Dark Matter Direct Detection with Spin-2 Mediators

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Alba Carrillo-Monteverde, **YJK**, Hyun Min Lee,
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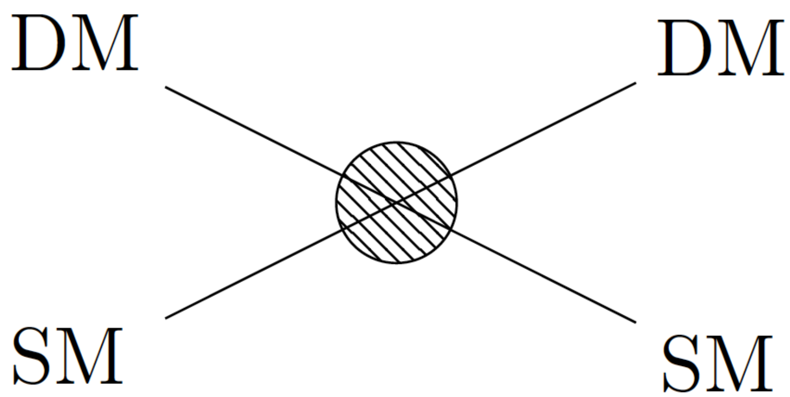
(arXiv:1803.02144)

COSMO 2018 / Dark Matter 2 / IBS Science and Culture Center, Daejeon

WIMP Dark Matter



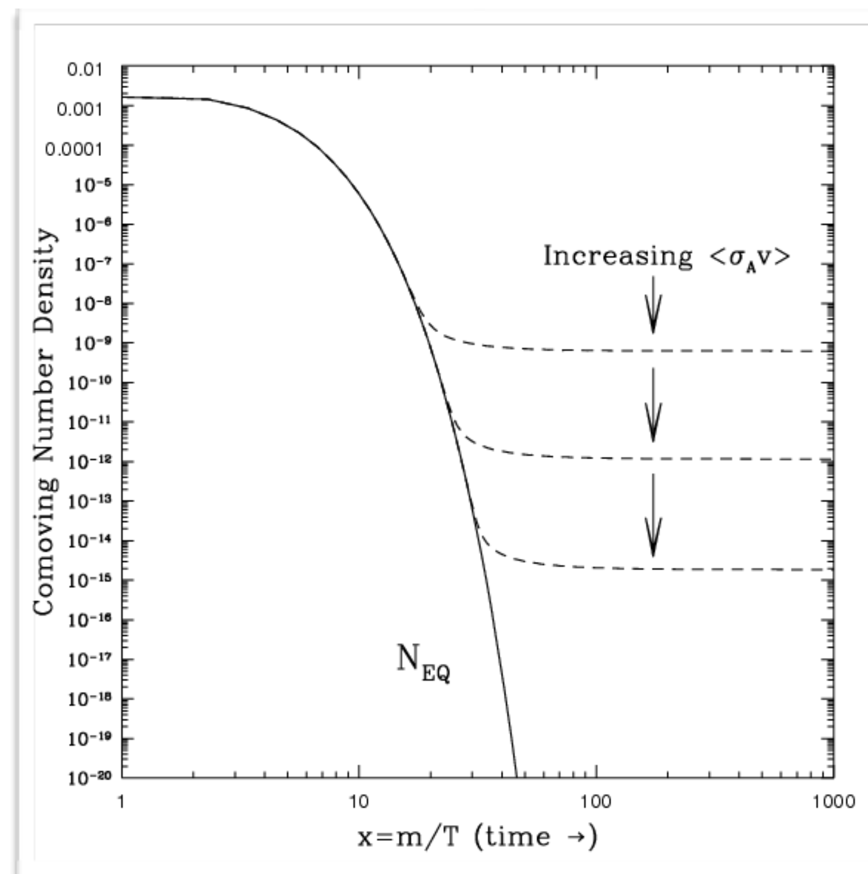
- About 25% of the total energy
- Not standard model particles (WIMP, SIMP, Forbidden DM and so on)

- Thermal WIMP was in the thermal equilibrium with the SM particles
- WIMP had 'freeze-out' from the thermal equilibrium (freeze-in is possible)

$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle_{\chi\bar{\chi}\to\psi\bar{\psi}}} \approx 0.12\left(\frac{0.01}{\alpha}\right)^2\left(\frac{m}{100\mathrm{GeV}}\right)^2$$

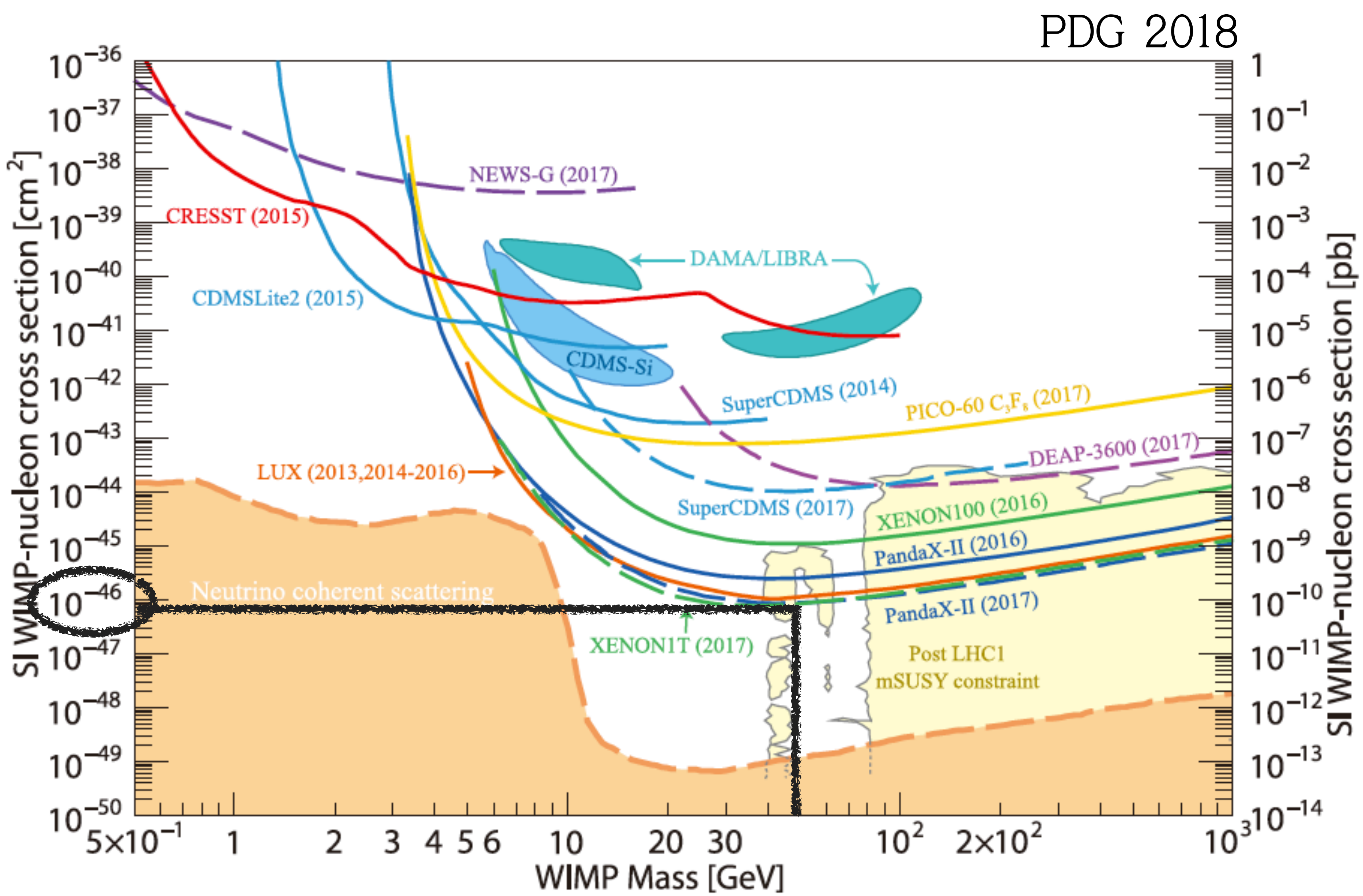
central value from Planck

weak scale



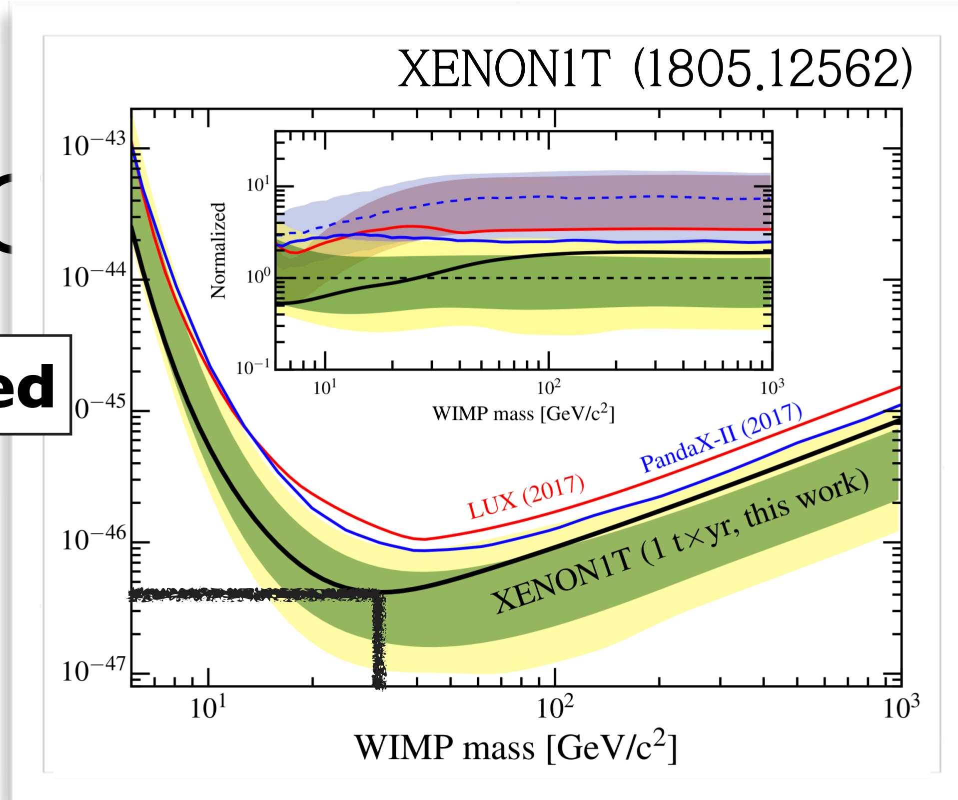
- Dark matter search : **Direct**, Indirect, Collider

