Probing pseudo-Nambu-Goldstone dark matter evading direct detection bounds

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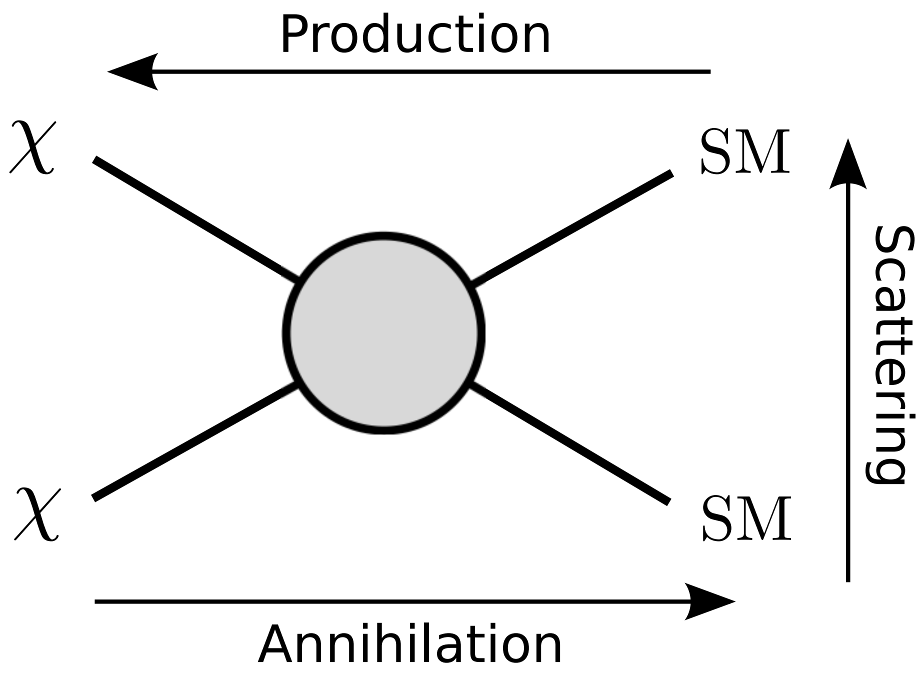
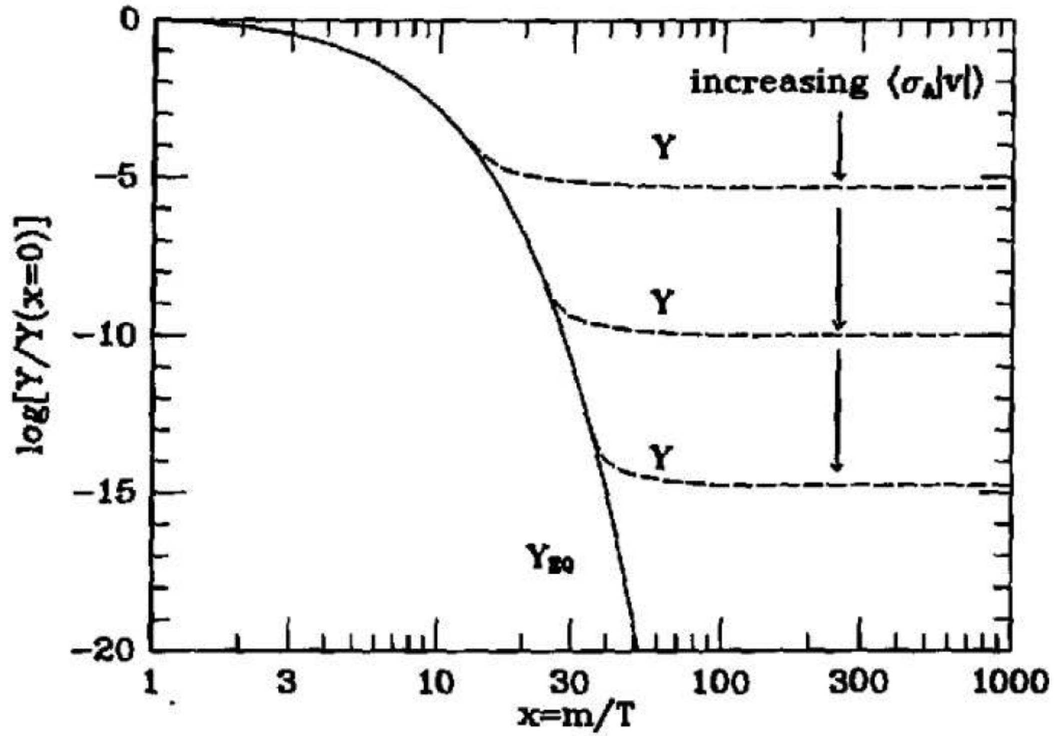
Based on
Phys. Rev. Lett. **119**, no.19, 191801 (2017)
JHEP **12**, 089 (2018), JHEP **05**, 057 (2020)
Phys. Rev. D **104**, no.3, 035011 (2021)
and work in progress

