Direct Detection of Vector Dark Matter

Natsumi Nagata

Nagoya University / University of Tokyo

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Based on [J. Hisano, K. Ishiwata, N. N., M. Yamanaka, Prog.Theor.Phys., vol.126, **3** (2011) 435.]

Outline

1. Introduction

2. Direct detection of vector dark matter

3. Application and Results

   The Minimal Universal Extra Dimension (MUED) model

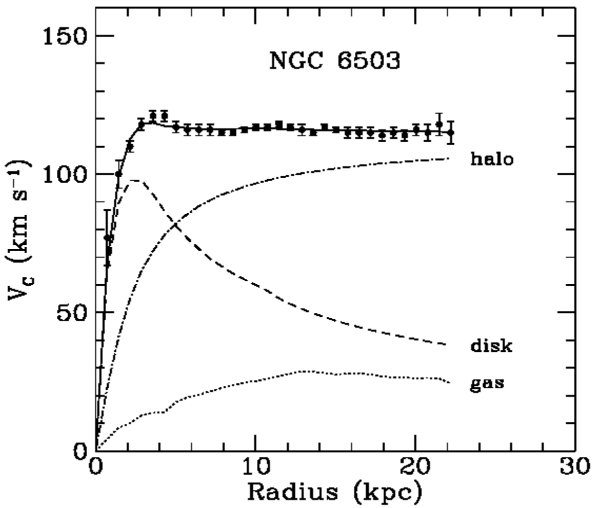
4. Summary

1. Introduction

Introduction

Observational evidence for dark matter (DM)

Galactic scale

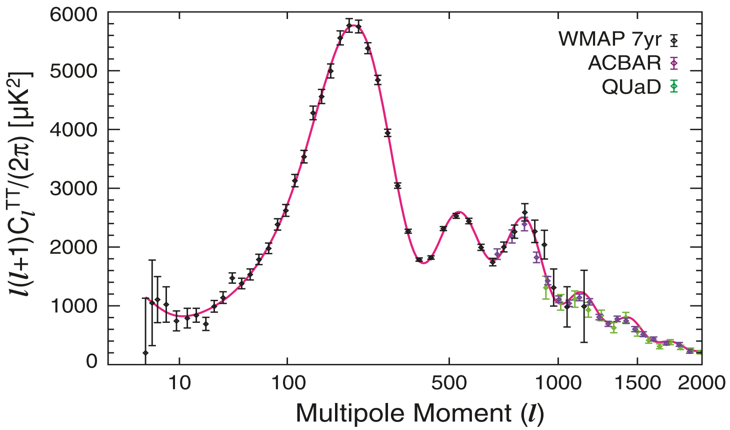


Begeman et. al. (1991).

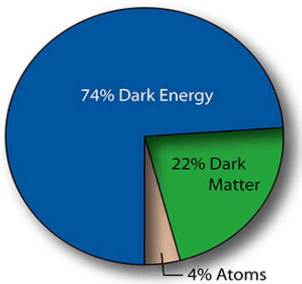
Scale of galaxy clusters

Clowe et. al. (2006).

Cosmological scale



Komatsu et. al. (2010).



http://map.gsfc.nasa.gov/

About 80% of the matter in the Universe is nonbaryonic dark matter.

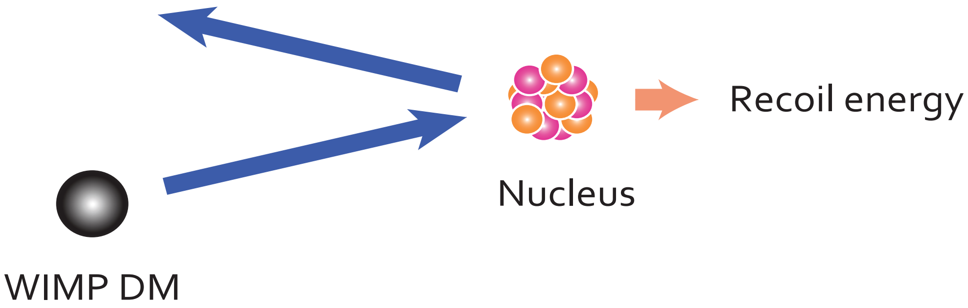
One of the most promising candidates for dark matter is

