Search for Gamma-Ray Spectral Lines from Dark Matter Annihilation up to 100 TeV toward the Galactic Center with MAGIC

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Linelike features in TeV γ rays constitute a "smoking gun" for TeV-scale particle dark matter and new physics. Probing the Galactic Center region with ground-based Cherenkov telescopes enables the search for TeV spectral features in immediate association with a dense dark matter reservoir at a sensitivity out of reach for satellite γ-ray detectors, and direct detection and collider experiments. We report on 223 hours of observations of the Galactic Center region with the MAGIC stereoscopic telescope system reaching γ-ray energies up to 100 TeV. We improved the sensitivity to spectral lines at high energies using large-zenith-angle observations and a novel background modeling method within a maximum-likelihood analysis in the energy domain. No linelike spectral feature is found in our analysis. Therefore, we constrain the cross section for dark matter annihilation into two photons to $\langle\sigma v\rangle \lesssim 5 \times 10^{-28}$ cm^3 s^{-1} at 1 TeV and $\langle\sigma v\rangle \lesssim 1 \times 10^{-25}$ cm^3 s^{-1} at 100 TeV, achieving the best limits to date for a dark matter mass above 20 TeV and a cuspy dark matter profile at the Galactic Center. Finally, we use the derived limits for both cuspy and cored dark matter profiles to constrain supersymmetric wino models.

Introduction.—Astrophysical observations suggest the presence of nonbaryonic cold dark matter (DM) [1–3]. An explanation for DM is the existence of a new class of nonrelativistic elementary weakly interacting massive particles (WIMPs) [4,5]. WIMPs are supposed to have decoupled from thermal equilibrium in the early Universe and, assuming the DM mass is on the electroweak scale in the GeV to TeV range, can fully account for the measured relic DM abundance [6]. Pairs of WIMPs annihilate, producing standard model particles including γ rays [7]. These γ-ray signals are expected to show distinct spectral features on the energy scale of the WIMP mass, especially if WIMPs directly annihilate into a photon and a second neutral particle like another photon, a Z boson, or h boson [8]. In such cases, monoenergetic photons are produced at energy $E_\gamma = m_{\rm DM}(1 - m_X^2/4m_{\rm DM}^2)$ in the center-of-mass frame, where $m_{\rm DM}$ and m_X are the rest masses of the DM and second product particle ($X = \gamma, Z, h$). In addition, internal bremsstrahlung in annihilations into charged standard model particles may result in a pronounced γ-ray spectral feature near the spectral endpoint [9]. Such sharp spectral features cannot be produced by known astrophysical processes. Hence, if discovered, a TeV γ-ray line would provide robust evidence for the existence of WIMP DM and new physics. The cross section for direct annihilation into photons is normally loop suppressed by a factor $\sim\alpha^2$, where α is the fine structure constant, compared to competing fermion and gauge boson channels [8,10]. However, mechanisms such as Sommerfeld enhancement [11,12] can significantly increase the signal. For instance, supersymmetric (SUSY) winos on the TeV scale are predicted to annihilate into γ rays with a cross section enhanced by several orders of magnitude compared with the loop-suppressed value [11,13–17].

If they exist, γ-ray signals from DM annihilation will most probably be first seen from nearby DM reservoirs such as the Galactic Center (GC) and dwarf spheroidal galaxies [18–20]. The GC region is particularly promising for such indirect searches for DM because of its high associated DM density. However, DM searches toward the direction of the GC [Sagittarius A* (Sgr A*)] are challenged by the extended astrophysical γ-ray emission detected up to TeV energies in the GC region [21–23]. γ-ray telescopes have already extensively searched for DM signatures toward the GC [24–34]. However, no unambiguous signal has been found so far. The strongest constraint to date on the cross section of WIMP annihilation into two photons in the TeV mass range up to 70 TeV is obtained from 254 hours of observations toward the GC with the H.E.S.S. telescopes [32]. In this Letter, we present new constraints on γ-ray lines from WIMP annihilation between 0.9 TeV and 100 TeV from over seven years of observation of the GC region with the MAGIC telescopes, improving previous limits above 20 TeV.

