Prospect of dark matter searches in split SUSY models

Nobuchika Okada\textsuperscript{1} and Hieu Minh Tran\textsuperscript{2*}

\textsuperscript{1} Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA
\textsuperscript{2} Hanoi University of Science and Technology, 1 Dai Co Viet Road, Hanoi, Vietnam
\textsuperscript{*} Corresponding author
E-mail: okadan@ua.edu, hieu.tranminh@hust.edu.vn

Abstract. The results from the XENON1T/Panda-X and IceCube experiments have set severe upper limits on spin-independent (SI) and spin-dependent (SD) scattering cross section of weakly interacting massive particles on nuclei. In the framework of split supersymmetry scenario supported by the LHC constraints, we investigate the prospect of dark matter (DM) direct and indirect detection experiments. Assuming a relation among gaugino masses at the grand unification scale, we have specified the parameter regions that predict the right DM relic abundance as well as satisfy the constraints on SI and SD scattering cross sections of DM. In the case of universal gaugino masses, the XENON1T/Panda-X results have ruled out completely the well-tempered neutralino region. We have found that 200 times smaller than the current IceCube bound is the sensitivity limit that a future DM indirect detection experiment should have at least in order to have a certain impact beyond the current XENON1T/Panda-X results. The future results from XENON1T will be able to test a signification portion of the Higgsino-like region. Although there are points in the Higgsino-like region that cannot be reached by future DM detection experiments, direct production channels of neutralino/chargino can be used to test the model at the LHC/HL-HLC. In the case of non-universal gaugino masses, beside showing the allowed parameter space, we have specified the regions that can be tested at both future DM direct and indirect detection experiments. One of them are Higgsino-like region, while the others two predict a well mixed bino-wino DM. The DM properties in each region have been examined and demonstrated with a benchmark of -ino spectrum. Interestingly, points in the mixed bino-wino region with rather light chargino can be tested the LHC 14 TeV.

1. Introduction
The standard model (SM) has been successfully described the world of elementary particles as observed at colliders. However, the origin of dark matter (DM) is still a puzzle within this framework. Since non of the SM particles is suitable as a DM candidate, extensions of the model involving a DM candidate are necessary. Among various proposals, we are interested in the minimal supersymmetric (SUSY) extension of the SM (MSSM) that is well motivated. The MSSM predicts a very good candidate for DM, the lightest neutralino. Additionally, in this model, three couplings of the SM gauge groups naturally unified at the scale of \(O(10^{16})\) GeV, suggesting that it is an effective theory of a underlying grand unification theory (GUT). Moreover, the Higgs boson mass that is a free parameter determined experimentally in the SM can be predicted in the MSSM.
The recent LHC results have constrained the lower mass limits of color superpartners to be up to nearly 2 TeV. It is indeed in agreement with the measurement of the SM-like Higgs boson mass \cite{1}. It has been pointed out that in many cases typical stop masses should be of $\mathcal{O}(10)$ TeV to provide corrections large enough to push up the Higgs boson mass from the electroweak scale to 125 GeV \cite{2}. Physics at such a high SUSY scale actually decouples from physics at $\mathcal{O}(1)$ TeV which can be tested at the LHC. Assuming other sfermions are also very heavy, this situation fits the split SUSY scenario where the gauge coupling unification and the dark matter prediction are considered as the primary motivations \cite{3}. Here, the sfermion sector is separated from the gaugino sector. The most interesting particle is the lightest neutralino playing the role of a DM candidate. In many cases, it is the only realistic probe of such a model.

