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Gamma-ray Spectral Line emission search from Dark Matter Annihilation up to 100 TeV towards the Galactic Centre with MAGIC

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The detection of line-like TeV gamma-ray features configures as a smoking gun for the discovery of TeV-scale particle dark matter. We report the first search for dark matter spectral lines in the Galactic Centre region up to gamma-ray energies of 100 TeV with the MAGIC telescopes (La Palma, Canary Islands). The Galactic Centre region is expected to host the closest dark matter halo of considerable size and is therefore well suited for this kind of searches. Observations at large zenith angles improve sensitivity for gamma rays in the TeV regime due to the increased telescope collection area. We present the results obtained with more than 200 hours of large-zenith angle observations of the Galactic Centre region, which allow us to obtain competitive limits to the dark matter annihilation cross-section at high particle masses ($< 5 \times 10^{-28}$ cm^3 s^{-1} at 1 TeV and $< 1 \times 10^{-25}$ cm^3 s^{-1} at 100 TeV), improving the best current constraints above 20 TeV. In addition, we also study the impact of an inner cored dark matter halo on probing the annihilation cross-section. Finally, we use the derived limits to constrain super-symmetric wino models.

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1. Introduction

Observations at various scales, such as those from the galaxy rotation curves, galaxy clusters, and the Cosmic Microwave Background (CMB), suggest that dark matter (DM) makes up a quarter of the total mass-energy density of the universe[1–3]. DM is considered to be composed of electrically neutral, stable particles that move non-relativistically, i.e., they are "cold" in the context of the Λ-CDM model. Good candidates that satisfies these characteristics are Weakly Interacting Massive Particles (WIMPs), which interact at the scale of weak interactions, and their typical mass range is thought to be on the order of GeV to TeV. WIMPs are considered to be remnants of the freeze-out from the thermal equilibrium state in the early universe since they stopped annihilation due to less frequent interactions. Indirect detection, a method to observe cosmic rays produced when DM particles annihilate, has pursued DM alongside accelerator experiments and underground experiments. These three methods complement one another, differing in the parameters of DM mass that they are sensitive at searching. Among them, indirect detection is good at searching for at the GeV-TeV scale particles. Furthermore, it is sensitive to the annihilation cross-section of DM, enabling the direct test of the thermal relic scenario and providing insights into the production process of DM.

In promising particle models beyond the standard model, such as supersymmetric (SUSY) particles, annihilation of DM particles with each other is predicted due to their Majorana nature, and the produced particles from this annihilation include gamma rays. Among the various particles produced from the annihilation of DM, gamma rays, being uncharged, are not affected by the galactic magnetic field like charged particles are, meaning they do not lose their signal arrival direction. Thus, it can be said that they are a direction-sensitive method of indirect DM detection. Moreover, as they possess spectral shapes corresponding to specific particle models, it is possible to discuss certain particle models by searching for the expected shape of the gamma-ray emission spectrum. The differential gamma-ray flux expected from DM annihilation consists of two terms as shown in the following equation:

$$\frac{d\Phi(\Delta\Omega)}{dE} = \frac{d\Phi^{PP}}{dE} \times J(\Delta\Omega) \tag{1}$$

$$\frac{d\Phi^{PP}}{dE} = \frac{1}{4\pi}\frac{\sigma v}{2m_{DM}^2} \times \sum_i Br_i \frac{dN^i}{dE} \tag{2}$$

$$J(\Delta\Omega) = \int_{\Delta\Omega}\int_{los} ds\, d\Omega\, \rho^2(s,\Omega) \tag{3}$$

The first term of Equation (1), $d\Phi^{PP}/dE$, is known as the "particle physics term," which is characterized by properties within the particle model of DM. Relevant parameters include the mass of DM m_{DM}, the cross-section times velocity σv also called annihilation cross-section, the branching ratio Br_i for each reaction i, and the gamma-ray flux dN^i/dE, among others. Often for simplicity in DM searches with gamma rays, the branching ratio is assumed to be 100% for one channel and 0 for the others.

The second term, $J(\Delta\Omega)$, is known as the J-factor, which is the integral of the DM density ρ in the line of sight, over the solid angle $\Delta\Omega$. This J-factor is very important to influence the sensitivity, as it linearly affects the amount of gamma-ray flux originating from DM, as seen in Equation (1).