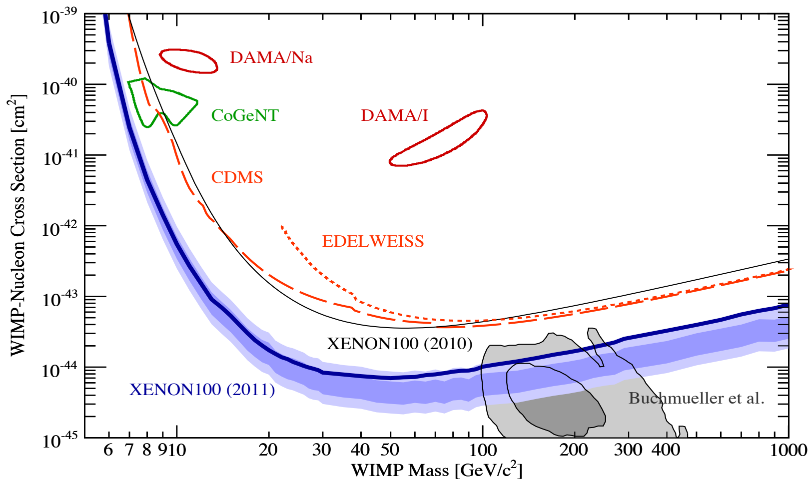
Weakly Interacting Massive Particles (WIMPs)

- have masses roughly between 10 GeV ~ a few TeV.
- interact only through weak and gravitational interactions.
- Their thermal relic abundance is naturally consistent with the cosmological observations [thermal relic scenario].
- appear in models beyond the Standard Model.

Introduction

Direct Detection Experiments





[XENON100 collaboration, arXiv: 1104. 2549]

- Xenon100 collaboration gives a stringent constraint on spin-independent elastic WIMP-nucleon scattering cross section.

$$\sigma_{\rm SI} > 7.0 \times 10^{-45} {\rm cm}^2$$ (for WIMPs of mass 50 GeV)

- Ton-scale detectors for direct detection experiments are expected to yield significantly improved sensitivities.

Motivation

To study the nature of dark matter based on direct detection experiments, the precise calculation of

WIMP-nucleon elastic scattering cross section

is required.

We evaluate this quantity on the assumption that

DM is a vector particle

H. C. Cheng, J. L. Feng, K. T. Matchev (2002)
G. Servant and T. M. P. Tait (2002)

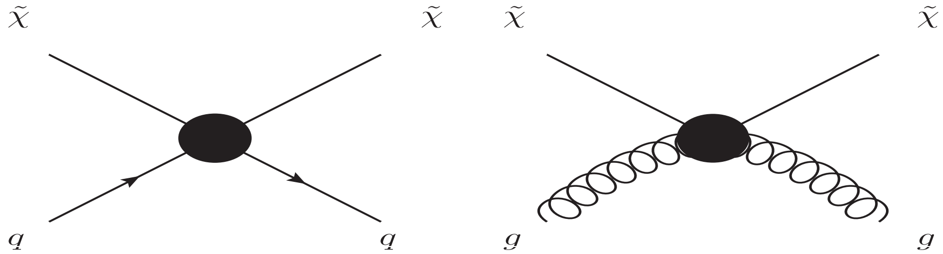
- KK photon DM in the MUED
- T-odd Heavy photon in the Littlest Higgs model

e.t.c....

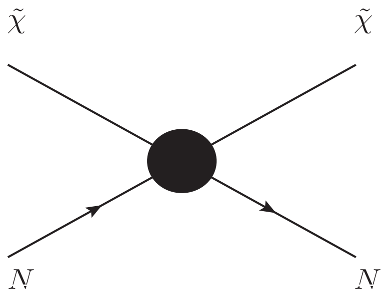
based on **The method of the effective theory**

Effective Theory

1. Formulate the effective Lagrangian of the WIMP DM with light quarks (u, d, s) and gluon by integrating out the rest of heavy particles in the high energy theory.



2. Evaluate the WIMP-nucleon elastic scattering cross section using the effective Lagrangian.



We need to evaluate the nucleon matrix element of quark/gluon operators in the effective Lagrangian.

