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

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Naoki Yamatsu (National Taiwan U.)

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

The 6th International Workshop on "Higgs as a Probe of New Physics 2023"

2023/06/06 @ Nambu Yoichiro Hall (Osaka Univ.)

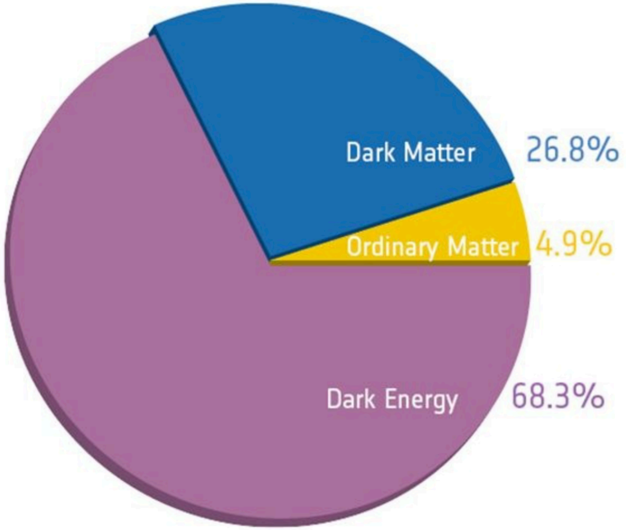
・Unknown matter (**Dark Matter**) accounts for 26.8% of the total in the universe

・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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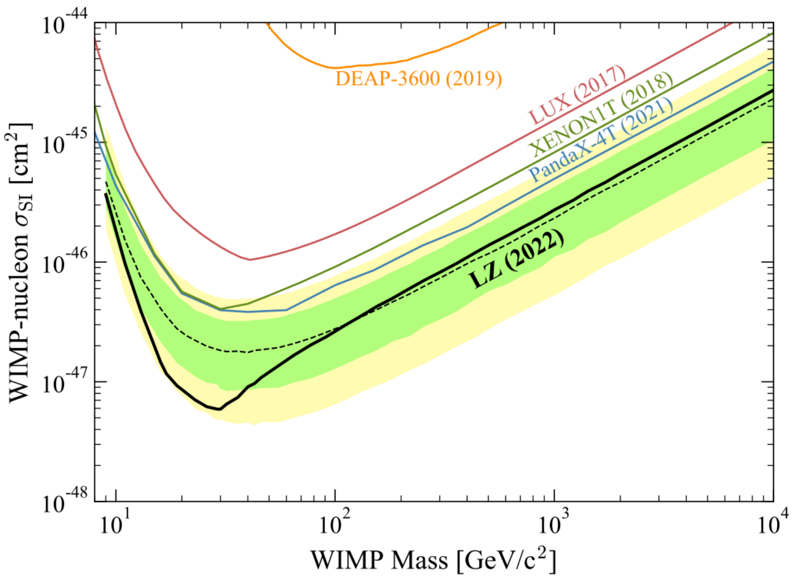

LZ collaborations [**2207.03764**]

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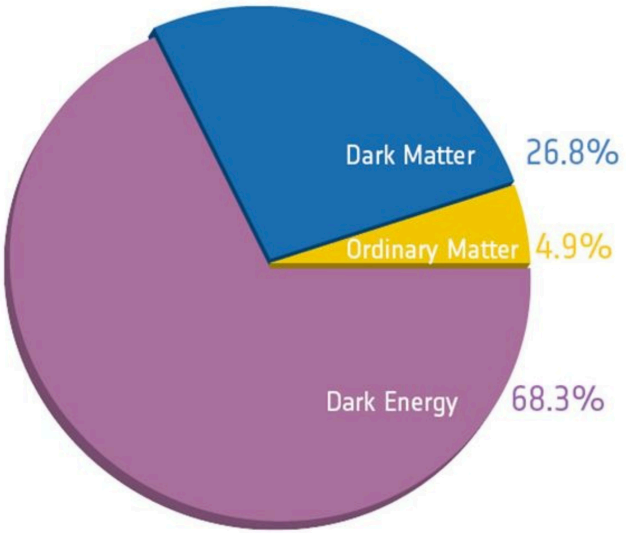

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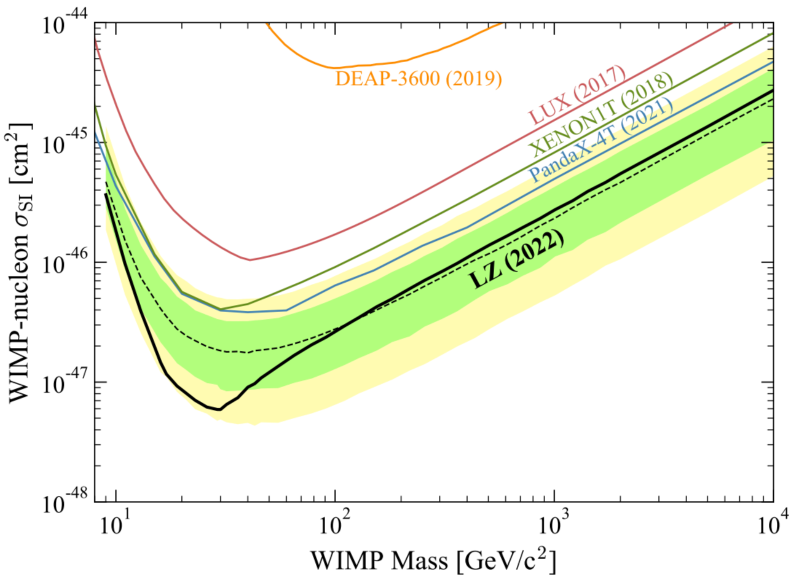

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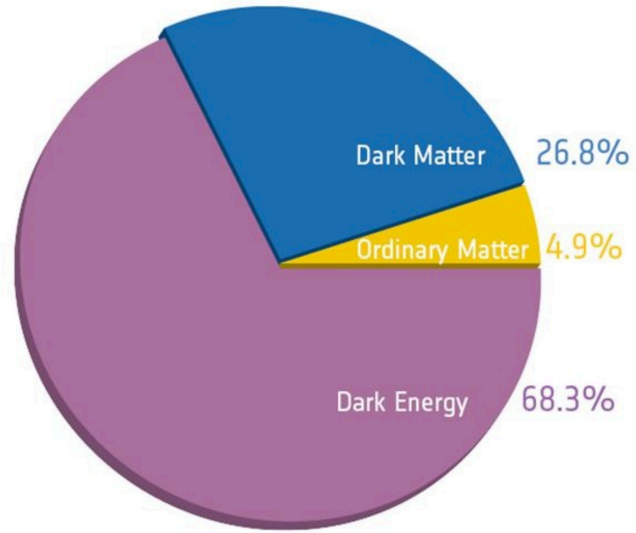

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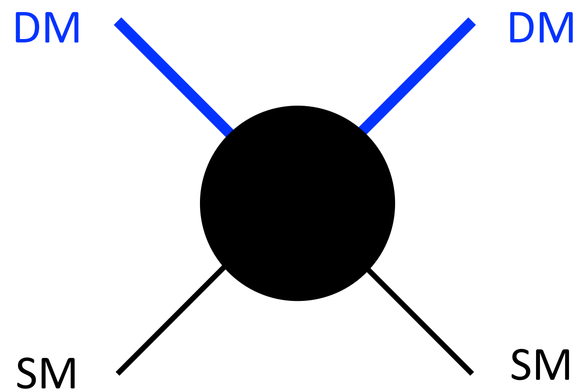

