How light a higgsino or a wino dark matter can become in a compressed scenario of MSSM

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Status of the SUSY WIMPs

- XENON1T has published first results. No sign of SUSY (or any other) WIMPs.
- Pure bino DM plagued with overabundance. Well-tempered ones strongly constrained by LUX/XENON1T data.
- Higgsino LSP $\Rightarrow \Omega_{\widetilde{\chi}_1^0} h^2 = 0.10(\frac{\mu}{1\ \mathrm{TeV}})^2$.
- For a wino LSP, $\Omega_{\tilde{W}} h^2 = 0.13(\frac{m_{\tilde{W}}}{2.5\ \mathrm{TeV}})^2 = 0.021 m_{\tilde{W}}^2$.
- Pure higgsino obtains right relic density for masses $\sim$ 1 TeV, Pure wino for $\sim$ 2.5 TeV.

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- Coannihilation can make significant difference. It may increase or decrease the relic density.
- In mSUGRA, bino-stau coannihilation widely studied $\Rightarrow$ reduction in relic density, but for a very small mass range because of the correlation of superpartner masses.
- pMSSM scenario : no correlation among sparticle masses $\Rightarrow$ can probe full potential of coannihilation.

- Boltzmann equation governing the number density of the i-th species:

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right)$$
$$- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) - \langle \sigma'_{Xji} v_{ij} \rangle \left(n_j n_X - n_j^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) \right]$$
$$- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\mathrm{eq}} \right) - \Gamma_{ji} \left(n_j - n_j^{\mathrm{eq}} \right) \right].$$

- Assuming $n = \sum_{i=1}^{N} n_i$ and $\frac{n_i}{n} \simeq \frac{n_i^{\mathrm{eq}}}{n^{\mathrm{eq}}}$,

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\mathrm{eff}} v \rangle \left(n^2 - n_{\mathrm{eq}}^2 \right),$$

$$\langle \sigma_{\mathrm{eff}} v \rangle = \frac{\sum_{ij} \langle \sigma_{ij} v_{ij} \rangle n_i^{\mathrm{eq}} n_j^{\mathrm{eq}}}{n^{\mathrm{eq}2}}.$$

- In the non-relativistic approximation, one has,

$$\frac{n_i^{eq}}{n^{eq}} = \frac{g_i \exp(-x\delta_i)(1+\delta_i)^{3/2}}{g_{eff}}.$$

where $g_{eff} = \sum_{i=1}^{N} g_i \exp(-x\delta_i)(1+\delta_i)^{3/2}$.

The effect of considering a coannihilating particle, depends on several factors :

- Various coannihilation cross-sections.
- Mass difference leading to exponential suppression, $\delta_i = \frac{m_{\chi_i'} - m_{\chi_0}}{m_{\chi_0}}$ or $\delta_{ij} = \frac{m_{\chi_i'} - m_{\chi_j}}{m_{\chi_i}}$,
- Appropriate weight factors arising out of internal *d.o.f.* g_is.

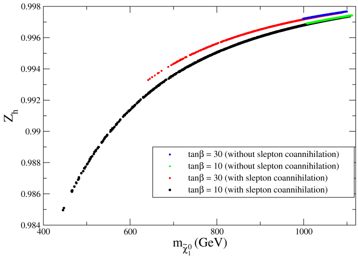
In the situation where self annihilation cross-section is $<<$ coannihilation cross-section, $\langle \sigma_{\rm eff} v \rangle$ is reduced.

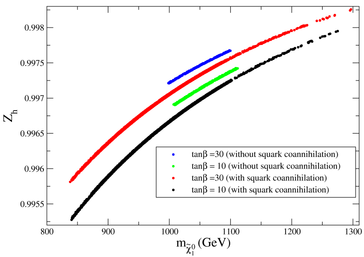
- For a higgsino $\Rightarrow m_{\widetilde{\chi}_1^\pm} \simeq m_{\widetilde{\chi}_2^0} \simeq m_{\widetilde{\chi}_1^0} \simeq \mu$. $g = 8$.
- For Wino $\Rightarrow m_{\widetilde{\chi}_1^\pm} \simeq m_{\widetilde{\chi}_1^0} \simeq M_2 \Rightarrow g = 6$.
- Large effective annihilation cross-section for the above two types of LSP $\Rightarrow$ underabundant DM for higgsino upto 1 TeV and wino upto 2.7 TeV.
- In the presence of a large number of coannihilating species each contributing small amount to the total cross-section $\Rightarrow \langle \sigma_{\rm eff} v \rangle$ is reduced.
- e.g. with sleptons, $g_L = g_R = 2$, $g_\nu = 1$. Thus, for coannihilating sleptons of all the three generations $g = 18$.
- Only first two generations of squark coannihilations considered. $g = 48$ after accounting for the color *d.o.f.*.

