A Model Independent Analysis of Dark Matter Direct Detections

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w/ A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers
arXiv: 1203.3542, and work in progress

Outline

- The effective field theory of DM direct detections

  Relativistic Interactions → Non-rel Operators → Nuclear Responses

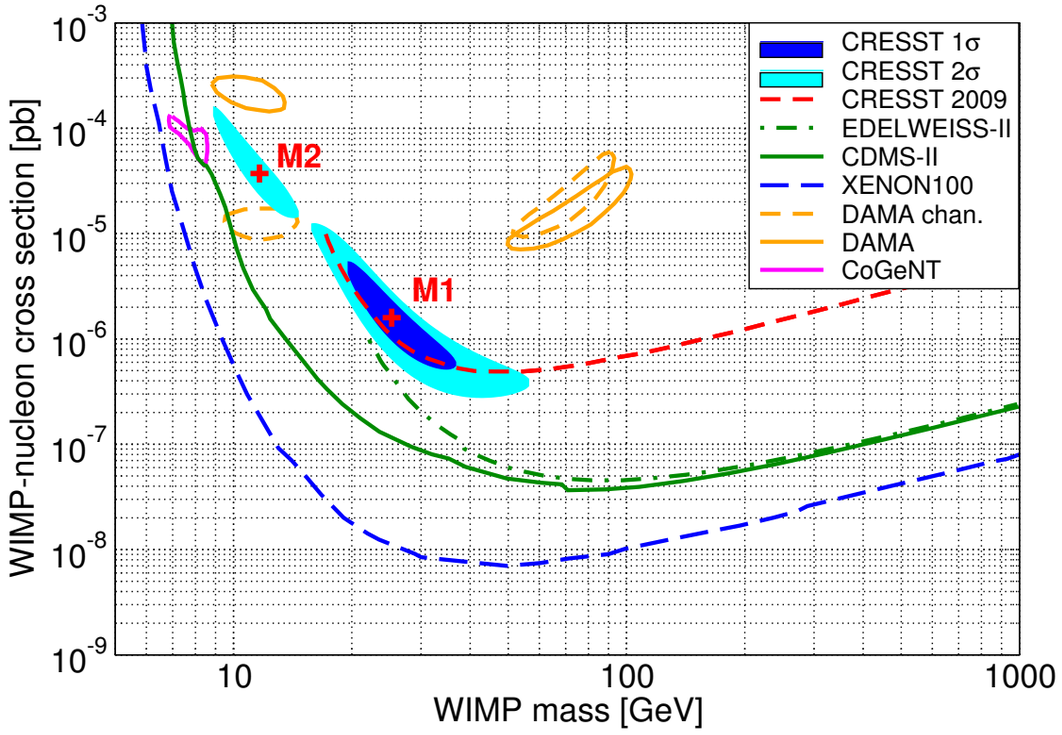
  (e.g. $\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{N}i\sigma_{\mu\alpha}q^{\alpha}N$) (e.g. $i\vec{S}_{\chi}\cdot(\vec{S}_{N}\times\vec{q})$) $_{f}\langle\chi, Nucleus|\mathcal{O}_{i}|\chi, Nucleus\rangle_{i}$

- Results of the model independent searches

  - How important are interferences of non-rel effective operators?

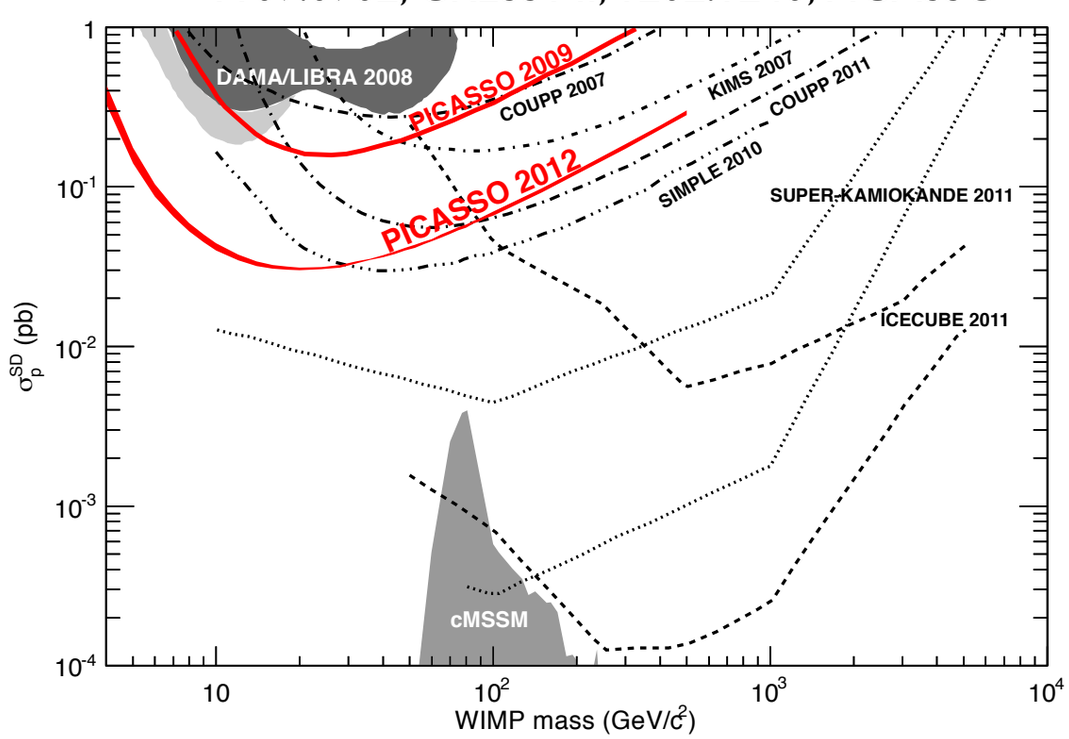
  - Are current DM experiments complementary?

