A model of pseudo-Nambu-Goldstone dark matter with two complex scalars

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Yu Hamada (DESY)

based on

arXiv:2401.02397, JHEP 05 (2024) 076

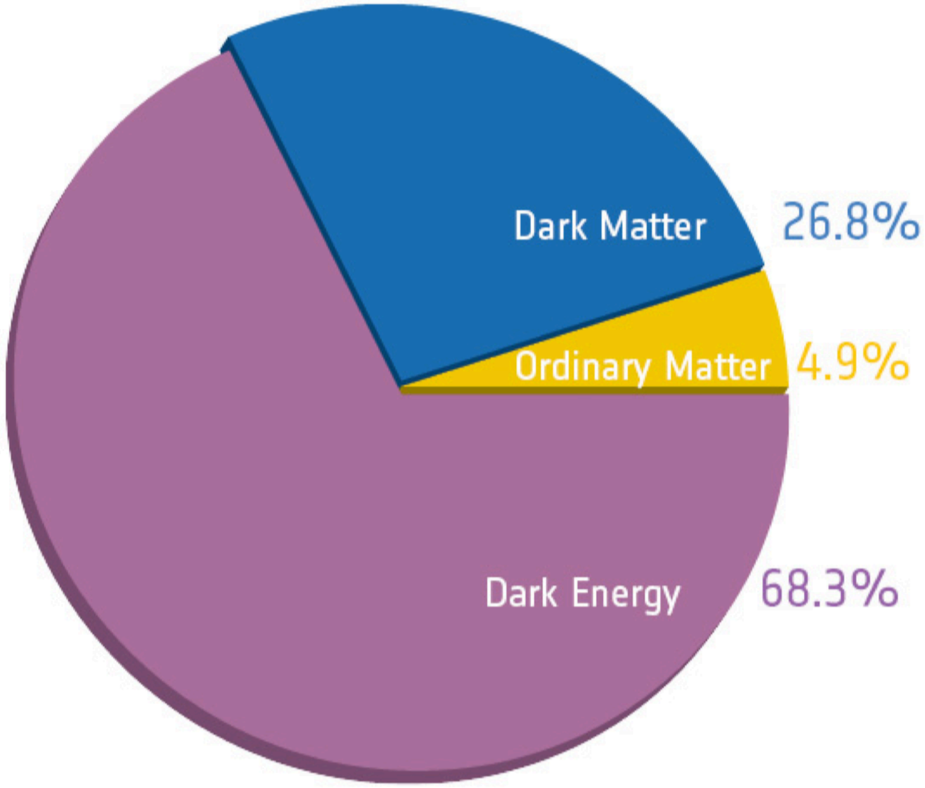
in collaboration with

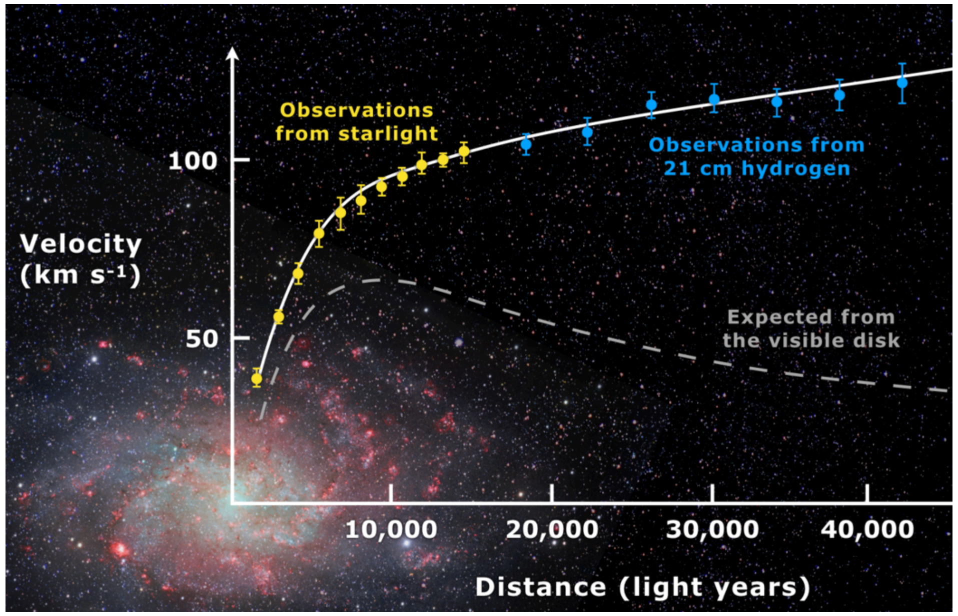
T. Abe (Tokyo U. of Science) and K. Tsumura (Kyushu U.)

Planck 2024 @ Lisbon, 4th June

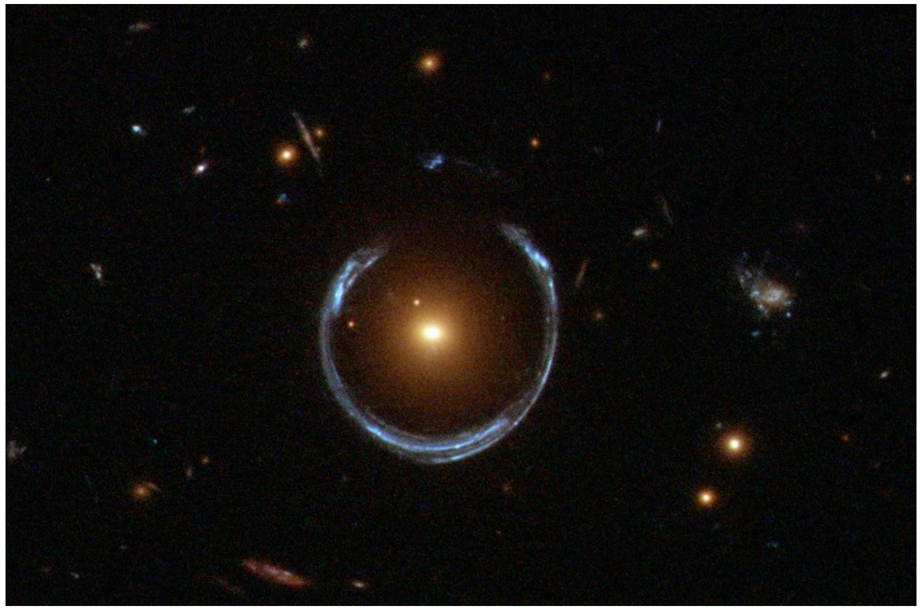
Dark matter

- There are many evidences for dark matter





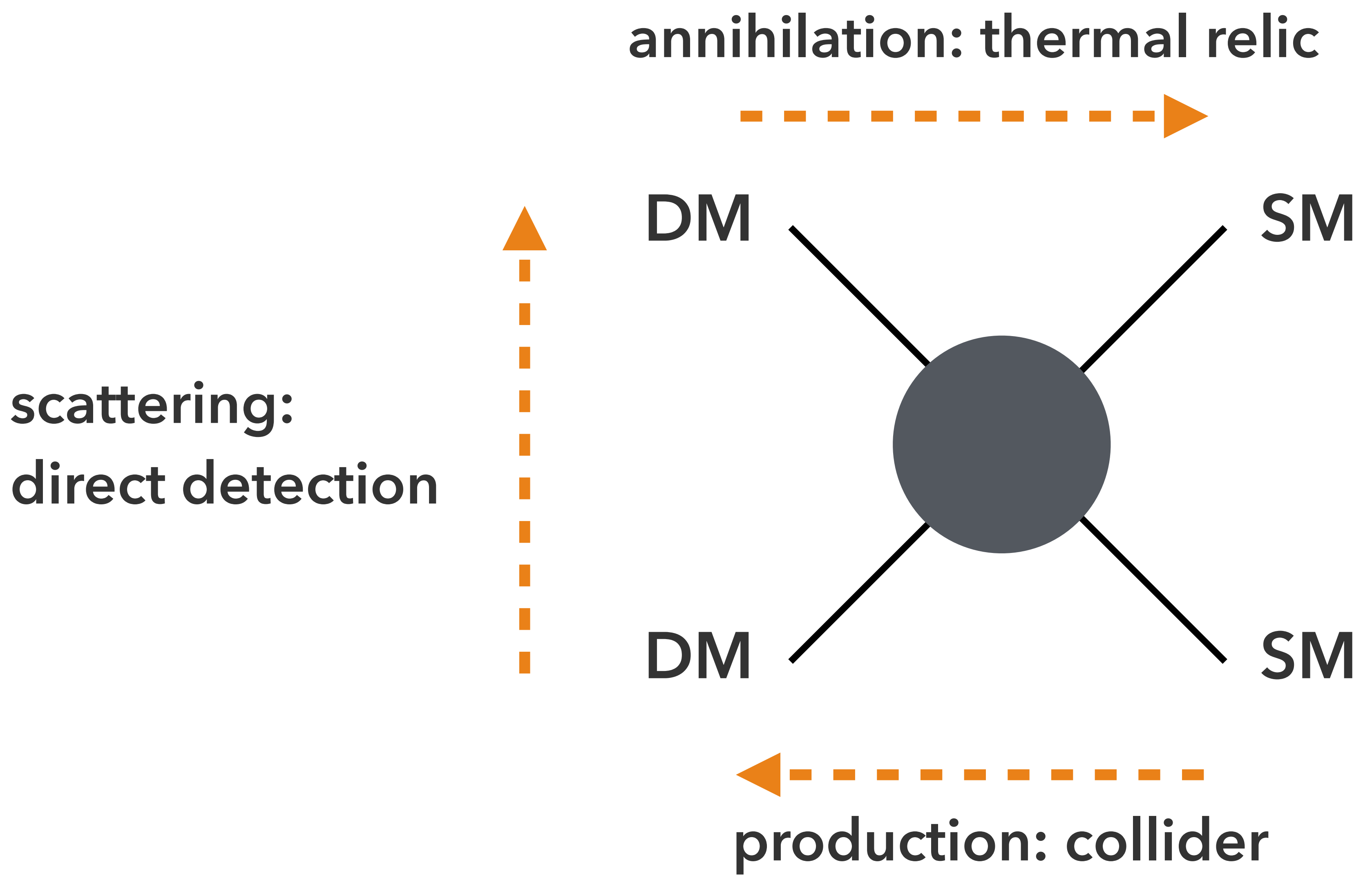
Galaxy rotation curve (from Wikipedia)



