

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)

安徽理工大学



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.

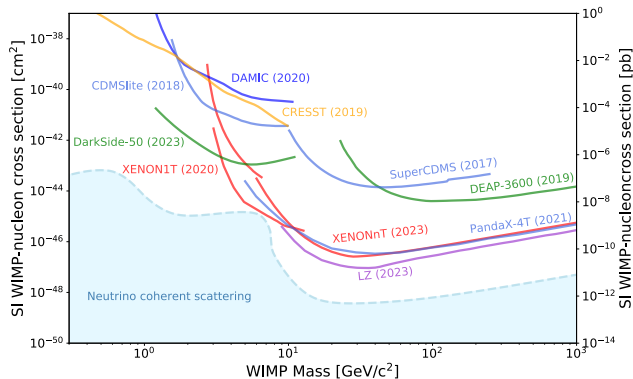


Figure: DM direct detection experimental limits, (PDG 2024)

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

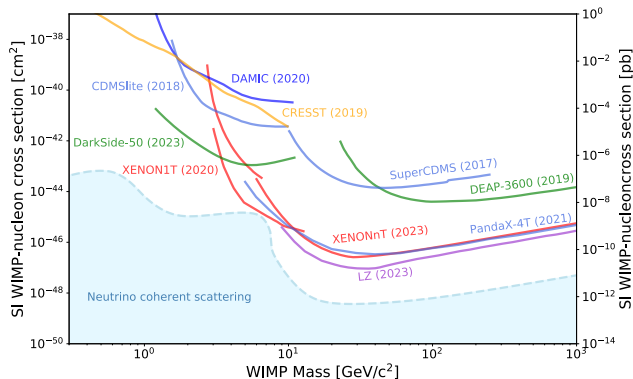


Figure: DM direct detection experimental limits, (PDG 2024)

- **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)

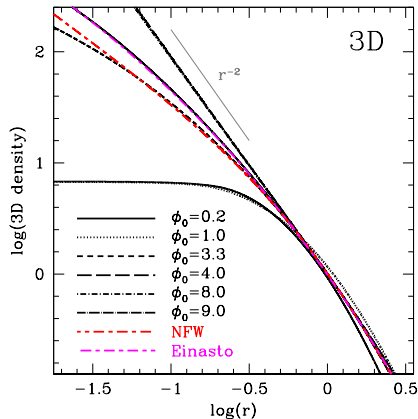


Figure: DM density profile

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

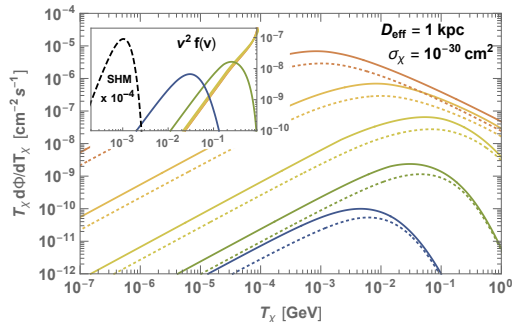
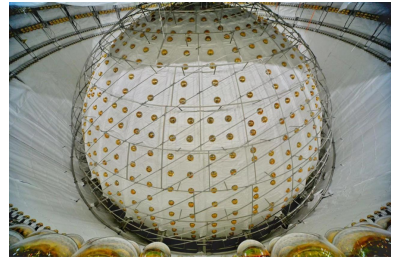
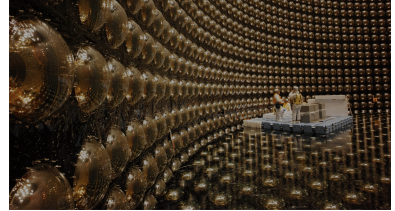
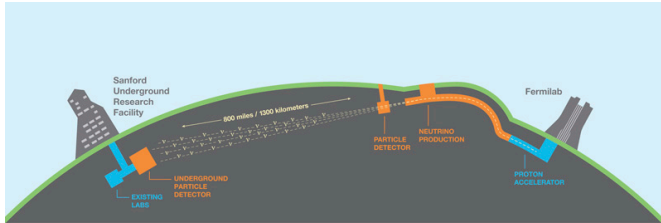


Figure: Flux of CRDM for different DM masses from 1 MeV to 10 GeV, (Bringmann and Pospelov, PRL 1810.10543)

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 ,
 $\chi(k) + N(p) \rightarrow \chi(k') + N(p')$ 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

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

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

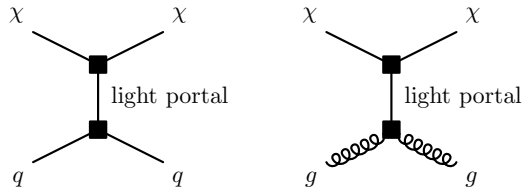


Figure: DM and quarks/gluons interaction via a light mediator.

