Sensitivity of ground-based Cherenkov telescopes for anisotropies in the cosmic gamma-ray background

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Abstract. Self-annihilating dark matter contributes to the extra galactic very high-energy γ-ray background. This contribution is expected to be anisotropic following the density distribution of non-baryonic dark matter. We explore the possibilities to search for these anisotropies with present and future ground-based gamma-ray experiments like H.E.S.S., MAGIC, or CTA. A multipole-expansion of simulated events is used to investigate the sensitivity for anisotropies detectable with narrow field of view observations.

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INTRODUCTION

The largest fraction of the mass in the universe is dark matter (DM). Some possibilities for its nature (expected by extensions of the standard model of elementary particle physics) are massive Majorana particles – like the hypothetical neutralino χ or the $B^{(1)}$ from Kaluza-Klein-theory (KK-theory). Then, in the self annihilation reactions (amongst others) photons would be produced. The energy spectrum of the produced photons reaches up to the DM particle rest mass. In this way the self-annihilating DM could deliver a contribution to the extra-galactic γ-ray background. Averaged over all directions, this contribution is given by (see [1]):

$$\frac{d\Phi}{dE_0} = \frac{c}{4\pi} \cdot \int dz \frac{e^{-\tau(E_0,z)}}{H_0 h(z)} \int dM \frac{dn}{dM}(M,Z)\frac{dN_\gamma}{dE}(E_0(1+z),M,z) \tag{1}$$

The function dN_γ/dE describes the energy spectrum for a DM halo with the mass M at the redshift z. The distribution of halo masses at the redshift z is described by dn/dM. The extra galactic infrared background light makes the universe opaque with an optical depth $\tau(E_0,z)$ for photons with an energy $E_0 > O(100\,\mathrm{GeV})$ due to the e^+e^--pair-production process.

The matter in the nearby universe ($d < O(100\,\mathrm{Mpc})$) is distributed neither isotropically nor homogeneously [2]. It builds a foam- or weblike structure. Also the γ-ray horizon due to the e^+e^--pair-production is of a similar order of magnitude. These facts lead to characteristic anisotropies in the arriving directions of the extra galactic γ-ray background [3, 4]. Since the emissivity of annihilating DM is proportional to ρ^2 while conventional sources contribute $\propto \rho$ to the γ-ray background, the anisotropies originating from DM annihilation are different from conventional sources. It is actually interesting to note that decaying DM only show an emissivity $\propto \rho$ just like ordenary sources.

The anisotropy spectrum is described by expanding the skymap of the intensity into spherical harmonics

$$\Phi(\vartheta,\varphi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\vartheta,\varphi) \tag{2}$$

The power spectrum

$$C_l = 1/(2l+1)\sum_{m=-l}^{l} |a_{lm}|^2 \tag{3}$$

characterizes the size spectrum of the anisotropies, where small sizes $\Delta\Theta$ are represented by large l (by $\Delta\Theta = \pi/l$).

COMPARISON BETWEEN FERMI/GLAST AND CHERENKOV TELESCOPES

The error δC_l^s of the power spectrum due to DM annihilation can be estimated with (see [3]):

$$\delta C_l^s = \sqrt{\frac{2}{(2l+1)\Delta l f_{\mathrm{sky}}}}\left(C_l^s + C_l^b + \frac{C_N}{W_l^2}\right) \tag{4}$$

The numbers C_l^s and C_l^b represent the measured power spectrum of the signal due to neutralino annihilation and the background due to conventional sources, while C_N

TABLE 1. Comparison between the parameters of FERMI/GLAST and Cherenkov telescopes for the abilitiy to measure the anisotropy spectrum originating from cosmological DM annihilation. The estimations of $\delta C_l^s(l=100)$ are done for $C_l^s \approx C_l^b \approx 6\cdot 10^{-6}$ and with equation 4.

