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

David Morrissey

Harvard University and TRIUMF
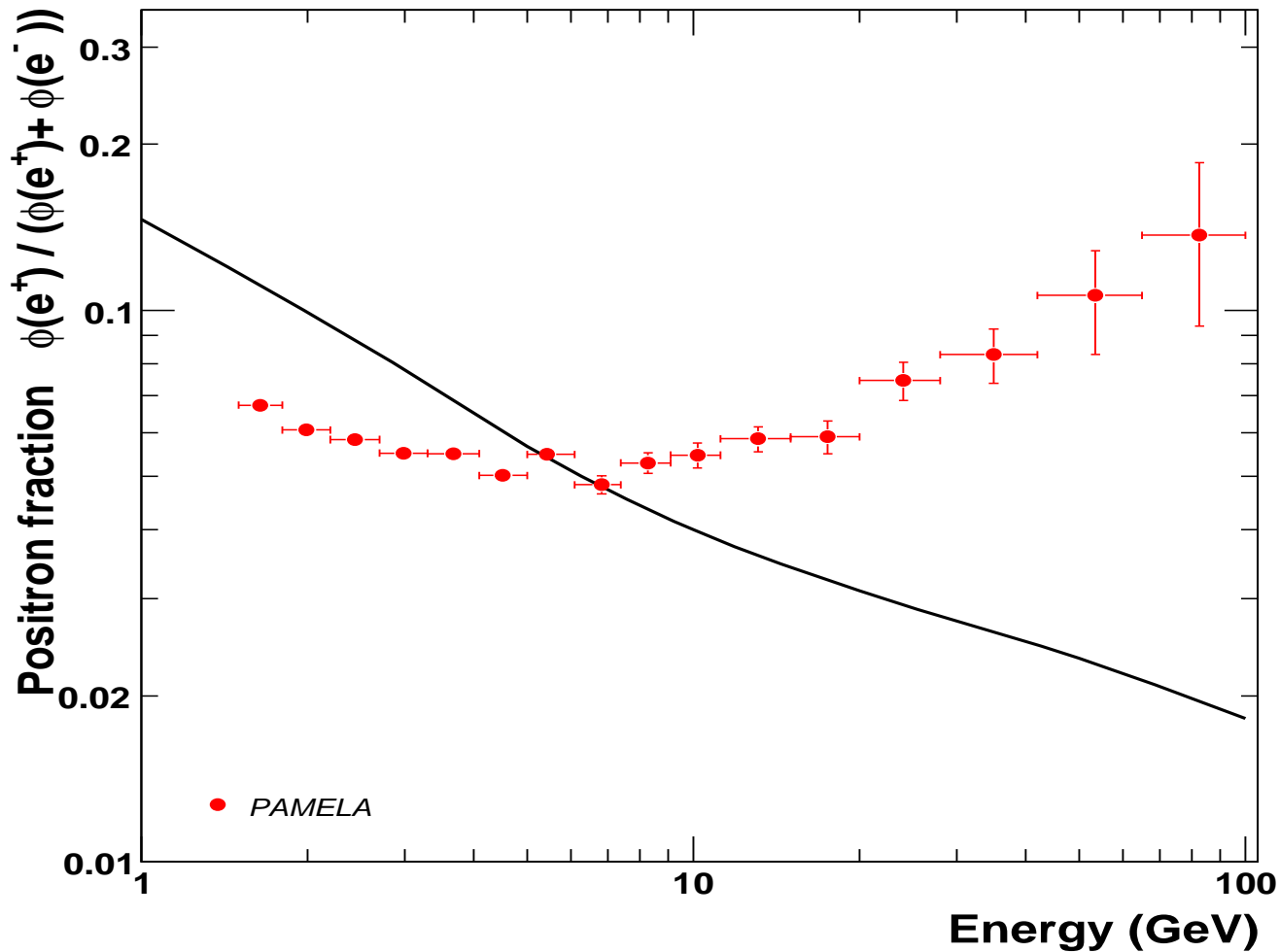
Quick Outline

- 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 $E \geq 10\,\text{GeV}$.

- 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:
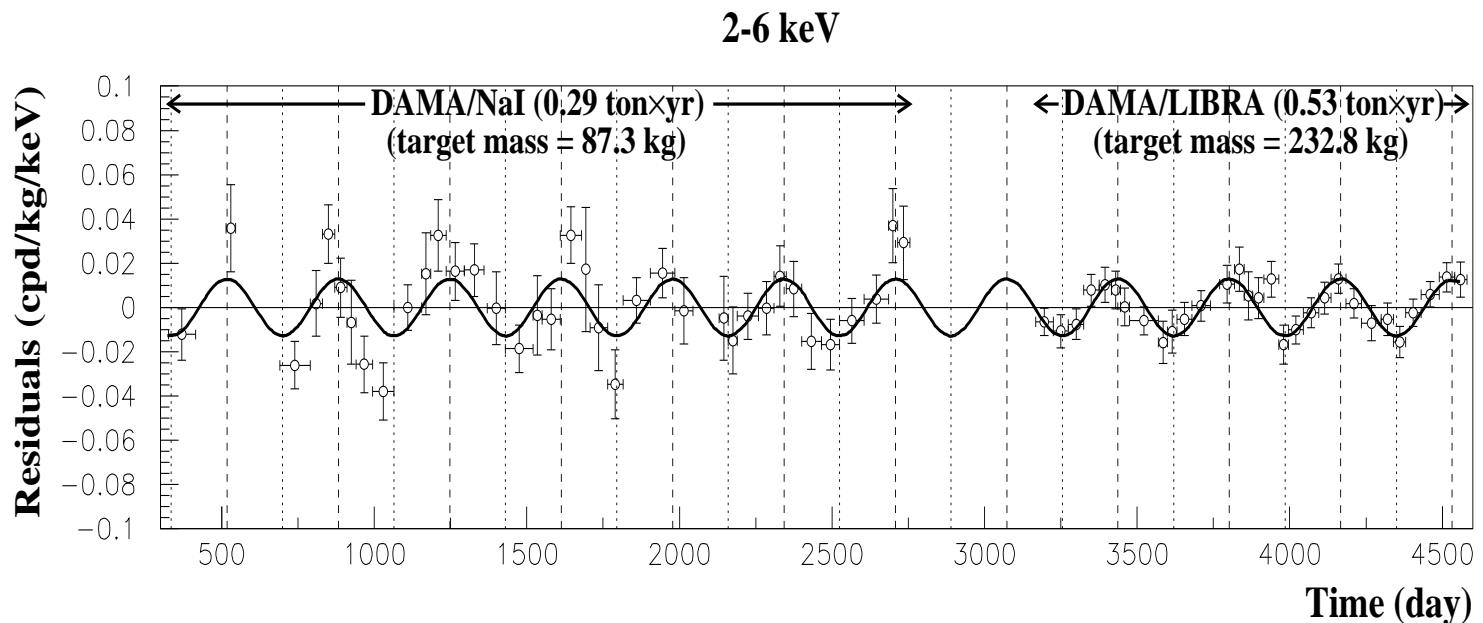
- Both period and phase match up with DM expectations.

