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# Direct detection with dark mediators

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ABSTRACT

We introduce *dark mediator Dark Matter* (dmDM) where the dark and visible sectors are connected by at least one light mediator $\phi$ carrying the same dark charge that stabilizes DM. $\phi$ is coupled to the Standard Model via an operator $\bar{q}q\phi\phi^*/\Lambda$, and to dark matter via a Yukawa coupling $y_\chi \overline{\chi^c}\chi\phi$. Direct detection is realized as the $2 \to 3$ process $\chi N \to \bar{\chi} N \phi$ at tree-level for $m_\phi \lesssim 10$ keV and small Yukawa coupling, or alternatively as a loop-induced $2 \to 2$ process $\chi N \to \chi N$. We explore the direct-detection consequences of this scenario and find that a heavy $\mathcal{O}(100$ GeV) dmDM candidate fakes different $\mathcal{O}(10$ GeV) standard WIMPs in different experiments. Large portions of the dmDM parameter space are detectable above the irreducible neutrino background and not yet excluded by any bounds. Interestingly, for the $m_\phi$ range leading to novel direct detection phenomenology, dmDM is also a form of Self-Interacting Dark Matter (SIDM), which resolves inconsistencies between dwarf galaxy observations and numerical simulations.



## 1. Introduction

In this letter, we present *dark mediator Dark Matter* (dmDM) to address two important gaps in the DM literature: exploring mediators with dark charge, and non-standard interaction topologies for scattering off nuclei. Additional details and constraints will be explored in a companion paper [1].

The existence of dark matter is firmly established by many astrophysical and cosmological observations [2], but its mass and coupling to the Standard Model (SM) particles are still unknown. Weakly Interacting Massive Particles (WIMPs) are the most popular DM candidates since they arise in many theories beyond the SM, including supersymmetry, and may naturally give the correct relic abundance [3]. However, improved experimental constraints – from collider searches, indirect detection and direct detection [4–11] – begin to set tight limits (with some conflicting signal hints) on the standard WIMP scenario with a contact interaction to quarks. This makes it necessary to look for a more complete set of DM models which are theoretically motivated while giving unique experimental signatures.

## 2. Dark mediator Dark Matter

Given its apparently long lifetime, most models of DM include some symmetry under which the DM candidate is charged to make it stable. An interesting possibility is that not only the DM candidate, but also the mediator connecting it to the visible sector is charged under this dark symmetry. Such a 'dark mediator' $\phi$ could only couple to the SM fields in pairs.

As a simple example, consider real or complex SM singlet scalars $\phi_i$ coupled to quarks, along with Yukawa couplings to a Dirac fermion DM candidate $\chi$. The terms in the effective Lagrangian relevant for direct detection are

$$\mathcal{L}_{\text{DM}} \supset \sum_{i,j}^{n_\phi} \frac{1}{\Lambda_{ij}} \bar{q}q\phi_i\phi_j^* + \sum_i^{n_\phi} \left(y_\chi^{\phi_i} \overline{\chi^c}\chi\phi_i + h.c.\right) + \ldots \tag{1}$$

where $\ldots$ stands for $\phi, \chi$ mass terms, as well as the rest of the dark sector, which may be more complicated than this minimal setup. This interaction structure can be enforced by a $\mathbb{Z}_4$ symmetry. To emphasize the new features of this model for direct detection, we focus on the minimal case with a single mediator $n_\phi = 1$ (omitting the $i$-index). However, the actual number of dark mediators is important for interpreting indirect constraints [1].

The leading order process for DM-nucleus scattering is $\chi N \to \bar{\chi} N \phi$ if $m_\phi \lesssim \mathcal{O}(10$ keV). However, an elastic scattering $\chi N \to \chi N$ is always present at loop-level since it satisfies all possible symmetries, see Fig. 1. Which of the two possibilities dominates direct detection depends on the size of the Yukawa couplings $y_\chi^{\phi_i}$ as well as the dark mediator masses.

