Asymmetric Dark Matter from a GeV Hidden Sector

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Non-Thermal Cosmological Histories of the Universe Workshop
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Outline

1. What is Asymmetric Dark Matter?
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 $O_{\text{asym}} \sim S^2 U^c D^c D^c$
   - Cosmology of the Asymmetry Transfer with $O_{\text{asym}} \sim S^2 (LH_u)^2$
5. ADM from a GeV Hidden Sector: The Phenomenology
6. Discussion and Conclusions
• We have little doubt that dark matter exists.
• In fact, WMAP has given us a high precision measurement of its relic density:
  \[ \Omega_{DM} h^2 = 0.1131 \pm 0.0034. \]
• **BUT** we still don’t know what it is...
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• In particular we would like to know its mass and couplings.
• How can we learn this information? Hopefully, we will see signals in direct detection, indirect detection, and/or at colliders.
• Perhaps we can then utilize these discoveries to wind back the Universe’s clock to temperatures of \( O(m_{DM}) \).
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• Perhaps we can then utilize these discoveries to wind back the Universe’s clock to temperatures of \( \mathcal{O}(m_{DM}) \).
• We all know the well motivated (dare I say miraculous?) example of the WIMP.
• Are there other canonical paradigms we should be exploring as well? Maybe we should hold a workshop on this subject.
• This is the age of precision cosmology — exemplified by the $\Lambda$CDM model with:

$$\rho_{\text{CC}} \approx 74\%; \quad \rho_{\text{DM}} \approx 22\%; \quad \rho_{\text{baryons}} \approx 4\%.$$ 

• Canonically, each of these energy densities has a very different origin:

$$\rho_{\text{CC}} \Leftrightarrow \text{vacuum energy}, \quad \rho_{\text{DM}} \Leftrightarrow \text{WIMPs}, \quad \rho_{\text{baryons}} \Leftrightarrow \text{baryogenesis}.$$ 

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

$$\frac{\rho_{\text{DM}}}{\rho_{\text{baryons}}} \approx \frac{m_{\text{DM}}}{m_{\text{proton}}} \approx 5.$$ 

Hence, asymmetric dark matter models predict light dark matter.
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• Specifically, these models are engineered such that the baryon asymmetry sets the DM asymmetry:

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- A DM and anti-DM state: $\chi$ and $\bar{\chi}$.
- A global symmetry, e.g. $U(1)_\chi$, for which $Q_{\chi} = -Q_{\bar{\chi}}$.
- An operator which relates $U(1)_\chi$ charges to $U(1)_{B-L}$ — it will have the schematic form $O_{ADM} \sim \chi^n O_{SM}^{B-L}$. 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 $m_{\text{DM}} \simeq 5 m_{\text{proton}}$.
- Observables beyond $\rho_{\text{DM}}$ (if we are lucky).
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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 $\sigma$ 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 $S_1$ signal.
- The ionization electrons are accelerated and eventually detected (also as scintillation light) and are reported as the $S_2$ signal.

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

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  \[ E_{nr} \sim \frac{S_1}{L_{\text{eff}}}, \]

  \[ E_{nr} = \frac{S_2}{Q_y}. \]

- Signals are normally reported in terms of $\ln(S_1/S_2)$ vs $S_1$.
- Note: There is a large experimental uncertainty in $L_{\text{eff}}$ 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 $\ln(S_1/S_2)$ vs $S_1$ nuclear recoil band, one can constrain a combination of $L_{\text{eff}}$ and $Q_y$. 
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- The shaded ellipse is the DAMA-CoGeNT allowed window.
- The solid lines are claimed to be the best fit for \( \mathcal{L}_{\text{eff}} \) and \( Q_y \) 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:

![Graph showing dark matter signals and constraints with labels such as CoGeNT 2008 and XENON10 S2-only (no discrimination).](image-url)
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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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• with the Lagrangian:

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

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:

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• Hence $\epsilon \langle D_Y \rangle \simeq 5 \text{ GeV}^2$ — 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 \(\tilde{S}/\tilde{T}\) \((\psi)\).

- Note that for \(\langle H' \rangle \neq 0\), there is a residual global \(U(1)\) which ensures the stability of the \(S - T\) superfield — the lightest state of this supermultiplet is a DM candidate.

