Spin-dependent constraints on neutralino dark matter in (N)MSSM

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based on:
Outline

- Introduction
- Experimental searches for Dark Matter
  - limits on spin-independent cross-sections ⇒ blind spots
  - new strong limits on spin-dependent cross-sections
- Bino-higgsino LSP in MSSM
- Singlino-higgsino LSP in NMSSM
- Conclusions
One of the motivations for SUSY extensions of the SM: they naturally can accommodate Dark Matter (DM) particles

- In many cases Lightest Supersymmetric Particle (LSP)
  - has mass of the order of the EW scale
  - has weak-strength interactions

⇒ LSP is a good candidate for DM

- Many Direct Detection (DD) and Indirect Detection (ID) experiments searching for DM particles
  - no (confirmed) positive results of these searches
- DM relic density is known with a good precision (especially with Planck data)
  - in general we have the upper bound on the LSP relic density
  - also the lower bound if LSP is to be dominant component of DM

- No DM particle discovered at LHC
  ⇒ Strong constraints on LSP interactions and SUSY spectrum

- Can all such constraints be fulfilled in (simple) SUSY models?
Constraints on interactions of DM particles with SM particles

Collider Search

Direct detection

Indirect detection

$\left( v \approx 0 \right)$

and thermal relic abundance

$\left( v > 0 \right)$
Experimental searches for DM

**DD experiments**
- searches for events of DM scattering on nuclei
- LUX, XENON, PandaX, LZ, CDMS, CRESST, PICO . . .
- very strong limits on $\sigma^{\text{SI}}$ and strong limits on $\sigma^{\text{SD}}$

**ID experiments**
- searches for products of DM annihilation
- IceCube, Fermi-LAT, AMS, MAGIC, HESS, ANTARES . . .
- typically less restrictive than the recent DD results

**LHC experiments**
- searches for production of DM particles
- limits on masses and interactions of other SUSY particles
- Higgs properties
Experimental bounds on $\sigma^{\text{SI}}$ are much stronger than on $\sigma^{\text{SD}}$

Limits presented by LUX at Moriond 2017:

$$\sigma^{\text{SI}} < 2.2 \cdot 10^{-46} \text{ cm}^2 \quad \text{for } m_{\text{LSP}} = 50 \text{ GeV}$$

$$\sigma^{\text{SD}} < 1.6 \cdot 10^{-41} \text{ cm}^2 \quad \text{for } m_{\text{LSP}} = 35 \text{ GeV}$$

But in some cases it is easier to fulfill bounds on $\sigma^{\text{SI}}$
We consider neutralino DM in MSSM and NMSSM with decoupled squarks (and gluinos)

DM-nucleon cross sections
- spin-independent
  - mediated by scalars and squarks
- spin-dependent
  - mediated by $Z$ and squarks

Blind-spots:
points in the parameter space for which DM-nucleon cross-section is very small (eg. below the neutrino background)
- possible for $\sigma^{\text{SI}}$
  - contributions from scalars may be small or may interfere destructively
- not possible for $\sigma^{\text{SD}}$
  - typically coupling to $Z$ can not be very small because it is important also for the relic abundance of DM
\[ \sigma^{SI} = \frac{4\mu_{\text{red}}^2}{\pi} \left[ Z f(p) + (A - Z) f(n) \right]^2 \]

\[ f^{(N)} \approx \sum_{i=1}^{2(3)} f_{h_i}^{(N)} \equiv \sum_{i=1}^{2(3)} \frac{\alpha_{h_i\chi\chi} \alpha_{h_iNN}}{2m_{h_i}^2} \]

\[ \alpha_{h_i\chi\chi} = \sqrt{2} \lambda (S_{i1} N_{14} N_{15} + S_{i2} N_{13} N_{15} + S_{i3} N_{13} N_{14}) - \sqrt{2} \kappa S_{i3} N_{15}^2 \]
\[ + g_1 (S_{i1} N_{11} N_{13} - S_{i2} N_{11} N_{14}) - g_2 (S_{i1} N_{12} N_{13} - S_{i2} N_{12} N_{14}) \]

\[ \alpha_{h_iNN} = \frac{m_N}{\sqrt{2} v} \left( \frac{S_{i1}}{\cos \beta} F^{(N)}_d + \frac{S_{i2}}{\sin \beta} F^{(N)}_u \right) \]

\( h_i \) scalar mass eigenstates

\( S_{ij} (N_{kl}) \) mixing matrix in the scalar (neutralino) sector

MSSM: \( i, j = 1, 2 \) \( k, l = 1, \ldots, 4 \)

