Hidden neutrino interactions with dark energy:

Effects on oscillation probabilities and tests with high-energy neutrinos

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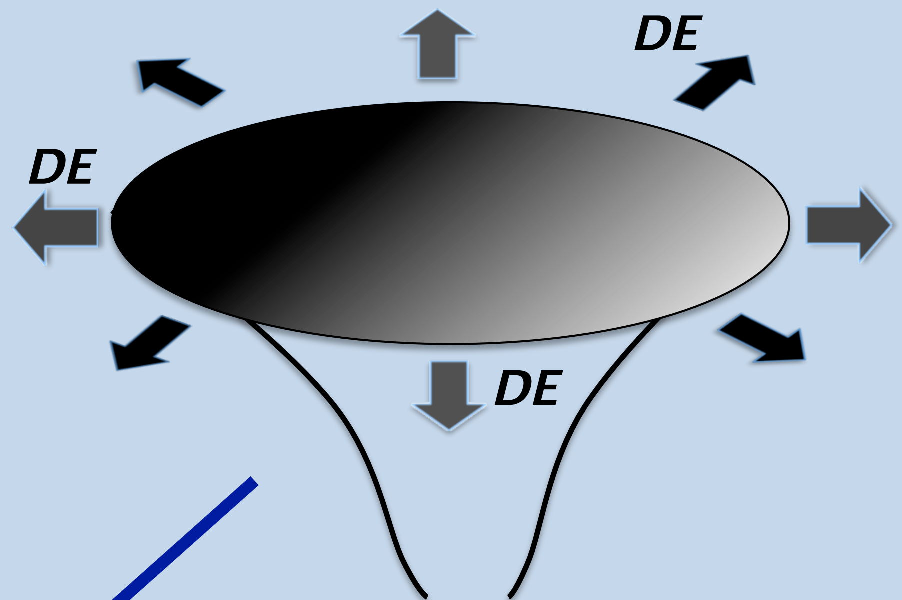
Introduction



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:

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

In this example: $a^\mu_L \sim \lambda \dot{\phi}(t) l^\mu / M_*$

The Dark Energy-Neutrino Coupling

Effective Hamiltonian in mass base:

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

$$(a_L)^\mu p_\mu \propto E(1 - \boldsymbol{v} \cdot \hat{\boldsymbol{p}})$$

↓

$$h_{eff}^{DE} = \begin{bmatrix} \pm k_1 (1 - \boldsymbol{v} \cdot \hat{\boldsymbol{p}}) & 0 & 0 \\ 0 & \pm k_2 (1 - \boldsymbol{v} \cdot \hat{\boldsymbol{p}}) & 0 \\ 0 & 0 & \pm k_3 (1 - \boldsymbol{v} \cdot \hat{\boldsymbol{p}}) \end{bmatrix}, \quad k_k - k_j = m_{eff_{kj}}$$

$$\Leftrightarrow \; h_{eff}^{vacuum} \propto \frac{\Delta m^2}{2E}$$

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$$\Leftrightarrow h_{eff}^{vacuum} \propto \frac{\Delta m^2}{2E}$$

$$a_L^{\mu} \sim \lambda \dot{\phi}(t) l^{\mu}/M_* , \quad m_{eff} \sim \Delta\lambda\dot{\phi}(t)/M_*$$