Effective operators of QCD sector reduction

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

► EoM:

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

► IBP:

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

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

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

Effective operators of dark matter sector

Scalar DM effective bilinear operators

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

Effective interaction

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

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

Nucleon matrix elements

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

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

Non-perturbative nucleon matrix elements of QCD operators

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

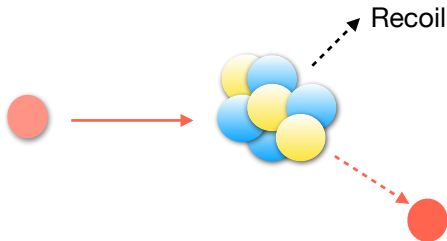
e.g., spin-2 matrix elements involving gravitational form factors (Tong, Ma & Yuan, JHEP 2203.13493; Hackett, Pefkou & Shanahan, PRL 2310.08484; Cao, Guo, Li & Yao, Nat.Comm. 2411.13398; Nair et al. 2506.07554)

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

Relativistic fermi gas model

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

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



Relativistic fermi gas model [Smith & Moniz NPB, 1972](#):

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

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

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

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

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

$$\begin{aligned} \mathcal{L}_{\text{spin-1}} = & \bar{\psi} (i \not{\partial} + g_1 \not{V} + g_2 \not{V} \gamma^5 - M) \psi + \bar{q} (g_1 \not{V} + g_2 \not{V} \gamma^5) q \\ & - \frac{1}{4} (\partial_\mu V_\nu - \partial_\nu V_\mu) (\partial^\mu V^\nu - \partial^\nu V^\mu) + \frac{1}{2} m_{\text{eff}}^2 V_\mu V^\mu \end{aligned}$$

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

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

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 $A_{nmk} = \int d^3\mathbf{p} \frac{p_0^n p_z^m |\mathbf{p}|^{2k}}{m_N^r} f(\mathbf{p}, q^0, \mathbf{q})$

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

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

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

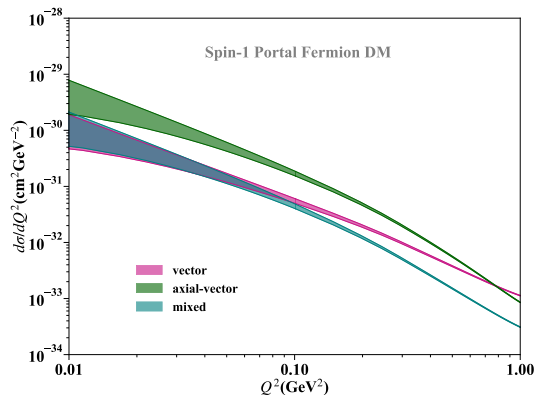
$$W_4 = \frac{m_T^2}{m_N^2} \left[A_{000} H_4 + \frac{m_N^2}{|\mathbf{q}|^2} \left(\frac{3}{2} A_{020} - \frac{1}{2} A_{001} \right) H_2 + A_{010} \frac{m_N}{|\mathbf{q}|} H_3 \right],$$

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

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 $\text{Diff}_L \times \text{Diff}_R \rightarrow \text{Diff}_V$

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

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

Example: spin-2 portal

Effective QCD operators for spin-2 portal model

$$\begin{aligned}\mathcal{O}_q^{(0)} &= m_q \bar{q} q, & \mathcal{O}_g^{(0)} &= G_{\mu\nu}^A G^{A\mu\nu} \\ \mathcal{O}_q^{(2)\mu\nu} &= \frac{1}{2} \bar{q} \left(\gamma^{\{\mu} i D_-^{\nu\}} - \frac{g^{\mu\nu}}{d} i \not{D}_- \right) q \\ \mathcal{O}_g^{(2)\mu\nu} &= -G^{A\mu\lambda} G^{A\nu}{}_{\lambda} + \frac{1}{d} g^{\mu\nu} (G_{\alpha\beta}^A)^2\end{aligned}$$

