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Expected exclusion limits to TeV dark matter from the Perseus Cluster with the Cherenkov Telescope Array

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Clusters of galaxies are the largest gravitationally-bound structures in the Universe. They are composed of galaxies and gas (approximately 15% of the total mass) mostly dark matter (DM, accounts up to 85% of the total mass). If the DM is composed of Weakly Interacting Massive Particles (WIMPs), galaxy clusters represent one of the best targets to search for gamma-ray signals induced by the decay of WIMPs, with masses around the TeV scale. Due to its sensitivity and energy range of operation (from 20 GeV to 300 TeV), the Cherenkov Telescope Array (CTA) Observatory has a unique opportunity to test WIMPs with masses close to the unitarity limit. This will complement the searches for DM from other gamma-ray observatories as well as direct and collider experiments. The CTA Observatory is planning to search for gamma-ray emission, either its origin may be cosmic-ray (CR) or DM related, in the Perseus galaxy cluster during the first years of operation. In this poster, we will present the software created to perform the analysis using the `ctools` software and the corresponding results.

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1. Introduction

At present, we have gravitational evidence at different scales of the Universe pointing to the existence of a Dark Matter (DM) that constitutes ~ 27% of the total energy content in the Universe. However, properties and nature of this DM are still unknown. Several particles appearing in extensions to the Standard Model (SM) have been proposed as candidates that can account for the DM in the Universe. One of the most studied candidates refers to a class of particles called Weakly Interactive Massive Particles (WIMPs) [1] with masses in the range from ~ 5 GeV up to hundreds of TeVs [2]. The annihilation or decay of these particles leads to the production of gamma rays with energies at GeV and TeV scales. This annihilation and decay of DM can occur in the halos of galaxies and galaxy clusters. Galaxy clusters, which approximately 85% of their content is DM, serve as ideal targets for searching for diffuse gamma-ray emission resulting from the decay of dark matter.

Several studies [see for example 3] have investigated the potential of galaxy clusters to search for diffuse gamma-ray emission induced by Cosmic Rays (CRs) and DM. One of the best targets to search for this diffuse emission is the Perseus cluster because of its expected content of DM, and the presence of radio relics that can help to constrain better the density profile of CRs in the IntraCluster Medium (ICM). Additionally, Perseus is the host of two AGNs, NGC 1275 and IC 310, also observed by gamma-ray observatories like *Fermi*-LAT [4, 5] and the MAGIC telescopes [6]. In this work we studied the expected sensitivity to gamma-ray emission induced by WIMPs annihilation and decay in Perseus from simulations of observations with the Cherenkov Telescope Array (CTA) observatory.

The CTA observatory (or simply CTAO) will be a gamma-ray observatory with two arrays of Imaging Air Cherenkov Telescopes (IACTs), one in La Palma, Canary Islands, Spain and the other in Paranal, Chile. CTA will operate in the energy range from 20 GeV up to 300 TeV, and it is expected that CTA will improve up to 10 times the sensitivity and angular resolution of previous IACT arrays [7].

2. Gamma-ray emission modeling

The gamma-ray emission model in the Perseus cluster considers the contribution to the total gamma-ray flux from the two AGNs located at the center of the cluster, NGC 1275 and IC 310; the annihilation or decay of DM particles in the cluster, and the gamma-ray emission induced by CRs interactions in the ICM.

Using deep observation of the Perseus Cluster with the MAGIC telescopes [8], the differential spectrum for NGC 1275 is well described by a power law:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = 2.1 \times 10^{-11} \left(\frac{E}{0.2\ \mathrm{TeV}}\right)^{-3.6}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}, \tag{1}$$

while, using observations of the galaxy IC 310 with an effective exposure time of 41 h, MAGIC obtains that the differential spectra is well fitted to [6]:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = 7.41 \times 10^{-13} \left(\frac{E}{1.0\ \mathrm{TeV}}\right)^{-1.81}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}. \tag{2}$$

The spatial emission for both galaxies, NGC 1275 and IC 310, is modeled by a point source.

