“The General Singlet Extensions of the MSSM (GSEMSSM) model and some cosmological consequences”

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Minimal Supersymmetric Standard Model (MSSM)

\[ W_{MSSM} = W_{2RC}^{MSSM} + W_{3RC}^{MSSM} \]

\[ W_{2RC}^{MSSM} = \mu (\tilde{H}_1 \tilde{H}_2)(\tilde{H}_1 \tilde{H}_2) \equiv \epsilon_{\alpha\beta} \tilde{H}_1^\alpha \tilde{H}_2^\beta \]

\[ W_{3RC}^{MSSM} = \sum_{i,j=1}^{3} \left[ f_{ij}^l (\tilde{H}_1 \tilde{L}_i) \tilde{c}_j + f_{ij}^d (\tilde{H}_1 \tilde{Q}_i) \tilde{d}_j \right. \]
\[ \left. + f_{ij}^u (\tilde{H}_2 \tilde{Q}_i) \tilde{u}_j \right] \]

\[ W_{2RV} = \sum_{i=1}^{3} \mu_{0i} (\tilde{L}_i \tilde{H}_2) \]

\[ W_{3RV} = \sum_{i,j,k=1}^{3} \left[ \lambda_{ijk} (\tilde{L}_i \tilde{L}_j) \tilde{c}_k + \lambda_{ijk}' (\tilde{L}_i \tilde{Q}_j) \tilde{d}_k \right. \]
\[ \left. + \lambda_{ijk}'' \tilde{u}_i \tilde{d}_j \tilde{d}_k \right] \]

\[ (\tilde{L}_i \tilde{H}_2) \subset (L_i \tilde{H}_2) = l_i \tilde{h}_2^+ - \nu_i \tilde{h}_2^0 \]

To get renormalizable interactions the superpotential has \([W] \leq 3\) it is because \(\Phi_1 \Phi_2 \Phi_3 \Phi_4 \propto A_1 A_2 A_3 A_4\) and they are no renormalizable at two loops
The MSSM suffers from the $\mu$-problem why

$$\mu = \mathcal{O}(M_W)$$

The Next to Minimal Supersymmetric
Standard Model (NMSSM)

new singlet superfield

$$\hat{S} \sim (1, 1, 0)$$

its (vev)

$$\langle S \rangle \equiv \frac{x}{\sqrt{2}} \quad x \simeq \mathcal{O}(v_1, v_2)$$

The fermionic field $\tilde{S}$ is known as singlino

$$W_{NMSSM} = W_3^{MSSM} + \lambda (\hat{H}_1 \hat{H}_2) \hat{S} - \frac{\kappa}{3} (\hat{S})^3$$

$$\mu \equiv \frac{\lambda x}{\sqrt{2}}$$
Scalar Potential at NMSSM

\[ V^{\text{NMSSM}} = M_{H_1}^2 |H_1|^2 + M_{H_2}^2 |H_2|^2 + M_S^2 |S|^2 \]
\[ - \left[ \lambda A_\lambda (H_1 H_2) S + \frac{(\kappa A_\kappa)}{3} (S)^3 + h.c. \right] \]
\[ + \left( |H_1|^2 + |H_2|^2 \right) |\lambda S|^2 \]
\[ + |\lambda (H_1 H_2) S + \kappa S|^2 |^2 \]
\[ + \frac{g^2}{8} (\bar{H}_1 \sigma^i H_1 + \bar{H}_2 \sigma^i H_2)^2 \]
\[ + \frac{g'^2}{8} (\bar{H}_1 H_1 - \bar{H}_2 H_2)^2 \]

1-) \( x \gg v_1, v_2 \) with \( \lambda \) and \( \kappa \) fixed

2-) \( x \gg v_1, v_2 \) with \( \lambda x \) and \( \kappa x \) fixed

in the last limit the MSSM with two Higgs doublets and no Higgs singlets is obtained
Charged Boson

\[
(M_{NMSSM}^{H^\pm})^2 = M_W^2 \left(1 - \frac{2\lambda^2}{g}\right) + \frac{2\lambda x}{\sin(2\beta)} (A\lambda + \kappa x)
\]

\(M_{H^\pm}^2\) may be less or greater than \(M_W^2\)

\[
\lambda = 0.87 \quad \kappa = 0.63
\]
Pseudo Scalars

\[
R = \lambda A \Sigma \frac{x v^2}{v_1 v_2}
\]

\[
S = \lambda v (A \Sigma - 3 \kappa x)
\]

\[
T = \lambda A \Sigma \frac{v_1 v_2}{x} + 3 \kappa A \kappa x + 3 \lambda \kappa v_1 v_2
\]

\[
A \Sigma = A_\lambda + \kappa x
\]

\[
v = \sqrt{v_1^2 + v_2^2}
\]

\[
M_{CP-odd}^2 M_{P_1}^2 < M_{P_2}^2
\]

\[
M_{P_1, P_2}^2 = \frac{1}{2} \left[ (T + R) \mp \sqrt{(T - R)^2 + 4 S^2} \right]
\]

very light pseudoscalars as required by cosmological analyses
Neutralinos at NMSSM The mass matrix to neutralinos we can get the following results

