Probing fundamental physics and cosmology using gamma-ray observations

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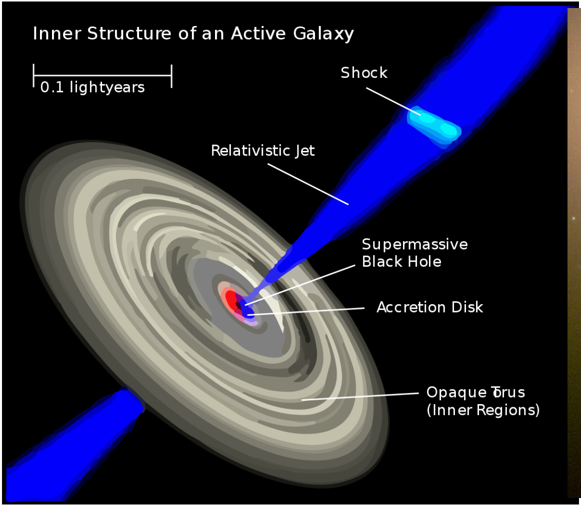
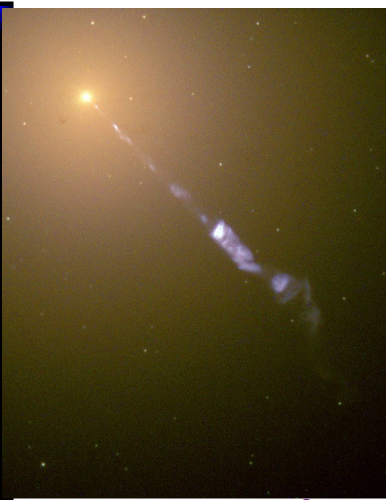
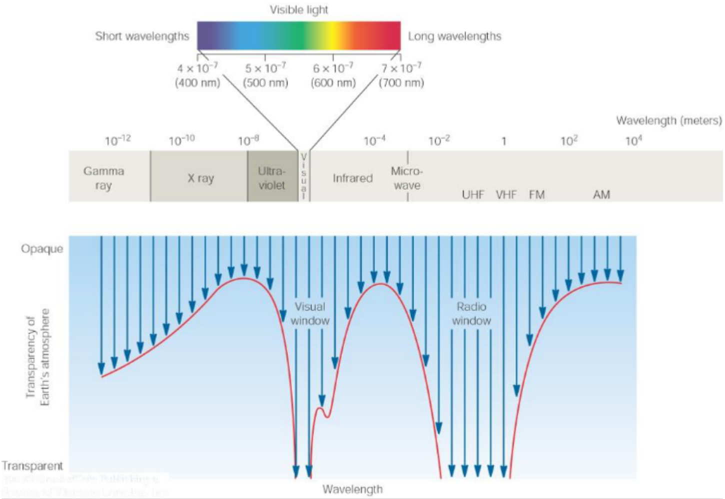
Outline

Gamma-ray sources (e.g., AGNs)



