Multi-Higgs portal dark matter under the CDMS II results

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Abstract

In a scenario of Higgs portal dark matter, Higgs exchange processes are essential for both dark matter annihilation in the early Universe and direct search experiments. The CDMS II collaboration has recently released their final results on direct dark matter searches. We study a scalar dark matter model with multi-Higgs doublets under the constraint from the CDMS II results and also from the WMAP data. We find that the possible maximal value for the branching ratio of the invisible decay of the Higgs boson can be significantly greater than that in the Higgs portal model with one Higgs doublet, in particular, for the case of the so-called Type-X Yukawa interaction. Therefore, the search for the invisible decay of the Higgs boson at the CERN Large Hadron Collider and future collider experiments would provide useful information not only for the nature of dark matter but also for the structure of the Higgs sector even without directly detecting any extra scalar boson.

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I. INTRODUCTION

Various astrophysical and cosmological observations provide evidence of the existence of dark matter (DM) \[1\]. The most interesting and promising candidate for DM is weakly interacting massive particles (WIMPs). WIMP DM is directly detectable. Many DM direct search experiments are operating and planned. For example, the ongoing experiments are DAMA/LIBRA \[2\], EDELWEISS II \[3\], ZEPLIN II \[4\], and XENON 10 \[5\]. Recently, CDMS II \[6\] has just finished, while XENON 1T, superCDMS, and XMASS \[7\] are planned. Direct DM searches have been done by looking for the elastic scattering of WIMP with target nuclei through nuclear recoil. Higgs-boson-exchange processes mainly lead to scalar (in other words, spin-independent (SM)) couplings between nuclei and WIMP. Hence, the structure of a Higgs sector and its coupling with DM are crucial for direct DM searches.

Among WIMP DM candidates, a class of models is categorized as “Higgs portal dark matter”, in which a DM particle interacts with Standard Model (SM) particles through only Higgs exchange processes. The minimal model was constructed by adding only one new $Z_2$ parity-odd real scalar field to the SM \[8, 9\]. A variety of such models has been proposed \[10–14\]. Some of them are motivated in the context of radiative seesaw models \[15, 13\].

A remarkable but common feature of Higgs portal DM models is the invisible decay of the Higgs boson due to Higgs-DM couplings for the case that the DM mass is smaller than one half of the Higgs boson mass \[15, 16\]. In the minimal Higgs portal DM model, the upper bound is obtained for the branching ratio of the invisible decay from the new CDMS II results \[17–20\].

In this Letter, we study a $Z_2$-odd scalar Higgs portal DM scenario in the framework of multi-Higgs doublet models. Such a scenario can appear, for example, in the effective theory of the three-loop-induced neutrino mass model \[13\], in which not only tiny neutrino masses but also DM as well as baryon asymmetry may be explained simultaneously by the TeV scale physics. The upper bound on the branching ratio of the Higgs boson invisible decay is evaluated in the model with two Higgs doublets and a real $Z_2$-odd singlet scalar field under the CDMS II results. In the analysis, a specific Yukawa interaction (the Type-X Yukawa interaction \[14, 21, 22\]) is employed, which is used in Ref. \[13\] and is defined under the other (softly broken) discrete symmetry ($\tilde{Z}_2$) for avoiding flavor changing neutral current (FCNC). We also give a comment on the results assuming the other types of Yukawa interaction, such
as so-called Type-II. We then discuss the difference of the upper bound from that in the
minimal model with one Higgs doublet. We show exclusive features of scalar Higgs portal
DM with multi-Higgs doublets.

