Beyond minimal gravity couplings and Dark matter

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Ref.)

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

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

B. M. Dillon, C. Han, M. M. Lee and M. Park (1606.07171) graviton collider search

A. Carrillo-Monteverde, YJK, H. M. Lee, M. Park and V. Sanz (1803.02144) quark coupling, direct detection

The 3rd IBS-KIAS Joint Workshop / High1 / Feb. 12, 2019

Graviton

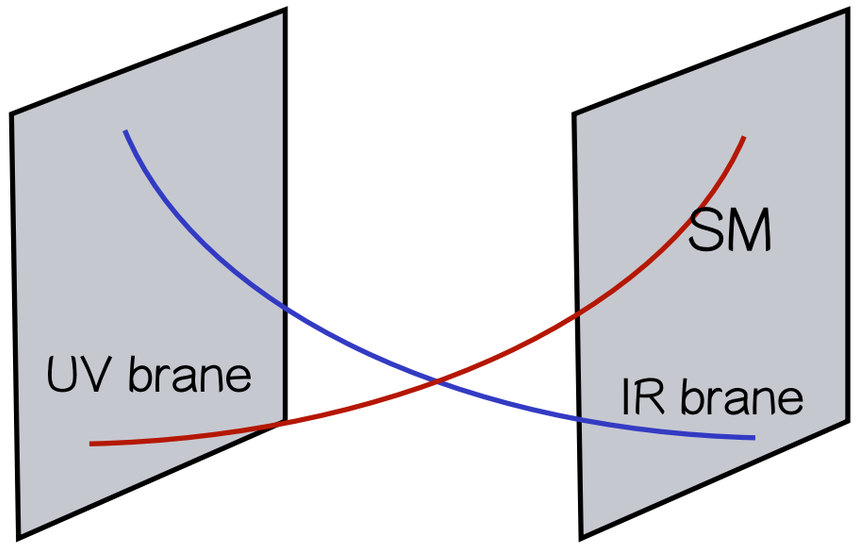
- Graviton has considered to explain weak gravity naturally.

1. Extra Dimensions

   Arkani-Hamed et al ('98),

   Randall & Sundrum ('99)

Gravity becomes weak as graviton is localized on UV brane.



2. KK graviton

   Higher dimensional graviton is expanded into massless graviton and Kaluza-Klein gravitons.

Kaluza-Klein gravitons can be massive spin-2 messengers.

We focus on the graviton with a light mass as a messenger.

Falkowski and Kamenik (1603.06980), H. M.Lee et al (1606.07171), B. M. Dilllon et al (1605.03087)

Gravity-mediated DM

Pauli-Fierz mass term for massive graviton

- Gravity action : $S = \int d^4x\sqrt{-g}\left(-\frac{2}{\kappa^2}R + \mathscr{L}_{\rm m} + \mathscr{L}_{\rm PF}\right)$

interaction b/w graviton and the SM or graviton and DM <u>via energy momentum tensor</u>

$$\mathscr{L}_m \Rightarrow -\frac{1}{\Lambda}G^{\mu\nu}\Big[c_{\rm DM}T^{\rm DM}_{\mu\nu} + c_V\Big(\frac{1}{4}g_{\mu\nu}F^{\lambda\rho}F_{\lambda\rho} + F_{\mu\lambda}F^{\lambda}_{\ \nu}\Big)$$

dark matter

graviton

gauge bosons

$$+c_\psi\left(\frac{i}{2}\left(\bar\psi\gamma_\mu\overleftrightarrow{D}_\nu\psi - g_{\mu\nu}\bar\psi\gamma_\rho\overleftrightarrow{D}^\rho\psi\right) + g_{\mu\nu}m_\psi\bar\psi\psi\right)$$

fermions

$$+c_H(-g_{\mu\nu}(D^\rho H)^\dagger D_\rho H + g_{\mu\nu}V(H) + 2(D_\mu H)^\dagger D_\nu H)\Big]$$

Higgs

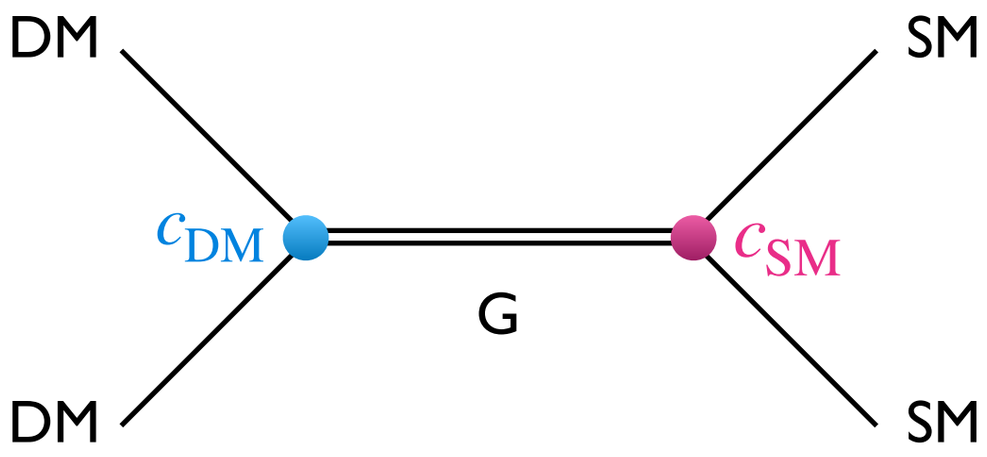
- Benchmark model : bulk RS model and dark brane model.

DM annihilations : SM

- Massive graviton can mediate dark matter and the SM particles.
- Dark matter annihilates into the SM particles via graviton propagator

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

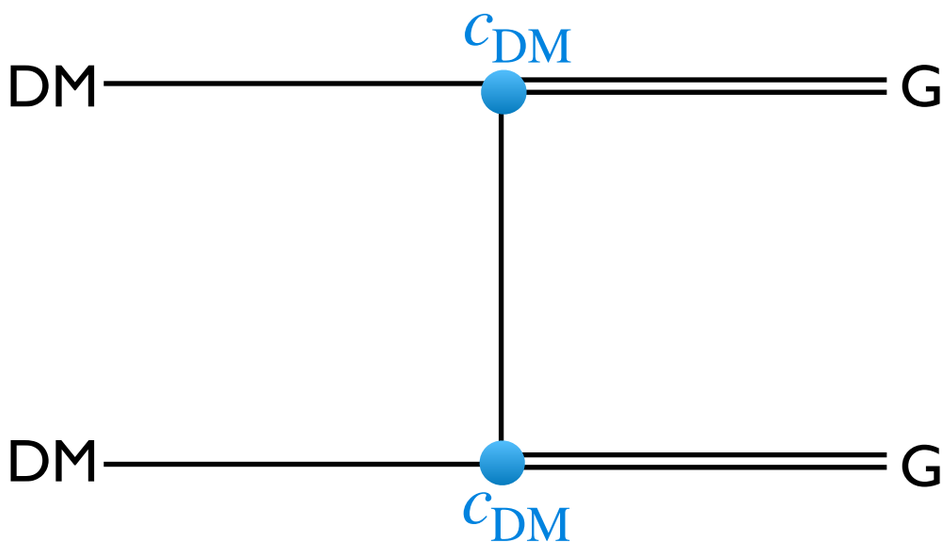
DM spin	
Spin-0	$(\sigma v_{\rm rel})_{SS\to \rm SM,SM}$: d-wave
Spin-1/2	$(\sigma v_{\rm rel})_{\chi\bar{\chi}\to \rm SM,SM}$: p-wave
Spin-1	$(\sigma v_{\rm rel})_{XX\to \rm SM,SM}$: s-wave

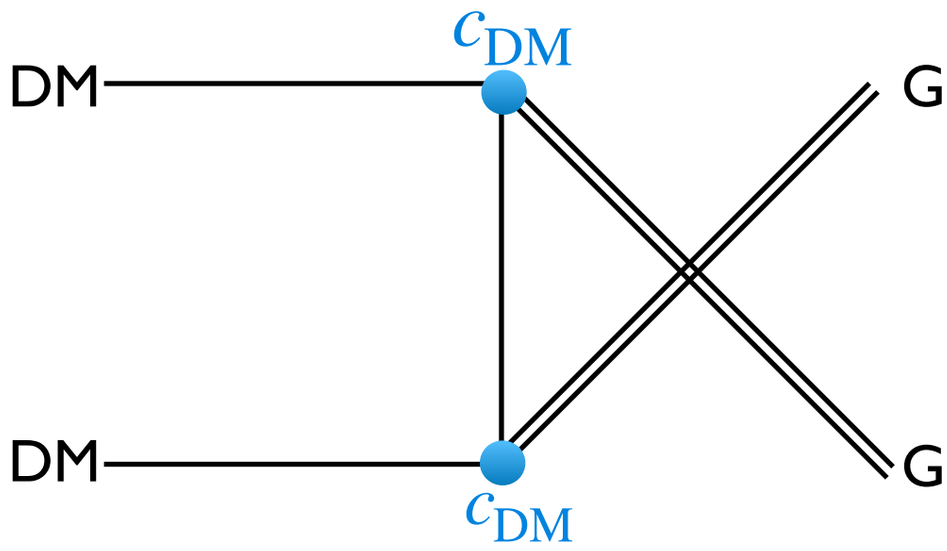


strongly constrained
by indirect detection

DM annihilations : gravitons

- If graviton mass is less then DM mass, 2 gravitons channel is open.

