擬南部-ゴールドストン暗黒物質とゲージ化された$U(1)_{B-L}$対称性

阿部慶彦
(京都大学)

共同研究者
藤間崇(金沢大学), 津村浩二(九州大学)

Based on JHEP05(2020)057[arXiv:2001.03954 [hep-ph]]

09/24/2020@Summer camp on ILC accelerator, physics and detectors 2020 (Online)

Pseudo-Nambu-Goldstone dark matter from *gauged* $U(1)_{B-L}$ symmetry

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Collaboration with

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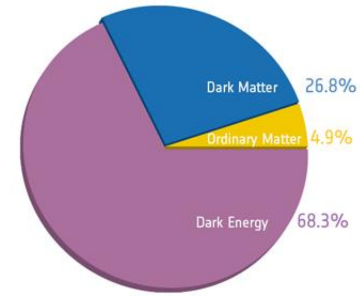
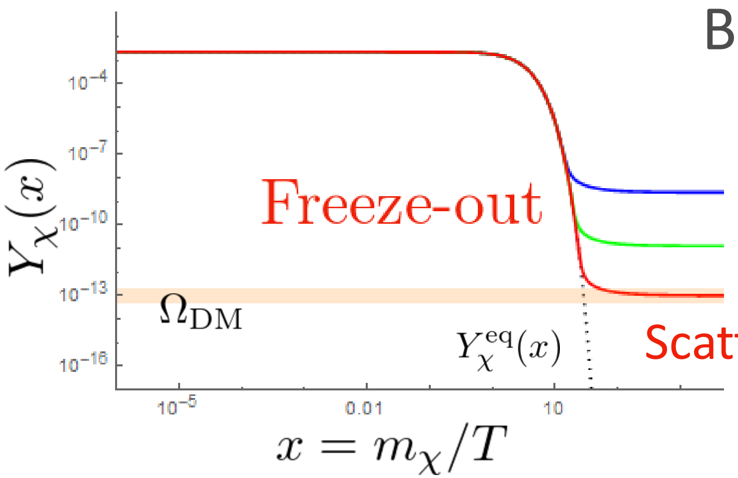
WIMP dark matter



- Dark matter
  - The existence of dark matter is inferred from various observations.
  - The nature of dark matter is still unknown.
  - Identification of dark matter ⇒ BSM

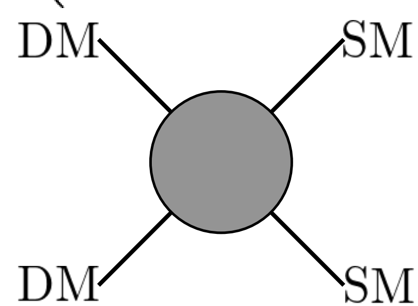
- WIMP dark matter
  - Dark matter relic abundance is realized as the thermal relic



Boltzmann equation for WIMP

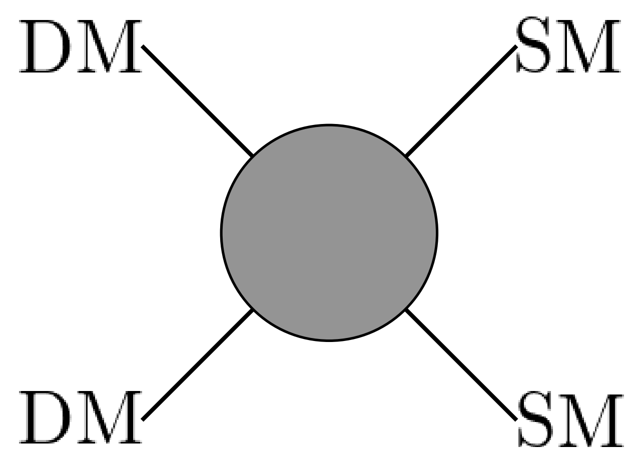
$$\frac{dY_\chi(x)}{dx} = \frac{\langle \sigma v \rangle s}{xH}\left(Y_\chi(x)^2 - Y_\chi^{\rm eq}(x)^2\right)$$

Scattering vs. Hubble

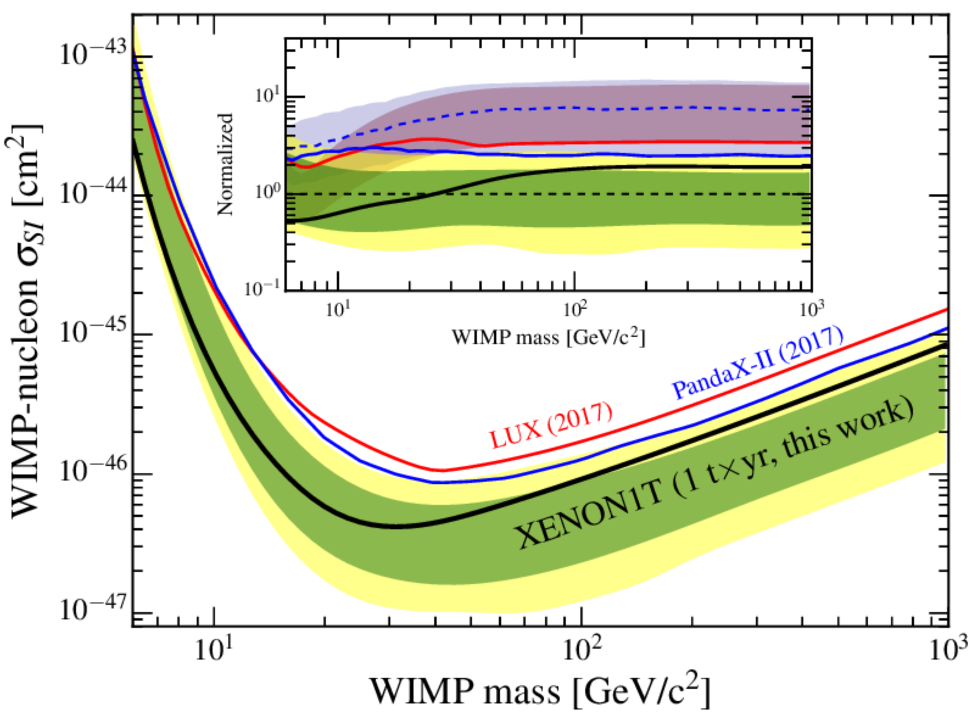


Direct detection experiments

- Direct detection experiments
  LUX, PandaX-II, XENON
  ⇒ **Severe constraints** on the the WIMP-nucleon cross section



Nuclear recoil by dark matter



XENON collaboration (2018)

① Pseudo-Nambu-Goldstone Dark Matter

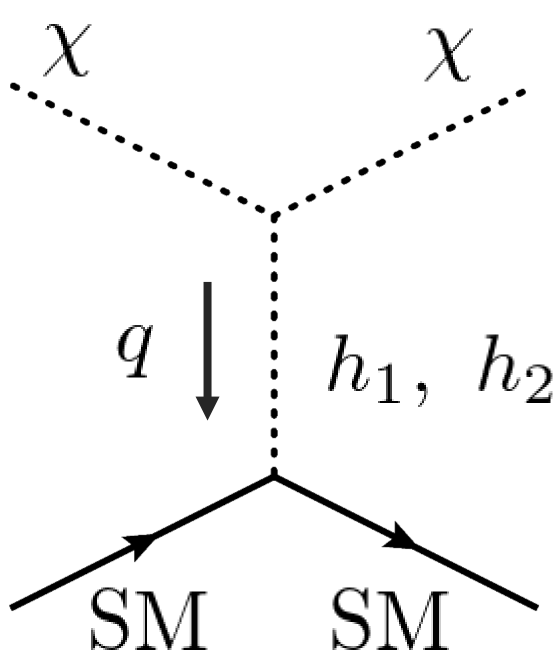
[Gross-Lebedev-Toma (2017),...]

- SM + singlet scalar S

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

Soft breaking term ⇒ creating DM mass

DM: $\chi = \sqrt{2}\,\mathrm{Im}(S)$



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

Scattering amplitude

$$i\mathcal{M} \sim -\frac{\sin\theta\cos\theta(m_{h_1}^2 - m_{h_2}^2)}{v_s m_{h_1}^2 m_{h_2}^2} q^2 \xrightarrow[q^2 \to 0]{} 0$$

Cf. soft pion theorem

Our motivation

- What is the origin for the soft breaking term?

$$V_{\rm soft}(H,S) = -\frac{m^2}{4}(S^2 + S^{*2}) \qquad U(1)_S \to \mathbb{Z}_2$$

Other term? Renormalizability? Symmetry?

- What is the UV physics of the pNGB dark matter model?

