Electroweak Dark Matter

Where do we stand?

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July 18, 2013

An updated version of:

arXiv:1109.2604 with Tim Cohen, Aaron Pierce and Dave Tucker-Smith (PRD 85 (2012) 075003)

arXiv:1202.0284 with Aaron Pierce (PRD 85 (2012) 043527)

Contents

Introduction and Motivation

The WIMP Miracle

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

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

Compelling paradigm:

- relates DM to known scale/interactions,
- implies rich DM phenomenology,
    1. direct detection,
    2. indirect detection,
    3. colliders.
- WIMPs present in BSM models, notably neutralinos in MSSM.

But 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.

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

JK, Pierce [arXiv:1202.0284]

No time like the present...

1. New information on the electroweak sector from LHC:
   - Discovery of the Higgs! Measure $m_h \approx 125$ GeV, Higgs couplings.

   ATLAS [arXiv:1207.7214], CMS [arXiv:1303.4571]

2. New limits on DM-nucleon scattering
   - Direct bounds on σ_{SI}.

     XENON100 [arXiv:1207.5988]

   - Indirect bounds on σ_{SD}.

     ICECUBE/DEEPCORE [arXiv:1212.4097]

3. New measurements of $\Omega_{\text{DM}} h^2$:

$$\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027 \qquad (2)$$

   Planck [arXiv:1303.5076]

4. Convergence of $\langle N | \bar{s}s | N \rangle$ values from lattice QCD

   e.g. Junnarkar, Walker-Loud [arXiv:1301.1114]

A Simple Model of Weakly-Interacting DM

Singlet-Doublet Dark Matter

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:

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

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

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

For $(\psi^0)^T = (N, \nu, \nu^c)$, mass terms given by:

$$\mathcal{L}_{\text{neutral mass}} = -\frac{1}{2}(\psi^0)^T \begin{pmatrix} M_N & \frac{\lambda}{\sqrt{2}}v & \frac{\lambda'}{\sqrt{2}}v \\ \frac{\lambda}{\sqrt{2}}v & 0 & M_D \\ \frac{\lambda'}{\sqrt{2}}v & M_D & 0 \end{pmatrix} \psi^0 + \text{h.c.} \tag{5}$$

Lightest neutral eigenstate $\nu_1 = \theta_1 N + \alpha_1 \nu + \beta_1 \nu^c$ is Majorana dark matter candidate provided $m_{\nu_1} < M_D$. Two other neutral Majorana fermions (ν_2, ν_3), and charged Dirac fermion ψ_E of mass M_D.

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]

Also played an important historical role in development of SUSY EW theories:

- Fayet [Nucl. Phys. B78, 14 (1974)]
- Fayet [Nucl. Phys. B90, 104 (1975)]

Alternative but philosophically similar approach – larger $SU(2)_L$ multiplets with $Y = 0$:

- Cirelli, Strumia, Tamburini [arXiv:0706.4071]

Simple...

Minimal model that can be compatible with experimental constraints.

- **Minimal:** DM interacts only with bosons of electroweak theory.
- **Compatible with experimental constraints:** Majorana DM avoids large σ_{SI} exhibited by Dirac DM.
  - No $(\bar{\nu}_1 \gamma^\mu \nu_1)(\bar{q} \gamma_\mu q)$ effective operator.
- **Mixing arises naturally from renormalizable operators.**

Only four parameters (excluding phase): $\{M_N, M_D, \lambda, \lambda'\}$.

For effects of phase, see: D'Eramo [arXiv:0705.4493]

...yet instructive.

Useful proxy for DM with electroweak interactions.

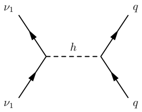
- Exhibits interesting features of thermal DM including resonant annihilation, coannihilation.

Phenomenology (directly) related to relic density.

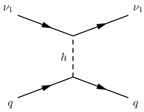
Interesting "limits."

- Cancel dark matter couplings to Z or h.