Our analysis : Higgsino DM

- $M_1 = 2\mu$ and $M_2 = 2.4\mu$, 100 GeV $< \mu <$ 2 TeV.
- Slepton coannihilation : For each μ, common input $m_{\tilde{l}}$ for all the three generations varied in the range 50% below and above μ.
- Squark mass parameters, M_3 are chosen to be large $\rightarrow$ 3 TeV, $M_A = 5$ TeV.
- A_t scanned from -2 TeV to -7 TeV so as to satisfy the higgs mass data.
- For Squarks coannihilations $\Rightarrow$ we consider only with the first two generations. Sleptons as well as the third generation of squarks taken to be heavy (3 TeV).
- Physical slepton (squark) masses stay within 20% of the LSP mass irrespective of the generation.
- We consider the limit $0.108 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.132$.

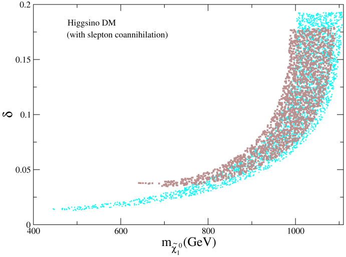
Higgsino : Z_h vs. $m_{\tilde{\chi}_1^0}$

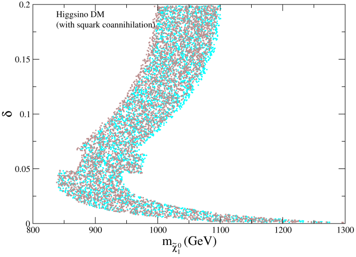




- $Z_h = N_{13}^2 + N_{14}^2$ vs. LSP mass. All points satisfy WMAP/PLANCK constraint.
- For slepton coannihilation, $m_{\tilde{\chi}_1^0} \sim 400(600)$ GeV for $\tan\beta = 10(30)$, consistent with relic density constraint.
- Larger L-R mixing for $\tan\beta = 30 \Rightarrow$ smaller parameter space available.
- For squark coannihilation, hardly any change in lower mass limit whereas, upper limit extends because, squark coannihilation dominates over EWino coannihilations.

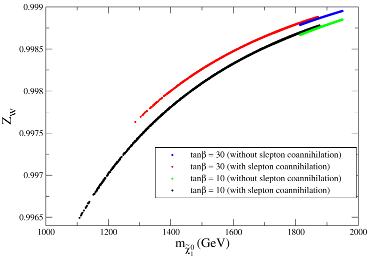
Higgsino : δ vs.$m_{\tilde{\chi}_1^0}$

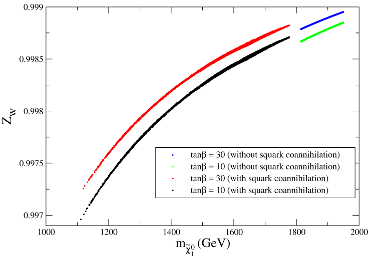




- $\delta \rightarrow$ average of all δ_i's appropriately weighted by their respective *d.o.f.*.
- Left $\Rightarrow$ higgsino-slepton, right $\Rightarrow$ higgsino-squark coannihilation. Cyan $\Rightarrow \tan\beta = 10$, Brown $\Rightarrow \tan\beta = 30$.
- Left region $\Rightarrow$ underabundant, Right region $\Rightarrow$ overabundant.
- For squarks with very small δ, squark coannihilation dominates.

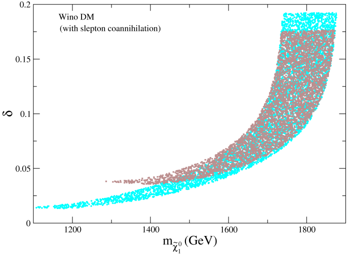
Wino DM : Z_W vs. $m_{\tilde{\chi}_1^0}$

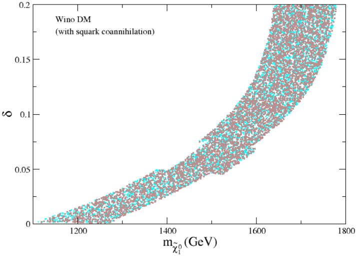




- $\mu = 2M_2, M_1 > \mu$.
- $M_A = 6$ TeV to avoid funnel region. M_3 large.
- $Z_W = N_{12}^2$. All the points satisfy relic density limits.
- $m_{\tilde{\chi}_1^0} \sim 1$ TeV satisfies relic density limits $\Rightarrow$ significant reduction in the lower mass limit.
- Without sfermion coannihilation, we get $m_{\tilde{\chi}_1^0} \sim 1.8$ TeV consistent with relic density constraint. This can be made to increase by considering very large μ and squark masses around 10 TeV and including Sommerfeld corrections.

