Asymmetric Dark Matter from a GeV Hidden Sector

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with Daniel Phalen, Aaron Pierce, and Kathryn Zurek

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October 21, 2010

Outline

1. What is Asymmetric Dark Matter?
2. Light Dark Matter Signals/Constraints: A Status Report
3. ADM from a GeV Hidden Sector: The Model
4. ADM from a GeV Hidden Sector: The Cosmology
    - The Transfer Operator and the Dark Matter Mass
    - The Cosmology of the Dark Matter
    - The Cosmology of the Dark Photon Supermultiplet
    - Cosmology of the Asymmetry Transfer with $\mathcal{O}_{\mathrm{asym}} \sim S^2 U^c D^c D^c$
    - Cosmology of the Asymmetry Transfer with $\mathcal{O}_{\mathrm{asym}} \sim S^2 (L H_u)^2$
5. ADM from a GeV Hidden Sector: The Phenomenology
6. Discussion and Conclusions

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- There can be little doubt that dark matter (DM) exists.
- In fact, WMAP has given us a high precision measurement of its relic density:

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- In particular we would like to know its properties (mass, spin, couplings, etc.).
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Yes: "Asymmetric Dark Matter."

- This is the age of precision cosmology — exemplified by the ΛCDM model with:

$$\rho_{\rm CC} \simeq 74\%; \qquad \rho_{\rm DM} \simeq 22\%; \qquad \rho_{\rm baryons} \simeq 4\%.$$

- Canonically, each of these energy densities has a very different origin: $\rho_{\rm CC} \Leftrightarrow$ vacuum energy, $\rho_{\rm DM} \Leftrightarrow$ WIMPs, $\rho_{\rm baryons} \Leftrightarrow$ baryogenesis.

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- For Asymmetric Dark Matter (ADM) models, the DM relic density is set by a DM-anti-DM asymmetry, $n_{\rm DM} - n_{\overline{\rm DM}}$.
- Specifically, these models are engineered such that the baryon asymmetry sets the DM asymmetry:

$$n_{\rm DM} - n_{\overline{\rm DM}} \sim n_{\rm baryons} - n_{\overline{\rm baryons}}.$$

- Then the difference in the energy density of DM vs. baryons is determined by the difference in their masses:

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- Hence, asymmetric dark matter models predict **light dark matter**.

Necessary ingredients for ADM models (D. E. Kaplan, M. Luty, K. Zurek [arXiv:0901.4117]):

- A DM and anti-DM state: χ and $\overline{\chi}$.
- An unbroken global symmetry, e.g. $U(1)_\chi$ for which $Q_\chi = -Q_{\overline{\chi}}$.
- An operator which relates $U(1)_\chi$ charges to $U(1)_{B-L}$ — it will have the schematic form $\mathcal{O}_{\mathrm{ADM}} \sim \chi^n \mathcal{O}^{\mathrm{SM}}_{B-L}$. This transfers the baryon/lepton asymmetry to the DM.
- A mechanism to annihilate away the relic symmetric component of the DM such that the cosmological relic density is set by the asymmetry.

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Additionally we would like:

- A simple model.
- A dynamical explanation for $m_{\text{DM}} \simeq 5\, m_{\text{proton}}$.
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I will present a supersymmetric model of a dark sector with a dark photon which has kinetic mixing with the SM photon that satisfies all of these conditions.

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Are we interested in light dark matter for other reasons?

There are (controversial) signals reported by:

- DAMA - Has observed an annual modulation signal with 8.9 σ confidence (R. Bernabei et al. [arXiv:1002.1028]).
- CoGeNT - Has observed an exponentially falling excess at low energies (C. E. Aalseth et al. [arXiv:1002.4703]).
- CDMS - Reported two signal events (Z. Ahmed et al. [arXiv:0912.3592]).

There are low mass constraints from:

- CDMS-Si (D. S. Akerib et al. [arXiv:astro-ph/0509259]).
- Xenon10 (J. Angle et al. [arXiv:0706.0039]).