- 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]
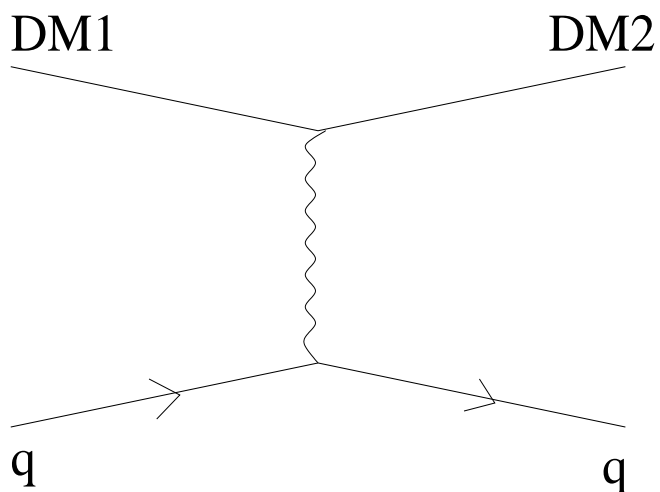
$$M_{DM1} \sim 100\,\text{GeV}, \quad M_{DM2} - M_{DM1} = \delta \sim 100\,\text{keV}$$

- 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 $v_x \lesssim$ 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: $(B = U(1)_Y, \quad X = U(1)_x)$

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

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

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

- New Z_x gauge boson with $M_{Z_x} \sim g_x v_x \sim$ GeV.

  ($v_x \sim$ GeV 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]
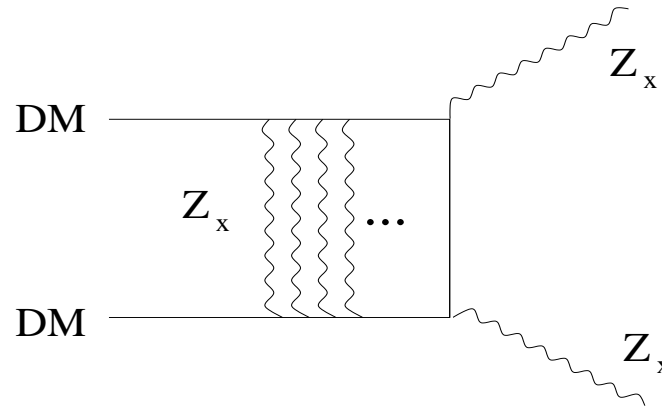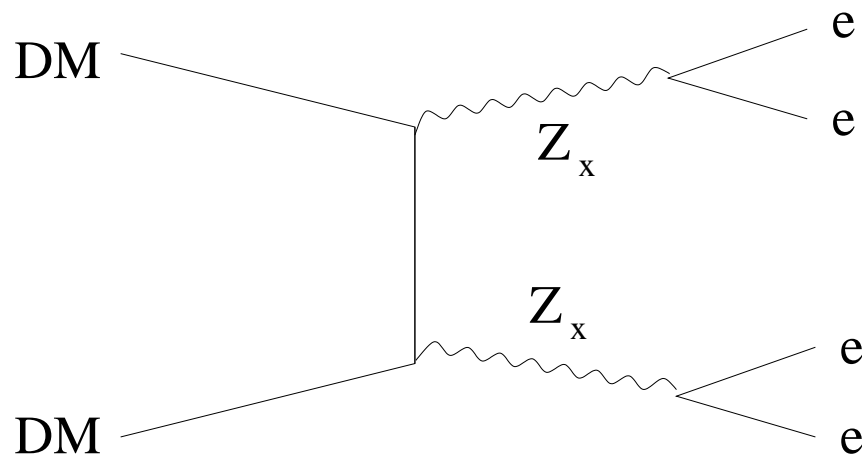

$$v_{DM}^{today} \sim 10^{-3}, \qquad v_{DM}^{freeze-out} \sim 0.1,$$

$$\langle \sigma v \rangle^{today} \simeq \langle \sigma v \rangle^{f.o.} \frac{\alpha\, m_{DM}}{M_{Z_x}} \quad \text{for } v \ll \sqrt{\frac{\alpha\, M_{Z_x}}{m_{DM}}}.$$

$$\Rightarrow M_{Z_x} \lesssim 1\,\text{GeV for sufficient enhancement}$$

- DM annihilation to leptons can be enforced by kinematics:

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

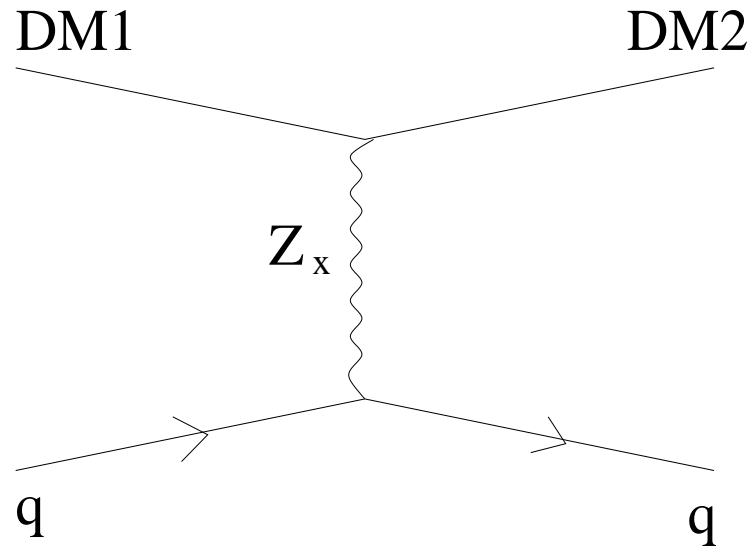- $M_{Z_x} \lesssim 280\,\text{MeV}$ allows only decays to e^+e^-, $\mu^+\mu^-$, ν's, γ's. (Decays to hidden sector stuff also possible if light enough.)

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

- Heavier Z_x can also decay to π's, τ's, . . .

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 gauge boson and 1 gaugino

- Chiral hidden superfields H and H^c with $U(1)_x$ charges $\pm x_H$

$$W_{hid} = \mu' H H^c \quad \text{with} \quad \mu' \sim \text{GeV}$$

$\langle H \rangle, \langle H^c \rangle \sim$ GeV induced by SUSY breaking

$\rightarrow$ 2 CP even scalars, 1 CP odd scalar, 2 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 $\chi^{hid}_{1,2,3}$ 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 χ_1^{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 $\pm x_D$,

$$W_{DM} \supset \mu_{DM} \, D D^c$$

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

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

- 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]

- $BR(\Upsilon(3s) \to \gamma\,\mu^{+}\mu^{-})$ [Essig *et al* '09, Battell *et al.* '09, Reece *et al.* 09]

  (if Z_x decays mostly to the SM - Sample #1.)

