IBS, Center for Theoretical Physics of the Universe

PASCOS 2021

26th International Symposium on Particles, Strings & Cosmology

Impact of the interference among the operators in dark matter direct detection Experiments

In collaboration with A. Brenner, G. Herrera, A. Ibarra, S. Kang, S. Scopel

arXiv: 2107.xxxxx

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17th June, 2021

Dark Matter: What we know?

- Weakly Interacting

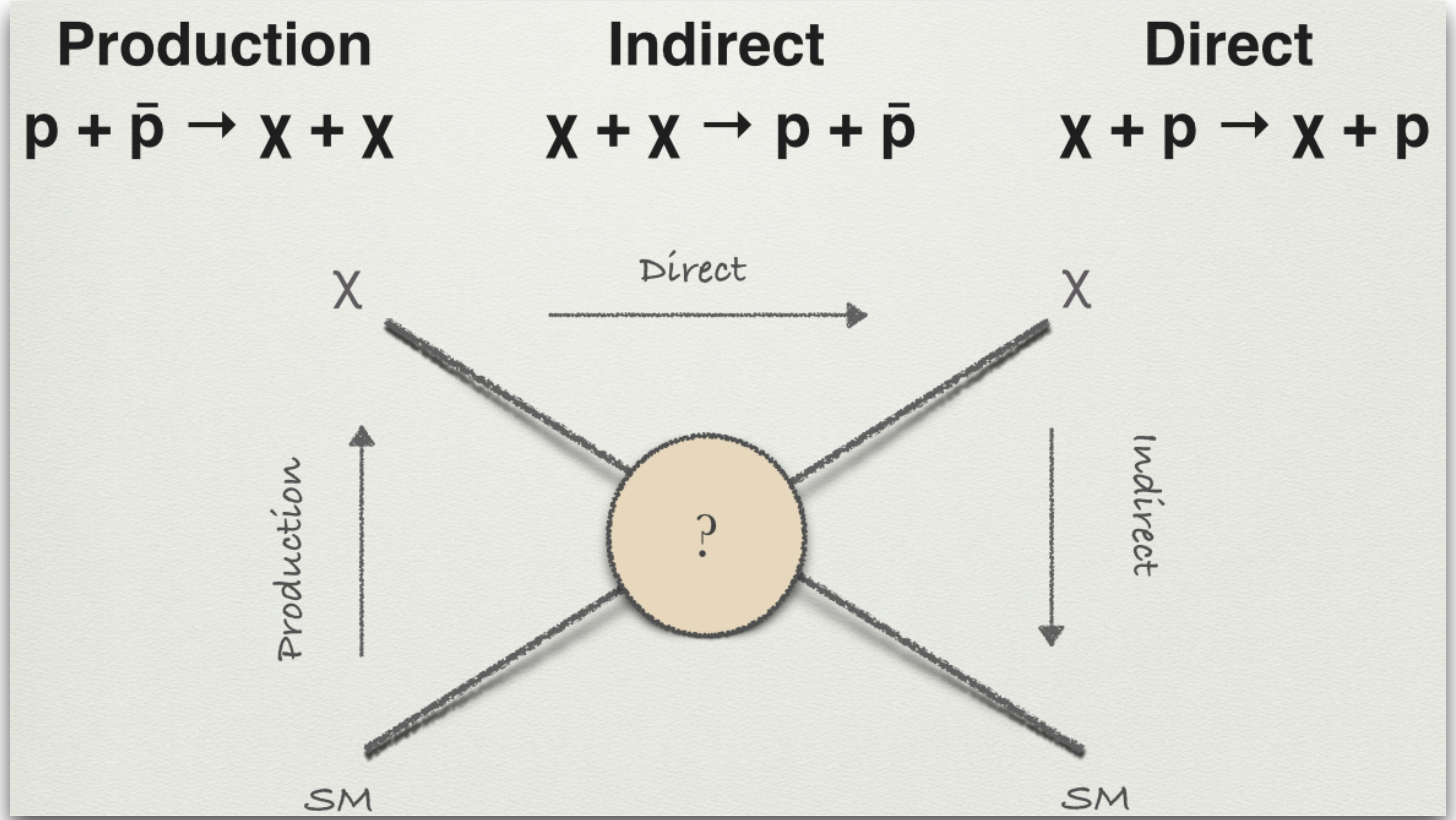
- Non-baryonic [e.g microlensing searches]

- Mostly cold [e.g clumsiness of structure formation]

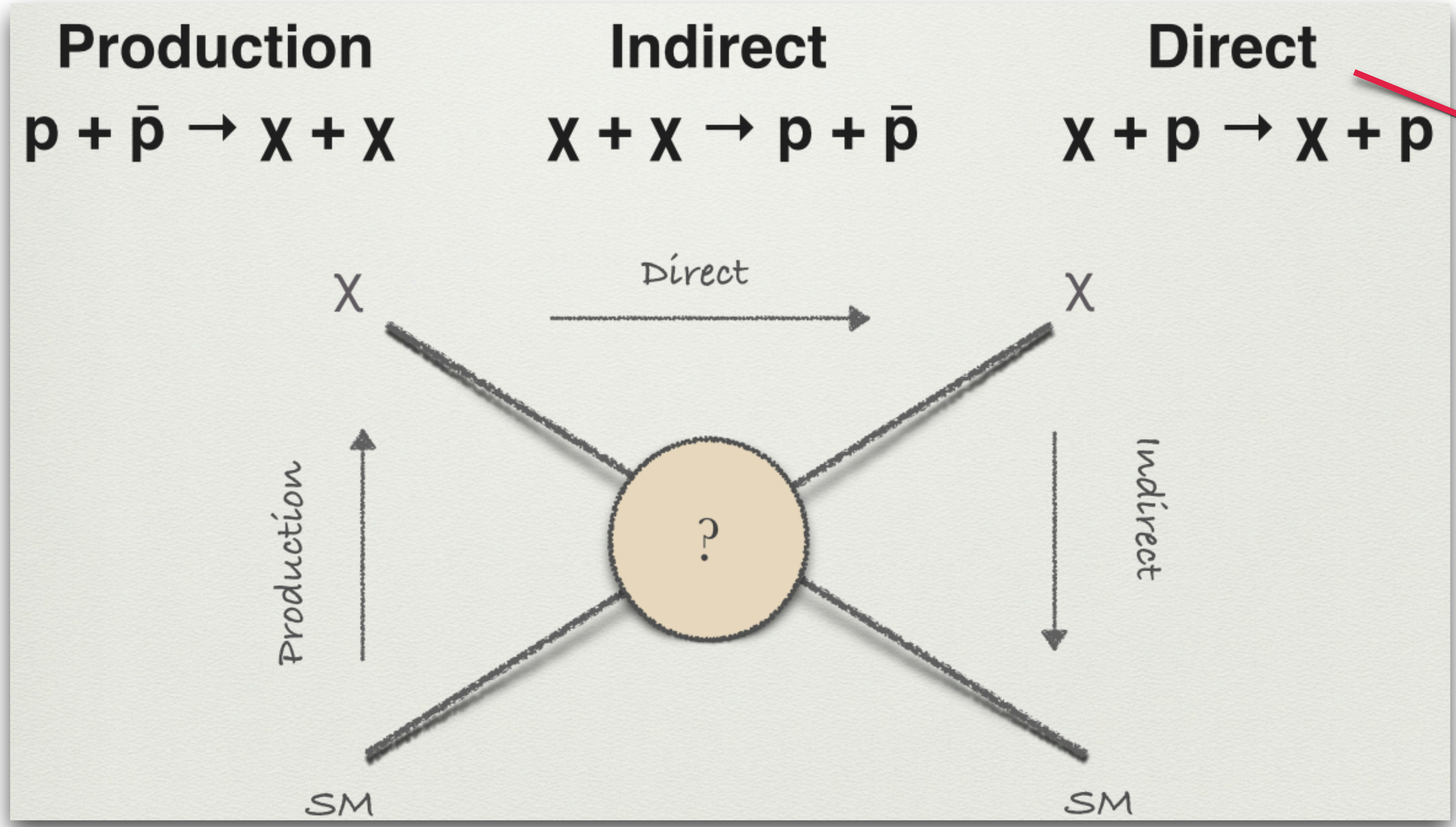
- Average mass density [from CMB, $\Omega h^2 = 0.112 \pm 0.006$]

