Gravity-mediated 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

KEK-PH2018 winter / KEK / Dec. 04, 2018

Outline

- Gravity-mediated model
- DM annihilation - indirect detection
- DM-nucleon scattering (effective operators) - direct detection
- Collider searches / quark coupling or other couplings
- Relic density
- Conclusion

Graviton

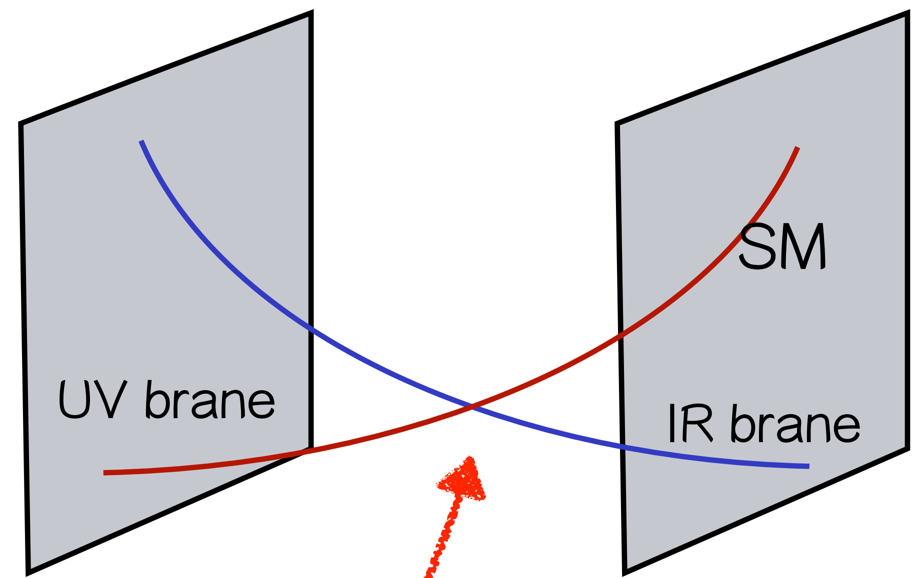
- Graviton has considered to explain weak gravity naturally.

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.

Also, it is localized on IR brane in RS model.

Gravity-mediated DM

graviton   dark matter

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

gauge bosons

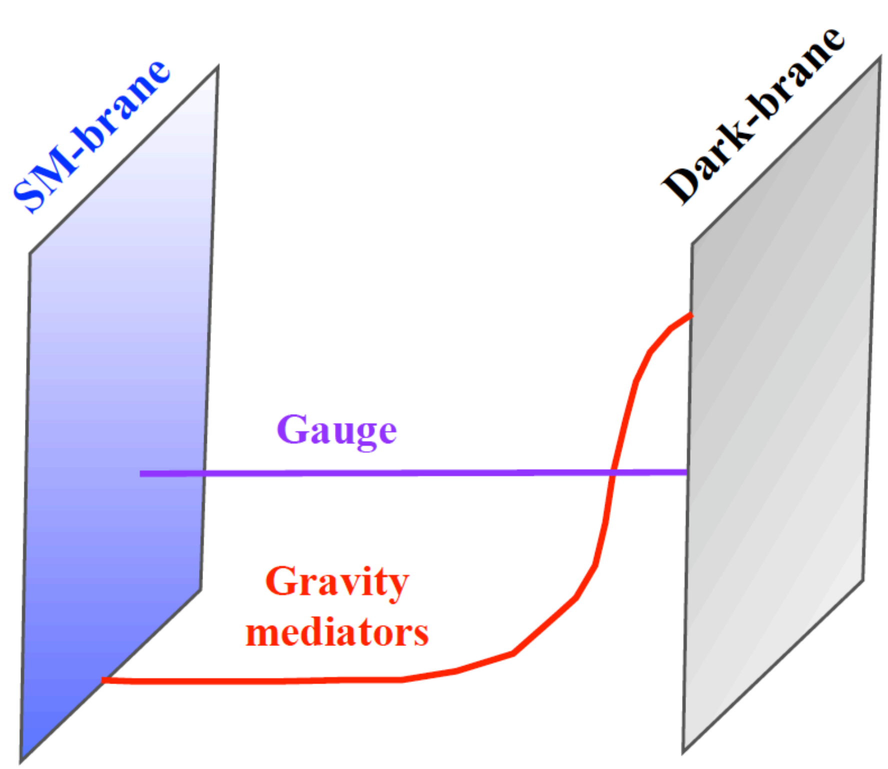
$$+ c_\psi \bigg(\frac{i}{2} \big(\bar\psi \gamma_\mu \overleftrightarrow{D}_\nu \psi - g_{\mu\nu} \bar\psi \gamma_\rho \overleftrightarrow{D}^\rho \psi \big) + g_{\mu\nu} m_\psi \bar\psi \psi \bigg)$$