Standard WIMP Interactions in Direct Detections vs New Models



SI interaction $\bar{\chi}\chi\bar{N}N$

1109.0702, CRESST-II, 1202.1240, PICASSO



SD interaction $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$

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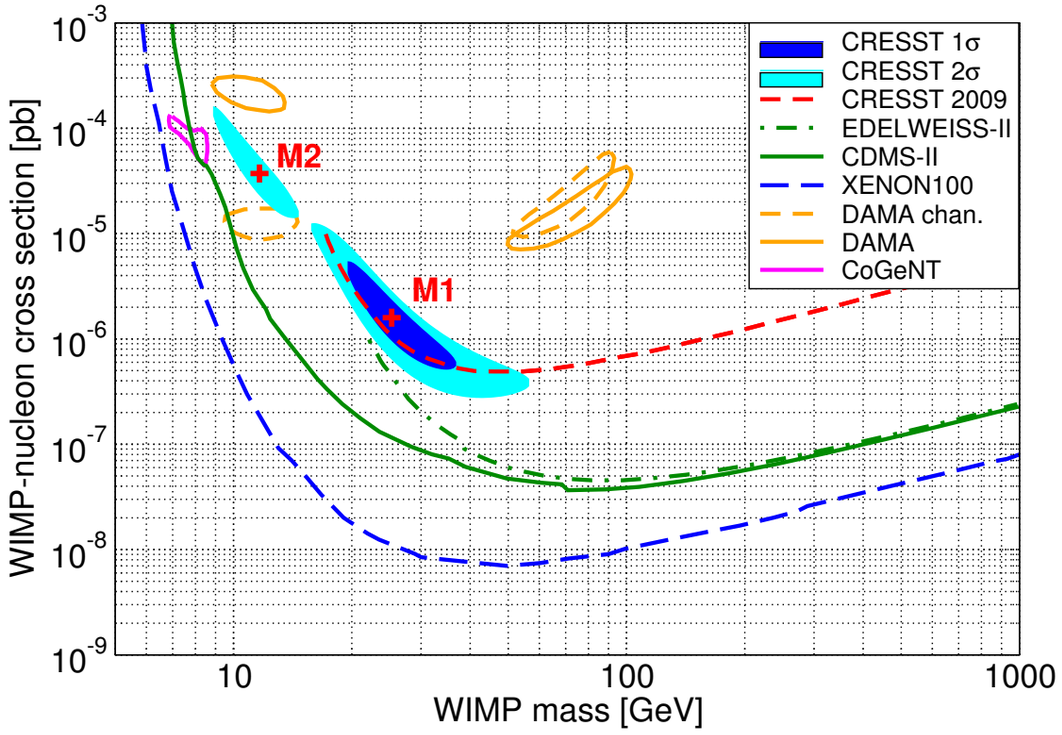

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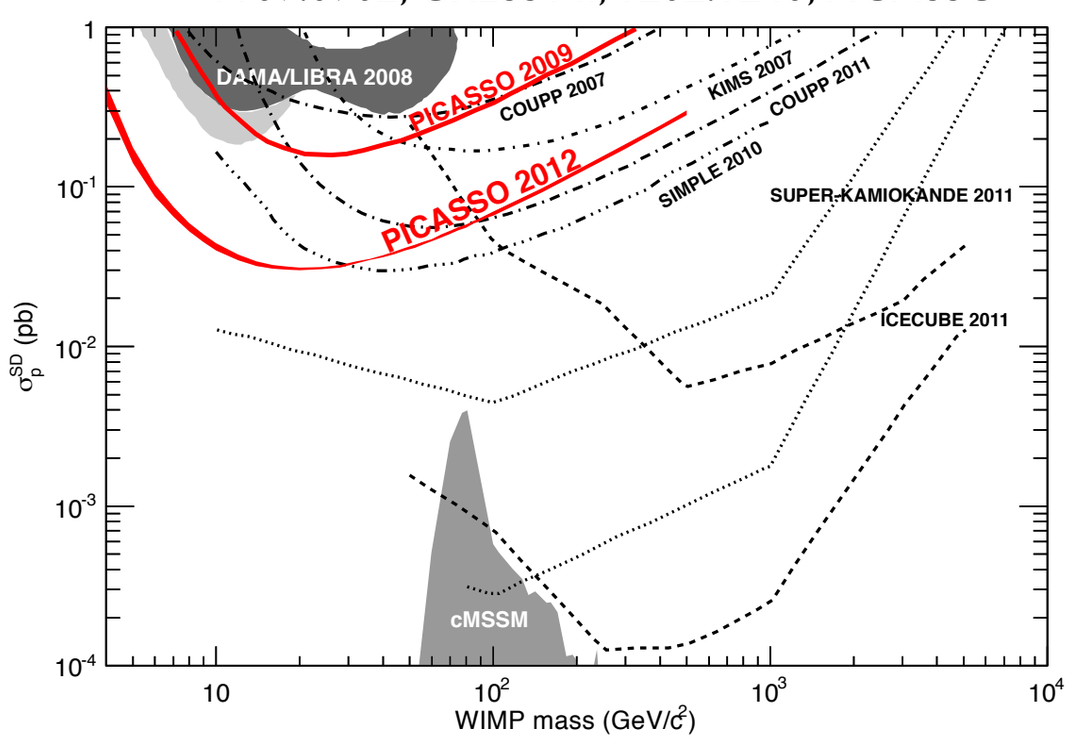


SI interaction $\bar{\chi}\chi\bar{N}N$

SD interaction $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$

Isospin-dependent DM [1102.43311],
Form factor DM [0908.3192, 0908,29911],
Inelastic DM [hep-ph/0101138],
Dark moment interactions [1007.4200, 1007.5325, 1203.6652],...

EFT of Direct Detections

Leading non-rel operators of DM-SM interactions

[1008.1591, Fan, Reese, Wang]

Relativistic operators ⟶ Non-relativistic operators

Why the next leading order (in q^2)?

