Effective theory for light portal dark matter detection

Qing Chen 陈清
安徽理工大学

力学与光电物理学院，基础物理中心

Based on arXiv: 2510.22966, 2310.03079
QC and Shuang-Yong Zhou 周双勇 (USTC)

第八届全国重味物理与QCD研讨会，重庆, 4/26/2026

Dark matter direct detection experiments

- Heavy WIMP:

  TeV mass $M \gg m_W$, cross section tiny, around neutrino floor. (QC and Hill, PLB 1912.07795 ; QC, Ding and Hill, PRD 2309.02715)

- HQET application in WIMP nucleon scattering, parametrized by the low velocity v of DM.

- All low spin electroweak multiplets cross sections around neutrino floor, except Higgsino-like WIMP deep below neutrino floor.

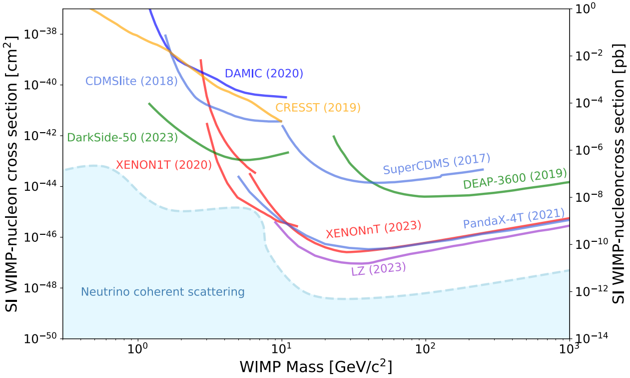


Figure: DM direct detection experimental limits, (PDG 2024)

Dark matter direct detection experiments

- Heavy WIMP:
  TeV mass $M \gg m_W$, cross section tiny, around neutrino floor. (QC and Hill, PLB 1912.07795 ; QC, Ding and Hill, RRD 2309.02715)

- Light DM:
  sub GeV mass M, 1 MeV$\sim$ 1 GeV

- Nuclear recoil energy of cold DM:
  $2M^2v^2/m_T$, $v \sim 0.001c$, m_T: nuclear target mass

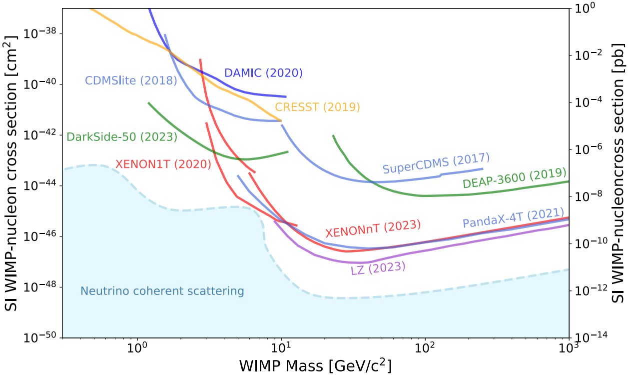


Figure: DM direct detection experimental limits, (PDG 2024)

Light portal dark matter

- Core-cusp problem:
  contradiction between cold DM simulation and observed flat core density profile

- Solution:
  DM self-interaction at small scale via a light mediator, $m \sim 1$ MeV to 10 GeV, coincidentally in the sub GeV regime.
  (Spergel and Steinhardt, PRL 9909386; Tulin and Yu, Phys. Rept. 1705.02358)

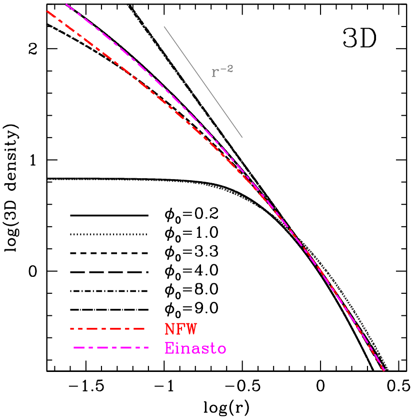


Figure: DM density profile

Light dark matter

- Cosmic ray boosted energetic DM: (semi)relativistic, high enough nuclear recoil.

