New Direct Detection Phenomenology from Dark Sectors

Felix Yu
Fermilab

arXiv:1205.xxxx

with Wolfgang Altmannshofer, Joachim Kopp

Phenomenology Symposium 2012, University of Pittsburgh
May 8, 2012

Motivation

- In the absence of non-gravitational signals, models of dark matter phenomenology have been driven by the WIMP scattering paradigm
  - The WIMP miracle is a very attractive starting point
- Yet we can readily construct huge variety of scattering signals
  - The SM is a very attractive starting point
- Non-minimal dark matter sectors with new dark dynamics can give new direct detection phenomenology

Recent work with dark dynamics

- Resonant scattering and recombination

Pospelov, Ritz (2008)

- Composite iDM, atomic DM

Alves, Behbahani, Schuster, Wacker (2009)
Kaplan, Krnjaic, Rehermann, Wells (2010)

- Quirky composite DM

Kribs, Roy, Terning, Zurek (2009)

- Hidden charged DM

Ackermann, Buckley, Carroll, Kamionkowski (2008)
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- Dynamical dark matter

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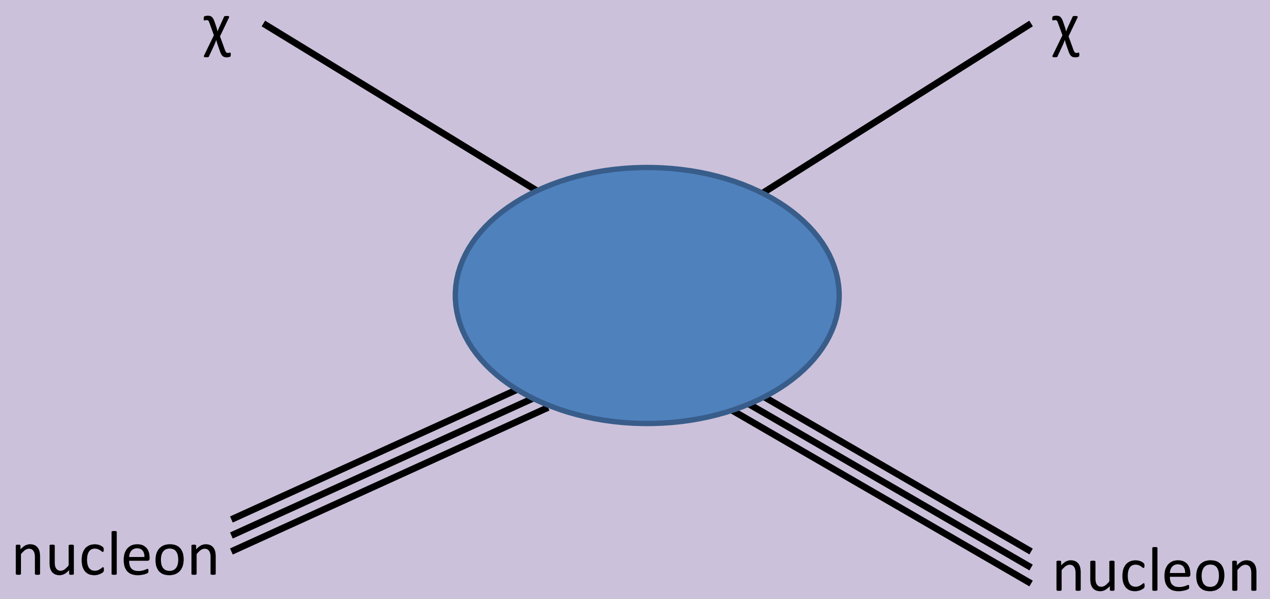
Inspired by the rich set of viable possibilities provided by dark dynamics, we identify a novel *multiple hit dark matter* signature for direct detection

