Loop Effect in Direct Dark Matter Detection

李佟
Nankai University

第二届北师大暗物质研讨会
2018年11月9-11日

Outline

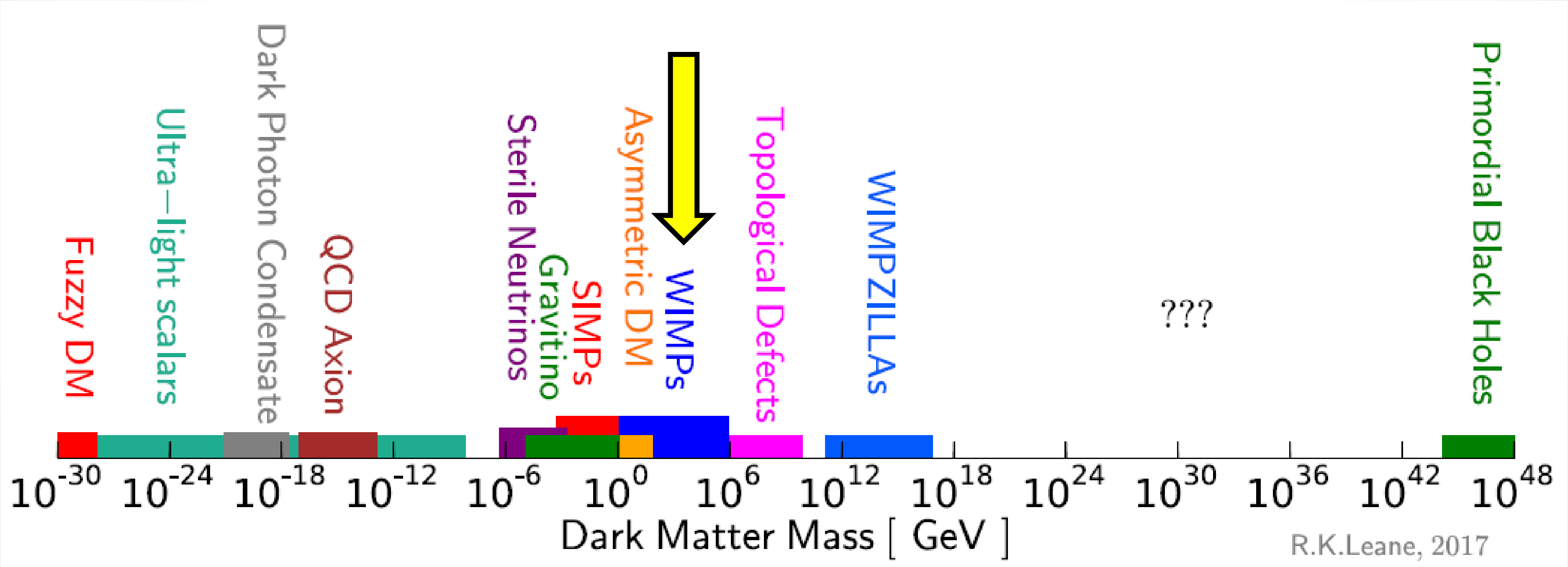
- Motivation
- Loop effect in DM DD and results
- Summary

Dark Matter evidence and WIMP paradigm

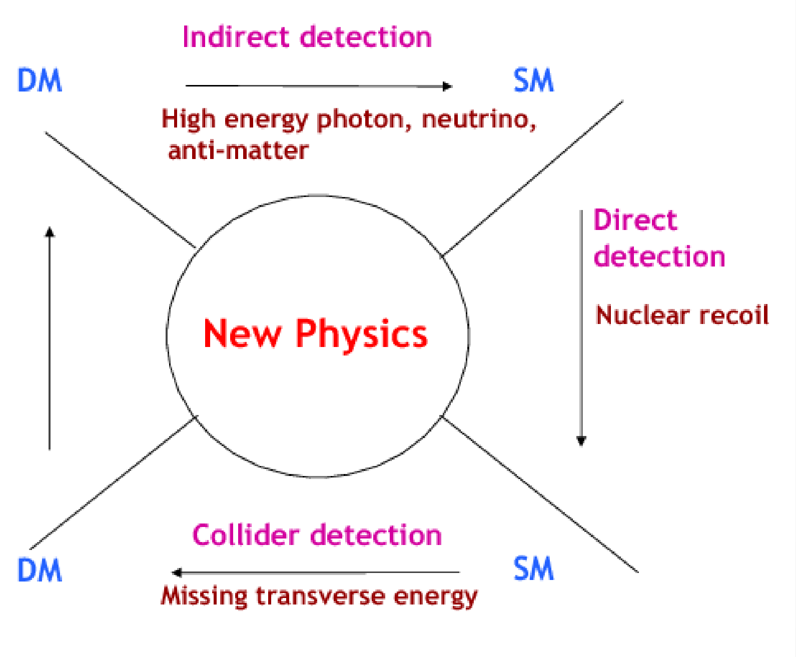
- Why Dark Matter? Indirect evidence:
  - velocities of galaxies in Coma cluster (Zwicky 1930's)
  - Galaxy rotation curves (Rubin 1960's)
  - Cosmic microwave background
  - Structure formation
  - Gravitational lensing

