Direct Detection of Dark Matter

From Microphysics to Observational Signatures

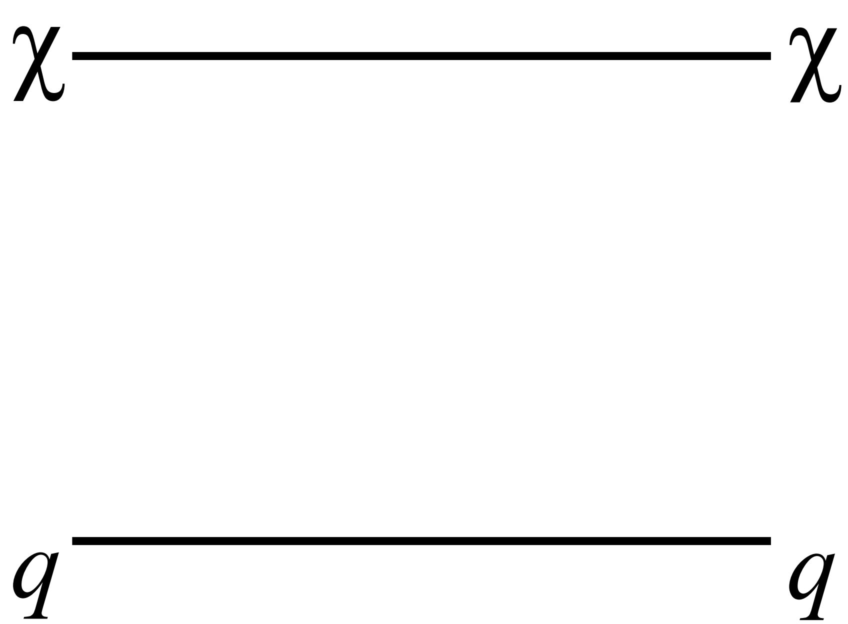
James Dent

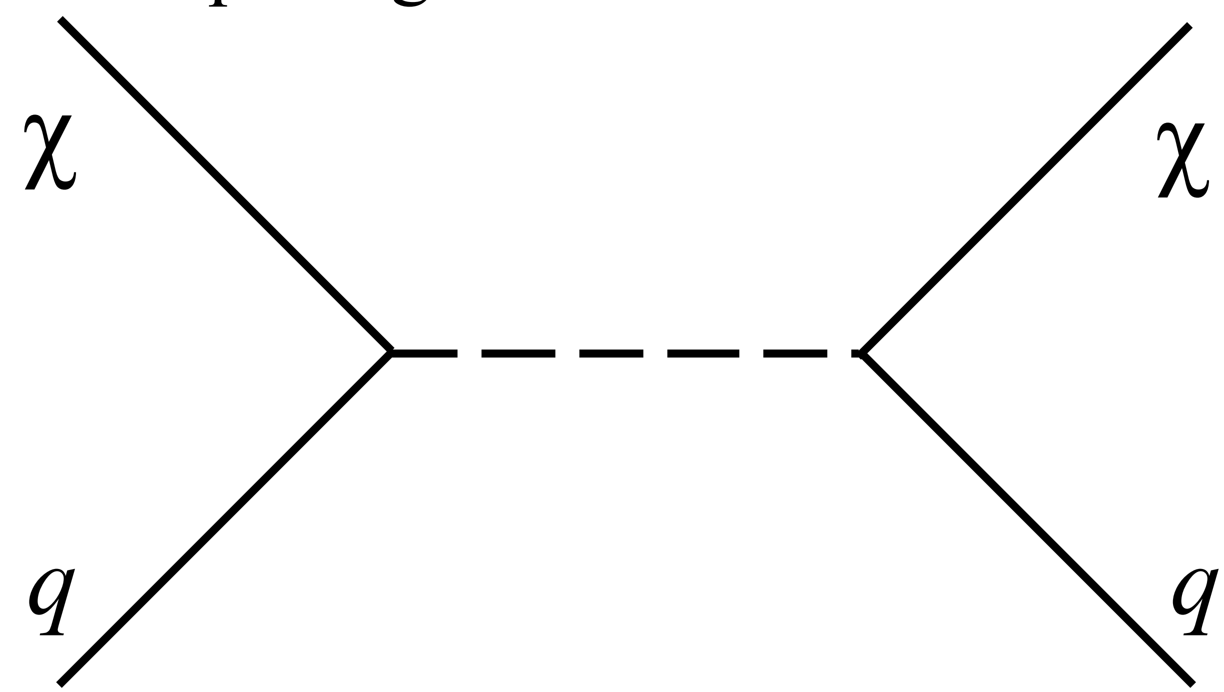
JBD, L.M. Krauss, J.L. Newstead, and S. Sabharwal, arXiv: 1505.03117

Texas A&M May 18, 2015

Direct Detection:
Standard Approach

Model WIMP-nuclear interactions as WIMP-quark/gluon interactions





Hadronic matrix elements encode nucleon interations

$$\langle N_o|\, m_q \bar{q} q \,|N_i\rangle \longrightarrow f_{Tq}^N \bar{N} N$$

$$\langle N_o|\, \bar{q}\gamma^5 q \,|N_i\rangle \longrightarrow \Delta\tilde{q}^N \bar{N}\gamma^5 N$$

$$\langle N_o|\, \bar{q}\gamma^\mu q \,|N_i\rangle \longrightarrow \mathcal{N}_q^N \bar{N}\gamma^\mu N$$

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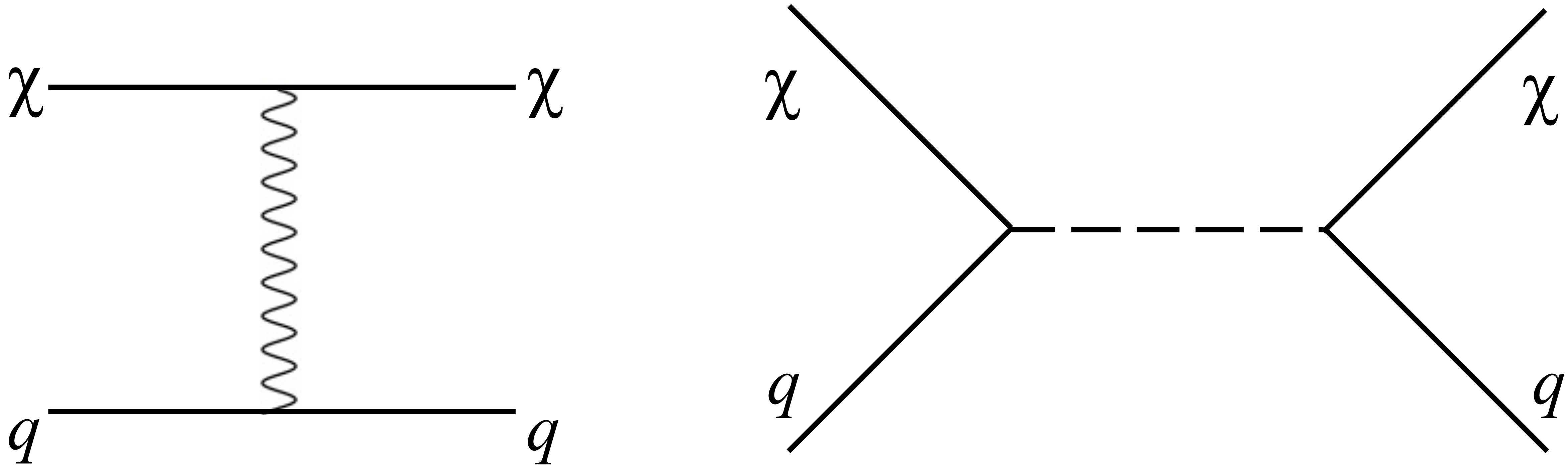

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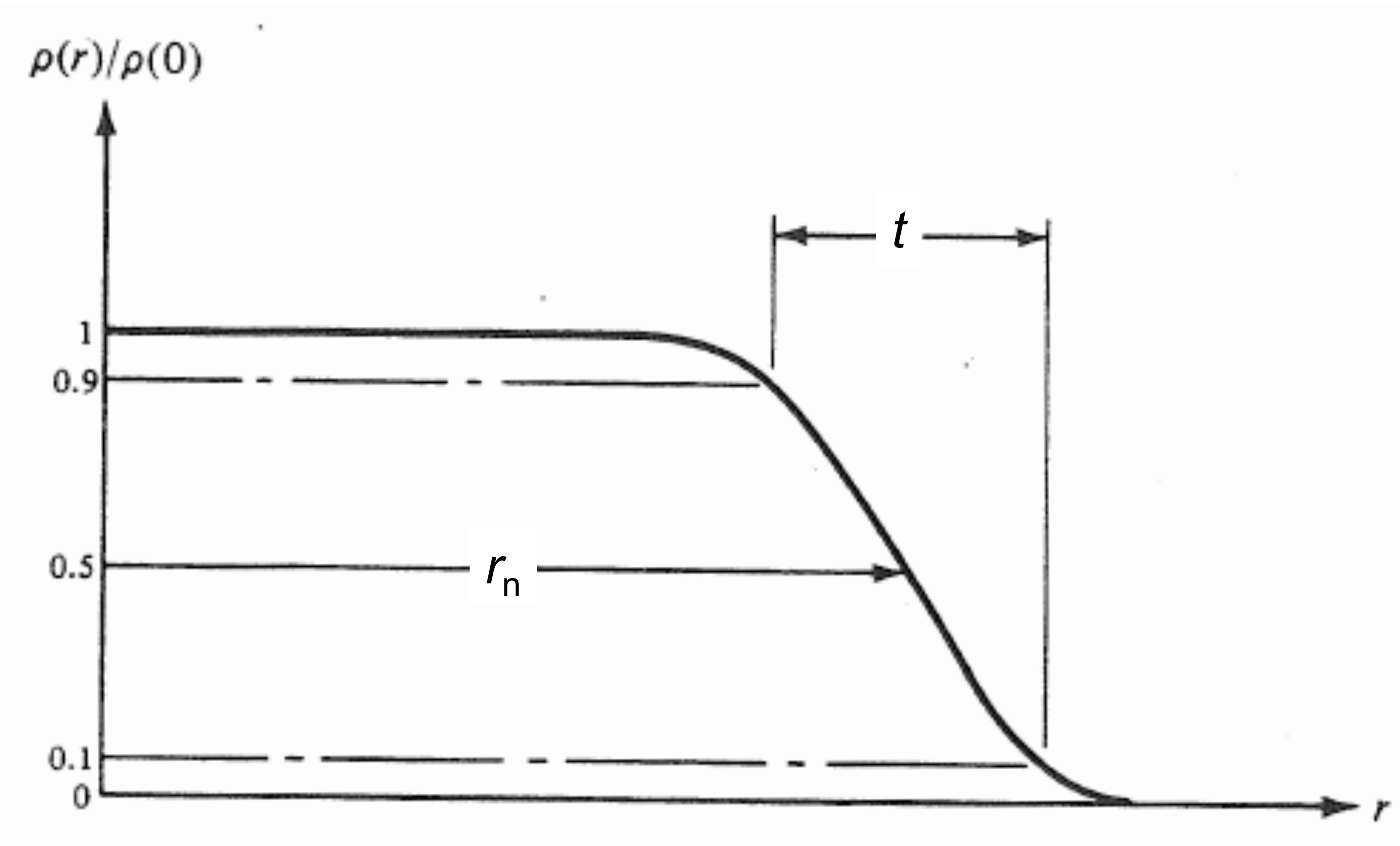
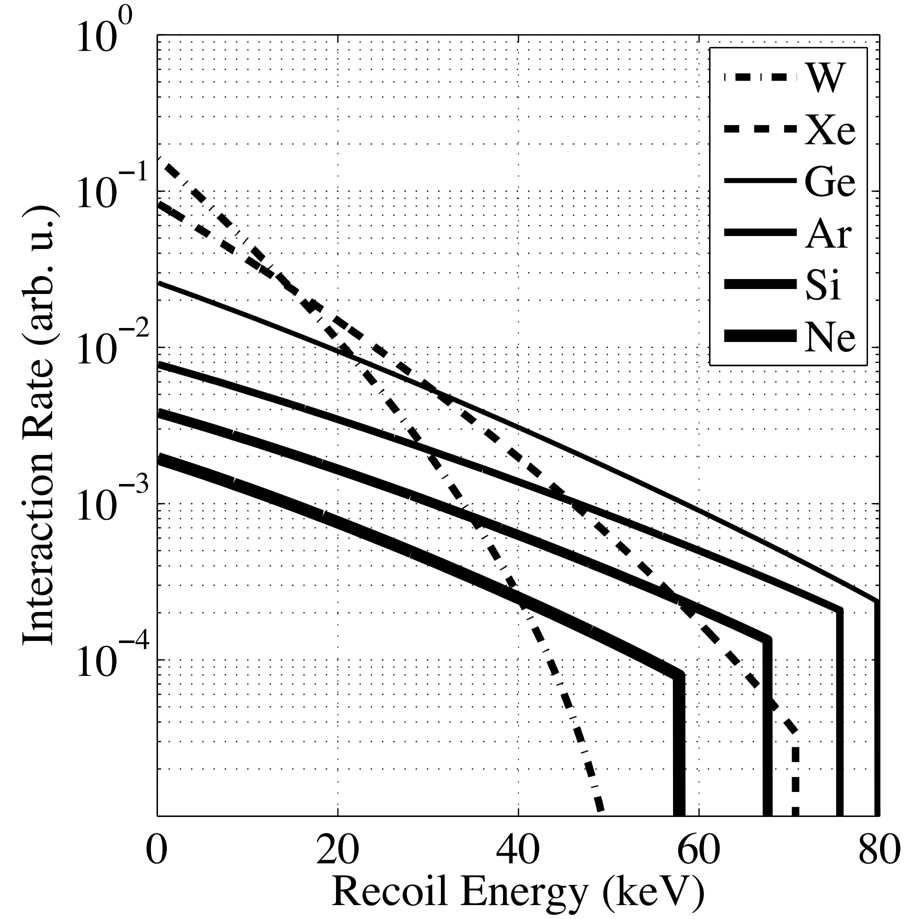
Interaction types include coupling to nuclear charge (spin-independent) or spin (spin-dependent), giving two nuclear response types

The non-zero nuclear size and momentum dependence is encoded in form factors





Target specific nuclear physics is also taken into account

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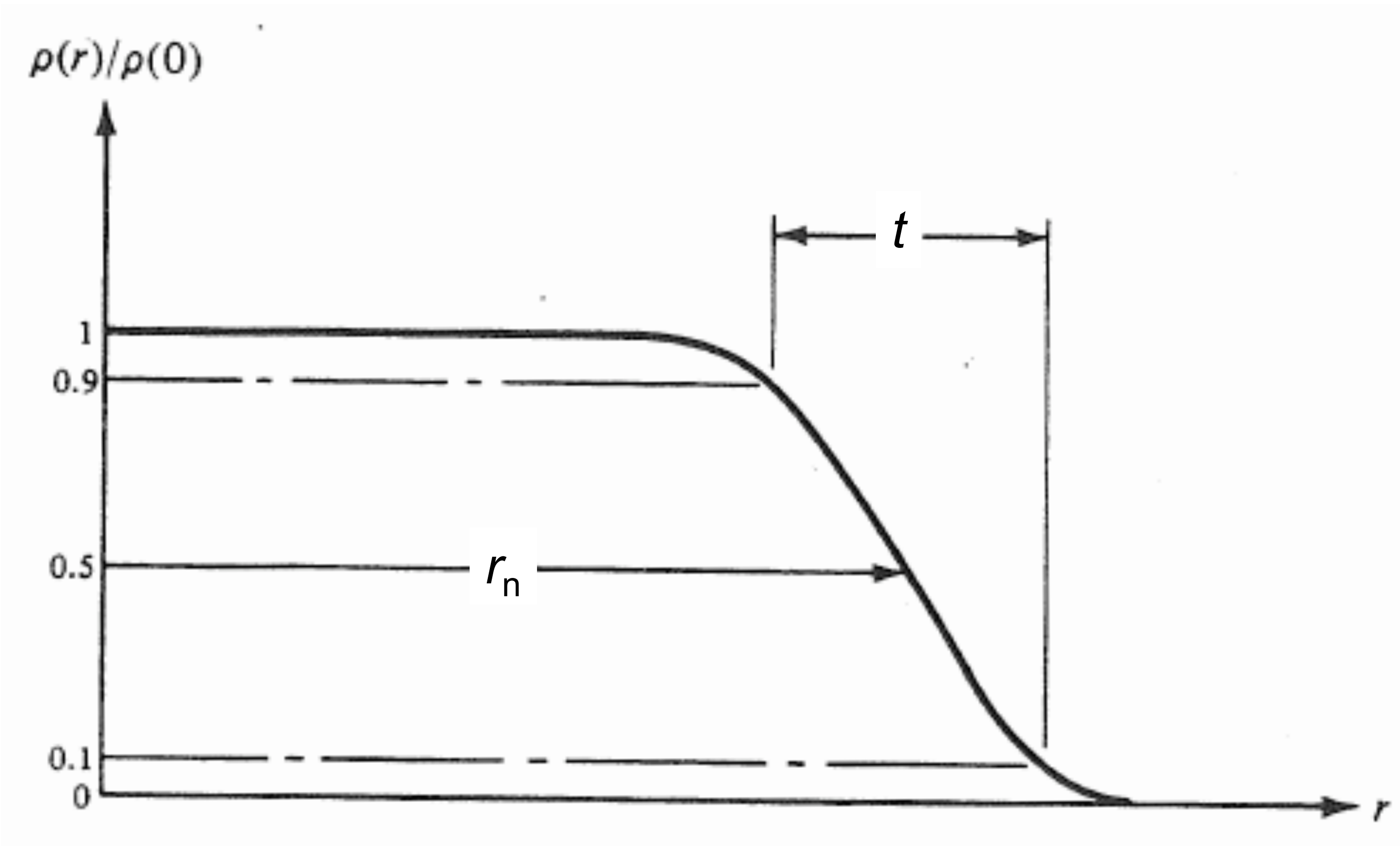

