Dark Matter in Gauge-Higgs Unification

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2018/12/13 Nambu Symposium
@Osaka City University

Introduction

The existence of DM is no boubt 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

In this talk,

Two possibilities of DM are discussed in the context of gauge-Higgs unification

PLAN

1: Introduction ✔

2: Fermion DM

3: $SU(2)_L$ Doublet Vector DM

4: Summary

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) 115023

Gauge-Higgs Unification?

0 mode of extra component of higher dim. gauge field is identified with SM Higgs

A_μ, $A_i \rightarrow$ SM Higgs

Higgs mass term is forbidden
by higher dimensional gauge symmetry

⇒ Quantum correction to Higgs mass is finite

⇒ Solution to Hierarchy problem in SM

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

BC S^1: $A_M(y+2\pi R) = A_M(y)$ $\quad$ $P=\mathrm{diag}(-,-,+)$

Z_2: $A_\mu(-y) = P^\dagger A_\mu(y) P$, $A_5(-y) = -P^\dagger A_5(y) P$

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

Only + has massless mode@KK scale

SU(3) → SU(2)×U(1)

A_5 → SM Higgs

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

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) triplets 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

$\Rightarrow$ 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 in terms of Majorana basis

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

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

DM-Higgs coupling

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

DM

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

Mass eigenstates

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

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

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

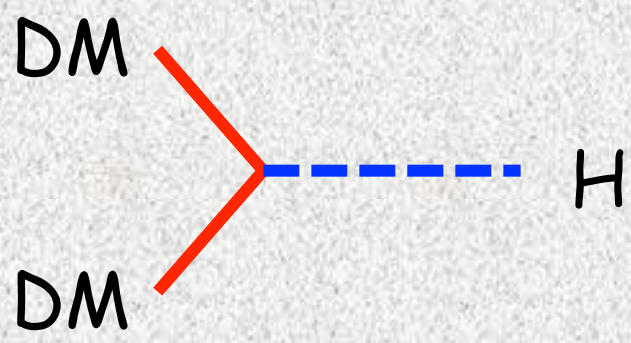
DM Relic Abundance

Interactions relevant to DM(=η_1) physics

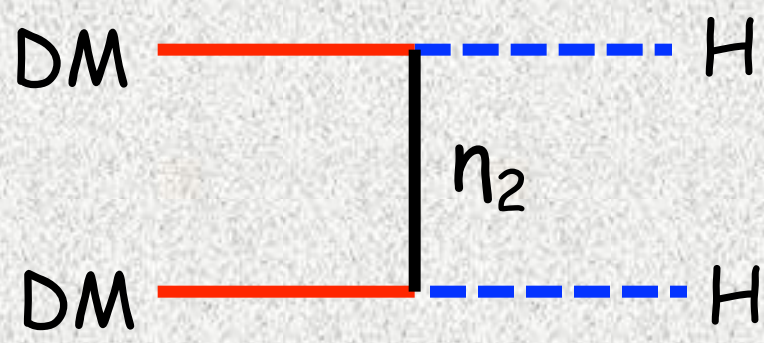
$$\mathcal{L}_{DM-H} = -\frac{1}{2}\left(\frac{m_W}{v}\right)C_1 h\bar{\psi}_{DM}\psi_{DM} - \frac{1}{2}\left(\frac{m_W}{v}\right)C_5 h\left(\bar{\eta}_2\psi_{DM} + h.c.\right)$$