The sensitivity to DM greatly varies depending on where to observe. In other words, the uncertainty of this value directly propagates to the sensitivity, so we need to handle this value carefully. For input to Equation (2), it is necessary to preselect which model to choose and understand what kind of gamma-ray emission spectrum is expected from it. Roughly speaking, emission spectrum shapes can be divided into two categories: line emission and broad spectrum. The former aims at emission that peaks at the mass of DM. This is mainly the case when DM annihilates to produce such as photon pairs or photons and Z bosons. Here, monochromatic gamma-ray emission is expected at an energy $E = m_{DM}(1 - m_\chi^2/4m_{DM}^2)$, where $\chi = \gamma$, Z, corresponding to the DM mass m_{DM}. If found, this would be conclusive evidence of a DM origin signal. On the other hand, broad spectra are produced through secondary radiation. In this case, the gamma-ray spectrum has a cutoff at the mass of the DM [4]. The Search for line emission originating from DM annihilation is not only about seeking the most straightforward signal, but also line emission is a good tool to explore the interesting new particle models. Generally, for a channel ($\gamma\gamma$ or γZ) that produces line emission from annihilation, it is generally loop-suppressed by α^2. However, when the mass of DM is sufficiently heavy (typically masses of TeV and above), an enhancement in this annihilation cross-section is expected. This effect is called Sommerfeld enhancement and is beneficial for the search for line emission in gamma rays [5]. In the SUSY model, Wino and Higgsino, which is the one of Neutralinos, have become benchmark models for line emission searches because they can explain the DM relic density very well when their masses are 3 TeV and 1 TeV, respectively [6].

2. The Galactic Centre observation with MAGIC

MAGIC (Major Atmospheric Gamma Ray Imaging Telescope) is a system for observing very-high-energy gamma rays, consisting of two Imaging Atmospheric Cherenkov Telescopes (IACTs) [7]. Located at the Roque de los Muchachos Observatory on the island of La Palma in the Spanish Canary Islands (~2200 m above sea level), the first telescope, MAGIC-I, has been operational since 2004, and the second, MAGIC-II, has been added in 2009. Observations are conducted using a method called stereo observation with two telescopes, which have identical shapes.

The Galactic Center of the Milky Way (the GC) is one of the most promising targets for observations searching for DM through very-high-energy gamma rays. This is because the expected J-factor value is maximized due to the high DM density and its relatively close distance. On the other hand, the GC requires various factors to be considered in the analysis, such as the source extension, the foreground of diffuse gamma rays and the contamination of gamma-ray sources. In particular, there is the uncertainty in the expected DM density close to the central region, which is known as the core-cusp problem. The core profile models have a roughly constant DM density toward the GC, while cuspy profile models shows a spiky DM density around the center, which is shown in Figure 1

In the observation of the GC, due to geographical conditions for MAGIC, the observable zenith angle tends to be large, approximately 60° or more. In the case of IACTs, observations are conducted with large zenith angles. Observing Cherenkov light from air showers entering at an angle can increase the effective detection area of primary particles. This method is referred to as the Large Zenith Angle observation method [8]. The sensitivity gets boosted towards higher energies than when MAGIC observes in the low zenith direction. On the other hand, a drawback of large

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zenith angle observations is that the threshold for gamma rays increases due to the lower Cherenkov light density at ground level, as the light spreads out before it reaches the ground. However, the energy threshold of MAGIC is still sufficiently low in case we focus on gamma-ray line emission from TeV DM.

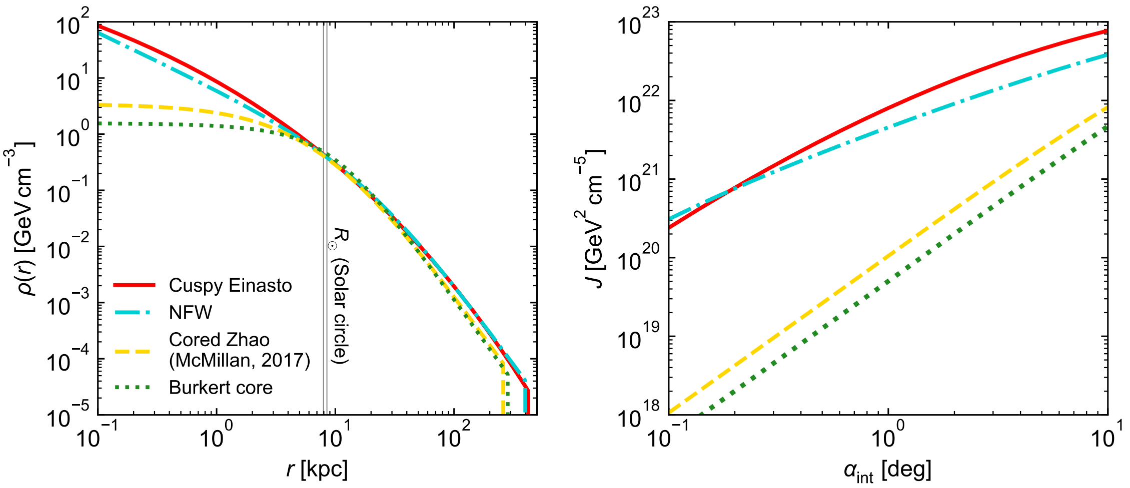

Figure 1: The spatial distribution showing each DM density model as a function of distance from the galaxy center [9].

