Direct Detection of Dark Matter

A General Framework and Collider Connections

James Dent
University of Louisiana at Lafayette

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Outline

Standard Approach

General Framework including non-standard interactions

Interference Effects in general

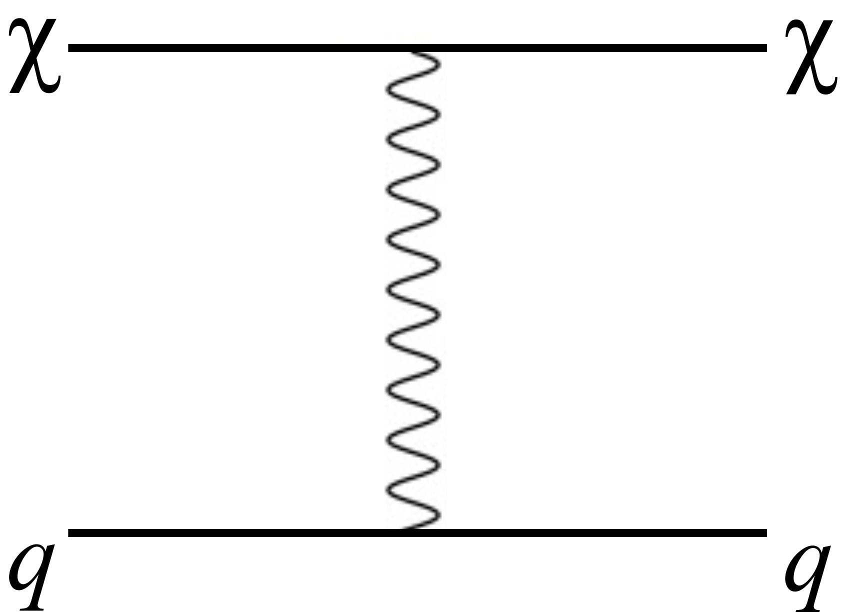
Approaches and identifications with more realistic models

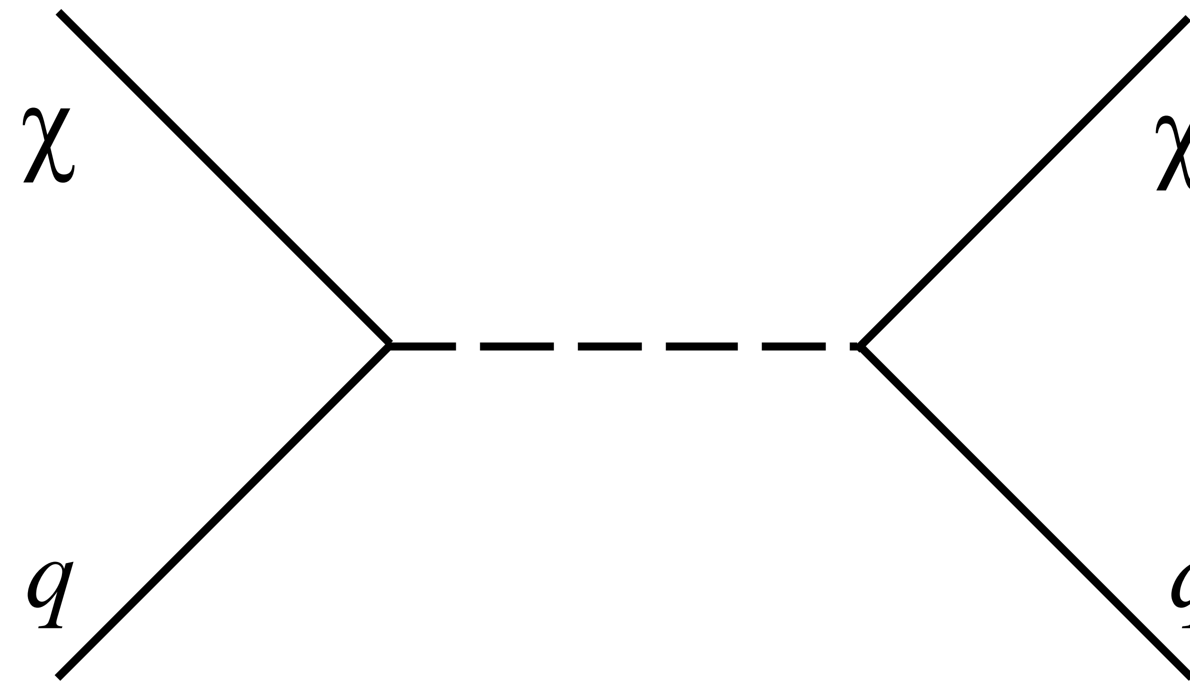
The Neutrino floor(s)

A few issues for connecting collider scales to direct detection scales

Direct Detection:
Standard Approach

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



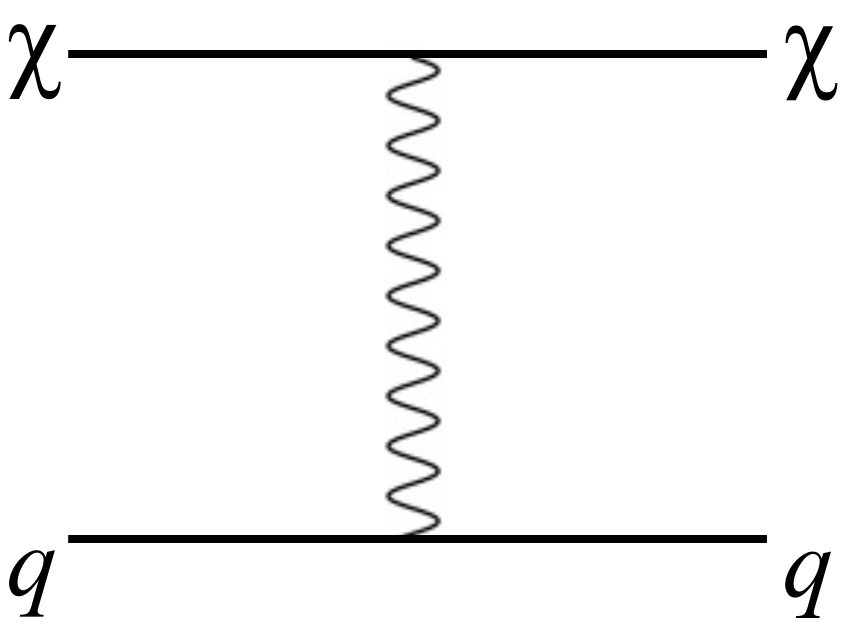


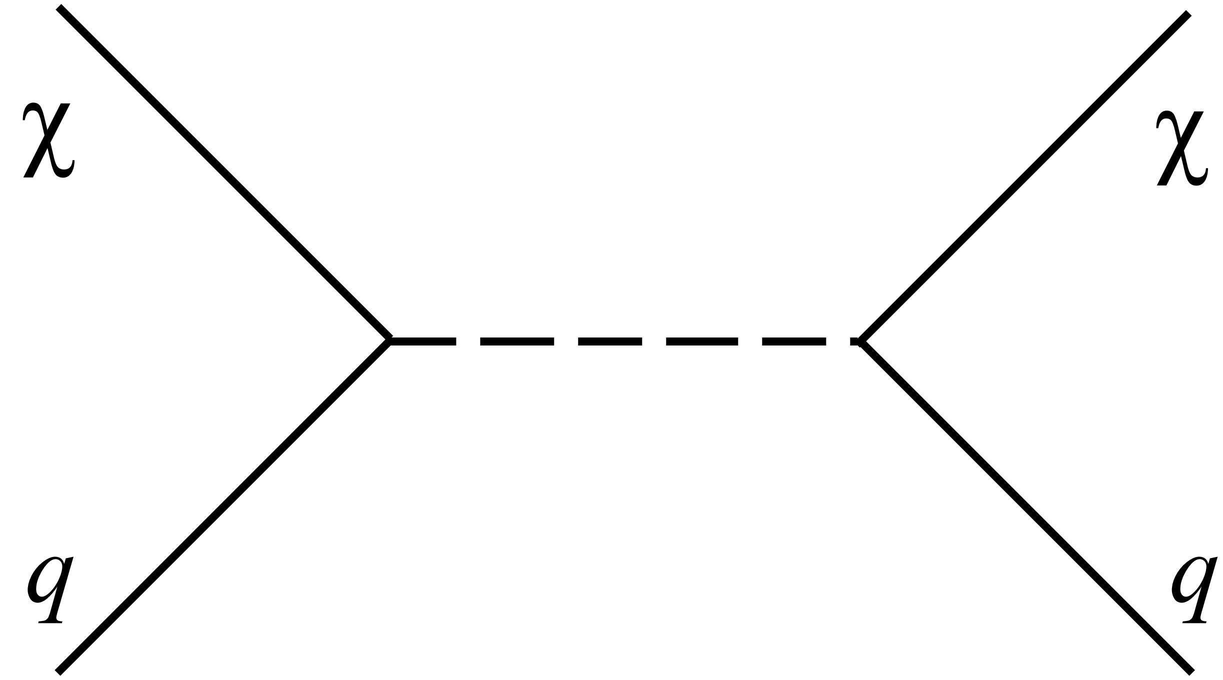
Typical momentum exchanged is $\mathcal{O}(\lesssim 100MeV)$

With an average recoil energy of $\langle E_R \rangle = \frac{1}{2} M_\chi \langle v \rangle^2 \ \mathcal{O}(few \times 10\text{keV})$
for comparable target and dark matter masses, while more generally this is multiplied by an additional factor

$$\frac{4M_\chi M_A}{(M_\chi + M_A)^2}$$

As is familiar, there are myriad interaction types





Hadronic matrix elements encode nucleon interactions

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

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

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

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

$$\langle N_o|\, \bar{q}\sigma^{\mu\nu} q\, |N_i\rangle \longrightarrow \delta_q^N \bar{N}\sigma^{\mu\nu} N$$

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

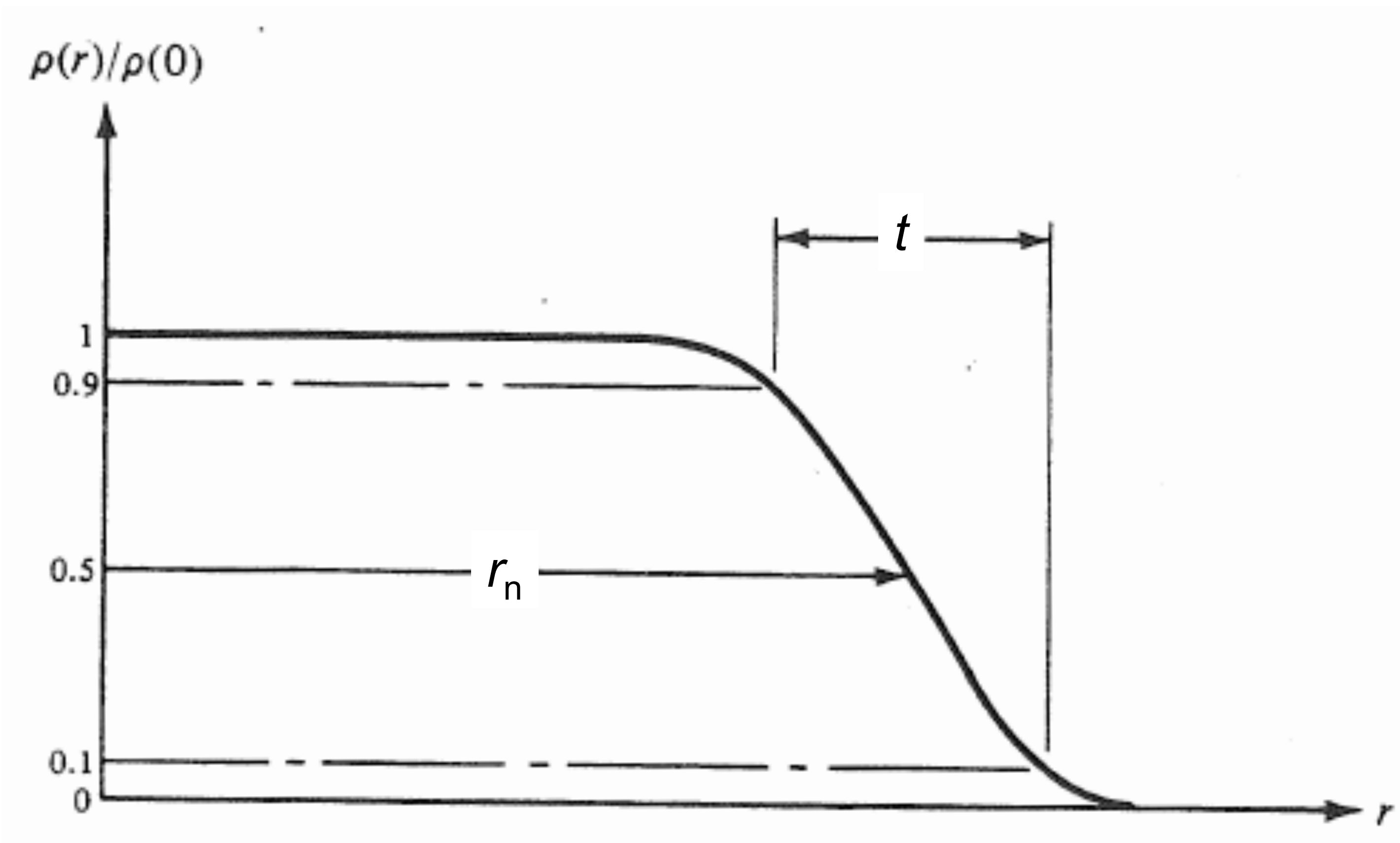
P. Agrawal, Z. Chacko, C. Kilic, and R.K. Mishra, arXiv:1003.1912

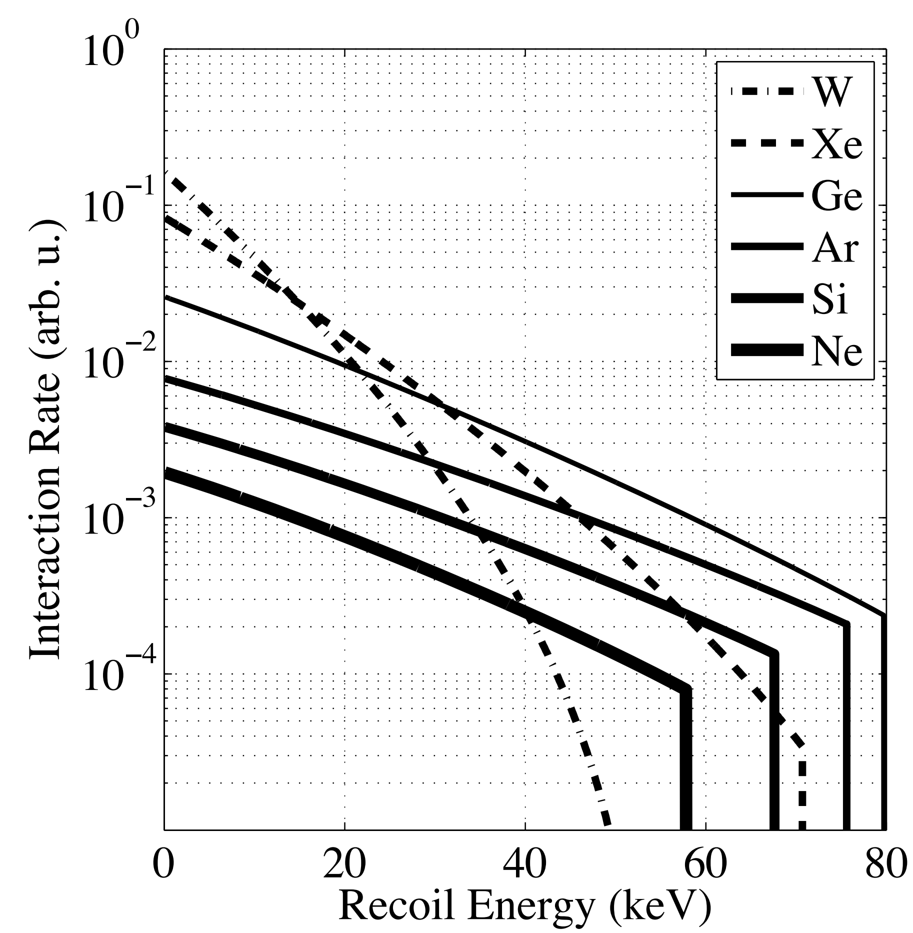
A. Crivellin, M. Hoferichter, and M. Procura, PRD 89 (2014), arXiv:1312.4951

M. Hoferichter, P. Klos, and A. Schwenk, Phys.Lett. B746 (2015) 410-416, arXiv:1503.04811

Coherent scattering occurs for $q < 1/R_{\text{Nucleus}} \simeq \text{MeV}\left(160/A_T^{1/3}\right)$

The non-zero nuclear size and momentum dependence is encoded in form factors, which can account for the loss of coherence at higher momentum transfers





Target specific nuclear physics is also taken into account

R. Schnee, arXiv:1101.5205
G.B. Gelmini, arXiv:1502.01320

The differential recoil rate is the primary quantity of interest

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{|\mathbf{v}|>v_{\min}} |\mathbf{v}| f(\mathbf{v}) \frac{d\sigma}{dE_R} d^3\mathbf{v}$$

astrophysics input

particle input

The minimum velocity which can contribute to a recoil is

$$v_{\min} = \frac{1}{\sqrt{2E_R m_N}} \left(\frac{E_R m_N}{\mu_{\chi N}} + \delta \right)$$

inelastic

$$\langle E_R \rangle = \frac{1}{2} M_\chi \langle v \rangle^2 \; \mathcal{O}(few \times 10\text{keV})$$

There is also a cut-off energy

$$E_{\max} = \frac{v_{\text{esc}}^2}{v_0^2} \langle E_{\text{R}} \rangle \approx 6 \langle E_{\text{R}} \rangle$$

The differential recoil rate is the primary quantity of interest

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{|\mathbf{v}|>v_{\min}} |\mathbf{v}| f(\mathbf{v}) \frac{d\sigma}{dE_R} d^3\mathbf{v}$$

astrophysics input   particle input

For actual detectors one must also account for the detector's efficiency and energy resolution.

WIMP-nucleon scattering is factorized

$$\frac{d\sigma_{\rm WN}(q)}{dq^2} = \frac{1}{\pi v^2}|\mathcal{M}|^2 = \frac{\sigma_{0\rm WN}F^2(q)}{4\mu_A^2 v^2}$$

$$\mu_A \equiv M_\chi M_A/(M_\chi + M_A)$$

With a form factor that incorporates momentum transfer

Spin-independent

Spin-dependent

$$\sigma_{0\rm WN} = \frac{4\mu_A^2}{\pi}\left[Z f_{\rm p} + (A-Z) f_{\rm n}\right]^2 + \frac{32 G_{\rm F}^2 \mu_A^2}{\pi}\frac{J+1}{J}\left(a_{\rm p}\langle S_{\rm p}\rangle + a_{\rm n}\langle S_{\rm n}\rangle\right)^2$$

$$\sigma_{0\rm WN,SI} = \sigma_{\rm SI}\frac{\mu_A^2}{\mu_{\rm n}^2}A^2$$

Heavy target enhancement

$$\langle S_{p,n}\rangle = \langle N|S_{p,n}|N\rangle$$

Nucleon spin expectation values

$$\sigma_{\rm SI} \equiv \frac{4\mu_{\rm n}^2 f_{\rm n}^2}{\pi}$$

Coherent scattering

V.V.Khoze’s talk

Values for nucleon properties for a various target materials

Nucleus	Z	Odd Nuc.	J	$\langle S_p \rangle$	$\langle S_n \rangle$	$\frac{4\langle S_p \rangle^2 (J+1)}{3J}$	$\frac{4\langle S_n \rangle^2 (J+1)}{3J}$
^{19}F	9	p	1/2	0.477	-0.004	9.1×10^{-1}	6.4×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.3×10^{-1}	8.9×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.2×10^{-1}	1.7×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.6×10^{-5}	6.8×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.5×10^{-2}	3.6×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.2×10^{-2}	5.6×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.5×10^{-3}	2.3×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.4×10^{-1}	1.0×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.0×10^{-6}	3.3×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.8×10^{-1}	1.0×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.1×10^{-3}	5.2×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.8×10^{-4}	1.2×10^{-1}

R.W. Schnee, arXiv:1101.5205

	NA(%)	J	$\lvert\langle S_p\rangle_{th}\rvert$ $\lvert\langle S_n\rangle_{th}\rvert$	$\langle S_p\rangle_{lit}$ $\langle S_n\rangle_{lit}$	$\lvert\langle L_p\rangle_{th}\rvert$ $\lvert\langle L_n\rangle_{th}\rvert$	$\langle L_p\rangle_{lit}$ $\langle L_n\rangle_{lit}$	$\lvert\tilde{\mu}_{th}\rvert$	$\tilde{\mu}_{lit}$	$\tilde{\mu}_{exp}$	Lit Ref.
^{19}F	100	1/2	0.475 0.009	0.4751 −0.0087	0.224 0.19	0.4751 −0.0087	2.911	2.91	2.6289	[42]
^{23}Na	100	3/2	0.248 0.02	0.2477 0.0199	0.912 0.321	0.2477 0.0199	2.219	2.22	2.2175	[42]
^{73}Ge	7.7	9/2	0.008 0.475	0.03 0.378	0.184 3.832	0.361 3.732	1.591	−0.92	−0.8795	[43]
^{127}I	100	5/2	0.264 0.066	0.309 0.075	1.515 0.655	1.338 0.779	2.74	2.775	2.8133	[40]
^{129}Xe	26.4	1/2	0.007 0.248	0.01 0.329	0.274 0.03	0.372 −0.185	0.636	−0.72	−0.778	[39], [40]
^{131}Xe	21.2	3/2	0.005 0.199	−0.009 −0.272	0.284 1.419	0.165 1.572	1.016	0.86	0.6919	[39], [40]

M.I. Gresham and K.M. Zurek, PRD 89 123521 (2014) arXiv:1401.3739

A More General Framework

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

$$1_\chi 1_N$$

Spin-independent

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

Spin-dependent

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

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

$$\vec{S}_\chi \cdot \vec{S}_N \equiv (\vec{S}_\chi \cdot \hat{q})(\vec{S}_N \cdot \hat{q}) + (\vec{S}_\chi \times \hat{q}) \cdot (\vec{S}_N \times \hat{q})$$

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

A.L. Fitzpatrick, W.C. Haxton, E. Katz, N. Lubbers, and Y. Xu, JCAP 1302 (2013) 004, arXiv:1203.3542

A.L. Fitzpatrick, W.C. Haxton, E. Katz, N. Lubbers, and Y. Xu, arXiv:1211.2818

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

From the general interaction

$$\mathcal{L}_{\rm int}(\vec{x}) = c\ \Psi^*_\chi(\vec{x})\mathcal{O}_\chi\Psi_\chi(\vec{x})\ \Psi^*_N(\vec{x})\mathcal{O}_N\Psi_N(\vec{x})$$

The scattering probability can be written as a factorized product of particle and nuclear physics responses

$$\frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\sum_{\rm spins}|\mathcal{M}|^2 \equiv \sum_k \sum_{\tau=0,1}\sum_{\tau'=0,1} \boxed{R_k\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}, \left\{c_i^\tau c_j^{\tau'}\right\}\right)}\boxed{W_k^{\tau\tau'}(\vec{q}^{\,2}b^2)}$$

particle nuclear

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

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

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

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

A.L. Fitzpatrick, W.C. Haxton, E. Katz, N. Lubbers, and Y. Xu, JCAP 1302 (2013) 004, arXiv:1203.3542
N. Anand, A.L. Fitzpatrick, and W.C. Haxton, Phys.Rev. C89, 065501 (2014) arXiv:1308.6288

There are fifteen combinations of these operators

Spin-independent

Spin-dependent

$\mathcal{O}_1$	$1_\chi 1_N$	$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$	$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$	$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$	$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
		$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$

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

$\bar{\chi}\chi$ $\qquad$ $\bar{\chi}\gamma^5\chi$ $\qquad$ 2×2

and four vector terms

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

$P^\mu\bar{\chi}\chi$ $\qquad$ $P^\mu\bar{\chi}\gamma^5\chi$ $\qquad$ 4×4

$\overline{}$

20

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

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 (isoscalar/isovector) couplings to protons and neutrons is incorporated

$$\mathcal{L}_{NR} = \sum_{\tau=0,1} \sum_{i=1}^{15} c_i^\tau \mathcal{O}_i t^\tau \qquad c_i^0 = \frac{1}{2}(c_i^{\mathrm{p}} + c_i^n) \quad c_i^1 = \frac{1}{2}(c_i^p - c_i^n)$$

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

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

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

Nuclear

DM

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

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

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

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

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

Plane waves associated with the nucleon states, which can be expanded in Bessel spherical and Bessel vector harmonics

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

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

Nuclear

DM

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

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

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

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

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

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

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

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

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

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

Spin-independent

Spin-dependent

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

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

$$\Sigma''_{JM} \equiv \left\{\frac{1}{q}\vec{\nabla}_i M_{JM}(q\vec{x}_i)\right\} \cdot \vec{\sigma}(i)$$

$$\tilde{\Phi}'_{JM} \equiv \left[\frac{1}{q}\vec{\nabla}_i \times \vec{M}_{JJ}^{M}(q\vec{x}_i)\right] \cdot \left[\vec{\sigma}(i) \times \frac{1}{q}\vec{\nabla}_i\right] + \frac{1}{2}\vec{M}_{JJ}^{M}(q\vec{x}_i) \cdot \vec{\sigma}(i)$$

$$\Phi''_{JM} \equiv i\left[\frac{1}{q}\vec{\nabla}_i M_{JM}(q\vec{x}_i)\right] \cdot \left[\vec{\sigma}(i) \times \frac{1}{q}\vec{\nabla}_i\right]$$

In the long wavelength limit these correspond to various physical interpretations

X		$\frac{4\pi}{2J+1} W_X^{(p,p)}(0)$
M	spin-independent	Z^2
Σ''	spin-dependent (longitudinal)	$4\,\frac{J+1}{3J}\langle S_p\rangle^2$
Σ'	spin-dependent (transverse)	$8\,\frac{J+1}{3J}\langle S_p\rangle^2$
Δ	angular-momentum-dependent	$\frac{1}{2}\frac{J+1}{3J}\langle L_p\rangle^2$
Φ''	angular-momentum-and-spin-dependent	$\sim\langle \vec{S}_p \cdot \vec{L}_p\rangle^{2\text{a}}$

M.I. Gresham and K.M. Zurek, PRD 89 123521 (2014) arXiv:1401.3739

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

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

$$\Sigma''_{JM} \equiv \left\{\frac{1}{q}\vec{\nabla}_i M_{JM}(q\vec{x}_i)\right\} \cdot \vec{\sigma}(i)$$

$$\tilde{\Phi}'_{JM} \equiv \left[\frac{1}{q}\vec{\nabla}_i \times \vec{M}_{JJ}^{M}(q\vec{x}_i)\right] \cdot \left[\vec{\sigma}(i) \times \frac{1}{q}\vec{\nabla}_i\right] + \frac{1}{2}\vec{M}_{JJ}^{M}(q\vec{x}_i) \cdot \vec{\sigma}(i)$$

$$\Phi''_{JM} \equiv i\left[\frac{1}{q}\vec{\nabla}_i M_{JM}(q\vec{x}_i)\right] \cdot \left[\vec{\sigma}(i) \times \frac{1}{q}\vec{\nabla}_i\right]$$

Projection	Charge/current	Operator	Even J	Odd J
Charge	Vector charge	M_{JM}	E-E	O-O
Charge	Axial-vector charge	$\tilde{\Omega}_{JM}$	O-E	E-O
Longitudinal	Spin current	Σ''_{JM}	O-O	E-E
Transverse magnetic	"	Σ_{JM}	E-O	O-E
Transverse electric	"	Σ'_{JM}	O-O	E-E
Longitudinal	Convection current	$\tilde{\Delta}''_{JM}$	E-O	O-E
Transverse magnetic	"	Δ_{JM}	O-O	E-E
Transverse electric	"	Δ'_{JM}	E-O	O-E
Longitudinal	Spin-velocity current	Φ''_{JM}	E-E	O-O
Transverse magnetic	"	$\tilde{\Phi}_{JM}$	O-E	E-O
Transverse electric	"	$\tilde{\Phi}'_{JM}$	E-E	O-O

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

$$\frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\sum_{\text{spins}}|\mathcal{M}|^2 \equiv \sum_k \sum_{\tau=0,1}\sum_{\tau'=0,1} R_k\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}, \left\{c_i^\tau c_j^{\tau'}\right\}\right)\ W_k^{\tau\tau'}(\vec{q}^{\,2}b^2)$$

$$
\begin{aligned}
R_M^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2}c_5^\tau c_5^{\tau'} + \vec{v}_T^{\perp 2}c_8^\tau c_8^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2}c_{11}^\tau c_{11}^{\tau'}\right] \\
R_{\Phi''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{\vec{q}^{\,2}}{4m_N^2}c_3^\tau c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2}c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2}c_{15}^{\tau'}\right) \\
R_{\Phi'' M}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= c_3^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2}c_{15}^\tau\right)c_{11}^{\tau'} \\
R_{\tilde{\Phi}'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{j_\chi(j_\chi+1)}{12}\left[c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2}c_{13}^\tau c_{13}^{\tau'}\right] \\
R_{\Sigma''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{\vec{q}^{\,2}}{4m_N^2}c_{10}^\tau c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \right. \\
&\left. \frac{\vec{q}^{\,2}}{m_N^2}(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}) + \frac{\vec{q}^{\,4}}{m_N^4}c_6^\tau c_6^{\tau'} + \vec{v}_T^{\perp 2}c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2}c_{13}^\tau c_{13}^{\tau'}\right] \\
R_{\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{1}{8}\left[\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2}c_3^\tau c_3^{\tau'} + \vec{v}_T^{\perp 2}c_7^\tau c_7^{\tau'}\right] + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \right. \\
&\left. \frac{\vec{q}^{\,2}}{m_N^2}c_9^\tau c_9^{\tau'} + \frac{\vec{v}_T^{\perp 2}}{2}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2}c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2}c_{15}^{\tau'}\right) + \frac{\vec{q}^{\,2}}{2m_N^2}\vec{v}_T^{\perp 2}c_{14}^\tau c_{14}^{\tau'}\right] \\
R_{\Delta}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{\,2}}{m_N^2}c_5^\tau c_5^{\tau'} + c_8^\tau c_8^{\tau'}\right] \\
R_{\Delta\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{j_\chi(j_\chi+1)}{3}\left[c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right].
\end{aligned}
$$

DM response functions

Operator interference is in evidence

Nuclear response functions

$$W_M^{\tau\tau'}(y) = \sum_{J=0,2,\ldots}^{\infty} \langle j_N || \; M_{J;\tau}(q) \; || j_N \rangle \langle j_N || \; M_{J;\tau'}(q) \; || j_N \rangle$$

$$W_{\Sigma''}^{\tau\tau'}(y) = \sum_{J=1,3,\ldots}^{\infty} \langle j_N || \; \Sigma''_{J;\tau}(q) \; || j_N \rangle \langle j_N || \; \Sigma''_{J;\tau'}(q) \; || j_N \rangle$$

$$W_{\Sigma'}^{\tau\tau'}(y) = \sum_{J=1,3,\ldots}^{\infty} \langle j_N || \; \Sigma'_{J;\tau}(q) \; || j_N \rangle \langle j_N || \; \Sigma'_{J;\tau'}(q) \; || j_N \rangle$$

$$W_{\Phi''}^{\tau\tau'}(y) = \sum_{J=0,2,\ldots}^{\infty} \langle j_N || \; \Phi''_{J;\tau}(q) \; || j_N \rangle \langle j_N || \; \Phi''_{J;\tau'}(q) \; || j_N \rangle$$

$$W_{\Phi'' M}^{\tau\tau'}(y) = \sum_{J=0,2,\ldots}^{\infty} \langle j_N || \; \Phi''_{J;\tau}(q) \; || j_N \rangle \langle j_N || \; M_{J;\tau'}(q) \; || j_N \rangle$$

$$W_{\tilde{\Phi}'}^{\tau\tau'}(y) = \sum_{J=2,4,\ldots}^{\infty} \langle j_N || \; \tilde{\Phi}'_{J;\tau}(q) \; || j_N \rangle \langle j_N || \; \tilde{\Phi}'_{J;\tau'}(q) \; || j_N \rangle$$

$$W_{\Delta}^{\tau\tau'}(y) = \sum_{J=1,3,\ldots}^{\infty} \langle j_N || \; \Delta_{J;\tau}(q) \; || j_N \rangle \langle j_N || \; \Delta_{J;\tau'}(q) \; || j_N \rangle$$

$$W_{\Delta\Sigma'}^{\tau\tau'}(y) = \sum_{J=1,3,\ldots}^{\infty} \langle j_N || \; \Delta_{J;\tau}(q) \; || j_N \rangle \langle j_N || \; \Sigma'_{J;\tau'}(q) \; || j_N \rangle .$$

Response function interference occurs

Within this framework

- Include general dark matter particle types
- Include general mediator particle types
- Explore possible operator degeneracies
- Determine the dominant operators
- Determine distinguishability at detectors
- Connect to models for astrophysical and collider searches

Simplified models for tree-level, renormalizable interactions have been examined

single dark matter particle, single mediator

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, PRD, arXiv: 1505.03117

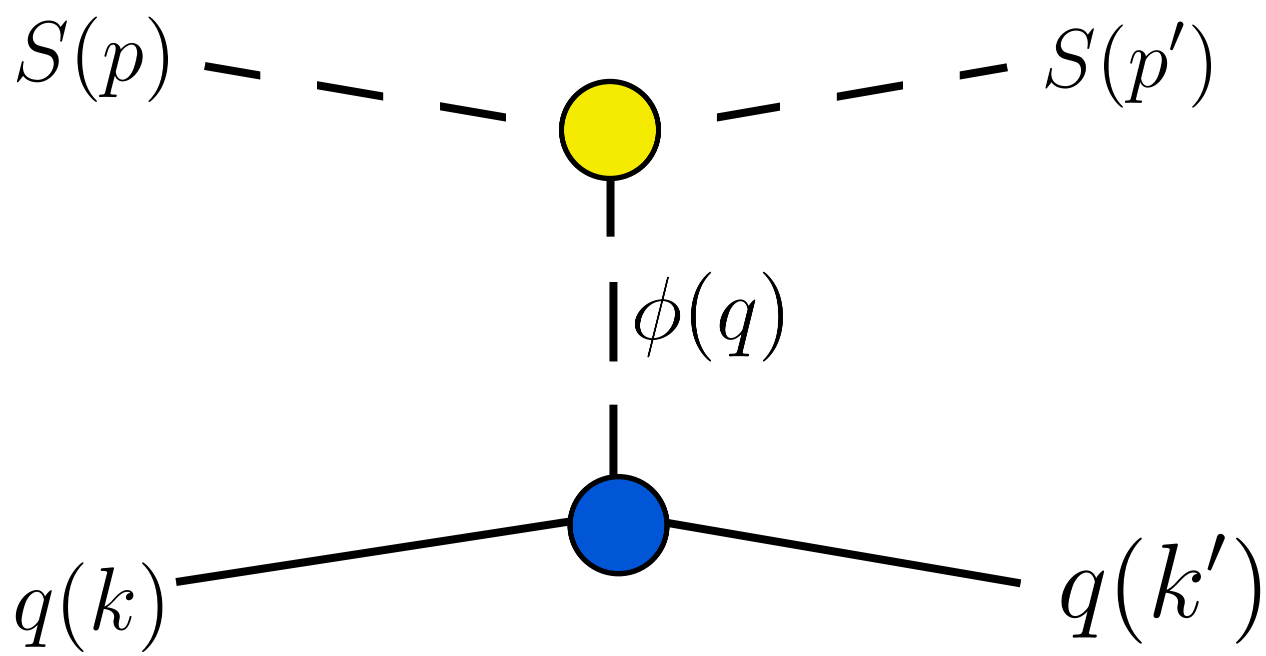
non-relativistic
reduction
match onto dark matter
and nuclear responses

$q\phi \quad \phi\chi$

$\mathcal{L}$ →  → $\frac{dR}{dE_R}$

Typically one integrates out the mediator, which amounts to assuming the mediator mass is much larger than the recoil momentum of the interaction

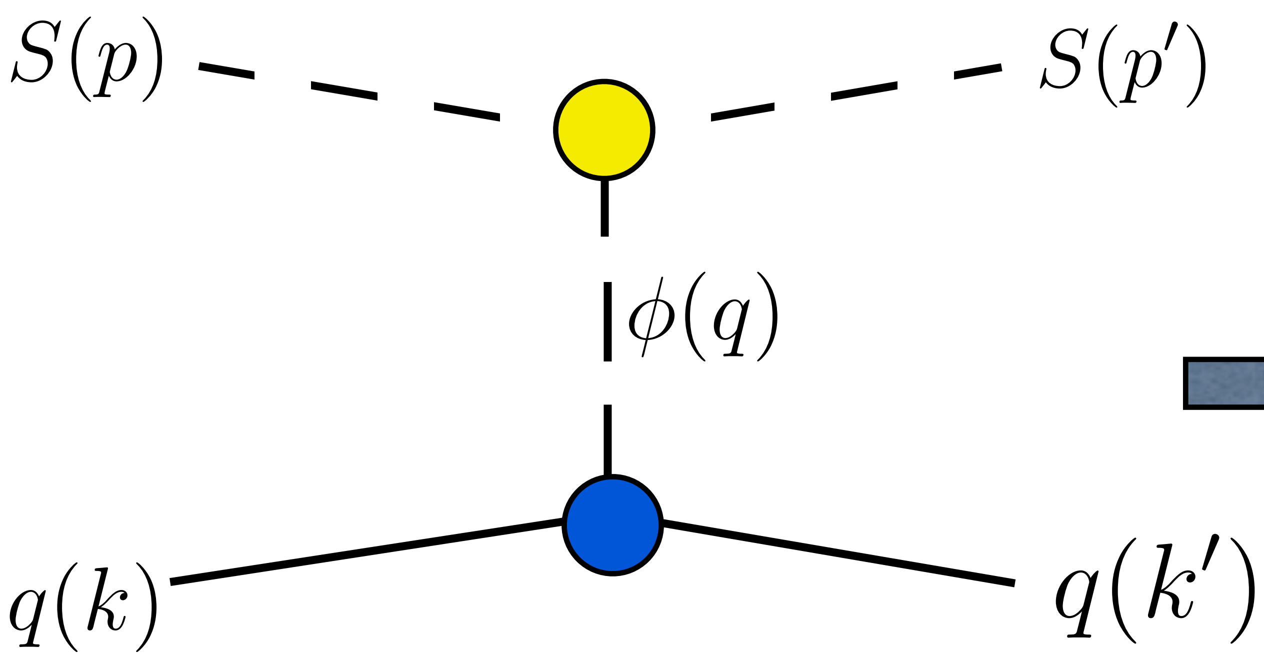
$$m_\phi^2 \gg q^2 = (p' - p)^2$$

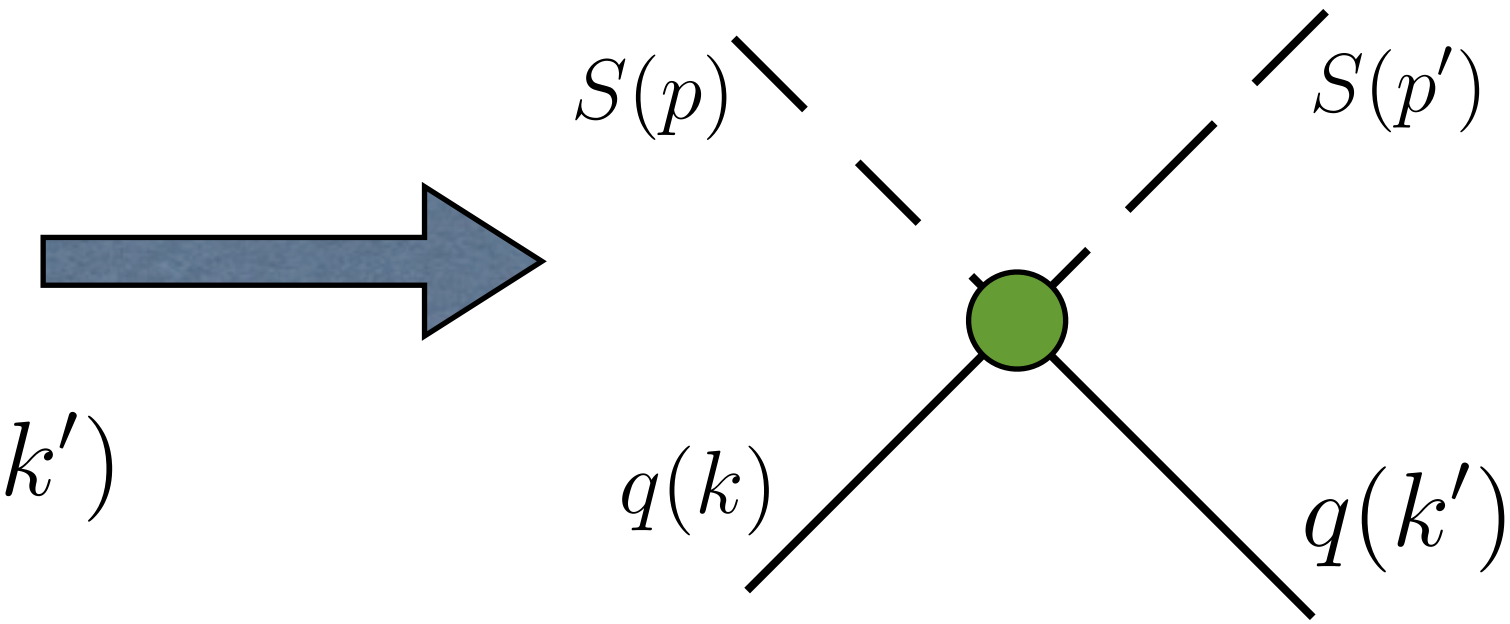


$$\begin{aligned}\mathcal{L}_{S\phi q} = \partial_\mu S^\dagger \partial^\mu S - m_S^2 S^\dagger S - \frac{\lambda_S}{2}(S^\dagger S)^2 \\ + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{m_\phi \mu_1}{3}\phi^3 - \frac{\mu_2}{4}\phi^4 \\ + i\bar{q}\not{D} q - m_q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

Typically one integrates out the mediator, which amounts to assuming the mediator mass is much larger than the recoil momentum of the interaction

