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Dark Matter with Pseudoscalar-Mediated Interactions Explains the DAMA Signal and the Galactic Center Excess

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We study a Dirac dark matter particle interacting with ordinary matter via the exchange of a light pseudoscalar, and analyze its impact on both direct and indirect detection experiments. We show that this candidate can accommodate the long-standing DAMA modulated signal and yet be compatible with all exclusion limits at $99_S\%$ C.L. This result holds for natural choices of the pseudoscalar-quark couplings (e.g., flavor universal), which give rise to a significant enhancement of the dark matter-proton coupling with respect to the coupling to neutrons. We also find that this candidate can accommodate the observed 1–3 GeV gamma-ray excess at the Galactic center and at the same time have the correct relic density today. The model could be tested with measurements of rare meson decays, flavor changing processes, and searches for axionlike particles with mass in the MeV range.

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Introduction.—Direct dark matter (DM) search experiments have undergone astonishing developments in recent years, achieving unprecedented sensitivity to weakly interacting massive particles (WIMPs) in the mass range from a few GeV to tens of TeV. The most stringent limits on the DM parameter space are set by LUX [1], XENON100 [2], and SuperCDMS [3] for spin-independent interactions, with PICASSO [4], SIMPLE [5], COUPP [6], and KIMS [7] setting relevant bounds for spin-dependent interactions and DM-proton couplings. While these and other searches did not find evidence for DM, four experiments have signals that can be interpreted as due to WIMP scatterings [8–11]. The significance of the excesses is mild (from 2σ to 4σ), except for DAMA's result [12], where the observation of an annually modulated rate as expected from the simplest model of DM halo, reaches the very high significance of 9.3σ. This achievement, however, has received a long-standing series of criticisms, given that the interpretation of the DAMA data in the light of many models of WIMP interactions is incompatible with all exclusion bounds.

Another claim of possible evidence of WIMP interactions comes from a 1–3 GeV γ-ray excess observed in the Galactic center (GC) [13] by the Fermi satellite. Although millisecond pulsars may be responsible for explaining the excess [14], the possibility of DM annihilation has attracted a lot of attention by the community. In fact, the excess can be fitted with models of annihilating DM which roughly provide the correct thermal relic density. In Ref. [15], for instance, it was shown that a Dirac WIMP interacting with standard model (SM) fermions through a pseudoscalar mediator can achieve the desired annihilation cross section, avoiding at the same time constraints from DM collider

searches, cosmic antiprotons and solar neutrino fluxes, and the cosmic microwave background. In fact, the point of Ref. [15] is that the DM might be "Coy," meaning that it can have a single detectable signature (in this case the annihilation into γ rays) while escaping all other searches.

In this Letter we show that Coy DM with a light pseudoscalar mediator can fit at the same time the GC γ-ray excess and the DAMA data, while being compatible with all null direct detection experiments.

The dark matter model.—The DM is a Dirac fermion χ with mass $m_{\rm DM}$, which interacts, with a coupling $g_{\rm DM}$, with a (real) pseudoscalar a with mass m_a coupled to the SM fermions:

$$\mathcal{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}}a\bar{\chi}\gamma_5\chi - ig\sum_f \frac{g_f}{\sqrt{2}}a\bar{f}\gamma_5 f. \qquad (1)$$

In the following we will consider two types of fermion couplings g_f: flavor-universal couplings $g_f = 1$ independent of the fermion type, and Higgs-like couplings proportional to the fermion masses $g_f = m_f/174$ GeV. Furthermore, for the direct detection analysis we will consider also the case of DM coupled equally to protons and neutrons (isoscalar interaction, also called "isospin-conserving"), as assumed, e.g., by Refs. [16,17]. (Notice that our use of the term "isoscalar" refers to the isospin symmetry between a proton and neutron. As it will become clear later on this does not imply, nor is implied by, isospin symmetry at the quark level.) In all cases we denote with g a multiplicative factor common to all couplings of a with SM fermions.

Direct detection.—When computing scattering cross sections at direct detection experiments, it is necessary

to bear in mind that the scattering occurs with the whole nucleus due to the small WIMP speed. Therefore, starting with an interaction Lagrangian with quarks as in Eq. (1), one needs first to determine the DM-nucleon effective Lagrangian and then to properly take into account the composite structure of the nucleus which results in the appearance of nuclear form factors in the cross section.

