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Study of Universe Transparency in an LIV Framework

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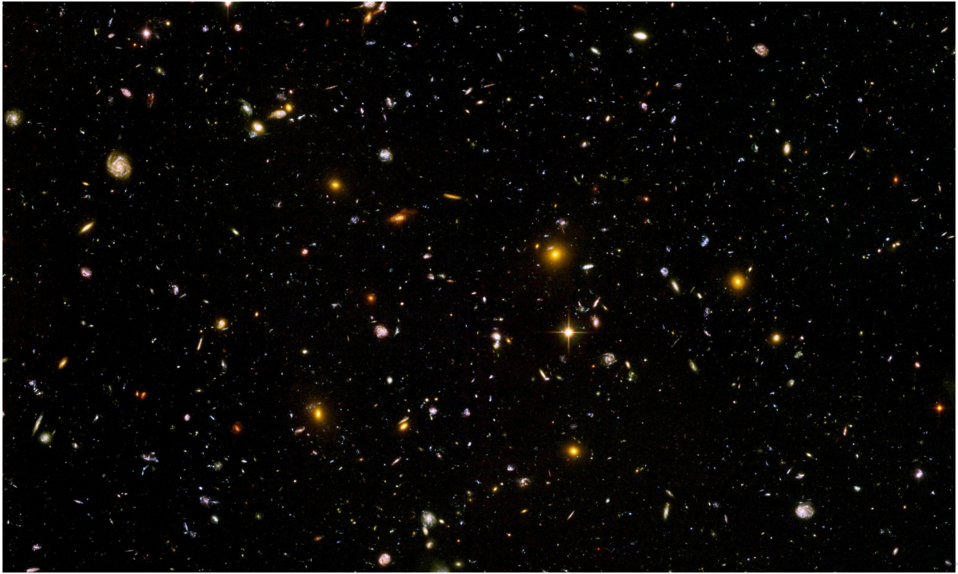
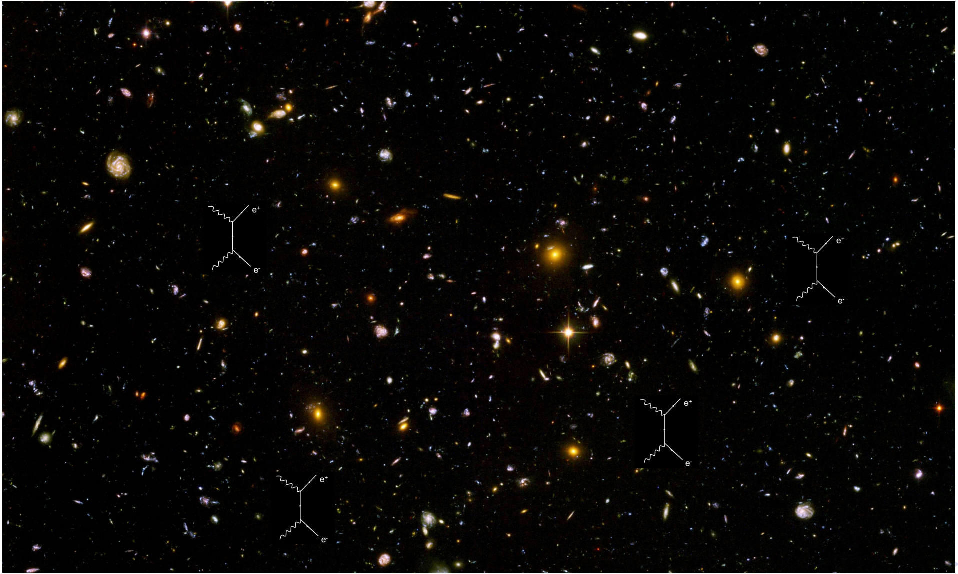
Backstory

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Motivation

[Cao Z., Aharonian F.A. et al., 2021]