The scattering of DM on nuclei can be probed by DM search experiments. Direct DM detection experiments can detect both spin-independent (SI) and spin-dependent (SD) interactions between DM and nuclei. For heavy material used in direct detection experiments (such as Xenon liquid), the SI cross sections causing the coherent recoil of the nucleus increase by a factor of square of the atomic number. Due to the enhancement of SI scattering cross sections related to coherent additivity, direct DM detection experiments are more sensitive to SI interactions than SD ones. On the other hand, indirect DM detection experiments look for various signals of DM annihilation in the galaxy using positrons \cite{4}, photons \cite{5}, or neutrinos \cite{6} from the outer space. When using gamma-ray emission from the halo of a galaxy to constrain a DM model, there is a difficulty that the true DM distribution of that galaxy needs to be understood \cite{7}. The neutrino telescopes such as IceCube \cite{8} measure the energetic neutrino flux produced from the decay of SM particles after the DM annihilation. It is determined by the capture rate of DM inside the Sun that is related to the scattering of DM on nuclei, assuming the equilibrium between that capture and annihilation of DM \cite{9}. Hence, neutrino telescopes are able to reliably constrain both SI and SD cross sections. Since the dominant element inside the Sun is hydrogen which is very light, the coherent enhancement of SI cross section does not apply. In comparison to direct detection experiments, the indirect detection method with neutrino telescopes currently provides better limits for the SD cross section \cite{10}.

The direct and indirect DM detection experiments have been more and more sensitive to the scattering between DM and nuclei. Since no signature of DM has been observed, the constraints from these experiments become more severe. The Large Underground Xenon (LUX) experiment announced the updated results that set a stringent limit for the SI scattering cross section between the DM and nucleon \cite{11}. It was shown that this constraint further ruled out the well-tempered neutralinos as DM in various models \cite{12, 13}. Recently, the XENON1T \cite{14} and the PandaX-II \cite{15} collaborations have released even more impressive results providing the stronger limits for this quantity. On the other hand, among indirect DM searches, the IceCube experiment currently provides the best limit on the SD cross section \cite{16}. This result has an important impact on DM models \cite{12}. The non-thermal wino DM is excluded by recent combined Fermi-LAT/MAGIC limits \cite{17} and new HESS results \cite{18} from continuum gamma ray \cite{12}. The thermal wino DM whose mass should be about 2.8 TeV in order to result in a right relic density is also excluded by a combination of Fermi-LAT and HESS data, assuming a favorable halo profile \cite{19}. In the same way, the simplest UV completion of the MSSM, namely the constrained MSSM, is disfavored in a substantial portions of its parameter space \cite{12, 20, 21}.

In this paper, we investigate the prospect of DM searches in the context of the GUT-inspired split SUSY scenario. All the scalar superpartners are assumed to have masses of $\mathcal{O}(10)$ TeV. At low energies, these fields have the only visible effect that provides adequate contributions to the Higgs boson mass via quantum corrections. Although a GUT relation between gaugino masses is assumed, it is not necessary to be universal \cite{20, 22}. It is determined by a specific GUT representation of the chiral superfield in the hidden sector that couples to the SUSY gauge kinetic function. Here we consider both cases of universal and non-universal gaugino masses.
The Higgsino DM was investigated in non universal gaugino mass model with the hidden sector belonging to $75$ and $200$ representations of the $SU(5)$ [20]. In the meanwhile, the correlation between the Higgsino DM and the high SUSY breaking scale was studied in Ref. [23] together with other DM properties. Our analysis focuses on the $SO(10)$ GUT with the hidden sector being a singlet representation in the universal gaugino mass case, and being a linear combination of a singlet and a $54$ representation in the non universal gaugino mass case. In spite of that, the result can be applied for the $SU(5)$ GUT or any GUT that contains one of these two gauge groups as a subgroup. We identify the allowed parameter space satisfying the constraints on the DM relic density as well as the SI and SD cross sections. Portions of the parameter space that can be tested in future DM detection experiments are pointed out. The properties of DM in each viable regions are analyzed in details.

The structure of this paper is as follows. In Section 2, we briefly discuss the GUT relation for gaugino masses which will be used subsequently. The results of the parameter scans are presented in Section 3. Here, we analyze the DM properties in the allowed regions and the impact of future DM search experiments. Finally, the conclusion is given in Section 4.