NMSSM: \( i, j = 1, 2, 3 \) \( k, l = 1, \ldots, 5 \)

\[ \sigma^{SD} = C \cdot 10^{-38} \text{cm}^2 \ (N_{13}^2 - N_{14}^2)^2 \]

If DM annihilation dominated by \( \chi\chi \to Z \to tt \) then \( \Omega h^2 \sim (\sigma^{SD})^{-1} \)

\[ \Omega h^2 \approx \left( \frac{0.05}{N_{13}^2 - N_{14}^2} \right)^2 \left[ \sqrt{1 - \frac{m_t^2}{m_\chi^2}} + \frac{3}{4x_f} \left( 1 - \frac{m_t^2}{2m_\chi^2} \right) \frac{1}{\sqrt{1 - \frac{m_t^2}{m_\chi^2}}} \right]^{-1} \]
Well-tempered bino-higgsino (higgsino-bino) neutralino in MSSM
- no resonant annihilation via s-channel
- no coannihilation with particles other than charginos and neutralinos

For heavy (decoupled) $H$ and $A$ we find

$$\alpha_{h\chi\chi} \approx -\sqrt{2}g_1 N_{11}^2 \frac{M_Z \sin \theta_W}{\mu} \frac{m_{\chi}/\mu + \sin(2\beta)}{1 - (m_{\chi}/\mu)^2}$$

$\Rightarrow$ it is easier to explore (exclude) parts of the parameter space with $M_1 \mu > 0$ because $\sigma^{SI}$ is bigger
For positive $M_1 \mu$ much stronger constraints from experiments sensitive to $\sigma^{SI}$

Almost pure higgsino with mass $\sim 1100$ GeV still allowed
For negative $M_1 \mu$ recent results excluded large part of the parameter space

Well-tempered bino-higgsino still allowed
but only for small values of $\tan \beta \Rightarrow$ stops must be heavy $m_{\tilde{t}} \gtrsim 50$ TeV

XENON1T sensitivity:
$\sigma^{\text{SI}}$ or $\sigma^{\text{SD}}$ alone may push this limit to about 200 TeV
$\sigma^{\text{SI}}$ and $\sigma^{\text{SD}}$ together to about 900 TeV
The exclusion/sensitivity regions change if the uncertainty in the relic abundance calculations are taken into account.

Ωh^2 calculated with MicrOMEGAs:
dashed – 80%  
solid – 100%  
dotted – 120%  
of the measured 0.12

Allowed region:  
below red;  
right from green;  
left from blue

Present limits for bino-higgsino LSP:
\[ \tan \beta \lesssim 3.0, 2.7, 2.4 \Rightarrow m_{\tilde{\chi}} \gtrsim 25, 50, 90 \text{ TeV} \]

In any case stops must be very heavy.
Allowing for relatively light \( H \) and \( A \) does not help much in the case of well-tempered bino-higgsino LSP

Bounds on \( \tan \beta \) obtained by ATLAS and CMS searches for \( H/A \to \tau\tau \) play important role

Small marginally allowed region
\[ m_\chi \sim 300 \text{ GeV}, \tan \beta \sim 7 \text{ and } m_A \sim 350 \text{ GeV} \]
likely to be excluded very soon

3 possibilities left in MSSM
- small \( \tan \beta \) and very heavy stops (at least 25 TeV)
  - sensitivity of LZ to \( \sigma^{SD} \) enough to probe the whole region
- almost pure higgsino
- tuned SUSY spectrum (resonant annihilation)
\[ \Omega h^2 \approx 0.12, \ m_{\text{LSP}} = 300 \text{ GeV}, \ \mu M_1 < 0 \]
There are many new interesting possibilities in NMSSM

Especially interesting are new singlet particles:
- singlino – additional component of LSP
- scalar – additional contribution to $\sigma^{\text{SI}}$
- pseudoscalar – new features of the relic abundance calculation

We concentrate on:
- singlino-higgsino LSP (all gauginos decoupled)
- LSP is thermal dominant component of DM
- blind-spots – points in the parameter space giving $\sigma^{\text{SI}}$ below the neutrino background
- impact of the present and planned measurements of $\sigma^{\text{SD}}$
Simple case with negligible
- contributions from $s$ and $H$ exchange to $\sigma^{\text{SI}}$
- mixing of $h$ with $s$ and $H$

Allowed regions
- small $\tan \beta$, $m_{\text{LSP}} \gtrsim 300$ GeV – will be fully explored by XENON1T
- $Z$ resonance – will be fully explored by LZ

