Lorentz Invariance Violation in astroparticle physics

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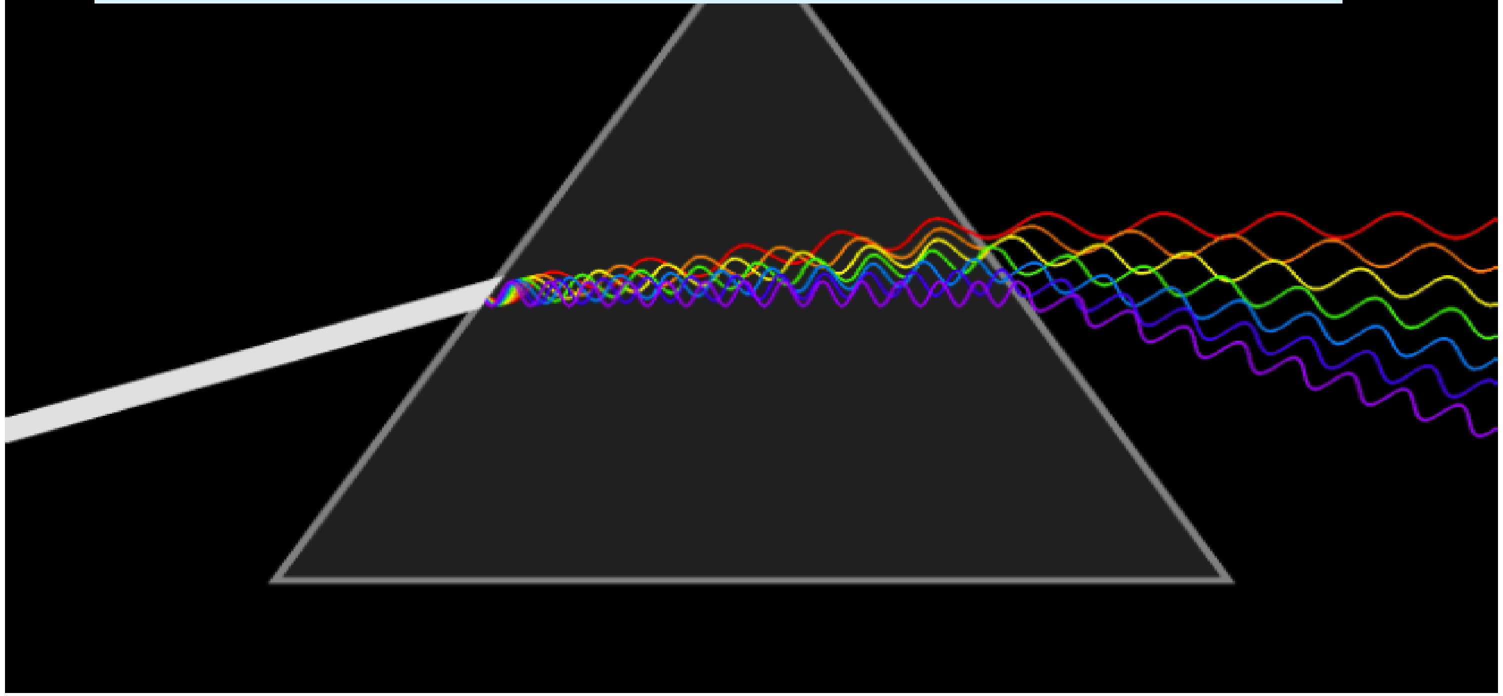
Introduction:

The **speed of light** in a **refractive medium** depends on its **wavelength**.

Refractive index is the ratio of speed of light in vacuum to the speed of light in matter $n \equiv c / v_p$