Neutrino Oscillations

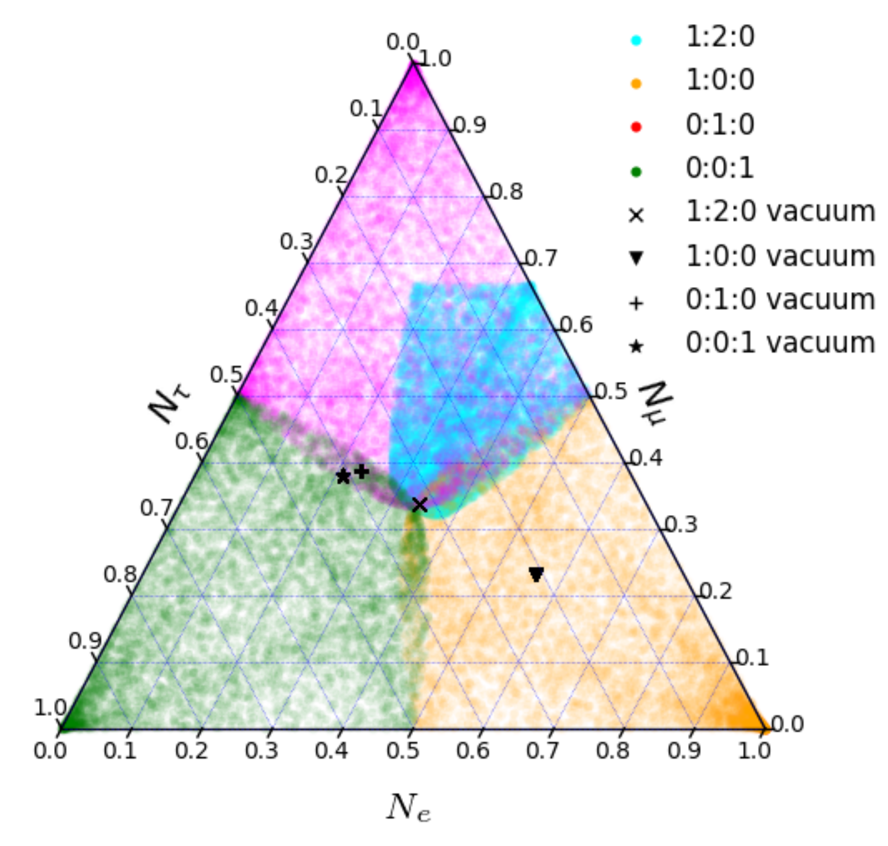
→ Implications of the Hamiltonian:

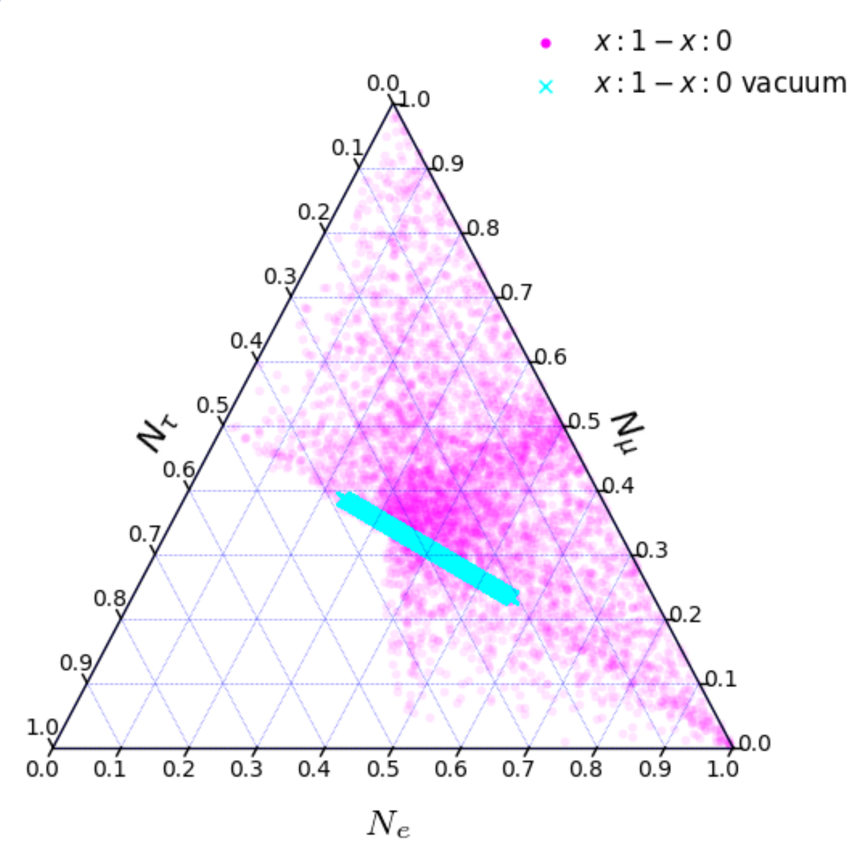
- ✧Different sign for neutrinos and anti-neutrinos
- ✧DE-induced mixing is energy-independent
- ✧DE-induced mixing is frame dependent