Similar to well-tempered bino-higgsino in MSSM
If the singlet-dominated scalar is light and contributes to $\sigma^{SI}$ the simple blind-point condition

$$\frac{m_\chi}{\mu} - \sin(2\beta) = 0$$

takes the form

$$\frac{\gamma + A_s}{1 - \gamma A_s} = -\eta$$

where

$$A_s \approx -\gamma \frac{1 + c_s}{1 + c_h} \left( \frac{m_h}{m_s} \right)^2 \quad c_{hi} \equiv 1 + \frac{\tilde{S}_{hi}\tilde{H}}{\tilde{S}_{hi}\tilde{h}} \left( \tan \beta - \frac{1}{\tan \beta} \right)$$

$$\gamma \equiv \frac{\tilde{S}_{h\tilde{s}}}{\tilde{S}_{h\tilde{h}}} \quad \eta \equiv \frac{N_{15}(N_{13}\sin \beta + N_{14}\cos \beta)}{N_{13}N_{14} - \frac{\kappa}{\lambda}N_{15}^2}$$

c_{hi} – ratio of the couplings, normalized to the SM values, of $h_i$ to the $b$ quarks and to the $Z^0$ bosons
For $m_s < m_h$ the $s$-$h$ mixing may increase $m_h$ by up to $\sim 5$ GeV

Regions with large $s$-$h$ mixing are allowed by all present data with resonant LSP annihilation

$\lambda = 0.5, \kappa = 0.1, \gamma = -0.4, m_a = 600$ GeV, $A_\kappa = -700$ GeV, $f_s + f_h = 0$
For $m_s < m_h$ the $s$-$h$ mixing may increase $m_h$ by up to $\sim 5$ GeV.

Regions with large $s$-$h$ mixing are allowed by all present data without resonant LSP annihilation.
There are correlations with the properties of Higgs

Increasing the $s$-$h$ mixing leads to growing change in $\tan \beta$ (necessary to keep the Blind Spot and correct value of $\Omega h^2$)

- sign of $\gamma$ is correlated with BR($h \to b\bar{b}$)
- values of $\tan \beta$ and $|\gamma|$ are related with stop masses necessary to get the correct Higgs mass

$\Rightarrow$ lighter stops are allowed when $\frac{\text{BR}(h \to b\bar{b})}{\text{BR}(h \to ZZ)}$ is below the SM value
For smaller $s$-$h$ mixing the lower bound on $m_{\text{LSP}}$ even in the $\mathbb{Z}_3$-symmetric NMSSM may be relaxed to

- about 250 GeV for moderate $\tan \beta$ (no resonant annihilation)
- below 150 GeV for big $\tan \beta$ (resonant annihilation with $a$ exchanged)

Parts of the allowed regions beyond the reach of XENON1T are important for non-resonant annihilation.
Conclusions

- Strong experimental limits on SI interactions of DM are fulfilled close to Blind Spots
- No analogous BS for SD interactions
- Regions close to BS for $\sigma^\text{SI}$ may be explored by combining data from experiments sensitive to $\sigma^\text{SD}$, from LHC and from the relic abundance

- MSSM: well-tempered bino-higgsino LSP allowed for
  - $m_{\text{LSP}} \gtrsim 250$ GeV, small $\tan \beta$ and very heavy stops (at least 25 TeV)
    - this region of the parameter space will be covered by LZ
  - small region $m_{\text{LSP}} \sim 300$ GeV, $\tan \beta \sim 8$, $m_A \sim 400$ GeV
    - region will be covered by XENON1T and LHC

- NMSSM singlino-higgsino LSP, heavy $s$ and $H$ scalars:
  - $m_{\text{LSP}} \gtrsim 300$ GeV, $\tan \beta \lesssim 3.5$
  - $m_{\text{LSP}} \lesssim 700$ GeV if $\lambda$ is to be perturbative till $M_{\text{GUT}}$
    - region will be covered by XENON1T
  - small region close to the $Z$ resonance (will be covered by LZ)
Conclusions

- **NMSSM singlino-higgsino LSP, light s and a:**
  - Light s gives more possibilities for SD blind spots
  - s as intermediate particle, s-h mixing
  - Light a and s give more possibilities to obtain correct $\Omega h^2$ without influencing $\sigma^{SD}$
  - s and a as intermediate particles, additional final states, interference
- Several kinds of allowed regions in the parameter space
  - Quite wide ranges of $m_{LSP}$ and $\tan \beta$
  - Even for the $\mathbb{Z}_3$-symmetric NMSSM
- Relatively light stops allowed, especially when
  - $m_s < m_h$
  - $BR(h \rightarrow b\bar{b})$ below the SM prediction
- Some parts of the allowed regions beyond XENON1T sensitivity