II. MODEL

We consider the model in which two Higgs doublet fields $\Phi_1$ and $\Phi_2$ and one real singlet
scalar field $\eta$ are included. A discrete $Z_2$ symmetry is introduced in the model, and the odd
charge is assigned for $\eta$ to guarantee the stability as a candidate of DM. The scalar potential
is given by

$$V = \frac{1}{2} \mu_\eta^2 \eta^2 + \lambda_\eta \eta^4 + \sum_{i=1,2} \sigma_i |\Phi_i|^2 \eta^2 + V(\Phi_1, \Phi_2),$$

(1)

where $\mu_\eta^2$ is the invariant squared mass of $\eta$, and $V(\Phi_1, \Phi_2)$ is the potential of the two Higgs
doublet model. We neglect the CP violating phase, so that all the coupling constants are
real. After electroweak symmetry breaking, neutral component fields in the Higgs doublets
are parameterized as

$$\phi_i^0 = \frac{1}{\sqrt{2}} (v_i + h_i + iz_i), \quad (i = 1, 2),$$

(2)

where $v_i$ are the vacuum expectation values (VEVs) that satisfy $v_1^2 + v_2^2 = v^2 = (246 \text{GeV})^2$ and $\tan \beta = v_2/v_1$. The mass matrix for $h_1$ and $h_2$ is diagonalized by introducing the mixing
angle $\alpha$, and two CP-even states $h$ and $H$ are the mass eigenstates of the CP-even bosons.
The CP-odd scalar bosons $z_1$ and $z_2$ mix with each other, and becomes the CP-odd Higgs
$A$ and the longitudinal mode of the $Z$ boson. In total, from $\Phi_1$ and $\Phi_2$ five physical states
appear; i.e., two CP-even ($h$, $H$), one CP-odd ($A$), and charged ($H^\pm$) scalar bosons.

In the limit of $\sin(\beta - \alpha) = 1$, $h$ is the SM-like Higgs boson; i.e, all the coupling constants
with SM fields coincide with those of the SM Higgs boson at the tree level. On the
other hand, $H$ does not receive the VEV in this limit. In this Letter, we always take this
limit (the SM-like limit) for simplicity. The mass of the SM-like Higgs boson $h$ is bounded
from below ($m_h > 114$ GeV) from the LEP experiment, while that of $H$ can be lower than
100 GeV because it does not couple to the weak gauge bosons in this limit.

\[ This potential has been studied in the different context in Ref. [24]. \]
Multi-Higgs doublet models in general suffer from dangerous FCNC. To avoid FCNC, we impose a softly broken discrete symmetry $\tilde{Z}_2$ under the transformation $\Phi_1 \rightarrow \Phi_1$ and $\Phi_2 \rightarrow -\Phi_2$. The Yukawa interactions are expressed in terms of mass eigenstates of the Higgs bosons as

$$L_{\text{THDM}}^{\text{yukawa}} = -\sum_{f=u,d,\ell} \left( \frac{m_f}{v} \xi_{h_f} f h + \frac{m_f}{v} \xi_{H_f} f H - \frac{i m_f}{v} \xi_{A_f} f A \right)$$

$$- \left\{ \sqrt{2} V_{ud} \left( m_u \xi_{A_L} P_L + m_d \xi_{A_R} P_R \right) + \sqrt{2} m_\ell \xi_{A} \ell H^+ + \text{H.c.} \right\},$$

where $P_{L/R}$ are projection operators for left-/right-handed fermions, and the factors $\xi_{\phi}$ are listed in TABLE I. There are four ways of charge assignment under this $\tilde{Z}_2$ parity, thus correspondingly four independent types of Yukawa interaction are possible \cite{26, 27}. The typical example of so-called Type-II Yukawa interactions is that of the minimal supersymmetric standard model. The Type-X Yukawa interaction \cite{14, 21–23}, where one of the Higgs doublet couples to only quarks and the other does to only leptons, is adopted in the model for radiative generation of tiny neutrino masses with including the scalar DM proposed in Ref. \cite{13}, whose Higgs sector contains two Higgs doublets and a DM candidate $Z_2$-odd singlet scalar field as well as some heavier particles. Therefore, our present model given in Eq. (1) can be regarded as the effective theory of the model in Ref. \cite{13}. Thus, in this Letter, we mainly study the model with the Type-X Yukawa interaction, and then give a short comment on the cases of the other types for Yukawa interactions.