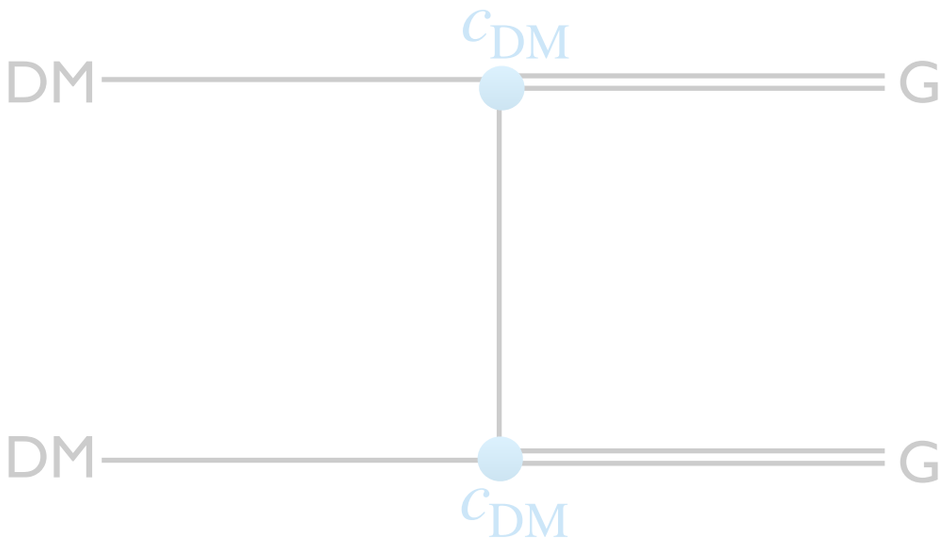


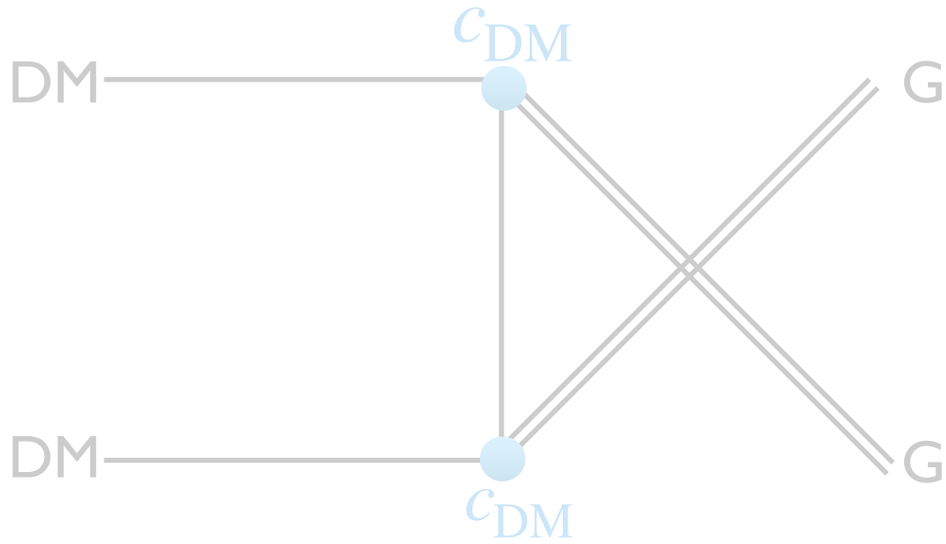


These are the minimal case we've considered.

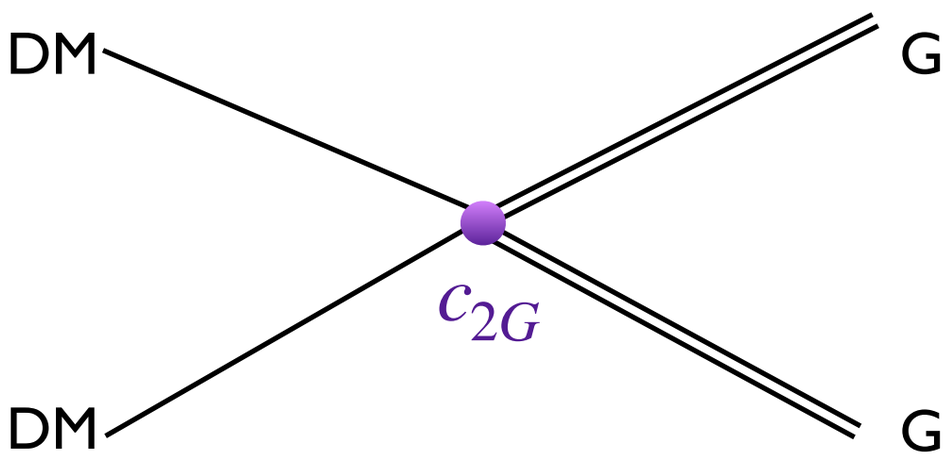
DM annihilations : gravitons

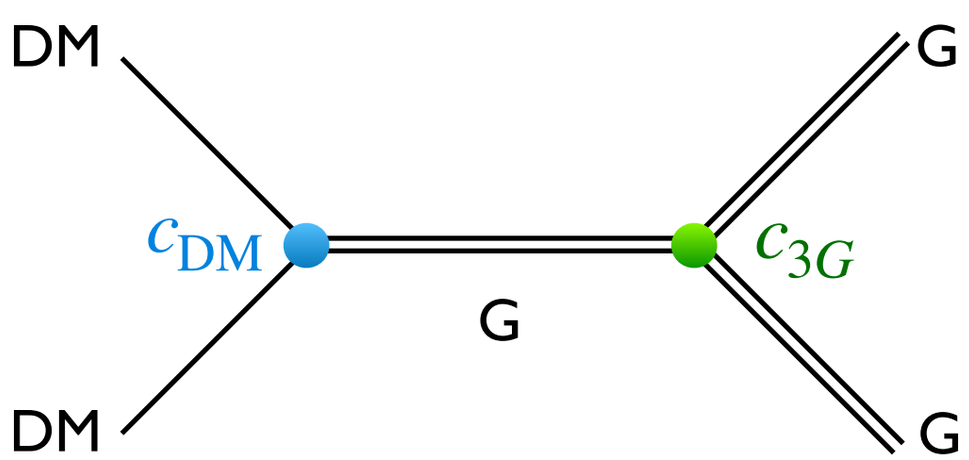
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These are the minimal case we've considered.





These are beyond minimal coupling of gravitons.

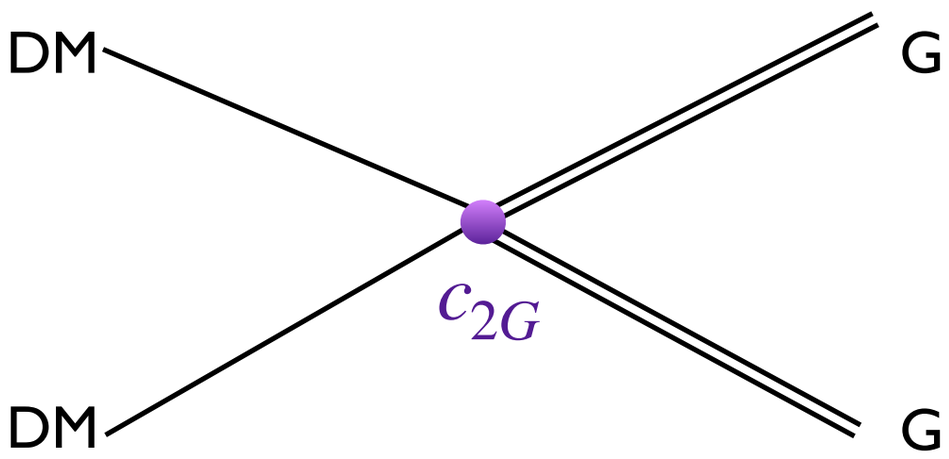
DM annihilations : gravitons

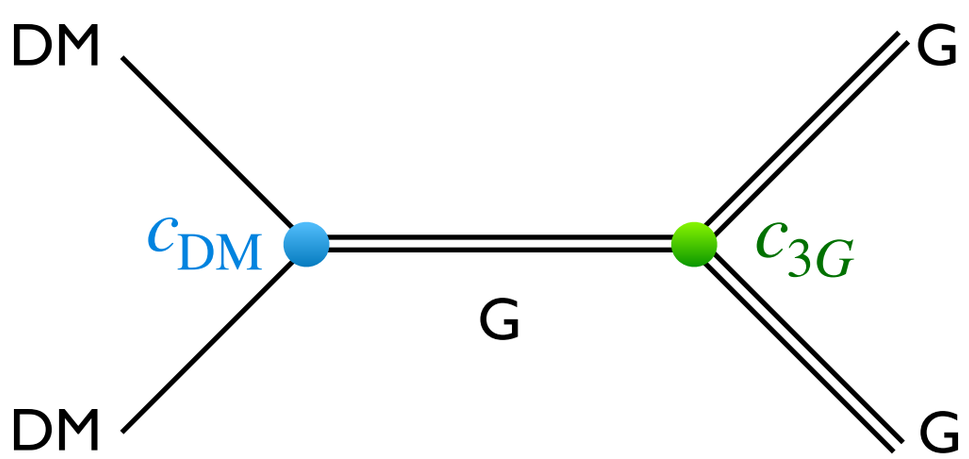
- If graviton mass is less then DM mass, 2 gravitons channel is open.

