SELF-INTERACTING DARK MATTER WITH A NEUTRINOPHILIC SCALAR MEDIATOR*

Arvind Rajaraman†, Jordan Smolinsky‡

Department of Physics and Astronomy, University of California
Irvine, California 92697, USA

(Received March 6, 2020; accepted June 17, 2020)

We examine the phenomenology of a simplified model of fermionic dark matter coupled to a light scalar mediator carrying lepton number 2. We find that the mediator can be very light and still consistent with laboratory and cosmological bounds. This model satisfies the thermal relic condition for natural values of dimensionless coupling constants and admits a mediator in the 10–100 MeV mass range favored by small-scale structure observations. As such, this model provides an excellent candidate for self-interacting dark matter.

DOI:10.5506/APhysPolB.51.1827

1. Introduction

The nature of dark matter remains among the most prominent questions in fundamental physics, and one of the best motivations for models of physics beyond the Standard Model (SM). While dark matter (DM) was discovered by its gravitational effects [1–3], it is still empirically unknown whether it participates in any other fundamental interaction.

The best-motivated theories of physics beyond the Standard Model, supersymmetric extensions of the SM, yield weakly interacting cold dark-matter candidates at the weak scale [4], and a great deal of effort has been focused on searching for such dark-matter candidates. However, many recent astrophysical observations have cast doubt on these models, since these models appear to be in tension with various observations of the inner halos of galaxies. This has led to the suggestion that dark matter in fact has large self interactions, and self-interacting dark matter can indeed solve many of

* Funded by SCOAP^3 under Creative Commons License, CC-BY 4.0.

† arajaram@uci.edu

‡ jsmolins@uci.edu

these problems [5–7]. In light of these small-scale structure observations, it is of great interest to consider models of dark matter coupled to a light boson, such as a dark photon [8, 9] or dark Higgs [10, 11] which can produce a large dark matter scattering cross section.

In this work, we will examine the phenomenology of a simplified model of fermionic dark matter coupled to a light complex scalar ϕ carrying lepton number 2. Such a light particle might be visible through its interactions with the Standard Model. Dark sector particles may be produced in colliders and found through their missing energy signatures [12–18], they may scatter off of SM detector constituents to produce an observable recoil [19], or they may annihilate or decay to produce a flux of energetic SM particles [20]. Finally, a model of dark matter must satisfy the combined constraints of all applicable laboratory tests and predict a cosmological abundance consistent with observations [21].

As we show in the next section, the neutrinophilic scalar portal model is a completely viable model of dark matter. The appropriate relic density is obtained through the coupling of the dark matter to the neutrinos. Other constraints are weak; indeed, such a model is hard to constrain, since even a very light scalar coupled only to the neutrinos and dark matter has relatively few signals [22, 23].

We also analyze the case when there are further interactions between the light scalar and the quarks of the Standard Model. The symmetries force such couplings to be nonrenormalizable. The interactions facilitated by these nonrenormalizable operators can be probed by colliders and direct detection experiments. We show that the current bounds on these interactions are very weak, even if the mediator is very light. This then shows that the neutrinophilic scalar portal can naturally accommodate self-interacting dark matter over a wide range of dark matter and mediator masses.

2. A simplified model of a neutrinophilic scalar mediator

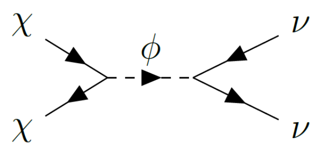
We consider a model of dark matter, where the dark matter is a Majorana fermion χ of mass m_χ. It is coupled to a scalar (the neutrinophilic scalar) of mass m_ϕ. The neutrinophilic scalar carries lepton number, so that its only tree-level interactions with the Standard Model come through coupling to the neutrino Majorana mass. We suppose that the dark-matter interaction with the neutrinophilic scalar follows the same structure (*i.e.* the dark matter effectively has lepton number), so that the leading interactions of the theory may be written as

$$\mathcal{L}_{\rm ren} = -g_\nu \overline{\nu_L^c}\nu_L\phi - g_\chi\overline{\chi^c}\chi\phi + \text{h.c.}\,, \tag{1}$$

where g_i are dimensionless coupling constants.

