Pseudo-Nambu-Goldstone Dark Matter from Non-Abelian Gauge Symmetry

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(South China Normal University 华南师范大学)

Collaborators：

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Based on Phys. Rev. D 106 (2022) 11, 115033 [**2210.08696**]

"Higgs 2023" @ Institute of High Energy Physics (IHEP), Chinese Academy of Science (CAS)
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New

C.W. Chang, K. Tsumura, **YU**, N Yamatsu,
“Pseudo-Nambu-Goldstone Dark Matter in SU(7) Grand Unification” **[2311.13753]**

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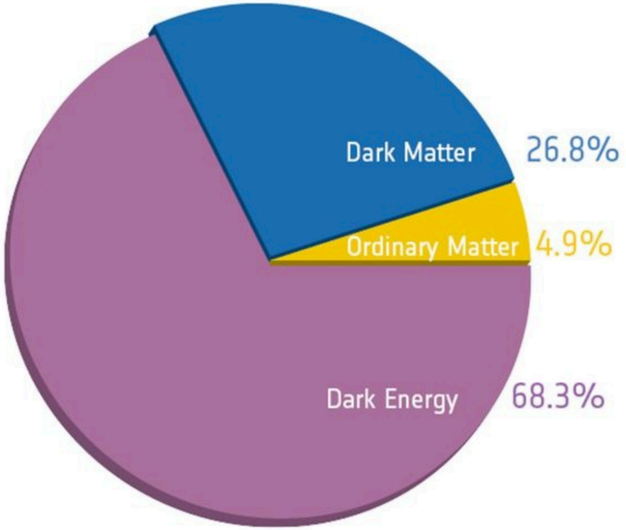
・Unknown matter (**Dark Matter**) accounts for 26.8% of the total in the universe

・An attractive candidate for a DM is …

WIMP (Weakly Interacting Massive Particle)

・thermally produced in the early universe

・severely constrained by the direct detection



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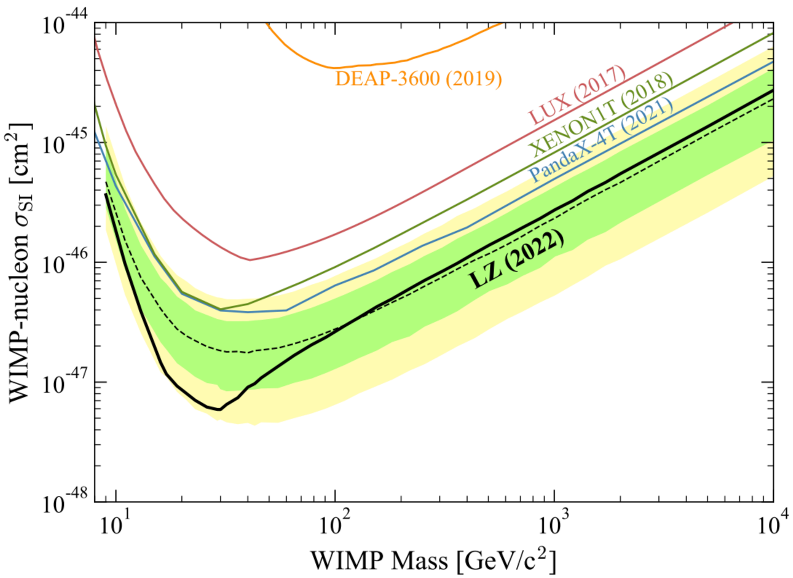

LZ collaborations [**2207.03764**]

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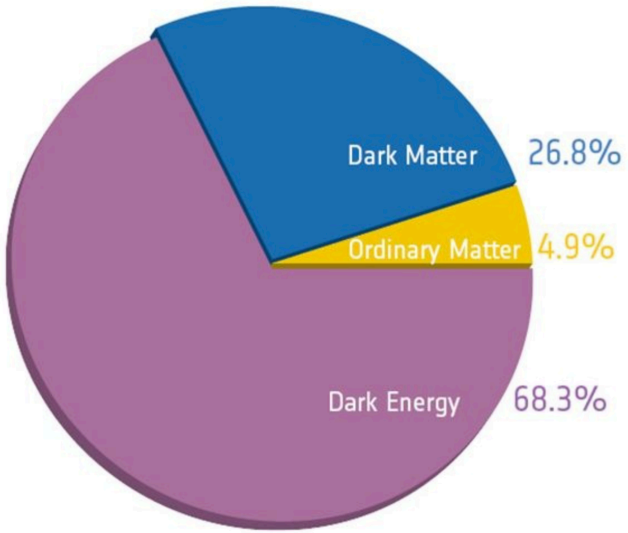

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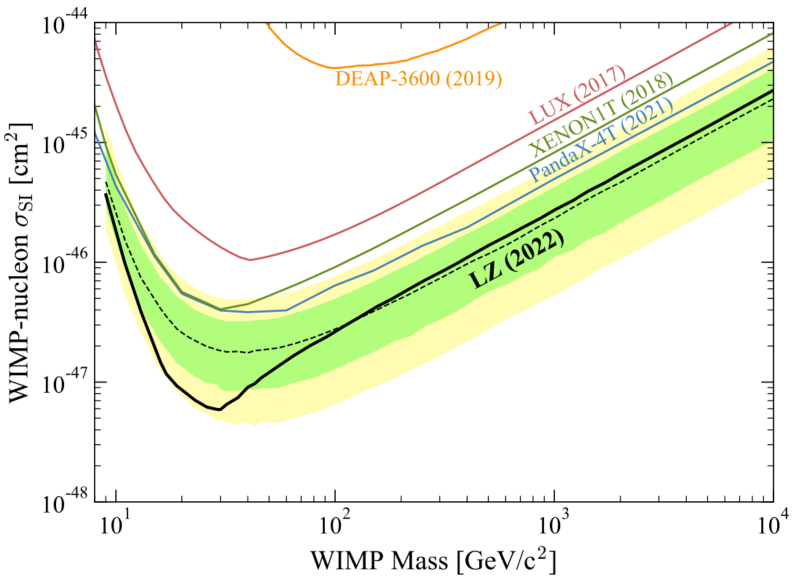

