Impact of leptonic unitary and Xenon-1T experiment on sneutrino DM physics in the NMSSM with Inverse-Seesaw mechanism

Junjie Cao\textsuperscript{a,b}, Yangle He\textsuperscript{a}, Lei Meng\textsuperscript{a}, Yusi Pan\textsuperscript{a}, Yuanfang Yue\textsuperscript{a}, Pengxuan Zhu\textsuperscript{a}

\textsuperscript{a} Department of Physics, Henan Normal University, Xinxiang 453007, China
\textsuperscript{b} Center for High Energy Physics, Peking University, Beijing 100871, China

E-mail: junjiec@itp.ac.cn, heyangle@htu.edu.cn, 1195630009@qq.com, panyusi0406@foxmail.com, yuanfang405@foxmail.com, zhupx99@icloud.com

Abstract: In the Next-to-Minimal Supersymmetric Standard Model with inverse seesaw mechanism for neutrino mass, the lightest sneutrino may act as a feasible DM candidate over broad parameter space. In this case, the upper bound on the unitary violation in neutrino sector and the recent XENON-1T experiment tightly limit the neutrino Yukawa couplings $Y_\nu$ and $\lambda_\nu$, and thus alter significantly the DM physics. In present work we study such an effect by encoding the constraints in a likelihood function and then performing elaborated scans over the vast parameter space of the theory by Nested Sampling algorithm. Our results for the posterior possibility distribution function indicate that the DM prefers to coannihilate with the Higgsinos to get its right relic density. The induced tuning is usually around 40, but can be reduced significantly to $1 \sim 10$ if other channels also play a role in the annihilation. On the other side, most samples in our results predict the DM-nucleon scattering rate under the neutrino floor with its related tuning parameter less than 10. The Higgsinos with mass around 100GeV are preferred, so there is no tension between the naturalness for Z boson mass and DM direct detection experiments.
1 Introduction

As the most popular ultraviolet-complete Beyond Standard Model, the Minimal Supersymmetric Standard Model (MSSM) with R-parity conservation predicts two kinds of electric neutral, possibly stable and weakly interactive massive particles, namely sneutrino and neutralino, which may act as dark matter (DM) candidates [1, 2]. In the 1990s, it was proven that the left-handed sneutrino as the lightest supersymmetric particle (LSP) predicts a much smaller relic abundance than its measured value as well as an unacceptably large DM-nucleon scattering rate due to its interaction with Z boson [3, 4]. This fact made the lightest neutralino (usually with bino field as its dominant component) the only reasonable DM candidate so that it has been studied intensively since then. However, with the rapid progress in DM direct detection (DD) experiments in recent years, the candidate becomes more and more tightly limited by the experiments [5–7] assuming that it is fully responsible for the measured relic density and that the Higgsino mass $\mu$ is less than about 300GeV, which is able to predict Z boson mass in a natural way [8]. These conclusions apply to the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [9], where sneutrino is pure left-handed and the lightest neutralino as a DM candidate may be either bino or singlino dominated [10]. In this context, we revive the idea of sneutrino DM in extended SUSY [11]. Explicitly speaking, motivated by the phenomenology
of neutrino oscillation, we augment the NMSSM with inverse seesaw mechanism by introducing two types of gauge singlet chiral superfields $\hat{\nu}_R$ and $\hat{X}$ for each generation matter, which have lepton number $-1$ and $1$ respectively and are called heavy neutrinos in literatures, and discuss whether the $\hat{\nu}_R$ (the scalar component of $\hat{\nu}_R$) and/or $\hat{x}$ (the scalar component of $\hat{X}$) dominated sneutrino can act as a feasible DM candidate. We show by analytic formulas that the resulting theory (abbreviated as ISS-NMSSM hereafter) is one of the most economic framework to generate neutrino mass and meanwhile to reconcile the DM DD experiments in a natural way [11].

It is well known that the introduction of the singlet field $\hat{S}$ in the NMSSM can solve the $\mu$ problem of the MSSM [10], enhance the theoretical prediction of the SM-like Higgs boson mass [12–14] as well as enrich the phenomenology of the NMSSM (see for example [16–21]). In the ISS-NMSSM, the $\hat{S}$ also plays extraordinary roles in generating heavy neutrino mass by the Yukawa interaction $\lambda_{\nu} \hat{S} \hat{\nu}_R \hat{X}$ and making the sneutrino DM compatible with various measurements [11]. The latter role can be understood from at least two aspects. One is that the newly introduced heavy neutrino fields are singlets under the gauge group of the SM model, so they can couple directly with $\hat{S}$ by the Yukawa coupling [11]. In this case, the scalar component fields of $\hat{\nu}_R$, $\hat{X}$ and $\hat{S}$ compose a secluded DM sector, which can account for the measured DM relic abundance by the annihilation $\tilde{\nu}_1 \tilde{\nu}_1^{\ast} \rightarrow A_1 A_1$ with $\tilde{\nu}_1$ and $A_1$ denoting the lightest sneutrino and the singlet-dominated CP-odd Higgs boson respectively. Since this sector communicates with the SM sector mainly by the small singlet-doublet Higgs mixing, the scattering of the $\tilde{\nu}_1$ DM with nucleon is naturally suppressed, which coincides with current DM direct search results. The other is that the singlet field can mediate the transition between $\tilde{\nu}_1$ pair and the Higgsino pair so that these particles were in thermal equilibrium in early Universe before their freeze-out. If their mass splitting is less than about 10%, the number density of the Higgsinos can track that of $\tilde{\nu}_1$ during freeze-out [22] (in literature such a phenomenon was called coannihilation [23]). Since in this case the couplings of $\tilde{\nu}_1$ with SM particles may be very weak, the scattering is also naturally suppressed. We emphasize that in either case the suppression favors small $\mu$ which appears in the $\tilde{\nu}_1 \tilde{\nu}_1 h_1$ interaction, and hence there is no tension any more between the naturalness for Z boson mass and DM DD experiments [11].

In the ISS-NMSSM, the DM annihilation rate and the DM-nucleon scattering rate depend not only on the coupling strength of $\tilde{\nu}_1$ with SM particles, which relies on the Yukawa coupling coefficients $\lambda_{\nu}$ and $Y_{\nu}$ (that arises from the $\tilde{\nu}_L \cdot \hat{H}_u \hat{\nu}_R$ interaction) and their corresponding soft breaking trilinear parameters $A_{\lambda_{\nu}}$ and $A_{Y_{\nu}}$, but also on Higgs mass spectrum and the mixings among the Higgs fields, which are ultimately determined by the parameters in Higgs sector [11]. As a result, the DM physics is quite complicated, and a comprehensive study of the model is necessary to figure out its key features. This motivates us to perform an elaborated scan over the vast parameter space of the theory by Nested Sampling algorithm [15]. In carrying
out such a study, we construct a likelihood function by LHC Higgs data, B-physics measurements and DM measurements like what we did in [24] for the Type-I seesaw extended NMSSM. Especially, we note that a large $\lambda_\nu$ and/or $Y_\nu$ can enhance significantly the DM-nucleon scattering rate, so they should be limited by the recent XENON-1T experiment [25]. We also note that the upper bound on the unitary violation in neutrino sector sets certain correlation between the couplings $\lambda_\nu$ and $Y_\nu$ [27], which in return can limit the parameter space of the ISS-NMSSM. Since these constraints were not considered before, we include them in the likelihood function, and find that they make the physical picture of the theory quite different from that in [11]. For example, our results for the posterior possibility distribution function (PDF) indicate that $Y_\nu \lesssim 0.08$ in $2\sigma$ credible region (CR)$^1$, which is significantly different from the results in Fig.5 of [11]. They also predict that about 95% samples predict the coannihilation of $\tilde{\nu}_1$ with the Higgsinos to get its right relic density, and more than 68% samples predict a suppressed DM-nucleon rate below neutrino floor. Obviously, these conclusions are interesting given the strong constraints of the DM DD experiments on the neutralino DM in the MSSM and the NMSSM.

