Simplified Models of Mixed Dark Matter

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Work with C. Cheung (JCAP02(2014)011 [hep-ph/1311.5896])

Complementarity for Dark Matter Searches

Theory input is required to compare the results of dark matter searches

A spectrum of approaches exists between complete models and effective theories

Candidates within larger BSM models

- Complete description of UV physics
- Unambiguous mapping between searches
- Restrictive frameworks often limiting

Effective theory provides general results

- Clear mapping between search strategies
- Concise examination of many theories
- Description suffers in collider searches

Simplifed models can bridge the gap between BSM frameworks and effective theory

Why Use Simplified Models?

Motivation is analogous to simplified models for collider searches

- In larger BSM theories dark matter dynamics are often defined by a small sub-set of parameters

Single interactions are often enough for searches

- Direct detection is often dominated by one interaction
- One interaction typically gives conservative bounds for indirect and collider searches

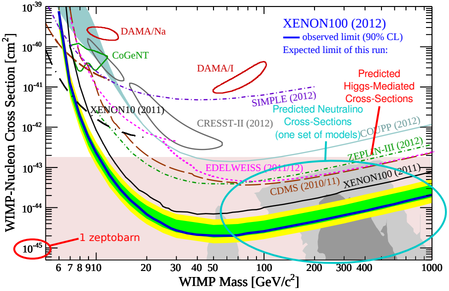
Thermal constraint requires all relevant interactions

- Theories reducing to a single effective operator are somewhat contrived
- Thermal production remains the strongest motivator for significant coupling to the SM

Direct Detection and Higgs Interactions

Simplified models producing DM-Higgs interactions are particularly important!

- Standard lore: direct detection is reaching the parameter space for neutralino scattering
- Sensitivity is strong for a much larger class of models where dark matter scatters through Higgs interactions



The strength of current and near-future direct detection experiments allows for exploration of DM interacting through the Higgs without requiring a full BSM framework!

Singlet and Minimal Dark Matter

A singlet with a Higgs portal is perhaps the simplest DM model

Silveira and Zee (1985), McDonald (1994)

- Relic density achieved through Higgs-mediated annihilation and annihilation to Higgs
  - Annihilation to $q\bar{q}$, $b\bar{b}$, $t\bar{t}$, WW, ZZ, HH
- Relic density maps directly to direct detection cross-section
- Within XENON1T sensitivity for $M_S \lesssim 10$ TeV

J. M. Cline, K. Kainulainen, P. Scott, and C. Weniger (2013)

Minimal dark matter annihilates through $\mathrm{SU}(2) \times \mathrm{U}(1)$ interactions

- Thermal relic only at a particular mass depending on representation and spin
- Direct detection prospects are generally weak

Simplified models with more freedom are desireable

Mixed Dark Matter

Mixed DM $\equiv$ Dark matter composed of neutral components from multiple representations

- Still only one dark matter particle

We are most interested in mixtures of states with different $\mathrm{SU}(2)$ representations

- Mixing requires Higgs vev insertions
- Produces a Higgs coupling

$$c_{h\chi\chi} h\chi\chi \ \text{(fermion)} \qquad\qquad a_{h\chi\chi} h\chi\chi \ \text{(scalar)}$$

- Generalization of "bino-Higgsino" mixing in the MSSM but with arbitrary representation, spin, and Higgs couplings

Will consider three models

Singlet-Doublet Fermion	Singlet-Doublet Scalar	Singlet-Triplet Scalar

Singlet-Doublet Fermion

Generalization of "bino-Higgsino" mixing in the MSSM or "singlino-Higgsino" mixing in the NMSSM

Cohen, Kearney, Pierce, Tucker-Smith (2012)

- Yukawa terms are no longer tied to gauge couplings or Higgs potential

Field	Charges	Spin
S	$(\mathbf{1}, 0)$	1/2
D_1	$(\mathbf{2}, -1/2)$	1/2
D_2	$(\mathbf{2}, 1/2)$	1/2

- Requires two doublets
  - Provides a doublet mass term
  - Eliminates anomalies

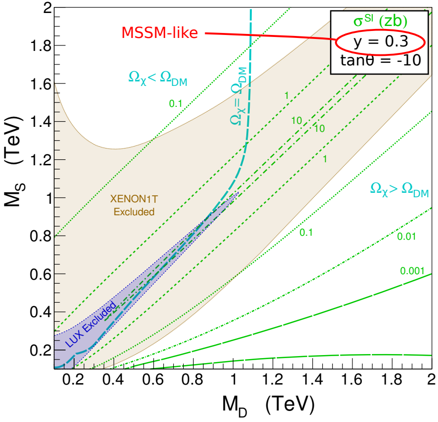
$$-\mathcal{L} = \frac{1}{2} M_S S^2 + M_D D_1 D_2 + y_{D_1} S H D_1 + y_{D_2} S H^\dagger D_2 + h.c.$$