We may fix the couplings through the thermal relic condition following the procedure and notation of [24]. There are two annihilation channels we need to consider.

If $m_\phi > m_\chi$, the dominant process will be $\chi\chi \to \nu\nu$, which is p-wave



$$\langle \sigma_{\chi\chi\to\nu\nu} v \rangle = \frac{3 g_\chi^2 g_\nu^2}{4\pi m_\chi^2} \frac{\left(1 - m_\nu^2/m_\chi^2\right)^{3/2}}{\left(4 - m_\phi^2/m_\chi^2\right)^2} \frac{1}{x} + \mathcal{O}\left(x^{-2}\right) , \tag{2}$$

where $x = m_\chi/T$, with T the temperature. In this regime, the thermal relic values of $g_\chi g_\nu$ will be determined both by m_χ and the ratio m_χ/m_ϕ. This dependence is shown in Fig. 1. In this figure, we have omitted analysis of the resonant regime $m_\phi - 2m_\chi \ll m_\chi$, in which the thermal relic target may be depressed by several orders of magnitude.

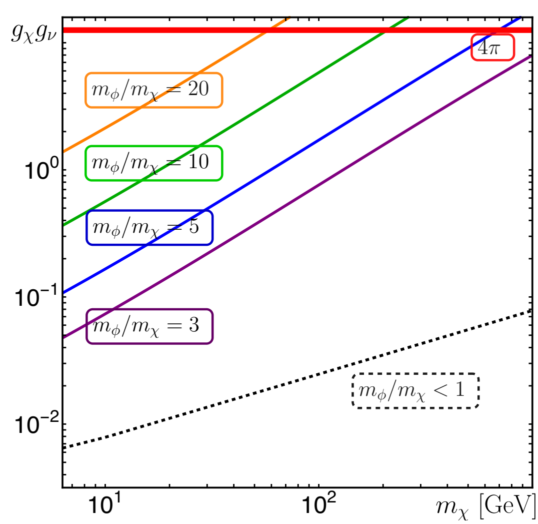
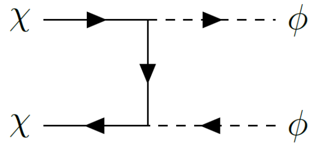


Fig. 1. (Color online) Thermal relic constraint on dark matter and neutrino coupling of the neutrinophilic scalar as a function of dark-matter mass m_χ, for indicated values of $m_\phi/m_\chi > 1$. Dashed: Relic constraint for $m_\phi/m_\chi < 1$, $g_\nu = 0.1$, only weakly sensitive to changes in m_ϕ. Thick gray/red: Perturbative upper limit on $g_\chi g_\nu$.

Secondly, the $\chi\chi \to \phi\phi$ process dominates the dark-matter annihilation in the regime of $m_\chi > m_\phi$. Its thermal averaged cross section is s-wave of



$$\langle \sigma_{\chi\chi\to\phi\phi} v \rangle = \frac{g_\chi^4}{16\pi m_\chi^2} \frac{\left(1 - m_\phi^2/m_\chi^2\right)^{3/2}}{\left(2 - m_\phi^2/m_\chi^2\right)^2} + \mathcal{O}\left(x^{-1}\right) . \tag{3}$$

Notice that the $\chi\chi \to \phi\phi$ annihilation has only weak dependence on m_ϕ, so that in the regime that this channel dominates, g_χ may be determined completely by the mass m_χ of the dark matter itself. Explicitly, the thermal relic condition in this regime furnishes the relation

$$\alpha_\chi \equiv g_\chi^2/4\pi \approx 0.07\ m_\chi/\mathrm{TeV} \qquad (m_\chi > m_\phi) . \tag{4}$$

Note that the mediator can be very light in this scenario. Note also that g_ν is not directly constrained by the thermal relic condition in the regime of $m_\phi < m_\chi$.

We, therefore, see that the thermal relic density condition can be satisfied over an enormous rage of parameter space, including relatively weak masses for the neutrinophilic scalar mediator.