Even in the SM-like limit, the total decay width of the SM-like Higgs boson $h$ in our model can drastically change from the SM value when $m_\eta < m_h/2$ because of the additional invisible $h \rightarrow \eta\eta$ decay. The total width of $h$ is given by

$$\Gamma_{\text{tot}} = \Gamma_{\text{vis}} + \Gamma_{\text{inv}},$$

\begin{table}[h]
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|}
\hline
 & $\xi_u^{\ell}$ & $\xi_d^{\ell}$ & $\xi_{h}^{\ell}$ & $\xi_u^{d}$ & $\xi_d^{d}$ & $\xi_{H}^{d}$ & $\xi_u^{\ell}$ & $\xi_d^{\ell}$ & $\xi_{A}^{\ell}$ \\
\hline
Type-I & $c_\alpha/s_\beta$ & $c_\alpha/s_\beta$ & $s_\alpha/s_\beta$ & $s_\alpha/s_\beta$ & cot $\beta$ & $\cot \beta$ & $\cot \beta$ & $\cot \beta$ \\
Type-II & $c_\alpha/s_\beta$ & $-s_\alpha/c_\beta$ & $s_\alpha/c_\beta$ & $c_\alpha/c_\beta$ & cot $\beta$ & $\tan \beta$ & $\tan \beta$ & $\tan \beta$ \\
Type-X & $c_\alpha/s_\beta$ & $c_\alpha/s_\beta$ & $s_\alpha/s_\beta$ & $s_\alpha/s_\beta$ & $c_\alpha/c_\beta$ & $c_\alpha/c_\beta$ & $c_\alpha/c_\beta$ & $c_\alpha/c_\beta$ \\
Type-Y & $c_\alpha/s_\beta$ & $-s_\alpha/c_\beta$ & $s_\alpha/c_\beta$ & $c_\alpha/c_\beta$ & $c_\alpha/c_\beta$ & $c_\alpha/c_\beta$ & $c_\alpha/c_\beta$ & $c_\alpha/c_\beta$ \\
\hline
\end{tabular}
\caption{The mixing factors in Yukawa interactions in Eq. (3)}
\end{table}
where $\Gamma_{\text{vis}}$ denotes the width for Higgs boson decays into SM particle contents.

In the SM-like limit, $\Gamma_{\text{vis}}$ in our model coincides with that in the SM at the lowest order. The invisible decay width $\Gamma_{\text{inv}}$ of the SM-like Higgs boson is computed as

$$\Gamma_{\text{inv}}(h \to \eta\eta) = \frac{v^2}{32\pi m_h} \sqrt{1 - \frac{4m^2_\eta}{m^2_h}} \left| -\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta \right|^2.$$  \hspace{1cm} (5)

The corresponding formula in the minimal Higgs portal DM model with a scalar doublet $\Phi$ and a real scalar field $\eta$ is obtained from Eq. (5) by replacing $(-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta)$ by $2\sigma_m$ when the DM-Higgs coupling is given by $L_{\text{int}} = \cdots - \sigma_m \eta^2 |\Phi|^2 \cdots$. The branching ratio for the invisible decay is given by

$$B_{\text{inv}}(h \to \eta\eta) \equiv \frac{\Gamma_{\text{inv}}}{\Gamma_{\text{tot}}}. \hspace{1cm} (6)$$

### III. UPPER BOUND ON THE INVISIBLE DECAY BRANCHING RATIO

Now we consider the invisible decay branching ratio of the SM-like Higgs boson $h$. The size is proportional to the square of the $h\eta\eta$ coupling, but constrained by two issues.

One is from the direct DM search, the most stringent bound comes from the latest CDMS II results for the relatively large mass region while the constraint from XENON 10 is slightly stronger for smaller mass values. A too large coupling conflicts with the fact that CDMS has just observed only two possible events and others have obtained null results until now. The DM SI cross section for a proton is given as

$$\sigma_{\text{SI}}^p = \frac{m^2_p}{\pi (m_\eta + m_p)^2} f^2_p,$$  \hspace{1cm} (7)

with

$$f_p \equiv \left( \sum_{q=u,d,s} f^{(p)}_{Tq} + \frac{2}{27} \sum_{q=c,b,t} f^{(p)}_{TGq} \right) \frac{f_q}{m_q}.$$  \hspace{1cm} (8)

where $m_p$ is the proton mass and $f_p$ is the effective coupling with proton and $f^{(p)}_q$ is the hadronic matrix elements. The effective coupling $f_q$ with a quark is model-dependent. In the model in Eq. (1) with the Type-X Yukawa coupling, this is calculated at the tree level as

$$f_q \equiv \frac{(-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta) \cos \alpha}{2m^2_h} + \frac{(\sigma_1 \cos \alpha \cos \beta + \sigma_2 \sin \alpha \sin \beta) \sin \alpha}{2m^2_H}, \hspace{1cm} (9)$$
In the minimal Higgs portal DM model, it is given by \( f_q/m_q = \sigma_m/m_h \).