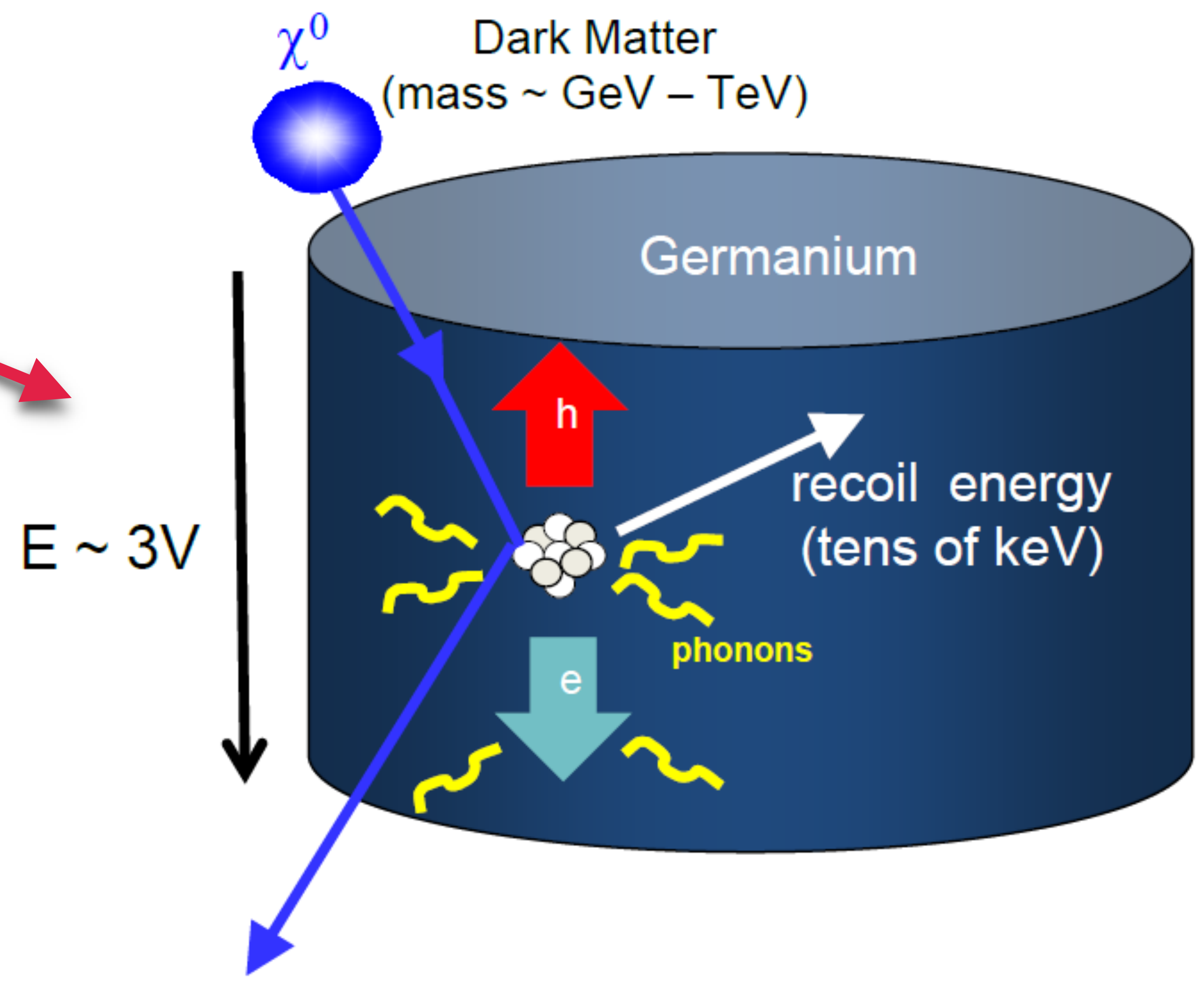
- There is no candidate in the standard model of particle physics

Dark Matter: Possible ways of detection?



Dark Matter: Possible ways of detection?





Dark Matter: What we don’t know?

- No direct detection

- Specific properties:

1. Mass
2. Couplings of particles — Particle Physics Uncertainties
3. Density distribution
4. Velocity distribution — Astrophysics Uncertainties

- The expected rate:

Astrophysical Uncertainties

$$\frac{dR}{dE_R}(t) = N_T \frac{\rho_\chi}{m_\chi} \int_{vmin} d^3 v_T f(\overrightarrow{v}_T, t) v_T \frac{d\sigma_T}{dE_R}$$

Particle Physics Uncertainties

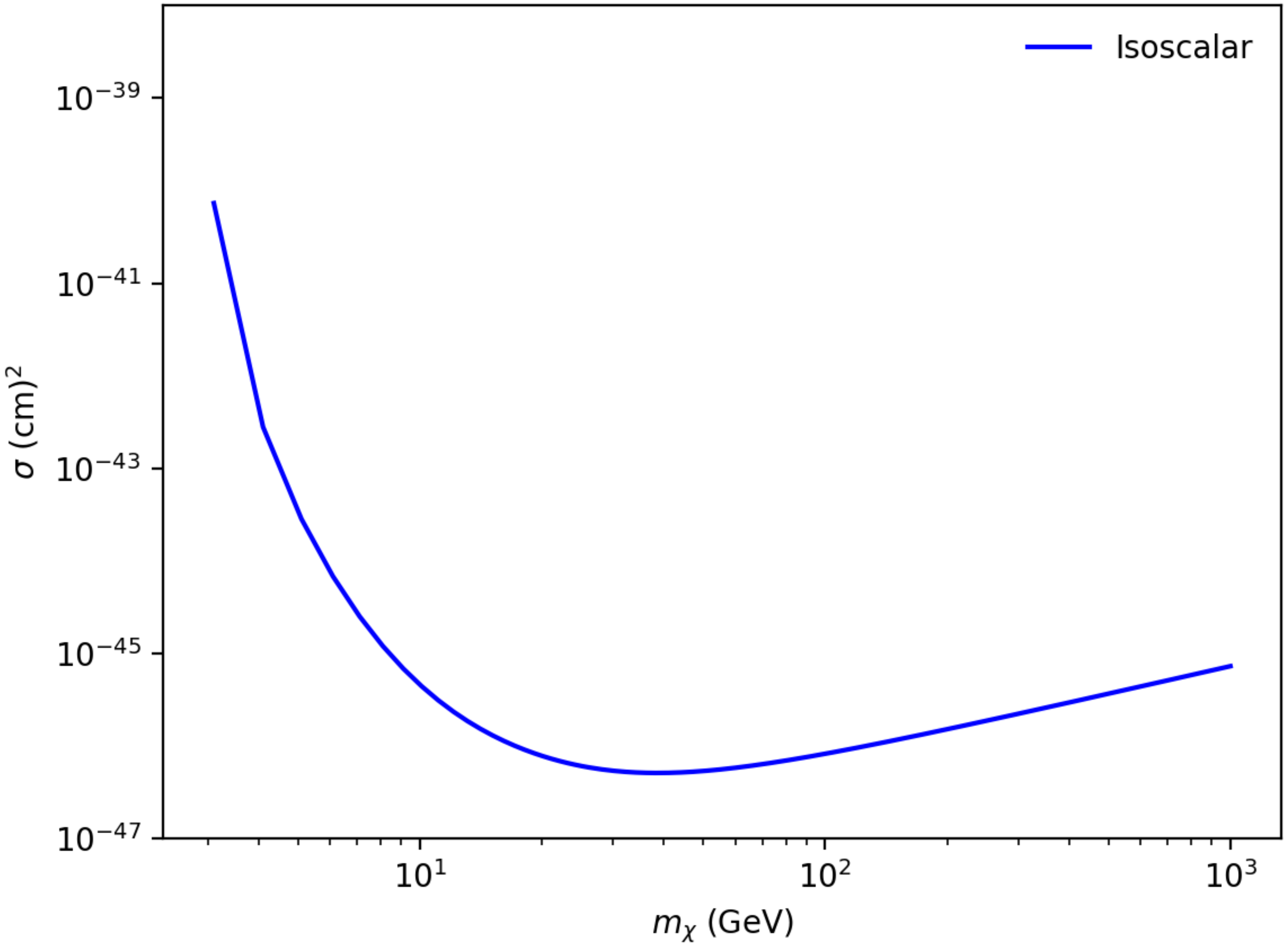
Assumptions:

