Studying cosmological gamma-ray propagation with the Cherenkov Telescope Array

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The measurement of γ rays originating from active galactic nuclei offers the unique opportunity to study the propagation of very-high-energy photons over cosmological distances. Most prominently, γ rays interact with the extragalactic background light (EBL) to produce electron-positron pairs, imprinting an attenuation signature on γ-ray spectra. The electron-positron pairs can also induce electromagnetic cascades whose detectability in γ rays depends on the intergalactic magnetic field (IGMF). Furthermore, physics beyond the Standard Model such as Lorentz invariance violation (LIV) or oscillations between photons and weakly interacting sub-eV particles (WISPs) could affect the propagation of γ rays. The future Cherenkov Telescope Array (CTA), with its unprecedented γ-ray source sensitivity, as well as enhanced energy and spatial resolution at very high energies, is perfectly suited to study cosmological effects on γ-ray propagation. Here, we present first results of a study designed to realistically assess the capabilities of CTA to probe the EBL, IGMF, LIV, and WISPs.

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1. Extragalactic $\gamma$ ray beacons and CTA

The Cherenkov Telescope Array (CTA, [1]) is the next-generation ground-based $\gamma$-ray observatory. With two sites equipped with a total of close to a hundred imaging atmospheric Cherenkov telescopes, the CTA Consortium and guest observers will have access to full-sky coverage, unveiling an unprecedented view of the $\gamma$-ray sky from 20 GeV up to 300 TeV. CTA observations of extragalactic sources will revolutionize the field of $\gamma$-ray cosmology, which aims at constraining the propagation of the highest-energy photons over cosmological scales observed thus far. In particular, the CTA Consortium has singled out key science projects [1] dedicated to extragalactic science including, but not limited to:

- **Extragalactic survey**: consisting in a blind survey of 25% of the sky down to $\sim 6$ mCrab, for a proposed total of $\sim 1000$ hours of observations over 10 years.

- **Transients**: among other things aiming at swift target-of-opportunity observations of $\gamma$-ray bursts, which could be detected beyond $z = 2$.

- **Active Galactic Nuclei** (AGN): with a long-term monitoring program of known variable objects ($\sim 1500$ hours proposed), a program aiming for a catalog of high-quality spectra ($\sim 600$ hours proposed), and a program aimed at catching flares, based on both external or internal triggers.

- **Clusters of galaxies**: focused in particular on the Perseus cluster, hosting the known $\gamma$-ray emitting AGN IC 310 and NGC 1275 ($\sim 300$ hours proposed).

In the following, we illustrate how these dedicated observation programs combined with the outstanding instrument response function (IRFs: effective area, energy resolution, angular resolution) of CTA will radically transform the field of $\gamma$-ray cosmology.

2. Interaction of $\gamma$ rays and diffuse background photons

The Universe is not fully transparent to $\gamma$ rays from extragalactic sources. These can annihilate with lower energy photons filling the voids, thus generating $e^+e^-$ pairs [2, 3]. These low energy photons ranging from UV to far infrared wavelengths constitute the extragalactic background light (EBL), which is the second most intense cosmic photon field after the cosmic microwave background (CMB). The amount of $\gamma$-ray absorption can be quantified by the $\gamma$ ray optical depth, $\tau$, which depends on the $\gamma$-ray energy, $E$, and the redshift of the source $z$, as follows:

$$\tau(E, z) = \int_0^z \frac{dL}{dz} \frac{\partial n}{\partial \epsilon}(\epsilon') \int_{\epsilon_{\rm thr}}^{\infty} \epsilon' \frac{\partial n}{\partial \epsilon}(\epsilon, \epsilon') \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E \times (1+z'), \epsilon, \mu)$$

(2.1)

where $\partial L/\partial z$ is the distance element, depending on the cosmology, $\partial n/\partial \epsilon$ is the EBL density per energy band, $\epsilon_{\rm thr}$ the threshold energy of the EBL photons, and $\sigma_{\gamma\gamma}$ the pair-creation cross section.

The number of $\gamma$ rays reaching Earth is reduced by a factor $\exp(-\tau(E,z))$ resulting in an increasingly weaker flux at higher energy and higher redshift. The $\gamma$-ray absorption due to the EBL shows a distinctive dependence on both redshift and energy, which was first extracted in Refs.
by constraining the normalization of template EBL models. These first detections at GeV-TeV energies are illustrated as red and light-blue points in Fig. 1 for the model from Ref. [6].

