On Nuclear Responses in Dark Matter Direct Detection

Moira Gresham

Whitman College, Walla Walla, WA

Santa Fe 2014 Summer Workshop

LHC After Higgs

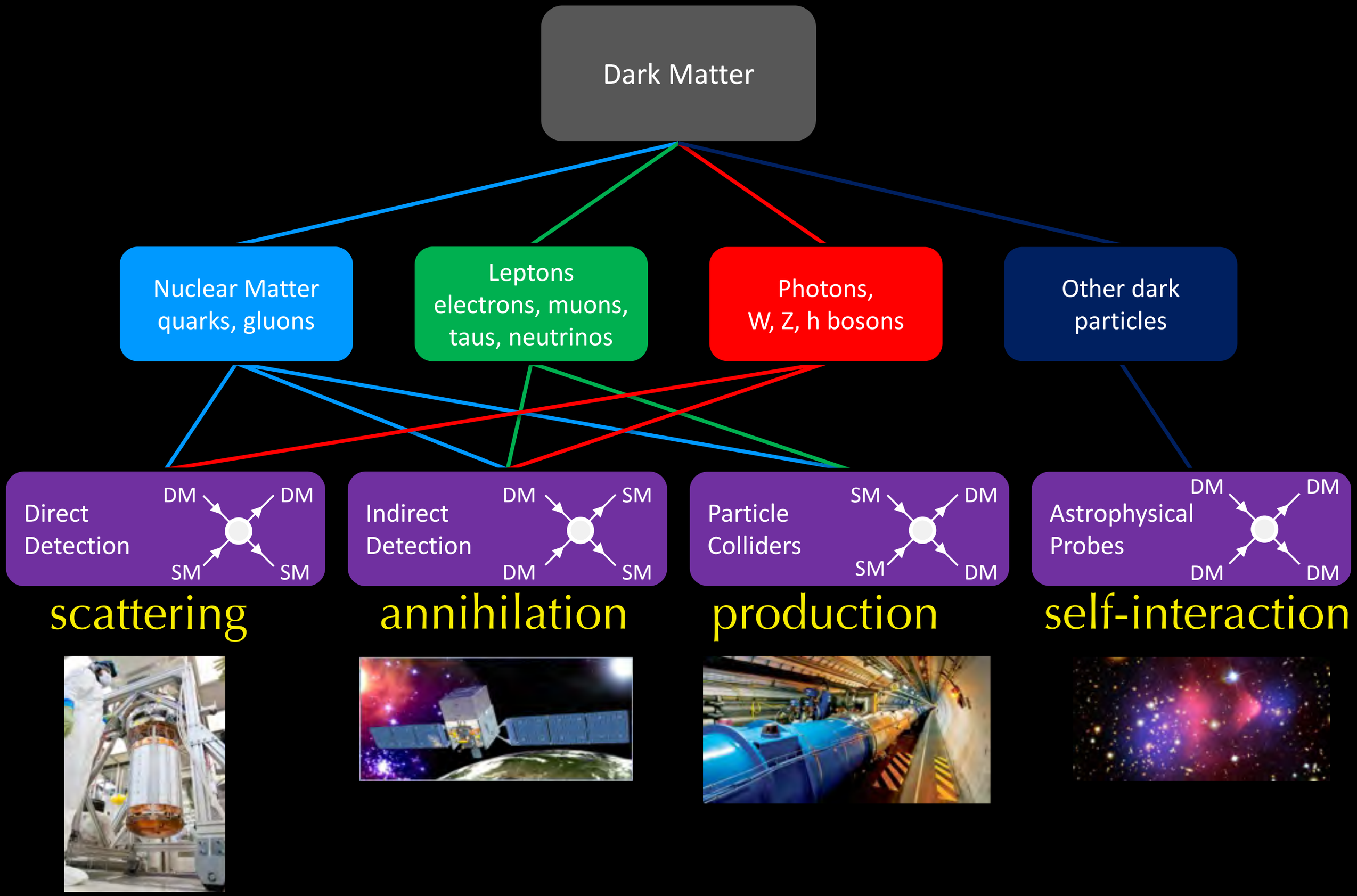
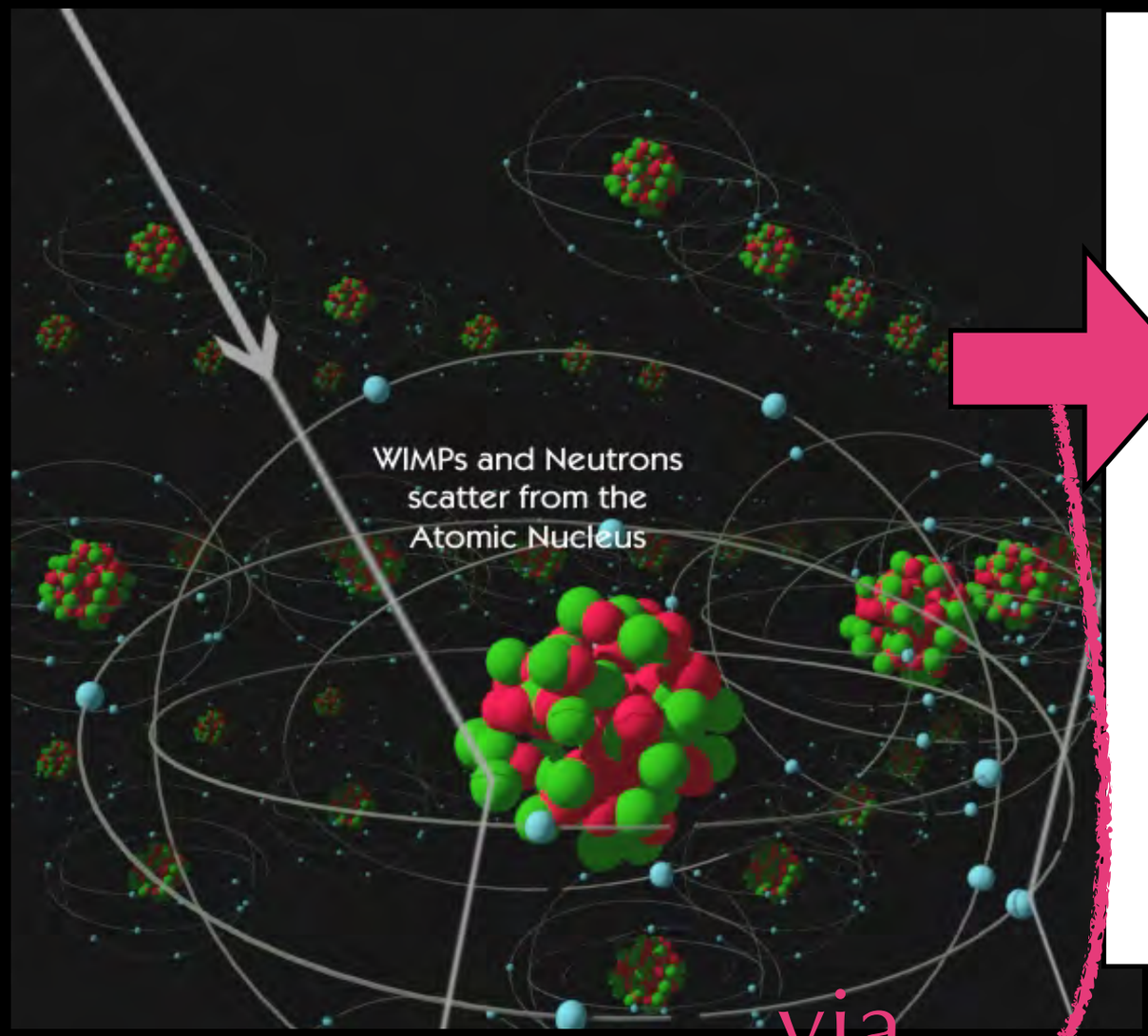
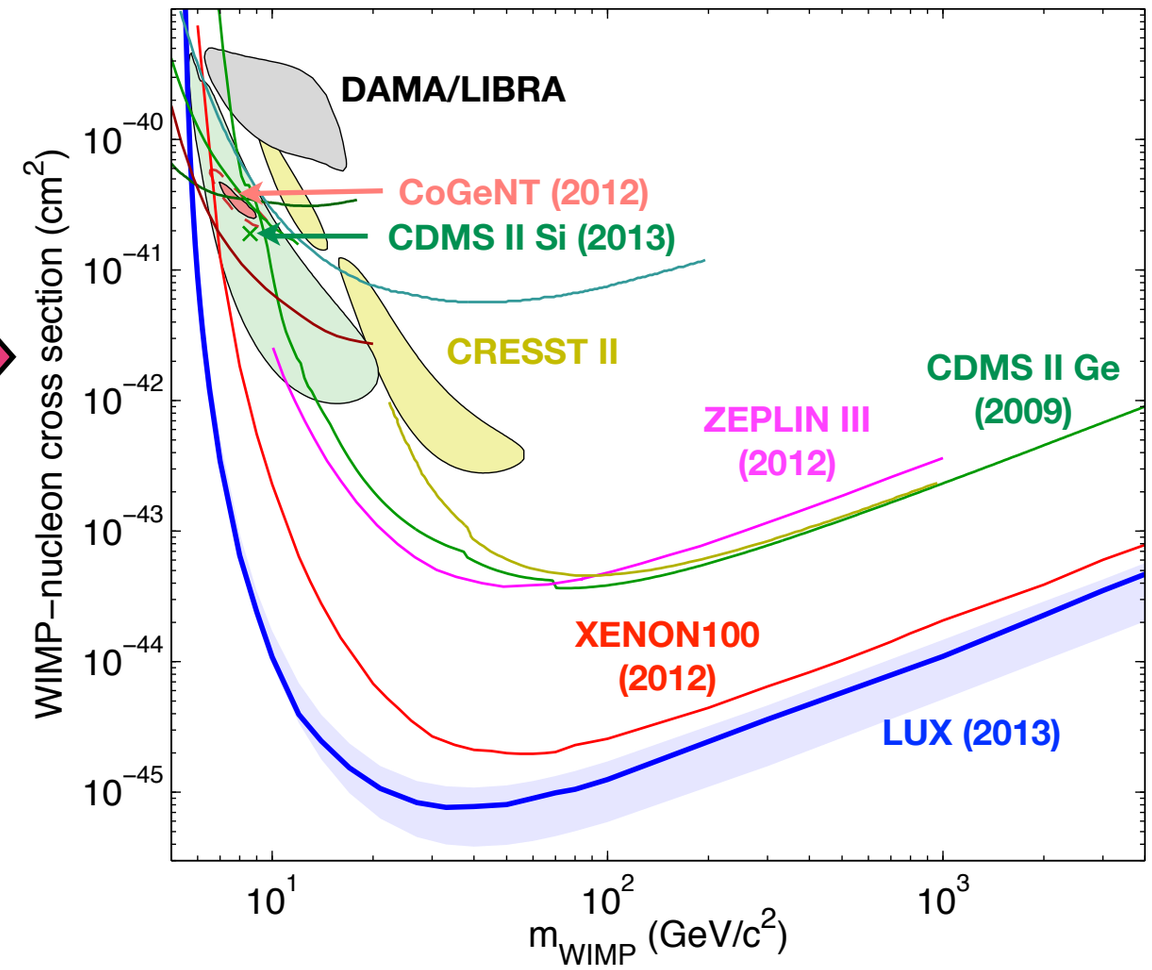


chart from Snowmass CF1 Summary 1310.8327





via

$$\frac{dR}{dE_R} = \frac{1}{m_T} \boxed{\frac{\rho_\chi}{m_\chi} \int_{v_{\min}} d^3\vec{v}\, v\, f(\vec{v})} \boxed{\frac{d\sigma_T}{dE_R}(v, E_R)}$$

astrophysics

particle &
nuclear physics

$$\left(\begin{array}{ll} T & = \text{target nucleus} \\ \chi & = \text{dark matter} \end{array} \right)$$

image and plot from Karen Gibson's 2014 Pheno talk

$$\frac{dR}{dE_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v_{\rm min}} d^3\vec{v}\, v f(\vec{v})\, \frac{d\sigma_T}{dE_R}(v, E_R)$$

$$\frac{d\sigma_T}{dE_R}_{\rm SI} = \frac{m_T}{2\mu_p^2 v^2}\sigma_p^{\rm SI}\left(Z + (A-Z)\frac{f_{\rm SI}^n}{f_{\rm SI}^p}\right)^2 F^2(y)$$

$$\boxed{\frac{dR}{dE_R}_{\rm SI} \sim \sigma(p\chi \to p\chi)\left[\int_{v_{\rm min}} d^3\vec{v}\,\frac{f(v)}{v}\right]\left[\text{Response}|_{y=0} F^2(y)\right]}$$

