Investigating the general dark matter-bound-electron interactions in effective field theories

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arXiv: 2405. 04855, arXiv: 2406.10912

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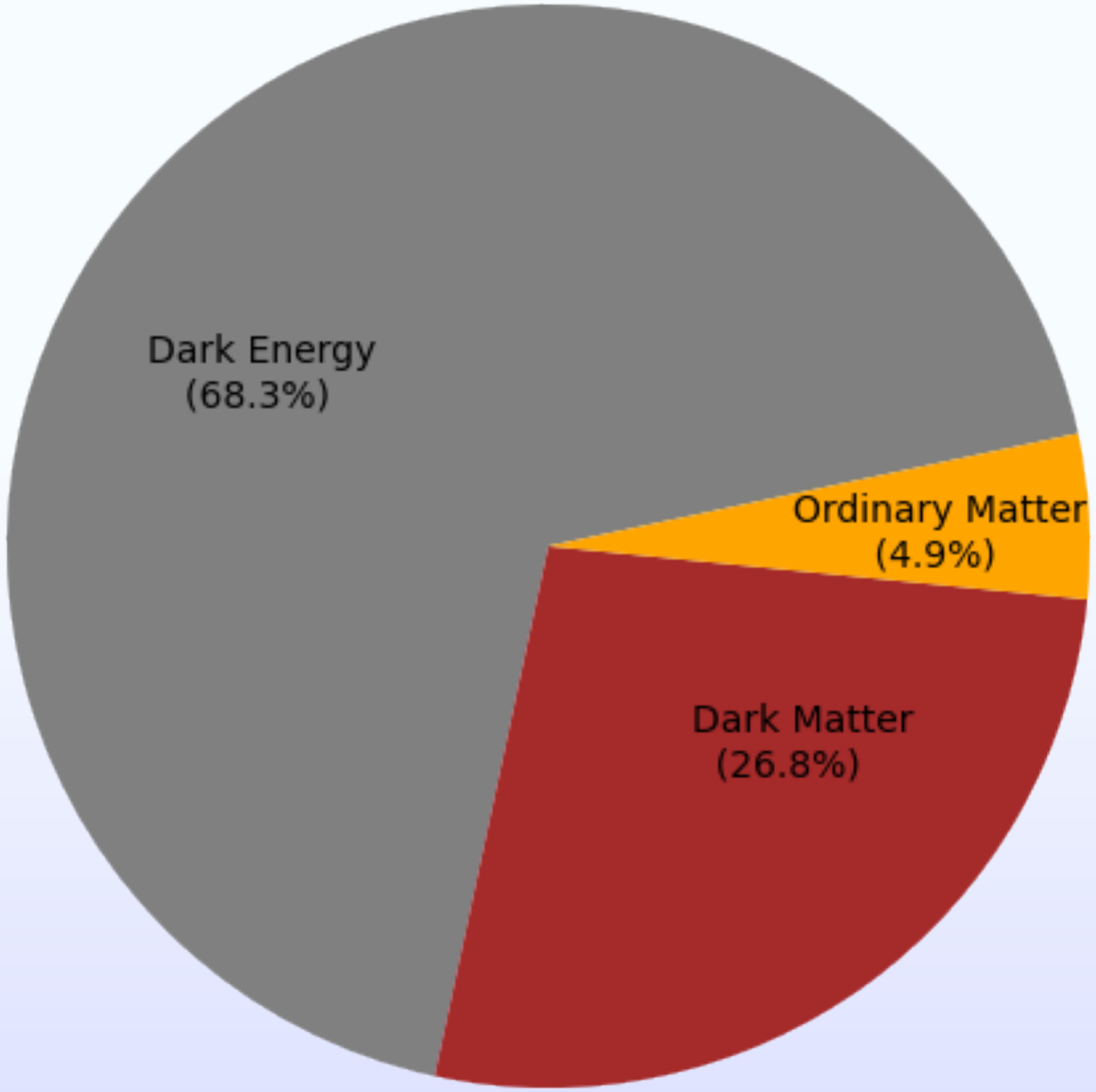
Evidence of the DM



- Galaxy rotation curves
- Gravitational lensing
- Bullet Cluster
- CMB power spectrum
- Structure formation
- N-body simulation
- ...

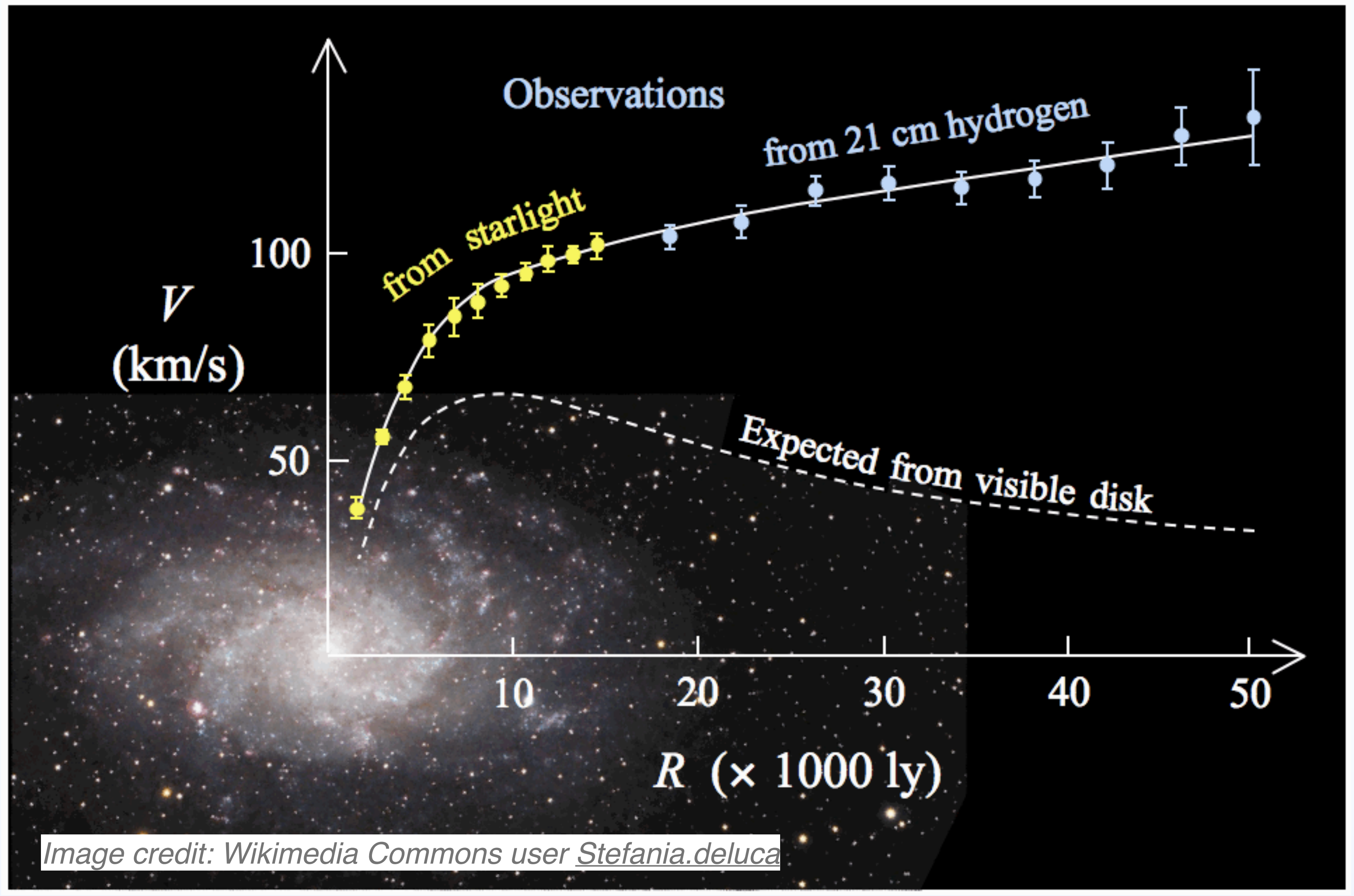


Image credit: Wikimedia Commons user Stefania.deluca

https://en.wikipedia.org/wiki/Dark_matter

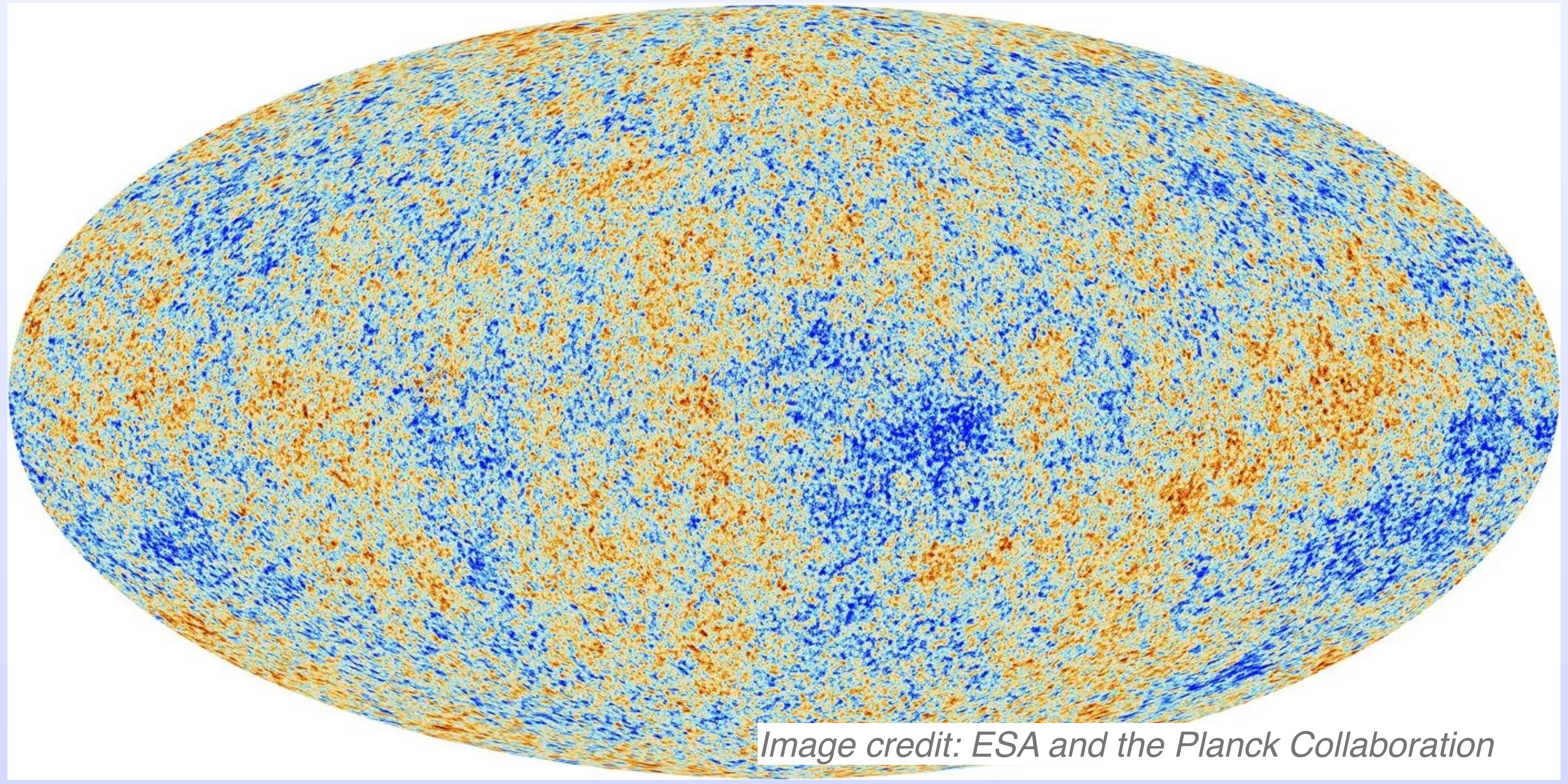
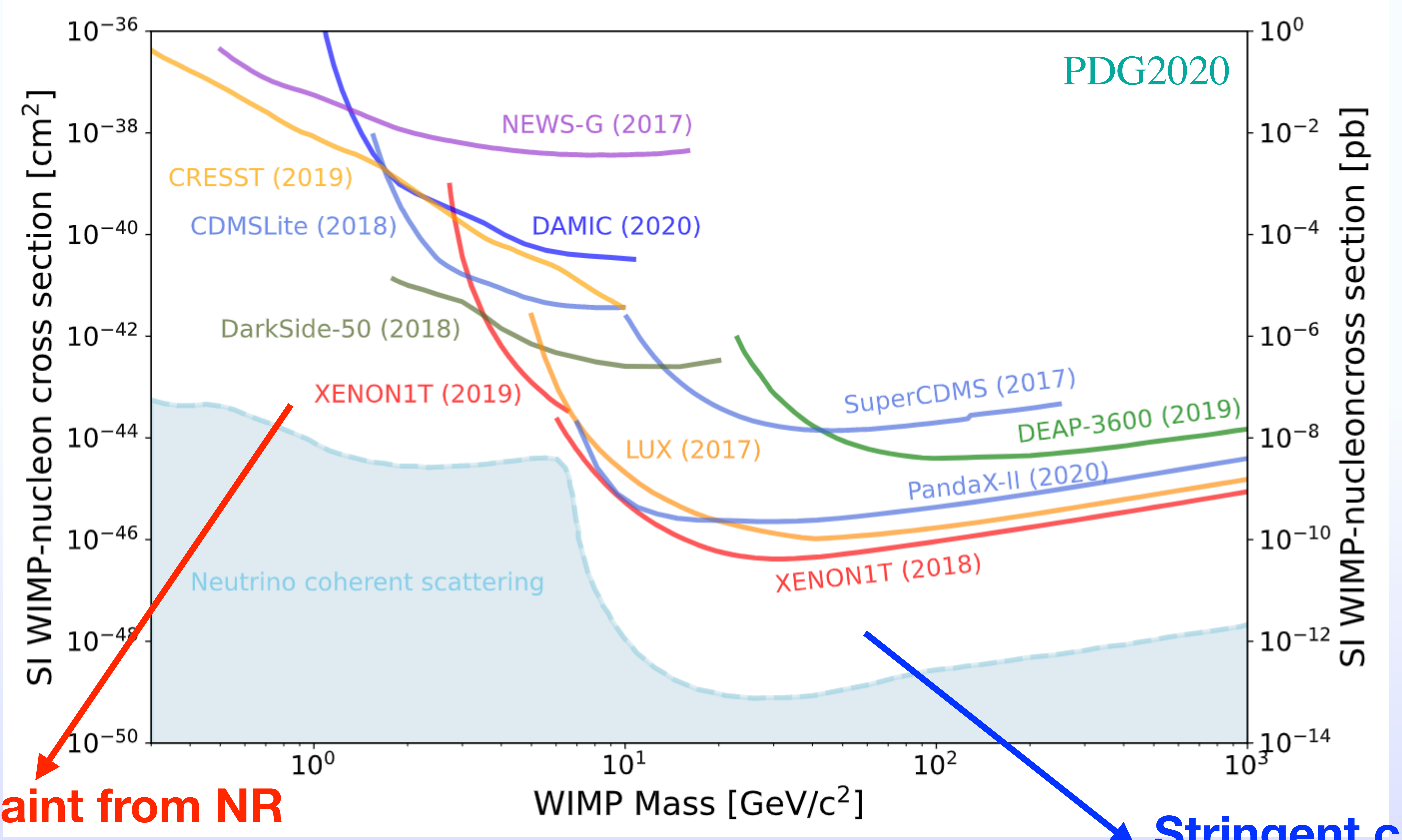


Image credit: ESA and the Planck Collaboration

Current constraints on DM-nucleon interaction



Weak constraint from NR

Stringent constraint

But can be probed through electron recoil via DM-electron interaction

Outline

- General DM-atom scattering formalism
- DM-electron interactions in the EFTs
- Constraints on non-relativistic and relativistic interactions
- Summary