Massive spin-2 propagator

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

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

Example: spin-2 portal

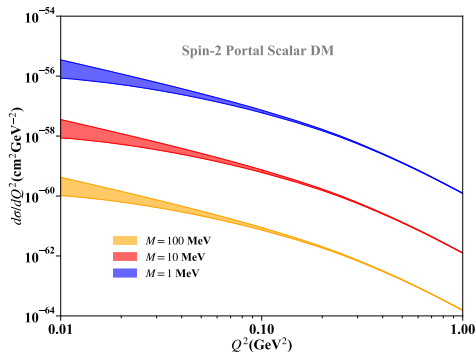
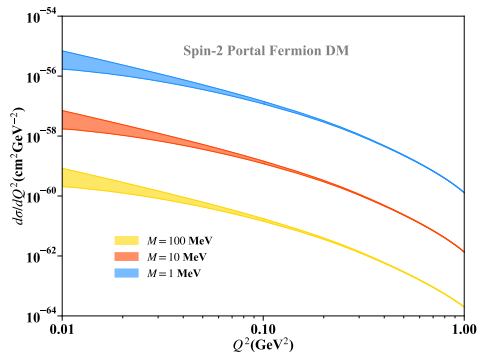


Figure: Differential cross sections for spin-2 portal (semi)relativistic dark matter and Argon nucleus scattering.

- ▶ 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!

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

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

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

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

Matching

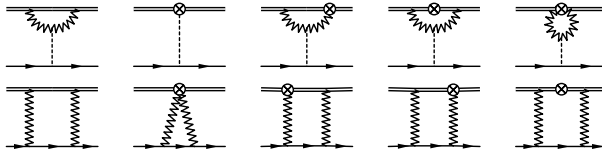
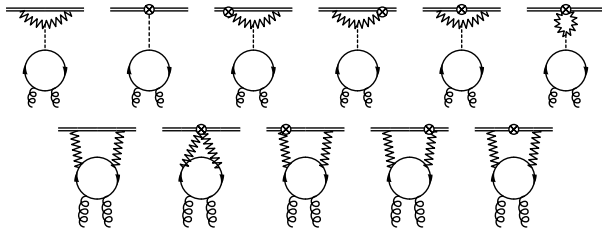


Figure: Diagrams contributing to quark operators matching. Double line denotes heavy WIMP, dashed line denotes Higgs boson, solid line denotes quark, zigzag line denotes W/Z bosons, encircled cross denotes insertion of a $1/M$ effective theory vertex.



Cross Sections

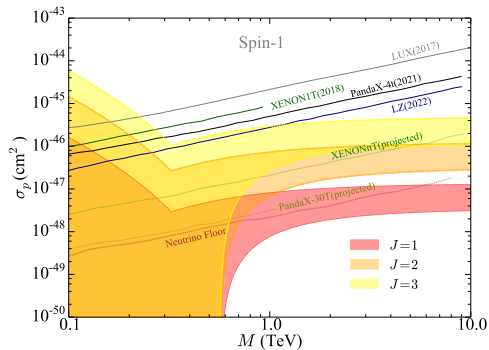
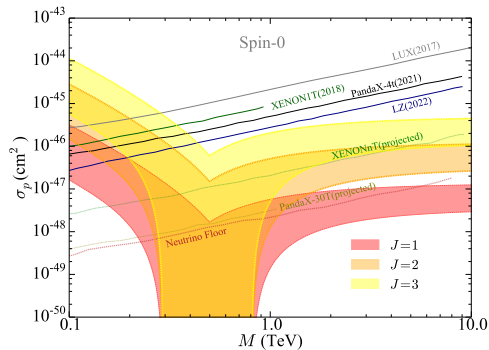


Figure: Scattering cross section for different bosonic WIMP multiplets on proton. (Qing Chen, Gui-Jun Ding and Richard J. Hill, PRD 2023, arXiv:2309.02715)

Cross Sections

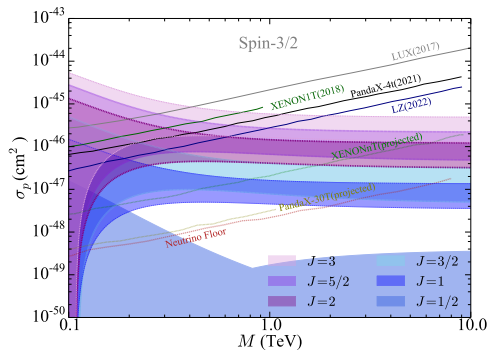
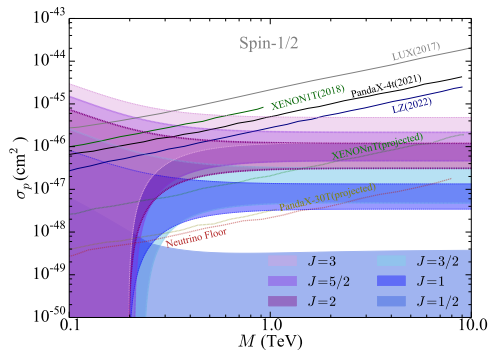


Figure: Scattering cross section for different fermionic WIMP multiplets on proton. (Qing Chen, Gui-Jun Ding and Richard J. Hill, PRD 2023, arXiv:2309.02715)