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

two main DM annihilation modes



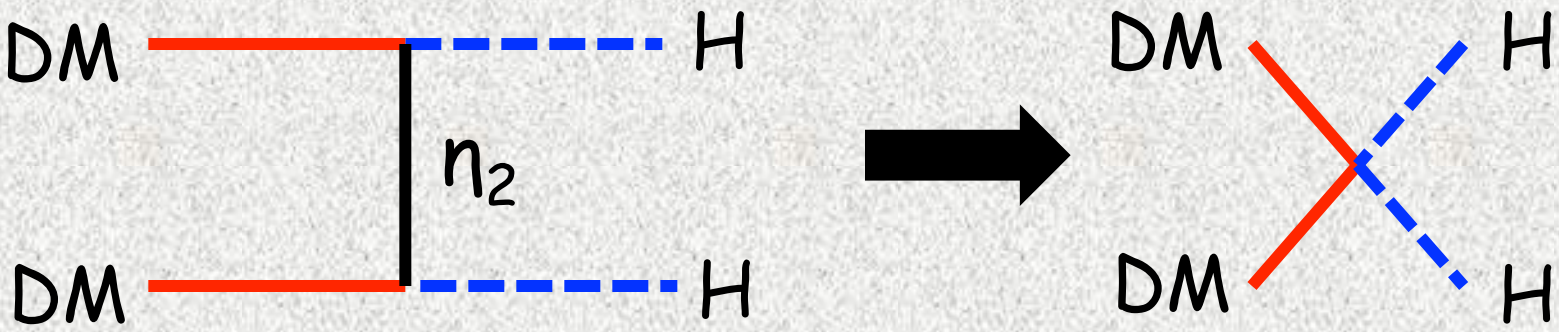
s-channel Higgs exchange



t/u-channel η_2 exchange

$|C_1| \ll 1$, $C_5 \sim 1$ ⇒ 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