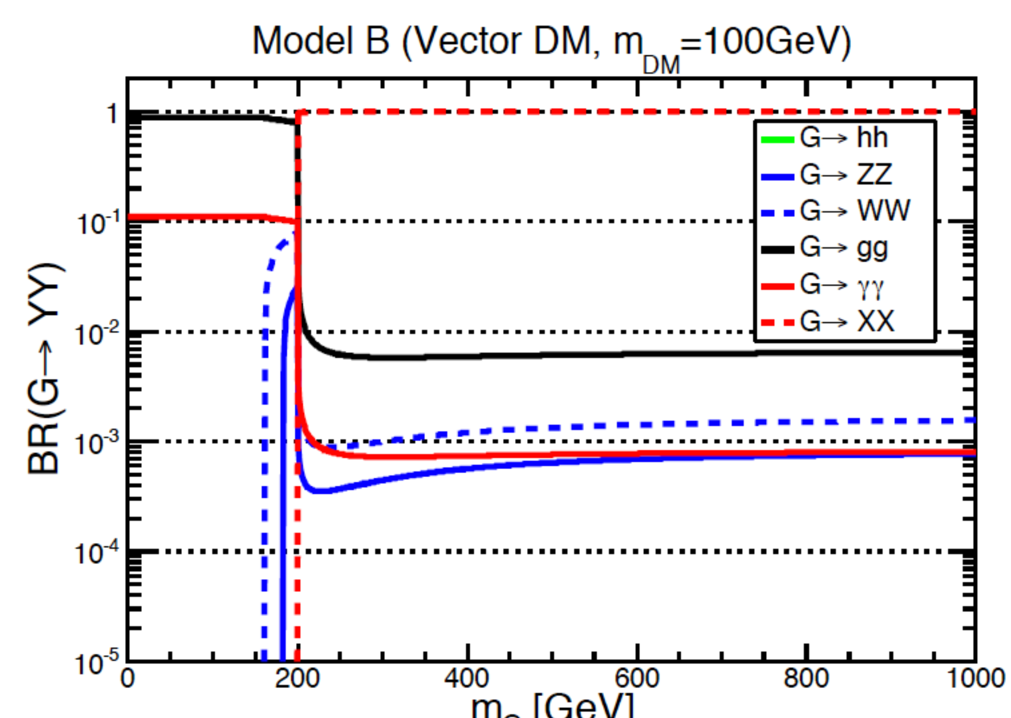
fermions

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

Higgs

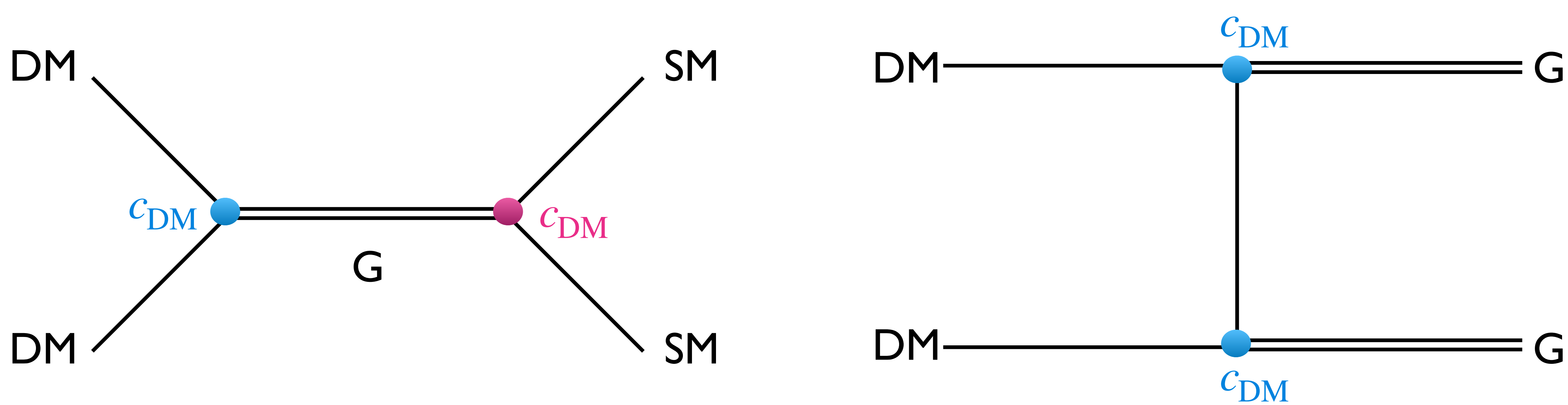
- Benchmark model : IR brane (Dark brane) - DM & UV brane - SM





DM annihilations

- KK graviton can mediate the annihilations of dark matter into the SM particles.
- If graviton mass is less then DM mass, 2 gravitons channel is open.



$$(\sigma v_{\rm rel})_{\rm DM,tot} = (\sigma v_{\rm rel})_{hh} + (\sigma v_{\rm rel})_{ZZ} + (\sigma v_{\rm rel})_{WW} + (\sigma v_{\rm rel})_{\gamma\gamma} + (\sigma v_{\rm rel})_{gg}$$

$$+(\sigma v_{\rm rel})_{\psi\bar{\psi}} + (\sigma v_{\rm rel})_{GG}$$

DM annihilations

- We considered all spins of dark matter.

t & u channels

Spin-0 $(\sigma v_{\rm rel})_{SS\to {\rm SM,SM}}$: d-wave

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

Spin-1/2 $(\sigma v_{\rm rel})_{\chi\bar\chi\to {\rm SM,SM}}$: p-wave

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

Spin-1 $(\sigma v_{\rm rel})_{XX\to {\rm SM,SM}}$: s-wave → strongly constrained by indirect detection

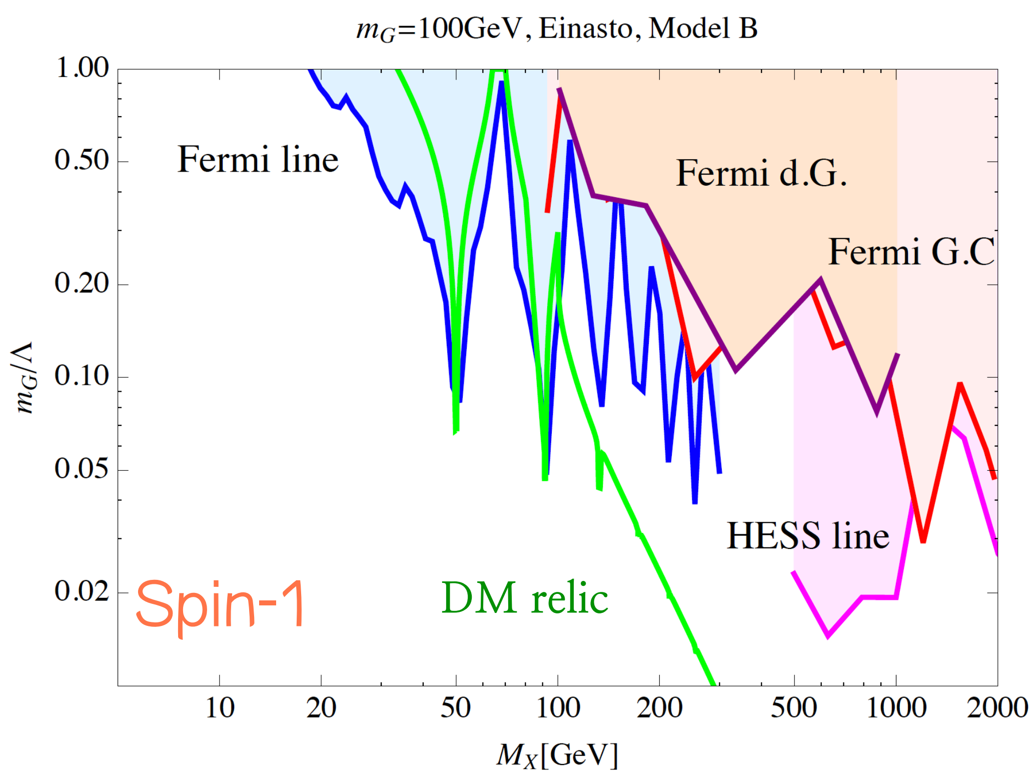
$$(\sigma v_{\rm rel})_{XX\to GG} \simeq \frac{c_X^4 m_X^2}{324\pi\Lambda^4}\frac{(1-r)^{1/2}}{r^4(2-r)^2}(176+192r+1404r^2$$
$$+1105r^4+362r^5+34r^6)$$

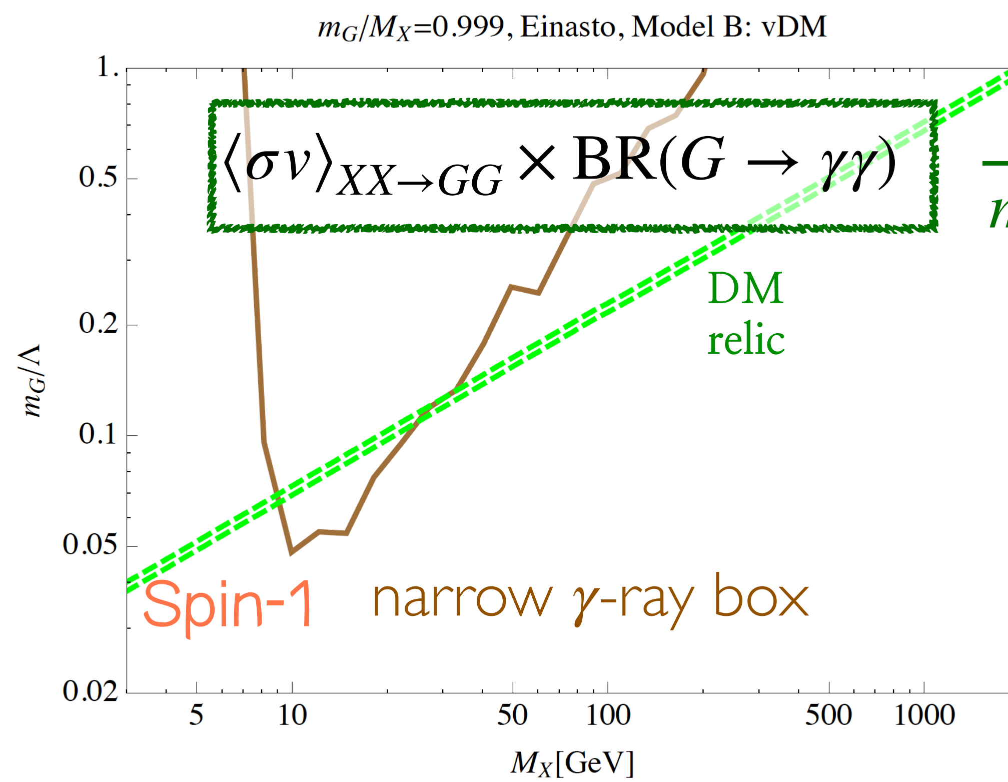
with $r=(m_G/m_{\rm DM})^2$.

