Multi-component Dark Matter in a Simplified E_6SSM

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in collaboration with S. Khalil, S. Moretti and H. Waltari

Motivations

- No reason for minimal DM sector
- Interesting parameter space regions could be saved from being excluded by (in)direct DM searches
- Due to $R-$parity, SUSY naturally has a DMC. But MSSM almost ruled out, need for non-minimal scenarios.
- E_6SSM: string inspired scenario based on

$$E_6 \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_N$$

- E_6SSM includes Type-I see-saw mechanism
- In this work: 2 DMCs (1 active, 1 inert)

Simplified E_6SSM

$$
\begin{aligned}
E_6 \quad &\longrightarrow \quad SO(10) \times U(1)_\psi \longrightarrow \boxed{SU(5) \;\times U(1)_N}^{*} \\
&\longrightarrow \quad SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N
\end{aligned}
$$

with $U(1)_N = \cos\vartheta \; U(1)_\chi + \sin\vartheta \; U(1)_\psi$, $\tan\vartheta = \sqrt{15}$

*decomposes as:

$$
\begin{aligned}
27_i \quad \rightarrow \quad & (10, \frac{1}{\sqrt{40}})_i + (\bar{5}, \frac{2}{\sqrt{40}})_i + (\bar{5}, \frac{-3}{\sqrt{40}})_i \\
& +(5, \frac{-2}{\sqrt{40}})_i + (1, \frac{5}{\sqrt{40}})_i + (1, 0)_i
\end{aligned}
$$

- Normal matter
- 3 gens Higgs doublets plus exotic $D, \bar{D}$
- 3 gens singlets S_i
- RH neutrinos

	Z_2^H	Z_2^L	Z_2^B	Z_2^M
S_α	-	$+$	$+$	$+$
$H_{d\alpha}, H_{u\alpha}$	-	$+$	$+$	$+$
S_3	$+$	$+$	$+$	$+$
H_{d3}, H_{u3}	$+$	$+$	$+$	$+$
Q_i, u_i^c, d_i^c	-	$+$	$+$	-
L_i, e_i^c	-	-	-	-
$\bar{D}_i, D_i$	-	$+$	-	$+$

- Z_2^H: to distinguish between 3rd active gen and inert gens
- Z_2^L or Z_2^B: to forbid proton decay, which is exact
- $Z_2^M \equiv R$: automatic due to the $U(1)_N$ presence

$$W = Y_u Q U^c H_u + Y_d Q D^c H_d + Y_e L E^c H_d + Y_\nu L \nu^c H_u + \lambda S H_d H_u$$

$$\langle H_{d3}^0 \rangle = \frac{v_d}{\sqrt{2}} = \frac{v \cos\beta}{\sqrt{2}}, \qquad \langle H_{u3}^0 \rangle = \frac{v_u}{\sqrt{2}} = \frac{v \sin\beta}{\sqrt{2}}, \qquad \langle S_3 \rangle = \frac{s}{\sqrt{2}}$$

- Active in basis $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}, \lambda_{B'}\right)$

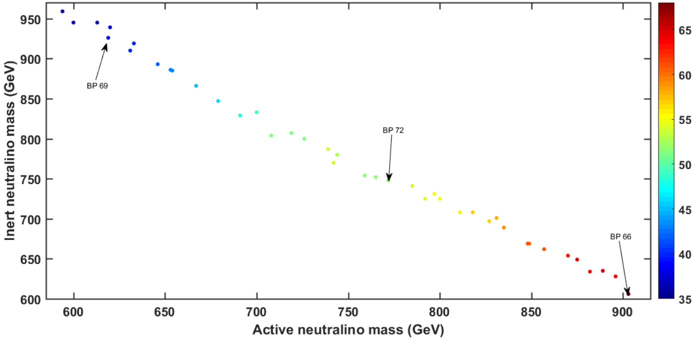
$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta & 0 & 0 \\ 0 & M_2 & M_Z c_W c_\beta & M_Z c_W s_\beta & 0 & 0 \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\frac{1}{\sqrt{2}} v_s \lambda & -\frac{1}{\sqrt{2}} \lambda v s_\beta & m_{\lambda_{B'} \tilde{H}_d^0} \\ M_Z s_W s_\beta & M_Z c_W c_\beta & -\frac{1}{\sqrt{2}} v_s \lambda & 0 & -\frac{1}{\sqrt{2}} \lambda v c_\beta & m_{\lambda_{B'} \tilde{H}_u^0} \\ 0 & 0 & -\frac{1}{\sqrt{2}} \lambda v s_\beta & -\frac{1}{\sqrt{2}} \lambda v c_\beta & 0 & \frac{1}{2}\sqrt{\frac{5}{2}} g_N v_s \\ 0 & 0 & m_{\tilde{H}_d^0 \lambda_{B'}} & m_{\tilde{H}_u^0 \lambda_{B'}} & \frac{1}{2}\sqrt{\frac{5}{2}} g_N v_s & M_1' \end{pmatrix}$$