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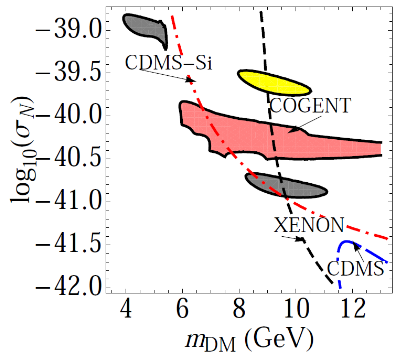
Is there a consistent dark matter interpretation? Have we in fact discovered dark matter?!?

- One analysis (L. Fitzpatrick, D. Hooper, K. Zurek [arXiv:1003.0014]) claims that there is a consistent picture where DAMA and CoGeNT (and CDMS?) can all be consistent with the null results.
- Requires assumptions about $\mathcal{L}_{\text{eff}}$ for Xenon10 and the fraction of channeling in DAMA.



- (See, e.g. (S. Chang, J. Liu, A. Pierce, N. Weiner, I. Yavin [arXiv:1004.0697]) for another analysis.)

Aside — Xenon10 (and low energy events):

- A dark matter particle scatters with the Xenon detector, resulting in ionized and excited Xenon atoms.
- These form excimers which de-excite on short time scales releasing scintillation light and ionization electrons.
- The scintillation light is detected and reported as the **S1** signal.
- The ionization electrons are accelerated and eventually detected (also as scintillation light) and are reported as the **S2** signal.

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- In order to extract the recoil energy (E_{nr}), one needs to know the following relations:

$$\begin{aligned} E_{\mathrm{nr}} &\sim \frac{\mathrm{S1}}{\mathcal{L}_{\mathrm{eff}}}, \\ E_{\mathrm{nr}} &= \frac{\mathrm{S2}}{\mathcal{Q}_y}. \end{aligned}$$

- Signals are normally reported in terms of $\ln(\mathrm{S1}/\mathrm{S2})$ vs S1.
- Note: There is a large experimental uncertainty in $\mathcal{L}_{\mathrm{eff}}$ for low energies.

Enter P. Sorensen:

Sorensen analysis 1 (P. Sorensen [arXiv:1007.3549]):

- Using a Monte Carlo simulation of the Xenon detector and the *shape* of the $\ln(\mathrm{S1}/\mathrm{S2})$ vs the S1 nuclear recoil band, one can constrain a combination of $\mathcal{L}_{\mathrm{eff}}$ and $\mathcal{Q}_y$.

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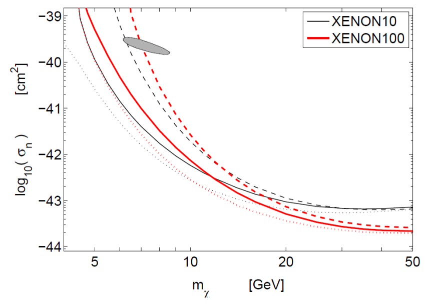
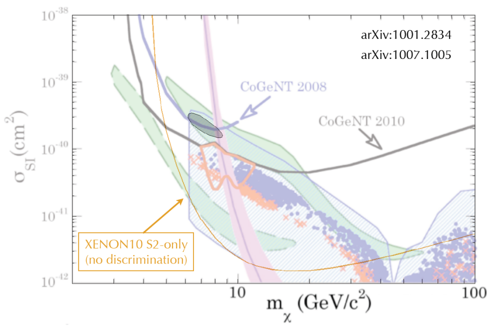


- The shaded ellipse is the DAMA-CoGeNT allowed window.
- The solid lines are claimed to be the best fit for $\mathcal{L}_{\mathrm{eff}}$ and $\mathcal{Q}_y$ using this updated analysis.