2. GUT relation between gaugino masses

In gravity mediation, the gaugino masses at the GUT scale are given by the interaction between the hidden sector and the gauge field strength superfield $W$ suppressed by the Planck scale $M_P$:

$$\mathcal{L} = \int d^2 \theta \frac{\Phi_{ab}}{M_P} W^a W^b,$$  

where $\Phi_{ab}$ is the chiral superfield in the hidden sector, and $a, b$ are indices of the adjoint representation of the GUT gauge group. For the $SO(10)$ GUT [22], $\Phi_{ab}$ is one of the irreducible representations contained in the symmetric product of two adjoint 45-dimensional representations:

$$(45 \otimes 45)_{\text{sym}} = 1 \oplus 54 \oplus 210 \oplus 770.$$  

If the hidden sector field is a singlet, the gauginos have a universal mass at the GUT scale. Otherwise, their masses are non universal. The ratios between the gaugino masses are determined by the group theoretical factors that depend on the symmetry breaking chain from the GUT gauge group down to the SM one [24]. In this case, the vacuum expectation value of the hidden sector field’s F-term breaks both the SUSY and the GUT gauge symmetry at the same time.

To protect the GUT from the gauge coupling blow-up below the Planck scale, the irreducible representation should not be too large. In the case of $SO(10)$, its dimension should be not larger than 126 [25]. Therefore, $1$ and $54$ representations are of our interest. The gaugino mass ratios at the GUT scale corresponding to the $54$ representation of the hidden sector superfield are determined as [24]

$$M_1 : M_2 : M_3 = -\frac{1}{2} : -\frac{3}{2} : 1.$$  

where $M_{1,2,3}$ are soft masses of bino, wino and gluino at the GUT scale.\(^1\)

In a general case, the hidden sector superfield can be a linear combination of the $1$ and $54$ representations respectively. The generalized GUT relation between gaugino masses reads

$$M_1 : M_2 : M_3 = \left(1 - \frac{1}{2}x\right) : \left(1 - \frac{3}{2}x\right) : (1 + x).$$  

\(^1\) The symmetry breaking chain is assumed to be $SO(10) \rightarrow SU(4) \times SU(2) \times SU(2) \rightarrow SU(3) \times SU(2) \times U(1)$. 

1
We see that, in the limit $x \to 0$, the universal gaugino mass relation is recovered corresponding to the case of a singlet hidden sector superfield. In the limit $x \to \infty$, the relation in Eq. 3 is recovered.

Regarding to the $SU(5)$ GUT, the $24$ representation in the hidden sector gives the same mass ratios as in Eq. (3) [26], while a linear combination between $1$ and $24$ representations results in Eq. (4). Therefore, our analysis applies for both $SO(10)$ and $SU(5)$ model, and any other GUTs that contain them as a subgroup.

Matter superfields unify distinctly in different GUT scenarios. This property can be used to probe the GUT gauge group [27]. However, in split SUSY scenario, all sparticles are too heavy to be detected at the LHC. Thus, a 100 TeV hadron collider is important to test the sfermion sector of these models. In the next Section, we focus our analysis on the ino sector that will be detectable in the near future.

3. Analysis and results

In split SUSY scenario, the free parameters relevant to the ino sector at low energies of the model include

$$\mu, M_1, \tan \beta,$$ (5)

for the case of universal gaugino mass at the GUT scale, and

$$\mu, M_1, \tan \beta, x,$$ (6)

for the case of non universal gaugino masses at the GUT scale. Assuming a 3 GeV theoretical uncertainty, we require the Higgs boson mass to be [1]

$$122 \text{ GeV} < m_h < 128 \text{ GeV}.$$ (7)

At the same time, the gluino mass must satisfy the lower bound of about 1580 GeV as determined at the LHC [28].

Although the ino sector is the most relevant one in split SUSY models, sparticle soft masses and trilinear couplings play the role of providing the corrections for the SM-like Higgs boson mass. Therefore, at low energies the sparticle soft masses are set to 10 TeV, and the trilinear couplings are set to 3840 GeV in our analysis.