● What is DM? WIMP miracle: 1970s -

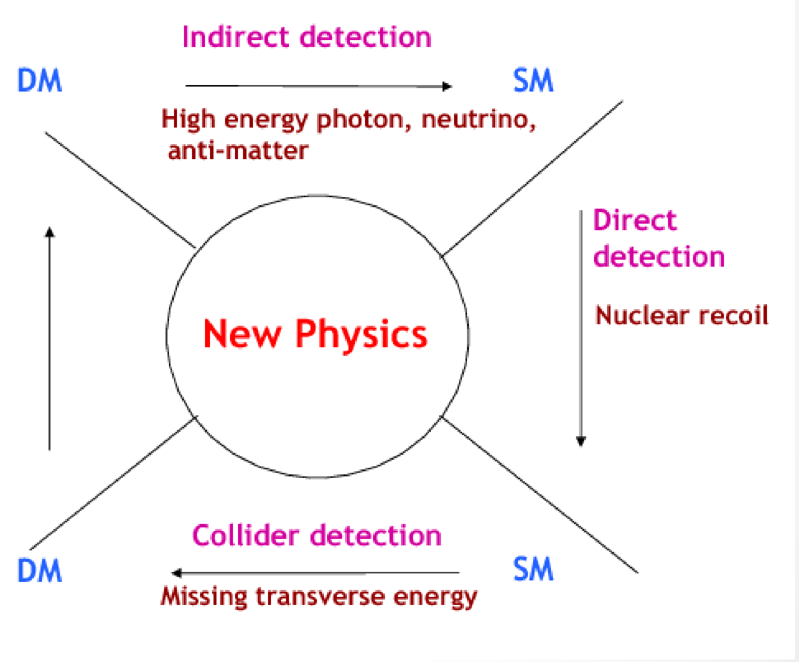
Weak scale particles with EW strength couplings give correct abundance



- Potential to be probed by three frontiers:
  - indirect detection
  - colliders
  - direct detection

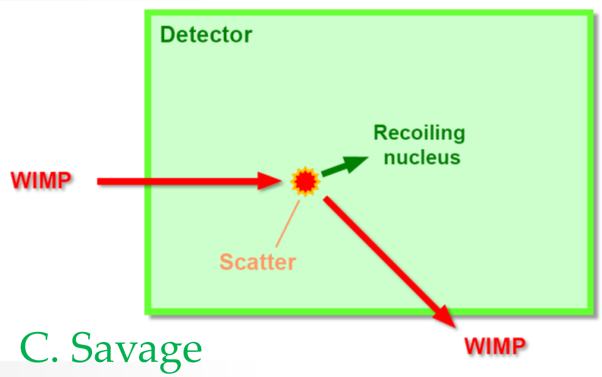


- Potential to be probed by three frontiers:
  - indirect detection
  - colliders
  - direct detection



Direct DM Detection

- Elastic scattering of WIMP off detector nuclei



C. Savage

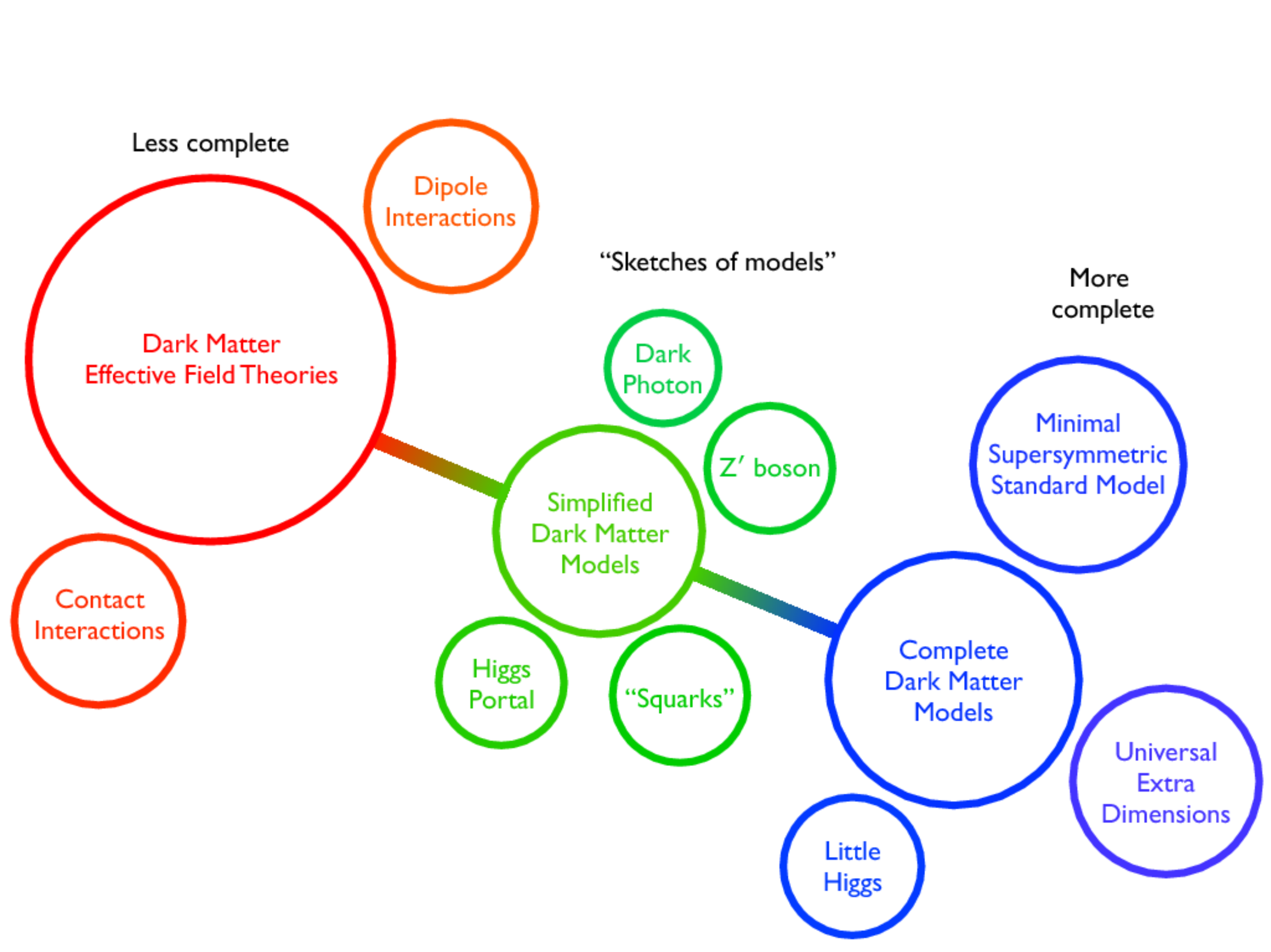
- ◆ Recoil energy: $E_{nr} \sim \frac{1}{2}\,\mu\, v^2 \sim O(10)$ keV
- ◆ Differential recoil rate:

$$\frac{dR}{dE_{\rm nr}} = \frac{n_\chi}{M}\left\langle v \frac{d\sigma}{dE_{\rm nr}} \right\rangle = \boxed{\frac{2\rho_\chi}{m_\chi}} \int d^3v\, v\, \boxed{f(\mathbf{v},t)}\, \boxed{\frac{d\sigma}{dq^2}(q^2,v)}$$

number density | velocity distro. | particle physics

- Particle physics cross section σ
  - ◆ spin-independent: couple to mass of nuclei ($\sigma \propto A^2$)
  - ◆ spin-dependent: couple to spin of nuclei
  - ◆ dependent on WIMP models

WIMP models



T. Tait

Application to colliders

DM EFT

$$\frac{1}{\Lambda^2}\bar{\chi}\mathcal{O}_1\chi\bar{q}\mathcal{O}_2 q$$

(EFT valid only if $Q^2 \ll \Lambda^2$!)

Cao et al., 2009
Beltran et al., 2010
Goodman et al., 2010

Simplified DM models

$$\lambda_\chi\bar{\chi}\mathcal{O}_1\chi S + \lambda_q\bar{q}\mathcal{O}_2 q S$$

(unitarity and gauge invariance spoiled!)

Abdallah et al., 2014, 2015
Abercrombie et al., 2015

Complete models

(e.g. Higgs portal, 2HDM)

See Dr. Jinmian Li's talk

EFT for direct detection

- In DM-nucleon scattering, the momentum transfer $q \sim O(10)$ MeV
  - EFT valid for a large range of parameters
  - Non-relativistic limit

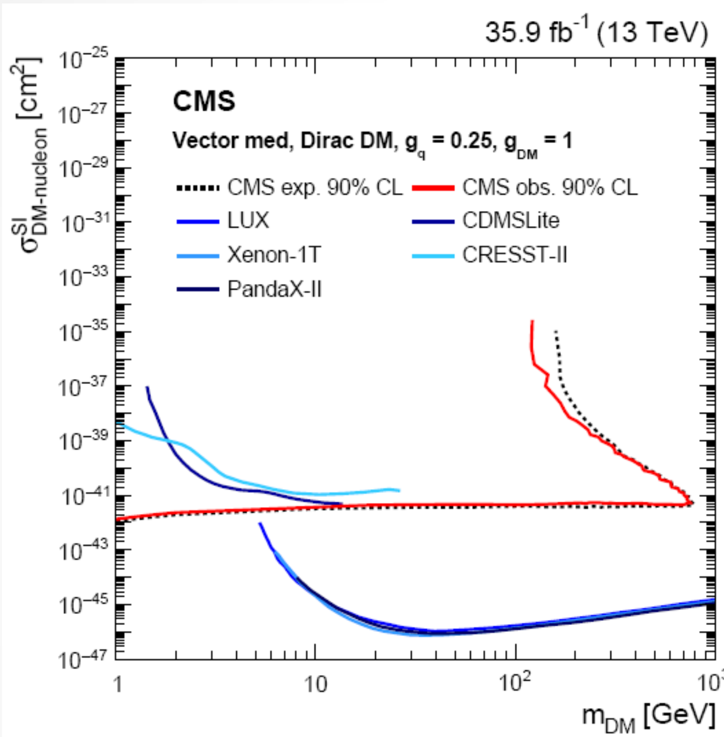
- DM-parton operators $\rightarrow$ non-relativistic DM-nucleon operators

