unstable neutrinos

#232

· addressing oscillation and decay ·

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Why study neutrinos that oscillate and decay?

In the Standard Model, neutrinos can only decay radiatively. With such a tiny neutrino mass, radiative decays are so unlikely that the neutrino has lifetime that is significantly longer than the Age of the Universe (a **stable particle**).

$$\nu_i \longrightarrow \nu_j$$

However, in some **BSM theories**—often when we add a neutrino mass-generation mechanism to the SM, we induce a non-radiative neutrino decay. In this work, we study **decay into a lighter neutrino mass eigenstate** (and a massless Majoron), and how this affects oscillation.

How can we simulate this physical system?

The interplay of oscillation and decay is studied with two methods:

1) the **density matrix approach** [1],

   + *More flexible and intuitive*
   - *Does not agree with the pheno approach in systems with more complex decay pattern*

2) and a **phenomenological approach** [2], working with transition probabilities,

   + *Computationally inexpensive*
   - *Cubersome formalism, difficult to add more effects*

Can we develop machinery that has the benefits of both approaches?

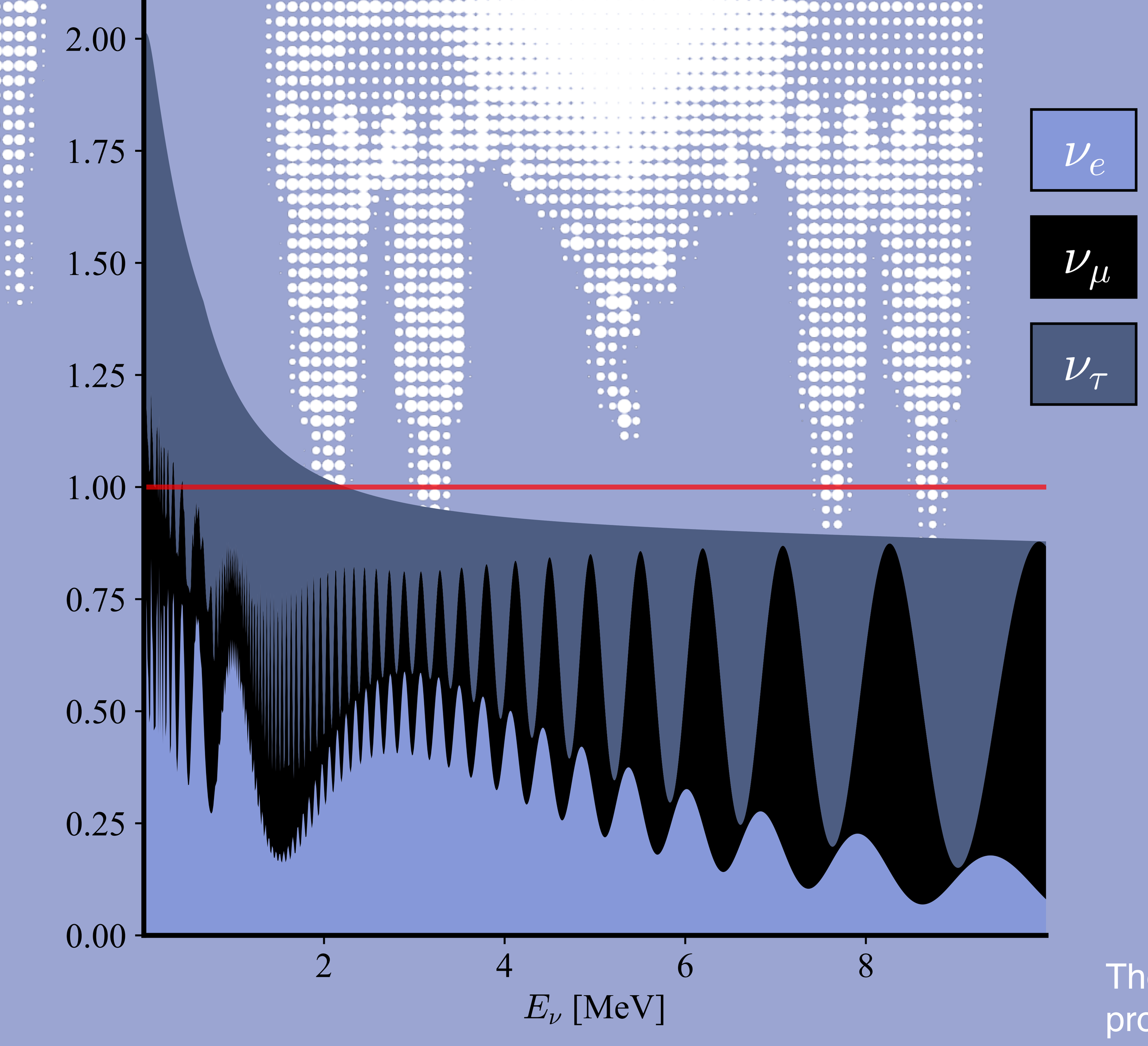
Density Matrix Approach

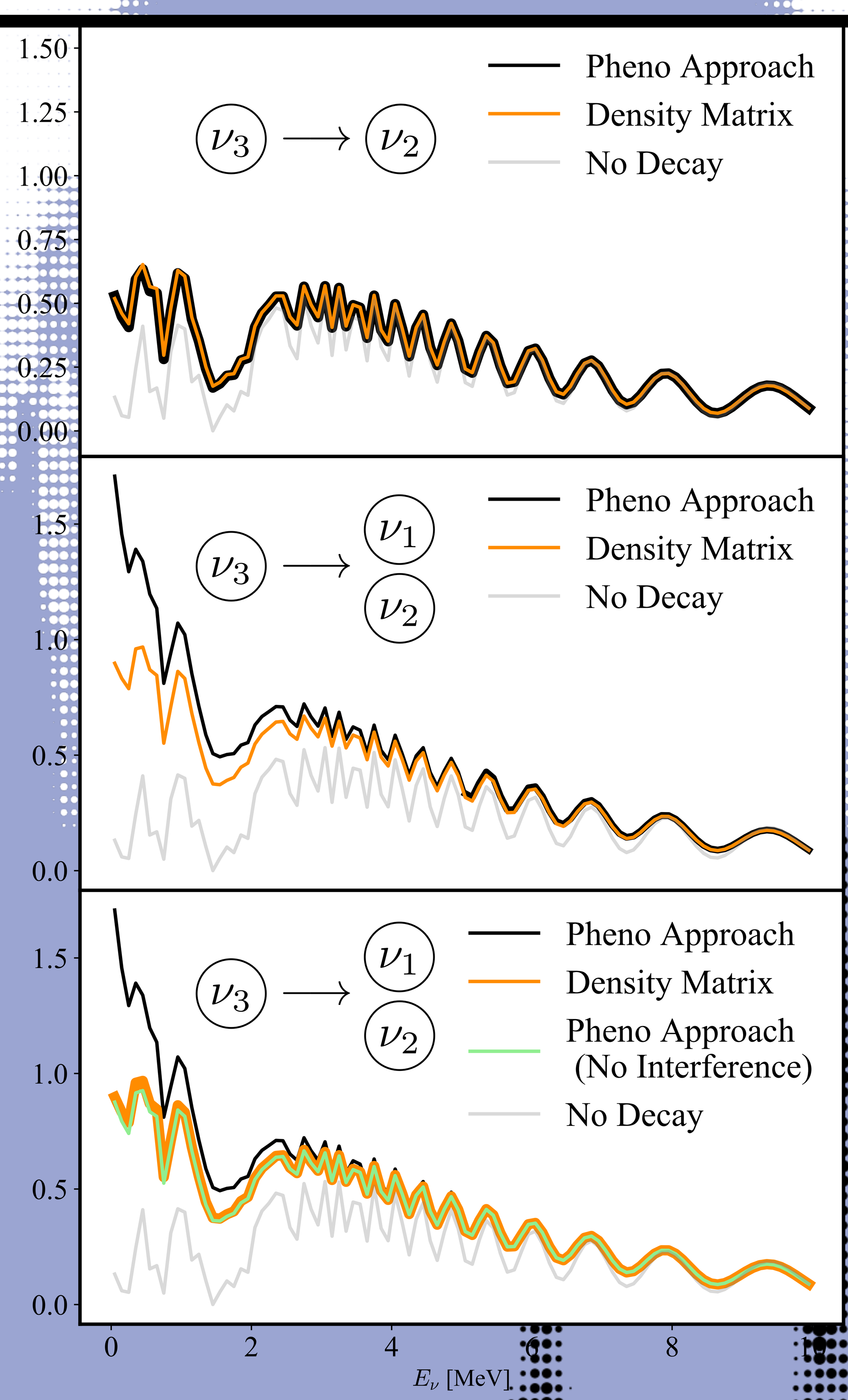
$$\frac{d\rho(E_j)}{dt} = -i\left[H, \rho(E_j)\right] - \frac{1}{2}\left\{\Gamma, \rho(E_j)\right\} + \sum_{\substack{i,j \\ i>j}} \int_{E_j^{\min}}^{E_j^{\max}} \rho_{ii}(E_i) \frac{d\Gamma_{ij}(E_i, E_j)}{dE_j}\, dE_i$$