Furthermore, our preceding calculations have assumed the standard cosmology. Nonstandard thermal histories for the universe may significantly change our result. For instance, quintessence models generating an early phase of kination dominance may satisfy the thermal relic constraint even with an annihilation cross section up to three orders of magnitude larger [25]. In such cosmologies, g_χ, g_ν could be much larger. We leave an analysis of this possibility to future work.

There are few other constraints on this model. The main one comes from indirect detection. However, because the primary final state of neutrinophilic scalar portal dark-matter annihilation is neutrinos, it is difficult to set meaningful constraints on the dark-matter annihilation. IceCube furnishes the strongest indirect detection limits on dark-matter annihilation to neutrinos, but these do not exclude the thermal relic cross section [20].

3. Nonrenormalizable interactions

To further probe experimental constraints on this model, we must enlarge our model to include couplings of the mediator to quarks and charged leptons.

There are no renormalizable couplings allowed between the mediator and any charged SM fermions, so we must introduce nonrenormalizable couplings. We will restrict our attention to dark matter coupling through either a scalar or a pseudoscalar quark current, and following the principle of minimal flavor violation, the coupling constants to these currents will be taken to be proportional to the quark masses. We, therefore, have

$$\mathcal{L} = \mathcal{L}_{\rm ren} + \mathcal{L}_{\rm nonren}\,, \tag{5}$$

where

$$\mathcal{L}_{\rm ren} = -g_\nu \overline{\nu_L^c}\nu_L\phi - g_\chi \overline{\chi^c}\chi\phi + \text{h.c.} \tag{6}$$

For the scalar current coupling, we take

$$\mathcal{L}_{\rm nonren} = \frac{1}{M_*^2}\sum_q m_q \phi^*\phi\bar{q}q \tag{7}$$

and for the pseudoscalar current coupling, we take

$$\mathcal{L}_{\rm nonren} = \frac{1}{M_*^2}\sum_q i m_q \phi^*\phi\bar{q}\gamma^5 q\,. \tag{8}$$

Note that the nonrenormalizable interactions correspond to C1 and C2 in the naming convention of [17].

Here, M_* is a scale associated with the UV completion of this theory. While the nondiscovery of New Physics at the LHC might suggest that this New Physics should be at least at a TeV, we shall remain agnostic, and not impose any theoretical prejudice on the parameters. The parameter space of this theory is then spanned by the parameters m_χ, m_ϕ, g_ν, g_χ, and M_*. We now map out the constraints that may be placed on this parameter space by colliders and direct detection.

3.1. Collider constraints

Due to the structure of the scalar interaction with the quarks, production of the dark matter at colliders is suppressed by a loop and a factor of g_χ^2 at the amplitude level. The dominant process observable at the LHC experiments ATLAS and CMS is then $pp \to \phi\phi^* + X$, where X is any SM final state. These events are marked by X recoiling against the invisible pair of mediators, which do not interact with particle detectors at the interaction point.

Leading limits on $\phi\phi^*$ production come from consideration of monojet + $\not{E}_{\rm T}$ events at ATLAS and CMS. The largest background contribution is from a jet recoiling against an off-shell Z boson that decays to neutrinos.

In order to reduce this background, the ATLAS search considers lepton-less events with a missing transverse energy of $\not{E}_{\rm T} > 350$ GeV and a primary jet $p_{\rm T} > 350$ GeV. The companion CMS analysis allows a lower primary jet $p_{\rm T} > 110$ GeV, while placing the same $\not{E}_{\rm T}$ cut. Combined limits from these monojet searches [12, 15], as well as mono-γ [14, 16], and mono-Z [13, 26] at the $\sqrt{s} = 7$ TeV LHC are presented in [18]. We reproduce their results in Fig. 2.