$$y = q^2 b^2/4$$

harmonic oscillator parameter (depends on atomic mass), ~ fermi

(m_χ-independent)

$$v_{\rm min} = \frac{q}{2\mu_T}$$

reduced mass

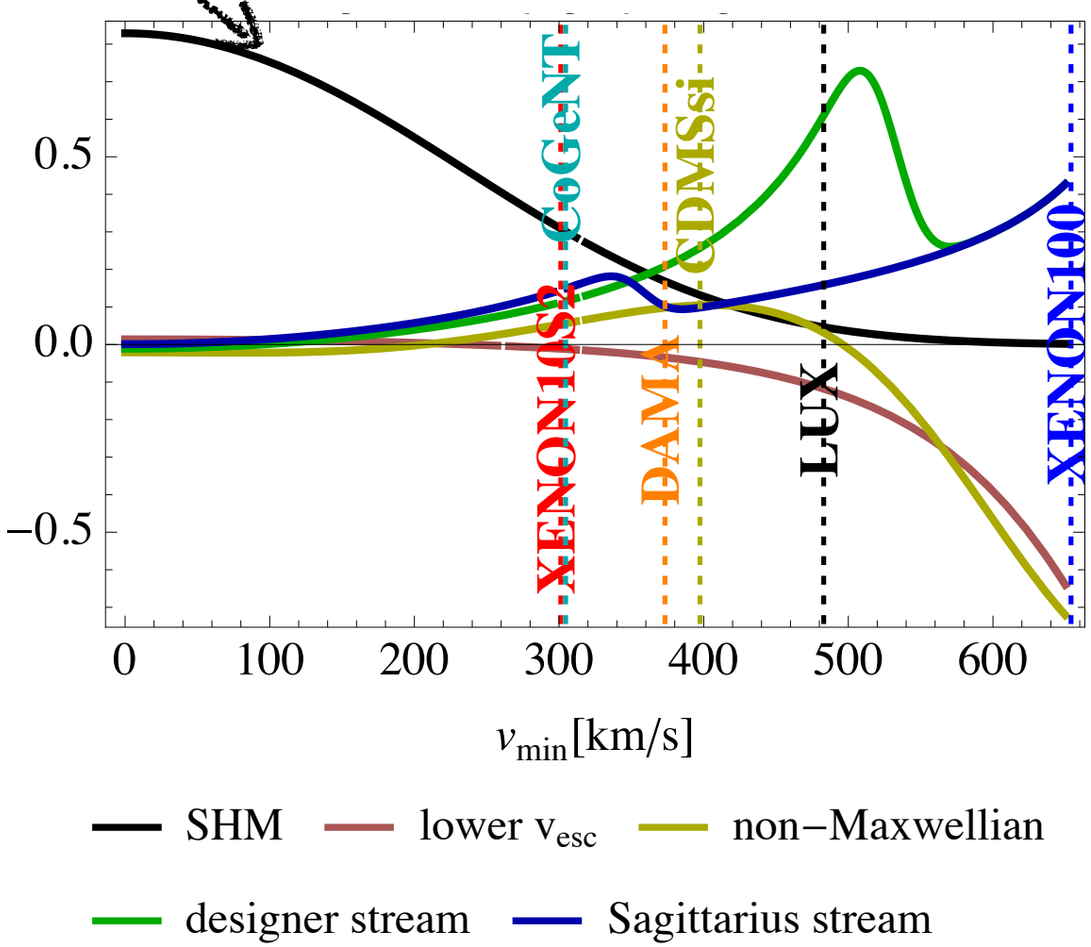
(m_χ-dependent)

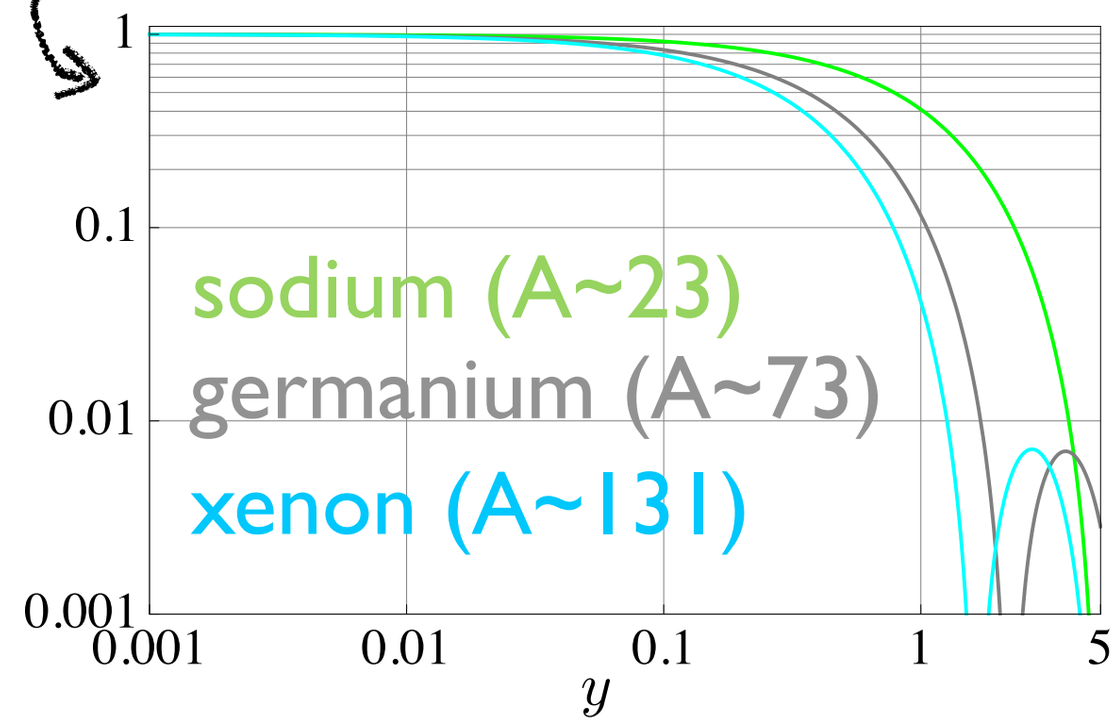
$$q = \sqrt{2 m_T E_R}$$

momentum transfer

(m_χ-independent)

$$\frac{dR}{dE_R}_{\rm SI} \sim \sigma(p\chi \to p\chi)\left[\int_{v_{\rm min}} d^3\vec{v}\,\frac{f(v)}{v}\right]\left[\text{Response}|_{y=0}F^2(y)\right]$$

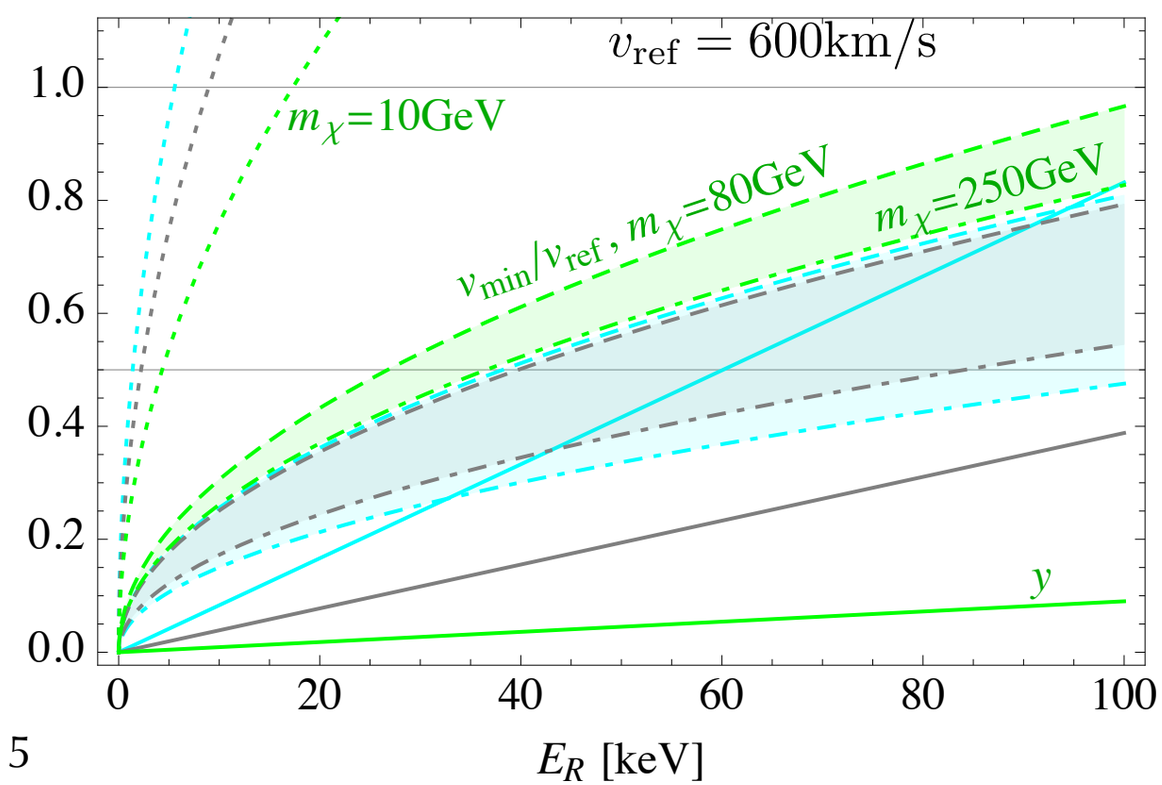




$$y = q^2 b^2/4$$

$$v_{\rm min} = \frac{q}{2\mu_T}$$

$$q = \sqrt{2 m_T E_R}$$



Inelastic Dark Matter*

David Smith[1] and Neal Weiner[2]

arXiv:hep-ph/0101138v1 15 Jan 2001

Annual Modulation of Dark Matter in the Presence of Streams

Chris Savage,[1,†] Katherine Freese,[1,†] and Paolo Gondolo[2,†]

arXiv:astro-ph/0607121v2 11 Aug 2006

Form Factor Dark Matter

Brian Feldstein, A. Liam Fitzpatrick, Emanuel Katz

arXiv:0908.2991v3 [hep-ph] 8 Jan 2010

Dark Moments and the DAMA-CoGeNT Puzzle

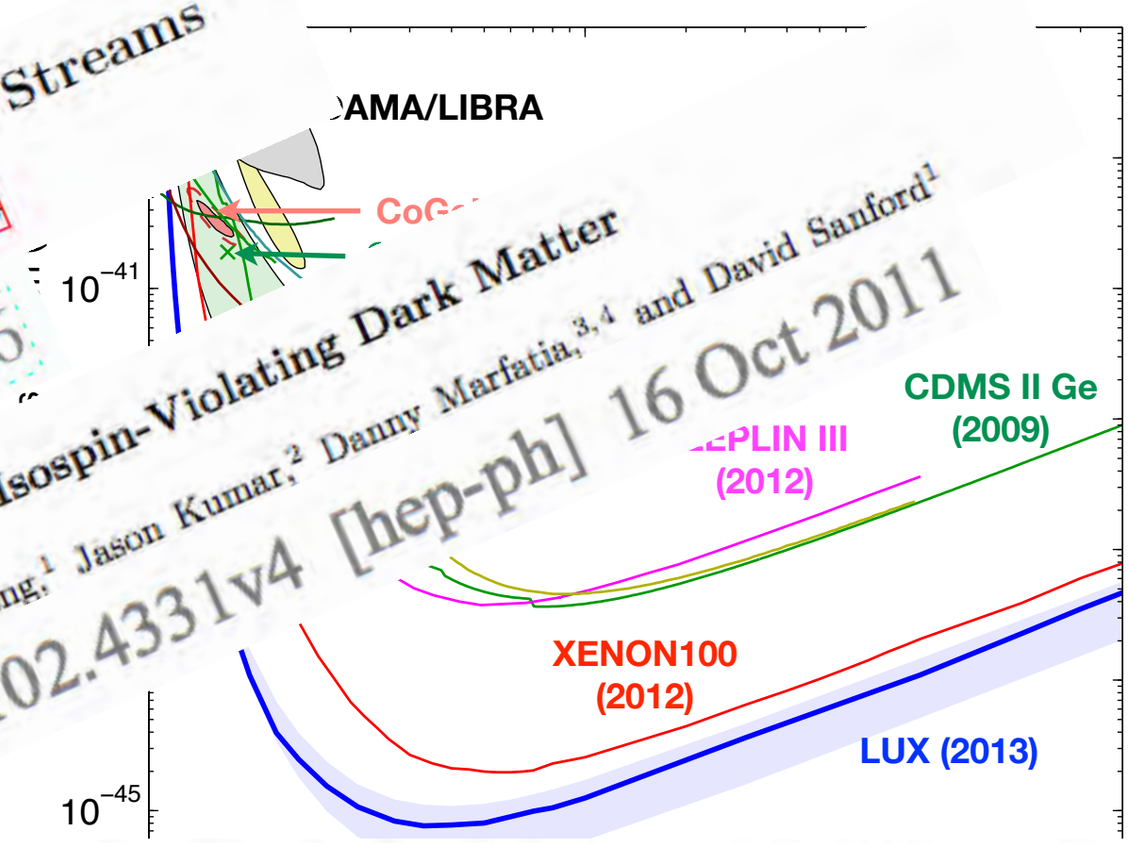
A. Liam Fitzpatrick[a] and Kathryn M. Zurek[b]

