigma}\cdot\vec{p} \end{pmatrix} & \text{continuous matter field} \\ \begin{pmatrix} -\vec{\sigma}\cdot\vec{p} & m^{LR} \\ m^{RL} & \vec{\sigma}\cdot\vec{p} \end{pmatrix} & \text{annihilation-creation} \end{cases}$$

Diagonalize to find the energy of the system.

$$\mathcal{H}_{FD} = \begin{pmatrix} -\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}\sqrt{\vec{p}^2+m^2} & 0 \\ 0 & \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}\sqrt{\vec{p}^2+m^2} \end{pmatrix}$$

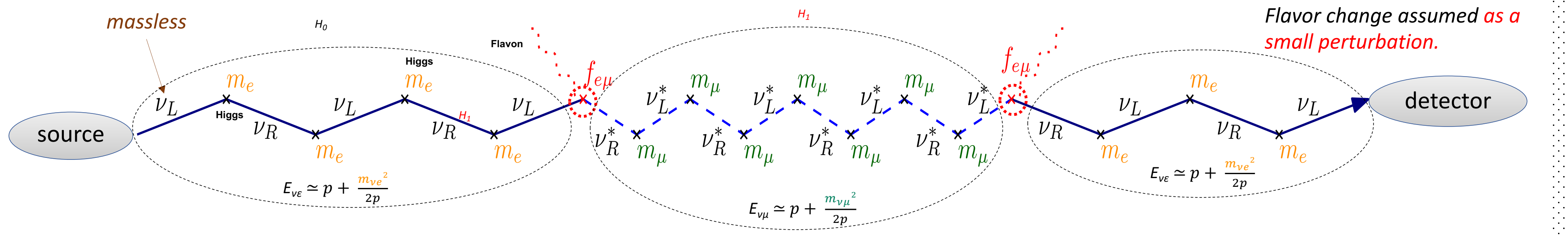
Foldy-Wouthuysen representation

Seesaw mechanism (Lagrangian approach)

$$\begin{pmatrix} 0 & m_{dirac} \\ m_{dirac} & M \end{pmatrix} \qquad \lambda_{\pm} = \frac{M \pm \sqrt{M + 4m_{dirac}{}^2}}{2}$$

$$\lambda_{+} \approx M \quad \text{or} \quad \lambda_{-} \approx \frac{m_{dirac}{}^2}{M}$$

Perturbation approach



Flavor change assumed as a small perturbation.

Model (2002.12269) assumes that flavor change occurs at discrete external points. No reason to diagonalize the entire system.

Energy state of the system (perturbation approach)

$$\begin{bmatrix} p + \frac{m^2_{\nu_e}}{2p} & f_{e\mu} \\ f_{e\mu} & p + \frac{m^2_{\nu_\mu}}{2p} \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} \equiv E_{sys} \begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix}$$

Flavon approach (a single wavefunction)

- **Standard approach in dynamical systems**
- **Oscillation model relies on this perturbation step. This is a new approach.**
- **Pauli rotation of systems is well known in other fields.**
- **Akin to excited and ground states.**

PMNS Reminder (multiple wavefunctions)

$$H\Psi = i\hbar\frac{\partial}{\partial t}\Psi = E\Psi \rightarrow \Psi = e^{-i\bar{E}t/\hbar}.$$

$$|\nu_e> = \cos\theta_{12}e^{-iE_1t/\hbar}|\nu_1> + \sin\theta_{12}e^{-iE_2t/\hbar}|\nu_2>$$
$$|\nu_\mu> = -\sin\theta_{12}e^{-iE_1t/\hbar}|\nu_1> + \cos\theta_{12}e^{-iE_2t/\hbar}|\nu_2>$$

PMNS

$$P_{ee} = |<\nu_e(t)|\nu_e>| = 1 - \sin^2(2\theta_{12})\sin^2(\frac{\Delta m^2_{12}}{4E_\nu}t)$$

***Constant amplitude**. Maximum number of neutrinos that can be lost*

Flavon (a single system wavefunction)

$$E_{sys} = f_{e\mu}\sigma_x + \Delta E\sigma_z + E_{tot}I, \qquad (23)$$

where $E_{tot} = p + (m^2_{\nu_e}/4p) + (m^2_{\nu_\mu}/4p)$, $\Delta E = (m^2_{\nu_e}/4p) - (m^2_{\nu_\mu}/4p)$, σ_x and σ_z are the Pauli matrices, and I is the identity matrix.