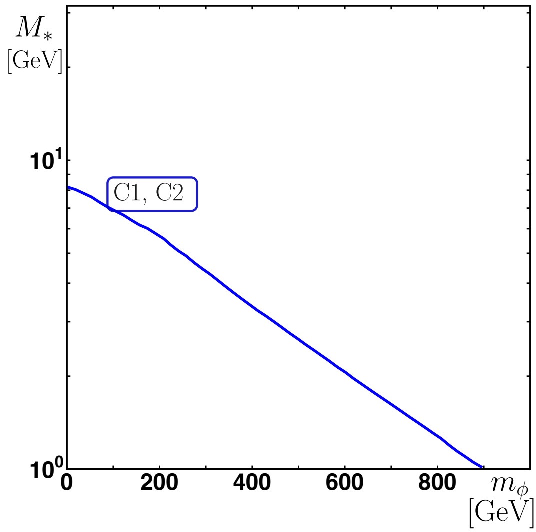


Fig. 2. Combined limit on Λ from ATLAS monojet [12], mono-γ [14], mono-Z [13, 26], and CMS monojet [15], and mono-γ [16] searches with $\sqrt{s} = 7$ TeV [18].

We see that colliders place relatively weak limits on M_*, owing to the momentum-independent contact interaction between the scalar and the quarks, and the lack of direct coupling to gluons. These constraints will become stronger if and when the current and future data from the LHC are used to constrain the monojet signature. Independent of the couplings between the mediator and the dark matter or neutrinos, we see that the neutrinophilic scalar is currently a viable mediator at nearly all masses, as long as $M_* \gtrsim 10$ GeV.

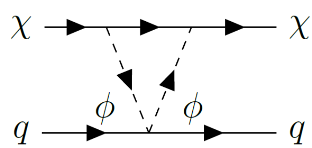
3.2. Direct detection

As the Earth traverses the dark-matter halo, dark-matter particles may scatter off of heavy nuclear targets, producing an observable recoil spectrum. In this model, the dominant contribution to direct detection occurs through the t-channel exchange of two scalars with the SM target. In the case that the mediator–quark interaction is described by the C1 operator, the dark matter scattering is spin-independent and the leading limits on its cross section come from XENON-1T [19]. Dark matter scattering through the C2 operator is spin-dependent and is most strongly constrained by LUX exclusions [27].

In this section, we present a calculation of the relevant cross sections for both types of mediator–quark interaction and the resulting limits on the model parameter space. Interactions between the dark matter and the SM fermions are automatically suppressed to one-loop order, which weakens the bounds.

3.2.1. Scalar current

The matrix element for the direct detection scattering process $\chi q \to \chi q$ with C1 operator is given by



In order to build up the nuclear cross section from the partonic matrix element above, we follow the procedure of [28]. The matrix element for direct detection factorizes into a universal, dark-matter-related piece which we call α_q, and a target-dependent Standard Model piece

$$\langle \mathcal{M} \rangle = \alpha_q \left\langle \bar{\psi}_q \psi_q \right\rangle , \tag{9}$$

where α_q is found after a loop calculation to be

$$\begin{aligned} \alpha_q \;=\; & \frac{g_\chi^2 m_q [\bar{u}_3 u_1]}{M_*^2} \frac{m_\chi}{4m_\chi^2 - t} \Big[2B_0(p_1 - p_3, m_\phi, m_\phi) - B_0(p_1, m_\phi, m_\chi) \\ & -B_0(p_3, m_\chi, m_\phi) + \left(8m_\chi^2 - 2m_\phi^2 - t\right) C_0(p_1, -p_3, m_\phi, m_\chi, m_\phi) \Big] . \end{aligned} \tag{10}$$

Here B_0, C_0 are the Passarino–Veltman functions [29]. Note that α_q is the same for both operators we will consider; the scalar/pseudoscalar nature of the mediator–quark operators will only affect scattering at the level of the nuclear form factors. The matrix element for the dark matter interacting with a nucleon through the scalar current is then

$$f_N^{\mathrm{S}} = m_N \sum_{q=u,d,s} \frac{\alpha_q}{m_q} f_N^{\mathrm{S}q} + \frac{2}{27} m_N f_N^{\mathrm{SG}} \sum_{q=c,b,t} \frac{\alpha_q}{m_q} , \tag{11}$$

where the numerical values of the form factors $f_N^{\mathrm{S}q}$ are [30, 31]