We evaluate the capabilities of CTA by simulating observations of 15 long-term monitored sources selected in the AGN key science project [1], with an exposure of 100 hours per source, expected to be reached after a 10-year long course. We extract the average GeV-TeV emission of each source from the 3FHL catalog [7] as cumulated by Fermi-LAT over 7 years. Each spectrum is either modeled as a power law or a log-parabola, depending on the significance of the curvature, to which we add an exponential cut-off at \(E'_{\text{cut}} = 1\) or 3 TeV in the frame of the emitting galaxy, that is at \(E_{\text{cut}} = E'_{\text{cut}}/(1+z)\) in the observer’s frame. Such cut-off values have proven to roughly reproduce the low flux states observed by current generation ground-based instruments such as H.E.S.S., MAGIC, and VERITAS. The absorption due to the EBL is in turn modeled according to Ref. [8].

To reconstruct the factor normalizing the amount of absorption due to the EBL, \(\alpha\), the intrinsic spectrum of each source is modeled as a power law with an exponential cut-off or as a log-parabola with an exponential cut-off, using as a first step the intrinsic model selected for the simulation. The intrinsic spectral parameters are left free to vary in the fitting procedure. Absorption is included by multiplying the intrinsic spectra by a factor \(\exp(-\alpha \times \tau(E,z))\). The parameter \(\alpha\) is common to multiple sources, which are grouped by redshift bins of width 0.1. The reconstructed normalization as a function of redshift is shown in Fig. 1.

\[\text{Normalized EBL opacity vs redshift} \]

\[0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \quad 1.2 \quad 1.4 \quad 1.6 \quad 1.8 \quad 2 \]

\[\text{Redshift } z\]

\[0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \]

\[\text{PRELIMINARY}\]

**Figure 1**: Normalization of the EBL vs redshift with respect to a template model, as measured by Fermi-LAT (light-blue squares) and H.E.S.S. (red circles), and as simulated for CTA (dark blue circles) within the AGN long-term monitoring program. **Note**: these preliminary points were obtained without cut-off, to be updated.

The order-of-magnitude improved sensitivity of CTA, combined with a dedicated AGN observation program, will enable for the first time the probe of the evolution of the EBL opacity at the XX% level up to a redshift of 0.5, relying solely on the long-term monitoring program. The study of flaring and transient sources up to and beyond a redshift \(z = 1\) is left for upcoming developments, together with detailed studies of the spectrum of the EBL.
3. Fate of the $e^+e^-$ pairs

If the $e^+e^-$ pairs resulting from the interaction of $\gamma$ rays with EBL photons predominantly cool through inverse-Compton scattering off CMB photons, they would initiate an electromagnetic cascade: the CMB photons are up-scattered to $\gamma$-ray energies and can again pair-produce on the EBL [9]. The spectral, spatial, and temporal signatures of this secondary $\gamma$-ray emission depends on the deflection of the $e^+e^-$ pairs in the intergalactic magnetic field (IGMF) [10, 11]. Therefore, the (non-) observation of this signal can be used to infer (or limit) the IGMF strength, $B$, and coherence length, $\lambda$; parameters that are currently only poorly constrained and could trace the possibly primordial origin of cosmic magnetism [12].

Observations of extreme blazars that show hard $\gamma$-ray spectra extending beyond TeV energies, or conversely optical depths $\tau \gg 1$, are best suited for searches of the cascade emission. Such sources provide a large energy flux that can be reprocessed into the cascade. Fermi-LAT and IACT observations of these objects have already been used to limit $B \gtrsim 10^{-19}$-$10^{-16}$ G due to the absence of a spectral bump at GeV energies (e.g. Ref. [13] for a recent analysis) or the non-observation of extended emission around these sources [14, 15]. These limits sensitively depend on the assumed intrinsic source spectrum [16] and source activity time [17].

With its improved sensitivity, energy range, and spatial resolution, CTA will be perfectly suited to search for cascade emission. Considering only the spectral features, CTA could improve current limits on the IGMF by more than an order of magnitude with the observation of only 4 extreme blazars [18]. These results were based on cascade simulations with a 1D Monte Carlo code [19] and early IRFs. In the left panel of Fig. 2, we show simulated CTA observations of the extreme blazar 1ES 0229+200, using the CRPropa 3D Monte-Carlo code to simulate the cascade [20].