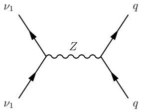
Phenomenology: Annihilation and DM-Nucleon Scattering



$\rightarrow$



(σ_{SI})



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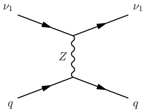
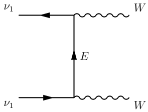
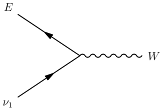


(σ_{SD})



$\rightarrow$ No tree-level nucleon scattering analog



$\rightarrow$ No tree-level nucleon scattering analog

Canceling $\nu_1\nu_1 Z$ or $\nu_1\nu_1 h$

$\underline{\nu_1\nu_1 Z \to 0}$

- Vanishes for ν_1 with equal amounts $\nu, \nu^c \Rightarrow \lambda = \pm\lambda'$.

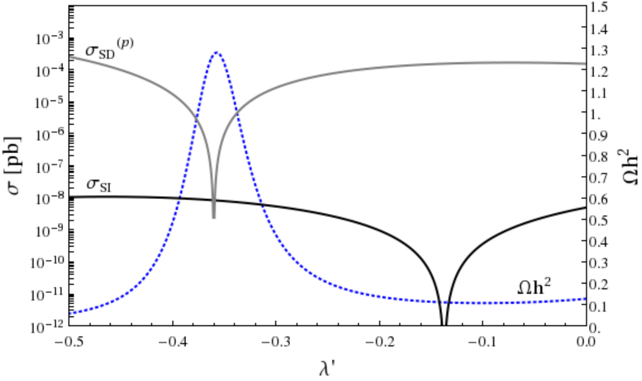
$\underline{\nu_1\nu_1 h \to 0}$

- For $M_N < M_D$, $m_{\nu_1} = M_N + vf(M_N, M_D, \lambda v, \lambda' v)$.
- By gauge invariance, $\nu_1\nu_1 h \propto f \Rightarrow$ solving $m_{\nu_1} = M_N$ cancels $\nu_1\nu_1 h$:

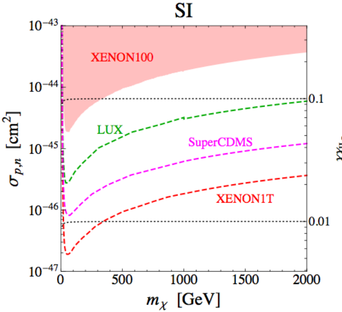
$$\lambda'_{\text{critical}} = -\lambda \frac{M_N}{M_D} \left(1 \pm \sqrt{1 - \left(\frac{M_N}{M_D}\right)^2} \right)^{-1} \tag{6}$$

- For $M_D < M_N$, $\lambda'_{\text{critical}} = -\lambda$. Correct $\Omega_{\text{DM}} h^2$ by coannihilation (requires $M_D \gtrsim 1$ TeV).

For example: $M_N = 200$ GeV, $M_D = 300$ GeV, $\lambda = 0.36$.



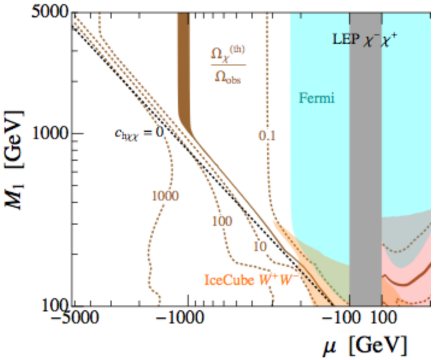
$$\nu_1\nu_1 h \to 0 \quad \Rightarrow \quad \lambda'_{\text{critical}} = -0.136 \text{ or } -0.942.$$



Cancellations and $\Omega_{\rm DM} h^2$ can be achieved for small $\tan\beta$ (shown: $\tan\beta = 2$).

From Cheung, Hall, Pinner and Ruderman [arXiv:1211.4873]

$$\mathcal{L} \subset \frac{c_{h\chi\chi}}{2} h(\chi\chi + \chi^\dagger\chi^\dagger) \tag{7}$$



Studying the Singlet-Doublet Model

- Collider constraints
- Indirect detection
- Technical details

Collider constraints: Higgs Properties

Higgs production and decay measurements $\Rightarrow$ bounds on $\text{Br}(h \to \text{inv})$.

Belanger et al. [arXiv:1302.5694]

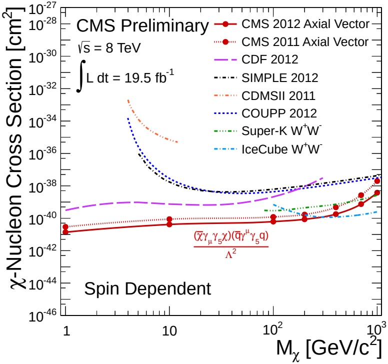
Ellis and You [arXiv:1303.3879]

Relevant for $m_{\nu_1} \leq \frac{m_h}{2}$ – large $\nu_1 \nu_1 h$ couplings can lead to large $\text{Br}(h \to \text{inv})$ in addition to large σ_{SI}.