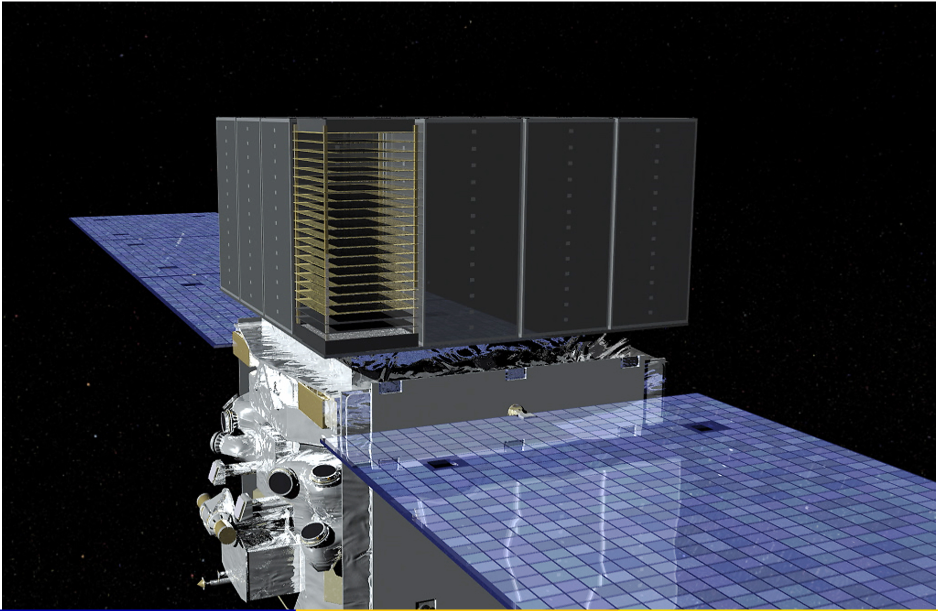


The Detection of Gamma-Rays



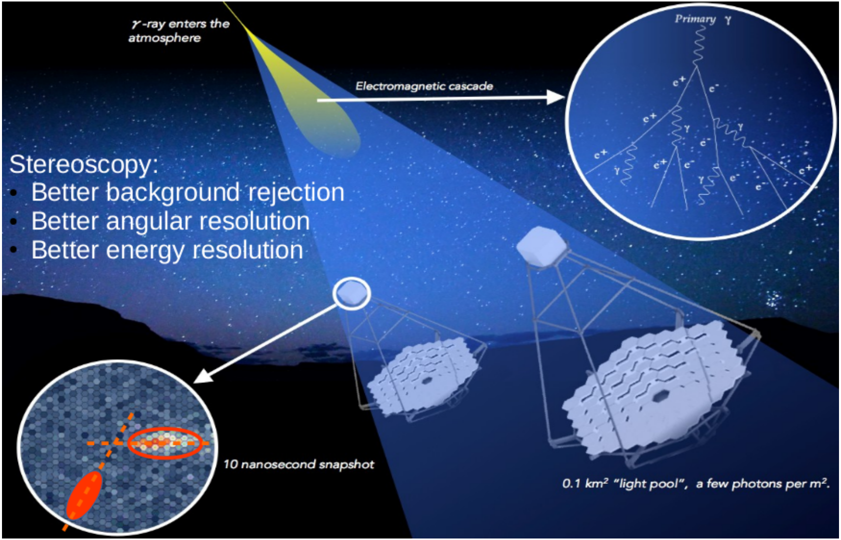
The atmosphere is opaque to gamma-rays!

Artist's view: Fermi LAT satellite detector



LAT Pair Conversion

Schematic drawing:
Imaging Atmospheric Cherenkov Technique



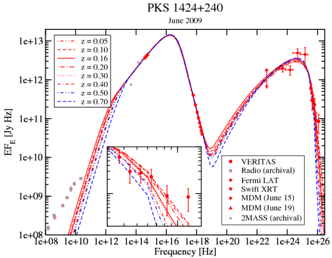
High Energy Stereoscopic System (H.E.S.S.)

High Altitude Water Cherenkov Observatory

Introduction:

Very High Energy gamma-rays (VHE; more than 100 GeV) from cosmological gamma-ray Sources such as Blazars can be absorbed by the Extragalactic Background Light (EBL), which leads to a high-energy cut-off at the VHE end of Blazar spectra.

- The **probability of absorption** depends on the **photon energy** and **redshift.**
- **This process has been intensively studied during the last few decades (e.g., Stecker 1969 - Aharonian et al. 2006).**



Acciari et al. 2010

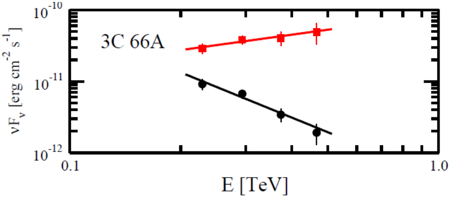
The spectral hardening

What is the problem?

- From recent observation, the universe is **more transparent** to the VHE gamma-rays **than was expected!**

Archambault et al. 2014

- These VHE signatures in the spectra of distant blazars are currently the subject of intensive research.



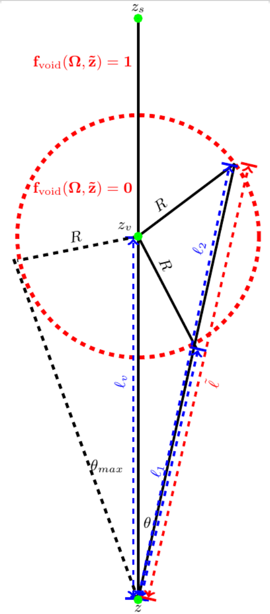
Finke et al. 2010

The spectral hardening

What is the solution ?!

- To explain this VHE gamma-ray imprint there are many suggestions:
  - The existence of exotic Axion Like Particles (ALPs) Dominguez et al. 2011
  - Interactions of extragalactic Ultrahigh Energy Cosmic Rays (UHECR) Essey et al. 2010
  - The existence of cosmic voids between such Blazar and the observer on the earth Furniss et al. 2013
- We did detailed calculations about the possibility of a cosmic void along the line of sight to such distant Blazar.
- We considered the possibility of Lorentz invariance violation and its astrophysical implications.

Void:



- **The void radius represented by R**
- **The void center represented by z_v**
- **The source located at z_s**
- **We set local star formation rate zero inside the void**

Abdalla & Böttcher 2017

EBL Calculation

By modifying the expression from Razzaque et al. (2009):

The spectral stellar radiation density:

$$\frac{dN(\epsilon, z)}{d\Omega d\epsilon dV} = \int_{\tilde{z}=z}^{\infty} d\tilde{z} \left|\frac{dt}{d\tilde{z}}\right| \Psi(\tilde{z}) f_{\text{void}}(\Omega, \tilde{z}) \int_{M_{min}}^{M_{max}} dM \left(\frac{dN}{dM}\right) \times \int_{\max\{0, z_d(M, z^{'})\}}^{\tilde{z}} dz^{'} \left|\frac{dt}{dz^{'}}\right| f_{esc}(\epsilon^{'}) \frac{dN(\epsilon^{'} M)}{d\epsilon^{'} dt} (1 + z^{'}), \quad (1)$$

where,

$$\left|\frac{dt}{dz'}\right|^{-1} = H_0(1 + z')\sqrt{(\Omega_m(1 + z')^3 + \Omega_\Lambda}$$

and

$$z_d(M, z') = -1 + \left(-\left(\frac{\Omega_\Lambda}{\Omega_m}\right)\left[\frac{3}{2}H_0 t_* \tanh^{-1}\sqrt{1 + \frac{\Omega_m}{\Omega_\Lambda}(1 + z')^3}\right]^2\right)^{\frac{1}{3}}.$$

