Fermion Dark Matter in Gauge-Higgs Unification

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References

“Fermion Dark Matter
in Gauge-Higgs Unification“

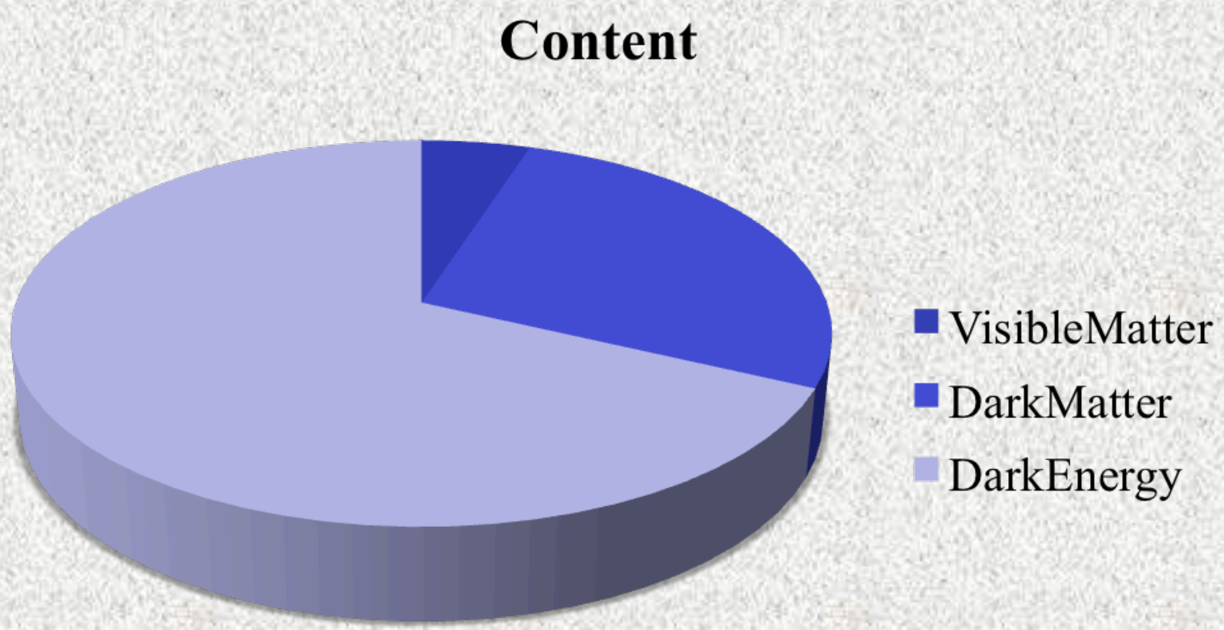
NM, T. Miyaji, N. Okada and S. Okada
JHEP1707 (2017) 048

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

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

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,

A possibility of DM is discussed

in the context of *gauge-Higgs unification*

PLAN

1: Introduction ✔
2: Model
3: DM Relic Abundance
4: Direct DM Detection
5: Higgs Mass RGE Analysis
6: Summary