$$\begin{aligned} f_p^{\mathrm{S}u} &= 0.021\,, \qquad f_n^{\mathrm{S}u} = 0.019\,, \\ f_p^{\mathrm{S}d} &= 0.041\,, \qquad f_n^{\mathrm{S}d} = 0.045\,, \\ f_p^{\mathrm{S}s} &= 0.017\,, \qquad f_n^{\mathrm{S}s} = 0.017\,, \end{aligned} \tag{12}$$

and $f_N^{\mathrm{SG}} = 1 - \sum_q f_N^{\mathrm{S}q}$. Combining the interactions with individual nucleons into the nuclear cross section yields

$$\sigma_{\mathrm{SI}} = \frac{4}{\pi}\mu_A^2 \left[Z f_p + (A-Z) f_n\right]^2 \,, \tag{13}$$

where μ_A is the reduced mass of the dark matter–nucleus system. Limits on the spin-independent cross section of dark matter–xenon scattering from XENON-1T [19] may now be directly translated into limits on g_χ/M_*. These limits are shown in Fig. 3.

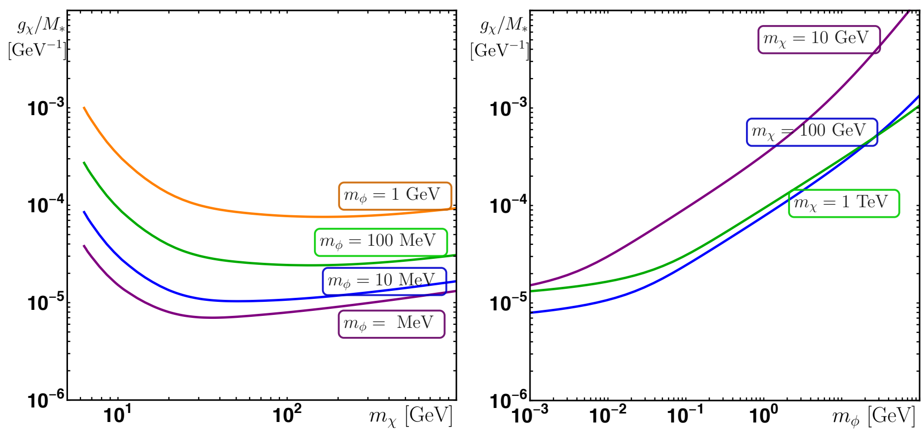


Fig. 3. Left: Direct detection limits on Majoron couplings from XENON-1T [19] as m_χ varies, with indicated Majoron masses. Right: The same, but for indicated values of m_χ as m_ϕ varies.

3.2.2. Pseudoscalar current

Now, we consider the case of the pseudoscalar operator. The quark-level operator C2 hadronizes to the pseudoscalar nuclear current

$$\frac{m_q}{M_*^2}\overline{q} i\gamma^5 q \to c_N \frac{m_N}{M_*^2}\overline{N} i\gamma^5 N\,, \tag{14}$$

with

$$c_N = \sum_{q=u,d,s} \left[1 - 6\frac{\overline{m}}{m_q}\right] \Delta_q^{(N)}\,, \tag{15}$$

where $\overline{m} \equiv \left[\sum_{q=u,d,s} m_q^{-1}\right]^{-1}$ and $\Delta_q^{(N)}$ are the quark spin contents of a nucleon, with numerical values [32]

$$\Delta_u^{(p)} = \Delta_d^{(n)} = 0.84\,, \tag{16}$$

$$\Delta_d^{(p)} = \Delta_u^{(n)} = -0.44\,, \tag{17}$$

$$\Delta_s^{(p,n)} = -0.03\,. \tag{18}$$

In the nonrelativistic limit, the nuclear current reduces to [33]

$$\overline{N} i\gamma^5 N \to -2i\vec{S}_N \cdot \vec{q}\,, \tag{19}$$

and the corresponding nuclear spin-averaged transition probability is given in terms of the nuclear form factors

$$\frac{1}{2j+1}\sum_{\text{spins}} \left| \langle A| \sum_N ic_N \vec{S}_N \cdot \vec{q}\,|A\rangle \right|^2 = \frac{m_A^2}{m_N^2} \sum_{N,N'=p,n} c_N c_{N'}\, F_{10,10}^{(N,N')}\left(v^2, q^2\right)\,, \tag{20}$$

