Cosmological Properties of the MSSM with a Minimal Singlet Sector

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Outline

1. The nMSSM;

   a minimal singlet extension of the MSSM.

2. Electroweak Baryogenesis

3. Charginos, Neutralinos, and Dark Matter

4. Higgs Bosons

The nMSSM

The MSSM faces a few difficulties:

- The tree-level mass of the lightest CP-even Higgs is bounded by M_Z:

  $$m_h^2 \leq M_Z^2 \cos^2 2\beta,$$

  but LEP II finds $m_h \gtrsim 114$ GeV.

- The parameter space consistent with electroweak baryogenesis is very constrained ($m_h \lesssim 120$ GeV), and depends sensitively on the stop parameters.

  [Laine+Rummukainen '00, Balazs *et al* '04]

- μ problem; the dimensionful coupling $\mu\,\hat{H}_1 \cdot \hat{H}_2$, with $\mu \sim \mathcal{O}$(TeV), is needed to break the electroweak symmetry, but it is difficult to explain why μ is so much smaller than M_{GUT} or M_{Pl}.

  (However, see [Giudice+Masiero '88].)

Adding a gauge singlet S helps:

- $\mu\, \hat{H}_1 \cdot \hat{H}_2 \to \lambda\, \hat{S}\, \hat{H}_1 \cdot \hat{H}_2$ solves the μ problem; S gets a VEV at a scale set by the soft terms.

- The upper bound on the lightest CP-even Higgs mass becomes

$$m_h^2 \le M_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{\bar{g}^2} \sin^2 2\beta \right).$$

- A new $S\, H_1 \cdot H_2$ trilinear soft term enlarges the parameter space consistent with electroweak baryogenesis.

  [Pietroni ’92, Davies *et al* ’96, Schmidt+Huber ’00, Kang *et al* ’04.]

But . . .

- The singlet must be charged under some additional symmetry to forbid new dimensionful ($d < 4$) couplings.

- The most popular choice is a $\mathbb{Z}_3$ symmetry, which yields the superpotential

$$W = \lambda \hat{S}\, \hat{H}_1 \cdot \hat{H}_2 + \kappa\, \hat{S}^3 + (\text{MSSM matter terms}).$$

This model is called the NMSSM,

the Next-to-Minimal Supersymmetric Standard Model.

- When S gets a VEV, the $\mathbb{Z}_3$ symmetry is broken producing unacceptable domain walls.

- The domain wall problem can be avoided by including non-renormalizable operators that break $\mathbb{Z}_3$.
However, these generate a large singlet tadpole which destabilizes the hierarchy.

A way out:

- Both problems can be avoided in a supergravity scenario by imposing a $\mathbb{Z}_5^R$ or $\mathbb{Z}_7^R$ R-symmetry on both the superpotential and the Kähler potential.

  [Pangiotakopoulos+Tamvakis '98/'99, Pangiotakopoulos+Pilaftsis '00, Dedes *et al* '00]

- These symmetries allow only $d \geq 4$ terms in the superpotential.

- A singlet tadpole is generated by non-renormalizable operators, but only at six or seven loop order.
  The loop suppression is strong enough that the induced tadpole does not destabilize the hierarchy.

- The symmetries also forbid all dangerous $d \leq 5$ B- and L-violating operators, and stabilize the LSP.

- We call this the nMSSM, the not-quite MSSM.

Potentials

- Superpotential:

$$W = \frac{m_{12}^2}{\lambda^2}\,\hat{S} + \lambda\,\hat{S}\,\hat{H}_1 \cdot \hat{H}_2 + (\text{MSSM matter terms}),$$

where $m_{12}^2/\lambda^2 = \mathcal{O}(\text{TeV}^2)$.

- Soft-breaking potential:

$$\begin{aligned} V_{soft} \quad &= \quad t_s(S + h.c.) \; + \; m_s^2|S|^2 \\ &\quad + a_\lambda(S\,H_1 \cdot H_2 + h.c.) \; + \; (\text{MSSM terms}). \end{aligned}$$

- The same superpotential and soft-breaking terms also arise in the low-energy limit the "Fat Higgs" model.
[Harnik *et.al.* '03]

