Cold Dark Matter and Leptogenesis in the SE_6SSM

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Outline

1. $U(1)_N$ extension of the MSSM
2. SE$_6$SSM
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4. Dark matter-nucleon scattering cross-section
5. Conclusions

Based on:

R. Nevzorov, On the Suppression of the Dark Matter-Nucleon Scattering Cross Section in the SE$_6$SSM, Symmetry **14** (2022) no.10, 2090 [arXiv:2209.00505 [hep-ph]].

R. Nevzorov, Leptogenesis as an origin of hot dark matter and baryon asymmetry in the E_6 inspired SUSY models, Phys. Lett. B **779** (2018) 223.

$U(1)_N$ extension of the MSSM

- At very high energies E_6 group can be broken to $SO(10) \times U(1)_\psi$ with sequential breakdown of $SO(10)$ to $SU(5) \times U(1)_\chi$ and $SU(5)$ to the SM gauge group $SU(3)_C \times SU(2)_W \times U(1)_Y$.
- Near the GUT scale $U(1)_\psi \times U(1)_\chi$ symmetry can be broken to $U(1)_N \times Z_2^M$, where $Z_2^M = (-1)^{3(B-L)}$ is a matter parity while B and L are baryon and lepton numbers.
- Only in this E_6 inspired $U(1)_N$ extension of the MSSM (E_6SSM) right–handed neutrinos N_i can be superheavy [S.F.King, S.Moretti, RN, Phys. Rev. D 73 (2006) 035009; Phys. Lett. B 634 (2006) 278.].
- To ensure anomaly cancellation the particle content of the E_6SSM is extended to include three complete 27_i representations of E_6.
- Thus the E_6SSM contains extra exotic matter beyond the MSSM:
  - SM singlet superfields S_i that carry non-zero $U(1)_N$ charge;
  - H_i^d and H_i^u that have quantum numbers of the MSSM Higgs doublets;
  - the exotic quarks ($\overline{D}_i$ and D_i) which are either diquarks or leptoquarks.

SE_6SSM

- Extra exotic matter may give rise to non-diagonal flavor transitions and rapid proton decay.
- In the modification of the E_6SSM (SE_6SSM) a single discrete $\tilde{Z}_2^H$ symmetry forbids flavor–changing transitions as well as the most dangerous baryon and lepton number violating operators.
  - The SE_6SSM implies that below the GUT scale M_X three complete 27-plets are accompanied by lepton doublets L_4 and $\overline{L}_4$, a pair of superfields S and $\overline{S}$ as well as four E_6 singlet superfields (ϕ and ϕ_i).
  - The supermultiplets ϕ, S, $\overline{S}$, L_4, $\overline{L}_4$ as well as $SU(2)_W$ doublets $H_d \equiv H_3^d$ and $H_u \equiv H_3^u$ are required to be even under the $\tilde{Z}_2^H$ symmetry whereas all other supermultiplets are odd [R. Nevzorov, Phys. Rev. D 87 (2013) 015029; P. Athron, M. Mühlleitner, R. Nevzorov, A.G. Williams, JHEP 1501 (2015) 153.].
- The presence of L_4 and $\overline{L}_4$ at low energies allows the lightest exotic colored state to decay before BBN and facilitates the unification of gauge couplings.

- In the SE_6SSM the sector responsible for the breakdown of the gauge symmetry is formed by the scalar components of ϕ, S, $\overline{S}$, H_d and H_u.
  - S and $\overline{S}$ can develop large vacuum expectation values (VEVs) along the D-flat direction breaking the $U(1)_N$ symmetry and generating masses of all exotic fermions and Z' boson.
- The conservation of Z_2^M and $\tilde{Z}_2^H$ symmetries implies that R–parity and Z_2^E symmetry are also conserved where $\tilde{Z}_2^H = Z_2^M \times Z_2^E$.
- Here we focus on the scenarios in which gravitino is the lightest R-parity odd state so that it is stable and contributes to the density of dark matter.
- In this case the lightest exotic state, which is odd under the Z_2^E symmetry, has to be stable as well.
- We assume that the lightest stable exotic state is predominantly formed by the fermion components of H_1^d and H_1^u.
- In order to find a viable scenarios with stable gravitino one needs to ensure that the lightest unstable R-parity odd (or exotic) state Y decays before BBN, i.e. its lifetime $\tau_Y \lesssim 1\,\mathrm{sec}$.

