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Lorentz Invariance Violation with Absorption of Astrophysical Gamma-rays by Solar Photons

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Introduction

Astrophysical γ-rays can annihilate into an electron and positron pair when they collide with solar photons ($\gamma + \gamma \rightarrow e^- + e^+$), resulting in an environment with increased opacity.

Lorentz Invariance Violation (LIV) is consistent with various models beyond the Standard Model, such as string theory, brane worlds, and loop quantum gravity. LIV can lead to two observable effects:

1. The speed of light is no longer constant at high energies.
2. Cross section modification of $\gamma\gamma$ interaction shown above.

In the presence of LIV, the normal relativistic dispersion relation for photons is modified from Eq. 1 to 2.

$$E^2 - p^2c^2 = 0 \tag{1}$$

$$E^2 - p^2c^2 = \pm E^2 \left(\frac{E}{E_{\rm LIV}} \right)^n \tag{2}$$

$E_{\rm LIV} = E_{\rm Planck} = 1.2 \times 10^{28}$ eV is the energy scale, n is an integer (the order of the leading correction), and "$+$" represents superluminal LIV, and "$-$" represents subluminal LIV.

Background

Preliminary calculations for the γ-ray absorption through solar photons were made by Balaji (2023); Loeb (2022) but these did not include LIV modifications.

LIV can lead to a number of potentially observable effects, including various astrophysical observables:

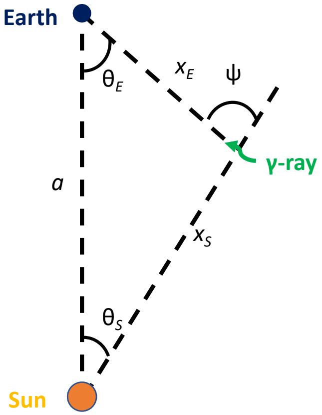
- Time-of-flight experiments with astrophysical γ-ray transients (e.g., Abdo et al., 2009; Ellis et al., 2019; Vasileiou et al., 2013).
- The lack of photon decay in Galactic γ-ray sources measured with HAWC (Albert et al., 2020).
- Modification of the threshold for pair production from photon-photon interactions. γ-rays from extragalactic sources, can be absorbed by photons from the extragalactic background light (EBL) (Abdo et al., 2009; Vasileiou et al., 2013).
- Extinction of photons from extragalactic γ sources from the sun by the pair production from photon-photon interactions.

Formalism

The $\gamma\gamma$ optical depth will be a function of the optical cross section ($\sigma_{\gamma\gamma}$), angle of interactions (θ_E, θ_S), distance of interactions (x_S, x_E) and the photon density of the photon field ($n(\varepsilon, \Omega)$).

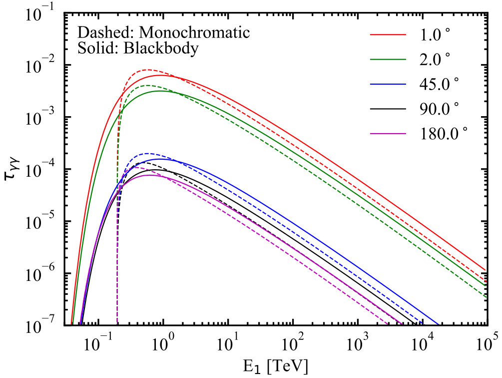
The photon density will be much greater near the Sun due to the number of Solar photons. Therefore, the probability photon-photon interaction will also be greater near the Sun. $\theta_E = 0^\circ$ is defined as facing directly towards the Sun, so smaller θ_E will result in a greater optical depth.

We can approximate the Sun either as a monochromatic or a blackbody source.



Geometry of solar system and γ-ray heading towards Earth. Distances and angles are labeled.

Monochromatic and Blackbody; Optical Depth vs. γ-ray Energy



Absorption optical depth for astrophysical γ-rays interacting with solar photons as a function of γ-ray energy, E_1, at different angular distances from the Sun (θ_E) as indicated by the legend. We show the monochromatic approximation (dashed curves) and blackbody approximation (Equation [solid curves).

Lorentz Invariance Violation

Subluminal LIV can modify the threshold for the $\gamma\gamma$ absorption cross section, leading to an increase or decrease in $\tau_{\gamma\gamma}$ compared to the case without LIV. There are (at least) two ways of implementing this used in the literature, that of Jacob & Piran (2008) and Fairbairn et al. (2014). The two formulations provide varying results.

