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Gamma-ray cosmology in the upcoming CTAO era

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The history of photon production and galaxy evolution since the epoch of reionization is encoded in the extragalactic background light (EBL). Above an energy threshold, γ-rays can interact with the optical and infrared photons that dominate the EBL, resulting in an absorption imprint in the spectra of extragalactic sources. The combined observations of the current generation of ground-based γ-ray instruments have recently enabled the first purely parametric γ-ray measurement of the EBL spectrum at $z = 0$ that is independent of models of the evolution of the EBL with redshift. In this work, we extend this γ-ray cosmology analysis to the next generation of γ-ray observatories, the Cherenkov Telescope Array Observatory (CTAO), which will bring improved sensitivity and energy resolution, and broader energy range. Using simulations of almost 3000 hours of observations, we demonstrate the unprecedented precision across the EBL spectrum that CTAO could achieve, and we explore the implications of such a precision for γ-ray cosmology. We show the potential for CTAO to measure H_0, the expansion rate of the Universe at $z = 0$, as well as to place constraints on diffuse emissions from exotic processes.

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1. Introduction

The cumulative emission of photons following the cosmic dark ages constitutes the extragalactic background light (EBL; see [1]), which is predominantly composed of the cosmic optical background (COB; 0.1 – 8 μm) and the cosmic infrared background (CIB; 8 – 1000 μm). The primary contributors to the EBL are resolved galaxies, observed as the integrated galactic light (IGL; see [2, 3]). Although the IGL can be measured with high precision through deep field surveys, it represents only a lower bound on the total EBL intensity, as unresolved, diffuse sources are also expected to contribute to its overall brightness. Gamma-ray cosmology provides an independent and complementary approach to constraining the EBL. At very-high energy (VHE; $E > 100$ GeV), γ-rays possess sufficient energy to interact with EBL photons, producing e^-/e^+ pairs. This interaction induces characteristic absorption features in the VHE spectra of extragalactic sources, which can be exploited to reconstruct the EBL.

The combined observations from the current generation of ground-based γ-ray instruments have enabled a precise measurement of the EBL, independent of both the IGL and models of EBL evolution (see [4]). The inferred EBL intensity at redshift $z = 0$ is found to be consistent with the IGL, thereby leaving limited room for additional diffuse components. In this work, we extend this analysis to the forthcoming generation of VHE γ-ray instruments, namely the Cherenkov Telescope Array Observatory (CTAO), which is expected to provide significantly improved γ-ray sensitivity and energy resolution, and will cover a broader energy range than current-generation instruments. We simulate CTAO observations using the Spectral TeV Extragalactic catalog, (STeVECat; see [5]).[1] In Sec. 2 we present the projected precision with which CTAO could constrain the intensity of the EBL. In Sec. 3, we examine the extent to which current and future EBL measurement precisions can be translated into constraints on decay of axion-like particles (ALPs), which are dark matter candidates. Lastly, in Sec. 4, we explore the potential of the CTAO to measure the Hubble constant H_0, corresponding to the expansion rate of the Universe at redshift $z = 0$. We adopt as a baseline a concordance ΛCDM model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, except in the last section in which we leave H_0 as a free parameter.

2. Prospects for EBL measurements at VHE

The γ-ray cosmology measurement of the EBL reported in [4] was derived using STeVECat (see [5]), currently the most comprehensive catalog of extragalactic VHE γ-ray spectra. In this work, we use STeVECat to simulate the set of extragalactic γ-ray emitters that would have been realistically observed by CTAO, had it operated contemporaneously with the current generation of VHE γ-ray instruments. A total of 228 spectra from STeVECat are selected, each with at least four spectral points and from sources with redshift $z > 0.01$. For the 38 spectra lacking recorded livetimes, we estimate the exposure by extrapolating from the duration of the observation campaign, based on the statistical distribution of the remaining dataset. For each spectrum, we select the best spectral model iteratively from a power law and log parabola, with or without an exponential cutoff, and using the EBL model of [6]. The best-fit spectral parameters are then used as inputs for the simulations, which are performed using Gammapy [7] and the publicly available instrument

[1] https://zenodo.org/records/8152245

response functions of the CTAO array (version `prod5 v0.1`). We simulate 2900 hours of CTAO observations, replicating approximately the planned time allocation for the active galactic nuclei observation program of the Observatory [8].

