


**Indirect signals of dark matter can change depending on where you look**Hooman Davoudiasl<sup>\*</sup> and Julia Gehrlein<sup>†</sup>*High Energy Theory Group, Physics Department, Brookhaven National Laboratory,  
Upton, New York 11973, USA* (Received 26 August 2022; accepted 15 December 2022; published 3 January 2023)

We propose that the nature of indirect signals of dark matter (DM) can depend on the Galactic environment they originate from. We demonstrate this possibility in models where DM annihilates into light mediators whose branching fractions depend on a long-range force sourced by ordinary matter. In particular, electromagnetic signals of DM may only arise near the centers of galaxies where the ordinary matter densities, and hence astrophysical background levels, are high. We briefly discuss how our model could explain the Galactic Center gamma ray excess, without leaving much of a trace in baryon-poor environments, like dwarf spheroidal galaxies. Similar spatial dependence of indirect signals can also apply to models featuring metastable DM decay into light mediators.

DOI: [10.1103/PhysRevD.107.023002](https://doi.org/10.1103/PhysRevD.107.023002)**I. INTRODUCTION**

Strong observational evidence demands that we introduce a new substance, dark matter (DM), in order to have a consistent description of nature. Candidates for DM currently cover a wide range of possibilities, and aside for some theoretical preferences—for example in favor of weak-scale particles that may be part of a larger electroweak sector—no particular model seems to stand out as the most likely possibility. However, the null results of searches for weak scale candidates in various experiments [1] have led to an expanded view of DM models. In particular, “dark sector” models that include light  $\sim$ GeV scale states have attracted a great deal of attention in recent years [2–4] (for more recent reviews see e.g., Refs. [5–7]) due to the possibility of detecting these dark sector states at low-energy, but high-intensity, facilities.

A minimal scenario of a “dark sector” can contain, in addition to the DM candidate, a light mediator which couples that sector feebly to the Standard Model (SM). Hence, in these models, it could be natural for DM to have only indirect annihilation or decay signals. However, given the structure of the SM visible sector, one may suspect that a dark sector may also allow for a range of states and interactions. Hence, models which go somewhat beyond the minimal scenario could also be considered and they

may lead to potential novel signals. This is the path we will take in this work.

In the following, we consider the case where the mass of the mediator is below the mass of DM, such that it annihilates directly into mediator particles and becomes a thermal relic. The light mediator in turn can further decay into SM particles leading to indirect detection signatures of DM. We will entertain the possibility that the light mediator in the dark sector interacts with the visible world through a coupling that varies depending on the baryon density of the ambient space. This is implemented by assuming an ultralight scalar that couples to nucleons and takes background values that depend on the nucleon density. We thus show that the DM annihilation final states can dominantly decay into luminous SM states, like charged leptons, only in baryon-rich environments, where separating background from the signal is typically difficult. As an interesting example of this possibility, we will examine how such a model may address the longstanding Galactic Center (GC) gamma ray excess [8], without having corresponding signals in baryon-poor regions of space, like the Galactic halo or dwarf spheroidal galaxies (dSphs).

Next, we will present model implementations of this idea which can give rise to environment-dependent signatures of DM. We will then outline some of the phenomenological consequences of the model. A summary and our concluding remarks will also be presented.

**II. MODEL IMPLEMENTATION**

The basic assumption of our proposal is that the relic abundance of DM is determined by its annihilation into a dark sector mediator  $\rho$ . This mediator eventually decays into visible and invisible particles, which we take to be the

<sup>\*</sup>hooman@bnl.gov<sup>†</sup>julia.gehrlein@cern.ch

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electrically charged SM states and neutrinos, respectively. We further posit that the coupling  $g'_v$  of  $\rho$  to visible SM states can depend on the ambient nucleon (baryon) density,  $g'_v \propto n_n$ . Here, we will take the coupling to invisible states  $g'_{\text{inv}}$  to be independent of the matter density. We will assume the DM to be a Dirac fermion  $\chi$  coupled to a dark-photon mediator  $A_d$ , associated with a  $U(1)_d$  gauge interaction as a possible realization of our scenario. Another possibility is a singlet scalar mediator, however, this option is disfavored in a straightforward explanation of the GC excess [9]. Hence, we will focus on the dark photon mediator when we discuss the phenomenology of our scenario.