Sorensen analysis 2 (P. Sorensen [Presented at IDM 2010]):

- The S1 signal has a small efficiency (when compared to the S2 signal) at low energy.
- The claim is that using only the *width* of the S2 signal, one can determine the position of the recoil event, yielding:



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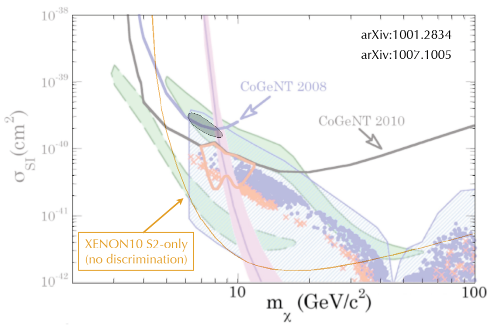

- Both analyses look bad for the DAMA-CoGeNT window.
- **BUT** our model provides a near-term probeable window for light dark matter direct detection experiments.

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- Introduce the following fields and a dark Abelian gauge group, $U(1)_d$:

field	S	T	H' (Dark Higgs)
$U(1)_d$ charge	0	$+1$	-1

- with the Lagrangian:

$$\mathcal{L}_d \supset \int d^2\theta \left(\lambda\, S\, T\, H' + \frac{\epsilon}{2}\, \mathcal{W}_d\, \mathcal{W}_Y\right).$$

which gives the scalar potential (neglecting SUSY breaking):

$$\frac{1}{2}\left(g_d(|T|^2 - |H'|^2) + \epsilon\langle D_Y\rangle\right)^2 + |\lambda|^2\left(|S|^2|H'|^2 + |S|^2|T|^2 + |T|^2|H'|^2\right).$$

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- The vacuum is supersymmetric: $\langle H'\rangle = \sqrt{\frac{\epsilon\langle D_Y\rangle}{g_d}}$; $\langle S\rangle = \langle T\rangle = 0$.
- From the MSSM: $\langle D_Y\rangle = \frac{g_Y v^2 c_{2\beta}}{4} \simeq (72\ \text{GeV})^2$.
- By integrating out heavy states with both $U(1)_Y$ and $U(1)_d$ charges:

$$\epsilon \sim \frac{g_Y\, g_d}{16\pi^2} \ln\frac{M'}{M} \sim 10^{-3}.$$

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$$\epsilon \sim \frac{g_Y\, g_d}{16\pi^2} \ln \frac{M'}{M} \sim 10^{-3}.$$

- Hence $\epsilon\langle D_Y\rangle \simeq 5$ GeV^2 — the GeV scale is dynamically generated from the weak scale!

The spectrum (**SUSY** contributions):

- A massive chiral superfield $(T - S)$ with **mass** $\lambda \langle H' \rangle$:
    - The singlet scalar (S),
    - The $U(1)_d$ charged scalar (T),
    - The Dirac fermion from $\tilde{S}/\tilde{T}$ (ψ).

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- A massive vector superfield $(H' - \gamma_d)$ with **mass** $\sqrt{2}\, g_d \langle H' \rangle$:
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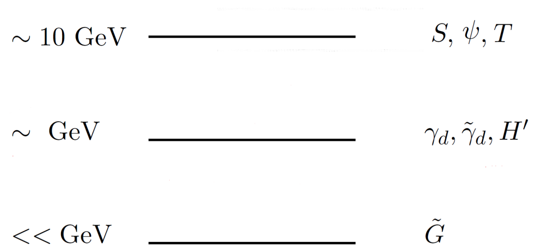
Summary of SUSY contributions to the spectrum:



- Recall that the Lagrangian is

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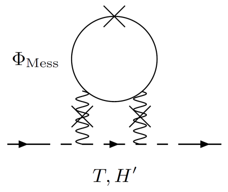
- Given the SUSY spectrum:
  - A massive chiral superfield $(T - S)$ with **mass** $\lambda\, \langle H' \rangle$:
  - A massive vector superfield $(H' - \gamma_d)$ with **mass** $\sqrt{2}\, g_d\, \langle H' \rangle$:

we require $\sqrt{2}\, g_d < \lambda \Rightarrow m_{\gamma_d} < m_{\mathrm{DM}}$. This allows the symmetric component of the DM to annihilate efficiently to dark photons.

