Neutrino Lorentz invariance violation from cosmic fields

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CPT Violation and Lorentz Invariance

CPT Symmetry: Relativistic quantum field theory (local).

- CPT symmetry assumes Minkowski spacetime; hermiticity of the Hamiltonian $\hat{H} = \hat{H}^\dagger$ and Lorentz invariance.
- $CPT \rightarrow m_{e^-} = m_{e^+}$, particle-antiparticle (mass) equality.
- Is CPT symmetry conserved at all energies E?
- Quantum gravity ($E_P \sim 10^{19}$ GeV), examples: string theory, loop quantum gravity, etc.
- String theory: Lorentz invariance violation (LIV) and CPT violation.
- LIV and CPT violation effects (ε) suppressed by $\varepsilon \lesssim 1/E_P$.

V. A. Kostelecky and S. Samuel, Phys. Rev. D 39 (1989); V. A. Kostelecky and R. Potting, Nucl. Phys. B 359 (1991); V. A. Kostelecky and R. Potting, Phys. Lett. B 381 (1996). G. Barenboim, Front. in Phys. 10 (2022); C. A. Moura and F. Rossi-Torres, Universe 8 (2022) no.1, 42.

Neutrino LIV from scalar fields

- Neutrino-scalar field interaction (ϕ)

$$-\mathcal{L}_{\text{eff}} = \frac{g_{\alpha\beta}}{\Lambda}\partial_\mu \phi \bar{\nu}_{\alpha L}\gamma^\mu \nu_{\beta L}.$$

P. H. Gu, X. J. Bi and X. m. Zhang, Eur. Phys. J. C 50 (2007), 655-659; F. Simpson, R. Jimenez, C. Pena-Garay and L. Verde, Phys. Dark Univ. 20 (2018), 72-77; N. Klop and S. Ando, Phys. Rev. D 97 (2018) no.6; T. Gherghetta and A. Shkerin, Phys. Rev. D 108 (2023) no.9, 9; G. Lambiase and T. K. Poddar, JCAP 01 (2024), 069.

- Neutrino-pseudoscalar interaction (ϕ)

$$-\mathcal{L}_{\text{eff}} = \frac{g_{\alpha\beta}}{\Lambda}\partial_\mu \phi \bar{\nu}_{\alpha L}\gamma^\mu \gamma_5 \nu_{\beta L}.$$

G. Y. Huang and N. Nath, Eur. Phys. J. C 78 (2018) no.11, 922.
R. Cordero and L. A. Delgadillo, Phys. Rev. D 110 (2024) 11.
https://arxiv.org/abs/2407.02729.

Effective Interaction Model: Neutrino-Scalar Field

$$-\mathcal{L}_{\text{eff}} = \lambda_{\alpha\beta}\frac{\partial^\mu \phi}{\Lambda}\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\beta L},$$

- $a^{\mu}_{\alpha\beta} = \lambda_{\alpha\beta}\partial^\mu\phi\Lambda^{-1}$, couplings $\lambda_{\alpha\beta} \sim \mathcal{O}(1)$.
- ϕ as dark matter or dark energy (DE) candidate.
- Neutrino *CPT*-odd LIV induced by ϕ.
- Klop, Ando: ϕ is DE, signals in neutrino oscillations.
- Cordero, Delgadillo: ϕ as dark matter (DM) candidate.

S. Ando, M. Kamionkowski and I. Mocioiu, Phys. Rev. D 80 (2009), 123522; N. Klop and S. Ando, Phys. Rev. D 97 (2018) no.6., R. Cordero, L. A. Delgadillo, PLB 853 (2024) 138687.