1. Couplings of DM particles : Spin-Independent iso-scalar interaction $(c_p = c_n)$

2. Velocity distribution: Maxwellian-Boltzmann distribution

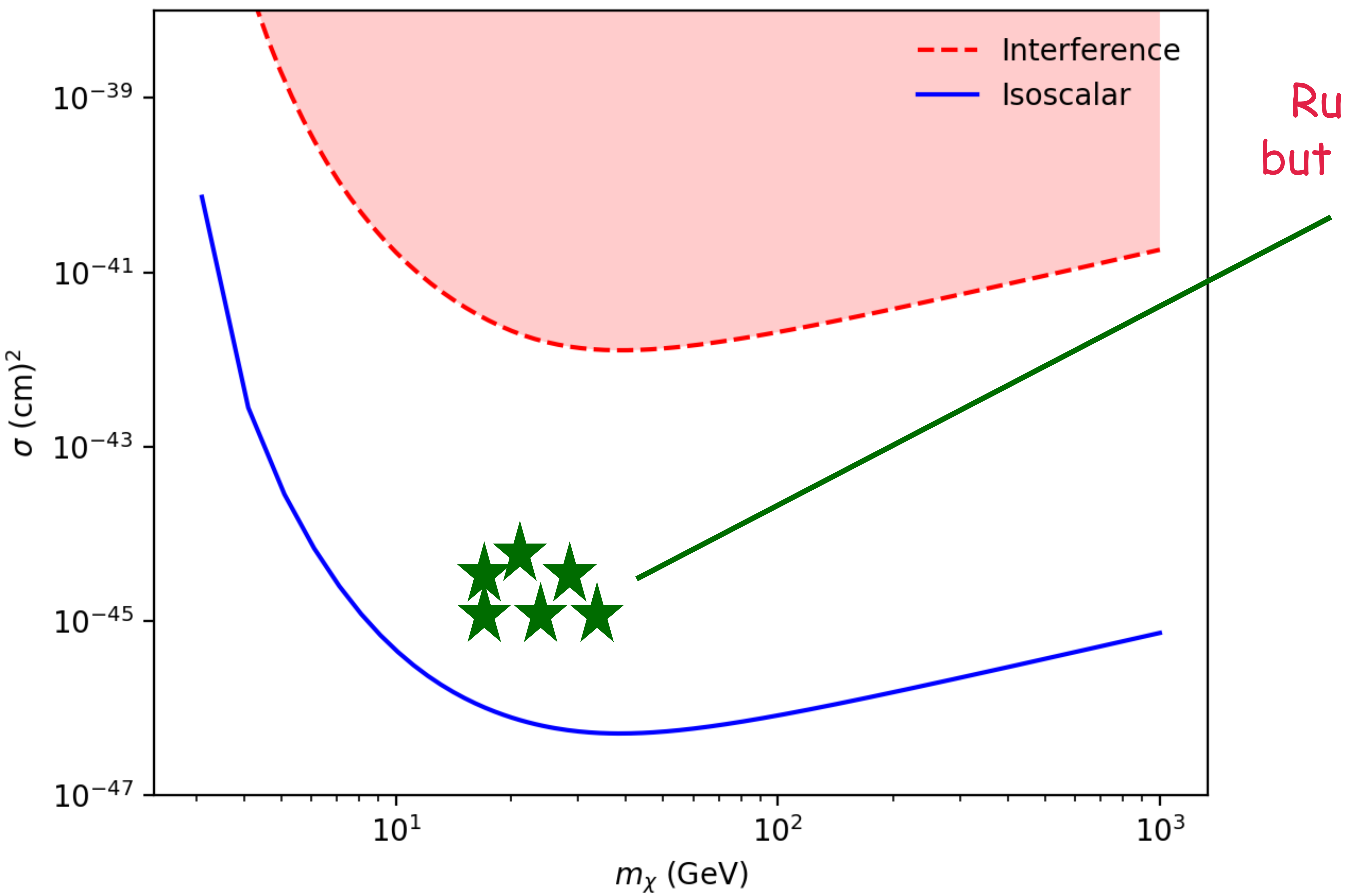
3. Density distribution: $\rho_\chi = 0.3 \ \mathrm{GeV/cm^3}$

Motivation



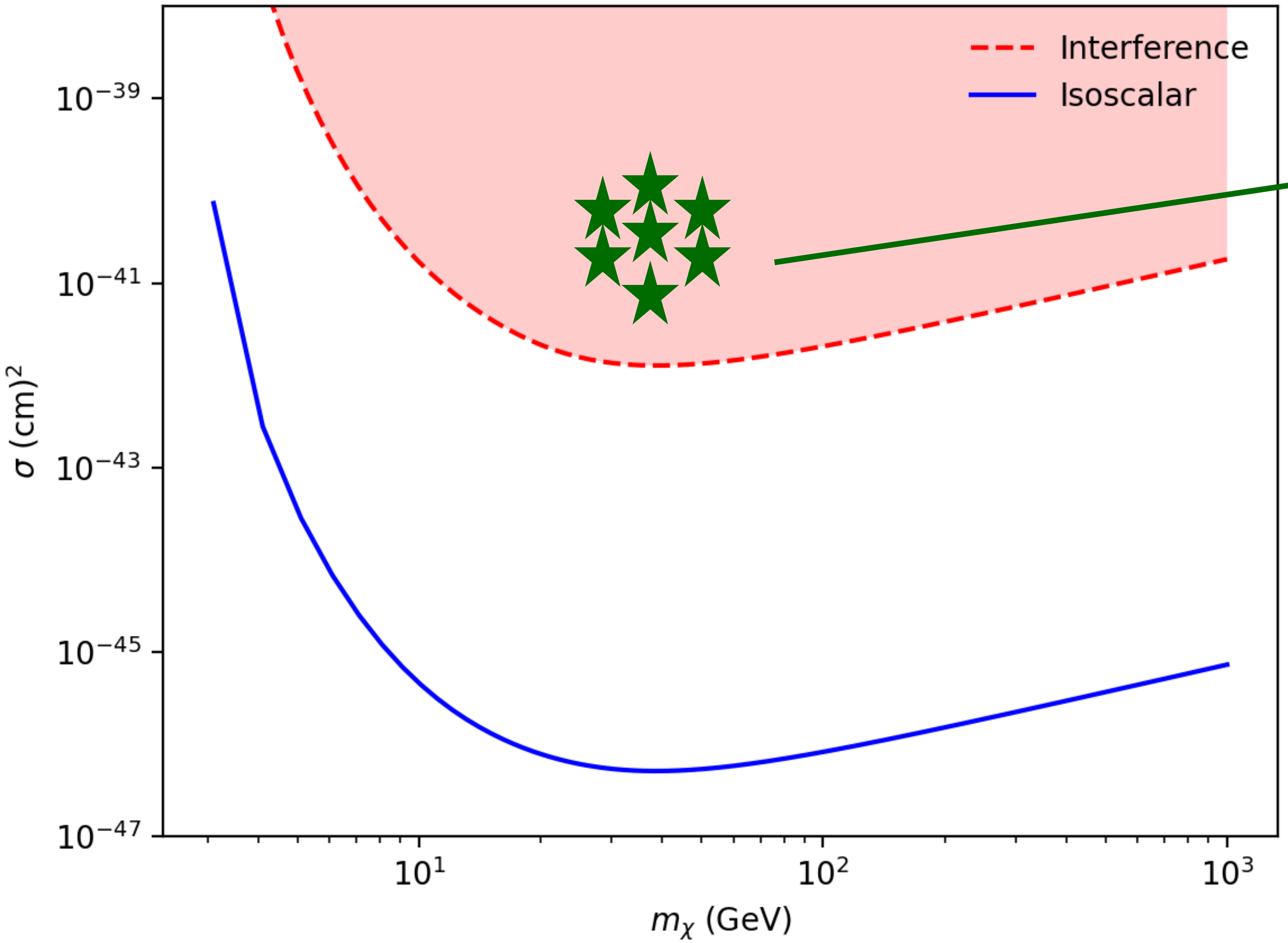
Isoscalar
10^{-39}
10^{-41}
10^{-43}
10^{-45}
10^{-47}
σ (cm)^2
10^1
10^2
10^3
m_χ (GeV)

Motivation



Ruled out by isoscalar limit
but allowed with interference
inclusion

Motivation



Completely ruled out

1. couplings of DM particles: Non-Relativistic Effective Field Theory

- Hamiltonian density of DM-nucleus interaction

$$H = \sum_{j=1}^{15} (c_j^0 + c_j^1 \tau_3)\mathcal{O}_j \;\; \text{with } c_j^0 = c^p + c^n, c_j^1 = c^p - c^n$$

- All operators are guaranteed to be Hermitian if built by

$$i\frac{\overrightarrow{q}}{m_N}, \overrightarrow{v}^{\perp}, \overrightarrow{S_\chi}, \overrightarrow{S_N} \quad \text{with } \overrightarrow{v}^{\perp} = \overrightarrow{v} + \frac{\overrightarrow{q}}{2\mu_{\chi N}}$$

Complete set of operators for DM with spin 1/2

$$\mathcal{O}_1 = 1_\chi 1_N;\ \mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp);\ \mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N;\ \mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp);\ \mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$$

$$\mathcal{O}_7 = \vec{S}_\chi \cdot \vec{v}^\perp;\ \mathcal{O}_8 = i\vec{S}_\chi \cdot \vec{v}^\perp;\ \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N});\ \mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N};\ \mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp);\ \mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N});\ \mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp);$$

$$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N})$$

Anand, Fitzpatrick, Haxton, Phys. Rev. C89, 065501 (2014), 1308.6288

For DM with spin $\geq 1/2$: Gondolo, Kang, Scopel, GT, PRD, to appear, 2008.05120

NREFT

- Differential cross-section

$$\frac{d\sigma_T}{dE_R} = \frac{2m_T}{4\pi v_T^2}\left[\frac{1}{2j_\chi+1}\frac{1}{2j_T+1}|\mathscr{M}_T|^2\right]$$

- Scattering amplitude

$$\frac{1}{2j_\chi+1}\frac{1}{2j_T+1}|\mathscr{M}_T|^2 = \frac{4\pi}{2j_T+1}\sum_{\tau,\tau'}\sum_k \overset{\text{Dark Matter}}{\overline{R_k^{\tau\tau'}}}\left[c_j^\tau, (v_T^\perp)^2, \frac{q^2}{m_N^2}\right]\overset{\text{Nuclear Physics}}{\overline{W_{Tk}^{\tau\tau'}}}(y)$$

Here, $k = M, \Phi'', \tilde{\Phi}', \Sigma', \Sigma'', \Delta, \Phi''M, \Delta\Sigma'$