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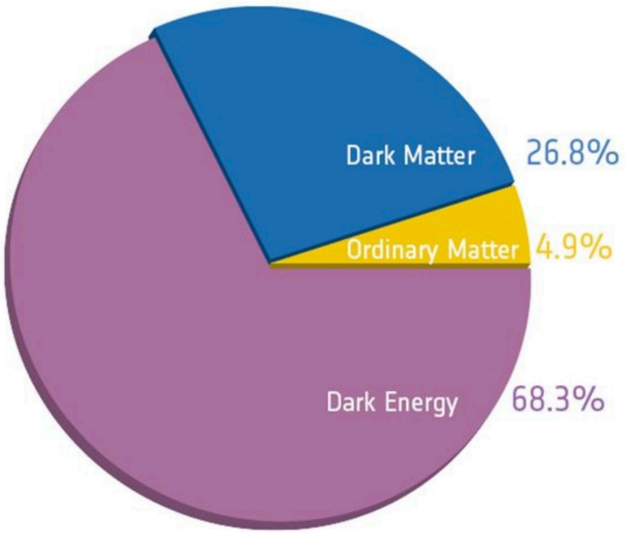

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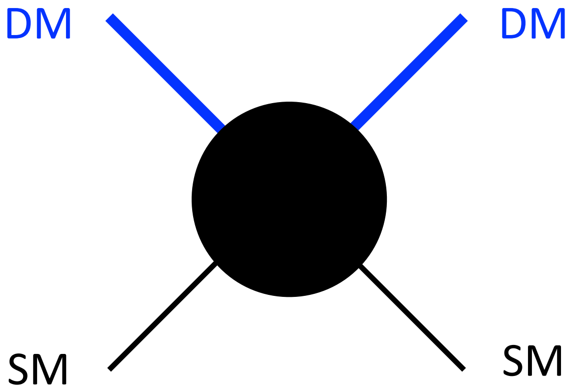

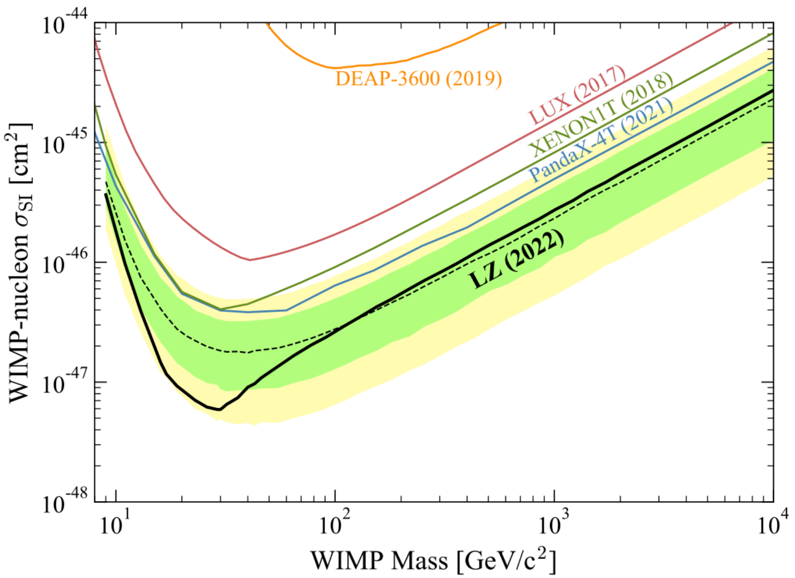

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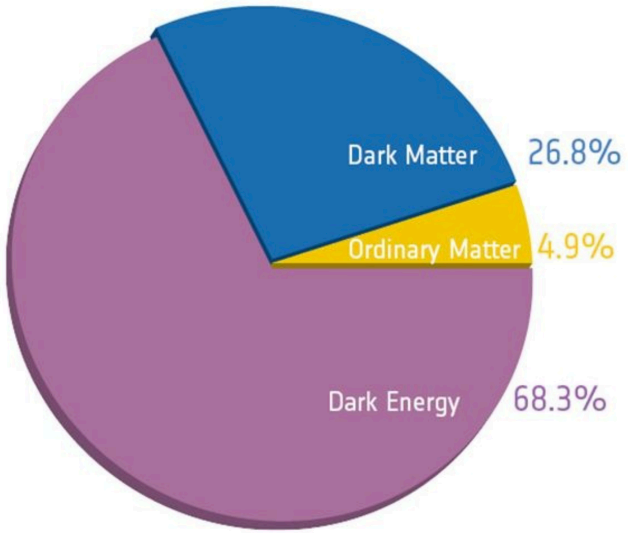

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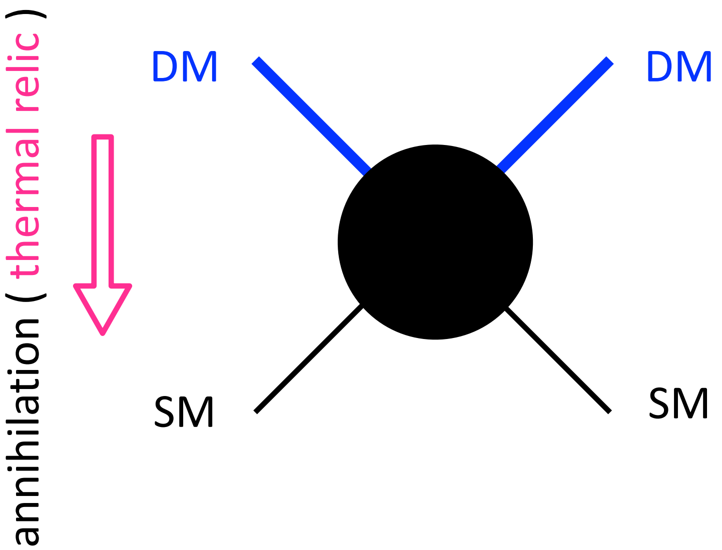

