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Gamma rays as probes of the Universe

Les rayons gamma, sondes de l'Univers

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ABSTRACT

The propagation of γ rays over very large distances provides new insights on the intergalactic medium and on fundamental physics. On their path to the Earth, γ rays can annihilate with diffuse infrared or optical photons of the intergalactic medium, producing e^+e^- pairs. The density of these photons is poorly determined by direct measurements due to significant galactic foregrounds. Studying the absorption of γ rays from extragalactic sources at different distances allows the density of low-energy diffuse photons to be measured. Gamma-ray propagation may also be affected by new phenomena predicted by extensions of the Standard Model of particle physics. Lorentz Invariance is violated in some models of Quantum Gravity, leading to an energy-dependent speed of light in vacuum. From differential time-of-flight measurements of the most distant γ-ray bursts and of flaring active galactic nuclei, lower bounds have been set on the energy scale of Quantum Gravity. Another effect that may alter γ-ray propagation is predicted by some models of String Theory, namely the mixing of the γ ray with a light fundamental boson called an "axion-like particle", which does not interact with low-energy photons. Such a mixing would make the Universe more transparent to γ rays than what would otherwise be, in a sense it decreases the amount of modification to the spectrum that comes from the extragalactic background light. The present status of the search for all these phenomena in γ-ray astronomy is reviewed.

RÉSUMÉ

La propagation des photons γ sur de très grandes distances nous permet de sonder le milieu intergalactique et fournit des tests de physique fondamentale. Au cours de leur chemin vers la Terre, ceux-ci peuvent s'annihiler avec les photons infrarouges et optiques du milieu intergalactique, produisant ainsi des paires e^+e^-. L'absorption des photons γ émis par des sources extragalactiques à différentes distances permet de mesurer ce fond diffus, par ailleurs très mal connu par des mesures directes en raison des importants rayonnements d'avant-plan dus à la Galaxie. La propagation des photons γ peut aussi être affectée par de nouveaux phénomènes prédits par des extensions du modèle standard de la physique des particules. L'invariance de Lorentz est violée dans certains modèles de gravité

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quantique où la vitesse de la lumière dans le vide varie avec l'énergie du photon γ. Les mesures différentielles de temps de vol sur les sursauts γ et sur les éruptions de noyaux actifs de galaxie ont permis d'obtenir des bornes inférieures sur l'échelle d'énergie de la gravité quantique. Un autre effet pouvant affecter la propagation des photons γ est prédit par des modèles de la théorie des cordes. Il s'agit du mélange quantique entre le photon et une particule légère de type « axion », qui n'interagit pas avec les photons infrarouge et optiques. En diminuant dans les spectres l'empreinte de l'absorption par le fond diffus, ce mélange rendrait l'Univers plus transparent que prévu aux photons γ. L'article présente l'état actuel des recherches sur l'ensemble de ces phénomènes en astronomie γ

1. Introduction

Gamma rays are powerful and important messengers from cosmic accelerators. In addition, the propagation of γ rays over very large distances offers a number of opportunities to investigate the extragalactic medium and to discover or constrain new phenomena predicted by some extensions of the Standard Model of particle physics. In this review, we focus on the following aspects:

- diffuse photons in the intergalactic medium with which γ rays may annihilate producing e^+e^- pairs, including the well-known cosmic microwave background (CMB), which affects only the propagation of ultra-high energy γ rays (PeV range), and the diffuse background of optical and infrared photons – the extragalactic background light (EBL) – which is poorly known from direct measurements, due to important galactic foregrounds;
- the effects of a possible Lorentz-invariance violation (LIV), as predicted by models of Quantum Gravity (QG);
- the mixing of photons with light fundamental bosons ($m\,c^2 = \mathcal{O}(\text{neV})$) such as axion-like particles (ALPs), as predicted by models of String Theory, an effect sensitive to the magnetic field strength in extragalactic space.

Gamma rays propagating over very large distances are particularly good probes of the last two effects. Lorentz-invariance violation, leading to an energy-dependent dispersion of photons, would affect propagating photons with a large product of energy E and distance d. Gamma-ray sources at cosmological distances reach values of $E \cdot d \approx$ TeV Gpc, challenging high-precision measurements in the laboratory. The mixing of photons with ALPs depends on the product of the magnetic field strength B and the propagation distance as shown in section 4.2. The largest values of the product $B \cdot d$ provide the highest sensitivity to this effect. Even with extremely low intergalactic magnetic fields ($\sim 10^{-13}$ T) this product can reach $B \cdot d \approx 3 \times 10^{11}$ T m with very distant sources, a value which is currently not achievable in laboratory environments.

While the production of γ rays from self-annihilating massive dark matter probes fundamental physics at the mass scale of supersymmetric particles, i.e. close to the electro-weak symmetry-breaking scale [1], searches for axion-like particles are sensitive to new physics at intermediate energies of 10^{11} GeV and processes leading to Lorentz invariance violation are expected to be related to the Planck scale ($E_{\text{Pl}} = \sqrt{\hbar c^5/G} \approx 10^{19}$ GeV). Therefore, the propagation of γ rays from distant sources brings new insights on presently unexplored energy domains of particle physics.

In section 2, those γ-ray sources most commonly used in the search for LIV and for photon–ALP mixing are reviewed. Section 3 describes γ-ray propagation in the presence of extragalactic background light and of magnetic fields. The phenomenology of LIV and the relevant constraints from γ-ray observations are presented in section 4.1, whereas the current understanding of photon–ALP mixing (PAM) and corresponding constraints are discussed in section 4.2.

2. Sources of high-energy photons used in the study of propagation effects

High-energy (HE, $E > 100$ MeV) and very-high-energy (VHE, $E > 100$ GeV) photons are produced in the framework of the most violent events occurring in the Universe such as stellar explosions or accretion on supermassive black holes. The relevant acceleration and radiation processes in the three types of sources considered here are briefly described below:

(i) **Gamma-ray bursts (GRBs)**: bright and short flashes of γ-rays are produced following the collapse of a massive star or the coalescence of compact objects in a binary system. This catastrophic event results in a strongly collimated relativistic plasma outflow in which multiple shells travel at different velocities, producing internal shocks. Charged particles accelerated in these shocks further radiate HE photons [2]. Due to the relativistic bulk flow of the emitting plasma, photons are strongly beamed in the reference frame of the observer who also experiences an apparent rapid variability. The prompt emission of photons lasting from less than a second up to a few minutes is of interest for the studies of fundamental physics. It is characterized by high fluxes in the MeV–GeV energy range, with a variability in time of the order of tens of milliseconds. The prompt emission is followed by counterparts at longer wavelengths covering longer periods (up to months or years). So far, GRB emission has not been detected at VHE energies.

(ii) **Active galactic nuclei (AGN)**: the accretion of matter onto supermassive black holes at the center of some galaxies is at the origin of their activity. HE and VHE γ rays originate from a strongly beamed emission in a jet of highly relativistic plasma, most probably via inverse Compton scattering. AGN are variable sources which are observed in two different regimes: steady state (i.e. slow evolution), and flaring states in which strong variations of the γ-ray flux are observed on periods from minutes to months [3]. Gamma-ray energy spectra from these objects suffer an exponential cut-off at the high-energy end, in the TeV regime. This cut-off is mostly related to the absorption of VHE photons through pair-production as discussed in section 3.1. Only AGN with their jet pointing towards the Earth (Blazars) can be used efficiently in LIV and PAM studies.

(iii) **Galactic pulsars**: HE photons are produced around magnetized rotating neutron stars, remnants of supernovae explosions. They are emitted by electrons accelerated to ultra-relativistic energies (Lorentz factors of 10^7) in the magnetosphere of the rotating neutron star. Several models have been proposed to describe the underlying processes, for a review see [4]. Although not very distant, pulsars complement the studies with GRBs and AGN with their very regular pulsed emission at the millisecond scale.

Detailed descriptions of the emission and the acceleration processes for the three types of sources can be found in both volumes of the present thematic issue on γ-ray astronomy [4,2,3].

3. Canonical propagation of high-energy γ rays

3.1. Radiation transport of energetic photons in the Universe

The propagation of energetic photons at energies considered here (10^9 eV to 10^{14} eV) is in most cases well approximated by the propagation in a classical vacuum. However, at cosmological distances, noticeable effects which are intimately linked to the properties of the intergalactic medium (radiation and thermal background plasma) as well as to the quantum electrodynamics (QED) vacuum, can be probed. Before considering modifications of the propagation by effects related to physics beyond the Standard Model, we briefly summarize the evolution of a monochromatic and linearly polarized beam propagating in the intergalactic medium.

The intergalactic medium at redshift z is filled with a very dilute and magnetized plasma (electron number density $n_\mathrm{e} \approx 0.24\ \mathrm{m}^{-3}(\Omega_\mathrm{b}/0.04)(z+1)^3$, with $\Omega_\mathrm{b} = \rho_\mathrm{b}/\rho_\mathrm{c}$ the average mass density of baryons in units of critical density $\rho_\mathrm{c} = 3H^2/(8\pi G)$ for a Hubble constant $H = 74\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$). The plasma frequency in the medium $\omega_\mathrm{pl} = (n_\mathrm{e} \mathrm{e}^2 m_\mathrm{e}^{-1} \epsilon_0^{-1})^{1/2}$ characterizes wave-like excitations of the fluid.

