X-Ray Lines from Dark Matter Annihilation at the keV Scale

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(Received 24 October 2017; revised manuscript received 4 December 2017; published 5 February 2018)

In 2014, several groups reported hints for a yet unidentified line in astrophysical x-ray signals from galaxies and galaxy clusters at an energy of 3.5 keV. While it is not unlikely that this line is simply a reflection of imperfectly modeled atomic transitions, it has renewed the community's interest in models of keV-scale dark matter, whose decay would lead to such a line. The alternative possibility of dark matter annihilation into monochromatic photons is far less explored, a lapse that we strive to amend in this Letter. More precisely, we introduce a novel model of fermionic dark matter χ with $\mathcal{O}(\mathrm{keV})$ mass, annihilating to a scalar state ϕ which in turn decays to photons, for instance via loops of heavy vectorlike fermions. The resulting photon spectrum is box shaped, but if χ and ϕ are nearly degenerate in mass, it can also resemble a narrow line. We discuss dark matter production via two different mechanisms—misalignment and freeze-in—which both turn out to be viable in vast regions of parameter space. We constrain the model using astrophysical x-ray data, and we demonstrate that, thanks to the velocity dependence of the annihilation cross section, it has the potential to reconcile the various observations of the 3.5 keV line. We finally argue that the model can easily avoid structure formation constraints on keV-scale dark matter.

DOI: 10.1103/PhysRevLett.120.061301

Many recent papers in astroparticle physics start out by exposing the waning of traditional dark matter (DM) candidates, especially the weakly interacting massive particle (WIMP) [1–3]. The present Letter is no exception. And while it is certainly too early to give up on the elegance of the thermal freeze-out mechanism for DM production, a look beyond is now more motivated than ever.

In this Letter, we will dwell on the possibility that DM is a fermion with a mass of only a few keV. Such DM candidates, which often go by the name of "sterile neutrinos" are well known for their potential to improve predictions for small scale structure (see for instance Ref. [4] and references therein), their clean observational signatures in the form of x-ray lines [4–9], and their tendency to evoke animated discussions among physicists [10–14]. Many such discussions were incited by recent claims for a yet-unidentified line at ∼3.5 keV in the x-ray spectra from galaxies and galaxy clusters [8,10–13,15–33]. Whether the origin of these lines is indeed related to DM physics [14,34–84], or simply to imperfect modeling of atomic physics effects [10,13,33,85], the controversy surrounding it cannot belie the fact that precision observations of the x-ray sky are a prime tool to search for keV-scale DM. While the overwhelming majority of studies on this topic focus on line signals from DM *decay*, we will here explore the possibility that such signals arise from DM *annihilation*.

We will introduce a toy model in which keV-scale Dirac fermions χ annihilate to pairs of new real scalars ϕ, which in turn decay to photons; see Fig. 1(a). These photons will have a box-shaped spectrum, which can be indistinguishable from a monochromatic line within experimental resolutions if χ and ϕ are nearly degenerate in mass. We will see below that the model can also explain the observed

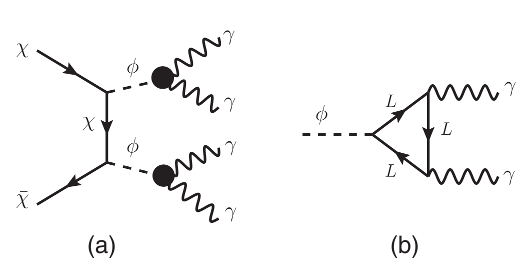

FIG. 1. (a) Feynman diagram for DM annihilation to photons via the intermediate scalar ϕ. Blobs represent the effective $\phi\gamma\gamma$ coupling from Eq. (1). Diagram (b) shows a possible UV completion for this vertex; see Eq. (2).

