Dark Matter,
Hidden Sectors from Gauge Kinetic Mixing,
and Jets of Leptons

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Quick Outline

- PAMELA and DAMA – possible new hints for dark matter
- A hidden sector with gauge kinetic mixing
- A simple supersymmetric example
- Constraints on light Abelian hidden sectors
- Collider Prospects
Possible New DM Signal #1: PAMELA

- Excess flux of cosmic ray $e^+$ with energy $E \geq 10$ GeV.

- Could arise from annihilation of DM in our galaxy!
• Puzzles for an annihilating DM explanation:

  – NO excess flux of anti-protons.
    → DM must annihilate mostly into leptons.

  – Large annihilation rate (today) is required.
    → non-thermal DM or enhanced annihilation now

• These puzzles motivate a class of hidden sector scenarios.

[Arkani-Hamed,Finkbeiner,Slatyer,Weiner ’08]
Possible New DM Signal #2: DAMA

- Looks for nuclear recoils induced by DM scattering.
- Sees an unexplained annual modulation:

\[
\text{Time (day)} \quad \text{Residuals (cpd/kg/keV)}
\]

- Both period and phase match up with DM expectations.
• Explanations using *ordinary* DM are in conflict with bounds from CDMS and XENON.

• **Inelastic dark matter** (iDM) can resolve this.

  **Assumption:** DM scatters coherently off nuclei preferentially into a slightly heavier state. [Tucker-Smith+Weiner '01]

\[
\text{DM}_1 \rightarrow \text{q} \quad \text{and} \quad \text{DM}_2 \rightarrow \text{q}
\]

\[M_{\text{DM}_1} \sim 100 \text{ GeV}, \quad M_{\text{DM}_2} - M_{\text{DM}_1} = \delta \sim 100 \text{ keV}\]

• Further motivates hidden sector scenarios.
A Hidden Sector with Gauge Kinetic Mixing

- Simple Hidden Sector:
  - exotic $U(1)_x$ gauge group
  - new SM-neutral fields charged under $U(1)_x$.
  - spontaneous breaking of $U(1)_x$ at scale $v_x \lesssim \text{GeV}$.
  - SM fields do not (initially) carry $U(1)_x$ charge.
  - new fields charged under the SM and $U(1)_x$ (optional)

- This hidden sector is not entirely hidden if there is gauge kinetic mixing.
• Gauge Kinetic Mixing: \((B = U(1)_Y, \quad X = U(1)_x)\)

\[
\mathcal{L} \supset -\frac{1}{2} \epsilon B_{\mu\nu} X^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu}.
\]

\(\epsilon \sim 10^{-4} - 10^{-2}\) from integrating out heavy states. [Holdom ’86]

• Rotate gauge fields to get diagonal kinetic terms . . .

• New \(Z_x\) gauge boson with \(M_{Z_x} \sim g_x v_x \sim \text{GeV}\).

\((v_x \sim \text{GeV} \text{ by assumption})\)

• \(U(1)_x\) effectively mixes with \(U(1)_{em}\) for \(M_{Z_x} \ll M_{Z_0}\).

SM states acquire \(Z_x\) couplings of \(-e c_W Q \epsilon\).

Hidden states DO NOT acquire electric charges.
Explaining PAMELA

- Assume DM with $M_{DM} \sim 100\,\text{GeV}$ is charged under $U(1)_x$.
- DM annihilation receives a Sommerfeld enhancement today for a light $Z_x$ gauge boson. [Hisano et al. '04, Arkani-Hamed et al. '08]

\[ v_{DM}^{\text{today}} \sim 10^{-3}, \quad v_{DM}^{\text{freeze-out}} \sim 0.1, \]

\[ \langle \sigma v \rangle^{\text{today}} \sim \langle \sigma v \rangle^{f.o.} \frac{\alpha m_{DM}}{M_{Z_x}} \quad \text{for} \quad v \ll \sqrt{\frac{\alpha M_{Z_x}}{m_{DM}}}. \]

$\Rightarrow M_{Z_x} \lesssim 1\,\text{GeV}$ for sufficient enhancement.
• DM annihilation to leptons can be enforced by kinematics:

[Arkani-Hamed,Finkbeiner,Slatyer,Weiner ’08]

\[ \phi \rightarrow e^+ e^-, \mu^+ \mu^-, \nu's, \gamma's. \]
(Decays to hidden sector stuff also possible if light enough.)