Our assumptions

- Renormalizable field theoretic description
- The *symmetry* of the UV physics maybe *gauge symmetry*

  (discrete symmetry should be gauged)

No global symmetry, landscape, swampland [Banks-Seiberg (2010)]

②

Gauged $U(1)_{B-L}$ model

[YA-Toma-Tsumura (2020), Okada-Raut-Shafi (2020)]

- Gauged $U(1)_{B-L}$ model

	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	$+1$	$+1$	$+2$

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

Ordinary $U(1)_{B-L}$ model

SM

Giving Majorana masses
$\Rightarrow$ type-I see-saw

+ RHν's ν_R + New gauge boson X_μ + Singlet scalar Φ

+ Singlet scalar S ← **New !!**

pNGB dark matter from gauged $U(1)_{B-L}$ model

- Intuitive story of our gauged $U(1)_{B-L}$ model

$$V(H,S,\Phi) = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 - \frac{\mu_\Phi^2}{2}|\Phi|^2 + \frac{\lambda_H}{2}|H|^4 + \frac{\lambda_S}{2}|S|^4 + \frac{\lambda_\Phi}{2}|\Phi|^4 + \lambda_{HS}|H|^2|S|^2 + \lambda_{H\Phi}|H|^2|\Phi|^2 + \lambda_{S\Phi}|S|^2|\Phi|^2 - \left(\frac{\mu_c}{\sqrt{2}}\Phi^* S^2 + \text{c.c.}\right)$$

Energy scale

$v_\phi \sim 10^{13}$ GeV: $U(1)_{B-L}$ is broken by v_ϕ $\quad |d\Phi + 2ig_{B-L}X|^2$

$\tilde{\chi}$ is eaten by $X_\mu \Rightarrow X_\mu$ becomes massive $m_X \sim v_\phi$

pNGB dark matter from gauged $U(1)_{B-L}$ model

- Intuitive story of our gauged $U(1)_{B-L}$ model

$$V(H,S,\langle\Phi\rangle) = -\frac{\mu_H^2}{2}|H|^2 + \frac{\lambda_{H\Phi}v_\phi^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_{S\Phi}v_\phi^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \frac{\lambda_S}{2}|S|^4$$
$$+ \lambda_{HS}|H|^2|S|^2 - \left(\frac{\mu_c v_\phi}{2}S^2 + \frac{\mu_c v_\phi}{2}S^{*2}\right)$$

Energy scale

$v_\phi \sim 10^{13}$ GeV: $U(1)_{B-L}$ is broken by v_ϕ $|d\Phi + 2ig_{B-L}X|^2$

$\tilde{\chi}$ is eaten by $X_\mu \Rightarrow X_\mu$ becomes massive $m_X \sim v_\phi$

$\approx$ Large VEV hierarchy ~ heavy particles decouple X_μ, ϕ

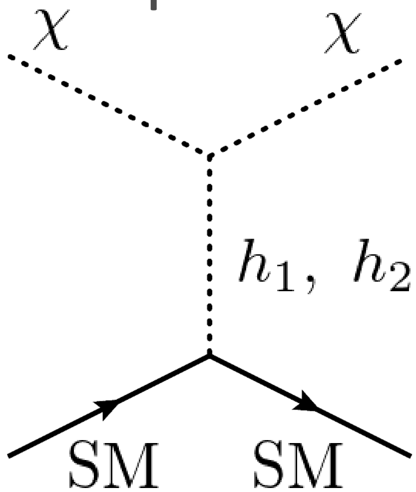
$v_s \sim$ TeV SM + singlet scalar S with S^2 term

$\Rightarrow$ pNGB dark matter χ + second Higgs h_2

$v \sim 246$ GeV (+ heavy particles effect through the mixings)

pNGB dark matter from gauged $U(1)_{B-L}$ model

- Amplitude for DM + SM → DM +SM



$$\kappa_{\chi\chi h_1} \approx -\frac{m_{h_1}^2 \sin\theta}{v_s}, \quad \kappa_{\chi\chi h_2} \approx +\frac{m_{h_2}^2 \cos\theta}{v_s},$$

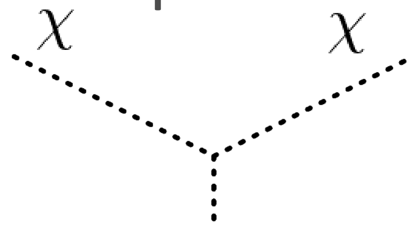
$$\kappa_{\chi\chi h_3} \approx +\frac{m_{h_3}^2}{v_s}\frac{\lambda_{S\Phi} v_s}{\lambda_\Phi v_\phi}$$

$$i\mathcal{M} \propto \frac{\sin\theta\cos\theta}{v_s}\left(-\frac{m_{h_1}^2}{q^2 - m_{h_1}^2} + \frac{m_{h_2}^2}{q^2 - m_{h_2}^2}\right) + \mathcal{O}(1/v_\phi)$$

The scattering amplitudes are suppressed in the same way as pNGB model in order $\mathcal{O}(1/v_\phi)$.

pNGB dark matter from gauged $U(1)_{B-L}$ model

- Amplitude for DM + SM → DM +SM



$$\kappa_{\chi\chi h_1} \approx -\frac{m_{h_1}^2 \sin\theta}{v_s}, \quad \kappa_{\chi\chi h_2} \approx +\frac{m_{h_2}^2 \cos\theta}{v_s},$$

Pseudo-Nambu-Goldstone dark matter from gauged $U(1)_{B-L}$ symmetry

$$v_s \quad \left(\quad q^2 - m_{h_1} \quad\quad q^2 - m_{h_2} \right)$$

The scattering amplitudes are suppressed in the same way as pNGB model in order $\mathcal{O}(1/v_\phi)$.

Long-lived Dark Matter

- Our DM χ is not stabilized due to the new interactions and scalar mixings.

- Constraints of our model from a conservative limit of the DM life-time
[Baring-Ghosh-Queiroz-Sinha (2015)]

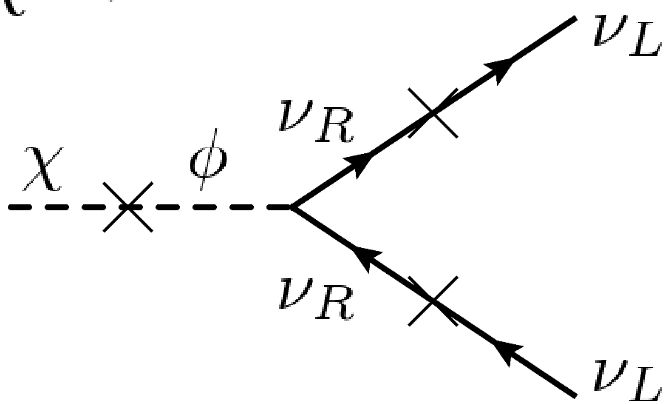
$$\tau_{\rm DM} \gtrsim 10^{27}\ {\rm s} \quad \Leftrightarrow \quad \Gamma_{\rm DM} \lesssim 6.6 \times 10^{-52}\ {\rm GeV}$$

- We have to check the decay cannels of this pNGB DM and calculate the decay widths.