The other is the cosmological DM abundance determined by thermal freeze out. The relic mass density is evaluated as

\[ \Omega_{\eta} h^2 = 1.1 \times 10^9 \frac{m_{\eta}/T_d}{\sqrt{g_* M_P \langle \sigma v \rangle}} \text{GeV}^{-1}, \tag{10} \]

with the Planck mass \( M_P \), the total number of relativistic degrees of freedom in the thermal bath \( g_* \), and the decoupling temperature \( T_d \). For the Type-X Yukawa interaction, the processes of \( \eta \eta \to b\bar{b} \) and \( \eta \eta \to \tau^+\tau^- \) are dominant when \( m_\eta < m_W \), and the thermal averaged product of annihilation cross section and relative velocity is evaluated as \[ \langle \sigma v \rangle \simeq \frac{s}{16 \pi m_\eta^2} \left[ 3m_h^2 \right] \left( \frac{-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta}{s - m_h^2 + im_h \Gamma_H^{\text{tot}}} \right) \left( \frac{\cos \alpha}{\sin \beta} \right) \]

\[ + \left( \frac{\sin \alpha}{\sin \beta} \right)^2 \frac{\sigma_1 \cos \alpha \cos \beta + \sigma_2 \sin \alpha \sin \beta}{s - m_h^2 + im_H \Gamma_H^{\text{tot}}} \left( \frac{\sin \alpha}{\sin \beta} \right) \]

\[ + \frac{\sigma_1 \cos \alpha \cos \beta + \sigma_2 \sin \alpha \sin \beta}{s - m_H^2 + im_H \Gamma_H^{\text{tot}}} \left( \frac{\cos \alpha}{\cos \beta} \right) \left( \frac{\cos \alpha}{\cos \beta} \right) \left( \frac{\sin \alpha}{\sin \beta} \right)^2 \bigg|_{s=4m_\eta^2}, \tag{11} \]

where \( \Gamma_H^{\text{tot}} \) is the total width of \( H \). In the minimal Higgs portal DM model, it is given as \( \langle \sigma v \rangle \sim 3s/(4\pi m_\eta^2) |\sigma_m/(s - m_h^2 + im_h \Gamma_H^{\text{tot}})|^2 \) with \( s \simeq 4m_\eta^2 \). Too large (small) coupling constants \( \sigma_i \) correspond to the over-annihilation (over-abundance) of DM. We evaluate the consistent parameter region of the \( h\eta\eta \) coupling and DM mass.

We examine the upper bound on \( B_{\text{inv}}(h \to \eta\eta) \) from the CDMS II and the XENON 10 for some parameter sets in the case of the Type-X interaction. As stated, we work in the SM-like limit \( \sin(\beta - \alpha) = 1 \). We use the average of the coupling constants \( \sigma \equiv (\sigma_1 + \sigma_2)/2 \) to show the typical scale of couplings and the difference \( \Delta \sigma \equiv \sigma_1 - \sigma_2 \) to see the effect of the difference instead of \( \sigma_1 \) and \( \sigma_2 \). For the numerical evaluation, we here show the results in the following two simple cases with \( \tan \beta = 1 \) (Set A) and \( \tan \beta = 10 \) (Set B). The mass of the SM-like Higgs boson \( h \) is set to be \( m_h = 120 \) GeV. The other input parameters are commonly taken as \( m_H = 90 \) GeV and \( \Delta \sigma = 0.02 \). These parameter sets are not excluded by the current data. We note that Set B approximately corresponds to the scenario discussed in Ref. [13] in the context of successful radiative seesaw scenario with satisfying the constraint from dark matter abundance and the condition for strongly first order phase transition for electroweak baryogenesis.