• \( M_{Z_x} \lesssim 280 \text{ MeV} \) allows only decays to \( e^+ e^-, \mu^+ \mu^-, \nu's, \gamma's. \)

• Kinetic mixing gives couplings mainly to EM charged states:
  \( e, \mu \) (or hidden) modes dominate for a light \( Z_x \).

• Heavier \( Z_x \) can also decay to \( \pi's, \tau's, \ldots \).
Explaining DAMA

- $Z_x$ mediates inelastic DM scattering at DAMA for

\[ M_{Z_x} \sim \text{GeV}, \quad \epsilon \sim 10^{-4}. \]

- The inelastic splitting can arise from the GeV scale in the hidden sector in several ways.

[Arkani-Hamed et al. 08, Baumgart et al. '09, Cui et al. '09; Alves et al. '09]
A Simple Supersymmetric Example

[DM, Poland, Zurek '09]

- $U(1)_x$ gauge multiplet
  \[ \rightarrow 1 \text{ gauge boson and } 1 \text{ gaugino} \]

- Chiral hidden superfields $H$ and $H^c$ with $U(1)_x$ charges $\pm x_H$
  \[
  W_{hid} = \mu' H H^c \quad \text{with} \quad \mu' \sim \text{GeV}
  \]
  \[
  \langle H \rangle, \langle H^c \rangle \sim \text{GeV} \quad \text{induced by SUSY breaking}
  \]
  \[ \rightarrow 2 \text{ CP even scalars, } 1 \text{ CP odd scalar, } 2 \text{ hidden "higgsinos"} \]

- SUSY breaking determines the mass spectrum.
Sample Spectrum #1

- CP even scalar $h_1$ slightly lighter than $Z_x$.
- CP even $h_2$ and CP odd $a_1$ scalars heavier than $Z_x$.
- 3 hidden neutralinos $\chi_{1,2,3}^{hid}$ heavier than $Z_x$.
  The lightest of these is stable if there is $R$-parity.
- Decays:
  - $Z_x$ decays to SM states through kinetic mixing
    $\rightarrow$ prompt for $\epsilon \gtrsim 10^{-4}$
  - $h_1$ decays to SM states through mixing with SM Higgs, or through off-shell/loop $Z_x$’s
    $\rightarrow$ collider stable
  - Other unstable states decay through hidden cascades
Sample Spectrum #2

- CP even scalar $h_1$ slightly lighter than $Z_x$.

- CP even $h_2$ and CP odd $a_1$ scalars heavier than $Z_x$.

- At least one hidden neutralino $\chi_{1}^{\text{hid}}$ lighter than $M_{Z_x}/2$. The lightest of these is stable if there is $R$-parity.

- Decays:
  - $Z_x$ decays mostly to hidden neutralinos
  - $h_1$ decays mostly to hidden neutralinos
  - Other unstable states decay through hidden cascades
Adding DM to the Example

- DM can be added by including chiral states $D, D^c$ with $U(1)_x$ charges $\pm x_D$,

$$W_{DM} \supset \mu_{DM} DD^c$$

- $D$ and $D^c$ must be odd under a new \textit{``$\mathbb{Z}_2$''} symmetry; $R$-parity is no longer enough.

- PAMELA, DAMA require $\mu_D \gtrsim 100$ GeV.

- PAMELA can be explained with Sample Spectrum #1.

- Accounting for DAMA requires more machinery.

[Cui et al. '09; Alves et al. '09]
Constraints on Light Abelian Sectors

- \((g-2)_{\mu,e}\) [Pospelov ’08]

- \(BR(\gamma(3s) \rightarrow \gamma \mu^+\mu^-)\) [Essig et al ’09, Battell et al. ’09, Reece et al. 09]
  (if \(Z_x\) decays mostly to the SM - Sample #1.)

- \(BR(\gamma(3s) \rightarrow \gamma + inv)\) [Essig et al ’09, Battell et al. ’09, Reece et al. 09]
  (if \(Z_x\) decays mostly to hidden stuff - Sample #2)

- Supernova cooling, beam dumps [Ahlers et al. 08, Bjorken et al. ’09]
• (\(\gamma(3S)\) constraint assumes \(Z_x\) decays to SM - Sample #1.)

- Fixed target experiments can improve these bounds.

[Bjorken, Essig, Schuster, Toro '09]
Collider Signals

• Many models and many possibilities!