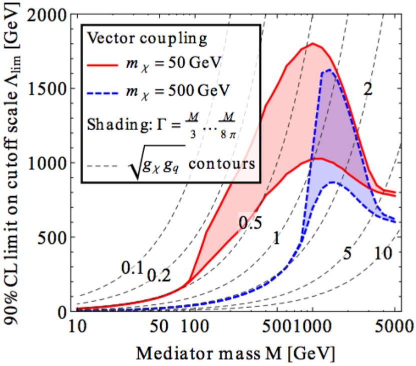
How do bounds compare?

Note: analogous $Z \to$ inv constraints much weaker.

Collider constraints: Monojets



From CMS
[CMS-PAS-EXO-12-048]



From Fox, Harnik, Kopp and Tsai
[arXiv:1103.0240]

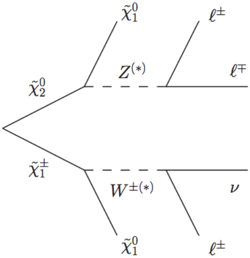
So bounds significantly weakened for light mediator ⇒ not (yet) an important constraint on this model.

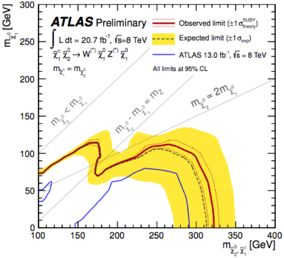
Collider constraints involving charged state

Previously, bound due to negative chargino searches at LEP:

- $M_D \geq 103$ GeV, or $M_D \geq 95$ GeV if $M_D - m_{\nu_1} \in [0.15, 3]$ GeV.

Now, bound due to negative three lepton searches:





From ATLAS [ATLAS-CONF-2013-035] (assuming $\tilde{\chi}_2^{0,\pm} \approx \widetilde{W}^{0,\pm}$, $\tilde{\chi}_1^0 \approx \tilde{B}$)

In our case, bounds weakened by mixing angles, different $SU(2)_L$ quantum numbers.

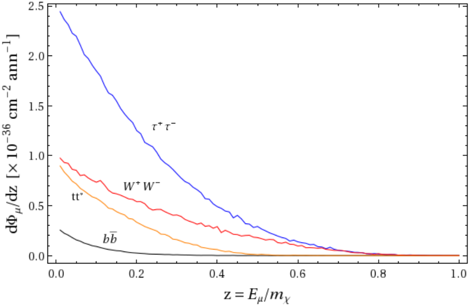
Indirect detection constraints

Strongest limits on σ_{SD} from neutrino telescopes (solar capture and annihilation).

- Super-K and, more recently, IceCube/DeepCore.

But limits are "model-dependent." Depend on:

- annihilation rate: are capture and annihilation in equilibrium?
- annihilation products: give rise to different neutrino/muon spectra.



$\mu^\pm$ spectra ($m_\chi = 160$ GeV)
From [arXiv:1202.0284]

How do they apply to this model?

Most relevant for points with

- small $\nu_1\nu_1 h$ coupling (avoiding $\textsc{Xenon}100$ bounds), and
- sizable $\nu_1\nu_1 Z$ coupling (relic abundance controlled by Z exchange).

Annihilation rate?

- For such points, correct $\Omega_{\text{DM}}h^2 \Rightarrow$ equilibrium.

Annihilation products?

$$\begin{aligned} m_{\nu_1} &\lesssim m_W & \nu_1\nu_1 &\to Z \to b\bar{b}, c\bar{c}, \tau^+\tau^- \\ m_W \lesssim m_{\nu_1} &\lesssim m_t & \nu_1\nu_1 &\to ZZ, W^+W^-, Zh \\ m_{\nu_1} &\gtrsim m_t & \nu_1\nu_1 &\to Z \to t\bar{t} \end{aligned}$$

Caveat: Indirect limits must be interpreted for each point.

