Lab report and sensitivity analysis of EGMF using CTAO DC-1 simulations

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This work was conducted under the supervision of Prof. Andrii Neronov.

1 Introduction

1.1 CTAO and the First Data Challenge

The Cherenkov Telescope Array Observatory (CTAO) is a project counting on building over sixty next-generation ground-based Imaging Air Cherenkov Telescopes, grouped in two sites, CTAO-North situated in Spain, and CTAO-South situated in Chile. CTAO will provide a never seen before sensitivity to Very High Energy gamma-rays. The construction of the telescope arrays is currently ongoing, with only a few telescopes built and functioning.

In 2017-2018 CTAO had the First Data Challenge (CTAO DC-1) where some scientists simulated hours of exposure of CTAO to different astronomical objects, trying to make it closest possible to the expected future real data, and with the goal of convalidating the softwares and workflows aimed to be used for when the project is ready and functioning.

Having access to this data is a great opportunity for students to learn to work with the CTAO pipeline. Since I was a beginner when I started, it was valuable for me to learn how to work with astrophysical data structures, instrument response functions, and other related concepts. This was the first part of my lab work, and it took place during the initial stage of the project. I did this learning primarily using the blazar sources Mrk 421 and 1ES 0229+200. The work done on these sources can be seen in Section 2.1.

1.2 Blazars and the measurement of Extra Galactic Magnetic field

Measuring the Extragalactic Magnetic Field strength is a very important goal in today's astrophysics, and it is deemed possible to constrain it using observations of VHE gamma-ray sources and their extended emission [NS09]. Blazars are excellent candidates for this analysis, as their spectra extend into the VHE gamma-ray range. In particular, Mrk 501 is a strong candidate, and the CTAO is expected to be sufficiently sensitive to its extended emission [KKNS21].

Having access to the CTAO DC-1 data it's a good opportunity to provide additional feedback on CTAO's sensitivity on Mrk 501 extended emission, on top of pre-existing expectations. This was part of the work presented here, and it can be found in the section 2.2.

1.3 Aim and Structure of this Work

This work utilizes the CTAO DC-1 simulations to perform two distinct analyses: first, a practical exercise to establish analysis procedures using the blazars Mrk 421 and 1ES 0229+200; and second, a sensitivity study for the detection of extended gamma-ray emission around Mrk 501: I applied a model injection technique to the DC-1 data, which contains no simulated extended emission, to quantitatively discuss CTAO's potential to detect IGMF influenced extended emissions. This analysis measures the minimum detectable extended emission strength by calculating the change in the fit statistic $\Delta\chi^2$ as a function of injected signal.

2 Results

2.1 Absence of 1ES 0229+200

My first task was to load the CTAO DC-1 data for the region around the blazar 1ES 0229+200, without initially knowing that the central source itself was not simulated, a fact later confirmed by the DC-1 authors. An overview of this region is shown in Figure 1, and the absence of the source it's pretty obvious if compared to the other two blazars in the same figure.