EBL Calculation

The lifetime t_* of a star can be calculated as

$$\mathbf{t_*} = \mathbf{t_\odot} \left(\frac{\mathbf{M}}{\mathbf{M_\odot}}\right) \left(\frac{\mathbf{L_\odot}}{\mathbf{L}}\right), \tag{2}$$

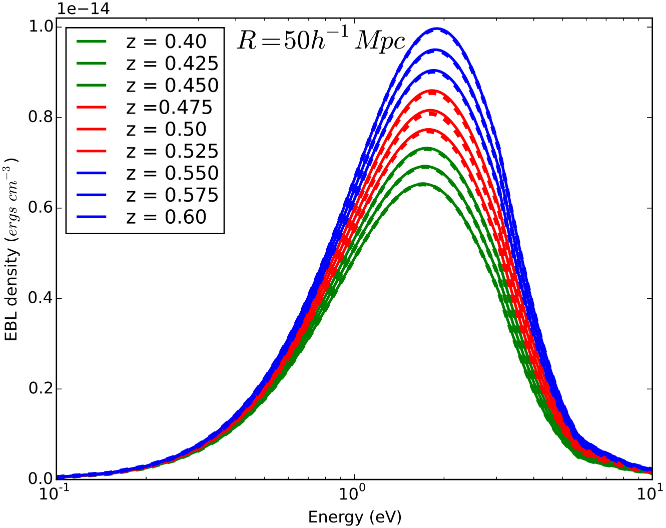
where L, M are the luminosity and mass of the main sequence star respectively. $L_\odot$, $M_\odot$ and $t_\odot$ are the solar luminosity, mass and lifetime respectively.

The comoving EBL energy density $\mu_{\epsilon_1}(\epsilon, z_1, \Omega)$:

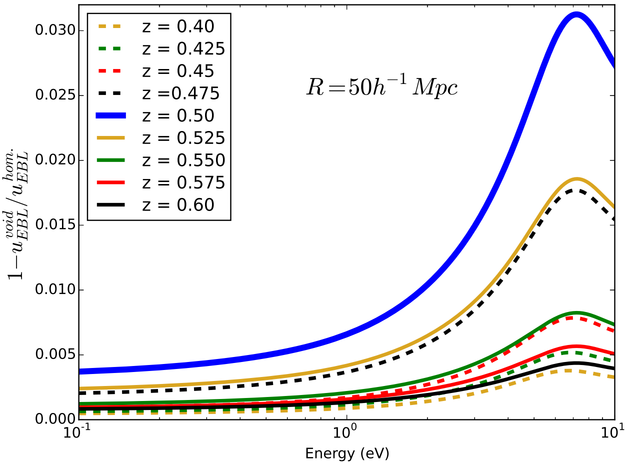
In comoving cordinates, the photon energy and volume can be transformed as $\epsilon_\mathbf{1} = \epsilon(\mathbf{1} + \mathbf{z_1})$ and $\mathbf{V_1} = \mathbf{V}/(\mathbf{1} + \mathbf{z_1})^\mathbf{3}$ respectively,

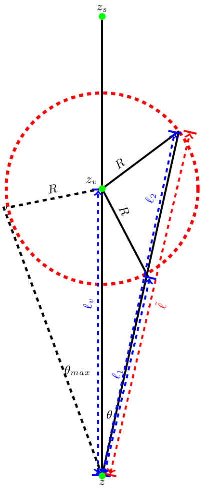
$$\mu_{\epsilon_\mathbf{1}}(\epsilon, \mathbf{z_1}, \mathbf{\Omega}) = (\mathbf{1} + \mathbf{z_1})^\mathbf{2}\ \epsilon_\mathbf{1}\ \frac{\mathbf{dN}(\epsilon_\mathbf{1}, \mathbf{z} = \mathbf{z_1})}{\mathbf{d\Omega\ d}\epsilon_\mathbf{1}\ \mathbf{dV}} \tag{3}$$

Results: EBL photon energy density

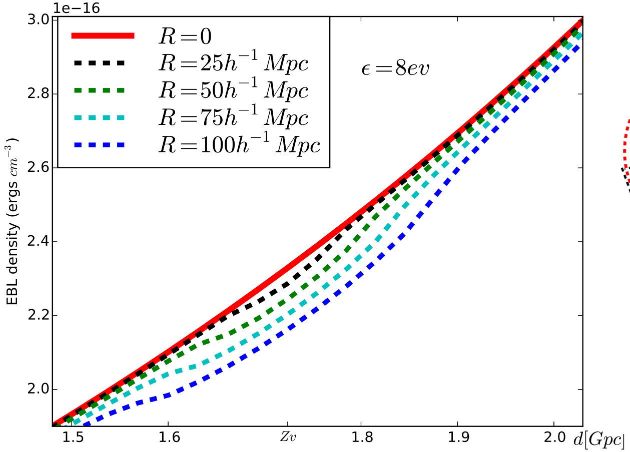


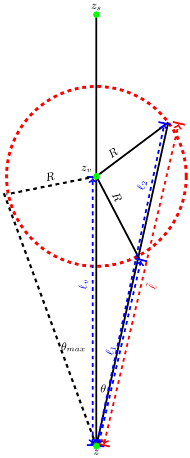
EBL energy density deficit due to the void