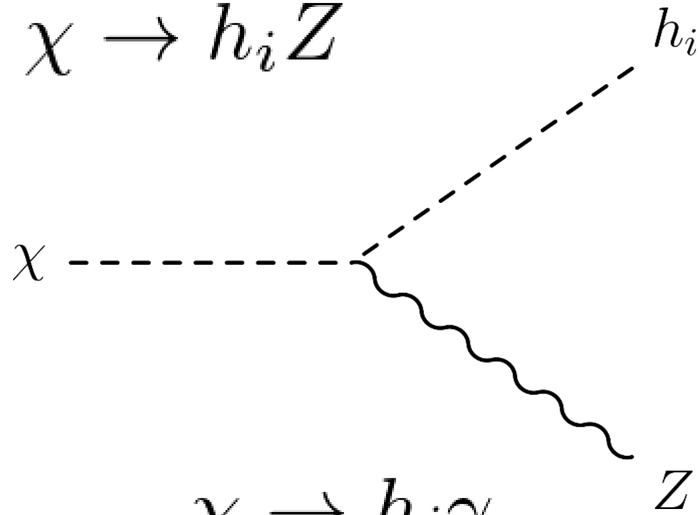
Long-lived DM

Two-body decay

$\chi \to \nu\nu$



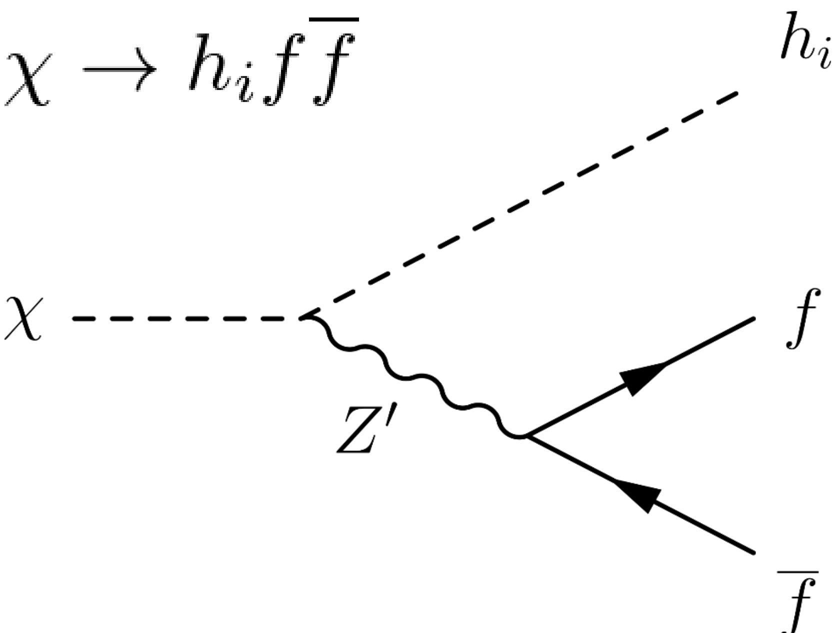
$\chi \to h_i Z$



$\chi \to h_i \gamma$

Three-body decay

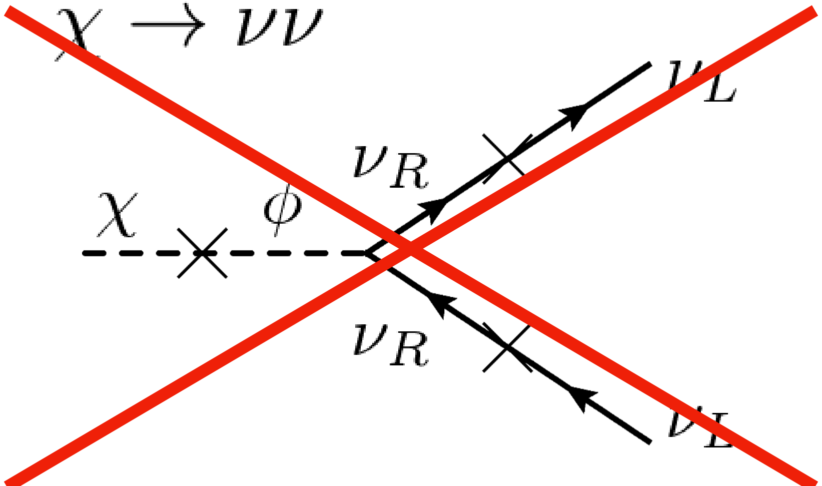
$\chi \to h_i f \overline{f}$



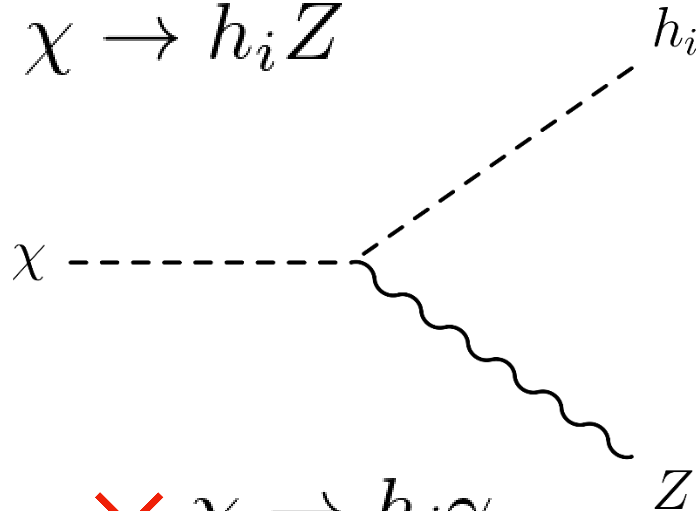
Long-lived DM

Two-body decay

~~$\chi \to \nu\nu$~~



$\chi \to h_i Z$

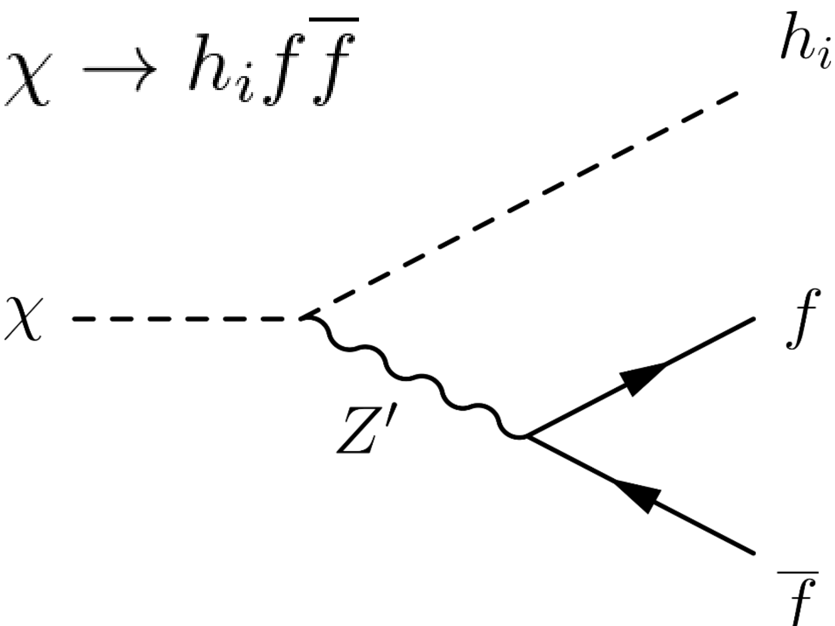


✕ $\chi \to h_i \gamma$

☹ helicity conservation

Three-body decay

$\chi \to h_i f \overline{f}$



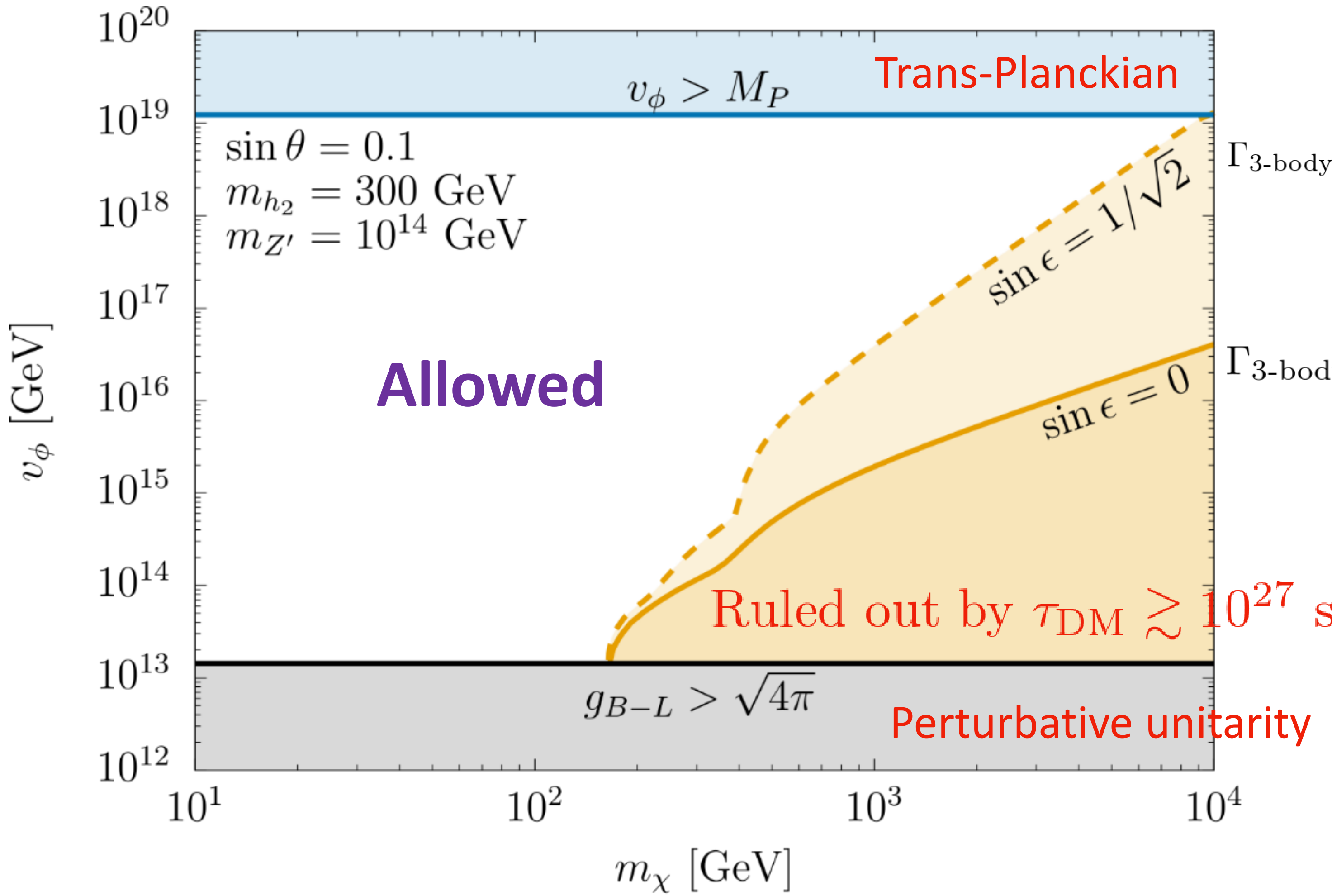
$$\Gamma_{\text{2-body}} \propto m_\chi^3$$