Direct Detection - experiments



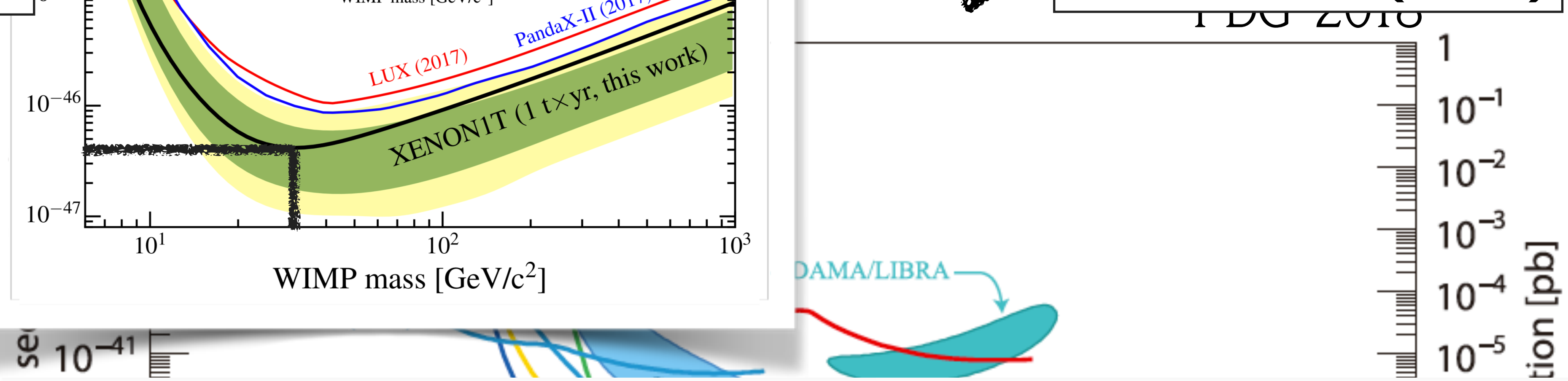
- 10^{-46} cm^2 constraint at 50 GeV

Direc experiments

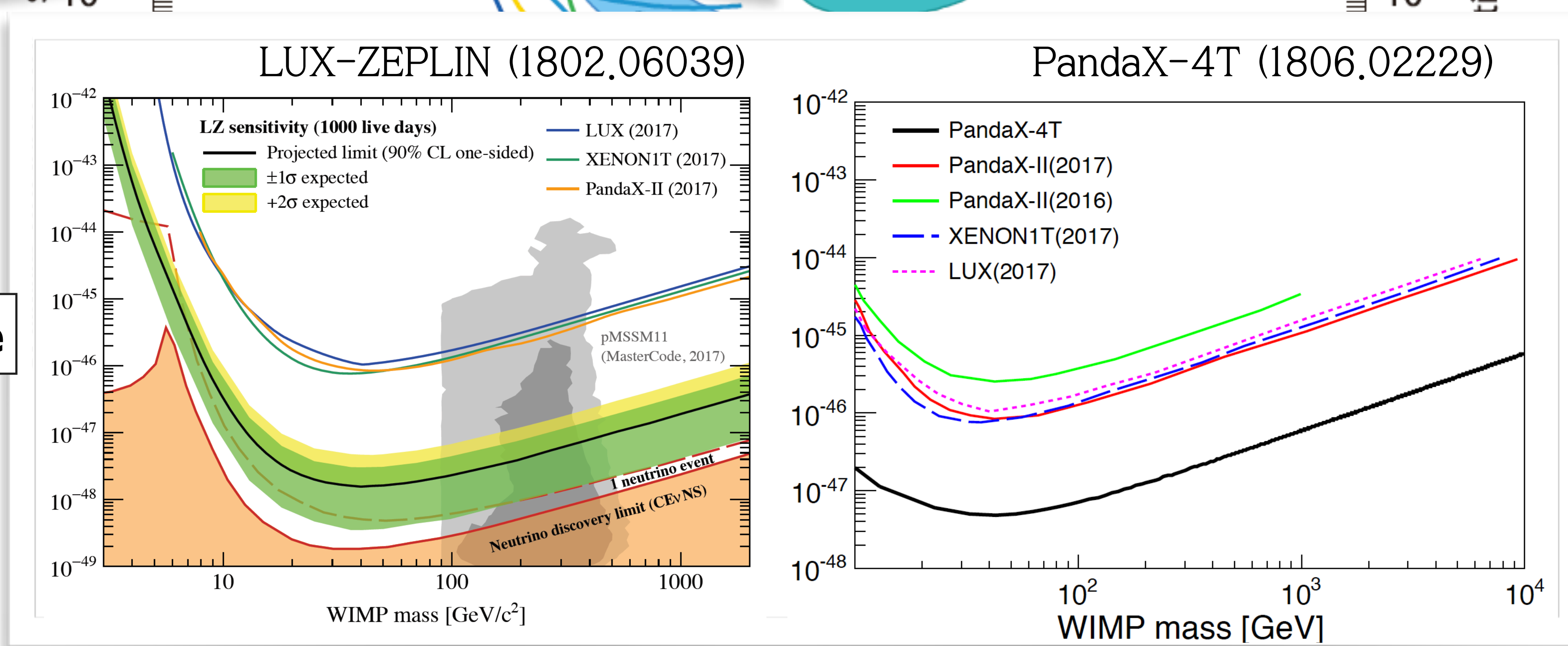


Updated

XENONnT (2019)



Future



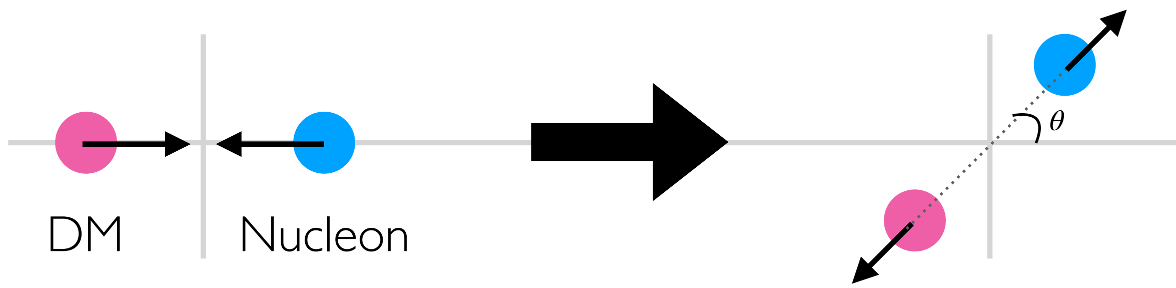
- 10^{-46} cm^2 constraint at 50 GeV
- Heavy DM bounds are getting strong. 4×10^{-47} cm^2 constraint at 30 GeV

Direct Detection - differential event rate

Fitzpatrick et al (1203.3542, 1308.6288)

In the CM frame, the relative velocity is v.

$$E_R = \frac{\vec{q}^{\,2}}{2m_T} = \frac{\mu_T^2 v^2}{m_T}(1-\cos\theta)$$: recoil energy for nucleon coherent scattering, m_T : target mass



The differential scattering event rate per recoil energy : Counts/keV/kg/day

$$\boxed{\frac{dR_D}{dE_R} = N_T \left\langle \frac{\rho_\chi m_T}{m_\chi \mu_T^2 v} \frac{d\sigma}{d\cos\theta} \right\rangle}$$

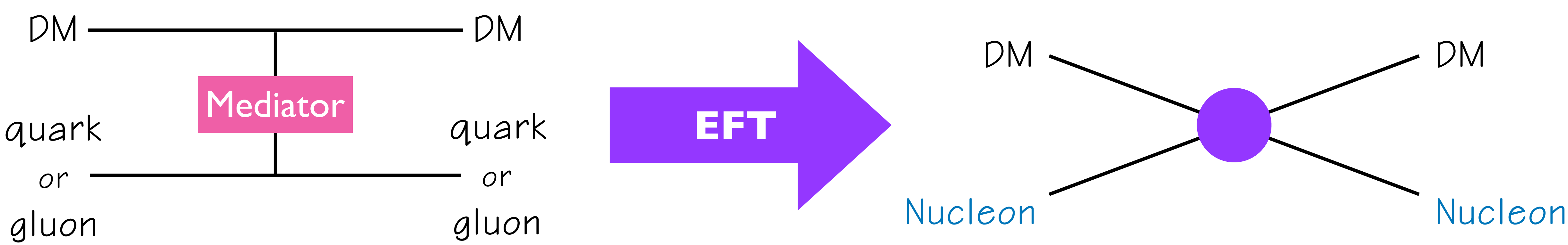
with scattering cross section depending on the detector material.

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\sum_{\text{spins}}\frac{1}{32\pi}\frac{|\mathcal{M}|^2}{(m_\chi+m_T)^2} \equiv \frac{m_T^2}{m_N^2}\sum_{i,j}\sum_{N,N'=n,p} c_i^{(N)} c_i^{(N')} \underline{F_{ij}^{(N,N')}(v^2,q^2)}$$

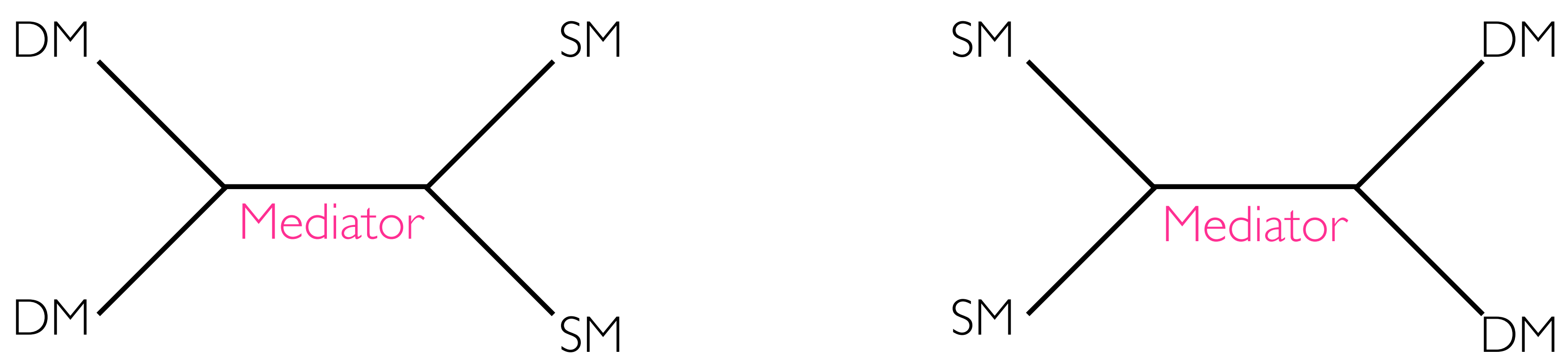
form factors are related to nucleon responses

Mediator and EFT

- 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.**



∴ "EFT is valid from freeze-out/LHC to DD"

Marco Cirelli et al (1307.5955), Kathryn M. Zurek et al (1506.04454), Andrea De Simone and Thomas Jacques (1603.08002)

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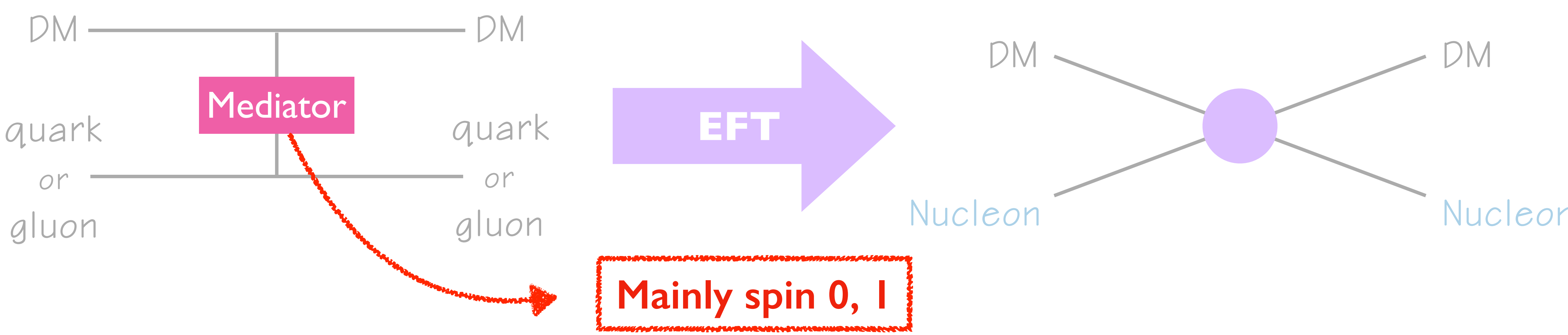