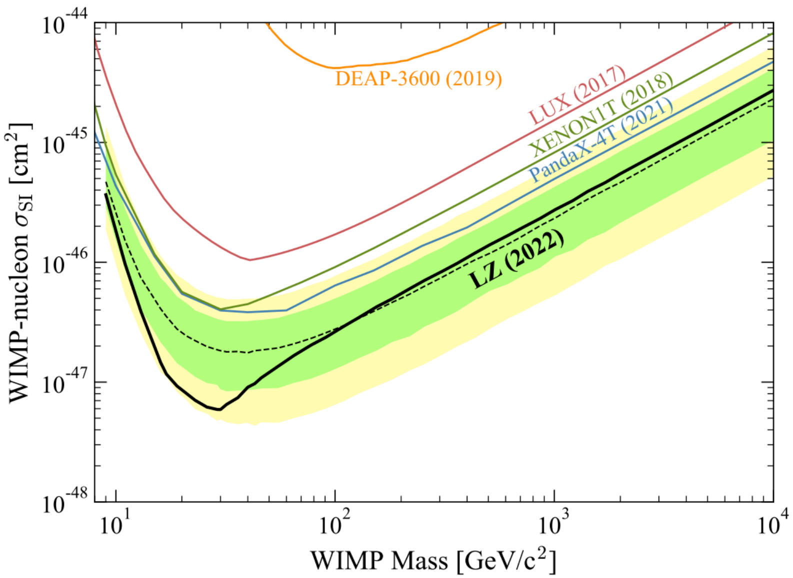

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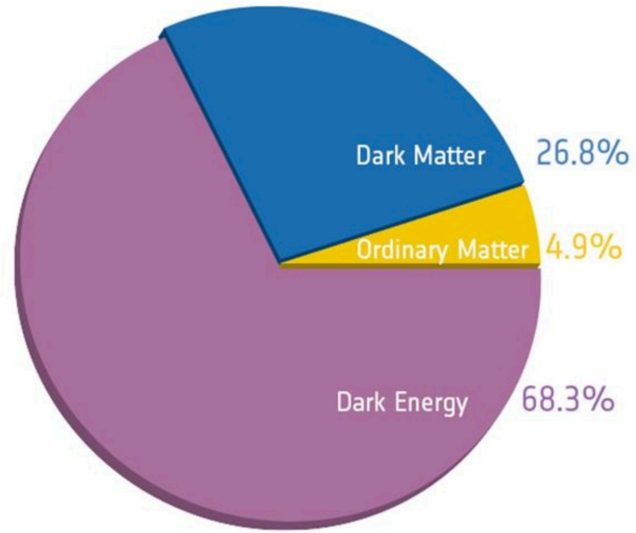

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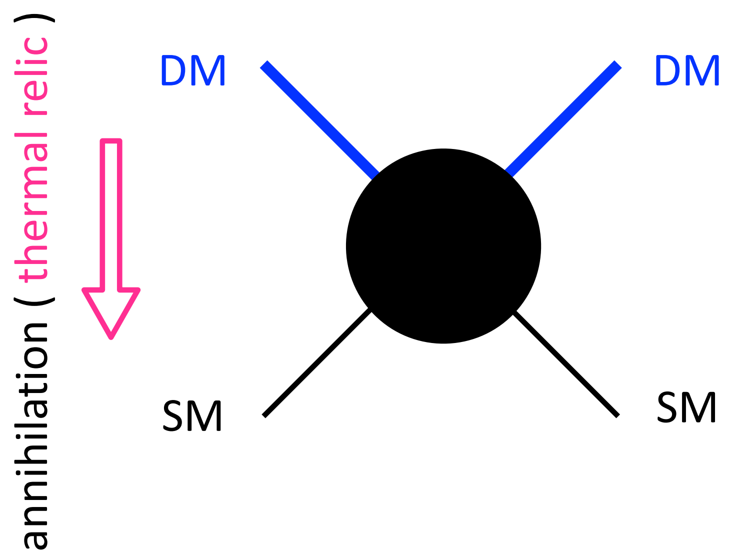

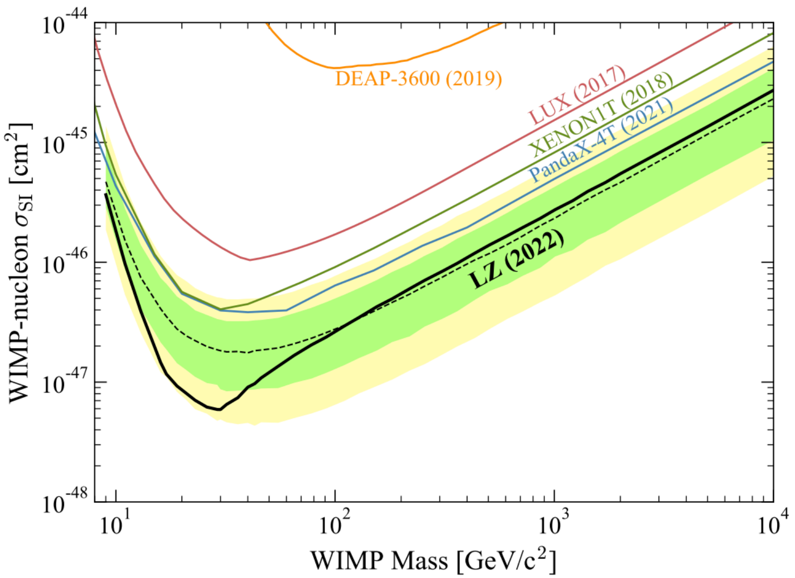

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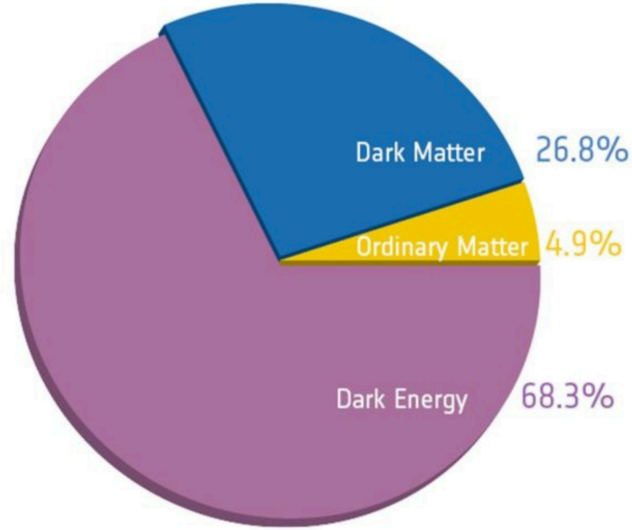

