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

Marek Olechowski

Institute of Theoretical Physics
Faculty of Physics, University of Warsaw

Corfu Summer Institute 2017

09.09.2017

based on:

M. Badziak, M.O. and P. Szczerbiak, Phys. Lett. B70 (2017) 226; JHEP 07 (2017) 050

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

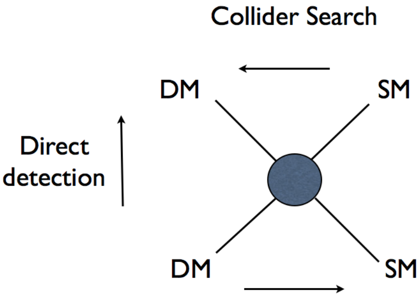
Introduction

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
- $\Rightarrow$ 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
- $\Rightarrow$ Strong constraints on LSP interactions and SUSY spectrum
- Can all such constraints be fulfilled in (simple) SUSY models?

Experimental searches for DM

Constraints on interactions of DM particles with SM particles



Collider Search

DM

SM

Direct detection

DM

SM

Indirect detection

$(v \approx 0)$

and thermal relic abundance

$(v > 0)$

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 σ^{SI} and strong limits on σ^{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 searches for DM

Experimental bounds on σ^{SI} are much stronger than on σ^{SD}

Limits presented by LUX at Moriond 2017:

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

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

But in some cases it is easier to fulfill bounds on σ^{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 σ^{SI}
  - contributions from scalars may be small or may interfere destructively
- not possible for σ^{SD}
  - typically coupling to Z can not be very small because it is important also for the relic abundance of DM

$$\sigma^{\rm SI} = \frac{4\mu_{\rm red}^2}{\pi}\,\frac{\left[Zf^{(p)} + (A-Z)f^{(n)}\right]^2}{A^2}$$

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

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

$$\alpha_{h_iNN} = \frac{m_N}{\sqrt{2}v}\left(\frac{S_{i1}}{\cos\beta}F_d^{(N)} + \frac{S_{i2}}{\sin\beta}F_u^{(N)}\right)$$

h_i scalar mass eigenstates
S_{ij} (N_{kl}) mixing matrix in the scalar (neutralino) sector
MSSM: $i,j=1,2$ $k,l=1,\dots,4$
NMSSM: $i,j=1,2,3$ $k,l=1,\dots,5$

$$\sigma^{\rm SD} = C\cdot 10^{-38}{\rm cm}^2\,\left(N_{13}^2 - N_{14}^2\right)^2$$

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

$$\Omega h^2 \approx \left(\frac{0.05}{N_{13}^2 - N_{14}^2}\right)^2\left[\sqrt{1-\frac{m_t^2}{m_\chi^2}} + \frac{3}{4x_f}\left(1-\frac{m_t^2}{2m_\chi^2}\right)\frac{1}{\sqrt{1-\frac{m_t^2}{m_\chi^2}}}\right]^{-1}$$

MSSM – heavy H

Well-tempered bino-higgsino (higgsino-bino) neutralino in MSSM

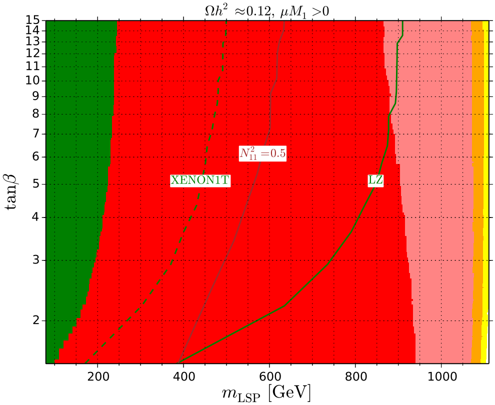
- no resonant annihilation via s-channel
- no coannihilation with particles other than charginos and neutralinos

For heavy (decoupled) H and A we find

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

⇒ it is easier to explore (exclude) parts of the parameter space with $M_1\mu > 0$ because σ^{SI} is bigger