DM-atom scattering

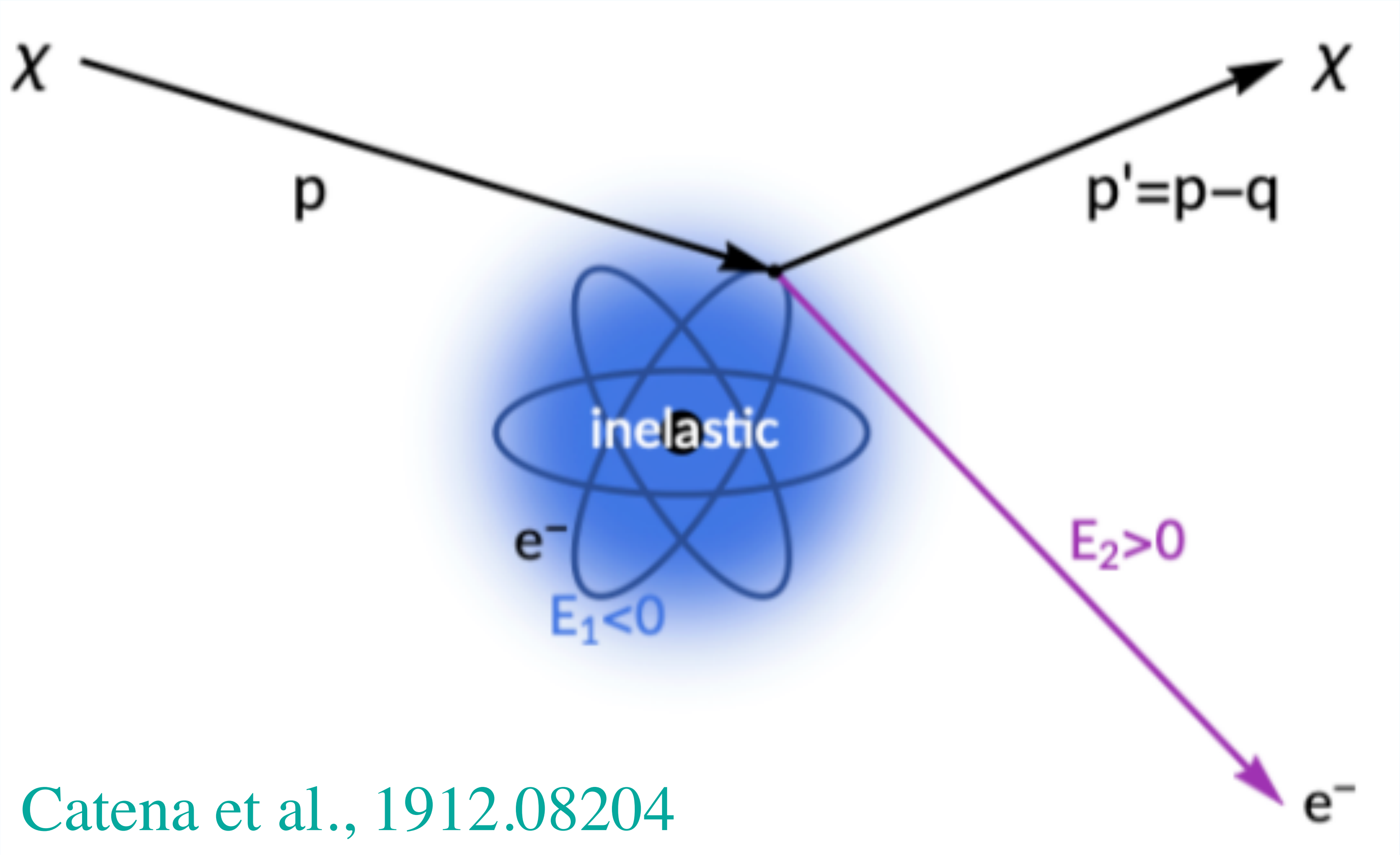
$$\text{DM} \quad + \quad (n,\ell,m) \equiv |1\rangle \quad \rightarrow \quad \text{DM} \quad + \quad (k',\ell',m') \equiv |2\rangle$$

$$\frac{\mathrm{d}\mathscr{R}^{n\ell}_{\text{ion}}}{\mathrm{d}\ln E_e} = \frac{n_x}{128\pi m_x^2 m_e^2}\int \mathrm{d}q\, q \int \frac{\mathrm{d}^3\mathbf{v}}{v} f_x(\mathbf{v})\Theta(v - v_{\text{min}})\,\overline{\left|\mathscr{M}^{n\ell}_{\text{ion}}\right|^2}$$

Momentum transfer

Velocity distribution

Key input



Catena et al., 1912.08204

Summing over all final atomic states

Free electron-DM amplitude

$$\overline{\left|\mathscr{M}^{n\ell}_{\text{ion}}\right|^2} \equiv \frac{4Vk'^3}{(2\pi)^3}\sum_{m=-\ell}^{\ell}\boxed{\sum_{\ell'=0}^{\infty}\sum_{m'=-\ell'}^{\ell'}}\overline{\left|\mathscr{M}_{1\to2}\right|^2}$$

$$\mathscr{M}_{1\to2} = \int\frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}\tilde{\psi}_2^*(\mathbf{k}+\mathbf{q})\mathscr{M}(\mathbf{q},\mathbf{v}_{\text{el}}^{\perp})\tilde{\psi}_1(\mathbf{k})$$

Bound electron-DM amplitude

Atomic wave-functions

A. Dedes I. Giomataris, K. Suxho, J.D. Vergados, 0907.0758

J. Kopp, V. Niro, T. Schwetz, J. Zupan, 0907.3159

R. Essig, J. Mardon, T. Volansky, 1108.5383,

R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky, 1206.2644

The usual case

— Dark photon model, SI and SD interactions, etc

A. Dedes I. Giomataris, K. Suxho, J.D. Vergados, 0907.0758
J. Kopp, V. Niro, T. Schwetz, J. Zupan, 0907.3159
R. Essig, J. Mardon, T. Volansky, 1108.5383,
R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky, 1206.2644

$$\mathscr{M}(\mathbf{q}, \mathbf{v}_{\mathrm{el}}^{\perp}) \to \mathscr{M}(\mathbf{q})$$

$$\Big\downarrow$$

$$\mathscr{M}_{1\to 2} = \mathscr{M}(q = \alpha m_e)\, F_{\mathrm{DM}}(q) f_{1\to 2}(\mathbf{q})$$

$$\Big\downarrow$$

$$\frac{d\mathscr{R}_{\mathrm{ion}}^{n\ell}}{d \ln E_e} = \frac{n_\chi \bar{\sigma}_e}{8\mu_{\chi e}} \times \int q \mathrm{d}q\, \eta(v_{\mathrm{min}})\, |f_{\mathrm{ion}}^{n\ell}(q)|^2\, |F_{\mathrm{DM}}(q)|^2$$

$$F_{\mathrm{DM}}(q) = \mathscr{M}(q)/\mathscr{M}(q = \alpha m_e)$$

$$f_{1\to 2}(\mathbf{q}) = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \tilde{\psi}_2^*(\mathbf{k} + \mathbf{q}) \tilde{\psi}_1(\mathbf{k}),$$

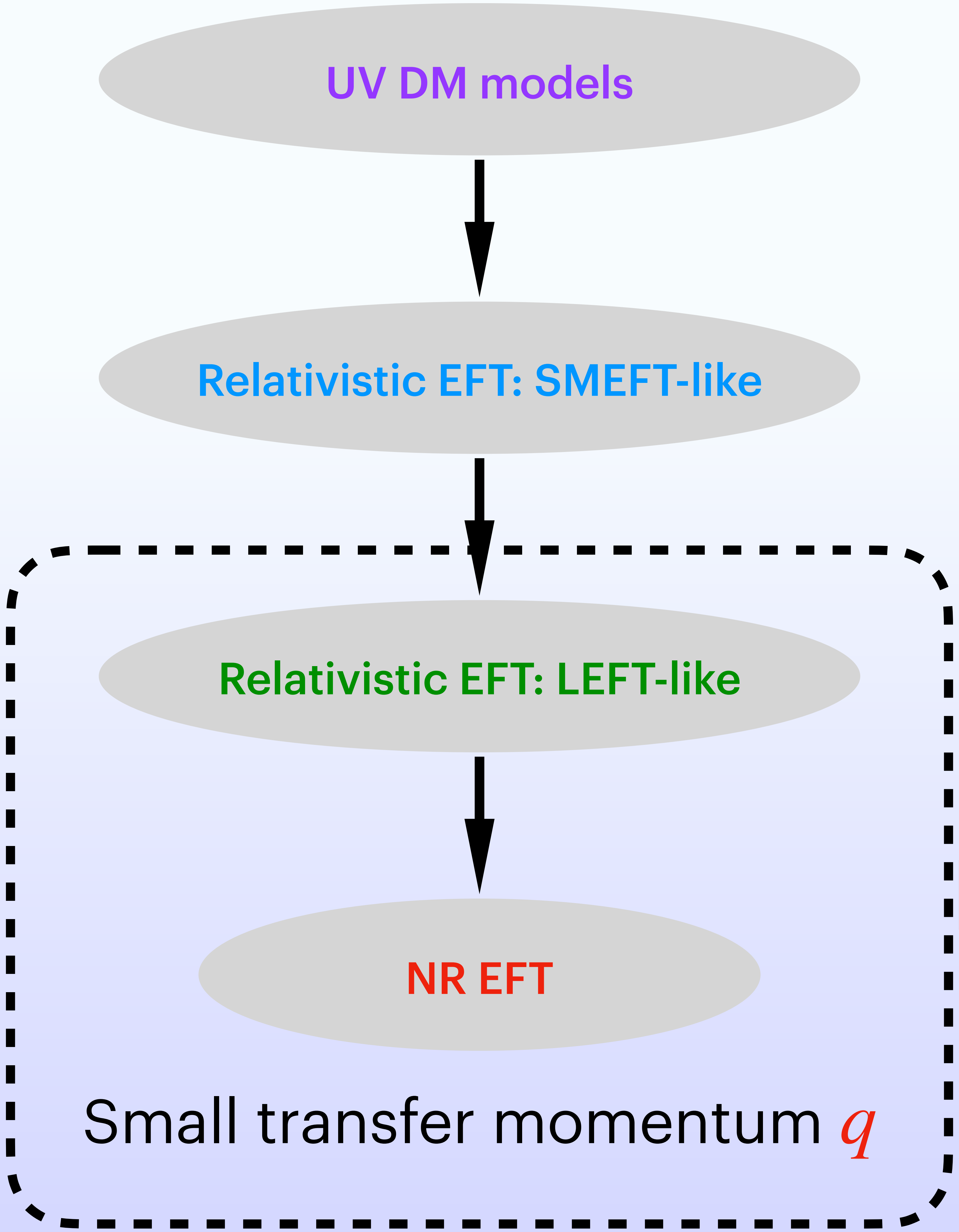
$$|f_{\mathrm{ion}}^{n\ell}(q)|^2 \propto \sum_{l'm'm} |f_{1\to 2}(\mathbf{q})|^2$$

$$\eta(v_{\mathrm{min}}) \equiv \int \mathrm{d}^3 \vec{v}\, f_\chi(\vec{v}) \frac{1}{v} \Theta(v - v_{\mathrm{min}})$$

- **Only one atomic response function (or K-factor) is used to describe the atom effect**
- **The velocity dependence can be integrated out**

How about the general case ?

To be as general as possible, we focus on the EFT approach



Small transfer momentum q

DM direct detection

NR operators

- Small momentum transfer q

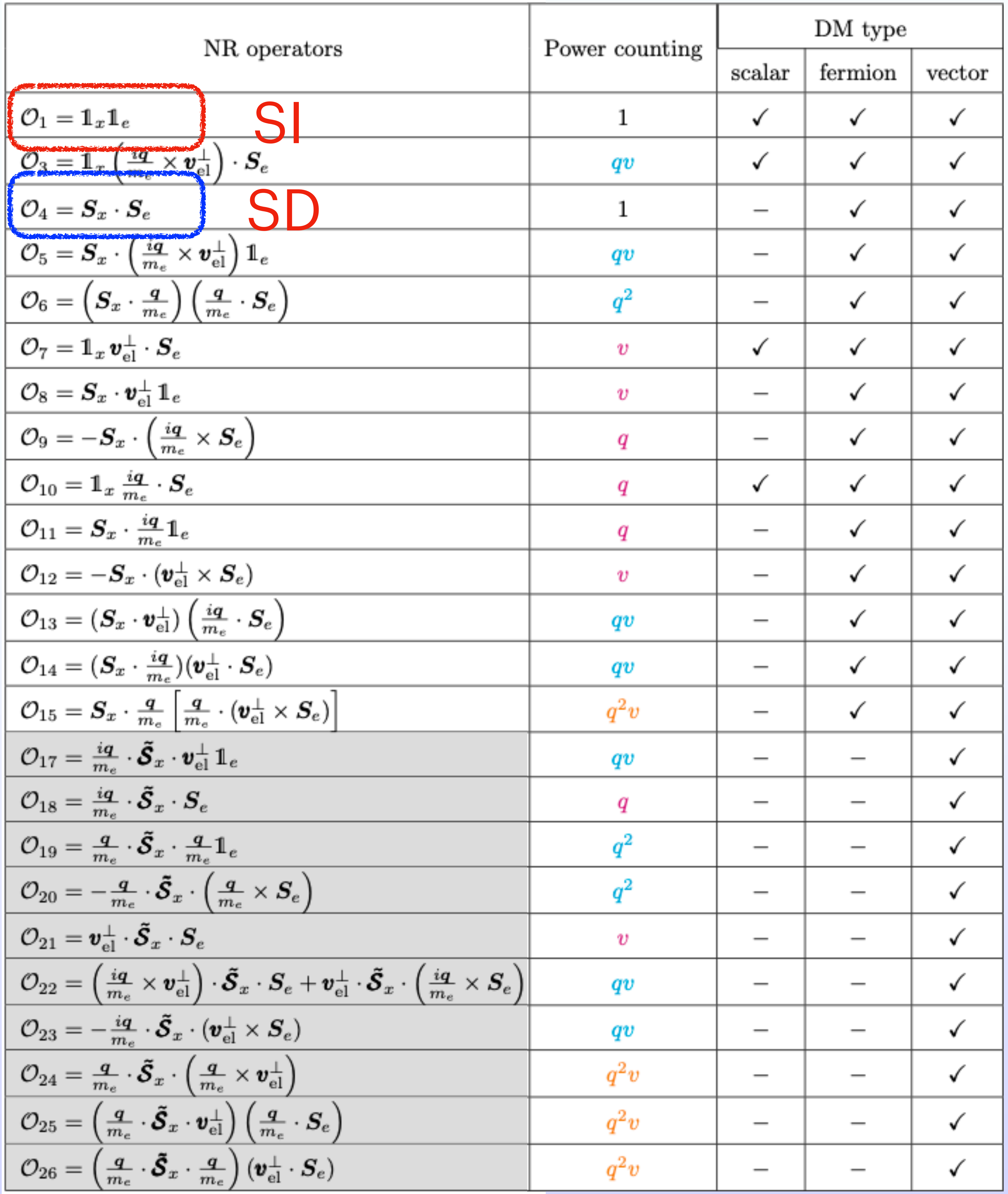
- Rotational and Galilean invariance:

$$\{\mathbb{1}_e, \boldsymbol{S}_e\} \otimes \{\mathbb{1}_x, \boldsymbol{S}_x, \tilde{\boldsymbol{S}}_x\} \otimes \{i\boldsymbol{q}, \boldsymbol{v}_{\rm el}^{\perp}\}$$

- Works well for the DM-nucleus scattering

- Relativistic correction could be important for the DM-electron scattering

- J. Fan, M. Reece, L.-T. Wang, 1008.1591
- R. Catena, K. Fridell, M. B. Kraus, 1907.02910