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- 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 $\epsilon$ suppressed interactions:

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\]

\[
\Rightarrow \Delta \tilde{m}^2_S = -\frac{2\lambda^2}{16\pi^2} (\Delta \tilde{m}_{H'}^2 + \Delta \tilde{m}_T^2) \ln \left( \frac{M_{\text{mess}}}{m_S} \right).
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- For canonical parameters:

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\Delta \tilde{m}_{T,H'}^2 \simeq (0.05 \text{ GeV})^2 \text{ and } \Delta \tilde{m}_{S}^2 \simeq -(0.02 \text{ GeV})^2 \lambda^2.
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The spectrum (SUSY breaking contributions):

• There are also corrections which do not quantitatively change the behavior of the model:

  \[ m^{(1,2)}_{\tilde{\gamma}_d} = \sqrt{2} g_D \langle H' \rangle \pm \epsilon^2 \left( \frac{m_Z^2 s_W s_2 \beta}{\mu} + \frac{m_{\tilde{\gamma}_d}^2}{M_1} \right), \]

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Summary of all contributions to the spectrum:

\[
\begin{array}{ccc}
\sim 10 \text{ GeV} & \psi & T \\
\sim \text{ GeV} & S & \gamma_d, \tilde{\gamma}_d, H' \\
<< \text{ GeV} & \tilde{G} & \\
\end{array}
\]

- 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

\[ O_{\text{asym}} = \frac{S^p O_{B-L}}{M_r}, \]

where the four lowest dimension MSSM operators with \( |Q_{B-L}| = 1 \) are \( LH_u, U^c D^c D^c, LLE^c, \) and \( LQD^c. \)
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where the four lowest dimension MSSM operators with \(|Q_{B-L}| = 1\) are \(LH_u, U^c D^c D^c, LLE^c\), and \(LQD^c\).

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

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

where \(B/(B - L) \simeq 0.35\) with \(O(10\%)\) uncertainty due to the details of the sphalerons decoupling and electroweak phase transition temperature.
We will focus on two specific transfer operators:

\[ \mathcal{O}^{(1)}_{\text{asym}} = \frac{S^2 U^c D^c D^c}{M^2} \left( \text{or} \frac{S^2 LLE^c}{M^2}, \text{etc.} \right), \]

\[ \mathcal{O}^{(-2)}_{\text{asym}} = \frac{S^2 (LH_u)^2}{M^3}. \]
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\[ \mathcal{O}_{\text{asym}}^{(1)} = \frac{S^2 U^c D^c D^c}{M^2} \left( \text{or} \frac{S^2 L L E^c}{M^2} \right), \]

\[ \mathcal{O}_{\text{asym}}^{(-2)} = \frac{S^2 (L H_u)^2}{M^3}. \]

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

\[ m_{\text{DM}}^{(1)} = 14.2 \text{ GeV} \Rightarrow \lambda \sqrt{\frac{\epsilon/gd}{10^{-1}}} \left( \frac{\sqrt{\langle D_Y \rangle}}{72 \text{ GeV}} \right) = 0.62, \]

\[ m_{\text{DM}}^{(-2)} = 7.1 \text{ GeV} \Rightarrow \lambda \sqrt{\frac{\epsilon/gd}{10^{-1}}} \left( \frac{\sqrt{\langle D_Y \rangle}}{72 \text{ GeV}} \right) = 0.31. \]
Now let us analyze the cosmology of the dark matter:

\[ \sim 10 \text{ GeV} \quad T \quad \psi \quad S \quad \text{dark matter superfield} \]

\[ \sim \text{ GeV} \quad \gamma_d, \tilde{\gamma}_d, H' \]

\[ < \sim \text{ GeV} \quad \tilde{G} \]
The asymmetric DM abundance:

- Assume that the suppression scale for $O_{\text{asym}}$ can be chosen such that the asymmetry is transferred to the dark sector before the electroweak phase transition (this implies a constraint on $M$ — we will discuss this in detail).
- Initially, the asymmetry is spread equally across $S$, $T$, and $\psi$.
- 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.
- As described before, we chose the mass of $S$ such that $\Omega_{\text{asym}} = \Omega_{\text{DM}}$. 
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- Assume that the suppression scale for $O_{\text{asym}}$ can be chosen such that the asymmetry is transferred to the dark sector before the electroweak phase transition (this implies a constraint on $M$ — we will discuss this in detail).

- Initially, the asymmetry is spread equally across $S$, $T$, and $\psi$.

- 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.

- As described before, we chose the mass of $S$ such that $\Omega_{\text{asym}} = \Omega_{\text{DM}}$.

