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

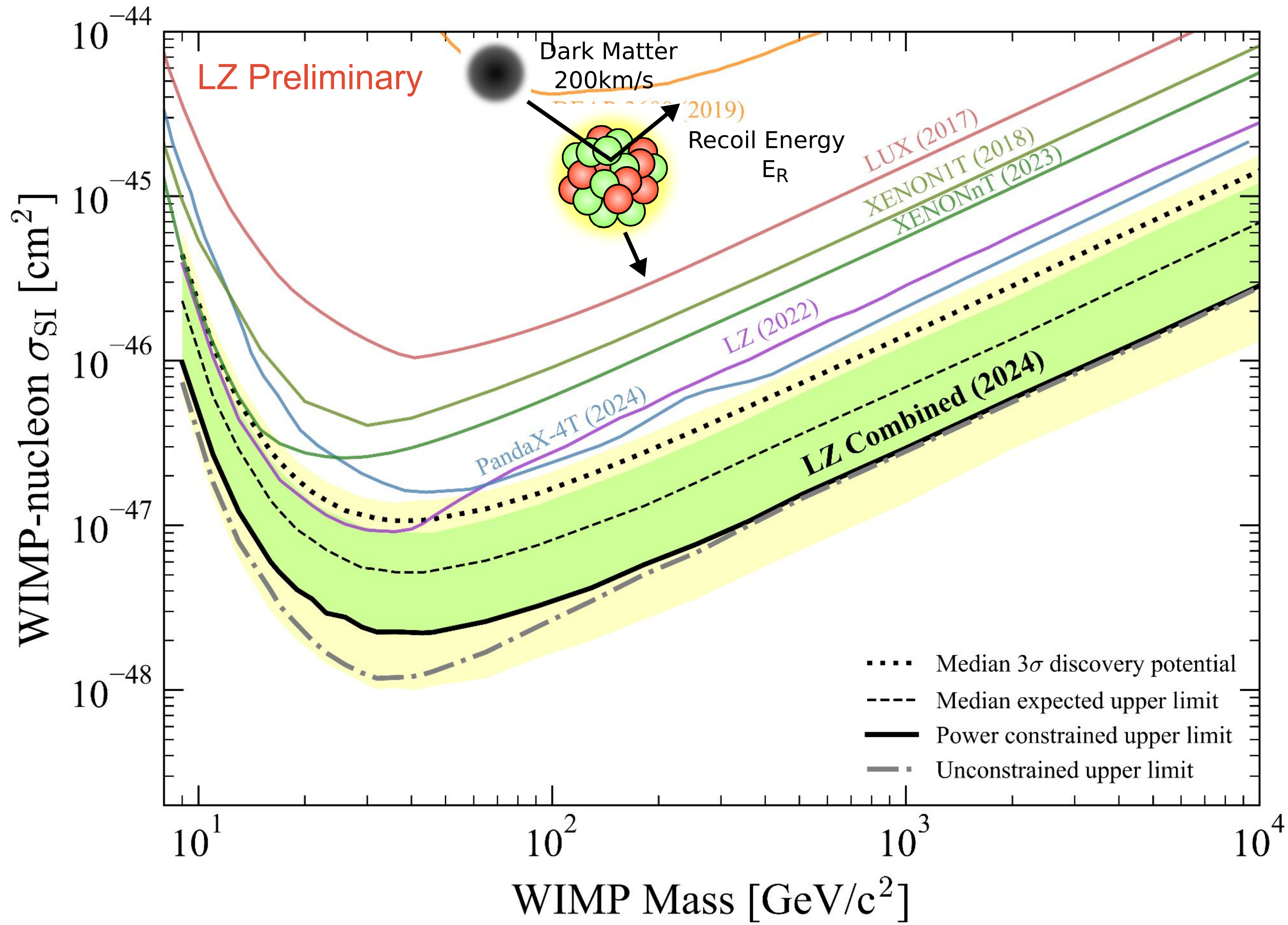
Takashi Toma (Kanazawa U.)

