PandaX limits on light dark matter with light mediator in the singlet extension of MSSM

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Abstract

Using the latest PandaX limits on light dark matter (DM) with light mediator, we check the implication on the parameter space of the general singlet extension of MSSM (without $Z_3$ symmetry), which can have a sizable DM self-interaction to solve the small-scale structure problem. We find that the PandaX limits can stringently constrain such a parameter space, depending on the coupling $\lambda$ between the singlet and doublet Higgs fields. For the singlet extension of MSSM with $Z_3$ symmetry, the so-called NMSSM, we also demonstrate the PandaX constraints on its parameter space which gives a light DM with correct relic density but without sufficient self-interaction to solve the small-scale structure problem. We find that in this NMSSM the GeV dark matter with a sub-GeV mediator has been stringently constrained.

PACS numbers: 14.80.Cp, 12.60.Fr, 11.30.Qc, 98.80.-k
I. INTRODUCTION

The large-scale structure of the universe (> 1 Mpc) can be successfully described by the ΛCDM (Lambda cold dark matter) cosmological model. However, the observation of small-scale structures [1], such as the Milky way and dwarf galaxies, seems to have tension with the simulations of collisionless cold dark matter. This dilemma is usually known as three problems: missing satellites [2], cusp vs core [3] and too big to fail [4]. A possible common solution to these issues is that the cold dark matter may have nontrivial self-interactions, namely the self-interacting dark matter (SIDM). Such SIDM can be realized in the DM models with a light mediator [5–7].

Note that the SIDM models with a light force carrier (< ∼ 100 MeV) can have a non-trivial velocity-dependent scattering cross section and may explain the small-scale structure problems [8, 9], which have been widely studied in the past few years. However, if the interaction between DM particle and the target nuclei is induced by a light mediator, the scattering cross section will be enhanced at low momentum transfer [10–13]. The current DM direct detection experiments have reached impressive sensitivities and are approaching the irreducible background neutrino floor. The null results produced strong constraints for various DM models. In particular, the PandaX-II collaboration has recently searched for the nuclear recoil signals of DM with light mediators [14]. Using data collected in 2016 and 2017 runs, they set strong upper limits on the DM-nucleon cross section for different mediator masses. On the other hand, if the light mediator mainly decays into the SM particles, such as γγ and e+e−, the injection of sizable energy densities into the visible sector thermal bath after the light elements may spoil the success of the big bang nucleosynthesis (BBN). This will produce a lower limit on the couplings between mediator and the SM particles and then may lead to a tension with the direct detections.

In this work, we investigate the implication of the PandaX limits on the parameter space of the singlet extension of MSSM with or without Z3 symmetry [15–17]. Such models can alleviate the little hierarchy problem by pushing up the SM-like Higgs boson mass to 125 GeV without heavy top-squarks [18] and the model with Z3 symmetry, the so-called NMSSM, can solve the notorious μ-problem in the MSSM [19] by dynamically generating the SUSY-preserving μ-term. For a rather small λ (the coupling between the singlet and doublet Higgs fields), the singlet sector can be almost decoupled from the electroweak symmetry breaking
sector and becomes a hidden sector of the model. The singlino-like DM will dominantly
annihilates into the SM particles through the s-channel light singlet-like Higgs bosons to
produce the correct DM relic density [20–22]. Note that the presence of light mediator can
lead to long-range attractive forces between DM particles and enhance the DM annihilation
cross section via the Sommerfeld effect at low temperature [23]. The previous study [23]
showed the general singlet extension of MSSM without \( Z_3 \) symmetry (hereafter is called
GNMSSM) can have a sizable DM self-interaction to solve the small-scale structure problem,
while the NMSSM can give a light DM with correct relic density but without sufficient self-
interaction to solve the small-scale structure problem.

The paper is organized as follows. In Sec. II we focus on the NMSSM and examine the
limits on the parameter space which has a light dark matter with light mediator. In Sec. III
we first show the parameter space of the GNMSSM which can solve the small-scale structure
problem, and then check the PandaX limits on the parameter space. Our conclusion is given
in Sec. IV.

II. CONSTRAINTS ON THE NMSSM

Since the NMSSM with \( Z_3 \) symmetry can give a light DM with correct relic density
but without sufficient self-interaction to solve the small-scale structure problem [23], in the
following we do not require it to solve the small-scale structure problem.

