Snowmass2021 - Letter of Interest

Constraining Lorentz Invariance Violation using All-Sky Time-Domain Astrophysics with Very-High-Energy Gamma Rays[*]

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: The rise of time-domain astrophysics at TeV energies is an unprecedented opportunity to study transient phenomena at the highest energies. This provides a window to probe models of Lorentz Invariance Violation in previously unexplored parameter spaces. The Southern Wide-field Gamma-ray Observatory (SWGO), a TeV observatory with sensitivity above the 100 GeV range, allows for all-sky coverage of the brightest gamma-ray bursts (GRBs) reaching Earth, and provides the chance to detect the highest-energy photons GRBs produce. This allows us to test photon dispersion relations at TeV energies, something previously unexplored, and requiring transient observations with short durations, at long distances, and measured to high energies— such as pulsars or GRBs.

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[*] 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 or string theory[12–21].

Recent studies have used high-energy photons from steady astrophysical sources to constrain LIV[22;23]. However, observation of astrophysical transients can also give competitive limits to LIV processes, without the assumption of superluminal LIV processes as is needed for the photon decay-based constraints. LIV is usually parameterized as an isotropic correction to the photon dispersion relation[24]:

$$E^2 = p^2c^2\left[1 \pm \left(\frac{pc}{E_{\mathrm{LIV}}^{(n)}}\right)^n\right] \ , \tag{1}$$

where $E_{\mathrm{LIV}}^{(n)}$ is the LIV energy scale at leading order n. In most theories, the leading order is either 1 (linear) or 2 (quadratic). This leads to photon propagation speed of

$$v = \frac{dE}{dp} \approx c\left[1 \pm \frac{n+1}{2}\left(\frac{pc}{E_{\mathrm{LIV}}^{(n)}}\right)^n\right] + \mathcal{O}\left(\left(\frac{pc}{E_{\mathrm{LIV}}^{(n)}}\right)^{2n}\right) \ . \tag{2}$$

Because the speed of photons is no longer constant with energy, photons emitted simultaneously will arrive at the observer spread over a time Δt, which depends on the energy of the photons produced and the distance to the source. For Galactic sources such as pulsars, this leads to a time delay between photons of

$$\Delta t = D\frac{n+1}{2c}\frac{(E_{\mathrm{max}}^n - E_{\mathrm{min}}^n)}{\left(E_{\mathrm{LIV}}^{(n)}\right)^n} \approx D\frac{n+1}{2c}\frac{E_{\mathrm{max}}^n}{\left(E_{\mathrm{LIV}}^{(n)}\right)^n} \ , \tag{3}$$

where D is the distance to the source and E_{max} and E_{min} are the maximum and minimum energy of the observation, respectively. For objects at cosmological distances, one must account for the redshift-dependent distance, but also the redshift of the photons traveling from the source. This yields a time delay:[25]

$$\Delta t \approx \frac{n+1}{2H_0}\frac{E_{\mathrm{max}}^n}{\left(E_{\mathrm{LIV}}^{(n)}\right)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_\Lambda + \Omega_M(1+z')^3}}dz' \ , \tag{4}$$

where Ω_Λ is the dark energy density, Ω_M is the matter density, and H_0 is the Hubble parameter.

To get strong limits on LIV, you must have observations with short durations, at long distances, and measured to high energies. Two main source classes considered for such constraints are pulsars (which have short distances but extremely short durations) and gamma-ray bursts (GRBs) (which have fairly short durations and occur at extremely long distances).

An ideal observatory to search for these transient sources is the Southern Wide-field Gamma-ray Observatory (SWGO)[26–28]. SWGO is planned to be located in the Southern Hemisphere, with an order-of-magnitude better sensitivity than the current High-Altitude Water Cherenkov (HAWC) Observatory[29]. SWGO will build on the HAWC water Cherenkov design in order to have a wide field-of-view, which will observe $\sim 2/3$ of the sky every day with a near-100% duty cycle. Additionally, the near-continuous duty cycle of this detector design makes it ideal for searches both for rare, isotropically distributed sources, like GRBs, and steady pulsing sources that require long observation time, like pulsars. The SWGO design also

Source	Experiment	$E_{\rm LIV}^{(1)}$ Limit[*]	$E_{\rm LIV}^{(2)}$ Limit[*]	Distance	Δt	$E_{\rm max}$
GRB090510	*Fermi*-LAT[10]	$9.1 \cdot 10^{19}$	$1.3 \cdot 10^{11}$	$z = 0.903$	combined methods	
Crab Nebula	Tibet[23]	–	$4.1 \cdot 10^{14}$	2 kpc	energy methods†	
Multi-source	HAWC[22]	$2.2 \cdot 10^{22}$	$1.2 \cdot 10^{15}$	1.8–2.4 kpc	energy methods†	
SWGO Pulsar	SWGO	$2.0 \cdot 10^{18}$	$1.8 \cdot 10^{11}$	2 kpc	1 ms	10 TeV
SWGO GRB	SWGO	$6.2 \cdot 10^{21}$	$3.5 \cdot 10^{12}$	$z = 0.25$	10 ms	1 TeV

Table 1: Compilation of the most stringent results on LIV published and the potential of the SWGO observatory, based on the reference scenarios described above.

[*] Limits are given in GeV

[†] Numbers for energy methods are for superluminal LIV only

will have the best sensitivity to multi-TeV photons in the Southern Hemisphere, giving it a long lever-arm on $E_{\rm max}$ with which to constrain LIV.

One feature that is common amongst pulsars (especially millisecond pulsars) and GRBs are fine temporal features in their emission. This is key to associating photons with each other and determining the Δt over which we consider the photons to be dispersed. Since photons become rarer (due to their power-law distribution) at higher energies, it becomes harder to identify the photons as being associated in time, this means that the detection of emission with high temporal accuracy at the lowest energies available (e.g. from satellite detection) can become key to associating a high-energy photon with a particular temporal feature in a pulsar pulse, or within a fast-rise-exponential-decay pulse in a GRB. This could constrain the time lag between photos to better than 1 ms from a GRB[30]. With these sorts of features, even a handful of TeV gamma rays seen from a GRB at a redshift of 0.25 would would be competitive with limits based on photon decay (See Table 1). Similarly, in pulsars, it is possible that SWGO will see features on millisecond timescales with its good sensitivity to >10 TeV photons[31].

Leveraging transient astrophysical phenomena to constrain small effects like those of LIV requires an observatory that can look across the sky to monitor repeating sources and search for rare events. High-energy reach is also needed to view these sources to the highest energies possible. SWGO, with its wide field-of-view, near-continuous duty cycle, and unprecedented high-energy sensitivity, is the ideal tool for this search.

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