We adopt the Bayesian analysis framework described in [4]. The intrinsic γ-ray spectra, prior to EBL absorption, are modeled using the log parabola with exponential cutoff. An additional parameter, ε, is introduced to account for potential systematic biases between the true and reconstructed energies of γ-ray events. All spectral parameters are marginalized over in the analysis. The EBL optical depth, $\tau(E, z)$, for γ-rays with observed energy E emitted at redshift z, is defined as

$$\tau(E,z) = \int_0^z \mathrm{d}z' \frac{\partial L}{\partial z'}(z') \int_0^\infty \mathrm{d}\epsilon' \frac{4\pi}{c} \frac{\nu I_\nu(\epsilon', z')}{\epsilon'^2} \int_{-1}^1 \mathrm{d}\mu' \frac{1-\mu'}{2} \sigma_{\gamma\gamma}\left(E(1+z'), \epsilon', \mu'\right), \quad (1)$$

where νI_ν is the EBL specific intensity, and $\sigma_{\gamma\gamma}$ corresponds to the Breit–Wheeler cross section. The comoving distance element in a flat ΛCDM cosmology is given by

$$\frac{\partial L}{\partial z} = \frac{c}{H_0} \frac{1}{1+z} \frac{1}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}. \quad (2)$$

The corresponding absorption imprint induced by the EBL on the γ-ray spectra is then given by $e^{-\tau}$. We assume that the spectral shape and redshift evolution of the EBL can be decoupled, which is an assumption that holds out to redshift $z \sim 1$, and we model νI_ν as a linear combination of eight Gaussian functions in log-space with fixed means and standard deviations.

We apply the Bayesian analysis framework to the simulated CTAO observations. In Fig. 1, we present a comparison between the EBL intensity reconstructed from archival STeVECat observations and that obtained from the simulated CTAO dataset. The reconstructed EBL intensity is overall consistent with the reference model, with the most significant deviation occurring at $\lambda = 35\,\mu$m, where a tension at the $2\,\sigma$ level is observed. In contrast to the analysis performed in [4], high-energy data from *Fermi*-LAT are not used as priors on the intrinsic spectral parameters. Despite this, the resulting relative uncertainties on the EBL intensity are below 4 % between 1 and 5 μm, and below 15 % between 400 nm and 120 μm. This represents a more than threefold and twofold improvement compared to previous constraints, which reported relative uncertainties below 12 % between 1 and 5 μm, and below 35 % between 400 nm and 120 μm.

3. Constraints on ALP-photon coupling

The agreement between the local EBL intensity derived from γ-ray observations [4] and that inferred from galaxy counts [2, 3] enables the constraint on potential EBL components beyond the IGL. One such component could originate from photons produced via the decay of hypothetical axion-like particles (ALPs; see [9, 10]). The axion is a pseudo-Nambu–Goldstone boson postulated in the context of the Peccei–Quinn mechanism to address the absence of charge-parity violation in quantum chromodynamics. This particle is expected to couple to photons through the Lagrangian interaction term $\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$, where $F_{\mu\nu}$ is the electromagnetic field strength tensor and $\tilde{F}^{\mu\nu}$ its dual, a is the axion field, and $g_{a\gamma}$ is the effective axion–photon coupling, which is expected to scale with the axion mass m_a. Both axions and ALPs (which generalize the axions by allowing independent mass and coupling) naturally emerge in some extensions of the Standard