In the NMSSM the superpotential of the doublet and singlet Higgs fields is given by

\[
\lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 ,
\]

where \( \hat{H}_u \) and \( \hat{H}_d \) are the Higgs doublet superfields, \( \hat{S} \) is the singlet superfield, and \( \lambda \) and \( \kappa \)
are dimensionless parameters. Note that the \( Z_3 \) symmetry is imposed in the superpotential
to forbid other terms of the singlet. The corresponding soft SUSY breaking terms are given by

\[
A_\lambda \lambda S H_u \cdot H_d + \frac{A_\kappa}{3} \kappa S^3 + h.c. .
\]

Then we can get three CP-even Higgs bosons (denoted as \( h_{1,2,3} \)), two CP-odd Higgs bosons
(denoted as \( a_{1,2} \)) and a pair of charged Higgs bosons. From Eq. (1), we can also see that
the interactions between the singlet and the SM sector are controlled by the parameter
\( \lambda \). The constraints on the singlet-like Higgs bosons and siglino-like DM from both collider experiments and dark matter detections can be satisfied if \( \lambda \) is sufficiently small. Since the spectrum of the NMSSM has been widely studied in the literature [16], here we concentrate on the dark singlet sector.

In the NMSSM, the dark matter can have three components: gaugino, higgsino and singlino. Assuming the gaugino unification relation \( M_2/M_1 \approx 2 \), we have three dark matter scenarios:

- **Bino-dominant dark matter.** As shown in [24], under current collider and DM relic density constraints, the SI cross section can exclude a large part of parameter space, especially, if such bino-like DM contains a sizable higgsino component, its scattering cross section with the nucleon may be large and thus subject to stringent constraints from the direct detection limits [25].

- **Higgsino-dominant dark matter.** As pointed in [26], the higgsino-dominant DM candidate around 1.1 TeV can satisfy all the constraints, including the relic density and current DM direct detections.

- **Singlino-dominant dark matter.** In order to explain the observation of CoGeNT [27], the analysis in [28] showed that in the Peccei-Quinn limit there can exist three light singlet-like particles (0.1-10 GeV): a scalar, a pseudoscalar and a singlino-like dark matter. For a certain parameter window, through annihilation into the light pseudoscalar the singlino dark matter can give the correct relic density, and through exchanging a light scalar in scattering off the nucleon a large cross section suggested by CoGeNT and DAMA/LIBRA [29] can be attained.

Since the first two scenarios are the same as in the MSSM, we focus on the third scenario which is called the dark light Higgs (DLH) scenario. As studied in [28], besides explaining the observation of CoGeNT and DAMA/LIBRA, the parameter space is also consistent with the experimental constraints form LEP, the Tevatron, \( \Upsilon \) and flavor physics. In fact, the DLH scenario is the only possibility for realizing the self-interaction in the NMSSM. However, as studied in [23], the direct detection limits give stringent constraints on the couplings between dark matter and SM particles, inducing a much small \( \lambda \). The will make \( \sigma_{\chi}/m_{\chi} \) too small to explain the small cosmological scale simulations.
FIG. 1: Scatter plots showing the spin-independent cross section between dark matter and nucleon with different mediator masses in the DLH scenario in the NMSSM with $Z_3$ symmetry. The light mediator $\phi$ is the lightest CP-even Higgs boson $h_1$ which is singlet dominant. All the points satisfy the constraints of the DM relic density and the SM like Higgs boson $h_2$ in the range of 123-127 GeV. The detection limits of PandaX [14] on light mediator are shown as the red lines. The detection limits of CDEX-10 [33], CDMSlite Run 2 SI[34], CRESST-III [35], LUX Combined[36], and XENON1T [37] are also shown.

In the following, we check the PandaX constraints on the DLH scenario which can have light singlino-like DM and light singlet-like Higgs bosons as the mediators. The light singlino-like DM particles mainly annihilate to SM particles through the resonance of the singlet-like pseudo-scalar $a_1$. The DM scatters off the nucleon with the light CP-even singlet-like Higgs boson $h_1$ as the mediator, and the scattering cross section is subject to the PandaX limits. Following Ref. [28], in order to approach the PQ symmetry limit, we define the parameter $\varepsilon \equiv \lambda \mu / m_Z$, $\varepsilon' \equiv A_\lambda / \mu \tan \beta - 1$. We perform a random scan* over the parameter space: $2 \leq \tan \beta \leq 50$, $0.05 \leq \lambda \leq 0.2$, $0.0005 \leq \kappa \leq 0.05$, $-0.1 \leq \varepsilon \leq 0.1$, $\varepsilon \sim \varepsilon'$, $|A_\kappa| < 500$ GeV, and $|\mu| < 1000$ GeV. The sfermion sector parameters are set at 6 TeV so that we can get a 125 GeV SM Higgs boson easily. In our scan we use the package NMSSMTTools [31] to obtain the parameter space with a singlet-like Higg boson $h_1$ lighter than 2 GeV. We require the DM thermal relic density in the $2\sigma$ range of the Planck value [32] and the mass of the SM-like Higgs $h_2$ in the range of 123-127 GeV.

