Constraints on the gravitino mass in iNMSSM models

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November 27, 2017

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In the second section the set of the used model is introduced and the embedding of the NMSSM in this set shown.

In the Phenomenology section two different models are analysed:

Case 1: iNMSSM with a hidden sector

Case 2: iNMSSM without a hidden sector

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3. Scale invariance forbids terms $\sim \mu H_u \cdot H_d$, $\sim S$, $\sim S^2$
4. A NMSSM model suitable for inflation with h as the inflaton field.
5. But: A scale invariant NMSSM may result in the domain wall problem (from $\mathbb{Z}_3$ symmetry).

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can lead to an accelerated expansion for the conditions:

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Thus inflation corresponds to a period of accelerated expansion, where ϵ is the first slow-roll parameter:

$$\frac{\ddot{a}}{a} = H^2(1 - \epsilon) \quad ; \quad \epsilon = -\frac{\dot{H}}{H^2}$$

For a slow rolling field ϕ this gives:

$$\frac{\ddot{a}}{a} = -\frac{1}{6}(\rho_\phi + 3p_\phi) = H^2(1-\epsilon) \quad ; \quad \rho_\phi = \frac{\dot{\phi}}{2} + V(\phi)\ ,\ p_\phi = \frac{\dot{\phi}}{2} - V(\phi)$$

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And for inflation to occur, both slow-roll parameters must satisfy:

$$\epsilon \approx \frac{M_P^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 < 1 \quad ; \quad |\eta| \approx \left| M_P^2 \frac{V_{,\phi\phi}}{V} - \epsilon \right| < 1$$

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Thus inflation ends when $\epsilon(\phi_{\text{end}}) = 1$ and $|\eta(\phi_{\text{end}})| = 1$.

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In the Jordan frame the simplest scalar-gravity part of the action reads:

$$\mathcal{L}_J^{\text{scalar-gravity}} = \sqrt{-g_J}\left[-\frac{\Phi}{6}R - \delta_{\alpha\overline{\beta}}\hat{\partial}_\mu z^\alpha \hat{\partial}^\mu \overline{z}^{\overline{\beta}} - V_J\right]$$

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$$\Phi = -3M_P^2 e^{-\frac{\mathcal{K}}{3M_P^2}} \quad \Leftrightarrow \quad \mathcal{K} = -3M_P^2 \log\left(-\frac{1}{3M_P^2}\Phi\right) \tag{1}$$

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With the Kähler potential $\mathcal{K}$ and superpotential W the potential is:

$$V_J = \frac{\Phi^2}{9M_P^2}\left[e^{\frac{\mathcal{K}}{M_P^2}}\left(-\frac{3W\overline{W}}{M_P^2} + \nabla_\alpha W g^{\alpha\overline{\beta}} \nabla_{\kappa^2\overline{\beta}} \overline{W}\right) + \frac{1}{2}(Re\ f)^{-AB} P_A P_B\right]$$

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The gravtino mass reads [1]: $m_{3/2} = \frac{\langle W \rangle}{M_P^2}$

CSS models

Canonical superconformal supergravity (CSS) models

Introduce a set of CSS models [2], that after gauge fixing, results in a superconformal action, due to a decoupled compensator multiplet X^0, Ω^0 and F^0 from the physical multiplets X^α.

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The conditions for such a set of models are the following:

(1) A *flat SU(1,n) Kähler manifold* for all $n+1$ chiral multiplets X^I, also for the compensator field X^0:

$$\mathcal{N}(X,\overline{X}) = -|X^0|^2 + |X^\alpha|^2 \quad , \quad \alpha = 1,\ldots,n$$

$$G_{I\bar{J}} = \mathcal{N}_{I\bar{J}} = \eta_{I\bar{J}}, \quad G^{I\bar{J}} = \eta^{I\bar{J}}, \quad \Gamma^I_{JK} = 0, \quad R_{I\bar{K}J\bar{L}} = 0$$

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The $SU(1,n)$ symmetry corresponds to a $(-++\ldots)$ signature metric, but has no physical meaning and will get broken by the potential terms.

(2) A cubic, X^0 *independent superpotential*, which breaks the SU(1,n):

$$\mathcal{W}(X) = \frac{1}{3} d_{\alpha\beta\gamma} X^\alpha X^\beta X^\gamma \quad \Rightarrow \quad \mathcal{W}_0 = \frac{\partial \mathcal{W}}{\partial X^0} = 0.$$

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$$k_A^\alpha = (m_A)^\alpha{}_\beta X^\beta \quad , \quad k_A^{\overline{\alpha}} = (\overline{m}_A)^{\overline{\alpha}}{}_{\overline{\beta}} X^{\overline{\beta}}$$

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This leads to:

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Superconformal embedding of the NMSSM into SUGRA

The superconformal symmetry can be broken via additional terms $\sim \chi(H_u \cdot H_d + h.c.)$ and $\sim \zeta \frac{|S|^4}{M_P^2}$ to the frame function.