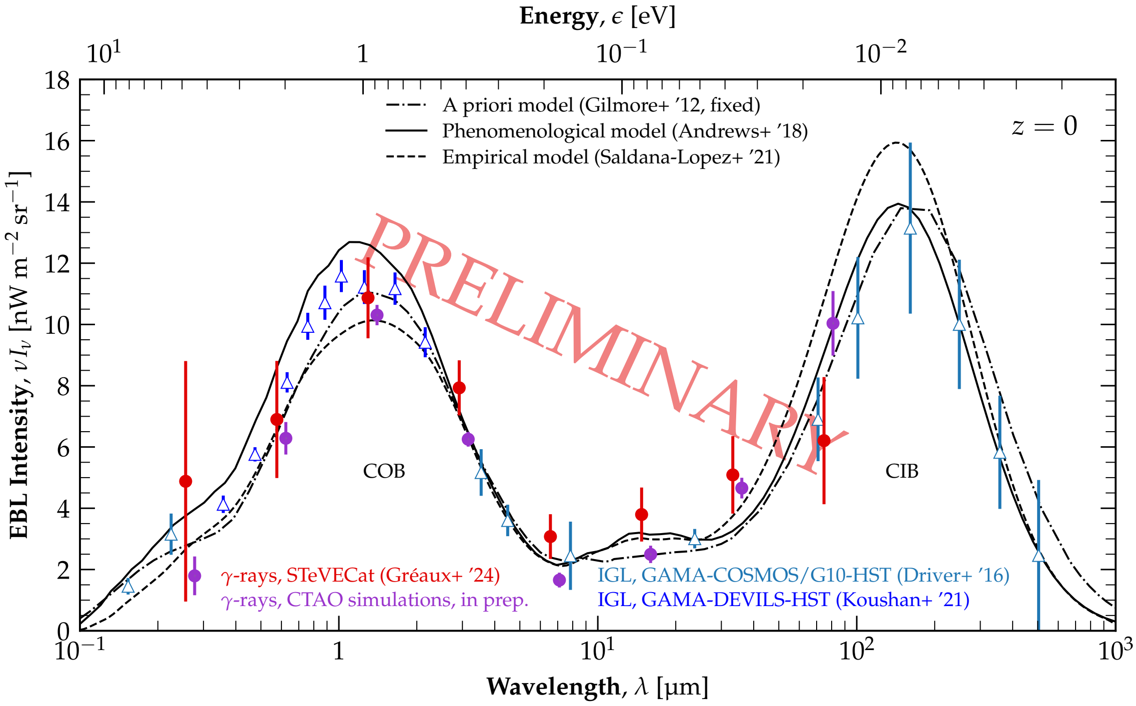

Figure 1: EBL intensity at redshift $z = 0$ as a function of wavelength. IGL measurements from [2] and [3] are shown as light blue and deep blue upward-pointing triangles, respectively. The γ-ray cosmology measurements from [4], based on data from STeVECat [5], are represented by red circles. Projected constraints derived from simulations of how STeVECat spectra would have been observed by CTAO are shown as purple circles.

Model and are viable dark matter candidates. ALPs can be probed through potential oscillations with γ-rays, as described in [11]. Instead of oscillations, we consider more massive ALPs that decay into two photons, each carrying half the rest mass energy of the parent particle, corresponding the wavelength λ_a. Following [9, 10], we assume the ALP emissivity follows a Dirac distribution in the comoving frame. Writing Ω_a for the present-day fractional density of ALPs, the contribution to the EBL intensity can be expressed as

$$\nu I_\nu^a(\lambda) = \frac{\Omega_a \rho_{c,0} c^4}{64\pi} \frac{\left(m_a c^2\right)^2 g_{a\gamma}^2}{\lambda H(z_*)} \Theta\left(\lambda - \lambda_a\right), \tag{3}$$

where $\rho_{c,0}$ is the critical density at redshift $z = 0$, Θ is the Heaviside step function, and $z^* = \lambda/\lambda_a - 1$ denotes the redshift at which ALP decay contributes to the observed wavelength λ.

We assume that ALPs make up the entirety of the dark matter content of the Universe, and we model the EBL intensity as the sum of the ALP-induced component described by Eq. 3 and the IGL inferred from galaxy counts in [2, 3]. This composite model is then compared to the EBL intensity measurements obtained from γ-ray observations from STeVECat reported in [4]. In Fig. 2, we present the 95 % confidence level upper limits on the ALP effective coupling $g_{a\gamma}$, and we compare these results to previous constraints. The limits derived from [4] represent a significant improvement over those obtained in [9], which were based on a smaller VHE dataset combined with high-energy γ-ray observations from the *Fermi* satellite and relied on an assumed redshift evolution