In order to couple the dark sector to the charged particles in the SM, we assume the kinetic mixing portal and invoke a dimension- $(4 + \mathcal{P})$  operator

$$\frac{1}{2 \cos \theta_W} \left( \frac{\phi}{\Lambda} \right)^{\mathcal{P}} F_{\mu\nu} F_d^{\mu\nu}, \quad (1)$$

where  $\mathcal{P}$  is a positive integer,  $\phi$  is an ultralight field,  $\Lambda$  is a high scale set by unspecified ultraviolet (UV) dynamics, and  $F_{\mu\nu}$  denotes the hypercharge field strength tensor. Here,  $F_{d\mu\nu} = \partial_\mu A_{d\nu} - \partial_\nu A_{d\mu}$  is the field strength tensor for a dark  $U(1)_d$  gauge interaction mediated by a “dark photon”  $A_d$  of mass  $m_d$  that couples with strength  $g_d$ . The normalization, using the weak mixing angle  $\theta_W$ , is chosen to yield a straightforward identification of the photon- $A_d$  kinetic mixing parameter  $\varepsilon$ , given by

$$\varepsilon \equiv \left( \frac{\phi}{\Lambda} \right)^{\mathcal{P}}. \quad (2)$$

In the following we will consider  $\mathcal{P} = 1$  for simplicity. In order to introduce a baryon density dependence in  $g'_v$ , we will employ a long-range force that couples to baryons, mediated by an ultralight scalar  $\phi$  of mass  $m_\phi$  which couples to a nucleon (baryon)  $n$  with strength  $g_n$ , according to

$$-\mathcal{L} = g_n \phi \bar{n} n + \frac{1}{2} m_\phi^2 \phi^2. \quad (3)$$

Such an ultralight scalar can be motivated in string theory inspired models like in Ref. [10] which also provide a possible UV completion of our scenario. The coupling of a long range force interacting with nucleons has been constrained to be  $g_n \lesssim 10^{-24}$  [11–13]. One could alternatively use a coupling to electrons, resulting in a scenario with essentially the same features.

We assume that the range of the interaction is  $\sim 1.5$  kpc such that it spans the whole GC, therefore we set  $m_\phi \sim 4 \times 10^{-27}$  eV. The field value of the ultralight scalar  $\phi$  depends on the nucleon (ordinary matter) density  $n_n$  as

$$\phi = \frac{g_n n_n}{m_\phi^2}, \quad (4)$$

where we have assumed a nonrelativistic matter population, which is a good assumption for physical regimes considered in our scenario.

In our convention, the coupling of the dark photon to protons is given by  $e\varepsilon$ , with  $e$  the electromagnetic coupling. The SM charged fermions  $f$  couple to  $A_d$  according to

$$e\varepsilon \sum_{i=q,l} Q_f^i \bar{f}_i \gamma_\mu A_d^\mu f_i, \quad (5)$$

where  $\varepsilon$  is the kinetic mixing parameter of  $A_d$  and hypercharge field strength tensors [14], and  $Q_f^i$  is the charge of a quark  $q$  or a lepton  $l$ . The dark photon couples to DM via

$$g_d A_d^\mu \bar{\chi} \gamma_\mu \chi, \quad (6)$$

where  $g_d$  is the  $U(1)_d$  coupling and we have assumed unit dark charge for  $\chi$ .

In addition, we allow the coupling of the dark photon to invisible states. We will assume that there is a dark sector fermion  $\psi$  of mass  $m_\psi \gg m_d$  charged under  $U(1)_d$ . In general, we need a dark Higgs field  $\Phi$ , in order to break  $U(1)_d$  and generate  $m_d = g_d \langle \Phi \rangle$ , with a vacuum expectation value (vev)  $\langle \Phi \rangle = v_\Phi / \sqrt{2}$ . One can then have an interaction of the form

$$\frac{\Phi H \bar{\psi} L}{M} + \text{H.c.}, \quad (7)$$

where  $H$  is the SM Higgs doublet and  $L$  is a lepton doublet;  $M$  is some UV mass scale. For simplicity, we have suppressed the flavor index of  $L$ , as we take the above operator to be flavor universal without changing the essential physics. Once both  $H$  and  $\Phi$  get vevs,  $\psi$  and SM neutrinos can mix; the mixing angle is given by