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

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

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

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

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

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

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

➡ Dirac mass terms to avoid massless modes

DM Lagrangian

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

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

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

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

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 by Majorana basis

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

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

SU(2) Singlet

SU(2) Doublet

DM-Higgs coupling

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

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

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

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

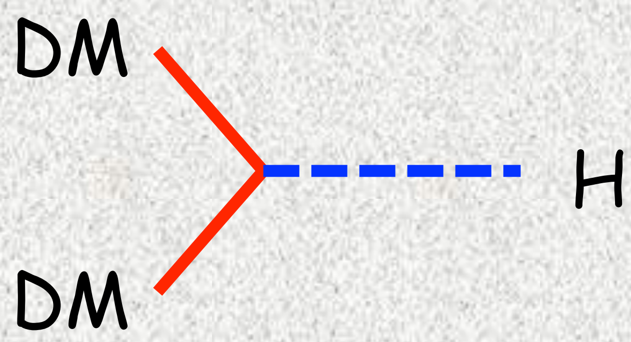
DM Relic Abundance

Interactions relevant to DM(=η_1) physics

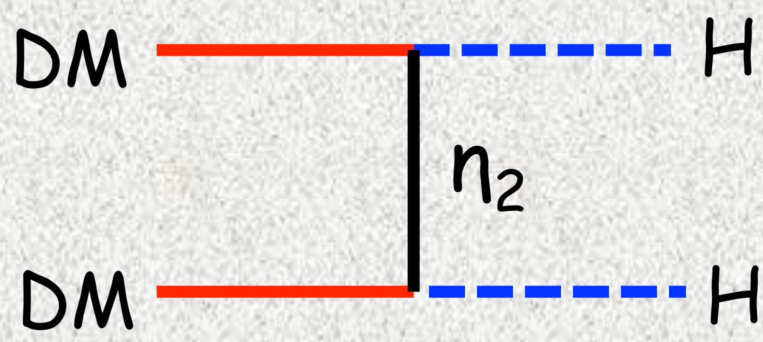
$$\mathcal{L}_{DM-H} = -\frac{1}{2}\left(\frac{m_W}{v}\right)C_1 h\overline{\psi}_{DM}\psi_{DM} - \frac{1}{2}\left(\frac{m_W}{v}\right)C_5 h\left(\overline{\eta}_2\psi_{DM} + h.c.\right)$$

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

two main DM annihilation modes



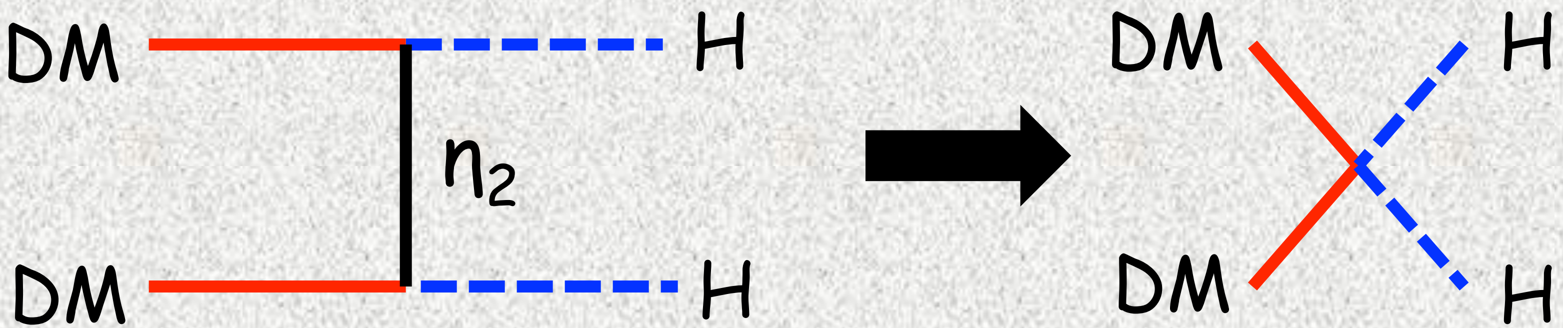
s-channel Higgs exchange



t/u-channel η_2 exchange

$|C_1| \ll 1$, $C_5 \sim 1$ $\Rightarrow$ 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)

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

NOT WORK

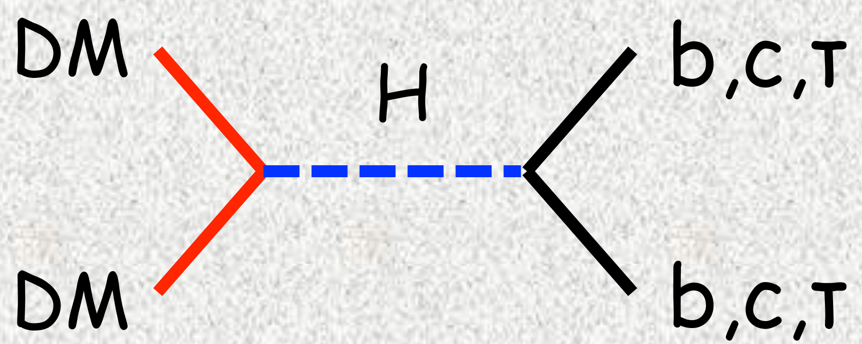
Our case: $\sigma_0 \sim 0.02$ pb for $C_5 \sim 1$, $m_2 \sim M \sim 1$ TeV