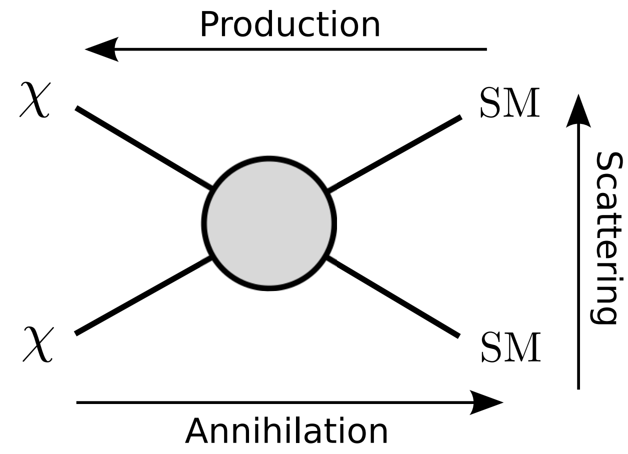
COSMO'24 @ Kyoto University
21st–25th Oct. 2024

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)

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

Status of direct detection experiments





- $\Omega h^2 = 0.12$
  $\Leftrightarrow \sigma v \sim 10^{-26}\text{cm}^3/\text{s}$
  $\Leftrightarrow \sigma_{\text{el}} \sim 10^{-36}\ \text{cm}^2$
  $(\sigma_{\text{el}} \lesssim 10^{-45}\ \text{cm}^2)$
  (loop)

LZ talk @ TeVPA2024

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

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

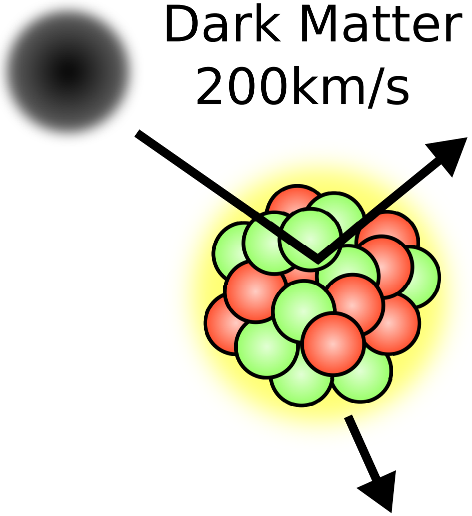
$$H = \begin{pmatrix} 0 \\ (v+\phi)/\sqrt{2} \end{pmatrix}, \qquad S = \frac{v_s + s + i\chi}{\sqrt{2}}$$

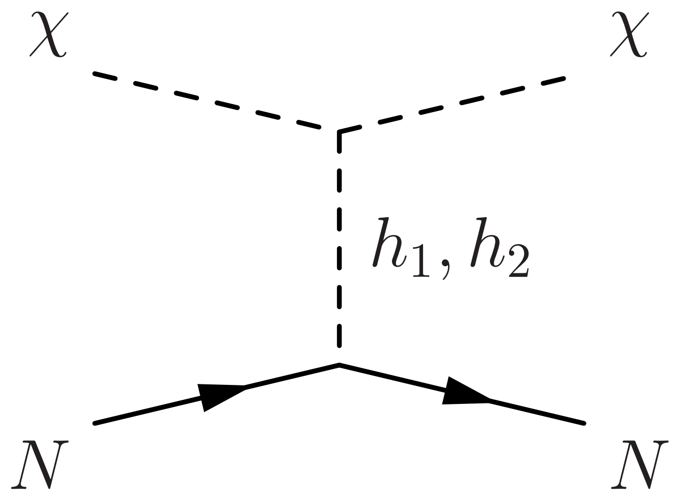
$$\begin{pmatrix} \phi \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

- $\sin\theta \lesssim 0.3$ $\leftarrow$ 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