Neutrino-Scalar Field Interaction: (ϕ as DM)

Bosonic Current

$$\mathcal{L}_{\phi,Z'} \supset M_{Z'}\partial^{\mu}\phi Z'_{\mu}, \tag{1}$$

Neutrino Current

$$\mathcal{L}_{\nu,Z'} \supset g_{\alpha\beta}\bar{\nu}_{\alpha L}\gamma_{\mu}\nu_{\beta L}Z'^{\mu}. \tag{2}$$

- Integrating out Z'_{μ} Eq. (1) and Eq. (2)

$$\mathcal{L}_{\phi,\nu} = g_{\alpha\beta}\frac{\partial^{\mu}\phi}{M_{Z'}}\bar{\nu}_{\alpha L}\gamma_{\mu}\nu_{\beta L},$$

- ϕ as DM, Z'_{μ} new vector boson.

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https://arxiv.org/abs/2407.18513

Induced CPT-odd LIV in Neutrinos

$$\mathcal{L}^{CPT}_{\phi,\nu} = a^{\mu}_{\alpha\beta}\bar{\nu}_{\alpha L}\gamma_{\mu}\nu_{\beta L},$$

CPT-odd LIV coefficients $a^{\mu}_{\alpha\beta}$

$$a^{\mu}_{\alpha\beta} \to g_{\alpha\beta}\frac{\partial^{\mu}\phi}{M_{Z'}},$$

- $g_{\alpha\beta}$: neutrino$-Z'_{\mu}$ couplings, $M_{Z'} \sim [10\text{ GeV}-\text{TeV}]$.
- ϕ as ULDM: $m_{\phi} \sim 10^{-15}$ eV with $V(\phi) \simeq m^2_{\phi}\phi^2$,

$$\phi(x^{\mu}) \simeq \frac{\sqrt{2\rho_{\phi}}}{m_{\phi}}\sin\left(m_{\phi}(t - \langle v_{\phi}\rangle \mathbf{x})\right) \sim \phi(t).$$

E. G. M. Ferreira, Astron. Astrophys. Rev. 29 (2021) no.1, 7; A. Suárez, V. H. Robles and T. Matos, Astrophys. Space Sci. Proc. 38 (2014), 107-142. R. Cordero, L. A. Delgadillo, PLB 853 (2024) 138687

Radiative Corrections

Lagrangian $\mathcal{L}_{\phi,\nu}^{CPT}$ induces radiative corrections to m_ϕ

$$\delta m_\phi \simeq \frac{g_{\alpha\beta} m_\phi}{\pi M_{Z'}} \tilde{\Lambda} \lesssim m_\phi \; (g_{\alpha\beta}/ \lesssim \pi) \; (\tilde{\Lambda}/M_{Z'}).$$

Neutrino mass corrections m_ν

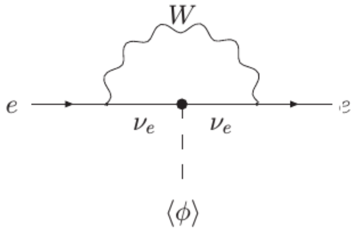
$$\delta m_\nu \simeq \frac{g_{\alpha\beta}^2 m_\nu}{\pi^2 M_{Z'}^2} \tilde{\Lambda}^2 \lesssim 10^{-3} m_\nu \; (g_{\alpha\beta}/ \lesssim 0.1) \; (\tilde{\Lambda}/M_{Z'}).$$

- Required ratio: $g_{\alpha\beta}/M_{Z'} \lesssim 10^{-13}$ eV^{-1}.
- Search for (Z'_μ) at colliders and $(a^\mu_{\alpha\beta})$ in neutrino oscillation experiments.

W. Abdallah, A. K. Barik, S. K. Rai and T. Samui, Phys. Rev. D 104 (2021) no.9, 095031; M. G. Aartsen et al. [IceCube], Nature Phys. 14 (2018) no.9; K. Abe et al. [Super-Kamiokande], Phys. Rev. D. 91 (2015) no.5.