2x2 matrices

$$U(t) = e^{-i(f_{e\mu}\sigma_x + \Delta E\sigma_z)t/\hbar}e^{-i(E_{tot}I)t/\hbar} = U_{osc}U_{E_\nu}$$

Flavon

$$P_{ee} = 1 - \frac{f_{e\mu}{}^2}{\left(\frac{\Delta m^2_{\nu_{\mu e}}}{4E_\nu}\right)^2 + f_{e\mu}{}^2}\sin^2\left(t\sqrt{\left(\frac{\Delta m^2_{\nu_{\mu e}}}{4E_\nu}\right)^2 + f_{e\mu}{}^2}\right)$$

***Amplitude not constant**: Energy dependence.*

A more precise formula

$$P_{ee} = 1 - \frac{f_{e\mu}{}^2}{\left(\frac{\Delta m^2_{\nu_{\mu e}}}{4E_\nu}\right)^2 + f_{e\mu}{}^2}\sin^2\left(t\sqrt{\left(\frac{\Delta m^2_{\nu_{\mu e}}}{4E_\nu}\right)^2 + f_{e\mu}{}^2}\right)$$

Short time scale

$$1 - f^2_{e\mu}t^2$$

No spectral feature

Long time scale

$$0.5\left(1 + (\Delta m^2_{\alpha\beta}/4E_\nu f_{\alpha\beta})^2\right)$$

~1/E² akin to MSW effect

2-flavor Model

$$U_{osc} = \begin{bmatrix} \cos(\delta t) - i\frac{\Delta E}{\delta}\sin(\delta t) & -i\frac{f_{e\mu}}{\delta}\sin(\delta t) \\ -i\frac{f_{e\mu}}{\delta}\sin(\delta t) & \cos(\delta t) + i\frac{\Delta E}{\delta}\sin(\delta t) \end{bmatrix} \equiv \begin{bmatrix} \tilde{c}_{e\mu} & \tilde{s}_{e\mu} \\ \tilde{s}_{e\mu} & \tilde{\bar{c}}_{e\mu} \end{bmatrix}$$

$$\delta \equiv \sqrt{\Delta E^2 + f^2_{e\mu}}$$

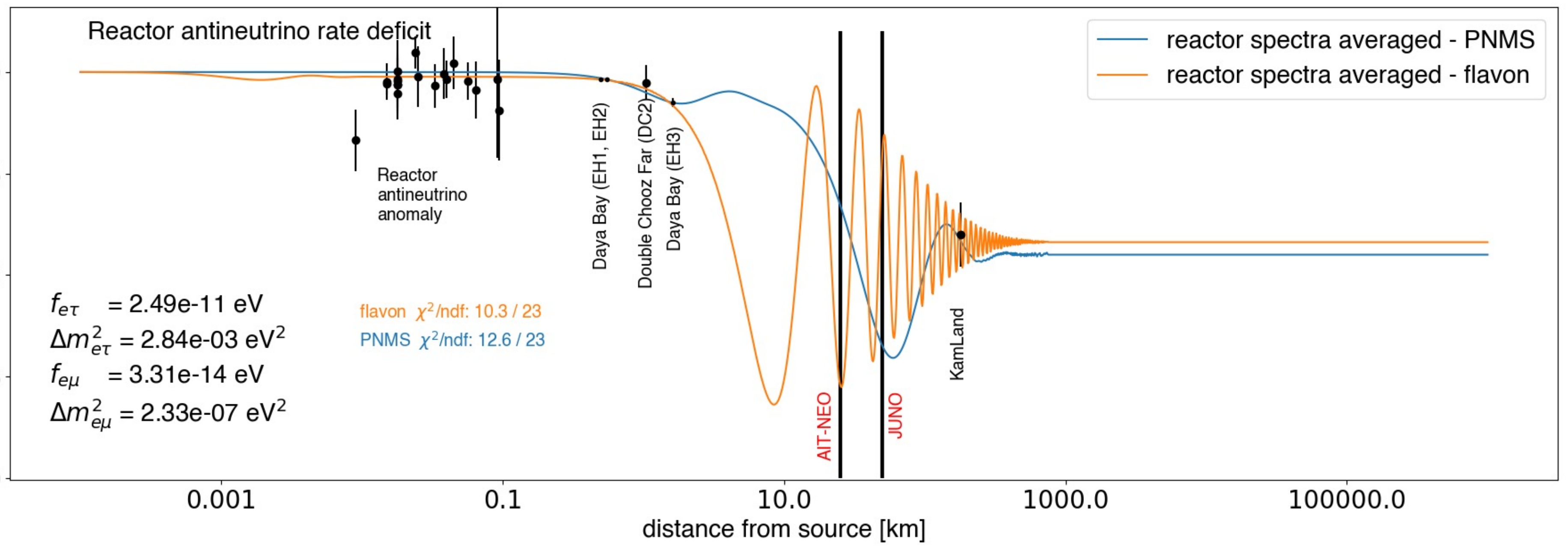
Port from a 2-flavor model to a 3-flavor model