* We did not use the machine learning scan [30] because the parameter space is not too large.
The results are shown in Fig. 1, in which we set the mass of $h_1$ to 1 MeV, 10 MeV and 1 GeV, respectively. In each panel we show the detected limits of PandaX under the corresponding mediator masses. For comparison, we also show the detection limits of CDEX-10 [33], CDMSlite Run 2 SI [34], CRESST-III [35], LUX Combined [36], and XENON1T [37]. We can see that the SI cross section is enhanced greatly as the mass of the light mediator decreases. This can be understood from the cross section [28]

$$\sigma_{SI} \approx \left[ \left( \frac{\varepsilon}{0.04} \right) + 0.46 \left( \frac{\Delta}{0.1} \right) \left( \frac{\mu}{\text{GeV}} \right) \right]^2 \left( \frac{y_{h_1\chi\chi}}{0.002} \right)^2 \frac{10^{-4}\text{cm}^2}{(m_{h_1}/1\text{GeV})^4},$$ (3)

where $y_{h_1\chi\chi}$ is the coupling strength of the Higgs boson $h_1$ and dark matter. This relation implies that the cross section increases as the fourth power of the inverse mass of light mediator. If the mass of the mediator is at the order of MeV, a lot of samples will exceed the detection limits and thus the DLH scenario of the NMSSM is severely constrained by PandaX and other experiments (except for the region outside the detection sensitivity, which has the dark matter lighter than 3.5 GeV for the PandaX results). Such stringent constraints are from the correlation between the dark matter relic density and the dark matter-nucleon scattering cross section: a proper relic density implies a non-negligible coupling $a_{1f\bar{f}}$ and the parameter $\lambda$ cannot be too small, and so the SI cross section will be enhanced by the mediator mass greatly, as shown in the above equation.

From Fig. 1 we see that the dark matter with a mediator at MeV order is also excluded by other direct detections. Only a small parameter space with a mediator mass around GeV and a dark matter mass is around several GeV can survive all the direct detection limits.

III. CONSTRAINTS ON THE GNMSSM

Compared with the NMSSM with $Z_3$ symmetry, the general singlet extension of MSSM (GNMSSM) has a larger parameter space, in which the $Z_3$ discrete symmetry is not imposed and the $\mu$ term can exist in the superpotential, together with the $\lambda S H_u \cdot H_d$ term (several other terms of the singlet superfield can also exist in the superpotential). Consequently, the dark Higgs sector (including a singlino-dominant dark matter) can be easily realized in the GNMSSM, which does not need the condition $\kappa \ll \lambda$. This means that a singlino-dominant dark matter can be obtained with a sizable $\kappa$ and in this case the coupling $h_1\chi\chi$ in dark matter self-interaction, which is proportional to $\kappa$, can be large.
As pointed in [38], in order to solve the small-scale simulation anomalies, the self-interaction between the dark matter is needed. In the non-relativistic limit, the scattering between dark matter can be described by quantum mechanics. The most recent simulations have shown that the ratio of between cross section $\sigma$ and the mass of the dark matter $m_\chi$ on dwarf scales (the characteristic velocity is 10 km/s) should be $\sigma/m_\chi \sim 0.1 - 10 \text{ cm}^2/\text{g}$ to solve the core-vs-cusp and too-big-to-fail problems, while the Milky Way (the characteristic velocity is 200 km/s) and cluster scales (the characteristic velocity is 1000 km/s) require $\sigma/m_\chi \sim 0.1 - 1 \text{ cm}^2/\text{g}$. It appears that all the data may be accounted for with a constant scattering cross section around $\sigma/m_\chi \sim 0.5 \text{ cm}^2/\text{g}$. The numerical input for the simulation of small scales is the differential cross section $d\sigma/d\Omega$, which is a function of the dark matter relative velocity $v$. Then the viscosity (or conductivity) cross section $\sigma_V$ [39] can be defined as