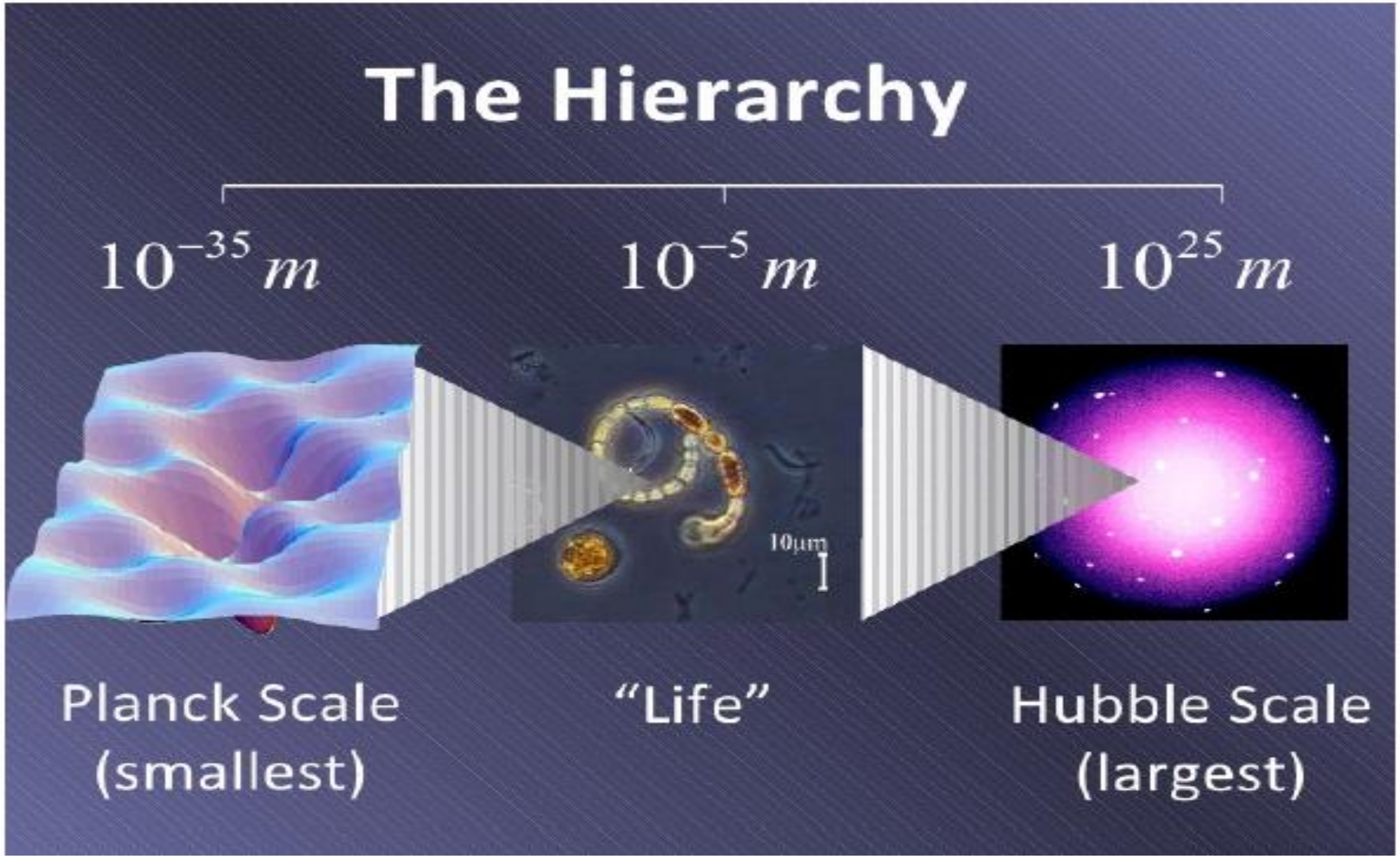


Credit: Lucas V. Barbosa

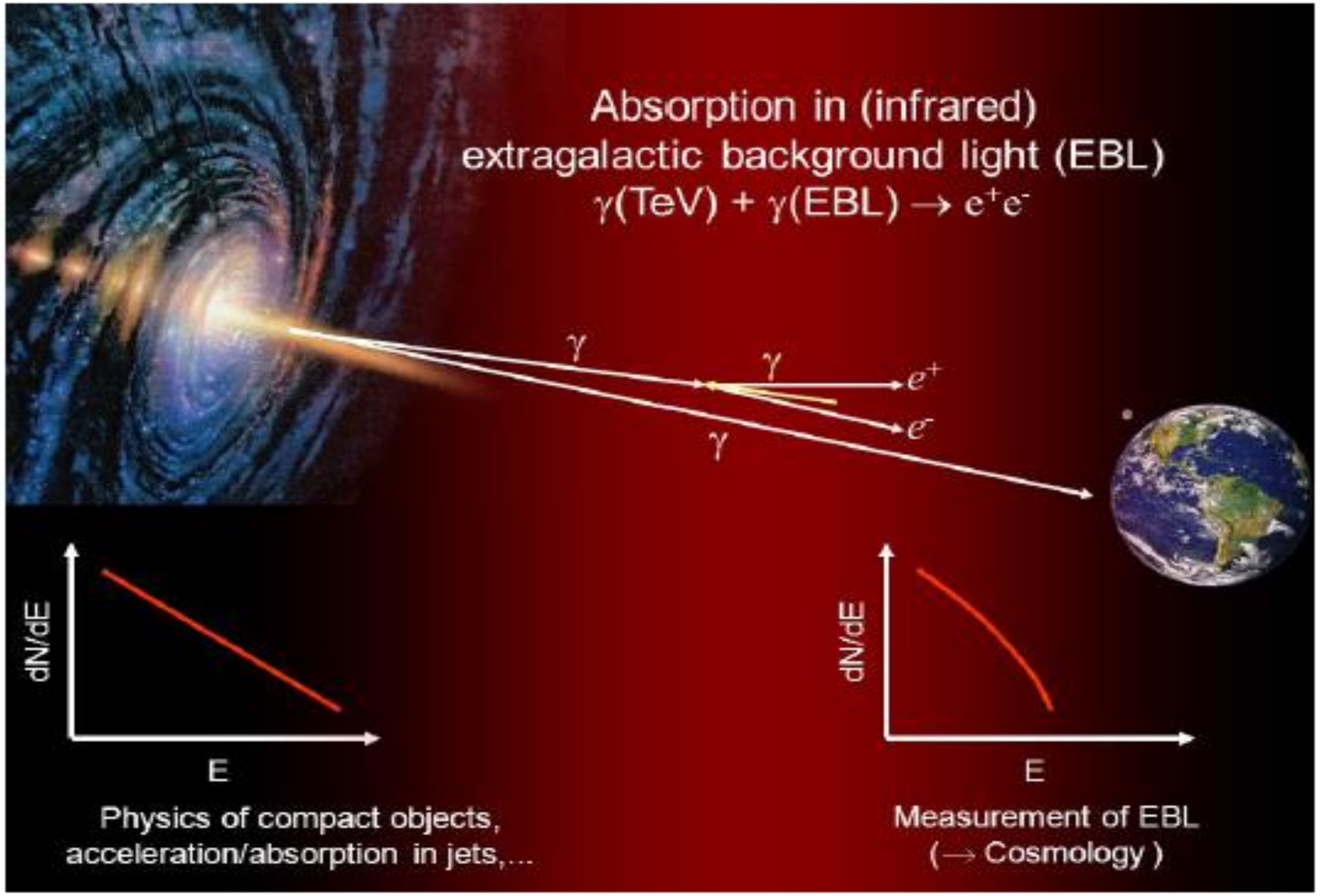
Lorentz Invariance Violation:

At quantum gravity scale, VHE-photons could be sensitive to the microscopic structure of spacetime. Higher energy photons are expected to propagate more slowly than their lower-energy counterparts

Image credits: Colin Gillespie, MGM; timeone.ca



- Quantum-gravity theories predict in general the breakdown of familiar physics when approaching the Planck energy scale, $E_P \sim 1.2 \times 10^{19}\,GeV$
- Currently such extreme energies are unreachable by experiments on Earth, but for photons traveling over cosmological distances the accumulated quantum gravity effect can be measured
- Studies of time delays in the arrival times of $\gamma-$ rays of different energies due to LIV effect can be used to probe fundamental physics.



Lorentz Invariance Violation: Temporal study

- At **Planck energy scale** Lorentz symmetry will breakdown, the deviation from Lorentz symmetry can be described by modification of **the dispersion relation** as follows:

$$E^2 = p^2c^2 + m^2c^4 + S\ E^2 \left(\frac{E}{E_{LIV}}\right)^n$$

where $S = -1$ for a subluminal case, $S = +1$ for a superluminal case, and n is the order of the leading correction.

The time-lag over energy difference can be written as:

$$\tau_n = \frac{\Delta t_n}{E_h^n - E_l^n} = S\ \frac{n+1}{2\ E_{LIV}} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

- **The rapid flux variability at multi-TeV energies observed during the flare of Mrk 501 on the night of June 23-24 (2014) is used to constrain the LIV scale.**

  For the case of linear perturbations (n=1), $E_{LIV} > 3.6 \times 10^{17}\ GeV$

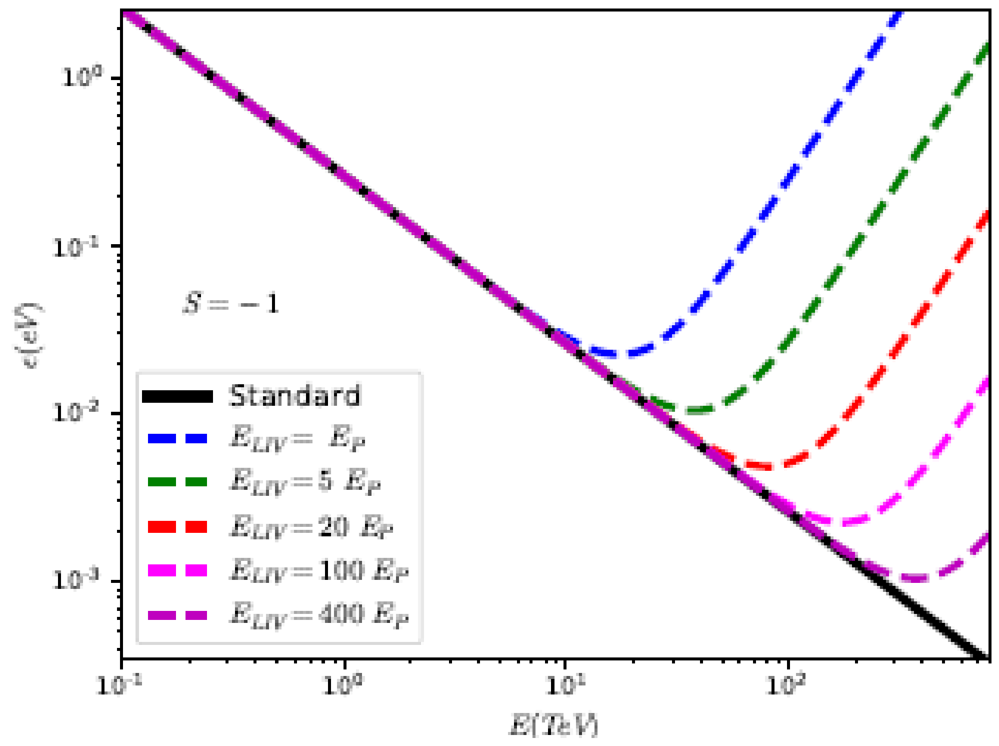
For more details, see H.E.S.S. collaboration 2019 (arXiv: 1606.08600v2)