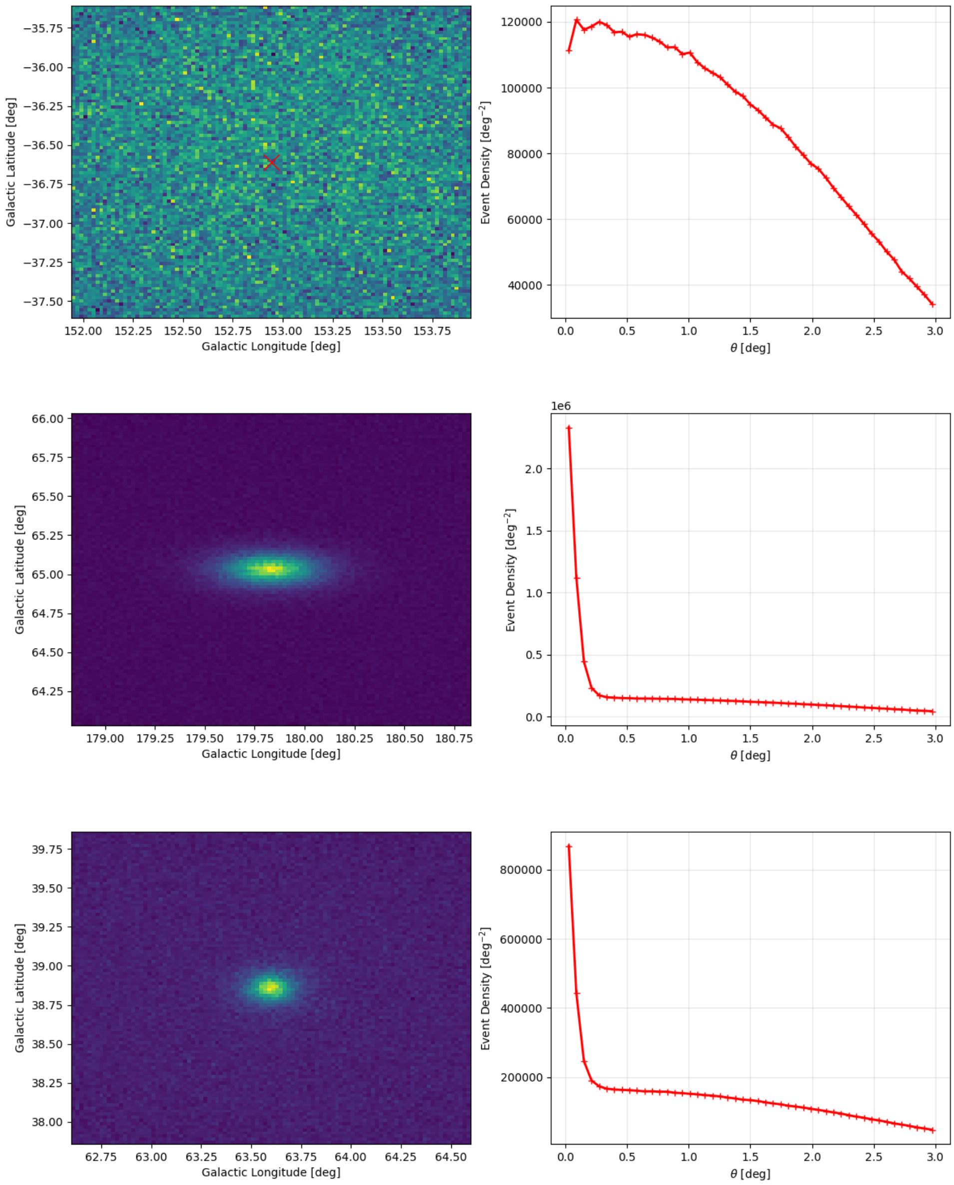

Figure 1: Overview of three CTAO DC-1 simulated sky regions: (Top) around 1ES 0229+200, 11.0 hr exposure, note the central source was not simulated; (Center) around Mrk 421, 16.2 hr exposure; (Bottom) around Mrk 501, 17.8 hr exposure.

For training purposes, a preliminary analysis was performed to demonstrate the procedure for assessing the absence of a significant source. To have a clearer idea on the state of the 1ES 0229+200 region it's useful to try to sutract the background. The background was estimated using a standard technique: sampling events from an off-source region located opposite the target relative to the telescope's pointing direction and subtracting this sample from the source region. As the data consist of multiple observational sessions with different telescope pointing positions, this procedure was performed individually for each pointing dataset. The results can be seen in Figure 2. Each bin in the net count plot admit zero inside the confidence interval, and additionally