As an example, we assume $B = 10^{-15}$ G and $\lambda = 1$ Mpc and that source has been active long enough such that all cascade photons have reached Earth. The intrinsic spectrum is described by a power law with index $\Gamma = 1.5$ and an exponential cut-off at 10 TeV and the EBL absorption is taken from Ref. [8]. Signal and background events are integrated within a region with a radius of 1°. The excess of secondary $\gamma$ rays is clearly visible below $\sim 500$ GeV in comparison to the spectrum simulated without the cascade contribution.

The spatial profile of the CRPropa simulation output is shown in the left panel of Fig. 2 for energies above XX GeV. The simulation output has been smoothed with a 2D Gaussian with a width of 0.1°, which roughly corresponds to the envisioned CTA point spread function above 100 GeV. A jet opening and observation angle of $\theta_{\text{jet}} = \theta_{\text{obs}} = 5^\circ$ are assumed, giving rise to the asymmetric shape of the emission (in accordance with e.g. Refs [21]). CHECK ASSUMPTION ON TIME DELAY, CHECK INTRINSIC SOURCE PARAMETERS, EBL, ENERGY INTEGRATION FOR SKYMAP WITH IEVGEN

Dedicated analysis tools are under development to simultaneously search for the spectral and spatial cascade signals, as predicted from these simulations. A comprehensive scan of the IGMF parameter space, allowing also for a turbulent or helical IGMF, together with a likelihood stacking analysis of numerous extreme blazars that will be observed with CTA, promise the best sensitivity for a detection of an IGMF signature so far.
4. Coupling $\gamma$ rays and WISPs

Measuring $\gamma$ rays from distant galaxies also probes the interaction between photons and weakly interacting sub-eV particles (WISPs). The photon-WISP interaction can leave unique features in the spectra of AGN, as photons oscillate into such particles in the presence of electro-magnetic fields (see e.g. Ref. [22] and references therein). Such particles arise in various extension of the standard model and are well-motivated particle candidates for cold dark matter (see e.g. Ref. [23]). The most prominent example of a WISP is the axion which was originally proposed to solve the so-called strong CP problem [24]. Observations of $\gamma$ rays from blazars are usually only sensitive to oscillations between photons and WISPs but axions could be probed in scenarios where the photon-axion coupling is exponentially enhanced [25].

One observable feature of photon-WISP oscillations are spectral irregularities that should be imprinted on spectra around a critical energy, $E_{\text{crit}} \sim 2.5\,\text{GeV} \left( m_a^2 - \omega_{\text{pl}}^2 / g^2_{11} B \mu G \right)$ (e.g. Ref. [26]), where $m_a$ is the WISP mass in neV, $\omega_{\text{pl}}$ is the plasma frequency of the medium in neV, $g_{11} = g_{\gamma\gamma} / 10^{-11} \, \text{GeV}^{-1}$ is the photon-WISP coupling, and $B \mu G$ is the external magnetic field in $\mu G$. The absence of irregularities in X-ray and $\gamma$-ray spectra of AGN in centers of galaxy clusters have already provided strong limits on $g_{\gamma\gamma}$ for masses below $m_a \lesssim 20\,\text{neV}$ (e.g. Refs. [27, 28]). With its large collection area and energy coverage, CTA is perfectly suited to extend WISP searches to regions where WISPs could constitute the entirety of dark matter.

Figure 3 shows a simulated observation of NGC 1275, the central galaxy of the Perseus cluster, including photon-WISP oscillations. We adopt the same assumptions for the cluster and Milky Way magnetic fields as in Ref. [27] and use a broken power law to model the intrinsic spectrum of the AGN. The spectral parameters are chosen such that the spectrum connects the spectra observed with *Fermi*-LAT [27] and MAGIC [29]. The MAGIC observations revealed a steep power law with index $\Gamma = 3.8$ between 90 GeV and 1.2 TeV. We assume a single possible realization of the turbulent magnetic field and WISP parameters $m_a = 50\,\text{neV}$ and $g_{\gamma\gamma} = 5 \times 10^{-12} \, \text{GeV}$. These parameters are currently not probed by any experiment and lie within the region where WISPs could constitute the
entire dark matter content of the Universe. The simulated spectrum including spectral irregularities is shown as a blue solid line in Fig. 3. Using the latest IRFs and assuming an observation time of 300 hours, as currently foreseen in the galaxy cluster key science project [1], results in the simulated black data points. A fit with a smooth log parabola (orange band) reveals distinctive residuals due to the photon-WISP oscillations and a large $\chi^2$/d.o.f. = 94.8/48, which corresponds to a $p$-value of $7 \times 10^{-5}$. This preliminary result demonstrates that CTA will be able to probe new regions of the WISP parameter space. Following e.g. Ref. [27], dedicated analysis techniques will be developed in the future in order to identify the full $(m_{\nu}, g_{\alpha\gamma})$ parameter space that can be probed with CTA.

