Thermal Dark Matter and the Higgs

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WIMP Dark Matter

Vanilla thermal production:
\[ \langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \]

but direct detection limits are very strong

Production and direct detection cross-sections must be decoupled (unless \( m_{\text{DM}} \gg 100 \text{ GeV} \))
2 ways of decoupling $\langle \sigma v \rangle$ and $\sigma^{\text{SI}} / \sigma^{\text{SD}}$
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Suppress coupling of DM candidate to all states which could mediate direct detection signals

Then, one needs to boost the annihilation cross section:

- co-annihilation
- resonant annihilation

Griest & Seckel, PRD 43, 3197 (1991)
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Both options require extended BSM sectors to supply either

- co-annihilation partners
- Multiple mediators allowing for destructive interference
Model-building

- Dark Matter candidate: Majorana fermion $\chi$
- Type II 2 Higgs Doublet Model (2HDM) ($H_u$, $H_d$)
- Invoke a $Z_3$ symmetry under which all scalars/fermions transform as $\psi \rightarrow e^{2\pi i} \psi$ to forbid Majorana mass for $\chi$
- Weak scale mass for $\chi$ can be obtained via the vacuum expectation value (vev) of an extra SM-singlet (complex) scalar $S$
  - Generates weak scale mass for $\chi$ if vev $\langle S \rangle$ from same mechanism as EWSB
  - $S$ couples to SM only via mixing with neutral components of $H_u$, $H_d$ after EWSB
Model-building

- Write down all operators to dimension $d \leq 6$ arising from integrating out a heavy $SU(2)$-doublet Dirac fermion (ignoring charged gauge boson interactions)

$$\mathcal{L} = -\delta \frac{\chi \bar{\chi}}{\mu} (H_u \cdot H_d) \left(1 - \frac{\lambda \hat{S}}{\mu}\right) - \kappa S \chi \bar{\chi} \left(1 + \xi \frac{H_d^\dagger H_d + H_u^\dagger H_u}{|\mu|^2}\right) + \text{h.c.}$$

$$+ \frac{\alpha}{|\mu|^2} \left\{ \chi^\dagger H_u^\dagger \bar{\sigma}^\mu \left[i \partial_\mu - \frac{g_1}{s_W} (T_3 - Q s_W^2) Z_\mu \right] (\chi H_u) \right. + \chi^\dagger H_d^\dagger \bar{\sigma}^\mu \left[i \partial_\mu - \frac{g_1}{s_W} (T_3 - Q s_W^2) Z_\mu \right] (\chi H_d) \right\},$$

- DM mass $m_\chi = 2\kappa \langle S \rangle$
- Heavy $SU(2)$-doublet fermion mass: $\mu = \lambda \langle S \rangle$
Model phenomenology. Higgs sector

- Rotate scalars to Higgs basis

\[
\begin{align*}
H^{SM} &= \sqrt{2} \text{Re} \left( \sin \beta H_u^0 + \cos \beta H_d^0 \right), \\
G^0 &= \sqrt{2} \text{Im} \left( \sin \beta H_u^0 - \cos \beta H_d^0 \right), \\
H^{NSM} &= \sqrt{2} \text{Re} \left( \cos \beta H_u^0 - \sin \beta H_d^0 \right), \\
A^{NSM} &= \sqrt{2} \text{Im} \left( \cos \beta H_u^0 + \sin \beta H_d^0 \right),
\end{align*}
\]

- SM-like
- Neutral Goldstone (Z)
- MSSM-like scalar
- MSSM-like pseudoscalar

+ scalar ($H^S$) and pseudoscalar ($A^S$) from singlet

- 125 GeV Higgs pheno requires approximate alignment: $h_{125} \sim H^{SM}$
Model phenomenology. DM

- Thermal production via
  - $\chi\chi \rightarrow q\bar{q}$ (important contribution from longitudinal $Z$/neutral Goldstone)
  - Usually small contributions from $\chi\chi \rightarrow h_i h_j \ / \ h_i a_j \ / \ WW \ / \ ZZ$

- SI Direct Detection mediated predominantly by CP-even Higgs bosons
  - EFT operators allow for blind spot where $g_{\chi\chi h} \rightarrow 0$
  - Presence of 3 CP-even Higgses allows for destructive interference

$d \geq 5$ operators
Model phenomenology. DM

\[ m_\chi = 300\text{ GeV}; \quad m_{H^{\text{NSM}}} = m_{A^{\text{NSM}}} = 500\text{ GeV}; \quad \tan \beta = 2; \]
\[ \sigma_p^{\text{SI}} \leq 3.0 \times 10^{-10}\text{ pb}; \quad \langle \sigma v \rangle_{x_F} = 2.3 \times 10^{-26}\text{ cm}^3\text{s}^{-1} \]

Example of allowed couplings / EFT parameters

(standard thermal production & current Direct Detection limits)
Does this really work? (aka UV completion)

\((Z_3\text{-invariant})\) Next to minimal Supersymmetric Standard Model (NMSSM)

- MSSM particle content + one extra SM-singlet chiral superfield
- Same Higgs sector as our model (2HDM+S)
- Fermionic component of singlet (‘singlino’) plays role of our DM candidate
- Mature numerical tools exist to study DM & collider phenomenology
- Besides the singlino, the NMSSM contains a second SM-singlet fermion, the bino
  - Smaller couplings to Higgs sector than singlino
  - EFT model can be extended in simple fashion to include bino
NMSSM: Singlino DM. Production

- predominantly vanilla thermal production dominated by annihilations into top quarks
- Longitudinal Z (neutral Goldstone mode) plays prominent role

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NMSSM: Singlino DM. Direct Detection

SI Direct Detection cross section suppressed by:

- Proximity to $h_{125}$ blind spot (Cheung+ 1406.6372, Badziak+ 1512.02472)
- Destructive interference between CP-even Higgs mass eigenstates
NMSSM: (new ‘well-tempered’) Bino DM

- Thermal production via co-annihilation with singlino
- SI Direct Detection cross section suppressed by $h_{125}$ blind spot proximity
As yet, SI limits are much more relevant

But, increasing sensitivity of SD experiments by \( \sim 2 \) orders of magnitude would probe most of the remaining parameter space!
Conclusions

● Stringent Direct Detection limits require decoupling of SI detection cross section and annihilation cross section
  ○ Either, one enhances the production cross-section by co-annihilation or resonant annihilation,
  ○ Or, one suppresses the SI detection cross section by destructive interference

● Qualitative features studied in Majorana DM + (2HDM+S) model

● Tested validity of results and extended numerical study in NMSSM
  ○ Singlino region: Vanilla thermal production (via the longitudinal $Z$), $h_{125}$ blind spot + destructive interference for direct detection
  ○ New ‘well-tempered’ Bino region: co-annihilation with singlino for thermal production, blind-spot for direct detection
  ○ Both can be probed by SD experiments in near future!