For the gamma-ray emission induced by hadronic interactions in the ICM, we used the `Minot` package [9] to compute the relevant quantities and obtain the spectral shape and a two-dimensional template of the spatial emission. Relevant parameters to the model for the gamma-ray emission induced by CRs are the ratio X_{500} of the CR energy density to thermal energy density at radius R_{500}[1], the acceleration efficiency of CRs η_{CRp} and spectral index of the injected CRs, α_{CRp}. For this analysis, we assume a baseline model as a conservative approach to the CRs budget in the Perseus cluster and, thus, for the gamma-ray emission from interactions in the ICM. Table 1 shows the model used for.

Model	X_{500} (%)	α_{CRp}	η_{CRp}	$F^{(\mathrm{had})}_{500,E_\gamma>150\ \mathrm{GeV}}$	$F^{(\mathrm{IC})}_{500,E_\gamma>150\ \mathrm{GeV}}$
				$(10^{-14}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1})$	
Baseline	1.0, [0.0, 20.0]	2.30, [2.0, 3.0]	1.0, [0.0, 1.5]	70.2, [0, 11373.8]	2.1, [0, 625.4]

Table 1: Summary of the parameter values and their explored range, and the γ-ray flux at CTA energies for the hadronic and inverse Compton emission (given as: reference value, [min, max]). The flux F_{500} is computed within θ_{500} by cylindrical integration for energies above 150 GeV and given in units of 10^{-14} cm^{-2} s^{-1}.

R_{200} [kpc]	M_{200} [10^{14} M$_\odot$]	c_{200}	r_s [kpc]	$\log_{10}\rho_0$ [M$_\odot$/kpc^3]	θ_{200} [deg]
7.52	5.03	370.82	6.08	1865.00	1.42

Table 2: Navarro-Frenk-White (NFW) density profile parameters for the Perseus galaxy cluster. R_{200} is the radius where the density is 200 times the critical density of the universe, in units of kpc. M_{200} is the mass at R_{200} in units of 10^{14} M$_\odot$, c_{200} is the concentration parameter, r_s is the scale radius of the density profile in units of kpc, ρ_0 is the normalization in units of M$_\odot$/kpc^3, and θ_{200} is the projected angle.

For the DM, we assume a conservative model for the DM density profile based on results from N-body simulations [10]. Table 2 shows the parameters associated to the DM density profile in the cluster. Here, we also include the prospective contribution of subhalos embedded in the main halo of the cluster. Then, the gamma-ray flux from annihilation of WIMPs in the cluster is computed as:

$$\frac{\mathrm{d}\Phi_\gamma^{\mathrm{DM,\,ann}}}{\mathrm{d}E} = \frac{\mathrm{d}N_\gamma^{\mathrm{DM}}}{\mathrm{d}E}\,\frac{\langle\sigma_\chi v\rangle}{8\pi\, m_\chi^2}\int_{\Delta\Omega}\mathrm{d}\Omega\int_{l.o.s.}\mathrm{d}l\ \rho_{\mathrm{DM}}^2(r(l)), \tag{3}$$

where the first term is the number of gamma rays as a function of the energy E for an annihilation channel and is called the DM annihilation spectrum, $\langle\sigma_\chi v\rangle$ is the thermal-averaged annihilation cross section, m_χ is the mass of the DM candidate, and ρ_{DM} is the density profile of DM in the cluster. The integral over ρ_{DM}^2 is along the line of sight ($l.o.s.$) between the observatory and the cluster, and the solid angle subtended by this line of sight. The integral term is called the astrophysical factor J. Given that the astrophysical factor is proportional to ρ_{DM}^2, the presence of subhalos, as considered in our model, enhance the gamma-ray flux (a boost factor) produced by the annihilation of DM particles in the cluster, and can tighten the constrains of $\langle\sigma_\chi v\rangle$.

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[1] R_{500} is the radius where the density is 500 times the critical density of the Universe

For decay of DM, a similar expression for the gamma-ray flux can be found:

$$\frac{\mathrm{d}\Phi_\gamma^{\mathrm{DM,\,dec}}}{\mathrm{d}E} = \frac{\mathrm{d}N_\gamma^{\mathrm{DM}}}{\mathrm{d}E} \frac{1}{4\pi\, m_\chi\, \tau_\chi} \int_{\Delta\Omega} \mathrm{d}\Omega \int_{l.o.s.} \mathrm{d}l\, \rho_{\mathrm{DM}}(r(l)), \tag{4}$$

where τ_χ is the lifetime of the DM candidate, and the integral term is called the astrophysical factor D. For this case, the gamma-ray flux only depends in the total mass of the cluster, and no enhancement from subhalos is expected.