Gravitational lens (from Wikipedia)

WIMP (Weakly Interacting Massive Particle)

- "weakly" interacting with SM sector
- explain DM relic with thermal freeze-out mechanism
- correlated processes → nice testability



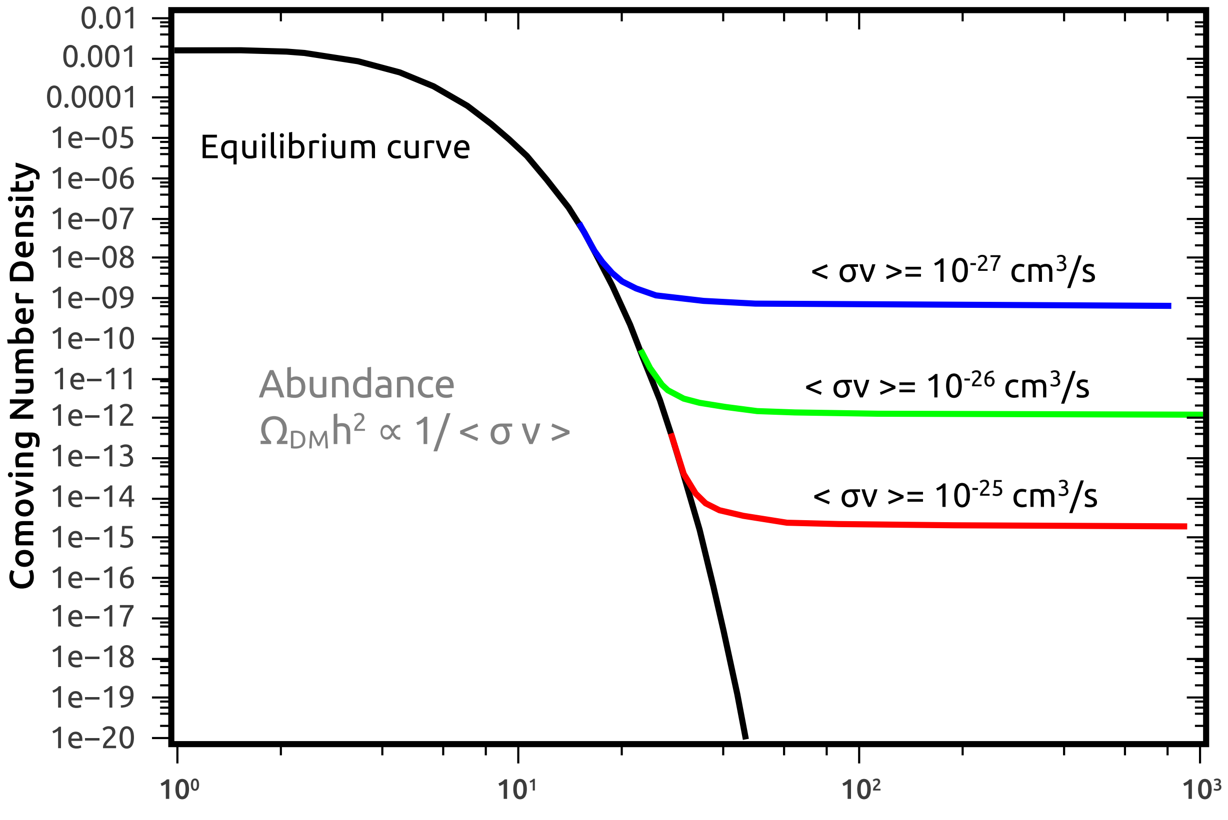
annihilation: thermal relic

scattering:
direct detection

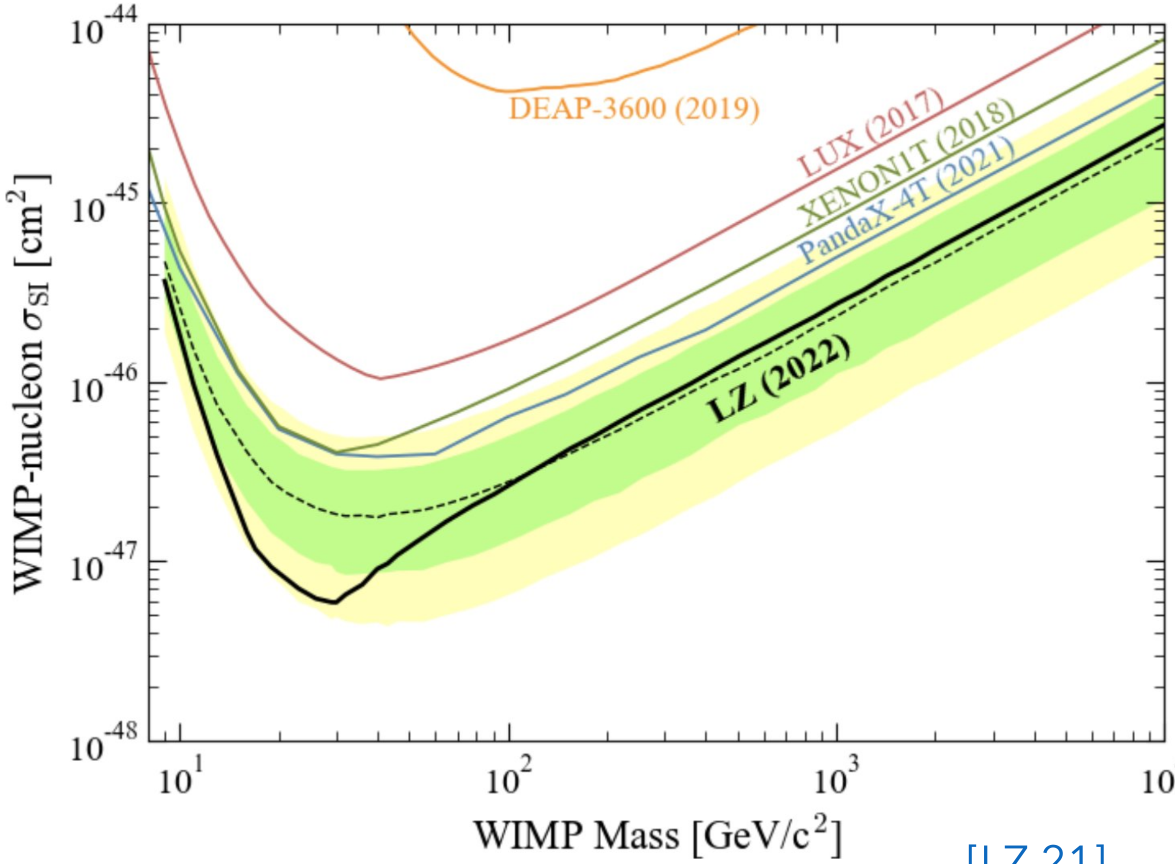
production: collider

DM relic vs Direct detection

- **must keep DM annihilation rate (DM relic)**
- **severe constraint on DM-nucleon σ_{SI} (direct detection)**



[Arcadi et.al. 1703.07364]



[LZ 21]

naively incompatible → needs some trick!

pseudo-Nambu-Goldston DM

[Gross-Lebedev-Toma '17]

$$V(\phi, H) = V_{\rm SM}(H) - \mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 + \lambda_{\phi H} |\phi|^2 |H|^2 + \left(\underset{\displaystyle\downarrow \atop \displaystyle m_{\rm DM}^2}{\mu_{\rm break}^2} \phi^2 + {\rm h.c.}\right)$$

- SM Higgs H + singlet complex scalar ϕ
- global $U(1)$: $\phi \to e^{i\theta}\phi$, softly broken by $\mu_{\rm break}$
- VEV $\langle \phi \rangle \neq 0$ → **pseudo NG boson w/ derivative interaction**

[cf. soft pion theorem]

pseudo-Nambu-Goldston DM

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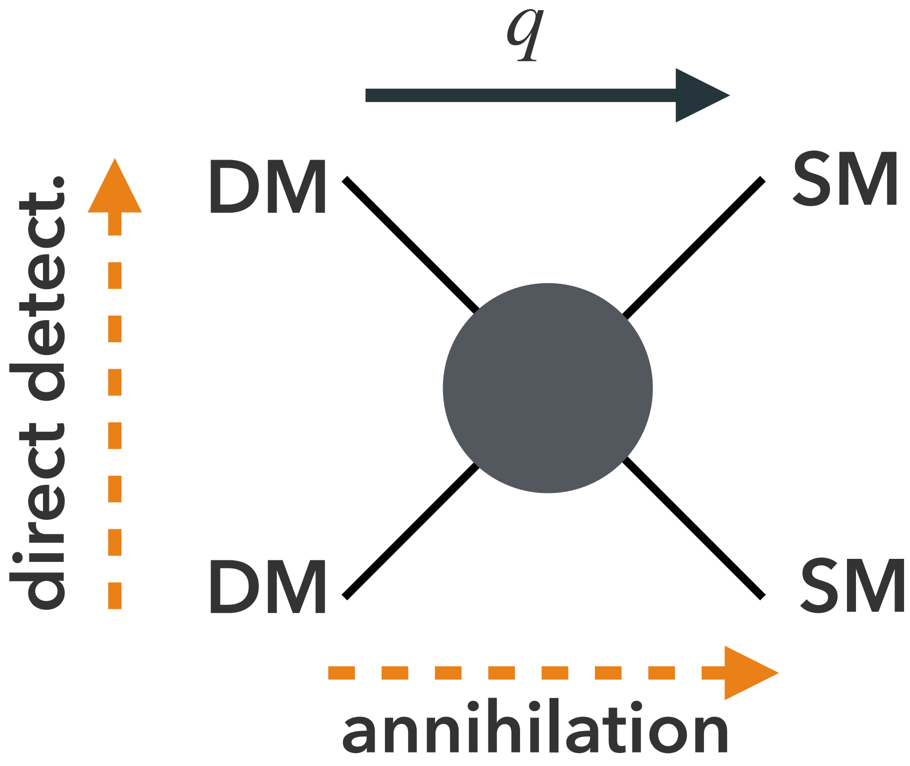

$$\underline{\propto q^2} = \begin{cases} t \simeq 0 & \textbf{@ direct detection} \\ s \simeq 4m_{\rm DM}^2 & \textbf{@ annihilation} \end{cases}$$

evade the dilemma elegantly!