Besides the plasma, an optical/infrared (extragalactic background light or EBL) and cosmic microwave (CMB) photon field with number density $n_\gamma = (n_\mathrm{CMB} + n_\mathrm{EBL})(z+1)^3$, with $n_\mathrm{CMB} \approx 4.1 \times 10^8\ \mathrm{m}^{-3}$ and $n_\mathrm{EBL} \approx 20\ \mathrm{m}^{-3}$ is present throughout the Universe.[1] Additional localized photon fields in the vicinity of galaxies and galaxy clusters can be neglected from the radiation transport in most circumstances [5,6]. The photon state propagating along the direction x_3 characterized by the vector of transverse field strength (ϵ_1, ϵ_2) with energy $\hbar\omega$ is described by the following equation (see, e.g., [7,8]):

$$\left(-\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}x_3} + \omega + \mathcal{M}\right)\begin{pmatrix}\epsilon_1\\ \epsilon_2\end{pmatrix} = 0 \tag{1}$$

where, in the simplified case of a homogeneous magnetic field with a transverse component $\mathbf{B}_\mathrm{T}$, the matrix

$$\mathcal{M} = \begin{pmatrix}\Delta_{11} & \Delta_{12}\\ \Delta_{21} & \Delta_{22}\end{pmatrix} \tag{2}$$

contains off-diagonal elements, which mix the two polarization states due to Faraday rotation and vacuum birefringence [9]. For the energies considered here, we safely neglect the Faraday rotation and only consider the effect of vacuum birefringence related to[2]:

$$\Delta_\mathrm{QED} = \omega \frac{\alpha}{45\pi}\left(\frac{B_\mathrm{T}}{B_\mathrm{c}}\right)^2 \tag{3}$$

with $\alpha = \mathrm{e}^2/(4\pi)$ the fine structure constant and $B_\mathrm{c} = m^2/e \approx 4.4 \times 10^{13}$ G the critical field. The off-diagonal terms are related to Δ_QED by:

$$\Delta_{12} = \Delta_{21} = \frac{3}{2}\Delta_\mathrm{QED} \sin\varphi \cos\varphi \quad \text{with} \quad \cos\varphi = \mathbf{B}_\mathrm{T} \cdot \mathbf{e}_1 / B_\mathrm{T}$$

[1] We neglect for now evolutionary effects for the EBL which are not of importance for the discussion but are included in the calculation presented.

[2] For easier reading, natural units, i.e. $\hbar = c = 1$, are used in Eq. (3), and those immediately following.

The diagonal terms include the effect of the background plasma $\Delta_{\rm pl} = -\omega_{\rm pl}^2/(2\omega)$, and of vacuum polarization:

$$\Delta_{11} = \Delta_{\rm pl} + \left(\frac{7}{2}\cos^2\varphi + 2\sin^2\varphi\right)\Delta_{\rm QED} \quad \text{and} \quad \Delta_{22} = \Delta_{\rm pl} + \left(2\cos^2\varphi + \frac{7}{2}\sin^2\varphi\right)\Delta_{\rm QED}$$

Note that $\Delta_{\rm QED} \propto \omega B^2$ dominates over $\Delta_{\rm pl}$ for sufficiently energetic photons or strong magnetic fields.

So far, the treatment of γ-ray propagation has not included inelastic interactions, like pair-production processes with low-energy background photons ($\gamma + \gamma \to e^+ + e^-$). Given the low matter density, γ-ray interactions in the medium are dominated by the latter process, characterized by the mean free path $\lambda_{\gamma\gamma}$, and additional interactions with the background plasma are negligible. Integrating the inverse of the mean free path of γ rays over the line of sight yields the optical depth $\tau_{\gamma\gamma} = \int \lambda_{\gamma\gamma}^{-1}(E)\,{\rm d}s$; the initial number of photons produced is thus reduced[3] at the detector by a factor $\exp(-\tau_{\gamma\gamma})$. In the standard scenario for photon propagation, $\lambda_{\gamma\gamma}^{-1}(E)$ is given by [11,12]:

$$\lambda_{\gamma\gamma}^{-1}(E) = \int \frac{{\rm d}n_\gamma(\epsilon)}{{\rm d}\epsilon}\,{\rm d}\epsilon \int \sigma_{\gamma\gamma}(\mu,\epsilon,E)\frac{1-\mu}{2}\,{\rm d}\mu \tag{4}$$

The first integration is over ϵ, the energy of the background photon, and the second over $\mu = \cos\theta$, θ being the angle between the propagation directions of the two photons, assuming that the differential number density ${\rm d}n_\gamma/{\rm d}\epsilon$ of background photons is isotropic. The mean free path is $\mathcal{O}(100\ \text{Mpc})$ for energies above 10 TeV and quickly grows to $\mathcal{O}(\text{Gpc})$ for energies $\approx$1 TeV. At energies below 100 GeV, the Universe is practically transparent to γ rays. The cross section $\sigma_{\gamma\gamma}$ averaged over the angle θ peaks at a value of $\epsilon E/m_{\rm e}^2 \approx 1.3$ which corresponds to a photon wavelength of $1.24\ \mu\text{m}/(E/1\ \text{TeV})$. The differential number density ${\rm d}n_\gamma/{\rm d}\epsilon$ is well known for the CMB and closely follows a thermal black-body spectrum, while it is rather difficult to measure or predict for the EBL. According to the current understanding, a strict lower limit can be derived from counting faint sources with, e.g., the Hubble space telescope, while a strict upper limit can be determined from measuring the large scale brightness of the sky, subsequently corrected by subtracting the dominant foreground emissions, those of the Galaxy and the interplanetary medium. For an extensive summary of the background photon field, see [13] and references therein. An intermediate value, most likely close to the reality, has been determined from the measurement of $\tau_{\gamma\gamma}(E)$ using γ-ray spectra measured with the Fermi-LAT instrument [14] and with the H.E.S.S. Cherenkov telescopes [15] (see Section 3.2).

To account for this absorption, the propagation matrix of Eq. (2) is modified by adding $-{\rm i}\lambda_{\gamma\gamma}^{-1}/2$ to the diagonal terms. The standard picture of pair-production leading to absorption is however a simplification, as the pairs produced are subsequently cooling either radiatively via synchrotron or inverse Compton effects or non-radiatively via plasma instabilities induced by the pairs propagating in the background plasma [16]. While it is not yet entirely clear which effect(s) dominate(s), there are two limiting cases:

(i) *Pair production cascade:* the pairs produce energetic photons via inverse Compton upscattering of the background radiation field (mainly CMB). These photons subsequently continue to increase the number of particles at the expense of reducing the average energy per particle: a pair/inverse-Compton cascade develops and channels the energy of the primary γ ray into a large number of lower-energy photons with energies below 100 GeV for which $\lambda_{\gamma\gamma}(E)$ exceeds a few Gpc.

(ii) *Quenched cascade:* in this case, the cascade is suppressed by pairs cooling predominantly through synchrotron radiation rather than by inverse Compton scattering ($\dot{E}_{\rm syn}/\dot{E}_{\rm IC} = u_{\rm B}/(u_{\rm CMB} + u_{\rm EBL}) > 1$). However, when comparing the magnetic energy density:

$$u_{\rm B} = \frac{B^2}{2\mu_0} = 0.024\ \text{eV}\,\text{m}^{-3}\left(\frac{B}{10^{-13}\ \text{T}}\right)^2 \quad \text{with that of the CMB} \quad u_{\rm CMB} = 2.5\times10^5\ \text{eV}\,\text{m}^{-3}(z+1)^4$$

this is obviously only of concern in regions with increased magnetic field strength (clusters of galaxies or environments of active galactic nuclei).

For powerful γ-ray sources with a γ-ray luminosity $L_\gamma > 10^{34}$ W, the excitation of two-stream instabilities by pairs propagating in the background plasma can dominate the energy losses. The growth rate of the instabilities $\propto \gamma L_\gamma/n_{\rm e}^{1/2}$, with γ the Lorentz factor of the pairs, can lead to a suppression of cascade formation [16].

While energy losses through synchrotron emission (dominant in case (ii) above) are generally not important, the subtle effect on the secondary γ-ray emission of the magnetic field deflecting the pairs provides an observational test of the intergalactic magnetic field by measuring the absorbed primary γ-ray component as well as the lower-energy secondary component. This in turn has been used to estimate lower bounds on the magnetic field [17].[4] However, non-radiative cooling effects may weaken these limits.

[3] Note that the integration over the path length ds to obtain $\tau_{\gamma\gamma}$ is sensitive to the actual cosmological model (see, e.g., [10]).

[4] For a review on the magnetic field in the intergalactic medium, see [18].

