Have we observed Lorentz invariance violation in very high-energy cosmic messengers?

José Manuel Carmona
(Work in collaboration with D. Boncioli, J.L. Cortés, J.J. Relancio, F. Rescic, M.A. Reyes, T. Terzić, F.I. Vrban)

23rd February, 2024

Universidad Zaragoza
1542
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Contents

What? Quantum gravity phenomenology?

Initial ideas in QG phenomenology

Initial ideas and suggestions to test quantum gravity by amplification mechanisms:

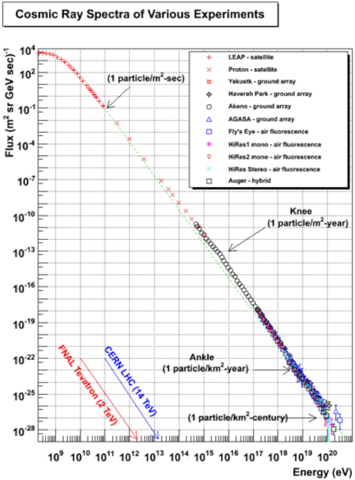
- Testing **CPT invariance** in neutral mesons
  [Ellis, Lopez, Mavromatos, Nanopoulos, PRD 1996]

$$\frac{|m_{K^0} - m_{\overline{K}^0}|}{m_{K^0}} \sim \mathcal{O}(10^{-19})$$

- **Time of flight studies** in GRBs (HEGRA, Whipple telescopes; EGRET satellite)
  [Amelino-Camelia, Ellis, Mavromatos, Nanopoulos, Sarkar, Nature 1998]

$$\Delta t \approx \xi \frac{E}{E_{\rm Pl}} \frac{L}{c}$$

The AGASA result and the GZK cutoff

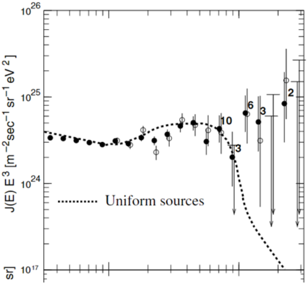


Cutoff GZK: $p + \gamma_{\text{CMB}} \to p + \pi$

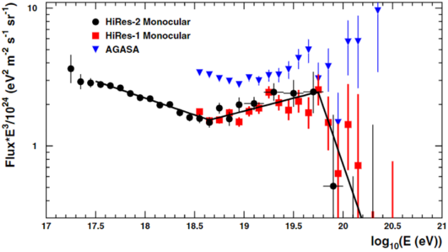
$$E_{\text{GZK}} \simeq \frac{m_p m_\pi}{2E_\gamma} \simeq 3 \times 10^{20}\,\text{eV} \times \left(\frac{2.7\,\text{K}}{E_\gamma}\right)$$

[Greisen, 1966; Zatsepin and Kuzmin, 1966]

The AGASA result and the GZK cutoff



[Takeda et al., Astrop. Phys. 2003, Akeno Giant Air Shower Array (AGASA) experiment]



[Abbasi et al., PRL 2008, High Resolution Fly's Eye (HiRES) experiment]

$$E^2 - p^2 - m^2 \simeq \xi_n E^2 \left(\frac{E}{E_{\rm Pl}}\right)^n$$

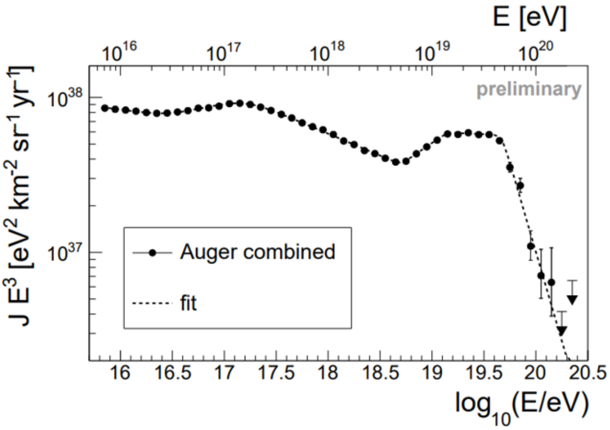
[Aloisio, Blasi, Ghia, Grillo, PRD 2000]

$\xi_n < 0$ No GZK cutoff

$\xi_n > 0$ $\xi_1 \lesssim 10^{-14}, \quad \xi_2 \lesssim 10^{-6}$

Have we observed new physics in VHE cosmic messengers?