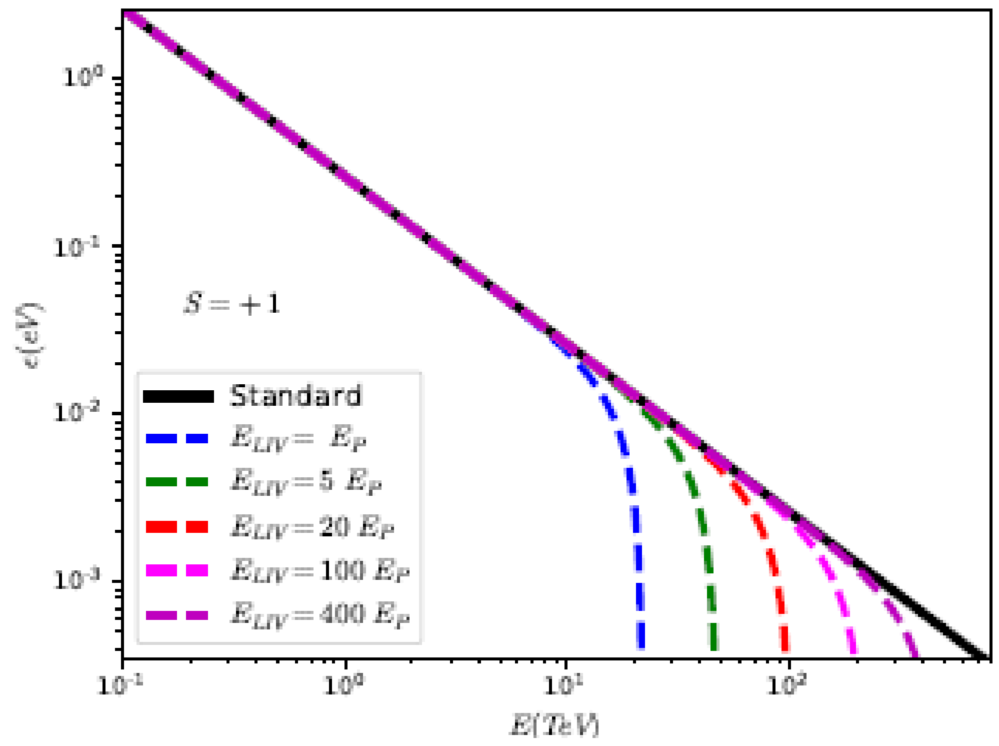
Lorentz Invariance Violation: The spectral study

- The **modified pair-production threshold** for $\mathbf{n} = 1$, can be written as:

$$\epsilon_{\min} = \frac{m^2 c^4}{E_\gamma} - S\left(\frac{E^2}{4E_{LIV}}\right)$$

where $E_{LIV} = E_P/\xi_1$, ξ_1 is dimensionless parameter.



