Snowmass2021 - Letter of Interest

Exploring Beyond-the-Standard-Model Physics using High-Energy Gamma Rays in Search of Signatures of Lorentz Invariance Violation[*]

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: Lorentz invariance may be violated at energies near the Planck scale in theories of quantum gravity and string theory. However, features of these processes can be revealed at lower, TeV-scale energies when looked at over cosmological distances. Superluminal violations of Lorentz invariance, for example, allow for the spontaneous decay of multi-TeV photons. To search for these violations requires an observatory that can view as many of the highest-energy astrophysical sources as possible to the highest energies, such as the Southern Wide-field Gamma-ray Observatory (SWGO).

[*]This Letter contains excerpts and material from White Papers submitted for the Astro2020 Decadal Survey [1;2]

Precise measurements of very-high-energy photons can be used as a test of the Lorentz symmetry[3–11]. As with any other fundamental principle, exploring its limits of validity has been an important motivation for theoretical and experimental research. Moreover, some Lorentz invariance violation (LIV) can be motivated as a possible consequence of theories beyond the Standard Model, such as quantum gravity phenomenology or string theory[12–21].

It has been shown that LIV can cause photons of sufficient energy to become unstable and decay rapidly[22]. This strongly restricts the propagation of photons to very short distances from the source, with the photons decaying well before the can arrive at Earth. LIV is usually parameterized as an isotropic correction to the photon dispersion relation:

$$E_\gamma^2 - p_\gamma^2 = \pm \frac{E_\gamma^{n+2}}{(E_{LIV}^{(n)})^n} \quad , \tag{1}$$

where $E_{\rm LIV}^{(n)}$ is the Lorentz invariance violation energy scale at leading order n. Superluminal effects in Eq. (1) allow photon decay, $\gamma \to e^- e^+$, above a certain energy threshold, such that no photons above that threshold should reach the Earth from astrophysical distances. Hence, a direct limit to $E_{\rm LIV}^{(n)}$ can be established by the observation of high-energy photons with energy E_γ, given by

$$E_{\rm LIV}^{(n)} > E_\gamma \left[\frac{E_\gamma^2 - 4m_{e^-}^2}{4m_{e^-}^2} \right]^{1/n} \quad . \tag{2}$$

The High-Altitude Water Cherenkov (HAWC) Observatory has recently published a catalog of high-energy gamma-ray sources, with four observed above 100 TeV[23] (shown in Figure 1). These observations have pushed the limits on LIV processes by orders of magnitude over earlier studies of the Crab nebula and gamma-ray bursts[24]. To push these observations further requires an observatory of similar design to HAWC— with a high energy threshold and large field-of-view to observe many potential high-energy sources. The highest-energy objects in the HAWC study have relatively large angular extent[23], which also argues for a wide field-of-view. As high-energy sources are typically Galactic sources, an ideal search location would be in the Southern Hemisphere, where the Galactic center and inner Galactic plane are located. The planned Southern Wide-field Gamma-ray Observatory (SWGO) meets all these criteria[25;26]. For a concrete example, the promising RX J1713.7-3946 source observed by H.E.S.S.[27] is shown in Figure 1 with the SWGO sensitivity overlaid. With the lack of an observed cutoff in the source, SWGO should be able to see photons up to PeV energies.

Projected SWGO limits on LIV from observations of PeV photons are shown in Figure 2 (Figure based on that presented in Ref. 28), compared to the leading limits from current-generation experiments. An instrument like SWGO would be able to constrain LIV to a level more than an order of magnitude better than the current observations.