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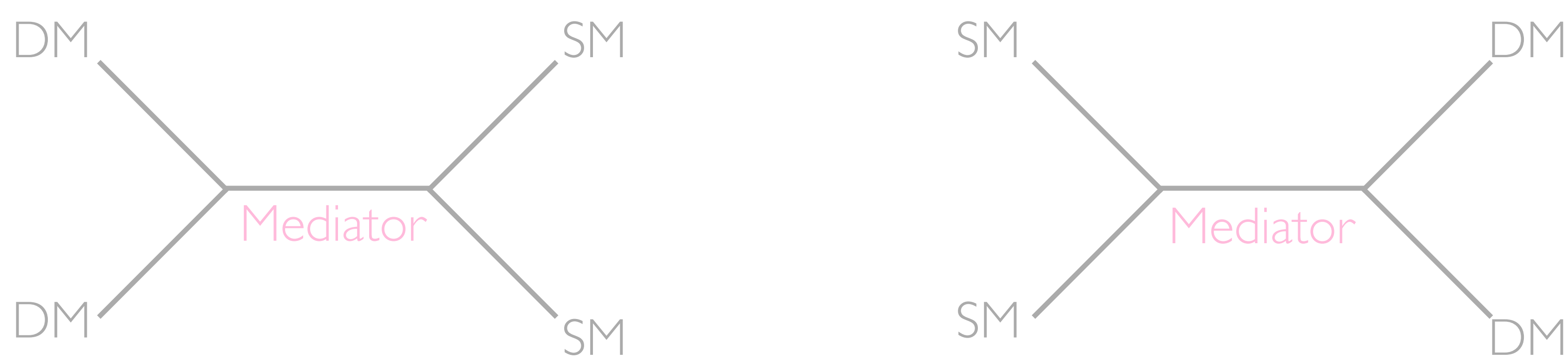

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We consider **Scattering** of **dark matter** and **nucleon**

in the spin-2 mediator model with the effective operators

and compute differential event rates for direct detection.

Spin-2 Graviton and Mediator model

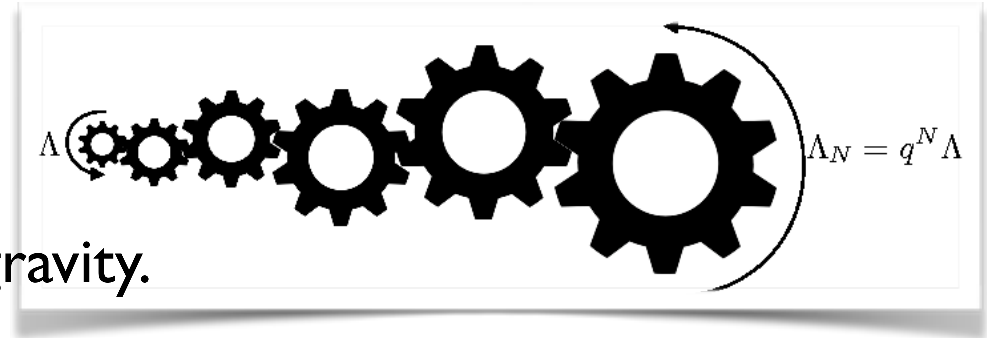
- Spin-2 graviton has been studied to explain weak gravity with the Extra dimension model, Kaluza-Klein tower, Clockwork theory and so on.

K. Choi and S. H. Im (1511.00132), D. E. Kaplan and R. Rattazzi (1511.01827), G. F. Giudice and M. McCulough (1610.07962), H. M. Lee (1708.03564)

For example) clockwork theory

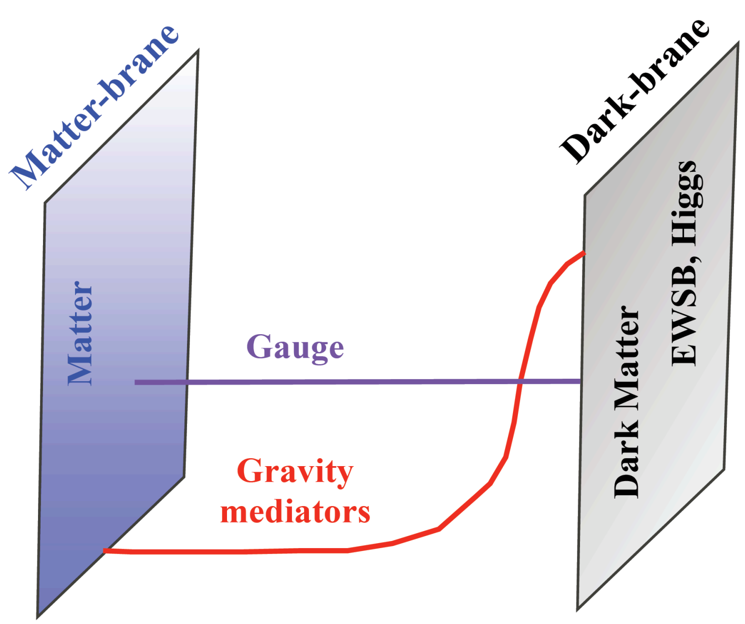
$$\phi_N = \frac{1}{q}\phi_{N-1} = \cdots \frac{1}{q^N}\phi_0$$

ground state of clock gear



can be graviton to explain weak gravity.

- There are gravity-mediated models H. M. Lee, M. Park and V. Sanz (1306.4107, 1401.5301)

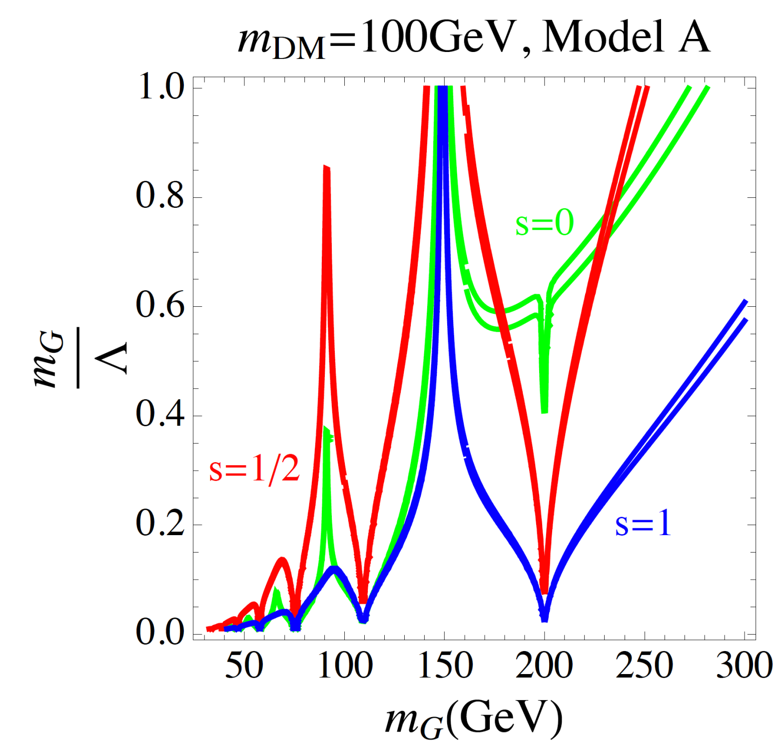


Bulk RS model : Model A

IR brane : Higgs, DM, top

UV brane : SM matter

Bulk : Gauge field



Spin-2 Mediator Model

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

- We consider the spin-2 mediator for dark matter in model-independent way.
- The tensor structure is dictated by Lorentz invariance only.

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

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

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

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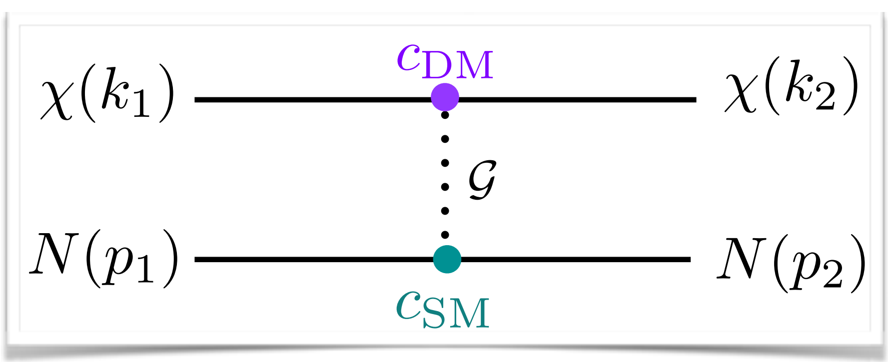
- We consider the tree-level scattering amplitude b/w DM and quark though a massive spin-2 propagator.

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

$q = k_2 - k_1 = p_1 - p_2$

Massive spin-2 propagator
satisfies transverse, traceless condition.



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

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

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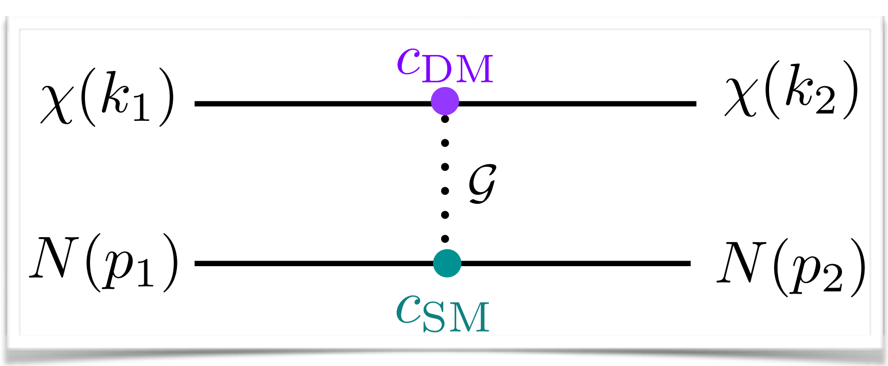

$$\mathcal{P}^{\mu\nu,\alpha\beta}(q) = \frac{1}{2}\left(G^{\mu\alpha}G^{\nu\beta} + G^{\nu\alpha}G^{\mu\beta} - \frac{2}{3}G^{\mu\nu}G^{\alpha\beta}\right)$$

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Integrated Out

$$\boxed{\mathcal{M} = \frac{ic_{\rm DM}c_{\rm SM}}{2m_G^2\Lambda^2}\left(2\underbrace{\tilde{T}^{\rm DM}_{\mu\nu}\tilde{T}^{{\rm SM},\mu\nu}}_{\text{traceless part}} - \frac{1}{6}\underbrace{T^{\rm DM}T^{\rm SM}}_{\text{trace}}\right)}$$

Matching with Form Factors

- Form factor for the scalar current

ψ : SM quarks

$q = p_1 - p_2$

Trace of the energy-momentum tensor : $T^{\psi} = -m_{\psi}\bar{u}_{\psi}(p_2)u_{\psi}(p_1)$