where m_A is the mass of the target nucleus with mass number A and $F_{10,10}^{(N,N')} = q^2 F_{\Sigma''}^{(N,N')}/4$ with $F_{\Sigma''}^{(N,N')}$ the axial longitudinal response function, tabulated for various nuclei in [33]. We will consider the bounds on spin-dependent dark matter scattering from the LUX experiment, and as such, use the form factors for ^{129}Xe and ^{131}Xe, weighted by their relative isotopic abundances, to calculate the predicted cross section for $N = p, n$. Spin-dependent direct detection limits on the proton and neutron cross section may be combined [34] according to

$$\left(\sqrt{\frac{\sigma_p^{\text{th}}}{\sigma_p^{\text{lim}}}} + \sqrt{\frac{\sigma_n^{\text{th}}}{\sigma_n^{\text{lim}}}}\right)^2 > 1\,, \tag{21}$$

where σ_N^{lim} is the empirical upper limit on the WIMP-nucleon cross section and σ_N^{th} is the model prediction. We use the spin-dependent cross section upper limits from LUX [27] in order to bound the combination g_χ/M_* as shown in Fig. 4.

The main result from these analysis is that extremely small values of the mediator mass (as small as a MeV) are viable.

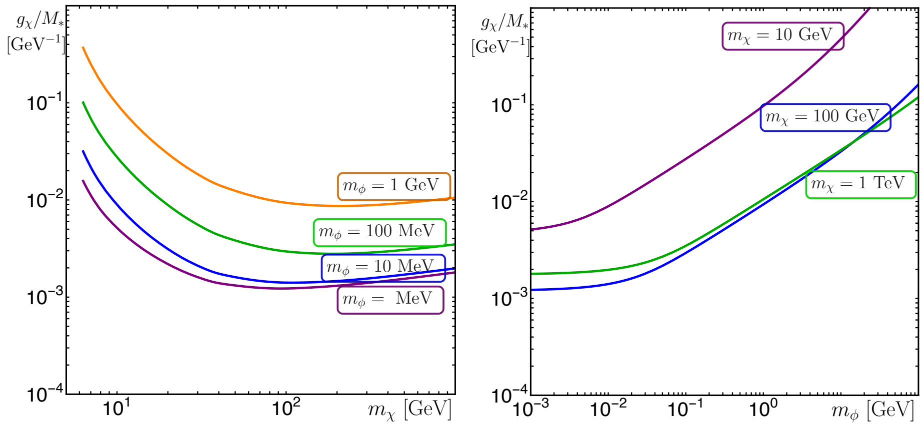


Fig. 4. Left: Spin-dependent direct detection limits on Majoron-quark couplings from LUX [27] as m_χ varies, with indicated Majoron masses. Right: The same, but for indicated values of m_χ as m_ϕ varies.

4. Conclusion

In this paper, we have constructed a model of neutrinophilic scalar mediators, and showed that in this model, the mediator field can be very light, allowing for the possibility of a self-interacting dark sector. We found that the dark matter reproduces the observed relic density using thermal freeze-out with natural values of dimensionless coupling constants.

We also analyzed the experimental constraints on interactions of the neutrinophilic scalar with charged Standard Model fermions coming from collider and direct detection experiments. We found that extremely light mediator masses were viable; the scalar could exist in the 10–100 MeV range favored by small scale structure observations without being excluded by colliders, and that weak scale dark matter coupling to this scalar is viable if the high-scale New Physics facilitating spin-independent (-dependent) direct detection occurs above ~ 10 TeV (~ 100 GeV).

Neutrinophilic scalar mediators are therefore an excellent candidate for a theory of self-interacting dark matter. At the same time, ongoing experiments at the LHC and future experiments like Belle 2 will further constrain this model of dark matter, either discovering these scalars or ruling out larger regions of parameter space. It would be very interesting to analyze the cosmology of these models and investigate whether the issues with small scale structure can be solved; we will perform this analysis in the future work.

This work is supported by NSF grant No. PHY–1620638. Numerical calculations were performed using Mathematica 11.1 [35]. Feynman diagrams were drawn using TikZ-Feynman [36].