Electroweak Baryogenesis

- The Universe contains more baryons than anti-baryons:

$$\frac{n_B}{n_\gamma} = \left(6.1^{+\,0.3}_{-\,0.2}\right) \times 10^{-10}.$$

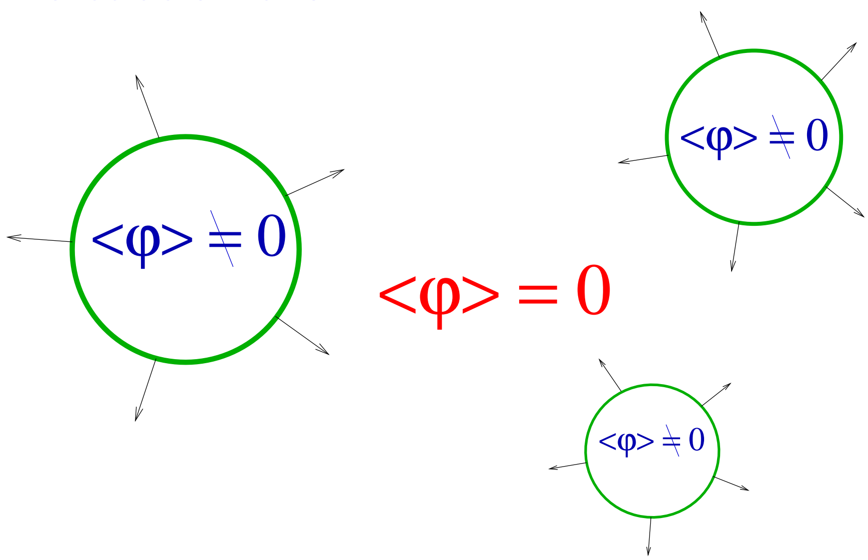
[WMAP '03]

- A net baryon number can be produced in the early Universe during the electroweak phase transition.

  $\Rightarrow$ electroweak baryogenesis (EWBG)

- If this transtion is first order, bubbles of broken phase nucleate within the symmetric phase, and expand out.

- Baryon number is generated by reactions in and around the bubble walls.

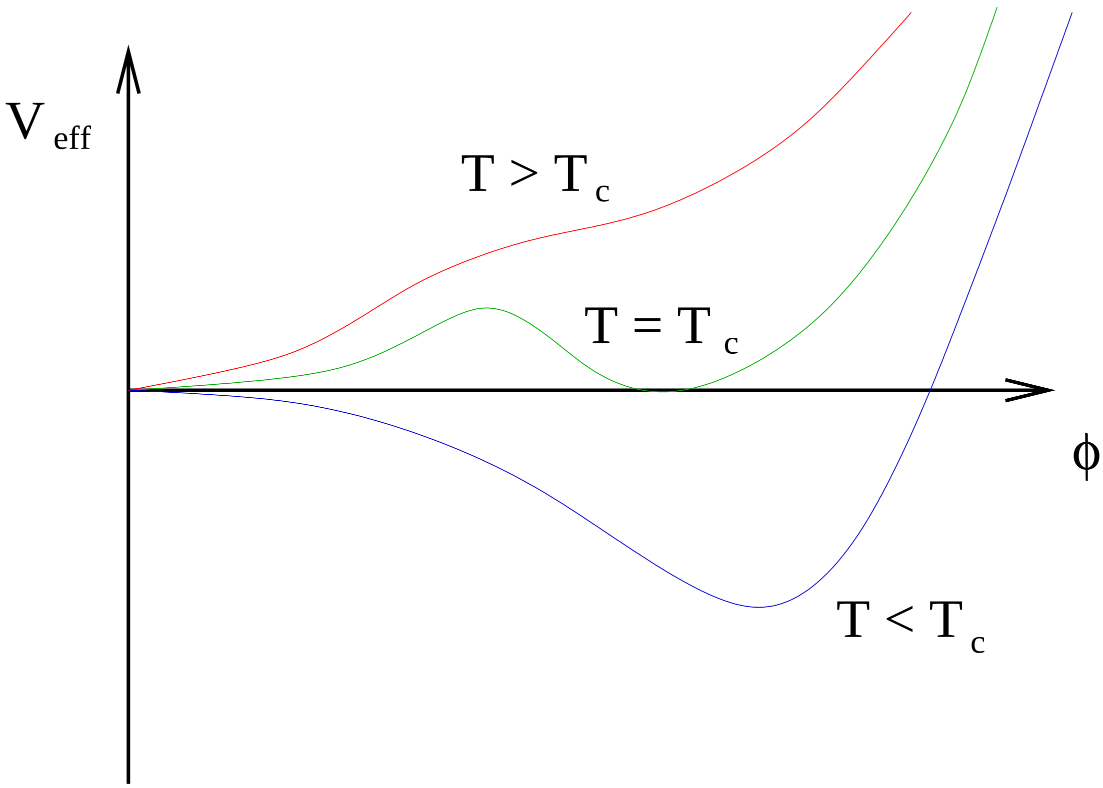


- For EWBG to work, the electroweak phase transition must be strongly first order:

$$\frac{\langle \phi(T_c) \rangle}{T_c} \gtrsim 1,$$

where $\phi = \sqrt{\phi_1^2 + \phi_2^2}$.