$$\theta \approx \frac{1}{2} \frac{v_\Phi v_H}{M m_\psi}, \quad (8)$$

where  $\langle H \rangle = v_H / \sqrt{2} \approx 174$  GeV. Note that since  $\psi$  is a Dirac fermion, the operator in Eq. (7) will not lead to a Majorana mass matrix for SM neutrinos and an additional mechanism—which we will not specify here—needs to be introduced for neutrino mass generation. With the above ingredients, we then find the dark photon neutrino coupling

$$g_\nu = g_d \theta^2. \quad (9)$$

The dark photon then couples to neutrinos in a flavor universal fashion

$$\frac{g_\nu}{2} \bar{\nu} A_d^\mu \gamma_\mu (1 - \gamma_5) \nu. \quad (10)$$

With the above interactions, the visible and invisible couplings are  $g_v^{A_d} \equiv Q_f^i \epsilon e$  and  $g_{\text{inv}}^{A_d} \equiv g_\nu$ , respectively.

If  $e\epsilon \gg g_\nu$ , the dominant branching fraction of  $A_d$  will be into charged SM particles, whereas for  $e\epsilon \ll g_\nu$ , the dominant branching fraction will be into neutrinos. The decay rate for  $A' \rightarrow \bar{\nu}\nu$  (into left-handed neutrinos) is

$$\Gamma(A_d \rightarrow \bar{\nu}\nu) = \frac{g_\nu^2}{24\pi} N_\nu m_d, \quad (11)$$

with  $N_\nu$  the number of neutrinos  $A_d$  decays into; we assume  $N_\nu = 3$ . The decay rate of  $A_d \rightarrow \bar{f}f$ , where  $f \in \text{SM}$  is a fermion of mass  $m_f$ , for charged leptons  $l$  is given by

$$\Gamma(A_d \rightarrow \bar{l}l) = \frac{1}{3} \alpha \epsilon^2 m_d \sqrt{1 - \frac{4m_l^2}{m_d^2}} \left(1 + \frac{2m_l^2}{m_d^2}\right) \quad (12)$$

and for quarks

$$\Gamma(A_d \rightarrow \bar{q}q) = N_c Q_q^2 \Gamma(A_d \rightarrow \bar{l}l)|_{m_l \rightarrow m_q}, \quad (13)$$

where  $\alpha \equiv e^2/(4\pi) \approx 1/137$  is the fine structure constant and  $Q_q$  is the electric charge of the quarks with  $N_c$  colors.

For the branching ratio into visible final states, we obtain

$$\text{Br}(A_d \rightarrow \bar{l}l, \bar{q}q) \approx \left(1 + 2.45 \frac{g_\nu^2}{\epsilon^2}\right)^{-1}. \quad (14)$$

Here, we have assumed that the mass of the dark photon  $m_d = 20$  GeV is large enough that it can decay into  $b$  quark pairs, but below top quark threshold. We will use this mediator mass as our reference value in what follows.

### III. GALACTIC NUCLEON DENSITIES

In order to show how our mechanism can be implemented, we need to estimate the baryon number density in different regions of galaxies. In the following, we will discuss the Milky Way as an example.

For simplicity, we will assume that the nucleon number distribution in the Galactic bulge<sup>1</sup> is roughly constant; from Refs. [15,16] we get  $\rho_{\text{bulge}} \approx 1 \times 10^9 M_\odot \text{ kpc}^{-3}$  assuming a radius of the Galactic bulge of  $\approx 1.5$  kpc. To account for the different models used to arrive at this number we will consider a 50% uncertainty on it in the following. This translates into a nucleon number density in the bulge of

$$n_n(\text{bulge}) = (1.6 - 4.7) \times 10^{-13} \text{ eV}^3. \quad (15)$$

The matter density of the Milky Way can be approximated as exponentially decreasing with distance to the Galactic Center and in the vertical direction, along

<sup>1</sup>In the following we will use ‘‘Galactic bulge’’ and ‘‘Galactic Center’’ interchangeably.

and away from the Galactic disk, respectively. From Ref. [17], we will use as total local matter density  $\rho_{\text{local}} = 9.7 \times 10^7 M_\odot \text{ kpc}^{-3} \approx 3.7 \times \text{GeV cm}^{-3}$  with the local DM density  $\rho_{\text{DM}} = 0.3 \text{ GeV cm}^{-3}$  which is known within a factor of 3. This translates to a local nucleon number density of

$$n_n(\text{local}) = (2.3 - 2.9) \times 10^{-14} \text{ eV}^3. \quad (16)$$

Therefore, we roughly estimate that the nucleon density around the solar system is  $\mathcal{O}(10)$  times smaller than that at the Galactic Center.