Expected gamma-ray flux.—The γ-ray differential flux from DM annihilation is represented by the equation

$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\frac{dN_\gamma}{dE}\times J(\Delta\Omega), \qquad (1)$$

with $\langle\sigma v\rangle$ the thermally averaged cross section of DM annihilation into a $\gamma\gamma$ pair, $m_{\rm DM}$ the WIMP mass, and dN_γ/dE the γ-ray yield per annihilation given by

$$\frac{dN_\gamma}{dE} = 2\delta(E - m_{\rm DM}). \qquad (2)$$

The so-called J-factor,

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \rho^2(l,\Omega)dl, \qquad (3)$$

is the integral of the squared DM density, ρ, over a solid angle $\Delta\Omega$ and along the observed line of sight (l.o.s.), calculated with the CLUMPY code [35].

The value of J constitutes the largest uncertainty on the expected annihilation signal from the GC region, as the DM distribution in the central few kpc of the Milky Way is observationally poorly constrained [36–38]. Therefore, we consider different DM density models of Milky-Way-like galaxies [39–42], bracketing the plausible range for the GC in agreement with observations. For the Lambda-cold dark matter prediction of a cuspy profile [43,44], we adopt the Navarro-Frenk-White (NFW) [45] and Einasto [46] models with the same parameters as in Refs. [26,32,47]. For the scenario of the inner Galaxy having formed a DM core due to baryonic feedback processes [48–51], we discuss the Burkert description [52] from Ref. [53] and the fit with a cored Hernquist-Zhao profile [54,55] from Ref. [56], both expressing an almost flat DM density distribution within the solar circle. Any scenario of smaller cores, as, e.g., discussed in Refs. [27,57], or density slopes shallower than the NFW profile results in a J factor bracketed by our profile assumptions. A detailed discussion of the profiles and parameter values is available in the Supplemental Material, Sec. A, provided with this Letter [58].

Observations.—We observed the GC with the MAGIC telescopes, located in the Roque de los Muchachos observatory (28 °N, 18 °W) at an altitude of 2200 m above sea level on the Canary Island of La Palma in Spain. The MAGIC system consists of two 17 m diameter imaging atmospheric Cherenkov telescopes [59]. For MAGIC the GC is visible at zenith angles larger than 58°. For observations at large zenith angles (LZA), the average distance between the core of the γ-ray-initiated particle cascade and the telescopes is much larger than for usual observations in the low-zenith range. Therefore, the Cherenkov light pool becomes wider, and fewer Cherenkov photons reach the detector due to the increased geometric distance and absorption in the atmosphere. This results in a higher energy threshold for the detection of γ rays. At the same time, above the threshold, it enlarges the effective collection area up to an order of

magnitude compared with low zenith angles [60]. Therefore, observing the GC under LZA conditions is well suited for searching linelike γ-ray emission from TeV-scale DM annihilations. We stress that LZA observations degrade the energy resolution only by a few percent [61].

The MAGIC telescopes have observed the GC region over seven years between April 2013 and August 2020 [23,60]. Observations were conducted in the so-called "Wobble mode" [62] with different pointing offsets of 0.4°, 0.5°, and 1.0° with respect to the direction of the GC (Sgr A*). The total dataset is divided in nine data subsets, differing in pointing direction of the telescopes and instrumental conditions. We removed low-quality data acquired during suboptimal observation conditions, e.g., bad weather or strong moonlight, and only kept events recorded at zenith angles between 58° and 70°. After those quality cuts, the total live time of the dataset is 223 hours. In Supplemental Material, Sec. B [58], we provide details on these data subsets and quality cuts. The data were processed with the MAGIC standard analysis software [63] which uses the random forest method [64] to estimate the energy and arrival direction of the incoming events and to classify the events into γ rays and cosmic-ray background.

Data analysis.—After the reconstruction, the cut in the particle classification variable was optimized to achieve the best sensitivity for a γ-ray detection above the hadronic background events. In order to test the data for the existence of a spectral line at the energy $E = m_{\mathrm{DM}}$, we applied the

sliding-window analysis technique [65,66]: in a defined energy range around E, a global fit to the energy distribution of events is performed within a large circular region of interest (ROI) around the GC by a model composed of the γ-ray line plus the background from other astrophysical γ-ray sources and residual charged cosmic rays. The ROI is required to be within a distance of 1.5° from the pointing direction to reduce uncertainties from the camera response close to the camera edge, resulting in different ROI sizes for the nine data subsets. The adopted ROIs are given in the Supplemental Material, Sec. B, to this Letter [58]. For all studied DM profiles, these ROIs were found to provide the best sensitivity to a line search.