→ Oscillation probability:

- ✧3 new mixing angles
- ✧1 extra CP-violating phase
- ✧2 independent effective mass parameters

Behavior of the probability





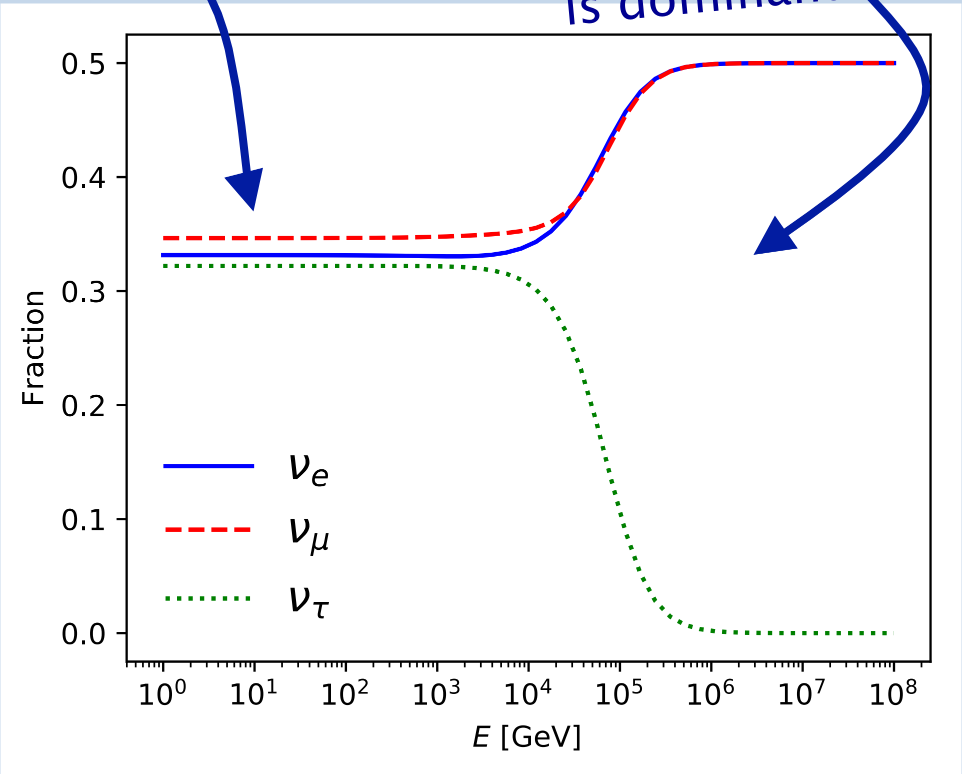
Behavior of the probability

Vacuum oscillation is dominant

Dark Energy oscillation is dominant

$\vartheta_{DE12} = 0.25\ \pi$

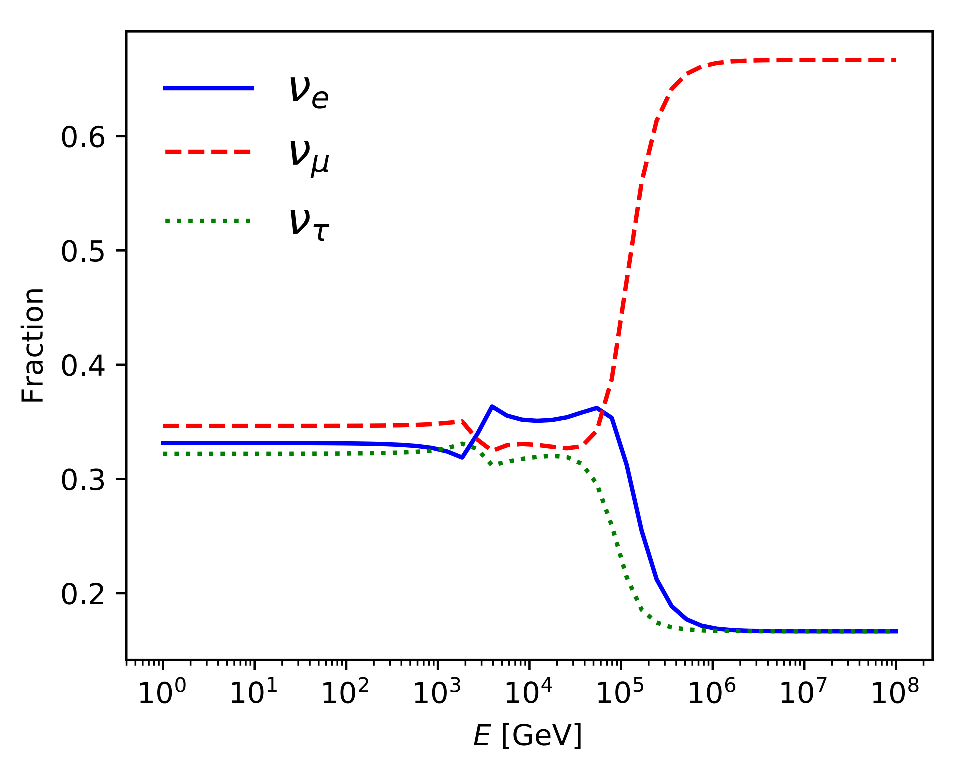
$\vartheta_{DE13}, \vartheta_{DE23} = 0$