REFERENCES

[1] V.C. Rubin, W.K. Ford, Jr., «Rotation of the Andromeda Nebula from a spectroscopic survey of emission regions», *Astrophys. J.* **159**, 379 (1970).

[2] V.C. Rubin, N. Thonnard, W.K. Ford, Jr., «Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 ($R = 4\,\mathrm{kpc}$) to UGC 2885 ($R = 122\,\mathrm{kpc}$)», *Astrophys. J.* **238**, 471 (1980).

[3] D. Clowe *et al.*, «A direct empirical proof of the existence of dark matter», *Astrophys. J.* **648**, L109 (2006), arXiv:astro-ph/0608407.

[4] G. Jungman, M. Kamionkowski, K. Griest, «Supersymmetric dark matter», *Phys. Rep.* **267**, 195 (1996), arXiv:hep-ph/9506380.

[5] N. Bernal *et al.*, «Production regimes for Self-Interacting Dark Matter», *J. Cosmol. Astropart. Phys.* **2016**, 018 (2016), arXiv:1510.08063 [hep-ph].

[6] O. Balducci, S. Hofmann, A. Kassiteridis, «Cosmological singlet diagnostics of neutrinophilic dark matter», *Phys. Rev. D* **98**, 023003 (2018), arXiv:1710.09846 [hep-ph].

[7] T. Ren, A. Kwa, M. Kaplinghat, H.-B. Yu, «Reconciling the diversity and uniformity of galactic rotation curves with Self-Interacting Dark Matter», *Phys. Rev. X* **9**, 031020 (2019), arXiv:1808.05695 [astro-ph.GA].

[8] B. Holdom, «Two U(1)'s and ϵ charge shifts», *Phys. Lett. B* **166**, 196 (1986).

[9] D.E. Morrissey, D. Poland, K.M. Zurek, «Abelian hidden sectors at a GeV», *J. High Energy Phys.* **0907**, 050 (2009), arXiv:0904.2567 [hep-ph].

[10] B. Patt, F. Wilczek, «Higgs-field portal into hidden sectors», arXiv:hep-ph/0605188.

[11] J. March-Russell, S.M. West, D. Cumberbatch, D. Hooper, «Heavy dark matter through the Higgs portal», *J. High Energy Phys.* **0807**, 058 (2008), arXiv:0801.3440 [hep-ph].

[12] ATLAS Collaboration (G. Aad *et al.*), «Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the ATLAS detector», *J. High Energy Phys.* **1304**, 075 (2013), arXiv:1210.4491 [hep-ex].

[13] ATLAS Collaboration (G. Aad *et al.*), «Measurement of ZZ production in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous ZZZ and $ZZ\gamma$ couplings with the ATLAS detector», *J. High Energy Phys.* **1303**, 128 (2013), arXiv:1211.6096 [hep-ex].

[14] ATLAS Collaboration (G. Aad *et al.*), «Search for dark matter candidates and large extra dimensions in events with a photon and missing transverse momentum in pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS detector», *Phys. Rev. Lett.* **110**, 011802 (2013), arXiv:1209.4625 [hep-ex].

[15] CMS Collaboration (S. Chatrchyan *et al.*), «Search for dark matter and large extra dimensions in monojet events in pp collisions at $\sqrt{s} = 7$ TeV», *J. High Energy Phys.* **1209**, 94 (2012), arXiv:1206.5663 [hep-ex].

[16] CMS Collaboration (S. Chatrchyan *et al.*), «Search for dark matter and large extra dimensions in pp collisions yielding a photon and missing transverse energy», *Phys. Rev. Lett.* **108**, 261803 (2012), arXiv:1204.0821 [hep-ex].

[17] J. Goodman *et al.*, «Constraints on dark matter from colliders», *Phys. Rev. D* **82**, 116010 (2010), arXiv:1008.1783 [hep-ph].

[18] N. Zhou, D. Berge, D. Whiteson, «Mono-everything: Combined limits on dark matter production at colliders from multiple final states», *Phys. Rev. D* **87**, 095013 (2013), arXiv:1302.3619 [hep-ex].