Magnetic dipole interaction [1007.4200,1007.5325]:

$$\mathcal{L} \supset g' Q' r \bar{\chi} \sigma^{\mu\nu} \chi F'_{\mu\nu} + \epsilon F_{\mu\nu} F'^{\mu\nu} \longrightarrow e g' \epsilon Q' r \bar{\chi} \sigma^{\mu\nu} q_\nu \chi \bar{N} \gamma_\mu N / m_A^2$$

DM - Nucleus interactions ⟶ Nuclear Responses

EFT of Direct Detections

$$\mathcal{L}_{\rm int} = \sum_{N=n,p} \sum_i c_i^{(N)} \mathcal{O}_i \chi^+ \chi^- N^+ N^-$$

Galilean-invariant, Hermitian quantities:

$i\vec{q}$ (transfer momentum)

$\vec{v}^{\perp} \equiv \frac{1}{2}(\vec{v}_{\chi,in} + \vec{v}_{\chi,out} - \vec{v}_{N,in} - \vec{v}_{N,out})$

$\vec{S_\chi}$ (DM spin)

$\vec{S_N}$ (nucleon spin)

Non-relativistic operators $\mathcal{O}_i$

$$\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3 : \quad \mathbf{1}, \quad (v^{\perp})^2, \quad i\vec{S}_N \cdot (\vec{q} \times \vec{v}^{\perp})$$

$$\mathcal{O}_4, \mathcal{O}_5, \mathcal{O}_6 : \quad \vec{S}_\chi \cdot \vec{S}_N, \quad i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^{\perp}), \quad (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$$

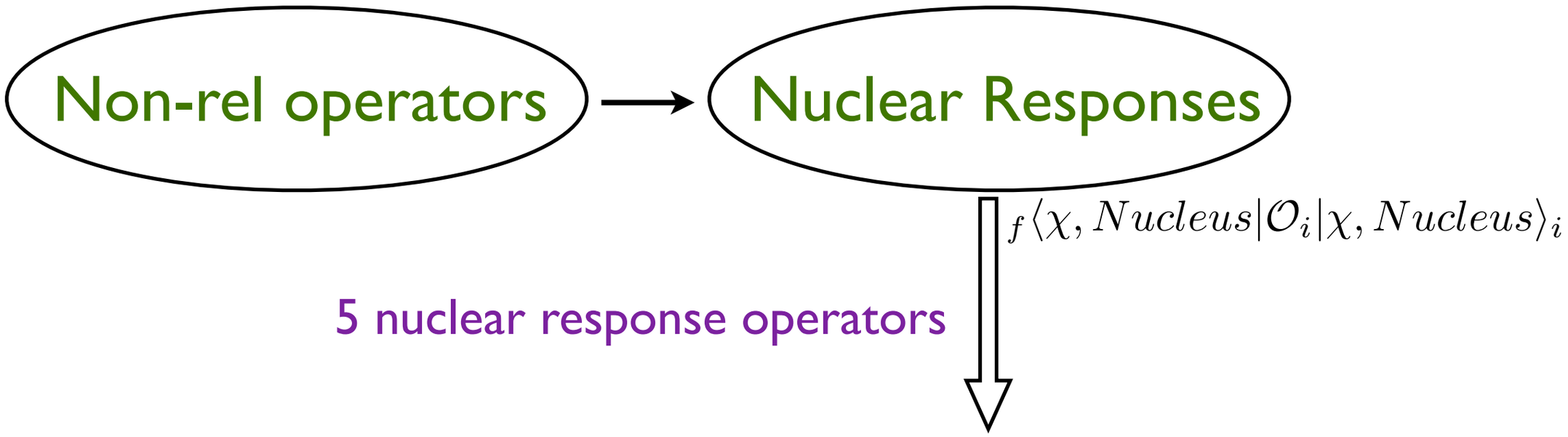
$$\mathcal{O}_7 : \quad \vec{S}_N \cdot \vec{v}^{\perp},$$

$$\mathcal{O}_8, \mathcal{O}_9 : \quad \vec{S}_\chi \cdot \vec{v}^{\perp}, \quad i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$

$$\mathcal{O}_{10} : \quad i\vec{S}_N \cdot \vec{q},$$

$$\mathcal{O}_{11} : \quad i\vec{S}_\chi \cdot \vec{q}.$$

EFT of Direct Detections



1. SI

SD
- 2. Longitudinal SD $\quad \langle f|\vec{q}\cdot\vec{S}_N|i\rangle$
- 3. Transverse SD $\quad \langle f|\vec{q}\times\vec{S}_N|i\rangle$

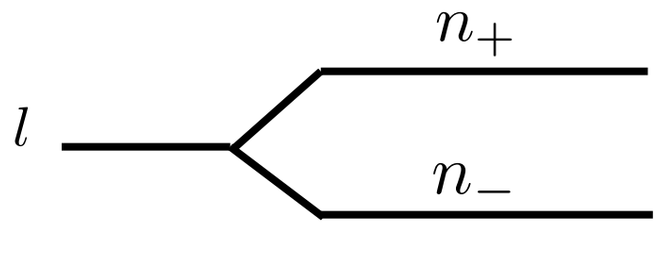
4. Angular momentum $\quad \langle f|\vec{L}_N|i\rangle$ [1007.4200, Chang, Weiner, Yavin]

5. Angular momentum - spin coupling $\quad \langle f|(\vec{L}\cdot\vec{S})_N|i\rangle$

(New operator, interferes with SI)

