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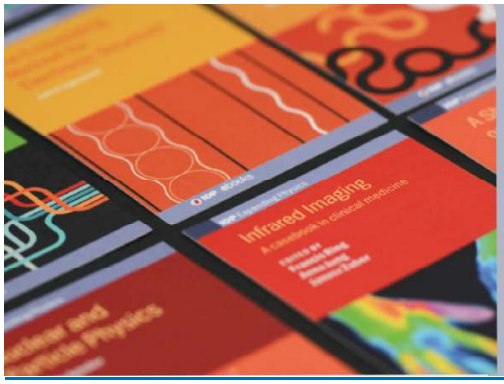
Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation



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1 Gamma-ray propagation on cosmic scales

Over the past decade, the study of γ-ray propagation over cosmological distances has emerged as a successful branch of ground-based γ-ray astronomy. This new field, sometimes called γ-ray cosmology, exploits bright and distant very-high energy (VHE, $E > 30\,\mathrm{GeV}$) emitters as beacons to probe the electromagnetic content and fabric of the Universe.

Gamma rays from extragalactic sources such as blazars, which are active galactic nuclei (AGN) with jets viewed at small angles [1], can interact en route to the observer through processes in the Standard Model of particle physics and beyond. The main effect impacting VHE γ-ray propagation is the production of electron-positron pairs on near-UV to far-infrared photon fields [2–4]. This process results in a horizon [5], located around a redshift $z \sim 1.2$ ($z \sim 0.03$) for γ rays with an energy of 100 GeV (10 TeV), beyond which the Universe is increasingly opaque to higher-energy emission and more-distant γ-ray sources (e.g., refs. [6–10]). This effect also provides a probe of a photon field that populates large voids: the extragalactic background light (EBL) [6]. The EBL is composed of the light emitted by stars, through nucleosynthesis, and by AGN, through accretion, since the epoch of reionization. About half of this light is absorbed by dust grains and reprocessed to mid- and far-infrared wavelengths, while the rest populates the near-UV to near-infrared range (see, e.g., ref. [11]). The EBL is thus a tracer of the integral cosmic star-formation history. While the specific intensity of the EBL remains uncertain due to the difficulties of foreground subtraction in direct observations, current-generation γ-ray observatories (in particular imaging atmospheric Cherenkov telescopes, IACTs: H.E.S.S. [12], MAGIC [13], VERITAS [14]) show agreement with expectations from galaxy counts at the $\sim 30\,\%$ level for EBL wavelengths up to a few tens of μm [15–19]. On the other hand, the redshift evolution of the EBL, partly probed by observations with the *Fermi* Large Area Telescope (LAT, [20]) up to hundreds of GeV [21, 22], remains poorly constrained by ground-based observatories due to the limited number of γ-ray sources detected beyond $z \sim 0.5$.

The electron-positron pairs produced by the interaction of γ rays with target EBL photons are sensitive, due to their charged nature, to the intergalactic magnetic field (IGMF), whose strength and coherence length remain poorly constrained [23]. An IGMF seed is often invoked for dynamo amplification to explain the $\sim \mu$G fields observed in galaxies and clusters of galaxies, but the IGMF origin remains disputed (see, e.g., refs. [23, 24]). It could be either of astrophysical origin, produced with the formation of large-scale structures, or it could be produced in first-order phase transitions prior to recombination. The reprocessing of the energy of the pairs through Comptonization of photons of the cosmic microwave background (CMB) is expected to produce a lower-energy γ-ray signal. For an IGMF strength $\lesssim 10^{-17}$ G and for primary γ-ray energies up to ~ 10 TeV, the γ-ray signal could be observed up to few hundreds of GeV as a beamed component with an extension $\lesssim 0.1^\circ$ (see, e.g., ref. [25]), and as an extended emission for higher field strengths [26]. The non-detection of such spectral and spatial features by current VHE observatories has constrained the IGMF strength to lie outside a range from 3×10^{-16} up to 7×10^{-14} G with at least 95 % confidence for a coherence length larger than 1 Mpc and blazar duty cycles $\gtrsim 10^5$ years [27, 28]. A combination of VHE observations and *Fermi*-LAT data discards configurations of the IGMF with smaller strength [25]. These constraints hold if electron-positron pairs lose their energy predominantly through inverse-Compton scattering with the CMB. The pairs could also lose their energy to the intergalactic plasma by cooling through plasma instabilities. The relative strength of plasma-instability and Compton cooling is under active theoretical debate (e.g., refs. [29–31]).

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