Hidden neutrino interactions with dark energy: Effects on oscillation probabilities and tests with high-energy neutrinos

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Introduction

Connection
Outline

- The Dark Energy-Neutrino coupling
- Effects in neutrino oscillations
- CP violating effects
- Sensitivity of (future) experiments
- Directional dependence
- Summary
The Dark Energy-Neutrino Coupling

A simple form of an interaction by DE–neutrino coupling is:

$$\mathcal{L}_{int} = -\lambda_{\alpha\beta} \frac{\partial_{\mu}\phi}{M_*} \bar{\nu}_\alpha \gamma^\mu (1 - \gamma_5)\nu_\beta$$

The matrix parameterizing the DE–induced neutrino physics is:

$$(a_L)_\mu^{ab} \propto \ell^\mu$$, with $\ell^\mu$ the parameterization of the preferred frame associated with the cosmic expansion.

In this example:

$$a_L^\mu \sim \lambda \phi(t)\ell^\mu / M_*$$
The Dark Energy-Neutrino Coupling

Effective Hamiltonian in mass base:

\[ h_{\text{eff}}^{DE} = \begin{pmatrix} (a_L)_{11}^\mu p_\mu / p & 0 & 0 \\ 0 & (a_L)_{22}^\mu p_\mu / p & 0 \\ 0 & 0 & (a_L)_{33}^\mu p_\mu / p \end{pmatrix} \]

\[ (a_L)^\mu p_\mu \propto E (1 - \mathbf{v} \cdot \hat{\mathbf{p}}) \]

\[ h_{\text{eff}}^{DE} = \begin{pmatrix} \pm k_1 (1 - \mathbf{v} \cdot \hat{\mathbf{p}}) & 0 & 0 \\ 0 & \pm k_2 (1 - \mathbf{v} \cdot \hat{\mathbf{p}}) & 0 \\ 0 & 0 & \pm k_3 (1 - \mathbf{v} \cdot \hat{\mathbf{p}}) \end{pmatrix}, \quad k_k - k_j = m_{\text{eff}kj} \]

\[ \leftrightarrow h_{\text{vacuum}}^{\text{vacuum}} \propto \frac{\Delta m^2}{2E} \]
The Dark Energy-Neutrino Coupling

Effective Hamiltonian in mass base:

\[
   h_{\text{eff}}^{DE} = \begin{bmatrix}
   (a_L)^\mu_{11}p_\mu/p & 0 & 0 \\
   0 & (a_L)^\mu_{22}p_\mu/p & 0 \\
   0 & 0 & (a_L)^\mu_{33}p_\mu/p
   \end{bmatrix}
\]

\[
   (a_L)^\mu p_\mu \propto E(1 - \mathbf{v} \cdot \mathbf{\hat{p}})
\]

\[
   h_{\text{eff}}^{DE} = \begin{bmatrix}
   \pm k_1(1 - \mathbf{v} \cdot \mathbf{\hat{p}}) & 0 & 0 \\
   0 & \pm k_2(1 - \mathbf{v} \cdot \mathbf{\hat{p}}) & 0 \\
   0 & 0 & \pm k_3(1 - \mathbf{v} \cdot \mathbf{\hat{p}})
   \end{bmatrix}, \quad k_k - k_j = m_{\text{eff}_{k_j}}
\]

\[
   h_{\text{vacuum}}^{\text{eff}} \propto \frac{\Delta m^2}{2E}
\]

\[
   a_L^\mu \sim \lambda \dot{\phi}(t)l^\mu/M_*, \quad m_{\text{eff}} \sim \Delta \lambda \dot{\phi}(t)/M_*
\]
Neutrino Oscillations

Implications of the Hamiltonian:
- Different sign for neutrinos and anti-neutrinos
- DE-induced mixing is energy-independent
- DE-induced mixing is frame dependent

Oscillation probability:
- 3 new mixing angles
- 1 extra CP-violating phase
- 2 independent effective mass parameters
Behavior of the probability
Behavior of the probability

\( \theta_{DE12} = 0.25 \pi \)

\( \theta_{DE13}, \theta_{DE23} = 0 \)

Vacuum oscillation is dominant

Dark Energy oscillation is dominant

\( M_{\text{eff}21} = 0.5 \times M_{\text{eff}31} = 10^{-26} \text{ GeV} \)
Behavior of the probability

$\theta_{DE13} = 0.25 \pi$

$\theta_{DE12}, \theta_{DE23} = 0$

$M_{\text{eff}21} = 0.5 \times M_{\text{eff}31} = 10^{-26} \text{ GeV}$
Behavior of the probability

\[ \vartheta_{DE23} = 0.25\pi \]

\[ \vartheta_{DE12}, \vartheta_{DE13} = 0 \]

\[ M_{\text{eff}21} = 0.5 \times M_{\text{eff}31} = 10^{-26} \text{ GeV} \]
Behavior of the probability

\[ \vartheta_{DE12}, \vartheta_{DE13}, \vartheta_{DE23} = 0.25 \, \pi \]

\[ M_{\text{eff}21} = 0.5 \cdot M_{\text{eff}31} = 10^{-26} \, \text{GeV} \]
$\delta_{DE} = 0.25 \pi$

Maximal mixing: $\theta_{DE12} = \theta_{DE13} = \theta_{DE23} = 0.25 \pi$

$M_{eff21} = 0.5 \times M_{eff31} = 10^{-26} \text{ GeV}$
CP violation

$$\delta_{DE} = 0.5 \pi$$

Maximal mixing: $\theta_{DE12} = \theta_{DE13} = \theta_{DE23} = 0.25 \pi$

$$M_{\text{eff}21} = 0.5 \times M_{\text{eff}31} = 10^{-26} \text{ GeV}$$
$\delta_{DE} = 0$

Maximal mixing: $\theta_{DE12} = \theta_{DE13} = \theta_{DE23} = 0.25 \pi$

$M_{\text{eff}21} = 0.5 \times M_{\text{eff}31} = 10^{-26} \text{ GeV}$
Sensitivity in experiments

IceCube

Experiments sensitive to UHE neutrinos

$\theta_{DE13}, \theta_{DE23} = 0$
Directional dependence

Smoking gun for a DE-effect would be the directional dependence $\propto (1 - \mathbf{v} \cdot \hat{\mathbf{p}})$

- Directional dependence in oscillations of cosmogenic neutrinos
- $\mathbf{v} \cdot \hat{\mathbf{p}} \sim 10^{-3}$
If DE is a dynamical field, effects could arise in neutrino oscillation similar to matter effects. This effect is small, but independent of energy and will become significant in neutrinos with high enough energies. The effect manifests at $E^*M_{\text{eff}} \sim 10^{-20}$ GeV. Current and future experiments are sensitive to $M_{\text{eff}}$ up to $10^{-27}$ to $10^{-31}$ GeV. Discovering the directional dependence would be the smoking gun for DE-neutrino coupling.