Since the DM is the lightest supersymmetric particle (LSP) and the sensitivities of DM detection experiments are continuously improved, it is the most feasible probe in split SUSY models. In this work, the DM relic density is constrained to be

$$0.11 < \Omega h^2 < 0.13,$$ (8)

which is compatible with the observation from Planck experiment [29]. The SD and SI cross sections between the DM particle and nuclei are well constrained from DM indirect and direct detection experiments. A severe limit of the former is set by IceCube experiment [16], while that of the latter is imposed by XENON1T experiment for $m_{DM} \lesssim 70 \text{ GeV}$ [14] and by PandaX-II experiments for $m_{DM} > 70 \text{ GeV}$ [15]. For numerical analysis, we use the packages SuSpect version 2.41 [30] to calculate the sparticle spectrum, and MicrOMEGAs version 4.3.1 [31] to calculate the neutralino relic abundance, SD and SI scattering cross sections between the neutralino DM and nuclei.

In the case of universal gaugino mass, we have performed a scan on the parameter space of $\{\mu, M_1\}$ with

$$30 \text{ GeV} \leq \mu \leq 2000 \text{ GeV},$$ (9)

$$30 \text{ GeV} \leq M_1 \leq 7000 \text{ GeV}.$$ (10)
We find that the results for different values of $\tan \beta$ are almost the same. Therefore, $\tan \beta = 10$ is chosen throughout this paper. In Fig. 1, we show the SI scattering cross section between neutralino DM and nuclei as a function of the DM mass. The region that satisfy the DM relic density are shown in blue. Unlike the CMSSM, in split SUSY models, there are neither stau coannihilation region nor bulk region. The regions resulting in the right DM relic abundance include the well-tempered neutralino and Higgsino-like neutralino regions. The pink solid curve in these figures represents the current most severe upper limit set by the combination of XENON1T and PandaX-II experiments. It excludes all the well-tempered neutralino region, and a non-negligible part of Higgsino-like region upto the DM mass of about 1050 GeV. Thus, there is no new physics to be expected below $\sim 1$ TeV in split SUSY scenario with universal gaugino masses. This implication is independent but in agreement with what we have obtained at the LHC so far. The black dashed curve in this figure is the future sensitivity of XENON1T experiment [32]. We can see that the viability of a large Higgsino DM region of the split SUSY model with the SI cross section as small as about $\sim O(10^{-10}$ pb) will be testable by this experiment.

![Figure 1. The SI cross section between the neutralino DM and nucleon as a function of the DM mass in the case of $\tan \beta = 10$. Pink solid curve: the combined XENON1T/PandaX-II upper limit; black dashed curve: the projected XENON1T sensitivity.](image)

For DM elastic scattering, the SI interactions are determined by the vector/scalar couplings, while the SD interactions determined by the axial vector couplings occurs through the Z boson exchange processes. In split SUSY models, contributions from squarks exchange diagrams to the SI cross section are negligible due to their large masses. The dominant contribution to the SI cross section is via the Higgs boson exchange in the t-channel. Because of the small Yukawa couplings of the first generation, the SI cross section is in general a few orders of magnitude smaller than the SD one. This fact can be seen in Fig. 2 in comparison to Fig. 1. Here, the SD cross section is depicted as a function of the DM mass. The blue color also indicates the region with the allowed DM relic density.

The IceCube experiment [16] recently provided a severe limit on the SD cross section, assuming the WIMP DM is annihilated 100% into a certain single channel of the types: $\tilde{\chi}^0_1 \tilde{\chi}_1^0 \rightarrow b\bar{b}, t\bar{t}, \tau^+\tau^-, \nu\bar{\nu}, gg, ZZ, W^+W^-$, and $hh$. For a generic model where the DM particle can decay into various channels with different final states, these limits could not be applied
directly. However, in the split SUSY scenario, the situation is simplified due to the negligible contribution from heavy sfermions. Indeed, only the channels with the final states $ZZ$, $W^+W^-$, and $hh$ effectively participate in the DM annihilation. The upper limits for $ZZ$ and $W^+W^-$ channels are almost degenerate, while the upper limit for $hh$ channel is a bit higher. In our analysis, to constrain the SD cross section we use the IceCube limit for the $W^+W^-$ channel that is shown in Fig. 2 as a pink solid curve.\(^2\)