This work is organized as follows. In section 2, we briefly introduce the theory of the ISS-NMSSM. In section 3, we describe the scan strategy adopted in this work. In section 4, we present numerical results and relevant discussions. Finally, we draw our conclusions in section 5.

\section{NMSSM with inverse seesaw}

Since the ISS-NMSSM has been introduced in detail in [11], we only recapitulate its key features in this section.

\subsection{Model Lagrangian}

The renormalizable superpotential and the soft breaking terms of the ISS-NMSSM take following form [11]

\begin{align*}
W &= \left[ W_{\text{MSSM}} + \lambda \tilde{s} \hat{H}_u \cdot \hat{H}_d + \frac{1}{3} \kappa \tilde{s} \tilde{s} \tilde{s} \right] + \left[ \frac{1}{2} \mu_{\chi} \tilde{X} \tilde{X} + \lambda_\nu \tilde{s} \tilde{\nu}_R \tilde{X} + Y_\nu \tilde{l} \cdot \tilde{H}_u \tilde{\nu}_R \right], \\
L^{\text{soft}} &= \left[ \left. L_{\text{MSSM}}^{\text{soft}} - m^2_{\tilde{S}} |S|^2 - \lambda A_\nu S \tilde{H}_u \cdot \tilde{H}_d - \frac{\kappa}{3} A_\nu S \tilde{s} \tilde{s} \tilde{s} \right] \\
&\quad - \left[ m^2_{\tilde{\nu}_R} \tilde{\nu}_R \tilde{\nu}_R + m^2_\chi \tilde{\chi} \tilde{\chi} + \frac{1}{2} B_{\mu_{\chi}} \tilde{\chi} \tilde{\chi} + (\lambda_\nu A_{\nu} S \tilde{\nu}_R \tilde{\nu}_R + Y_\nu A_{\nu} \tilde{l} \tilde{H}_u + \text{h.c.}) \right],
\end{align*}

where $W_{\text{MSSM}}$ and $L_{\text{MSSM}}^{\text{soft}}$ represent those for the MSSM without the $\mu$-term, terms in the first bracket on the right side of each equation make up the Lagrangian of the

---

$^1$In Bayesian statistics, the distribution of the samples obtained in the scan with nested sampling algorithm is described by the quantities such as marginal posterior PDF and credible regions, which are defined by the integration of the posterior PDF over an user-defined volume. A brief introduction of the concepts is presented in [26].
NMSSM and those in the second bracket are needed to implement supersymmetric inverse seesaw mechanism. Note that all the coefficients in the second brackets are $3 \times 3$ matrices in flavor space.

Same as the NMSSM, the Higgs sector of the ISS-NMSSM consists of three CP-even Higgs bosons $h_i$ and two CP-odd Higgs bosons $A_j$, which are labelled by the convention $m_{h_1} < m_{h_2} < m_{h_3}$ and $m_{A_1} < m_{A_2}$ in this work.

### 2.2 Unitary Constraints

In the interaction basis $(\nu_L, \nu_R^*, x)$, the neutrino mass matrix is [11]

$$ M_{\text{ISS}} = \begin{pmatrix} 0 & M_D^T & 0 \\ M_D & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}, \quad (2.1) $$

where the $3 \times 3$ Dirac mass matrices are given by $M_D = \frac{v_u}{\sqrt{2}} Y_{\nu}$ and $M_R = \frac{v_s}{\sqrt{2}} \lambda_{\nu}$ with $v_u$ and $v_s$ being the vacuum expectation values of the field $H_u$ and $S$, respectively. This matrix is diagonalized by a $9 \times 9$ unitary matrix $U_{\nu}$

$$ U_{\nu}^* M_{\text{ISS}} U_{\nu}^\dagger = \text{diag}(m_i, m_{H_j}), $$

to get three light neutrinos and six heavy neutrinos. Without loss of generality, the rotation matrix $U_{\nu}^\dagger$ can be decomposed into the blocks

$$ (U_{\nu}^\dagger)_{9 \times 9} = \begin{pmatrix} U_{3\times3} & X_{3\times6} \\ Y_{6\times3} & Z_{6\times6} \end{pmatrix}, \quad (2.2) $$

with $U_{3\times3}$ being the submatrix that encodes in the neutrino oscillation information and should be consistent with neutrino experimental results. On the other side, one can also extract the effective mass matrix of the light active neutrinos from Eq.(2.1), which is given by

$$ M_{\text{light}} \simeq M_D^T M_R^{-1} \mu_X \mu_X^{-1} M_D \equiv F \mu_X F^T \quad (2.3) $$

with $F \equiv M_D^T M_R^{-1}$. This matrix is diagonalized by the well-known unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$ U_{\text{PMNS}}^T M_{\text{light}} U_{\text{PMNS}} = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}). \quad (2.4) $$

Generally speaking, due to the mixings among the states $(\nu_L, \nu_R^*, x)$, the matrix $U_{3\times3}$ in Eq.(2.2) does not coincide with the $U_{\text{PMNS}}$, instead they are related by

$$ U_{3\times3} \simeq \left(1 - \frac{1}{2} FF^\dagger \right) U_{\text{PMNS}} \equiv (1 - \eta) U_{\text{PMNS}}. $$
In this sense, $\eta \equiv \frac{1}{2} F F^\dagger$ is a measure of the non-unitarity of the matrix $U_{3\times3}$, and a global fit to low energy experimental data requires that [28]

$$\sqrt{2|\eta|_{ee}} < 0.050, \sqrt{2|\eta|_{\mu\mu}} < 0.021, \sqrt{2|\eta|_{\tau\tau}} < 0.075,$$

$$\sqrt{2|\eta|_{e\mu}} < 0.026, \sqrt{2|\eta|_{e\tau}} < 0.052, \sqrt{2|\eta|_{\mu\tau}} < 0.035.$$  

These inequalities indicate $U_{PMNS} \simeq U_{3\times3}$ to a good approximation.

From Eq.(2.3), one can express the parameter $\mu_X$ in terms of the measurements of $m_{\nu_i}$ and $U_{PMNS}$ [27, 29]

$$\mu_X = M_R^T m_D^{-1} U_{PMNS} m_{\nu_i} \text{diag} U_{PMNS}^\dagger m_D^{-1} M_R,$$

with $m_{\nu_i} \text{diag} = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$. This expression indicates that one may set $Y_{\nu}$ and $\lambda_{\nu}$ to be flavor diagonal, and attribute the neutrino experimental data solely to the non-diagonality of $\mu_X$. In this case, the unitary constraint becomes

$$\left[ \lambda_{\nu} \right]_{11} > 14.1, \quad \left[ \lambda_{\nu} \right]_{22} > 33.7, \quad \left[ \lambda_{\nu} \right]_{33} > 9.4.$$  \hspace{1cm} (2.5)

These inequalities indicate that for given $\lambda$, $\mu$ and $v_u$, the ratio $[\lambda_{\nu}]_{33}/[Y_{\nu}]_{33}$ is least constrained.