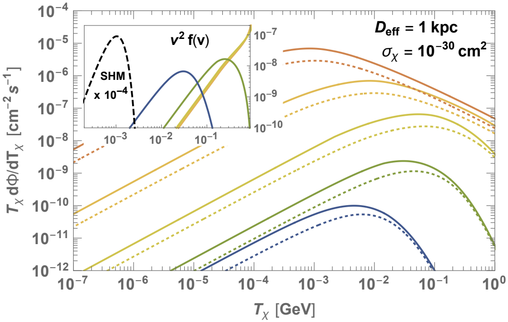
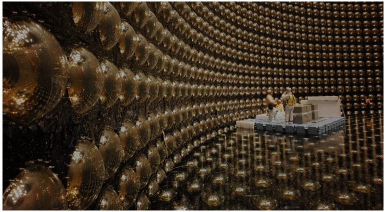


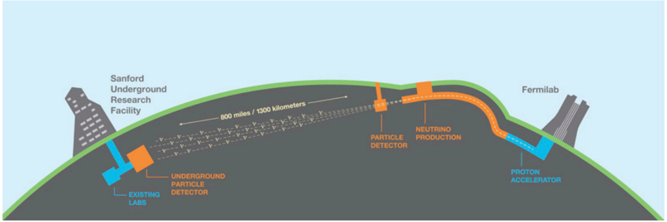
Figure: Flux of CRDM for different DM masses from 1 MeV to 10 GeV, (Bringmann and Pospelov, PRL 1810.10543)

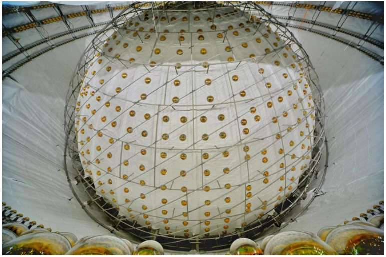
High threshold experiments

Large-volume neutrino experiments with recoil energies in the 10-100 MeV.

- Super/Hyper Kamiokande
- JUNO
- DUNE







Effective operators of light-portal dark matter

Energetic light DM scattering on nucleus target via a light mediator with mass m,
$\chi(k) + N(p) \to \chi(k') + N(p')$ with momentum transfer $Q \sim m$ $(q = p' - p, Q^2 = -q^2)$

$$O_\chi \frac{\Xi}{\partial^2 - m^2} O_{q/g}$$

Building blocks: Field contents, Lorentz structures and derivatives

$$1,\ i\gamma^5,\ \gamma^\mu,\ \gamma^\mu\gamma^5, \sigma^{\mu\nu}$$

$$i\partial_-^\mu,\ iD_-^\mu,\ \partial_+^\mu$$

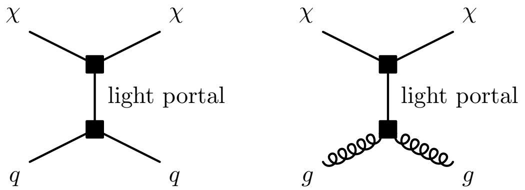


Figure: DM and quarks/gluons interaction via a light mediator.

Effective operators of QCD sector reduction

Effective quark and gluon operators with Equation-of-Motion & Integration-By-Part to remove redundancy

- EoM:

$$
\begin{aligned}
&\bar{q} i \overleftrightarrow{\not{D}}_{-} q = m_q \bar{q} q \,, \quad \bar{q} \not{\partial}_{+} q = 0 \,, \quad \bar{q} i \overleftrightarrow{\not{D}}_{-} \gamma^5 q = 0 \,, \\
&\bar{q} \gamma^{[\alpha} i D_{-}^{\nu]} q + \frac{1}{4} \epsilon^{\mu\nu\alpha\beta} \bar{q} \partial_{+\mu} \gamma_\beta \gamma^5 q = 0 \,, \\
&\bar{q} D_{-}^2 q + \frac{1}{4} \bar{q} \partial_{+}^2 q - \frac{g_s}{2} \bar{q} \sigma^{\mu\nu} G_{\mu\nu} q = -m_q^2 \bar{q} q \,, \\
&\bar{q} \partial_{+\nu} i D_{-\alpha} q - 2 \bar{q} D_{-}^{\mu} \sigma_{\mu\nu} D_{-\alpha} q + i g_s \bar{q} \sigma_{\mu\nu} G_{\alpha}{}^{\mu} q + g_s \bar{q} G_{\alpha\nu} q = 0 \,, \ldots
\end{aligned}
$$

