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Gamma-ray line constraints on coy dark matter

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Coy dark matter is an effective scheme in which a fermionic dark matter candidate interacts with the standard model fermions via a pseudoscalar mediator. This simple setup avoids the strong constraints posed by direct detection experiments in a natural way and explains, on top of the observed dark matter relic abundance, the spatially extended γ-ray excess recently detected at the Galactic Center. In this paper we study the phenomenology of coy dark matter accounting for a novel signature of the model: the diphoton annihilation signal induced by the standard model fermions at the loop level. By challenging the model with the observations of spheroidal dwarf satellite galaxies and the results of γ-ray line searches obtained by the Fermi LAT experiment, we assess its compatibility with the measured dark matter relic abundance and the Galactic Center excesses. We show that despite the γ-ray line constraint rules out a significant fraction of the considered parameter space, the region connected to the observed Galactic Center excess remains currently viable. Nevertheless, we find that next-generation experiments such as DAMPE, HERD and GAMMA-400 have the potential to probe exhaustively this elusive scenario.

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I. INTRODUCTION

The matter content of our Universe is dominated by a component which, differently from ordinary matter, interacts at most very weakly with the photons of the standard model (SM)—the dark matter (DM). It is usually assumed that DM consists of stable and weakly-interacting massive particles (WIMPs), which are thermal relics of dynamics once active in the hot early Universe. The reason behind the success of this picture is that particles with masses and annihilation cross sections set by the electroweak scale yield, in a natural way, DM relic densities of the order of the observed one. The basis of this remarkable coincidence lies in the freeze-out mechanism (for a review: [1,2]), a natural consequence of the interplay between particle physics and an expanding Universe. For its simplicity and the appealing connection to frameworks like supersymmetry, the WIMP model became the paradigm of DM and shaped the dedicated long term experimental program.

To date, in spite of the intense experimental effort, the nature and the properties of DM remain still a puzzle. Furthermore, the negative results of dedicated experiments accumulated so far have started to shake the belief of the community in the WIMP paradigm. In fact, the nondetection of supersymmetric partners of SM particles at collider experiments has impaired the attractiveness of supersymmetric theories, which traditionally provide a strong theoretical framework for WIMPs. Moreover, recent constraints from direct detection experiments started to challenged WIMP-nucleon scattering cross sections of the order of the typical weak-scale value, thereby excluding substantial parts of the parameter spaces of traditional WIMP models. On the other hand, during the last decade, indirect detection experiments have reported anomalies that could be a first manifestation of DM. In 2008 the PAMELA satellite measured an excess of cosmic positrons above the energy of 20 GeV that could be a byproduct of DM annihilation/decay in our Galaxy (e.g., [3,4]). The signal was later confirmed by subsequent analyses from the Fermi LAT and AMS-02 collaborations [5–7]. Similarly, in 2009 the Fermi LAT data [8] revealed a spatially extended γ-ray excess at the Galactic Center (GC) in the energy windows of 1–5 GeV [9–19]. Hints of a γ-ray line at 130 GeV were also found [20–23] in the Fermi LAT data, but unfortunately faded away as a statistical fluctuation in later analyses. Intriguingly, these features all point to DM annihilation cross sections of the order of the freeze-out one in WIMP models, $\langle\sigma_{\mathrm{ann}}\mathrm{v}\rangle \simeq 3\times10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$, supporting the fascinating idea that DM interactions could originate the observed signals. However, we remind that the environment where such phenomenon are observed, mainly the GC, is an extremely complex region filled with stars, stellar relics, dust, gas, and subject to intense cosmic rays. As active astrophysical processes like millisecond pulsar populations [24] or ultraenergetic events from the past [25] also can explain the mentioned observations, it is currently not possible to discern their origin.

In order to investigate whether DM dynamics is behind the mentioned signals, we explore here complementary phenomenological implications within the framework of “coy dark matter” (CoyDM) [26]: a model that draws from the WIMP paradigm but eludes the stringent direct detection bounds in a natural way. In this effective scheme, DM is a new Dirac fermion that interacts with the SM content by the exchange of a pseudoscalar mediator. DM can then annihilate into SM fermions to give rise to the observed DM relic abundance, via the freeze-out mechanism, and to secondary photon signals in DM dense regions such as the GC or dwarf satellite galaxies. Interestingly, owing to the pseudoscalar nature of the mediator, the scattering of CoyDM on nucleons is here a spin-dependent process and furthermore suppressed by the fourth power of the transferred momentum. The corresponding direct detection constraints are consequently orders of magnitudes weaker than the spin-independent bounds that apply to traditional WIMP scenarios, and allow the CoyDM model to match the observed signals without fine tunings in its parameters [26].