DM relic abundance. At low energies, the phenomenology of our model is captured by an effective Lagrangian consisting of just the ϕ couplings to photons and χ:

$$\mathcal{L}_{\rm eff} \supset \frac{\alpha}{4\pi\Lambda} F_{\mu\nu}F^{\mu\nu}\phi + y\phi\bar{\chi}\chi, \tag{1}$$

where y is a new dimensionless coupling constant, $F^{\mu\nu}$ is the electromagnetic field strength tensor, α is the electromagnetic fine structure constant, and Λ is the suppression scale of the dimension-5 interaction. We will see below that explaining the 3.5 keV line while satisfying all constraints requires $y \sim \text{few} \times 10^{-5}$ and $\Lambda \sim 10$–100 PeV.

Equation (1) can be completed to a renormalizable model for instance by introducing heavy vectorlike leptons L with charge assignment $(0, 1, -2)$ under $SU(3)_c \times SU(2)_L \times U(1)_Y$:

$$\mathcal{L} \supset \bar{L}i\not{D}L - m_L\bar{L}L + y\phi\bar{\chi}\chi + g\phi\bar{L}L, \tag{2}$$

where D^μ is the gauge covariant derivative, m_L is the mass of the heavy leptons, and g is the dimensionless L-ϕ coupling constant. In this UV completion,

$$\frac{1}{\Lambda} = \frac{4gm_L}{\mu^2} f(4m_L^2/\mu^2), \tag{3}$$

where μ is the renormalization scale, which we take equal to m_ϕ, and the loop function corresponding to the diagram in Fig. 1(b) is given by [86]

$$f(\tau) = \begin{cases} 1 - (\tau - 1)(\csc^{-1}\sqrt{\tau})^2) & \tau \geq 1 \\ 1 + \frac{\tau-1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \tau < 1 \end{cases}. \tag{4}$$

DM annihilation.—The cross section for the DM annihilation process $\bar{\chi}\chi \to \phi\phi$ depends on the relative mass difference $\delta \equiv (m_\chi - m_\phi)/m_\chi$ of χ and ϕ and on the relative velocity $v_{\rm rel}$ of the annihilating DM particles. In the Milky Way, $v_{\rm rel} \sim 200$ km/sec, while in galaxy clusters, $v_{\rm rel} \sim 1000$ km/sec. If $|\delta| \ll v_{\rm rel}^2$, the annihilation cross section is

$$\sigma_{\rm ann}v_{\rm rel} = \frac{y^4 v_{\rm rel}^3}{16\pi m_\chi^2}. \tag{5}$$

For $\delta \gg v_{\rm rel}^2$, we find

$$\sigma_{\rm ann}v_{\rm rel} = \frac{\sqrt{\delta}[2\delta(\delta+2)+3]y^4 v_{\rm rel}^2}{24\pi(1+\delta)^4 m_\chi^2}. \tag{6}$$

Note the different dependence on $v_{\rm rel}$ in these two limiting cases. A small value of δ could be naturally explained in a supersymmetric extension of the model, with χ and ϕ residing in the same supermultiplet [87–89].

The decay rate of ϕ to two photons is $\Gamma_{\phi\to\gamma\gamma} = \alpha^2 m_\phi^3/[(4\pi)^3\Lambda^2]$. For DM annihilation in the Milky Way, this implies that the morphology of the photon signal traces the distribution of DM only if $\Lambda \lesssim 2.5\ \text{PeV} \times (m_\phi/\text{keV})^3$. Then, the intermediate ϕ particles travel for $\lesssim$1 kpc before decaying, so the wash out of the annihilation signal due to their long lifetime is degenerate with the large uncertainties in the Milky Way's DM halo profile at radius $\lesssim$1 kpc [90].

