# Testing Lorentz invariance violation using cosmogenic neutrinos

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COST CA18108 Fourth Annual Conference, Rijeka (Croatia)

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# Introduction

Neutrinos are very special astrophysical messengers which are only affected by the expansion of the Universe in a standard scenario.

In quantum gravity models, the effects of Lorentz Invariance Violation (LIV) increase with the energy.

Consequently, cosmogenic neutrinos, produced during the propagation of Ultra High-Energy Cosmic Rays (UHECR), provide one of the best playgrounds to test LIV models.

# Theoretical framework

We consider a superluminal neutrino LIV model, in which the free Lagrangian is modified,

$$\mathcal{L}_{\mathsf{free}} = \bar{\nu}_L (i\gamma^\mu \partial_\mu)\nu_L - \frac{1}{\Lambda^n}\bar{\nu}_L \gamma^0 (i\partial_0)^{n+1}\nu_L \,, \tag{1}$$

such that a Modified Dispersion Relation (MDR) emerges for the neutrino and antineutrino,

$$\begin{aligned} E_\nu &= \; |\vec{p}_\nu|\left[1 + \left(\frac{|\vec{p}_\nu|}{\Lambda}\right)^n\right], \\ E_{\bar{\nu}} &= \; |\vec{p}_{\bar{\nu}}|\left[1 + (-1)^n\left(\frac{|\vec{p}_{\bar{\nu}}|}{\Lambda}\right)^n\right]. \end{aligned} \tag{2}$$

For $n = 2$ both particles are superluminal. For $n = 1$, neutrinos are superluminal and antineutrinos subluminal.

Superluminal (anti)neutrinos are unstable and can decay emitting an electron-positron (VPE) or neutrino-antineutrino (NSpl) pair,

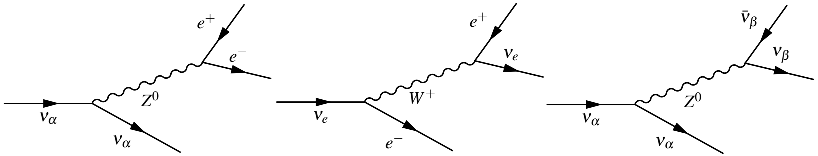


**Figure 1:** From left to right:
(a) Neutral channel of the VPE (b) Charged channel of the VPE (c) Neutral channel of the NSpl.

The VPE has a (kinematical) threshold $E_{\text{th}}^{(e)} := \left(2m_e^2\Lambda^n\right)^{1/(2+n)}$.
The NSpl threshold is negligible.

One can use the collinearity[1] of the decays at very high energies to compute the total decay widths and the energy fractions probability distribution of the particles of the final state.

$$\begin{aligned}
\Gamma^{(e)}_{\nu_{\mu,\tau}} &= \frac{E^5}{192\pi^3}\frac{g^4}{M_W^4}\left[(s_W^2-1/2)^2+(s_W^2)^2\right]\left(\frac{E}{\Lambda}\right)^{3n} c_n^{(e)}\,, \\
\Gamma^{(e)}_{\nu_e} &= \frac{E^5}{192\pi^3}\frac{g^4}{M_W^4}\left[(s_W^2-3/2)^2+(s_W^2)^2\right]\left(\frac{E}{\Lambda}\right)^{3n} c_n^{(e)}\,, \\
\Gamma^{(\nu)}_{\nu_\alpha} &= 3\times\frac{E^5}{192\pi^3}\frac{g^4}{M_W^4}\left(\frac{E}{\Lambda}\right)^{3n} c_n^{(\nu)}\,,
\end{aligned} \tag{3}$$

[1]PRD 107 043001 (2023)