EFT of Direct Detections

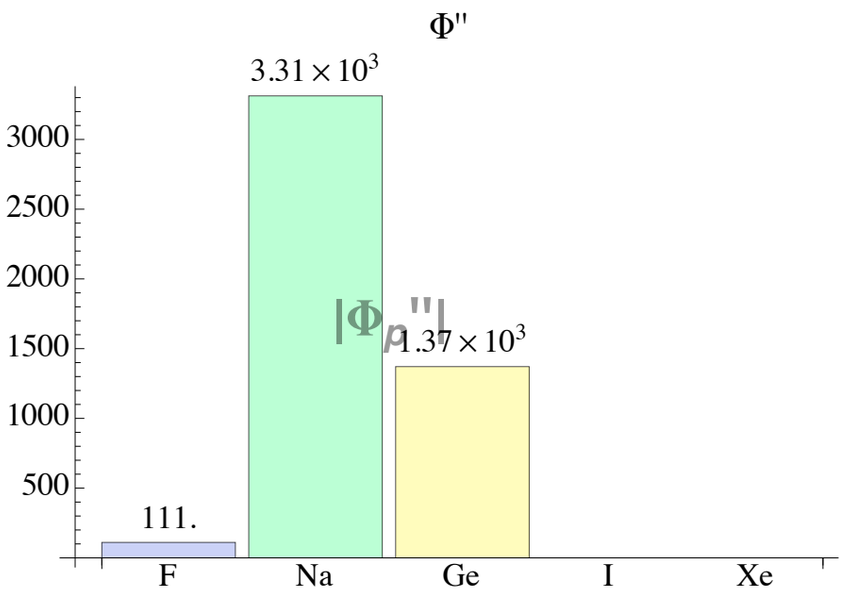
... in particular, for $(\vec{L}\cdot\vec{S})_N$, there is an $l^2_{highest}$ enhancement.

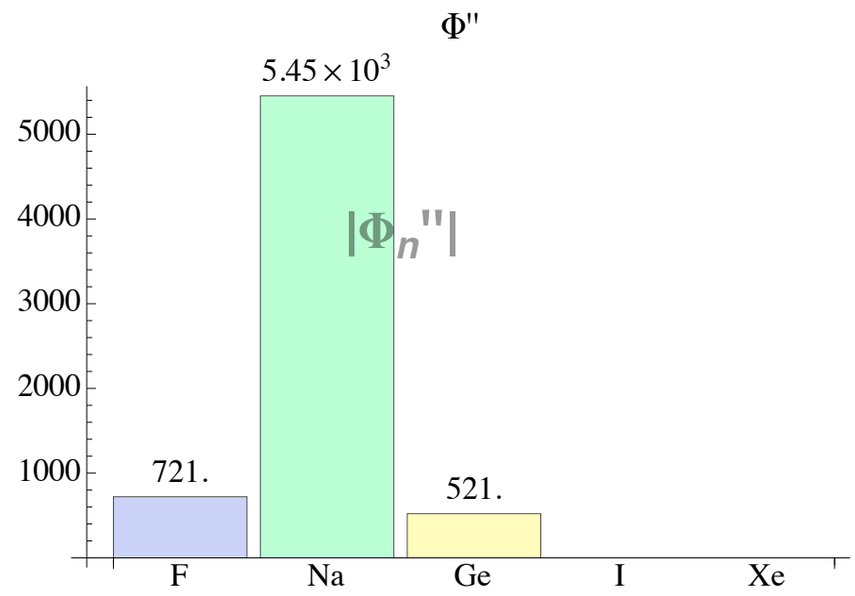


$$l - \frac{1}{2} \qquad \vec{l}\cdot\vec{s} \sim -(l+1)/2 \qquad \Delta n_\pm \sim l$$

$$l + \frac{1}{2} \qquad \vec{l}\cdot\vec{s} \sim l/2 \qquad (\vec{L}\cdot\vec{S})_N \sim l^2_{highest}$$

At low DM mass :



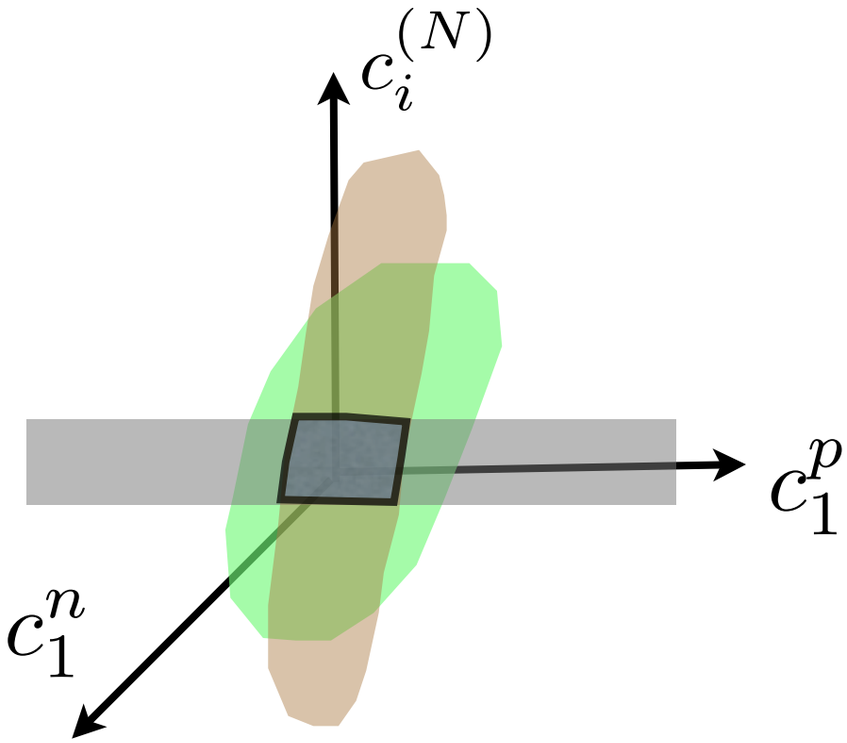


$$\int_{v_{\min}=\frac{q}{2\mu_T}} d^3v \frac{f(v)}{v} \int_0^\infty qdqF(q^2)$$

w/ form factors defined as $$\frac{1}{2j_\chi+1}\frac{1}{2j+1}\sum_{\text{spins}}|\mathcal{M}|^2 = \frac{m_T^2}{m_N^2}\sum_{i,j=1}^{12}\sum_{N,N'=p,n} c_i^{(N)}c_j^{(N')}F_{ij}^{(N,N')}(v^2,q^2)$$

Understanding nuclear targets in probing the larger parameter space

Xe, Ge, F, Na, I, (W, Si, O, ...)