3D-flavor electron neutrino model

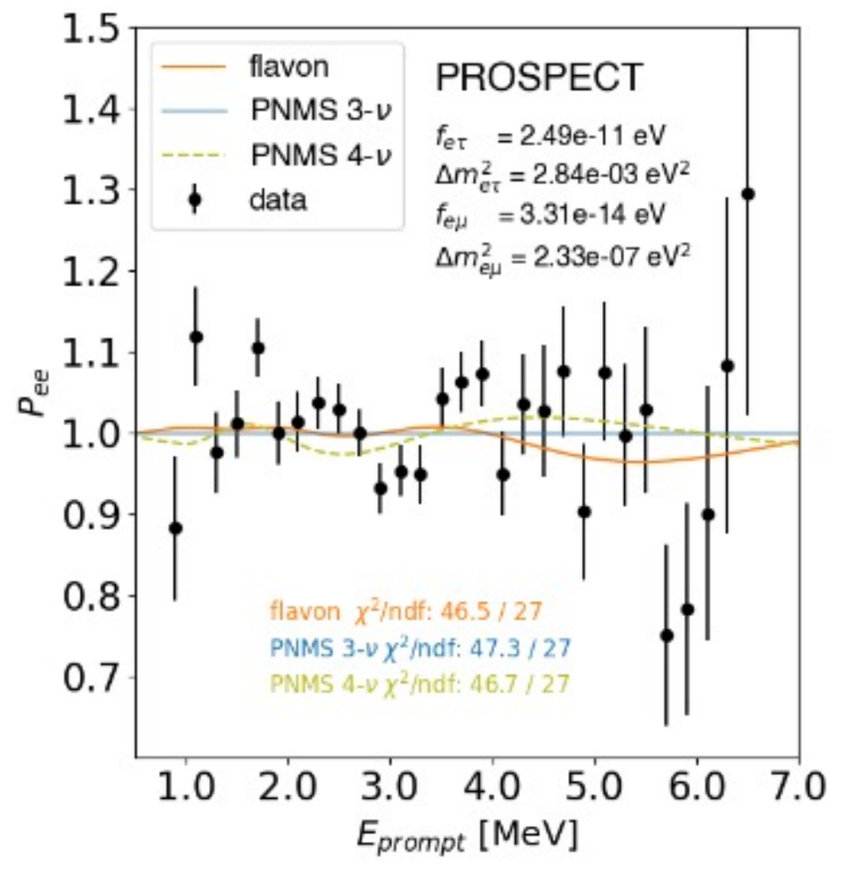
$$P_{ee} = |\langle e|R_x(\delta'_{\mu\tau}t)R_y(\delta'_{e\tau}t)R_z(\delta'_{e\mu}t)|e\rangle|^2$$
$$P_{ee} \approx |\langle e|\tilde{c}_{e\mu}\tilde{c}_{e\tau}|e\rangle|^2 = P^{2D}_{\nu_e\not\to\nu_\mu}P^{2D}_{\nu_e\not\to\nu_\tau}$$