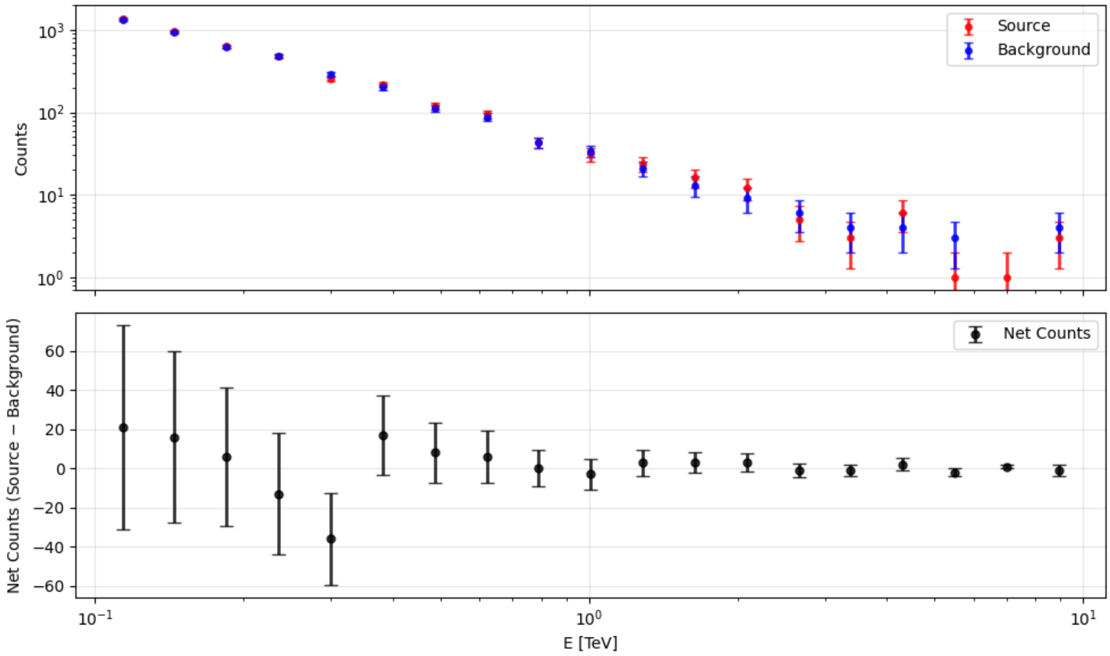

Figure 2: Spectrum of the background subtracted region around 1ES 0229+200.

a formal t-test fails to reject the null hypothesis of zero mean ($p = 0.586$). This is consistent with the expectation where the central source was not simulated in the DC-1 dataset.

2.2 Mrk 501

In [KKNS21] the detectability of extended emission of Mrk 501 with the CTAO was estimated as a function of intergalactic magnetic field strength, using high-energy gamma-ray simulations. It's therefore natural now to do a similar analysis using the CTAO DC-1 simulated data and see if there are any differences.

Figure 3 presents the obtained angular spectral energy distribution for three distinct energy ranges, obtained after a background removal, whose method was explained in section 1. The data are presented in a format that facilitates direct comparison with the models shown in Figure 3 of [KKNS21], that were extrapolated using an online tool and added to the plot.

It's important to note that in DC-1 the extended emission was not simulated, this allows us to measure statistically the detectability of the extended emission using a fit model with injected extended emission. The statistical procedure is as follows:

1. Define the null model: a composite model of the form BACKGROUND + POINT_SOURCE, where the background is constant and the point source is modeled with a Gaussian $e^{-\frac{\theta^2}{2\sigma^2}}$. All model parameters are determined by fitting this null model to the DC-1 angular SED data.

2. Inject extended emission: Holding the source and background parameters fixed at their best-fit values from the null model, inject an extended emission component. This component is a renormalization of the extended emission component extrapolated from the predictions in [KKNS21]. I.e. the coloured components in Figure 3. The injection strength is varied from 0.0 to 5.0 across 100 steps.

3. Calculate the detection statistic: For each injection strength, compute the χ^2 of the data against the combined (BACKGROUND + POINT_SOURCE + EXTENDED) model. The key metric is the change in fit quality, $\Delta\chi^2 = \chi^2 - \chi_0^2$, where χ_0^2 is the value for the null model.