# of constraining directions

=

# of nuclear orbitals with non-zero S matrix of these operators

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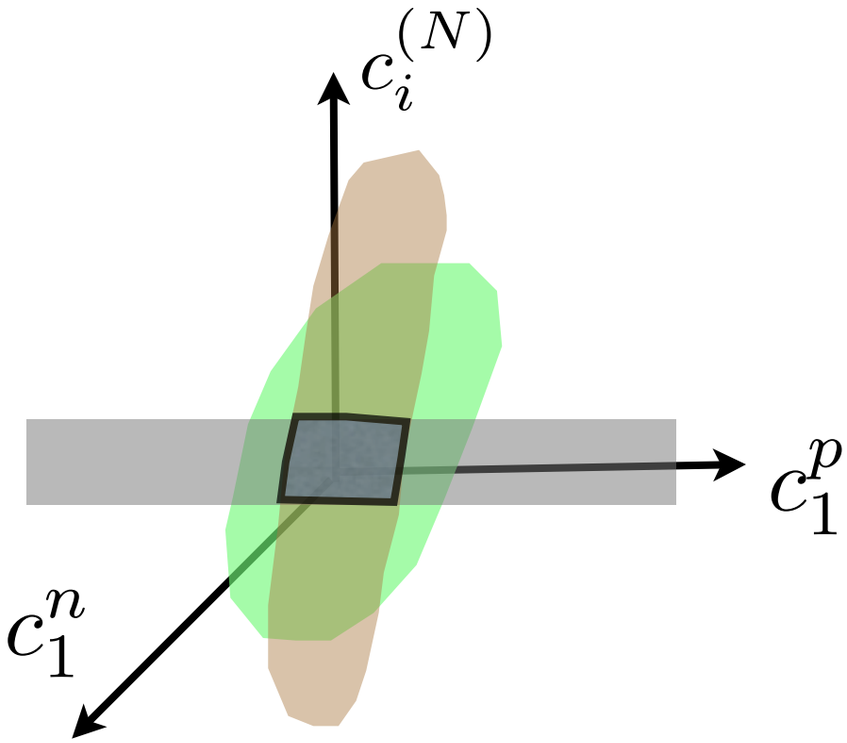

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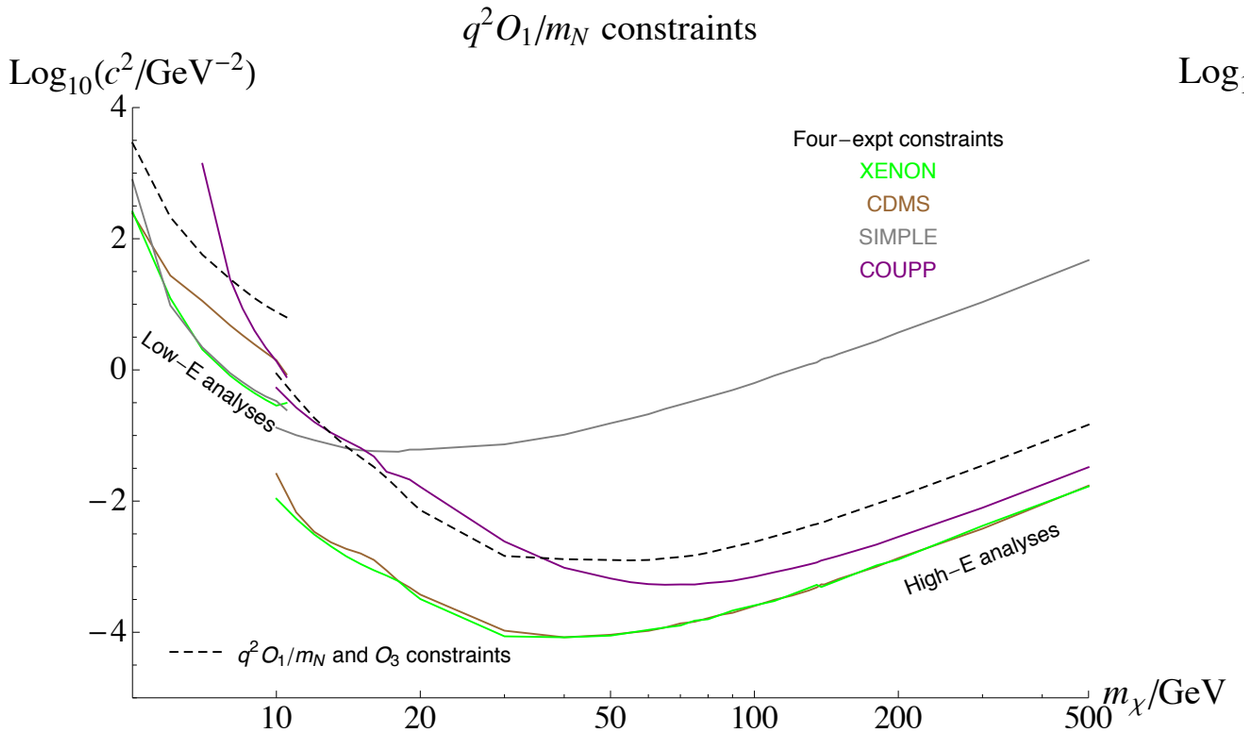
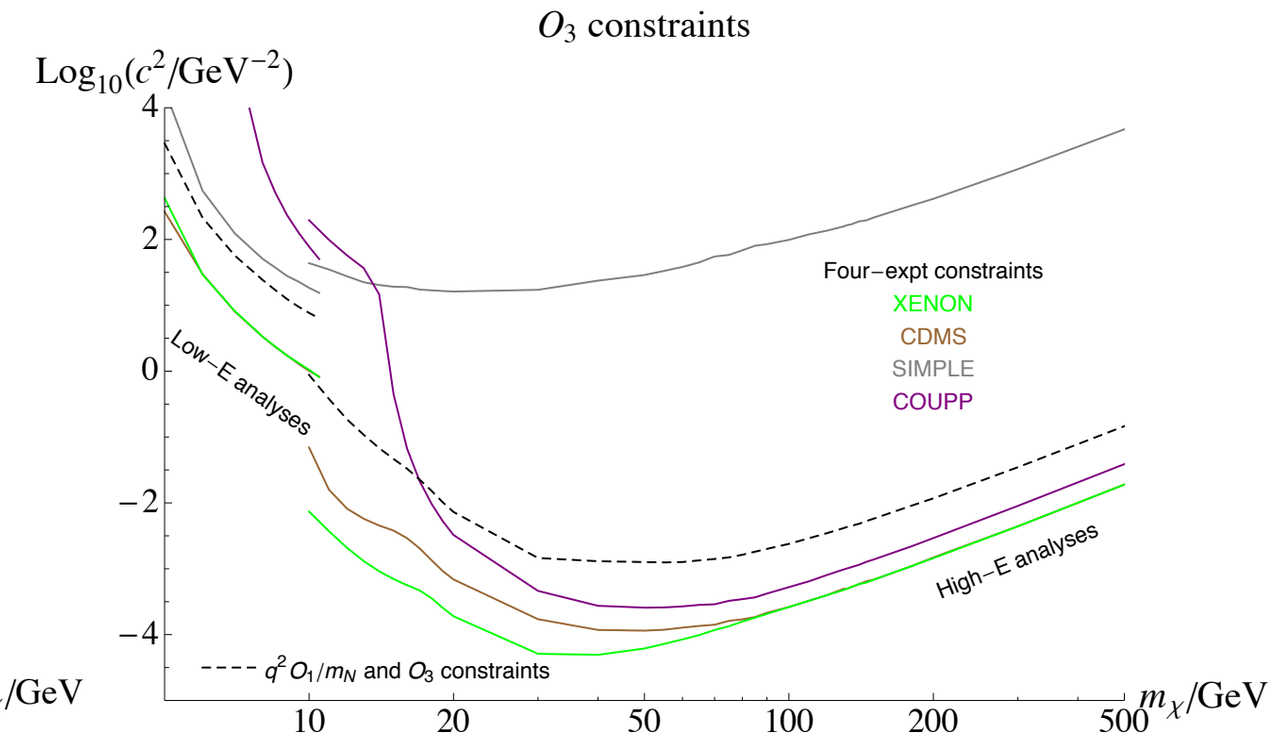
Flat directions for small-spin targets at low energy

