Direct detection constraints on thermal singlino-higgsino dark matter in NMSSM

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The NMSSM

Next-to-minimal supersymmetric standard model (NMSSM) is considered as a promising alternative to well-known and widely studied MSSM. Its superpotential and soft lagrangian density are obtained by extending the MSSM with an additional chiral SM-singlet superfield S:

$$W = \lambda S H_u H_d + \xi_F S + \frac{1}{2}\mu' S^2 + \frac{1}{3}\kappa S^3$$

$$-\mathcal{L}_{\rm soft} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2$$

$$+A_\lambda \lambda H_u H_d S + \frac{1}{3} A_\kappa \kappa S^3 + m_3^2 H_u H_d + \frac{1}{2} m_S'^2 S^2 + \xi_S S + h.c.$$

In the simplest and most widely studied version, known as the scale-invariant or $\mathbb{Z}_3$-symmetric NMSSM, green terms vanish. The S superfield may influence both the scalar (additional scalar: s and pseudoscalar: a) and neutralino sector (additional fermion: singlino), allowing for much richer phenomenology than the usual MSSM. In our work we considered thermally produced singlino-higgsino dark matter (gauginos are decoupled) with relic density consistent with WMAP/Planck observations i.e. $\Omega h^2 \approx 0.12$.

Direct detection

In recent years we have observed a rapid increase in sensitivity of spin-independent (SI) direct detection of dark matter (especially LUX experiment). It is believed that this trend will continue in the coming years (XENON1T, LZ) and finally we will be able to reach the irreducible neutrino background (NB). This motivates us to consider the so-called *blind spots* in parameter space of NMSSM corresponding to SI cross section below NB. Moreover, the recent strong constraints from PANDA and LUX on spin-dependent (SD) direct detection inspired us additionally to put the current and future limits on spin-dependent cross section for our blind spots.

In our numerical analysis (see plots) we depicted the current SD bounds from LUX and IceCube (IC) by green and cyan colours respectively. Future sensitivities of XENON1T and LZ are denoted by green continuous and dashed lines. We also imposed constraints from LEP (red), LHC (grey), invisible Z^0 decay $\Gamma_{Z^0}^{\rm inv}$ (yellow), unphysical global minimum UM (brown) and Landau pole below the GUT scale LP (red line).

Theoretical analysis

The only important contribution at the tree level to $\sigma_{SI}^{(N)}$ comes from scalars' exchange in t channel (we assume that sfermions are heavy):

$$\sigma_{SI}^{(N)} \sim f_N^2 \qquad f_N \simeq \sum_{i=1}^{3} \frac{\alpha_{\chi\chi h_i}\alpha_{h_i NN}}{2m_{h_i}^2}$$

where $\alpha_{\chi\chi h_i}$, $\alpha_{h_i NN}$ denote couplings of the LSP to scalar mass eigenstates $h_i (= h, H, s)$ and to nucleon $N(= p, n)$ respectively. We approximate $\sigma_{SI}^{(p)} \simeq \sigma_{SI}^{(n)}$. In our work we analyzed two interesting cases:

- Only h exchange (BS1): We assume $m_h \ll m_s, m_H$. For convenience we define the following parameters:

  $$\gamma \equiv \frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}} \qquad \eta \equiv \frac{N_{15}(N_{13}\sin\beta + N_{14}\cos\beta)}{N_{13}N_{14} - \frac{\kappa}{\lambda}N_{15}^2}$$

  where $|\gamma| \sim \sqrt{|\Delta_{\rm mix}|}$ and $m_h = \hat{M}_{hh} + \Delta_{\rm mix}$. $\tilde{S}_{i\hat{j}}$ is the diagonalization matrix in the interaction basis rotated by the angle β (e.g. $\tilde{S}_{h\hat{s}}$ is the contribution of s to SM-like Higgs h). Then, the blind spot condition takes a very simple form:

  $$\gamma = -\eta$$

  Because $\Delta_{\rm mix} < 0$, we prefer $|\gamma| \sim |\eta| \ll 1$ and hence strongly singlino(higgsino)-dominated LSP.