- For $m_Y \simeq 1\,\text{TeV}$ one can get $\tau_Y \lesssim 1\,\text{sec}$ if gravitino mass $m_{3/2} \lesssim 1\,\text{GeV}$.
- When gravitinos originate from scattering of particles in the thermal bath their contribution to the dark matter density is proportional to the reheating temperature T_R

$$\Omega_{3/2}h^2 \sim 0.27 \left(\frac{T_R}{10^8\,GeV}\right)\left(\frac{1\,\text{GeV}}{m_{3/2}}\right)\left(\frac{M_{\tilde{g}}}{1\,\text{TeV}}\right)^2 .$$

- Since $\Omega_{3/2}h^2 \leq 0.12$ for $m_{3/2} \simeq 1\,\text{GeV}$ and gluino mass $M_{\tilde{g}} \gtrsim 3\,\text{TeV}$ one finds an upper bound $T_R \lesssim 10^{6-7}\,\text{GeV}$.
- Even for so low reheating temperatures the appropriate amount of the lepton asymmetry can be induced within the SE_6SSM via the decays of the lightest right-handed neutrino/sneutrino (N_1 / $\widetilde{N}_1$).
- Due to sphaleron interactions the generated lepton asymmetry is converted into the baryon asymmetry.

Leptogenesis

- The interactions of the superfields N_i are described by
$$W_N = \frac{1}{2} M_i N_i N_i + \tilde{h}_{ij} N_i (H_u L_j) + h_{i\alpha} N_i (H^u_\alpha L_4)\,.$$
- After inflation the lightest right-handed neutrino/sneutrino (N_1 / $\widetilde{N}_1$) with mass M_1 may be produced by thermal scattering if $T_R > M_1$.
- To guarantee that leptogenesis takes place we set $M_1 \simeq 10^5$ GeV.
- We also assume that $M_{2,3} \lesssim 10^6$ GeV.
- In order to reproduce the left–handed neutrino mass scale $m_\nu \lesssim 0.1\,\text{eV}$ the couplings of ordinary leptons L_j to N_i should be rather small, i.e. $|\tilde{h}_{ij}|^2 \ll 10^{-8}$, and can be ignored.
- Then the lepton asymmetry can be generated via the decays
$N_1 \to L_4 + H^u_\alpha, \quad N_1 \to \widetilde{L}_4 + \widetilde{H}^u_\alpha, \quad \widetilde{N}^*_1 \to L_4 + \widetilde{H}^u_\alpha, \quad \widetilde{N}_1 \to \widetilde{L}_4 + H^u_\alpha\,.$
- This process is controlled by the set of CP asymmetries
$$\varepsilon^\alpha_{1,\ell_4} = \varepsilon^\alpha_{1,\tilde{\ell}_4} = \varepsilon^\alpha_{\tilde{1},\ell_4} = \varepsilon^\alpha_{\tilde{1},\tilde{\ell}_4} = \frac{\Gamma^\alpha_{N_1\ell_4} - \Gamma^\alpha_{N_1\bar{\ell}_4}}{\sum_\beta \left(\Gamma^\beta_{N_1\ell_4} + \Gamma^\beta_{N_1\bar{\ell}_4}\right)}\,.$$