• Not Uncommon Features:
  – missing energy
  – displaced tracks
  – collimated “jets” of leptons

• Sample Spectra #1-2 can exhibit all of these features.
Production

- Heavy ($\sim$ TeV) states charged under both the SM and $U(1)_x$ can be produced efficiently and decay/radiate to the hidden $U(1)_x$ sector.

  $\rightarrow$ Hidden Valley [Strassler+Zurek ’06; Strassler ’06x]

- MSSM cascades end at the $U(1)_x$ LSP (assuming $R$-parity).

  SUSY kinetic mixing:

  \[ W \supset \int d^2 \theta \epsilon B^\alpha W_\alpha \supset \epsilon \tilde{B}^\dagger \sigma \cdot \partial \tilde{X} \]

  $\Rightarrow$ kinetic mixing between $U(1)_Y$ and $U(1)_x$ gauginos

  Induces $\tilde{B} \rightarrow \tilde{H} H^*$ decays.

  [Arkani-Hamed+Weiner ’08; Baumgart et al. ’09]
Decays

- **Sample Spectrum #1:**
  - boosted hidden neutralino cascades emit $h_1$'s, $Z_x$'s
  - $Z_x$ decays to light SM states $\Rightarrow \ell$'s or $\pi$'s
  - $h_1$ is long-lived on collider scales $\Rightarrow E_T$
  
  \[ e.g. \quad \chi_1^{vis} \rightarrow h_1 + \chi_2^{hid} \rightarrow h_1 + (\chi_1^{hid} + Z_x) \rightarrow E_T + \ell^+\ell^- \]
  
  $M_{\ell^+\ell^-} \simeq M_{Z_x}$ but boosted, possibly displaced
  $E_T$ set by $M_{\chi_1^{vis}}$

- **Sample Spectrum #2:**
  - hidden neutralino cascades remain hidden
• Many other possibilities:

- longer $U(1)_x$-sector cascades
- events initiated by heavy states with SM and $U(1)_x$ charges
- more complicated light $U(1)_x$ sectors
- $U(1)_x$ mixing with non-Abelian hidden gauge groups
  → hidden parton shower
Summary

- Light Abelian hidden sectors are consistent with data and may help account for PAMELA and DAMA.

- These can lead to novel signatures at colliders. → interesting independently of the DM story!

- In SUSY with $R$-parity, the MSSM LSP will decay to hidden sector particles.

- The resulting hidden sector cascade can generate decays back to SM states.

- Such decays could yield collimated lepton pairs.
Extra Slides
Indirect Dark Matter Signals
DM in our Galaxy

- Flat galactic disc surrounded by a spherical DM halo:

- DM density is largest at the galactic center.

- DM in the halo can annihilate producing particle fluxes.
  \[ \rightarrow e^-, e^+, p, \bar{p}, \gamma, \ldots \]
PAMELA - Cosmic Ray Positrons

- PAMELA sees an excess of $e^+$ over background.

- No excess flux of anti-protons is observed.
DM Annihilation to Leptons

- Most DM candidates decay too democratically.
  
  \[ \chi \chi \rightarrow W^+ W^- \rightarrow q \bar{q}, \ell \nu \ell \]  
  can give too many antiprotons.

- DM could be a heavy “lepton”.
  
  [Kribs+Harnik ’08; Pontón+Randall ’08; Zurek ’08; Phalen,Pierce,Weiner ’09;…]

- DM decays to leptons can be enforced by kinematics:
  
  [Arkani-Hamed,Finkbeiner,Slatyer,Weiner ’08; Nomura+Thaler ’08]

\[ M_{Z_x} < 280 \text{ MeV} \] allows only decays to \( e^+ e^- \), \( \mu^+ \mu^- \), \( \nu \)'s, \( \gamma \)'s.
Enhanced DM Annihilation Today

- Need $\langle \sigma v \rangle_{\text{today}} \gtrsim 10 \langle \sigma v \rangle_{\text{freeze-out}}$ for thermal relic DM.

- DM could be produced non-thermally.

