Freeze-in sterile neutrino dark matter in feeble gauged *B-L* model

Takashi Shimomura
(Miyazaki U.)

PRD 106, 103513 (2022) and arXiv:2024.00654

in collaboration with

Shintaro Eijima (Niigata U.), Osamu Seto (Hokkaido U.),
Yoshiki Uchida (South China Normal U.)

Long-Lived Particle2024@Tokyo U., 2024/7/2

Introduction

Two open questions in particle physics and cosmology

- Neutrino Mass
  - Very tiny compared with other SM particles

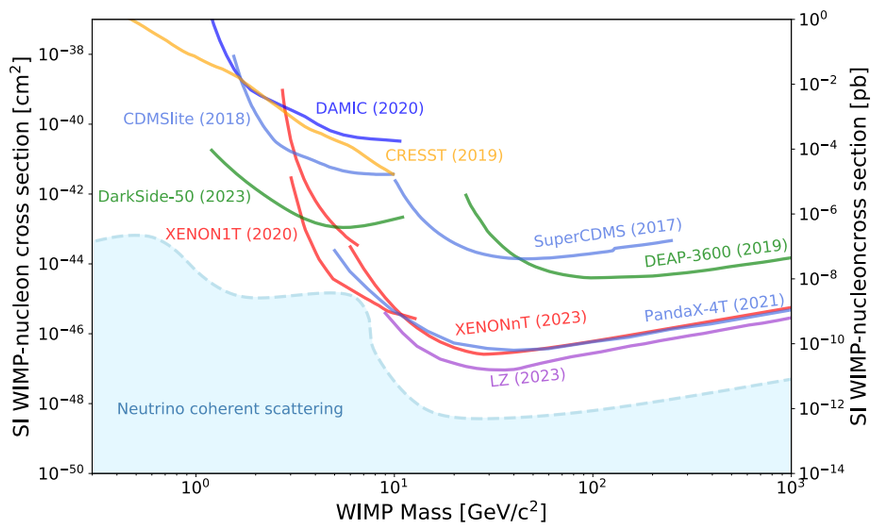
$$\Delta m^2_{12} = 7.53 \times 10^{-5}\ \mathrm{eV}^2, \quad \Delta m^2_{32} = 2.45\ (2.55) \times 10^{-3}\ \mathrm{eV}^2 \qquad \text{[PDG]}$$

$$\Sigma m_\nu < 0.13\ \mathrm{eV}, \quad N_{\mathrm{eff}} = 2.99 \pm 0.17 \qquad \text{[Planck 2018]}$$

  - The origin of the masses will be BSM physics.

- Dark Matter
  - No candidate in the SM particle content.
  - Dark matter must be new particle.
  - WIMP dark matter has been tightly constrained.
  - Other possibility might be considered.

[PDG 2024]



Introduction

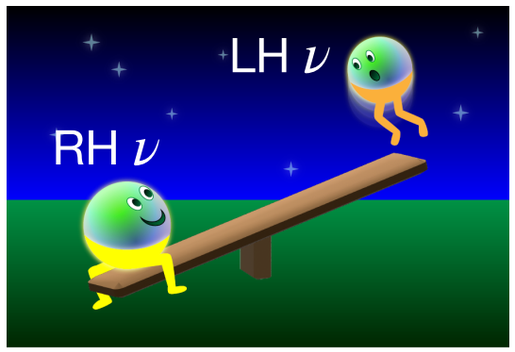
▸ Right-handed neutrino is a possible solution to both problems.