The first step is accomplished in our case by taking the following effective DM-nucleon interaction Lagrangian, valid in the regime of contact interaction:

$$\mathcal{L}_{\text{eff}} = \frac{1}{2\Lambda_a^2} \sum_{N=p,n} g_N \bar{\chi}\gamma^5 \chi \bar{N}\gamma^5 N, \quad (2)$$

where $\Lambda_a \equiv m_a/\sqrt{g_{\text{DM}}g}$. The proton and neutron coupling constants are given by

$$g_N = \sum_{q=u,d,s} \frac{m_N}{m_q}\left[g_q - \sum_{q'=u,\ldots,t} g_{q'}\frac{\bar{m}}{m_{q'}}\right]\Delta_q^{(N)}, \quad (3)$$

where $\bar{m} \equiv (1/m_u + 1/m_d + 1/m_s)^{-1}$ and we use

$$\Delta_u^{(p)} = \Delta_d^{(n)} = +0.84,$$
$$\Delta_d^{(p)} = \Delta_u^{(n)} = -0.44,$$
$$\Delta_s^{(p)} = \Delta_s^{(n)} = -0.03, \quad (4)$$

for the quark spin content of the nucleon [18].

It is important to notice here that g_p is *naturally* larger (in modulus) than g_n in both the flavor-universal and Higgs-like coupling scenarios. This will have important phenomenological consequences. In fact, since the interaction [Eq. (2)] measures a certain component of the spin content of the nucleus carried by nucleons [19], a large g_p/g_n will favor those nuclides (like ^{23}Na, ^{127}I and ^{19}F) with a large spin due to their unpaired proton rather than ^{129,131}Xe nuclei with an unpaired neutron. Given that the most stringent bounds for most DM-nucleus interactions are given at present by experiments using xenon (LUX, XENON100) while DAMA employs sodium and iodine, a large value of g_p/g_n would go in the direction of reconciling them. (We do not consider germanium detectors as their sensitivity to spin-dependent interaction via unpaired protons is smaller than, e.g., COUPP in the mass range relevant for Coy DM.) From the values in Eq. (4) we get $g_p/g_n = -16.4$ for flavor-universal and -4.1 for Higgs-like interactions. The relative size of the two couplings depends on the actual values of the $\Delta_q^{(N)}$'s, which are uncertain (see, e.g., Table 4 in Ref. [20] for a comparison of the different values found in the literature); the values in Eq. (4) are conservative in the sense that they minimize the ratio g_p/g_n, with respect to what is obtained with other choices of the $\Delta_q^{(N)}$'s (a second set of values from Ref. [18], which brackets from above the possible values of g_p/g_n,

yields a coupling ratio which is 2.7 and 1.3 times larger than the one given by Eq. (4), for flavor-universal and Higgs-like couplings, respectively). Notice that, as long as $g_u = g_d = g_s$, the contribution of the light quarks cancels in Eq. (3), and one may therefore set $g_u = g_d = g_s = 0$ as in hadronic axion models [21]. Finally, we will also use isoscalar interactions, i.e., by setting $g = g_p = g_n$ without using Eq. (3), as assumed in Refs. [16,17].

Once the DM-nucleon Lagrangian is established, one needs to determine the DM interaction cross section with the nucleus. This is customarily done by coherently adding the amplitudes of interaction with the different nucleons in the nucleus, and multiplying by an appropriate nuclear form factor that parametrizes the loss of coherence in the scattering with increasing exchanged momentum. While form factors for the standard spin-independent and spin-dependent interactions have been extensively studied, little is known of form factors for other interactions. Notice that the Lagrangian [Eq. (2)] corresponds in the nonrelativistic limit to a DM-nucleon interaction $(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$, with $\vec{S}_\chi$, $\vec{S}_N$ and $\vec{q}$ the DM spin, nucleon spin, and exchanged momentum, respectively, while the standard spin-dependent interaction corresponds to $\vec{S}_\chi \cdot \vec{S}_N$. At the nuclear level, the difference stands in the fact that the former interaction only measures the component of the nucleon spin in the nucleus that is longitudinal to $\vec{q}$, while the latter couples to both longitudinal and transverse components. Therefore, it is not justified to use the standard spin-dependent form factor for the interaction in Eq. (2) as done, e.g., in Refs. [15,22], although in some cases it could be used as a proxy [16]. The form factor to be used in this case has been computed in Ref. [19] using standard shell model techniques.

