Self-Interacting Dark Matter Through the Majoron Portal

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Abstract

We examine the phenomenology of the majoron portal: 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.

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I. 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 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, like 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 \( \phi \) carrying lepton number 2. We call this field the “majoron” because if it had a vacuum expectation value, it would induce a majorana mass term for the neutrinos [12–15] (often the majoron is taken to refer to the phase of this field alone). If the majoron is long-lived, it may itself be the dark matter [16–27], but in this work we consider the case of a short-lived majoron. The majoron can then mediate interactions between the dark matter and the Standard Model; this is therefore the “majoron portal”.

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 [28–34], they may scatter off of SM detector constituents to produce an observable recoil [35], or they may annihilate or decay to produce a flux of energetic SM particles [36]. Finally, a model of dark matter must satisfy the combined constraints of all applicable laboratory tests and predict a cosmological abundance consistent with observations [37].

As we show in the next section, the majoron 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 [38, 39]

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 majoron portal can naturally accommodate self interacting dark matter, over a wide range of dark matter and mediator masses.

II. A SIMPLIFIED MODEL OF A MAJORON MEDIATOR

We consider a model of dark matter, where the dark matter is a Majorana fermion \( \chi \) of mass \( m_\chi \). It is coupled to a scalar (the majoron) of mass \( m_\phi \). The majoron 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 majoron follows the same structure (i.e. the dark matter effectively has lepton number),
so that the leading interactions of the theory may be written
\[
\mathcal{L}_{\text{ren}} = -g_\nu \bar{\nu}_L \nu_L \phi - g_\chi \bar{\chi} \chi \phi + \text{h.c.}
\]
(1)
where \(g_i\) are dimensionless coupling constants.

We may fix the couplings through the thermal relic condition, following the procedure
and notation of [40]. 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:
\[
\langle \sigma_{\chi \chi \to \nu \nu} \rangle = \frac{3g_\chi^2 g_\nu^2 (1 - m_\nu^2 / m_\chi^2)^{3/2}}{4\pi m_\chi^2} \frac{1}{x + \mathcal{O}(x^{-2})}
\]
(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 \(m_\chi\) and the ratio \(m_\chi / m_\phi\). 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: Thermal relic constraint on dark matter and neutrino coupling of majoron as a function of
dark matter mass \(m_\chi\), for indicated values of \(m_\phi / m_\chi\). Red: Perturbative upper limit on \(g_\chi g_\nu\).

Secondly, the process \(\chi \chi \to \phi \phi\) dominates the dark matter annihilation in the regime
\(m_\chi > m_\phi\). Its thermal averaged cross section is s-wave:
\[
\chi \to \phi \phi
\]
\[ \langle \sigma_{\chi \chi \to \phi \phi} \rangle = \frac{g_\chi^4}{16\pi m_\chi^2} \frac{(1-m_\phi^2/m_\chi^2)^{3/2}}{(2-m_\phi^2/m_\chi^2)^2} + O(x^{-1}) . \] 

(3)

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

\[ \alpha_\chi \equiv \frac{g_\chi^2}{4\pi} \approx 0.07 \frac{m_\chi}{\text{TeV}} \quad (m_\chi > m_\phi) . \] 

(4)

Note that the mediator can be very light in this scenario.

We therefore see that the thermal relic density condition can be satisfied over an enormous range of parameter space, including relatively light masses for the majoron mediator field.

There are few other constraints on this model. The main one comes from indirect detection. However, because the primary final state of majoron 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 [36].

### III. 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 majoron 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

\[ \mathcal{L} = \mathcal{L}_{\text{ren}} + \mathcal{L}_{\text{nonren}} \] 

(5)

where

\[ \mathcal{L}_{\text{ren}} = -g_\nu \bar{\nu}_L \nu_L \phi - g_\chi \bar{\chi} \chi \phi + \text{h.c.} . \] 

(6)

For the scalar current coupling, we take

\[ \mathcal{L}_{\text{nonren}} = \frac{1}{M_*^2} \sum_q m_q \phi^* \phi \bar{q} q \] 

(7)

and for the pseudoscalar current coupling, we take

\[ \mathcal{L}_{\text{nonren}} = \frac{1}{M_*^2} \sum_q i m_q \phi^* \phi \gamma^5 \bar{q} q \] 

(8)

Note that the nonrenormalizable interactions correspond to C1 and C2 in the naming convention of [33].

Here \( M_* \) is a scale associated with the UV completion of this theory. While the non-discovery 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 \( m_\chi, m_\phi, g_\nu, g_\chi, \) and \( M_* \). We now map out the constraints that may be placed on this parameter space by colliders and direct detection.
A. Collider Constraints

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

Leading limits on $\phi\phi^*$ production come from consideration of monojet + $E_T$ 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 $E_T > 350$ GeV and a primary jet $p_T > 350$ GeV. The companion CMS analysis allows a lower primary jet $p_T > 110$ GeV while placing the same $E_T$ cut. Combined limits from these monojet searches [28, 31], as well as mono-\(\gamma\) [30, 32], and mono-Z [29, 41] at the $\sqrt{s} = 7$ TeV LHC are presented in [34], we reproduce their results in Fig. 2.