- DM properties can change after freeze-out. \cite{Cohen,DM,Pierce '08}

  e.g. “Modulus” field phase transition after freeze-out

  $$\mathcal{L} \supset (m_{\text{DM}}^{(0)} + \zeta P) \Psi_{\text{DM}} \Psi_{\text{DM}}$$

  $$P \to \langle P \rangle \sim 100 \text{ GeV} \quad \text{at} \quad T < T_{f.o.} \sim m_{\text{DM}}^{(0)}/20$$

  $$m_{\text{DM}} : \quad m_{\text{DM}}^{(0)} \to m_{\text{DM}}^{(0)} + \zeta \langle P \rangle.$$  

  $\Rightarrow$ modified DM properties today relative to freeze-out

  The excitation around $\langle P \rangle$ must be very light: $m_{P} \lesssim \text{GeV}.$
DM annihilation can get a Sommerfeld enhancement today.

[Hisano et al. '04; Arkani-Hamed, Finkbeiner, Slatyer, Weiner '08; Pospelov+Ritz '08]

e.g. Light $Z_x$ Exchange

\[ \langle \sigma v \rangle_{\text{today}} \sim 10^{-3}, \quad \langle \sigma v \rangle_{\text{freeze-out}} \sim 0.1, \]

\[ \langle \sigma v \rangle_{\text{today}} \approx \langle \sigma v \rangle_{\text{f.o.}} \frac{\alpha m_{DM}}{M_{Z_x}} \quad \text{for} \quad v \ll \sqrt{\frac{\alpha M_{Z_x}}{m_{DM}}}. \]

\[ \Rightarrow M_{Z_x} \lesssim 1 \text{ GeV for sufficient enhancement} \]
Alternatives to Dark Matter Annihilation

- New cosmic ray signals could come from pulsars.
  
  [Hooper et al. '08; Yuksel et al. '08; Profumo '08]
  
  - Large astrophysics uncertainties.
  - Not expected but could be possible?

- Decaying dark matter.
  
  [Hamaguchi+Yanagida '08, Dimopoulos et al. '08]
  
  - Annihilating DM can produce too many $\gamma$ rays.
  - $\gamma$ flux from annihilations ($\sim n_{DM}^2$) is enhanced in the GC.
  - $\gamma$ flux from decays ($\sim n_{DM}$) is less enhanced.
DAMA and Inelastic Dark Matter
Dark Matter in our Galaxy

- Flat galactic disc surrounded by a spherical DM halo.

\[ v_{us} \approx (250 \text{ km/s}) + (30 \text{ km/s})(0.51) \cos(2\pi t/yr - June 2). \]

- \( v_{DM} \sim \) Maxwell distribution with \( \langle v \rangle \approx 250 \text{ km/s}. \)
• This DM flux can scatter off nuclei.
  → look for nuclear recoils with $E \leq 2m_Nv^2 \sim 100$ keV.

• Scattering rate is proportional to the net DM flux.

• Low momentum transfer → coherent scattering:
  $$\sigma_{NI}^{SI} \propto \sigma_n \frac{[(A - Z)f_n + Zf_p]^2}{f_n^2}$$
  (spin-independent).
Experimental Limits (Low Background)

Spin-independent cross section [$\text{cm}^2$]

WIMP mass [$\text{GeV}/c^2$]

[CDMS '08]
Annual Modulation at DAMA

- DM flux varies annually due to the motion of the Earth. ⇒ annual modulation of the DM scattering rate
  [Drukier,Freese,Spergel ’86]

- DAMA/NaI and DAMA/LIBRA searched for this variation in nuclear recoils using NaI-based detectors.

![Residuals (cpd/kg/keV) vs Time (day)](chart.png)

- Time (day)
- Residuals (cpd/kg/keV)
- 2-6 keV

DAMA/NaI (0.29 ton × yr)
(target mass = 87.3 kg)

DAMA/LIBRA (0.53 ton × yr)
(target mass = 232.8 kg)
Dark Matter Explanations for DAMA

• If the DAMA signal is DM what does it tell us?

• Heavy DM scattering off Iodine ($A \approx 127$) is ruled out.

![Graph showing WIMP mass vs. spin-independent cross-section](image)

[Freese, Gelmini, Gondolo, Savage ’08]

• Light DM? Inelastic DM?
Light Dark Matter and DAMA

- CDMS (Ge) is insensitive to lighter ($m \lesssim 10$ GeV) DM:  
  $\rightarrow$ recoil energy of the Ge ($A=72$) nucleus is too small.

- DAMA contains Na ($A=23$) $\rightarrow$ larger recoil from light DM.

