Ultra-high-energy event KM3-230213A constraints on Lorentz Invariance Violation in neutrino sector

arXiv: 2502.09548 [hep-ph], EPJ C 85 (2025) 5, 545

Petr Satunin

INR RAS

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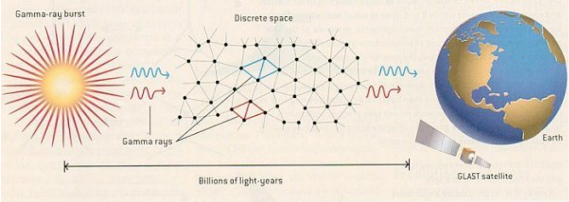
Lorentz Invariance Violation (LIV) motivation

Approaches to **quantum gravity** with LIV:

- Discrete spacetime (LQG etc..) L.Smolin 2004 etc..



- Gravity models with high order spatial derivatives
  Loop diagrams in quantum gravity converge due to high order momentum terms in dispersion relation for gravitons,

$$E^2 = k^2 \pm \frac{k^4}{\Lambda^2} \pm \frac{k^6}{\Lambda'^4}$$

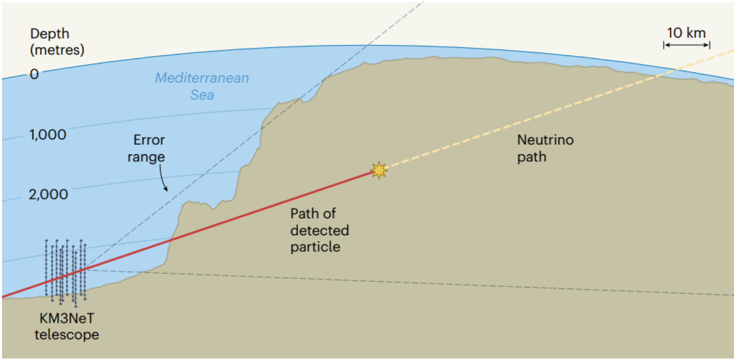
  Hořava-Lifshitz gravity P.Hořava 2009, D.Blas, O.Pujolas, S.Sibiryakov 2010
  LIV in matter sector arises as the loop correction due to matter-gravity interaction. A.Eichhorn, A.Platania, M.Schiffer 2020

The most energetic event of elementary primary particle

LIV effect grows with energy $\rightarrow$ need larger energies to test smaller LIV

Ultra-high-energy neutrino event KM3-230213A KM3NeT coll., Nature, 2025

$$E_\nu = 220^{+570}_{-100} \quad \text{PeV}$$



Model

LIV Lagrangian respecting $SU(2)_L$:

$$\mathcal{L}_{\text{LIV}}^{(\nu),n} = \frac{s_n}{\Lambda^n}\,\bar{l}^{\alpha}{}_L\gamma^0\,(iD_0)^{n+1}\,l_L^{\alpha}\,.$$

$n = (1,2)$. Λ_n – LIV mass scale, $s_n = \pm$, l_L^{α} – lepton spinor

Dispersion relations:

$$n = 1, \qquad E^2 = k^2 \pm s_1\frac{k^3}{\Lambda},$$

CPT-odd, different sign $\pm$ for different chiralities;

$$n = 2, \qquad E^2 = k^2 + s_2\frac{k^4}{\Lambda^2},$$

CPT-even, same sign for different chiralities

Superluminal neutrino. Decay channels

Superluminal dispersion relation

$$E^2 = k^2 + \frac{k^4}{\Lambda^2}$$

LIV neutrino decay channels:

- pair production $\nu_\alpha \to \nu_\alpha e^+ e^-$
- neutrino splitting $\nu_\alpha \to \nu_\alpha \nu_\beta \bar{\nu}_\beta$

$$\Gamma_{\nu_\alpha \to \nu_\alpha \nu_\beta \bar{\nu}_\beta} \approx G_F^2 \frac{E^5}{6\,\pi^3} \left(\frac{E}{\Lambda}\right)^{3n} c^{(\nu)}.$$

J. M. Carmona, J. L. Cortes, J. J. Relancio, and M. A. Reyes, Decay of superluminal neutrinos in the collinear approximation, Phys. Rev. D 107, 043001 (2023), arXiv:2210.02222 [hep-ph].