Indirect detection

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

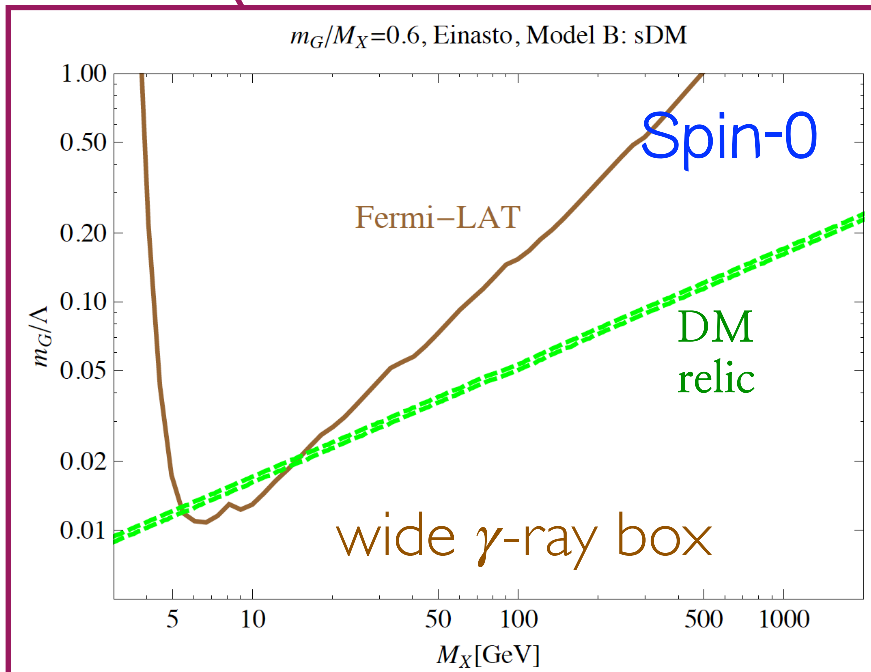
- Astrophysical bounds are DM spin-dependent.
- Therefore, we can distinguish DM spins from Indirect detection.

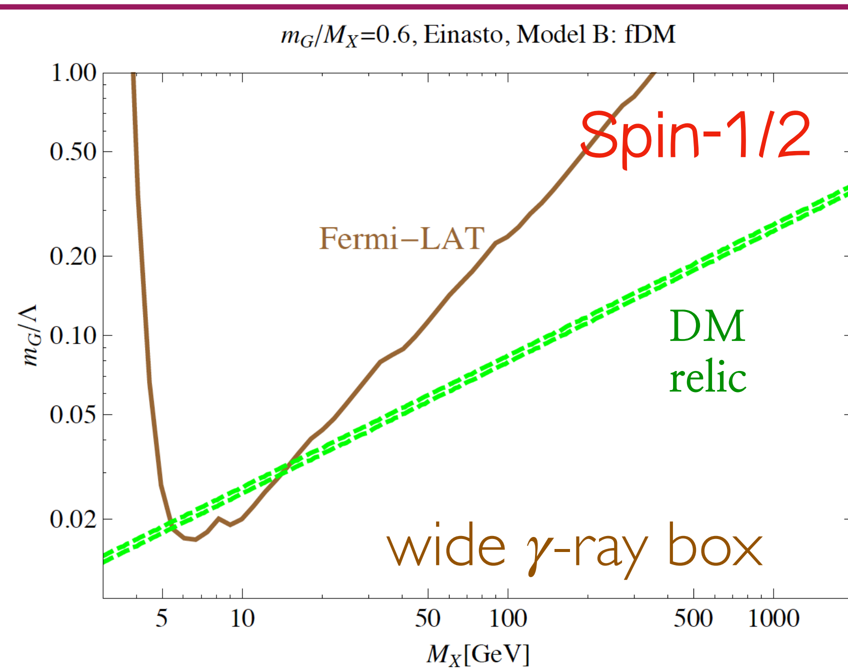


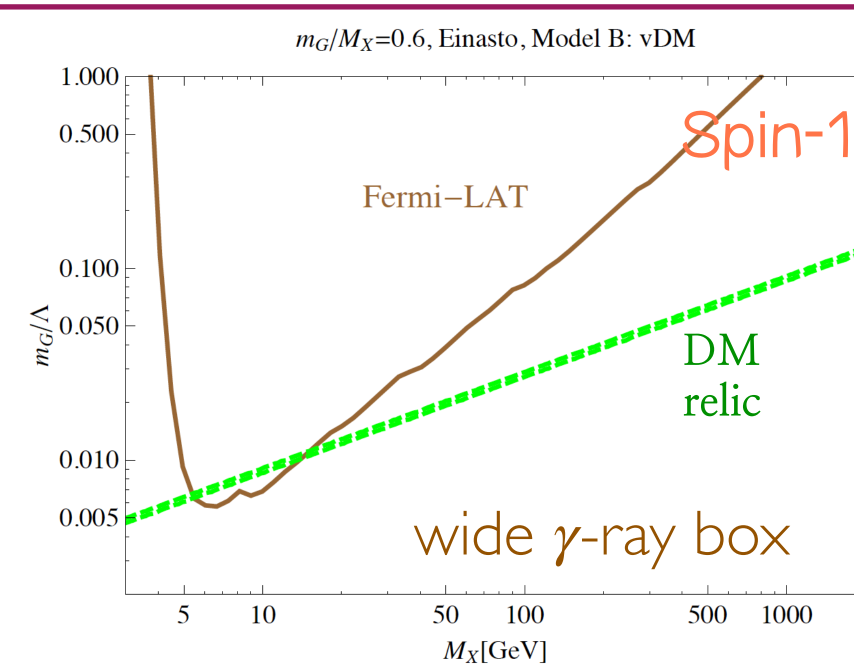


$$\boxed{\langle\sigma v\rangle_{XX\to GG}\times \mathrm{BR}(G\to\gamma\gamma)}\qquad \frac{m_G}{m_{\rm DM}}\lesssim 1$$

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



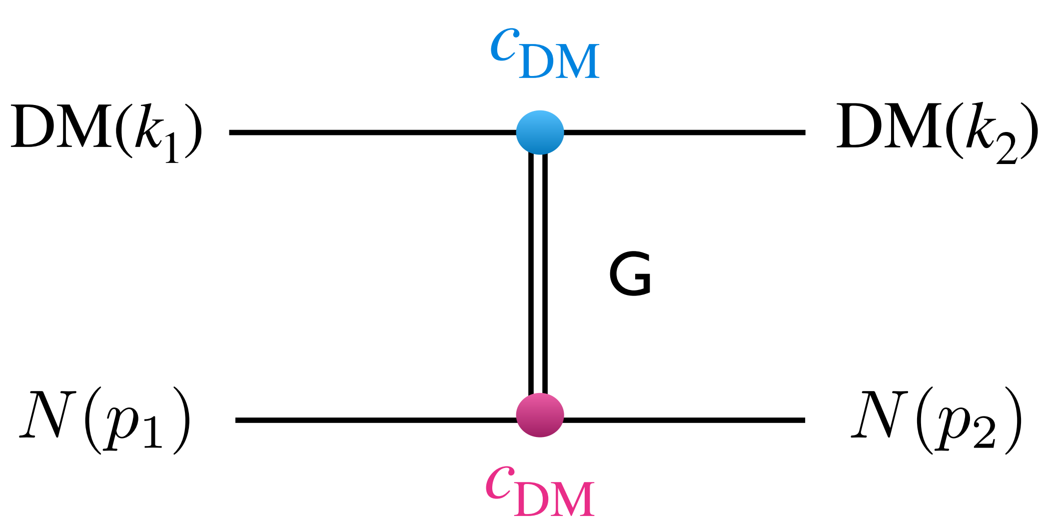




DM-nucleon scattering

- 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

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

Matching - Scalar form factor

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

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

Matching - Gravitational form factor

- Matrix elements of the energy-momentum tensor $\longrightarrow$ 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 $\boxed{\langle N(p_2)|\tilde{T}^{\psi}_{\mu\nu}|N(p_1)\rangle = F_T(q^2)\tilde{T}^N_{\mu\nu}}$