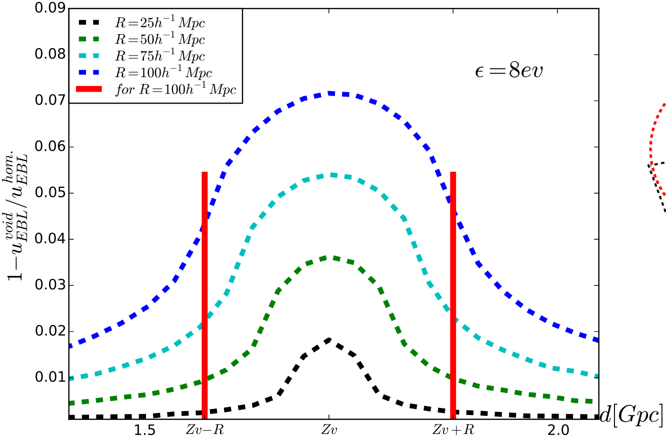


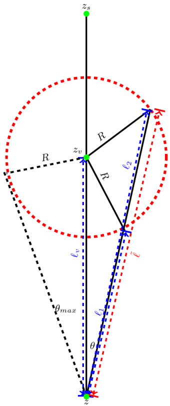
EBL photon energy density as a function of distance



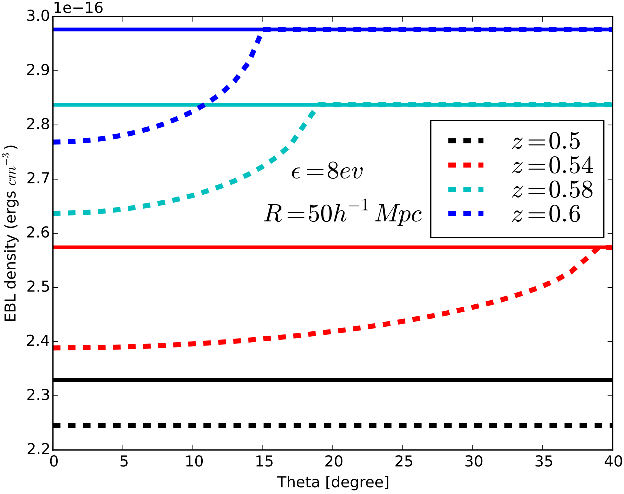


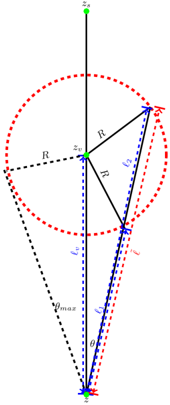
EBL photon energy density as a function of distance





Angle dependence of the EBL energy density





Opacity Calculation

The optical depth due to $\gamma - \gamma$ absorption for a γ-ray photon from a source at redshift z_s with observed energy E, as *Gould & Schréder (1967)*:

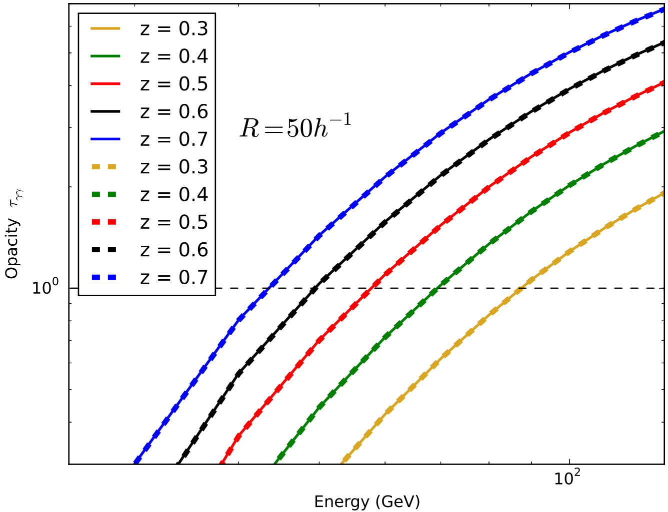
The Opacity:

$$\tau_{\gamma\gamma}(\mathbf{E}, \mathbf{z_s}) = \mathbf{c}\int_0^{\mathbf{z_s}} \mathbf{dz_1} \left| \frac{\mathbf{dt}}{\mathbf{dz_1}} \right| \oint \mathbf{d\Omega} \int_{\frac{\mathbf{m_e^2c^4}}{\mathbf{E(1+z1)}}}^{\infty} \mathbf{d\epsilon_1} \frac{\mu_{\epsilon_1}(\epsilon_1, \mathbf{z_1}, \Omega)}{\epsilon_1} (1-\mu)\sigma_{\gamma\gamma}(\mathbf{s}).$$