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

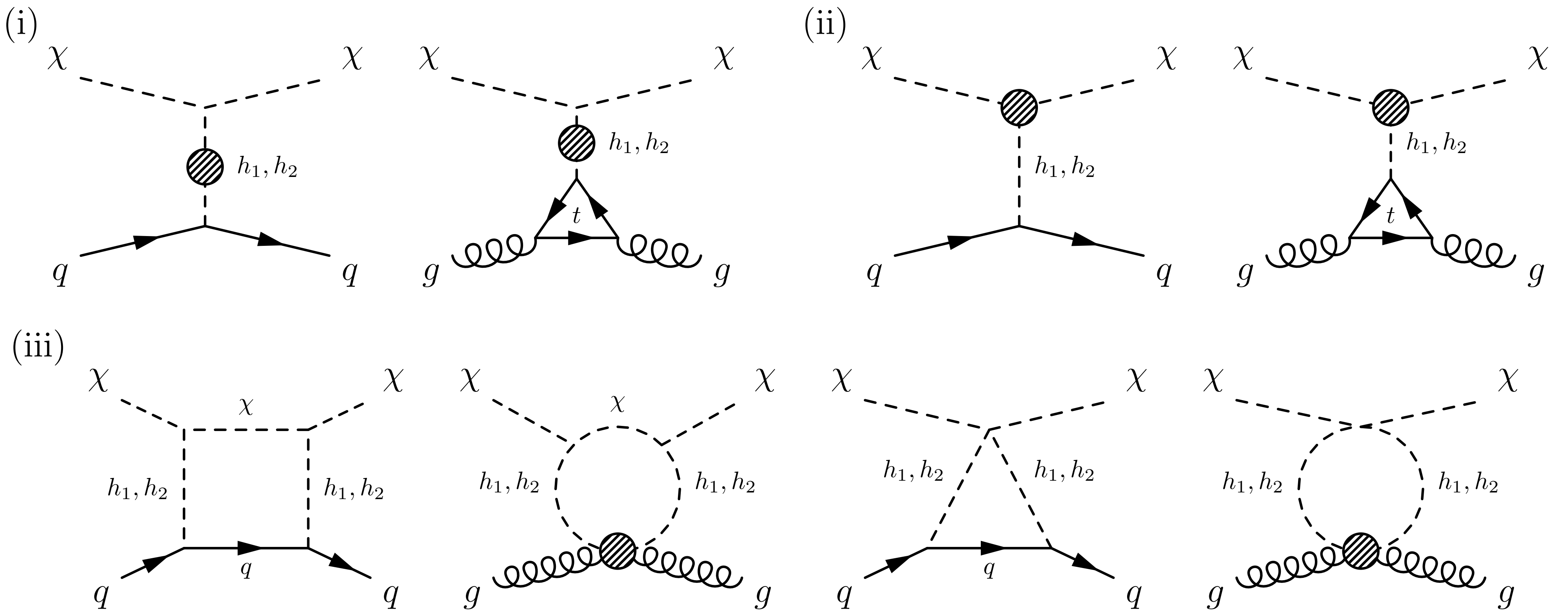
$\Rightarrow$ Naturally evade the direct detection bounds

- The cancellation is due to nature of Goldstone boson

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]