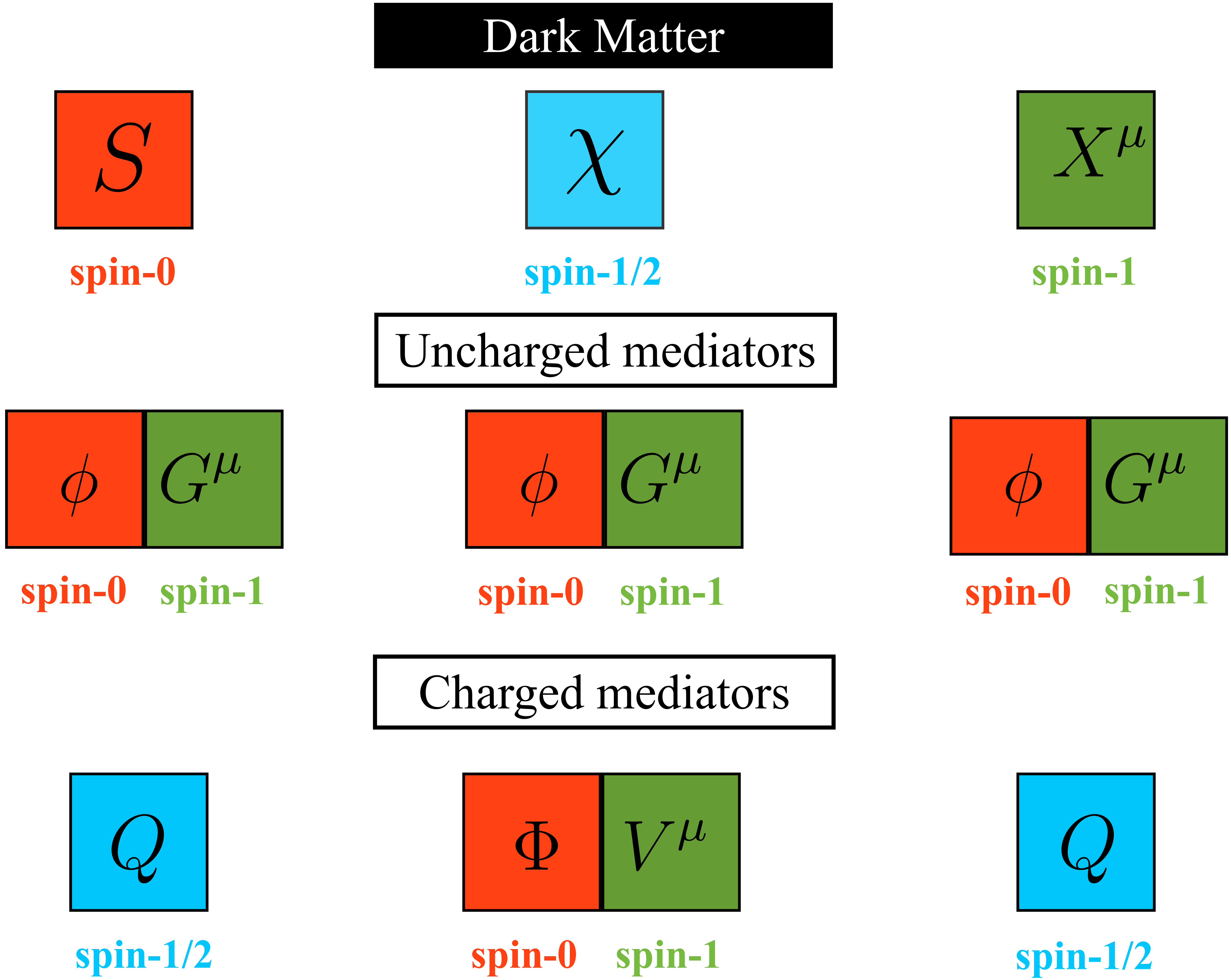
$$m_\phi^2 \gg q^2 = (p' - p)^2$$





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

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



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

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

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

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

$$S_{ij} = \tfrac{1}{2}\left(\epsilon_i^\dagger \epsilon_j + \epsilon_j^\dagger \epsilon_i\right)$$

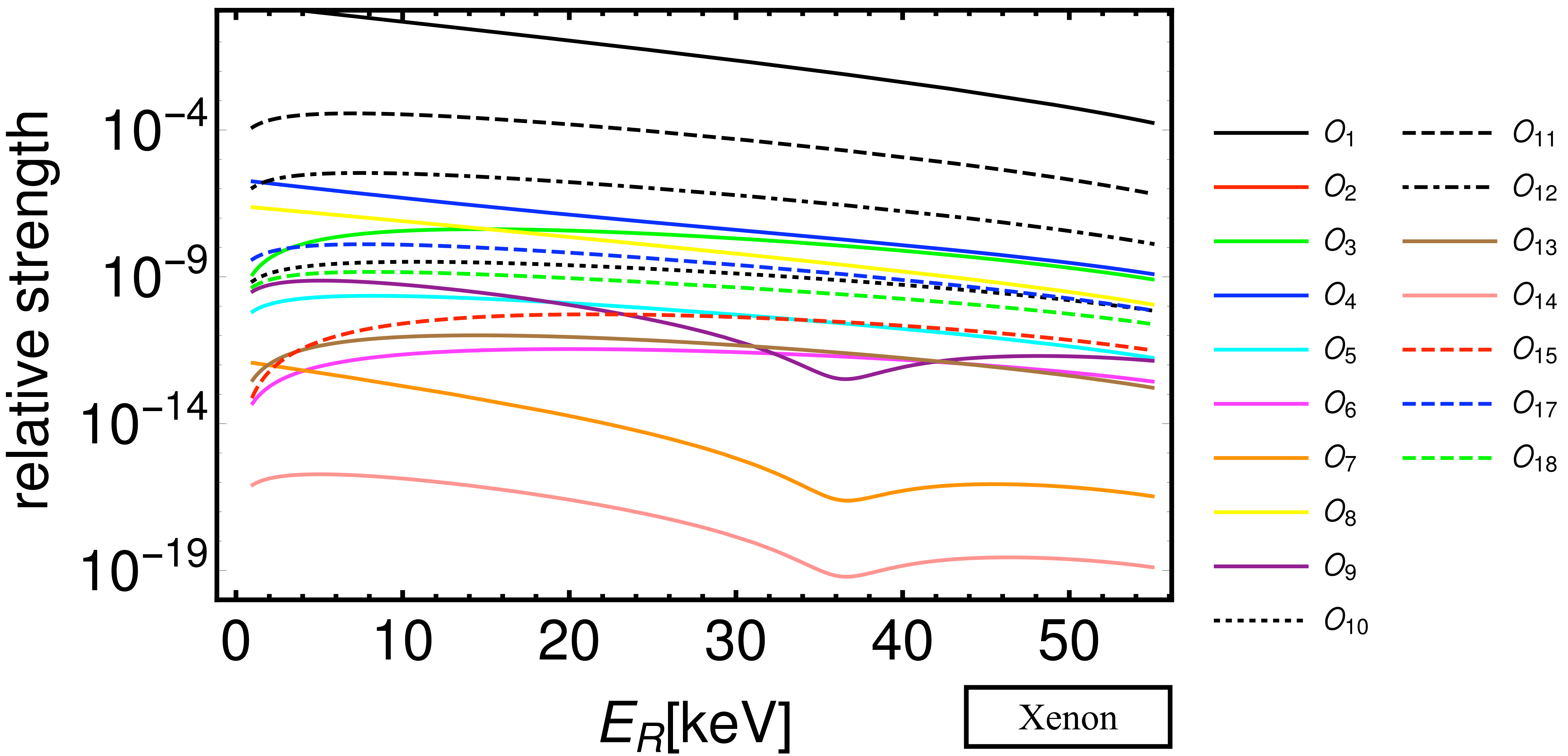
J. Fan, M. Reece, and L-T. Wang, JCAP 1011 (2010) 042, arXiv:1008.1591

J. Hisano, K. Ishiwata, N. Nagata, M. Yamanaka, Prog.Theor.Phys. 126 (2011), arXiv:1012.5455

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

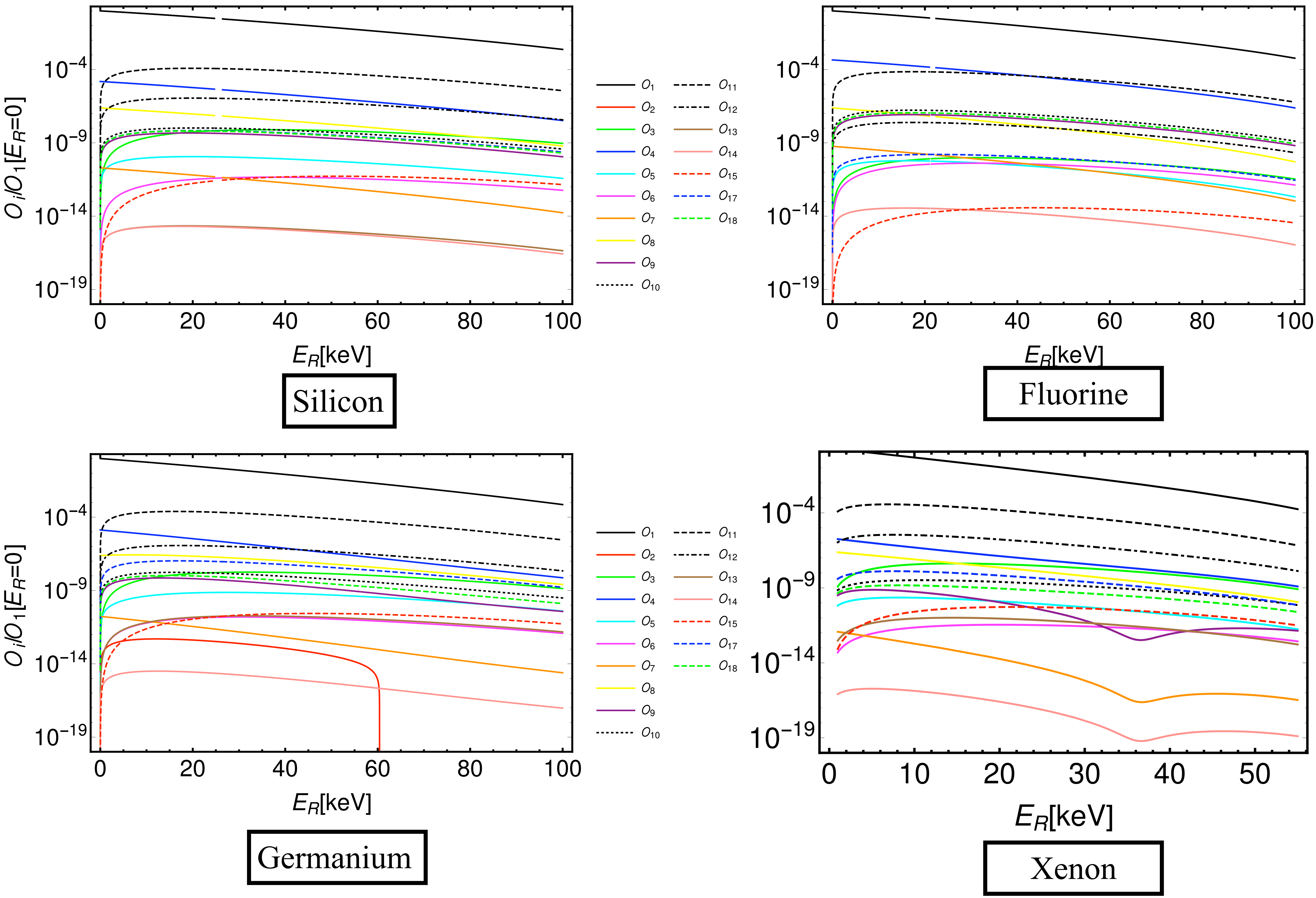
- Some EFT O_i terms do not appear at leading order

- As expected/known degeneracies arise and non-standard interactions are found to dominate for certain interaction types

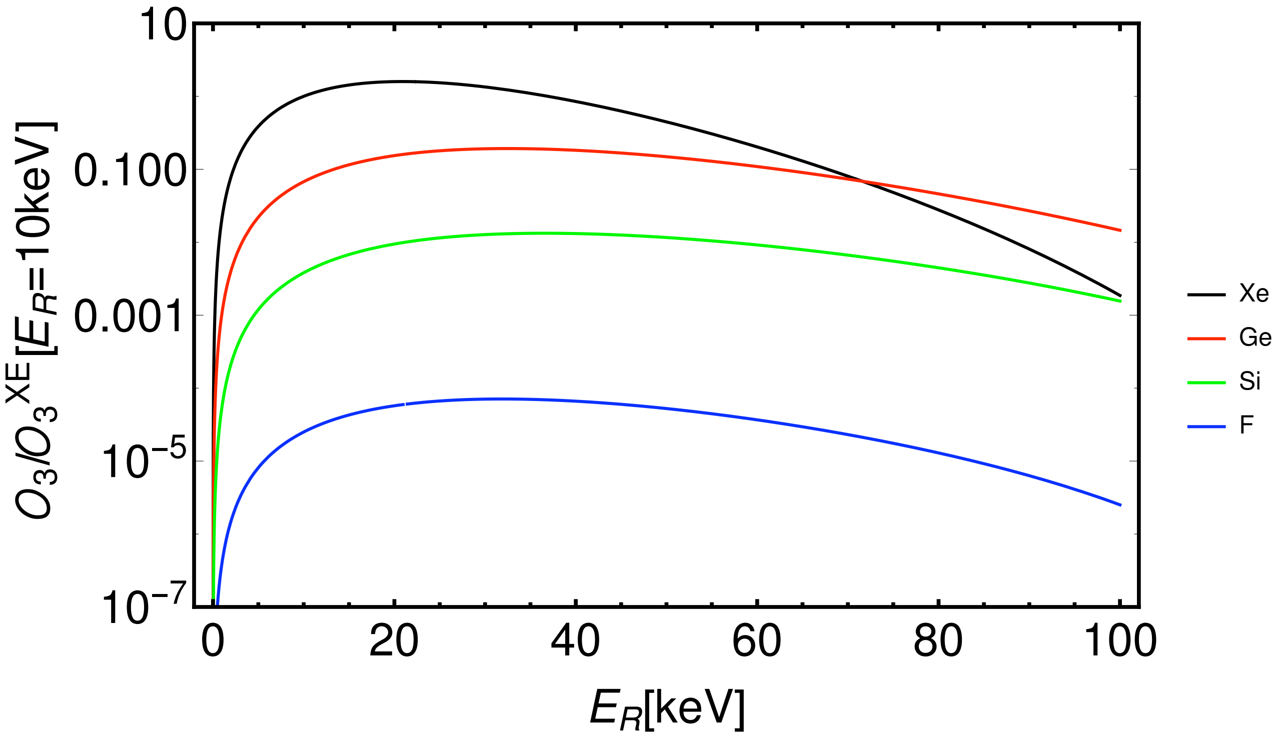


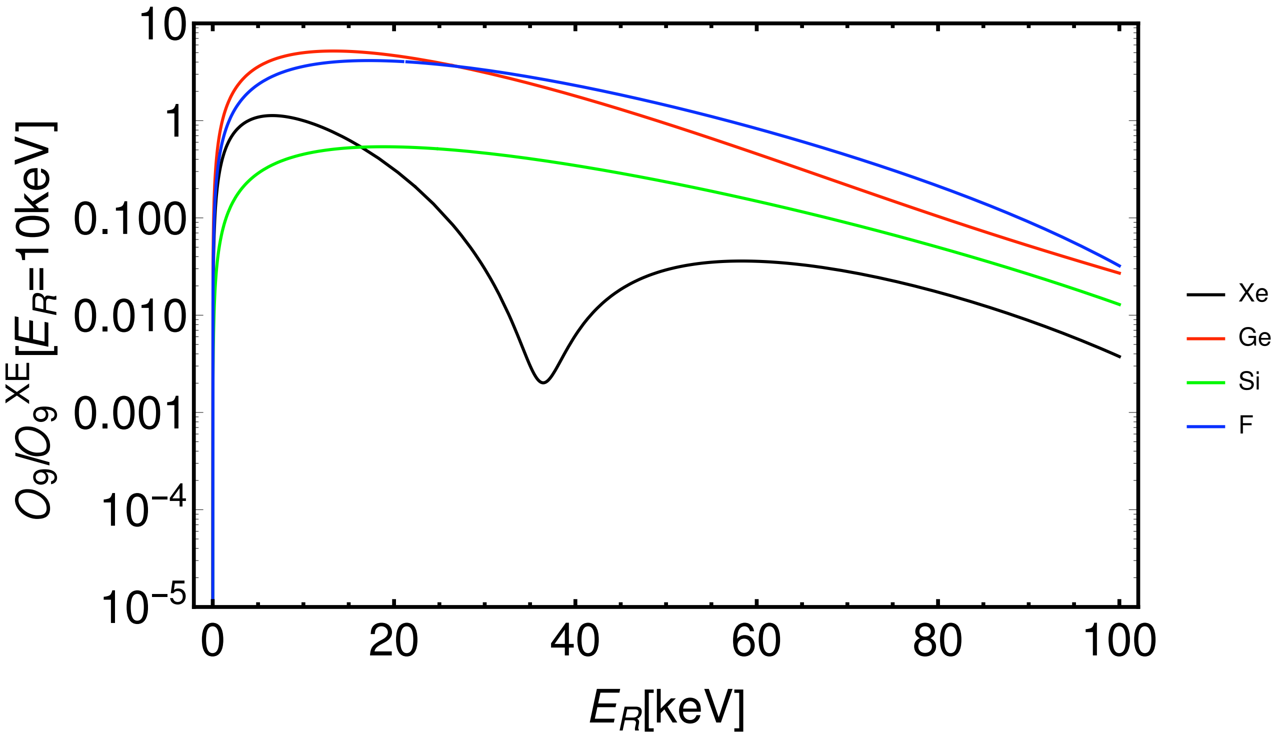
Relative strength of operators, in order to compare which operators dominate when more than one are present

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



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





$\mathcal{O}_3$ $\quad i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$

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

Response of a given operator shown for various target elements

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

- Two non-relativistic operators, O_1 and O_{10}, are ubiquitous, arising for all WIMP spins 0, 1/2, and 1

$$1_\chi 1_N \qquad i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$$

- In five scenarios for spin 0, 1/2, or 1 dark matter, 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)											✓							

S

spin-0

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

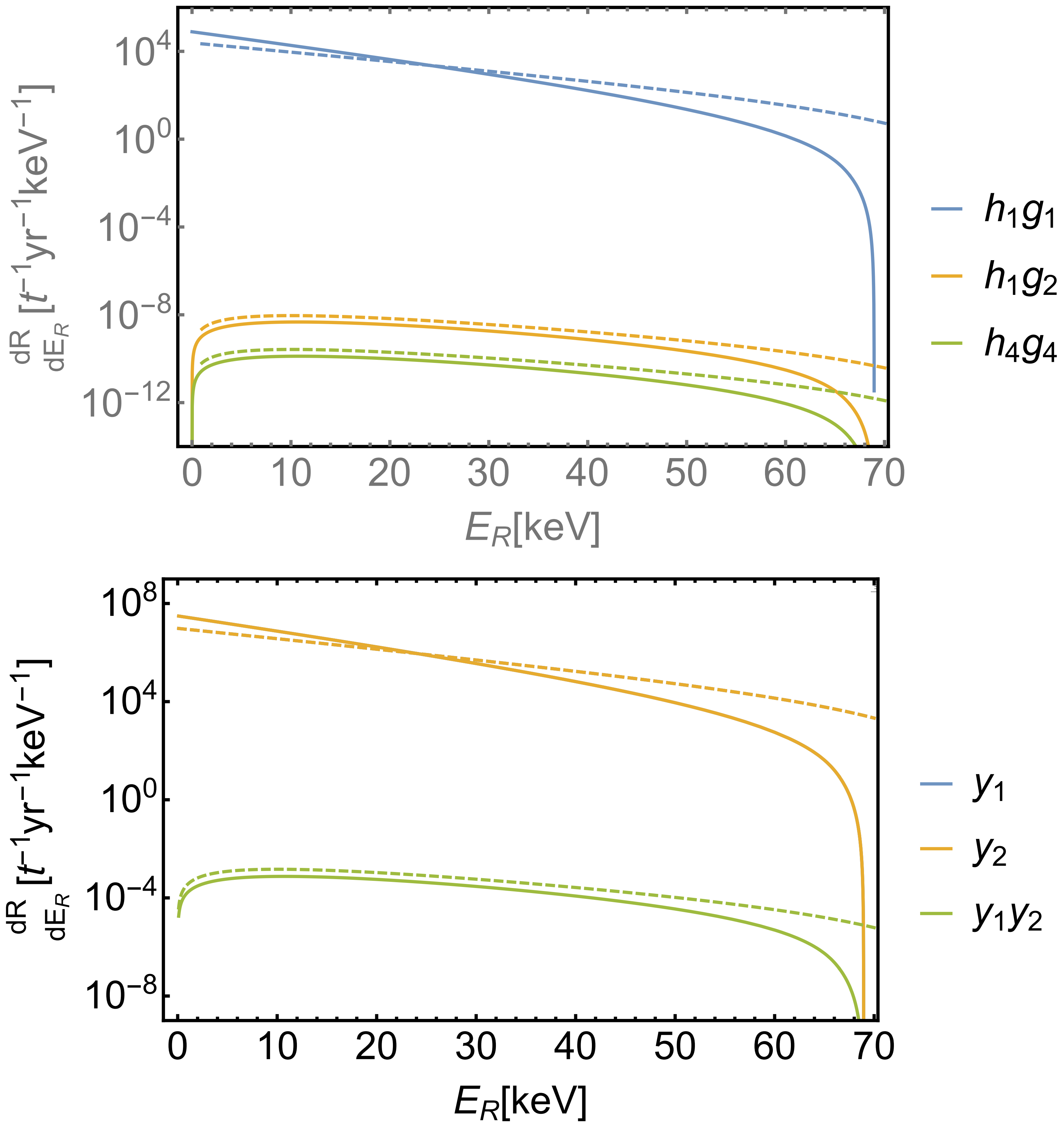
$\mathcal{O}_1$ $1_\chi 1_N$

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

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

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

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



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

χ **spin-1/2**

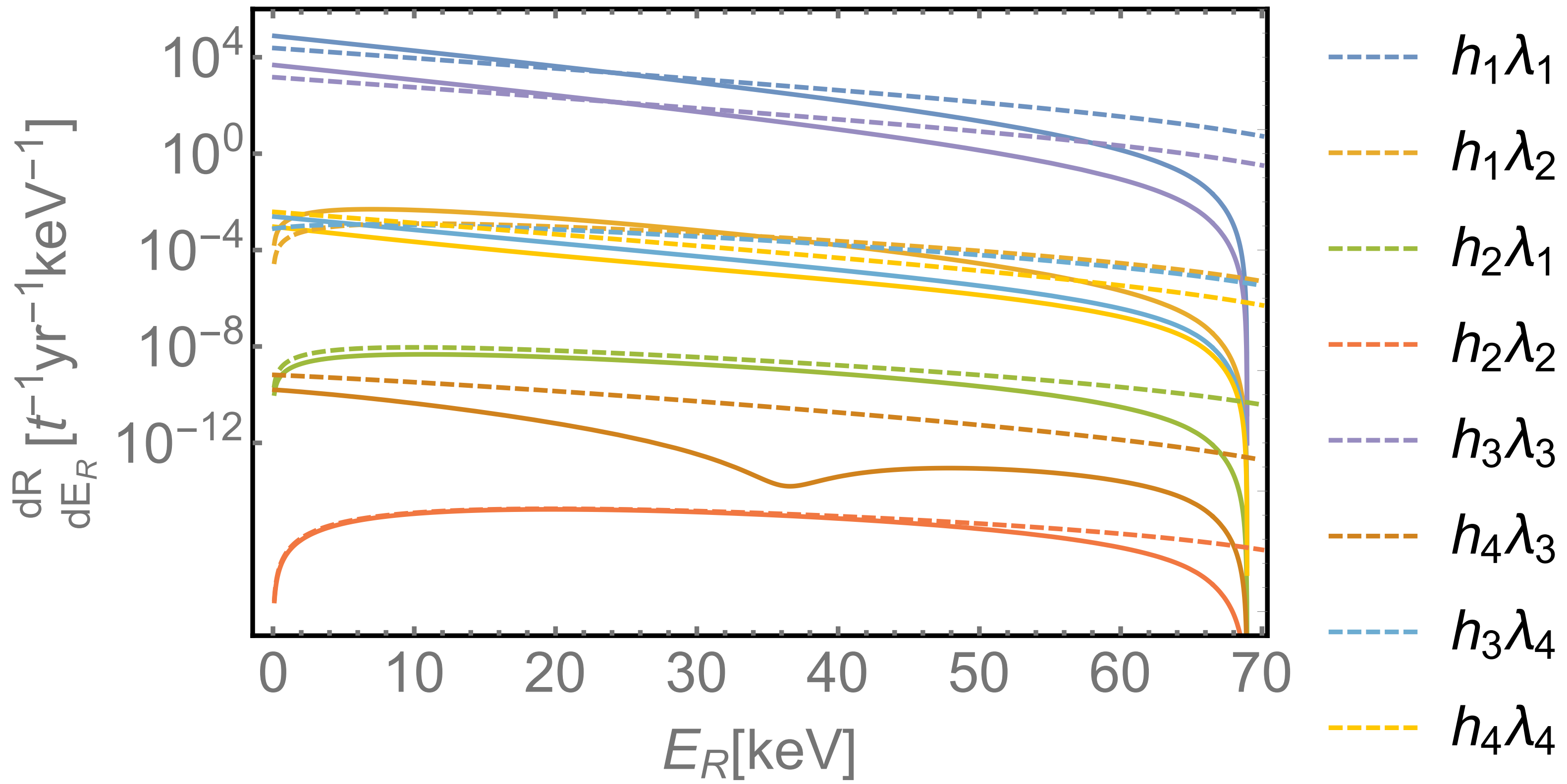
Scalar Mediator		
$\bar{\chi}\chi\bar{q}q$	$\longrightarrow$	$\left(\frac{h_1^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_1$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_{10}$
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\longrightarrow$	$\left(-\frac{h_1^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_{11}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_6$

Vector Mediator		
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\left(-\frac{h_3^N\lambda_3}{m_G^2}\right)\mathcal{O}_1$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\left(-\frac{2h_4^N\lambda_3}{m_G^2}\right)\left(-\mathcal{O}_7+\frac{m_N}{m_\chi}\mathcal{O}_9\right)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\left(-\frac{2h_3^N\lambda_4}{m_G^2}\right)(\mathcal{O}_8+\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\left(\frac{4h_4^N\lambda_4}{m_G^2}\right)\mathcal{O}_4$

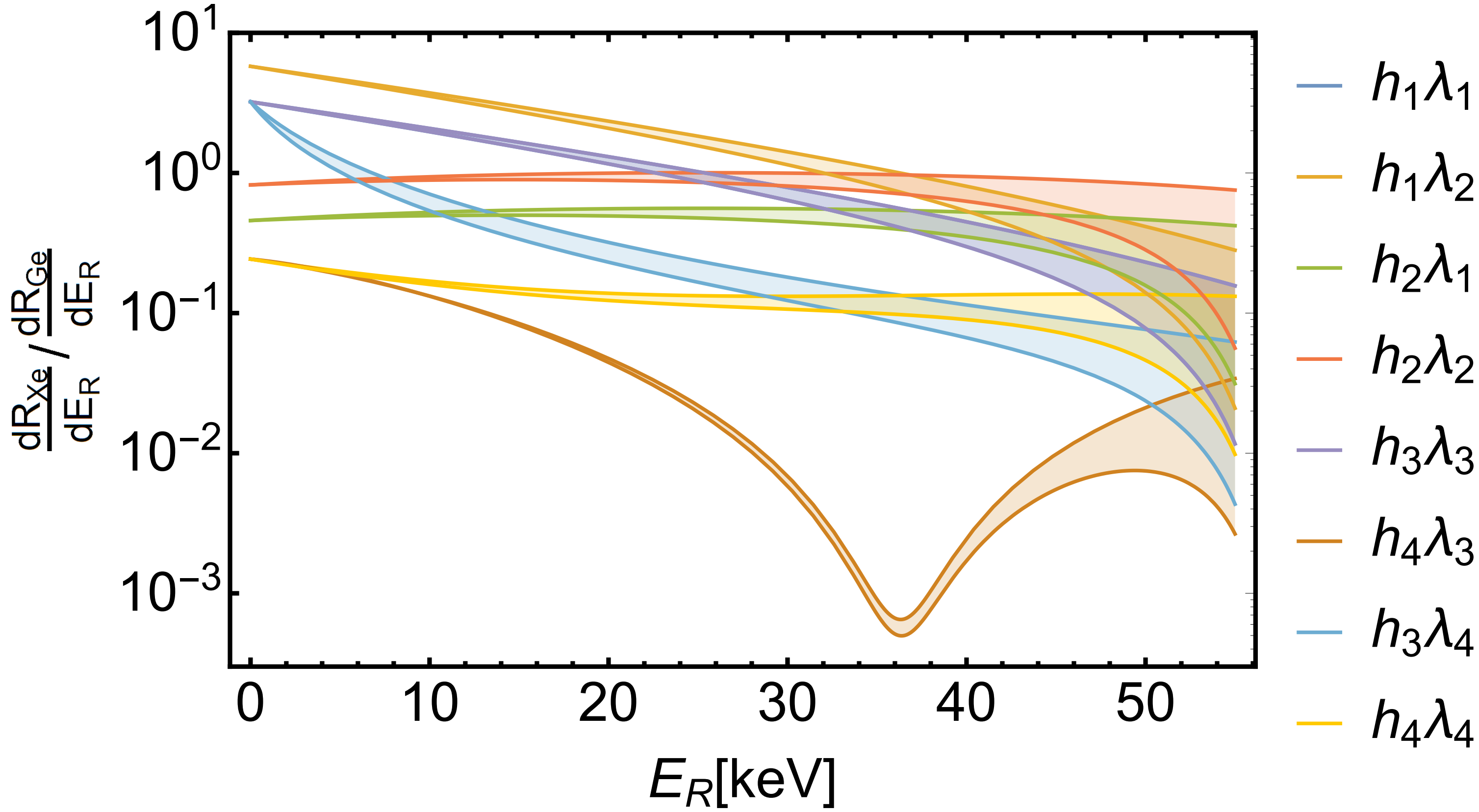
Charged Scalar Mediator		
$\bar{\chi}\chi\bar{q}q$	$\longrightarrow$	$\frac{l_2^\dagger l_2-l_1^\dagger l_1}{4m_\Phi^2}f_{Tq}^N\mathcal{O}_1$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$i\frac{l_1^\dagger l_2-l_2^\dagger l_1}{4m_\Phi^2}\Delta\tilde{q}^N\mathcal{O}_{10}$
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\longrightarrow$	$i\frac{l_2^\dagger l_1-l_1^\dagger l_2}{4m_\Phi^2}\frac{m_N}{m_\chi}f_{Tq}^N\mathcal{O}_{11}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\frac{l_1^\dagger l_1-l_2^\dagger l_2}{4m_\Phi^2}\frac{m_N}{m_\chi}\Delta\tilde{q}^N\mathcal{O}_6$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$-\frac{l_1^\dagger l_1+l_2^\dagger l_2}{4m_\Phi^2}\mathcal{N}_q^N\mathcal{O}_1$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\frac{l_1^\dagger l_2+l_2^\dagger l_1}{2m_\Phi^2}\mathcal{N}_q^N(\mathcal{O}_8+\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\frac{l_1^\dagger l_2+l_2^\dagger l_1}{2m_\Phi^2}\Delta_q^N(\mathcal{O}_7-\frac{m_N}{m_\chi}\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$-\frac{l_1^\dagger l_1+l_2^\dagger l_2}{m_\Phi^2}\Delta_q^N\mathcal{O}_4$
$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$\longrightarrow$	$\frac{l_2^\dagger l_2-l_1^\dagger l_1}{m_\Phi^2}\delta_q^N\mathcal{O}_4$
$\epsilon_{\mu\nu\alpha\beta}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma^{\alpha\beta}q$	$\longrightarrow$	$\frac{l_2^\dagger l_1-l_1^\dagger l_2}{m_\Phi^2}\delta_q^N(i\mathcal{O}_{10}-i\frac{m_N}{m_\chi}\mathcal{O}_{11}+4\mathcal{O}_{12})$

Charged Vector Mediator		
$\bar{\chi}\chi\bar{q}q$	$\longrightarrow$	$\frac{d_2^\dagger d_2-d_1^\dagger d_1}{4m_V^2}f_{Tq}^N\mathcal{O}_1$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$i\frac{d_2^\dagger d_1-d_1^\dagger d_2}{4m_V^2}\Delta\tilde{q}^N\mathcal{O}_{10}$
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\longrightarrow$	$i\frac{d_2^\dagger d_1-d_1^\dagger d_2}{4m_V^2}\frac{m_N}{m_\chi}f_{Tq}^N\mathcal{O}_{11}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\frac{d_2^\dagger d_2-d_1^\dagger d_1}{4m_V^2}\frac{m_N}{m_\chi}\Delta\tilde{q}^N\mathcal{O}_6$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\frac{d_2^\dagger d_2+d_1^\dagger d_1}{8m_V^2}\mathcal{N}_q^N\mathcal{O}_1$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$-\frac{d_2^\dagger d_1+d_1^\dagger d_2}{4m_V^2}\mathcal{N}_q^N(\mathcal{O}_8+\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\frac{d_2^\dagger d_1+d_1^\dagger d_2}{4m_V^2}\Delta_q^N(\mathcal{O}_7-\frac{m_N}{m_\chi}\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$-\frac{d_2^\dagger d_2+d_1^\dagger d_1}{2m_V^2}\Delta_q^N\mathcal{O}_4$

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

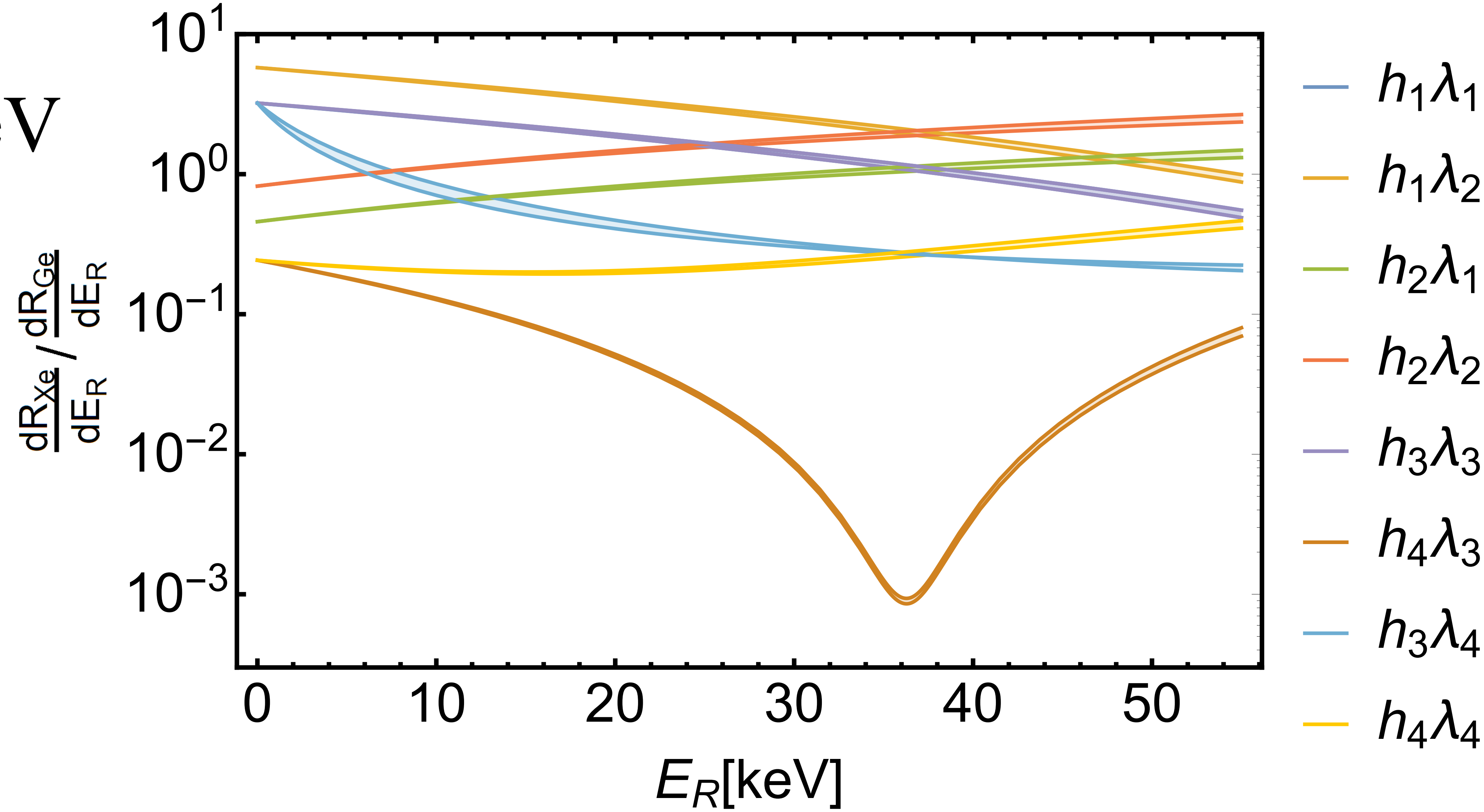


50GeV



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

500GeV



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)											✓	✓	✓					✓

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

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

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

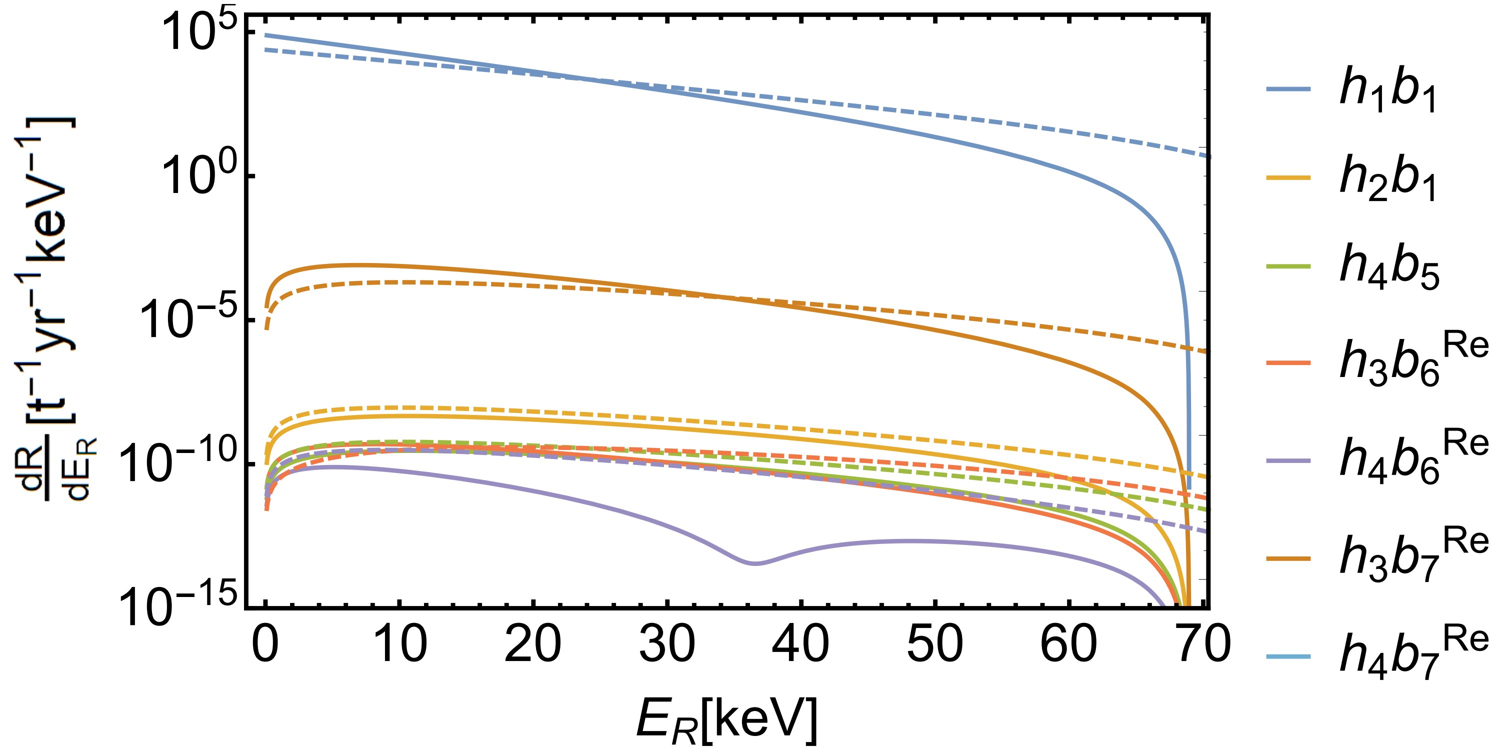
$\mathcal{O}_{17}$ $\quad i\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp$