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

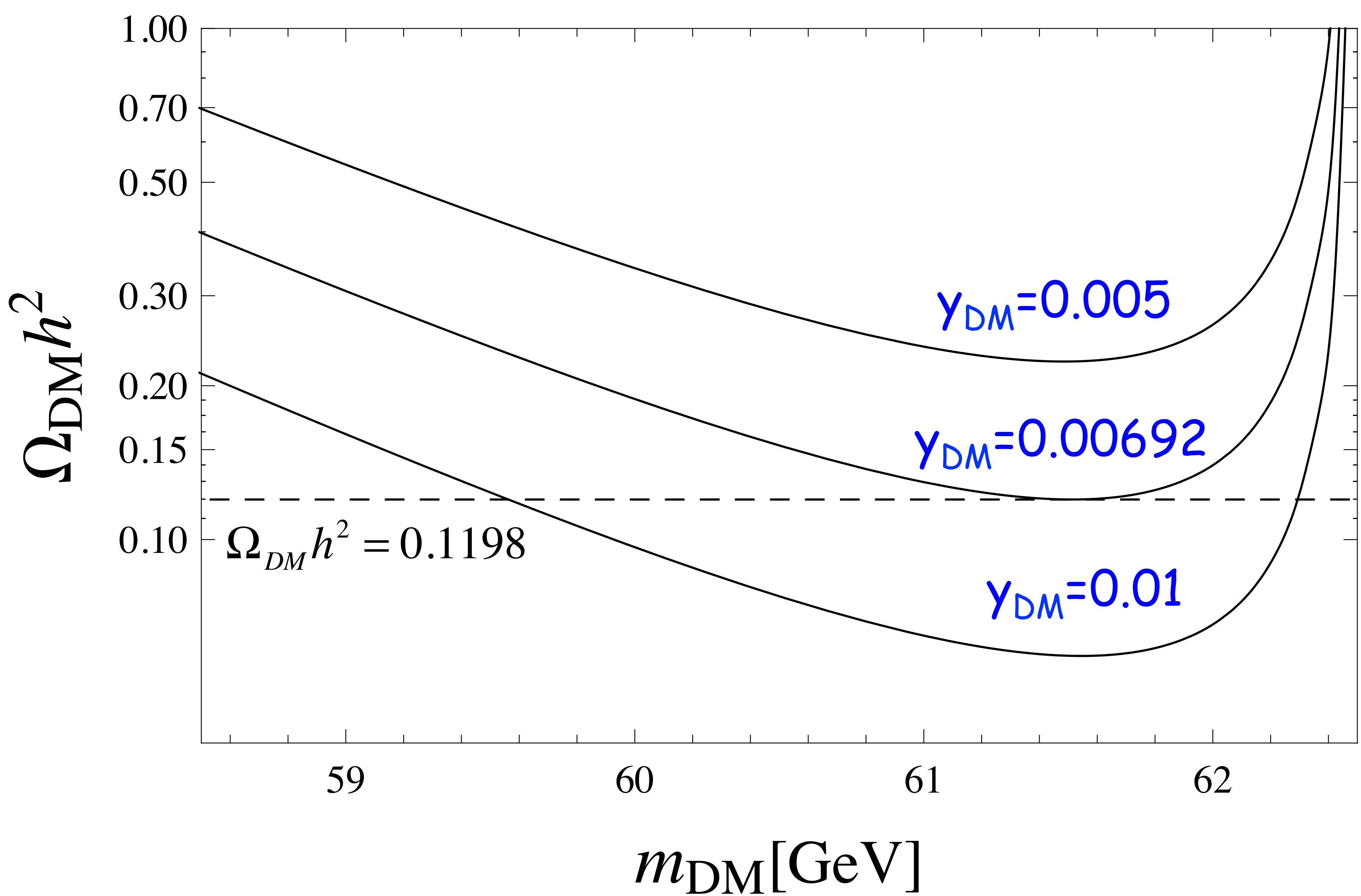
Cross section

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

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



DM relic density as a function of m_{DM}



