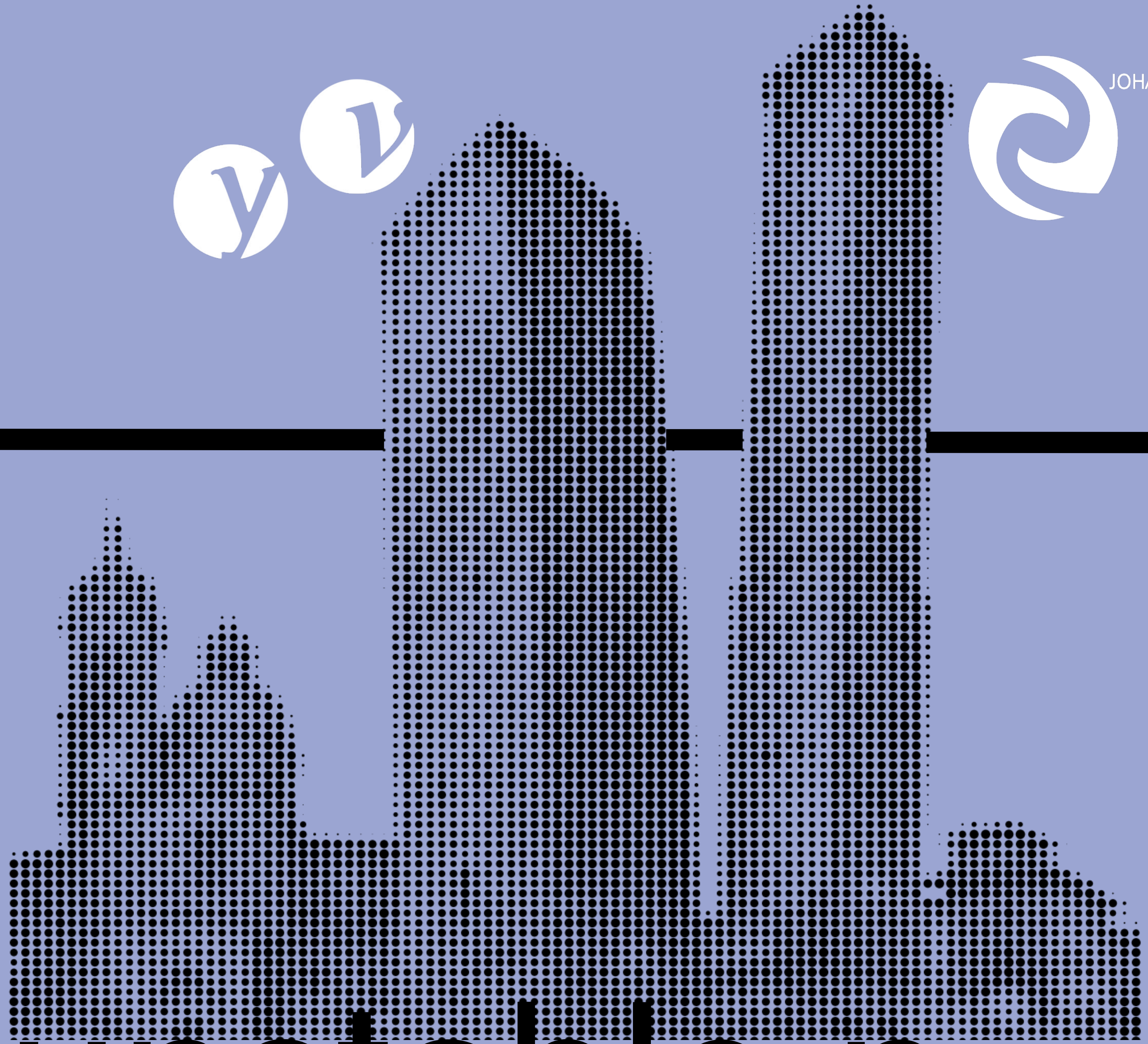
JOHANNES GUTENBERG UNIVERSITÄT MAINZ PRISMA+