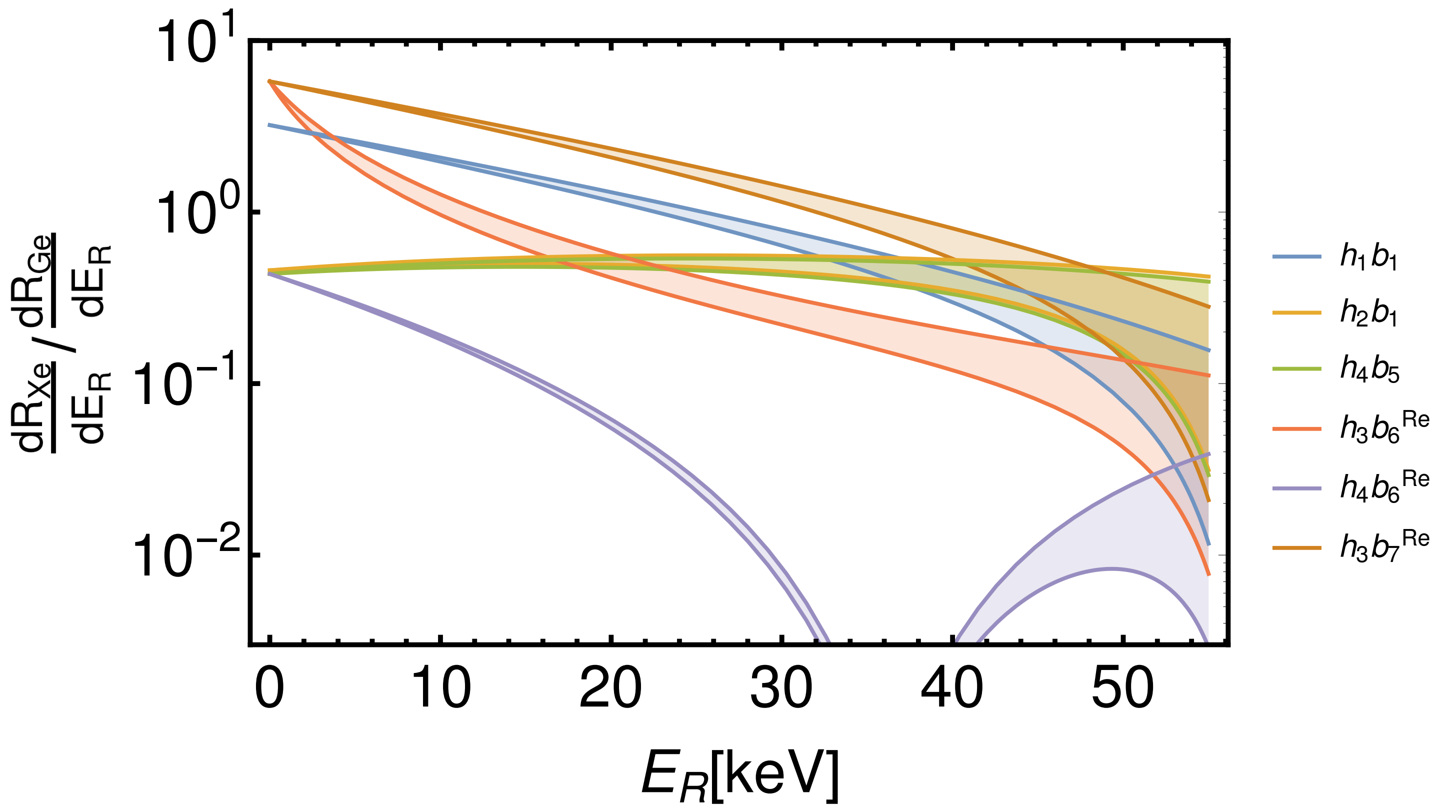
$\mathcal{O}_{18}$ $\quad i\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N$

$$X^\mu$$

spin-1

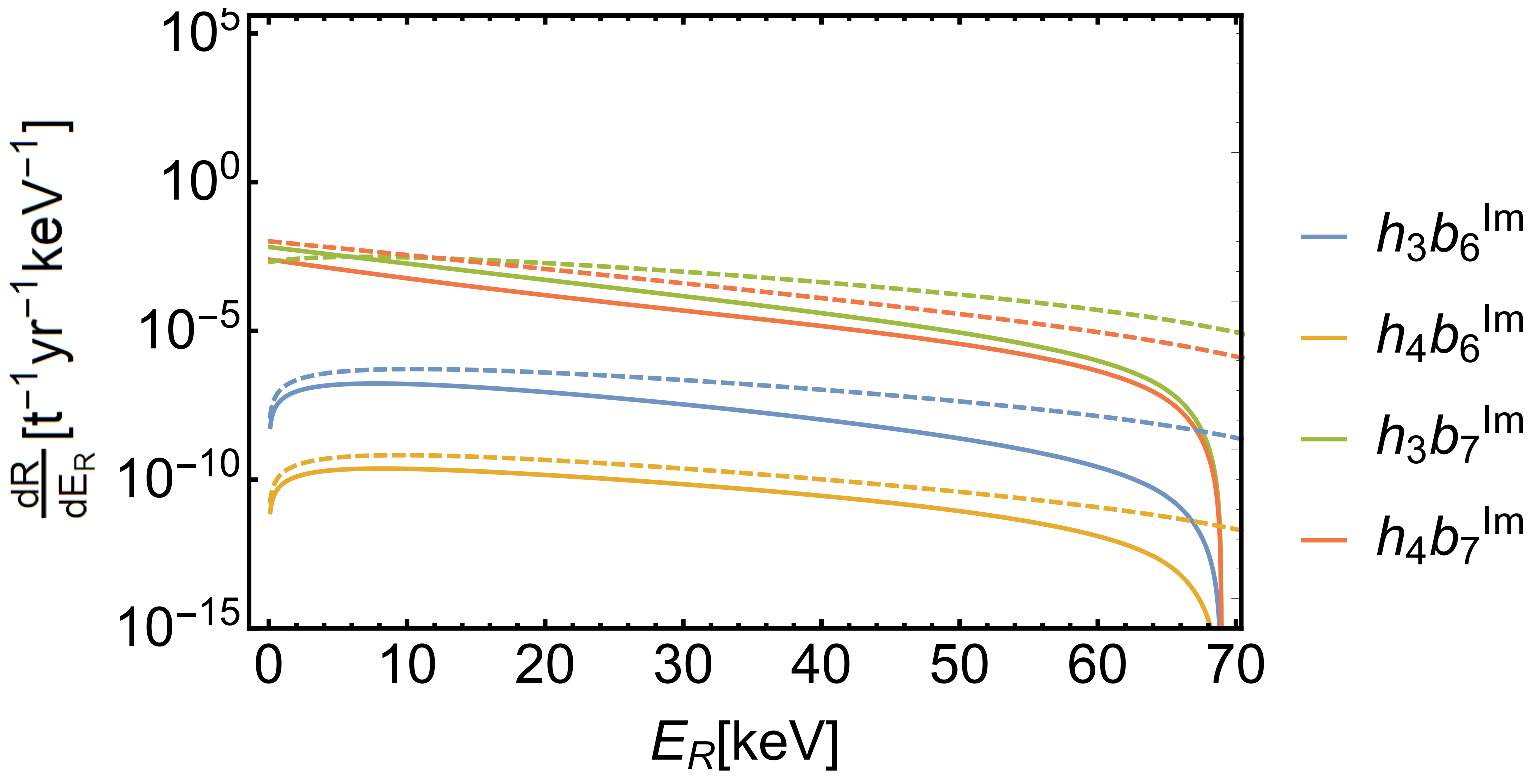
$\partial_\nu (X^{\nu\dagger} X_\mu + X^\dagger_\mu X^\nu)(\bar{q}\gamma^\mu q)$	$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\epsilon_{\mu\nu\rho\sigma} \left(X^{\nu\dagger} \partial^\rho X^\sigma + X^\nu \partial^\rho X^{\sigma\dagger} \right) (\bar{q}\gamma^\mu q)$	$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\partial_\nu (X^{\nu\dagger} X_\mu - X^\dagger_\mu X^\nu)(\bar{q}\gamma^\mu q)$	$\mathcal{O}_{17}$	$i\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp$
$\partial_\nu (X^{\nu\dagger} X_\mu - X^\dagger_\mu X^\nu)(\bar{q}\gamma^\mu \gamma^5 q)$	$\mathcal{O}_{18}$	$i\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N$

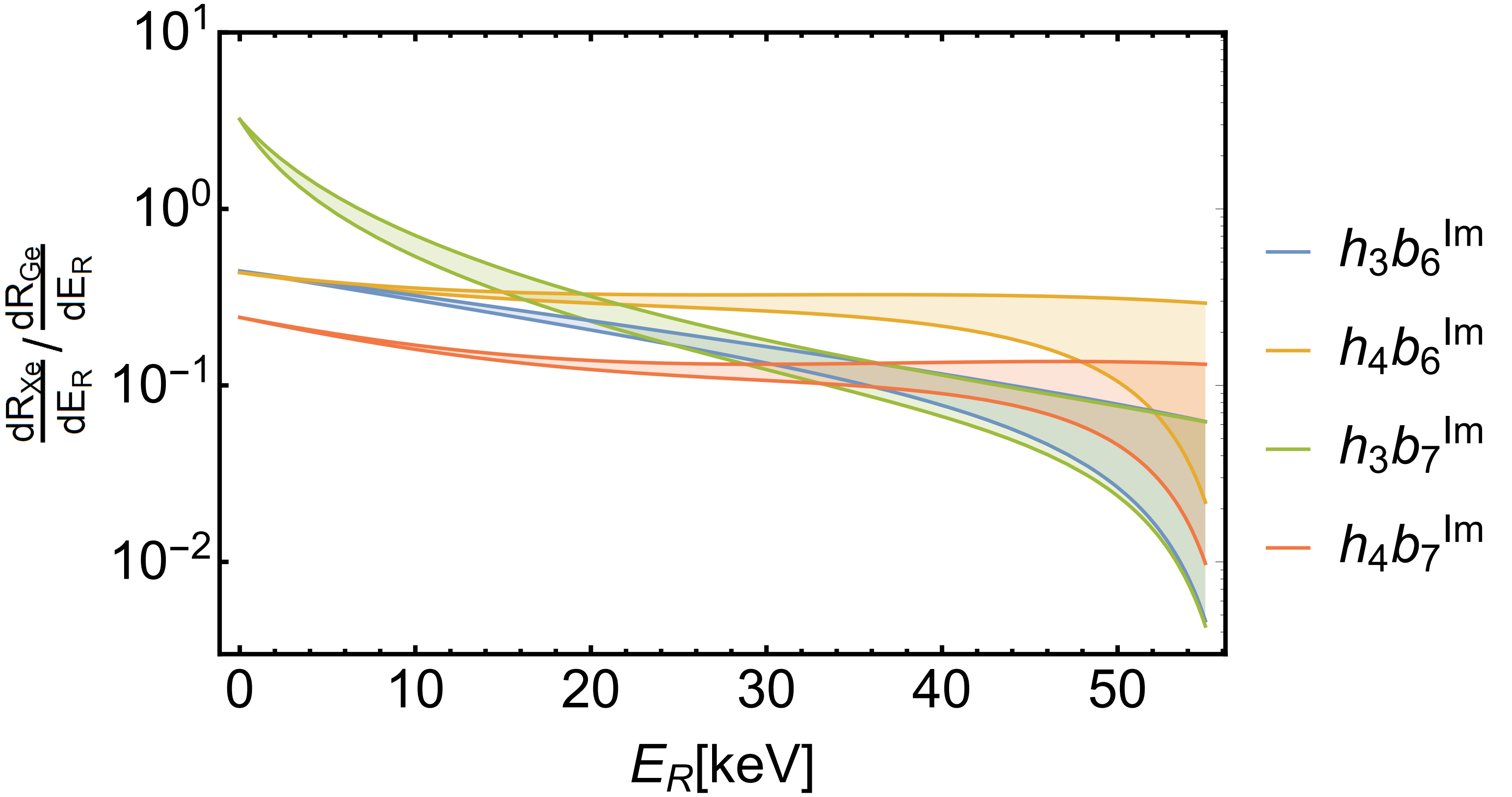




50 GeV spin-1 WIMP off of ^{73}Ge (dashed) and ^{131}Xe (solid)

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

Interference Effects

In the full amplitude, two types of interference effects arise

$$c_i^{\tau} c_j^{\tau'}$$

isoscalar/isovector

operator/operator

$\mathcal{O}_1/\mathcal{O}_3$

$\mathcal{O}_4/\mathcal{O}_5$

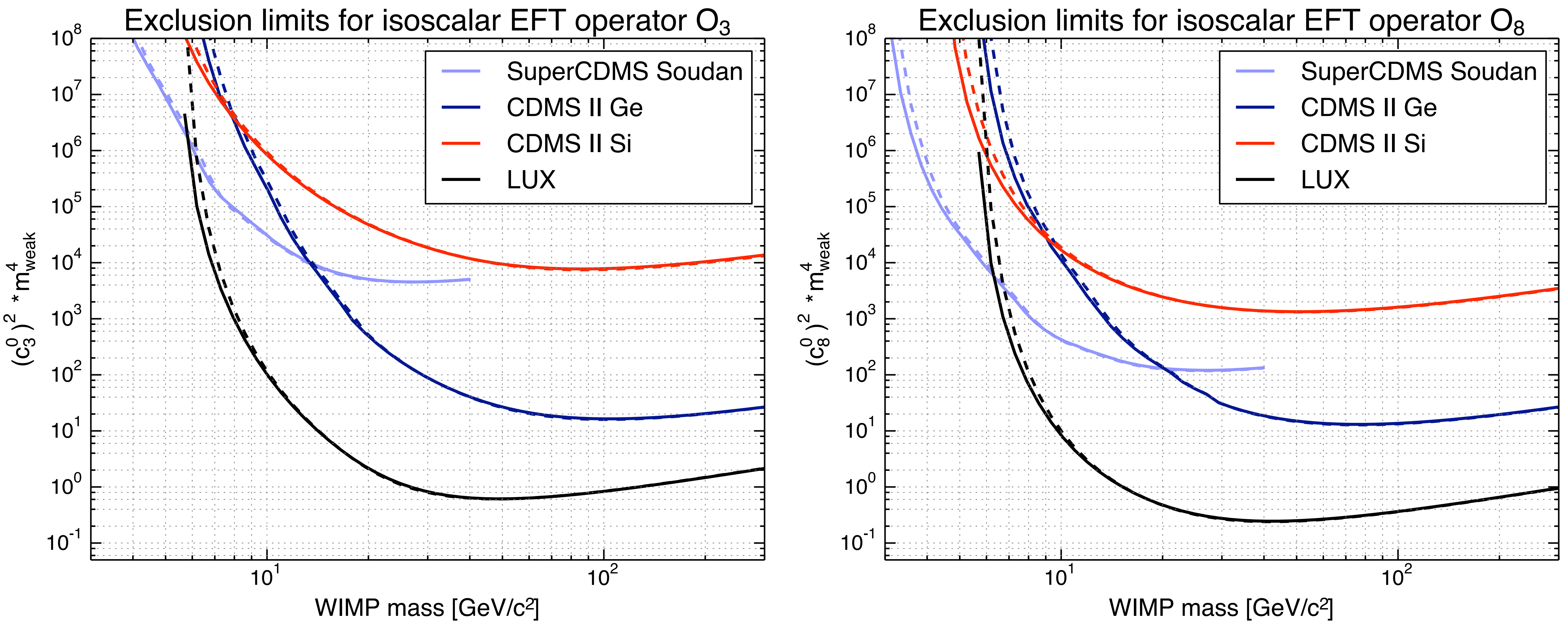
$\mathcal{O}_4/\mathcal{O}_6$

$\mathcal{O}_8/\mathcal{O}_9$

$\mathcal{O}_{11}/\mathcal{O}_{12}$

$\mathcal{O}_{11}/\mathcal{O}_{15}$

$\mathcal{O}_{12}/\mathcal{O}_{15}$

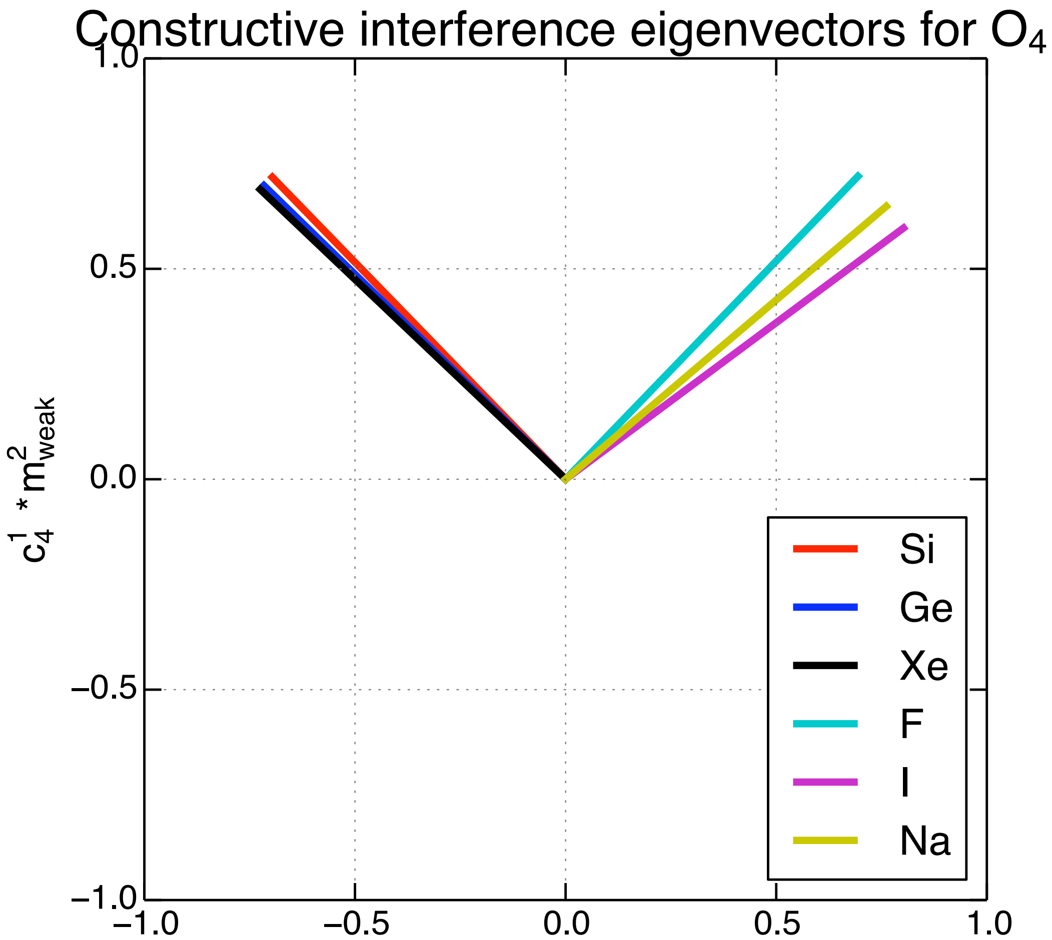


The SuperCDMS collaboration examined the sensitivity of current and upcoming experiments to non-standard operators with an eye on interference effects.

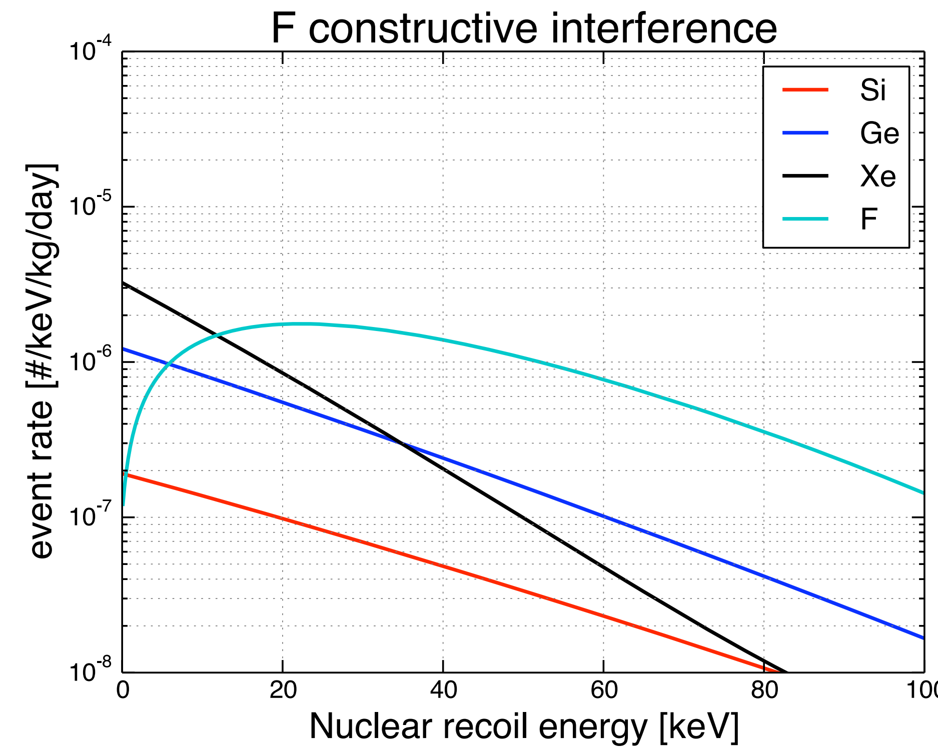
They also studied the effects of a non-SHM velocity distribution

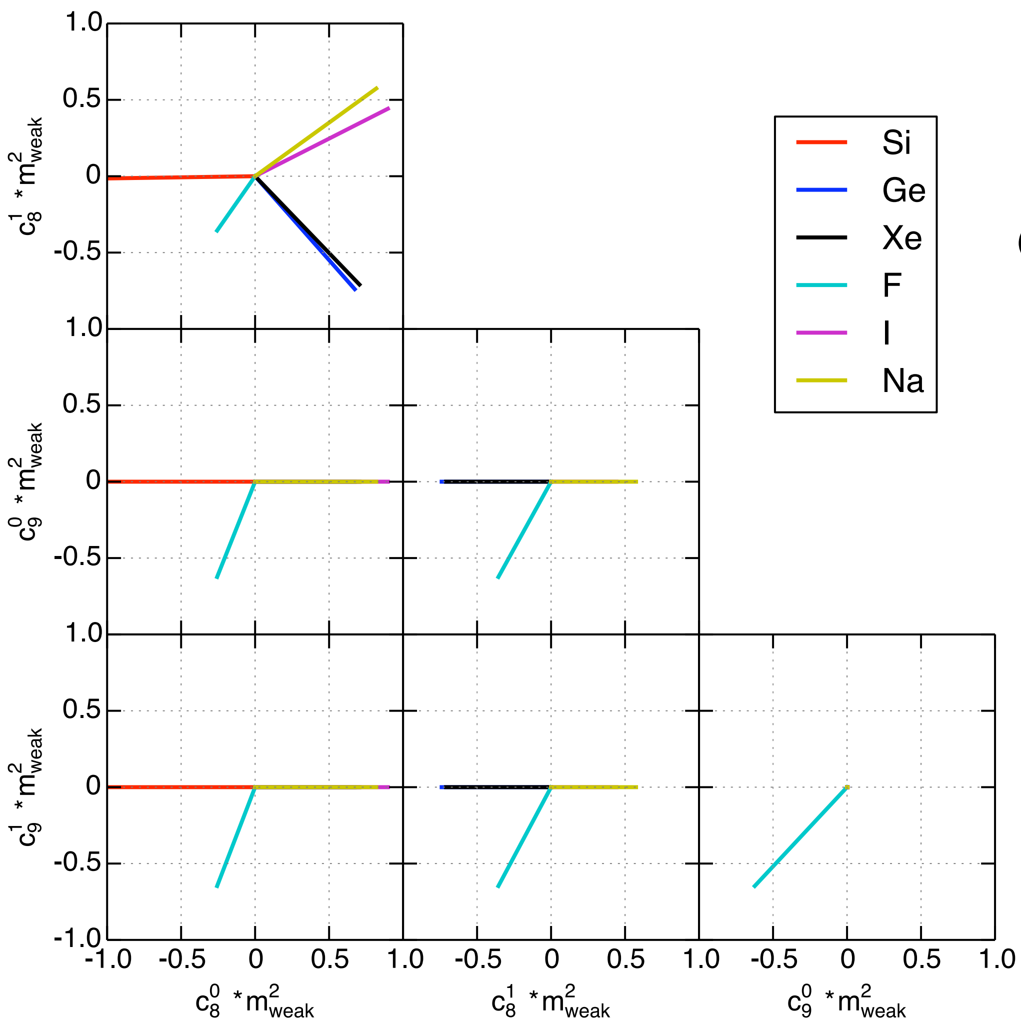
$$f(v) = \exp\left[-\frac{v}{v_0}\right]\left(v_{esc}^2 - v^2\right)^p$$

SuperCDMS Collaboration (K. Schneck et al.), PRD 91 (2015), arXiv:1503.03379



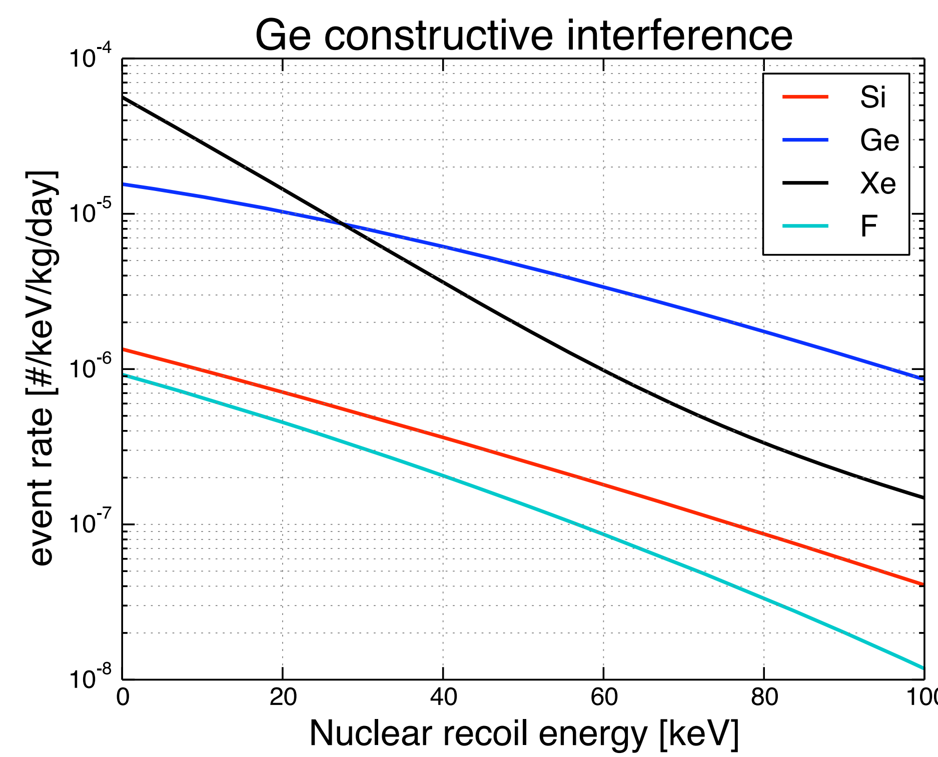
$$\begin{bmatrix} c_i^0 & c_i^1 & c_j^0 & c_j^1 \end{bmatrix} \begin{bmatrix} A_{ii}^{00} & A_{ii}^{01} & A_{ij}^{00} & A_{ij}^{01} \\ A_{ii}^{10} & A_{ii}^{11} & A_{ij}^{10} & A_{ij}^{11} \\ A_{ji}^{00} & A_{ji}^{01} & A_{jj}^{00} & A_{jj}^{01} \\ A_{ji}^{10} & A_{ji}^{11} & A_{jj}^{10} & A_{jj}^{11} \end{bmatrix} \begin{bmatrix} c_i^0 \\ c_i^1 \\ c_j^0 \\ c_j^1 \end{bmatrix}$$

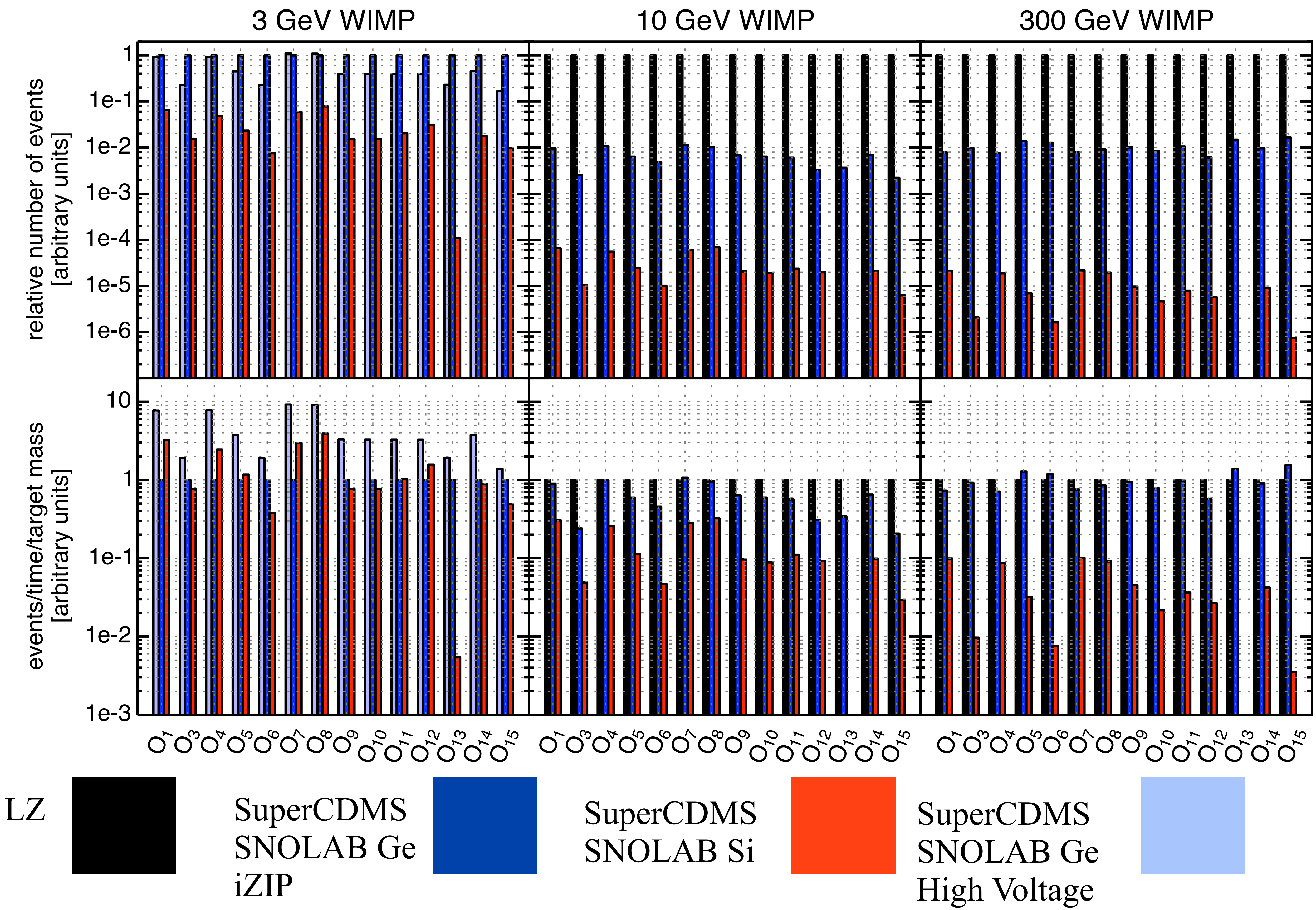




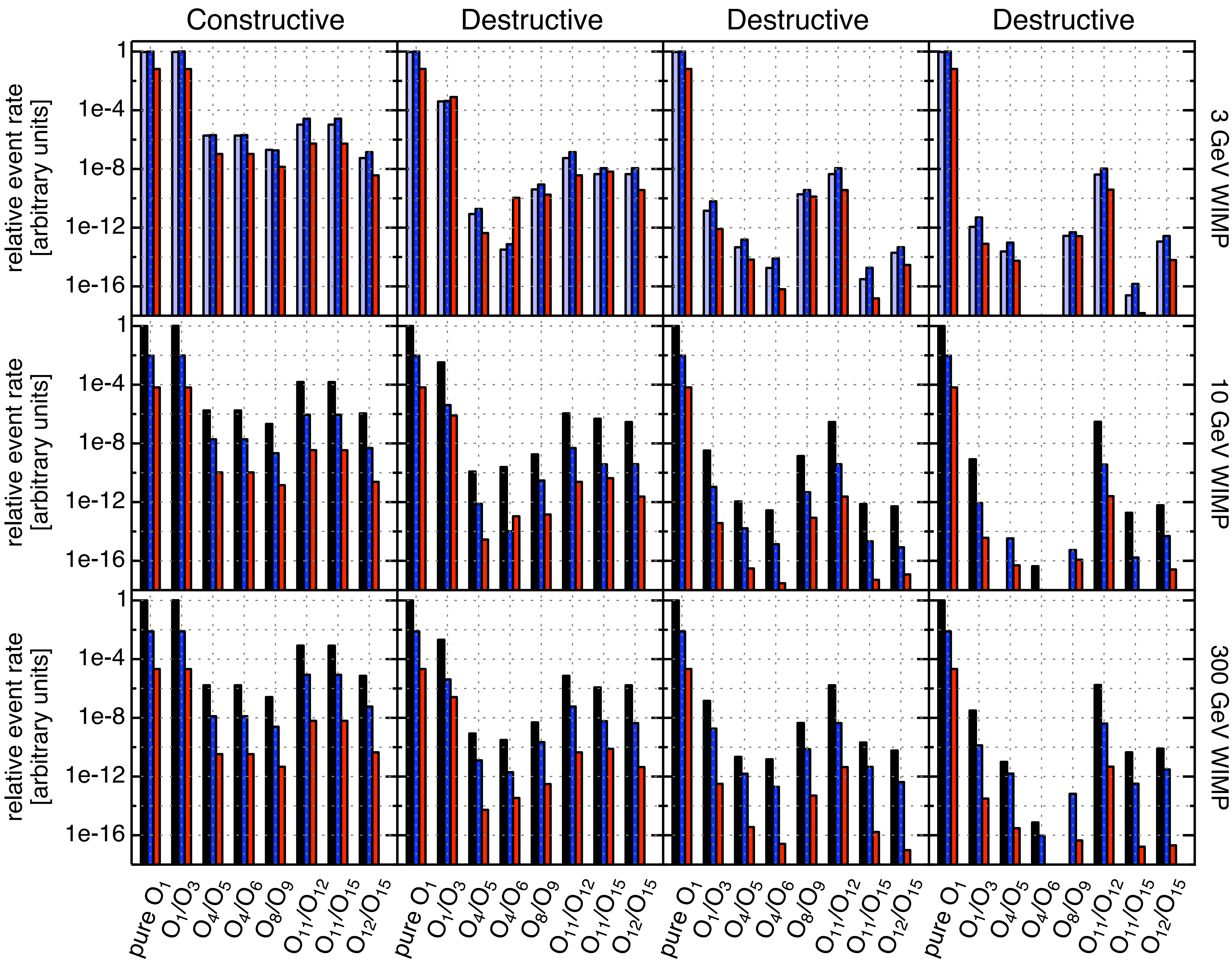
General interference

$\mathcal{O}_8/\mathcal{O}_9$

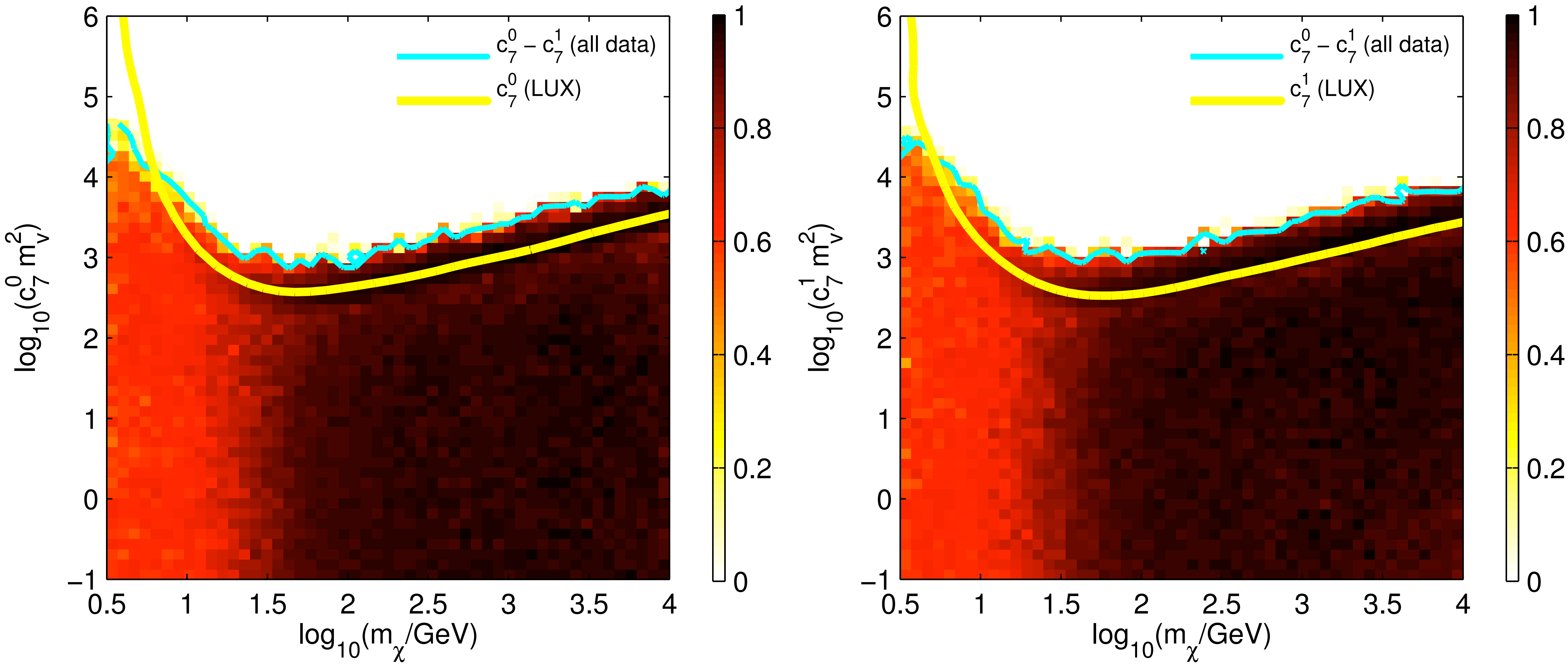




3 GeV WIMP
10 GeV WIMP
300 GeV WIMP
relative number of events
[arbitrary units]
events/time/target mass
[arbitrary units]
1
1e-1
1e-2
1e-3
1e-4
1e-5
1e-6
10
1e-3
O1 O3 O4 O5 O6 O7 O8 O9 O10 O11 O12 O13 O14 O15
LZ
SuperCDMS SNOLAB Ge iZIP
SuperCDMS SNOLAB Si
SuperCDMS SNOLAB Ge High Voltage

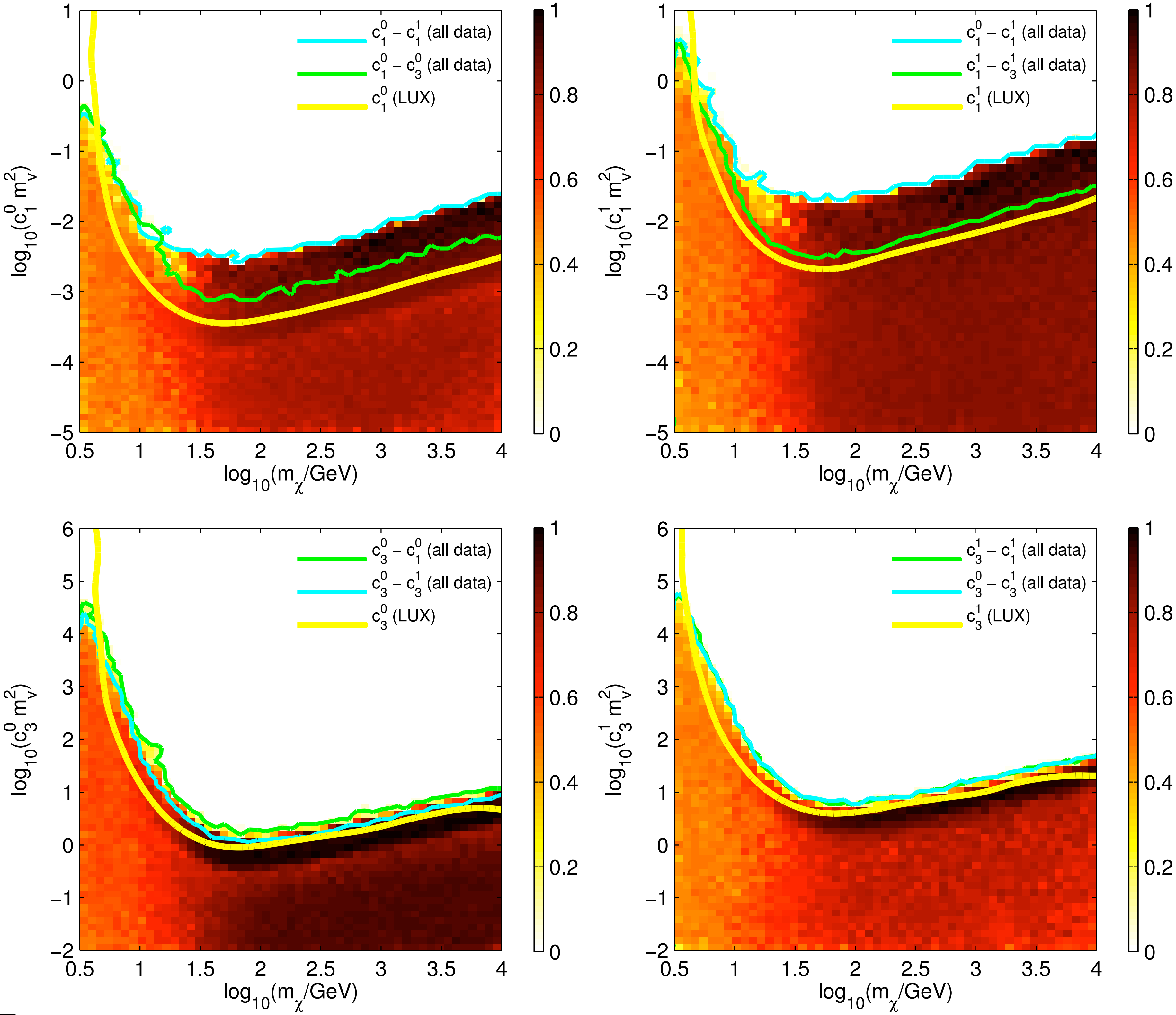


Constructive
Destructive
Destructive
Destructive
relative event rate [arbitrary units]
1
1e-4
1e-8
1e-12
1e-16
3 GeV WIMP
10 GeV WIMP
300 GeV WIMP
pure O1
O1/O3
O4/O5
O4/O6
O8/O9
O11/O12
O11/O15
O12/O15