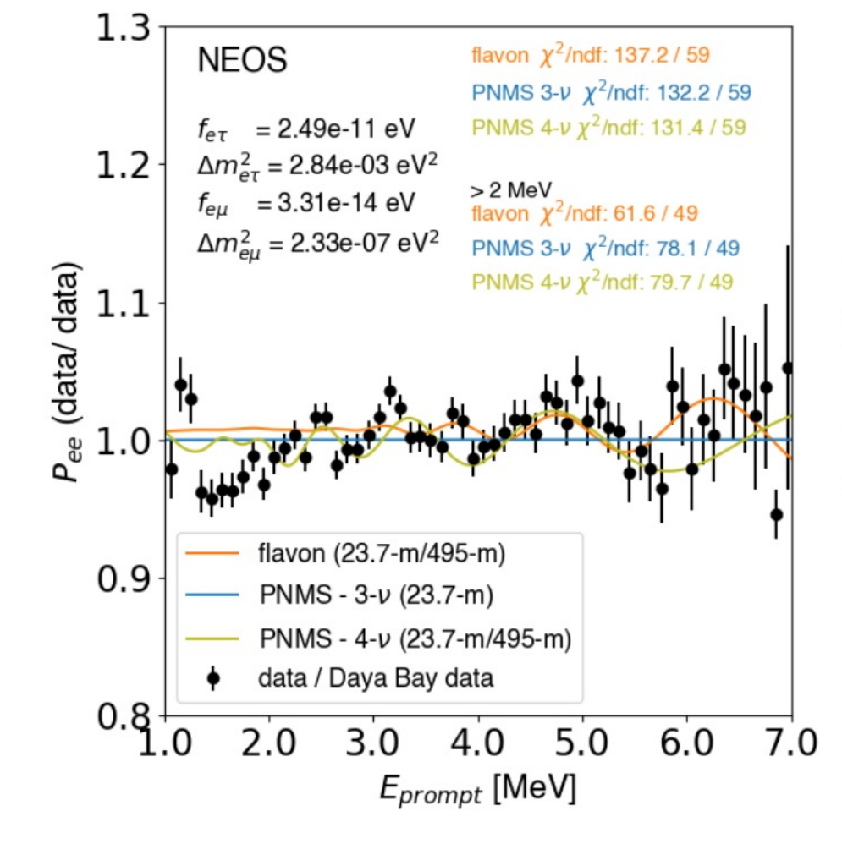
Reproduces reactor and solar data

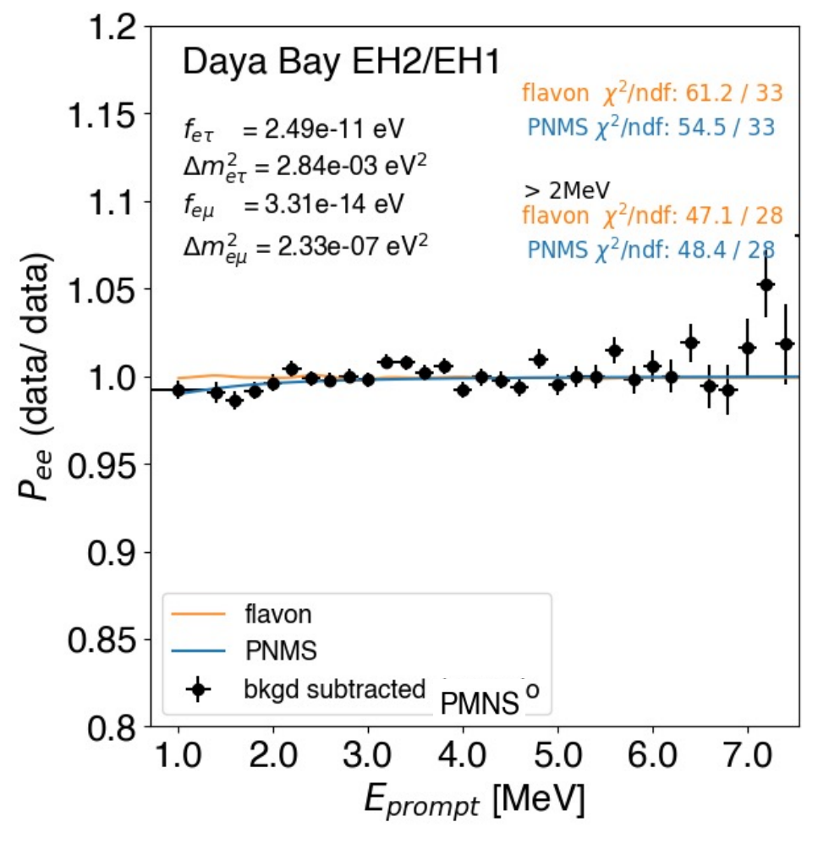
Allows the possibility to explain the short baseline anomaly (here assumed at 3%).

