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CTA sensitivity for probing cosmology and fundamental physics with gamma rays

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The Cherenkov Telescopic Array (CTA), the next-generation ground-based gamma-ray observatory, will have unprecedented sensitivity, providing answers to open questions in gamma-ray cosmology and fundamental physics. Using simulations of active galactic nuclei observations foreseen in the CTA Key Science Program, we find that CTA will measure gamma-ray absorption on the extragalactic background light with a statistical error below 15% up to the redshift of 2 and detect or establish limits on gamma halos induced by the intergalactic magnetic field of at least 0.3 pG. Extragalactic observations using CTA also demonstrate the potential for testing physics beyond the Standard Model. The best state-of-the-art constraints on the Lorentz invariance violation from astronomical gamma-ray observations will be improved at least two- to threefold. CTA will also probe the parameter space where axion-like particles can represent a significant proportion – if not all – of dark matter. Joint multiwavelength and multimessenger observations, carried out together with other future observatories, will further foster the growth of gamma-ray cosmology.

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1. Introduction

Study of γ-ray propagation from bright and distant astrophysical emitters at very-high energies (VHE, $E > 30\,\mathrm{GeV}$) over cosmological distances has emerged as a successful branch of ground-based gamma-ray astronomy over the past decade. Gamma rays emitted by extragalactic sources (e.g. blazars) can interact along their way to the observer, producing of e^+e^- pairs on near-UV to far-infrared photon fields. This results in an absorption horizon for γ rays, beyond which the received emission is suppressed [e.g. 1]. This effect makes it possible to probe the extragalactic background light (EBL), populating the voids of the Large Scale Structure. The uncertain specific intensity of EBL has been shown to agree with expectations from galaxy counts at the $\sim 30\,\%$ level (for EBL wavelengths up to a few tens of μm) based on the data from the current-generation γ-ray observatories (H.E.S.S., MAGIC, VERITAS) (e.g. [2] and references therein). The redshift evolution of EBL however remains poorly constrained by the ground-based telescopes due to small number of γ-ray sources detected beyond $z \sim 0.5$.

Absorption of γ rays on EBL results in generation of e^+e^- pairs, whose propagation is subject to the intergalactic magnetic field (IGMF). The basic properties of IGMF – strength and coherence length – as well as its origin, remain poorly constrained [3]. These pairs reprocess their emission via Inverse Compton scattering of the cosmic microwave background (CMB) photons, resulting in a lower-energy γ-ray signal. The non-detection of the latter in spectral and spatial searches by current γ-ray telescopes has constrained the IGMF strength to be $\gtrsim 10^{-14}$ Gauss for a coherence length larger than a megaparsec and blazar duty cycles $\gtrsim 10^5$ years; see [2] and references therein. The same e^+e^- pairs could also lose their energy through plasma instabilities, whose relative strength to Inverse Compton cooling is under active theoretical debate.

Propogation of γ-rays could also be altered in non-standard scenarios, such as Lorentz invariance violation (LIV) or coupling of γ rays to axion-like particles (ALPs) inside magnetic fields. These scenarios may result in reduction of the opacity of the Universe to multi-TeV gamma ray propagation and specific spectral signatures of Active Galactic Nuclei (AGN) embedded in the magnetic field of their parent clusters; see [2] for a deeper review.

In the near future, Cherenkov Telescope Array (CTA) will open a new page in the studies of VHE blazars. In what follows, we investigate how the CTA AGN [4] and Cluster of Galaxies [5] Key Science Projects can be used to probe γ-ray cosmology. We explore the CTA potential in the so-called Alpha and Omega configurations to measure the EBL imprint in the blazar spectra and to constrain or detect IGMF, ALPs and LIV signatures with deep targeted observations of distant AGNs.

2. CTA measurement of EBL intensity

The specific intensity of EBL can be parametrised by its optical depth $\tau(E_\gamma)$ to the penetrating γ rays. Constraints on it have already been derived with current γ-ray telescopes assuming its linear scaling with respect to a given EBL-model, i.e. $\tau'(E_\gamma) = \alpha \times \tau(E_\gamma)$ (e.g. [6]). In this work, we adopt a similar parametrization in order to illustrate the overall performance of CTA compared to the currently existing instruments and assess its capability to constrain the redshift dependence of the normalization coefficient, α. To this end, out of the database of VHE AGN spectra expected