Radiative Corrections

Lagrangian $\mathcal{L}_{\phi,\nu}^{CPT}$ induces CPT violation in electrons e



P. H. Gu, X. J. Bi and X. m. Zhang, Eur. Phys. J. C 50 (2007), 655-659.

$$\mathcal{L}_{1-\text{loop}} = \tilde{a}_e^{\mu} \bar{e} \gamma_{\mu} (1 - \gamma_5) e, \quad \tilde{a}_e^{\mu} \simeq g_{ee} \frac{\partial^{\mu}\phi}{M_{Z'}} \frac{\alpha M_{Z'}^2}{8\pi \sin^2 \theta_W M_W^2},$$

α fine structure constant, θ_W Weinberg angle. Experimental bounds: $\tilde{a}_e^T < 5 \times 10^{-25}$ GeV, $\tilde{a}_e^X < 10^{-25}$ GeV.

$$\tilde{a}_e^T \lesssim 10^{-26} \text{ GeV } (g_{ee} \lesssim 10^{-1})(M_{Z'}/3M_W), \quad \tilde{a}_e^X \lesssim 10^{-3} \tilde{a}_e^T.$$

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Neutrino-Scalar Field Interaction Potential

In early epochs, $\mathcal{L}_{\phi,\nu}^{CPT}$ induces potential

$$V(\dot{\phi}) = \frac{g_{\alpha\beta} n_\nu}{M_{Z'}} \dot{\phi}.$$

- n_ν neutrino number density, $\phi(x^\mu) \simeq \phi(t)$.

ϕ evolution with interaction (Q)

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = -\frac{Q}{\dot{\phi}},$$

$$Q = \tilde{g}_{\alpha\beta} n_\nu \ddot{\phi} \quad \text{(Simpson et al.)}$$

$$\ddot{\phi}\left(1 + \frac{g_{\alpha\beta} n_\nu}{M_{Z'} \dot{\phi}}\right) + 3H\dot{\phi} + \frac{dV(\phi, \dot{\phi})}{d\phi} = 0.$$

F. Simpson, R. Jimenez, C. Pena-Garay and L. Verde, Phys. Dark Univ. 20 (2018), 72-77.

Scalar Field Evolution: Energy Exchange (Q)

- $Q = \tilde{g}_{\alpha\beta} n_\nu \ddot{\phi}$ (Simpson et al.), ϕ behaves as DE, $\phi =$ constant.
- Proposal: $Q = m_\nu \tilde{g}_{\alpha\beta} n_\nu \dot{\phi}$ ($Q \propto \dot{\phi}$, Boehmer et al.).
- Is ϕ a ULDM candidate?

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi, \dot{\phi})}{d\phi} + \frac{g_{\alpha\beta} n_\nu m_\nu}{M_{Z'}} = 0.$$

- ϕ as ULDM, but oscillations delayed if:

$$\frac{g_{\alpha\beta} n_\nu m_\nu}{M_{Z'}} \lesssim \left| \frac{dV(\phi, \dot{\phi})}{d\phi} \right| \sim m_\phi^2 |\phi|.$$

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C. G. Boehmer, G. Caldera-Cabral, R. Lazkoz and R. Maartens, Phys. Rev. D 78 (2008), 023505.

Lorentz Invariance Violation (LIV) in Neutrinos

LIV/CPT Parameterization (effective theory $E \ll E_P$):

$$\mathcal{L}^{\psi}_{\text{eff}} = \mathcal{L}^{\psi}_{\text{SM}} + \mathcal{L}_{\text{LIV}} + \text{h.c.},$$

$$\mathcal{L}_{\text{LIV}} = -\frac{1}{2}\Big\{ p^{\mu}_{\alpha\beta}\bar{\psi}_\alpha\gamma_\mu\psi_\beta + q^{\mu}_{\alpha\beta}\bar{\psi}_\alpha\gamma_\mu\gamma_5\psi_\beta - i r^{\mu\nu}_{\alpha\beta}\bar{\psi}_\alpha\gamma_\mu\partial_\nu\psi_\beta - i s^{\mu\nu}_{\alpha\beta}\bar{\psi}_\alpha\gamma_\mu\gamma_5\partial_\nu\psi_\beta \Big\},$$

For neutrinos, we define:

$$(a_L)^{\mu}_{\alpha\beta} = (p+q)^{\mu}_{\alpha\beta} \ [\text{Energy}], \quad (c_L)^{\mu\nu}_{\alpha\beta} = (r+s)^{\mu\nu}_{\alpha\beta} \ [E^0].$$

V.A. Kostelecky and M. Mewes, Phys. Rev. D 69 (2004). G. Barenboim, Front. in Phys. 10 (2022); C. A. Moura and F. Rossi-Torres, Universe 8 (2022) no.1, 42.