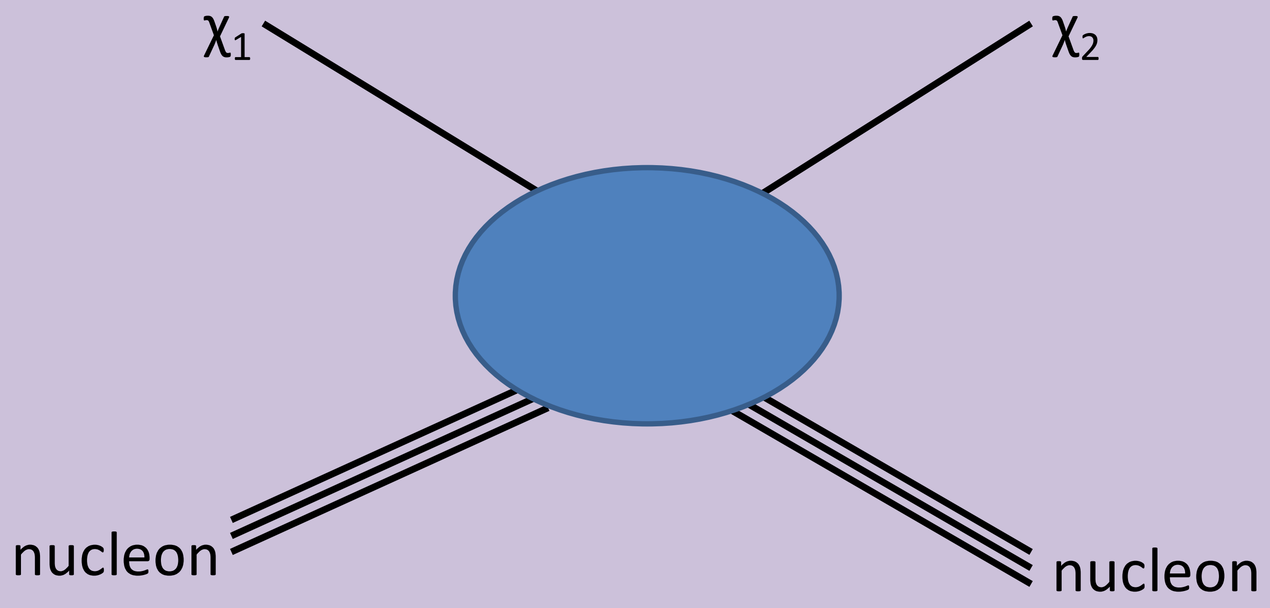
Direct Detection Phenomenology

- Traditional direct detection experiments focus on WIMP elastic scattering



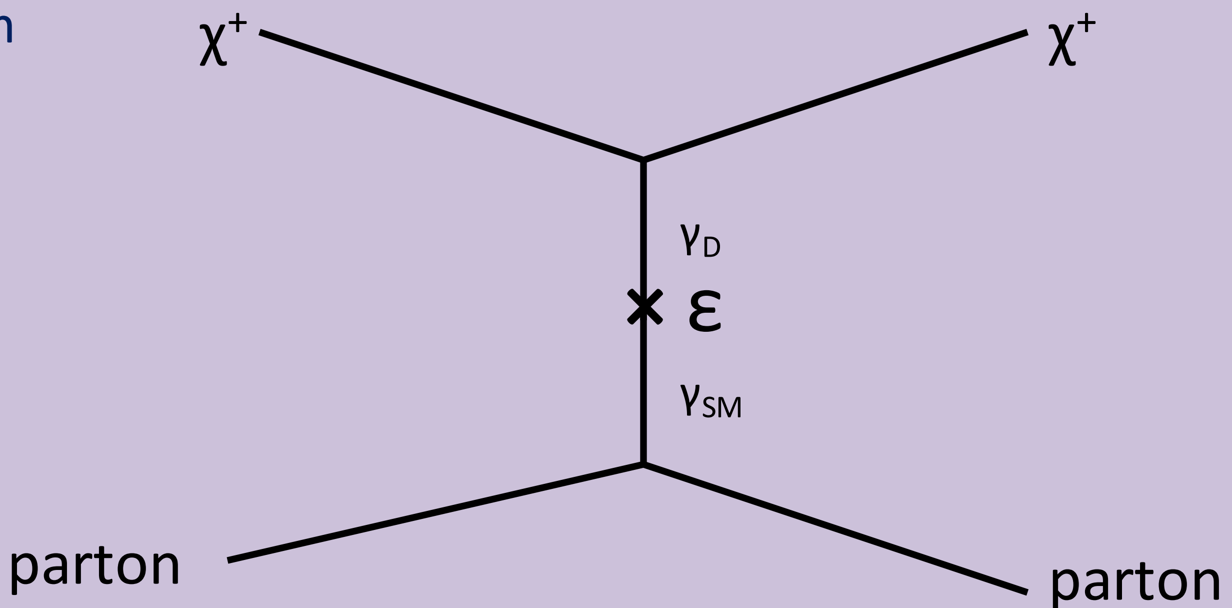
Direct Detection Phenomenology

- Motivated primarily by PAMELA, a resurgence of interest in inelastic DM models has occurred



Direct Detection Phenomenology

- We consider a toy model with χ^+, γ_D (and χ^0 spectator), with kinetic mixing between $U(1)_D$ and $U(1)_{em}$