In the attempt to bound the properties of this elusive framework, in this paper we detail a yet unexplored feature of coy dark matter; the diphoton signal originated at the loop level by its interactions with the SM fermions. DM annihilations resulting into a diphoton final state induce line features in the cosmic γ-ray spectrum, which are easily distinguished from the power-law background due to astrophysical processes. Motivated by this observation, we explore the parameter space of CoyDM by challenging the model with: (i) the observed DM relic abundance, (ii) the constraints imposed by observations of dwarf spheroidal satellites [27], (iii) the bounds resulting from γ-ray line searches in the GC region [28] and (iv) the broad photon excess detected at the GC in an energy window of 1–5 GeV [9–19].[1] In the context of γ-ray line searches, we also evaluate the reach of forthcoming experiments such as DAMPE [31–34], HERD [35] and GAMMA-400 [36], showing the region of parameter space that these could probe. With our analysis we show that the γ-ray line searches based on the Fermi LAT data significantly bound the properties of CoyDM, although the current constraints are not able to probe the region of the parameter space associated to the detected GC excess. Remarkably, we find instead that the next-generation experiments have the capability to exhaustively explore the considered parameter region. In fact, these experiments can potentially preclude CoyDM from explaining the observed GC excess, and even relegate the model to narrow corners of its parameter space where the DM relic abundance bound is matched only owing to resonance effects.

The paper is organized as follows. In Sec. II we briefly review the model and introduce the cross sections relevant for our analysis, highlighting the diphoton one. The details of our investigation and the considered experimental constraints are specified in Sec. III, where we show the impact of the mentioned bounds on the parameter space of CoyDM. Finally, in Sec. IV we draw our conclusions.

II. COY DARK MATTER

Following the proposal of Boehm *et al.* [26], our DM candidate is a Dirac fermion χ with mass m_χ. The interactions of χ with the SM content are mediated by a new pseudoscalar field a, of mass m_a, according to the effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} - i\frac{g_\chi}{\sqrt{2}} a\bar{\chi}\gamma^5\chi - i\sum_f \frac{g_f}{\sqrt{2}} a\bar{f}\gamma^5 f + \text{H.c.}, \qquad (1)$$

where f runs on the SM fermions and

$$g_f \coloneqq A_f y_f = A_f \frac{\sqrt{2} m_f}{v} \qquad (2)$$

being $v = 246$ GeV the Higgs boson vacuum expectation value. The couplings of the pseudoscalar mediator to the SM fermions are assumed proportional to the corresponding Higgs Yukawa couplings, in agreement with the minimal flavour violation ansatz [37]. In the following analysis we will set the proportionality factor $A_f = 1$, commenting however on the impact of a different choice on our results.

In this setup, the DM annihilation rate into SM fermions at the present era amounts to

$$\langle \sigma_{\chi\chi\to f\bar{f}} \mathrm{v} \rangle_0 \simeq \frac{C_f (g_\chi g_f)^2}{8\pi} \frac{m_\chi^2 \sqrt{1 - m_f^2/m_\chi^2}}{(m_a^2 - 4m_\chi^2)^2 + m_a^2 \Gamma_a^2} \qquad (3)$$

where C_f is the color multiplicity of a SM fermion f and, as customary, we approximated the thermal average by retaining the s-wave contribution only. In the above formula we indicated with Γ_a the total decay width of a, given by

$$\Gamma_a = \sum_{\bar{f}} \frac{C_f g_{\bar{f}}^2 m_a}{16\pi} \sqrt{1 - \frac{4m_{\bar{f}}^2}{m_a^2}}, \qquad (4)$$

where $\bar{f}$ runs on fermions, DM included, with masses $m_{\bar{f}} < m_a/2$ and we neglected higher order contributions which allow the pseudoscalar mediator to decay into the SM gauge bosons.