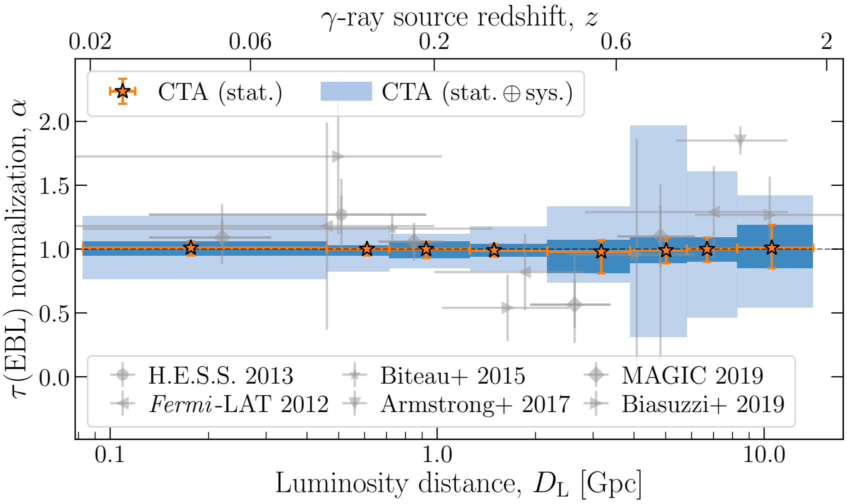

Figure 1: Reconstructed EBL scale factor as a function of redshift. Extracted from [2].

from the CTA AGN KSP, we select a list of candidates expected to be detected at energies beyond the cosmic γ-ray horizon. In total, we simulate around 830 hours of CTA observations.

In order to reconstruct the scale factor α of the benchmark EBL model, we simulate both signal and background counts for each of the blazars selected above and marginalize over their respective intrinsic spectral parameters. To estimate the uncertainties on α, we generate 1000 realizations of the source spectra in each redshift bin and reconstruct the optical-depth normalization for each of these. The systematic uncertainties are estimated via a similar procedure employing the Instrument Response Functions (IRF) bracketing approach.

The obtained results are summarized in Fig. 1. The optical depth scale factor α is reconstructed with an average statistical uncertainty of $< 15\%$. The systematic uncertainty, however, varies from 12% to 50% depending on the redshift. One may note that uncertainties on α resulting from IRF bracketing up to $z = 0.65$ are comparable to those stemming from the state-of-the-art EBL models.

In spite of its simplicity, the performed analysis provides a first illustration of what CTA is expected to deliver. Still, at small redshifts, constraints from blazars with cut-offs at 10 TeV will crucially affect the CTA capability to probe the cosmic infrared background component up to 100 μm, a wavelenth range that is still under-constrained. Low-energy observations of γ-ray sources beyond redshift $z \sim 0.5$ will be important to constrain interactions with UV photons down to 0.1 μm. The CTA low-energy capabilities will also be crucial to constrain the cosmic star formation history, particularly up to its peak located at $z \sim 1.5 - 2.5$. High-precision CTA measurements combined with a large source sample detected beyond $z = 1$ with *Fermi*-LAT may make it possible to probe not only the EBL spectrum at $z = 0$ in the wide $0.1 - 100\,\mu$m range, but also its evolution over cosmic time, including – by means of the integral nature of EBL – contributions from distant UV sources beyond $z \sim 2$.

Though AGN observations will be essential to constrain the EBL spectrum and evolution, complementary constraints on cosmological parameters, such as H_0 and Ω_M, can be expected as well. Indeed, the optical depth $\tau(E_\gamma)$ is roughly proportional to the EBL density and inversely proportional to H_0 (e.g. [7]). Consequently, H_0 uncertainty at least as large as that on the scale factor α may be expected for an EBL spectrum fixed to the level expected from galaxy counts. Dedicated studies will be required to assess the full potential of CTA to constrain cosmological parameters.

3. CTA sensitivity to IGMF

CTA observations promise to address at once several aspects of IGMF influence on the VHE appearance of blazars: time delay of the cascade emission, presence of broad spectral features due to the cascade contribution, and extended emission around otherwise point-like source; see [2] for a deeper review.

Here, we restrict ourselves to IGMF strengths which could result in spectral and morphological signatures in γ-ray observations, i.e. higher than those probed with time delays. We perform simulations of the prototypical extreme blazar 1ES 0229+200, which, owing to its hard intrinsic γ-ray spectrum extending to ~ 10 TeV, and the lack of strong γ-ray variability, is perhaps one of the best-suited sources for cascade signatures searches.