2. Direct Detection of vector dark matter

Effective Lagrangian for Vector Dark Matter

$$\mathcal{L}_q = \frac{d_q}{M}\epsilon_{\mu\nu\rho\sigma}B^\mu i\partial^\nu B^\rho \bar{q}\gamma^\sigma\gamma_5 q$$ ← Spin-dependent interaction

$$+f_q m_q B^\mu B_\mu \bar{q}q \ + \frac{g_q}{M^2}B^\rho i\partial^\mu i\partial^\nu B_\rho \mathcal{O}^q_{\mu\nu}$$

$$\mathcal{L}_G = f_G B^\mu B_\mu G^a_{\mu\nu}G^{a\mu\nu}$$

Spin-independent interaction

B^μ : DM m_q : quark mass M : DM mass

Scalar-type interaction

$f_q m_q B^\mu B_\mu \bar{q}q$ $f_G B^\mu B_\mu G^a_{\mu\nu}G^{a\mu\nu}$

- Couplings of DM with "nucleon mass"
- Nucleon matrix element is evaluated with lattice simulations

Twist-2 operator

$$\mathcal{O}^q_{\mu\nu} \equiv \frac{1}{2}\bar{q}i\left(D_\mu\gamma_\nu + D_\nu\gamma_\mu - \frac{1}{2}g_{\mu\nu}\not{D}\right)q$$

Twist-2-type interaction

- Couplings of DM with "quark momentum"
- Parton Distribution Functions (PDF)

Gluon contribution

Scalar-type interactions, $f_q m_q B^\mu B_\mu \bar{q} q$, $f_G B^\mu B_\mu G^a_{\mu\nu} G^{a\mu\nu}$, induce

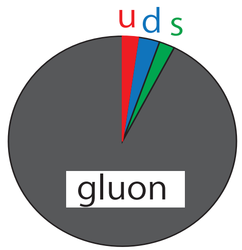
The couplings of DM with "nucleon mass"

Nucleon matrix elements:

$$\langle N | m_q \bar{q} q | N \rangle = m_N f_{Tq} \qquad f_{Tq} \sim 0.03 \qquad m_N : \text{nucleon mass}$$

By using the trace anomaly of the energy momentum tensor in QCD,

$$\langle N | G^a_{\mu\nu} G^{a\mu\nu} | N \rangle = -\frac{8\pi}{9\alpha_s} m_N f_{TG} \qquad 1 - \sum_{q=u,d,s} f_{Tq} \equiv f_{TG}$$



Mass fractions for proton

This enhancement originates from the large gluon contribution to the nucleon mass.

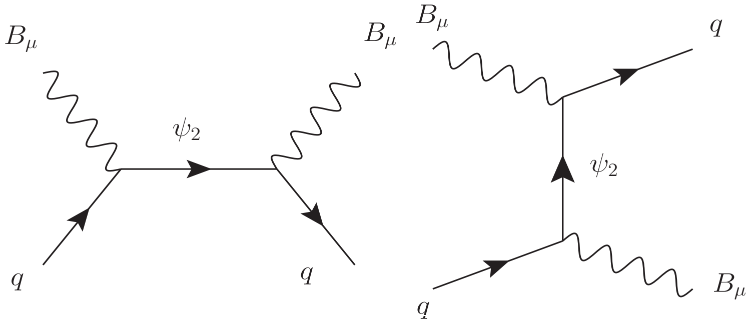
The gluon contribution turns out to be comparable to the quark contribution even if the DM-gluon interaction is induced by higher loop diagrams.

General results

Lagrangian:

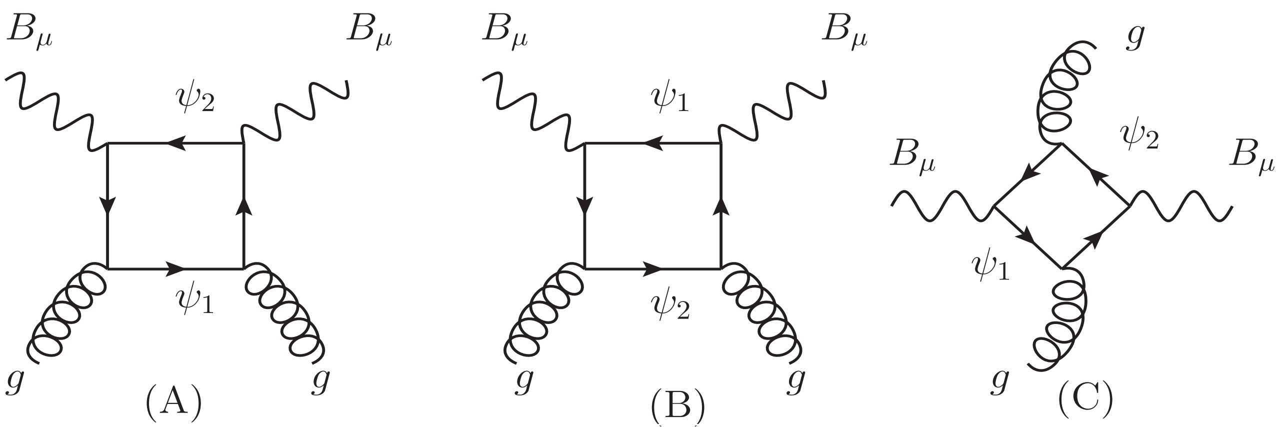
$$\mathcal{L}_{\rm int} = \bar{\psi}_2(a\gamma^\mu + b\gamma^\mu\gamma_5)\psi_1 B_\mu + \text{h.c.} \qquad \psi_i : \text{colored fermions}$$