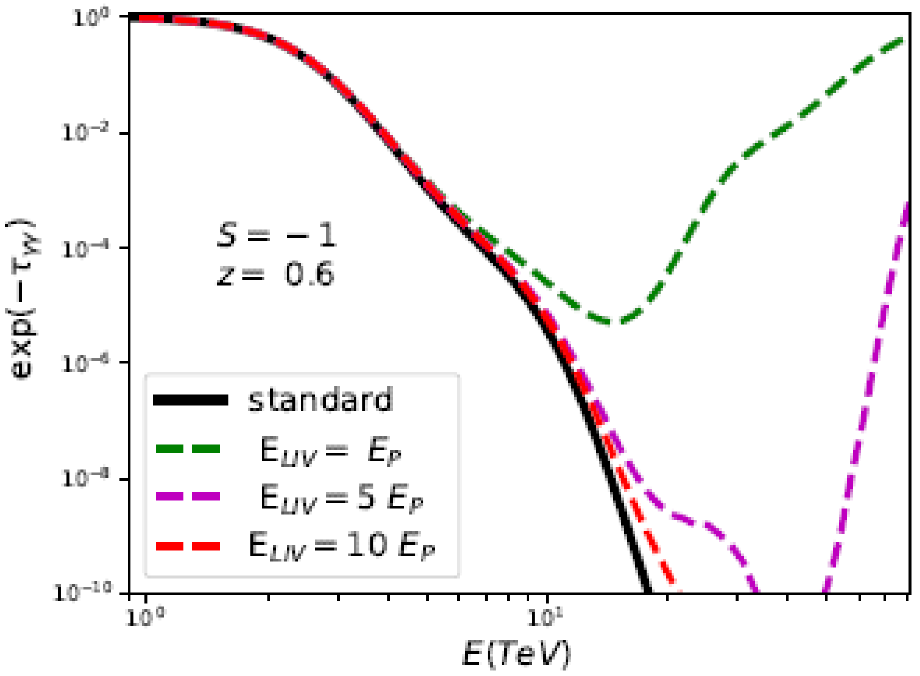


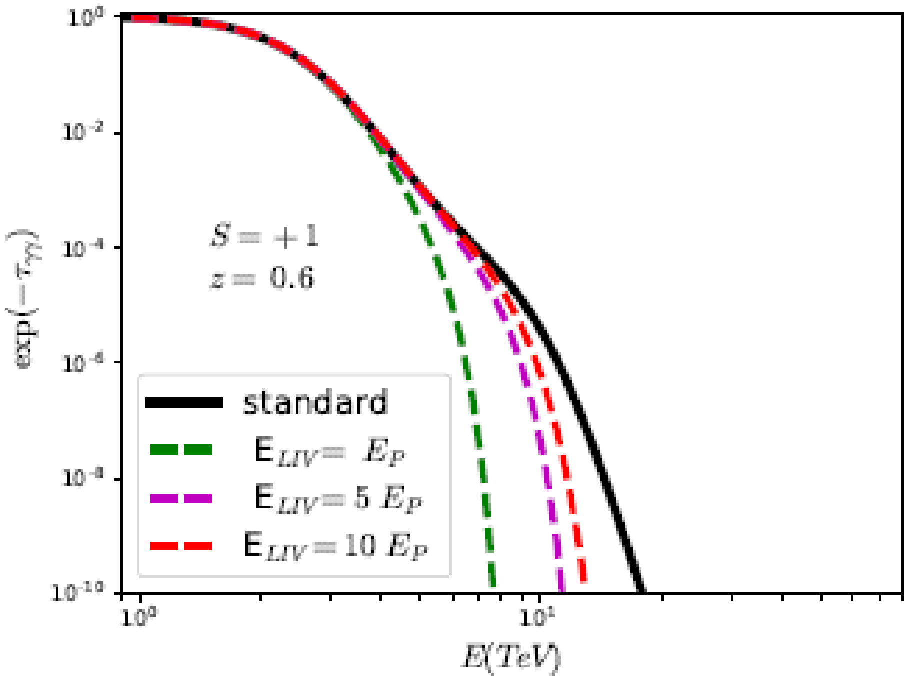
LIV: Cosmic opacity:

The standard relation for optical depth $\tau_{\gamma\gamma}(E_\gamma, z_s)$ at the energy E_γ and for a source at redshift z_s is modified as (Fairbairn et al. 2014)

$$\tau_{\gamma\gamma}(E_\gamma, z_s) = \frac{c}{8E_\gamma^2}\int_0^{z_s}\frac{dz}{H(z)(1+z)^3}\int_{\epsilon_{min}}^{\infty}\frac{n(\epsilon, z)}{\epsilon^2}\int_{smin(z)}^{smax(z)}[s - m_\gamma^2 c^4]\sigma_{\gamma\gamma}(s)ds$$

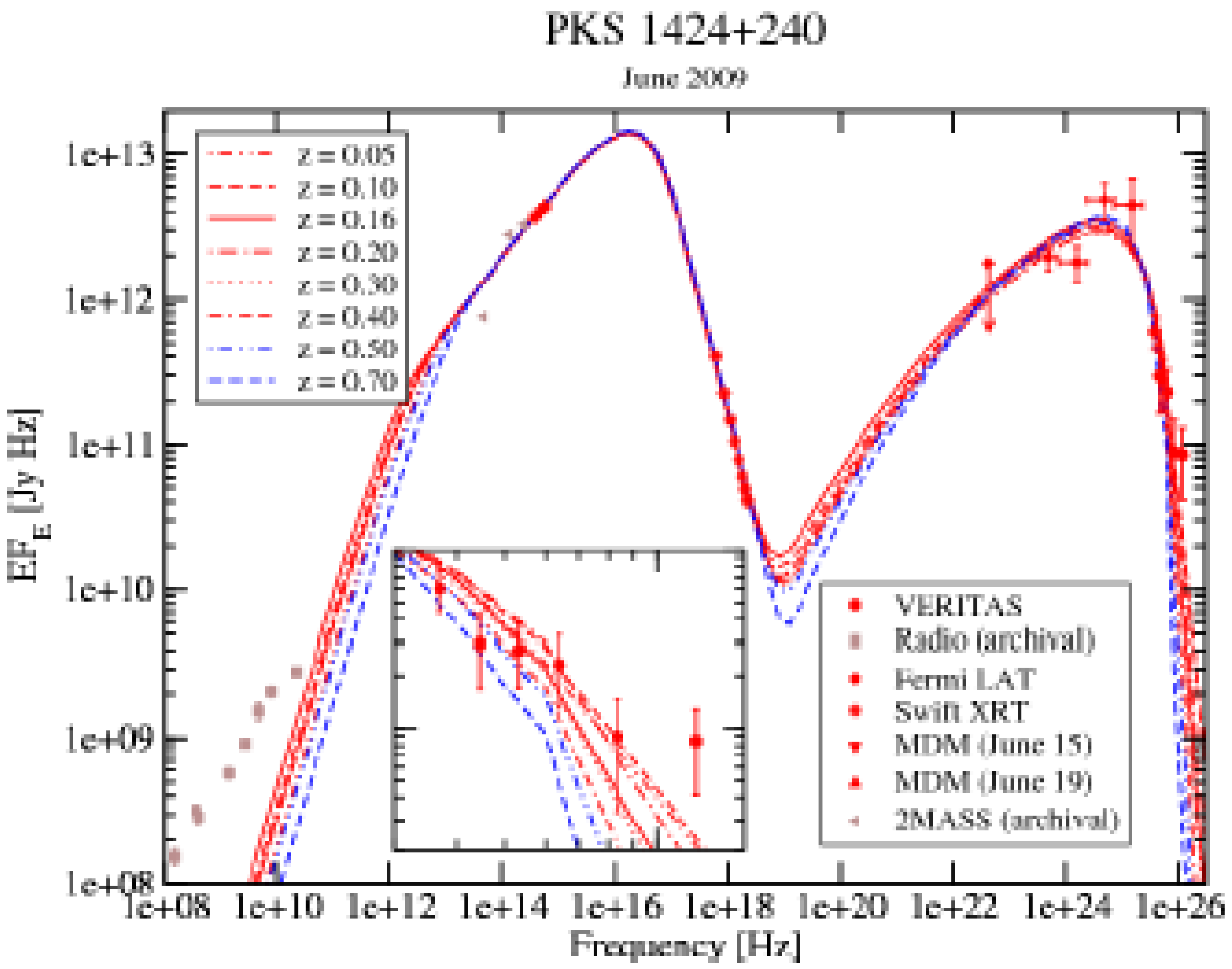
where $smin = 4m_e^2c^4$, $smax = 4\epsilon E_\gamma(1+z) + m_\gamma^2 c^4$ and $m_\gamma^2 c^4 \equiv S\frac{E^3}{E_{LIV}}$.





