Lightest neutralino in the MNSSM

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Introduction

- Recent observations indicate that $22\% - 25\%$ of the energy density of the Universe exists in the form of stable non–baryonic, non–luminos (dark) matter.
- The existence of dark matter is the strongest piece of evidence for physics beyond the SM.
- In the MSSM the lightest SUSY particle (LSP) can play the role of dark matter.
- In most SUSY scenarios the LSP is the lightest neutralino.
- Since neutralinos are heavy weakly interacting particles they can
  - explain the large scale structure of the Universe;
  - provide the correct relic abundance of dark matter.

- But MSSM being incorporated in supergravity or GUTs suffers from the μ problem. Indeed, in SUGRA models

$$W_{SUGRA} = W_0(h_m) + \mu(h_m)(\hat{H}_d\hat{H}_u) + h_t(h_m)(\hat{Q}\hat{H}_2)\hat{U}^c_R + \dots\,,$$

where $\mu(h_m) \sim M_{Pl}$ or $\mu(h_m) = 0$.

- The correct pattern of electroweak symmetry breaking requires

$$\mu(h_m) \sim 100 - 1000\,\text{GeV}\,.$$

- In the NMSSM the superpotential is invariant under Z_3 discrete symmetry, i.e.

$$\mu(\hat{H}_d\hat{H}_u) \to \lambda\hat{S}(\hat{H}_d\hat{H}_u) + \frac{\varkappa}{3}\hat{S}^3\,.$$

- At the EW scale field S acquires VEV inducing an effective μ term

$$\mu_{eff} = \lambda\langle S\rangle\,.$$

- However VEVs of the Higgs fields break Z_3 symmetry resulting in the formation of domain walls which create unacceptably large CMB anisotropies.
- Non–renormalizable operators that break Z_3 symmetry give rise to quadratically divergent tadpole contributions destabilising the mass hierarchy.

> A.Vilenkin, Phys.Rep. 121 (1985) 263;
> S.A.Abel, S.Sarkar, P.L.White, Nucl.Phys.B 454 (1995) 663.

- The Z_2^R or Z_5^R symmetries allow to suppress the potentially harmful operators.

> C.Panagiotakopoulos, K.Tamvakis, Phys.Lett.B 446 (1999) 224;
> C.Panagiotakopoulos, K.Tamvakis, Phys.Lett.B 469 (1999) 145.

- High order operators do not affect mass hierarchy but prevent the appearance of domain walls.

Neutralino sector in the MNSSM

- The superpotential of the corresponding simplest extension of the MSSM – Minimal Non–minimal Supersymmetric Standard Model (MNSSM) is

$$W_{MNSSM} = \lambda \hat{S}(\hat{H}_d \hat{H}_u) + \xi\,\hat{S} + W_{MSSM}(\mu = 0)\,.$$

  where $\xi \lesssim$ (TeV)^2.

C.Panagiotakopoulos, A. Pilaftsis, Phys. Rev. D **63** (2001) 055003;
A.Dedes, C.Hugonie, S.Moretti, K.Tamvakis, Phys. Rev. D **63** (2001) 055009.

- High order operators which are not forbidden by Z_5^R symmetry induce linear term $\xi\,\hat{S}$ in the superpotential that breaks Z_3 and Peccei–Quinn symmetries.
- The neutralino sector of the MNSSM is formed by the superpartners of the neutral gauge bosons ($\tilde{W}_3,\ \tilde{B}$) and neutral Higgsino fields ($\tilde{H}_d^0$, $\tilde{H}_u^0$, $\tilde{S}$).

- In the field basis $(\tilde{B},\, \tilde{W}_3,\, \tilde{H}_d^0,\, \tilde{H}_u^0,\, \tilde{S})$ the neutralino mass matrix takes a form

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta & 0 \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta & 0 \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu_{eff} & -\frac{\lambda v}{\sqrt{2}} s_\beta \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu_{eff} & 0 & -\frac{\lambda v}{\sqrt{2}} c_\beta \\ 0 & 0 & -\frac{\lambda v}{\sqrt{2}} s_\beta & -\frac{\lambda v}{\sqrt{2}} c_\beta & 0 \end{pmatrix},$$

$$s_W = \sin\theta_W, \quad c_W = \cos\theta_W, \quad s_\beta = \sin\beta, \quad c_\beta = \cos\beta, \quad \mu_{eff} = \frac{\lambda s}{\sqrt{2}},$$

$$\tan\beta = \frac{v_2}{v_1}, \quad \langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \quad \langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad \langle S \rangle = \frac{s}{\sqrt{2}}.$$

- The spectrum of neutralino is defined by

$$\lambda\,, \qquad \mu_{eff}\,, \qquad \tan\beta\,, \qquad M_1\,, \qquad M_2\,.$$

- The direct chargino searches set limits on

$$|M_2|\,, \quad |\mu_{eff}| > 90 - 100\,\text{GeV}\,.$$

- In SUSY GUT's one gets

$$M_2 = \frac{\alpha_2(M_Z)}{\alpha_1(M_Z)}\,M_1 \simeq 2\,M_1\,.$$

- The requirement of validity of perturbation theory up to the GUT scale constrains the allowed range of λ

$$\lambda(M_Z) \lesssim 0.7\,.$$

- When λ is small the non–observation of Higgs boson at LEP rules out low values of $\tan\beta \lesssim 2.5$.

