Dark Matter in Gauge-Higgs Unification

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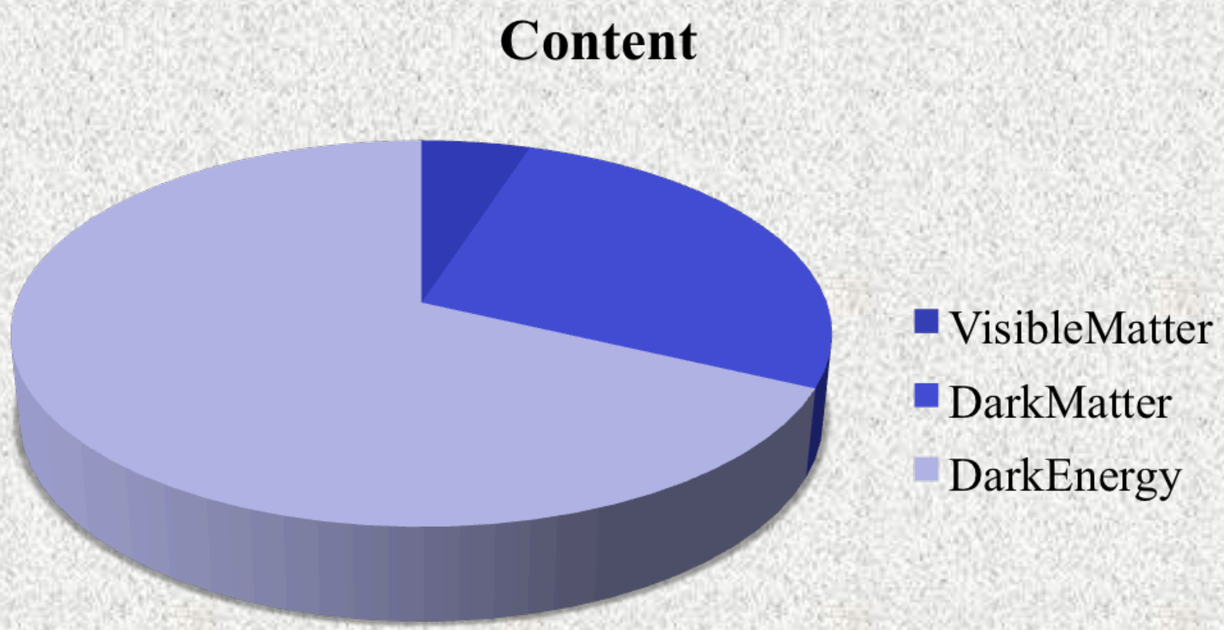
Introduction

The existence of DM is certain from the various observations, but its origin is still a mystery



We know...

DM is NOT a particle in the SM

Physics beyond the SM

Numerous possibilities considered

In this talk,

Some possibilities of DM is discussed in the context of gauge-Higgs unification

PLAN

1: Introduction ✔
2: Fermion DM
3: $SU(2)_L$ Doublet Vector DM

Fermion DM

"Fermionic Dark Matter
in Gauge-Higgs Unification"

NM, T. Miyaji, N. Okada and S. Okada
JHEP1707 (2017) 048

"Fermionic Minimal Dark Matter
in 5D Gauge-Higgs Unification"

NM, N. Okada and S. Okada
PRD96 (2017) no.11 115023

Consider 5D SU(3)×U(1)′ GHU model on S^1/Z_2

BC $\quad S^1$: $A_M(y+2\pi R) = A_M(y)$

Z_2: $A_\mu(-y) = P^\dagger A_\mu(y)P$, $A_y(-y) = -P^\dagger A_y(y)P$, $P=\mathrm{diag}(-,-,+)$

$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ (-,-) & (-,-) & (+,+) \end{pmatrix}, A_5 = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}$$

Only (+,+) has massless mode@KK scale

SU(3) → SU(2)xU(1)
A_5 → SM Higgs

$$A_\mu^{(0)} = \frac{1}{2}\begin{pmatrix} W_\mu^3 + B_\mu^3/\sqrt{3} & \sqrt{2}W_\mu^+ & 0 \\ \sqrt{2}W_\mu^- & -W_\mu^3 + B_\mu^3/\sqrt{3} & 0 \\ 0 & 0 & -2B_\mu/\sqrt{3} \end{pmatrix}, A_5^{(0)} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ H^- & H^{0*} & 0 \end{pmatrix}$$

In a simple GHU model, it is known that
Higgs mass & $H \to \gamma\gamma$ cannot be reproduced

↓

To avoid these problems,
extra fermions are often introduced and
play an important role

NM & Okada, PRD87 (2013) 095019

It is natural to ask
if these fermions can be
DM candidate or not

DM Lagrangian

$$\mathcal{L}_{DM} = \bar{\psi} i \not{D} \psi + \bar{\tilde{\psi}} i \not{D} \tilde{\psi} - M\left(\bar{\psi}\tilde{\psi} + \bar{\tilde{\psi}}\psi\right)$$

$$+\delta(y)\left[\frac{m}{2}\bar{\psi}_{3R}^{(0)c}\psi_{3R}^{(0)} + \frac{\tilde{m}}{2}\bar{\tilde{\psi}}_{3L}^{(0)c}\tilde{\psi}_{3L}^{(0)} + h.c.\right]$$

A pair of SU(3) triplet with opposite Z_2 parity

$$\not{D} = \Gamma^M\left(\partial_M - igA_M - ig'A'_M\right)$$

$$\psi = \left(\psi_1, \psi_2, \psi_3\right)^T, \quad \tilde{\psi} = \left(\tilde{\psi}_1, \tilde{\psi}_2, \tilde{\psi}_3\right)^T$$

$$\psi(-y) = +P\gamma^5\psi(y), \quad \tilde{\psi}(-y) = -P\gamma^5\tilde{\psi}(y)$$

➡ Dirac mass terms to avoid massless modes

DM Lagrangian

$$\mathcal{L}_{DM} = \bar{\psi} i \not{D} \psi + \bar{\tilde{\psi}} i \not{D} \tilde{\psi} - M \left(\bar{\psi} \tilde{\psi} + \bar{\tilde{\psi}} \psi \right) + \delta(y) \left[\frac{m}{2} \bar{\psi}^{(0)c}_{3R} \psi^{(0)}_{3R} + \frac{\tilde{m}}{2} \bar{\tilde{\psi}}^{(0)c}_{3L} \tilde{\psi}^{(0)}_{3L} + h.c. \right]$$

Brane localized Majorana masses for $SU(2)_L \times U(1)_Y$ singlets

No DM-DM-Z coupling

⇒ No spin-independent cross section with nuclei via Z-boson exchange

Mass matrix of DM sector

$$\mathcal{L}^{0-mode}_{mass} = -\frac{1}{2}\left(\bar{\chi}\ \bar{\tilde{\chi}}\ \bar{\omega}\ \bar{\tilde{\omega}}\right)\begin{pmatrix} m & M & m_W & 0 \\ M & \tilde{m} & 0 & -m_W \\ m_W & 0 & 0 & M \\ 0 & -m_W & M & 0 \end{pmatrix}\begin{pmatrix} \chi \\ \tilde{\chi} \\ \omega \\ \tilde{\omega} \end{pmatrix}$$

Lightest ⇒ DM

$$m_1 = \frac{1}{2}\left(m - \sqrt{4m_W^2 + (m-2M)^2}\right),\ m_2 = \frac{1}{2}\left(m + \sqrt{4m_W^2 + (m-2M)^2}\right)$$

$$m_3 = \frac{1}{2}\left(m - \sqrt{4m_W^2 + (m+2M)^2}\right),\ m_4 = \frac{1}{2}\left(m + \sqrt{4m_W^2 + (m+2M)^2}\right)$$

$m = \tilde{m}$ for simplicity

Written in terms of Majorana basis

$$\chi \equiv \psi_{3R}^{(0)} + \psi_{3R}^{(0)c},\quad \tilde{\chi} \equiv \tilde{\psi}_{3L}^{(0)} + \tilde{\psi}_{3L}^{(0)c}$$

$$\omega \equiv \psi_{2L}^{(0)} + \psi_{2L}^{(0)c},\quad \tilde{\omega} \equiv \tilde{\psi}_{2R}^{(0)} + \tilde{\psi}_{2R}^{(0)c}$$

DM-Higgs coupling

$$\mathcal{L}_{Higgs\ coupling} = -\frac{1}{2}\left(\frac{m_W}{v}\right) h \left(\bar{\chi}\ \bar{\tilde{\chi}}\ \bar{\varpi}\ \bar{\tilde{\varpi}}\right) \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} \chi \\ \tilde{\chi} \\ \omega \\ \tilde{\omega} \end{pmatrix}$$

DM

$$= -\frac{1}{2}\left(\frac{m_W}{v}\right) h \left(\bar{\eta}_1\ \bar{\eta}_2\ \bar{\eta}_3\ \bar{\eta}_4\right) \begin{pmatrix} C_1 & C_5 & 0 & 0 \\ C_5 & C_2 & 0 & 0 \\ 0 & 0 & C_3 & C_6 \\ 0 & 0 & C_6 & C_4 \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \end{pmatrix}$$

DM-Higgs coupling is NOT free parameters in GHU, but a gauge coupling

Mass eigenstates

$$C_i \equiv 4u_i / c_i^2 \,(i = 1 \sim 4),\ C_5 \equiv 2(u_1 + u_2)/c_1 c_2\,,\ C_6 \equiv 2(u_3 + u_4)/c_3 c_4$$

$$u_i \equiv (m_i - M)/m_W\,,\ c_i \equiv \sqrt{2(u_i^2 + 1)}$$

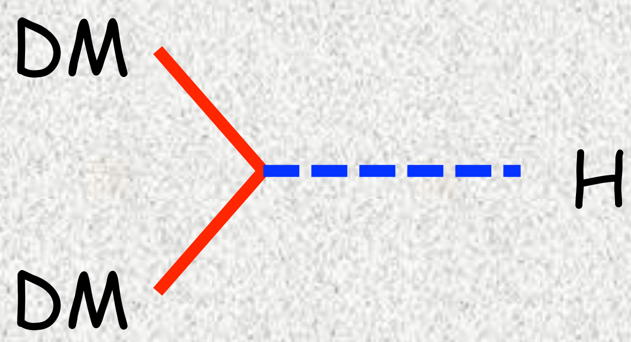
DM Relic Abundance

Interactions relevant to DM($=\eta_1$) physics

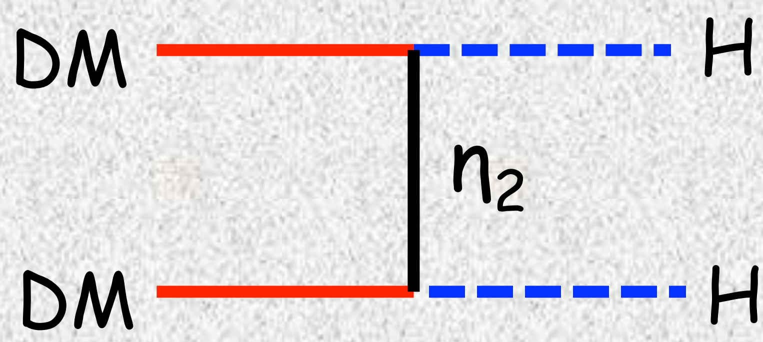
$$\mathcal{L}_{DM-H} = -\frac{1}{2}\left(\frac{m_W}{v}\right)C_1 h\bar{\psi}_{DM}\psi_{DM} - \frac{1}{2}\left(\frac{m_W}{v}\right)C_5 h\left(\bar{\eta}_2\psi_{DM} + h.c.\right)$$