- Gravity action : $S = \int d^4x\sqrt{-g}\left(-\frac{2}{\kappa^2}R + \mathscr{L}_{\mathrm{m}} + \mathscr{L}_{\mathrm{PF}}\right)$

From Einstein-Hilbert action and higher order of matter Lagrangian

(Higher order of E-H actions are ignored. ex : αR^2)





These are beyond minimal coupling of gravitons.

DM annihilations : gravitons

t- & u-channel diagrams

Seagull & s-channel diagrams

Spin-0

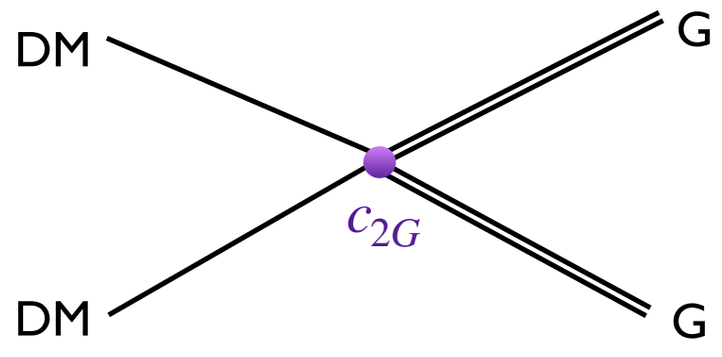
$$(\sigma v_{\rm rel})_{SS\to GG} \simeq \frac{4c_S^4 m_S^2}{9\pi\Lambda^4}\frac{(1-r)^9}{r^4(2-r)^2}$$

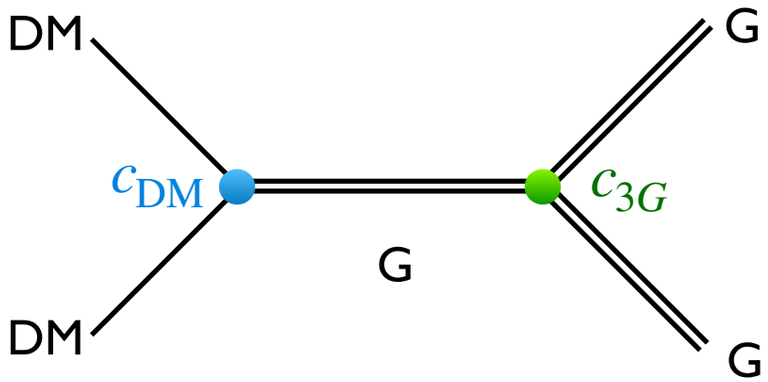
Spin-1/2

$$(\sigma v_{\rm rel})_{\chi\bar{\chi}\to GG} \simeq \frac{c_\chi^4 m_\chi^2}{16\pi\Lambda^4}\frac{(1-r)^{7/2}}{r^2(2-r)^2}$$

Spin-1

$$(\sigma v_{\rm rel})_{XX\to GG} \simeq \frac{c_X^4 m_X^2}{324\pi\Lambda^4}\frac{(1-r)^{1/2}}{r^4(2-r)^2} \times (176 + 192r + 1404r^2 + 1105r^4 + 362r^5 + 34r^6)$$