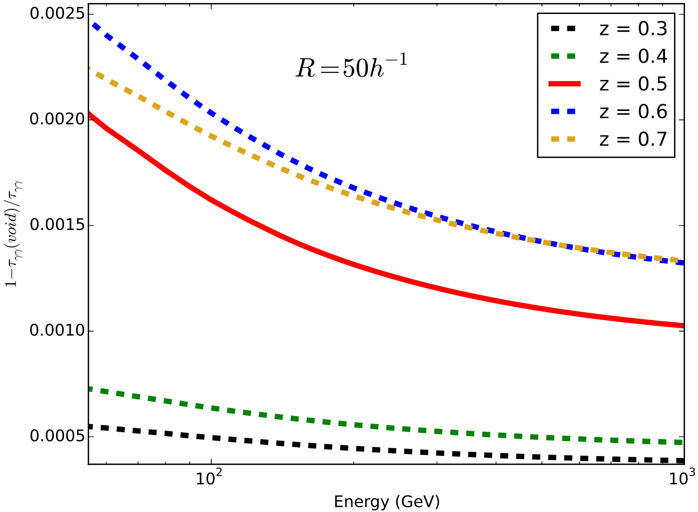
The γ γ pair-production cross section $\sigma_{\gamma\gamma}(s)$ can be written as:

$$\sigma_{\gamma\gamma}(\mathbf{s}) = \frac{1}{2}\pi \mathbf{r_e^2}(1-\beta_{\mathbf{cm}}^2)\left[(3-\beta_{\mathbf{cm}}^4)\ln\left(\frac{1+\beta_{\mathbf{cm}}}{1-\beta_{\mathbf{cm}}}\right) - 2\beta_{\mathbf{cm}}(2-\beta_{\mathbf{cm}}^2)\right].$$

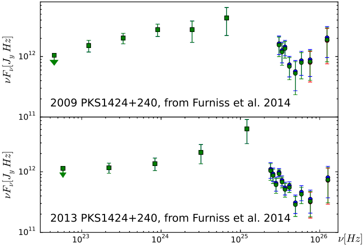
EBL $\gamma\gamma$ opacity as a function of γ-ray photon-energy

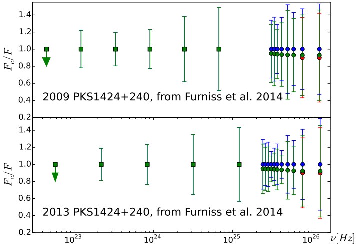


Opacity deficit due to the presence of the void



Application to PKS 1424+240

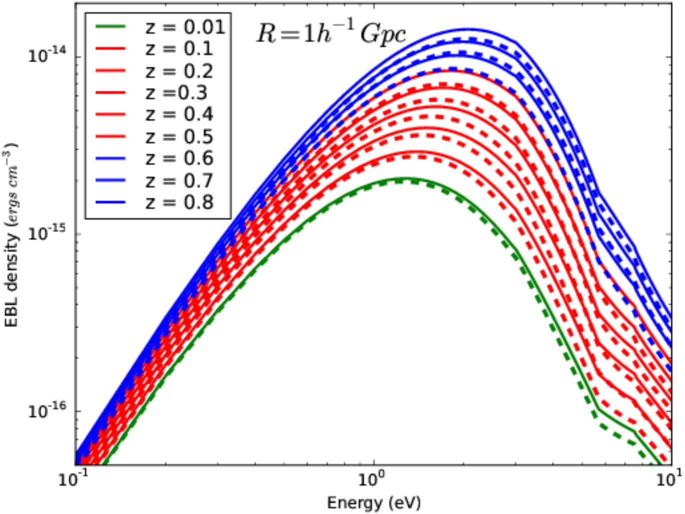




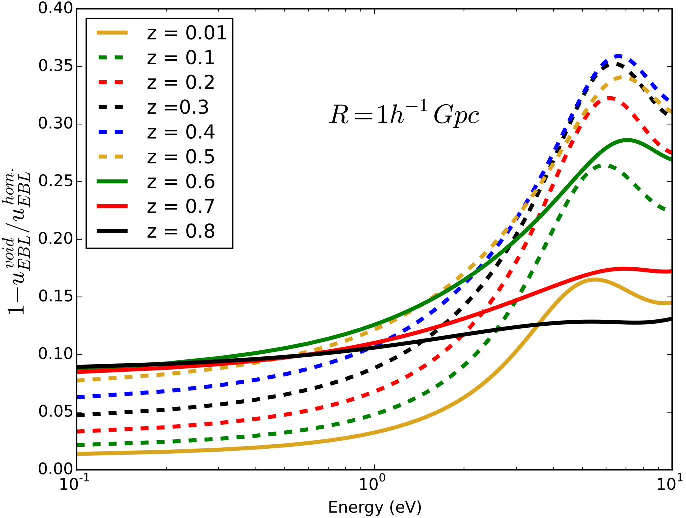
VHE γ-ray spectra of PKS1424+240, from Archambault et al. (2014).

- The blue points show the EBL-corrected spectrum using the *Gilmore et al. (2012)*
- The red points represent the reduced EBL correction, using the linear scaling of $\tau_{\gamma\gamma}$ with the line-of-sight galaxy density, as suggested by *Furniss et al. (2015)*
- **The green points represent the current model**

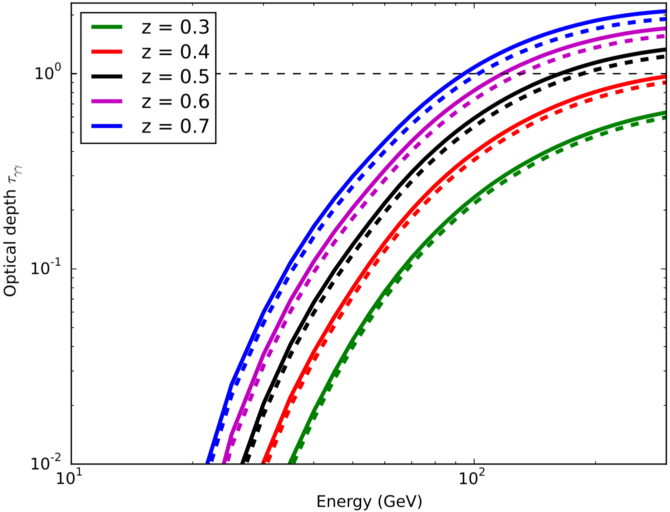
EBL reduction due to an accumulation of voids



