Dark Matter Direct Detection with Spin-2 Mediators

Yoo-Jin Kang

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Alba Carrillo-Monteverde, **YJK**, Hyun Min Lee,
Myeonghun Park and Veronica Sanz,
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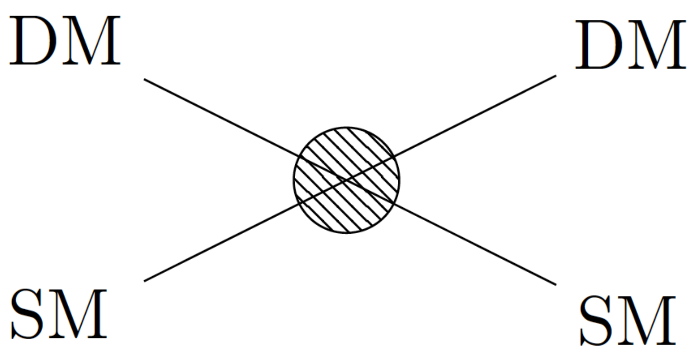
Dark matter and Direct detection



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- Many DM searches (Direct, Indirect, Collider)

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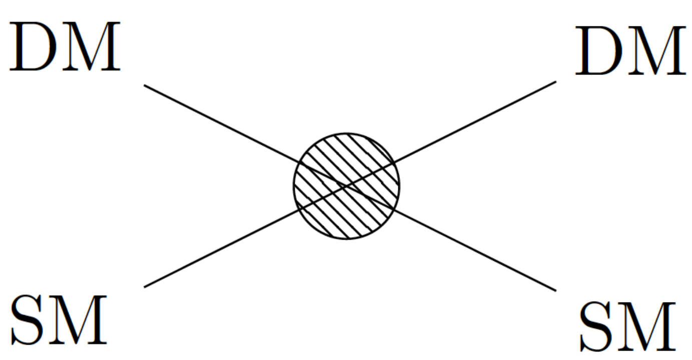

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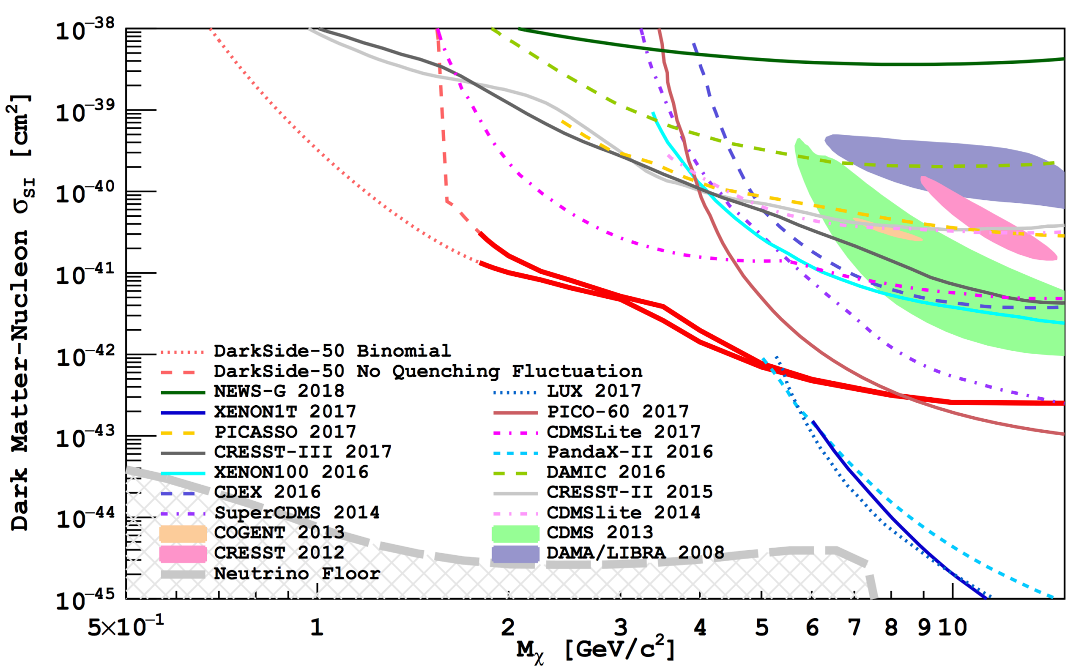
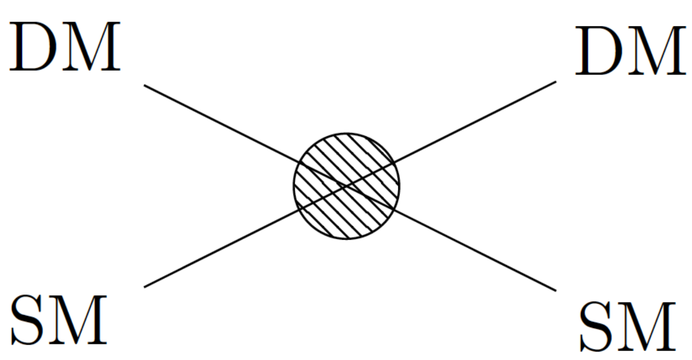


DarkSide-50 (1802.06994)

Experiment	Target
LUX	Xe
XENON1T	Xe
PandaX-II	Xe
SuperCDMS	Ge
CDMSlite	Ge
XENON10	Xe
DarkSide-50	Ar
CRESST-II	$CaWO_4$
LZ (Project)	Xe

Dark matter and Direct detection



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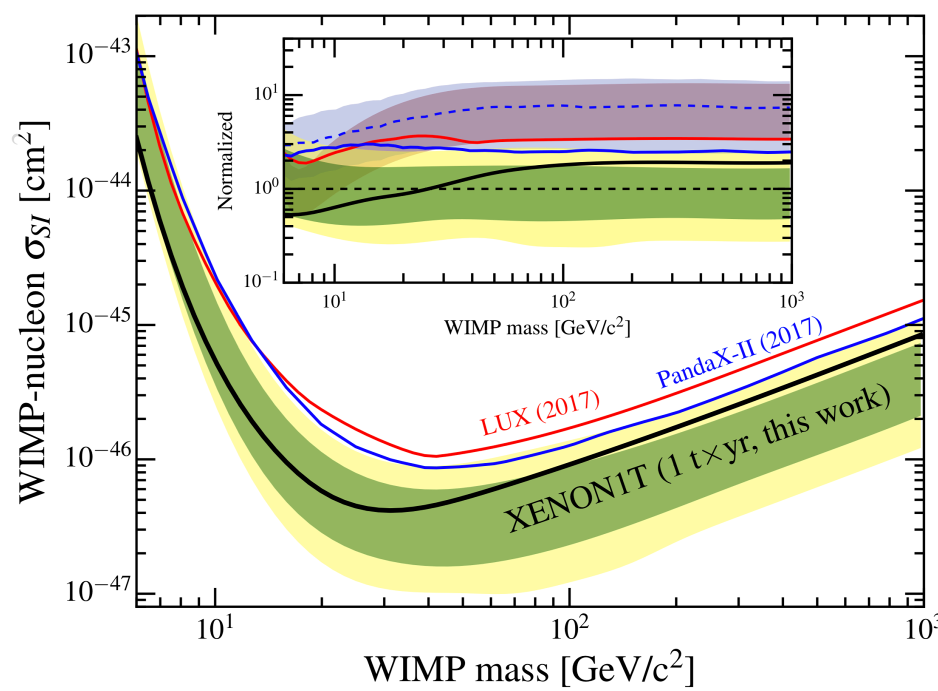

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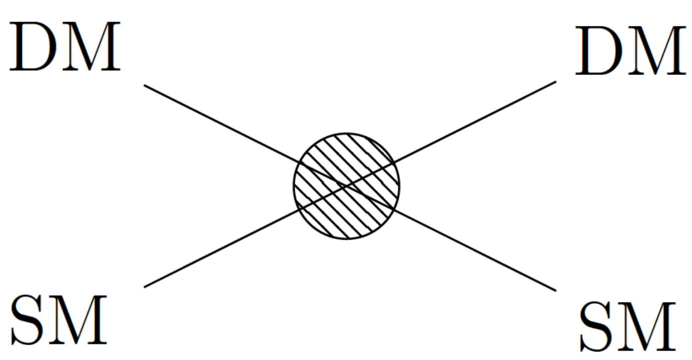