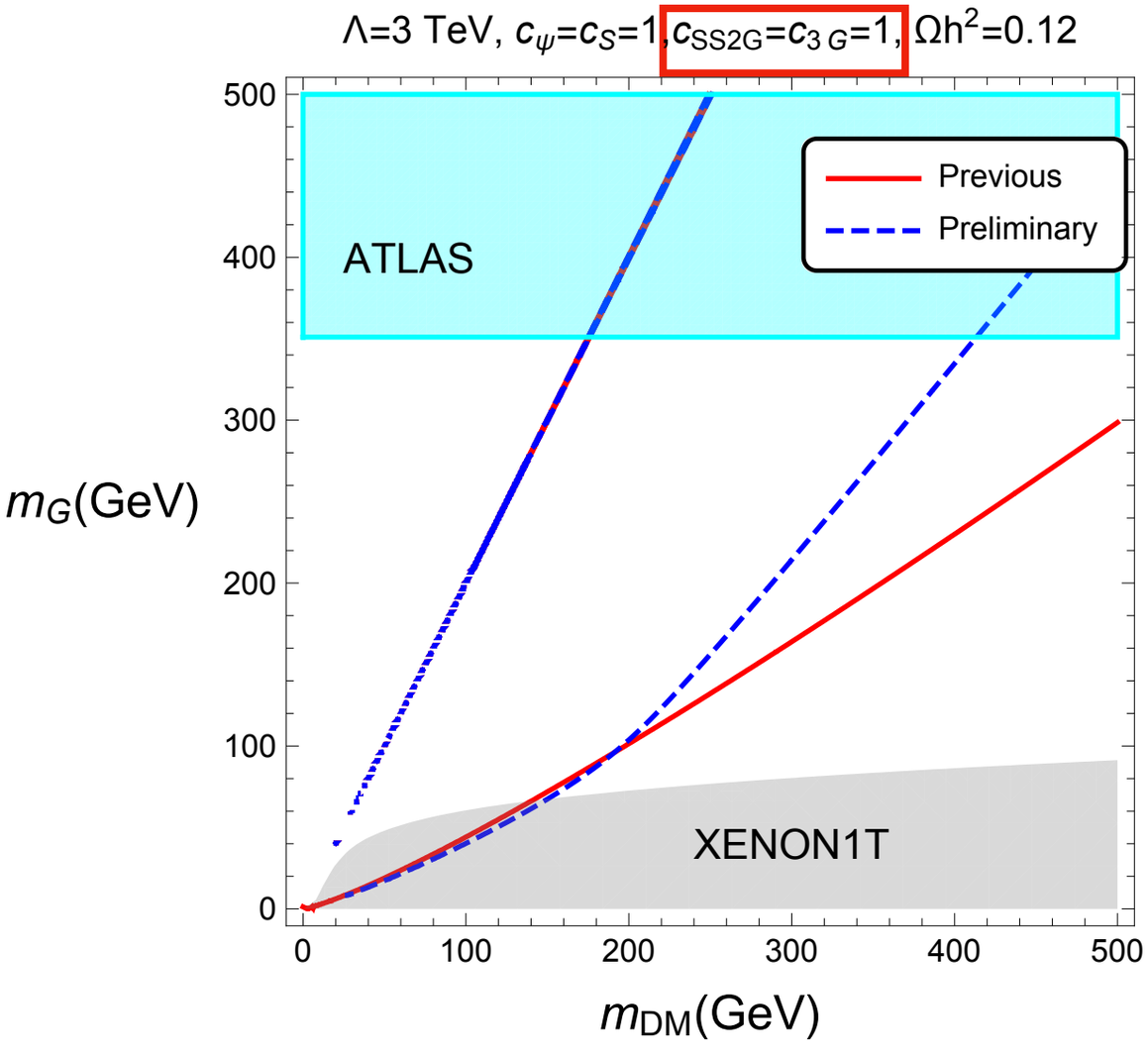


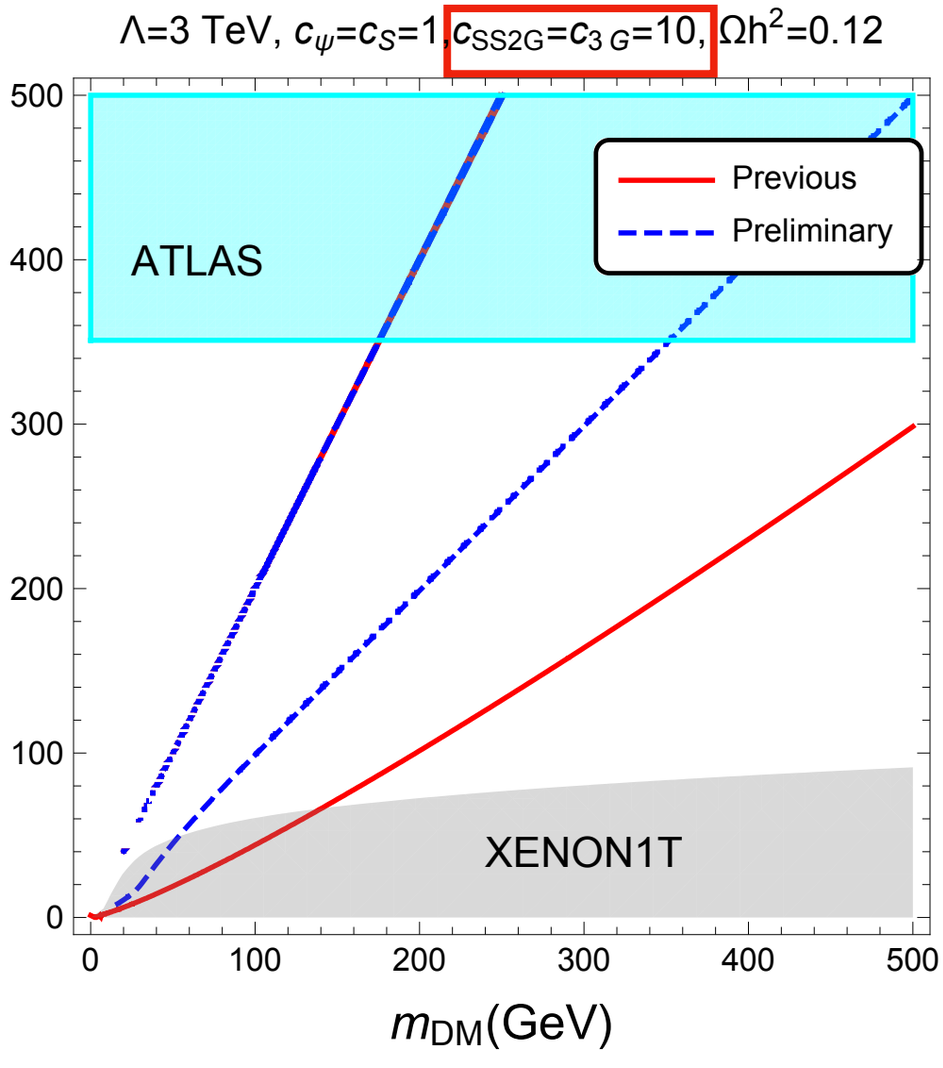
work in progress...

with $r = (m_G/m_{\rm DM})^2$

Relic density

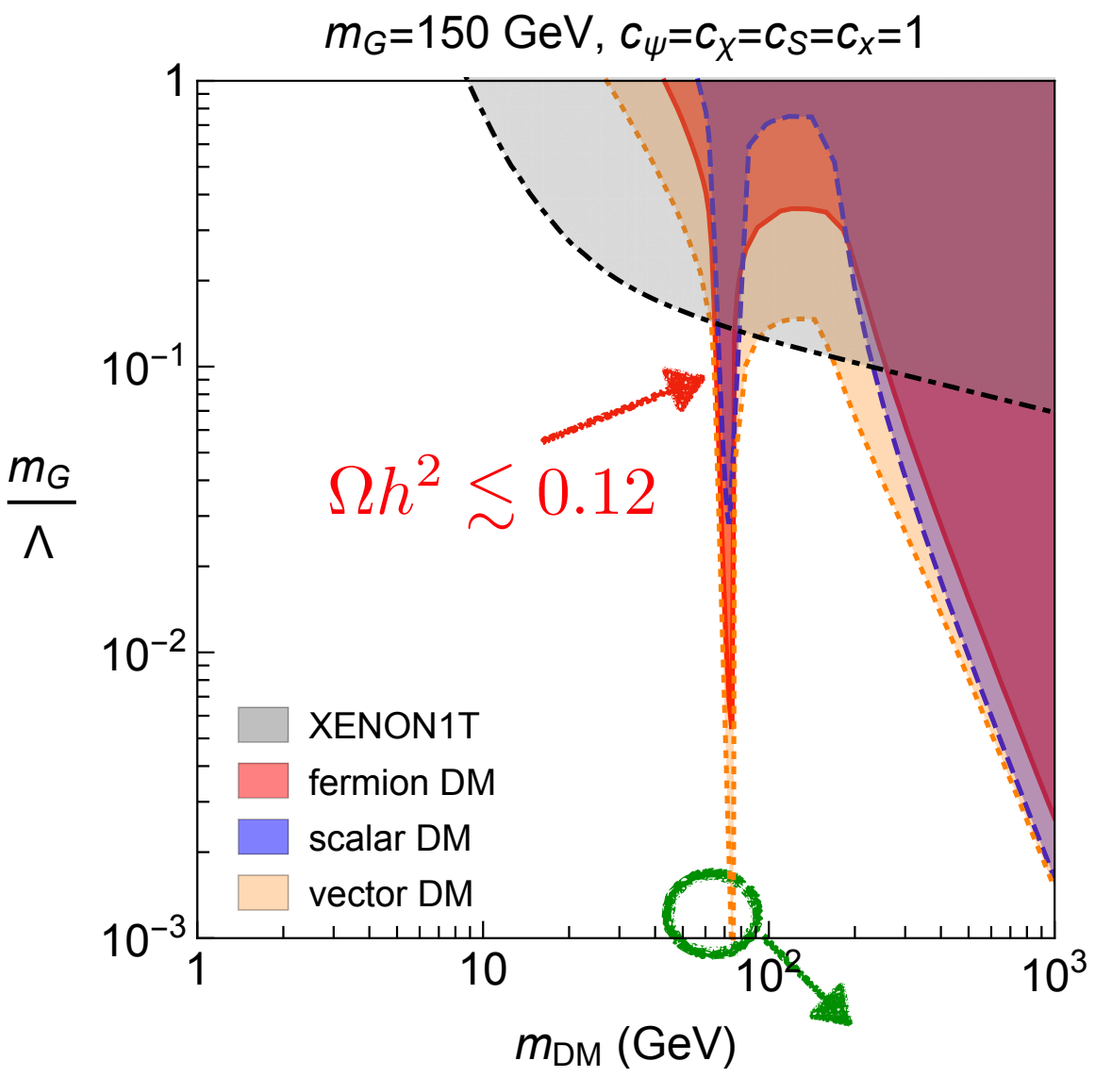
- The multiple gravitons couplings can affect the DM relic density.
- Red : previous work result (minimal graviton coupling)
- Blue : expected result (beyond minimal graviton coupling)

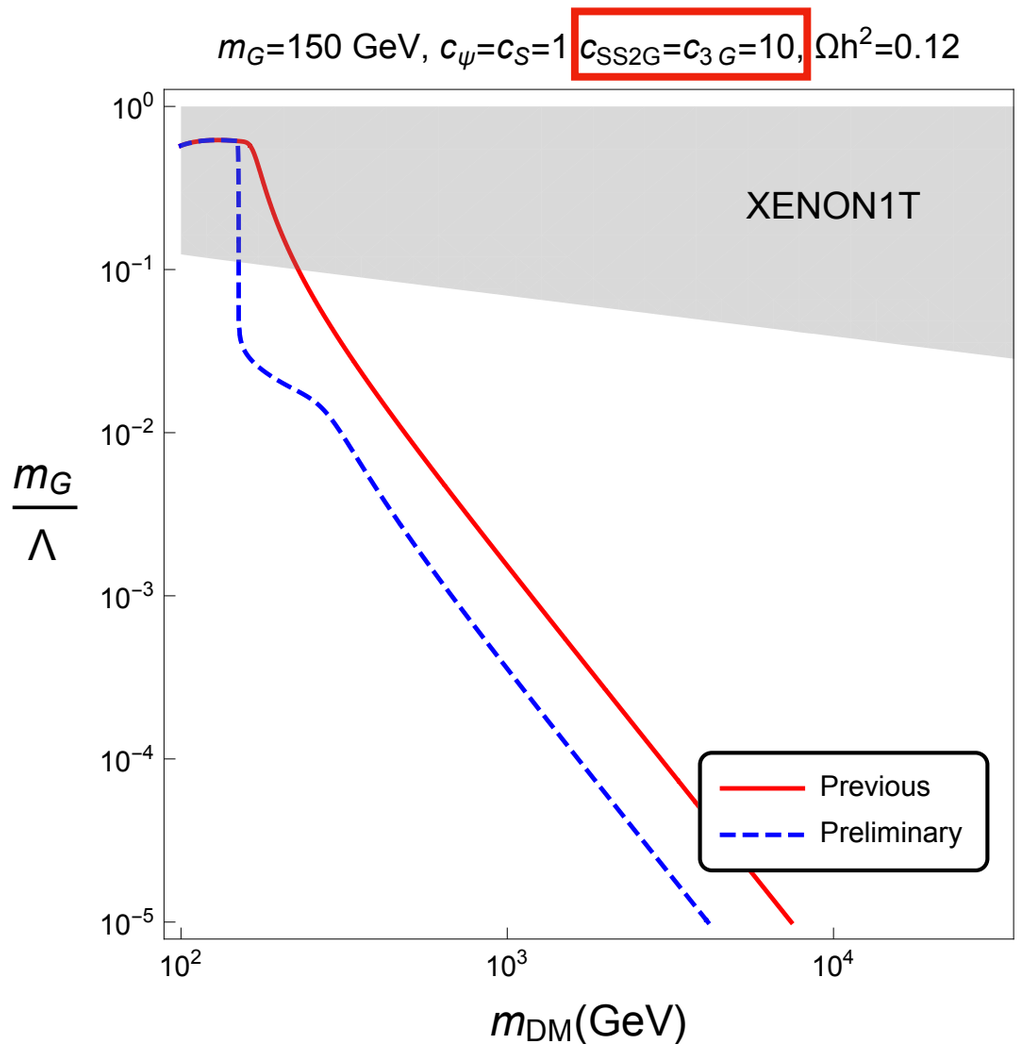




Relic density

- The relic region below m_{DM}=250 GeV is excluded by direct detection, except the resonance region in this parameter space.
- In this result, we consider the only quark couplings for SM.
- The multiple gravitons couplings can affect the DM relic density.