NR operators	Power counting	DM type		
		scalar	fermion	vector
$\mathcal{O}_1 = \mathbb{1}_x \mathbb{1}_e$	1	✓	✓	✓
$\mathcal{O}_3 = \mathbb{1}_x \left(\frac{i\boldsymbol{q}}{m_e} \times \boldsymbol{v}_{\rm el}^{\perp}\right) \cdot \boldsymbol{S}_e$	qv	✓	✓	✓
$\mathcal{O}_4 = \boldsymbol{S}_x \cdot \boldsymbol{S}_e$	1	–	✓	✓
$\mathcal{O}_5 = \boldsymbol{S}_x \cdot \left(\frac{i\boldsymbol{q}}{m_e} \times \boldsymbol{v}_{\rm el}^{\perp}\right) \mathbb{1}_e$	qv	–	✓	✓
$\mathcal{O}_6 = \left(\boldsymbol{S}_x \cdot \frac{\boldsymbol{q}}{m_e}\right) \left(\frac{\boldsymbol{q}}{m_e} \cdot \boldsymbol{S}_e\right)$	q^2	–	✓	✓
$\mathcal{O}_7 = \mathbb{1}_x \boldsymbol{v}_{\rm el}^{\perp} \cdot \boldsymbol{S}_e$	v	✓	✓	✓
$\mathcal{O}_8 = \boldsymbol{S}_x \cdot \boldsymbol{v}_{\rm el}^{\perp} \mathbb{1}_e$	v	–	✓	✓
$\mathcal{O}_9 = -\boldsymbol{S}_x \cdot \left(\frac{i\boldsymbol{q}}{m_e} \times \boldsymbol{S}_e\right)$	q	–	✓	✓
$\mathcal{O}_{10} = \mathbb{1}_x \frac{i\boldsymbol{q}}{m_e} \cdot \boldsymbol{S}_e$	q	✓	✓	✓
$\mathcal{O}_{11} = \boldsymbol{S}_x \cdot \frac{i\boldsymbol{q}}{m_e} \mathbb{1}_e$	q	–	✓	✓
$\mathcal{O}_{12} = -\boldsymbol{S}_x \cdot (\boldsymbol{v}_{\rm el}^{\perp} \times \boldsymbol{S}_e)$	v	–	✓	✓
$\mathcal{O}_{13} = (\boldsymbol{S}_x \cdot \boldsymbol{v}_{\rm el}^{\perp}) \left(\frac{i\boldsymbol{q}}{m_e} \cdot \boldsymbol{S}_e\right)$	qv	–	✓	✓
$\mathcal{O}_{14} = (\boldsymbol{S}_x \cdot \frac{i\boldsymbol{q}}{m_e})(\boldsymbol{v}_{\rm el}^{\perp} \cdot \boldsymbol{S}_e)$	qv	–	✓	✓
$\mathcal{O}_{15} = \boldsymbol{S}_x \cdot \frac{\boldsymbol{q}}{m_e} \left[\frac{\boldsymbol{q}}{m_e} \cdot (\boldsymbol{v}_{\rm el}^{\perp} \times \boldsymbol{S}_e)\right]$	q^2v	–	✓	✓
$\mathcal{O}_{17} = \frac{i\boldsymbol{q}}{m_e} \cdot \tilde{\boldsymbol{S}}_x \cdot \boldsymbol{v}_{\rm el}^{\perp} \mathbb{1}_e$	qv	–	–	✓
$\mathcal{O}_{18} = \frac{i\boldsymbol{q}}{m_e} \cdot \tilde{\boldsymbol{S}}_x \cdot \boldsymbol{S}_e$	q	–	–	✓
$\mathcal{O}_{19} = \frac{\boldsymbol{q}}{m_e} \cdot \tilde{\boldsymbol{S}}_x \cdot \frac{\boldsymbol{q}}{m_e} \mathbb{1}_e$	q^2	–	–	✓
$\mathcal{O}_{20} = -\frac{\boldsymbol{q}}{m_e} \cdot \tilde{\boldsymbol{S}}_x \cdot \left(\frac{\boldsymbol{q}}{m_e} \times \boldsymbol{S}_e\right)$	q^2	–	–	✓
$\mathcal{O}_{21} = \boldsymbol{v}_{\rm el}^{\perp} \cdot \tilde{\boldsymbol{S}}_x \cdot \boldsymbol{S}_e$	v	–	–	✓
$\mathcal{O}_{22} = \left(\frac{i\boldsymbol{q}}{m_e} \times \boldsymbol{v}_{\rm el}^{\perp}\right) \cdot \tilde{\boldsymbol{S}}_x \cdot \boldsymbol{S}_e + \boldsymbol{v}_{\rm el}^{\perp} \cdot \tilde{\boldsymbol{S}}_x \cdot \left(\frac{i\boldsymbol{q}}{m_e} \times \boldsymbol{S}_e\right)$	qv	–	–	✓
$\mathcal{O}_{23} = -\frac{i\boldsymbol{q}}{m_e} \cdot \tilde{\boldsymbol{S}}_x \cdot (\boldsymbol{v}_{\rm el}^{\perp} \times \boldsymbol{S}_e)$	qv	–	–	✓
$\mathcal{O}_{24} = \frac{\boldsymbol{q}}{m_e} \cdot \tilde{\boldsymbol{S}}_x \cdot \left(\frac{\boldsymbol{q}}{m_e} \times \boldsymbol{v}_{\rm el}^{\perp}\right)$	q^2v	–	–	✓
$\mathcal{O}_{25} = \left(\frac{\boldsymbol{q}}{m_e} \cdot \tilde{\boldsymbol{S}}_x \cdot \boldsymbol{v}_{\rm el}^{\perp}\right) \left(\frac{\boldsymbol{q}}{m_e} \cdot \boldsymbol{S}_e\right)$	q^2v	–	–	✓
$\mathcal{O}_{26} = \left(\frac{\boldsymbol{q}}{m_e} \cdot \tilde{\boldsymbol{S}}_x \cdot \frac{\boldsymbol{q}}{m_e}\right) (\boldsymbol{v}_{\rm el}^{\perp} \cdot \boldsymbol{S}_e)$	q^2v	–	–	✓

Calculation of matrix element squared— method 1

Free electron case

Catena et al., Phys. Rev. Res. 2, 033195 (2020) (110+ citations)

$$\mathscr{M}(\mathbf{q}, \mathbf{v}_{\rm el}^{\perp}) = \mathscr{M}(\mathbf{q}, \mathbf{v}_{0}^{\perp}) + \mathbf{k} \cdot \nabla_{\mathbf{k}} \mathscr{M}(\mathbf{q}, \mathbf{v}_{\rm el}^{\perp})$$

$$\mathbf{v}_{\rm el}^{\perp} = \mathbf{v} - \mathbf{q}/(2\mu_{xe}) - \mathbf{k}/m_e$$

$$\mathbf{v}_{0}^{\perp} \equiv \mathbf{v} - \mathbf{q}/(2\mu_{xe})$$

Bound electron case

$$\mathscr{M}_{1\to 2} = f_{1\to 2}(\mathbf{q})\mathscr{M}(\mathbf{q}, \mathbf{v}_{0}^{\perp}) + \mathbf{f}_{1\to 2}(\mathbf{q}) \cdot \nabla_{\mathbf{k}} \mathscr{M}(\mathbf{q}, \mathbf{v}_{\rm el}^{\perp})$$

$$f_{1\to 2}(\mathbf{q}) = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \tilde{\psi}_2^*(\mathbf{k}+\mathbf{q})\tilde{\psi}_1(\mathbf{k})$$

$$\mathbf{f}_{1\to 2}(\mathbf{q}) = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \tilde{\psi}_2^*(\mathbf{k}+\mathbf{q})\frac{\mathbf{k}}{m_e}\tilde{\psi}_1(\mathbf{k})$$

A new vector form factor

$$\overline{\left|\mathscr{M}_{\rm ion}^{n\ell}\right|^2} = \sum_{i=1}^{4} R_i^{n\ell}(q, v) W_i^{n\ell}(k', q)$$

DM response functions

1 usual $|f_{\rm ion}^{n\ell}(q)|^2$ + 3 new atomic response functions

Catena et al., Phys. Rev. Res. 2, 033195 (2020)

- A crucial minus sign is missed from p-space to x-space

$$\mathbf{f}_{1\to 2}(\mathbf{q}) = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \tilde{\psi}_2^*(\mathbf{k}+\mathbf{q}) \frac{\mathbf{k}}{m_e} \tilde{\psi}_1(\mathbf{k}) \quad \rightarrow \quad \mathbf{f}_{1\to 2}(\mathbf{q}) = \int d^3\mathbf{r}\, \psi_2^*(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} \frac{-i\nabla}{m_e} \psi_1(\mathbf{r})$$

Will affect all operators containing $\mathbf{v}_{\mathrm{el}}^{\perp}$ and lead to almost an order of magnitude difference for the rate

- The DM response functions Rs also contain atomic information and the power counting is not obvious

Calculation of matrix element squared— our method

Free electron case

arXiv: 2405. 04855

$$\mathscr{M}(\mathbf{q}, \mathbf{v}_{\rm el}^{\perp}) = \mathscr{M}(\mathbf{q},0) + \mathbf{v}_{\rm el}^{\perp} \cdot \nabla_{\mathbf{v}_{\rm el}^{\perp}} \mathscr{M}(\mathbf{q}, \mathbf{v}_{\rm el}^{\perp})$$

Bound electron case

$$\mathscr{M}_{1\to2} = f_{\rm S}(\mathbf{q})\mathscr{M}_{\rm S} + \mathbf{f}_{\rm V}(\mathbf{q}) \cdot \mathbf{M}_{\rm V}$$

$$f_{\rm S}(\mathbf{q}) \equiv f_{1\to2}(\mathbf{q})$$

$$\mathbf{f}_{\rm V}(\mathbf{q}) \equiv \mathbf{v}_0^{\perp} f_{1\to2}(\mathbf{q}) - \mathbf{f}_{1\to2}(\mathbf{q})$$

$$\overline{|\mathscr{M}_{1\to2}|^2} = a_0|f_{\rm S}|^2 + a_1|\mathbf{f}_{\rm V}|^2 + \frac{a_2}{x_e}\left|\frac{\mathbf{q}}{m_e}\cdot\mathbf{f}_{\rm V}\right|^2 + \boxed{i\,a_3\frac{\mathbf{q}}{m_e}\cdot(\mathbf{f}_{\rm V}\times\mathbf{f}_{\rm V}^*) + 2\,\mathfrak{I}\left[a_4 f_{\rm S}\mathbf{f}_{\rm V}^*\cdot\frac{\mathbf{q}}{m_e}\right]}$$

Due to the property of atomic wave functions

$$\overline{\left|\mathscr{M}_{\rm ion}^{n\ell}\right|^2} \equiv \frac{4Vk'^3}{(2\pi)^3}\sum_{m=-\ell}^{\ell}\sum_{\ell'=0}^{\infty}\sum_{m'=-\ell'}^{\ell'}\overline{|\mathscr{M}_{1\to2}|^2} = a_0\widetilde{W}_0 + a_1\widetilde{W}_1 + a_2\widetilde{W}_2$$

The merit of our approach

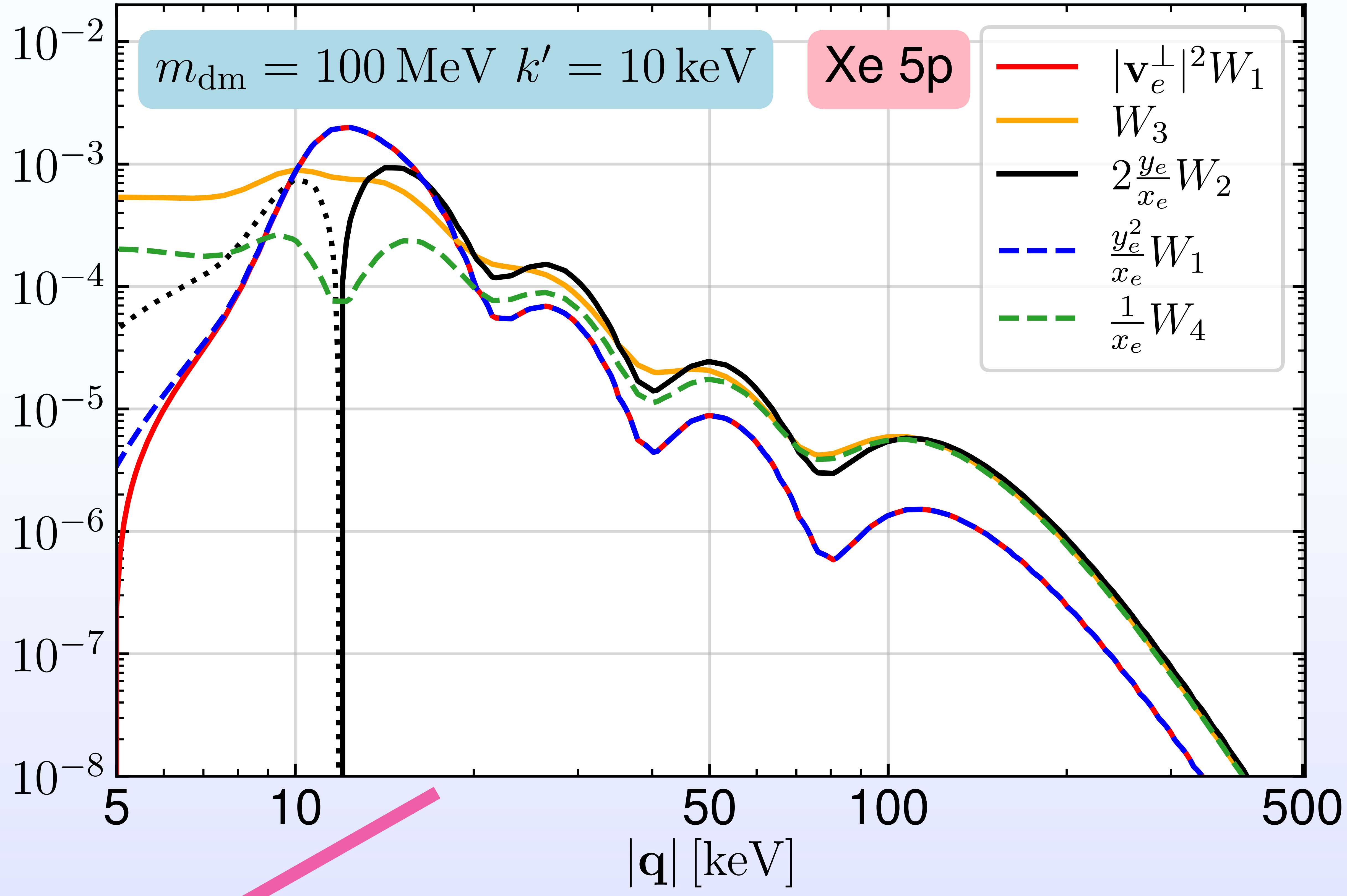
- Correctly incorporate the minus sign

- Only three atomic response functions

$$\widetilde{W}_0 = W_1$$

$$\widetilde{W}_1 = |\mathbf{v}_0^\perp|^2 W_1 - 2\frac{m_e \mathbf{q}\cdot\mathbf{v}_0^\perp}{\mathbf{q}^2} W_2 + W_3$$

$$\widetilde{W}_2 = \frac{(\mathbf{q}\cdot\mathbf{v}_0^\perp)^2}{\mathbf{q}^2} W_1 - 2\frac{m_e \mathbf{q}\cdot\mathbf{v}_0^\perp}{\mathbf{q}^2} W_2 + \frac{m_e^2}{\mathbf{q}^2} W_4$$



The minus sign leads to a strong cancellation among W_2 and $W_{3,4}$

DM response functions

$$\overline{\left|\mathcal{M}_{\text{ion}}^{n\ell}\right|}^{2} = a_0\widetilde{W}_0 + a_1\widetilde{W}_1 + a_2\widetilde{W}_2$$

- a_0 and $a_{1,2}$ involve different NR operators
- Clear power counting for q
- Do not contain any atomic properties

Type	DM response functions
Scalar DM	$a_0 = \underline{\lvert c_1\rvert^2} + \frac{1}{4}\lvert c_{10}\rvert^2 x_e$ $a_1 = \underline{\frac{1}{4}\lvert c_7\rvert^2} + \frac{1}{4}\lvert c_3\rvert^2 x_e$ $a_2 = -\frac{1}{4}\lvert c_3\rvert^2 x_e$
Fermion DM	$a_0 = \underline{\lvert c_1\rvert^2} + \underline{\frac{3}{16}\lvert c_4\rvert^2} + \left(\frac{1}{8}\lvert c_9\rvert^2 + \frac{1}{4}\lvert c_{10}\rvert^2 + \frac{1}{4}\lvert c_{11}\rvert^2 + \frac{1}{8}\Re[c_4 c_6^*]\right) x_e + \frac{1}{16}\lvert c_6\rvert^2 x_e^2$ $a_1 = \underline{\frac{1}{4}\lvert c_7\rvert^2} + \frac{1}{4}\lvert c_8\rvert^2 + \frac{1}{8}\lvert c_{12}\rvert^2 + \left(\frac{1}{4}\lvert c_3\rvert^2 + \frac{1}{4}\lvert c_5\rvert^2 + \frac{1}{16}\lvert c_{13}\rvert^2 + \frac{1}{16}\lvert c_{14}\rvert^2 - \frac{1}{8}\Re[c_{12} c_{15}^*]\right) x_e$ $+\frac{1}{16}\lvert c_{15}\rvert^2 x_e^2$ $a_2 = -\left(\frac{1}{4}\lvert c_3\rvert^2 + \frac{1}{4}\lvert c_5\rvert^2 - \frac{1}{8}\Re[c_{12} c_{15}^*] - \frac{1}{8}\Re[c_{13} c_{14}^*]\right) x_e - \frac{1}{16}\lvert c_{15}\rvert^2 x_e^2$
Vector DM	$a_0 = \underline{\lvert c_1\rvert^2} + \underline{\frac{1}{2}\lvert c_4\rvert^2} + \left(\frac{1}{3}\lvert c_9\rvert^2 + \frac{1}{4}\lvert c_{10}\rvert^2 + \frac{2}{3}\lvert c_{11}\rvert^2 + \frac{5}{36}\lvert c_{18}\rvert^2 + \frac{1}{3}\Re[c_4 c_6^*]\right) x_e$ $+ \left(\frac{1}{6}\lvert c_6\rvert^2 + \frac{2}{9}\lvert c_{19}\rvert^2 + \frac{1}{12}\lvert c_{20}\rvert^2\right) x_e^2$ $a_1 = \underline{\frac{1}{4}\lvert c_7\rvert^2} + \frac{2}{3}\lvert c_8\rvert^2 + \frac{1}{3}\lvert c_{12}\rvert^2 + \frac{5}{36}\lvert c_{21}\rvert^2 + \left(\frac{1}{4}\lvert c_3\rvert^2 + \frac{2}{3}\lvert c_5\rvert^2 + \frac{1}{6}\lvert c_{13}\rvert^2 + \frac{1}{6}\lvert c_{14}\rvert^2 + \frac{1}{6}\lvert c_{17}\rvert^2\right.$ $\left.+\frac{3}{8}\lvert c_{22}\rvert^2 + \frac{7}{72}\lvert c_{23}\rvert^2 - \frac{1}{3}\Re[c_{12} c_{15}^*] + \frac{1}{12}\Re[c_{21} c_{25}^*] - \frac{1}{18}\Re[c_{21} c_{26}^*] + \frac{1}{12}\Re[c_{22} c_{23}^*]\right) x_e$ $+ \left(\frac{1}{6}\lvert c_{15}\rvert^2 + \frac{1}{6}\lvert c_{24}\rvert^2 + \frac{1}{24}\lvert c_{25}\rvert^2 + \frac{1}{18}\lvert c_{26}\rvert^2\right) x_e^2$ $a_2 = -\left(\frac{1}{4}\lvert c_3\rvert^2 + \frac{2}{3}\lvert c_5\rvert^2 - \frac{1}{18}\lvert c_{17}\rvert^2 + \frac{7}{24}\lvert c_{22}\rvert^2 + \frac{1}{72}\lvert c_{23}\rvert^2 - \frac{1}{3}\Re[c_{12} c_{15}^*] - \frac{1}{3}\Re[c_{13} c_{14}^*]\right.$ $\left.-\frac{1}{36}\Re[c_{21} c_{25}^*] - \frac{1}{6}\Re[c_{21} c_{26}^*] + \frac{1}{4}\Re[c_{22} c_{23}^*]\right) x_e$ $- \left(\frac{1}{6}\lvert c_{15}\rvert^2 + \frac{1}{6}\lvert c_{24}\rvert^2 - \frac{1}{72}\lvert c_{25}\rvert^2 - \frac{1}{9}\Re[c_{25} c_{26}^*]\right) x_e^2$