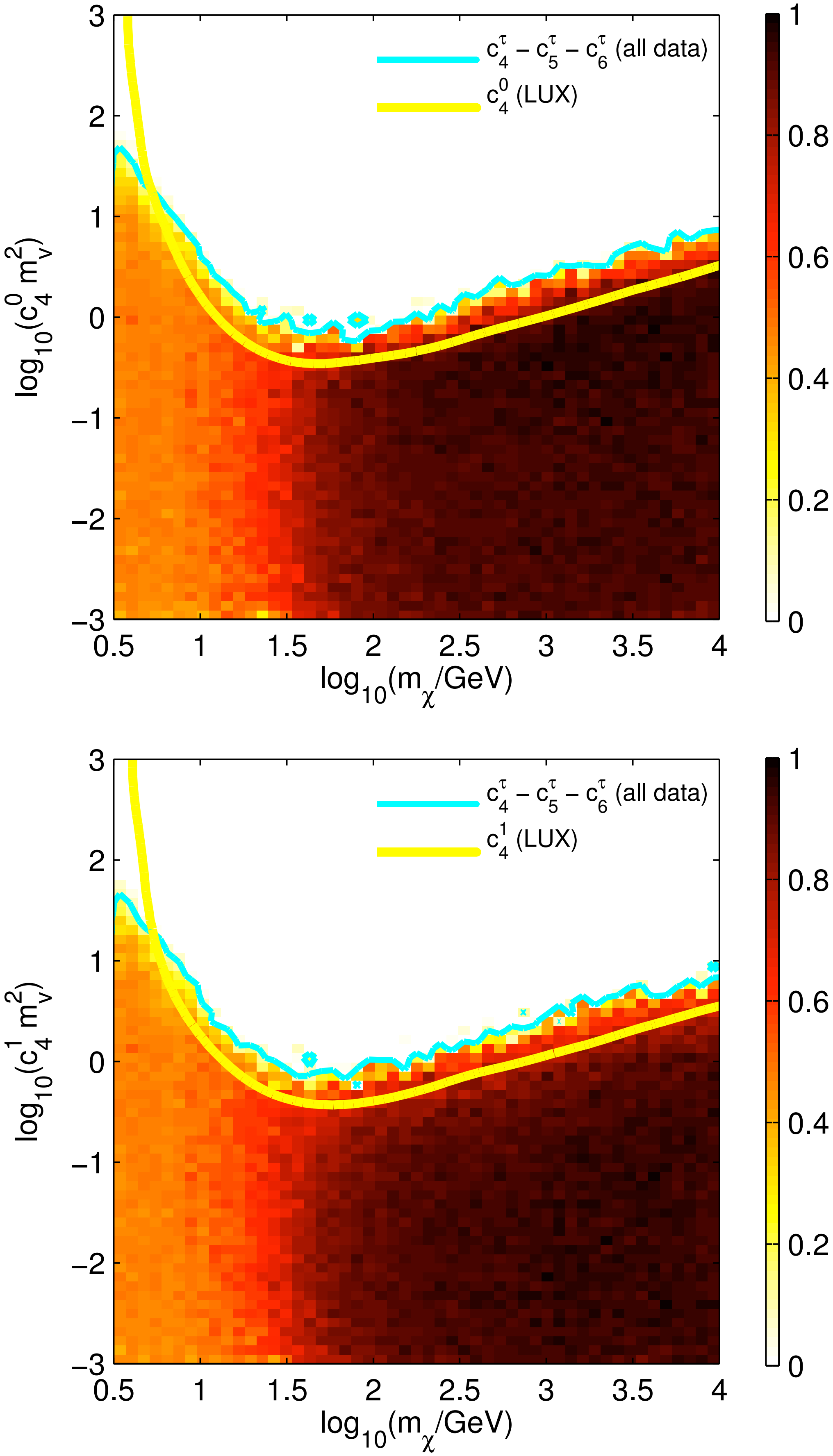
A global analysis of current data shows isoscalar/isovector interference generally makes exclusion limits weaker

R. Catena and P. Gondolo, JCAP **1508** (2015), arXiv:1504.06554



$\mathcal{O}_1/\mathcal{O}_3$

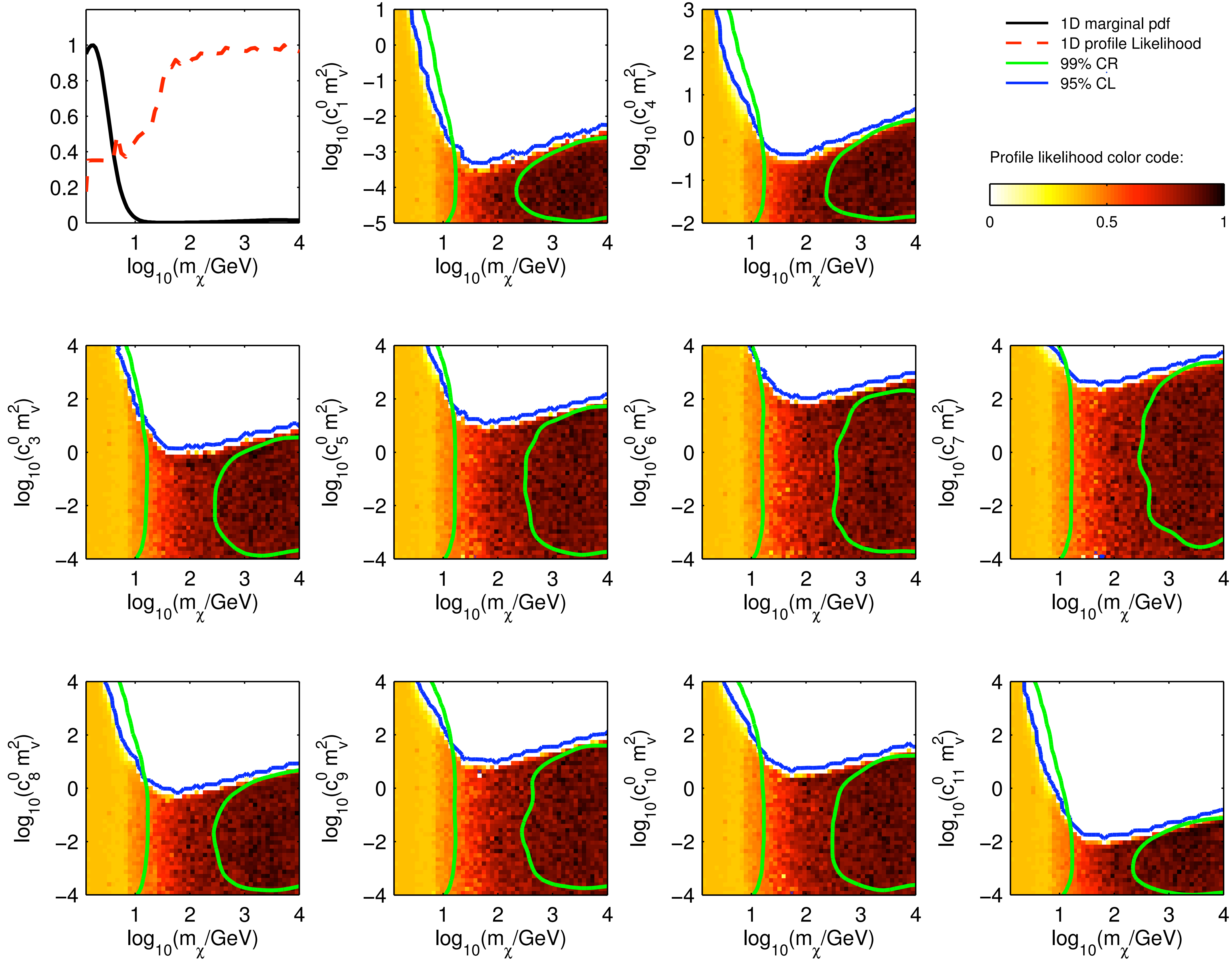
operator interference tends to have a smaller effect



$\mathcal{O}_4/\mathcal{O}_5$

$\mathcal{O}_4/\mathcal{O}_6$

The usual spin-dependent operator suffers from less interference effects than does the spin-independent



Current experiments constrain some non-standard interactions at the same level or more than the standard spin-dependent interaction

R. Catena and P. Gondolo, JCAP **1409** (2014), arXiv:1405.2637

Model reconstructions

Model reconstructions

Model reconstructions

Model reconstructions

Model reconstructions

Model reconstructions

Model reconstructions

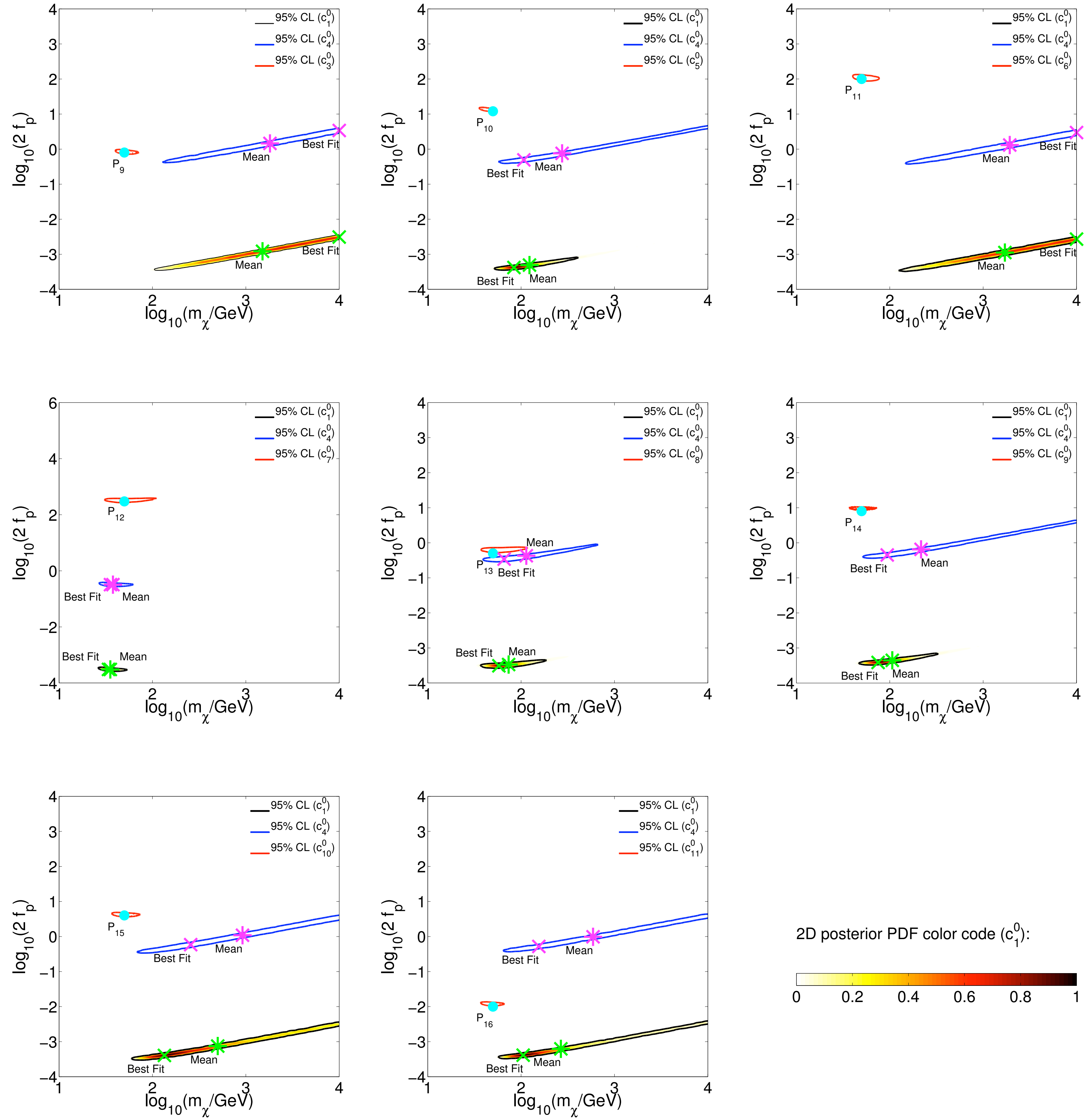
Model reconstructions

Model reconstructions

Model reconstructions

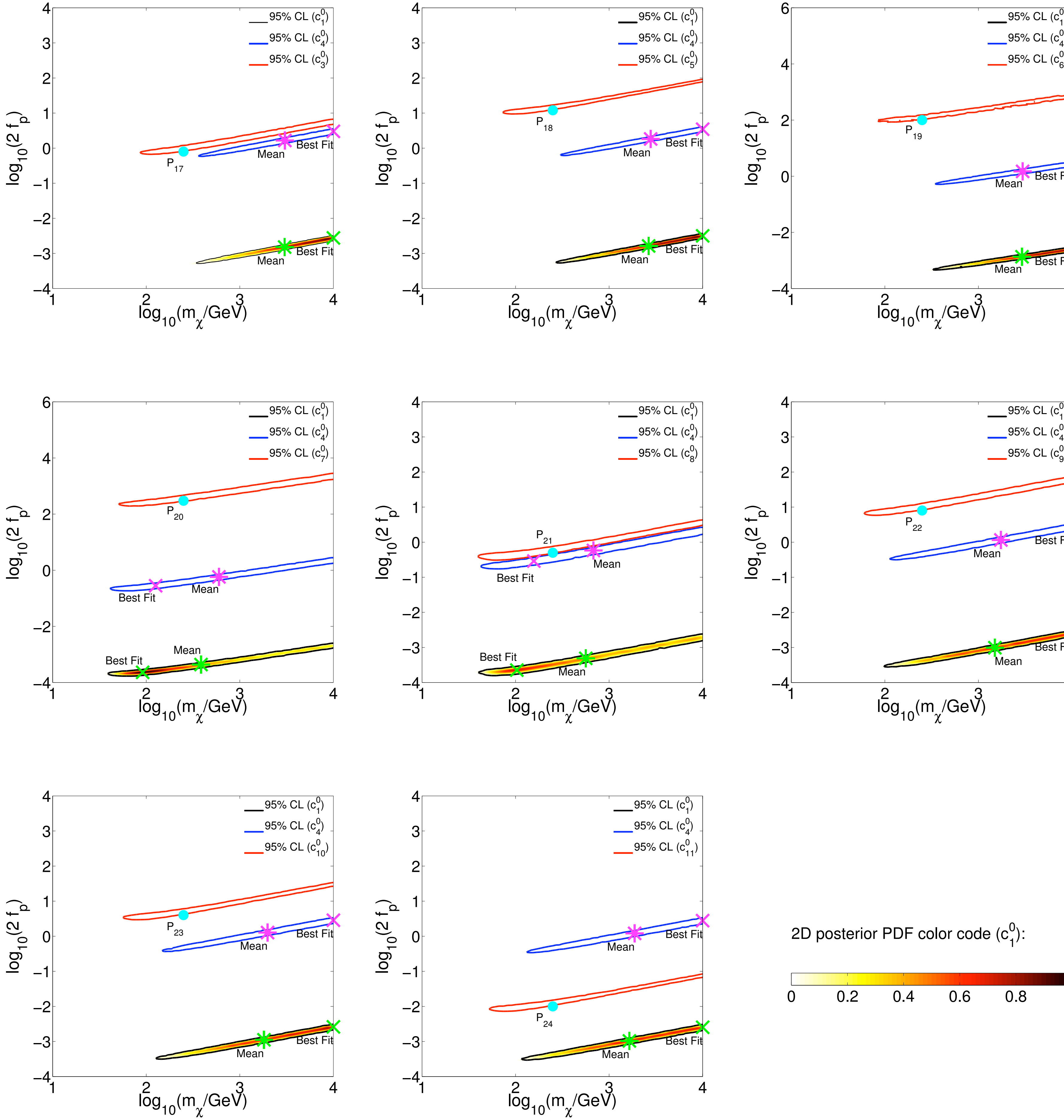
50GeV

Theoretical bias in the fits for ton-scale Ge and Xe



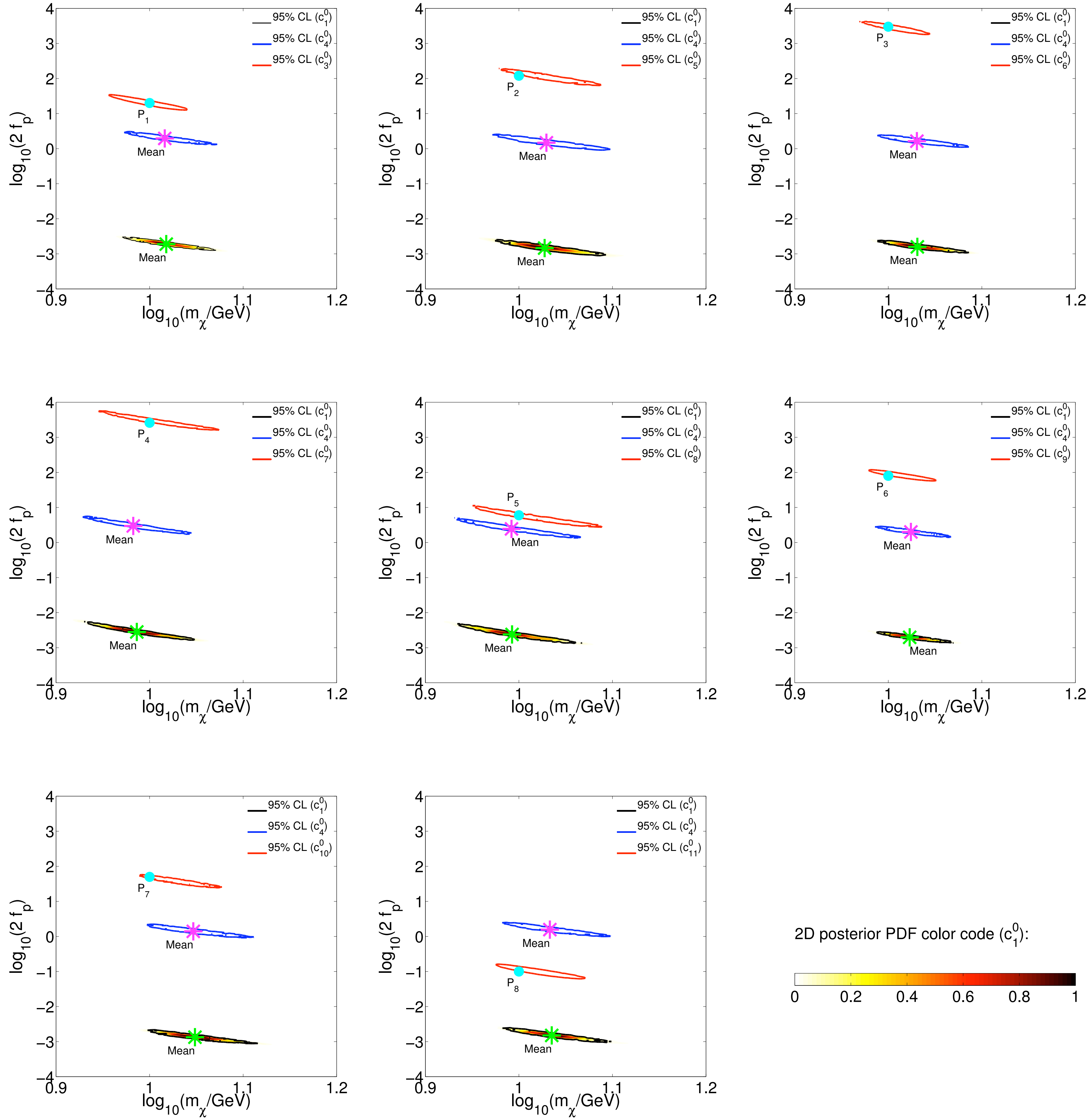
R. Catena, JCAP **1409** (2014), arXiv:1407.0127

250GeV

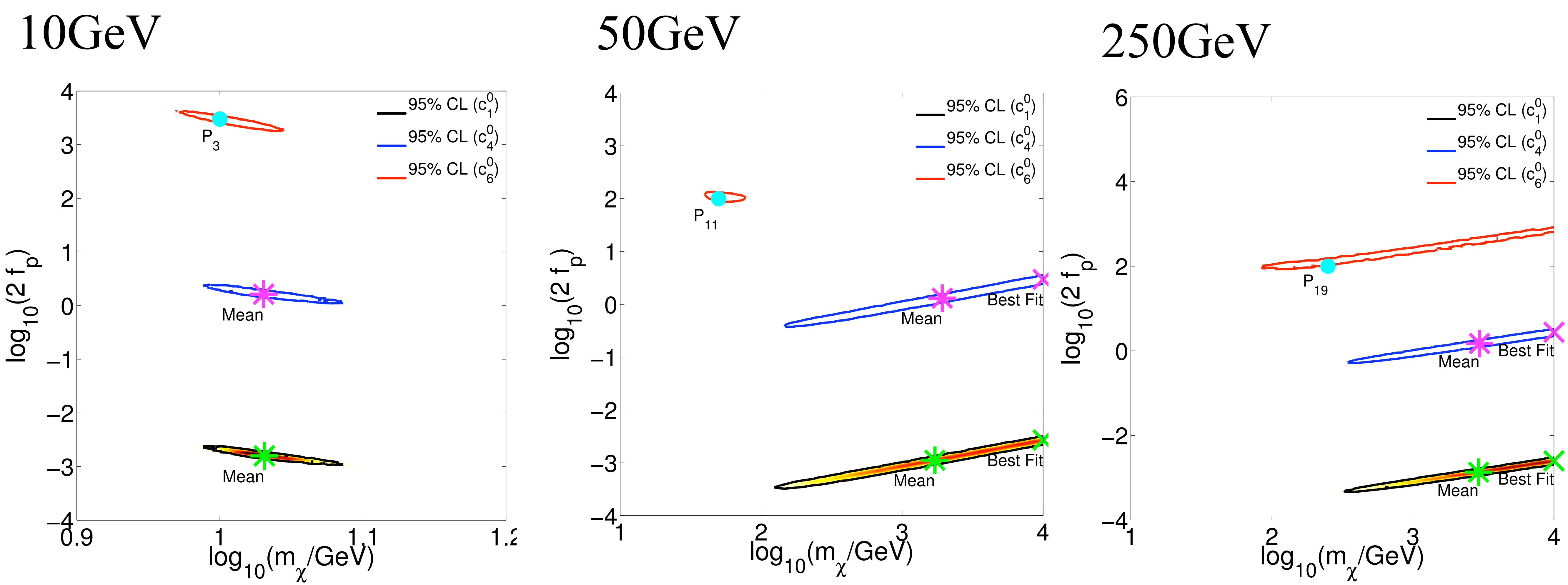


95% CL (c_1^0)
95% CL (c_4^0)
95% CL (c_3^0)
95% CL (c_5^0)
95% CL (c_6^0)
95% CL (c_7^0)
95% CL (c_8^0)
95% CL (c_9^0)
95% CL (c_{10}^0)
95% CL (c_{11}^0)
P_{17}
P_{18}
P_{19}
P_{20}
P_{21}
P_{22}
P_{23}
P_{24}
Best Fit
Mean
$\log_{10}(2 f_p)$
$\log_{10}(m_\chi/\mathrm{GeV})$
2D posterior PDF color code (c_1^0):
0
0.2
0.4
0.6
0.8
1

10GeV



95% CL (c$_1^0$)
95% CL (c$_4^0$)
95% CL (c$_3^0$)
95% CL (c$_5^0$)
95% CL (c$_6^0$)
95% CL (c$_7^0$)
95% CL (c$_8^0$)
95% CL (c$_9^0$)
95% CL (c$_{10}^0$)
95% CL (c$_{11}^0$)
P$_1$
P$_2$
P$_3$
P$_4$
P$_5$
P$_6$
P$_7$
P$_8$
Mean
log$_{10}$(2 f$_p$)
log$_{10}$(m$_\chi$/GeV)
2D posterior PDF color code (c$_1^0$):
0
0.2
0.4
0.6
0.8
1



Fitting a non-standard interaction with SI/SD assumptions

Anapole

$$\mathcal{L}_{\text{int}}^{\text{anapole}} = \frac{f_a}{M^2}\bar{\chi}\gamma^\mu\gamma^5\chi\mathcal{J}_\mu^{\text{EM}} \quad \rightarrow \frac{2f_a}{M^2}\sum_{N=n,p}(Q_N\mathcal{O}_8 + \tilde{\mu}_N\mathcal{O}_9)$$

Magnetic dipole

$$\mathcal{L}_{\text{int}}^{\text{magnetic dipole}} = \frac{f_{\text{md}}}{M^2}\bar{\chi}\frac{i\sigma^{\mu\nu}q_\nu}{\Lambda}\chi\mathcal{J}_\mu^{\text{EM}} \quad \rightarrow \frac{2f_{\text{md}}}{M^2}\sum_{N=n,p}\left(Q_N\left(\frac{m_N}{\Lambda}\mathcal{O}_5 - \frac{\vec{q}^2}{4m_\chi\Lambda}\mathcal{O}_1\right)\right.$$
$$\left. + \tilde{\mu}_N\left(\frac{m_N}{\Lambda}\mathcal{O}_6 - \frac{\vec{q}^2}{m_N\Lambda}\mathcal{O}_4\right)\right).$$

Electric dipole

$$\mathcal{L}_{\text{int}}^{\text{electric dipole}} = \frac{f_{\text{ed}}}{M^2}\bar{\chi}\frac{\sigma^{\mu\nu}q_\nu\gamma^5}{\Lambda}\chi\mathcal{J}_\mu^{\text{EM}} \quad \rightarrow \frac{2f_{\text{ed}}}{M^2}\sum_{N=n,p}\left(-Q_N\frac{m_N}{\Lambda}\mathcal{O}_{11} + \tilde{\mu}_N\left(\frac{m_N}{\Lambda}\mathcal{O}_{15} + \frac{m_\chi\vec{q}^2}{4m_N^2\Lambda}\mathcal{O}_{11}\right)\right)$$

LS generating

$$\mathcal{L}_{\text{int}}^{\text{LS}} = \frac{f_{\text{LS}}}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\sum_{N=n,p}\left(\kappa_1^N\frac{q_\alpha q^\alpha}{m_N^2}\bar{N}\gamma^\mu N + \kappa_2^N\bar{N}\frac{i\sigma^{\mu\nu}q_\nu}{2m_N}N\right)$$
$$\rightarrow \frac{f_{\text{LS}}}{\Lambda^2}\sum_{N=n,p}\left(\left(\frac{\kappa_2^N}{4} - \kappa_1^N\right)\frac{\vec{q}^2}{m_N^2}\mathcal{O}_1 - \kappa_2^N\mathcal{O}_3 + \kappa_2^N\frac{m_N}{m_\chi}\left(\frac{\vec{q}^2}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6\right)\right)$$

M.I. Gresham and K.M. Zurek, PRD 89 123521 (2014) arXiv:1401.3739

Anapole

$$\mathcal{L}_{\rm int}^{\rm anapole} = \frac{f_a}{M^2}\bar{\chi}\gamma^\mu\gamma^5\chi\mathcal{J}_\mu^{\rm EM}$$

Leading vector coupling for Majorana dark matter

$$\mathcal{J}_\mu^{\rm EM} \equiv \sum_{N=n,p}\bar{N}\left(Q_N\frac{K_\mu}{2m_N} - \tilde{\mu}_N\frac{i\sigma_{\mu\nu}q^\nu}{2m_N}\right)N$$

Electromagnetic current for nucleons

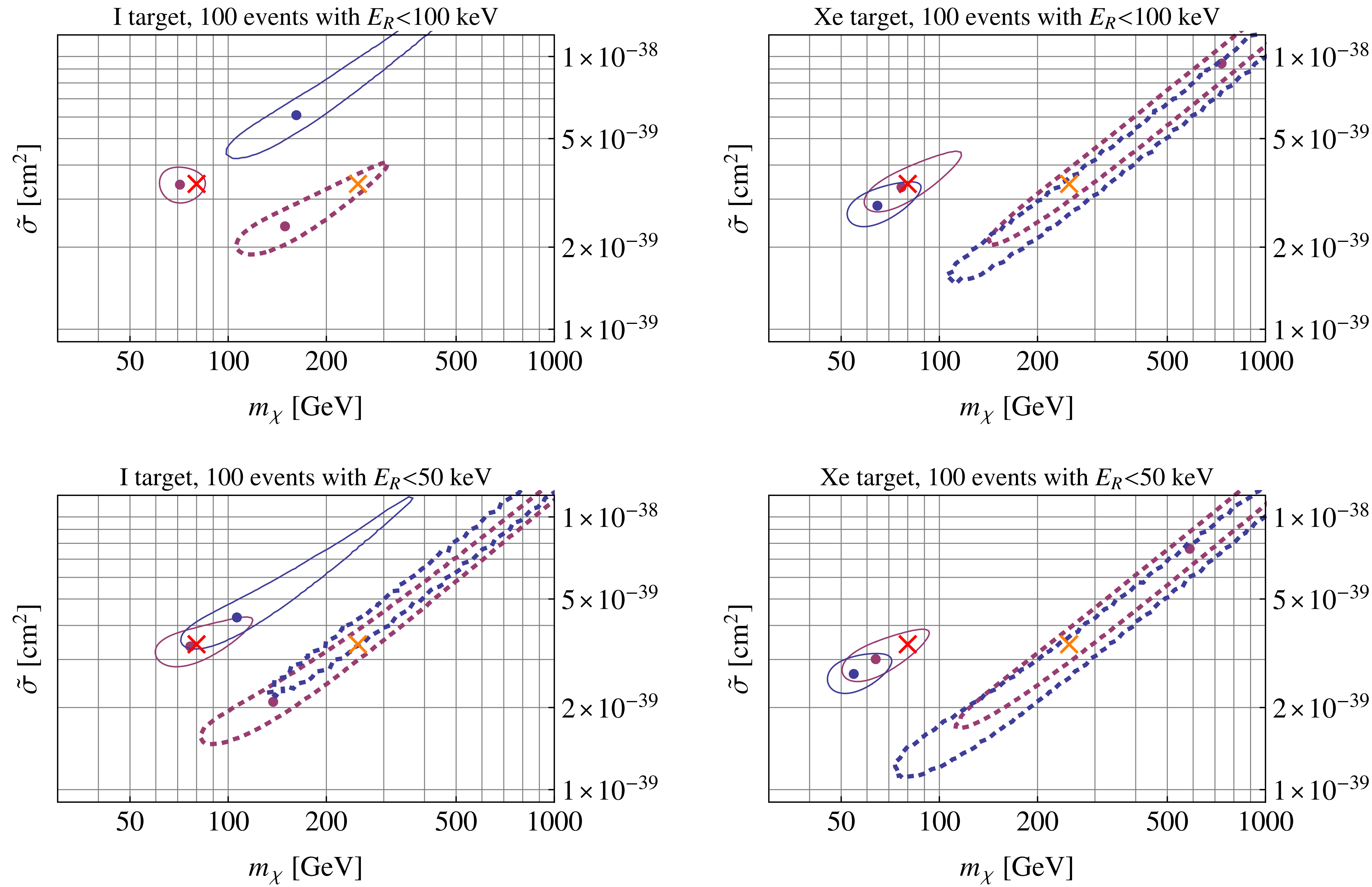
$$\mathcal{L}_{\rm int}^{\rm anapole} \rightarrow \frac{2f_a}{M^2}\sum_{N=n,p}(Q_N\mathcal{O}_8 + \tilde{\mu}_N\mathcal{O}_9)$$

Nuclear effects

$$\tilde{\mu}_T = 2\tilde{\mu}_p\langle S_p\rangle + 2\tilde{\mu}_n\langle S_n\rangle + \langle L_p\rangle$$

$$\sigma_T^{\rm anapole} = \frac{\mu_T^2}{\pi}\left(\frac{f_a}{M^2}\right)^2 C_\chi\Bigg\{\vec{v}_T^{\perp 2}\tilde{W}_M^{(p,p)} + \frac{\vec{q}^2}{m_N^2}\Bigg[\tilde{W}_\Delta^{(p,p)} - \tilde{\mu}_n\tilde{W}_{\Delta\Sigma'}^{(p,n)} - \tilde{\mu}_p\tilde{W}_{\Delta\Sigma'}^{(p,p)} + \frac{1}{4}(\tilde{\mu}_p^2\tilde{W}_{\Sigma'}^{(p,p)} + 2\tilde{\mu}_n\tilde{\mu}_p\tilde{W}_{\Sigma'}^{(p,n)} + \tilde{\mu}_n^2\tilde{W}_{\Sigma'}^{(n,n)})\Bigg]\Bigg\}$$

Nuclear responses including interference



Fits to simulated data for 80GeV and 250GeV dark matter on Iodine and Xenon targets for true and standard form factors

Future prospects for distinguishing models

V. Glusevic, M. Gresham, S.D. McDermott, A.H.G. Peter, and K. Zurek, arXiv:1506.04454

Model name	Lagrangian	$\vec{q}$, v Dependence	Response	f_n/f_p
SI	$\bar{\chi}\chi\bar{N}N$	1	M	$+1$
SD	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu\gamma_5 N$	1	$\Sigma' + \Sigma''$	–1.1
Anapole	$\bar{\chi}\gamma^\mu\gamma_5\chi\partial^\nu F_{\mu\nu}$	$v^{\perp 2}$ $\vec{q}^2/m_N^2$	M $\Delta + \Sigma'$	photon–like
Millicharge	$\bar{\chi}\gamma^\mu\chi A_\mu$	$m_N^2 m_\chi^2/\vec{q}^4$	M	photon–like
MD (light med.)	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	$1 + \frac{v^{\perp 2} m_N^2}{\vec{q}^2}$ 1	M $\Delta + \Sigma'$	photon–like
ED (light med.)	$\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi F_{\mu\nu}$	$m_N^2/\vec{q}^2$	M	photon–like
MD (heavy med.)	$\bar{\chi}\sigma^{\mu\nu}\partial_\mu\chi\partial^\alpha F_{\alpha\nu}$	$\frac{\vec{q}^4}{\Lambda^4} + \frac{v^{\perp 2} m_N^2 \vec{q}^2}{\Lambda^4}$ $\vec{q}^4/\Lambda^4$	M $\Delta + \Sigma'$	photon–like
ED (heavy med.)	$\bar{\chi}\sigma^{\mu\nu}\gamma_5\partial_\mu\chi\partial^\alpha F_{\alpha\nu}$	$\vec{q}^2 m_N^2/\Lambda^4$	M	photon–like
SI_{q^2}	$i\bar{\chi}\gamma_5\chi\bar{N}N$	$\vec{q}^2/m_\chi^2$	M	$+1$
SD_{q^2} (Higgs-like/flavor–univ.)	$i\bar{\chi}\chi\bar{N}\gamma_5 N$	$\vec{q}^2/m_N^2$	Σ''	$+1/-0.05$
SD_{q^4} (Higgs-like/flavor–univ.)	$\bar{\chi}\gamma_5\chi\bar{N}\gamma_5 N$	$\vec{q}^4/m_\chi^2 m_N^2$	Σ''	$+1/-0.05$
$\vec{L}\cdot\vec{S}$-like	$\bar{\chi}\gamma_\mu\chi\frac{\partial^2\bar{N}\gamma^\mu N}{m_N^2} +$ $+\bar{\chi}\gamma_\mu\chi\frac{\partial_\nu\bar{N}\sigma^{\mu\nu}N}{2m_N}$	$\vec{q}^4/m_N^4$ $\vec{q}^4/m_N^4$ $\frac{\vec{q}^2 v^{\perp 2}}{m_N^2} + \frac{\vec{q}^4}{m_\chi^2 m_N^2}$	M Φ'' Σ'	$+1$

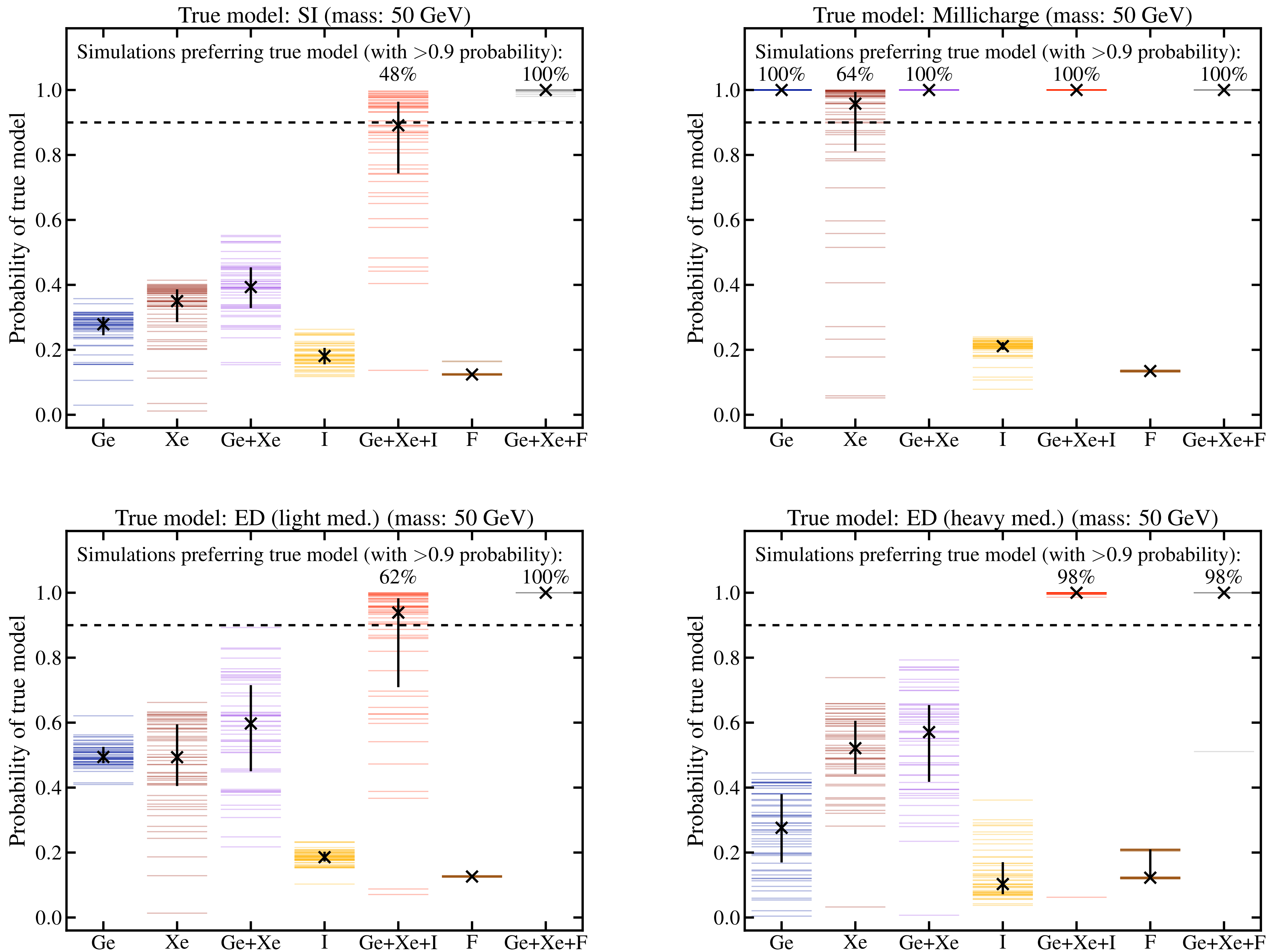
Simulated over 8000 recoil energy spectra for various models

Future prospects for distinguishing models

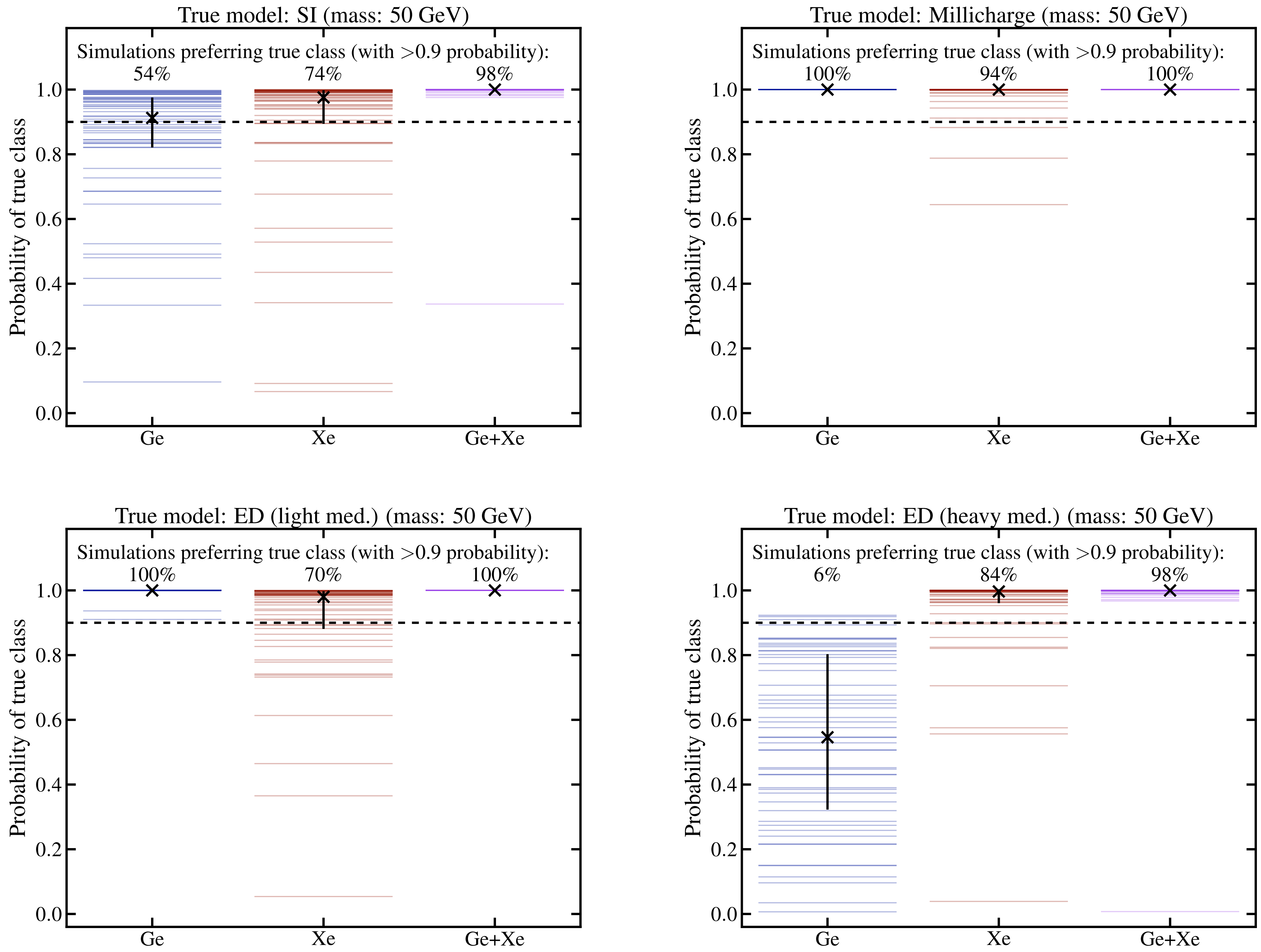
Label	A (Z)	Energy window [keVnr]	Exposure [kg-yr]
Xe	131 (54)	5-40	2000
Ge	73 (32)	0.3-100	100
I	127 (53)	22.2-600	212
F	19 (9)	3-100	606
Na	23 (11)	6.7-200	38
Ar	40 (18)	25-200	3000
He	4 (2)	3-100	300
Xe(lo)	131 (54)	1-40	2000
Xe(hi)	131 (54)	5-100	2000
Xe(wide)	131 (54)	1-100	2000
I(lo)	127 (53)	1-600	212
XeG3	131 (54)	5-40	40 000
I+	127 (53)	1-600	424
F+	19 (9)	3-100	1200