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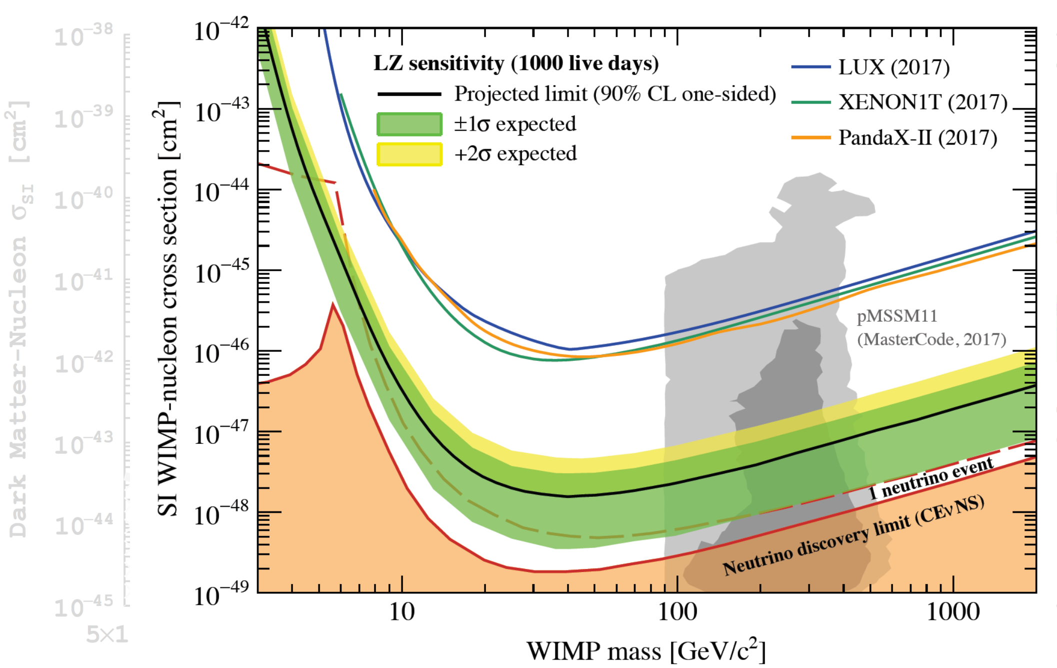
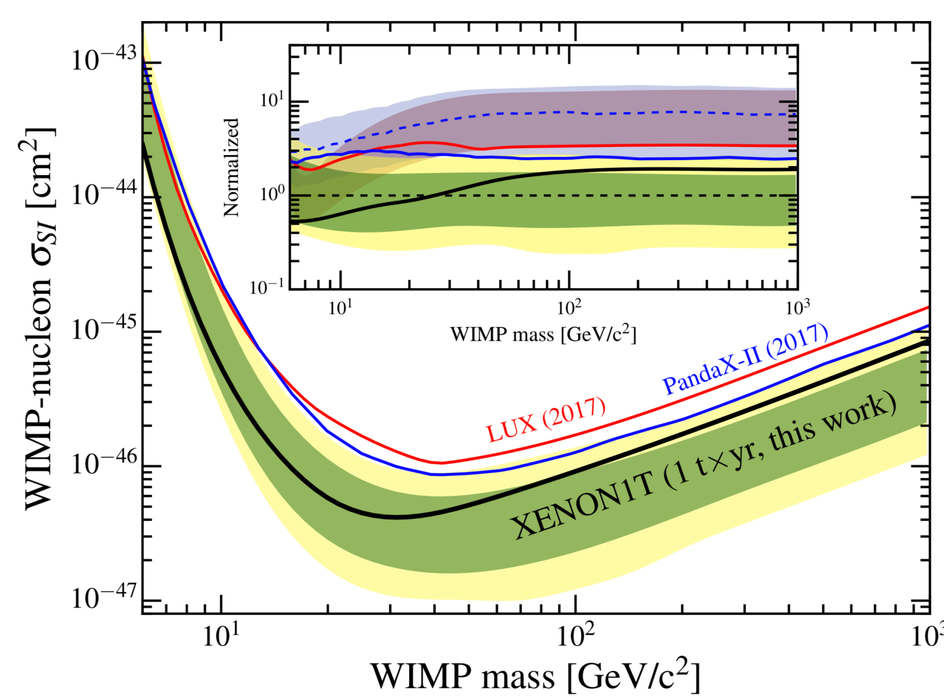


LUX-ZEPLIN (1802.06039)



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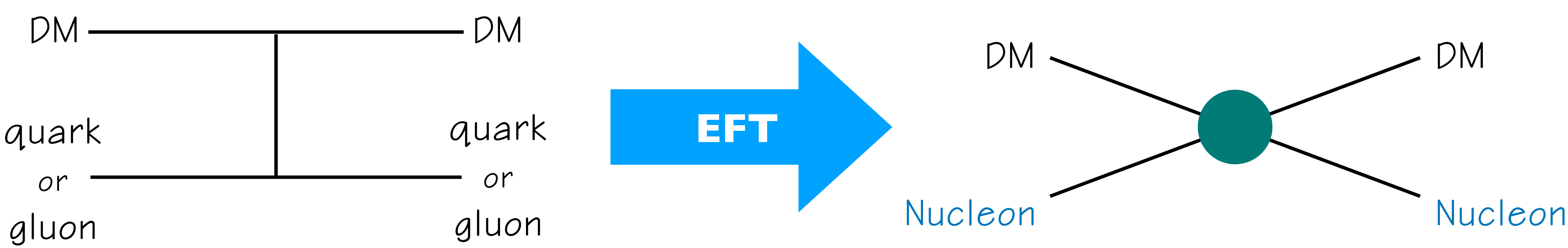
EFT approaches in DM detection

- EFT approaches are suitable with scattering processes b/w DM and nucleons.
- Mediators can be directly produced in the early Universe or at the LHC.

  Integrating out mediators leads to the effective operators for Direct Detection.

→ "Valid from freeze-out/LHC to DD"



K. Ishiwata et al (1409.8290),
Marco Cirelli et al (1307.5955), Kathryn M. Zurek et al (1506.04454),
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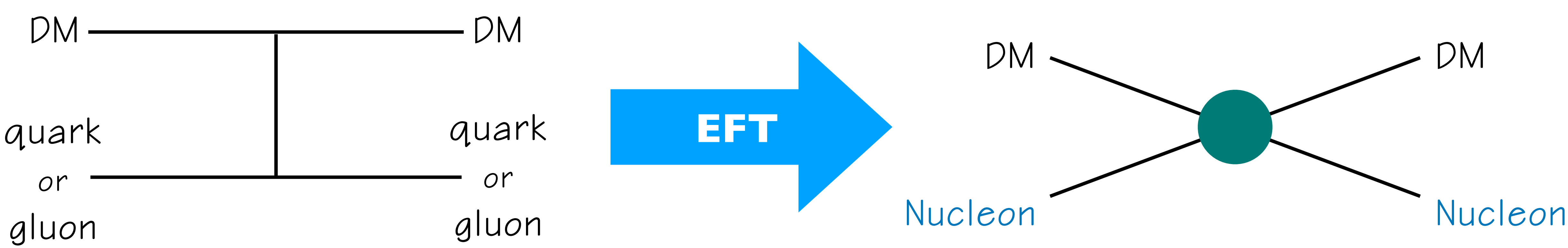

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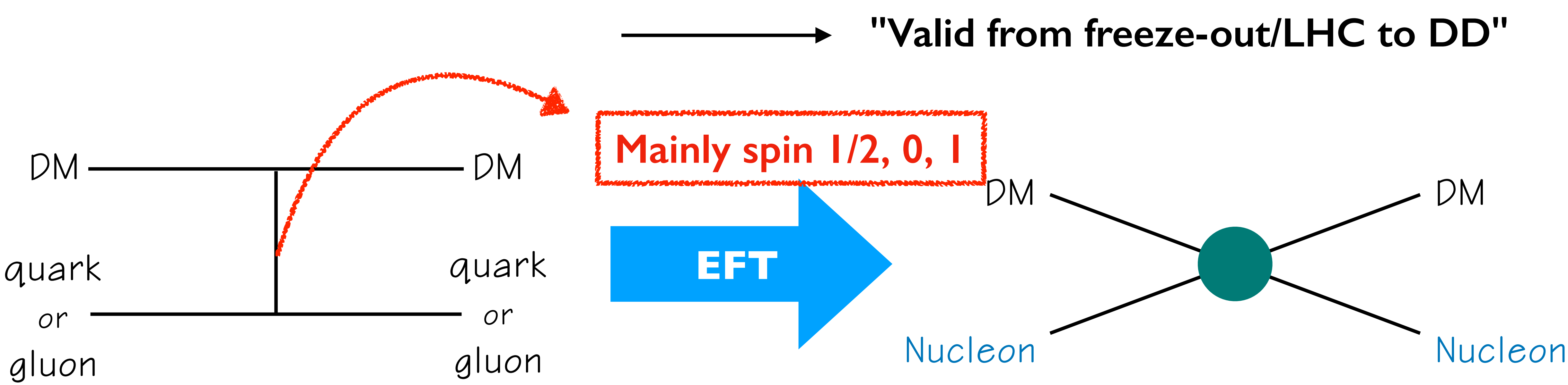

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We consider **Scattering** of **dark matter** and **nucleon**

in the spin-2 mediator model with the effective operators

and compute differential event rates for direct detection.