arXiv:1007.5325v2 [hep-ph] 9 Aug 2010

Momentum Dependent Dark Matter Scattering

Spencer Chang,[1] Aaron Pierce,[2] and Neal Weiner[3]

arXiv:0908.3192v2 [hep-ph] 16 Aug 2010



Isospin-Violating Dark Matter

Jonathan L. Feng,[1] Jason Kumar,[2] Danny Marfatia,[3,4] and David Sanford[1]

arXiv:1102.4331v4 [hep-ph] 16 Oct 2011

Integrating Out Astrophysical Uncertainties

Patrick J. Fox,[1,2] Jia Liu,[3] and Neal Weiner[3,2]

arXiv:1011.1915v2 [hep-ph] 3 Nov 2011

Double-Disk Dark Matter

JiJi Fan, Andrey Katz, Lisa Randall, and Matthew Reece

arXiv:1303.1521v2 [astro-ph.CO] 31 Jul 2013

Non-relativistic effective theory of dark matter direct detection

JiJi Fan, Matthew Reece, Lian-Tao Wang

(Submitted on 9 Aug 2010 (v1), last revised 10 Dec 2010 (this version, v2))

arXiv:1008.1591

The Effective Field Theory of Dark Matter Direct Detection

A. Liam Fitzpatrick, Wick Haxton, Emanuel Katz, Nicholas Lubbers, Yiming Xu

(Submitted on 15 Mar 2012 (v1), last revised 28 Aug 2012 (this version, v3))

arXiv:1203.3542

- includes momentum-suppressed interactions
- points out that momentum/velocity-suppressed interactions generically give rise to "novel" nuclear responses

On the Effect of Nuclear Response Functions in Dark Matter Direct Detection

Moira I. Gresham, Kathryn M. Zurek

arXiv:1401.3739

Motivating question:

How important are these novel nuclear responses?

Depending what you mean by "important"...

- trivially important,
- more important for highly momentum-suppressed interactions and big target nuclei with large spin, especially if large nuclear recoil energies are probed in the experiment

Review and Motivation

Effective Theory of Dark Matter Direct Detection

Effect of Nuclear Responses in Direct Detection

Review and Motivatio

Effective Theory of Dark Matter Direct Detection

Effect of Nuclear Responses in Direct Detection

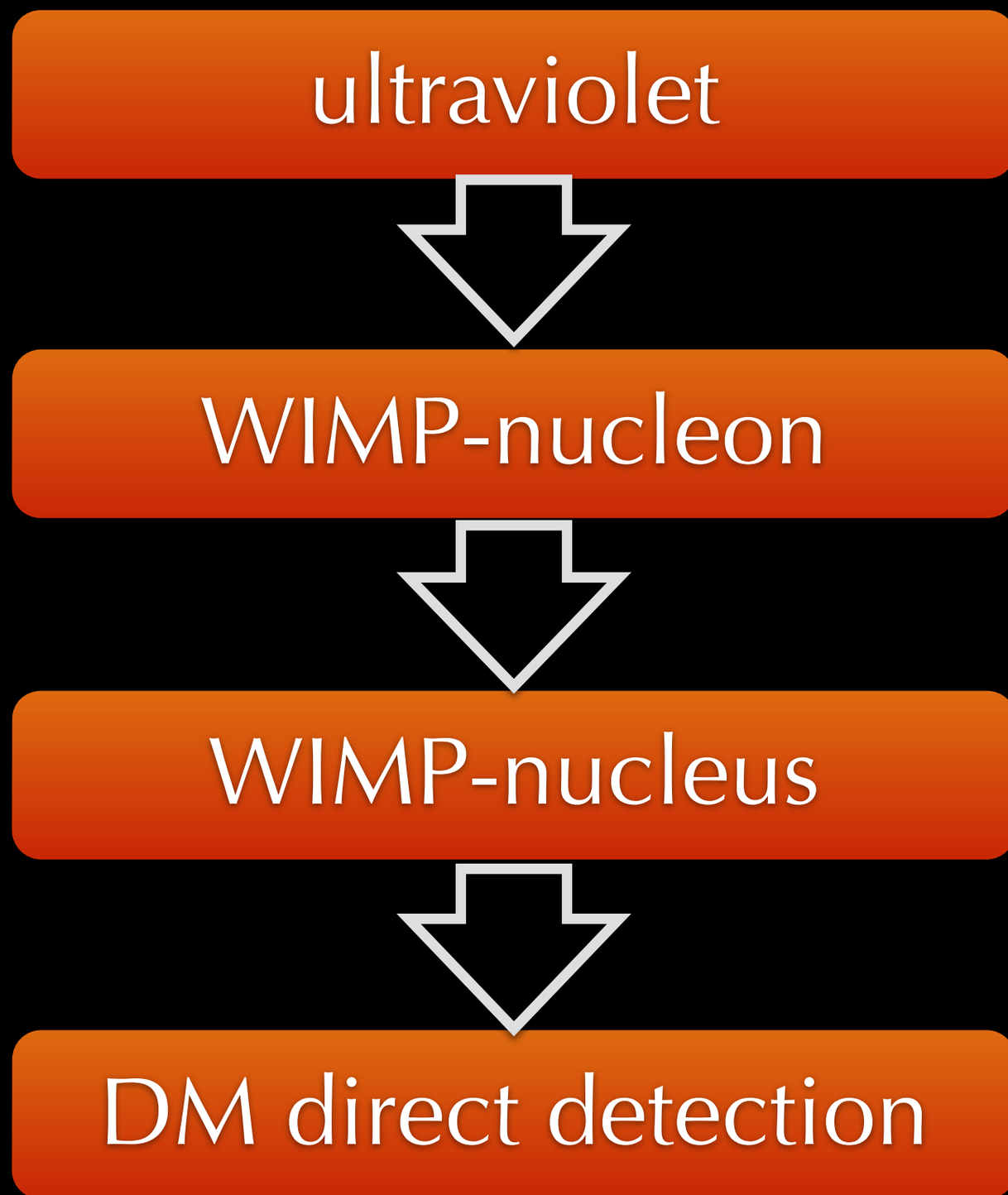
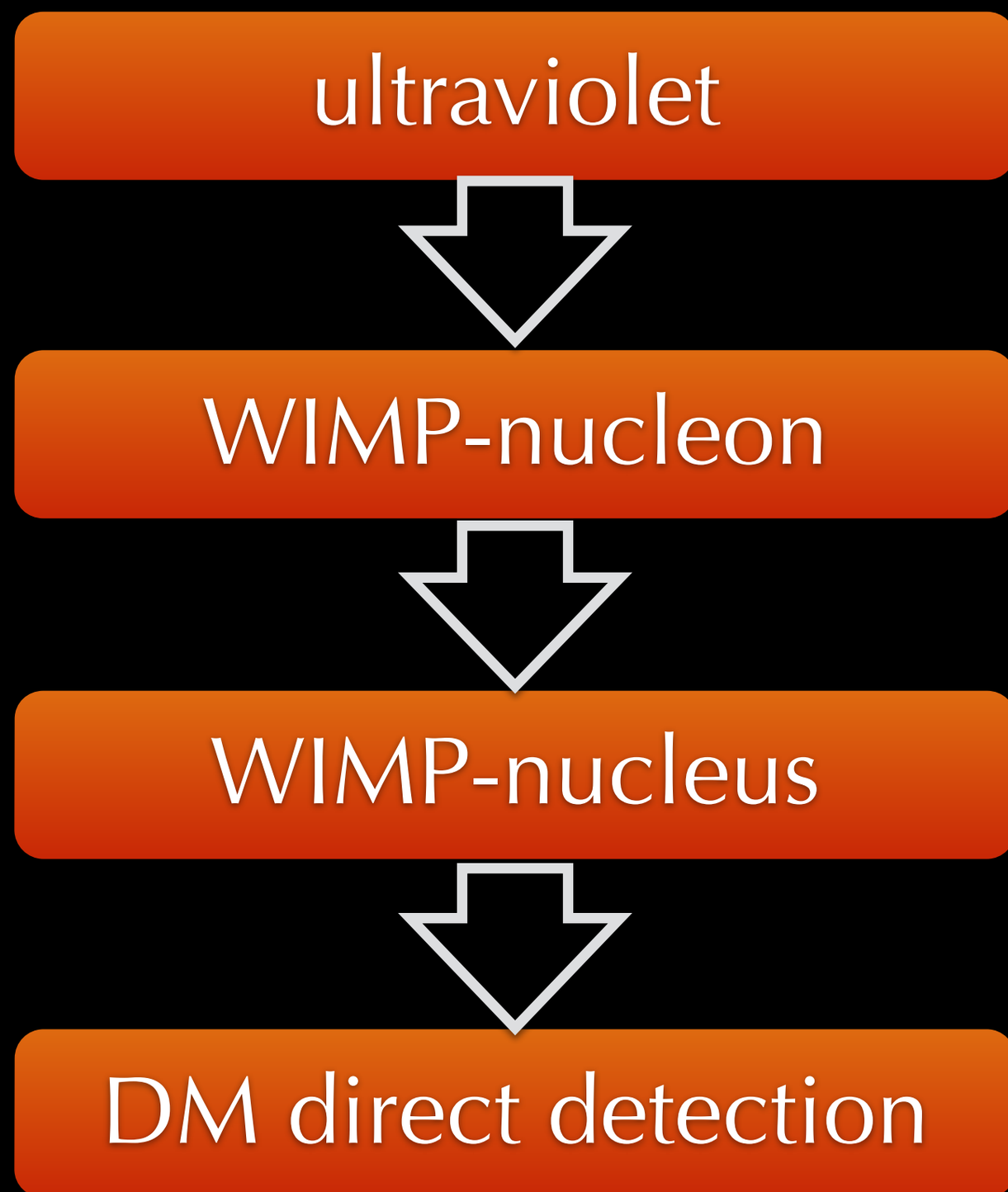


figure idea taken from W. Haxton, UCLA dark matter workshop slide



(~10 relevant non-relativistic operators)

(5 independent types of nuclear responses)

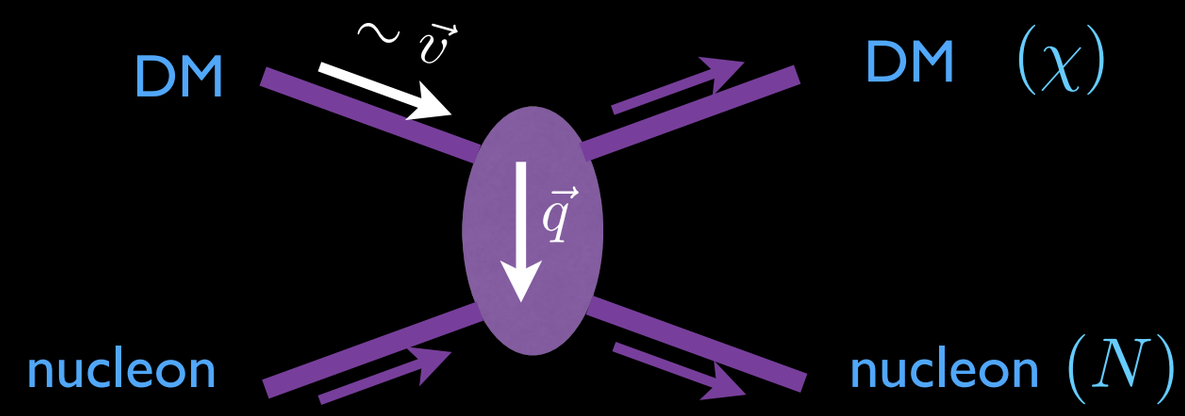
figure idea taken from W. Haxton, UCLA dark matter workshop slide

ultraviolet

WIMP-nucleon

WIMP-nucleus

DM direct detection



non-rel operator building blocks

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

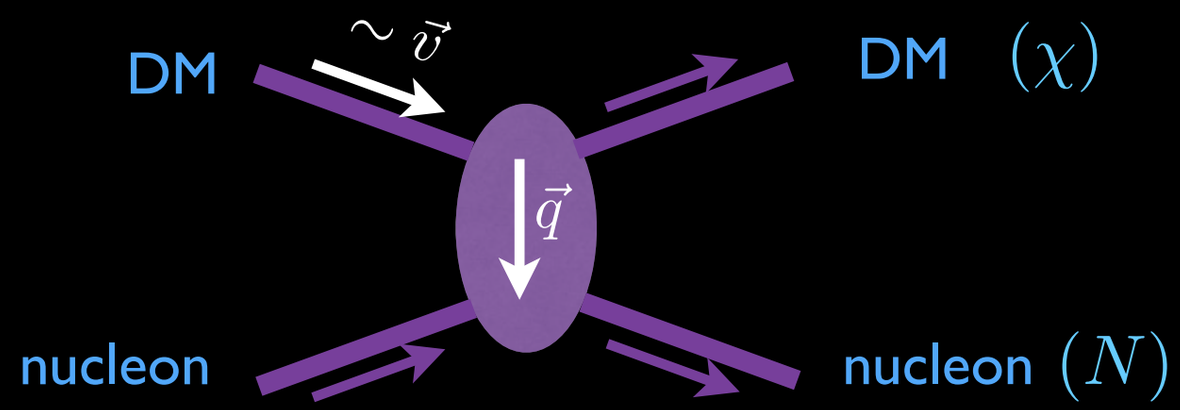
$$\vec{v}^\perp \equiv \vec{v} + \frac{\vec{q}}{2\mu_N} \qquad \vec{S}_N$$

$$\mathcal{L}_{\rm int} \sim \bar{\chi}\mathcal{O}_\chi \chi \bar{N}\mathcal{O}_N N$$

$$\text{SI}: \ \bar{\chi}\chi\bar{N}N \to \mathbf{1}_\chi \mathbf{1}_N$$

$$\text{SD}: \ \bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N \to \vec{S}_\chi \cdot \vec{S}_N$$