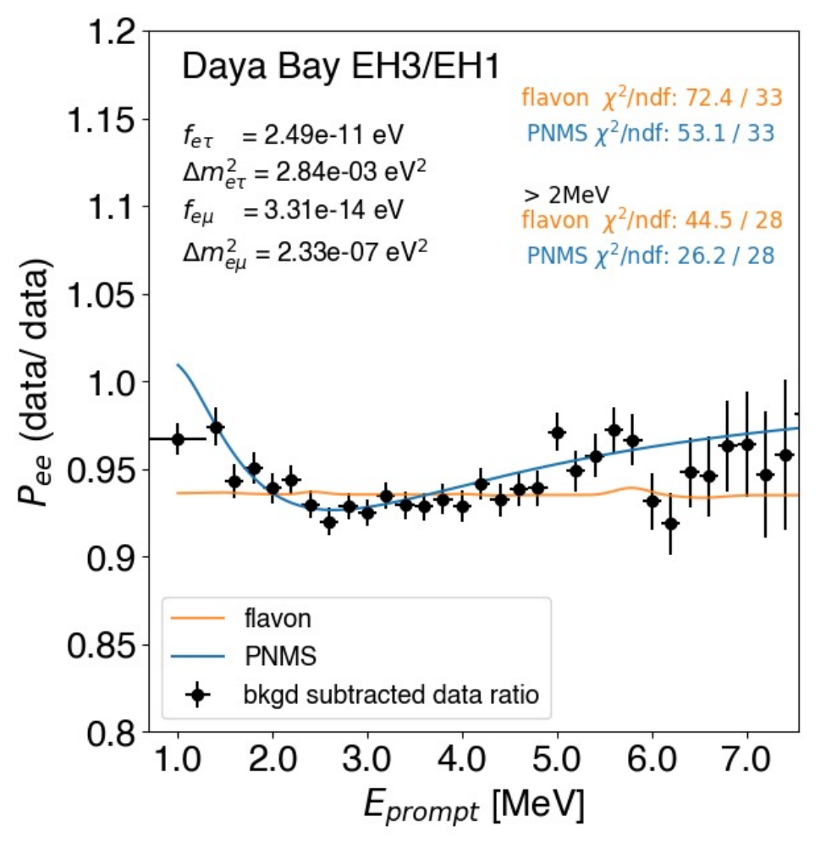


Reactor neutrino spectral feature reproduced with only 3 neutrino flavors

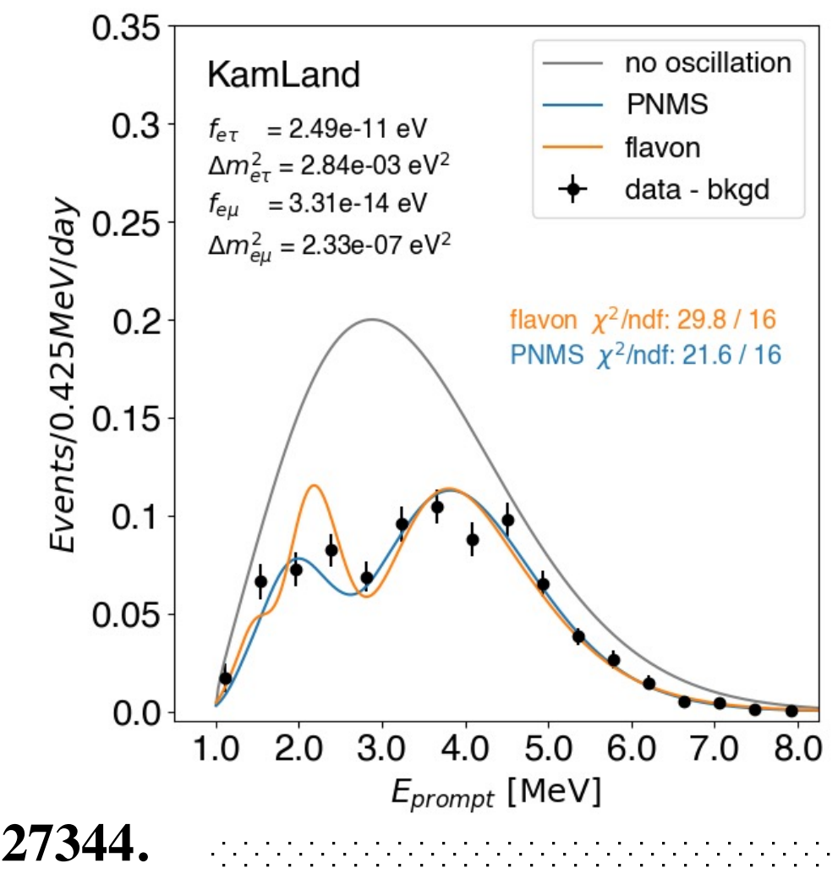




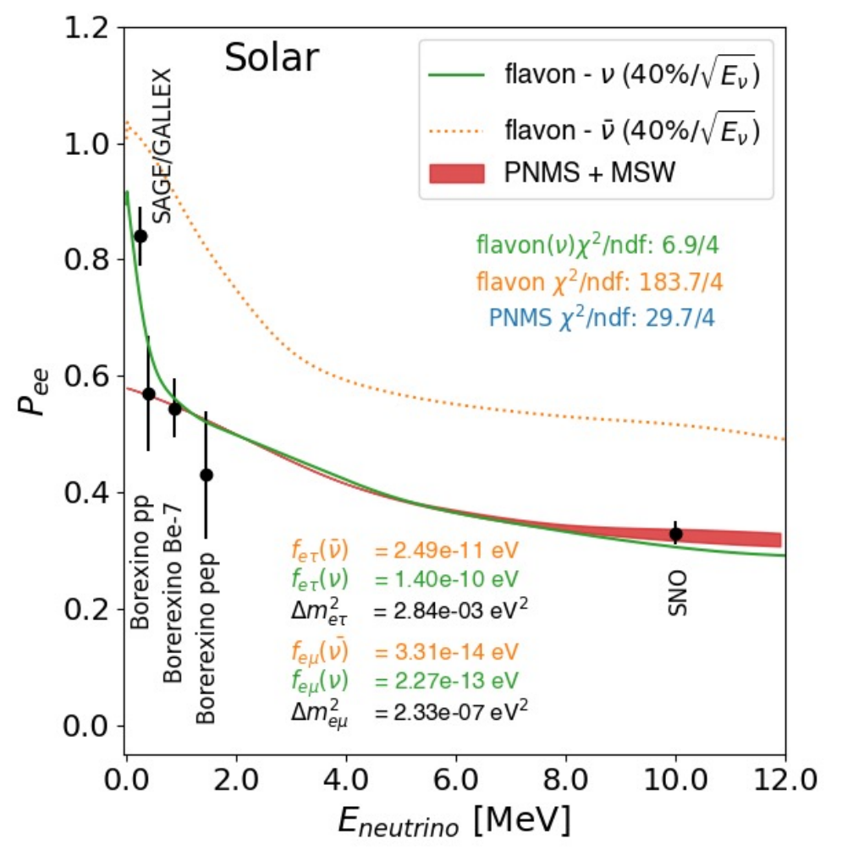