- Inert in basis $\left(\tilde{h}_{d1}^{0,I}, \tilde{h}_{d2}^{0,I}, \tilde{h}_{u1}^{0,I}, \tilde{h}_{u2}^{0,I}\right)$

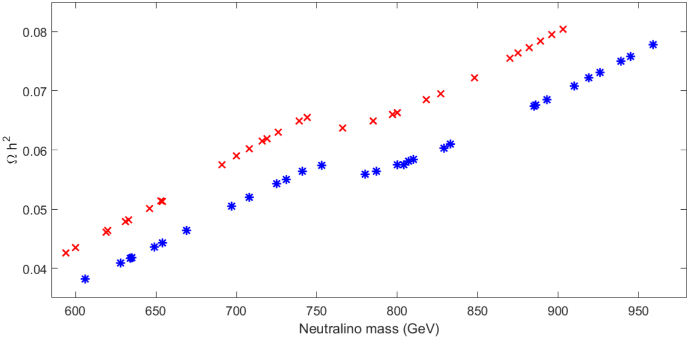
$$m_{\tilde{\chi}^{0,I}} = \begin{pmatrix} 0 & 0 & -\frac{1}{\sqrt{2}} v_s \lambda_{311} & -\frac{1}{\sqrt{2}} v_s \lambda_{312} \\ 0 & 0 & -\frac{1}{\sqrt{2}} v_s \lambda_{321} & -\frac{1}{\sqrt{2}} v_s \lambda_{322} \\ -\frac{1}{\sqrt{2}} v_s \lambda_{311} & -\frac{1}{\sqrt{2}} v_s \lambda_{312} & 0 & 0 \\ -\frac{1}{\sqrt{2}} v_s \lambda_{321} & -\frac{1}{\sqrt{2}} v_s \lambda_{322} & 0 & 0 \end{pmatrix}$$

* inert singlinos massless and decoupled

Two DM candidates

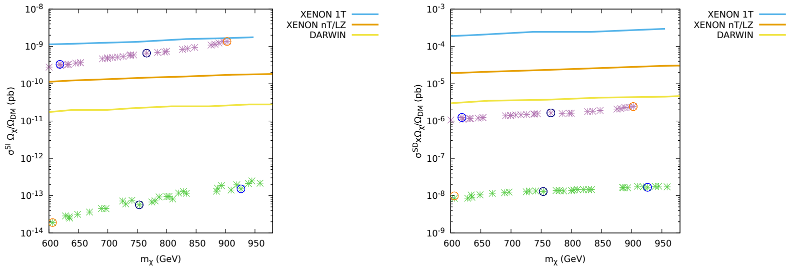


- Fixed $\Omega h^2 = \Omega_{\tilde{\chi}^0} + \Omega_{\tilde{\chi}^{0,I}} = 0.12 \pm 0.0012$
- Selected points where both DMCs where contributing similarly
- Each annihilate nearly independently, fixing: $m_{\tilde{\chi}^0} + m_{\tilde{\chi}^{0,I}} = 1.53 \pm 0.03$ TeV
- Both DMCs are Higgsino-like

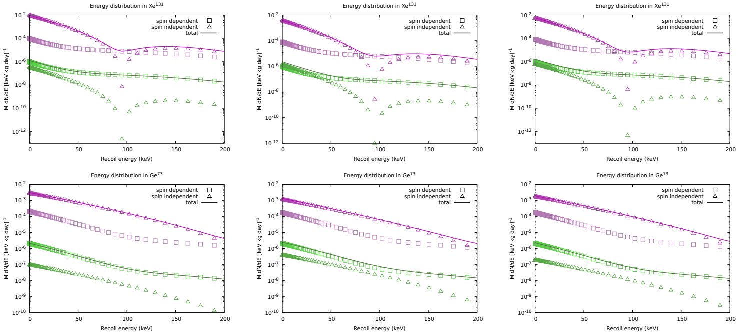


- Relic density of active Higgsino (red) and inert Higgsino (blue)
- The difference between both DMCs is due to larger mass splitting (with the corresponding chargino) in the active sector

