



Direct Detection of KK Photon Dark Matter

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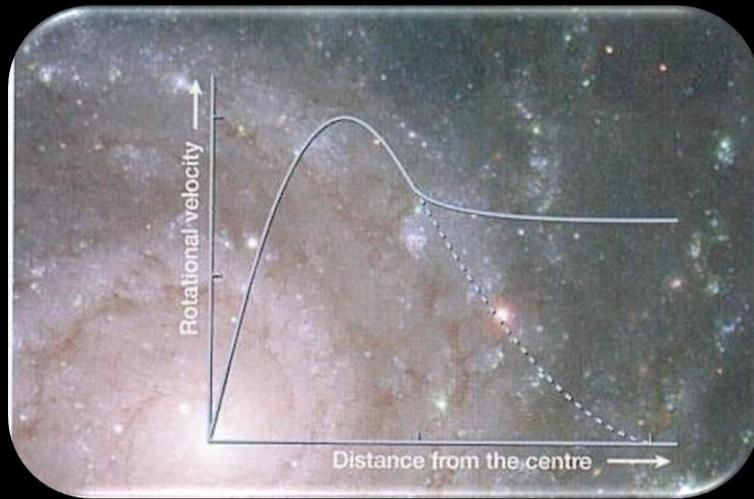
Based on arXiv:1012.5455(J. Hisano, K. Ishiwata, N. Nagata, and MY)



Introduction



Introduction



✂ Candidate of dark matter
Weakly Interacting
Massive Particle (WIMP)

✂ Promising scenario

Thermal relic scenario in
TeV scale models beyond SM

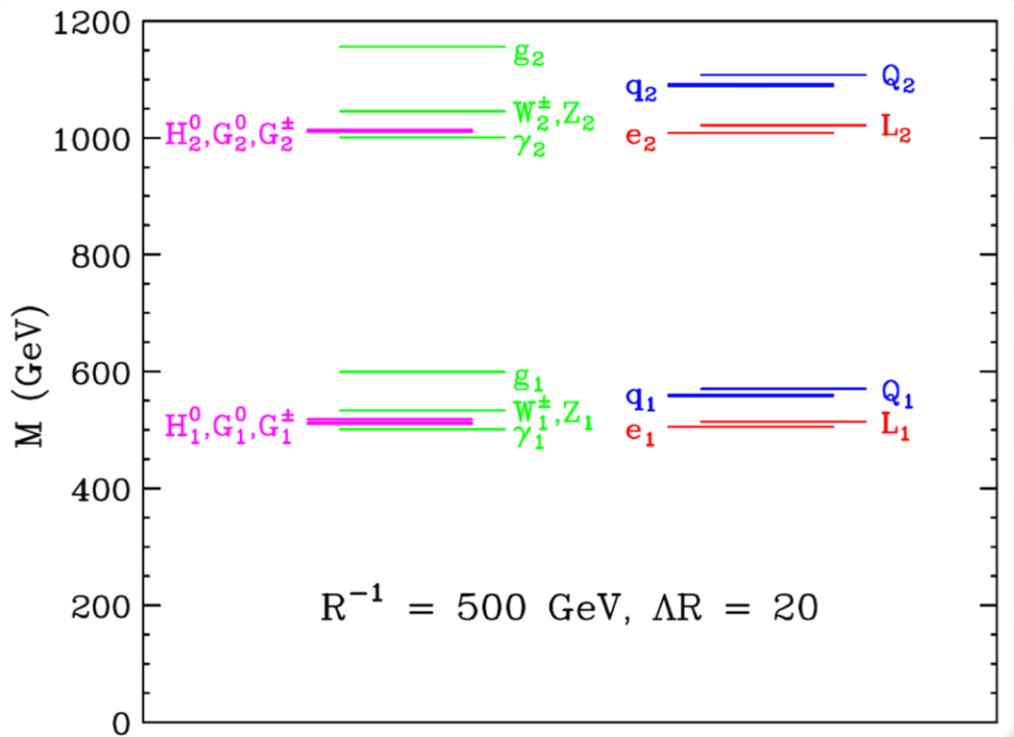


One of the leading candidates
Kaluza-Klein photon in universal extra dimension model

Universal Extra Dimension (UED) model

[Appelquist, Cheng, Dobrescu PRD67 (2000)]

- 5-dimensional space-time (time 1 + space 4)
- All SM particles propagate along extra dimensional space
- **Many** Kaluza-Klein (KK) particles for **one** SM particle



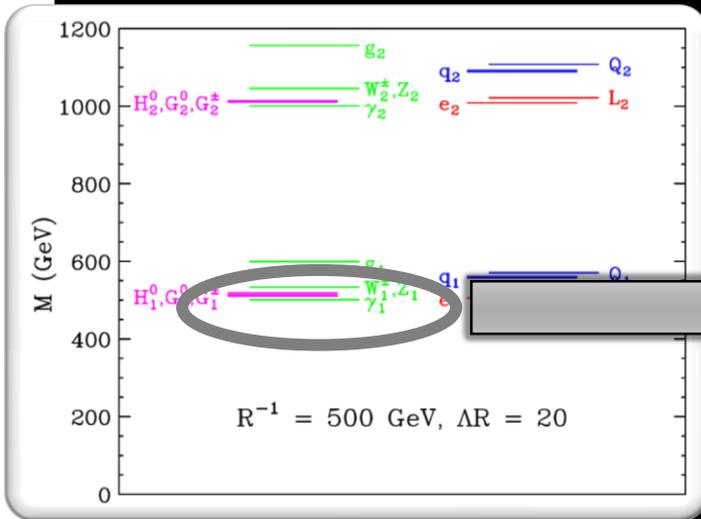
Mass spectrum $1/R, 2/R, 3/R, \dots$
for each particle species

$1/R$: compactification scale
of extra dimension $\sim \mathcal{O}(\text{TeV})$

[Datta, Kong, Matchev PRD72 (2005)]

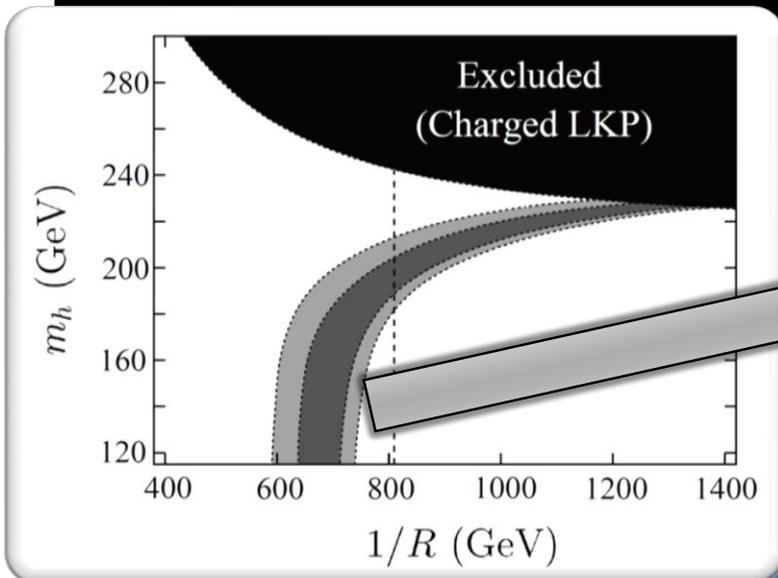
WIMP dark matter in UED model

■ Stability of Lightest KK Particle (LKP) is ensured by KK-parity



KK-parity $\left(\begin{array}{l} - : \text{KK particles with odd KK number} \\ + : \text{KK particles with even KK number} \end{array} \right)$

LKP : KK photon $\gamma^{(1)}$
WIMP dark matter candidate



Allowed region of relic abundance
 $600\text{GeV} \lesssim 1/R \lesssim 1400\text{GeV}$

DM direct detection experiment

- Cutoff scale of UED model
- Information of dark matter

- Identification of dark matter
- Establishment of UED model

Collider experiment

- Compactification scale $1/R$
- Particle contents

Need complementary tests
from different type experiments

DM direct detection experiment

- Cutoff scale of UED model
- Information of dark matter

Insufficient points in previous calculations

- Gluon contribution is not taken into account
- Twist-2 operator is not treated correctly

Purpose in this talk

Calculation of the cross section of DM-nucleon scattering including all of effective operators precisely