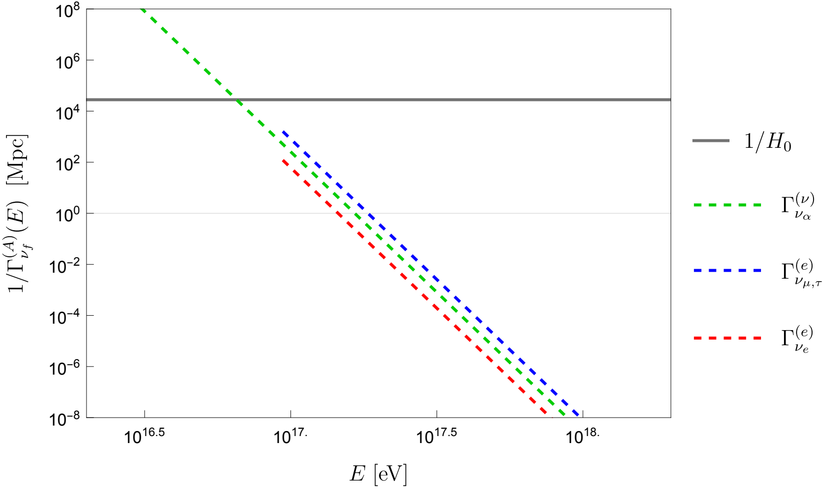


**Figure 2:** The decay lengths of NSpl (green), muon/tau VPE (blue) and electron VPE (red) in Mpc for $\Lambda = M_P$ and $n = 2$. The VPE is only defined above $E^{(e)}_{\text{th}}$. The inverse of $H_0$ is shown in a horizontal dark gray line.

The total decay widths can be written in terms of certain energy scales, $E^{(e)}_{\nu_{\mu,\tau}}$, $E^{(e)}_{\nu_e}$, and $E^{(\nu)}_{\nu_\alpha}$, which act as "effective" or dynamical thresholds,

$$\Gamma^{(e)}_{\nu_{\mu,\tau}}/H_0 \equiv \left(E/E^{(e)}_{\nu_{\mu,\tau}}\right)^{5+3n}, \ \ \Gamma^{(e)}_{\nu_e}/H_0 \equiv \left(E/E^{(e)}_{\nu_e}\right)^{5+3n}, \\ \text{and} \quad \Gamma^{(\nu)}_{\nu_\alpha}/H_0 \equiv \left(E/E^{(\nu)}_{\nu_\alpha}\right)^{5+3n}. \tag{4}$$

If the energy of the neutrino is above a dynamical threshold, it will decay without changing its redshift, the necessary times until falling below the threshold (instantaneous approximation). This predicts a cutoff in the neutrino spectrum.

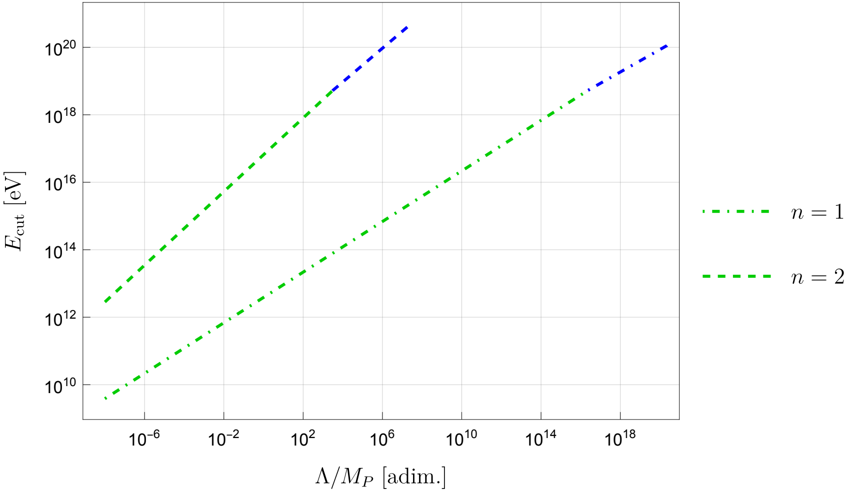


**Figure 3:** Approximate energy of the superluminal cutoff as a function of $\Lambda$ for $n = 1$ (dash-doted) and $n = 2$ (dashed). The green part is controlled by the dynamical threshold of the NSpl and the blue one by the kinematical threshold of the VPE.