$M_{eff21} = 0.5 * M_{eff31} = 10^{-26}$ GeV

Behavior of the probability

$\vartheta_{DE13} = 0.25\ \pi$
$\vartheta_{DE12}, \vartheta_{DE23} = 0$



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Behavior of the probability

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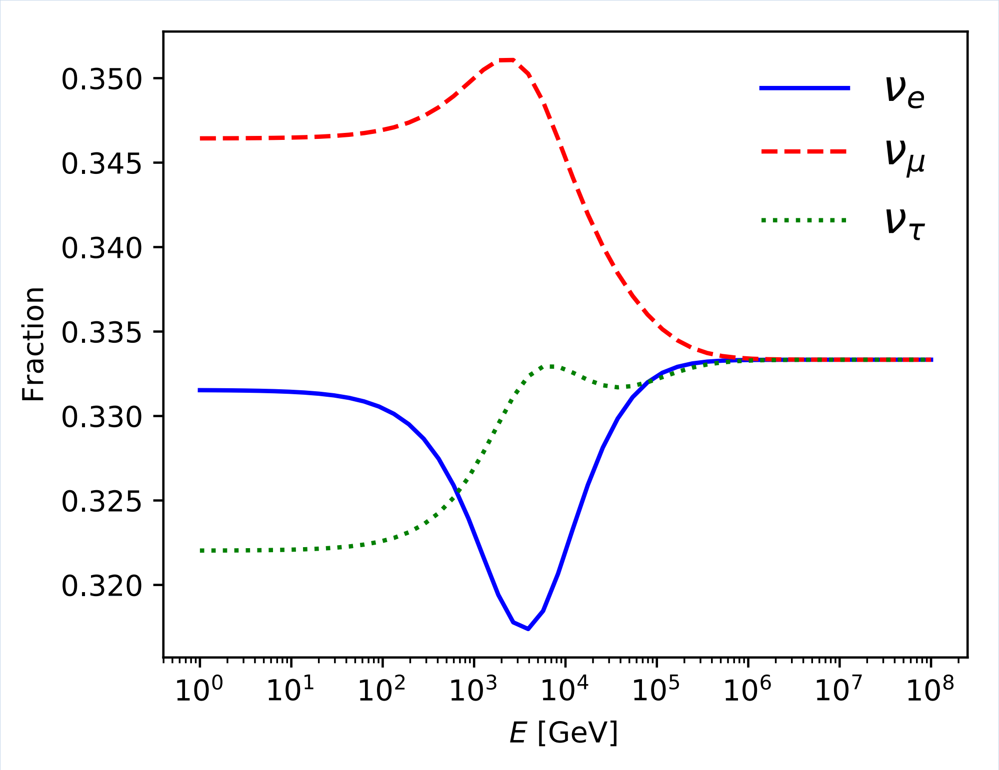