  $BR(\Upsilon(3s) \to \gamma + inv)$ [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]

- ($\Upsilon(3s)$) constraint assumes Z_x decays to SM - Sample #1.)
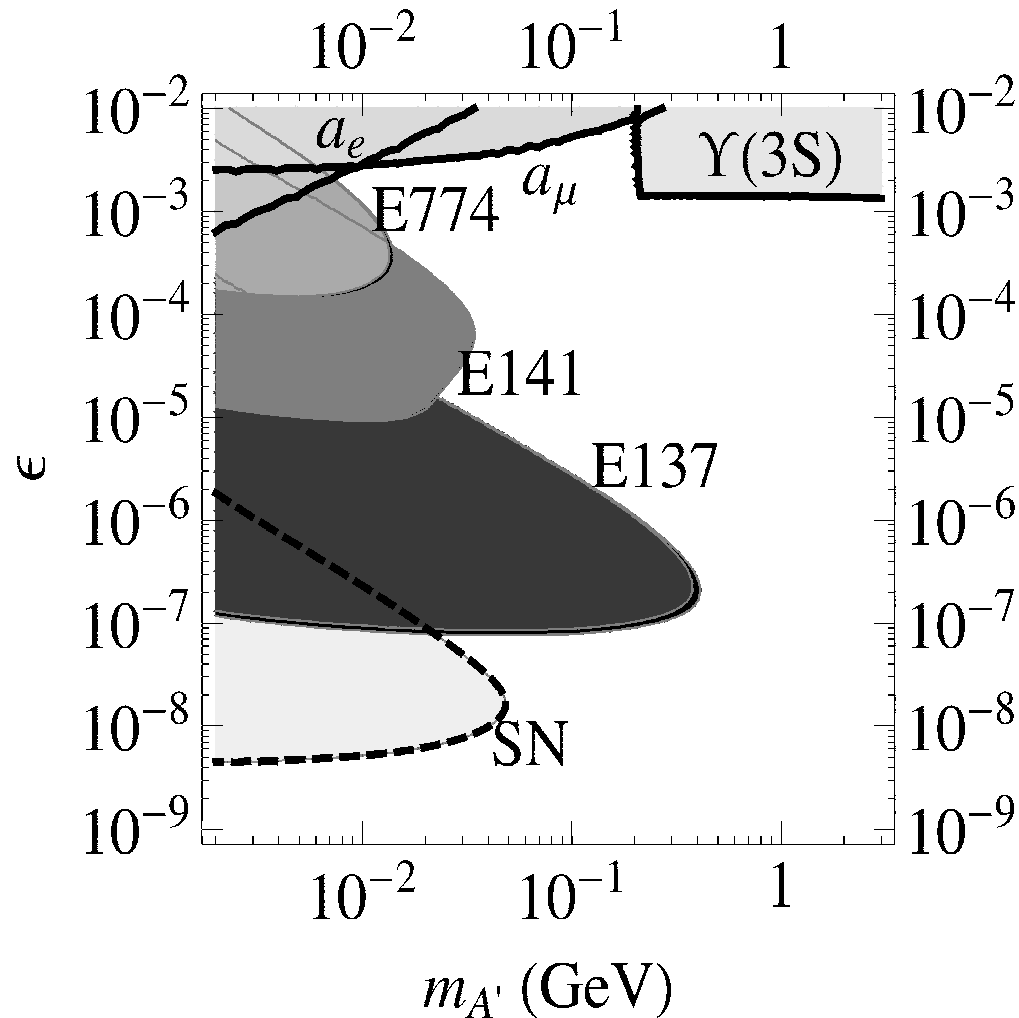
[Bjorken,Essig,Schuster,Toro '09]

- Fixed target experiments can improve these bounds.

[Bjorken *et al.* '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 π's

  - h_1 is long-lived on collider scales $\Rightarrow \not{E}_T$

  $$e.g. \quad \chi_1^{vis} \to h_1 + \chi_2^{hid} \to h_1 + \left(\chi_1^{hid} + Z_x \right)$$
  $$\to \not{E}_T + \ell^+ \ell^-$$

  $M_{\ell^+ \ell^-} \simeq M_{Z_x}$ but boosted, possibly displaced

  $\not{E}_T$ 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

    $\rightarrow$ 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.
  $\rightarrow$ 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