Cons of original pNG DM model

$$V(\phi, H) = V_{\rm SM}(H) - \mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 + \lambda_{\phi H} |\phi|^2 |H|^2 + \left(\mu_{\rm break}^2 \phi^2 + \rm h.c.\right)$$

- SSB of $\mathbb{Z}_2$ → **domain wall problem**
- **other soft-breaking terms ϕ, ϕ^3 are dropped by hand**

→ **needs to be improved**

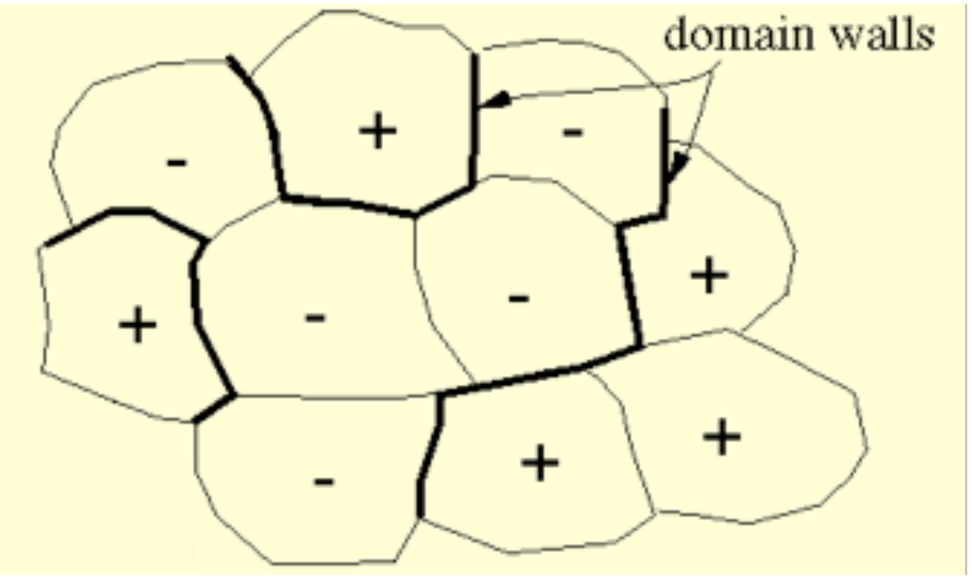

fig. from https://www.ctc.cam.ac.uk/outreach/origins/cosmic_structures_two.php

- other pNG DM models in literature:

[Abe-Toma-Tsumura 2001.03954] [Okada-Raut-Shafi, 2001.05910]
[Abe et. al., 2104.13523] [Okada et. al., 2105.03419]
[Abe- Hamada, 2205.11919] [Liu et. al., 2208.06653]
[Otsuka- et. al. 2210.08696] [Chiang et. al., 2311.13753]

We propose an alternative pNG DM model

Plan of talk

- Introduction
- Our model
- Prediction and constraints
- Summary

Our model

Model

[Abe-**YH**-Tsumura 2401.02397]

- scalar extension w/ two singlet complex scalars ϕ_1, ϕ_2
- impose $\underline{U(1)_1 \times U(1)_2} = U(1)_V \times U(1)_A$

  (phase rot. of ϕ_1, ϕ_2)

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unique soft-breaking term

$$\begin{aligned} V(H, \phi_1, \phi_2) = m_1^2 \left(|\phi_1|^2 + |\phi_2|^2\right) - \underline{\left(m_{12}^2 \phi_1^* \phi_2 + \text{h.c.}\right)} \\ + \frac{\lambda_1}{2} \left(|\phi_1|^4 + |\phi_2|^4\right) + \lambda_3 |\phi_1|^2 |\phi_2|^2 \\ - m_H^2 |H|^2 + \lambda_H |H|^4 + \lambda_{H1} |H|^2 \left(|\phi_1|^2 + |\phi_2|^2\right) \end{aligned}$$

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- $\langle \phi_1 \rangle = \langle \phi_2 \rangle = v_s/2$ → spontaneously breaks **only** two $U(1)$'s

→ **no DW problem**

Particle contents

[Abe-**YH**-Tsumura 2401.02397]

- convenient to introduce "Higgs basis"

$$\phi_+ \equiv \frac{1}{\sqrt{2}}\left(\phi_1 + \phi_2\right) \qquad \phi_- \equiv \frac{1}{\sqrt{2}}\left(\phi_1 - \phi_2\right)$$

$\mathbb{Z}_2$ **even** $\mathbb{Z}_2$ **odd,** $\langle \phi_- \rangle = 0$

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- expand around VEVs:

$$H = \begin{pmatrix} i\pi_W^+ \\ \frac{1}{\sqrt{2}}\left(v_h + \sigma + i\pi_Z\right) \end{pmatrix} \quad \phi_+ = \frac{1}{\sqrt{2}}\left(v_s + s_+ + i\pi_V\right) \quad \phi_- = \frac{1}{\sqrt{2}}\left(s_- + ia\right)$$

mix to be h, h'

stable pNG DM coming from $U(1)_A$

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stable pNG DM

coming from $U(1)_A$

- s_- is also $\mathbb{Z}_2$ odd → assume $m_{s_-} > m_{\rm DM}$

Gauge kinetic mixing

[Abe-**YH**-Tsumura 2401.02397]

- the new gauge field V_μ mixes with SM Y_μ: $\mathscr{L}_{\rm mix} = -\frac{\sin\epsilon}{2} Y^{\mu\nu} V_{\mu\nu}$

  → obtain masses from VEVs of SM Higgs H and new scalar ϕ_+

  → mass eigenstates: $Z_\mu \ A_\mu \ Z'_\mu \longleftarrow$ **new massive gauge boson**

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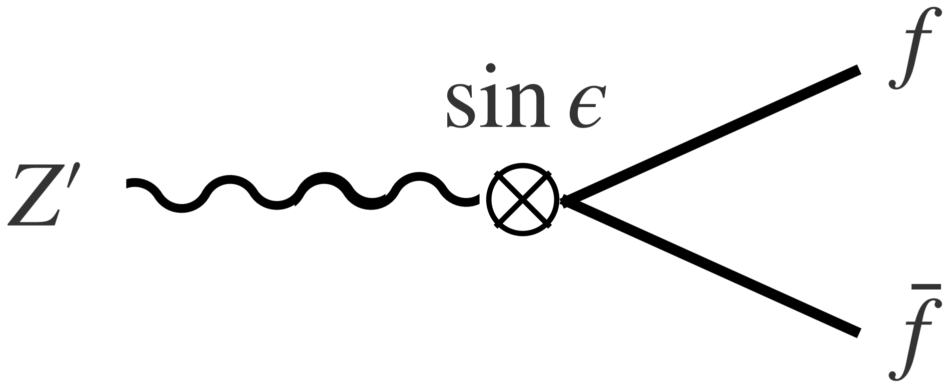
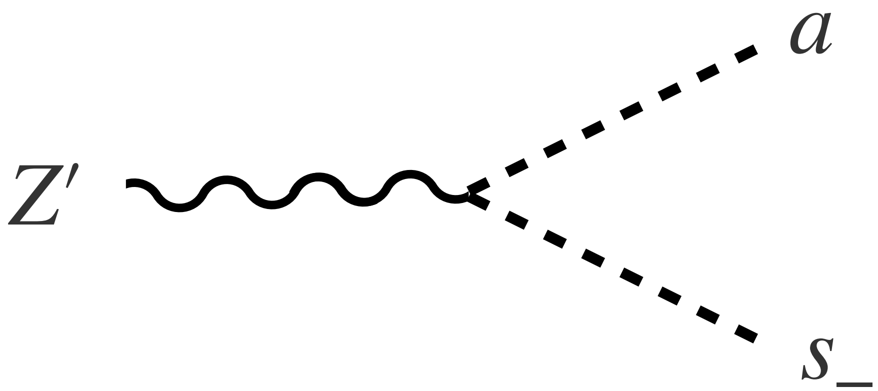
- Z' boson easily decays to SM particles



Cf.)