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The scale-free NMSSM model, has one gauge singlet and two gaugle doublet chiral superfields $z_H = \{S, H_u, H_d\}$:

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With $H_u \cdot H_d = -H_u^0 H_d^0 + H_u^+ H_d^-$ and the truncation $(\bigtriangledown)$:

$$H_u^+ = H_d^- = 0.$$

Phenomenology

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The effective superpotential breaks the $\mathbb{Z}_3$ symmetry and may solve the domain wall problem.

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$$\Rightarrow m_{3/2} = e^{\frac{\mathcal{K}}{2M_P^2}} \frac{\langle W\rangle}{M_P^2} \approx \frac{\langle W_{hid}\rangle}{M_P^2}$$

Expanding $\mathcal{K}$ from (1) for $\langle\phi^a\rangle \ll M_P$:

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V_{eff} then yields (with NMSSM truncation, D-flat direction (see Case 2.)):

$$V_{\text{eff}} \sim \lambda^2 h^4 + \rho s^4 + s^2 h^2(\lambda^2 + 2|\lambda\rho|) + h^2\chi^2 m_{3/2}^2 - s h^2 \chi \lambda m_{3/2} + \mathcal{O}\left(\frac{1}{M_P^2}\right)$$

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$$\left.\frac{\partial V_{\text{eff}}}{\partial s}\right|_{\langle s\rangle,\langle h\rangle} = 0 \quad , \quad \left.\frac{\partial^2 V_{\text{eff}}}{\partial s^2}\right|_{\langle s\rangle,\langle h\rangle} > 0 \quad , \quad \left.\frac{\partial^2 V_{\text{eff}}}{\partial h^2}\right|_{\langle s\rangle,\langle h\rangle} > 0 \qquad (2)$$

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These conditions in the minimum of the potential do not constrain $m_{3/2}$.

But $\frac{\partial V_{\text{eff}}}{\partial h}\Big|_{\langle s\rangle,\langle h\rangle} = 0$ cannot be satisfied without adding soft breaking terms:

$$V_{\text{soft}}^{W_{\text{eff}}} \sim A_\lambda \lambda S H_u \cdot H_d + A_\rho \rho S^3 + B_\mu \mu_{\text{eff}} H_u \cdot H_d + h.c. \tag{3}$$

$V_{\text{soft}}^{W_{\text{eff}}}$ contains the $\mathbb{Z}_3$ non-invariant term:

$$\Delta V = \frac{3}{2} B_\mu \chi m_{3/2} (H_u \cdot H_d + h.c.)$$

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$\mathbb{Z}_3$ symmetry does not lead to the domain wall problem if the difference in vacuum energy between different vacua (which are degenerate for $\chi = 0$) is greater than [4]:

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For[1] $B_\mu \sim v \quad \Rightarrow \quad m_{3/2} > 10^{-30} v \sim 10^{-19} eV$

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$$m_{3/2} \gtrsim \frac{B_\mu + \lambda s}{\chi} + \frac{1}{\chi}\sqrt{B_\mu^2 + \lambda(s(B_\mu + A_\lambda) - \lambda v^2 - |\rho| s^2)}$$

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With $B_\mu \sim \lambda s \sim v$ and $\chi \sim 10^5 \quad \Rightarrow \quad m_{3/2} \gtrsim 1MeV$

From the potetial an effective μ term arises from the terms $\sim \lambda S H_u \cdot H_d$ and $\chi m_{3/2} H_u \cdot H_d$, which should be of the order [3]:

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For $1 \gtrsim \rho \sim \lambda \gtrsim 10^{-4}$; $\frac{\chi}{\lambda} \sim 10^5$; $A_\lambda \sim A_\rho \sim 10^3 GeV$ one obatins:

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Thus for the gravitino mass: $10 MeV \lesssim m_{3/2} \lesssim 100 GeV$

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The first case studied is with a cubic superpotential that breaks the $SU(1,n)$ symmetry of the Kähler manifold.

The second case considers an addintional term $\sim M_P^3$ in the superpotential to tune the vacuum energy to $\gtrsim 0$, s.t. the $SU(1,n)$ symmetry is later broken by the potential terms.

iNMSSM: the model

Starting with the frame function, using the truncation ($\bigtriangledown$):

$$\Phi(z,\overline{z}) = -3M_P^2 + |S|^2 + |H_u^0|^2 + |H_d^0|^2 - \frac{3}{2}\chi(H_u^0 H_d^0 + \overline{H_u^0}\,\overline{H_d^0}) - \zeta\frac{|S|^4}{M_P^2}$$

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The D-term potential, where $\vec{\sigma}$ are the pauli matrices:

$$V_J^D = \frac{g'}{8}(|H_u^0|^2 - |H_d^0|^2)^2 + \frac{g}{8}(H_u^\dagger\vec{\sigma}H_u + H_d^\dagger\vec{\sigma}H_d)^2$$