### 2.3 Sneutrino DM

In the work [11], we have discussed in detail the squared masses of CP-even and CP-odd sneutrinos, which depend on $Y_{\nu}$, $\lambda_{\nu}$, $A_{\nu}$, $A_{\lambda_{\nu}}$, $\mu_X$, $B_{\mu_X}$ and the soft breaking masses $m_{\tilde{l}_1}$, $m_{\tilde{l}_2}$ and $m_{\tilde{x}}$, and are $9 \times 9$ matrices in three generation ($\tilde{l}_L, \tilde{l}_R, \tilde{x}$) basis. About the masses, three points should be noted. First, only $\mu_X$ among the input parameters must be flavor non-diagonal to predict neutrino oscillation, but since $\mu_X$ is usually less than 10KeV [29], one can safely neglect it in calculating the masses. In this case, the mass matrices are flavor diagonal if there is no flavor mixings for the other parameters, so one can work in one generation ($\tilde{l}_L, \tilde{l}_R, \tilde{x}$) basis to simplify the study of sneutrino DM physics. In this work, we take the third generation sneutrinos as DM sector since the unitary bound on this sector is the weakest. Second, the mass matrix for CP-even sneutrinos is related with that for CP-odd sneutrinos by the substitution $\mu_X \rightarrow -\mu_X$ and $B_{\mu_X} \rightarrow -B_{\mu_X}$. Since the quantities $\mu_X$ and $B_{\mu_X}$ represent the degree of lepton number violation, they should be suppressed greatly. In the limit $\mu_X = 0$ and $B_{\mu_X} = 0$, any CP-even sneutrino is accompanied with a mass-degenerate CP-odd sneutrino. The sneutrino as an mass eigenstate then corresponds to a complex field, and it has its anti-particle [30]. If alternatively $B_{\mu_X}$ takes a small value, such as 100GeV$^2$, the mass splitting between the CP-even and CP-odd states is usually less than 1GeV for $m_\tilde{\nu} \sim 100$GeV, and one may call such a sneutrino pseudo-complex particle [31, 32]. We checked that, as far as the cases
| Parameter       | Prior PDF | Range      | Parameter       | Prior PDF | Range      |
|-----------------|-----------|------------|-----------------|-----------|------------|
| $\lambda$       | Flat      | (0,0.7)    | $\kappa$        | Flat      | (-0.7,0.7) |
| $Y_\nu, \lambda_\nu$ | Log       | (0.001,0.7) | $\tan \beta$   | Log       | (1,60)     |
| $\mu$ (GeV)     | Log       | (100,300)  | $m_{\tilde{\nu}}, m_\tilde{x}$ (GeV) | Log       | (0,300)    |
| $A_t$ (TeV)     | Log       | (-5,5)     | $A_\kappa, A_\nu, A_{\lambda_\nu}$ (TeV) | Log       | (-1,1)     |

*Table 1.* Parameter space considered in this work, and the prior PDFs of the input parameters.

discussed in this work are concerned, the DM observables such as its relic density and scattering rate with nucleon are very insensitive to the value of $B_{\mu X}$ [11], but in practice setting $B_{\mu X} = 0$ can reduce drastically our computing time since much more Feynman diagrams have to be calculated to get the observables when $B_{\mu X} \neq 0$. In the following, we set $\mu_X = 0$ (since we are not interested in neutrino physics in this work) and $B_{\mu X} = 0$ to speed up our calculation. Third, since the mixings of the fields ($\tilde{\nu}_R, \tilde{x}$) with $\tilde{\nu}_L$ are proportional to $Y_\nu, Y_\nu \sim 0$ required by the unitary constraint implies that the $\tilde{\nu}_L$ component in a $\tilde{\nu}_R$ and/or $\tilde{x}$ dominated sneutrino DM is suppressed so that the coupling of $\tilde{\nu}_1$ with Z boson is negligibly small. In this case, $\tilde{\nu}_1$ mainly couples with the singlet dominated Higgs bosons.

It used to be thought that the sneutrino DM in extended SUSY mainly annihilated by following channels to get right relic density [33, 34]

- $\tilde{\nu}_1 \tilde{\nu}_1 \rightarrow ss$ with $s$ denoting a singlet dominated Higgs boson, which may proceed by corresponding four-point scalar coupling, $s$-channel mediation of a CP-even Higgs boson and $t/u$- exchange of a sneutrino state.

- $\tilde{\nu}_1 \tilde{\nu}_1 \rightarrow \eta\eta^*$ with $\eta$ denoting any of SM particles or heavy neutrinos. This annihilation is mediated by a CP-even Higgs bosons, and since the involved interactions are usually weak, one of the bosons must be around resonance to make the contribution significant.

In the following, however, we will show by Bayesian analysis that $\tilde{\nu}_1$ highly prefers to coannihilate with Higgsinos to get it right relic density, although sometimes the annihilation channels listed above may also play a role. This is a new point of view.

### 2.4 Scattering of Sneutrino DM with Nucleon

In the ISS-NMSSM, the scattering of $\tilde{\nu}_1$ with nucleon $N$ ($N = p, n$) is mediated mainly by CP-even Higgs bosons. Consequently, the spin independent cross section of the scattering is given by [11]

$$
\sigma_{\tilde{\nu}_1-N}^{SI} = \frac{F_u^{(N)2}}{16\pi m^2_{\tilde{\nu}}} \times \left\{ \sum_i \left[ \frac{C_{\tilde{\nu}_i \tilde{\nu}_h}}{m^2_{\tilde{\nu}_i} m_{\tilde{\nu}_h}} \left( \frac{S_{12}}{\sin \beta} + \frac{S_{11}}{\cos \beta} \frac{F_d^N}{F_u} \right) \right]^2 \right\}.
$$
Table 2. Other fixed parameters in the scans where $m_\tilde{q}$ and $m_{\tilde{t}}$ are soft-breaking masses with $\tilde{q} = \tilde{Q}, \tilde{U}, \tilde{D}$ and $\tilde{t} = \tilde{L}, \tilde{E}$, $A_i$ with $i = u, d, c, s, t, \mu, \tau$ are trilinear soft-breaking coefficients for squarks, sleptons and Higgs respectively, and $1$ is unit matrix in flavor space. Besides, we assume the Yukawa couplings $Y_\nu$ and $\lambda_\nu$ and the soft-breaking masses $m_\tilde{g}$ and $m_\tilde{\chi}$ are flavor diagonal with their 11 and 22 elements presented in the table. We also set $\mu_X = 0$ and $B_{\mu_X} = 0$ in this work so that CP-even and CP-odd sneutrinos are degenerate in mass. All these parameters are unimportant in sneutrino DM physics.

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| $m_\tilde{q}$ | $2 \text{ TeV} \times 1$ | $A_{u,c,d,s}$ | $2 \text{ TeV}$ | $A_\lambda$ | $2 \text{ TeV}$ |
| $m_{\tilde{t}}$ | $0.4 \text{ TeV} \times 1$ | $A_{e,\mu,\tau}$ | $0.4 \text{ TeV}$ | $[Y_\nu]_{11,22}$ | $0.01$ |
| $[m_{\tilde{\chi}}]_{11,22}$ | $0.4 \text{ TeV}$ | $[m_{\tilde{\chi}}]_{11,22}$ | $0.4 \text{ TeV}$ | $[\lambda_\nu]_{11,22}$ | $0.3$ |
| $M_1$ | $0.4 \text{ TeV}$ | $M_2$ | $0.8 \text{ TeV}$ | $M_3$ | $2.4 \text{ TeV}$ |