We will use the blackbody approximation of the Sun from now on as it is more accurate. Using the Jacob & Piran (2008) approach, LIV modifies the $\gamma\gamma$ absorption cross section by changing the input from

$$\sigma_{\gamma\gamma}\left[\frac{\varepsilon\varepsilon_1(1-\cos\psi)}{2}\right] \tag{3}$$

to

$$\sigma_{\gamma\gamma}\left[\frac{\varepsilon\varepsilon_1(1-\cos\psi)}{2(1+0.25(\varepsilon_1/\varepsilon_{\mathrm{LIV}})^n\varepsilon_1^2)}\right] . \tag{4}$$

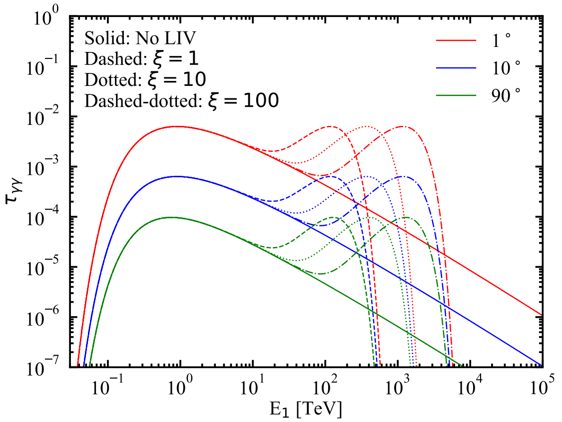
Lorentz Invariance Violation (Jacob & Piran (2008) approach); Optical Depth vs γ-ray Energy

The optical depth for the $\gamma\gamma$ interaction can be modelled for the LIV case by

$$\tau_{\gamma\gamma}(\varepsilon_1,\mu_E) = \frac{L_S}{4m_e c^3}\frac{15}{\Theta^4\pi^5}\int_0^\infty d\varepsilon \frac{\varepsilon^2}{\exp(\varepsilon/\Theta)-1} \times \int_0^\infty dx_E \frac{1-\cos\psi}{x_S^2} \times \sigma_{\gamma\gamma}\left[\frac{\varepsilon\varepsilon_1(1-\cos\psi)}{2(1+0.25(\varepsilon_1/\varepsilon_{\rm LIV})^n\varepsilon_1^2)}\right] . \quad (5)$$

We parameterize LIV using the LIV parameter, $\xi \equiv E_{\rm LIV}/E_{\rm Planck}$.

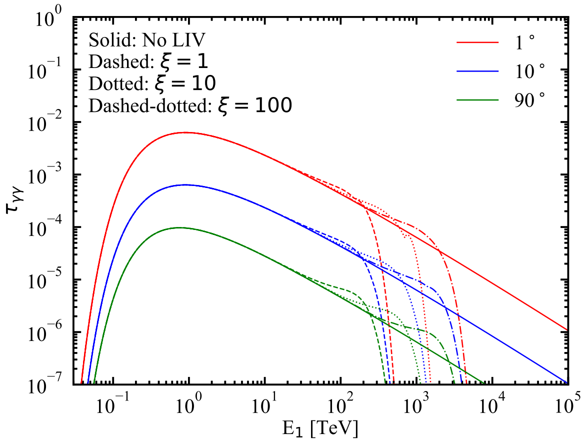
We show for the first time that subluminal LIV can cause an increase in absorption on the decreasing end of the non-LIV optical depth.



Absorption optical depth for astrophysical γ-rays interacting with solar photons as a function of γ-ray energy, E_1, at different angular distances from the Sun (θ_E) as indicated by the legend, using the blackbody approximation.

Lorentz Invariance Violation (Fairbairn et al. (2014) approach); Optical Depth vs. γ-ray Energy

$$\tau_{\gamma\gamma}(\varepsilon_1,\mu_E) = \frac{L_S}{4m_e c^3}\frac{15}{\Theta^4\pi^5}\int_0^\infty d\varepsilon \frac{\varepsilon^2}{\exp(\varepsilon/\Theta)-1} \times \int_0^\infty dx_E \frac{1-\cos\psi}{x_S^2} \times \sigma_{\gamma\gamma}\left[\frac{\varepsilon\varepsilon_1(1-\cos\psi)}{2} - \frac{(\varepsilon_1/\varepsilon_{LIV})^n\varepsilon_1^2}{4}\right] \quad (6)$$



Same as the earlier Jacob & Piran (2008) approach plot but now using Fairbairn et al. (2014) approach.