We consider WIMPs with masses in the range from 50 GeV and 100 TeV, and two representative channels for annihilation and decay (τ leptons and b quarks) [2]. To compute the spectral part of the gamma-ray flux induced by DM interactions, we use the tables from the project `PPPC4DMID` [2] to compute the number of photons produced for a candidate with mass m_χ and for each annihilation/decay channel. The astrophysical factors J and D, related to the spatial morphology of the emission, are computed using the publicly available code `Clumpy` [11].

Finally, for the DM induced gamma-ray emission, one of the most important source of uncertainty comes from the knowledge of the DM density profile and the distribution of subhalos, with changes in the exclusion limits up to one order of magnitude with respect to the model we present in this work. The corresponding analysis to take into account this uncertainty is presented in a future CTA Consortium publication (in preparation).

3. Observation setup

To compute the sensitivity of CTA to annihilation and decay of WIMPs in the Perseus cluster, we first create a set of observations simulated using the public code `ctools` [12]. The observations comprises a total of 300 h of the region of the Perseus cluster.

The simulated observations consider gamma-ray events with energies between 30 GeV and 100 TeV, and divided in 10 energy bins separated in log scale. The total duration of the observations was obtained from the stack of 300 individual observations with a duration of 1 h. The Region Of Interest (ROI) used for the simulation has an angular radius of 3 degrees and center at 1 degree from the center of the Perseus Cluster.

We use the Instrument Response Functions (IRFs), corresponding to the Omega configuration [13]. In order to take into account the statistical fluctuations from the background, we perform 100 repetitions changing the random seed for the background estimation in the simulation. A recent configuration of the CTA telescopes, the Alpha configuration, will be used for the first phase of construction. A comparison between the sensitivity of both configurations will not change the results obtained in this analysis, and will decrease the expected limits only by a factor of approximately 1.3 times for energies around 1 TeV.

4. Analysis with `ctadmtool`

For the analysis of the simulated observations, we use the Maximum Likelihood Estimation (MLE) method. We use a template-fitting approach, where we consider all the models of gamma-ray

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[2] Other channels follow the same spectrum shape as the two channels used for the analysis.

emission (NGC 1275, IC 310, DM and CR) in the ROI and simultaneously fit the free parameters of each model to describe the simulated data. In case we do not observe a positive detection of the DM signal, then we proceed to compute the upper-limit to the integral flux and convert to the exclusion limit (95% C.L.) to $\langle \sigma_{\mathrm{WIMP}} v \rangle$ and τ_{WIMP} for WIMPs.

The calculation of best-fit parameters and exclusion limits for DM from CTA is integrated in the public code `ctadmtool`[3]. `ctadmtool` is based in `ctools` and `gammalib` [12], and allows the user to test different masses for WIMPs. `ctadmtool` computes the best-fit parameter for every mass value, the correlation matrix for the free parameters in the total emission model, and the test statistic TS for every gamma-ray emission component. In case of no detection ($TS < 25$) of a signal induced by DM, `ctadmtool` computes the exclusion limit to the integral flux and $\langle \sigma_\chi v \rangle$ or τ_χ for every mass point, and save all the results to a FITS file. The comparison of our results with the canonical ones obtained using `gammapy` and `dmtools_gammapy`[4] are presented in a future CTA Consortium publication (in preparation).