Direct DM Detection

DM-Nucleon scattering via Higgs exchange

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

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

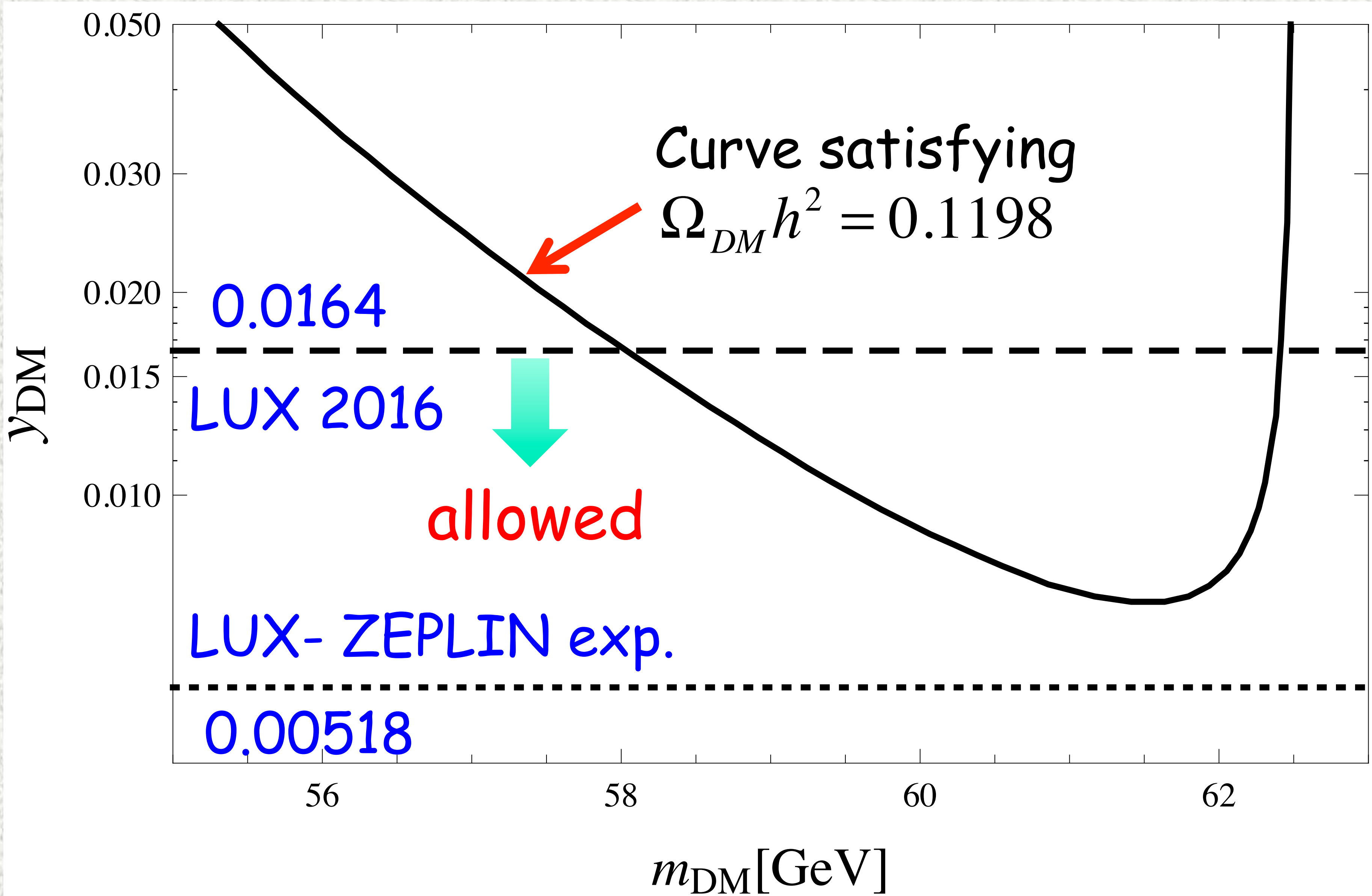
$$m_{DM} = m_h/2 = 62.5 GeV, m_N = 0.939 GeV$$