$$\Gamma_{\text{3-body}} \propto m_\chi^5$$

Allowed region in the (m_χ, v_ϕ) plane

$$m_{h_2} = 300\ \text{GeV}, \quad m_{Z'} = 10^{14}\ \text{GeV}$$

$$-\frac{\sin\epsilon}{2} B_{\mu\nu} X^{\mu\nu}$$

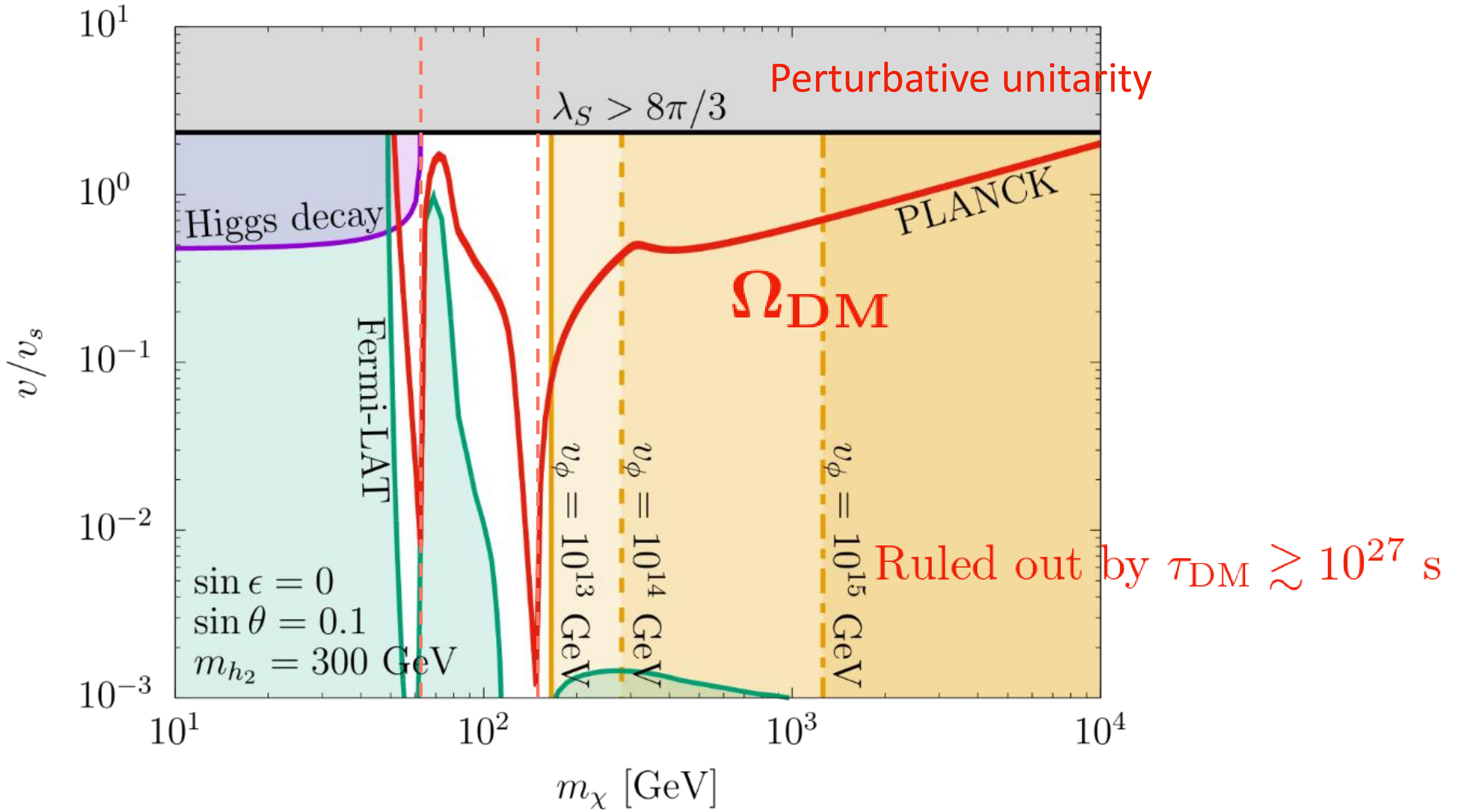


$$\Gamma_{3\text{-body}}\big|_{\sin\epsilon\to 1/\sqrt{2}} \propto \frac{m_\chi^5}{v_\phi^2}$$

$$\Gamma_{3\text{-body}}\big|_{\sin\epsilon\to 0} \propto \frac{m_\chi^5}{v_\phi^4}$$

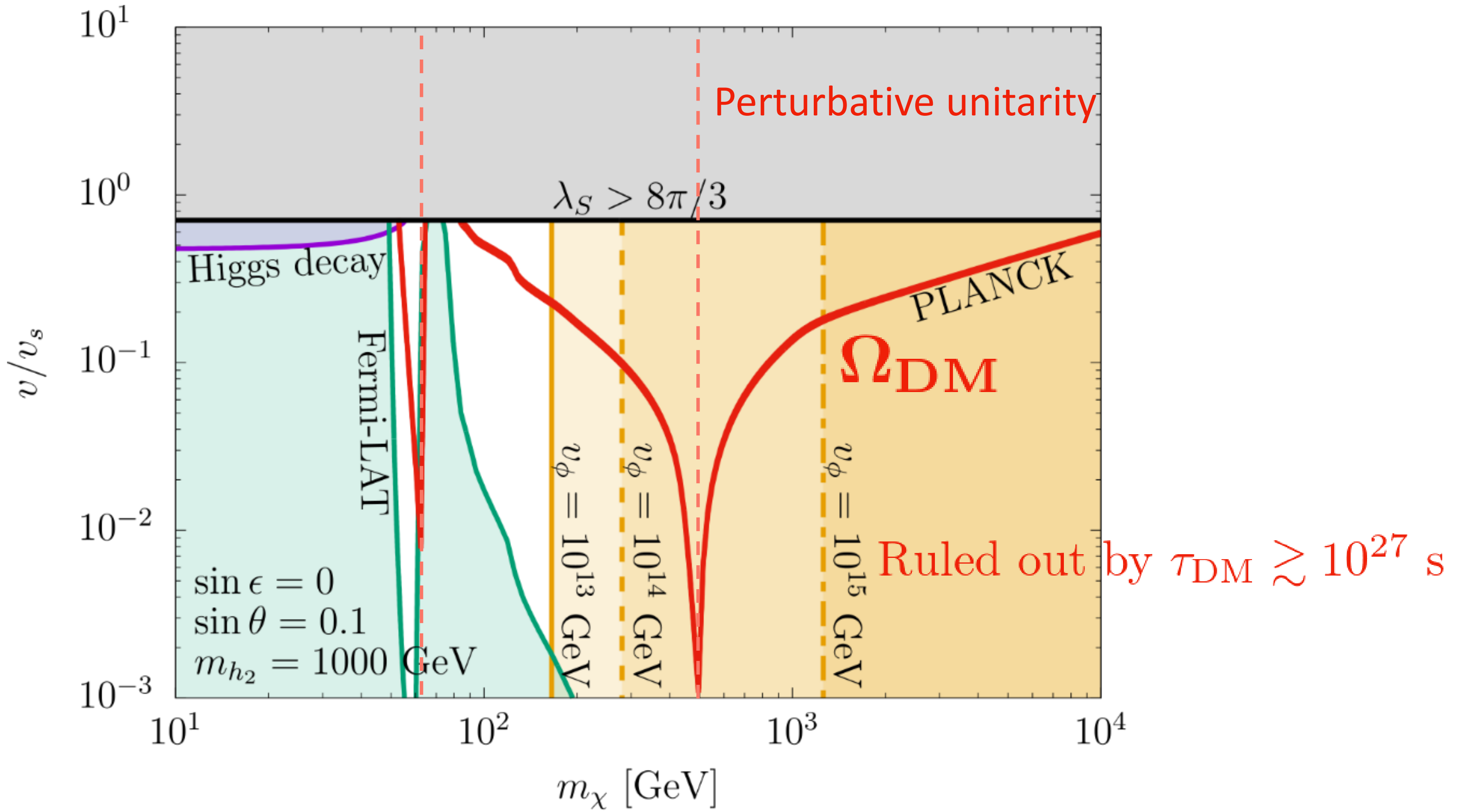
Allowed region in the $(m_\chi, v/v_s)$ plane

$$m_{h_2} = 300\ \text{GeV}, \quad \sin\epsilon = 0$$



Allowed region in the $(m_\chi, v/v_s)$ plane

$$m_{h_2} = 1000\ \text{GeV}, \quad \sin\epsilon = 0$$



Summary

- We studied the pNGB dark matter scenario derived from the *gauged* $U(1)_{B-L}$ model.