MSSM – heavy s



σ^{SI} **excluded by**
old LUX
new LUX

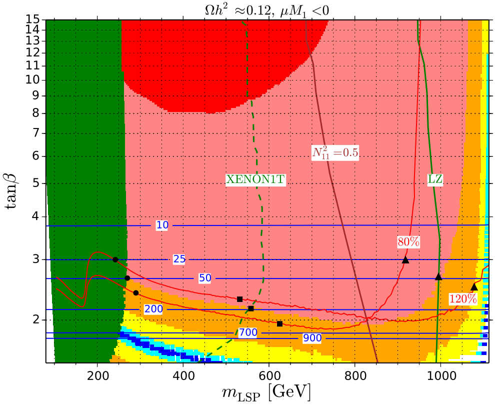
σ^{SI} **sensitivity of**
XENON1T
LZ

σ^{SD} **excluded by**
new LUX

For positive $M_1\mu$ much stronger constraints from experiments sensitive to σ^{SI}

Almost pure higgsino with mass ~ 1100 GeV still allowed

MSSM – heavy s



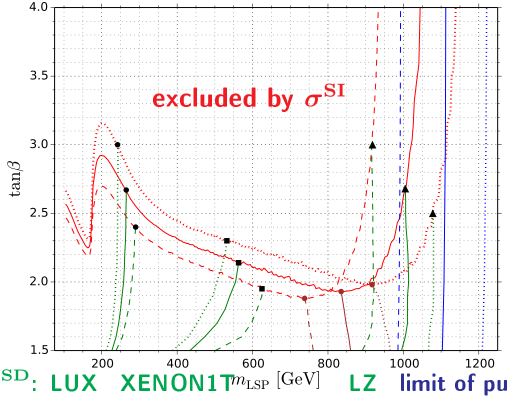
$\sigma^{\rm SI}$ below
LZ sensitivity
ν background

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:
$\sigma^{\rm SI}$ or $\sigma^{\rm SD}$ alone may push this limit to about 200 TeV
$\sigma^{\rm SI}$ and $\sigma^{\rm SD}$ together to about 900 TeV

MSSM – heavy H

The exclusion/sensitivity regions change if the uncertainty in the relic abundance calculations are taken into account



σ^{SD}: LUX XENON1T LZ limit of pure higgsino

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:
$\tan\beta \lesssim 3.0,\ 2.7,\ 2.4 \quad \Rightarrow \quad m_{\tilde{t}} \gtrsim 25,\ 50,\ 90$ TeV
In any case stops must be very heavy

MSSM – light H

Allowing for relatively light H and A does not help much in the case of well-tempered bino-higgsino LSP

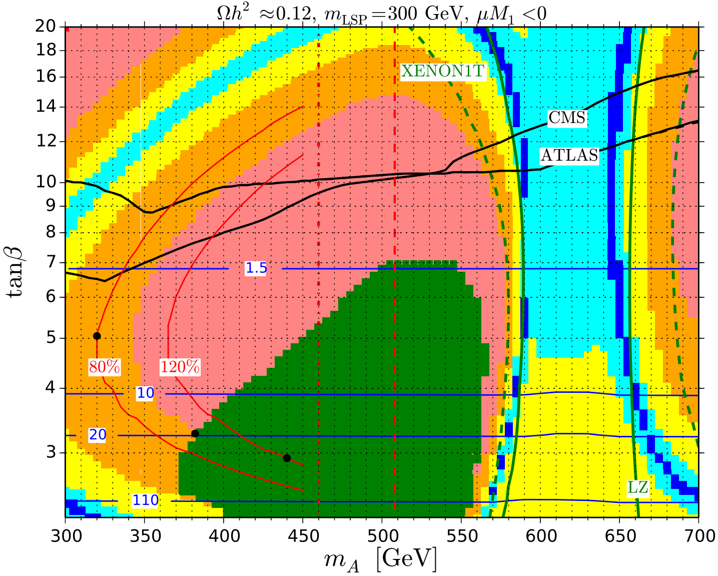
Bounds on $\tan\beta$ obtained by ATLAS and CMS searches for $H/A \to \tau\tau$ play important role

Small marginally allowed region
$m_\chi \sim$ 300 GeV, $\tan\beta \sim 7$ and $m_A \sim$ 350 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 σ^{SD} enough to probe the whole region
- almost pure higgsino
- tuned SUSY spectrum (resonant annihilation)