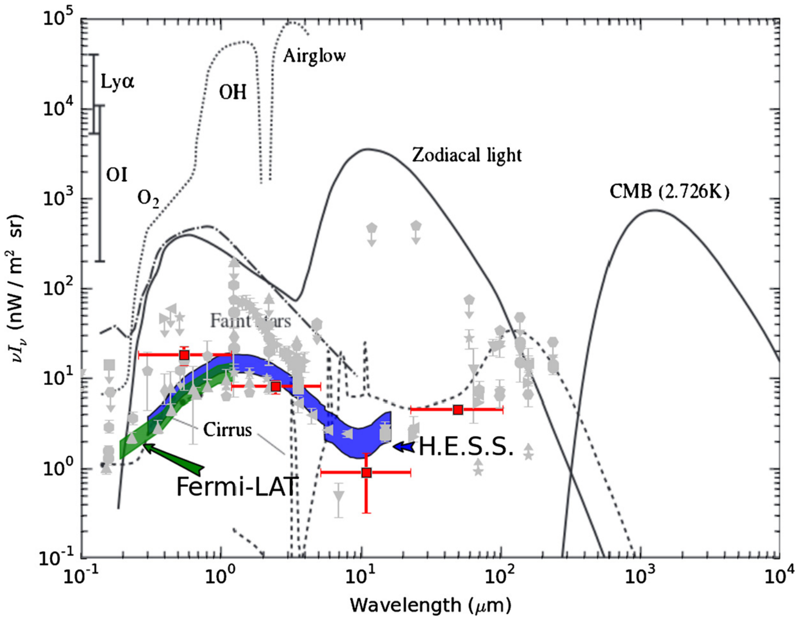

Fig. 1. The sky brightness from ultra-violet to cm-wavelengths (adapted from [51]). To be noted the large foreground emission in the optical to mid-infrared (at ≈10 μm) from the interplanetary medium (zodiacal) as well as from the atmosphere. The contribution of direct stellar light and stellar light scattered by the interstellar medium (cirrus) as well as atmospheric glow are indicated as well. The measurements of the extragalactic background light (in grey and colored markers, for a list of references used here, see the text and [23]) falls in three categories: (i) estimates from source counts and fluctuation measurements, (ii) estimates from integral measurements, and (iii), marked as green and blue bands and red markers with horizontal bars, estimates derived from absorption features in γ-ray spectra. The estimates (i) and (ii) have to be considered as lower and upper limits respectively, given that the source counts are not complete and would miss a truly isotropic component and (ii) suffer from obvious large foregrounds and from unresolved source contributions.

The secondary effects of photon pair-production effectively modify the dispersion relation, implying a change of the optical depth. In some specific scenarios, the generated secondary photons may even dominate the observed γ-ray spectra of distant sources [19].

Introduction of LIV into dispersion relations would lead to a modification of its real component for sufficiently energetic photons. On the other hand, both LIV and PAM act on absorption processes and modify the optical depth τ as discussed in subsections 3.2, 4.1, and 4.2 respectively. In consequence, LIV as well as PAM would lead in the most general case to a directional as well as distance dependence of the dispersion relation.

3.2. Inferring the optical/near-infrared background light from γ-ray spectra

In intergalactic space, the integrated light (ultra-violet, optical, infrared) emitted by distant sources (first stars, galaxies in the early Universe, and any potentially unknown radiation process), forms a mostly isotropic background glow. This radiation component is not to be confused with the cosmic microwave background which is of primordial origin. It carries however vital information on the star formation history of the Universe as well as on the amount of "shining" matter. Any, at this point unknown, light-producing mechanism (first stars, decaying particles) which may have been important in the early Universe could have left its imprint in the spectral energy distribution of this light [20–24]. For an observer on Earth, this extragalactic background light (EBL) is difficult to measure directly as it is small with respect to more prominent foreground emission from the planetary and inter-stellar medium (see Fig. 1 for the spectral energy distribution of the night-sky brightness). The most common approaches have been either related to the counting of faint sources up to the instrumental sensitivity limit[5] (e.g., [25–40]) or measuring the integrated emission subsequently corrected by the model-dependent subtraction of the foreground emission (e.g., [41–50]).[6] Both approaches suffer from the inherent problem that they should be interpreted either as a lower limit (given the limited instrumental sensitivity) or as an upper limit (given that the measurement is done in an integrated way and the foreground emission dominates). Claims for detection have been controversial and not consistent with each other, highlighting the systematic uncertainties which are present.

A promising indirect method which is not contaminated by the disturbing foreground emission is related to the close link between the photon number density in the intergalactic space and the photon-pair absorption (see Eq. (4)). Recalling

[5] Unresolved sources contribute to the noise spectrum.
[6] For further references, see [13].

that the peak in the pair-production rate is reached for a wavelength of 1.24 μm/(E/1 TeV), it is clear that the EBL-induced absorption mostly affects observations in the energy band from 100 GeV to 100 TeV. With the advent of γ-ray measurements from the ground, observations of γ rays up to TeV energies are possible, where absorption through pair-production processes should start to affect the energy spectra.

The discovery of γ-ray emission above 10 TeV from low redshift blazars (Mkn 421 and Mkn 501 at $z = 0.03$) were used to derive the first meaningful constraint on the level of the EBL in the mid-infrared (e.g., [52,53]).

The problem of determining the EBL spectrum n_γ by estimating the optical depth $\tau_{\gamma\gamma}(E)$ from the measured spectrum requires however some assumptions. The early efforts to derive constraints (upper limit on $\tau_{\gamma\gamma}(E)$) were troubled by rather strict assumptions on the shape of the intrinsic spectrum of the γ-ray sources as well as on the spectrum of the background light n_γ. The most common procedure used is to vary the level of the EBL until the corrected γ-ray spectrum shows an apparent unphysical behavior [54–58].

More elaborate approaches include the use of multiple source spectra [59–61] or multi-wavelength observations and models of the γ-ray spectra to reduce the uncertainties related to the unknown intrinsic spectrum [62–64].

Additionally, the shape of the EBL spectrum has been left to vary freely in order to eliminate a model uncertainty [65,66], and the energy range has been extended by including Fermi-LAT observations [67–69]. The result of these approaches have been upper limits on the intensity of the EBL which exclude some integrated measurements and start to close-in on the lowest possible level of the EBL set by optical source count measurements with the Hubble space telescope.

In recent years, the γ-ray energy spectra of AGN have considerably improved in number and in precision. The approaches described above are based upon a comparison of a reconstructed intrinsic spectrum with some assumption on the allowed shape at the emission. This in turn has been used to constrain the maximum optical depth and therefore the level of n_γ under some assumption of its shape. With the improved energy spectra, it has become feasible to search for features related to absorption, e.g., a gradual softening of the energy spectrum. Since this effect is related to the distance of the source, source-intrinsic effects can be ruled out as being responsible for the observation of an increased curvature with increasing redshift of the source.

By fixing the EBL spectrum shape to a fiducial model-dependent one and leaving only a normalization factor ζ to vary, ($n_\gamma = \zeta \cdot n_{\rm fid}$), the characteristic softening of the energy spectrum depends only on the value of ζ. By combining various energy spectra from sources at different z, this method allows ζ to be measured and the intrinsic spectra to be reconstructed at the same time.

This method has been successfully applied to H.E.S.S. observations of AGN providing the first measurement of the EBL level [15]. The result, consistent with previous upper bounds, is found about 20% above the lower limit from source counts (see the blue band in Fig. 1). In parallel to the EBL estimate from ground-based observations, the large sample of γ-ray emitting BL Lac objects detected with the Fermi-LAT instrument has been used to determine a value of ζ in a similar approach [14,70]. The two independent measurements agree quite well (see Fig. 1) and complement each other since the ranges of the covered wavelengths are partly overlapping.

Results of a recent study deriving the EBL from γ-ray spectra of 38 sources are also shown in Fig. 1 by red markers with horizontal bars [71]. The resulting EBL estimate shows notable deviations from model predictions (especially in the lowest band centered at 0.5 μm) and is in tension with lower bounds from source counts in the mid infrared. Future studies and observations will clarify these discrepancies (see section 4.2.1 on possible interpretation of this result in the context of photon–ALP mixing).

Measurements of the opacity of the Universe to the HE and VHE γ rays emitted by extragalactic sources and the knowledge of the underlying processes contributing to the EBL effects are of great importance for standard astrophysics and for physics beyond the Standard Model of particle physics and cosmology. The studies of the EBL phenomena are necessary for AGN and GRB source modeling; they lead to the evaluation of the diffuse radiation fields and of the magnetism of the Universe at large scales and affect LIV and ALP search analyses, as presented in the following sections.

4. Modifications of the canonical γ-ray propagation

4.1. Phenomenology of Lorentz-invariance violation

Lorentz Invariance (LI) is a basic component of Einstein's Special Relativity. It is strictly valid in Quantum Mechanics and has been verified in various accelerator experiments at the electro-weak scale. It is currently assumed that its applicability ranges up to energies close to the Planck energy, $E_{\rm Pl} \simeq 1.22 \times 10^{19}$ GeV, above which known laws of physics are supposed to break down. Testing LI with cosmic γ rays allows probing the full domain of its applicability in the highest observable energy regime.

On the other hand, Lorentz Invariance Violation (LIV) has also been largely predicted in the framework of various classes of Quantum Gravity (QG) models. This effect should occur at the Quantum Gravity energy scale E_{QG}, expected to be of the order of the Planck scale [72] (in some cases lower, e.g., in some Loop Quantum Gravity models [73,74], or in some string-theory (M-theory) models).