- IBP:

$$
|\phi|^2 \bar{q} \partial_{+}^{\mu} \partial_{+}^{\nu} q \to \phi^* \partial_{+}^{\mu} \partial_{+}^{\nu} \phi \bar{q} q
$$

Effective operators of QCD sector

Effective quark and gluon bilinear operators through dim-5

Dimension	Quark operators	
3	$\bar{q}\gamma^\mu q$	$\bar{q}\gamma^\mu\gamma^5 q$
4	$m_q\bar{q}q$	$m_q\bar{q}i\gamma^5 q$
	$\bar{q}(\gamma^{\{\mu}iD_-^{\nu\}} - \frac{g^{\mu\nu}}{4}i\not{D}_-)q$	$\bar{q}\gamma^{\{\mu}iD_-^{\nu\}}\gamma^5 q$
	$im_q\bar{q}\sigma^{\mu\nu}\gamma^5 q$	
5	$\bar{q}D_-^2 q$	$\bar{q}D_-^2 i\gamma^5 q$
	$\bar{q}(D_-^{\{\mu}D_-^{\nu\}} - \frac{g^{\mu\nu}}{4}D_-^2)q$	$\bar{q}D_-^{\{\mu}D_-^{\nu\}}i\gamma^5 q$
	$\bar{q}D_-^{\{\lambda}D_-^{[\mu\}}\sigma^{\nu]}{}_\lambda q$	$\bar{q}D_-^2\sigma^{\mu\nu}q$

Dimension	Gluon operators	
4	$G^{A\,\mu\nu}G^A_{\mu\nu}$	$G^{A\,\mu\nu}\tilde{G}^A_{\mu\nu}$
	$-G^{A\mu\lambda}G^{A\nu}{}_\lambda + \frac{1}{d}g^{\mu\nu}(G^A_{\alpha\beta})^2$	
5	$G^{A\,\alpha\beta}iD_-^\mu G^A_{\alpha\beta}$	$G^{A\,\alpha\beta}iD_-^\mu\tilde{G}^A_{\alpha\beta}$

Scalar DM effective bilinear operators

Dimension	Scalar DM	
2	$\lvert\phi\rvert^2$	
3	$\phi^* i\partial_-^\mu \phi$	$\phi^* \partial_+^\mu \phi$
4	$\phi^* \partial_+^2 \phi$	$\phi^* \partial_-^2 \phi$
	$\phi^* (\partial_-^\mu \partial_-^\nu - \frac{g^{\mu\nu}}{4}\partial_-^2)\phi$	$\phi^* (\partial_+^\mu \partial_+^\nu - \frac{g^{\mu\nu}}{4}\partial_+^2)\phi$
	$\phi^* i\partial_+^{\{\mu} \partial_-^{\nu\}} \phi$	$\phi^* i\partial_+^{[\mu} \partial_-^{\nu]} \phi$
5	$\phi^* i\partial_-^2 \partial_-^\mu \phi$	$\phi^* \partial_-^2 \partial_+^\mu \phi$
	$\phi^* i\partial_+^2 \partial_-^\mu \phi$	$\phi^* \partial_+^2 \partial_+^\mu \phi$