- Usual SI and SD intereactions

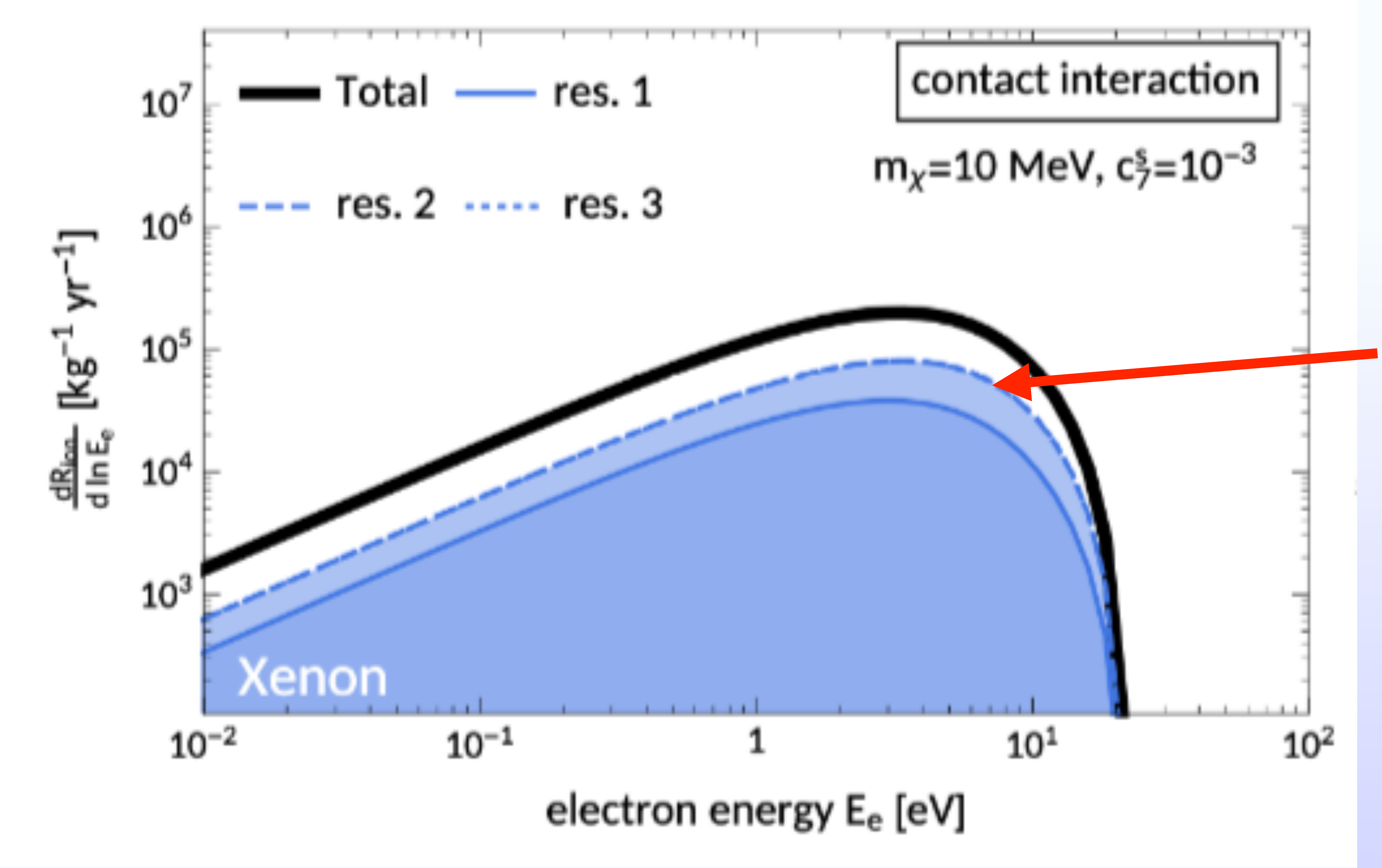
Only $W_1(\widetilde{W}_0)$ is enough

$$x_e = \frac{\mathbf{q}^2}{m_e^2}$$

Example: contributions from different response functions for $\mathcal{O}_7$

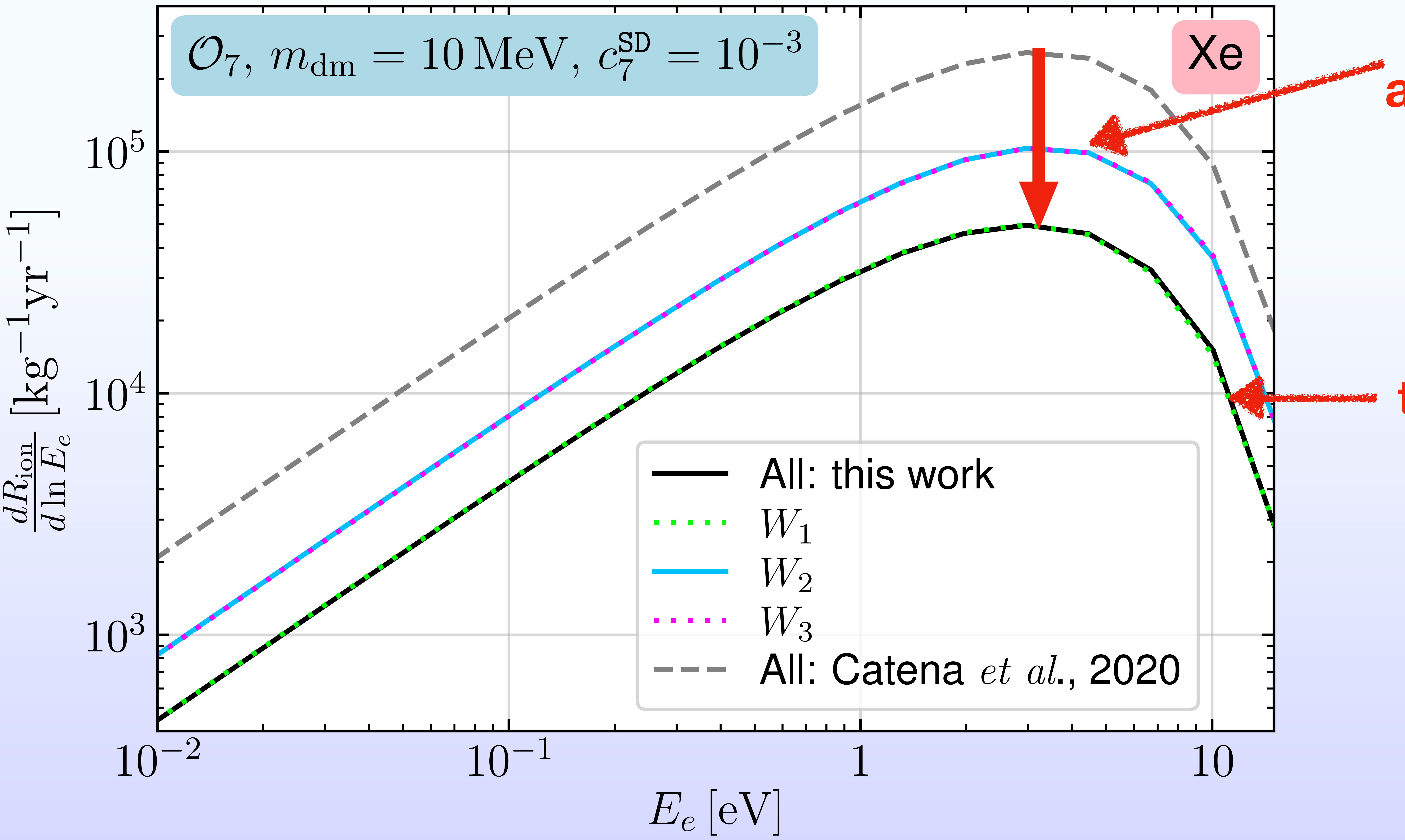
$$\mathcal{O}_7 = \mathbb{1}_x \, \boldsymbol{v}_{\rm el}^{\perp} \cdot \boldsymbol{S}_e$$

Catena et al., 1912.08204



Contributions from W_2 and W_3 dominate

Revisited event rate from $\mathcal{O}_7$

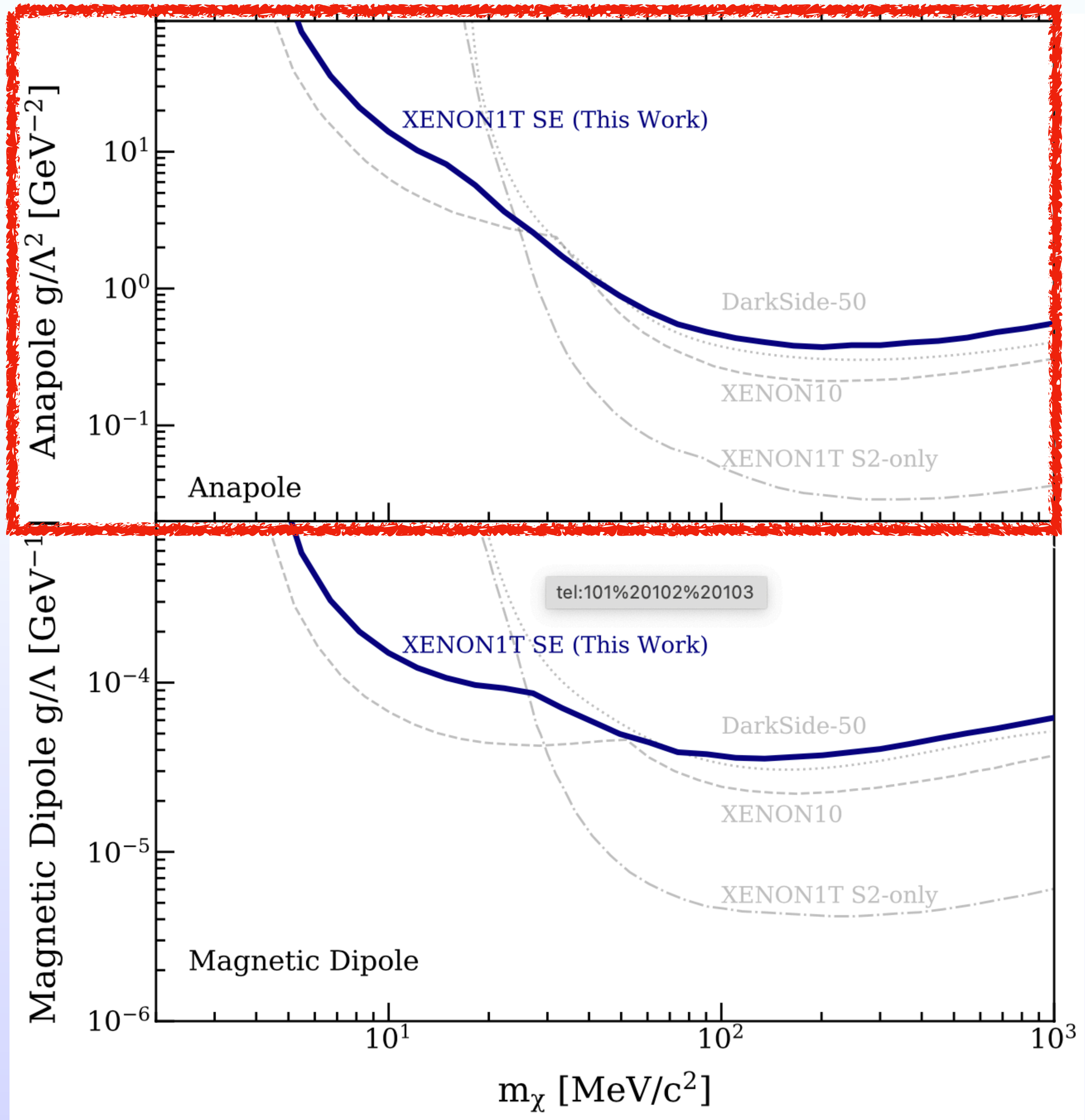


The event rate is weaken by about one order of magnitude

Constructive interference turns into strong cancellation between W_2 and W_3, leaving W_1 contribution dominant

XENON1T SE constraints on EM form factors of DM

XENON Collaboration, 2112.12116

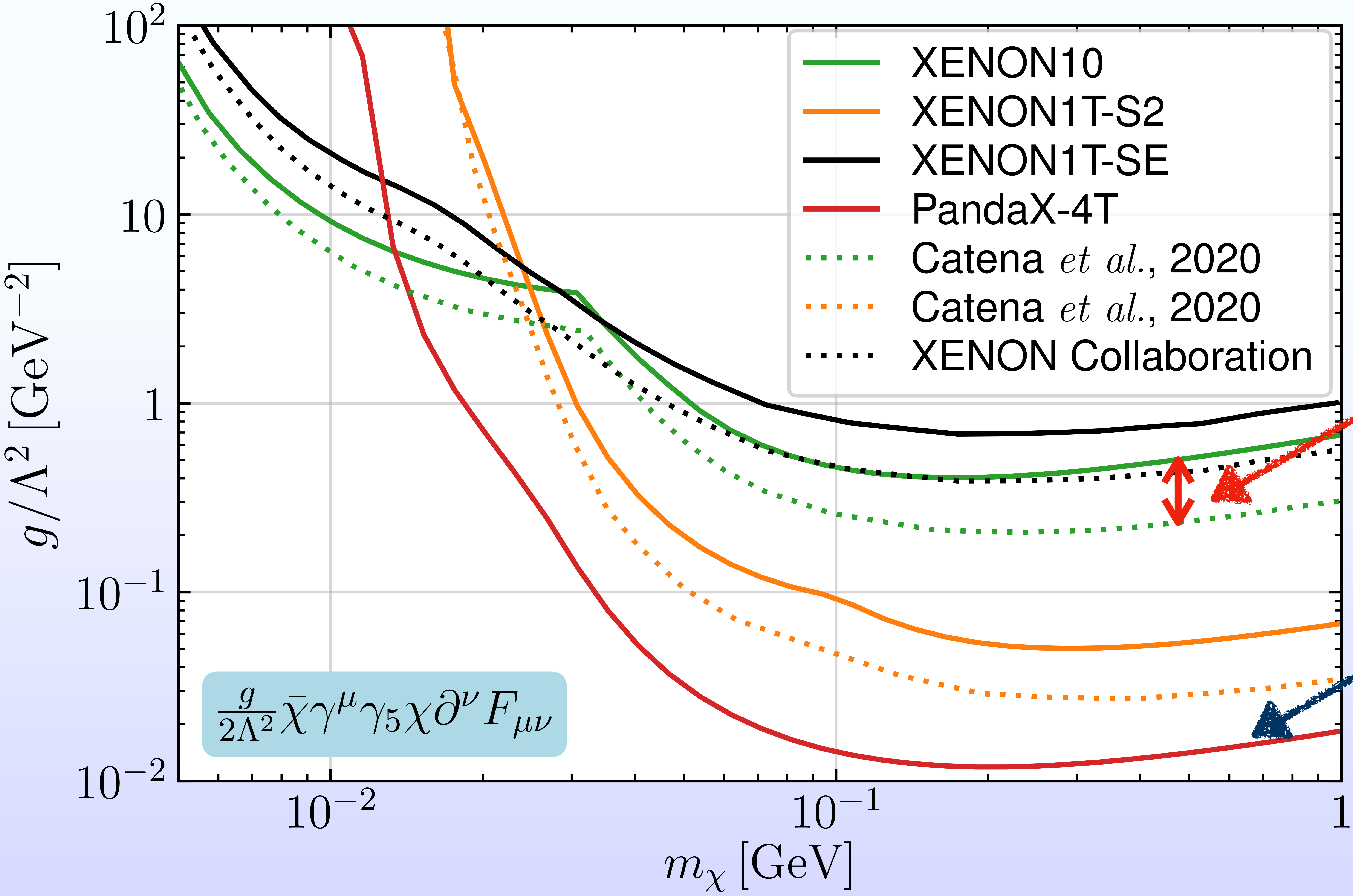


$$a_\chi(\bar{\chi}\gamma^\mu\gamma_5\chi)\partial^\nu F_{\mu\nu} \to 8a_\chi e\, m_\chi m_e \left(\mathcal{O}_8 - \mathcal{O}_9\right)$$

The constraint on the anapole operator greatly affected by the new atomic response functions

Revisited constraints on the anapole operator

$$a_\chi(\bar{\chi}\gamma^\mu\gamma_5\chi)\partial^\nu F_{\mu\nu} \rightarrow 8a_\chi e\, m_\chi m_e \left(\mathcal{O}_8 - \mathcal{O}_9\right)$$



The constraints are weakened by a factor of 2 if the sign of W_2 is corrected.

