What can nEDM tell us about the EFT of DM-quark scattering?

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Manuel Drees, RM - arXiv:1907.10075
PLB B799 (2019) 135039

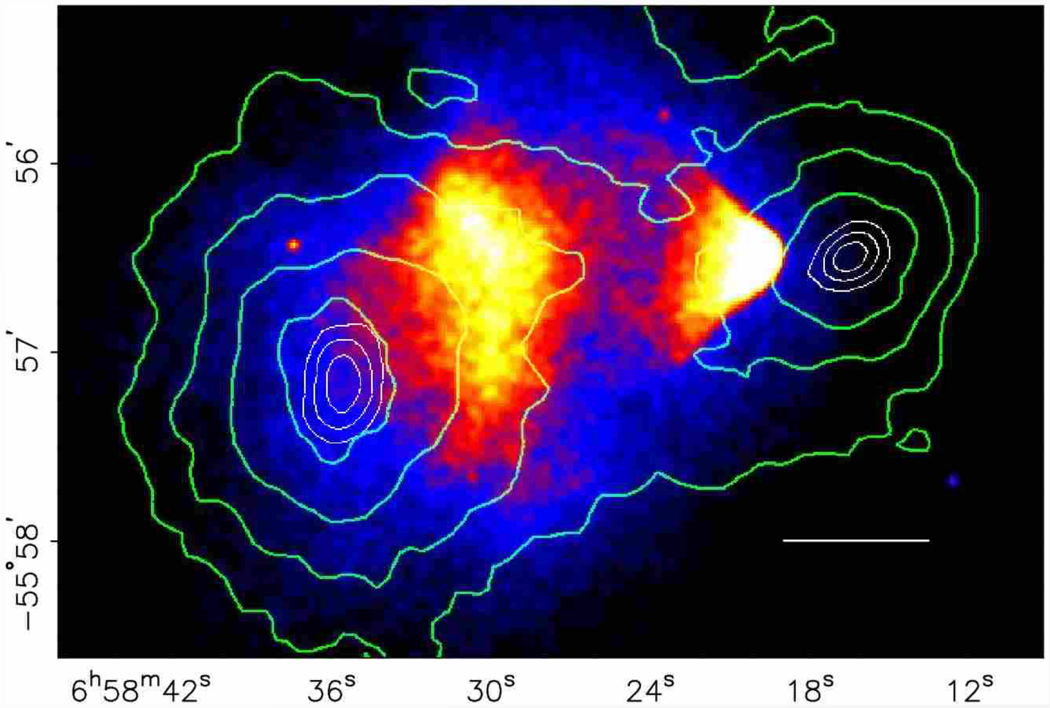
January 23, 2020
GGI Lectures - Student Seminar

Contents

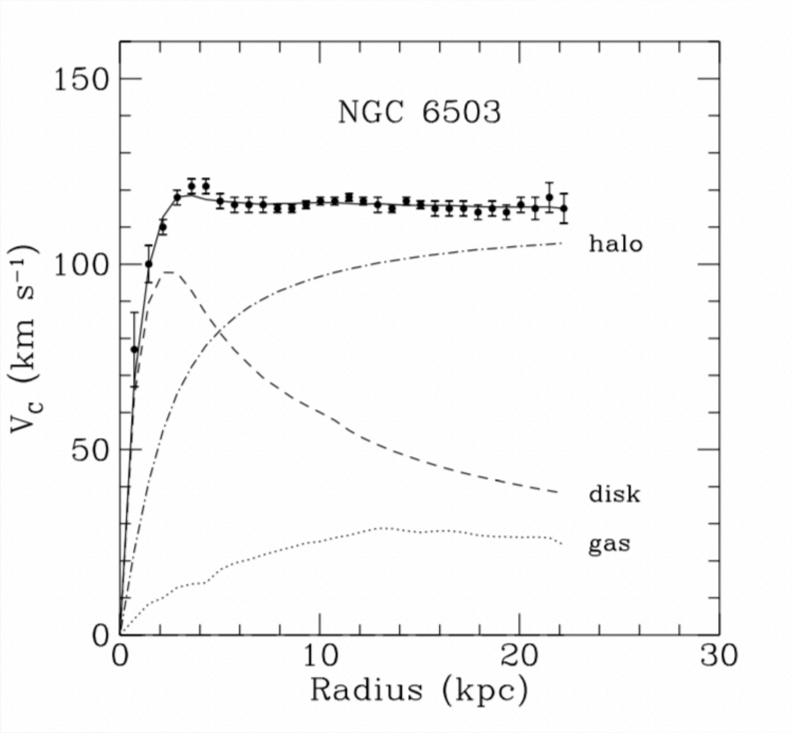
- Dark Matter Direct Detection
- Non-Relativistic Effective Field Theory (NREFT) of DM-quark scattering
- Simplified Models: better or worse?
- neutron EDM takes a razor to NREFT operators

Dunkle Materie

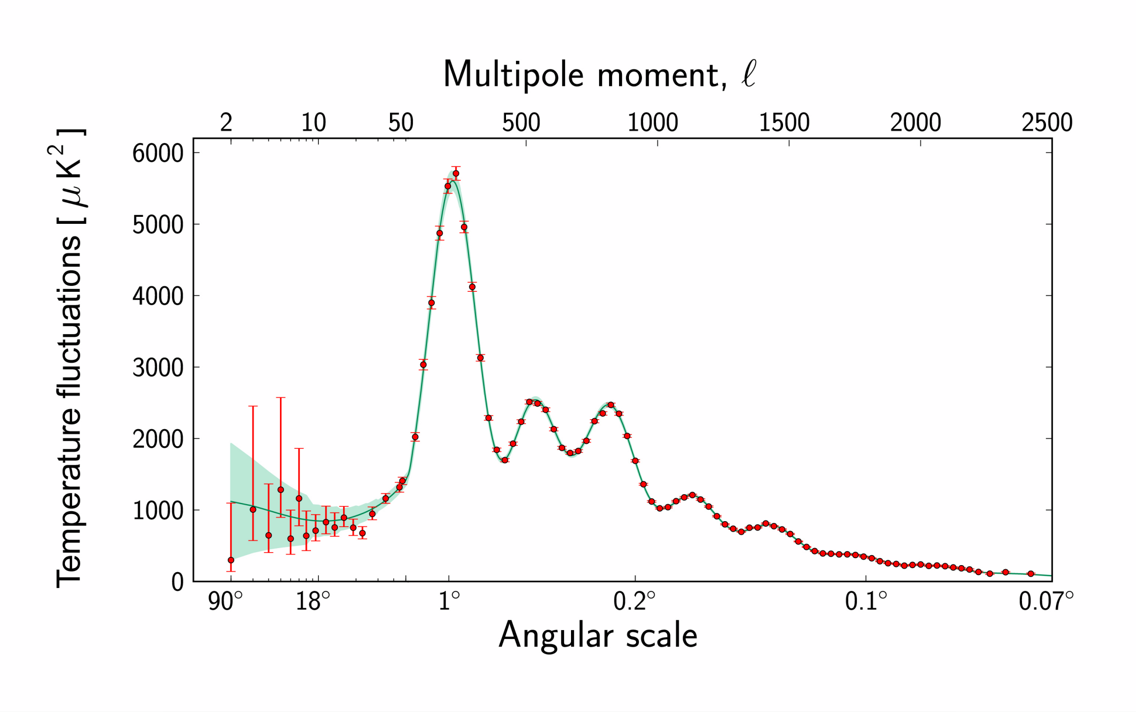
Zwicky ’32; Rubin and Ford ’72, ‘80



Clowe et al., Astrophys.J. 648 (2006) L109-L113



Begeman, Not R. Astr. Soc. (1991)



PLANCK 2018

Direct Detection ("You Shook Me")

Goodman and Witten - Phys.Rev. D31 (1985) 3059

Drukier, Freese and Spergel - Phys.Rev. D33 (1986) 3495-3508

- DM velocity in the solar neighbourhood $v/c \sim \mathcal{O}(10^{-3})$
  Non-Relativistic!

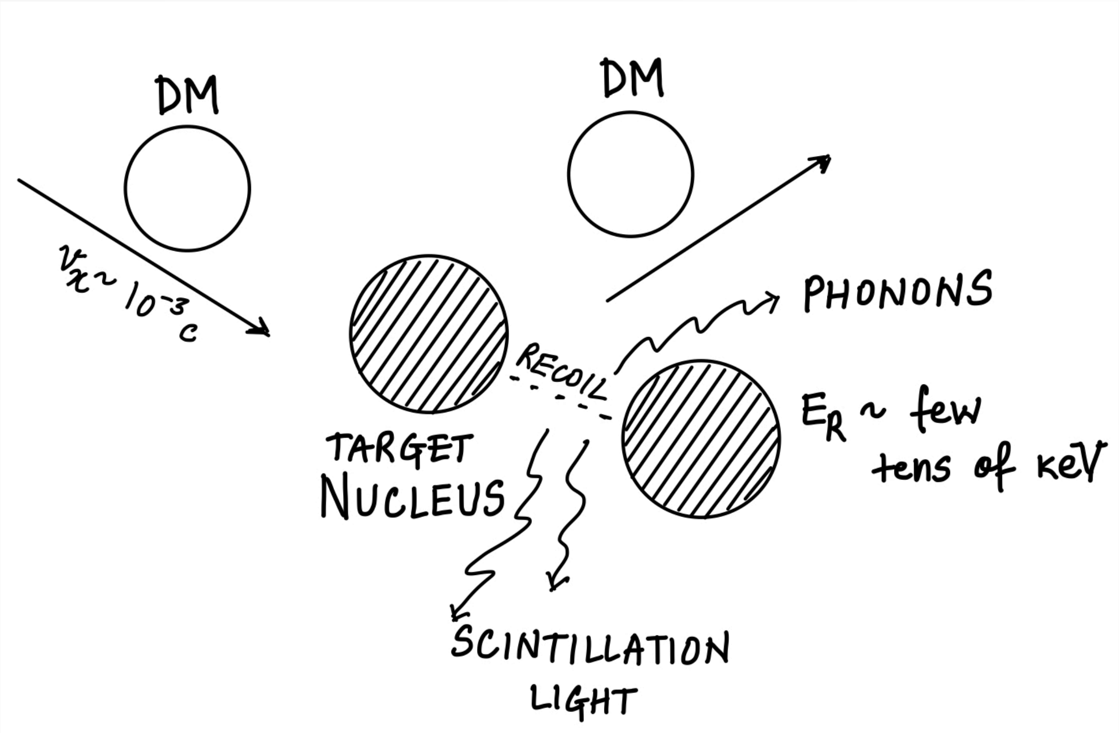
- DM with weak-scale masses and electroweak-strength couplings to SM

$$\Omega_\chi h^2 \approx \frac{T_0^3}{M_{Pl}^3 \langle \sigma_{ann} v \rangle} \simeq \frac{0.1\, pb\, c}{\langle \sigma_{ann} v \rangle}$$

For a GeV-ish DM (WIMP),

- Momentum transfer ~ $\mathcal{O}$(10-100 MeV)
- Recoil Energy ~ $\mathcal{O}$(keV)

$$E_R = \frac{q^2}{2m_N} \qquad |q| \simeq \min[m_\chi v, m_A v]$$



Look for light or heat or charge!