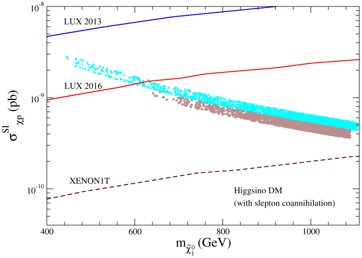
Wino DM : δ vs. $m_{\tilde{\chi}_1^0}$

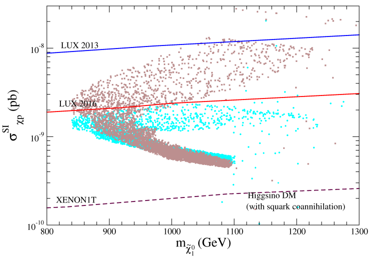




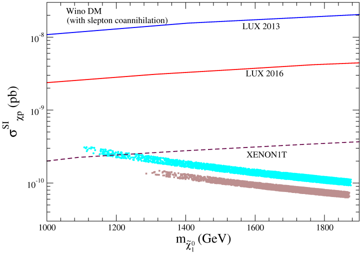
- The lower limit decreases significantly, but the upper limit hardly changes.
- Since we are in a region with $m_{\tilde{\chi}_1^0} \sim 1$ TeV, we can safely ignore Sommerfeld corrections.

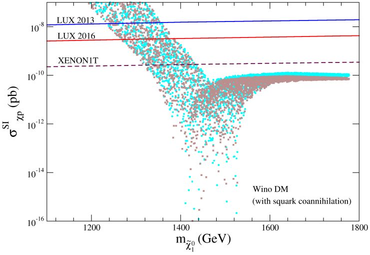
Direct detection





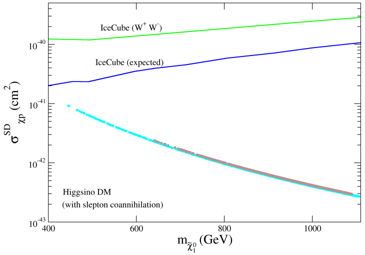
- Spin-independent LSP-proton scattering cross-section expected to be small for pure higgsino/wino.
- For reasonably large squark masses, Higgs exchange diagram dominates SI scattering cross-section.
- However, for nearly degenerate squark masses, squark-quark-LSP effective coupling drastically increases $\Rightarrow$ squark exchange contribution becomes significant.
- Depending on the competition of the two diagrams, various cross-section values are obtained $\Rightarrow$ Some already excluded by LUX, some will be probed in near future by XENON1T.

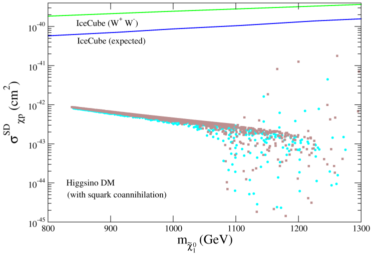


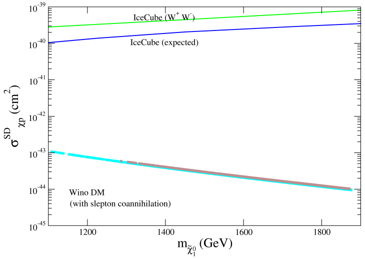


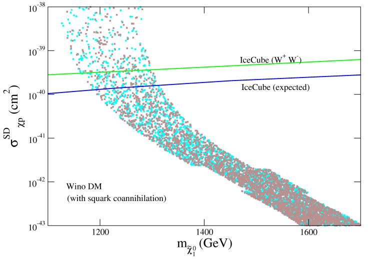
- Wide range of cross-section values for squark coannihilation depending on the relative magnitude of h or squark exchange diagrams.
- Cross-section drops down far below projected XENON1T limit in some places due to cancellation between the two diagrams.