CPT-even SME $C^{\mu\nu}_{\alpha\beta}$ in neutrino oscillations

- Effective Hamiltonian (Neutrino Oscillations)

$$H_{\text{eff}} = H_{\text{vacuum}} + H_{\text{matter}} + H_{\text{LIV}},$$

- LIV Hamiltonian, CPT-even (T-time and Z-spatial) SME coefficients:

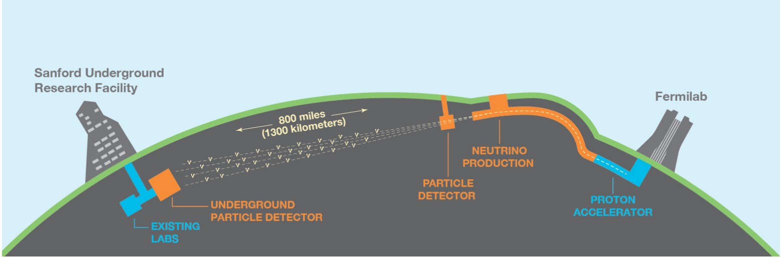
$$H_{\mathrm{LIV}} = -\frac{E_\nu}{2}\left[(3-\hat{N}_Z^2)(c_L)^{TT}_{\alpha\beta} + (3\hat{N}_Z^2 - 1)(c_L)^{ZZ}_{\alpha\beta} - 2\hat{N}_Z(c_L)^{TZ}_{\alpha\beta}\right].$$

Neutrinos $E_\nu \gtrsim$ GeV: Higher sensitivity to LIV and CPT effects!

V.A. Kostelecky and M. Mewes, Phys. Rev. D 69 (2004). G. Barenboim, Front. in Phys. 10 (2022); C. A. Moura and F. Rossi-Torres, Universe 8 (2022) no.1, 42.

Tensorial neutrino interaction with cosmic fields: Sensitivity to CPT-even SME ($C^{\mu\nu}_{\alpha\beta}$) in DUNE

Deep Underground Neutrino Experiment (DUNE)



$$H_{\rm LIV} = -\frac{E_\nu}{2}\left[(3-\hat{N}_Z^2)(c_L)^{TT}_{\alpha\beta} + (3\hat{N}_Z^2-1)(c_L)^{ZZ}_{\alpha\beta} - 2\hat{N}_Z(c_L)^{TZ}_{\alpha\beta}\right].$$

DUNE: $E_\nu \sim 3$ GeV, $\hat{N}^Z \simeq 0.16$.

J. S. Diaz, V. A. Kostelecky and M. Mewes, Phys. Rev. D 80, 076007 (2009) R. Cordero, L. A. Delgadillo, O. G. Miranda, C. Moura, EPJC (2025) 85:6

Tensorial neutrino interaction with cosmic fields

$$-\mathcal{L}_{\text{eff}} = -i\frac{\lambda_{\alpha\beta}}{M_*^4}\, T_\varphi^{\mu\nu}\,\bar{\nu}_{\alpha L}\gamma_\mu\partial_\nu\nu_{\beta L}$$