Effective interaction

Lowest order DM and QCD interaction, classified by the mediator's spins,

portal	scalar DM	fermion DM
spin-0	$\vert\phi\vert^2 P^{(0)} m_q \bar{q} q$	-
	$\vert\phi\vert^2 P^{(0)} m_q \bar{q} i\gamma^5 q$	-
	$\vert\phi\vert^2 P^{(0)} G^{A\,\mu\nu} G^A_{\mu\nu}$	-
	$\vert\phi\vert^2 P^{(0)} G^{A\,\mu\nu} \tilde{G}^A_{\mu\nu}$	-
spin-1	$\phi^* i\partial^\mu_- \phi P^{(1)}_{\mu\nu} \bar{q}\gamma^\nu q$	$\bar{\psi}\gamma^\mu\psi P^{(1)}_{\mu\nu} \bar{q}\gamma^\nu q$
	$\phi^* i\partial^\mu_- \phi P^{(1)}_{\mu\nu} \bar{q}\gamma^\nu\gamma^5 q$	$\bar{\psi}\gamma^\mu\psi P^{(1)}_{\mu\nu} \bar{q}\gamma^\nu\gamma^5 q$
	$\phi^* \partial^\mu_+ \phi P^{(1)}_{\mu\nu} \bar{q}\gamma^\nu q$	$\bar{\psi}\gamma^\mu\gamma^5\psi P^{(1)}_{\mu\nu} \bar{q}\gamma^\nu q$
	$\phi^* \partial^\mu_+ \phi P^{(1)}_{\mu\nu} \bar{q}\gamma^\nu\gamma^5 q$	$\bar{\psi}\gamma^\mu\gamma^5\psi P^{(1)}_{\mu\nu} \bar{q}\gamma^\nu\gamma^5 q$
spin-2	$\vert\phi\vert^2 g^{\mu\nu} P^{(2)}_{\mu\nu\alpha\beta} \bar{q} \left(\gamma^{\{\alpha} iD^{\beta\}}_- - \frac{g^{\alpha\beta}}{4} i\not{D}_-\right) q$	-
	$\vert\phi\vert^2 g^{\mu\nu} P^{(2)}_{\mu\nu\alpha\beta} \bar{q}\gamma^{\{\alpha} iD^{\beta\}}_- \gamma^5 q$	-
	$\vert\phi\vert^2 g^{\mu\nu} P^{(2)}_{\mu\nu\alpha\beta} \left[-G^{A\,\alpha\lambda} G^{A\,\beta}_{\lambda} + \frac{1}{4} g^{\alpha\beta} \left(G^A_{\rho\sigma}\right)^2\right]$	-

Nucleon matrix elements

Amplitude $\chi(k) + N(p) \to \chi(k') + N(p')$

$$\mathcal{M} = \sum_i \sum_{q,\, g} c_i \langle \chi(k') | \mathcal{O}^i_\chi | \chi(k) \rangle P^i \langle N(p') | \mathcal{O}^i_{q/\, g} | N(p) \rangle \,,$$

Non-perturbative nucleon matrix elements of QCD operators

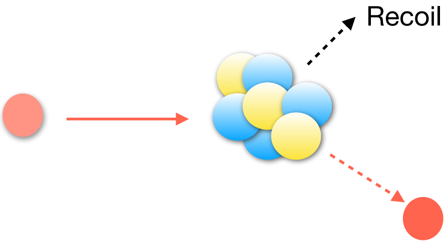
$$\langle N(p') | O_{q/g} | N(p) \rangle$$

e.g., spin-2 matrix elements involving gravitational form factors (Tong, Ma & Yuan, JHEP 2203.13493; Hackett, Pefkou & Shanahan, PRL 2310.08484; Cao, Guo, Li & Yao, Nat.Comm. 2411.13398; Nair et al. 2506.07554)

$$\begin{aligned} &\langle N(p') | \bar{q} \left(\gamma^{\{\mu} i D_-^{\nu\}} - \frac{g^{\mu\nu}}{4} i \not{D}_- \right) q | N(p) \rangle \\ &= \frac{1}{m_N} \bar{u}\left(p'\right) \left[P^\mu P^\nu A_q(t) + i P^{\{\mu} \sigma^{\nu\}\rho} q_\rho J_q(t) + \frac{1}{4} \left(q^\mu q^\nu - g^{\mu\nu} q^2 \right) D_q(t) \right] u\left(p\right) \end{aligned}$$