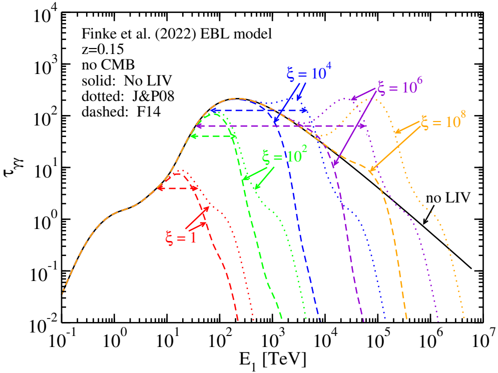
Lorentz Invariance Violation on Extragalactic Background Light Absorption

Extragalactic Background Light (EBL) is the accumulated radiation originating from diffuse extragalactic sources.

Subluminal LIV has been shown to cause a decrease in the optical depth on the increasing end of the non-LIV optical depth.

Here we show that at higher energies subluminal LIV can cause an increase during the decreasing side of non-LIV optical depth; effect seen before in the solar absorption case.

This increase is unfortunately nonphysical due to Cosmic Ray Background (CMB), which makes it difficult to observe γ-ray source above 1 PeV.



EBL absorption optical depth versus γ-ray energy for the EBL model of Finke et al. (2022) at $z = 0.15$. For the LIV curves from the Jacob & Piran (2008) formulation, the dashed lines with arrows indicate the $\tau_{\gamma\gamma}$ at lower energies where the $\tau_{\gamma\gamma}$ at higher energies are sampling, due to the LIV effect. Absorption by cosmic microwave background photons is not included in this plot.

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An Experiment for Solar Absorption I

Observations at energies greater than 10 TeV are hard to make with current observatories. So we can only make estimates regarding the non-LIV case.

These calculations in the preceding sections make potentially observable predictions for the non-LIV case. The $\gamma\gamma$ absorption is greatest at smaller angular distances from the Sun, implying that that one would need to search for this effect while an astrophysical source is near the Sun. Atmospheric Cherenkov telescopes cannot observe the sun so we have to rely on Water Cherenkov Observatories.

We searched the TevCat (`http://tevcat.uchicago.edu`; Wakely & Horan (2008)) for astrophysical sources that get within 10° of the Sun. Two sources stand out as the brightest: the Crab (Aharonian et al., 2021; Cao et al., 2021a) and LHAASO J1825$-$1326 (Cao et al., 2021b). These sources will only be observable with high absorption for only 20 days in a year, which limits our measurements. We calculate the time of detection for the Crab and LHAASO J1825$-$1326 as seen by HAWC and LHAASO for a 3σ measurement at $\theta_E = 2^\circ$ and $\Omega = 10^{-3}$ srad by the table in the next slide.

We take into account the Poisson uncertainties and the signal to noise ratio at these energies, with $B \gg S$, so that $\sqrt{S+B}/S \approx \sqrt{B}/S$. **Where the background is interpreted from the Cosmic ray background in Chapter 29 of Tanabashi et al. (2018)**.

An Experiment for Solar Absorption II

Table : Detection of non-LIV absorption $\tau_{\gamma\gamma}$ at 1 TeV by VHE γ-ray instruments.

	Crab	LHAASO J1825−1326
Φ_S [cm^{-2} (S) $^{-1}$]	4×10^{-11}	1.5×10^{-11}
Φ_{CR} [cm^{-2} (S) $^{-1}$ srad^{-1}]	1.4×10^{-5}	1.4×10^{-5}
$\tau_{\gamma\gamma}(\theta_E = 2^\circ)$	3×10^{-3}	3×10^{-3}
HAWC f_r	6×10^{-3}	6×10^{-3}
HAWC A_{eff} [km^2]	0.02	0.02
HAWC Δt [year]	560	4000
LHAASO f_r	2×10^{-3}	2×10^{-3}
LHAASO A_{eff} [km^2]	0.1	0.1
LHAASO Δt [year]	37	260

An Experiment for Solar Absorption III

We also searched the *Fermi*-LAT Third Hard Source Catalog (Ajello et al., 2017) for sources that get within 10 degrees of the Sun. 253 sources matched the criteria and were seperated into three energy bins, 50-150 GeV, 150-500 GeV, and 500-2000 GeV. Since the *Fermi*-LAT is a sky survey instrument, it's field of view needs to be accounted for in the time of detection as well as the smaller effective area compared to HAWC and LHAASO. We find that the timescale of this measurement through the *Fermi*-LAT is not possible during the mission's lifetime.

