Neutralino dark matter in the NMSSM

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Plan:
- A good dark matter candidate - **WIMPs**
- Introducing the **NMSSM**
- NMSSM **dark matter:** results and discussion

A good dark matter candidate

- **No emission/absorption** of **electromagnetic** radiation (any λ)
- **Gravitational** interactions on array of scales

  tiny dwarf galaxies, large spirals (Milky Way), clusters of galaxies ...

- **Correct relic density**

  Astrophysical bounds $\Rightarrow$ $0.1 \lesssim \Omega_{\text{dark}}\, h^2 \lesssim 0.3$

  Cosmological observations $\Rightarrow$ **WMAP**: $0.095 \lesssim \Omega_{\text{dark}}\, h^2 \lesssim 0.112$

  $\Omega_{\text{TOTAL}} = \Omega_\Lambda + \Omega_{\text{matter}} = 1.02 \pm 0.02$ $\boxed{\Omega_{\text{dark}} \approx \mathbf{25\,\%}\ \Omega_{\text{TOTAL}}}$

- **Cold dark matter** requires candidate from **physics beyond SM**$^{\nu_R}$

Arise in **well-motivated** models (SUSY, Large Extra Dimensions, etc)

- **Phenomenologically viable** $\Rightarrow$ low-energy scenario compatible with

  LEP/Tevatron bounds: direct searches, precision measurements, etc

  Other **accelerator** constraints: B- and K-decays, $(g-2)_\mu$, ...

Weakly Interacting Massive Particles

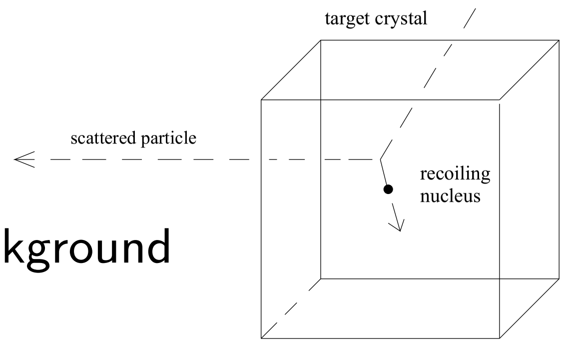
The most promising (non-baryonic) **cold dark matter** candidates

WIMPs:
- Heavy 4th generation neutrino (ruled out for $m < 1.5$ TeV)
- Extra scalar fields (little Higgs model, N=2 SUSY, LEDs,...)
- **SUSY** $(\tilde{\nu},\ \tilde{\chi}_1^0,\ \tilde{G},\ \tilde{a})$

- WIMPs arise in well motivated extensions of the standard model
- Stable particles, no electromagnetic interactions; WIMP $\overset{\text{weak}}{\leftrightsquigarrow}$ matter
- WIMP masses typically lie in the range 10 GeV up to a few TeV
- If WIMPs do indeed fulfil above conditions $\rightarrow$ **correct relic abundance**

WIMP direct detection (indirect detection also possible...)

WIMP dark matter can be detectable via observation of WIMP-matter scattering in a detector



WIMP signal: excess of recoil events above expected background

SUSY dark matter beyond the MSSM - the NMSSM

Add **singlet** superfield $\boldsymbol{S}$ to the MSSM

Next-to-Minimal Supersymmetric Standard Model

⇒ Elegant **solution to the μ-problem** of the MSSM

$\mu H_1 H_2 \to \lambda S H_1 H_2 \;\Rightarrow$ Dynamically generated μ: $\mu_{\text{eff}} = \lambda \langle S \rangle$

Scale-invariant superpotential: EW, SUSY scale only appearing via $\mathcal{L}_{\text{soft}}$

⇒ **Less severe** "Higgs - little fine tuning problem" of the MSSM

⇒ Formally...

$$\textbf{NMSSM} = \text{MSSM} + \hat{S} \begin{cases} 2 \text{ extra } \textbf{Higgs} \text{ (CP-even, CP-odd)} \\ 1 \text{ additional } \textbf{neutralino} \end{cases}$$

$$\boldsymbol{W} = Y_u H_2 Q u + Y_d H_1 Q d + Y_e H_1 L e - \boldsymbol{\lambda} S H_1 H_2 + \tfrac{1}{3} \boldsymbol{\kappa} S^3$$

$$-\mathcal{L}_{\text{soft}}^{\text{Higgs}} = m_{H_i}^2 H_i^* H_i + \boldsymbol{m_S^2} S^* S + \left(-\boldsymbol{\lambda} \boldsymbol{A_\lambda} S H_1 H_2 + \tfrac{1}{3} \boldsymbol{\kappa} \boldsymbol{A_\kappa} S^3 + \text{H.c.}\right)$$