$\mu \approx m_Z$, CTEQ

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

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

second moments of 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

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

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

in the Graviton mediator model

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

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 $\vec{S}_N$

Differential Event Rate

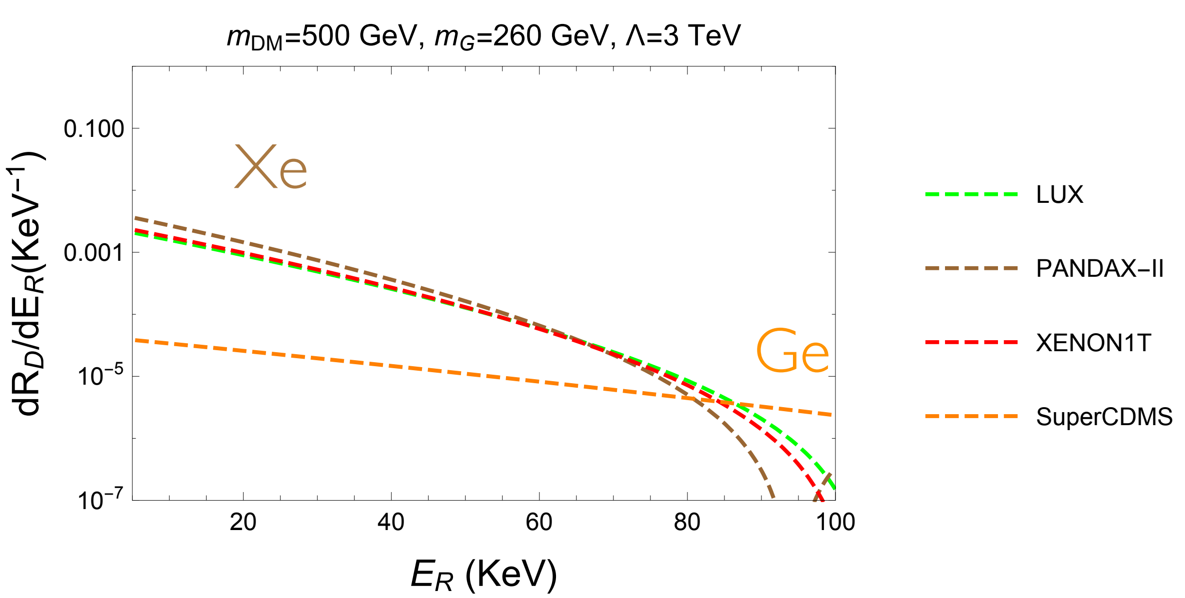
- We can calculate the recoil energy spectrum.

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

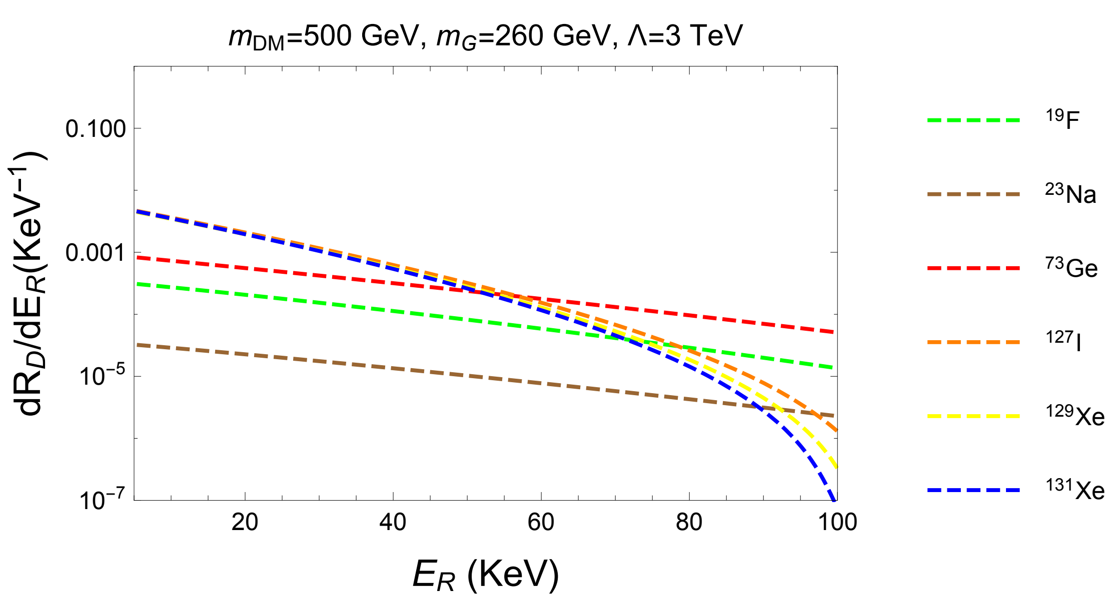
$$\frac{d\sigma}{d\cos\theta} = \frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\sum_{\text{spins}}\frac{1}{32\pi}\frac{|\mathcal{M}|^2}{(m_\chi+m_T)^2} \equiv \frac{m_T^2}{m_N^2}\sum_{i,j}\sum_{N,N'=n,p} c_i^{(N)}c_i^{(N')}\underline{F_{ij}^{(N,N')}(v^2,q^2)}$$

related to nucleus responses functions

Current Exp.



Mock Exp.



by "dmformfactor" mathematica package Fitzpatrick et al (1308.6288)

Direct detection

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

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

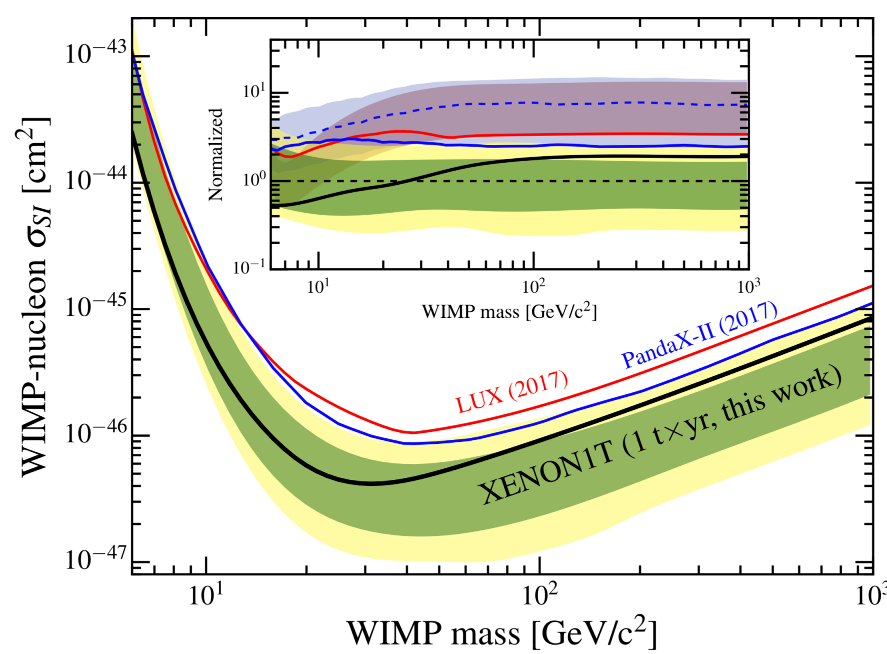
Due to trace part of the $T_{\mu\nu}$

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

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)