Many astrophysical constraints on DM come from observations of the Galactic halo which avoid complicated background events from bright sources in the Galactic plane [18].

We will adopt the signal region in Ref. [19], as an example, which roughly corresponds to Galactic latitudes  $|b| > 20^\circ$ , or  $\sim 3$  kpc above the Galactic plane. With a scale height  $\sim 1$  kpc, we expect that the nucleon density is reduced at this latitude by  $e^{-3} \sim 0.05$ . Given that the DM density increases as one approaches the GC, we may assume that the lowest latitudes would have the dominant annihilation rate for DM. Hence, as a conservative estimate we take

$$n_n(\text{halo}) \sim 0.1 n_n(\text{bulge}) \sim 3 \times 10^{-14} \text{ eV}^3, \quad (17)$$

for our benchmark halo nucleon density.

Finally, DM annihilation constraints from dSphs apply. In these objects, the nucleon density is very low as they are DM dominated; only  $\mathcal{O}(1\%)$  of the total matter is contained in baryons as can be deduced from their mass-to-light ratios, which are of order  $\mathcal{O}(100)$  [20,21]. Typical total masses of dSphs are  $\mathcal{O}(10^7 M_\odot)$  [22]. The size of dSphs is around  $\mathcal{O}(1)$  kpc, which roughly coincides with the Compton wavelength of  $\phi$ , and we therefore treat the matter density as constant. We find that typical nucleon densities in these dwarf galaxies are

$$n_n(\text{dSphs}) \sim 10^{-17} \text{ eV}^3, \quad (18)$$

which is about four orders of magnitude smaller than at the GC.

## IV. PHENOMENOLOGY

### A. Indirect signature of DM

In our model, we predict that luminous indirect signals of DM depend on its surrounding nucleon density.<sup>2</sup> Such signals can decrease drastically moving away from the Galactic Center to other regions of space with lower  $n_n$ . This is a manifestation of the changing branching

<sup>2</sup>See Ref. [23] for a model of nonlocal boosted DM annihilation signals which can potentially explain the GC excess (for an earlier related idea, see also Ref. [24]).

ratios of the mediator, whose decay is dominated by electrically charged states in baryon-rich environments and neutrinos (or other invisible states) in baryon-poor ones. Here we show how this feature can be used to provide a possible explanation for the long-standing GC gamma-ray excess [8].

In order to explain the GC excess, different final states can be invoked [25]. Instead of performing a detailed fit, here we use the general observation that DM mass around 20–40 GeV can accommodate the GC excess assuming annihilation into quarks and leptons with  $\langle\sigma v\rangle \approx \text{few} \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$  [25–27]. This cross section is also close to the value required to obtain the correct relic abundance. Hence to demonstrate the viability of our model, we set  $m_\chi = 40 \text{ GeV}$  in what follows. Notice however that constraints on energy injection into the CMB [28,29] on  $s$ -wave annihilation, for DM lighter than  $\sim 10 \text{ GeV}$ , can be avoided in our model for the chosen reference value of 40 GeV. Also, during the CMB era the dark photon branching fraction into electrons is  $\sim 15\%$  in our scenario [30], which can allow lighter DM if needed.