Matching from quark to nucleon : $\langle N(p_2)|m_{\psi}\psi\bar{\psi}|N(p_1)\rangle = F_S(q^2)m_N\bar{u}_N(p_2)u_N(p_1)$

J. Zupan et al (1708.02678, 1710.10218)

If q=0, $\langle N(p)|m_{\psi}\psi\bar{\psi}|N(p)\rangle = \underline{f^N_{T\psi}}m_N\bar{u}_N(p)u_N(p)$

mass fraction of light quarks in a nucleon

f^p_{Tu}	0.023	f^n_{Tu}	0.017
f^p_{Td}	0.032	f^n_{Td}	0.017
f^p_{Ts}	0.020	f^n_{Ts}	0.020

K. Ishiwata et al (1012.5455)
A. Corsetti et al (hep-ph/0003186)
H. Ohki et al (0806.4744)
H. Y. Cheng `1989

Gravitational Form Factors

- Gravitational form factor ➡ Matrix elements of the energy-momentum tensor

$p' = (p_1 + p_2)/2$

$$\langle N(p_2)|T^{\psi}_{\mu\nu}|N(p_1)\rangle = \bar{u}_N(p_2)\left[A(q^2)\gamma_{(\mu}p'_{\nu)} + B(q^2)\frac{i}{2m_N}p'_{(\mu}\sigma_{\nu)\lambda}q^{\lambda} + C(q^2)\frac{1}{m_N}(q_\mu q_\nu - \eta_{\mu\nu}q^2)\right]u_N(p_1)$$

$$= -2A(q^2)T^N_{\mu\nu} + \frac{1}{m_N}\bar{u}_N(p_2)\left[B(q^2)\frac{i}{2}p_{(\mu}\sigma_{\nu)\lambda}q^{\lambda} + C(q^2)(q_\mu q_\nu - \eta_{\mu\nu}q^2)\right]u_N(p_1)$$

All defined inside nucleon. mass fraction related to spin information pressure distribution

In the case of 5-dimensional AdS spacetime and the transverse-traceless gauge, the remaining term is only A term in the 5D action.

$\therefore$ we can set $A(q^2) \neq 0,\ B(q^2) = C(q^2) = 0$

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

Therefore, the traceless part is $\langle N(p_2)|\tilde{T}^{\psi}_{\mu\nu}|N(p_1)\rangle = F_T(q^2)\tilde{T}^N_{\mu\nu}$ with $F_T(q^2) \equiv -2A(q^2)$

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If q=0, $\langle N(p)\,|\,\tilde{T}^{\psi}_{\mu\nu}\,|\,N(p)\rangle = -\dfrac{F_T(0)}{m_N}\Big(p_\mu p_\nu - \dfrac{1}{4}m_N^2 g_{\mu\nu}\Big)\bar{u}_N(p)u_N(p)$

and $F_T(0) = \psi(2) + \bar{\psi}(2) = \int_0^1 dx[\psi(x) + \bar{\psi}(x)]$

second moments of PDF

$\mu \approx m_Z$, CTEQ

$u(2) + \bar{u}(2)$	0.22+0.034
$d(2) + \bar{d}(2)$	0.11+0.036
$s(2) + \bar{s}(2)$	0.026+0.026
$c(2) + \bar{c}(2)$	0.019+0.019
$b(2) + \bar{b}(2)$	0.012+0.012

K. Ishiwata et al (1012.5455)
J. Huston et al (hep-ph/0201195)

Effective Operators

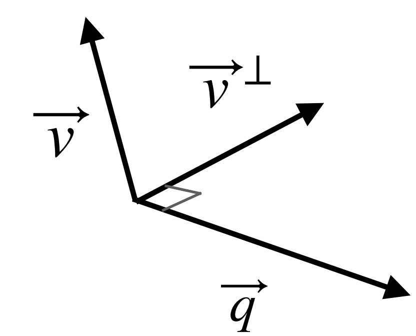
- Elastic scattering of WIMP & Nucleon

Fitzpatrick et al (1203.3542, 1308.6288)

$$\mathscr{L}_{\rm int}(\vec{x}) = \underline{c\Psi^*_\chi(\vec{x})\mathscr{O}_\chi\Psi_\chi(\vec{x})}\ \underline{\Psi^*_N(\vec{x})\mathscr{O}_N\Psi_N(\vec{x})}$$

- Amplitude : $\sum_{i=1}^{\mathcal{N}} \left(c_i^{(n)}\mathcal{O}_i^{(n)} + c_i^{(p)}\mathcal{O}_i^{(p)} \right)$ $\mathcal{O}_i$ is formed from the $\mathcal{O}_\chi$ and $\mathcal{O}_N$

- 4 basic Hermitian quantities



1. Momentum transfer $\vec{q}$
2. Relative perpendicular velocity $\vec{v}^\perp \equiv \vec{v} + \dfrac{\vec{q}}{2\mu_N}$
3. Spin of WIMP $\vec{S}_\chi$
4. Spin of nucleon $\vec{S}_N$

where μ_N : reduced mass of DM and nucleon and $\vec{v}^\perp \cdot \vec{q} = 0$

Effective Operators

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

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

Effective Lagrangians

Unsuppressed operator for
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

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

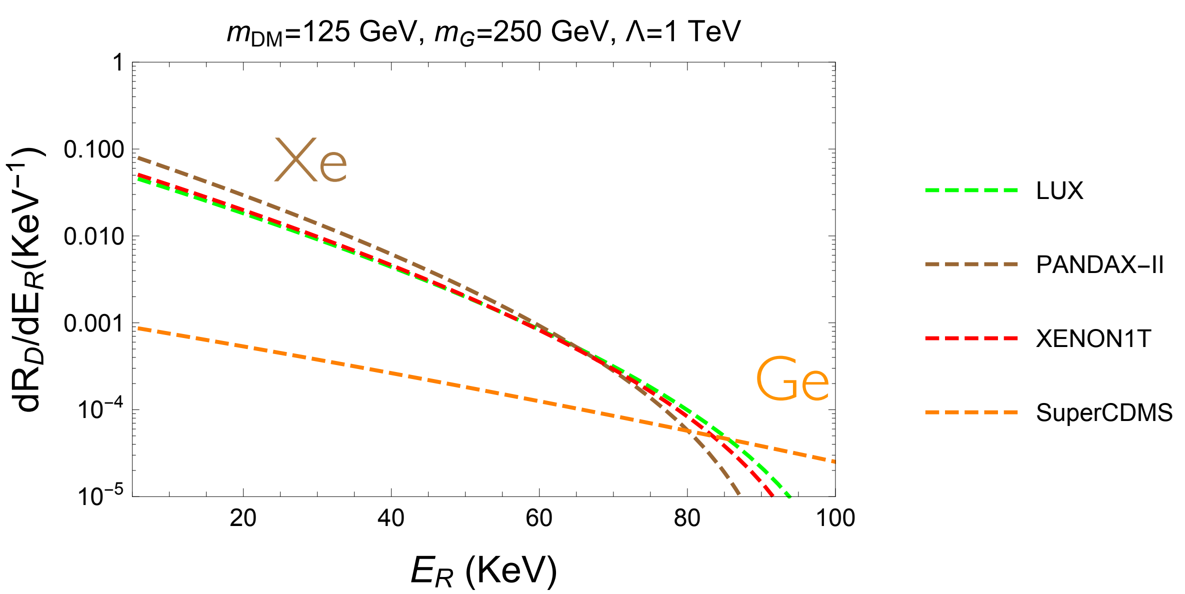
As a result, leading terms are independent of DM spins.

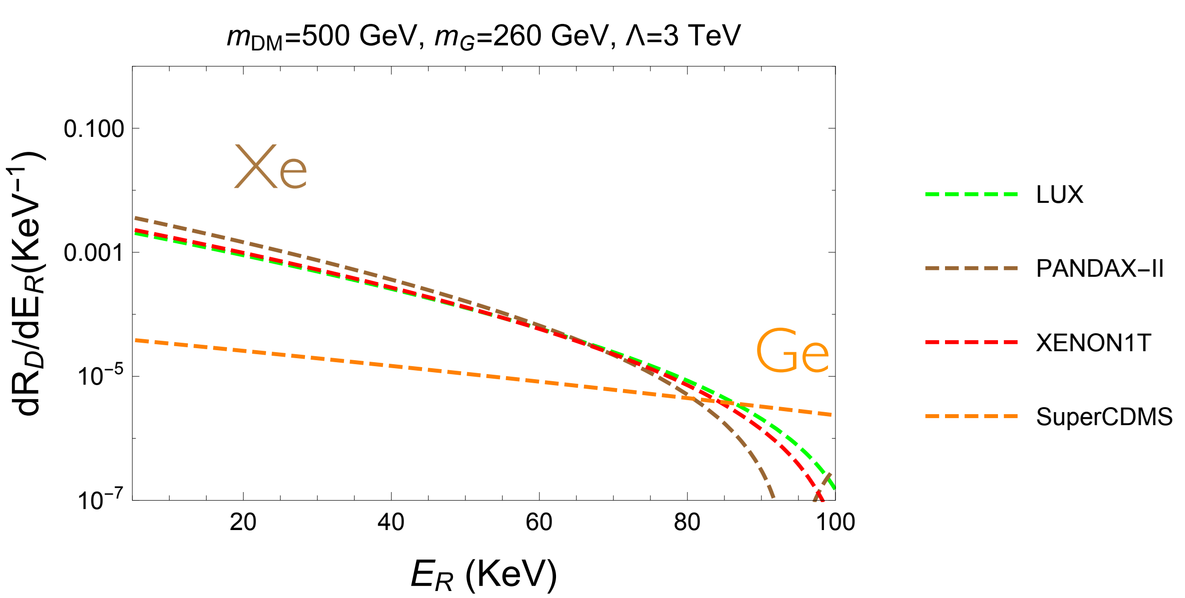
Dimension : $\int \frac{d^3p}{(2\pi)^3\sqrt{2E}}a_N^{(\dagger)}$ and $\int \frac{d^3p}{(2\pi)^3\sqrt{2E}}a_\chi^{(\dagger)}$ per each nucleon & DM state are to be multiplied.