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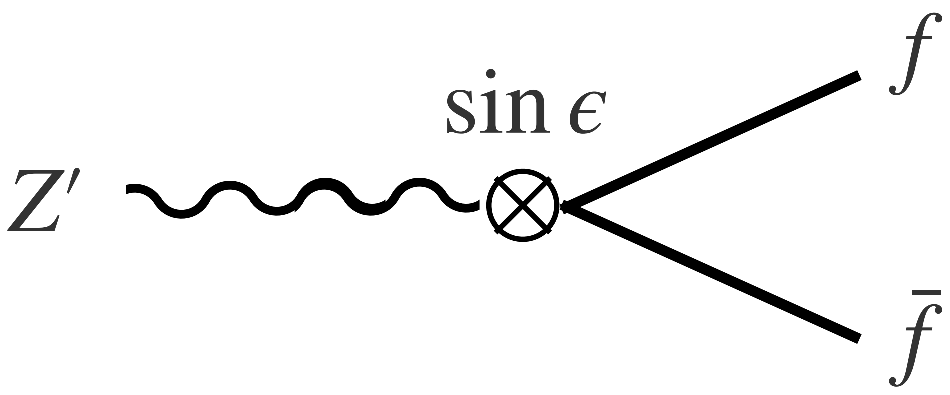

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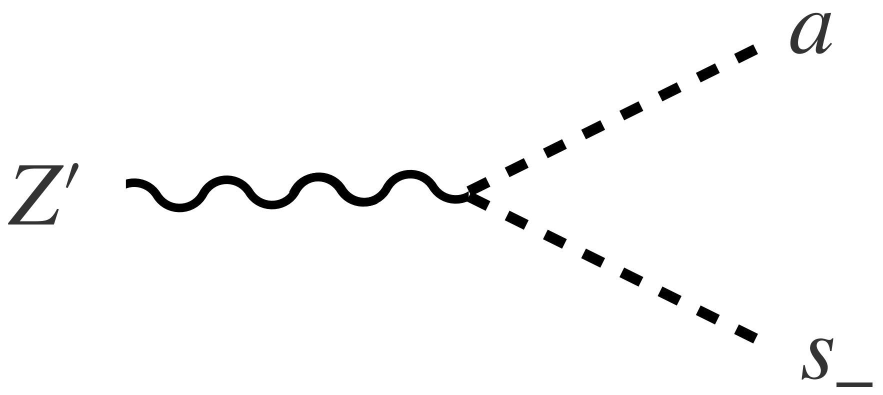

bonus: Z' can be taken light, say, $m_{Z'} \sim \mathcal{O}(100)\,\mathrm{GeV}$

→ **its coupling constant remains sufficiently perturbative**

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Prediction and constraints

Direct detection @ tree level

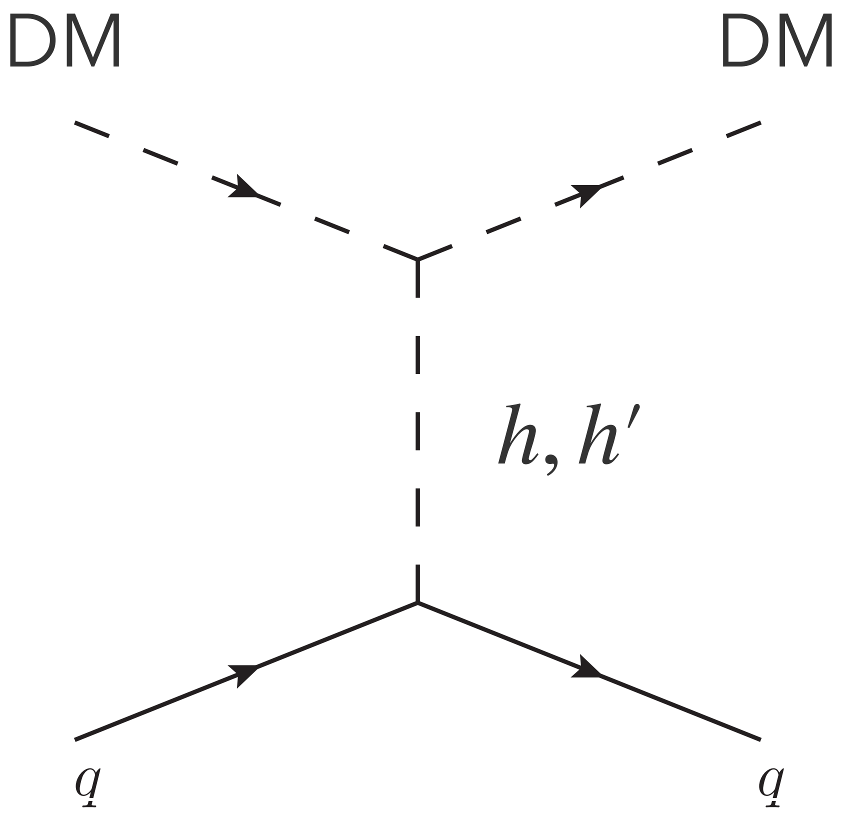
[Abe-**YH**-Tsumura 2401.02397]

- easily shown in non-linear rep.

$$\phi_1 = \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}}v_s + s_1\right)\exp\left[+i\frac{\pi_a}{v_s}\right]$$

DM

$$\phi_2 = \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}}v_s + s_2\right)\exp\left[-i\frac{\pi_a}{v_s}\right]$$



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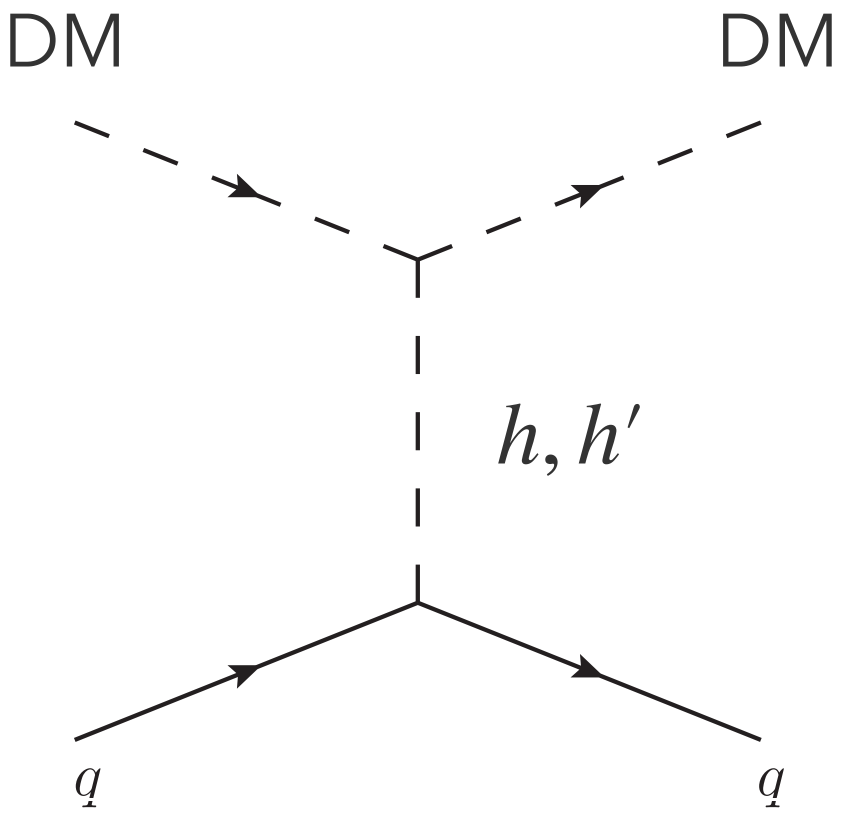

- relevant cubic coupling

$s_+ = \left(s_1 + s_2\right)/\sqrt{2}$ = (linear comb of $h\,h'$)

$$\mathscr{L}\Big|_{s\pi_a\pi_a} = -\frac{2}{v_s}\left[s_+\pi_a\,\underbrace{\left(\partial^2 + m_{\mathrm{DM}}^2\right)\pi_a}_{\substack{\to 0 \\ \text{on-shell cond.}}} + \pi_a\partial_\mu\pi_a\,\underbrace{\partial^\mu s_+}_{\substack{\to 0 \\ \text{low } q}}\right]$$

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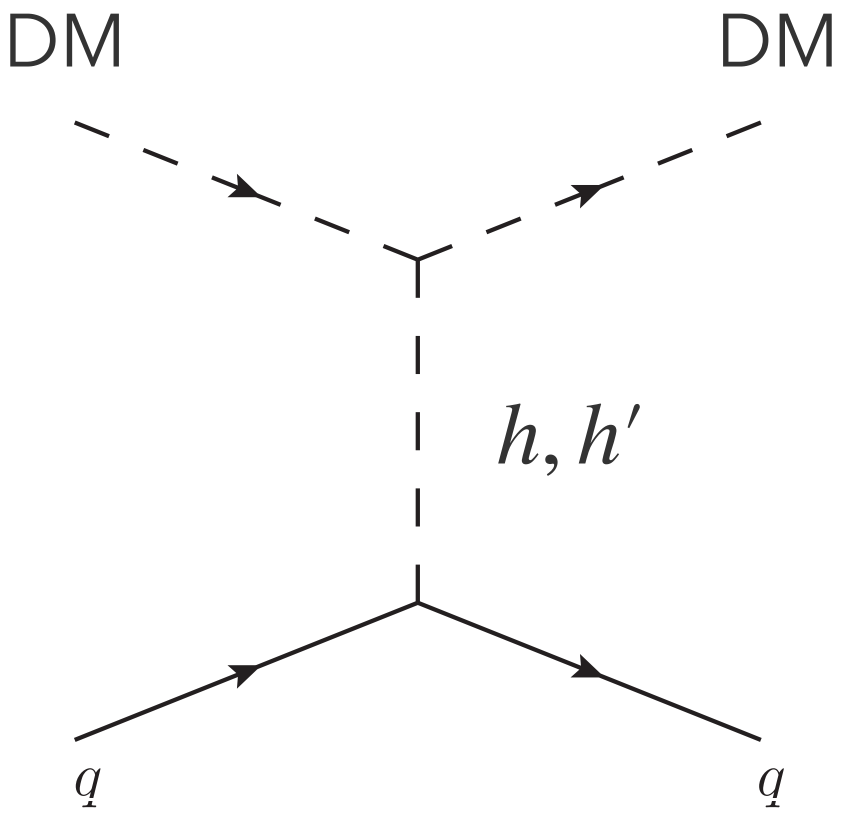