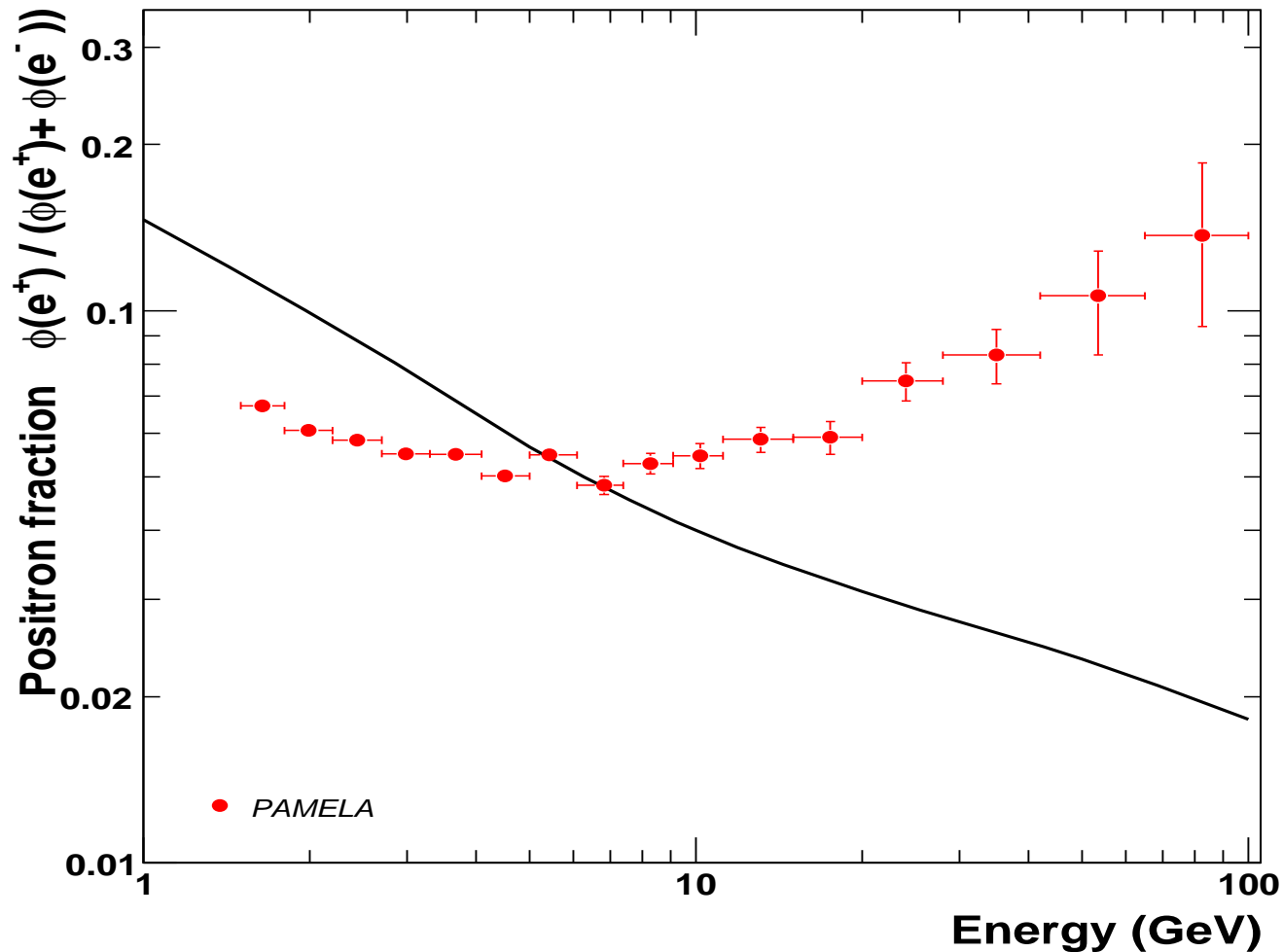- Flat galactic disc surrounded by a sherical DM halo:
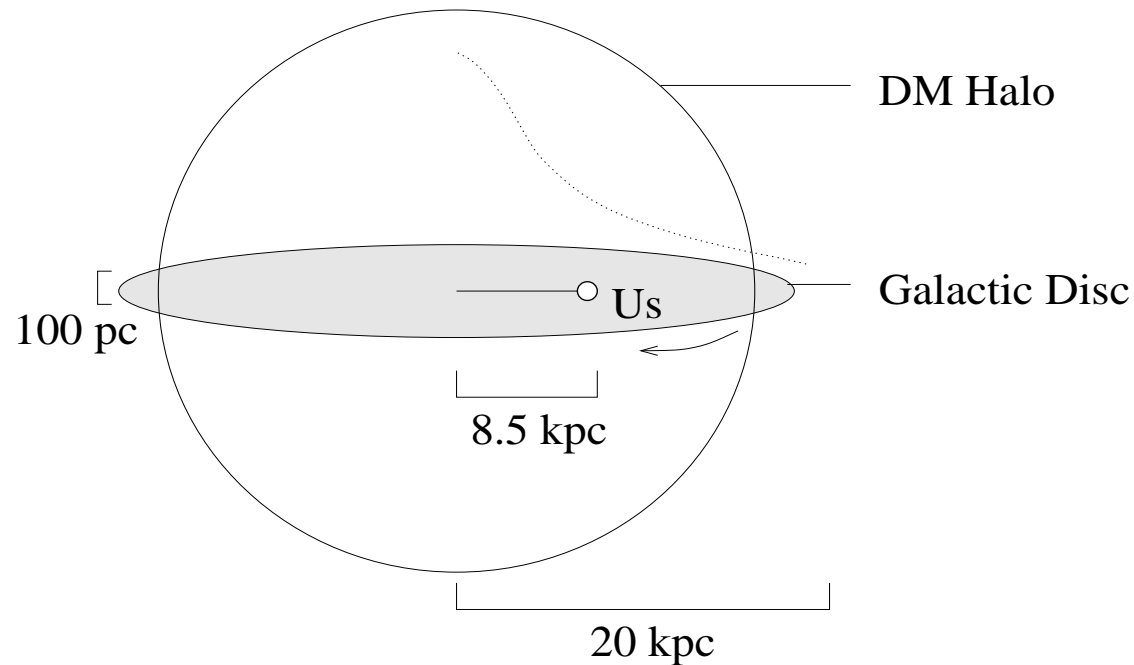
- DM density is largest at the galactic center.

- DM in the halo can annihilate producing particle fluxes.

$$\rightarrow e^-, e^+, p, \bar{p}, \gamma, \ldots$$

PAMELA - Cosmic Ray Positrons

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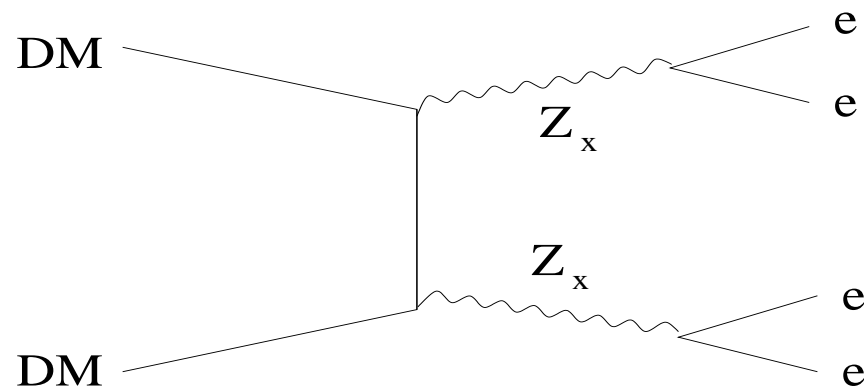

- No excess flux of anti-protons is observed.

DM Annihilation to Leptons

- Most DM candidates decay too democratically.

  e.g. $\chi\chi \to W^+W^- \to q\bar{q}, \ell\nu_\ell$ 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^-, $\mu^+\mu^-$, ν's, γ's.

Enhanced DM Annihilation Today

- Need $\langle \sigma\, v \rangle^{today} \gtrsim 10 \langle \sigma\, v \rangle^{freeze-out}$ for thermal relic DM.

- DM could be produced non-thermally.

- DM properties can change after freeze-out. [Cohen,DM,Pierce '08]

  e.g. "Modulus" field phase transition after freeze-out

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

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

$$m_{DM} \;:\; m_{DM}^{(0)} \to m_{DM}^{(0)} + \zeta\, \langle P \rangle.$$
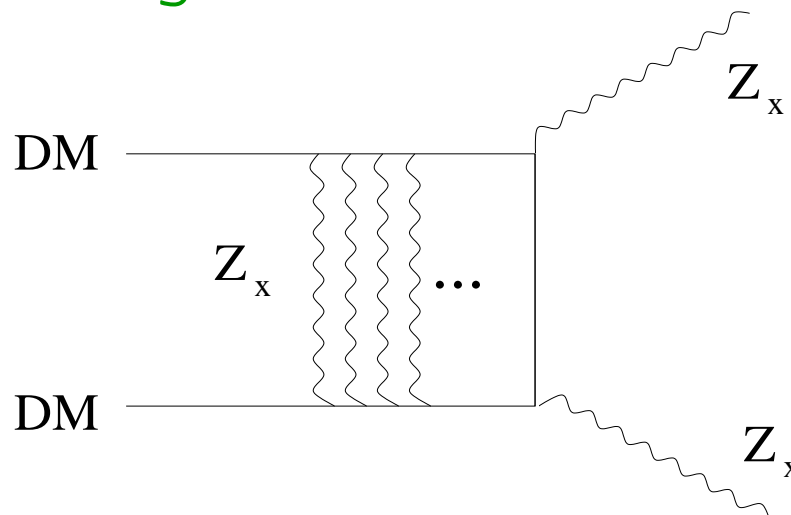
$\Rightarrow$ modified DM properties today relative to freeze-out

