Massive spin-2 mediated dark matter

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Alba Carrillo-Monteverde, **YJK**, Hyun Min Lee,
Myeonghun Park and Veronica Sanz,
JHEP 1806 (2018) 037 (arXiv:1803.02144)

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Outline

I. Dark matter introduction

II. Spin-2 mediator between DM & SM

III. Effective operators for direct detection

IV. Relic density and constraints

V. Conclusion

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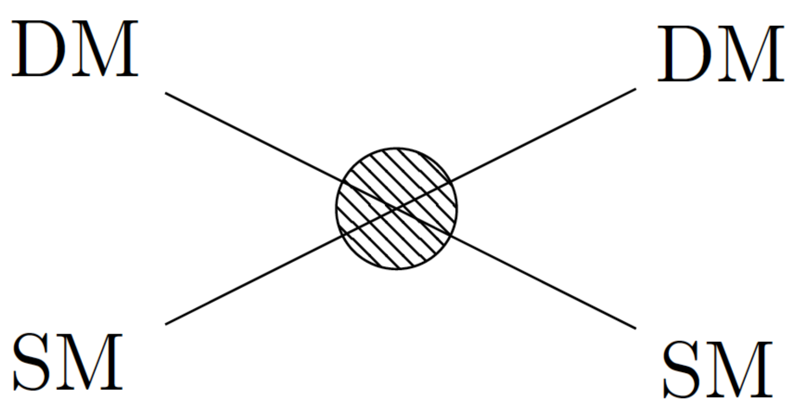
WIMP dark matter



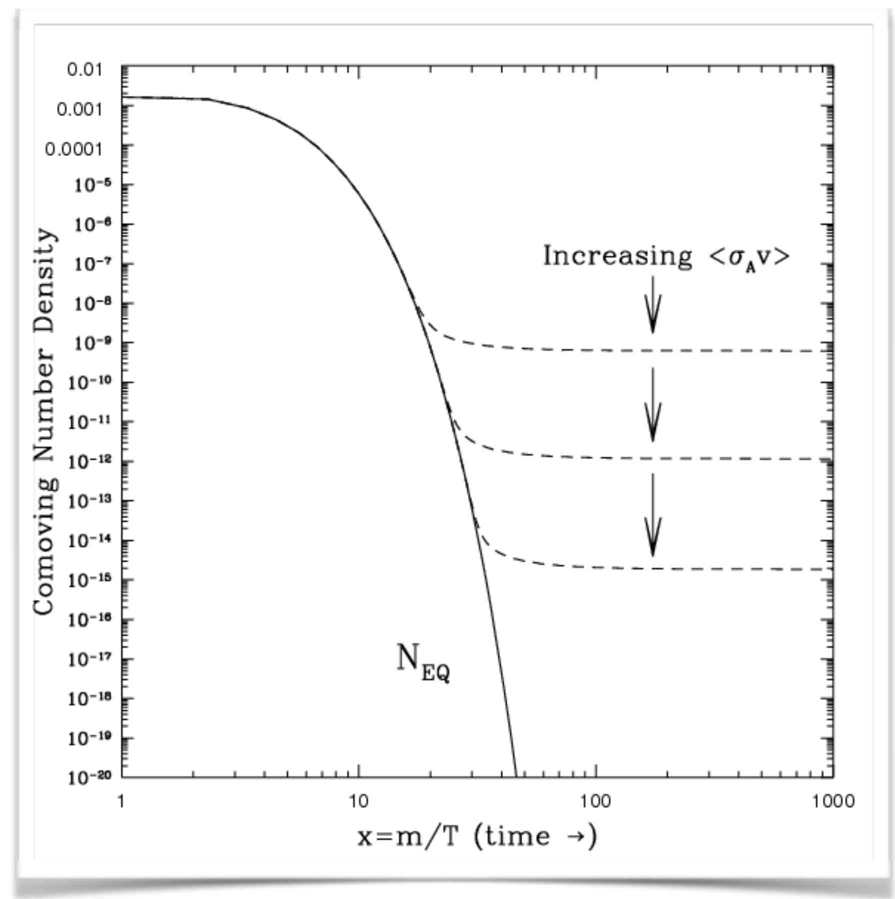
- About 25% of the total energy
- Not standard model particles (WIMP, SIMP, Forbidden DM and so on)

- Thermal WIMP was in the thermal equilibrium with the SM particles
- WIMP had 'freeze-out' from the thermal equilibrium (cf. freeze-in is also 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

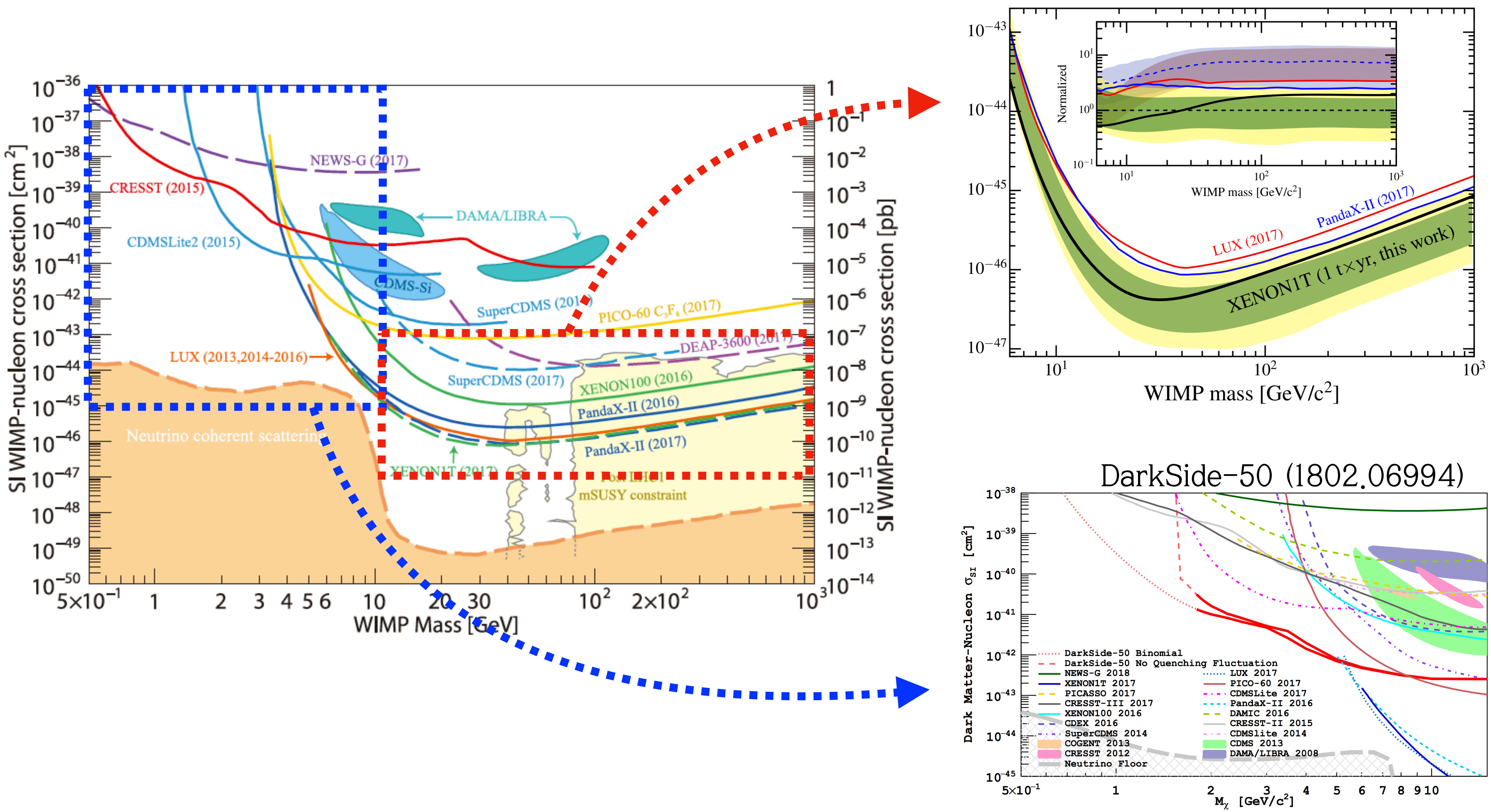
weak scale



- Dark matter search : Direct, Indirect, Collider

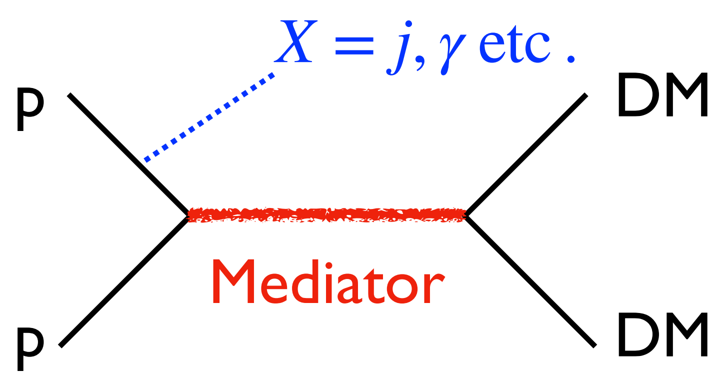
Dark matter search - Direct detection

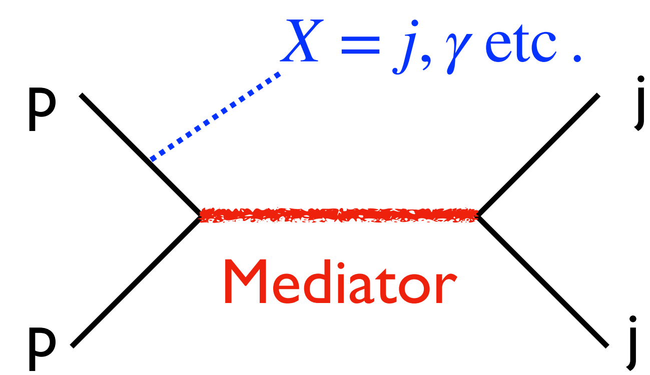
- Direct detection bounds are getting strong. Especially XENON1T updated the strongest bound. Also, light DM area has been covered.



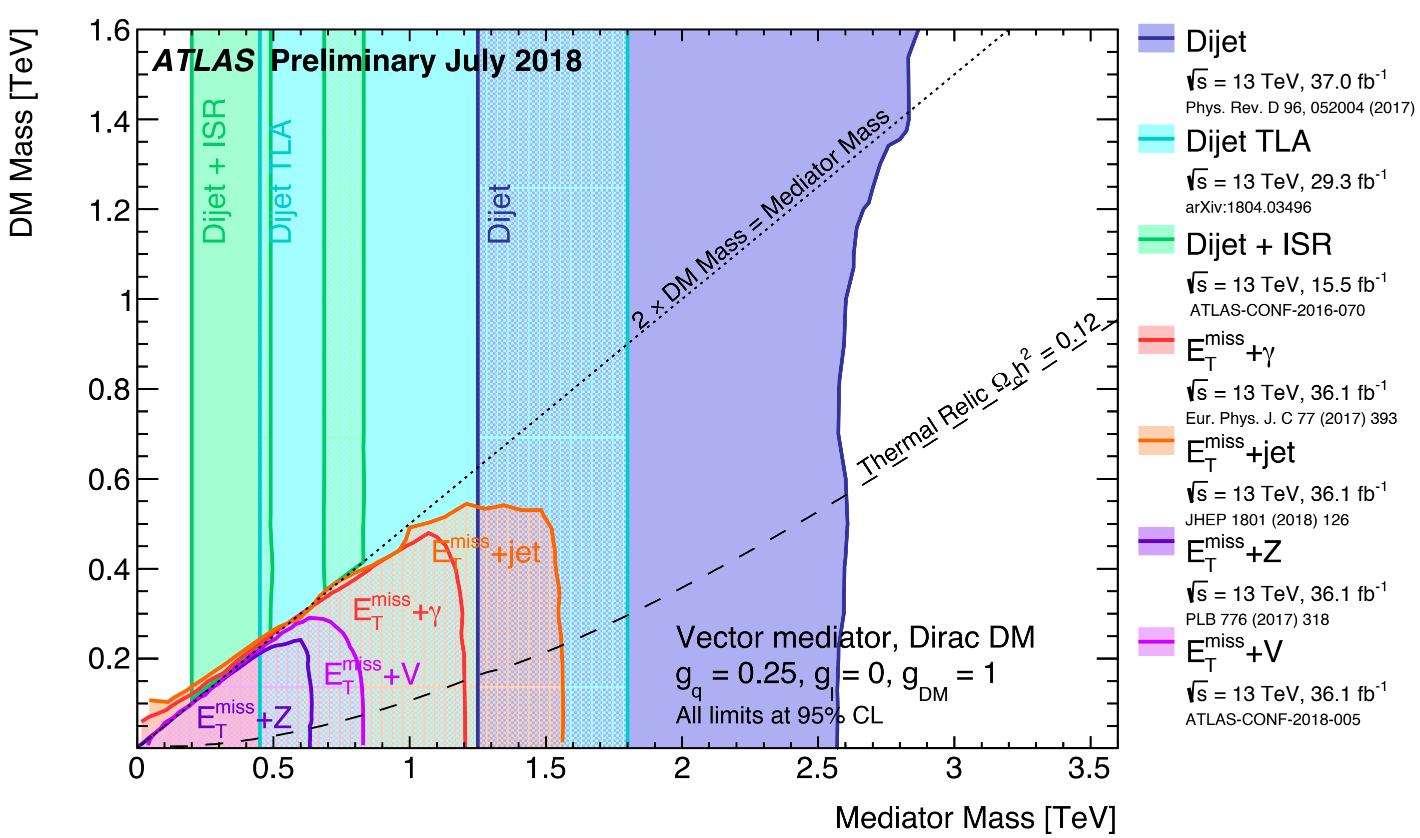
Dark matter search - Collider

- If mediators couple to the DM and SM, it is constrained by collider search in mono-X or dijet search at the LHC -> Mediator models can be measurable!