Article

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

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The extension of the cosmic-ray spectrum beyond 1 petaelectronvolt (PeV; 10^{15} electronvolts) indicates the existence of the so-called PeVatrons—cosmic-ray factories that accelerate particles to PeV energies. We need to locate and identify such objects to find the origin of Galactic cosmic rays[1]. The principal signature of both electron and proton PeVatrons is ultrahigh-energy (exceeding 100 TeV) γ radiation. Evidence of the presence of a proton PeVatron has been found in the Galactic Centre, according to the detection of a hard-spectrum radiation extending to 0.04 PeV (ref. [2]). Although γ-rays with energies slightly higher than 0.1 PeV have been reported from a few objects in the Galactic plane[3–6], unbiased identification and in-depth exploration of PeVatrons requires detection of γ-rays with energies well above 0.1 PeV. Here we report the detection of more than 530 photons at energies above 100 teraelectronvolts and up to 1.4 PeV from 12 ultrahigh-energy γ-ray sources with a statistical significance greater than seven standard deviations. Despite having several potential counterparts in their proximity, including pulsar wind nebulae, supernova remnants and star-forming regions, the PeVatrons responsible for the ultrahigh-energy γ-rays have not yet been firmly localized and identified (except for the Crab Nebula), leaving open the origin of these extreme accelerators.

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Conditions:

- Invariance under rotations
- CPT and P invariance
- No dimension 5 operators ([Bolokhov, Pospelov; 2008])
- Only operators quadratic in the fields

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Lagrangian:

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\kappa\bar{\psi}\gamma^{i}D_{i}\psi + \frac{ig}{M^2}D_{j}\bar{\psi}\gamma^{i}D_{i}D^{j}\psi + \frac{\xi}{4M^2}F_{kj}\partial_{i}^{2}F^{kj}, \tag{1}$$

Modified dispersion relations

Photon:

$$E^2 = k^2 + \frac{\xi k^4}{M^2} \tag{2}$$

Fermions:

$$\begin{aligned} E_e^2 &= m^2 + p^2 \left(1 + \kappa + \frac{gp^2}{M^2}\right)^2 \\ &\approx m^2 + p^2(1 + 2\kappa) + \frac{2gp^4}{M^2} \end{aligned} \tag{3}$$

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Minimal model: $g = \kappa = 0$ [Jacobson et al; 2003]. Scale of Lorentz Violation:

$$\Lambda_{LV} \equiv \frac{M}{\sqrt{\xi}} \tag{4}$$

Two types of modifications

Kinematical:

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Dynamical:

$$\sum_{\lambda=1,2} \varepsilon_\mu^\lambda \varepsilon_\nu^\lambda = \mathrm{diag}\left(-\frac{E_\gamma^2}{k^2}, 1, 1, 1\right) \tag{6}$$

Observed flux:

$$\Phi_{\rm obs}(\rm E) = e^{(-\tau_\gamma(\rm E, z_s))} \times \Phi_{\rm int}(\rm E(1 + z_s)) \tag{7}$$

Optical depth

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For local observations (Milky Way):

$$\tau_\gamma(E,z_s) = \underbrace{\int_0^{d} dl}_{d} \underbrace{\int_{-1}^{1} d\cos\theta \frac{1-\cos(\theta)}{2} \int_{\varepsilon_{\rm thr}(E,\theta)}^{\infty} d\varepsilon n_\gamma(\varepsilon)\sigma_{\gamma\gamma}(E,\varepsilon,\theta)}_{\frac{1}{\lambda_\gamma}} \tag{9}$$

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$$\Rightarrow \tau_\gamma \approx \frac{d}{\lambda_\gamma} \tag{10}$$

Pair production:

$$\gamma_{\mathrm{VHE}} + \gamma_{\mathrm{soft}} \rightarrow \mathrm{e}^{-} + \mathrm{e}^{+} \tag{11}$$

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Consequences of modifications:

- Threshold condition

$$\mathrm{E}\varepsilon(1 - \cos\theta) - \frac{\mathrm{E}^4}{2\Lambda_{\mathrm{LV}}^2} = 2\mathrm{m}^2 \tag{12}$$