Impact of operator interference in DM direct detection

- The interaction Hamiltonian

$$H = \sum_{j=1}^{15} (c_j^0 + c_j^1 \tau_3) \mathcal{O}_j$$

- Rate in an experiment

$$R(c) = c_k^T \mathbb{R} c_k$$

$$c_k = (c_1^0, c_1^1, c_3^0, c_3^1, \ldots\ldots c_{15}^0, c_{15}^1)$$

Catena, Ibarra, Wild, JCAP 1605 (2016), 05, 039
Catena, Ibarra, Rappelt, Wild, JCAP 07 (2018) 028

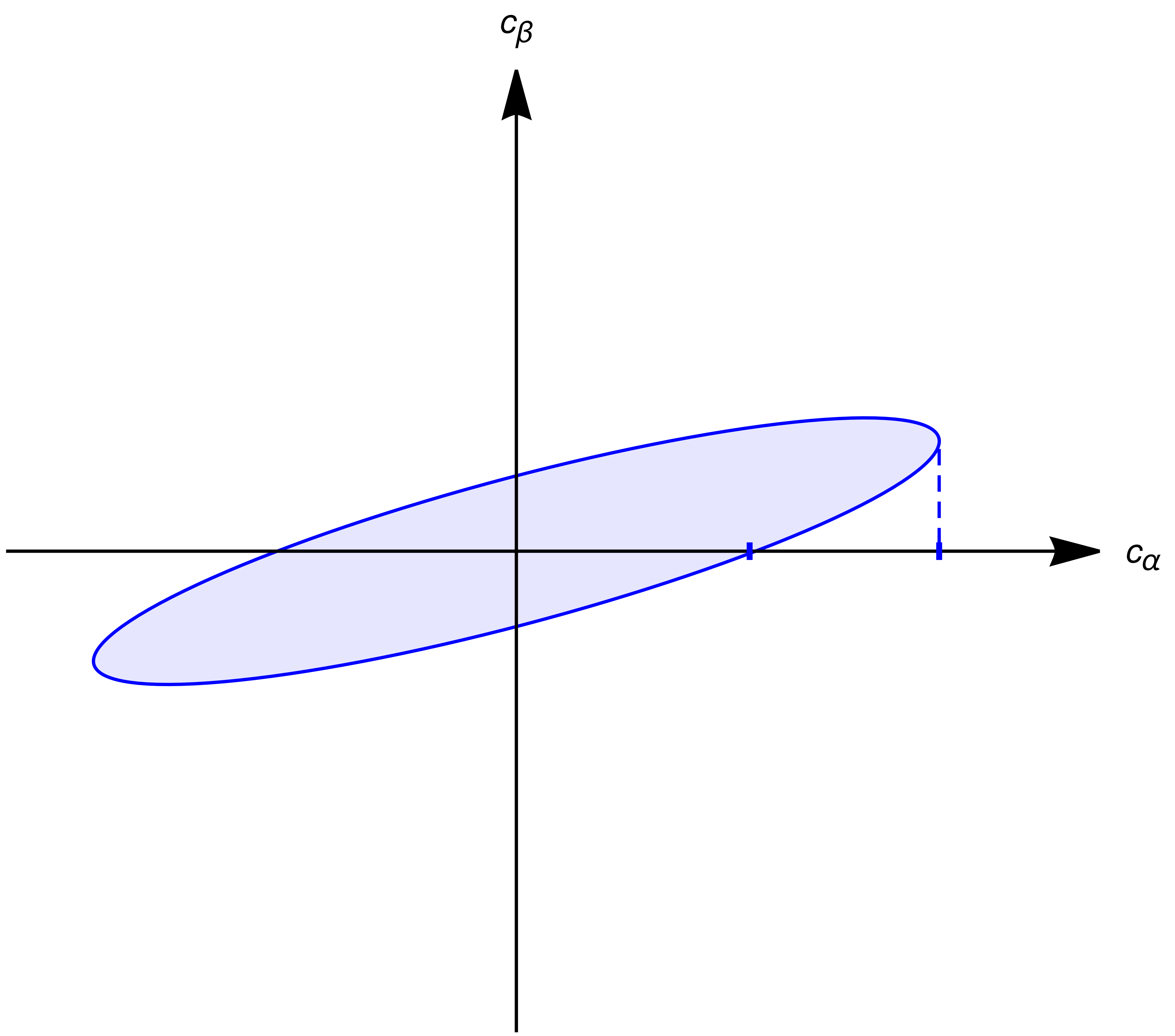
For a spin-1/2 DM
$\mathbb{R} : 28 \times 28$

- $\mathbb{R}$ Matrix depends on: DM mass, density and velocity distribution

Impact of operator interference in DM direct detection

- Rate in an experiment

$$c_k^T \mathbb{R} c_k \leq R^{u.l.}$$



Catena, Ibarra, Wild, JCAP 1605 (2016), 05, 039
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Interference for DM with spin $\geq$1/2

$$
\begin{aligned}
R_M^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= 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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= 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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'} \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], \qquad (38) \\
R_{\Sigma'}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'} + \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)\right. \\
&\quad \left. + \frac{\vec{q}^{\,2}}{2m_N^2}\vec{v}_T^{\perp 2} c_{14}^\tau c_{14}^{\tau'}\right], \\
R_{\Delta}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \frac{j_\chi(j_\chi+1)}{3}\left[c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right].
\end{aligned}
$$

Interference terms

Anand, Fitzpatrick, Haxton, Phys. Rev. C89, 065501 (2014), 1308.6288

For DM with spin $\geq 1/2$: Gondolo, Kang, Scopel, GT, PRD, to appear, 2008.05120