Collaborators: Gross, Lebedev, Ishiwata, Abe, Tsumura, Yamatsu, and more

Thermal dark matter

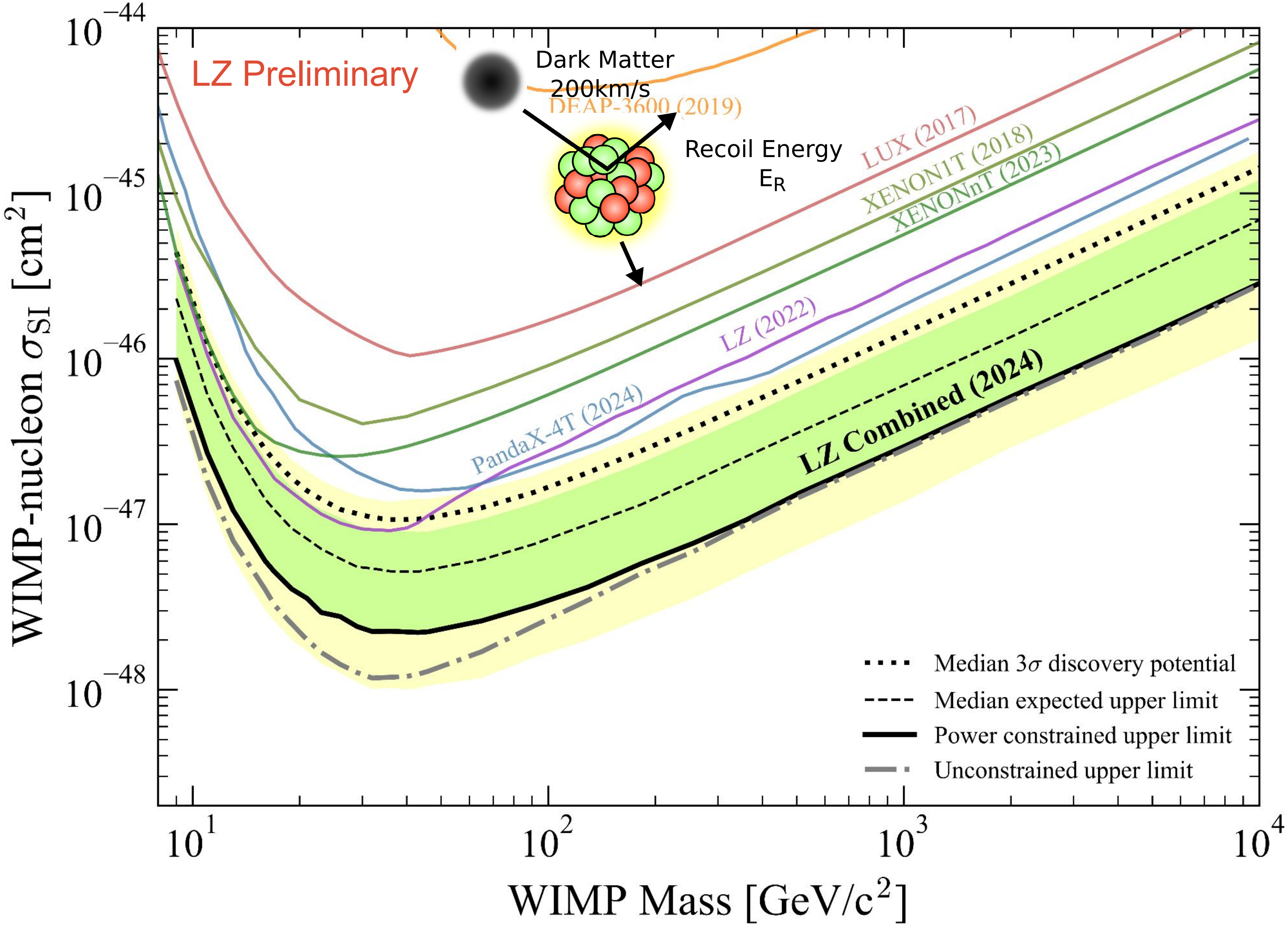


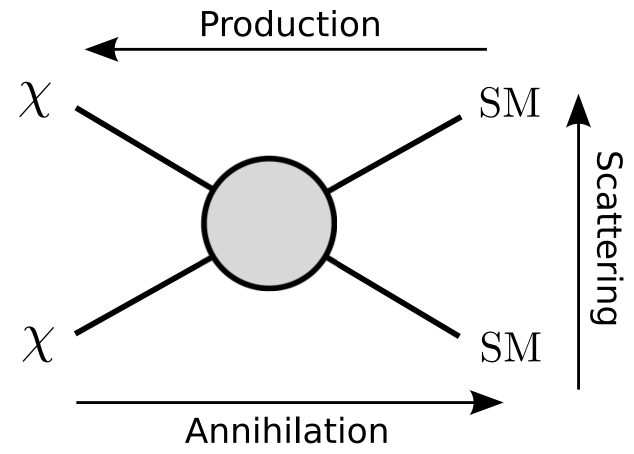


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right)$$

- WIMPs are thermalized with SM particles in early universe.
- To get $\Omega_\chi h^2 = 0.12$, roughly $\sigma \sim$ 1pb $\sim 10^{-26}$cm^3/s $\sim 10^{-36}$cm^2
- Almost independent on DM mass

Status of direct detection experiments





- $\Omega h^2 = 0.12$
  $\Leftrightarrow \sigma_{\rm el} \sim 10^{-36}$ cm^2
  ($\sigma_{\rm el} \lesssim 10^{-45}$ cm^2)
  (loop)

LZ talk @ TeVPA2024

- LZ gives the strongest bound 2.2×10^{-48} cm^2 at 43 GeV.
- Need a way to evade the bound

Wayout

- v_χ dependent cross section ($v_\chi \sim 10^{-3}$)

  Ex.1 pNG DM ($i\mathcal{M} \propto v_\chi^2$)

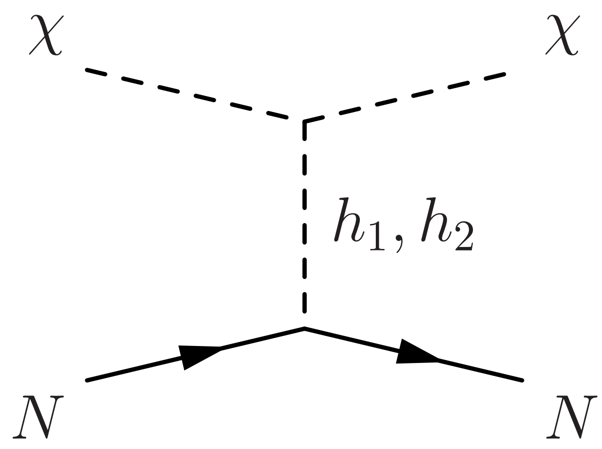
  C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

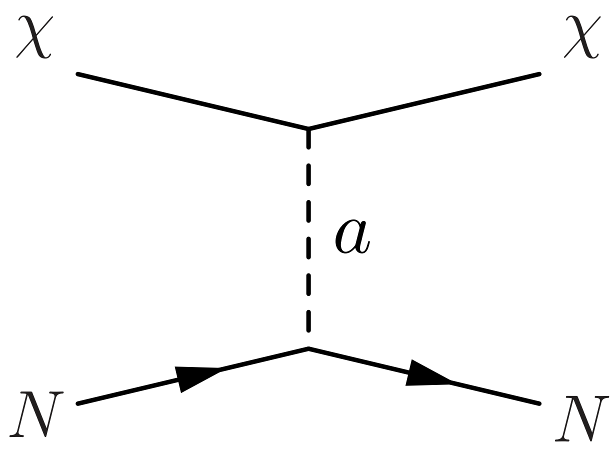
  Ex.2 Fermionic DM with Pseudo-scalar int.

  $$\mathcal{L} = a\overline{\chi}\gamma_5\chi$$

  T. Abe, M. Fujiwara, J. Hisano, JHEP (2019) [arXiv:1810.01039]

- Challenging to explore with standard way of direct detection experiments





$\Rightarrow$ These DM could be detected if boosted.

The pNG DM model

The pNG DM model

C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

- Introduce a complex scalar field $S = (s + i\chi)/\sqrt{2}$ (DM: χ)
- Global $U(1)$ symmetry is assumed (invariant under $S \to e^{i\alpha} S$)

$$\mathcal{V} = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4$$
$$- \left(\frac{\mu_S'^2}{4} S^2 + \mathrm{H.c.}\right) \quad \leftarrow \text{soft breaking mass term}$$

- After H and S get VEVs, ϕ and s mix

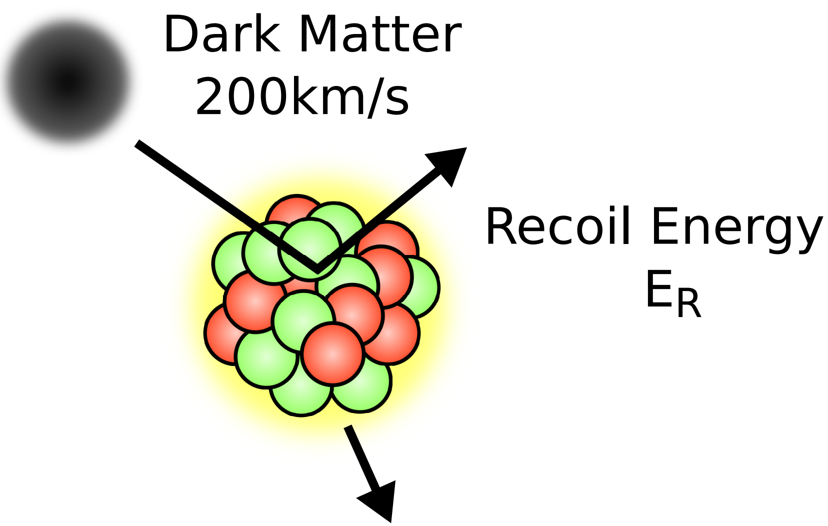
$$H = \begin{pmatrix} 0 \\ (v+\phi)/\sqrt{2} \end{pmatrix}, \qquad S = \frac{v_s + s + i\chi}{\sqrt{2}}$$