Rescaling σ_{SD}

Can rescale quoted limits using relative $\mu^{\pm}$ fluxes from different channels.

For $m_{\nu_1} \lesssim m_W$: softness of muons from $b\bar{b}$ makes Super-K limits strongest as $E_\mu^{\text{thresh}} = 2$ GeV (though IceCube becoming competitive).

$$\frac{\Phi_\mu^{\tau^+\tau^-}}{\Phi_\mu^{b\bar{b}}}(E_\mu \geq 2 \text{ GeV}) \approx 25 \quad \Rightarrow \quad 0.87\Phi_\mu^{b\bar{b}} + 0.05\Phi_\mu^{\tau^+\tau^-} \approx 2.2\Phi_\mu^{b\bar{b}}. \quad (8)$$

For $m_{\nu_1} \gtrsim m_t$: hardest neutrinos from W's produced in $t \to bW^+$ decay. Thus, limits comparable to, but slightly worse than, W^+W^- limits.

$$\frac{\Phi_\mu^{W^+W^-}}{\Phi_\mu^{t\bar{t}}}(E_\mu \geq 10 \text{ GeV}) \approx 2, \qquad \frac{\Phi_\mu^{W^+W^-}}{\Phi_\mu^{t\bar{t}}}(E_\mu \geq 35 \text{ GeV}) \approx 4. \quad (9)$$

Parameter Scans

- Implemented model in `micrOmegas` v3.1. Parameter scans over:
  - $0 \text{ GeV} \leq M_N \leq 800$ GeV,
  - $80 \text{ GeV} \leq M_D \leq 2$ TeV,
  - $-2 \leq \lambda \leq 2$,
  - $0 \leq \lambda' \leq 2$,

  subject to requirements that
  - $40 \text{ GeV} \leq m_{\nu_1} \leq 500$ GeV,
  - $0.1145 \leq \Omega h^2 \leq 0.1253$ (Planck $\pm 2\sigma$ range),
  - $-0.07 \leq \Delta T \leq 0.21$.
- Collider bounds:
  - $\text{Br}(h \to \text{inv}) \leq 0.2$
  - $M_D + m_{\nu_2} \geq 375$ GeV for $m_{\nu_1} \leq 100$ GeV.
- Caveats:
  - Three-body final states (near thresholds).
  - Loop-level DM-nucleon scattering.

Results

σ_{SI} against m_{ν_1}

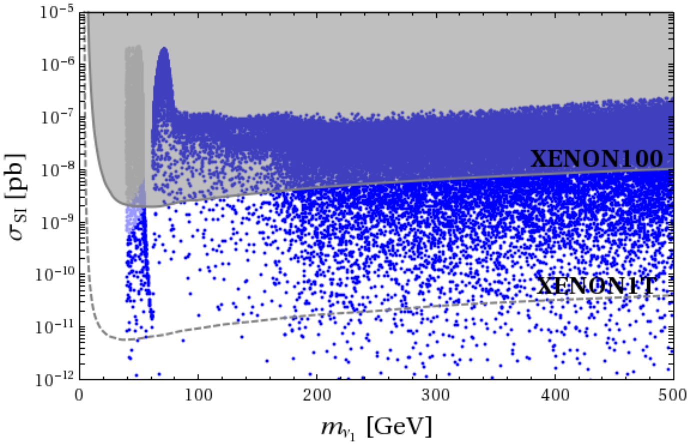


Figure : Limits shown are current XENON100 [arXiv:1207.5988] (solid), and projected XENON1T [arXiv:0902.4253] (dashed). Blue points have $\text{Br}(h \to \text{inv}) \leq 0.2$, light blue have $0.2 < \text{Br}(h \to \text{inv}) \leq 0.5$.