MSSM – light H


$\Omega h^2 \approx 0.12$, $m_{\rm LSP} = 300$ GeV, $\mu M_1 < 0$
20
18
16
14
12
10
9
8
7
6
5
4
3
$\tan\beta$
300
350
400
450
500
550
600
650
700
m_A [GeV]
XENON1T
CMS
ATLAS
LZ
1.5
10
20
110
80%
120%

NMSSM

There are many new interesting possibilities in NMSSM

Especially interesting are new singlet particles:

- singlino – additional component of LSP
- scalar – additional contribution to σ^{SI}
- pseudoscalar – new features of the relic abundance calculation

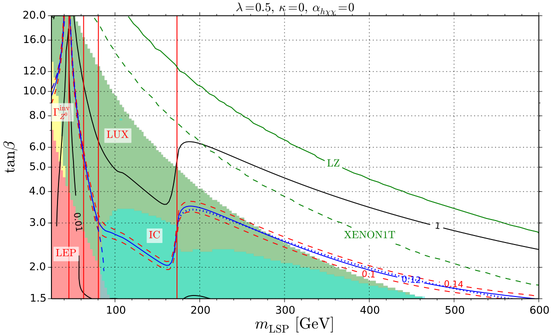
We concentrate on:

- singlino-higgsino LSP (all gauginos decoupled)
- LSP is thermal dominant component of DM
- blind-spots – points in the parameter space giving σ^{SI} below the neutrino background
- impact of the present and planned measurements of σ^{SD}

NMSSM – heavy s

Simple case with negligible

- contributions from s and H exchange to $\sigma^{\rm SI}$
- mixing of h with s and H



LUX limits on $\sigma^{\rm SD}$ stronger than the corresponding limits from IceCube

Allowed regions

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

Similar to well-tempered bino-higgsino in MSSM

NMSSM – light s

If the singlet-dominated scalar is light and contributes to $\sigma^{\rm SI}$ the simple blind-point condition

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

takes the form

$$\frac{\gamma + \mathcal{A}_s}{1 - \gamma \mathcal{A}_s} = -\eta$$

where

$$\mathcal{A}_s \approx -\gamma \frac{1 + c_s}{1 + c_h} \left(\frac{m_h}{m_s}\right)^2 \qquad c_{h_i} \equiv 1 + \frac{\tilde{S}_{h_i \hat{H}}}{\tilde{S}_{h_i \hat{h}}} \left(\tan\beta - \frac{1}{\tan\beta}\right)$$

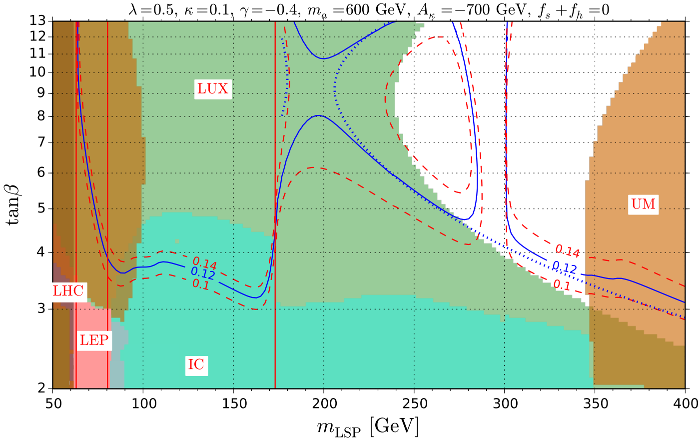
$$\gamma \equiv \frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}} \qquad \eta \equiv \frac{N_{15}(N_{13}\sin\beta + N_{14}\cos\beta)}{N_{13}N_{14} - \frac{\kappa}{\lambda}N_{15}^2}$$

c_{h_i} – ratio of the couplings, normalized to the SM values, of h_i to the b quarks and to the Z^0 bosons

