Perspectives on ASTRI observations of AGNs and connections with fundamental physics

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Abstract. With the lack of knowledge of the nature of dark matter and dark energy constituting the majority of our Universe and the search for a unified theory able to describe all particle interactions, the hunt for new physics is nowadays compelling and the astrophysical environment represents a favored place for such studies. We show the high discovery potential of the ASTRI Mini-Array in this respect to study several scenarios: axion-like particles, Lorentz invariance violation, hadron beam.

1 Introduction

Very-high-energy (VHE) astrophysics represents a privileged environment for carrying out studies concerning fundamental physics. The high energies achievable in sources such as blazars [1] (a class of active galactic nuclei, AGNs) allow us to access sectors of particle physics that are difficult to explore in laboratory experiments. Energies in the few hundreds of GeV – hundreds of TeV range are achieved by the ASTRI Mini-Array, a project whose purpose is to construct, deploy and operate an array of nine 4-meter class Cherenkov telescopes at Observatorio del Teide in Tenerife (Spain) with unprecedented sensitivity and energy/angular resolution [2]. The ASTRI Mini-Array will produce exciting new observational data at VHE, which could provide us with information on several fundamental physics scenarios [2]: axion-like particles (ALPs), Lorentz invariance violation (LIV), hadron beam. We concentrate on the blazars Markarian 501 and 1ES 0229+200 since their spectra extend above 10 TeV, where the mentioned new physics phenomena produce detectable effects. We discuss the consequences on these blazar spectra of the above-mentioned models and we show that the oncoming data from the ASTRI Mini-Array are able to shed light on these scenarios of new physics. The paper is structured as follows: we introduce ALPs in Sect. 2, LIV in Sect. 3 and hadron beam in Sect. 4, while we discuss our results and draw our conclusions in Sect. 5.

2 Axion-like particles

ALPs – a generalization of the axion (see e.g. [3]) – are very light, neutral, spin-zero pseudo-scalar bosons predicted by string theory [4] and are presently among the best candidates for dark matter (see e.g. [5]). ALPs denoted by a with mass m_a and interacting with photons with coupling $g_{a\gamma\gamma}$ are described by the Lagrangian

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\, g_{a\gamma\gamma}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}\, a = g_{a\gamma\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a\,, \tag{1}$$

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where **E** and **B** are respectively the electric and magnetic components of the electromagnetic tensor $F_{\mu\nu}$ with $\tilde{F}^{\mu\nu}$ its dual. The most reliable bounds to date on the ALP parameter space $(m_a,\, g_{a\gamma\gamma})$ are represented by the limits derived in [6–8]. QED vacuum polarization [9] and photon dispersion on the CMB [10] effects must also be considered. In Eq. (1) **E** represents the photon electric field, while **B** is the external magnetic field, in whose presence two effects arise: (i) photon-ALP oscillations [9, 11], (ii) the change of photon polarization state [9, 11]. ALPs have huge impact in astrophysical context (for reviews, see [12–14]) and they produce effects on both astrophysical spectra [15–22] and photon polarization [23–29]. We presently have three hints at ALP existence: two arise from blazars [18, 21] and the most recent and strongest one from GRB 221009A [22, 30]. In order to infer the ALP effects on the final spectra of Markarian 501 and 1ES 0229+200, we evaluate the photon-ALP conversion in all magnetized media crossed by the photon-ALP beam following the procedure developed in [20]: (i) blazar jet, starting where photons are emitted, (ii) host galaxy, (iii) extragalactic space, (iv) Milky Way. In all crossed regions average values of the physical quantities are considered. We assume typical values of ALP parameters: $m_a = \mathcal{O}(10^{-10})\,\mathrm{eV}$, $g_{a\gamma\gamma} = \mathcal{O}(10^{-11})\,\mathrm{GeV}^{-1}$. In blazar spectra, photon-ALP interaction produces a photon excess above $\mathcal{O}(10)$ TeV (with respect to EBL [31] absorption only) and spectral irregularities at lower energies.

3 Lorentz invariance violation

Several theories proposed to describe gravity in a quantum fashion predict a violation of the Lorentz invariance above an energy threshold $E_{\rm LIV}$ (see [32]). LIV phenomenology is rich of effects which differentiate it from standard physics expectations [33]. Among several LIV effects, we are interested in the modification of the photon dispersion relation reading

$$E^2 - p^2 = -\frac{E^{n+2}}{E^n_{\rm LIV}}\,, \tag{2}$$

where E and p represent photon energy and momentum, respectively. Equation (2) provokes a modification in the threshold of the process $\gamma\gamma \to e^+e^-$ with a resulting variation of the optical depth of photons propagating over cosmological distances. This LIV effect is relevant for photons with $E \gtrsim \mathcal{O}(10)$ TeV, which experience a larger Universe transparency, as shown in [34]. Therefore, Markarian 501 and 1ES 0229+200 with spectra extending above 10 TeV are optimal targets for LIV studies. In Eq. (2) for the case $n = 1$ we assume $E^{(1)}_{\rm LIV}$ in the range 3×10^{28} eV $< E^{(1)}_{\rm LIV} < 2 \times 10^{29}$ eV: these are values around current LIV bounds [35].