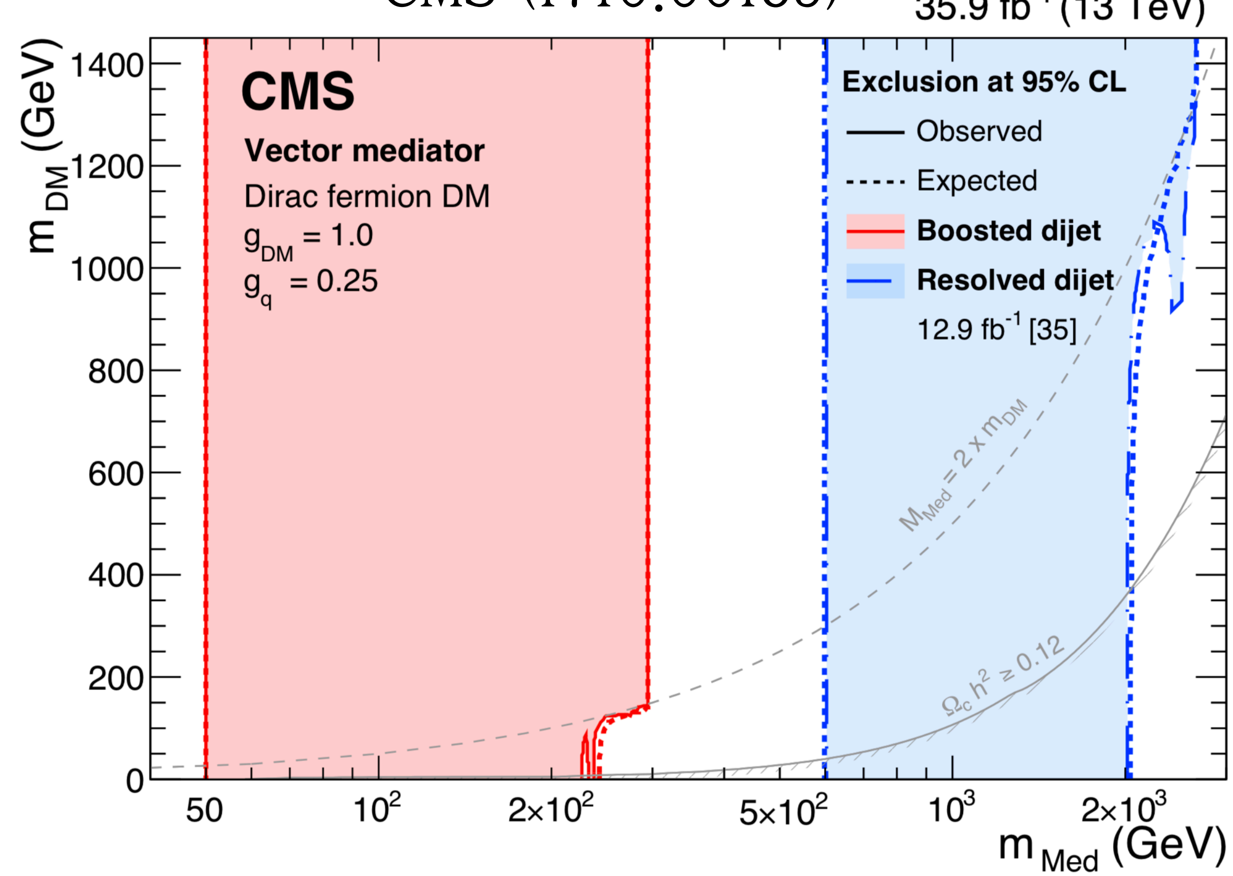




Ex) vector mediator with Dirac fermion DM



CMS (1710.00159)



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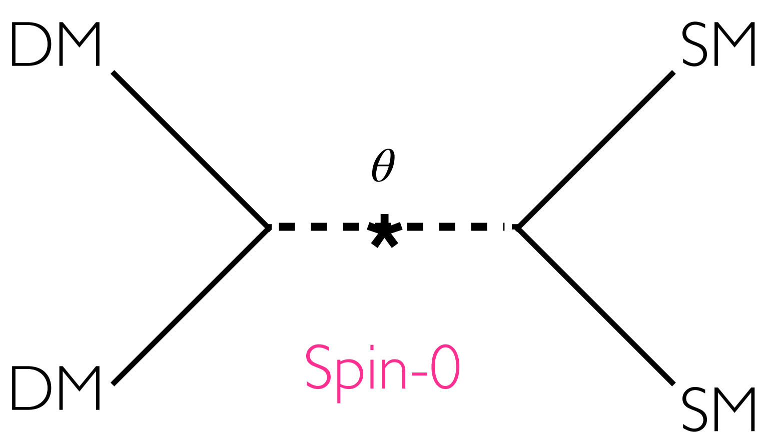
Mediator models - Motivation

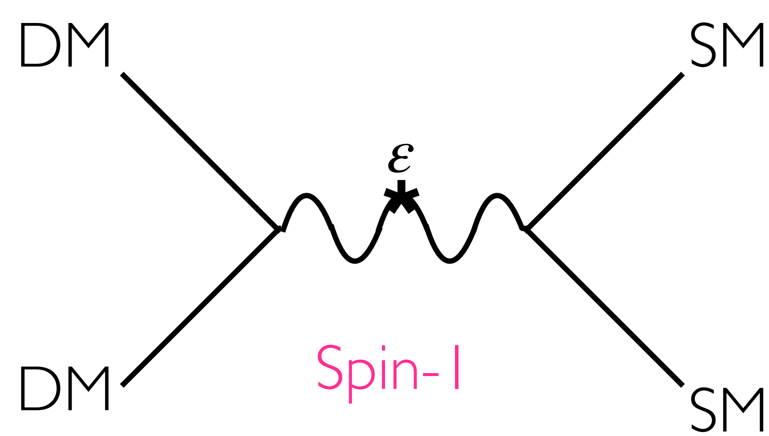
- Mediator models can be measurable at the LHC
- Integrating mediator out leads to the effective operators for direct detection.



Spin-0

Real / Pseudo scalar

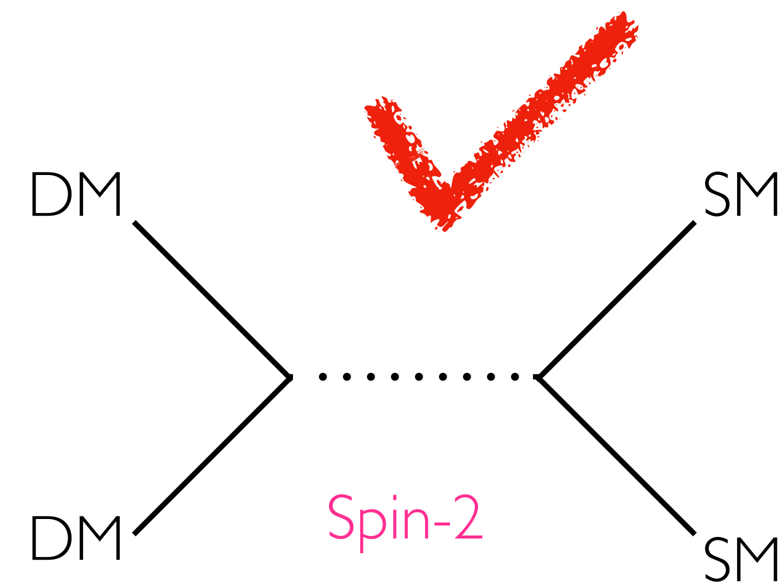
S-M. Choi, YJK, H. M. Lee (1605.04804)



Spin-1

$U(1)_d$ gauge boson

S-M. Choi, YJK, H. M. Lee (1610.04748)



Spin-2

Massive graviton

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

Today's Topic

Spin-2 particle - Motivation

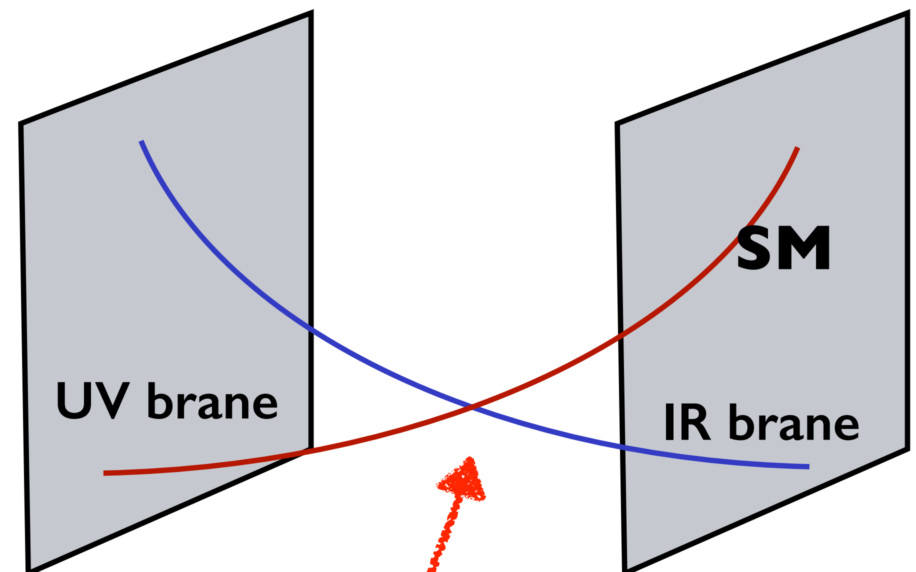
- Spin-2 particle has considered to explain weak gravity naturally.

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.

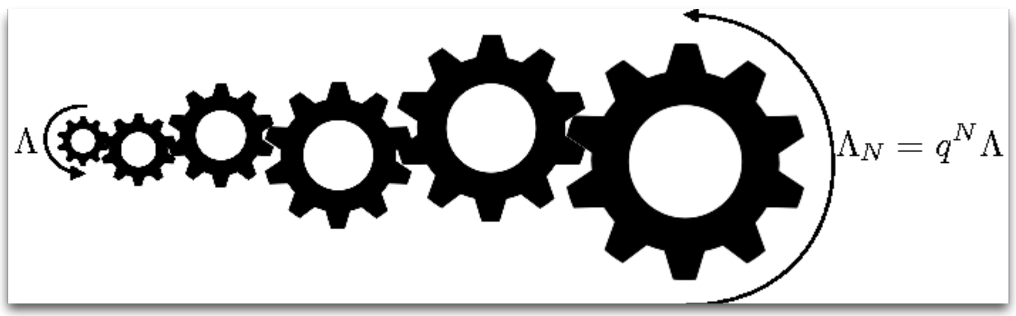
   Kaluza-Klein gravitons can be massive spin-2 messengers.

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

Spin-2 particle - Motivation

- Spin-2 particle has considered to explain weak gravity naturally.

3. Clockwork theory



$$\phi_N = \frac{1}{q}\phi_{N-1} = \cdots \frac{1}{q^N}\phi_0$$: ground state of clock gear

ϕ_i can be graviton to explain weak gravity.

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)

Well motivated!!