We now estimate the required mediator coupling to achieve the correct relic density of  $\chi$  [31,32]

$$\Omega h^2 = \frac{1.04 \times 10^9 x_F}{M_{\text{Pl}} \sqrt{g_\star} \langle\sigma v\rangle} \approx 0.12, \quad (19)$$

with  $x_F = m_\chi/T_F$  fixing the DM freeze-out temperature which we take to be  $x_F \approx 20$  Planck mass  $M_{\text{Pl}} \approx 1.2 \times 10^{19} \text{ GeV}$ , and  $g_\star \approx 80$  the number of effective degrees of freedom at freeze-out. The annihilation cross section is given by [33]

$$\sigma v(\bar{\chi}\chi \rightarrow A_d A_d) \approx \frac{g_d^4}{16\pi m_\chi^2} \sqrt{1 - \frac{m_d^2}{m_\chi^2}}. \quad (20)$$

From Eq. (19) together with Eq. (20) and  $m_d = 20 \text{ GeV}$ , the correct relic density can be reproduced with  $g_d \approx 0.11$ . As mentioned before, this also allows one to get an annihilation cross section consistent with the explanation for the GC excess, assuming that the  $A_d$  branching fraction into charged SM states is  $\approx 1$ .

Our model has to face additional bounds on which we comment below. DM annihilation in the Galactic halo constrains the cross section to be an order of magnitude smaller than the preferred cross section for the GC excess [19].<sup>3</sup> The DM explanation of the GC excess is further constrained, due to lack of a striking annihilation signal from DM-rich and baryon-poor environments like dSphs where all searches so far have come up empty

<sup>3</sup>Nevertheless, there is a potential hint for DM annihilation in the outer halo of the Andromeda galaxy [34]. However, this DM interpretation is subject to astrophysical modeling [35].

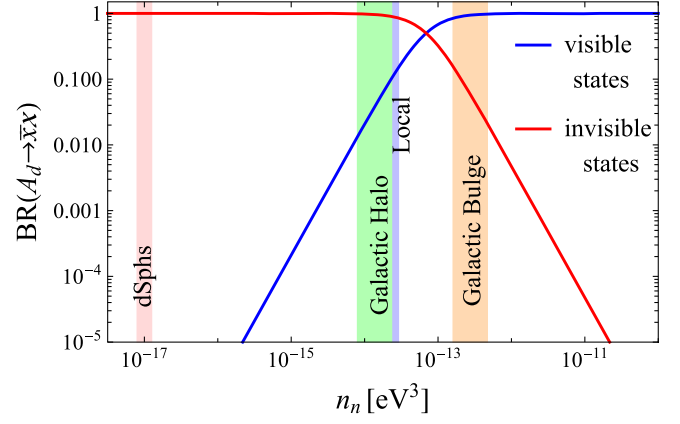


FIG. 1. Branching ratios of the dark photon in visible and invisible particle pairs  $\bar{\chi}\chi$  as a function of the nucleon number density, using the benchmark parameters from Table I. We use  $g_\nu/\varepsilon(\text{bulge}) \approx 0.15$ . We also indicate the ranges of nucleon number densities corresponding to the Galactic bulge, Earth Galactic neighborhood, Galactic halo, and the one of dwarf spheroidal galaxies.

handed [36,37]. To show how our model can evade these constraints we show in Fig. 1, the branching ratios of the dark photon into visible (charged) and invisible (neutrino) states using Eqs. (14), as a function of the nucleon density for fiducial parameters of the model given in Table I. We see that with a dark photon mediator our model can provide a consistent description of the GC data and the constraints from the halo and dSphs, as discussed earlier, assuming  $g_\nu/\varepsilon(\text{bulge}) \approx 0.15$ . For our reference values in Table I, we then have  $g_\nu \approx 2.8 \times 10^{-6}$ . Note that for possible values of  $v_\Phi$  and  $m_\psi$  near the weak scale,  $M \sim 10^5 \text{ TeV}$  which is a reasonably large value for the effective field theory (EFT).

There are also constraints from galaxy groups [38].<sup>4</sup> However, these constraints are weaker by an order of magnitude than the constraints from the Galactic halo and can therefore be easily satisfied by our model.

In baryon-poor environments, the dominant DM signal comes from the decay of the dark photon into neutrinos. The constraints on this channel come, for example, from DM annihilations into neutrinos in the Galactic halo which is constrained to be  $\langle\sigma v\rangle(\bar{\chi}\chi \rightarrow \bar{\nu}\nu)^{\text{exp}}(\text{halo}) \lesssim 10^{-23} \text{ cm}^3 \text{ s}^{-1}$  [39] which is a few orders of magnitude weaker than the constraint on visible final state particles. Another interesting signature of DM-neutrino interactions is the scattering of DM on neutrinos mediated by  $A_d$ . However for the reference values in Table I, our typical predictions for the scattering cross section are several orders of magnitude below current bounds [40–44] such that all constraints coming from neutrino-DM scattering can be evaded.