(for more detail/precise definitions, see 1203.3542. See also 1211.2818, 1308.6288)



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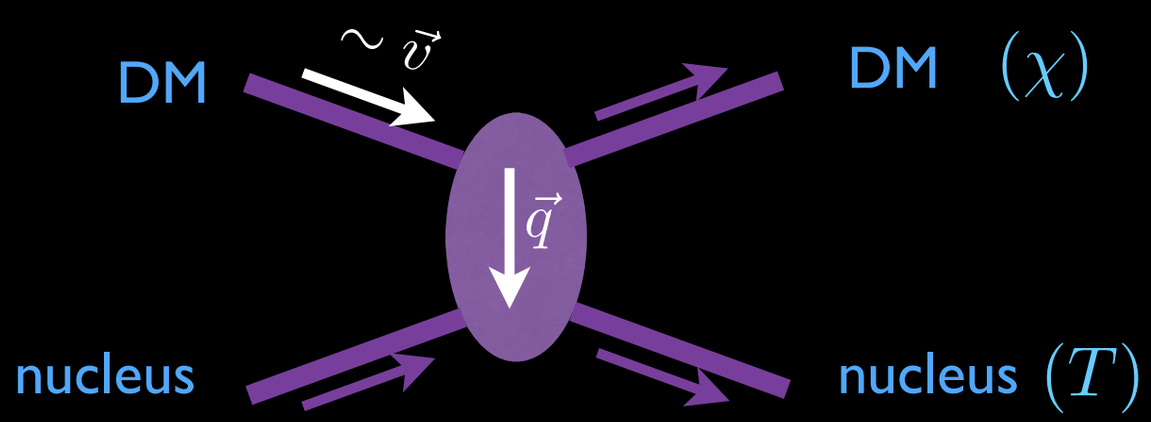
WIMP-nucleon

WIMP-nucleus

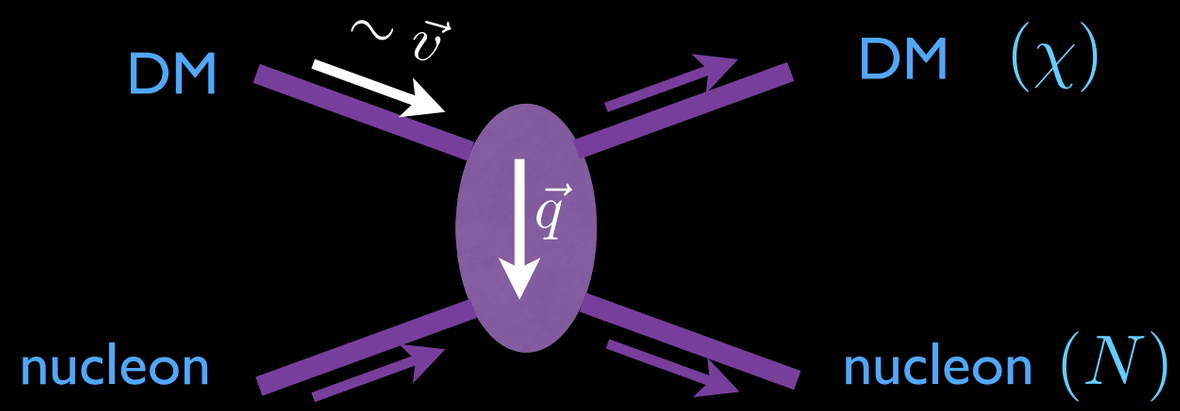


(usual) spin-independent response

(M)

$\sim Z$ for proton coupling

$\sim (A - Z)$ for neutron coupling



WIMP-nucleon

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

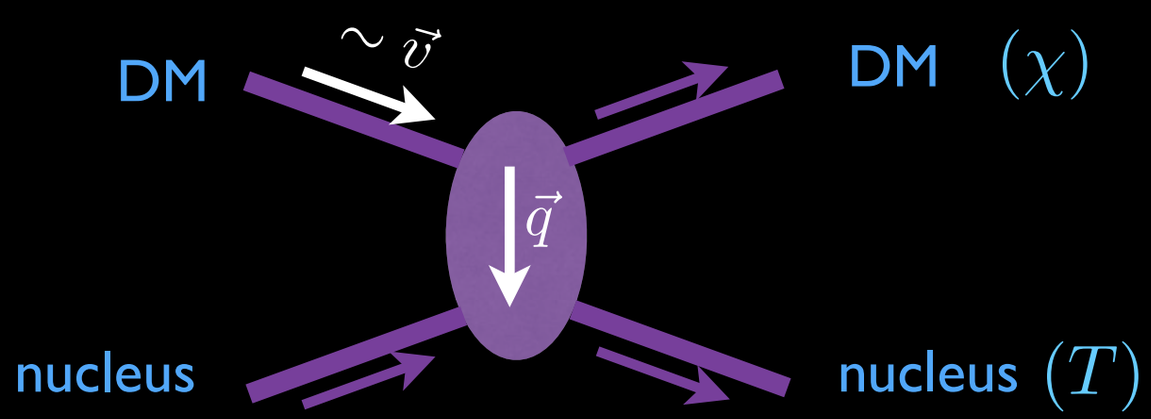
$$= (\vec{S}_\chi \cdot \hat{q})(\vec{S}_N \cdot \hat{q}) + (\vec{S}_\chi \times \hat{q}) \cdot (\vec{S}_N \times \hat{q})$$

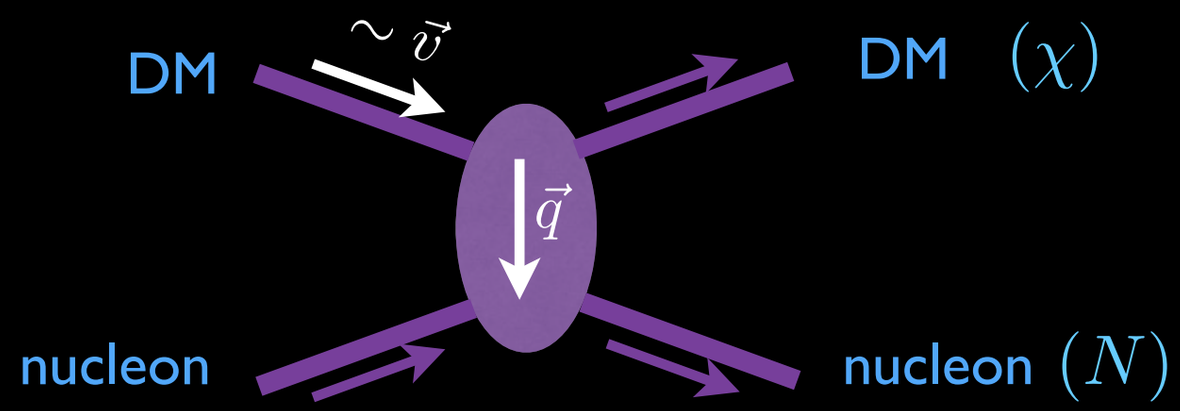
longitudinal spin-dependent response (Σ'')

+

transverse spin-dependent response (Σ')

WIMP-nucleus





$$\begin{cases} \text{non-rel operator building blocks} \\ i\dfrac{\vec{q}}{m_N} \qquad \vec{S}_\chi \\ \vec{v}^\perp \equiv \vec{v} + \dfrac{\vec{q}}{2\mu_N} \qquad \vec{S}_N \end{cases}$$

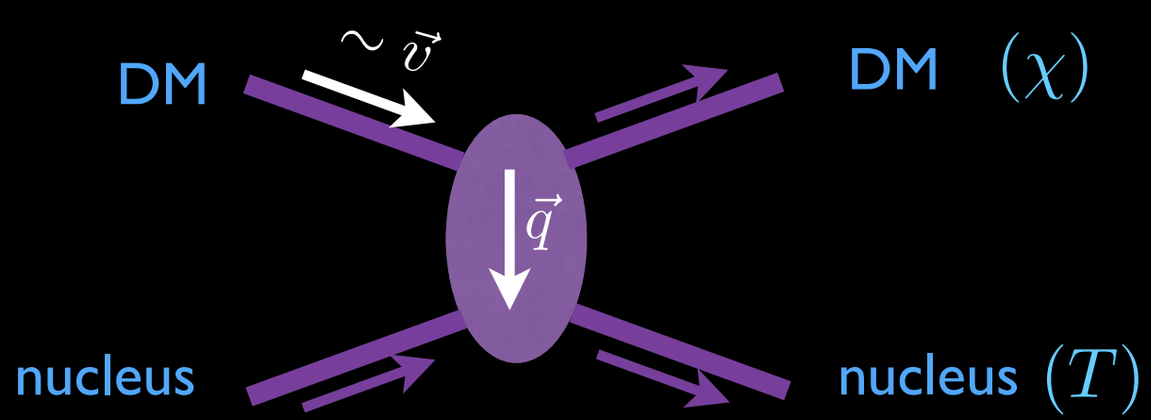
WIMP-nucleon

operators involving $\vec{v}^\perp$

(usually)

orbital angular momentum-dependent responses (Δ, Φ'')

WIMP-nucleus



Response functions, $W_X^{(N,N')}(y)$ encapsulate the nuclear physics portion of the scattering cross-section.

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	$\sim \langle \vec{S}_p \cdot \vec{L}_p\rangle^2$

Review and Motivatio

Effective Theory of Dark Matter Direct Detection

Effect of Nuclear Responses in Direct Detection

Use UV-motivated models to explore the "importance" of the novel response functions.

$$\mathcal{L}_{\rm int}^{\rm pseudoscalar} = \frac{1}{M^2}\sum_{N=n,p}\left(f_1^N i\bar{\chi}\gamma^5\chi\bar{N}N + f_2^N i\bar{\chi}\chi\bar{N}\gamma^5 N + f_3^N\bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N\right)$$

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

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

$$\mathcal{L}_{\rm int}^{\rm magnetic\ dipole} = \frac{f_{\rm md}}{M^2}\bar{\chi}\frac{i\sigma^{\mu\nu}q_\nu}{\Lambda}\chi\mathcal{J}_\mu^{\rm EM}$$

$$\mathcal{L}_{\rm int}^{\rm electric\ dipole} = \frac{f_{\rm ed}}{M^2}\bar{\chi}\frac{\sigma^{\mu\nu}q_\nu\gamma^5}{\Lambda}\chi\mathcal{J}_\mu^{\rm EM}$$

$$\mathcal{L}_{\rm int}^{\rm LS} = \frac{f_{\rm LS}}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\sum_{N=n,p}\left(\kappa_1^N\frac{q_\alpha q^\alpha}{m_N^2}\bar{N}\gamma^\mu N + \kappa_2^N\bar{N}\frac{i\sigma^{\mu\nu}q_\nu}{2m_N}N\right)$$

Individual spin responses and orbital angular momentum responses naturally arise and dominate.