- Light DM is constrained by the DAMA energy spectra.  
  [Chang,Pierce,Weiner '08; Fairbairn,Zupan '08]

[Freese,Gelmini,Gondolo,Savage '08]
Inelastic Dark Matter (iDM)

- Assumption: DM scatters coherently off nuclei preferentially into a slightly heavier state. \([\text{Tucker-Smith+Weiner '01}]\)

\[M_{DM2} - M_{DM1} = \delta > 0\]

- Modified scattering kinematics enhances the modulated signal at DAMA and fixes the spectrum.
To produce a nuclear recoil with energy $E_R$, the minimum DM velocity is

$$v_{min} = \frac{1}{\sqrt{2m_N E_R}} \left( \frac{m_N E_R}{\mu_N} + \delta \right).$$

Signal Rate:

$$\frac{dR}{dE_R} \propto \int_{v_{min}} d^3v \ f(\vec{v}, \vec{v}_e) \ v \ \frac{d\sigma}{dE_R}.$$ 

DM velocities are $\sim$ Maxwellian with a cutoff $v_{esc}$, with a net boost from the motion of the Earth:

$$f(\vec{v}, \vec{v}_e) = 0 \ \text{unless} \ |\vec{v} + \vec{v}_e| < v_{esc}.$$ 

iDM: $v_{min}$ is less for I ($A \approx 127$) than for Ge ($A \approx 72$).

$\Rightarrow$ enhancement at DAMA relative to CDMS.
- $M_{DM} = 100$ GeV, 1000 GeV

DAMA 90, 99% allowed ellipses, 99 % c.l. exclusions

- iDM can work for $M \sim 100$ GeV, $\delta \sim 100$ keV.

[Chang et al. '08; March-Russell et al. '08; Cui et al. '09; Alves et al. '09]
iDM Scattering through a Light Hidden $U(1)_x$

- Can arise if SM couplings come only from kinetic mixing,

$$\mathcal{L} \supset -\frac{1}{2} \epsilon B_{\mu \nu} X^{\mu \nu} - \frac{1}{4} B_{\mu \nu} B^{\mu \nu} - \frac{1}{4} X_{\mu \nu} X^{\mu \nu}.$$  

$\epsilon \sim 10^{-4} - 10^{-2}$ from integrating out heavy states. [Holdom '86]

- $U(1)_x$ effectively mixes with $U(1)_{em}$ for $M_{Z'} \ll M_{Z0}$.

SM states acquire $Z'$ couplings of $-e c_W Q \epsilon$.

$$\sigma^0_p = \left(\frac{g_x x_{DM}}{0.5 GeV} M_{Z'} \right)^2 \left(\frac{\epsilon}{10^{-3}}\right)^2 (2.1 \times 10^{-36} \text{ cm}^2)$$

- A multi-GeV mass $Z'$ is allowed for $\epsilon \lesssim 10^{-2}$ [Pospelov '08]
Hidden $U(1)_x$ SUSY iDM

- SUSY is a natural setting for a light hidden $U(1)_x$. Gauge mediation in the visible sector breaks SUSY in the hidden sector through kinetic mixing: [Zurek '08]

\[ m_{\text{hid}} \sim \epsilon m_{E^c}, \]
\[ M_{Z_x} \lesssim \epsilon^2 M_1. \]

- Gravity mediation can contribute for $m_{3/2} \sim \text{GeV}$.

- $U(1)_x$ breaking can be induced by soft masses, $D$-terms ($\sim \sqrt{\epsilon} v$) naturally on the order of a GeV. [Baumgart,Cheung,Ruderman,Wang,Yavin '09, Cui et al. '09]
• Minimal hidden $U(1)_x$ iDM Model:

$$W \supset \mu' H H^c + M_a a a^c + \frac{1}{2} M_s S^2 + \lambda_1 S a^c H + \ldots,$$

• For $M_s \sim M_a \gg \langle H^c \rangle \sim \mu'$,

$$W_{\text{eff}} \supset -\frac{\lambda_1}{2 M_s} (a^c H)^2 + \ldots$$

$\Rightarrow$ iDM from $a^c$ for $M_s \sim \text{TeV}$ and $\langle H^c \rangle \sim \mu' \sim \text{GeV}$

• Multi-$\mu$ Mystery: $\mu' \ll M_s, M_a$?

  - $\mu' \sim \text{GeV}$ from an NMSSM-mechanism in hidden sector. 
    [Zurek '08, Chun+Park '08]
  
  - Gaugino mediation with residual anomaly mediation in the hidden sector. [Katz+Sundrum '09]