Go deep underground and wait...

SuperCDMS, EDELWEISS, CRESST, CDEX-10, LUX,
PandaX-II, XENON1T, DarkSide-50, DEAP-3600, ~~DAMA/LIBRA~~

- The rate, differential in recoil energy, for DM-nucleus scattering per unit time per unit detector mass

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi\, m_N} \int_{v>v_{\min}}^{v_{\rm esc}} d^3v\, v\, f(v,t)\, \frac{d\sigma}{dE_R} \qquad \text{where} \quad v_{\min} = \sqrt{\frac{m_N\, E_R^{\rm th}}{2\mu_{\chi\, N}^2}}$$

$$R = \text{Exposure} \times \int dE_R\, \epsilon(E_R)\, \frac{dR}{dE_R}$$

- A lot of experimental details go into calculating R, but roughly

$$R \sim 0.2\, \frac{events}{tonne\ year}\left[\frac{A}{100} \times \frac{\sigma_{\chi-N}}{10^{-46}\ cm^{-2}} \times \frac{\langle v\rangle}{220\ km\, s^{-1}} \times \frac{\rho_\chi}{0.3\, GeV\ cm^{-3}}\right]$$

Either it couples to spin or not!

Spin Independent or Spin Dependent Interactions

- One has to specify the DM-quark interactions! $\Longrightarrow \frac{d\sigma_{\chi N}}{dE_R} = \frac{m_N}{2\,\pi\,v^2}\,\langle\,|\,\mathscr{M}_{sc}|^2\,\rangle$

- Reduce theory bias and consider relativistic effective operators

Spin Independent

$\bar{\chi}\chi\,\bar{N}N$

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\pi v^2}\,[Zf_p + (A-Z)f_n]^2\,F_{SI}^2(q^2)$$

- A^2 enhancement
- favourable target: nuclei with large A

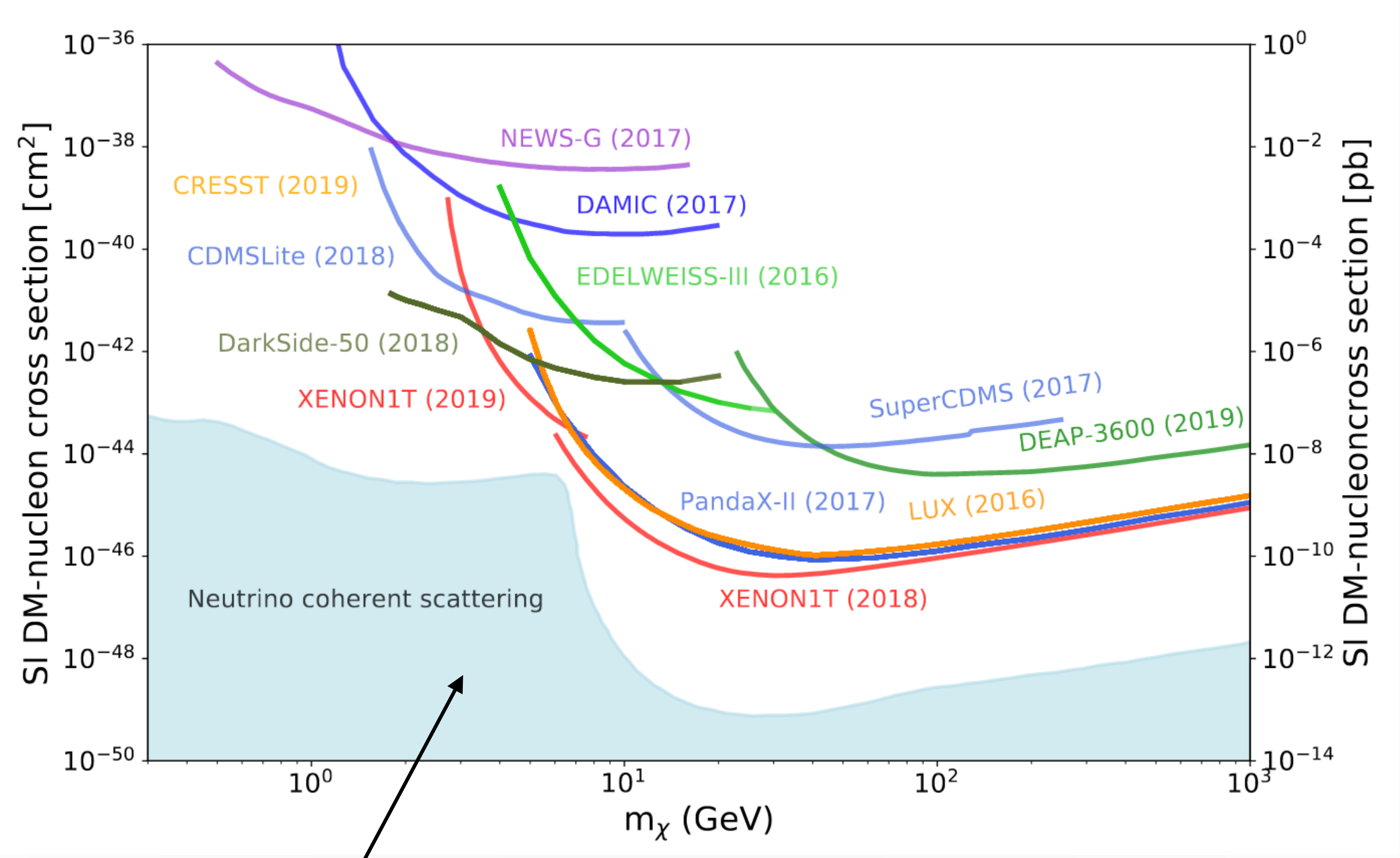
Spin Dependent

$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{N}\gamma^\mu\gamma^5 N$

$$\frac{d\sigma}{dE_R} = \frac{8m_N}{\pi v^2}\,G_F^2\,\frac{J(J+1)}{J}[a_p\,\langle S_p\rangle + a_n\,\langle S_n\rangle]^2\,F_{SD}^2(q^2)$$

- No enhancement, spin averaged squared scaling
- favourable target: nuclei with net non-zero angular momentum

What's been probed so far!

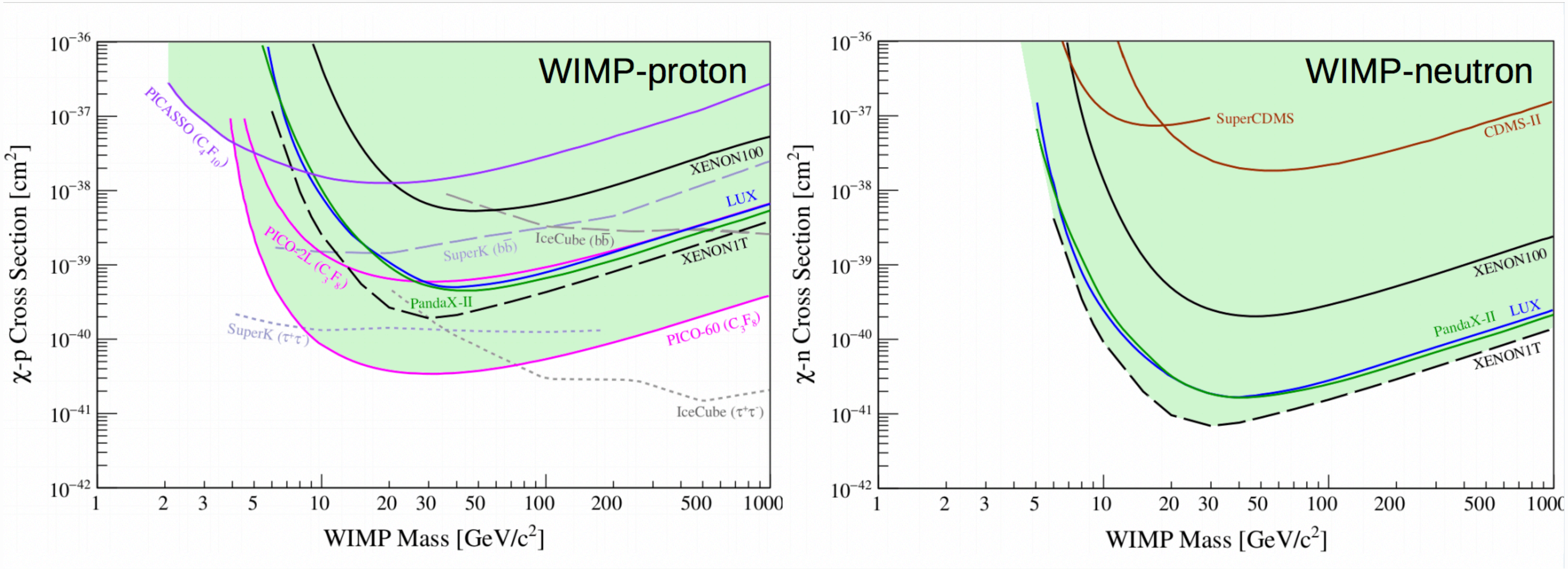


Baudis and Profumo, PDG 2019

irreducible background due to
coherent neutrino-nucleus scattering

Cabrera, Krauss and Wilczek - Phys.Rev.Lett. 55 (1985) 25;
Monroe and Fisher - Phys. Rev. D76 (2007) 033007

What's been probed so far!