$$\simeq \frac{1}{2}\left(\frac{m_W}{v}\right)\left(\frac{2m_W}{2M-m}\right)h\bar{\psi}_{DM}\psi_{DM} - \frac{1}{2}\left(\frac{m_W}{v}\right)h\left(\bar{\eta}_2\psi_{DM} + h.c.\right)\left(M \gg m_W\right)$$

two main DM annihilation modes



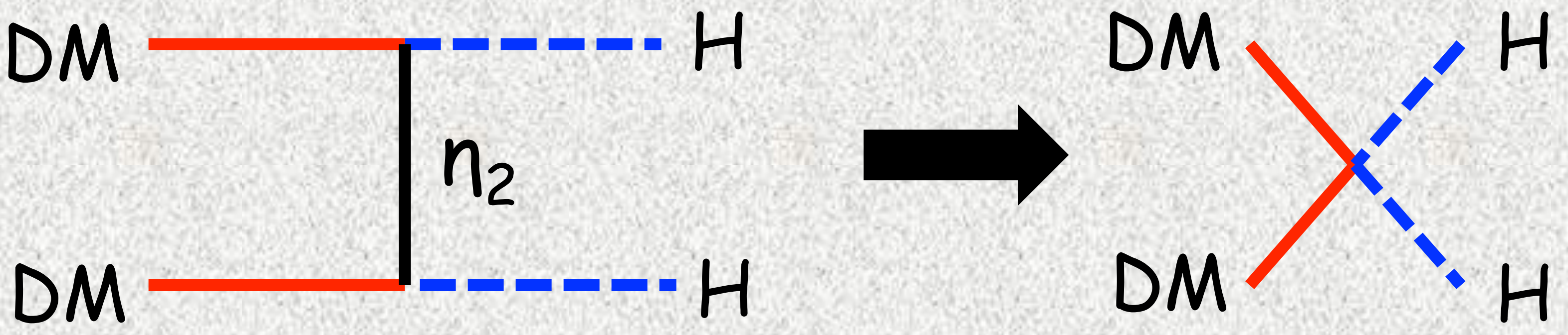
s-channel Higgs exchange



t/u-channel η_2 exchange

$|C_1| << 1$, $C_5 \sim 1$ ⇒ the latter is dominant for $m_{DM} > m_h$

Let us first estimate



$$\mathcal{L}^{eff}_{DM-H} = \frac{1}{2}\left(\frac{m_W}{v}\right)^2 \frac{C_5^2}{m_2} hh\bar{\psi}_{DM}\psi_{DM}$$

$$\Rightarrow \sigma v_{rel} = \frac{1}{64\pi^2}\left(\frac{m_W}{v}\right)^4 \left(\frac{C_5^2}{m_2}\right)^2 v_{rel} \equiv \sigma_0 v_{rel}$$

Observed DM relic density (Planck 2015)

$$\Omega_{DM}h^2 = 0.1198 \pm 0.0015 \Rightarrow \sigma_0 \sim 1pb$$

Our case: $\sigma_0 \sim 0.02$ pb for $C_5 \sim 1$, $m_2 \sim M \sim 1$ TeV

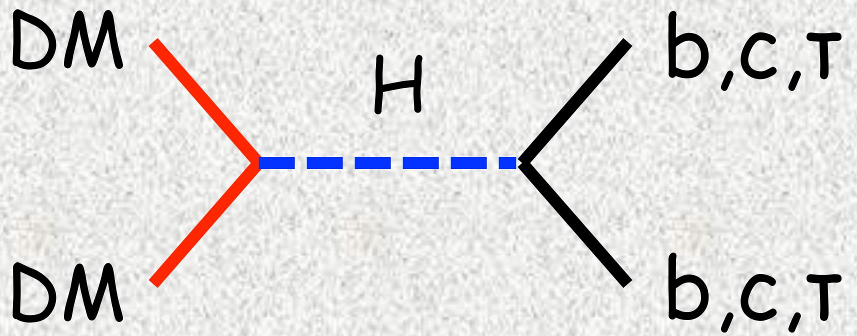
NOT WORK

Although the coupling between DM & Higgs is suppressed, s-channel Higgs exchange annihilation can be enhanced at $m_{DM}\sim m_h/2=62.5$GeV

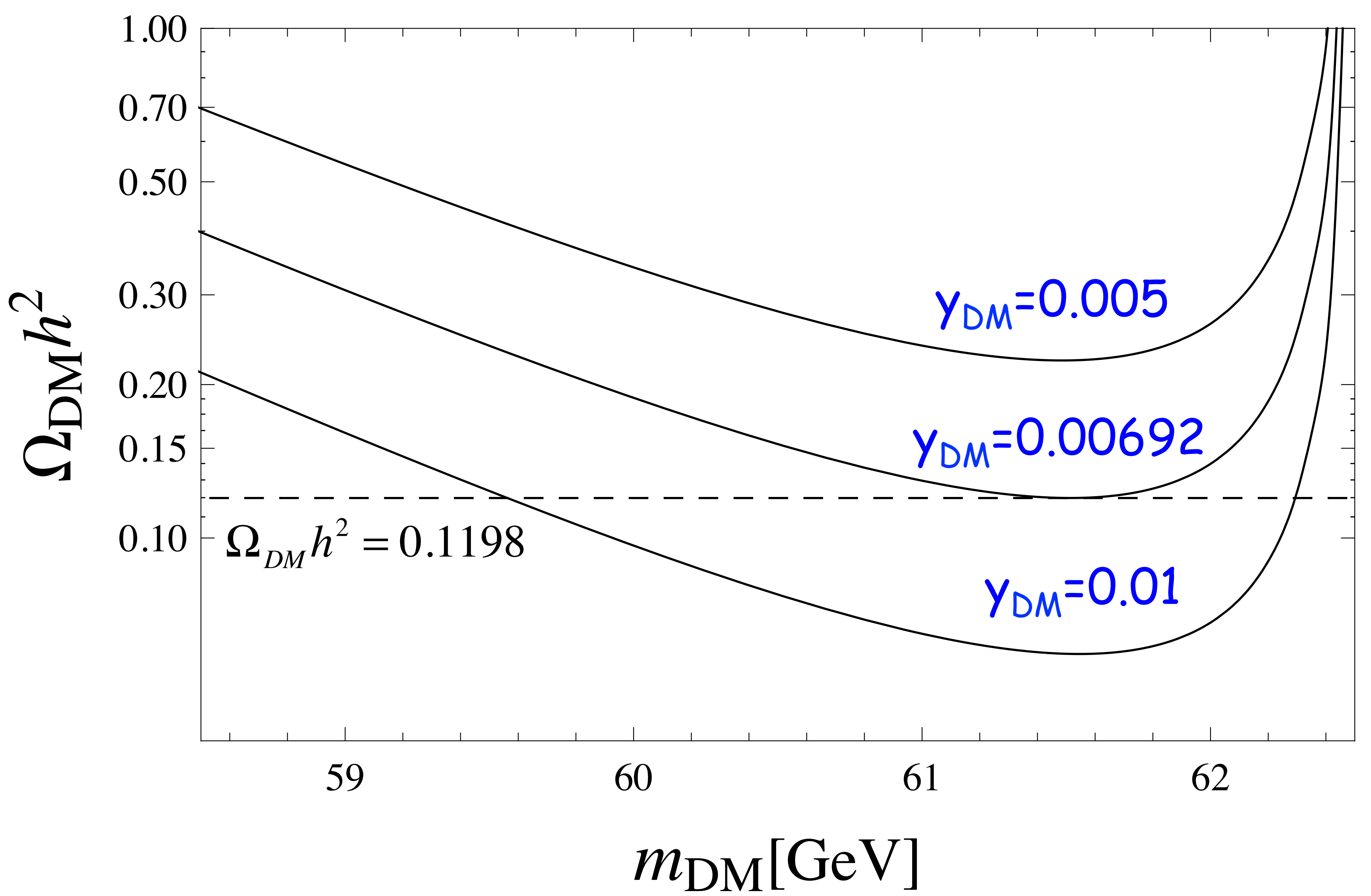
Cross section

$$\sigma(s)_{\psi_{DM}\psi_{DM}\to h\to f\bar{f}}=\frac{y_{DM}^2}{16\pi}\left[3\left(\frac{m_b}{v}\right)^2+3\left(\frac{m_c}{v}\right)^2+\left(\frac{m_\tau}{v}\right)^2\right]\frac{\sqrt{s\left(s-4m_{DM}^2\right)}}{\left(s-m_h^2\right)^2+m_h^2\Gamma_h^2}$$

$$y_{DM}=\left(\frac{m_W}{v}\right)|C_1|,\ \ \Gamma_h=\Gamma_h^{SM}+\Gamma_h^{new},\quad \Gamma_h^{new}=\begin{cases}0 & m_h<2m_{DM}\\ \frac{m_h}{16\pi}\left(1-\frac{4m_{DM}^2}{m_h^2}\right)^{3/2}y_{DM}^2 & m_h>2m_{DM}\end{cases}$$



DM relic density as a function of m_{DM}



Direct DM Detection

DM-Nucleon scattering via Higgs exchange

$$\sigma_{DM+N\to DM+N} = \frac{1}{\pi}\left(\frac{y_{DM}}{v}\right)^2 \left(\frac{m_N m_{DM}}{m_N + m_{DM}} \frac{1}{m_h^2}\right)^2 f_N^2 \simeq 4.47\times 10^{-7}\, pb \times y_{DM}^2$$

$$f_N^2 = \left(\sum_{q=u,d,s} f_{T_q} + \frac{2}{9} f_{TG}\right)^2 m_N^2 \simeq 0.0706 m_N^2,$$