We use the CRPropa code[1] to simulate the development of electromagnetic cascades, assuming a randomly oriented IGMF in uniform cells of 1 Mpc size with the field strength fixed in each simulation. We employ the simplifying assumption, for 1ES 0229+200, of a conical jet with a 10° opening angle, tilted by an angle of 5°. The source intrinsic spectrum is taken to be a power law with an exponential cut-off at $E'_{\rm cut} = 10$ TeV. Finally, we use ctools to simulate a 50-hr long CTA observation and to compute the likelihood for a given set of spectral parameters for each tested IGMF setup.

The CTA sensitivity to IGMF-induced effects is quantified combining both spectral and morphological information. This combination is enabled by updating the extended emission model at each step of the fit according to the point source spectral parameters, using a pre-computed cascade emission library for various IGMF strengths. The detection significance of the cascade component is thus computed self-consistently accounting for both its spectral and morphological features.

It follows that CTA will be able to detect a cascade emission, provided that the IGMF strength smaller than 2×10^{-13} G (for an aligned jet and a coherence length of 1 Mpc). CTA measurements will thus almost close the gap between the existing IGMF constraints and the maximal field strength consistent with galaxy formation models [2]. The derived sensitivity region where the IGMF could be detected with CTA is shown in Fig. 2 along with the existing constraints from various instruments.

It should be noted that blazar duty cycles shorter than $\sim 10^7$ yr would substantially reduce CTA sensitivity to IGMF-induced signatures – e.g. a 30-fold IGMF limit degradation was found in [8] for an activity time scale reduced from 10^7 to 10^4 and from 10^4 to 10 years. A similar degradation should also apply here. On the other hand, a combination of CTA and *Fermi*-LAT data could further broaden the probed parameter space with suitable AGNs, providing contemporaneous observations that are required for variable γ-ray sources.

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[1] `https://crpropa.desy.de/`

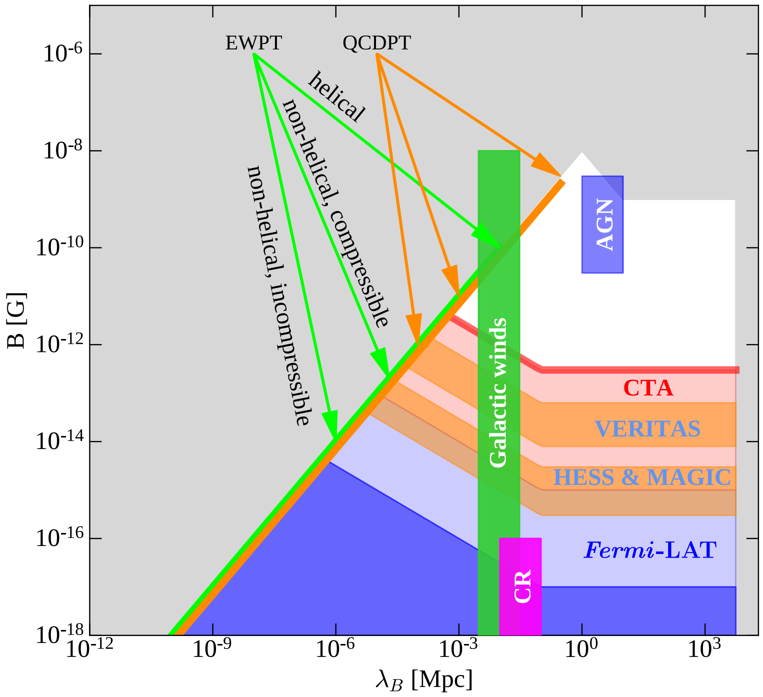

Figure 2: Sensitivity of CTA to IGMF signatures compared to existing observational constraints and theoretical predictions as a function of the IGMF strength B and coherence scale λ_B. The red line marks the maximal IGMF strength that would be detectable at $\gtrsim 5\sigma$ level in a 50 hour long CTA observation of 1ES 0229+200, assuming the $\sim 10^7$ yr source activity. The white region is beyond the sensitivity of the instruments discussed here. Extracted from [2].

4. CTA sensitivity to ALP signatures in NGC 1275 observations

Gamma ray to ALP conversions can lead to distinctive signatures in AGN spectra, including a reduced effective optical depth and oscillatory patterns in AGN spectra that depend on the morphology of the traversed magnetic fields. The search for such features at γ-ray energies has already resulted in the strongest bounds on the photon-ALP coupling to date for the ALP masses between 4 neV and 100 neV ([2] and references therein).