M. Schumann, ZPW 2019 "A New Look at Dark Matter"

Non-Relativistic Effective Field Theory (NREFT)

Fan, Reece and Wang - JCAP 1011 (2010) 042; Fitzpatrick et al. - JCAP 1302 (2013) 004; Anand, Fitzpatrick and Haxton - Phys.Rev. C89 (2014) no.6, 065501

- Galilean symmetry dictates the basis of operators

$$i\vec{q}\,,\ \vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\,\mu_N}\,,\ \vec{S}_N\,,\ \vec{S}_\chi$$

$$\mathcal{O}_1 = 1_\chi 1_N \qquad \mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^{\perp}$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}) \qquad \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N \qquad \mathcal{O}_{10} = i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}) \qquad \mathcal{O}_{11} = i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$$

$$\mathcal{O}_6 = (\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi) \qquad \mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^{\perp})$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^{\perp} \qquad \mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^{\perp})(\frac{q}{m_N} \cdot \vec{S}_N)$$

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

NLO +NNLO terms retained

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SI → $\mathcal{O}_1 = 1_\chi 1_N$

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

SD → $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

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

$\mathcal{O}_6 = (\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^{\perp}$

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

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($\mathcal{O}_{10}$–$\mathcal{O}_{12}$): P-odd, T-odd

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

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

$\vec{v}_T,\ \vec{q} \xrightarrow{P,T} -\vec{v}_T,\ -\vec{q}$

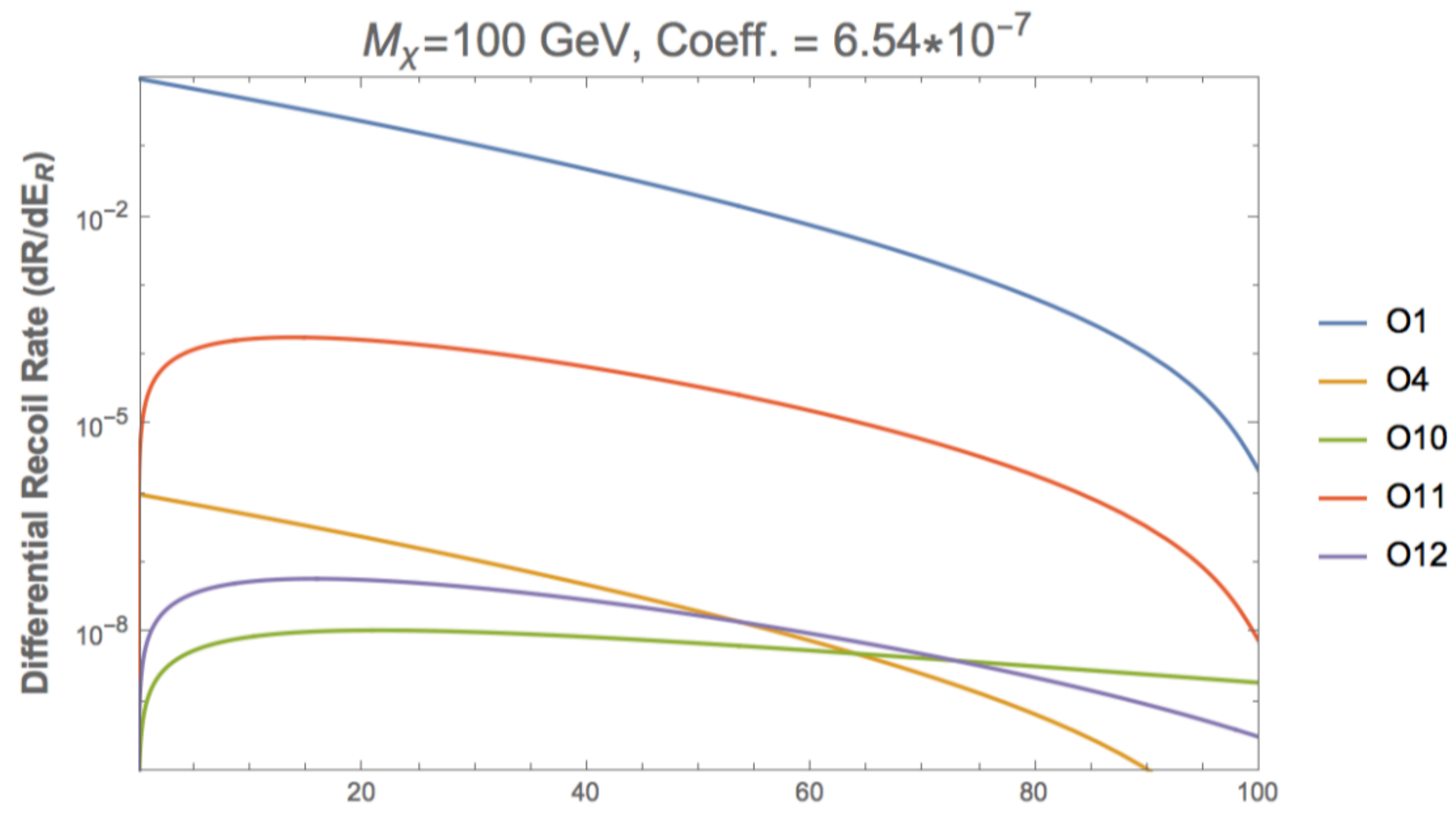
$\vec{S} \xrightarrow{P} \vec{S}$ $\quad i \xrightarrow{T} -i$

$\vec{S} \xrightarrow{T} -\vec{S}$

NLO +NNLO terms retained

Hierarchy: not all operators are equal!

- Suppression of operators due to
  - DM velocity $\quad \vec{v}_T^{\,2} \sim \mathcal{O}(10^{-6})$
  - Momentum transfer $\quad \vec{q}^{\,2}/m_N^2 \sim \mathcal{O}(10^{-2})$



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

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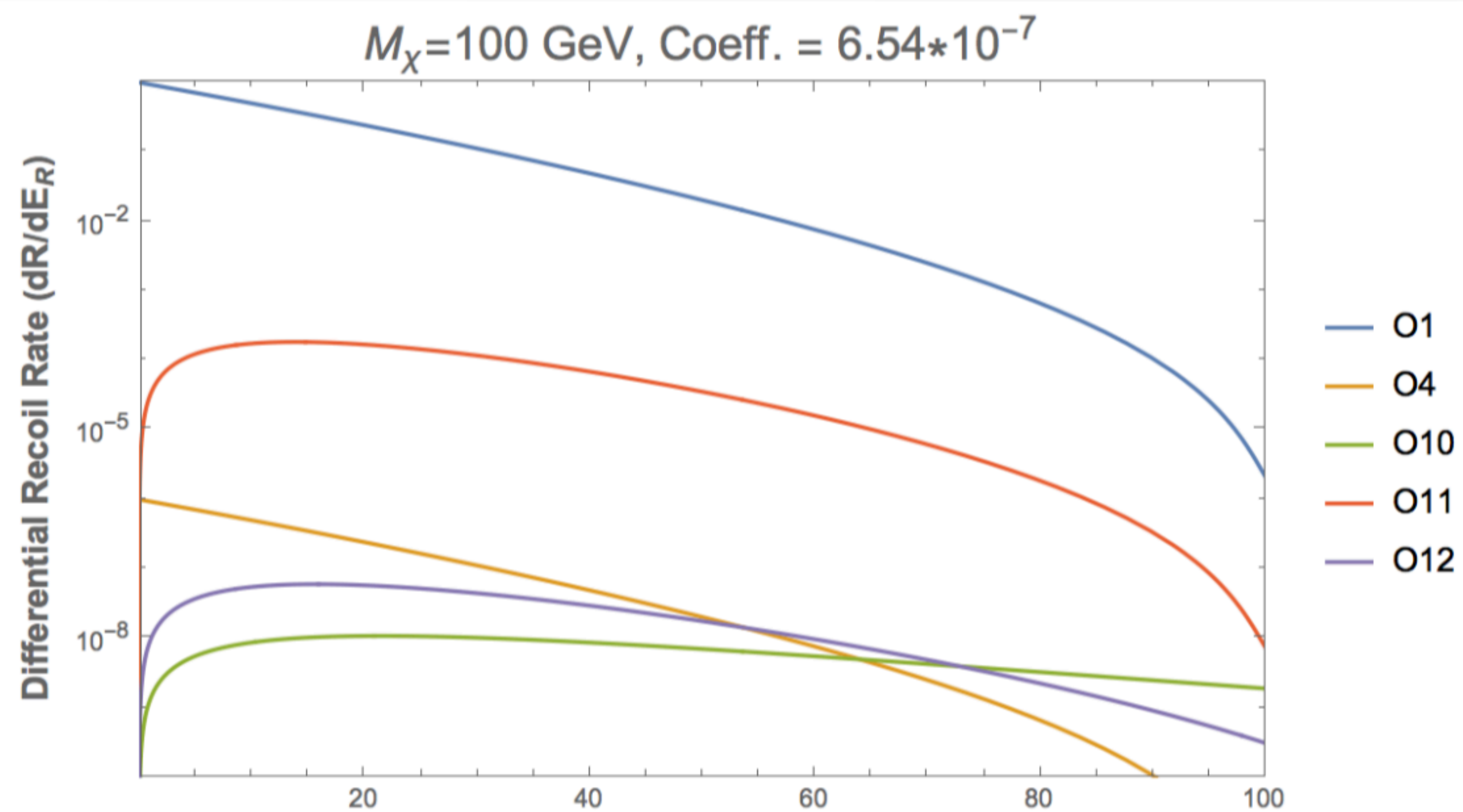


$$\mathcal{O}_{10} = i\frac{\vec{q}}{m_N}\cdot\vec{S}_N$$

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

$$\mathcal{O}_{12} = \vec{S}_\chi\cdot(\vec{S}_N\times\vec{v}^\perp)$$

- Global scans found P-odd,T-odd operators operators to be <u>as strongly constrained as zeroth order SD interactions</u> by experiments!

