Disentangling Lorentz symmetry breaking and deformation in photon absorption

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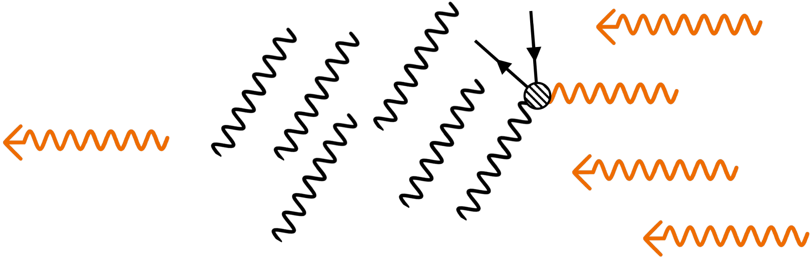
Gamma ray transparency of the universe

High-energy **gamma rays** can *disappear from the flux* as they propagate.



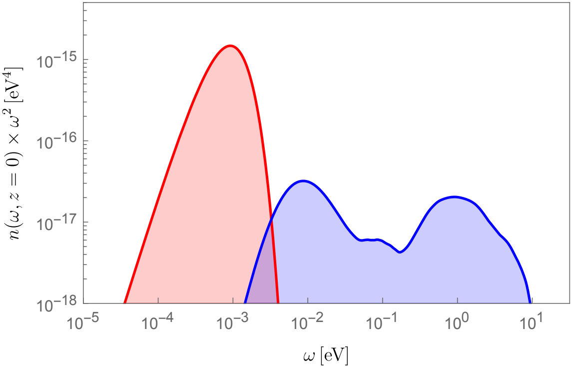
$$\mathcal{P}_{\mathrm{SV}}(E, z_s) = \frac{\Phi_d(E)}{\Phi_s((1+z_s)E)} \quad < \; 1\,. \tag{1}$$

The decrease in flux is characterized by the **opacity**,

$$\mathcal{P}_{\mathrm{SV}}(E, z_s) = \exp\big(-\tau(E, z_s)\big)\,, \tag{2}$$

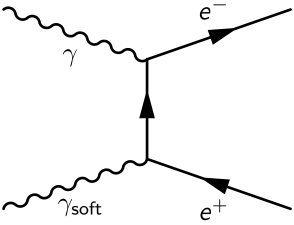
which can be computed as

$$\tau(E, z_s) = \underbrace{\int_0^{z_s} dz\,\frac{dl}{dz}}_{\text{trajectory path}} \quad \underbrace{\int_{-1}^{1} d\cos\theta\left(\frac{1-\cos\theta}{2}\right)}_{\text{angle between photons}} \underbrace{\int_{\omega_{\mathrm{th}}(E,\theta)}^{\infty} d\omega}_{\text{soft photon energy}} \quad \underbrace{n(\omega, z)}_{\text{soft photon density}} \quad \underbrace{\sigma(E(1+z), \omega, \theta)}_{\text{cross section}}\,. \tag{3}$$



Gamma rays above TeV energies can interact with the **EBL** [Saldana-Lopez:2020qzx]. For those around PeV, the **CMB** dominates.

The dominant interaction is **electron-positron pair production** (Breit-Wheeler process) with *low-energy photons* from the backgrounds.



$$\gamma(E, \vec{k}) + \gamma_{\text{soft}}(\omega, \vec{q}) \rightarrow e^-(E_-, \vec{p}_-) + e^+(E_+, \vec{p}_+) \tag{4}$$

The **cross section** is proportional to the integral of the squared amplitude, with a constant $\mathcal{K}$ that only depends on the initial *free states*,

$$\sigma \propto \underbrace{\int [d\mathcal{PS}]\,|\mathcal{A}_{\gamma\gamma\to e^- e^+}|^2}_{\doteq\,\mathcal{F}} \quad \to \quad \sigma = \frac{1}{\mathcal{K}} \times \mathcal{F}\,. \tag{5}$$

It takes non-zero values above the *threshold*,

$$\bar{s} = \frac{2E\omega(1-\cos\theta)}{4m_e^2} > 1\,. \tag{6}$$

The result of Breit and Wheeler [Breit:1934zz] shows,

$$\mathcal{K}_{\mathsf{SR}} = 8 m_e^2 \bar{s}\,, \tag{7}$$

$$\mathcal{F}_{\mathsf{SR}} = 4\pi\alpha^2 \left[\left(2 + \frac{2}{\bar{s}} - \frac{1}{\bar{s}^2}\right) \ln\left(\frac{1+\sqrt{1-\frac{1}{\bar{s}}}}{1-\sqrt{1-\frac{1}{\bar{s}}}}\right) - \left(2 + \frac{2}{\bar{s}}\right)\sqrt{1-\frac{1}{\bar{s}}}\right]. \tag{8}$$

Violation of the Lorentz invariance

When Lorentz invariance is broken, different particles can have different **modified energy-momentum relations** (MDR).