Previous modifications to WIMP-nucleon scattering kinematics include the introduction of a mass splitting [12–14]; considering matrix elements $|\mathcal{M}|^2$ with additional velocity- or momentum

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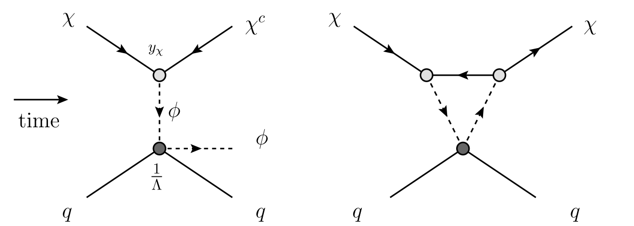


**Fig. 1.** The quark-level Feynman diagrams responsible for DM-nucleus scattering in *dark mediator Dark Matter* (dmDM). Left: the $2 \to 3$ process at tree-level. Right: the loop-induced $2 \to 2$ process. The arrows indicate flow of dark charge.

transfer suppressions (for a complete list see e.g. [15]), especially at low DM masses close to a GeV [16]; light scalar or 'dark photon' mediators (see e.g. [17] which give large enhancements at low nuclear recoil); various forms of composite dark matter [18–22] which may introduce additional form factors; DM-nucleus scattering with intermediate bound states [23] which enhances scattering in a narrow range of DM velocities; and induced nucleon decay in Asymmetric Dark Matter models [24]. Notably missing from this list are alternative process topologies for DM-nucleus scattering. This omission is remedied by the dmDM scenario.

dmDM is uniquely favored to produce a detectable $2 \to 3$ scattering signal at direct detection experiments. This is because it contains two important ingredients: (1) a light mediator with non-derivative couplings to enhance the cross section, compensating for the large suppression of emitting a relativistic particle in a non-relativistic scattering process, and (2) a scalar as opposed to a vector mediator, allowing it to carry dark charge (without a derivative coupling). This imposes selection rules which make the $2 \to 2$ process subleading in $y_\chi$. These ingredients are difficult to consistently implement in other model constructions without violating constraints on light force carriers.

The effect of strong differences between proton and neutron coupling to DM have been explored by [25]. To concentrate on the kinematics we shall therefore assume the operator $\bar{q}q\phi\phi^*/\Lambda$ is flavor-blind in the quark mass basis. Above the electroweak symmetry breaking scale this operator is realized as $\bar{Q}_L H q_R \phi\phi^*/M^2$. It can be generated by integrating out heavy vector-like quarks which couple to the SM and $\phi$ [1], giving $1/\Lambda = y_Q^2 y_h v/M_Q^2$. This UV completion allows for large direct detection cross sections without being in conflict with collider bounds, but may be still probed at the 14 TeV LHC.

## 3. Nuclear recoil spectrum

We start by examining the novel $2 \to 3$ regime of dmDM. The DM-nucleus collision is inelastic, not by introducing a new mass scale like a splitting, but by virtue of the process topology. The nuclear recoil spectrum is different compared to previously explored scenarios. This is illustrated in Fig. 2, where we compare nuclear recoil spectra of standard WIMPs to dmDM for fixed velocity and different nucleus mass, *before* convolving with various form factors and the ambient DM speed distribution. The observable dmDM differential cross section is independent of $m_\phi$ for $m_\phi \lesssim$ keV and can be well described by the function

$$\frac{d\sigma_{2\to3}}{dE_r} \simeq \frac{\mathcal{C}}{E_r}\left(1 - \sqrt{\frac{E_r}{E_r^{\max}}}\right)^2, \tag{2}$$

where $\mathcal{C} = 1.3 \times 10^{-42}$ $(\mathrm{TeV}/\Lambda)^2$ cm$^2$ and $E_r^{\max} = \frac{2\mu_{\chi N}^2}{m_N} v^2$, same as the WIMP case for a given DM velocity. (We emphasize that this is a phenomenological description, the actual spectra were produced in MadGraph, see Section 5.) The first factor comes from the light