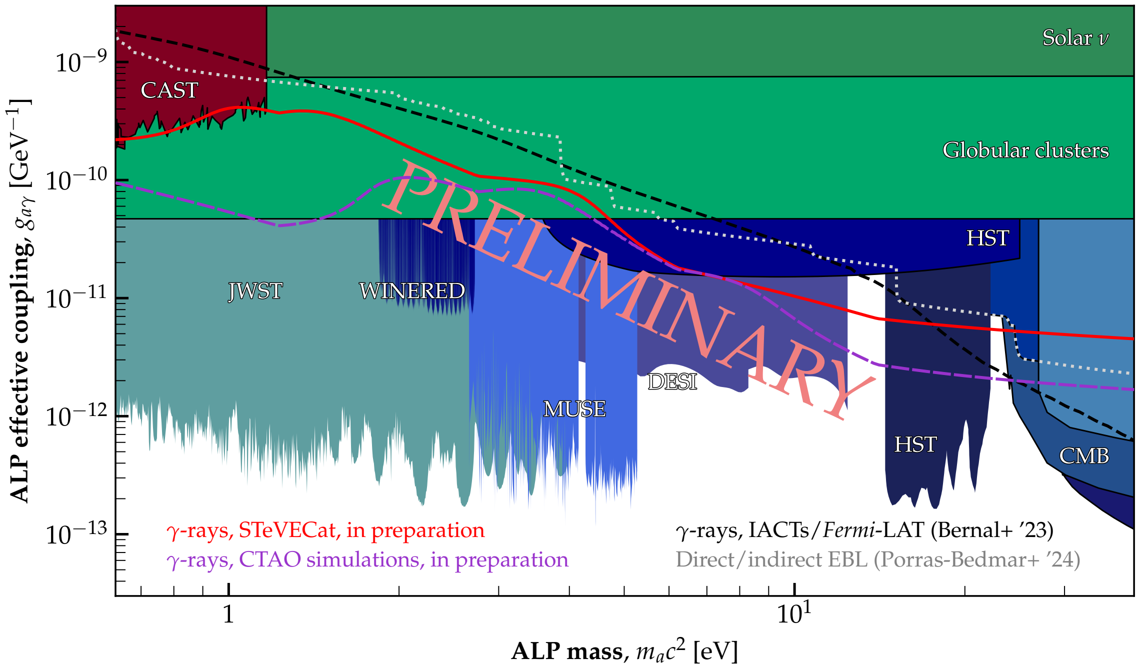

Figure 2: Effective axion–photon coupling, $g_{a\gamma}$, as a function of ALP mass, m_a. The red solid line indicates the upper limits derived from γ-ray measurements reported in [4], while the purple long-dashed line corresponds to limits obtained from simulated CTAO observations based on the STeVECat dataset, as described in Sec. 2. For comparison, the black dashed line shows constraints derived from combined VHE and HE γ-ray observations in [9], and the dotted gray line reflects limits based on direct and indirect EBL measurements from [10]. Parameter space above each curve is excluded. The shaded regions represent exclusion bounds from other searches compiled in [12], where the red area denotes constraints from helioscope experiments, the green areas indicate bounds from stellar emission analyses, and the blue regions correspond to limits from dark matter decay.

model for the EBL. In particular, for ALP masses between 7.5 and 15 eV, we achieve a factor of two to three enhancement in sensitivity. We are able to bridge the gap in the parameter space between the regions probed by the Hubble Space Telescope (HST), by the Dark Energy Spectroscopic Instrument (DESI), and by observations of the cosmic microwave background (CMB). Furthermore, we show in Fig. 2 the projected exclusion limits derived from the EBL intensities obtained in Sec. 2 using simulated CTAO observations of STeVECat. These results indicate that CTAO should enable a further tightening of the constraints on the ALP effective coupling, potentially yielding more than a twofold improvement and complementing measurements from other instruments.

4. The future of Hubble constant measurements

The Hubble constant, H_0, is a fundamental parameter in cosmology which quantifies the present-day expansion rate of the Universe. Over the past decade, increasingly precise measurements have revealed a persistent discrepancy between the value of H_0 inferred from early-Universe observations of the CMB, and that obtained from local distance-ladder methods (see [13, 14]). The value of H_0 can also be constrained through the propagation of VHE γ-rays (see [4]). As shown in