The above cross section regulates the intensity of the potential signal from DM annihilations emitted at the GC and dwarf spheroidal satellites of the Milky Way. In the following we will also consider the results of γ-ray line

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[1] Although we focus here on the constraints posed by the measurements of the cosmic photon spectrum, we remark that CoyDM has the potential to explain γ-ray lines possibly detected in the cosmic spectrum, for instance the ~40 GeV excess reported in Ref. [29]. The same excess is also found at the GC and galaxy clusters, albeit at a lower significance [28,30]. As we will demonstrate, the CoyDM is able to reproduce such signals owing to annihilations via the $\gamma\gamma$ final state, induced at the loop level by the charged fermions of the SM.

searches obtained by the Fermi LAT collaboration, which bound the loop level $\gamma\gamma$-channel annihilation rate,[2]

$$\langle\sigma_{\chi\chi\to\gamma\gamma}\text{v}\rangle = \frac{g_\chi^2\alpha^2}{16\pi^3}\frac{\left|\sum_f C_f Q_f^2 g_f m_f \mathcal{F}(\frac{m_\chi^2}{m_f^2})\right|^2}{(4m_\chi^2 - m_a^2)^2 + m_a^2\Gamma_a^2}. \tag{5}$$

Here α is the fine structure constant, f is running on the fermions in the loop that connects the pseudoscalar mediator to the SM photons while Q_f, m_f and C_f are, respectively, the electric charge, mass and colour multiplicity of these particles. The loop function that enters the above expression is given by [39,40]

$$\mathcal{F} = \begin{cases} \arcsin^2(\sqrt{x}) & \text{if } x \leq 1 \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-x^{-1}}}{1-\sqrt{1-x^{-1}}}\right) - i\pi\right]^2 & \text{if } x > 1 \end{cases}. \tag{6}$$

We find that the large contributions from the light quarks are compensated by the smallness of the associated couplings $g_f \propto m_f/v$. Consequently the annihilation rate of DM into photons is dominated by the contributions of heavy quarks running in the loop.

For the chosen set of pseudoscalar-SM couplings, the γ-ray line cross section is typically suppressed by a few orders of magnitude with respect to the $f\bar{f}$ one. However, we remark that line signals in the galactic photon spectrum can be distinguished from the power-law astrophysical background more easily than distributed excesses due to primary fermionic annihilation channels.

III. INDIRECT DETECTION AND RELIC ABUNDANCE BOUNDS

The model, as delineated in the previous section, is completely specified by three parameters: m_a, m_χ and g_χ. Our exploration of the corresponding parameter space focuses on the ranges reported in Table I. We explore a range of mediator masses complementary to that probed by flavor physics constraints [41], whereas the values of DM mass that we consider are motivated by the phenomenology of the GC excess.

In this regard, previous analysis of the GC excess [15–18,42] found that the detected photon signal is best reproduced by DM annihilation proceeding via the bottom-quark channel. In the considered CoyDM model, if the mass of the DM particle χ is below the mass of the top quark, the dominant annihilation channel is precisely $\chi\chi \to b\bar{b}$ because of the hierarchy in the pseudoscalar couplings to the SM fermions. In particular, the choice $m_\chi \simeq 30$ GeV allows us to fit the γ-ray excess for a natural value of the DM annihilation cross section $\sim\langle\sigma_{\text{ann}}\text{v}\rangle \simeq 3\times10^{-26}$ cm^3 s^{-1}.

TABLE I. The ranges considered for the CoyDM parameters in the performed scan. We set $A_f = 1$, cf. Eq. (2).

Parameter	Lower bound	Upper bound	Step
m_a (GeV)	5	300	5
m_χ (GeV)	20	120	1
g_χ	10^{-2}	10	10^{-3}

We remark that the excess can also be reproduced via the $\chi\chi \to \tau\bar{\tau}$ channel, see for instance [43,44], although in this case a lower DM mass $m_\chi \simeq 10$ GeV is required and the quality of the fit worsens with respect to the $b\bar{b}$-channel result.

Having delineated the region of the parameter space that our analysis explores, we detail below the constraints that we consider.

(i) DM relic abundance

For every point in the parameter space we check whether the current constraint on the DM relic abundance is satisfied. This quantity is computed through the dedicated function provided by the MICROMEGAs v.4.3.2 library [45,46]. We consider a point successful if it yields a relic abundance $\Omega_{\text{DM}}h^2 \in [0.1118, 0.1199]$, corresponding to the 3σ bound from the Planck experiment [47].

(ii) GC excess

In this study we adopt the best-fit values obtained in Ref. [42] for the cross section $\langle\sigma_{\chi\chi\to b\bar{b}}\text{v}\rangle$; a point successfully reproduces the GC excess if according to Eq. (3) it leads to a $b\bar{b}$-channel annihilation cross section within 3σ from the best fit value of Ref. [42].