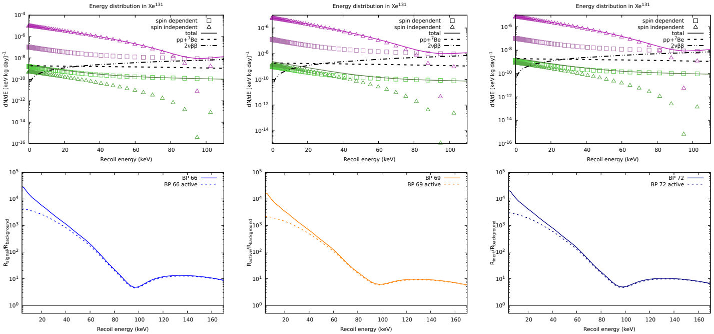
SI (left) and SD (right) cross sections of active neutralino (purple) and inert neutralino (green) scattering with protons:



- All points satisfy XENON-1T exclusion
- Active neutralino is within the region for future experiments



Event rate (times WIMP mass) vs recoil energy for the selected BPs 66, 69 and 72 in detector material made of Xe (top) and Ge (bottom).



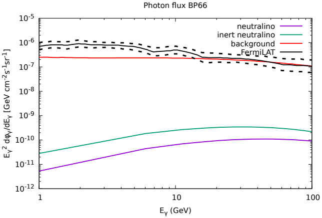
- Top: Nuclear recoil spectrum for the selected BPs 66, 69 and 72 in a liquid Xe detector.
- Also shown are the expected backgrounds.
- Bottom: Ratio of active plus inert neutralino (solid) and active neutralino only (dotted) signal rates to the total background ones as obtained from the top plots.

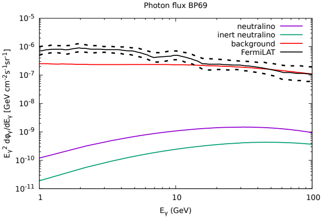
Indirect detection

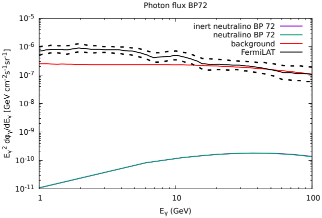
BP	m (GeV)	$\langle\sigma^{\text{ann}}_{WW} v\rangle(cm^3/s)$	$\langle\sigma^{\text{ann}}_{ZZ} v\rangle(cm^3/s)$	$\langle\sigma^{\text{ann}}_{h_1 Z} v\rangle(cm^3/s)$
66 (active)	903	6.67×10^{-27}	5.03×10^{-27}	5.94×10^{-28}
66 (inert)	606	1.45×10^{-26}	1.18×10^{-26}	4.74×10^{-29}
69 (active)	619	1.41×10^{-26}	1.09×10^{-26}	1.16×10^{-27}
66 (inert)	926	6.67×10^{-27}	5.03×10^{-27}	5.94×10^{-29}
72 (active)	766	9.51×10^{-27}	7.66×10^{-27}	7.68×10^{-29}
72 (inert)	753	9.48×10^{-27}	7.64×10^{-27}	7.62×10^{-29}

- Different astrophysical signatures can be studied: γ-ray excess from galactic centre, or positron/antiproton flux excess
- For lower masses of DMCs than in the present work we could get better contribution, if inert is the lightest it would be complementary to DD detection of active

Indirect detection







Future and present work in progress

In collaboration with: S. Khalil, K. Kowalska, S. Moretti, H. Waltari

- Small mass splitting between chargino and neutralino give place to long-lived particles (LLP) signatures: displaced vertices, disappearing tracks, etc.
- Perform recast of experimental searches for LLP
- Relaxing the constraint of both DMCs contributing similarly: intersting scenario with big mass gap between the DMCs
- Heavy active Higgsino could be observed at DD (Xenon-nT/LZ/Darwin), or ID (CTA/HESS/HAWK)
- Light inert Higgsino could be searched at colliders
- Inert Higgsino is very challenging, could lowering $m_{Z'}$ give interesting signatures?

Conclusions

- We studied E_6SSM with 2 DMCs: active & inert Higgsino
- Fixed $\Omega h^2 = 0.12 \pm 0.0012$ with both DMCs contributing similarly
- $m_{\tilde{\chi}^0} + m_{\tilde{\chi}^{0,I}} \sim 1.5$ TeV
- Active Higgsino can be tested at DD (Xenon-nT/LZ/Darwin)
- Recoil energy shape could help to distinguish between single or multi-DM model
- Inert Higgsino cannot be detected at DD, but with smaller mass could contribute to astrophysical fluxes (complementarity!)