Catena and Gondolo - JCAP 1409 (2014) no.09, 045; Catena - JCAP 1407 (2014) 055

If contributions of $\mathcal{O}_1$ to the DM-nucleon scattering cross sections vanish, what are the prospects of detecting signals from P-odd, T-odd operators at direct detection experiments?

- Need a CP violating theory to generate P-odd, T-odd NREFT operators
  [CPT Theorem]

- nEDM: a powerful probe of flavour diagonal CP violating SM extensions

$$|d_N| < 2.9 \times 10^{-29} \;\; e\,.\,cm \;\; (90\,\%\,C\,.\,L.)$$

Particle Data Group (PDG) - Phys,Rev. D98 (2018) no.3, 030001
Pendelbury et al. - Phys.Rev. D92 (2015) no.0, 092003

- investigate P-odd, T-odd NREFT operators using simplified models respecting SU(3) $\times$ U(1)   Dent et al. - Phys.Rev. D92 (2015) no.6, 063515

Model I

- Complex spin-0 DM S and heavy quark-like mediator Q_k; odd under a $\mathbb{Z}_2$

- CP broken explicitly: complex and flavour universal scalar and pseudo-scalar couplings

$$\mathcal{L}^{\text{Model I}} = \mathcal{L}_{SM} + \partial_\mu S^\dagger \partial_\mu S - m_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2 + i\bar{Q}_k \not{D} Q_k - m_{Q_k} \bar{Q}_k Q_k - S\bar{Q}_k (y_1^q + y_2^q \gamma^5) q_l - S^\dagger \bar{q}_l (y_1^{q\,\dagger} - y_2^{q\,\dagger} \gamma^5) Q_k$$

- U(1) invariance implies that at least two mediators required if DM S is to couple to both u- and d-type quarks

- Assume each mediator Q_k couples to a single SM quark q to avoid FCNCs

Model I

- Integrating out the mediator Q_k gives the following effective operators

$$\mathcal{L}_{\rm eff}^{\rm Model\ I} \supset c_1^{q,d5}\,(S^\dagger S)\,\bar{q}\,q \;+\; c_{10}^{q,d5}\,(S^\dagger S)\,\bar{q}\,i\gamma^5\,q \;+\; c_1^{q,d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\,q \;+\; c_7^{q,d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\gamma^5\,q\,.$$

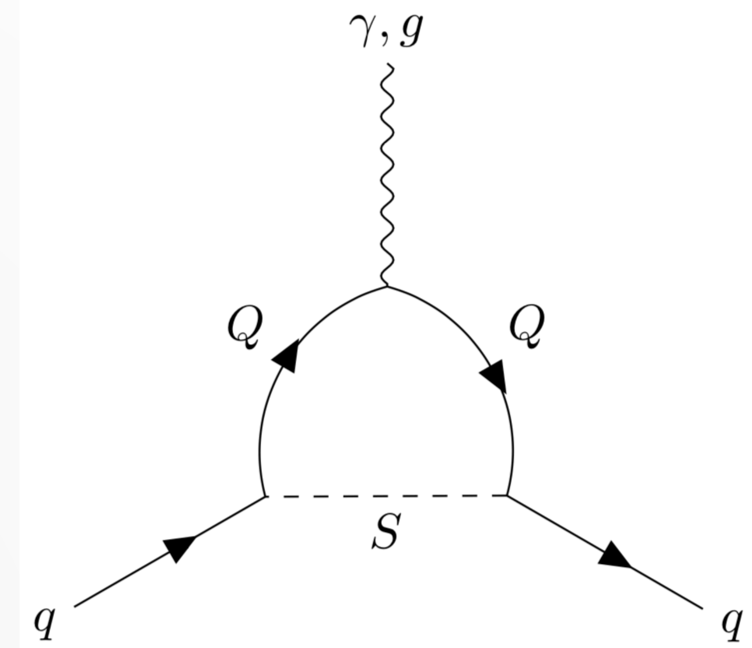
$S^\dagger \Gamma_S S\ \bar{N}\,\Gamma_N\,N$		$c_i^q\ \mathcal{O}_i$
$c_1^{q,d5} S^\dagger S\ \bar{q}q$	$\longrightarrow$	$\left(\frac{m_{Q_q}}{m_S}\frac{\lvert y_1^q\rvert^2-\lvert y_2^q\rvert^2}{m_{Q_q}^2-m_S^2}+\frac{m_q}{m_S}\frac{\lvert y_1^q\rvert^2+\lvert y_2^q\rvert^2}{m_{Q_q}^2-m_S^2}\right) f_{Tq}^N\,\mathcal{O}_1$
$c_{10}^{q,d5} S^\dagger S\ \bar{q}i\gamma^5 q$	$\longrightarrow$	$\frac{m_{Q_q}}{m_S}\frac{\mathrm{Im}(y_1^q y_2^{q\,\dagger})}{m_{Q_q}^2-m_S^2}\,2\tilde{\Delta}^N\,\mathcal{O}_{10}$
$c_1^{q,d6} i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\ \bar{q}\gamma^\mu q$	$\longrightarrow$	$\frac{\lvert y_1^q\rvert^2+\lvert y_2^q\rvert^2}{m_{Q_q}^2-m_S^2}\,\mathcal{N}_q^N\,\mathcal{O}_1$
$c_7^{q,d6} i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\ \bar{q}\gamma^\mu\gamma^5 q$	$\longrightarrow$	$-\frac{\mathrm{Re}(y_1^q y_2^{q\,\dagger})}{m_{Q_q}^2-m_S^2}\,2\Delta_q^N\,\mathcal{O}_7$

← P-odd, T-odd (highlighting the $c_{10}^{q,d5}$ row)

- quark EDM: coefficient of a dim-5 P-odd, T-odd term $-\frac{i}{2}\,\bar{q}\,\sigma_{\mu\nu}\gamma_5\,q\,F^{\mu\nu}$ at vanishing momentum transfer

$$d_q|_{\text{Model I}} = \frac{1}{(4\pi)^2}\,eQ_Q\,m_Q\,\underline{\text{Im}(y_1 y_2^\dagger)}\,F(m_q^2, m_S^2, m_Q^2)$$

$$F(m_q^2, m_S^2, m_Q^2) = \int_0^1 dz \frac{(1-z)^2}{z^2 m_q^2 + z(m_S^2 - m_Q^2 - m_q^2) + m_Q^2}$$



- use lattice results and QCD sum rules

$$d_n = g_T^u d_u + g_T^d d_d + g_T^s d_s + 1.1\,e\,(0.5\,\tilde{d}_u + \tilde{d}_d)$$

$$g_T^u = -0.233(28) \quad g_T^d = 0.774(66) \quad g_T^s = 0.009(8)$$

(assume PQ mechanism)

PNDME Collaboration - Phys.Rev. D92 (2015) no.9, 094511;
Bhattacharya et al. - Phys.Rev.Lett. 115 (2015) no.21, 212002;
Pospelov and Ritz - Phys.Rev. D63 (2001) 073015

- However, $\mathcal{O}_1$ dominates scattering; its contribution can be made to vanish iff

$$S^\dagger S\,\bar{q}q \longrightarrow \left(\frac{m_Q}{m_S}\frac{|y_1|^2 - |y_2|^2}{m_Q^2 - m_S^2} + \frac{m_q}{m_S}\frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\right) f_{Tq}^N\,\mathcal{O}_1$$

$$i\left(S^\dagger \overleftrightarrow{\partial}_\mu S\right)\,\bar{q}\gamma^\mu q \longrightarrow \frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\,\mathcal{N}_q^N\,\mathcal{O}_1$$