- h and s exchange (BS2): We assume $m_s < m_h$ in order to have $\Delta_{\rm mix} > 0$. Let us define a ratio of s and h contributions to $\sigma_{SI}^{(N)}$:

  $$\mathcal{A}_s \equiv \frac{\alpha_{sNN}}{\alpha_{hNN}} \frac{\tilde{S}_{s\hat{s}}}{\tilde{S}_{h\hat{h}}} \left(\frac{m_h}{m_s}\right)^2 \approx -\gamma \frac{1+c_s}{1+c_h} \left(\frac{m_h}{m_s}\right)^2$$

  For $\tan\beta \gg 1$, c_i is the ratio of $h_i b\bar{b}$ and $h_i ZZ$ couplings normalized to the SM values. Then, the blind spot condition generalizes to:

  $$\frac{\gamma + \mathcal{A}_s}{1 - \gamma\mathcal{A}_s} = -\eta$$

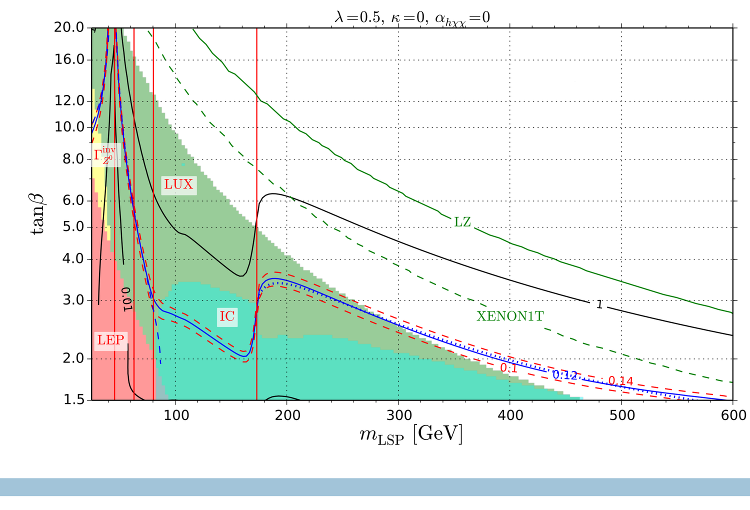
The dominant contribution at the tree level to $\sigma_{\rm SD}^{(N)}$ comes from t-channel exchange of Z^0 boson and is proportional to the difference of d and u-type higgsino contributions squared:

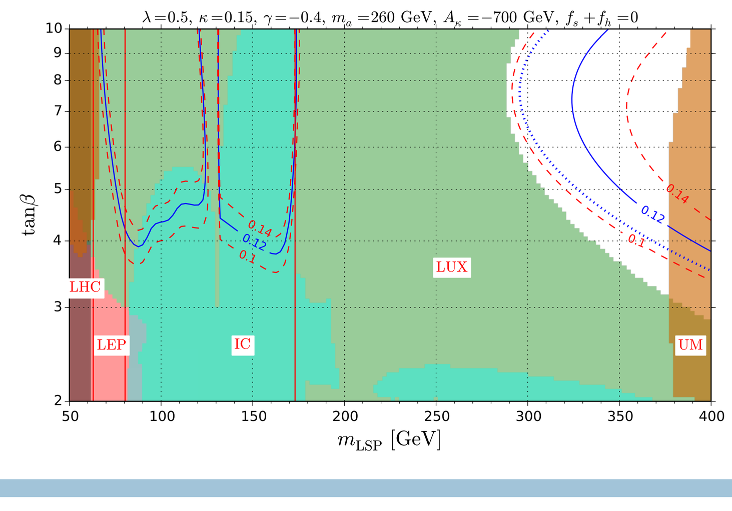
$$\sigma_{\rm SD}^{(N)} \sim 10^{-38}\,{\rm cm}^2 \left(N_{13}^2 - N_{14}^2\right)^2 \qquad N_{13}^2 - N_{14}^2 = \frac{\left[1 - (m_\chi/\mu)^2\right](1 - N_{15}^2)\cos 2\beta}{1 + (m_\chi/\mu)^2 - 2(m_\chi/\mu)\sin 2\beta}$$

Vanishing $\sigma_{\rm SD}^{(N)}$ may be obtained for $\tan\beta = 1$, pure singlino LSP ($N_{15}^2 = 1$) or pure higgsino LSP ($m_\chi/\mu = 1$). In our case none of these options holds so SD constraints provide an excellent test of our scenario.