Spin-2 Mediator Model

$$\mathcal{L}_{\text{int}} = -\frac{c_{\text{SM}}}{\Lambda}\mathcal{G}^{\mu\nu}T^{\text{SM}}_{\mu\nu} - \frac{c_{\text{DM}}}{\Lambda}\mathcal{G}^{\mu\nu}T^{\text{DM}}_{\mu\nu}$$

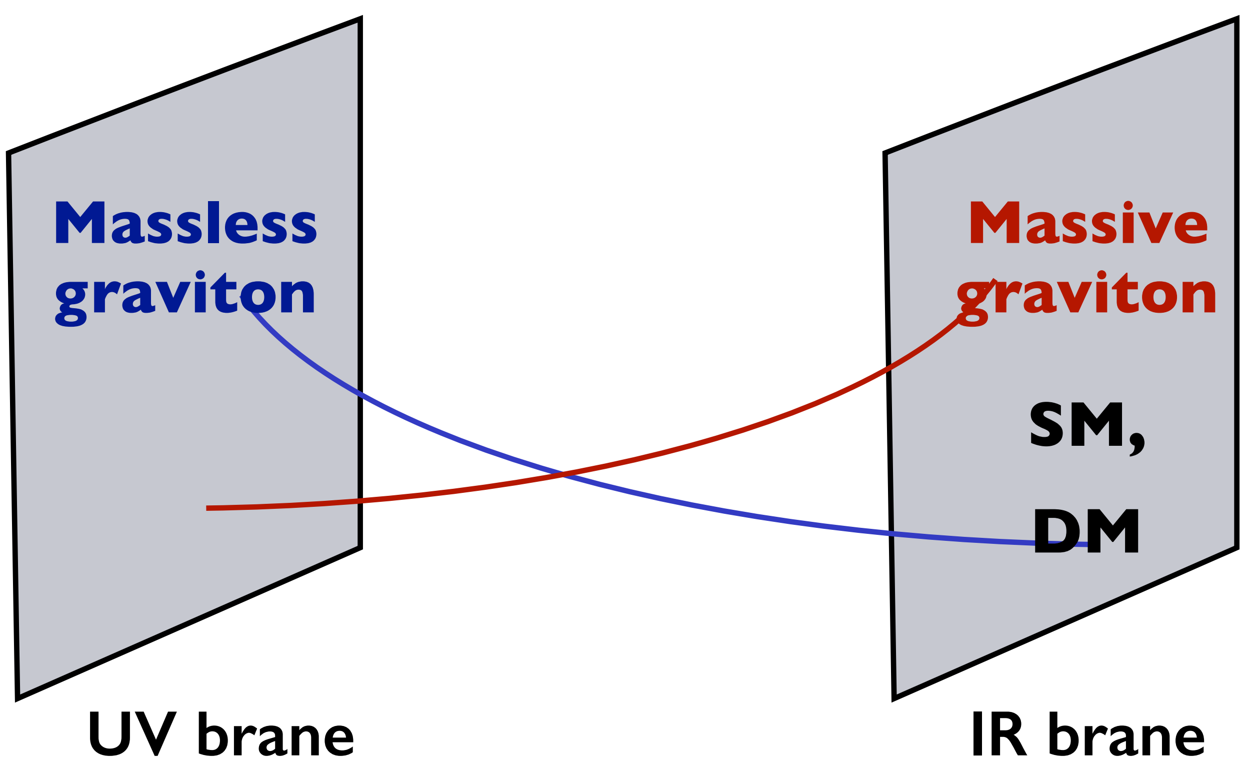
$\mathcal{G}^{\mu\nu}$: massive spin-2 mediator

$T_{\mu\nu}$: energy-momentum tensor

H. M. Lee, M. Park and V. Sanz (1306.4107, 1401.5301)

For example, Randall-Sundrum model in extra dimension

Massless graviton is localized on UV brane



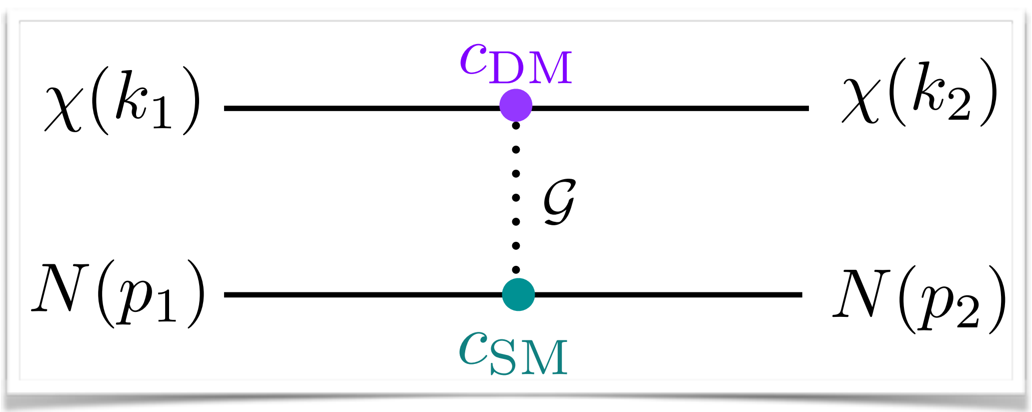
SM particles, dark matter and massive graviton are localized on IR brane

Spin-2 Mediator Model

We consider the tree-level scattering amplitude b/w DM and quark though
a massive spin-2 mediator

$$\mathcal{M} = -\frac{c_{\rm DM} c_{\rm SM}}{\Lambda^2} \frac{i}{q^2 - m_G^2} T^{\rm DM}_{\mu\nu}(q) \mathcal{P}^{\mu\nu,\alpha\beta}(q) T^{\rm SM}_{\alpha\beta}(-q)$$

Massive spin-2 propagator



$$\mathcal{P}^{\mu\nu,\alpha\beta}(q) = \frac{1}{2}\left(G^{\mu\alpha}G^{\nu\beta} + G^{\nu\alpha}G^{\mu\beta} - \frac{2}{3}G^{\mu\nu}G^{\alpha\beta}\right)$$

$$G^{\mu\nu} \equiv \eta^{\mu\nu} - \frac{q^\mu q^\nu}{m_G^2}$$

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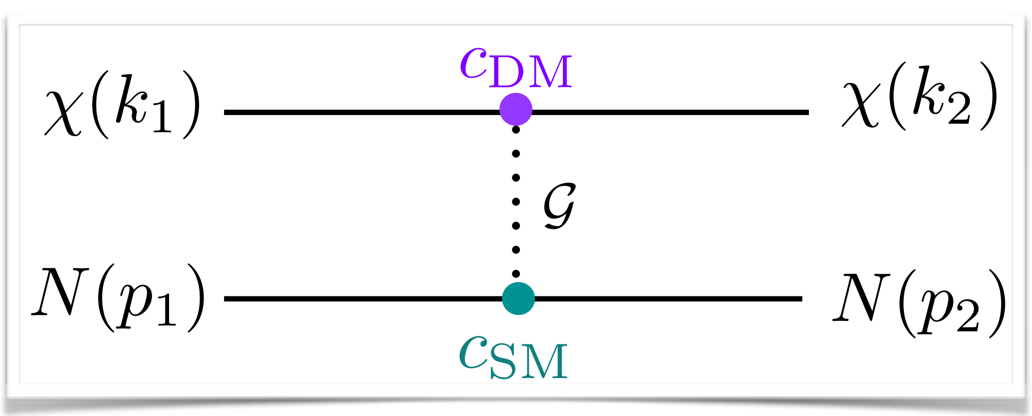