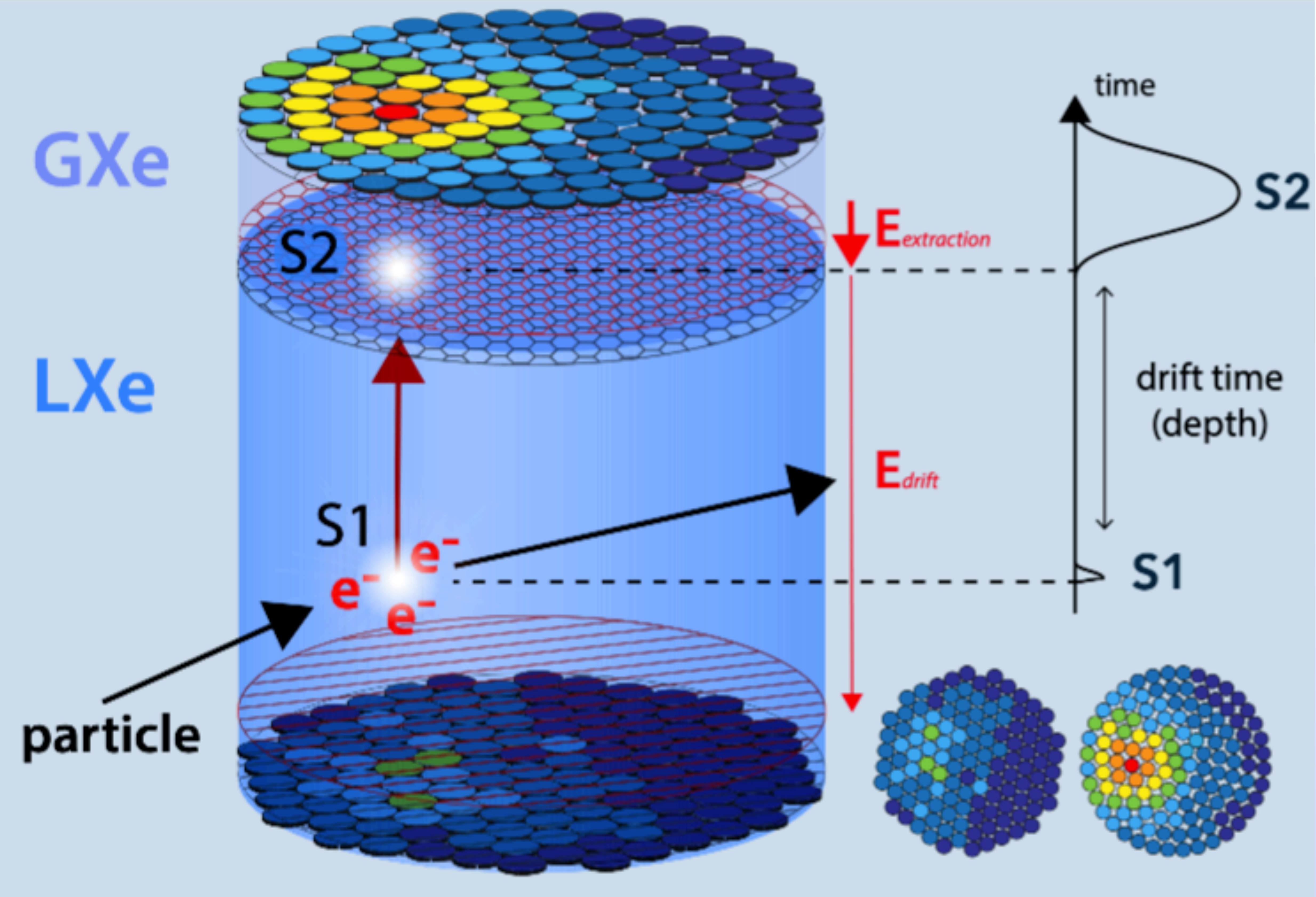
PandaX-4T set the most stringent constraint when $m_\chi \gtrsim 20$ MeV

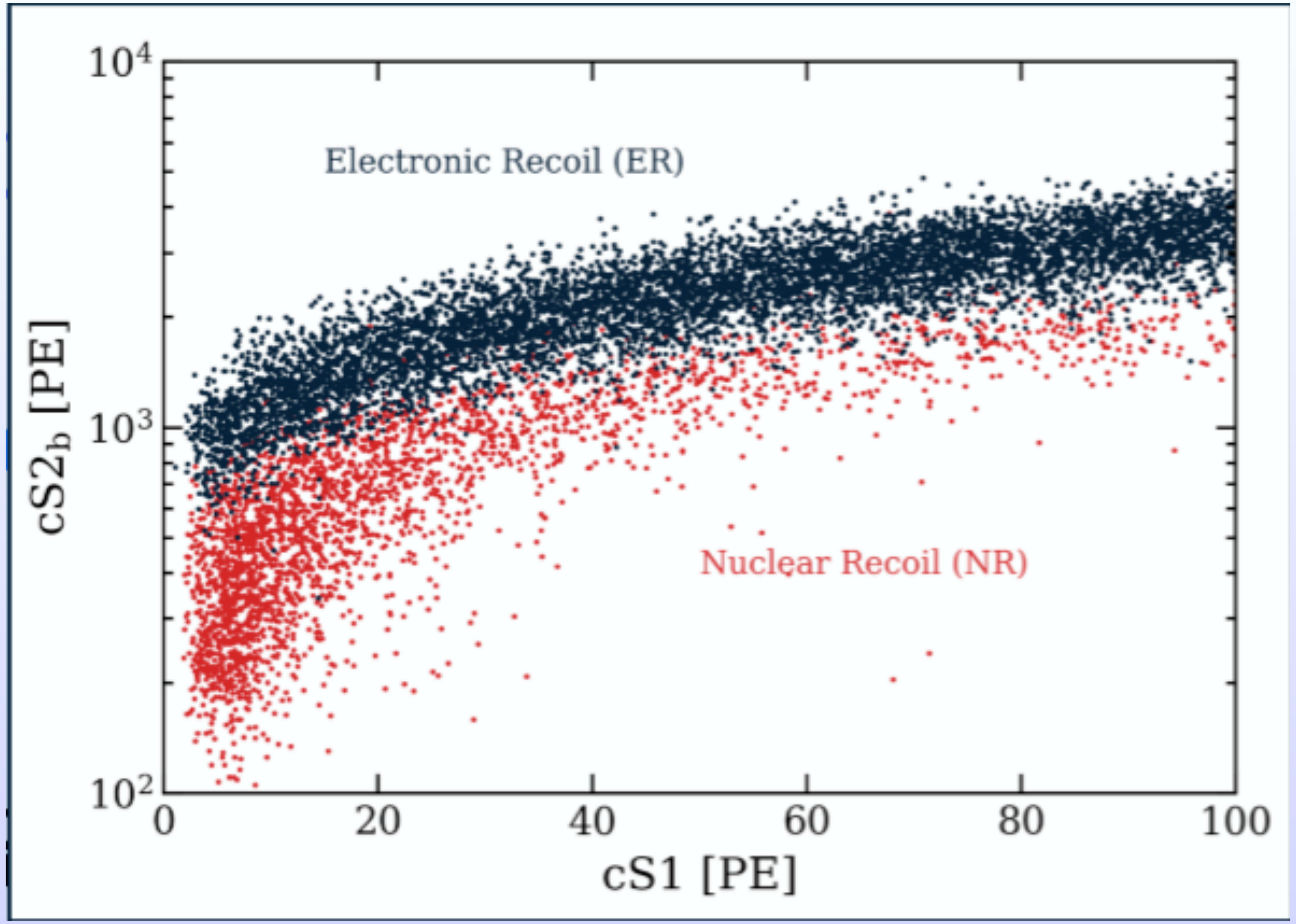
Constraints on non-relativistic interactions

$$\frac{\mathrm{d}N_s}{\mathrm{d}N_{\mathrm{PE}}} = \epsilon\,\omega\,\frac{1}{m_T}\sum_{n\,\ell}\sum_{n_e=1}^{\infty}\frac{\mathrm{d}\mathcal{R}_{\mathrm{ion}}^{n\ell}}{\mathrm{d}n_e}P(N_{\mathrm{PE}}|n_e)$$

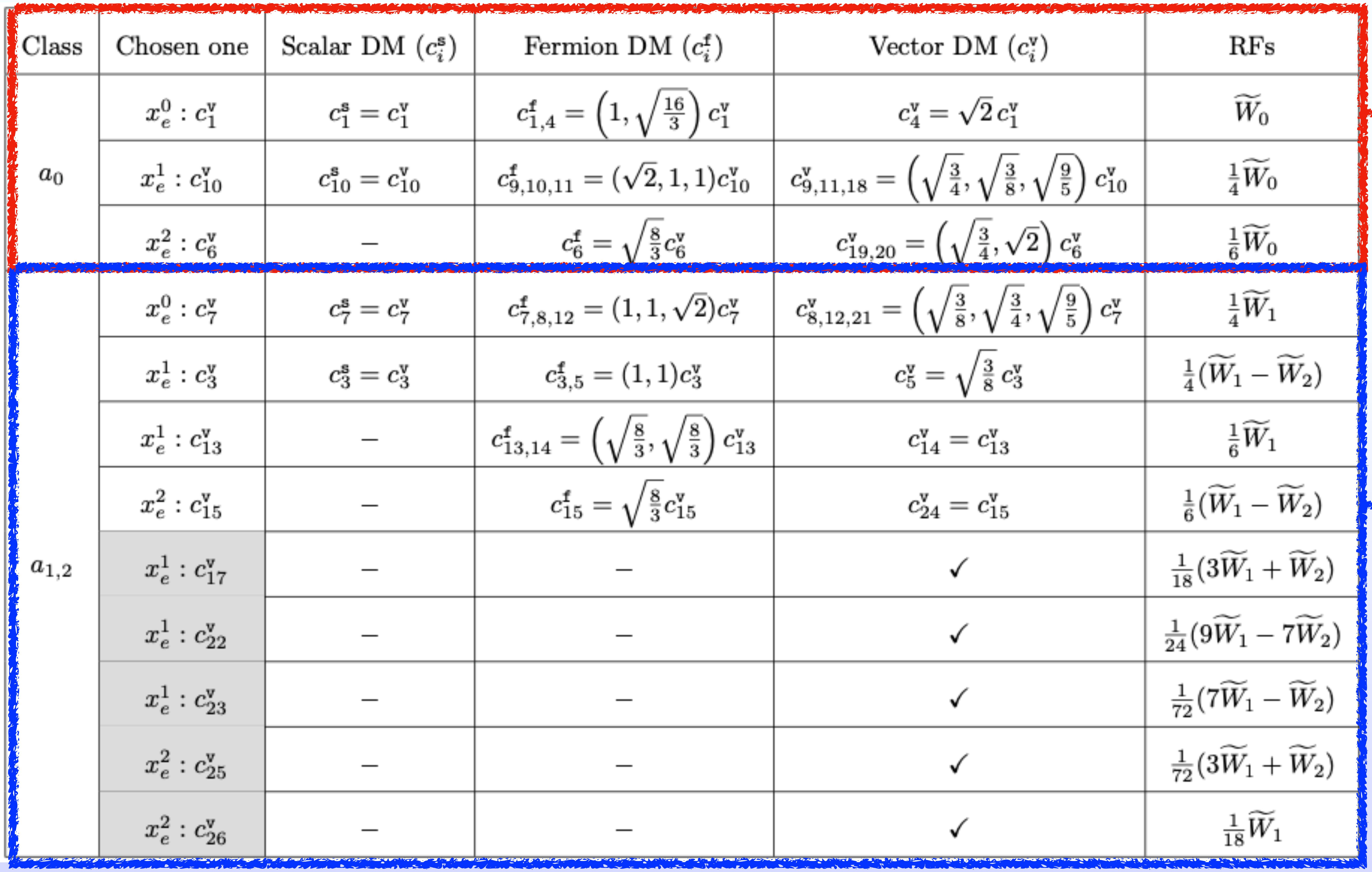
XENON10 collaboration, 1104.3088
XENON collaboration, 1907.11485]
PandaX collaboration , 2212.10067

Using S2-only data from xenon experiments, including XENON10, XENON1T, and PandaX-4T





12 independent constraints



Class	Chosen one	Scalar DM (c_i^s)	Fermion DM (c_i^f)	Vector DM (c_i^v)	RFs
a_0	$x_e^0 : c_1^v$	$c_1^s = c_1^v$	$c_{1,4}^f = \left(1, \sqrt{\frac{16}{3}}\right) c_1^v$	$c_4^v = \sqrt{2}\, c_1^v$	$\widetilde{W}_0$
	$x_e^1 : c_{10}^v$	$c_{10}^s = c_{10}^v$	$c_{9,10,11}^f = (\sqrt{2}, 1, 1) c_{10}^v$	$c_{9,11,18}^v = \left(\sqrt{\frac{3}{4}}, \sqrt{\frac{3}{8}}, \sqrt{\frac{9}{5}}\right) c_{10}^v$	$\frac{1}{4}\widetilde{W}_0$
	$x_e^2 : c_6^v$	–	$c_6^f = \sqrt{\frac{8}{3}} c_6^v$	$c_{19,20}^v = \left(\sqrt{\frac{3}{4}}, \sqrt{2}\right) c_6^v$	$\frac{1}{6}\widetilde{W}_0$
$a_{1,2}$	$x_e^0 : c_7^v$	$c_7^s = c_7^v$	$c_{7,8,12}^f = (1, 1, \sqrt{2}) c_7^v$	$c_{8,12,21}^v = \left(\sqrt{\frac{3}{8}}, \sqrt{\frac{3}{4}}, \sqrt{\frac{9}{5}}\right) c_7^v$	$\frac{1}{4}\widetilde{W}_1$
	$x_e^1 : c_3^v$	$c_3^s = c_3^v$	$c_{3,5}^f = (1, 1) c_3^v$	$c_5^v = \sqrt{\frac{3}{8}}\, c_3^v$	$\frac{1}{4}(\widetilde{W}_1 - \widetilde{W}_2)$
	$x_e^1 : c_{13}^v$	–	$c_{13,14}^f = \left(\sqrt{\frac{8}{3}}, \sqrt{\frac{8}{3}}\right) c_{13}^v$	$c_{14}^v = c_{13}^v$	$\frac{1}{6}\widetilde{W}_1$
	$x_e^2 : c_{15}^v$	–	$c_{15}^f = \sqrt{\frac{8}{3}} c_{15}^v$	$c_{24}^v = c_{15}^v$	$\frac{1}{6}(\widetilde{W}_1 - \widetilde{W}_2)$
	$x_e^1 : c_{17}^v$	–	–	✓	$\frac{1}{18}(3\widetilde{W}_1 + \widetilde{W}_2)$
	$x_e^1 : c_{22}^v$	–	–	✓	$\frac{1}{24}(9\widetilde{W}_1 - 7\widetilde{W}_2)$
	$x_e^1 : c_{23}^v$	–	–	✓	$\frac{1}{72}(7\widetilde{W}_1 - \widetilde{W}_2)$
	$x_e^2 : c_{25}^v$	–	–	✓	$\frac{1}{72}(3\widetilde{W}_1 + \widetilde{W}_2)$
	$x_e^2 : c_{26}^v$	–	–	✓	$\frac{1}{18}\widetilde{W}_1$