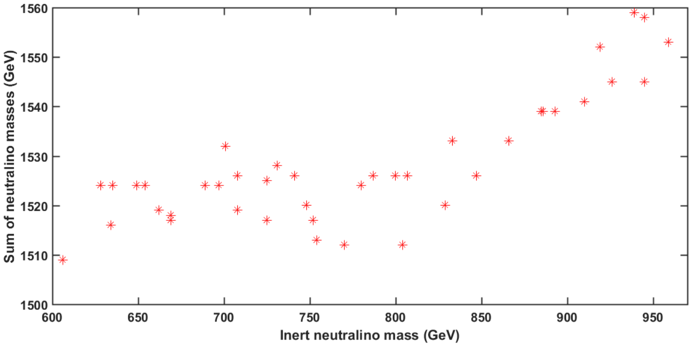
Thanks for

your attention!

BACKUP

SLIDES

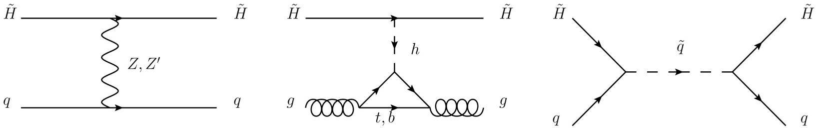
Two DM candidates



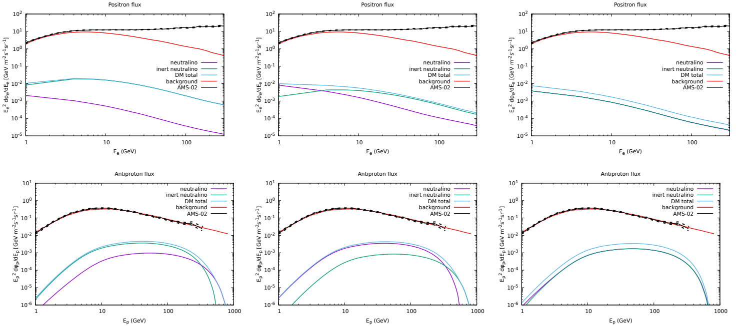
Mass splittings chargino-neutralino larger in the active sector:

- $\tilde{\chi}^{\pm}\tilde{\chi}^{0I} \to \tilde{\chi}^{0}\tilde{\chi}^{\pm I}$ always allowed
- $\tilde{\chi}^{\pm I}\tilde{\chi}^{0} \to \tilde{\chi}^{0I}\tilde{\chi}^{\pm}$ threshold

Direct detection



Indirect detection



Nuclear recoil spectrum

Recoil energy $E_R \longrightarrow$ amount of transferred energy, E_R, to the nucleus by the WIMP:

$$E_R = \frac{\mu_N^2 v^2 (1 - \cos\theta_{CM})}{m_N}.$$

Differential event rate [/keV/kg/day] (nuclear recoil energy distro):

$$\frac{dN}{dE_R} = \frac{\rho_0}{m_N m_\chi} \int_{v<v_{min}} v f(v) \frac{d\sigma}{dE_R}(v, E_R) dv$$

$$\Rightarrow N = \int_{E_T}^{E_{max}} dE_R \frac{\rho_0}{m_N m_\chi} \int_{v<v_{min}} v f(v) \frac{d\sigma}{dE_R}(v, E_R) dv$$

But $\frac{d\sigma}{dE_R} = (\frac{d\sigma}{dE_R})_{SI} + (\frac{d\sigma}{dE_R})_{SD}$.

$$(\frac{d\sigma}{dE_R})_{SI} = \frac{m_N \sigma_0^{SI} F^2(E_R)}{2\mu_N^2 v^2}, \; \sigma_0^{SI} = \frac{4\mu_N^2 A^2 f^P}{\pi}$$

$$(\frac{d\sigma}{dE_R})_{SD} = \frac{16 m_N}{\pi v^2}, \; \sigma_0^{SD} = \frac{32\mu_N^2 \Lambda^2 G_F^2}{\pi} J(J+1)$$

σ_0^{SI} depends on A^2 (num of nucleons), σ_0^{SD} is dependent on the angular momentum $J(J+1)$

arXiv:2008.06778