Constraints on Non-rel Operators

SI operator and $(\vec{L}\cdot\vec{S})_N$ -- Release of constraint by O(10)





$$\mathcal{O}_1 = \mathbf{1}$$

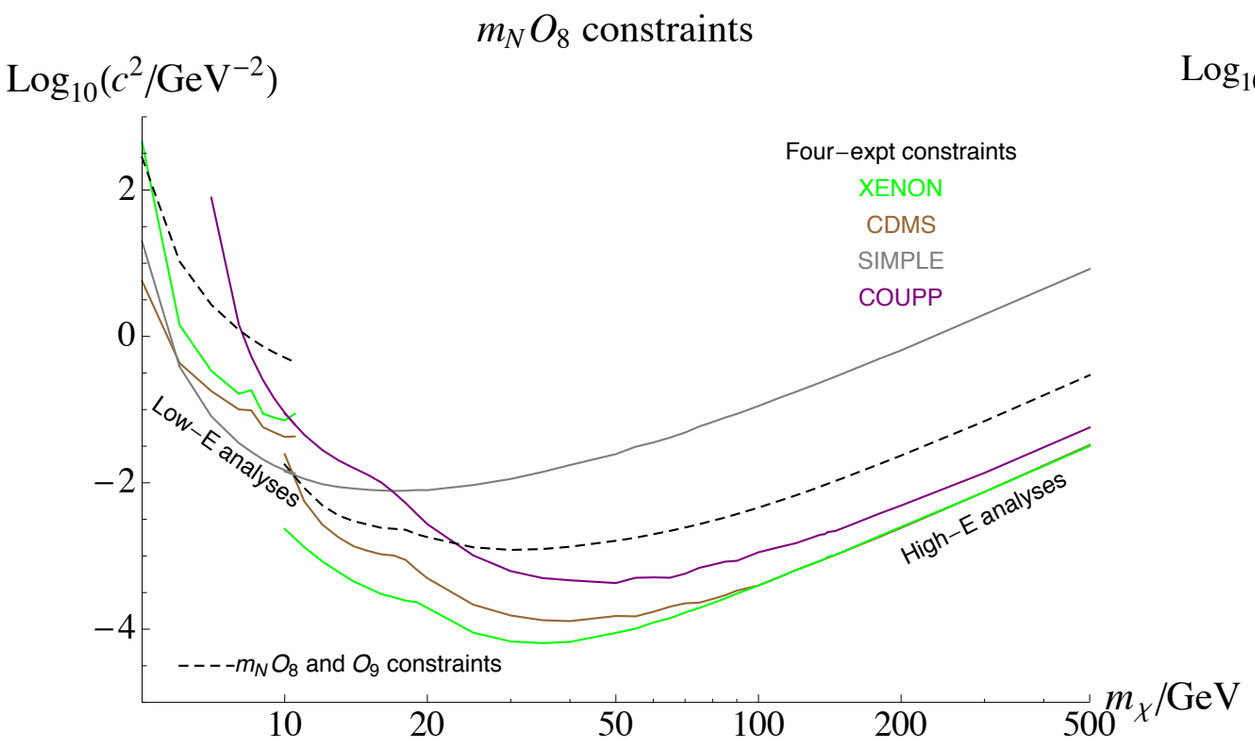
$$\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q}\times\vec{v})$$