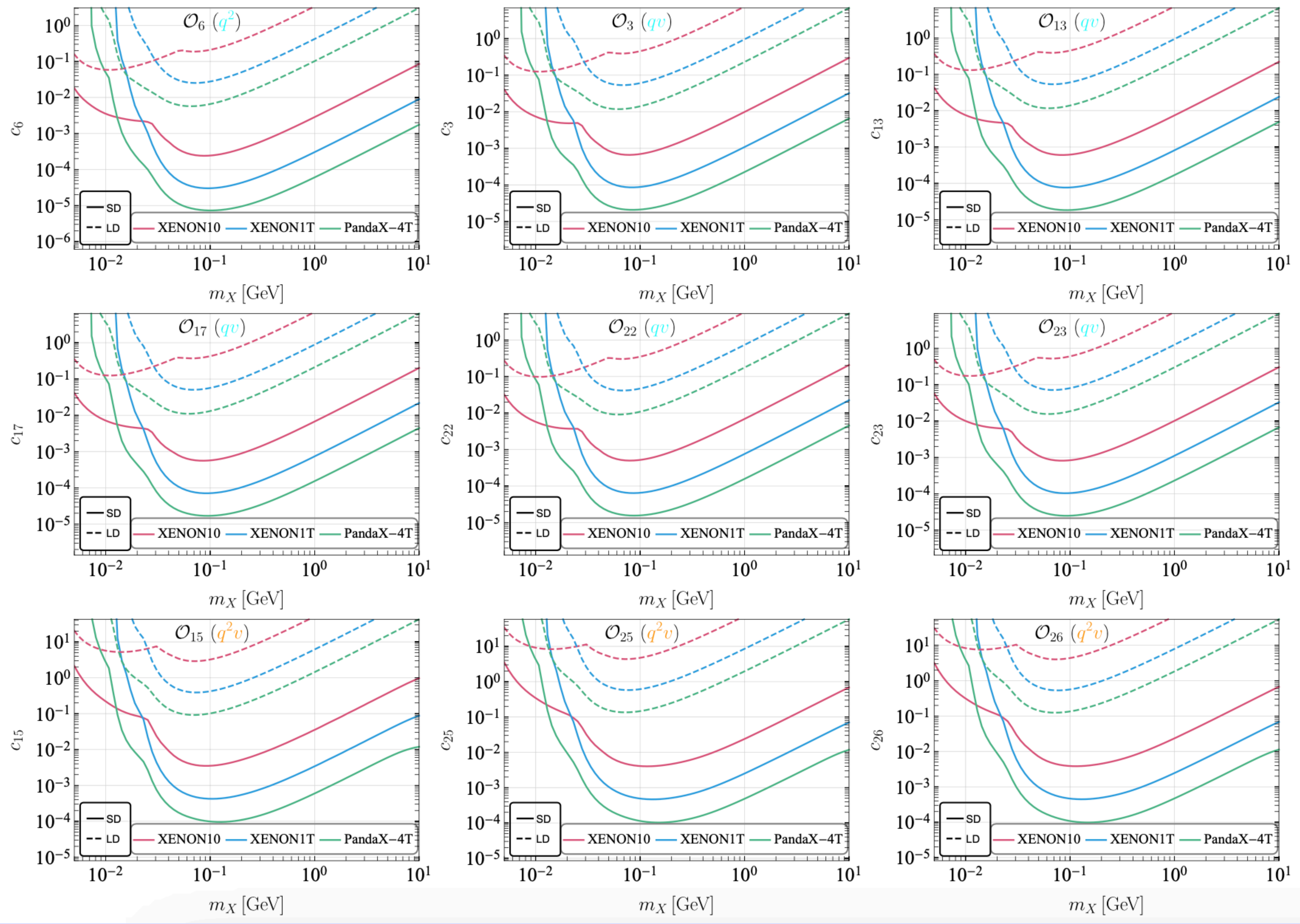
Velocity-independent

Velocity-dependent

Constraints on the NR operators

SD → LD : $c_i \to c_i(\alpha_{\text{em}} m_e)^2/\mathbf{q}^2$

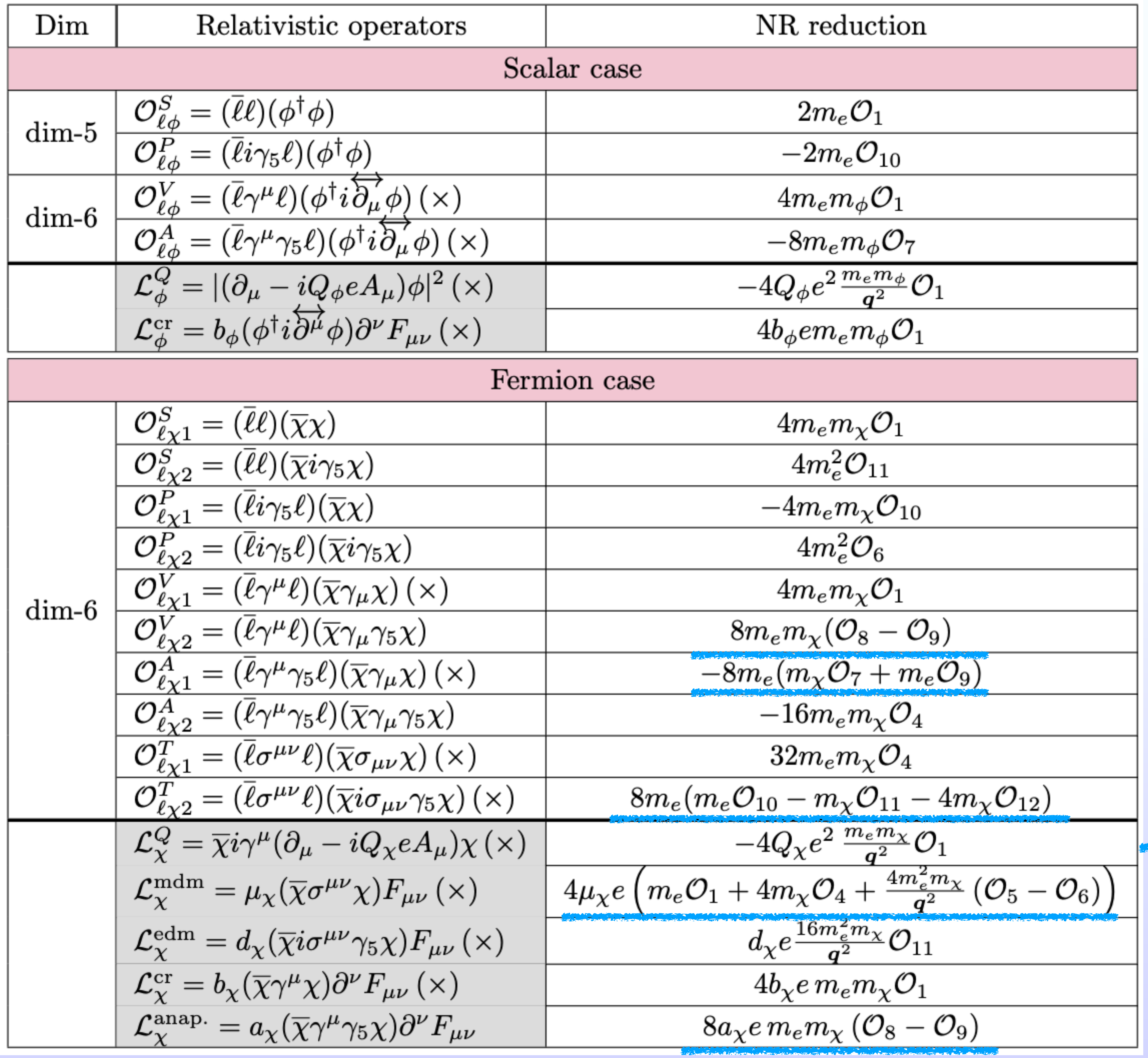
- **The constriants follows consistently with the power counting of q and/or v**
- **The suppression from v is comparable with that from q**
- $q/v \to \mathcal{O}(10^{-1})$



PandaX-4T sets the most stringent constraints when $m_X \gtrsim 20\ \mathrm{MeV}$

Constraints on the relativistic operators

Scalar and fermion DM cases



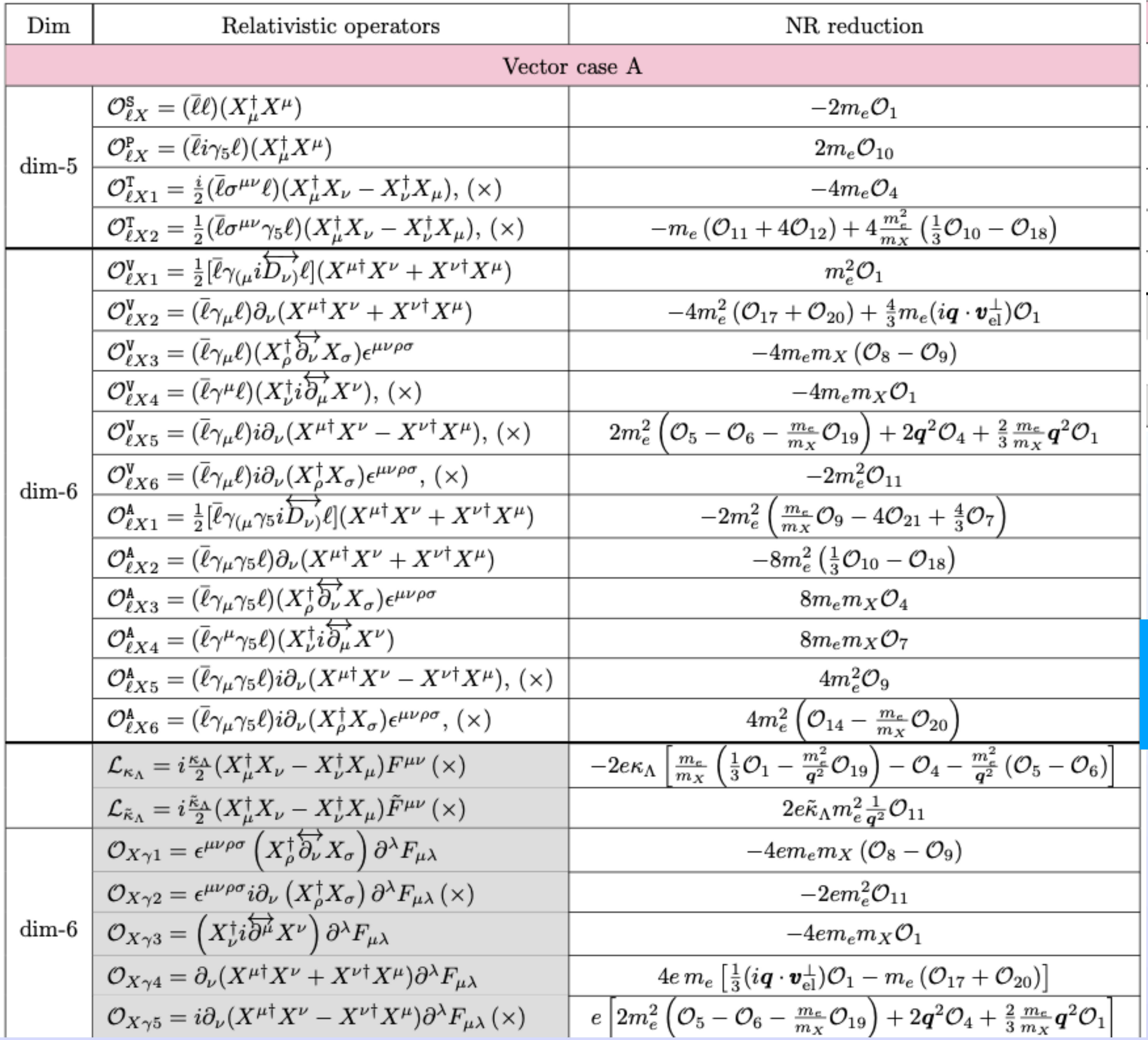
Dim	Relativistic operators	NR reduction
	Scalar case	
dim-5	$\mathcal{O}^S_{\ell\phi} = (\bar{\ell}\ell)(\phi^\dagger\phi)$	$2m_e\mathcal{O}_1$
	$\mathcal{O}^P_{\ell\phi} = (\bar{\ell}i\gamma_5\ell)(\phi^\dagger\phi)$	$-2m_e\mathcal{O}_{10}$
dim-6	$\mathcal{O}^V_{\ell\phi} = (\bar{\ell}\gamma^\mu\ell)(\phi^\dagger i\overleftrightarrow{\partial}_\mu\phi)\,(\times)$	$4m_e m_\phi\mathcal{O}_1$
	$\mathcal{O}^A_{\ell\phi} = (\bar{\ell}\gamma^\mu\gamma_5\ell)(\phi^\dagger i\overleftrightarrow{\partial}_\mu\phi)\,(\times)$	$-8m_e m_\phi\mathcal{O}_7$
	$\mathcal{L}^Q_\phi = \lvert(\partial_\mu - iQ_\phi eA_\mu)\phi\rvert^2\,(\times)$	$-4Q_\phi e^2\frac{m_e m_\phi}{\boldsymbol{q}^2}\mathcal{O}_1$
	$\mathcal{L}^{\rm cr}_\phi = b_\phi(\phi^\dagger i\overleftrightarrow{\partial}^\mu\phi)\partial^\nu F_{\mu\nu}\,(\times)$	$4b_\phi e m_e m_\phi\mathcal{O}_1$
	Fermion case	
dim-6	$\mathcal{O}^S_{\ell\chi1} = (\bar{\ell}\ell)(\overline{\chi}\chi)$	$4m_e m_\chi\mathcal{O}_1$
	$\mathcal{O}^S_{\ell\chi2} = (\bar{\ell}\ell)(\overline{\chi}i\gamma_5\chi)$	$4m_e^2\mathcal{O}_{11}$
	$\mathcal{O}^P_{\ell\chi1} = (\bar{\ell}i\gamma_5\ell)(\overline{\chi}\chi)$	$-4m_e m_\chi\mathcal{O}_{10}$
	$\mathcal{O}^P_{\ell\chi2} = (\bar{\ell}i\gamma_5\ell)(\overline{\chi}i\gamma_5\chi)$	$4m_e^2\mathcal{O}_6$
	$\mathcal{O}^V_{\ell\chi1} = (\bar{\ell}\gamma^\mu\ell)(\overline{\chi}\gamma_\mu\chi)\,(\times)$	$4m_e m_\chi\mathcal{O}_1$
	$\mathcal{O}^V_{\ell\chi2} = (\bar{\ell}\gamma^\mu\ell)(\overline{\chi}\gamma_\mu\gamma_5\chi)$	$\underline{8m_e m_\chi(\mathcal{O}_8 - \mathcal{O}_9)}$
	$\mathcal{O}^A_{\ell\chi1} = (\bar{\ell}\gamma^\mu\gamma_5\ell)(\overline{\chi}\gamma_\mu\chi)\,(\times)$	$\underline{-8m_e(m_\chi\mathcal{O}_7 + m_e\mathcal{O}_9)}$
	$\mathcal{O}^A_{\ell\chi2} = (\bar{\ell}\gamma^\mu\gamma_5\ell)(\overline{\chi}\gamma_\mu\gamma_5\chi)$	$-16m_e m_\chi\mathcal{O}_4$
	$\mathcal{O}^T_{\ell\chi1} = (\bar{\ell}\sigma^{\mu\nu}\ell)(\overline{\chi}\sigma_{\mu\nu}\chi)\,(\times)$	$32m_e m_\chi\mathcal{O}_4$
	$\mathcal{O}^T_{\ell\chi2} = (\bar{\ell}\sigma^{\mu\nu}\ell)(\overline{\chi}i\sigma_{\mu\nu}\gamma_5\chi)\,(\times)$	$\underline{8m_e(m_e\mathcal{O}_{10} - m_\chi\mathcal{O}_{11} - 4m_\chi\mathcal{O}_{12})}$
	$\mathcal{L}^Q_\chi = \overline{\chi}i\gamma^\mu(\partial_\mu - iQ_\chi eA_\mu)\chi\,(\times)$	$-4Q_\chi e^2\,\frac{m_e m_\chi}{\boldsymbol{q}^2}\mathcal{O}_1$
	$\mathcal{L}^{\rm mdm}_\chi = \mu_\chi(\overline{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}\,(\times)$	$\underline{4\mu_\chi e\left(m_e\mathcal{O}_1 + 4m_\chi\mathcal{O}_4 + \frac{4m_e^2 m_\chi}{\boldsymbol{q}^2}\,(\mathcal{O}_5 - \mathcal{O}_6)\right)}$
	$\mathcal{L}^{\rm edm}_\chi = d_\chi(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)F_{\mu\nu}\,(\times)$	$d_\chi e\frac{16m_e^2 m_\chi}{\boldsymbol{q}^2}\mathcal{O}_{11}$
	$\mathcal{L}^{\rm cr}_\chi = b_\chi(\overline{\chi}\gamma^\mu\chi)\partial^\nu F_{\mu\nu}\,(\times)$	$4b_\chi e\,m_e m_\chi\mathcal{O}_1$
	$\mathcal{L}^{\rm anap.}_\chi = a_\chi(\overline{\chi}\gamma^\mu\gamma_5\chi)\partial^\nu F_{\mu\nu}$	$\underline{8a_\chi e\,m_e m_\chi\,(\mathcal{O}_8 - \mathcal{O}_9)}$

$$u^s(\boldsymbol{p}) = \frac{1}{\sqrt{4m}}\begin{pmatrix}(2m - \boldsymbol{p}\cdot\boldsymbol{\sigma})\xi^s \\ (2m + \boldsymbol{p}\cdot\boldsymbol{\sigma})\xi^s\end{pmatrix} + \mathcal{O}(\boldsymbol{p}^2)$$