LIV: Compton scattering

- **Motivation**: Likely to be paramount importance to produce non-thermal emission gamma-rays in the GeV-TeV regime from many astrophysical sources.



LIV: Compton scattering

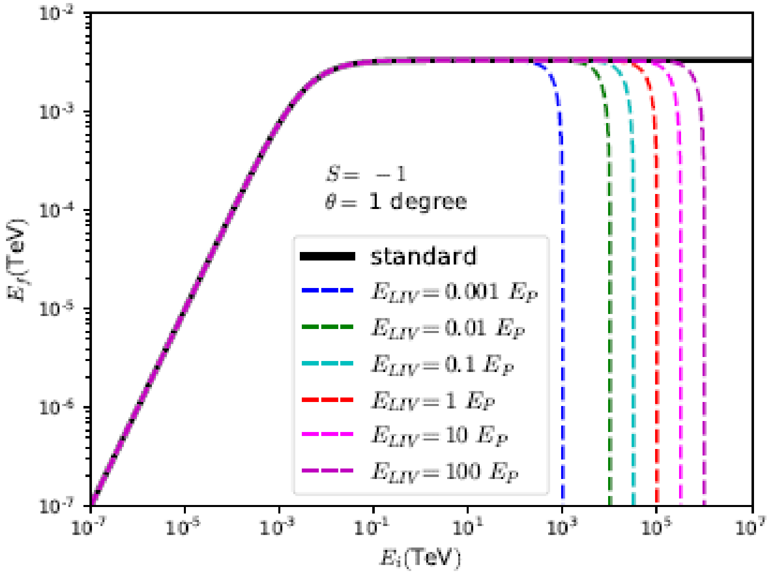
- **Compton scattering** is the process whereby photons gain or lose energy from collisions with electrons

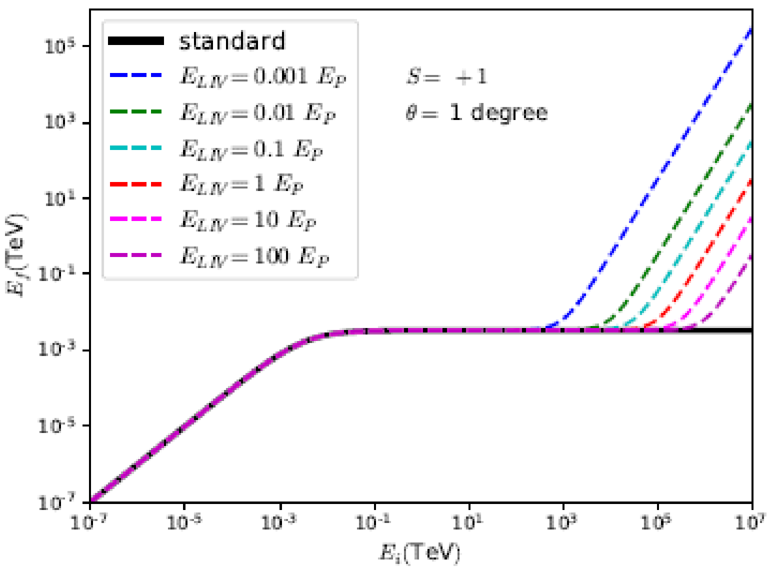
$$\left(E_{\gamma i}/c, \overrightarrow{P}_{\gamma i}\right) + \left(E_{ei}/c, \overrightarrow{P}_{ei}\right) = \left(E_{\gamma f}/c, \overrightarrow{P}_{\gamma f}\right) + \left(E_{ef}/c, \overrightarrow{P}_{ef}\right),$$

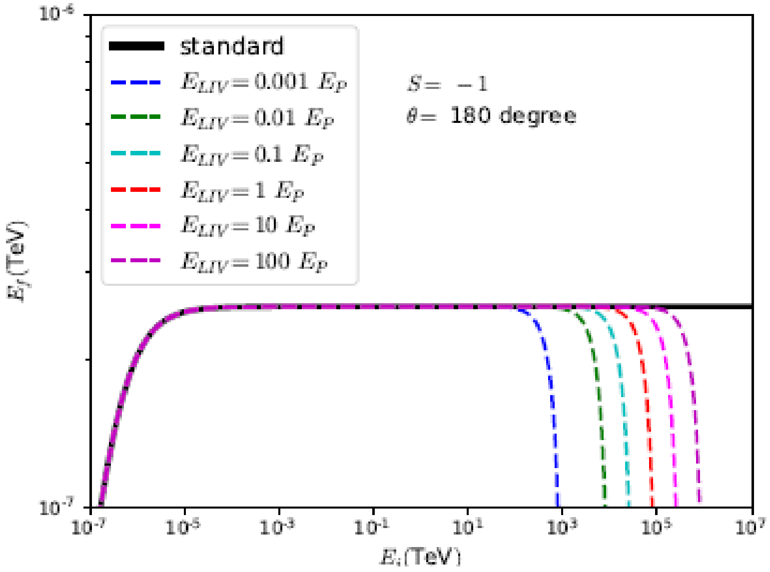
- **Using energy-momentum conservation with the LIV-modified dispersion relation. we derive the scattered photon energy Ef as a function of incoming photon energy Ei and scattering angles**