Using the set of simulated observations described above, we compute the TS and correlation matrices for 10 mass points in the range from 50 GeV to 100 TeV. From this step in the analysis, we found that the galaxy NGC 1275 has a big impact in the TS for the CRs and DM components in the cluster, in particular for masses of WIMPs lower than 10 TeV. Figure 1 shows the TS obtained for each component in the emission model as a function of DM mass for annihilation to τ leptons[5]. We can observe that the value of TS obtained for NGC 1275 decreases for lower masses up to half of the minimal value obtained for $m_\chi > 10$ TeV. The decrease in NGC 1275 TS for lower masses is related to a false detection of the gamma-ray signal induced by DM annihilation. This effect is explained due to the spatial morphology of DM- and CR- induced gamma-ray signals, as both emissions have their peaks in the center of the Perseus Cluster, where NGC 1275 is also located. This property of the DM and CR emission models seems to maximize the entanglement of the gamma-ray signal in the center of the cluster, and a possible leaking of the emission from NGC 1275 leads to a false detection of the DM component. This is observed for every annihilation/decay channel.

In order to avoid the contamination of the signal from NGC 1275, we place a circular mask centered in the position of NGC 1275. Table 3 shows the angular radius of the mask as a function of the energy. We select five different gamma-ray energy ranges according to the angular resolution of the CTA North array. The size was selected to be twice the angular resolution for the lower bound in the energy interval to remove 95 % of the photons coming from NGC 1275.

The main disadvantage of this analysis technique (Template fitting + mask), is that the CTA sensitivity is reduced because we cover the region where the DM- and CR- induced gamma-ray signal have their maximum. With this analysis, we do not find evidence for a signal induced by annihilation or decay of DM particles.

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[3] The code is available in `https://github.com/sergiohcdna/ctadmtool`

[4] The code is available in `https://github.com/peroju/dmtools_gammapy`

[5] We do not plot the TS associated with the galaxy IC 310, as this value is constant for all the masses considered in the analysis.

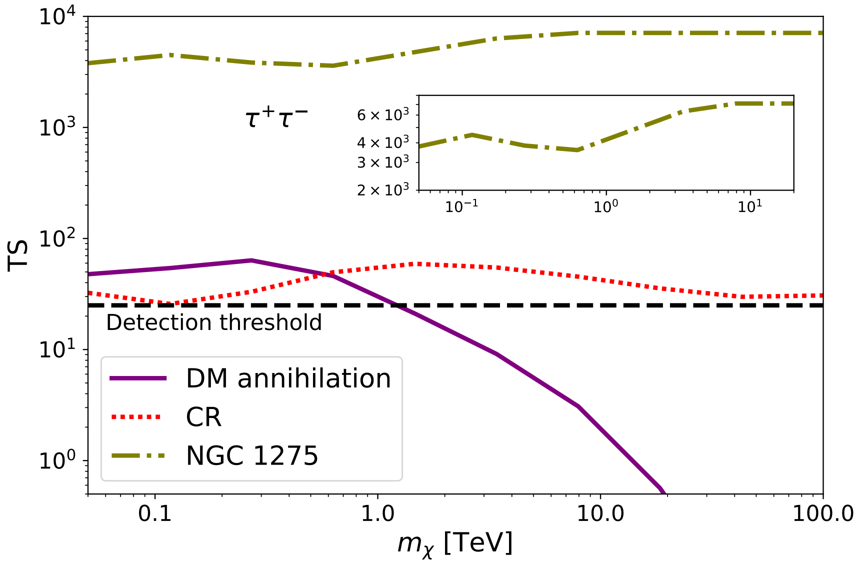

Figure 1: Average values of TS for NGC 1275 (olive line), CR (red line) and DM (purple line) induced emission as a function of the DM mass. For the DM emission model, we consider annihilation to leptons τ. The dashed black line represents the detection threshold, $TS \geq 25$. We observe that for DM masses below 1 TeV, the NGC 1275 TS decreases with respect to the value obtained for higher masses (10 TeV). This decrement appear to be correlated with a false detection of the DM signal.

Energy Range (TeV)	θ_{mask} (deg)
0.03 - 0.06	0.50
0.06 - 0.15	0.30
0.15 - 1.00	0.20
1.00 - 10.0	0.12
10.0 - 100.0	0.08

Table 3: Angular sizes (radii) of the mask applied to the simulation in the center of the Perseus cluster. The size is set to 2 times the value of the angular resolution of the CTA North Array at the energy corresponding to the lower extreme of each energy interval [14].