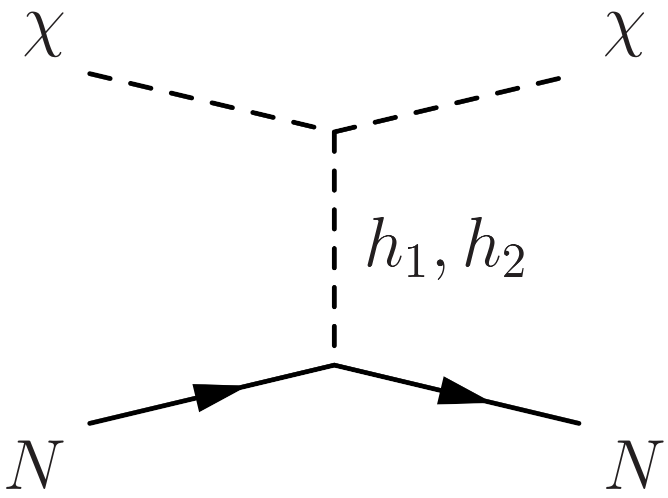
$$\begin{pmatrix} \phi \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

- $\sin\theta \lesssim 0.3$ $\leftarrow$ Constrained by EWPT, h_2 direct search at LHC

Direct detection (tree level)

C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]





- Scattering amplitude cancels between h_1, h_2 mediated diagrams

$$i\mathcal{M} \sim i\left(\frac{m_{h_1}^2}{q^2 - m_{h_1}^2} - \frac{m_{h_2}^2}{q^2 - m_{h_2}^2}\right) \sim i\frac{q^2(m_{h_1}^2 - m_{h_2}^2)}{m_{h_1}^2 m_{h_2}^2} \quad \rightarrow \quad 0$$

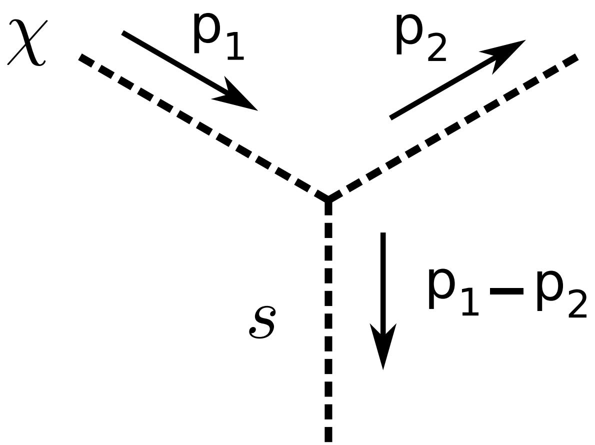
$\Rightarrow$ Naturally evade the direct detection bounds

- The cancellation is due to nature of Goldstone boson

Direct detection (tree level)

C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

Rewrite with $S = \frac{(v_s + s)}{\sqrt{2}} e^{i\chi/v_s} \quad \Rightarrow \quad \mathcal{L} \supset \frac{1}{v_s} s \left[(\partial_\mu \chi)^2 - m_\chi^2 \chi^2 \right]$



$$\rightarrow i\mathcal{M} \sim -\frac{i}{v_s}(p_1 - p_2)^2 \sim -\frac{i}{v_s} m_\chi^2 v_\chi^2 \rightarrow 0$$

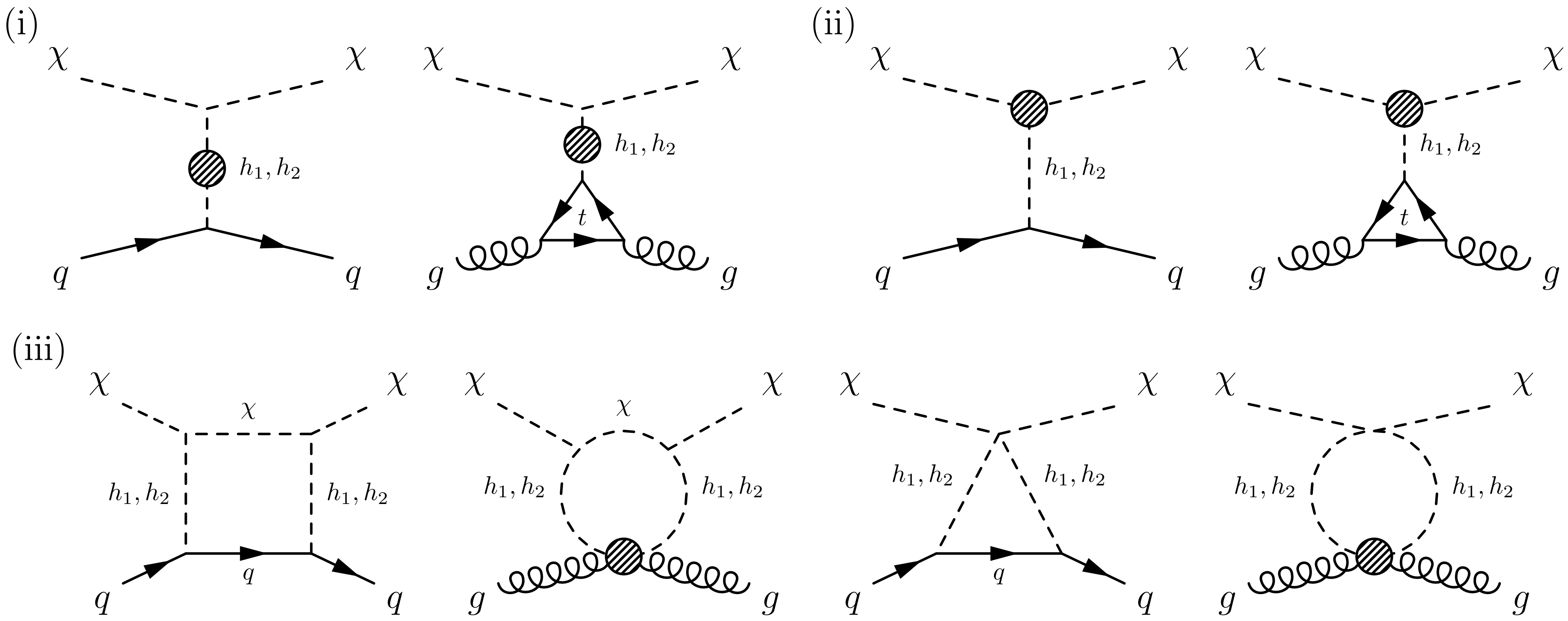
$$v_\chi \sim \mathcal{O}(10^{-3})$$

- The cancellation is due to nature of Goldstone boson
- All interactions are written with derivative couplings $\mathcal{L}_{\rm int} = \mathcal{L}_{\rm int}(\partial_\mu \chi)$
- Only 4 independent parameters $(m_\chi,\ m_{h_2},\ \sin\theta,\ v_s\ (\lambda_S))$

Direct detection (1-loop level)