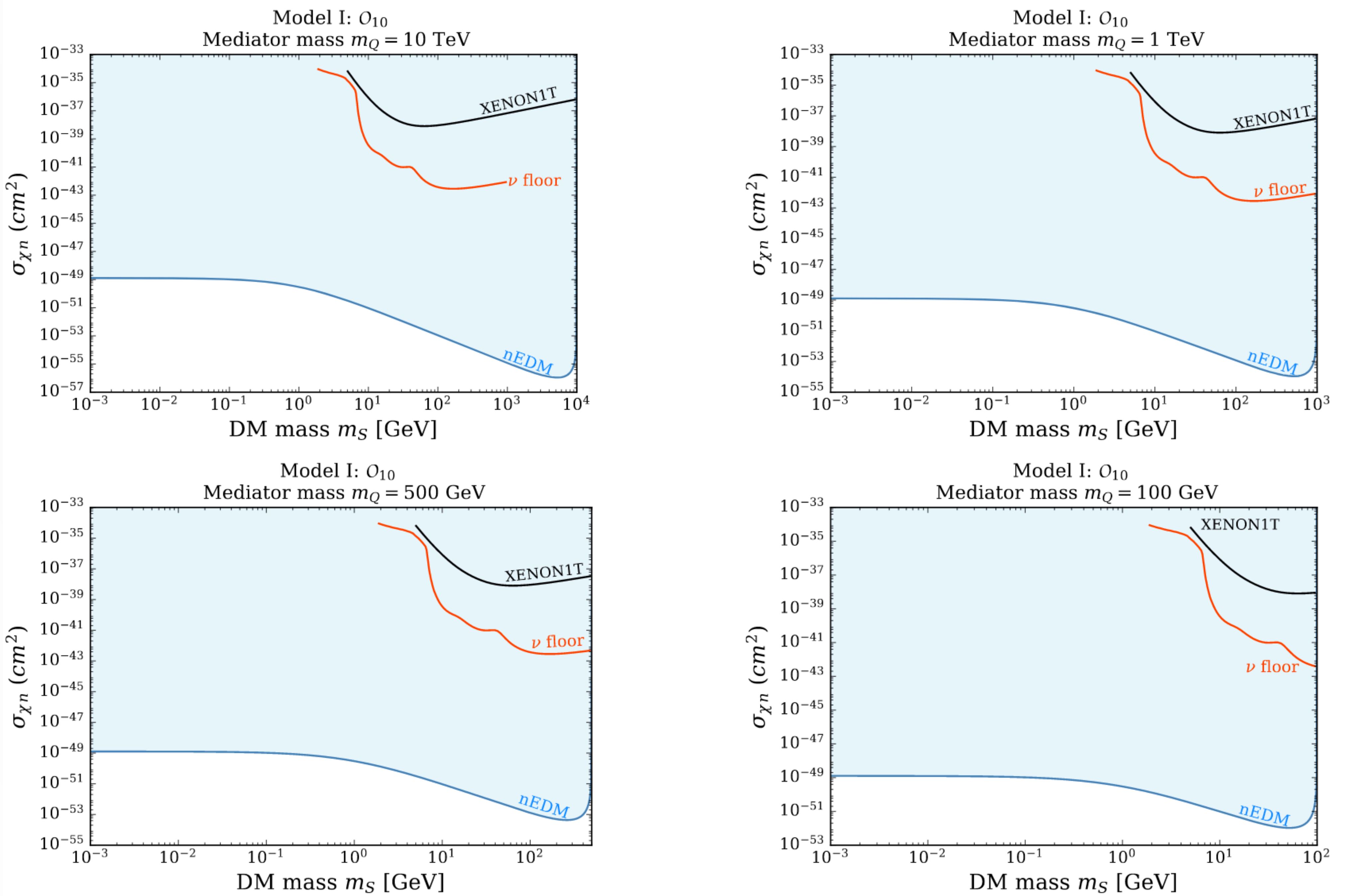
$$f_T^N \equiv \textstyle\sum_q \langle \bar{N}|\,\bar{q}q\,|N\rangle$$
$$\mathcal{N}^N \equiv \textstyle\sum_q \langle \bar{N}|\,\bar{q}\gamma^\mu q\,|N\rangle$$

$$\left|y_1^N\right|^2 = \left(\frac{1 - \frac{\mathcal{N}^N}{f_T^N}\frac{m_S}{m_Q}}{1 + \frac{\mathcal{N}^N}{f_T^N}\frac{m_S}{m_Q}}\right)\left|y_2^N\right|^2$$

- Convert the constraint on $\Im(y_1 y_2^\dagger)$ from nEDM to a cross section using

$$\sigma_{\mathcal{O}_{10}} = \frac{3\mu_{\chi N}^2}{\pi}(c_{10}^N)^2$$

$$d_q|_{\text{Model I}} = \frac{1}{(4\pi)^2}\, eQ_Q\, m_Q\, \text{Im}(y_1 y_2^\dagger)\, F(m_q^2, m_S^2, m_Q^2) \qquad S^\dagger S\, \bar{q} i\gamma^5 q \longrightarrow \frac{m_Q}{m_S}\frac{\text{Im}(y_1 y_2^\dagger)}{m_Q^2 - m_S^2}\, 2\tilde{\Delta}^N\, \mathcal{O}_{10}$$



Model II

- Spin-1/2 DM χ and complex spin-0 mediator Φ_q; odd under a $\mathbb{Z}_2$

- CP broken explicitly: complex and flavour universal scalar and pseudo-scalar couplings

$$\mathcal{L}^{\text{Model II}} = \mathcal{L}_{SM} + i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi + (\partial_\mu\Phi_q^\dagger)(\partial^\mu\Phi_q) - m_{\Phi_q}^2\Phi_q^\dagger\Phi_q - \frac{\lambda_{\Phi_q}}{2}(\Phi_q^\dagger\Phi_q)^2 - (l_1^q\Phi_q^\dagger\bar{\chi}q + l_2^q\Phi_q^\dagger\bar{\chi}\gamma_5 q + h.c.)$$

- generates 9 distinct NREFT operators (and 10 effective dim-6 operators)

Model II

- integrating out the heavy complex scalar Φ_q and using Fierz identities results in

$\bar{\chi}\chi\,\bar{q}q$	$\longrightarrow$	$\frac{1}{4}\frac{\|l_2\|^2-\|l_1\|^2}{m_\Phi^2-m_\chi^2}f_{Tq}^N\,\mathcal{O}_1$	$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q$	$\longrightarrow$	$\frac{\mathrm{Re}(l_1l_2^\dagger)}{m_\Phi^2-m_\chi^2}\mathcal{N}_q^N\,(\mathcal{O}_8+\mathcal{O}_9)$
$\bar{\chi}\chi\,\bar{q}i\gamma^5q$	$\longrightarrow$	$-\frac{1}{2}\frac{\mathrm{Im}(l_1l_2^\dagger)}{m_\Phi^2-m_\chi^2}\Delta\tilde{q}^N\,\mathcal{O}_{10}$	$\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5q$	$\longrightarrow$	$\frac{\mathrm{Re}(l_1l_2^\dagger)}{m_\Phi^2-m_\chi^2}\Delta_q^N\,(-\mathcal{O}_7+\frac{m_N}{m_\chi}\mathcal{O}_9)$
$\bar{\chi}i\gamma^5\chi\,\bar{q}q$	$\longrightarrow$	$-\frac{1}{2}\frac{\mathrm{Im}(l_1l_2^\dagger)}{m_\Phi^2-m_\chi^2}\frac{m_N}{m_\chi}f_{Tq}^N\,\mathcal{O}_{11}$	$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5q$	$\longrightarrow$	$-\frac{\|l_2\|^2+\|l_1\|^2}{m_\Phi^2-m_\chi^2}\Delta_q^N\mathcal{O}_4$
$\bar{\chi}i\gamma^5\chi\,\bar{q}i\gamma^5q$	$\longrightarrow$	$\frac{1}{4}\frac{\|l_2\|^2-\|l_1\|^2}{m_\Phi^2-m_\chi^2}\frac{m_N}{m_\chi}\,\Delta\tilde{q}^N\mathcal{O}_6$	$\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q$	$\longrightarrow$	$\frac{\|l_2\|^2-\|l_1\|^2}{m_\Phi^2-m_\chi^2}\delta_q^N\mathcal{O}_4$
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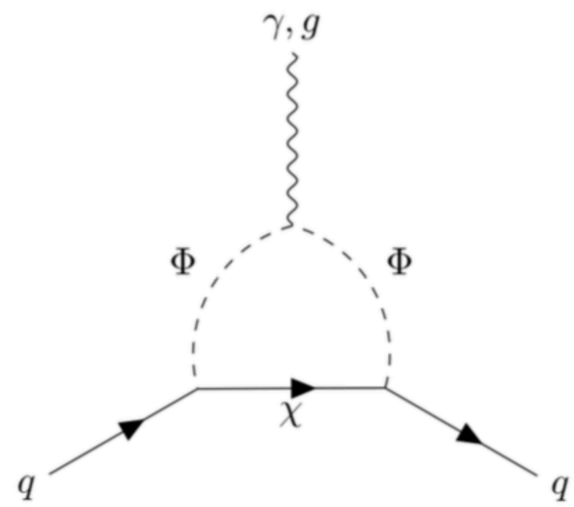
$$d_q|_{\text{Model II}} = \frac{1}{(4\pi)^2}\, eQ_\Phi\, m_\chi\, \underline{\text{Im}(l_1 l_2^\dagger)}\, G(m_q^2, m_\Phi^2, m_\chi^2)$$

$$G(m_q^2, m_\Phi^2, m_\chi^2) = \int_0^1 dz\, \frac{z(1-z)}{z^2 m_q^2 + z(m_\chi^2 - m_\Phi^2 - m_q^2) + m_\Phi^2}$$



- Like before, almost all of the parameter space is dominated by $\mathcal{O}_1$ unless its coefficient is suppressed by 10^{-4} or less

$$\bar{\chi}\chi\, \bar{q}q \longrightarrow \frac{1}{4}\frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2} f_{Tq}^N\, \mathcal{O}_1 \qquad \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{q}\gamma_\mu\gamma^5 q \longrightarrow -\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\Delta_q^N \mathcal{O}_4$$

$$\bar{\chi}\gamma^\mu\chi\, \bar{q}\gamma_\mu q \longrightarrow -\frac{1}{4}\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N\, \mathcal{O}_1 \qquad \bar{\chi}i\gamma^5\chi\, \bar{q}q \longrightarrow -\frac{1}{2}\frac{\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N\, \mathcal{O}_{11}$$

- or when the couplings obey the cancellation relation

$$\boxed{\left|l_1^N\right|^2 = \left(\frac{1 - \frac{\mathcal{N}^N}{f_T^N}}{1 + \frac{\mathcal{N}^N}{f_T^N}}\right)\left|l_2^N\right|^2}$$