- This is the decaying dark matter then we showed the life-time is long enough to be dark matter.

- We have found the parameter space consistent with the relevant constraints.

- This model can be explored by the planned gamma-ray observations.

e.g. CTA, LHASSO

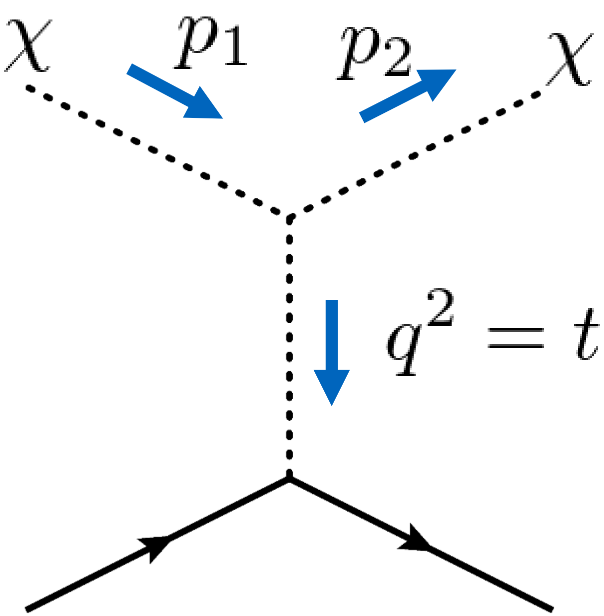
Backup

Nature of interactions of (p)NGBs

- Toy model $$S = \frac{v_s + s}{\sqrt{2}} e^{i\chi/v_s}$$ Non-linear rep.

$$\mathcal{L} \supset |\partial_\mu S|^2 + |\partial_\mu H|^2 - \lambda_{HS}|H|^2|S|^2 - \frac{m^2}{4}\left(S^2 + S^{*2}\right)$$

$$\sim \underline{\frac{1}{2}\left(1 + \frac{\phi}{v_s}\right)^2 \left((\partial_\mu \chi)^2 - m^2\chi^2\right)} - \lambda_{HS} v_s s |H|^2$$



$$i\mathcal{M} \supset \lambda_{HS} \frac{\left((-ip_1)\cdot(ip_2) - m^2\right)}{t - m_s^2}$$

$$\sim \lambda_{HS} \frac{t}{t - m_s^2}$$

$$\lim_{t \to 0} \mathcal{M} = 0$$

Boltzmann equation

- Boltzmann equation for dark matter $Y_\chi(x) = n_\chi/s, \quad x = m_\chi/T$

$$\frac{dY_\chi(x)}{dx} = -\frac{\langle\sigma v\rangle}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\left(Y_\chi(x)^2 - Y_\chi^{\mathrm{eq}}(x)^2\right)$$

$$s(T) = \frac{2\pi^2}{45}g_*^S T^3, \quad H(T) = \sqrt{\frac{4\pi^3}{45}g_*}\frac{T^2}{M_P}$$

$$Y_\chi^{\mathrm{eq}} = n_\chi^{\mathrm{eq}}/s, \quad n_\chi^{\mathrm{eq}} = \frac{m_\chi^2 T^2}{2\pi^2}K_2(m_\chi/T)$$

$$\langle\sigma v\rangle = \frac{1}{n_\chi^{\mathrm{eq}2}}\frac{1}{2^5\pi^4}\left(\frac{m_\chi}{x}\right)\int_{4m_\chi^2}^{\infty} ds\,(s-4m_\chi^2)\sqrt{s}K_1(x\sqrt{s}/m_\chi)\sigma(s)$$

σ: Total dark matter annihilation cross section

Gauged $U(1)_{B-L}$ model

Lagrangian

- Covariant derivative

$$D_\mu = D_\mu^{\rm SM} + i g_{B-L} X_\mu$$

- Kinetic term of new sectors

Gauge kinetic mixing

$$\mathcal{L}_K = |D_\mu S|^2 + |D_\mu \Phi|^2 + \overline{\nu_R} i \not{D} \nu_R - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin\epsilon}{2} X_{\mu\nu} B^{\mu\nu}$$

- Yukawa interactions among SM leptons, RHν's and scalars

$$\mathcal{L}_Y = -(y_\nu)_{ij} \tilde{H}^\dagger \overline{\nu_{Ri}} L_j - \frac{(y_\Phi)_{ij}}{2} \Phi \overline{\nu_{Ri}^c} \nu_{Rj} + \text{h.c.}$$

Giving Majorana masses

- Scalar potential

$$V(H,S,\Phi) = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 - \frac{\mu_\Phi^2}{2}|\Phi|^2 + \frac{\lambda_H}{2}|H|^4 + \frac{\lambda_S}{2}|S|^4 + \frac{\lambda_\Phi}{2}|\Phi|^4$$
$$+ \lambda_{HS}|H|^2|S|^2 + \lambda_{H\Phi}|H|^2|\Phi|^2 + \lambda_{S\Phi}|S|^2|\Phi|^2 - \left(\frac{\mu_c}{\sqrt{2}}\Phi^* S^2 + \text{c.c.}\right)$$

Scalar sector

- Parametrization

$$H = \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}, \quad S = \frac{v_s + s + i\eta_s}{\sqrt{2}}, \quad \Phi = \frac{v_\phi + \phi + i\eta_\phi}{\sqrt{2}}$$

- Type-I see-saw mechanism identifies the scale of VEV v_ϕ.

$$\boxed{v_\phi \sim 4.3 \times 10^{14}\ \mathrm{GeV}\left(\frac{y_\nu^2}{y_\Phi}\right)} \gg v,\ v_s$$

- Masses of the heaviest CP-even scalar ϕ and massive vector boson Z'_μ

$$m_\phi,\ m_{Z'} \sim v_\phi$$

Mass spectrum of scalar sectors

- Mass eigenstates

$$\tan 2\theta \approx \frac{2vv_s(\lambda_{HS}\lambda_\Phi - \lambda_{H\Phi}\lambda_{S\Phi})}{v^2(\lambda_{H\Phi}^2 - \lambda_H\lambda_\Phi) - v_s^2(\lambda_{S\Phi}^2 - \lambda_S\lambda_\Phi)}$$

  - CP-even scalars

SM-like Higgs boson

$$\begin{pmatrix} h \\ s \\ \phi \end{pmatrix} \approx \begin{pmatrix} 1 & 0 & \frac{\lambda_{H\Phi}v}{\lambda_\Phi v_\phi} \\ 0 & 1 & \frac{\lambda_{S\Phi}v_s}{\lambda_\Phi v_\phi} \\ -\frac{\lambda_{H\Phi}v}{\lambda_\Phi v_\phi} & -\frac{\lambda_{S\Phi}v_s}{\lambda_\Phi v_\phi} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

$$m_{h_1}^2 \approx \lambda_H v^2 - \frac{\lambda_{H\Phi}^2\lambda_S - 2\lambda_{HS}\lambda_{H\Phi}\lambda_{S\Phi} + \lambda_\Phi\lambda_{HS}^2}{\lambda_{S\Phi} - \lambda_{S\Phi}^2}v^2,$$ ← 125 GeV

$$m_{h_2}^2 \approx \frac{\lambda_S\lambda_\Phi - \lambda_{S\Phi}^2}{\lambda_\Phi}v_s^2 + \frac{(\lambda_\Phi\lambda_{HS} - \lambda_{H\Phi}\lambda_{S\Phi})^2}{\lambda_\Phi(\lambda_S\lambda_\Phi - \lambda_{S\Phi}^2)}v^2, \quad m_{h_3}^2 \approx \lambda_\Phi v_\phi^2$$

  - CP-odd scalars

pNGB (dark matter)

$$\begin{pmatrix} \eta_s \\ \eta_\phi \end{pmatrix} = \frac{1}{(v_s^2 + 4v_\phi^2)^{1/2}} \begin{pmatrix} 2v_\phi & v_s \\ -v_s & 2v_\phi \end{pmatrix} \begin{pmatrix} \chi \\ \tilde{\chi} \end{pmatrix}$$

Eaten by X_μ

$$m_\chi^2 = \frac{\mu_c(v_s^2 + 4v_\phi^2)}{4v_\phi}$$

Gauge kinetic mixing

$SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ gauge group

- Kinetic term

$$\mathcal{L}_{GK} = -\frac{1}{2}\mathrm{tr}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sin\epsilon}{2}B_{\mu\nu}X^{\mu\nu}$$

- Mass term

$$\mathcal{L}_M = \frac{1}{2}\begin{pmatrix} B_\mu & W^3_\mu X_\mu \end{pmatrix}\begin{pmatrix} \sin^2\theta_W m_{\tilde{Z}}^2 & -\sin\theta_W\cos\theta_W m_{\tilde{Z}}^2 & 0 \\ -\sin\theta_W\cos\theta_W m_{\tilde{Z}}^2 & \cos^2\theta_W m_{\tilde{Z}}^2 & 0 \\ 0 & 0 & m_X^2 \end{pmatrix}\begin{pmatrix} B^\mu \\ W^{3\mu} \\ X^\mu \end{pmatrix}$$

$$\sin\theta_W \equiv \frac{g_1}{\sqrt{g_1^2+g_2^2}}, \quad \cos\theta_W \equiv \frac{g_2}{\sqrt{g_1^2+g_2^2}},$$

$$m_{\tilde{Z}}^2 \equiv \frac{g_1^2+g_2^2}{4}v^2, \quad m_X^2 \equiv g_{B-L}^2(v_s^2+4v_\phi^2)$$