5. Results

Using the template fitting method and masking NGC 1275, we do not find any possible signal associated with a gamma-ray signal induced by DM annihilation or decay. Then, we compute the 95% C.L. exclusion limits to $\langle\sigma_\chi v\rangle$ and τ_χ as a function of the mass of the DM candidate. Figure 2 shows the exclusion limits of $\langle\sigma_\chi v\rangle$ (left panel) and τ_χ (right panel). We show also the comparison with results from recent searches for DM induced gamma-ray signals in galaxy clusters.

For annihilation, we observe that the expected exclusion limits for DM masses greater than $\sim$ 200 GeV improve the limits up to a factor of two times with respect to the results of the combined

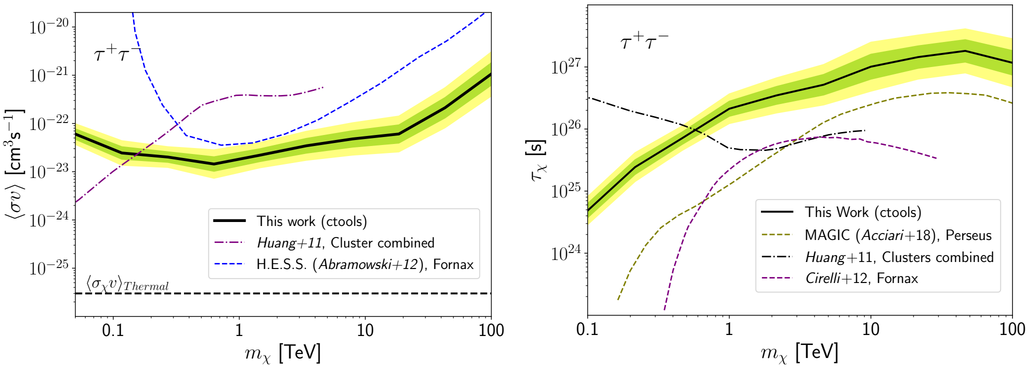

Figure 2: CTA sensitivity to DM annihilation and decay in the Perseus cluster. Exclusion limits (95% C.L.) were obtained with `ctadmtool` for the template fitting plus a mask centered in the position of NGC 1275. Solid black lines correspond to the average value for 100 realizations, and green (yellow) bands show the $1\sigma(2\sigma)$ dispersion around the average value. We consider only annihilation/decay to leptons τ. **Left panel:** Exclusion limits for $\langle\sigma_\chi v\rangle$ as a function of the DM mass. The dashed black line corresponds to the thermal value of the annihilation cross-section, $\langle\sigma_\chi v\rangle_{thermal} = 3 \times 10^{-26}$ cm^3 s^{-1}. The region above the curve is excluded. **Right panel:** Exclusion limits for τ_χ as a function of the DM mass. The region below the curves is excluded.

searches in a sample of galaxy clusters using data from the *Fermi*-LAT telescope [15] and results for the Fornax cluster using the H.E.S.S. telescopes [16]. In the other hand, the expected limits for decay show an improvement up to one order of magnitude with respect to the results previously obtained for the Fornax [17] and Perseus [18] clusters. In particular, the limits obtained from observations with the MAGIC telescopes use the same analysis strategy as we used in this analysis [18], showing the observational challenge due to the different emission components in the region, and the validity of the strategy used in this work.

6. Conclusions

We computed the expected exclusion limits (95% C.L.) for $\langle\sigma_\chi\ v\rangle$ and τ_χ from the Perseus cluster as would be observed by the CTA Observatory. We obtained the limits for simulated observations of the Perseus cluster with a total exposure of 300 h for annihilation and decay of WIMPs with masses in the range from 50 GeV up to 100 TeV. The CTA expected limits improve the current observed exclusion limits for $m_\chi \geq$ 500 GeV for both, annihilation and decay. For the analysis we present here, using the code `ctadmtool`, we need to consider masking the galaxy NGC 1275 due to the false detection when using only the template fitting approach. This false detection is related to the possible leaking of gamma-ray events comming from NGC 1275. This emission also impacts the results obtained for the CR-induced gamma-ray emission. The strategy analysis proposed in this scenario is supported by the previous observations and results of the MAGIC collaboration for the observation of the Perseus cluster with a total effective exposure of ~ 250 h.

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