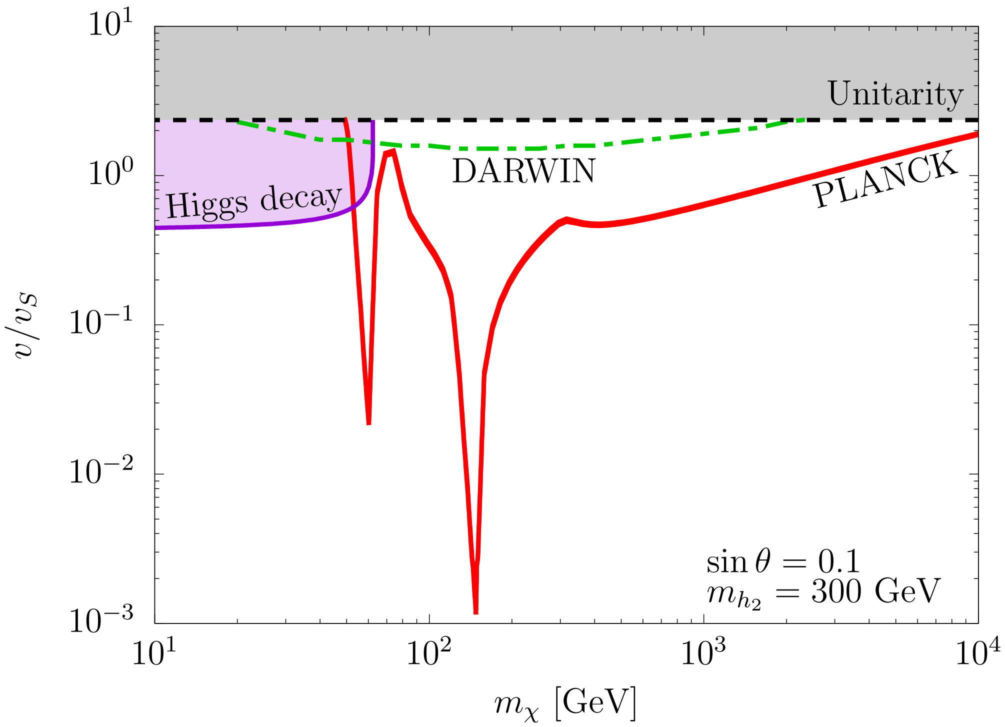
- Constant amplitude at 1-loop level

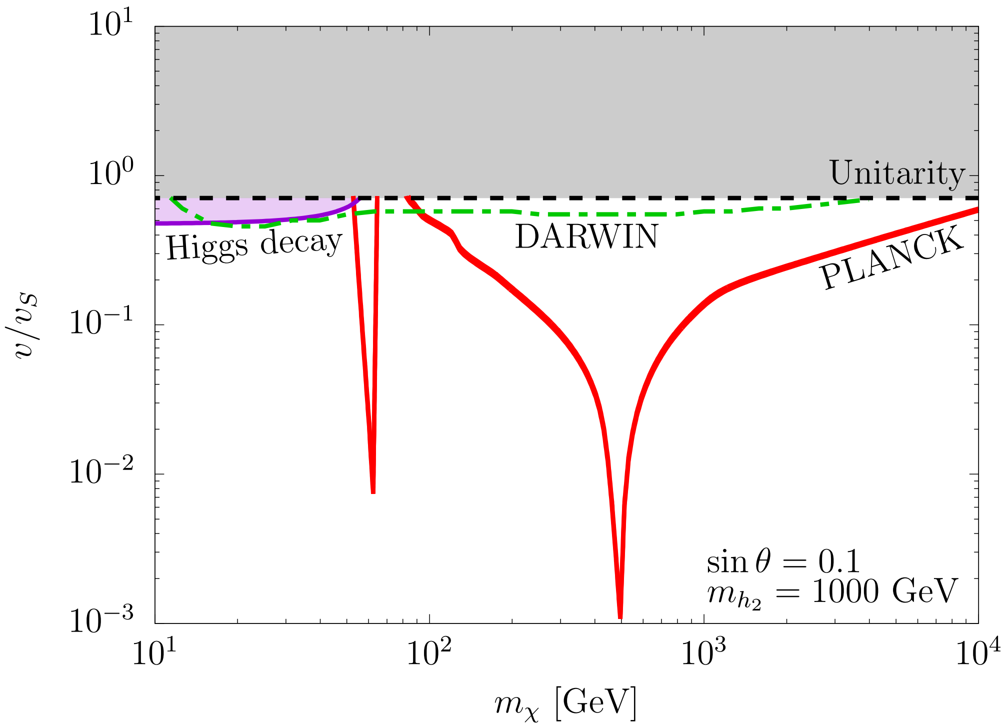


- (i) self-energy correction
- (ii) vertex correction
- (iii) box and triangle $\rightarrow$ two Yukawa couplings (sub-dominant)