3. Data Analysis

The dataset used in this study consists of 272.2 hours of observational data of the GC, collected from 2013 to 2020. The zenith angle distribution ranges from 58 to 70 degrees. Not all of the acquired data could not be used for analysis, and several quality cuts were applied. These were mainly based on a) atmospheric transparency, b) night sky brightness, and c) quality of shower images. The observational time after the cuts is 220 hours. The region of the interests (ROIs) and the pointing direction in observations of the telescope, represented in galactic coordinates, are shown in Figure 2. The offset angle varied from time to time because datasets for different physics targets were collected for this DM search. The ROI was limited to a radius of 1.5 degrees from the camera center of the telescope since the response of the MAGIC's focal camera was relatively flat (the total field of view of MAGIC is a radius of 1.75 degrees). That is, the ROIs were set so that the offset angle plus the distance from the GC equals 1.5 degrees as shown in Fig 2.

In this study, it was focused that gamma rays originating from DM had a peak structure at a characteristic mass in the energy spectrum. Therefore, we assumed that all other astrophysical backgrounds followed a smooth function, starting with a power law with a sliding window. The 68 % containment range of the energy resolution ($2\sigma_E$) is used to define the range of an n energy window, which was log-centered at $m_{\rm DM}$ with width $\pm\ 4\sigma_E$. After determining the baseline for a background model, we searched for the peak structure on it with the following likelihood function Eq 4:

$$\mathcal{L}_i(\langle\sigma v\rangle; \nu_i \,|\mathcal{D}_i) = \mathcal{L}_i(\langle\sigma v\rangle; b_i, \tau_i \,|\{E'_j\}_{j=1,\ldots,N_{\mathrm{ON},i}}, N_{\mathrm{ON},i})$$

$$= \frac{(g_i + \tau_i b_i)^{N_{\mathrm{ON},i}}}{N_{\mathrm{ON},i}!} e^{-(g_i+\tau_i b_i)} \times \frac{1}{g_i + \tau_i b_i} \prod_{j=1}^{N_{\mathrm{ON}}} (g_i f_g(E'_j) + \tau_i b_i f_b(E'_j)) \tag{4}$$

$$\times \mathcal{T}(\tau_i | \tau_{\mathrm{obs},i}, \sigma_{\tau,i})$$

Here, g and b represent the estimated number of gamma-ray and background events, respectively. N_{ON} is the number of events observed within the ROIs and the sliding window. f_g and f_b are the probability density functions for the signal and the background. The signal model is a δ-function smeared by the energy resolution, and the background model is obtained from the power-law fitting within the sliding window. τ is the normalization factor for the background model.

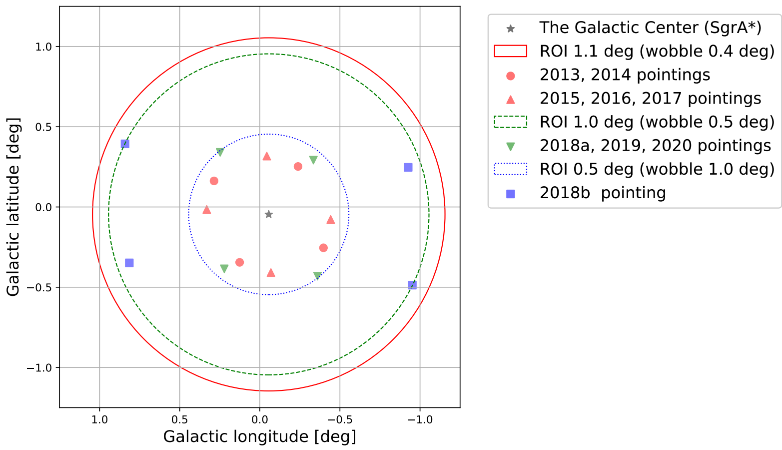

Figure 2: The Region Of Interests (ROIs) used for analysis and the pointing direction of the telescope [9].

The advantage of the analysis with this sliding window is that it does not lose sensitivity even when the DM density distribution is a core distribution. A commonly used approach in previous studies [10] involved observing the region with high DM density as the ON region and the region distant from the center with a lower density as the OFF region. The background was assumed to be similarly distributed. The residual after background subtraction is considered to be a contribution from DM, and the signal is searched in this way. In this case, if the spatial DM density distribution is a core, taking the residual would cancel out the DM component, which leads to a loss in sensitivity. However, with the sliding window, there is no need to take the residual, and it allows us to take the contribution of DM from all regions within the field of view into account. Therefore, it has the advantage of keeping good sensitivity with core models' assumption.