# Modified cosmogenic neutrino spectrum

We implemented the instantaneous approximation in SimProp[2], a Monte Carlo software focused in the propagation of cosmic rays and the produced particles from interactions with the CMB and EBL.

```
//Check whether the particle (neutrino or antineutrino) is superluminal.
//If the particle is subluminal, propagate it trivially to Earth.
//If it is not, continue.

//Check if the energy is below any threshold (kinematical or dynamical).
//If the energy is below, set the corresponding decay width to zero.
//If it is not, compute the value.

//If all the decay widths are zero, propagate it trivially to Earth.
//If they are not, randomly choose a process to undergo with a probability
//proportional to their decay widths.

//Depending of the chosen effect, randomly sample the energies of the
//final particles from the final energy distributions.
```

[2] JCAP 11 009 (2017)

The production of cosmogenic neutrinos will depend on the astrophysical scenario set for the emission of the cosmic rays from their sources.

We have considered a pure protons UHECR composition, emitted by three possible source distributions (uniform, proportional to the SFR and to the AGN distributions[3], and with an emission spectrum $E^{-\gamma}$ with $\gamma = 2.6$, 2.5 and 2.4, respectively.

The UHECR interactions with the CMB and EBL will produce cosmogenic neutrinos around two characteristic energies: $10^{16}$–$10^{17}$ eV for the EBL, and $10^{18}$–$10^{19}$ eV for the CMB.

[3] JCAP 10 006 (2015)

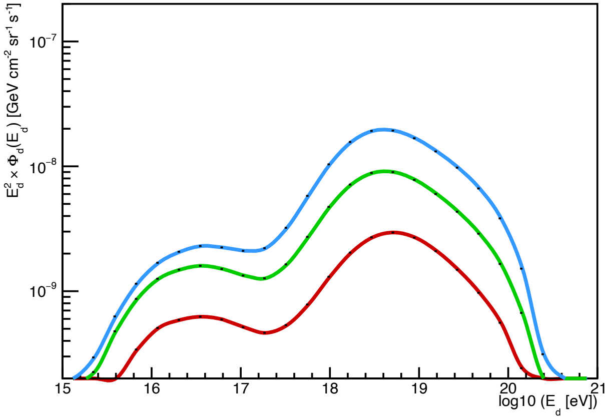


**Figure 4:** Cosmogenic neutrino flux at Earth using standard neutrino propagation, considering proton interactions with the CMB and EBL, for a uniform (red), SFR (green) and AGN (blue) proton source distribution.

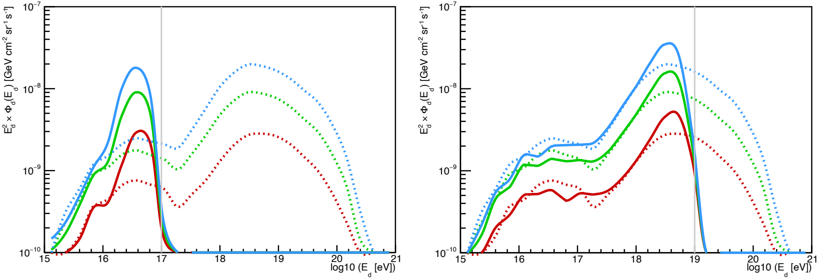


**Figure 5:** Cosmogenic neutrino flux at Earth for a superluminal cutoff at $E_{\text{cut}} = 10^{17}\,\text{eV}$ (left) and $10^{19}\,\text{eV}$ (right), for $n = 2$, and for a uniform (red), SFR (green), and AGN (blue) source distribution. The corresponding SR scenario for each case are shown in dotted lines.