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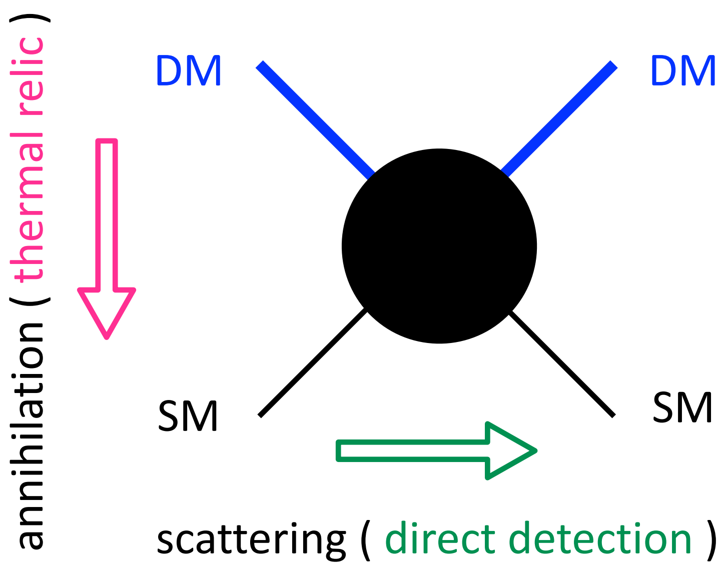

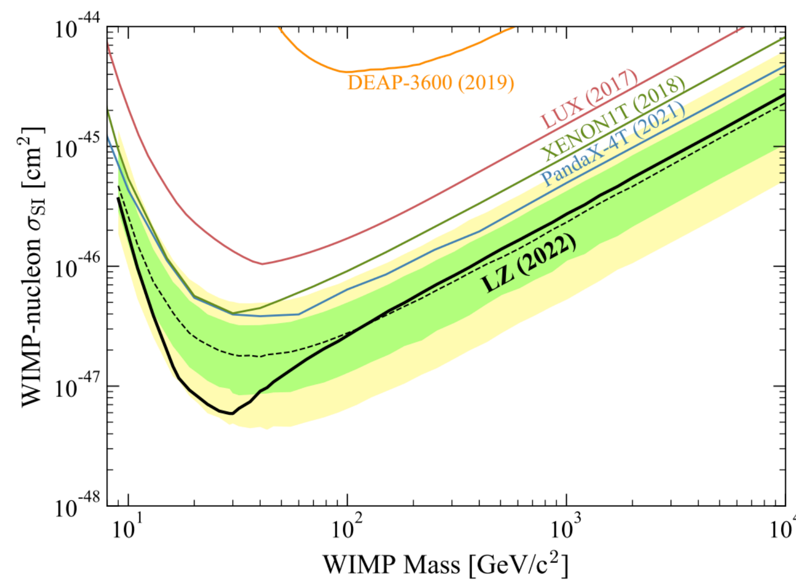

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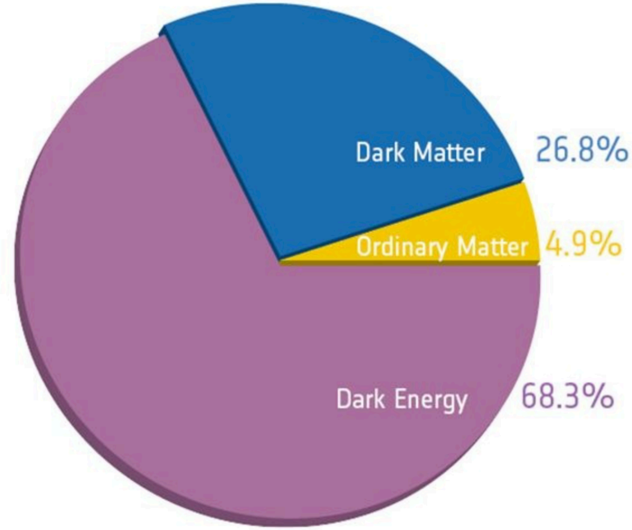

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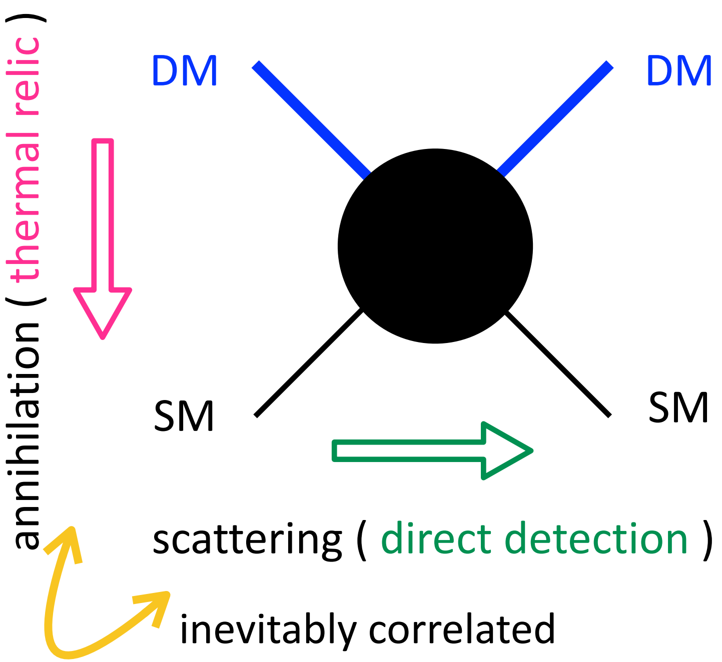

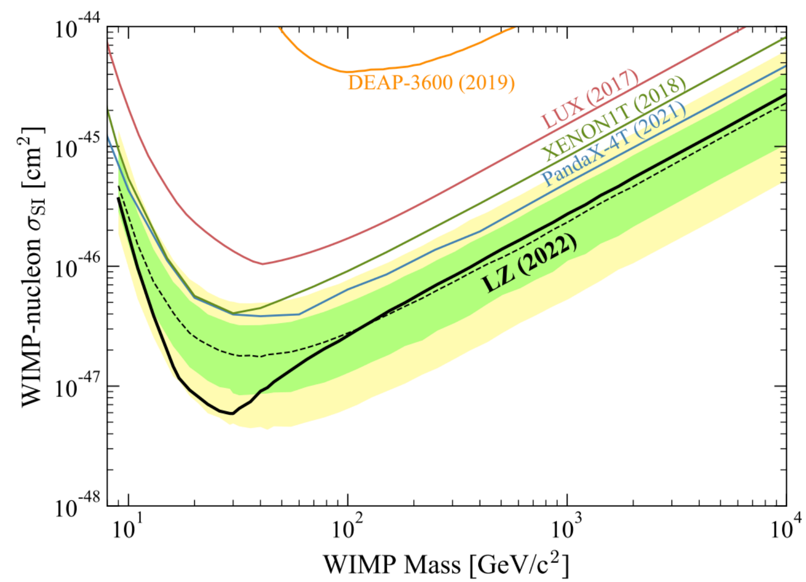

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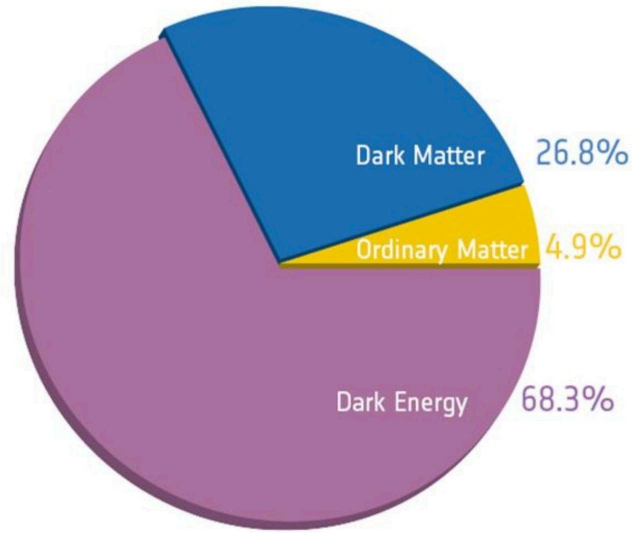