Impact of operator interference in DM direct detection: single experiment

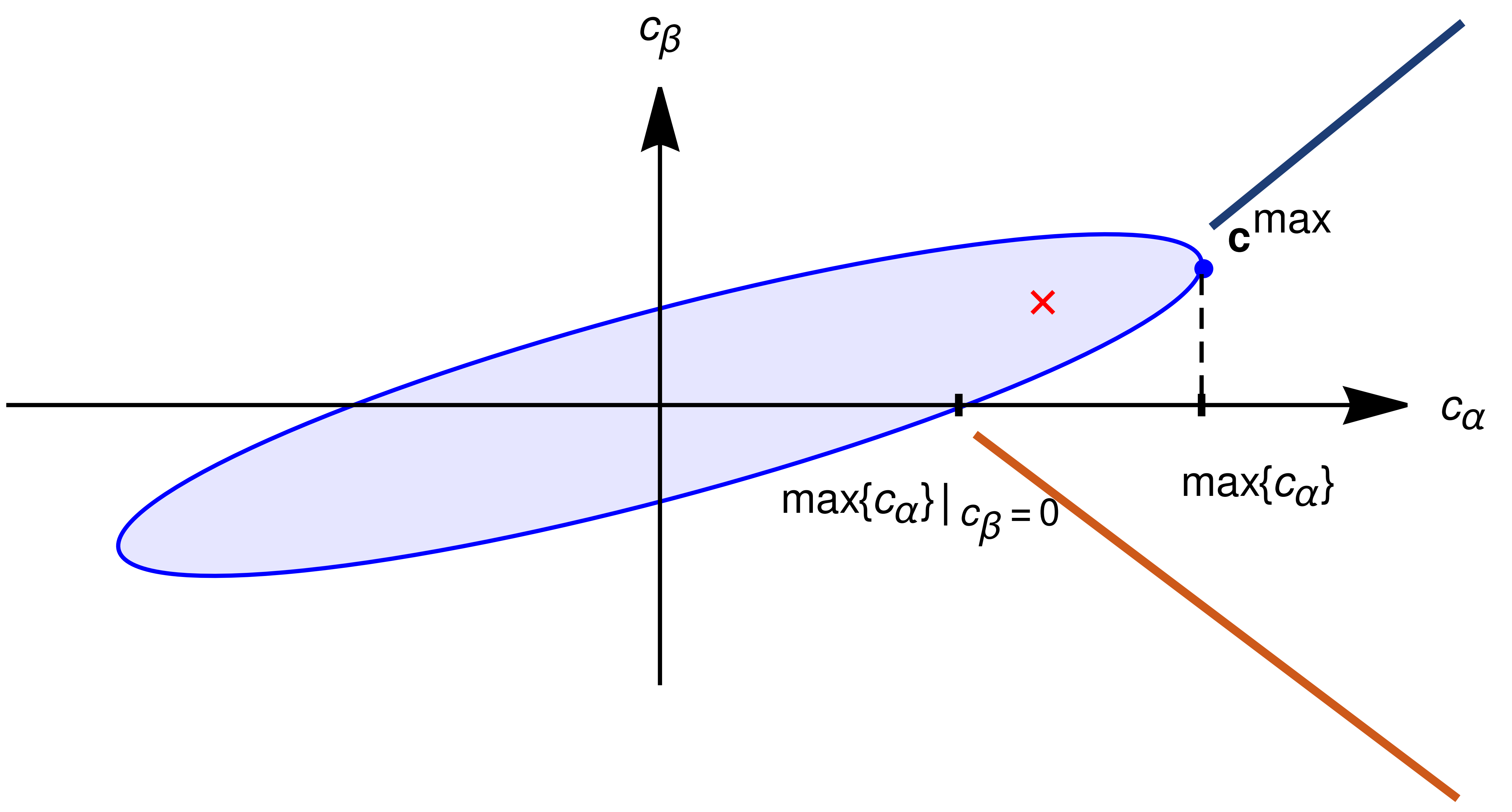
- Construct the Lagrangian

$$L = c_\alpha - \lambda(R(c) - R^{u.l.})$$

- Maximum coupling

$$c_\alpha^{\max} = \sqrt{(\mathbb{R}^{-1})_{\alpha\alpha} R^{u.l.}}$$

$$\mathbb{R} : 28 \times 28$$



Brenner, Ibarra, Rappelt, arXiv: 2011.02929

Using WimPyDD: https://wimpydd.hepforge.org

Jeong, Kang, Scopel, GT, arXiv: 2106.06207

Impact of operator interference in DM direct detection: combined experiments

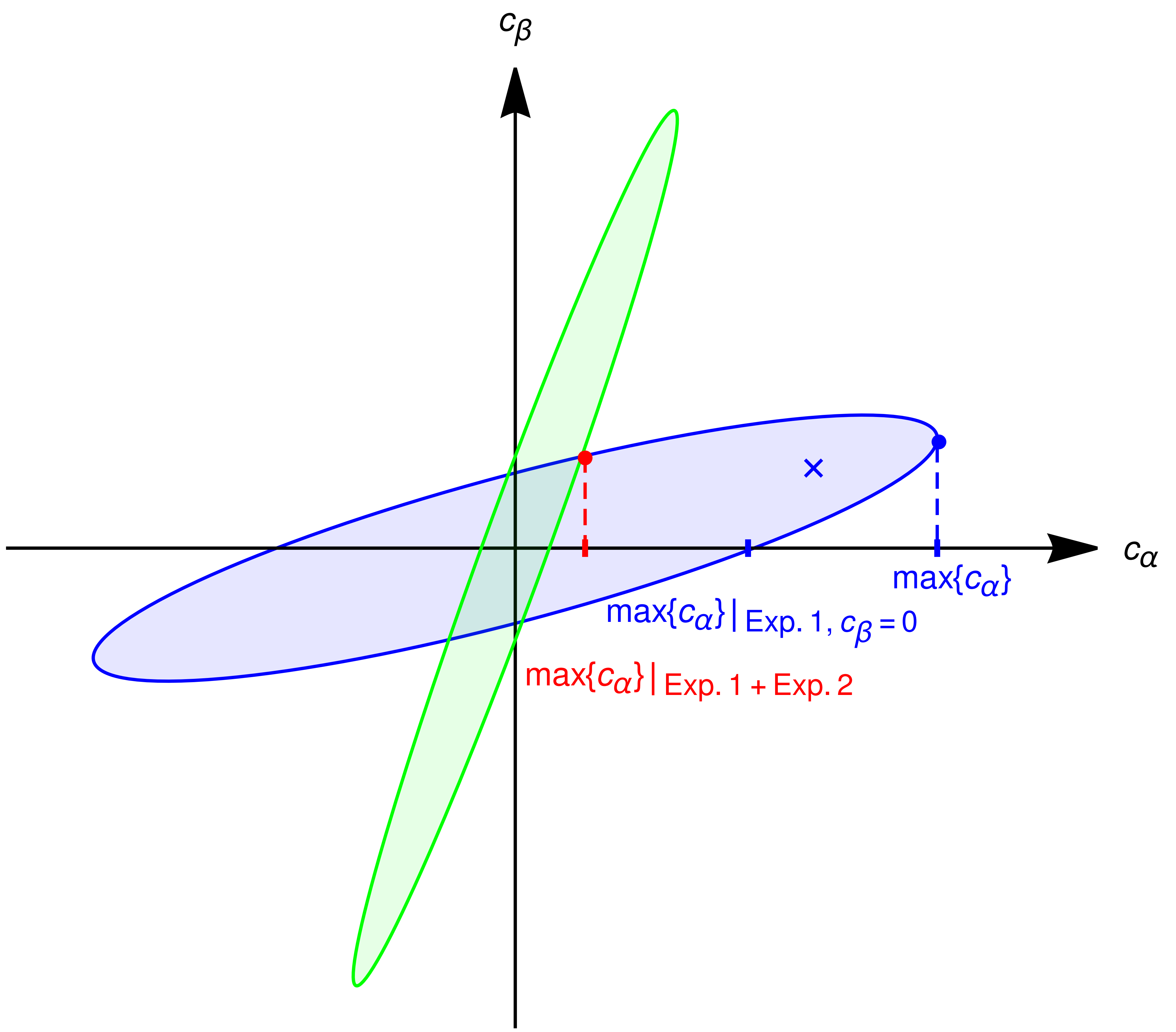
- Construct the Lagrangian

$$L = c_\alpha - \lambda \left(\sum_{\exp}^{n} \left[\chi^2_{\exp} - \chi^2_{\exp,\min} \right] - 2.71 \right)$$

$$\chi^2_{\exp} = -2 \ln \left[\mathscr{L}(m_\chi, N^{\rm sig}_{\exp}) \right]$$

- Maximum coupling

$$c_\beta^{\max} = \frac{\delta_\alpha}{4\lambda} (X_{\alpha\beta})^{-1}$$



In preparation: Brenner, Herrera, Ibarra, Scopel, Kang, GT, arXiv: 2107.xxxxx

Impact of operator interference in DM direct detection: combined experiments

$$X_{\alpha\beta} = \sum_{\text{exp}}^{n} \left[(\mathbb{R}_{\text{exp}})_{\alpha\beta} \left(1 - \frac{N_{\text{exp}}^{\text{obs}}}{N_{\text{exp}}^{\text{sig}} + N_{\text{exp}}^{\text{back}}} \right) \right]$$

- Expected events in an experiment

$$\sum_{\text{exp}}^{n} N_{\text{exp}}^{\text{sig}} = \frac{1}{16\lambda^2} \sum_{\text{exp}}^{n} \left(X^{-1}\, \mathbb{R}_{\text{exp}}\, X^{-1} \right)_{\alpha\alpha}$$