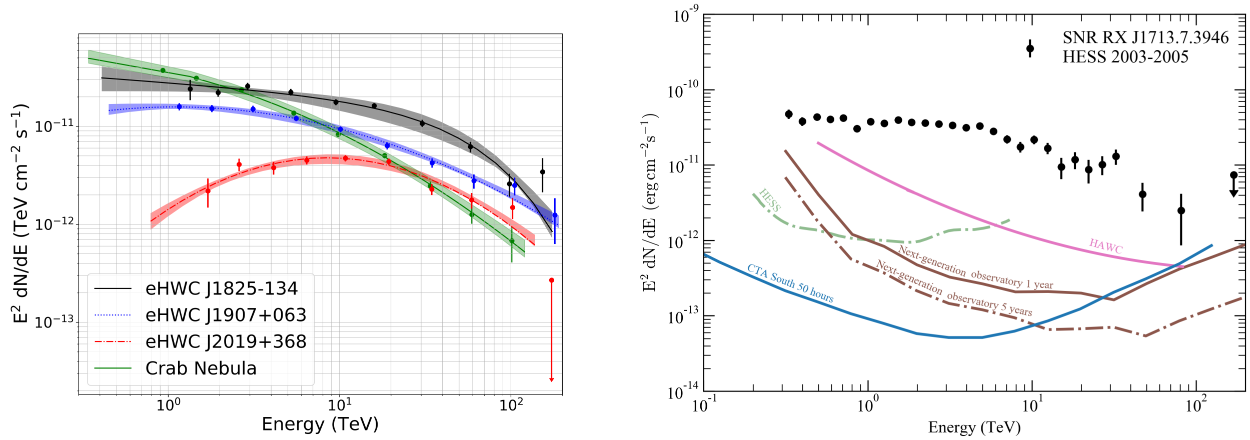

Figure 1: (Left) Current gamma-ray observations by HAWC show that many Galactic sources have spectra that extend above 100 TeV[23]. (Right) One promising source for high-energy LIV searches in the Southern Hemisphere, RXJ1713.7-3946, observed by H.E.S.S.[27], overlaid with the differential sensitivity threshold of H.E.S.S. and HAWC experiments and the estimated thresholds of CTA and the next-generation SWGO at 1 and 5 years. Galactic sources like this supernova remnant are more readily found in a Southern Hemisphere sky, where the Galactic Center passes overhead.

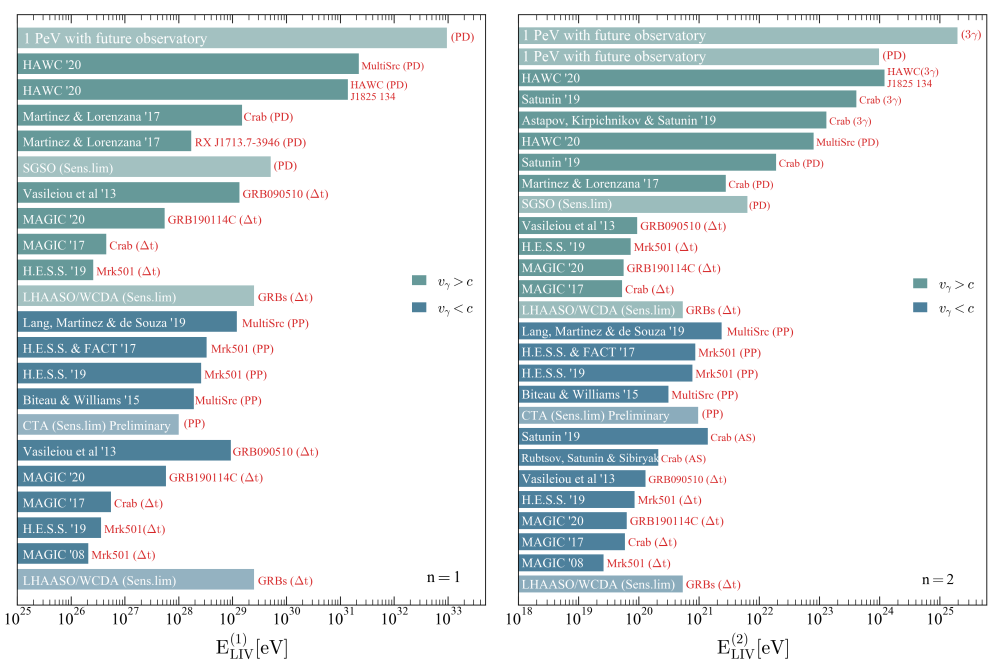

Figure 2: The strongest $E^{(1,2)}_{\rm LIV}$ limits from LIV searches, in the photon sector with astroparticle tests of energy-dependent time delays (Δt), pair-production threshold shifts (PP), photon decay into electron-positron pairs (PD), photon splitting (3γ), and suppression of air-shower formation (AS) (from bottom to top, Refs. 3–7;9;10;24–26;29–35). The leading limits from HAWC are based on constraining photons above 250 TeV in Galactic sources, as considered in Ref.[24]. If SWGO were able to improve the photon constraints from such sources to PeV energies, these limits would be further improved by orders of magnitude (shown in light green at the top of both panels).

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