Singlet-Doublet Dark Matter

WIMPs in Light of Recent Experimental Results

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Based on:

arXiv:1109.2604 with Tim Cohen, Aaron Pierce and Dave Tucker-Smith

arXiv:1202.0284 with Aaron Pierce

Motivation

The WIMP Miracle

Weakly-Interacting Massive Particles (WIMPs) with thermal history give approximately the correct dark matter relic density.

$$\Omega_{\rm DM} h^2 \sim \mathcal{O}(0.1) \tag{1}$$

Promising from phenomenological standpoint – interact with SM particles, so may be observed experimentally:

1. Direct detection.
2. Indirect detection.
3. Colliders.

Recent Experimental Results

1. New limits on σ_{SI} from XENON100.

   [arXiv:1104.2549]

2. New information on the electroweak sector from LHC:
   - 115 GeV $\lesssim m_h \lesssim$ 130 GeV.
   - Potential signal at $m_h \approx 125$ GeV.

   ATLAS [arXiv:1202.1408]

   CMS [arXiv:1202.1488]

3. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP7) and other data on large scale structure:

$$\Omega_{\mathsf{DM}} h^2 = 0.1123 \pm 0.0035 \tag{2}$$

   [arXiv:1001.4538]

Where are the WIMPs?

Lack of (unequivocal) signal thus far constrains the viability of strictly weakly-interacting dark matter – that is, dark matter whose interactions and annihilations are controlled by the electroweak (W, Z, Higgs) bosons.

Goal: To investigate the extent to which weakly-interacting dark matter remains an attractive scenario in light of recent experimental results, using the minimal singlet-doublet dark matter model.

Cohen, Pierce, JK, Tucker-Smith [arXiv:1109.2604]

This talk will focus on the fermionic singlet-doublet model – paper also includes investigation of scalar singlet-doublet model.

The Singlet-Doublet Model

Extension to the Standard Model consisting of:

- Gauge singlet fermion N.
- Vector-like pair of fermionic electroweak doublets

$$D = \begin{pmatrix} \nu \\ E \end{pmatrix}, \qquad D^c = \begin{pmatrix} -E^c \\ \nu^c \end{pmatrix} \tag{3}$$

  with hypercharges $-\frac{1}{2}$ and $+\frac{1}{2}$ respectively.
- $\mathbb{Z}_2$ symmetry under which SM fields are even and non-SM fields are odd – ensures stability of lightest new field (ν_1).
- Interactions and mass terms:

$$\Delta\mathcal{L} = -\lambda DHN - \lambda' \tilde{H} D^c N - M_D D D^c - \frac{1}{2} M_N N^2 + \text{ h.c.} \tag{4}$$

  $SU(2)$ indices contracted with ϵ^{ij}, $\tilde{H} \equiv i\sigma^2 H$.

SUSY analog: Bino-Higgsino dark matter with $M_2 \to \infty$.

An appealing model

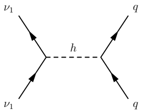
Minimal model that can be compatible with experimental constraints.

- **Minimal:** dark matter interacts only with bosons of electroweak theory.
- **Compatible with experimental constraints:** generates Majorana dark matter, avoiding large σ_{SI} exhibited by Dirac dark matter.
- **Mixing arises naturally from renormalizable operators:** no need for higher order terms suppressed by new physics scale etc.

Previous studies of other features of this model include:

Arkani-Hamed, Dimopolous, Kachru [arXiv:0501082]
Mahbubani, Senatore [arXiv:0510064]
D'Eramo [arXiv:0705.4493]
Enberg, Fox, Hall, Papaioannou, Papucci [arXiv:0706.0918]

Phenomenology: Annihilation and DM-Nucleon Scattering



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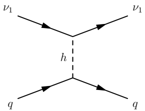
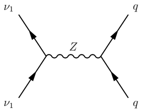


(σ_{SI})



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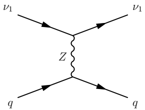
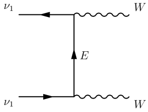
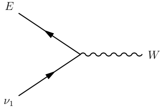


(σ_{SD})