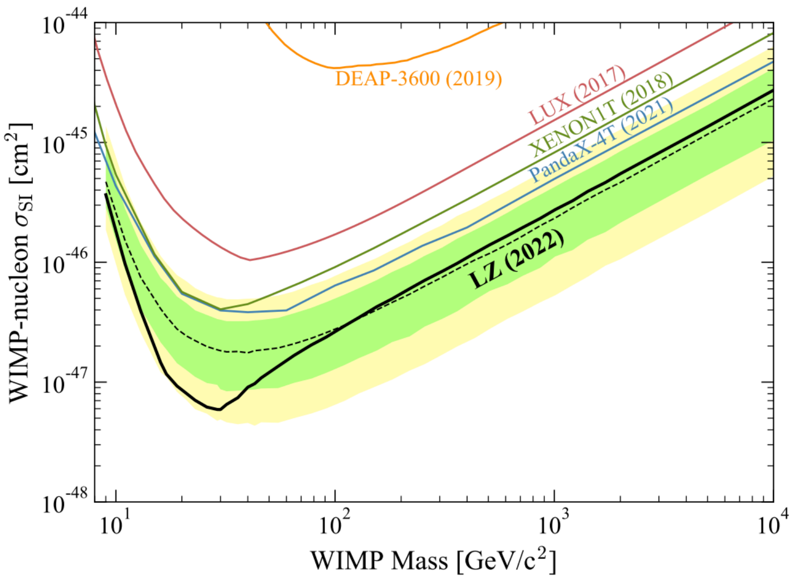

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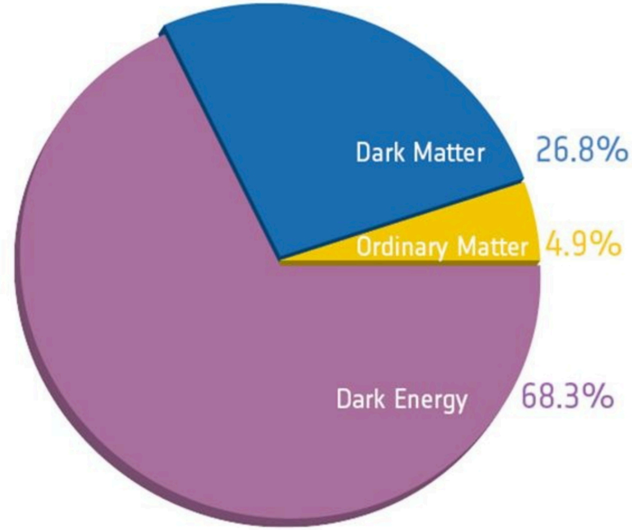

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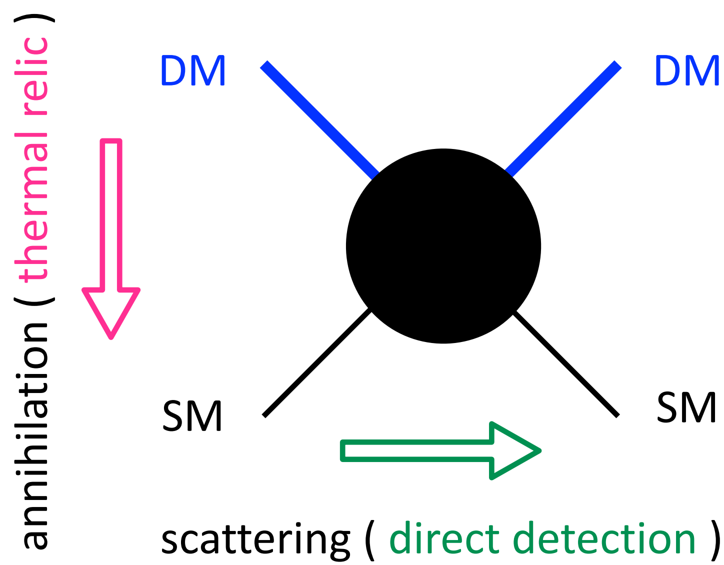

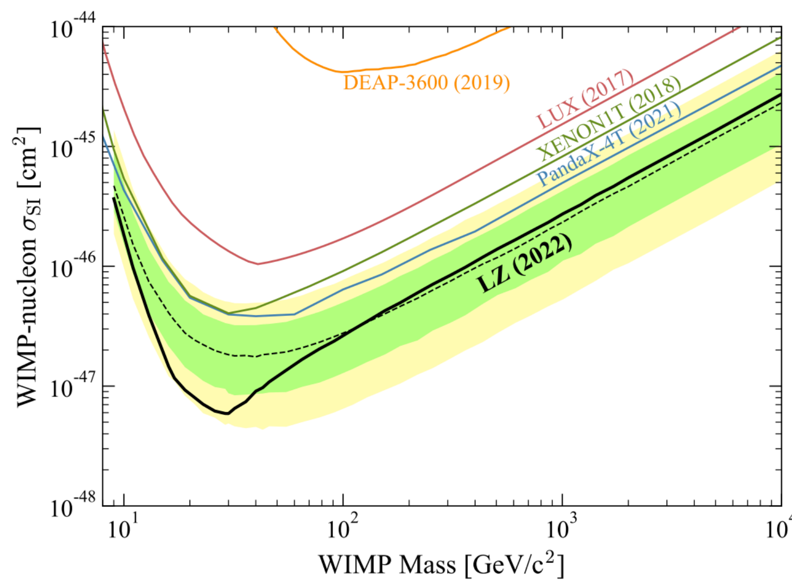

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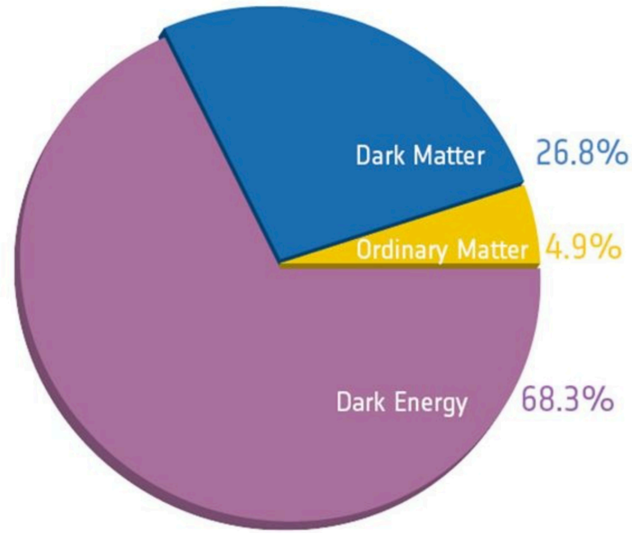

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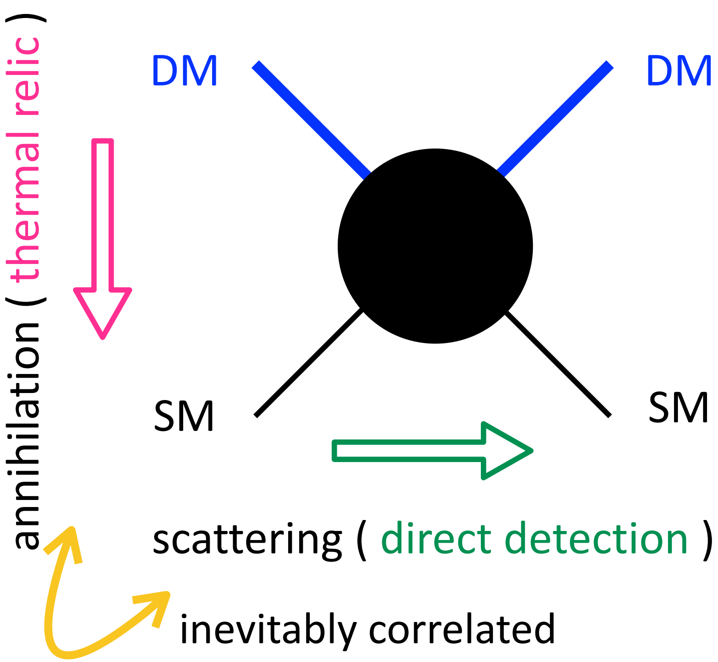