- This is determined by $V_{eff}(\phi, T)$:



- In the SM and MSSM, the potential has the form:

$$V_{eff} \simeq (-m^2 + A\,T^2)\phi^2 - B\,T\,\phi^3 + C\,\phi^4 + \ldots.$$

B drives the transition to be first order.

$B = 0$ at tree-level in the SM and MSSM.

- SM: the PT isn't strong enough.

- MSSM: one-loop corrections to V_{eff} from a light stop ($m_{\tilde{t}_1} < m_t$) can make the PT strong enough, but only for $m_h < 120$ GeV.

  [Carena *et al* '96, Laine '96, Losada '97, Laine+Rummukainen '00]

- In the nMSSM, the potential has the approximate form:

  (*i.e.* tree-level + dominant one-loop high-T terms)

$$\begin{aligned} V_{eff} &\simeq (-m^2 + A\,T^2)\phi^2 \;+\; \tilde{\lambda}^2\phi^4 \\ &\qquad + \; 2t_s\phi_s \;+\; 2\tilde{a}\,\phi_s\phi^2 \;+\; \lambda^2\phi^2\phi_s^2 \end{aligned}$$

  with $\tilde{a} = \frac{1}{2}\,a_\lambda\,\sin 2\beta$, $\tilde{\lambda}^2 = \frac{\lambda^2}{4}\sin^2 2\beta + \frac{\bar{g}^2}{2}\cos^2 2\beta$.

- Along the trajectory $\frac{\partial V}{\partial \phi_s} = 0$, the potential reduces to

$$V_{eff} = (-m^2 + A\,T^2)\phi^2 \;-\; \left(\frac{t_s + \tilde{a}\,\phi^2}{m_s^2 + \lambda^2\phi^2}\right) + \tilde{\lambda}^2\phi^4.$$

- At the critical temperature,

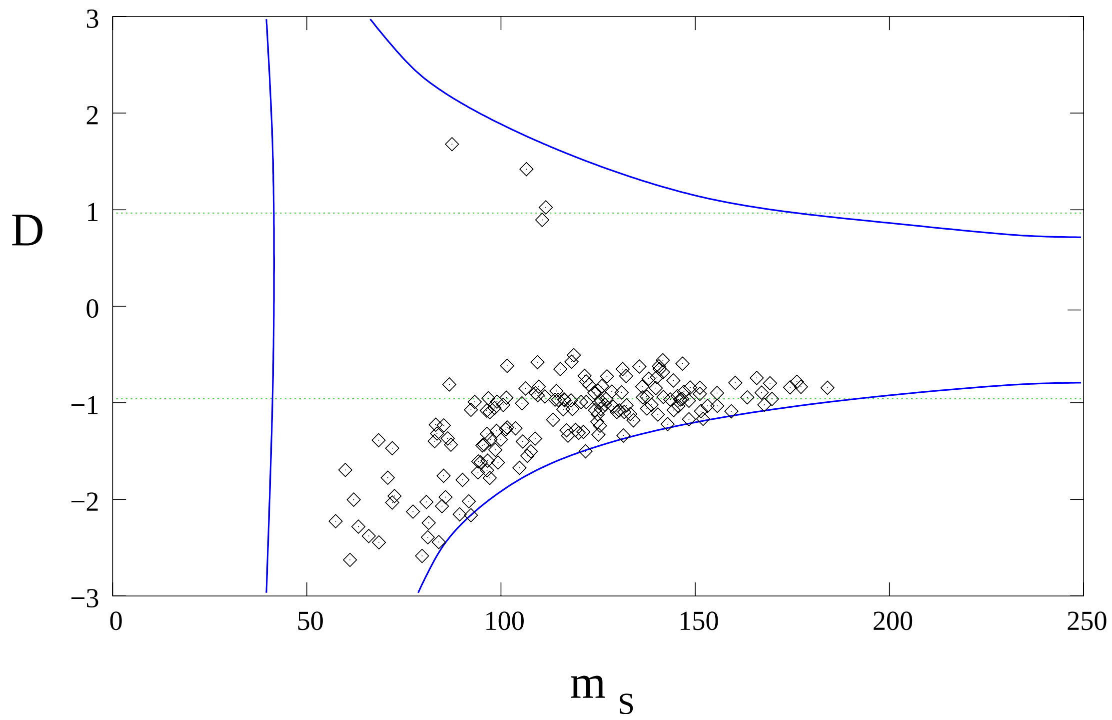
$$\begin{aligned} V(\phi_c, T_c) &= V(\phi = 0, T_c) \\ \left.\frac{\partial V}{\partial \phi}\right|_{\phi=\phi_c} &= 0. \end{aligned}$$