<sup>4</sup>Though, the morphology of the emission from these objects is not resolved by observations.

TABLE I. The fiducial parameters of the model. The first line represents our reference values for the scenario and the second line sets the effective theory scale which fixes  $g_\nu$  and  $\varepsilon(\text{bulge})$  and  $\varepsilon_\oplus = \varepsilon(\text{Earth})$ .

$m_\phi$	$g_n$	$m_d$	$g_d$	$m_\chi$	$g_\nu/\varepsilon(\text{bulge})$
$4 \times 10^{-27}$ eV	$10^{-24}$	20 GeV	0.11	40 GeV	0.15
$\Lambda$	$g_\nu$	$\varepsilon(\text{bulge})$	$\varepsilon_\oplus$		
$10^{17}$ GeV	$2.8 \times 10^{-6}$	$1.9 \times 10^{-5}$	$1.5 \times 10^{-11}$		

Similarly, at these tiny couplings ( $\varepsilon$ ,  $g_\nu$ ), no laboratory neutrino experiments probe our scenario.

### B. Direct detection phenomenology

Important constraints on the DM parameter space come from the absence of direct detection signals in large scale experiments. In our model, the local baryon density corresponding to the Earth's position in the Milky Way leads to a kinetic mixing parameter

$$\varepsilon_\oplus \approx (1.5 \times 10^{-11}) \left( \frac{10^{17} \text{ GeV}}{\Lambda} \right), \quad (21)$$

which is multiple orders of magnitude smaller than the bounds on dark photons from laboratory experiments [45,46]. The DM-nucleon scattering cross section is given by [47]

$$\sigma_{\chi p} = \frac{16\pi\mu_{\chi p}^2 \varepsilon^2 \alpha_d}{m_d^4}, \quad (22)$$

where  $\alpha_d = g_d^2/4\pi$  and  $\mu_{\chi p}$  is the  $\chi$ -proton reduced mass. The current best constraints on DM-nucleon scattering for  $m_\chi = 40$  GeV is  $\sigma_{\chi p}^{\text{exp}} \lesssim 9 \times 10^{-48} \text{ cm}^2$  [48]. With our benchmark values, we obtain

$$\sigma_{\chi p} \approx 2 \times 10^{-58} \text{ cm}^2 \times \left( \frac{\varepsilon_\oplus}{1.5 \times 10^{-11}} \right)^2 \left( \frac{20 \text{ GeV}}{m_d} \right)^4 \left( \frac{g_d}{0.11} \right)^2. \quad (23)$$

We thus see that for  $\sigma_{\chi p}$  to be close to the current bound—and therefore provide a target for direct detection experiments—we would need  $\varepsilon_\oplus$  to be about five orders of magnitude larger, which requires  $\Lambda \sim 10^{12}$  GeV as we can see from Eq. (21). However, as discussed below, this could be too low for a consistent EFT implementation.

Another way to constrain DM is to consider that, in general, it can accumulate in astronomical objects and annihilate, leading to their anomalous heating [49–52]. However, in our specific model realization with  $\Lambda \sim 10^{17}$  GeV we have  $\sigma_{\chi p} \sim 10^{-58} \text{ cm}^2$  which is smaller than

the typically required cross section for DM accumulation in compact stars [53]. In other realizations of our scenario  $\sigma_{\chi p}$  may be larger, potentially leading to the aforementioned heating effects. This requires  $A_d$  to decay into SM fermions within the star and a DM mass not much smaller than  $\sim 10$  GeV, as we will explain below.