Differential Event Rate

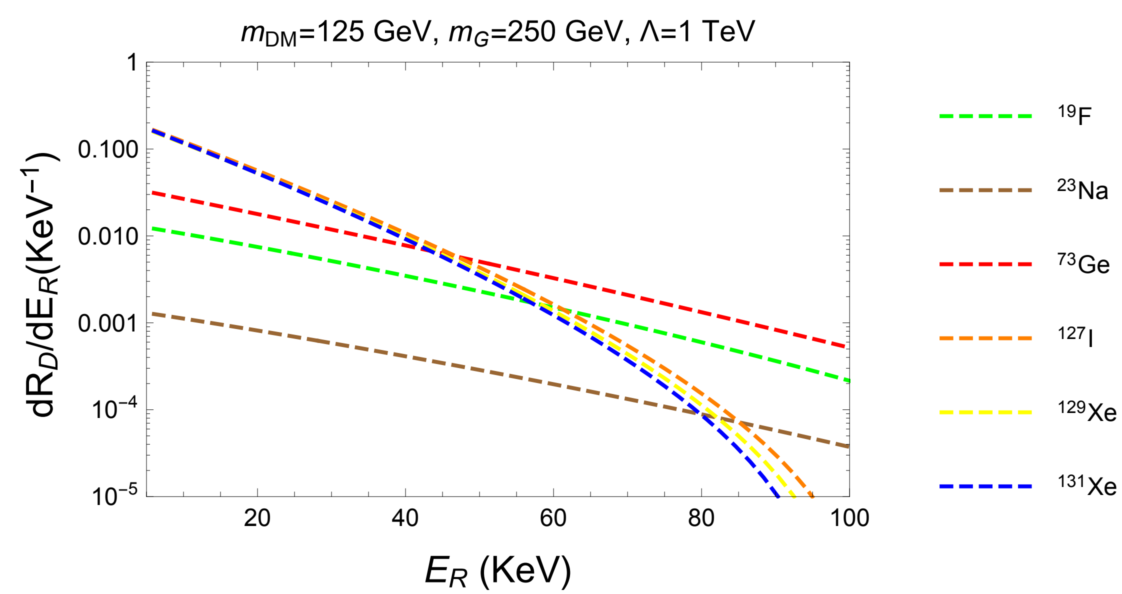
$$\frac{dR_D}{dE_R} \propto \frac{d\sigma}{d\cos\theta} \propto \sum_{i,j} \sum_{N,N'=n,p} c_i^{(N)} c_i^{(N')} F_{ij}^{(N,N')}$$

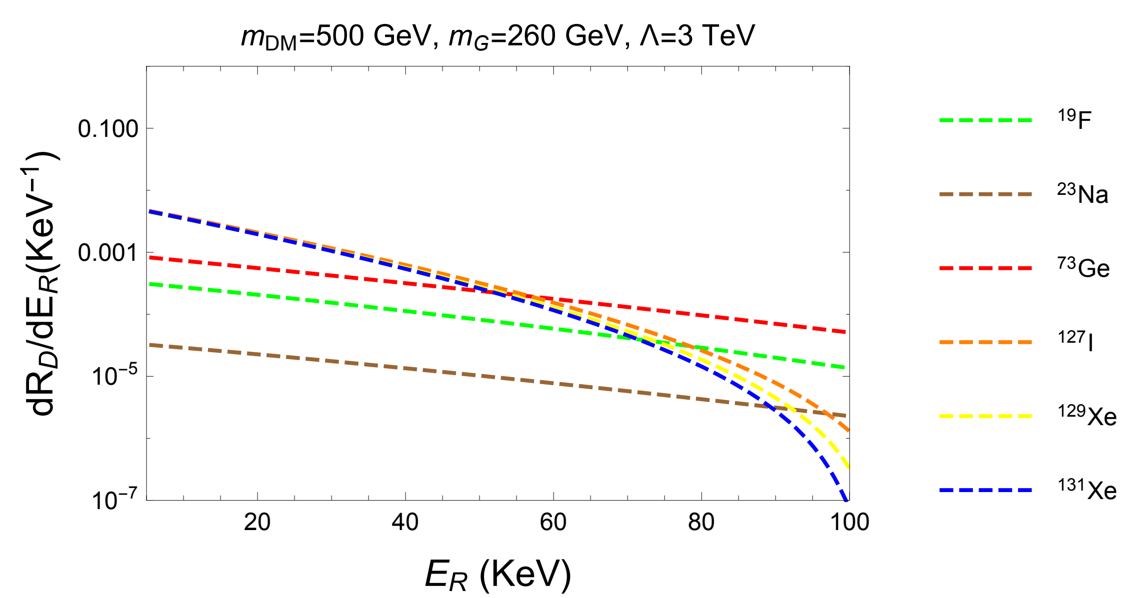
Current Exp.





Mock Exp.

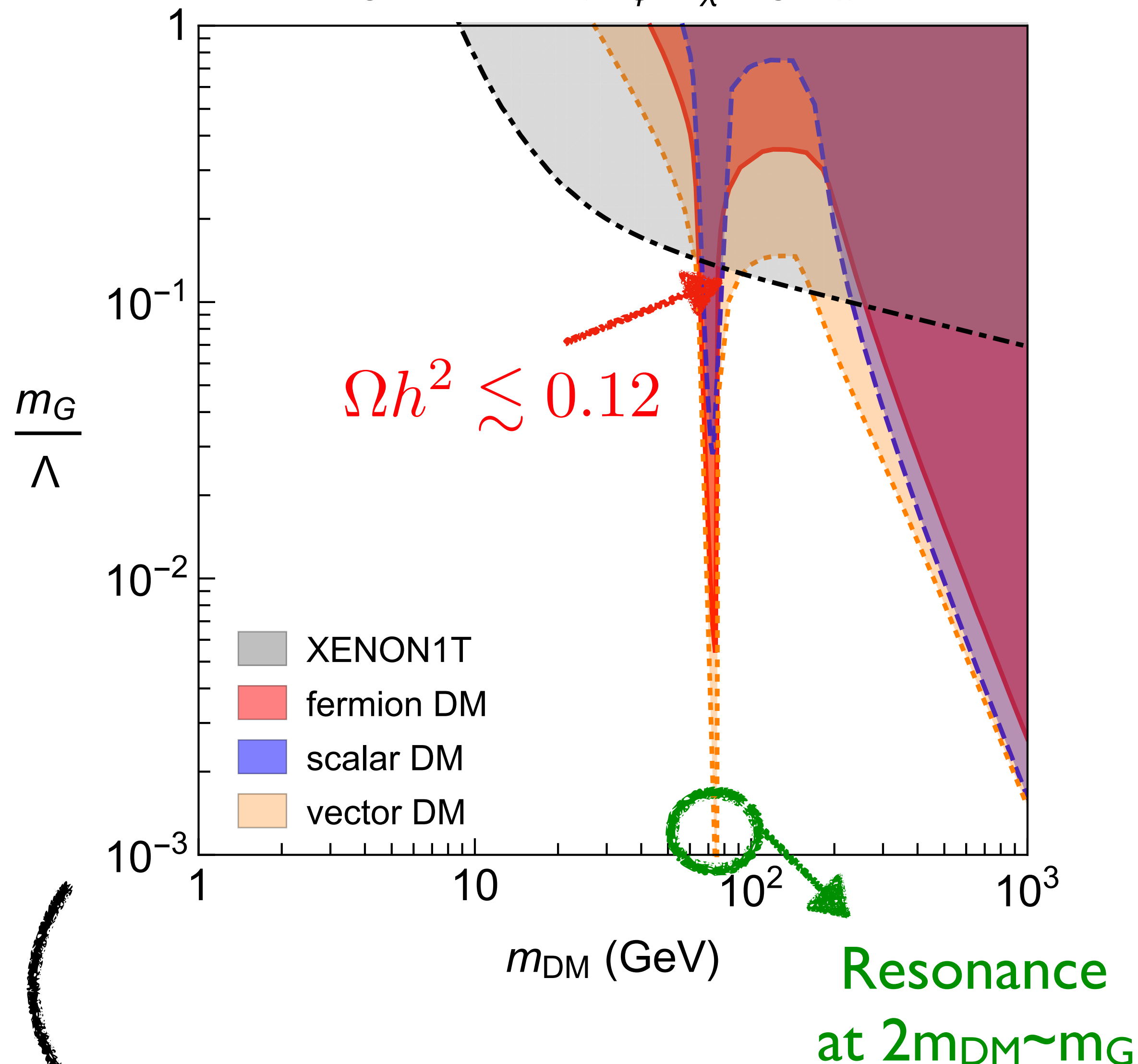


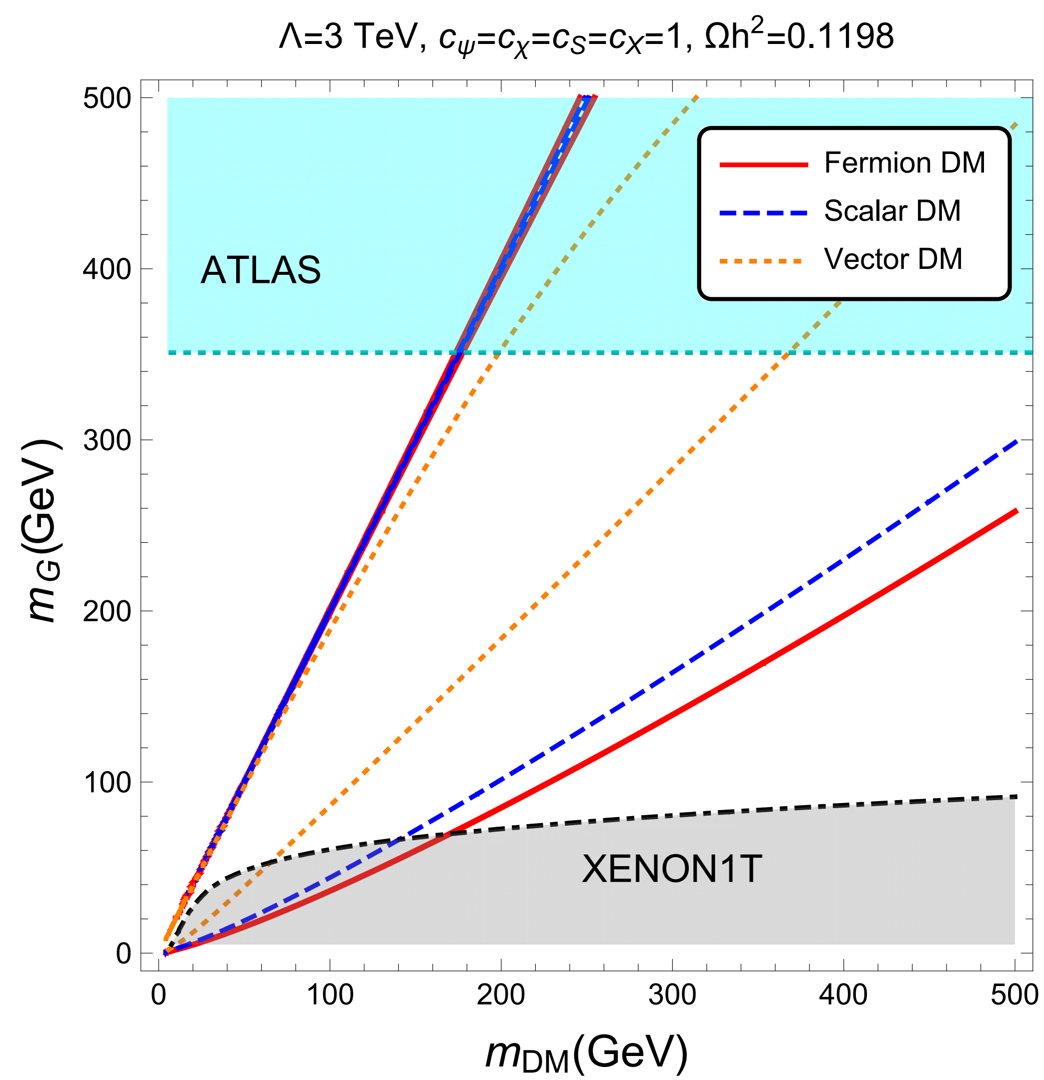


by dmformfactor mathematica package Fitzpatrick et al (1308.6288)

Relic Density Condition

Dark matter can annihilate into SM quarks or Spin-2 particles





- 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.