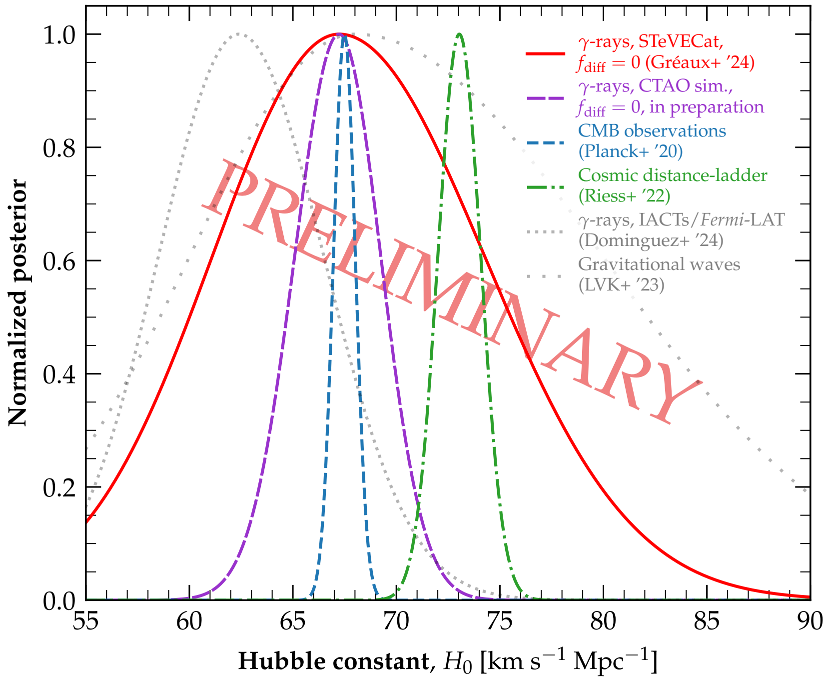

Figure 3: Normalized posterior distribution for H_0. The measurements obtained from CMB observations [13], from the cosmic distance-ladder [14], and from gravitational waves [16] are shown in dashed blue, dashed-dotted green, and loosely dotted gray, respectively. The γ-ray measurement from [15] is shown in dotted gray. The measurement from [4] and measurement prospects from CTAO simulations are shown in red and dashed purple, respectively, considering the value $f_{\mathrm{diff}} = 0$.

Eq. 2, the EBL intensity derived from γ-ray measurements scale inversely with H_0. By contrast, EBL determinations based on galaxy counts are independent of H_0, as they are derived from integrated flux measurements (see [15]). These estimates, however, do not consider potential diffuse components beyond the IGL. Assuming that such diffuse components exhibit a spectral shape similar to that of the IGL, their fractional contribution to the total EBL can be parameterized by f_{diff}, such that EBL measurements derived from IGL scale as $(1 + f_{\mathrm{diff}})$. Consequently, the ratio between IGL-based and γ-ray-based EBL measurements becomes proportional to $H_0/(1 + f_{\mathrm{diff}})$. Using the IGL determinations from [2, 3] as priors, [4] inferred a value of $H_0 = 67^{+7}_{-6}$ km s^{-1} Mpc$^{-1}\times(1+f_{\mathrm{diff}})$.

Forthcoming large-scale surveys conducted by the Euclid mission, the Vera C. Rubin Observatory, and observations with the James Webb Space Telescope are expected to reduce the uncertainties on IGL measurements to the percent level [1]. On the other hand, instruments performing low-surface brightness measurements, such as SPHEREx, are also expected to increase the precision on the total intensity of the EBL and on f_{diff} [17]. In order to assess the precision with which CTAO could constrain H_0, we apply the same procedure as described in [4] to the CTAO observations simulated using STeVECat. We use as priors the IGL measurements from [2, 3], assuming an increased precision due to the forthcoming surveys. Assuming that f_{diff} can be measured with sufficient accuracy, we find that a precision of 3 % on H_0 could be achieved by CTAO. This would represent a significant improvement over the 10 % uncertainty attained by current-generation γ-ray instruments. We show in Fig. 3 what this precision would represent for the results reported in [4], and compare the resulting posterior distribution to other measurements of H_0. Such a precision could potentially help to draw conclusions on the Hubble tension, especially when combined with other γ-ray cosmology measurements of the EBL using the redshift evolution of the EBL (see [15]), instead of its spectrum at redshift $z = 0$.

5. Conclusion

The recent progress in VHE γ-ray astronomy has led to the precise measurement of the EBL [4], in agreement with the leading estimates from galaxy counts [2, 3]. This concordance has allowed a determination of the Hubble constant, independently from the ongoing Hubble tension between CMB observations and distance-ladder-based measurements. In this work, we extend these efforts by deriving new γ-ray constraints based on EBL intensity measurements, placing limits on the decay rate of hypothetical ALPs. We improve the constraints previously obtained with γ-rays, and we exclude a part of the parameter space not previously accessible to other instruments. Furthermore, we extend the Bayesian analysis framework of [4] to simulated STeVECat data [5]. We show that CTAO could achieve relative uncertainties on the intensity of the EBL below 5 % between 1 and 5 μm, and below 15 % between 400 nm and 120 μm. Such precision would surpass the precision of current IGL-based EBL estimates, and could substantially improve constraints on diffuse photon backgrounds, including ALP decay. These findings complement the parameter space explored by studies of low-mass ALPs via γ-ray oscillations [11].

In addition, we show that future IGL measurements with percent-level accuracy [1], when combined with CTAO data, could enable a determination of H_0 with a precision at the 3 % level. The combination of such a measurement at $z = 0$ with estimates derived from the redshift evolution of the EBL [15] could provide a powerful, independent avenue to address the Hubble tension. Furthermore, while the present analysis is limited to redshifts $z \leq 1$ due to the range of the STeVECat simulation, the CTAO is expected to detect sources at higher redshifts. Exploiting the full reach of the observatory should yield unprecedented results for γ-ray cosmology, which will require a comprehensive understanding of all relevant systematic uncertainties, including those associated with instrumental response, energy calibration, and source modeling.

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