Relativistic fermi gas model

Dark matter direct detection experiments take place on compound nuclei versus isolated nucleons.



$$N \to \mathcal{N} \quad ?$$

Relativistic fermi gas model Smith & Moniz NPB, 1972:

$$\sigma_{\text{nuclear}} = 2V \int \frac{d^3\mathbf{p}}{(2\pi)^3} n_i(\mathbf{p}) \sigma_{\text{free}} \left[1 - n_f(\mathbf{p}')\right]$$

$$n_i(\mathbf{p}) = \theta\left(p_F - \mathbf{p}\right), \quad n_f(\mathbf{p}') = \theta\left(p_F - \mathbf{p}'\right) \quad V = 3\pi^2 A/(2p_F^3)$$

Relativistic fermi gas model

Cross section of DM scattering on a nucleus. Introduce the binding energy ϵ_b such that $p^0 = E_p - \epsilon_b$, and $p'^0 = E_{p'}$, with $E_p = (m_N^2 + |\mathbf{p}|^2)^{1/2}$ and $E_{p'} = (m_N^2 + |\mathbf{p}'|^2)^{1/2}$.

Key step: nucleon to nucleus tensor conversion

$$\int d^3\mathbf{p}\, p_\mu p_\nu p_\alpha p_\beta \to \int d^3\mathbf{p}\, f(\mathbf{p}) \times \text{ tensor of} \{\mathrm{p}_\mathrm{T}^\mu,\ \mathrm{q}^\nu\}$$

Example: spin-1 portal

Simple spin-1 portal effective interaction in momentum space

$$\mathcal{L}_{\text{int}} = \alpha_1 \frac{\bar{\psi}\gamma^\mu\psi\bar{q}\gamma_\mu q}{q^2 - m_{\text{eff}}^2} + \alpha_2 \frac{\bar{\psi}\gamma^\mu\gamma^5\psi\bar{q}\gamma_\mu\gamma^5 q}{q^2 - m_{\text{eff}}^2} + \alpha_3 \frac{\bar{\psi}\gamma^\mu\gamma^5\psi\bar{q}\gamma_\mu q}{q^2 - m_{\text{eff}}^2} + \alpha_4 \frac{\bar{\psi}\gamma^\mu\psi\bar{q}\gamma_\mu\gamma^5 q}{q^2 - m_{\text{eff}}^2}$$

Possible UV Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{spin}-1} = &\bar{\psi}\left(i\partial\!\!\!/ + g_1 V\!\!\!/ + g_2 V\!\!\!/\gamma^5 - M\right)\psi + \bar{q}\left(g_1 V\!\!\!/ + g_2 V\!\!\!/\gamma^5\right)q \\ &-\frac{1}{4}\left(\partial_\mu V_\nu - \partial_\nu V_\mu\right)\left(\partial^\mu V^\nu - \partial^\nu V^\mu\right) + \frac{1}{2}m_{\text{eff}}^2 V_\mu V^\mu\end{aligned}$$

Matching

$$\alpha_1 = g_1^2,\ \alpha_2 = g_2^2,\ \alpha_3 = \alpha_4 = g_1 g_2$$

Example: spin-1 portal

Amplitude squared

$$\sum_{\text{spins}} |\mathcal{M}|^2 = \frac{1}{\left(q^2 - m_{\text{eff}}^2\right)^2} T^{\chi}_{\mu\nu} T^{N\,\mu\nu}$$

Nucleon tensor

$$T^{N\,\mu\nu} = g^{\mu\nu} H_1 + \frac{p^\mu p^\nu}{m_N^2} H_2 + \frac{p^\mu q^\nu + p^\nu q^\mu}{2m_N^2} H_3 + \frac{q^\mu q^\nu}{m_N^2} H_4 + i\epsilon^{\alpha\beta\mu\nu} \frac{p_\alpha q_\beta}{m_N^2} H_5$$

H_i are form factors.