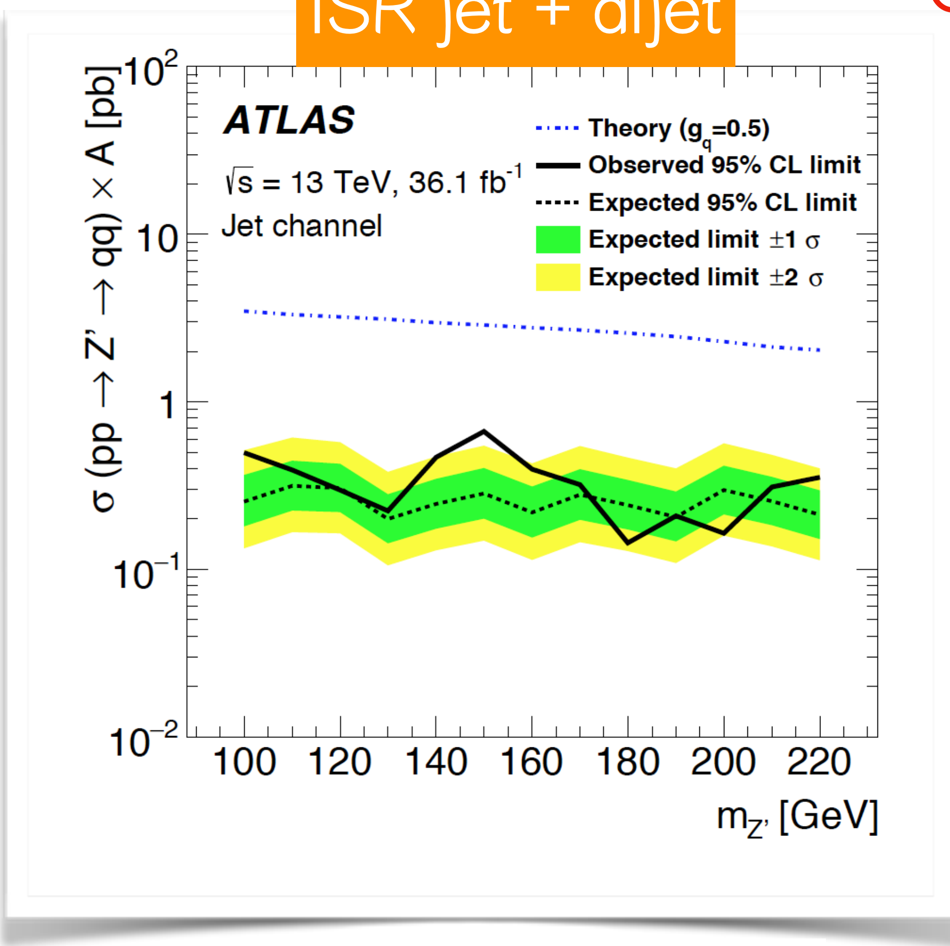
Collider searches for quark coupling

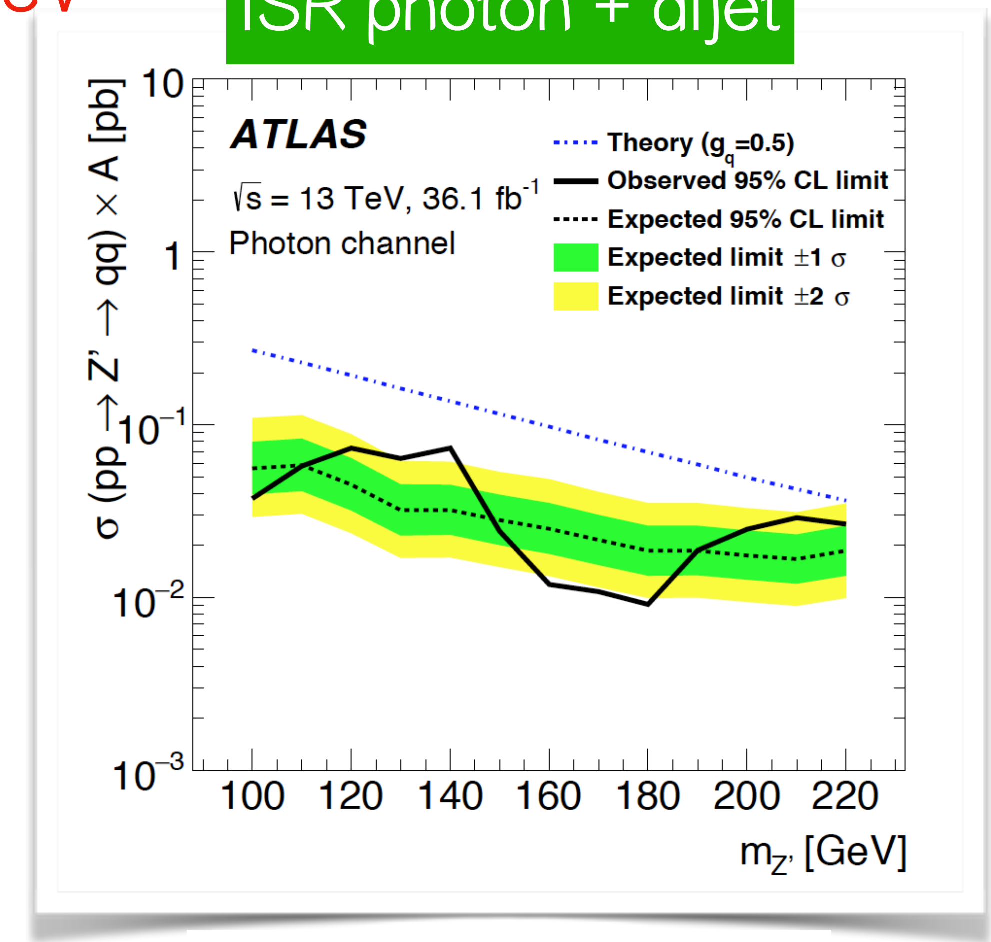
- There are ATLAS dijet constrains to $BR(G \to q\bar{q})$.

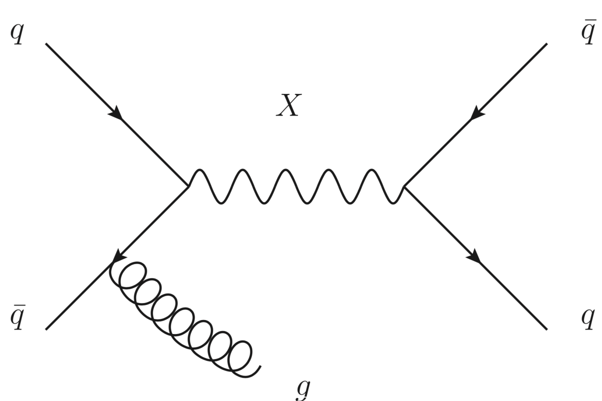
ISR jet + dijet

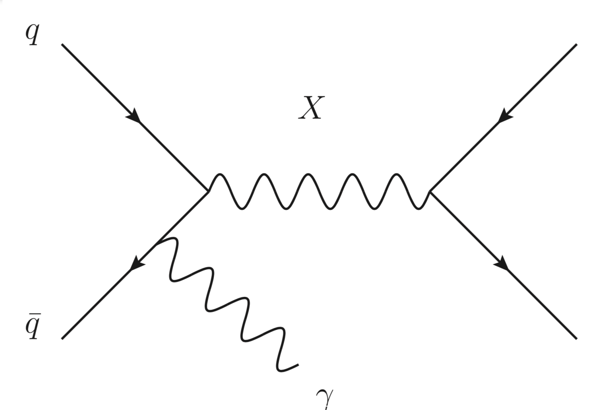
Over 100 GeV

ISR photon + dijet









ATLAS (1801.08769)