⇒ Richer and more complex **phenomenology** - extra Higgs, neutralino

⇒ Important implications for **dark matter analysis!**

NMSSM neutralino dark matter

Neutralino sector: 5 Majorana fermions

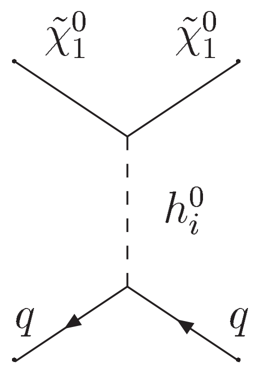
$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0 + N_{15}\tilde{S}$$

Neutral Higgs sector: 2 pseudoscalar and 3 **scalar bosons**

$$h_1^0 = S_{11}H_1^0 + S_{12}H_2^0 + S_{13}S$$

Very light singlet-like Higgs and **singlino-like** $\tilde{\chi}_1^0$ can escape detection (e.g. reduced coupling to Z boson) $\Rightarrow$ **experimentally viable**

Implications for **Dark Matter:** Neutralino-nucleon cross section $\sigma_{\tilde{\chi}_1^0-p}$



Higgs-exchange + Squark-exchange (spin-independent)

$$\sigma_{\tilde{\chi}_1^0-p} \propto \alpha_{3i}^h = \sum_{a=1}^{3} \frac{1}{m_{h_a^0}^2} C_Y^i \, \mathrm{Re}\left[C_{HL}^a\right]$$

$$C_{HL}^a = 2\{-g\,(N_{12}^* - \tan\theta_W N_{11}^*)\,(S_{a1}N_{13}^* - S_{a2}N_{14}^*) + $$

$$+\sqrt{2}\lambda\,[S_{a3}N_{13}^*N_{14}^* + N_{15}^*\,(S_{a2}N_{13}^* + S_{a1}N_{14}^*)] - \sqrt{2}\kappa\, S_{a3}N_{15}^*N_{15}^*\}$$

$$C_Y^{1(2)} = -\frac{g\,m_{u(d)}}{2M_W \sin(\cos)\beta} S_{a2(1)}$$

Exchange of light Higgs (not pure singlet) $\Rightarrow$ enhancement to $\sigma_{\tilde{\chi}_1^0-p}$

NMSSM neutralino dark matter

Neutralino sector:
- 5 Majorana fermions
- $\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0 + N_{15}\tilde{S}$

Neutral Higgs sector:
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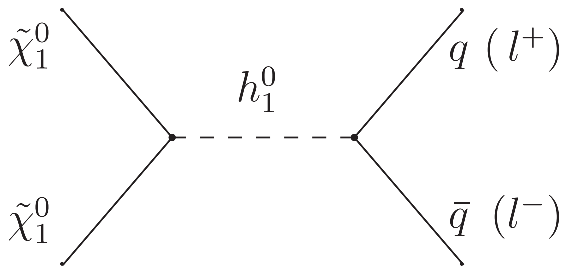
Implications for **Dark Matter:** Neutralino relic density Ωh^2



New open channels! Additional resonances!

Extra Higgs: annihilation via s-channel Higgs resonances

Light $h_1^0,\ a_1^0 \Rightarrow$ new annihilation channels

$Zh_1^0,\ h_1^0h_1^0,\ h_1^0a_1^0,\ \ldots$
- $s-$channel : $Z,\ h_1^0,\ a_1^0$
- $t-$channel : $\tilde{\chi}_1^0$ exchange

In general, **large** $\sigma_{\tilde{\chi}_1^0-p}$ are associated with Ωh^2 **below** observed values

Exploring the NMSSM parameter space

- Unconstrained low energy NMSSM $\lambda\,,\kappa\,,\mu(=\lambda s)\,,A_\lambda\,,A_\kappa\,,M_1\,,M_2\,,M_{\text{SUSY}}$ free
- Minimisation of the potential   [exclusion of over 2/3 of parameter space]
- Absence of Landau poles for λ, κ, Y_t and Y_b below M_{GUT}
- Computation of the NMSSM spectrum

  Higgs, chargino and neutralino masses and mixings; couplings
- Experimental constraints

  Neutralino: Γ_Z^{inv}, direct production $\sigma(e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0)$; Bounds on $m_{\tilde{\chi}_1^+}$ and m_{H^+}

  Neutral Higgs: Constraints on production rates (all LEP channels)

  NMHDECAY

  Rare B- and K-meson decays $\Rightarrow$ SUSY contributions to BR($b \to s\gamma$)!