For $\delta \lesssim 10^{-5} - 10^{-4}$ so that the photon signal from DM annihilation appears monochromatic within experimental energy resolutions, we compare the signals predicted by our model to data in Fig. 2. The shaded exclusion regions in this plot are based on reinterpreting existing limits on DM *decay* to monochromatic photons by equating the photon flux in the two cases:

$$\frac{\Gamma_\chi}{4\pi m_\chi}\int dld\Omega\rho_{\rm DM}(l,\Omega) = \frac{4}{16\pi m_\chi^2}\int dld\Omega d^3v_{\rm rel}\rho_{\rm DM}^2(l,\Omega)\sigma_{\rm ann}v_{\rm rel}f(l,\Omega,v_{\rm rel}). \tag{7}$$

Here, Γ_χ is the DM decay rate, $\rho_{\rm DM}$ is the DM density, and $f(l,\Omega,v_{\rm rel})$ is the DM velocity distribution at distance l along the line of sight in solid angle direction Ω. We obtain

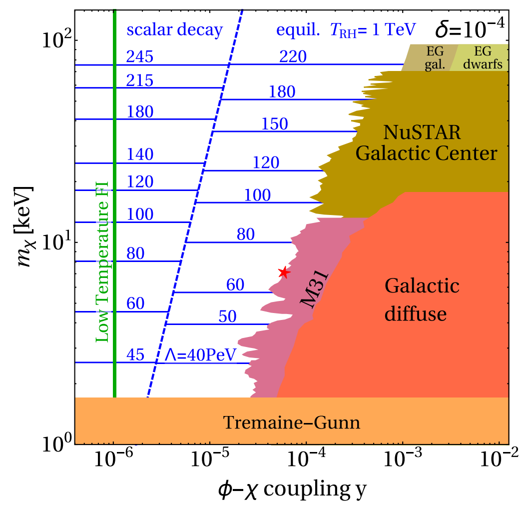

FIG. 2. Parameter space of the annihilating keV-scale DM models defined in Eqs. (1) and (2). We show the relevant constraints as a function of the DM mass m_χ and the Yukawa coupling between χ and the mediator ϕ, assuming a degeneracy parameter of $\delta \equiv (m_\chi - m_\phi)/m_\chi = 10^{-4}$. Shaded regions are excluded by x-ray observations of the Andromeda Galaxy (M31) [5], the Galactic Center (NuSTAR Galactic Center) [97], the galactic (Galactic diffuse) [7] and extragalactic (EG. gal and EG. dwarfs) [6] diffuse x-ray background, and by Pauli blocking arguments (Tremaine-Gunn) [98,99]. The red star [100] corresponds to the excess of monochromatic x rays at 3.5 keV observed in Refs. [8,15]. Horizontal blue lines indicate the suppression scale Λ of the $\phi\gamma\gamma$ coupling required to obtain the correct DM relic abundance via UV freeze-in, assuming $T_{\rm RH} = 1$ TeV. To the right of the dashed line, part of the initially produced abundance of χ gets transferred to ϕ via $\phi\phi \leftrightarrow \bar{\chi}\chi$ at $T \sim$ keV. The region to the right of the dashed line can also be reached via freeze-in through misalignment (see text). The vertical green band indicates where low temperature freeze-in via $\phi\phi \to \bar{\chi}\chi$ yields the correct relic abundance.

$f(l, \Omega, v_{\rm rel})$ numerically by evaluating Eddington's formula [91] (see Ref. [92] for possible shortcomings of this approach due to baryonic effects). The factor 4 on the right-hand side of Eq. (7) accounts for the number of photons produced in each annihilation $\bar{\chi}\chi \to \phi\phi \to 4\gamma$. For the limits based on diffuse extragalactic x rays from galaxies and dwarf galaxies ("EG gal." and "EG dwarfs"), Eq. (7) receives redshift-dependent corrections [93,94]. Among these is a factor $\Delta^2(z) \equiv \Delta^2(0)/(1+z)^3$ [93,95] that accounts for the stronger clumping of DM at late times in cosmological history. We conservatively choose $\Delta^2(0) = 10^6$ [96]. We moreover assume that the DM velocity distributions $f(l, \Omega, v_{\rm rel})$ of distant galaxies and dwarf galaxies follow those of the Milky Way and of Milky Way dwarfs, respectively.