The advantage of the sliding-window technique compared with spatial background subtraction methods [67] is that it does not require a background sky region off the target (OFF region). In particular, for spatially extended emission, the signal may leak into an OFF region, reducing or even removing the sensitivity to the signal. The approach of a sliding-window fit on the energy spectrum does not suffer from this limitation. However, the sliding-window technique is susceptible to a poor background modeling, which we addressed by a careful evaluation of the resulting systematic uncertainties. We searched for a spectral line at 18 different energies, between 0.9 TeV and 100 TeV and set constraints on $\langle \sigma v \rangle$ with the maximum likelihood method. For every data subset i (here $i = 1, \ldots, 9$), we modeled the likelihood function as

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

$$= \underbrace{\frac{(g_i + \tau_i b_i)^{N_{\mathrm{ON},i}}}{N_{\mathrm{ON},i}!} e^{-(g_i + \tau_i b_i)}}_{(a)} \times \underbrace{\prod_{j=1}^{N_{\mathrm{ON},i}} \frac{1}{g_i + \tau_i b_i} [g_i f_g(E'_j) + \tau_i b_i f_b(E'_j)]}_{(b)} \times \underbrace{\mathcal{T}(\tau_i | \tau_{\mathrm{obs}}, \sigma_\tau)}_{(c)}. \quad (4)$$

In Eq. (4), the vector $\boldsymbol{\nu}_i$ denotes the nuisance parameters, and $\mathcal{D}_i$ represents the ith data subset. Term (a) is the Poisson likelihood term for the total number of events observed in the region defined by the energy window around m_{DM} and the sky region around the pointing direction, with g_i and b_i the mean number of signal and background events, respectively, and $N_{\mathrm{ON},i}$ the number of observed events in the ROI and energy window. Term (b) is the joint unbinned likelihood for the observed values of the estimated energies E'_j. Here, f_g and f_b are the probability density functions (PDFs) of E' for the signal and background events, respectively. $f_g(E') = G(E'|E)$ corresponds to the convolution of the assumed signal spectrum of a sharp spectral line at energy E with the energy dispersion G of the telescopes obtained from Monte Carlo simulations. $f_b(E')$ is the assumed background spectral shape in the energy window. The 68% containment range of the energy

resolution, $2\sigma_E$, was used to define the energy window, log centered at m_{DM} with width $\pm 4\sigma_E$. This width was found to provide the best sensitivity while keeping systematic biases from the background modeling to a minimum. We modeled the combined astrophysical γ-ray and cosmic-ray backgrounds by interpolating the energy spectrum inside the energy window with a power-law function. Term (c), $\mathcal{T}$, is the likelihood term for the normalization τ_i of the background, parametrized by a Gaussian function with mean τ_{obs} and variance σ_τ^2. τ_{obs} and σ_τ^2 were estimated from test datasets free of γ-ray sources, taken off the GC region and in a similar zenith angle range as the dataset on the GC. σ_τ includes both statistical and systematic uncertainties and was found to be smaller than 1% of τ_{obs}. Details and supporting figures on the determination of τ_{obs} and σ_τ are provided in the Supplemental Material, Sec. C, to this Letter [58]. b_i and τ_i are nuisance parameters, while g_i

depends on the free parameter $\langle \sigma v \rangle$ through the following equation:

$$g_i(\langle \sigma v \rangle) = T_{\text{obs},i} \int_{E'_{\min,i}}^{E'_{\max,i}} dE' \int_0^\infty dE \frac{d\Phi(\langle \sigma v \rangle)}{dE}$$
$$\times \bar{A}_{\text{eff},i}(E) G_i(E'|E), \tag{5}$$

where $T_{\text{obs},i}$ is the observation time for each data subset i, and E and E' are the true and the reconstructed energies. $E'_{\min,i}$ and $E'_{\max,i}$ are the minimum and maximum reconstructed energies in the energy window. The morphology-averaged effective collection area is given by [20,68]

$$\bar{A}_{\text{eff},i}(E) = \int_{\text{ROI}} d\Omega' \int d\Omega \frac{d\mathcal{J}(P)}{d\Omega}$$
$$\times A_{\text{eff},i}(E, P) R(P'|E, P). \tag{6}$$