Model	Relativistic Ops.	Nonrel. Ops.	Resp.
pseudo-mediated	$\mathcal{O}_2^{\rm rel}=i\bar{\chi}\chi\bar{N}\gamma^5 N$	$\mathcal{O}_{10}=i\vec{S}_N\cdot\frac{\vec{q}}{m_N}$	Σ''
	$\mathcal{O}_3^{\rm rel}=i\bar{\chi}\gamma^5\chi\bar{N}N$	$\mathcal{O}_{11}=i\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}$	M
	$\mathcal{O}_4^{\rm rel}=\bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N$	$\mathcal{O}_6=(\vec{S}_\chi\cdot\frac{\vec{q}}{m_N})(\vec{S}_N\cdot\frac{\vec{q}}{m_N})$	Σ''
magnetic dipole	$\mathcal{O}_9^{\rm rel}=\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\frac{K_\mu}{m_M}\bar{N}N$	$\mathcal{O}_1=\mathbf{1}_\chi\mathbf{1}_N,\mathcal{O}_5=i\vec{S}_\chi\cdot(\frac{\vec{q}}{m_N}\times\vec{v}^\perp)$	M,Δ
	$\mathcal{O}_{10}^{\rm rel}=\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\mathcal{O}_4=\vec{S}_\chi\cdot\vec{S}_N,\mathcal{O}_6$	Σ'',Σ'
anapole	$\mathcal{O}_{13}^{\rm rel}=\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$	$\mathcal{O}_8=\vec{S}_\chi\cdot\vec{v}^\perp$	M,Δ
	$\mathcal{O}_{14}^{\rm rel}=\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\frac{i\sigma_{\mu\nu}q^\nu}{m_M}N$	$\mathcal{O}_9=i\vec{S}_\chi\cdot(\vec{S}_N\times\frac{\vec{q}}{m_N})$	Σ'
electric dipole	$\mathcal{O}_{17}^{\rm rel}=i\frac{P^\mu}{m_M}\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$	$\mathcal{O}_{11}=i\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}$	M
	$\mathcal{O}_{18}^{\rm rel}=i\frac{P^\mu}{m_M}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\frac{i\sigma_{\mu\nu}q^\nu}{m_M}N$	$\mathcal{O}_{11},\mathcal{O}_{15}=-\left(\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}\right)\left((\vec{S}_N\times\vec{v}^\perp)\cdot\frac{\vec{q}}{m_N}\right)$	M,Φ'',Σ'
$\vec{L}\cdot\vec{S}$-generating	$\mathcal{O}_5^{\rm rel}=\frac{P^\mu}{m_M}\bar{\chi}\chi\frac{K_\mu}{m_M}\bar{N}N$	$\mathcal{O}_1$	M
	$\mathcal{O}_6^{\rm rel}=\frac{P^\mu}{m_M}\bar{\chi}\chi\bar{N}\frac{i\sigma_{\mu\nu}q^\nu}{m_M}N$	$\mathcal{O}_1,\mathcal{O}_3=i\vec{S}_N\cdot\left(\frac{\vec{q}}{m_N}\times\vec{v}^\perp\right)$	$M,\Phi''\,\Sigma'$
	and $\mathcal{O}_{10}^{\rm rel}$ (see above)		

E.g. Anapole:

$$(\tilde{\mu} = \frac{\text{magnetic moment}}{\text{nuclear magneton}})$$

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

according to shell model: $\tilde{\mu}_T = 2\tilde{\mu}_p\langle S_p\rangle + 2\tilde{\mu}_n\langle S_n\rangle + \langle L_p\rangle$

small E_R

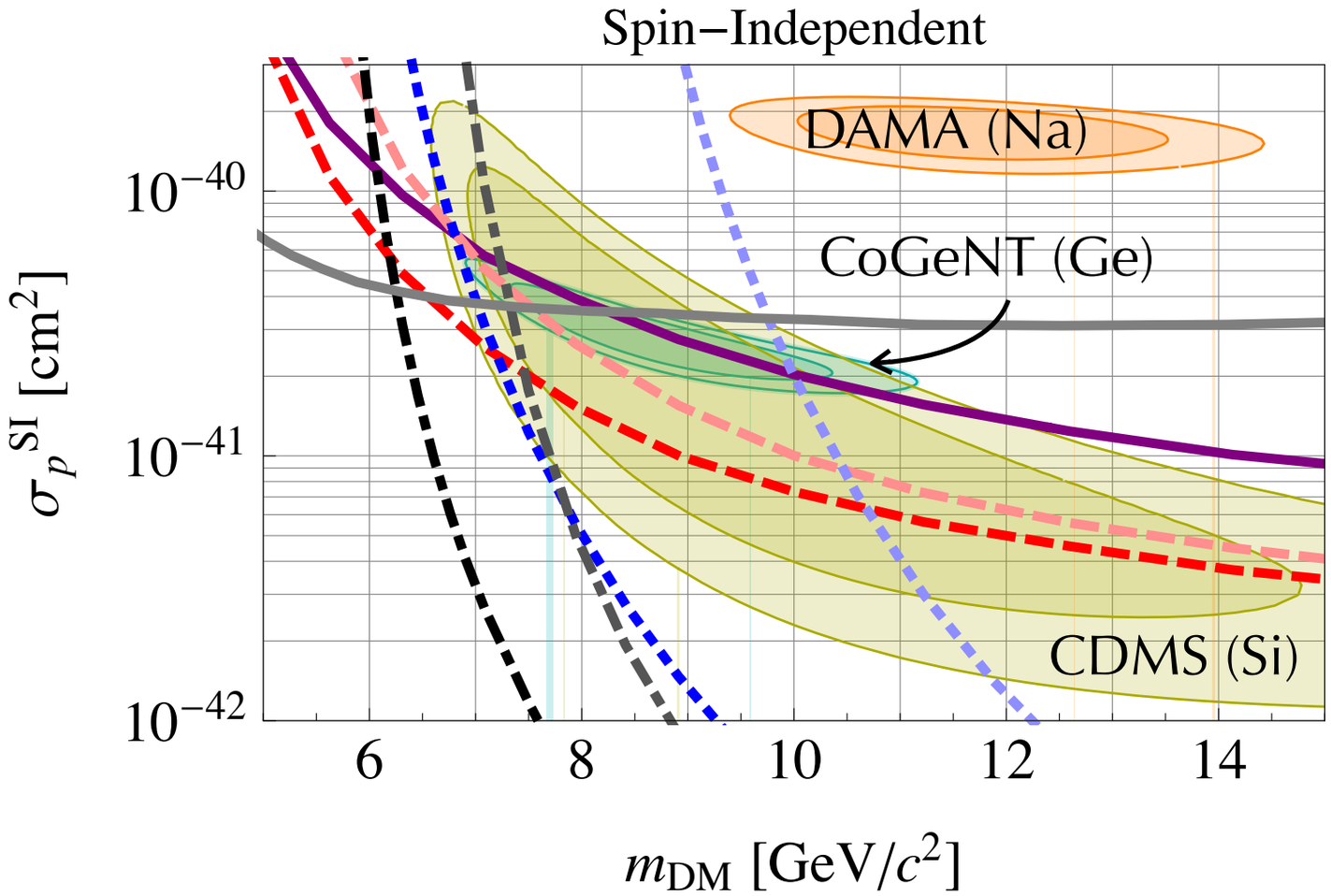
$$\sigma_T^{\text{anapole}} = \frac{\mu_T^2}{\pi}\left(\frac{f_a}{M^2}\right)^2 \left((\vec{v}^2 - \frac{\vec{q}^2}{4\mu_T^2}) Z^2 F(E_R)^2 + \vec{q}^2 \frac{J+1}{6J}\frac{\tilde{\mu}_T^2}{m_N^2}\right)$$

same as in

Dark Moments and the DAMA-CoGeNT Puzzle

A. Liam Fitzpatrick[a] and Kathryn M. Zurek[b]

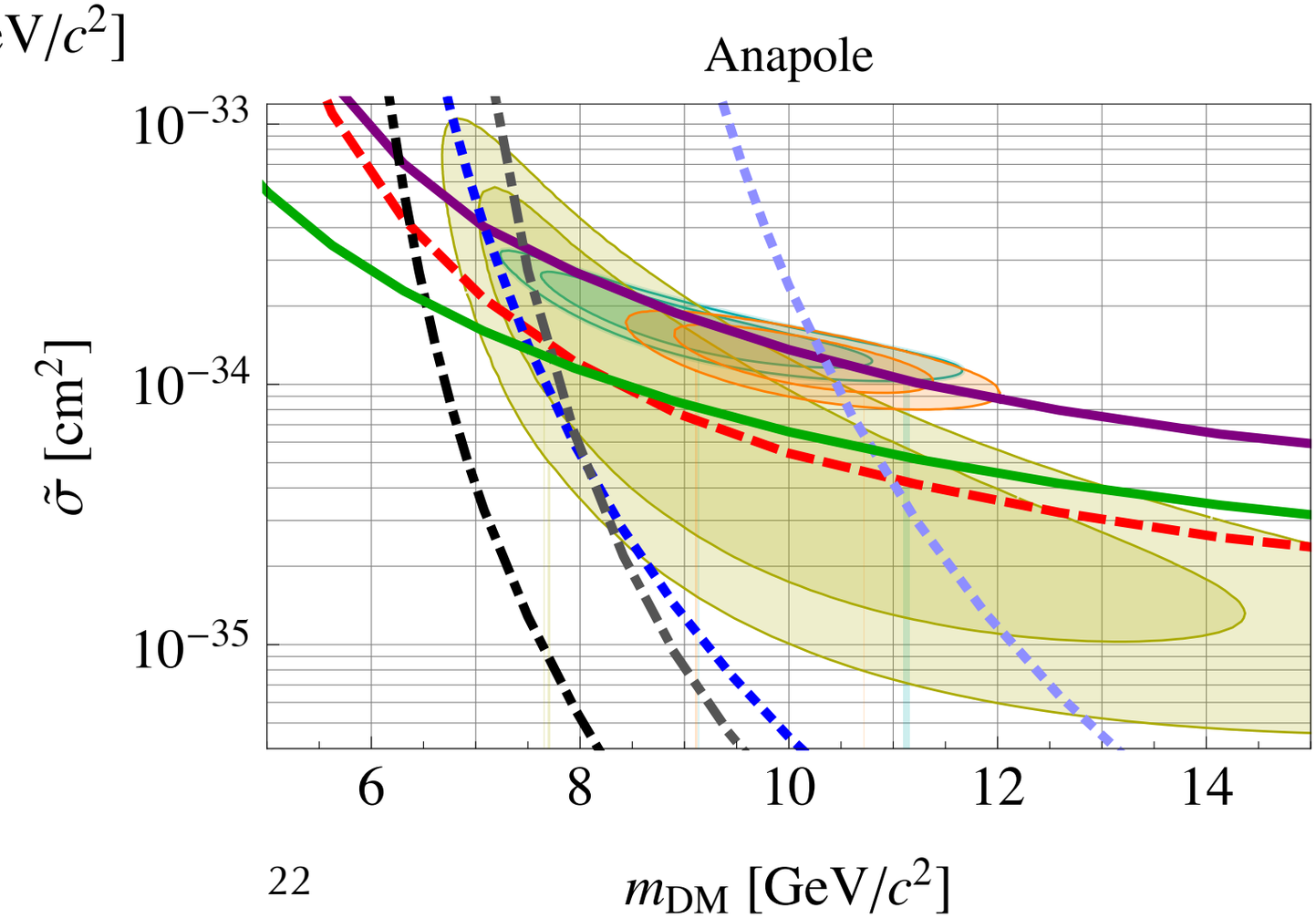
arXiv:1007.5325v2 [hep-ph] 9 Aug 2010



Exploit the enhanced (proton) orbital angular momentum response of Na to shift DAMA region of interest relative to Ge and Si.

This kind of trick is not new. EFT allows for a more systematic exploration of such possibilities…

See e.g. 1211.2818 by Fitzpatrick et al.



figs from 1311.2082

Sensitivity of various targets is well-characterized* by the zero-momentum transfer limit of the relevant response function.

	Fluorine	Sodium	Germanium	Iodine	Xenon
$A=$	19	23	70,72,73,74,76	127	128-132,134,136
$(N,N') =$	(p,p) (n,n)	(p,p) (n,n)	(p,p) (n,n)	(p,p) (n,n)	(p,p) (n,n)
$\tilde{W}_M^{(N,N')}(0)$	81 100	121 144	1024 1658	2809 5476	2911 5984
$\tilde{W}_{\Sigma'}^{(N,N')}(0)$	1.81 $< 10^{-3}$	0.273 0.002	$< 10^{-3}$ 0.057	0.26 0.016	$< 10^{-3}$ 0.168
$\tilde{W}_{\Sigma''}^{(N,N')}(0)$	0.903 $< 10^{-3}$	0.136 $< 10^{-3}$	$< 10^{-3}$ 0.029	0.13 0.008	$< 10^{-3}$ 0.084
$\tilde{W}_{\Delta}^{(N,N')}(0)$	0.025 0.018	0.231 0.029	$< 10^{-3}$ 0.231	0.536 0.100	0.015 0.119
$\tilde{W}_{\Phi''}^{(N,N')}(0)$	0.039 0.255	1.48 2.43	45.3 15.4	201 44.4	117 202

*This is true at least for light targets and/or light DM.

table from 1401.3739

The fact that the hierarchy of sensitivity of various DD targets is *different* for the novel responses is important. (At some level this is really just an acknowledgement that orbital angular momentum could be playing a role in the interaction.)