4. Results

After estimating systematic errors using Monte Carlo (MC) and control region data, these values were applied to the data from the Milky Way Galactic Center region. No significant signal excess was obtained, so upper limits were set on the annihilation cross-section for each DM mass at the 95% confidence level. Figure 3 shows the limit on the annihilation cross-section for 18 DM masses ranging from 900 GeV to 100 TeV with previous results for the comparison. In the region above (with larger annihilation cross-section values), the limit curve in the figure is excluded. In the comparison figure, the results from this study are plotted using the Cored Zhao distribution and the Cuspy Einasto distribution as examples for each conservative Core and reasonable Cuspy assumption, based on Figure 1. When assuming the Einasto distribution, the result was almost equivalent to the previous result of the H.E.S.S. telescope in the region where the mass is several TeV, and it was able to show the best sensitivity from around 20 TeV. As a result, it was possible to achieve the highest sensitivity in the world for the line emission search from 1 TeV to 100 TeV. The mass range around 2.7 TeV to 3.0 TeV is most preferred because, if a Wino exists in this region, it can explain nearly all of the current residual DM[6]. In this study, in addition to the Einasto and NFW distributions which are cuspy, for the first time, we have reached a sensitivity to the annihilation cross-section where SUSY-Wino could become DM when assuming a core distribution.

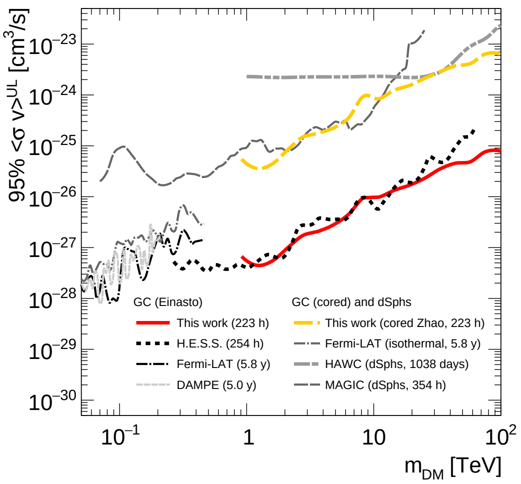

Figure 3: Obtained limits by this work for the Einasto (red solid line) and cored Zhao (yellow dashed line, [11]) profiles [12], in comparison with previous works by MAGIC (long gray dashed line, [13]), *Fermi*-LAT (black and gray dash-dotted lines, [14]), H.E.S.S. (black dotted line, [15]), HAWC (gray dash-dotted-dotted line, [16]), and DAMPE (short gray dashed line, [17]).

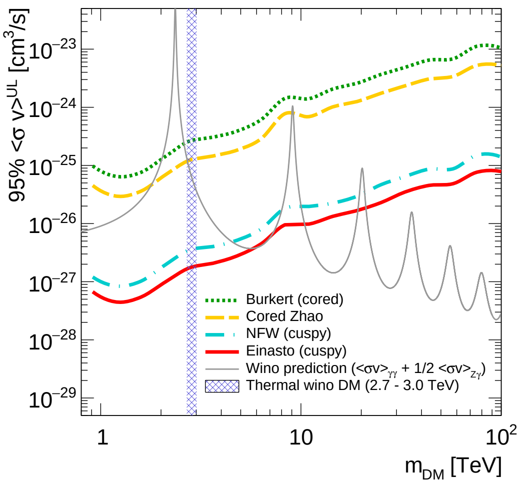

Figure 4: Upper limits in comparison with the limit curves assuming the density distributions shown Fig. 1. The black solid line represents the annihilation cross-section expected when SUSY-Wino emits line emissions. The blue band near 3 TeV represents the mass region that can particularly explain the residual amount of DM[6].

5. Summary

Indirect dark matter searches with gamma-ray are complementary to other WIMP searches. In particular, it allows us to access heavy dark matter models in TeV scale. Imaging Atmosphreic Chrenkov Telescopes have a good sensitivity on Very-High-Energy Gamma-ray. This study presents the results of a search for dark matter through observations of the Galactic Center of the Milky Way using the MAGIC Telescope. We achieved the world-leading sensitivity for line emission searches from dark matter annihilation from 900 GeV to 100 TeV, making use of large zenith angle observations, and constrained on SUSY-Wino with different dark matter density profiles, including both Cuspy and Core profiles.

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