Focusing specifically on the signal at 3.5 keV, Fig. 3 demonstrates that our scenario can align the different observations and nonobservations of the line. We have taken into account an uncertainty of roughly a factor of 2 in the DM velocity distribution for each astrophysical target, based on varying the parameters of the underlying NFW profiles within the ranges found in the literature [14]. For cumulative data sets from several sources, we sum Eq. (7) over all of them, weighted by the individual exposure times. For quasidegenerate DM and ϕ masses with $\delta = 10^{-4}$, we find that the 1σ confidence regions overlap for all observations except those from the Chandra deep field [101]. The alignment between different observations is thus

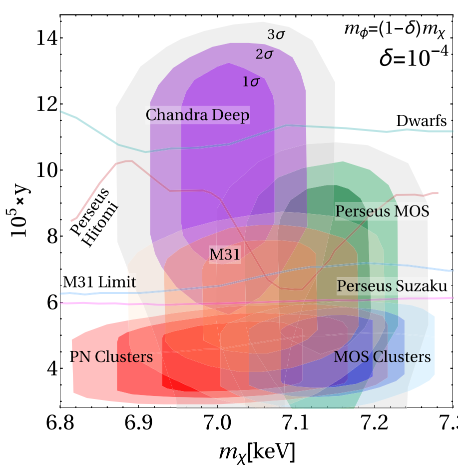

FIG. 3. Parameter regions of our annihilating DM scenario favored by observations of the 3.5 keV x-ray line $(1, 2, 3\sigma)$, and 90% CL exclusion limits from null results. We have assumed a degeneracy parameter of $\delta \equiv (m_\chi - m_\phi)/m_\chi = 10^{-4}$. From the compilation in Ref. [102], we adopt observations from stacked galaxy clusters using the MOS and PN instruments on the XMM Newton satellite [8], from the Perseus cluster alone [8], from the Andromeda Galaxy (M31) [15], and from the Chandra Deep Field [101]. Limits are based on nonobservations in M31 [5], dwarf spheroidal galaxies [18], and the Perseus cluster [21,85], and the regions above the solid lines are excluded.

marginally better than for decaying DM [102]. For $\delta = 10^{-4}$, Eqs. (5) and (6) contribute roughly equally for galaxy clusters, while Eq. (6) dominates for galaxies and dwarf galaxies. When compared to exclusion limits, our scenario fares better than decaying DM because the limit from dwarf galaxies is less relevant thanks to the strong dependence of the annihilation cross section on the DM velocity. We remark that future high-resolution observations of the 3.5 keV line [103,104] could potentially distinguish our model from models of decaying DM and from astrophysical explanations of the line by studying the line shape.

Dark matter production.—In the current literature, three major mechanisms are being discussed for the production of keV-scale DM: (i) nonresonant oscillations of active neutrinos ν_a to sterile neutrinos ν_s (Dodelson, Widrow [105]); (ii) resonant $\nu_a \to \nu_s$ oscillations (Shi, Fuller [106]); (iii) freeze-in of heavy particles [107,108], followed by their decay to keV-scale ν_s [109–111]. The parameter space for mechanisms (i) and (ii) is heavily constrained by searches for x-ray lines [5–7,97] and by structure formation [112–119] (see also Ref. [120]).

The model defined by Eq. (1) and its UV completion in Eq. (2) (or minimal extensions thereof, see below) enable several new DM production mechanisms, all of them based on freeze-in of dark sector particles. For a numerical analysis, it is convenient to parametrize the DM abundance by the DM yield $Y \equiv n_{\rm DM}/S(T)$. Here, $S(T) \equiv 2\pi^2 g_*^S(T) T^3/45$ is the entropy density of the Universe at temperature T, and the number of effective relativistic degrees of freedom is g_*^S [121]. The Boltzmann equation governing freeze-in for a general process $AB \to CD$ can be written as [122–124]

$$\frac{dY}{dT} = -\frac{1}{512\pi^6 H(T) S(T)} \times \int_0^\infty ds d\Omega P_{AB} P_{CD} \frac{\overline{|\mathcal{M}|^2}_{AB\to CD}}{\sqrt{s}} K_1(\sqrt{s}/T). \qquad (8)$$