The symmetric DM abundance:

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

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

which is clearly subdominant to the asymmetric abundance.
Now let us analyze the cosmology of the dark photon superfield:

\[ \sim 10 \text{ GeV} \quad \psi \quad \tilde{S} \quad T \]

\[ \sim \text{ GeV} \quad \gamma_d, \tilde{\gamma}_d, H' \quad \text{dark photon superfield} \]

\[ \ll \text{ GeV} \quad \tilde{G} \]
• $\gamma_d$ and $h'$ both “quickly” decay to the MSSM via $\epsilon$ suppressed interactions.

• $\tilde{\gamma}_d$ is lives long enough to potentially effect big bang nucleosynthesis predictions:

$$\tau(\tilde{\gamma}_d \to \gamma \tilde{G}) = 190 \, \text{s} \left( \frac{10^{-3}}{\epsilon} \right)^2 \left( \frac{\text{GeV}}{m\tilde{\gamma}_d} \right)^5 \left( \frac{\sqrt{F}}{50 \, \text{TeV}} \right)^4.$$
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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 $\tilde{\gamma}_d \tilde{\gamma}_d \rightarrow \gamma_d \gamma_d$ 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).
What is Asymmetric Dark Matter?

Light Dark Matter Signals/Constraints: A Status Report

ADM from a GeV Hidden Sector: The Model

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ADM from a GeV Hidden Sector: The Phenomenology

Discussion and Conclusions
General considerations for $\mathcal{O}_{\text{asym}}$:

- We assume that an unspecified baryogenesis mechanism generated a baryon asymmetry at “high” temperatures.
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- Then once the transfer operator is in equilibrium, the baryon/lepton asymmetry is distributed to the dark matter as well.
- If this operator is still in equilibrium when $T \lesssim m_{\text{DM}}$, the dark matter density becomes Boltzmann suppressed and the simple relation $m_{\text{DM}} \simeq 5 m_{\text{proton}}$ no longer holds.
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- This is referred to as “washout” of the relic density.
- Hence, we will always require that the operator decouple before $T \sim m_{\text{DM}}$.
- Note that we can further require the operator decouple before the electroweak phase transition which changes the relevant chemical potential analysis, leading to $\mathcal{O}(1)$ changes in the relationship between $m_{\text{DM}}$ and $m_{\text{proton}}$. 
Models with $\mathcal{O}_{\text{asym}} \sim S^2 U^c D^c D^c$:

- The dominant constraint on the suppression scale $M$ comes from the requirement of *when* the operator decouple.

- There are two relevant processes:
  - $SS \leftrightarrow \psi U^c \psi D^c D^c$
    - Potentially Boltzmann suppressed due to squark in the final state: $\Gamma \sim \text{Exp}(-m_{\text{squark}}/T)$.
  - $S\psi S \leftrightarrow \psi U^c \psi D^c \psi D^c$
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- Requiring out of equilibrium before $T \sim m_{\text{DM}} \Rightarrow M \gtrsim 2$ TeV  
  (loop suppressed process dominates).
- Requiring out of equilibrium before $T \sim T_{\text{EWPT}} \Rightarrow M \gtrsim \mathcal{O}(100)$ TeV  
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- Requiring out of equilibrium before $T \sim T_{\text{EWPT}} \Rightarrow M \gtrsim \mathcal{O}(100) \text{ TeV}$ (both processes contribute with the same strength).
- Note that the same basic constraints will hold if $U^c D^c D^c$ is replaced by $LLE^c$ or $LQD^c$. 
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ADM from a GeV Hidden Sector: The Phenomenology

Discussion and Conclusions
Models with $\mathcal{O}_{\text{asym}} \sim S^2 (L H_u)^2$:

- The dominant washout process is $S \ S \leftrightarrow \nu^\dagger \nu^\dagger$.
- Insisting that this decouple before $T \sim m_{\text{DM}}$ ($T \sim T_{\text{EWPT}}$) implies $M > 20 \ (30) \ \text{TeV}$.
Models with $\mathcal{O}_{\text{asym}} \sim S^2(LH_u)^2$:

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For models with Majorana neutrinos ($\mathcal{V}_{\text{MSSM}} \in (LH_u)^2/M_\nu$):

- 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.,

  \[
  \Delta m_S \simeq \frac{1}{16\pi^2} \frac{v^2 c_\beta^2 \mu^2}{M^3} \frac{m_\nu}{m_S} \log \left( \frac{\tilde{m}_{\nu L}}{M_{\text{mess}}} \right) \simeq 4 \times 10^{-22} \ \text{GeV} \left( \frac{10^5 \ \text{GeV}}{M} \right)^3.
  \]
When $H \sim \Delta m_S$, $S - S^\dagger$ oscillations commence and the relic density re-symmetrizes.