In preparation: Brenner, Herrera, Ibarra, Scopel, Kang, GT, arXiv: 2107.xxxxx

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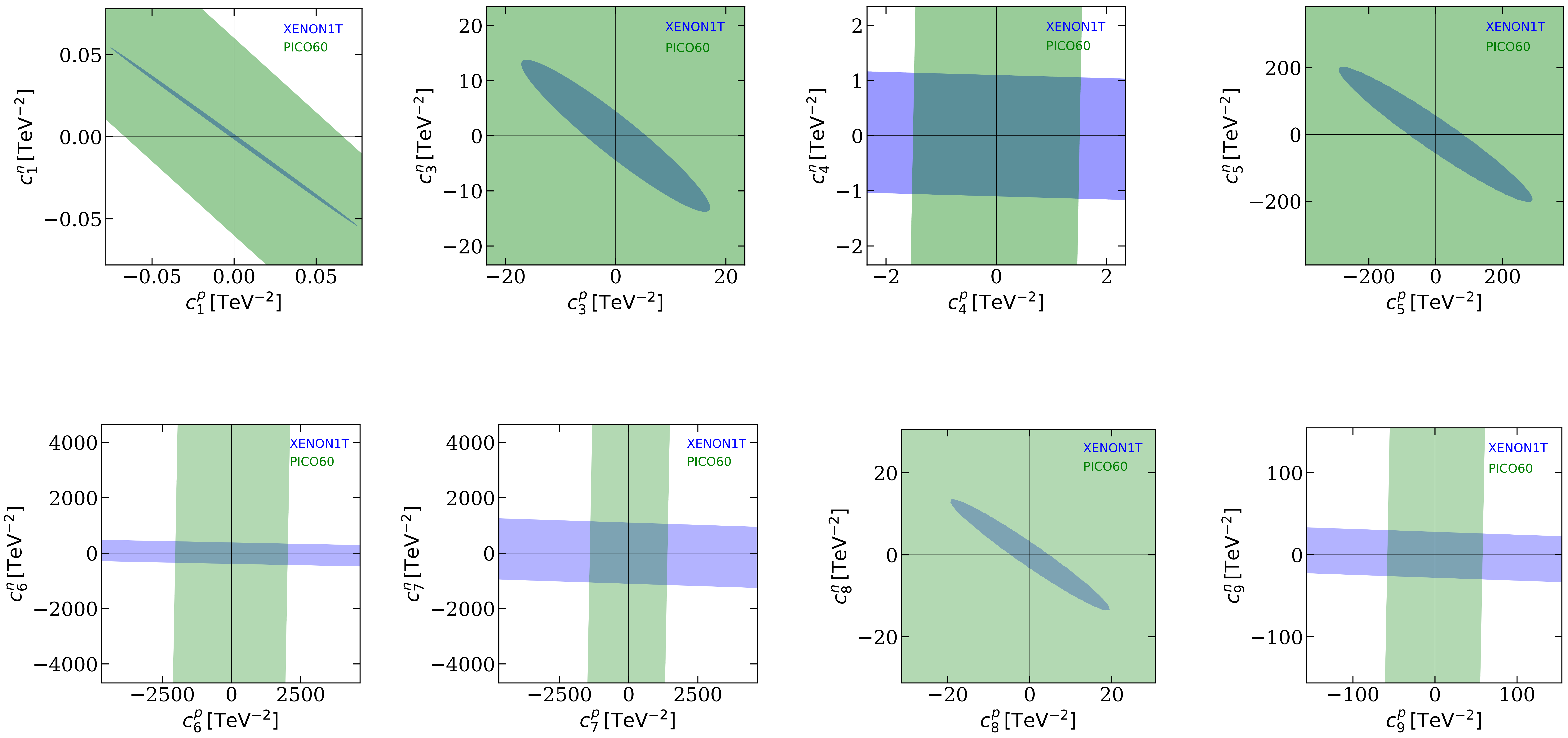
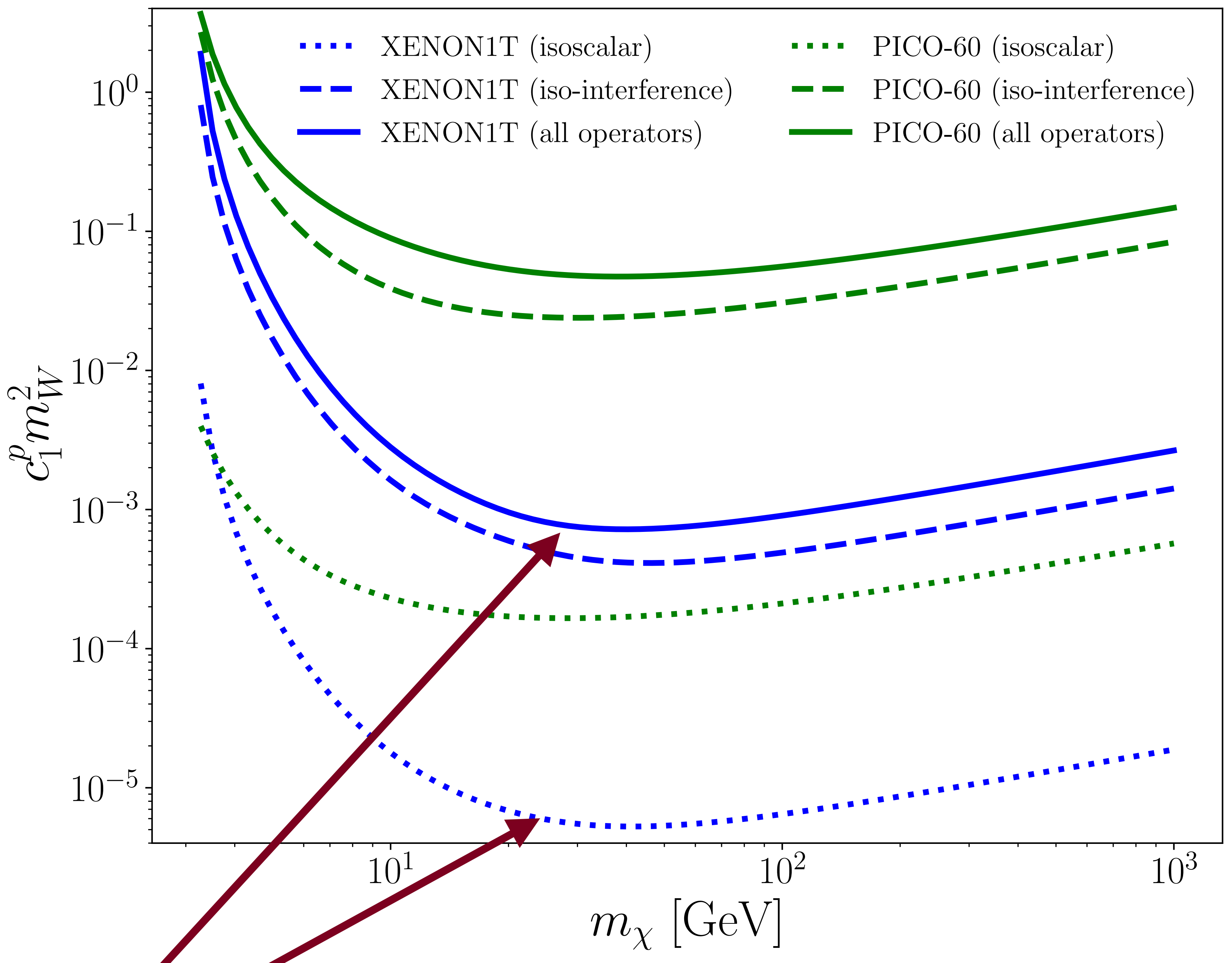