JG|U

CERN

INVISIBLES24



unstable neutrinos

George Parker,
Joachim Kopp, Michael Wurm

examples of neutrino decay

sterile neutrino decay $\nu_{\mathrm{s}} \longrightarrow \nu_j + \mathbb{J}$

invisible neutrino decay $\nu_i \longrightarrow \nu_{\mathrm{s}} + \mathbb{J}$

visible neutrino decay $\nu_i \longrightarrow \nu_j + \mathbb{J}$

approaches

$$\frac{d\rho}{dt} = -i\,[H,\rho] - \frac{1}{2}\{\Gamma,\rho\} + \sum_{\substack{i,j\\ i>j}} \int_{\Delta E_j} \rho_{ii} \frac{d\Gamma^{\nu_i\to\nu_j}}{dE_j}\, dE_i$$

density matrix

Propagation
Depletion
Regeneration

2017 Exploring a nonminimal sterile neutrino model involving decay at IceCube
Moss, Moulai, Argüelles + Conrad

2019 Decaying sterile neutrinos and the short baseline oscillation anomalies
Dentler, Esteban, Kopp + Machado

$$P_{\alpha\beta}^{\nu_i\to\nu_j} = \left|\sum_i e^{-i\frac{\Delta m^2_{i1}}{2E_j}L} e^{-\frac{1}{2}\Gamma_i L}\right|^2 + \int_{\Delta E_j}\int_L \left|\sum_{\substack{i,j\\ i>j}} \mathcal{A}^{\nu_i\to\nu_j}\right|^2 dl\, dE_i$$

phenomenological

2001 A combined treatment of neutrino decay and neutrino oscillations
Lindner, Ohlsson, Winter

2005 Explaining LSND by a decaying sterile neutrino
Palomares-Ruiz, Pascoli + Schwetz

2017 Visible neutrino decay at DUNE
Coloma + Peres

2017 Visible neutrino decay in the light of appearance and disappearance long baseline experiments
Gago, Gomes, Gomes, Jones-Perez + Peres

2020 Visible Decay of Astrophysical Neutrinos at IceCube
Abdullahi + Denton

approaches

$$\frac{d\rho}{dt} = -i\,[H,\rho] - \frac{1}{2}\{\Gamma,\rho\} + \sum_{\substack{i,j \\ i>j}} \int_{\Delta E_j} \rho_{ii} \frac{d\Gamma^{\nu_i\to\nu_j}}{dE_j}\, dE_i$$

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phenomenological

Intuitive and adaptable
Easy to add more complex system dynamics

Computationally cheap

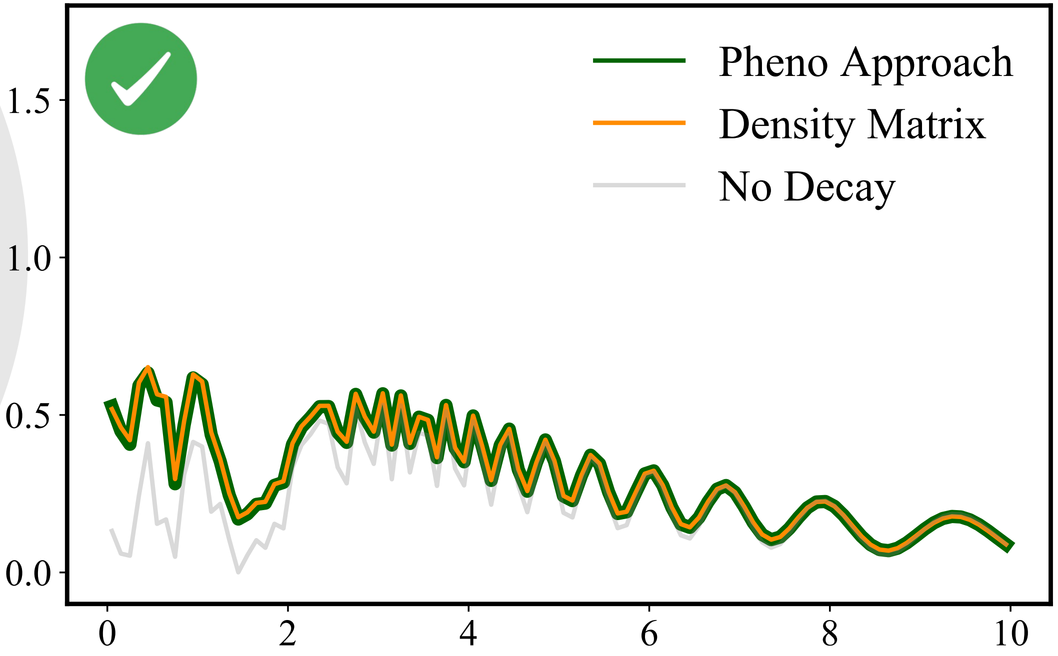
Do they agree?