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{The SD cross section between the dark matter particle and nuclei as a function of the DM mass in the case of $\tan\beta=10$. Pink solid curve: IceCube-$W^+W^-$ upper limit; black dashed curve: 200 times smaller than the current upper limit.}
\end{figure}

In Fig. 2, we observe that the IceCube bound has excluded a small portion of the parameter space with the well-tempered neutralino DM having a mass upto about 400 GeV. Therefore, the XENON1T/PandaX-II constraint is much more severe than the IceCube one. Comparing these two figures, we find that a future DM indirect detection experiment need to have a sensitivity (black dashed curve in Fig. 2) at least 200 times smaller than the current IceCube-$W^+W^-$ limit in order to probe the blue parameter region that is not excluded by the XENON1T/PandaX-II limit.

In both Figs. 1 and 2, we see a common property of the two blue strips that the more Higgsino-dominant the DM is, the smaller the SD and SI scattering cross sections are. In fact, the blue strips extend down almost vertically toward zero pb in the Higgsino-like region. It is due to the characteristic of the lightest neutralino components

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{h}_u + N_{14}\tilde{h}_d,$$

where the bino and wino components, $N_{11}$ and $N_{12}$, tend to zero, and the Higgsino components, $N_{13}$ and $N_{14}$, have equal magnitudes but opposite signs in the limit of extremely heavy gauginos. As a results, there are cancellations among terms of the SD and SI scattering cross sections, for examples,

\(^2\) It is worth to note that the $W^+W^-$ channel only works if the DM mass is larger than or equals the $W$ boson mass. For $m_{\text{DM}} < m_W$, the $W^+W^-$ channel is forbidden, and the DM can only annihilate into light SM fermions, such as $bb$, $\tau^+\tau^-$ or $\nu\bar{\nu}$. This case is more severely constrained by Super-Kamiokande experiment [33]. However, in the case of universal gaugino masses, the region with $m_{\text{DM}} < m_W$ is excluded by the LHC due to the too light gluino [28].
a cancellation between $\tilde{h}_u\tilde{h}_u Z$ and $\tilde{h}_d\tilde{h}_d Z$ couplings of the SD interactions, and a cancellation between $W\tilde{h}_uh$ and $W\tilde{h}_dh$ couplings of the SI interactions. Therefore, no matter how sensitive the direct and indirect DM detection experiments are, there is always a region in the parameter space with the Higgsino-like DM that these experiments cannot probe. In spite of that, since the DM mass in this region is almost fixed to about 1.1 TeV, the direct productions of the Higgsino-like neutralino/chargino will be feasible channels to test this region at colliders such as the LHC or the future HL-LHC (High Luminosity LHC).

In Fig. 3, we summarize the status of the split SUSY model with universal gaugino masses on the plane of the free parameters ($\mu, M_1$). Points belonging to the colored regions predict the right DM relic density as in Eq. (8). The thin strip correspond to the well-tempered neutralino whose relic density is achieved by its pair annihilation via the Higgs and Z boson exchange in the s-channel, and the coannihilation with the chargino-NLSP. Points in the thick strip predict a Higgsino-like neutralino DM with a mass of around 1.1 TeV. Its relic density is determined by the coannihilations among the almost degenerate neutralinos and chargino. The red region are excluded by the combined XENON1T/PandaX-II limit on the SI cross section. It includes the well-tempered neutralino region corresponding to $\mu \lesssim 1$ TeV and a part of the Higgsino-like region with the bino mass $M_1 \lesssim 1.4$ TeV. The green region contains all the points that are can be discovered by the XENON1T experiment in the near future. We see that, with the projected sensitivity, it will be able to test the bino mass upto about 2.3 TeV. It is also the exclusion limit for $\tilde{\chi}_2^0$ mass in this scenario in the case of null result. The rest of the Higgsino-like DM region presented in blue predicts the SI cross section beyond the reach of XENON1T. Going upward along the blue region, the DM neutralino becomes more and more Higgsino dominant, while its mass is almost the same to ensure the right relic abundance.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Parameter space for the case of $\tan \beta = 10$. The colored regions satisfy the DM relic density. Red: excluded by the combined XENON1T/PandaX-II limit, green: testable at the XENON1T experiment with the projected sensitivity, blue: beyond the sensitivity of XENON1T.}
\end{figure}