e.g. Dirac fermion DM χ

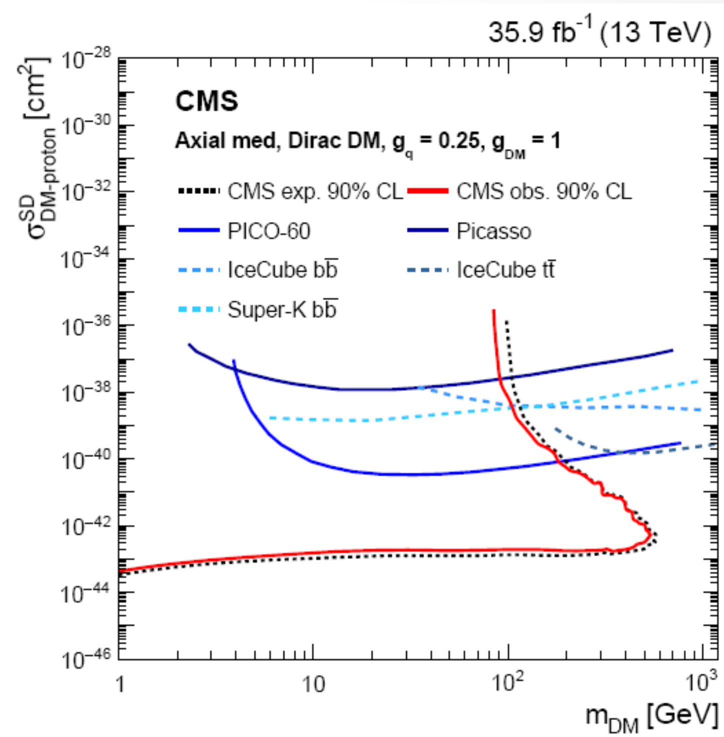
dim-6 EFT operator	DD suppression effect
$\bar{\chi}\chi\bar{q}q$	1
$\bar{\chi}i\gamma_5\chi\bar{q}q$	$\vec{s}_\chi \cdot \vec{q}$
$\bar{\chi}\chi\bar{q}i\gamma_5 q$	$\vec{s}_N \cdot \vec{q}$
$\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q$	$(\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	1
$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q$	$\vec{s}_\chi \cdot (\vec{s}_N \times \vec{q})$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma_5 q$	$\vec{s}_\chi \cdot (\vec{s}_N \times \vec{q})$
$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$	$\vec{s}_\chi \cdot \vec{s}_N$

unsuppressed SI cross section

cross section suppressed by the spin of the nucleus or DM $\vec{s}_N$ or $\vec{s}_\chi$, the scattering momentum exchange $\vec{q}$ or both, rendering weak DD constraints strong SI constraint on $\overline{\chi}\gamma^{\mu}\chi\overline{q}\gamma_{\mu}q$



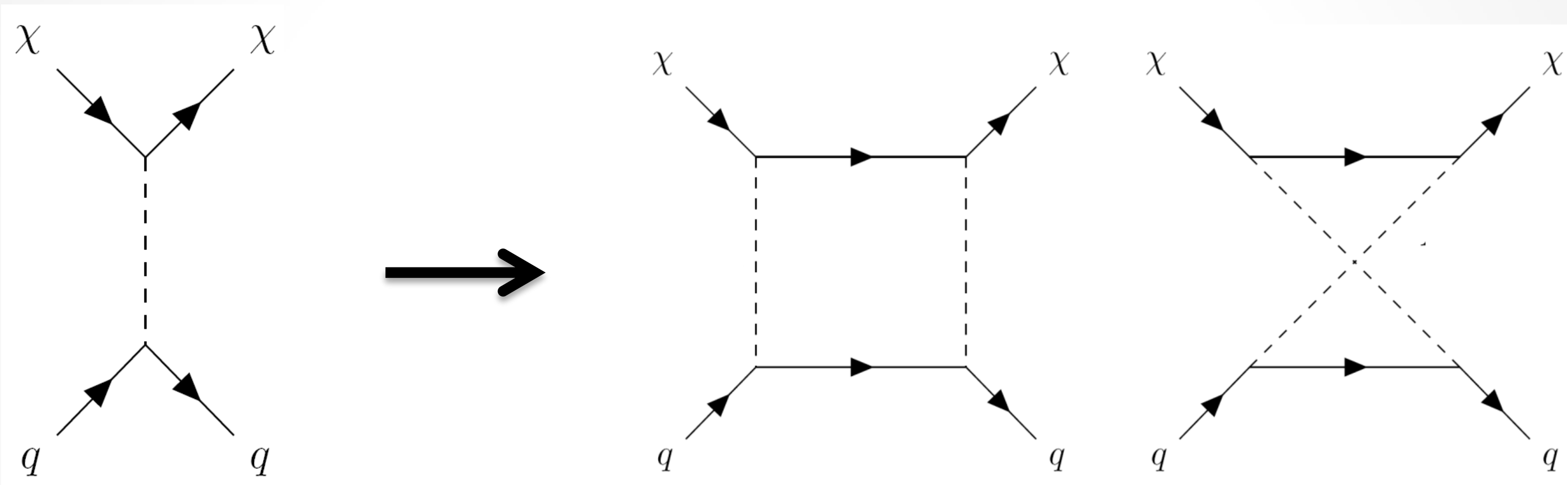
weak SD constraint on $\overline{\chi}\gamma^{\mu}\gamma_5\chi\overline{q}\gamma_{\mu}\gamma_5 q$



- Plenty of DM-parton operators lead to highly suppressed scattering rate

Not the End

- From tree to loop



- Unsuppressed SI interactions are generated

  e.g. the case of pseudoscalar mediator:

$$\bar{\chi}\gamma_5(\not{q}+m_\chi)\gamma_5\chi = -\bar{\chi}\,(\not{q}-m_\chi)\,\chi$$