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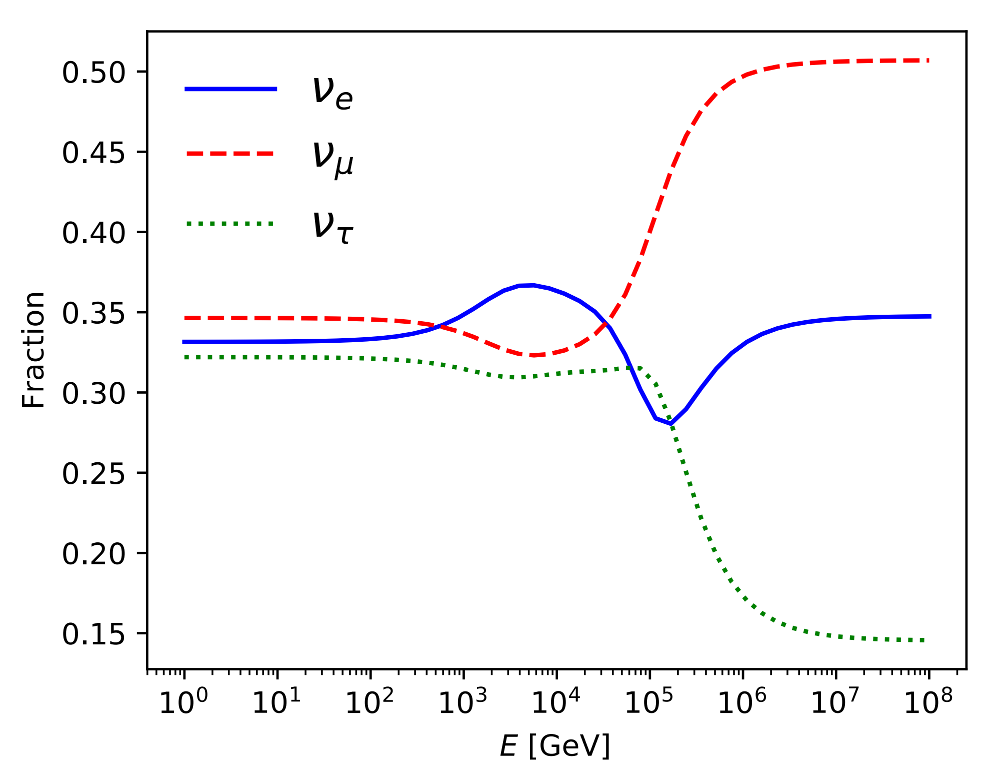
Behavior of the probability

ϑ_{DE12} ,ϑ_{DE13} ,ϑ_{DE23} =0.25 π



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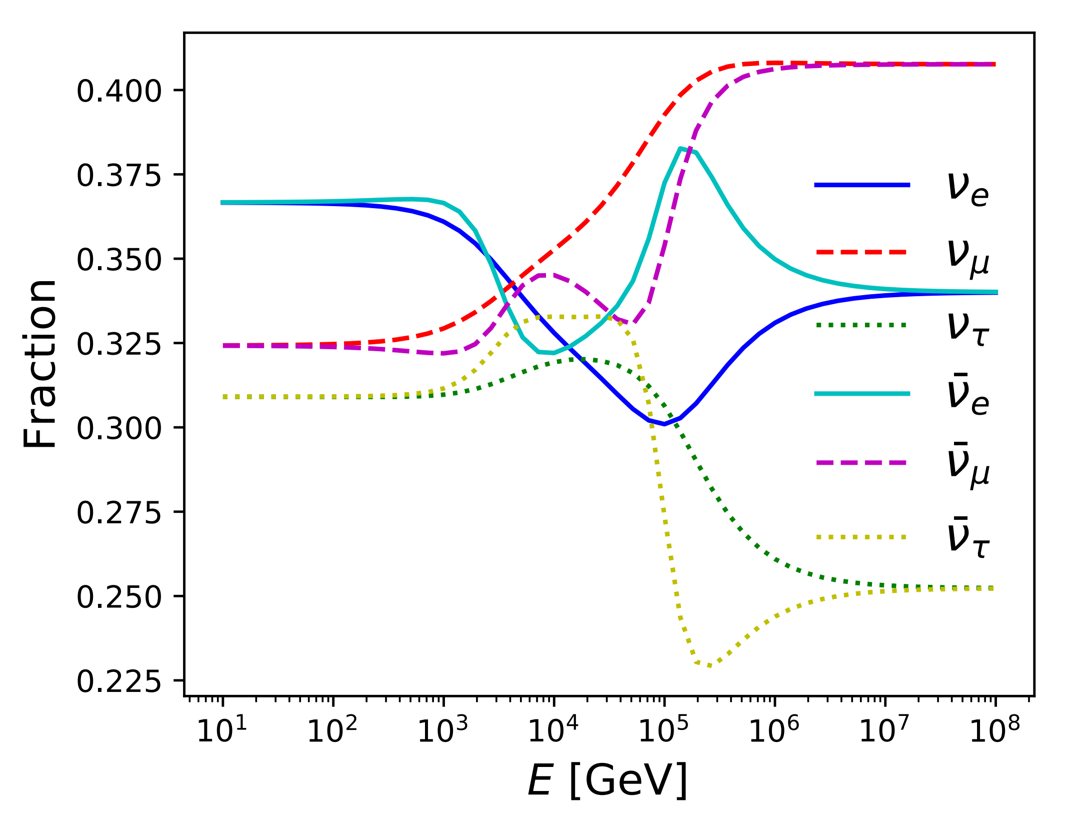
CP violation