NMSSM – light s

For $m_s < m_h$ the s-h mixing may increase m_h by up to ~ 5 GeV

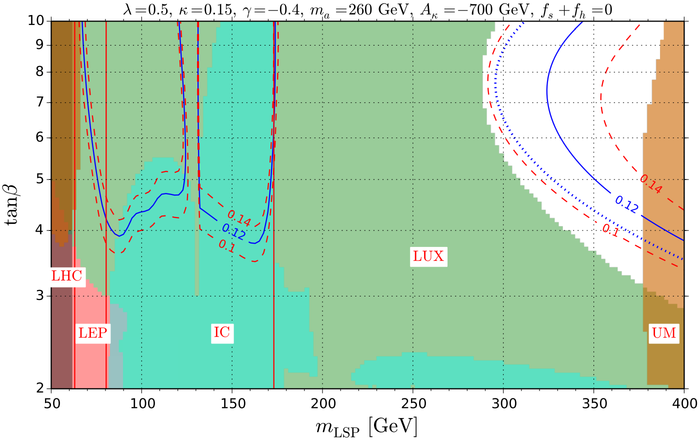
Regions with large s-h mixing are allowed by all present data with resonant LSP annihilation



NMSSM – light s

For $m_s < m_h$ the s-h mixing may increase m_h by up to ~ 5 GeV

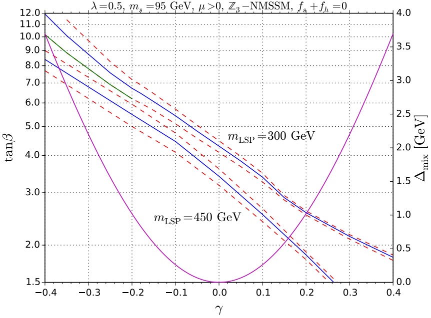
Regions with large s-h mixing are allowed by all present data without resonant LSP annihilation



NMSSM – light s

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 Ωh^2)



$\tan\beta$ grows (decreases) for negative (positive) mixing parameter γ

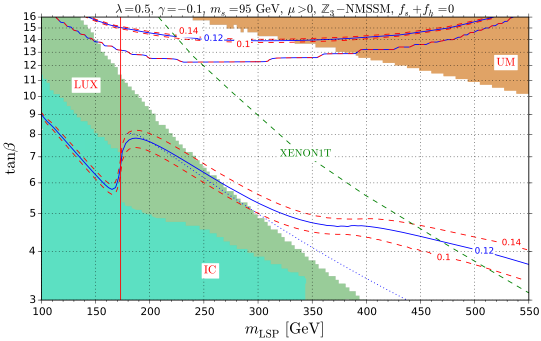
- **sign of γ is correlated with BR($h\to b\bar{b}$)**
- **values of $\tan\beta$ and $|\gamma|$ are related with stop masses necessary to get the correct Higgs mass**

$\Rightarrow$ lighter stops are allowed when $\frac{\mathrm{BR}(h\to b\bar{b})}{\mathrm{BR}(h\to ZZ)}$ is below the SM value

NMSSM – $\mathbb{Z}_3$-symmetric

For smaller s-h mixing the lower bound on m_{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

(sa, ha ect. final states 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 σ^{SI} may be explored by combining data from experiments sensitive to σ^{SD}, from LHC and from the relic abundance

- MSSM: well-tempered bino-higgsino LSP allowed for
  - $m_{\mathrm{LSP}} \gtrsim$ 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 $m_{\mathrm{LSP}} \sim 300$ 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:
  - $m_{\mathrm{LSP}} \gtrsim$ 300 GeV, $\tan\beta \lesssim 3.5$
  - $m_{\mathrm{LSP}} \lesssim$ 700 GeV if λ is to be perturbative till M_{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 Ωh^2 without influencing $\sigma^{\rm SD}$
        - s and a as intermediate particles, additional final states, interference
    - several kinds of allowed regions in the parameter space
        - quite wide ranges of $m_{\rm LSP}$ and $\tan\beta$
        - even for the $\mathbb{Z}_3$-symmetric NMSSM
    - relatively light stops allowed, especially when
        - $m_s < m_h$
        - BR($h \to b\bar{b}$) below the SM prediction
    - some parts of the allowed regions beyond XENON1T sensitivity