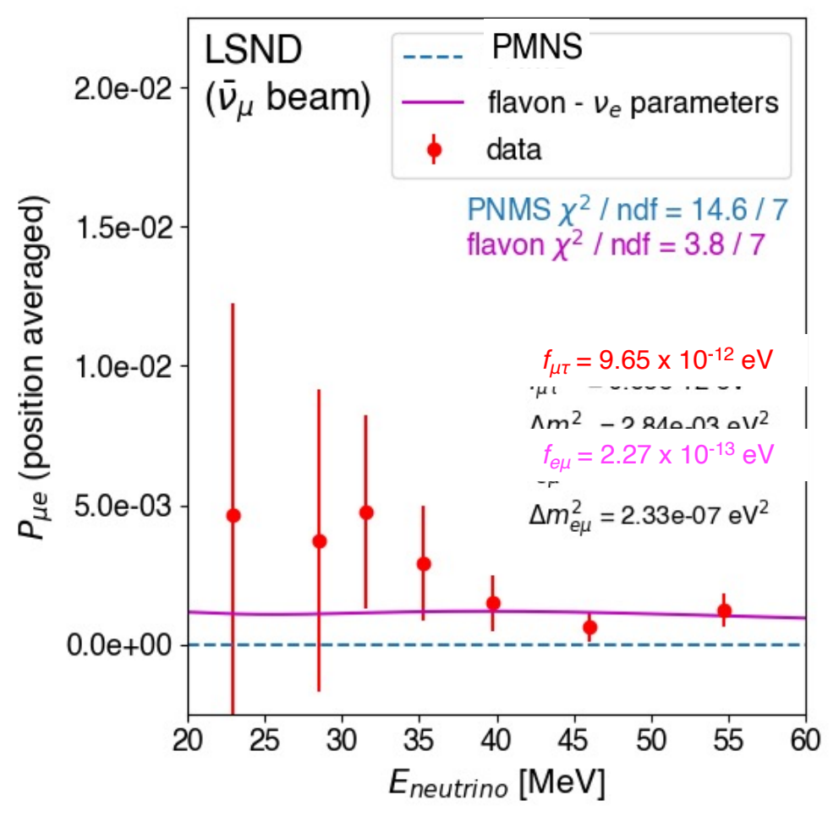
Long-baseline reactor neutrino, solar, and accelerator beam sectors



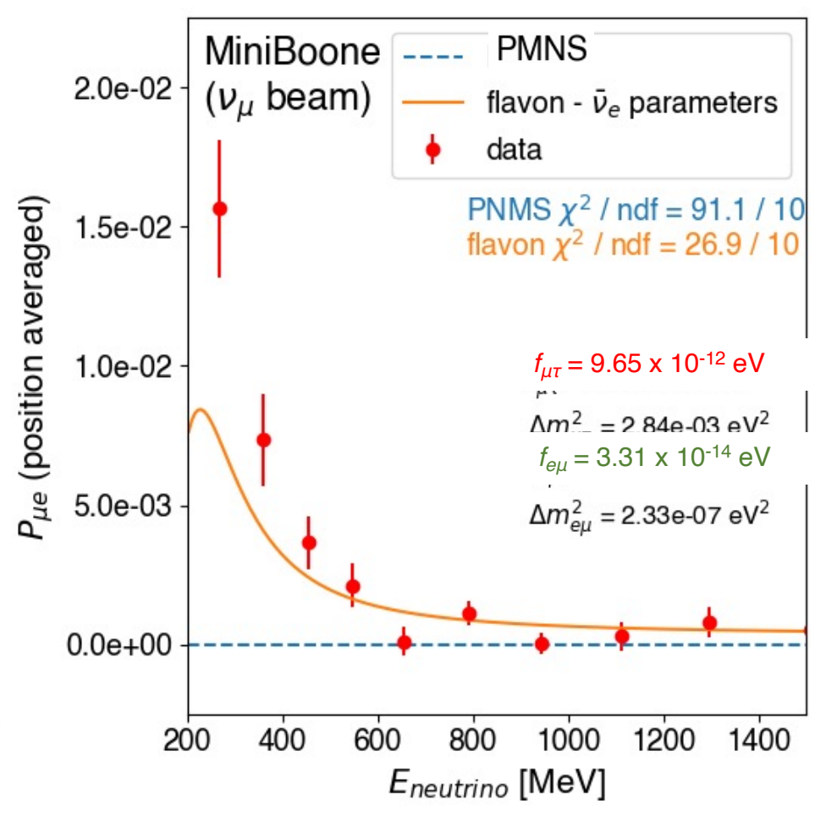
e-neutrinos and e-antineutrinos oscillate differently