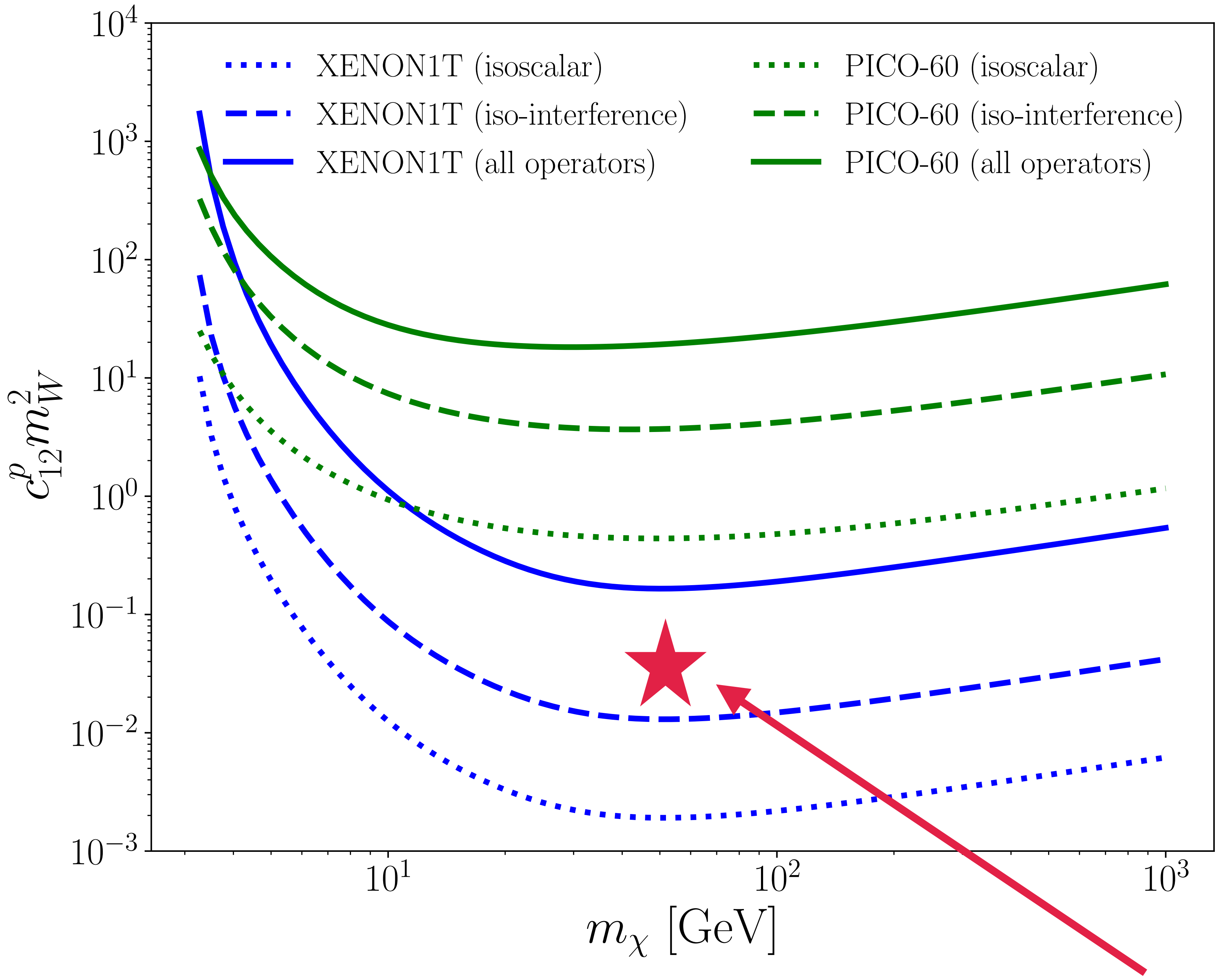
Results: single experiment

$M(q^0)$ $c_1 c_3$



2 orders of magnitude

$\Phi(q^2)$, $\Sigma(q^0)$ $c_{11}c_{12}$, $c_{12}c_{15}$

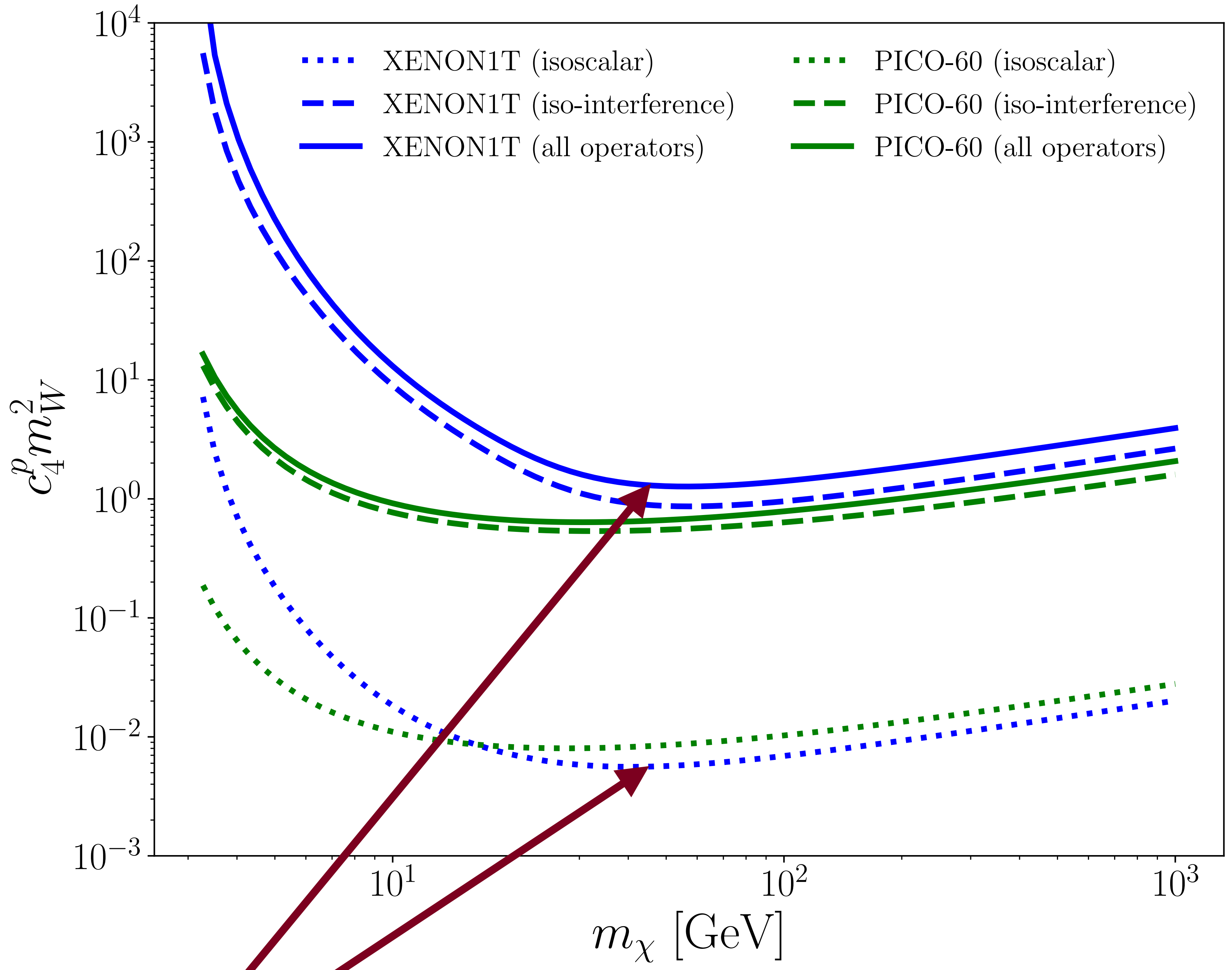


allowed or not?