[19] XENON Collaboration (E. Aprile *et al.*), «Dark matter search results from a one ton-year exposure of XENON1T», *Phys. Rev. Lett.* **121**, 111302 (2018), arXiv:1805.12562 [astro-ph.CO].

[20] IceCube Collaboration (M.G. Aartsen *et al.*), «Search for neutrinos from dark matter self-annihilations in the center of the Milky Way with 3 years of IceCube/DeepCore», *Eur. Phys. J. C* **77**, 627 (2017), arXiv:1705.08103 [hep-ex].

[21] Planck Collaboration (N. Aghanim *et al.*), «Planck 2018 results. VI. Cosmological parameters», arXiv:1807.06209 [astro-ph.CO].

[22] A. Olivares-Del Campo, C. Bœhm, S. Palomares-Ruiz, S. Pascoli, «Dark matter–neutrino interactions through the lens of their cosmological implications», *Phys. Rev. D* **97**, 075039 (2018), arXiv:1711.05283 [hep-ph].

[23] R. Primulando, P. Uttayarat, «Dark matter–neutrino interaction in light of collider and neutrino telescope data», *J. High Energy Phys.* **1806**, 26 (2018), arXiv:1710.08567 [hep-ph].

[24] P. Gondolo, G. Gelmini, «Cosmic abundances of stable particles: Improved analysis», *Nucl. Phys. B* **360**, 145 (1991).

[25] C. Pallis, «Quintessential kination and cold dark matter abundance», *J. Cosmol. Astropart. Phys.* **2005**, 015 (2005), arXiv:hep-ph/0503080.

[26] L.M. Carpenter *et al.*, «Collider searches for dark matter in events with a Z boson and missing energy», *Phys. Rev. D* **87**, 074005 (2013), arXiv:1212.3352 [hep-ex].

[27] LUX Collaboration (D.S. Akerib *et al.*), «Limits on spin-dependent WIMP-nucleon cross section obtained from the complete LUX exposure», *Phys. Rev. Lett.* **118**, 251302 (2017), arXiv:1705.03380 [astro-ph.CO].

[28] M. Backović *et al.*, «Direct detection of dark matter with MadDM v.2.0», *Phys. Dark Univ.* **9–10**, 37 (2015), arXiv:1505.04190 [hep-ph].

[29] R.K. Ellis, Z. Kunszt, K. Melnikov, G. Zanderighi, «One-loop calculations in quantum field theory: From Feynman diagrams to unitarity cuts», *Phys. Rep.* **518**, 141 (2012), arXiv:1105.4319 [hep-ph].

[30] J.M. Alarcon, J. Martin Camalich, J.A. Oller, «Chiral representation of the πN scattering amplitude and the pion–nucleon sigma term», *Phys. Rev. D* **85**, 051503 (2012), arXiv:1110.3797 [hep-ph].

[31] J.M. Alarcon, L.S. Geng, J. Martin Camalich, J.A. Oller, «The strangeness content of the nucleon from effective field theory and phenomenology», *Phys. Lett. B* **730**, 342 (2014), arXiv:1209.2870 [hep-ph].

[32] H.-Y. Cheng, C.-W. Chiang, «Revisiting scalar and pseudoscalar couplings with nucleons», *J. High Energy Phys.* **1207**, 009 (2012), arXiv:1202.1292 [hep-ph].

[33] A.L. Fitzpatrick *et al.*, «The effective field theory of dark matter direct detection», *J. Cosmol. Astropart. Phys.* **1302**, 004 (2013), arXiv:1203.3542 [hep-ph].

[34] D.R. Tovey *et al.*, «A new model-independent method for extracting spin-dependent cross section limits from dark matter searches», *Phys. Lett. B* **488**, 17 (2000), arXiv:hep-ph/0005041.

[35] Wolfram Research, Inc., Mathematica, Version 11.1, Champaign, Illinois, 2017.

[36] J. Ellis, «TikZ-Feynman: Feynman diagrams with TikZ», *Comput. Phys. Commun.* **210**, 103 (2017), arXiv:1601.05437 [hep-ph].