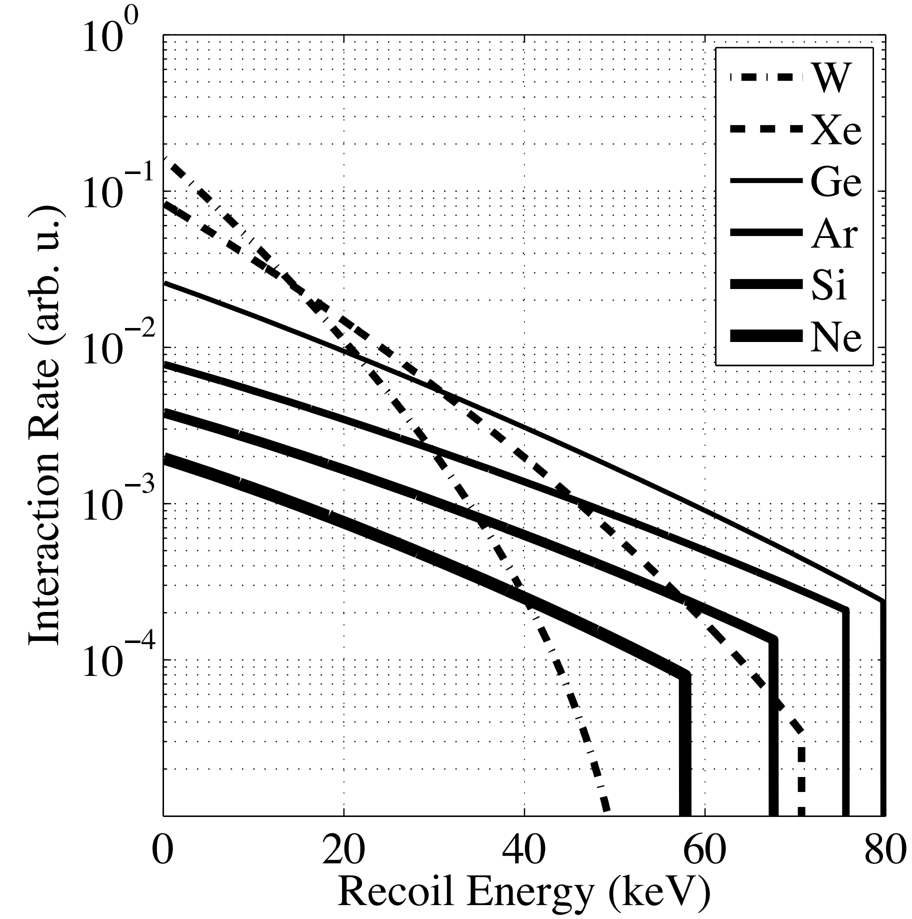

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R. Schnee, arXiv:1101.5205

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Nucleon spin expectation values

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It has been shown that the standard approach neglects a large set of possible non-relativistic operators beyond the SI/SD ones

$$1_\chi 1_N \qquad\qquad \vec{S}_\chi \cdot \vec{S}_N$$

There also exist four more nuclear responses that arise in the most general nucleus-WIMP elastic scattering

$$M,\ \Phi'',\ \Sigma',\ \Delta,\ \Sigma'',\ \tilde{\Phi}'$$

A.L. Fitzpatrick, W.C. Haxton, E. Katz, N. Lubbers, and Y. Xu, JCAP 1302 (2013) 004, arXiv:1203.3542
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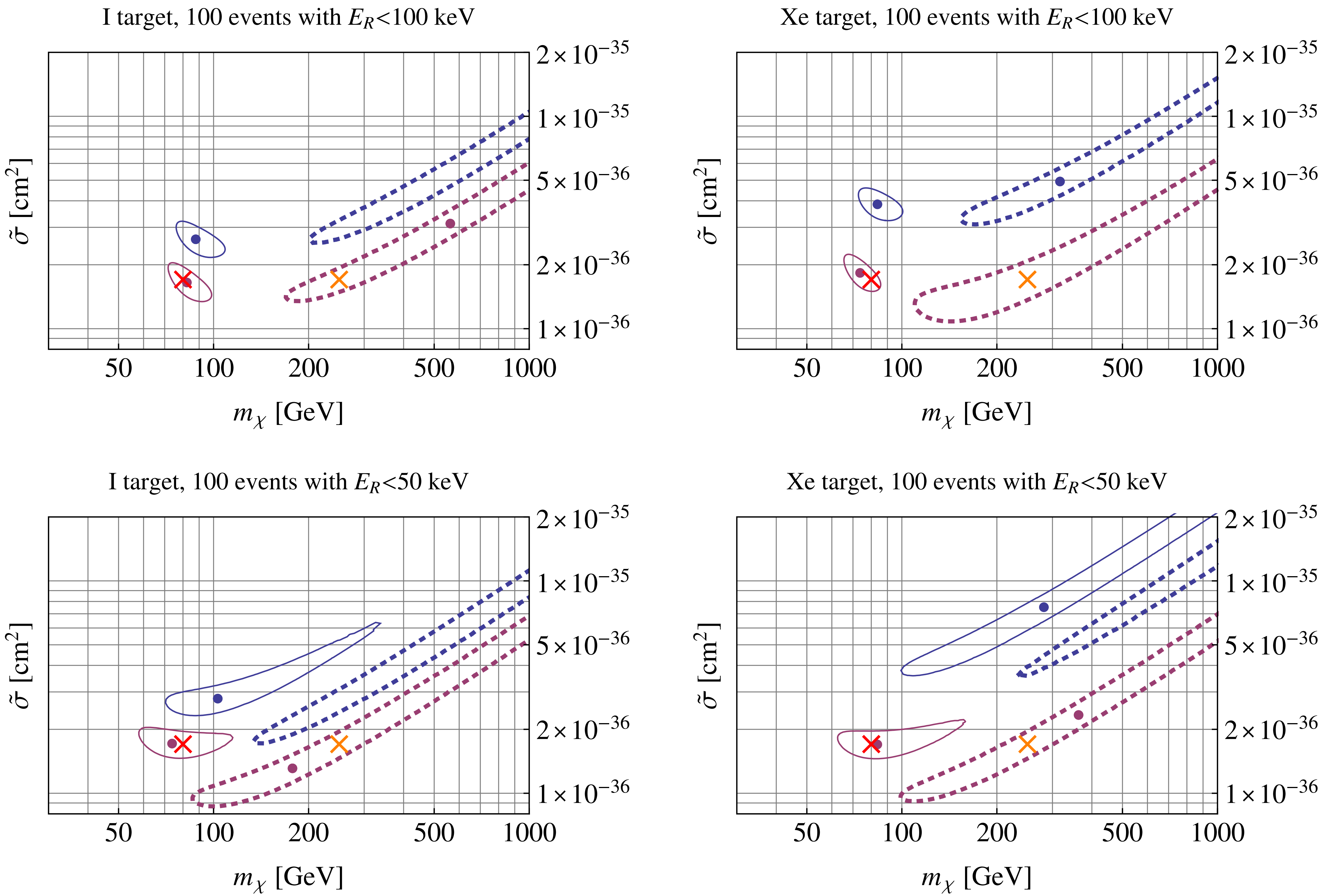
Gresham & Zurek (2014) showed that wildly incorrect interpretations are possible if only the standard SI/SD responses are used



$$\langle\phi(x_1)\cdots\phi(x_k)\rangle_J \equiv e^{-iW[J]}\int\mathcal{D}\phi[\phi(x_1)\cdots\phi(x_k)]\,e$$

$$iW[J]\} = \int\mathcal{D}\phi\,\exp\left\{i\int d^4x[\mathcal{L}[\phi]+J\phi]\right\}$$

Effective Field Theory

$$\Gamma[\varphi] \equiv W[J(\varphi)] - \int d^4x$$

Incorporating Galilean invariance, energy conservation, and Hermiticity, all non-relativistic operators will be built out of four quantities

Exchanged momentum $i\frac{\vec{q}}{m_N}, \quad \vec{v}^{\perp}, \quad \vec{S}_\chi, \quad \vec{S}_N$ Nucleon spin

DM spin

Relative velocities

$$\vec{v}^{\perp} = \frac{1}{2}\left(\vec{v}_{\chi,in} - \vec{v}_{N,in} + \vec{v}_{\chi,out} - \vec{v}_{N,out}\right) \qquad \vec{v}^{\perp} \cdot \vec{q} = 0$$

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There are fifteen combinations of these operators

$\mathcal{O}_1$	$1_\chi 1_N$	$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$	$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
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$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$	$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$	$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
		$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$

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$$c_1 1_\chi 1_N$$

Standard practice has been to start with effective interaction terms, and then reduce in the non-relativistic limit

$$\mathcal{L}_{\text{int}}^{\text{SI}}(\vec{x}) = c_1 \bar{\Psi}_\chi(\vec{x})\Psi_\chi(\vec{x})\bar{\Psi}_N(\vec{x})\Psi_N(\vec{x})$$

$$\mathcal{L}_{\text{int}}^{\text{SD}} = c_4 \bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$$

$$c_1 1_\chi 1_N$$

$$-4c_4\vec{S}_\chi \cdot \vec{S}_N$$

From the relativistic EFT there are 20 combinations of fermionic bilinears

From two scalar $\bar{\chi}\chi$ $\bar{\chi}\gamma^5\chi$ 2×2

$\bar{\chi}\gamma^\mu\chi$ $\bar{\chi}\gamma^\mu\gamma^5\chi$

and four vector terms 4×4

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———

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After performing a non-relativistic reduction, these 20 operators can be written in terms of the 15 O_i

In general one can write down the non-relativistic Lagrangian

$$\mathcal{L}_{NR} = \sum_{\alpha=n,p} \sum_{i=1}^{15} c_i^\alpha \mathcal{O}_i^\alpha$$

General isospin couplings can be incorporated

$$\mathcal{L}_{NR} = \sum_{\tau=0,1} \sum_{i=1}^{15} c_i^\tau \mathcal{O}_i t^\tau$$

The total interaction can be considered as a sum over single nucleon interactions

$$\sum_{\tau=0,1} \sum_{i=1}^{15} c_i^\tau \mathcal{O}_i t^\tau \rightarrow \sum_{\tau=0,1} \sum_{i=1}^{15} c_i^\tau \sum_{j=1}^{A} \mathcal{O}_i(j) t^\tau(j)$$

The DM-nucleon interactions can then be written

$$\sum_{\tau=0,1} \left\{ l_0^\tau S + l_0^{A\tau} T + \vec{l}_5^\tau \cdot \vec{P} + \vec{l}_M^\tau \cdot Q + \vec{l}_E^\tau \cdot \vec{R} \right\} t^\tau(i)$$

$$\sum_{\tau=0,1} \left\{ l_0^\tau S + l_0^{A\tau} T + \vec{l}_5^\tau \cdot \vec{P} + \vec{l}_M^\tau \cdot Q + \vec{l}_E^\tau \cdot \vec{R} \right\} t^\tau(i)$$

Nuclear

DM

$$S = \sum_{i=1}^{A} e^{-i\vec{q}\cdot\vec{x}_i}$$

$$T = \sum_{i=1}^{A} \frac{1}{2M} \left[-\frac{1}{i} \overleftarrow{\nabla}_i \cdot \vec{\sigma}(i) e^{-i\vec{q}\cdot\vec{x}_i} + e^{-i\vec{q}\cdot\vec{x}_i} \vec{\sigma}(i) \cdot \frac{1}{i} \overrightarrow{\nabla}_i \right]$$

$$\vec{P} = \sum_{i=1}^{A} \vec{\sigma}(i) e^{-i\vec{q}\cdot\vec{x}_i}$$

$$\vec{Q} = \sum_{i=1}^{A} \frac{1}{2M} \left[-\frac{1}{i} \overleftarrow{\nabla}_i e^{-i\vec{q}\cdot\vec{x}_i} + e^{-i\vec{q}\cdot\vec{x}_i} \frac{1}{i} \overrightarrow{\nabla}_i \right]$$

$$\vec{R} = \sum_{i=1}^{A} \frac{1}{2M} \left[\overleftarrow{\nabla}_i \times \vec{\sigma}(i) e^{-i\vec{q}\cdot\vec{x}_i} + e^{-i\vec{q}\cdot\vec{x}_i} \vec{\sigma}(i) \times \overrightarrow{\nabla}_i \right]$$

Given a non-relativistic reduction, one can identify the dark matter operator coefficients

$$\sum_{\tau=0,1} \left\{ l_0^\tau S + l_0^{A\tau} T + \vec{l}_5^\tau \cdot \vec{P} + \vec{l}_M^\tau \cdot Q + \vec{l}_E^\tau \cdot \vec{R} \right\} t^\tau(i)$$

Nuclear

DM

$$l_0^\tau = c_1^\tau + i c_5^\tau \vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_T^\perp \right) + c_8^\tau (\vec{S}_\chi \cdot \vec{v}_T^\perp) + i c_{11}^\tau \frac{\vec{q} \cdot \vec{S}_\chi}{m_N}$$

$$l_0^{A\tau} = -\frac{1}{2} \left[c_7^\tau + i c_{14}^\tau \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \right]$$

$$\vec{l}_5 = \frac{1}{2} \left[c_3^\tau i \frac{\left(\vec{q} \times \vec{v}_T^\perp \right)}{m_N} + c_4^\tau \vec{S}_\chi + c_6^\tau \frac{(\vec{q} \cdot \vec{S}_\chi)\vec{q}}{m_N^2} + c_7^\tau \vec{v}_T^\perp + i c_9^\tau \frac{(\vec{q} \times \vec{S}_\chi)}{m_N} + i c_{10}^\tau \frac{\vec{q}}{m_N} \right)$$

$$c_{12}^\tau (\vec{v}_T^\perp \times \vec{S}_\chi) + i c_{13}^\tau \frac{(S_\chi \cdot \vec{v}_T^\perp)\vec{q}}{m_N} + i c_{14}^\tau \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \vec{v}_T^\perp + c_{15}^\tau \frac{(\vec{q} \cdot \vec{S}_\chi)(\vec{q} \times \vec{v}_T^\perp)}{m_N^2} \Bigg]$$

$$\vec{l}_M = c_5^\tau \left(i \frac{\vec{q}}{m_N} \times \vec{S}_\chi \right) - \vec{S}_\chi c_8^\tau$$

$$\vec{l}_E = \frac{1}{2} \left[c_3^\tau \frac{\vec{q}}{m_N} + i c_{12}^\tau \vec{S}_\chi - c_{13}^\tau \frac{(\vec{q} \times \vec{S}_\chi)}{m_N} - i c_{15}^\tau \frac{(\vec{q} \cdot \vec{S}_\chi)\vec{q}}{m_N^2} \right]$$

These coefficients apply to the dark matter in and out states

The dark matter-nucleus amplitude can be written as

$$\mathcal{M} = \sum_{\tau=0,1} \langle j_\chi, M_\chi; j_N, M_N| \left\{ l_0^\tau S + l_0^{A\tau} T + \vec{l}_5^\tau \cdot \vec{P} + \vec{l}_M^\tau \cdot Q + \vec{l}_E^\tau \cdot \vec{R} \right\} t^\tau(i) |j_\chi, M_\chi; j_N, M_N\rangle$$

which can further be reduced to the standard nuclear electroweak responses

$$\mathcal{M} = \sum_{\tau=0,1} \langle j_\chi, M_{\chi f}; j_N, M_{Nf}| \Bigg(\sum_{J=0} \sqrt{4\pi(2J+1)}(-i)^J \left[l_0^\tau M_{J0;\tau} - i l_0^{A\tau} \frac{q}{m_N} \tilde{\Omega}_{J0;\tau}(q) \right]$$
$$+ \sum_{J=1} \sqrt{2\pi(2J+1)}(-i)^J \sum_{\lambda \pm 1} (-1)^\lambda \Big\{ l_{5\lambda}^\tau [\lambda \Sigma_{J-\lambda;\tau}(q) + i \Sigma'_{J-\lambda;\tau}(q)]$$
$$- i \frac{q}{m_N} l_{M\lambda}^\tau [\lambda \Delta_{J-\lambda;\tau}(q)] - i \frac{q}{m_N} l_{E\lambda}^\tau [\lambda \tilde{\Phi}_{J-\lambda;\tau}(q) + i \tilde{\Phi}'_{J-\lambda;\tau}(q)] \Big\}$$
$$+ \sum_{J=0}^{\infty} \sqrt{4\pi(2J+1)}(-i)^J \left[i l_{50}^\tau \Sigma''_{J0;\tau}(q) + \frac{q}{m_N} l_{M0}^\tau \tilde{\Delta}''_{J0;\tau}(q) + \frac{q}{m_N} l_{E0}^\tau \tilde{\Phi}''_{J0;\tau}(q) \right] \Bigg) |j_\chi, M_{\chi i}; j_N, M_{Ni}\rangle$$

Assuming P and CP are good symmetries of the nuclear ground state leaves one with 6 responses

$$M, \Phi'', \Sigma', \Delta, \Sigma'', \tilde{\Phi}'$$

$$M_{JM}(q\vec{x}) \equiv j_J(qx)Y_{JM}(\Omega_x)$$

$$\vec{M}_{JL}^{M} \equiv j_J(qx)\vec{Y}_{JLM}(\Omega_x)$$

$$\Delta_{JM} \equiv \vec{M}_{JJ}^{M}(qx_i) \cdot \frac{1}{q}\vec{\nabla}_i$$

$$\Sigma'_{JM} \equiv -i\left\{\frac{1}{q}\vec{\nabla}_i \times \vec{M}_{JJ}^{M}(q\vec{x}_i)\right\} \cdot \vec{\sigma}(i)$$

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\end{aligned}$$

To calculate cross-sections, one needs to square the amplitude, average over initial spins and sum over final states.