In a neutron star, with a nucleon density  $\sim 10^{38} \text{ cm}^{-3}$  and neutrino nucleon cross section  $\sigma_{\nu n} \sim 10^{-37} \text{ cm}^2$  [17] at  $E_\nu \sim 10$  GeV, we roughly estimate the mean free path of neutrino products of DM annihilation to be  $\sim 0.1$  cm. This is very small compared to the  $\sim 10$  km size of the neutron star [54]. Hence, the neutrinos can typically deposit their energy quite efficiently inside the neutron star, after DM annihilation. The situation is similar for white dwarfs whose nucleon density is about eight orders of magnitude smaller, i.e.,  $\sim 10^{30} \text{ cm}^{-3}$ . This implies that the mean free path of a neutrino of  $\sim 10$  GeV energy is  $\sim 10^2$  km in the white dwarf, which is much smaller than its size of  $\sim 10^4$  km [54]. Therefore, even in the case where DM accumulates in a star our scenario does not predict distinct heating signatures depending on the baryon density of the Galactic environment.

### C. Additional constraints and considerations

#### 1. Thermalization and Higgs portal constraints

From the cosmological history of the dark sector, a number of constraints on the model parameters apply. The dark sector needs to be in thermal equilibrium with the SM at  $T \sim m_\chi$ . The Hubble constant, at this temperature, is  $H(T = 40 \text{ GeV}) \approx 1.66\sqrt{g_\star}T^2/M_{\text{Pl}} \approx 2 \times 10^{-15} \text{ GeV}$ , for our reference  $m_\chi$  value. Quite generally, we assume that a Higgs portal coupling  $\Phi^\dagger \Phi H^\dagger H$  can easily achieve this, once both fields get vevs, as thermalization does not require a large degree of  $H - \Phi$  mixing. For  $m_\phi \sim 1 - 100$  GeV the mixing angles is required to be  $\sin^2 \alpha \gtrsim 5 \times 10^{-9}$  [55].

#### 2. Consistency of the EFT approach

A lower bound on  $\Lambda$  arises from the validity of our approach. To ensure that the coupling of the dark photon to the SM can be described by an EFT, we require that  $\phi = g_n n_n / m_\phi^2 < \Lambda$  at all times, in particular in the early Universe where the matter densities are very large but the horizon scale is small. The maximal value of  $\phi$  corresponds to the case where the horizon size of the Universe is close to the wavelength of  $\phi$ . For increasing temperatures the Hubble length squared decreases as  $1/T^4$  while the nucleon density follows  $T^3$  such that the value of  $\phi$  decreases like  $1/T$  for larger temperatures [56]. For  $m_\phi \sim (1.5 \text{ kpc})^{-1}$  the temperature at which the horizon scale corresponds to the wavelength of  $\phi$  is  $T_m \approx 4$  eV. The nucleon density at this temperature is

$$n_n(T_m) \approx 8.0 \times 10^{-9} \text{ eV}^3. \quad (24)$$

Using Eq. (4) with  $g_n = 10^{-24}$ , we find a field value of

$$\phi_{\text{max}} = \phi(T_m) \approx 5 \times 10^{20} \text{ eV}. \quad (25)$$

Note that the above estimate is only valid up to a temperature where the baryon density is set by the baryon asymmetry, corresponding to  $T \ll 1 \text{ GeV}$ . At  $T \sim 1 \text{ GeV}$ , which is the minimum required for standard freeze-out with our DM parameters, the baryon density is set by the thermal population of quarks and antiquarks. We then have (see, e.g., Refs. [57,58] for discussions of the relevant physics)

$$\phi \sim \frac{g_n m_q T^2}{H(T \sim \text{GeV})^2}, \quad (26)$$

where  $m_q \sim \text{MeV}$  is a light quark mass,  $H(T \sim \text{GeV}) \sim 10^{-9} \text{ eV}$ , and hence  $\phi \sim 10^{18} \text{ eV}$  for  $g_n \sim 10^{-24}$ . Here, we have minimally assumed that  $\phi$  couples to light quarks, above the confinement scale, with the same strength as it couples to nucleons. Based on all of the above, we see that  $\Lambda \sim 10^{17} \text{ GeV}$ , as assumed in the text, is large enough to yield a consistent EFT.