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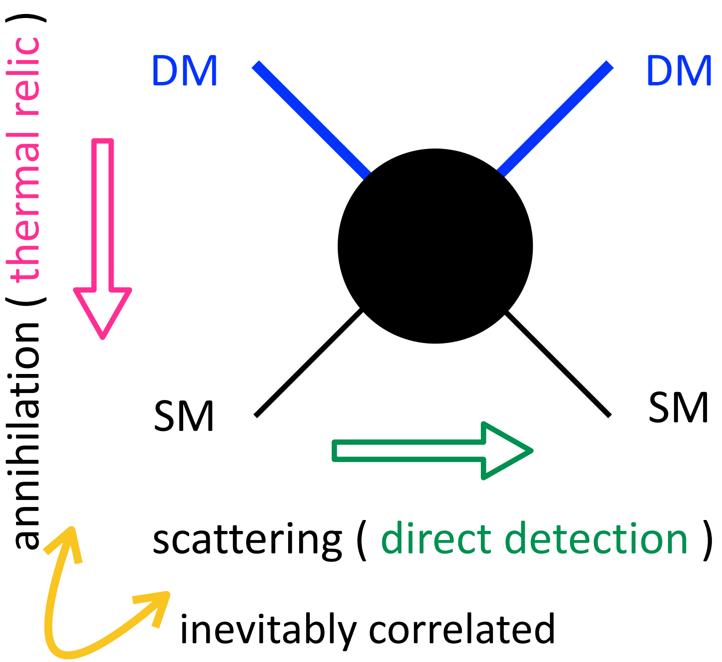

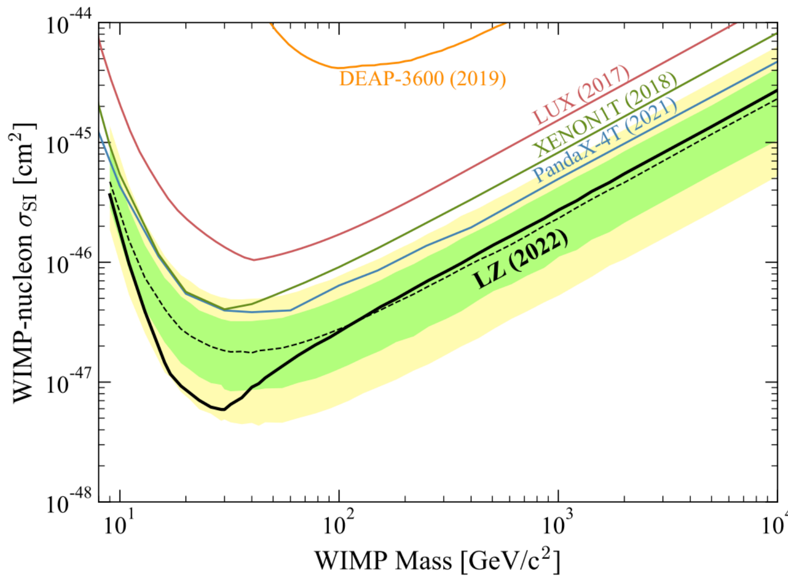

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Stronger DM-SM interaction helps DM to stay longer in thermal bath, leading to $\Omega h^2 \simeq 0.12$, but also increases DM-nucleon scattering.

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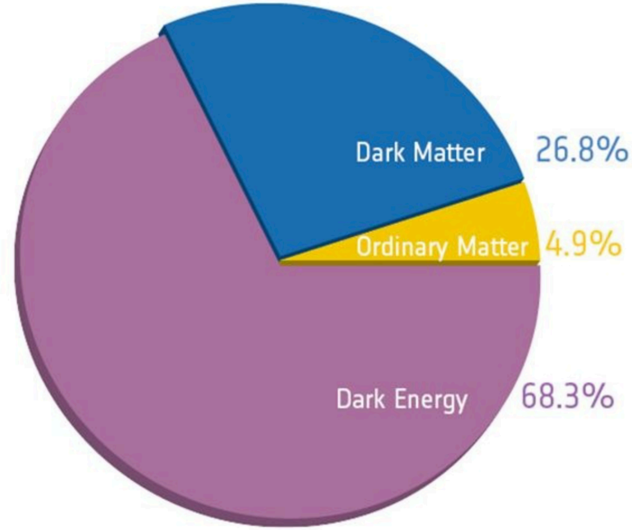

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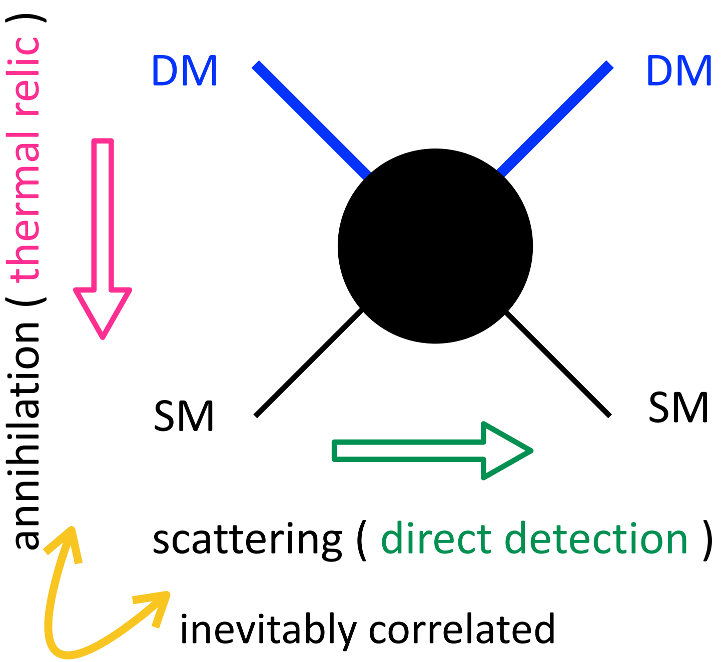

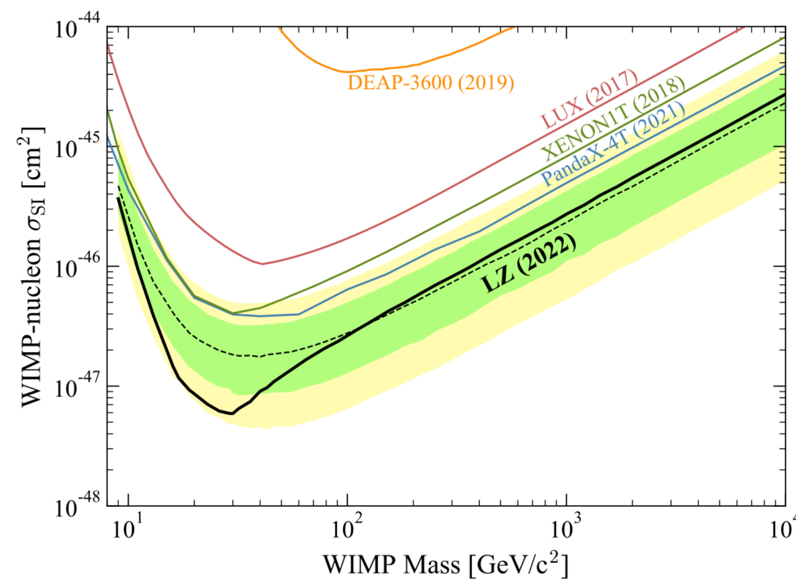

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To realize viable WIMP model, we must address this dilemma.