Direct detection of WIMP dark matter

Direct detection of KK photon dark matter

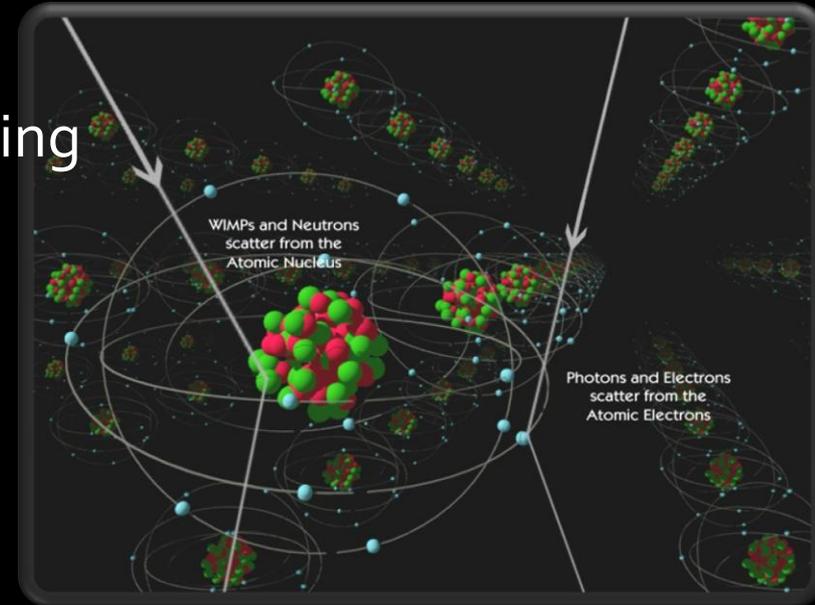
Cross section of DM-nucleon scattering

$$\sigma = \frac{1}{\pi} \left(\frac{m_T}{M_{\text{DM}} + m_T} \right)^2 |n_p f_p + n_n f_n|^2$$

m_T Target nucleus mass

M_{DM} Dark matter mass

$n_p(n)$ Number of proton(neutron) in the target nucleus

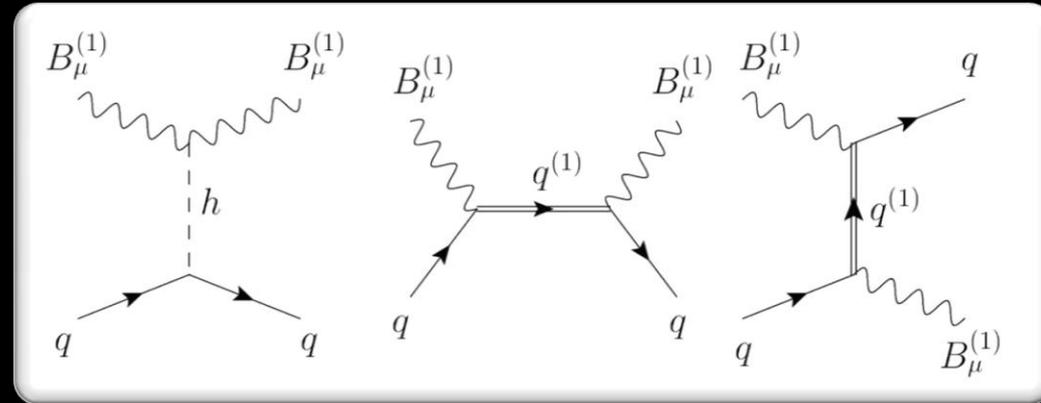


Effective coupling of vector dark matter with nucleon

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

Direct detection of KK photon dark matter

Light quark contributions



Effective Lagrangian

$$\mathcal{L}^{\text{eff}} = f_q m_q B^\mu B_\mu \bar{q} q$$

Coefficient in the effective Lagrangian

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

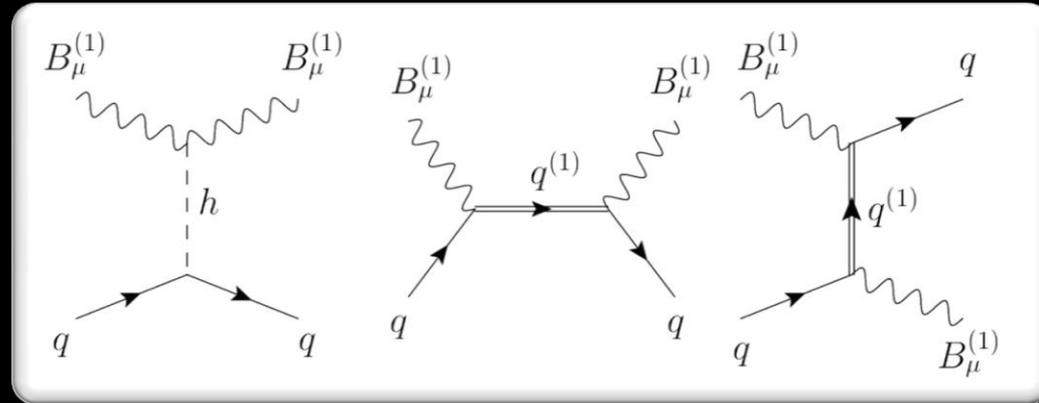
Effective coupling of vector dark matter with nucleon

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

$$\langle N | m_q \bar{q} q | N \rangle / m_N \equiv f_{Tq}$$

Direct detection of KK photon dark matter

Light quark contributions



Effective Lagrangian

$$\mathcal{L}^{\text{eff}} = \frac{g_q}{M_{\text{DM}}^2} B^\rho i \partial^\mu i \partial^\nu B_\rho \mathcal{O}_{\mu\nu}^q$$

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

Coefficient in the effective Lagrangian

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

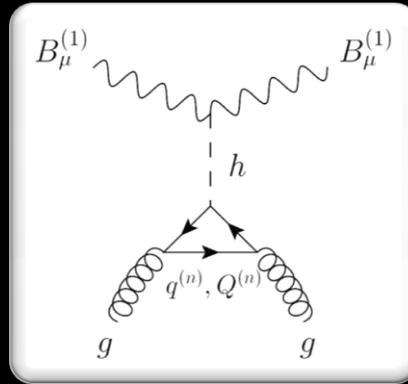
Effective coupling of vector dark matter with nucleon

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

$q(2) + \bar{q}(2)$: Coefficient determined by parton distribution function

Direct detection of KK photon dark matter

Gluon contribution



Effective Lagrangian

$$\mathcal{L}_G^{\text{eff}} = f_G B^\rho B_\rho G^{a\mu\nu} G_{\mu\nu}^a$$

Coefficient in the effective Lagrangian

$$f_G^{(\text{iii})} = \frac{g_1^2 \alpha_s}{48\pi m_h^2} \left[(c_c + c_b + c_t) + c_t \sum_n \frac{2m_t^2}{m_{t^{(n)}} m_{T^{(n)}}} \right]$$

Effective coupling of vector dark matter with nucleon

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

$$1 - \sum_{u,d,s} f_{Tq} \equiv f_{TG}$$

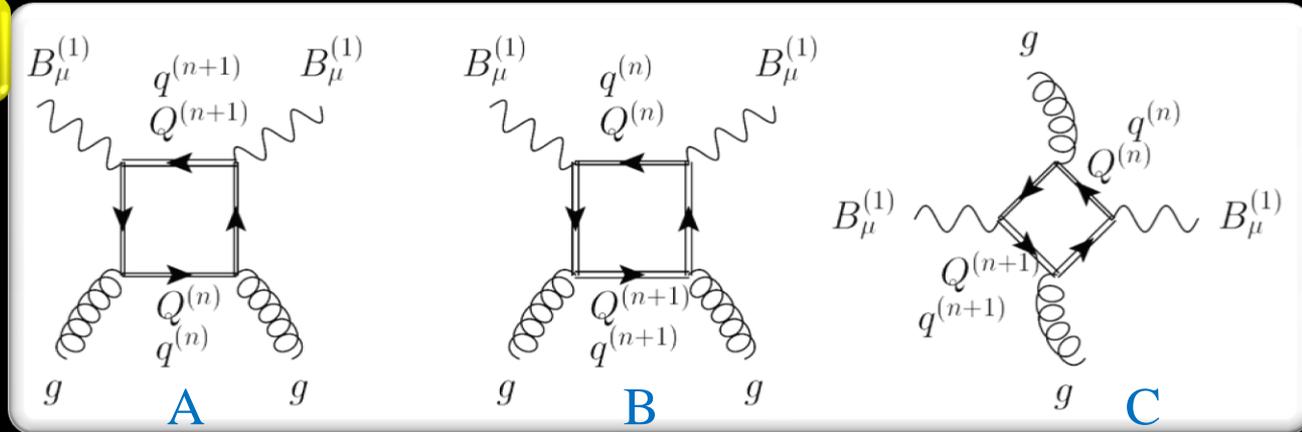
$$f_G = f_G^{(\text{i})} + f_G^{(\text{ii})} + f_G^{(\text{iii})}$$