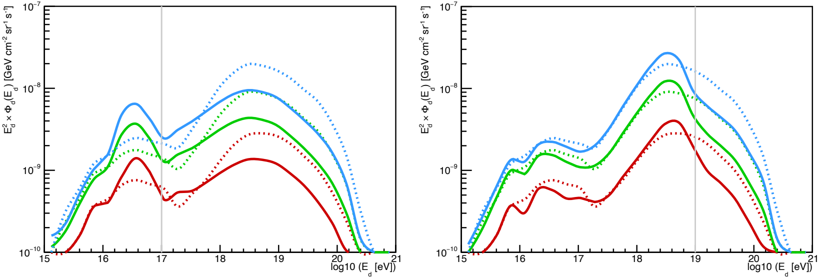


**Figure 6:** Cosmogenic neutrino flux at Earth for a superluminal cutoff at $E_{\text{cut}} = 10^{17}\,\text{eV}$ (left) and $10^{19}\,\text{eV}$ (right), for $n = 1$, and for a uniform (red), SFR (green), and AGN (blue) source distribution. The corresponding SR scenario for each case are shown in dotted lines.

To test the sensitivities of the current and future experiments to these new physics scenarios one can compute the expected number of neutrino events using the exposure of different experiments.

Currently, we have not detected neutrino events in the energy range of the cosmogenic neutrinos. Then, we can reject at the 90% Confidence Level (CL) all the models of LIV with a prediction in the number of expected neutrino events higher than $N = 2.39$[4].

[4] PRD 57 3873 (1998)

We have computed the expected number of events between $10^{16}$–$10^{17}$ eV (EBL peak) and $10^{18}$–$10^{19}$ eV (CMB peak), from the cosmogenic neutrino flux produced by a uniform UHECRs source distribution, and using the current exposure of Pierre Auger and IceCube, and for a 2.1- and 8.0-year window for IceCube Gen2.

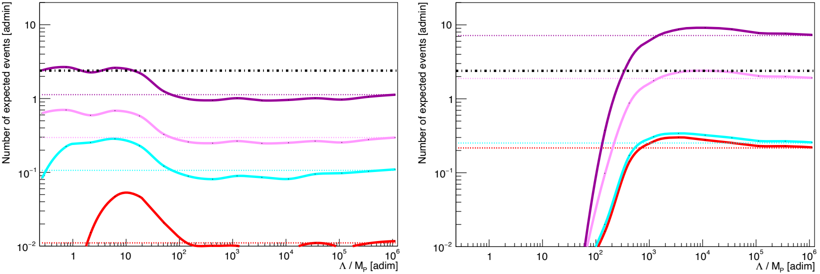


**Figure 7:** Number of expected events with energies between $10^{16}$–$10^{17}$ (left) and $10^{18}$–$10^{19}$ (right) eV by current Pierre Auger (red) and IceCube (cyan) observatories, and by a 2.1-year-old (light magenta) and 8.0-year-old (dark magenta) IceCube Gen2, with respect to the scale of new physics $\Lambda$ and for $n = 2$. The corresponding SR scenario for each case is shown in dotted lines. The statistical 90% CL UL for absence of events ($N_d = 2.39$) is shown in a dot-dashed black line.

Alternatively, the non-detection of events between $10^{18}$–$10^{19}$ eV by IceCube Gen2 would favour a superluminal LIV model with $\Lambda < 1.49 \cdot 10^2 M_P$ and $n = 2$ (i.e. with a cutoff before $E_{\text{cut}} \approx 10^{18}\,\text{eV}$), as a possible explanation to the lack of expected events.

In a more optimistic scenario in which a non-zero flux of cosmogenic neutrinos is detected, the detection of neutrino events at a certain energy $E_d$ necessarily implies that, if there exists a superluminal cutoff, it must be at energies $E_{\text{cut}} > E_d$, which in turn can be translated into a bound on the value of $\Lambda$.