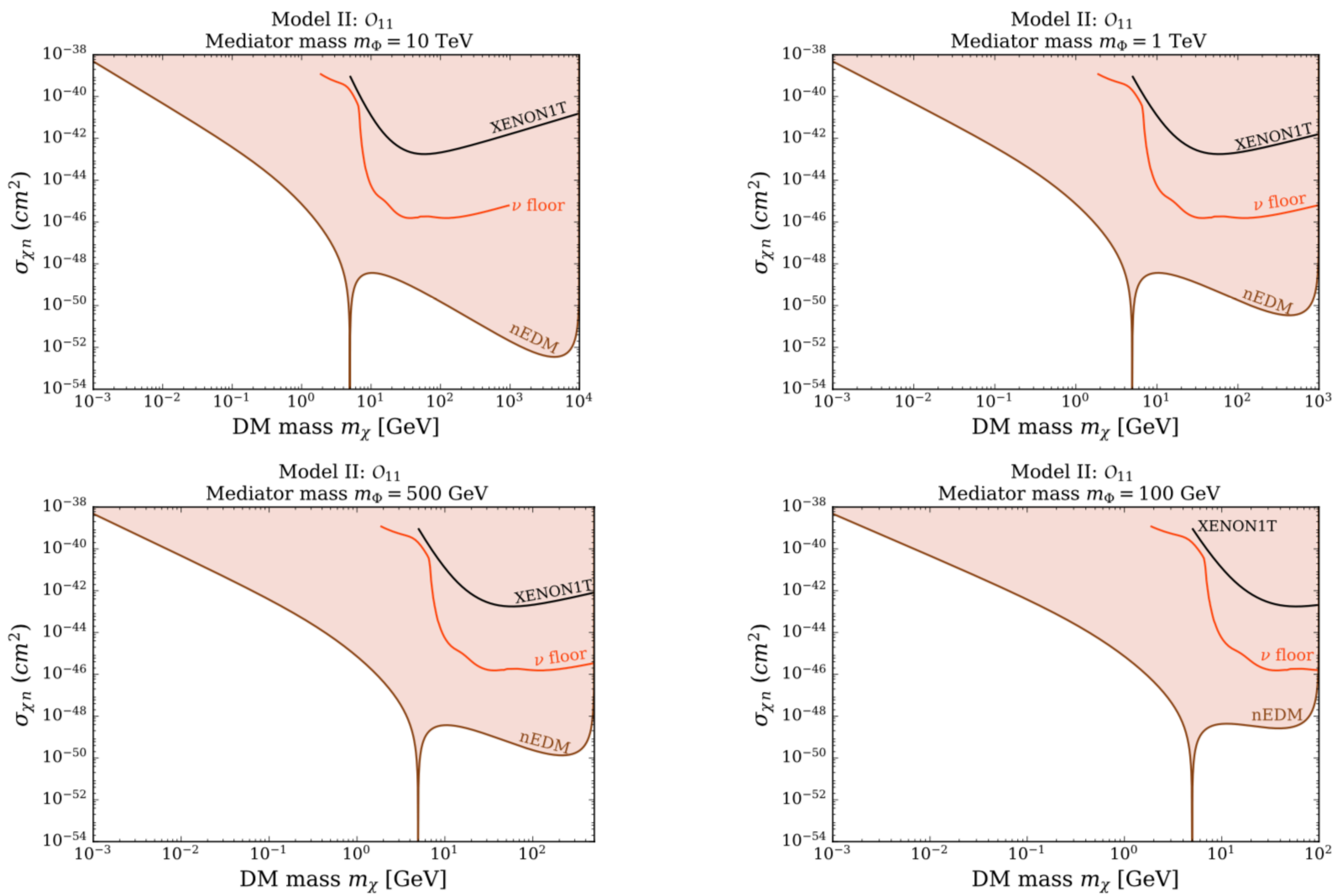
$$f_T^N \equiv \textstyle\sum_q \langle \bar{N}|\, \bar{q}q\, |N\rangle$$
$$\mathcal{N}^N \equiv \textstyle\sum_q \langle \bar{N}|\, \bar{q}\gamma^\mu q\, |N\rangle$$

scattering now dominated by $\mathcal{O}_{11}$ and not $\mathcal{O}_4$!

- convert the constraint on $\Im(l_1 l_2^\dagger)$ from nEDM into a cross section using

$$\sigma_{\mathcal{O}_{11}} = \frac{\mu_{\chi N}}{\pi}(c_{11}^N)^2$$

$$d_q|_{\text{Model II}} = \frac{1}{(4\pi)^2}\, eQ_\Phi\, m_\chi\, \text{Im}(l_1 l_2^\dagger)\, G(m_q^2, m_\Phi^2, m_\chi^2) \qquad \bar{\chi} i\gamma^5 \chi\, \bar{q}q \longrightarrow -\frac{1}{2}\frac{\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N\, \mathcal{O}_{11}$$



Conclusions

- nEDM constraints on P-odd, T-odd NREFT cross sections are many orders of magnitude stronger than the neutrino floor

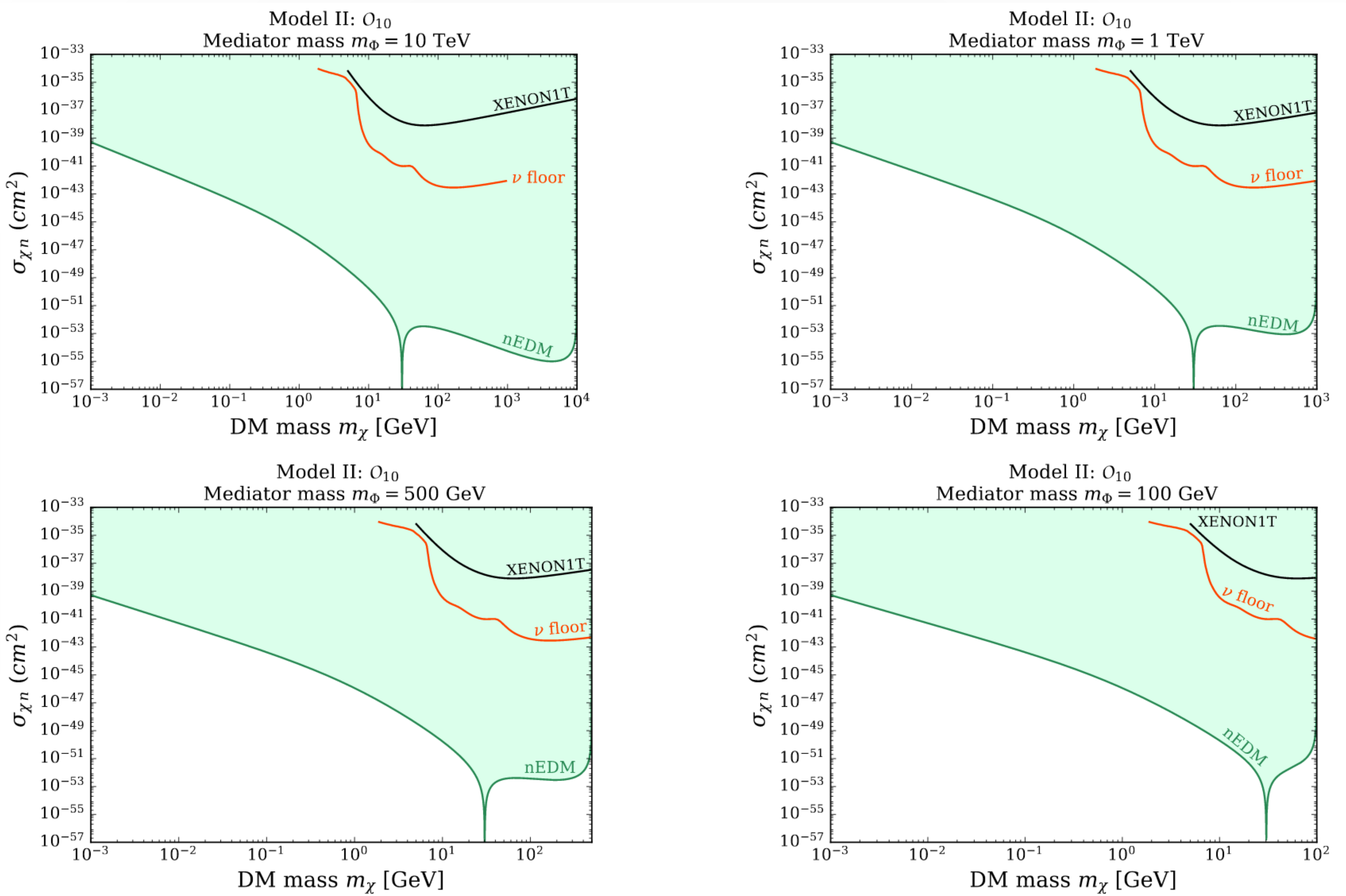
- current and future direct detection experiments are insensitive to such interactions