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Integrated Out

$$\mathcal{M} = \frac{i c_{\rm DM} c_{\rm SM}}{2 m_G^2 \Lambda^2}\left(2\tilde{T}^{\rm DM}_{\mu\nu}\tilde{T}^{{\rm SM},\mu\nu} - \frac{1}{6} T^{\rm DM} T^{\rm SM}\right)$$

traceless part   trace

DM energy-momentum tensor

H. M. Lee, M. Park and V. Sanz
(1306.4107, 1401.5301)

Fermion DM

$$T^\chi = -\frac{1}{4}\bar{u}_\chi(k_2)\Big(-6(\not{k}_1+\not{k}_2)+16m_\chi\Big)u_\chi(k_1)$$

$$\tilde{T}^\chi_{\mu\nu} = -\frac{1}{4}\bar{u}_\chi(k_2)\Big(\gamma_\mu(k_{1\nu}+k_{2\nu})+\gamma_\nu(k_{1\mu}+k_{2\mu})-\frac{1}{2}\eta_{\mu\nu}(\not{k}_1+\not{k}_2)\Big)u_\chi(k_1)$$

Scalar DM

$$T^S = -(4m_S^2-2(k_1\cdot k_2))$$

$$\tilde{T}^S_{\mu\nu} = -\Big(k_{1\mu}k_{2\nu}+k_{2\mu}k_{1\nu}-\frac{1}{2}\eta_{\mu\nu}(k_1\cdot k_2)\Big)$$

functions of its momentums

Vector DM

$$T^X = 2m_X^2\eta_{\alpha\beta}\epsilon^\alpha(k_1)\epsilon^{*\beta}(k_2)$$

$$\tilde{T}^X_{\mu\nu} = -\Big(m_X^2C_{\mu\nu,\alpha\beta}+W_{\mu\nu,\alpha\beta}+\frac{1}{2}m_X^2\eta_{\mu\nu}\eta_{\alpha\beta}\Big)\epsilon^\alpha(k_1)\epsilon^{*\beta}(k_2)$$

where

$$C_{\mu\nu,\alpha\beta} \equiv \eta_{\mu\alpha}\eta_{\nu\beta}+\eta_{\nu\alpha}\eta_{\mu\beta}-\eta_{\mu\nu}\eta_{\alpha\beta}$$

$$W_{\mu\nu,\alpha\beta} \equiv -\eta_{\alpha\beta}k_{1\mu}k_{2\nu}-\eta_{\mu\alpha}(k_1\cdot k_2\,\eta_{\nu\beta}-k_{1\beta}k_{2\nu})+\eta_{\mu\beta}k_{1\nu}k_{2\alpha} -\frac{1}{2}\eta_{\mu\nu}(k_{1\beta}k_{2\alpha}-k_1\cdot k_2\,\eta_{\alpha\beta})+(\mu\leftrightarrow\nu).$$

Matching from Quark to Nucleon

$$\langle N(p_2)|T^{\psi}|N(p_1)\rangle = -F_S(q^2) m_N \bar{u}_N(p_2) u_N(p_1)$$

(━ : Gravitational form factors)

$$\langle N(p_2)|\tilde{T}^{\psi}_{\mu\nu}|N(p_1)\rangle = -2(A(q^2) + B(q^2))\tilde{T}^N_{\mu\nu} + \frac{1}{m_N}\bar{u}_N(p_2)\Big[-2B(q^2)\Big(p_\mu p_\nu - \frac{1}{4}g_{\mu\nu}p^2\Big) + C(q^2)\Big(q_\mu q_\nu - \frac{1}{4}\eta_{\mu\nu}q^2\Big)\Big]u_N(p_1)$$

$$p = (p_1 + p_2)/2$$
$$q = p_2 - p_1$$

$$= F_T(q^2)\tilde{T}^N_{\mu\nu}$$ with $A(q^2) = -F_T(q^2)/2,\ B(q^2) = C(q^2) = 0$

by holographic QCD

Z. Abidin and C. E. Carlson (0903.4818)

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The twist-2 operators for nucleons with **zero momentum transfer**,

quark : $\langle N(p)|\tilde{T}^q_{\mu\nu}|N(p)\rangle = \frac{1}{m_N}\Big(p_\mu p_\nu - \frac{1}{4}m_N^2 g_{\mu\nu}\Big)(q(2)+\bar{q}(2))\,\bar{u}_N(p)u_N(p)$

second moments of the PDF $\int_0^1 dx\ x[q(x)+\bar{q}(x)]$

gluon : $\langle N(p)|\tilde{T}^g_{\mu\nu}|N(p)\rangle = \frac{1}{m_N}\Big(p_\mu p_\nu - \frac{1}{4}m_N^2 g_{\mu\nu}\Big)G(2)\,\bar{u}_N(p)u_N(p)$

second moments of the PDF $\int_0^1 dx\ x\ g(x)$

Effective Operators

Elastic scattering of WIMP & Nucleon $\mathcal{L}_{\rm int}(\vec{x}) = c\ \underline{\Psi^*_\chi(\vec{x})\mathcal{O}_\chi\Psi_\chi(\vec{x})}\ \underline{\Psi^*_N(\vec{x})\mathcal{O}_N\Psi_N(\vec{x})},$

Effective operator : $\sum_{i=1}^{\mathcal{N}}\left(c_i^{(n)}\mathcal{O}_i^{(n)} + c_i^{(p)}\mathcal{O}_i^{(p)}\right)$

$\mathcal{O}_i$ is formed from the $\mathcal{O}_\chi$ and $\mathcal{O}_N$

The complete set of Hermitian quantities for Galilean invariance

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

where μ_N : reduced mass of DM and nucleon

$\vec{v}^\perp \cdot \vec{q} = 0$

Non-relativistic Operators

$$\begin{aligned}
\mathcal{O}_1 &= 1_\chi 1_N \\
\mathcal{O}_2 &= (v^\perp)^2 \\
\mathcal{O}_3 &= i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp) \\
\mathcal{O}_4 &= \vec{S}_\chi \cdot \vec{S}_N \\
\mathcal{O}_5 &= i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp) \\
\mathcal{O}_6 &= (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N}) \\
\mathcal{O}_7 &= \vec{S}_N \cdot \vec{v}^\perp \\
\mathcal{O}_8 &= \vec{S}_\chi \cdot \vec{v}^\perp
\end{aligned}$$

and so on

Fitzpatrick et al (1203.3542, 1308.6288)

Effective Operators in Spin-2 Model

		$\mathcal{O}_i$	$\sum_k \mathcal{O}_k^{\mathrm{NR}}$
$S_{\mathrm{DM}} = \frac{1}{2}$	F	$(\bar{\chi}\chi)\left(\bar{N}N\right)$	$4m_\chi m_N \mathcal{O}_1^{NR}$
	F	$(\bar{\chi}\chi)\left(K_\nu \bar{N} i\sigma^{\nu\lambda} q_\lambda N\right)$	$4m_\chi^2 \vec{q}^2 \mathcal{O}_1^{NR} - 16 m_\chi^2 m_N^2 \mathcal{O}_3^{NR}$
	F	$(P_\mu \bar{\chi} i\sigma^{\mu\rho} q_\rho \chi)\left(\bar{N}N\right)$	$-4m_N^2 \vec{q}^2 \mathcal{O}_1^{NR} + 16 m_\chi m_N^3 \mathcal{O}_5^{NR}$
	F	$(\bar{\chi} i\sigma^{\mu\rho} q_\rho \chi)\left(\bar{N} i\sigma^{\nu\lambda} q_\lambda N\right)$	$16 m_\chi m_N (\vec{q}^2 \mathcal{O}_4^{NR} - m_N^2 \mathcal{O}_6^{NR})$
	F	$(P_\mu \bar{\chi} i\sigma^{\mu\rho} q_\rho \chi)\left(K_\nu \bar{N} i\sigma^{\nu\lambda} q_\lambda N\right)$	$-4m_\chi m_N(\vec{q}^2 \mathcal{O}_1^{NR} - 4m_N^2 \mathcal{O}_3^{NR})$ $\times(\vec{q}^2 \mathcal{O}_1^{NR} - 4 m_\chi m_N \mathcal{O}_5^{NR})$
$S_{\mathrm{DM}} = 0$	S	$(S^* S)(\bar{N}N)$	$2m_N \mathcal{O}_1^{NR}$
	S	$i(S^* \partial_\mu S - S \partial_\mu S^*)(\bar{N}\gamma^\mu N)$	$4m_S m_N \mathcal{O}_1^{NR}$
$S_{\mathrm{DM}} = 1$	V	$\bar{N}N$	$2m_N f(\epsilon_1, \epsilon_2^*) \mathcal{O}_1^{\mathrm{NR}}$
	V	$\epsilon_{1,2}^\alpha \bar{N} i\sigma_{\alpha\lambda} q^\lambda N$	$4im_N^2\left(\vec{s}_N \cdot (\vec{\epsilon}_{1,2} \times \frac{\vec{q}}{m_N})\right)$
	V	$k_{1,2\nu} \bar{N} i\sigma^{\nu\lambda} q_\lambda N$	$m_\chi\left(\vec{q}^2 \mathcal{O}_1^{\mathrm{NR}} - 4m_N^2 \mathcal{O}_3^{\mathrm{NR}}\right)$

Spin-2 mediator model has dimension-8 operator.