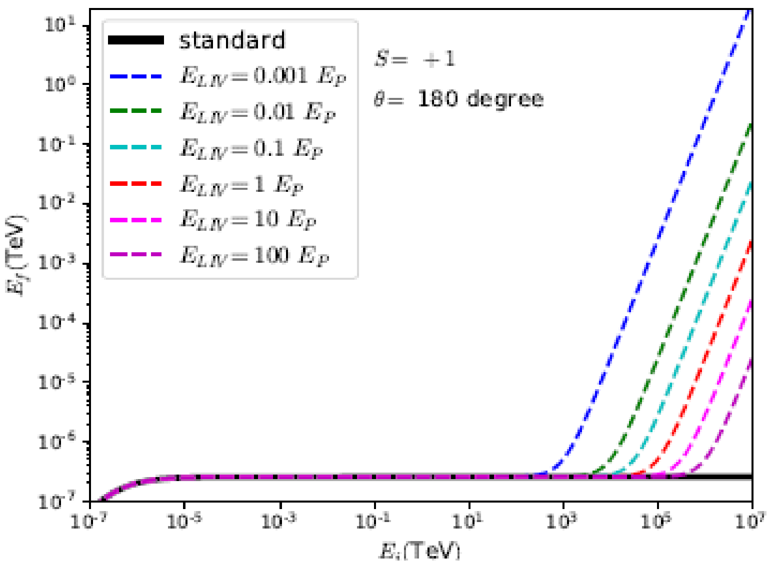
$$2E_{\gamma i}E_{\gamma f}+2(E_{\gamma f}-E_{\gamma i})m_e c^2 = S\left(\frac{E_{\gamma i}^3}{E_{LIV}}+\frac{E_{\gamma f}^3}{E_{LIV}}\right)$$
$$+\,2\mu E_{\gamma i}E_{\gamma f}\left(1-S\,\frac{E_{\gamma i}}{2E_{LIV}}-S\,\frac{E_{\gamma f}}{2E_{LIV}}\right).$$