Table : Detection of non-LIV absorption $\tau_{\gamma\gamma}$ by *Fermi*-LAT 3FHL sources.

	50-150 GeV	150-500 GeV	500-2000 GeV
Φ_S	3.9×10^{-9}	9.9×10^{-10}	2.3×10^{-10}
$\tau_{\gamma\gamma}(\theta_E = 10^\circ)$	2.4×10^{-5}	3.8×10^{-4}	6.3×10^{-4}
$A_{\rm eff}$ [cm^2]	9000	9000	9000
Δt [year]	3×10^9	4×10^7	7×10^7

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Summary

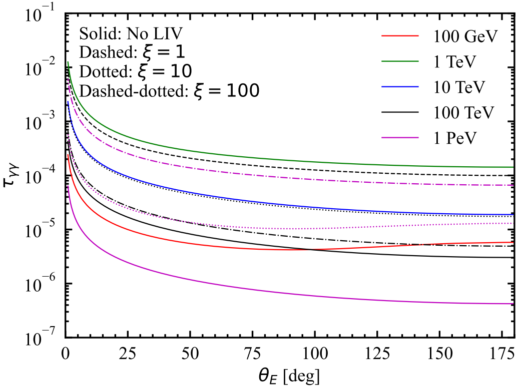
- Compared with constraints on LIV from the EBL, the main advantage to this method is the higher degree of certainty and that the absorbing photon source (the Sun) has a known spectrum that is approximated well by a blackbody. The disadvantage of using the Sun is that the absorption is much smaller than with the EBL; for solar photons, $\tau_{\gamma\gamma} \sim 10^{-2}$ at most.
- **For the first time, we show that subluminal LIV can lead to a decrease or increase in the absorption optical depth from the pair production process compared to the non-LIV case, depending on the spectrum of the absorbing photon source.**
- We show that the LIV and non-LIV effects are unlikely to be observed with water Cherenkov observatories like HAWC or LHAASO.
- As pointed out by Loeb (2022), this solar absorption effect causes the γ-ray background at $\gtrsim 100\ \mathrm{GeV}$ to have a greater anisotropy than the cosmic microwave background from the solar system's motion relative to the cosmic frame.

Check out our paper, Finke & Patel (2024) $\rightarrow$

Backup

Lorentz Invariance Violation (Jacob & Piran (2008) approach); Optical Depth vs. Angular Distances

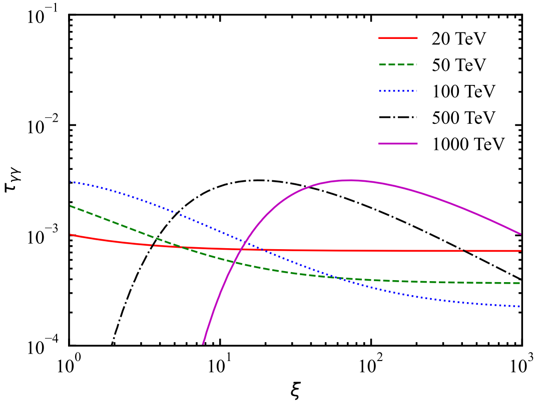
As seen from the earlier plot, the absorption optical depth for γ-rays interacting with solar photons is greatest at angular distances θ_E closest to the Sun. This optical depth also decreases with increasing θ_E with the exception of a few cases (1 PeV, $\xi = 10$ and 100 GeV, No LIV).



Absorption optical depth for astrophysical γ-rays interacting with solar photons as a function of angular distances from the Sun (θ_E), for different γ-ray energies as indicated by the legend, using the blackbody approximation. The 1 TeV curve has been scaled up by a factor of 2 and the 100 TeV $\xi = 1$ curve has been scaled up by a factor of 1.5 for clarity.

Lorentz Invariance Violation (Jacob & Piran (2008) approach); Optical Depth vs. LIV Parameter

In general, observations of photons with higher energies yield the greatest constraining power for LIV.



Absorption optical depth for astrophysical γ-rays interacting with solar photons as a function of ξ for $n = 1$ and $\theta_E = 2°$, for different γ-ray energies, E_1, as indicated by the legend, using the blackbody approximation.

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