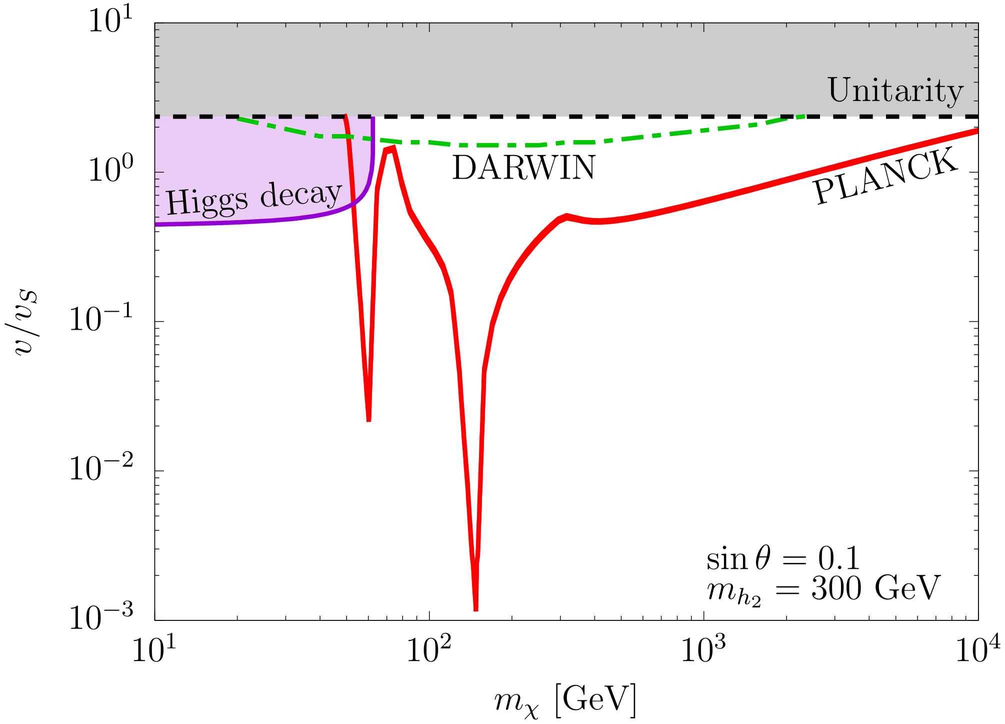
D. Azevedo et al., JHEP [arXiv:1810.06105]
K. Ishiwata, TT, JHEP [arXiv:1810.08139]
S. Glaus et al., JHEP [arXiv:2008.12985]

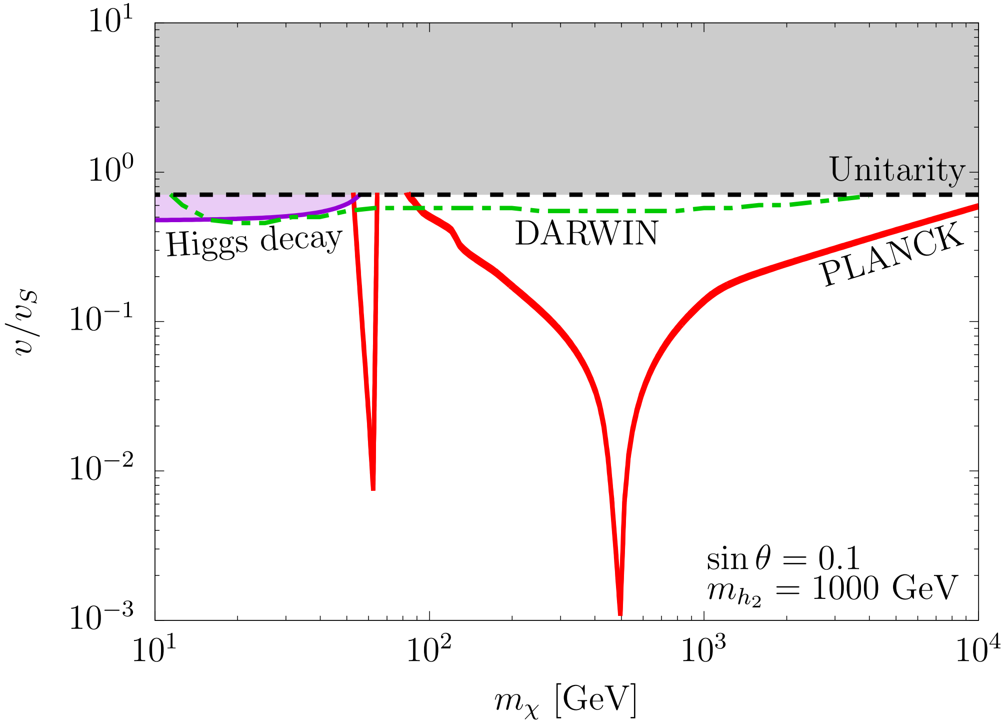
- Constant amplitude at 1-loop level



- (i) self-energy correction
- (ii) vertex correction
- (iii) box and triangle $\rightarrow$ two Yukawa couplings (sub-dominant)

Numerical calculations K. Ishiwata, TT, JHEP [arXiv:1810.08139]



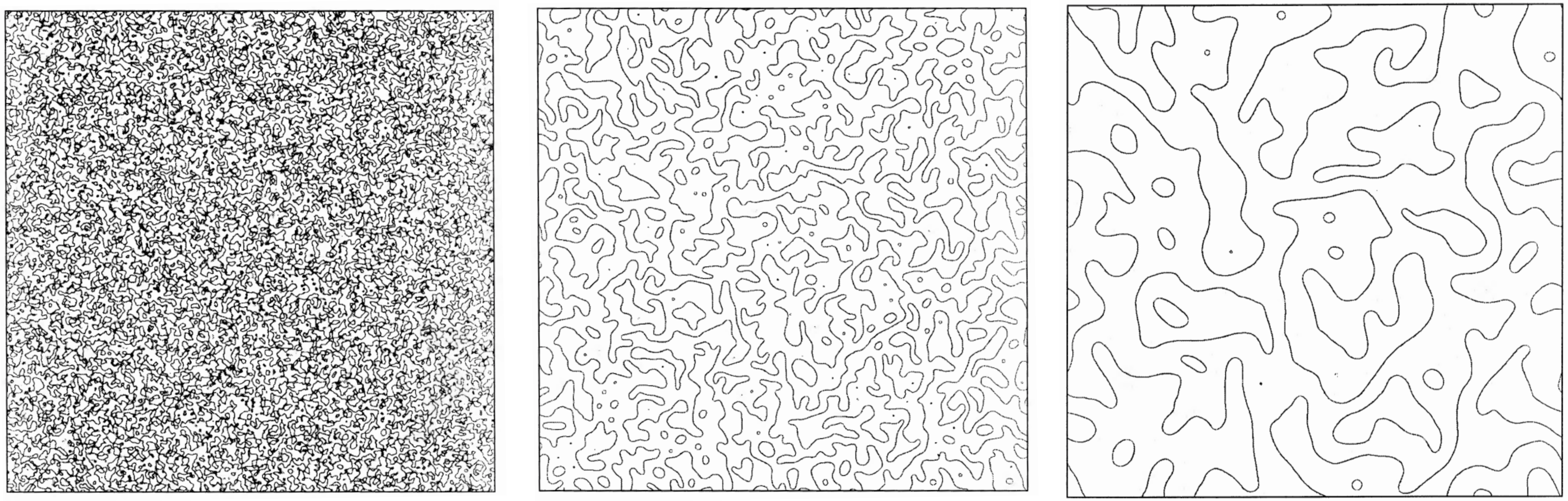


- $\sin\theta = 0.1$
- Unitarity bound: $\lambda_S \leq 8\pi/3$
- Higgs Invisible decay $\mathrm{Br}(h_1 \to \mathrm{inv}) \lesssim 20\%$ at LHC
- $\Omega h^2 = 0.12$ (PLANCK)
- $\sigma_{\mathrm{SI}}^p = \mathcal{O}(10^{-48})\ \mathrm{cm}^2$ at most

Extension of the model

Domain wall problem

- Domain walls due to spontaneous breaking of $\mathbb{Z}_2$ symmetry
  $\Rightarrow$ distort CMB
- Solutions: · UV completion
  · low energy inflation after the $\mathbb{Z}_2$ breaking
  · decay before BBN (making the domain wall unstable)



time evolution $\rightarrow\rightarrow\rightarrow$

Press, Ryden, Spergel ApJ (1989)