  Muon anomalous magnetic moment $\Rightarrow$ SUSY contributions to saturate a_μ^{exp}
- Cosmological constraints: Ωh^2 compatibility (astro & WMAP)   **MicrOMEGAS**
- Neutralino-nucleon cross section - comparison with detector sensitivities

  Interested in **NMSSM-like scenarios** (light h_1^0, $\tilde{\chi}_1^0$) inducing **large** $\sigma_{\tilde{\chi}_1^0-p}$

Looking for NMSSM-like dark matter scenarios

★ **Regimes** where **singlet-singlino** components are **“active”**

Lightest Higgs is not doublet-like (important **singlet** composition)

& **lightest neutralino** has large **singlino** component

★ **Typically** found for

⇒ Low $\tan\beta$, small μ ($\lesssim M_1$), small A_λ ...

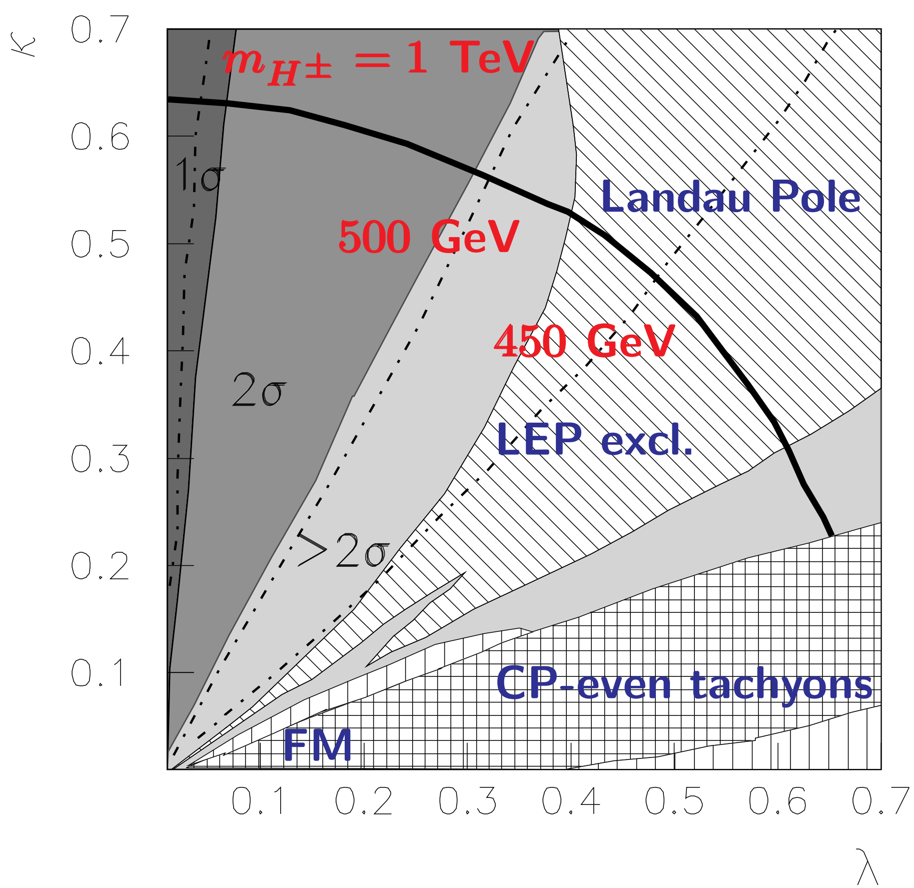
⇒ In the parameter space generated by the new couplings in W_{NMSSM}

$$(\lambda - \kappa) : \begin{cases} \textbf{Singlino-like } \tilde{\chi}_1^0 & \leftrightarrow \quad \text{small } \kappa/\lambda \\ \textbf{Singlet-like } h_1^0 & \leftrightarrow \quad \text{small } \kappa \end{cases}$$

★ In general **likely** to exhibit **large $\sigma_{\tilde{\chi}_1^0 - p}$!**

But ... to which extent can we find viable DM scenarios in this limit??