4 Hadron beam

In hadronic models the blazar second spectral hump at gamma-ray energies is due to protons emitting synchrotron radiation or interacting with photons through photomeson reactions [36, 37]. A hadronic model variation consists in the possibility that hadrons accelerated in the jet and generating the "hadron beam" can interact, close to Earth, with background photons (EBL) producing electromagnetic cascades with a resulting hardening of observed photon spectrum [38, 39]. This effect is observed above $\mathcal{O}(10)$ TeV and becomes more evident for farther sources. If the hadron beam crosses intense magnetic fields, it can be strongly deflected increasing the luminosity budget necessary to produce a sizable amount of secondary photons [40]. Furthermore, the hadron beam scenario is not consistent with rapidly varying sources since the cascade process generates a time spread [39]. Therefore, the hadron beam model is considered for 1ES 0229+200 but not for the highly variable blazar Markarian 501.

5 Results and Conclusions

In Figure 1 we show the Markarian 501 and 1ES 0229+200 spectra within conventional physics and when we consider scenarios beyond the standard one: (i) ALPs, (ii) LIV, (iii) hadron beam. Figure 1 shows that both ALP and hadron beam scenarios predict a photon

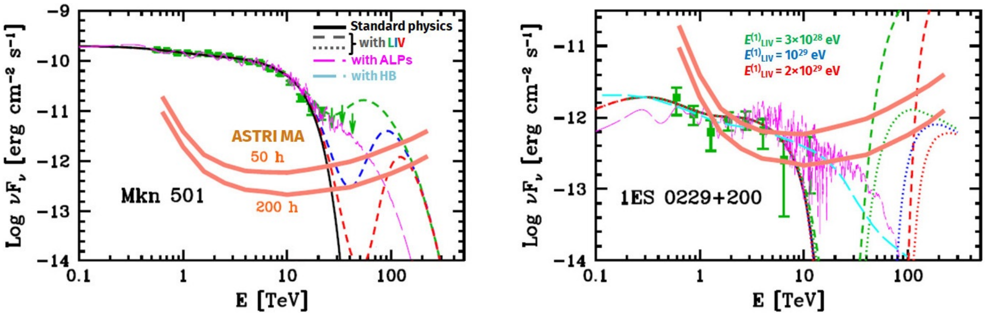

Figure 1. Spectra of Markarian 501 and 1ES 0229+200 within conventional physics and when we consider other scenarios: (i) ALPs, (ii) LIV, (iii) hadron beam (HB). The ASTRI Mini-Array sensitivity curves at 50 h and 200 h of exposure are also shown. For Markarian 501 (observational data are from HEGRA [41]) an intrinsic cut-off power-law spectrum is assumed. For 1ES 0229+200 (observational data are from H.E.S.S. [42]) we take an intrinsic cut-off power-law spectrum in standard physics, and in the ALP and hadron beam scenarios, while we consider an unbroken (short dashed lines) or a broken (dotted lines) power-law spectrum for the LIV scenario, since the latter are the only spectral models able to produce detectable LIV-induced effects within current bounds. (Credit: Figure adapted from [2]).

excess above ~ 10 TeV, while LIV produces a minimum around ~ 40 TeV and a subsequent peak around ~ 100 TeV. The ALP scenario also predicts a peculiar feature: spectral irregularities in the observed spectra, which may be used to disentangle among the different models, as discussed in [43]. In fact, a possible observation by ASTRI Mini-Array of Markarian 501 and/or 1ES 0229+200 (or similar sources) around ~ 100 TeV would be an indication of LIV effects, while a detection of photon excess in the $(10 - 30)$ TeV energy range may be due to both ALP and hadron beam scenarios. Data by CTAO [44] may extend ASTRI Mini-Array results discriminating between the two models: spectral irregularities detected by CTAO would indicate ALP effects, the absence of these features would suggest a hadron beam scenario. The hint at ALP existence coming from GRB 221009A observed above 10 TeV shows the importance of GRBs for fundamental physics studies [22, 30]: ASTRI Mini-Array might detect close TeV GRBs (redshift $z < 0.4$). The ASTRI Mini-Array will benefit from collaboration with other observatories like CTAO [44], LHAASO [45], Fermi [46], IXPE [47], COSI [48]. In conclusion, we have shown the high discovery potential of ASTRI Mini-Array concerning fundamental physics studies: exciting discoveries await us in this field.

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