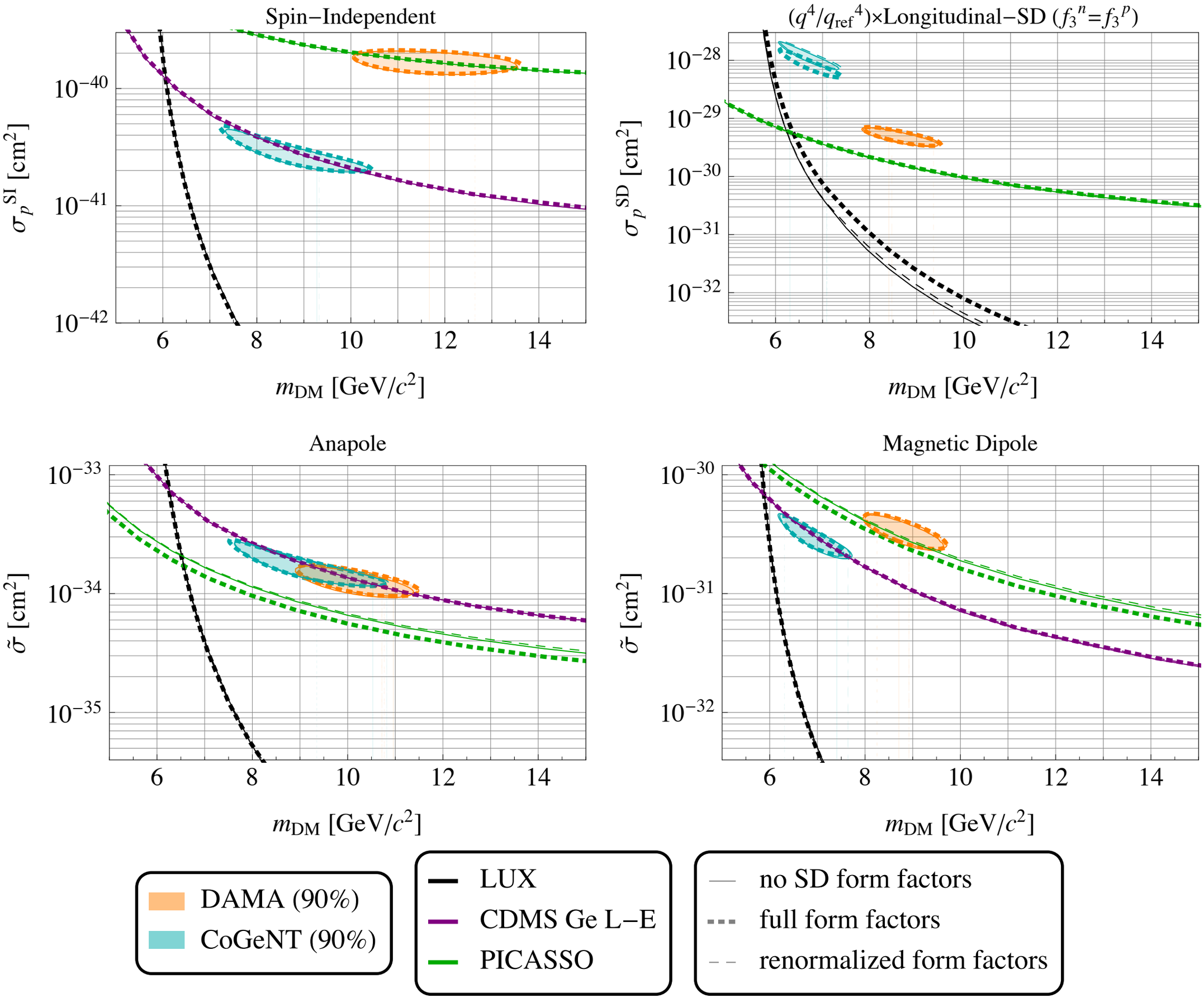
It's also important to have nuclear physics calculations under control so that we know more precisely what the hierarchy is....

	NA(%)	J	spin angular momentum $\lvert\langle S_p\rangle_{\rm th}\rvert$	$\langle S_p\rangle_{\rm lit}$	orbital angular momentum $\lvert\langle L_p\rangle_{\rm th}\rvert$	$\langle L_p\rangle_{\rm lit}$	magnetic moment $\lvert\tilde{\mu}_{\rm th}\rvert$	$\tilde{\mu}_{\rm lit}$	$\tilde{\mu}_{\rm exp}$
			$\lvert\langle S_n\rangle_{\rm th}\rvert$	$\langle S_n\rangle_{\rm lit}$	$\lvert\langle L_n\rangle_{\rm th}\rvert$	$\langle L_n\rangle_{\rm lit}$			
^{19}F	100	1/2	0.475	0.4751	0.224	0.2235	2.911	2.91	2.6289
			0.009	−0.0087	0.19	−0.1899			
^{23}Na	100	3/2	0.248	0.2477	0.912	0.9115	2.219	2.22	2.2175
			0.02	0.0199	0.321	0.3207			
^{129}Xe	26.4	1/2	0.007	0.01	0.274	0.372	0.636	-0.72	-0.778
			0.248	0.329	0.03	−0.185			

th = given the Fitzpatrick et al responses

lit = given the most state-of-the-art nuclear physics calculation in the literature

exp = measured

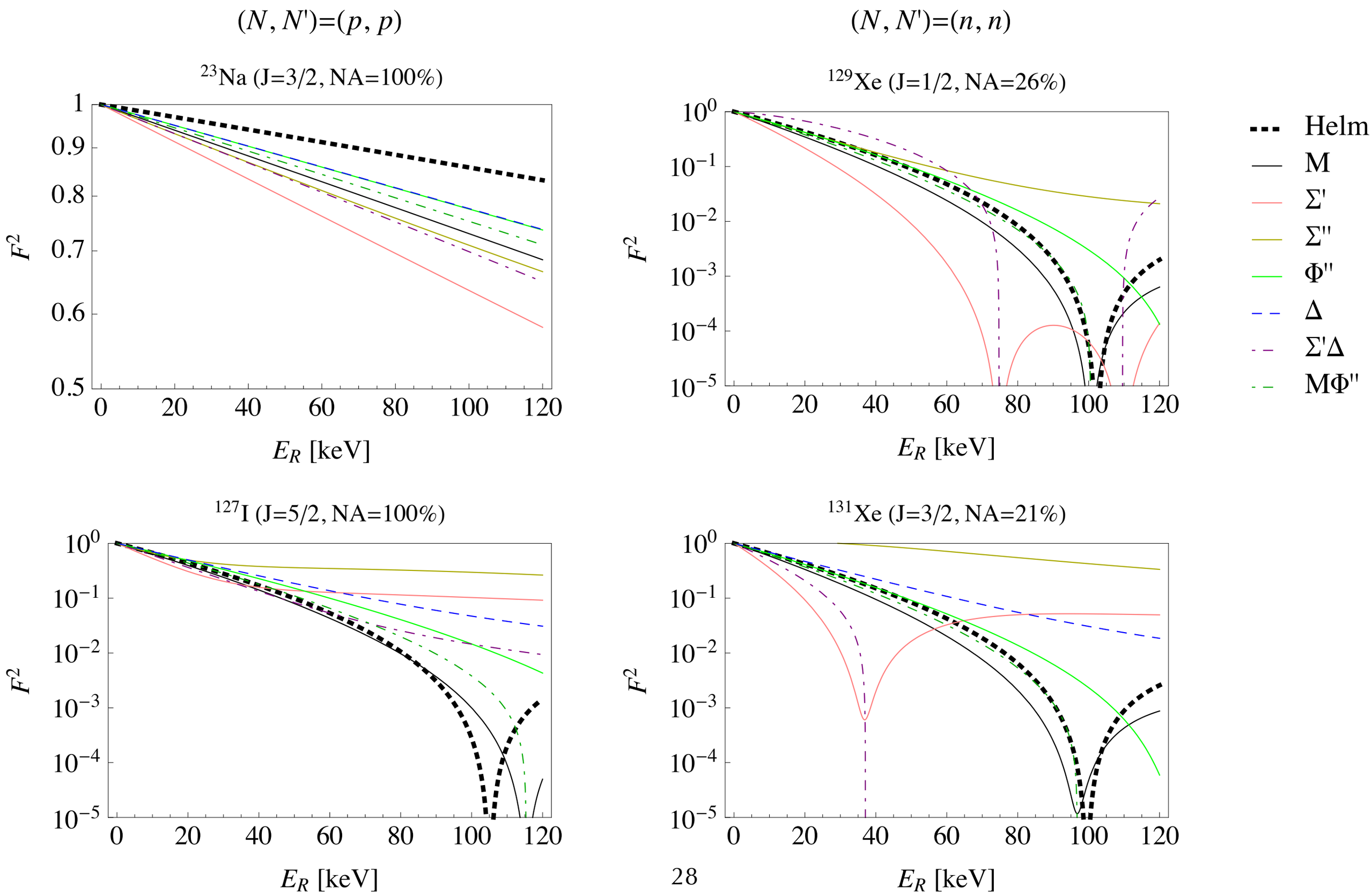

Spin−Independent
σ_p^{SI} [cm^2]
10^{-40}
10^{-41}
10^{-42}
6
8
10
12
14
m_{DM} [GeV/c^2]
$(q^4/q_{ref}{}^4)\times$Longitudinal−SD ($f_3{}^n=f_3{}^p$)
σ_p^{SD} [cm^2]
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
6
8
10
12
14
m_{DM} [GeV/c^2]
Anapole
$\tilde{\sigma}$ [cm^2]
10^{-33}
10^{-34}
10^{-35}
6
8
10
12
14
m_{DM} [GeV/c^2]
Magnetic Dipole
$\tilde{\sigma}$ [cm^2]
10^{-30}
10^{-31}
10^{-32}
6
8
10
12
14
m_{DM} [GeV/c^2]
DAMA (90%)
CoGeNT (90%)
LUX
CDMS Ge L−E
PICASSO
no SD form factors
full form factors
renormalized form factors

The fact that the hierarchy of sensitivity of various DD targets is *different* for the novel responses is important. (At some level this is really just an acknowledgement that orbital angular momentum could be playing a role in the interaction.)

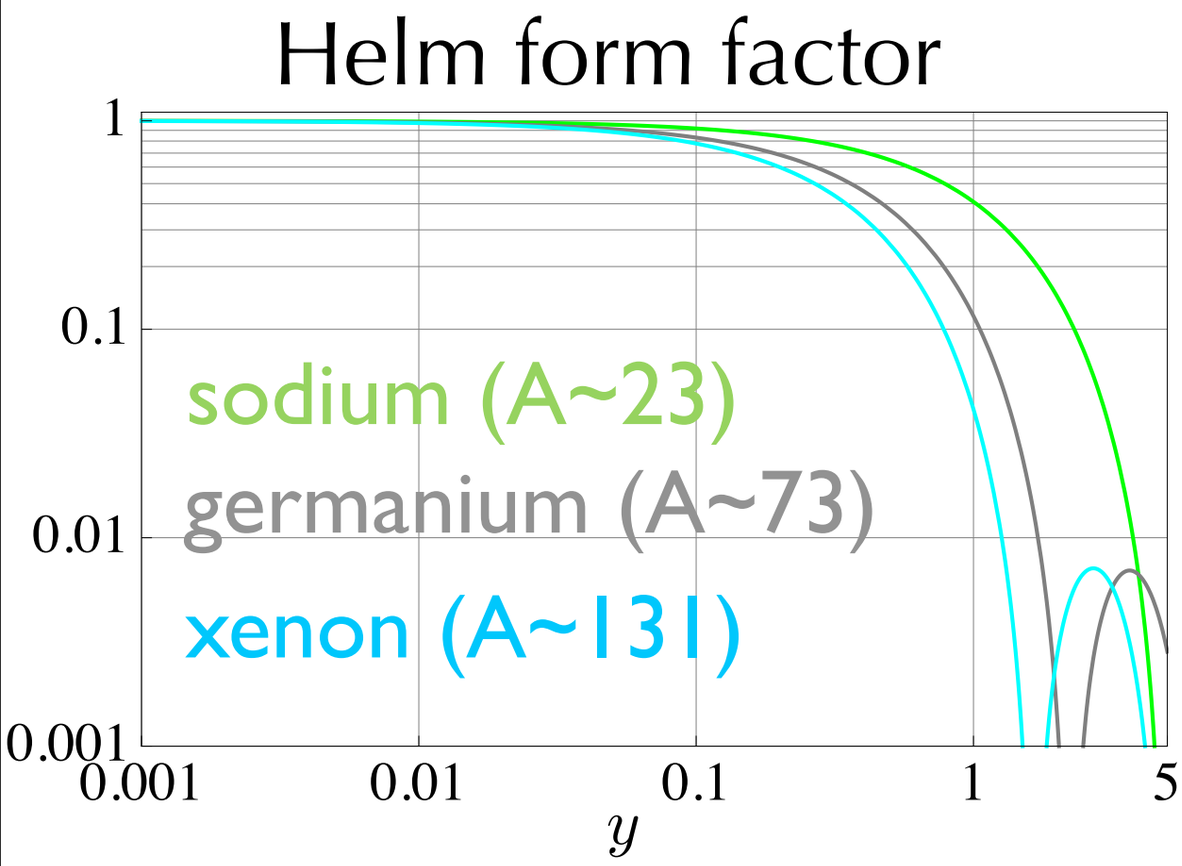
It's also important to have nuclear physics calculations under control so that we know precisely what the hierarchy is....