- The A^2 enhancement compensates loop suppression

Freytsis, Ligeti, 2010
Ipek, McKeen, Nelson, 2014
Arcadi, Lindner, Queiroz, Rodejohann, Vogl, 2017
Bell, Busoni, Sanderson, 2018
TL, 2018

- Effective Lagrangian from the loop process
  $\chi(p_\chi)q(p_q) \to \chi(p'_\chi)q(p'_q)$ with $q \equiv p_\chi - p'_\chi = p'_q - p_q$

$$\mathcal{L} = A\bar{u}(p'_q)\gamma^\mu u(p_q)\bar{u}(p'_\chi)\gamma_\mu u(p_\chi) + B\bar{u}(p'_q)u(p_q)\bar{u}(p'_\chi)u(p_\chi)$$
$$+ \bar{u}(p'_q)\left(C_1 \not{p}_\chi + C_2 \not{p}'_\chi\right)u(p_q)\bar{u}(p'_\chi)u(p_\chi) + D\bar{u}(p'_q)\not{q}u(p_q)\bar{u}(p'_\chi)u(p_\chi)$$
$$+ E\bar{u}(p'_q)u(p_q)\bar{u}(p'_\chi)\not{p}'_q u(p_q) + \bar{u}(p'_q)\left(F_1 \not{p}_\chi + F_2 \not{p}'_\chi\right)u(p_q)\bar{u}(p'_\chi)\not{p}'_q u(p_\chi)$$
$$+ G\bar{u}(p'_q)\not{q}u(p_q)\bar{u}(p'_\chi)\not{p}'_q u(p_\chi)$$

Arcadi et al., 2017

- By making repeated use of the EoM,

$$C_{V,q}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q + C_{S,q}\bar{\chi}\chi\bar{q}q$$

$$C_{V,q} = A + m_q E + 2m_\chi m_q(F_1 + F_2)$$
$$C_{S,q} = B$$

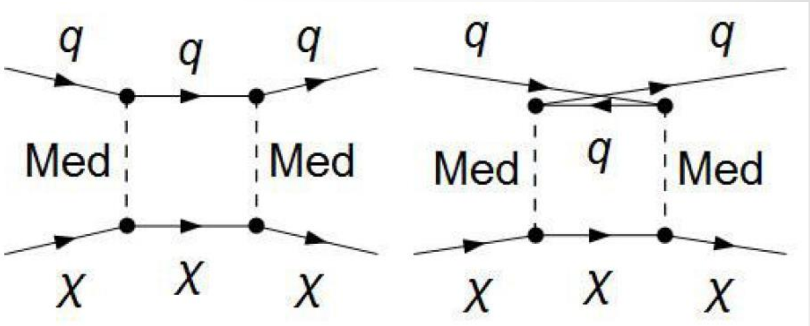
- In the framework of simplified models

TL, arXiv: 1804.02120

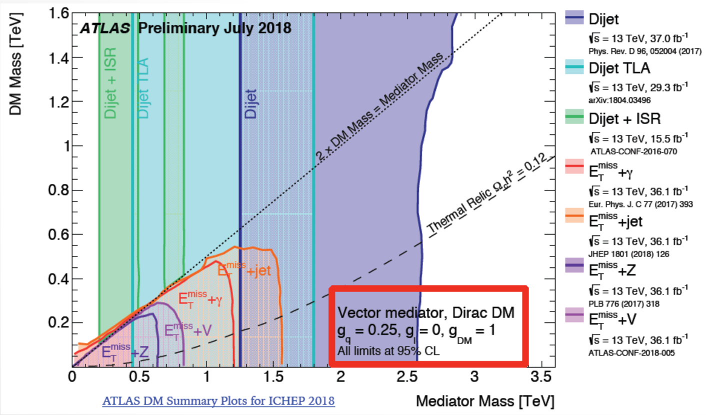
$$\mathcal{L}_{\mathrm{D2}} = -i g_\chi^{\mathrm{D2}} S_2 \bar{\chi}\gamma_5\chi - S_2 \sum_q g_q^{\mathrm{D2}} \frac{m_q}{v_0} \bar{q} q,$$

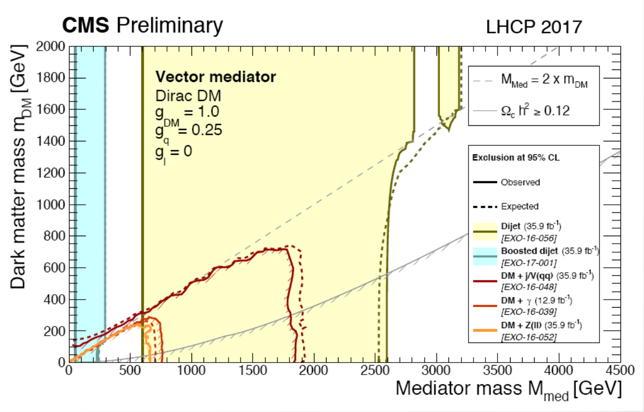
$$\mathcal{L}_{\mathrm{D3}} = - g_\chi^{\mathrm{D3}} S_3 \bar{\chi}\chi - i S_3 \sum_q g_q^{\mathrm{D3}} \frac{m_q}{v_0} \bar{q}\gamma_5 q,$$

$$\mathcal{L}_{\mathrm{D4}} = -i g_\chi^{\mathrm{D4}} S_4 \bar{\chi}\gamma_5\chi - i S_4 \sum_q g_q^{\mathrm{D4}} \frac{m_q}{v_0} \bar{q}\gamma_5 q,$$