Direct detection of KK photon dark matter

New contribution

Gluon contribution

$$n = 0$$



Effective Lagrangian

$$\mathcal{L}_G^{\text{eff}} = f_G B^\rho B_\rho G^{a\mu\nu} G_{\mu\nu}^a$$

Effective coupling of vector dark matter with nucleon

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

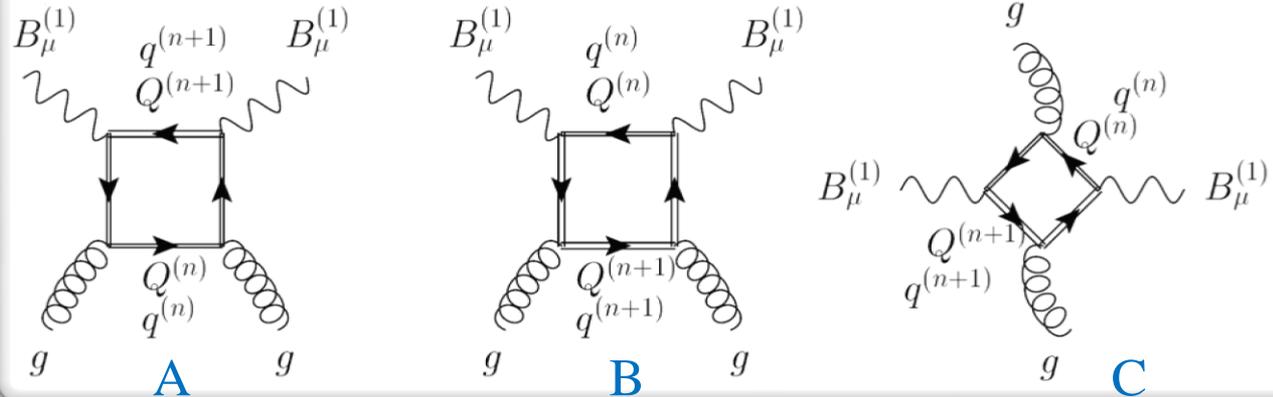
$$f_G = f_G^{(i)} + f_G^{(ii)} + f_G^{(iii)}$$

Direct detection of KK photon dark matter

New contribution

Gluon contribution

$$n = 0$$



Coefficient in the effective Lagrangian

$$f_G^{(i)} = \frac{\alpha_s}{4\pi} \sum_{q=c,b,t} c_q \left[(a_{Q^{(1)q}}^2 + b_{Q^{(1)q}}^2) f_+^{(A)}(M; m, m_{Q^{(1)}}) + (a_{Q^{(1)q}}^2 - b_{Q^{(1)q}}^2) f_-^{(A)}(M; m, m_{Q^{(1)}}) \right]$$

$$+ \frac{\alpha_s}{4\pi} \sum_{q=\text{all}} \sum_{I=B, C} \left[(a_{Q^{(1)q}}^2 + b_{Q^{(1)q}}^2) f_+^{(I)}(M; m, m_{Q^{(1)}}) + (a_{Q^{(1)q}}^2 - b_{Q^{(1)q}}^2) f_-^{(I)}(M; m, m_{Q^{(1)}}) \right]$$

+ (terms for $SU(2)_L$ singlet KK quark)

c_q : QCD correction

$f_{\pm}^{(A, B, C)}$: Function obtained by loop calculation

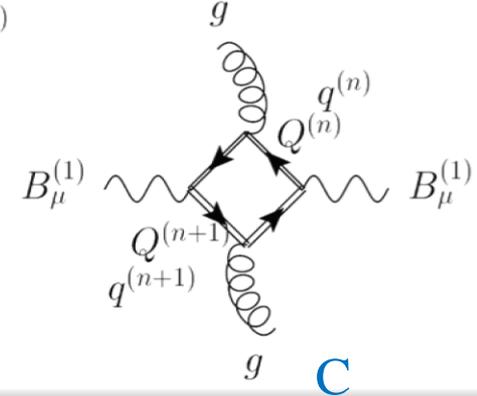
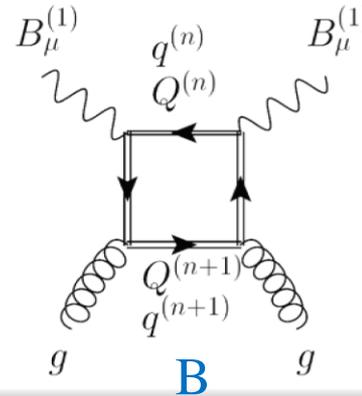
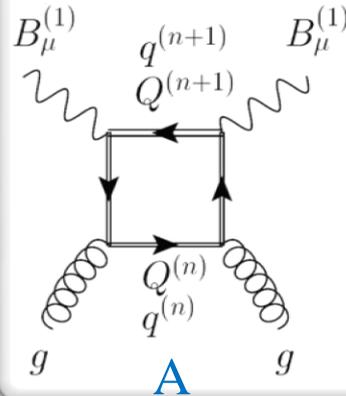
$a_{Q^{(1)q}}, b_{Q^{(1)q}}$: Function of gauge coupling, hyper-charge, and mixing angle of KK quark mass matrix

Direct detection of KK photon dark matter

New contribution

Gluon contribution

$$n \neq 0$$



$$f_G^{(ii)} = \frac{\alpha_s}{4\pi} \sum_{q=\text{all}} \sum_{I=A,B,C} \left\{ a_{q^{(n+1)}q^{(n)}}^2 [f_+^{(I)}(M; m_{q^{(n)}}, m_{q^{(n+1)}}) + f_-^{(I)}(M; m_{q^{(n)}}, m_{q^{(n+1)}})] \right. \\ + a_{Q^{(n+1)}Q^{(n)}}^2 [f_+^{(I)}(M; m_{Q^{(n)}}, m_{Q^{(n+1)}}) + f_-^{(I)}(M; m_{Q^{(n)}}, m_{Q^{(n+1)}})] \\ + b_{Q^{(n+1)}q^{(n)}}^2 [f_+^{(I)}(M; m_{q^{(n)}}, m_{Q^{(n+1)}}) - f_-^{(I)}(M; m_{q^{(n)}}, m_{Q^{(n+1)}})] \\ \left. + b_{q^{(n+1)}Q^{(n)}}^2 [f_+^{(I)}(M; m_{Q^{(n)}}, m_{q^{(n+1)}}) - f_-^{(I)}(M; m_{Q^{(n)}}, m_{q^{(n+1)}})] \right\}$$

Effective coupling of vector dark matter with nucleon

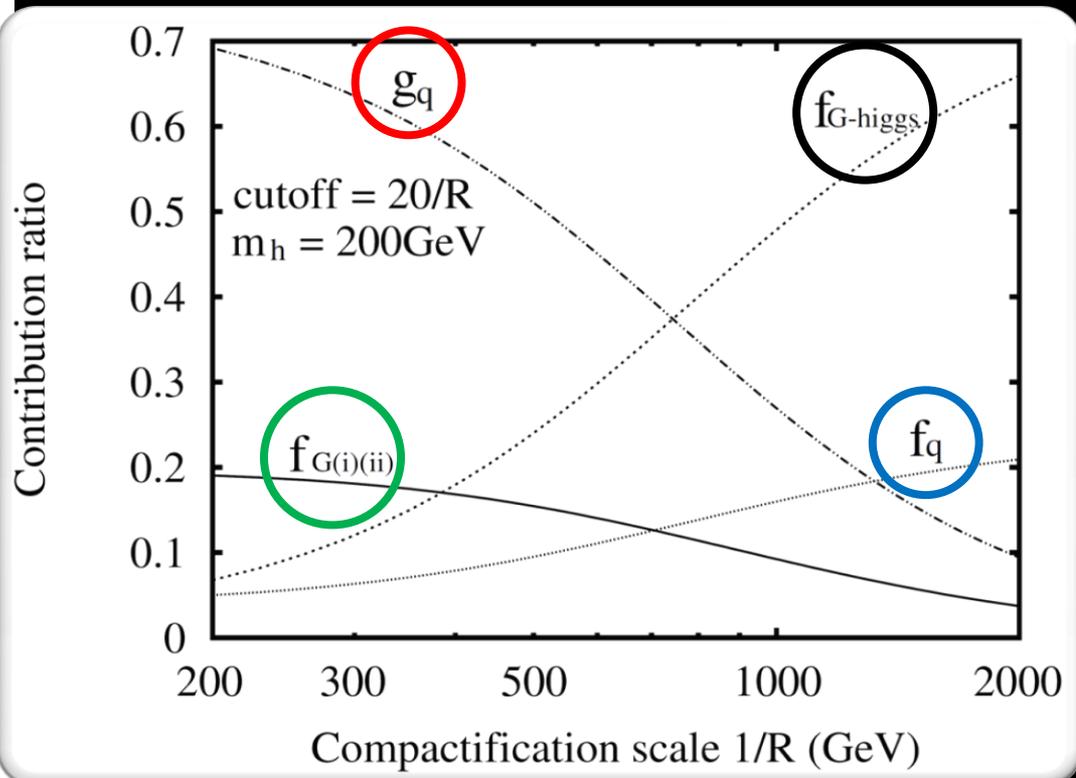
$$f_N/m_N = \sum_{q=u,d,s} f_q f_{Tq} + \sum_{q=u,d,s,c,b} \frac{3}{4} (q(2) + \bar{q}(2)) f_q - \frac{8\pi}{9\alpha_s} f_{TG} f_G$$