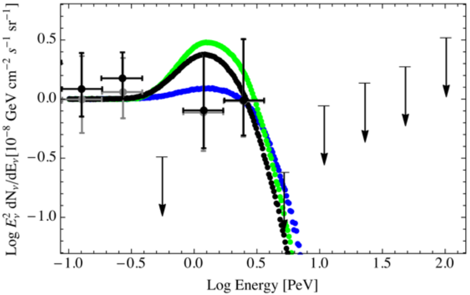
The UHECR spectrum and the muon puzzle



[Pierre Auger Collaboration, PoS (ICRC 2021)]

Muon puzzle: *PA Collab, PRL 2016; Dembinski et al., EPJ Web Conf. (UHECR 2018):*
"We combine data from eight leading air shower experiments to cover shower energies from PeV to tens of EeV. Above 10 PeV, we find a muon deficit in simulated air showers for each of the six considered hadronic interaction models. The deficit is increasing with shower energy. For the models EPOS-LHC and QGSJet-II.04, the slope is found significant at 8 sigma."

The spectrum of astrophysical neutrinos



Astrophysical neutrino flux from IceCube data (points)

[IceCube Collab., PRL 2014]

Neutrino spectrum with LIV propagation, showing a cutoff

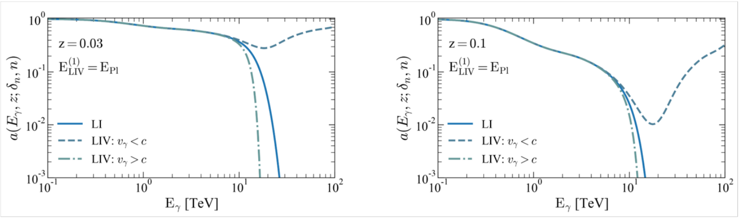
[Stecker, Scully, Liberati, Mattingly, PRD 2015]

Transparency of the Universe

High-energy photons are absorbed in photon backgrounds,

$\Phi_{\mathbf{obs}}(E, z) = \exp(-\tau(E, z))\Phi(E(1+z))$

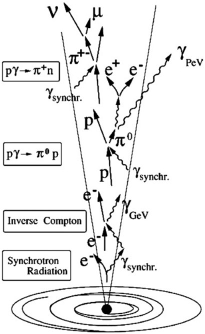
$a(E_\gamma, z; \delta_n, n) = \exp(-\tau)$ Absorption of TeV photons in the EBL

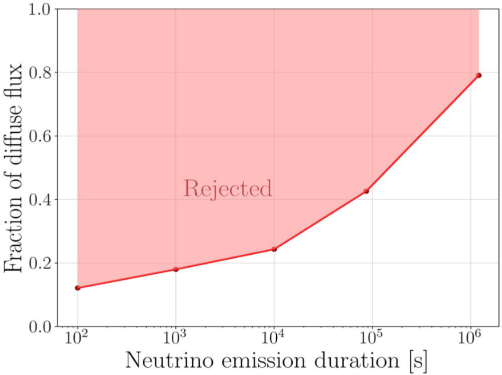


[Martínez-Huerta, Lang, de Souza, Symmetry 12,8 (2020)]

- Sensitivity of $E^{(1)}_{\mathrm{LIV}}$ to the Planck scale
- LHAASO results severely constrains the superluminal scenario because of pair-emission $(\gamma \to e^+e^-)$ and photon splitting $(\gamma \to 3\gamma)$ processes

Where are the GRB neutrinos?





IceCube Collab, ApJ 2022

ANTARES Collab, MNRAS 2021

What are the implications of LIV in the cosmic messengers?

Neutrinos could be unstable particles!