Cross section calculation

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- Due to $\mathrm{g}_{\mu\nu} \rightarrow \mathrm{g}_{\mu\nu} + \mathrm{diag}(\mathrm{E}_\gamma^2/\Lambda_{\mathrm{LV}}^2, 0, 0, 0)$ we have

$$\langle|\mathrm{M}_{\mathrm{TOT}}|^2\rangle = \langle|\mathrm{M}_{\mathrm{QED},\Lambda}|^2\rangle + \langle|\mathrm{M}_{\mathrm{MOD}}|^2\rangle \tag{13}$$

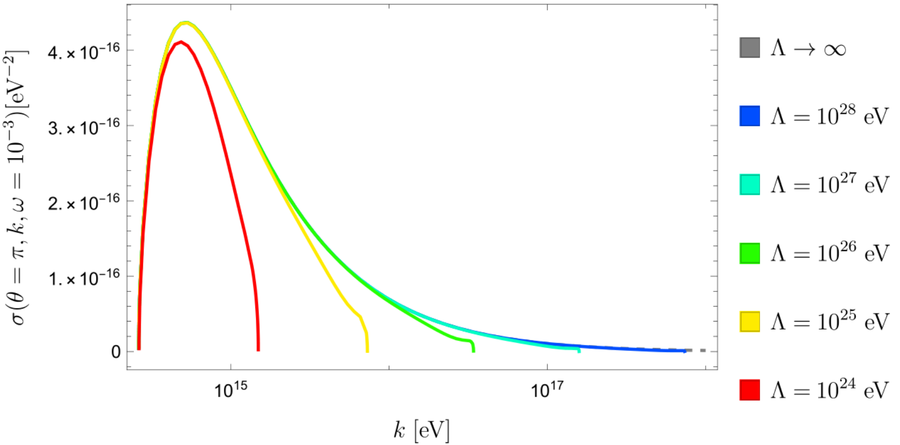
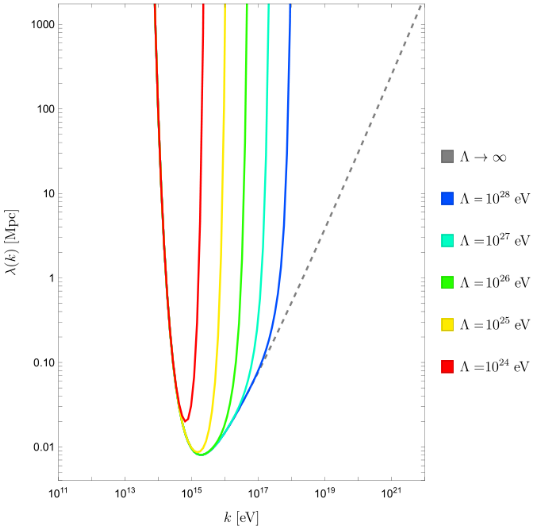
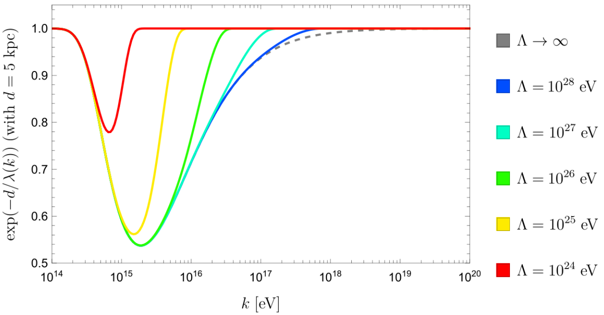


Figure 1: Cross section for the subluminal case with $\omega = 10^{-3}$ eV , $\theta = \pi$.

Mean free path





Take-home message:

- Both kinematical and dynamical modifications play a role

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- Understand uncertainties introduced by choosing different backgrounds
- Connect to current experimental observations
- Study the transparency in a Doubly Special Relativity (DSR) framework

References

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