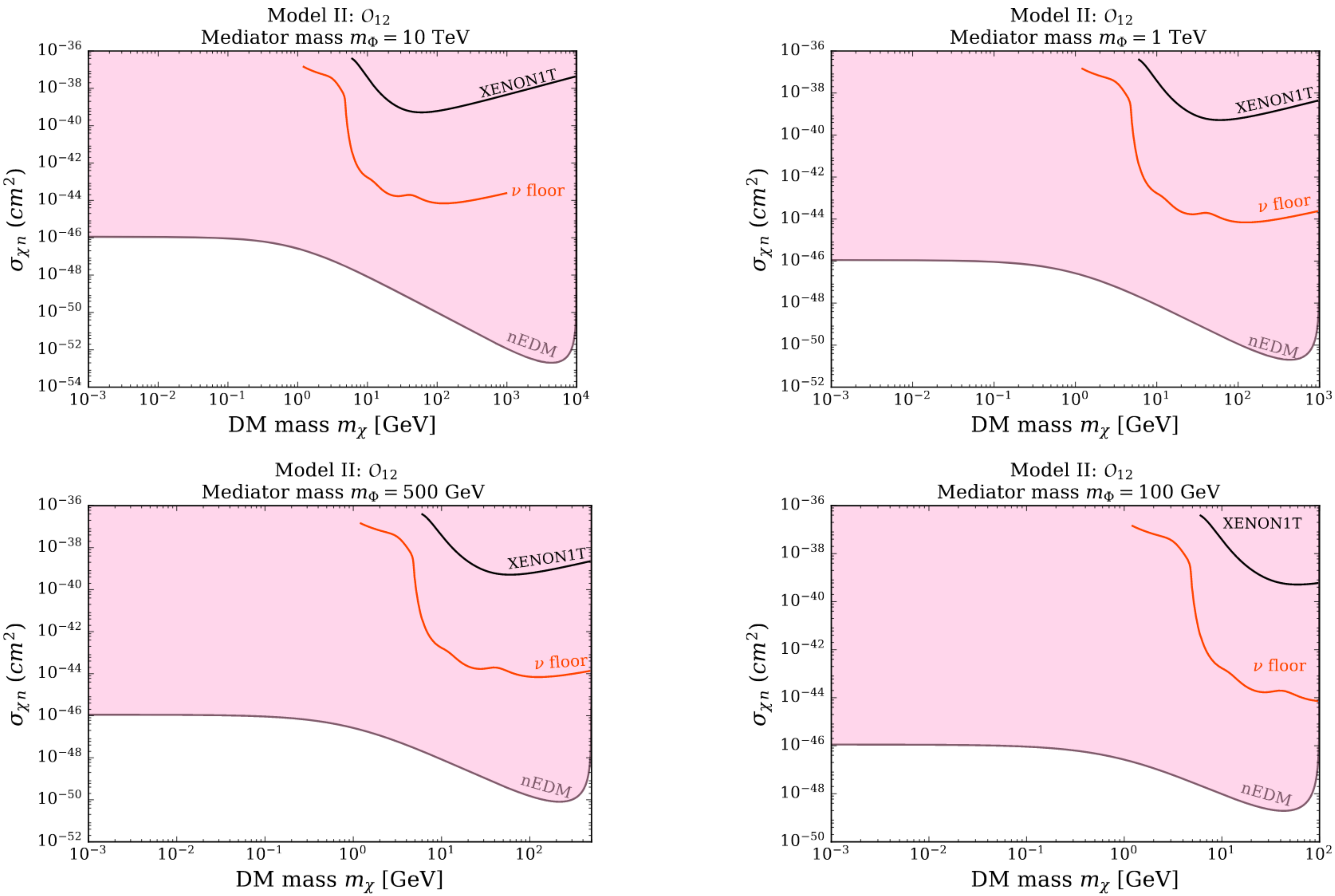
- global scans can be misleading; make establish a connection with particle physics models

- NREFT has phenomenological redundancies; not all operators may be relevant

Thank you!

Backups


Model II: $\mathcal{O}_{10}$
Mediator mass $m_\Phi = 10$ TeV
XENON1T
ν floor
nEDM
$\sigma_{\chi n}$ (cm^2)
DM mass m_χ [GeV]
Model II: $\mathcal{O}_{10}$
Mediator mass $m_\Phi = 1$ TeV
XENON1T
ν floor
nEDM
$\sigma_{\chi n}$ (cm^2)
DM mass m_χ [GeV]
Model II: $\mathcal{O}_{10}$
Mediator mass $m_\Phi = 500$ GeV
XENON1T
ν floor
nEDM
$\sigma_{\chi n}$ (cm^2)
DM mass m_χ [GeV]
Model II: $\mathcal{O}_{10}$
Mediator mass $m_\Phi = 100$ GeV
XENON1T
ν floor
nEDM
$\sigma_{\chi n}$ (cm^2)
DM mass m_χ [GeV]


Model II: $\mathcal{O}_{12}$
Mediator mass $m_\Phi = 10$ TeV
XENON1T
ν floor
nEDM
$\sigma_{\chi n}$ (cm^2)
DM mass m_χ [GeV]
Model II: $\mathcal{O}_{12}$
Mediator mass $m_\Phi = 1$ TeV
XENON1T
ν floor
nEDM
$\sigma_{\chi n}$ (cm^2)
DM mass m_χ [GeV]
Model II: $\mathcal{O}_{12}$
Mediator mass $m_\Phi = 500$ GeV
XENON1T
ν floor
nEDM
$\sigma_{\chi n}$ (cm^2)
DM mass m_χ [GeV]
Model II: $\mathcal{O}_{12}$
Mediator mass $m_\Phi = 100$ GeV
XENON1T
ν floor
nEDM
$\sigma_{\chi n}$ (cm^2)
DM mass m_χ [GeV]

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi m_N}{2\pi m_\chi} \int_{v_{\rm min}}^{v_{\rm esc}} \frac{f(v)}{v}\, J_\chi\, J_N\, \sum\nolimits_{\rm spins} |\mathcal{M}_{\rm sc}|^2\, d^3v$$

$$J_\chi J_N \sum_{\rm spins} |\mathcal{M}_{\rm sc}|^2 = \sum_{\substack{k'=M,\Sigma'',\\ \Sigma''}} R_k^{NN'}(v^2,\vec{q}^{\,2})\, W_k^{NN'}(\vec{q}^{\,2}b^2) + \sum_{\substack{k'=\Delta,\Delta\Sigma',\\ \Phi'',\Phi'' M}} \frac{\vec{q}^{\,2}}{m_N^2} R_k^{NN'}(v^2,\vec{q}^{\,2})\, W_k^{NN'}(\vec{q}^{\,2}b^2)$$

DM Response Functions

Anand, Fitzpatrick and Haxton - Phys.Rev. C89 (2014) no.6, 065501

$$\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}\Big[c_4^\tau c_4^{\tau'} + \\
&\quad \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'}\Big] \\
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}\Big[c_4^\tau c_4^{\tau'} + \\
&\quad \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'}\Big] \\
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}$$

Model I

$$\mathcal{L}^{\text{Model I}} = \mathcal{L}_{SM} + \partial_\mu S^\dagger \partial_\mu S - m_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2$$
$$+ i\bar{Q} \not{D} Q - m_Q \bar{Q} Q$$
$$- S\bar{Q}(y_1 + y_2\gamma^5) q - S^\dagger \bar{q}(y_1^\dagger - y_2^\dagger \gamma^5) Q$$

$$\mathcal{M}_{Sq\to Sq} = \frac{m_Q}{m_Q^2 - m_S^2}\left[(|y_1|^2 - |y_2|^2)\,\bar{u}(k_2)\,u(p_2) - 2\,\mathrm{Im}(y_1 y_2^\dagger)\,\bar{u}(k_2)\,i\gamma^5\,u(p_2)\right]$$
$$+ \frac{1}{m_Q^2 - m_S^2}(|y_1|^2 + |y_2|^2)\left[m_q\,\bar{u}(k_2)\,u(p_2) + \bar{u}(k_2)\,\frac{\not{p}_1 + \not{k}_1}{2}\,u(p_2)\right]$$
$$+ \frac{1}{m_Q^2 - m_S^2}\,2\,\mathrm{Re}(y_1 y_2^\dagger)\left[\bar{u}(k_2)\,\frac{\not{p}_1 + \not{k}_1}{2}\gamma^5\,u(p_2)\right]$$

$$\mathcal{L}_{\text{eff}}^{\text{Model I}} \supset c_1^{d5}\,(S^\dagger S)\,\bar{q}\,q + c_{10}^{d5}\,(S^\dagger S)\,\bar{q}\,i\gamma^5\,q + c_1^{d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\,q + c_7^{d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\gamma^5\,q$$

$$S^\dagger S\,\bar{q}q \longrightarrow \left(\frac{m_Q}{m_S}\frac{|y_1|^2 - |y_2|^2}{m_Q^2 - m_S^2} + \frac{m_q}{m_S}\frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\right) f_{Tq}^N\,\mathcal{O}_1$$

$$S^\dagger S\,\bar{q}i\gamma^5 q \longrightarrow \frac{m_Q}{m_S}\frac{\mathrm{Im}(y_1 y_2^\dagger)}{m_Q^2 - m_S^2}\,2\tilde{\Delta}^N\,\mathcal{O}_{10}$$

$$i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\,\bar{q}\gamma^\mu q \longrightarrow \frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\,\mathcal{N}_q^N\,\mathcal{O}_1$$

$$i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\,\bar{q}\gamma^\mu\gamma^5 q \longrightarrow -\frac{\mathrm{Re}(y_1 y_2^\dagger)}{m_Q^2 - m_S^2}\,2\Delta_q^N\,\mathcal{O}_7$$