Here, $H(T) \simeq 1.66\sqrt{g_*(T)}T^2/M_{\rm Pl}$ is the Hubble rate, g_* is the corresponding effective number of relativistic degrees of freedom (which for our purposes equals g_*^S), and $M_{\rm Pl}$ is the Planck mass. The squared matrix element $\overline{|\mathcal{M}|^2}_{AB\to CD}$ (summed over initial and final state spins) describes the relevant particle physics, s is the center of mass energy, the modified Bessel function of the second kind $K_1(\sqrt{s}/T)$ describes Boltzmann suppression at high $\sqrt{s}$, and $P_{AB} \equiv \sqrt{[s-(m_A+m_B)^2][s-(m_A-m_B)^2]/(4s)}$ is a kinematic factor. If more than one $2 \to 2$ process contributes to DM production, the right-hand sides of Eq. (8) should be summed over all relevant processes.

Ultraviolet (UV) freeze-in through the ϕ-photon couplings.—The dominant DM production processes in the effective theory from Eq. (1) are $\gamma f \to \phi f$ and $\bar{f} f \to \gamma\phi$ (where f denotes a SM fermion), followed by the decay $\phi \to \bar{\chi}\chi$. This decay can occur even if $m_\phi < 2m_\chi$ because quantum corrections can raise the effective mass of ϕ at high temperature. If ϕ has a self-coupling of the form $[\lambda/4!]\phi^4$, these corrections are of order $(m_\phi^{\rm eff})^2 \sim (\lambda/4!)(n_\phi/n_\phi^{\rm eq})T^2$ [125], where n_ϕ is the number density of ϕ, $n_\phi^{\rm eq}$ is its value in thermal equilibrium, and λ is a dimensionless coupling constant. As the ϕ self-coupling is not forbidden by any symmetry, it should be included in Eqs. (1) and (2) anyway.

By integrating Eq. (8) with the upper integration limit set to the reheating temperature after inflation, $T_{\rm RH}$, the DM yield is found to be

$$Y_{\rm UV} \simeq \frac{20\,400\alpha^3 M_{\rm Pl} T_{\rm RH}}{16 \times 1.66 \times \pi^8 [g_*(T_{\rm RH})]^{3/2}\Lambda^2}. \tag{9}$$

Here, the infrared divergence in $\gamma f \to \phi f$ has been regularized by the effective photon mass in the plasma. The DM abundance today is then

$$\Omega h^2|_{\rm UV} \simeq 105.31 \times \left(\frac{\rm PeV}{\Lambda}\right)^2 \left(\frac{T_{\rm RH}}{\rm TeV}\right)\left(\frac{100}{g_*(T_{\rm RH})}\right)^{\frac{3}{2}}\left(\frac{m_\chi}{\rm keV}\right). \tag{10}$$

The subscript "UV" in the above expressions indicates that the DM abundance is set at $T_{\rm RH}$ [124].