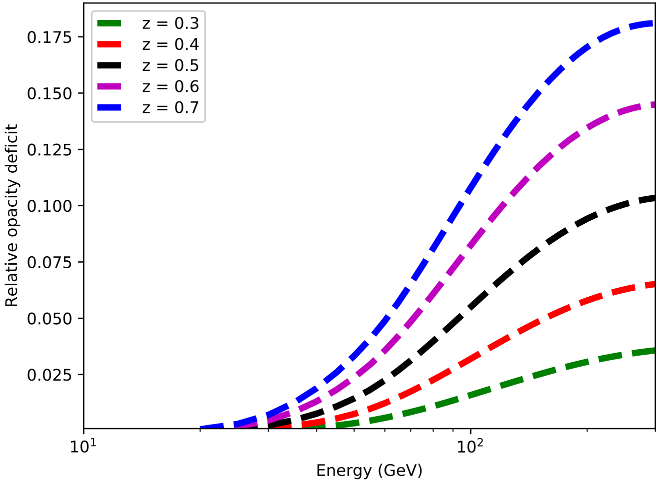
EBL deficit due to an accumulation of voids



Opacity deficit due to the presence of the voids

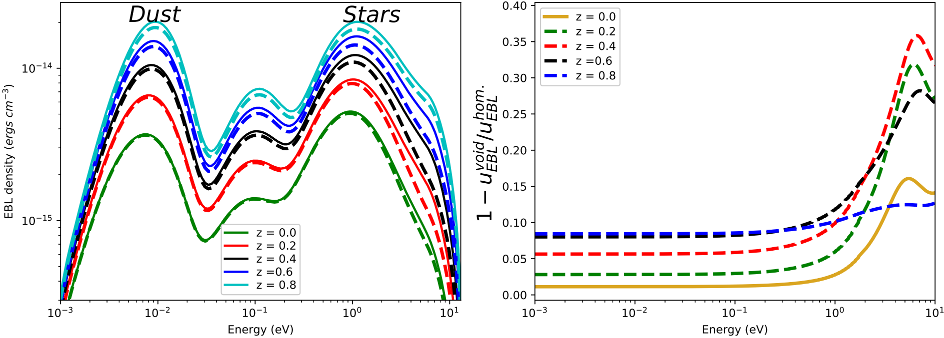


Opacity deficit due to the presence of the voids



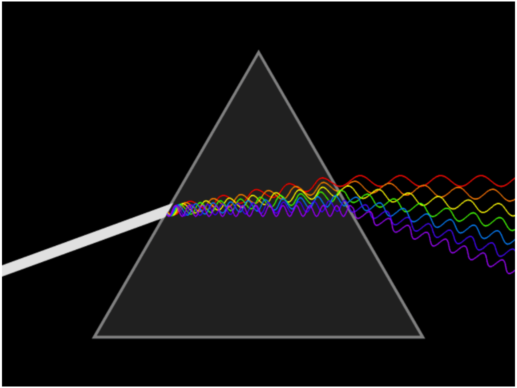
Modifying Finke et al. 2010 EBL model

The impact of **10 typical voids** **of radius $R = 100h^{-1}$Mpc distribution along the line of sight,** **centered at redshift $z = 0.3$.**



Lorentz-Invariance Violation

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

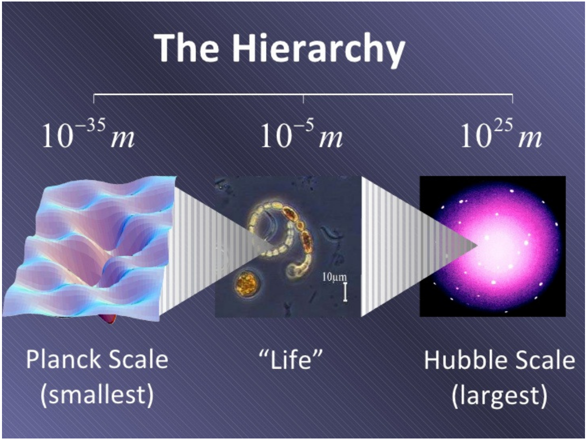


Credit: Lucas V. Barbosa

Lorentz-Invariance Violation

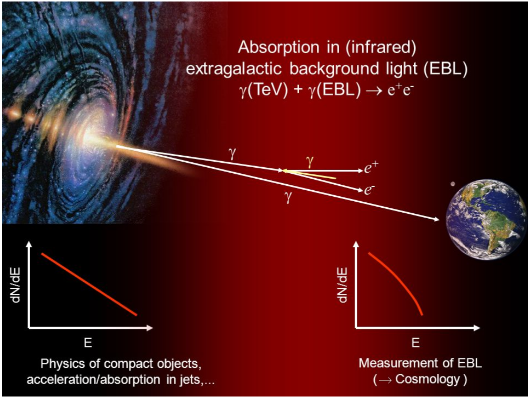
At quantum gravity scale, VHE photons could be sensitive to the microscopic structure of space-time. Higher energy photons are expected to propagate more slowly than their lower-energy counterparts.