Constraining the parameter space: $b \to s\gamma$ and a_μ



Large $\sigma_{\tilde{\chi}_1^0 - p} \Rightarrow$ low $\tan\beta$, small A_λ...

★ **BR($b \to s\gamma$)** [exp: $(3.55 \pm 0.27) \times 10^{-4}$]

$$(\lambda, \kappa) \begin{cases} \tan\beta = 3, \; A_\lambda = 200 \text{ GeV} \\ \mu = 130 \text{ GeV}, \; A_\kappa = -200 \text{ GeV} \end{cases}$$

V_{CKM} flavour violation, heavy gluino

Dominant contribution from $H^\pm$-t loops

$$m_{H^\pm} \sim \frac{2\mu}{\sin 2\beta}\left(\frac{\mu\kappa}{\lambda} + A_\lambda\right) - v^2\lambda^2 + M_W^2$$

BR$(b \to s\gamma)|_{\text{exp}}$ favours larger A_λ, $\tan\beta$

★ **a_μ** [exp: $a_\mu^{\text{NP}} \approx (2.76 \pm 0.8) \times 10^{-9}$]

$\mathcal{O}$(1 TeV) soft breaking terms ⇒ **negligible SUSY contributions**, $\mathcal{O}(10^{-11})$

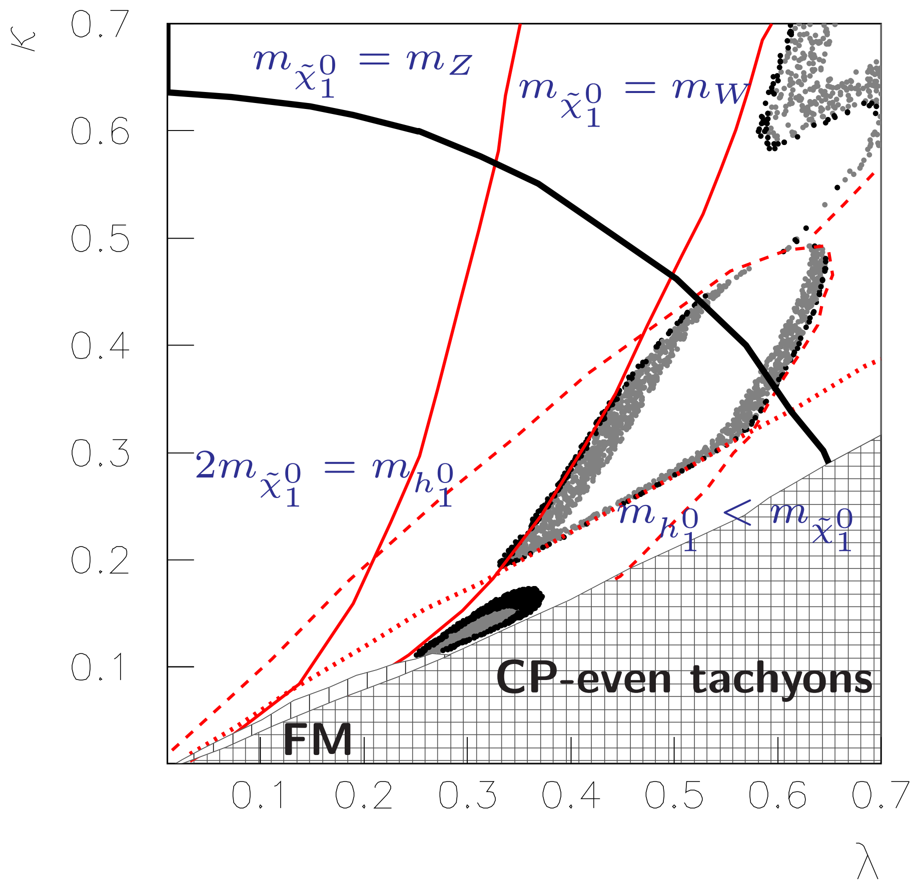
Saturating $a_\mu^{\text{exp}} \Rightarrow$
$a_\mu^{\text{SUSY}} \sim \mathcal{O}(10^{-9})$

$$\begin{cases} \text{large } \tan\beta; \; \text{large } \tilde{\mu}_{LR} \; (A_E \sim -2.5 \text{ TeV}) \\ m_{\tilde{E},L} \lesssim 200 \text{ GeV}; \; M_1 \lesssim 215 \text{ GeV} \Rightarrow \text{light sleptons, bino} \end{cases}$$