- $M \gtrsim 10^5$ 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 $SS^\dagger \rightarrow \bar{\gamma}d\bar{\gamma}d$) since this would result in a reduction of the relic density.

- Quantitatively, oscillations must occur at $T \lesssim m_S^3/\lambda^4 \sim 0.1 - 100$ GeV.

- Since $M > 30$ TeV, $\mathcal{O}_{\text{asym}}$ decouples before the electroweak phase transition.
There are various scenarios depending on further restrictions of $M$:

- $10^5 \text{ GeV} \lesssim M \lesssim 10^{10} \text{ GeV}$
  - The oscillations occur before the CMB decouples.
  - The process $SS^\dagger \rightarrow \tilde{\gamma}_d \tilde{\gamma}_d \rightarrow \gamma \gamma \tilde{G} \tilde{G}$ 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 $m_S = 7.1 \text{ GeV}$
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- $10^{10}$ GeV $\lesssim M \lesssim 10^{12}$ GeV
  - Oscillations occur after the CMB decouples.
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  - The most relevant process is $SS^\dagger \rightarrow \gamma_d \gamma_d \rightarrow e^+ e^- e^+ e^-$
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- **$M \gtrsim 10^{12}$ 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 $\tilde{\gamma}_d \rightarrow \gamma \tilde{G}$ decays. We also note the region which could solve the lithium-7 problem (K. Jedamzik [arXiv:hep-ph/0604251]).
- Direct searches for $\gamma_d$ (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 $\lambda$ before the GUT scale (or before 10 TeV).
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No Landau pole for $\lambda$ before 10 TeV.
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 $\epsilon$)
  - $S - T$ mixing which is proportional to $A_\lambda$ (small for gauge mediation) which induces non-zero $S'$ interactions with the dark photon.
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  - $S - T$ mixing which is proportional to $A_\lambda$ (small for gauge mediation) which induces non-zero $S$ interactions with the dark photon.
- However, at 1-loop the following diagram is non-zero (for $\langle H' \rangle \neq 0$):

  ![Diagram](image)

  - This leads to an effective coupling between $S$ and $\gamma_d$:

    $$\frac{\lambda^2 g_d}{16\pi^2} \left( \frac{4g_d^4 - \lambda^4}{2(2g_d^2 - \lambda^2)^2} \right) \log \left( \frac{\lambda^2}{2g_d^2} \right) S^\dagger \partial_\mu S \gamma_d^\mu \equiv g_d q_{\text{eff}} S^\dagger \partial_\mu S \gamma_d^\mu.$$
• This gives a non-trivial spin-independent direct detection cross section for DM scattering off protons (in the limit $\lambda \gg g_d$):

$$\sigma_p = \frac{4 g_W^4 c_W^4 \mu_{S,p}^2}{\pi c_{2\beta}^2 m_W^4} q_{\text{eff}}^2 \approx (9.1 \times 10^{-42} \text{cm}^2) \lambda^4.$$
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. \( \tilde{\ell} \rightarrow \ell \tilde{\gamma}_d \).
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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: \( \tilde{\chi}^0_1 \rightarrow \tilde{\gamma}_d h' \).
  - Then \( h' \) will decay via \( \epsilon \) induced mixing with the MSSM Higgs boson, which could result in “lepton jets.”
  - For the largest values of \( \epsilon \) the MSSM Higgs could decay to the dark matter or dark Higgs boson with \( \text{BR} \sim \mathcal{O}(10\%) \).
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- **The asymmetry transfer operator.**
  - For \( \mathcal{O}_{\text{asym}} \sim S^2 U^c D^c D^c \), 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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• Variations on this paradigm (loop suppression to link the GeV scale to the weak scale):
  
  • the mass scale is transfered to the dark sector using “singlet mediation” where a weak scale singlet mass is transfered to the dark sector at 1-loop via Yukawa interactions (D. Morrissey, D. Poland, K. Zurek [arXiv:0904.2567]),
  
  • the TeV scale is transfered to the MSSM via gravity or gaugino mediation and to the dark sector via anomaly mediation (A. Katz, R. Sundrum [arXiv:0902.3271]).
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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 $O_{\text{asym}} \sim S^2 L H_u$ 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 $m_S = 14.2$ 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 than that allowed by WMAP.