Example: spin-1 portal

Nucleon level and nucleus level conversion

$$T^{N\,\mu\nu} = g^{\mu\nu}W_1 + \frac{p_T^\mu p_T^\nu}{m_T^2}W_2 + \frac{p_T^\mu q^\nu + p_T^\nu q^\mu}{2m_T^2}W_3 + \frac{q^\mu q^\nu}{m_T^2}W_4 + i\epsilon^{\alpha\beta\mu\nu}\frac{p_{T\alpha}q_\beta}{m_T^2}W_5$$

Rest target $p_T^\mu = m_T\delta_0^\mu$, basis integral $A_{nmk} = \int d^3\mathbf{p}\,\frac{p_0^n p_z^m |\mathbf{p}|^{2k}}{m_N^r} f(\mathbf{p},\, q^0,\, \mathbf{q})$

$$W_1 = A_{000}H_1 + \frac{1}{2}(A_{020} - A_{001})H_2\,,$$

$$W_2 = \left[\frac{1}{2}\left(1 - \frac{q_0^2}{|\mathbf{q}|^2}\right)A_{001} - \frac{1}{2}\left(1 - 3\frac{q_0^2}{|\mathbf{q}|^2}\right)A_{020} + A_{200} - 2\frac{q_0}{|\mathbf{q}|}A_{110}\right]H_2\,,$$

$$W_3 = \frac{m_T}{m_N}\left(A_{100} - A_{010}\frac{q_0}{|\mathbf{q}|}\right)H_3 + \frac{m_T}{|\mathbf{q}|}\left[(A_{001} - 3A_{020})\frac{q_0}{|\mathbf{q}|} + 2A_{110}\right]H_2\,,$$

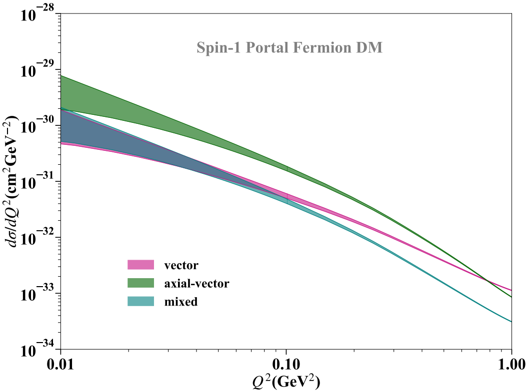
$$W_4 = \frac{m_T^2}{m_N^2}\left[A_{000}H_4 + \frac{m_N^2}{|\mathbf{q}|^2}\left(\frac{3}{2}A_{020} - \frac{1}{2}A_{001}\right)H_2 + A_{010}\frac{m_N}{|\mathbf{q}|}H_3\right]\,,$$

$$W_5 = \frac{m_T}{m_N}\left[A_{010}\frac{q_0}{|\mathbf{q}|} - A_{100}\right]H_5\,,$$

Example: spin-1 portal

Differential cross section of spin-1 portal DM scattering on Argon (A=40) nucleus target, $M = 0.1$ GeV, $T = 1$ GeV, $p_F = 0.27$GeV, $m_{\text{eff}} = 0.001$ GeV to 0.1 GeV (Tulin, Yu and Zurek, 1302.3898),

- vector $\alpha_1 = 0.001$, $\alpha_2 = \alpha_3 = \alpha_4 = 0$
- axial-vector
  $\alpha_2 = 0.001$, $\alpha_1 = \alpha_3 = \alpha_4 = 0$
- mixed $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0.001$



Example: spin-2 portal

Bi-gravity portal model (QC and Zhou, 2310.03079),symmetry breaking $\mathrm{Diff}_L \times \mathrm{Diff}_R \to \mathrm{Diff}_V$

$$S_{\text{bi-gravity}} = \frac{1}{2} M_{\text{pl}}^2 \int d^4x \sqrt{|\det g|}\, R[g] + \frac{1}{2} M_f^2 \int d^4x \sqrt{|\det f|}\, R[f] + \frac{1}{4} M_f^2 m^2 \int d^4x \sqrt{|\det f|} \sum_{n=0}^{4} \alpha_n U_n[K[g,f]]$$

$$S = S_{\text{bi-gravity}} + \int d^4x \sqrt{|\det g^{\text{eff}}|}\, \mathcal{L}_{\text{SM}} + \int d^4x \sqrt{|\det f^{\text{eff}}|}\, \mathcal{L}_{\text{DM}}$$