# Conclusions

The cosmogenic neutrino flux is strongly influenced by the astrophysical scenario for the cosmic rays. For instance, if one includes a more realistic model with heavy nuclei, as reported by the Pierre Auger Observatory[5], the associated cosmogenic neutrino fluxes are smaller than those of the pure proton case.

Given the limitations of this work, a more general analysis is planned for the future; however, the present study already shows the potential of cosmogenic neutrinos to put constraints on the scale of LIV in the neutrino sector.

[5] JCAP 05 024 (2023)

**Thank you for your attention**

# Extra slides

In order to preserve $\mathrm{SU(2)_L \times U(1)_Y}$ gauge invariance, we can make the LIV term to involve the neutrino through the product with a complex scalar field, related with the Higgs doublet $\Phi = (\Phi^+ \; \Phi^0)^T$.

$$\bar{f}_{lL}\tilde{\Phi} = \begin{pmatrix} \bar{\nu}_{lL} & \bar{l}_L \end{pmatrix} \cdot \begin{pmatrix} \Phi^{0*} \\ -\Phi^- \end{pmatrix} , \quad \text{and} \quad \tilde{\Phi}^\dagger f_{lL} = \begin{pmatrix} \Phi^0 & \Phi^+ \end{pmatrix} \cdot \begin{pmatrix} \nu_{lL} \\ l_L \end{pmatrix} . \tag{5}$$

When one substitute the Higgs doublet by the Vacuum Expectation Value, we obtain a term quadratic in the neutrino field.

$$\langle\tilde{\Phi}\rangle \approx \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \quad \rightarrow \quad (\bar{f}_{lL}\tilde{\Phi})\,(\tilde{\Phi}^\dagger f_{lL}) \approx \frac{v^2}{2}\,\bar{\nu}_{lL}\,\nu_{lL} \,, \tag{6}$$

The constant $c_n^{(e)}$, from the VPE decay width, takes, for $n = 1$ and 2, the following values

$$c_1^{(e)} := \frac{121}{840} \approx 0.144\,, \quad c_2^{(e)} := \frac{81}{455} \approx 0.178\,. \tag{7}$$

Similarly, for the constant $c_n^{(\nu)}$, from the NSpl, we find

$$c_1^{(\nu)} := \frac{11}{450} \approx 0.024\,, \quad c_2^{(\nu)} := \frac{237}{10010} \approx 0.024\,. \tag{8}$$

We also computed the mean values of the energy fractions.

**Table 1:** Mean value of the final energy fractions after a muon or tau neutrino electron-positron pair emission.

| | $\langle x' \rangle$ | $\langle x_- \rangle$ | $\langle x_+ \rangle$ |
|---|---|---|---|
| $n = 1$ | 0.26 | 0.40 | 0.34 |
| $n = 2$ | 0.30 | 0.38 | 0.32 |

**Table 2:** Mean value of the final energy fractions after an electron neutrino electron-positron pair emission.

| | $\langle x' \rangle$ | $\langle x_- \rangle$ | $\langle x_+ \rangle$ |
|---|---|---|---|
| $n = 1$ | 0.26 | 0.50 | 0.24 |
| $n = 2$ | 0.30 | 0.47 | 0.23 |

**Table 3:** Mean value of the final energy fractions after a neutrino-antineutrino pair emission.

| | $\langle x' \rangle$ | $\langle x_- \rangle$ | $\langle x_+ \rangle$ |
|---|---|---|---|
| $n = 1$ | 0.30 | 0.30 | 0.40 |
| $n = 2$ | 0.38 | 0.38 | 0.24 |

The compatibility with the IceCube measurements impose a minimum value of the scale $\Lambda$.

**Table 4:** Updated constraints of the scale of new physics of a superluminal neutrino LIV scenario, from the detection of a neutrino compatible with the Glashow resonance (6.3 PeV).

| | $n = 1$ | $n = 2$ |
|---|---|---|
| $\Lambda/M_p >$ | $3.71 \cdot 10^8$ | $1.38 \cdot 10^{-2}$ |