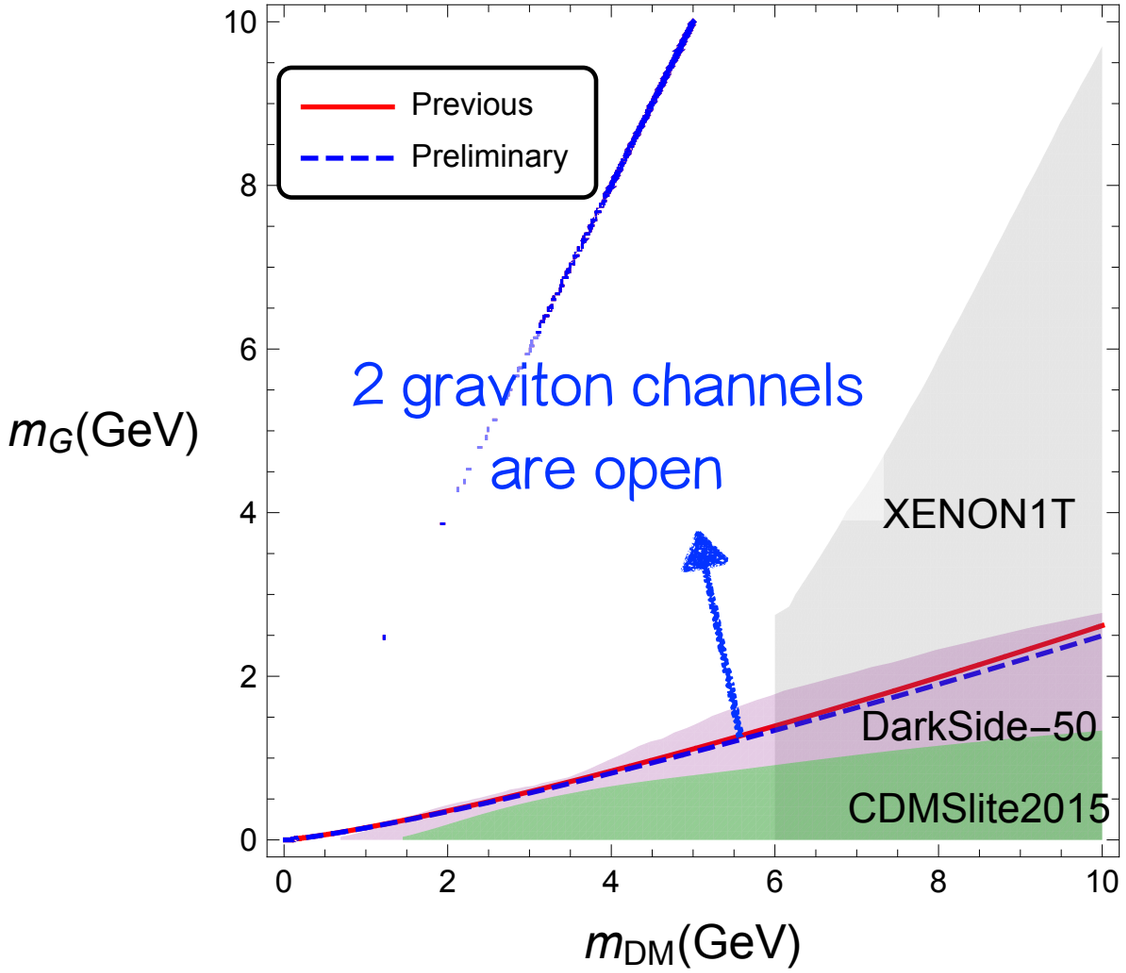


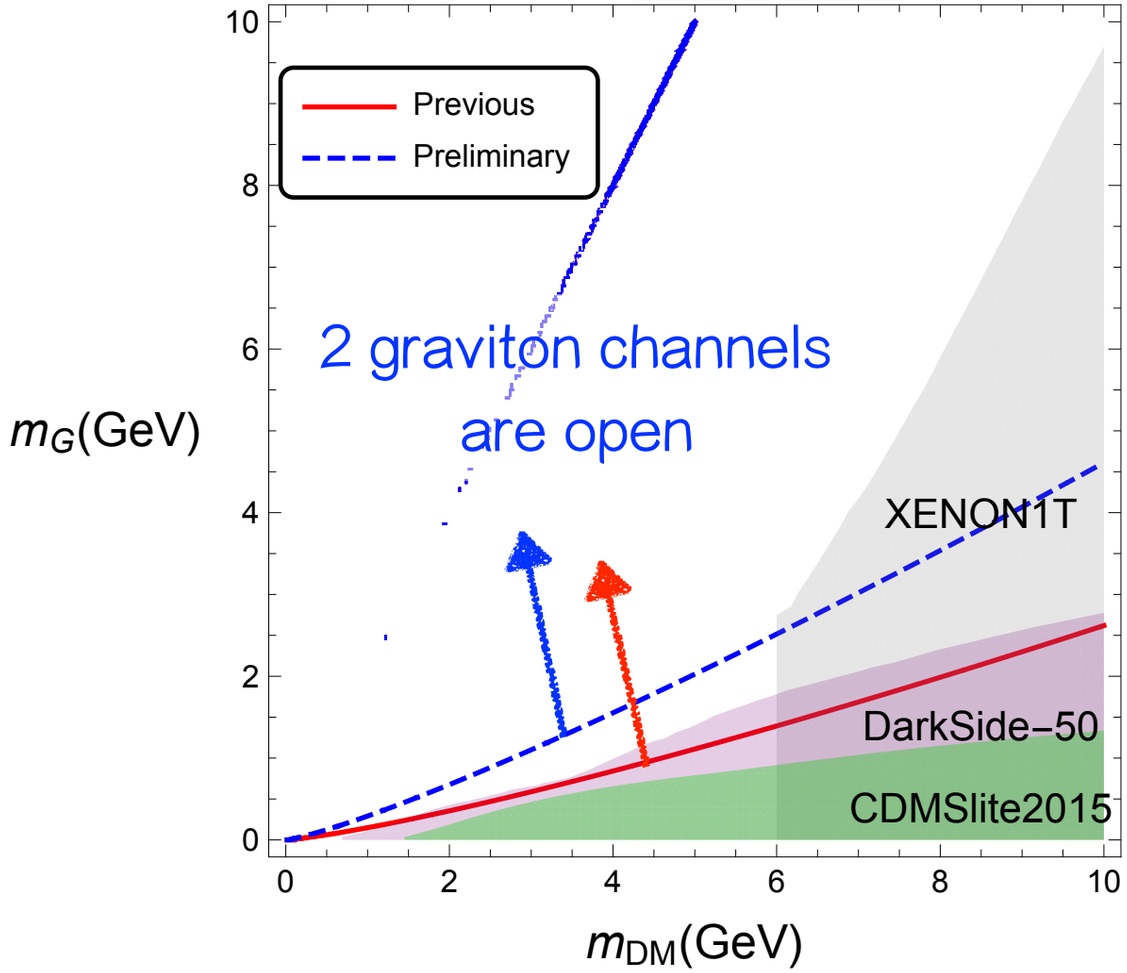


Resonance at $2m_{DM} \sim m_G$

Relic density

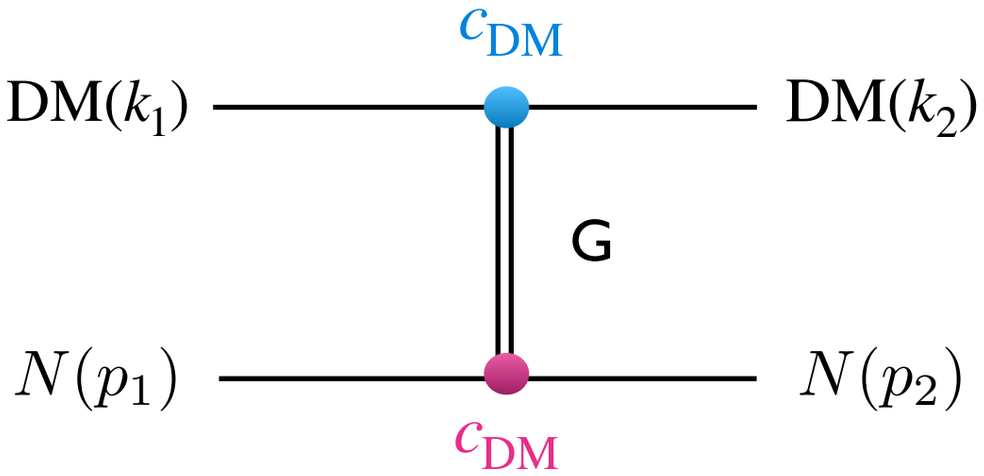
- We also considered the light dark matter case ~ 10 GeV
- Light DM experiments give contributions : DarkSide-50, CDMSlite and CRESST.
- Red : previous work result (minimal graviton coupling)
- Blue : expected result (beyond minimal graviton coupling)





Direct detection : DM-N scattering

- The tree-level scattering amplitude b/w DM and quark through a massive spin-2 propagator.