Gauge kinetic mixing

$SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ gauge group

- Mixing

$$\tilde{V}_{GK} = \begin{pmatrix} 1 & 0 & -\tan\epsilon \\ 0 & 1 & 0 \\ 0 & 0 & 1/\cos\epsilon \end{pmatrix}, \qquad \tan 2\zeta = \frac{-m_{\tilde{Z}}^2 \sin_W \sin 2\epsilon}{m_X^2 - m_{\tilde{Z}}^2(\cos^2\epsilon - \sin^2\theta_W \sin^2\epsilon)}$$

$$U_G = \begin{pmatrix} \cos\theta_W & -\sin\theta_W & 0 \\ \sin\theta_W & \cos\theta_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\zeta & -\sin\zeta \\ 0 & \sin\zeta & \cos\zeta \end{pmatrix}$$

$$\begin{pmatrix} B_\mu \\ W_\mu^3 \\ X_\mu \end{pmatrix} = \tilde{V}_{GK} U_G \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

- Mass eigenvalues

$$m_Z^2 = \frac{1}{2}\left[\overline{M}^2 - \sqrt{\overline{M}^4 - \frac{4 m_{\tilde{Z}}^2 m_X^2}{\cos^2\epsilon}}\right], \quad m_{Z'}^2 = \frac{1}{2}\left[\overline{M}^2 - \sqrt{\overline{M}^4 + \frac{4 m_{\tilde{Z}}^2 m_X^2}{\cos^2\epsilon}}\right]$$

$$\overline{M}^2 \equiv m_{\tilde{Z}}^2(1 + \sin^2\theta_W \tan^2\epsilon) + m_X^2/\cos^2\epsilon$$

Interactions

- Scalar-dark matter-massive gauge boson

$$\mathcal{L}_{Zh_i\chi} = \sum_i g_{B-L} \frac{\sin\zeta}{\cos\epsilon} \frac{U_{si}}{\sqrt{1+v_s^2/4v_\phi^2}} Z_\mu (h_i \partial^\mu \chi - \chi \partial^\mu h_i),$$

$$\mathcal{L}_{Z'h_i\chi} = \sum_i g_{B-L} \frac{\cos\zeta}{\cos\epsilon} \frac{U_{si}}{\sqrt{1+v_s^2/4v_\phi^2}} Z'_\mu (h_i \partial^\mu \chi - \chi \partial^\mu h_i)$$

- Massive gauge boson-fermion

$$\mathcal{L}_{Z'\overline{f}f} = -Z'_\mu \overline{f} \gamma^\mu \left[g_V^f + g_A^f \gamma_5 \right] f$$

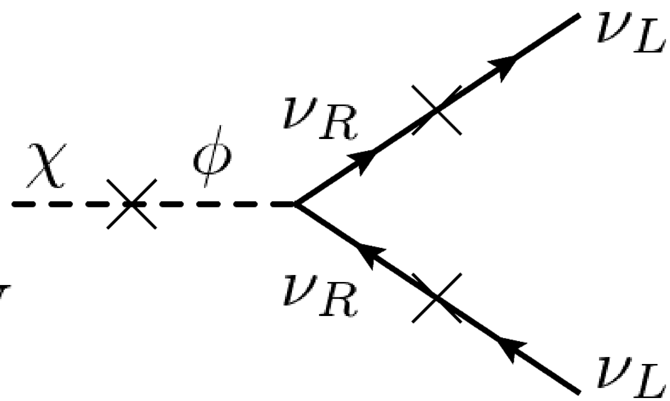
$$\begin{aligned} g_V^f =& -\frac{g_2}{2} T_3^f \sin\zeta \cos\theta_W + g_1 (Q_{\rm em}^f - F_3^f)(\sin\zeta \sin\theta_W - \cos\zeta \tan\epsilon) \\ & + g_{B-L} Q_{B-L}^f \frac{\cos\zeta}{\cos\epsilon}, \\ g_A^f =& \frac{g_2}{2} T_3^f \sin\zeta \cos\theta_W \end{aligned}$$

Long-lived dark matter

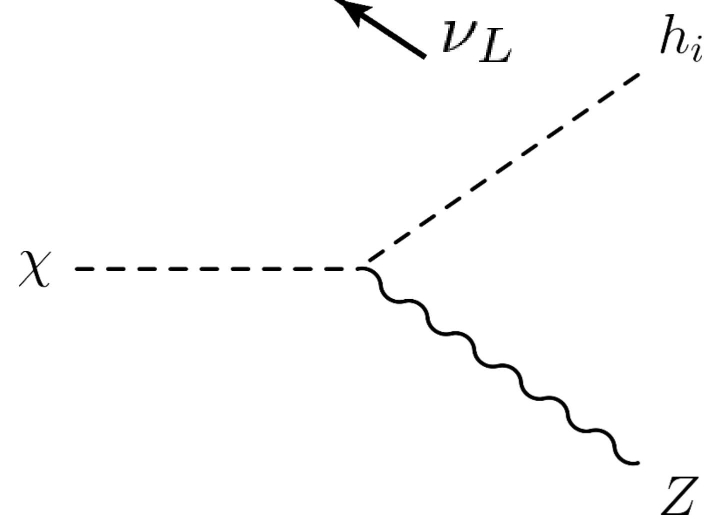
Two body decay

- $\chi \to \nu\nu$

$$\Gamma_{\chi\to\nu\nu} \lesssim 10^{-67}\ \text{GeV}$$



- $\chi \to h_i\, Z$



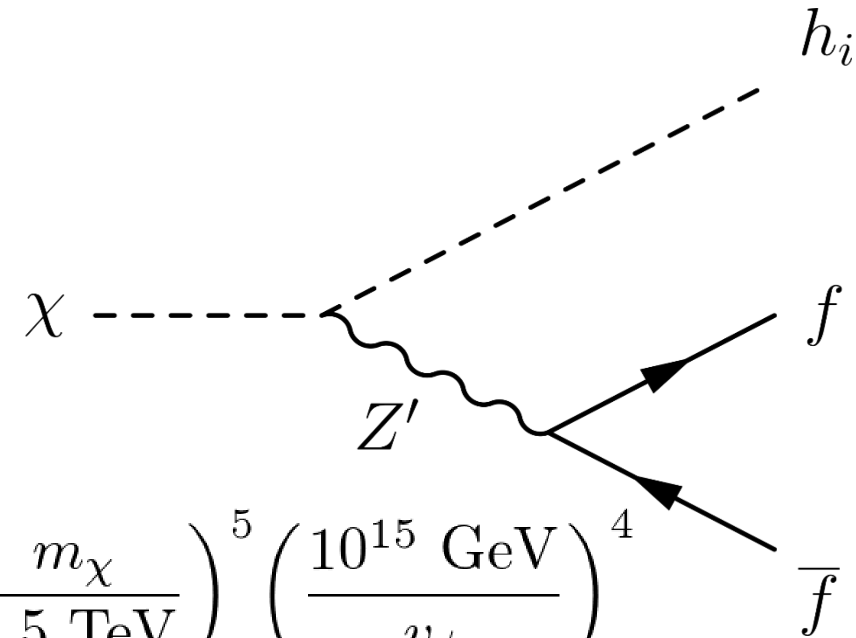
$$\Gamma_{\text{2-body}} \approx \frac{g_{B-L}^2}{16\pi m_{Z'}^4} m_Z^2 m_\chi^3 \sin^2\theta_W \sin^2\epsilon$$

$$= 5.8\times 10^{-52}\ \text{GeV} \left(\frac{m_\chi}{0.5\ \text{TeV}}\right)^3 \left(\frac{10^{15}\ \text{GeV}}{m_{Z'}}\right)^2 \left(\frac{10^{15}\ \text{GeV}}{v_\phi}\right)^2 \left(\frac{\sin\epsilon}{1/\sqrt{2}}\right)^2$$