Result : Effective Lagrangian

Unsuppressed operator for spin-independent DM-nucleon scattering

Fermion DM

$$\mathcal{L}_{\chi,\text{eff}} \approx \frac{c_\chi c_\psi m_\chi^2 m_N^2}{2m_G^2\Lambda^2}\left[\left\{6F_T\left(1+\frac{\vec{q}^{\,2}}{3m_N^2}+\frac{\vec{q}^{\,2}}{3m_\chi^2}\right)-\frac{2}{3}F_S\right\}\mathcal{O}_1^{\text{NR}} - 8F_T\mathcal{O}_3^{\text{NR}} - \frac{4\vec{q}^{\,2}}{m_\chi m_N}F_T\mathcal{O}_4^{\text{NR}}\right.$$

$$\left. -\frac{8m_N}{m_\chi}F_T\left(1+\frac{\vec{q}^{\,2}}{8m_N}\right)\mathcal{O}_5^{\text{NR}} + \frac{4m_N}{m_\chi}F_T\mathcal{O}_6^{\text{NR}} + \frac{4m_N}{m_\chi}F_T\mathcal{O}_3^{\text{NR}}\mathcal{O}_5^{\text{NR}}\right]$$

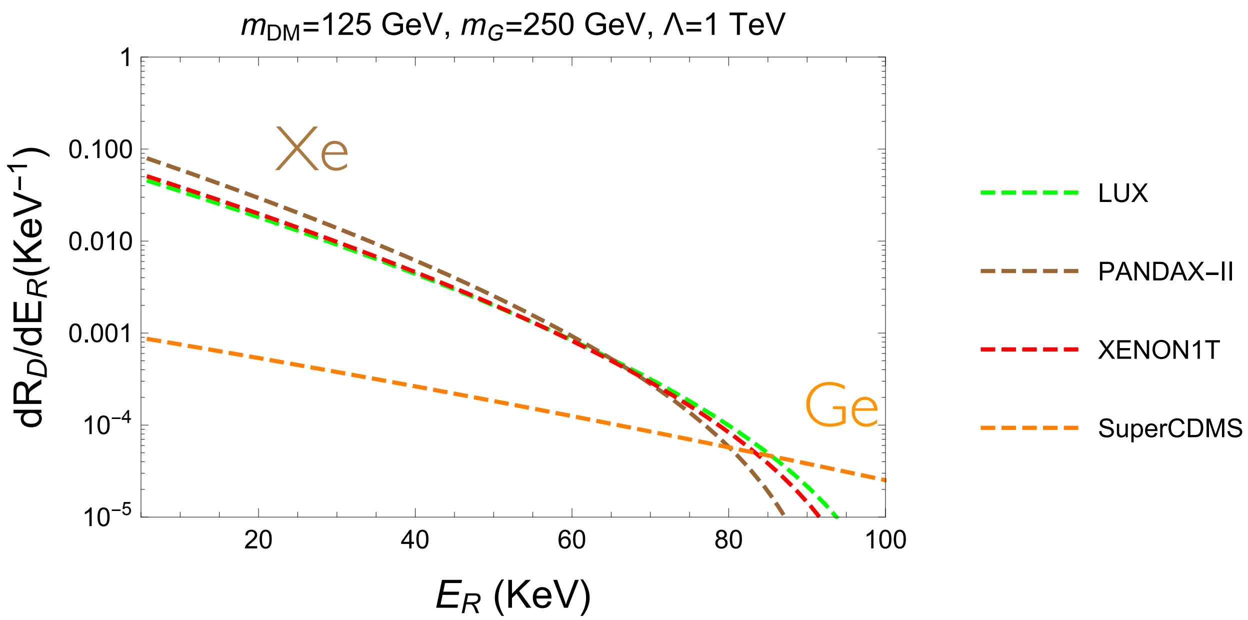
Scalar DM

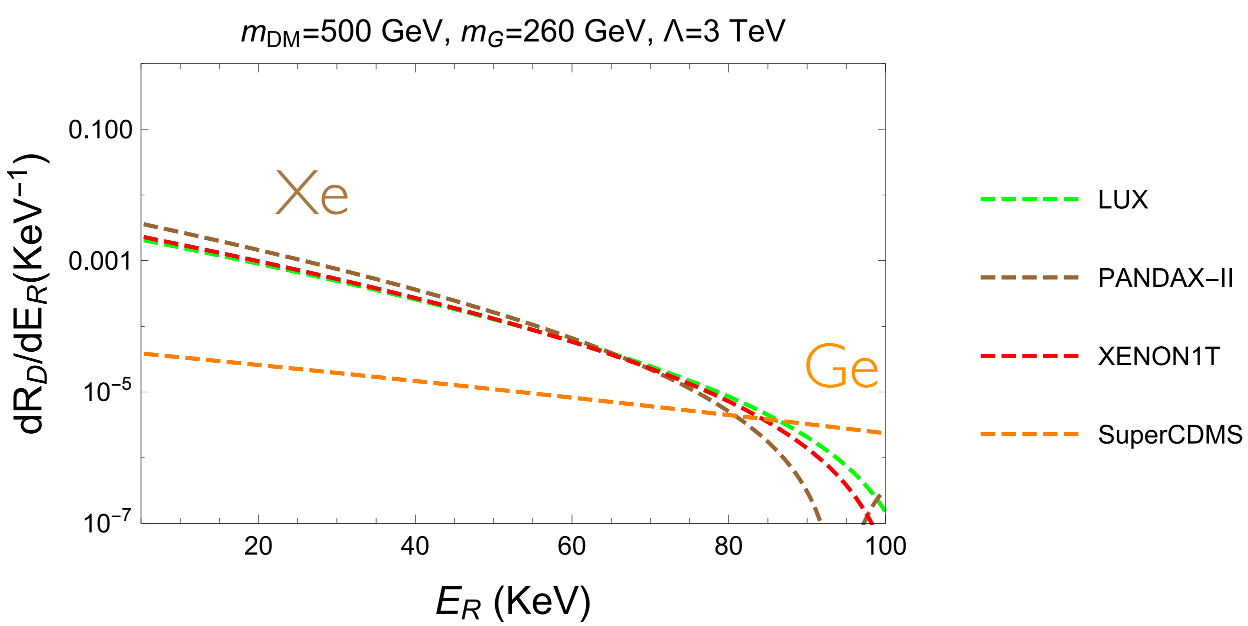
$$\mathcal{L}_{S,\text{eff}} = \frac{c_S c_\psi m_S^2 m_N^2}{2m_G^2\Lambda^2}\left[F_T\left(6-\frac{\vec{q}^{\,2}}{m_S^2}\right)-\frac{2}{3}F_S\left(1-\frac{\vec{q}^{\,2}}{2m_S^2}\right)\right]\mathcal{O}_1^{\text{NR}}$$

$\int \frac{d^3p}{(2\pi)^3\sqrt{2E}}a_N^{(\dagger)}$ and $\int \frac{d^3p}{(2\pi)^3\sqrt{2E}}a_\chi^{(\dagger)}$ per each nucleon & DM state are to be multiplied.