$q = k_2 - k_1 = p_1 - p_2$

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

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

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

It satisfies traceless and transverse condition. $\eta^{\alpha\beta}\mathscr{P}_{\mu\nu,\alpha\beta} = 0, \quad q^\alpha \mathscr{P}_{\mu\nu,\alpha\beta} = 0$

Integrated out

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

Direct detection : matching q to N

ψ : SM quarks

Trace part : $T^{\psi} = -m_{\psi}\bar{u}_{\psi}(p_2)u_{\psi}(p_1) \longrightarrow \langle N(p_2)|m_{\psi}\psi\bar{\psi}|N(p_1)\rangle = F_S(q^2)m_N\bar{u}_N(p_2)u_N(p_1)$

Traceless part : $\langle N(p_2)|\tilde{T}^{\psi}_{\mu\nu}|N(p_1)\rangle = F_T(q^2)\tilde{T}^{N}_{\mu\nu}$

J. Zupan et al (1708.02678, 1710.10218)

If momentum transfer is 0,

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

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)

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

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

second moments of the PDF

$u(2)+\bar{u}(2)$	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

$\mu \approx m_Z$, CTEQ

In detail : A. Carrillo-Monteverde, YJK, H. M. Lee, M. Park and V. Sanz (1803.02144)

Direct detection : bounds

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

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

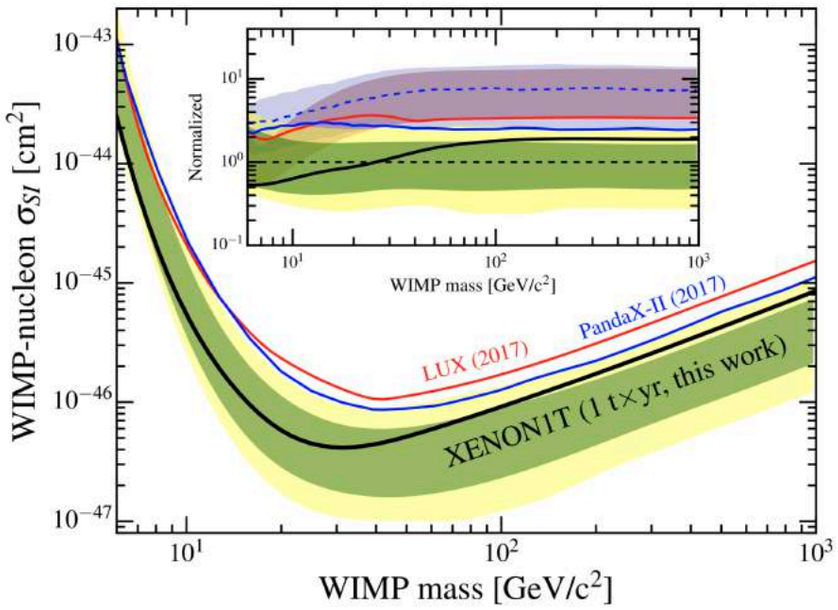
$$f^{\rm DM}_{p,n} = \frac{c_{\rm DM} m_N m_{\rm DM}}{4 m_G^2 \Lambda^2}\left(\sum_{\psi=u,d,s,c,b} 3 c_\psi (\psi(2) + \bar{\psi}(2)) + \sum_{\psi=u,d,s} \frac{1}{3} c_\psi f^{p,n}_{T\psi} \right)$$

Due to trace part of the $T_{\mu\nu}$

Due to traceless part of the $T_{\mu\nu}$

It's constrained by XENON1T

XENON1T (1805.12562)

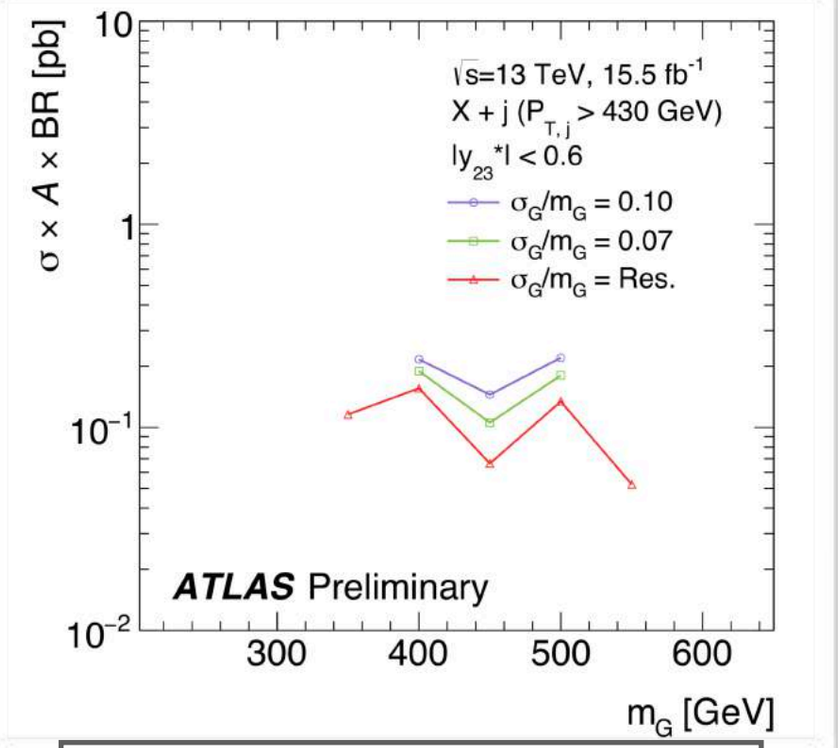


c.f.-scalar med. (Higgs portal) $f^{\rm DM}_{p,n} = m_N\left(\sum_{\psi=u,d,s} f^{p,n}_{T\psi} \frac{\mathcal{M}_\psi}{m_\psi} + \frac{2}{27} f^{p,n}_H \sum_{\psi=c,b,t} \frac{\mathcal{M}_\psi}{m_\psi} \right)$ Y. Mambrini (1108.0671)

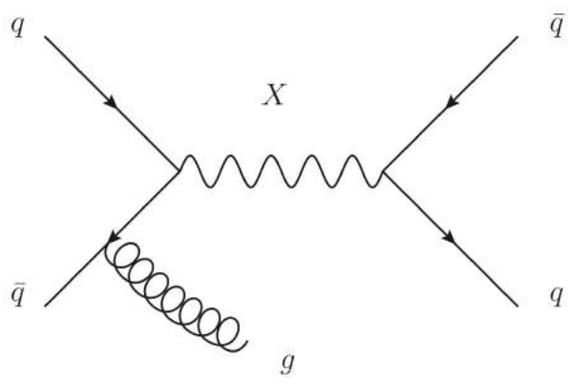
Collider searches : quark coupling

- There are ATLAS dijet constrains to $BR(G \to q\bar{q})$.