(iii) Bound from observations of dwarf galaxies

Observations of the dwarf spheroidal satellites of the Milky Way by the Fermi LAT pose a stringent bound on the DM annihilation rate for the quark and tauonic channels. In our analysis we require that $\langle\sigma_{\chi\chi\to b\bar{b}}\text{v}\rangle$ fall within the 95% confidence interval from Ref. [27].

(iv) The **γ**-ray line constraint

As mentioned before, despite the reduced cross section, γ-ray lines are easily recognizable over the power-law spectrum of astrophysical background. For this reason we check that the values obtained for the diphoton cross section via Eq. (5) comply with the observed bound from Ref. [28]. To this purpose, we adopted the strongest constraint arising from observation of the most central part of the Galaxy, denoted as the region R3 in Ref. [28]. We also consider the impact of the DAMPE [31,32,34], HERD [35] and GAMMA-400 [36] next generation experiments by estimating their reach for the same region from Refs. [31,32,34,48–51].

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[2] We disregard here the loop-level decay of the mediator to a digluon final state. In fact, although the cross section is clearly larger than the diphoton one, the signal is bogged down by the hadronization of the final state gluons, which distributes the signal over a wide energy band as in the case of the b-channel [38].

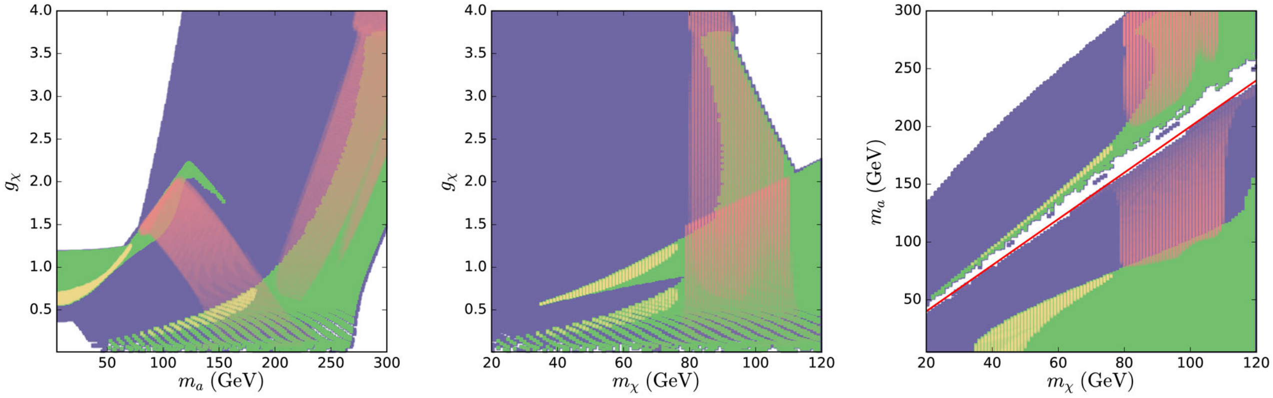

FIG. 1. The explored parameter space of the CoyDM model. The blue region indicates the area where the observed DM relic abundance is matched. The green areas, instead, single out the parameters of the model which satisfy the bound from dwarf satellite galaxies on top of the DM relic abundance. In the yellow regions, as well as obeying the previous constraint, the model is able to reproduce the broad photon excess detected at the Galactic Center. The red areas, instead, are excluded by the nonobservation of γ-ray lines in the photon spectrum detected by the Fermi LAT satellite (observed limit [28]).

The scan plots in Fig. 1 show projections of the parameter space of the model in the considered ranges and the effect of the mentioned constraints. We highlight in blue the regions of the parameter space which result in the correct DM relic abundance. Although the required values are achieved in most of the considered configurations, the strict bound posed by observations of dwarf spheroidal satellite galaxies restrict considerably the viable parameter space [27]. We highlight in green the regions where both the bound on the annihilation cross section from dwarf spheroidal satellites and that on the DM relic abundance are satisfied. The red regions, instead, delineate the areas that are excluded by the statistical constraint from the nonobservation of γ-ray lines in the cosmic photon spectrum [28] by the Fermi LAT experiment. Finally, in the yellow regions, the model satisfies the DM abundance constraint, the constraint on $\langle \sigma_{\chi\chi\to b\bar{b}} \mathrm{v} \rangle$ due to observations of the dwarf satellite galaxies and reproduces, as well, the broad photon excess observed at the GC [15–18,42]. We signaled with a red line in the rightmost panel the points that satisfy the resonance condition $m_a = 2m_\chi$. Neighboring configurations are excluded because of the large resonant enhancement to the total annihilation cross section.