Covers the targets for the next generation of ton-scale detectors

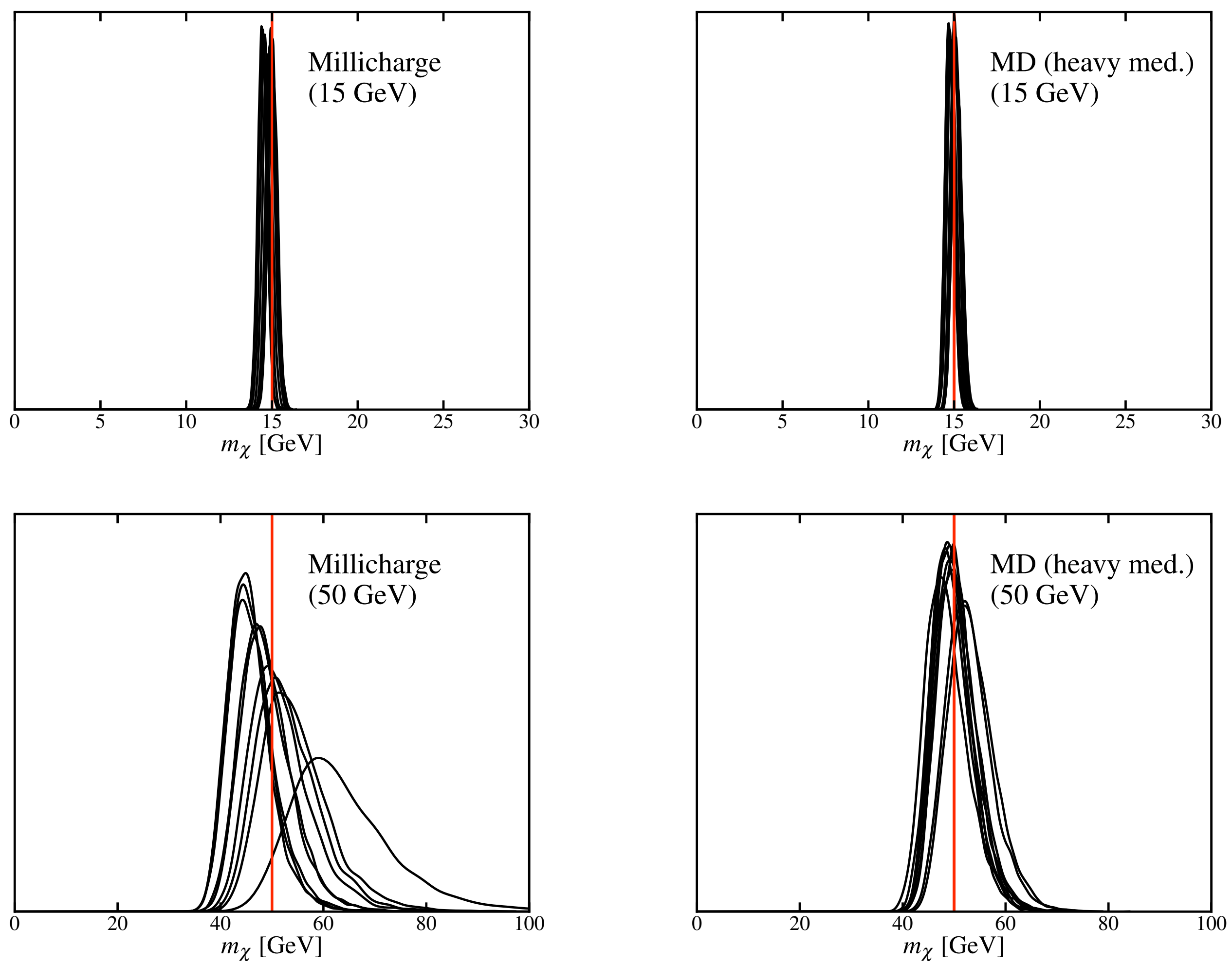
V. Glusevic, M. Gresham, S.D. McDermott, A.H.G. Peter, and K. Zurek, arXiv:1506.04454



Excellent target complementarity is exhibited, and prospects of model selection are good for cross-sections just below current limits

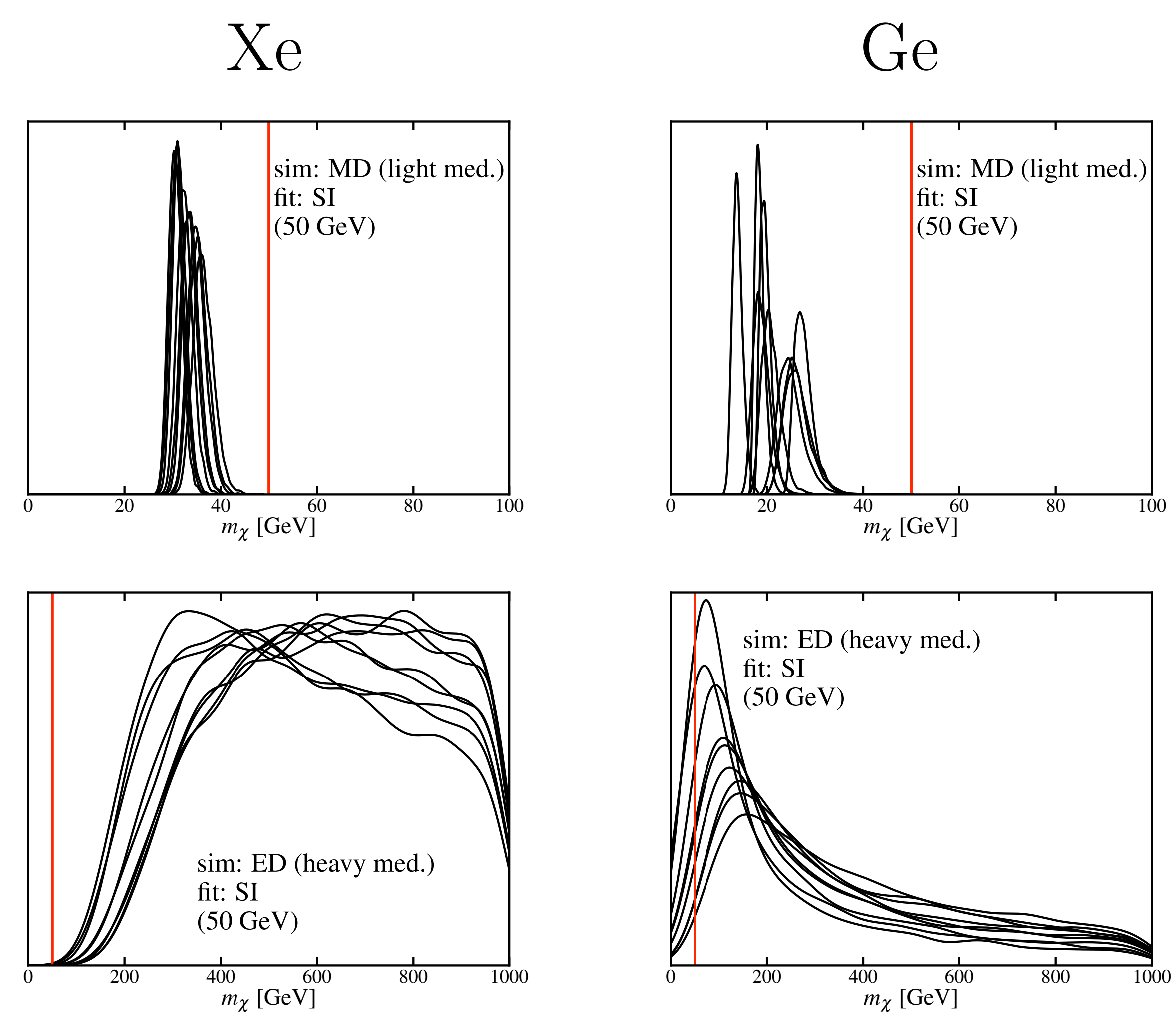


Ge and Xe together may be able to distinguish the energy dependence class of the interactions



Mass reconstruction can be good if the correct underlying model is chosen (Ge, Xe, F)

Lower mass fits are better as well



As expected, it is not as accurate if the wrong model is fit

Fit model then reconstruct mass

Annual Modulation

Annual Modulation

Annual Modulation

Annual Modulation

Annual Modulation

Annual Modulation

Annual Modulation

Annual Modulation

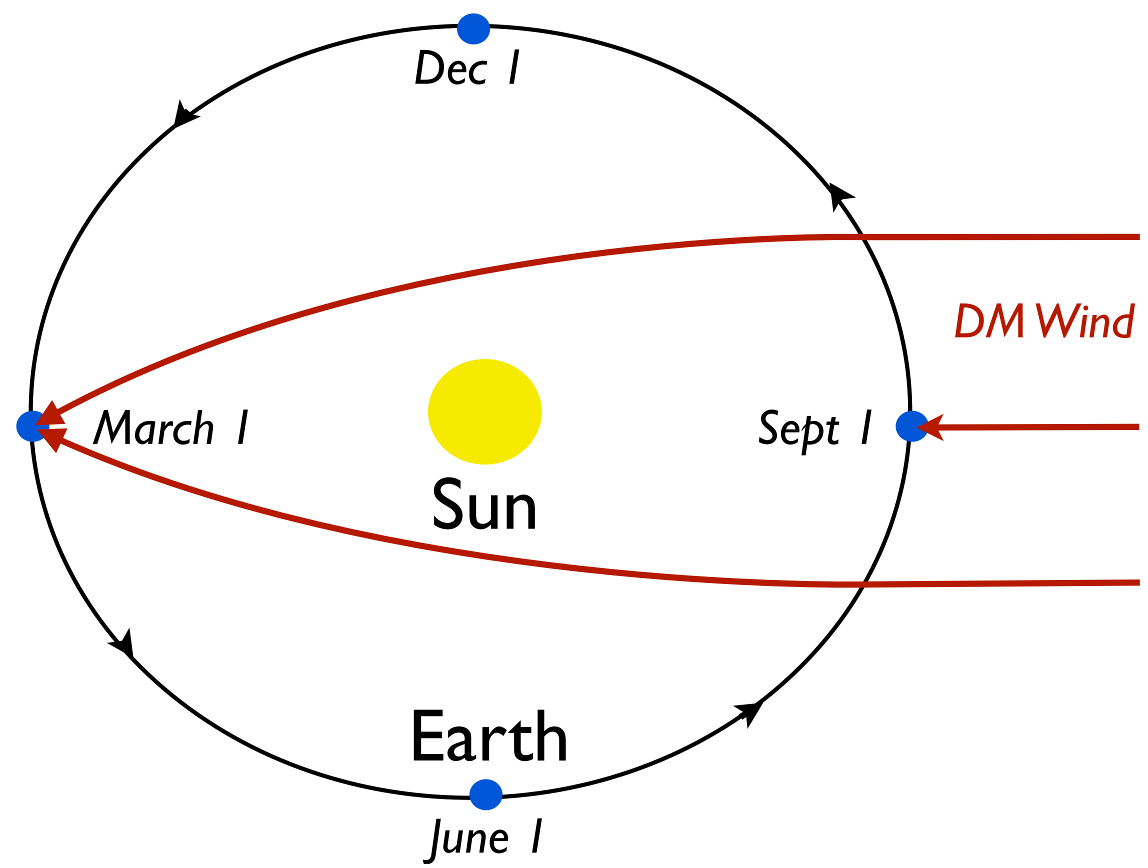
Annual Modulation

As the Earth moves around the Sun, the nuclear recoil rate due to dark matter interactions acquires a time dependence (annual modulation)

$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}}(E_\mathrm{R}, t) = S_0(E_\mathrm{R}) + S_\mathrm{m}(E_\mathrm{R}) \cos\left(\frac{2\pi}{1\ \mathrm{year}}(t - t_0) \right)$$

Other mechanisms such as gravitational focusing can have a significant impact on the phase of the modulation, which can vary depending on v_{min}

This can in turn create interesting effects for some velocity dependent interactions.



S.K. Lee, M. Lisanti, A.H.G. Peter, and B.R. Safdi, PRL **112** (2014) arXiv:1308.1953

M.S. Alenazi and P. Gondolo, PRD **74** (2006) astro-ph/0608390

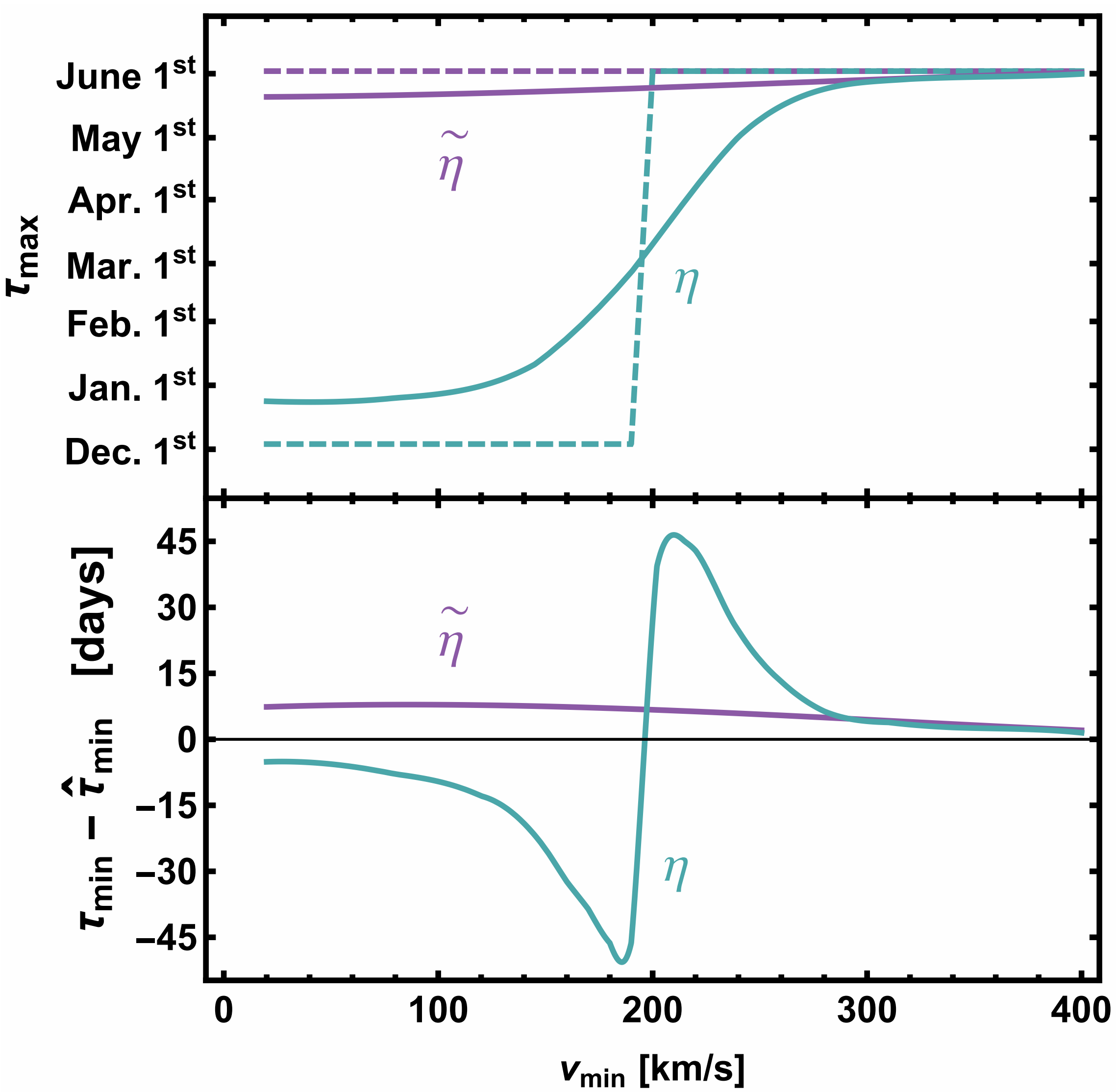
S.K. Lee, M. Lisanti, and B.R. Safdi, JCAP **1311** (2013) arXiv:1307.5323

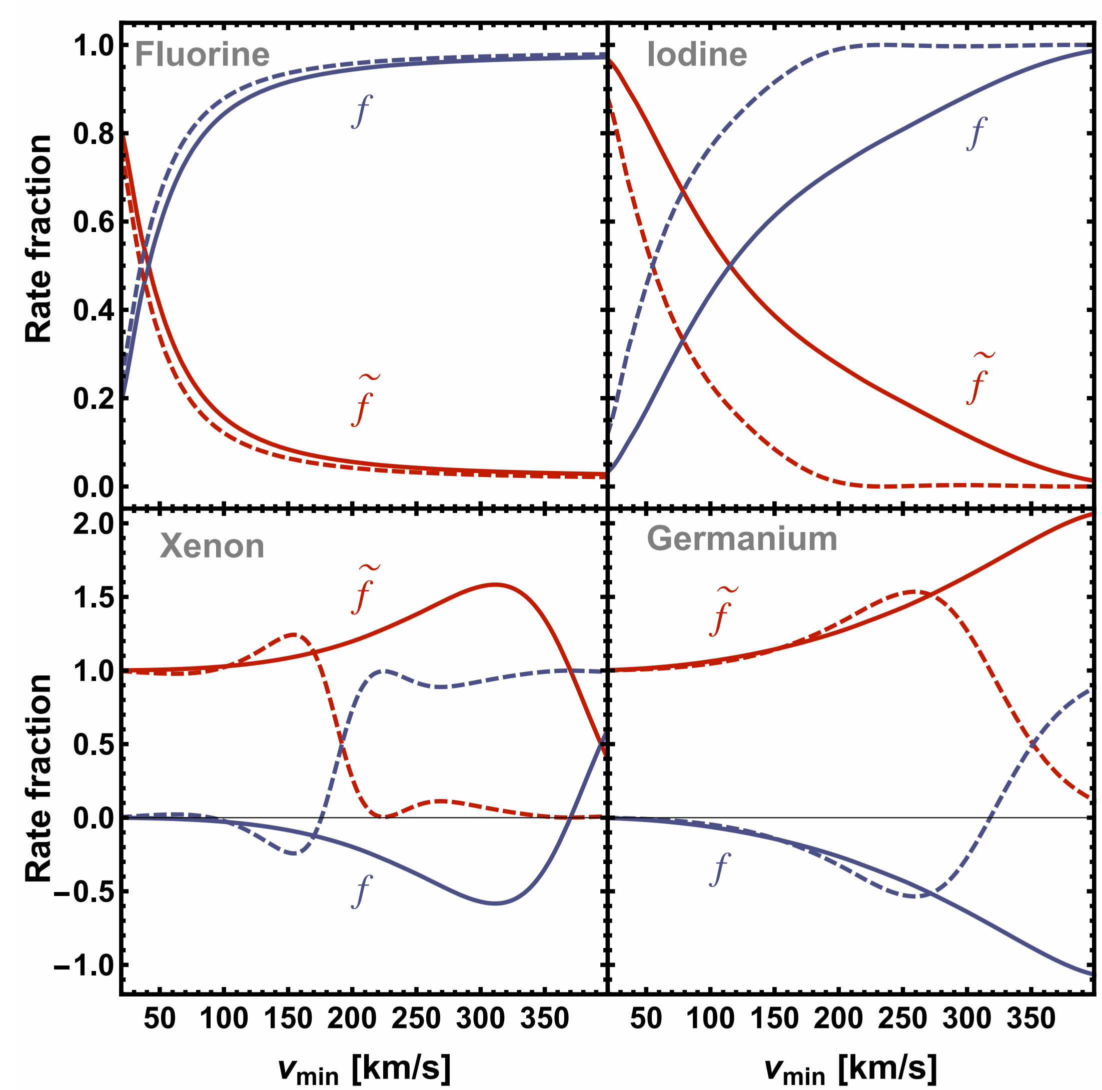
E. Del Nobile, G.B. Gelmini, and S.J. Witte, JCAP **1508** (2015) arXiv:1505.07538

An example $\mathscr{L} = (\lambda_\chi/2)\,\bar\chi\sigma_{\mu\nu}\chi F^{\mu\nu}$

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}}(v_\mathrm{min}, v) = \alpha\lambda_\chi^2 \left\{ Z_T^2 \frac{m_T}{2\mu_T^2}\left[\frac{1}{v_\mathrm{min}^2} - \frac{1}{v^2}\left(1 - \frac{\mu_T^2}{m^2}\right)\right] F_{\mathrm{SI},T}^2(E_\mathrm{R}(v_\mathrm{min})) + \frac{\hat\lambda_T^2}{v^2}\frac{m_T}{m_p^2}\left(\frac{S_T+1}{3S_T}\right) F_{\mathrm{M},T}^2(E_\mathrm{R}(v_\mathrm{min})) \right\}$$

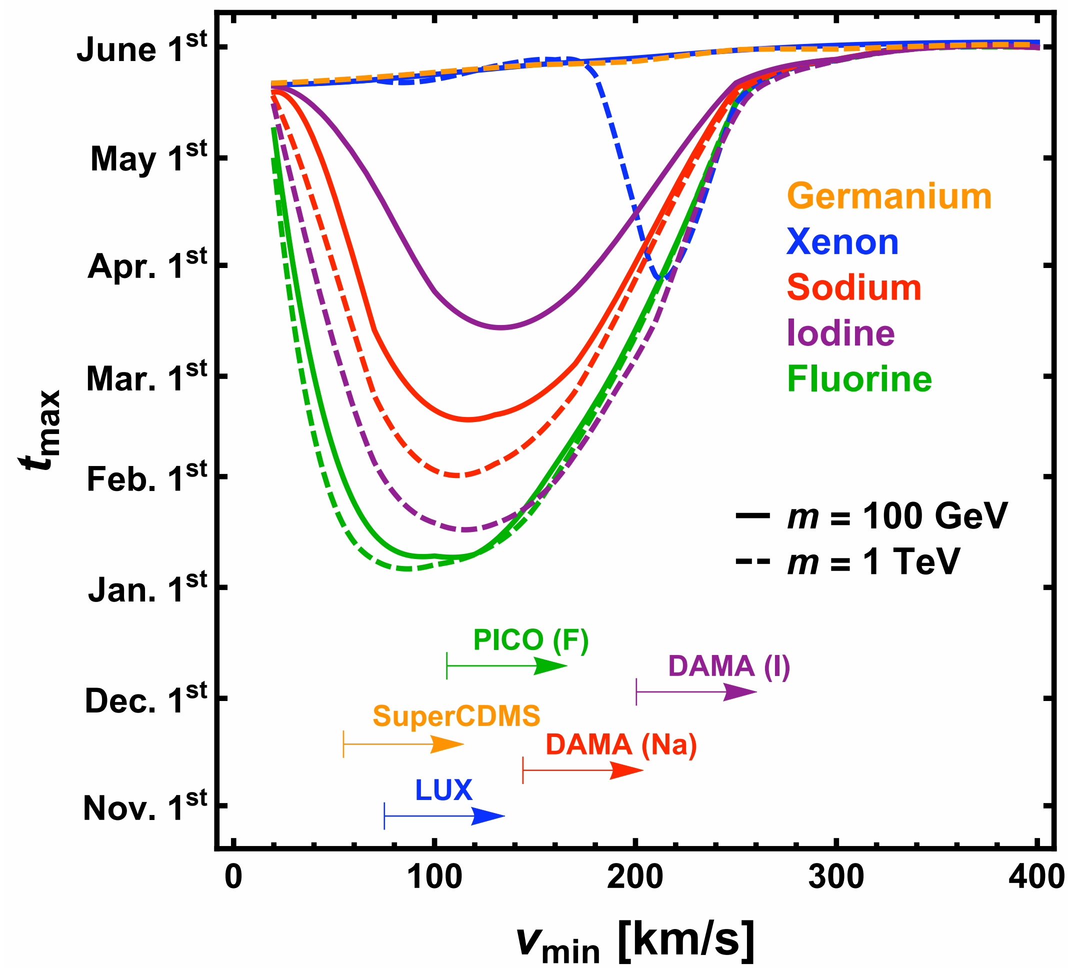
$$\tilde\eta(v_\mathrm{min}, t) \equiv \int_{v \geqslant v_\mathrm{min}} v\, f(\boldsymbol{v}, t)\, \mathrm{d}^3v \qquad \eta(v_\mathrm{min}, t) \equiv \int_{v \geqslant v_\mathrm{min}} \frac{f(\boldsymbol{v}, t)}{v}\, \mathrm{d}^3v$$

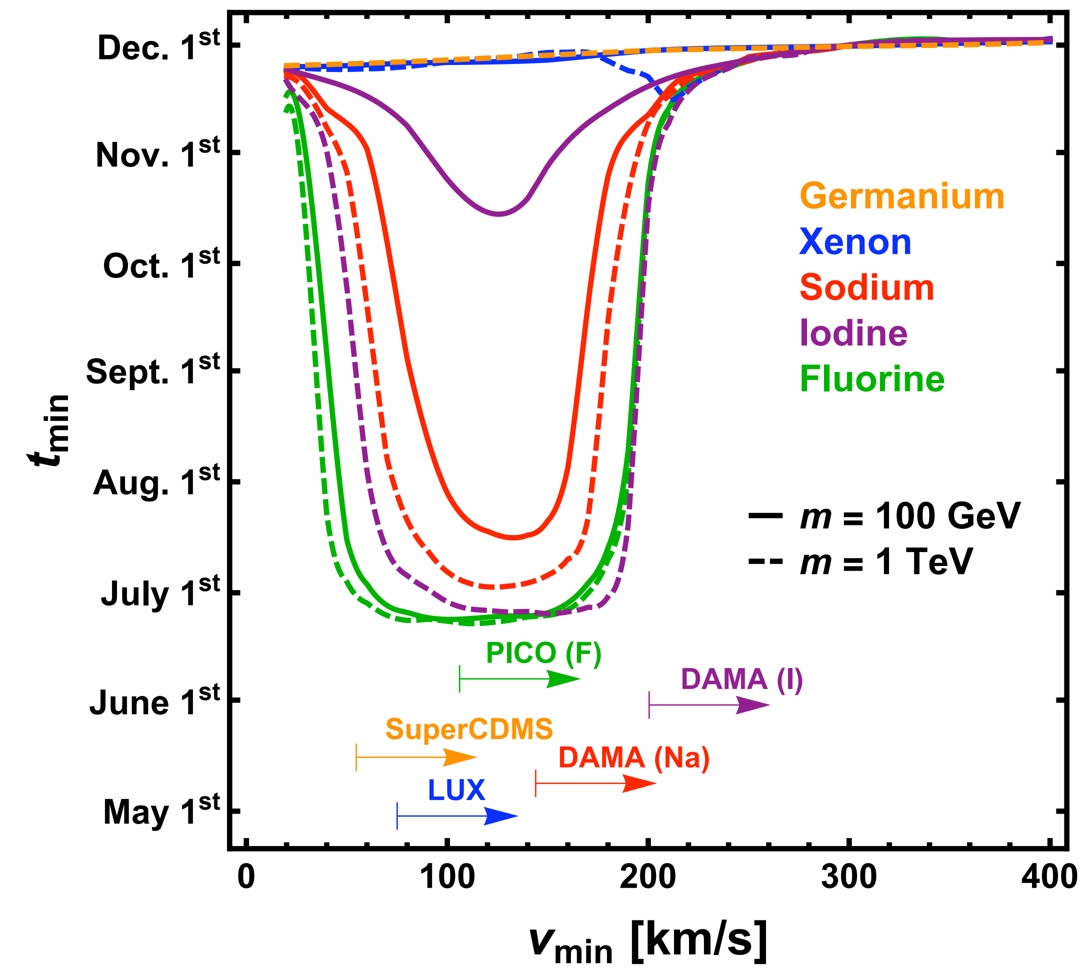




$\tilde f \equiv \tilde r/(r + \tilde r)$ $\qquad f \equiv r/(r + \tilde r)$

E. Del Nobile, G.B. Gelmini, and S.J. Witte, PRD **91** (2015) arXiv:1504.06772

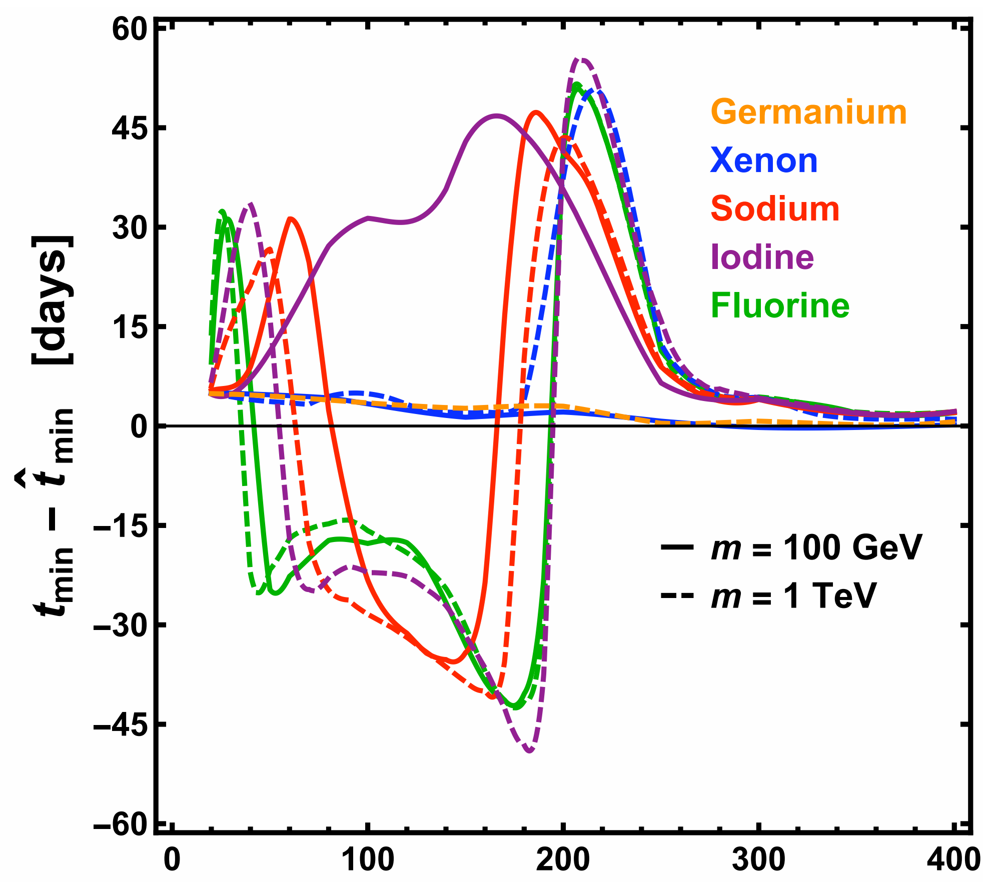




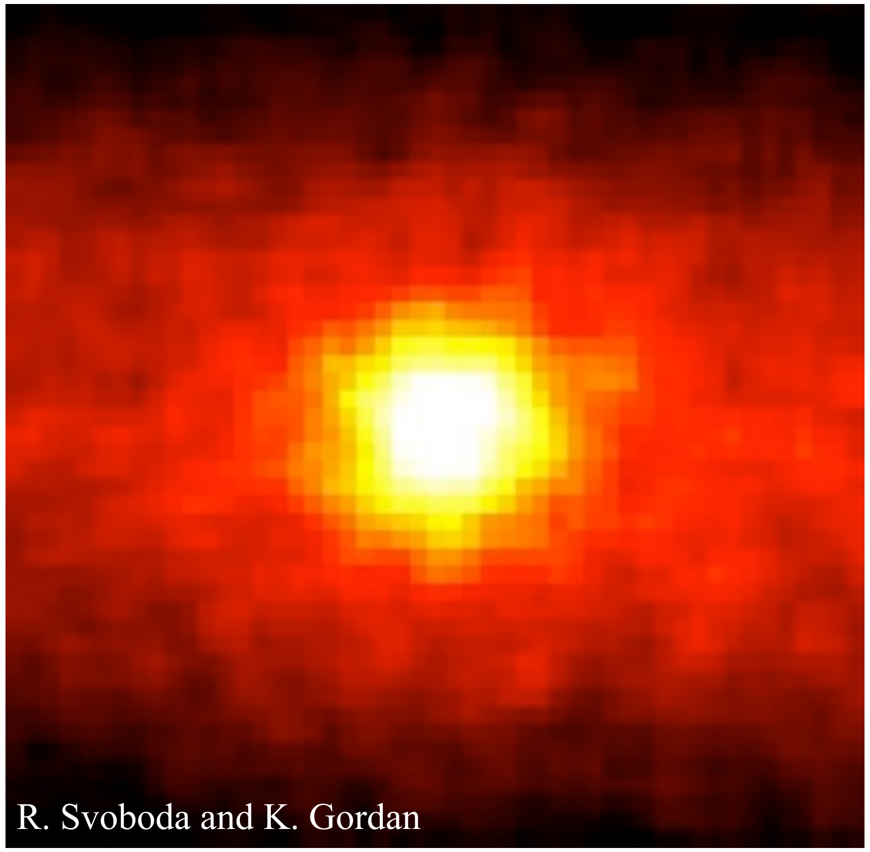
Target dependence for the time of maximum and minimum scattering rate

Difference between the time of minimum scattering rate and six months from the maximum time as a function of target element.

Factorizability of the velocity dependence of the cross-section could possibly be determined from multiple experiments



The Neutrino Floor



Solar neutrinos

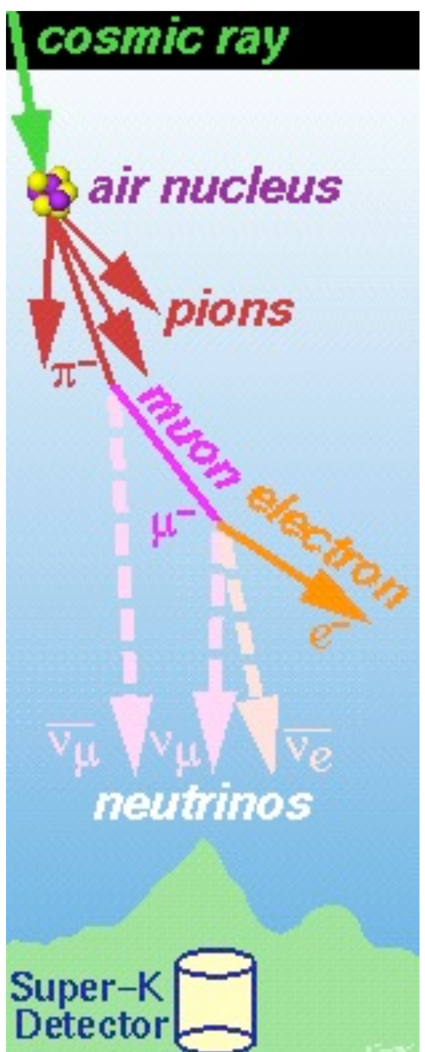
$$^{8}\mathrm{B} \rightarrow {}^{7}\mathrm{Be}^{*} + e^{+} + \nu_e$$