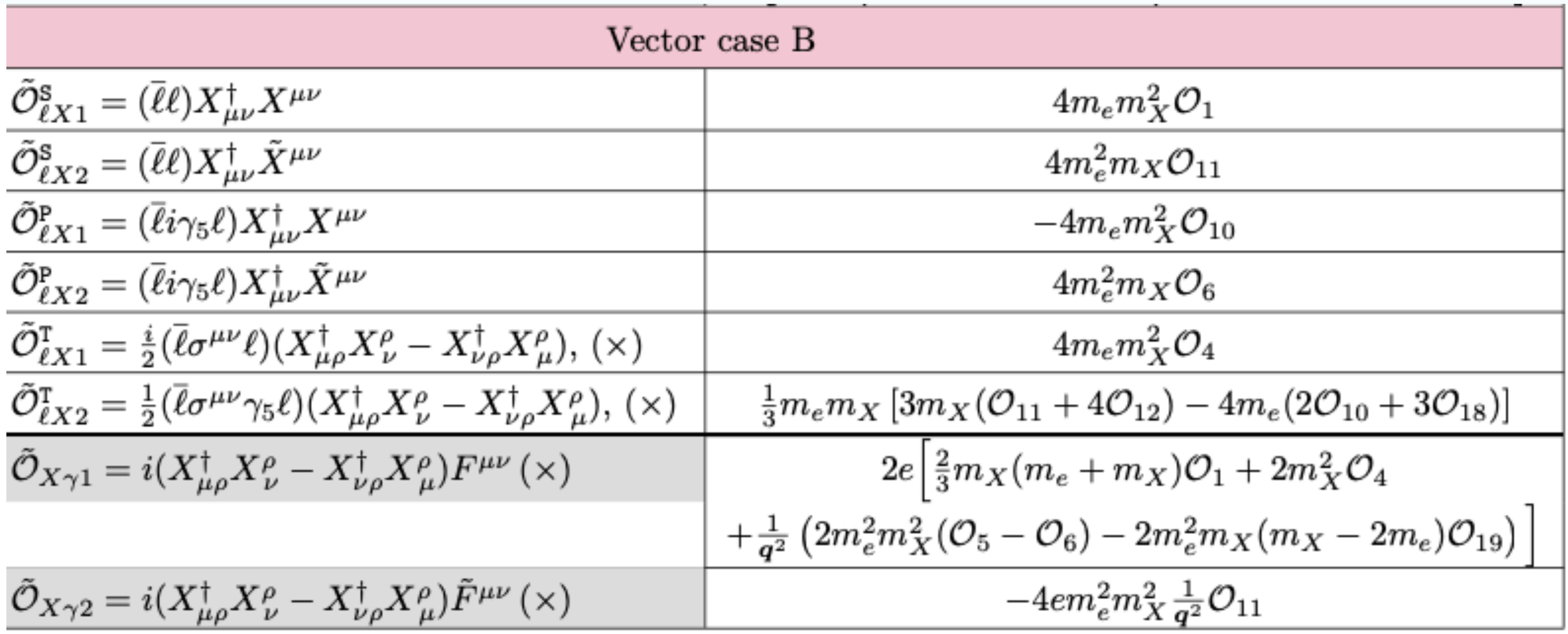
$$\xi^{s'\dagger}\xi^s \to \mathbb{1}, \quad \xi^{s'\dagger}\frac{\boldsymbol{\sigma}}{2}\xi^s \to \boldsymbol{S},$$

$\longrightarrow$ **interference effect**

Vector DM case



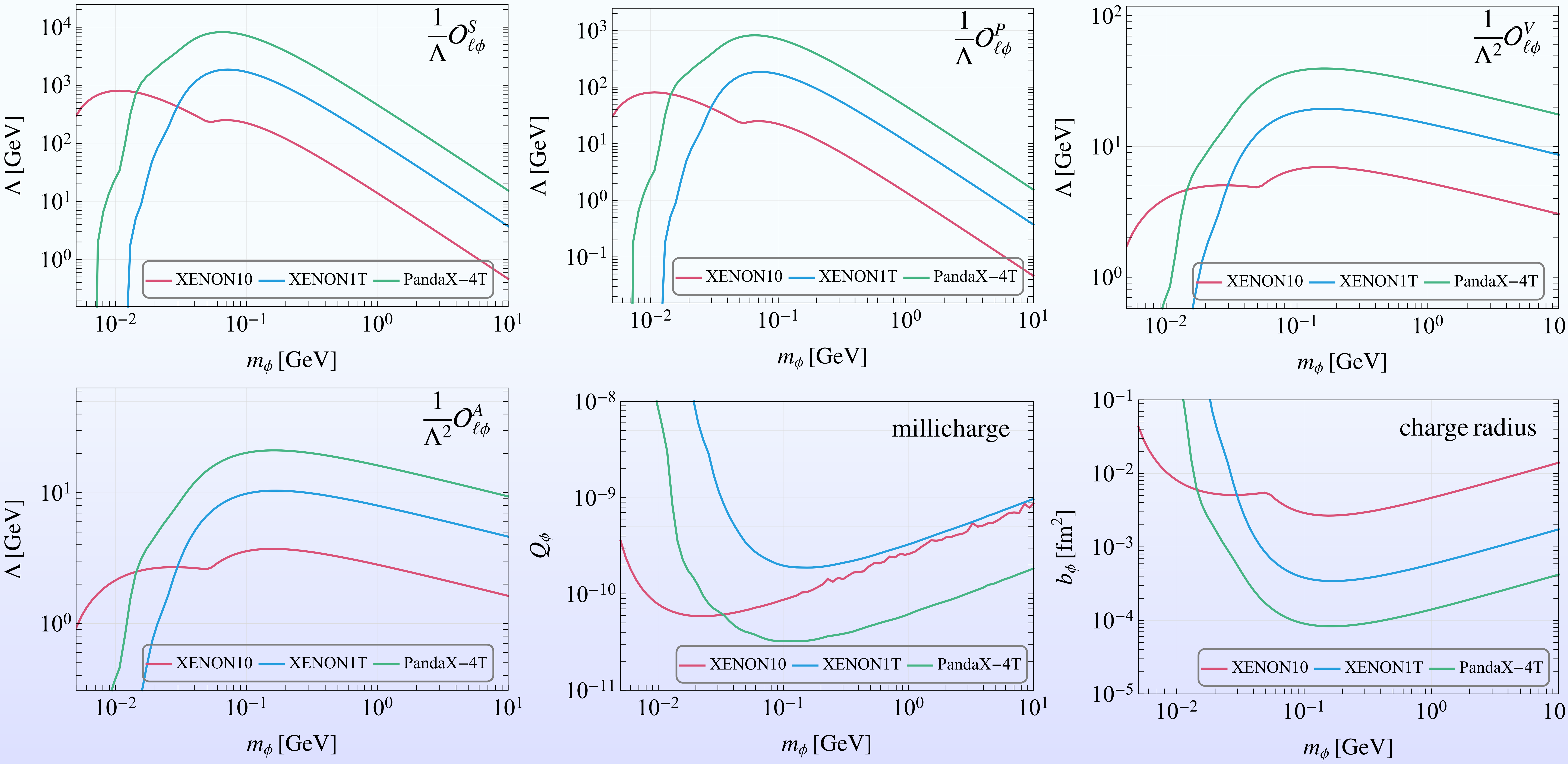
Dim	Relativistic operators	NR reduction
Vector case A		
dim-5	$\mathcal{O}^{\mathtt{S}}_{\ell X} = (\bar\ell\ell)(X^\dagger_\mu X^\mu)$	$-2m_e\mathcal{O}_1$
	$\mathcal{O}^{\mathtt{P}}_{\ell X} = (\bar\ell i\gamma_5\ell)(X^\dagger_\mu X^\mu)$	$2m_e\mathcal{O}_{10}$
	$\mathcal{O}^{\mathtt{T}}_{\ell X1} = \frac{i}{2}(\bar\ell\sigma^{\mu\nu}\ell)(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu)$, $(\times)$	$-4m_e\mathcal{O}_4$
	$\mathcal{O}^{\mathtt{T}}_{\ell X2} = \frac{1}{2}(\bar\ell\sigma^{\mu\nu}\gamma_5\ell)(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu)$, $(\times)$	$-m_e(\mathcal{O}_{11}+4\mathcal{O}_{12}) + 4\frac{m_e^2}{m_X}\left(\frac{1}{3}\mathcal{O}_{10}-\mathcal{O}_{18}\right)$
dim-6	$\mathcal{O}^{\mathtt{V}}_{\ell X1} = \frac{1}{2}[\bar\ell\gamma_{(\mu}i\overleftrightarrow{D}_{\nu)}\ell](X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$	$m_e^2\mathcal{O}_1$
	$\mathcal{O}^{\mathtt{V}}_{\ell X2} = (\bar\ell\gamma_\mu\ell)\partial_\nu(X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$	$-4m_e^2(\mathcal{O}_{17}+\mathcal{O}_{20}) + \frac{4}{3}m_e(i\boldsymbol{q}\cdot\boldsymbol{v}^\perp_{\rm el})\mathcal{O}_1$
	$\mathcal{O}^{\mathtt{V}}_{\ell X3} = (\bar\ell\gamma_\mu\ell)(X^\dagger_\rho\overleftrightarrow{\partial}_\nu X_\sigma)\epsilon^{\mu\nu\rho\sigma}$	$-4m_e m_X(\mathcal{O}_8-\mathcal{O}_9)$
	$\mathcal{O}^{\mathtt{V}}_{\ell X4} = (\bar\ell\gamma^\mu\ell)(X^\dagger_\nu i\overleftrightarrow{\partial}_\mu X^\nu)$, $(\times)$	$-4m_e m_X\mathcal{O}_1$
	$\mathcal{O}^{\mathtt{V}}_{\ell X5} = (\bar\ell\gamma_\mu\ell)i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu)$, $(\times)$	$2m_e^2\left(\mathcal{O}_5-\mathcal{O}_6-\frac{m_e}{m_X}\mathcal{O}_{19}\right) + 2\boldsymbol{q}^2\mathcal{O}_4 + \frac{2}{3}\frac{m_e}{m_X}\boldsymbol{q}^2\mathcal{O}_1$
	$\mathcal{O}^{\mathtt{V}}_{\ell X6} = (\bar\ell\gamma_\mu\ell)i\partial_\nu(X^\dagger_\rho X_\sigma)\epsilon^{\mu\nu\rho\sigma}$, $(\times)$	$-2m_e^2\mathcal{O}_{11}$
	$\mathcal{O}^{\mathtt{A}}_{\ell X1} = \frac{1}{2}[\bar\ell\gamma_{(\mu}\gamma_5 i\overleftrightarrow{D}_{\nu)}\ell](X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$	$-2m_e^2\left(\frac{m_e}{m_X}\mathcal{O}_9 - 4\mathcal{O}_{21} + \frac{4}{3}\mathcal{O}_7\right)$
	$\mathcal{O}^{\mathtt{A}}_{\ell X2} = (\bar\ell\gamma_\mu\gamma_5\ell)\partial_\nu(X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$	$-8m_e^2\left(\frac{1}{3}\mathcal{O}_{10}-\mathcal{O}_{18}\right)$
	$\mathcal{O}^{\mathtt{A}}_{\ell X3} = (\bar\ell\gamma_\mu\gamma_5\ell)(X^\dagger_\rho\overleftrightarrow{\partial}_\nu X_\sigma)\epsilon^{\mu\nu\rho\sigma}$	$8m_e m_X\mathcal{O}_4$
	$\mathcal{O}^{\mathtt{A}}_{\ell X4} = (\bar\ell\gamma^\mu\gamma_5\ell)(X^\dagger_\nu i\overleftrightarrow{\partial}_\mu X^\nu)$	$8m_e m_X\mathcal{O}_7$
	$\mathcal{O}^{\mathtt{A}}_{\ell X5} = (\bar\ell\gamma_\mu\gamma_5\ell)i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu)$, $(\times)$	$4m_e^2\mathcal{O}_9$
	$\mathcal{O}^{\mathtt{A}}_{\ell X6} = (\bar\ell\gamma_\mu\gamma_5\ell)i\partial_\nu(X^\dagger_\rho X_\sigma)\epsilon^{\mu\nu\rho\sigma}$, $(\times)$	$4m_e^2\left(\mathcal{O}_{14}-\frac{m_e}{m_X}\mathcal{O}_{20}\right)$
	$\mathcal{L}_{\kappa_\Lambda} = i\frac{\kappa_\Lambda}{2}(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu)F^{\mu\nu}\,(\times)$	$-2e\kappa_\Lambda\left[\frac{m_e}{m_X}\left(\frac{1}{3}\mathcal{O}_1 - \frac{m_e^2}{\boldsymbol{q}^2}\mathcal{O}_{19}\right) - \mathcal{O}_4 - \frac{m_e^2}{\boldsymbol{q}^2}(\mathcal{O}_5-\mathcal{O}_6)\right]$
	$\mathcal{L}_{\tilde\kappa_\Lambda} = i\frac{\tilde\kappa_\Lambda}{2}(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu)\tilde F^{\mu\nu}\,(\times)$	$2e\tilde\kappa_\Lambda m_e^2\frac{1}{\boldsymbol{q}^2}\mathcal{O}_{11}$
dim-6	$\mathcal{O}_{X\gamma1} = \epsilon^{\mu\nu\rho\sigma}\left(X^\dagger_\rho\overleftrightarrow{\partial}_\nu X_\sigma\right)\partial^\lambda F_{\mu\lambda}$	$-4em_e m_X(\mathcal{O}_8-\mathcal{O}_9)$
	$\mathcal{O}_{X\gamma2} = \epsilon^{\mu\nu\rho\sigma}i\partial_\nu\left(X^\dagger_\rho X_\sigma\right)\partial^\lambda F_{\mu\lambda}\,(\times)$	$-2em_e^2\mathcal{O}_{11}$
	$\mathcal{O}_{X\gamma3} = \left(X^\dagger_\nu i\overleftrightarrow{\partial^\mu}X^\nu\right)\partial^\lambda F_{\mu\lambda}$	$-4em_e m_X\mathcal{O}_1$
	$\mathcal{O}_{X\gamma4} = \partial_\nu(X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)\partial^\lambda F_{\mu\lambda}$	$4e\,m_e\left[\frac{1}{3}(i\boldsymbol{q}\cdot\boldsymbol{v}^\perp_{\rm el})\mathcal{O}_1 - m_e(\mathcal{O}_{17}+\mathcal{O}_{20})\right]$
	$\mathcal{O}_{X\gamma5} = i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu)\partial^\lambda F_{\mu\lambda}\,(\times)$	$e\left[2m_e^2\left(\mathcal{O}_5-\mathcal{O}_6-\frac{m_e}{m_X}\mathcal{O}_{19}\right) + 2\boldsymbol{q}^2\mathcal{O}_4 + \frac{2}{3}\frac{m_e}{m_X}\boldsymbol{q}^2\mathcal{O}_1\right]$



Vector case B	
$\tilde{\mathcal{O}}^{\mathtt{S}}_{\ell X1} = (\bar\ell\ell)X^\dagger_{\mu\nu}X^{\mu\nu}$	$4m_e m_X^2\mathcal{O}_1$
$\tilde{\mathcal{O}}^{\mathtt{S}}_{\ell X2} = (\bar\ell\ell)X^\dagger_{\mu\nu}\tilde X^{\mu\nu}$	$4m_e^2 m_X\mathcal{O}_{11}$
$\tilde{\mathcal{O}}^{\mathtt{P}}_{\ell X1} = (\bar\ell i\gamma_5\ell)X^\dagger_{\mu\nu}X^{\mu\nu}$	$-4m_e m_X^2\mathcal{O}_{10}$
$\tilde{\mathcal{O}}^{\mathtt{P}}_{\ell X2} = (\bar\ell i\gamma_5\ell)X^\dagger_{\mu\nu}\tilde X^{\mu\nu}$	$4m_e^2 m_X\mathcal{O}_6$
$\tilde{\mathcal{O}}^{\mathtt{T}}_{\ell X1} = \frac{i}{2}(\bar\ell\sigma^{\mu\nu}\ell)(X^\dagger_{\mu\rho}X^\rho_\nu - X^\dagger_{\nu\rho}X^\rho_\mu)$, $(\times)$	$4m_e m_X^2\mathcal{O}_4$
$\tilde{\mathcal{O}}^{\mathtt{T}}_{\ell X2} = \frac{1}{2}(\bar\ell\sigma^{\mu\nu}\gamma_5\ell)(X^\dagger_{\mu\rho}X^\rho_\nu - X^\dagger_{\nu\rho}X^\rho_\mu)$, $(\times)$	$\frac{1}{3}m_e m_X[3m_X(\mathcal{O}_{11}+4\mathcal{O}_{12}) - 4m_e(2\mathcal{O}_{10}+3\mathcal{O}_{18})]$
$\tilde{\mathcal{O}}_{X\gamma1} = i(X^\dagger_{\mu\rho}X^\rho_\nu - X^\dagger_{\nu\rho}X^\rho_\mu)F^{\mu\nu}\,(\times)$	$2e\left[\frac{2}{3}m_X(m_e+m_X)\mathcal{O}_1 + 2m_X^2\mathcal{O}_4\right.$ $\left.+\frac{1}{\boldsymbol{q}^2}\left(2m_e^2m_X^2(\mathcal{O}_5-\mathcal{O}_6) - 2m_e^2m_X(m_X-2m_e)\mathcal{O}_{19}\right)\right]$
$\tilde{\mathcal{O}}_{X\gamma2} = i(X^\dagger_{\mu\rho}X^\rho_\nu - X^\dagger_{\nu\rho}X^\rho_\mu)\tilde F^{\mu\nu}\,(\times)$	$-4em_e^2m_X^2\frac{1}{\boldsymbol{q}^2}\mathcal{O}_{11}$

All possible leading-order vector DM operators coupling to electron and photon fields

Constraints on the scalar DM case



$$\mathcal{O}^S_{\ell\phi} = (\bar{\ell}\ell)(\phi^\dagger\phi)$$

$$\mathcal{O}^P_{\ell\phi} = (\bar{\ell}i\gamma_5\ell)(\phi^\dagger\phi)$$

$$\mathcal{O}^V_{\ell\phi} = (\bar{\ell}\gamma^\mu\ell)(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi)\,(\times)$$

$$\mathcal{O}^A_{\ell\phi} = (\bar{\ell}\gamma^\mu\gamma_5\ell)(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi)\,(\times)$$

$$\mathcal{L}^Q_\phi = |(\partial_\mu - iQ_\phi e A_\mu)\phi|^2\,(\times)$$

$$\mathcal{L}^{\rm cr}_\phi = b_\phi(\phi^\dagger i\overleftrightarrow{\partial^\mu}\phi)\partial^\nu F_{\mu\nu}\,(\times)$$