$\delta_{DE} = 0.25\ \pi$



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

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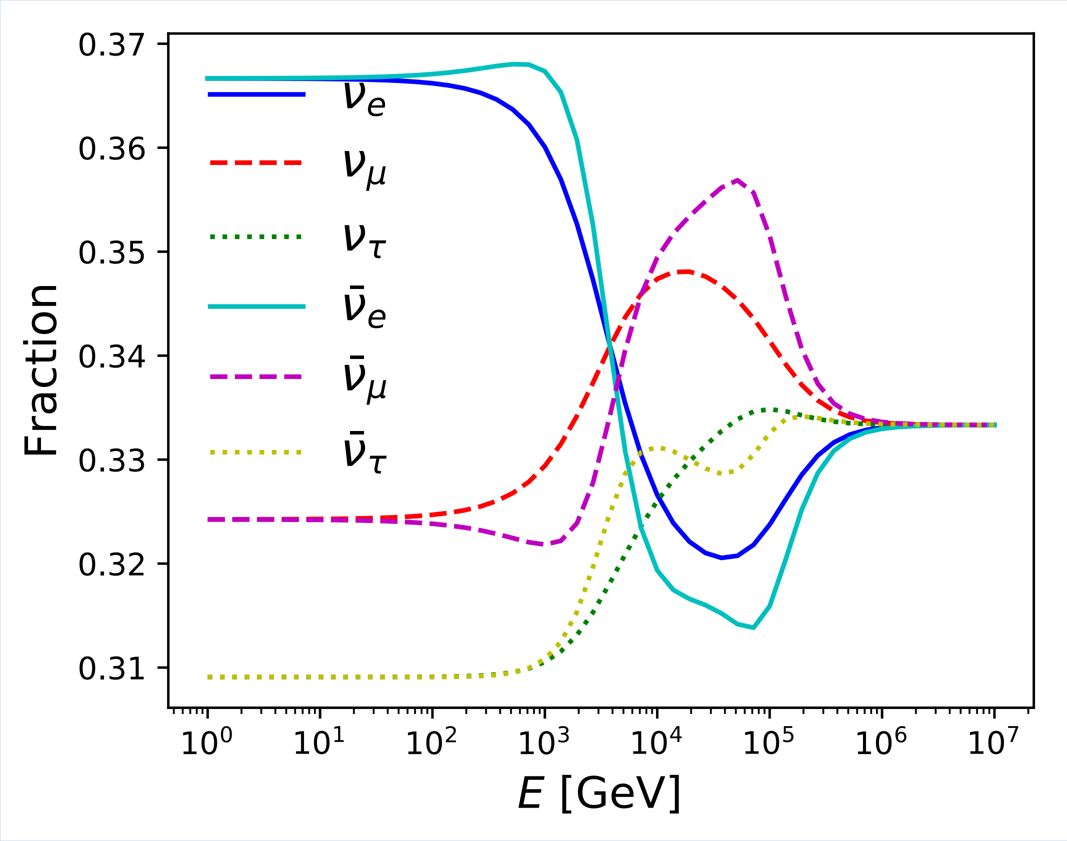
CP violation