where $\mu_{\text{red}} = m_N/(1 + m_N^2/m_{\tilde{N}}^2)$ represents the reduced mass of nucleon with $m_{\tilde{N}}$, $F_u^{(N)} = f_u^{(N)} + \frac{4}{3} f_G^{(N)}$ and $f_d^{(N)} = f_d^{(N)} + f_s^{(N)} + \frac{2}{3} f_G^{(N)}$ are nucleon form factors with $f_q^{(N)} = m_N^{-1} \langle N | m_q q | N \rangle$ and $f_G^{(N)} = 1 - \sum_q f_q^{(N)}$ for $q = u, d, s$ [2], $S_{ij}$ is the $(i,j)$ element of the matrix $S$ which is used to diagonalize the CP-even Higgs mass matrix in the basis $(H_d, H_u, s)$, and the coefficient for the $\tilde{\nu}_1^* \tilde{\nu}_1 h_i$ interaction is given by

$$C_{\tilde{\nu}_1^* \tilde{\nu}_1 h_i} = S_{i1} C_{\tilde{\nu}_1^* \tilde{\nu}_1 H_d} + S_{i2} C_{\tilde{\nu}_1^* \tilde{\nu}_1 H_u} + S_{i3} C_{\tilde{\nu}_1^* \tilde{\nu}_1 s},$$

with

$$C_{\tilde{\nu}_1^* \tilde{\nu}_1 H_d} \simeq \lambda_\nu v_u Z_{12} Z_{13},$$

$$C_{\tilde{\nu}_1^* \tilde{\nu}_1 H_u} \simeq -Y_\nu^2 v_u Z_{12} Z_{12},$$

$$C_{\tilde{\nu}_1^* \tilde{\nu}_1 s} \simeq -2 \kappa \lambda_\nu v_s Z_{12} Z_{13} - \sqrt{2} \lambda_\nu A_\lambda \nu Z_{12} Z_{13} - \lambda_\nu^2 v_s,$$

under the assumption $\tan \beta \gg 1$ and $Z_{11} \simeq 0$ ($Z$ denotes the rotation matrix to diagonalize the sneutrino mass matrix, namely $\tilde{\nu}_1 = Z_{11} \tilde{\nu}_L + Z_{12} \tilde{\nu}_R^* + Z_{13} \tilde{\chi}$).

These formulae indicate that a large Yukawa coupling $\lambda_\nu$ or $Y_\nu$ can enhance significantly the scattering rate, and thus they are limited by the recent XENON-1T results.

### 3 Survey the Property of Sneutrino DM

In order to study the property of the sneutrino DM in the ISS-NMSSM, we use the package SARAH-4.11.0 [35–37] to build relevant computer model files, the codes SPHeno-4.0.3 [38] and FlavorKit[39] to generate particle spectrums and calculate low energy flavor observables respectively, and the package MicrOMEGAs 4.3.4[40–42] to compute DM observables, such as its relic density and its scattering rate with nucleon, by assuming that the lightest sneutrino is the only DM candidate in the universe. We
also consider the data of the discovered Higgs boson with the code \texttt{HiggsSignal-2.0.0}\cite{43} and the bound from the direct search for extra Higgs bosons at LEP, Tevatron and LHC by the code \texttt{HiggsBounds-5.0.0}\cite{44}. In calculating the radiative correction to the mass spectrum of the Higgs bosons, we note that the \texttt{SPheno-4.0.3} only includes full one- and two-loop effects by a diagrammatic approach with vanishing external momenta\cite{38}. This leaves an uncertainty less than about 3 GeV for the mass of the discovered Higgs boson, and must be taken into account in performing the Higgs data fit by the \texttt{HiggsSignal-2.0.0}. All these calculations are necessary to get physical parameter points of the model.

3.1 Scan Strategy

Noting that the property of the sneutrino DM depends on the parameters in both sneutrino sector and Higgs sector, we perform sophisticated scans\footnote{In order to make our results as complete as possible, we adopt the MultiNest algorithm introduced in \cite{15} to search for physical parameter points which are favored by both theory and experiments. We improve the statistics of the calculation by performing four independent scans for the $h_1$ scenario introduced below, and setting the $nlive$ parameter in MultiNest to be 2000 in each of the scans. As a result, we totally computed about $1 \times 10^9$ physical points in our study. We remind that one frequently encounters in the scan the points where either the squared mass of any scalar particle is negative or the LSP is not a sneutrino. These samples must be abandoned.} over the parameter ranges listed in Table 1. The other unimportant parameters are fixed in Table 2, and all the parameters are defined at the scale $Q = 1\text{TeV}$. We focus on the parameter space due to following considerations:

- Since the parameter space is huge, we fix $A_\lambda$ in Higgs sector, which is closely related with $m_{H^\pm}$\cite{10}, at 2TeV to simplify the analysis. In fact, $m_{H^\pm} \gtrsim 800\text{GeV}$ is favored by the recent global fit of the MSSM\cite{45}, and the effect of the heavy doublet-dominated Higgs bosons on the DM physics is not important.

- We fix $m_{\tilde{Q}_3} = m_{\tilde{U}_3} = m_{\tilde{D}_3} = 2\text{TeV}$, set $A_t = A_b$ and vary $A_t$ within the range $|A_t| \leq 5\text{TeV}$ to take into account the important radiative correction from top/stop and bottom/sbottom loops to the Higgs mass spectrum. We remind that the color and charge symmetries of the theory remain unbroken for such a setting\cite{46, 47}.

- The ranges of the parameters $\lambda$, $\kappa$, $Y_\nu$, $\lambda_\nu$ and $\tan \beta$ are motivated by the perturbativity of the theory up to Planck scale\cite{10}.

- Naturalness in predicting Z boson mass prefers $\mu \sim \mathcal{O}(10^2\text{GeV})$\cite{10}, so we require $100\text{GeV} \leq \mu \leq 300\text{GeV}$ with the lower bound coming from the LEP search for chargino and neutralinos, and the upper bound imposed by hand.

- Roughly speaking, the lightest sneutrino as a DM candidate requires at least one of the soft breaking mass for third generation sneutrino, i.e. $m_{\tilde{\nu}}$ or $m_\tilde{z}$ in
Table 1, to be less than the Higgsino mass $\mu$. We assume for simplicity that all of them are upper bounded by 300GeV.

- Given that $|A_\kappa| \lesssim 300\text{GeV}$ is favored by Higgs spectrum [24], we require it to be less than 1TeV.

- Since $A_\nu$ and $A_{\lambda\nu}$ can enhance significantly the DM-nucleon scattering rate [11] and that the soft-breaking sneutrino masses are upper bounded by about 300GeV, the two parameters should not be excessively large from naturalness consideration.

- We require the other dimensional parameters sufficiently large to escape the constraints from the direct search for sparticles at the LHC.

In the scan, we take flat distribution for the parameters $\lambda$ and $\kappa$, and log distribution for the other input parameters in the scan. This is based on following considerations:

- One of the advantages of the Bayesian analysis is that one can encode his prior knowledge into the prior PDF of the input parameters so that the collapse from prior to posterior would be more efficient [48]. As far as the parameters $Y_\nu$, $\lambda_\nu$, $A_\nu$ and $A_{\lambda\nu}$ are concerned, we know in advance that they should be relatively small since they determine the couplings of the sneutrino DM and are thus limited by various experimental measurements [11]. The log distribution focuses on the case.

- It has been proven that the prior distribution for the parameters in Higgs sector is able to get reasonable posterior PDFs in a fast way [24].

- Similar setting for the prior distribution of input parameters has been widely adopted in studying the phenomenology of the NMSSM, see for example [49, 50].