The sensitivity analysis was performed by coupling the 0.5–1.5 TeV and 1.5–4.0 TeV energy ranges, while the 4.0–10.0 TeV range was left behind, as it contained insufficient data. The results are shown in Figure 4. If the theoretical predictions are correct, CTAO should be sufficiently sensitive to detect the extended emission from Mrk 501 in the presence of an IGMF of approximately 10^{-12} G with 3σ confidence. This level of detectability is not expected for stronger IGMF values.

According to [KKNS21], with an exposure time comparable to ours, CTAO should be sensitive to IGMF strengths up to $\sim 3\times10^{-12}$ G. However, a notable difference exists between their assumed background noise level and that of the DC-1 simulation. The background in the DC-1 data is higher by a factor of ≈ 4, which directly reduces the expected detectability of the extended emission.

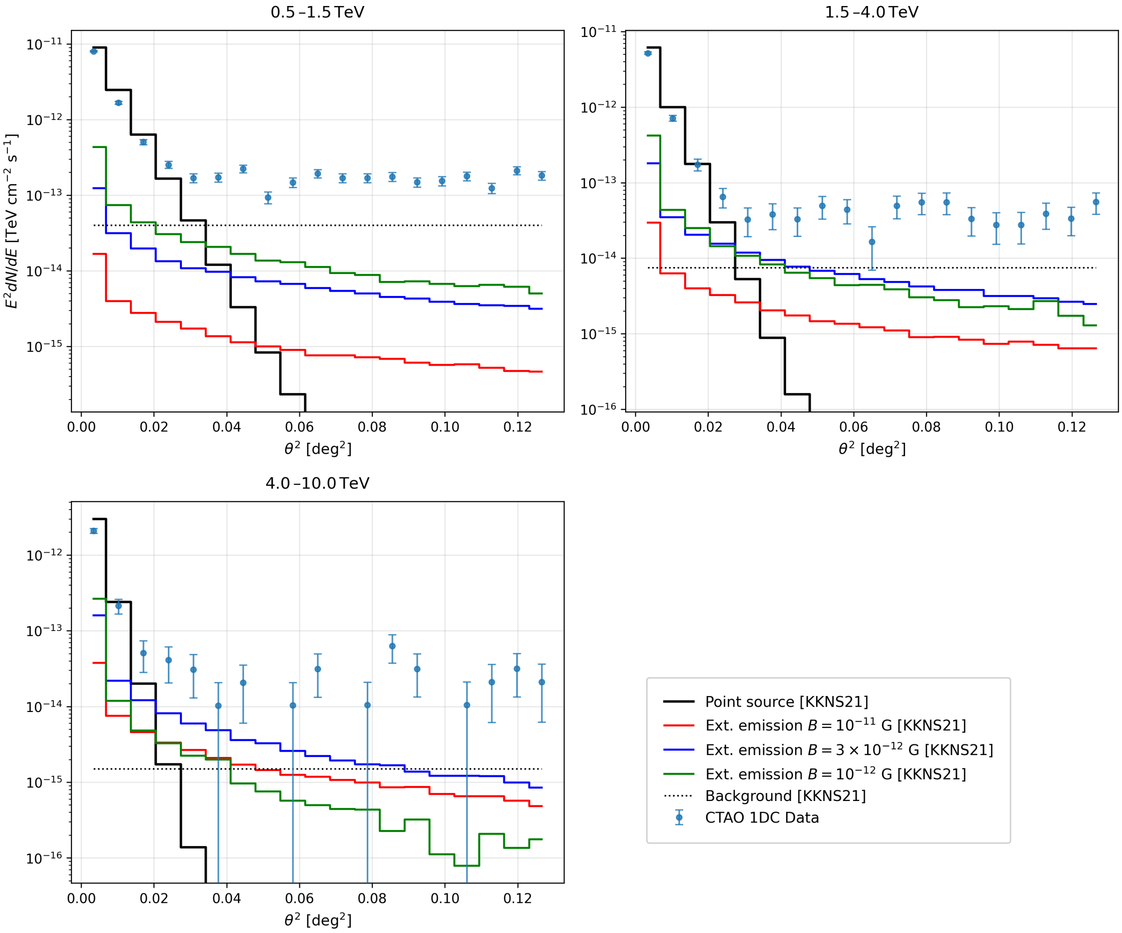

Figure 3: Mrk 501 SED from CTA 1DC data, plotted over the data from F.3 of [KKNS21].