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P. Agrawal, Z. Chacko, C. Kilic, and R.K. Mishra, arXiv:1003.1912

N. Anand, A.L. Fitzpatrick, and W.C. Haxton, Phys.Rev. C89, 065501 (2014)

JBD, L.M. Krauss, J.L. Newstead, and S. Sabharwal, arXiv: 1505.03117

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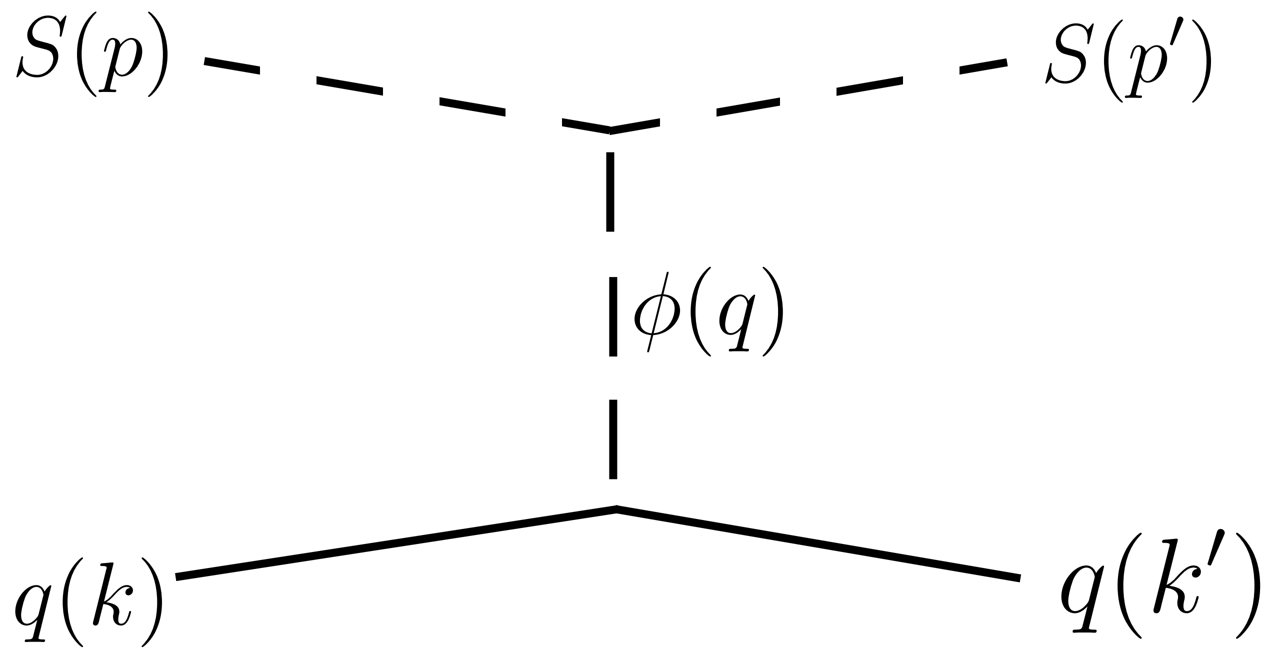
For our cases of interest we integrate out the mediator, which amounts to assuming the mediator mass is much larger than the recoil momentum of the interaction

$$m_\phi^2 \gg q^2 = (p' - p)^2$$



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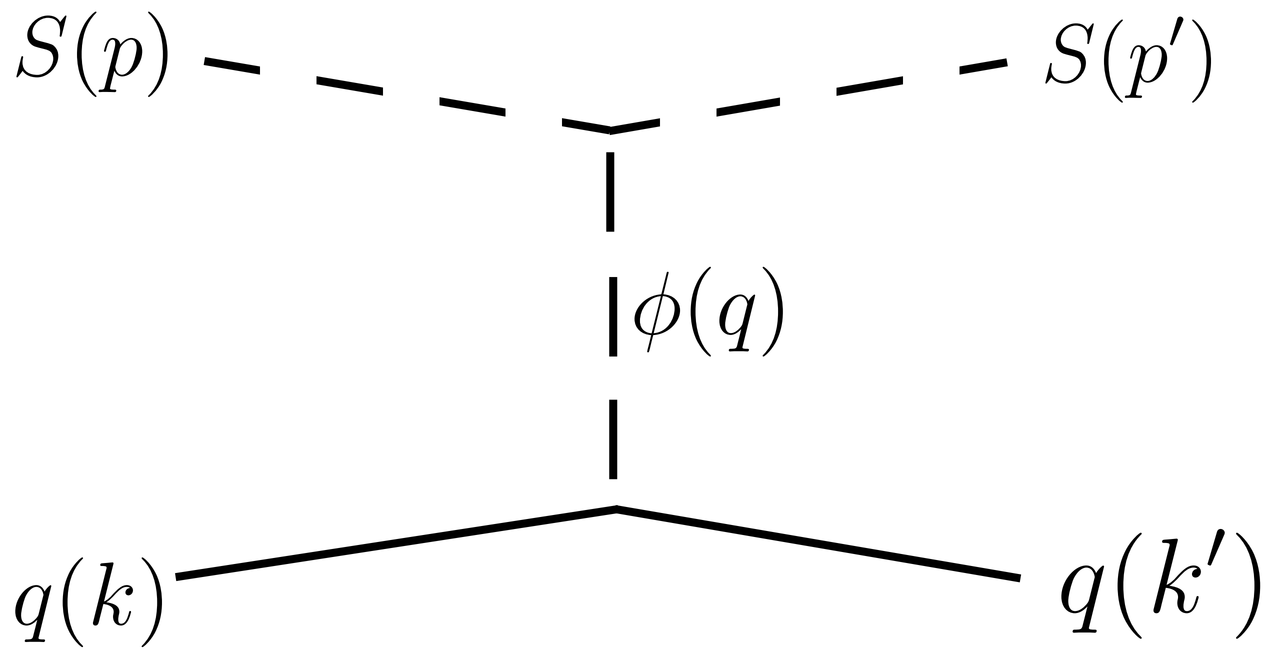

$$\begin{aligned}\mathcal{L}_{S\phi q} = &\ \partial_\mu S^\dagger \partial^\mu S - m_S^2 S^\dagger S - \frac{\lambda_S}{2}(S^\dagger S)^2 \\ &+ \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{m_\phi \mu_1}{3}\phi^3 - \frac{\mu_2}{4}\phi^4 \\ &+ i\bar{q}\not{D} q - m_q \bar{q} q \\ &- g_1 S^\dagger S \phi - \frac{g_2}{2} S^\dagger S \phi^2 - h_1 \bar{q} q \phi - i h_2 \bar{q}\gamma^5 q \phi\end{aligned}$$

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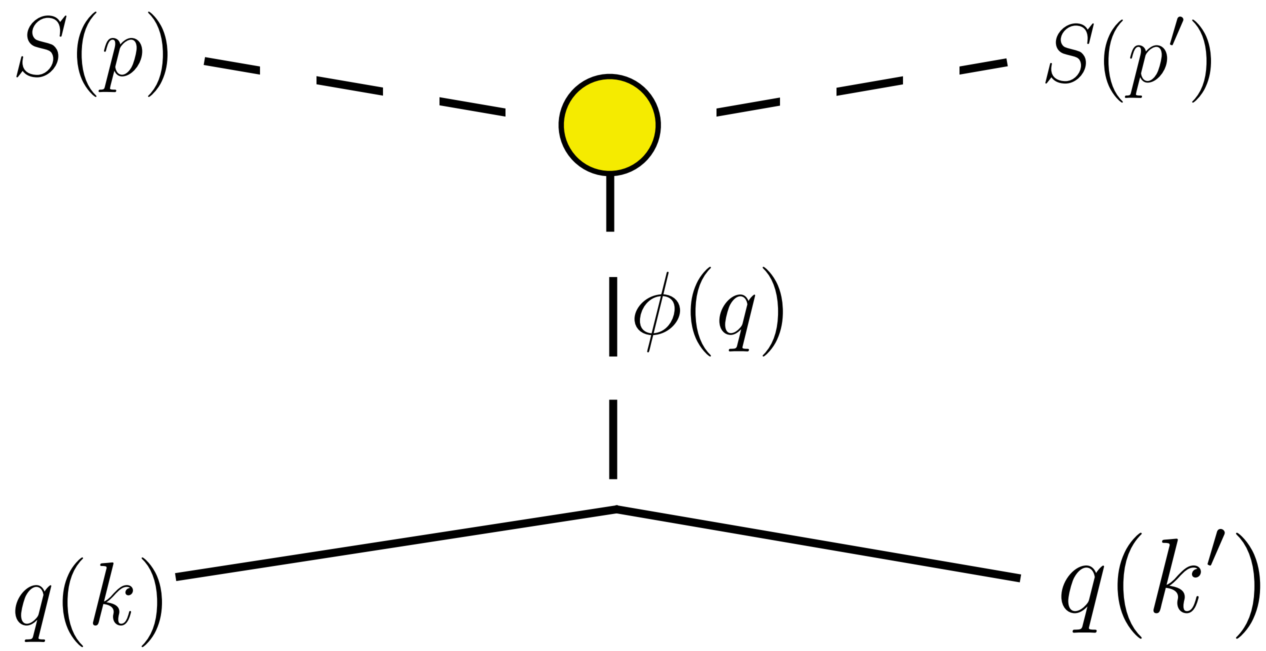

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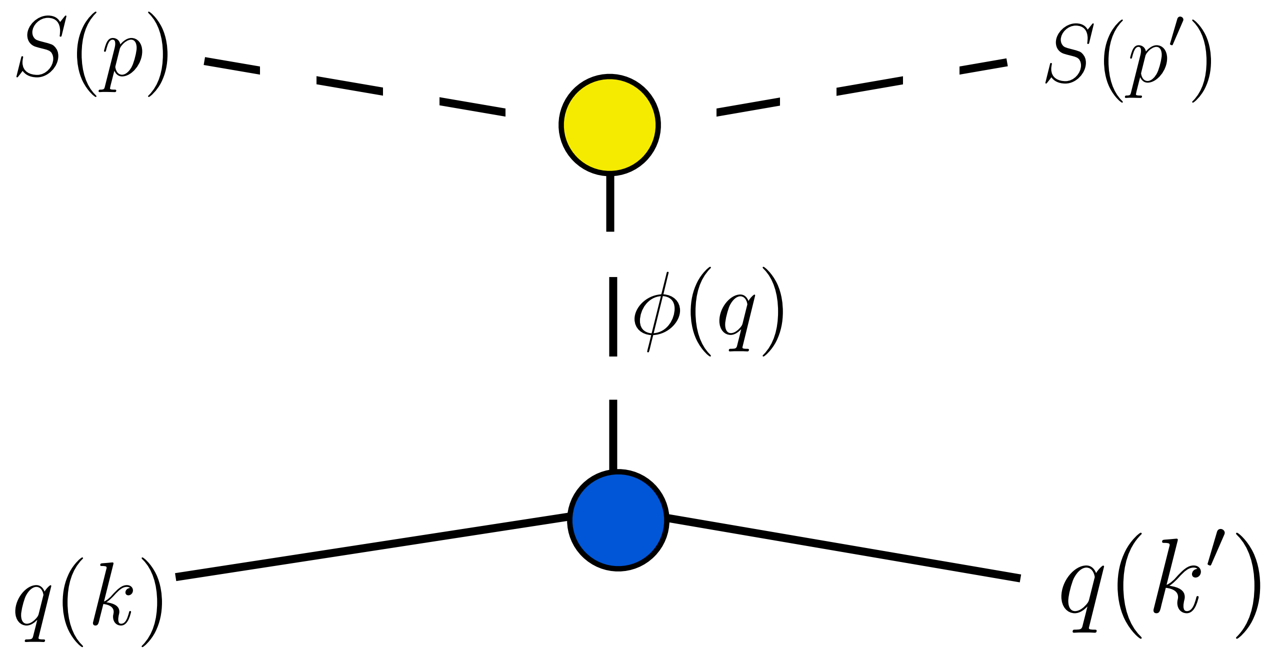

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For our cases of interest we integrate out the mediator, which amounts to assuming the mediator mass is much larger than the recoil momentum of the interaction

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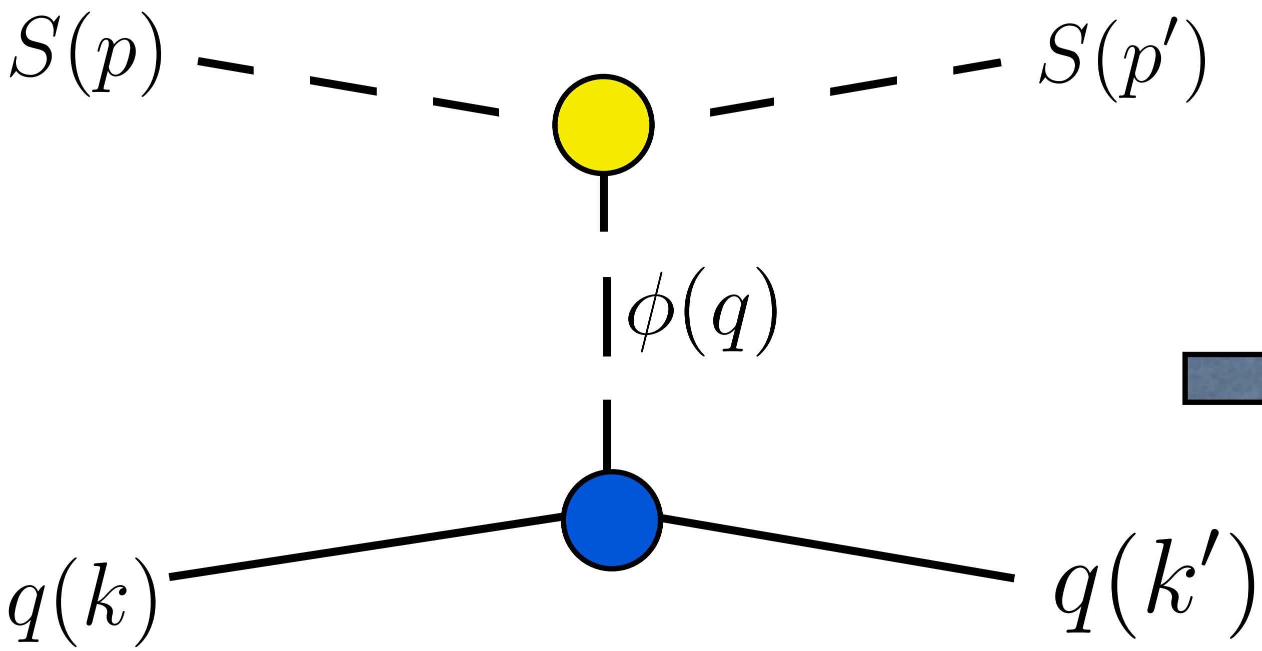

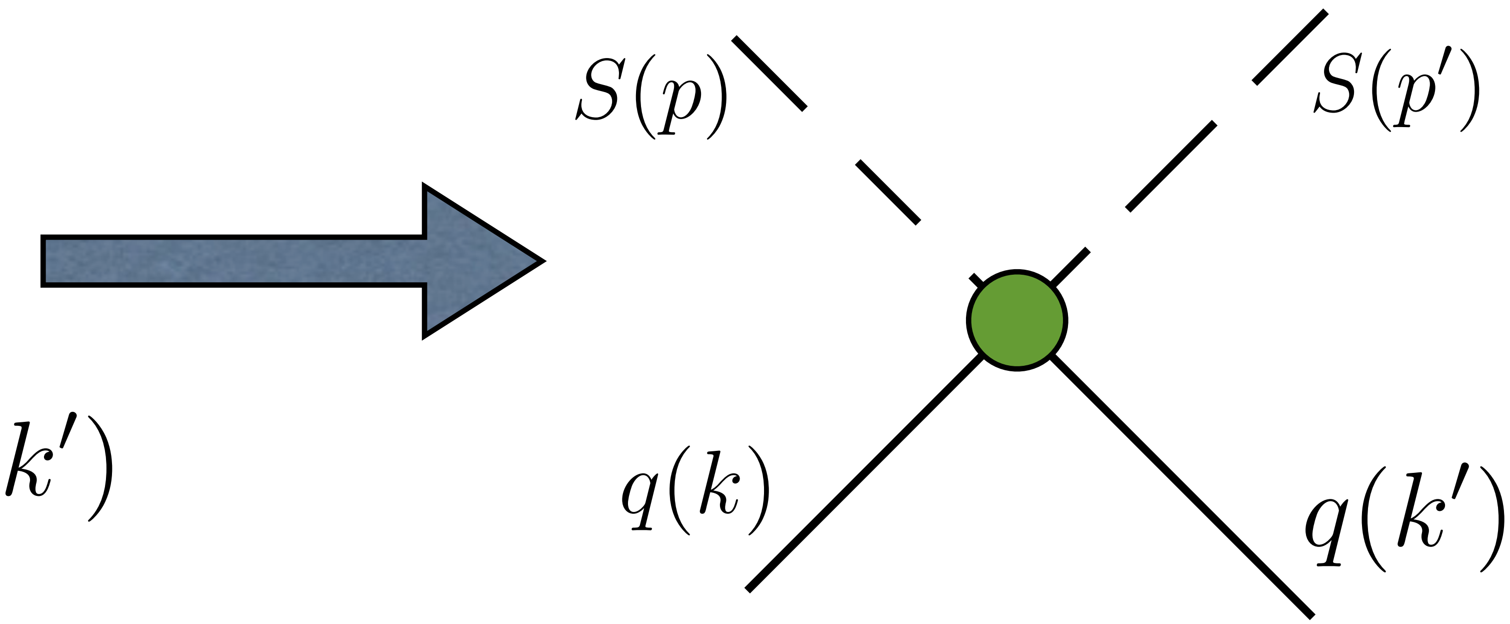

$$\begin{aligned}
\mathcal{L}_{S\phi q} = {} & \partial_\mu S^\dagger \partial^\mu S - m_S^2 S^\dagger S - \frac{\lambda_S}{2}(S^\dagger S)^2 \\
& + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{m_\phi \mu_1}{3}\phi^3 - \frac{\mu_2}{4}\phi^4 \\
& + i\bar{q}\not{D}q - m_q \bar{q}q \\
& - g_1 S^\dagger S \phi - \frac{g_2}{2} S^\dagger S \phi^2 - h_1 \bar{q}q\phi - i h_2 \bar{q}\gamma^5 q \phi
\end{aligned}$$

$$\mathcal{L}_{eff} \supset \frac{h_1 g_1}{m_\phi^2} S^\dagger S \bar{q} q$$

We have analyzed the cases:

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Dark Matter

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S	χ	X^μ
spin-0	**spin-1/2**	**spin-1**

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Uncharged mediators

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Uncharged mediators

ϕ	G^μ	ϕ	G^μ	ϕ	G^μ
spin-0	**spin-1**	**spin-0**	**spin-1**	**spin-0**	**spin-1**

We have analyzed the cases:

Dark Matter

S — spin-0

χ — spin-1/2

X^μ — spin-1

Uncharged mediators

ϕ — spin-0 | G^μ — spin-1

ϕ — spin-0 | G^μ — spin-1

ϕ — spin-0 | G^μ — spin-1

Charged mediators

We have analyzed the cases:

Dark Matter

S	χ	X^μ
spin-0	spin-1/2	spin-1

Uncharged mediators

ϕ	G^μ	ϕ	G^μ	ϕ	G^μ
spin-0	spin-1	spin-0	spin-1	spin-0	spin-1

Charged mediators

Q	Φ	V^μ	Q
spin-1/2	spin-0	spin-1	spin-1/2

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- Two additional non-relativistic operators must be included in the vector dark matter case

$$\mathcal{O}_{17} \equiv \frac{i\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp$$

$$\mathcal{O}_{18} \equiv \frac{i\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N$$

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J. Fan, M. Reece, and L-T. Wang, JCAP 1011 (2010) 042, arXiv:1008.1591

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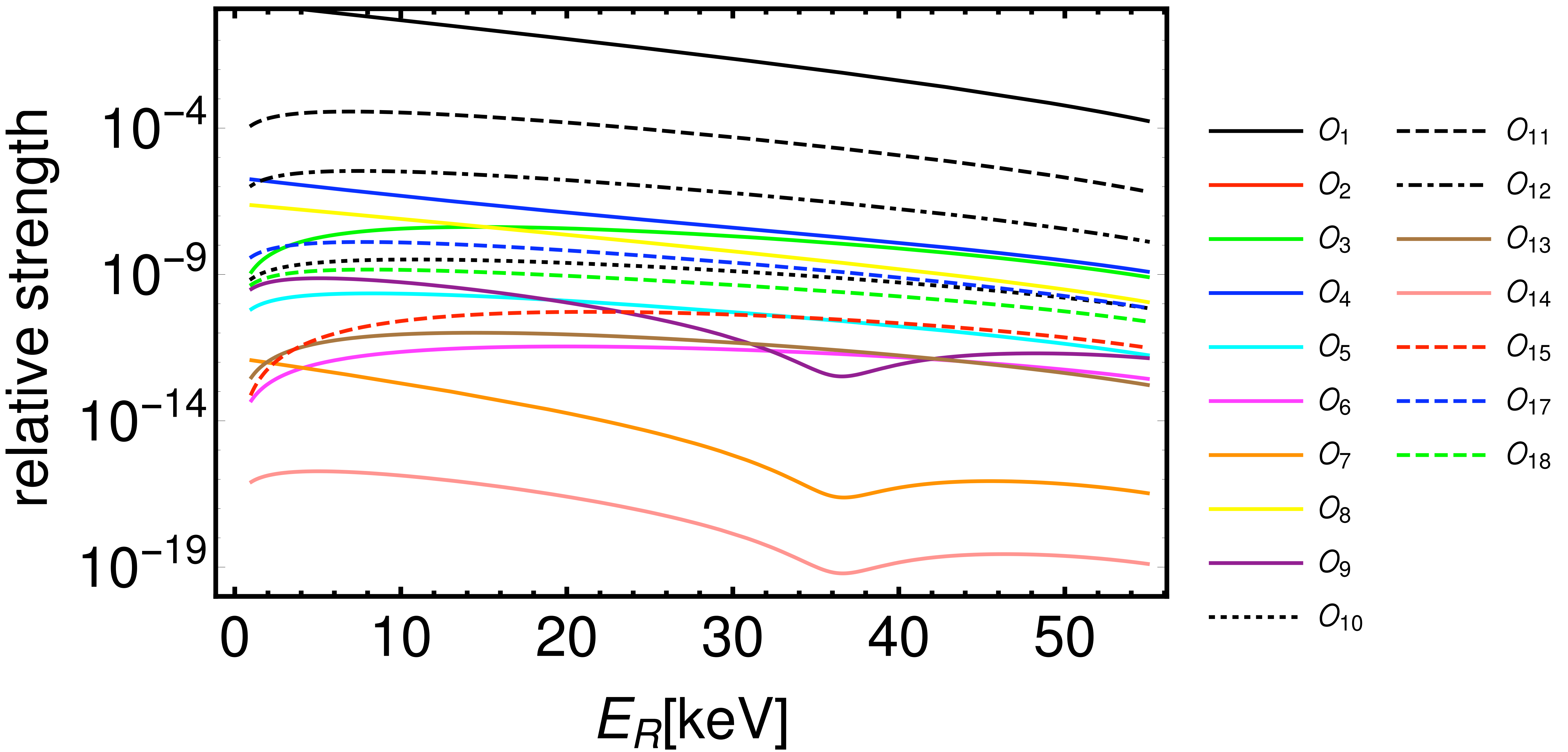
- Some EFT O_i terms do not appear
- We calculated the leading order operator for each distinct interaction in a minimal fashion: only a single set of two couplings is non-zero
- Non-standard interactions were found to dominate for certain interaction types



Relative strength of operators, in order to compare which operators dominate when more than one are present

- Aside from scalar WIMPs each particular spin produces some non-relativistic operators that are unique to that spin

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- In five scenarios relativistic operators generate unique non-relativistic operators at leading order.

- The operators can produce radically different energy dependence for scattering off different nuclear targets. Thus, a complementary use of different target materials will be helpful in order to reliably distinguish between different particle physics model possibilities for WIMP dark matter.

Spin-0 WIMP		$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
	(h_1, g_1)	✓																	
	(h_2, g_1)											✓							
	(h_4, g_4)											✓							
	(y_1)	✓										✓							
	(y_2)	✓										✓							
	(y_1, y_2)											✓							

WIMP spin	Mediator spin	$\mathcal{L}$ terms	leading NR operator	Eqv. M_m
0	0	h_1, g_1	$\mathcal{O}_1$	13 TeV
0	0	h_2, g_1	$\mathcal{O}_{10}$	14 GeV
0	1	h_4, g_4	$\mathcal{O}_{10}$	8 GeV
0	$\frac{1}{2}^*$	y_1	$\mathcal{O}_1$	3.2 PeV
0	$\frac{1}{2}^*$	y_2	$\mathcal{O}_1$	3.2 PeV
0	$\frac{1}{2}^*$	y_1, y_2	$\mathcal{O}_{10}$	41 GeV

S

spin-0

Spin-0 WIMP		$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
	(h_1, g_1)	✓																	
	(h_2, g_1)											✓							
	(h_4, g_4)											✓							
	(y_1)	✓										✓							
	(y_2)	✓										✓							
	(y_1, y_2)											✓							

S

spin-0

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0	$\frac{1}{2}^*$	y_1	$\mathcal{O}_1$	3.2 PeV
0	$\frac{1}{2}^*$	y_2	$\mathcal{O}_1$	3.2 PeV
0	$\frac{1}{2}^*$	y_1, y_2	$\mathcal{O}_{10}$	41 GeV

$\mathcal{O}_1$ $1_\chi 1_N$

$\mathcal{O}_{10}$ $i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$

S

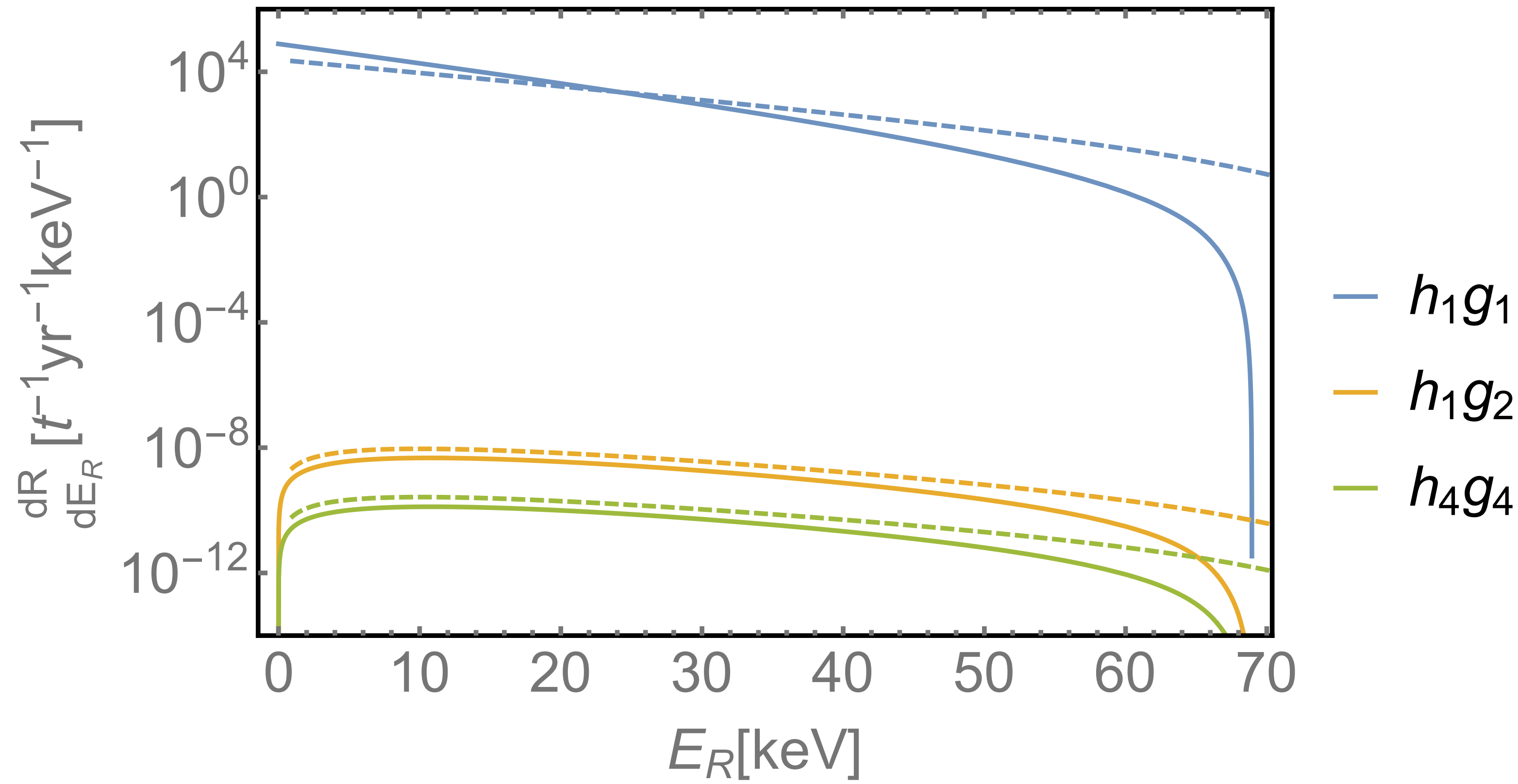
spin-0

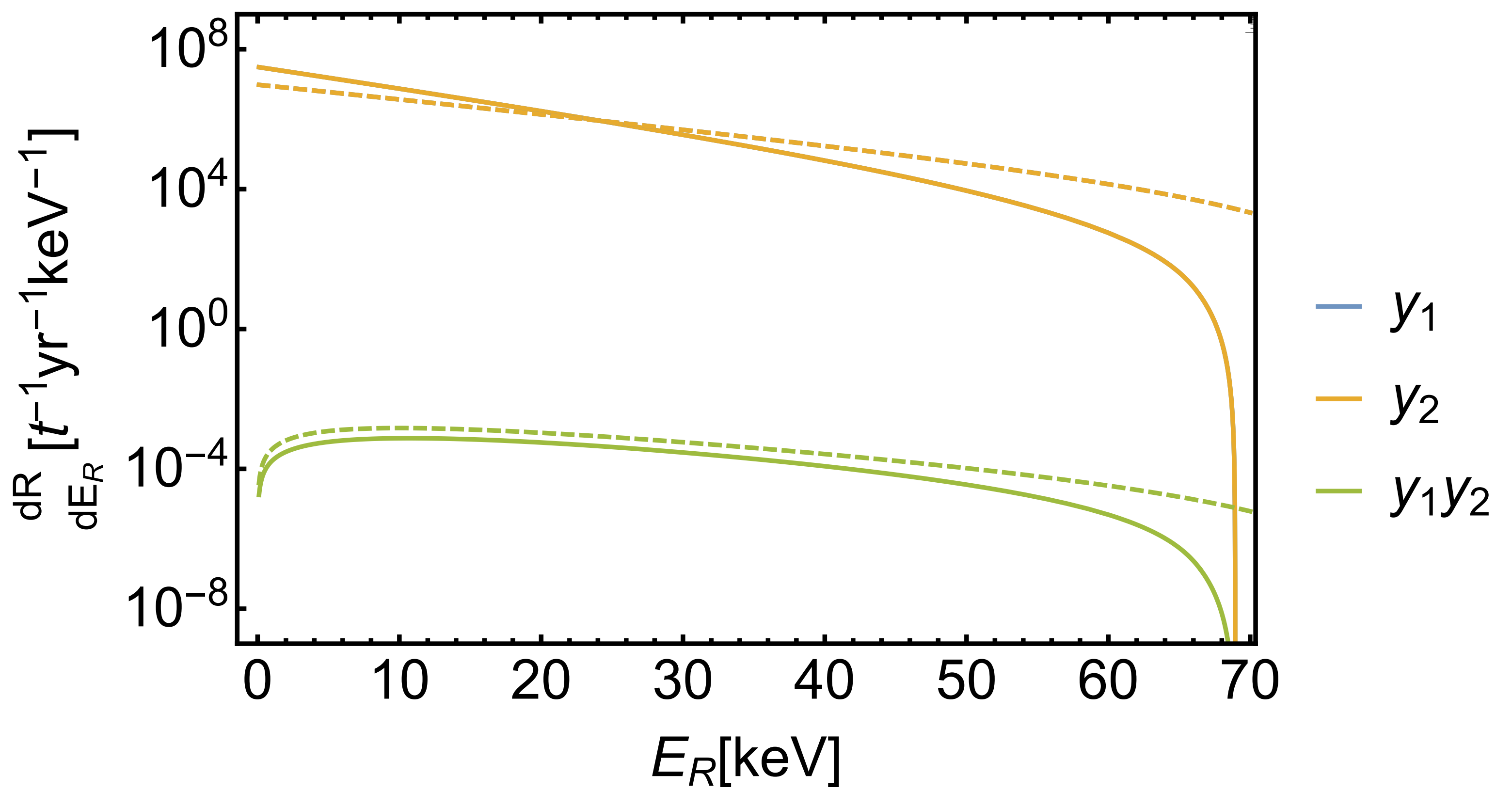
$$(S^\dagger S)(\bar{q}\gamma^5 q)$$

$$(S^\dagger S)(\bar{q}q) \qquad i(S^\dagger \partial_\mu S - \partial_\mu S^\dagger S)(\bar{q}\gamma^\mu\gamma^5 q)$$

$\mathcal{O}_1$ $1_\chi 1_N$

$\mathcal{O}_{10}$ $i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$





50 GeV spin-0 WIMP off of ^{73}Ge (dashed) and ^{131}Xe (solid) with 1TeV mediator

χ

spin-1/2

Spin-$\frac{1}{2}$ WIMP	$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
(h_1, λ_1)	✓																	
(h_2, λ_1)											✓							
(h_1, λ_2)												✓						
(h_2, λ_2)							✓											
(h_3, λ_3)	✓																	
(h_4, λ_3)								✓		✓								
(h_3, λ_4)									✓	✓								
(h_4, λ_4)				✓														
(l_1)	✓			✓			✓											
(l_2)	✓			✓			✓											
(d_1)	✓			✓			✓											
(d_2)	✓			✓			✓											

WIMP spin	Mediator spin	$\mathcal{L}$ terms	leading NR operator	Eqv. M_m
$\frac{1}{2}$	0	h_1, λ_1	$\mathcal{O}_1$	12.7 TeV
$\frac{1}{2}$	0	h_2, λ_1	$\mathcal{O}_{10}$	293 GeV
$\frac{1}{2}$	0	h_1, λ_2	$\mathcal{O}_{11}$	14 GeV
$\frac{1}{2}$	0	h_2, λ_2	$\mathcal{O}_6$	1.9 GeV
$\frac{1}{2}$	1	h_3, λ_3	$\mathcal{O}_1$	6.3 TeV
$\frac{1}{2}$	1	h_4, λ_3	$\mathcal{O}_9$	6.4 GeV
$\frac{1}{2}$	1	h_3, λ_4	$\mathcal{O}_8$	180 GeV
$\frac{1}{2}$	1	h_4, λ_4	$\mathcal{O}_4$	135 GeV
$\frac{1}{2}$	0*	l_1	$\mathcal{O}_1$	7.1 TeV
$\frac{1}{2}$	0*	l_2	$\mathcal{O}_1$	5.5 TeV
$\frac{1}{2}$	1*	d_1	$\mathcal{O}_1$	5.9 TeV
$\frac{1}{2}$	1*	d_2	$\mathcal{O}_1$	6.7 TeV

Spin-$\frac{1}{2}$ WIMP		$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
	(h_1, λ_1)	✓																	
	(h_2, λ_1)											✓							
	(h_1, λ_2)												✓						
	(h_2, λ_2)							✓											
	(h_3, λ_3)	✓																	
	(h_4, λ_3)								✓		✓								
	(h_3, λ_4)									✓	✓								
	(h_4, λ_4)				✓														
	(l_1)	✓			✓			✓											
	(l_2)	✓			✓			✓											
	(d_1)	✓			✓			✓											
	(d_2)	✓			✓			✓											

WIMP spin	Mediator spin	$\mathcal{L}$ terms	leading NR operator	Eqv. M_m
$\frac{1}{2}$	0	h_1, λ_1	$\mathcal{O}_1$	12.7 TeV
$\frac{1}{2}$	0	h_2, λ_1	$\mathcal{O}_{10}$	293 GeV
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$\frac{1}{2}$	0	h_2, λ_2	$\mathcal{O}_6$	1.9 GeV
$\frac{1}{2}$	1	h_3, λ_3	$\mathcal{O}_1$	6.3 TeV
$\frac{1}{2}$	1	h_4, λ_3	$\mathcal{O}_9$	6.4 GeV
$\frac{1}{2}$	1	h_3, λ_4	$\mathcal{O}_8$	180 GeV
$\frac{1}{2}$	1	h_4, λ_4	$\mathcal{O}_4$	135 GeV
$\frac{1}{2}$	0*	l_1	$\mathcal{O}_1$	7.1 TeV
$\frac{1}{2}$	0*	l_2	$\mathcal{O}_1$	5.5 TeV
$\frac{1}{2}$	1*	d_1	$\mathcal{O}_1$	5.9 TeV
$\frac{1}{2}$	1*	d_2	$\mathcal{O}_1$	6.7 TeV