Numerical calculations

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





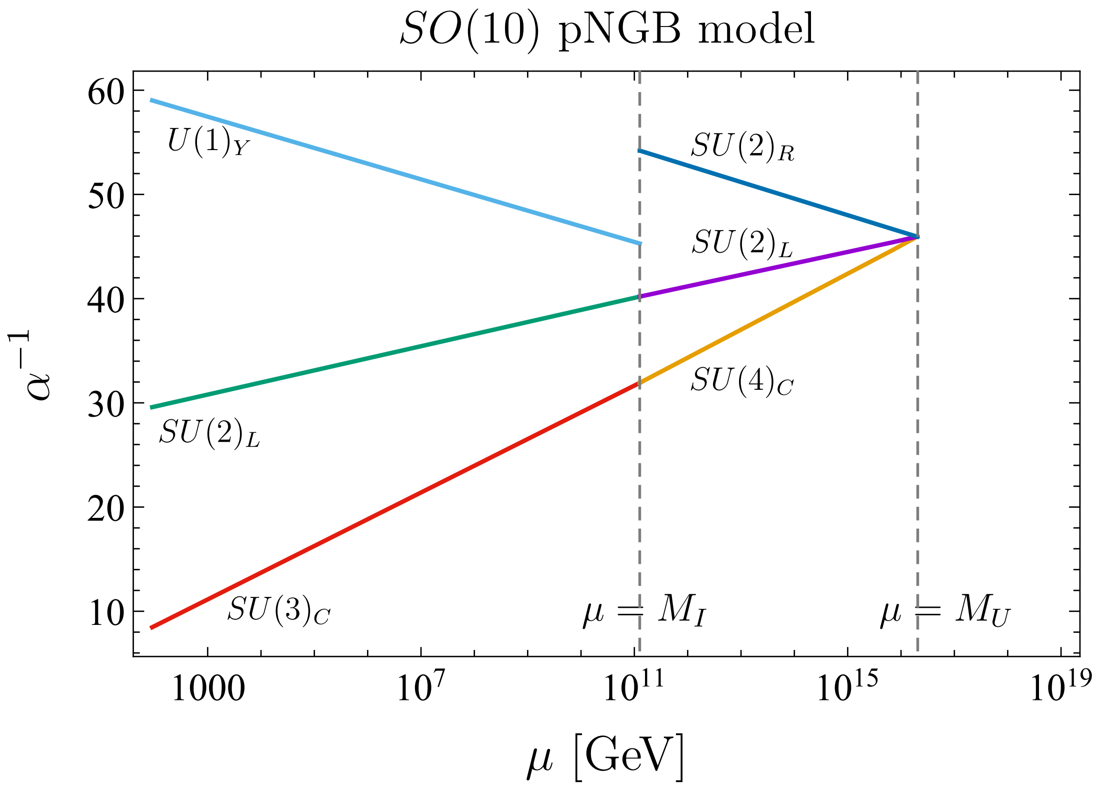
- $\sin\theta = 0.1$
- Unitarity bound: $\lambda_S \leq 8\pi/3$
- Higgs Invisible decay $\mathrm{Br}(h_1 \to \mathrm{inv}) \lesssim 20\%$ at LHC
- $\sigma_{\mathrm{SI}}^p = \mathcal{O}(10^{-48})\ \mathrm{cm}^2$ at most

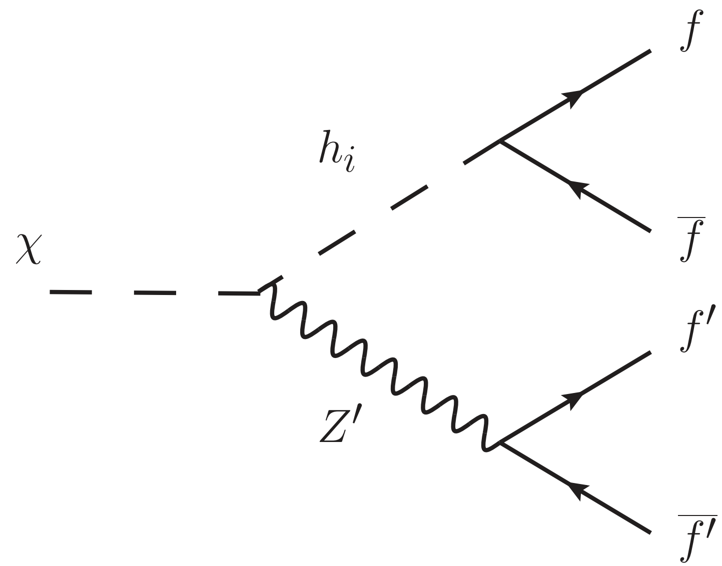
Possible extension of the pNG DM model

Y. Abe, TT, K. Tsumura, JHEP (2020), Y. Abe, TT, K. Tsumura, N. Yamatsu, PRD (2021)

- Gauged $U(1)_{B-L}$ extension
  - · Solution for domain wall problem
  - · Origin of soft breaking term

    $\mu\Phi S^2 \Rightarrow \mu\langle\Phi\rangle S^2 = \mu_S'^2 S^2$
  - · Neutrino masses
  - · Gauge coupling unification