comparison

1) Single decay

$\nu_3 \longrightarrow \nu_2$

$\nu_\mu \to \nu_e$ oscillation probability



OFF-DIAGON ALLEY

WC2 CITY OF LONDON

$$\frac{d\rho}{dt} = -i\,[H,\rho] - \frac{1}{2}\{\Gamma,\rho\} + \sum_{\substack{i,j\\ i>j}} \int_{\Delta E_j} \rho_{ii} \frac{d\Gamma^{\nu_i\to\nu_j}}{dE_j}\, dE_i$$

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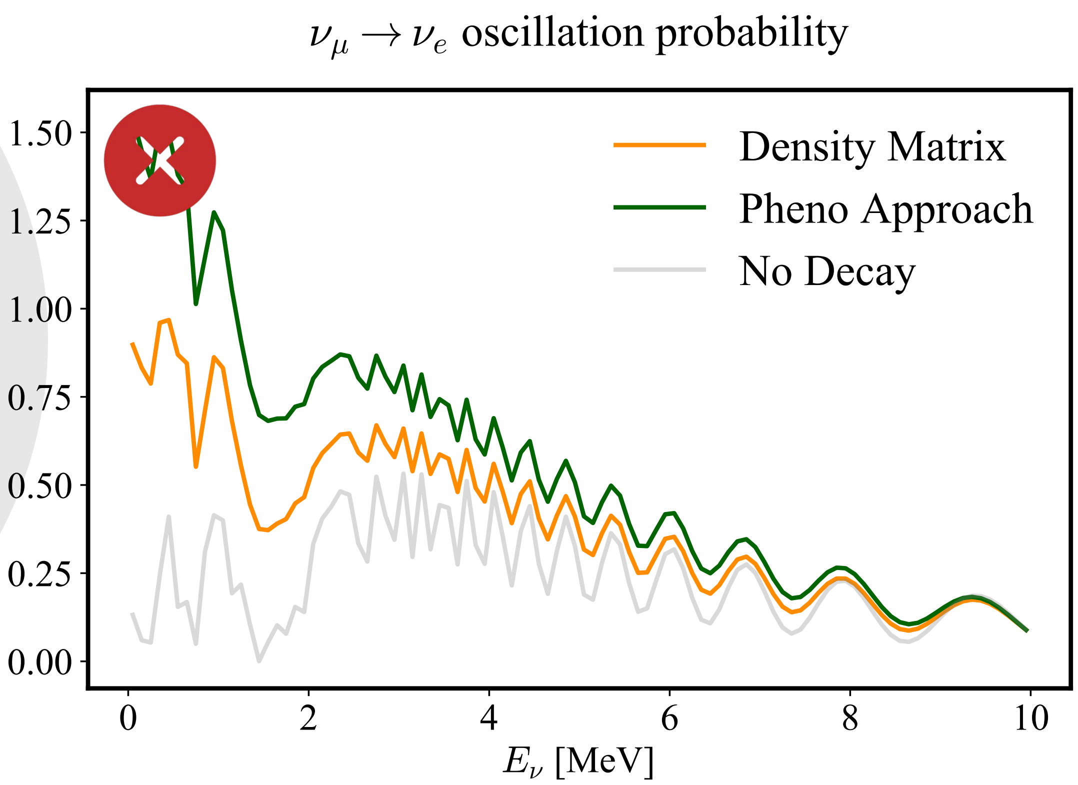
comparison

1) Single decay

$\nu_3 \longrightarrow \nu_2$

2) Multiple decays

$\nu_3 \longrightarrow \nu_1, \nu_2$



$$\rho = \begin{pmatrix} \rho_{00} & \rho_{01} & \rho_{02} \\ \rho_{10} & \rho_{11} & \rho_{12} \\ \rho_{20} & \rho_{21} & \rho_{22} \end{pmatrix}$$

$$\int_{E_j^{\min}}^{E_j^{\max}} \sum_i P^{\text{decays}}_{\nu_i \to \nu_j} + \sum_{\substack{i,j,m,n \\ i\neq j, m\neq n}} P^{\text{interference}}_{\substack{\nu_i \to \nu_j \\ \nu_m \to \nu_n}} \, dE_i$$

$$\frac{d\rho}{dt} = -i\,[H,\rho] - \frac{1}{2}\{\Gamma,\rho\} + \sum_{\substack{i,j \\ i>j}} \int_{\Delta E_j} \rho_{ii} \frac{d\Gamma^{\nu_i \to \nu_j}}{dE_j} \, dE_i$$

$$P^{\nu_i \to \nu_j}_{\alpha\beta} = \left| \sum_i e^{-i \frac{\Delta m^2_{i1}}{2E_j} L} e^{-\frac{1}{2}\Gamma_i L} \right|^2 + \int_{\Delta E_j} \int_L \left| \sum_{\substack{i,j \\ i>j}} \mathcal{A}^{\nu_i \to \nu_j} \right|^2 dl\, dE_i$$

a new approach?