χ

spin-1/2

$\mathcal{O}_4$ $\quad \vec{S}_\chi \cdot \vec{S}_N$

$\mathcal{O}_6$ $\quad (\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$

$\mathcal{O}_8$ $\quad \vec{S}_\chi \cdot \vec{v}^\perp$

$\mathcal{O}_9$ $\quad i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$

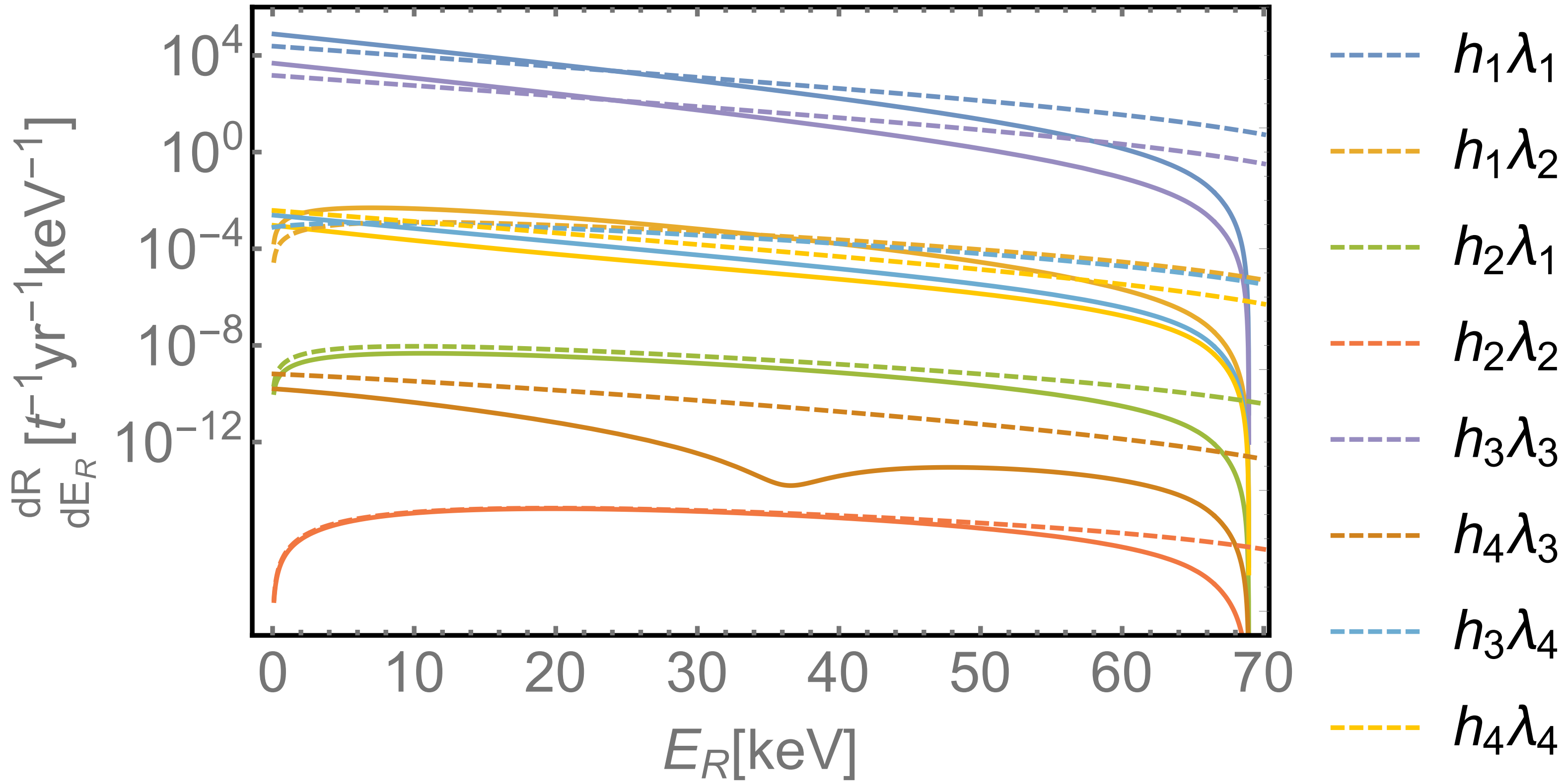
$\mathcal{O}_{11}$ $\quad i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$

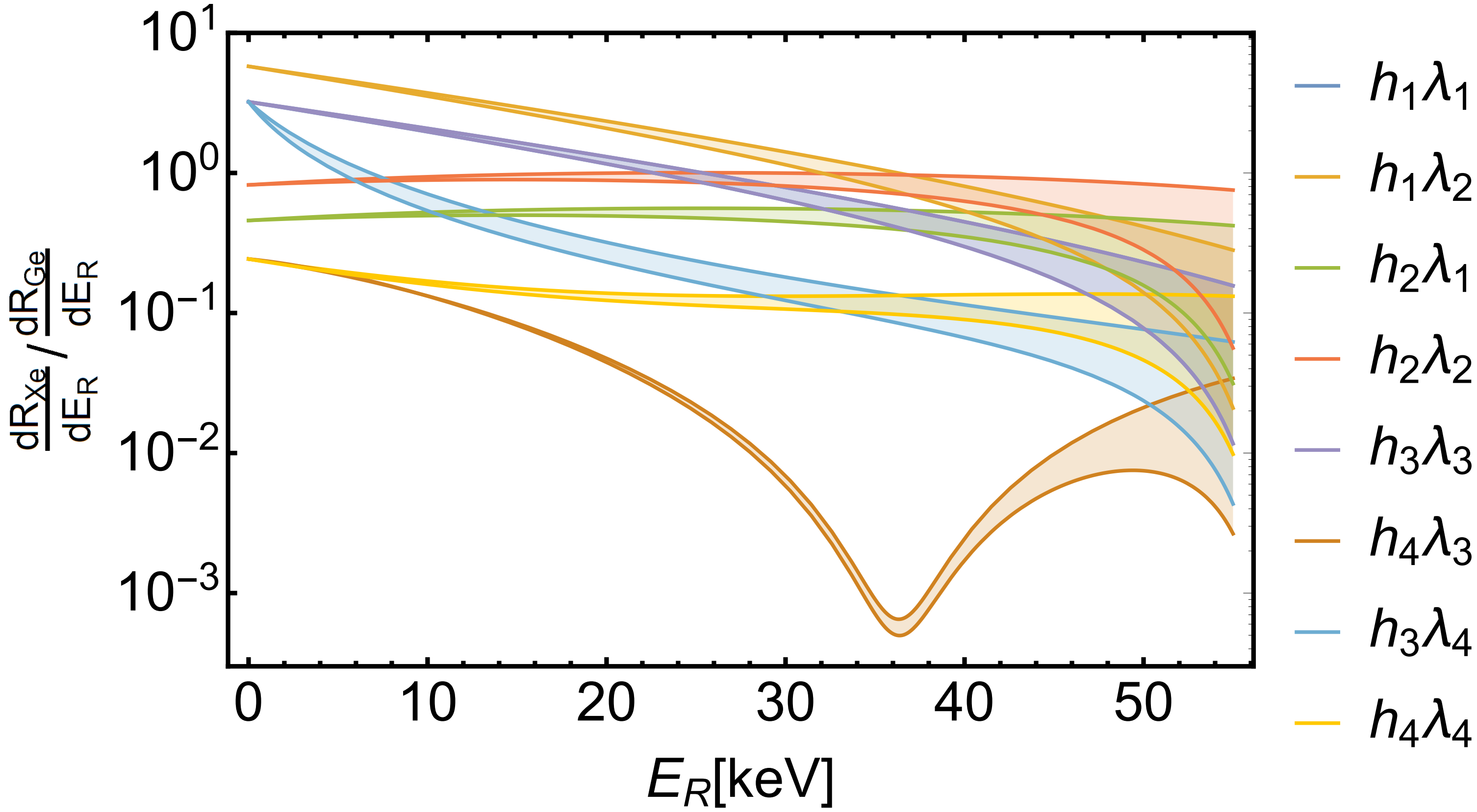
$$\chi$$

spin-1/2

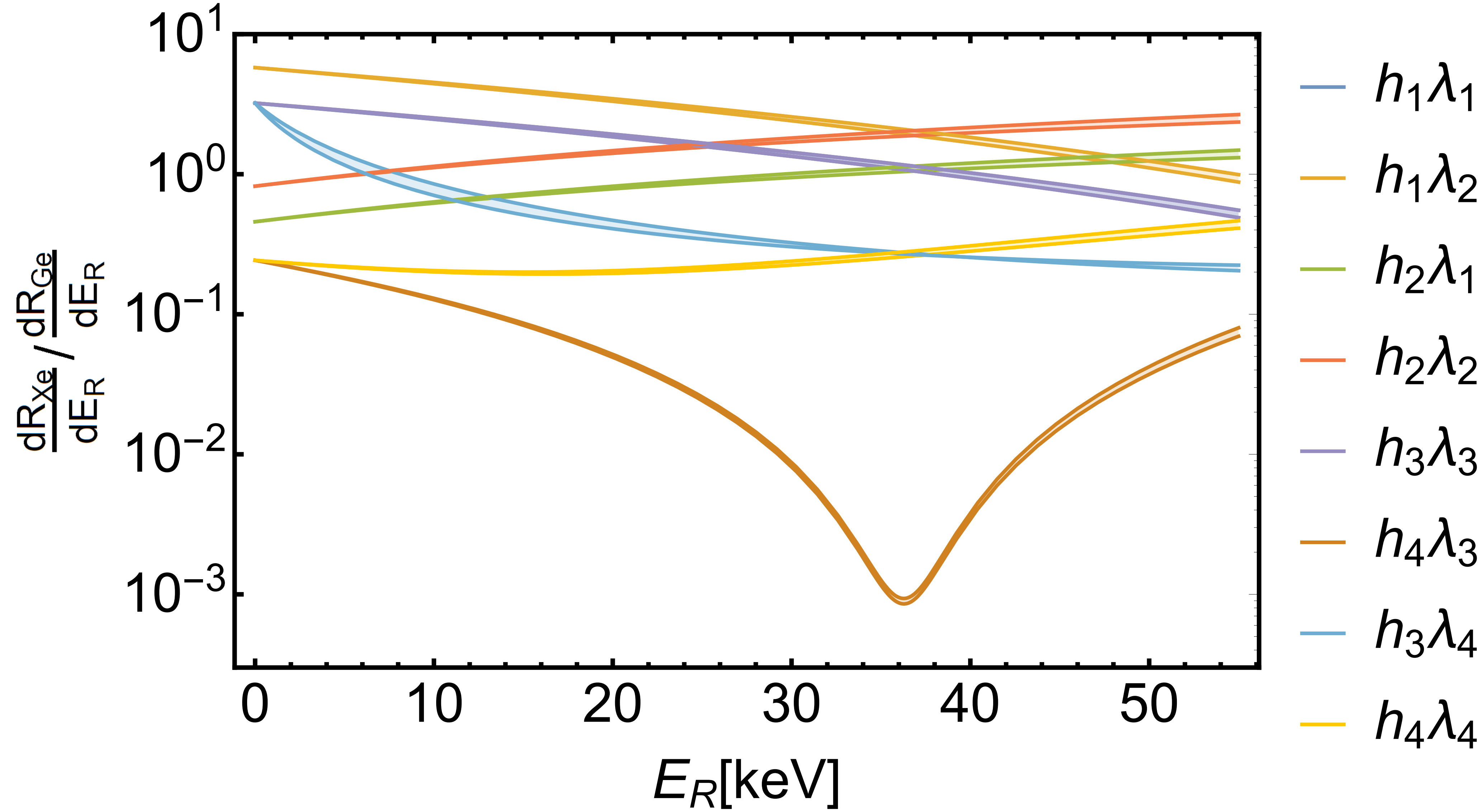
$\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}\gamma_{\mu}\gamma^{5}q$	$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$
$\bar{\chi}\gamma^{5}\chi\bar{q}\gamma^{5}q$	$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}\gamma_{\mu}q$	$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^{\perp}$
$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}\gamma^{5}q$	$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\bar{\chi}\gamma^{5}\chi\bar{q}q$	$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$

50 GeV spin-1/2 WIMP off of ^{73}Ge (dashed) and ^{131}Xe (solid) for a 1TeV mediator





Ratio of rates for 50GeV spin-1/2 WIMP off Xe and Ge including astrophysical uncertainties



Ratio of rates for 500GeV spin-1/2 WIMP off Xe and Ge including astrophysical uncertainties

		$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
Spin-1 WIMP	(h_1, b_1)	✓																	
	(h_2, b_1)											✓							
	(h_4, b_5)											✓							
	(h_3, b_6)					✓	✓	✓										✓*	
	(h_4, b_6)										✓								✓*
	(h_3, b_7)									✓*	✓*		✓						
	(h_4, b_7)				✓*	✓		✓								✓			
	(y_3)	✓			✓							✓	✓	✓					✓
	(y_4)	✓			✓							✓	✓	✓					✓
	(y_3, y_4)											✓	✓	✓					✓

X^μ

spin-1

WIMP spin	Mediator spin	$\mathcal{L}$ terms	leading NR operator	Eqv. M_m
1	0	h_1, b_1	$\mathcal{O}_1$	13 TeV
1	0	h_2, b_1	$\mathcal{O}_{10}$	10 GeV
1	1	h_4, b_5	$\mathcal{O}_{10}$	5.1 GeV
1	1	$h_3, b_6^{\rm Re}(b_6^{\rm Im})$	$\mathcal{O}_5(\mathcal{O}_{17})$	5.5 GeV(23 GeV)
1	1	$h_4, b_6^{\rm Re}(b_6^{\rm Im})$	$\mathcal{O}_9(\mathcal{O}_{18})$	3 GeV(4.6 GeV)
1	1	$h_3, b_7^{\rm Re}(b_7^{\rm Im})$	$\mathcal{O}_{11}(\mathcal{O}_8)$	186 GeV(228 GeV)
1	1	$h_4, b_7^{\rm Re}(b_7^{\rm Im})$	$\mathcal{O}_{14}(\mathcal{O}_4)$	65 MeV (172 GeV)
1	$\frac{1}{2}^*$	y_3	$\mathcal{O}_1$	3.2 PeV
1	$\frac{1}{2}^*$	y_4	$\mathcal{O}_1$	3.2 PeV
1	$\frac{1}{2}^*$	y_3, y_4	$\mathcal{O}_{11}$	120 TeV

Spin-1 WIMP

	$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
(h_1, b_1)	✓																	
(h_2, b_1)											✓							
(h_4, b_5)											✓							
(h_3, b_6)					✓	✓	✓										✓*	
(h_4, b_6)										✓								✓*
(h_3, b_7)									✓*	✓*		✓						
(h_4, b_7)				✓*	✓		✓								✓			
(y_3)	✓			✓							✓	✓	✓					✓
(y_4)	✓			✓							✓	✓	✓					✓
(y_3, y_4)											✓	✓	✓					✓

WIMP spin	Mediator spin	$\mathcal{L}$ terms	leading NR operator	Eqv. M_m
1	0	h_1, b_1	$\mathcal{O}_1$	13 TeV
1	0	h_2, b_1	$\mathcal{O}_{10}$	10 GeV
1	1	h_4, b_5	$\mathcal{O}_{10}$	5.1 GeV
1	1	$h_3, b_6^{\rm Re}(b_6^{\rm Im})$	$\mathcal{O}_5(\mathcal{O}_{17})$	5.5 GeV(23 GeV)
1	1	$h_4, b_6^{\rm Re}(b_6^{\rm Im})$	$\mathcal{O}_9(\mathcal{O}_{18})$	3 GeV(4.6 GeV)
1	1	$h_3, b_7^{\rm Re}(b_7^{\rm Im})$	$\mathcal{O}_{11}(\mathcal{O}_8)$	186 GeV(228 GeV)
1	1	$h_4, b_7^{\rm Re}(b_7^{\rm Im})$	$\mathcal{O}_{14}(\mathcal{O}_4)$	65 MeV (172 GeV)
1	$\frac{1}{2}^*$	y_3	$\mathcal{O}_1$	3.2 PeV
1	$\frac{1}{2}^*$	y_4	$\mathcal{O}_1$	3.2 PeV
1	$\frac{1}{2}^*$	y_3, y_4	$\mathcal{O}_{11}$	120 TeV

X^μ

spin-1

$\mathcal{O}_5$ $\quad i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$

$\mathcal{O}_{11}$ $\quad i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$

$\mathcal{O}_{17}$ $\quad i\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp$

$\mathcal{O}_{18}$ $\quad i\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N$