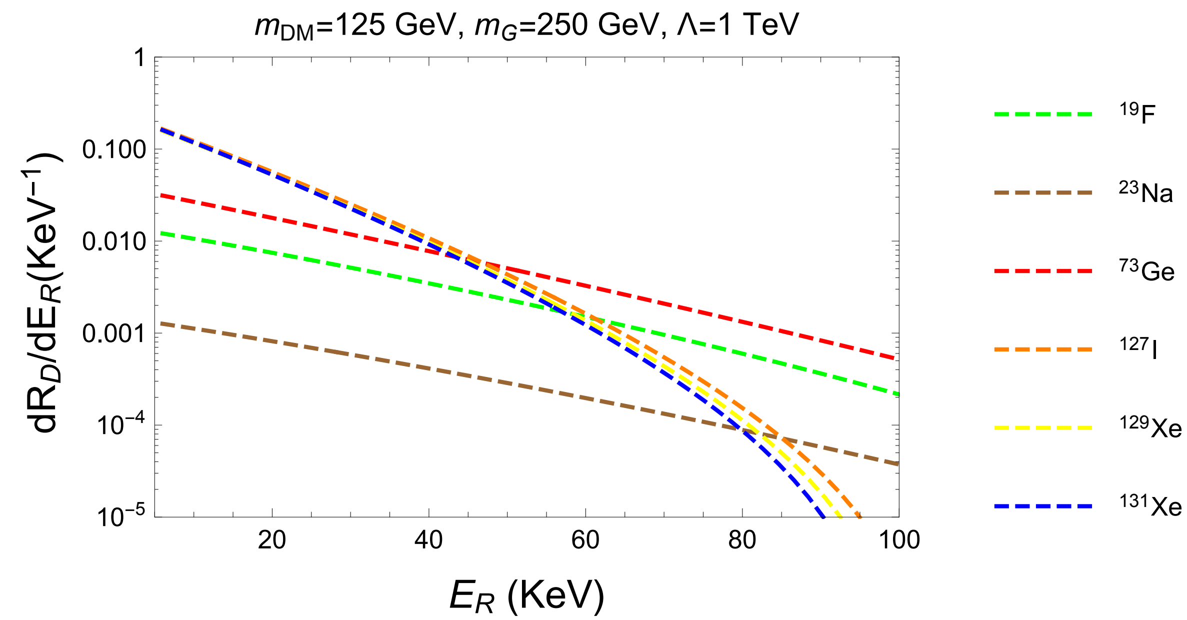
Heavy DM and Direct Detection

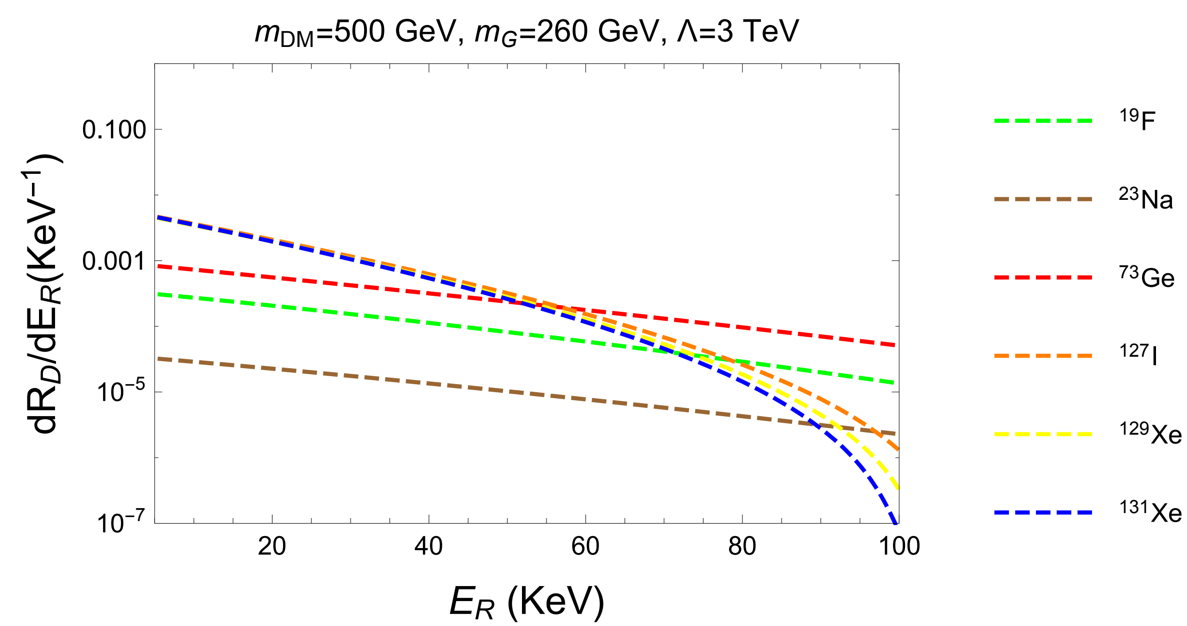
Current Exp.





Mock Exp.



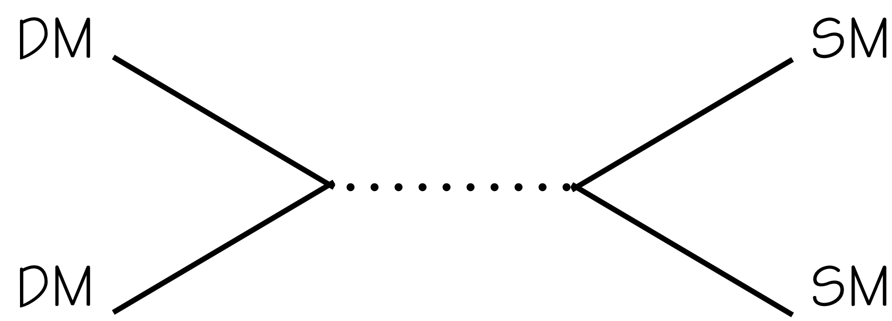


by dmformfactor mathematica package

package : Fitzpatrick et al (1203.3542, 1308.6288)

Relic Density condition

Annihilation cross section



$$S_{\rm DM} = \frac{1}{2} \quad \bullet \quad (\sigma v)_{\chi\bar{\chi}\to\psi\bar{\psi}} = v^2 \cdot \frac{N_c c_\chi^2 c_\psi^2}{72\pi\Lambda^4} \frac{m_\chi^6}{(4m_\chi^2 - m_G^2)^2 + \Gamma_G^2 m_G^2} \left(1 - \frac{m_\psi^2}{m_\chi^2}\right)^{\frac{3}{2}} \left(3 + \frac{2m_\psi^2}{m_\chi^2}\right)$$

p-wave

$$S_{\rm DM} = 0 \quad \bullet \quad (\sigma v)_{SS\to\psi\bar{\psi}} = v^4 \cdot \frac{N_c c_S^2 c_\psi^2}{360\pi\Lambda^4} \frac{m_S^6}{(m_G^2 - 4m_S^2)^2 + \Gamma_G^2 m_G^2} \left(1 - \frac{m_\psi^2}{m_S^2}\right)^{\frac{3}{2}} \left(3 + \frac{2m_\psi^2}{m_S^2}\right)$$