Spin-2 mediator model

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

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

where $\mathscr{G}^{\mu\nu}$: massive spin-2 mediator, $T_{\mu\nu}$: energy-momentum tensor

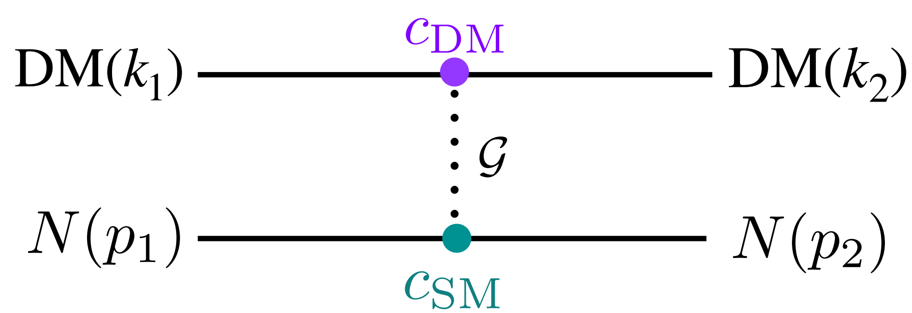
Dark matter can be spin-0, 1 and 1/2

In this work, we considered only quark coupling among the SM particles

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

Spin-2 mediator model

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



$$\mathcal{M} = -\frac{c_{\rm DM}c_{\rm SM}}{\Lambda^2}\frac{i}{q^2 - m_G^2}T^{\rm DM}_{\mu\nu}(q)\mathcal{P}^{\mu\nu,\alpha\beta}(q)T^{\rm SM}_{\alpha\beta}(-q) \qquad q = k_2 - k_1 = p_1 - p_2$$

where $\mathcal{P}^{\mu\nu,\alpha\beta}$: massive spin-2 propagator

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

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

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

Spin-2 mediator model

- When the mediator is integrated out, the amplitude is consisted of trace part and traceless part of the energy momentum tensor

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

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

if fermionic DM

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

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

We consider spin-0,1 and 1/2 types of dark matter

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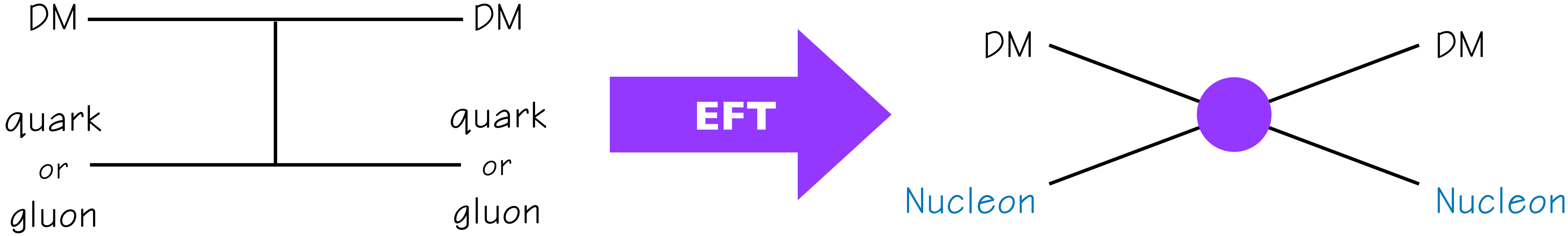
Effective field theory approaches

- EFT approaches are suitable with scattering processes b/w DM and nucleons.



- The scattering at experiments depends on the detector material.

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

form factors are related to nucleon responses

And the form factors for the basic response depending on each detector are provided in the reference such as F, Na, Ge, Xe

Fitzpatrick et al (1203.3542, 1308.6288)

Effective operators

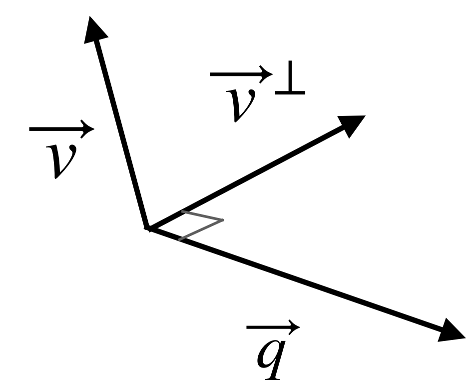
- Consider the elastic scattering of dark matter and nucleon.
- The interaction Lagrangian can be written by effective operators

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

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

- 4 basic Hermitian quantities

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



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

Fitzpatrick et al (1203.3542, 1308.6288)

Effective operators

Interactions involving spin-0 or 1 mediator

LO → $\mathcal{O}_1 = 1_\chi 1_N$

$\mathcal{O}_2 = (v^\perp)^2$

$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$

LO → $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$

$\mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$

NLO { $\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$, $\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$

Other interactions not involving spin-0 or 1 mediator

NLO → $\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$

$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$

$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$

$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N})$

$\mathcal{O}_{16} = -((\vec{S}_\chi \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N}).$

↓

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

Fitzpatrick et al (1203.3542, 1308.6288)

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

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

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

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

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

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

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

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

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

second moments of PDF

$\mu \approx m_Z$, 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 in spin-2 med. model

- Dimension 8 operators emerge because of the spin-2 mediator.

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

Effective operators in spin-2 med. model

- Leading terms are independent of DM spins.

- Fermion DM

Unsupressed operator for DM-nucleon scattering

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

- Scalar DM

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

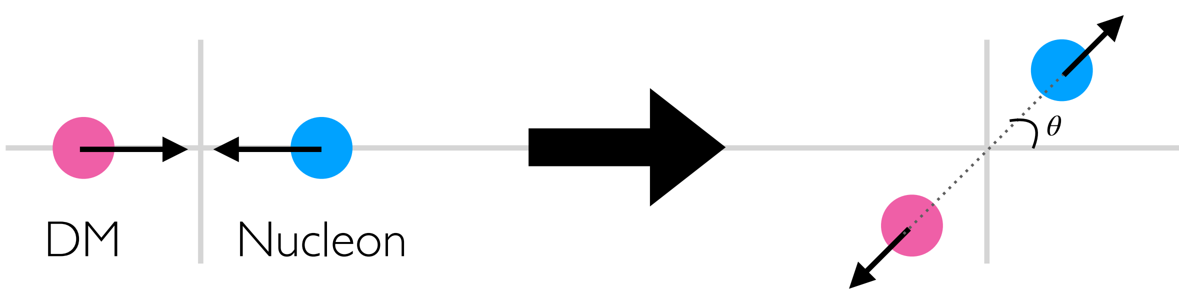
Dimension : $\int \frac{d^3p}{(2\pi)^3\sqrt{2E}}a_N^{(\dagger)}$ and $\int \frac{d^3p}{(2\pi)^3\sqrt{2E}}a_\chi^{(\dagger)}$ per each nucleon & DM state are to be multiplied.

Effective operators and direct detection

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, where m_T : target mass



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

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

with scattering cross section depending on the detector material.

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

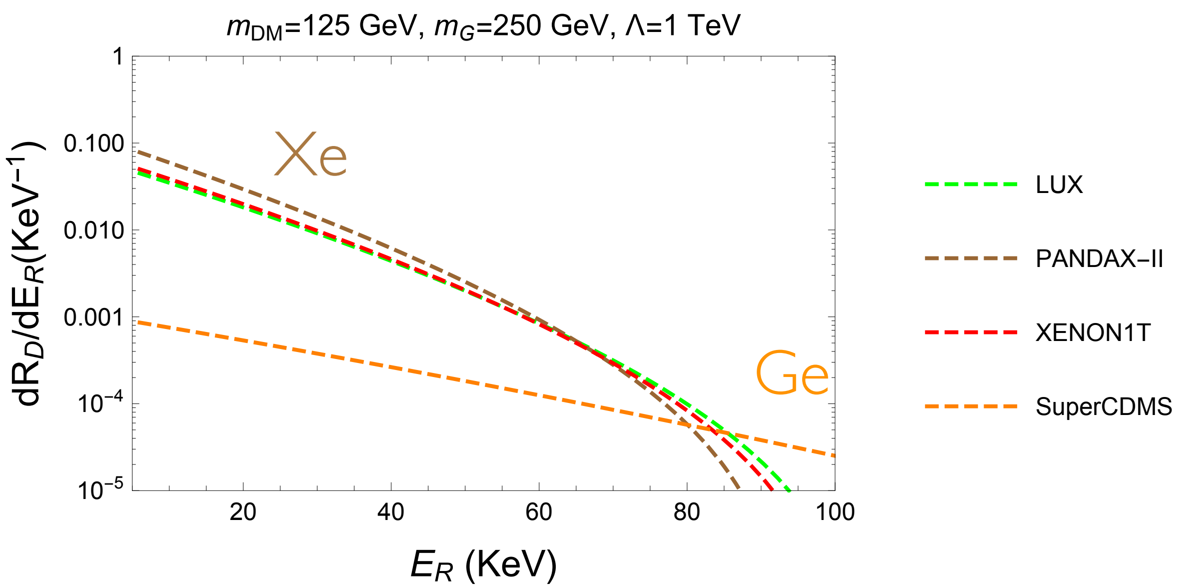
form factors are related to nucleon responses

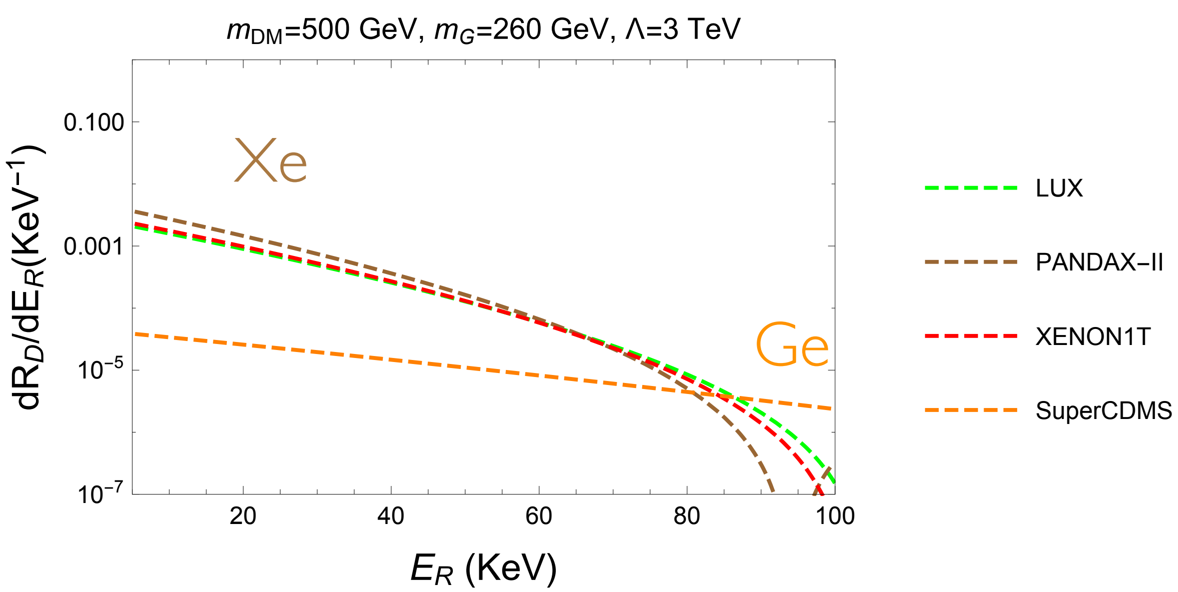
Differential Event Rate

- We can calculate the recoil energy spectrum.