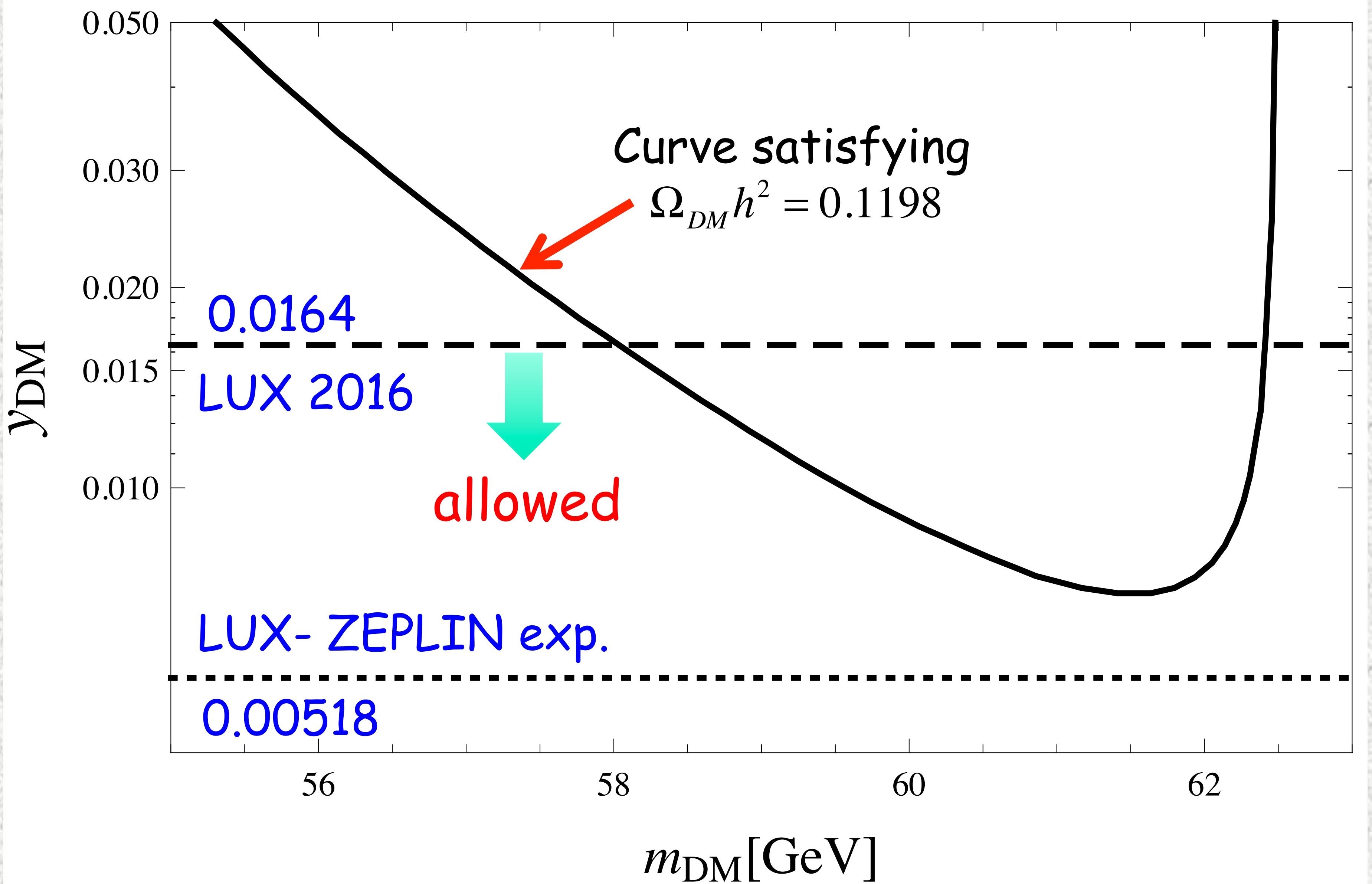
$$m_{DM} = m_h/2 = 62.5 GeV, m_N = 0.939 GeV$$

Exp. bound

$\sigma_{DM\text{-}N} \leqq 1.2\times 10^{-10}$ pb $\Rightarrow y_{DM} \leqq 0.0164$ (LUX 2016)

$\sigma_{DM\text{-}N} \leqq 1.2\times 10^{-11}$ pb $\Rightarrow y_{DM} \leqq 0.00518$ (LUX-ZEPLIN)

Upper bound for y_{DM}



Higgs mass RGE analysis

Higgs mass analysis by 4D EFT approach

In GHU, m_H likely to be small $\because$ loop generated

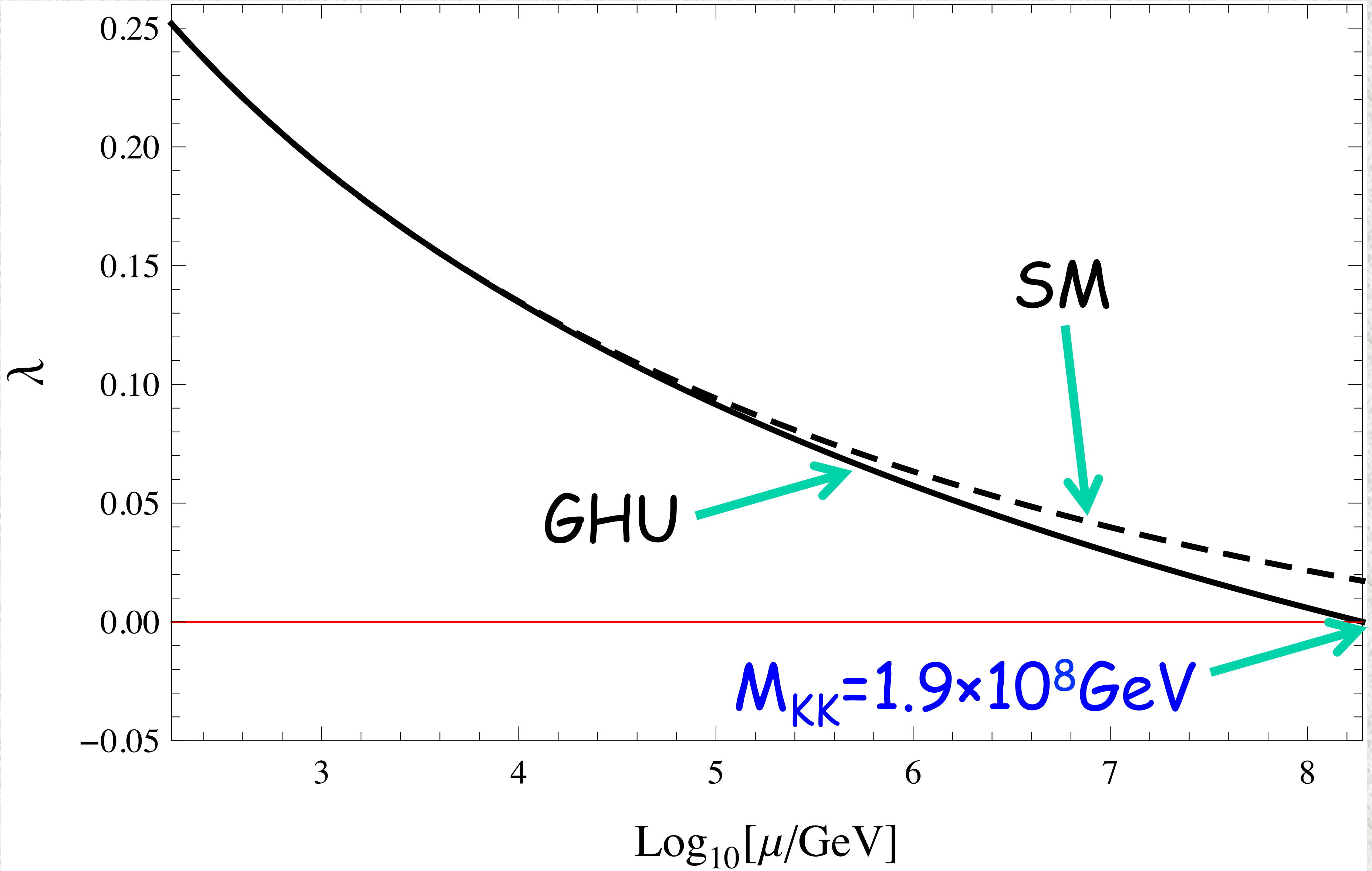
m_h=125GeV cannot be realized by only the SM fields

In 4D effective theory approach,
solve 1-loop RGE for Higgs quartic coupling λ
by imposing BC $\lambda=0$@M_{KK} "gauge-Higgs condition"

Haba, Matsumoto, Okada & Yamashita (2006, 2008)

Can extra fields introduced for DM help to reproduce m_h=125GeV??

RG evolution of Higgs quartic coupling with M=1TeV



Improvements

Previous result is unnatural

$\downarrow$

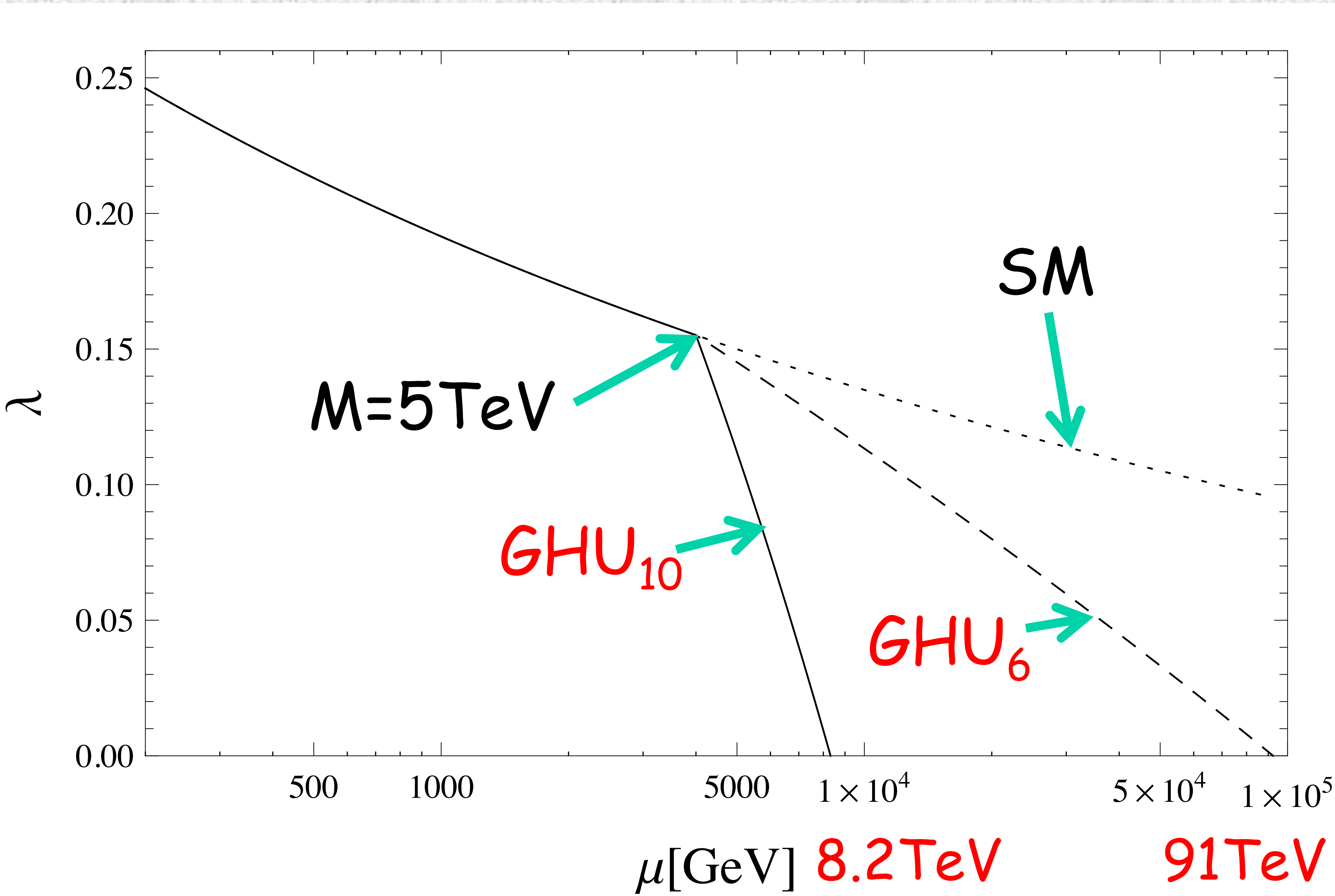
One of the ways lowering M_{KK} is to introduce extra fermions in higher dim. rep. of SU(3)