- $CPT-$even LIV coefficients of the SME $(c_L)^{\mu\nu}_{\alpha\beta} = c^{\mu\nu}_{\alpha\beta}$:
$$c^{\mu\nu}_{\alpha\beta} \to \frac{\lambda_{\alpha\beta}}{M_*^4}\, T_\varphi^{\mu\nu}.$$
- $T_\varphi^{\mu\nu}(\varphi) \to \varphi$ as either dark matter or dark energy candidate.
- Isotropic LIV coefficients $(c_L)^{00}_{\alpha\beta} = c^{00}_{\alpha\beta}$:
$$c^{00}_{\alpha\beta} \to \frac{\lambda_{\alpha\beta}}{M_*^4}\, T_\varphi^{00} = \frac{\lambda_{\alpha\beta}}{M_*^4}\,\rho_\varphi.$$
- $Z-$spatial LIV coefficients $(c_L)^{33}_{\alpha\beta} = c^{ZZ}_{\alpha\beta}$:
$$c^{ZZ}_{\alpha\beta} \to \frac{\lambda_{\alpha\beta}}{M_*^4}(T_\varphi^{ZZ} + \delta T_\varphi^{ZZ}). \quad (3)$$

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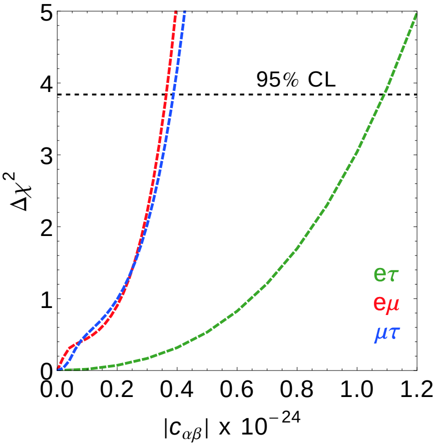
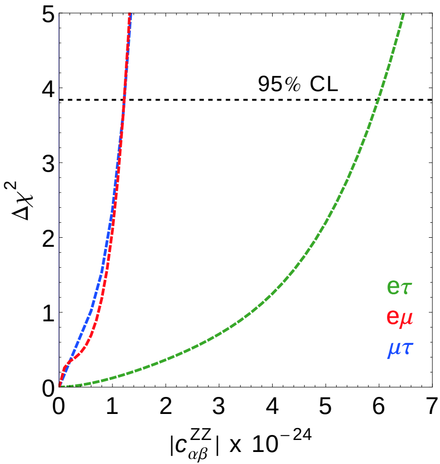
Future Sensitivity in DUNE ($C^T_{\alpha\beta} = C_{\alpha\beta}$, $C^{ZZ}_{\alpha\beta}$)





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Future Sensitivities at DUNE

Table: DUNE projected sensitivities, last column shows the interaction energy scale M_* associated to the SME coefficients $c^{\mu\nu}_{\alpha\beta}$.

Sensitivity	Interaction energy scale
$\lvert c_{\alpha\beta}\rvert \sim [1-10]\times 10^{-25}$	$M_* \sim [3-6]\times 10^{4}$ eV $\left(\rho^{\rm DM}_{\varphi,\odot}\right)$
$\lvert c^{ZZ}_{\alpha\beta}\rvert \sim [1-10]\times 10^{-24}$	$M_* \sim [2-3]\times 10^{3}$ eV $\left(\rho^{\rm DE}_{\varphi}\right)$
$c_{ee} - c_{\tau\tau} \simeq 1.3\times 10^{-24}$	$M_* \sim 3\times 10^{4}$ eV $\left(\rho^{\rm DM}_{\varphi,\odot}\right)$
$c_{\mu\mu} - c_{\tau\tau} \simeq 2.2\times 10^{-24}$	$M_* \sim 3\times 10^{4}$ eV $\left(\rho^{\rm DM}_{\varphi,\odot}\right)$
$c^{ZZ}_{ee} - c^{ZZ}_{\tau\tau} \simeq 5.0\times 10^{-24}$	$M_* \sim 2\times 10^{3}$ eV $\left(\rho^{\rm DE}_{\varphi}\right)$
$c^{ZZ}_{\mu\mu} - c^{ZZ}_{\tau\tau} \simeq 7.0\times 10^{-24}$	$M_* \sim 2\times 10^{3}$ eV $\left(\rho^{\rm DE}_{\varphi}\right)$