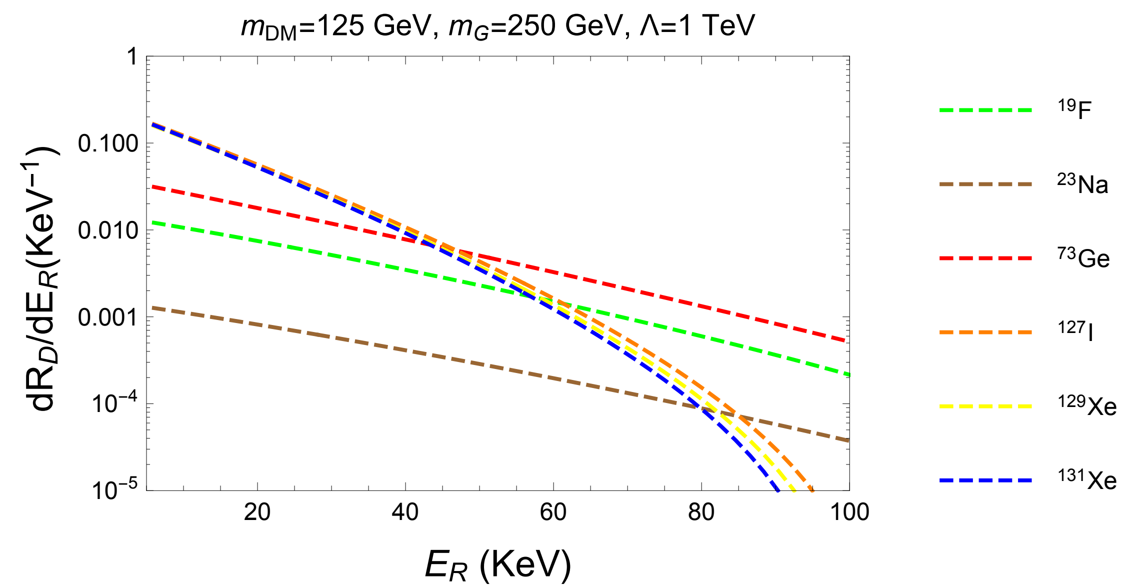
$$\frac{dR_D}{dE_R} \propto \frac{d\sigma}{d\cos\theta} \propto \sum_{i,j} \sum_{N,N'=n,p} c_i^{(N)} c_i^{(N')} F_{ij}^{(N,N')}$$

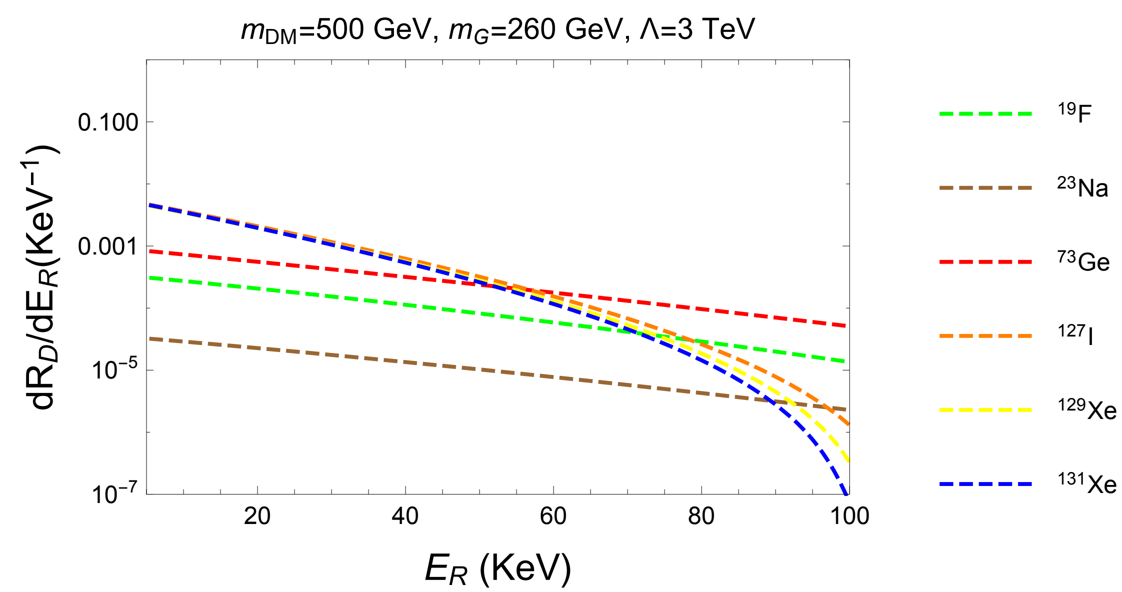
Current Exp.





Mock Exp.





by dmformfactor mathematica package Fitzpatrick et al (1308.6288)

Outline

I. Dark matter introduction

II. Spin-2 mediator between DM & SM

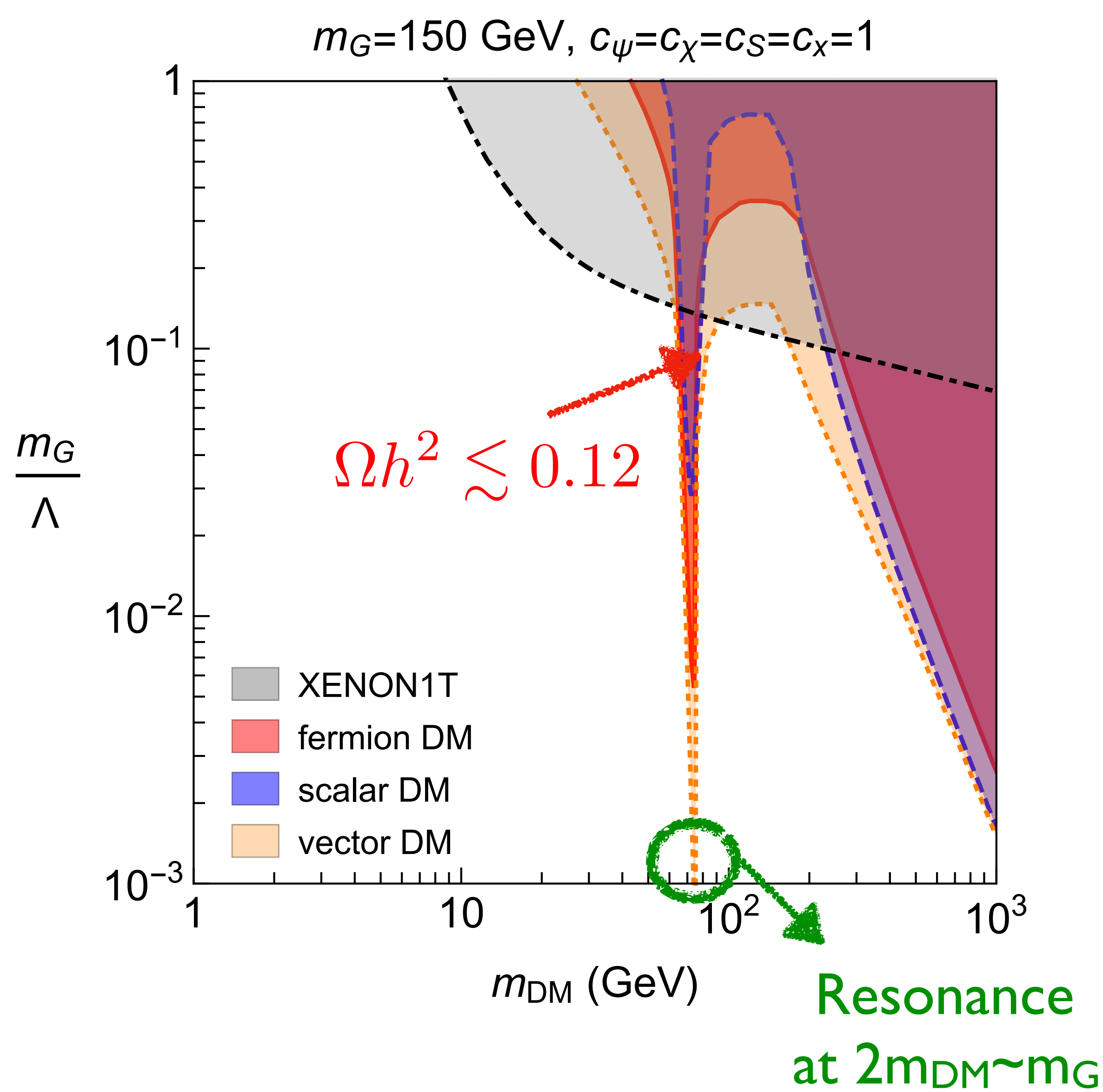
III. Effective operators for direct detection

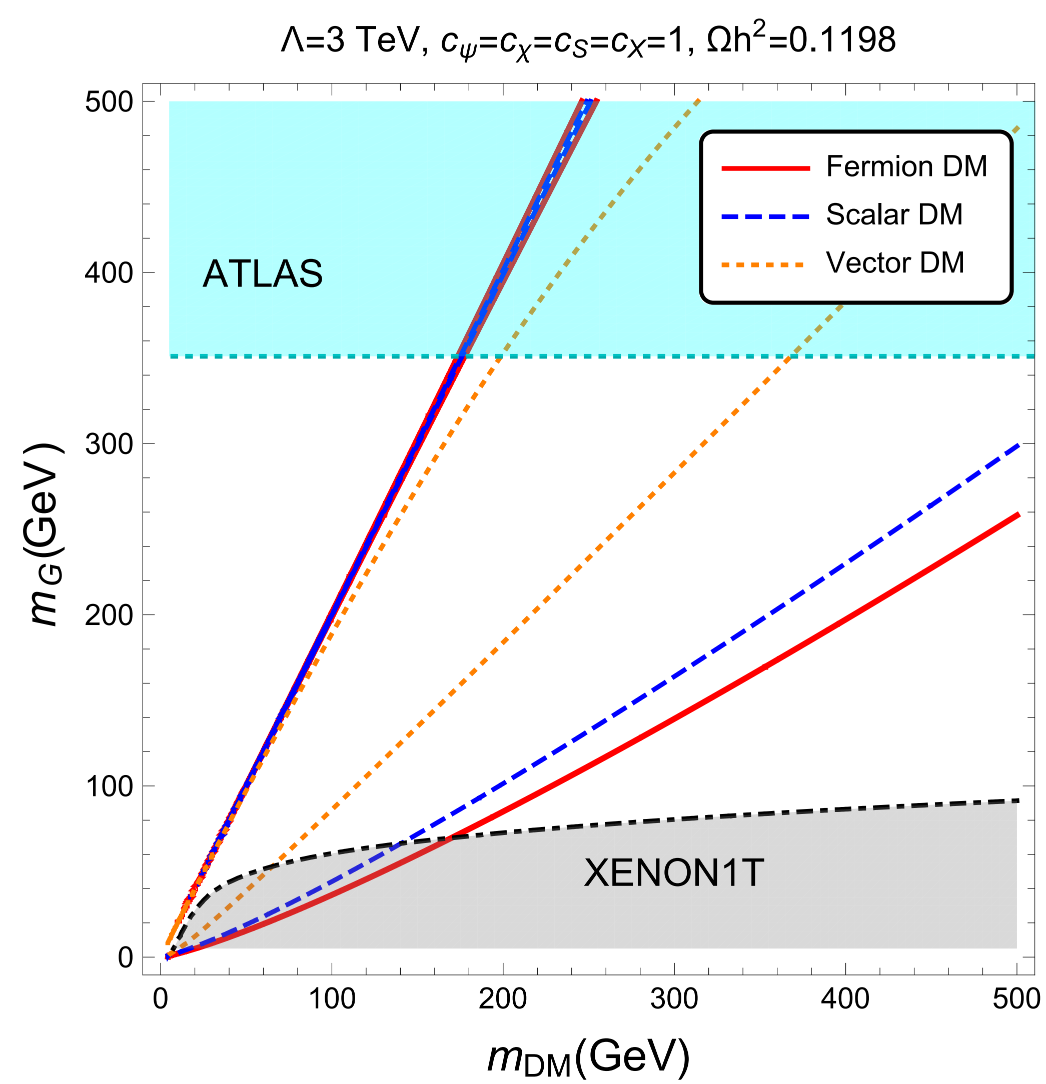
IV. Relic density and constraints

V. Conclusion

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.
- If we consider gluon coupling, relic density lines will be lower.





Constraints - direct detection

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

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

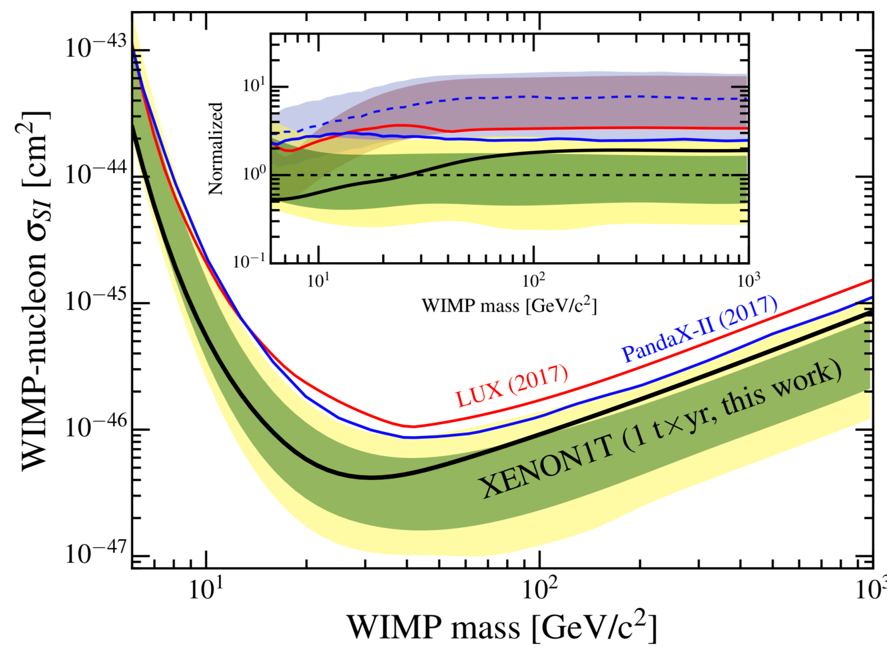
Due to trace part of the $T_{\mu\nu}$

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

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

It's constrained by XENON1T

XENON1T (1805.12562)