What type of WIMP model would solve this dilemma?

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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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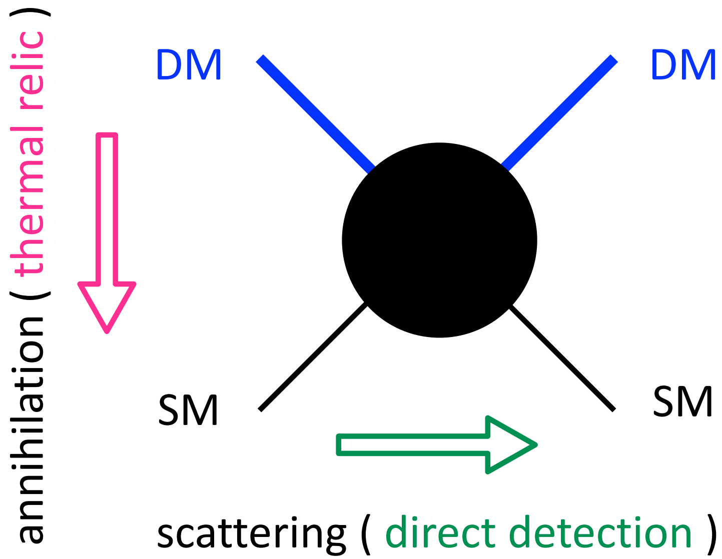
DM communicates with SM particles via derivative interaction



Small momentum transfer

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symmetry : $G_{\rm SM} \times U(1)_{\rm global}$

new fields : complex $S \in \mathbf{1}_0$

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

Mentioned by
Prof. Bohdan Grzadkowski on the 1st day

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Origin for pNGB mass ⇒ $$-\frac{\mu_S'^2}{4}S^2 + \text{h.c.}$$

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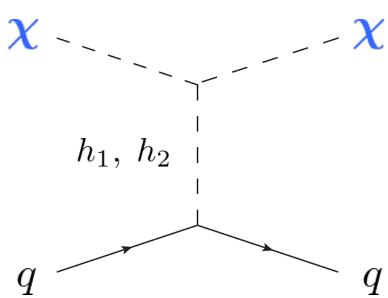
$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}, \quad S = \frac{v_s + \tilde{s} + i\chi}{\sqrt{2}} \qquad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

χ : pNGB DM

DM-quark scattering



$$\propto \quad \sin\theta\cos\theta\left(\frac{m_{h_2^2}}{t - m_{h_2}^2} - \frac{m_{h_1}^2}{t - m_{h_1}^2}\right) \underset{t \to 0}{\longrightarrow} 0$$

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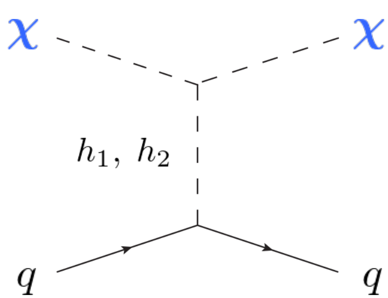

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Original pNGB DM model has several problems to be solved ...

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Problems to be solved

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To construct a feasible model, we need appropriate UV completions

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

Y. Abe, T. Toma, and K. Tsumura, JHEP 05 (2020) 057, [**2001.03954**]
Y. Abe, T. Toma, K. Tsumura, and N. Yamatsu, Phys.Rev.D 104 (2021) 3, 035011 [**2104.13523**]

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	Q_L	L	u_R^c	d_R^c	e_R^c	ν_R^c	H	S_1	S_2
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$+1/6$	$-1/2$	$-2/3$	$+1/3$	$+1$	0	$+1/2$	0	0
$U(1)_{B-L}$	$+1/3$	-1	$-1/3$	$-1/3$	$+1$	$+1$	0	$+1$	$+2$

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	Q_L	L	u_R^c	d_R^c	e_R^c	ν_R^c	H	S_1	S_2
$SU(2)_L$	**2**	**2**	**1**	**1**	**1**	**1**	**2**	**1**	**1**
$U(1)_Y$	$+1/6$	$-1/2$	$-2/3$	$+1/3$	$+1$	0	$+1/2$	0	0
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① $V(H,S_1,S_2) \ni \kappa S_2^* S_1^2 + \text{h.c.} \;\rightarrow\; \frac{1}{2} m_{\rm DM}^2 \chi^2$

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

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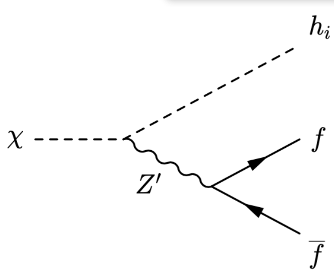

$\propto m_\chi^5 / m_{Z'}^4$

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

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

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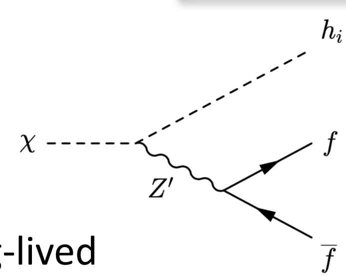

$\propto m_\chi^5 / m_{Z'}^4$

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

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

Brief Summary

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① $\mu''_S S^3$, $\mu'''_S |S|^2 S$, … are dropped by hands

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the only allowed soft-breaking term

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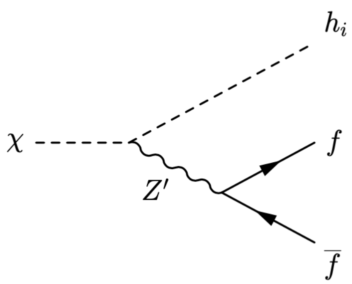

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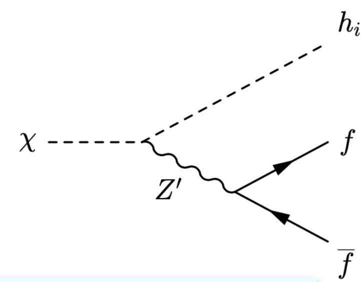

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Goal UV completion of pNGB-DM model with no large hierarchy

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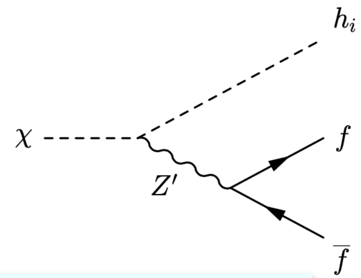