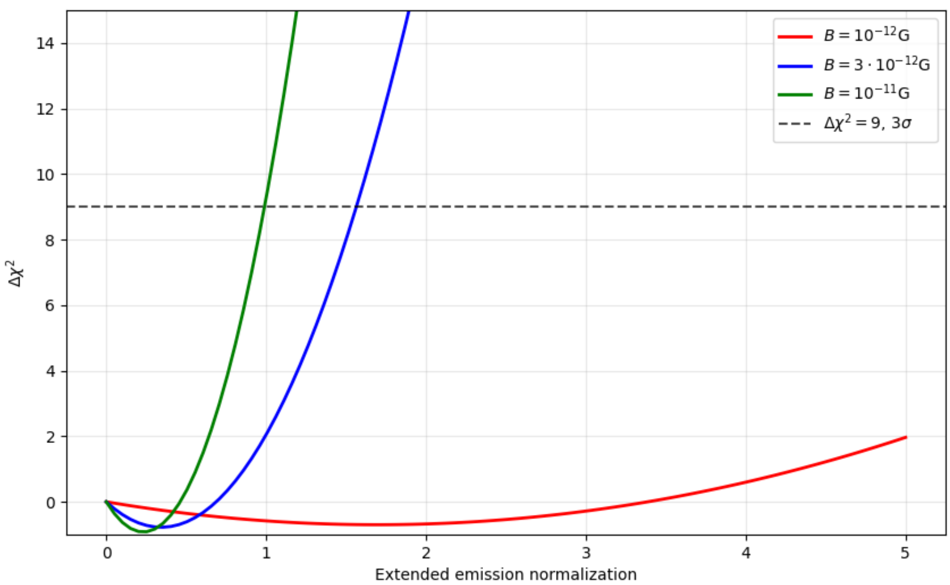

Figure 4: Sensitivity of CTAO for three IGMF strengths, using [KKNS21] extended emission prediction, and CTAO DC-1 data of 17.8hr of exposure around the blazar Mrk 501.

3 Conclusions

This work allowed me to learn different tools to explore three HE gamma-rays sources using the data from CTAO DC-1, and being able to make a direct comparison with an existing study that predicted CTAO sensitivity to the Mrk 501 extended emission. The results show that CTAO is sensitive with 3σ confidence to probe the extended emission of Mrk 501 in the case of an EGMF of strength 10^{-12}G. Note that the validity of this sensitivity analysis relies on the assumption that the CTAO DC-1 simulation provides a robust and precise model of the instrumental response to the point-source emission of Mrk 501 in the absence of any extended emission. And it relies heavly on the accuracy of the SED for the extended emission that was extrapolated from [KKNS21] and injected to test detectability. Any significant deviation of the real extended emission from this assumed template would alter the detection threshold.

Code availability

All the code developed for the analysis and figures used in this report is available in the github repository `https://github.com/Nico812/CTAO-1DC-Blazars-analysis-TP5.git`.

References

[KKNS21] Alexander Korochkin, Oleg Kalashev, Andrii Neronov, and Dmitri Semikoz. Sensitivity reach of gamma-ray measurements for strong cosmological magnetic fields. *The Astrophysical Journal*, 906(2):116, January 2021.

[NS09] A. Neronov and D. V. Semikoz. Sensitivity of γ-ray telescopes for detection of magnetic fields in the intergalactic medium. *Physical Review D*, 80(12), December 2009.

[OC21] Cherenkov Telescope Array Observatory and Cherenkov Telescope Array Consortium. Ctao instrument response functions - prod5 version v0.1, September 2021.

This research has made use of the CTA instrument response functions provided by the CTA Consortium and Observatory, see CTA Performance (version prod5 v0.1; [OC21]) for more details.