Here, we focus on the CTA sensitivity to these spectral features using simulated observations of the radio galaxy NGC 1275, located in the center of the Perseus cluster. We simulate CTA observations of the Perseus cluster and NGC 1275 to assess its sensitivity to ALP-induced oscillations assuming (i) a 300 hour exposure during a quiescent state with an intrinsic spectrum equal to the average spectrum observed with MAGIC and (ii) a 10 hour exposure during an active state, using the flare spectrum obtained with MAGIC during an event also followed with VERITAS, as described in [2]. Generating 100 random realizations of cluster magnetic-field configurations, we numerically calculate, using the GAMMAALPs code,[2] the probability to observe at Earth a γ ray of either polarization for an initially unpolarized photon beam.

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[2] `https://github.com/me-manu/gammaALPs`; see also these proceedings

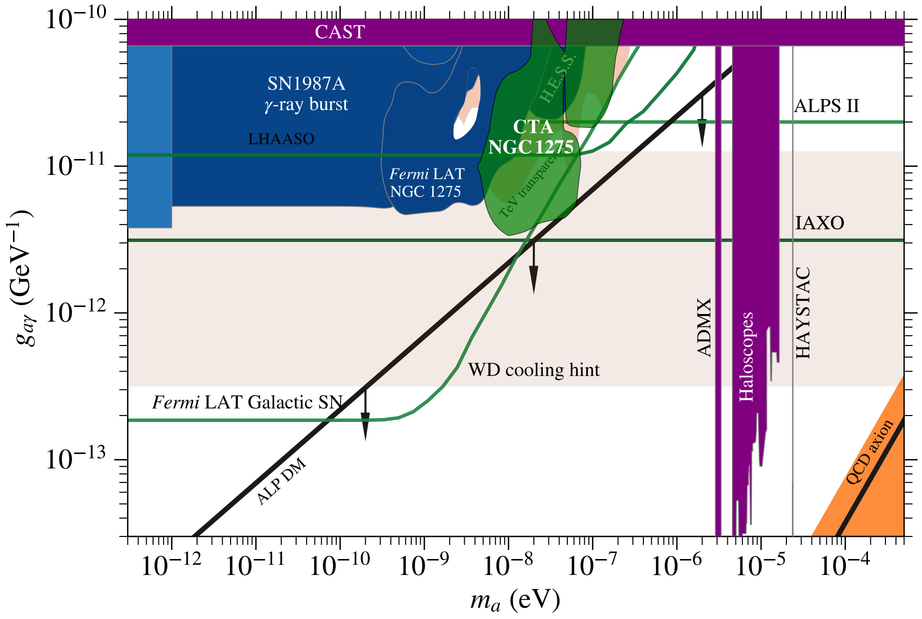

Figure 3: Estimated exclusion regions on ALPs from CTA observations (green filled region) compared to other exclusion regions (blue and purple shaded regions) and sensitivities (green lines). Extracted from [2].

The resulting upper limits on the detectable gamma ray to ALP coupling $g_{a\gamma}$ obtained for the fiducial cluster magnetic-field setup and the flaring state of NGC 1275 are compared to other limits and sensitivities in Fig. 3. Notably, CTA observations will improve upon H.E.S.S. limits on photon-ALP coupling by almost an order of magnitude. CTA will also probe ALP masses an order of magnitude higher than those already probed by *Fermi*-LAT observations of the same radio galaxy. Between ~ 20 neV and ~ 130 neV, CTA could deliver the most constraining limits on ALPs to date and will even start exploring the parameter space range where dark matter could consist entirely of ALPs. Furthermore, CTA observations promise to be more sensitive than future searches with LHAASO for the γ-ray diffuse emission anisotropy above several tens of TeV [9]. In the same energy range, CTA observations could also reach a sensitivity similar to future observations with the IAXO and ALPS II laboratory experiments. Observations of several different sources can be combined to further enhance the CTA sensitivity. At the same time it is worth noting that, in contrast to dedicated laboratory searches, the CTA constraints will be dominated by systematic uncertainties in the model assumptions.

5. CTA sensitivity to LIV signatures in blazar spectra

VHE emission and long distances to γ-ray sources provide a unique opportunity for observational constraints on LIV signatures. The potential signatures of LIV in the γ-ray band are manifold and include, in particular, energy-dependent time delays, vacuum Cherenkov radiation, photon decay and shifts of the pair-production threshold (see [2] and references therein). In this work, we focus on the CTA potential to test LIV-induced modifications of the pair-production threshold in γ-ray interactions with EBL. If pair-production is affected by LIV, this channel would become a sensitive probe of first- and second-order modifications of dispersion relations.