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Goal UV completion of pNGB-DM model with no large hierarchy

We want to explain the origin of pNGB mass,

and want a stable DM so that we don't need to introduce large hierarchy

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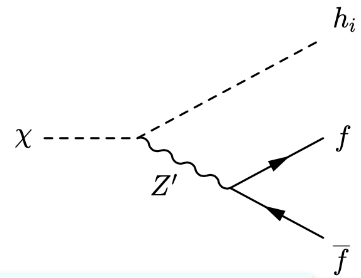

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Hint : SM scalar sector $G_{\text{SM}} = SU(2)_L \times U(1)_Y$

$$V_{\text{SM}}(H) = -\mu_H^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

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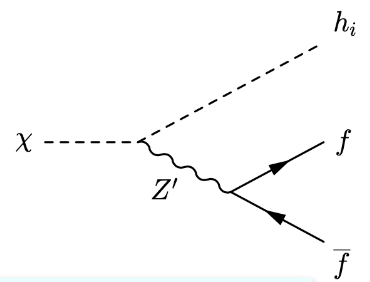

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$$V_{\text{SM}}(H) = -\frac{\mu_H^2}{2}\left((\phi_1)^2 + (\phi_2)^2 + (\phi_3)^2 + (\phi_4)^2\right) + \frac{\lambda}{4}\left((\phi_1)^2 + (\phi_2)^2 + (\phi_3)^2 + (\phi_4)^2\right)^2$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

accidental global symmetry : $G_{\text{global}} = O(4) \ \simeq \ SU(2)_L \times SU(2)_R$

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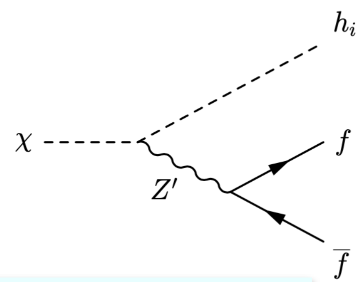

$U(1)_{B-L}$ breaking scale must be much high : $v_{B-L} \simeq 10^{15}\text{GeV}$

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

Hint : SM scalar sector $\quad G_{\text{SM}} = SU(2)_L \times U(1)_Y$

$$V_{\text{SM}}(H) = -\frac{\mu_H^2}{2}\left((\phi_1)^2 + (\phi_2)^2 + (\phi_3)^2 + (\phi_4)^2\right) + \frac{\lambda}{4}\left((\phi_1)^2 + (\phi_2)^2 + (\phi_3)^2 + (\phi_4)^2\right)^2$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

accidental global symmetry : $G_{\text{global}} = O(4) \ \simeq \ SU(2)_L \times SU(2)_R \ \underset{\langle H \rangle \neq 0}{\longrightarrow} \ SU(2)_V$: custodial sym.

Our Model

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

Goal

UV completion of pNGB-DM model with no large hierarchy

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

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

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

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

	$SU(2)_L$	$U(1)_Y$	$SU(2)_D^{\mathrm{gauge}}$
H	$\mathbf{2}$	$1/2$	$\mathbf{1}$
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$$V(H, \Phi, \Delta)$$

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

Mass terms

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

4-point self-int.

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

4-point int.

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

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

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$$V(H, \Phi, \Delta) \qquad \Sigma = (\tilde{\Phi}, \Phi)$$

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

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

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

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

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

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

Accidentally 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**]

$$V(H,\Phi,\Delta) = -\mu_H^2 H^\dagger H - \frac{1}{2}\mu_\Phi^2 \mathrm{Tr}\left[\Sigma^\dagger\Sigma\right] - \frac{1}{2}\mu_\Delta^2 \mathrm{Tr}\left[\Delta^2\right] + \lambda_H \left(H^\dagger H\right)^2 + \frac{\lambda_\Phi}{4}\left(\mathrm{Tr}\left[\Sigma^\dagger\Sigma\right]\right)^2 + \frac{\lambda_\Delta}{4}\left(\mathrm{Tr}\left[\Delta^2\right]\right)^2 + \lambda_{H\Phi}\left(H^\dagger H\right)\mathrm{Tr}\left[\Sigma^\dagger\Sigma\right] + \lambda_{H\Delta}\left(H^\dagger H\right)\mathrm{Tr}\left[\Delta^2\right] + \frac{\lambda_{\Phi\Delta}}{2}\mathrm{Tr}\left[\Sigma^\dagger\Sigma\right]\mathrm{Tr}\left[\Delta^2\right] - \sqrt{2}\kappa\mathrm{Tr}\left[\sigma_3\Sigma^\dagger\Delta\Sigma\right]$$

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

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

Global symmetry breaking pattern

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

- Approximate symmetry

$$SU(2)_L^{\mathrm{dark}} \times SU(2)_R^{\mathrm{dark}} \xrightarrow[\langle\Phi\rangle \neq 0]{} SU(2)_V^{\mathrm{dark}} \xrightarrow[\langle\Delta\rangle \neq 0]{} U(1)_V^{\mathrm{dark}}$$

\# of broken generators = (3+3) - 1 = 5

Total NGBs

- Exact symmetry

$$SU(2)_L^{\mathrm{dark}} \times U(1)_R^{\mathrm{dark}} \xrightarrow[\langle\Phi\rangle \neq 0]{} U(1)_V^{\mathrm{dark}}$$

\# of broken generators = (3+1) - 1 = 3

would-be NGBs

\# of pNGB is 2 (= 5 - 3) ⇨ complex pNGB with $U(1)_V^{\mathrm{dark}}$ charge

Experimental constraints

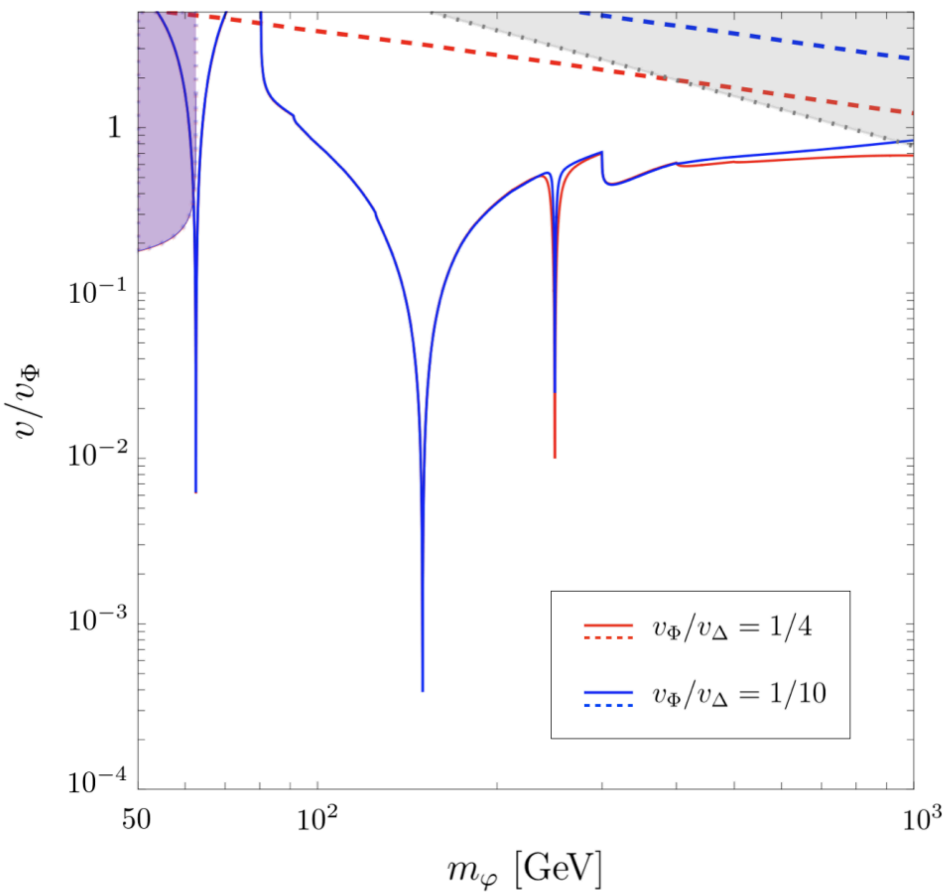
Benchmark

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**]