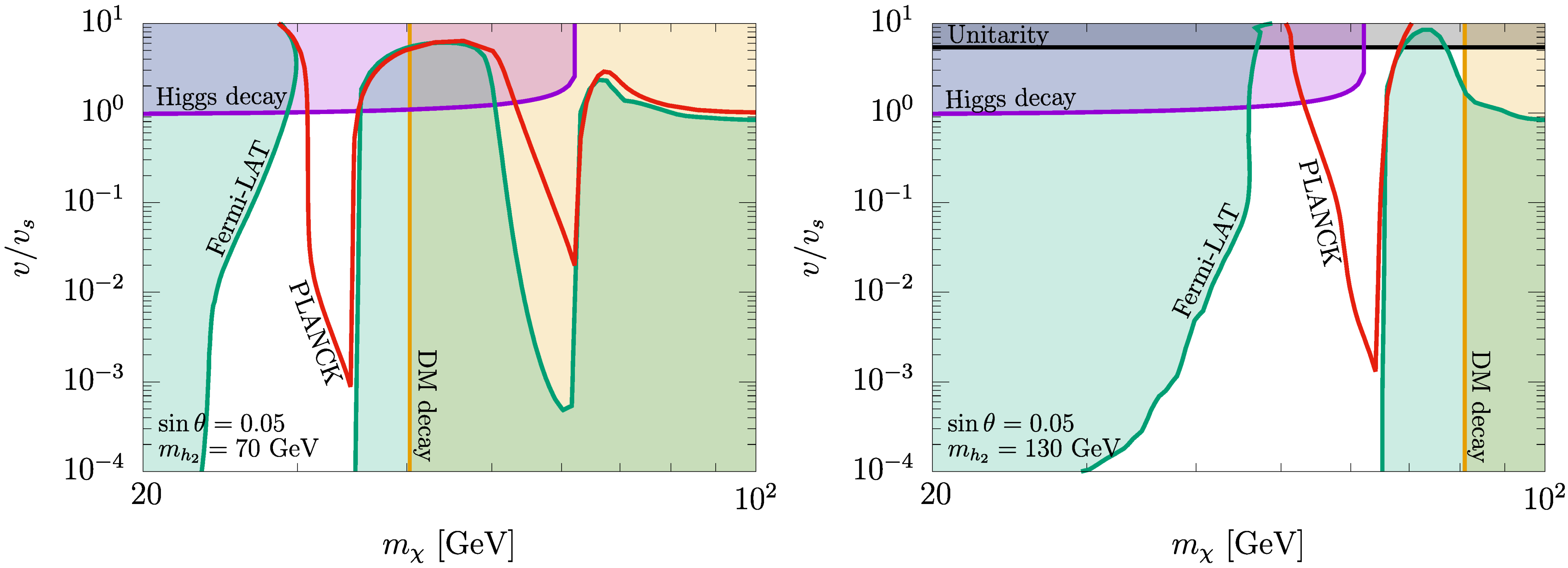




- Prediction: DM decay

  $\Rightarrow$ indirect detection signals

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 production
- close to the h_2 resonance