$\sigma_{\rm SD}^{(p)}$ against m_{ν_1}

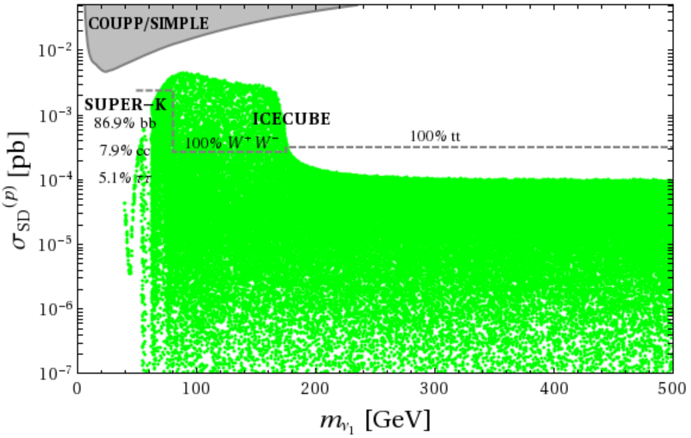


Figure : Direct (solid) limits from SIMPLE/COUPP [arXiv:1204.3094], indirect (dashed) limits from SUPER-K [arXiv:0404025] ($m_{\nu_1} \leq m_W$), ICECUBE/DEEPCORE [arXiv:1212.4097] ($m_{\nu_1} \geq m_W$).

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

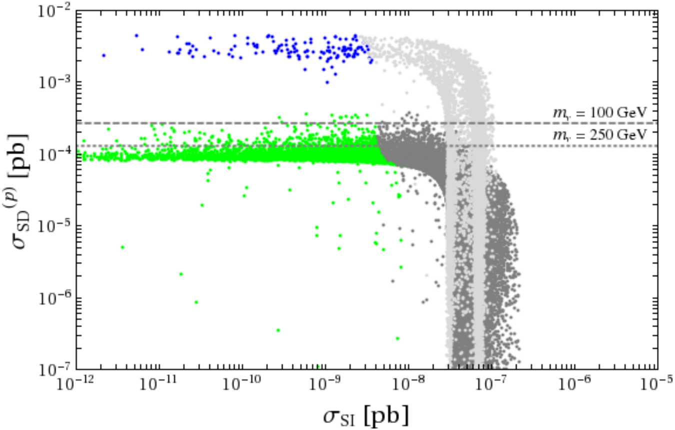


Figure : Blue (light gray) $\equiv$ (excluded) points with 85 GeV $\leq m_{\nu_1} \leq$ 160 GeV. Green (dark gray) $\equiv$ (excluded) points with $m_{\nu_1} \geq 175$ GeV. Dotted lines are indirect limits from IceCube/DeepCore assuming annihilation to W^+W^-.

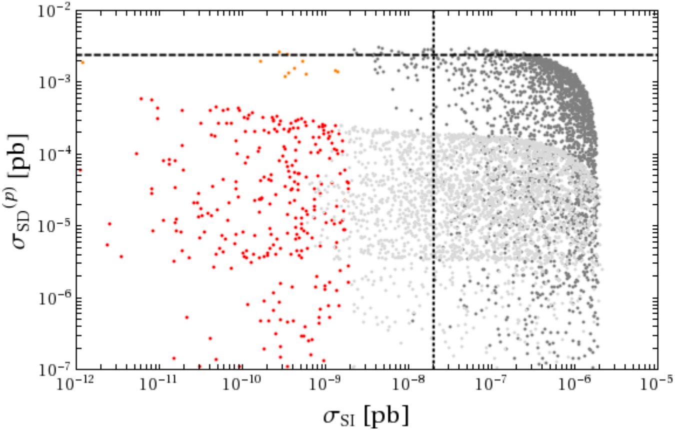


Figure : Red (light gray) $\equiv$ (excluded) points with 40 GeV $\leq m_{\nu_1} \leq$ 62.5 GeV. Orange (dark gray) $\equiv$ (excluded) points with 62.5 GeV $\leq m_{\nu_1} \leq$ 75 GeV. Dashed line is indirect limit from Super-K, dotted is approximate Xenon100 bound.

Summary for Singlet-Doublet Dark Matter

Mass regime	Status
$m_{\nu_1} \lesssim m_W$	Permitted, provided $m_{\nu_1} \approx \frac{m_h}{2}$ or $\frac{m_Z}{2}$ ("resonant" annihilation in Early Universe)
$m_W \lesssim m_{\nu_1} \lesssim m_t$	Largely excluded
$m_{\nu_1} \gtrsim m_t$	Permitted, provided $\nu_1 \nu_1 h$ coupling suppressed Should soon be probed at IceCube/DeepCore

General exception: mass coincidence, permitting coannihilation (or t- and u-channel exchange of heavier states).

- Loop-level detection signals may soon be relevant.

Other Implications? An “Oasis in the Desert?”