UV completion Y. Abe, TT, K. Tsumura, JHEP (2020) [arXiv:2001.03954]

- Origin of the soft breaking term? $\frac{m_\chi^2}{4}S^2 + \mathrm{H.c.}$

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

- Gauged $U(1)_{B-L}$ extension (New fields: ν_R, Φ)
- Potential $\mathcal{V} \supset \mu_c \Phi^* S^2 + \mathrm{h.c.} \to m_\chi^2 S^2$ at low energy
  The soft breaking term is induced.
- 3 ν_R for anomaly cancellation
- Seesaw for ν mass: $\mathcal{L} \supset \Phi \nu_R \nu_R$

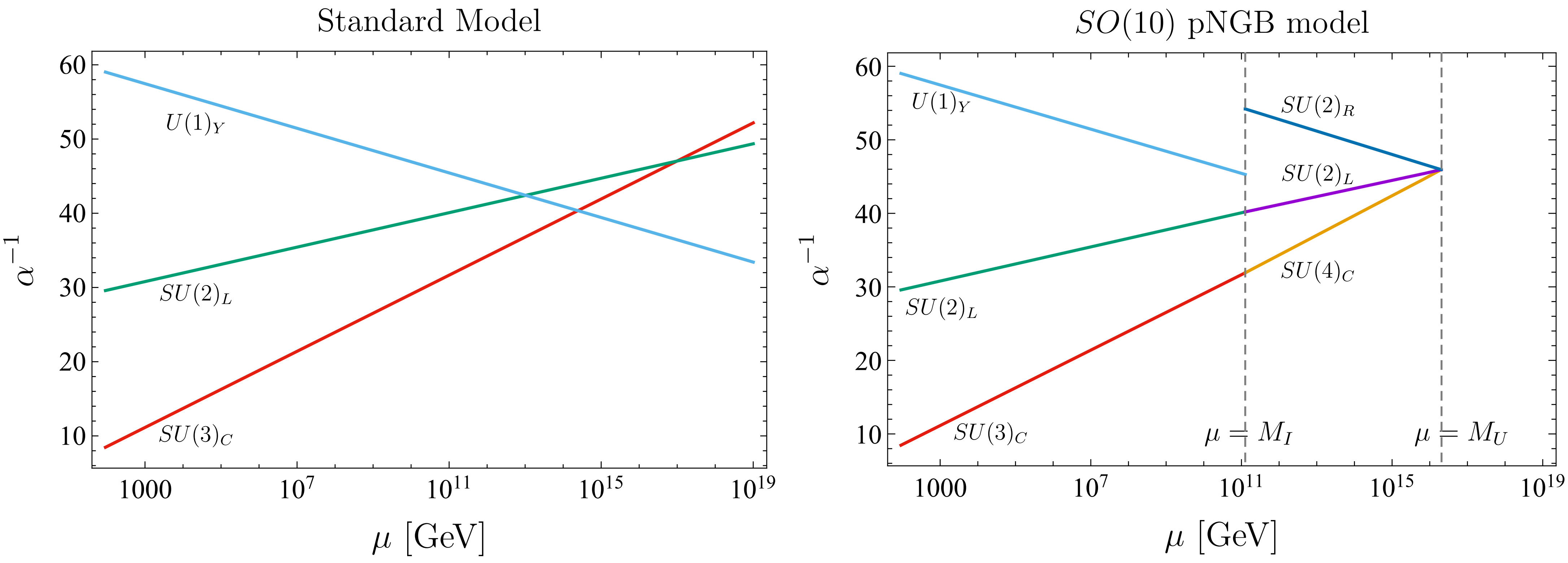
GUT embedding

Y. Abe, TT, K. Tsumura, N. Yamatsu, PRD (2021) [arXiv:2104.13523]

		fermions	H	S	Φ	~~SO(10)~~
	A_μ	Ψ_{16}	Φ_{10}	Φ_{16}	$\Phi_{\overline{126}}$	Φ_{210}
$SO(10)$	**45**	**16**	**10**	**16**	$\overline{\mathbf{126}}$	**210**

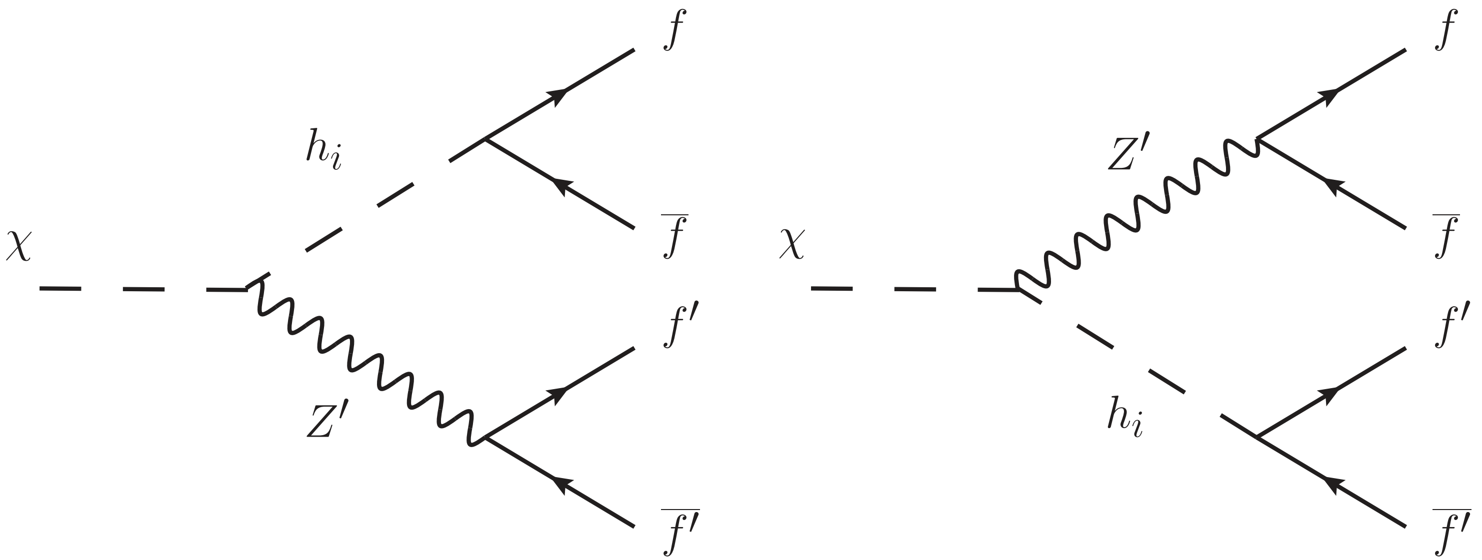
- We embed the UV complete model in SO(10) GUT.
- The pNG model is reproduced at low energy.
- Breaking pattern: $SO(10) \;\to\; G_{\rm PS} \;\to\; G_{\rm SM}$
  at $\mu = M_U$ at $\mu = M_I$
  Pati-Salam symmetry: $G_{\rm PS} = SU(4)_C \times SU(2)_L \times SU(2)_R$
- GUT scale (M_U)
  Intermediate scale (M_I) = breaking scale of $U(1)_{B-L}$,
  Determined by matching conditions of gauge couplings