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

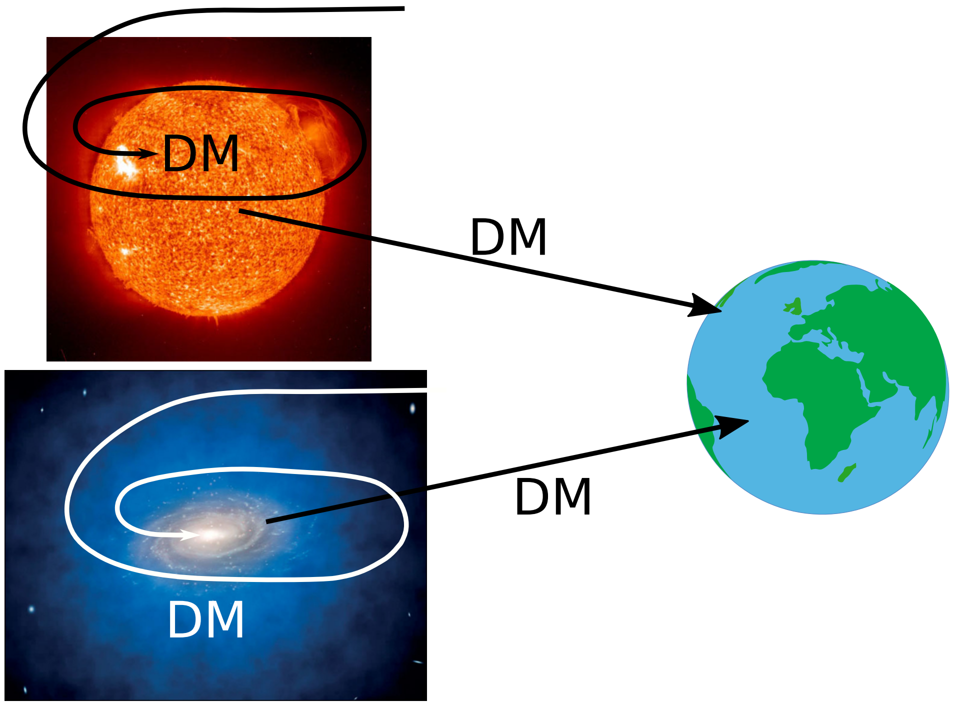
	DW problem	stable/decaying	real/complex	Landau pole
Global U(1)	$\times$	stable	real	$\checkmark$
Gauged $U(1)_{B\text{-}L}$	$\checkmark$	decaying	real	$\checkmark$
SO(10) GUT	$\checkmark$	decaying	real	$\checkmark$
Hidden gauged U(1)	$\checkmark$	decaying	real	$\checkmark$
Global SU(2) with gauged U(1)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

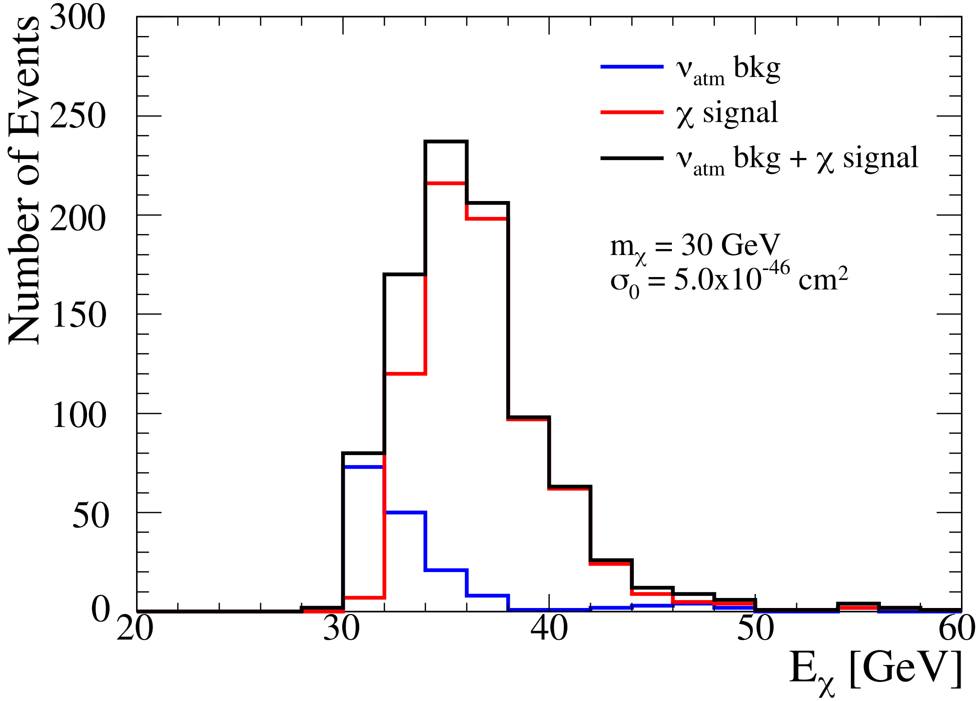
Abe, Hamada, Tsumura, JHEP 05 076 (2024)

- No domain wall
  Two component DM $\Rightarrow$ production of boosted DM

How to probe pNG DM

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





Summary

1. Dark matter direct detection experiments impose the strong bounds on the scattering cross section.
   Wayout: suppression of scattering ⇒ pNG DM
2. Further extensions of the pNG DM model have been proposed.
3. Strong pNG DM signals are expected if DM is boosted.