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FIG. 1: [Left] The constraint on the decay branching ratio $B_{\text{inv}}(h \rightarrow \eta\eta)$ for the invisible decay of the SM-like Higgs boson into a DM pair from the CDMS II results and the XENON 10 results in Set A. [Right] The thermal abundance $\Omega h^2$ of DM as a function of the DM mass in Set A with $\sigma = 0.076$.

FIG. 2: [Left] The constraint on the decay branching ratio $B_{\text{inv}}(h \rightarrow \eta\eta)$ for the invisible decay of the SM-like Higgs boson into a DM pair from the CDMS II results and the XENON 10 results in Set B. [Right] The thermal abundance $\Omega h^2$ of DM as a function of the DM mass in Set B with $\sigma = 0.068$.

The left panel of Fig. 1 shows the constraint on the Higgs invisible decay branching ratio from direct DM searches in the model with the Type-X Yukawa interaction and $\sin(\beta - \alpha) = 1$ for Set A ($m_h, m_H, \Delta \sigma, \tan \beta) = (120 \text{ GeV}, 90 \text{ GeV}, 0.02, 1)$. The upper bound on $B_{\text{inv}}(h \rightarrow \eta\eta)$ does not depend on the DM mass much and about $B_{\text{inv}}(h \rightarrow \eta\eta) \sim 0.8$ is allowed for $m_\eta \lesssim 50 \text{ GeV}$, while the bound becomes stringent for $m_\eta > 55 \text{ GeV}$. Around $m_\eta \approx 43 \text{ GeV}$ (near the $H$-resonance), we can obtain the maximal value of $B_{\text{inv}}(h \rightarrow \eta\eta) \approx 0.8$
which corresponds to $\sigma \simeq 0.076$ through Eqs. (5) and (6). The right figure shows the point $(m_\eta, \sigma) \simeq (43 \text{ GeV}, 0.076)$ with the same other parameters indeed satisfies the WMAP constraint $\Omega h^2 \simeq 0.1$.

The left panel of Fig. 2 similarly shows the constraint on the Higgs invisible decay branching ratio from direct DM searches in the model with the Type-X Yukawa interaction and
\[
\sin(\beta - \alpha) = 1 \text{ for Set B } (m_h, m_H, \Delta \sigma, \tan \beta) = (120 \text{ GeV}, 90 \text{ GeV}, 0.02, 10).
\]
As compared to Set A shown in Fig. 1, the bound on $B_{\text{inv}}(h \to \eta \eta)$ becomes stringent. However, a large $B_{\text{inv}}(h \to \eta \eta) \simeq 0.7$ is still realized for $m_\eta \simeq 43 \text{ GeV}$ (near the $H$-resonance) and the large invisible width is obtained for $\sigma \simeq 0.068$. This point satisfies the WMAP constraint on the DM abundance as shown in the right figure.

We have observed that there are the parameter sets in our model with the Type-X Yukawa interaction and $\sin(\beta - \alpha) = 1$, in which a maximal values of $B_{\text{inv}}(h \to \eta \eta)$ suggested by the direct search results are consistent with the WMAP results. In Set A (Set B), $B_{\text{inv}}(h \to \eta \eta) = 0.8$ (0.7) can be realized for $m_h = 120 \text{ GeV}$ and $m_\eta \simeq 43 \text{ GeV}$ around the edge of the resonance of $H$. On the other hand, in the model with the minimal Higgs portal DM model, we obtain $B_{\text{inv}}(h \to \eta \eta) \lesssim 0.63$ for the same value of $m_h$ but for $m_\eta \sim 55 \text{ GeV}$ (near the $h$ resonance) in the same calculation manner\(^2\). Therefore, if $B_{\text{inv}}(h \to \eta \eta) \gg 0.63$ will be measured at the LHC, it will indicate a non-minimal Higgs sector in the Higgs portal DM scenario even when no extra Higgs boson will be found there yet.