The DM interaction cross section with a target nucleus with mass m_T is

$$\frac{d\sigma_T}{dE_R} = \frac{1}{128\pi}\frac{q^4}{\Lambda_a^4}\frac{m_T}{m_{\text{DM}}^2 m_N^2}\frac{1}{v^2}\sum_{N,N'=p,n} g_N g_{N'} F_{\Sigma''}^{(N,N')}(q^2), \quad (5)$$

with v the DM speed in Earth's frame, $E_R = q^2/2m_T$ the nuclear recoil energy and $F_{\Sigma''}^{(N,N')}$ the (squared) form factors. The large suppression factor q^4/m_a^4 for large mediator mass is the reason why the interaction in Eq. (2) has often been neglected. Given this suppression in the nonrelativistic limit, one should check that radiative corrections do not produce unsuppressed interactions that are therefore comparable to the Born cross section at low velocities; however, the Lagrangian [Eq. (2)] is known to not produce such interactions [23]. It should also be checked that higher order QCD corrections do not spoil the enhancement of the WIMP-proton coupling with respect to the WIMP-neutron one, as from Eq. (3) which is valid at lowest order [24,25]. However, since pseudoscalar currents can only be coupled to an odd number of mesons as opposed, e.g., to scalar
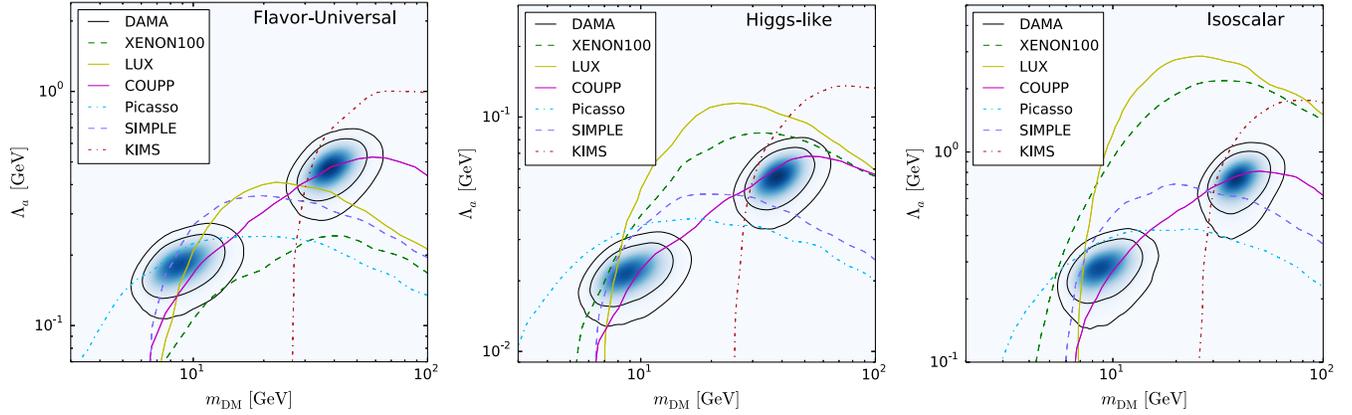
FIG. 1 (color online).   Two-dimensional credible regions for DAMA (shaded area and black solid lines, 90% and 99% C.L.) and exclusion limits (99_S% C.L.) in the (m_{DM}, Λ_a) plane, for flavor-universal (left), Higgs-like (center), and isoscalar (right) couplings.

currents, we expect any corrections to be of the order of only 10% or less [26].

The scattering rate is

$$\frac{dR_T}{dE_R} = \frac{\xi_T}{m_T} \frac{\rho}{m_{DM}} \int_{v \geq v_{min}} d^3 v v f(\vec{v}) \frac{d\sigma_T}{dE_R}, \qquad (6)$$

with ξ_T the target's mass fraction in the detector, ρ the local DM density, and $f(\vec{v})$ the DM velocity distribution in Earth's frame, corresponding to a truncated Maxwell-Boltzmann with characteristic speed v_0 and escape velocity v_{esc} in the galactic frame. Considering elastic scattering and denoting with μ_T the DM-nucleus reduced mass, $v_{min} = \sqrt{m_T E_R / 2\mu_T^2}$ is the minimum speed a WIMP needs in order to impart the target nucleus with a recoil energy E_R. In order to compare with the experimental results, the rate in Eq. (6) must be convolved with the detector resolution function and the experimental efficiency (see, e.g., Refs. [20,27]).