Here, P and P' are the true and reconstructed incoming directions corresponding to the differential solid angles $d\Omega$ and $d\Omega'$, respectively. $d\mathcal{J}(\mathcal{P})/d\Omega$ is the PDF for the arrival direction of γ rays from DM annihilation around the GC. $A_{\text{eff}}(E, P)$ is the effective collection area for γ rays of energy E and arrival direction P. R is the PDF of the direction estimator. We computed $\bar{A}_{\text{eff}}$ numerically from a sample of γ rays simulated with arrival directions distributed according to $d\mathcal{J}(\mathcal{P})/d\Omega$, applying the so-called "Donut" Monte Carlo method [68].

The total likelihood $\mathcal{L}$ is the product of the nine individual likelihood terms $\mathcal{L}_i$, corresponding to the nine considered data subsets:

$$\mathcal{L}(\langle \sigma v \rangle; \boldsymbol{\nu} | \mathcal{D}) = \prod_{i=1}^9 \mathcal{L}_i(\langle \sigma v \rangle; \boldsymbol{\nu}_i | \mathcal{D}_i). \tag{7}$$

Finally, we defined the test statistic (TS):

$$\text{TS} = -2 \ln \lambda_P(\langle \sigma v \rangle | \mathcal{D}) = -2 \ln \left(\frac{\mathcal{L}(\langle \sigma v \rangle; \hat{\hat{\boldsymbol{\nu}}} | \mathcal{D})}{\mathcal{L}(\widehat{\langle \sigma v \rangle}; \hat{\boldsymbol{\nu}} | \boldsymbol{D})} \right), \tag{8}$$

where $\widehat{\langle \sigma v \rangle}$ and $\hat{\boldsymbol{\nu}}$ in the denominator are the values that maximize $\mathcal{L}$. In the numerator, $\hat{\hat{\boldsymbol{\nu}}}$ is the value maximizing $\mathcal{L}$ for a given $\langle \sigma v \rangle$. The distribution of the TS asymptotically approaches the $\chi^2_{k=1}$ distribution with 1 degree of freedom according to Wilks's theorem [69]. In the absence of signal, by solving $-2 \ln \lambda_P = 2.71$, we determined the one-sided 95% confidence level (CL) to set upper limits on $\langle \sigma v \rangle$. Because of $\langle \sigma v \rangle$ lying at the boundary of the parameter space, the coverage of our confidence intervals is not exactly 95%. However, by construction (and confirmed using simulations), our recipe produces overcoverage, similarly to other results [28,32,70,71] derived using similar prescriptions [72].

Results and discussion.—The analysis revealed no significant linelike γ-ray excess in the GC region. Therefore we derived upper limits on $\langle \sigma v \rangle$ of annihilations into two γ rays for DM particle masses between 0.9 TeV and 100 TeV (black dots in Fig. 1, for a cuspy Einasto density profile). We confirmed the consistency of our results with the null hypothesis by performing 300 simulations of the expected background and computing for each tested DM mass the median, the 68%, and the 95% containment bands of the obtained distribution of limits on $\langle \sigma v \rangle$ (dotted black curve, green and yellow bands in Fig. 1).

We tested the dependence of our limits on a systematic uncertainty on the energy resolution and a possible bias: we mimicked a detector response with energy resolution of $\sigma_E/E = 25\%$, and found our limits to worsen by about 30%. Correspondingly, a misestimation of the energy scale of 15% due to unaccounted miscalibration of the telescopes affects our limits by 30%.