- H^u_α can be redefined so that only H^u_1 interacts with L_4 and N_1 so that h_{12} may be set to zero and $\varepsilon^2_{1,\ell_4} = \varepsilon^2_{1,\tilde{\ell}_4} = \varepsilon^2_{\tilde{1},\ell_4} = \varepsilon^2_{\tilde{1},\tilde{\ell}_4} = 0$.
- Assuming that the sparticle mass scale M_S is negligibly small as compared with M_1, $h_{j1} = |h_{j1}| e^{i\varphi_{j1}}$ and M_j are real one finds

$$\varepsilon^1_{1,\ell_4} = \varepsilon^1_{1,\tilde{\ell}_4} = \varepsilon^1_{\tilde{1},\ell_4} = \varepsilon^1_{\tilde{1},\tilde{\ell}_4} = \varepsilon = \frac{1}{8\pi}\left[\sum_{j=2,3} |h_{j1}|^2 f\left(\frac{M_j^2}{M_1^2}\right)\sin 2\Delta\varphi_{j1}\right]$$

$$\Delta\varphi_{j1} = \varphi_{j1} - \varphi_{11}\,, \qquad f(z) = \frac{2\sqrt{z}}{1-z} - \sqrt{z}\,\ln\left(\frac{1+z}{z}\right).$$

- For $h_{31} = 0$ and $h_{21} = 0.1$ one can obtain $\varepsilon \simeq 0.01$ if $M_2 \approx M_1$.
- The induced baryon asymmetry can be estimated as follows

$$Y_{\Delta B} \sim 10^{-3}\Big(\varepsilon\cdot\eta\Big)\,, \qquad Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s}\bigg|_0 = (8.75 \pm 0.23)\times 10^{-11}\,.$$

- In the strong washout scenario the efficiency factor η is given by

$$\eta \simeq \frac{H(T = M_1)}{\Gamma_1}\,, \qquad H = 1.66 g_*^{1/2}\frac{T^2}{M_P}\,, \qquad \Gamma_1 = \frac{|h_{11}|^2}{8\pi} M_1\,.$$

- For $\varepsilon \simeq 0.01$ the observed $Y_{\Delta B}$ can be reproduced if $|h_{11}| \sim 0.001$.

Dark matter-nucleon scattering cross section

- The scalar components of ϕ_i, S_i, H^u_α and H^d_α do not acquire VEVs.
- Their fermion components form the exotic (inert) neutralino and chargino states.
- When the components of ϕ_i are very heavy the interactions of S_i, H^u_α and H^d_α are described by

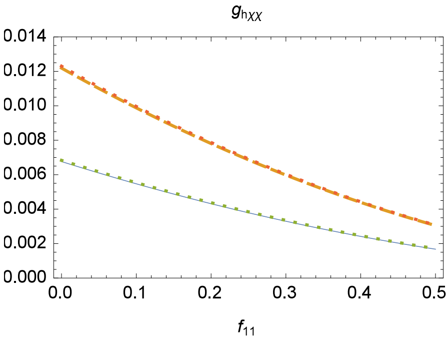
$$W_{IH} \simeq -\widetilde{\mu}_i S_i S_i + \lambda_{\alpha\alpha} S (H^d_\alpha H^u_\alpha) + \tilde{f}_{i\alpha} S_i (H^d_\alpha H_u) + f_{i\alpha} S_i (H_d H^u_\alpha)\,.$$

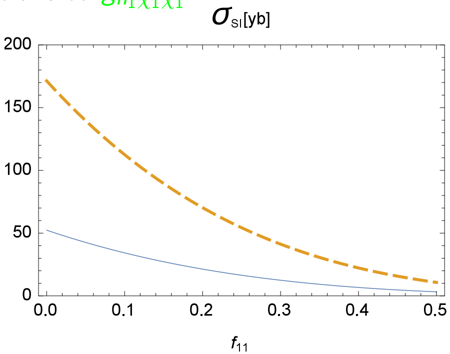
- Here we assume that H^d_1 and H^u_1 mostly interact with S_1, H_u and H_d, whereas all other couplings of H^u_1 and H^d_1 are very small.
- The mass of the lightest exotic chargino is determined by $\mu_{11} = \lambda_{11}\langle S\rangle$, i.e. $m_{\chi_1^\pm} = |\mu_{11}|$.
- If $|\widetilde{\mu}_1|$ is considerably larger than $|\mu_{11}|$, $\langle H_d\rangle = v_1$ and $\langle H_u\rangle = v_2$ the mass of the lightest exotic state χ_1 is given by

$$m_{\chi_1} \simeq m_{\chi_1^\pm} - \Delta_1\,, \qquad \Delta_1 \simeq \frac{(\tilde{f}_{11} v_2 + f_{11} v_1)^2}{2(\widetilde{\mu}_1 - m_{\chi_1^\pm})}\,.$$