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 majoron and the dark matter or neutrinos, we see that the majoron is currently a viable mediator at nearly all masses, as long as $M_* \gtrsim 10$ GeV.

B. 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 majoron-quark interaction is described by operator C1, the
dark matter scattering is spin-independent and the leading limits on its cross section come
from XENON-1T [35]. Dark matter scattering through the C2 operator is spin-dependent
and is most strongly constrained by LUX exclusions [42].

In this section we present a calculation of the relevant cross sections for both types of
majoron-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.

1. Scalar current

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

$$\begin{array}{c}
\chi \\
\phi
\end{array} \xrightarrow{\alpha_q} \begin{array}{c}
\chi \\
\phi
\end{array}$$

In order to build up the nuclear cross section from the partonic matrix element above,
we follow the procedure of [43]. The matrix element for direct detection factorizes into a
universal, dark-matter related piece which we call $\alpha_q$, and a target-dependent Standard
Model piece

$$\langle M \rangle = \alpha_q \langle \bar{\psi} \psi \rangle ,$$

where $\alpha_q$ is found after a loop calculation to be

$$\alpha_q = \frac{g^2 m_q [\bar{u} u_1]}{M^2} \frac{m_{\chi}}{4m^2_{\chi} - t} \left[ 2B_0(p_1 - p_3, m_{\phi}, m_{\chi}) - B_0(p_1, m_{\phi}, m_{\chi}) 
- B_0(p_3, m_{\chi}, m_{\phi}) + (8m^2_{\chi} - 2m^2_{\phi} - t)C_0(p_1, -p_3, m_{\phi}, m_{\chi}, m_{\phi}) \right] .$$

Here $B_0, C_0$ are the Passarino-Veltman functions [44]. Note that $\alpha_q$ is the same for both
operators we will consider; the scalar/pseudoscalar nature of the majoron-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

$$f^S_N = m_N \sum_{q=u,d,s} \frac{\alpha_q}{m_q} f^{Sq}_N + \frac{2}{27} m_N f^{SG}_N \sum_{q=c,b,t} \frac{\alpha_q}{m_q} ,$$

where the numerical values of the form factors $f^{Sq}_N$ are [45, 46]

$$f^{Su}_p = 0.021, f^{Su}_n = 0.019$$

$$f^{Sd}_p = 0.041, f^{Sd}_n = 0.045$$

$$f^{Ss}_p = 0.017, f^{Ss}_n = 0.017 ,$$

and $f^{SG}_N = 1 - \sum_q f^{Sq}_N$. Combining the interactions with individual nucleons into the nuclear
cross section yields

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

(13)
FIG. 3: Left: Direct detection limits on majoron couplings from XENON-1T [35] as $m_\chi$ varies, with indicated majoron masses. Right: Same, but for indicated values of $m_\chi$ as $m_\phi$ varies.

where $\mu_A$ 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 [35] may now be directly translated into limits on $g_\chi/M_\ast$. These limits are shown in Fig. 3.

2. Pseudoscalar Current

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

$$\frac{m_q}{M^2_\ast} \bar{q} i \gamma^5 q \rightarrow c_N \frac{m_N}{M^2_\ast} \bar{N} i \gamma^5 N,$$

with

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

where $\bar{m} \equiv \left[ \sum_{q=u,d,s} m_q^{-1} \right]^{-1}$ and $\Delta_q^{(N)}$ are the quark spin contents of a nucleon, with numerical values [47]:

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

In the nonrelativistic limit, the nuclear current reduces to [48]

$$\bar{N} i \gamma^5 N \rightarrow -2i S_N \cdot q,$$

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

$$\frac{1}{2j + 1} \sum_{\text{spins}} |\langle A | \sum_N c_N S_N \cdot q | A \rangle|^2 = \frac{m_A^2}{m_N^2} \sum_{N,N'=p,n} c_N c_{N'} F_{10,10}^{(N,N')} (v^2, q^2),$$
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 [48]. 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 [49] according to

$$\left(\sqrt{\frac{\sigma_{th}^p}{N}} + \sqrt{\frac{\sigma_{th}^n}{N}}\right)^2 > 1,$$

where $\sigma_{th}^N$ is the empirical upper limit on the WIMP-nucleon cross section and $\sigma_{th}^N$ is the model prediction. We use the spin-dependent cross section upper limits from LUX [42] in order to bound the combination $g_{\chi}/M_*$ as shown in Fig. 4.

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

IV. CONCLUSION

In this paper we have constructed a model of majoron portal dark matter, 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 majoron with charged Standard Model fermions coming from collider and direct detection experiments. We found that extremely light mediator masses were viable; the majoron 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 majoron is viable if the high scale new
physics facilitating spin-independent (-dependent) direct detection occurs above $\sim 10$ TeV ($\sim 100$ GeV).

Majoron portal dark matter is 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 majoron portal dark matter 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 future work.

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