3.2 Likelihood Function

We construct a likelihood function for the scan

$$L(\Theta) = L_{\text{Higgs}} \times L_{\text{Br}(B_s\rightarrow\mu^+\mu^-)} \times L_{\text{Br}(B_s\rightarrow X_s\gamma)} \times L_{\Omega_{\tilde{\nu}_1}} \times L_{\Omega_{\tilde{\ell}}} \times L_{\text{ID}} \times L_{\text{Unitary}},$$

and briefly introduce each contribution on the right side of the equation as follows:

- For the likelihood function in Higgs sector, we consider the case that the lightest CP-even higgs boson $h_1$ acts as the SM-like Higgs boson discovered at the LHC. Compared with the case that the second lightest CP-even Higgs as the
discovered Higgs boson, this case is much more strongly supported by LHC data, which corresponds to a Jeffreys’ scale of about $4^{3}$.

The expression of $\mathcal{L}_{\text{Higgs}}$ is given by

$$
\mathcal{L}_{\text{Higgs}} = e^{-\frac{1}{2}(\chi^2_h+A^2)},
$$

(3.2)

where $\chi^2_h$ represents the fit of the predicted properties of $h_1$ to relevant LHC data with its value calculated by the peak-centered method in HiggsSignal [43], and $A^2$ reflects whether the parameter point is allowed or excluded by the direct search for extra Higgs at colliders. In more detail, we take a total (theoretical and experimental) uncertainty of 3GeV for $m_{h_1}$ in calculating the $\chi^2_h$ with the HiggsSignal, and set by the output of the HiggsBounds either $A^2 = 0$ (experimentally allowed) or $A^2 = 200$ (an arbitrary large number, corresponding to the case of being experimentally excluded).

- For any observable with a measured central value, such as $\text{Br}(B_s \rightarrow \mu^+\mu^-)$, $\text{Br}(B_s \rightarrow X_s\gamma)$ and DM relic density $\Omega_{\tilde{\nu}}$ in this work, we take them Gaussian distributed, i.e.

$$
\mathcal{L} = e^{-\frac{[O_{\text{th}}-O_{\text{exp}}]^2}{2\sigma^2}},
$$

(3.3)

where $O_{\text{th}}$ and $O_{\text{exp}}$ represent the theoretical prediction and the experimental central value of the observable $O$ respectively, and $\sigma$ denotes the total (theoretical and experimental) uncertainty.

- For the likelihood function of DM DD experiments $\mathcal{L}_{DD}$, we adopt a Gaussian form with a mean value of zero[53]:

$$
\mathcal{L} = e^{-\frac{\delta^2 \sigma}{2\sigma}},
$$

(3.4)

where $\sigma$ represents DM-nucleon scattering rate, and $\delta_\sigma$ is expressed by the formula $\delta^2_\sigma = UL_\sigma^2/1.64^2 + (0.2\sigma)^2$ with $UL_\sigma$ corresponding to the recent XENON1T bound on $\sigma$ at 90% confidence level [25], and $0.2\sigma$ parameterizing theoretical uncertainties.

- For the likelihood function of the DM indirect search from dwarf galaxies $\mathcal{L}_{ID}$, we utilize the data provided by Fermi-LAT collaboration [54] and the likelihood function proposed in [55, 56]. We do not consider the constraint on line signal of $\gamma$-ray from Fermi-LAT data since it is rather weak [57].

$^3$Given two scenarios to be compared beside one another, Jeffreys’ scale presents a calibrated spectrum of significance for the relative strength between the Bayesian evidences of the scenarios [51]. For the application of Jeffreys’ scale in particle physics, see for example [52].
| Parameters | $1\sigma$ CR       | $2\sigma$ CR       | Parameters | $1\sigma$ CR       | $2\sigma$ CR       |
|------------|---------------------|---------------------|------------|---------------------|---------------------|
| $\lambda$  | (0.10, 0.30)        | (0.05, 0.40)        | $m_{\tilde{\nu}_1}$ (GeV) | (100, 220)        | (10, 240)          |
| $\kappa$   | (-0.50, 0.40)       | (-0.65, 0.65)       | $m_{\tilde{\tau}}$ (GeV) | (100, 230)        | (10, 280)          |
| $\tan\beta$| (9, 32)             | (6, 50)             | $A_t$ (GeV) | (-3500, 2600)      | (-4200, 3200)      |
| $Y_\nu$    | (0.003, 0.03)       | (0.002, 0.09)       | $A_\nu$ (GeV) | (-65, 120)        | (-290, 350)        |
| $\lambda_\nu$ | (0.025, 0.30)    | (0.006, 0.49)       | $A_{\lambda_\nu}$ (GeV) | (-160, 80)        | (-750, 550)        |
| $\mu$ (GeV) | (115, 200)         | (105, 250)          | $A_{\lambda_\nu}$ (GeV) | (-110, 100)       | (-660, 500)        |

Table 3. One dimensional $1\sigma$ and $2\sigma$ credible regions for the input parameters obtained in the scan. These ranges reflect the preference of our results.

Figure 1. Marginal posterior PDF of the ISS-NMSSM on $\mu - m_{\tilde{\nu}_1}$ plane (left panel) and the required tuning to get right DM relic density (right panel). The right panel is based on 6000 unweighted samples, which is only a small portion of the data collected in this work. The tuning parameter $\Delta_\Omega$ is defined in Eq.(4.1).

- For the likelihood function of the unitary constraint in Eq.(2.5), we take following form

$$L_{Unitary} = \begin{cases} 
exp[-\frac{1}{2} \left( \frac{r - 9.6}{0.2r} \right)^2] & \text{if } r \leq 9.6 \\
1 & \text{if } r > 9.6 
\end{cases}$$

with $r \equiv [\lambda_\nu]_{33}\mu/([Y_\nu]_{33}\lambda v_u)$.

4 Numerical Results

In this section, we study the property of the sneutrino DM $\tilde{\nu}_1$ by providing some numerical results. We first show one dimensional CRs of the input parameters in
Table 3. Comparing the results in Fig. 5 of [11], one can learn that the favored range of $Y_\nu$ is drastically reduced since in present work we update the constraints in [11] by including those from the leptonic unitary and the latest XENON-1T experiment. As we will show below, this makes the physical picture of the ISS-NMSSM quite simple. One can also learn that the $2\sigma$ regions of the input parameters are within the parameter space we considered in Table 1, which proves that the setting of the parameter space in Table 3 is reasonable.

In order to figure out the main annihilation mechanism of $\tilde{\nu}_1$, we show the two-dimensional (2D) marginal posterior PDF on $\mu - m_{\tilde{\nu}}$ plane in the left panel of Fig. 1. From the $1\sigma$ and $2\sigma$ CRs, one can infer that $\tilde{\nu}_1$ prefers to coannihilate with the Higgsinos to get its right relic density. We regard this as a key feature of the ISS-NMSSM, and they are obtained only by Nested Sampling algorithm with the new constraints considered. Note that the Higgsino mass $\mu$ prefers to be less than 200GeV, which makes the ISS-NMSSM capable to predict $Z$ boson mass in a natural way. The underlying reason is that, as we emphasized in [24], we have set $A_\lambda \equiv 2$TeV in this work, so the effective Higgs potential at electroweak scale contains only the SM model Higgs field and the singlet field. Given $v = 246$GeV for the SM Higgs field, the natural choice of the singlet vev $v_s$ should be around $v$, which implies a light $\mu \equiv v_s \sqrt{2} \sim 100$GeV.