The spectrum (**SUSY breaking** contributions):

- We assume *gauge mediation* such that the messengers are only charged under $SU(3) \times SU(2) \times U(1)_Y$ of the MSSM. Then SUSY breaking feeds into the dark sector via ϵ suppressed interactions:



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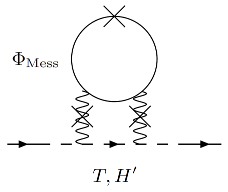

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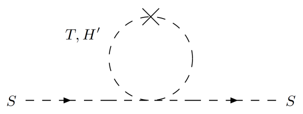

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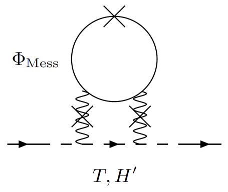

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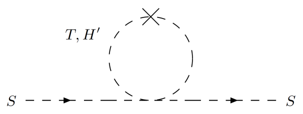

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- For canonical parameters:
  $\Delta\tilde{m}^2_{T,H'} \simeq (0.05 \text{ GeV})^2$ and $\Delta\tilde{m}^2_S \simeq -(0.02 \text{ GeV})^2\lambda^2$.

The spectrum (**SUSY breaking** contributions):

- There are also corrections which do not quantitatively change the behavior of the model:
  - $m_{\tilde{\gamma}_d}^{(1,2)} = \sqrt{2} g_D \langle H' \rangle \pm \epsilon^2 \left(\frac{m_Z^2 s_W^2 s_{2\beta}}{\mu} + \frac{m_{\tilde{\gamma}_d}^2}{M_1} \right)$,
  - $\Delta m_{h'}^2 = \frac{\lambda^4 v_H^2}{16\pi^2} \log \frac{m_T^2}{m_\psi^2} \simeq \frac{\lambda^2}{8\pi^2} \Delta \tilde{m}_T^2$.

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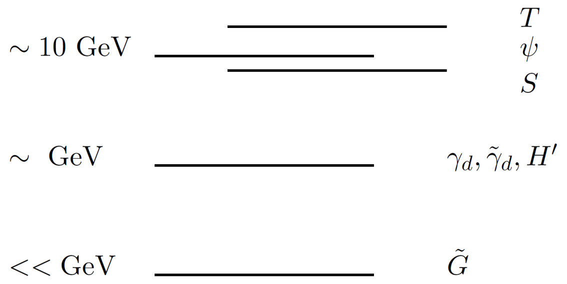
Summary of all contributions to the spectrum:



- Note that S is the *lightest* state of the massive chiral superfield. Therefore, it is the DM.

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- First we must specify the asymmetry transfer operator

$$\mathcal{O}_{\rm asym} = \frac{S^p \mathcal{O}_{B-L}}{M^r},$$

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- We will (usually) assume that the asymmetry transfer decouples before the electroweak phase transition, which implies

$$m_{\text{DM}} = \frac{158}{33}\frac{p}{|Q_{B-L}|}\frac{\Omega_{\text{DM}}}{\Omega_B}\frac{B}{B-L}m_p \simeq (7.1\ \text{GeV})\frac{p}{|Q_{B-L}|},$$

  where $B/(B-L)$ is the ratio of the B asymmetry to the $B-L$ asymmetry; $B/(B-L) \simeq 0.35$ with $\mathcal{O}(10\%)$ uncertainty due to the details of the sphalerons decoupling and electroweak phase transition temperature.