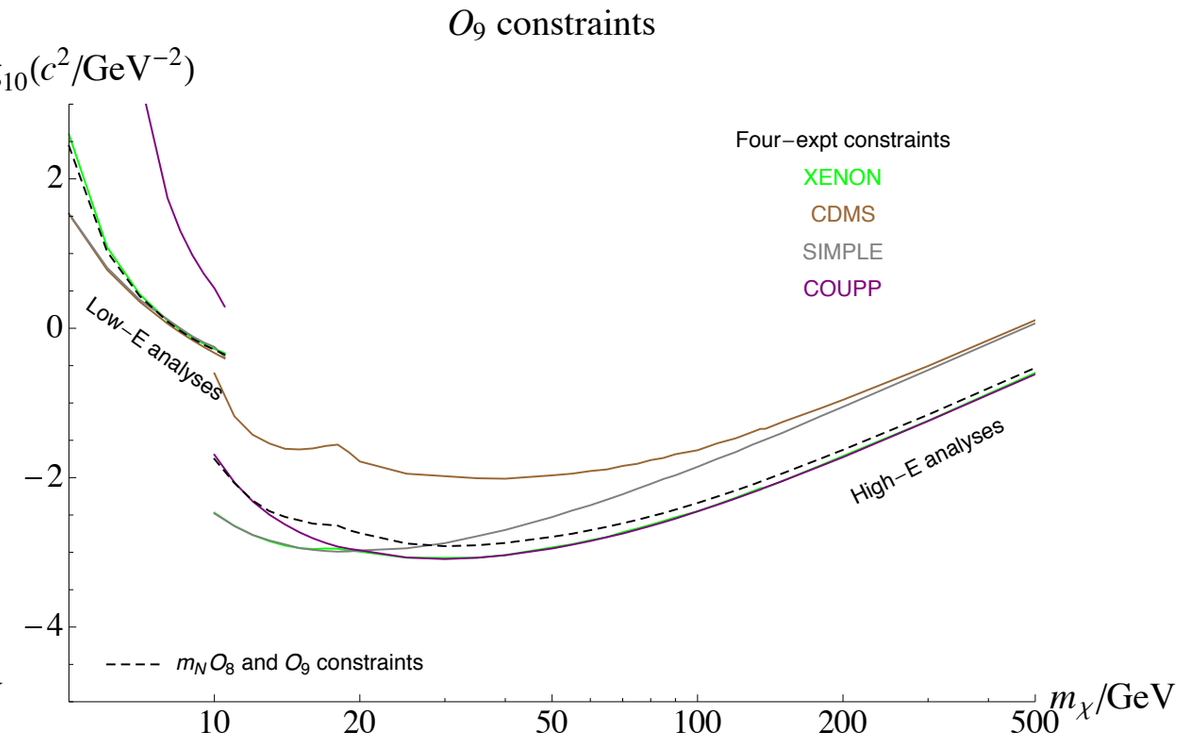
with $c^2 \equiv \sum_N (c_i^{(N)})^2$

$$P^\mu \bar{\chi}\chi\bar{N} i\sigma_{\mu\alpha}q^\alpha N \rightarrow 4m_\chi^2 q^2\mathcal{O}_1 + 16 m_N m_\chi^2 \mathcal{O}_3$$

Constraints on Non-rel Operators

$\vec{L}_N$ and $\vec{S}_N$





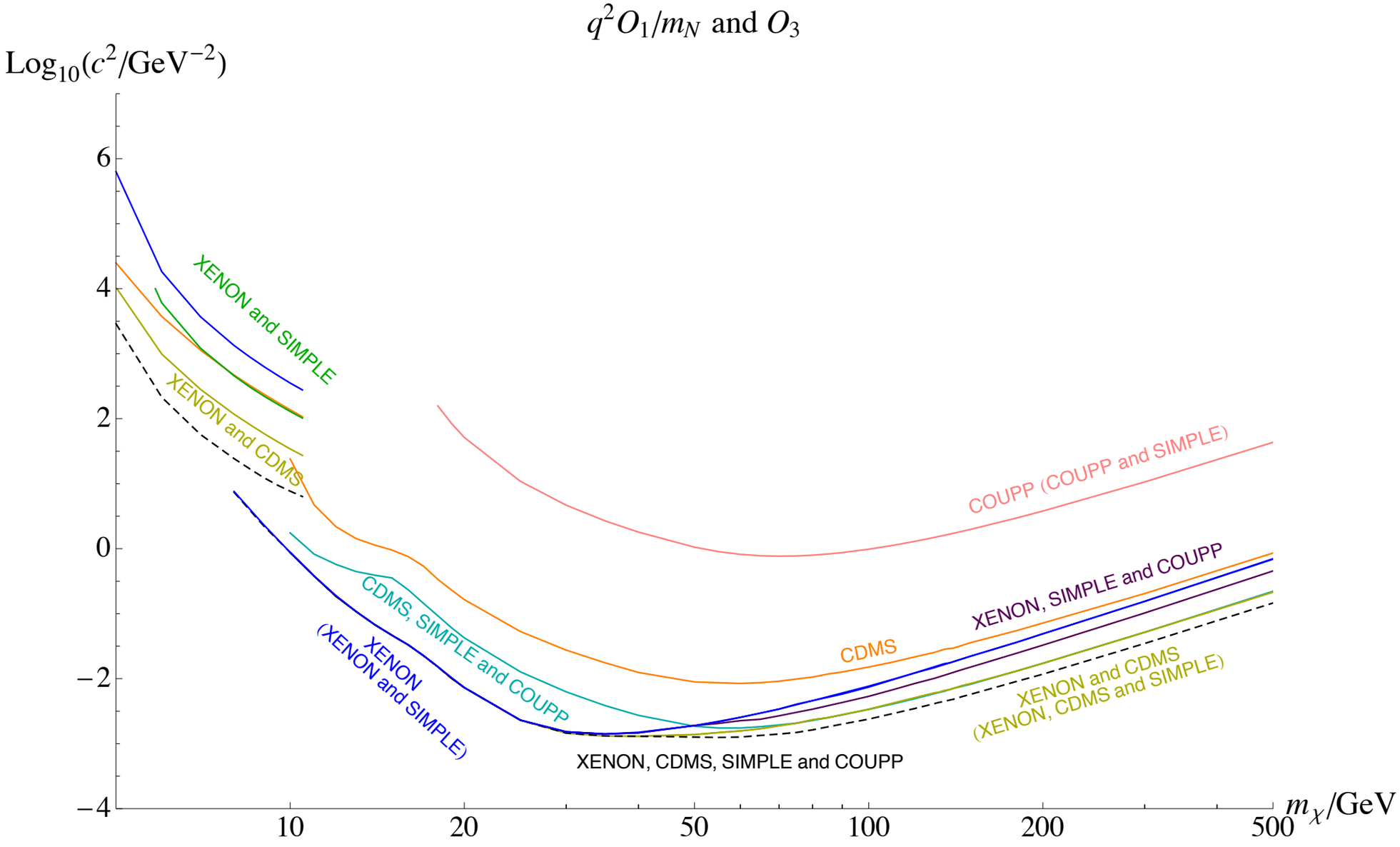
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