LIV in the neutrino sector parametrized by a **high-energy scale Λ**

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

producing a **modified dispersion relation,**

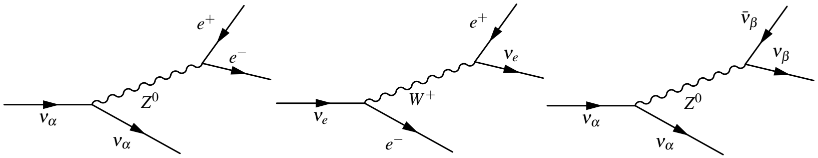
$$\begin{aligned} E_\nu &= |\vec{p}_\nu|\left[1 + \left(\frac{|\vec{p}_\nu|}{\Lambda}\right)^n\right], \\ E_{\overline{\nu}} &= |\vec{p}_{\overline{\nu}}|\left[1 + (-1)^n\left(\frac{|\vec{p}_{\overline{\nu}}|}{\Lambda}\right)^n\right]. \end{aligned}$$

$n = 1$ Superluminal neutrinos and subluminal antineutrinos

$n = 2$ Both neutrinos and antineutrinos are superluminal particles

Neutrinos could be unstable particles!

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



VPE (Neutral channel / Charged channel) *Nspl (Neutral channel)*

- VPE has a (kinematical) threshold $E_{\rm th}^{(n)} \coloneqq \left(2 m_e^2 \Lambda^n\right)^{1/(2+n)}$
- The NSpl threshold is negligible

Neutrinos could be unstable particles!

We can use the **collinearity** of the high-energy interactions to compute the **total decay widths**

[Carmona, Cortés, Relancio, Reyes, PRD 2023]

$$\Gamma^{(n)}_{\nu_\alpha \to \nu_\alpha + l + \bar{l}}(E) = 10^{-4}\, G_F^2 \left[E^5 \left(\frac{E}{\Lambda} \right)^{3n} \right] \kappa^{(n)}_{\nu_\alpha, l}$$

$\kappa^{(n)}_{\nu_\alpha, l}$

Decay	$n = 1$	$n = 2$
$\nu_{\mu,\tau} \to \nu_{\mu,\tau} e^+ e^-$	1.01	1.24
$\nu_e \to \nu_e e^+ e^-$	13.0	16.1
$\nu_\alpha \to \nu_\alpha \nu_\beta \bar{\nu}_\beta$	1.29	1.29

Neutrinos could be unstable particles!

If we define an **energy scale** $E_\alpha^{(n)}$ at which the decay rate equals the expansion rate,

$$\Gamma_\alpha^{(n)}(E)\big|_{E=E_\alpha^{(n)}} \;=\; H_0\,.$$

then we can write

$$\Gamma_\alpha^{(n)}(E) \;=\; H_0\left(E/E_\alpha^{(n)}\right)^{5+3n}$$

- As a consequence of the **strong energy dependence** of the decay width, $E_\alpha^{(n)}$ acts as an **'effective' threshold** for the decay of superluminal neutrinos, producing a **cutoff** in their energy spectrum

$n=1$ $$E_{\rm max}^{(1)} \approx 3.88\,{\rm TeV}\left(\frac{\Lambda}{M_P}\right)^{3/8}$$

$n=2$ $$E_{\rm max}^{(2)} \approx 6.53\times 10^4\,{\rm TeV}\left(\frac{\Lambda}{M_P}\right)^{6/11}$$

Time delay studies are incomplete!

Another consequence of LIV modified dispersion relations is **energy-dependent** neutrino propagation **velocities,** even in the massless limit, leading to a modification of their **time of flight**

$$v = \frac{dE}{dp} \approx 1 \pm (n+1)\left(\frac{E}{\Lambda}\right)^n$$

$n = 1$ $$\delta t_{\mathrm{LIV}}^{(1)} \approx \pm 7.22 \times 10^3\,\mathrm{s}\,\left(\frac{E}{100\,\mathrm{TeV}}\right)\left(\frac{\Lambda}{M_P}\right)^{-1} I_1(z)$$