The blue lines in Fig. 2 indicate the value of Λ needed to obtain the correct DM relic abundance today, $\Omega h^2 = 0.12$ [126]. We see that a UV freeze-in scenario with $\Lambda \sim 65$ PeV could explain the 3.5 keV line. To the right of the dashed diagonal blue line, ϕ and χ come into mutual equilibrium via $\phi\phi \leftrightarrow \bar{\chi}\chi$ after freeze-in is completed. This reduces the resulting DM abundance by a factor 0.8, and slightly smaller Λ is required to compensate. In this regime, it is imperative that ϕ decays only after ϕ and χ have decoupled again at $T \lesssim$ keV. Otherwise, the DM abundance would be depleted too strongly. We have checked that this condition is always satisfied in the parameter regions not yet ruled out by x-ray constraints. A potential problem for parameter points to the right of the dashed line arises because the photons from $\phi \to \gamma\gamma$ decays at sub-keV temperatures could leave an observable imprint in the CMB or in the spectrum of extragalactic background light [127–129]. One way of avoiding these constraints is to postulate an additional decay mode for ϕ that is several orders of magnitude faster than $\phi \to \gamma\gamma$, for instance, a decay to pairs of light ($\ll$ keV) fermions $\bar{\chi}'\chi'$. In this case, the coupling y in Figs. 2 and 3 needs to be rescaled by a factor $[{\rm BR}(\phi \to \gamma\gamma)]^{-1/4}$. To avoid ϕ decaying while still in equilibrium with χ, ${\rm BR}(\phi \to \gamma\gamma) \gtrsim 2.1 \times 10^{-3}({\rm keV}/m)^{1/3}(y/10^{-4})^{16/9}(20~{\rm PeV}/\Lambda)^{10/9}$ is required, where y is the yet unrescaled coupling plotted in Figs. 2 and 3.

Note also that parameter points with $m_\phi \lesssim$ few hundred keV and $\Lambda \lesssim 20$ PeV [and correspondingly lower $T_{\rm RH}$ according to Eq. (10)] are disfavored because ϕ production in stars could violate bounds on anomalous stellar energy loss [128,130,131].

Let us finally remark that in deriving Eqs. (9) and (10) we have assumed that DM production starts only when reheating is completed and the Universe follows standard cosmology from $T_{\rm RH}$ onwards. It is, however, possible that reheating proceeds relatively slowly and the Universe maintains a temperature close to $T_{\rm RH}$ for a relatively long time at the end of inflation, while Hubble expansion and inflaton decay balance each other. In such a situation, more time is available for DM production and the resulting Ωh^2 is increased unless Λ is increased appropriately.

Freeze-in through the misalignment mechanism.—At the end of inflation, the field ϕ may be in a coherent state, with the same expectation value $\langle\phi\rangle$ throughout the visible Universe [132–134]. When the Hubble expansion rate $H(T)$ drops below $m_\phi/3$, the field begins to oscillate about its potential minimum at $\phi = 0$. In the language of quantum field theory, such oscillations correspond to an abundance of ϕ particles. At later times, ϕ and χ come into thermal contact, and a fraction of the ϕ energy density is transferred to χ. (χ production via $\phi \to \bar{\chi}\chi$ is not possible here since the dark sector will never become hot enough for thermal corrections to raise $m_\phi^{\rm eff}$ above $2m_\chi$.) The resulting relic abundance of χ is [55,64]

$$\Omega h^2 \simeq 0.39 \times \left(\frac{T_{\rm RH}}{\rm TeV}\right)\left(\frac{\langle\phi\rangle_0}{10^{13}~{\rm GeV}}\right)^2, \tag{11}$$

where $\langle\phi\rangle_0$ is the initial value of the field. If the main production channel for dark sector particles is misalignment, Λ can be larger than for freeze-in through the ϕ-photon coupling.

Low temperature freeze-in.—If the reheating temperature $T_{\rm RH}$ is larger than the cutoff scale of the effective theory, the computation of the DM abundance must be based on a UV completion of Eq. (1), such as Eq. (2). In this case, for not too small Yukawa coupling g, the scalar ϕ will be in thermal equilibrium with L and with SM particles. χ can then freeze in via $\phi \to \bar{\chi}\chi$ and $\phi\phi \to \bar{\chi}\chi$. The DM abundance is approximately

$$\Omega h^2 \simeq \begin{cases} 0.002 \times \left(\frac{y}{10^{-6}}\right)^2\left(\frac{\lambda}{10^{-8}}\right)^{\frac{3}{2}} & ({\rm FI~via}~\phi \to \bar{\chi}\chi) \\ 0.094 \times \left(\frac{y}{10^{-6}}\right)^4 & ({\rm FI~via}~\phi\phi \leftrightarrow \bar{\chi}\chi) \end{cases}. \tag{12}$$

The second line of Eq. (12) corresponds to the narrow green band in Fig. 2. In principle, DM could also be produced directly in annihilations of heavy vectorlike leptons, $\bar{L}L \to \bar{\chi}\chi$. However, for the large g and small m_L required to generate the correct relic abundance this way, ϕ particles would be efficiently produced in stars (unless $m_\phi \gtrsim$ few $\times$ 100 keV), which is excluded [128,130,131].