Tests of LIV with high-energy photons from distant sources were first proposed by [75,76], according to a scenario of brane-type models [76] in which QG effects result in an anomalous refractive index. During their propagation through the extragalactic medium on cosmological distances, photons from distant astrophysical sources, such as γ-ray bursts (GRBs) and active galaxies, may cumulate tiny QG effects due to the foamy structure of the quantum vacuum. As photon energies are spread over a large range, these QG effects can be detected as corrections to the standard energy-momentum relation written here for real photons. Eq. (5) shows a simple modification of this relation due to LIV terms:

$$E^2 \simeq p^2c^2 \times \left[1 - \sum_n s_\pm \left(\frac{E}{E_{\mathrm{QG}}}\right)^n\right] \tag{5}$$

where c is the usual speed of light (i.e. at the limit of zero photon energy), $s_\pm$ is a theory-dependent factor equal to $+1$ (-1) leading to a decreasing (increasing) photon speed with increasing photon energy, corresponding to the "subluminal" or "superluminal" case. For $E \ll E_{QG}$, the lowest order term in the series not suppressed by the theory is expected to dominate the sum. If the $n = 1$ term is suppressed, e.g., if some symmetry law is involved, the next term $n = 2$ will dominate.

The power of a given source to constrain LIV increases with its distance, its variability in time and the hardness of its energy spectrum. The first two qualities for a given source provide the best limits on the LIV $n = 1$ parameter (case of the high-redshift GRBs), whereas the number of VHE photons plays a crucial role in the determination of the $n = 2$ term (case of TeV blazars). The next generation of the ground-based Atmospheric Cherenkov Telescopes (ACTs) [77] will be able to take advantage of these three factors more efficiently. The practical way to detect the correction terms in formula (5) consists in measuring the arrival time and energy of each photon, which allows energy-dependent light curves of the source to be reconstructed, from which a search for a possible time lag between them can be made. For sources at cosmological distances, the analysis of time lags as a function of the redshift requires a correction due to the expansion of the Universe [78], which depends on the cosmological model. For a given value of the parameter n in Eq. (5) ($n = 1$ or 2), the mean value of arrival time delays Δt between photons emitted at the same time at the source and detected with energies E and $E + \Delta E$ respectively, is related to ΔE by the equation:

$$\tau_n \equiv \frac{\Delta t}{\Delta E^n} \approx s_\pm \frac{(n+1)}{2E^n_{\mathrm{QG}} H_0} \int_0^z \frac{(1+z')^n \,\mathrm{d}z'}{\sqrt{\Omega_{\mathrm{m}}(1+z')^3 + \Omega_\Lambda}} \tag{6}$$

According to [79], the cosmological parameters were set to $\Omega_{\mathrm{m}} = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 2.3 \times 10^{-18}\ \mathrm{s}^{-1}$ in most of the studies considered here.

Various data sets provided by HE and VHE γ-ray astronomy have been used to set limits on the energy scale at which Quantum Gravity effects causing LIV may arise. Until now, mainly time-delay measurements as a function of photon energy were performed assuming a deterministic time of flight vs. energy relation. Stochastic (or "fuzzy") effects postulated by some of the QG models ([76] and references therein) have largely not been investigated yet. Therefore, only deterministic time-dispersion results are discussed here and constraints are set on LIV-induced time delays described by the linear or quadratic term in relation (5). These limits were translated into mainly one-sided 95% confidence limits (CLs) on the QG energy scale in case of linear and quadratic scenarios. The CL calculations followed usual procedures depending on the method used for the extraction of results. In most of the earlier publications, the contributions of systematic errors were not taken into account and the statistical treatment was not always rigorous. Only the latest analyses of a giant flare of PKS 2155-304 and of four remarkable Fermi GRBs (GRB 080916C, GRB090510, GRB090902B, GRB090926A) took these aspects into account using a semi-bayesian methodology, i.e. mixing frequentist and bayesian approaches in different steps.

Results on time-delay measurements and on the corresponding constraints on the E_{QG} during the last 10 years were obtained from satellite experiments and ground-based Cherenkov telescopes observing various sources, such as AGN, GRBs, and pulsars. Indeed, the potential of each time-delay measurement depends on the following conditions:

– the nature of the source, particularly, its variability time-scale;
– the detector performance, i.e. acceptance, angular and energy resolutions;
– the analysis method used to extract possible LIV effects, while controlling systematic errors due to the experimental setup as well as to the nature of the source.

The impact of each aspect is briefly discussed in the following.

(i) *Importance of the variety of sources (GRBs, AGN and pulsars)*. Considering different types of sources is crucial for LIV studies. In LIV effects, photon energies are affected according to the source redshift, which is not necessarily the case if observed delays refer to the emission time at the source. Therefore, population studies at different redshifts allow to discriminate between the two interpretations. Moreover, the coverage of a large energy range (from MeV to TeV) strengthens the overall conclusions from these analyses. The important properties of the considered sources are summarized in Table 1 for GRBs, AGN and pulsars. In particular, close millisecond pulsars offer the opportunity of combining a high variability and a high duty-cycle of observations, unlike GRBs and AGN.

(ii) *Detector response and performance*. The quality factors for LIV studies are a large acceptance, an excellent time resolution for the observation of transient events and a good energy resolution. The best cases considered up to now correspond to a short GRB detected by Fermi-LAT (GRB 091015) providing an important sample of photons in the GeV range and

Table 1
General properties of sources of interest in use for LIV studies.

Property	GRBs	AGN	Pulsars
Redshift	<8.2	<0.8	0
Energy range	<100 GeV	<10 TeV	<300 GeV
Relevant time scales	10–100 ms	1–10 min	10 ms
Intrinsic effects	known	moderate	under control
Best results	GRB 090510 (Fermi)	PKS 2155-304 (H.E.S.S.)	CRAB (VERITAS)

Table 2
Most successful methods developed for LIV studies and used in different analyses.

Method	Experiment	Remarks
Cross-correlation function (CCF)	BATSE (GRBs), H.E.S.S. (AGN)	Low systematics
Energy Cost function (ECF)	MAGIC (AGN)	Good precision
Wavelet transform (CWT)	BATSE HETE-2 SWIFT (GRBs), H.E.S.S. (AGN)	Dependence on LC binning
Likelihood fit	INTEGRAL Fermi (5GRBs), MAGIC H.E.S.S. (AGN)	Most precise with low statistics
Sharpness maximization (SMM)	Fermi (GRBs)	Dependence on source effects
Pair View (PV)	Fermi (GRBs)	Good performance with moderate statistics

to a giant flare of the active galaxy PKS 2155-304 as observed in 2006 with H.E.S.S., yielding thousands of γ rays in the TeV range.

(iii) *Analyses and methods dedicated to the search for LIV effects*. Table 2 lists the variety of methods which were developed and used in LIV studies. The most accurate results came from studies based on maximum likelihood methods. However, due to the importance of the results for physics, a cross-check is mandatory with methods probing different aspects of the light-curves. Systematic effects should also be addressed in a complete way and their values propagated when deriving the QG limits. Indeed, the precision measurements of the time-lags require excellent statistical calibration procedures and a good understanding of systematic uncertainties.

4.1.1. Experimental results from the astrophysical observations of GRBs, AGN and pulsars

In the pre-Fermi era, considerable efforts were already dedicated to GRB measurements in the keV–MeV range, e.g., by Lamon et al. [80] with INTEGRAL, by Bolmont et al. [81] using HETE-2 detections of 15 GRBs and by Rodríguez-Martínez et al. [82] using Swift and Konus–Wind observations of GRB 051221A. At that time, Ellis et al. [83] combined the results from HETE-2, BATSE and Swift GRBs deriving the limit $E_{QG} > 2.1\ 10^{16}$ GeV at 95% CL, still three orders of magnitude below E_{Pl}.

The main break-through in time-of-flight LIV studies came with the Fermi mission and the following detection of numerous GRBs with photon energies up to a hundred GeV, taking advantage of the unprecedented sensitivity of the Fermi Large Area Telescope (LAT) [84,85]. The first publications providing constraints combine data from the Fermi-LAT and those from the Gamma-ray Burst Monitor (GBM) on GRBs 080916C [86] and 090510 [87] (see also Shao et al. [88] and Nemiroff et al. [89] using multiple Fermi GRBs). These data yielded limits on the linear term in relation (5) at the level of the Planck scale, disfavoring several QG models which predict significant deviations at this level. Following subsequent theoretical discussions, new studies were carried out on four "golden" GRBs (GRB 080916C, GRB 090510, GRB 090902B, GRB 090926A), providing important samples of photons in the GeV range, excellent variability in time, and redshift values distributed between 0.9 and 4.3. More robustness on experimental analyses was required at that time. This was fulfilled by cross-checking the three most efficient statistical methods and a better control of systematic uncertainties, resulting in a recent publication by Vasileiou et al. [90]. Fig. 2 shows the τ_n parameters of formula (6) (τ_1 for the linear case, τ_2 for the quadratic term) obtained for the four GRBs with the three methods, each probing different aspects of GRB light-curves. In Fig. 2, the k_n parameters ($n = 1$ or 2) in abscissa are measures of the source distances which take account of the expansion of the Universe during the propagation of photons [78]. Clearly, all values of τ_n are compatible with 0 for the four GRBs with the three methods.[7]

Since no LIV effects have been detected in the preceding analysis, only lower bounds have been set on the linear and quadratic terms of formula (5); they are shown in Fig. 3.[8] Only those on the linear term obtained from GRB 090510 with the three methods exceed the Planck energy scale, the other three GRBs providing bounds an order of magnitude lower. Including systematic effects at the level of statistical errors (i.e. introducing a 100% error increase into likelihood calculations) does not change any of the presented conclusions. The limits on the quadratic term are of the order 10^{11} GeV

[7] The error bars in the figure reflect internal properties of each GRB, in particular the statistics of photons observed in the GeV range. The most precise measurement comes from GRB 090510 which presents the fastest flux variations, at the level of few tens of millisecond. This measurement yields the most stringent limit on the QG energy scale despite the low redshift value of GRB 090510.