• Seesaw mechanism [Minkowski (1977), Yanagida (1979), Gell-Mann et al (1979)]

$$\mathscr{L}_\nu = m_D \overline{\nu_L} \nu_R + \frac{M}{2} \overline{\nu_R^c} \nu_R + \mathrm{h.c.}$$

- Active neutrino $\nu_a \simeq \nu_L$, mostly SU(2) doublet

$$m_{\nu_a} \simeq \frac{m_D^2}{M} \qquad (M \gg m_D)$$



• Sterile neutrino dark matter

- Sterile neutrino $\nu_s \simeq \nu_R$, mostly SM singlet

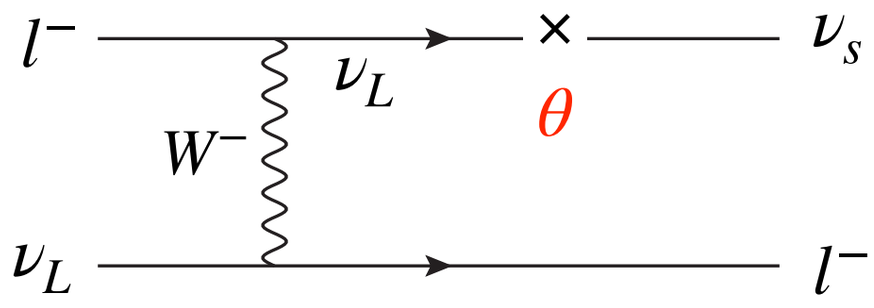
$$m_{\nu_s} \simeq M$$

Massive and Very weakly interacting with the SM sector

→ Dark matter candidate

Freeze-in

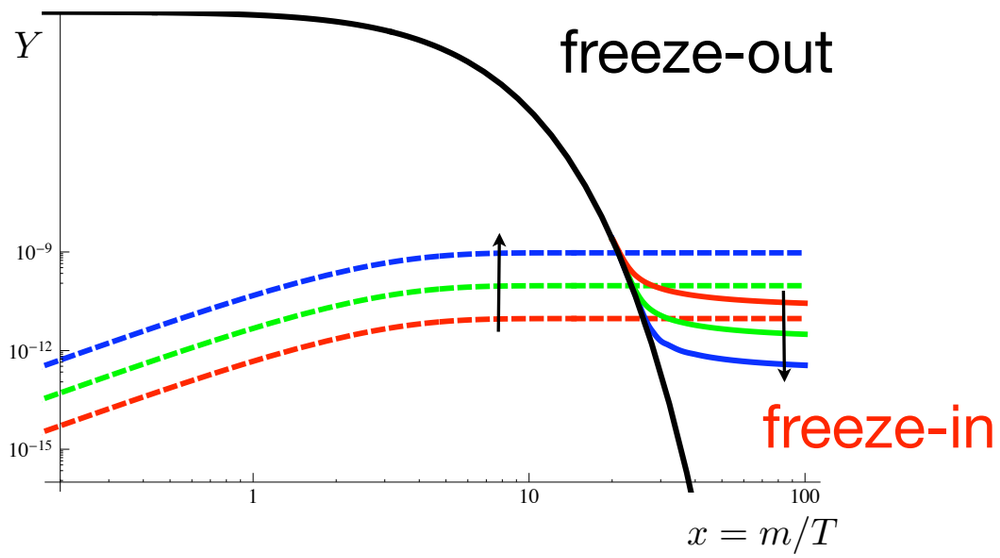
- Freeze-in Production
  - Dodelson-Widrow mechanism [Dodelson and Widrow, PRL (1994)]



where $\theta = \dfrac{m_D}{M}$

active-sterile mixing

  - Due to $\theta \ll 1$, the sterile neutrino DM is never thermalized



[Hall, Jedamzik et al, JEHP (2010)]