- This has a solution provided

$$|D| = \frac{1}{\tilde{\lambda}\,m_s^3}\left|\lambda^2\,t_s - \tilde{a}\,m_s^2\right| > 1 \;\; .$$

$\Rightarrow$ terms in the tree-level potential can make the phase transition first-order.

- We consider heavier stops: $m_{\tilde{t}}^2 \gtrsim (500\ \text{GeV})^2$.
- A numerical analysis of the full one-loop potential supports the $|D| > 1$ condition:



- Dots $\leftrightarrow$ parameter sets with $\phi_c/T_c > 1$.
- Blue lines $\leftrightarrow$ region consistent with collider bounds. ($\Rightarrow$ sufficiently heavy Higgs bosons, -inos, . . .)
- EWBG $\Rightarrow$ $m_s \lesssim 200$ GeV.

Charginos, Neutralinos and Dark Matter

- The chargino mass matrix is identical to the MSSM, but with $\mu \to -\lambda\, v_s$.
- The fermion component of $\hat{S}$, the singlino, produces a fifth neutralino state.

$$\mathcal{M}_{\tilde{N}} = \begin{pmatrix} M_1 & \cdot & \cdot & \cdot & \cdot \\ 0 & M_2 & \cdot & \cdot & \cdot \\ -c_\beta s_w M_Z & c_\beta c_w M_Z & 0 & \cdot & \cdot \\ s_\beta s_w M_Z & -s_\beta c_w M_Z & \lambda v_s & 0 & \cdot \\ 0 & 0 & \lambda v_2 & \lambda v_1 & 0 \end{pmatrix}$$

- We relate M_1 to M_2 by universality and allow for a common phase; $M_2 = |M_2|\, e^{i\phi} \simeq \frac{\alpha_2}{\alpha_1}\, M_1$.
- $\lambda(M_Z) \lesssim 0.8$ for perturbative unification.
- There is always a light neutralino: $m_{\tilde{N}_1} \lesssim 60$ GeV.

e.g.
$$m_{\tilde{N}_1} \simeq \frac{2\,\lambda\, v_1\, v_2\, v_s}{v_1^2 + v_2^2 + v_s^2},$$

for M_1, $M_2 \to \infty$, and $\tan\beta \gg 1$ or $v_s \gg v$.

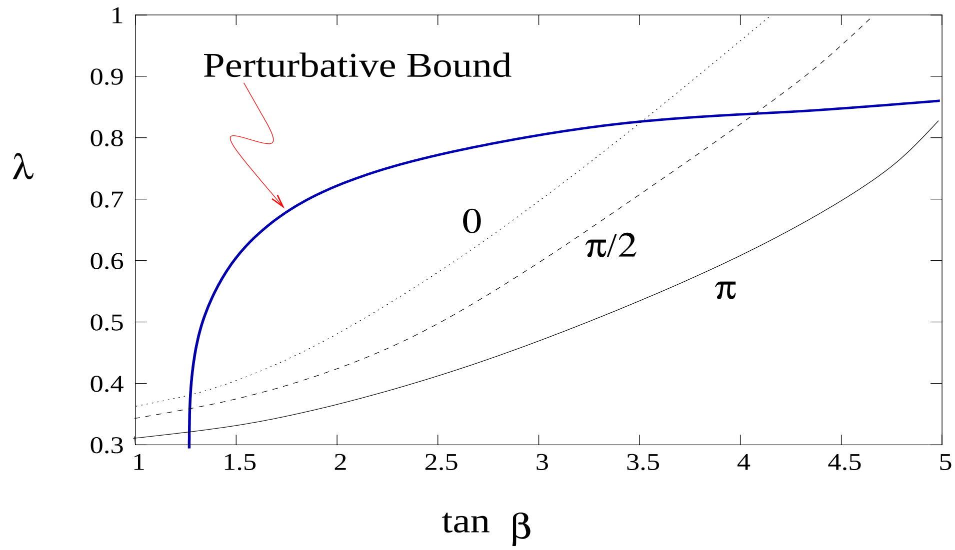
- The lightest neutralino is the LSP, and is mostly singlino.
- $\mathbb{Z}_5^R$ or $\mathbb{Z}_7^R$ make the LSP stable on cosmological scales.