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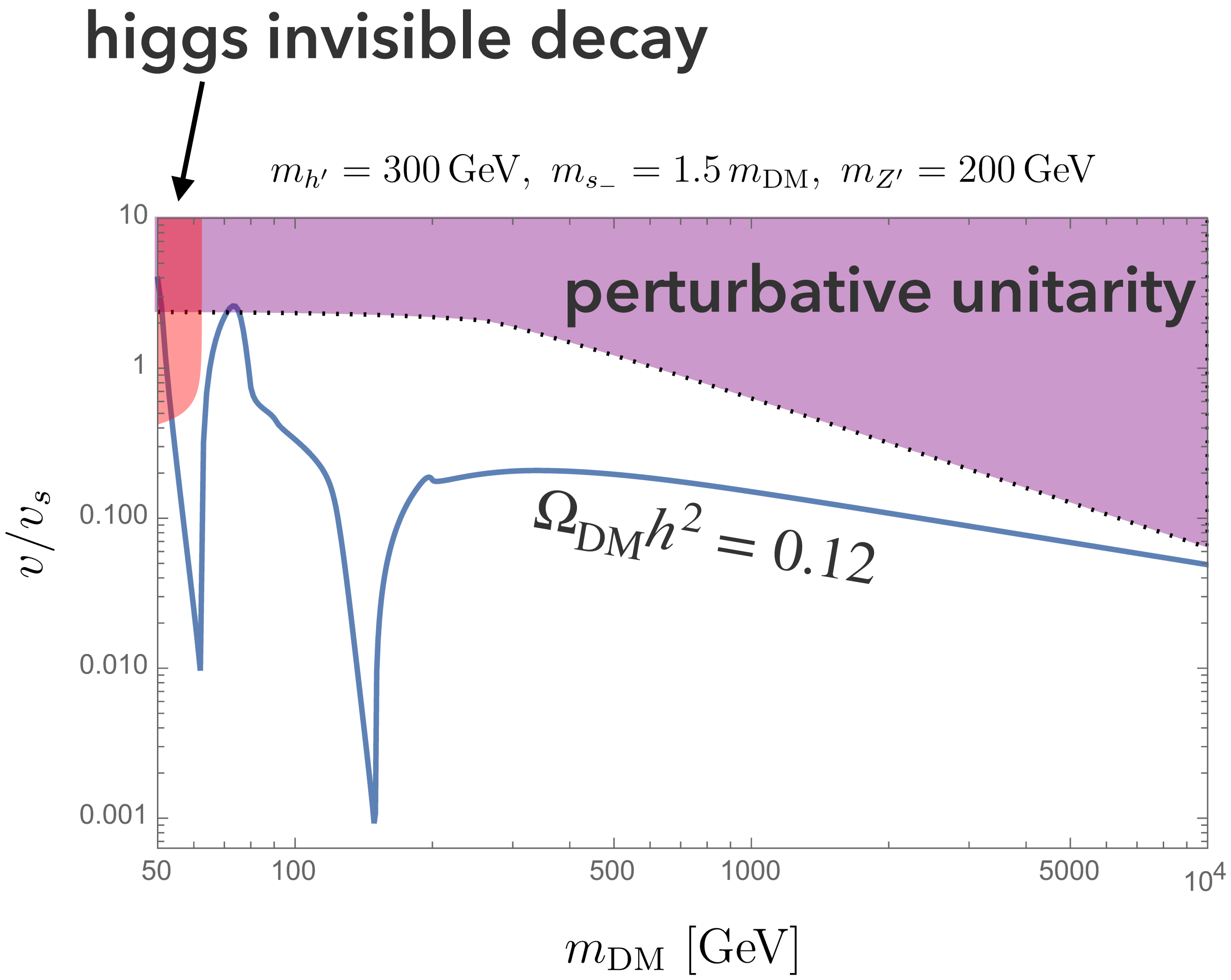
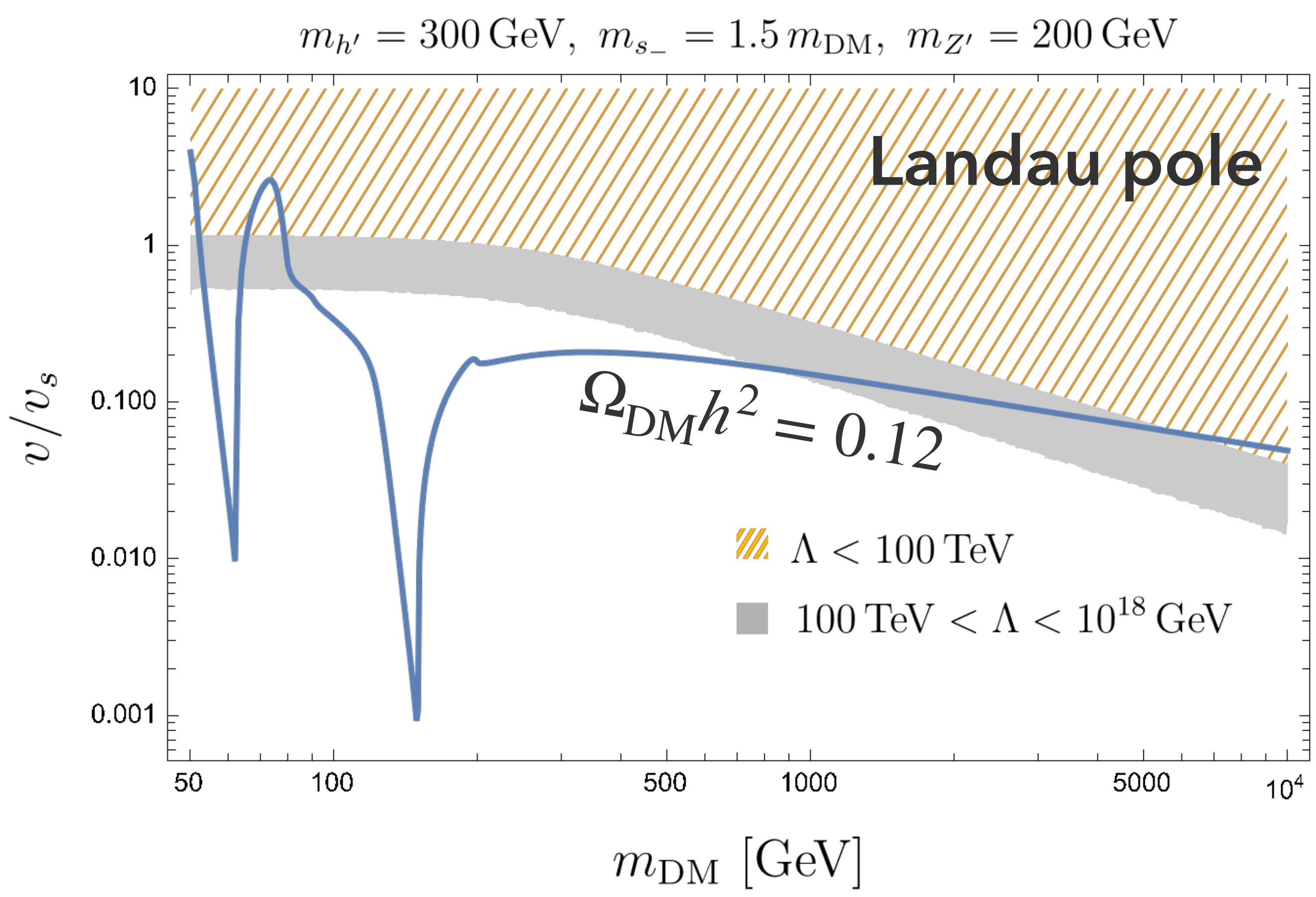
vanishes!

DM thermal relic

[Abe-**YH**-Tsumura 2401.02397]