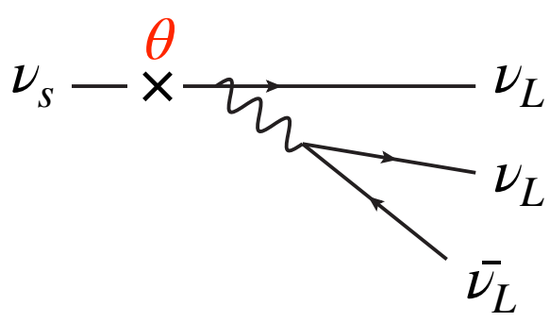
Sterile ν abundance

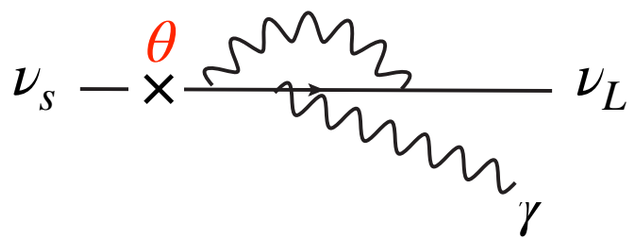
$$\Omega_{\nu_s} h^2 = 0.1 \left(\frac{\theta^2}{3 \times 10^{-9}} \right) \left(\frac{m_s}{3 \text{ keV}} \right)^{1.8}$$

[Shakya, MPLA (2016)]

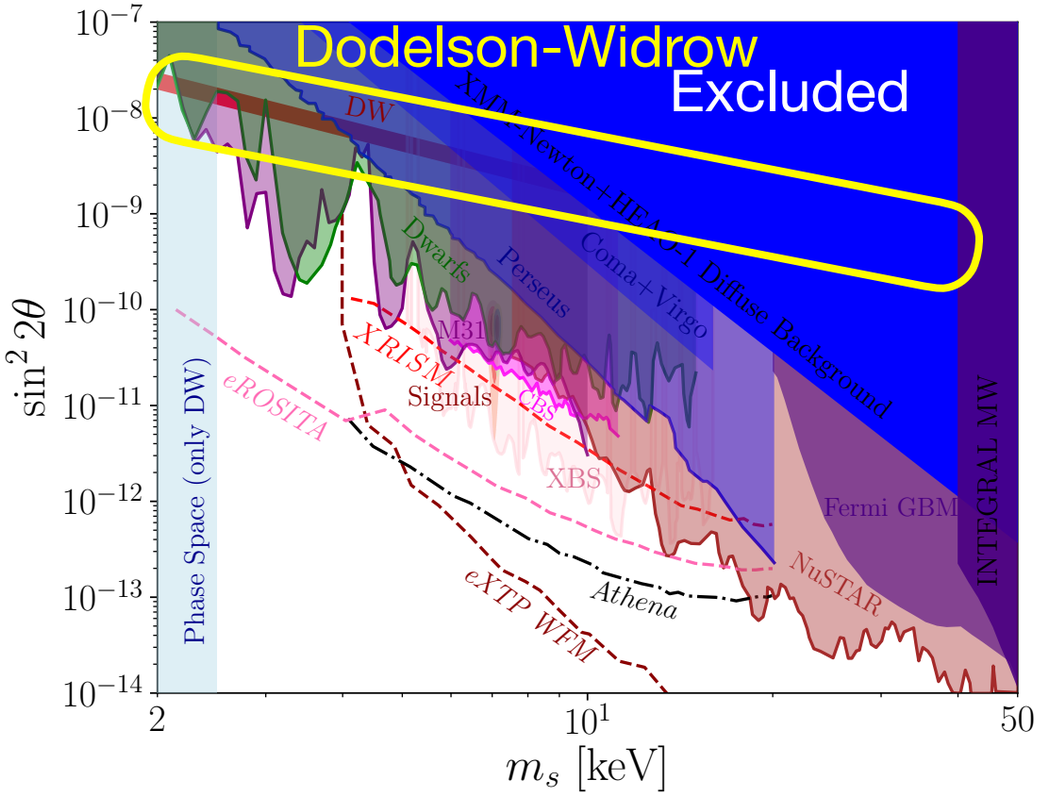
Sterile ν DM

- X-ray and Lyman-α observations searched for the sterile neutrino DM
  - Radiative decay [Pal and Wolfenstein, PRD (1982)]





$$\Gamma_{\nu\gamma} = 5.5 \times 10^{-22} \theta^2 \left(\frac{m_s}{\text{keV}} \right)^5 \text{/sec}\,.$$



[Gerbino et al, 2203.07377]

- Rule out sterile ν DM from the DW mech.