- Only dependent on $m_\chi, m_{Med} \equiv m_S$ if setting all $g_\chi = g_q = 1$
- Quark bilinear scaled by SM quark mass
- Vector or axial-vector scenario highly constrained by Z'→dijet search at LHC





- After integrating out the loop diagrams, the scalar interaction is

$$\sum_q \frac{m_q^2}{v_0^2} \mathcal{C}(m_{\mathrm{DM}}, m_{\mathrm{Med}}, m_q)\, \overline{\mathrm{DM}}\,\mathrm{DM}\,\bar{q}q$$

- The vector interaction contributed by valence quarks only, neglected
- Only heavy quark contribution relevant in the scalar current

$$m_Q QQ = -\frac{\alpha_s}{12\pi} G_{\mu\nu} G^{\mu\nu}$$

$$\frac{\alpha_s}{\pi} \langle n | G_{\mu\nu} G^{\mu\nu} | n \rangle = -\frac{8}{9} m_N f_{TG}$$

- The loop-induced WIMP-nucleon SI cross section:

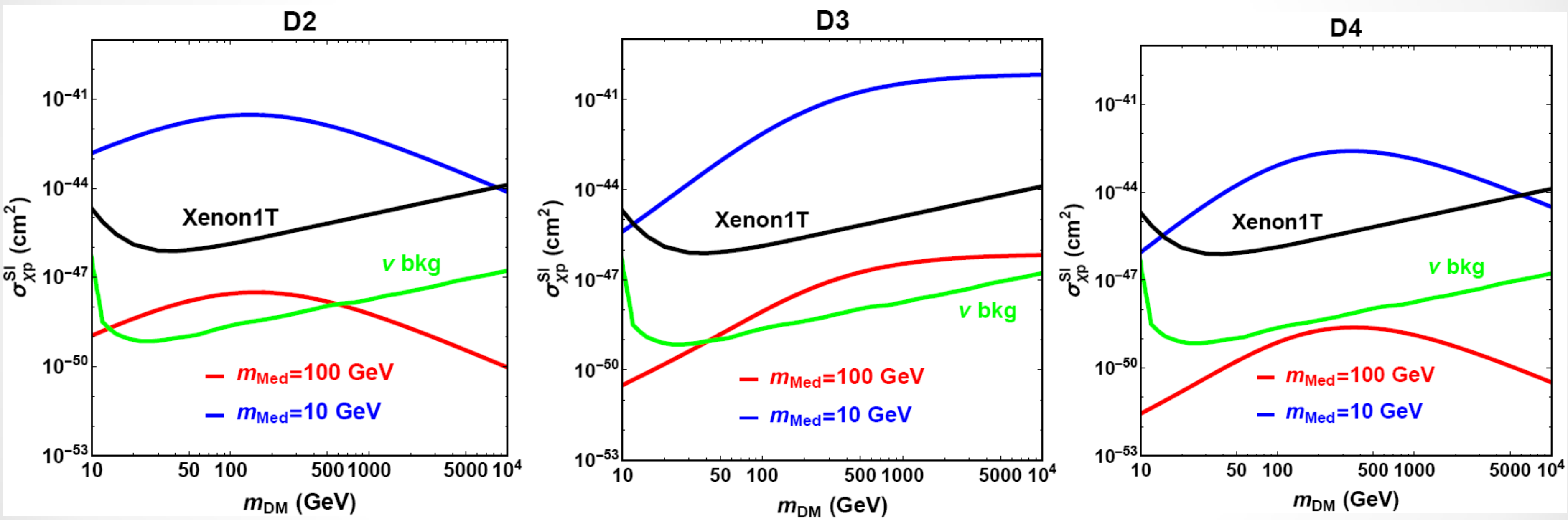
$$\sigma^{\rm SI}_{{\rm DM}N} = \frac{\mu^2_{\rm DMN}}{\pi}|\mathcal{I}_i(m_{\rm DM}, m_{\rm Med})|^2,$$

$$\mathcal{I}_i(m_{\rm DM}, m_{\rm Med}) \approx \sum_{q=c,b,t} \frac{m_q m_N}{v_0^2} \frac{2}{27} f_{\rm TG} \mathcal{C}_i(m_{\rm DM}, m_{\rm Med}, m_q),$$

- $\mathcal{C}_i$ coefficients in expression of Passarino-Veltman functions

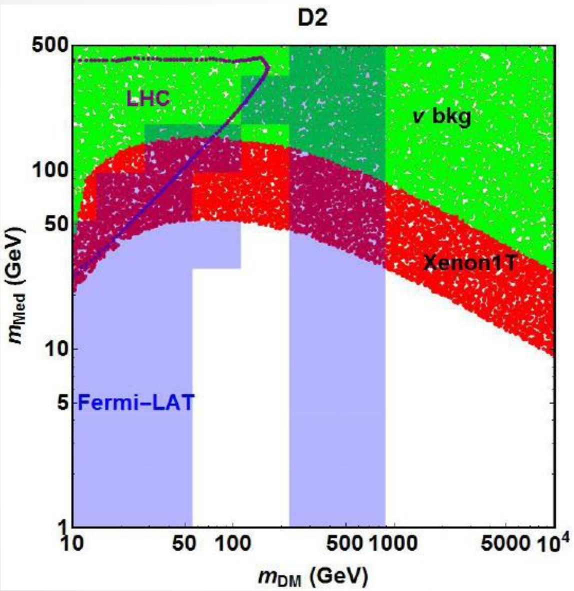
Results

$\mathrm{D2} : \bar{\chi}\gamma_5\chi \oplus \bar{q}q$ $\mathrm{D3} : \bar{\chi}\chi \oplus \bar{q}\gamma_5 q$ $\mathrm{D4} : \bar{\chi}\gamma_5\chi \oplus \bar{q}\gamma_5 q$