  $\Rightarrow$ dark matter candidate.
- Annihilation Modes:
  - s-channel Z^0 $(m_{\tilde{N}_1} \sim M_Z/2)$
  - s-channel Higgs $(\lambda \hat{S}\, \hat{H}_1 \cdot \hat{H}_2 \subset W)$
- Higgsino mixing increases the mass and couplings.

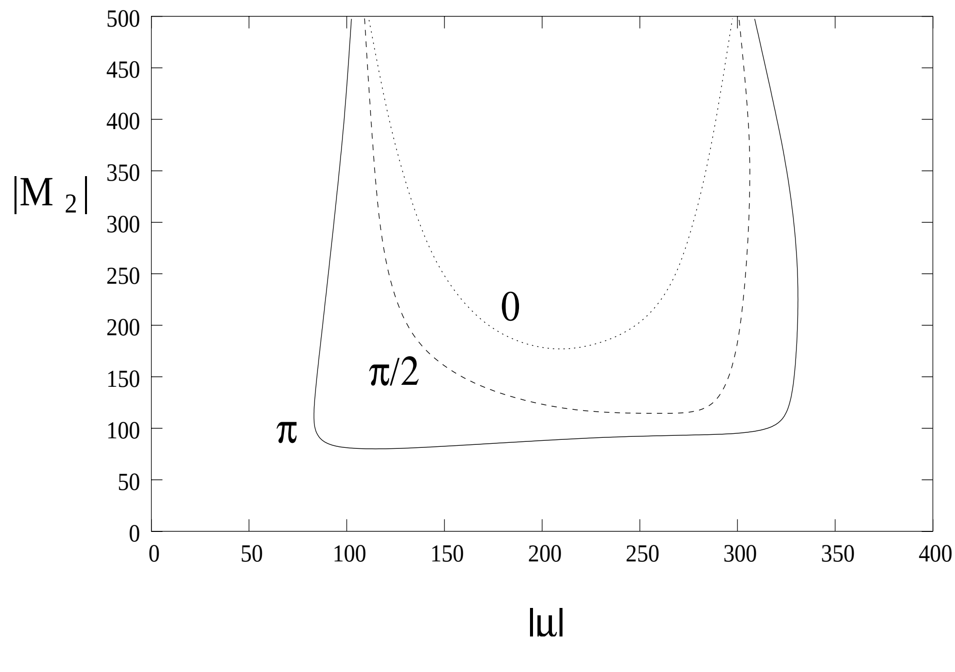
  $\tan\beta \gg 1$ or $v_s \gg v \Rightarrow$ small mixing.

  $\tan\beta \sim 1$ and $v_s \sim v \Rightarrow$ large mixing.
- A very weakly coupled LSP leads to an unacceptably large neutralino relic density.
- If $m_{\tilde{N}_1} < M_Z/2$, too much mixing produces too large a contribution to the Z width.
- Necessary condition: $m_{\tilde{N}_1} > 25$ GeV.