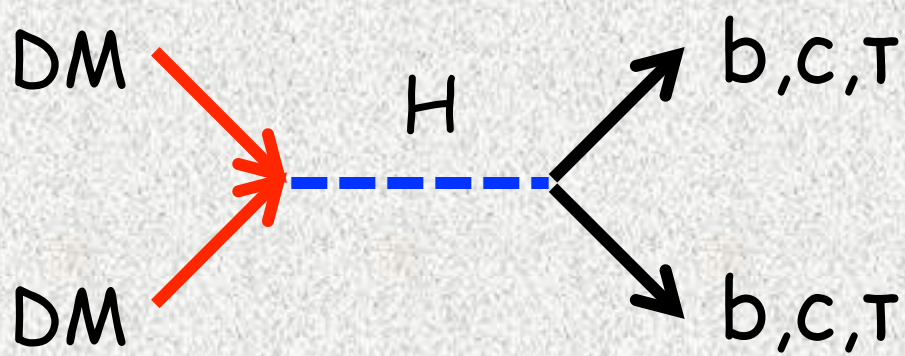
NOT WORK

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

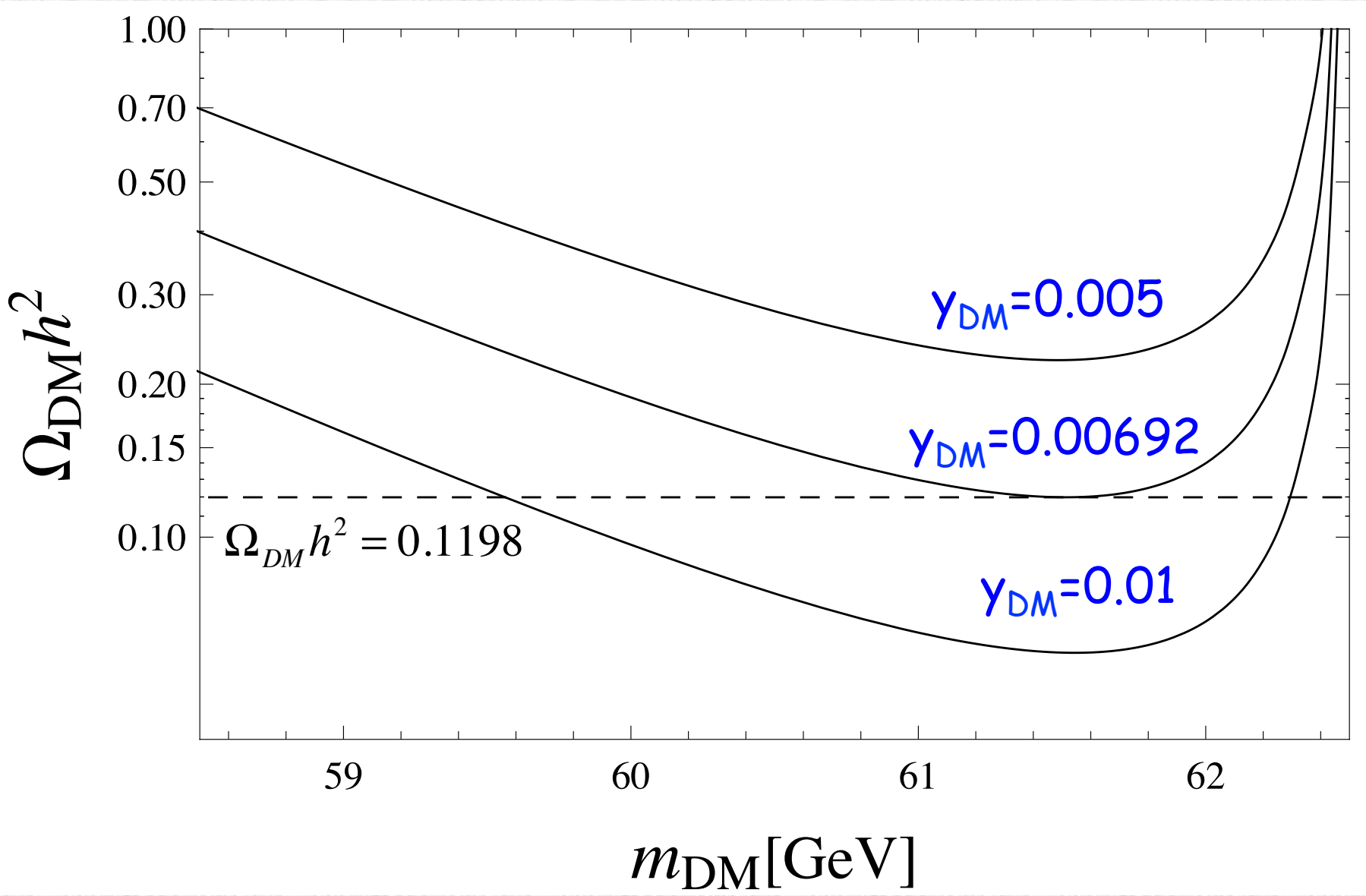
Cross section

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

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



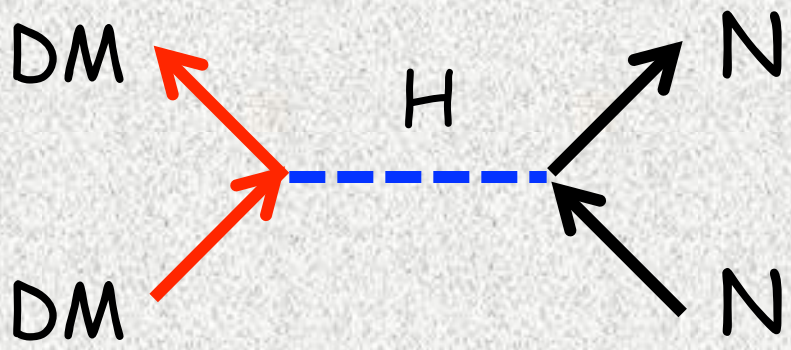
DM relic density as a function of m_{DM}



Direct DM Detection

DM-Nucleon scattering via Higgs exchange

$$\sigma_{DM+N\to DM+N} \simeq 4.47\times 10^{-7}\, pb \times y_{DM}^2\,,\;\; y_{DM} \approx \frac{m_W}{v}\frac{m_W}{2M-m}$$