In the case of non-universal gaugino masses, the generalized GUT relation (4) has been translated into a relation between gaugino masses at low energies by using their renormalization
group equations. We have performed a scan over the parameter space of \((x, \mu, M_1)\):

\begin{align}
-10 < x < 10, \\
30 \text{ GeV} < \mu < 2000 \text{ GeV}, \\
30 \text{ GeV} < M_1 < 7000 \text{ GeV},
\end{align}

with \(\tan \beta = 10\). The results are presented in Figs. 4 and 5 where all the points satisfy the measured DM relic density, as well as the current XENON1T/PandaX-II and IceCube-\(W^+W^-\) upper bounds. We find that the combined XENON1T/PandaX-II constraint is not only more severe than the IceCube one but indeed all the points complying the former also satisfy the later.

In Fig. 4, most of the points have a DM mass around 1.1 TeV. They predict the Higgsino-like neutralino to be a DM candidate. The separated point with \(m_{DM} \approx 60 \text{ GeV}\) stays in the Higgs resonance region where the DM annihilation occurs through the SM-like Higgs boson exchanged in the s-channel. Other separated points can be classified into two types, those close to \(x = -1\) and those close to \(x = \frac{2}{3}\). For the former type, the correct DM relic density is ensured by the gluino pair annihilation into the SM particles that becomes very efficient when the gluino is light. For the latter type, the DM relic density is enhanced by the light wino. In this figure, there are three white gaps in the Higgsino-like region with the DM mass around 1.1 TeV. The reasons are as follows. For \(x \approx -1\), the gluino is the LSP that is not acceptable. For \(x \approx \frac{2}{3}\), the DM relic abundance is too small to fit the observation result since the DM is the wino-like neutralino. For the big gap with \(x\) being between 1.2 and 3.3, the gluino is too heavy such that its justifications to the softfermion masses via renormalization group equations are important. As a result, the top squark becomes light and eventually tachyonic.\(^3\) Most of the points in Fig. 4 that correspond to the positive Higgsino \(\tilde{h}_u\) component, \(\mathcal{N}_{13} > 0\), are represented by blue dots. There is only a small fraction of the Higgsino-like region correspond to \(\mathcal{N}_{13} < 0\) which is depicted in green.\(^4\) However, these green dots are distinct from all other Higgsino-like blue dots in terms of SD and SI cross sections. Fig. 5 shows the scatter plot on the plane of \((\sigma_{SI}^{\chi p}, \sigma_{SD}^{\chi p})\) where the color codes are the same as in the previous figure. Points belong to the Higgsino-like region are aligned in two straight strips. The green strip corresponds to the Higgsino \(\tilde{h}_u\) component \(\mathcal{N}_{13} < 0\), while the blue one corresponds to \(\mathcal{N}_{13} > 0\). The separated points in Fig. 4 scatter around these two strips of Fig. 5, and have \(\mathcal{N}_{13} > 0\).