[8] In the determination of these limits, Monte Carlo simulations were used to evaluate the statistical power of each method.

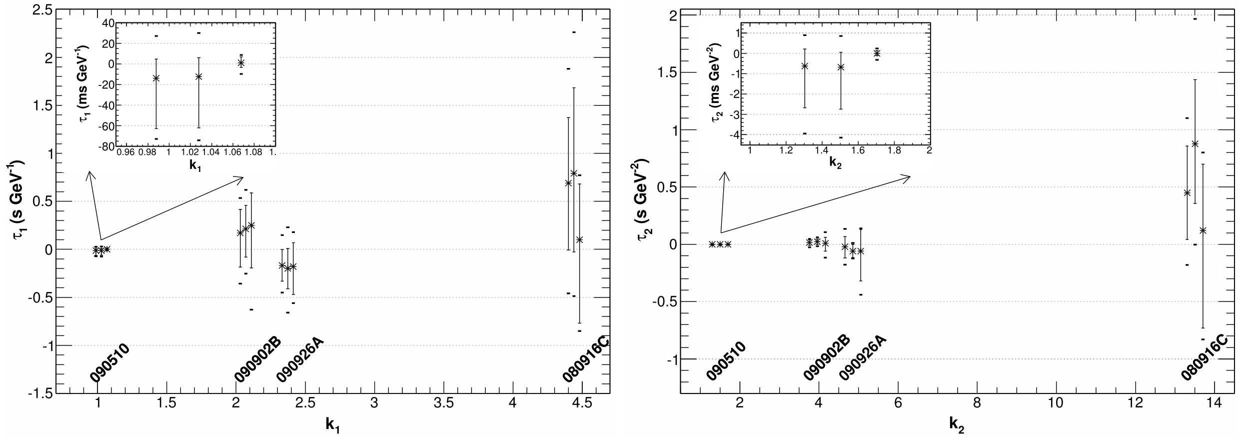

Fig. 2. Results on the parameters τ_n defined in formula (6) from four Fermi GRB, data when applying three different methods in the analysis (left $n = 1$, right $n = 2$). The parameters in abscissa k_1 and k_2 are distance measures taking account of the expansion of the Universe during photon propagation. The most precise measurement was obtained with GRB 090510 with the likelihood approach. It should be noticed that the statistical errors increase with redshift of the source due to a more limited statistics of detected photons (from [90]).

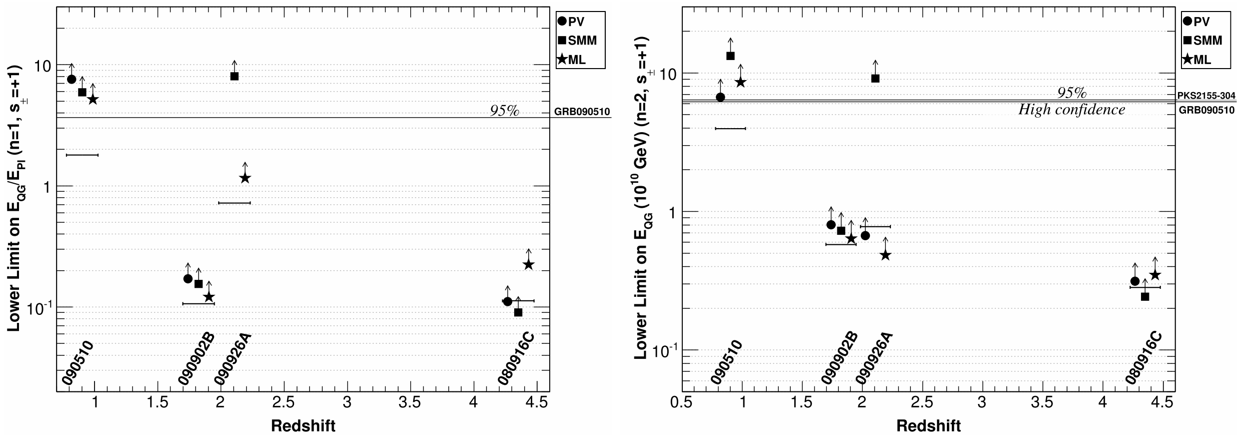

Fig. 3. 95% CLs on QG energy scale with four Fermi GRB data when applying three different methods in the analysis (left $n = 1$, right $n = 2$). The most performing result was obtained with GRB 090510, well above E_{Pl}. The horizontal bars for GRB reflects averaged over three method values of the CLs when the systematic errors have been included (from [90]).

at best, far from the Planck scale. The limitation of time-of-flight studies with astrophysical sources arises from the restricted range in γ-ray energies due to the opacity of the extragalactic medium which affects their propagation through space (see Section 3).[9] Additional studies taking into account a possible dependence of the speed of light on photon helicity leading to much more stringent limits on LIV are presently underway.

In addition to the studies with GRBs, TeV observations of bright AGN flares provided the opportunity to make LIV studies in complementary energy and redshift ranges. AGN observed at TeV energies are less variable than GRBs and have only moderate redshifts, but they provide an extended range of photon energies and usually data samples with higher statistics. In particular, the TeV range is of great importance for constraining the quadratic term in the dispersion relation (5).

Historically, the first attempt to constrain LIV parameters with VHE photons from active galaxies was performed by the Whipple Observatory with data from a Mkn 421 flare in 1996 [93]. The obtained constraint on the QG energy scale was limited by the low statistics of the data sample and the small redshift ($z = 0.03$) of Mkn 421 leading to $E_{QG} > 10^{16}$ GeV, at the level of those obtained with GRBs detected by the hard X-ray missions at that time, far below E_{Pl}. These studies were followed by further AGN flare analyses by MAGIC and H.E.S.S. Cherenkov telescopes with an increased potential due to their improved performance. With the use of sophisticated statistical methods to extract robust limits on the QG scale, constraints on LIV effects were found to be competitive with respect to those obtained from GRBs. The analysis of a flare of Mkn 501 [94,95] by MAGIC and that of the exceptional flare of PKS 2155-304 in 2006 [96,97] by H.E.S.S. lead to bounds

[9] Various models describing the EBL that causes energy loss in the propagation of the photons have been proposed and compared to measurements on high redshift extragalactic sources [91,92].

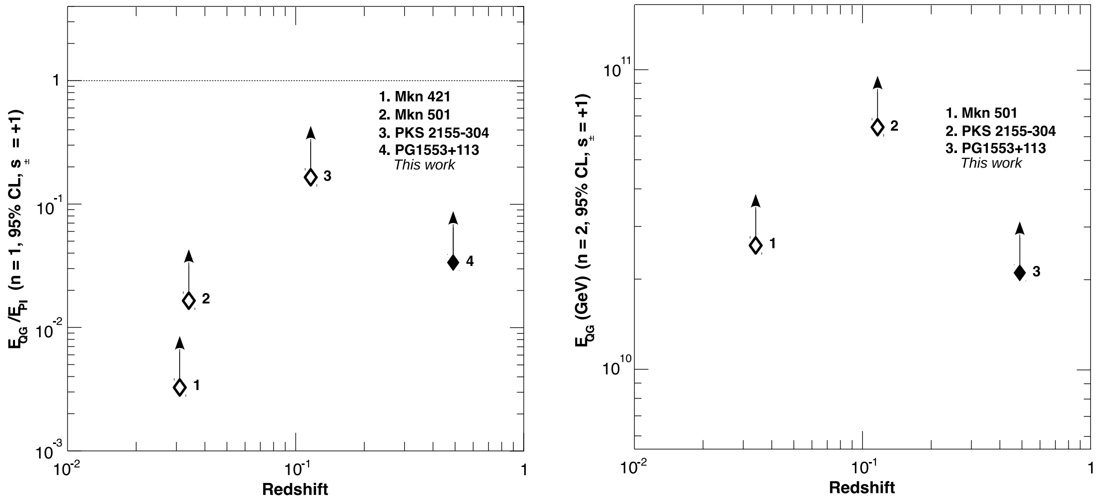

Fig. 4. 95% CLs on QG energy scale with three AGN data from Whipple, MAGIC and H.E.S.S. (left $n = 1$, right $n = 2$). The most performing result was provided with giant flare of PKS 2155-304 in 2006 with thousands of photons were recorded by H.E.S.S. (from [97]). The PG 1553 + 113 results are in press [98].

Table 3
Summary of the results from searches for LIV effects obtained till 2014 with GRBs and AGN. The best limits on the linear dispersion term come from four Fermi GRBs and from the flare of PKS 2155-304 with H.E.S.S. for the linear dispersion term. The best limits on the quadratic term are of the same order of magnitude for GRBs and AGN. Only studies of the four Fermi GRBs and of the flare of PKS 2155-304 take systematic effects into account.