- We will focus on two specific transfer operators (the superscript is the Q_{B-L} of the operator):

$$\begin{aligned}\mathcal{O}^{(1)}_{\text{asym}} &= \frac{S^2 U^c D^c D^c}{M^2}\left(\text{ or } \frac{S^2 L L E^c}{M^2}, \text{ etc.}\right),\\ \mathcal{O}^{(-2)}_{\text{asym}} &= \frac{S^2 (L H_u)^2}{M^3}.\end{aligned}$$

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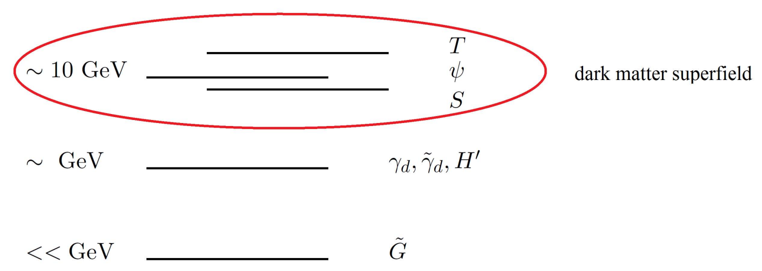
- Again, assuming that the asymmetry transfer decouples before the electroweak phase transition, we find

$$m^{(1)}_{\text{DM}} = 14.2 \text{ GeV} \;\;\Rightarrow\;\; \lambda \sqrt{\frac{\epsilon/g_d}{10^{-1}}}\left(\frac{\sqrt{\langle D_Y\rangle}}{72 \text{ GeV}}\right) = 0.62,$$

$$m^{(-2)}_{\text{DM}} = 7.1 \text{ GeV} \;\;\Rightarrow\;\; \lambda \sqrt{\frac{\epsilon/g_d}{10^{-1}}}\left(\frac{\sqrt{\langle D_Y\rangle}}{72 \text{ GeV}}\right) = 0.31.$$

Now let us analyze the cosmology of the dark matter:



The **asymmetric** DM abundance:

- Assume that the suppression scale for $\mathcal{O}_{\rm asym}$, M, can be chosen such that the asymmetry is transferred to the dark sector before the electroweak phase transition (this implies a constraint on, M — this will be discussed in detail).
- Initially, the asymmetry is spread equally across S, T, and ψ (ψ is the $\tilde{S}-\tilde{T}$ Dirac fermion).
- Then $T \rightarrow \psi + \tilde{G}$ and $\psi \rightarrow S + \tilde{G}$ on non-cosmological timescales.
- Since these decays are invisible to the MSSM, they have no effect on the predictions of big bang nucleosynthesis.
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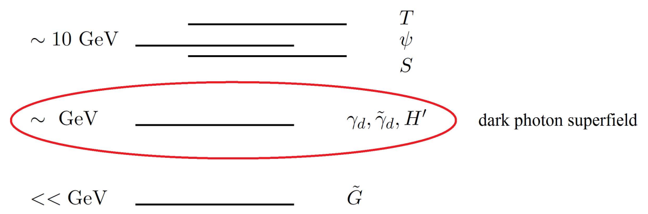
The **symmetric** DM abundance:

- S annihilations are dominated by the process $S\,S^\dagger \to \tilde{\gamma}_d\,\overline{\tilde{\gamma}}_d$ which leads to

$$\Omega_S^{\text{sym}} h^2 \simeq 2 \times 10^{-8} \lambda^{-4} \left(\frac{m_S}{7\ \text{GeV}}\right)^2 \ll 0.1$$

which is clearly subdominant to the asymmetric abundance.

Now let us analyze the cosmology of the dark photon superfield:



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$$\tau(\tilde{\gamma}_d \to \gamma\,\tilde{G}) = 190\ \mathrm{s}\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{\mathrm{GeV}}{m_{\tilde{\gamma}_d}}\right)^5\left(\frac{\sqrt{F}}{50\ \mathrm{TeV}}\right)^4.$$

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- This effect depends on the abundance of the $\tilde{\gamma}_d$ at the time of their decay. Although $m_{\gamma_d} \simeq m_{\tilde{\gamma}_d}$, the tail of the Boltzmann distribution for $\tilde{\gamma}_d$ allows the process $\tilde{\gamma}_d\,\overline{\tilde{\gamma}}_d \to \gamma_d\,\gamma_d$ to proceed with the approximate annihilation cross section

$$\langle\sigma_{\tilde{\gamma}_d} v\rangle \simeq \frac{g_d^4}{16\pi m_{\tilde{\gamma}_d}^2} v_{f.o.} \simeq 7\times 10^{-24}\text{cm}^3/\text{s}\left(\frac{g_d}{0.1}\right)^4\left(\frac{1\text{ GeV}}{m_{\tilde{\gamma}_d}}\right)^2\left(\frac{v_{f.o.}}{0.3}\right) .$$

- Therefore, the potential to effect BBN leads to a constraint on the $\epsilon - g_d$ parameter space (to be shown later).