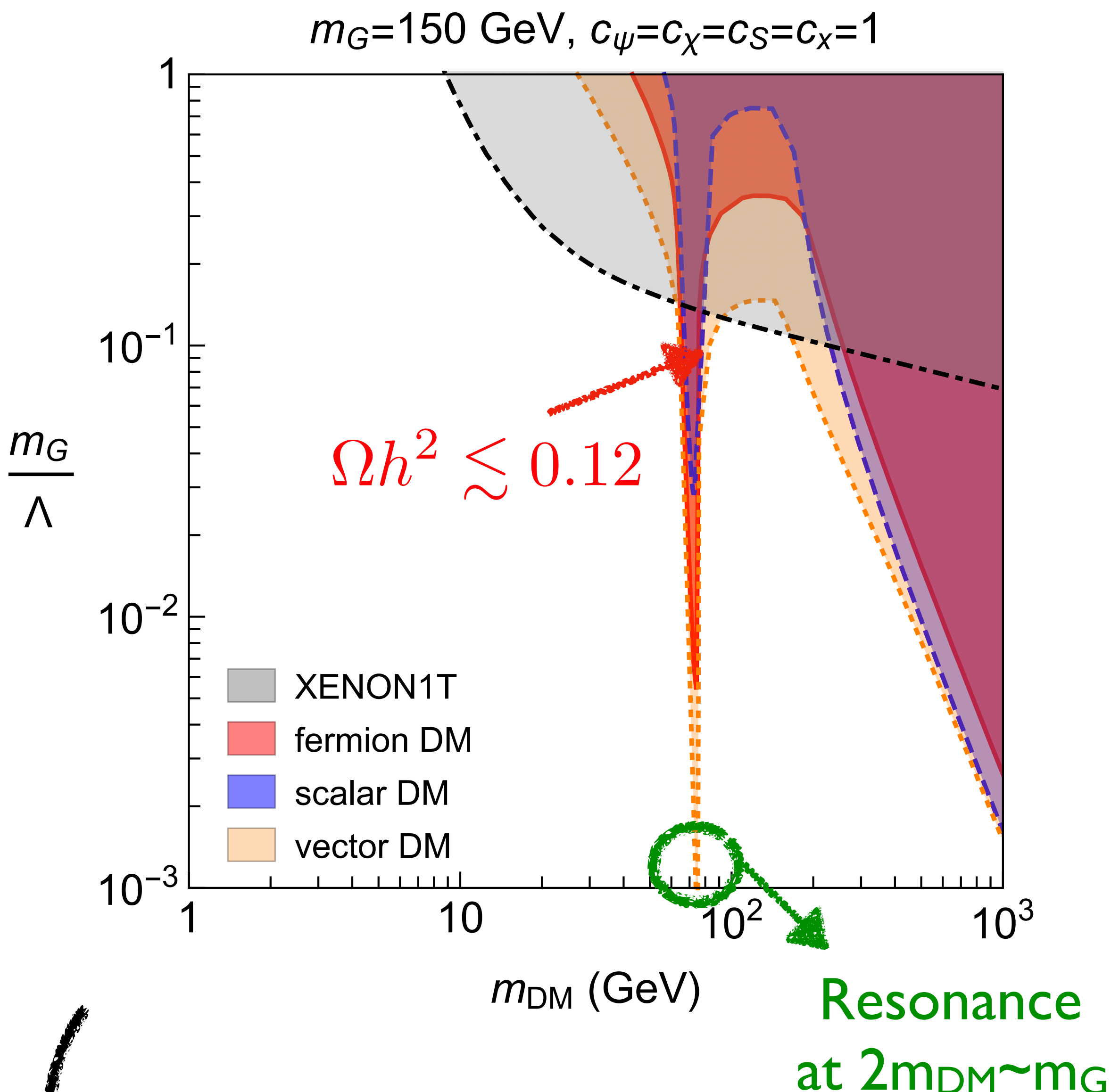
d-wave

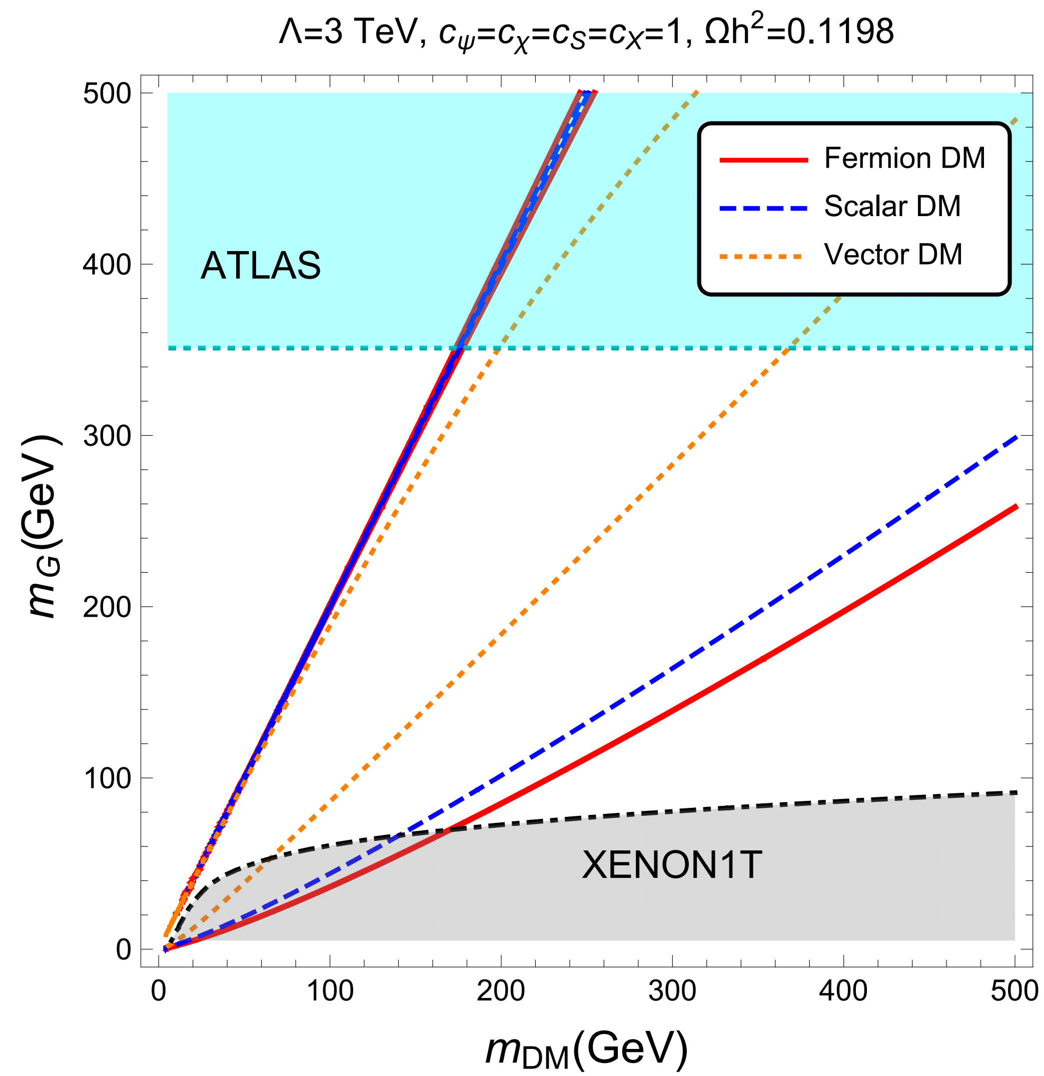
$$S_{\rm DM} = 1 \quad \bullet \quad (\sigma v)_{XX\to\psi\bar{\psi}} = \frac{4N_c c_X^2 c_\psi^2}{27\pi\Lambda^4} \frac{m_X^6}{(4m_X^2 - m_G^2)^2 + \Gamma_G^2 m_G^2} \left(1 - \frac{m_\psi^2}{m_X^2}\right)^{\frac{3}{2}} \left(3 + \frac{2m_\psi^2}{m_X^2}\right)$$

s-wave ⟶ constrained by indirect detection

H. M. Lee, M. Park and V. Sanz (1306.4107, 1401.5301)

Relic Density Condition





- The relic region below m_{DM}=250 GeV is excluded by direct detection, except the resonance region.
- If we consider gluon contribution, relic density lines will be lower.

SI scattering cross section

Spin-independent scattering cross section in the spin-2 med. model

$$\sigma^{\rm SI}_{{\rm DM}-N} = \frac{\mu_N^2}{\pi A^2}(Z f_p^{\rm DM} + (A-Z) f_n^{\rm DM})^2$$

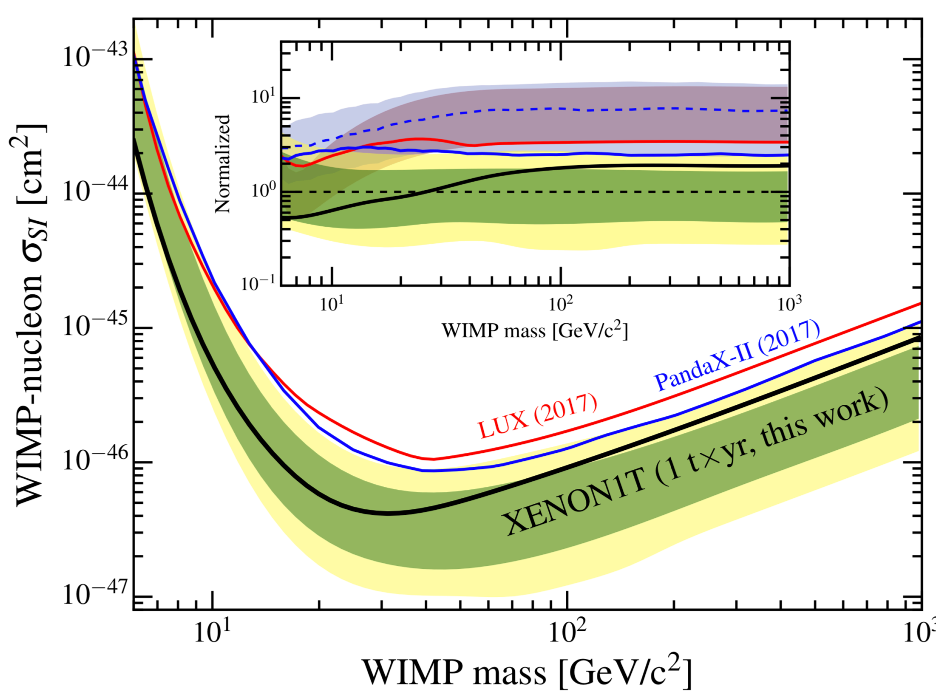
$$f_{p,n}^{\rm DM} = \frac{c_{\rm DM} m_N m_{\rm DM}}{4 m_G^2 \Lambda^2}\left(\sum_{\psi=u,d,s,c,b} 3c_\psi(\psi(2)+\bar{\psi}(2)) + \sum_{\psi=u,d,s}\frac{1}{3}c_\psi f_{T\psi}^{p,n}\right)$$

c.f.-scalar med. (Higgs portal) $f_{p,n}^{\rm DM} = m_N\left(\sum_{\psi=u,d,s} f_{T\psi}^{p,n}\frac{\mathcal{M}_\psi}{m_\psi} + \frac{2}{27}f_H^{p,n}\sum_{\psi=c,b,t}\frac{\mathcal{M}_\psi}{m_\psi}\right)$