Image credits: Colin Gillespie, MGM; timeone.ca



Lorentz-Invariance Violation

- 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 can be used to probe fundamental physics (Lorentz & Brun 2016; H.E.S.S. 2019).



Lorentz-Invariance Violation

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

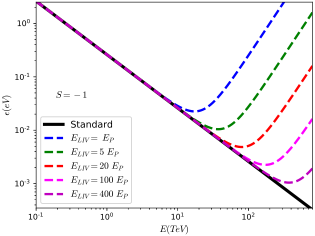
$$\mathbf{E}^2 = \mathbf{p}^2\mathbf{c}^2 + \mathbf{m}^2\mathbf{c}^4 + \mathbf{S}\ \mathbf{E}^2 \left(\frac{\mathbf{E}}{\mathbf{E}_{\mathbf{LIV}}}\right)^{\mathbf{n}} \tag{4}$$

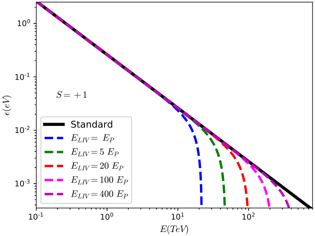
  where $\mathbf{S} = -1$ **for a subluminal case**, $\mathbf{S} = +1$ **for a superluminal case**, **and n is the order of the leading correction**.

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

$$\epsilon_{\mathbf{min}} = \frac{\mathbf{m}^2\mathbf{c}^4}{\mathbf{E}_\gamma} - \mathbf{S}\left(\frac{\mathbf{E}^2}{4\mathbf{E}_{\mathbf{LIV}}}\right) \tag{5}$$

  where $\mathbf{E}_{\mathbf{LIV}} = \mathbf{E}_{\mathbf{P}}/\xi_1$, ξ_1 is dimensionless parameter.



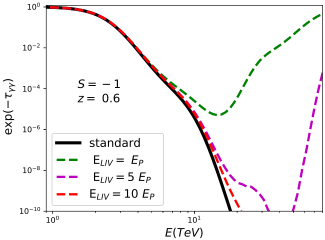


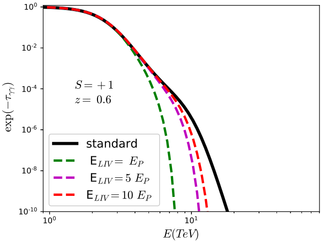
LIV: Cosmic opacity

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)

$$\tau_{\gamma\gamma}(E_\gamma, z_s) = \frac{c}{8E_\gamma^2}\int_0^{z_s}\frac{dz}{H(z)(1+z)^3}\int_{\epsilon_{min}}^{\infty}\frac{n(\epsilon,z)}{\epsilon^2}\int_{smin(z)}^{smax(z)}[s - m_\gamma^2 c^4]\sigma_{\gamma\gamma}(s)ds \tag{6}$$

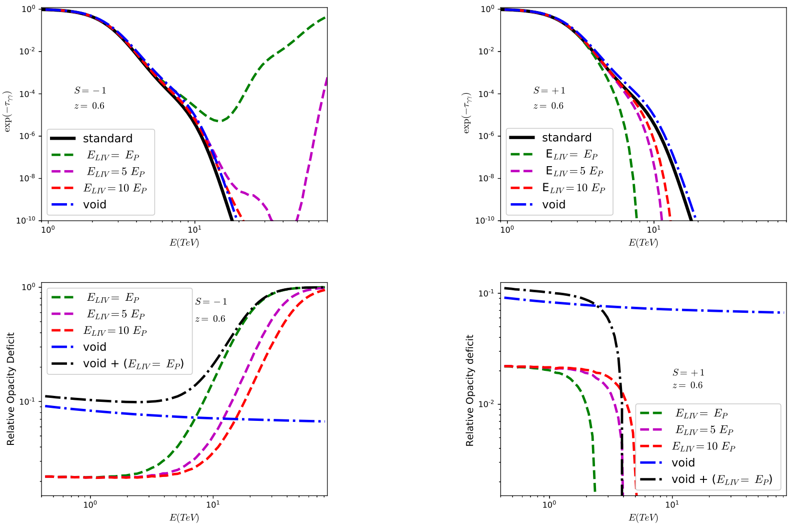
where $smin = 4m_e^2c^4$, $smax = 4\epsilon E_\gamma(1+z) + m_\gamma^2c^4$ and $m_\gamma^2c^4 \equiv S\frac{E^3}{E_{LIV}}$.