Source	Experiment	E_{QG} (GeV) linear term	E_{QG} (GeV) quadratic term
GRB 021206	RHESSI	1.5×10^{17} GeV	
9 GRBs	BATSE + OSSE	0.7×10^{16} GeV	
15 GRBs	HETE-2	0.4×10^{16} GeV	
17 GRBs	INTEGRAL	0.4×10^{11} GeV	
35 GRBs	BATSE + HETE-2 + SWIFT	1.4×10^{16} GeV	
GRB 090510	GBM + Fermi-LAT	1.2×10^{19} GeV	0.5×10^{11} GeV
4 GRBs	Fermi-LAT	2.5×10^{19} GeV	0.4×10^{11} GeV
Mkn 501	Whipple	0.6×10^{16} GeV	
Mkn 501	MAGIC	0.2×10^{18} GeV	0.3×10^{11} GeV
PKS 2155-304	H.E.S.S.	2.1×10^{18} GeV	0.5×10^{11} GeV

on the QG energy scale only an order of magnitude below E_{Pl}, as shown in Fig. 4. Nevertheless, these results are of great interest for the overall physics picture as they complete the redshift range not covered by the GRB studies. Moreover, in the future, additional progress could be obtained by combining GRB and AGN results.

The first results of interest on LIV effects obtained from pulsars came with the discovery of the VHE periodic emission from the Crab pulsar up to few hundreds of GeV by VERITAS in 2013. Pulsars offer the advantage of a permanent emission with extremely sharp time variations of the order of tens of milliseconds. LIV studies with pulsars are submitted to different systematic uncertainties as compared to GRBs or AGN; in particular, the slow-down processes of their emission period in time are well measured and under control. The present limit obtained from the observation of the Crab pulsar above 100 GeV by VERITAS is of $E_{QG} > 0.02 E_{Pl}$ for the linear dispersion term [99].

In summary, the results on searches for LIV effects obtained up to 2014 with time-of-flight studies with GRBs and AGN are presented in Table 3, showing the substantial progress achieved in the last 10 years. The best limits on the linear dispersion term are those obtained from four Fermi GRBs and from the flare of PKS 2155-304 with H.E.S.S. The best limits on the quadratic term are of the same order of magnitude for GRBs and AGN, much below E_{Pl}. Only the studies of the four Fermi GRBs and of the flare of PKS 2155-304 take systematic effects into account.

On the other hand, while differential time-of-flight measurements with HE and VHE photons provide the most generic and model-independent insight into LIV effects, another approach based on TeV blazar energy spectra has been proposed [100,101]. The γ-ray absorption process by the EBL ($\gamma + \gamma \rightarrow e^+ + e^-$) could be affected by LIV modifying the energy threshold of the reaction. However, population studies depending on source redshifts are also needed in order to disentangle genuine LIV effects from possible source-induced spectral modifications. More recently, as mentioned in section 3.2, modifications of the pair-production thresholds have been investigated in order to extract LIV effects from the spectral shapes of a substantial set of AGN. In this study [71], the lower limit on the QG scale, found to be around 0.6 Planck scale, can be considered as competitive with those obtained from time-of-flight measurements on GRBs and AGN until now. However, in this type of analysis combining measurements from different experiments, the detailed instrumental response must be taken into account since systematic effects play a crucial role in the determination of the limits on LIV parameters.[10]

4.1.2. Discussion of results on LIV and future prospects

One limiting, not yet well studied problem in the interpretation of the results concerns the impact of the emission processes at the source, which depends on the type of object. As an example, it is known that GRBs suffer from intrinsic lags [102,103] as observed already by BATSE: at higher energies, emission peaks at shorter times and photons arrive earlier. Correlations were observed between time-lags and peak luminosity in the keV–MeV range. First tests with Fermi GRBs in GeV energy range including spectral variations have shown no major change in the LIV results and values of the QG energy scale E_{QG}. These effects, related to the underlying mechanism of the GRB emission need further studies with more sources in the analysis.

The search for the LIV-induced effects in the light-curves and spectra of GRBs, AGN and pulsars assuming a deterministic dispersion relation in vacuum made big progress in the last ten years. The study on GRB 090510 provided the most stringent and experimentally solid bound above Planck scale for the linear term, but not an ultimate one, as a unique event. Other results with GRBs, AGN and pulsars, point at limits an order of magnitude below the Planck scale. To make our conclusion robust on the physics side and discuss the validity of proposed theoretical models, more observations of exceptional events as the prompt GRB 090510 or giant flares of high redshift AGN as of the one observed on PKS 2155-304 in 2006 are needed. Also, a combination of already existing results taking into account the redshift of each source would be a step forward in this domain. The stacking procedure would provide a most robust result on LIV effects averaged over systematic uncertainties and almost free from the internal time-delays of each source.

4.2. Phenomenology of photon–ALP mixing

While in the previous section, effects of LIV on the arrival time of photons are considered, we now turn to the possible modification of the optical depth for γ-ray sources. Such an effect can be induced by photons mixing with new particles which are well-motivated phenomenologically as well as theoretically. The axion field was introduced in the framework of an extension of the Standard Model, in order to solve a problem related to CP conservation in strong interactions [104]. This conservation is puzzling since, in the Quantum Chromodynamics (QCD) Lagrangian, a CP-violating term is expected, of the form:

$$\mathcal{L}_{\text{strong,CP}} = \frac{\alpha_s}{8\pi}\,\bar{\theta}\, G_{a\mu\nu}\tilde{G}_a^{\mu\nu} \tag{7}$$

in which α_s is the strong coupling constant, G represents the QCD field tensors and $\tilde{G}$ its dual, and $\bar{\theta}$ is an unpredicted CP violating phase $-\pi \le \bar{\theta} \le \pi$. A priori, a value $\bar{\theta} = \mathcal{O}(1)$ could be expected. However, the experimental fact that the electric dipole moment of the neutron is extremely small ($d_n < 2.9 \times 10^{-28}$ $e \cdot$ m at 90% confidence limit [105]) translates into the constraint $|\bar{\theta}| < 10^{-10}$. The fine-tuning of $\bar{\theta}$ was elegantly solved by Peccei and Quinn by adding a new spontaneously broken global symmetry $U(1)_{\text{pq}}$ [104] with the resulting so-called *axion* field A, with decay constant f_A, canceling out dynamically the CP-violating term according to the modified Lagrangian:

$$\mathcal{L}_{\text{strong, CP}} = \frac{\alpha_s}{8\pi}\left(\bar{\theta} - \frac{A}{f_A}\right) G_{a\mu\nu}\tilde{G}_a^{\mu\nu} \tag{8}$$

A reaches its minimum value $\bar{\theta} f_A$ through non-perturbative effects in QCD.

The oscillation of the field around its minimum gives rise to the axion as a pseudo Nambu–Goldstone boson whose mass is fixed to $m_A \approx 0.6$ meV$(f_A/10^{10}$ GeV$)^{-1}$, with some model dependence on how the additional $U(1)$ symmetry is broken. For a review on the QCD axion, see, e.g., [106].[11]

As a pseudo-scalar boson, the axion a can be coupled to photons through the Primakoff effect[12] ($\gamma +$ (possibly virtual) $\gamma \to a$). The mixing of axions (pseudo-scalar boson) with photons (vector bosons) requires an external field, the axion–two photon interaction being described by the Lagrangian:

$$\mathcal{L}_{A\gamma\gamma} = -\frac{G_{A\gamma\gamma}}{4} A F_{\mu\nu}\tilde{F}^{\mu\nu} = G_{A\gamma\gamma}\,\mathbf{E}\cdot\mathbf{B} \tag{9}$$

where $F_{\mu\nu}$ is the electromagnetic field tensor and $\tilde{F}^{\mu\nu}$ its dual. The coupling constant $G_{A\gamma\gamma} \propto 1/f_A \propto m_A$ is proportional to the mass of the axion. Intensive searches using both laboratory experiments and astrophysical observations have led to constraints on the photon–axion coupling and therefore on its mass to be below a few 10 meV (for an overview see [106]).

[10] It should be noticed here, that blazar energy spectra are also basic ingredients of ALP studies, thus implying a close connection between the LIV and the ALP induced modifications, see the discussion in the end of this article.

[11] For a simple analogy of the Peccei–Quinn mechanism with a snooker table, see [107].

[12] This effect is well-known in the production of pseudo-scalar mesons such as π^0s.