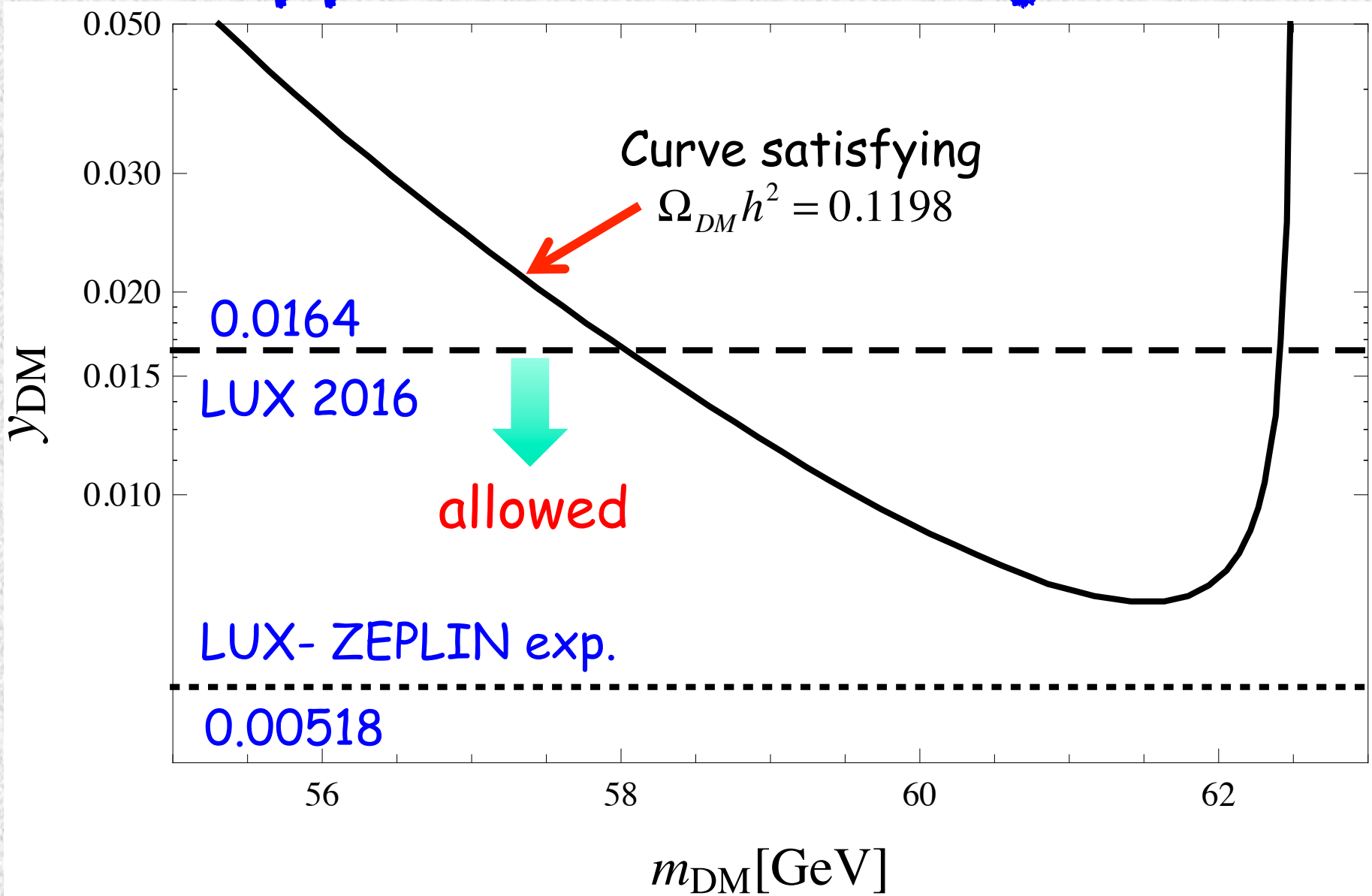
<u>Exp. bound</u>

$\sigma_{DM\text{-}N} \leqq 1.2\times 10^{-10}$ 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}



$SU(2)_L$ 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

BC S^1: $A_M(y+2\pi R) = A_M(y)$ $\quad$ $P=\mathrm{diag}(-,-,+)$

Z_2: $A_\mu(-y) = P^\dagger A_\mu(y) P$, $A_5(-y) = -P^\dagger A_5(y) P$

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

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

SU(3) → SU(2)xU(1)

A_5 → SM Higgs

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

DM Lagrangian

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

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

X^2_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

$$\int dy \mathcal{L}_{DM} \supset -\int dy Tr\left[F_{\mu 5}F^{\mu 5}\right]$$

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

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

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

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

X_μ lightest??