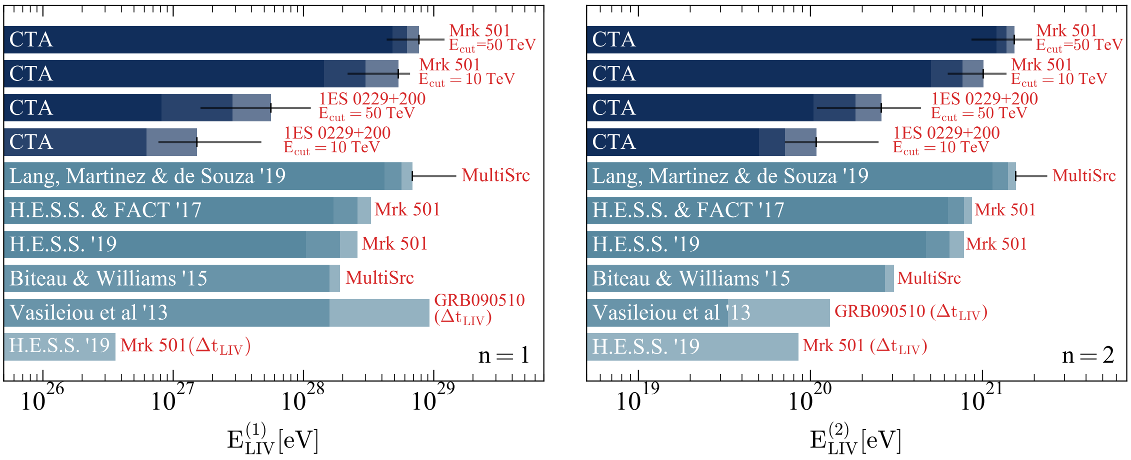

Figure 4: Comparison of LIV energy scales that can be excluded with CTA and existing subluminal searches in the photon sector. Higher confidence levels in the $2, 3, 5\sigma$ sequence are marked with darker colors. Extracted from [2].

Accounting for LIV, the pair production threshold energy for photon-photon head-on collisions is modified as: $\epsilon'_{th} = \frac{m_e^2}{E'_\gamma} + \frac{E'^{n+1}_\gamma}{4\left(E^{(n)}_{\rm LIV}\right)^n}$ where n is the LIV leading order. The Lorenz invariance scenario is recovered with $E_{\rm LIV} \to \infty$.

In the presence of LIV, the observed source spectrum is modified depending on the value of $E_{\rm LIV}$ ([2] and references therein). Increased EBL and gamma ray interaction energy thresholds reduce the number of targets that the highest-energy γ rays may interact with, increasing the transparency of the Universe to γ rays with energies above tens of TeV.

In this work, we investigate the CTA potential to detect LIV on a test case of two blazars, namely Mrk 501 and 1ES 0229+200. Both of them have the spectra that may extent beyond several tens of TeV, while being located sufficiently far so that the γ rays with energy above few TeV are subject to absorption on EBL. This makes them good targets to search for possible γ-ray opacity reduction due to LIV presence (e.g. [10]). A flaring state of Mrk 501 is simulated with a 10 hour long CTA exposure, whereas a long-term observation of 1ES 0229+200 is simulated with a 50 hour one. We assume that the intrinsic spectra of both objects are power laws with exponential cut-offs, whose (comoving) values are set to $E'_{\rm cut} = 10$ and 50 TeV correspondingly. These values are compatible with observations of these objects during their extreme states. We use with GAMMAPY and CTOOLS to perform these simulations.

To exclude LIV signatures in simulated spectra, we fit the spectra simulated both with and without LIV effects assuming LIV leading orders $n = 1, 2$. We then compare the best-fit likelihood values to assess the significance of the LIV contribution. We also account for the uncertainty in the EBL intensity in the models used. The resulting LIV energy scales that can be excluded with CTA based on our calculations are shown in Fig. 4, along with the limits from current-generation instruments using similar analysis techniques.

The predicted CTA limits are more than one order of magnitude better than the recent limits based on energy-dependent time delays stemming from H.E.S.S. observations of Mrk 501

("H.E.S.S.'19" band in Fig. 4). The CTA limits are also 2-3x more constraining than those obtained by any of currently operating instruments using the same channel and observations of a single source. Similar prospects can be expected for the multi-source analysis (see the "Lang *et al.* '19" band in the same figure). Complemented with constraints on time delays from blazars, γ-ray bursts and pulsars, this makes CTA a promising explorer of fundamental symmetries in the photon sector at energy scales that remain beyond the reach of accelerator-based experiments.

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