What about the energy (momentum) dependence of the novel responses?

Energy dependence of various nuclear responses

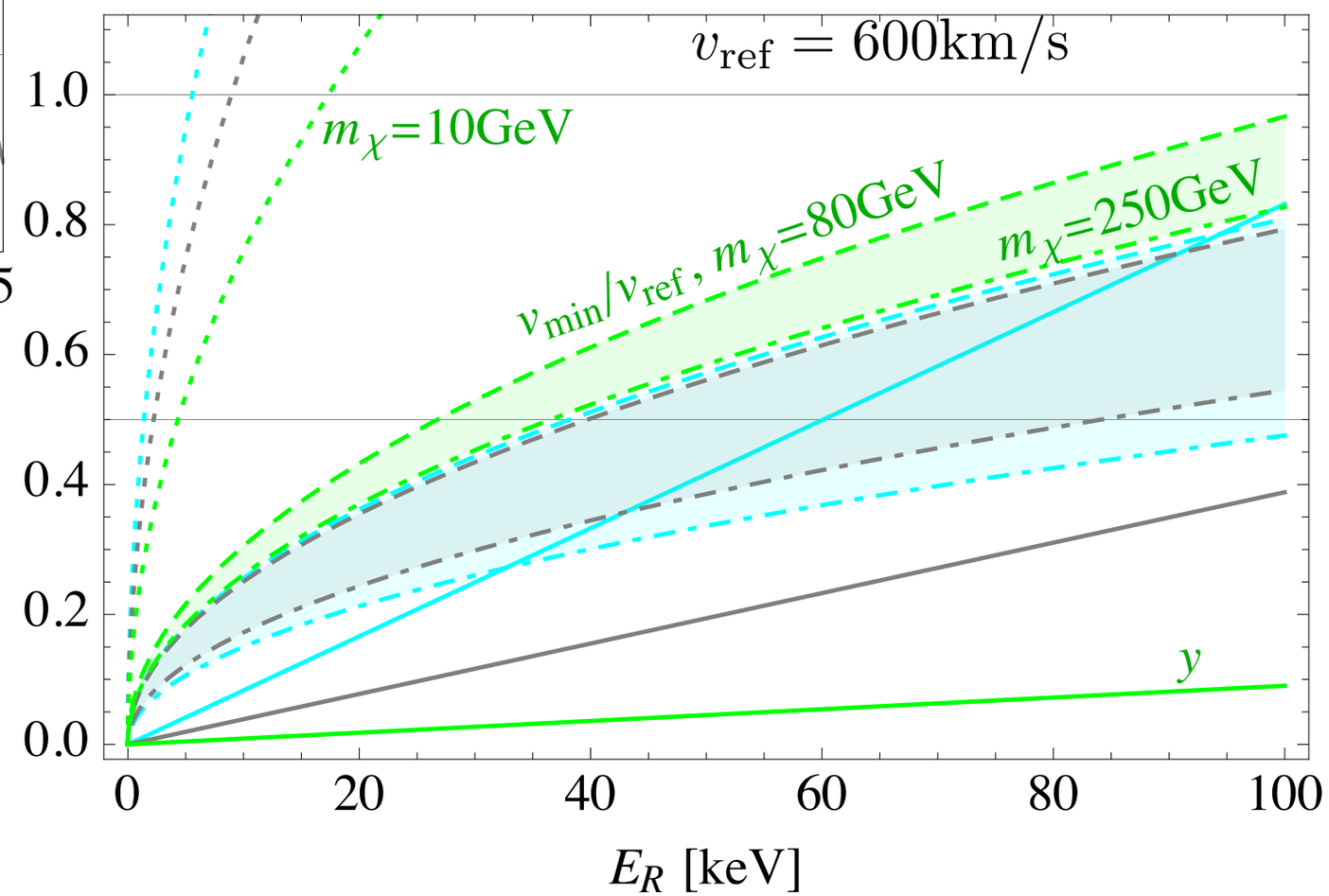


Recall… nuclear size, *b*, sets the relevant scale for the energy dependence.

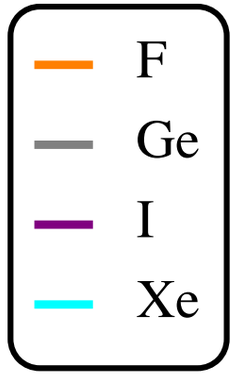


$$y = q^2 b^2/2$$

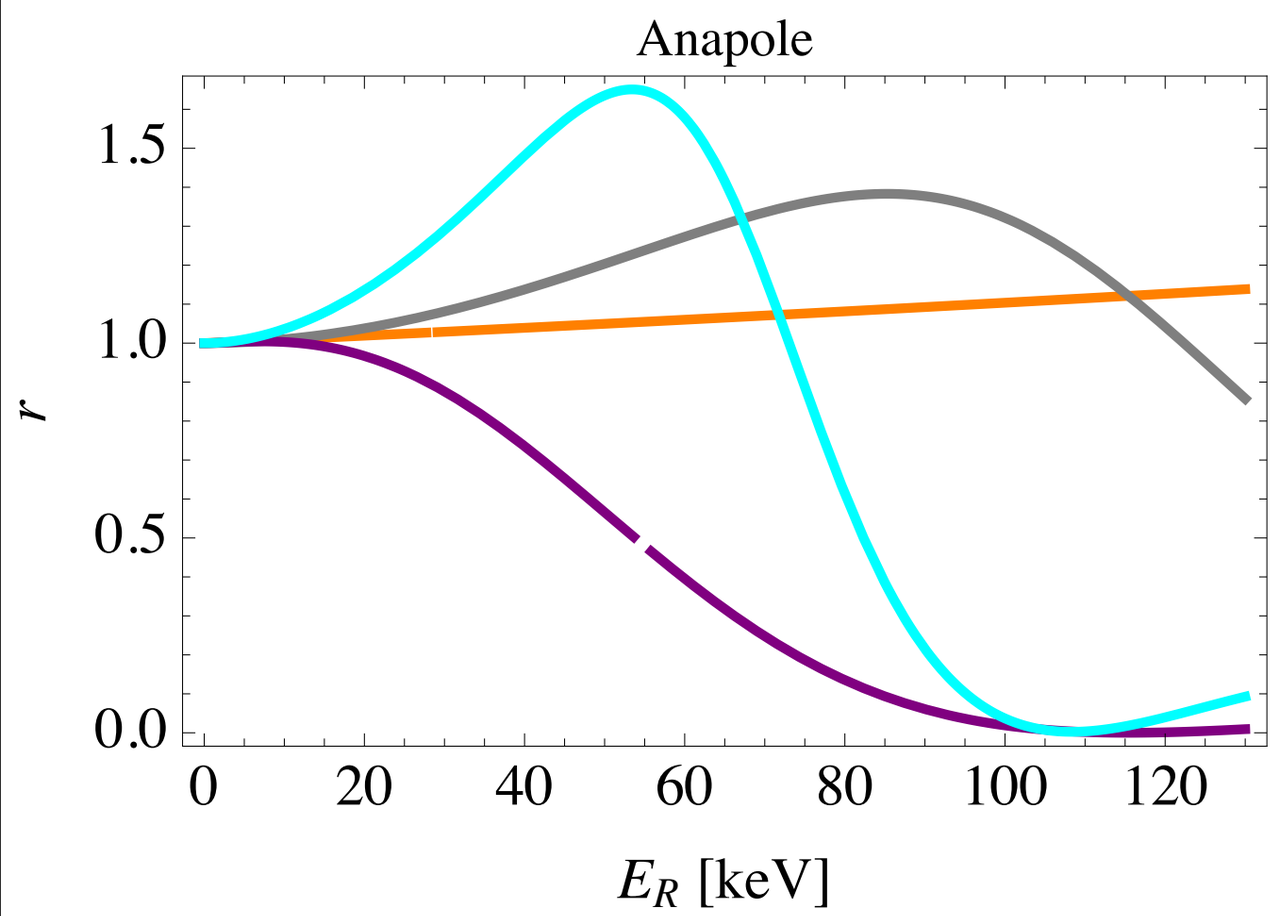
$$q = \sqrt{2 m_T E_R}$$

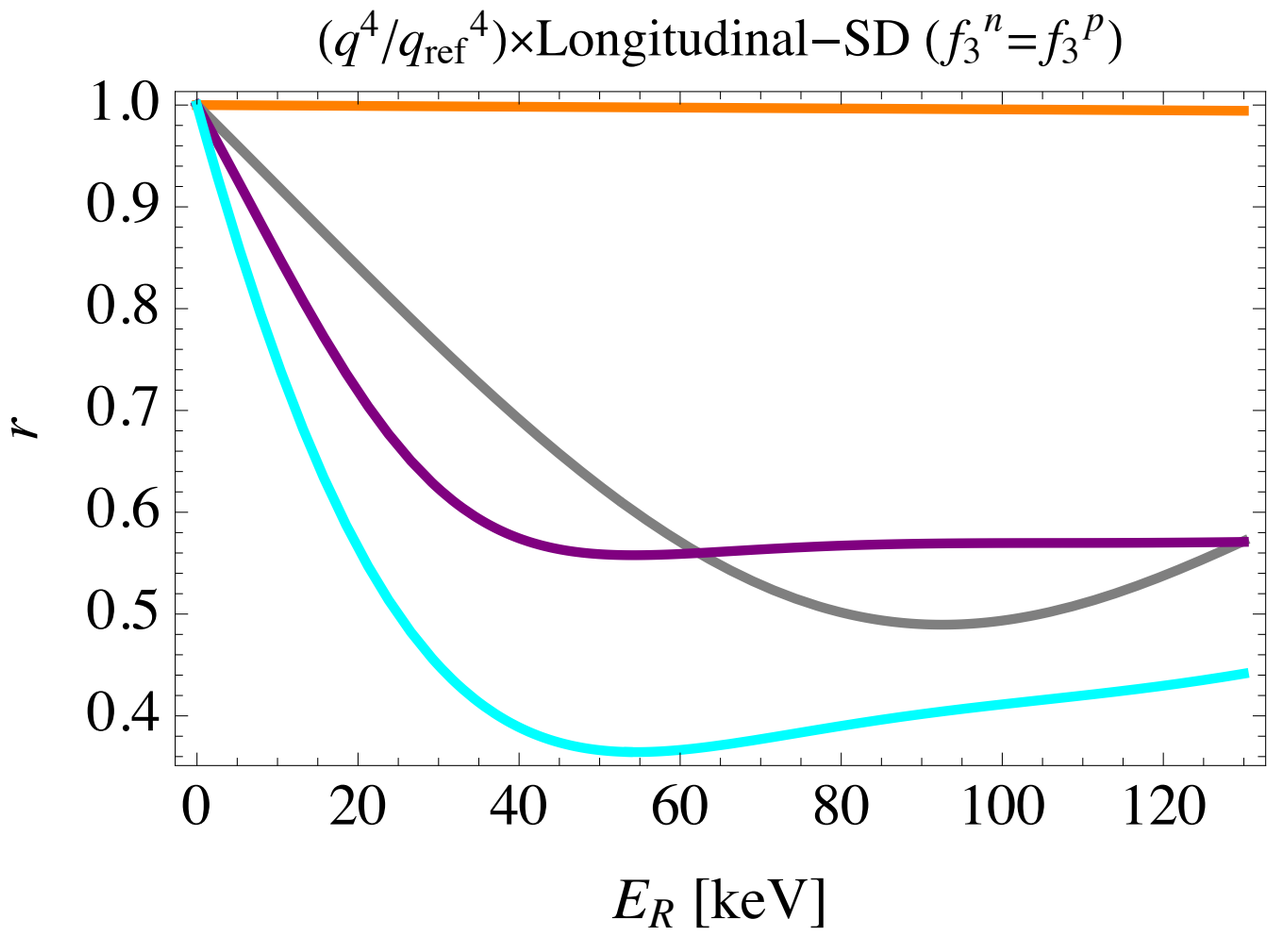


Use foil form factors to explore the potential impact of the novel energy dependence of novel nuclear response functions.