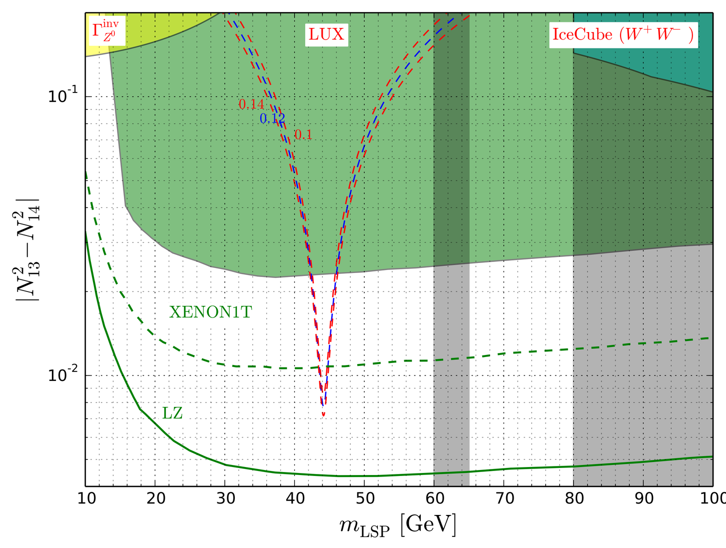
Results: general NMSSM

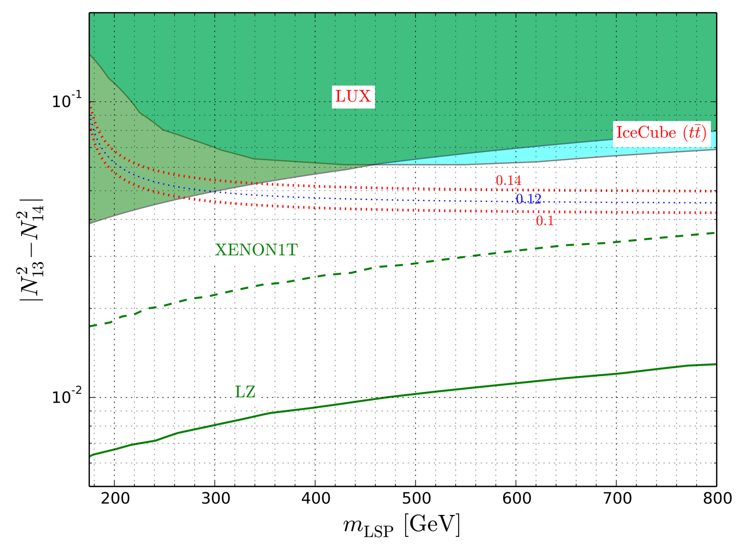
Below we present a comparison between BS1 and BS2 in general NMSSM. Continuous/dashed or dotted blue lines correspond to numerical (`MicrOMEGAs`)/theoretical lines of relic density consistent with observations (theoretical uncertainty is denoted by dashed red lines).





For $m_H, m_s \gg m_h$ (BS1) there are two generic mechanisms which can provide correct relic density i.e. resonance with Z^0 and annihilation into $t\bar{t}$. As we can see (plots below), there are two LSP mass regions still allowed by the experiments, however XENON1T and LZ will be able to completely probe both of them. In the case when s is light (BS2), additional mechanisms appear (resonance with a and annihilation into sa, ha etc.) allowing for more freedom even for sizeable linear correction to the Higgs mass ($|\gamma| \approx 0.4 \Rightarrow \Delta_{\rm mix} \approx 4$ GeV).