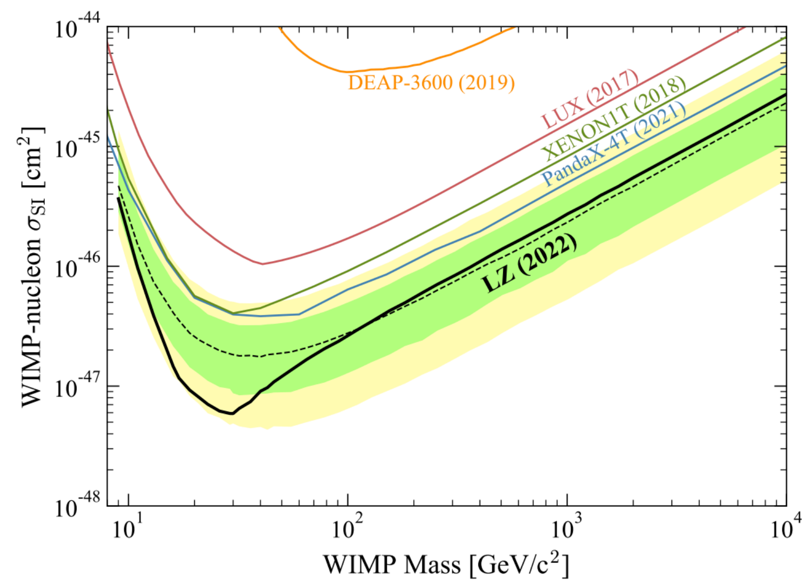

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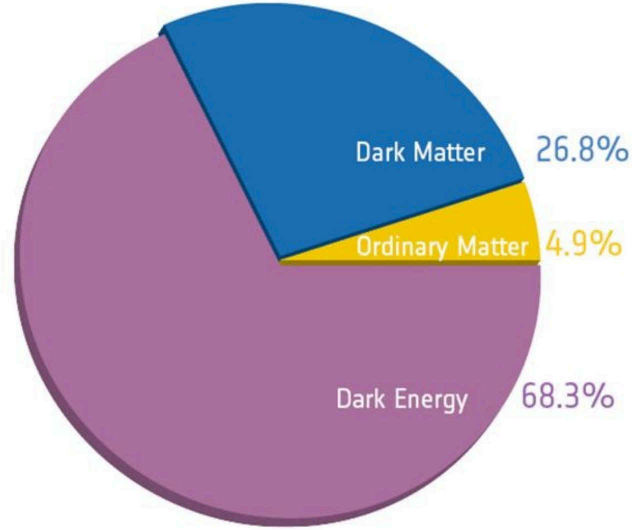

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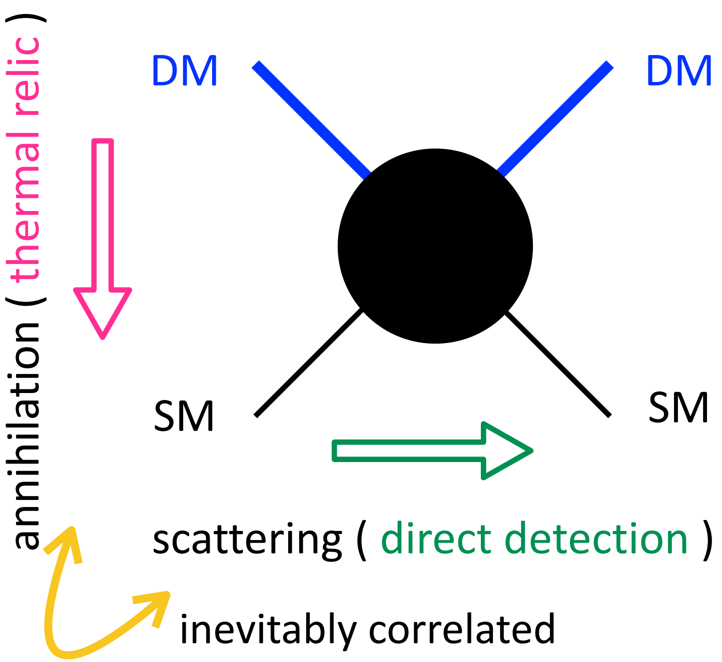

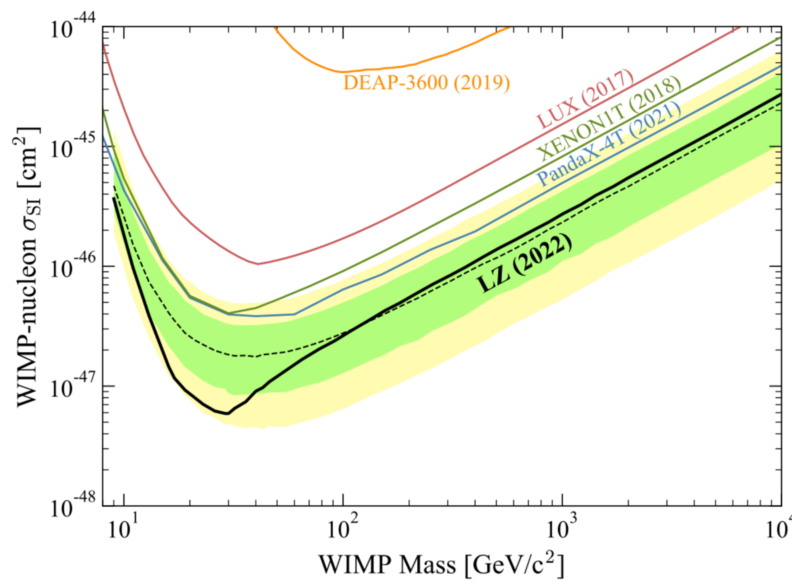

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Stronger DM-SM interaction helps DM to stay longer in thermal bath, leading to $\Omega h^2 \simeq 0.12$, but also increases DM-nucleon scattering.