Indirect detection









Benchmark Points

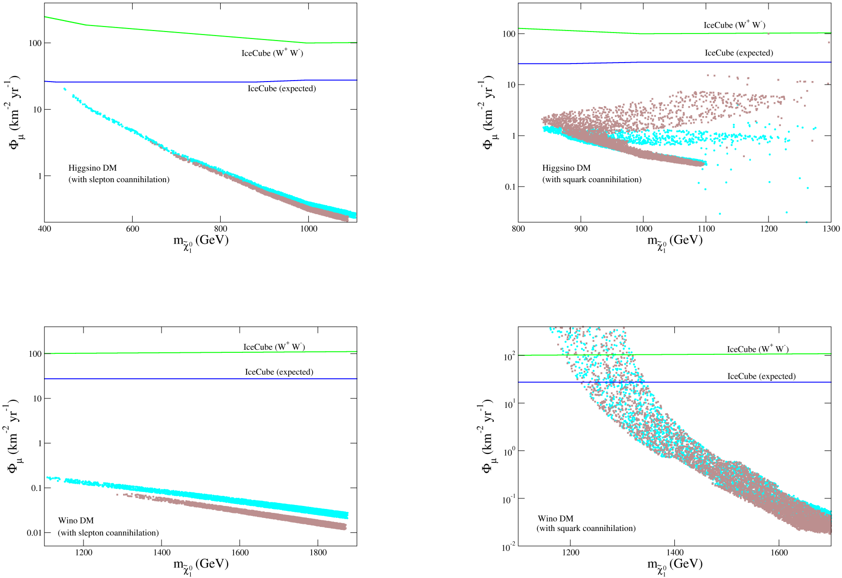
Parameters	Higgsino DM		Wino DM	
Points	BP1	BP2	BP3	BP4
M_1 (GeV)	1221.5	1502.8	2339.2	2847.8
M_2 (GeV)	1465.8	1803.4	974.7	1186.6
μ (GeV)	610.8	751.4	1949.3	2373.2
$M_{\tilde{q}_{L,R}}$ (GeV)	3000	539.6	4000	944.4
$M_{\tilde{l}_{L,R}}$ (GeV)	628.4	3000	1026.3	4000
$m_{\tilde{\chi}_1^0}$ (GeV)	617.3	760.5	1011.1	1188.5
$m_{\tilde{\chi}_1^\pm}$ (GeV)	620.4	763.1	1011.1	1188.5
$m_{\tilde{\chi}_2^0}$ (GeV)	1499	767	1969	2392
$m_{\tilde{\chi}_3^0}$ (GeV)	1198	1471.8	1969.8	2393
$M_{\tilde{(e,\mu)}_L}$ (GeV)	630	3000	1027.2	4000
$M_{\tilde{(e,\mu)}_R}$ (GeV)	630	3000	1027.2	4000
$m_{\tilde{\tau}_1}$ (GeV)	621.7	2998	1011.1	3995.2
$m_{\tilde{\tau}_2}$ (GeV)	638	3000	1043	4005.2
$M_{\tilde{\nu}}$ (GeV)	625.3	2999	1024.4	3999.5
$M_{\tilde{u}_L}$ (GeV)	3000	792.8	4130.7	1228
$M_{\tilde{d}_L}$ (GeV)	3000	796.8	4131.4	1230.5
$M_{\tilde{u}_R}$ (GeV)	3000	793.7	4130.9	1228.5
$M_{\tilde{d}_R}$ (GeV)	3000	795	4131.1	1229.4
$\Omega_{\tilde{\chi}} h^2$	0.126	0.092	0.091	0.09
σ_{SI} $\times 10^{-9}$ (pb)	1.39	1.69	0.33	1.21
σ_{SD} $\times 10^{-6}$ (pb)	2.64	1.2	0.15	11.3
$\Phi_\mu (km^{-2} yr^{-1})$	4	2.1	0.2	4

Conclusion

- Strong coannihilations among $m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_2^0}$ makes higgsino DM underabundant upto a mass of 1 TeV in the absence of sfermion coannihilation.
- Similar situation for wino LSP with $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_1^\pm}$ coannihilations upto a mass of $\sim$ 2.7 TeV.
- Squark and slepton coannihilations can significantly change the picture.
- With slepton coannihilations higgsino LSP $\sim$ 450 GeV can be consistent with relic density constraint.
- Wino DM with masses around 1 TeV is found to satisfy relic density limits.
- For LSP-squark coannihilation, squark exchange diargram for LSP-proton scattering contributes significantly to direct detection. In some region it may dominate over the h-exchange contribution.
- Indirect detection does not put any additional constraint.
- The scenarios being very compressed is hard to probe at the LHC. But future colliders may probe them conclusively.