$$\sigma_V = \int d\Omega \sin^2 \theta \frac{d\sigma}{d\Omega} ,$$

where the weight of $\sin^2 \theta$ is needed since both forward and backward scattering amplitudes will diverge. Such singularities correspond to the poles in the $t$- and $u$-channel diagrams for the identical dark matter candidate. Within the resonance region, $\sigma_V$ must be computed by solving the Schrödinger equation. Detail of the solution can be found in [23]. As there are symmetric ($\sigma_{VS}$) and antisymmetric ($\sigma_{VA}$) cross section for Majorana fermion dark matter models. In our following analysis, we assume that the dark matter scatters randomly. Thus the average cross section will be

$$\sigma_V = \frac{1}{4}\sigma_{VS} + \frac{3}{4}\sigma_{VA}.$$  

(5)

Now we turn to the dark Higgs sector of the GNMSSM for the explanation of the small cosmological structure problem. The renormalizable superpotential for the singlet is given by

$$W = \eta \hat{S} + \frac{1}{2} \mu_s \hat{S}^2 + \frac{1}{3} \kappa \hat{S}^3 ,$$

(6)

and the soft SUSY breaking terms take the form

$$-\mathcal{L}_{\text{soft}} = m_s^2 |S|^2 + \left( C_\eta \eta S + \frac{1}{2} B_s \mu_s S^2 + \frac{1}{3} \kappa A_k S^3 + \text{h.c.} \right) .$$

(7)

where $\eta, \mu_s, m_s^2, C_\eta, B_s$ are the additional input parameters in the GNMSSM, compared with the NMSSM. After the scalar component gets a VEV, we can get one CP-even Higgs $h$ and
FIG. 2: The scatter plots of the GNMSSM satisfying the DM relic density, taken from [23]. The blue points satisfy the simulation in the Dwarf scale, while the red and green points satisfy the simulation in the Milky Way with a characteristic velocity of 200 km/s and 1000 km/s, respectively.)

A detailed study of the GNMSSM in solving the small cosmological scale anomalies is presented in [23]. Here we just demonstrate the parameter space in Fig. 2. We can see that a part of the parameter space can satisfy simultaneously the requirements of the dwarf, the Milky Way and galaxy cluster scales to solve the small scale anomalies. In this part of the parameter space the masses of dark matter and mediator are quite restrained.

For the connection between the electroweak sector and the dark light singlet sector, the mixing angles between singlet and doublet fields depend on the off-diagonal elements divided by the differences between diagonal elements. For example, the mixing between $H_d$ and $S$ is proportional to

$$\theta_{ds} \sim \frac{\mathcal{M}_{S,13}^2}{|\mathcal{M}_{S,11}^2 - \mathcal{M}_{S,33}^2|} \sim \lambda \times \text{(electro-weak variables)}$$

(8)

where $\mathcal{M}$ is the $3 \times 3$ Higgs mass matrix [15–17]. If the mediator $h_1$ is around several MeV, the input electroweak parameters give $\mathcal{M}_{S,13}^2$ and $\mathcal{M}_{S,33}^2$ much smaller than the electroweak scale. Thus we can define the following two angles for the mixing between singlet and doublet
FIG. 3: Scatter plots of the GNMSSM parameter space which can satisfy the dark matter relic density and solve the small cosmological structure problem, displayed on the plane of the dark matter mass versus the mediator mass. The red points are excluded by the PandaX limits.

\[ l = 2 \times 10^{-5} \]
\[ l = 1 \times 10^{-4} \]

where \( \alpha_d \) and \( \alpha_u \) are two new parameters for the mixing angles. By such a parameterization, we can calculate the corresponding cross section. For example, the coupling strength between singlet and up type quarks is given by

\[ Y_q \lambda \alpha_u \sin \beta, \quad Y_q \lambda \alpha_u \sin \beta, \quad (10) \]

and for the down type quarks is given by

\[ Y_q \lambda \alpha_d \cos \beta. \quad (11) \]

By the parameterizations above, we can calculate the spin-independent DM-nucleon scattering cross section [40, 41]:

\[ \sigma^{SI} = \frac{4m_f^2}{\pi} f_N^2 \quad (12) \]
where
\[ m_r = \frac{m_\chi m_N}{m_\chi + m_N} \] (13)
is the reduced dark matter mass, and \( f_N \) is the effective coupling of the DM with nucleon.