Both production & decay depend on θ

↓

Alternative production mechanism

Gauged *B-L* model

* *B* = Baryon number
L = Lepton number

Gauged *B-L* Model

- Extend the SM gauge group to $SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

	Q	u	d	L	e_R	ν_R	H	Φ
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$\frac{1}{2}$	0
$U(1)_{B-L}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	-1	-1	0	2

New particles

- 3 generations of RH neutrino for anomaly cancellation
  - → Two for Seesaw mechanism
  - → One for sterile ν dark matter
- Gauge boson Z' of the *B-L* symmetry
- Scalar Φ for spontaneous breaking of the *B-L* symmetry
  - → New production processes of DM

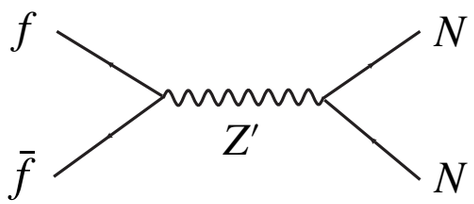
Dark Matter Production

- The sterile DM scenario in *B-L* model has been studied comprehensively
  - Different mass spectrum ($m_N \sim 10$ keV, $m_{Z'} > 2m_N$, $m_{Z'} < 2m_N$)
  - Thermal production has been excluded.
  - Non-thermal production or freeze-in is viable scenario.

[Khalil, Seto, JCAP (2008)], [Kaneta, Kang, Lee, JHEP (2017)], [Biswas, Gupta, JCAP (2016)], [Seto, TS, PLB (2020)],

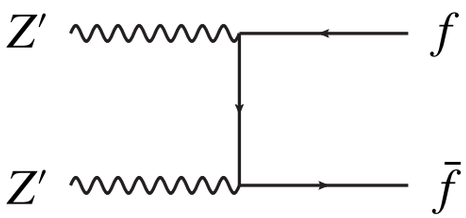
- $Z' \to NN$ forbidden case $(2m_N > m_{Z'})$
  - Production only by Z' $(\propto g_{B-L}^4)$