1-) The singlino, $\tilde{S}$, does not mix directly with the gauginos

2-) The singlino, $\tilde{S}$, mix directly with the higgsinos $\tilde{H}_1^0$ and $\tilde{H}_2^0$

3-) If $|x| \gg v_{1,2}$ the singlino decouples from the other four neutralinos, which will be MSSM-like

4-) If $|\kappa|$ is very small this singlinolike state will become the LSP
Some motivation to generalize NMSSM

The existence of a “light” chiral gauge singlet superfield in the observable sector can cause difficulties

1-) The stability of gauge hierarchy

2-) The superpotential of NMSSM possesses a discrete $\mathbb{Z}_3$ symmetry

General Singlet Extensions MSSM (GSEMSSM)
\[ W_{GSEMSSM} = \mu \left( \hat{H}_1 \hat{H}_2 \right) + \lambda \left( \hat{H}_1 \hat{H}_2 \right) \hat{S} \]
\[ + \left( \xi_F M_n^2 \right) \hat{S} + \frac{\mu_2}{2} \left( \hat{S} \right)^2 + \frac{\kappa}{3} \left( \hat{S} \right)^3 \]
\[ + \sum_{i,j=1}^{3} \left[ f_{ab}^l \left( \hat{H}_1 \hat{L}_a \right) \tilde{\ell}_b^c + f_{ij}^d \left( \hat{H}_1 \hat{Q}_i \right) \tilde{d}_j^c \right] \]
\[ + f_{ij}^u \left( \hat{H}_2 \hat{Q}_i \right) \tilde{u}_j^c \]

If

\[ \mu = \xi_F = \mu_2 = 0 \]

Next-to-the-Minimal Supersymmetric Standard-Model (NMSSM)

\[ \mu = \mu_2 = \kappa = 0 \]

nearly Minimal Supersymmetric Model (nMSM)
\[ M_{H^\pm}^2 = M_W^2 \left( 1 - \frac{2\lambda^2}{g^2} \right) \frac{2C_1}{\sin(2\beta)} \]

\[ M_{H_{1,2}^{PS}}^2 = \frac{1}{2} \left[ \frac{2C_1}{\sin(2\beta)} + C_2 \right. \]

\[ \pm \sqrt{\left( \frac{2C_1}{\sin(2\beta)} + C_2 \right)^2 + \frac{16M_W^2C_3^2}{g^2}} \]

\[ M_{H_1^{PS}}^2 \geq 0 \quad \rightarrow \quad C_2 \geq 0 \]

- No absolute bound on the masses of the physical pseudoscalars can be given

- \( H_{1,2}^{PS} \) can both be very light

upper bound on the mass of the lightest neutral scalar \( H_1^0 \)

\[ M_{H_1^0}^2 \leq M_Z^2 \left[ \cos^2(2\beta) + \frac{2\lambda^2}{g^2} \cos^2\theta_W \sin^2(2\beta) \right] \]
MSSM with 3 RHN superpotential

\[ W = W_{MSSM}^{LC} + \sum_{i,j,k=1}^{3} \left( f_{ij}^{\nu} \hat{H}_2 \hat{L}_i \hat{\nu}_j^c + h_{ij}^{\nu} \hat{H}_2 \hat{H}_1 \hat{\nu}_i^c \right) \\
+ \frac{1}{2} M_{ij} \hat{\nu}_i^c \hat{\nu}_j^c + \frac{1}{3} \kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c \]

- Neutrino masses \( f^{\nu} \leq 10^{-12} \)

- Good Dark Matter sneutrinos

- Leptogenesis (CP phases in sneutrino)

- Flat Direction (Inflanton) \( \hat{H}_2 \hat{L} \hat{\nu}^c, \hat{H}_2 \hat{H}_1 \hat{\nu}^c \)

\( \mu \nu SSM \)

sneutrinos acquire vev’s

\[
\mu \equiv h_{ij}^{\nu} \langle \tilde{\nu}_i^c \rangle \quad \mu_{0i} \ll \mu \\
\mu_{0i} \equiv \sum_{j=1}^{3} f_{ij}^{\nu} \langle \tilde{\nu}_j^c \rangle \quad f^{\nu} \leq 10^{-6}
\]

same results to upper bound light \( H \) last page