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- I will refer to this as "washout" of the relic density.
- Hence, we will always require that the operator decouples *before* $T \sim m_{\rm DM}$.
- Note that we can further require the operator decouples before the electroweak phase transition which changes the relevant chemical potential analysis, leading to $\mathcal{O}(1)$ changes in the relationship between $m_{\rm DM}$ and $m_{\rm proton}$.

Models with $\mathcal{O}_{\rm asym} \sim S^2 U^c D^c D^c$:

- The dominant constraint on the suppression scale M comes from the requirement of *when* the operator decouples.
- There are two relevant processes:
  - $S\,S \leftrightarrow \psi_{U^c}\psi_{D^c}D^c$
    - Potentially Boltzmann suppressed due to squark in the final state: $\Gamma \sim \mathrm{Exp}(-m_{\rm squark}/T)$.
  - $S\psi_S \leftrightarrow \psi_{U^c}\psi_{D^c}\psi_{D^c}$
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- The dominant washout process is $S\,S \leftrightarrow \nu^\dagger\,\nu^\dagger$.
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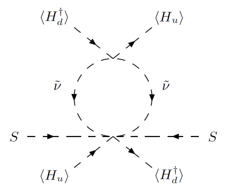
For models with Majorana neutrinos ($\mathcal{W}_{\rm MSSM} \in (LH_u)^2/M_\nu$):

- The following loop is non-vanishing:



- This is an effective b-term for S, $b_S SS$, which violates S-number and splits the real and imaginary parts by $\Delta m_S = b_S/m_S$, i.e.,

$$\Delta m_S \simeq \frac{1}{16\pi^2}\frac{v^2 c_\beta^2 \mu^2}{M^3}\frac{m_\nu}{m_S}\log\left(\frac{\tilde{m}_{\nu_L}}{M_{\rm mess}}\right) \simeq 4\times 10^{-22}\ {\rm GeV}\left(\frac{10^5\ {\rm GeV}}{M}\right)^3.$$

When $H \sim \Delta m_S$, $S - S^\dagger$ oscillations commence and the relic density re-symmetrizes.

- $M \gtrsim 10^5\ \mathrm{GeV}$
  - This constraint comes from requiring the now symmetric relic density of the DM to *not* begin re-annihilating (due to the large symmetric annihilation cross section for $S\,S^\dagger \to \tilde{\gamma}_d\,\overline{\tilde{\gamma}}_d$) since this would result in a *reduction* of the relic density.
  - Quantitatively, oscillations must occur at $T \lesssim m_S^3/\lambda^4 \sim 0.1 - 100\ \mathrm{GeV}$.
  - Since $M > 30\ \mathrm{TeV}$, $\mathcal{O}_{\rm asym}$ decouples before the electroweak phase transition.

There are various scenarios depending on further restrictions of M:

- $10^5\ \mathrm{GeV} \lesssim M \lesssim 10^{10}\ \mathrm{GeV}$
  - The oscillations occur before the CMB decouples.
  - The process $S\, S^\dagger \to \tilde{\gamma}_d\, \overline{\tilde{\gamma}}_d \to \gamma\, \gamma\, \tilde{G}\, \tilde{G}$ can effect the reionization depth of the CMB.
  - To be consistent with observation, $\lambda \lesssim 0.1$ (T. Slatyer, N. Padmanabhan, D. Finkbeiner [arXiv:0906.1197]).
  - This is only marginally consistent with other constraints (to be shown) when one requires that $m_S = 7.1\ \mathrm{GeV}$ (requires $(\epsilon/g_d)_{\rm max} \sim (7\times 10^{-3}/7\times 10^{-3})$).