	FERMI/GLAST	current Cherenkov telescopes (H.E.S.S.)
Effective area A_{eff}	$1\,\text{m}^2$	$10^5\,\text{m}^2$ (future experiments $\times 25$)
Angular resolution (per event)	$1^\circ - 0.12^\circ$	0.08°
Fraction of observed sky $\Omega/4\pi$	0.08 (fov) - 1 (survey)	$4\cdot 10^{-4}$ (fov) - 10^{-2} (survey)
Energy range	$20\,\text{MeV} - 300\,\text{GeV}$	$100\,\text{GeV} - 100\,\text{TeV}$ (future experiments: $> 10\,\text{GeV}-$
$A_{\text{eff}} T_{\text{obs}} \Omega/4\pi$	$1.2\cdot 10^{11}\,\text{cm}^2\,\text{s}$ in 2 yrs	$8\cdot 10^{11}\,\text{cm}^2\,\text{s}$ in 500 h
$\delta C_l^s(l=100)$	$1.7\cdot 10^{-7}$	$2.6\cdot 10^{-6}$

represents the anisotropies due to Poisson noise. The function W_l is the windowing function of the point spread function of the detector. The value f_{sky} is the fraction of the observed sky and Δl is the width of the investigated l-bin.

The characteristic values of these variables for FERMI/GLAST and for Cherenkov telescopes are listed in Table 1. While Cherenkov telescopes with a comparable small field of view can only observe a small fraction of the sky, FERMI/GLAST observes the entire sky. On the other hand Cherenkov telescopes have a by many orders of magnitude larger effective area. The angular resolution of Cherenkov telescopes of $\sigma_{\text{CT}} = 0.08^\circ$ leads to a maximal observable l (smallest observable anisotropy size) of $l_{\text{max, CT}} \approx 2000$, while FERMI/GLAST is only able to reach $l_{\text{max, FERMI}} \approx 200$. On the other hand FERMI/GLAST observes the full sky and can investigate smaller multipole moments than Cherenkov telescopes ($l_{\text{min, CT}} \approx 20$). The mean exposure towards each point of the sky $A_{\text{eff}} T_{\text{obs}} \Omega/4\pi$ is comparable large for both instrument systems. Due to the smaller event statistic the estimated error on the multipole moment $\delta C_l^s(l=100)$ is larger for current Cherenkov teleskope experiments. This difference will be compensated in future experiments.

The potentials to observe anisotropies in the γ-ray background of FERMI/GLAST and Cherenkov telescopes are comparable and complement each other due to the differences in the energy range, the angular resolution, and the fraction of the observed sky.

EXPANSION INTO MULTIPOLES

The intensity skymap of the cosmic γ-ray background is given by an event list of the considered observatories. For the multipole analysis, the event list can be used in a simple way, which will be described in this section.

The expansion is done with the equation

$$a_{lm} = \int d\Omega\, Y_{lm}^{\star}(\vartheta,\varphi)\Phi(\vartheta,\varphi) \tag{5}$$

The intensity function Φ is given by the event list (ϑ_i,φ_i) $(i \in 1,\ldots,N)$

$$\Phi = \frac{1}{N}\sum_{i=1}^{N} \delta^2(\vartheta-\vartheta_i,\varphi-\varphi_i) \tag{6}$$

This reduces the integral in equation 5 to the sum

$$a_{lm} = \sum_{i=1}^{N} Y_{lm}^{\star}(\vartheta_i,\varphi_i) \tag{7}$$

To demonstrate the abilities of this method a toy Monte Carlo simulation was performed. Assuming a field of view of 5° diameter we sample the multipole distribution for fixed values of $l = 500$ and $m = 250$ and a variable signal to noise ratio with 20000 random events. Extrapolating a rough power law fit of the extragalactic γ-ray background measured by EGRET (see [5]), this number of photon events is reached after above 500 h to 1000 h observation time with an actual Cherenkov telescope system with an energy threshold of 200 GeV. With CTA this number will be reached with less observation time (roughly 5 h – 10 h). The multipole expansion was done with 10 realizations of this distribution and the result was compared with the expansion of an event list with a flat distribution (also 10 realizations). The result is shown in Figure 1.

For a signal to noise ratio $S/N = 1$ the difference between the event list with multipole moment and the list with uniform distribution at $l = 500$ is clearly and significant visible. The difference can be seen for $S/N = 0.25$, too. The field of view leads to a windowing function which is non-zero also for $l \neq 500$.

The simulated field of view has a sharp edge. In realistic observations the acceptance of the instrument does not show such behaviour. A more realistic acceptance edge would reduce the oscillations of the windowing functions at large l depending on the width of the edge region.

SUMMARY AND OUTLOOK

We investigate a multipole expansion tool for the analysis of the γ-ray background with FERMI/GLAST and Cherenkov telescopes. FERMI/GLAST and Cherenkov telescopes complement each other in energy range and angular resolution.