$$f_G = f_G^{(i)} + f_G^{(ii)} + f_G^{(iii)}$$



Numerical result and discussion

Significance of gluon contribution

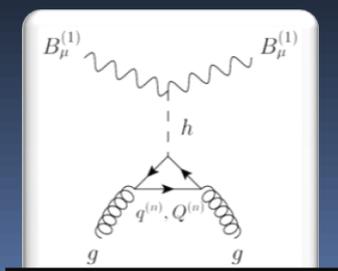
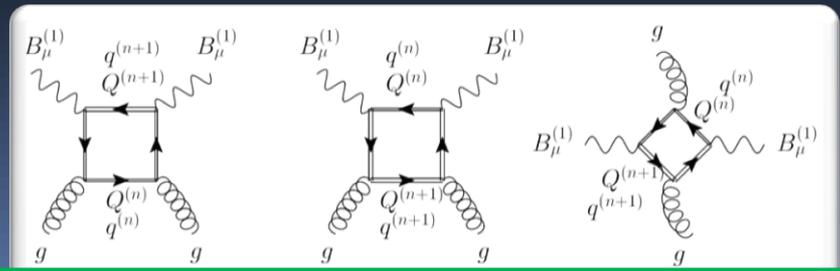


Each contribution of coefficients
in effective coupling

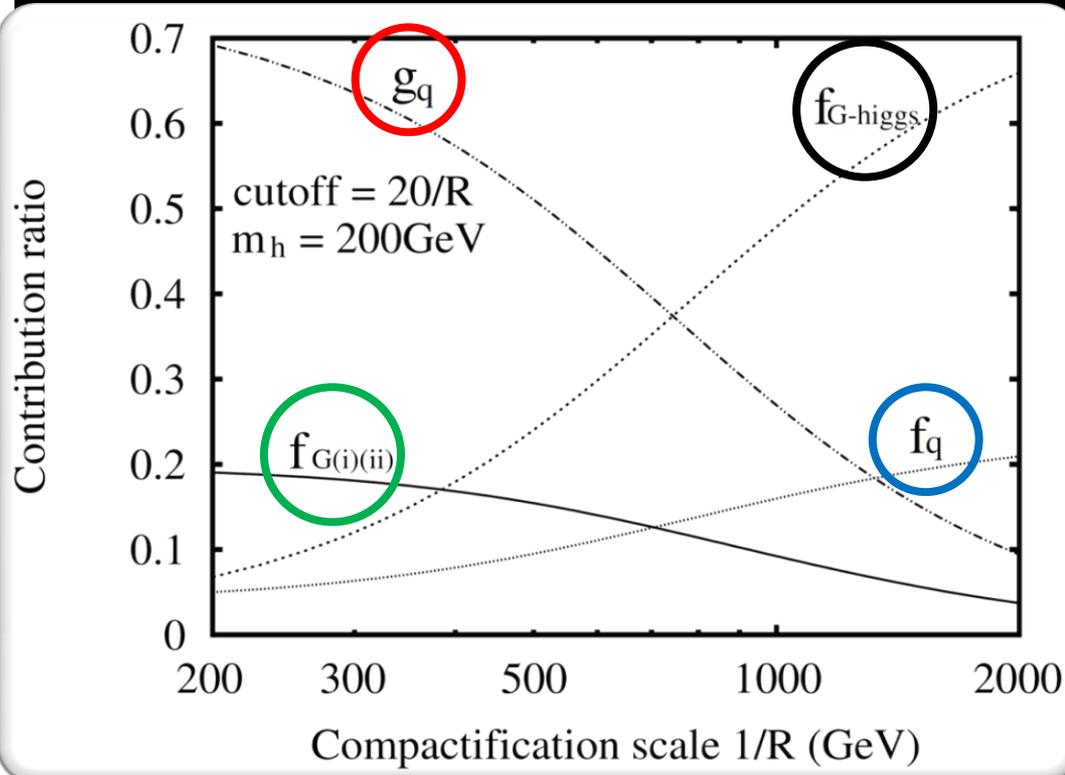
$$\frac{\text{Each contribution}}{\text{Sum of all contributions}}$$

Effective coupling
of DM with nucleon

$$f_N/m_N = \underbrace{\sum_{q=u,d,s} f_q f_{Tq}}_{\text{blue underline}} + \underbrace{\sum_{q=u,d,s,c,b} \frac{3}{4} (q(2) + \bar{q}(2)) g_q}_{\text{red underline}} - \frac{8\pi}{9\alpha_s} f_{TG} f_G$$



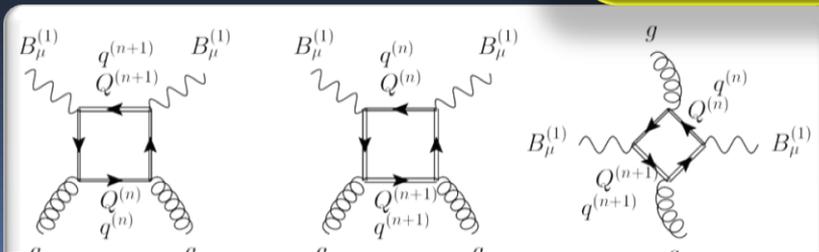
Significance of gluon contribution



Each contribution of coefficients
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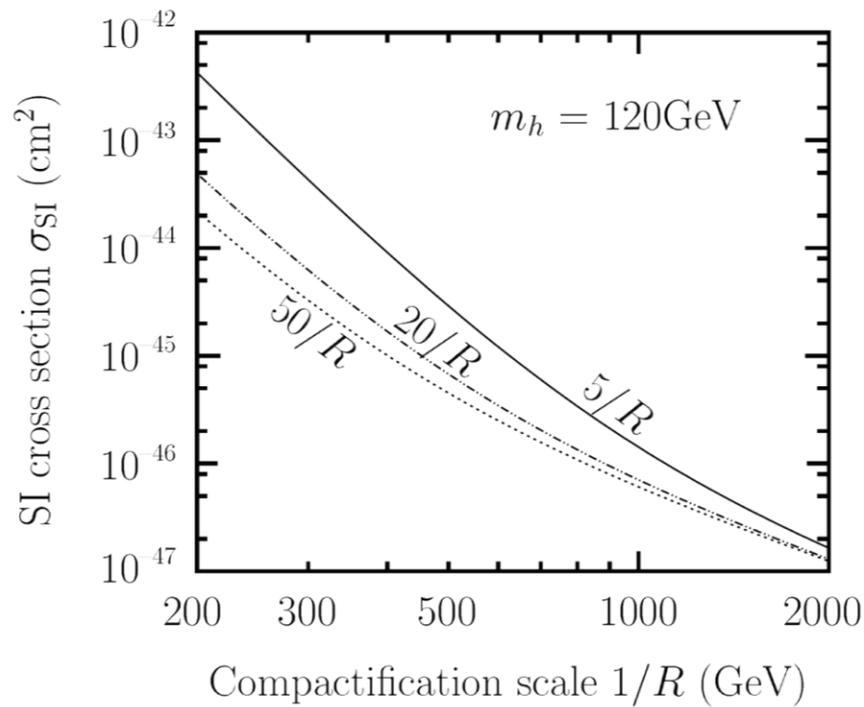
Each contribution
Sum of all contributions

Gluon contribution is important !