We analyze data by LUX, XENON100, PICASSO, SIMPLE, COUPP, KIMS and DAMA. We use Bayesian statistics to infer the 99_S% credible interval for the exclusion limits and both the 90% and 99% credible regions for DAMA from the posterior probability density function. Details are given in Refs. [28,29], where it was demonstrated that the procedure is robust against the choice of the prior probability distributions for the parameters m_{DM} and Λ_a and matches well a profile likelihood analysis. We consider log priors for both our relevant parameters: the DM mass m_{DM}, from 1 GeV to 1 TeV, and the scale Λ_a, from 0.01 GeV to 100 GeV, not to favor a particular mass scale range. For each experiment we marginalize over the nuisance parameters, given by the uncertain astrophysical parameters ρ, v_0, v_{esc} (the central values for the Gaussian priors are $\bar{\rho} = 0.3$ GeV/cm^3, $\bar{v}_0 = 230$ km/s and $\bar{v}_{esc} = 544$ km/s), as well as the experimental uncertainties as described in Refs. [28,29]. The details on the likelihood

functions for the LUX and COUPP experiments are provided as Supplemental Material [30].

Figure 1 shows the results of our analysis for our three choices of couplings: flavor-universal, Higgs-like, and isoscalar. The two DAMA regions correspond, respectively, to scattering off Na (peaked around $m_{DM} \sim 8$ GeV) and I (peaked around $m_{DM} \sim 40$ GeV). Part of the regions is compatible with all null experiments for flavor-universal couplings at 99_S% C.L. Notice how the large enhancement of the WIMP-proton coupling with respect to the WIMP-neutron coupling suppresses the LUX and XENON100 bounds but not COUPP, PICASSO, SIMPLE, and KIMS. For Higgs-like couplings the LUX and XENON100 bounds are less suppressed due to the reduced g_p/g_n enhancement, and the exclusion limits disfavor both sodium and iodine regions. In the isoscalar case, instead, there is no enhancement and DAMA is largely disfavored at 99_S% C.L. by both XENON100 and LUX.

It is intriguing that the allowed DAMA iodine region lies in the ballpark of DM masses that can account for the γ-ray GC excess. In the following we investigate whether the two signals can be both accommodated within the Coy DM scenario.

The GC excess.—Various authors reported evidence for an excess of 1–3 GeV γ rays from the GC. Taking as a reference Fig. 15 of Ref. [13], DM particles with a mass $m_{DM} \sim 20$–40 GeV annihilating mostly into quarks with a cross section $\langle \sigma v \rangle \sim 1$–$2 \times 10^{-26}$ cm^3/s are shown to fit the spectrum of the observed excess. In particular, the results of the fit are shown for models with flavor-universal and Higgs-like couplings (right panel), and can be then directly compared with our results. (Notice that Ref. [13] assumes, in the definition of the γ-ray flux, that the DM is self-conjugated. This implies that, in order to predict the same signal in the GC, our cross section needs to be a factor of 2 larger than the one found in Ref. [13].)

In this section we show that the Coy DM interpretation of the DAMA data is compatible with a DM explanation of

the GC excess. In fact, χ can annihilate to SM fermions through s-channel pseudoscalar exchange, thus generating a secondary photon flux. The requirement of fitting the γ-ray excess can then be used to disentangle the pseudoscalar mass m_a from the product $g_{DM}g$ in Λ_a, that is the parameter constrained by DAMA. As we will see, there is room in the parameter space favored by DAMA (and allowed by the other experiments) to explain the GC excess, for pseudoscalar masses $m_a \ll m_{DM}$. This opens up the possibility to also break the degeneracy between g_{DM} and g by demanding that the correct relic density is achieved in the early universe via $\bar{\chi}\chi \to \bar{f}f$ and $\bar{\chi}\chi \to aa$ annihilations (the latter process being p-wave suppressed today), since the two cross sections have different dependence on g_{DM} and g.

In summary, from the three observables: (i) DAMA signal in direct searches, (ii) γ-ray excess in the GC, and (iii) correct relic density obtained by solving the Boltzmann equation, we can fully determine the free parameters of the Coy DM Lagrangian for our choices of pseudoscalar coupling to SM fermions, flavor-universal, and Higgs-like. Formulas for the annihilation cross sections are provided as Supplemental Material [30]. For (ii), unlike direct DM searches, indirect detection signals are different if the DM particles couple democratically with all quarks or just with the heavy ones, and we study these two cases separately. We dub these two scenarios "Universal (democratic)" and "Universal (heavy flavors)," respectively. We neglect annihilation to leptons as the produced γ-ray flux is smaller than the one due to annihilation into quarks, at equal couplings; the reduction factor can vary between 2 and 17 depending on the choice of the couplings. Notice that coupling to leptons is unessential for the purposes of fitting the GC excess and of studying direct detection experiments, unless it is much larger than the coupling to quarks. However, leptonic couplings are tightly bound by precision measurements of the electron and muon anomalous magnetic moments. For a pseudoscalar that only couples to heavy quarks, our model is compatible with these measurements as shown in the Supplemental Material to this Letter [30].