$\sin\xi = 0.1,\ \ \sin\epsilon = 10^{-4}$

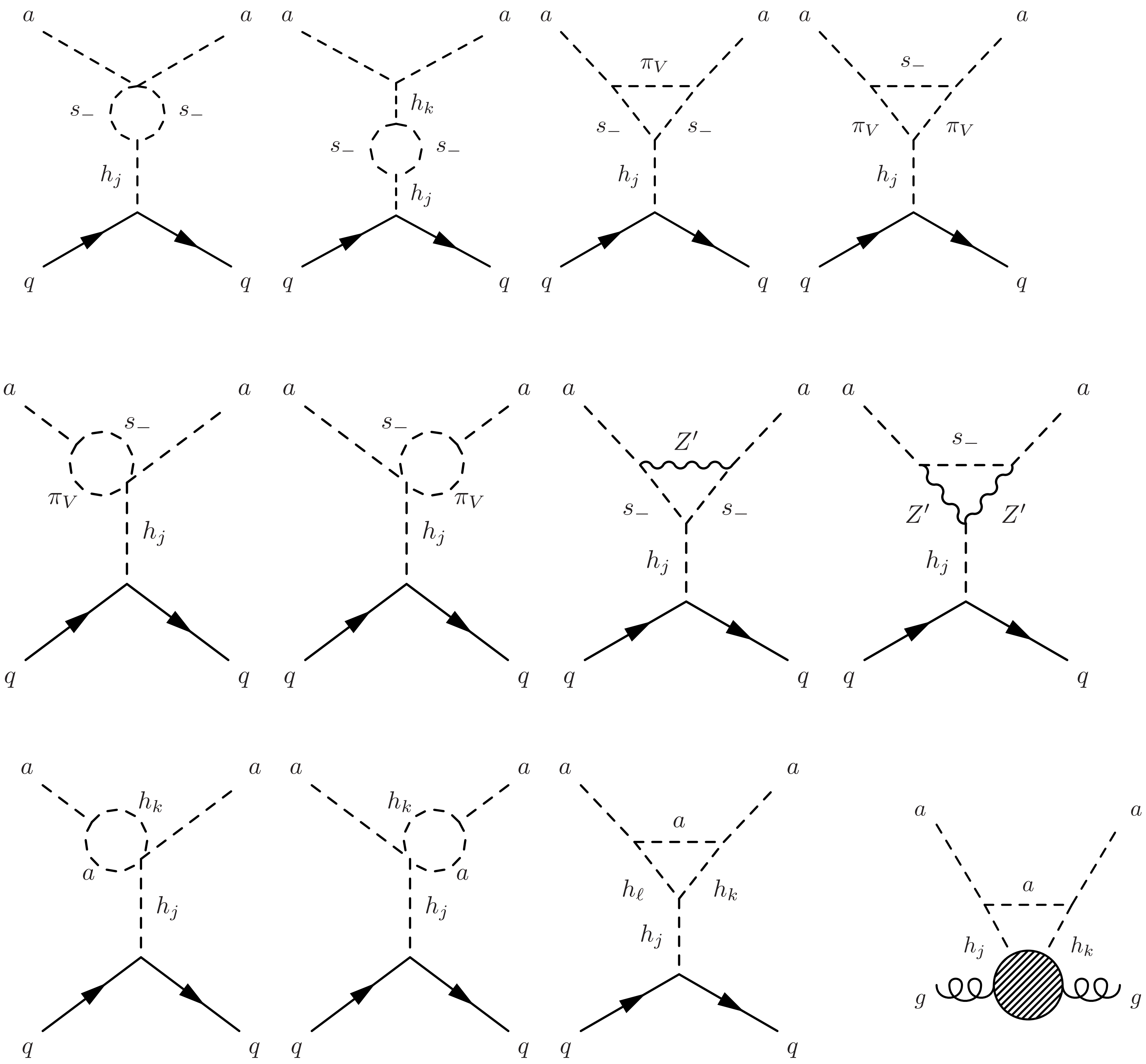




less constrained by perturbativity and Landau pole, thanks to the light Z' mass

Direct detection @ loop level

[Abe-**YH**-Tsumura 2401.02397]



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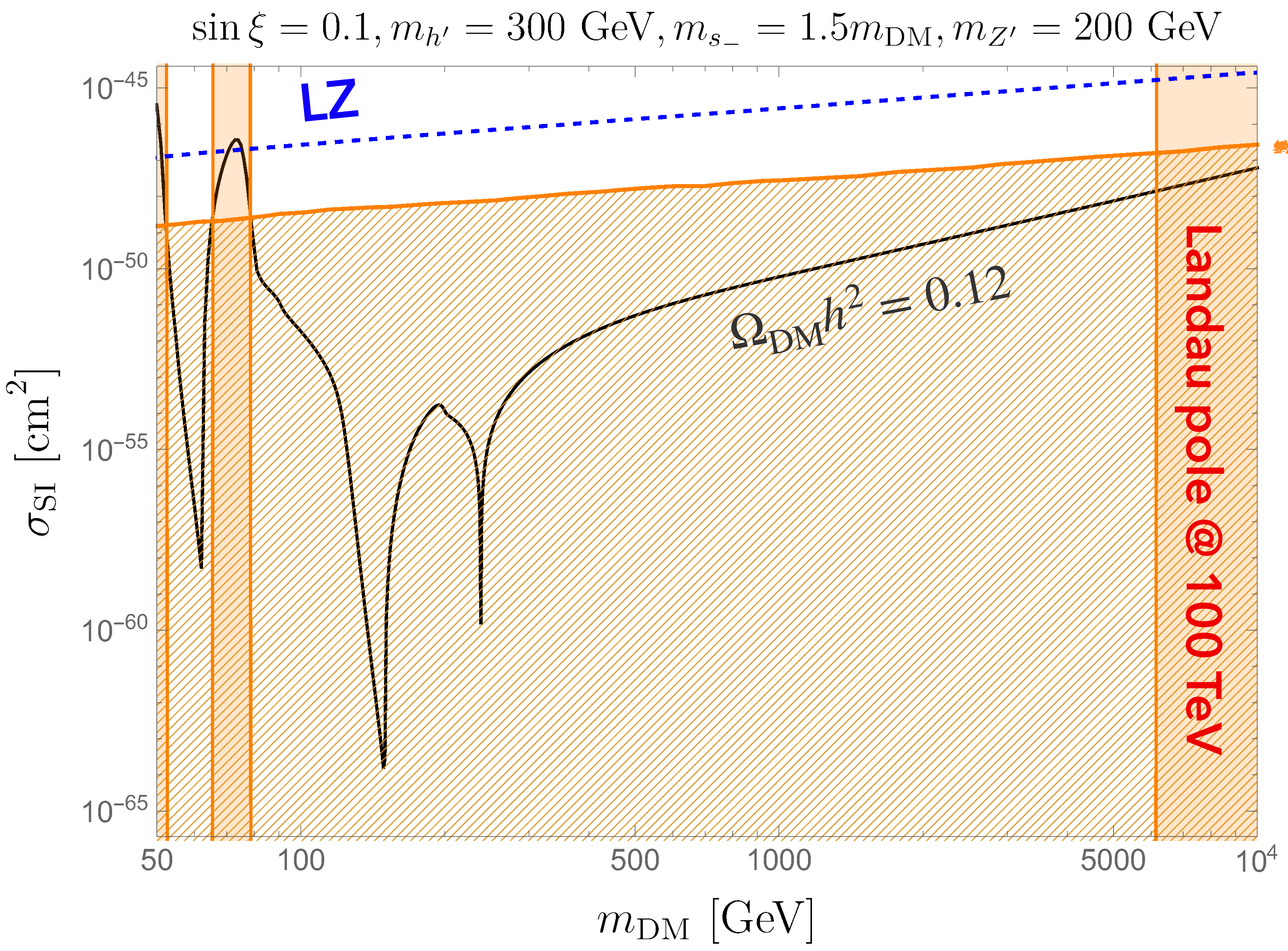


Neutrino fog

To test the model, we should go into neutrino fog!

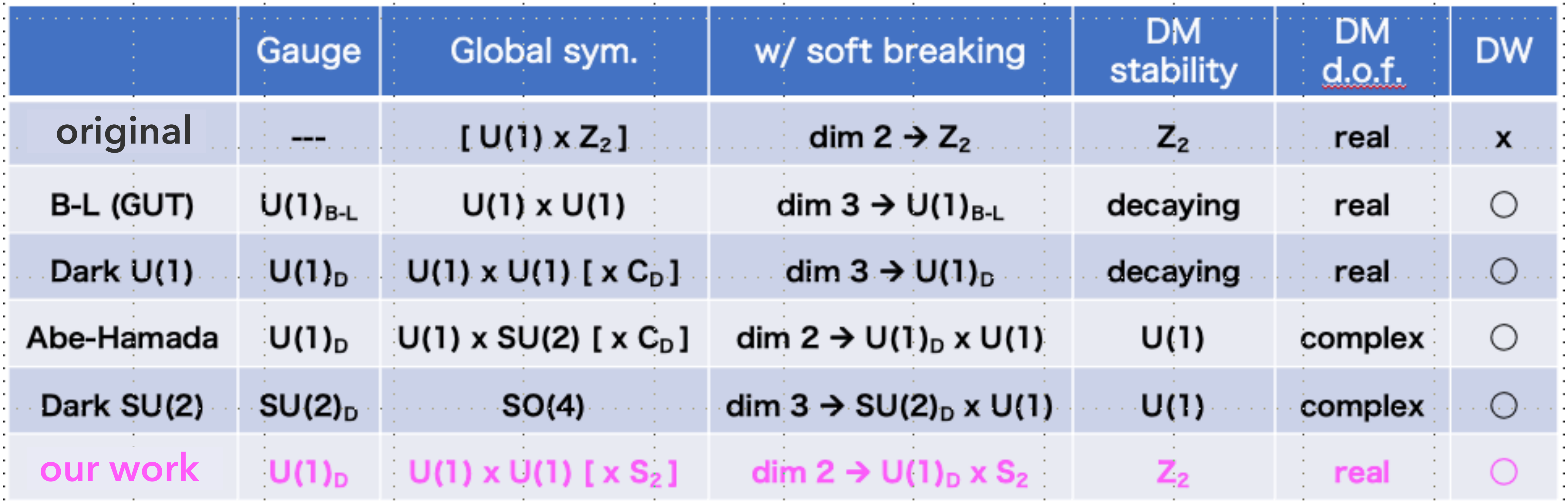
Summary

- pNG DM models evade direct detection constraint keeping the thermal DM relic.
- The original model suffers from DW problem and assumes the other soft-breaking terms to vanish.
- We proposed a new pNG DM model in which dark sector consists of two scalars ϕ_1, ϕ_2 and gauge boson Z'_μ
- pNG DM comes from SSB of $U(1)_A$ and is stabilized by exchange symmetry $\phi_1 \leftrightarrow \phi_2$.
- Direct detection signal is covered by neutrino fog

→ experiments must go further!