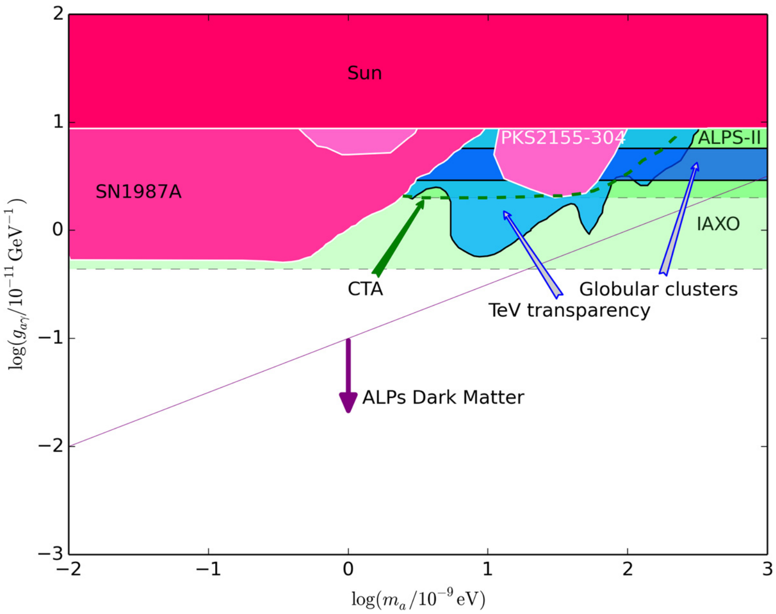

Fig. 5. ALPs parameter space: coupling ($g_{a\gamma}$) versus mass (m_a). The plot is centered on the region where γ-ray observations are sensitive. The diagonal line marks the approximate upper bound of the region of parameter space which would explain the non-baryonic dark matter present in the Universe [110]. Experimental bounds from observations of the sun (CAST experiment [111]), of the active galactic nucleus PKS 2155-304 (H.E.S.S. experiment [112]), and the non-observation of γ-rays from SN 1987 (Solar maximum explorer [113]) are indicated by white boundaries, the pink regions being excluded by these observations. The black lines indicate boundaries of the parameter space which are favored by observations. The enclosed blue regions would explain the anomalous transparency of the Universe to TeV γ-rays [114] and the ratio of horizontal branch stars to red giant stars in globular clusters [115]. One should note the considerable overlap in parameter space of these two independent measurements. The dashed lines indicate the sensitivity of future experiments including the "light-shining through the wall" experiment ALPS-II [116], the planned helioscope IAXO [117], and the future ground-based γ-ray telescope system (CTA) [118].

In a more generic fashion, additional fundamental pseudo-scalars are motivated in specific string compactification models [108], where, besides the QCD axions, further fundamental pseudo-scalars could exist with a logarithmic mass hierarchy (for a review, see e.g., [109]). These so-called *axion-like* particles (ALPs) would share similar couplings to photons via $\mathcal{L}_{a\gamma\gamma} = -1/4\, g_{a\gamma}\, a\ \mathbf{E}\cdot\mathbf{B}$, with a being the ALP-field, $g_{a\gamma}$ its coupling, **E** the electric field, e.g., of a propagating electro-magnetic wave, and **B**, e.g., an external magnetic field.

For ALPs, there is generally no a priori constraint favoring particular regions in the parameter space of mass m_a and coupling $g_{a\gamma}$, unless more specific assumptions on theoretical grounds are included. The above mentioned string compactification model would favor $\mathcal{O}(100)$ different ALPs at logarithmically spaced mass values with couplings between $\approx 10^{-13}$ GeV^{-1} and a few 10^{-11} GeV^{-1} [108].

In Fig. 5, a region of the ALPs-parameter space is shown which is relevant for γ-ray observations. In case of a non-thermal cosmological production of ALPs through the vacuum alignment mechanism [119], ALPs represented below the diagonal magenta-colored line labeled *ALP DM* in Fig. 5 would be candidates for non-baryonic cold dark matter.[13] The most important and strongest constraints are included in the plot as white lines. Values of coupling represented above the white line (pink shades) have been excluded through the following studies:

- searches for ALPs escaping from the hot core of the sun and re-converting into X-ray photons in a transverse magnetic field of a helioscope (e.g., the CAST experiment [111])[14];
- non-detection of γ-rays from the collapsing proto-neutron star in SN1987 [113];
- searches for irregularities in the γ-ray spectrum of the AGN PKS2155-304 [112], see also Section 4.2.2.

The sensitivity of future searches is indicated by light/green shaded regions for the next-generation "light-shining through a wall" experiment ALPS-II [116] and the planned helioscope IAXO [117]. The existing hints for the existence of ALPs are marked as black lines with the blue shaded areas favored by the observational data, e.g., on an anomalous transparency with respect to γ-rays [121,114] and on the live-time of horizontal branch stars in globular clusters [115].

[13] One should note that the previously described axion which solves the CP-problem would be represented outside of the boundaries of the plot. Similarly, searches for ALPs dark matter using micro-wave cavities (so-called haloscopes) start at larger mass values.

[14] A similar constraining bound not shown in Fig. 5 has been derived from the existence of the blue-loop phase in the evolution of massive stars [120].

If nature is so generous as to provide these additional fields as the remnants of physics at a higher energy scale, γ-ray observations would be sensitive to ALPs at a mass scale of $m_a < 10^{-6}$ eV and couplings as low as $g_{a\gamma} = \mathcal{O}(10^{-11}\ \text{GeV}^{-1})$. This mass range is mainly fixed through the external magnetic fields that affect the mixing of photons and ALPs.

The theoretical problem of γ-rays propagating in the presence of an ALP and external magnetic field has been considered by a number of authors since [7]; a recent and fairly complete description of the problem and its solution including absorption effects has been given in [122,123]. The photon state described by the polarization vector $\{\epsilon_1, \epsilon_2\}$ introduced in Section 3 mixes in the presence of an external magnetic field with the ALP state a. The resulting evolution of a photon/ALP-state $\{\epsilon_1, \epsilon_2, a\}$ propagating in the presence of an external magnetic field $\mathbf{B}$ is described by [124,122]:

$$-\mathrm{i}\frac{\partial}{\partial x_3}\begin{pmatrix}\epsilon_1\\ \epsilon_2\\ a\end{pmatrix} = \begin{pmatrix}\Delta_{11} - \mathrm{i}\frac{\lambda_{\gamma\gamma}^{-1}}{2} & \Delta_{12} & \Delta_{a\gamma}\cos\varphi\\ \Delta_{21} & \Delta_{22} - \mathrm{i}\frac{\lambda_{\gamma\gamma}^{-1}}{2} & \Delta_{a\gamma}\sin\varphi\\ \Delta_{a\gamma}\cos\varphi & \Delta_{a\gamma}\sin\varphi & \Delta_a\end{pmatrix}\begin{pmatrix}\epsilon_1\\ \epsilon_2\\ a\end{pmatrix} \tag{10}$$

where Δ_{11}, $\Delta_{12} = \Delta_{21}$, Δ_{22}, and φ, already defined in Sect. 3, are related to the effect of the magnetized background plasma, and to the polarization of the vacuum on the propagating beam. Effects of the Faraday rotation can be neglected at the high energies considered here. The mixing of photons with ALPs in the beam is mediated by the term:

$$\Delta_{a\gamma} = \frac{1}{2} g_{a\gamma} |\mathbf{B}(1 - \mathbf{e}_3)| \approx 1.52 \times 10^{-2} \left(\frac{g_{a\gamma}}{10^{-11}\ \text{GeV}^{-1}}\right)\left(\frac{B_\perp}{10^{-13}\ \text{T}}\right)\ \text{Mpc}^{-1} \tag{11}$$

For a homogeneous medium (constant field B, constant plasma density) and in the absence of absorption, the probability $p_{\gamma\to a}$ of a photon state to convert into an ALP-state after propagating a distance L is given by

$$p_{\gamma\to a} = \sin^2(2\vartheta)\ \sin^2\left(\frac{L\Delta_{\text{osc}}}{2}\right) \tag{12}$$

with the oscillation wave number Δ_{osc} and mixing angle ϑ given by:

$$\Delta_{\text{osc}} = 2\Delta_{a\gamma}\sqrt{1 + \left(\frac{E_c}{E}\right)^2} \tag{13}$$

and

$$\sin(2\vartheta) = \frac{2\Delta_{a\gamma}}{\Delta_{\text{osc}}} = \frac{1}{\sqrt{1 + \left(\frac{E_c}{E}\right)^2}} \tag{14}$$

respectively. At energies exceeding the critical energy E_c

$$E_c = \frac{|m_a^2 - \omega_{\text{pl}}^2|}{4\Delta_{a\gamma}} \approx 2.5 \times 10^{-1}\ \text{GeV}\frac{|m_a^2 - \omega_{\text{pl}}^2|}{(10^{-9}\ \text{eV})^2}\left(\frac{10^{-13}\ \text{T}}{B_\perp}\right)\left(\frac{10^{-11}\ \text{GeV}^{-1}}{g_{a\gamma}}\right) \tag{15}$$

the mixing angle $\vartheta = \pi/4$ leads to maximum mixing, independent of the energy of the photon. The critical energy separates the strong-mixing regime ($E \gg E_c$) from the no-mixing regime ($E \ll E_c$) with a transition region ($E = \mathcal{O}(E_c)$). In the strong mixing regime $\Delta_{\text{osc}} \approx 2\Delta_{a\gamma}$ and the corresponding oscillation length $\Delta_{\text{osc}}^{-1} \approx (2\Delta_{a\gamma})^{-1} = \mathcal{O}(100)$ Mpc for magnetic fields of less than 10^{-13} T, typical of the intergalactic medium. The propagation in an inhomogeneous medium with varying strength and orientation of the magnetic field can be treated with a cell-like approach, where the photon–ALP beam is propagated over cells of size similar to that expected for the coherence length of the magnetic field $\mathcal{O}$(Mpc) [122]. Alternatively, the expected turbulent spectrum of magnetic field strength can be considered directly via Fourier transformations as suggested in [125] with results similar to the cell-like approach.

In the past decade, a number of approaches have been suggested and used to search for signatures of PAM through observations of γ-ray sources, which are detailed in the following sections.