Long-lived dark matter

Three body decay

- $\chi \to h_i f \bar{f}$



$$\Gamma_{3\text{-body}}\Big|_{\sin\epsilon\to 0} \approx \frac{13}{16}\frac{g_{B-L}^4}{1536\pi^3}\frac{m_\chi^5}{m_{Z'}^4}$$

$$\approx 5.3\times 10^{-52}\ \text{GeV}\left(\frac{m_\chi}{0.5\ \text{TeV}}\right)^5\left(\frac{10^{15}\ \text{GeV}}{v_\phi}\right)^4$$

$$\Gamma_{3\text{-body}}\Big|_{\sin\epsilon\to 1/\sqrt{2}} \approx \frac{g_{B-L}^2}{768\pi^3}\frac{m_\chi^5}{m_{Z'}^4}\left(10g_1^2 - 8\sqrt{2}g_1 g_{B-L} + 26 g_{B-L}^2\right)$$

$$\approx 4.1\times 10^{-52}\ \text{GeV}\left(\frac{m_\chi}{0.5\ \text{TeV}}\right)^5\left(\frac{10^{15}\ \text{GeV}}{m_{Z'}}\right)^2\left(\frac{10^{15}\ \text{GeV}}{v_\phi}\right)^2$$

$$\times\left[1 - \frac{2\sqrt{2}}{5}\frac{m_{Z'}}{g_1 v_\phi} + \frac{13}{20}\frac{m_{Z'}^2}{g_1^2 v_\phi^2}\right]$$

Numerical Analysis

Numerical Analysis

- Parameter sets

$$m_{h_2} = 300 \text{ or } 1000 \text{ GeV}, \quad m_{h_3} = 10^{13} \text{ GeV},$$

$$\sin\theta = 0.1, \quad \lambda_{H\Phi} = \lambda_{S\Phi} = 10^{-6}$$

$$m_{Z'} = 10^{14} \text{ or } 10^{15} \text{ GeV},$$

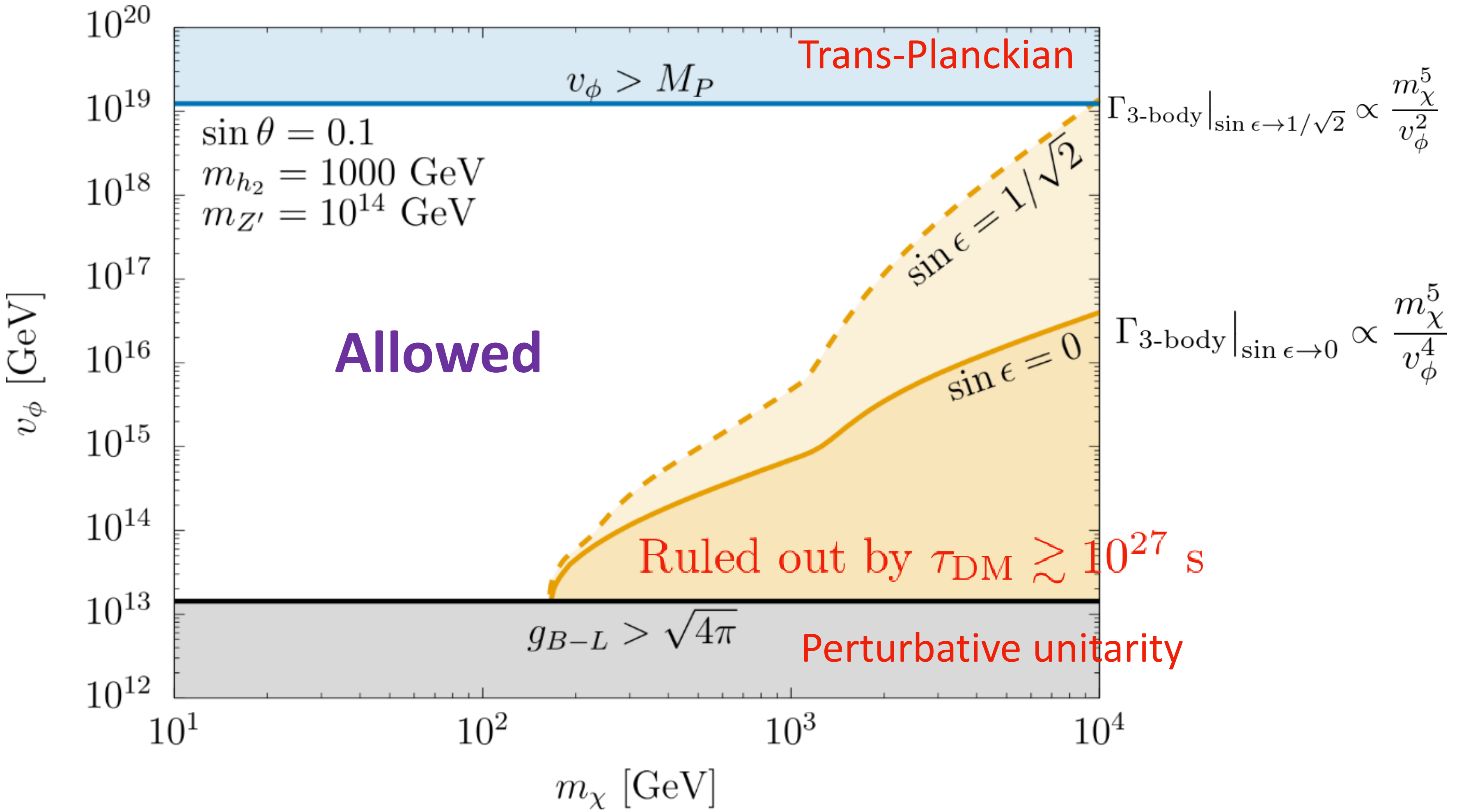
$$\sin\epsilon = 0 \text{ or } \frac{1}{\sqrt{2}}$$

B-L gauge coupling and quartic coupling are fixed by

$$g_{B-L}^2 \approx \frac{m_{Z'}^2}{4v_\phi^2}, \quad \lambda_\Phi \approx \frac{m_{h_3}^2}{v_\phi^2}$$