Propagation

Depletion

Regeneration





These plots represent transition probabilities of muon neutrinos oscillating into electron neutrinos across a 50 km baseline.

Phenomenological Approach

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

What is the source of the discrepancy?

If we turn off the interference terms in the pheno approach, we get the same oscillations as with density matrices – **the density matrix approach does not account for interference**.

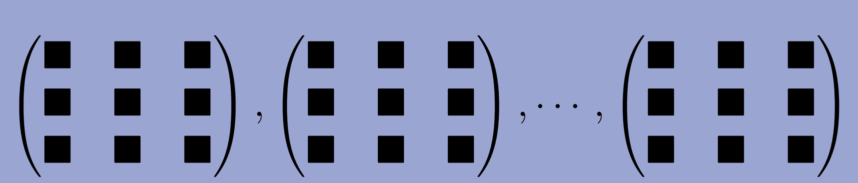
Can we try any other approaches? Yes! What about using the **Lindbladian**?

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

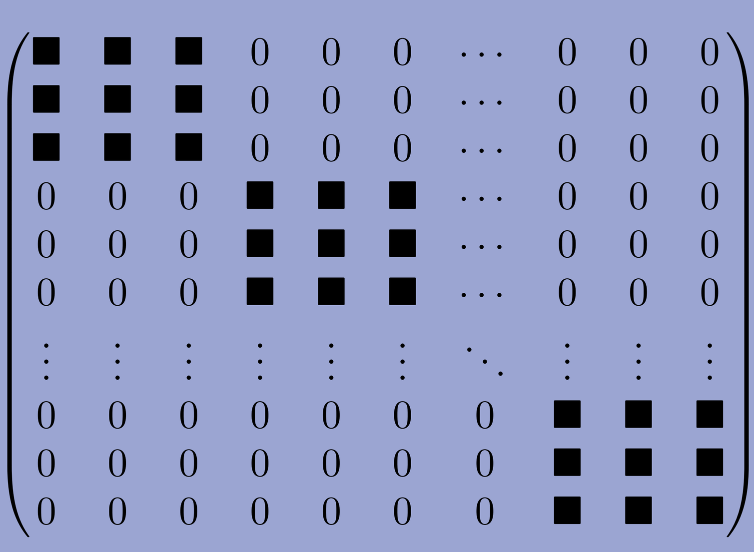
$$L_{ij} = \left[\int_{E_i^{\min}}^{E_i^{\max}} \sqrt{\frac{d\Gamma_{ij}(E_i, E_j)}{dE_j}}\, dE_i \right]$$

How is this approach different? Well, we enlarge our system from $3\times3\times N$, to $3N\times3N$, therefore, interference is accounted for with the **off-diagonal terms**, or *coherences*. The initial states of the system are:

(a)



(b)



Which techniques from other areas of physics can we use?

Open quantum systems are used to study the interaction of a physical system with its environment. From this area, we can use the GSKL master equation [3,4] or *Lindbladian*:

$$\dot{\rho} = -i[H, \rho] + \sum_k \left(L_k \rho L_k^\dagger - \frac{1}{2}\left\{ L_k^\dagger L_k, \rho \right\} \right),$$

where L_k are operators that describe **environment-system interactions**. This formalism has been used extensively to study decoherence in neutrino systems.

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

However, as the second (non-neutrino) decay product escapes, this renders this decay **irreversible**, and this process is best described with an open quantum system.

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References:
[1] Z. Moss, M. H. Moulai, C. A. Argüelles, and J. M. Conrad, *Exploring a nonminimal sterile neutrino model involving decay at IceCube*, Phys. Rev. D97 (2018), no. 5 055017, [arXiv:1711.05921]
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Questions about this poster? Contact me: **geparker@uni-mainz.de**