Cutoff scale dependence

Spin-independent cross section with proton



For cutoff scale n/R

KK particles up to the n -th mode are included

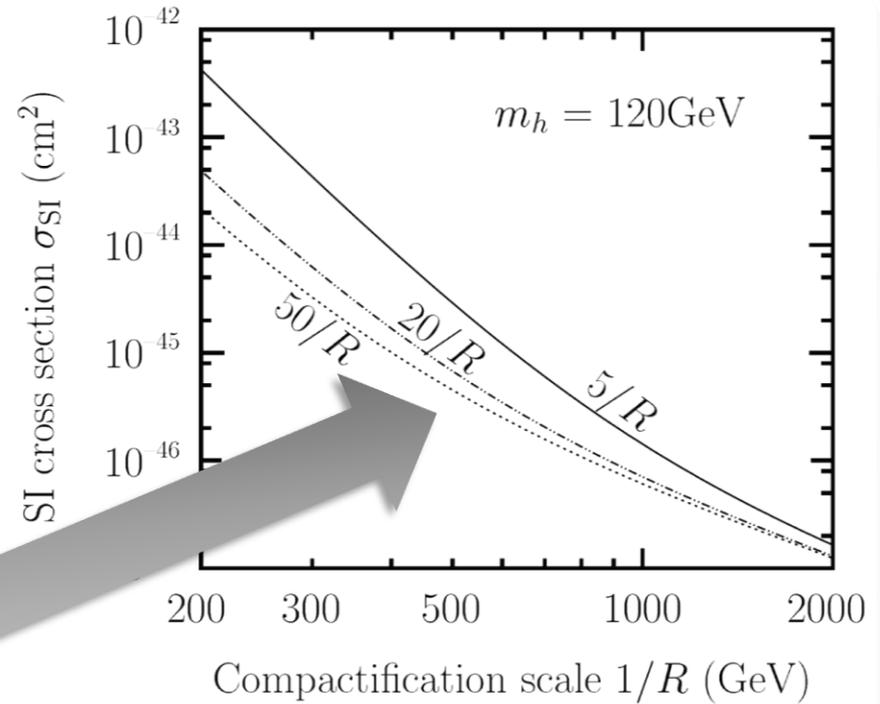


Large cutoff = large number of KK particle contributions

Cutoff scale dependence

Spin-independent cross section with proton

Why cross section tends to be small for larger cutoff ??



For cutoff scale n/R

KK particles up to the n -th mode are included



Large cutoff = large number of KK particle contributions

Cutoff scale dependence

KK quark mass

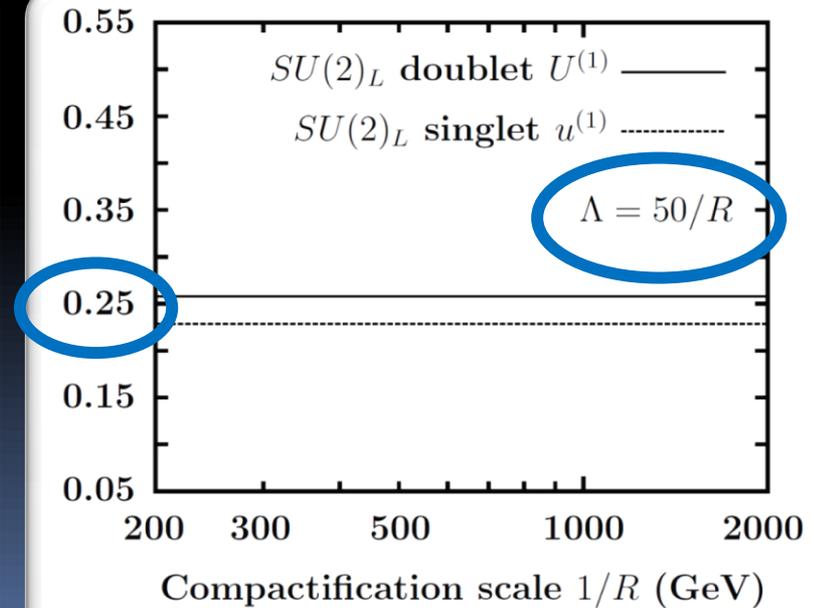
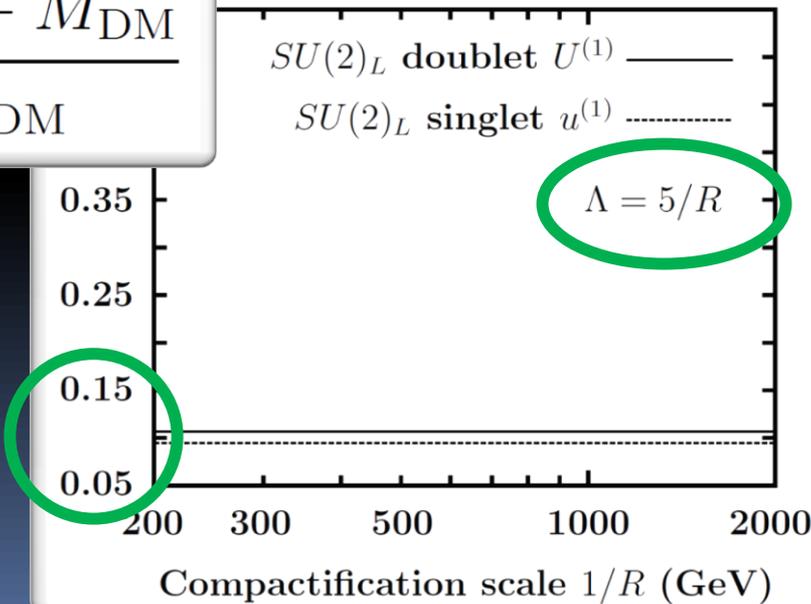
$$m_{u^{(n)}/U^{(n)}} = n/R + m_{\text{SM}u} + \delta m_{u^{(n)}/U^{(n)}}$$

Radiative correction

$$\delta m_{u^{(n)}} = \left(3g_s^2 + g_1^2 \right) \frac{n}{R} \frac{\ln(\Lambda^2 R^2)}{16\pi^2} \propto \ln(\Lambda^2)$$

$$\delta m_{U^{(n)}} = \left(3g_s^2 + \frac{27}{16}g_2^2 + \frac{1}{16}g_1^2 \right) \frac{n}{R} \frac{\ln(\Lambda^2 R^2)}{16\pi^2} \propto \ln(\Lambda^2)$$

$$\frac{m_{q^{(1)}} - M_{\text{DM}}}{M_{\text{DM}}}$$



Cutoff scale dependence

KK quark mass

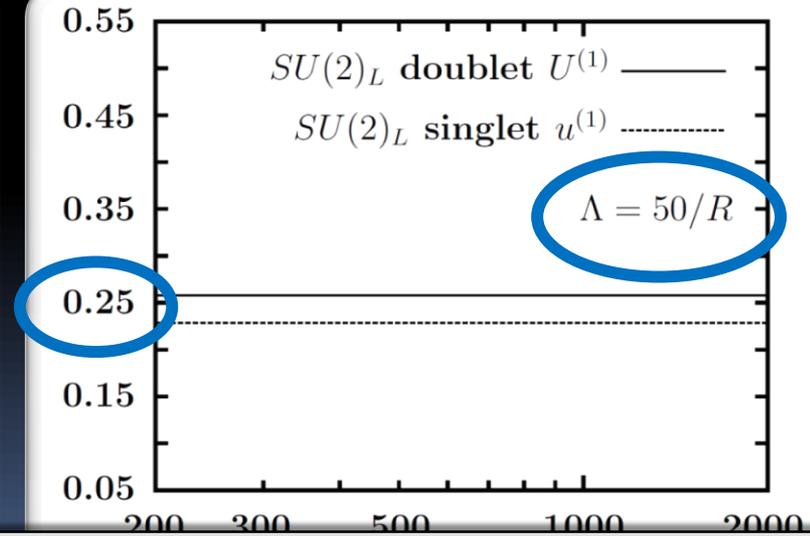
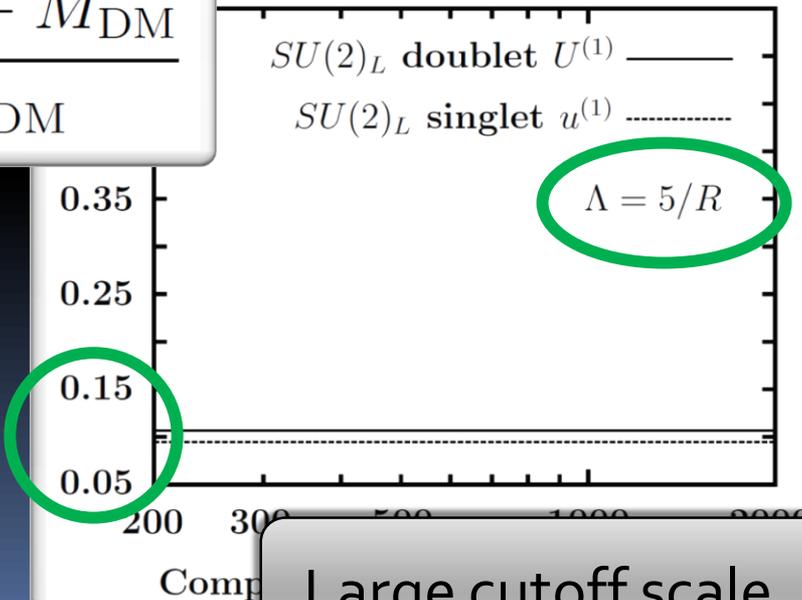
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Radiative correction