Single-particle

$$E^2 = m_\alpha^2 + \vec{p}^2 \pm \vec{p}^2 \left(\frac{|\vec{p}|}{\Lambda_\alpha}\right)^n$$

Focusing on photons,

- the linear ($n = 1$) case is highly constrained by the absence of vacuum birefringence,
- the superluminal quadratic ($n = 2$) case is dominated by photon decay.

We focus on the *subluminal quadratic case*,

$$E^2 = \vec{p}^{\,2} \left[1 - \left(\frac{|\vec{p}|}{\Lambda_{\text{LIV}}} \right)^2 \right] . \tag{9}$$

The MDR produces a **modified threshold condition**,

$$\bar{\tau}_{\mathrm{LIV}} = \underbrace{\frac{2E\omega(1-\cos\theta)}{4m_e^2}}_{\bar{s}} - \underbrace{\frac{E^4}{4m_e^2\Lambda_{\mathrm{LIV}}^2}}_{\bar{\mu}} > 1\,, \tag{10}$$

and a **modified cross section** [Carmona:2024thn],

$$\mathcal{K}_{\mathrm{LIV}} \approx \mathcal{K}_{\mathrm{SR}}\,, \tag{11}$$

$$\mathcal{F}_{\mathrm{LIV}} = 4\pi\alpha^2\left[\left(2+\frac{2\bar{\tau}(1-2\bar{\mu})}{(\bar{\tau}+\bar{\mu})^2}-\frac{(1-\bar{\mu})}{(\bar{\tau}+\bar{\mu})^2}\right)\times\ln\left(\frac{1+\sqrt{1-1/\bar{\tau}}}{1-\sqrt{1-1/\bar{\tau}}}\right)-\left(2+\frac{2\bar{\tau}(1-4\bar{\mu})}{(\bar{\tau}+\bar{\mu})^2}\right)\sqrt{1-1/\bar{\tau}}\right]. \tag{12}$$

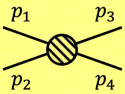
Deformation of the Lorentz invariance

In doubly special relativity, the **conservation laws are modified**, and there may be a *universal modified energy-momentum relation*.

Single-particle

$$m^2 = C(E^2, \vec{p}^2, |\vec{p}|/\Lambda)$$

Multi-particle



$$p_1 \oplus p_2 = p_3 \oplus p_4$$

Focusing on photons,

- observability of scenarios with a MDR is dominated by time delays,
- however, models without a MDR predict modified interactions even without time delays.

One example of the latter is the *classical basis* of κ-Poincaré,

$$(a \oplus b)_0 = a_0 \Pi(b) + \frac{1}{\Pi(a)} \left(b_0 + \frac{\vec{a} \cdot \vec{b}}{\Lambda_{\mathrm{DSR}}} \right) , \tag{13}$$

$$(a \oplus b)_i = a_i \Pi(b) + b_i \, , \tag{14}$$

with $\Pi(a) = \frac{a_0}{\Lambda_{\mathrm{DSR}}} + \sqrt{1 + \frac{a_0^2 - |\vec{a}|^2}{\Lambda_{\mathrm{DSR}}^2}}$.

The composition of momenta produces a **modified threshold condition**,

$$\bar{\tau}_{\text{DSR}} = \frac{2E\omega(1-\cos\theta)}{4m_e^2(1+E/\Lambda_{\text{DSR}})} > 1\,, \tag{15}$$

and a **modified cross section**[1] [Carmona:2025fdu],

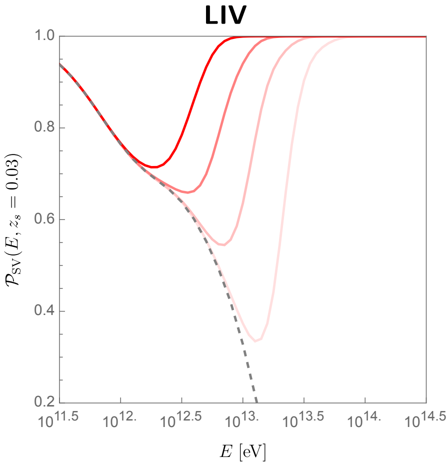
$$\mathcal{K}_{\text{DSR}} = \mathcal{K}_{\text{SR}} \tag{16}$$

$$\mathcal{F}_{\text{DSR}} \approx \mathcal{F}_{\text{SR}}(\bar{s} \to \bar{\tau}_{\text{DSR}}) \tag{17}$$