① 1st KK photon mass = 1/R ⇒ True

Brane localized kinetic term effects are studied

Carena, Tait & Wagner (2002)

1st KK mode mass of W, Z, γ can be larger than 1/R

If we take c_L, c_Y < 0, $m_{\text{KK photon}}$ > n/R

⇒ X_μ is LKP

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

X_μ lightest??

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

1st KK fermion mass^2
except for top

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

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

⇒ X_μ is lighter

X_μ lightest??

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

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

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

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

1-loop corrections to KK masses lead to

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

⇒ X_μ lightest

Z coupling of DM

Z-DM-DM O(1) coupling

⇒ excluded from direct detection exp.

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

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

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

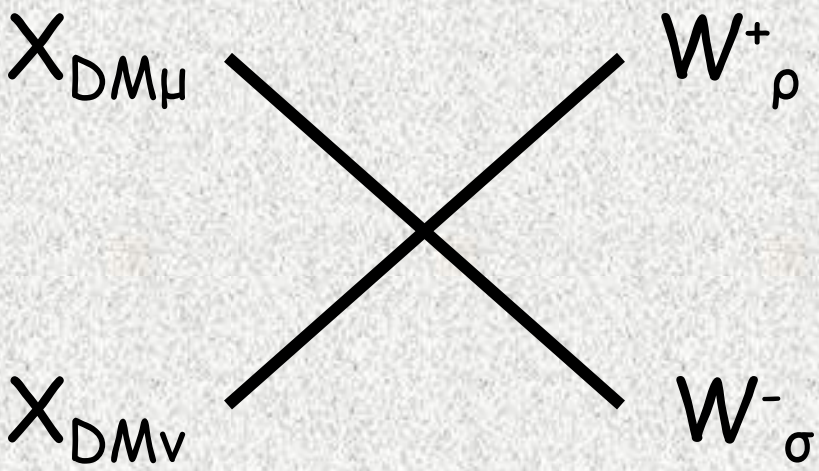
$$\left.+2\partial_\mu X_\nu\left\{X_{DM}^\mu\left(-W^{3\nu} + \sqrt{3}B^\nu\right) - X_{DM}^\nu\left(-W^{3\mu} + \sqrt{3}B^\mu\right)\right\}\right]$$

No Z-X_{DM}-X_{DM} coupling!!

Relic abundance of vector DM

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

$$\mathcal{L}_{4D} \supset -g^2 \left(\eta^{\mu\nu}\eta^{\rho\sigma} - \eta^{\mu\rho}\eta^{\nu\sigma} \right) X_{DM\mu} X_{DM\nu} W^+_\rho W^-_\sigma$$



$$\Rightarrow \quad \sigma v_{rel} = \frac{5g^4}{48\pi m_{DM}}$$

$\Omega_{DM} h^2 \sim 0.1 \Rightarrow m_{DM} \sim$ 1.5 TeV (g=0.65)

Summary

- Fermion DM scenario in GHU
- DM is an almost SU(2)xU(1) singlet in extra SU(3) multiplets
- DM of 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
- Allowed parameter region will be covered by the future LUX-ZEPLIN exp.

Summary

- A new vector DM scenario also proposed
- DM is the 1st KK $SU(2)_L$ doublet vector field
- Stable by KK parity ⇒ LKP
- Model-independent ∵ a partner of Higgs
- No DM-DM-Higgs/Z couplings

  ⇒ Severe constraints from direct DM detection exp. can be evaded
- Observed relic abundance obtained by TeV scale DM