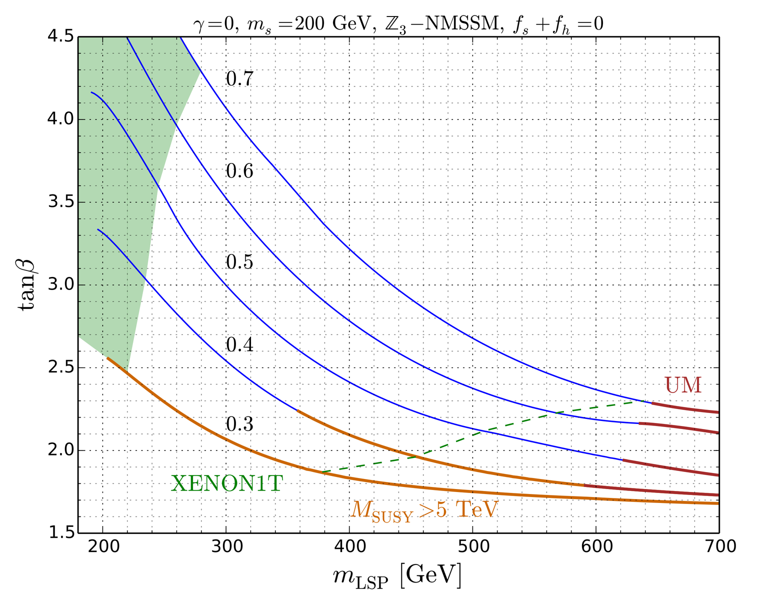


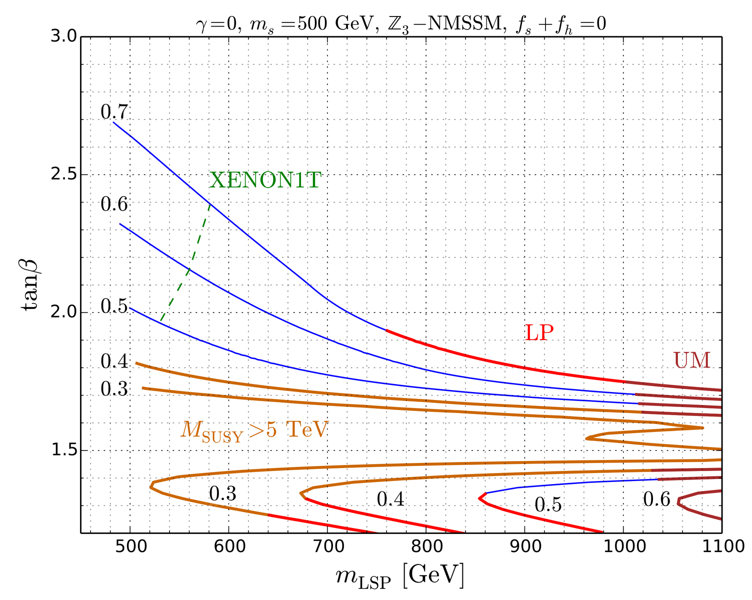
Results: $\mathbb{Z}_3$-NMSSM

In $\mathbb{Z}_3$-NMSSM some parameters are correlated e.g. ${\rm sgn}(m_\chi\mu) = {\rm sgn}(\kappa)$. For singlino-like LSP we have additionally $|\kappa| < \frac{1}{2}\lambda$. Moreover, the following mass sum rule holds:

$$m_s^2 + \frac{1}{3}m_a^2 \approx m_{\rm LSP}^2 + \gamma^2(m_s^2 - m_h^2) \quad \Rightarrow \quad m_{\rm LSP} > m_s$$

Let us first discuss the case of heavy singlet (BS1). Below we present contour lines of $\Omega h^2 \approx 0.12$ for $m_s = 200$ and 500 GeV for a few values of λ. Because of the fact that $m_{\rm LSP} > m_s$ additional annihilation channels (especially into sa) allow for reduced annihilation into $t\bar{t}$ and hence smaller higgsino contribution to the LSP. In consequence, larger LSP masses consistent with WMAP/Planck and perturbativity up to the GUT scale are possible than in the case with both singlets decoupled. For the same reason large enough LSP masses are beyond the reach of XENON1T.





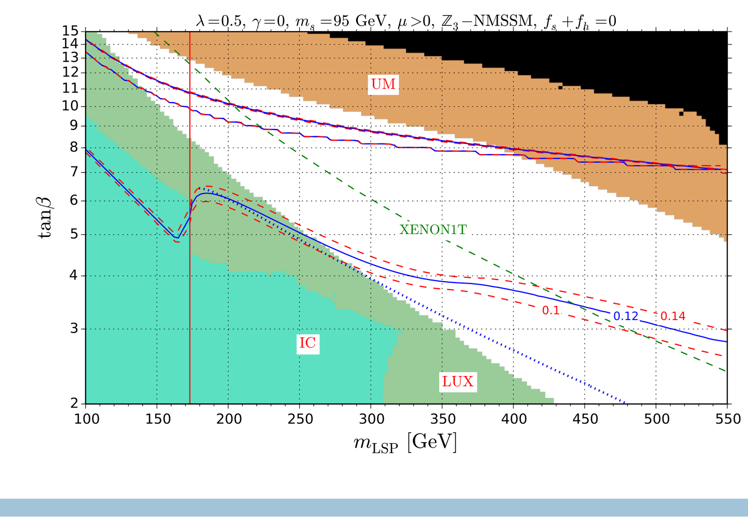
If the singlet-like scalar is light (BS2), the loop corrections to s and a can no longer be neglected, which under some circumstances allows for resonant LSP annihilation via the s-channel exchange of a:

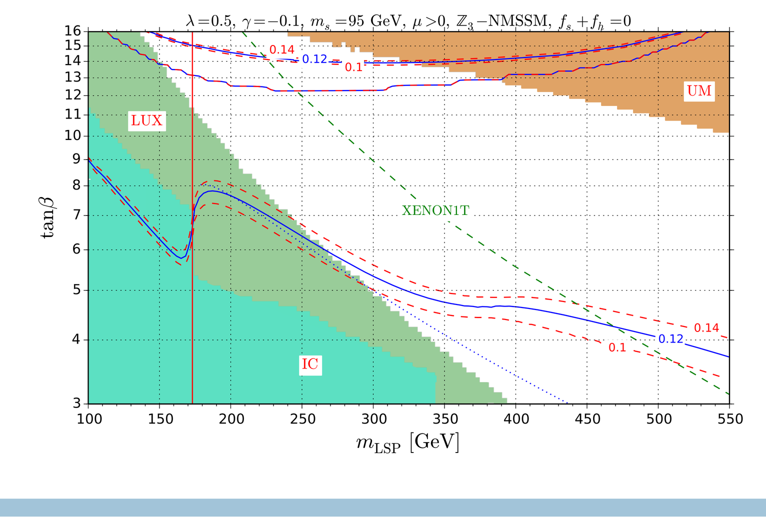
$$m_a \approx 2m_{\rm LSP} \quad \Rightarrow \quad m_s^2 + \frac{1}{3}m_{\rm LSP}^2 + \gamma^2\left(m_h^2 - m_s^2\right) \approx \Delta_{\hat{s}\hat{s}} + \frac{1}{3}\Delta_{\hat{a}\hat{a}}$$

Substituting the explicit form of the leading corrections, for $\tan\beta \gg 1$ we get the following relation between $m_{\rm LSP}$ and $\tan\beta$ (for other parameters fixed):

$$m_s^2 \approx m_{\rm LSP}^2 \left[\left(\frac{\lambda\tan\beta}{2\pi}\right)^2 \ln\left(\frac{2M_{\rm SUSY}}{m_{\rm LSP}\tan\beta}\right) - \frac{1}{3}\right]$$

Below we present the situation for $\gamma = 0$ and -0.1 ($\lambda = 0.5$, $m_s = 95$ GeV, $M_{\rm SUSY} = 4$ TeV). Lower blue lines correspond to the standard annihilation into $t\bar{t}$ (plus contributions from sa etc.) whereas upper ones are correlated with the resonance with a (see the relation above). Similarly to the previous case, some parts of the LSP mass range will note be probed by XENON1T.





Conclusions and outlook

- We derived current constraints and prospects for SD direct detection for SI blind spots in NMSSM with thermal singlino-higgsino LSP with $\Omega h^2 \approx 0.12$.
- If $m_H, m_s \gg m_h$ the allowed mass regions are $m_{\rm LSP} \sim 41-46$ and $300-800$ GeV and will be almost entirely probed by XENON1T.
- If m_s is small, in general NMSSM it is possible to obtain sizeable positive linear correction to the Higgs mass $\Delta_{\rm mix} \sim 4$ GeV with all considered experimental bounds fulfilled.
- In $\mathbb{Z}_3$-NMSSM we have $m_{\rm LSP} > m_s$ and additional annihilation channels (mainly sa) and resonanse with a relax the SD bounds. In particular, $m_{\rm LSP} \gtrsim 400$ GeV may not be explored by XENON1T.
- Indirect detection might be an excellent complement of our experimental constraints, especially for points in parameter space with LSP annihilation enhanced at $v \approx 0$.

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