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 ∵ loop generated

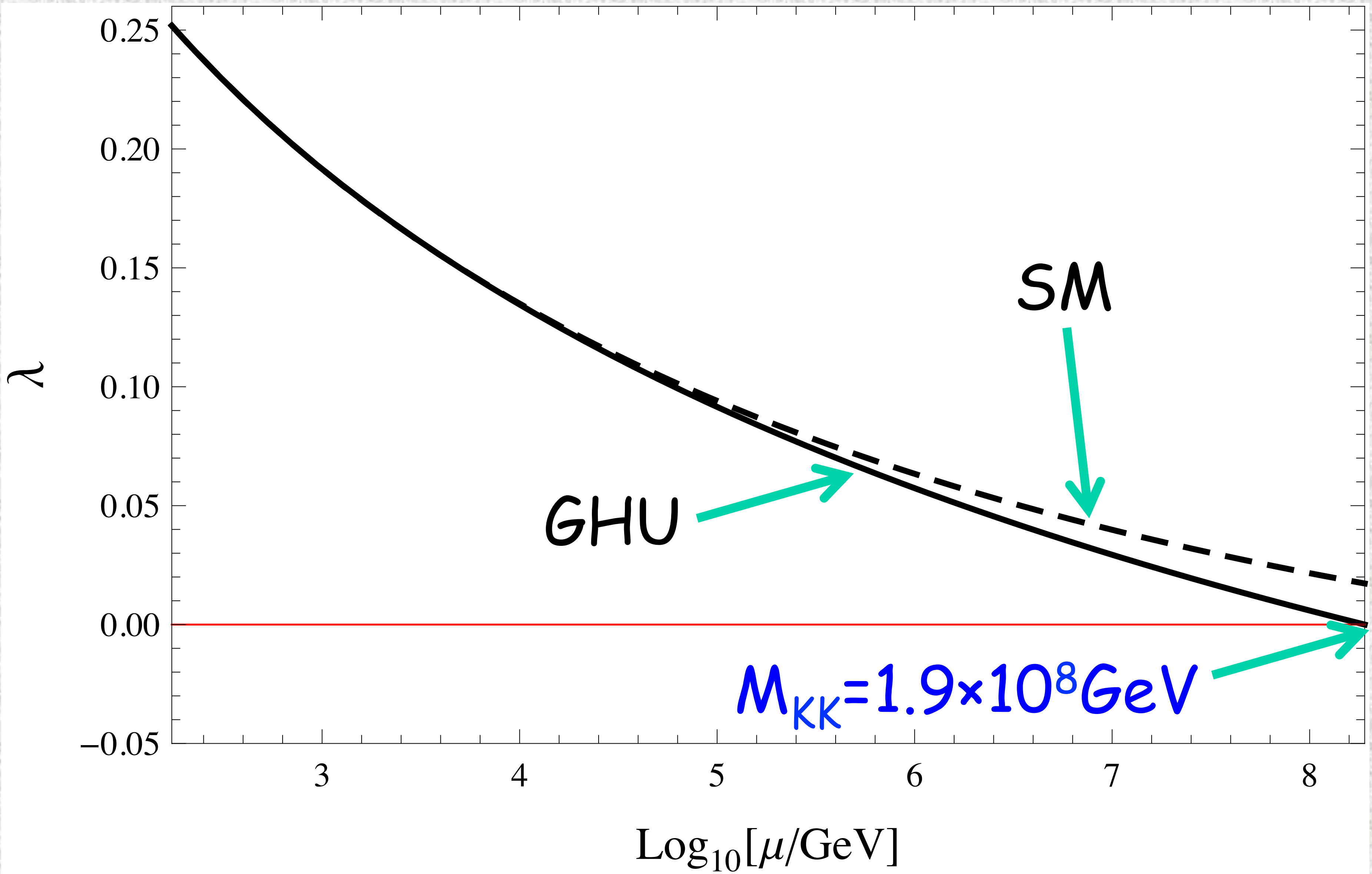
m_h=125GeV cannot be realized by only the SM fields