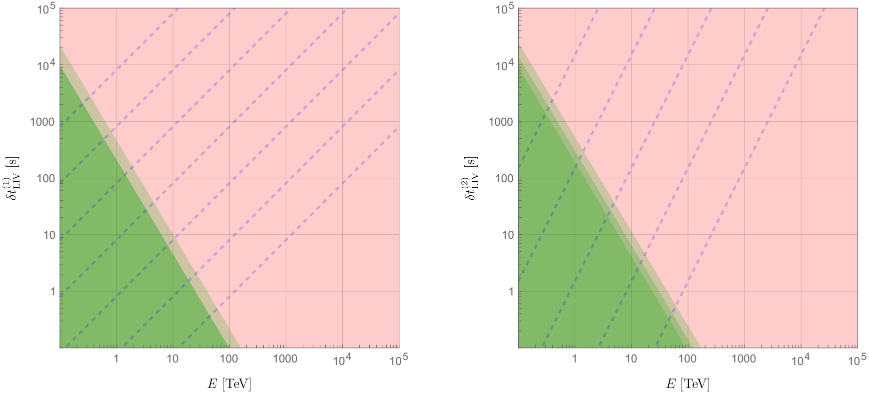
$n = 2$ $$\delta t_{\mathrm{LIV}}^{(2)} \approx \pm 8.89 \times 10^{-11}\,\mathrm{s}\,\left(\frac{E}{100\,\mathrm{TeV}}\right)^2\left(\frac{\Lambda}{M_P}\right)^{-2} I_2(z)$$

where

$$I_n(z) = \int_0^z dz' \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$

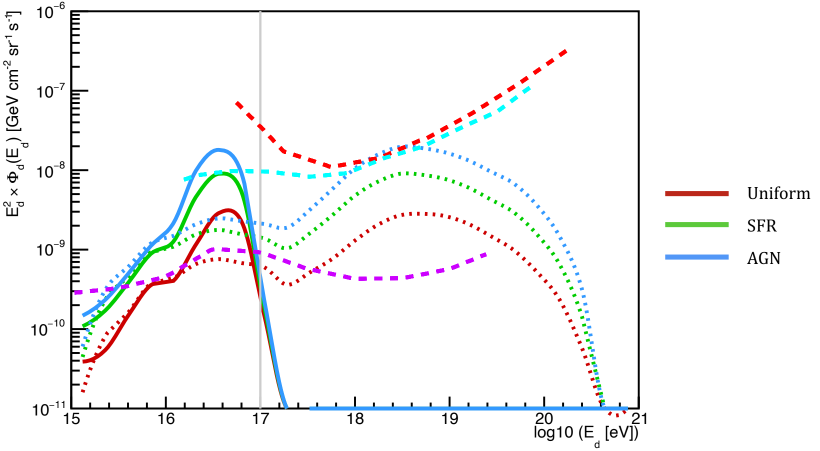
Time delays studies are incomplete!

The observation of superluminal neutrinos is **correlated** with their possible time delays with respect to photons



Allowed (green) and excluded (red) regions for superluminal neutrino events, for $n = 1$ (left) and $n = 2$ (right), and from the lightest to the darker green, for $z = 0.1$, 1 and 3.
Dashed blue lines show points with constant Λ (from top-left to bottom-right: $\log_{10}(\Lambda/M_P) = -2, -1, 0, 1, 2, 3$ and 4).

Cosmogenic neutrinos could be nearer than we thought!



Cosmogenic neutrino flux at Earth for $n = 2$, $\Lambda/M_P = 2.19$ and for different models for the production of the UHECR, and the 90% CL upper limits of IceCube (cyan), Auger (red), and IceCube-Gen2 (purple)

[Reyes, Boncioli, Carmona, Cortés, PoS(ICRC2023)]

LIV in photons

Modified dispersion relation for photons:

$$E^2 - \vec{k}^2 = E^2 \sum_{n=1}^{\infty} S_n \left(\frac{E}{E_{\mathrm{LIV},n}} \right)^n \qquad S_n = \pm 1 \;\; \textit{(+ SuL ; − SubL)}$$