### 3. Long range force constraints

A more stringent possible lower bound on the value of  $\Lambda$  can be motivated from constraints on long-range forces acting on matter, given some reasonable assumptions on the UV physics. The operator in Eq. (1) can typically be generated by loops of heavy states  $\Psi$  that carry hypercharge and dark charge. One then expects analog ‘‘kinetic’’ operators that couple  $\phi$  to a pair of hypercharge or  $A_d$  gauge bosons, characterized by UV scales  $\Lambda_Y$  and  $\Lambda_d$ , respectively. We may assume that the dark  $U(1)_d$  charge of  $\Psi$  is  $\mathcal{O}(1)$ , but it has fractional hypercharge  $q_Y^\Psi \ll 1$ , leading to a hierarchy,  $\Lambda_Y \gg \Lambda \gg \Lambda_d$ . Thus,  $\Lambda_d$  would be associated with the dominant dimension-5 operator and could, through a loop process, lead to a coupling of  $\phi$  and  $\chi$  with strength  $g_\chi$ . This would establish a long range force acting on DM [59], which is constrained by bounds from tidal streams [60,61],

$$g_\chi \lesssim 3 \times 10^{-18} \left( \frac{m_\chi}{40 \text{ GeV}} \right), \quad (27)$$

for  $m_\phi \lesssim 10^{-27} \text{ eV}$ , which is of similar order as our chosen value of  $m_\phi$ .

Using a simple 1-loop estimate, connecting  $\phi$  to  $\chi$ , we have

$$g_\chi \sim \frac{g_d^2 m_\chi}{16\pi^2 \Lambda_d}. \quad (28)$$

Following the above setup, if we choose  $q_Y^\Psi \sim 10^{-5}$  we find an effective value  $\Lambda \sim 10^{17} \text{ GeV}$  and  $\Lambda_Y \sim 10^{22} \text{ GeV}$ .<sup>5</sup> An estimate of a loop generated correction to  $g_n$ , analogous to that in Eq. (28), then yields  $\delta g_n \sim 10^{-25}$ , which allows a consistent set of parameters, including typical quantum corrections. Therefore, we choose  $\Lambda \approx 10^{17} \text{ GeV}$  as our benchmark value.

## V. SUMMARY AND CONCLUSIONS

In this paper, we examined the possibility that dark matter interacts with the visible world through light mediators whose couplings may vary, depending on the baryon density of the Galactic environment. This setup can be realized if there is a long range force that acts on baryons through the exchange of an ultralight scalar, whose background value also sets the strength of the mediator coupling to charged (visible) states. Assuming that the mediator in addition has constant couplings with neutrinos (invisible particles), one may arrange for a circumstance where dark matter annihilation would lead to luminous products, i.e., charged fermions, only in baryon rich Galactic environments, while resulting in neutrinos elsewhere. The scenario considered here then provides for the unusual possibility that *visible* dark matter annihilation signals are only to be found in the most challenging parts of galaxies; regions of dense baryon content and thus large astrophysical backgrounds.

As an interesting possibility, we then examined how our model could explain the Galactic Center gamma ray excess as a signal of dark matter annihilation, while resulting in no corroborating electromagnetic signal in relatively baryon-poor environments, like the Galactic halo or dwarf spheroidal galaxies. We implemented this scenario with a dark photon mediator, whose kinetic mixing with hypercharge scales with baryon number density.

Using a fiducial set of parameters, we showed that explaining the Galactic Center excess may require only a mild variation of dark photon properties, as a function of baryon density. To avoid possible conflict with bounds on long range forces acting on ordinary matter, the local interactions of dark matter with nucleons may be too weak to lead to future direct detection signals. This also implies inefficient accumulation of DM in stellar objects and likely the absence of anomalous heating signals.

Our proposal is testable in the sense that any significant signals of DM annihilation from baryon-poor regions of galaxies can challenge the assumptions of the scenario. Also, as a general feature, our model implementation relies on a long range scalar force that acts on ordinary matter. While the strength of this force is not predicted in our setup,

<sup>5</sup>Note that while this value is above  $M_p$ , it is a result of the tiny value of  $q_Y^\Psi \ll 1$  which translates into a small coefficient of the operator and we are not invoking super-Planckian massive states  $\Psi$ .

the typical parameters we have advocated point to a force accessible by possible future improved experiments. In addition, we have argued that constraints on the strength of the long-range interaction require a high UV scale. This, in turn, makes it less likely that foreseeable direct detection experiments would uncover ambient DM through its scattering from ordinary matter [62,63]. We close by pointing out that a similar dependence on the Galactic

baryon density variation may also alter the indirect signals of metastable dark matter decay, in alternative models.

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