$$^{3}\mathrm{He} + \mathrm{p} \rightarrow {}^{4}\mathrm{He} + e^{+} + \nu_e$$

electron capture on $^{7}\mathrm{Be}$

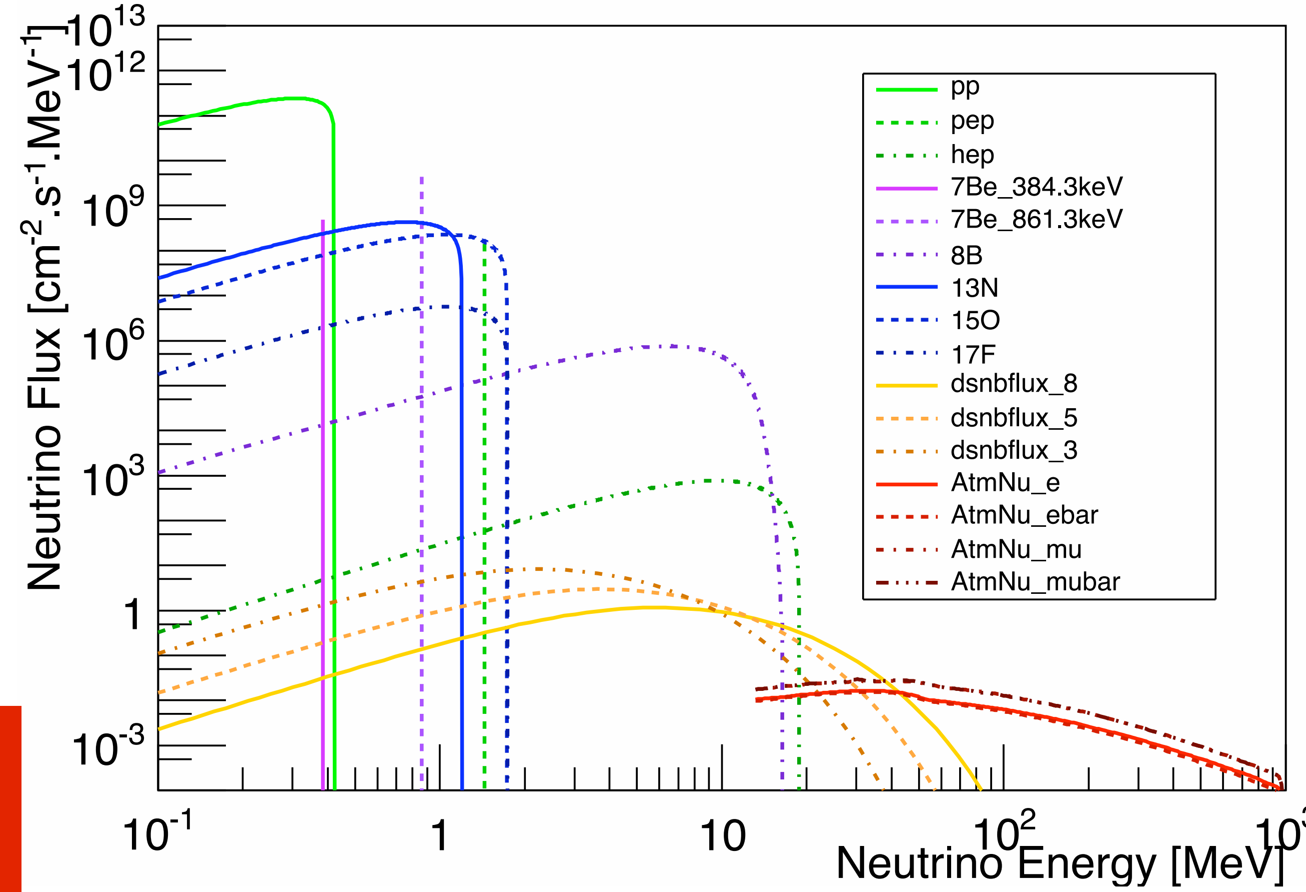
neutrinos from the CNO cycle

Solar neutrinos

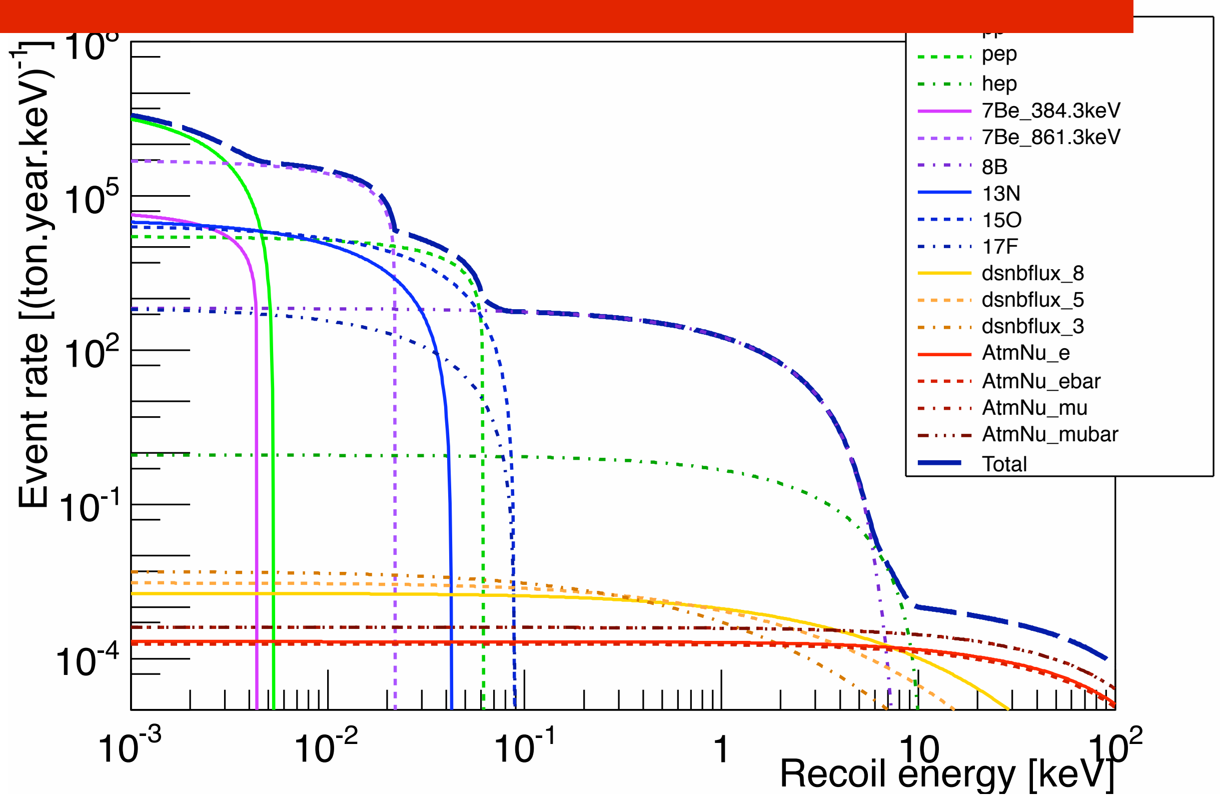


Diffuse SN background

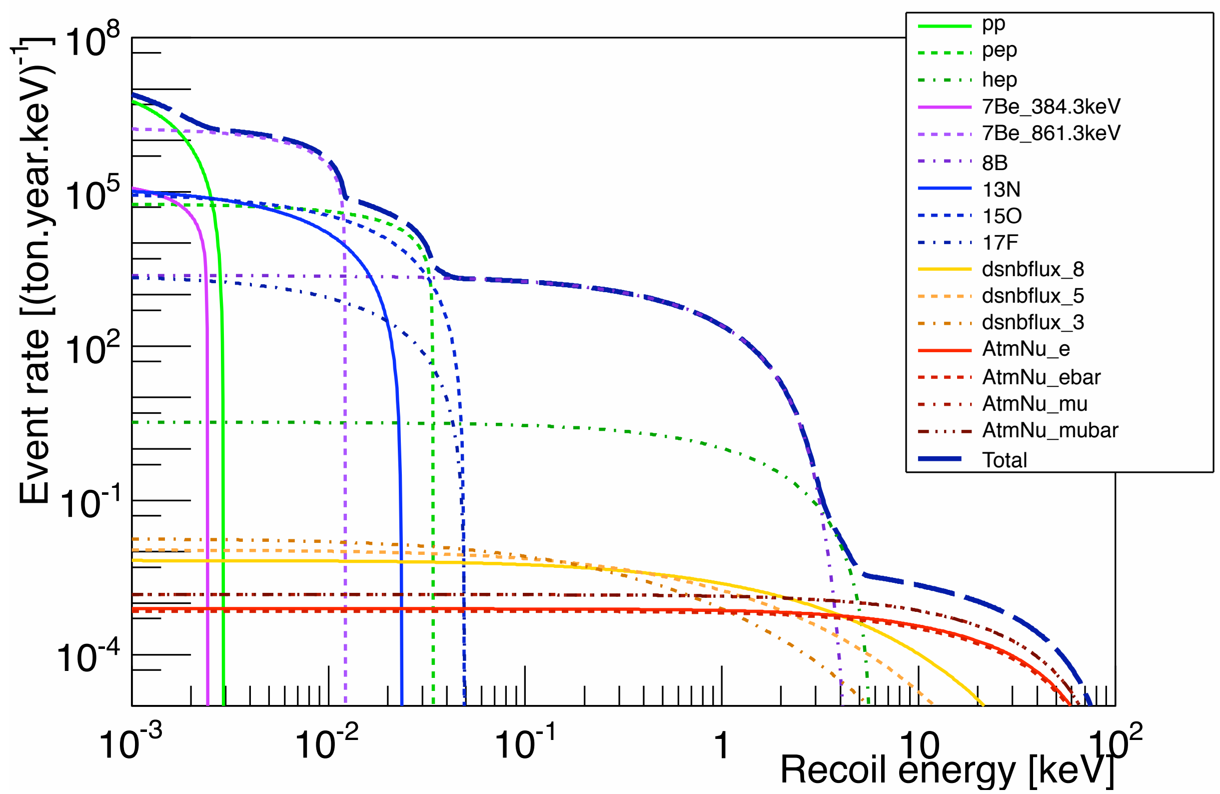
Neutrino Fluxes from each source



Recoil spectra due to neutrinos

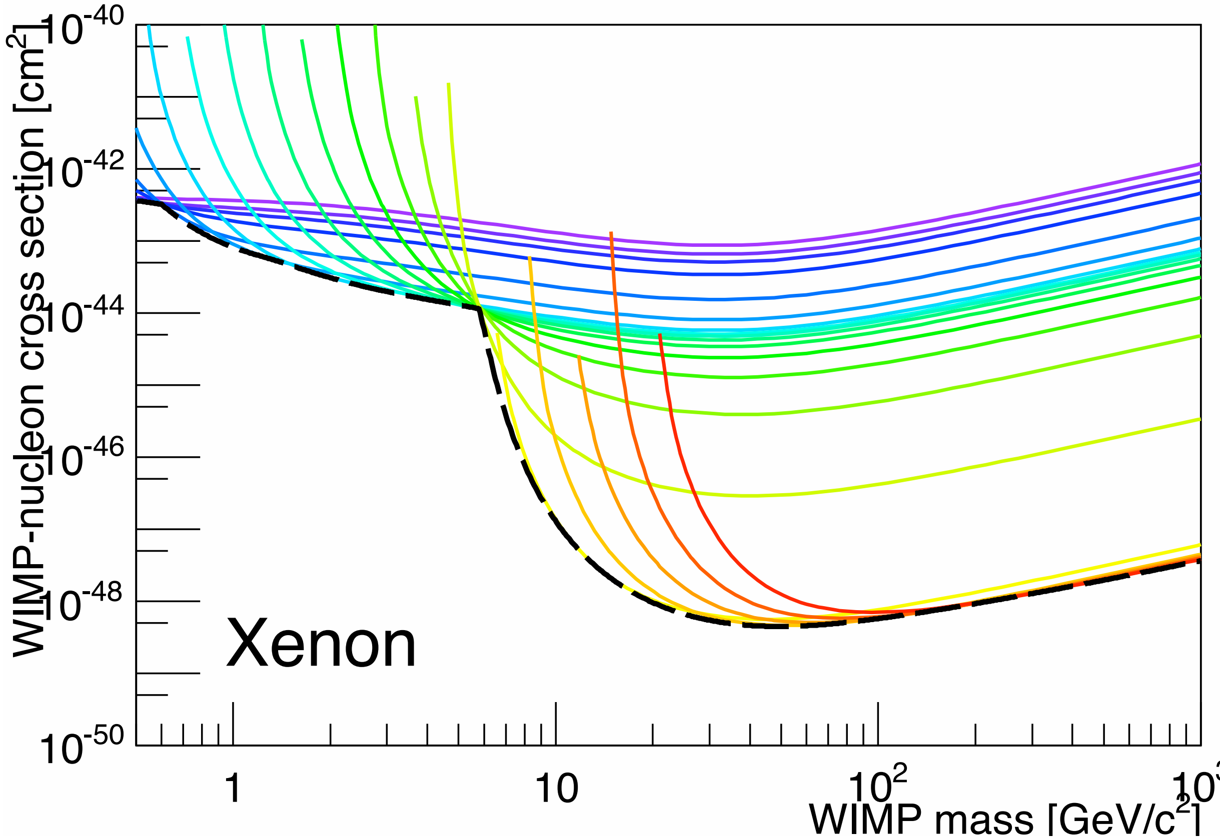


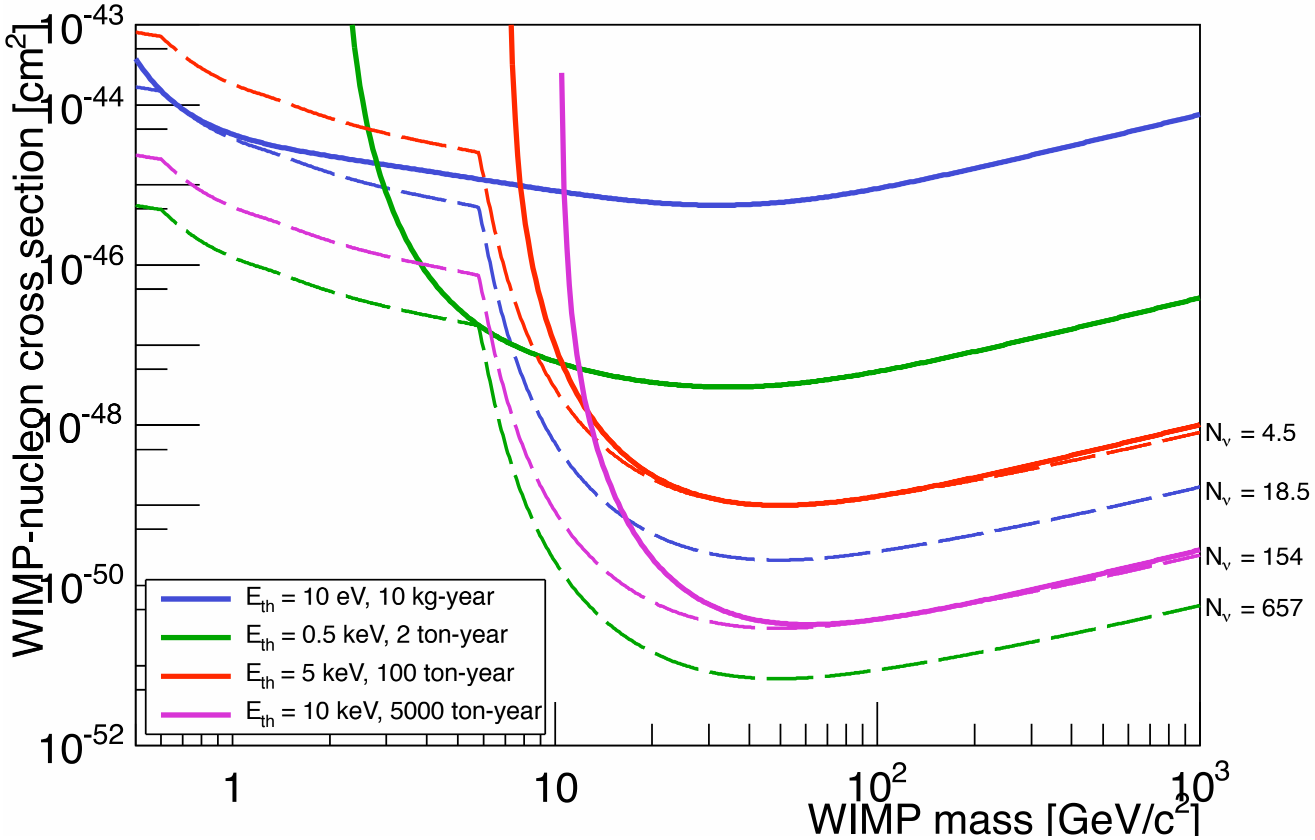
Germanium



Xenon

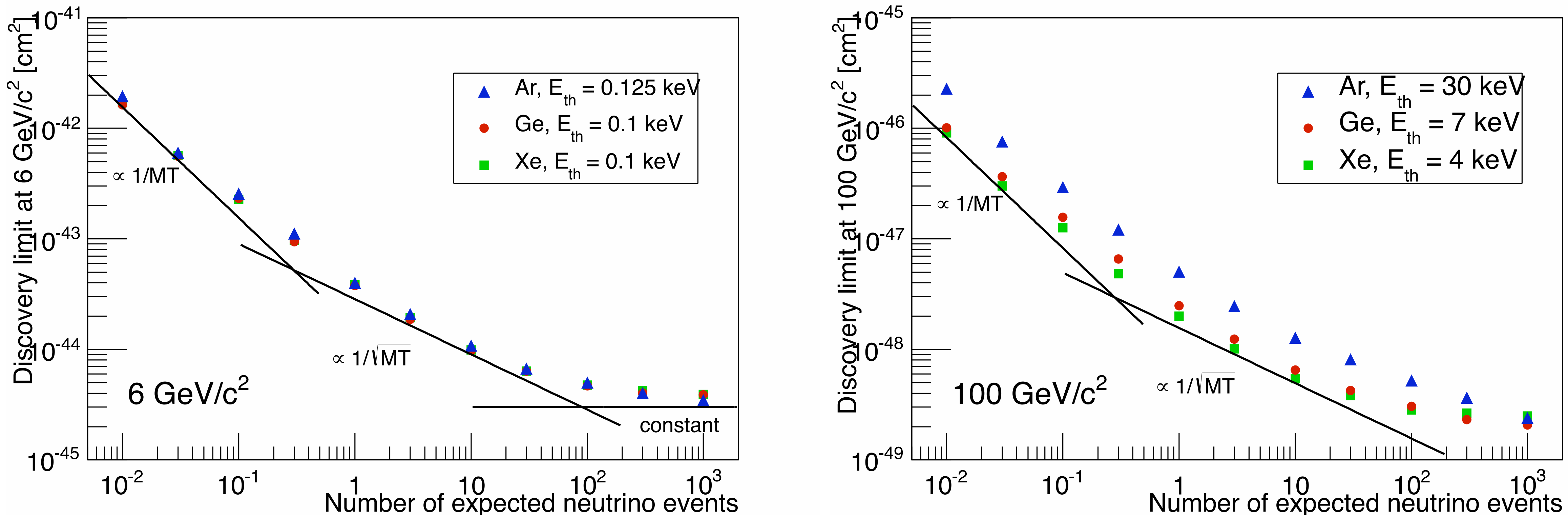
J. Billard, L. Strigari, and E. Figueroa-Feliciano, PRD 89 (2014), arXiv:1307.5458





Sensitivity curves for Xenon

Reach is a neutrino background of one event obtained for various thresholds (.001 keV-100 keV) and (background free) threshold/exposure (10 kg-yr-5,000 ton-yr) combinations

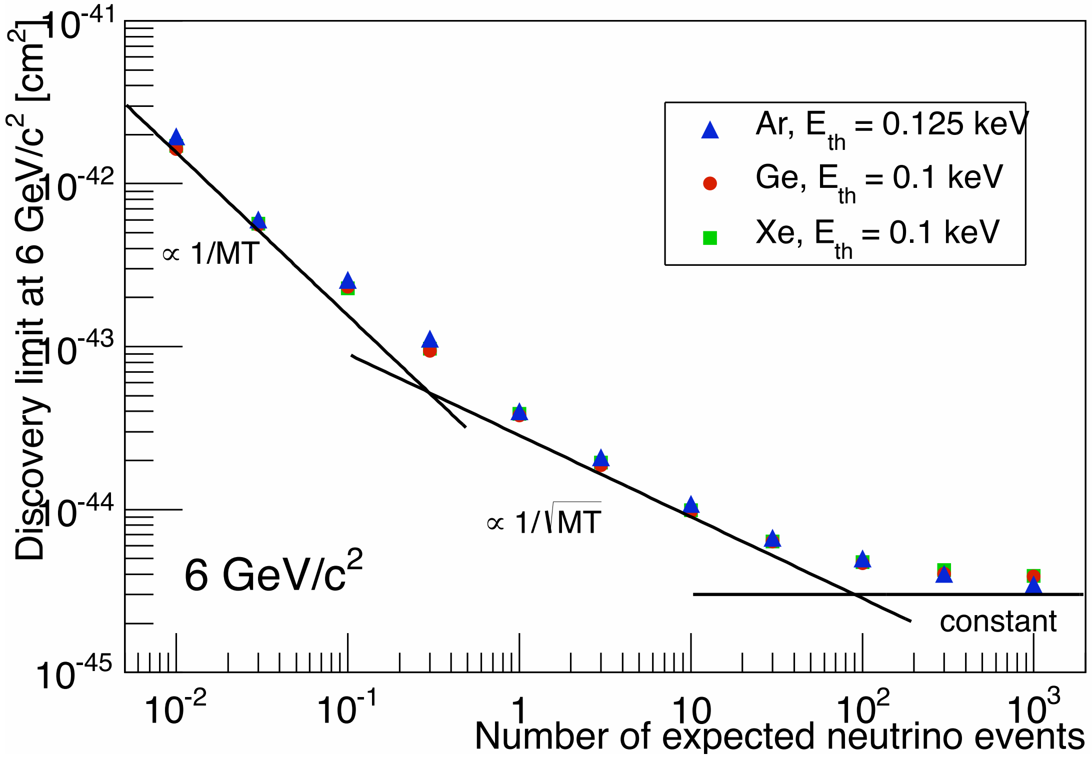


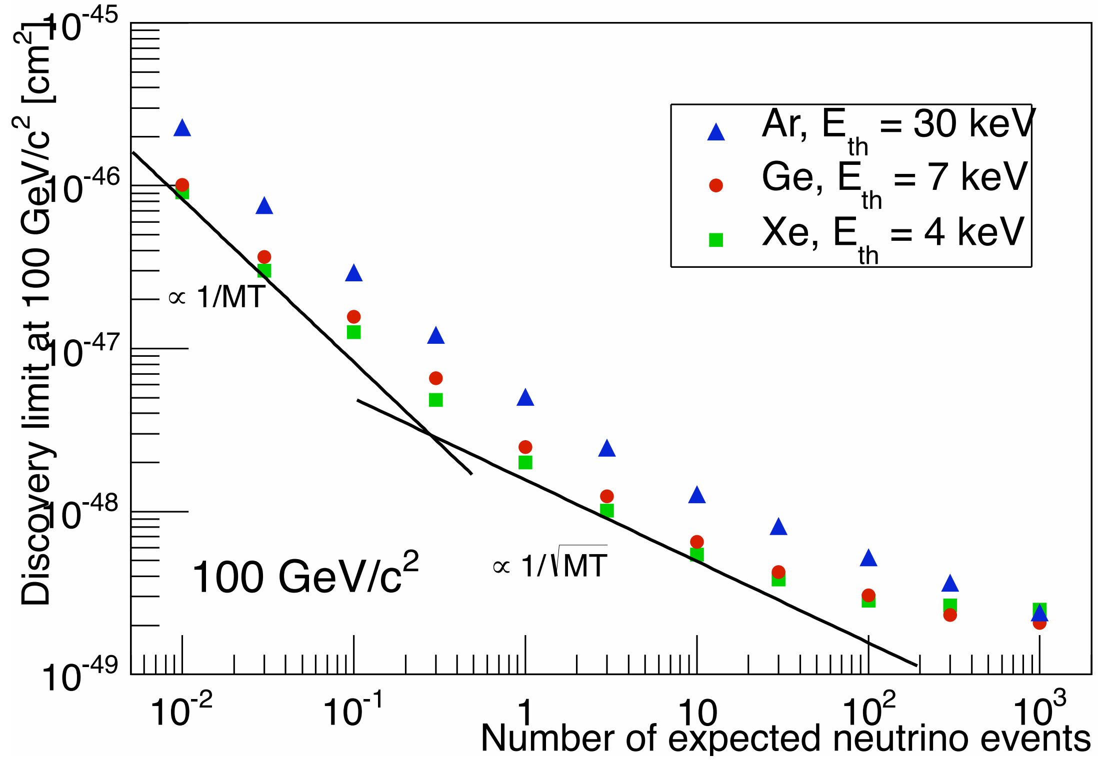
Discovery limits as a function of background neutrino events for Argon, Germanium, and Xenon.

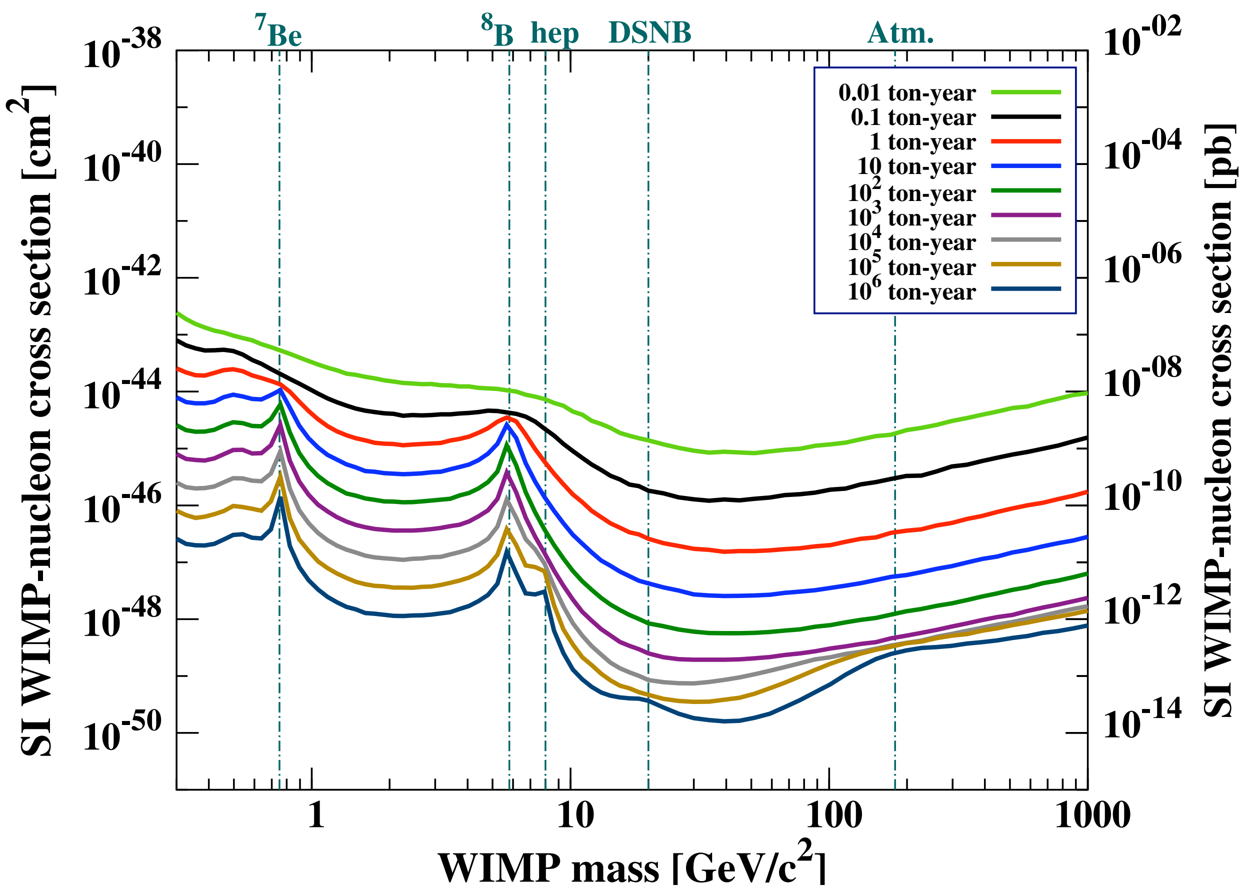
A given experiment has a 90% probability to obtain at least a 3σ detection

6GeV WIMP: Ge 240 kg-yr, Xe 130 kg-year, Ar 430 kg-yr

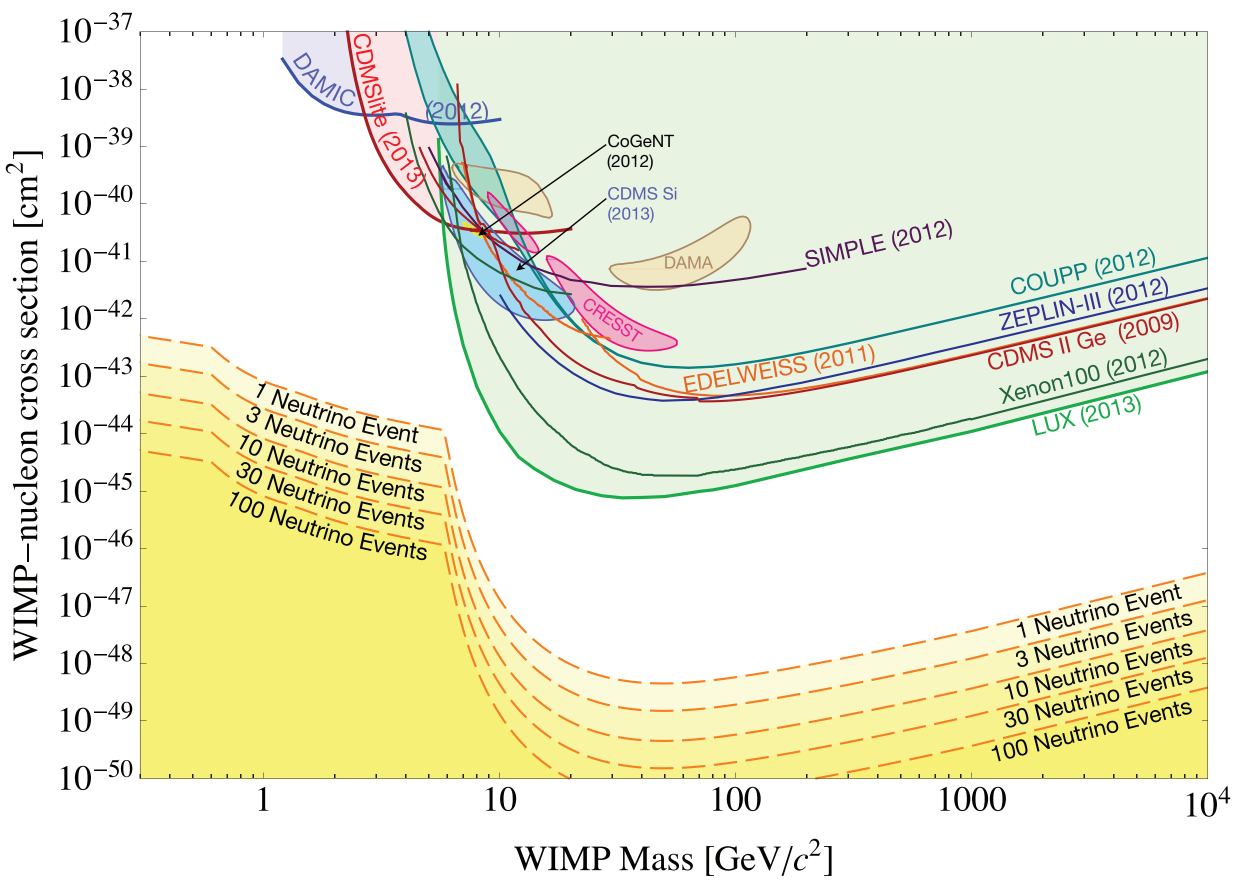
100GeV WIMP: Ge 32.5 ton-yr, Xe 21.5 ton-year, Ar 98 ton-yr

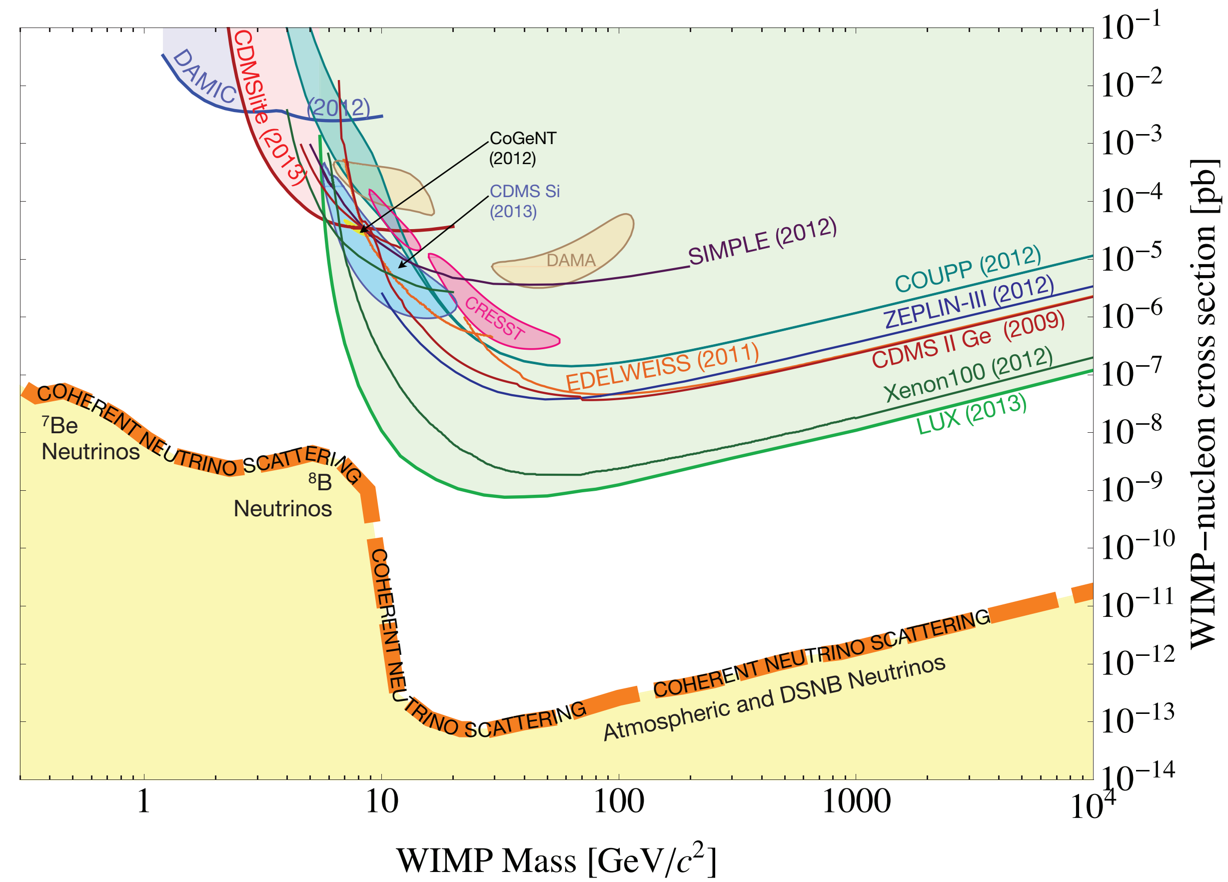






Discover limit for Xenon

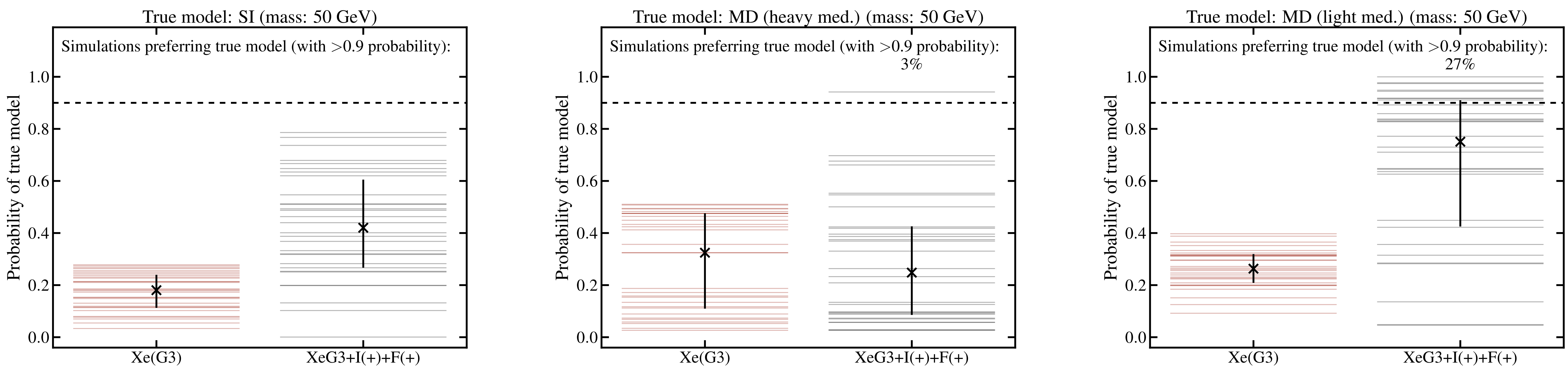




The direct detection limits after LUX along with the neutrino background

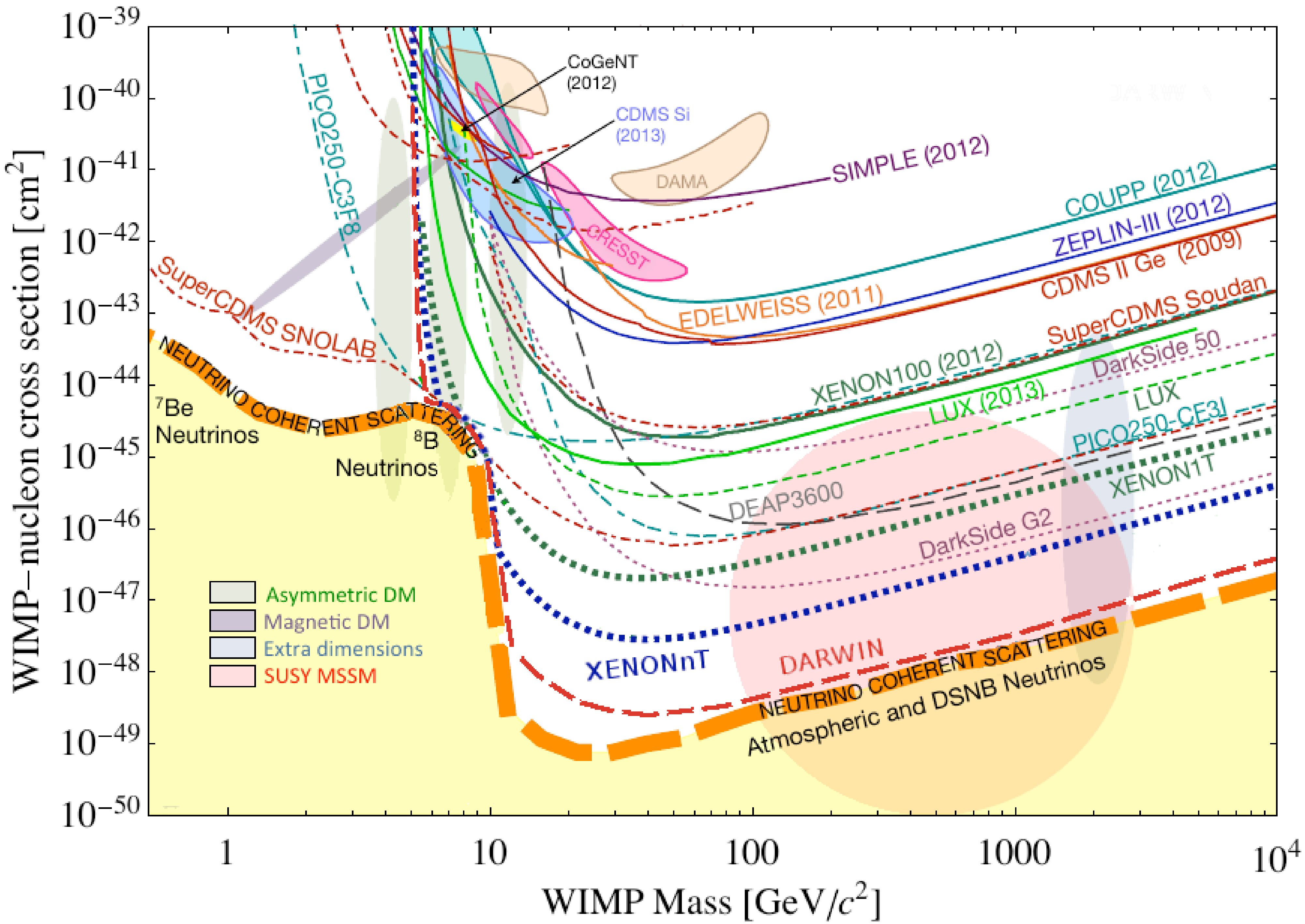
Right: combined discovery limits of two Xe-based pseudo-experiments with threshold of 3 eV and 4 keV, 500 neutrino events.

Label	A (Z)	Energy window [keVnr]	Exposure [kg-yr]
XeG3	131 (54)	5-40	40 000
I+	127 (53)	1-600	424
F+	19 (9)	3-100	1200



If a signal is not seen at the next generation of experiments, future prospects may be quite diminished

V. Glusevic, M. Gresham, S.D. McDermott, A.H.G. Peter, and K. Zurek, arXiv:1506.04454



The ultimate reach and extent of direct detection experiments

...perhaps not...

Fit for Xenon

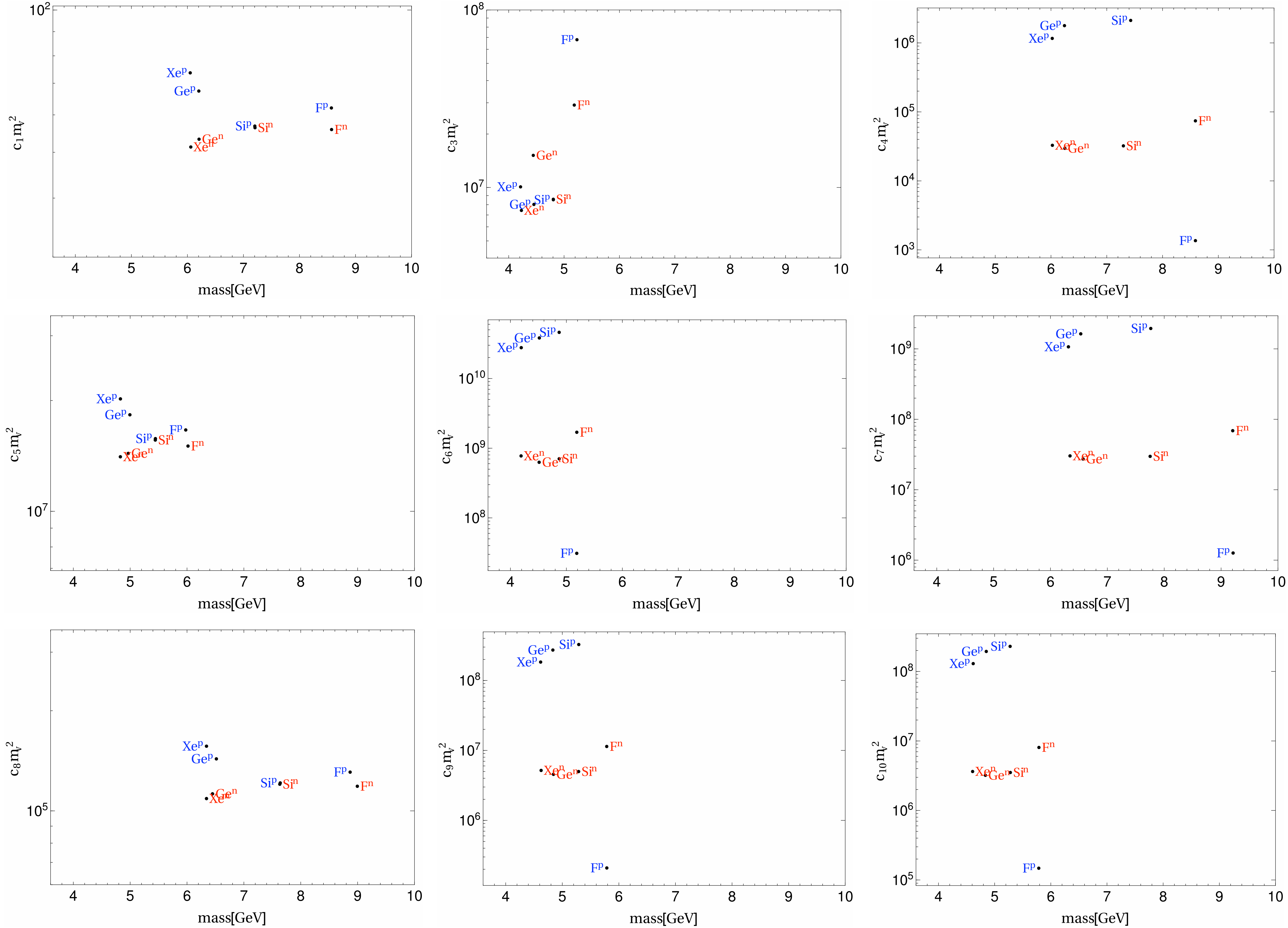
We have fit the various $\mathcal{O}_i$ to the neutrino rate for the 8B neutrino flux, with exposures chosen to give 200 expected neutrino events

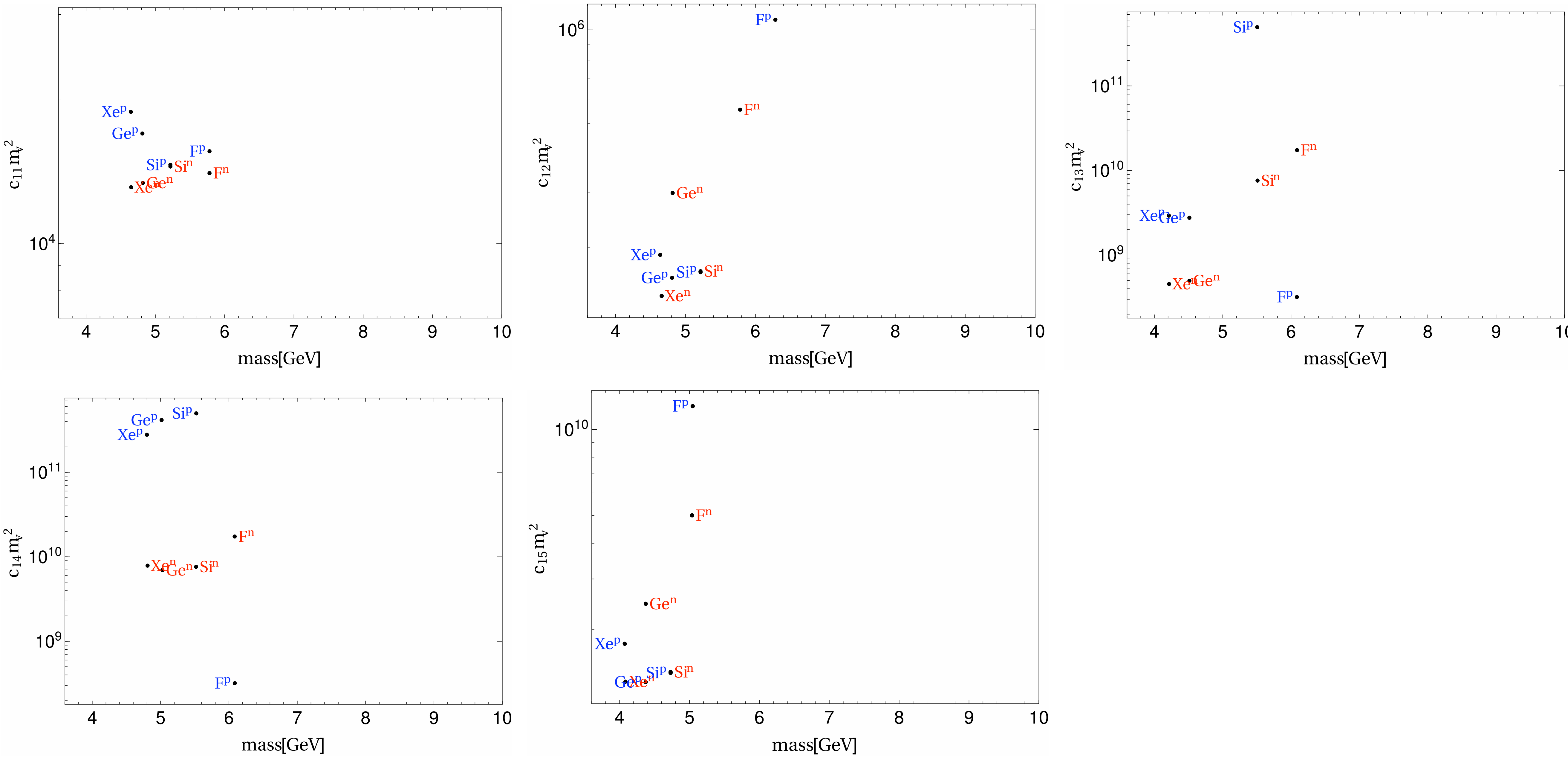
Target	threshold (low/high)
xenon	3.0 eV / 4.0 keV
germanium	5.3 eV / 7.9 keV
silicon	14 eV / 20 keV
flourine	33 eV / 28keV

Operator	Mass (GeV)	Exp. (t.y)
$\mathcal{O}_1$	6	3.4
$\mathcal{O}_4$	6	2.8
$\mathcal{O}_7$	6.2	1.7
$\mathcal{O}_8$	6.3	3.4
q^2 and $q^2 v_T^2$		
$\mathcal{O}_5$	4.8	0.47
$\mathcal{O}_9$	4.6	0.42
$\mathcal{O}_{10}$	4.6	0.42
$\mathcal{O}_{11}$	4.6	0.51
$\mathcal{O}_{12}$	4.6	0.35
$\mathcal{O}_{14}$	4.8	0.47
$q^2 v_T^2$, q^4 and $q^4 v_T^2$		
$\mathcal{O}_3$	4.2	0.28
$\mathcal{O}_6$	4.2	0.37
$\mathcal{O}_{13}$	4.2	0.34
$\mathcal{O}_{15}$	4.1	0.27