Gauge coupling unification

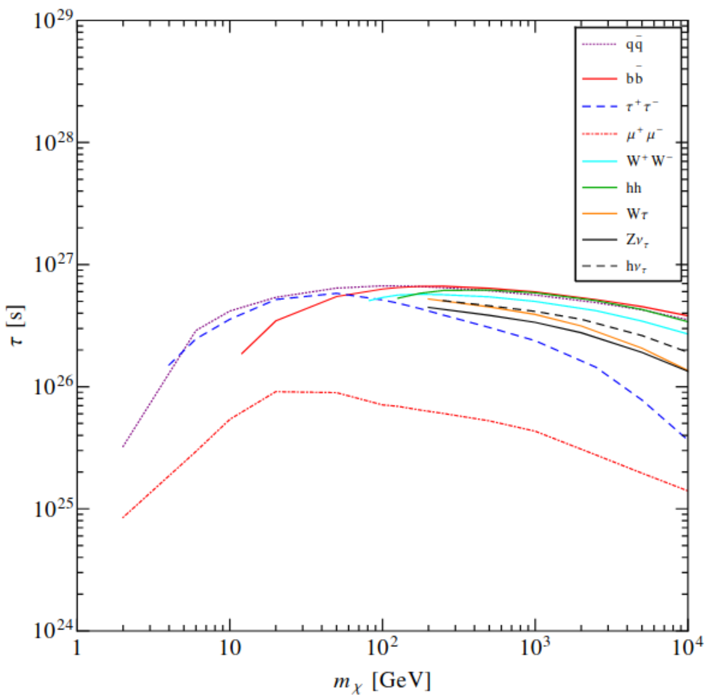


- Intermediate scale, GUT scale: determined by matching conditions of gauge couplings
- $v_\phi = M_I = 1.26 \times 10^{11}$ GeV, $M_U = 2.06 \times 10^{16}$ GeV
  $g_{B-L} = 0.38$ at $\mu = M_I$

DM decay

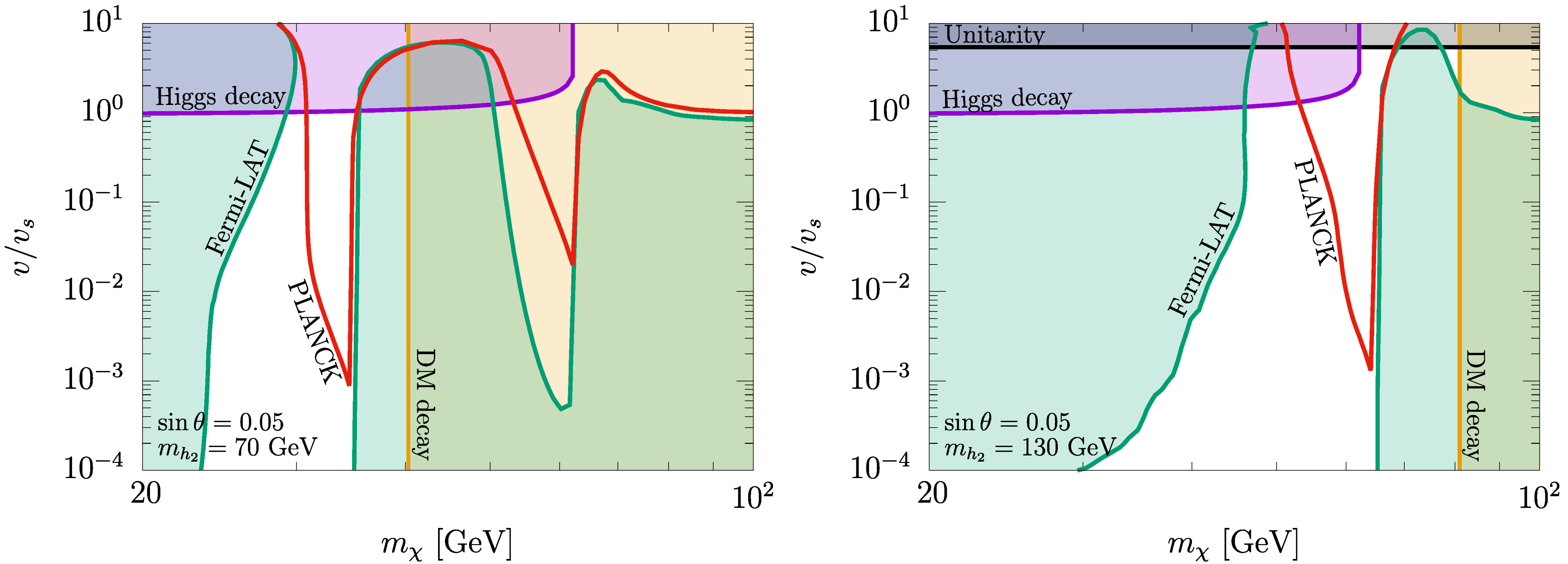


- DM lifetime: $\tau_{\rm DM} \gtrsim 10^{17}$ sec at least (the age of the universe).
- Cosmic ray observations give stronger limits: $\tau_{\rm DM} \gtrsim 10^{27}$ sec.
  3-body decays $\chi \to f\overline{f}h_i, f\overline{f}Z$ if $m_\chi \gtrsim m_{h_i}, m_Z \to$ excluded



Baring et al. (2015)

Parameter space



- $v/v_s \sim \sqrt{\lambda_S}$
- $\tau_\chi \gtrsim 10^{27}$ sec
- Fermi-LAT: $\chi\chi \to b\bar{b}, WW \to$ gamma-ray production
- close to the h_2 resonance

Boosting mechanism

Other variations of pNG DM models

- THDM + S with global U(1) Zhang, Cai, Jiang, Tang, Yu, Zhang, JHEP 05 (2021) 160
  $\Rightarrow$ Gravitational waves from strong 1st order phase transition

- Various pNG DM models

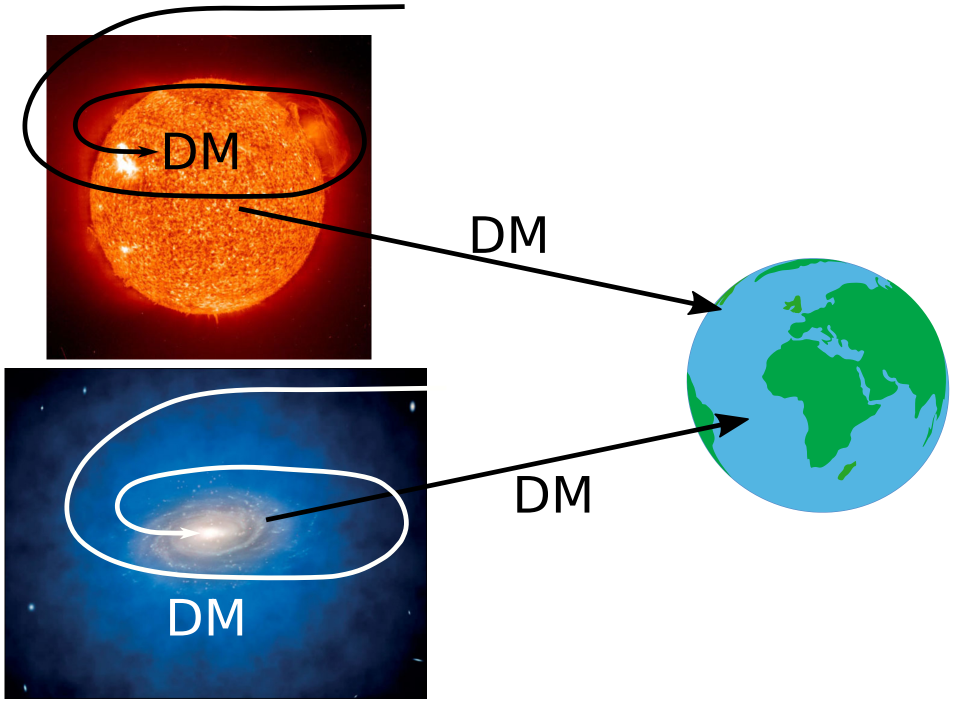
	DW problem	stable/decaying	real/complex	Landau pole
Global U(1)	$\times$	stable	real	✓
Gauged $U(1)_{B-L}$	✓	decaying	real	✓
SO(10) GUT	✓	decaying	real	✓
Hidden gauged U(1)	✓	decaying	real	✓
Global SU(2) with gauged U(1)	✓	stable	complex	$\times$
Gauged SU(2)	✓	stable	complex	✓
Gauged U(1) with 2 scalars	✓	stable	real	✓