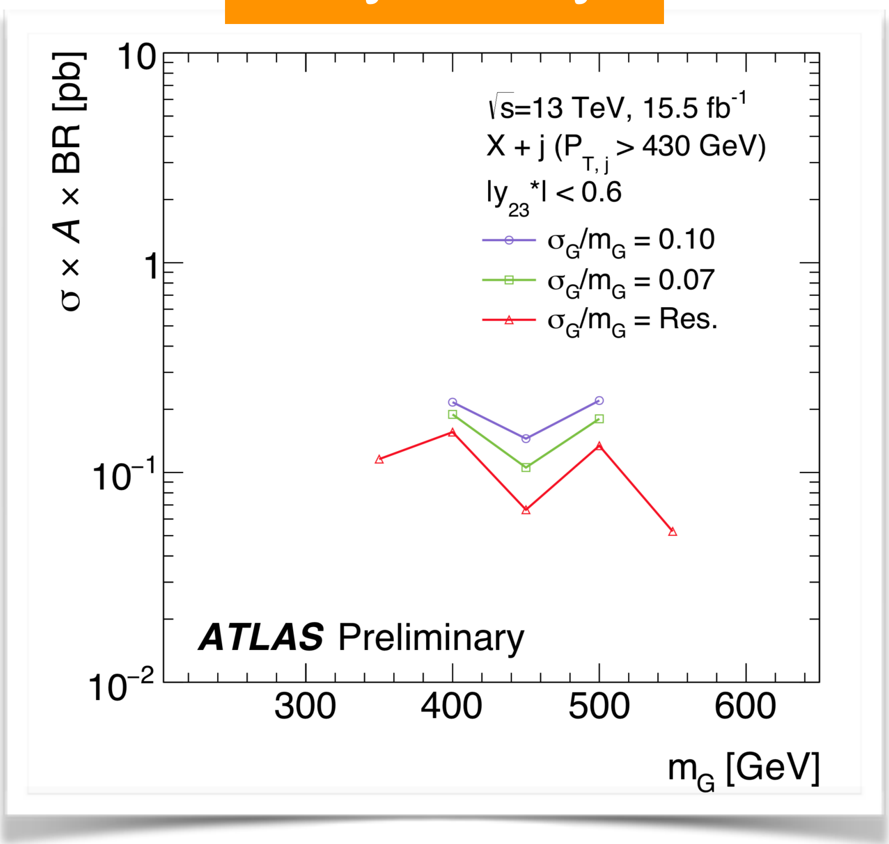
Collider searches for quark coupling

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

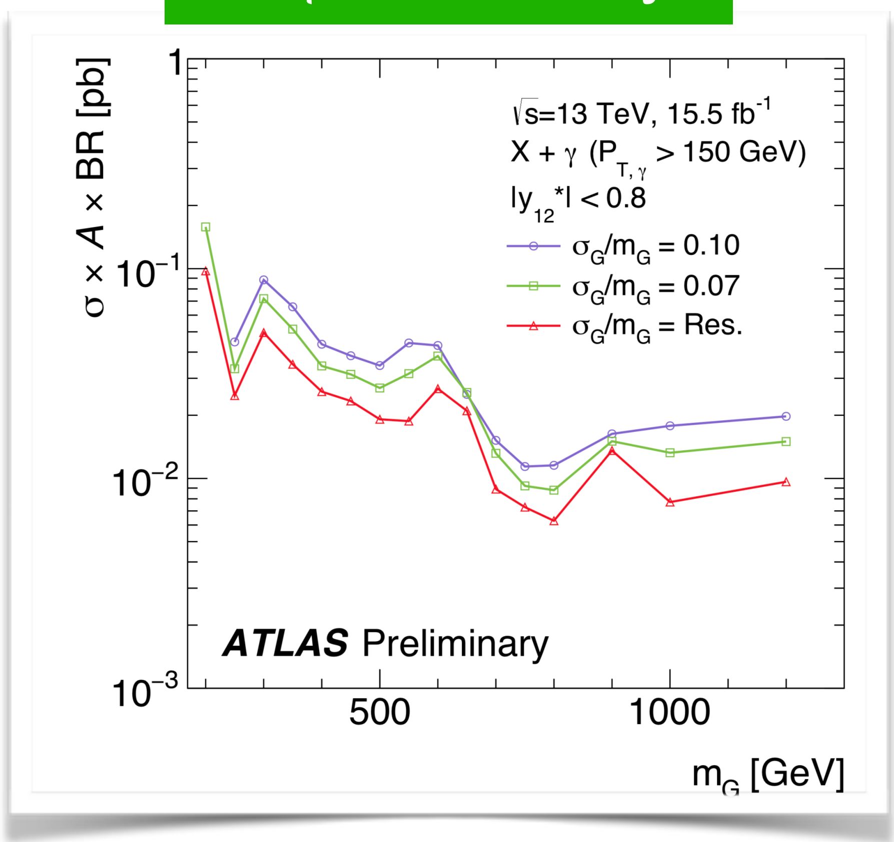
Over 300 GeV

Over 500 GeV

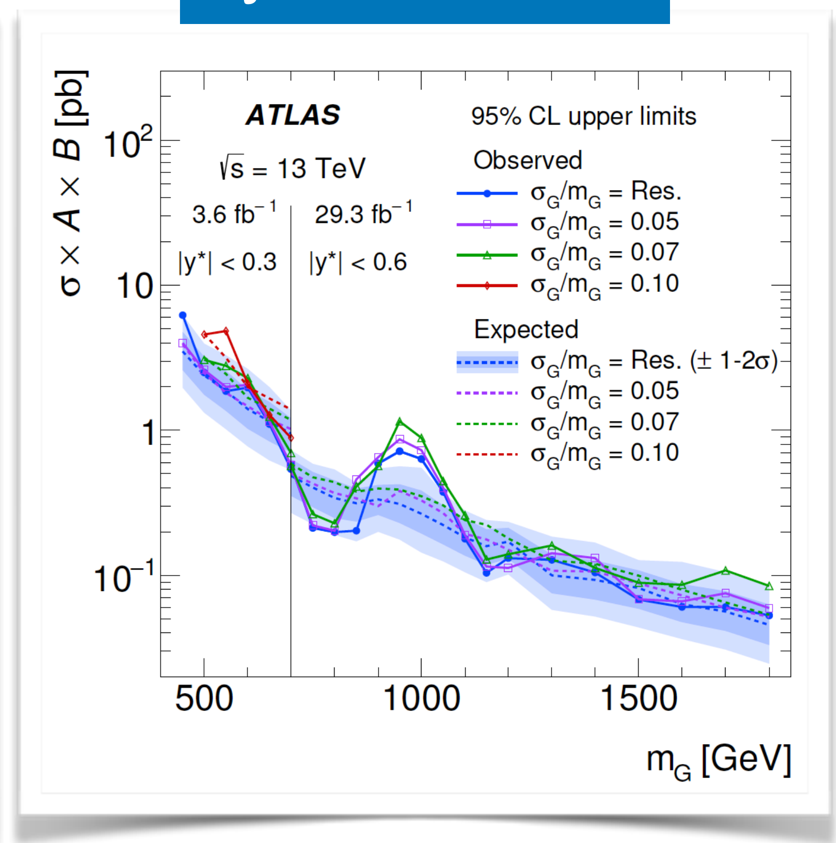
ISR jet + dijet



ISR photon + dijet



dijet resonance



ATLAS-CONF-2016-070

ATLAS (1804.03496)