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$$\frac{m_{q^{(1)}} - M_{\text{DM}}}{M_{\text{DM}}}$$



Large cutoff scale



Large mass splitting

Cutoff scale dependence

Effective Lagrangian for DM direct detection

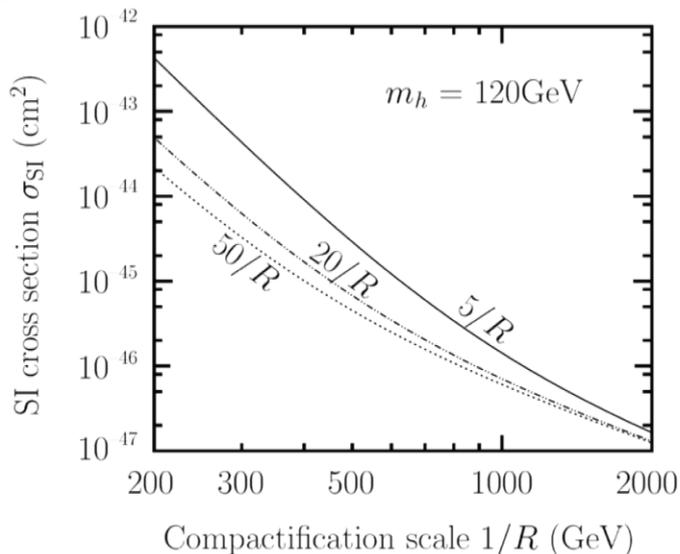
$$\mathcal{L}^{\text{eff}} = f_q m_q B^\mu B_\mu \bar{q}q + \frac{g_q}{M_{\text{DM}}^2} B^\rho i \partial^\mu i \partial^\nu B_\rho \mathcal{O}_{\mu\nu}^q$$

Coefficients of the effective Lagrangian

$$g_q = -g_1^2 M_{\text{DM}}^2 \left[\frac{Y_{qL}^2}{(m_{U^{(1)}}^2 - M_{\text{DM}}^2)^2} + \frac{Y_{qR}^2}{(m_{u^{(1)}}^2 - M_{\text{DM}}^2)^2} \right]$$

$$f_q = -\frac{g_1^2}{4m_h^2} - \frac{g_1^2}{4} \left[Y_{qL}^2 \frac{m_{U^{(1)}}^2}{(m_{U^{(1)}}^2 - M_{\text{DM}}^2)^2} + Y_{qR}^2 \frac{m_{u^{(1)}}^2}{(m_{u^{(1)}}^2 - M_{\text{DM}}^2)^2} \right] + \frac{g_1^2 Y_{qL} Y_{qR}}{m_{U^{(1)}} + m_{u^{(1)}}} \left[\frac{m_{U^{(1)}}}{m_{U^{(1)}}^2 - M_{\text{DM}}^2} + \frac{m_{u^{(1)}}}{m_{u^{(1)}}^2 - M_{\text{DM}}^2} \right]$$

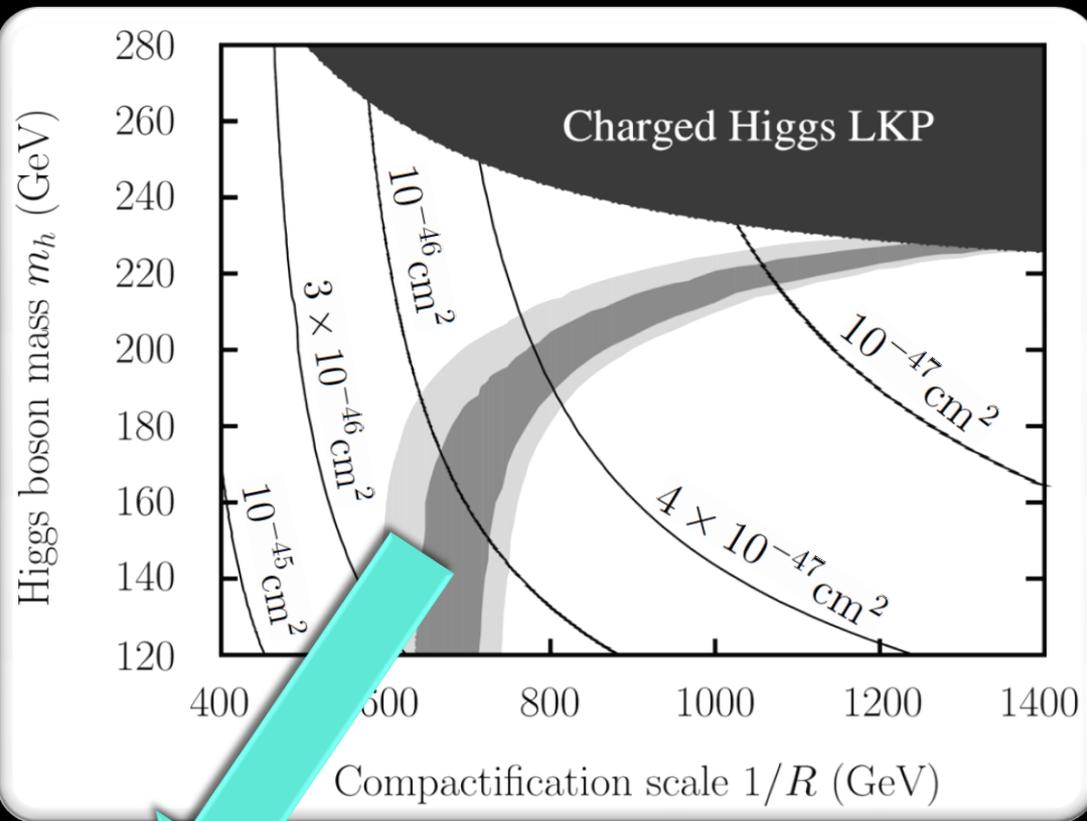
Large mass splitting \longleftrightarrow Small effective coupling