X^μ

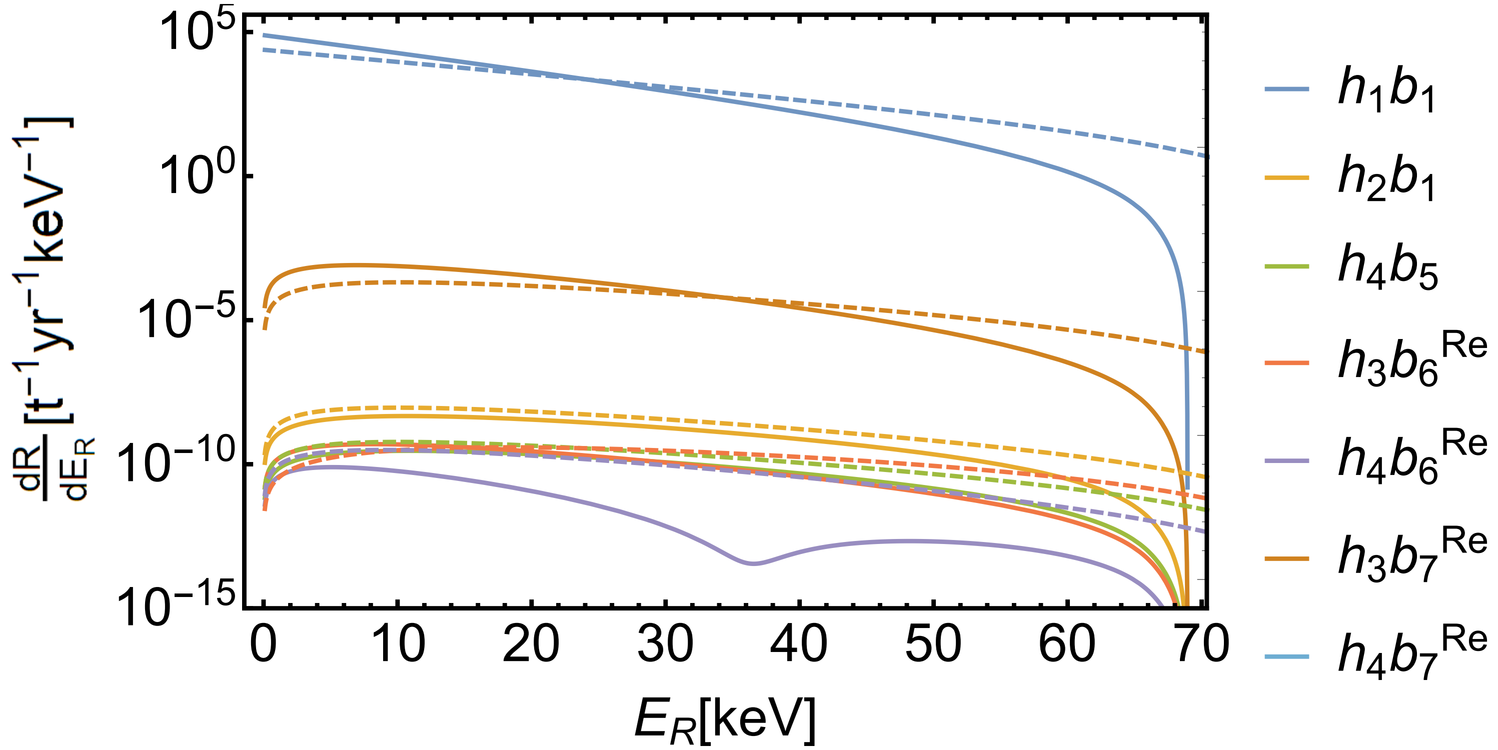
spin-1

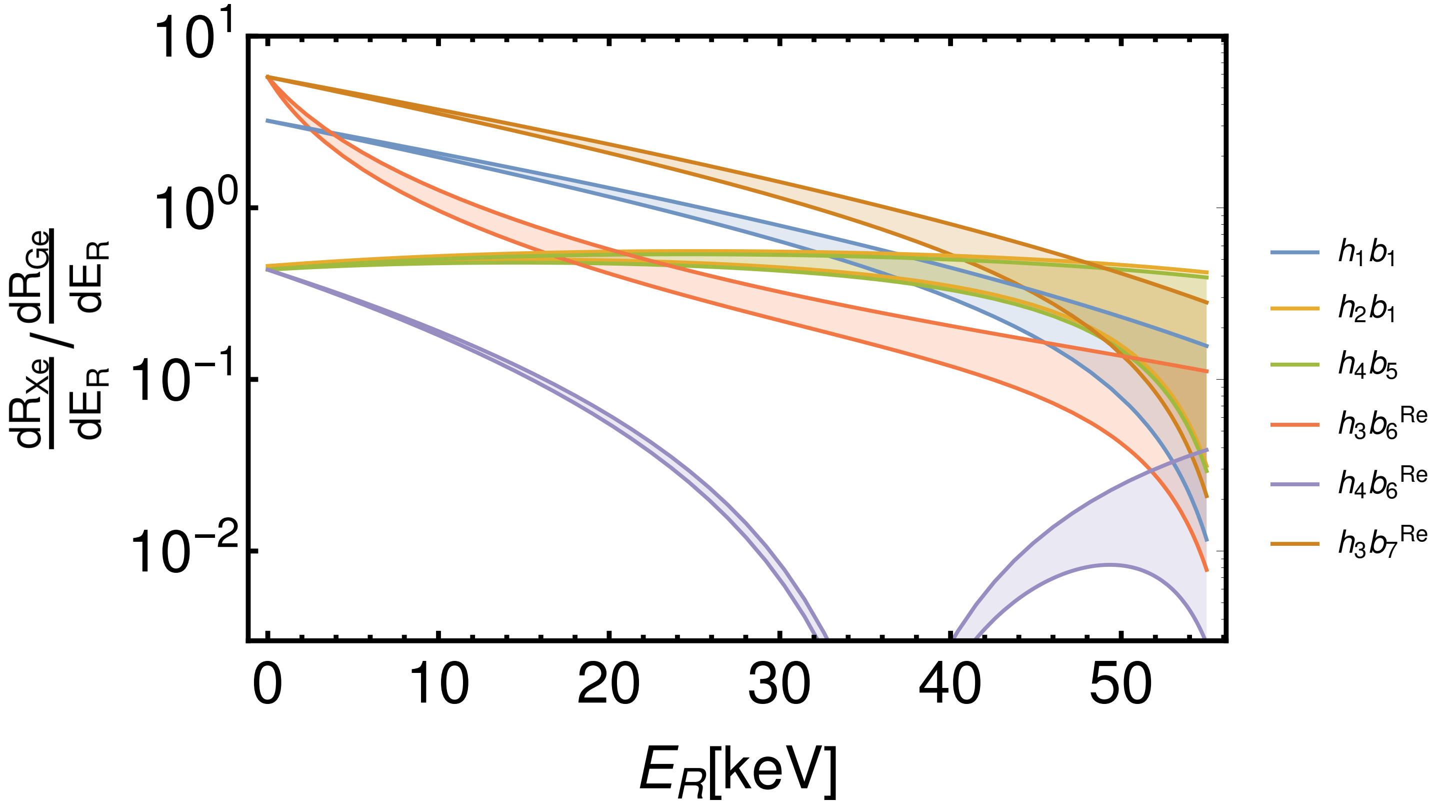
$$\partial_\nu(X^{\nu\dagger}X_\mu + X^\dagger_\mu X^\nu)(\bar{q}\gamma^\mu q) \quad \mathcal{O}_5 \quad i\vec{S}_\chi \cdot (\tfrac{\vec{q}}{m_N} \times \vec{v}^\perp)$$

$$\epsilon_{\mu\nu\rho\sigma}\left(X^{\nu\dagger}\partial^\rho X^\sigma + X^\nu\partial^\rho X^{\sigma\dagger}\right)(\bar{q}\gamma^\mu q) \quad \mathcal{O}_{11} \quad i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$$

$$\partial_\nu(X^{\nu\dagger}X_\mu - X^\dagger_\mu X^\nu)(\bar{q}\gamma^\mu q) \quad \mathcal{O}_{17} \quad i\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp$$

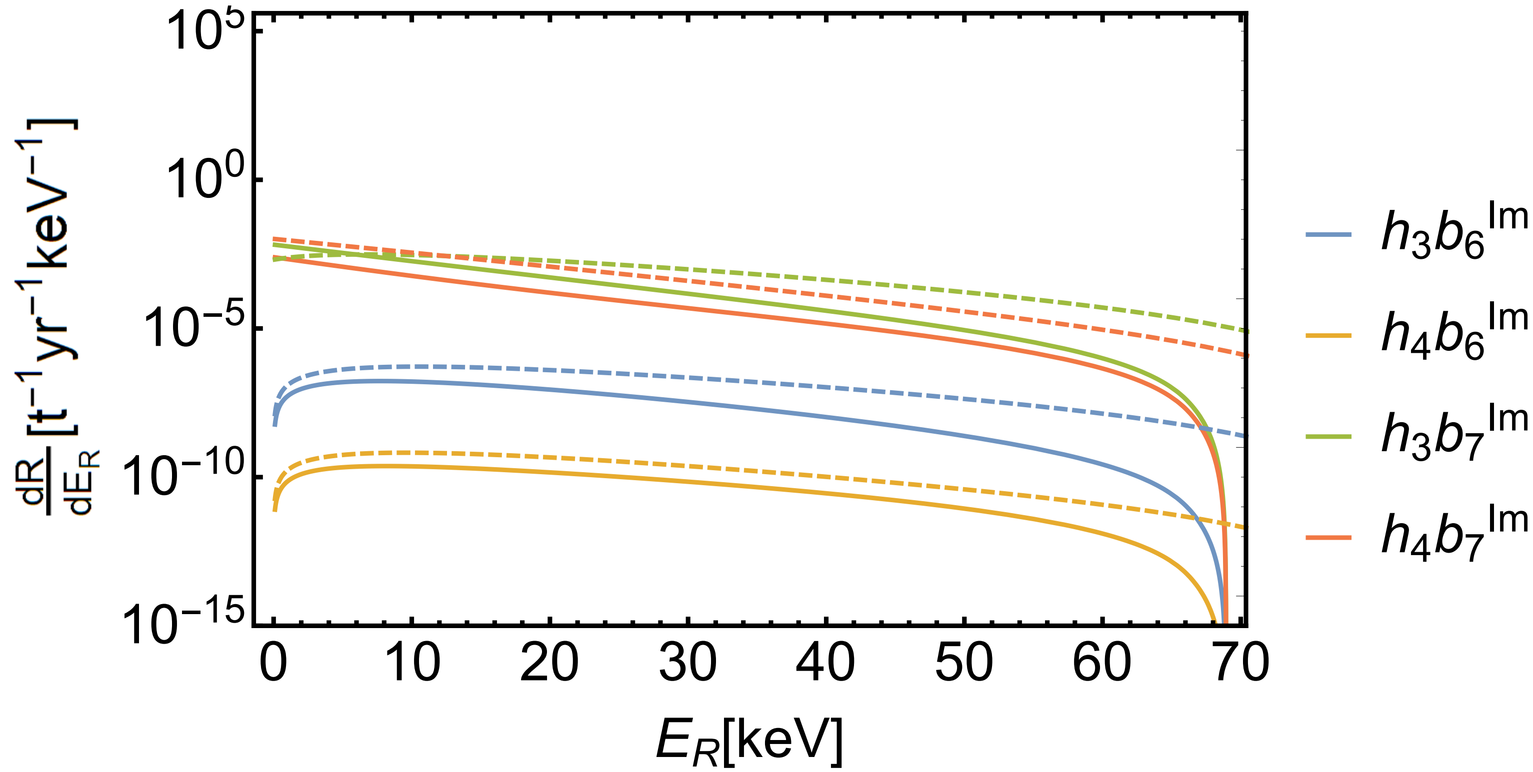
$$\partial_\nu(X^{\nu\dagger}X_\mu - X^\dagger_\mu X^\nu)(\bar{q}\gamma^\mu\gamma^5 q) \quad \mathcal{O}_{18} \quad i\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N$$

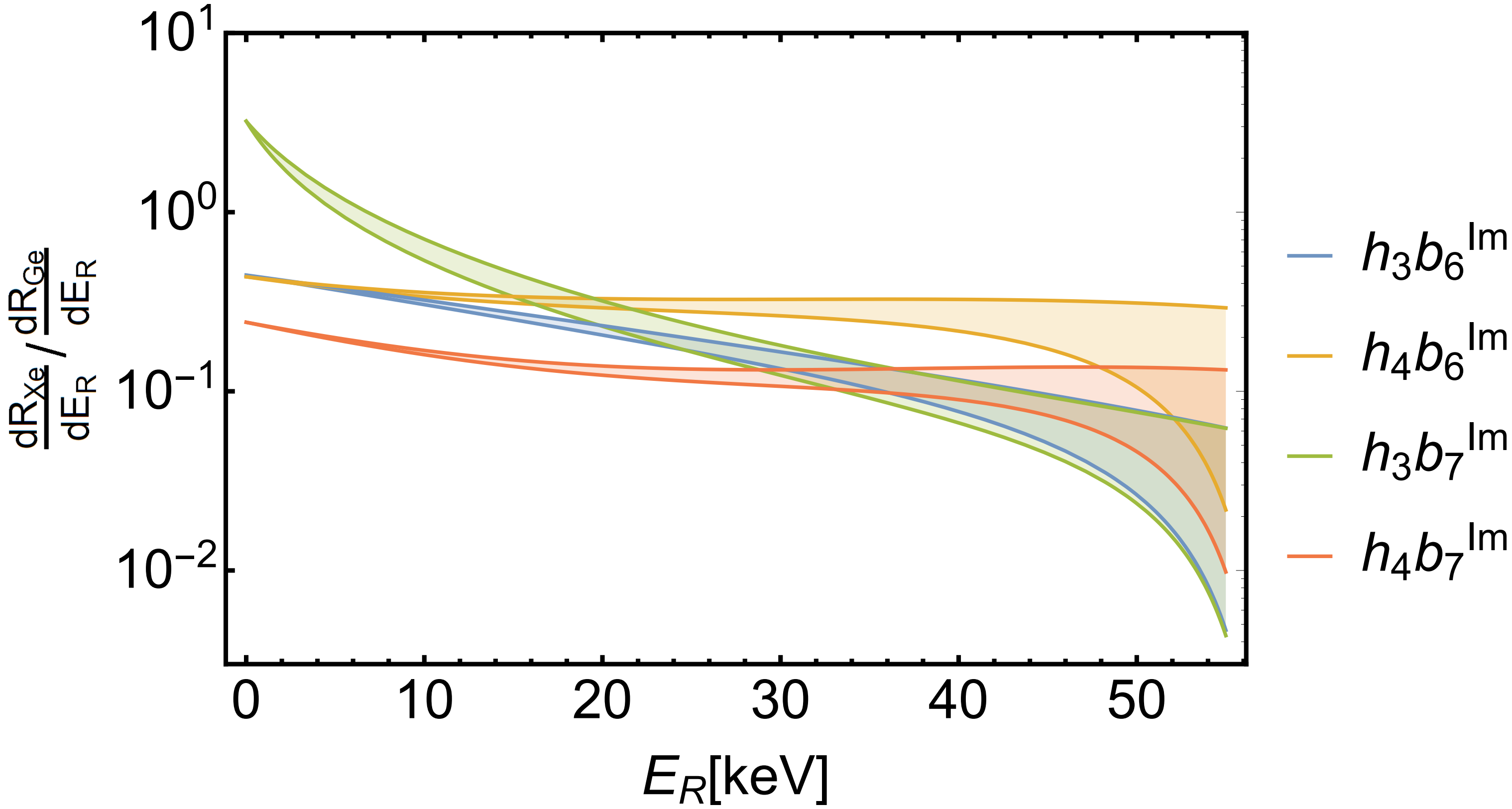




50 GeV spin-1 WIMP off of ^{73}Ge (dashed) and ^{131}Xe (solid)

50 GeV spin-1 WIMP off of ^{73}Ge (dashed) and ^{131}Xe (solid)





Ratio of rates for 50GeV spin-1 WIMP off Xe and Ge including astrophysical uncertainties

Conclusions

As direct detection experiments becoming increasingly more sensitive, a discovery requires accurate modeling to discern paticle properties

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An ongoing program with much to do!

Direct Detection of Dark Matter

From Microphysics to Observational Signatures

James Dent

JBD, L.M. Krauss, J.L. Newstead, and S. Sabharwal, arXiv: 1505.03117

UNIVERSITY OF LOUISIANA Lafayette

Texas A&M May 18, 2015

One can also decompose the velocity difference into a center-of-mass piece and intrinsic parts

$$\vec{v}^{\perp} \rightarrow \{\vec{v}_\chi - \vec{v}_N(i), i = 1, ..., A\}$$
$$\equiv \vec{v}_T^{\perp} - \{\dot{\vec{v}}_N(i), i = 1, ..., A-1\}$$

where the nuclear center-of-mass (Target) is described by

$$\vec{v}_T^{\perp} = \vec{v}_\chi - \frac{1}{2A}\sum_{i=1}^{A}\left[\vec{v}_{N,in}(i) + \vec{v}_{N,out}(i)\right]$$

The nucleon velocities are decomposed into internal and 'in' and 'out' segments

Operators are decomposed as in

$$\vec{v}^{\perp} \cdot \vec{S}_N \rightarrow \sum_{i=1}^{A}\frac{1}{2}\left[\vec{v}_{\chi,in} + \vec{v}_{\chi,out} - \vec{v}_{N,in}(i) - \vec{v}_{N,out}(i)\right] \cdot \vec{S}_N(i)$$
$$= \vec{v}_T^{\perp} \cdot \sum_{i=1}^{A}\vec{S}_N(i) - \left\{\sum_{i=1}^{A}\frac{1}{2}\left[\vec{v}_{N,in}(i) + \vec{v}_{N,out}(i)\right] \cdot \vec{S}_N(i)\right\}_{int}$$

The nucleon positions and momenta are replace by operators which account for the non-zero nuclear size

$$\vec{v}_{N,in} \rightarrow \vec{p}_{N,in}/M \rightarrow i\overleftarrow{\nabla}/M$$

$$\vec{v}_{N,out} \rightarrow \vec{p}_{N,out}/M \rightarrow -i\overrightarrow{\nabla}/M$$

$$e^{-i\vec{q}\cdot\vec{x}}$$

The DM-nucleon interactions can then be written

$$\sum_{\tau=0,1} \left\{ l_0^\tau S + l_0^{A\tau} T + \vec{l}_5^\tau \cdot \vec{P} + \vec{l}_M^\tau \cdot Q + \vec{l}_E^\tau \cdot \vec{R} \right\} t^\tau(i)$$