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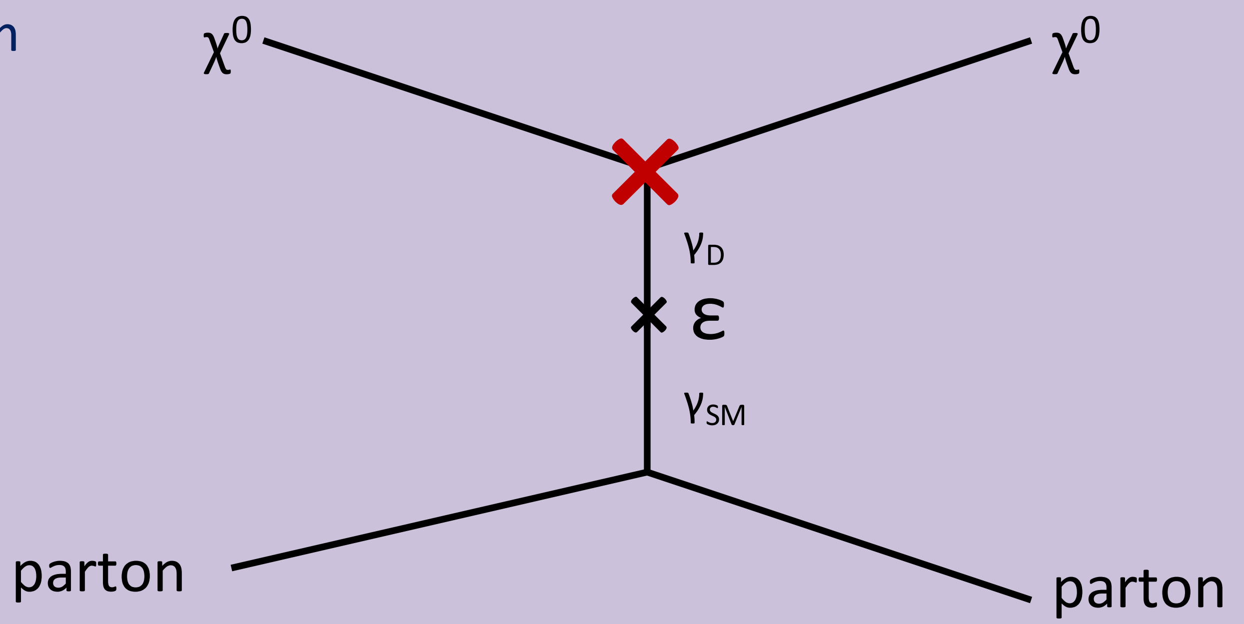
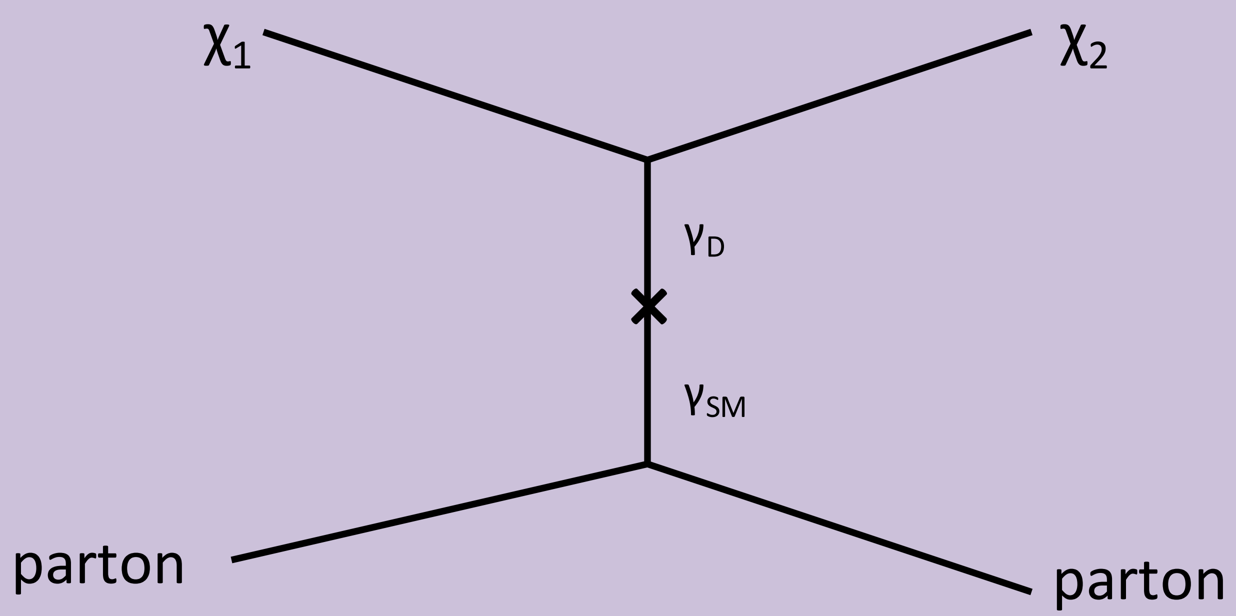