Since the singlet sector is much lighter than the electroweak scale, we can neglect the contribution of the squarks and the supersymmetric loop contribution. Thus \( f_N \) can be written as

\[ \frac{f_N}{m_N} = \sum_{q=u,d,s} \frac{f_{Tq}^N m_q}{m_N} f_q + \frac{2}{27} f_{TG}^N \sum_{q=c,b,t} \frac{f_H^q}{m_q}, \] (14)

where \( f_{Tq}^N \) denotes the fraction of the nucleon mass \( m_N \) that is due to the light quark \( q \), and

\[ f_{TG}^N = \frac{2}{27} (1 - f_{Tu}^N - f_{Td}^N - f_{Ts}^N) \] (15)
is the heavy quark contribution to \( m_N \), which is induced via gluon exchange. A detailed calculation of these parameters \( f_{Tq} \) can be found in [40]. In our calculation, we use \( \sigma_{\pi N} = 64 \) MeV and \( \sigma_0 = 35 \) MeV to get the values of \( f_{Tq}^N \).

Fig. 3 shows the PandaX constraints on the GNMSSM parameter space in which all the points satisfy the DM relic density and the scattering cross section for the small cosmological structures. Here we set \( \tan \beta = 2 \) and \( \alpha_u = \alpha_d = 0.001 \) for the demonstration. We also checked the results of other different values of \( \tan \beta \) and \( \alpha_u, \alpha_d \), and found that the results are similar. We can see that when \( \lambda \) is less that of \( 10^{-5} \), the dark sector can survive safely. As \( \lambda \) increases, the constraints become stringent.

Note that since there exist light singlet Higgs bosons and singlino-like DM, the SM-like Higgs will have additional decay channels \( h_{SM} \rightarrow h_1 h_1, h_{SM} \rightarrow a_1 a_1 \) and \( h_{SM} \rightarrow \chi \chi \), in which the first two channels are exotic decays and the last one is the invisible decay. Their branching ratios are determined by the coupling parameters \( \lambda \) and \( \kappa \). These decays can give interesting phenomenology [42]

We should note that the singlet CP-even Higgs boson can not be too dark, it must decay before the start of the Big Bang Nucleosynthesis (BBN) (\( \sim 1 \) sec) so its decay products will not affect BBN. But if the singlet Higgs couples to the SM particles sizably, the direct detection rate of dark matter will be enhanced greatly by the light mediator. One way to solve such an obstacle is to add a right-handed neutrino to the GNMSSM [43]. Another point we would like to address is that the light dark matter in our analysis is around GeV.
scale. For sub-GeV ultra light dark matter, the dark matter particles can be boosted by the cosmic rays and the detection sensitivity can be much enhanced [44]. Also, for a heavy dark matter above TeV, recently the DAMPE collaboration reported the cosmic $e^+ + e^-$ flux excess [45] which seems to favor a TeV-scale leptophilic dark matter [46].

IV. CONCLUSION

Using the newest limits given by the PandaX collaboration on the zero-momentum dark matter-nucleon cross section, we checked the implication on the supersymmetric dark models, especially on the parameter space of light dark matter and mediator. We first analyzed the spectrum of NMSSM with $Z_3$ symmetry and GNMSSM without $Z_3$ symmetry, and found out a way to parameterize the connection between singlet sector and the SM sector. Then we examined the parameter space of the two models under the limits of PandaX and other direct detections. We obtained the following observations:

- The PandaX limits exclude the case of dark matter above 3.5 GeV. The left space are excluded by the requirement of the self-interaction which gives a stringent constraints on the mass of mediator. The reason is the correlation between the dark matter relic density and the dark matter nucleon cross section. Thus, the NMSSM with $Z_3$ symmetry is excluded by the PandaX and the requirement of explanation for the small structure problems.

- It is easy to realize self-interaction in the GNMSSM, in which the singlet sector can be a dark sector. In the dark sector, the correct relic density and a proper self-interaction can be obtained. Compared to the simple one-mediator model, the supersymmetric model can have a larger parameter space, and the mass of the dark matter and mediator can be relaxed.

- By our parameterization for the connection between singlet sector and the SM sector, we find that PandaX results can give a constraint on the coupling strength between the two sector. Only a very small $\lambda$ is allowed.

In all, the PandaX limits give us a very good test for the self-interaction dark matter models. More precision measurements of the light mediator and dark matter, together with the self-interaction physics need to be further studied.
Acknowledgments

This work was supported by the Natural Science Foundation of China under grant number 11775012.

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