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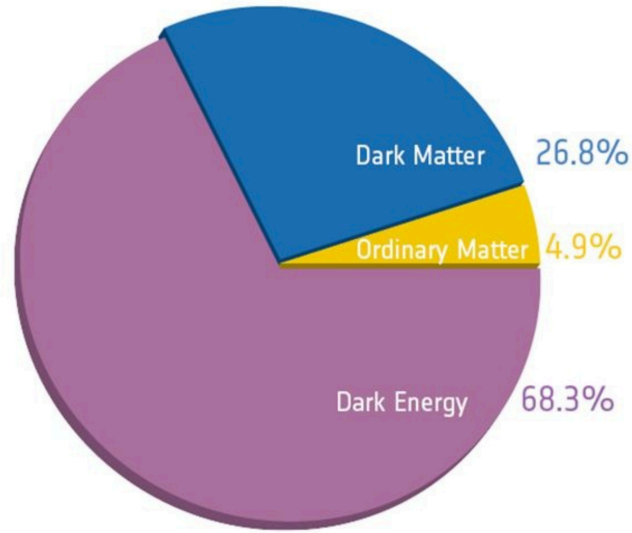

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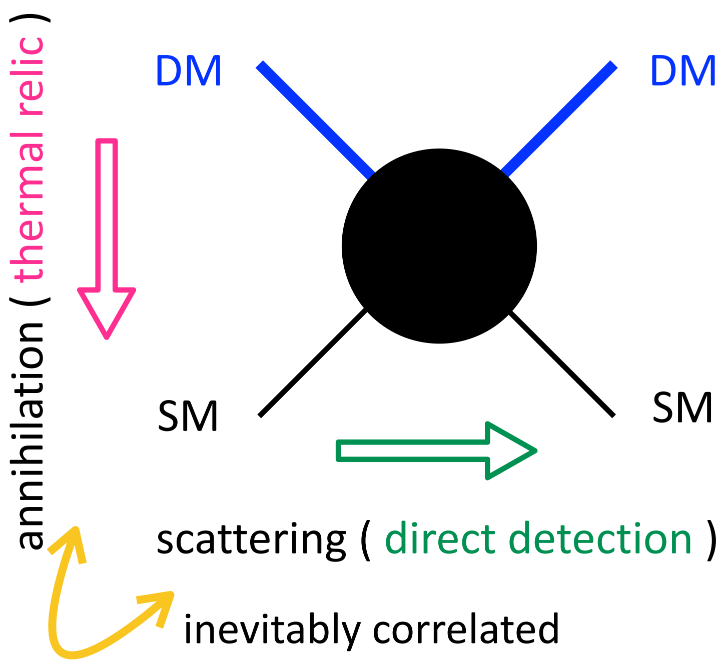

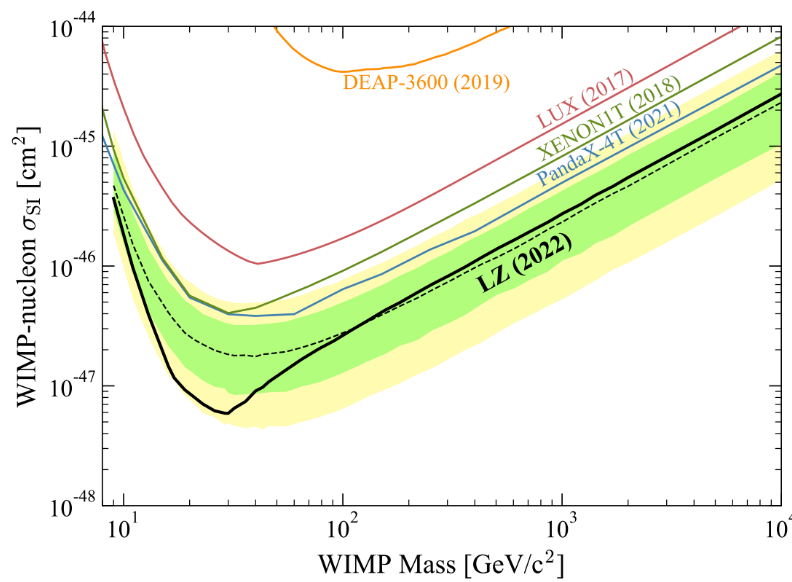

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Stronger DM-SM interaction helps DM to stay longer in thermal bath, leading to $\Omega h^2 \simeq 0.12$, but also increases DM-nucleon scattering.

To realize viable WIMP model, we must address this dilemma.

What type of WIMP model would solve this dilemma?

C. Gross, O. Lebedev, and T, Toma
Phys. Rev. Lett. 119 (2017) 19, 191801, [**1708.02253**]

pseudo Nambu-Goldstone Boson Dark Matter (pNGB-DM)

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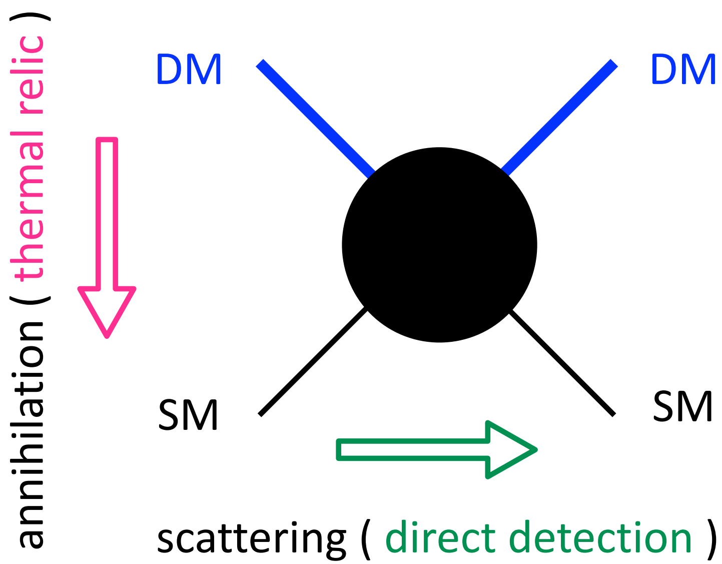
DM communicates with SM particles via derivative interaction



Small momentum transfer

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symmetry : $G_{\rm SM} \times U(1)_{\rm global}$ new fields : complex $S \in \mathbf{1}_0$

$$V(H,S) = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4$$

Origin for pNGB mass

$$-\frac{\mu_S'^2}{4}S^2 + \text{h.c.}$$

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Problems : $\mu_S'' S^3$, $\mu_S'''|S|^2 S$, ... are dropped by hands