Figure 2 compares our limits on $\langle \sigma v \rangle$ with previous results by other instruments. The result by the H.E.S.S. telescopes from 2018 [32] relies on the same Einasto DM halo as in our analysis. Also, the results by *Fermi*-LAT for 5.8 years of data [28] and recently by DAMPE for five years of data [73] are given for an almost identical Einasto halo as in our Letter. Our result using the Einasto profile is competitive with the current best limits in the mass range of a few TeV and improves the best limits above 20 TeV by a factor of 1.5 to 2. This improvement in sensitivity is due to increased statistics at TeV energies by LZA observations. Figure 2 also shows how the uncertain knowledge about the DM distribution in the inner Galaxy [53,56] impacts our
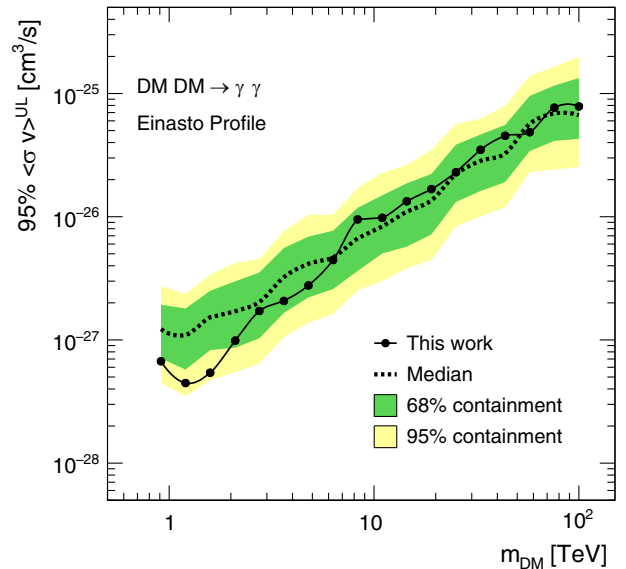

FIG. 1. 95% CL upper limits on the annihilation cross section $\langle \sigma v \rangle$ into two γ rays assuming the Einasto profile, as a function of energy. Observed limits (black dots) are shown together with the mean expected limits (black dotted line) and the 68% (green) and 95% (yellow) containment bands.
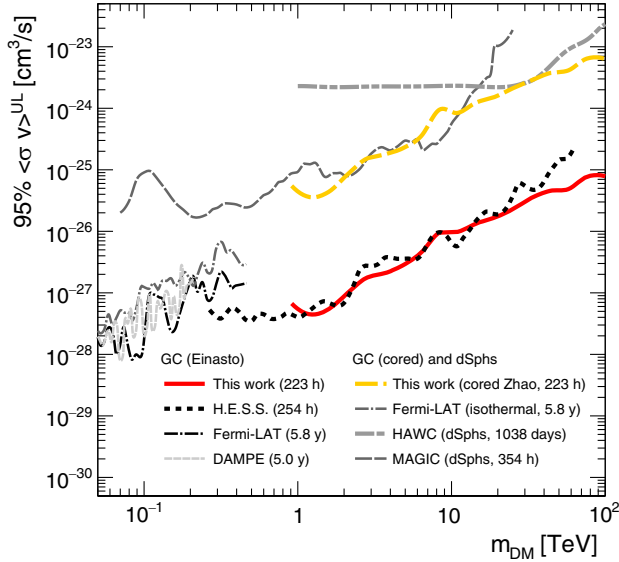
FIG. 2. 95% CL upper limits to γ-ray spectral lines from DM annihilation for the Einasto (red solid line) and cored Zhao (yellow dashed line, [56]) profiles, in comparison to previous works by MAGIC (long gray dashed line, [71]), *Fermi*-LAT (black and gray dash-dotted lines, [28]), H.E.S.S. (black dotted line, [32]), HAWC (gray dash-dotted-dotted line, [70]), and DAMPE (short gray dashed line, [73]). dSphs: dwarf spheroidal galaxies.
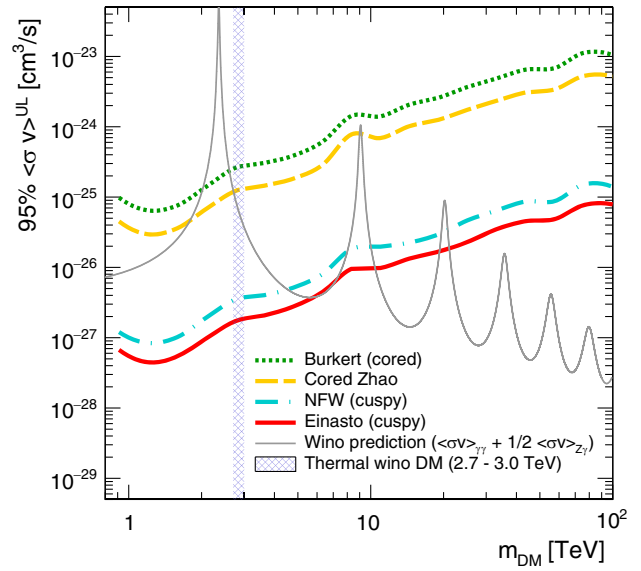
FIG. 3. Upper limits for the four DM density profiles considered in this Letter: the cuspy Einasto Galactic density profile (red solid line), the NFW profile (cyan dashed line), a DM core according to Ref. [56] (yellow dashed line), and the Burkert fit from Ref. [53] (green dotted line), compared against the total $\langle\sigma v\rangle$ corresponding to annihilation of two SUSY winos [i.e., $SU(2)_L$ triplets] into a $\gamma\gamma$ pair according to Refs. [11,13–15] (gray solid line; see text for details). The vertical blue hatched region indicates wino masses from 2.7 to 3.0 TeV which are consistent with the observed DM relic density [14].