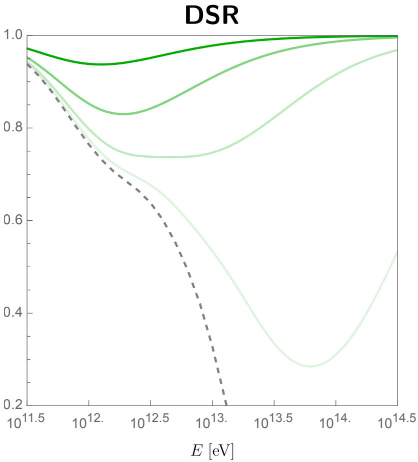
[1] note this is different from taking $\sigma_{\text{DSR}} \approx \sigma_{\text{SR}}(\bar{s} \to \bar{\tau}_{\text{DSR}})$

Comparison

Prob. survival from extragalactic source

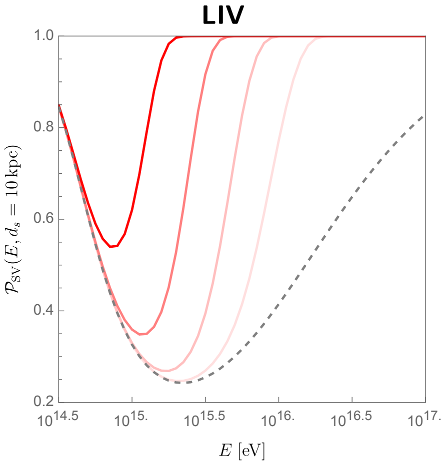


$\log_{10}(\Lambda_{\rm LIV}/\mathrm{eV}) \sim 19, 19.5, 20, 20.5$

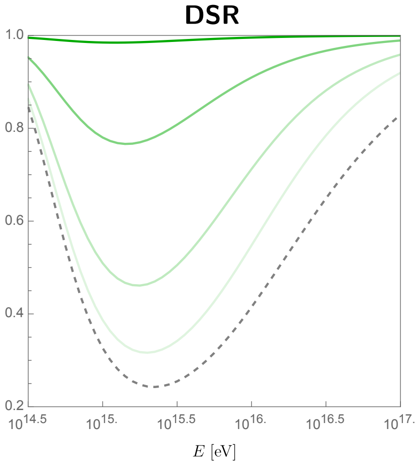


$\log_{10}(\Lambda_{\rm DSR}/\mathrm{eV}) \sim 12, 12.5, 13, 13.5$

Prob. survival from galactic source

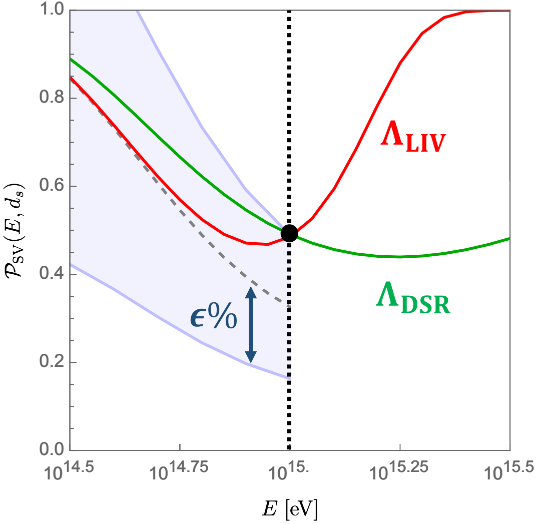


$\log_{10}(\Lambda_{\rm LIV}/{\rm eV}) \sim 22.5, 23, 23.5, 24$



$\log_{10}(\Lambda_{\rm DSR}/{\rm eV}) \sim 14.5, 15, 15.5, 16$

Bounds



1.0
0.8
0.6
0.4
0.2
0.0
$\mathcal{P}_{\rm SV}(E, d_s)$
$10^{14.5}$
$10^{14.75}$
$10^{15.}$
$10^{15.25}$
$10^{15.5}$
E [eV]
$\Lambda_{\rm LIV}$
$\Lambda_{\rm DSR}$
$\epsilon\%$