The invisible decay of the Higgs boson can be detected at the CERN Large Hadron Collider (LHC) if $B_{\text{inv}}(h \to \eta \eta) > 0.25$ \cite{29}. At the International Linear Collider (ILC), invisible decays of the SM-like Higgs boson $h$ can be tested when $B_{\text{inv}}(h \to \eta \eta) >$ only a few % \cite{30}. Therefore, we can distinguish the maximal value of the branching ratio evaluated in our model from the upper bound in the minimal one doublet model with a $Z_2$-odd singlet scalar boson.

As we have seen, the extra scalar boson $H$ has to be lighter than the SM-like Higgs boson $h$ in order to obtain $B_{\text{inv}}(h \to \eta \eta) \gtrsim 0.63$. Phenomenology of extra Higgs bosons in the Type-X two Higgs doublet model has been studied in Ref. \cite{14, 21, 23, 31}. At the LHC

\(^2\) In Refs. \cite{17} and \cite{18}, somewhat larger values are reported for the upper bound of $B_{\text{inv}}(h \to \eta \eta)$ in the minimal Higgs portal DM model. The difference between our result and their results mainly comes from the different choice for the values of the hadronic matrix elements. In our analysis, the values in Ref. \cite{28} are consistently used.
such a light $H$ ($m_H \sim 90$ GeV) can be produced via gluon fusion processes $gg \rightarrow H$ and $gg \rightarrow gH$, and also the Drell-Yan type processes $q\bar{q}' \rightarrow HH^+$ and $q\bar{q} \rightarrow AH$. The decay pattern of $H$ largely depends on $\tan\beta$. For $\tan\beta \sim 1$, it decays mainly into $bb$, while for $\tan\beta \sim 10$ the leptonic decay modes into $\tau^+\tau^-$ and $\mu^+\mu^-$ are dominant. If such a light $H$ is identified and large $B_{\text{inv}}(h \rightarrow \eta\eta) \gtrsim 0.63$ is confirmed at the LHC, then the two Higgs portal DM scenario can be tested. On the other hand, if only $B_{\text{inv}}(h \rightarrow \eta\eta) \gg 0.63$ is measured at the LHC without detecting $H$, then we could obtain indirect information on the extended Higgs sector in the Higgs portal DM scenario before direct detection of the extra Higgs bosons.

In this Letter, we have studied only two Higgs doublet model with Type-X Yukawa coupling. However, relaxation of the upper bound on the invisible decay branching ratio seems to be generic for other multi-Higgs doublet models as well\textsuperscript{3}. The essence of this enhancement comes from the fact that the relevant interaction of DM for direct DM search experiments is both $h$-mediation and $H$-mediation, while only the coupling with $h$ is relevant to the invisible decay of the SM-like Higgs boson. Detailed study will be shown elsewhere \cite{32}.

IV. CONCLUSIONS

We studied the branching ratio of the Higgs invisible decay in the model with multi-Higgs doublets and one scalar singlet DM field, mainly assuming the Type-X Yukawa interaction. We could rewrite the latest CDMS II and XENON 10 excluded region into an upper bound of Higgs invisible decay for a given parameter set. If the two suspicious CDMS events are indeed due to the WIMPs, we will measure such a large invisible decay branching ratio of the SM-like Higgs for $m_\eta \sim m_H/2$ in multi-Higgs doublet models.

As compared to the case of the minimal Higgs portal DM model, in the two Higgs doublet portal DM model it is still allowed to have a larger value of the invisible decay branching ratio such as 0.8 (for Set A) or even larger. We emphasize that this conclusion for Set A is almost independent of the type of Yukawa interaction, although we have analyzed\textsuperscript{3} it is easily understood from Eq. (3) that for $\sin(\beta - \alpha) = 1$ and $\tan\beta = 1$ the visible width of the extra Higgs boson $H$ is independent of the types of Yukawa interaction\textsuperscript{[21]}, and the abundance of $\eta$ is also calculated to be almost common when the mass of $\eta$ to be near the $H$ and $h$ resonances. Therefore, our result of $B_{\text{inv}}(h \rightarrow \eta\eta) \lesssim 0.8$ for Set A is essentially independent of the type of Yukawa interaction.
the invisible decay branching ratio assuming the Type-X Yukawa interaction\(^4\). Therefore, we conclude that precise determination of the invisible decay branching ratio at the LHC or future collider experiments would give useful information not only for the nature of dark matter but also for the structure of the Higgs sector even without detecting any extra scalar boson directly.