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

$$v_{DM}^{today} \sim 10^{-3}, \qquad v_{DM}^{freeze-out} \sim 0.1,$$

$$\langle \sigma v \rangle^{today} \simeq \langle \sigma v \rangle^{f.o.} \frac{\alpha\, m_{DM}}{M_{Z_x}} \quad \text{for } v \ll \sqrt{\frac{\alpha\, M_{Z_x}}{m_{DM}}}.$$

$\Rightarrow M_{Z_x} \lesssim 1 \,\text{GeV}$ 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?
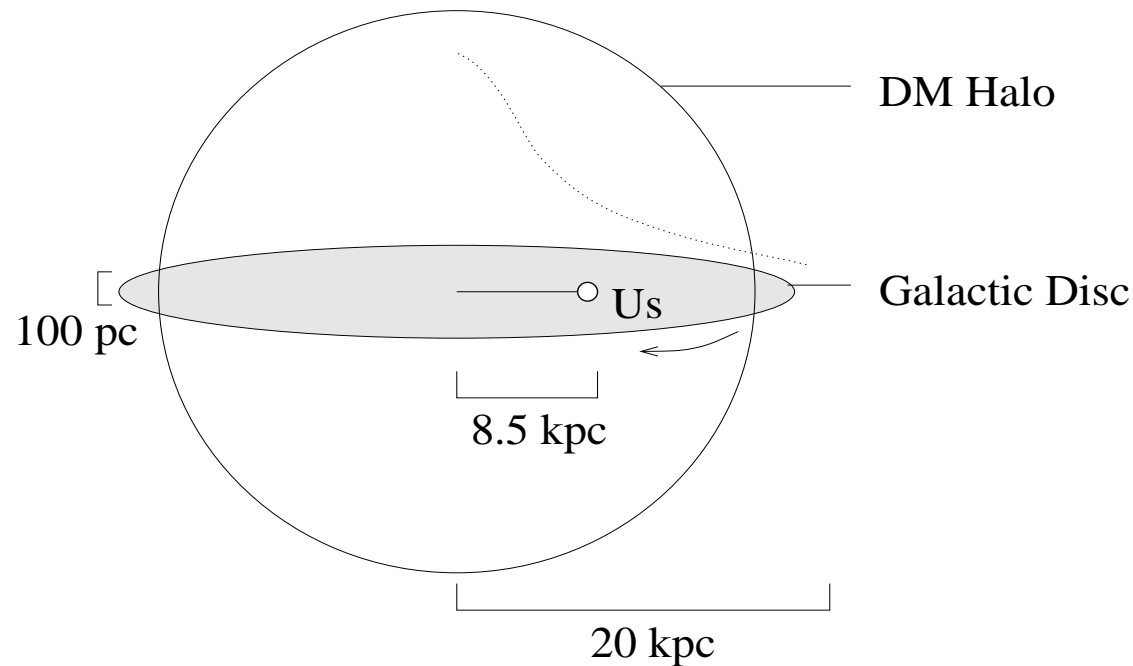
- Decaying dark matter.

  [Hamaguchi+Yanagida '08, Dimopoulos *et al.* '08]

  – Annihilating DM can produce too many γ rays.

  – γ flux from annihilations ($\sim n_{DM}^2$) is enhanced in the GC.

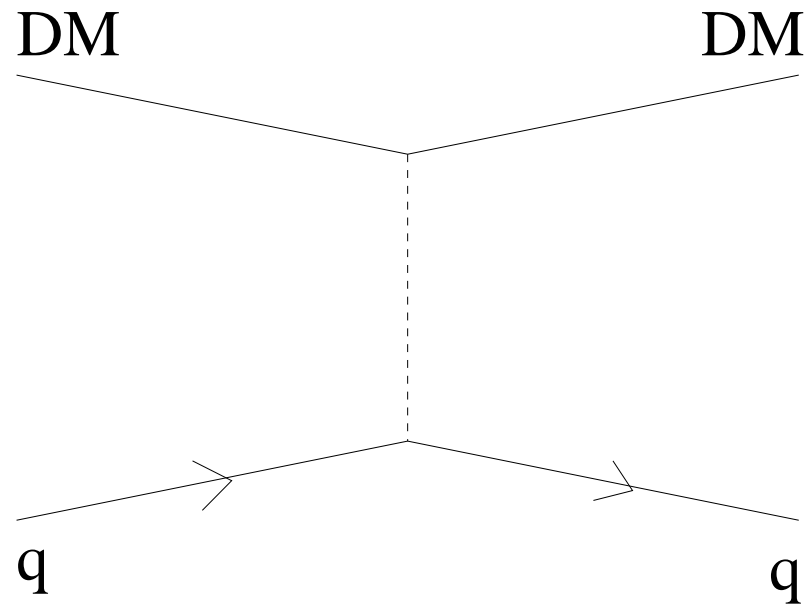 – γ flux from decays ($\sim n_{DM}$) is less enhanced.

DAMA and Inelastic Dark Matter

Dark Matter in our Galaxy

- Flat galactic disc surrounded by a spherical DM halo.

- $v_{us} \simeq (250\,km/s) + (30\,km/s)(0.51)\cos(2\pi t/yr - June\ 2)$.