Solutions : gauged $U(1)_{B-L}$ model

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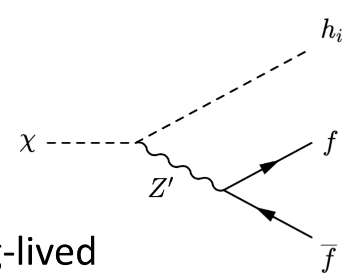
Y. Abe, T. Toma, K. Tsumura, and N. Yamatsu, Phys.Rev.D 104 (2021) 3, 035011 [**2104.13523**]

$v_{B-L} \simeq 10^{15}\text{GeV}$
" **hierarchy problem** "

*pNGB DM **decays***



$\propto m_\chi^5/m_{Z'}^4$

Z' : $U(1)_{B-L}$ gauge field

Higher $U(1)_{B-L}$ breaking scale required to make DM long-lived

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Hint : custodial symmetry

$$V_{\rm SM}(H) = -\mu_H^2 H^\dagger H + \lambda (H^\dagger H)^2 \qquad H = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix}$$

$G_{\rm SM} = SU(2)_L \times U(1)_Y$ invariant

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$W_\mu^\pm$ and Z_μ form a $SU(2)_V$ triplet.

$m_W \simeq m_Z$

Accidental global symmetry : $G_{\rm global} = O(4) \simeq SU(2)_L \times SU(2)_R \xrightarrow[\langle H \rangle \neq 0]{} SU(2)_V$: custodial sym.

Our Model

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UV completion of pNGB-DM model & predict stable DM

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H. Otsuka, K. Tsumura, **YU**, N. Yamatsu, Phys. Rev. D 106 (2022) 11, 115033 [**2210.08696**]

We consider $G_{\rm SM} \times SU(2)_D^{\rm gauge}$ symmetry

and introduce $\Phi \in \mathbf{2}$, $\Delta \in \mathbf{3}$ under $SU(2)_D^{\rm gauge}$

$$\Sigma = \left(\tilde{\Phi}, \Phi \right)$$

	$SU(2)_L$	$U(1)_Y$	$SU(2)_D^{\rm gauge}$
H	$\mathbf{2}$	$1/2$	$\mathbf{1}$
Φ	$\mathbf{1}$	0	$\mathbf{2}$
Δ	$\mathbf{1}$	0	$\mathbf{3}$

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Φ	$\mathbf{1}$	0	$\mathbf{2}$
Δ	$\mathbf{1}$	0	$\mathbf{3}$

$$\Sigma = (\tilde{\Phi}, \Phi)$$

$$V(H, \Phi, \Delta)$$

$$= -\mu_H^2 H^\dagger H - \frac{1}{2}\mu_\Phi^2 {\rm Tr}\left[\Sigma^\dagger \Sigma\right] - \frac{1}{2}\mu_\Delta^2 {\rm Tr}\left[\Delta^2\right]$$

Mass terms

$$+ \lambda_H \left(H^\dagger H\right)^2 + \frac{\lambda_\Phi}{4}\left({\rm Tr}\left[\Sigma^\dagger \Sigma\right]\right)^2 + \frac{\lambda_\Delta}{4}\left({\rm Tr}\left[\Delta^2\right]\right)^2$$

4-point self-int.

$$+ \lambda_{H\Phi}\left(H^\dagger H\right){\rm Tr}\left[\Sigma^\dagger \Sigma\right] + \lambda_{H\Delta}\left(H^\dagger H\right){\rm Tr}\left[\Delta^2\right] + \frac{\lambda_{\Phi\Delta}}{2}{\rm Tr}\left[\Sigma^\dagger \Sigma\right]{\rm Tr}\left[\Delta^2\right]$$

4-point int.

$$-\sqrt{2}\kappa {\rm Tr}\left[\sigma_3 \Sigma^\dagger \Delta \Sigma\right]$$

$V(H,\Phi,\Delta)$ has " **Dark custodial symmetry** "

H. Otsuka, K. Tsumura, **YU**, N. Yamatsu, Phys. Rev. D 106 (2022) 11, 115033 [**2210.08696**]

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and introduce $\Phi\in\mathbf{2}$, $\Delta\in\mathbf{3}$ under $SU(2)_D^{\rm gauge}$

	$SU(2)_L$	$U(1)_Y$	$SU(2)_D^{\rm gauge}$
H	$\mathbf{2}$	$1/2$	$\mathbf{1}$
Φ	$\mathbf{1}$	0	$\mathbf{2}$
Δ	$\mathbf{1}$	0	$\mathbf{3}$

$$\Sigma=(\tilde\Phi,\Phi)$$

$$V(H,\Phi,\Delta)$$

$$=-\mu_H^2H^\dagger H-\frac{1}{2}\mu_\Phi^2{\rm Tr}\left[\Sigma^\dagger\Sigma\right]-\frac{1}{2}\mu_\Delta^2{\rm Tr}\left[\Delta^2\right]$$

Mass terms

$$+\lambda_H\left(H^\dagger H\right)^2+\frac{\lambda_\Phi}{4}\left({\rm Tr}\left[\Sigma^\dagger\Sigma\right]\right)^2+\frac{\lambda_\Delta}{4}\left({\rm Tr}\left[\Delta^2\right]\right)^2$$

4-point self-int.

$$+\lambda_{H\Phi}\left(H^\dagger H\right){\rm Tr}\left[\Sigma^\dagger\Sigma\right]+\lambda_{H\Delta}\left(H^\dagger H\right){\rm Tr}\left[\Delta^2\right]+\frac{\lambda_{\Phi\Delta}}{2}{\rm Tr}\left[\Sigma^\dagger\Sigma\right]{\rm Tr}\left[\Delta^2\right]$$

4-point int.

$$-\sqrt{2}\kappa{\rm Tr}\left[\sigma_3\Sigma^\dagger\Delta\Sigma\right]$$

$V(H,\Phi,\Delta)$ has " **Dark custodial symmetry** "

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$$+\lambda_{H\Phi}\left(H^\dagger H\right){\rm Tr}\left[\Sigma^\dagger\Sigma\right]+\lambda_{H\Delta}\left(H^\dagger H\right){\rm Tr}\left[\Delta^2\right]+\frac{\lambda_{\Phi\Delta}}{2}{\rm Tr}\left[\Sigma^\dagger\Sigma\right]{\rm Tr}\left[\Delta^2\right]$$

$$-\sqrt{2}\kappa{\rm Tr}\left[\sigma_3\Sigma^\dagger\Delta\Sigma\right]$$

Invariant under

global " **Dark custodial symmetry** "