As for UV freeze-in, ϕ needs to be depleted after χ production is over, for instance, by introducing an invisible decay mode like $\phi \to \bar{\chi}'\chi'$. Note that ϕ particles abundant during Big Bang nucleosynthesis (BBN) at $T \sim$ MeV do *not* violate the constraint on the effective number of neutrino species, $N_{\rm eff} = 2.85 \pm 0.28$ [135]. The reason is that, by the time of BBN, the dark sector has been sufficiently diluted by entropy production in the SM sector, which occurs when heavy SM particles disappear from the primordial plasma.

Structure formation.—Some of the strongest constraints on keV-scale DM candidates are based on their potential impact on structure formation as observed using Lyman-α data [83,112,114,117–119,136–138] and counts of galaxies [115] and dwarf galaxies [114,119]. Albeit suffering from systematic uncertainties that are difficult to control [116,139], these observations are sensitive to the suppression of structure at small ($\lesssim$Mpc) scales caused by DM particles whose kinetic energy is not completely negligible yet when structure formation begins. For DM with an initially thermal momentum spectrum, a lower mass bound of $\gtrsim$4.65 keV at 95% C.L. has been quoted [118], while for sterile neutrinos produced through oscillations, the bound is significantly stronger [114,118] and appears to be in conflict with attempts to explain the 3.5 keV line in such scenarios.

In our model of annihilating DM, the initial momentum spectrum of χ depends on the DM production mechanism. For freeze-in via misalignment, it is very cold and therefore consistent with constraints. For UV freeze-in through the ϕ-photon coupling and for low temperature freeze-in, it is slightly harder than thermal because the freeze-in rate is biased towards higher energies. However, since the dark and visible sectors decouple at $T \gtrsim 100$ GeV, the effective temperature of the dark sector is reduced by an entropy dilution factor $[g_*(100\ \mathrm{GeV})/g_*(1\ \mathrm{eV})]^{1/3} \simeq 2.9$ compared to the photon temperature, improving the situation. For χ production via $\phi \to \bar{\chi}\chi$, each DM particles receives only half the energy of the parent particle, reducing the DM temperature by another factor of 2. For UV freeze-in there is, moreover, the possibility that the dark sector cools via self-interactions, $\phi\phi \to 4\phi$, mediated by the same quartic coupling $(\lambda/4!)\phi^4$ that enabled thermal corrections to m_ϕ. The corresponding increase in ϕ number density can be compensated by an appropriate adjustment of Λ, which controls the initial freeze-in. For $m_\phi \sim 7$ keV, choosing $\lambda \sim 10^{-3}$ boosts the rate of $\phi\phi \to 4\phi$ above the Hubble rate at $m_\phi \lesssim T \lesssim 100$ keV. We have checked that the inverse process $4\phi \to \phi\phi$ never dominates over $\phi\phi \to 4\phi$, even when the dark sector turns nonrelativistic.

We are grateful to Kenny Ng for providing the astrophysical J factor underlying the NuSTAR limit in Fig. 2. Moreover, we have greatly benefited from discussions with Andrew Long, Alexander Merle, Lian-Tao Wang, Neal Weiner, and Felix Yu. The authors have received funding from the German Research Foundation (DFG) under Grants No. EXC-1098, No. KO 4820/1–1, No. FOR 2239, and No. GRK 1581, and from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 637506, "νDirections"). J. L. acknowledges support by the Oehme Fellowship.

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