The tree-level diagrams (Quark contribution)



We obtained effective couplings by evaluating these diagrams

1-loop diagrams (Gluon contribution)



J. Hisano, K. Ishiwata, N. N, and M. Yamanaka, Prog. Theor. Phys. Vol. 126, No. **3** (2011) 435.

3. Application and Results

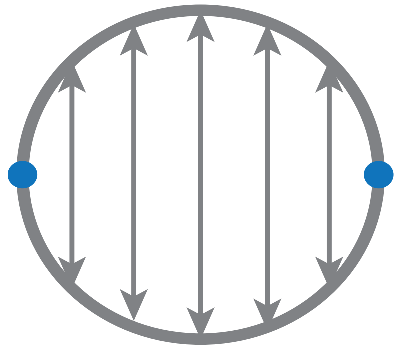
The Minimal Universal Extra Dimension (MUED) model

KK photon DM

Minimal UED model

Minimal Universal Extra Dimension (MUED) model

- One extra dimension is compactified on an $S^1/\mathbb{Z}_2$ orbifold.
- All of the SM particles propagate in the extra dimension.
- KK partiy conservation prevent the lightest KK-odd particle (LKP) from decaying to the SM particles.



→

- KK number even : KK parity +1
- KK number odd : KK parity -1

- 3 parameters undetermined

- Radius of the extra dimension : R
- Higgs boson mass
- Cutoff scale : Λ

T. Appelquist, H. C. Cheng, B. A. Dobrescu (2001)
H. C. Cheng, K. T. Matchev, M. Schmaltz (2002)

KK photon DM

Mass spectrum in the MUED

- n-th KK particles are degenerate in mass at tree level.

  (Mass of the n-th KK particles) $\sim$ n/R

- Radiative corrections give rise to the mass differences.

Point

- The first KK photon is the LKP → DM

  where the Higgs-boson mass is within the region allowed by the recent LHC results

- Small Cutoff → Small quantum corrections

  → Degenerate mass spectrum

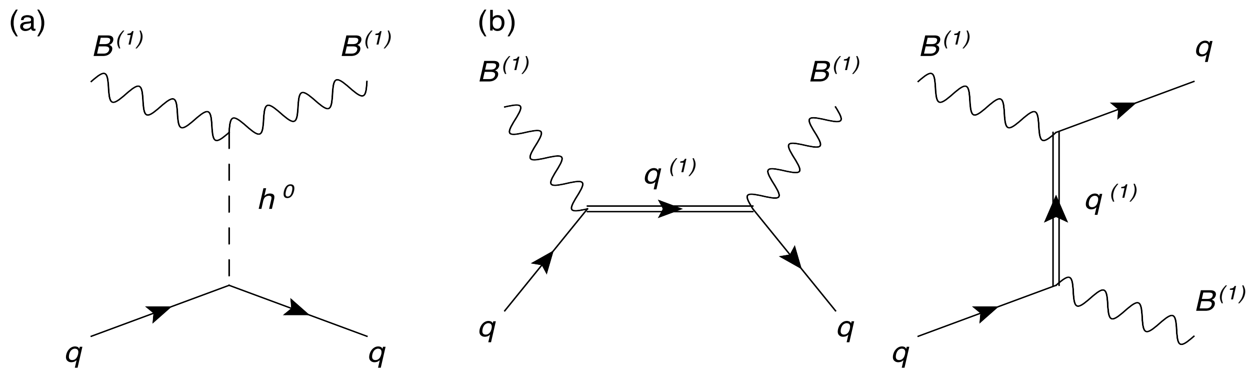
•Probing this model is difficult since the QCD jets become soft

•DM direct detection rate increases in such cases

KK photon DM

Quark & Higgs contribution | Tree-level

The tree-level diagrams:



$B^{(1)}$: KK photon DM

$q^{(1)}$: the first KK quark

h^0 : Higgs boson

The effective couplings:

$$f_q = -\frac{g_1^2}{4m_h^2} - \frac{g_1^2}{4}\left[Y_{\rm qL}^2 \frac{m_{Q^{(1)}}^2}{(m_{Q^{(1)}}^2 - M^2)^2} + Y_{\rm qR}^2 \frac{m_{q^{(1)}}^2}{(m_{q^{(1)}}^2 - M^2)^2}\right] + \frac{g_1^2 Y_{\rm qL} Y_{\rm qR}}{m_{Q^{(1)}} + m_{q^{(1)}}}\left[\frac{m_{Q^{(1)}}}{m_{Q^{(1)}}^2 - M^2} + \frac{m_{q^{(1)}}}{m_{q^{(1)}}^2 - M^2}\right],$$

$$g_q = -g_1^2 M^2 \left[\frac{Y_{\rm qL}^2}{(m_{Q^{(1)}}^2 - M^2)^2} + \frac{Y_{\rm qR}^2}{(m_{q^{(1)}}^2 - M^2)^2}\right].$$

m_h : Higgs boson mass

$Y_{q\rm L},\ Y_{q\rm R}$: hypercharge

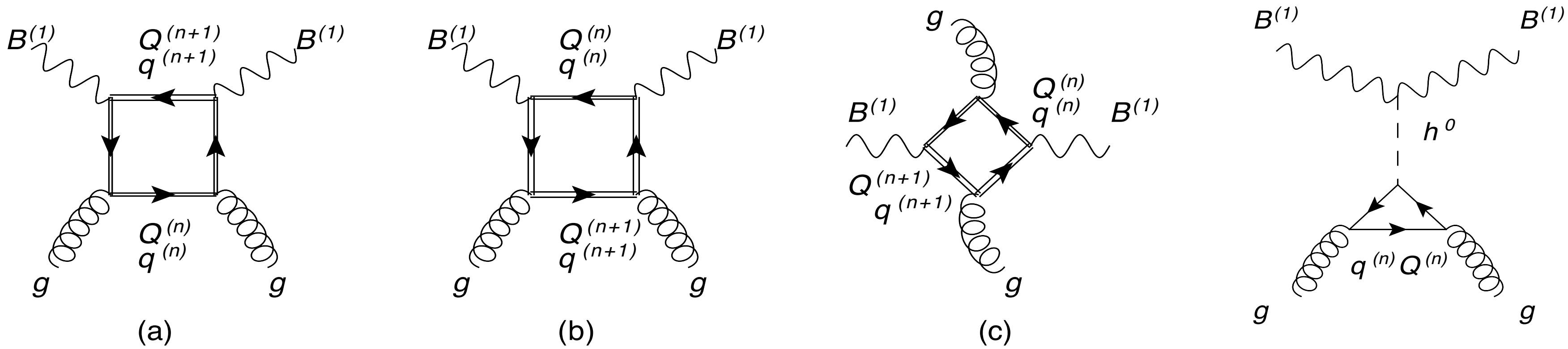
M : DM mass

$m_{Q^{(1)}},\ m_{q^{(1)}}$: $1_{\rm st}$ KK quark mass

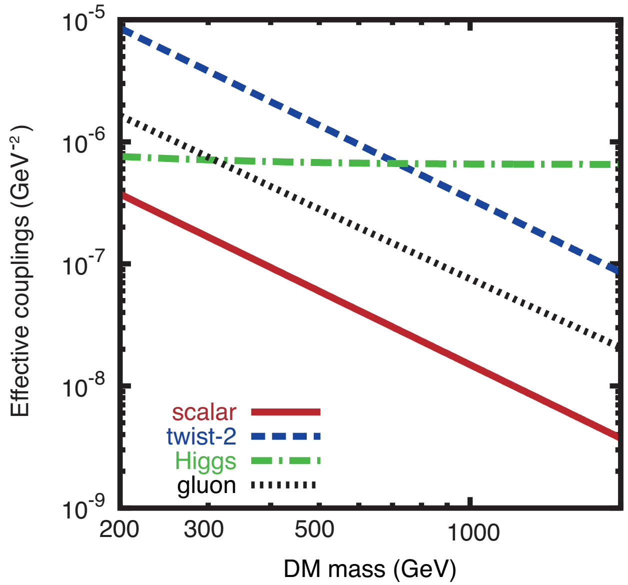
KK photon DM

Gluon contribution | 1-loop

1-loop diagrams:



Each contribution in the spin-independent effective DM-proton coupling



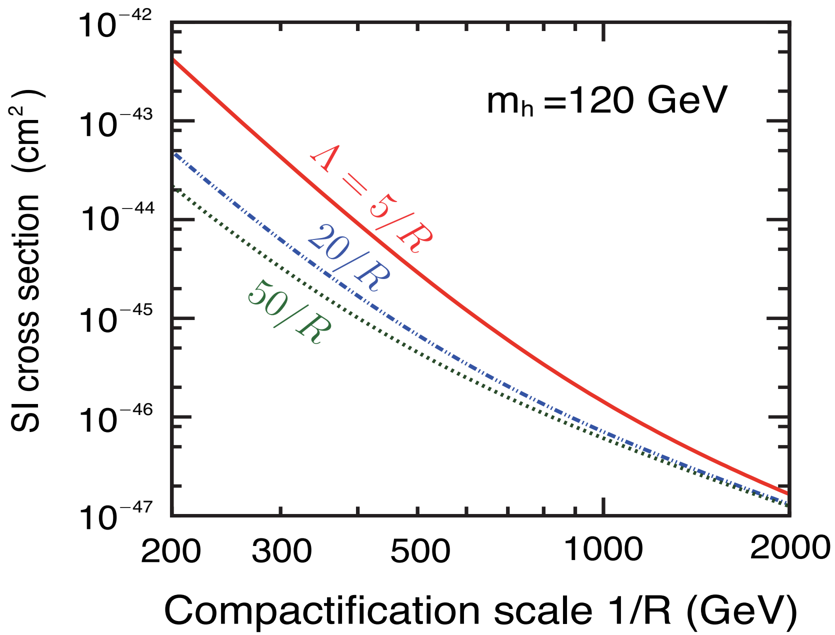
$$m_h = 120 \text{ GeV}$$

$$(m_{1\text{st}} - M)/M = 0.1$$

All of the contributions have the same sign (additive).

KK photon DM

SI scattering cross section



SI scattering cross section of KK Photon DM with a proton

Large Cutoff → Small SI scattering cross section

We obtain the SI cross section which is larger than those in the previous work by almost an order of magnitude.

J. Hisano, K. Ishiwata, N. N, and M. Yamanaka, Prog. Theor. Phys. Vol. 126, No. **3** (2011) 435.

4. Summary

Summary

- We evaluate the elastic scattering cross sections of vector DM with nucleon based on the method of effective theory.

- The interaction of DM with gluon as well as quarks yields sizable contribution to the cross section, though the gluon contribution is induced at loop level.

- The cross section of the first Kaluza-Klein photon dark matter turns out to be larger by up to a factor of ten than those evaluated in the previous work.

Backup

Effective Lagrangian for Vector Dark Matter

$$\mathcal{L}_q^{\rm eff} = f_q m_q B^\mu B_\mu \bar{q}q + \frac{d_q}{M}\epsilon_{\mu\nu\rho\sigma} B^\mu i\partial^\nu B^\rho \bar{q}\gamma^\sigma\gamma^5 q + \frac{g_q}{M^2} B^\rho i\partial^\mu i\partial^\nu B_\rho \mathcal{O}^q_{\mu\nu},$$

$$\mathcal{L}_G^{\rm eff} = f_G B^\rho B_\rho G^{a\mu\nu} G^a_{\mu\nu} + \frac{g_G}{M^2} B^\rho i\partial^\mu i\partial^\nu B_\rho \mathcal{O}^g_{\mu\nu},$$

B_μ : real vector field
m_q : quark mass
M : DM mass

Twist-2 operators

$$\mathcal{O}^q_{\mu\nu} \equiv \frac{1}{2}\bar{q}i\left(D_\mu\gamma_\nu + D_\nu\gamma_\mu - \frac{1}{2}g_{\mu\nu}\not{D}\right)q\ ,$$

$$\mathcal{O}^g_{\mu\nu} \equiv \left(G^{a\rho}_\mu G^a_{\rho\nu} + \frac{1}{4}g_{\mu\nu}G^a_{\alpha\beta}G^{a\alpha\beta}\right)\ .$$

— : Spin-dependent
— : Spin-independent
— : negligible

Nucleon matrix elements

- The mass fractions (for the scalar-type quark operators)

$$\langle N|m_q\bar{q}q|N\rangle/m_N \equiv f_{Tq} \ , \qquad 1-\sum_{q=u,d,s} f_{Tq} \equiv f_{TG}$$

m_N : nucleon mass

- For the twist-2 operators

$$\begin{aligned}\langle N(p)|\mathcal{O}^q_{\mu\nu}|N(p)\rangle &= \frac{1}{m_N}(p_\mu p_\nu - \frac{1}{4}m_N^2 g_{\mu\nu})\ (q(2)+\bar{q}(2))\ , \\ \langle N(p)|\mathcal{O}^g_{\mu\nu}|N(p)\rangle &= \frac{1}{m_N}(p_\mu p_\nu - \frac{1}{4}m_N^2 g_{\mu\nu})\ G(2)\ .\end{aligned}$$