![Simulated CTA spectrum](image)

**Figure 3:** Simulated observation of NGC 1275 including the effect of photon-WISP oscillations in one random realization of the turbulent magnetic field of the Perseus cluster and the coherent magnetic field of the Milky Way.

5. Probing physics up to the Planck scale and above

Finally, studying $\gamma$ rays at the highest energies enables the search for Lorentz invariance violation (LIV). While quantum-gravity phenomenology is still an exploratory field, a leading-order modification of the photon (and lepton) dispersion relation could become important close to a so-called quantum gravity energy scale, $E_{QG}$, around e.g. the Planck scale, $E_{Planck} = \sqrt{\hbar c^5/G} = 1.22 \times 10^{28}$ eV [30]. While such an effect has often been searched for in the time domain (e.g. with GRBs [31]), which assumes that the Hamiltonian relation $v = \partial E/\partial p$ is still valid close to $E_{QG}$, a complementary channel has been identified in the modification of the pair-creation threshold, which in turns assumes conservation of the four-vector momentum in a preferred frame [32, 33, 34].

For subluminal effects and assuming that only the photons are affected, the threshold for pair-creation is modified as $E_{thr} > m_{\nu}^2 c^4/E \times [1 + (E/E_{QG})^{n+2}]$, where $E$ is the EBL photon energy, $E_{QG}$ the $\gamma$-ray energy, $n$ the order of the modification ($n = 1, 2$ for a linear/quadratic modification), and $E_{\gamma,11V} = [4m_{\nu}^2c^4E_{QG}^2]^{1/(n+2)}$. Such a modification would thus result in an increase of the EBL photon threshold energy, hence a decrease in the number of target photons with which $\gamma$ rays can interact, yielding an anomalous transparency of the Universe to $\gamma$ rays above a few tens of TeV. Limits at the Planck scale level have already been obtained for a linear modification, and at the level of a few $10^{20}$ eV for a quadratic modification (e.g. Ref. [35]).

Figure 4 illustrates the potential of CTA to probe linear (left) and quadratic (right) modifications. We simulate the spectrum of the nearby blazar Mrk 501 ($z = 0.034$) observed by HEGRA in 1997 [36]. Correcting for EBL absorption as in Ref. [35] results in an intrinsic spectrum well described by a power-law of index $\Gamma = 2.24$ up to 21 TeV. We conservatively add an exponential
cut-off at 20 TeV to avoid overoptimistic predictions at the highest energies. Order of magnitude deviations from classical absorption can be observed in the simulated spectrum between 20 and 30 TeV, assuming a modification at the Planck scale for the linear correction and at $E_{QG} = 10^{21}$ eV for the quadratic one. Following e.g. Ref. [35], a scan as a function of $E_{QG}$ will be developed to determine the constraints that can be expected from CTA observations of AGN above tens of TeV.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Simulated observation of Mrk 501 during a flaring state including a linear (left) and quadratic (right) LIV modification of the pair creation threshold.}
\end{figure}

6. Conclusion

We have presented a preliminary study of the CTA sensitivity to signatures imprinted on $\gamma$-ray spectra due to a variety of effects that might occur during the propagation of $\gamma$ rays over cosmological distances. The results make use of the latest CTA IRFs and state-of-the-art numerical calculations to evaluate the expected signals in the different tested scenarios. Albeit preliminary, our findings already demonstrate the capability of CTA to probe various science cases ranging from cosmology (EBL and IGMF) to fundamental physics (WISP dark matter and LIV) with unprecedented sensitivity. A systematic study that will address the full potential of CTA and the development of dedicated analysis techniques is currently in preparation within the CTA Consortium.

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