$(H\to H)$

$$\Delta\to U_L^{\rm dark}\,\Delta\,U_L^{\rm dark\,\dagger}$$

$$\Sigma\to U_L^{\rm dark}\,\Sigma\,U_R^{\rm dark\,\dagger}$$

$V(H, \Phi, \Delta)$ has " **Dark custodial symmetry** "

H. Otsuka, K. Tsumura, **YU**, N. Yamatsu, Phys. Rev. D 106 (2022) 11, 115033 [**2210.08696**]

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Δ	$\mathbf{1}$	0	$\mathbf{3}$

$$\Sigma = \left(\tilde{\Phi}, \Phi \right)$$

$$V(H, \Phi, \Delta)$$

$$= -\mu_H^2 H^\dagger H - \frac{1}{2}\mu_\Phi^2 {\rm Tr}\left[\Sigma^\dagger \Sigma\right] - \frac{1}{2}\mu_\Delta^2 {\rm Tr}\left[\Delta^2\right]$$

$$+ \lambda_H \left(H^\dagger H\right)^2 + \frac{\lambda_\Phi}{4}\left({\rm Tr}\left[\Sigma^\dagger \Sigma\right]\right)^2 + \frac{\lambda_\Delta}{4}\left({\rm Tr}\left[\Delta^2\right]\right)^2$$

$$+ \lambda_{H\Phi}\left(H^\dagger H\right){\rm Tr}\left[\Sigma^\dagger \Sigma\right] + \lambda_{H\Delta}\left(H^\dagger H\right){\rm Tr}\left[\Delta^2\right] + \frac{\lambda_{\Phi\Delta}}{2}{\rm Tr}\left[\Sigma^\dagger \Sigma\right]{\rm Tr}\left[\Delta^2\right]$$

$$- \sqrt{2}\kappa {\rm Tr}\left[\sigma_3 \Sigma^\dagger \Delta \Sigma\right]$$

Explicitly breaks

global " **Dark custodial symmetry** "

$$(H \to H)$$

$$\Delta \to U_L^{\rm dark} \Delta U_L^{\rm dark\,\dagger}$$

$$\Sigma \to U_L^{\rm dark} \Sigma U_R^{\rm dark\,\dagger}$$

$V(H,\Phi,\Delta)$ has " **Dark custodial symmetry** "

H. Otsuka, K. Tsumura, **YU**, N. Yamatsu, Phys. Rev. D 106 (2022) 11, 115033 [**2210.08696**]

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$$+\lambda_{H\Phi}\left(H^\dagger H\right){\rm Tr}\left[\Sigma^\dagger\Sigma\right] + \lambda_{H\Delta}\left(H^\dagger H\right){\rm Tr}\left[\Delta^2\right] + \frac{\lambda_{\Phi\Delta}}{2}{\rm Tr}\left[\Sigma^\dagger\Sigma\right]{\rm Tr}\left[\Delta^2\right]$$

$$-\sqrt{2}\kappa {\rm Tr}\left[\sigma_3 \Sigma^\dagger \Delta \Sigma\right]$$

Explicitly breaks

global " **Dark custodial symmetry** "

Even after $\langle\Phi\rangle \neq 0$ & $\langle\Delta\rangle \neq 0$, the exact $U(1)_{\rm global}$ remains unbroken