Cosmological constraints

An example: $\tan\beta = 5$, $A_\lambda = 400$ GeV, $A_\kappa = -200$ GeV, $\mu = 130$ GeV

$M_1 = 160$ GeV [GUT-relation for M_i, compatible with BR($b \to s\gamma$), a_μ]



Ωh^2: spectrum of $\tilde{\chi}^0$, h^0

MSSM-like scenarios (WMAP)

doublet-like h_1^0, bino-Higgsino $\tilde{\chi}_1^0$

NMSSM-like scenarios:

$\mu \lesssim M_1$, Higgsino-singlino $\tilde{\chi}_1^0$

WMAP (●) / astrophysical (●) bound:

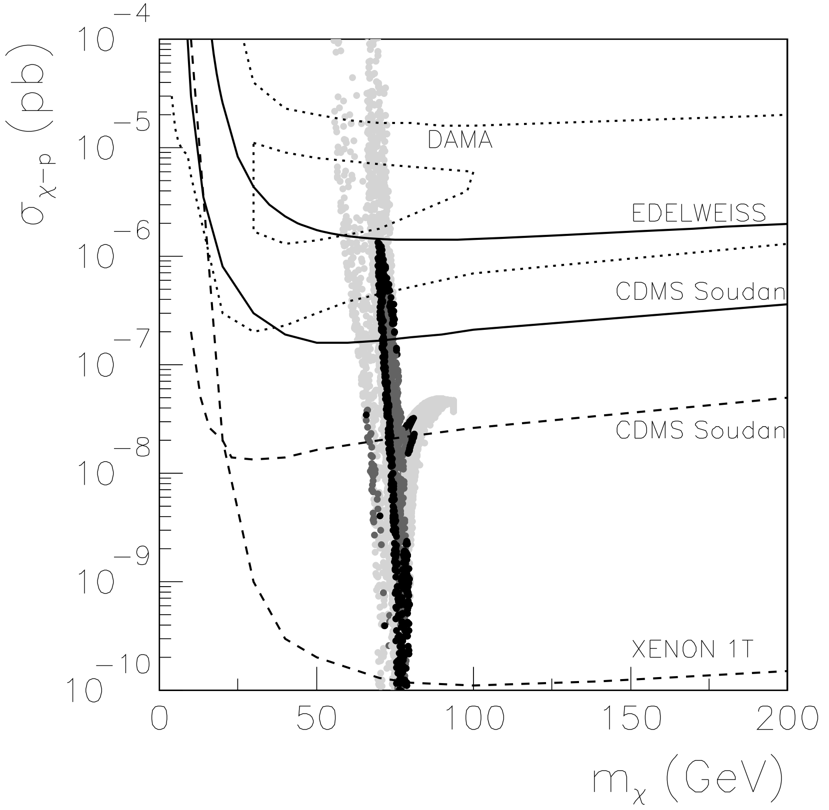
large $\tilde{S}$ component, **light** $\tilde{\chi}_1^0$

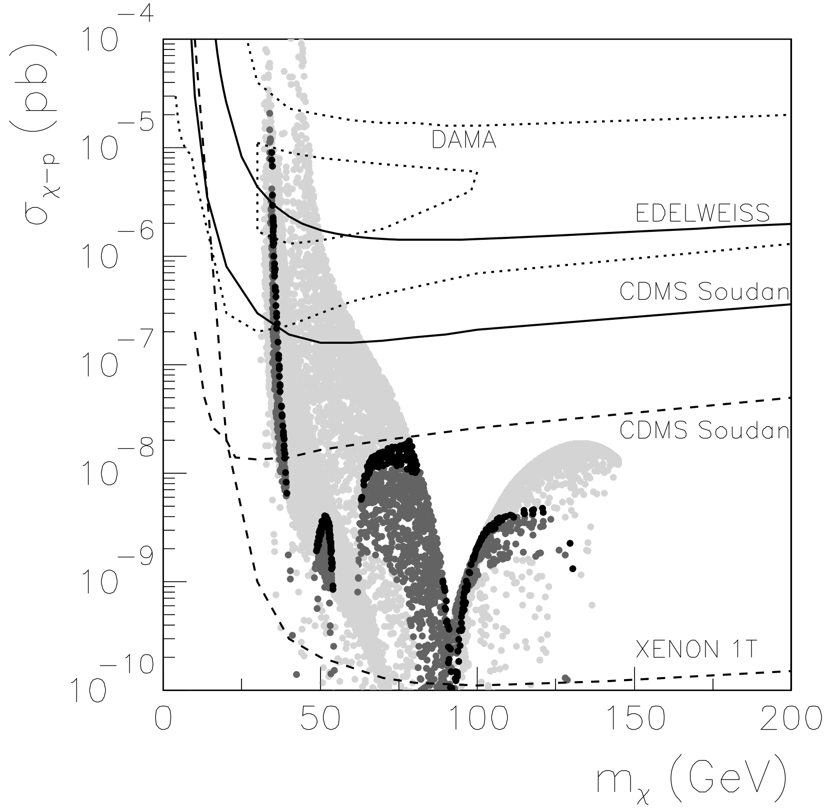
Kinematically forbid $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z, W, h_1^0$