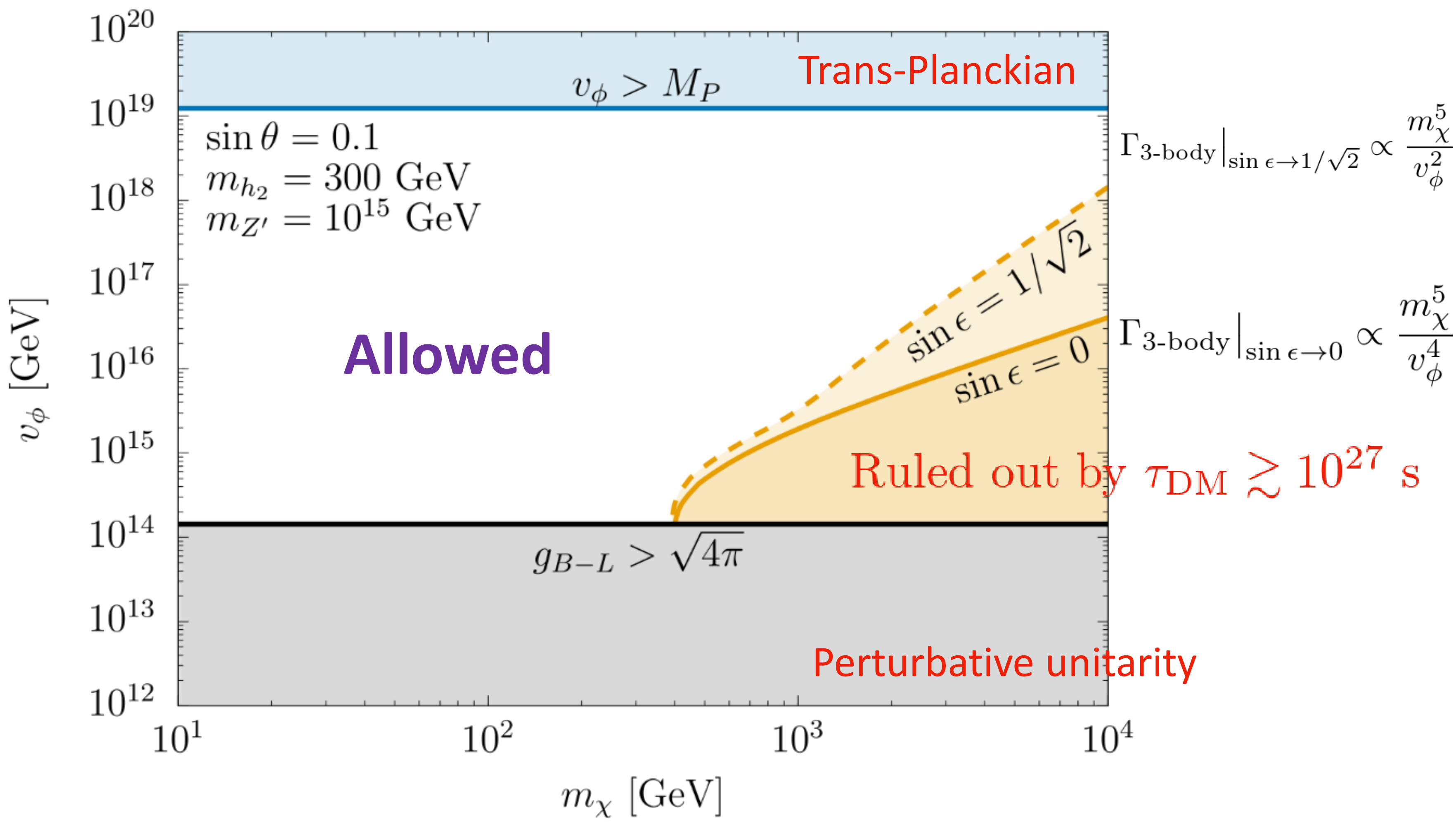
Allowed region in the (m_χ, v_ϕ) plane

$$m_{h_2} = 1000\ \text{GeV}, \quad m_{Z'} = 10^{14}\ \text{GeV}$$



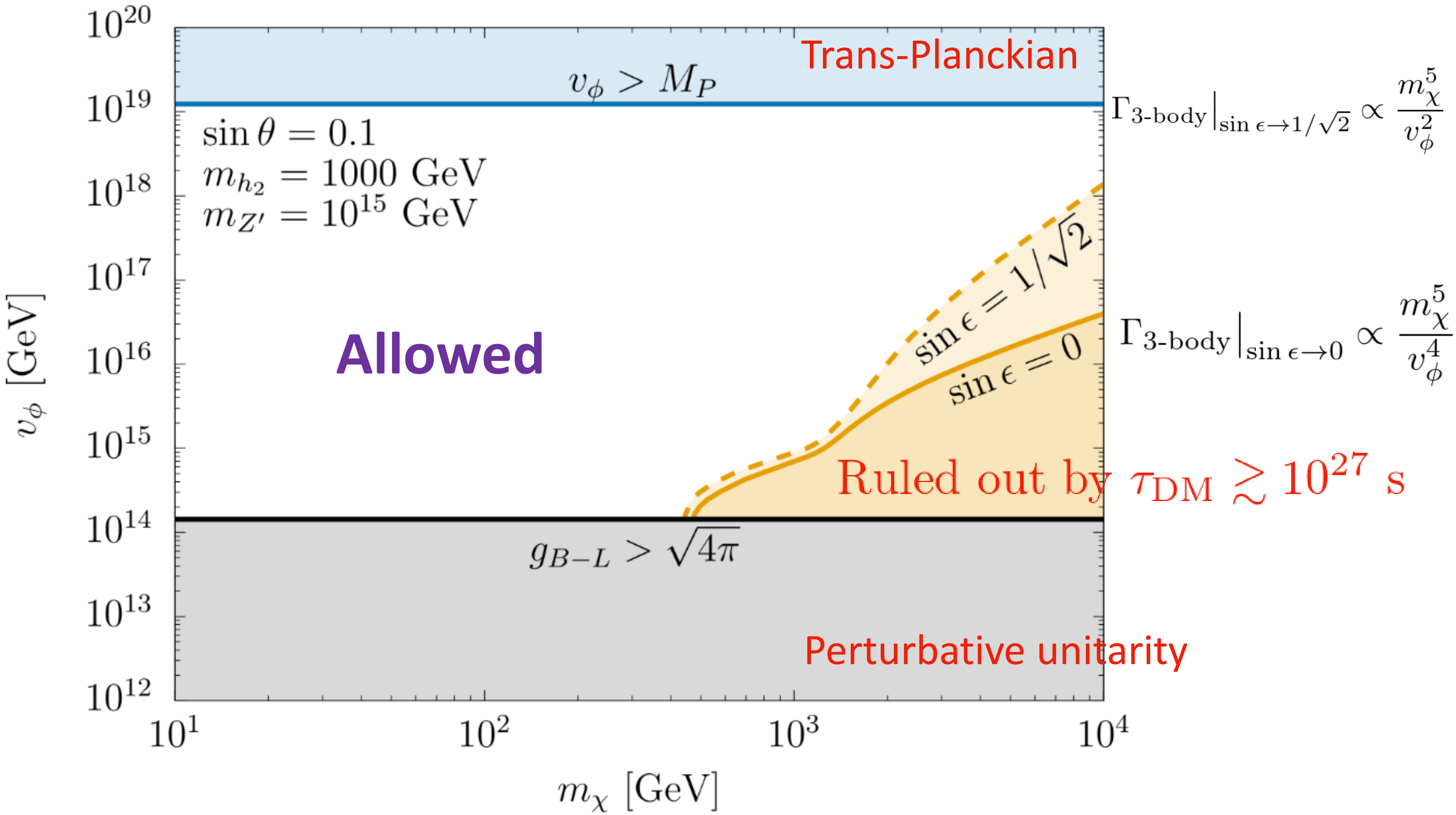
Allowed region in the (m_χ, v_ϕ) plane

$$m_{h_2} = 300\ \mathrm{GeV}, \quad m_{Z'} = 10^{15}\ \mathrm{GeV}$$



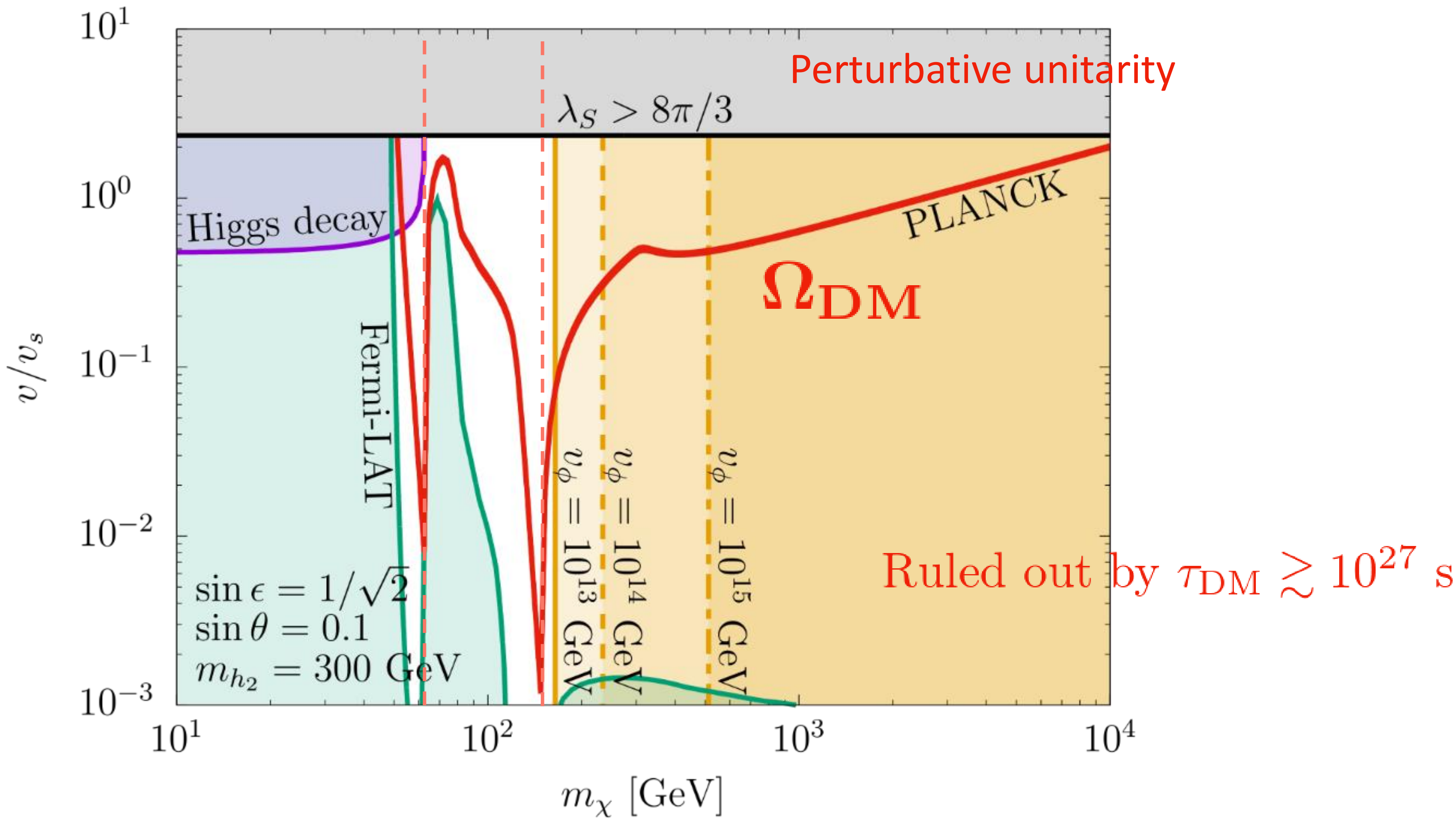
Allowed region in the (m_χ, v_ϕ) plane

$$m_{h_2} = 1000\ \text{GeV}, \quad m_{Z'} = 10^{15}\ \text{GeV}$$



Allowed region in the$(m_\chi, v/v_s)$plane

$$m_{h_2} = 300\ \mathrm{GeV}, \quad \sin\epsilon = 1/\sqrt{2}$$



Allowed region in the $(m_\chi, v/v_s)$ plane

$$m_{h_2} = 1000 \text{ GeV}, \quad \sin\epsilon = 1/\sqrt{2}$$