Effective Action   Non-rel limit   Operator Matching

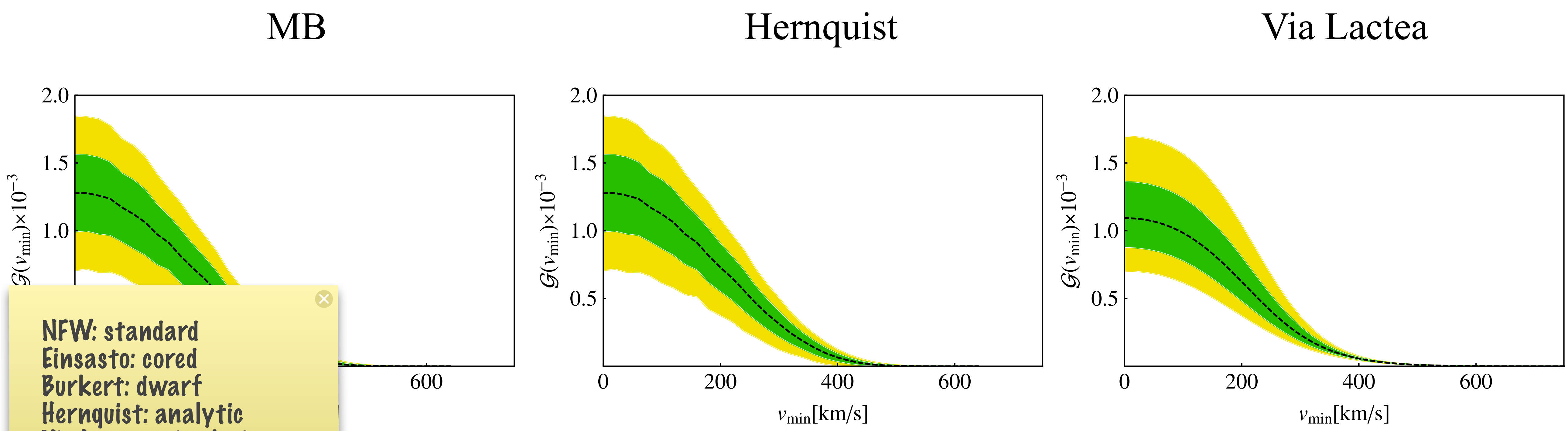
j	$\mathcal{L}^j_{\rm int}$	Nonrelativistic reduction	$\sum_i c_i \mathcal{O}_i$	P/T
1	$\bar\chi\chi\bar N N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
2	$i\bar\chi\chi\bar N\gamma^5 N$	$i\frac{\vec q}{m_N}\cdot\vec S_N$	$\mathcal{O}_{10}$	O/O
3	$i\bar\chi\gamma^5\chi\bar N N$	$-i\frac{\vec q}{m_\chi}\cdot\vec S_\chi$	$-\frac{m_N}{m_\chi}\mathcal{O}_{11}$	O/O
4	$\bar\chi\gamma^5\chi\bar N\gamma^5 N$	$-\frac{\vec q}{m_\chi}\cdot\vec S_\chi\frac{\vec q}{m_N}\cdot\vec S_N$	$-\frac{m_N}{m_\chi}\mathcal{O}_6$	E/E
5	$\bar\chi\gamma^\mu\chi\bar N\gamma_\mu N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
6	$\bar\chi\gamma^\mu\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}N$	$\frac{\vec q^{\,2}}{2m_N m_{\rm M}}1_\chi 1_N+2\big(\frac{\vec q}{m_\chi}\times\vec S_\chi+i\vec v^\perp\big)\cdot\big(\frac{\vec q}{m_{\rm M}}\times\vec S_N\big)$	$\frac{\vec q^{\,2}}{2m_N m_{\rm M}}\mathcal{O}_1-2\frac{m_N}{m_{\rm M}}\mathcal{O}_3+2\frac{m_N^2}{m_{\rm M}m_\chi}\big(\frac{q^2}{m_N^2}\mathcal{O}_4-\mathcal{O}_6\big)$	E/E
7	$\bar\chi\gamma^\mu\chi\bar N\gamma_\mu\gamma^5 N$	$-2\vec S_N\cdot\vec v^\perp+\frac{2}{m_\chi}i\vec S_\chi\cdot(\vec S_N\times\vec q)$	$-2\mathcal{O}_7+2\frac{m_N}{m_\chi}\mathcal{O}_9$	O/E
8	$i\bar\chi\gamma^\mu\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$2i\frac{\vec q}{m_{\rm M}}\cdot\vec S_N$	$2\frac{m_N}{m_{\rm M}}\mathcal{O}_{10}$	O/O
9	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\chi\bar N\gamma_\mu N$	$-\frac{\vec q^{\,2}}{2m_\chi m_{\rm M}}1_\chi 1_N-2\big(\frac{\vec q}{m_N}\times\vec S_N+i\vec v^\perp\big)\cdot\big(\frac{\vec q}{m_{\rm M}}\times\vec S_\chi\big)$	$-\frac{\vec q^{\,2}}{2m_\chi m_{\rm M}}\mathcal{O}_1+\frac{2m_N}{m_{\rm M}}\mathcal{O}_5-2\frac{m_N}{m_{\rm M}}\big(\frac{\vec q^{\,2}}{m_N^2}\mathcal{O}_4-\mathcal{O}_6\big)$	E/E
10	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}N$	$4\big(\frac{\vec q}{m_{\rm M}}\times\vec S_\chi\big)\cdot\big(\frac{\vec q}{m_{\rm M}}\times\vec S_N\big)$	$4\big(\frac{\vec q^{\,2}}{m_{\rm M}^2}\mathcal{O}_4-\frac{m_N^2}{m_{\rm M}^2}\mathcal{O}_6\big)$	E/E
11	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\chi\bar N\gamma^\mu\gamma^5 N$	$4i\big(\frac{\vec q}{m_{\rm M}}\times\vec S_\chi\big)\cdot\vec S_N$	$4\frac{m_N}{m_{\rm M}}\mathcal{O}_9$	O/E
12	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$-\big[i\frac{\vec q^{\,2}}{m_\chi m_{\rm M}}-4\vec v^\perp\cdot\big(\frac{\vec q}{m_{\rm M}}\times\vec S_\chi\big)\big]\frac{\vec q}{m_{\rm M}}\cdot\vec S_N$	$-\frac{m_N}{m_\chi}\frac{\vec q^{\,2}}{m_{\rm M}^2}\mathcal{O}_{10}-4\frac{\vec q^{\,2}}{m_{\rm M}^2}\mathcal{O}_{12}-4\frac{m_N^2}{m_{\rm M}^2}\mathcal{O}_{15}$	O/O
13	$\bar\chi\gamma^\mu\gamma^5\chi\bar N\gamma_\mu N$	$2\vec v^\perp\cdot\vec S_\chi+2i\vec S_\chi\cdot\big(\vec S_N\times\frac{\vec q}{m_N}\big)$	$2\mathcal{O}_8+2\mathcal{O}_9$	O/E
14	$\bar\chi\gamma^\mu\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}N$	$4i\vec S_\chi\cdot\big(\frac{\vec q}{m_{\rm M}}\times\vec S_N\big)$	$-4\frac{m_N}{m_{\rm M}}\mathcal{O}_9$	O/E
15	$\bar\chi\gamma^\mu\gamma^5\chi\bar N\gamma^\mu\gamma^5 N$	$-4\vec S_\chi\cdot\vec S_N$	$-4\mathcal{O}_4$	E/E
16	$i\bar\chi\gamma^\mu\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}\gamma^5 N$	$4i\vec v^\perp\cdot\vec S_\chi\frac{\vec q}{m_{\rm M}}\cdot\vec S_N$	$4\frac{m_N}{m_{\rm M}}\mathcal{O}_{13}$	E/O
17	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\gamma^5\chi\bar N\gamma_\mu N$	$2i\frac{\vec q}{m_{\rm M}}\cdot\vec S_\chi$	$2\frac{m_N}{m_{\rm M}}\mathcal{O}_{11}$	O/O
18	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}N$	$\frac{\vec q}{m_{\rm M}}\cdot\vec S_\chi\big[i\frac{\vec q^{\,2}}{m_N m_{\rm M}}-4\vec v^\perp\cdot\big(\frac{\vec q}{m_{\rm M}}\times\vec S_N\big)\big]$	$\frac{\vec q^{\,2}}{m_{\rm M}^2}\mathcal{O}_{11}+4\frac{m_N^2}{m_{\rm M}^2}\mathcal{O}_{15}$	O/O
19	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\gamma^5\chi\bar N\gamma_\mu\gamma^5 N$	$-4i\frac{\vec q}{m_{\rm M}}\cdot\vec S_\chi\vec v_\perp\cdot\vec S_N$	$-4\frac{m_N}{m_{\rm M}}\mathcal{O}_{14}$	E/O
20	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}\gamma^5 N$	$4\frac{\vec q}{m_{\rm M}}\cdot\vec S_\chi\frac{\vec q}{m_{\rm M}}\cdot\vec S_N$	$4\frac{m_N^2}{m_{\rm M}^2}\mathcal{O}_6$	E/E

N. Anand, A.L. Fitzpatrick, and W.C. Haxton, Phys.Rev. C89, 065501 (2014)

Various profiles and their uncertainties

NFW: standard
Einsasto: cored
Burkert: dwarf
Hernquist: analytic
Via Lactea: simulation
MB: isothermal sphere

Various profiles and their uncertainties



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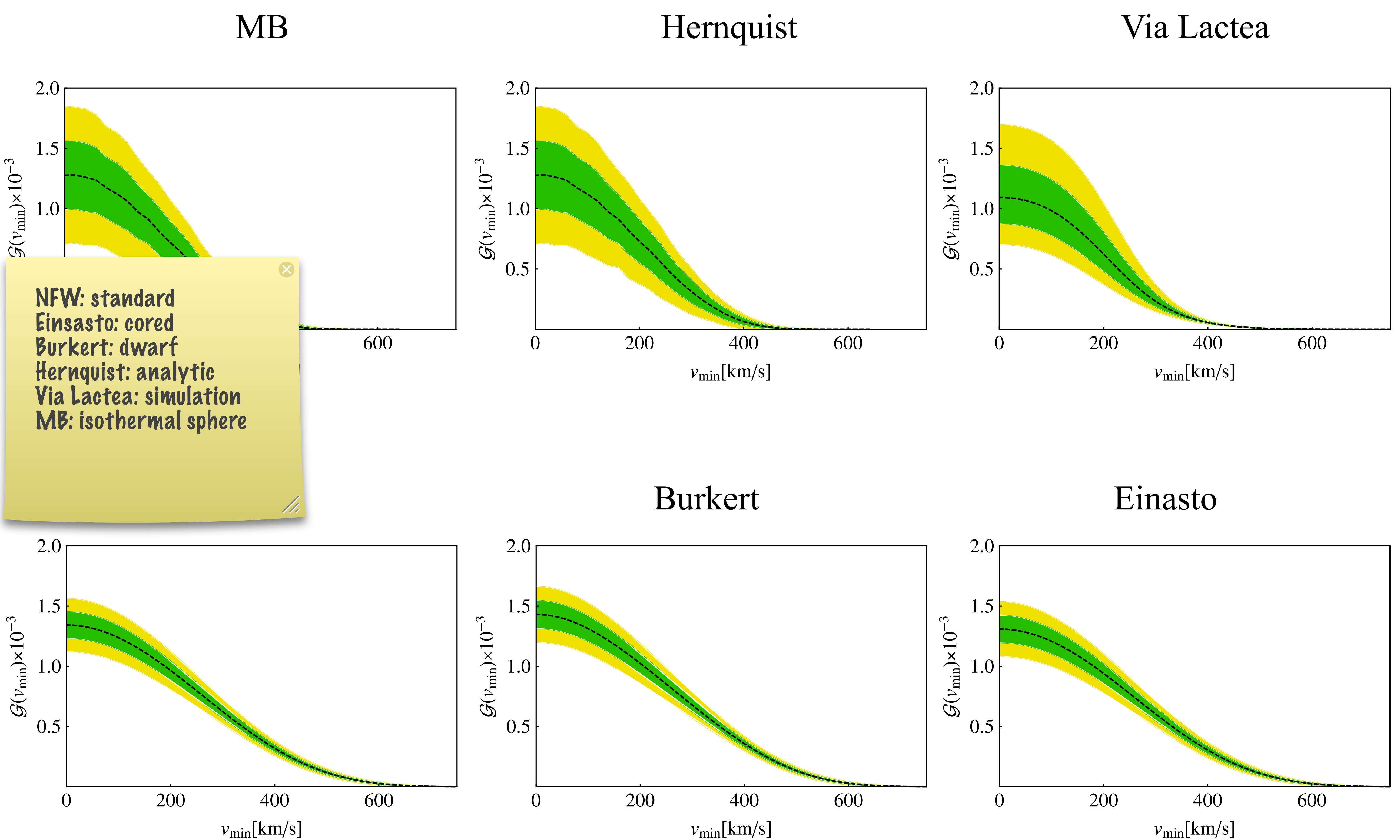
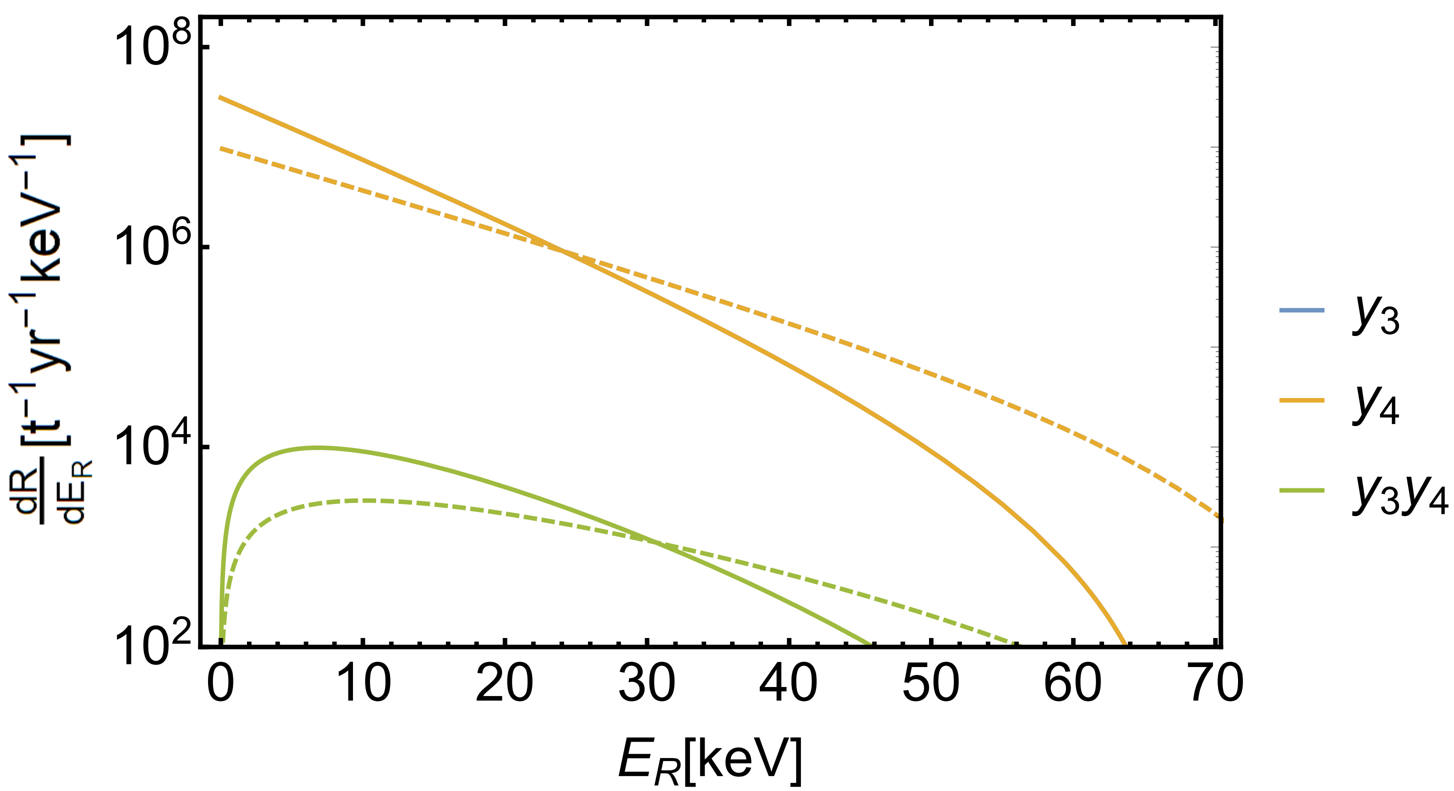
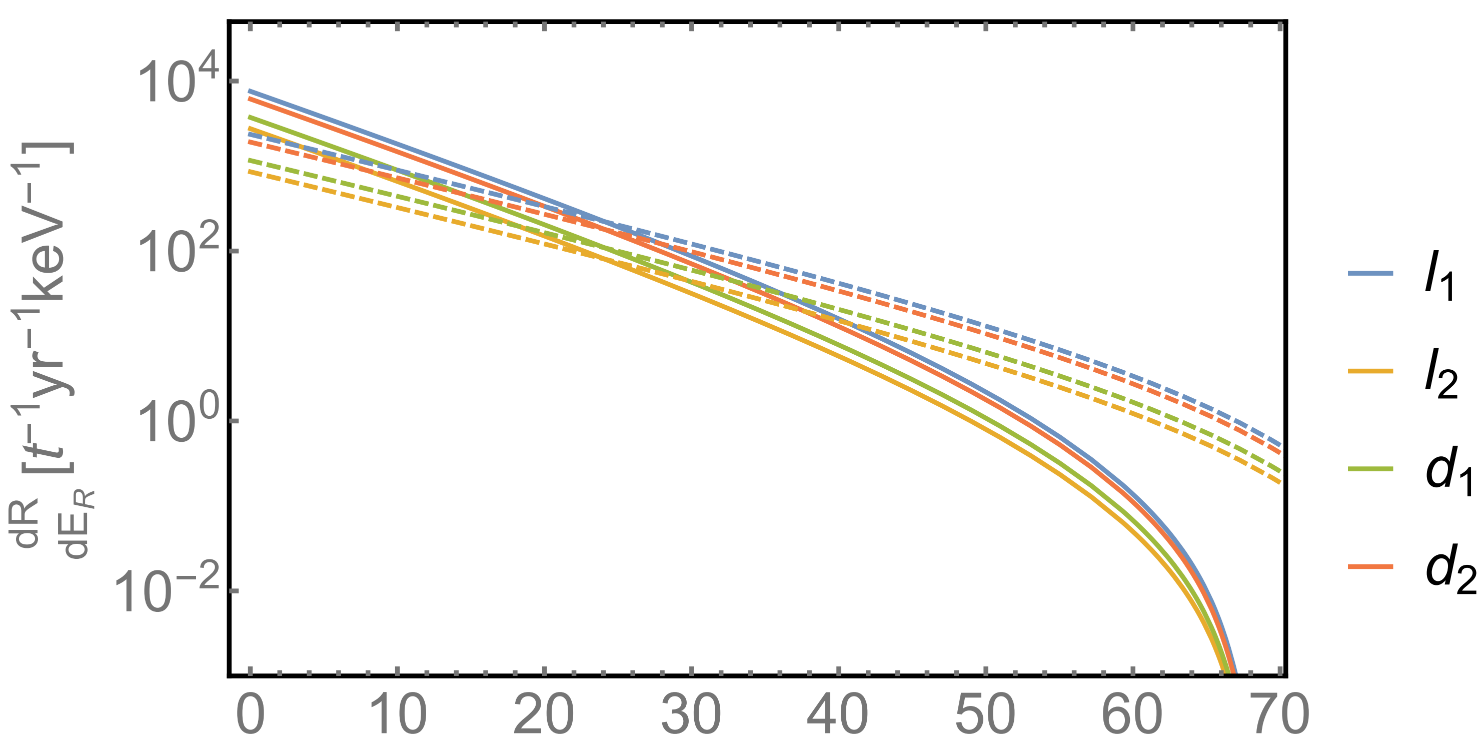