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

↓

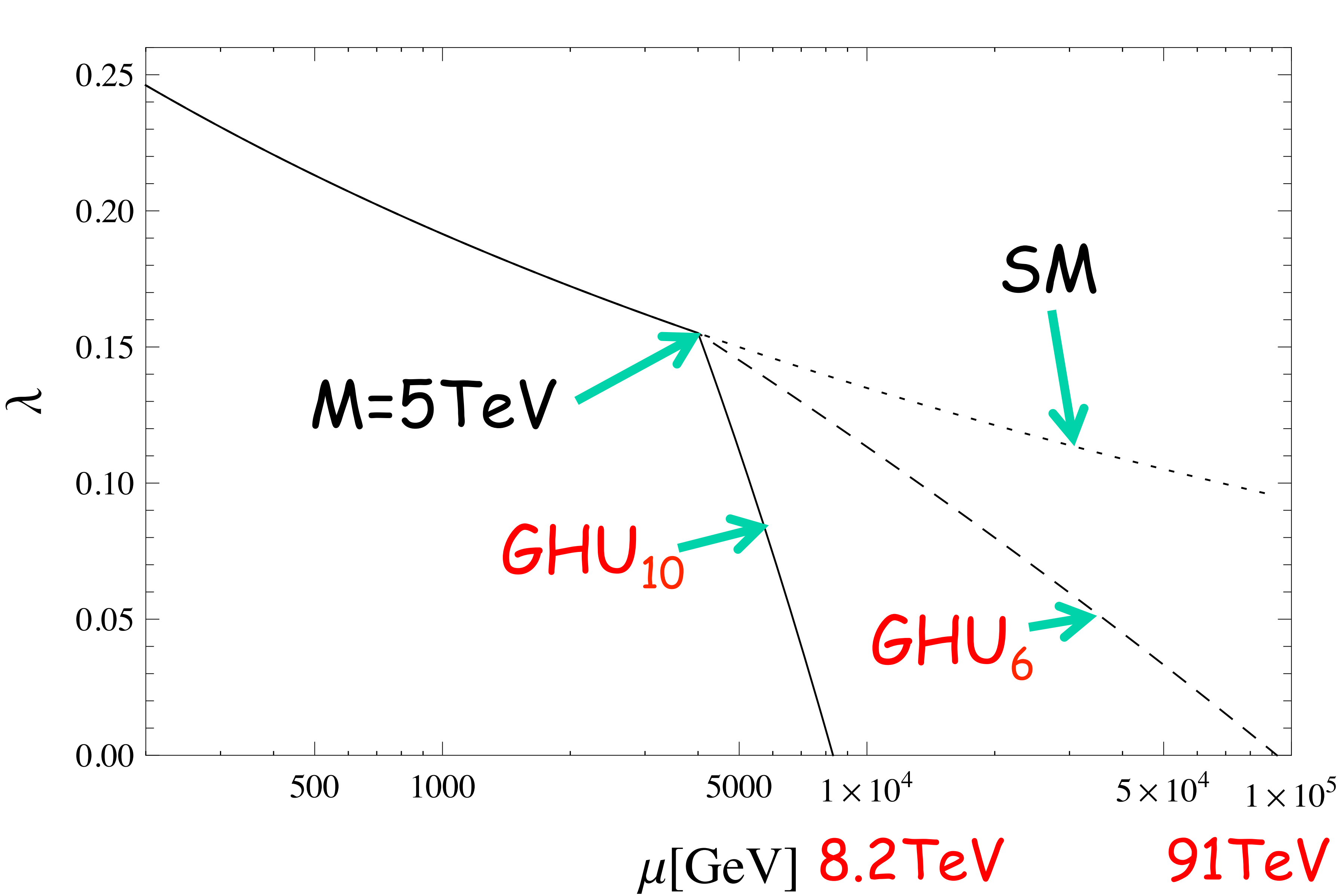
One of the ways lowering M_{KK} is to introduce extra fermions in higher dim. rep. of SU(3)

↓

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}\sim$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)'

$U(1)'$	$6=1\oplus2\oplus3$	$U(1)'$	$10=1\oplus2\oplus3\oplus4$
$2/3$	$(0)_0\oplus\begin{pmatrix}1\\0\end{pmatrix}_{1/2}\oplus\begin{pmatrix}2\\1\\0\end{pmatrix}_1$	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	$(-3)_{-3}\oplus\begin{pmatrix}-2\\-3\end{pmatrix}_{-5/2}\oplus\begin{pmatrix}-1\\-2\\-3\end{pmatrix}_{-2}\oplus\begin{pmatrix}0\\-1\\-2\\-3\end{pmatrix}_{-3/2}$

Thank you
for
your attention!!