Compatible region close to tachyon border: **Light, singlet-like Higgs**

NMSSM-like dark matter scenarios ⇒ excellent prospects for **direct detection**

Prospects for NMSSM dark matter detection





$\left\{ \begin{array}{l} \tan\beta = 5, \mu = 130 \text{ GeV}, M_1 = 160 \text{ GeV} \\ A_\lambda = 200 \text{ GeV}, \ A_\kappa = -200 \text{ GeV} \end{array} \right.$ $\left\{ \begin{array}{l} \tan\beta = 5, \mu = 160 \text{ GeV}, M_1 = 330 \text{ GeV} \\ A_\lambda = 570 \text{ GeV}, \ A_\kappa = -60 \text{ GeV} \end{array} \right.$

⋆ Large predictions for $\sigma_{\tilde{\chi}_1^0-p}$ found! Even within DAMA reach!!

⇒ t-channel exchange of **singlet-like** very **light** h_1^0 (25-50 GeV), singlino LSP

⋆ ⋆ Modify the Bino mass (cannot saturate a_μ)

⇒ **Resonances** appear as **funnels** in $\sigma_{\tilde{\chi}_1^0-p}$ (e.g. $m_{\chi_1^0} = M_Z/2$, $m_{\chi_1^0} = m_{h_1^0}/2$)

Conclusions

- **Neutralino dark matter in the NMSSM**
  - ⋆ Thourough analysis of the **low-energy NMSSM** parameter space
  - ⋆ Include **LEP**, **meson** decays, a_μ and **astrophysical** constraints
  - ⋆ Computed **theoretical predictions** for $\sigma_{\tilde{\chi}_1^0-p}$
- Stringent **constraints** on the **NMSSM** parameter space
  - ⋆ Enhancing a_μ favours **small slepton and gaugino masses**
  - ⋆ Potentially **large** contributions to BR$(b \to s\gamma)$ ($H^\pm$ mediated)
  - ⋆ Ωh^2: **light neutralinos** (kinematically unaccessible channels);
    singlino-like $\tilde{\chi}_1^0$ (suppress annihilations)
- Prospects for **direct detection** of NMSSM $\tilde{\chi}_1^0$ **dark matter**
  - ⋆ **Large** values of $\sigma_{\tilde{\chi}_1^0-p}$ attainable, *within reach of present detectors*
  - ⋆ Exchange of **light singlet-like Higgses** in t-channel ($m_{h_1^0} \sim 50$ GeV)
  - ⋆ Light, **singlino-Higgsino**-like $\tilde{\chi}_1^0$ - characteristic of **NMSSM**

Additional slides

Minimisation of $V_{\rm neutral}^{\rm Higgs}$ - the NMSSM parameter space

Ensuring minimum of $V_{\rm neutral}^{\rm Higgs}$ with respect to the phases of the VEV's:

$\Rightarrow$ excludes combinations of signs for the parameters

Conventions: $\tan\beta,\ \lambda$ positive; $s,\ \kappa,\ A_\lambda,\ A_\kappa \in$

For $\kappa > 0$, minima possible if

(i) $\mathrm{sign}(s) = \mathrm{sign}(A_\lambda) = -\mathrm{sign}(A_\kappa)$

(ii) $\mathrm{sign}(s) = -\mathrm{sign}(A_\lambda) = -\mathrm{sign}(A_\kappa)$, with $|A_\kappa| > 3\lambda v_1 v_2 |A_\lambda|/(-|sA_\lambda| + \kappa|s^2|)$