e-neutrinos and μ-antineutrinos share parameters



μ-neutrinos and e-antineutrinos share parameters

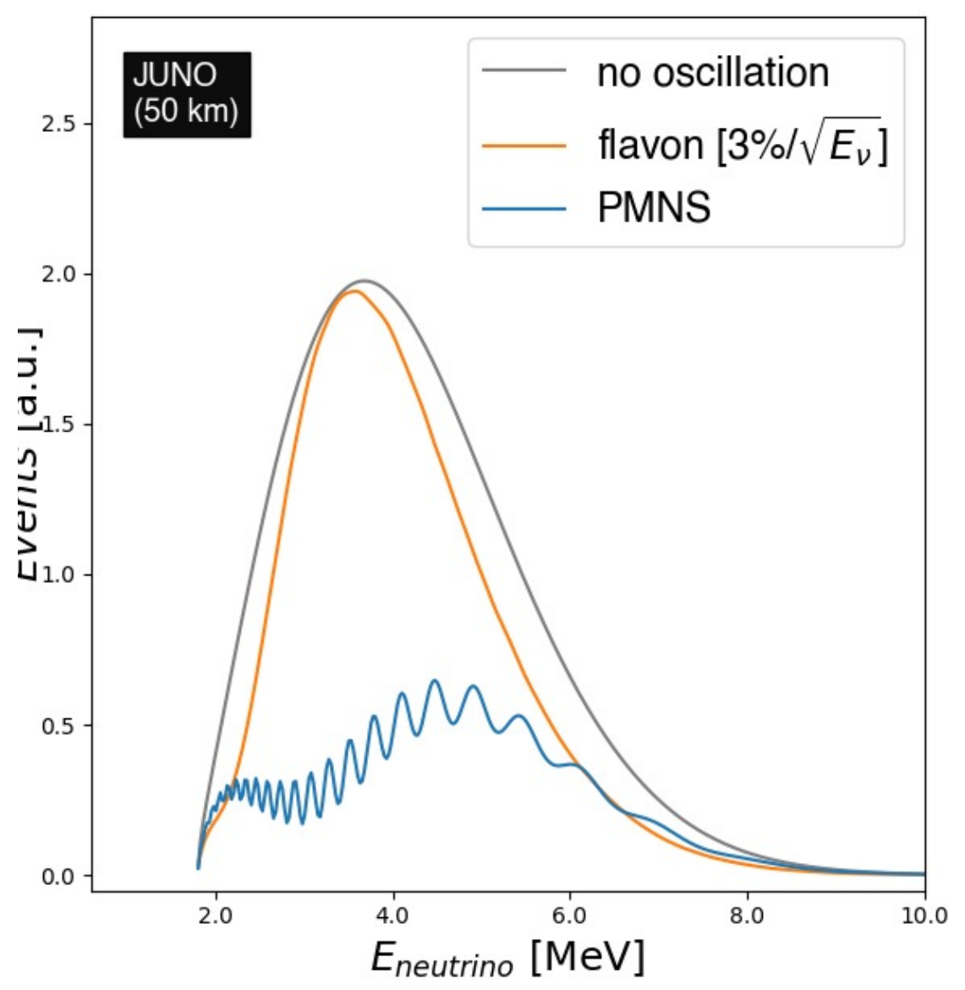


Testable prediction

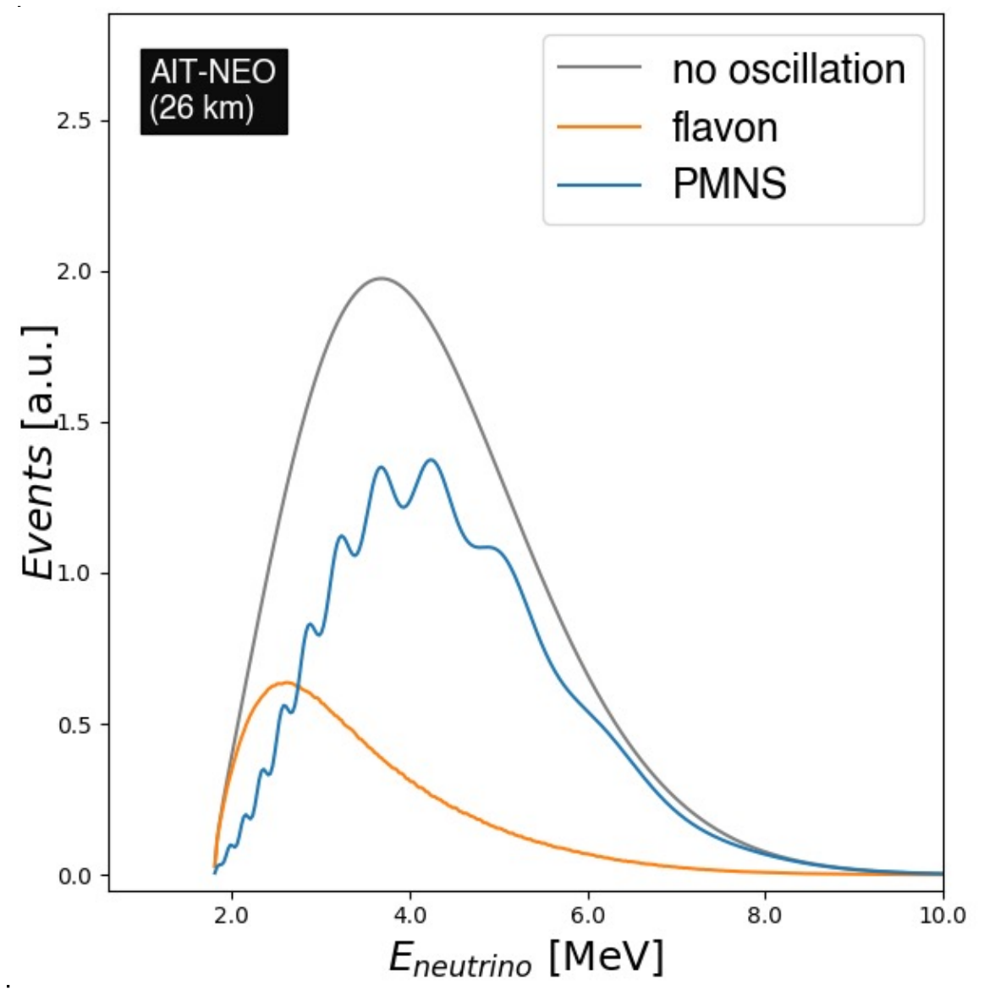
JUNO (50 km) will be very sensitive to the Flavon model