Cross section tends to be small for larger cutoff scale

Direct detection experiments have the sensitivity to cutoff scale

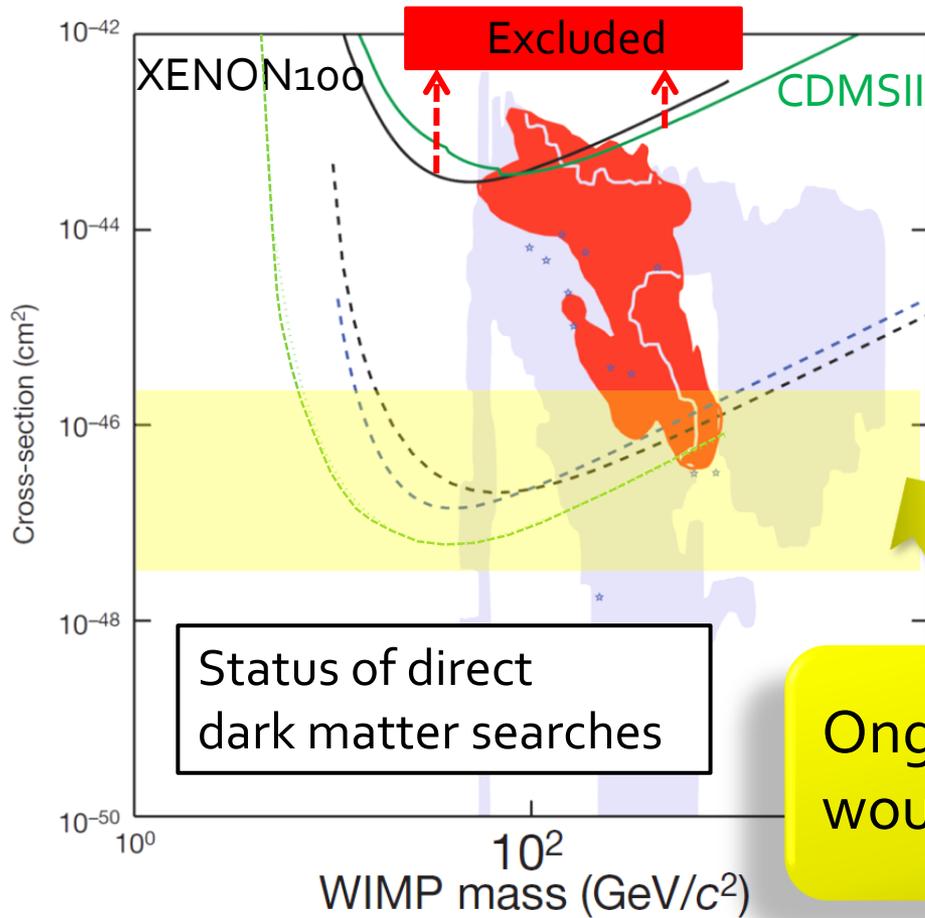
Relic abundance and WIMP-proton cross section



Allowed region in light of WIMP relic abundance

Cross section in the allowed region

$$3 \times 10^{-46} \text{ cm}^2 - 5 \times 10^{-48} \text{ cm}^2$$



Ongoing and future experiments would reach sensitivities in this range

[G. Bertone Nature 468 (2010)]

Cross section in the allowed region

$$3 \times 10^{-46} \text{ cm}^2 - 5 \times 10^{-48} \text{ cm}^2$$

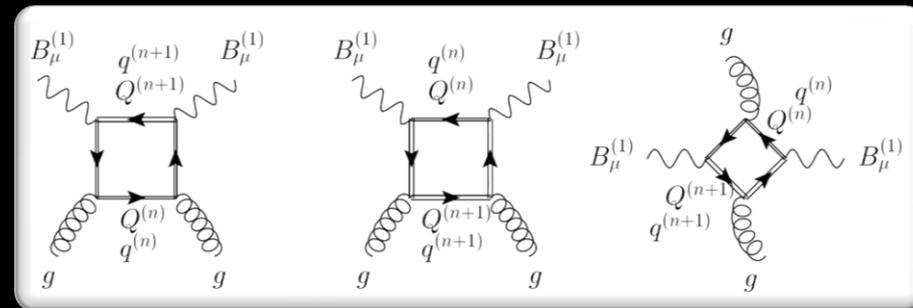


Summary



- Direct detection experiments serve information for WIMP dark matter, and significant for the model development
- We calculated WIMP-nucleon cross section including effective operators correctly

Though gluon contribution had not been taken into account, it could be sub-leading contribution



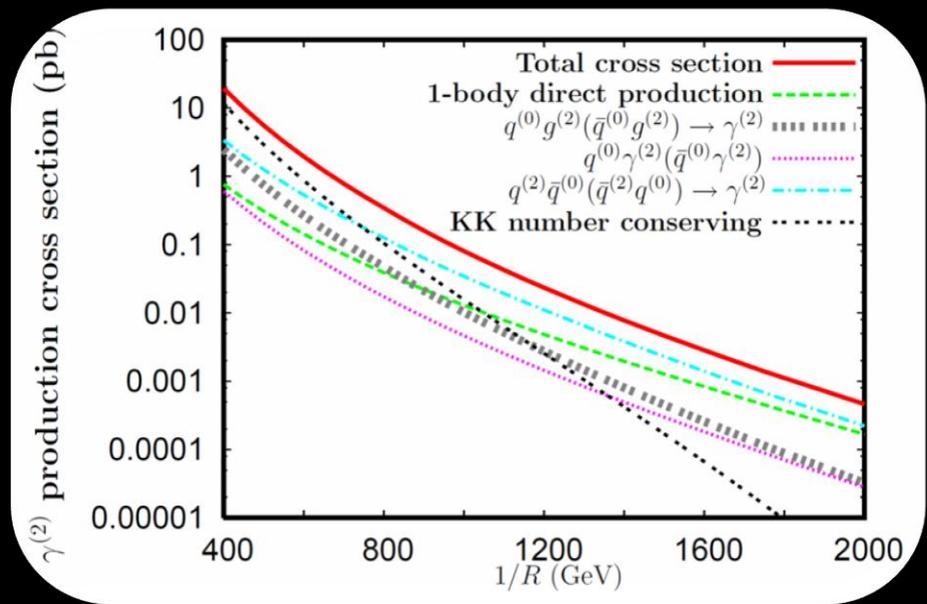
- Calculated cross section is larger than those in previous works by up to a factor of 10
- In WMAP allowed region: $3 \times 10^{-46} \text{ cm}^2 \text{ — } 5 \times 10^{-48} \text{ cm}^2$
Future direct detection experiments will discover the signature !
- Application of calculated results to general vector dark matter case is straightforward



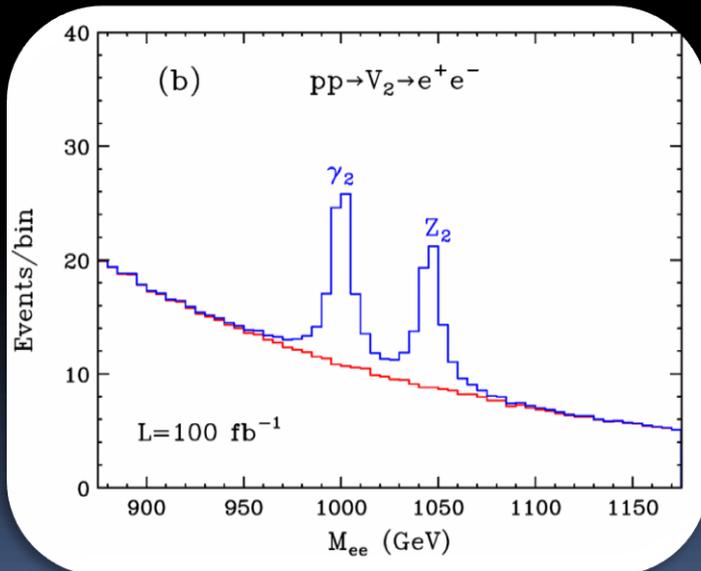
Appendix

Approach to UED model

Collider experiment



[S. Matsumoto, J. Sato, M. Senami, MY, PRD80 (2009)]



[A. Datta, K. Kong, K. T. Matchev PRD 72 (2005)]

Advantage

- Compactification scale $1/R$
- Particle contents

Disadvantage

- Cutoff scale of UED model
- Information of dark matter

Universal Extra Dimension (UED) model

[Appelquist, Cheng, Dobrescu PRD67 (2000)]

- 3 families from anomaly cancellation

[Dobrescu, Poppitz PRL 68 (2001)]

- Preventing rapid proton decay from non-renormalizable operators

[Appelquist, Dobrescu, Ponton, Yee PRL 87 (2001)]

- Existence of dark matter

[Servant, Tait NPB 650 (2003)]