- The contribution of χ_1 to the dark matter density can be estimated as
$$\Omega_{\tilde{H}} h^2 \simeq 0.1 \left(\frac{\mu_{11}}{1\,\text{TeV}}\right)^2 .$$
- Thus in the phenomenologically viable scenarios $\mu_{11} < 1.1\,\text{TeV}$.
- Since the couplings of gravitino to the SM particles are negligibly small, the interactions of the dark matter with the baryons are determined by the couplings of χ_1.
- The dominant contribution to the spin–independent (SI) dark matter-nucleon scattering cross section σ_{SI} comes from the t–channel exchange of the lightest CP-even Higgs boson h_1 with mass m_{h_1}
$$\sigma_{SI} = \frac{2 m_r^2 m_N^2}{\pi v^2 m_{h_1}^4} |g_{h_1\chi_1\chi_1} F^N|^2 , \quad F^N = \sum_{q=u,d,s} f_{Tq}^N + \frac{2}{27} \sum_{Q=c,b,t} f_{TQ}^N ,$$
$$m_r = \frac{m_{\chi_1} m_N}{m_{\chi_1} + m_N}, \quad m_N f_{Tq}^N = \langle N | m_q \bar{q} q | N \rangle, \quad f_{TQ}^N = 1 - \sum_{q=u,d,s} f_{Tq}^N .$$
- Here $v = \sqrt{v_1^2 + v_2^2} \simeq 174\,\text{GeV}$, $g_{h_1\chi_1\chi_1} \simeq \Delta_1/(\sqrt{2} v)$ and hadronic matrix elements $f_{Ts}^N \simeq 0.0447$, $f_{Td}^N \simeq 0.0191$ and $f_{Tu}^N \simeq 0.0153$.

- We set $\tilde{f}_{11} = -0.5$, $\tan\beta = \dfrac{v_2}{v_1} = 2$ and $\widetilde{\mu}_1 = 2\,\text{TeV}$.
- The values of σ_{SI} remain smaller than 60 yb for $m_{\chi_1} \simeq \mu_{11} = 200\,\text{GeV}$ (solid lines) and 300 yb for $m_{\chi_1} \simeq \mu_{11} = 1\,\text{TeV}$ (dashed lines) which are the values of the experimental bounds on σ_{SI} obtained by the LZ experiment [J. Aalbers, et al. [LUX-ZEPLIN Collaboration], arXiv:2207.03764].
- The suppression of σ_{SI} is caused by large $\widetilde{\mu}_1$ as well as by the partial cancellation of different contributions to $g_{h_1\chi_1\chi_1}$.





Conclusions

- We explored the SE_6SSM scenarios in which cold dark matter density is formed by the gravitino and the lightest exotic neutralino χ_1.
- The phenomenological viability of these scenarios implies that the gravitino mass $m_{3/2}$ should be smaller than 1 GeV and the reheating temperatures T_R has to be lower than 10^6 GeV.
- Even for so low T_R the decays of the lightest right–handed neutrino/sneutrino can induce the observed baryon asymmetry.
- In the scenarios under consideration there is a part of the SE_6SSM parameter space in which the dark matter–nucleon scattering cross section is substantially smaller than the present experimental limits.
- In these scenarios the lightest exotic chargino $\chi_1^{\pm}$ as well as the lightest exotic neutralino states χ_2 and χ_1 are nearly degenerate and have masses below 1.1 TeV.
- Since the mass splitting between these states is very small the decay products of χ_2 and $\chi_1^{\pm}$ are too soft so that they escape detection.