$\downarrow$

6 and 10 reps are studied

DM physics unchanged
as long as the SM singlet is identified as DM

RG evolution of Higgs quartic coupling with M=5TeV



Summary

- Fermion DM scenario in the context of GHU
- DM is identified with the linear combination of the electric-charge neutral components in extra SU(3) multiplets
- DM with mass $m_{DM} \sim m_h/2$ can reproduce the observed relic density
- Allowed parameter region is found to be constrained by the LUX results

Summary

- Entire allowed parameter region will be covered by the LUX-ZEPLIN exp. in a near future

- REG analysis shows that m_h=125GeV is realized at M_{KK}~91TeV(6-plet), 8.2TeV(10-plet) with M=5TeV

- Other possibilities for different U(1)' charges

  ⇒ Minimal DM scenario in the context of GHU

  (Cirelli, Fornengo & Strumia, 2007)

Other charge assignments of U(1)'

$U(1)'$	$6=1\oplus 2\oplus 3$	$U(1)'$	$10=1\oplus 2\oplus 3\oplus 4$
$2/3$	$(0)_0\oplus\begin{pmatrix}1\\0\end{pmatrix}_{1/2}\oplus\begin{pmatrix}2\\1\\0\end{pmatrix}_1$	1	$(0)_0\oplus\begin{pmatrix}1\\0\end{pmatrix}_{1/2}\oplus\begin{pmatrix}2\\1\\0\end{pmatrix}_1\oplus\begin{pmatrix}3\\2\\1\\0\end{pmatrix}_{3/2}$
$-1/3$	$(-1)_{-1}\oplus\begin{pmatrix}0\\1\end{pmatrix}_{-1/2}\oplus\begin{pmatrix}1\\0\\-1\end{pmatrix}_0$	0	$(-1)_{-1}\oplus\begin{pmatrix}0\\-1\end{pmatrix}_{-1/2}\oplus\begin{pmatrix}1\\0\\-1\end{pmatrix}_0\oplus\begin{pmatrix}2\\1\\0\\-1\end{pmatrix}_{1/2}$
$-4/3$	$(-2)_{-2}\oplus\begin{pmatrix}-1\\0\end{pmatrix}_{-3/2}\oplus\begin{pmatrix}0\\-1\\-2\end{pmatrix}_{-1}$	-1	$(-2)_{-2}\oplus\begin{pmatrix}-1\\-2\end{pmatrix}_{-3/2}\oplus\begin{pmatrix}0\\-1\\-2\end{pmatrix}_{-1}\oplus\begin{pmatrix}1\\0\\-1\\-2\end{pmatrix}_{-1/2}$
		-2	$(-3)_{-3}\oplus\begin{pmatrix}-2\\-3\end{pmatrix}_{-5/2}\oplus\begin{pmatrix}-1\\-2\\-3\end{pmatrix}_{-2}\oplus\begin{pmatrix}0\\-1\\-2\\-3\end{pmatrix}_{-3/2}$

This work

$SU(2)_L$ Doublet Vector DM

"$SU(2)_L$ Doublet Vector Dark Matter from Gauge-Higgs Unification"

NM, N. Okada and S. Okada

PRD98 (2018) 075021

Consider 5D SU(3) GHU model on S^1/Z_2

Boundary conditions $A_M(y+2\pi R) = A_M(y)$

$A_\mu(-y) = P^\dagger A_\mu(y) P \quad A_y(-y) = -P^\dagger A_y(y) P$

$P = \mathrm{diag}(-,-,+)$

$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ (-,-) & (-,-) & (+,+) \end{pmatrix}, \quad A_5 = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}$$

Only (+,+) has massless mode@KK scale

$$A_\mu^{(0)} = \frac{1}{2} \begin{pmatrix} W_\mu^3 + B_\mu^3/\sqrt{3} & \sqrt{2} W_\mu^+ & 0 \\ \sqrt{2} W_\mu^- & -W_\mu^3 + B_\mu^3/\sqrt{3} & 0 \\ 0 & 0 & -2B_\mu/\sqrt{3} \end{pmatrix}, \quad A_5^{(0)} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ H^- & H^{0*} & 0 \end{pmatrix}$$

DM Lagrangian

$$\mathcal{L}_{DM} = -\frac{1}{2}Tr\left[F_{MN}F^{MN}\right] - \left(\frac{c_L}{2}Tr\left[W_{\mu\nu}W^{\mu\nu}\right] + \frac{c_Y}{2}Tr\left[B_{\mu\nu}B^{\mu\nu}\right]\right)\left(\delta(y)+\delta(y-\pi R)\right)$$

$$A_\mu^{(0)} = \frac{1}{2}\begin{pmatrix} W_\mu^3 + \frac{1}{\sqrt{3}}B_\mu & \sqrt{2}W_\mu^+ & 0 \\ \sqrt{2}W_\mu^- & -W_\mu^3 + \frac{1}{\sqrt{3}}B_\mu & 0 \\ 0 & 0 & -\frac{2}{\sqrt{3}}B_\mu \end{pmatrix}, A_\mu^{(1)} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & X_\mu^1 \\ 0 & 0 & X_\mu^2 \\ X_\mu^{1*} & X_\mu^{2*} & 0 \end{pmatrix}$$

X_μ is an $SU(2)_L$ doublet 1st KK gauge boson

$\Rightarrow$ model independent DM candidate

DM Lagrangian

$$\mathcal{L}_{DM} = -\frac{1}{2} Tr\left[F_{MN}F^{MN}\right]$$
$$-\left(\frac{c_L}{2} Tr\left[W_{\mu\nu}W^{\mu\nu}\right] + \frac{c_Y}{2} Tr\left[B_{\mu\nu}B^{\mu\nu}\right]\right)\left(\delta(y) + \delta(y - \pi R)\right)$$

- Brane localized terms are $SU(2)_L \times U(1)_Y$ invariant not $SU(3)$ since it is explicitly broken by B.C.
- Brane localized gauge kinetic terms are necessary to reproduce Weinberg angle ($SU(3)$: $\sin^2\theta_W = 3/4$)

DM Lagrangian

$$\mathcal{L}_{DM} = -\frac{1}{2}Tr\left[F_{MN}F^{MN}\right] - \left(\frac{c_L}{2}Tr\left[W_{\mu\nu}W^{\mu\nu}\right] + \frac{c_Y}{2}Tr\left[B_{\mu\nu}B^{\mu\nu}\right]\right)\left(\delta(y) + \delta(y - \pi R)\right)$$

- All brane localized gauge kinetic terms are set to be symmetric @y=0, πR to preserve KK-parity for DM stability

DM mass spectrum

$$\int dy \mathcal{L}_{DM} \supset -\int dy Tr\left[F_{\mu y} F^{\mu y}\right]$$

$$\supset -\frac{g^2 v^2}{8} \eta^{\mu\nu} \left(X_\mu^2 - X_\mu^{2*}\right)\left(X_\nu^2 - X_\nu^{2*}\right) + \frac{1}{2R^2} \eta^{\mu\nu} \left(X_\mu^{2*} X_\nu^2\right)$$

$$= \frac{1}{2}\left(\frac{1}{R}\right)^2 \eta_{\mu\nu} \left(X_{DM}^\mu X_{DM}^\nu\right) + \frac{1}{2}\left(\left(\frac{1}{R}\right)^2 + 4m_W^2\right) X^\mu X_\mu$$

$$X_{DM\mu} \equiv \frac{1}{\sqrt{2}}\left(X_\mu^2 + X_\mu^{2*}\right),\ X_\mu \equiv \frac{1}{\sqrt{2}}\left(X_\mu^2 - X_\mu^{2*}\right)$$

$m_{DM}{}^2 = (1/R)^2$ light & No Higgs coupling

$m_X{}^2 = (1/R)^2 + 4m_W{}^2$

X_μ lightest??

① 1^{st} KK photon mass = $1/R$ ⇒ True

Brane localized kinetic term effects are studied

Carena, Tait & Wagner (2002)

1^{st} KK photon mass can be larger than $1/R$

If we take $c_L, c_Y < 0$,

$m_n > n/R$ ⇒ X_μ is LKP

X_μ lightest??

② 1^{st} KK fermion mass = $1/R$ ⇒ NOT true

1^{st} KK fermion mass^2
except for top

$$= M^2 + (1/R \pm m_f)^2$$

($\because$ $m_f \sim M \exp[-\pi MR]$)

Not DM candidate ($M > m_f$)

X_μ lightest??