4.2.1. Anomalous transparency for γ-ray photons

Provided that the conversion probability $p_{\gamma\to a} \times p_{a\to\gamma}$ exceeds the probability for absorption, γ-rays can effectively mix with ALPs before being attenuated due to pair-production and further re-convert into photons closer to the observer. In the equilibrium case of strong mixing, one third of the intensity of the photon beam will be propagating effectively as an ALP beam. The initial conversion of γ-rays can take place in the vicinity of the emitting region, e.g., in AGN jets [126–128], in the magnetized intergalactic plasma of galaxy clusters hosting AGN [121], or even in the magnetic field of the intergalactic medium [122]. While the photonic part of the beam is on average attenuated, the ALP beam does not suffer from any losses. When the beam propagates in the magnetic field of our host galaxy, the conversion $p_{a\to\gamma}$ will lead to the appearance of photons in excess of the attenuated beam.

This mechanism leads to a modification of the optical depth in the part of the observed energy spectra submitted to absorption. The energy at which the optical depth is sufficiently large depends on the distance of the source as well as on the structure of the intervening magnetic field. Given the unknown strength of the transverse field, it is not predictable and leads to a stochastic process of conversion/re-conversion, first pointed out in [122].

The effect has been claimed to be present consistently in various analyses of γ-ray spectra observed with atmospheric Cherenkov telescopes [129,123,130,131]. Subsequent discoveries of a number of additional sources strengthen these indications [132,133]. Furthermore, the observation of γ-ray-like extensive air showers at energies $>2 \times 10^{17}$ GeV has been suggested to be consistent with PAM [134]. As discussed previously, the spectral energy density of the EBL has been extracted in the range of 0.2–100 µm using γ-ray spectra of 38 AGN [71]. Even though the authors claim that they find no direct indications for a pair-production anomaly in the extended data-set, the resulting EBL has however two surprising features: a large intensity in the lowest wavelength interval (see Fig. 1), which is not expected from any EBL model and tension with the lower bounds from galaxy counts in the near to mid infrared. Furthermore, their model dependent estimate of the Hubble constant deviates by 2.6 σ (statistical uncertainties only) from the value inferred using, e.g., the Planck data [135]. Even though it is too early to draw firm conclusions, the new study demonstrates that the EBL inferred from γ-ray observations only, may require additional explanations and could point towards an anomalous transparency of the Universe to VHE γ-rays, either through PAM or LIV. Such indications are consistent with the PAM scenario studied in [114] where the photon–ALP conversion takes place predominantly in the magnetic field of the source environment, while the back-conversion takes place in the Galactic magnetic field. The favored regime of coupling and mass, i.e. the region marked *TeV transparency* in Fig. 5, is not ruled out by current laboratory experiments.

The re-conversion of the un-attenuated ALP beam in the Galaxy depends on the strength of the transverse Galactic magnetic field. Even though the large scale structure of the Galactic magnetic field has been studied through polarization data of background radio-galaxies (see, e.g., [136]), the constraints on the strength and orientation of the field outside of the Galactic plane are poorly known. Independently of the particular assumption on the magnetic field structure, it is clear that the re-conversion probability depends on the line-of-sight towards the γ-ray source. This in turn is a unique signature for the interpretation of γ-ray data with PAM [137]. However, the sensitivity of current instruments is not sufficient to detect the directional dependence. Future observatories such as Cherenkov Telescope Array (CTA) [77], even with a rather small data-set of four γ-ray sources, will be sensitive to couplings as low as $g_{a\gamma} > 2 \times 10^{-11}$ GeV^{-1} and $m_a < 100$ neV [118].

4.2.2. Excess noise in γ-ray spectra

The studies discussed so far have been considering the regime of strong mixing where the transparency for pair-production is modified ($E \gg E_c$). At smaller energies, the mixing is less efficient and the propagation in a turbulent/randomized magnetic field leads to additional fluctuations in the observed energy spectra. This effect was first studied in the context of optical spectra from distant quasars [138]. For γ-ray spectra, this approach has been used by the H.E.S.S. collaboration to exclude ALP parameters (i.e. in Fig. 5 the regions marked *PKS 2155-304*) from the well-measured spectrum of a low redshift AGN ($z = 0.116$) [112]. This method is only sensitive in a narrow mass range, because the irregularities are produced for photons of energies similar to the critical energy. Furthermore, the method is more sensitive to the assumed magnetic field; therefore, the two pink exclusion patches shown in Fig. 5 are derived for two different types of magnetic fields.

4.2.3. Disappearance of galactic γ-ray emission

While the conversion/re-conversion leads to the appearance of photons in the optically thick part of energy spectra, the mixing can also lead to an energy-dependent suppression because of photons converting into undetected ALPs. The photon–ALP conversion depends strongly on the line-of-sight orientation with respect to the large scale magnetic field in the Galaxy. This is specifically true for photon beams propagating across different spiral arms. While the propagation in the turbulent magnetic field of galaxy clusters or in the intergalactic medium is not predictable, only the regular component of the Galactic magnetic field is of importance here since, for its turbulent part, the conversion probability is too small to matter. Therefore, the effect can be predicted and an actual set of parameters (mass and coupling) can be determined quite accurately. Initial analyses of HE γ-ray spectra from Galactic pulsars are encouraging [139] and can be extended to other Galactic sources.

4.2.4. Discussion and outlook

The γ-ray observations of sources at very large distances have revealed a puzzling effect where energy spectra tend to be less affected by absorption than predicted in the framework of standard photon propagation. New experiments with more data and better instrumentations, (e.g., the Cherenkov Telescope Array (CTA)) are needed. The notable differences between the two scenarios (ALPs vs. cascades) would be the following:

- Observation of a variability of distant γ-ray sources that is not predicted if a substantial part of the emission is produced in cascades. The latter tend to smear out the variability over time-scales of years [140].
- Angular dependence of the re-conversion effect. In the ALP-scenario, the re-conversion of ALPs in the propagating beam is efficiently taking place in the Galactic magnetic field. Even though the precise structure of the field is not well known, differences in the spectra due to PAM effects will be observable using a large sample of AGN at various distances [141].

– Conversion in the Galactic magnetic field. With sufficiently precise spectra from various Galactic sources, the expected coupling and mass from the anomalous transparency will lead to modulations (photon disappearance at some energies) for Galactic γ-ray sources where the line-of-sight happens to cross spiral arms. In other sources, this effect should be absent [139].

Finally, other independent observations of, e.g., horizontal branch stars in globular clusters [115] or of linear polarization of optical emission from magnetic white dwarfs [142] have the potential to probe the same parameter space of photon–ALP coupling as favored from the anomalous transparency observations. A combined analysis of the available data is pointing towards a consistent picture of new physics at the intermediate energy scale [143].

5. Summary and general discussion

The analyses of a large sample of astrophysical sources, as described in this paper, has brought a new insight into the amount of optical/infrared background light as well as in the area of fundamental physics by testing otherwise well established symmetries and possible implications of their breaking at different energy scales. These searches do not require new or specific astrophysical observations, still leading to results of great importance.

The results on the extragalactic background light inferred from absorption features in γ-ray spectra have helped clarify the amount of optical/infrared light present in the Universe. This in turn can be used to constrain the star-formation history and contributions from new phenomena injecting additional light in the early Universe.

At present, the limits on the energy scale of Quantum Gravity, obtained with a good control of systematics, are close to the Planck scale in case the speed of light varies linearly with photon energies. On the other hand, the quadratic term in the dispersion relations is poorly constrained and needs not only further observations but also a better sensitivity of the experiments in the highest energy part of spectra taking EBL attenuation into account. Verifying the constancy of the speed of light in vacuum is a crucial test of a cornerstone assumption of Einstein's theory. The new potential will come from the CTA project [77], where population studies will provide a gain in sensitivity of an order of magnitude in the energy range of interest, leading to limits on the linear term easily reaching the Planck scale for many sources and, for the quadratic term [144], to bounds two orders of magnitude higher than the present ones.

The spectroscopy of distant AGN spectra at energies well beyond the γ-ray horizon, where the optical depth $\tau_{\gamma\gamma}$ is greater than unity, is sensitive to a possible anomalous transparency of the Universe. Much progress in this field has been achieved in the past years due to a refined understanding of the attenuating background photon field, and to an increase in the number of objects where γ-ray emission is detected at a level above that expected from the absorption process [121]. This has been interpreted in the context of photon–ALP mixing (PAM) [114]. The coupling $g_{\mathrm{a}\gamma}$ between photons and a new light ($m_a < 10^{-6}$ eV) pseudoscalar boson required to explain the observations, points towards new physics at energies in the range 10^{11}–10^{12} GeV, a scale intermediate between that of electro-weak symmetry breaking and the Planck scale. Even though the anomalous transparency could be interpreted in different scenarios as well (e.g., LIV [145] or secondary emission of cascades [19]), the theoretical understanding gives clear predictions which will help distinguish between different interpretations in the future. The observation of various independent phenomena related to the propagation of γ-rays clearly demonstrates that the sensitivity to PAM is comparable to or even better than any other experimental observations. The unique mass and coupling regime probed by γ-ray observations is at the same time accessible to the next generation of helioscopes (IAXO [117]) and "light-shining-through the wall" experiments (ALPS-II [116]). Even the existing CAST experiment after substantial upgrades of the detector system has started to probe the regime favored by the anomalous transparency observations [146].

Finally, it should be underlined that those searches for deviations from the Standard Model based on the propagation of energetic photons from astrophysical sources require taking account of various cross-correlated effects when interpreting results. In particular, a clear connection exists between LIV and PAM effects as presented in this paper.

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