- $n = 1$

Birefringence:	$E_{\mathrm{LIV},1} \gg E_{\mathrm{Pl}}$
SuL, photon decay:	$E_{\mathrm{LIV},1} \gtrsim 10^3 E_{\mathrm{Pl}}$
Time delays:	$E_{\mathrm{LIV},1} \gtrsim E_{\mathrm{Pl}}$

- $n = 2$

SuL, photon decay:	$E_{\mathrm{LIV},2} \gtrsim 10^{-4} E_{\mathrm{Pl}}$
Time delays:	$E_{\mathrm{LIV},2} \gtrsim 10^{-8} E_{\mathrm{Pl}}$
SubL, Univ transparency:	$E_{\mathrm{LIV},2} \gtrsim 10^{-7} E_{\mathrm{Pl}}$

The $n = 2$ subluminal case offers two complementary phenomenological windows

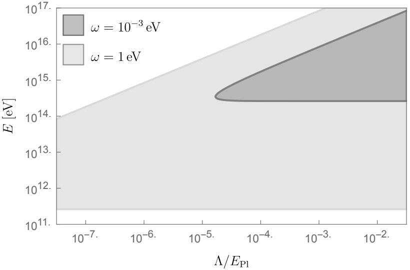
Transparency studies of the Universe underestimate LIV!

Pair creation: $\gamma_{\text{VHE}}(k) + \gamma_{\text{soft}}(q) \to e^-(p_-) + e^+(p_+)$

- Threshold in SR: $\bar{s} \equiv \dfrac{2E\omega(1-\cos\theta)}{4m_e^2} \geqslant 1$

A subluminal LIV for the photon increases the transparency of the Universe to VHE gamma rays

- Modified photon dispersion relation: $E^2 - \vec{k}^2 = -\dfrac{E^4}{\Lambda^2}$
- New threshold condition: $\bar{\tau} \equiv \bar{s} - \bar{\mu} \geqslant 1$, where $\bar{\mu} = \dfrac{E^4}{4m_e^2\Lambda^2}$



Transparency studies of the Universe underestimate LIV!

SR: $\sigma_{SR}(E, \omega, \theta) = \frac{1}{\mathcal{K}(\overline{s})} \mathcal{F}_{BW}(\overline{s}) \quad \mathcal{K}(\overline{s}) = 8 m_e^2 \overline{s}$

$$\mathcal{F}_{BW}(\overline{s}) = 4\pi\alpha^2 \left[\left(2 + \frac{2}{\overline{s}} - \frac{1}{\overline{s}^2}\right) \ln\left(\frac{1+\sqrt{1-1/\overline{s}}}{1-\sqrt{1-1/\overline{s}}}\right) - \left(2 + \frac{2}{\overline{s}}\right)\sqrt{1-1/\overline{s}} \right]$$

LIV:

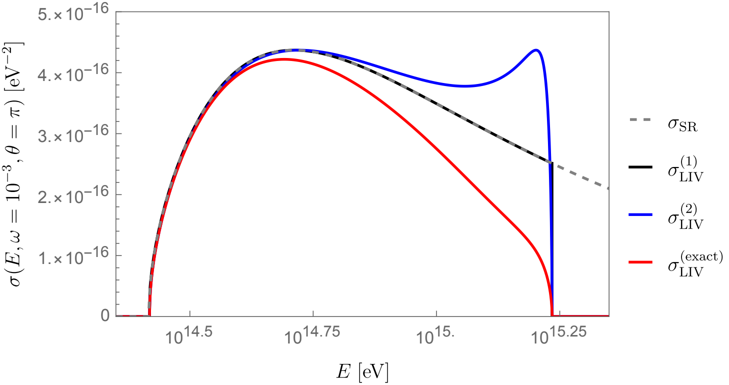
[Martínez-Huerta et al, Symmetry 2020] $\sigma_{LIV}^{(1)} \approx \sigma_{SR}(\overline{s})$

[Tavecchio, Bonnoli, A&A 2016] $\sigma_{LIV}^{(2)} \approx \sigma_{SR}(\overline{\tau})\,, \quad \overline{\tau} \equiv \overline{s} - \overline{\mu}$