Dark Matter Relic Density - Bounds

- The same spin-independent scattering cross section for all the spins of DM

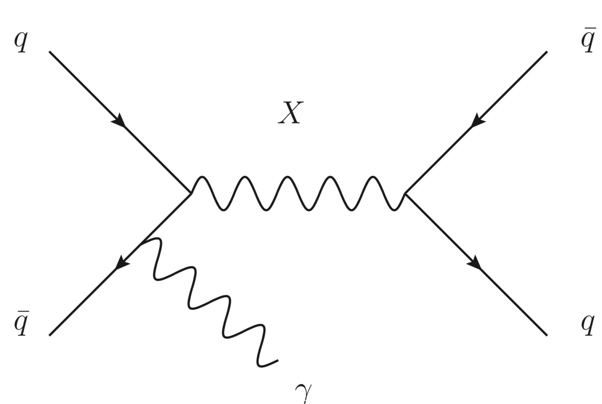
$$\sigma^{\mathrm{SI}}_{\mathrm{DM}-N} = \frac{\mu_N^2}{\pi A^2}\left(Z f_p^{\mathrm{DM}} + (A-Z) f_n^{\mathrm{DM}}\right)^2$$

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

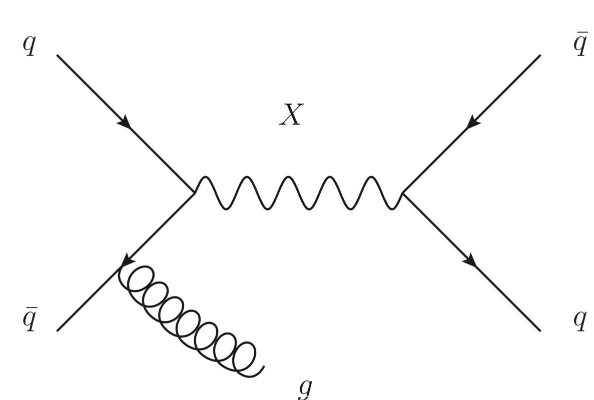
c.f.−scalar med. (Higgs portal) $f^{\mathrm{DM}}_{p,n} = m_N\left(\sum_{\psi=u,d,s} f^{p,n}_{T\psi}\frac{\mathcal{M}_\psi}{m_\psi} + \frac{2}{27} f^{p,n}_{H} \sum_{\psi=c,b,t} \frac{\mathcal{M}_\psi}{m_\psi}\right)$

Y. Mambrini (1108.0671)

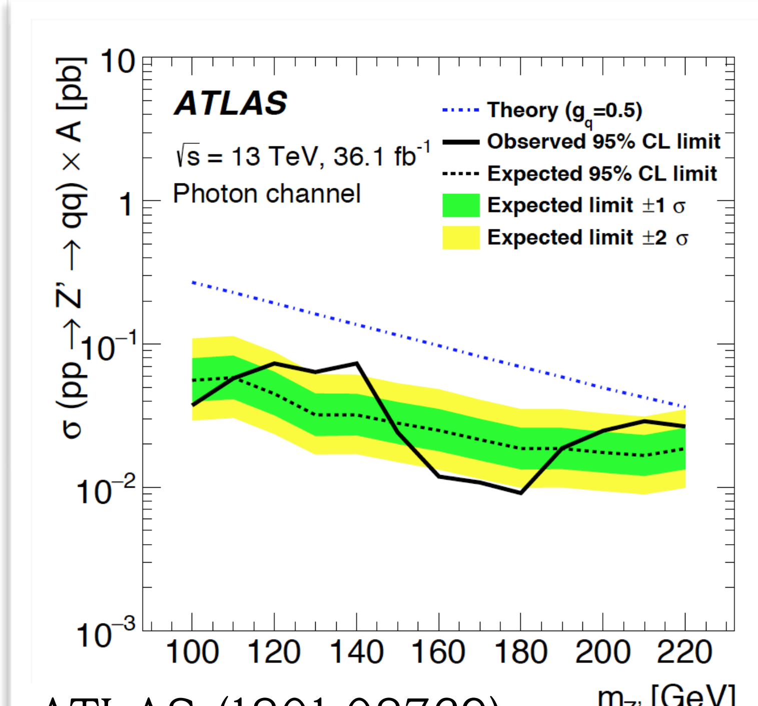
- ATLAS dijet constraints to $BR(G \to q\bar{q})$.



ISR photon + dijet



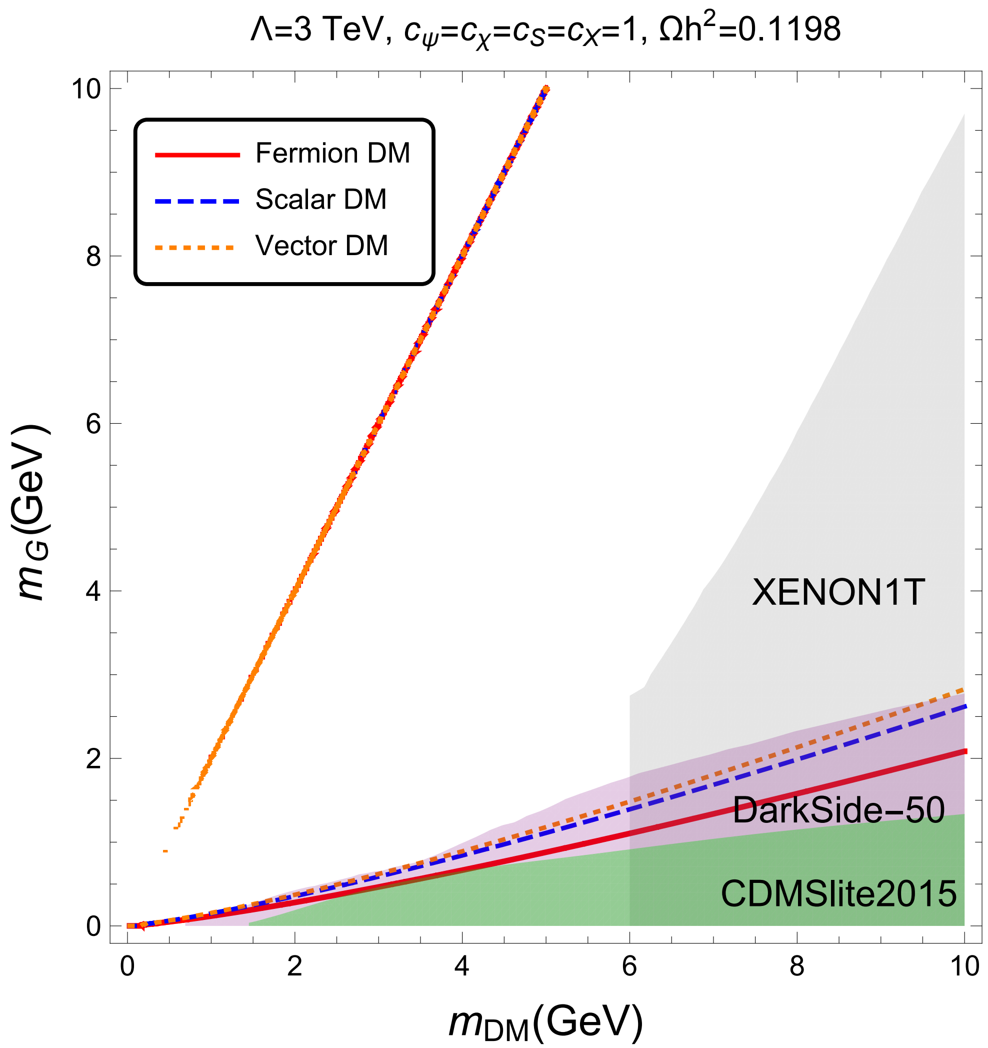
ISR jet + dijet



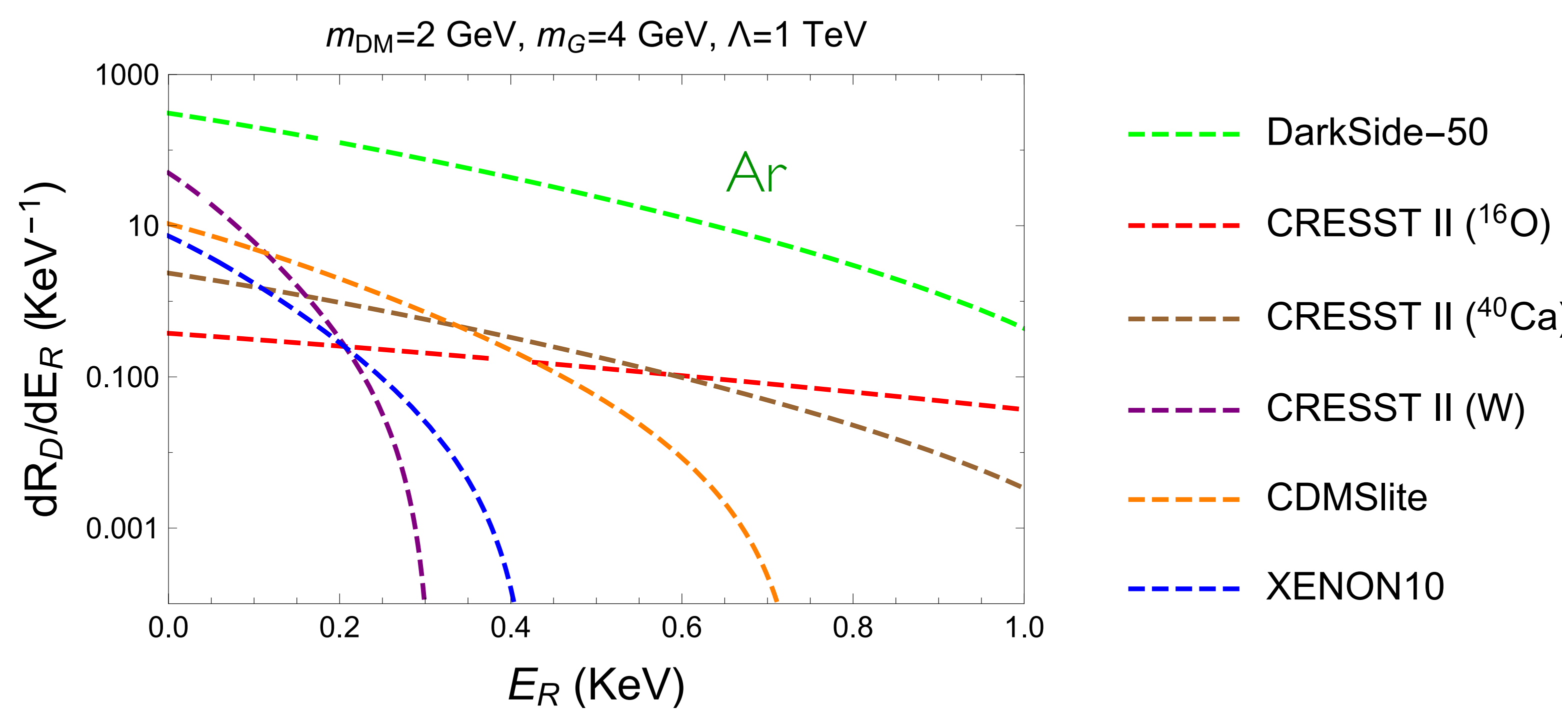
ATLAS (1801.08769)

Dark Matter Relic Density - Light DM

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



Light dark matter experiments constrain strongly
: 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 introduced the effective operators up to dimension-8 due to the massive spin-2 mediator and the effective Lagrangian using gravitational form factors.
- We show the differential event rates for DM-nucleon scattering via spin-2 mediator.
- The relic density condition is constrained by direct detection and LHC dijet searches.
- When the gluon coupling is sizable, we have to consider gluon contribution - work in progress