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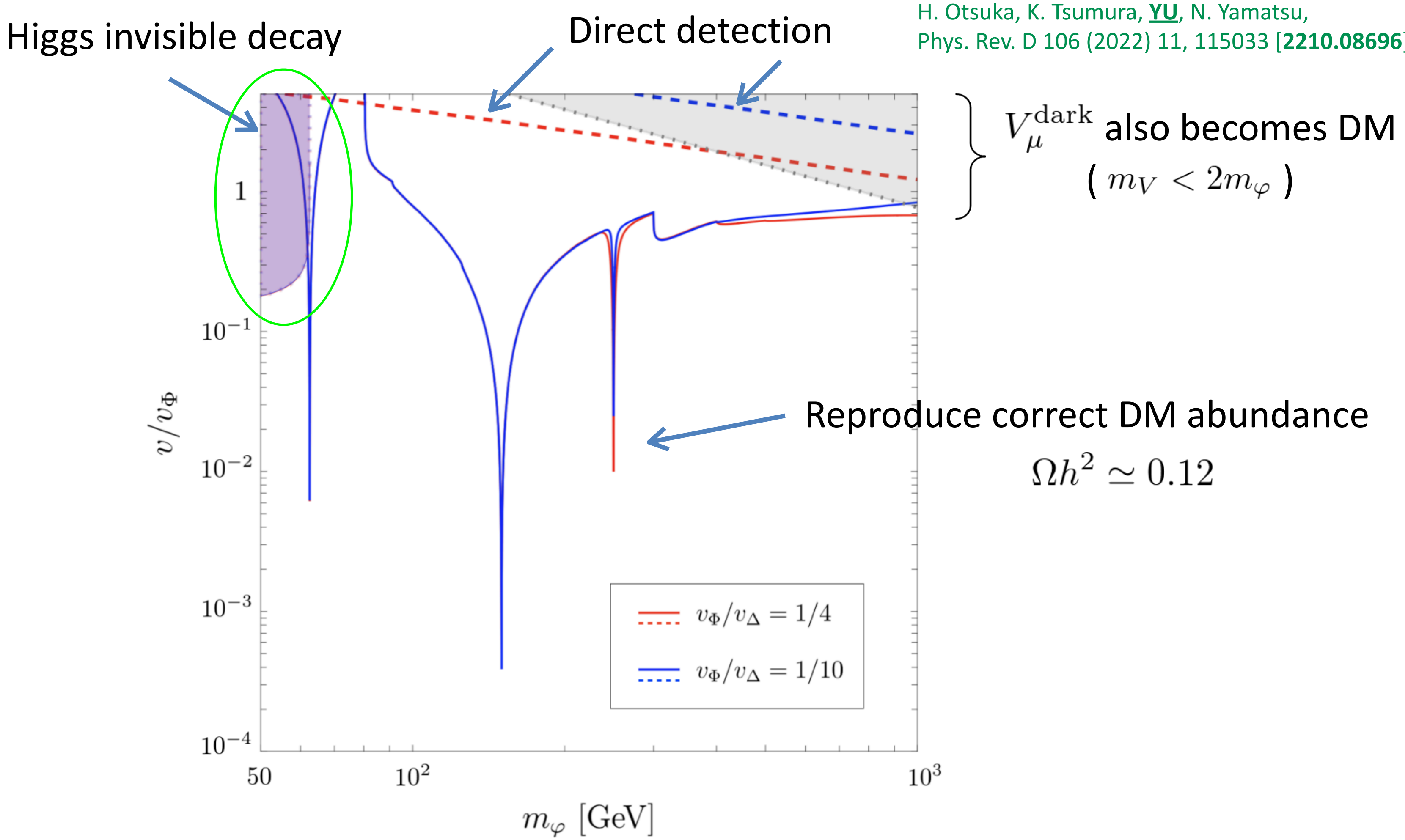

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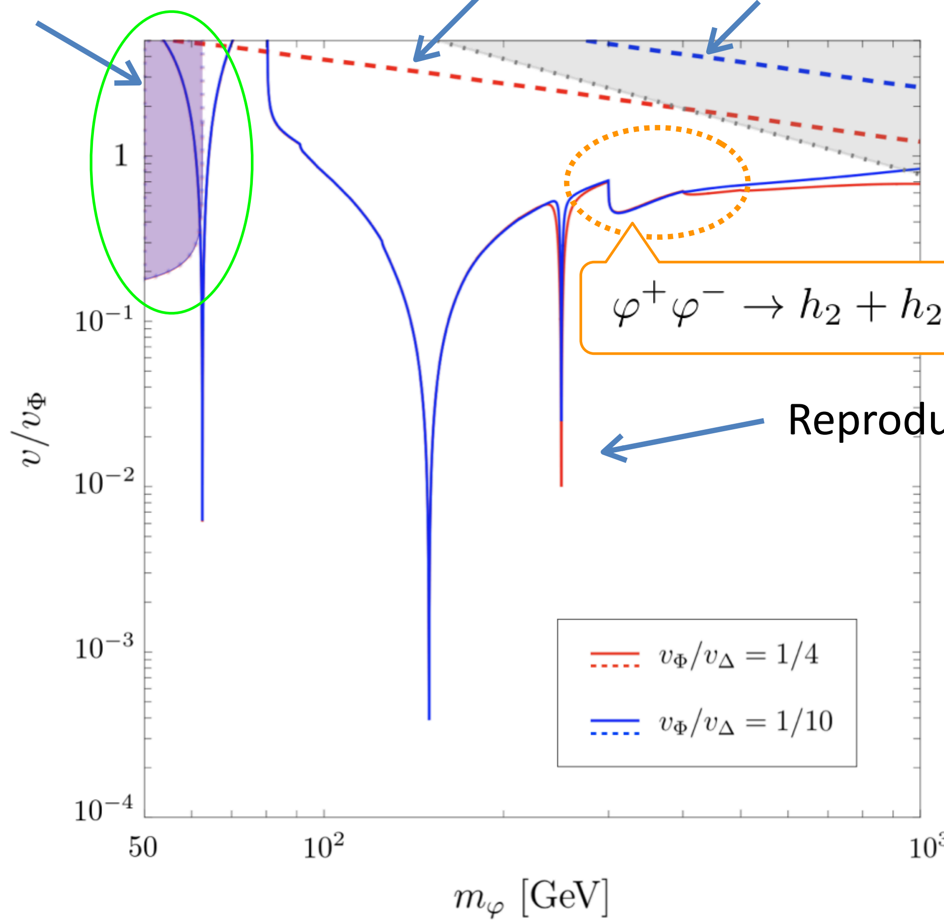
H. Otsuka, K. Tsumura, **YU**, N. Yamatsu,
Phys. Rev. D 106 (2022) 11, 115033 [**2210.08696**]