It is well known that the coannihilation usually induces a great fine tuning to get the right DM relic density. We investigate this issue in the ISS-NMSSM by defining the tuning of the density as

$$\Delta_\Omega = \text{Max} \left( \frac{\partial \ln \Omega h^2}{\partial \ln p_i} \right), \quad (4.1)$$

with $p_i$ denoting any of the input parameters in Table 1 and Max representing the maximum over all the parameters. In the right panel of Fig. 1, we project 6000 unweighted samples obtained in the scans on $\mu - m_{\tilde{\nu}}$ plane with the color bar representing the value of $\Delta_\Omega$. This panel indicates that $\Delta_\Omega$ varies from 38 to 120 with the largest tuning from the resonant annihilation region, i.e. $m_{\tilde{\nu}_1} \simeq m_{h_1}/2$, and as far as the coannihilation region is concerned, the tuning is concentrated in the range from 38 to 50. We checked that, although the probability of occurrence by Bayesian statics is less than one thousandth, there exist some samples with $\Delta_\Omega < 10$, which implies that the model does not need tuning to get the right density. These samples are characterized by the property that $\tilde{\nu}_1$ usually annihilated by multi-channels (e.g. $\tilde{\nu}_1\tilde{\nu}_1^* \rightarrow A_1 A_1$, $\tilde{\nu}_1\tilde{\nu}_1^* \rightarrow h_i^* \rightarrow XY$ and $\tilde{\nu}_1\tilde{H}, \tilde{H}\tilde{H} \rightarrow XY$ with $X$ and $Y$ denoting any SM particles) and each channel played a significant role in contributing to the density.

---

Note that these points only correspond to a small portion of the samples we collected, but they are enough to illustrate the feature of $\Delta_\Omega$. We transfer our data (weighted samples) to the unweighted points by the acceptance-rejection method.
Figure 2. Same as Fig. 1 except that the results are shown on $\sigma_{\tilde{\nu}_1-p}^{SI} - m_{\tilde{\nu}_1}$ plane and the color on the right panel denotes the tuning to get $\sigma_{\tilde{\nu}_1}^{SI}$, which is defined by Eq.(4.2).

5. About the samples in Fig.1, it should be noted that, if the mass splitting between the Higgsinos and $\tilde{\nu}_1$ is larger than about 70 GeV, they may be tightly limited by the LHC search for Di-tau plus $E_T^\text{miss}$ signal since the ISS-NMSSM contributes to the signal by the process $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ with $\tilde{\chi}_1^- \to \tau \tilde{\nu}_1$ [24]. In particular, this requires $\mu \lesssim 130 \text{GeV}$ for the resonance region if $Br(\tilde{\chi}_1^- \to \tau \tilde{\nu}_1) = 100\%$. Obviously, the coannihilation region is unaffected since the $\tau$ lepton is soft in this case.

Next we turn to the scattering of $\tilde{\nu}_1$ with nucleon. Similar to Fig.1, we show in Fig.2 the 2D CRs on $\sigma_{\tilde{\nu}_1-p}^{SI} - m_{\tilde{\nu}_1}$ plane and project the samples on the same plane with the color bar denoting the tuning for $\sigma_{\tilde{\nu}_1-p}^{SI}$ defined by

$$\Delta_\sigma = \text{Max}(\frac{\partial \ln \sigma_{\tilde{\nu}_1-p}^{SI}}{\partial \ln p_i}).$$  \hspace{1cm} (4.2)

The left panel indicates that the 1σ CR splits into two isolated islands with different features. For the island with $m_{\tilde{\nu}_1} \simeq m_{h_1}/2$, $\tilde{\nu}_1$ annihilates mainly by the resonance of $h_1$, and the scattering rate is above the neutrino floor. This island, however, is tightly limited by the LHC search for sparticles as mentioned before. By contrast, the samples in the other island coannihilated with the Higgsinos, and most of them in 1σ CR predict the scattering rate below the neutrino floor. The right panel shows the tuning induced by the scattering cross section, and it reveals that $\Delta_\sigma \lesssim 20$ for nearly all samples. The underlying reason for the low tuning is that there are various mechanisms to suppress the scattering rate in the ISS-NMSSM, which was illustrated analytically in [11].

\footnote{In this case, $\langle \sigma v \rangle_0$ is usually around $10^{-26} \text{cm}^3 \text{s}^{-1}$, so the constraint the DM indirect search}
Finally, we show in Table 4 the detailed information of the best fit point obtained in the scans. We find its total $\chi^2$ at 74.9, which mainly comes from the $\chi^2_h$ calculated by the HiggsSignal with 74 observables considered in the Higgs data fit [43]. For the sake of comparison, we also provide in Table 5 the information of another benchmark point with a lower tuning to get the relic density.

Table 4. Details of the best fit point obtained in the scans.

| Parameters | Value | Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|------------|-------|
| $\lambda$ | 0.13  | $\kappa$  | -0.60 | $\tan \beta$ | 34.9  |
| $Y_\nu$ | $5.6 \times 10^{-3}$ | $\lambda_\nu$ | $1.4 \times 10^{-2}$ | $\mu$ | 127.2 GeV |
| $A_t$ | 2292.0 GeV | $A_\kappa$ | 208.6 GeV | $A_\nu$ | -166.9 GeV |
| $A_{\lambda_\nu}$ | 45.7 GeV | $m_{\tilde{\chi}}$ | 259.2 GeV | $m_2$ | 117.4 GeV |
| $m_{\nu_1}$ | 116.7 GeV | $m_{h_1}$ | 125.1 GeV | $m_{h_2}$ | 1162.6 GeV |
| $m_{h_3}$ | 2539.8 GeV | $m_{A_1}$ | 616.4 GeV | $m_{A_2}$ | 2540.0 GeV |
| $m_{\tilde{\chi}_1}$ | 124.0 GeV | $m_{\tilde{\chi}_2}$ | -136.2 GeV | $m_{\tilde{\chi}_3}$ | 130.5 GeV |
| $\sigma_{SI}^{\tilde{\nu}-p}$ | $1.0 \times 10^{-51}$ cm$^2$ | $\langle \sigma v \rangle_0$ | $4.7 \times 10^{-34}$ cm$^3$s$^{-1}$ | $\Omega h^2$ | 0.12 |
| $S_{11}$ | -0.029 | $S_{12}$ | -0.999 | $S_{13}$ | 0.003 |
| $S_{21}$ | -0.004 | $S_{22}$ | -0.003 | $S_{23}$ | -0.999 |
| $S_{31}$ | 0.999 | $S_{32}$ | -0.029 | $S_{33}$ | -0.004 |
| $Z_{11}$ | $1.10 \times 10^{-6}$ | $Z_{12}$ | 0.060 | $Z_{13}$ | 0.998 |
| $\Delta_\Omega$ | 42.18 | $\Delta_\sigma$ | 11.1 | $\chi^2$ | 74.9 |

Table 5. Detailed information of a benchmark point with a lower tuning to get right relic density.

| Parameters | Value | Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|------------|-------|
| $\lambda$ | 0.25  | $\kappa$  | -0.40 | $\tan \beta$ | 36.7  |
| $Y_\nu$ | $4.9 \times 10^{-3}$ | $\lambda_\nu$ | 0.22 | $\mu$ | 104 GeV |
| $A_t$ | 2570 GeV | $A_\kappa$ | 97.0 GeV | $A_\nu$ | 5.9 GeV |
| $A_{\lambda_\nu}$ | 163 GeV | $m_{\tilde{\chi}}$ | 30.1 GeV | $m_2$ | 3.7 GeV |
| $m_{\nu_1}$ | 88.3 GeV | $m_{h_1}$ | 125 GeV | $m_{h_2}$ | 300 GeV |
| $m_{h_3}$ | 2700 GeV | $m_{A_1}$ | 218 GeV | $m_{A_2}$ | 2700 GeV |
| $m_{\tilde{\chi}_1}$ | 103 GeV | $m_{\tilde{\chi}_2}$ | -109 GeV | $m_{\tilde{\chi}_3}$ | 107 GeV |
| $\sigma_{SI}^{\tilde{\nu}-p}$ | $1.0 \times 10^{-47}$ cm$^2$ | $\langle \sigma v \rangle_0$ | $7.84 \times 10^{-28}$ cm$^3$s$^{-1}$ | $\Omega h^2$ | 0.112 |
| $S_{11}$ | -0.027 | $S_{12}$ | -0.997 | $S_{13}$ | 0.068 |
| $S_{21}$ | -0.012 | $S_{22}$ | -0.068 | $S_{23}$ | -0.998 |
| $S_{31}$ | 0.999 | $S_{32}$ | 0.027 | $S_{33}$ | 0.011 |
| $M_{13}$ | $-1.85 \times 10^{-5}$ | $M_{16}$ | -0.014 | $M_{19}$ | 1.00 |
| $\Delta_\Omega$ | 18.0 | $\Delta_\sigma$ | 18.5 | $\chi^2$ | 77.0 |