Effective QCD operators for spin-2 portal model

$$\mathcal{O}_q^{(0)} = m_q \bar{q} q \,, \quad \mathcal{O}_g^{(0)} = G^A_{\mu\nu} G^{A\,\mu\nu}$$

$$\mathcal{O}_q^{(2)\mu\nu} = \frac{1}{2} \bar{q} \left(\gamma^{\{\mu} i D_-^{\nu\}} - \frac{g^{\mu\nu}}{d} i \not{D}_- \right) q$$

$$\mathcal{O}_g^{(2)\mu\nu} = -G^{A\mu\lambda} G^{A\nu}{}_{\lambda} + \frac{1}{d} g^{\mu\nu} (G^A_{\alpha\beta})^2$$

Massive spin-2 propagator

$$P^{(2)}_{\mu\nu\alpha\beta} = \left(\frac{1}{2} \tilde{\eta}_{\mu\alpha} \tilde{\eta}_{\nu\beta} + \frac{1}{2} \tilde{\eta}_{\mu\beta} \tilde{\eta}_{\nu\alpha} - \frac{1}{3} \tilde{\eta}_{\mu\nu} \tilde{\eta}_{\alpha\beta} \right) \frac{-i}{q^2 - m_{\rm eff}^2 + i\epsilon}$$

with $\tilde{\eta}_{\mu\nu} = -\eta_{\mu\nu} + q_\mu q_\nu / m_{\rm eff}^2$

Example: spin-2 portal

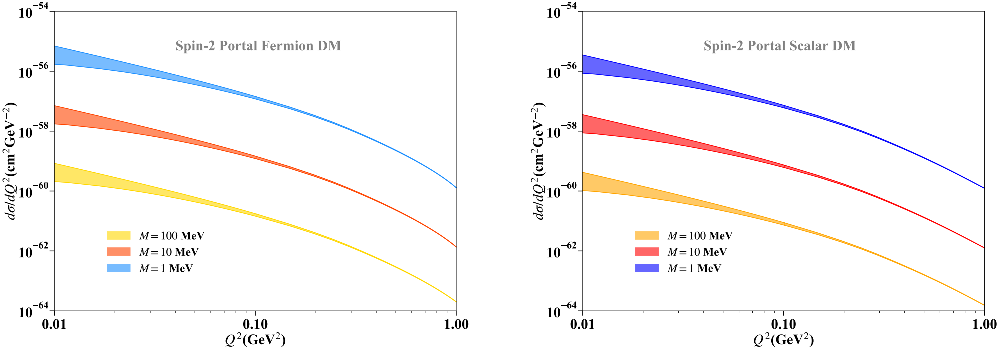


Figure: Differential cross sections for spin-2 portal (semi)relativistic dark matter and Argon nucleus scattering.

Summary and Outlook

- A general framework for cross section computation on detecting light-portal dark matter with proper treatment of finite momentum transfer.
- Effective DM and QCD non-local interaction through dimension-8.
- LQCD matrix elements input and Relativistic Fermi gas model being applied and developed to higher ranks to account for nuclear effect.
- With DM flux information input, event rate can be computed and compared with experiments.

Thank you!

Heavy WIMP EFT

Self-conjugate (Majorana) particle χ is a representation of $SU(2)_W \times U(1)_Y$ with mass $M \gg m_W$. The effective theory in the one-heavy-particle sector takes the form

$$\mathcal{L}_{\rm HWET} = \bar{\chi}_v^{(\mu)} \left[iv \cdot D - \delta M - \frac{D_\perp^2}{2M} - \frac{f(H)}{M} - \frac{g(W,B)}{M} + \dots \right] \chi_{v(\mu)}$$

where $D_\perp^\mu = D^\mu - v^\mu (v \cdot D)$.