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    - The most relevant process is $S\,S^\dagger \to \gamma_d\,\gamma_d \to e^+\,e^-\,e^+\,e^-$
    - This implies $\lambda \lesssim 0.3$ (A. Belikov, D. Hooper [arXiv:0904.1210]) which alleviates some of the tension with achieving $m_S = 7.1\ \mathrm{GeV}$.

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- $M \gtrsim 10^{12} \text{ GeV}$
  - The DM has not begun oscillating yet and the relic density is still asymmetric.
  - The same would be true if the neutrino masses are Dirac.

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Constraints on $\epsilon - g_d$ plane:

- Big bang nucleosynthesis constraints from late $\tilde{\gamma}_d \to \gamma\, \tilde{G}$ decays. We also note the region which could solve the lithium-7 problem (K. Jedamzik [arXiv:hep-ph/0604251]).
- Direct searches for γ_d (R. Essig, J. Kaplan, P. Schuster, N. Toro [arXiv:1004.0691]).
- Precision electroweak constraints on $\gamma_d - Z^0$ mixing (S. Gopalakrishna, S. Jung, J. Wells [arXiv:0801.3456]):

$$\frac{\epsilon}{\sqrt{1 - m_{\gamma_d}/m_{Z^0}}} \lesssim 10^{-2}.$$

- No Landau pole for λ before the GUT scale (or before 10 TeV).

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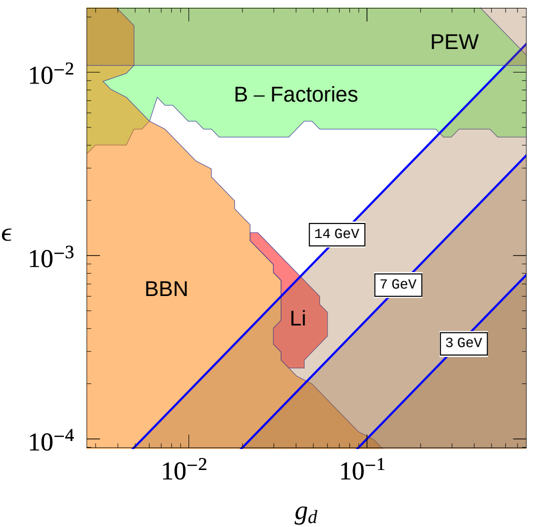

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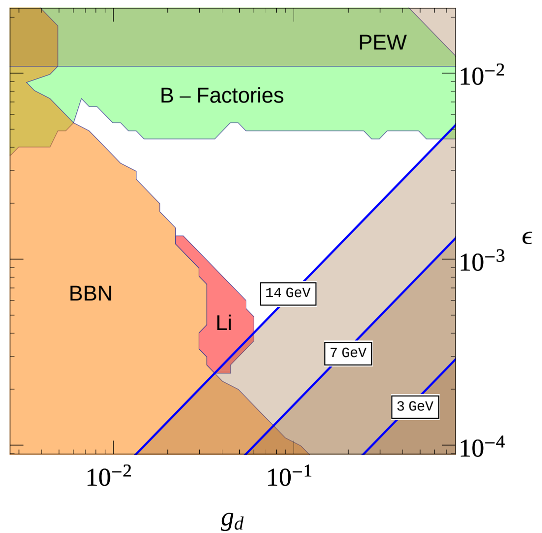

Direct Detection:

- Recall that the DM state, S, is neutral under the dark $U(1)$.
- Tree level direct detection (subdominant):
  - h' exchange (and subsequent $h - h'$ mixing via ϵ)
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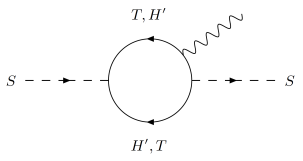
- However, at 1-loop the following diagram is non-zero (for $\langle H' \rangle \neq 0$):