$$\nu_i \longrightarrow \nu_j + \mathbb{J}$$

We can treat this as an open quantum system, using a Lindblad-type 'decay' term to replace the Depletion and Regeneration parts of the previous approaches.

$$\frac{d\rho}{dt} = -i\,[H,\rho] + \sum_{\substack{i,j \\ i>j}} \left(L_{ij}\rho L_{ij}^\dagger - \frac{1}{2}\left\{ L_{ij}^\dagger L_{ij}, \rho \right\} \right),$$

$$\text{where } L_{ij} = \left[\int_{E_i^{\min}}^{E_i^{\max}} \sqrt{\frac{d\Gamma_{ij}(E_i, E_j)}{dE_j}}\; dE_j \right]$$

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$$\begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}, \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}, \cdots, \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}$$

We can enlarge the system from 3x3xN to a 3N x 3N

$$\begin{pmatrix}
\blacksquare & \blacksquare & \blacksquare & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\
\blacksquare & \blacksquare & \blacksquare & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\
\blacksquare & \blacksquare & \blacksquare & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\
0 & 0 & 0 & \blacksquare & \blacksquare & \blacksquare & \cdots & 0 & 0 & 0 \\
0 & 0 & 0 & \blacksquare & \blacksquare & \blacksquare & \cdots & 0 & 0 & 0 \\
0 & 0 & 0 & \blacksquare & \blacksquare & \blacksquare & \cdots & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & \blacksquare & \blacksquare & \blacksquare
\end{pmatrix}$$

Thanks for listening!