- **Expected neutrino event rate 2.5x nominal rate**
- **No spectral features are expected**
- **JUNO will be able to confirm this model shortly after operation starts with high level of confidence**

electron antineutrinos at local maxima in mid-range



electron antineutrinos at local minima in mid-range



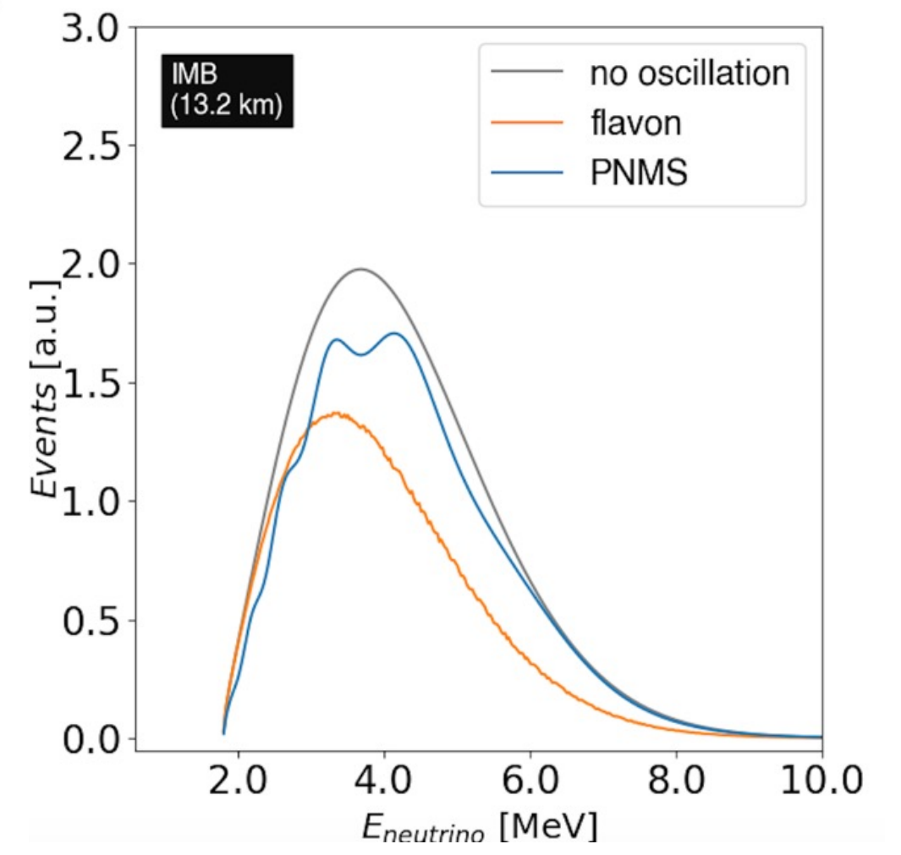
An experiment at a 25km will have sensitivity

- **Expected neutrino event rate 0.35x/0.15x nominal rate (depending on detector medium choice)**
- **No spectral features are expected**

An experiment at a 13km will have sensitivity

- **Expected neutrino event rate 0.74x nominal rate**
- **No spectral features are expected**
- **Lower cost**

electron antineutrinos at local minima in mid-range



Discussion

- **I'm putting forward a new measurable quantity to observe neutrino mixing – the flavon mass. This replaces the concept of mixing angles.**
- **The flavor mass and flavor states are the same state in this model, i.e., an electron neutrino has an electron neutrino mass. Flavon mass only acts as perturbation.**
- **Model is based on a perturbation approach and uses standard dynamical methods.**
- **The Flavon model will be tested at upcoming antineutrino reactor experiments**
- **The precise formula can explain short baseline rates and spectral features without the need for sterile neutrinos**

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL-POST-822897