Collider searches for other couplings

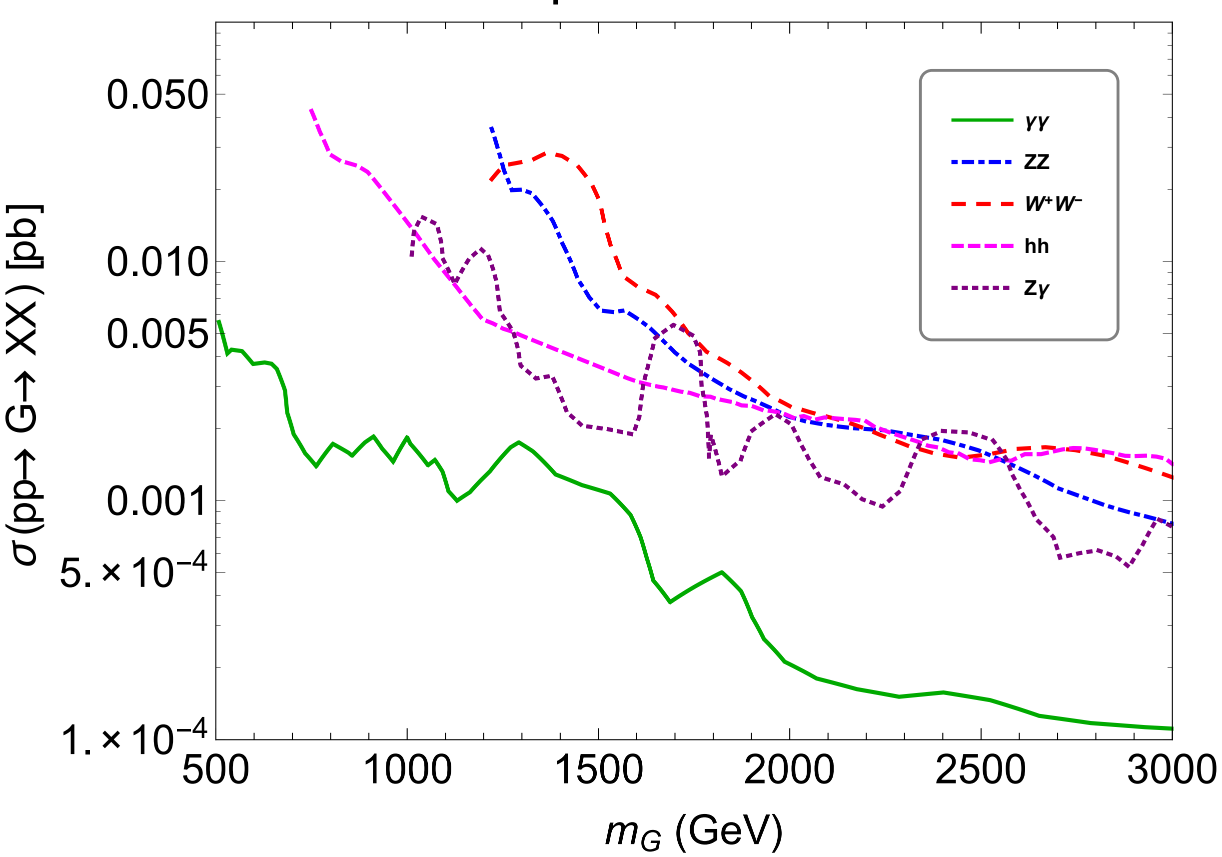
- We can consider gauge bosons, lepton pair and Higgs pair final states at the LHC.

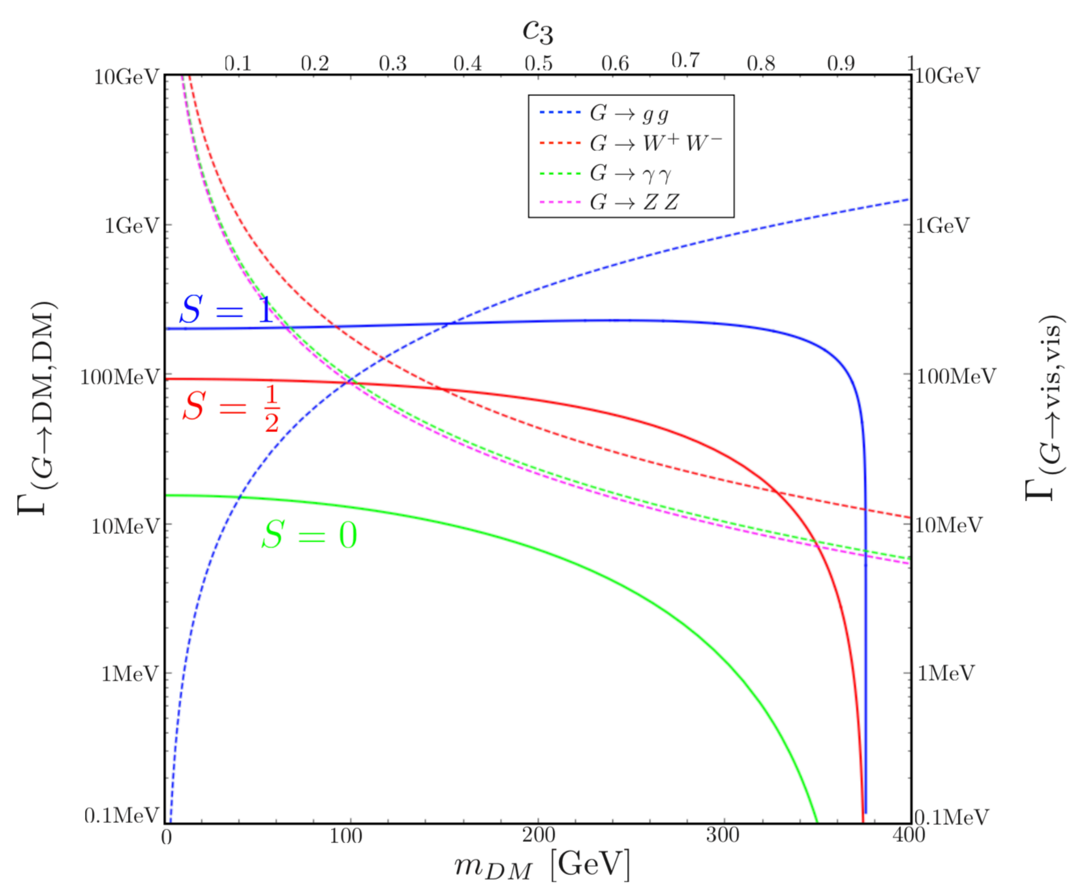
K. Yamashita et al (1807.09643, 1701.07008)
– today's talk

- 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)