Backup

Comparison w/ other pNG DM models



	Gauge	Global sym.	w/ soft breaking	DM stability	DM d.o.f.	DW
original	---	[U(1) x Z_2]	dim 2 → Z_2	Z_2	real	x
B-L (GUT)	$U(1)_{B\text{-}L}$	U(1) x U(1)	dim 3 → $U(1)_{B\text{-}L}$	decaying	real	○
Dark U(1)	$U(1)_D$	U(1) x U(1) [x C_D]	dim 3 → $U(1)_D$	decaying	real	○
Abe-Hamada	$U(1)_D$	U(1) x SU(2) [x C_D]	dim 2 → $U(1)_D$ x U(1)	U(1)	complex	○
Dark SU(2)	$SU(2)_D$	SO(4)	dim 3 → $SU(2)_D$ x U(1)	U(1)	complex	○
our work	$U(1)_D$	U(1) x U(1) [x S_2]	dim 2 → $U(1)_D$ x S_2	Z_2	real	○

Constraints

- perturbative unitarity

$$|\lambda_H| < 4\pi,$$

$$|2\lambda_1 - \lambda_3| < 8\pi,$$

$$|\lambda_3| < 8\pi,$$

$$\left|2\lambda_1 + \lambda_3 + 6\lambda_H \pm \sqrt{(2\lambda_1 + \lambda_3 - 6\lambda_H)^2 + 16\lambda_{H1}^2}\right| < 16\pi$$

- potential boundedness from below

$$\lambda_1 > 0,\ \lambda_H > 0,\ \lambda_1 + \lambda_3 > 0,$$

$$\lambda_{H1} + \sqrt{2\lambda_1\lambda_H} > 0,\ \lambda_{H1} + \sqrt{(\lambda_1 + \lambda_3)\lambda_H} > 0$$

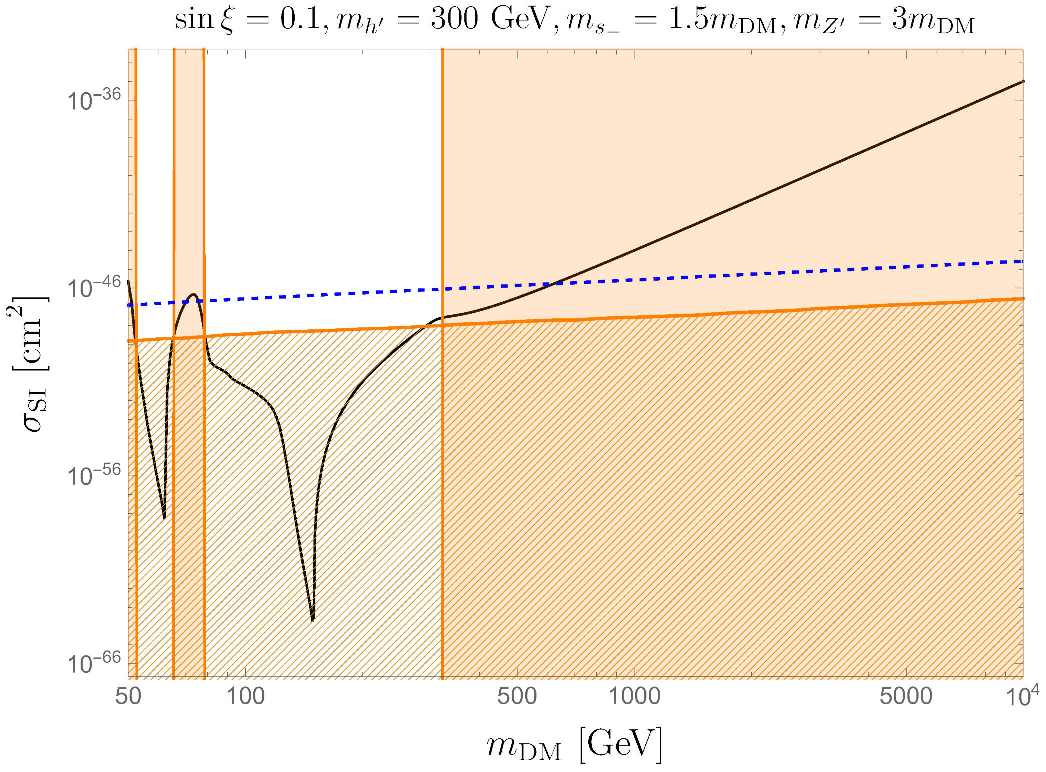
1-loop RGE

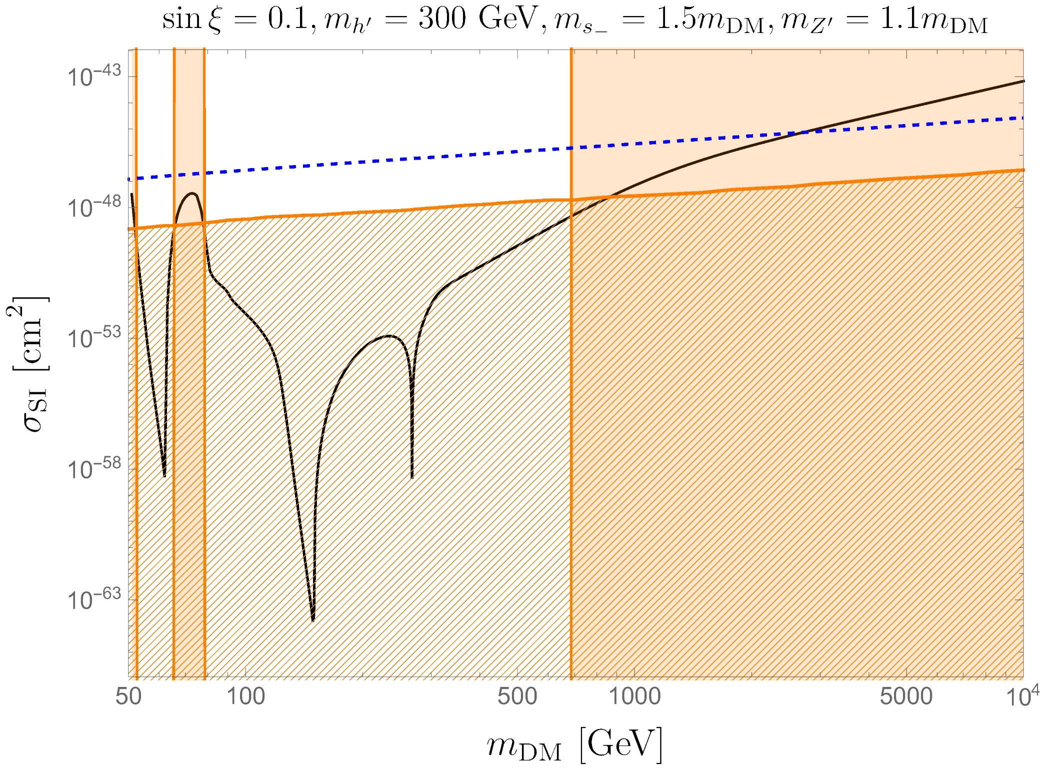
$$(4\pi)^2\beta_{\lambda_1} \equiv (4\pi)^2\,\frac{\mathrm{d}\lambda_1(\mu)}{\mathrm{d}\ln\mu} = 10\lambda_1^2 + 2\lambda_3^2 + 12g_V^4 - 12g_V^2\lambda_1,$$

$$(4\pi)^2\beta_{\lambda_3} \equiv (4\pi)^2\,\frac{\mathrm{d}\lambda_2(\mu)}{\mathrm{d}\ln\mu} = 4\lambda_3^2 + 8\lambda_1\lambda_3 + 12g_V^4 - 12g_V^2\lambda_3,$$

$$(4\pi)^2\beta_{g_V} \equiv (4\pi)^2\,\frac{\mathrm{d}g_V(\mu)}{\mathrm{d}\ln\mu} = \frac{2}{3}g_V^3$$

Other benchmarks


$\sin\xi = 0.1, m_{h'} = 300\ \mathrm{GeV}, m_{s_-} = 1.5 m_{\mathrm{DM}}, m_{Z'} = 3 m_{\mathrm{DM}}$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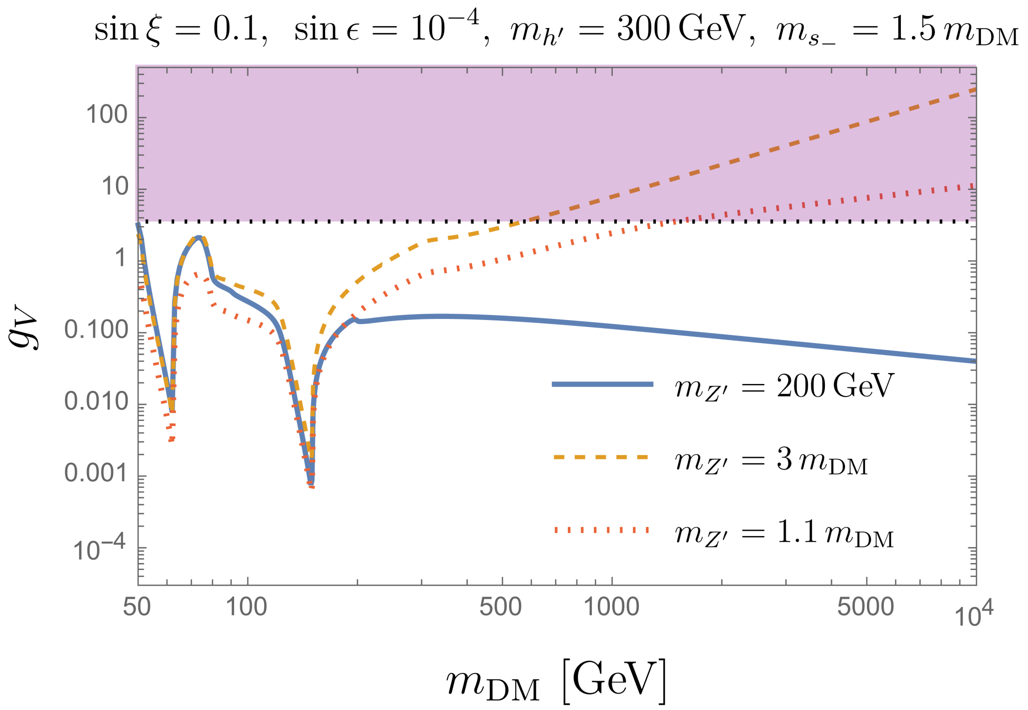
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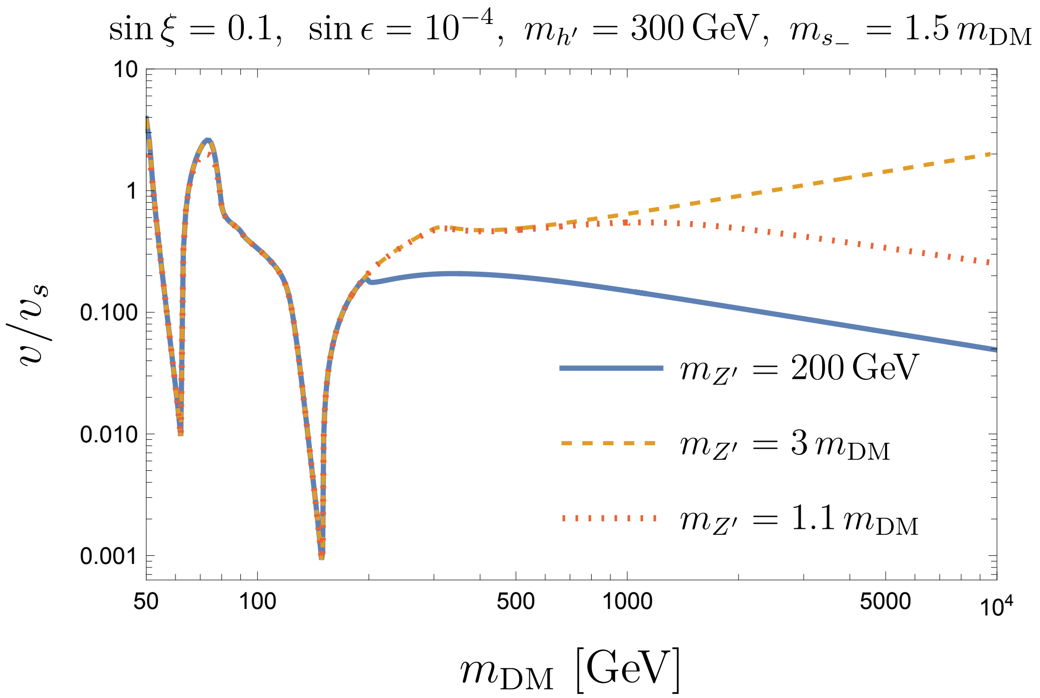
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DM relic vs Direct detection