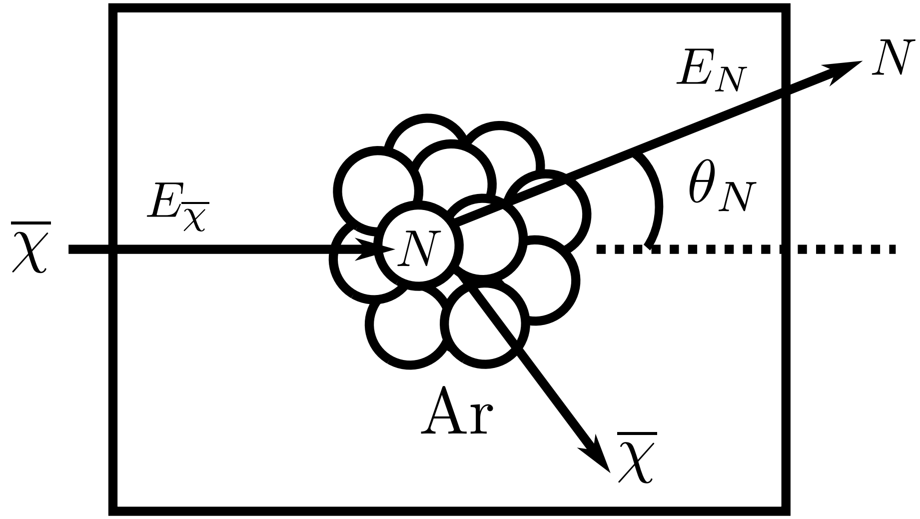
Abe, Hamada, Tsumura, JHEP 05 076 (2024)

- No domain wall
  Two component DM $\chi_2\chi_2 \to \chi_1\chi_1$
  Semi-annihilating DM $\chi\chi \to \chi\phi$
  $\Rightarrow$ DM is accelerated

How to probe pNG DM

- PNG DM can be detectable if boosted by some mechanism.
  $\sigma_{\rm el} \propto Q^4 \Rightarrow$ strong enhancement of signals $\Rightarrow \nu$ detectors (DUNE)
- Boosting mechanisms
  - Semi-annihilations
  - Decay or annihilations of heavy particles
  - Up-scattering with high energy cosmic-rays



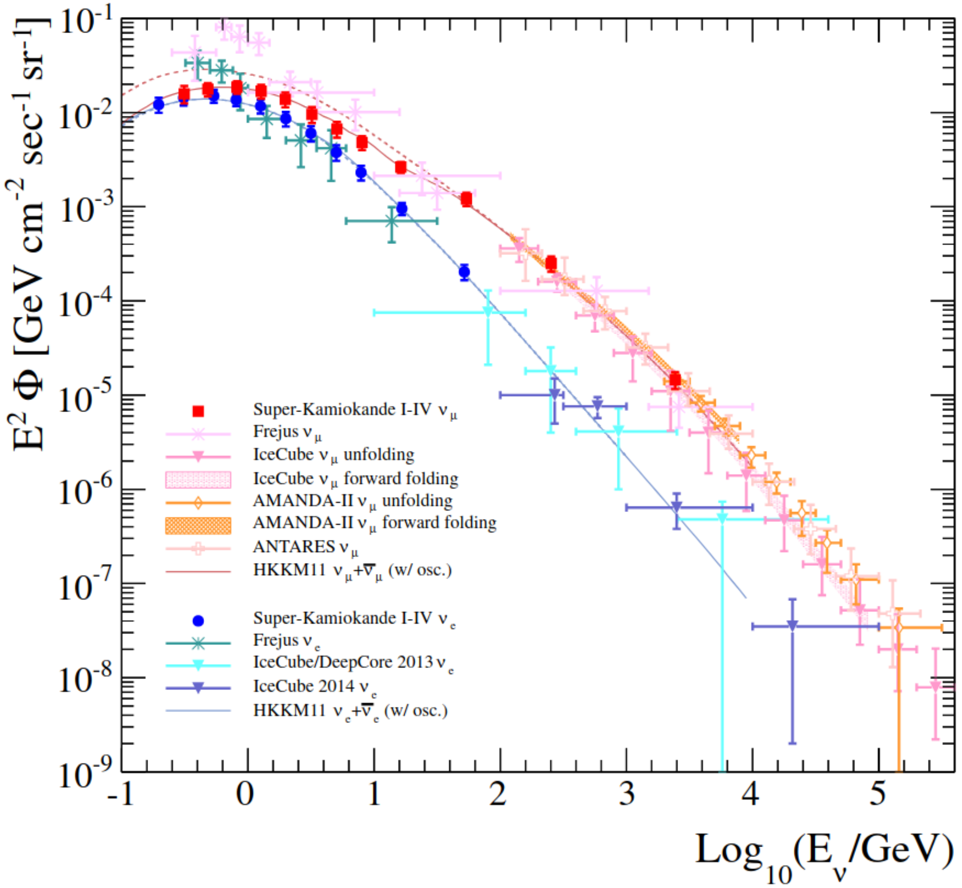


How to probe pNG DM 2

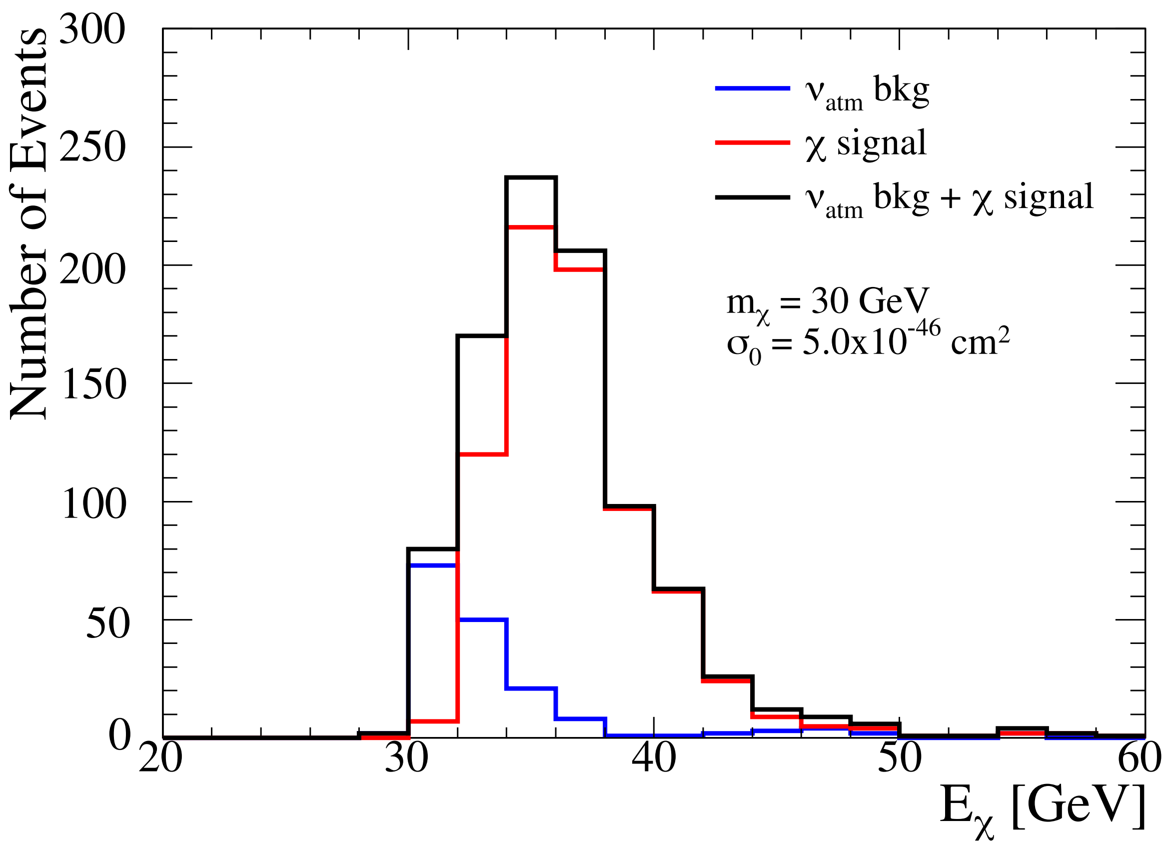
- Simplest option: $\mathbb{Z}_3$ symmetry $\Rightarrow$ semi-annihilation ($\chi\chi \to \chi Z'$)