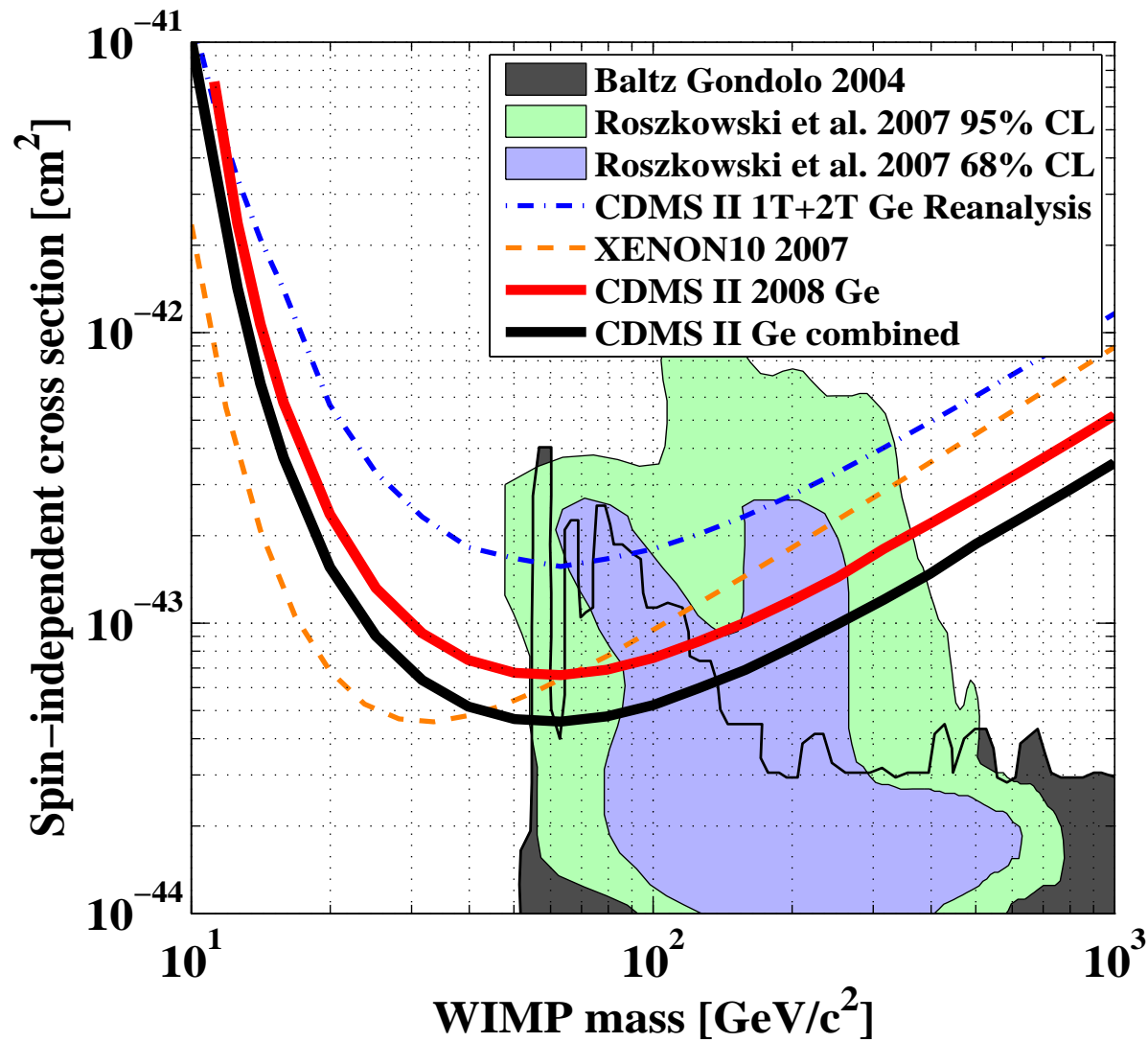- $v_{DM} \sim$ Maxwell distribution with $\langle v \rangle \simeq 250\,km/s$.

- This DM flux can scatter off nuclei.

  $\rightarrow$ look for nuclear recoils with $E \leq 2m_N v^2 \sim 100\,\text{keV}$.

- Scattering rate is proportional to the net DM flux.

- Low momentum transfer $\rightarrow$ coherent scattering:

$$\sigma_N^{SI} \propto \sigma_n^0 \frac{[(A-Z)f_n + Zf_p]^2}{f_n^2} \qquad \text{(spin-independent)}.$$

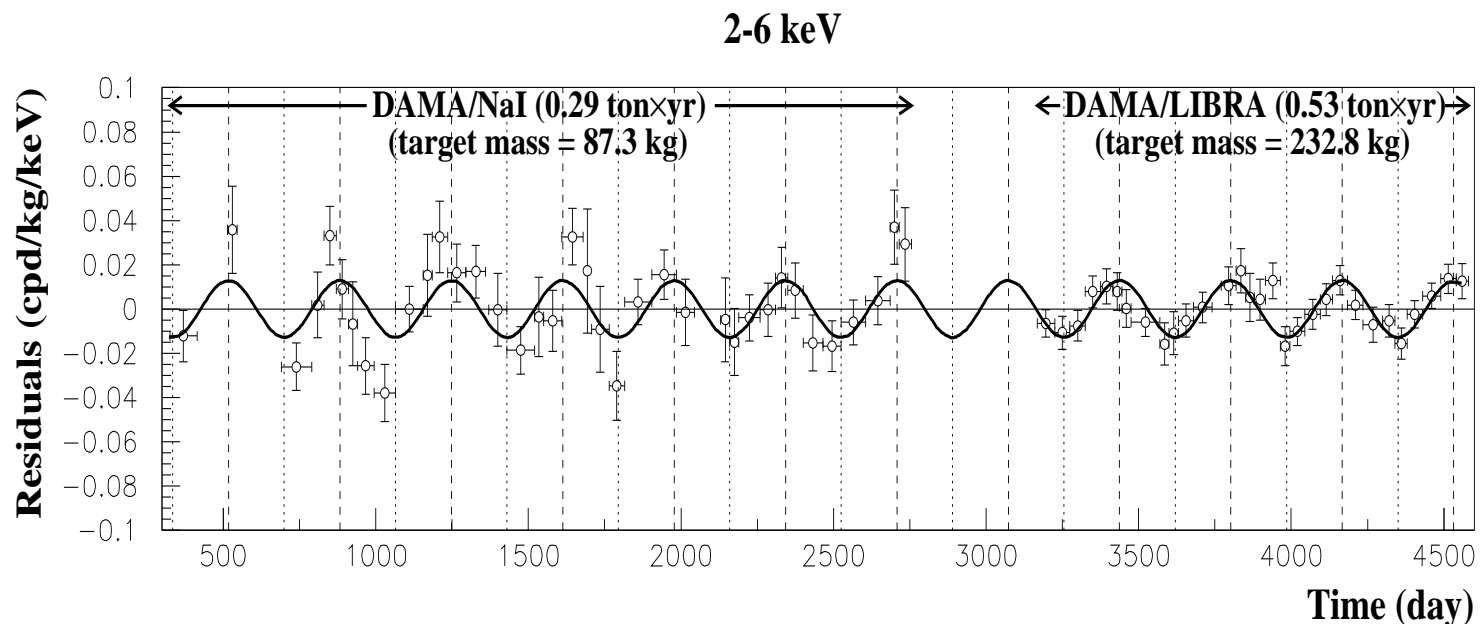# Experimental Limits (Low Background)

[CDMS '08]

Annual Modulation at DAMA

- DM flux varies annually due to the motion of the Earth.