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Summary

- Neutrino–ultralight DM interaction ($m_\phi \sim 10^{-15}$ eV):

$$\mathcal{L}_{\phi,\nu} = g_{\alpha\beta} \frac{\partial^\mu \phi}{M_{Z'}} \bar{\nu}_{\alpha L} \gamma_\mu \nu_{\beta L}.$$

- Signatures via Z'_μ searches and neutrino oscillations:

$$a^\mu_{\alpha\beta} \to g_{\alpha\beta} \frac{\partial^\mu \phi}{M_{Z'}}, \quad a^T_{\alpha\beta} \lesssim 10^{-25} \text{ GeV}, \ \ a^X_{\alpha\beta} \lesssim 10^{-28} \text{ GeV}.$$

- Depending on $\nu - \phi$ energy exchange (Q), scalar field behaves as DE or DM.
- Tensorial–neutrino interaction: $T^{\mu\nu}_\varphi(\varphi) \to \varphi$ as either DM or DE candidate.
- *CPT*-even SME coefficients related to the energy-momentum tensor:

$$c^{\mu\nu}_{\alpha\beta} \to \frac{\lambda_{\alpha\beta}}{M^4_*} T^{\mu\nu}_\varphi.$$

- Competitive sensitivities to the *CPT*-even SME coefficients at DUNE.

Thank you for your attention!

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BACK UP: Scalar Field Evolution ($T \gtrsim 1$ eV, $n_\nu \sim 0.1 T^3$)

Equation of Motion: $\phi(t) \to \phi(T)$

$$H(t) = \frac{1}{2t} \simeq 1.66\sqrt{g_*}\frac{T^2}{M_{\rm Pl}},$$

g_*: relativistic degrees of freedom.

$$\phi(T) \to \left(\frac{d\phi}{dT} - \frac{0.1 g_{\alpha\beta} M_{\rm Pl}}{(1.66)\sqrt{g_*} M_{Z'}}\right)\frac{d^2\phi}{dT^2} =$$
$$\left(\frac{(0.3) g_{\alpha\beta} M_{\rm Pl}}{M_{Z'}(1.66)\sqrt{g_*}\,T} - \frac{m_\phi^2 M_{\rm Pl}^2 \phi}{(1.66)^2 g_* T^6}\right)\frac{d\phi}{dT}.$$

Thus: $\phi =$ constant is a solution!

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LIV and CPT Violation in Neutrino sector

CPT-odd LIV coefficients: $CPT(a^{\mu}_{\alpha\beta}) = (-)a^{\mu}_{\alpha\beta}$,

$$CPT(\bar{\psi}_\alpha\gamma_\mu\psi_\beta) = (-)\bar{\psi}_\alpha\gamma_\mu\psi_\beta, \quad CPT(\bar{\psi}_\alpha\gamma_\mu\gamma_5\psi_\beta) = (-)\bar{\psi}_\alpha\gamma_\mu\gamma_5\psi_\beta,$$

$$CPT(\partial_\nu) = (-)\partial_\nu, \quad CPT(\bar{\psi}_\alpha\partial^\mu\gamma_\mu\psi_\beta) = (-)^2\bar{\psi}_\alpha\partial^\mu\gamma_\mu\psi_\beta.$$

CPT-even LIV coefficients: $CPT(c^{\mu\nu}_{\alpha\beta}) = (-)^2 c^{\mu\nu}_{\alpha\beta}$,

$$CPT(\bar{\psi}_\alpha\gamma_\mu\partial_\nu\psi_\beta) = (-)^2\bar{\psi}_\alpha\gamma_\mu\partial_\nu\psi_\beta,$$
$$CPT(\bar{\psi}_\alpha\gamma_\mu\gamma_5\partial_\nu\psi_\beta) = (-)^2\bar{\psi}_\alpha\gamma_\mu\gamma_5\partial_\nu\psi_\beta.$$

G. Barenboim, Front. in Phys. 10 (2022).