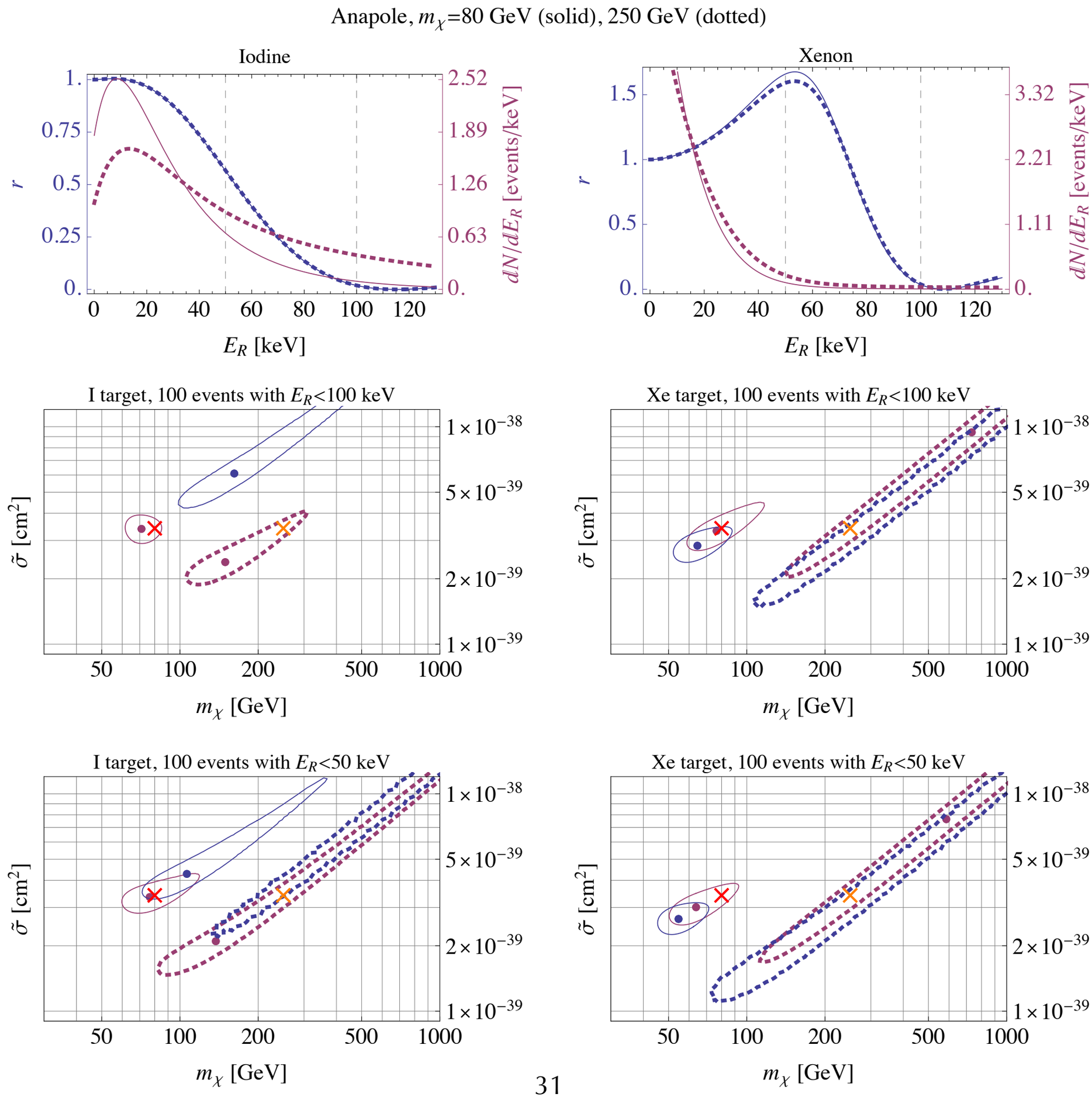
r = foil rate / correct rate





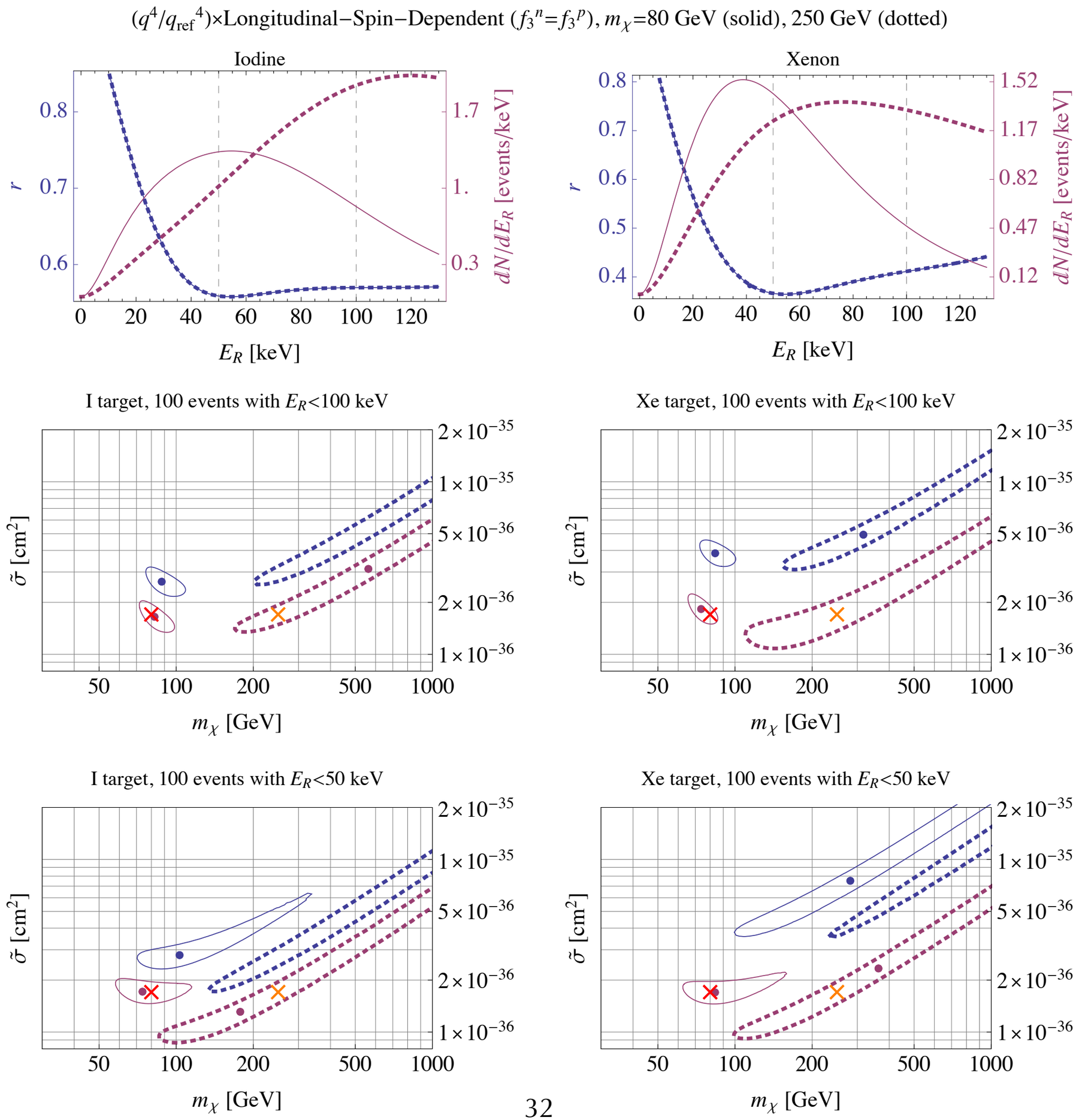
see 1401.3739, Sec. III

Effect on a potential signal



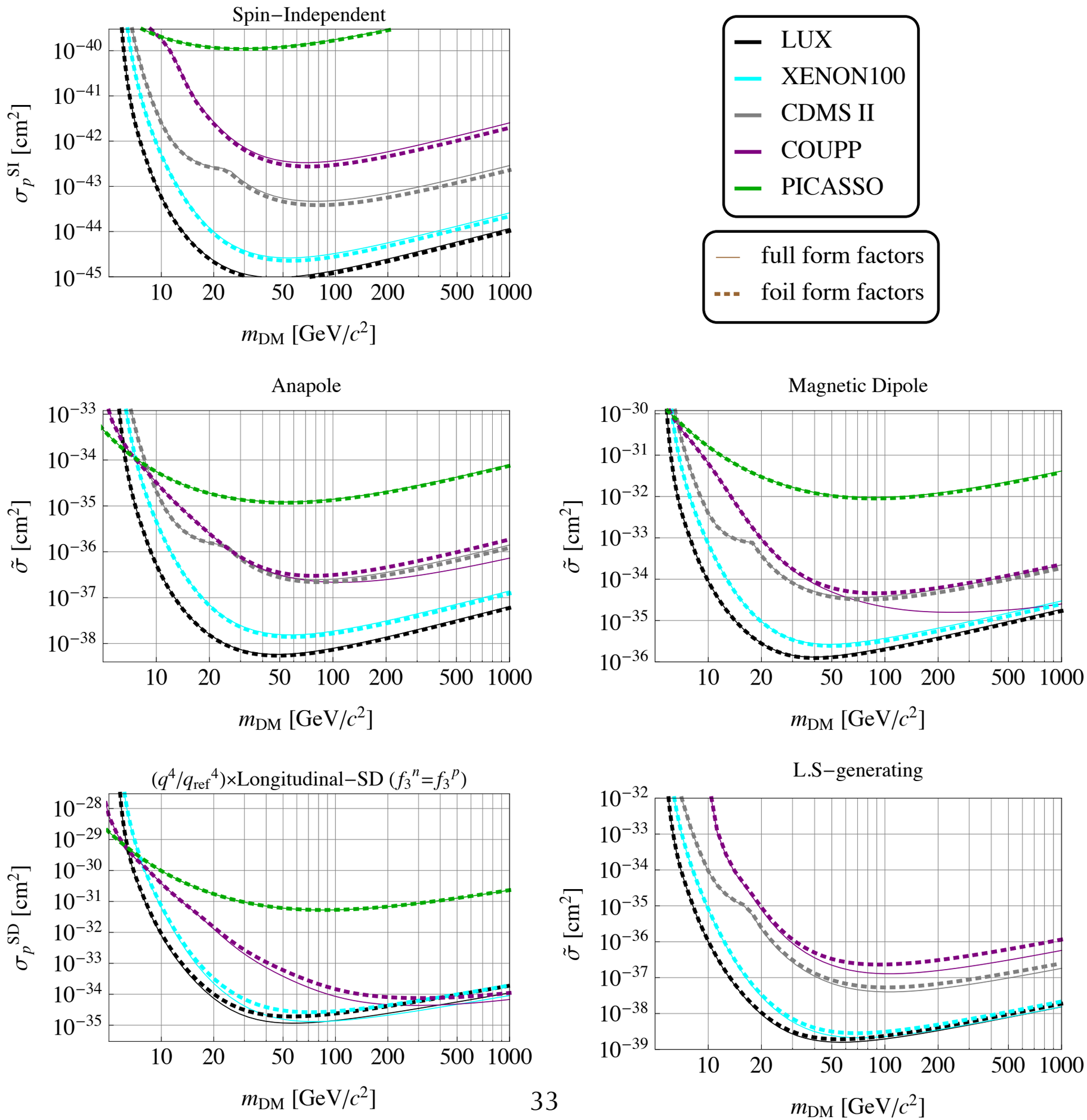
see 1401.3739, Sec. III

Effect on a potential signal



see 1401.3739, Sec. III

Effect on constraints



see 1401.3739, Sec. III

On the Effect of Nuclear Response Functions in Dark Matter Direct Detection

Moira I. Gresham, Kathryn M. Zurek

arXiv:1401.3739

Motivating question:

How important are these novel nuclear responses?

Depending what you mean by "important"...

- trivially important,
- more important for highly momentum-suppressed interactions and big targets with large spin, especially if large nuclear recoil energies are probed