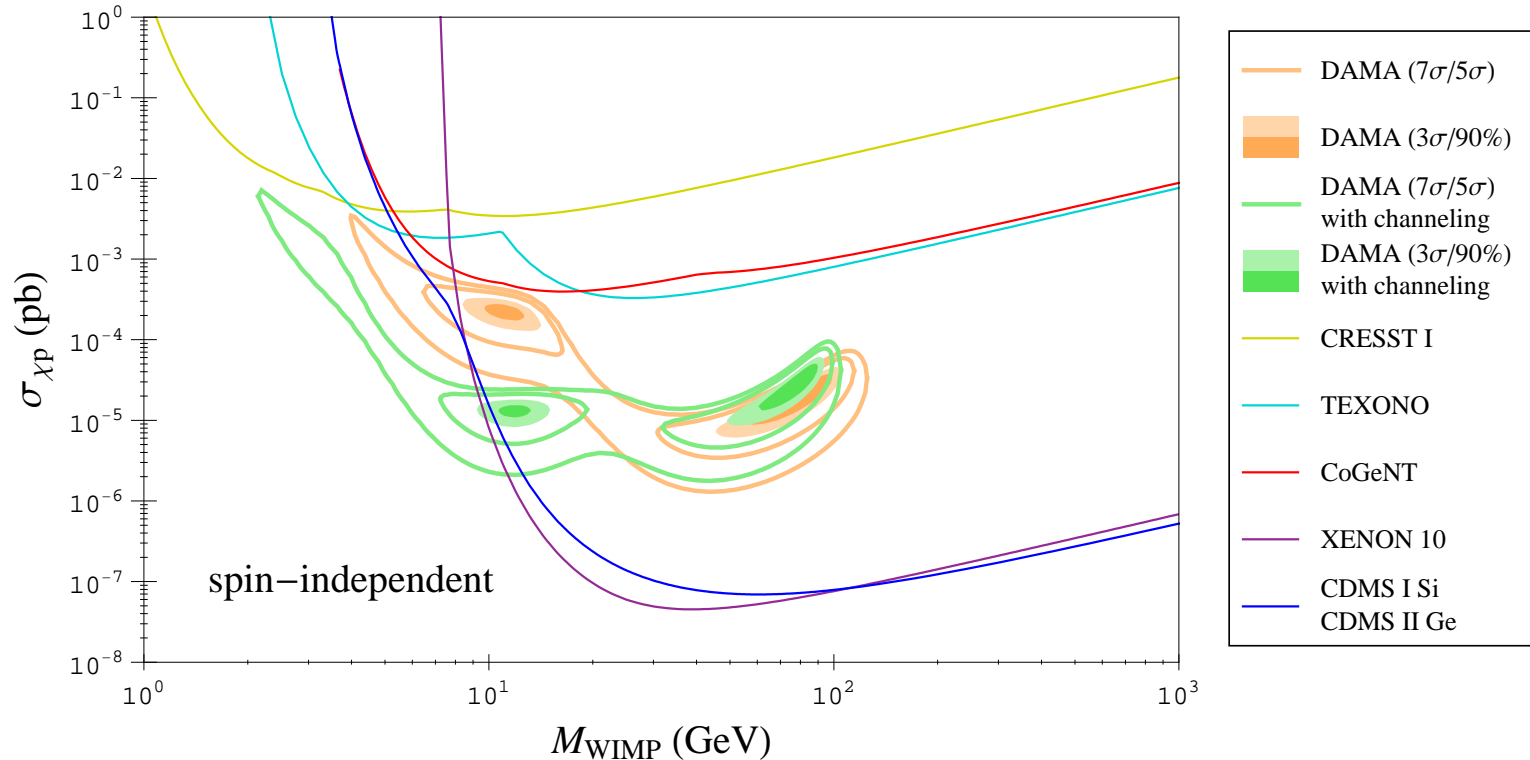 ⇒ annual modulation of the DM scattering rate

  [Drukier,Freese,Spergel '86]

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

Dark Matter Explanations for DAMA

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

- Heavy DM scattering off Iodine ($A \simeq 127$) is ruled out.

[Freese,Gelmini,Gondolo,Savage '08]

- Light DM? Inelastic DM?

Light Dark Matter and DAMA

- CDMS (Ge) is insensitive to lighter ($m \lesssim 10 \, \text{GeV}$) 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]
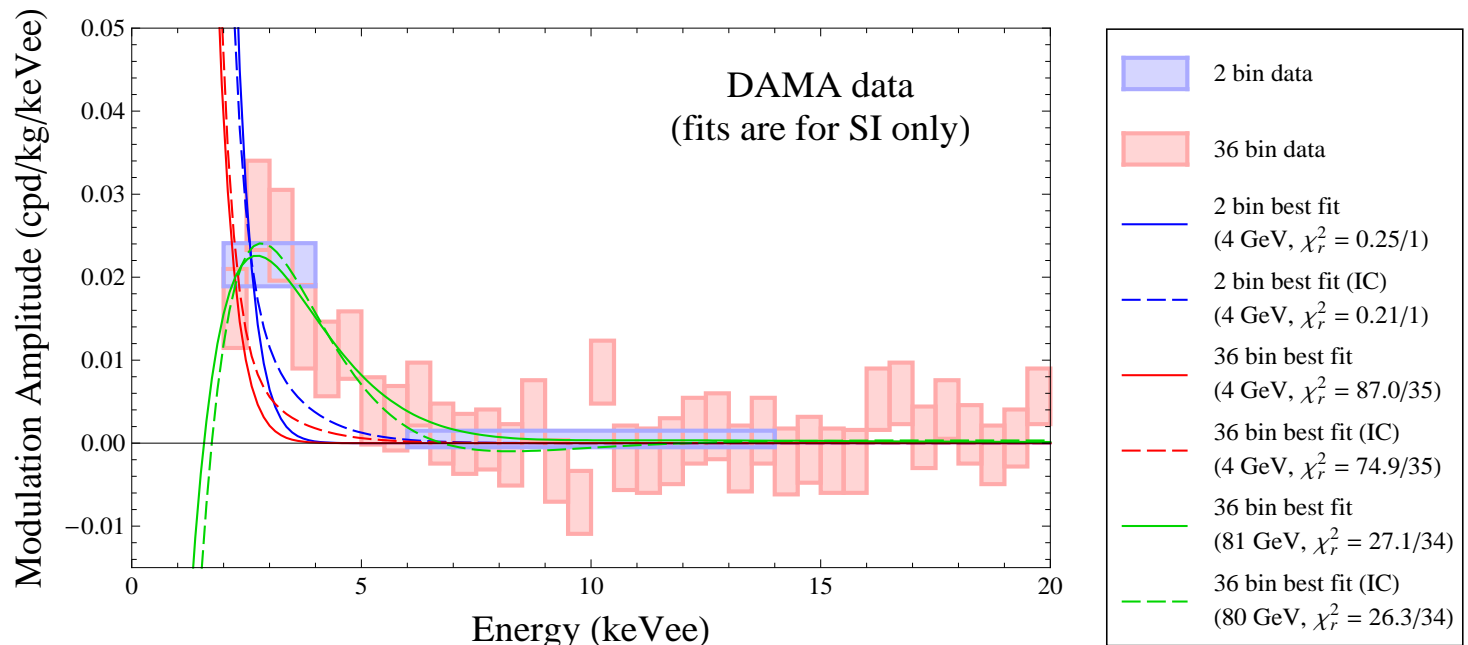
Inelastic Dark Matter (iDM)