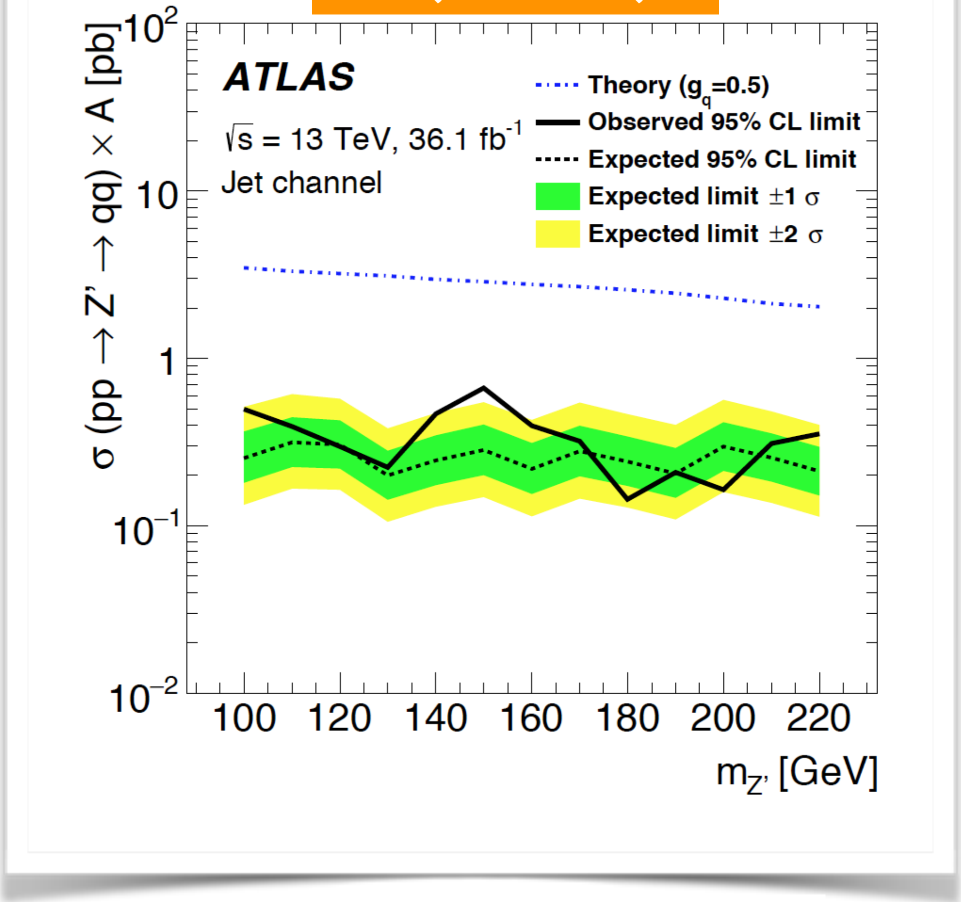
c.f.-scalar med. (Higgs portal) $f^{\rm DM}_{p,n} = m_N\left(\sum_{\psi=u,d,s} f^{p,n}_{T\psi}\frac{\mathcal{M}_\psi}{m_\psi} + \frac{2}{27} f^{p,n}_H \sum_{\psi=c,b,t}\frac{\mathcal{M}_\psi}{m_\psi}\right)$ Y. Mambrini (1108.0671)

Constraints - Collider search

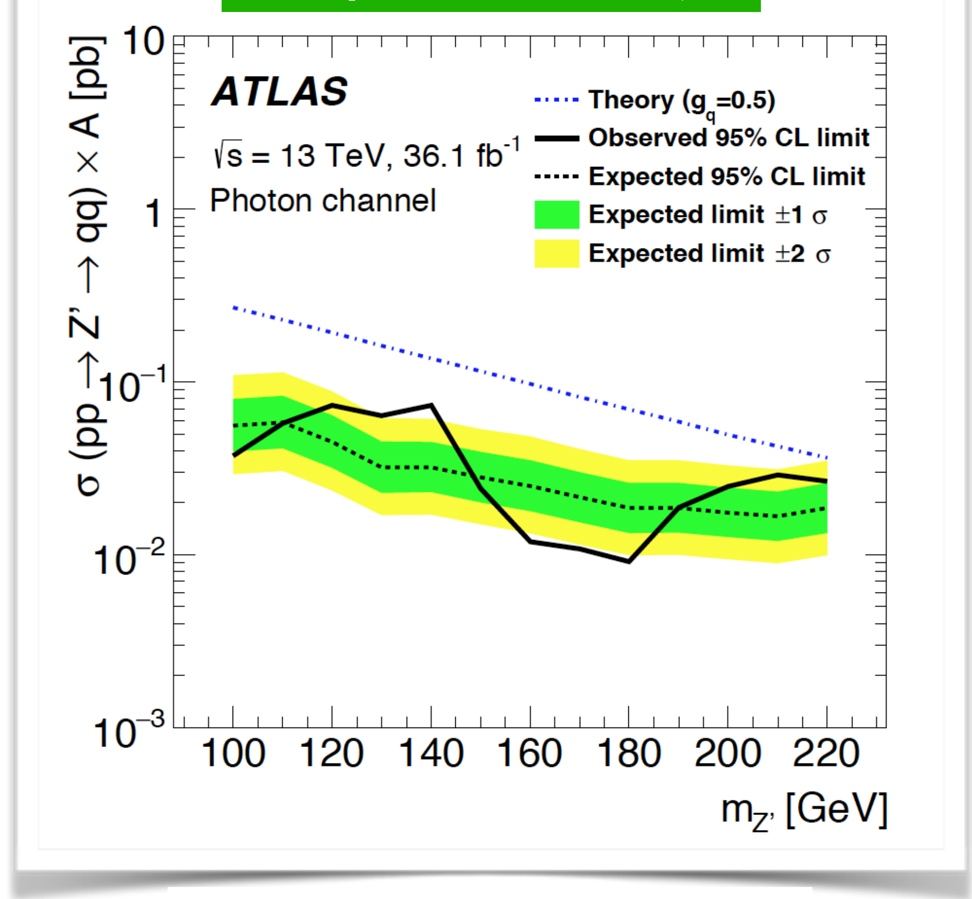
- There are ATLAS dijet constrains to $BR(G \to q\bar{q})$.

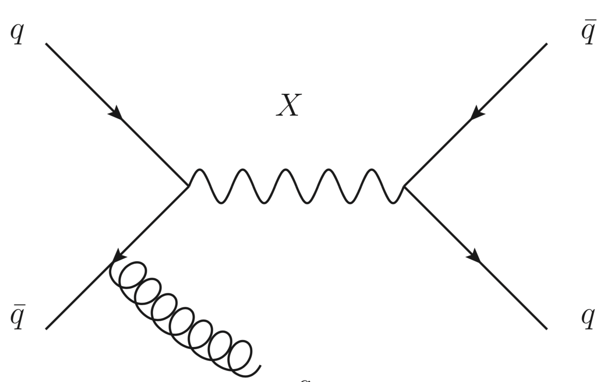
For 100 GeV~ mediator.

ISR jet + dijet

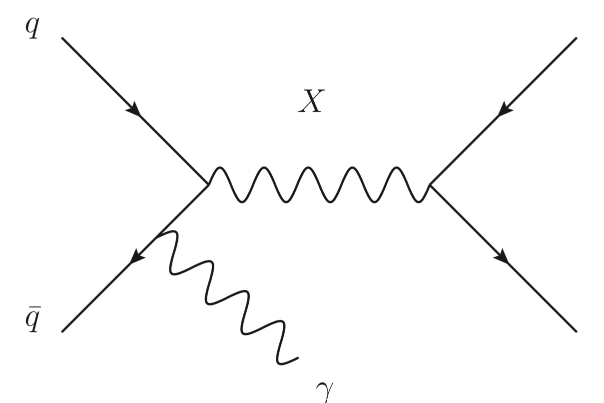


ISR photon + dijet





ATLAS (1801.08769)



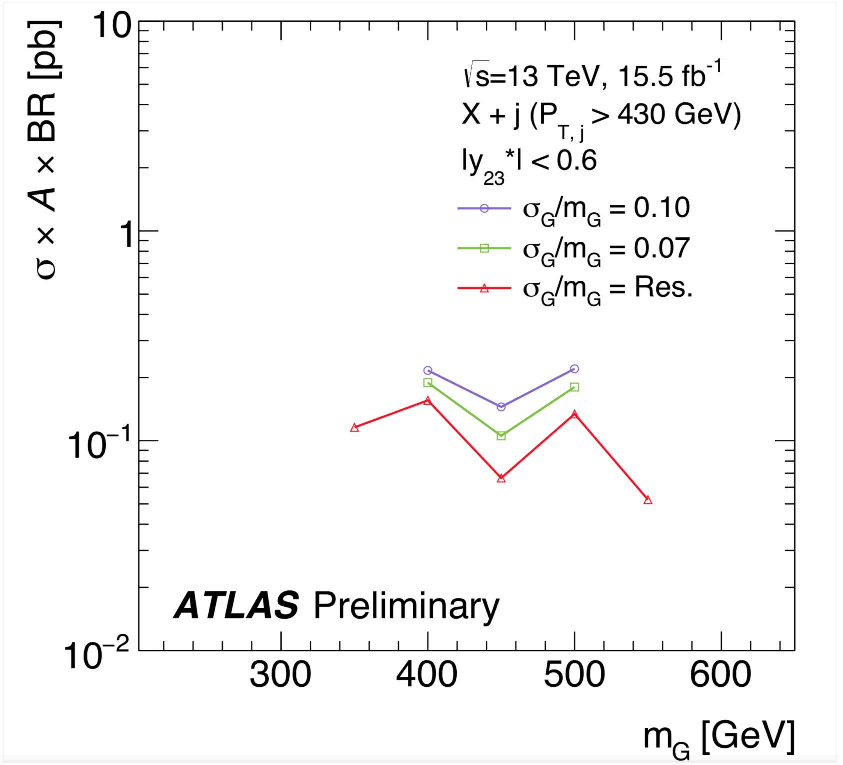
Constraints - Collider search

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

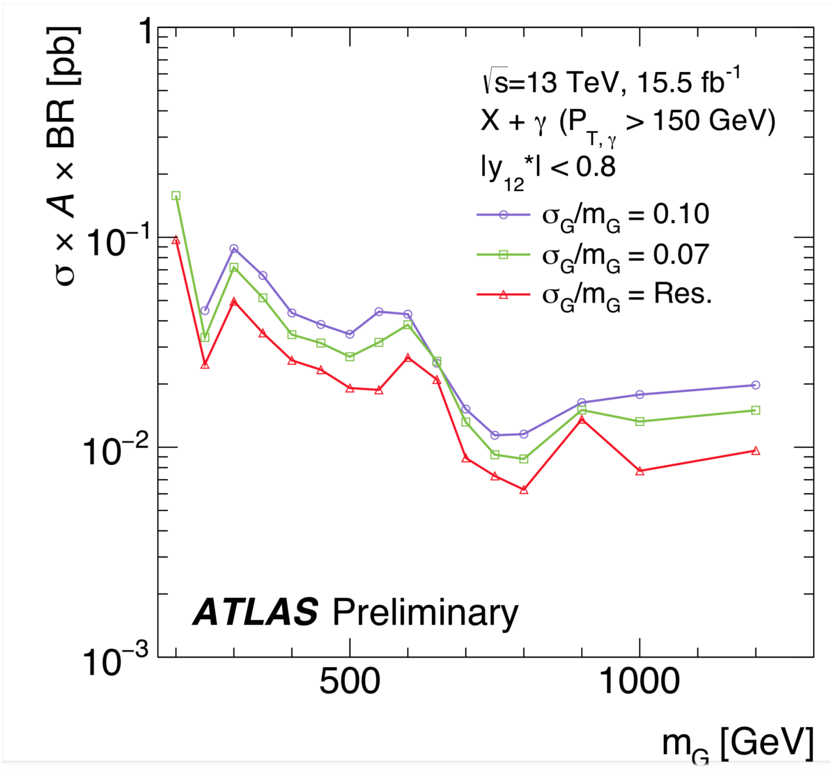
For 300 GeV~ mediator.

For 500 GeV~ mediator.