The tool is tested with a toy Monte Carlo simulation of event lists with given anisotropy and signal to noise ratio. The anisotropy was found in an event list with $S/N = 0.25$ for a current generation Cherenkov telescope experiment. Future Cherenkov telescope systems will have a by a factor of ≈ 25 larger effective area and the energy threashold will be decreased ba a factor of ≈ 10. So the abilities to search for anisotropies will be increadsed.

We are working on the simulation of a given realistic anisotropy power spectrum. The differences in the energy spectrum of DM annihilation (see [6]) and conventional sources could help further to distinguish between the origins of the anisotropic γ-ray background.

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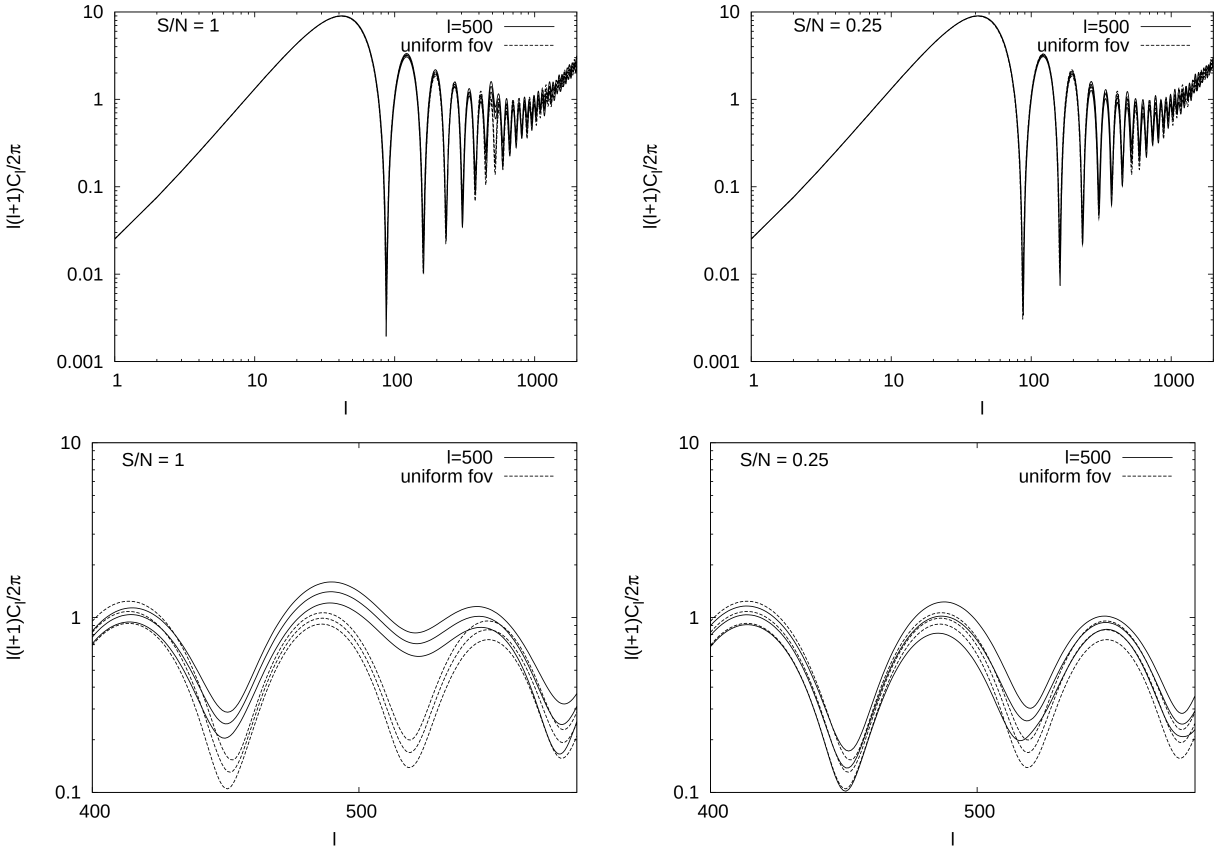

FIGURE 1. Result of the multipole analysis of event lists distributed randomly with a multipole moment of $l = 500$, $m = 250$ (solid lines describe mean value as well as the estimated 1σ interval), for $S/N = 1.0$ (left) and $S/N = 0.25$ (right). The error intervals are the RMS of the results from 10 realizations. The dashed lines show the error interval of the multipole analyses of a flat event distribution in the field of view. Top: Range of multipoles l from 1 to 2000. Bottom: Explored view for $l \approx 500$.