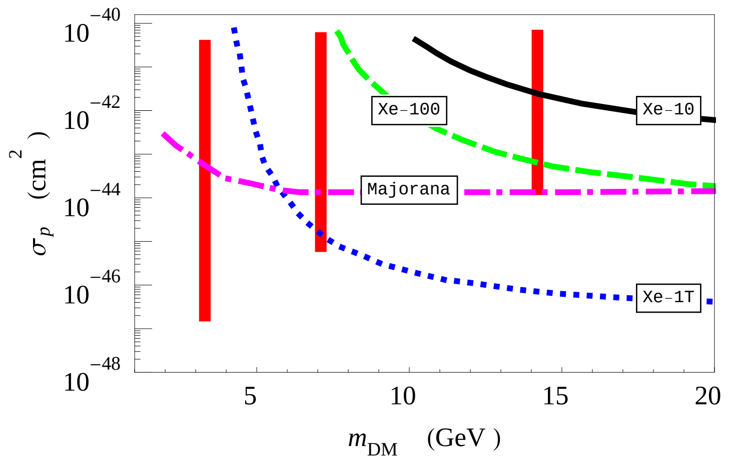


- This leads to an effective coupling between S and γ_d:

$$\frac{\lambda^2 g_d}{16\pi^2}\left(\frac{4g_d^4 - \lambda^4 + 4\lambda^2 g_d^2 \log\left(\frac{\lambda^2}{2g_d^2}\right)}{2(2g_d^2 - \lambda^2)^2}\right) S^\dagger \overleftrightarrow{\partial_\mu} S \gamma_d^\mu \equiv g_d q_{\text{eff}} S^\dagger \overleftrightarrow{\partial_\mu} S \gamma_d^\mu .$$

- This gives a non-trivial spin-independent direct detection cross section for DM scattering off protons (in the limit $\lambda \gg g_d$):

$$\sigma_p = \frac{4}{\pi}\frac{g_W^4 c_W^4 \mu_{S,p}^2}{c_{2\beta}^2 m_W^4} q_{\text{eff}}^2 \simeq (9.1\times 10^{-42}\text{cm}^2)\lambda^4.$$



Collider Signatures — there are three portals into the dark sector:

- Photon kinetic mixing.
    - The MSSM LSP can decay to the dark sector.
    - If it has electroweak quantum numbers it will decay to its SM partner and a dark gaugino (which will manifest as missing energy): e.g. $\tilde{\ell} \to \ell\,\tilde{\gamma}_d$.

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- Higgs boson mixing.
    - If the MSSM LSP is a neutralino it will decay to a dark gaugino and a dark Higgs boson: $\tilde{\chi}_1^0 \to \tilde{\gamma}_d\, h'$.
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- The asymmetry transfer operator.
  - For $\mathcal{O}_{\rm asym} \sim S^2 U^c D^c D^c$, the UV completion is necessarily colored. For the lowest allowed values for the suppression scale M, these states could be produced at the LHC.

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- This model provides a target cross section for current low mass direct detection experiments.

THANK YOU

Are there any questions?

BACKUP SLIDES

Here I argue that the asymmetry transfer operator $\mathcal{O}_{\text{asym}} \sim S^2 L H_u$ is **not** allowed.

- In order to avoid washout (the operator decouples before $T \sim m_S$)
$$M \gtrsim 3 \times 10^8 \text{ GeV}.$$
- In order for the operator to decouple before the EWPT (using $\langle H' \rangle = 0$),
$$M \gtrsim 6 \times 10^7 \text{ GeV}.$$
- Hence, the operator decouples before the EWPT and $m_S = 14.2 \text{ GeV}$.
- Since this operator allows the decay $\psi \to S^\dagger \nu^\dagger$, it can lead to a resymmetrization of the dark matter and the constraints from the CMB apply, $\lambda \lesssim 0.1$.
- It is not possible to achieve $m_S = 14.2$ GeV with this constraint.
- In order to avoid the CMB constraint requires $M \gtrsim 10^{16}$ GeV, but for this large of a value for M, the temperature required for the operator to *ever* have been in equilibrium is higher then that allowed by WMAP.