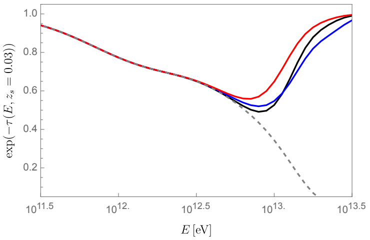
[New calculation] $\sigma_{LIV}^{(exact)} = \frac{1}{\mathcal{K}(\overline{s})} \mathcal{F}_{LIV}(\overline{\tau}, \overline{\mu})$

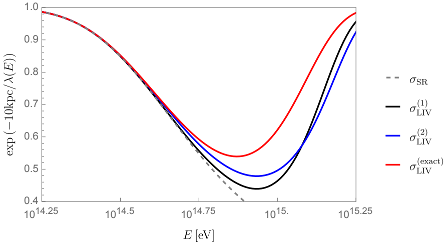
$$\mathcal{F}_{LIV}(\overline{\tau}, \overline{\mu}) = 4\pi\alpha^2 \left[\left(2 + \frac{2\overline{\tau}(1-2\overline{\mu})}{(\overline{\tau}+\overline{\mu})^2} - \frac{(1-\overline{\mu})}{(\overline{\tau}+\overline{\mu})^2}\right) \times \ln\left(\frac{1+\sqrt{1-1/\overline{\tau}}}{1-\sqrt{1-1/\overline{\tau}}}\right) - \left(2 + \frac{2\overline{\tau}(1-4\overline{\mu})}{(\overline{\tau}+\overline{\mu})^2}\right)\sqrt{1-1/\overline{\tau}} \right]$$

Transparency studies of the Universe underestimate LIV!



Transparency studies of the Universe underestimate LIV!





$z = 0.03$		
ε	30%	50%
$\Lambda^{(2)}/E_{\mathrm{Pl}}$	$1.6 \cdot 10^{-8}$	$1.1 \cdot 10^{-8}$
$\Lambda^{(\mathrm{expl.})}/E_{\mathrm{Pl}}$	$2.0 \cdot 10^{-8}$	$1.5 \cdot 10^{-8}$

$d = 10\,\mathrm{kpc}$		
ε	30%	50%
$\Lambda^{(2)}/E_{\mathrm{Pl}}$	$1.3 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
$\Lambda^{(\mathrm{expl.})}/E_{\mathrm{Pl}}$	$1.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$

- The use of the standard approximation produces a $\sim 25\%$ underestimate in the bounds on the LIV scale with respect to the explicit calculation

Conclusions: Have we observed LIV in cosmic messengers?

- **High-energy astrophysics** has the potential to reveal experimental signatures of a **QG theory:** tiny effects in the interaction and propagation of the cosmic messengers may show up in observations thanks to the **amplification** offered by time delays or by threshold anomalies
- A number of *'anomalies'* could be *'explained'* by invoking LIV effects. However, LIV analyses need to be performed in a **consistent** way
- Better sensitivity to these effects requires specific improvements in the **instrumental capabilities** with respect to
  - *Energy and angular resolution* (correlation between messengers and source identification)
  - *Rejection properties* (sensitivity to low fluxes)
  - *Flavour and particle-antiparticle* determination for astrophysical neutrinos
  - Discrimination power on the *mass composition* for UHECRs

What's next?

- A **new generation** of instruments in the near future (CTA, LHAASO, KM3NeT, IceCubeGen-2, Askaryan detectors, LIGO and other GW detector upgrades) will deepen in the *new astrophysical windows* recently opened and improve the *sensitivity to the fluxes* of the cosmic messengers in their highest energy ranges
- These experimental advancements will have to be accompanied by **theoretical developments** in the *astrophysical modelling*, in the *methods of analysis* (such as a proper combination of samples corresponding to sources of different redshifts), in the *simulation codes* that model the propagation of messengers and the development of showers in the atmosphere to include QG effects, as well as in a *complete and consistent* formulation of the phenomenological consequences of *LIV* models
- **QGMM network site:** https://sites.google.com/view/qgmm

Thank you for your attention