$\rightarrow$ No tree-level nucleon scattering analog



$\rightarrow$ No tree-level nucleon scattering analog

Technical Details

Parameter Scans

- Implemented model in `micrOmegas`.
- Perform parameter scans over ranges
  - $0 \text{ GeV} \leq M_N \leq 800 \text{ GeV}$,
  - $80 \text{ GeV} \leq M_D \leq 2 \text{ TeV}$,
  - $-2 \leq \lambda \leq 2$,
  - $0 \leq \lambda' \leq 2$,

  subject to requirements that
  - $40 \text{ GeV} \leq m_{\nu_1} \leq 500 \text{ GeV}$,
  - $0.1053 \leq \Omega h^2 \leq 0.1193$ ($\pm 2\sigma$ range),
  - $-0.07 \leq \Delta T \leq 0.21$.
- Take $m_h = 125$ GeV.
- Note that `micrOmegas` does not include 3-body final states, so results slightly off near W^+W^- and $t\bar{t}$ thresholds. Also, does not include loop contributions to scattering, so $\sigma_{\text{SI}} \lesssim 10^{-10}$ pb should be take as demonstrative and not exact – similar caveats hold for σ_{SD}.

Indirect Detection via Solar Neutrinos

- Annihilation of WIMPs captured in Sun can produce detectable ν.
- Signal depends on annihilation branching ratios.
- Performed general analysis of neutrino flux from different annihilation final states, with focus on key 3-body final states – details can be found in arXiv:1202.0284 (with Aaron Pierce).
    - 3-body final states can have significant effect on limits near threshold.
- Used results to determine indirect detection limits for Singlet-Doublet model.

Results

$\sigma_{\rm SI}$ against m_{ν_1}

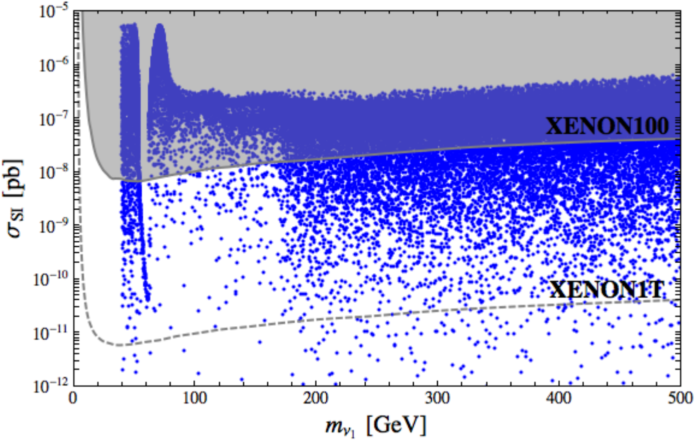


Figure: Limits shown are current XENON100 [arXiv:1104.2549] (solid), and projected XENON1T [arXiv:0902.4253] (dashed).

$\sigma_{SD}^{(p)}$ against m_{ν_1}

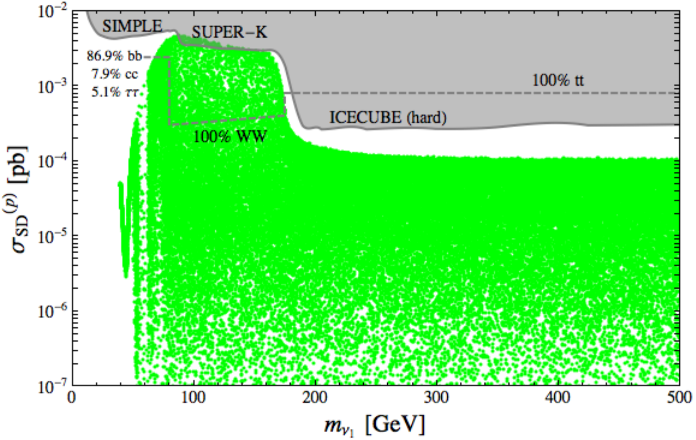


Figure: Limits shown from SIMPLE [arXiv:1106.3014] ($m_{\nu_1} \leq m_W$), SUPER-K [arXiv:0404025] ($m_W \leq m_{\nu_1} \leq m_t$), ICECUBE (hard) [arXiv:0902.2460] ($m_{\nu_1} \geq m_t$). Also shown are derived limits from arXiv:1202.0284.