Direct Detection Phenomenology

- We add a small $U(1)_D$ breaking term
- Leads to mixing between χ^0 and χ^+



Toy Model

- Lagrangian

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu} + i\bar{\chi}^{+}\not{D}'_{\mu}\chi^{+} + i\bar{\chi}^{0}\not{\partial}_{\mu}\chi^{0}$$
$$- (\chi^0, \chi^+)\begin{pmatrix} m_{00} & m_{0+} \\ m_{+0} & m_{++}\end{pmatrix}\begin{pmatrix}\chi^0 \\ \chi^+\end{pmatrix}.$$

- Diagonalize mass matrix to obtain eigenstates

$$\begin{pmatrix}\chi^0 \\ \chi^+\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\chi_1 \\ \chi_2\end{pmatrix} \equiv U\begin{pmatrix}\chi_1 \\ \chi_2\end{pmatrix}$$

- Will take sin θ to be very small, so χ_1 is mostly comprised of neutral χ^0

Toy Model

- Take $\Delta m_{21} \approx 100$ keV, assume χ_2 decays to light dark sector that do not comprise a significant fraction of DM density
- Initial scattering is controlled by cross section of (assuming $U(1)_D$ unit charge) χ^+

$$\sigma_{\chi^+ p} = \frac{\epsilon^2 e^2 g'^2}{M_{A'}^4} \mu_{\chi p}^2$$

  - Replace $g' \to g' \sin\theta$ for χ_1 cross section
  - Replace $g' \to g' \cos\theta$ for χ_2 cross section
  - Thus, the χ_1 cross section suppressed by kinetic mixing and mixing angle, while the χ_2 cross section only suppressed by kinetic mixing

Toy Model

- Borrowing terminology from neutrino physics, the initial scattering of χ_0 projects out the χ^+ component, which propagates as mixture of χ_1 and (mostly) χ_2

$$\sigma_{\chi^+ p} = \frac{\epsilon^2 e^2 g'^2}{M_{A'}^4} \mu_{\chi p}^2$$

  – Subsequent scatterings are not suppressed by mixing angle!

Toy Model – Concrete example

- Mean free path of χ^+ in matter

$$\lambda = \frac{\mu_{\chi p}^2}{Z_{\text{eff}}^2 \sigma_{\chi^+ p} \mu_{\chi N}^2 n}$$

  – If we consider liquid Xe target, Z_{eff} = 0.5 Z_{Xe}, m_χ=100 GeV, $m_{A'}$=100 MeV, g'=0.6, ε=4 ×10^{-3} gives λ ≈ 0.1 cm
    - Corresponds to $\sigma(\chi^+ p) \approx 10^{-30}$ cm^2

  – We find we need $\sin^2\theta \approx 10^{-15}$ to have the initial scattering at traditional WIMP rates

$$\sigma_{\chi^+ p} = \frac{\epsilon^2 e^2 g'^2}{M_{A'}^4} \mu_{\chi p}^2 \qquad g' \to g' \sin\theta$$