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



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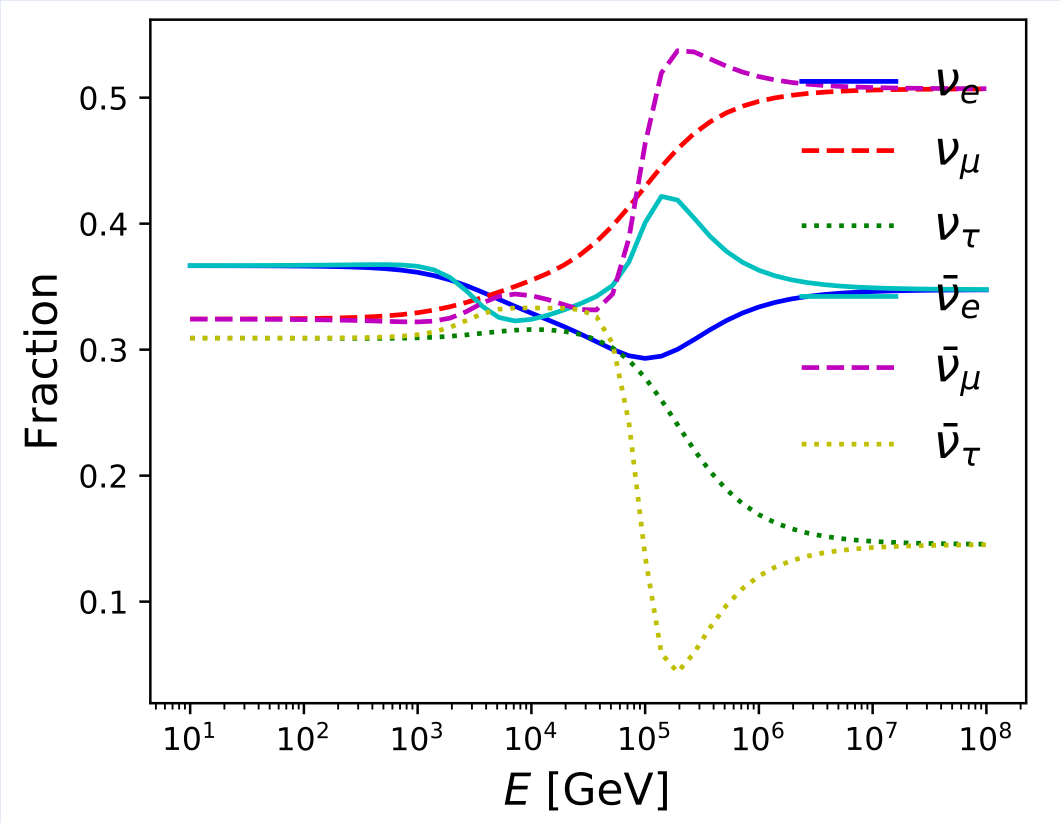
$\delta_{DE} = 0$