Here $c^{(\nu)} \approx 0.024$, G_F is the Fermi constant.

$$\Lambda = \begin{cases} \left(1.3 \cdot 10^{-4}\, G_F^2 L E^5\right)^{1/3} \times E, & n = 1, \\ \left(1.3 \cdot 10^{-4}\, G_F^2 L E^5\right)^{1/6} \times E, & n = 2, \end{cases} \qquad (1)$$

where $L = \Gamma^{-1}_{\nu \to \nu\nu\bar{\nu}}$ is the mean free path of the neutrino associated with the splitting. We take it as the distance to the possible source.

Neutrino splitting constraints (superluminal)

KM3-230213A energy: $E = 220^{+570}_{-100}$ PeV
3 cases of KM3-230213A origin:

In the galactic scenario, we take $L = 10$ kpc, so eq. (1) reads,

$$\Lambda = \begin{cases} 5.3^{+156.2}_{-4.2} \times 10^{29}\ \text{GeV}, & n = 1, \\ 1.1^{+10.2}_{-0.7} \times 10^{19}\ \text{GeV}, & n = 2. \end{cases} \tag{2}$$

Assuming extragalactic origin (now preferred) we take $L = 10$ Mpc,

$$\Lambda = \begin{cases} 5.3^{+156.2}_{-4.2} \times 10^{30}\ \text{GeV}, & n = 1, \\ 3.4^{+32.3}_{-2.3} \times 10^{19}\ \text{GeV}, & n = 2. \end{cases} \tag{3}$$

Assuming cosmogenic origin we put $L = 100$ Mpc,

$$\Lambda = \begin{cases} 1.2^{+33.6}_{-1.0} \times 10^{31}\ \text{GeV}, & n = 1, \\ 5.0^{+47.4}_{-3.3} \times 10^{19}\ \text{GeV}, & n = 2. \end{cases} \tag{4}$$

Pair production

$$\nu_\mu \to \nu_\mu e^+ e^-$$

Superluminal d.r.: $E^2 = k^2 + \frac{k^4}{\Lambda^2}$, $\quad E = 220^{+570}_{-100}$ PeV
Threshold process. For fixed E p.p. occurs if $\Lambda < \Lambda_{thr}$

$$\Lambda_{thr} = \frac{E^2}{\sqrt{6}m_e} = 3.9^{+46.0}_{-2.7} \times 10^{19}\,\text{GeV}, \qquad n = 2.$$

P.P. threshold near the splitting bound
Highly above threshold, neglecting m_e,

$$\Gamma_{\nu_\mu \to \nu_\mu e^+ e^-} = \Gamma_{\nu_\mu \to \nu_\mu \nu_\beta \bar{\nu}_\beta} \approx G_F^2 \frac{E^5}{6\,\pi^3} \left(\frac{E}{\Lambda}\right)^{3n} \times 0.024.$$

Can improve the splitting bound in 2 times, precise calculations near threshold are needed.

What could we say about subluminal dispersion relation?

$m_{eff}^2 \equiv E^2 - k^2 = \pm \frac{k^{n+2}}{\Lambda^n}$. "+" – superluminal, "−" – subluminal

General considerations for arbitrary particle:

- **Superluminal LIV:** $m_{eff}^2 > 0$. Some decay channels kinematically allowed (phase volume grows) $\rightarrow$ particle becomes unstable $\rightarrow$ particle decays before reaching detector
- **Subluminal LIV:** $m_{eff}^2 < 0$. Kinematics: Phase volume shrinks even for existing scattering processes $\rightarrow$ cross-sections decreases. Detection: showers become deeper.
  - Example: QED with subluminal photon, Bethe-Heitler cross-section decreases, showers become deeper (see G.Rubtsov, PS, S.Sibiryakov PRD 2012, also A.Sharofeev's talk)
- Neutrino-nucleus cross-section – should be suppressed in subluminal case — — but not calculated yet.

  Naive estimation: suppression if $\left(-m_{\nu,eff}^2\right) \gg m_\mu^2$

  One event — too low statistics

Conclusion

Superluminal LIV — Conservative bound

KM3-230213A energy taken as the low bound of the 68% CL confidence interval, $E = 120$ PeV; extragalactic origin. Neutrino splitting bound:

$$\Lambda > \begin{cases} 1.1 \times 10^{30}\,\text{GeV}, & n = 1, \\ 1.1 \times 10^{19}\,\text{GeV}, & n = 2. \end{cases}$$

Taking into account e^+e^- pair production can strengthen the bound up to 2 times

Subluminal LIV

No actual bound from KM3-230213A event
May be an interesting ask to study Neutrino-nucleus scattering suppresion in case of subluminal LIV

Thank you for your attention!