Upper bound on the mass of χ_1^0

- In order to find theoretical bounds on the neutralino masses $m_{\chi_i^0}$ it is convenient to consider matrix $M_{\tilde{\chi}^0} M^\dagger_{\tilde{\chi}^0}$.
- The eigenvalues of $M_{\tilde{\chi}^0} M^\dagger_{\tilde{\chi}^0}$ are equal to $|m_{\chi_i^0}|^2$.
- In the basis $\left(\tilde{B},\, \tilde{W}_3,\, -\tilde{H}_d^0 s_\beta + \tilde{H}_u^0 c_\beta,\, \tilde{H}_d^0 c_\beta + \tilde{H}_u^0 s_\beta,\, \tilde{S}\right)$ the bottom-right 2×2 block of $M_{\tilde{\chi}^0} M^\dagger_{\tilde{\chi}^0}$ takes a form

$$\begin{pmatrix} |\mu_{eff}|^2 + \sigma^2 & \nu^* \mu_{eff} \\ \nu \mu^*_{eff} & |\nu|^2 \end{pmatrix},$$

$$\sigma^2 = M_Z^2 \cos^2 2\beta + |\nu|^2 \sin^2 2\beta\,, \qquad \nu = \frac{\lambda v}{\sqrt{2}}\,.$$

- Since the minimal eigenvalue of $M_{\tilde{\chi}^0} M^\dagger_{\tilde{\chi}^0}$ is less than its smallest diagonal element, $|m_{\chi_1^0}| \lesssim |\nu|$.

- The mass of the lightest neutralino must be also smaller than the minimal eigenvalue of bottom-right 2×2 submatrix of $M_{\tilde{\chi}^0} M^\dagger_{\tilde{\chi}^0}$, i.e.

$$|m_{\chi_1^0}|^2 \lesssim \frac{1}{2}\left[|\mu_{eff}|^2 + \sigma^2 + |\nu|^2 - \sqrt{\left(|\mu_{eff}|^2 + \sigma^2 + |\nu|^2\right)^2 - 4|\nu|^2\sigma^2}\right].$$

- The lightest neutralino mass vanish when $\lambda \to 0$.
- The upper bound on $m_{\chi_1^0}$ decreases when $|\mu_{eff}|$ grow and at large $|\mu_{eff}| >> M_Z$

$$|m_{\chi_1^0}|^2 \lesssim \frac{|\nu|^2\sigma^2}{\left(|\mu_{eff}|^2 + \sigma^2 + |\nu|^2\right)}.$$

- Taking into account the restrictions on μ_{eff} and $\lambda(M_Z)$ we find

$$|m_{\chi_1^0}|^2 < 0.8\, M_Z^2 \Longrightarrow m_{\chi_1^0} \lesssim 80 - 85\,\text{GeV}.$$

Approximate solution for $m_{\chi_1^0}$

- Neutralino masses obey characteristic equation

$$\det\left(M_{\tilde{\chi}^0} - \varkappa I\right) = \left(M_1 M_2 - (M_1 + M_2)\varkappa + \varkappa^2\right)\left(\varkappa^3 - (\mu_{eff}^2 + \nu^2)\varkappa + \right.$$
$$\left. + \nu^2 \mu_{eff}\sin 2\beta\right) + M_Z^2\left(\tilde{M} - \varkappa\right)\left(\varkappa^2 + \mu_{eff}\sin 2\beta\varkappa - \nu^2\right) = 0\,,$$

  where $\tilde{M} = M_1 c_W^2 + M_2 s_W^2$ and $\varkappa$ is an eigenvalue of $M_{\tilde{\chi}^0}$.