σ_{SI} against $\sigma_{\text{SD}}^{(p)}$ (high mass region, $m_{\nu_1} \geq 85$ GeV)

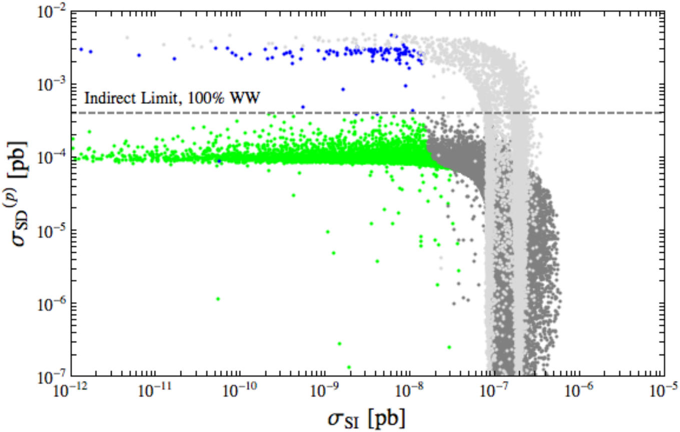


Figure: Blue (light gray) $\equiv$ (excluded) points with 85 GeV $\leq m_{\nu_1} \leq$ 160 GeV. Green (dark gray) $\equiv$ (excluded) points with $m_{\nu_1} \geq$ 175 GeV.

σ_{SI} against $\sigma_{\mathrm{SD}}^{(p)}$ (low mass region, $m_{\nu_1} \leq 70$ GeV)

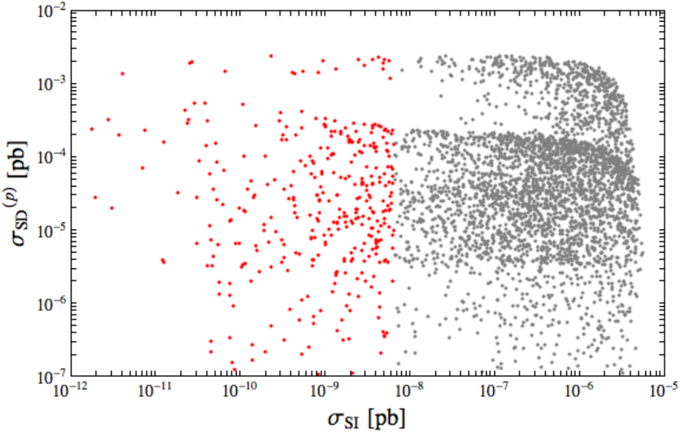


Figure: Red (gray) $\equiv$ (excluded) points with $m_{\nu_1} \leq 70$ GeV.

Conclusions

- Majority of parameter space should be probed in near future by combination of direct and indirect detection experiments.
- Majorana dark matter whose thermal relic abundance and neutrino signals are both controlled by annihilation via an s-channel Z boson is *excluded* for 70 GeV $\lesssim m_{\rm DM} \lesssim m_W$.
- Singlet-Doublet model severely constrained for $m_W \lesssim m_{\nu_1} \lesssim m_t$.
- Limited remaining options for avoiding direct and indirect detection bounds
  1. $m_{\nu_1} \approx M_D$ or $m_{\nu_1} \approx m_{\nu_2}$ such that relic density can be set by coannihilation while dark matter-nucleon scattering is small.
  2. $m_{\nu_1} \leq m_t \Rightarrow m_{\nu_1} \approx \frac{m_h}{2}$ or $m_{\nu_1} \approx \frac{m_Z}{2}$: proximity of dark matter mass to Higgs or Z pole allows right relic density to be achieved with very small coupling, reducing dark matter-nucleon scattering.
  3. $m_{\nu_1} \geq m_t$: Relic density set by annihilation via an *s*-channel Z boson. Should be probed in near future, notably by DeepCore.

Thank you!