Thank you!

Indirect detection : muon flux



- For the generic higgsino LSP case one has $\Omega_{\widetilde{\chi}_1^0} h^2 = 0.10(\frac{\mu}{1\ \mathrm{TeV}})^2$, where μ is given in TeV. A similar relation for a wino LSP with mass $m_{\tilde{W}}$ reads $\Omega_{\tilde{W}} h^2 = 0.13(\frac{m_{\tilde{W}}}{2.5\ \mathrm{TeV}})^2 = 0.021 m_{\tilde{W}}^2$, denoting a factor of 5 stronger effective annihilation cross section compared to the higgsino case. As we will see the squark-squark coannihilation contributions are not large enough to supersede the generic wino DM depletion cross section. Hence, the wino dominated LSP scenario with squark coannihilations will not encounter any stretching of the LSP mass region satisfying the relic density data on the higher side.

$$\mathcal{L} \subset f_q^{\tilde{q}} [\bar{\tilde{\chi}} \tilde{\chi}][\bar{q} q]$$

as well as the vector/axial-vector form

$$\mathcal{L} \subset [\bar{\tilde{\chi}} \gamma^\mu \gamma^5 \tilde{\chi}][\bar{q} \gamma_\mu (c_q^{\tilde{q}} + d_q^{\tilde{q}} \gamma^5) q],$$

where $f_q^{\tilde{q}}$, $c_q^{\tilde{q}}$, and $d_q^{\tilde{q}}$ are effective coupling constants:

$$\begin{aligned}
f_q^{\tilde{q}} &= -\frac{1}{4} \sum_{i=1}^{2} \frac{a_{\tilde{q}_i}^2 - b_{\tilde{q}_i}^2}{m_{\tilde{q}_i}^2 - (m_{\tilde{\chi}} + m_q)^2} \\
c_q^{\tilde{q}} &= -\frac{1}{2} \sum_{i=1}^{2} \frac{a_{\tilde{q}_i} b_{\tilde{q}_i}}{m_{\tilde{q}_i}^2 - (m_{\tilde{\chi}} + m_q)^2} \\
d_q^{\tilde{q}} &= \frac{1}{4} \sum_{i=1}^{2} \frac{a_{\tilde{q}_i}^2 + b_{\tilde{q}_i}^2}{m_{\tilde{q}_i}^2 - (m_{\tilde{\chi}} + m_q)^2}.
\end{aligned}$$

$$\begin{aligned}
b_{\tilde{q}_1} &= \frac{1}{2}[\cos\theta_{\tilde{q}}(X_{q0} - Z_{q0}) + \sin\theta_{\tilde{q}}(-Y_{q0} + Z_{q0})] \\
b_{\tilde{q}_2} &= \frac{1}{2}[-\sin\theta_{\tilde{q}}(X_{q0} - Z_{q0}) + \cos\theta_{\tilde{q}}(-Y_{q0} + Z_{q0})]
\end{aligned}$$

where $\theta_{\tilde{q}}$ is the squark mixing angle of left and right squarks into physical squarks and

$$\begin{aligned}
X_{q0} &= -\sqrt{2} g_2 [T_{q3} N_{12} - \tan\theta_W (T_{q3} - e_q) N_{11}] \\
Y_{q0} &= \sqrt{2} g_2 \tan\theta_W e_q N_{11} \\
Z_{q0} &= \begin{cases} -\frac{g_2 m_u N_{14}}{\sqrt{2} \sin\beta m_W} & \text{for up-type quarks} \\ -\frac{g_2 m_d N_{13}}{\sqrt{2} \cos\beta m_W} & \text{for down-type quarks.} \end{cases}
\end{aligned}$$

$$
\begin{aligned}
a_{\tilde{q}_1} &= \frac{1}{2}[\cos\theta_{\tilde{q}}(X_{q0} + Z_{q0}) + \sin\theta_{\tilde{q}}(Y_{q0} + Z_{q0})] \\
a_{\tilde{q}_2} &= \frac{1}{2}[-\sin\theta_{\tilde{q}}(X_{q0} + Z_{q0}) + \cos\theta_{\tilde{q}}(Y_{q0} + Z_{q0})]
\end{aligned}
$$