Limits on the production cross section

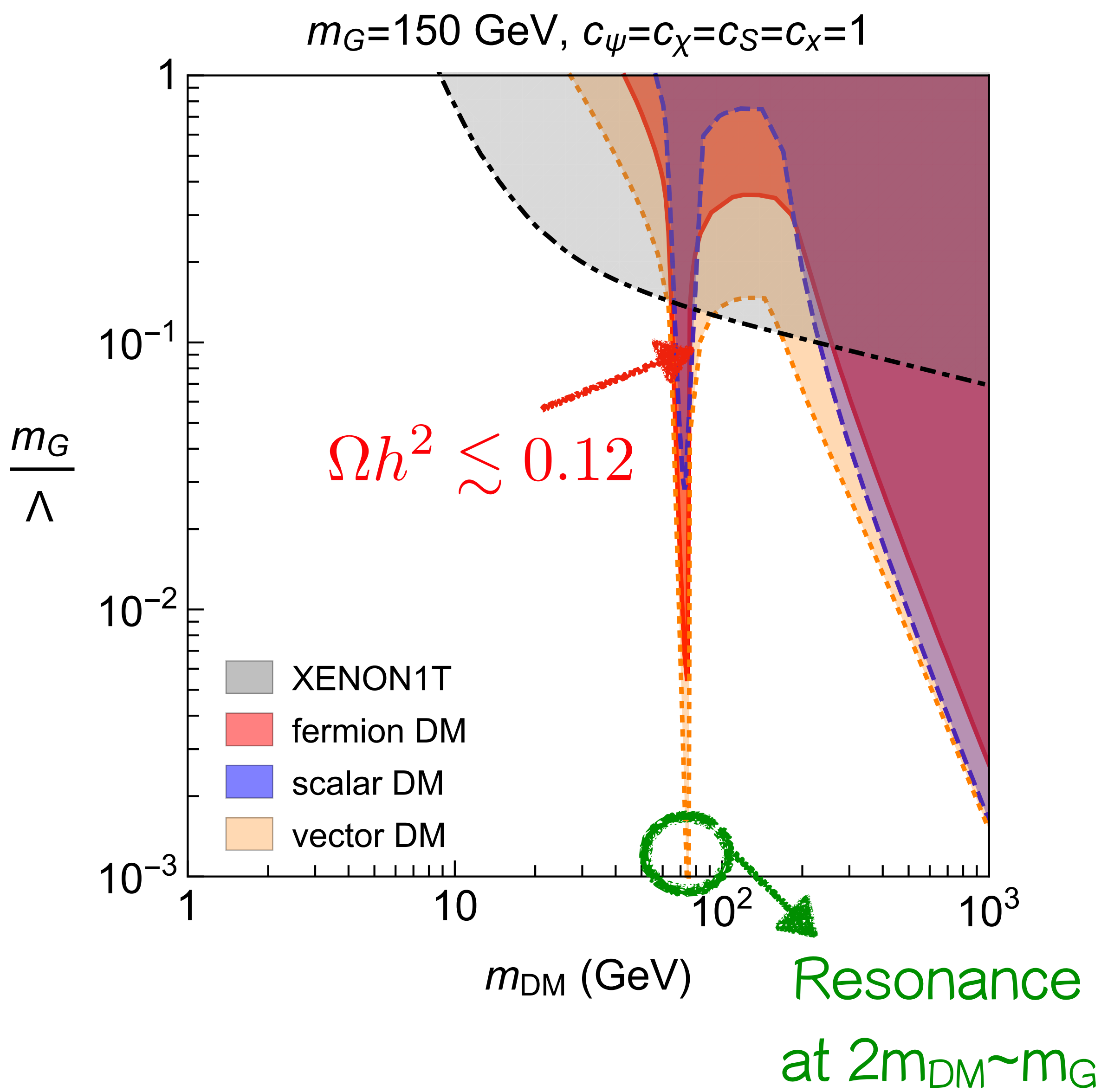


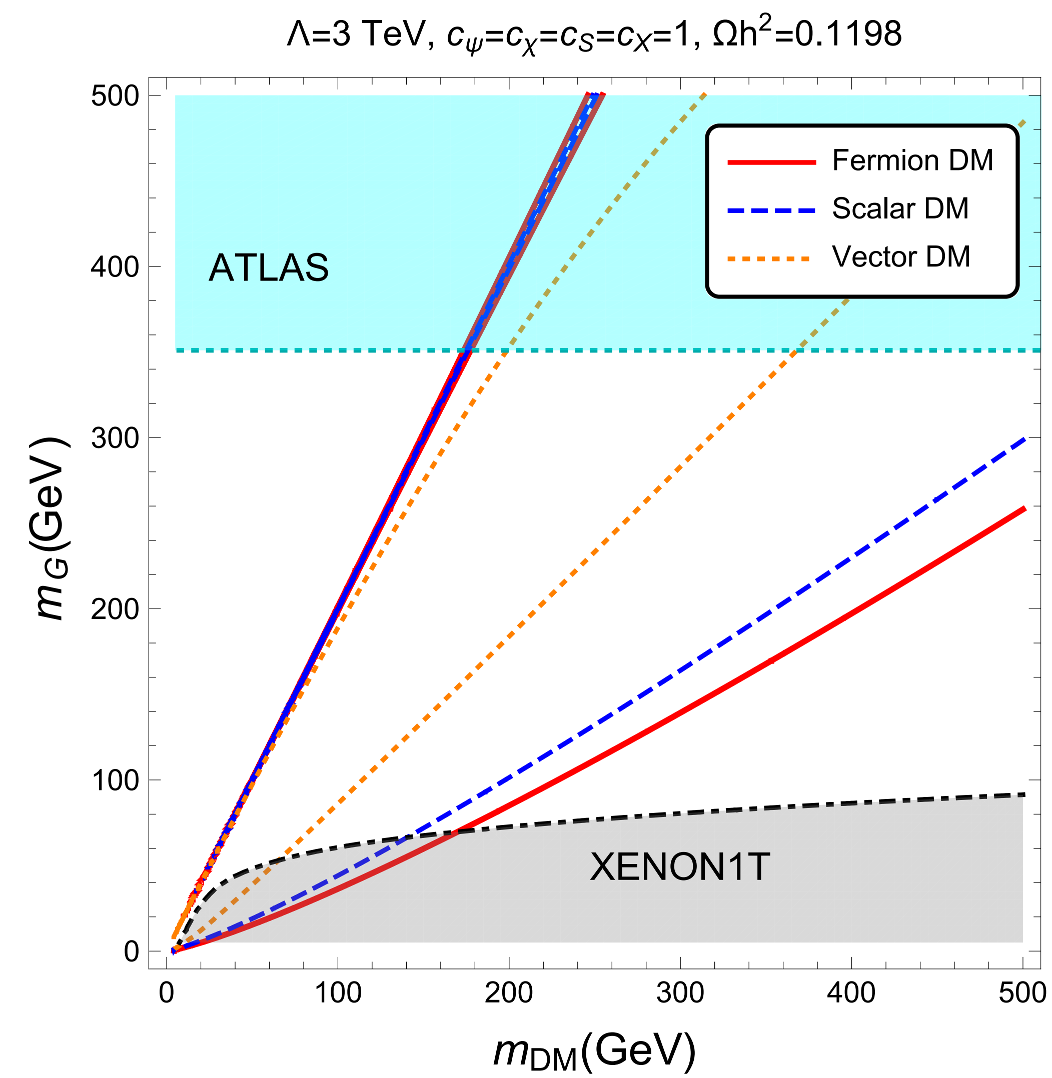


$\gamma\gamma$: CMS 1809.00327 / ZZ : CMS 1803.03838 / WW : CMS 1802.0407 / hh : CMS 1808.01473 / $Z\gamma$: ATLAS 1805.01908

Relic density

- The relic region below m_{DM}=250 GeV is excluded by direct detection, except the resonance region.
- It can be tested at the LHC and direct detection.
- In this result, we consider other couplings except quark to be zero.





Conclusion

- We considered gravity-mediated dark matter model (DM spin-0,1 and 1/2).
- KK graviton can mediate DM annihilation into the SM. ⇒ Indirect detection
- We considered dark matter and nucleon scattering (especially quark) via graviton propagator. ⇒ calculated differential event rate with effective operator ⇒ direct detection
- We showed the relic density of dark matter has enough parameter space consistent with indirect detection, direct detection and LHC dijet searches.
- Future work : KK graviton mediator in general warped backgrounds.