Back up

Effective Operators

Interactions involving spin-0 or 1 mediator

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

$$
\text{NLO} \left\{ \begin{aligned}
\mathcal{O}_7 &= \vec{S}_N \cdot \vec{v}^\perp \\
\mathcal{O}_8 &= \vec{S}_\chi \cdot \vec{v}^\perp
\end{aligned} \right.
$$

Other interactions not involving spin-0 or 1 mediator

$$
\begin{aligned}
\text{NLO} \rightarrow \mathcal{O}_{12} &= \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp) \\
\mathcal{O}_{13} &= i(\vec{S}_\chi \cdot \vec{v}^\perp)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right) \\
\mathcal{O}_{14} &= i\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)(\vec{S}_N \cdot \vec{v}^\perp) \\
\mathcal{O}_{15} &= -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right) \\
\mathcal{O}_{16} &= -\left((\vec{S}_\chi \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right).
\end{aligned}
$$

$$
\mathcal{O}_{16} = \mathcal{O}_{15} + \frac{\vec{q}^{\,2}}{m_N^2}\mathcal{O}_{12},
$$

Fitzpatrick et al (1203.3542, 1308.6288)

Energy-Momentum Tensor

- The energy momentum tensor depends on the spin and is function of its momentums

Fermion DM

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

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

Scalar DM

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

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

in the momentum space

Vector DM

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

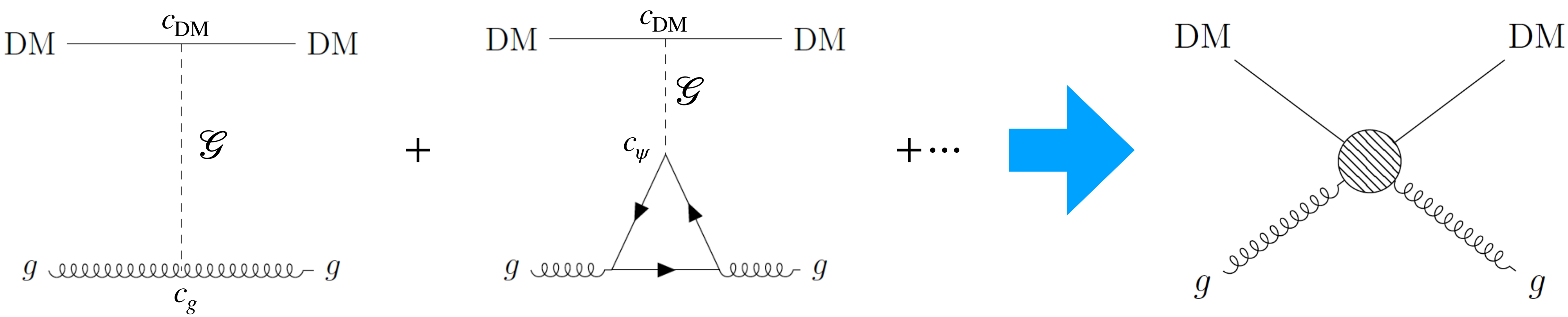
$$\tilde{T}^{X}_{\mu\nu} = -\Big(m_X^2 C_{\mu\nu,\alpha\beta} + W_{\mu\nu,\alpha\beta} + \frac{1}{2}m_X^2 \eta_{\mu\nu}\eta_{\alpha\beta}\Big)\epsilon^{\alpha}(k_1)\epsilon^{*\beta}(k_2)$$

where

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

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

Gluon contribution



Tree　　　　One-loop

Trace part : $f_{TG} \approx 1 - \sum_{u,d,s} f_{Tq}$ for scalar current

Trace-free part : $\langle N(p) | \tilde{T}^g_{\mu\nu} | N(p) \rangle = \frac{1}{m_N}\left(p_\mu p_\nu - \frac{1}{4} m_N^2 g_{\mu\nu}\right) G(2) \bar{u}_N(p) u_N(p),$ $\quad G(2) = \int_0^1 dx \;\; x g(x)$

G(2)=0.48 at the m_Z scale using CTEQ parton distribution

DM annihilation cross section

$$S_{\rm DM}=\frac{1}{2}$$

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

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

$$(\sigma v)_{\chi\bar\chi\to GG}=\frac{c_\chi^4 m_\chi^2}{16\pi\Lambda^4}\frac{(1-r_\chi)^{\frac{7}{2}}}{r_\chi^4(2-r_\chi)^2}\qquad r_\chi=\left(\frac{m_G}{m_\chi}\right)^2$$

$$S_{\rm DM}=0$$

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

$$(\sigma v)_{SS\to GG}=\frac{4c_S^4 m_S^2}{9\pi\Lambda^4}\frac{(1-r_S)^{\frac{9}{2}}}{r_S^4(2-r_S)^2}\qquad r_S=\left(\frac{m_G}{m_S}\right)^2$$

$$S_{\rm DM}=1$$

s-wave ⟶ constrained by indirect detection

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

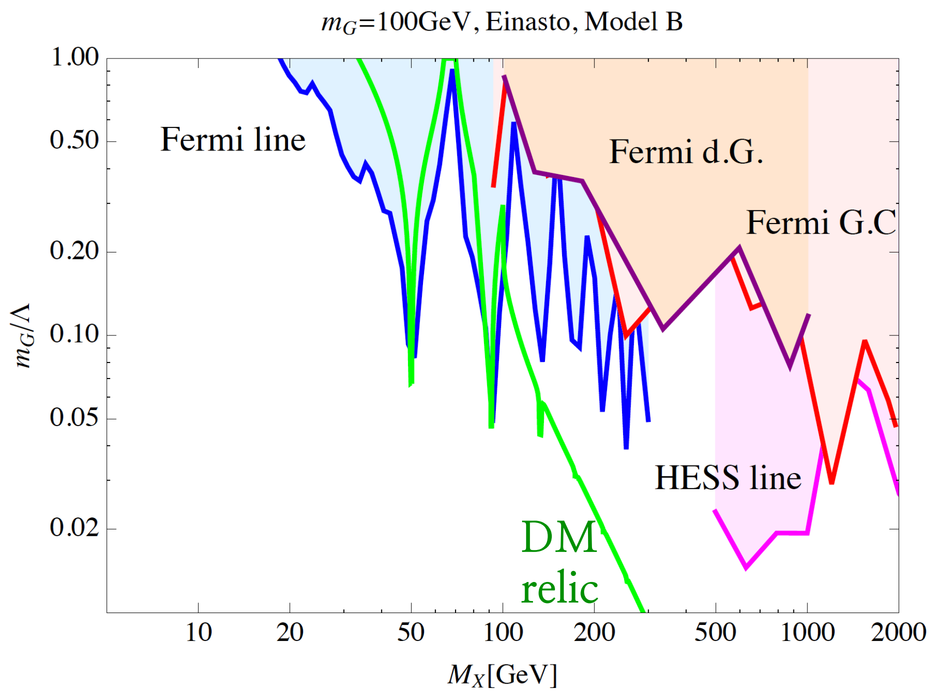
$$r_X=\left(\frac{m_G}{m_X}\right)^2$$

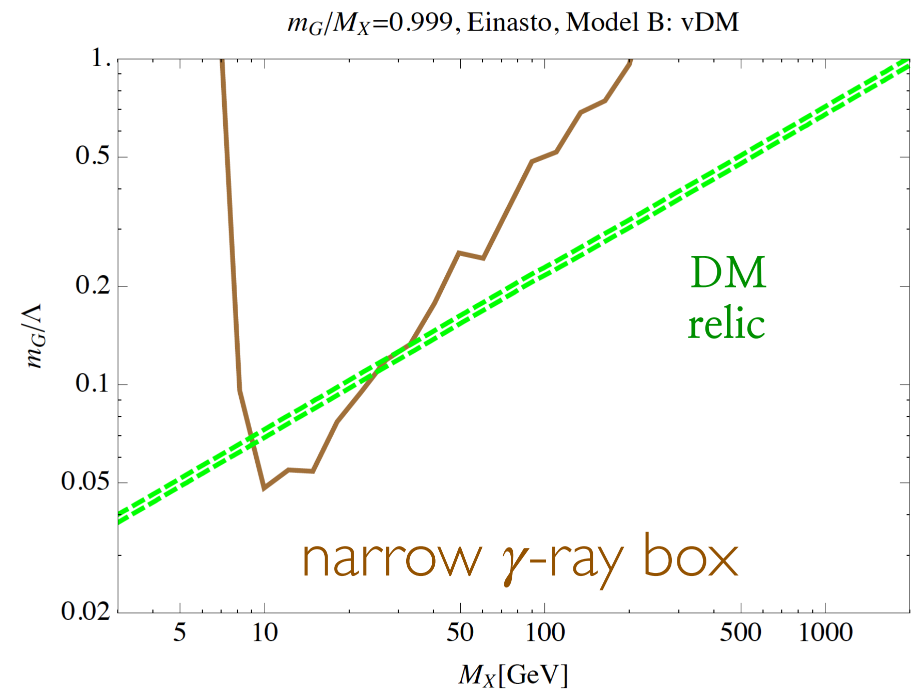
$$(\sigma v)_{XX\to GG}=\frac{c_X^4 m_X^2}{324\pi\Lambda^4}\frac{\sqrt{1-r_X}}{r_X^4(2-r_X)^2}\left(176+192r_X+1404r_X^2-3108r_X^3+1105r_X^4+362r_X^5+34r_X^6\right)$$

Indirect Detection

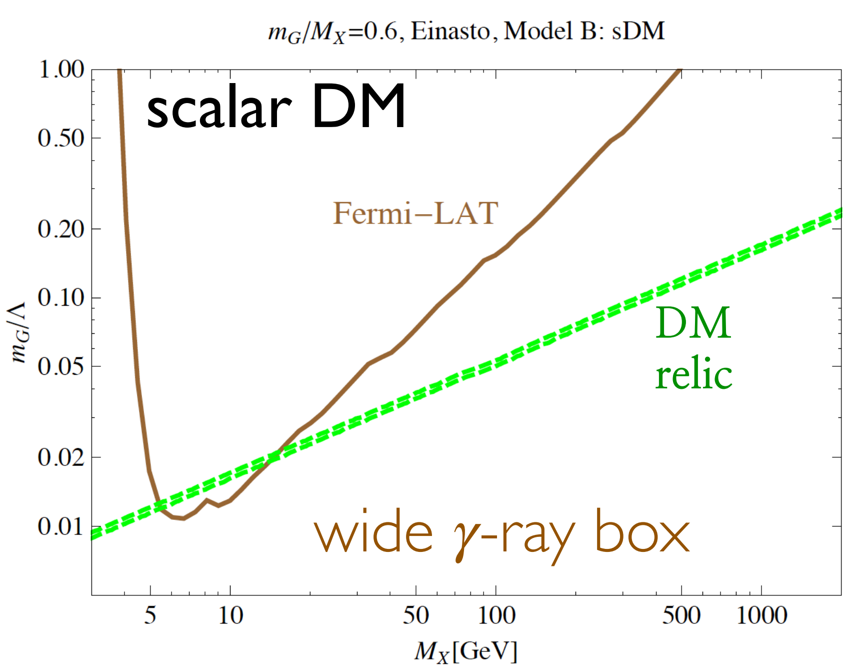
H. M. Lee, M. Park and V. Sanz (1401.5301)