Keep annihilation rate

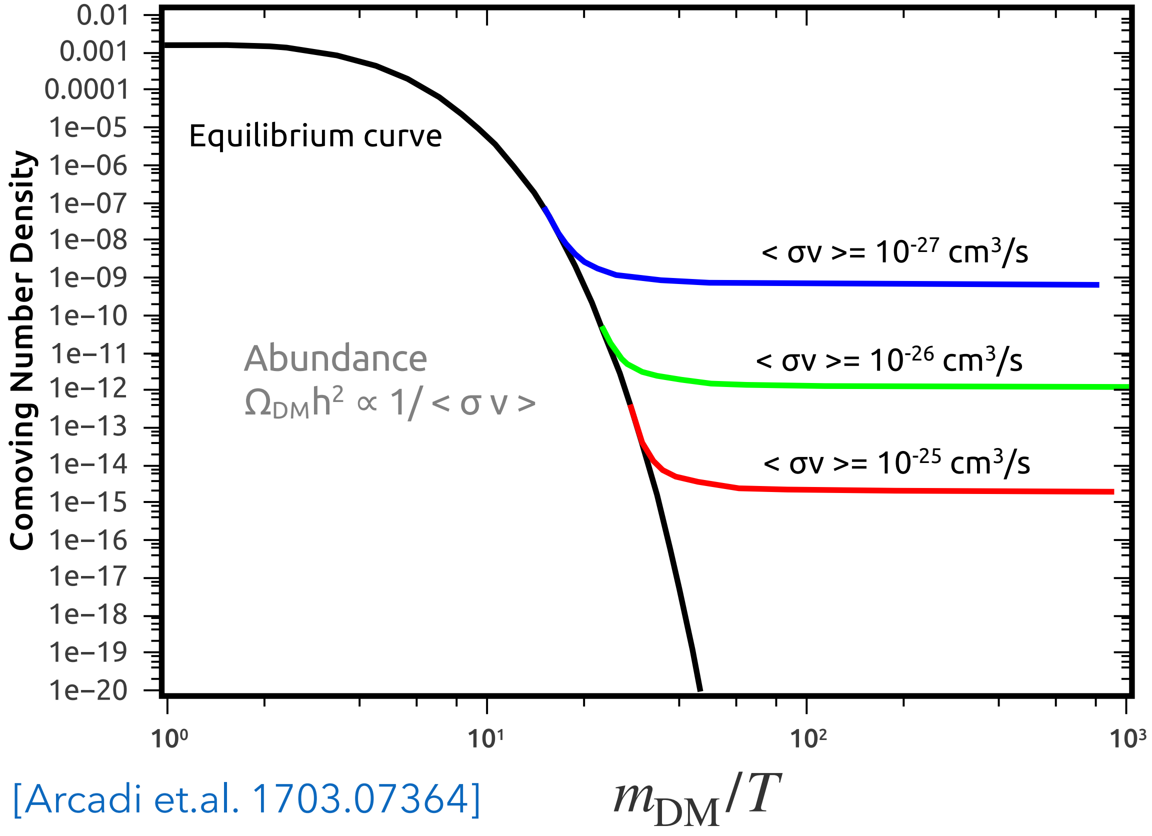
(DM relic)

$$\langle \sigma v \rangle \sim 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \sim 10^{-19}\,\mathrm{cm}^2$$

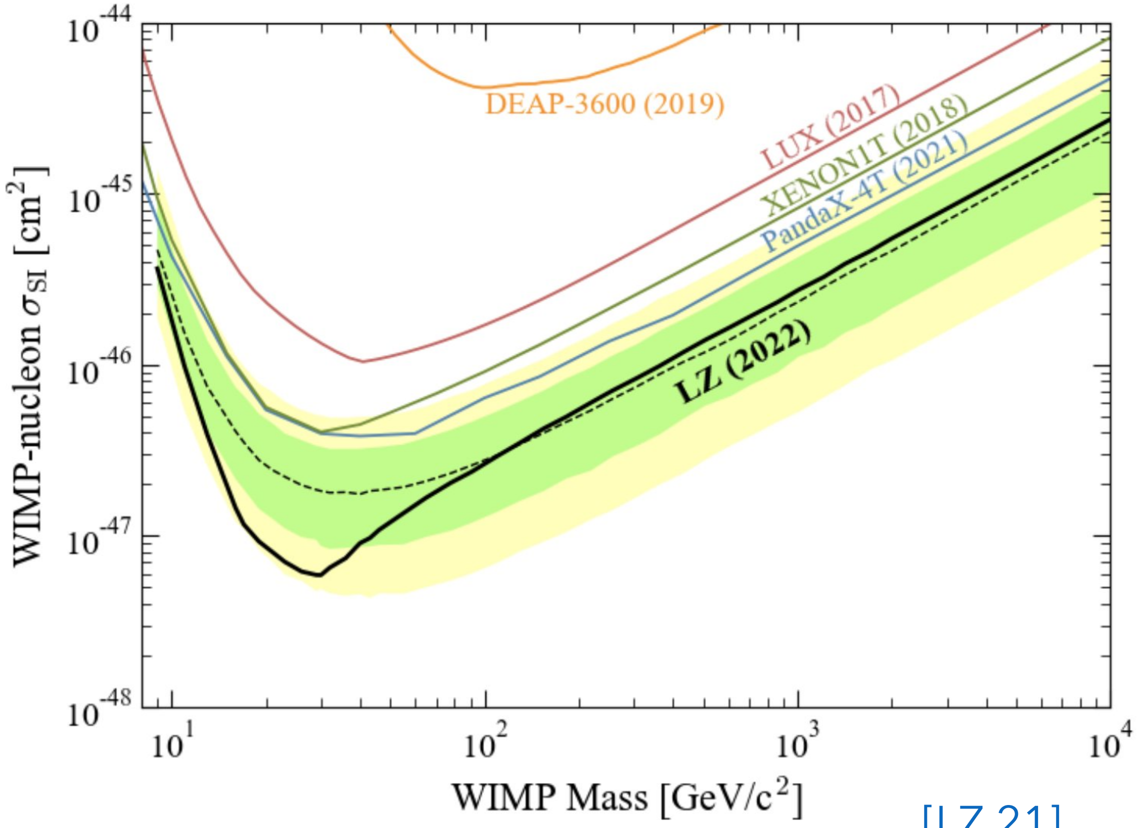
Suppress SI cross section

(direct detection)

$$\sigma_{\mathrm{SI}} \lesssim 10^{-47}\,\mathrm{cm}^2$$



[Arcadi et.al. 1703.07364]



[LZ 21]

seems incompatible → needs some trick!

$\mathcal{O}(4)$ symmetric limit

- assuming $\lambda_1 = \lambda_3$,

$$V(H,\phi_+,\phi_-) = m_1^2(|\phi_+|^2 + |\phi_-|^2) - m_{12}^2(|\phi_+|^2 - |\phi_-|^2) \\ + \frac{\lambda_1}{2}\left(|\phi_+|^2 + |\phi_-|^2\right)^2 \\ - m_H^2|H|^2 + \lambda_H|H|^4 + \lambda_{H1}|H|^2\left(|\phi_+|^2 + |\phi_-|^2\right)$$

- emergent $\mathcal{O}(4)$ symmetry (softly broken by m_{12}^2)

→ degeneracy $m_{s_-} = m_{\mathrm{DM}}$

- stable DM: $\phi_- = \frac{1}{\sqrt{2}}(s_- + ia)$

→ equivalent to previous model (Abe-Hamada)