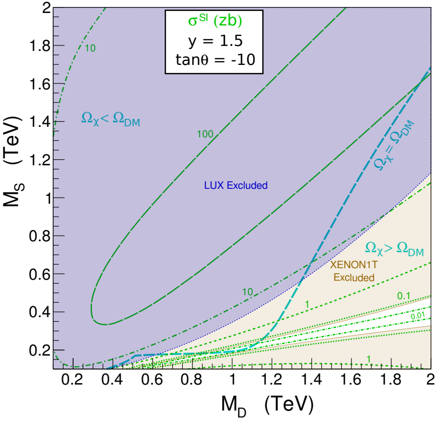
- A polar representation makes formulation simpler

$$y_{D_1} = y \cos\theta \qquad y_{D_2} = y \sin\theta$$

- $y \approx g'/\sqrt{2}$ for bino-Higgsino; $y = \lambda$ for singlino-Higgsino

Relic Density and Direct Detection





No abundance re-scaling away from the thermal line

- Strong bounds on thermal region from LUX
- Exceptional reach for XENON1T
- Regions with vanishing cross-section exist

Fixing the Relic Density

In WIMP models, the most interesting region is the $\Omega_\chi = \Omega_{DM}$ slice of parameter space

- Provides an explanation for all of dark matter without needing further candidates or high-scale physics
- Correlation often exist between early annihilation and current searches
  - Mixing produces both annihilation and a Higgs coupling for mixed DM

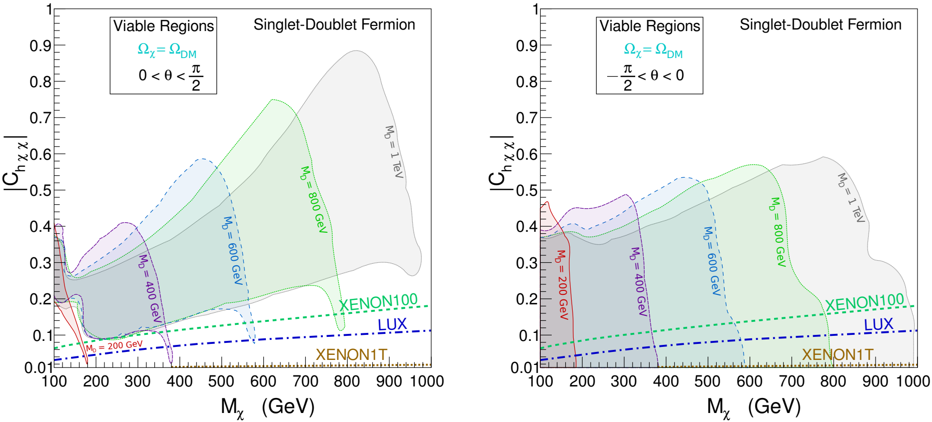
Direct detection has strong sensitivity to σ^{SI}

…but two classes of thermal models exhibit $\sigma^{SI} \to 0$

- Well-tempered models can exhibit significant mixing for $y \to 0$ if $|M_S - M_D| \to 0$
- A *blind spot* exists for spin-independent searches if $M_\chi + M_D \sin 2\theta = 0$

Summary of Singlet-Doublet Fermion

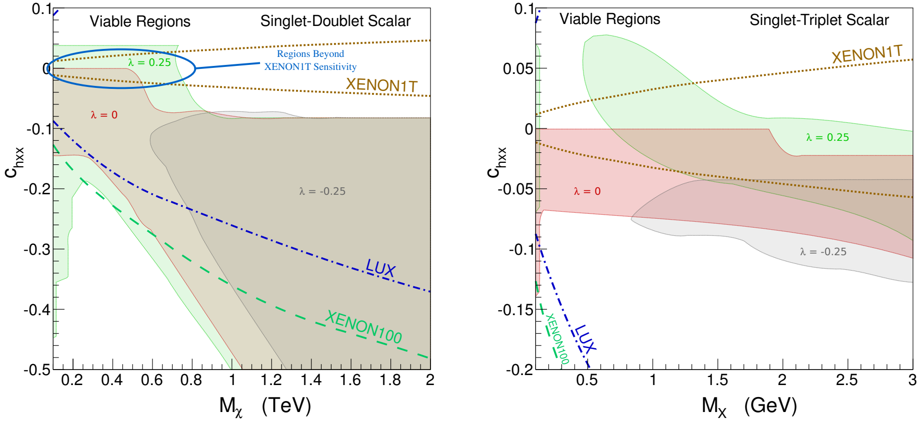
Allowed regions for singlet-doublet fermion



- For $\tan\theta > 0$ only coannihilation regions with $M\chi \to M_D$ survive LUX
- For $\tan\theta < 0$ blind-spots occur, but require significant fine-tuning after XENON1T

Other Mixed Dark Matter Models

Allowed region for scalar mixed DM models



- Most of the singlet-doublet scalar model space lies within XENON1T sensitivity
- Significant regions of singlet-triplet scalar model space lies beyond XENON1T sensitivity

Conclusion

- Simplified models are valuable for dark matter searches, particularly when considering the relic density
- Higgs-mediated models are particularly relevant for direct detection
- Mixing of multiple $\mathrm{SU}(2) \times \mathrm{U}(1)$ states implies a Higgs coupling
- The bulk of singlet-doublet models (both fermion and scalar) are within future sensitivity, while many singlet-triplet models lie beyond XENON1T reach
- Many possible future directions
  - Spin-dependent constraints
  - Indirect detection constraints
  - $\Gamma(h \to \text{invis.})$ and other precision constraints
  - Consider non-perturbativity bounds
  - Examine stability bounds for scalar models
  - Examine mixing of higher dimensional representations
  - Allow for non-renormalizable operators (singlet-quadruplet, singlet-quintuplet, etc.)
  - Compare with collider constraints