② 1^{st} KK fermion mass = $1/R$ ⇒ NOT true

$$1^{st} \text{ KK top mass}^2 = (1/R \pm m_f)^2$$

$(\because\ m_f \sim M \exp[-\pi MR]\ )$

The 1^{st} KK top with $(1/R - m_{top})$ lighter than the 1^{st} KK $SU(2)_L$ doublet gauge boson

Quantum corrections to KK masses lead to

1^{st} KK top > 1^{st} KK $SU(2)_L$ doublet gauge boson as in UED

⇒ X_μ lightest

Z coupling of DM

Z-DM-DM O(1) coupling

$\Rightarrow$ excluded from direct detection exp.

$$\mathcal{L}_{5D} \supset -\frac{1}{2}Tr\left[F_{MN}F^{MN}\right] \supset igTr\left[\left(\partial_\mu A_\nu - \partial_\nu A_\mu\right)\left[A^\mu, A^\nu\right]\right]$$

$$\supset \frac{ig}{4}\Bigg[-2\partial_\mu\left(W_\nu^3 + \frac{1}{\sqrt{3}}B_\nu\right)\left(-X_{DM}^\mu X^\nu + X_{DM}^\nu X^\mu\right)$$

$$+2\partial_\mu X_{DM\nu}\left\{-X^\mu\left(-W^{3\nu} + \sqrt{3}B^\nu\right) + X^\nu\left(-W^{3\mu} + \sqrt{3}B^\mu\right)\right\}$$

$$+2\partial_\mu X_\nu\left\{X_{DM}^\mu\left(-W^{3\nu} + \sqrt{3}B^\nu\right) - X_{DM}^\nu\left(-W^{3\mu} + \sqrt{3}B^\mu\right)\right\}\Bigg]$$

such coupling is absent!!

Relic abundance of vector DM

Rough estimate $X_{DM} X_{DM} \to W^+ W^-$

$$\mathcal{L}_{4D} = -\frac{1}{2}\left(D_\mu \chi_\nu - D_\nu \chi_\mu\right)^\dagger \left(D^\mu \chi^\nu - D^\nu \chi^\mu\right)$$

$$\supset -g^2\left(\eta^{\mu\nu}\eta^{\rho\sigma} - \eta^{\mu\rho}\eta^{\nu\sigma}\right) X_{DM\,\mu} X_{DM\,\nu} W_\rho^+ W_\sigma^-$$

$$\chi_\mu = \begin{pmatrix} X_\mu^1 \\ X_\mu^2 \end{pmatrix}$$

$$\Rightarrow \sigma v_{rel} = \frac{5g^4}{48\pi m_{DM}} \sim 1\ \mathrm{pb}\ (\Omega_{DM} h^2 \sim 0.1)$$

$\Rightarrow m_{DM} \sim$ 1.5 TeV (g=0.65)

Summary

- We have proposed
  a new vector DM scenario in GHU
- DM is the 1st KK $SU(2)_L$ doublet vector field
- Stability is ensured by KK parity ⇒ LKP
- Our DM is model-independent
  ∵ $SU(2)_L$ doublet vector is
  a gauge-Higgs partner of Higgs doublet

Summary

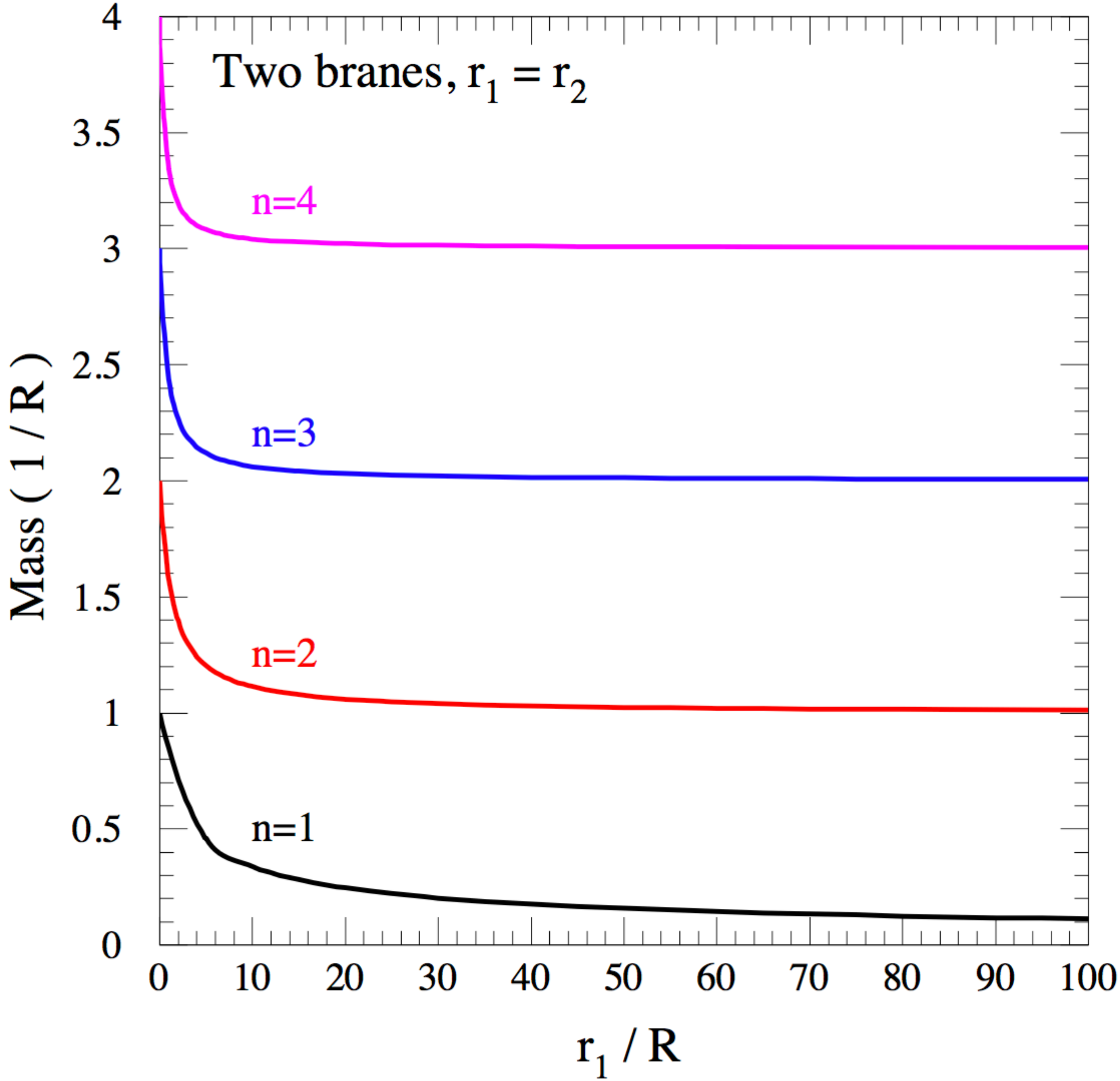
- Because of higher-dim. gauge structure, we have no DM-DM-Higgs/Z coupling

  ⇒ Severe constraints from direct DM detection exp. can be evaded

- Observed relic abundance of DM is obtained through DM+DM→W^+W^- for a TeV scale DM mass

Backup

$$
\begin{aligned}
m_3^2 - m_1^2 &= \frac{1}{4}\left[\left(m+2M\right)^2 - \left(m-2M\right)^2 + 2m\left\{ \sqrt{4m_W^2 + \left(m-2M\right)^2} - \sqrt{4m_W^2 + \left(m+2M\right)^2} \right\} \right] \\
&= \frac{1}{4}\left[4Mm + 2m\frac{-4Mm}{\sqrt{4m_W^2 + \left(m-2M\right)^2} + \sqrt{4m_W^2 + \left(m+2M\right)^2}} \right] \\
&\approx Mm\left[1 - \frac{m}{2M} \right] > 0 \left(M \gg m, m_W \right)
\end{aligned}
$$



Two branes, $r_1 = r_2$
n=4
n=3
n=2
n=1
Mass (1 / R)
r_1 / R
0
0.5
1
1.5
2
2.5
3
3.5
4
0
10
20
30
40
50
60
70
80
90
100

X_μ lightest??

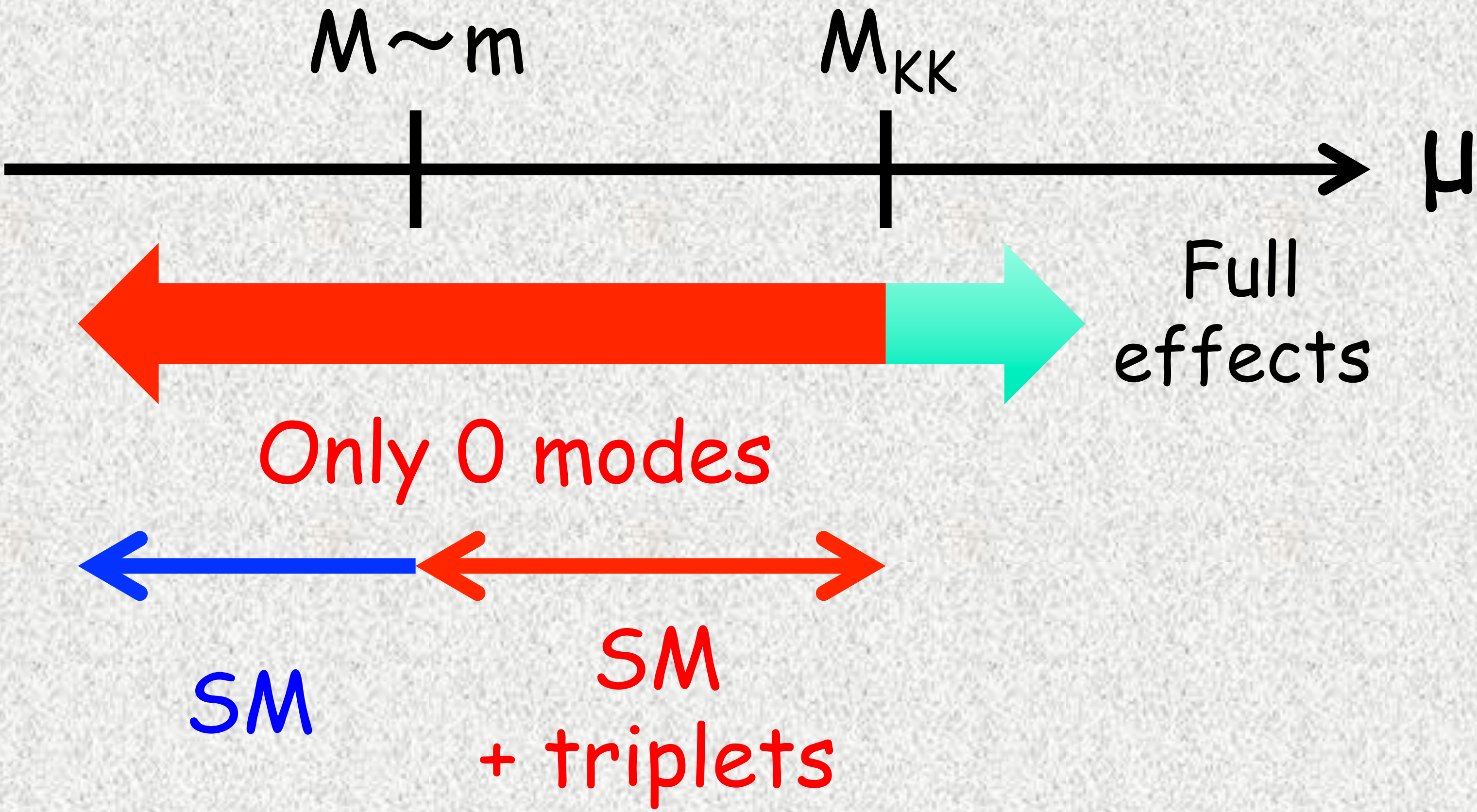
② 1st KK fermion mass =1/R ⇒ NOT true

In the 2nd approach,

1st KK fermion mass^2
except for top

$$= M^2 + (1/R \pm m_f)^2$$

Not DM candidate



Technical simplifications:

Mass splitting in triplet zero modes ignored and their masses are set to be M

Boltzmann eq.