Finally, we show in Table 4 the detailed information of the best fit point obtained in the scans. We find its total $\chi^2$ at 74.9, which mainly comes from the $\chi^2_h$ calculated by the HiggsSignal with 74 observables considered in the Higgs data fit [43]. For the sake of comparison, we also provide in Table 5 the information of another benchmark point with a lower tuning to get the relic density.

---

from dwarf galaxies can play a role [11].
5 Conclusion

Motivated by the more and more tight limitation from DM DD experiments on the traditional neutralino DM in natural SUSY, we study the implication of the lightest sneutrino $\tilde{\nu}_1$ in the ISS-NMSSM as a DM candidate by considering the constraints from leptonic unitary and the recent XENON-1T experiment, which were neglected before. We encode the constraints in a likelihood function, and perform sophisticated scans over the vast parameter space of the model by Nested Sampling method. Our results for the posterior PDF reveal that the DM physics is rather simple, which can be summarized as follows:

- The DM prefers to coannihilate with the Higgsinos to get its right relic density. This usually induces a tuning about 40, but once the other annihilation channels, such as $\tilde{\nu}_1\tilde{\nu}_1^* \rightarrow A_1A_1$, also play a role, the tuning can be reduced to $1 \sim 10$.

- Most strikingly, the DM-nucleon scattering in the ISS-NMSSM can be suppressed by several mechanisms [11]. Especially, its rate tends to be under the neutrino floor without any tuning, and thus the scattering may not be detected in future.

- The Higgsino mass $\mu$ prefers to be around 100GeV, so there is no tension between the naturalness for Z boson mass and DM direct detection experiments.

Obviously, given these attractive features, the ISS-NMSSM should be paid due attention.

At the end of this work, we want to clarify several points:

- Our results do not forbid the case that the annihilation $\tilde{\nu}_1\tilde{\nu}_1^* \rightarrow A_1A_1$ is the dominant annihilation channel. We just state that the possibility for this case is rather low by Bayesian statics.

- Our study actually shows the existence of certain parameter space in the ISS-NMSSM where both DM observable and electroweak symmetry breaking can occur without fine tuning. This is a good feature of the theory beside its capability to generate neutrino mass.

- As was pointed out in the appendix B of [24], the posterior PDFs about the annihilation mechanism and the DM-nucelon scattering are not sensitive to the prior PDF we use. By contrast, although the preference of a low $\mu$ is somewhat dependent on the prior PDF, our choice in Table 1 can produce stable and reasonable results in a relatively fast way.

- Our calculation is computationally expensive. In fact, it took us about 0.6 million core-hours for Intel I9 7900X CPU to finish the calculation.
Acknowledgement

We thank Dr. Xiaofei Guo and Liangliang Shang for helpful discussion about the code SARAH. This work is supported by the National Natural Science Foundation of China (NNSFC) under grant No. 11575053.

References

[1] J. S. Hagelin, G. L. Kane and S. Raby, Nucl. Phys. B 241, 638 (1984). doi:10.1016/0550-3213(84)90064-6

[2] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267, 195 (1996) doi:10.1016/0370-1573(95)00058-5 [hep-ph/9506380].

[3] T. Falk, K. A. Olive and M. Srednicki, Phys. Lett. B 339, 248 (1994) doi:10.1016/0370-2693(94)90639-4 [hep-ph/9409270].

[4] C. Arina and N. Fornengo, JHEP 0711, 029 (2007) doi:10.1088/1126-6708/2007/11/029 [arXiv:0709.4477 [hep-ph]].

[5] H. Baer, V. Barger and H. Serce, Phys. Rev. D 94, no. 11, 115019 (2016) doi:10.1103/PhysRevD.94.115019 [arXiv:1609.06735 [hep-ph]].

[6] P. Huang, R. A. Roglans, D. D. Spiegel, Y. Sun and C. E. M. Wagner, Phys. Rev. D 95, no. 9, 095021 (2017) doi:10.1103/PhysRevD.95.095021 [arXiv:1701.02737 [hep-ph]].

[7] M. Badziak, M. Olechowski and P. Szczerbiak, Phys. Lett. B 770, 226 (2017) doi:10.1016/j.physletb.2017.04.059 [arXiv:1701.05869 [hep-ph]].

[8] H. Baer, V. Barger, P. Huang and X. Tata, JHEP 1205, 109 (2012) doi:10.1007/JHEP05(2012)109 [arXiv:1203.5539 [hep-ph]].

[9] J. Cao, Y. He, L. Shang, W. Su, P. Wu and Y. Zhang, JHEP 1610, 136 (2016) doi:10.1007/JHEP10(2016)136 [arXiv:1609.00204 [hep-ph]].

[10] U. Ellwanger, C. Hugonie and A. M. Teixeira, Phys. Rept. 496, 1 (2010) doi:10.1016/j.physrep.2010.07.001 [arXiv:0910.1785 [hep-ph]].

[11] J. Cao, X. Guo, Y. He, L. Shang and Y. Yue, JHEP 1710, 044 (2017) doi:10.1007/JHEP10(2017)044 [arXiv:1707.09626 [hep-ph]].

[12] L. J. Hall, D. Pinner and J. T. Ruderman, JHEP 1204, 131 (2012) doi:10.1007/JHEP04(2012)131 [arXiv:1112.2703 [hep-ph]].

[13] U. Ellwanger, JHEP 1203, 044 (2012) doi:10.1007/JHEP03(2012)044 [arXiv:1112.3548 [hep-ph]].

[14] J. J. Cao, Z. X. Heng, J. M. Yang, Y. M. Zhang and J. Y. Zhu, JHEP 1203, 086 (2012) doi:10.1007/JHEP03(2012)086 [arXiv:1202.5821 [hep-ph]].

[15] F. Feroz, M. P. Hobson and M. Bridges, Mon. Not. Roy. Astron. Soc. 398, 1601 (2009) doi:10.1111/j.1365-2966.2009.14548.x [arXiv:0809.3437 [astro-ph]].
[16] J. Cao, F. Ding, C. Han, J. M. Yang and J. Zhu, JHEP 1311, 018 (2013) doi:10.1007/JHEP11(2013)018 [arXiv:1309.4939 [hep-ph]].

[17] U. Ellwanger and A. M. Teixeira, JHEP 1410, 113 (2014) doi:10.1007/JHEP10(2014)113 [arXiv:1406.7221 [hep-ph]].

[18] J. Cao, L. Shang, P. Wu, J. M. Yang and Y. Zhang, Phys. Rev. D 91, no. 5, 055005 (2015) doi:10.1103/PhysRevD.91.055005 [arXiv:1410.3239 [hep-ph]].

[19] J. Cao, L. Shang, P. Wu, J. M. Yang and Y. Zhang, JHEP 1510, 030 (2015) doi:10.1007/JHEP10(2015)030 [arXiv:1506.06471 [hep-ph]].