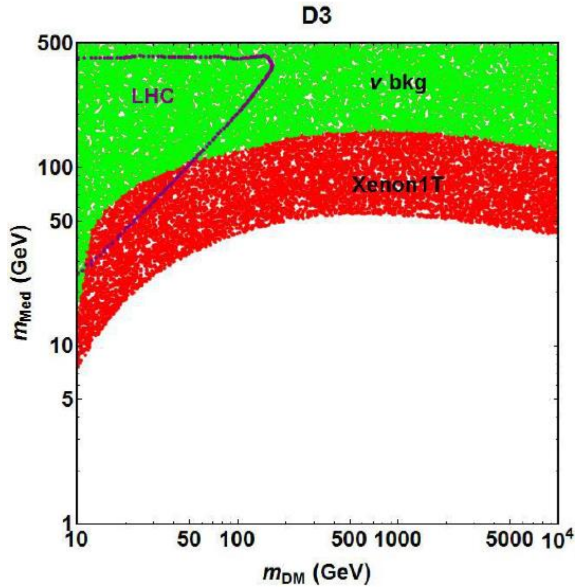


- Allowed region of m_{Med} vs. m_{DM}, complementary to Fermi-LAT (dwarf galaxies) and LHC (mono-jet)

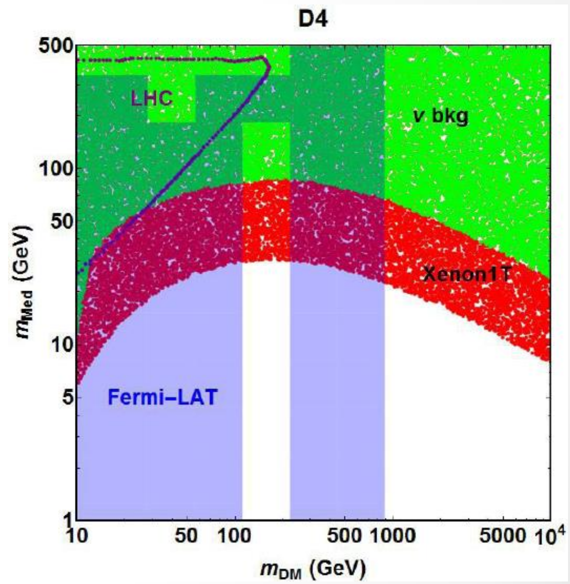
$\mathrm{D2}: \bar{\chi}\gamma_5\chi \oplus \bar{q}q$



$\mathrm{D3}: \bar{\chi}\chi \oplus \bar{q}\gamma_5 q$



$\mathrm{D4}: \bar{\chi}\gamma_5\chi \oplus \bar{q}\gamma_5 q$



Still not the End

- Completion of simplified models restores gauge-invariance, new degrees of freedom and additional diagrams
- Contributions from twist-2 operators

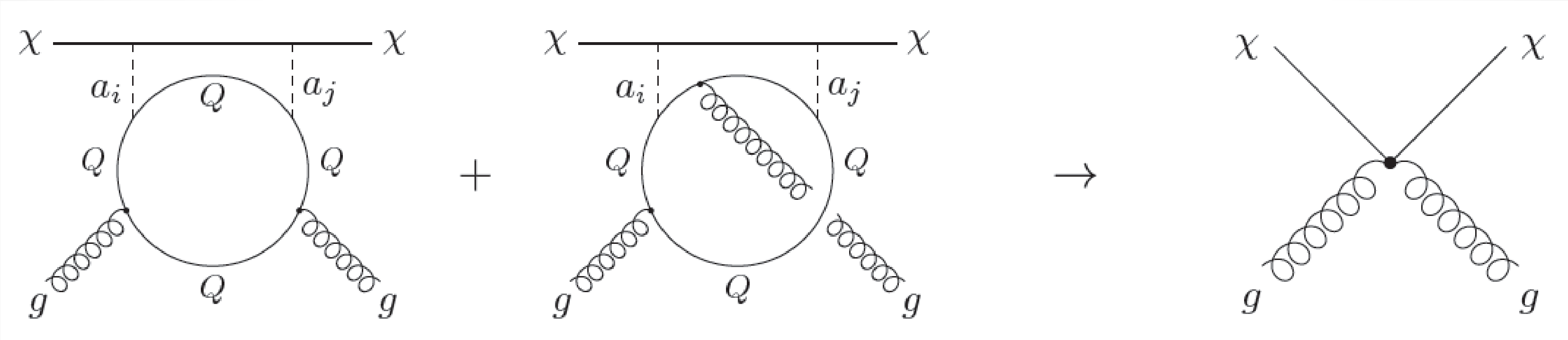
$$C_q^{(1)} \bar{\chi} i\partial^\mu \gamma^\nu \chi \mathcal{O}^q_{\mu\nu} + C_q^{(2)} \bar{\chi} i\partial^\mu i\partial^\nu \chi \mathcal{O}^q_{\mu\nu} \qquad \mathcal{O}^q_{\mu\nu} = \frac{i}{2}\bar{q}\left(\partial_\mu\gamma_\nu + \partial_\nu\gamma_\mu - \frac{1}{2}g_{\mu\nu}\not{\partial}\right) q$$