comparison

1) Single decay

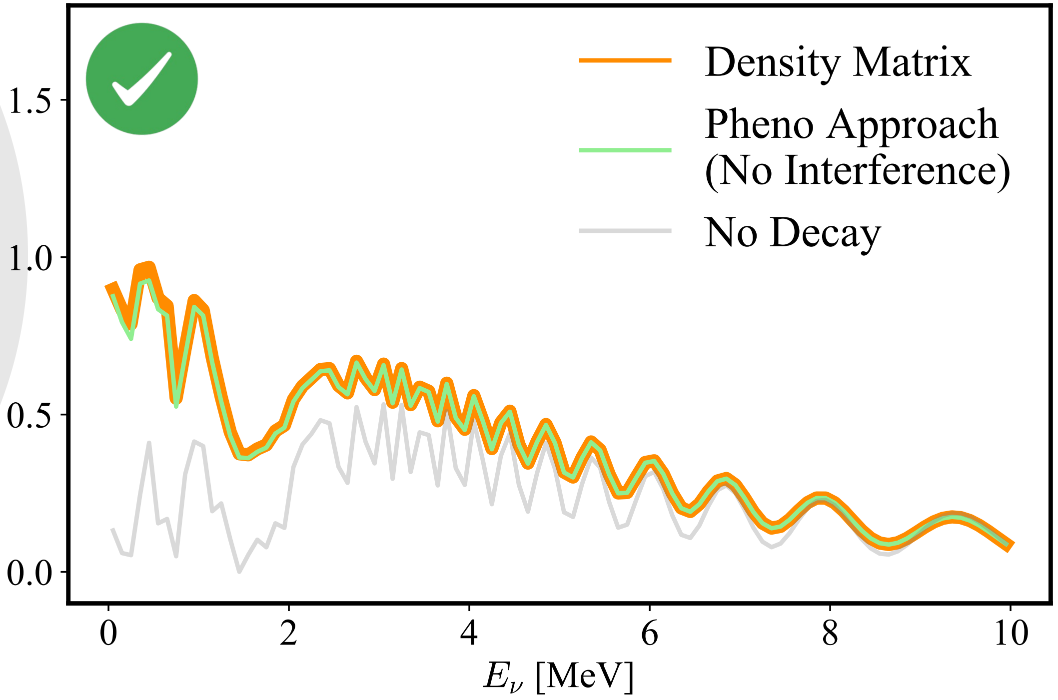
$$\nu_3 \longrightarrow \nu_2$$

2) Multiple decays

$$\nu_3 \longrightarrow \nu_1, \nu_2$$

3) Multiple decays without interference

$\nu_\mu \to \nu_e$ oscillation probability



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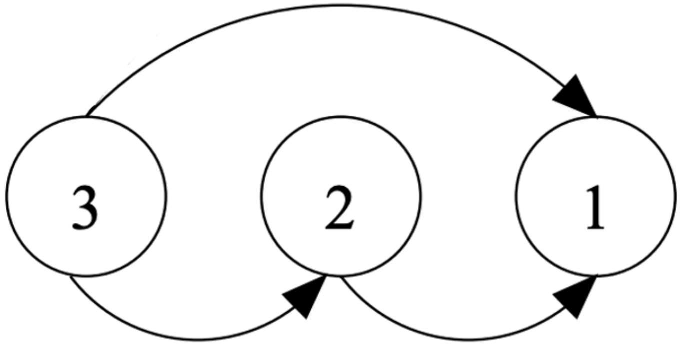
$$\int_{E_j^{\mathrm{min}}}^{E_j^{\mathrm{max}}} \sum_i P^{\mathrm{decays}}_{\nu_i \to \nu_j} + \sum_{\substack{i,j,m,n \\ i \neq j, m \neq n}} P^{\mathrm{interference}}_{\substack{\nu_i \to \nu_j \\ \nu_m \to \nu_n}} \, dE_i$$

$$\frac{d\rho}{dt} = -i\,[H,\rho] - \frac{1}{2}\{\Gamma,\rho\} + \sum_{\substack{i,j \\ i>j}} \int_{\Delta E_j} \rho_{ii} \frac{d\Gamma^{\nu_i \to \nu_j}}{dE_j} \, dE_i$$

$$P_{\alpha\beta}^{\nu_i \to \nu_j} = \left| \sum_i e^{-i \frac{\Delta m^2_{i1}}{2E_j} L} e^{-\frac{1}{2}\Gamma_i L} \right|^2 + \int_{\Delta E_j} \int_L \left| \sum_{\substack{i,j \\ i>j}} \mathcal{A}^{\nu_i \to \nu_j} \right|^2 dl\, dE_i$$

benchmark model

Ordering:
1) Normal $m_3 > m_2 > m_1$
2) Inverted $m_3 > m_2 > m_1$



Coupling with massless scalar, J
1) Scalar $g_s = 0.3$
2) Pseudoscalar

Distance:
50 km

Daughter chirality (two-body decay):
1) Conserving $\nu_\alpha \rightarrow \nu_\beta + \text{J}$ (Dirac)
2) Violating $\nu_\alpha \rightarrow \bar{\nu}_\beta + \text{J}$

Neutrino mass:
1) Hierarchical ($m_1 \rightarrow 0$) $m_1 = 0.01$ eV
2) Quasi-degenerate ($m_1 > m_{2,3}$)

Energy range:
$0 - 10$ MeV

Geometrical factors:
Ignored (isotropic neutrino source)