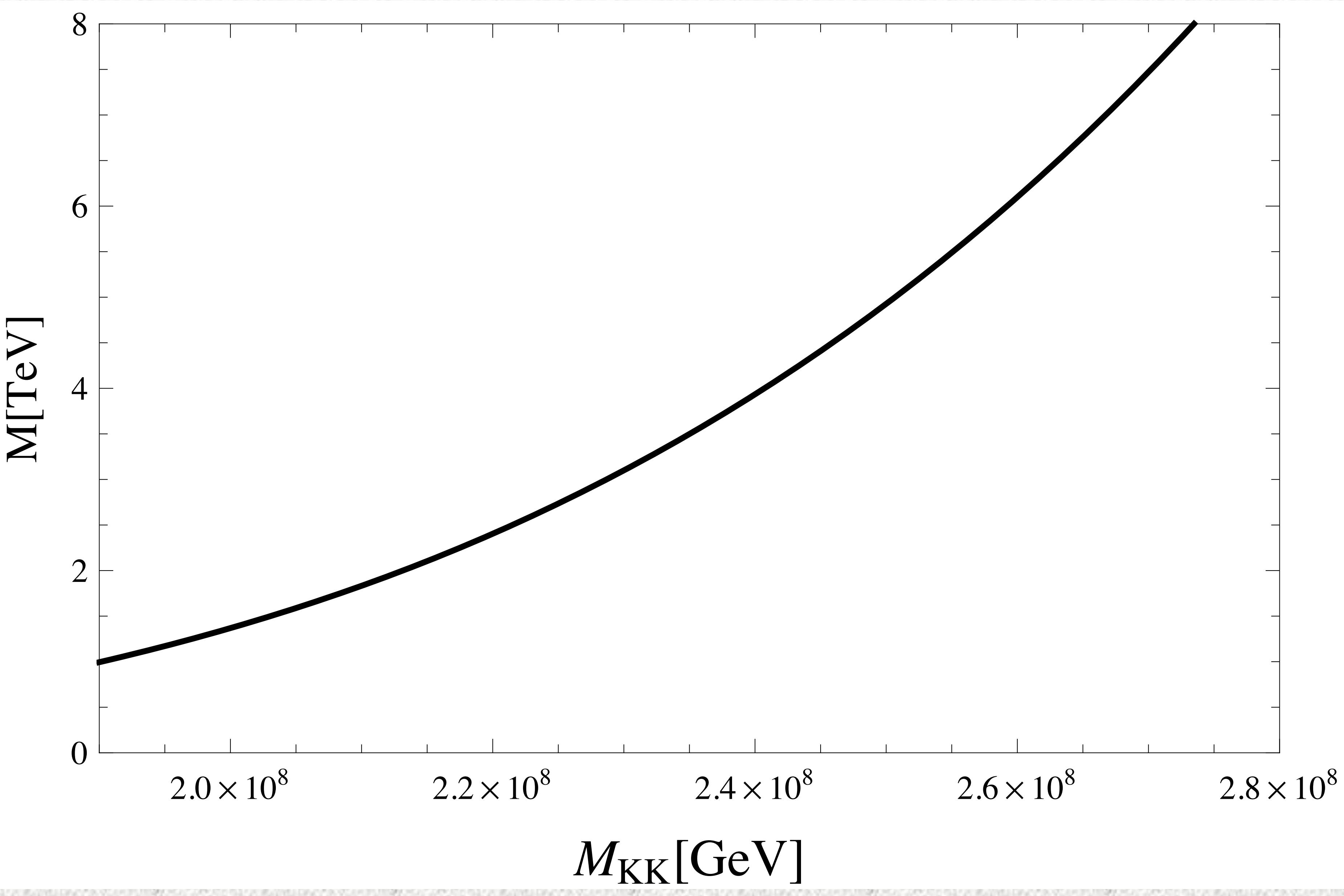
$$\frac{dY}{dx} = -\frac{xs\langle\sigma v\rangle}{H(m_{DM})}\left(Y^2 - Y_{EQ}^2\right)$$

$$x \equiv \frac{m_{DM}}{T},\;\; Y \equiv \frac{n}{s},\;\; s = \frac{2\pi^2}{45} g_* \frac{m_{DM}^3}{x^3},\;\; H(m_{DM}) = \sqrt{\frac{\pi^2}{90} g_*}\,\frac{m_{DM}^2}{M_P},\;\; Y_{EQ} = \frac{g_{DM}}{2\pi^2 s}\frac{m_{DM}^3}{x} K_2(x)$$

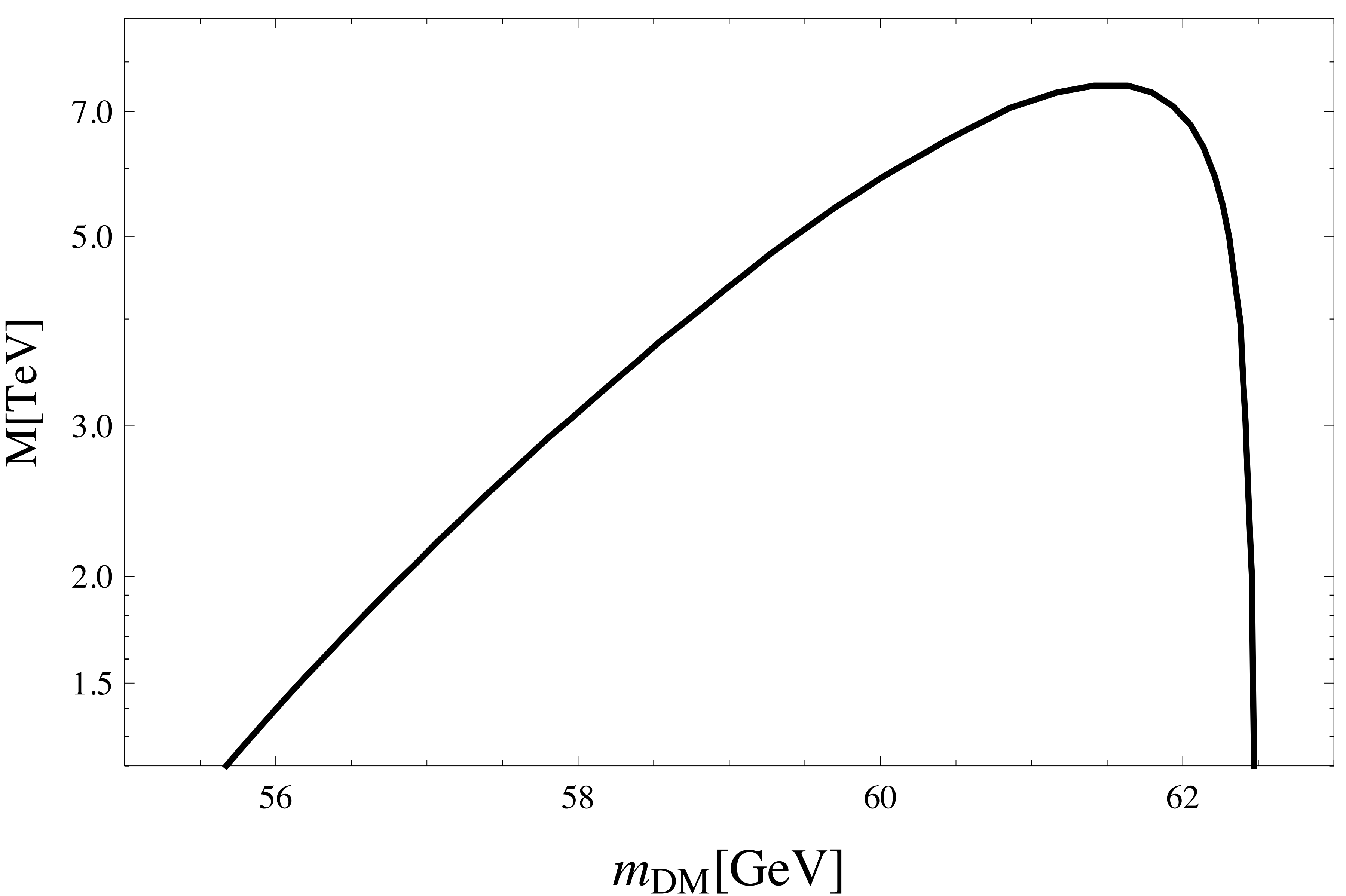
DM relic density

$$\Omega h^2 = \frac{m_{DM} s_0 Y(\infty)}{\rho_c / h^2} = \frac{2890\,cm^{-3}}{1.05\times 10^{-5}\,GeV/cm^3} m_{DM} Y(\infty)$$

Relation between M & M_{KK}



Bulk mass vs m_{DM}



SM RGEs@2-loop (μ<M)

Gauge couplings

$$\frac{dg_i}{d\ln\mu} = \frac{b_i}{16\pi^2} g_i^3 + \frac{g_i^3}{\left(16\pi^2\right)^2}\left(\sum_{j=1}^{3} B_{ij} g_j^2 - C_i y_t^2\right)$$

$$b_i = \left(\frac{41}{10}, -\frac{19}{6}, -7\right), \quad B_{ij} = \begin{pmatrix} \frac{199}{50} & \frac{27}{10} & \frac{44}{5} \\ \frac{9}{10} & \frac{35}{6} & 12 \\ \frac{11}{10} & \frac{9}{2} & -26 \end{pmatrix}, \quad C_i = \left(\frac{17}{10}, \frac{3}{2}, 2\right)$$