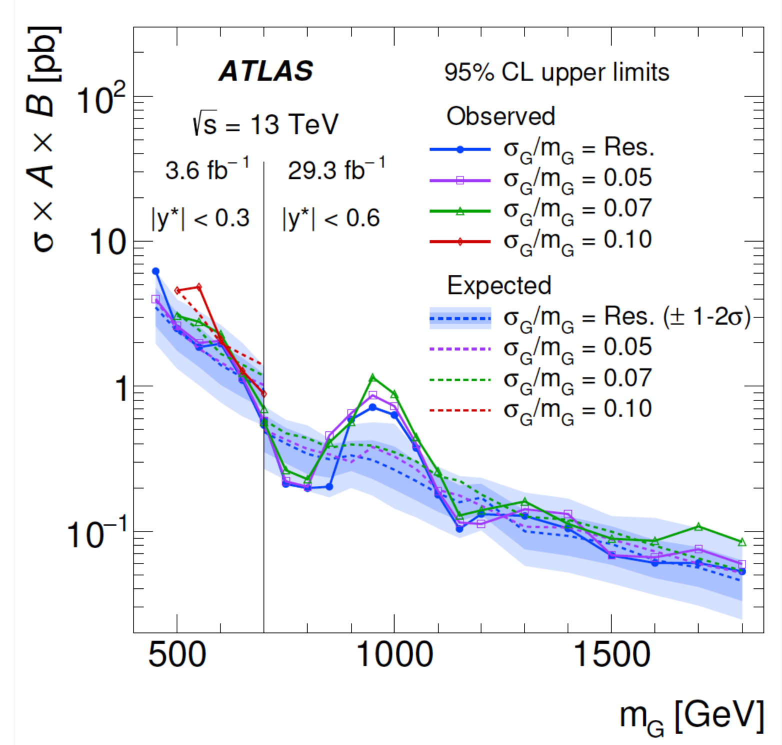
ISR jet + dijet



ISR photon + dijet



dijet resonance



ATLAS-CONF-2016-070

ATLAS (1804.03496)

Constraints - Collider search

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

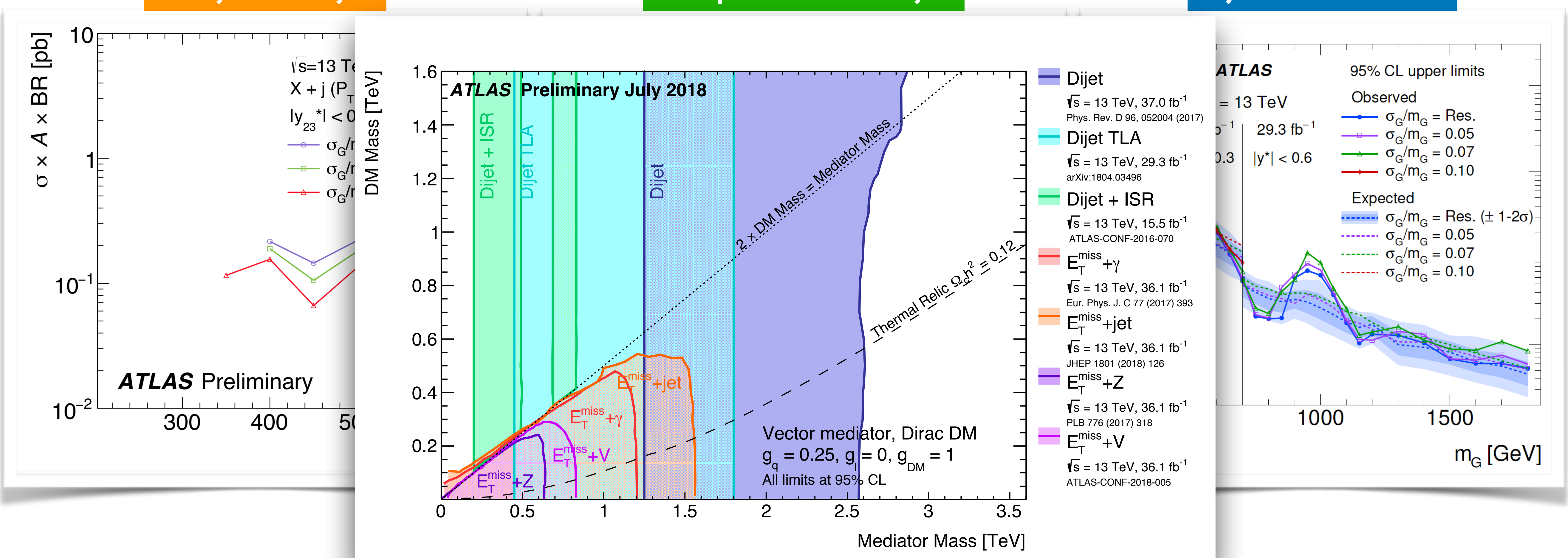
For 300 GeV~ mediator.

For 500 GeV~ mediator.

ISR jet + dijet

ISR photon + dijet

dijet resonance



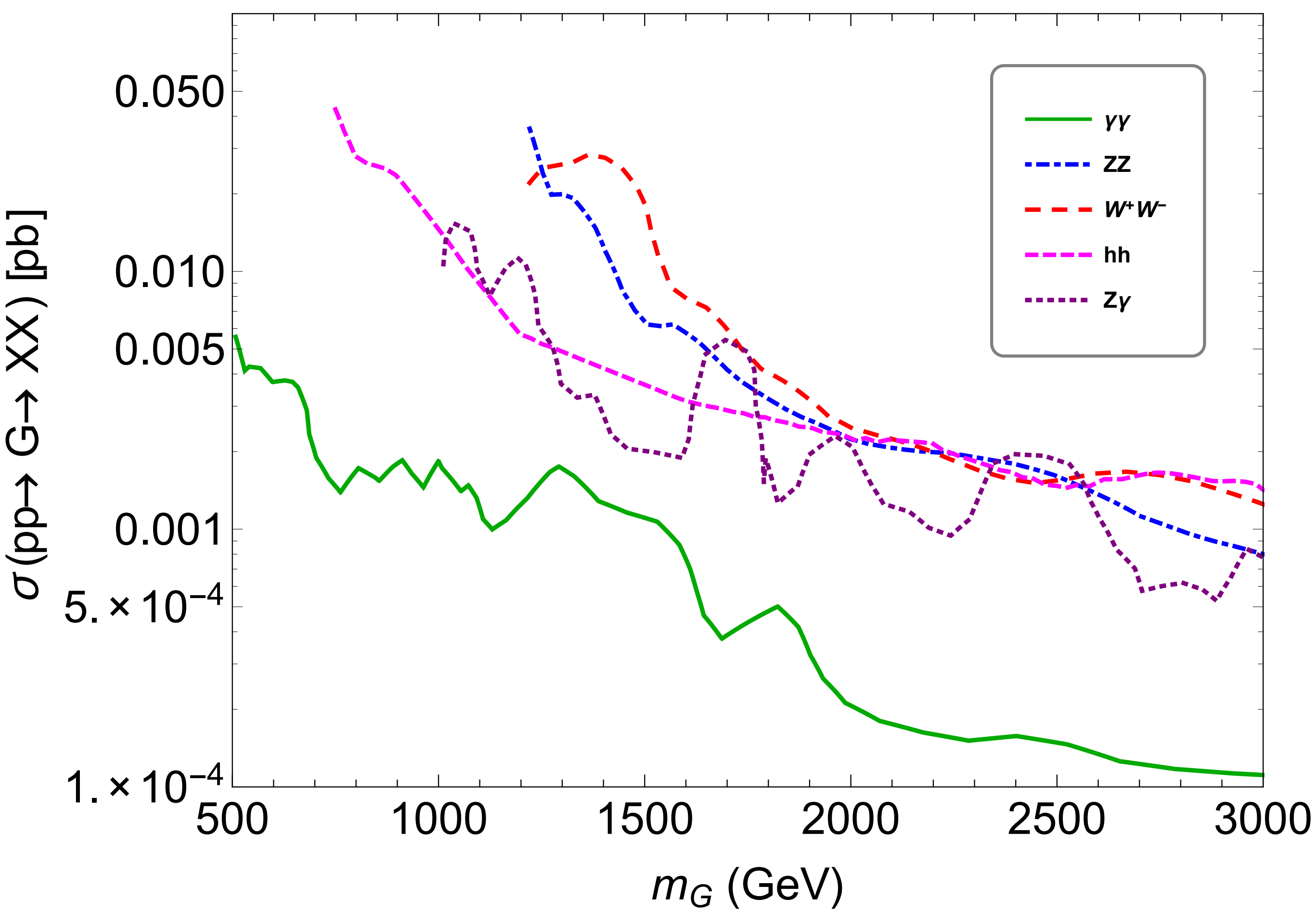
ATLAS-CONF-2016-070

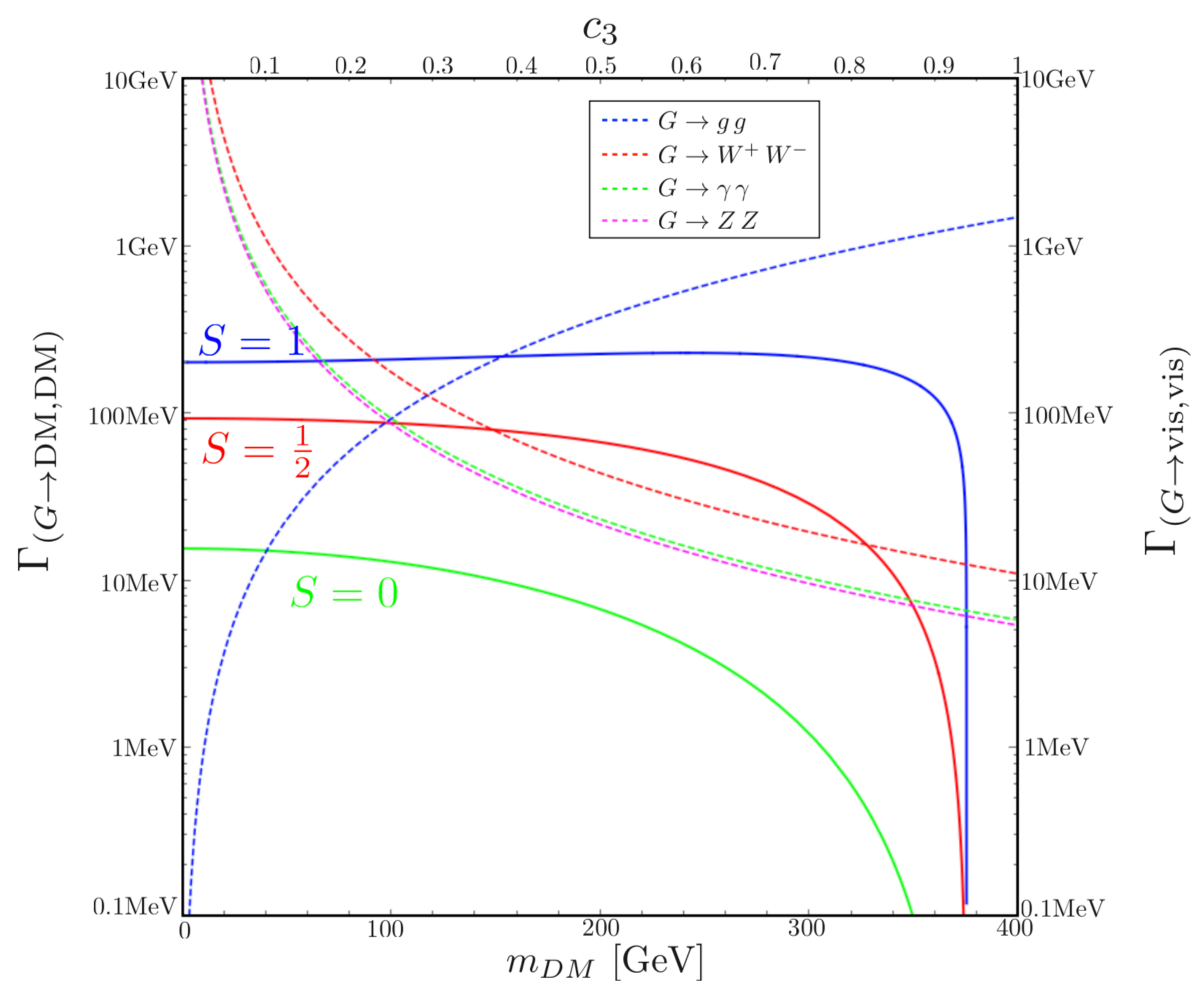
ATLAS (1804.03496)

Collider searches for other couplings

- If spin-2 particle couples to gauge bosons and Higgs, we can consider gauge bosons or Higgs pair final states at the LHC.
- In this case, these couplings would affect the DM phenomenology as well as the LHC searches. B. M. Dillon, C. Han, H. M. Lee and M. Park (1606.07171)