Table I reports the approximate best fit values of the DM mass and the thermally averaged annihilation cross section, as extracted from Fig. 15 of Ref. [13], for our different choices of g_f. Adopting these values, from conditions

TABLE I. Approximate best fit values of the DM mass and the thermally averaged annihilation cross section extracted from Fig. 15 of Ref. [13], for different choices of the pseudoscalar coupling to SM fermions. The values for the Universal (heavy flavors) case have been determined by taking the average of the best fit values for the $b\bar{b}$ and $c\bar{c}$ channels.

	m_{DM}^{best}	$\langle\sigma v\rangle_{best}$
Universal (democratic)	22 GeV	1.1×10^{-26} cm^3/s
Universal (heavy flavors)	31 GeV	1.4×10^{-26} cm^3/s
Higgs-like	33 GeV	1.6×10^{-26} cm^3/s

(i), (ii) and (iii) we obtain the following sets of values of the couplings g_{DM} and g, together with the corresponding value of m_a from the DAMA iodine best fit point:

Universal (democratic): $gg_f \simeq 7.7 \times 10^{-3}$, $g_{DM} \simeq 0.64$, and $m_a \simeq 35$ MeV. This scenario is favored by direct detection (see Fig. 1, left); however, the DM mass required for the GC excess is outside of the 99% C.L. of DAMA iodine region (see Table I).

Universal (heavy flavors): $gg_f \simeq 1.8 \times 10^{-2}$ for the heavy flavors and 0 otherwise, $g_{DM} \simeq 0.72$, and $m_a \simeq 56$ MeV. This is the best-case scenario, as the DM mass required to fit the γ-ray excess is fully compatible with the DAMA iodine signal.

Higgs-like: $gg_f \simeq 1.15m_f/174$ GeV, $g_{DM} \simeq 0.69$, and $m_a \simeq 52$ MeV. Here the GC signal is compatible with the DAMA iodine allowed region, which is however excluded at $99_S\%$ C.L. by LUX and XENON100 as shown in Fig. 1 (center).

For direct detection, the favored values of the pseudoscalar mass are of the same order as the typical momentum transfer. Therefore, we expect small changes in our fit to DAMA data due to the onset of the long-range regime; however, this will not modify our conclusions. Such a light mediator might be problematic because it could be stable or have a long lifetime (on cosmological time scales), thus constituting a sizable component of the DM or otherwise injecting unwanted energy after the time of big bang nucleosynthesis. However, the pseudoscalar state always decays before the time of big bang nucleosynthesis, either at tree level or at one loop. Interesting constraints on this model may come from studies of rare meson decays, flavor observables, and from searches for axionlike particles with mass in the MeV range. We notice, however, that these small values of m_a are below the sensitivity of *BABAR* [39], which is the most constraining collider experiment for light pseudoscalars. It is intriguing that light mediators, with mass around 1–100 MeV, are advocated by models of self-interacting DM to solve the small scale structures problem of the collisionless DM paradigm [40], although a careful study of the self-interaction potential from the Lagrangian [Eq. (1)] is in order to ensure that Coy DM can accommodate the structure anomalies.

Conclusions.—We have shown that a Dirac DM particle interacting with ordinary matter via the exchange of a light pseudoscalar can accommodate the DAMA data while being compatible with all null direct DM searches. Moreover, it can provide a DM explanation of the GC excess in γ rays and achieve the correct relic density. The best fit of both the direct and indirect detection signals is obtained when the pseudoscalar mediator is much lighter than the DM mass and has universal coupling with heavy quarks, as in hadronic axion models. The leptonic couplings are strongly constrained by precision measurements of the magnetic moment of the electron and muon,

but they do not enter the analysis and can be safely taken to be zero.

The $99_S\%$ C.L. compatibility of DAMA with the null searches is determined by the significant enhancement of the coupling to protons with respect to the coupling to neutrons, occurring for natural choices of the pseudoscalar coupling to quarks. It is intriguing to notice that our results could also be extended to the case of a massless mediator since the typical momentum transfer in direct detection is of the order of m_a.

Since the phenomenological success of this model relies on the enhancement of the DM-proton coupling with respect to the DM-neutron one, as well as on the adopted nuclear form factor, a careful assessment of uncertainties and corrections to these quantities is in order. The model could be tested with measurements of rare meson decays, flavor changing processes, and searches for axionlike particles with mass in the MeV range.

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