- More accurate calculation regarding the DM-gluon effective operator $\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

$$m_Q QQ = -\frac{\alpha_s}{12\pi} G_{\mu\nu} G^{\mu\nu}$$

approximation not appropriate when $m_Q > m_{Med}$

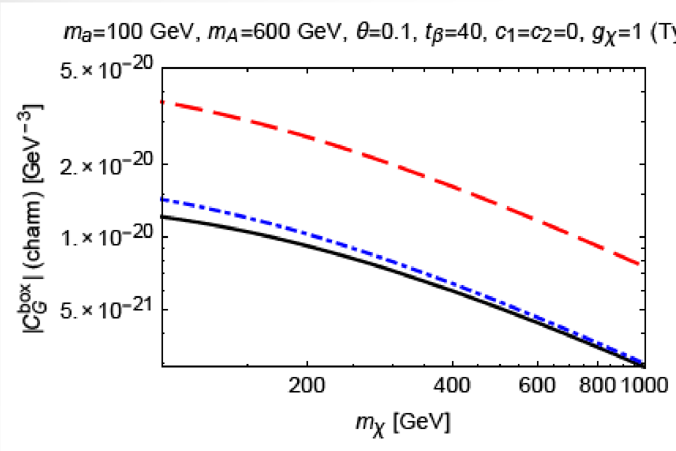
- It is necessary to calculate the two-loop diagrams and read out the effective operator $\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$ directly

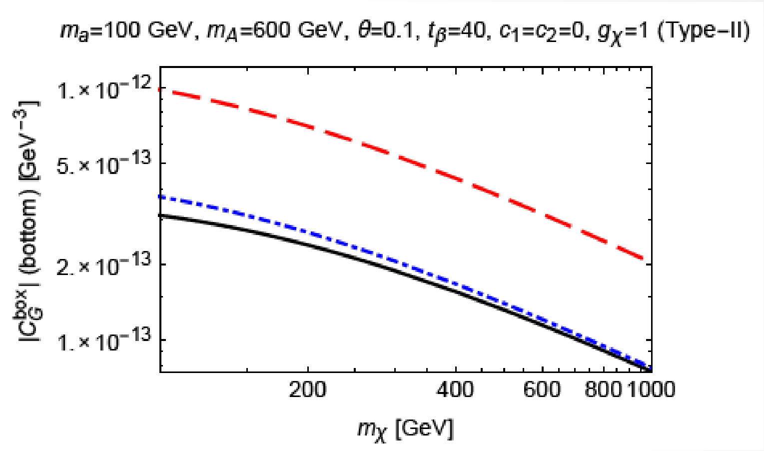


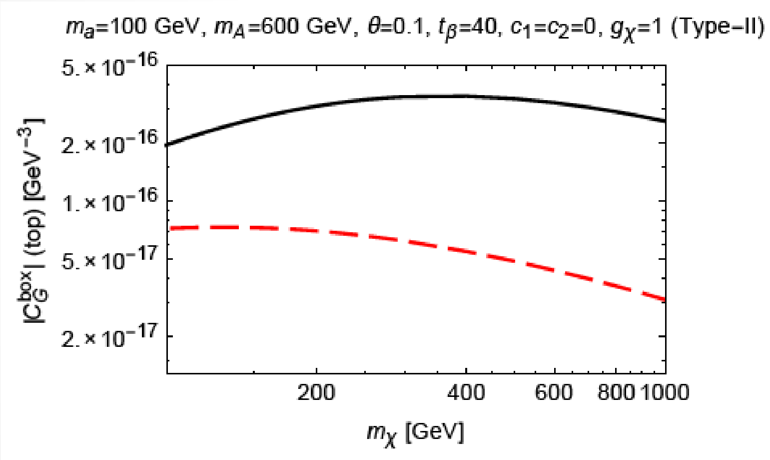
Abe, Fujiwara, Hisano, 2018

- Use the Fock-Schwinger gauge for the gluon to extract out the bilinear term of the gluon field strength from the WIMP two-point function

Comparison







- Black: approximate calculation
  Blue: with twist-2
  Red: two-loop calculation
- Small twist-2 contribution
- Underestimated approximate calculation for c, b quark, ~40%
- Overestimated approximate calculation for t quark
- Dominant b quark loop, thus the total cross section underestimated

Summary

- The tree-level amplitude for the DM-nucleon elastic scattering is usually suppressed.
- Loop diagrams induce unsuppressed SI contribution.
- The loop corrections are essential to discuss the sensitivities of the DD experiments for the model prediction.

Summary

- The tree-level amplitude for the DM-nucleon elastic scattering is usually suppressed.
- Loop diagrams induce unsuppressed SI contribution.
- The loop corrections are essential to discuss the sensitivities of the DD experiments for the model prediction.

Thank you!