Top Yukawa

$$\frac{dy_t}{d\ln\mu} = y_t\left(\frac{1}{16\pi^2}\beta_t^{(1)} + \frac{1}{\left(16\pi^2\right)^2}\beta_t^{(2)}\right)$$

$$\beta_t^{(1)} = \frac{9}{2}y_t^2 - \left(\frac{17}{20}g_1^2 + \frac{9}{4}g_2^2 + 8g_3^2\right)$$

$$\beta_t^{(2)} = -12y_t^4 + \left(\frac{393}{80}g_1^2 + \frac{225}{16}g_2^2 + 36g_3^2\right)y_t^2$$

$$+\frac{1187}{600}g_1^4 - \frac{9}{20}g_1^2g_2^2 + \frac{19}{15}g_1^2g_3^2 - \frac{23}{4}g_2^4 + 9g_2^2g_3^2 - 108g_3^4$$

$$+\frac{3}{2}\lambda^2 - 6\lambda y_t^2$$

Higgs quartic cpoupling

$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\beta_\lambda^{(1)} + \frac{1}{\left(16\pi^2\right)^2}\beta_\lambda^{(2)}$$

$$\beta_\lambda^{(1)} = 12\lambda^2 - \left(\frac{9}{5}g_1^2 + 9g_2^2\right)\lambda + \frac{9}{4}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2 g_2^2 + g_2^4\right)$$
$$+12y_t^2\lambda - 12y_t^4$$

$$\beta_\lambda^{(2)} = -78\lambda^3 + 18\left(\frac{3}{5}g_1^2 + 3g_2^2\right)\lambda^2 - \left(\frac{73}{8}g_2^4 - \frac{117}{20}g_1^2 g_2^2 - \frac{1887}{200}g_1^4\right)\lambda - 3\lambda y_t^4$$
$$+\frac{305}{8}g_2^6 - \frac{289}{40}g_1^2 g_2^4 - \frac{1677}{200}g_1^4 g_2^2 - \frac{3411}{1000}g_1^6 - 64g_3^2 y_t^4 - \frac{16}{5}g_1^2 y_t^4 - \frac{9}{2}g_2^4 y_t^2$$
$$+10\lambda\left(\frac{17}{20}g_1^2 + \frac{9}{4}g_2^2 + 8g_3^2\right)y_t^2 - \frac{3}{5}g_1^2\left(\frac{57}{10}g_1^2 - 21g_2^2\right)y_t^2 - 72\lambda^2 y_t^2 + 60y_t^6$$

Boundary conditions@top pole mass

$$g_1(M_t) = \sqrt{\frac{5}{3}}\left(0.35761 + 0.00011(M_t - 173.10) - 0.00021\left(\frac{M_W - 80.384}{0.014}\right)\right)$$

$$g_2(M_t) = 0.64822 + 0.00004(M_t - 173.10) - 0.00011\left(\frac{M_W - 80.384}{0.014}\right)$$

$$g_3(M_t) = 1.1666 + 0.00314\left(\frac{\alpha_s - 0.1184}{0.0007}\right)$$

$$y_t(M_t) = 0.93558 + 0.0055(M_t - 173.10) - 0.00042\left(\frac{\alpha_s - 0.1184}{0.0007}\right)$$
$$- 0.00042\left(\frac{M_W - 80.384}{0.014}\right)$$

$$\lambda(M_t) = 2\left(0.12711 + 0.00206(M_h - 125.66) - 0.00004(M_t - 173.10)\right)$$

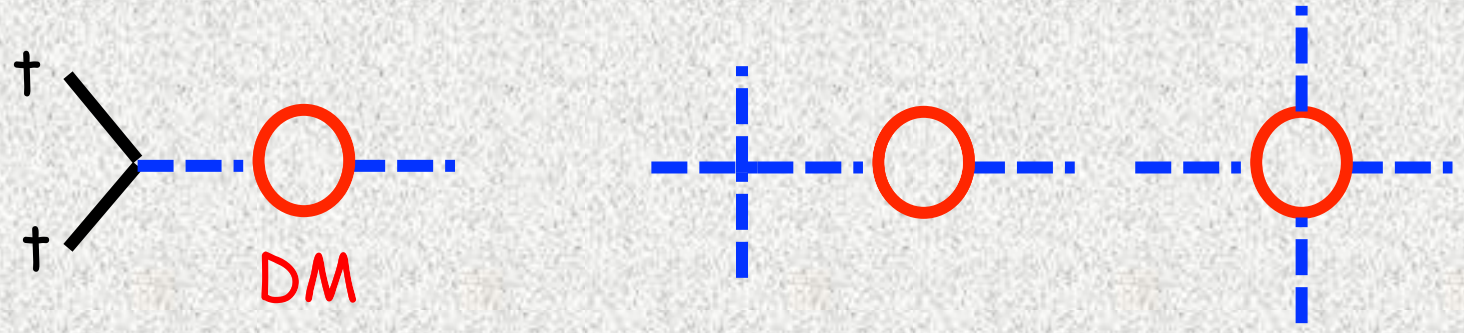
For μ ≧ M, triplet zero modes contribute and RGE is correspondingly modified

$$\Delta b_1 = \Delta b_2 = \frac{2}{3}$$

SU(2), U(1)$_Y$ gauge couplings

Top Yukawa and Higgs quartic couplings

$$\beta_t^{(1)} \to \beta_t^{(1)} + 2y_t |Y_S|^2, \quad \beta_\lambda^{(1)} \to \beta_\lambda^{(1)} + 8\lambda |Y_S|^2 - 8|Y_S|^4$$



For μ ≧ M, triplet zero modes contribute and RGE is correspondingly modified

DM-DM-Higgs Yukawa coupling

$$16\pi^2 \frac{dY_S}{d\ln\mu} = Y_S\left[3y_t^2 - \left(\frac{9}{20}g_1^2 + \frac{9}{4}g_2^2\right) + \frac{7}{2}\left|Y_S\right|^2\right]$$

Boundary conditions@M_{KK}

$$\lambda(M_{KK}) = 0, \quad \left|Y_S(M_{KK})\right| = g_2(M_{KK})/\sqrt{2}$$

DM mass terms

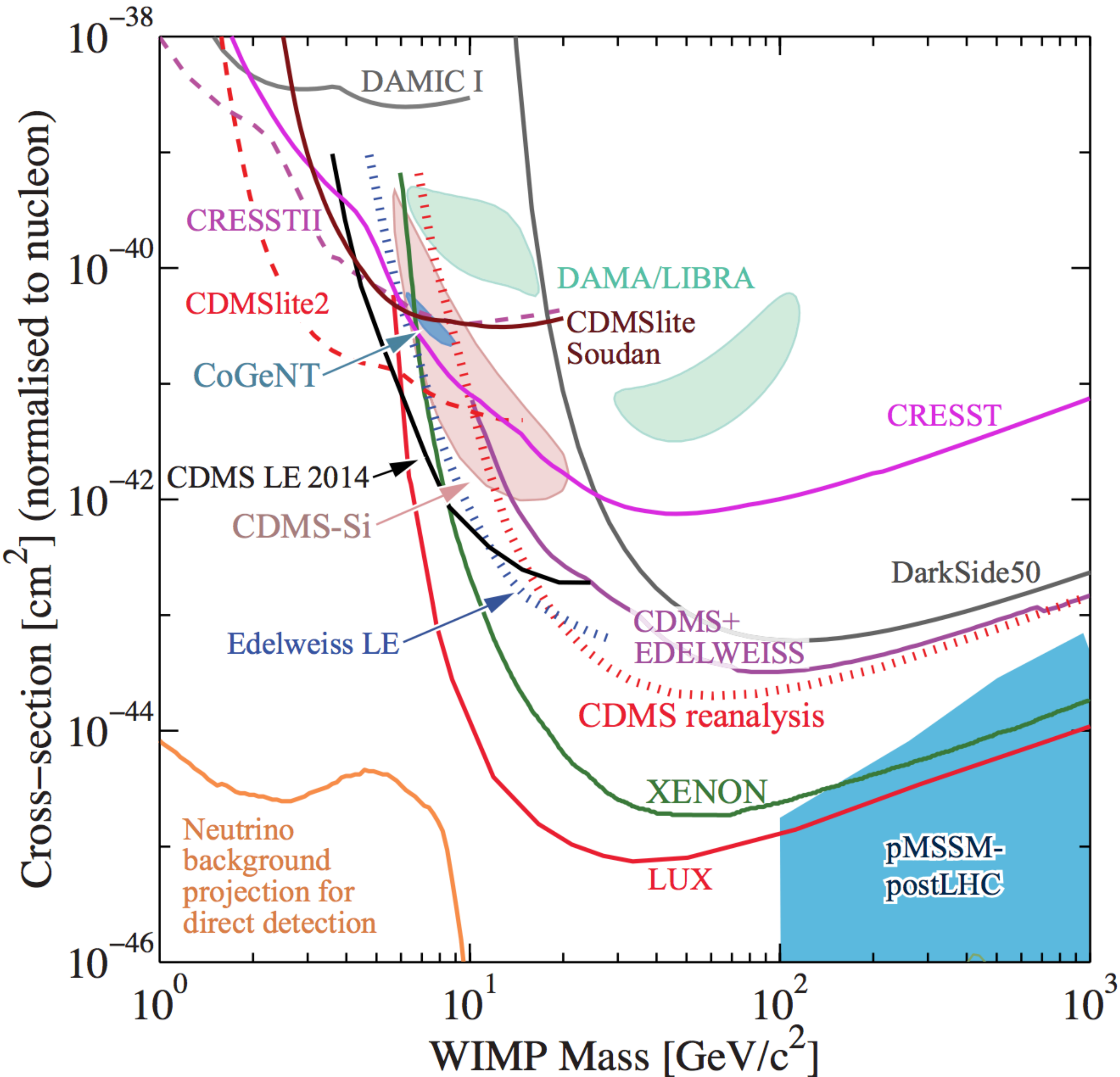
$$\mathcal{L}_{mass} = \bar{\psi} i \Gamma^5 \left(\partial_y - ig\left\langle A_y \right\rangle\right)\psi + \bar{\tilde{\psi}} i \Gamma^5 \left(\partial_y - ig\left\langle A_y \right\rangle\right)\tilde{\psi} - M\left(\bar{\psi}\tilde{\psi} + \bar{\tilde{\psi}}\psi\right)$$