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

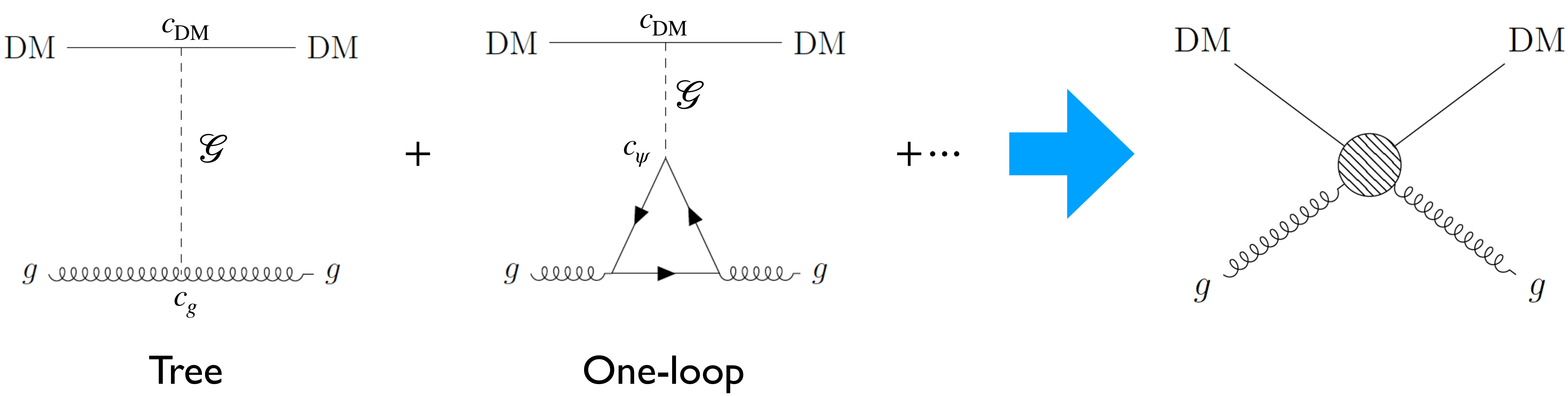
C. Han, H. M. Lee, M. Park and V. Sanz (1512.06376)

V. Conclusion

- We consider the spin-2 mediator model between DM (spin-0,1 and 1/2) and SM quarks. -> **Measurable at LHC**
- The mediator which is integrated out induces effective operator. **Valid from Collider search / DM annihilation to direct detection**
- We show the differential event rate for direct detection experiments.
- DM relic density condition is constrained by **direct detection** and **LHC dijet searches**.
- **We can expect searching for spin-2 particle** as a mediator between DM and SM in dijet search or other gauge boson and Higgs pair searches at collider.
- Direct detection with gluon coupling is work in progress -> only Twist-2 operator in tree-level.

Back up

Gluon contribution



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

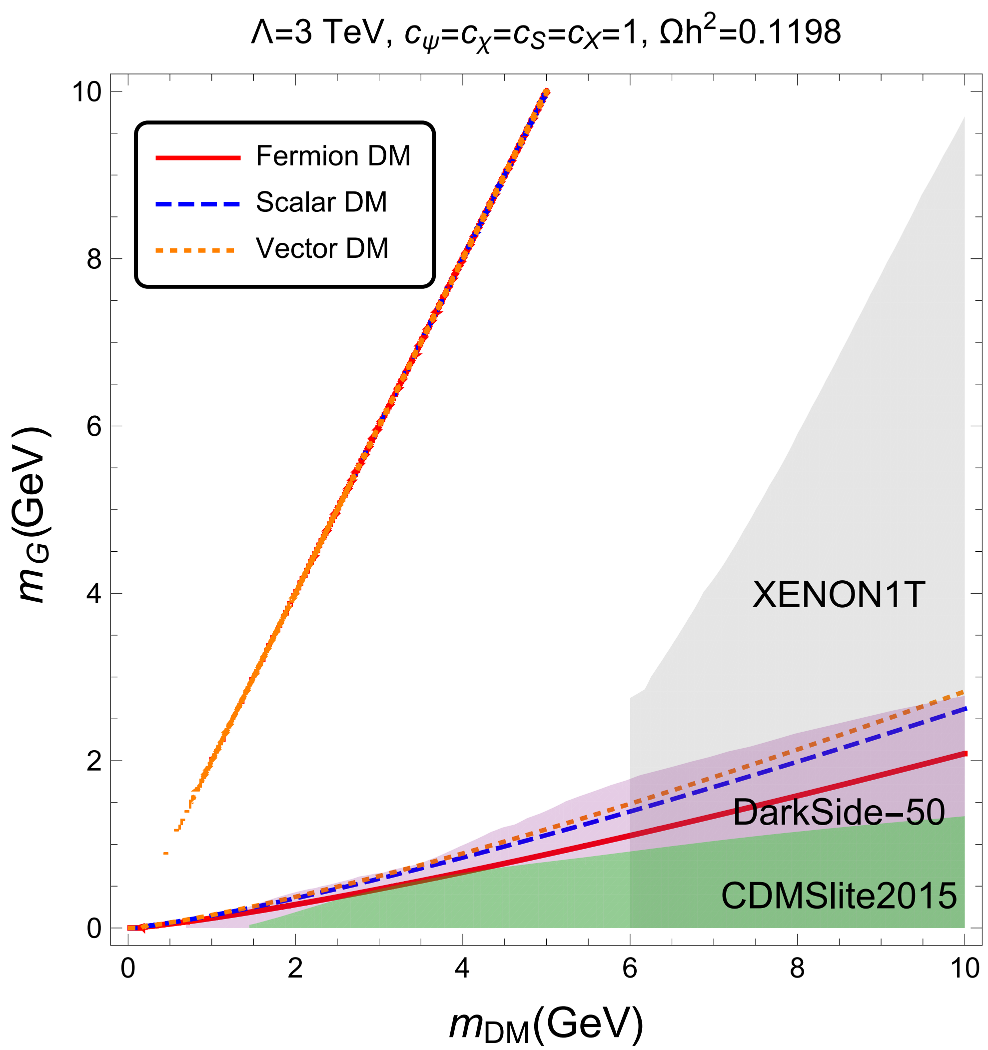
Trace-free part : $\langle N(p) | \tilde{T}^g_{\mu\nu} | N(p) \rangle = \frac{1}{m_N}\left(p_\mu p_\nu - \frac{1}{4} m_N^2 g_{\mu\nu}\right) G(2) \bar{u}_N(p) u_N(p),$ $\quad G(2) = \int_0^1 dx\ xg(x)$

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

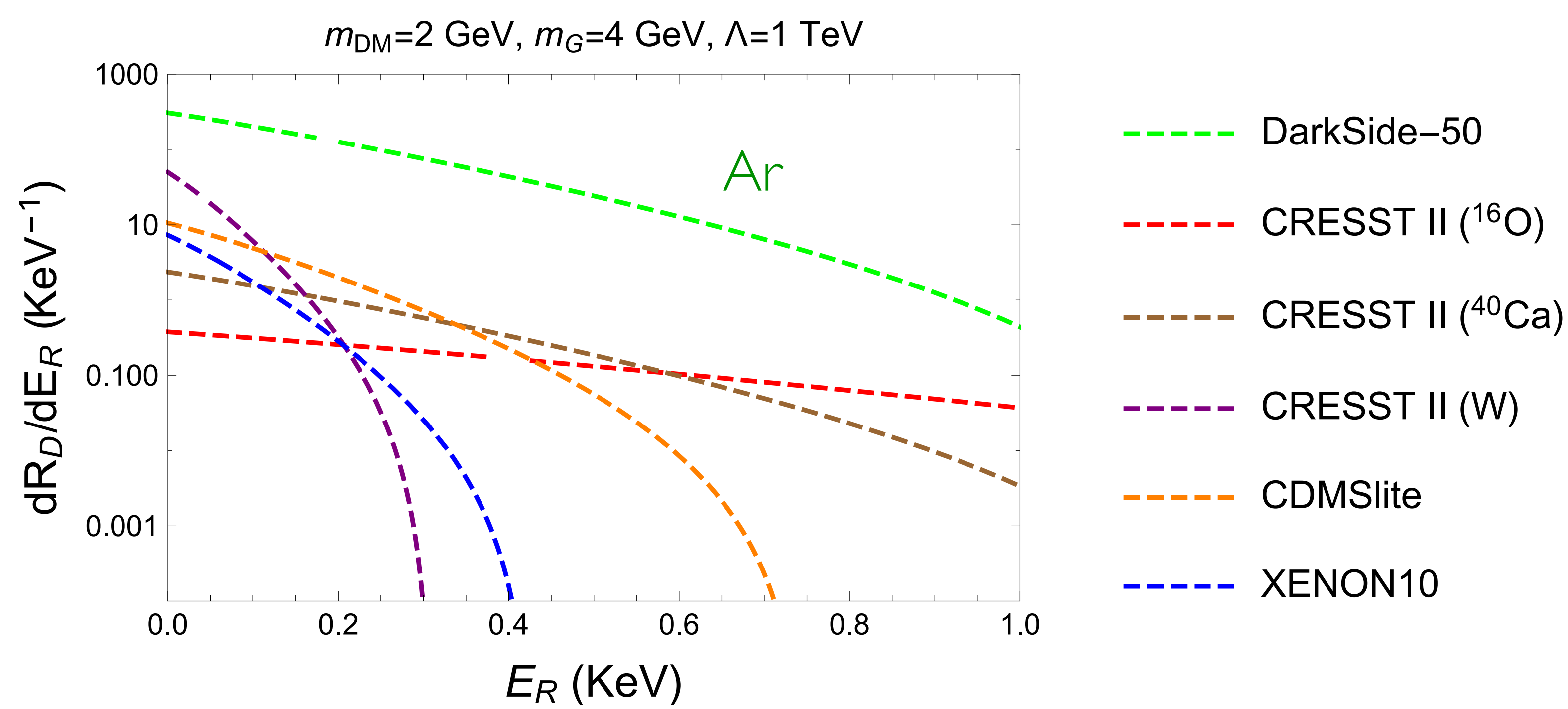
Tree-level has only trace-free part -> twist-2 operator ➡ $T^g_{\mu\nu} = \tilde{T}^g_{\mu\nu} = -G_{\mu\rho}G_\nu^{\ \rho} + \frac{1}{4}\eta_{\mu\nu}G_{\rho\sigma}G^{\rho\sigma}$

Light DM case $m_{\mathrm{DM}} \lesssim 10\ \mathrm{GeV}$

- 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

DM annihilation cross section

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

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

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

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

$$r_\chi=\left(\frac{m_G}{m_\chi}\right)^2$$

$S_{\rm DM}=0$

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

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

$$r_S=\left(\frac{m_G}{m_S}\right)^2$$

$S_{\rm DM}=1$

s-wave ⟶ constrained by indirect detection

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

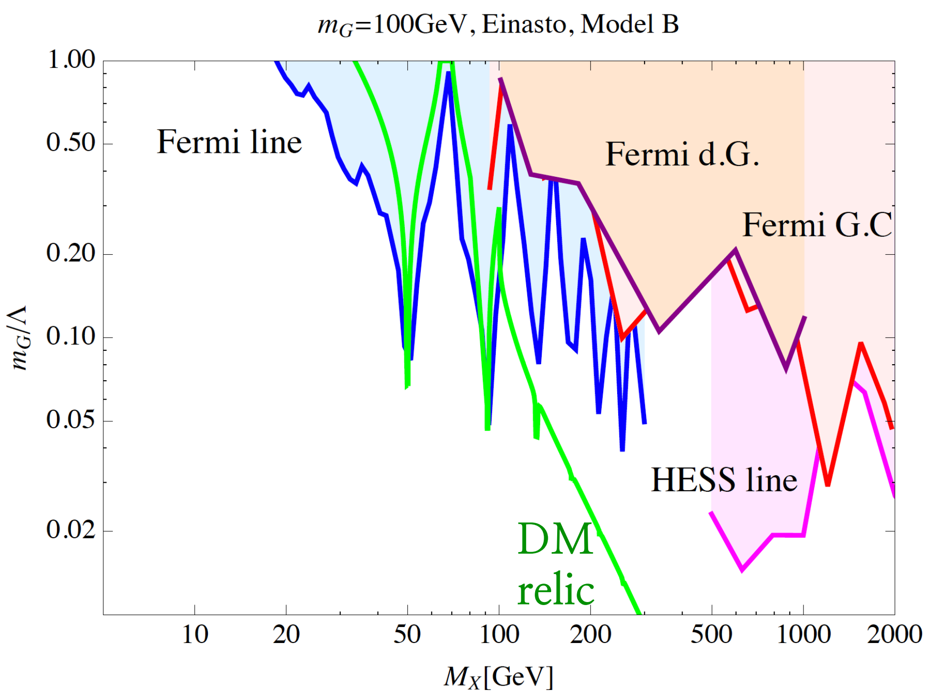
$$r_X=\left(\frac{m_G}{m_X}\right)^2$$

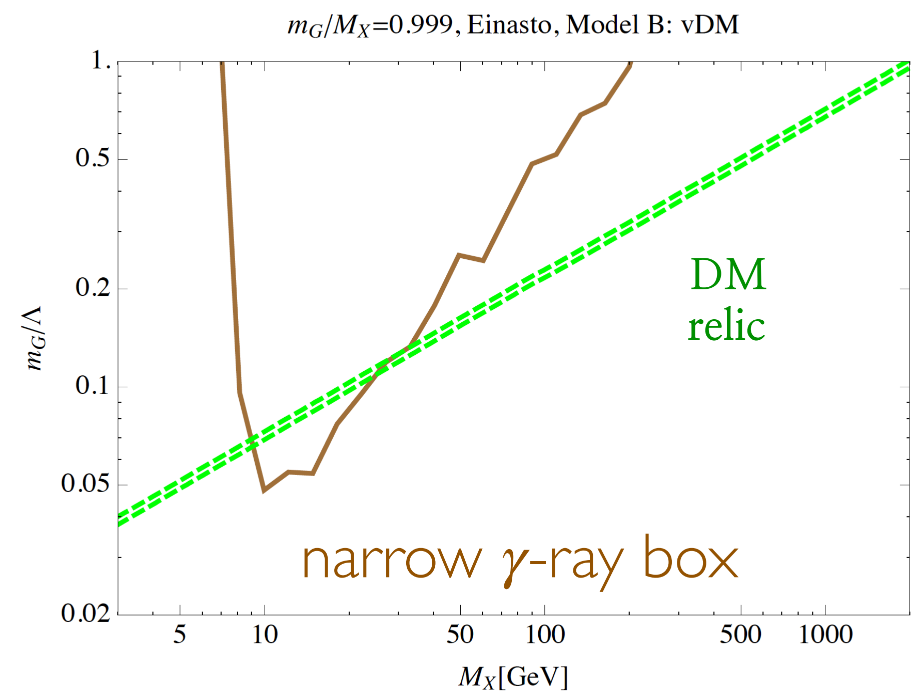
$$(\sigma v)_{XX\to GG}=\frac{c_X^4 m_X^2}{324\pi\Lambda^4}\frac{\sqrt{1-r_X}}{r_X^4(2-r_X)^2}\left(176+192r_X+1404r_X^2-3108r_X^3+1105r_X^4+362r_X^5+34r_X^6\right)$$