Mixed DM Phenomenology

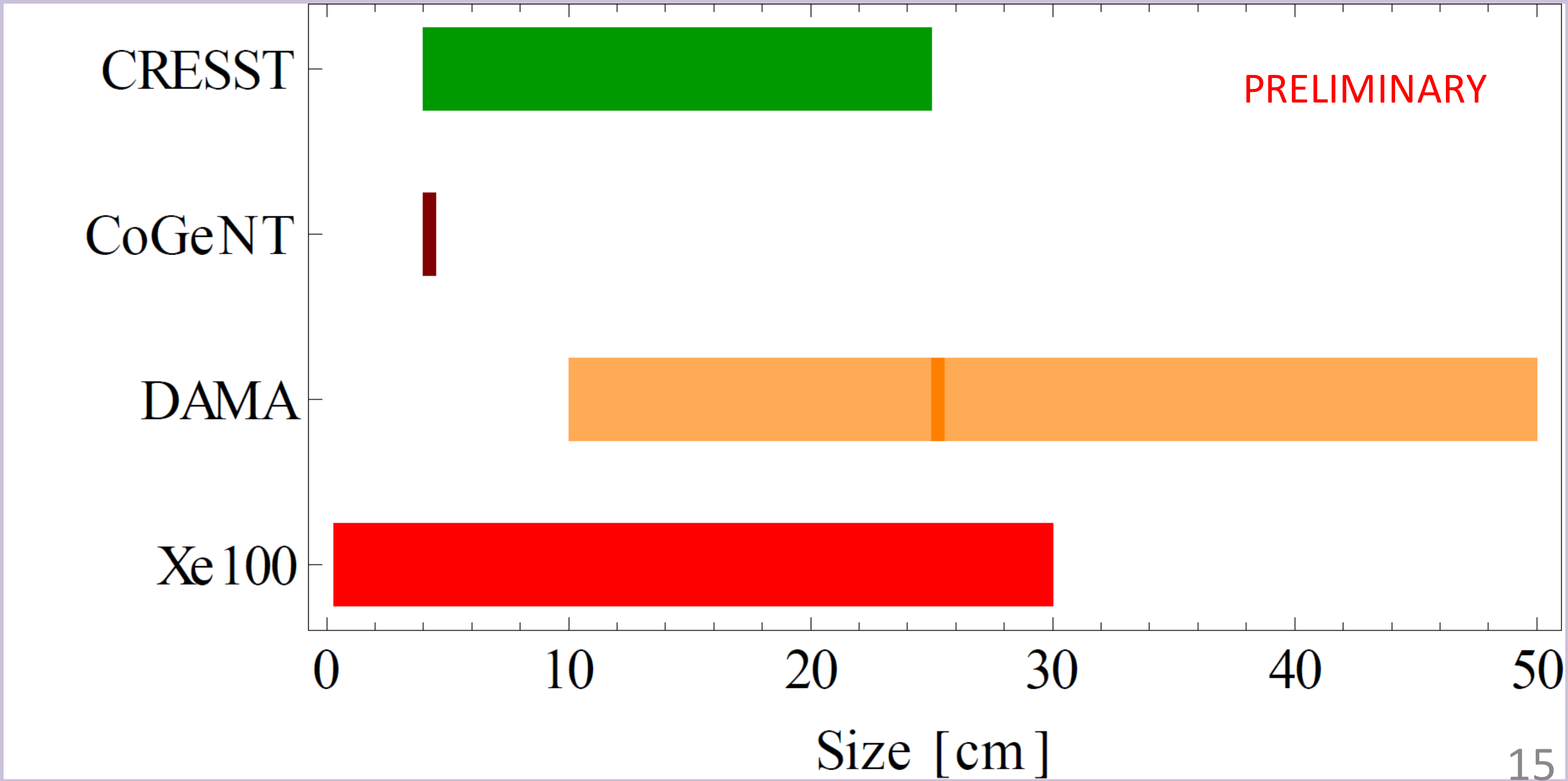
- Secondary scatterings are unsuppressed

$$\sigma_{\chi+p} = \frac{\epsilon^2 e^2 g'^2}{M_{A'}^4}\mu_{\chi p}^2 \qquad g' \to g' \cos\theta$$

  - Subsequent evolution of χ_2 is model-dependent, but one characteristic signature is a **multiple hit track** similar to neutron background
    - Track length determined by lifetime of χ_2, which is mainly constrained by BBN
    - We can choose average $N\lambda_{mfp}$ to be longer than detector fiducial volume, so χ_2 decays outside the detector
  - Detector sensitivity to this multiple hit signature will be driven by accumulated energy profile and spatial resolution
    - Detectors with good spatial resolution will reject this signature as part of the neutron background

Multiple Hit Signature

- Choose $N\lambda_{mfp}$ to right of left edge, λ_{mfp} to left of right edge
- Left edge determined by detector spatial resolution
- Right edge determined by edge of fiducial region



Summary

- Motivated by the rich possibilities of dark dynamics, we construct a DM model with a multiple hit signature, markedly different from traditional WIMP scattering
  - Constructing complete models that motivate the parameter choices used is well underway
  - Further work will investigate possibilities for retooling direct detection analyses (and perhaps neutrino detectors) to test alternatives to the WIMP paradigm

Multiple Hit Signature

	Xenon-100	DAMA	CoGeNT	CRESST
Spatial resolution	< 3 mm [10]	10 cm (x,y), 25 cm (z) [11]	—	4 cm [12]
Size of fiducial volume	30 cm [10]	50 cm (x, y), 25 cm (z) [11]	~ 4 cm	25 cm
Energy threshold (event)	8.4 keVnr [10]	2 keVee [11]	0.5 keVee [13]	10–19 keVnr [12]
Energy threshold (individual recoil)	$\simeq 3$ keVnr	0.13–0.18 keVee [11]	~ 3 eV	none