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\[1\] e.g., D. N. Spergel et al. [WMAP Collaboration], Astrophys. J. Suppl. 170, 377 (2007).
\[2\] R. Bernabei et al. [DAMA Collaboration], Eur. Phys. J. C 56, 333 (2008).
\[3\] A. Broniatowski et al., Phys. Lett. B 681, 305 (2009).
\[4\] V. N. Lebedenkov et al., Phys. Rev. D 80 052010 (2009).
\[5\] J. Angle et al. [XENON10 Collaboration], Phys Rev Lett. 101, 091301 (2008).
\[6\] Z. Ahmed et al. [The CDMS Collaboration], [arXiv:0912.3592](https://arxiv.org/abs/0912.3592).
\[7\] K. Abe et al. [The XMASS Collaboration], Astropart. Phys. 31, 290 (2009).
\[8\] J. McDonald, Phys. Rev. D 50, 3637 (1994).
\[9\] C. P. Burgess, M. Pospelov and T. ter Veldhuis, Nucl. Phys. B 619, 709 (2001).
\[10\] N. G. Deshpande and E. Ma, Phys. Rev. D 18, 2574 (1978).
\[11\] E. Ma, Phys. Rev. D 73, 077301 (2006).
\[12\] R. Barbieri, L. J. Hall and V. S. Rychkov, Phys. Rev. D 74, 015007 (2006).
\[13\] M. Aoki, S. Kanemura and O. Seto, Phys. Rev. Lett. 102, 051805 (2009);
    M. Aoki, S. Kanemura and O. Seto, Phys. Rev. D 80, 033007 (2009).
\[14\] H. S. Goh, L. J. Hall and P. Kumar, JHEP 0905, 097 (2009).
\[15\] M. C. Bento, O. Bertolami, R. Rosenfeld and L. Teodoro, Phys. Rev. D 62, 041302 (2000).
\[16\] M. C. Bento, O. Bertolami and R. Rosenfeld, Phys. Lett. B 518, 276 (2001).
\[17\] X. G. He, T. Li, X. Q. Li, J. Tandean and H. C. Tsai, [arXiv:0912.4722](https://arxiv.org/abs/0912.4722) [hep-ph].
\[18\] M. Farina, D. Pappadopulo and A. Strumia, [arXiv:0912.5038](https://arxiv.org/abs/0912.5038) [hep-ph].

\(^4\) See Footnote 3.
[19] M. Kadastik, K. Kannike, A. Racioppi and M. Raidal, arXiv:0912.3797 [hep-ph].
[20] K. Cheung and T. C. Yuan, arXiv:0912.4599 [hep-ph].
[21] M. Aoki, S. Kanemura, K. Tsumura and K. Yagyu, Phys. Rev. D 80, 015017 (2009).
[22] S. Su and B. Thomas, Phys. Rev. D 79, 095014 (2009).
[23] H. E. Logan and D. MacLennan, Phys. Rev. D 79, 115022 (2009).
[24] B. Grzadkowski and P. Osland, arXiv:0910.4068 [hep-ph].
[25] J. F. Gunion and H. E. Haber, Phys. Rev. D 67, 075019 (2003).
[26] V. D. Barger, J. L. Hewett and R. J. N. Phillips, Phys. Rev. D 41, 3421 (1990).
[27] Y. Grossman, Nucl. Phys. B 426, 355 (1994).
[28] J. R. Ellis, K. A. Olive and C. Savage, Phys. Rev. D 77, 065026 (2008).
[29] Di Girolamo and B, Neukermans, L 2003 Atlas Note ATL-PHYS-2003-006;
    M. Warsinsky [ATLAS Collaboration], J. Phys. Conf. Ser. 110, 072046 (2008).
[30] M. Schumacher, Report No. LC-PHSM-2003-096.
[31] A. Belyaev, R. Guedes, S. Moretti and R. Santos, arXiv:0912.2620 [hep-ph].
[32] M. Aoki, S. Kanemura and O. Seto, work in progress.