Indirect detection bounds

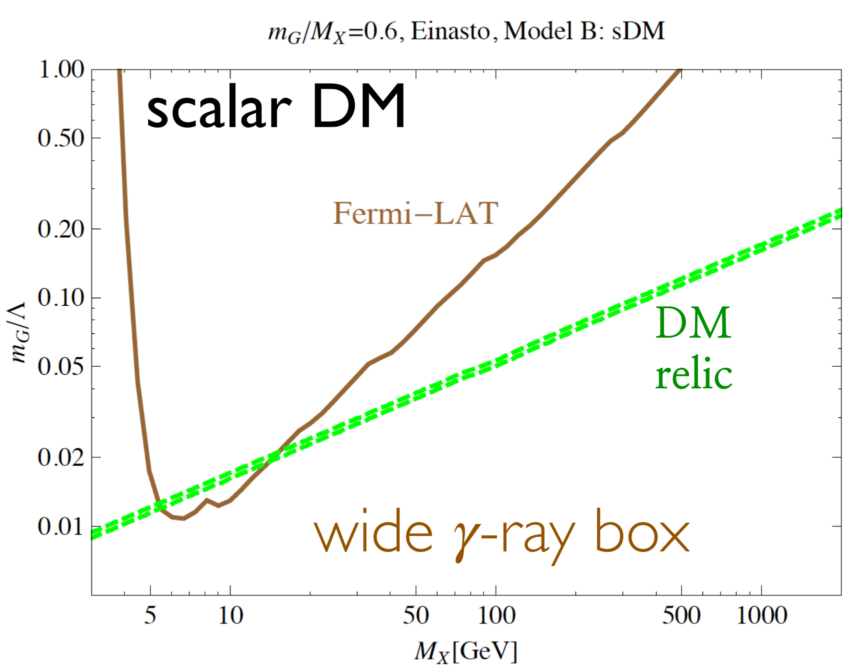
H. M. Lee, M. Park and V. Sanz (1401.5301)

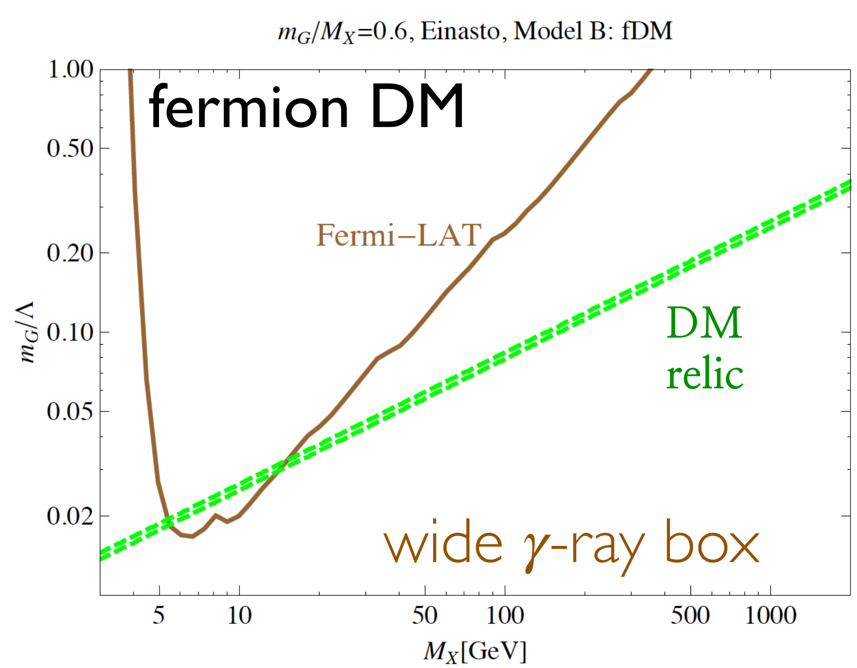
vector DM

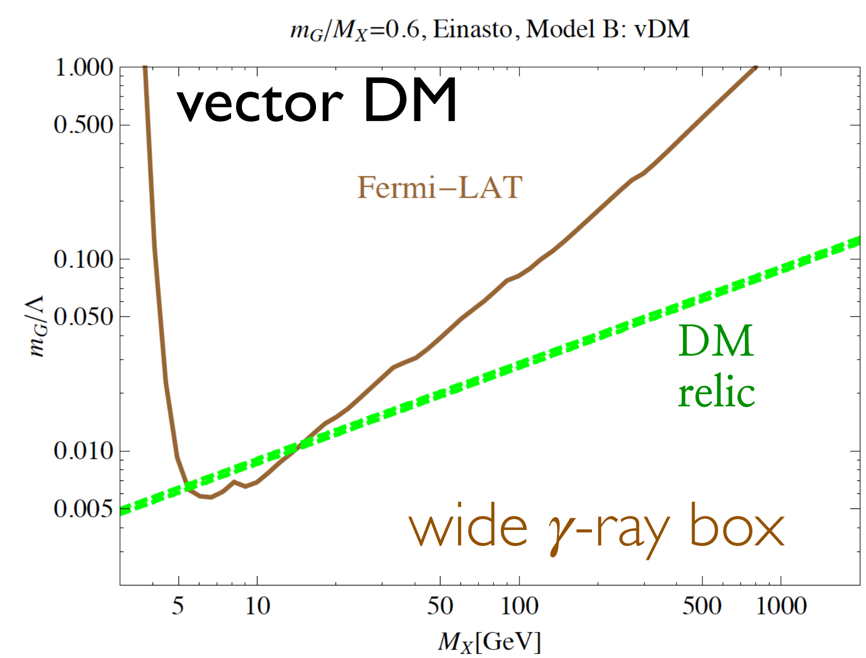




Astrophysical bounds are DM spin-dependent.
Therefore, we can distinguish DM spins from Indirect detection.







Spin-dependent cross section

- WIMP model-independent formula

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

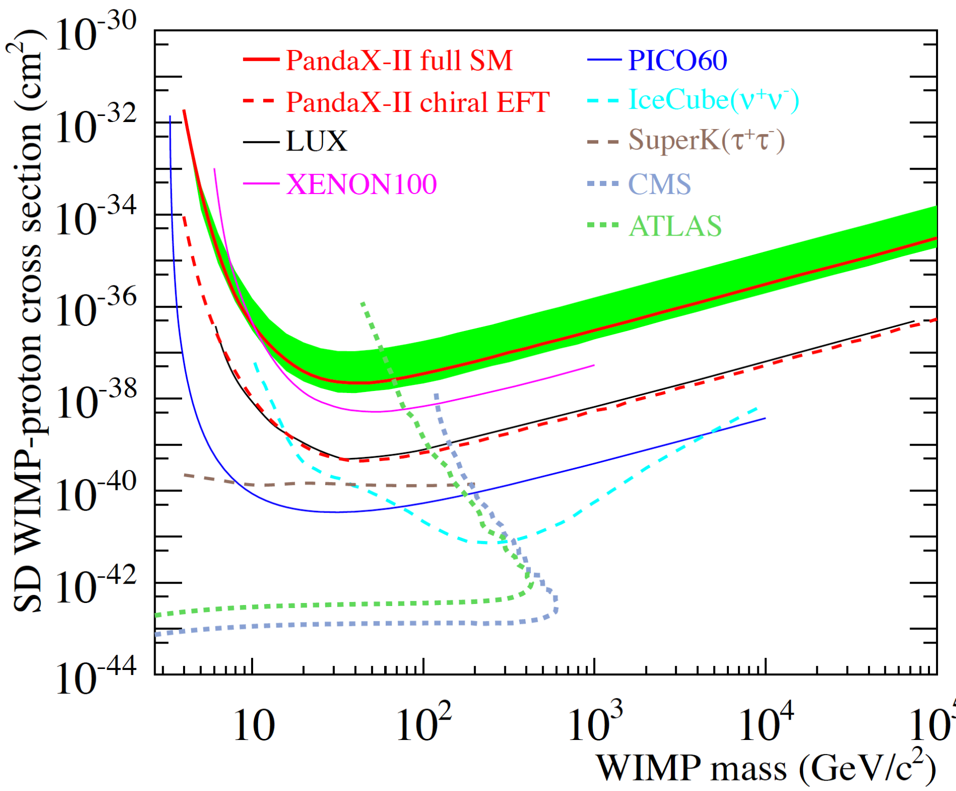
with assuming that $\sigma_A \simeq \sigma_A^n$ and $\sigma_A \simeq \sigma_A^p$

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

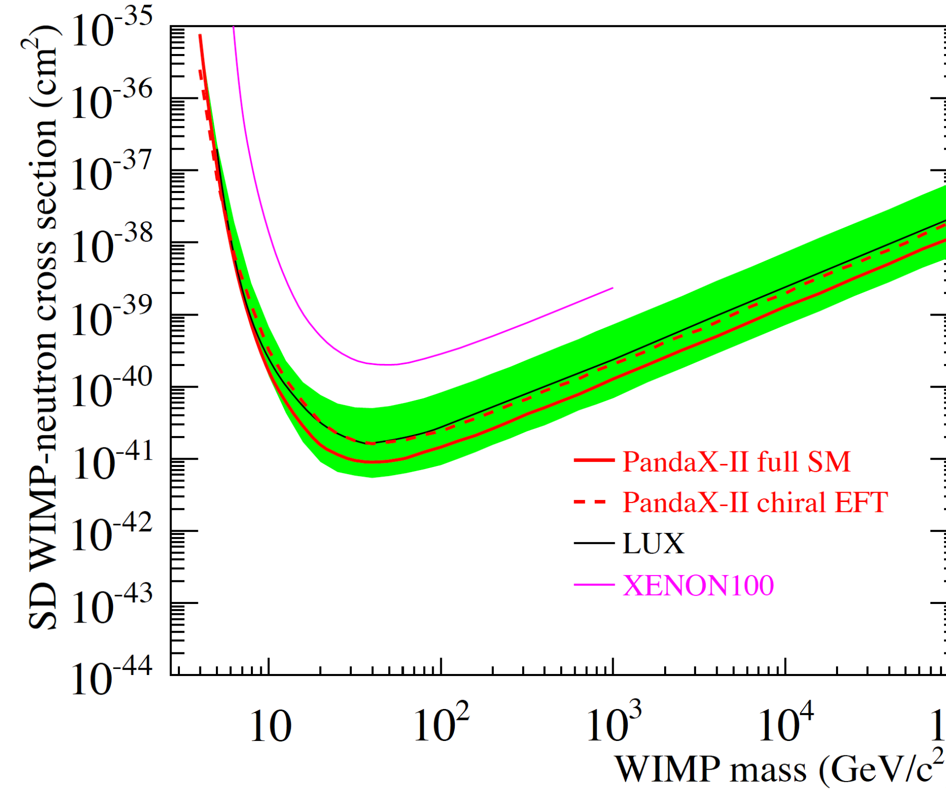
P. Gondolo et al (hep-ph/0005041)

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

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

- 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 $\frac{dR_D}{dE_R}$.