limits. In case of an extended DM core around the GC, our constraints on $\langle\sigma v\rangle$ worsen by about 2 orders of magnitude. This degradation is caused by the shallower profile shape resulting in a lower J factor in the ROI. We emphasize that our analysis allows one to derive limits for such cored profiles, which is challenging for spatial background subtraction methods, as applied by, e.g., Refs. [30,32]. Our conservative limits on $\langle\sigma v\rangle$, corresponding to the lowest DM density in the inner Galaxy compatible with observational data, are comparable to the current most stringent limits from observation of dwarf galaxies, as shown for MAGIC [71] by the gray dashed curve in Fig. 2.

Our upper limits are able to constrain heavy SUSY models for both cuspy and cored profiles. In Fig. 3, we show our limits for the two cuspy and two cored profiles considered in this Letter compared with the total cross section of the two annihilation processes into $\gamma\gamma$ and $Z\gamma$ pairs for the wino model from Refs. [11,13–15]. The factor $1/2$ for the $Z\gamma$ channel expresses that in the calculation of our limits we have assumed the production of two γ rays per annihilation process [Eq. (2)], whereas for this channel only one is produced. The resonances in the thin gray curve show the Sommerfeld enhancement of the branching ratio and overall annihilation cross section for winos of the respective masses. Therefore, for the cuspy profiles, we can exclude wino annihilations for masses below 5 TeV and especially in the range between 2.7 and 3.0 TeV, found to produce a consistent thermal relic DM abundance [14] (blue hatched band in Fig. 3). In turn, for the most

conservative assumptions about a cored halo profile, a 2.7 TeV wino would be just marginally in agreement with our null measurement.

Conclusion and summary.—We have presented a search for spectral lines in γ rays from 0.9 TeV to 100 TeV toward the Galactic Center using 223 hours of observations with the MAGIC telescopes. The sensitivity at these high energies is boosted by the large telescope acceptance in LZA observations. In the analysis, we have used a sliding-window technique in the energy domain to search for a linelike signal on the top of the astrophysical γ-ray and cosmic-ray backgrounds. This approach has provided us with an unprecedented sensitivity to search for a signal from either a localized or very extended region in the sky. With this, we could probe the GC region for emission from DM annihilation for both the optimistic and conservative assumptions of a cuspy or cored Galactic DM halo. We have not found a significant signal of linelike γ-ray emission and have computed upper limits on the WIMP annihilation cross section $\langle\sigma v\rangle$. Around 1 TeV, the observed upper limits reach $\simeq 5 \times 10^{-28}$ cm^3 s^{-1} with the Einasto profile and $\simeq 8 \times 10^{-26}$ cm^3 s^{-1} with the Burkert profile. At 100 TeV the limits reach below 1×10^{-25} cm^3 s^{-1} in the Einasto case and $\simeq 1 \times 10^{-23}$ cm^3 s^{-1} in the Burkert case. This represents competitive limits on the linelike annihilation of TeV DM into γ rays, with up to a factor 2 better sensitivity above

20 TeV compared with previous measurements, and for the first time probed up to 100 TeV with imaging air Cherenkov telescopes.

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