Initial state:
Pure ν_μ source

existing constraints

Neutrino decay can be probed across a wide range of baselines and technologies

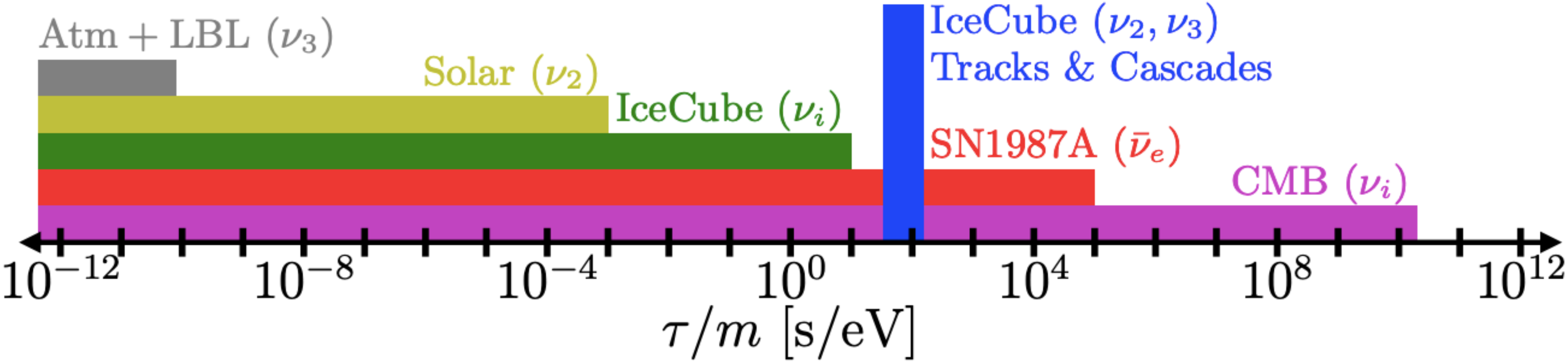


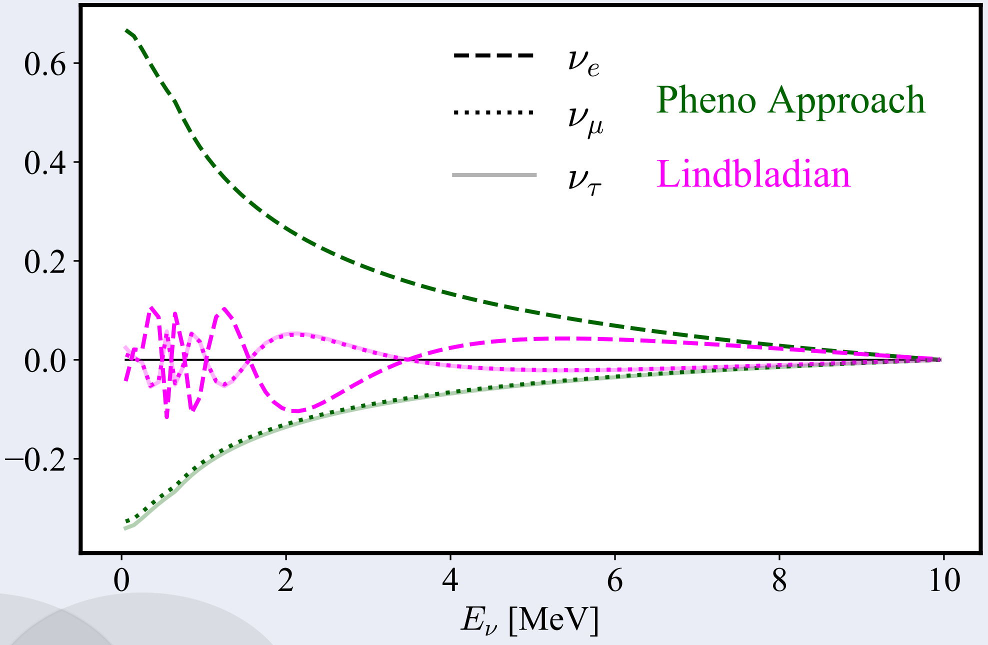
Image from Abdullahi&Denton arxiv.2005.07200

A massless scalar coupling to neutrinos would have an impact on the neutrino free-streaming length in the early Universe - strongest bounds from the CMB

approaches to neutrino decay

$$\frac{d\rho(E_j)}{dt} = -i\left[H, \rho(E_j)\right] - \frac{1}{2}\left\{\Gamma, \rho(E_j)\right\} + \sum_{\substack{i,j \\ i>j}} \int_{E_j^{\min}}^{E_j^{\max}} \rho_{ii}(E_i)\frac{d\Gamma_{ij}(E_i, E_j)}{dE_j}\, dE_i$$

$\nu_\mu \to \nu_x$ Interference Component



$$P^{\text{vis}}_{\nu_i \to \nu_j}(E_j, L) = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i\frac{\Delta m^2_{i1}}{2E_j}L} e^{-\frac{1}{2}\Gamma_i L} \right|^2 + \int_{E_j^{\min}}^{E_j^{\max}} \int_0^L \left| \sum_{\substack{i,j \\ i>j}} U^*_{\alpha i} U_{\beta j} e^{-\frac{im_j^2 + \alpha_j}{2E_j}(L-l)} \times \sqrt{\frac{d\Gamma_{ij}(E_i, E_j)}{dE_j}} e^{-\frac{im_i^2+\alpha_i}{2E_i} l} \right|^2 dl\, dE_i$$

$\nu_\mu \to \nu_e$ oscillation probability