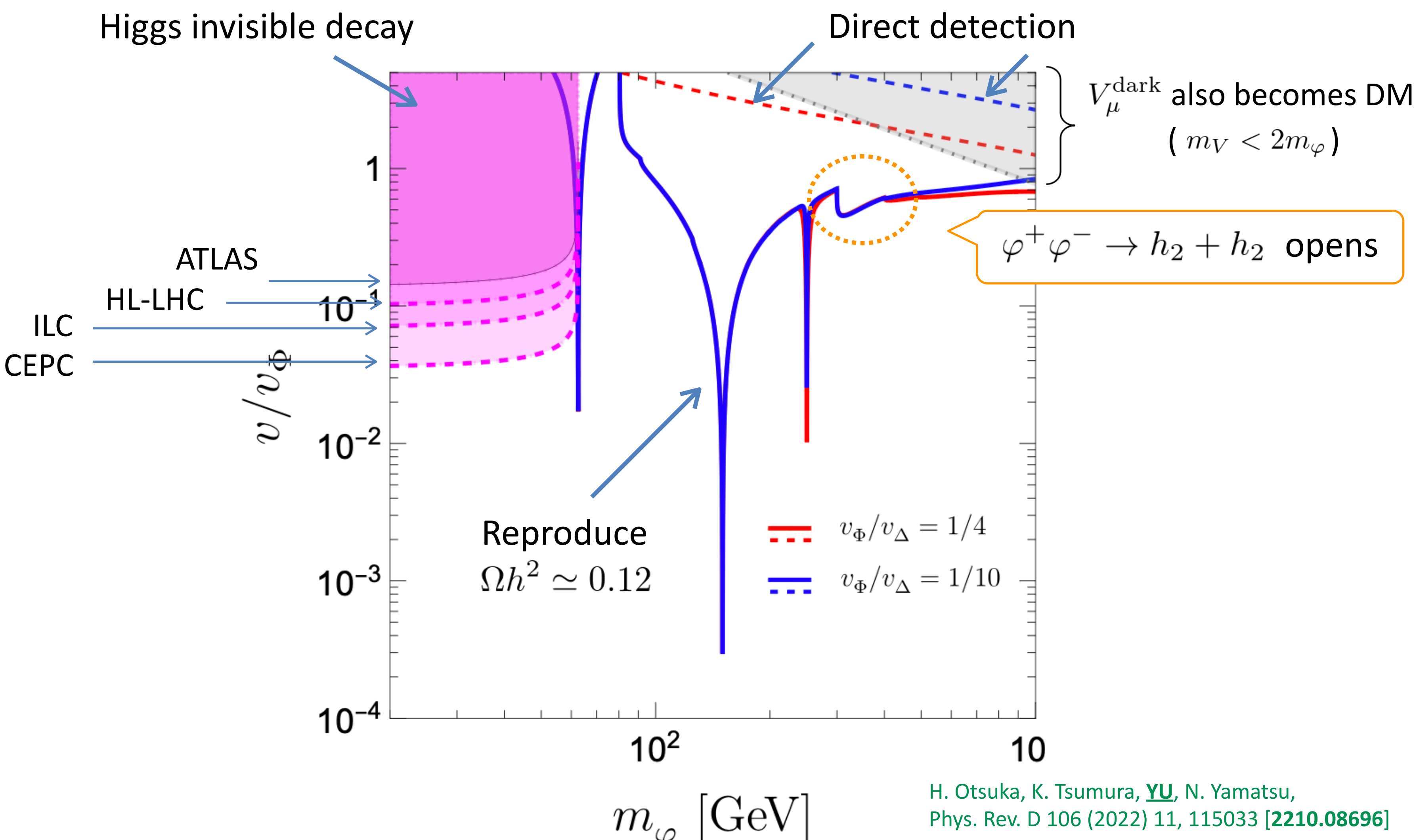
⇒ ensures stability of pNGB-DM

c.f.) T. Abe and Y. Hamada, PTEP 2023 (2023) no.3, 033B04, [**2205.11919**]

Benchmark scalar mass : $(m_{h_1}, m_{h_2}, m_{h_3}) = (125,\ 300,\ 500)\ \mathrm{GeV}$

mixing angle : $(\sin\alpha_x, \sin\alpha_y, \sin\alpha_z) = (0.06,\ 0.05,\ 0.1)$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_x & \sin\alpha_x \\ 0 & -\sin\alpha_x & \cos\alpha_x \end{pmatrix} \begin{pmatrix} \cos\alpha_y & 0 & \sin\alpha_y \\ 0 & 1 & 0 \\ -\sin\alpha_y & 0 & \cos\alpha_y \end{pmatrix} \begin{pmatrix} \cos\alpha_z & \sin\alpha_z & 0 \\ -\sin\alpha_z & \cos\alpha_z & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ \phi_3 \\ \eta_3 \end{pmatrix}$$



H. Otsuka, K. Tsumura, **YU**, N. Yamatsu,
Phys. Rev. D 106 (2022) 11, 115033 [**2210.08696**]

Summary

- In the original abelian pNGB DM model, particular soft-breaking terms are included, and their origins are not addressed.

- UV completed models are proposed, but all of them predict decaying DM. In order to make DM long-lived, we must introduce large hierarchy in symmetry breaking scales.

- We construct pNGB-DM model with non-abelian gauge symmetry. Unbroken dark custodial symmetry ensure stability of pNGB DM. We don’t need to introduce large hierarchy.

Back Up

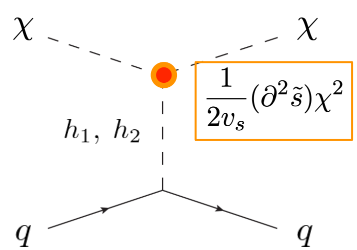
Goal UV completion of pNGB-DM model with no large hierarchy

But, this is not the end of the story …

Three-point breaking term may spoil the cancellation

- **Two-point** breaking term T. Abe and Y. Hamada, [**2205.11919**]

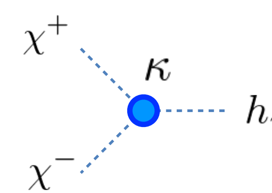
$$\mu_\chi^2 \left(\phi^\dagger T^3 \phi\right) \Rightarrow$$ Origin of pNGBs' mass

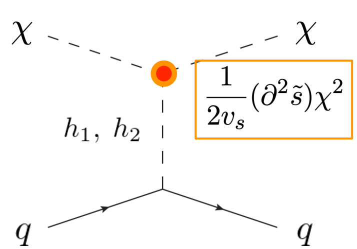


$$\propto \quad t = (p_2 - p_1)^2 \quad \underset{t\to 0}{\longrightarrow} \quad 0$$

- **Three-point** breaking term **Our Model**

$$\kappa\, \Phi^\dagger \Delta \Phi \qquad \begin{matrix}\Phi \in \mathbf{2} \\ \Delta \in \mathbf{3}\end{matrix} \Rightarrow$$ Origin of pNGBs' mass & **interactions**





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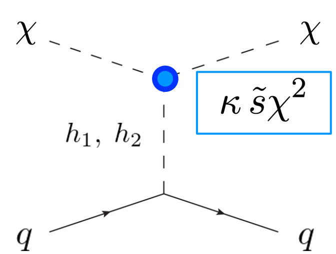
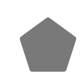
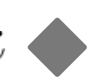


$\propto \quad t$  $+ \ \kappa$ 

We must make sure *DM-nucleon scattering is suppressed enough*

Soft breaking terms

- Soft-breaking = Quadratic

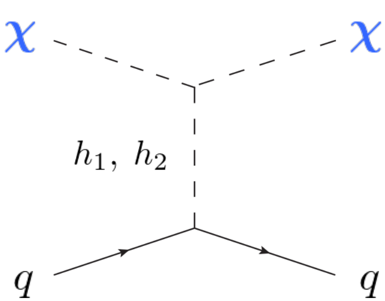
$$V_{\rm SM}(H) + \lambda_{HS}|H|^2|S|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_S}{2}|S|^4 - \left(\frac{\mu_S'^2}{4}S^2 + \text{h.c.}\right)$$

C. Gross, O. Lebedev, and T, Toma, Phys. Rev. Lett. 119 (2017) 19, 191801, [**1708.02253**]

- Soft-breaking = Quadratic + tadpole

$$V_{\rm SM}(H) + \lambda_{HS}|H|^2|S|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_S}{2}|S|^4 - \left(\frac{\mu_S'^2}{4}S^2 + \text{h.c.}\right) + \left(aS + \text{h.c.}\right)$$

V. Barger, P. Langacker, M. McCaskey, M. Ramsey-Musolf and G. Shaughnessy, Phys. Rev. D 79 (2009), 015018, [**0811.0393**]
G. C. Cho, C. Idegawa and E. Senaha, Phys. Lett. B 823 (2021), 136787, [**2105.11830**]



$$\propto \left\{ \left(-\frac{m_{h_1}^2}{t - m_{h_1}^2} + \frac{m_{h_2}^2}{t - m_{h_2}^2}\right) \simeq 0 \quad @\ t \to 0\right.$$

$$\left. + \frac{\sqrt{2}a}{v_S}\left(-\frac{1}{t - m_{h_1}^2} + \frac{1}{t - m_{h_2}^2}\right) \right\} \simeq 0 \quad @\ m_{h_1} \simeq m_{h_2}$$

Based on Idegawa-san's slide