(iii) $\mathrm{sign}(s) = \mathrm{sign}(A_\lambda) = \mathrm{sign}(A_\kappa)$, with $|A_\kappa| < 3\lambda v_1 v_2 |A_\lambda|/(|sA_\lambda| + \kappa|s^2|)$

For $\kappa < 0$, minima possible if

(iv) $\mathrm{sign}(s) = \mathrm{sign}(A_\lambda) = \mathrm{sign}(A_\kappa)$, with $|A_\kappa| > 3\lambda v_1 v_2 |A_\lambda|/(|sA_\lambda| - \kappa|s^2|)$

In addition three minimization conditions for the Higgs VEV's:

$$m_{H_1}^2,\ m_{H_2}^2,\ m_S^2 = f(\lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ v_1,\ v_2,\ s)$$

NMSSM: $\tilde{\chi}^0$ and scalar Higgs mass matrices

CP-even Higgs

$$\mathcal{M}^2_{S,11} = M_Z^2 \cos^2\beta + \lambda s \tan\beta (A_\lambda + \kappa s)$$
$$\mathcal{M}^2_{S,22} = M_Z^2 \sin^2\beta + \lambda s \cot\beta (A_\lambda + \kappa s)$$
$$\mathcal{M}^2_{S,33} = 4\kappa^2 s^2 + \kappa A_\kappa s + \frac{\lambda}{s} A_\lambda v_1 v_2$$
$$\mathcal{M}^2_{S,12} = \left(\lambda^2 v^2 - \frac{M_Z^2}{2}\right) \sin 2\beta - \lambda s \, (A_\lambda + \kappa s)$$
$$\mathcal{M}^2_{S,13} = 2\lambda^2 v_1 s - \lambda v_2 \, (A_\lambda + 2\kappa s)$$
$$\mathcal{M}^2_{S,23} = 2\lambda^2 v_2 s - \lambda v_1 \, (A_\lambda + 2\kappa s)$$

$$h_a^0 = S_{ab} H_b^0$$

CP-odd Higgs

$$\mathcal{M}^2_{P,11} = \frac{2\lambda s}{\sin 2\beta} \, (\kappa s + A_\lambda)$$
$$\mathcal{M}^2_{P,22} = \lambda \left(2\kappa + \frac{A_\lambda}{2s}\right) v^2 \sin 2\beta - 3\kappa A_\kappa s$$
$$\mathcal{M}^2_{P,12} = \lambda v \, (A_\lambda - 2\kappa s)$$

$$a_i^0 = P_{ij} P_j^0$$

Neutralino Sector

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta & 0 \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta & 0 \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\lambda s & -\lambda v_2 \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\lambda s & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa s \end{pmatrix}$$

On the experimental constraints:

- LEP: direct bounds on masses of $H^{\pm}$, $\tilde{\chi}^{\pm}$, $\tilde{q}$, $\tilde{l}$;
- LEP: Invisible decay width of the Z boson: $Z \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$ and $Z \to h^0 a^0$;
- LEP: neutral Higgs (all LEP channels):
  $e^+e^- \to h^0 Z$ (IHDM);
  $e^+e^- \to h^0 Z$ (DHDM) $[h^0 \to \{b\bar{b},\ \tau^+\tau^-,\ 2\,\text{jets},\ \gamma\gamma,\ \text{inv}\}\ ]$;
  $e^+e^- \to h^0 a^0$ (APM) $[h^0 a^0 \to \{4b's,\ 4\tau's,\ 6b's\}\ ]$;
- K-meson decays: Light a_1^0 indirect contributions: $K - \bar{K}$ mixing;
- B-meson decays
  Light a_1^0 indirect contributions to $B - \bar{B}$ mixing, $B \to \mu^+\mu^-$,
  $B \to X_s \mu^+\mu^-$, $B^- \to K^- \nu\bar{\nu}$, $B \to K_S^0 X^0$;
  Direct production (large $\tan\beta$) via $b \to s a^0$, $B \to K a^0$, and $B \to \pi a^0$;
  $b \to s\gamma$: NLO contributions (only LO SUSY contributions to Wilson coeffs.);
- $a_\mu = (g_\mu - 2)$.