Thus the NMSSM potential depends on 3 superfields:

$$S = se^{i\alpha}/\sqrt{2} \quad , \quad H_u^0 = h_1 e^{i\alpha_1}/\sqrt{2} \quad , \quad H_d^0 = h_2 e^{i\alpha_2}/\sqrt{2}$$

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This model is suitable for inflation with the slow-roll parameters:

$$\epsilon \simeq \frac{64M_P^4}{3\chi^2 h^4} \quad , \quad \eta \simeq -\frac{16M_P^2}{3\chi h^2} \quad , \quad N \sim 60 \quad , \quad \chi \simeq 10^5\lambda$$

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The full Jordan frame potential is very complicated but expanding it for $\langle h \rangle$, $\langle s \rangle$ after inflation gives (for this approximation $V_{\text{J}}^F = V_{\text{E}}^F$) :

$$V_J^F(s, h; \rho, \lambda, \chi, \zeta) \sim \lambda^2 h^4 + \rho^2 s^4 + h^2 s^2 (\lambda^2 - |\lambda \rho|) + \mathcal{O}\left(\frac{1}{M_P^2}\right)$$

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The minimum of V_J^F is at $\langle h \rangle = \langle s \rangle = 0$ and thus $m_{3/2} = 0$.

⇒ Soft breaking terms are needed, which become important after inflation![2]

$$V_{\text{soft}} \sim -\lambda A_\lambda s h^2 - \rho A_\rho s^3$$

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Analysing the minimum of $V = V_J^F + V_{\text{soft}}$ one obtains:

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The approximation $\langle s \rangle^2 \ll M_P^2$ is valid up to $\langle s \rangle \sim 10^{18} GeV$.

$$m_{3/2} \simeq \frac{\langle W \rangle}{M_P^2} \simeq \frac{A_\rho^3}{\rho^2 M_P^2} < 10 GeV \qquad (\text{for } A_\rho \sim 10^3 GeV)$$

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With $\langle s \rangle > v$: $\quad \Rightarrow \quad 10^{-23} eV < m_{3/2} < 10 GeV$

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iNMSSM with vacuum tuning

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Now consider the case of adding a constant term $\sim M_P^3$ to the superpotential to tune the vacuum energy to $\simeq 0$.

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The new contributions to the potential are:

$$\Delta V \sim \zeta \gamma^2 M_P^2 s^2 - \chi \lambda \gamma M_P h^2 s + \frac{\zeta \lambda \chi \gamma h^2 s^3}{M_P} + \frac{\zeta \rho \gamma s^5}{M_P} + \mathcal{O}\left(\frac{1}{M_P^3}\right)$$

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The full potential can be analysed for 2 different cases:

$$1)\ \ \rho^2 s^4 \ll \zeta \gamma^2 M_P^2 s^2 \quad ; \quad 2)\ \ \rho^2 s^4 \gg \zeta \gamma^2 M_P^2 s^2$$

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Case $1)$ is only valid for $\gamma > 10^{-13}$ $(*)$.

The vaccum conditions for s (2) then yield:

$$\frac{\partial V}{\partial s} = 0 \quad \Rightarrow \quad \langle s \rangle \sim \frac{\chi\lambda v^2}{\zeta\gamma M_P} \quad ; \quad \frac{\partial^2 V}{\partial s^2} > 0 \quad \Rightarrow \quad \langle s \rangle \gtrsim \frac{\chi\lambda v^2}{\zeta\gamma M_P}$$

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And the gravitino mass is given by:

$$\Rightarrow \quad m_{3/2} \simeq \frac{\rho\chi^3\lambda^3 v^6}{\zeta^3\gamma^3 M_P^5} + \gamma M_P \overset{*}{\simeq} \gamma M_P$$

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Case 2) is valid for $\gamma < 10^{-17}$ $(\star)$ and yields for s $(s \gg v)$:

$$\frac{\partial V}{\partial s} = 0 \quad \Rightarrow \quad \langle s \rangle \sim \left(\frac{\chi\lambda\gamma M_P v^2}{\rho^2}\right)^{\frac{1}{3}}$$

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For $10^{-17} < \gamma < 10^{-13}$, $\frac{\rho\langle s \rangle^3}{M_P^2} \ll \gamma M_P$ and thus for all γ:

$$m_{3/2} \simeq \gamma M_P$$

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Constraints on $m_{3/2}$

The vacuum conditions for h constrain γ to:

$$\frac{\partial V}{\partial h} = 0 \quad , \quad \frac{\partial^2 V}{\partial h^2} > 0 \quad \Rightarrow \quad \gamma > \frac{v}{\chi M_P}$$

Thus the gravitino mass in this model with

$$W = \lambda S H_u^0 H_d^0 + \frac{\rho}{3} S^3 + \gamma M_P^3$$

can be constrained to:

$$m_{3/2} \gtrsim \frac{v}{\chi} \sim 1MeV$$

Conclusions

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Thus these different models constrain the gravitino mass to the range:

$$10MeV \lesssim m_{3/2} \lesssim 10GeV$$

Thank you!

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