A finer scan has been performed focusing on the range \(0 < x < 1\) where we find points testable at both experiments, the XENON1T with the projected sensitivity and indirect DM searches with the sensitivity two orders of magnitude smaller than the present IceCube-\(W^+W^-\) limit. The results are depicted in Figs. 6, 7 and 8 where the future testable points are represented by pink dots. These points are classified into two distinct regions:

(i) The thin strip in Fig. 6 with the DM mass below 1 TeV and \(x \approx 0.86\). As \(x\) is mostly fixed in this region, there is a linear relation between \(M_1\) and \(M_2\) (Fig. 7). The neutralino LSP is a good mixture of bino and wino. The right DM relic density is achieved not by its direct annihilation, but mainly by the annihilation and coannihilation among the second lightest neutralino and the chargino into SM particles.

(ii) The thin strip in Fig. 6 with the DM mass below 1 TeV and \(x \approx 0.38\). This region has the same properties as the region (i), but the sign of \(M_2\) is opposite (Figs. 8 and 7).

Fig. 9 shows the result of this parameter scan in the plane of the SI and SD cross sections. The Higgsino-like points line up in two separated straight narrow strips, while other points

\(^3\) We note that there are points where stops are too light for the SM-like Higgs boson mass to satisfy the constraint (7). It is due to the fact that the inputs for softfermion masses and trilinear couplings are fixed in the code. In principal, this can be alleviated by increasing the softfermion soft masses and the trilinear couplings.

\(^4\) Note that for all the points of the scan, the Higgsino \(\tilde{h}_d\) component is always negative, \(\mathcal{N}_{14} < 0\).
Figure 4. Scatter plot on the plane $(x, m_{DM})$. All the points here satisfy the DM relic density constraint, the current XENON1T/PandaX-II and IceCube-$W^+W^-$ upper bounds. The green and blue dots represent points with negative and positive $N_{13}$ respectively.

Figure 5. Scatter plot on the plane $(\sigma_{\chi^0 p}^{SI}, \sigma_{\chi^0 p}^{SD})$. The colored codes are the same as in Fig. 4.

scatter in a larger region around the upper strip. Going along these strips from the top right to the bottom left, the neutralino DM is more Higgsino-dominated since the gauginos are more heavy. On the other hand, the points predicting well-mixed bino-wino DM scatter in a wider region of the plane. As expected, the points testable at future direct and indirect DM detection (pink dots) locate at the top right corner with relatively large $\sigma_{\chi^0 p}^{SI}$ and $\sigma_{\chi^0 p}^{SD}$.

In Table 1, we present three benchmark mass spectra of the ino sector corresponding to the above two regions of pink dots for demonstration. The neutralino DM has the right relic abundance, and the SI and SD cross sections are within the reach of future DM detection.
Figure 6. Scatter plot on the plane \((x, m_{DM})\). All the points here satisfy the DM relic density constraint, current XENON1T/PandaX-II and IceCube-\(W^+W^-\) limits. Pink dots: points can be tested at the XENON1T with the projected sensitivity and a future indirect DM search with the sensitivity two orders of magnitude smaller than the current IceCube-\(W^+W^-\) limit; blue dots: points that can not be tested in near future experiments with sensitivities like the above two.

Figure 7. Scatter plot on the plane spin-independent and spin-dependent cross sections \((M_1, M_2)\). The color codes are the same as in Fig. 6.

experiments. Although DM searches are the only feasible way to test the Higgsino-like point, it is interesting that the last two benchmarks with the well-mixed bino-wino DM have the chargino mass of \(\mathcal{O}(500)\) GeV. Therefore, they can be tested at the LHC 14 TeV in the near future.
Figure 8. Scatter plot on the plane spin-independent and spin-dependent cross sections ($M_2$, $\mu$). The color codes are the same as in Fig. 6.

Figure 9. Scatter plot on the plane spin-independent and spin-dependent cross sections ($\sigma_{SI}^{X-p}, \sigma_{SD}^{X-p}$). The color codes are the same as in Fig. 6.