Constraints on the fermion DM EM property

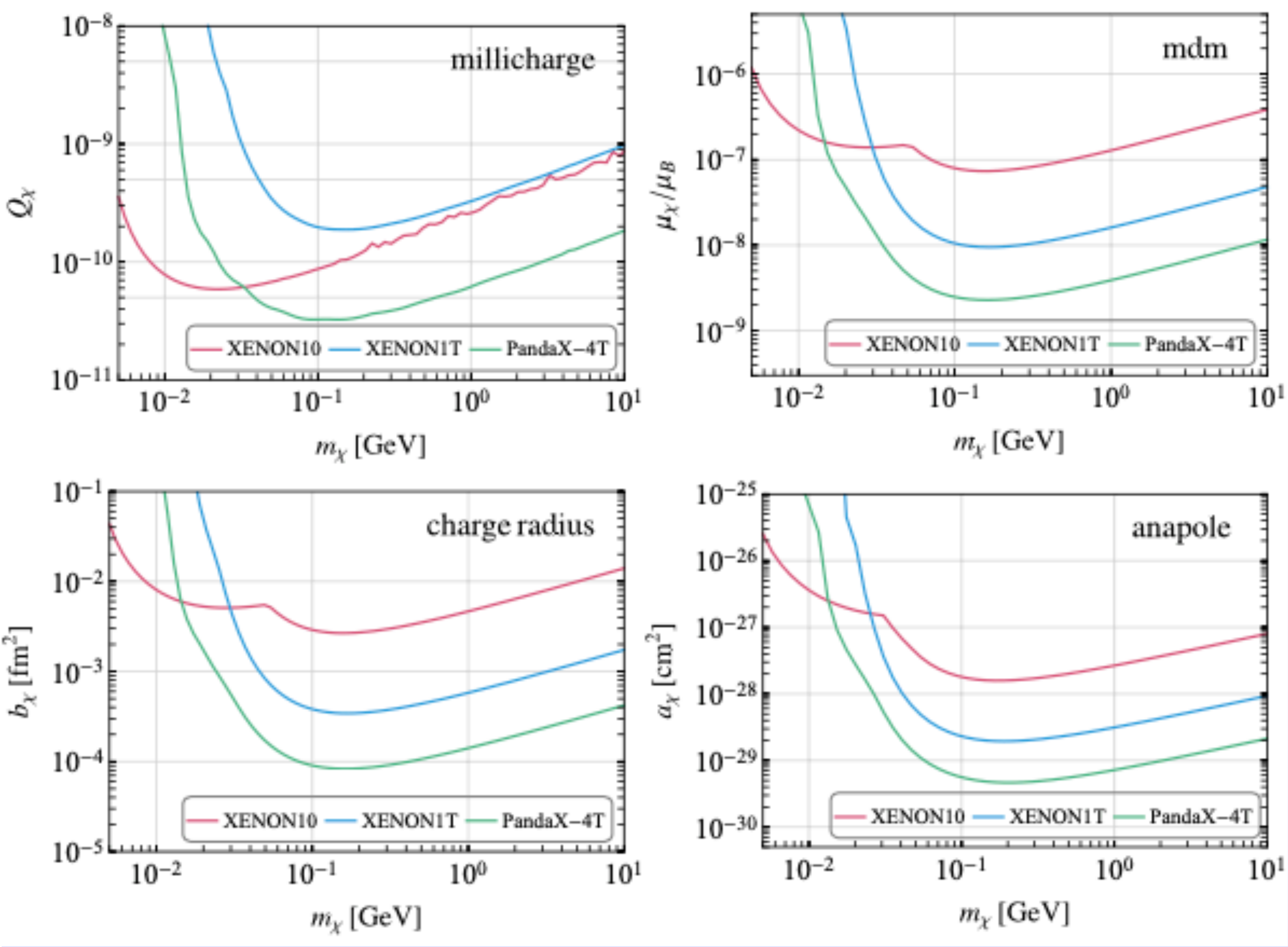
$$\mathcal{L}_\chi^Q = \overline{\chi} i \gamma^\mu (\partial_\mu - i Q_\chi e A_\mu)\chi \, (\times)$$

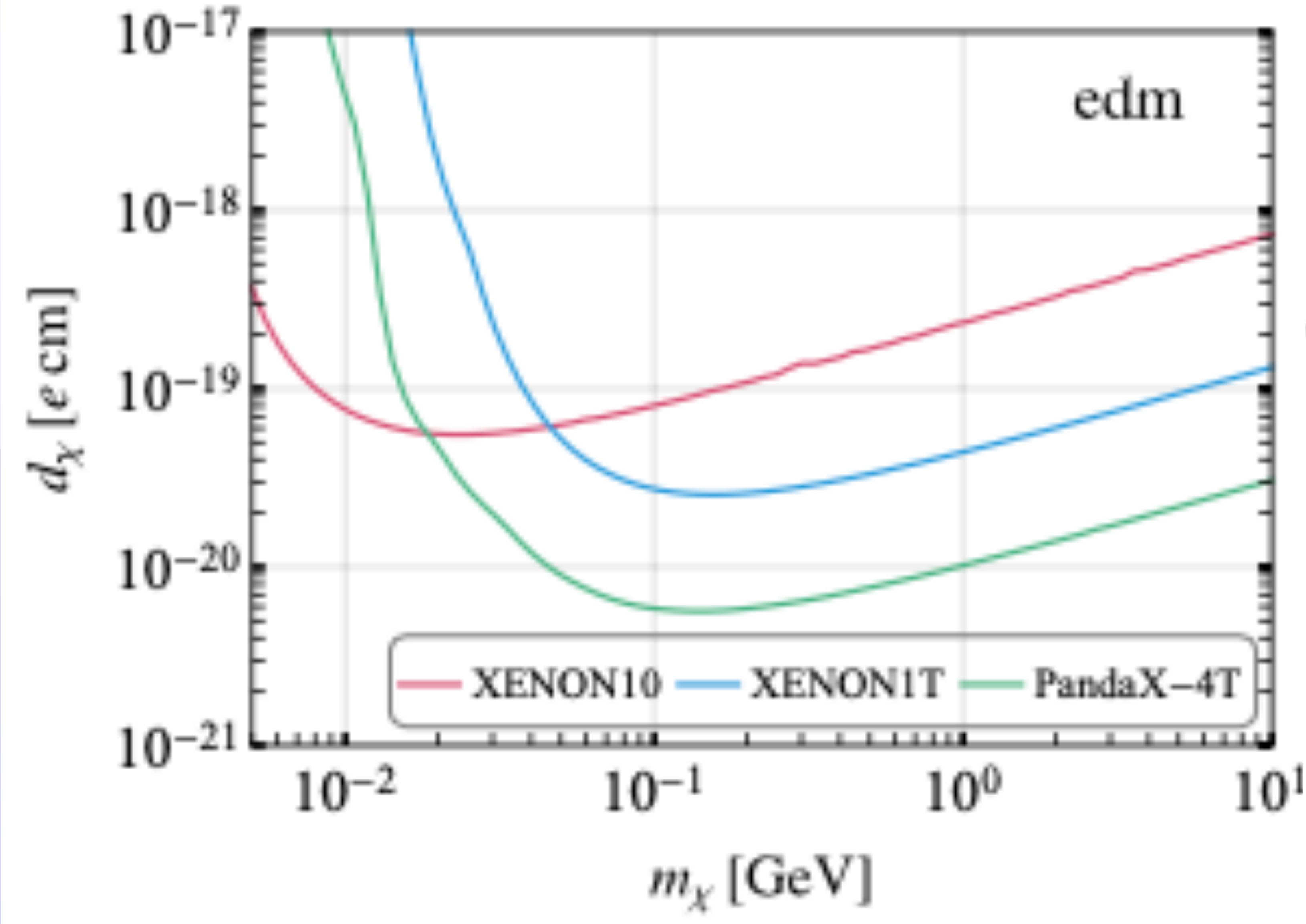
$$\mathcal{L}_\chi^{\rm mdm} = \mu_\chi (\overline{\chi} \sigma^{\mu\nu} \chi) F_{\mu\nu} \, (\times)$$

$$\mathcal{L}_\chi^{\rm edm} = d_\chi (\overline{\chi} i \sigma^{\mu\nu} \gamma_5 \chi) F_{\mu\nu} \, (\times)$$

$$\mathcal{L}_\chi^{\rm cr} = b_\chi (\overline{\chi} \gamma^\mu \chi) \partial^\nu F_{\mu\nu} \, (\times)$$

$$\mathcal{L}_\chi^{\rm anap.} = a_\chi (\overline{\chi} \gamma^\mu \gamma_5 \chi) \partial^\nu F_{\mu\nu}$$





Comporison with the NR data

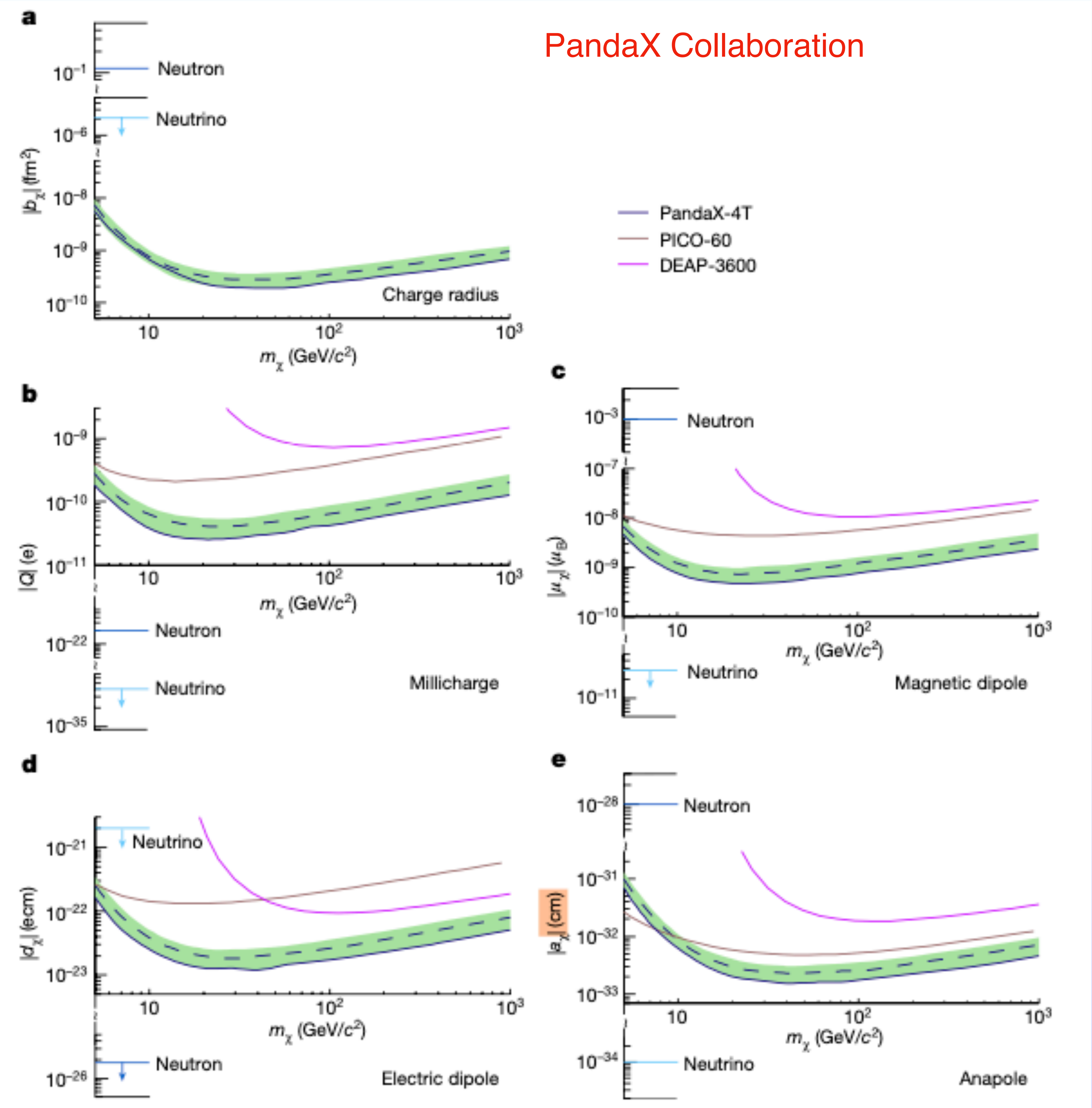
- Complementarity

NR is sensitive for m_χ above a few GeVs

ER is sensitive to m_χ below 10 GeV

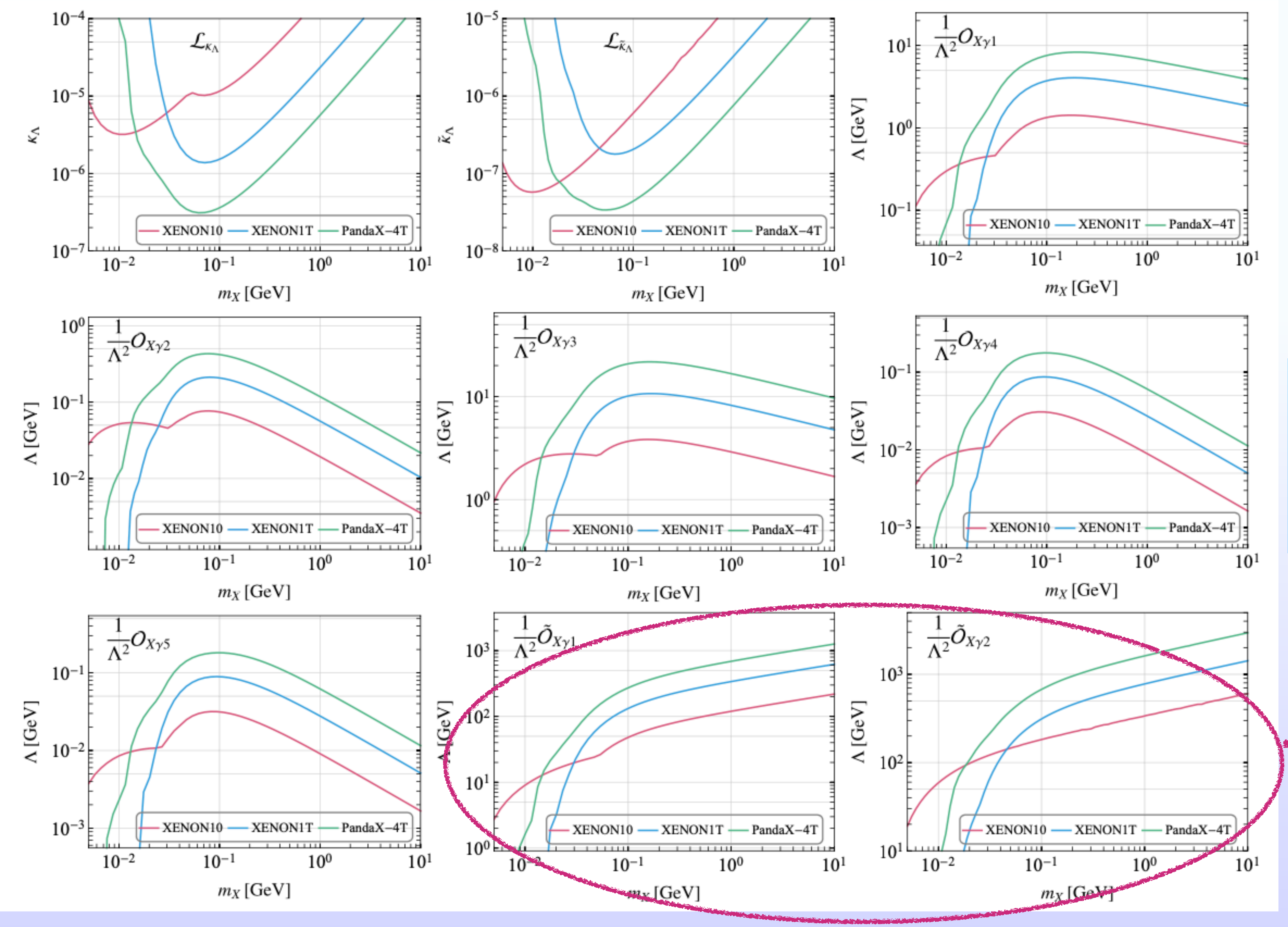
- Generally, the NR constraints are stronger than those of ER.

- For millicharge and mdm, the ER constraint is comparable to that of NR



PandaX Collaboration

Constraints on the vector DM case



Some examples involving photon field

Different behavior due to different parametrization and DM mass dependence

Become stronger as m_X increase

Summary

- We find a crucial minus sign was missed for W_2 in 1912.08204, which has significant phenomenological consequences on some specific DM scenarios.
- A more compact amplitude squared is provided for the general DM-electron interactions for three DM scenarios.
- A matching dictionary between the relativistic and NR operators is given.
- The constraints from the xenon target experiments were studied, and we find the PandaX-4T set the most stringent constraints on the effective operators when $m_{\rm DM} \gtrsim 20~{\rm MeV}$.

Thanks for your attention !