$$E_\chi = \frac{5m_\chi^2 - m_{Z'}^2}{4m_\chi}, \quad \gamma_\chi \equiv \frac{E_\chi}{m_\chi} = \frac{5}{4} - \frac{m_{Z'}^2/m_\chi^2}{4} \leq 1.25$$

- Atmospheric ν background and signals



http://www-rccn.icrr.u-tokyo.ac.jp/mhonda/public/



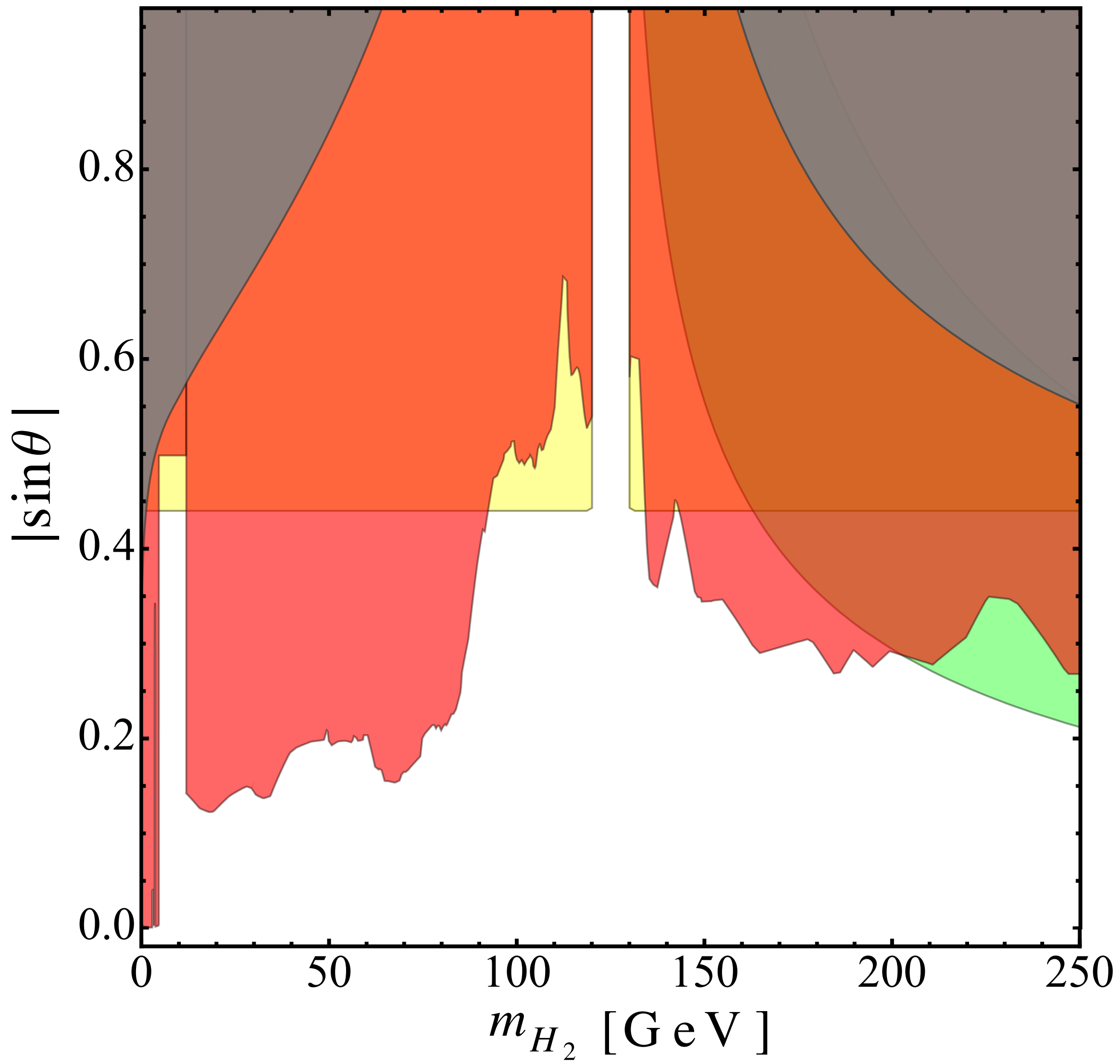
Summary

1. Thermal DM is strongly constrained by direct detection experiments.
   $\Rightarrow$ pNG DM $\sigma_{\rm el} \propto v_\chi^4$.
2. Further extensions of the pNG DM model have been proposed.
   $\Rightarrow$ Solution for the domain wall problem and origin of S^2 term
3. Strong pNG DM signals are expected if it is boosted.
   $\Rightarrow$ Extended models with semi-annihilations

Backup

Bound on $\sin\theta$

Falkowski, Gross, Lebedev, JHEP 1505 (2015) [arxiv:1502.01361]



- Red: h_2 direct search at LHC
- Yellow: h_1 coupling measurements
- Green: Favored region from stability of scalar potential
- Gray: Electroweak precision tests
- $|\sin\theta| \lesssim 0.3$ if $m_{h_2} \gtrsim m_{h_1}$
- $m_\chi \lesssim m_{h_2}$ (above EW scale)

The pNG DM model

C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

- χ is mass eigenstate itself $m_\chi^2 = \mu_S'^2$
  Invariant under $S \to S^*$, $\Rightarrow \chi$ can be a DM candidate
- Higgs portal DM
- Scalar potential $\mathcal{V} = \mu_{h_1\chi\chi} h_1 \chi^2 + \mu_{h_2\chi\chi} h_2 \chi^2 + \cdots$

$$\mu_{h_1\chi\chi} = -\frac{m_{h_1}^2 \sin\theta}{v_s}, \quad \mu_{h_2\chi\chi} = \frac{m_{h_2}^2 \cos\theta}{v_s},$$

SM Yukawa int. $\mathcal{L} \supset y_q \Big(\cos\theta h_1 + \sin\theta h_2 \Big) \overline{q} q$

$$\lambda_H = \frac{\cos^2\theta m_{h_1}^2 + \sin^2\theta m_{h_2}^2}{v^2}, \quad \lambda_S = \frac{\sin^2\theta m_{h_1}^2 + \cos^2\theta m_{h_2}^2}{v_s^2},$$

$$\lambda_{HS} = \frac{\sin\theta\cos\theta(m_{h_2}^2 - m_{h_1}^2)}{v v_s}$$