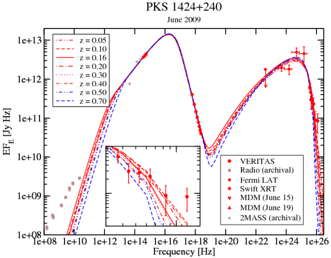
LIV and Void: Cosmic opacity

- **Comparison between the impact of 10 typical voids size $R = 100h^{-1}$Mpc and the effect of Lorentz Invariance Violation**



LIV: Compton scattering

- **One of the most important fundamental high-energy radiation mechanisms is Compton scattering.**
- **In the leptonic Blazar models, the high-energy component is produced by Compton scattering.**



- **The question that could arise is, could the influence of the LIV effect on the Compton scattering process explain the spectral hardening of the VHE end of spectra of several Blazars?**

LIV: Compton scattering

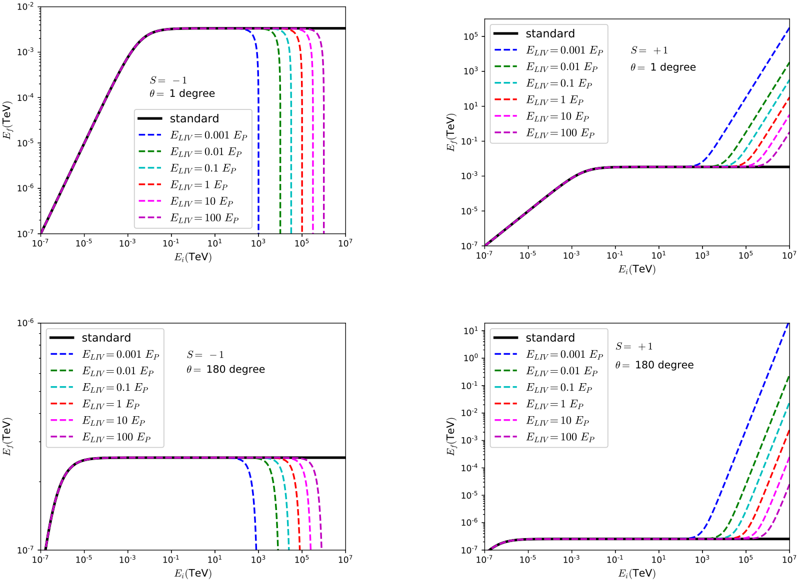
- Compton scattering is the process whereby photons gain or lose energy from collisions with electrons

$$\left(E_{\gamma i}/c, \overrightarrow{P}_{\gamma i}\right) + \left(E_{ei}/c, \overrightarrow{P}_{ei}\right) = \left(E_{\gamma f}/c, \overrightarrow{P}_{\gamma f}\right) + \left(E_{ef}/c, \overrightarrow{P}_{ef}\right), \quad (7)$$

- Using energy-momentum conservation with the LIV-modified dispersion relation (4) we derive the scattered photon energy $\mathbf{E_f}$ as a function of incoming photon energy $\mathbf{E_i}$ and scattering angles θ

$$\begin{aligned} 2E_{\gamma i}E_{\gamma f}+2(E_{\gamma f}-E_{\gamma i})m_e c^2 = S \left(\frac{E_{\gamma i}^3}{E_{LIV}} + \frac{E_{\gamma f}^3}{E_{LIV}}\right) \\ + 2\mu E_{\gamma i}E_{\gamma f}\left(1 - S\,\frac{E_{\gamma i}}{2E_{LIV}} - S\,\frac{E_{\gamma f}}{2E_{LIV}}\right). \end{aligned} \quad (8)$$

LIV: Compton scattering

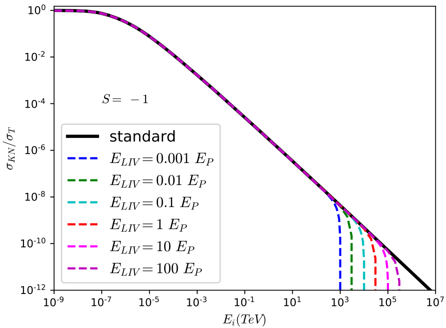


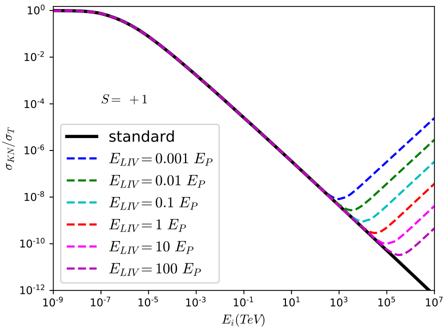
LIV: Compton scattering

- **To modify the Klein-Nishina cross-section considering the LIV effect, we used the modified photon energy E_f in the Klein-Nishina formula:**

$$\sigma_{KN} = \int \frac{d\sigma_{KN}}{d\Omega} d\Omega = \int \frac{3}{16\pi} \frac{E_f}{E_i} \left(\frac{E_i}{E_f} + \frac{E_f}{E_i} - \sin^2\theta \right) d\Omega, \quad (9)$$

and integrate numerically!





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 (e.g., with the CTA). This could be important to probe fundamental physics**
- **The LIV Signatures in Compton scattering processes could be important for very large incoming photon energies of $>$ 1PeV.**
- **The spectral hardening of several observed VHE gamma-ray sources (e.g. blazars) with energy from 100 GeV up to few TeVs (e.g. PKS 1424+240) still remains puzzling.**
- **The EBL energy density along the line of sight depends on the expansion of the universe and is therefore cosmology dependent. So, gamma-ray observation could be important to constrain cosmological models (see, e.g., Domínguez 2013).**
- **For more details, see, Abdalla, H. Böttcher, M., 2017, ApJ, 835, 23, arXiv:1701.00956 and Abdalla, H. & Böttcher, M., 2018, ApJ, 865, 159, arXiv: 1809.00477.**

Thank You !!!

NWU