[20] J. Cao, Y. He, L. Shang, W. Su and Y. Zhang, JHEP 1608, 037 (2016) doi:10.1007/JHEP08(2016)037 [arXiv:1606.04416 [hep-ph]].

[21] U. Ellwanger and C. Hugonie, arXiv:1806.09478 [hep-ph].

[22] M. J. Baker et al., JHEP 1512, 120 (2015) doi:10.1007/JHEP12(2015)120 [arXiv:1510.03434 [hep-ph]].

[23] K. Griest and D. Seckel, Phys. Rev. D 43, 3191 (1991). doi:10.1103/PhysRevD.43.3191

[24] J. Cao, X. Guo, Y. Pan, L. Shang and Y. Yue, arXiv:1807.03762 [hep-ph].

[25] E. Aprile et al. [XENON Collaboration], arXiv:1805.12562 [astro-ph.CO].

[26] A. Fowlie and M. H. Bardsley, Eur. Phys. J. Plus 131, no. 11, 391 (2016) doi:10.1140/epjp/i2016-16391-0 [arXiv:1603.00555 [physics.data-an]].

[27] J. Baglio and C. Weiland, JHEP 1704, 038 (2017) doi:10.1007/JHEP04(2017)038 [arXiv:1612.06403 [hep-ph]].

[28] E. Fernandez-Martinez, J. Hernandez-Garcia and J. Lopez-Pavon, JHEP 1608, 033 (2016) doi:10.1007/JHEP08(2016)033 [arXiv:1605.08774 [hep-ph]].

[29] E. Arganda, M. J. Herrero, X. Marcano and C. Weiland, Phys. Rev. D 91, no. 1, 015001 (2015) doi:10.1103/PhysRevD.91.015001 [arXiv:1405.4300 [hep-ph]].

[30] J. Guo, Z. Kang, T. Li and Y. Liu, JHEP 1402, 080 (2014) doi:10.1007/JHEP02(2014)080 [arXiv:1311.3497 [hep-ph]].

[31] S. L. Chen and Z. Kang, Phys. Lett. B 761, 296 (2016) doi:10.1016/j.physletb.2016.08.051 [arXiv:1512.08780 [hep-ph]].

[32] Z. Kang, J. Li, T. Li, T. Liu and J. M. Yang, Eur. Phys. J. C 76, no. 5, 270 (2016) doi:10.1140/epjc/s10052-016-4114-9 [arXiv:1102.5644 [hep-ph]].

[33] D. G. Cerdeno, C. Munoz and O. Seto, Phys. Rev. D 79, 023510 (2009) doi:10.1103/PhysRevD.79.023510 [arXiv:0807.3029 [hep-ph]].

[34] D. G. Cerdeno and O. Seto, JCAP 0908, 032 (2009) doi:10.1088/1475-7516/2009/08/032 [arXiv:0903.4677 [hep-ph]].

[35] F. Staub, Comput. Phys. Commun. 185, 1773 (2014) doi:10.1016/j.cpc.2014.02.018 [arXiv:1309.7223 [hep-ph]].
[36] F. Staub, Comput. Phys. Commun. 184, 1792 (2013) doi:10.1016/j.cpc.2013.02.019 [arXiv:1207.0906 [hep-ph]].
[37] F. Staub, arXiv:0806.0538 [hep-ph].
[38] W. Porod and F. Staub, Comput. Phys. Commun. 183, 2458 (2012) doi:10.1016/j.cpc.2012.05.021 [arXiv:1104.1573 [hep-ph]].
[39] W. Porod, F. Staub and A. Vicente, Eur. Phys. J. C 74, no. 8, 2992 (2014) doi:10.1140/epjc/s10052-014-2992-2 [arXiv:1405.1434 [hep-ph]].
[40] D. Barducci, G. Belanger, J. Bernon, F. Boudjema, J. Da Silva, S. Kraml, U. Laa and A. Pukhov, arXiv:1606.03834 [hep-ph].
[41] G. Belanger, F. Boudjema, C. Hugonie, A. Pukhov and A. Semenov, JCAP 0509, 001 (2005) doi:10.1088/1475-7516/2005/09/001 [hep-ph/0505142].
[42] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. 185, 960 (2014) doi:10.1016/j.cpc.2013.10.016 [arXiv:1305.0237 [hep-ph]].
[43] P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak and G. Weiglein, JHEP 1411, 039 (2014) doi:10.1007/JHEP11(2014)039 [arXiv:1403.1582 [hep-ph]].
[44] P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak and G. Weiglein, Eur. Phys. J. C 75, no. 9, 421 (2015) doi:10.1140/epjc/s10052-015-3650-z [arXiv:1507.06706 [hep-ph]].
[45] E. Bagnaschi et al., Eur. Phys. J. C 78, no. 3, 256 (2018) doi:10.1140/epjc/s10052-018-5697-0 [arXiv:1710.11091 [hep-ph]].
[46] J. h. Park, Phys. Rev. D 83, 055015 (2011) doi:10.1103/PhysRevD.83.055015 [arXiv:1011.4939 [hep-ph]].
[47] D. Chowdhury, R. M. Godbole, K. A. Mohan and S. K. Vempati, JHEP 1402, 110 (2014) Erratum: [JHEP 1803, 149 (2018)] doi:10.1007/JHEP03(2018)149, 10.1007/JHEP02(2014)110 [arXiv:1310.1932 [hep-ph]].
[48] P. Gregory, Bayesian Logical Data Analysis for the Physical Sciences. Cambridge University Press, 2005.
[49] K. Kowalska, S. Munir, L. Roszkowski, E. M. Sessolo, S. Trojanowski and Y. L. S. Tsai, Phys. Rev. D 87, 115010 (2013) doi:10.1103/PhysRevD.87.115010 [arXiv:1211.1693 [hep-ph]].
[50] P. Athron, C. Balazs, B. Farmer, A. Fowlie, D. Harries and D. Kim, JHEP 1710, 160 (2017) doi:10.1007/JHEP10(2017)160 [arXiv:1709.07895 [hep-ph]].
[51] H. Jeffreys (1961). The Theory of Probability (3rd ed.). Oxford. p. 432.
[52] F. Feroz, B. C. Allamach, M. Hobson, S. S. AbdusSalam, R. Trotta and A. M. Weber, JHEP 0810, 064 (2008) doi:10.1088/1126-6708/2008/10/064 [arXiv:0807.4512 [hep-ph]].
[53] S. Matsumoto, S. Mukhopadhyay and Y. L. S. Tsai, Phys. Rev. D 94 (2016) no.6, 065034 doi:10.1103/PhysRevD.94.065034 [arXiv:1604.02230 [hep-ph]].
see website: www-glast.stanford.edu/pub_data/1048

[55] L. M. Carpenter, R. Colburn, J. Goodman and T. Linden, Phys. Rev. D 94, no. 5, 055027 (2016) doi:10.1103/PhysRevD.94.055027 [arXiv:1606.04138 [hep-ph]].

[56] X. J. Huang, C. C. Wei, Y. L. Wu, W. H. Zhang and Y. F. Zhou, Phys. Rev. D 95, no. 6, 063021 (2017) doi:10.1103/PhysRevD.95.063021 [arXiv:1611.01983 [hep-ph]].

[57] S. Li et al., arXiv:1806.00733 [astro-ph.HE].

[58] S. Chang, R. Edezhath, J. Hutchinson and M. Luty, Phys. Rev. D 89, no. 1, 015011 (2014) doi:10.1103/PhysRevD.89.015011 [arXiv:1307.8120 [hep-ph]].