JBD, B. Dutta, L. Strigari, and J. Newstead, *to appear*

Similarly, for Ge, Si, and F



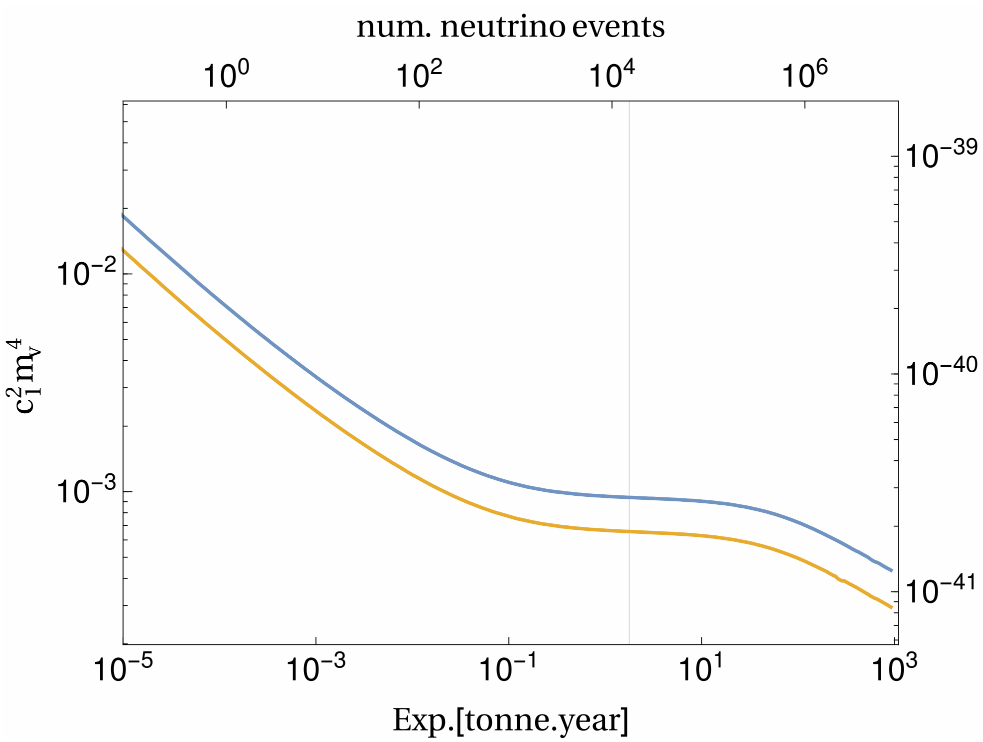


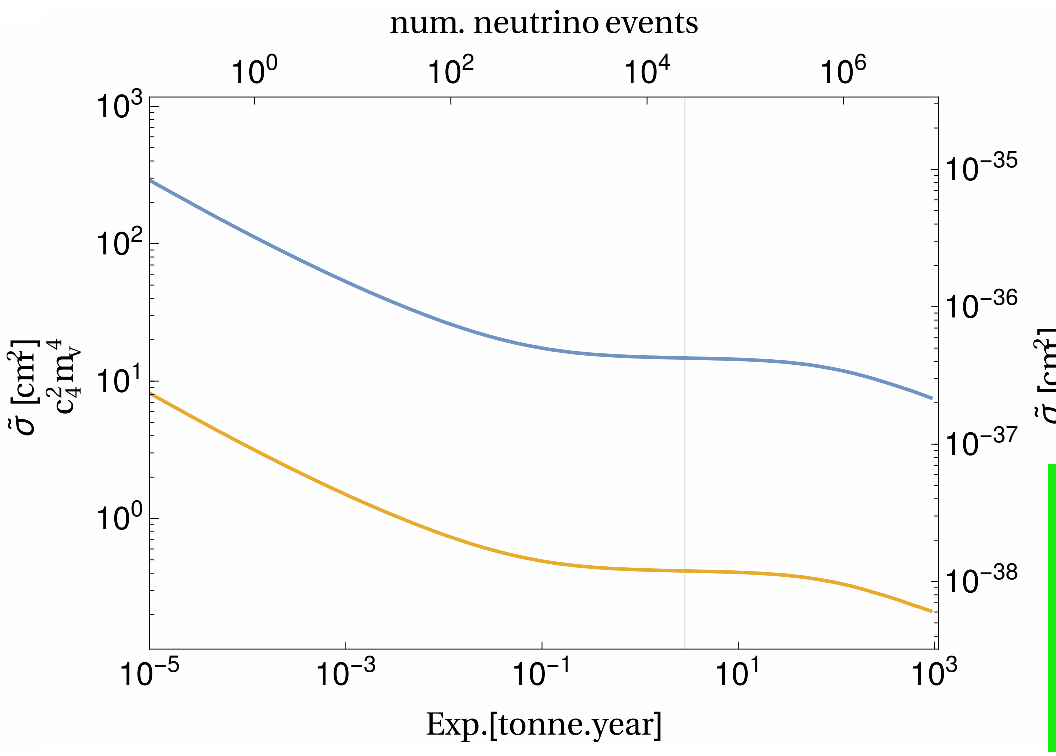
c11 mv2
10^4
Xe^p
Ge^p
F^p
Si^p
Si^n
F^n
Xe^n
Ge^n
mass[GeV]
c12 mv2
10^6
F^p
F^n
Ge^n
Xe^p
Ge^p
Si^p
Si^n
Xe^n
mass[GeV]
c13 mv2
10^11
10^10
10^9
Si^p
F^n
Si^n
Xe^p
Ge^p
Xe^n
Ge^n
F^p
mass[GeV]
c14 mv2
10^11
10^10
10^9
Ge^p
Si^p
Xe^p
F^n
Xe^n
Ge^n
Si^n
F^p
mass[GeV]
c15 mv2
10^10
F^p
F^n
Ge^n
Xe^p
Si^p
Si^n
mass[GeV]
4 5 6 7 8 9 10

Discovery Potential

We've calculated the smallest cross-section which will produce a 3σ fluctuation above the background 90% of the time

$\mathcal{O}_1$

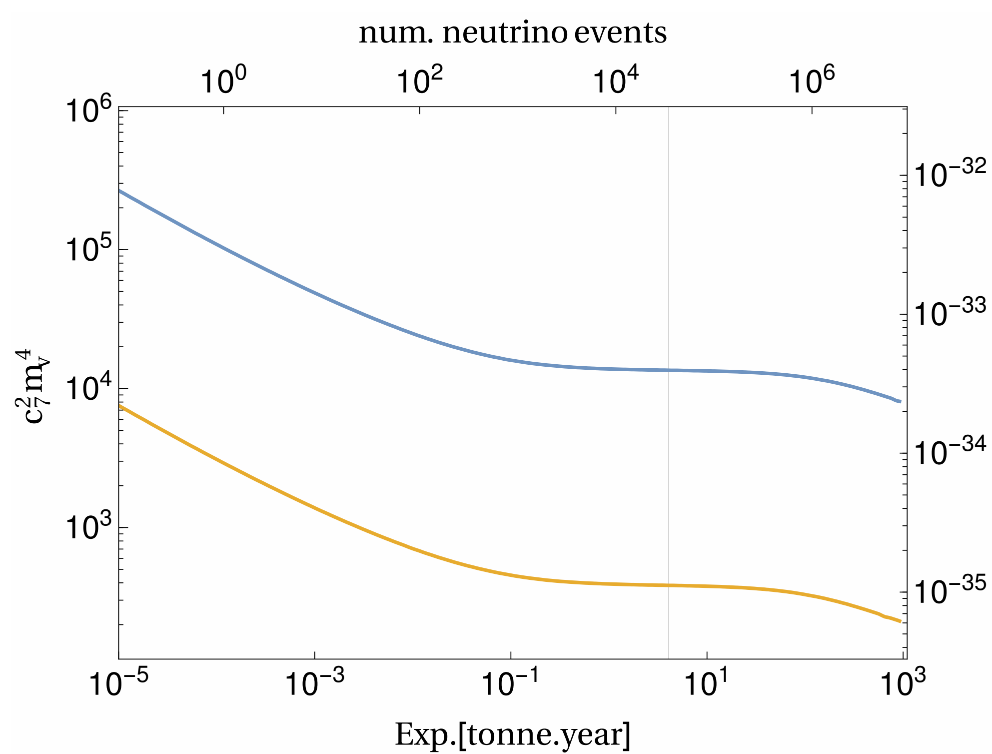


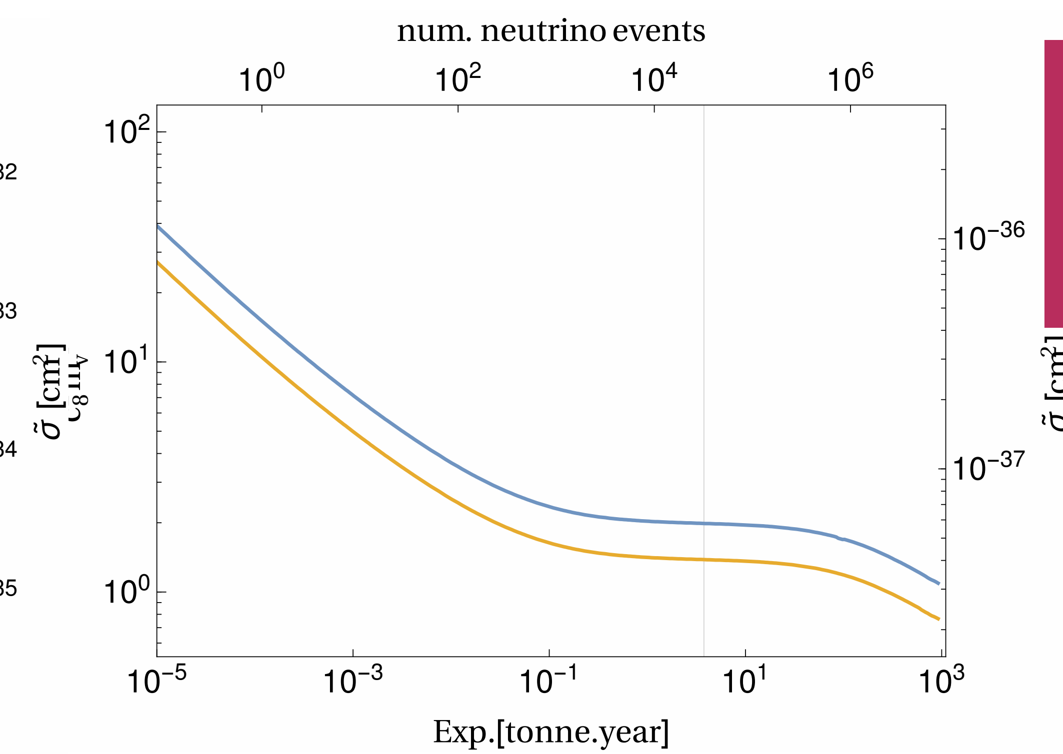


$\mathcal{O}_4$

The standard floor is recovered for the first set of operators

$\mathcal{O}_7$

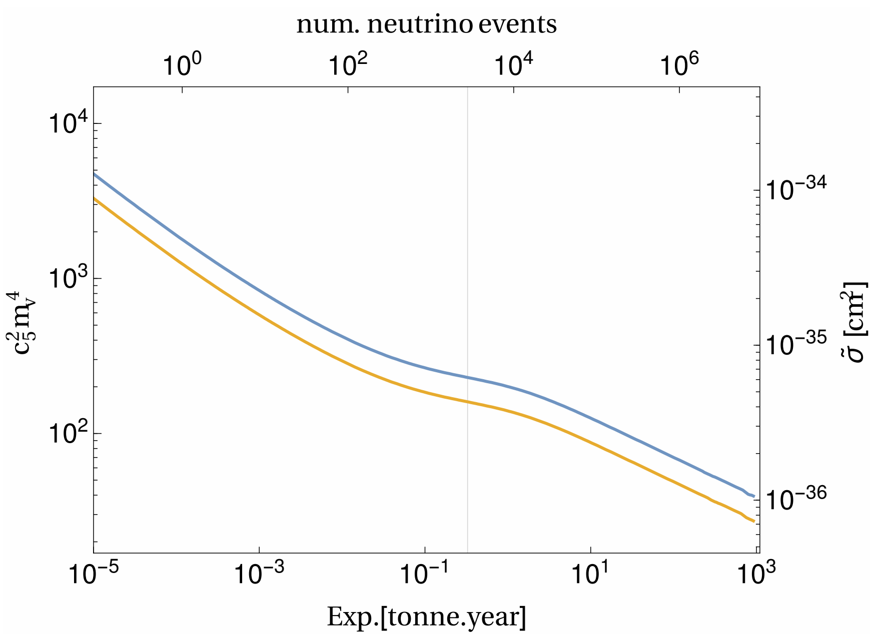


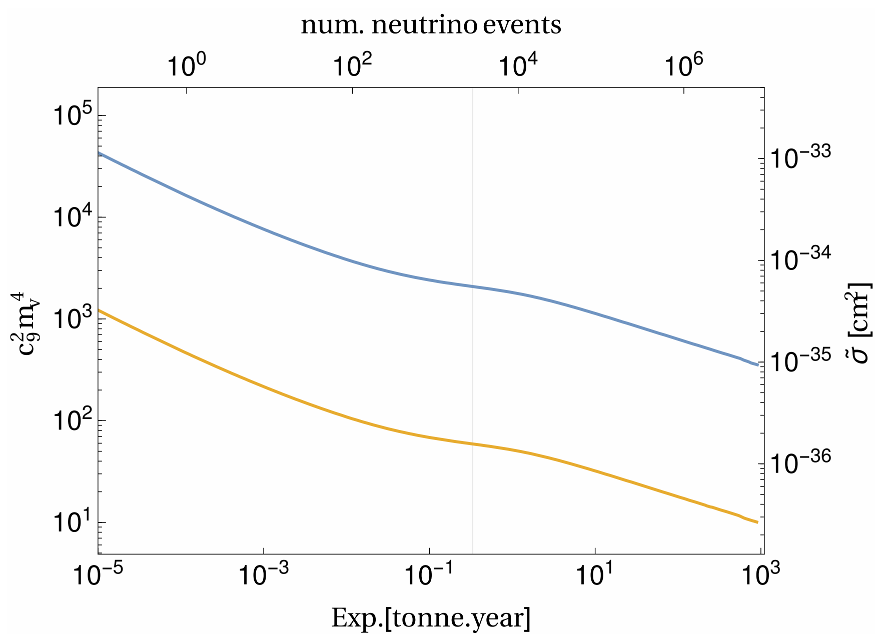


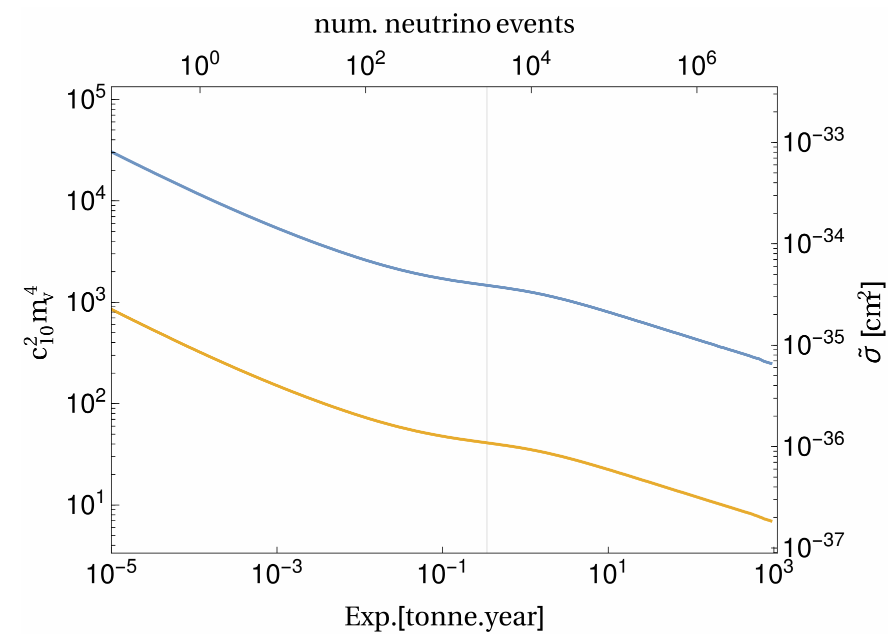
$\mathcal{O}_8$

q^2 and $q^2 v_T^2$

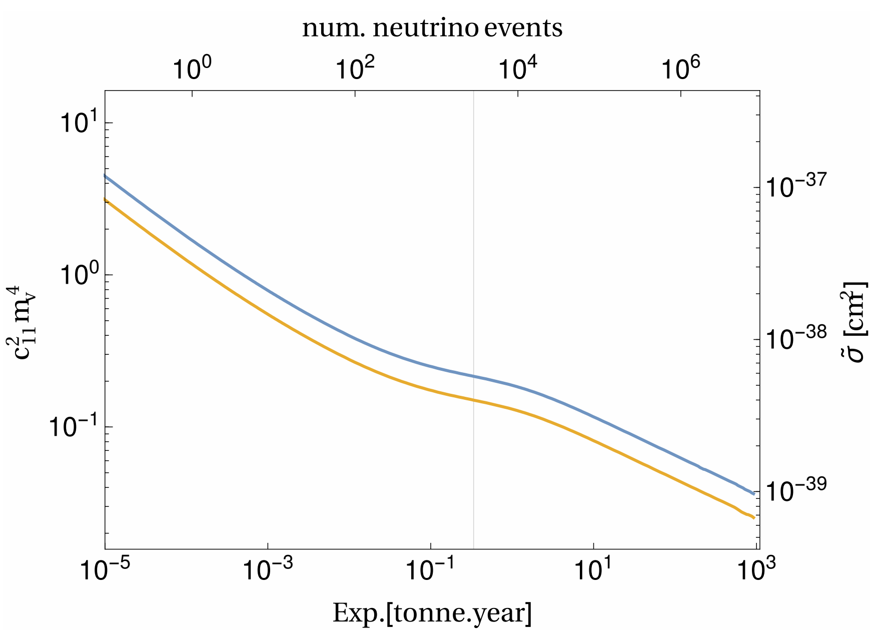
$\mathcal{O}_5$ $\mathcal{O}_9$ $\mathcal{O}_{10}$

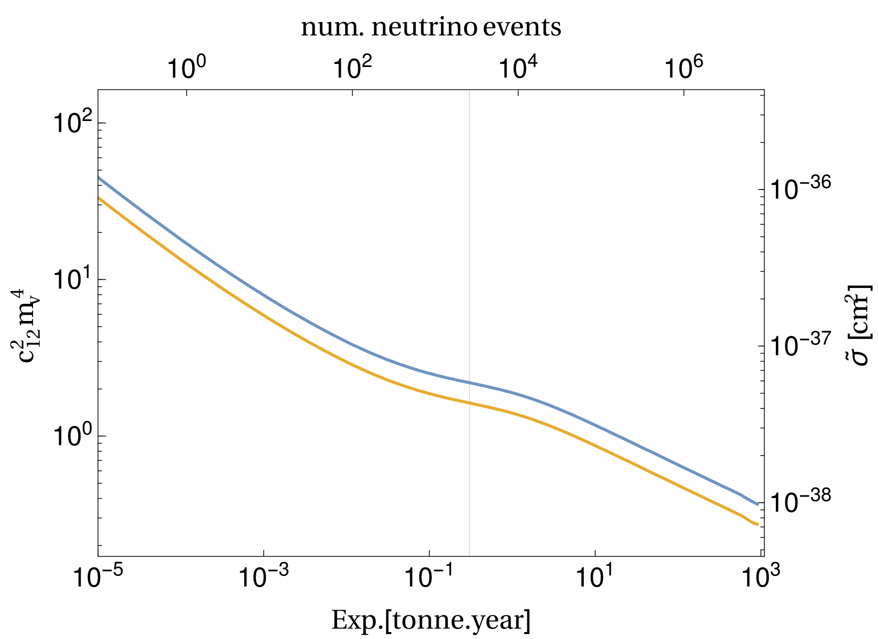


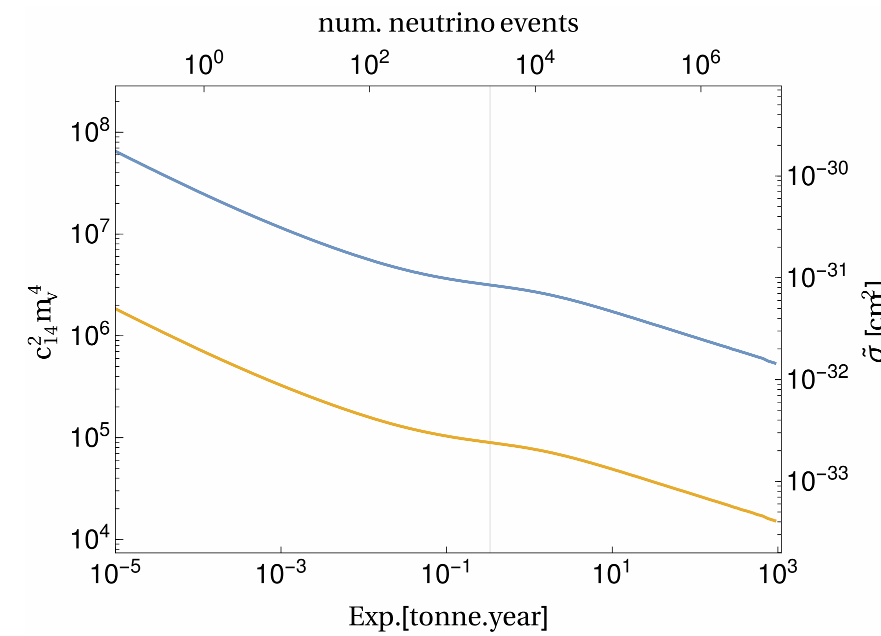




but disappears for different momentum dependent operators



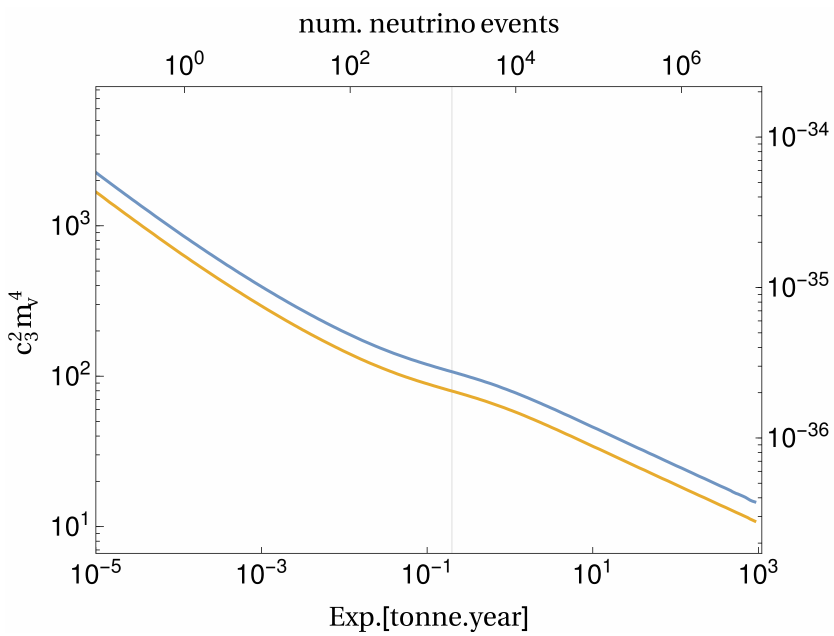


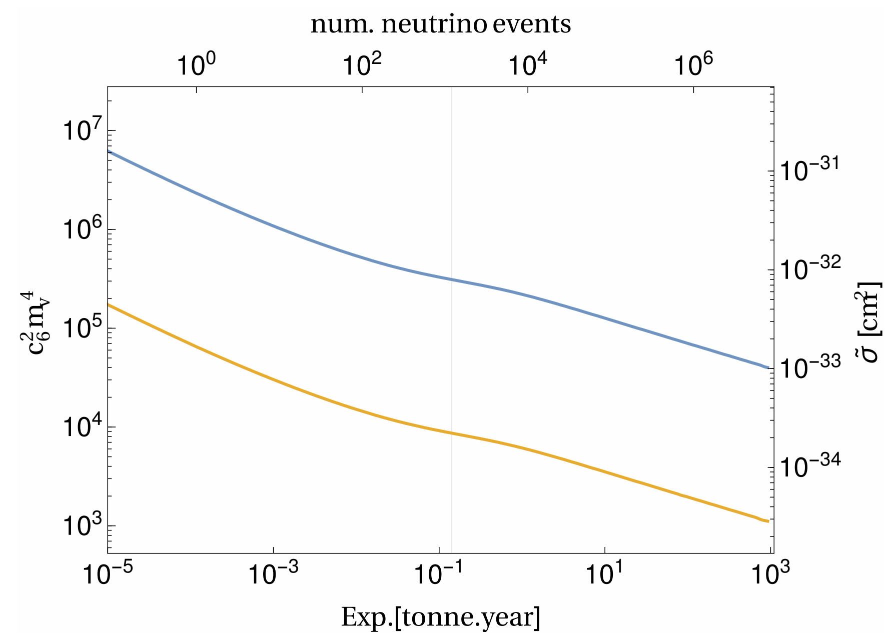


$\mathcal{O}_{11}$ $\mathcal{O}_{12}$ $\mathcal{O}_{14}$

$q^2 v_T^2$, q^4 and $q^4 v_T^2$

$\mathcal{O}_3$

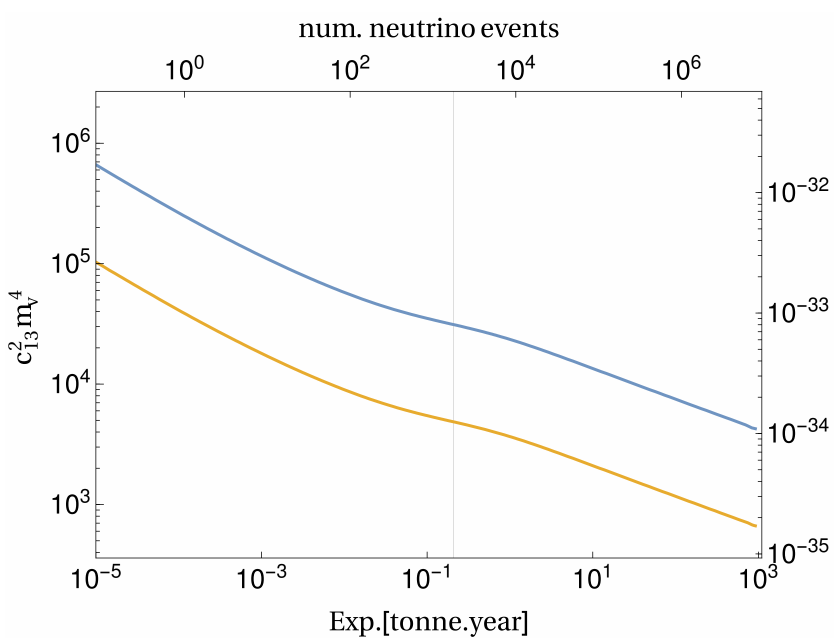


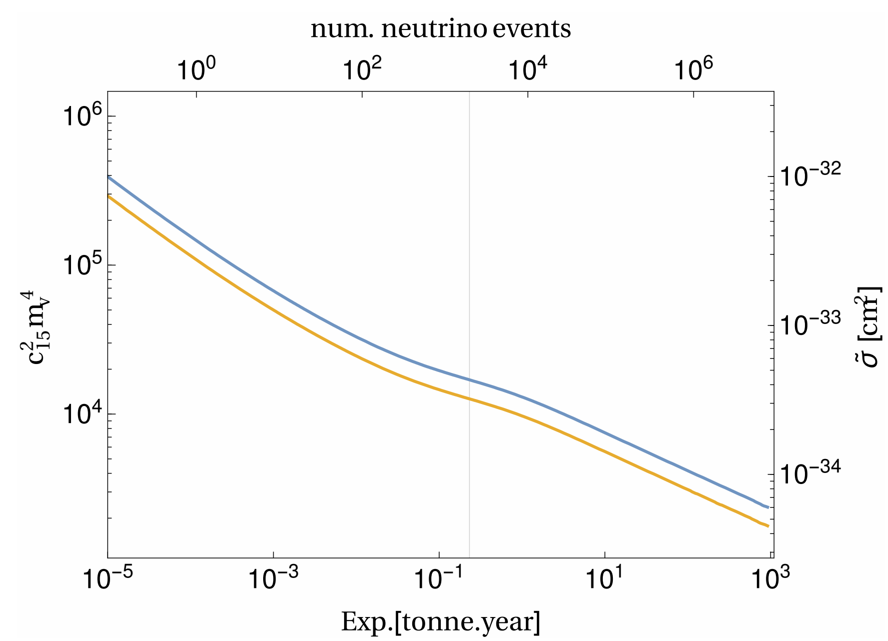


$\mathcal{O}_6$

but disappears for different momentum dependent operators

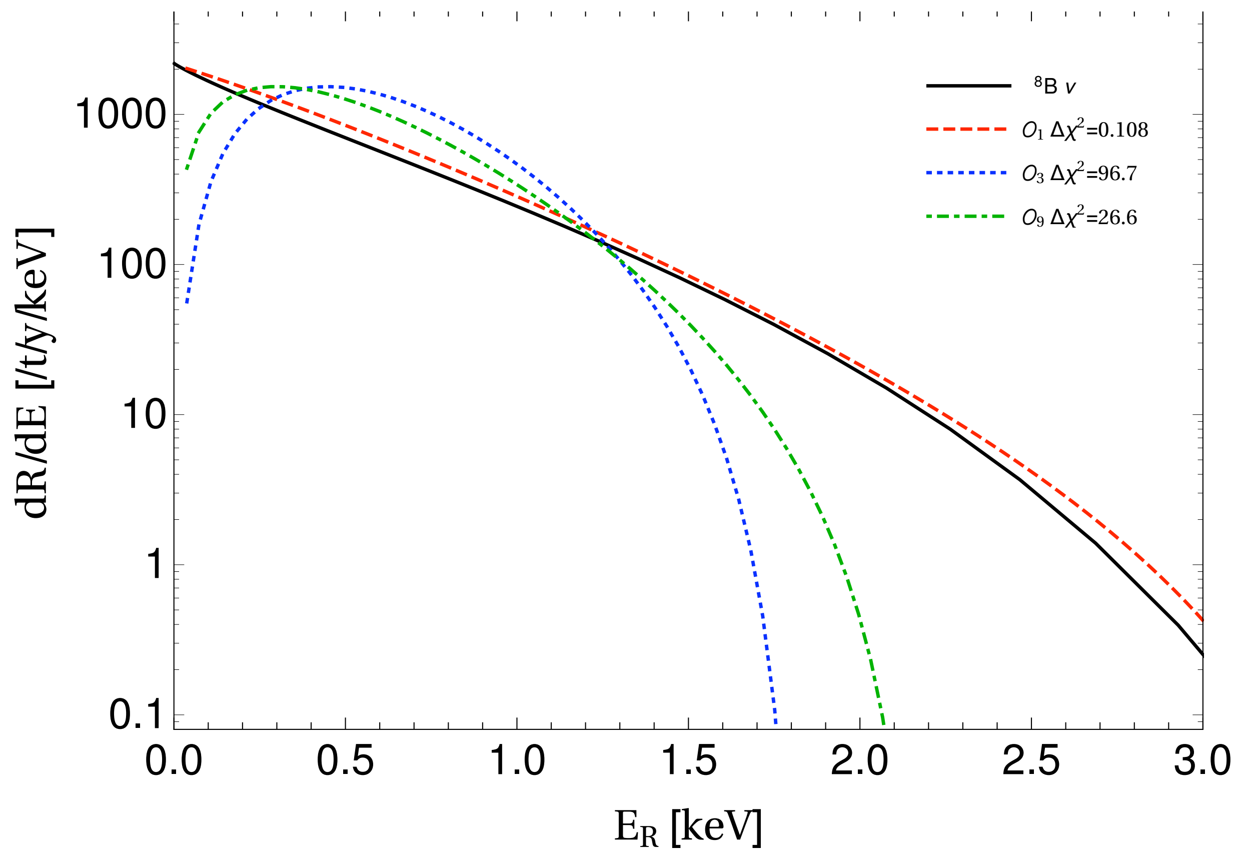
$\mathcal{O}_{13}$

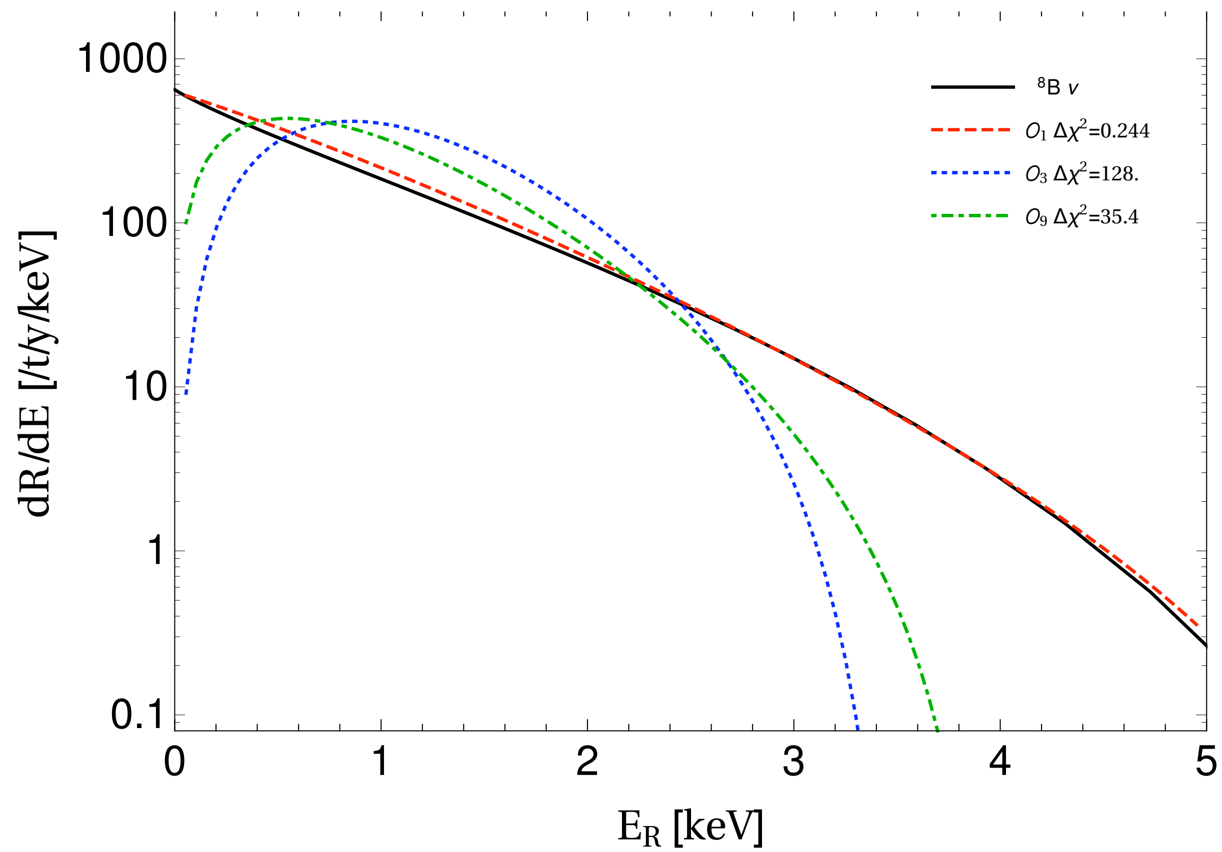




$\mathcal{O}_{15}$

Sample max likelihood rates fit to the boron-8 neutrino rate





$\mathcal{O}_3$ $$i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}\right)$$

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

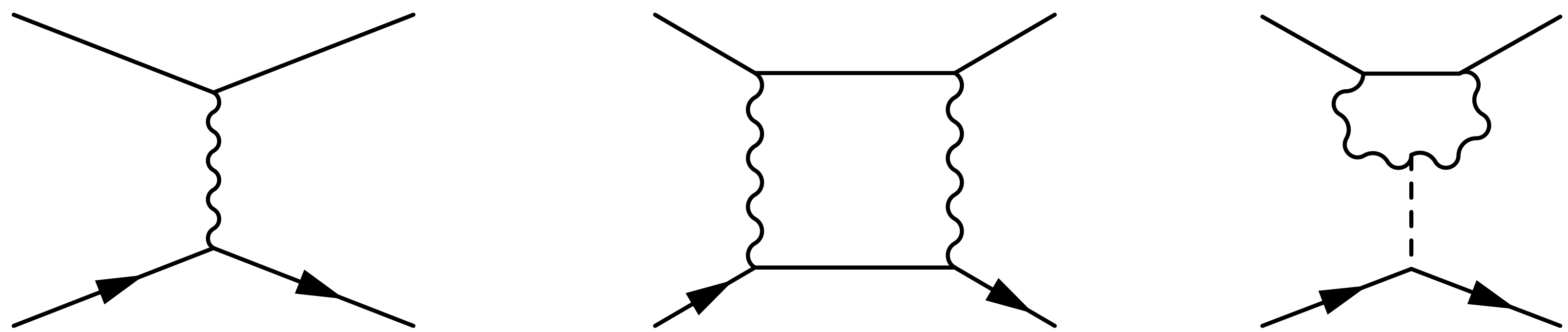
Xenon

Germanium

Connecting the Scales

Operator Uniqueness

An issue that arises is whether one could begin at a high scale with one type of operator as dominant and end at a low scale with a different leading order operator.