■The second moments of the parton distribution functions (PDFs)

$$\begin{aligned}q(2)+\bar{q}(2) &= \int_0^1 dx\ x\ [q(x)+\bar{q}(x)]\ , \\ G(2) &= \int_0^1 dx\ x\ g(x)\ .\end{aligned}$$

Trace anomaly of energy-momentum tensor in QCD

The matrix element of gluon field strength tensor can be evaluated by using the trace anomaly of the energy-momentum tensor in QCD

■The trace anomaly of the energy-momentum tensor in QCD

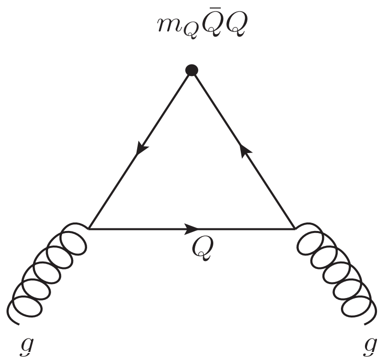
$$\Theta^{\mu}_{\mu} = \frac{\beta(\alpha_s)}{4\alpha_s} G^a_{\mu\nu} G^{a\mu\nu} + \sum_{q=u,d,s} m_q \bar{q} q + \sum_{Q=c,b,t} m_Q \bar{Q} Q$$

$$m_N$$

$$\beta(\alpha_s) = -\frac{7\alpha_s^2}{2\pi} \quad (\text{for} \quad N_F = 6)$$

$$\sum_{q=u,d,s} m_N f_{Tq}$$

$$m_Q \bar{Q} Q \rightarrow -\frac{\alpha_s}{12} G^a_{\mu\nu} G^{a\mu\nu}$$



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

M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Phys. Lett. B **78** (1978) 443.

SI coupling of Vector DM with nucleon

The effective coupling of DM with nucleon is given as follows:

$$\mathcal{L}_{eff} = f_N \bar{\tilde{\chi}} \tilde{\chi} \bar{N} N$$

$$f_N/m_N = \sum_{q=u,d,s} f_q f_{Tq} + \sum_{q=u,d,s,c,b} \frac{3}{4} \left(q(2) + \bar{q}(2)\right) g_q - \frac{8\pi}{9\alpha_s} f_{TG} f_G + \frac{3}{4} G(2) g_G \,,$$

Suppressed by α_s

The gluon contribution can be comparable to the quark contribution even if the DM-gluon interaction is induced by higher loop diagrams.

For proton	
f_{Tu}	0.023
f_{Td}	0.034
f_{Ts}	0.025
For neutron	
f_{Tu}	0.019
f_{Td}	0.041
f_{Ts}	0.025

Second moment at $\mu = m_Z$			
$G(2)$	0.48		
$u(2)$	0.22	$\bar{u}(2)$	0.034
$d(2)$	0.11	$\bar{d}(2)$	0.036
$s(2)$	0.026	$\bar{s}(2)$	0.026
$c(2)$	0.019	$\bar{c}(2)$	0.019
$b(2)$	0.012	$\bar{b}(2)$	0.012

Long-distance contribution vs. Short-distance contribution

We classify these contributions into two types:

Long-distance contribution

- Diagrams in which loop momentum around the quark mass scale dominates the loop integration yield long-distance contribution.
- One should not include the long-distance contribution of light quarks.

→ The corresponding effect is included in the mass fraction $\langle N | m_q \bar{q} q | N \rangle$

Short-distance contribution

- Diagrams where the typical loop momentum is around the scale of heavy particles (DM, squark, …) yield short-distance contribution.
- All quarks contribute to the short-distance contribution.