4. Conclusions
The recent results from the XENON1T/PandaX-II and IceCube experiments have set severe limits on the SI and SD cross sections of the DM scattering on nuclei. On the other hand, the current constraints from the LHC suggest that sfermions should be heavy. This situation fits the split SUSY scenario where the sfermion sector decouples from the low energy theory, and only the ino sector is relevant in terms of phenomenology. Within this context, we have investigated the prospect of DM searches in split SUSY models assuming a relation between gaugino masses at the GUT scale. We have found that, in the case of universal gaugino
Table 1. Benchmark mass spectra for the ino sector. The units of masses and cross sections are GeV and pb respectively.

| Region | (i) | (ii) |
|--------|-----|------|
| $x$    | 0.864 | 0.380 |
| $\mu$  | 831.550 | 877.000 |
| $M_1$  | 527.192 | 450.544 |
| $\tilde{\chi}_1^0$ | 520 | 444 |
| $\tilde{\chi}_2^0$ | 549 | 474 |
| $\tilde{\chi}_3^0$ | 859 | 902 |
| $\tilde{\chi}_4^0$ | 861 | 911 |
| $\tilde{\chi}_1^\pm$ | 549 | 473 |
| $\tilde{\chi}_2^\pm$ | 863 | 910 |
| $\tilde{g}$ | 8667 | 4302 |
| $\Omega h^2$ | 0.1188 | 0.1191 |
| $\sigma_{\chi^0-p}^{SI}$ | $3.178 \times 10^{-10}$ | $3.142 \times 10^{-10}$ |
| $\sigma_{\chi^\pm-p}^{SD}$ | $7.039 \times 10^{-7}$ | $8.450 \times 10^{-7}$ |

masses, the combined XENON1T/PandaX-II constraint is more severe than the IceCube one. It rules out the parameter region with a well-tempered neutralino LSP that is a good mixture of bino and Higgsino. A future indirect DM detection needs a sensitivity about 200 times smaller than the current IceCube bound in order to probe the parameter region that is not excluded by the XENON1T/PandaX-II limit. The Higgsino-like DM region is still allowed. We have shown the XENON1T experiment with the projected sensitivity will be able to probe a significant part of this region in the near future. For the Higgsino-like DM region far beyond the reach of future DM detection experiments, we have pointed out that direct productions of the neutralino/chargino NLSP are feasible channels at the LHC or the HL-LHC to test the model. In the case of non-universal gaugino masses, the parameter space satisfying all the considered DM constraints has been identified. In particular, we have pinpointed the regions that can be tested at the XENON1T experiment with the projected sensitivity and an indirect DM search with the sensitivity of two orders of magnitude smaller than the current IceCube limit. The DM properties have been examined for each region together with representative benchmarks. According to that, these regions predict a mixed bino-wino DM. Interestingly, in the mixed bino-wino regions, the parameter points predicting rather light chargino can be tested at the LHC 14 TeV.

Acknowledgments
The works of N.O. and H.M.T are respectively supported in part by the United States Department of Energy under grant number de-sc0012447, and Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 103.01-2017.301.

References
[1] Aad G et al [ATLAS and CMS Collaborations] 2015 Phys. Rev. Lett. 114 191803 [arXiv:1503.07589 [hep-ex]].
[2] See for examples, Tran M H and Nguyen T H 2019 Phys. Rev. D 99 035040 [arXiv:1812.11757 [hep-ph]]; Fukuyama T, Okada N and Tran M H 2017 Phys. Lett. B 767 295 [arXiv:1611.08341 [hep-ph]]; Okada N and Tran M H 2016 Phys. Rev. D 94 075016 [arXiv:1606.05329 [hep-ph]]; Okada N and Tran M H 2013 Phys. Rev. D 87 035024 [arXiv:1212.1866 [hep-ph]]; and references therein.
[3] Arkani-Hamed N and Dimopoulos S 2005 JHEP 0506 073 [hep-th/0405159]; Giudice G F and Romanino A 2004 Nucl. Phys. B 699 65 Erratum: [Nucl. Phys. B 706, 487 (2005)] [hep-ph/0406088].
[4] Accardo L et al [AMS Collaboration] 2014 Phys. Rev. Lett. 113 121101