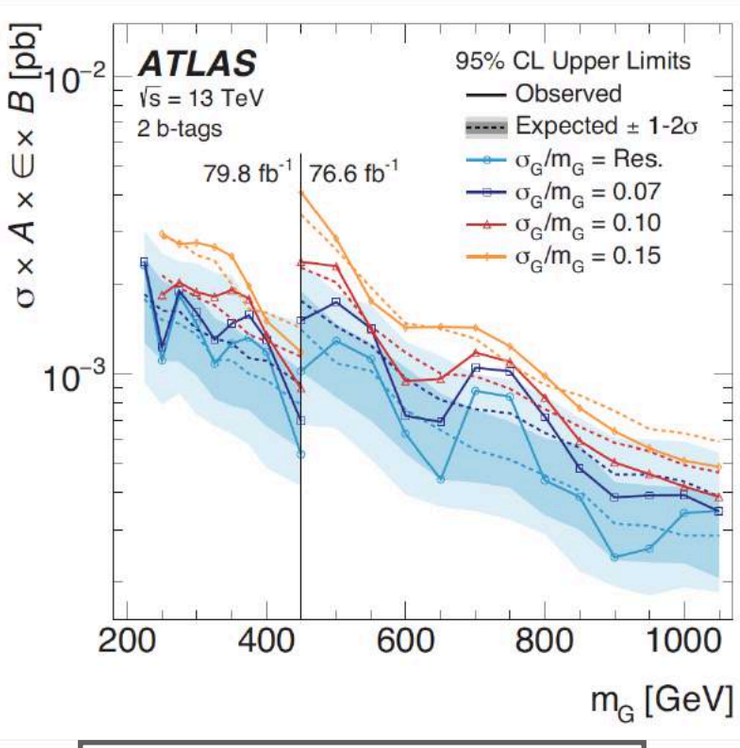
ISR jet + dijet



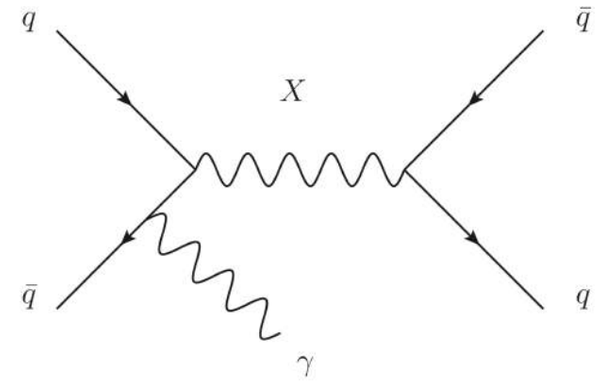
ATLAS-CONF-2016-070



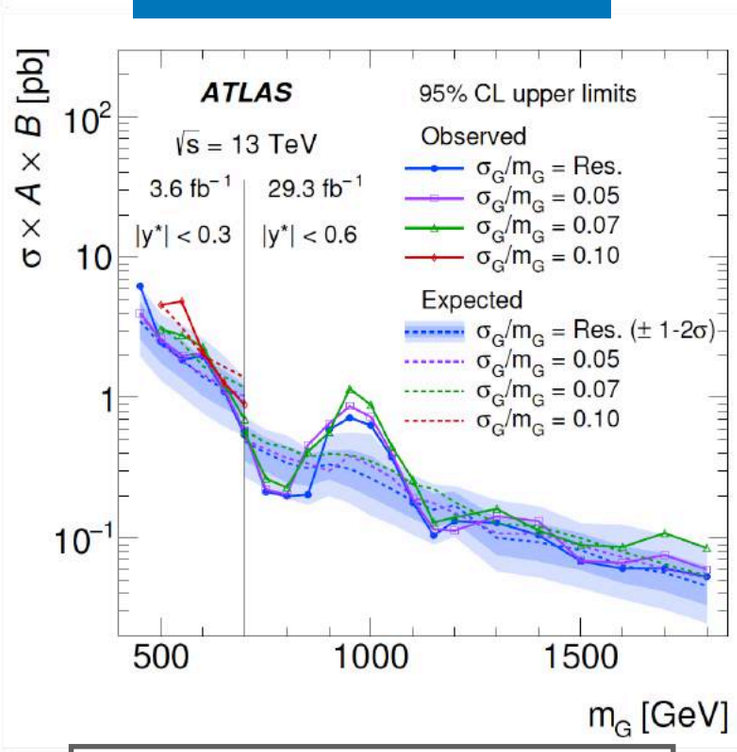
ISR photon + dijet



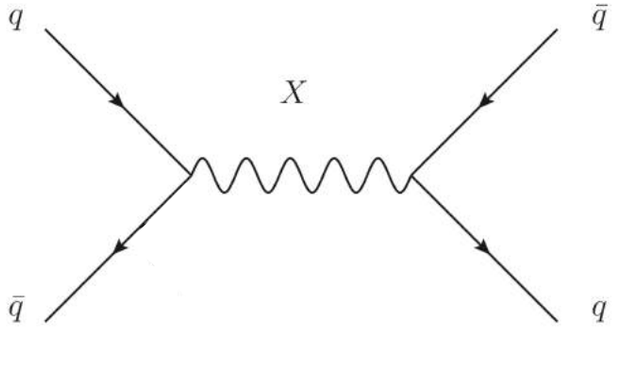
ATLAS (1901.10917)



dijet resonance



ATLAS (1804.03496)



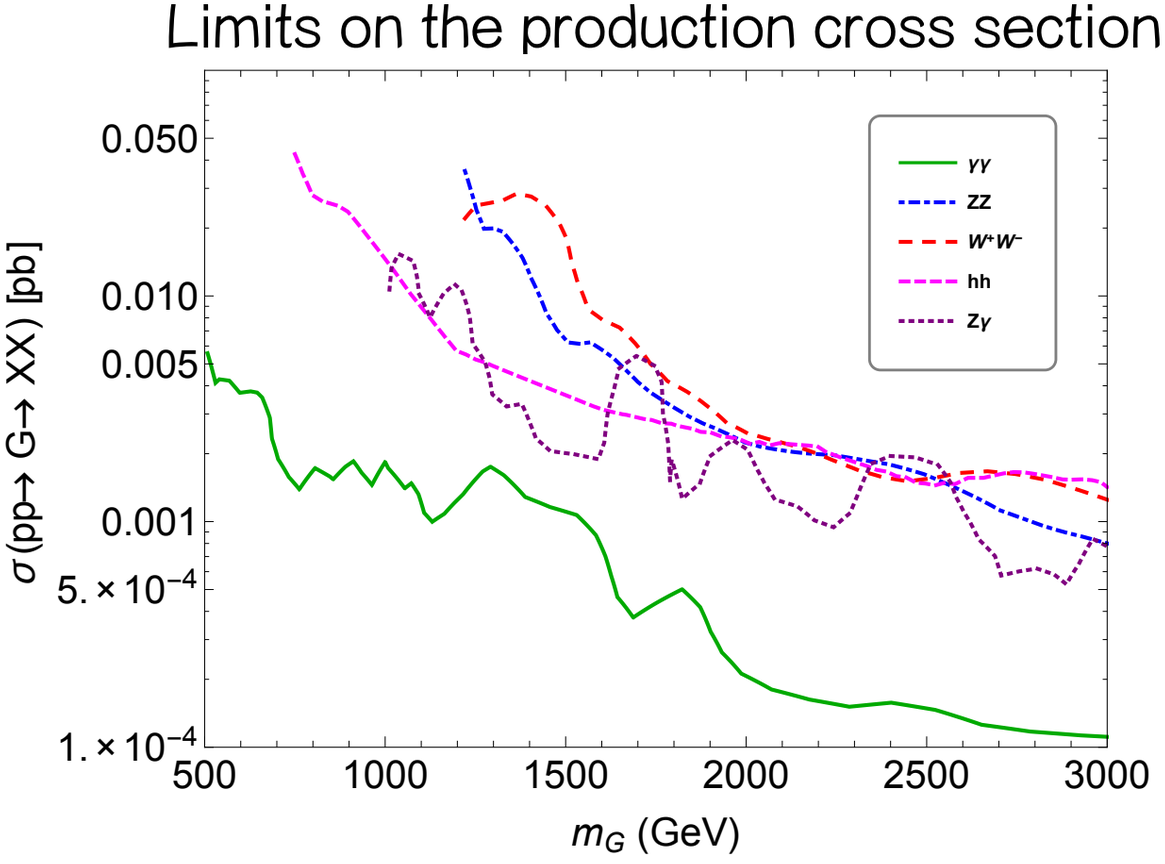
Collider searches : other couplings

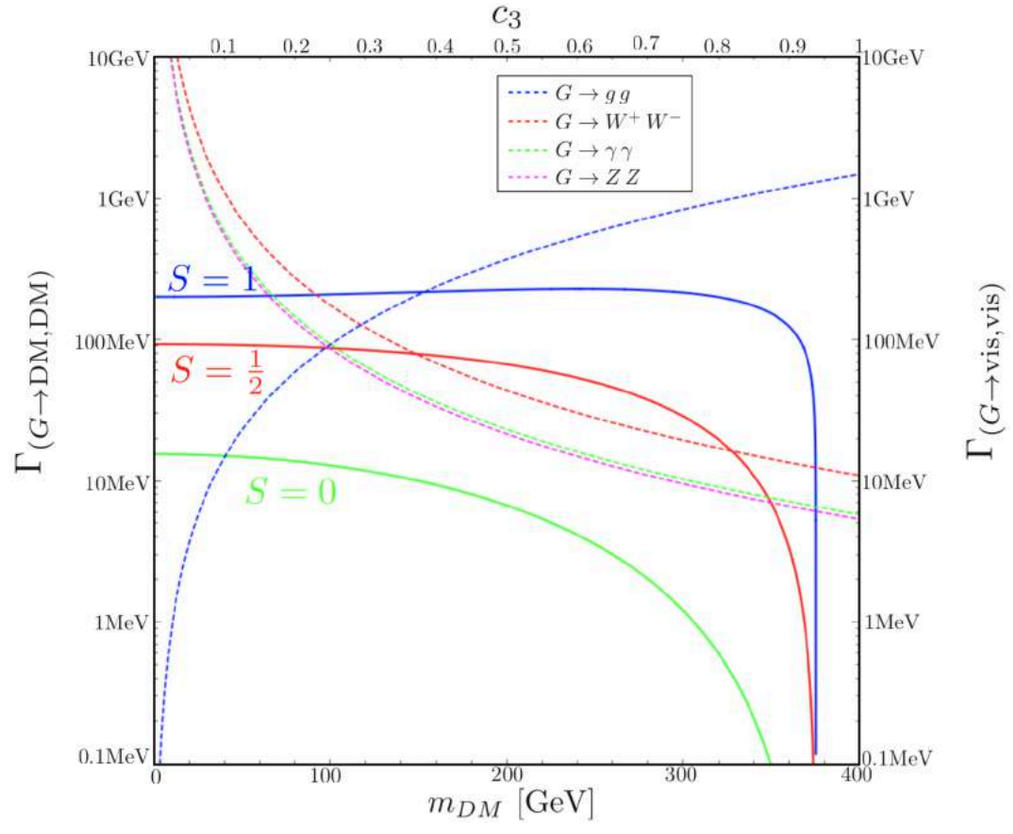
- We can consider gauge bosons, lepton pair and Higgs pair final states at the LHC.