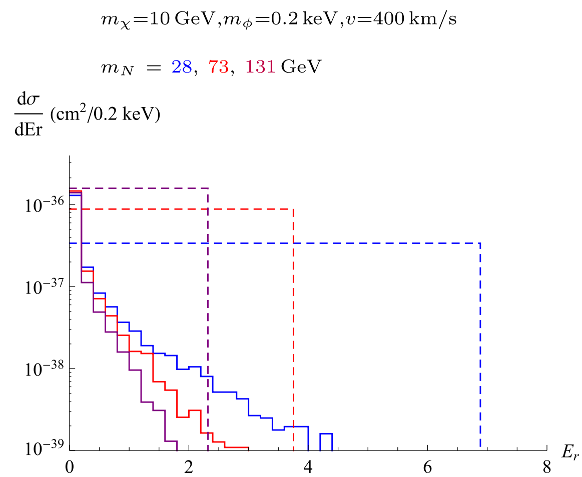


**Fig. 2.** Nuclear recoil spectra of dmDM (without nuclear/nucleus form factors and coherent scattering enhancement) for $y_\chi = 1$, $\Lambda = 1$ TeV in a Silicon, Germanium and Xenon target. The dashed lines are spectra of standard WIMP scattering (via operator $\bar{q}q\bar{\chi}\chi/\tilde{\Lambda}^2$, with $\tilde{\Lambda} = 7$ TeV) shown for comparison. dmDM spectra computed with `MadGraph5` [26] and `FeynRules1.4` [27].

mediator propagator $(2m_N E_r)^{-2}$ as well the integrated phase space of the escaping $\phi$. The cross section suppression (second factor) is more pronounced as the DM becomes lighter or slower, and as the nucleus becomes heavier, both of which reduces $E_r^{\max}$. This is because massless $\phi$ emission carries away a more significant fraction of the total collision energy if the heavy particle momenta are smaller. The maximum kinematically allowed nuclear recoil is then less likely.

When $n_\phi = 1$, the $2 \to 2$ process will dominate direct detection for Yukawa coupling $y_\chi$ above some threshold, or if $m_\phi \gtrsim 10$ keV. For the purpose of calculating the matrix element, the loop diagram in Fig. 1 (right) is equivalent to the operator

$$\frac{y_\chi^2}{2\pi^2}\frac{1}{\Lambda q}(\bar{\chi}\chi\bar{N}N), \tag{3}$$

where $q = \sqrt{2m_N E_r}$ is the momentum transfer in the scattering. Effectively, this is identical to a standard WIMP with a $\bar{\chi}\chi\bar{N}N$ contact operator, but with an additional $1/E_r$ suppression in the cross section. This gives a similar phenomenology as a light mediator being exchanged at tree-level with derivative coupling.

Note that the relative importance of these two scattering processes is highly model dependent. For example, if $n_\phi = 2$ the dominant scalar-DM coupling could be $\bar{q}q\phi_1\phi_2^*/\Lambda_{12}$. In that case, the $2 \to 2$ operator above is $\propto y_\chi^{\phi_1} y_\chi^{\phi_2}$ and can be suppressed without reducing the $2 \to 3$ rate by taking $y_\chi^{\phi_2} \gg y_\chi^{\phi_1}$. The scattering behavior of both the $2 \to 3$ and $2 \to 2$ regimes necessitates a reinterpretation of all DM direct detection bounds. We will do this below.

## 4. Indirect constraints

Direct detection experiments probe the ratio $y_\chi/\Lambda$ and $y_\chi^2/\Lambda$ for $2 \to 3$ and $2 \to 2$ scattering respectively. However, indirect constraints on dmDM from cosmology, stellar astrophysics and collider experiments are sensitive to the Yukawa coupling and $\Lambda$ separately. In [1] we conduct an extensive study of these bounds, including the first systematic exploration of constraints on the $\bar{q}q\phi\phi^*/\Lambda$ operator with light scalars $\phi$. Since these constraints (in particular, Eqs. (4) and (5) below) provide important context for our results on direct detection, we summarize the two most important results here. For details we refer the reader to [1].