Bounds

Extragalactic ($z_s = 0.03$, $E = 10\,\mathrm{TeV}$)			
ϵ	30%	40%	50%
Λ_{LIV} [eV]	2.5×10^{20}	2.2×10^{20}	1.9×10^{20}
Λ_{DSR} [eV]	7.6×10^{13}	5.5×10^{13}	4.2×10^{13}

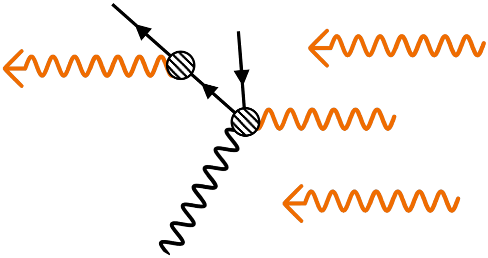
Galactic ($d_s = 10\,\mathrm{kpc}$, $E = 1\,\mathrm{PeV}$)			
ϵ	30%	40%	50%
Λ_{LIV} [eV]	2.2×10^{24}	1.9×10^{24}	1.7×10^{24}
Λ_{DSR} [eV]	6.1×10^{15}	4.5×10^{15}	3.6×10^{15}

Correlation with other interactions

In *special relativity* and *doubly special relativity*, **vacuum Cherenkov** emission is **forbidden**.

$$e^{\pm} \to e^{\pm} + \gamma \tag{18}$$

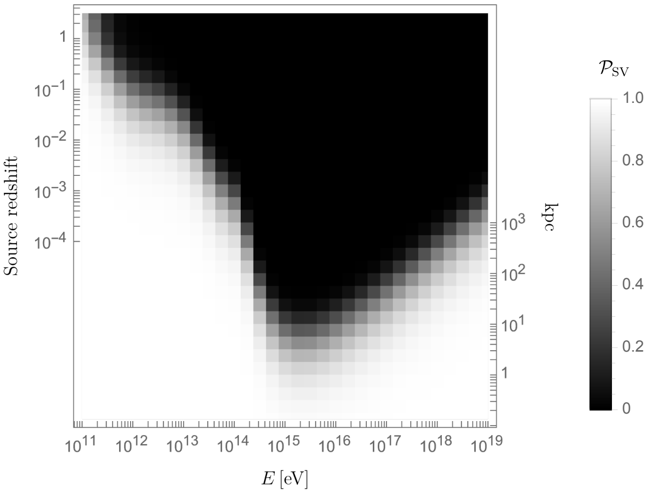
However, this effect is **allowed** if one *breaks Lorentz invariance*, which may increase the gamma-ray flux at lower energies.



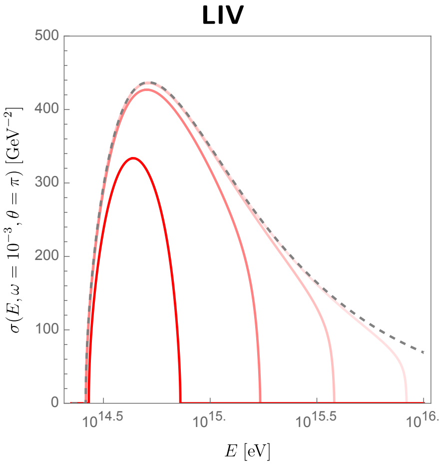
Thanks for your attention

Extra slides

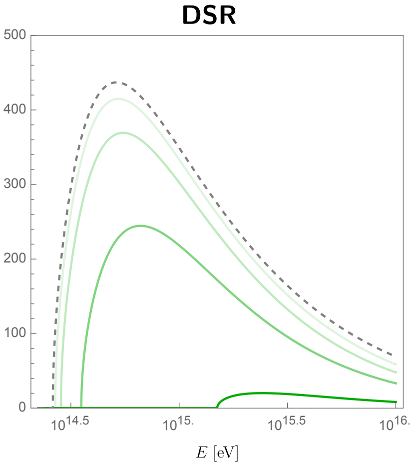
Prob. survival on SR



Cross section



$\log_{10}(\Lambda_{\text{LIV}}/\text{eV}) \sim 23.5, 24, 24.5, 25$



$\log_{10}(\Lambda_{\text{DSR}}/\text{eV}) \sim 14.5, 15, 15.5, 16$