- Explaining cosmic ray excess anomaly

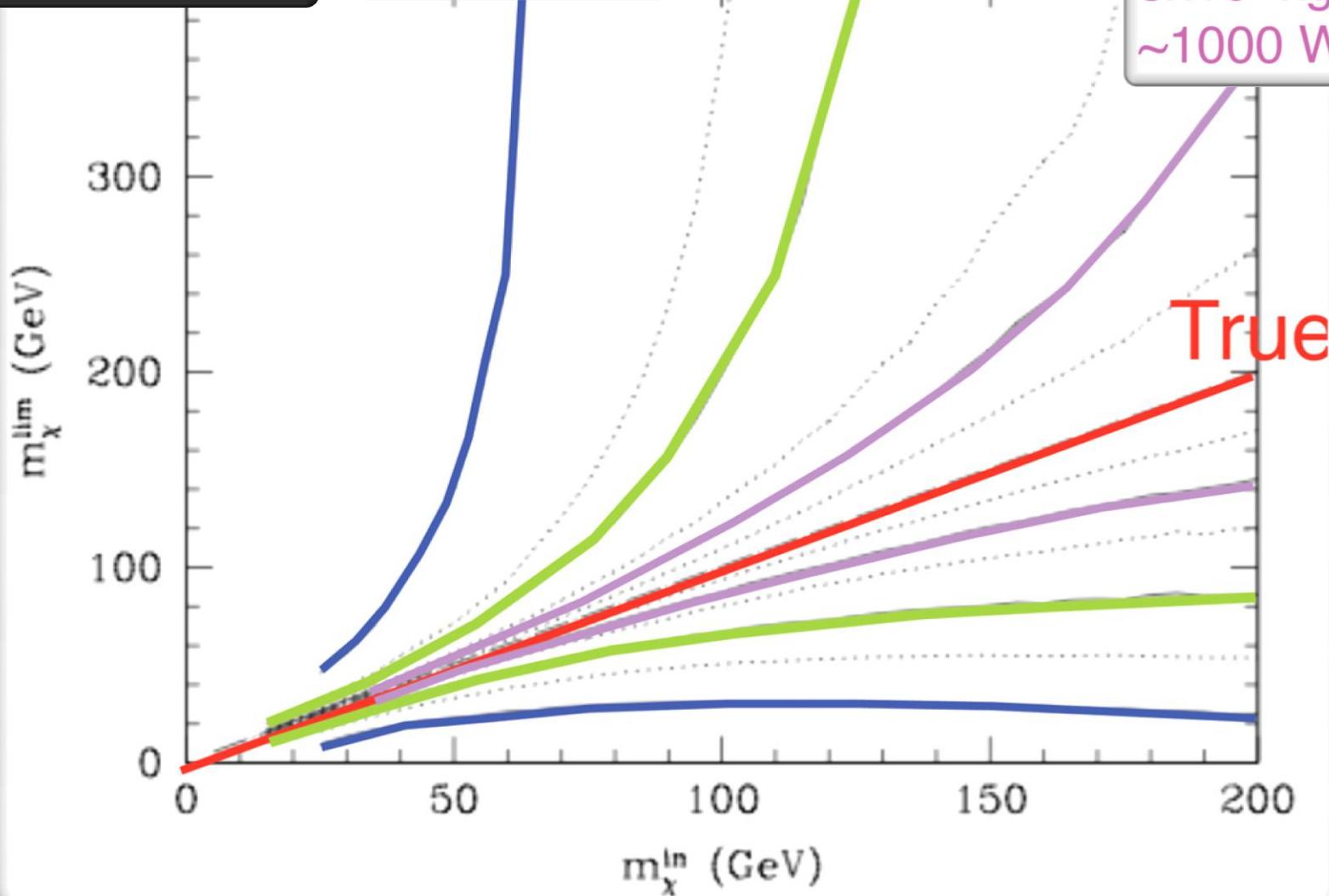
[J. Chang *et al.* Nature 456 (2008)]

10^{-8} pb, Ge
95% solid,

3×10^3 kg day
 ~ 10 WIMPs

3×10^4 kg day
 ~ 100 WIMPs

3×10^5 kg day
 ~ 1000 WIMPs



$$\begin{aligned}
f_+^{(A)}(M; m_1, m_2) &= \frac{1}{6\Delta^2 M^2} \left[\Delta [M^2(m_2^2 - m_1^2) + m_1^2(m_1^2 + 5m_2^2)] \right. \\
&\quad \left. - 6m_1^2 m_2^2 [(m_2^2 - m_1^2)^2 - M^2(m_1^2 + 3m_2^2)] \right] - \frac{m_1^2}{12M^4} \ln \left(\frac{m_1^2}{m_2^2} \right) \\
&+ \frac{m_1^2 L}{12\Delta^2 M^4} \left[(m_2^2 + m_1^2 - M^2)\Delta^2 + 2m_2^2 \Delta \{5m_2^4 + 20m_1^2 m_2^2 - m_1^4 + M^2(9m_2^2 + m_1^2)\} \right. \\
&\quad \left. + 12m_2^4 \{M^2(m_2^4 + 10m_1^2 m_2^2 + 5m_1^4) - (m_2^2 - m_1^2)^2(m_2^2 + 3m_1^2)\} \right]
\end{aligned}$$

$$\begin{aligned}
f_-^{(A)}(M; m_1, m_2) &= -\frac{m_2}{6m_1 \Delta^2} \left[\Delta(2m_2^2 + m_1^2 - 2M^2) + 6m_1^2 m_2^2 (m_2^2 - m_1^2 - M^2) \right] \\
&\quad + \frac{m_1 m_2^3 \{ \Delta + m_1^2 (m_2^2 - m_1^2 + M^2) \}}{\Delta^2} L
\end{aligned}$$

$$\Delta(M; m_1, m_2) \equiv M^4 - 2M^2(m_1^2 + m_2^2) + (m_2^2 - m_1^2)^2,$$

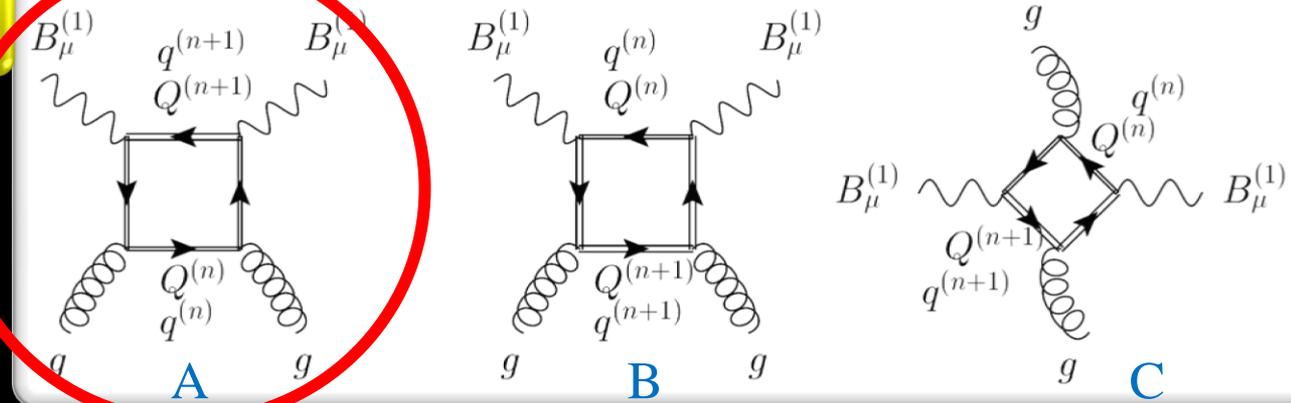
$$L(M; m_1, m_2) \equiv \begin{cases} \frac{1}{\sqrt{|\Delta|}} \ln \left(\frac{m_2^2 + m_1^2 - M^2 + \sqrt{|\Delta|}}{m_2^2 + m_1^2 - M^2 - \sqrt{|\Delta|}} \right) & (\Delta > 0) \\ \frac{2}{\sqrt{|\Delta|}} \tan^{-1} \left(\frac{\sqrt{|\Delta|}}{m_2^2 + m_1^2 - M^2} \right) & (\Delta < 0) \end{cases}$$

Direct detection of KK photon dark matter

New contribution

Gluon contribution

$$n = 0$$



Coefficient in the effective Lagrangian

$$f_G^{(i)} = \frac{\alpha_s}{4\pi} \sum_{q=c,b,t} c_q \left[(a_{Q^{(1)q}}^2 + b_{Q^{(1)q}}^2) f_+^{(A)}(M; m, m_{Q^{(1)}}) + (a_{Q^{(1)q}}^2 - b_{Q^{(1)q}}^2) f_-^{(A)}(M; m, m_{Q^{(1)}}) \right] \\ + \frac{\alpha_s}{4\pi} \sum_{q=\text{all}} \sum_{I=B, C} \left[(a_{Q^{(1)q}}^2 + b_{Q^{(1)q}}^2) f_+^{(I)}(M; m, m_{Q^{(1)}}) + (a_{Q^{(1)q}}^2 - b_{Q^{(1)q}}^2) f_-^{(I)}(M; m, m_{Q^{(1)}}) \right] \\ + (\text{terms for } SU(2)_L \text{ singlet KK quark})$$

We must not include light quark contributions into diagram A

- To evade double-counting (their contributions are included in f_{T_q})
- Loop integral is dominated by light quark mass scale, and we cannot employ perturbative approach at smaller scale than QCD scale