What if we did observe singlet-doublet (or similar) WIMPs?

Achieving correct relic density generally requires relatively large Yukawas.

- Coupling to Z controlled by singlet-doublet mixing, which is controlled by λ, λ'.

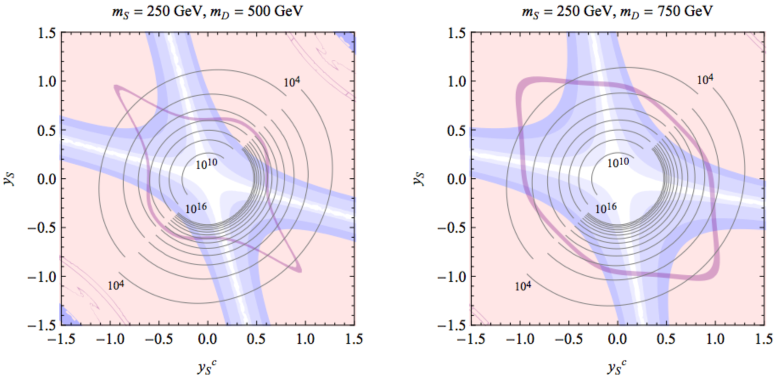
For $m_h \approx 125$ GeV, Higgs vacuum in SM is metastable.

- New, large Yukawas can drive vacuum unstable at $\Lambda < M_{\mathrm{P}}$.
- May imply new dynamics below Planck scale.
- Possibility explored by Cheung, Papucci and Zurek.

[arXiv:1203.5106]

- Perhaps particularly interesting for $M_D < M_N$, $\lambda' \approx -\lambda$ (for which detection prospects are extremely limited).

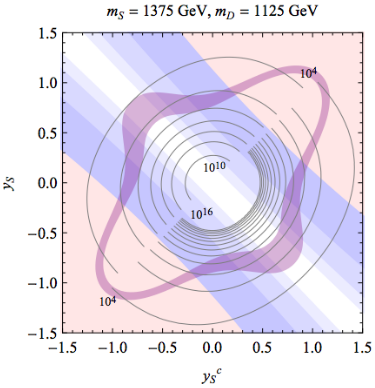
$M_N < M_D$

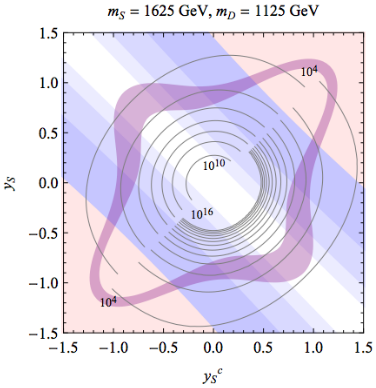


From Cheung, Papucci and Zurek [arXiv:1203.5106].

Purple band has $\Omega_{\rm DM} h^2 = 0.11 \pm 0.1$, and red (blue) is excluded (permitted) by XENON100 (2011) results. Also shown are contours of Λ at which vacuum becomes metastable (upper left) or unstable (lower right).

$M_D < M_N$





From Cheung, Papucci and Zurek [arXiv:1203.5106].

Color scheme same as previous slide.

Conclusions

or

Where we stand

So where do we stand?

Situation is becoming squeezed for *strictly* weakly-interacting dark matter (at least in minimal models).

Searches highly complementary:

- SI and SD signals not necessarily both present.

Limited remaining options for avoiding direct and indirect detection bounds:

1. "resonant" annihilation in Early Universe, i.e. $m_{\nu_1} \approx \frac{m_h}{2}$ or $\frac{m_Z}{2}$ (collider bounds may help),
2. coannihilation, or
3. $m_{\nu_1} \gtrsim m_t$, $\nu_1 \nu_1 h$ coupling suppressed and $\Omega_{\mathrm{DM}} h^2$ set by s-channel Z annihilation (should be probed by IceCube/DeepCore soon).

What next?

What if we do see electroweak dark matter soon?

- That would be awesome.
- Perhaps hints at new dynamics between EW and Planck scales.

What if we don't?

- Maybe we're just unlucky? When do we give up on WIMPS?
- Alternatives to the WIMP paradigm:
  - axions, asymmetric dark matter, WIMPless DM etc.
- New search strategies?

Thank you!