- Because in the MNSSM $|m_{\chi_1^0}|$ is considerably smaller than $|m_{\chi_2^0}|$ one can ignore $\varkappa^3$, $\varkappa^4$ and $\varkappa^5$ terms in the characteristic equation so that it reduces to

$$\varkappa^2 - B\,\varkappa + C = 0\,.$$

- Then the approximate solution for $m_{\chi_1^0}$ can be written as

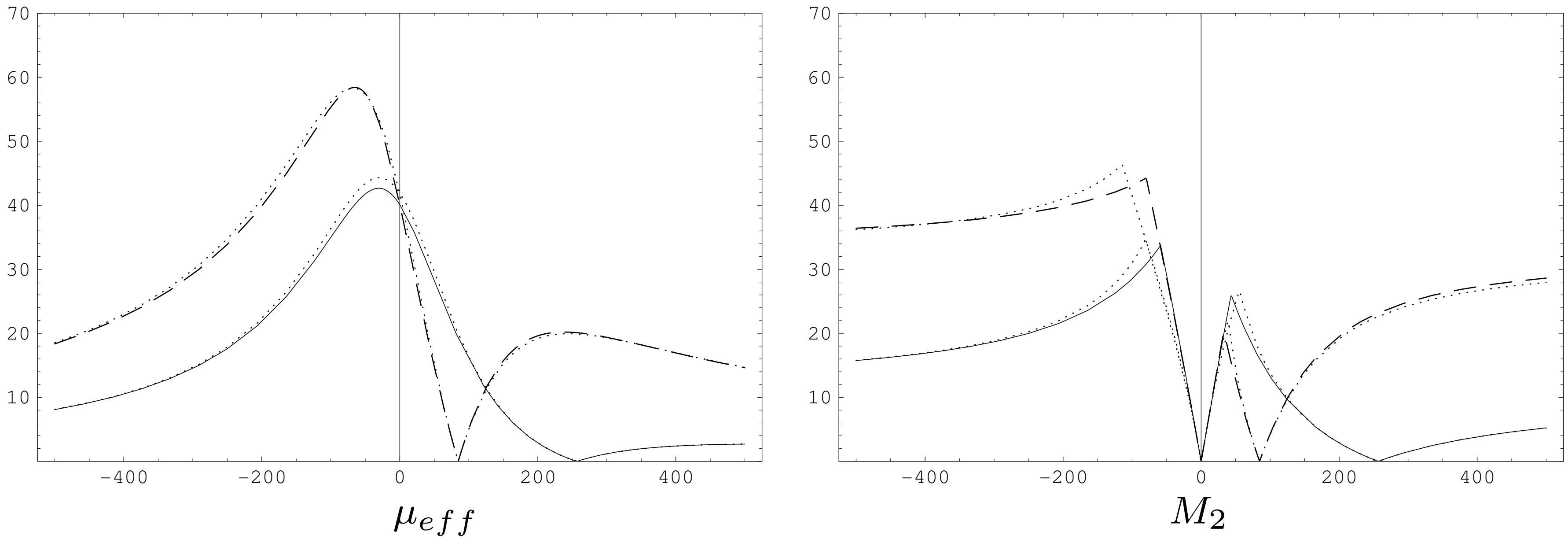
$$|m_{\chi_1^0}| = \text{Min}\left\{\frac{1}{2}\left|B - \sqrt{B^2 - 4\,C}\right|,\ \frac{1}{2}\left|B + \sqrt{B^2 - 4\,C}\right|\right\}\,.$$

- B and C are given by

$$B = \frac{M_1 M_2}{M_1+M_2} + \left(\frac{\nu^2}{\mu_{eff}^2+\nu^2} - \frac{M_Z^2}{\mu_{eff}^2+\nu^2}\frac{\tilde{M}}{M_1+M_2}\right)\mu_{eff}\sin 2\beta - \frac{M_Z^2\nu^2}{(M_1+M_2)(\mu_{eff}^2+\nu^2)},$$