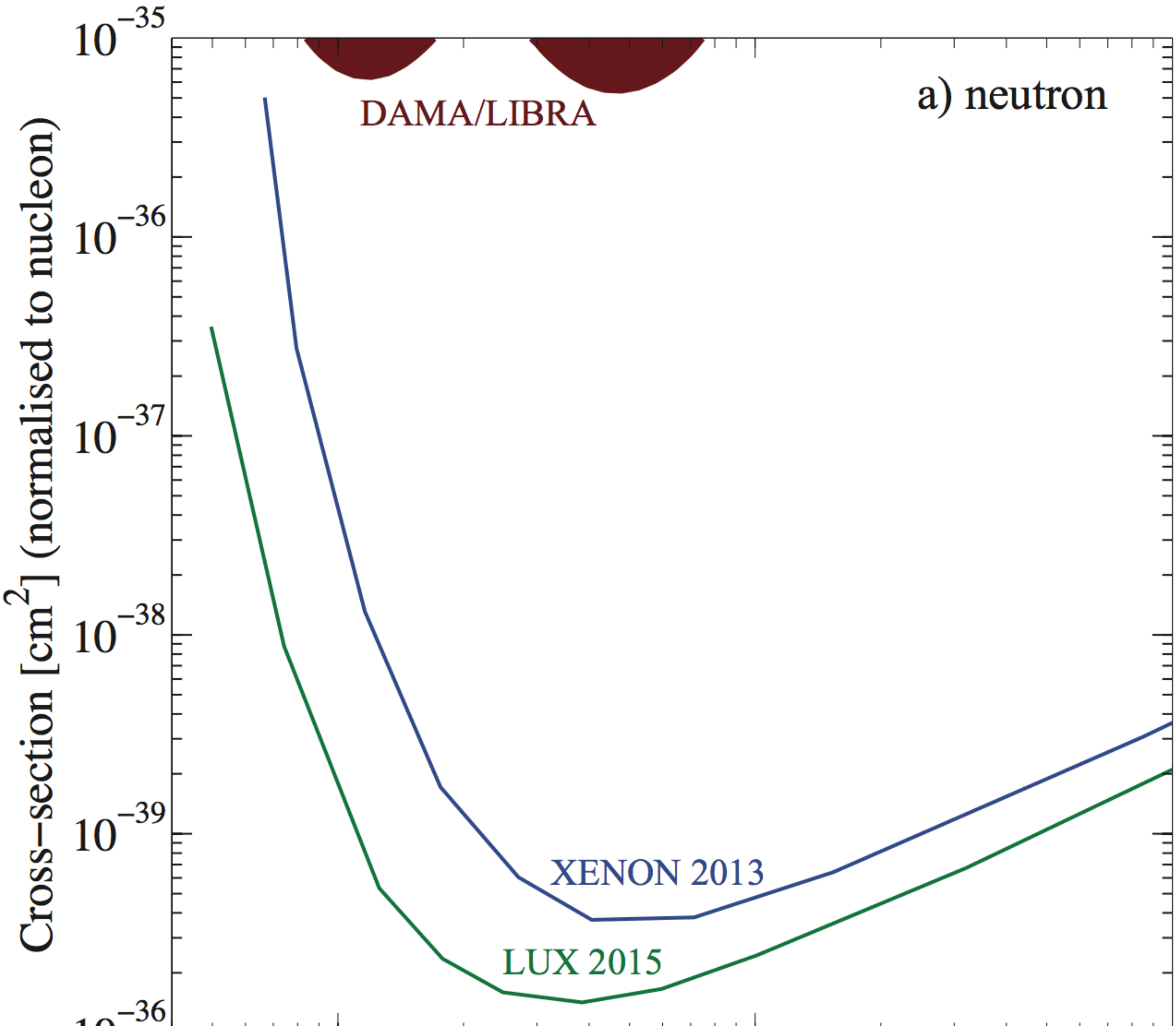
$$+\delta(y)\left[\frac{m}{2}\bar{\psi}_{3R}^{(0)c}\psi_{3R}^{(0)c} + \frac{\tilde{m}}{2}\bar{\tilde{\psi}}_{3L}^{(0)c}\psi_{3L}^{(0)c} + h.c.\right]$$

$$\supset -m_W\left(\bar{\psi}_{2L}^{(0)}\psi_{3R}^{(0)} - \bar{\tilde{\psi}}_{3L}^{(0)}\psi_{2R}^{(0)}\right) - M\left(\bar{\psi}_{2L}^{(0)}\tilde{\psi}_{2R}^{(0)} + \bar{\tilde{\psi}}_{3L}^{(0)}\psi_{3R}^{(0)}\right)$$

$$-\frac{m}{2}\bar{\psi}_{3R}^{(0)c}\psi_{3R}^{(0)c} - \frac{\tilde{m}}{2}\bar{\tilde{\psi}}_{3L}^{(0)c}\psi_{3L}^{(0)c} + h.c.$$

	Target	Fiducial Mass [kg]	Cross section [pb]	WIMP mass [GeV]
Spin independent low mass (>10GeV)				
LUX	Xe	118	7.6×10^{-10}	30
Xenon100	Xe	34	2.0×10^{-9}	55
CDMS/EDW	Ge	12	2.0×10^{-8}	100
DarkSide	Ar	46	6.1×10^{-8}	100
CRESST	CaWO4 -W	4	1×10^{-6}	50
Spin independent low mass (<10GeV)				
LUX	Xe	118	1×10^{-8}	10
SuperCDMS	Ge LE	≈ 4.2	5×10^{-7}	10
SuperCDMS	Ge LE	≈ 4.2	3×10^{-5}	5
SuperCDMS	Ge HV	0.6	3×10^{-4}	3.3
CRESST	CaWO4 -O	0.25	2×10^{-3}	2.3
DAMIC	Si	0.01	1×10^{-2}	1.5
Spin dependent p				
PICO	F	2.9	1×10^{-3}	30
Spin dependent n				
LUX	Xe	118	3×10^{-4}	40


DAMIC I
CRESSTII
DAMA/LIBRA
CDMSlite2
CDMSlite
Soudan
CoGeNT
CRESST
CDMS LE 2014
CDMS-Si
DarkSide50
CDMS+
EDELWEISS
Edelweiss LE
CDMS reanalysis
XENON
Neutrino
background
projection for
direct detection
LUX
pMSSM-
postLHC
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{0}
10^{1}
10^{2}
10^{3}
Cross−section [cm^2] (normalised to nucleon)
WIMP Mass [GeV/c^2]



a) neutron
DAMA/LIBRA
XENON 2013
LUX 2015
Cross–section [cm^2] (normalised to nucleon)
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-36}

Spin-dependent coupling ← axial-vector current

$$\mathcal{L}_A \sim \bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5 q$$

Total cross section@zero momentum transfer

$$\sigma_{0\,spin} = \frac{32}{\pi}G_F^2\left(\frac{m_N m_\chi}{m_N + m_\chi}\right)^2 \Lambda^2 J(J+1) \approx m_N^2 \left(m_\chi \gg m_N\right)$$

Spin-independent coupling ← scalar, vector, tensor currents

$$\mathcal{L}_{S,V} \sim \bar{\chi}\chi\bar{q}q, \bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$$

$$\sigma_{0\,scalar} = \frac{4}{\pi}\left(\frac{m_N m_\chi}{m_N + m_\chi}\right)^2 \left[Zf_p + (A-Z)f_n\right]^2 \approx m_N^4 \left(m_\chi \gg m_N\right)$$

$$\sigma_{0\,vector} = \frac{1}{64\pi}\left(\frac{m_N m_\chi}{m_N + m_\chi}\right)^2 \left[2Zb_p + (A-Z)b_n\right]^2 \approx m_N^4 \left(m_\chi \gg m_N\right)$$

For large DM mass,

spin-independent >> spin-dependent

DM is Majorana ⇒ No vector coupling

(∵ anti-sym for x↔xbar)

⇒ required for forbidding a vector coupling through Z-boson exchange already excluded

[$\sigma(xN \to xN) \sim O(10^{-7})\mathrm{pb} \sim O(10^{-43})\mathrm{cm}^2$

w/ $m_{DM} \sim 1\mathrm{TeV}$]

Quantum corrections to 1st KK mass in UED

Cheng, Matchev & Schmaltz, PRD66 (2002) 036005

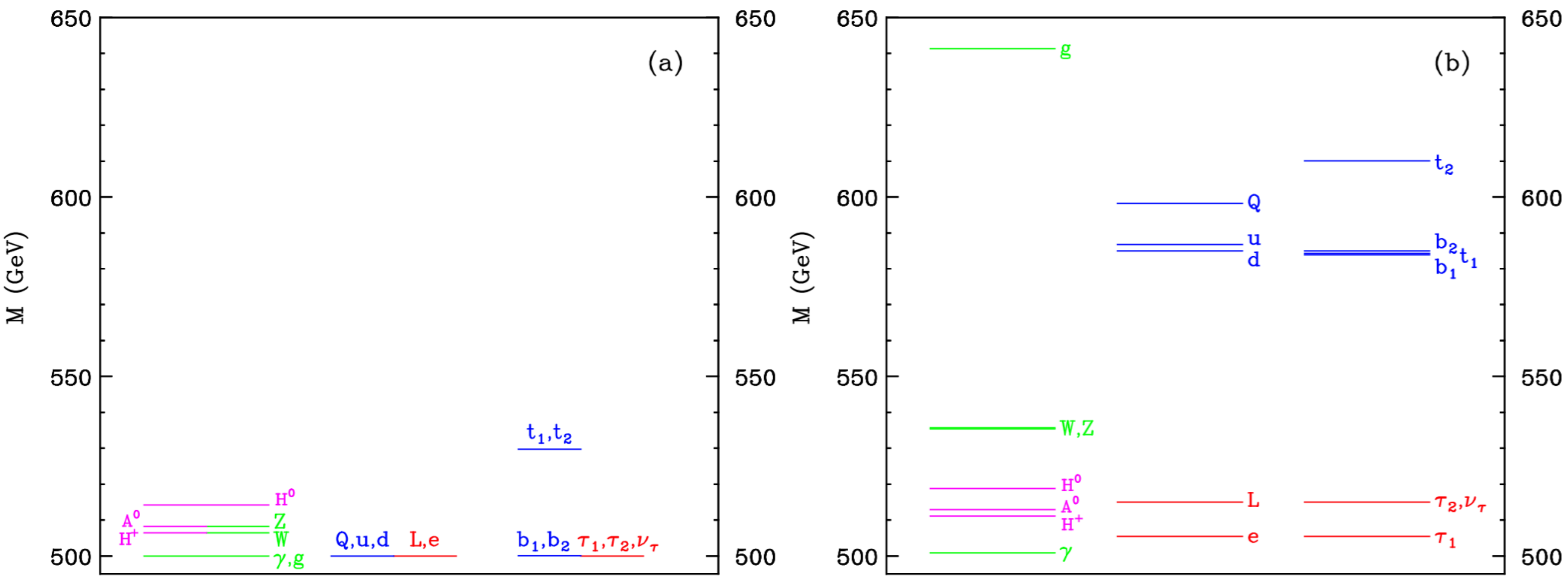


FIG. 6: The spectrum of the first KK level at (a) tree level and (b) one-loop, for $R^{-1} = 500$ GeV, $\Lambda R = 20$, $m_h = 120$ GeV, $\overline{m}_H^2 = 0$, and assuming vanishing boundary terms at the cut-off scale Λ.

However, a translation by πR in the x_5 direction remains a symmetry of the orbifold.
Under this transformation the even number (n=even) KK modes are invariant while the odd number (n=odd) KK modes change sign.
Therefore, KK parity $(-1)^{KK}$ (not the Z_2 in S^1/Z_2) is still a good symmetry. Note that KK-parity is a flip of the line segment about it's center at $x_5 = \pi R/2$ combined with the Z_2 transformation which flips the sign of all odd fields.