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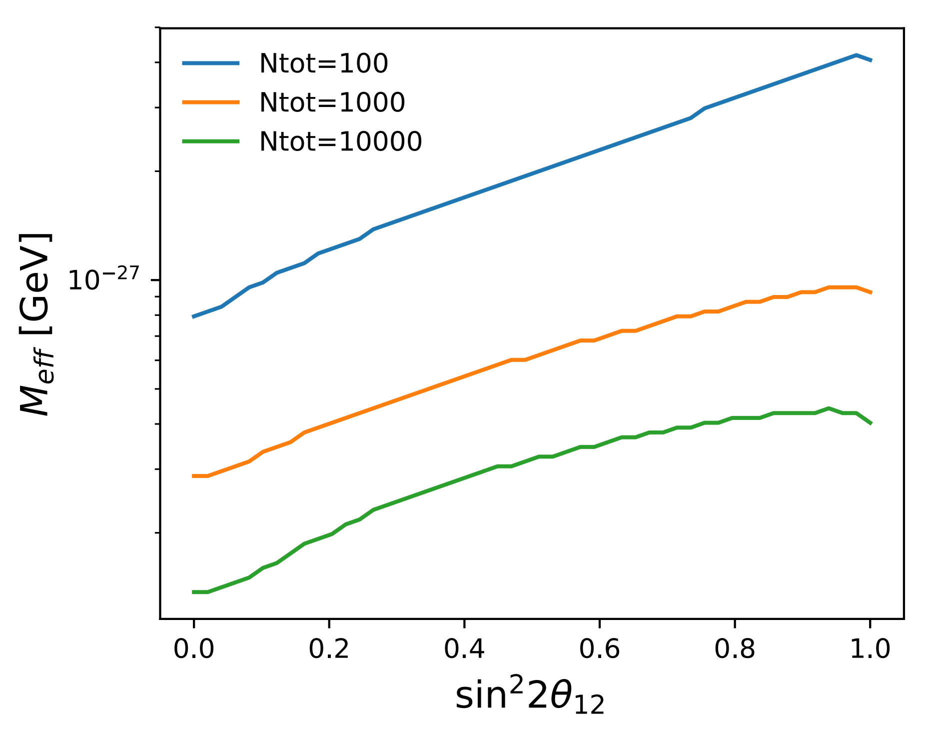
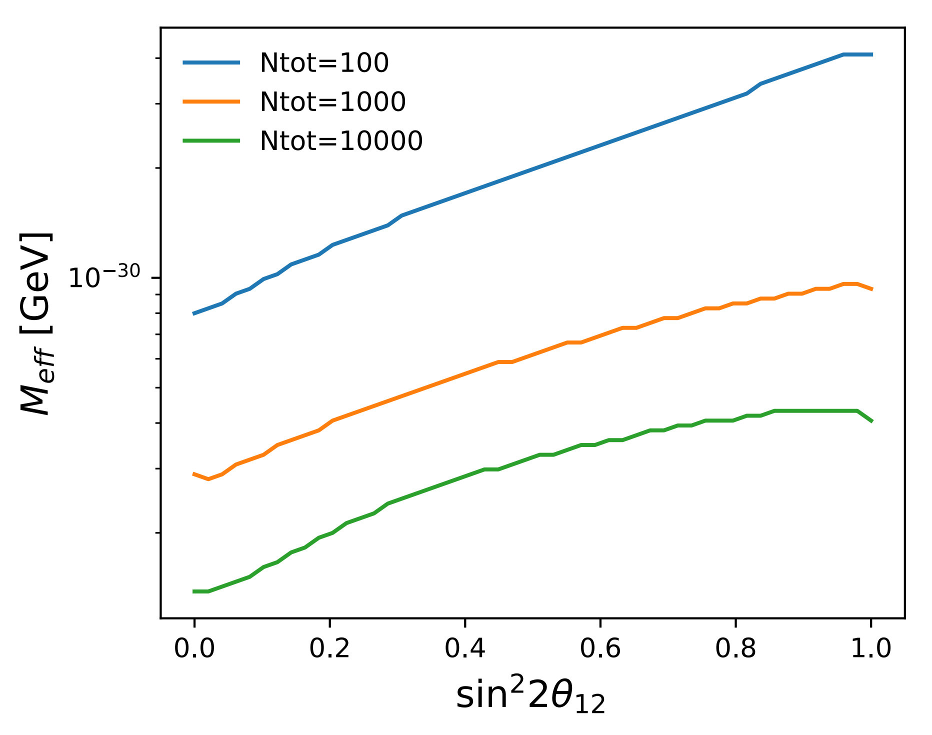
Sensitivity in experiments



IceCube



Experiments sensitive to UHE neutrinos

$\vartheta_{DE13}, \vartheta_{DE23} = 0$

Directional dependence

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

- ✧ Directional dependence in oscillations of cosmogenic neutrinos
- ✧ $\boldsymbol{v} \cdot \hat{\boldsymbol{p}}$ ~10^{-3}

Summary

- ✧ 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 $E*M_{eff} \sim 10^{-20}$ GeV
- ✧ Current and future experiments are sensitive to M_{eff} up to 10^{-27} to 10^{-31} GeV
- ✧ Discovering the directional dependence would be the smoking gun for DE-neutrino coupling