The constraints posed by the γ-ray line searches are exposed in greater detail in Fig. 2. Here we plot the relevant annihilation rate $\langle \sigma_{\chi\chi\to\gamma\gamma} \mathrm{v} \rangle$ as a function of the DM mass m_χ, adopting the same color code as in Fig. 1. The red ovals highlight the 1, 2 and 3σ confidence intervals for the GC excess fit, whereas the light blue regions represents the observed 95% confidence level limit from the Fermi LAT γ-ray line searches. The semitransparent red areas are thus excluded by the Fermi LAT constraint at a 95% confidence level.

We remark that our results hold regardless of the specific DM profile adopted. Different choices of the latter, in fact, can be modeled in a multiplicative factor $A = [0.17, 5.3]$ [42] which affects the gamma-ray line constraint and the GC excess in the same way. Considering a different profile would then shift both the line constraints and the red ovals of the GC excess in Fig. 2 by the same amount. As our main result depends on the ratio between these two quantities, Fig. 3, the effects of the A factor cancel out.[3]

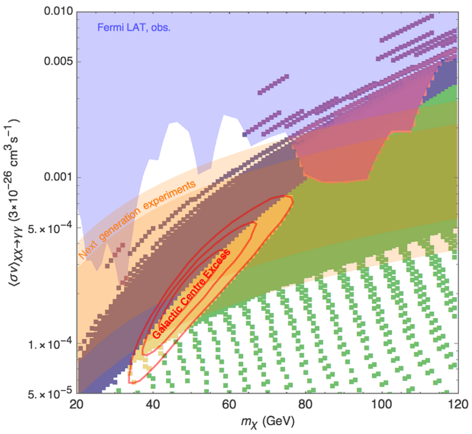

FIG. 2. Constraints posed by the γ-ray line searches on the parameter space of the coy dark matter model. The adopted color code is the same as in Fig. 1. The red ovals highlight the regions where the model fits the broad photon excess at the Galactic Center with a confidence level of 1, 2 and 3σ. The light blue region shows instead the current 95% confidence level bound from the Fermi LAT γ-ray line searches, which excludes the region of the parameter space shaded in semitransparent red. The orange bands show our estimates for the 68% (darker) and 95% (lighter) containment limits of the exclusion bound that next-generation experiments will cast.

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[3] This holds provided that both the best-fit and the constraint are based on the same (or at least similar) region of the DM profile, as it is in our case.

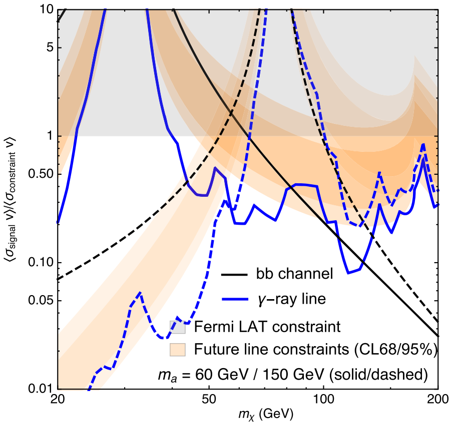

FIG. 3. Sensitivity of the constraints from γ-ray line searches and observations of dwarf spheroidal satellites to the enhancement factor A_f in Eq. (2). The blue and black lines show the ratios of potential signal annihilation rates with respect to the corresponding bounds, respectively for the $\gamma\gamma$ and $b\bar{b}$ channel. The solid and dashed lines are for two different mediator mass, respectively $m_a = 60$ GeV and $m_a = 150$ GeV. The light gray shading denotes the experimental exclusion area, where the signal annihilation rates overshoot their bounds. The orange bands denote instead our estimate for the 68% and 95% containment regions of next-generation experiments.