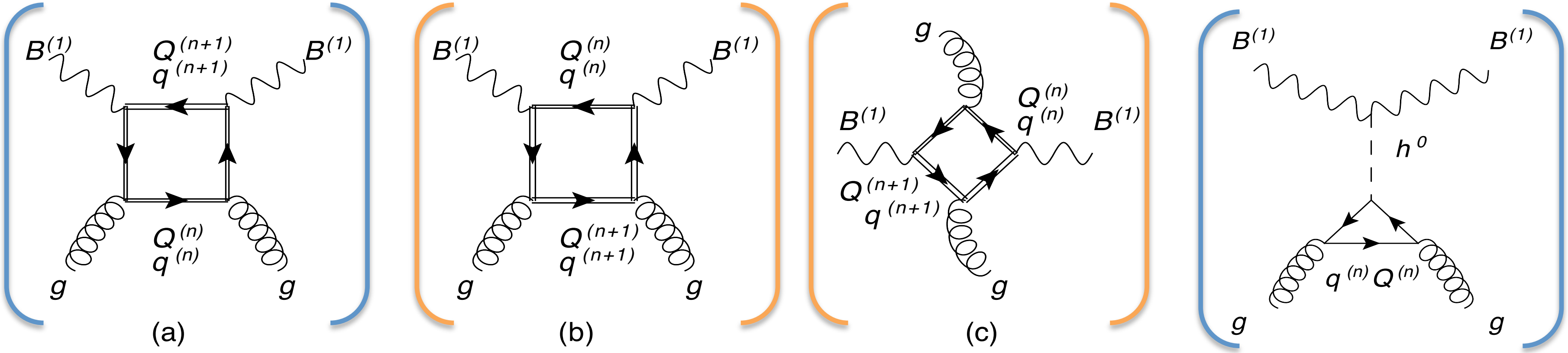
$$f_G = \sum_{q=\mathrm{all}} f_G^{\mathrm{SD}}|_q + \sum_{Q=c,b,t} f_G^{\mathrm{LD}}|_Q$$

J. Hisano, K. Ishiwata, N. Nagata, Phys. Rev. D **82**, 115007 (2010).

KK photon DM

Gluon contribution | 1-loop

1-loop diagrams:



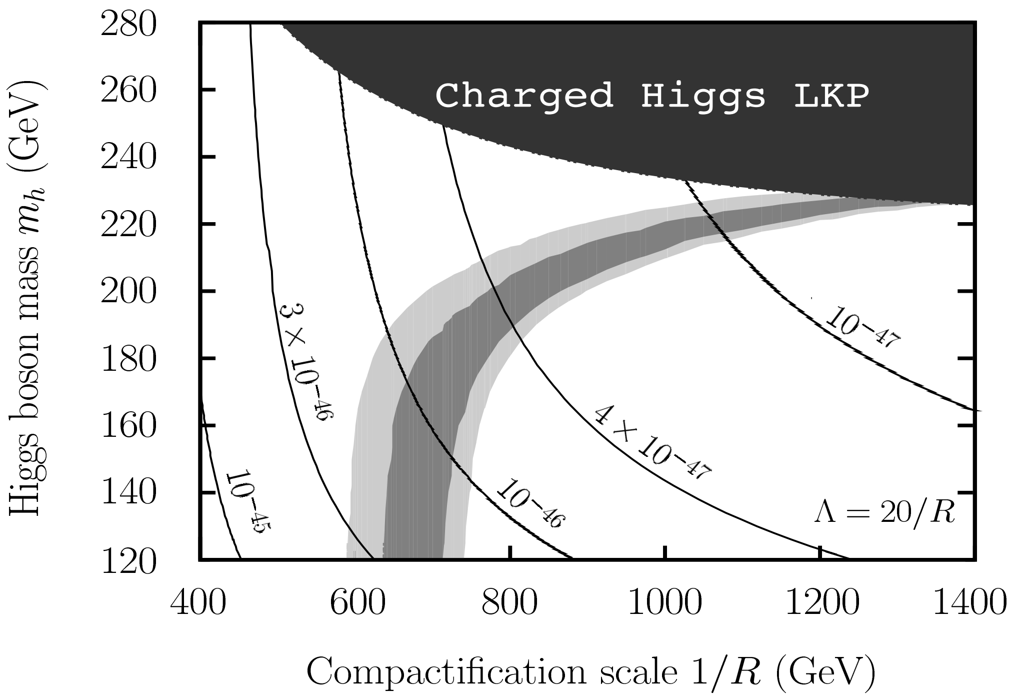
Long-distance | Short-distance | Short-distance | Long-distance

Remark:

You should not include the long-distance contribution of light quarks (u, d, s) into the perturbative calculation.

KK photon DM

SI scattering cross section



We obtain the SI cross section $\sigma_{SI} = 10^{-46} \sim 10^{-47}$ cm^2, which is larger than those in the previous works by almost an order of magnitude.

J. Hisano, K. Ishiwata, N. Nagata, and M. Yamanaka, Prog. Theor. Phys. Vol. 126, No. **3** (2011) 435.

M. Kakizaki, S. Matsumoto and M. Senami, Phys. Rev. D **74**, 023504 (2006).