Higgs invisible decay

Direct detection



V_μ^{dark} also becomes DM
($m_V < 2m_\varphi$)

$\varphi^+\varphi^- \to h_2 + h_2$ opens

Reproduce correct DM abundance
$\Omega h^2 \simeq 0.12$

Experimental constraints

Benchmark

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

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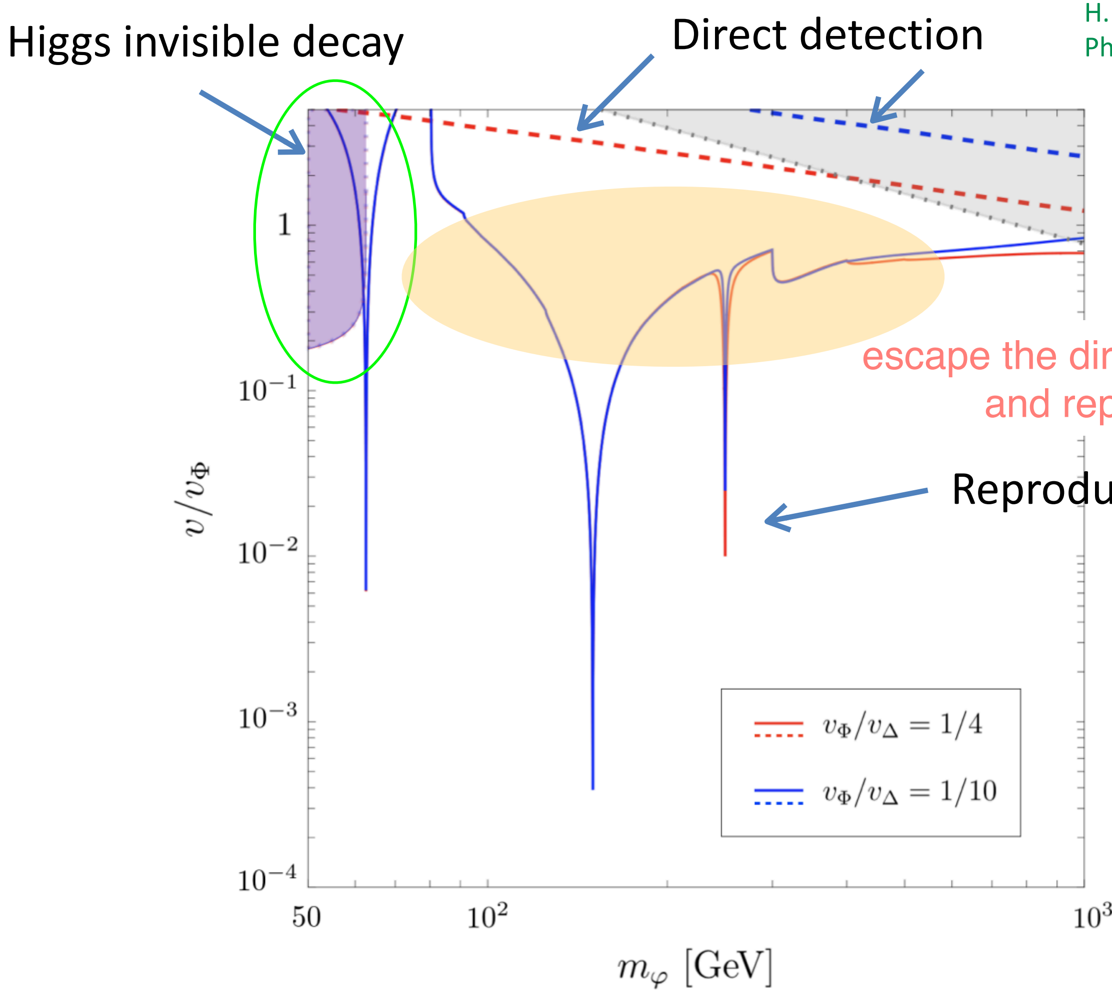
H. Otsuka, K. Tsumura, **YU**, N. Yamatsu, Phys. Rev. D 106 (2022) 11, 115033 [**2210.08696**]



V_μ^{dark} also becomes DM ($m_V < 2m_\varphi$)

Reproduce correct DM abundance

$\Omega h^2 \simeq 0.12$

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

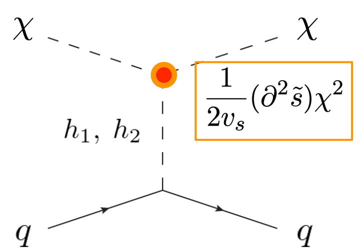
Goal UV completion of pNGB-DM model with no large hierarchy

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**]

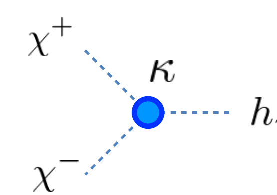
$\mu_\chi^2 \left(\phi^\dagger T^3 \phi\right)$ ⇨ Origin of pNGBs' mass

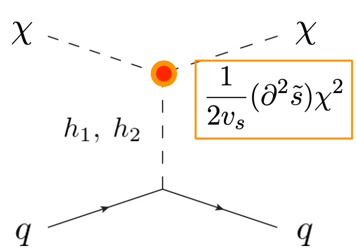


$$\propto \quad t = (p_2 - p_1)^2 \ \xrightarrow[t \to 0]{} \ 0$$

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

$\kappa\, \Phi^\dagger \Delta \Phi$ $\Phi \in \mathbf{2}$, $\Delta \in \mathbf{3}$ ⇨ Origin of pNGBs' mass & interactions





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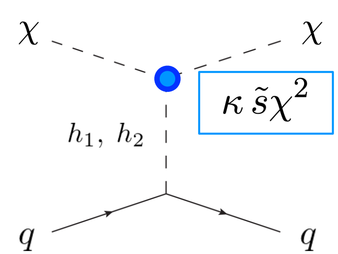


$\propto \quad t$ ⬟ $+ \ \kappa$ ◆

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

Soft breaking terms

- Soft-breaking = Quadratic

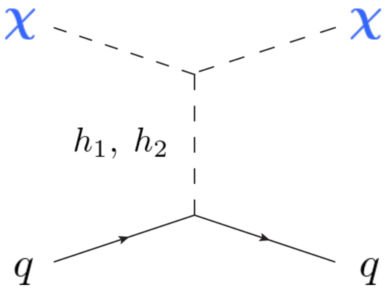
$$V_{\rm SM}(H) + \lambda_{HS}|H|^2|S|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_S}{2}|S|^4 - \left(\frac{\mu_S'^2}{4}S^2 + {\rm h.c.}\right)$$

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

- Soft-breaking = Quadratic + tadpole

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

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