The reach of next generation experiments [31,32,34–36] is indicated by the orange bands, which represent our estimate based on the specifications in Refs. [31,32,34, 48–50] for the 95% (lighter) and 68% (darker) containment limits of the expected exclusion bound. As we can see, for their improved energy resolution, these experiments can probe a vast majority of the considered parameter space, covering in particular almost the totality of the region where the CoyDM model reproduces the GC photon excess. The possibility that the mentioned future observations could provide such an exhaustive test of this elusive model is indeed intriguing. Notice also that the next generation experiments could reach diphoton cross sections below about 3×10^{-30} cm^3 s^{-1}, forcing the CoyDM model to satisfy the DM relic abundance constraint only through resonance effects. The latter result in the periodic pattern shown in the bottom part of the figure, the spacing of which reflects the values of the adopted increment steps, see Table I. Finally, we remark that the bound cast by γ-ray line searches is also strengthened in extension of this framework that contain new charged heavy states coupled to the pseudoscalar mediator.

To conclude our analysis, we investigate the impact that larger values of the enhancement factor A_f in Eq. (2) have on the analyzed bounds. Given that both the annihilation rates in Eq. (3) and (5) scale as $\langle\sigma_{f\bar{f}\to b\bar{b}/\gamma\gamma}{\rm v}\rangle \propto A_f^2$, we compute the ratios between these quantities and the corresponding experimental constraints, cast respectively by observation of dwarf spheroid satellites [27] and γ-ray line searches [28]. The ratios are illustrated in Fig. 3, where the case of $b\bar{b}$-channel is plotted in black whereas the diphoton one is shown in blue. The solid and dashed lines represent different choices of the mediator mass: $m_a = 60$ GeV and $m_a = 150$ GeV respectively. We shaded in gray the region of the plot where the considered annihilation rates overshoot the corresponding constraints, being thereby excluded at progressive significances by such observations. The constraint on the $b\bar{b}$ annihilation channel is tighter than the γ-ray line one on most of the considered DM mass range, independently of the chosen mediator mass m_a. For larger values of the enhancement factor A_f and a fixed mediator mass, the constraint of dwarf spheroidal satellites has the potential to rule out areas in the parameter space characterized by $m_\chi \lesssim 100$ GeV. For higher DM masses, the γ-ray line searches are generally expected to be more sensitive to enhancements in the pseudoscalar mediator couplings to the SM fermions. In Fig. 3 we also show the estimated 68% and 95% containment bands for the considered next-generation experiments, respectively shaded in dark and light orange. The experiments will probe approximately the same DM mass range as the current searches, although at a much higher sensitivity.

IV. RESULTS

The coy dark matter model reconciles dynamics typical of the WIMP paradigm with the latest results of direct detection experiments. Owing to the pseudoscalar nature of the mediator, that bridges here the dark and visible sectors, the coy dark matter model naturally evades the stringent bounds on the spin-independent cross section associated to elastic dark matter-nucleon scatterings. Current measurements of the corresponding spin-dependent cross section, which in principle could constrain the model, are not yet sensitive enough to cast effective bounds.

In order to explore the coy dark matter scenario, in this paper we have investigated the related phenomenology in the context of indirect detection experiments, with particular attention to possible γ-ray lines signatures. More in detail, we scanned a sensible region of the associated parameter space assessing the impact of the considered bounds: the observed dark matter abundance, the broad γ-ray excess detected at the Galactic Center, the γ-ray observations of the dwarf spheroidal satellite galaxies of the Milky Way and the searches for γ-ray lines in the Galactic photon spectrum by the Fermi LAT. The last observable has been discussed also in relation to the upcoming DAMPE, HERD and GAMMA-400 experiments.

Our results can be summarized as follows:

(i) The coy dark matter model is able to give rise to the observed dark matter relic abundance in a vast part of the considered parameter space via the freeze-out mechanism, implemented here predominantly by dark matter annihilation to the $b\bar{b}$ and aa final states. However, the observational γ-ray bounds from the dwarf spheroidal satellites limit noticeably the number of successful solutions.

(ii) The mentioned bounds do not preclude the model from fitting the 1–5 GeV γ-ray excess detected at the Galactic Center via the same $b\bar{b}$ final state.

(iii) The constraints cast by γ-ray line searches started to probe the scenario, excluding a sizeable area of the parameter space for dark matter masses larger than about 80 GeV. Unfortunately, the current data is not able to test the regions where the coy dark matter model can explain the Galactic Center excess.

(iv) The above-listed next-generation γ-ray experiments have the potential to perform an exhaustive test of the scenario. Our estimate of the 68% and 95% containment bands for the expected exclusion limit cover almost the totality of the considered parameter space, including the region associated to the γ-signal detected at the Galactic Center. It is possible that next-generation experiments will corner the model to narrow regions of its parameter space where the DM relic abundance constraint is satisfied only via resonance effects in the dark matter annihilation process.

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