Additional Material

σ_{SI} against m_{ν_1} against time

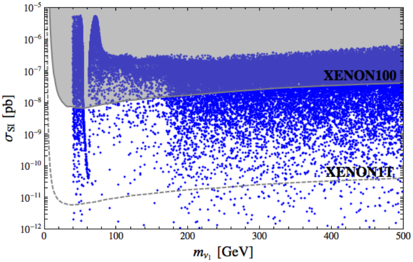


Figure : May 2012

$$f_{Ts}^{(p,n)} = 0.259$$

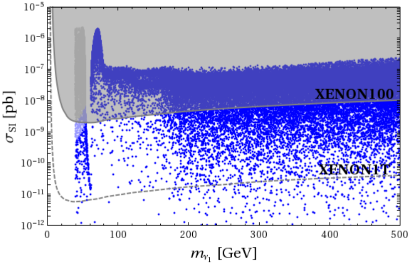
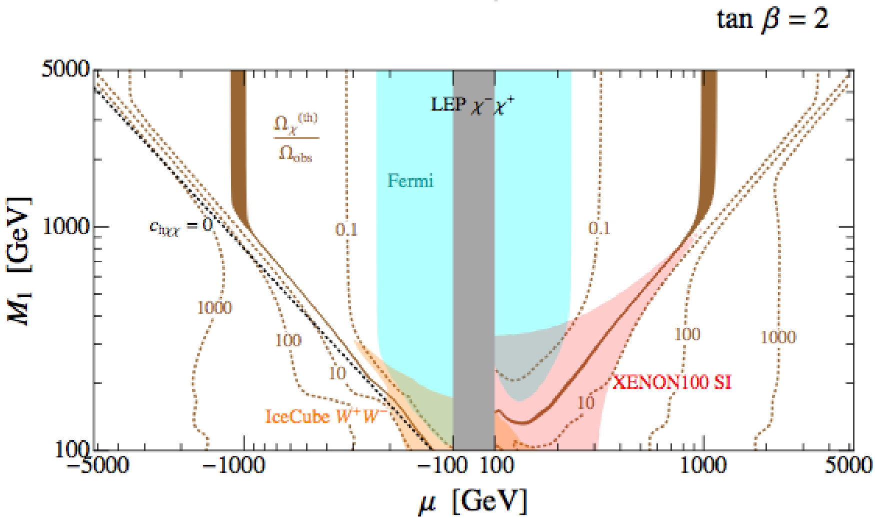


Figure : July 2013

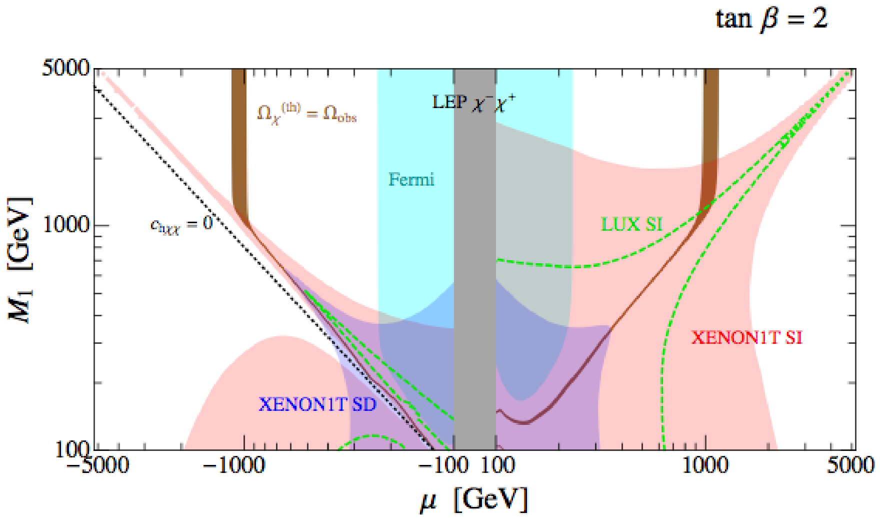
$$f_{Ts}^{(p,n)} = 0.045$$

SUSY Blind Spots: Full Figure



From Cheung, Hall, Pinner and Ruderman, [arXiv:1211.4873]

SUSY Blind Spots: Projections



From Cheung, Hall, Pinner and Ruderman, [arXiv:1211.4873]