LIV: Compton scattering







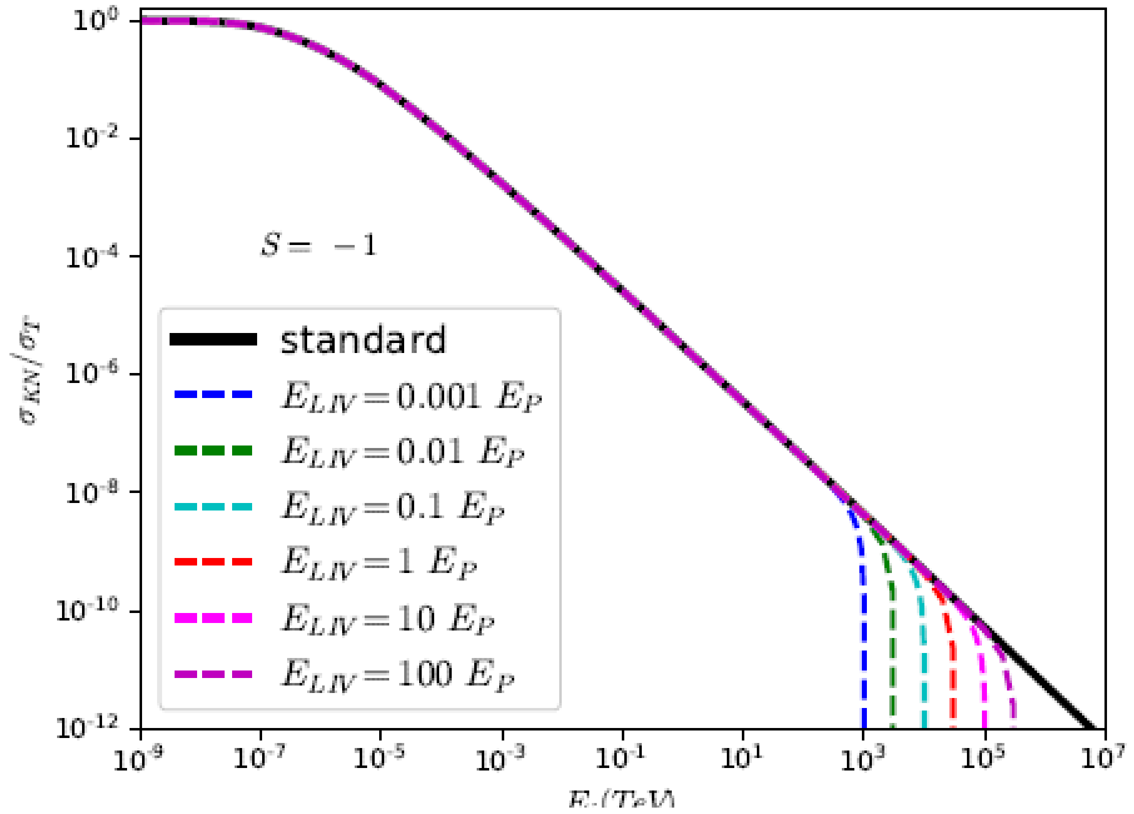


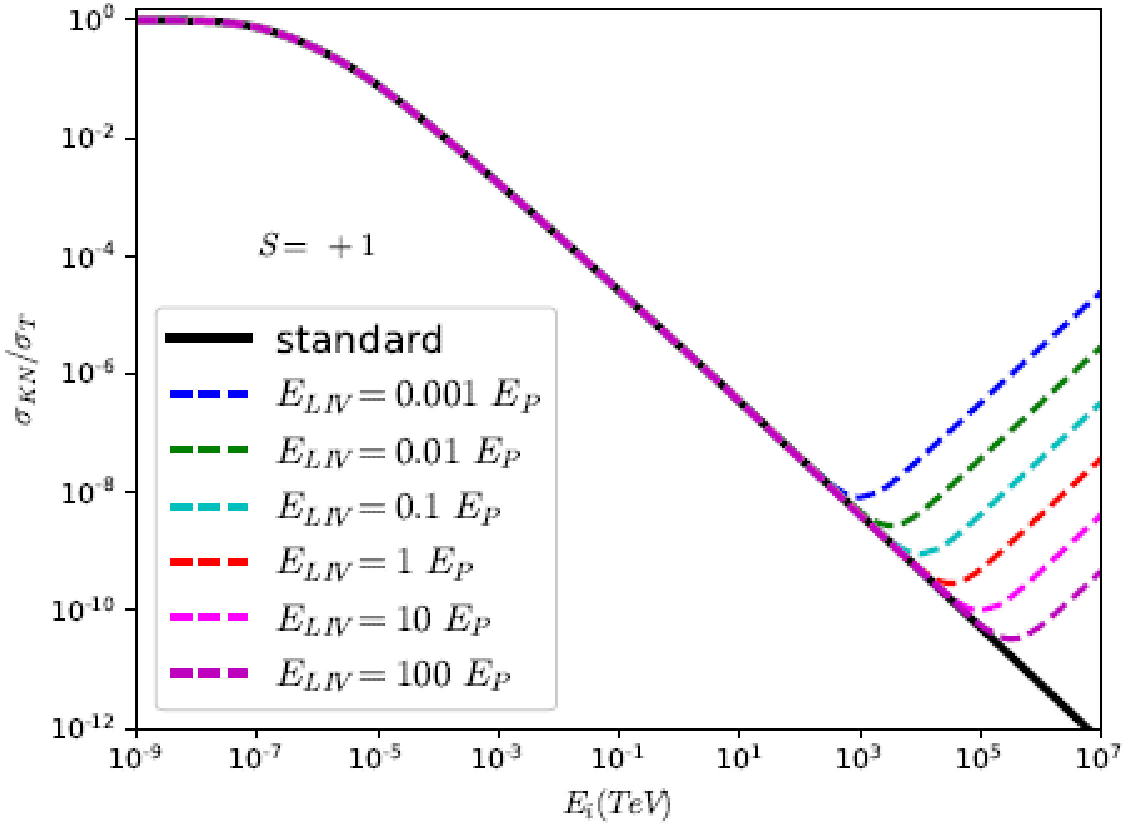
LIV: Compton scattering

- To modify the Klein-Nishina cross-section considering the LIV effect, we used the modied photon energy Ef in the Klein-Nishina formula:

$$\sigma_{\mathrm{KN}} = \int \frac{d\sigma_{\mathrm{KN}}}{d\Omega} d\Omega = \int \frac{3}{16\pi} \frac{\mathrm{E_f}}{\mathrm{E_i}} \left(\frac{\mathrm{E_i}}{\mathrm{E_f}} + \frac{\mathrm{E_f}}{\mathrm{E_i}} - \sin^2\theta \right) d\Omega,$$

and integrate numerically!





LIV from multimessenger:

- **The observation by the IceCube Collaboration of a high-energy (E≳200 TeV) neutrino from the direction of the blazar TXS 0506+056 and the coincident observations of enhanced gamma-ray emissions from the same object by MAGIC, VERITAS, HESS, Fermi-LAT, AGILE and Swift can be used to set stringent constraints on Lorentz violation in the propagation of neutrinos.**

For n=1, Ellis et al 2018 found that $E_{LIV} > 3.6 \times 10^{17}\ GeV$ **(arXiv:1807.05155).**

- Also **LIV signature can be tested using Ultra High-Energy Cosmic Rays, for more details** *(see, Anchordoqui & Soriano 2018).*

Summary and Conclusions:

- **EBL absorption at E > 10 TeV could be suppressed by LIV effects, opening up the possibility of detecting extragalactic sources at those extreme energies**

- **The LIV Signatures in Compton scattering processes could be important for very large incoming photon energies of > 1PeV. For more details,** Abdalla, H. & Boettcher, M., 2018, ApJ, 865, 159

- **The advent of multimessenger neutrino/photon astronomy, might made possible a breakthrough in the exploration of Lorentz symmetry using neutrinos.**

- **The future Cherenkov Telescope Array (CTA) expected to provide excellent opportunities to test this hypothesis.**

Thank you !