- Assumption: DM scatters coherently off nuclei preferentially into a slightly heavier state. [Tucker-Smith+Weiner '01]
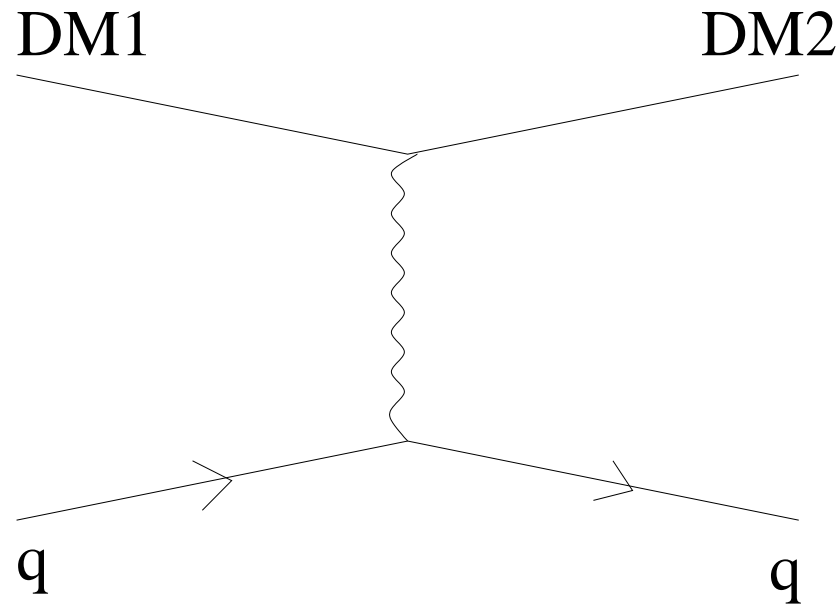
$$M_{DM2} - M_{DM1} = \delta > 0$$

- 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:

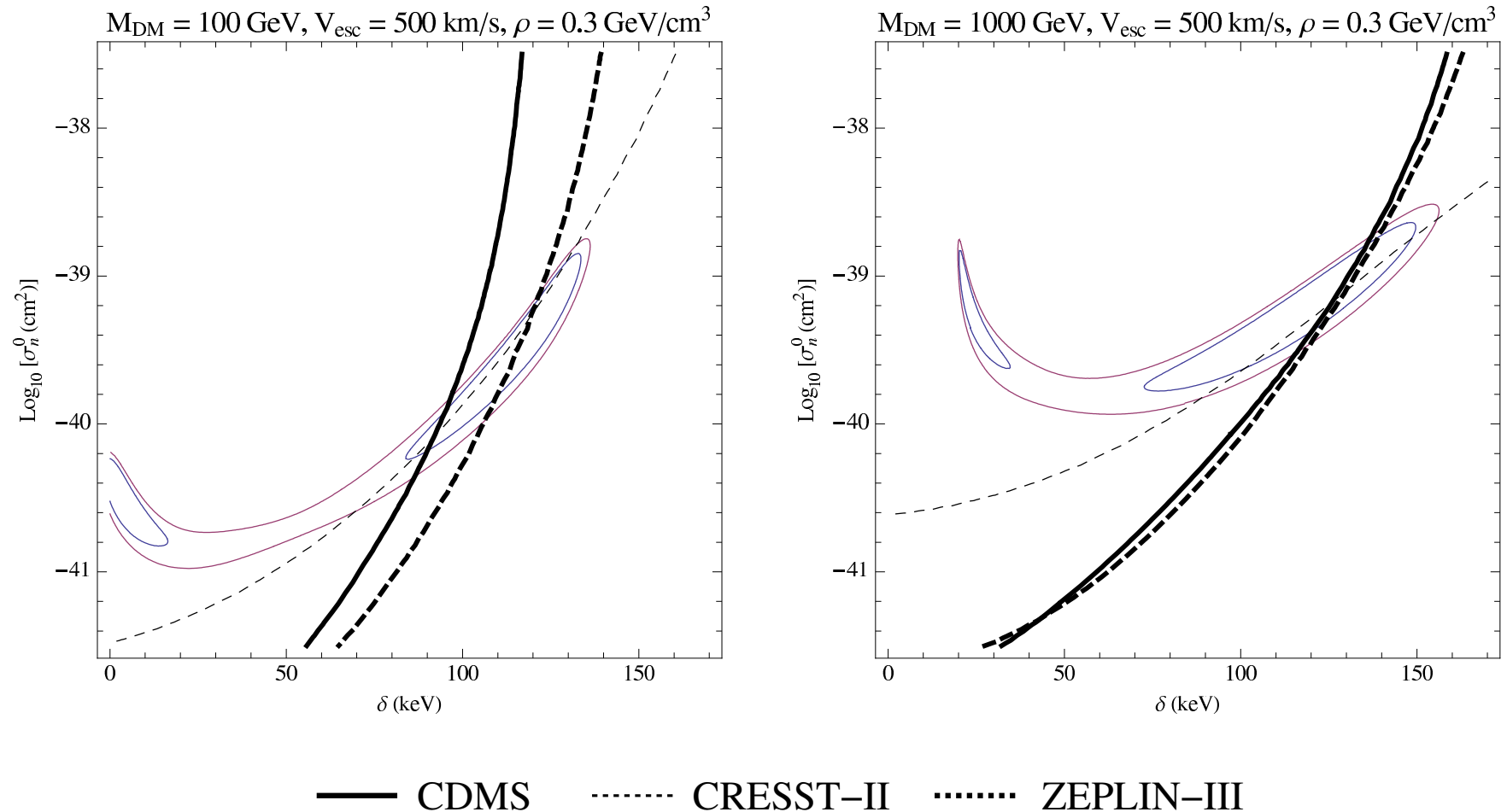$$\frac{dR}{dE_R} \propto \int_{v_{min}} d^3v \, f(\vec{v}, \vec{v}_e) \, v \, \frac{d\sigma}{dE_R}.$$

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

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

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

$\Rightarrow$ enhancement at DAMA relative to CDMS.

- $M_{DM} = 100\,\text{GeV},\ 1000\,\text{GeV}$

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

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

[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,

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

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

- $U(1)_x$ effectively mixes with $U(1)_{em}$ for $M_{Z'} \ll M_{Z^0}$.

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

$$\sigma_p^0 = \left(\frac{g_x\,x_{DM}}{0.5}\right)^2 \left(\frac{\text{GeV}}{M_{Z'}}\right)^4 \left(\frac{\epsilon}{10^{-3}}\right)^2 (2.1 \times 10^{-36}\,cm^2)$$

- 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]

$$m_{hid} \sim \epsilon \, m_{E^c},$$
$$M_{\tilde{Z}_x} \lesssim \epsilon^2 M_1.$$

- Gravity mediation can contribute for $m_{3/2} \sim$ 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:

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

- For $M_s \sim M_a \gg \left\langle H^{(c)} \right\rangle \sim \mu'$,

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

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

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

  $-$ $\mu' \sim$ 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]