K. Yamashita et al (1807.09643, 1701.07008)

- In this case, these couplings would affect the DM phenomenology as well as the LHC searches.

C. Han, H. M. Lee, M. Park and V. Sanz (1512.06376)





$\gamma\gamma$: CMS 1809.00327 / ZZ : CMS 1803.03838 / WW : CMS 1802.0407 / hh : CMS 1808.01473 / Zγ : ATLAS 1805.01908

Conclusion

- We have considered gravity-mediated dark matter model (DM spin-0,1 and 1/2). Especially, massive graviton can mediate DM and the SM.

- When DM annihilation channel into gravitons is open, multiple graviton couplings can affect DM annihilation.

- We have showed the relic density of dark matter has enough parameter space consistent with direct detection and LHC dijet searches in the cases of beyond minimal graviton couplings.
  - work in progress

Back up

Matching - Gravitational form factor

- Matrix elements of the energy-momentum tensor

→ Gravitational form factor

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

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

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

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

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

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

Effective Operators

Fitzpatrick et al (1203.3542, 1308.6288)

$S_{\rm DM}$	$\mathcal{O}_i$	$\Sigma_k \mathcal{O}_k^{\rm NR}$
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	$\epsilon_{1,2}^\alpha \bar{N} i\sigma_{\alpha\lambda}\frac{q^\lambda}{m_N}N$	$4im_N^2\left(\vec{S_N}\cdot(\vec{\epsilon}_{1,2}\times\frac{\vec{q}}{m_N})\right)$
1	$k_{1,2\nu}\bar{N} i\sigma^{\nu\lambda}\frac{q_\lambda}{m_N}N$	$m_\chi(\vec{q}^{\,2}\mathcal{O}_1^{\rm NR} - 4m_N^2 \mathcal{O}_3^{\rm NR})$

in the Graviton mediator model

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

1. Momentum transfer $\vec{q}$

2. Relative perpendicular velocity

$$\vec{v}^\perp \equiv \vec{v} + \frac{\vec{q}}{2\mu_N}$$

3. Spin of WIMP $\vec{S}_\chi$

4. Spin of nucleon $\vec{S}_N$

Effective Lagrangian

Unsuppressed operator
for DM-nucleon scattering

Fermion DM

$$\mathscr{L}_{\chi,\text{eff}} \approx \frac{c_\chi c_\psi m_\chi^2 m_N^2}{2m_G^2\Lambda^2}\left[\left\{6F_T\left(1+\frac{\vec{q}^{\,2}}{3m_N^2}+\frac{\vec{q}^{\,2}}{3m_\chi^2}\right)-\frac{2}{3}F_S\right\}\mathcal{O}_1^{\text{NR}}-8F_T\mathcal{O}_3^{\text{NR}}-\frac{4\vec{q}^{\,2}}{m_\chi m_N}F_T\mathcal{O}_4^{\text{NR}}\right.$$
$$\left.-\frac{8m_N}{m_\chi}F_T\left(1+\frac{\vec{q}^{\,2}}{8m_N}\right)\mathcal{O}_5^{\text{NR}}+\frac{4m_N}{m_\chi}F_T\mathcal{O}_6^{\text{NR}}+\frac{4m_N}{m_\chi}F_T\mathcal{O}_3^{\text{NR}}\mathcal{O}_5^{\text{NR}}\right]$$

Scalar DM

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

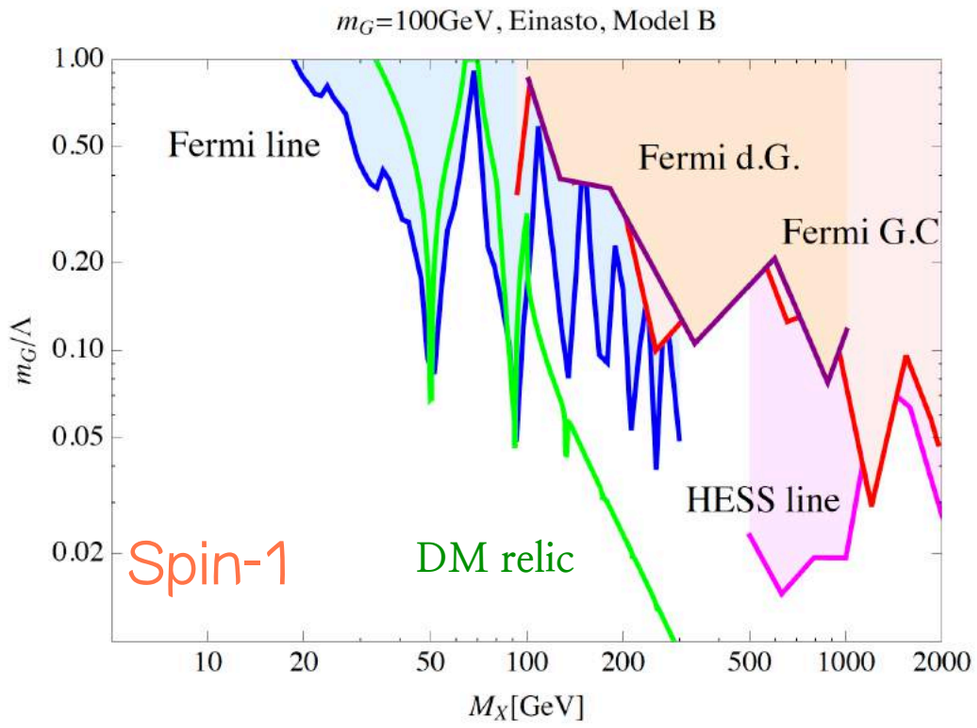
As a result, leading terms are independent of DM spins.

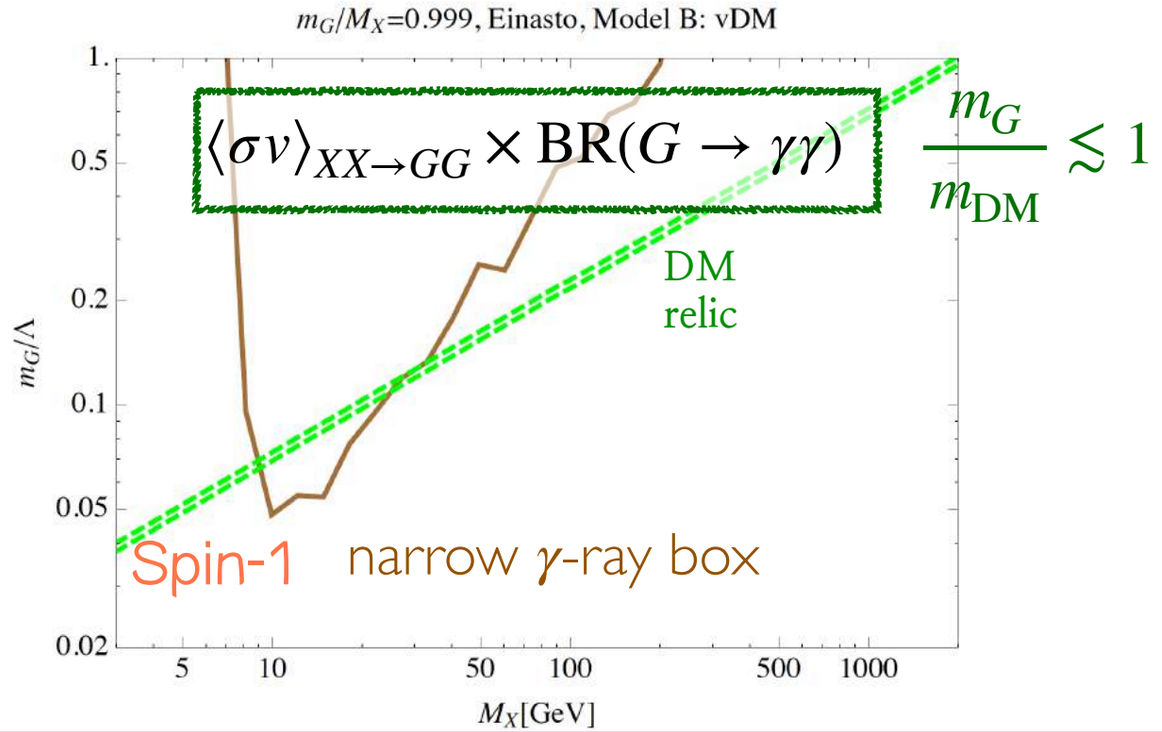
Dimension : $\int \frac{d^3p}{(2\pi)^3\sqrt{2E}}a_N^{(\dagger)}$ and $\int \frac{d^3p}{(2\pi)^3\sqrt{2E}}a_\chi^{(\dagger)}$ per each nucleon & DM state are to be multiplied.

Indirect detection

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

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





$\frac{m_G}{m_{\mathrm{DM}}} = 0.6$