- Kinetic terms: Universal
- Interaction terms: UV and representation-dependent

Matching

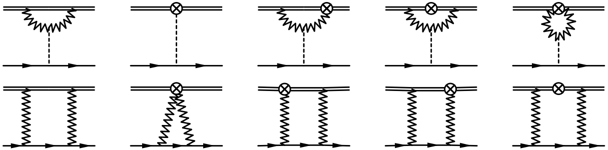
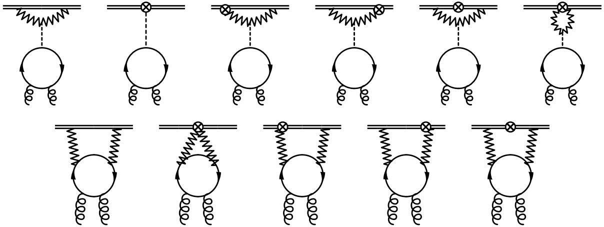


Figure: Diagrams contributing to quark operators matching. Double line denotes heavy WIMP, dashed line denotes Higgs boson, solid line denotes quark, zigzag line denotes W/Z bosons, encircled cross denotes insertion of a $1/M$ effective theory vertex.



Cross Sections

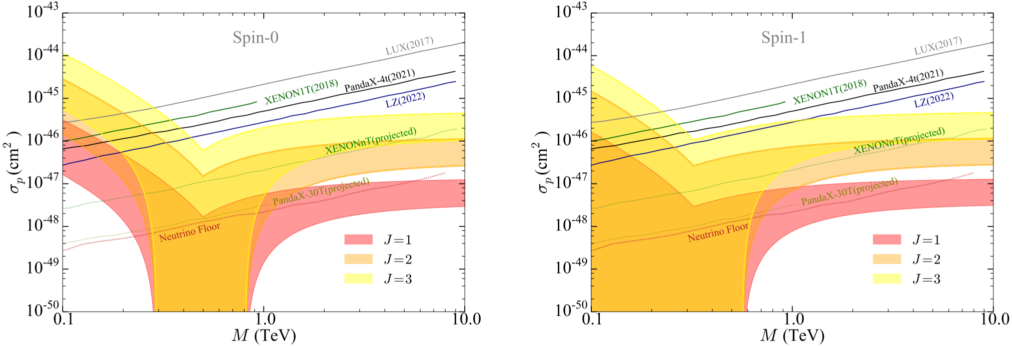


Figure: Scattering cross section for different bosonic WIMP multiplets on proton. (Qing Chen, Gui-Jun Ding and Richard J. Hill, PRD 2023, arXiv:2309.02715)

Cross Sections

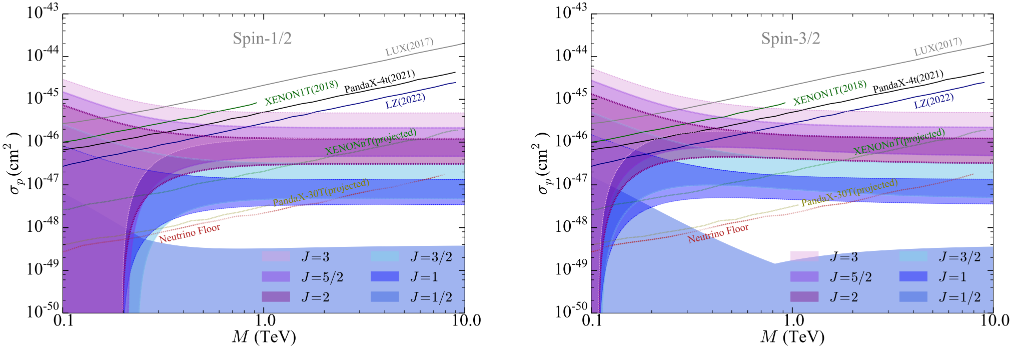


Figure: Scattering cross section for different fermionic WIMP multiplets on proton. (Qing Chen, Gui-Jun Ding and Richard J. Hill, PRD 2023, arXiv:2309.02715)