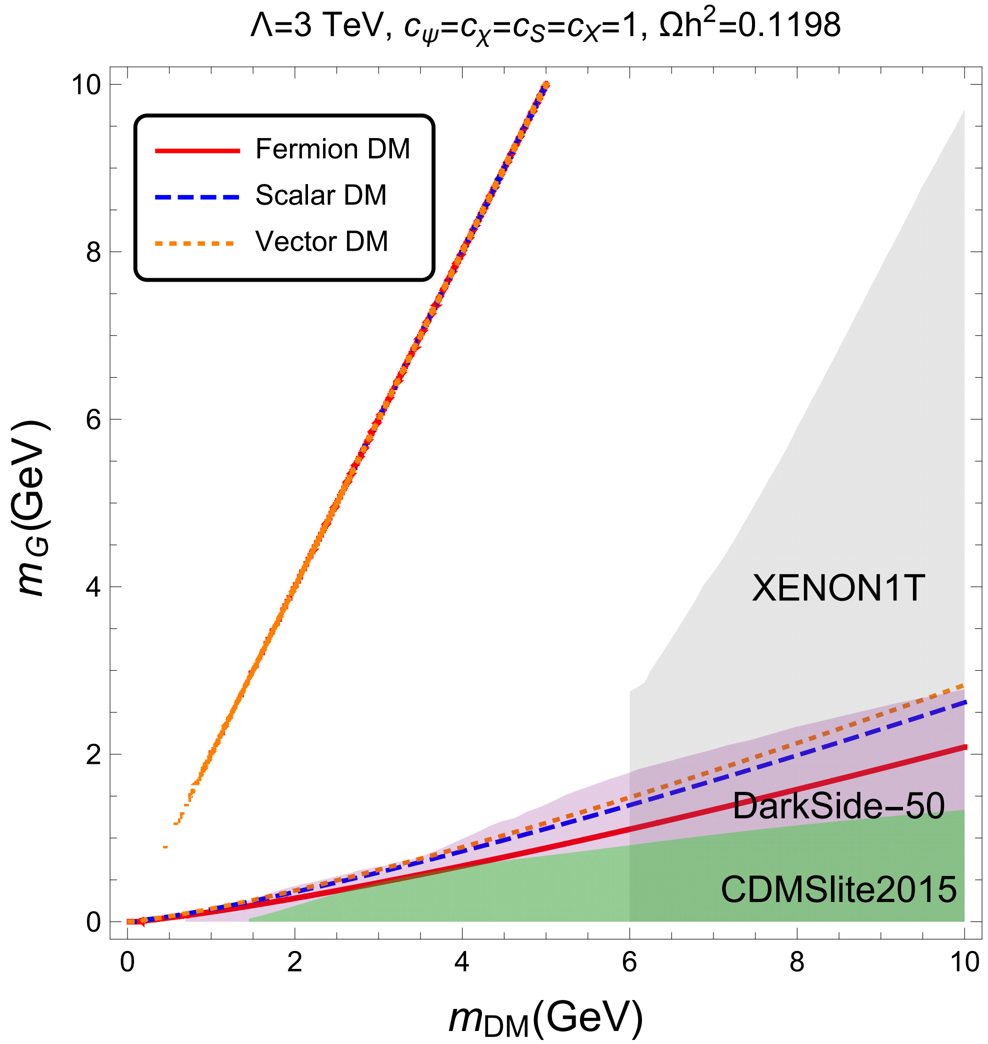
Y. Mambrini (1108.0671)

It's constrained by XENON1T

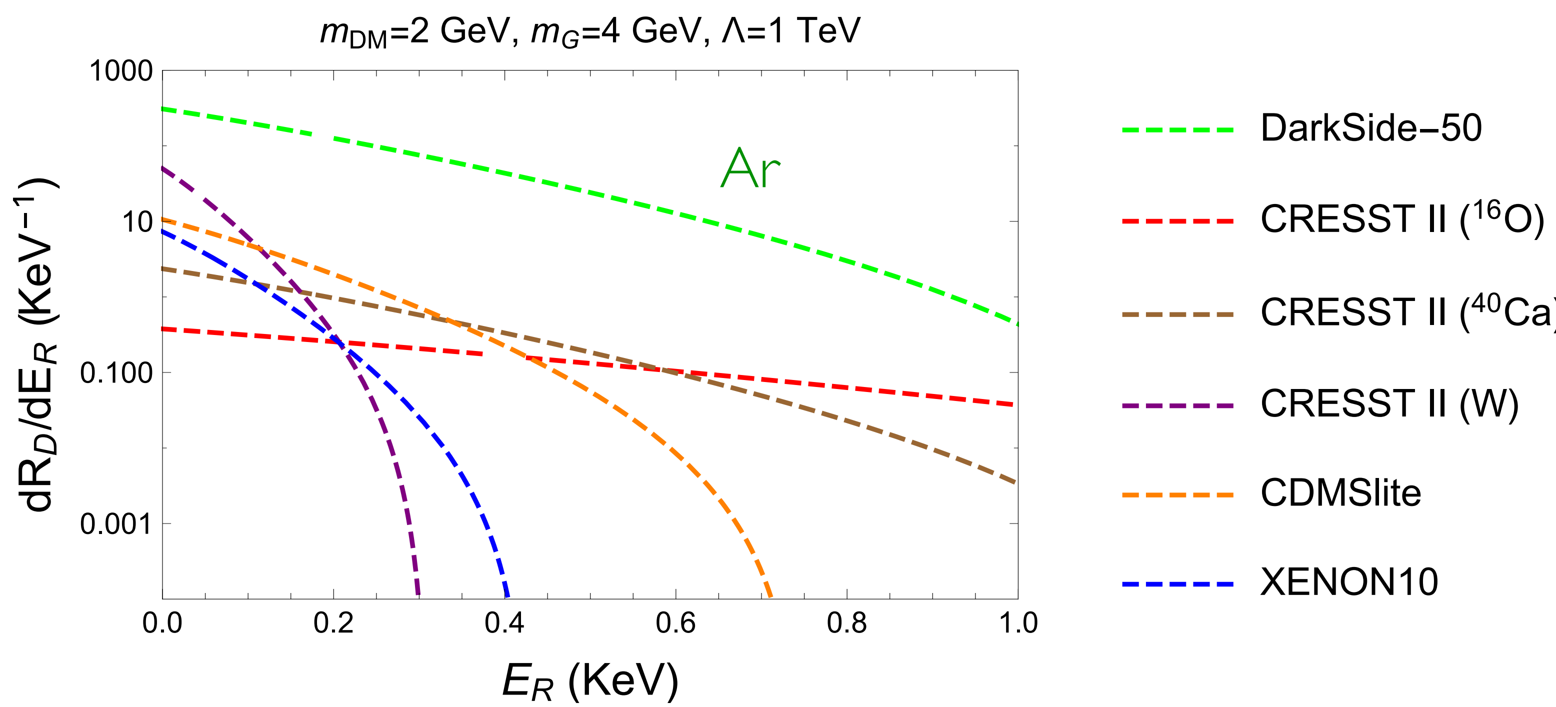
XENON1T (1805.12562)



Light DM $m_{\rm DM} \lesssim 10\ {\rm GeV}$



Light dark matter experiments for sub-GeV constrain such as DarkSide-50, CDMSlite and so on.



Relic density condition
Mediator resonances become important.

Differential event rates for fermion DM in the current direct detection experiments

Summary

- We have presented the effective interactions up to dimension-8 between DM and the SM quarks due to the massive spin-2 mediator.
- We have shown the differential event rates for DM-nucleon scattering. (Xe and Ge are expected to have large event rate)
- We have imposed the bounds from direct detection, relic density condition as well as LHC dijet searches on to the parameter space.
- The gluon coupling can be sizable. (work in progress)