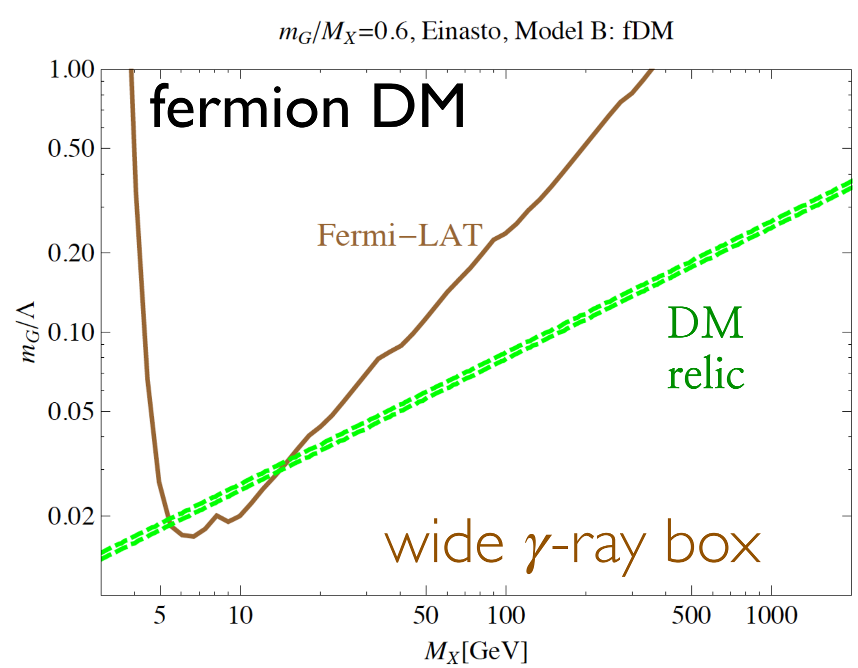
vector DM

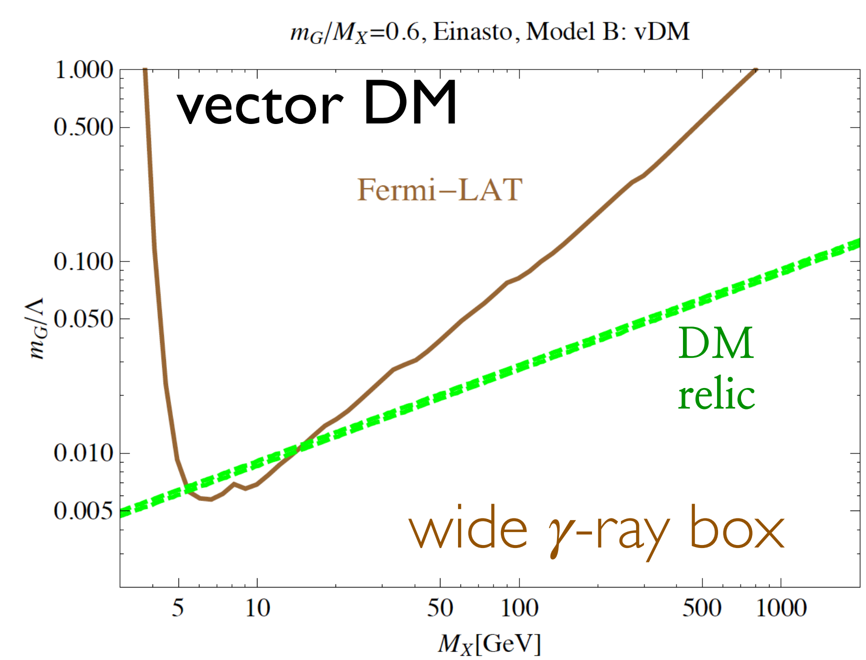




Astrophysical bounds are DM spin-dependent.
Therefore, we can distinguish DM spins from Indirect detection.







Spin-dependent cross section

- WIMP model-independent formula

$$\sigma_p^{\mathrm{lim(A)}} = \sigma_A^{\mathrm{lim}} \frac{\mu_p^2}{\mu_A^2} \frac{1}{C_A^p/C_p}\ , \quad \sigma_n^{\mathrm{lim(A)}} = \sigma_A^{\mathrm{lim}} \frac{\mu_n^2}{\mu_A^2} \frac{1}{C_A^n/C_n}$$

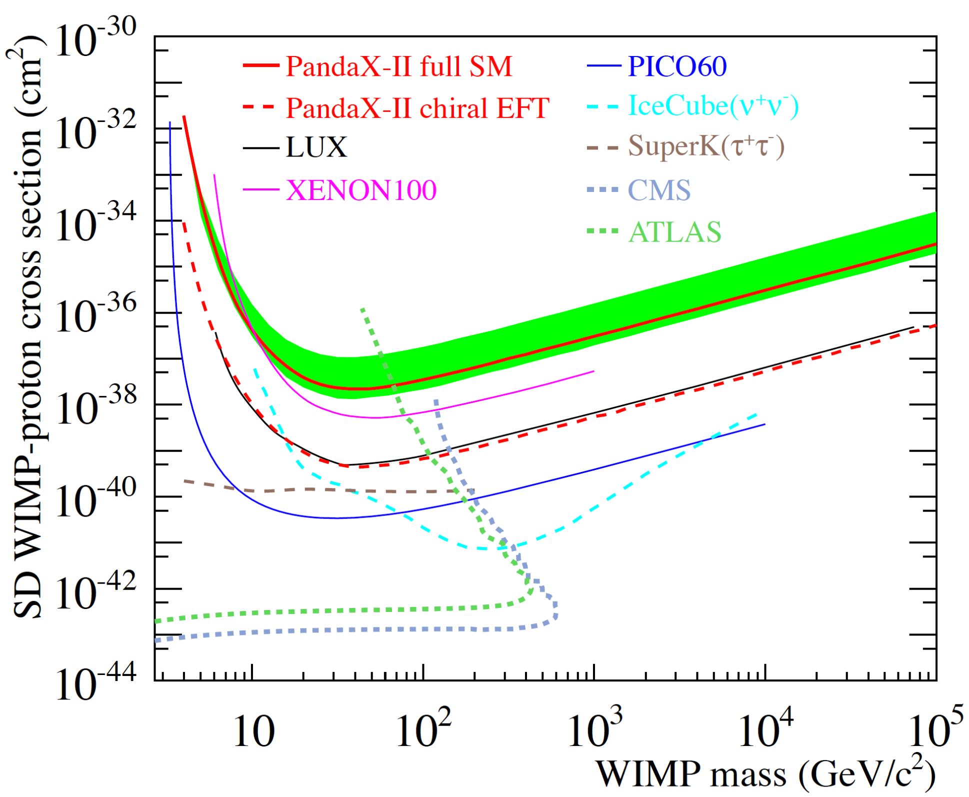
with assuming that $\sigma_A \simeq \sigma_A^n$ and $\sigma_A \simeq \sigma_A^p$

where $\frac{C_A^p}{C_p} = \frac{4}{3}\langle S_p\rangle^2 \frac{J+1}{J}\ , \quad \frac{C_A^n}{C_n} = \frac{4}{3}\langle S_n\rangle^2 \frac{J+1}{J}$

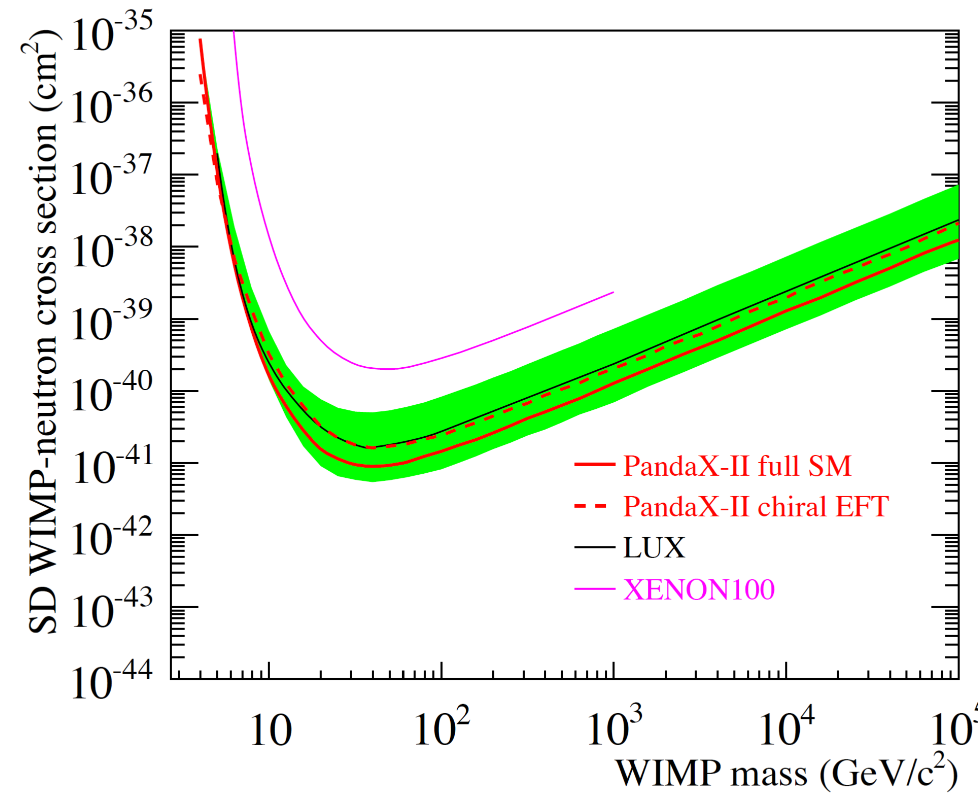
P. Gondolo et al (hep-ph/0005041)

Nucleus	Z	J	$\langle S_p\rangle$	$\langle S_n\rangle$	C_A^p/C_p	C_A^n/C_n
^{19}F	9	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{73}Ge	32	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{127}I	53	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}

^{27}Al, ^{29}Si, ^{35}Cl, ^{39}K, ^{93}Nb, ^{125}Te also ...



PandaX-II Collaboration (1807.01936)



Inelastic scattering

L. Baudis et al (1309.0825)

- Start from energy, momentum conservation for WIMP-nucleus scattering

$$\frac{q_i^2}{2m_\chi} = \frac{q_f^2}{2m_\chi} + E_R + E^*, \quad \vec{q} = \vec{q}_i - \vec{q}_f \quad \text{with} \quad E_R = \frac{q^2}{2m_A}.$$

WIMP initial,
final momentum

$$q^2 - (2\mu_A v_i \cos\beta)q + 2\mu_A E^* = 0 \quad \text{with} \quad v_i = \frac{q_i}{m_\chi}$$ and β is the angle between q_i, q

- From the solution, we can derive the minimum and maximum recoil energy.

$$E_{R,\min(\max)} = \frac{(\mu_A v_i)^2}{2m_A}\left(1 \mp \sqrt{1 - \frac{2E^*}{\mu_A v_i^2}}\right)^2, \qquad v_{\min} = \sqrt{2E^*/\mu_A}$$

- Experiments can search for a total energy deposition, $E_{\rm obs} = f(E_R) \times E_R + E^*$

$f(E_R)$ is an energy-dependent quenching factor for nuclear recoils.

Only this fraction of the nuclear recoil energy will be transferred to electronic excitations.

- Therefore, we need to calculate $\frac{dR_D}{dE_{\rm obs}}$ instead of $\frac{dR_D}{dE_R}$.