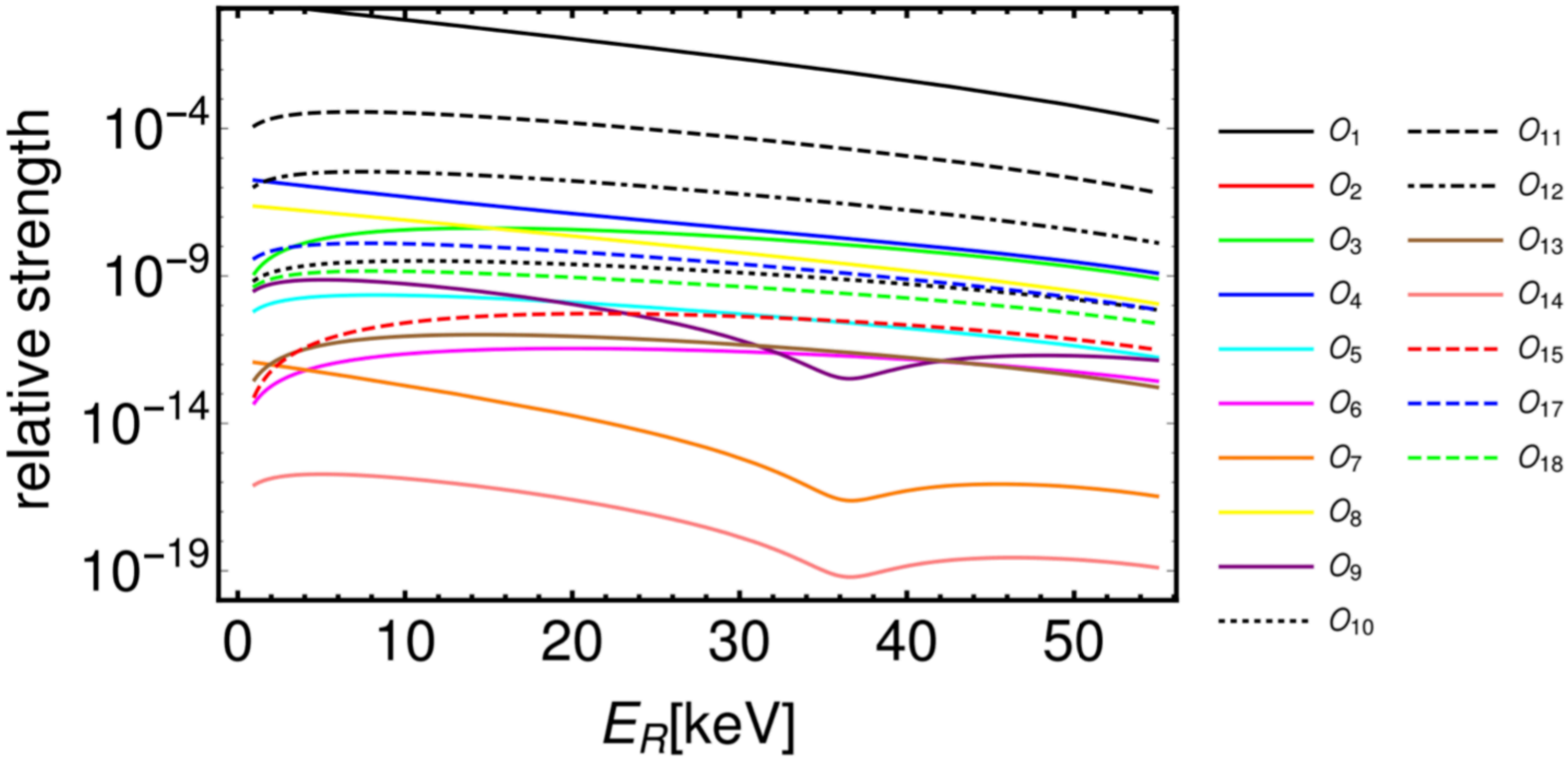
Model II

$$
\begin{aligned}
\mathcal{L}^{\text{Model II}} &= \mathcal{L}_{SM} + i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi \\
&+ (\partial_\mu\Phi^\dagger)(\partial^\mu\Phi) - m_\Phi^2\Phi^\dagger\Phi - \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2 \\
&- (l_1\Phi^\dagger\bar{\chi}q + l_2\Phi^\dagger\bar{\chi}\gamma_5 q + h.c.)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{M}_{\chi q\to\chi q} = \frac{1}{m_\Phi^2 - m_\chi^2}\Big(& l_1 l_1^\dagger\,[\bar{u}(k_2)v(k_1)]\,[\bar{v}(p_1)v(p_2)] - l_1 l_2^\dagger\,[\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1)v(p_2)] \\
& + l_1^\dagger l_2\,[\bar{u}(k_2)v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)] - l_2 l_2^\dagger\,[\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)]\Big)
\end{aligned}
$$

$\bar{\chi}\chi\,\bar{q}q$	$\longrightarrow$	$\frac{1}{4}\frac{\lvert l_2\rvert^2 - \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2} f_{Tq}^N\,\mathcal{O}_1$	$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q$	$\longrightarrow$	$\frac{\text{Re}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N\,(\mathcal{O}_8 + \mathcal{O}_9)$
$\bar{\chi}\chi\,\bar{q}i\gamma^5 q$	$\longrightarrow$	$-\frac{1}{2}\frac{\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\Delta\tilde{q}^N\,\mathcal{O}_{10}$	$\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\frac{\text{Re}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\Delta_q^N\,(-\mathcal{O}_7 + \frac{m_N}{m_\chi}\mathcal{O}_9)$
$\bar{\chi}i\gamma^5\chi\,\bar{q}q$	$\longrightarrow$	$-\frac{1}{2}\frac{\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N\,\mathcal{O}_{11}$	$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$-\frac{\lvert l_2\rvert^2 + \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2}\Delta_q^N\mathcal{O}_4$
$\bar{\chi}i\gamma^5\chi\,\bar{q}i\gamma^5 q$	$\longrightarrow$	$\frac{1}{4}\frac{\lvert l_2\rvert^2 - \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi}\,\Delta\tilde{q}^N\mathcal{O}_6$	$\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q$	$\longrightarrow$	$\frac{\lvert l_2\rvert^2 - \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2}\delta_q^N\mathcal{O}_4$
$\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q$	$\longrightarrow$	$-\frac{1}{4}\frac{\lvert l_2\rvert^2 + \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N\,\mathcal{O}_1$	$\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\,\bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q$	$\longrightarrow$	$\frac{2\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\delta_q^N\left(\mathcal{O}_{11} - \frac{m_N}{m_\chi}\mathcal{O}_{10} - 4\mathcal{O}_{12}\right)$

Dent et al. - Phys.Rev. D92 (2015) no.6, 063515



Cancellation relation

$$f_T^N = \sum_{u,d,s} \frac{m_N}{m_q} f_{Tq}^N + \frac{2}{27}\left(1 - \sum_{u,d,s} f_{Tq}^N\right) \sum_{c,b,t} \frac{m_N}{m_q}$$

$$\frac{\mathcal{N}^N}{f_T^N} = \begin{cases} 0.212^{+0.043}_{-0.038}, & N = n \\ 0.219^{+0.051}_{-0.044}, & N = p \end{cases}$$

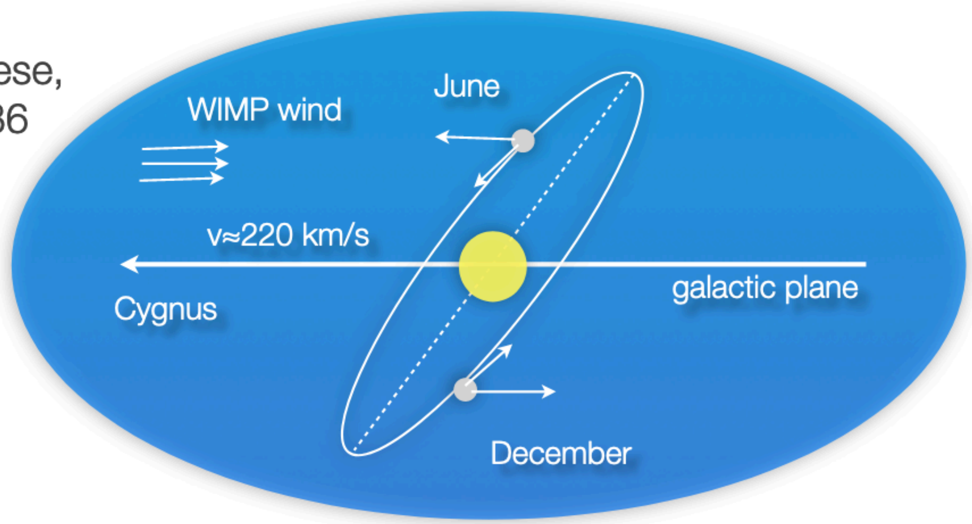
strong isospin violation

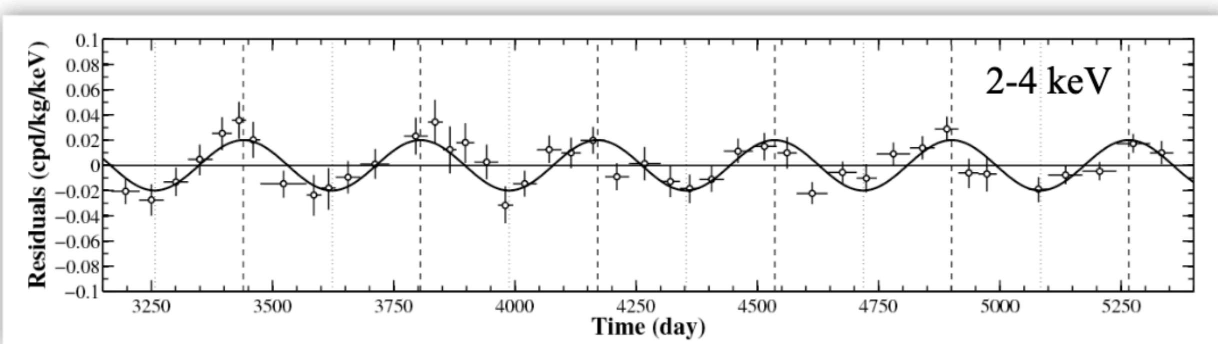
$$\left|y_1^N\right|^2 = \left(\frac{1 - \frac{\mathcal{N}^N}{f_T^N}\frac{m_S}{m_Q}}{1 + \frac{\mathcal{N}^N}{f_T^N}\frac{m_S}{m_Q}}\right)\left|y_2^N\right|^2$$

$$|y_1^n|^2 = \left(\frac{1 - 0.212^{+0.043}_{-0.038}\frac{m_S}{m_Q}}{1 + 0.212^{+0.043}_{-0.038}\frac{m_S}{m_Q}}\right)|y_2^n|^2$$

$$|y_1^p|^2 = \left(\frac{1 - 0.219^{+0.051}_{-0.044}\frac{m_S}{m_Q}}{1 + 0.219^{+0.051}_{-0.044}\frac{m_S}{m_Q}}\right)|y_2^p|^2$$

Drukier, Freese, Spergel 1986





R. Bernabei et al, EPJ-C67 (2010)

D. Spergel 1988

Motion of the Earth and the detection of weakly interacting massive particles

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If the galactic halo is composed of weakly interacting massive particles (WIMP's), then cryogenic experiments may be capable of detecting the recoil of nuclei struck by the WIMP's. Earth's motion relative to the galactic halo produces a seasonal modulation in the expected event rate. The direction of nuclear recoil has a strong angular dependence that also can be used to confirm the detection of WIMP's. I calculate the angular dependence and the amplitude of the seasonal modulation for an isothermal halo model.