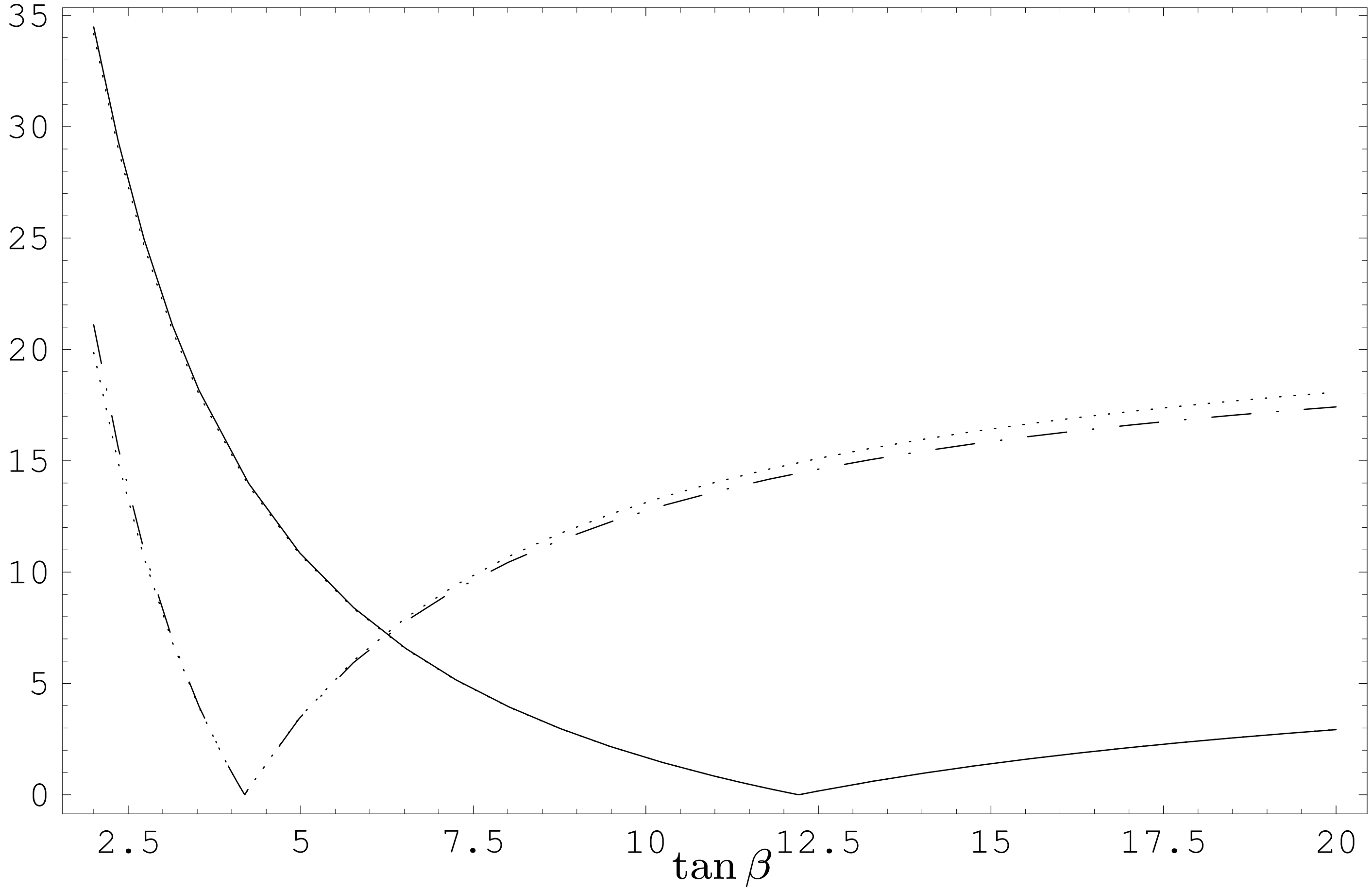
$$C = \frac{\nu^2}{\mu_{eff}^2+\nu^2}\left(\frac{M_1 M_2}{M_1+M_2}\mu_{eff}\sin 2\beta - \frac{\tilde{M}}{M_1+M_2}M_Z^2\right).$$

Lightest neutralino mass for $\lambda = 0.7$, $M_1 = 0.5 M_2$ and $\tan\beta = 10,\ 3$.



- When $|m_{\chi_1^0}|$ is close to its maximum value the lightest neutralino is basically formed by $\tilde{B}$ and $\tilde{S}$.

Lightest neutralino mass for $\lambda = 0.7$, $M_1 = 0.5\, M_2$, $M_2 = \mu_{eff}$



- When $|m_{\chi_1^0}|$ is considerably less than M_Z the lightest neutralino is predominantly singlino.
- If either μ_{eff} or $M_{1,2} \gg M_Z$ then

$$|m_{\chi_1^0}| \simeq \frac{|\mu_{eff}|\nu^2 \sin 2\beta}{\mu_{eff}^2 + \nu^2}\,.$$

  - The lightest neutralino mass decreases with raising of μ_{eff} and $\tan\beta$.
  - Since the correct EW symmetry breaking requires $\mu_{eff} = const$ when $\lambda \to 0$ the lightest neutralino mass is proportional to λ^2 at small values of λ.
- At very large $\tan\beta$

$$|m_{\chi_1^0}| \to \frac{\nu^2 M_Z^2}{\mu^2 + \nu^2}\left|\frac{\tilde{M}}{M_1 M_2}\right|.$$

  - The lightest neutralino mass reduces when M_1 and M_2 grow.

Conclusions

- We have argued that in contrast with the MSSM the allowed range of the mass of the lightest neutralino in the MNSSM is limited.
- In the allowed part of the parameter space the lightest neutralino mass does not exceed $80 - 85$ GeV.
- We have found the approximate solution for the lightest neutralino mass.
  - At large values of μ–term $m_{\chi_1^0}$ is inversely proportional to μ_{eff}.
  - $|m_{\chi_1^0}|$ vanishes in the limit when $\lambda \to 0$.
  - $|m_{\chi_1^0}|$ decreases with raising of $\tan\beta$, M_1, and M_2.
- In the allowed part of the parameter space the lightest neutralino is predominantly singlino that makes rather difficult its observation at future colliders.