J.L. Newstead, T.D. Jacques, L.M. Krauss, JBD, and F. Ferrer, Phys.Rev.D 88 (2013) 7, 076011,arXiv:1306.3244

Vector dark matter



Spin-1/2 dark matter



Quark bilinears: hadronic matrix elements

$$\begin{aligned}
\langle N_o|\, m_q\bar{q}q\,|N_i\rangle &\longrightarrow f^N_{Tq}\bar{N}N \\
\langle N_o|\, \bar{q}\gamma^5 q\,|N_i\rangle &\longrightarrow \Delta\tilde{q}^N\bar{N}\gamma^5 N \\
\langle N_o|\, \bar{q}\gamma^\mu q\,|N_i\rangle &\longrightarrow \mathcal{N}^N_q\bar{N}\gamma^\mu N \\
\langle N_o|\, \bar{q}\gamma^\mu\gamma^5 q\,|N_i\rangle &\longrightarrow \Delta^N_q\bar{N}\gamma^\mu\gamma^5 N \\
\langle N_o|\, \bar{q}\sigma^{\mu\nu} q\,|N_i\rangle &\longrightarrow \delta^N_q\bar{N}\sigma^{\mu\nu} N
\end{aligned}$$

for the heavy quarks

$$\langle N|\, m_q\bar{q}q\,|N\rangle = \frac{2}{27}m_N F^N_{TG} = \frac{2}{27}m_N\left(1-\sum_{q=u,d,s} f^N_{Tq}\right)$$

Summing over all the quarks one finds

$$h^N_1 = \sum_{q=u,d,s} h^q_1\frac{m_N}{m_q}f^N_{Tq} + \frac{2}{27}f^N_{TG}\sum_{q=c,b,t} h^q_1\frac{m_N}{m_q}$$

The psuedo-scalar bilinear

$$h_2^N = \sum_{q=u,d,s} h_2^q \Delta\tilde{q}^N - \Delta\tilde{G}^N \sum_{q=c,b,t} \frac{h_2^q}{m_q}$$

The vector bilinear essentially gives the number operator:

$$h_3^N = \begin{cases} 2h_3^u + h_3^d & N = p \\ h_3^u + 2h_3^d & N = u \end{cases}$$

The psuedo-vector bilinear counts the contributions of spin to the nucleon (note that sometimes this coupling has a G_F factored out to make it dimensionless)

$$h_4^N = \sum_{q=u,d,s} h_4^q \Delta_q^N$$

We use the values

$$
\begin{aligned}
f^n_{Tu} &= \ 0.014 & f^p_{Tu} &= 0.02 \\
f^n_{Td} &= \ 0.036 & f^p_{Td} &= 0.026 \\
f^n_{Ts} &= \ 0.118 & f^p_{Ts} &= 0.118 \\
\Delta^n_u &= -0.427 & \Delta^p_u &= 0.842 \\
\Delta^n_d &= \ 0.842 & \Delta^p_d &= -0.427 \\
\Delta^n_s &= -0.085 & \Delta^p_s &= -0.085 \\
\Delta\tilde{u}^n &= -108.03 & \Delta\tilde{u}^p &= 110.55 \\
\Delta\tilde{d}^n &= \ 108.60 & \Delta\tilde{d}^p &= -107.17 \\
\Delta\tilde{s}^n &= -0.57 & \Delta\tilde{s}^p &= -3.37 \\
\Delta\tilde{G}^n &= 35.7\mathrm{MeV} & \Delta\tilde{G}^p &= 395.2\mathrm{MeV}
\end{aligned}
$$

P. Agrawal, Z. Chacko, C. Kilic, and R. K. Mishra, arXiv:1003.1912 [hep-ph].

K. R. Dienes, J. Kumar, B. Thomas and D. Yaylali, Phys. Rev. D **90**, no. 1, 015012 (2014) [arXiv:1312.7772 [hep-ph]].

Assuming a universal coupling of the mediators to all quarks, the nucleon level couplings can be written as

$$
\begin{aligned}
h_1^N &= f_T^N h_1 \\
h_2^N &= \tilde{\Delta}^N h_2 \\
h_3^N &= \mathcal{N}^N h_3 \\
h_4^N &= \Delta^N h_4
\end{aligned}
$$

where we have defined,

$$
\begin{aligned}
f_T^n &= 11.93 & f_T^p &= 12.31 \\
\tilde{\Delta}^n &= -0.07 & \tilde{\Delta}^p &= -0.28 \\
\mathcal{N}^n &= 3 & \mathcal{N}^p &= 3 \\
\Delta^n &= 0.33 & \Delta^p &= 0.33 \\
\delta^n &= 0.564 & \delta^p &= 0.564
\end{aligned}
$$

Scalar DM

$$\mathcal{L}_{S\phi q} = \partial_\mu S^\dagger \partial^\mu S - m_S^2 S^\dagger S - \frac{\lambda_S}{2}(S^\dagger S)^2$$
$$+\frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2}m_\phi^2 \phi^2 - \frac{m_\phi \mu_1}{3}\phi^3 - \frac{\mu_2}{4}\phi^4$$
$$+i\bar{q}\not{D}q - m_q \bar{q}q$$
$$-g_1 m_S S^\dagger S \phi - \frac{g_2}{2}S^\dagger S \phi^2 - h_1 \bar{q}q\phi - i h_2 \bar{q}\gamma^5 q \phi,$$

$$\mathcal{L}_{SGq} = \partial_\mu S^\dagger \partial^\mu S - m_S^2 S^\dagger S - \frac{\lambda_S}{2}(S^\dagger S)^2$$
$$-\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \frac{1}{2}m_G^2 G_\mu G^\mu - \frac{\lambda_G}{4}(G_\mu G^\mu)^2$$
$$+i\bar{q}\not{D}q - m_q \bar{q}q$$
$$-\frac{g_3}{2}S^\dagger S G_\mu G^\mu - i g_4 (S^\dagger \partial_\mu S - \partial_\mu S^\dagger S)G^\mu$$
$$-h_3(\bar{q}\gamma_\mu q)G^\mu - h_4(\bar{q}\gamma_\mu \gamma^5 q)G^\mu.$$

Spinor DM

$$
\begin{aligned}
\mathcal{L}_{\chi\phi q} = & \; i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi \\
& + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \frac{m_\phi\mu_1}{3}\phi^3 - \frac{\mu_2}{4}\phi^4 \\
& + i\bar{q}\not{D}q - m_q\bar{q}q \\
& - \lambda_1\phi\bar{\chi}\chi - i\lambda_2\phi\bar{\chi}\gamma^5\chi - h_1\phi\bar{q}q - ih_2\phi\bar{q}\gamma^5 q,
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\chi G q} = & \; i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi \\
& - \frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \frac{1}{2}m_G^2 G_\mu G^\mu \\
& + i\bar{q}\not{D}q - m_q\bar{q}q \\
& - \lambda_3\bar{\chi}\gamma^\mu\chi G_\mu - \lambda_4\bar{\chi}\gamma^\mu\gamma^5\chi G_\mu \\
& - h_3\bar{q}\gamma_\mu q G^\mu - h_4\bar{q}\gamma_\mu\gamma^5 q G^\mu.
\end{aligned}
$$

Vector DM

$$\mathcal{L}_{X\phi q} = -\frac{1}{2}\mathcal{X}^\dagger_{\mu\nu}\mathcal{X}^{\mu\nu} + m_X^2 X^\dagger_\mu X^\mu - \frac{\lambda_X}{2}(X^\dagger_\mu X^\mu)^2$$
$$+\frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{m_\phi\mu_1}{3}\phi^3 - \frac{\mu_2}{4}\phi^4$$
$$+i\bar{q}\not{D}q - m_q\bar{q}q$$
$$-b_1 m_X\phi X^\dagger_\mu X^\mu - \frac{b_2}{2}\phi^2 X^\dagger_\mu X^\mu - h_1\phi\bar{q}q - ih_2\phi\bar{q}\gamma^5 q.$$

$$\mathcal{L}_{XGq} = -\frac{1}{2}\mathcal{X}^\dagger_{\mu\nu}\mathcal{X}^{\mu\nu} + m_X^2 X^\dagger_\mu X^\mu - \frac{\lambda_X}{2}(X^\dagger_\mu X^\mu)^2$$
$$-\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \frac{1}{2}m_G^2 G_\mu^2 - \frac{\lambda_G}{4}(G_\mu G^\mu)^2$$
$$+i\bar{q}\not{D}q - m_q\bar{q}q$$
$$-\frac{b_3}{2}G_\mu^2(X^\dagger_\nu X^\nu) - \frac{b_4}{2}(G^\mu G^\nu)(X^\dagger_\mu X_\nu) - \Big[ib_5 X^\dagger_\nu\partial_\mu X^\nu G^\mu$$
$$+b_6 X^\dagger_\mu\partial^\mu X_\nu G^\nu + b_7\epsilon_{\mu\nu\rho\sigma}(X^{\dagger\mu}\partial^\nu X^\rho)G^\sigma + h.c.\Big]$$
$$-h_3 G_\mu\bar{q}\gamma^\mu q - h_4 G_\mu\bar{q}\gamma^\mu\gamma^5 q$$

Scalar DM, charged mediator

$$\mathcal{L}_{SQq} = \partial_\mu S^\dagger \partial^\mu S - m_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2$$
$$+ i\bar{Q}\not{D}Q - m_Q \bar{Q}Q$$
$$+ i\bar{q}\not{D}q - m_q \bar{q}q$$
$$-(y_1 S\bar{Q}q + y_2 S\bar{Q}\gamma^5 q + h.c.),$$

Spinor DM, charged mediator

$$\begin{aligned}\mathcal{L}_{\chi\Phi q} = {} & i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi \\ & +(\partial_\mu\Phi^\dagger)(\partial^\mu\Phi) - m_\Phi^2\Phi^\dagger\Phi - \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2 \\ & +i\bar{q}\not{D}q - m_q\bar{q}q \\ & -(l_1\Phi^\dagger\bar{\chi}q + l_2\Phi^\dagger\bar{\chi}\gamma^5 q + h.c.),\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\chi V q} = {} & i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi \\ & -\frac{1}{2}\mathcal{V}^\dagger_{\mu\nu}\mathcal{V}^{\mu\nu} + m_V^2 V_\mu^\dagger V^\mu \\ & +i\bar{q}\not{D}q - m_q\bar{q}q \\ & -(d_1\bar{\chi}\gamma^\mu q V_\mu^\dagger + d_2\bar{\chi}\gamma^\mu\gamma^5 q V_\mu^\dagger + h.c.),\end{aligned}$$

Vector DM, charged mediator

$$\mathcal{L}_{XQq} = -\frac{1}{2}\mathcal{X}^{\dagger}_{\mu\nu}\mathcal{X}^{\mu\nu} + m_X^2 X^{\dagger}_{\mu} X^{\mu} - \frac{\lambda_X}{2}(X^{\dagger}_{\mu} X^{\mu})^2$$
$$+ i\bar{Q}\not{D}Q - m_Q\bar{Q}Q$$
$$+ i\bar{q}\not{D}q - m_q\bar{q}q$$
$$-(y_3 X_\mu \bar{Q}\gamma^\mu q + y_4 X_\mu \bar{Q}\gamma^\mu\gamma^5 q + h.c.),$$

TABLE II. Non-zero c_i coefficients for a spin−0 WIMP

	Uncharged Mediator	Charged Mediator
c_1	$\frac{h_1^N g_1}{m_\phi^2}$	$\frac{y_1^\dagger y_1 - y_2^\dagger y_2}{m_Q m_S} f_T^N$
c_{10}	$\frac{-ih_2^N g_1}{m_\phi^2} + \frac{2ig_4 h_4^N}{m_G^2}\frac{m_N}{m_S}$	$i\frac{y_2^\dagger y_1 - y_1^\dagger y_2}{m_Q m_S}\tilde{\Delta}^N$

TABLE III. c_i coefficients for a spin-$\frac{1}{2}$ WIMP

	Uncharged Mediator	Charged Mediator
c_1	$\frac{h_1^N \lambda_1}{m_\phi^2} - \frac{h_3^N \lambda_3}{m_G^2}$	$\left(\frac{l_2^\dagger l_2 - l_1^\dagger l_1}{4m_\Phi^2} + \frac{d_2^\dagger d_2 - d_1^\dagger d_1}{4m_V^2}\right) f_T^N + \left(-\frac{l_2^\dagger l_2 + l_1^\dagger l_1}{4m_\Phi^2} + \frac{d_2^\dagger d_2 + d_1^\dagger d_1}{8m_V^2}\right)\mathcal{N}^N$
c_4	$\frac{4h_4^N \lambda_4}{m_G^2}$	$\frac{l_2^\dagger l_2 - l_1^\dagger l_1}{m_\Phi^2}\delta^N - \left(\frac{l_1^\dagger l_1 + l_2^\dagger l_2}{m_\Phi^2} + \frac{d_2^\dagger d_2 - d_1^\dagger d_1}{2m_V^2}\right)\Delta^N$
c_6	$\frac{h_2^N \lambda_2 m_N}{m_\phi^2 m_\chi}$	$(\frac{l_1^\dagger l_1 - l_2^\dagger l_2}{4m_\Phi^2} + \frac{d_2^\dagger d_2 - d_1^\dagger d_1}{4m_V^2})\frac{m_N}{m_\chi}\tilde{\Delta}^N$
c_7	$\frac{2h_4^N \lambda_3}{m_G^2}$	$(\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{2m_\Phi^2} + \frac{d_1^\dagger d_2 + d_2^\dagger d_1}{4m_V^2})\Delta^N$
c_8	$-\frac{2h_3^N \lambda_4}{m_G^2}$	$(\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{2m_\Phi^2} - \frac{d_1^\dagger d_2 + d_2^\dagger d_1}{4m_V^2})\mathcal{N}^N$
c_9	$-\frac{2h_4^N \lambda_3 m_N}{m_\chi m_G^2} - \frac{2h_3^N \lambda_4}{m_G^2}$	$(\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{2m_\Phi^2} - \frac{d_1^\dagger d_2 + d_2^\dagger d_1}{4m_V^2})\mathcal{N}^N - (\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{2m_\Phi^2} - \frac{d_1^\dagger d_2 + d_2^\dagger d_1}{4m_V^2})\frac{m_N}{m_\chi}\Delta^N$
c_{10}	$\frac{h_2^N \lambda_1}{m_\phi^2}$	$i(\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{4m_\Phi^2} + \frac{d_2^\dagger d_1 - d_1^\dagger d_2}{4m_V^2})\tilde{\Delta}^N - i\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{m_\Phi^2}\delta^N$
c_{11}	$-\frac{h_1^N \lambda_2 m_N}{m_\phi^2 m_\chi}$	$i(\frac{l_2^\dagger l_1 - l_1^\dagger l_2}{4m_\Phi^2} + \frac{d_2^\dagger d_1 - d_1^\dagger d_2}{4m_V^2})\frac{m_N}{m_\chi} f_T^N + i\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{m_\Phi^2}\frac{m_N}{m_\chi}\delta^N$
c_{12}	0	$\frac{l_2^\dagger l_1 - l_1^\dagger l_2}{m_\Phi^2}\delta^N$

TABLE IV. c_i coefficients for a spin-1 WIMP

	Uncharged Mediator	Charged Mediator
c_1	$\frac{b_1 h_1^N}{m_\phi^2}$	$\frac{y_3^\dagger y_3 - y_4^\dagger y_4}{m_Q m_X} f_T^N$
c_4	$\frac{4\mathrm{Im}(b_7) h_4^N}{m_G^2}$	$2\frac{y_3^\dagger y_3 - y_4^\dagger y_4}{m_Q m_X} \delta^N$
c_5	$\frac{\mathrm{Re}(b_6) h_3^N}{m_G^2} \frac{m_N}{m_X}$	0
c_8	$\frac{2\mathrm{Im}(b_7) h_3^N}{m_G^2}$	0
c_9	$-\frac{2\mathrm{Re}(b_6) h_4^N}{m_G^2} \frac{m_N}{m_X} + \frac{2\mathrm{Im}(b_7) h_3^N}{m_G^2}$	0
c_{10}	$\frac{b_1 h_2^N}{m_\phi^2} - \frac{3 b_5 h_4^N}{m_G^2} \frac{m_N}{m_X}$	$i\frac{y_4^\dagger y_3 - y_3^\dagger y_4}{m_Q m_X} \tilde{\Delta}^N$
c_{11}	$\frac{\mathrm{Re}(b_7) h_3^N}{m_G^2} \frac{m_N}{m_X}$	$i\frac{y_4^\dagger y_3 - y_3^\dagger y_4}{m_Q m_X} \delta^N$
c_{12}	0	$2i\frac{y_3^\dagger y_4 - y_4^\dagger y_3}{m_Q m_X} \delta^N$
c_{14}	$-\frac{2\mathrm{Re}(b_7) h_4^N}{m_G^2} \frac{m_N}{m_X}$	0
c_{17}	$-\frac{4\mathrm{Im}(b_6) h_3^N}{m_G^2} \frac{m_N}{m_X}$	0
c_{18}	$\frac{4\mathrm{Im}(b_6) h_4^N}{m_G^2} \frac{m_N}{m_X}$	$-2i\frac{y_4^\dagger y_3 - y_3^\dagger y_4}{m_Q m_X} \delta^N$