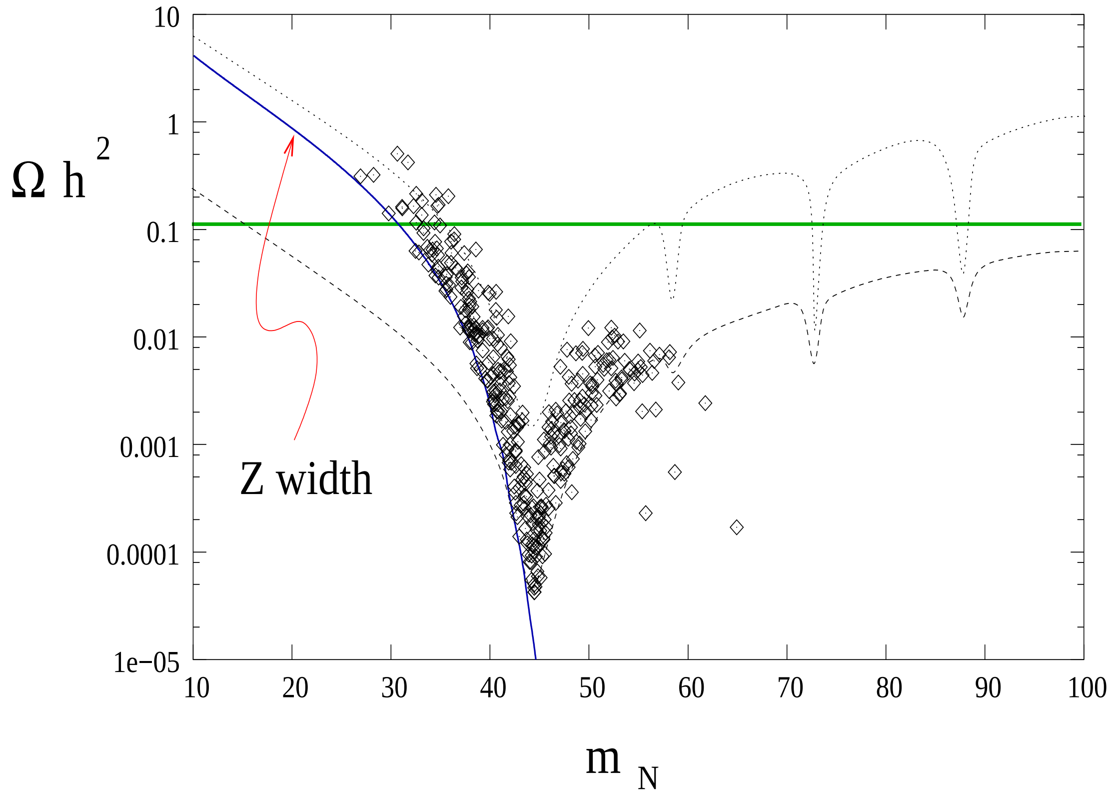
- Allowed region in the $\tan\beta - \lambda$ plane.



- Allowed region in the $|\mu| - |M_2|$ plane. ($\mu = -\lambda\, v_s$)



- Neutralino relic densities consistent with EWBG.



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- Dots = parameter sets consistent with EWBG.
- Green line = WMAP result;

  $\Omega_{DM}\, h^2 = 0.113^{+0.016}_{-0.018}$.
- Blue line = LEP Z-width constraint.

  $\Gamma(Z \to \tilde{N}_1 \tilde{N}_1) < 2.0$ MeV.
- Dotted/dashed lines = “typical” values of the mixing parameters.

Higgs Bosons

- Physical states: 3 CP-even, 2 CP-odd, 1 charged.

- For $M_a^2 \to \infty$, the charged state, and one CP-even state and one CP-odd state decouple.

- The remaining CP-odd state has mass

$$m_P^2 = m_s^2 + \lambda^2 v^2.$$

and is pure singlet.

- The remaining CP-even states have mass matrix

$$M_S^2 = \begin{pmatrix} M_Z^2 \cos^2 2\beta + \lambda^2\, v^2\ \sin^2 2\beta & \cdot \\ v(a_\lambda \sin 2\beta + 2\,\lambda^2 v_s) & m_s^2 + \lambda^2 v^2 \end{pmatrix}.$$

This is in basis (S_1, S_2), where S_1 is SM-like, and S_2 is a singlet.

- Perturbativity ($\lambda \lesssim 0.8$) $\Rightarrow$

$$M_Z^2 \cos^2 2\beta + \lambda^2\, v^2\, \sin^2 2\beta \lesssim (115\,\text{GeV})^2.$$

- EWBG $\Rightarrow$

$$m_s^2 + \lambda^2 v^2 \lesssim (250\,\text{GeV})^2.$$

- If both conditions hold, there are always two light CP-even states, and one light CP-odd state.

- The lightest CP-even and CP-odd states usually decay invisibly into pairs of the neutralino LSP.

Summary

- The nMSSM solves the μ problem
  while avoiding the domain wall problem of the NMSSM.

- New terms in the scalar potential can make the
  electroweak phase transition strongly first order,
  as required for EWBG.

- The lightest neutralino is the LSP,
  and is a good dark matter candidate for
  $m_{\tilde{N}_1} = 30 - 40$ GeV.