(a) Tree level (b) Loop processes

$$\frac{g_2^2}{2\cos^2\theta_W} T_3^q \, \frac{Q}{2} \, \frac{1}{m_Z^2} \, \bar{\chi}\gamma^\mu\gamma^5\chi \, \bar{q}\gamma_\mu\gamma^5 q$$

SD

$$\frac{1}{4\pi} \, \frac{g_2^4 \, Q^2}{\cos^4\theta_W \, m_Z} \left[\frac{(T_3^q)^2}{2m_Z^2} + \frac{1}{4m_h^2}\right] m_q \, \bar{\chi}\chi \, \bar{q}q$$

SI

M. Freytsis and Z. Ligeti, PRD **83** (2011), arXiv:1012.5317

M.A. Fedderke, J.-Y. Chen, E.W. Kolb, and L.-T. Wang, JHEP **1408** (2014), arXiv:1404.2283

S. Matsumoto, S. Mukhopadhyay, Y.-L. Sming Tsai, JHEP **1410** (2014), arXiv:1407.1859

R.J. Hill and M.P. Solon, PRD **91** (2015) arXiv:1409.8290

Operator Uniqueness

An example was obtained for the Higgs portal interaction

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi}\left(i\partial\!\!\!/ - M_0\right)\chi + \Lambda^{-1}\left(\cos\theta\ \bar{\chi}\chi + \sin\theta\ \bar{\chi}i\gamma_5\chi\right)\ H^\dagger H$$

After EWSB: $$H^\dagger H \longrightarrow \frac{\langle v\rangle^2}{2} + \langle v\rangle h + \frac{h^2}{2}$$

A chiral rotation and field redefinition is needed for a real mass

$$\chi \to \exp\left(i\gamma_5\ \alpha/2\right)\chi \quad \Rightarrow \quad \bar{\chi} \to \bar{\chi}\exp\left(i\gamma_5\ \alpha/2\right)$$

It is found that even for an initially pure pseudoscalar interaction $\cos\theta = 0,\ \sin\theta = \pm 1$

a scalar term will be generated

$$\Lambda^{-1}\left[-\frac{\langle v\rangle^2}{2\Lambda M}\ \bar{\chi}\chi \pm \sqrt{1-\left(\frac{\langle v\rangle^2}{2\Lambda M}\right)^2}\ \bar{\chi}i\gamma_5\chi\right]\left(\langle v\rangle h + h^2/2\right)$$

M.A. Fedderke, J.-Y. Chen, E.W. Kolb, and L.-T. Wang, JHEP **1408** (2014), arXiv:1404.2283

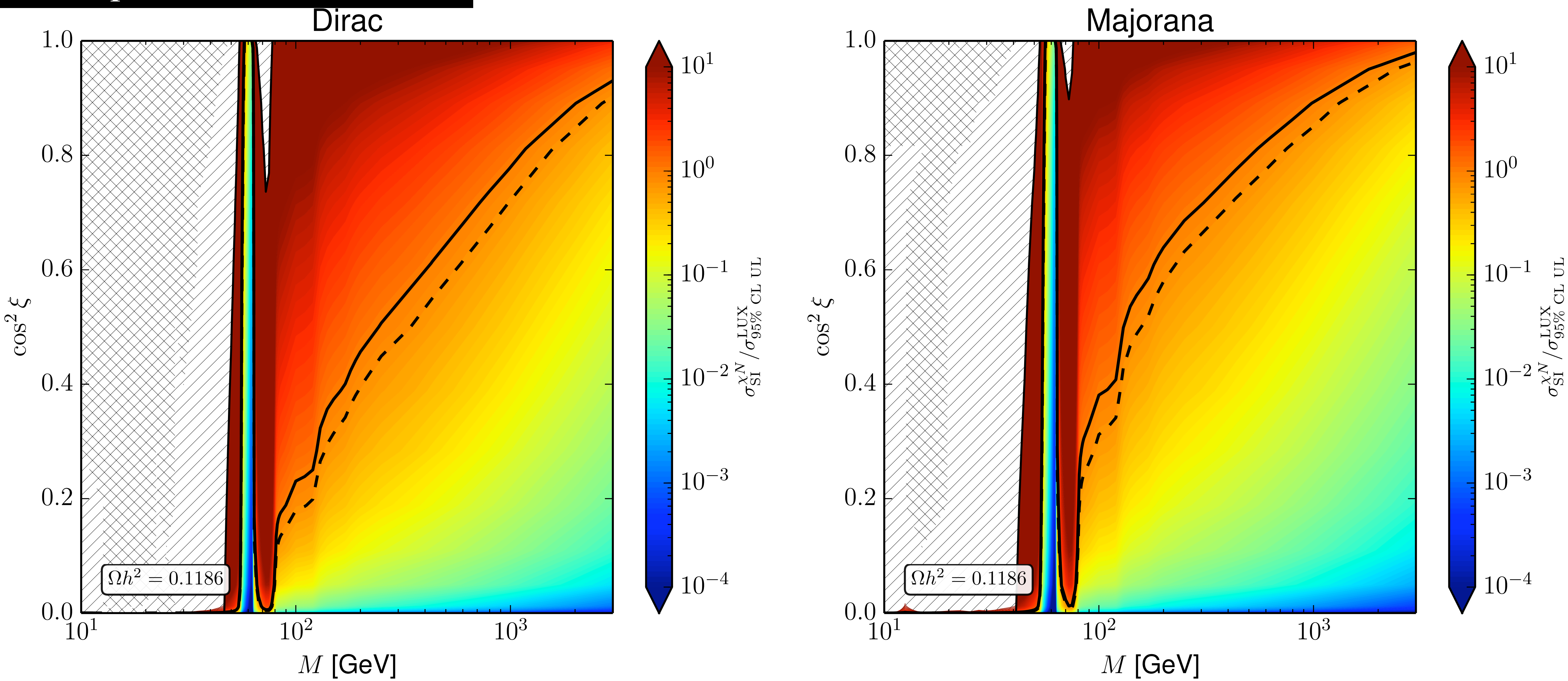
S. Matsumoto, S. Mukhopadhyay, Y.-L. Sming Tsai, JHEP **1410** (2014), arXiv:1407.1859

R.J. Hill and M.P. Solon, PRD **91** (2015) arXiv:1409.8290

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi} i \partial\!\!\!/ \chi - \bar{\chi} M \chi + \Lambda^{-1} \left(\langle v \rangle h + \frac{1}{2} h^2 \right) \left[\cos\xi \ \bar{\chi}\chi + \sin\xi \ \bar{\chi} i \gamma_5 \chi \right]$$

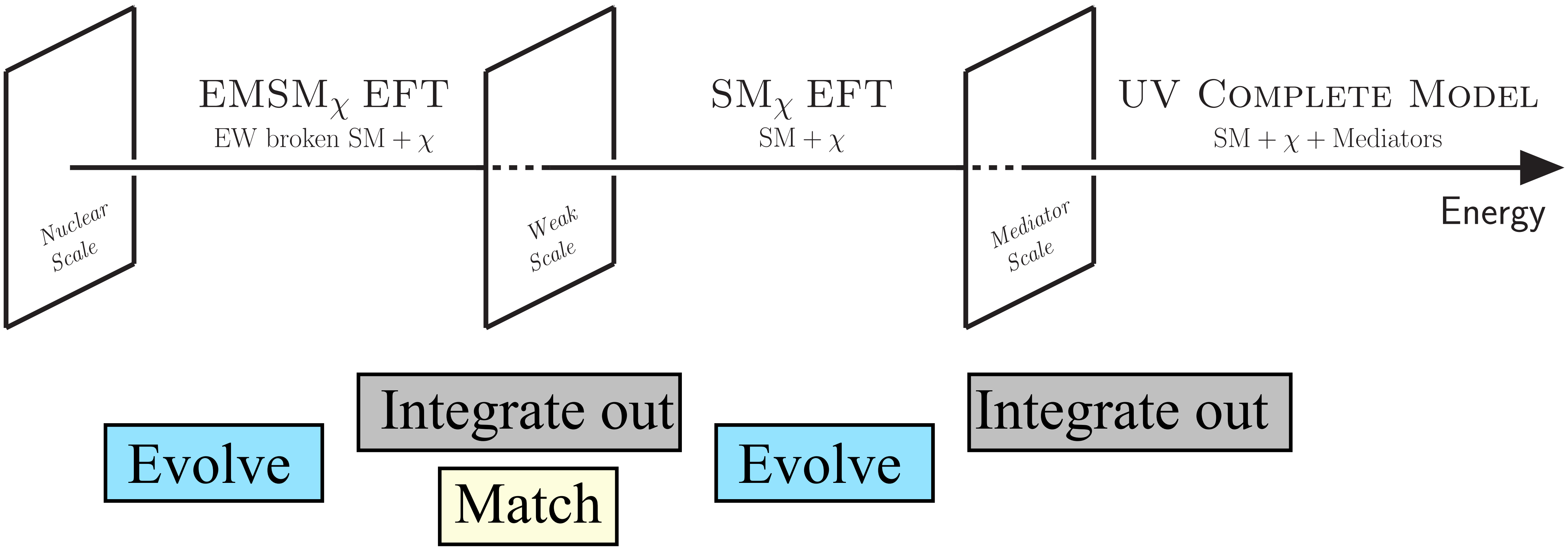
$$\cos\xi = \frac{M_0}{M} \left[\cos\theta - \frac{\langle v \rangle^2}{2\Lambda M_0} \right] \qquad \text{and} \qquad \sin\xi = \frac{M_0}{M} \sin\theta$$

Spin-Independent Constraints



$$\sigma_{\rm SI}^{\chi N} = \frac{\langle |\mathcal{M}| \rangle}{16\pi (M + M_N)^2} = \frac{1}{\pi} \left(\frac{\mu_{\chi N}}{m_h^2} \right)^2 \left(\frac{f_N}{\Lambda} \right)^2 \left[\cos^2\xi + \frac{1}{2} \left(\frac{\mu_{\chi N}}{M} \right)^2 \nu_\chi^2 \right]$$

In order to fully exploit complementarity between direct detection and collider searches, one needs to properly connect the scale of the mediator mass to the nuclear scale



$$\mathcal{L}_{\mathrm{SM}_\chi} = \mathcal{L}_{\mathrm{SM}} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \sum_{d>4}\sum_{\alpha}\frac{c_\alpha^{(d)}}{\Lambda^{d-4}}\mathcal{O}_\alpha^{(d)}$$

F. D'Eramo and M. Procura, JHEP (2015), arXiv:1411.3342

SM_χ EFT

Symbol	Operator	Symbol	Operator	Symbol	Operator
$\mathcal{O}^{(i)}_{\Gamma q}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{q^i_L}\gamma_\mu q^i_L$	$\mathcal{O}^{(i)}_{\Gamma l}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{l^i_L}\gamma_\mu l^i_L$	$\mathcal{O}^{(i)}_{\Gamma H}$	$\overline{\chi}\,\Gamma^\mu\chi\,H^\dagger i\overleftrightarrow{D}_\mu H$
$\mathcal{O}^{(i)}_{\Gamma u}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{u^i_R}\gamma_\mu u^i_R$	$\mathcal{O}^{(i)}_{\Gamma e}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{e^i_R}\gamma_\mu e^i_R$		
$\mathcal{O}^{(i)}_{\Gamma d}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{d^i_R}\gamma_\mu d^i_R$				

Wilson coefficients are evolved
$$\frac{d\,\mathcal{C}_{\mathrm{SM}_\chi}}{d\ln\mu} = \gamma_{\mathrm{SM}_\chi}\mathcal{C}_{\mathrm{SM}_\chi}$$

Wilson coefficients are matched at the EWSB scale including effects from integrating out weak scale particles

EMSM_χ

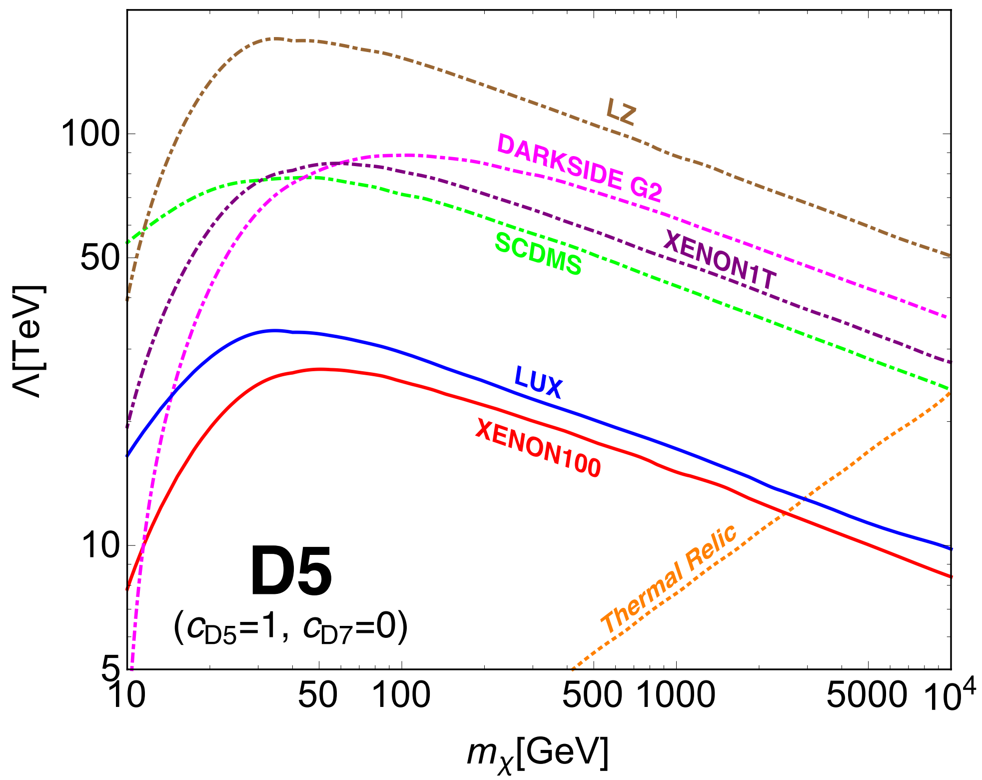
Symbol	Operator	Symbol	Operator	Symbol	Operator
$\mathcal{O}^{(i)}_{\Gamma Vu}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{u^i}\gamma_\mu u^i$	$\mathcal{O}^{(i)}_{\Gamma Vd}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{d^i}\gamma_\mu d^i$	$\mathcal{O}^{(i)}_{\Gamma Ve}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{e^i}\gamma_\mu e^i$
$\mathcal{O}^{(i)}_{\Gamma Au}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{u^i}\gamma_\mu\gamma_5 u^i$	$\mathcal{O}^{(i)}_{\Gamma Ad}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{d^i}\gamma_\mu\gamma_5 d^i$	$\mathcal{O}^{(i)}_{\Gamma Ae}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{e^i}\gamma_\mu\gamma_5 e^i$

Wilson coefficients are evolved
$$\frac{d\,\mathcal{C}_{\mathrm{EMSM}_\chi}}{d\ln\mu} = \gamma_{\mathrm{EMSM}_\chi}\mathcal{C}_{\mathrm{EMSM}_\chi}$$

Arrive at Wilson coefficients at the nuclear scale c_N

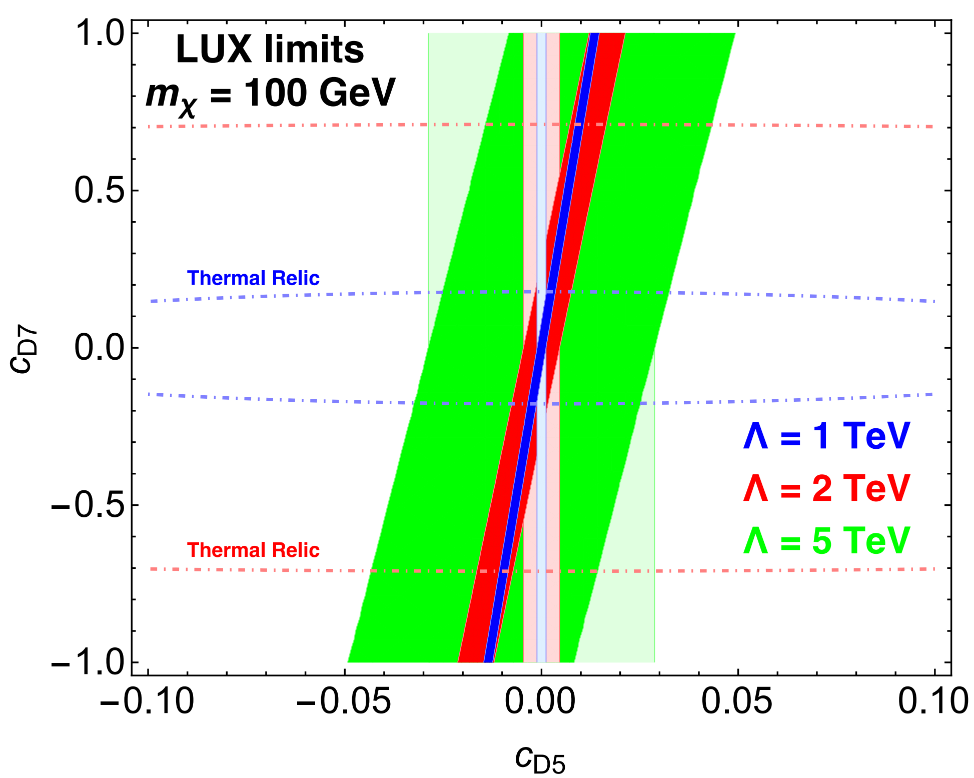
Operator Mixing

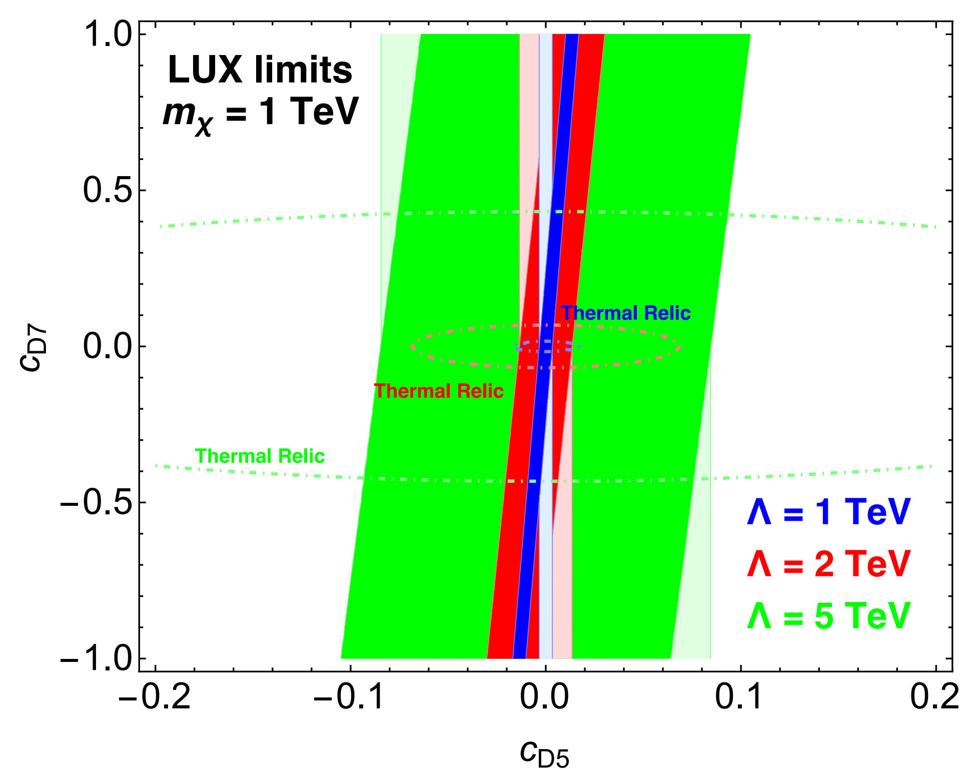
Limits can be altered when loop effects are included...



$$\mathcal{L}_{D5} = \frac{c_{D5}}{\Lambda^2}\,\overline{\chi}\,\gamma^\mu\chi\,\left[\sum_i \overline{u^i}\gamma_\mu u^i + \sum_i \overline{d^i}\gamma_\mu d^i\right]$$

$$\mathcal{L}_{D7} = \frac{c_{D7}}{\Lambda^2}\,\overline{\chi}\,\gamma^\mu\chi\,\left[\sum_i \overline{u^i}\gamma_\mu\gamma_5 u^i + \sum_i \overline{d^i}\gamma_\mu\gamma_5 d^i\right]$$

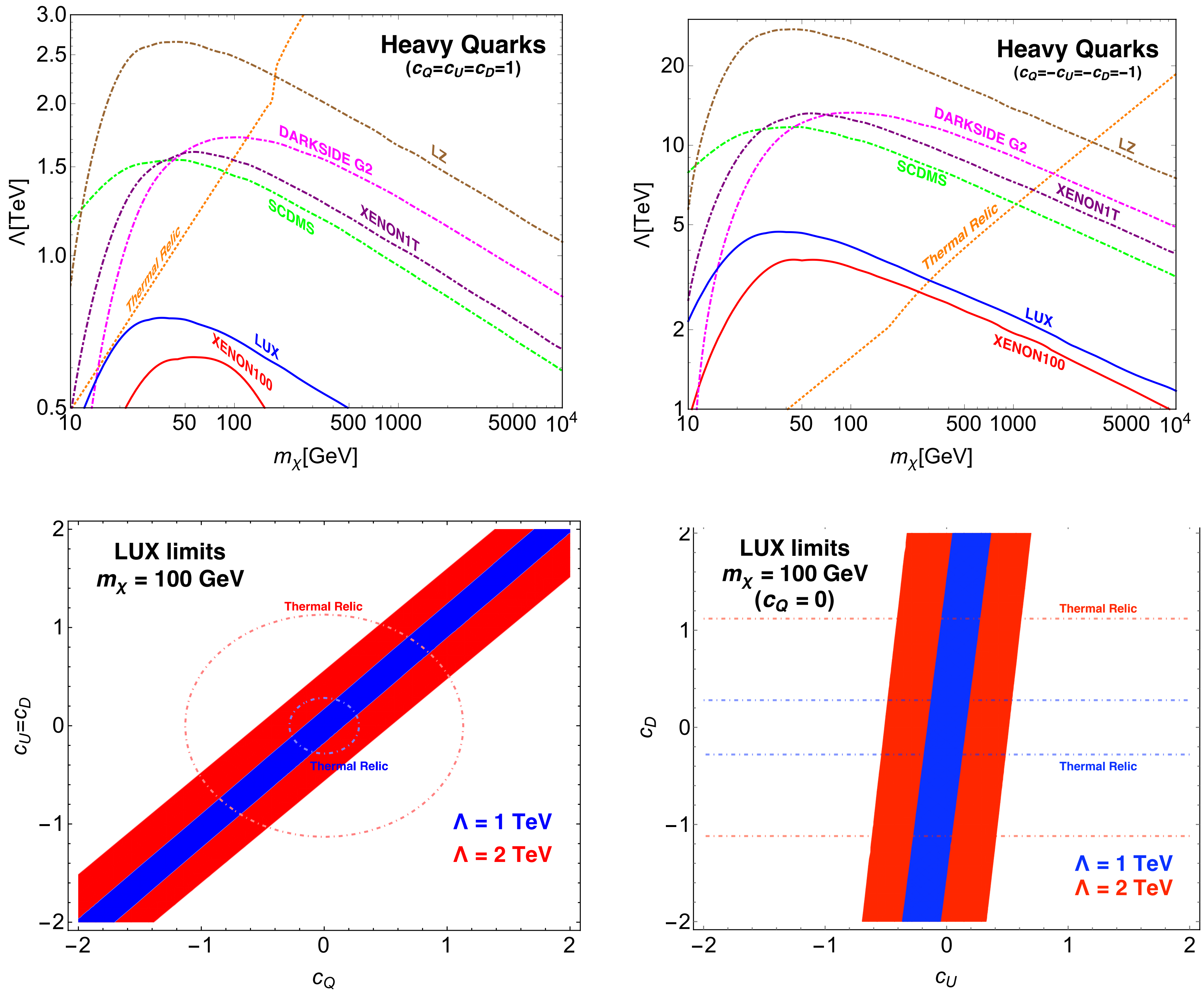




Operator Mixing

Vector and axial-vector current coupling to heavy quarks

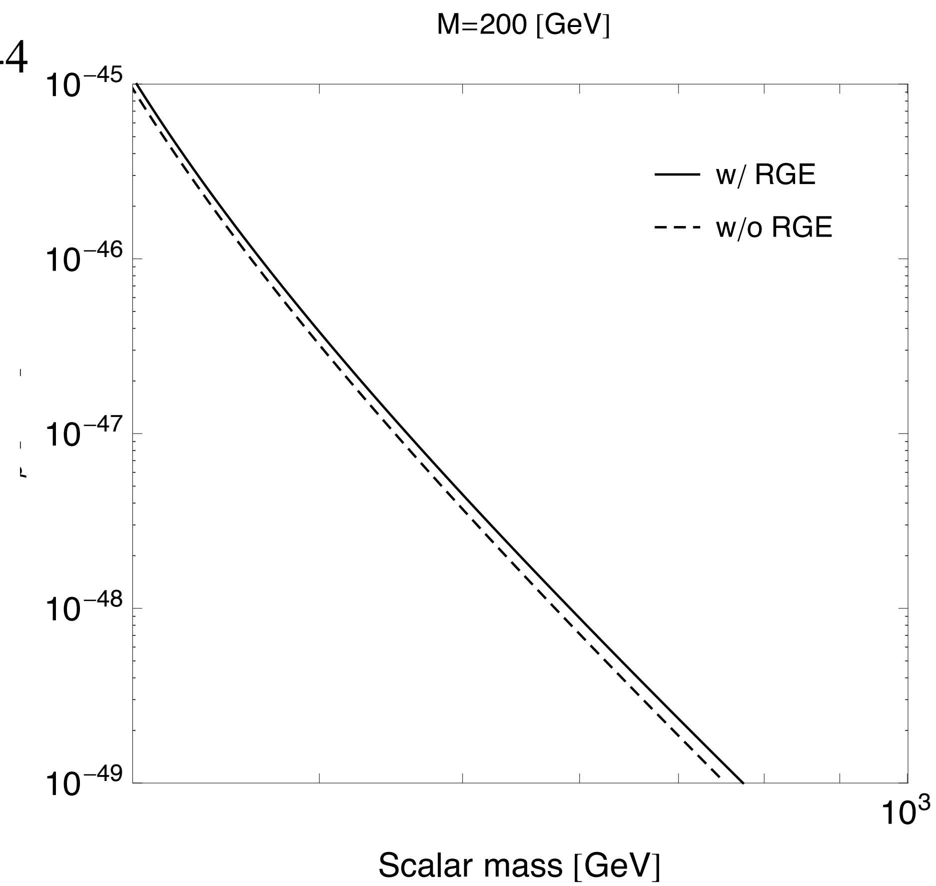
...especially when they are the leading order contribution



Leading order QCD loop effects on the Wilson coefficients for colored mediator exchanges have been calculated for Majorana, scalar, and real vector boson dark matter

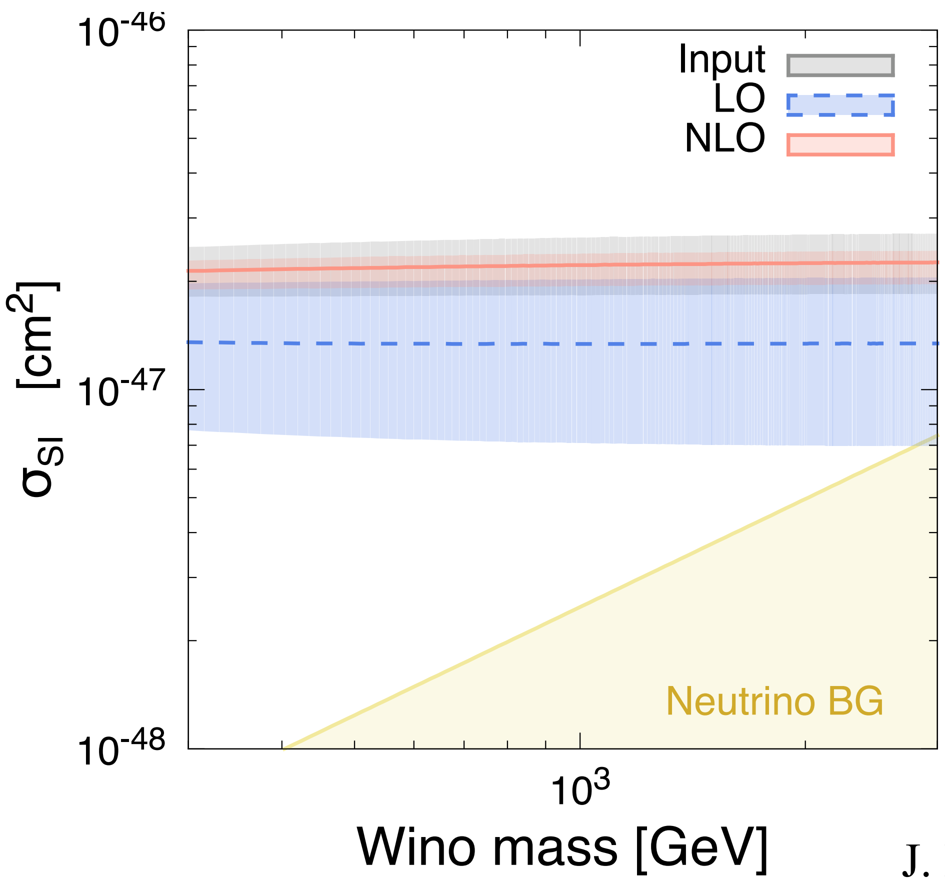
J. Hisano, R. Nagai, and N. Nagata, JHEP **1505** (2015), arXiv:1502.02244

$\mathcal{O}(10)\%$ effects on the cross-section were found



Scattering cross section σ_p

An NLO calculation for WINO dark matter (and a generic $SU(2)_L$ dark matter) was carried out



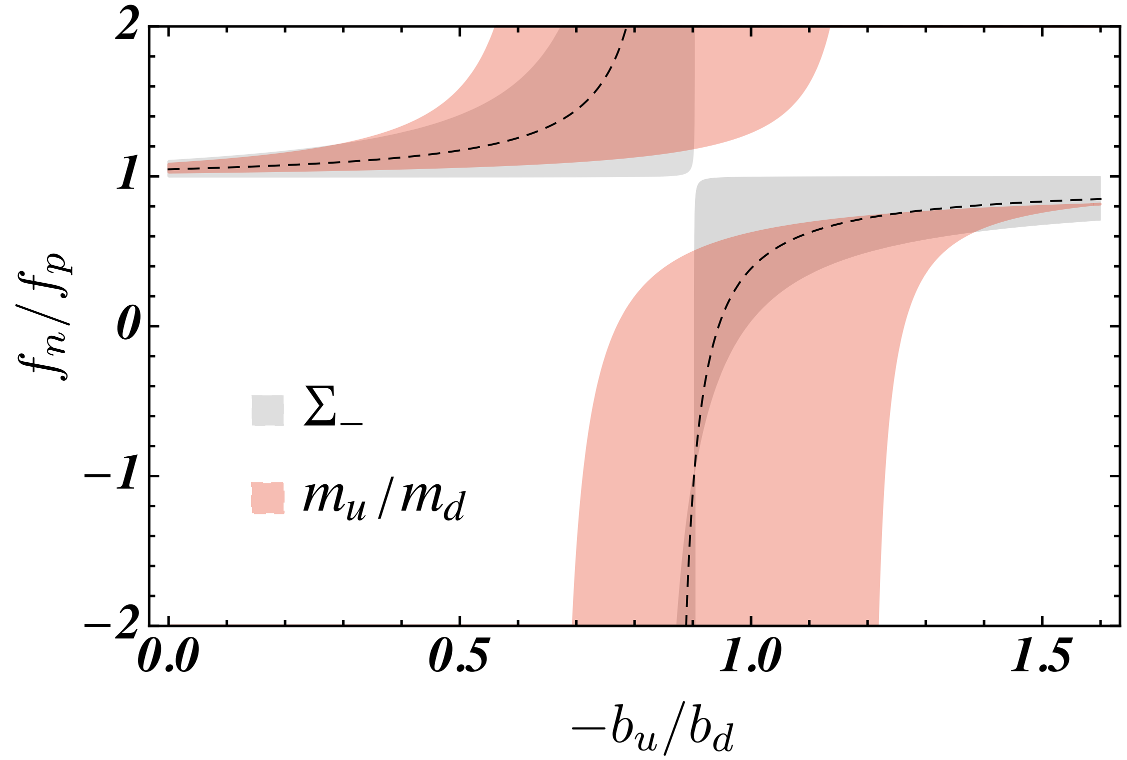
The theoretical uncertainty is much smaller and the central cross-section value is about 70% larger than for LO corrections alone.

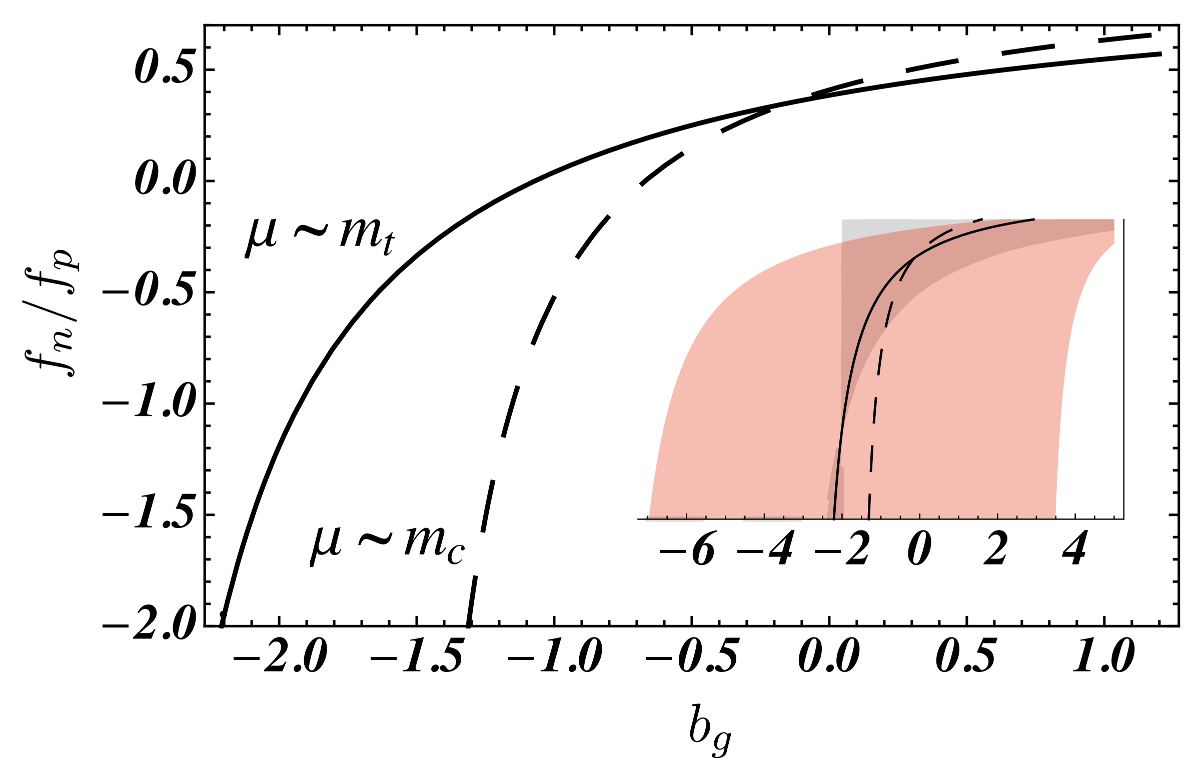
J. Hisano, K. Ishiwata, and N. Nagata, JHEP **1506** (2015), arXiv:1504.00915

One must also account for hadronic matrix element evaluation

$$\langle p|O_u|p\rangle = \langle n|O_d|n\rangle\,, \quad \langle p|O_d|p\rangle = \langle n|O_u|n\rangle\,, \quad \langle p|O_s|p\rangle = \langle n|O_s|n\rangle$$

which can include important uncertainties, for example in quark mass ratios or nucleon form factors due to quark currents, renormalization scale choice





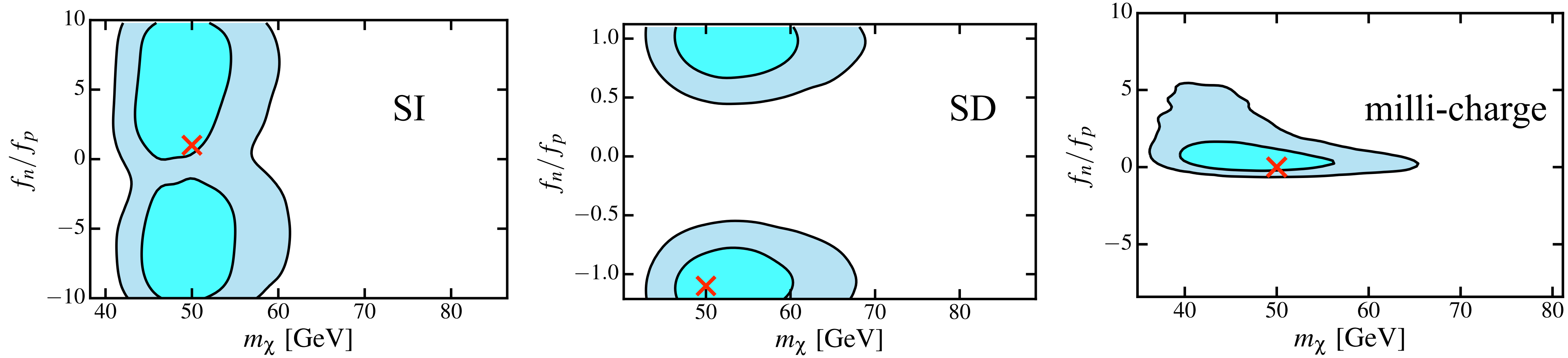
$$R_{ud} \equiv \frac{m_u}{m_d} = 0.49 \pm 0.13\,, \quad R_{sd} \equiv \frac{m_s}{m_d} = 19.5 \pm 2.5$$

$$\mathcal{L}_{\chi,SM} = \frac{1}{\Lambda^2}\bar{\chi}\chi\left[b_u\bar{u}u + b_d\bar{d}d + \frac{b_g}{\Lambda}(G^a_{\mu\nu})^2\right]$$

$$\Sigma_- = (m_d - m_u)\langle N|(\bar{u}u - \bar{d}d)|N\rangle = \pm 2(2)\,\text{MeV}$$

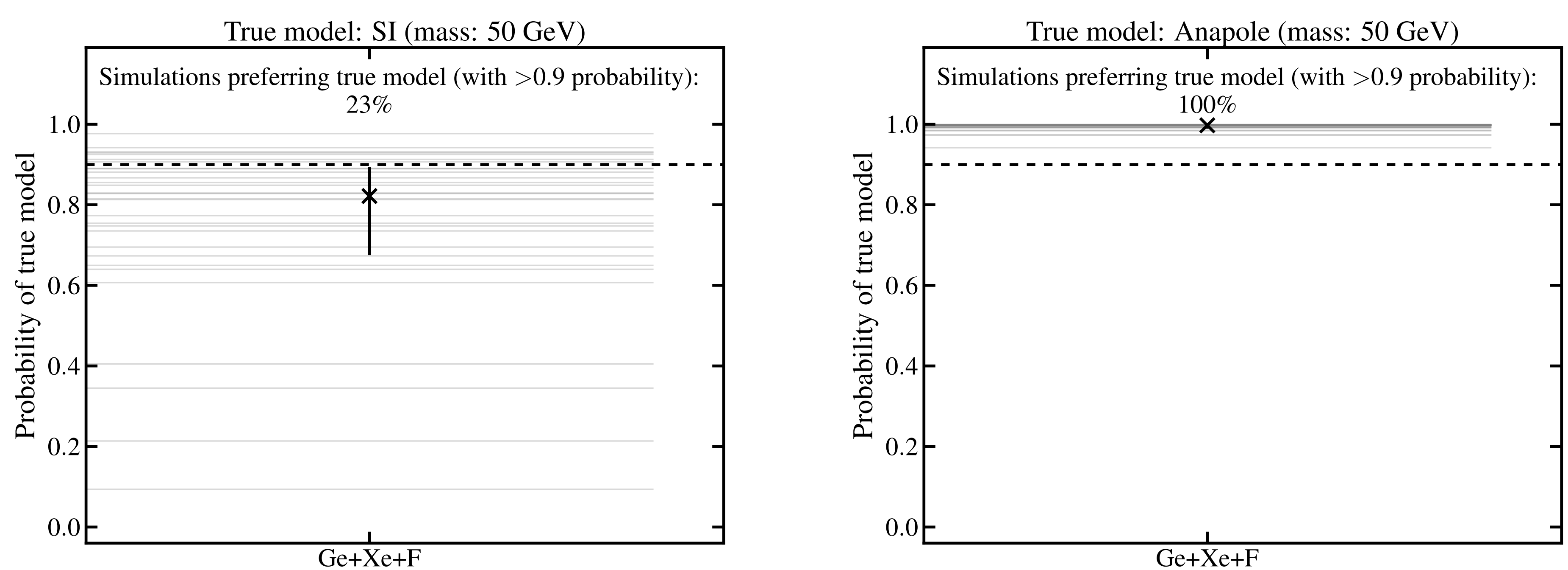
R.J. Hill and M.P. Solon, PRD **91** (2015) arXiv:1401.3339

R.J. Hill and M.P. Solon, PRD **91** (2015) arXiv:1409.8290



Analysis including Ge, Xe, and F with fn/fp a free parameter

These type of uncertainties obviously can greatly effect data interpretations,



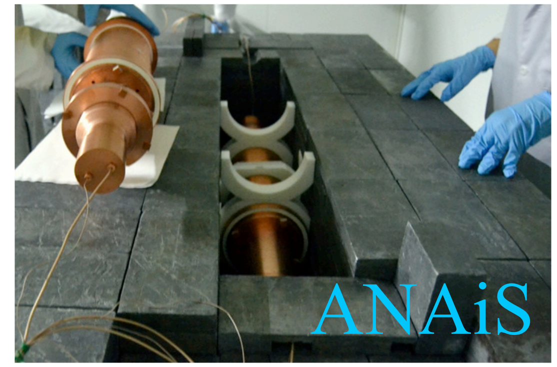
V. Glusevic, M. Gresham, S.D. McDermott, A.H.G. Peter, and K. Zurek, arXiv:1506.04454

The Future and Summary

SuperCDMS

SNOLAB

~400 kg cryogenic
Ge and Si
2019



NaI Scintillators
112.5kg
2016

KamLAND-PICO
proposed NaI

EURECA

cryogenic ton scale
Ge and $CaW0_4$

NaI Scintillators
17kg prototype (current)
250kg future

Xe
XENON
Dark Matter Project

~ 1 t liquid xenon
2015

LZ

~ 7 t liquid xenon
2018

KIMS

CsI 103.4kg
future 200kg NaI,
CaMoO

DARWIN

20t liquid xenon
and
10t liquid argon

PANDA X

~ .5t (current)
1.5t (future)liquid xe

XMASS

DEAP 3600

~ 1t (2015)
50t!!
(future)liquid
argon

darkside
two-phase argon TPC for Dark Matter Direct Detection

~ 50kg (current)
3.3t (future)liquid argon

835kg liquid xenon
future ~5t
eventually ~24t

PICASSO and COUPP formed

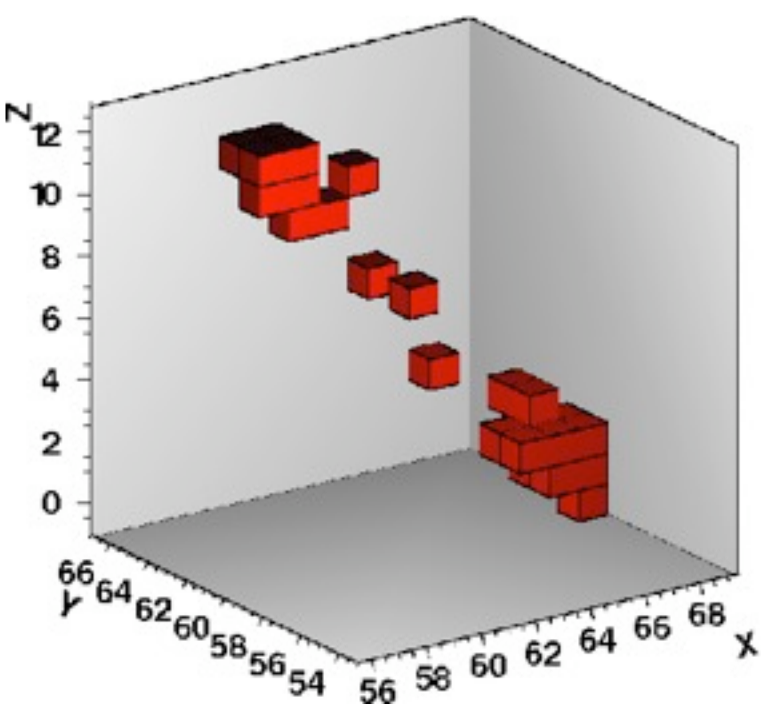
PICO

37kg of CF_3I and 3kg of C_3F_8
future 500kg

CS_2 , O_2 and CF_4 gas
future 8 m^3 experiment

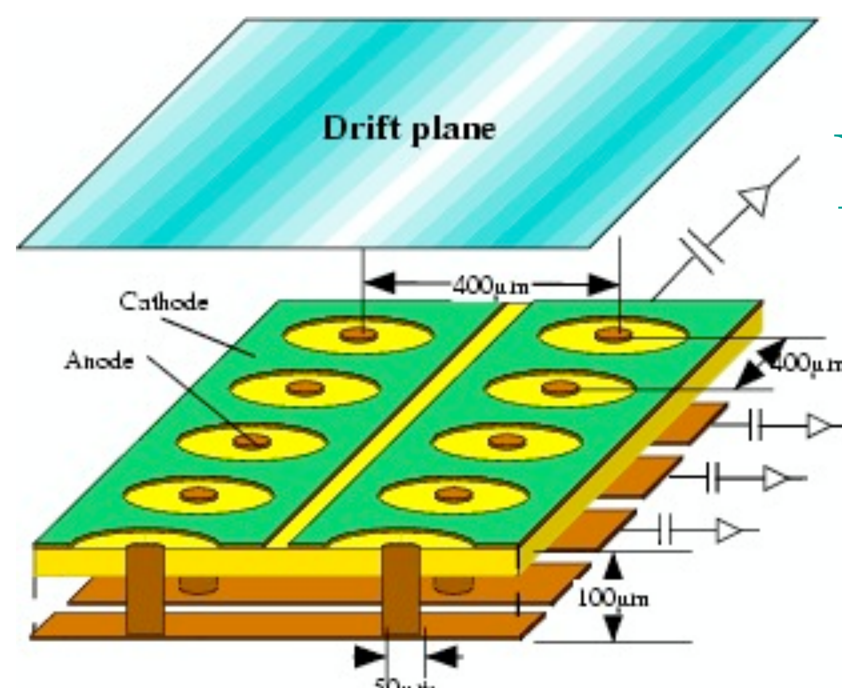
DMTPC

CF_4 gas
future $O(m^3)$



$^4He + 5\%C_4H_{10}$

MIMAC



NEWAGE

CF_4 gas

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

Nuclear-WIMP interactions which include responses beyond the standard ones could avoid misinterpretations of the particle nature of dark matter

A general array of single WIMP, single mediators interactions has been studied and non-standard responses arise at leading order for some interaction types

The use of a variety of detector materials can be significant for discovery and model discrimination

The neutrino background may have less of an effect on some non-standard operators

Precise model constraints will need to be carried out

Complementarity from colliders and astrophysical probes is also vital, and these should include proper handling of the scale differences and uncertainties

Thanks