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

$$\bar{\chi}\gamma^\mu\gamma^5\chi K_\mu \bar{N}N \rightarrow 16 m_N^2 m_\chi \mathcal{O}_8$$

$$\bar{\chi}\gamma^\mu\gamma^5\chi \bar{N} i\sigma_{\mu\alpha}q^\alpha N \rightarrow 16 m_\chi m_N \mathcal{O}_9$$

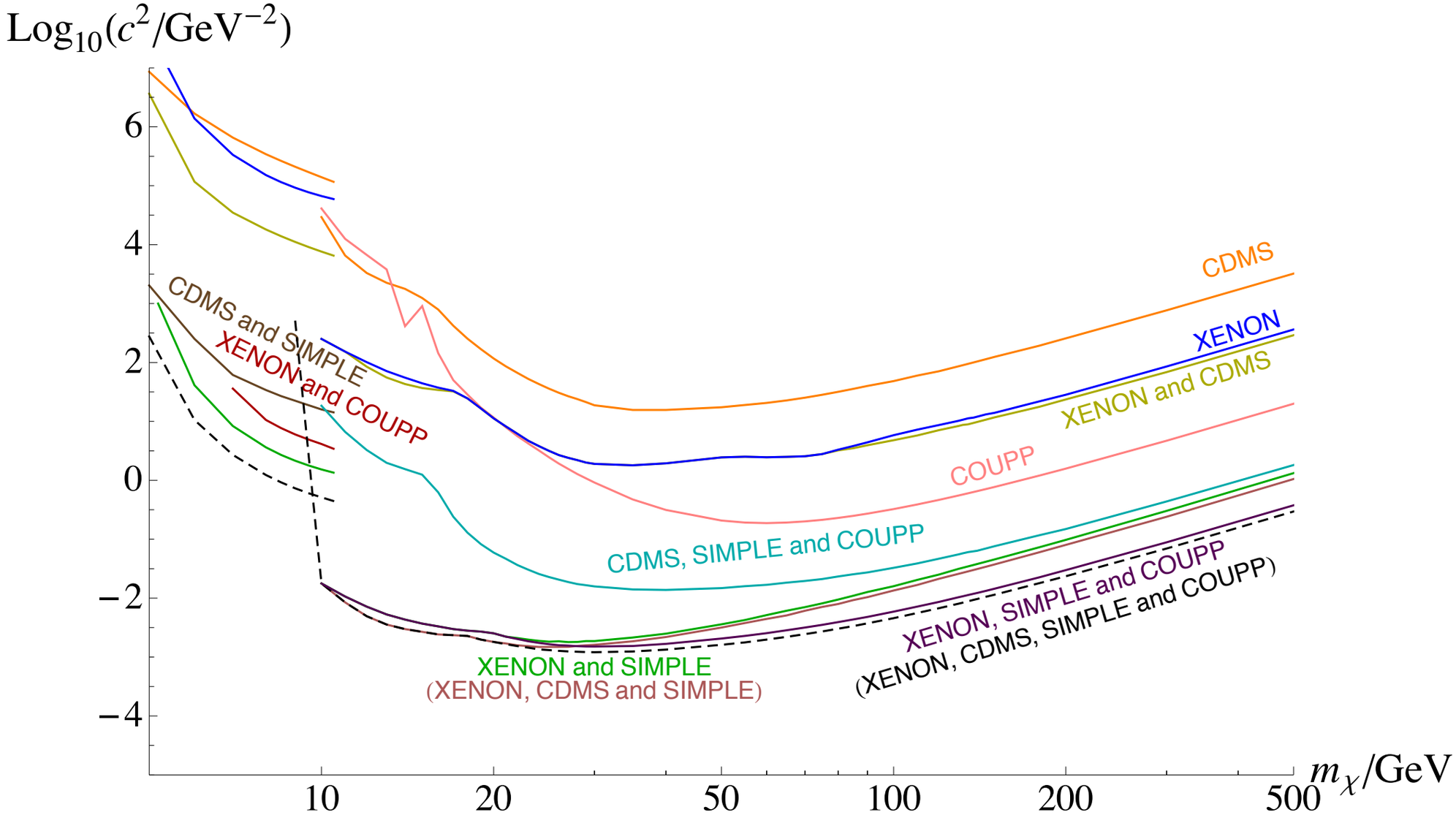
Are direct detections complementary in probing new operators



SI operator and $\left(\vec{L}\cdot\vec{S}\right)_N$

Are direct detections complementary in probing new operators

$m_N O_8$ and O_9



$\vec{L}_N$ and $\vec{S}_N$

Conclusions

- An EFT of DM direct detections
- New non-relativistic interaction $(\vec{L}\cdot\vec{S})_N$
- Release of constraint coming from interference in $(1, (\vec{L}\cdot\vec{S})_N)$ sector
- Nuclear targets have orthogonal sensitivity.

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Thanks!