In preparation: Brenner, Herrera, Ibarra, Kang, Scopel, GT, arXiv: 2107.xxxxx

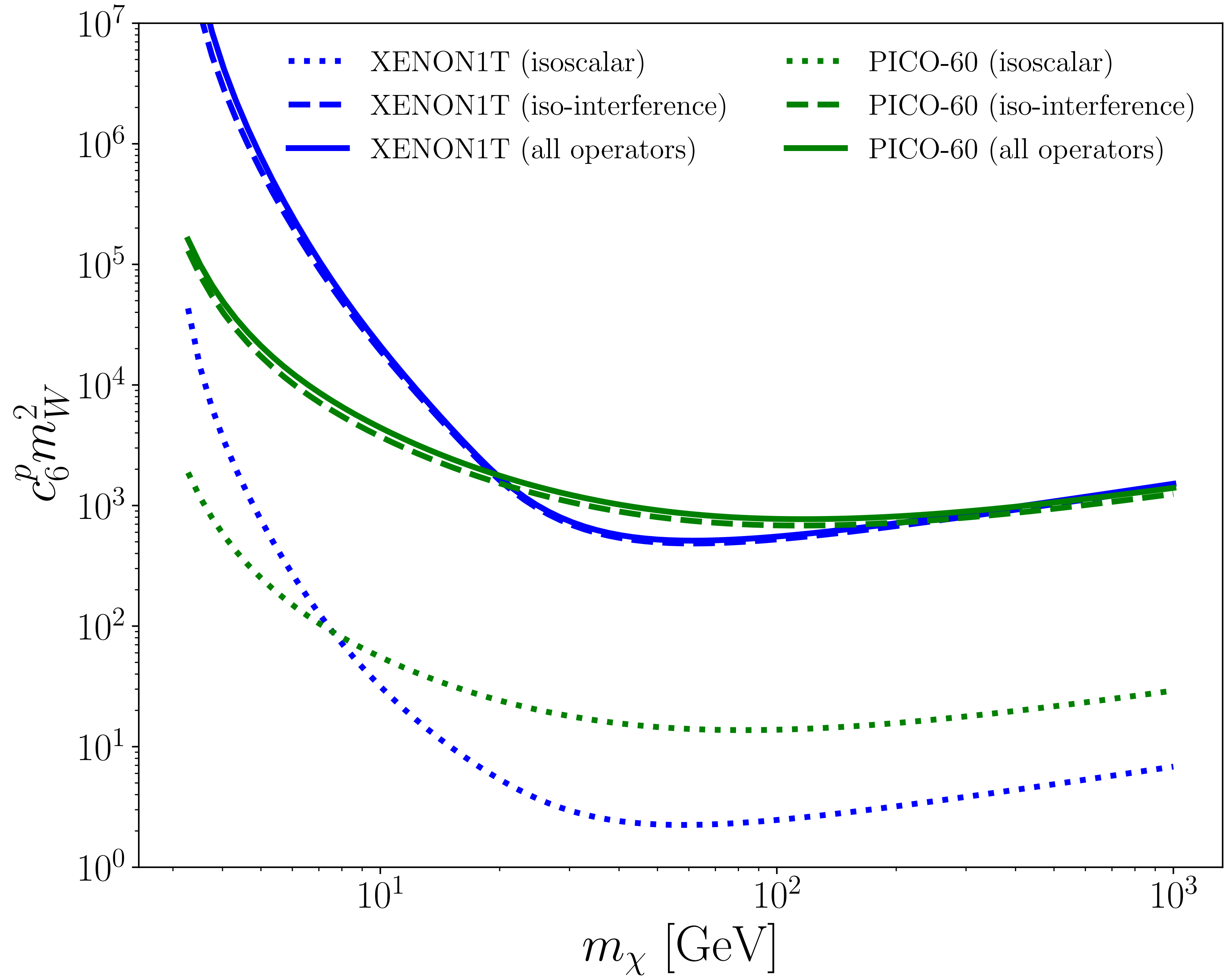
Results: single experiment

$\Sigma(q^0)$ $c_4c_5,\ c_4c_6$



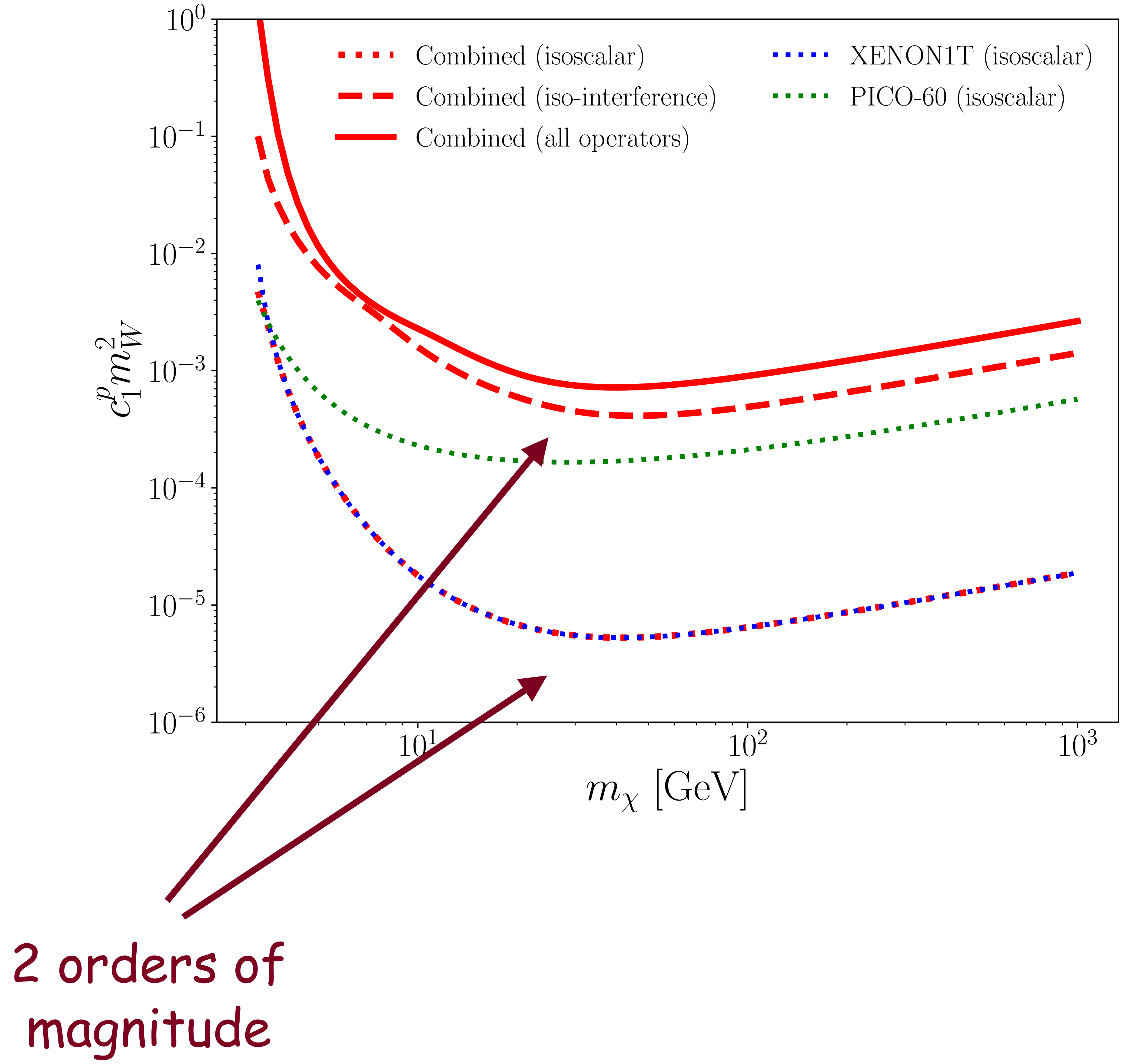
3 orders of magnitude

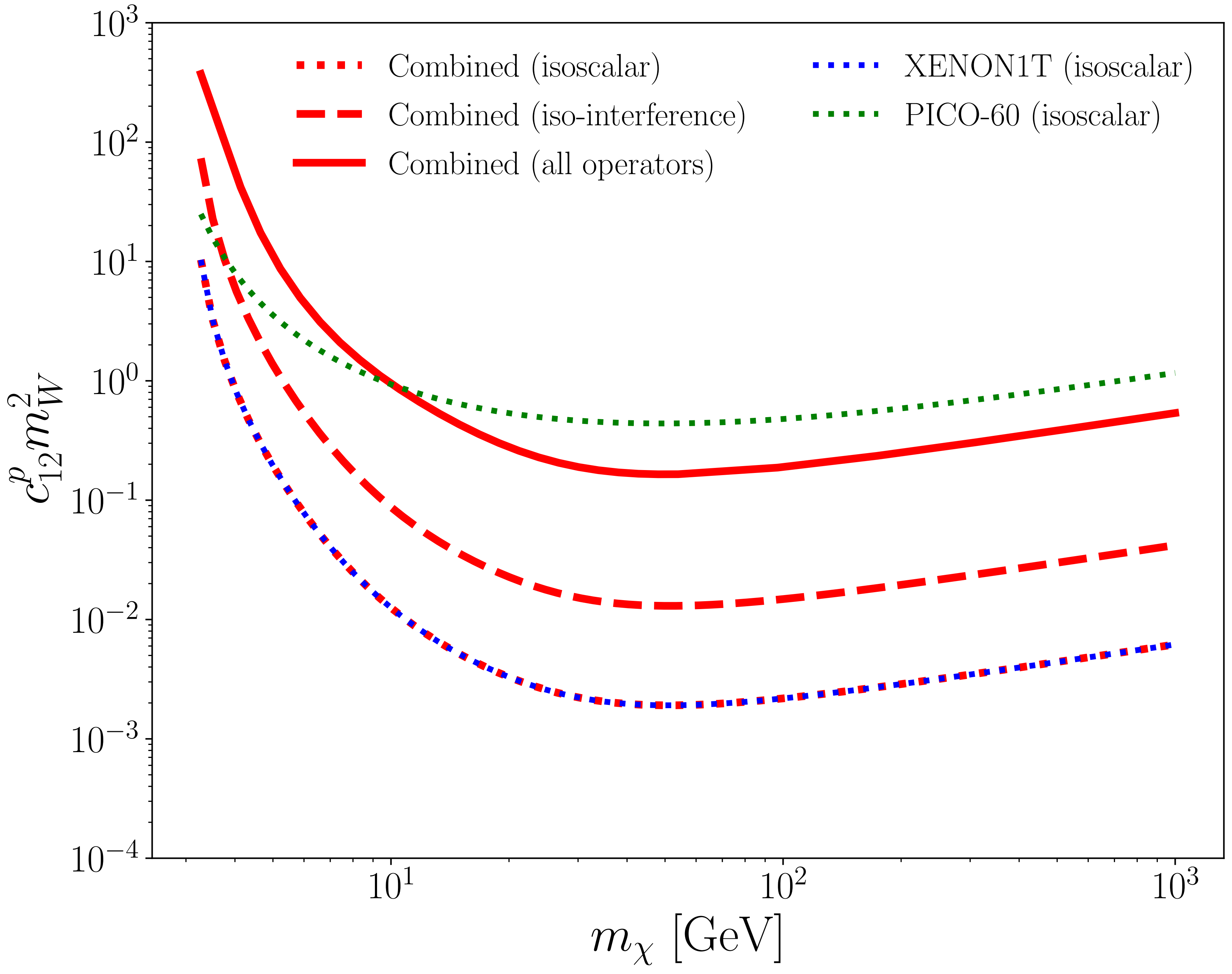
$\Sigma(q^4)$ c_4c_6



In preparation: Brenner, Herrera, Ibarra, Kang, Scopel, GT, arXiv: 2107.xxxxx

Results: combined experiment





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Summary

- Consideration of single coupling leads to stringent exclusion limits
- Interference between different coupling strengths is an important effect to take into account
- Extended method developed by Brenner et. al. to direct detection experiments
- Generalised the method for combined experiments
- For some of the coupling strengths, the limit is relaxed by 2 to 3 orders of magnitude
- As a result, parameter space of different models might be actually allowed
- Practical application: useful for model builders (the closest thing you can get to a model-independent bound)

Mapping between DM and nuclear response functions

$\mathbf{c_j}$	$R_{0k}^{\tau\tau'}$	$R_{1k}^{\tau\tau'}$	$\mathbf{c_j}$	$R_{0k}^{\tau\tau'}$	$R_{1k}^{\tau\tau'}$
c_1	$M(q^0)$	-	c_3	$\Phi''(q^4)$	$\Sigma'(q^2)$
c_4	$\Sigma''(q^0)$,$\Sigma'(q^0)$	-	c_5	$\Delta(q^4)$	$M(q^2)$
c_6	$\Sigma''(q^4)$	-	c_7	-	$\Sigma'(q^0)$
c_8	$\Delta(q^2)$	$M(q^0)$	c_9	$\Sigma'(q^2)$	-
c_{10}	$\Sigma''(q^2)$	-	c_{11}	$M(q^2)$	-
c_{12}	$\Phi''(q^2)$,$\tilde{\Phi}'(q^2)$	$\Sigma''(q^0)$,$\Sigma'(q^0)$	c_{13}	$\tilde{\Phi}'(q^4)$	$\Sigma''(q^2)$
c_{14}	-	$\Sigma'(q^2)$	c_{15}	$\Phi''(q^6)$	$\Sigma'(q^4)$

Recoil Energy and transfer momentum

$$v_{min}^2 = \frac{q^2}{4\mu_T^2} = \frac{m_T E_R}{2\mu_T^2},$$

$$v_{min}^* = \sqrt{\frac{2\delta}{\mu_{\chi N}}},$$

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

DM Velocity distribution

$$
\begin{aligned}
f(\vec{v}_T, t) &= N\left(\frac{3}{2\pi v_{rms}^2}\right)^{3/2} e^{-\frac{3|\vec{v}_T + \vec{v}_E|^2}{2v_{rms}^2}} \Theta(u_{esc} - |\vec{v}_T + \vec{v}_E(t)|), \\
N &= \left[\mathrm{erf}(z) - \frac{2}{\sqrt{\pi}} z e^{-z^2}\right]^{-1},
\end{aligned}
$$

$$
|\vec{v}_E(t)| = v_\odot + v_{orb} \cos\gamma \cos\left[\frac{2\pi}{T_0}(t - t_0)\right],
$$

Interference

for O_1, (1)

$$R_{exp.} \propto \left[C_p Z + (A-Z) C_n \right]^2$$

$$R_{exp.} \propto C_p^2 \left[Z + (A-Z) \frac{C_n}{C_p} \right]^2$$

Compare, $R_{ob} = R_{exp.}$

$$\Rightarrow \quad C_p^2 = \frac{R_{ob}}{\left[Z + (A-Z) \frac{C_n}{C_p} \right]^2}$$

or

$$C_p = \frac{\sqrt{R_{ob}}}{\left[Z + (A-Z) \frac{C_n}{C_p} \right]}$$

C_p^{max}, when $Z = -(A-Z) \frac{C_n}{C_p}$.

Similarly for operator interference,

$$\left\{ C_p^{max} = \frac{\sqrt{R_{ob}}}{\left[a O_1 + ab O_3 + ba O_3 + b O_3 \right]} \right\}$$