$(a)\ f\bar{f} \leftrightarrow (Z')^* \leftrightarrow NN$

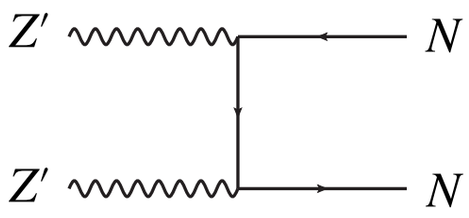


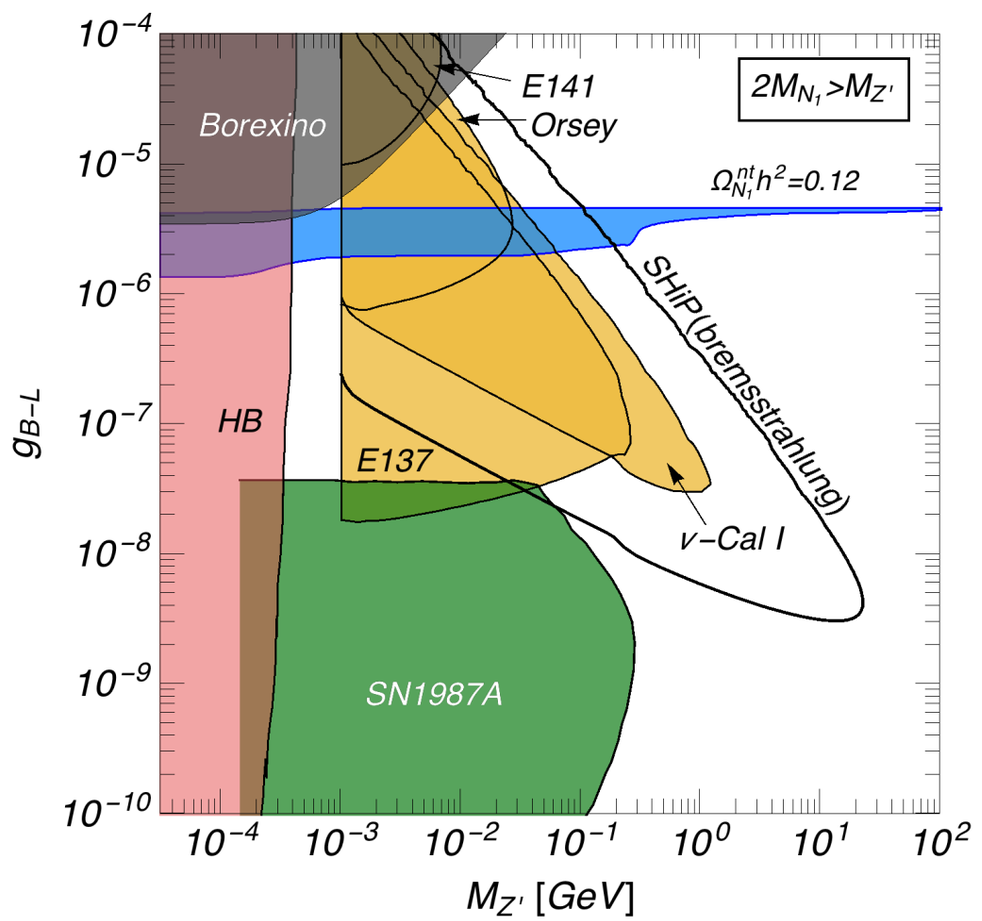
(*N* : sterile ν DM)

$(b)\ Z'Z' \leftrightarrow f\bar{f}$



$(c)\ Z'Z' \leftrightarrow NN$



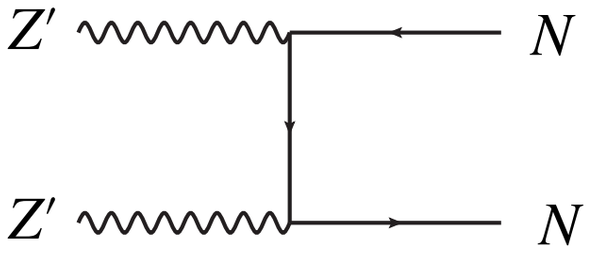


New Production Processes

We consider the following new processes, which are discarded in the previous studies,

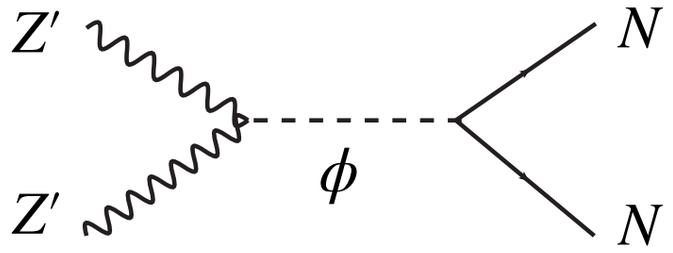
- Longitudinal polarizations of Z'
- intermediate ϕ contribution
- $\gamma \to Z'$ conversion
- Inverse-decay productions of Z' and ϕ

Longitudinal pol.



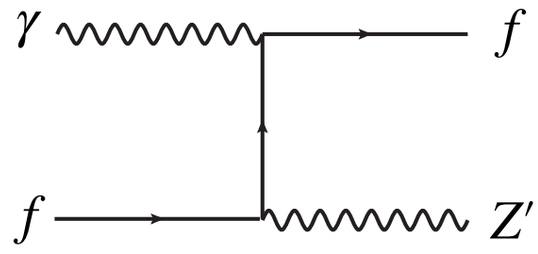
$$\propto g_{B-L}^4 \frac{s^2}{m_{Z'}^4}$$

Scalar (for unitarity)



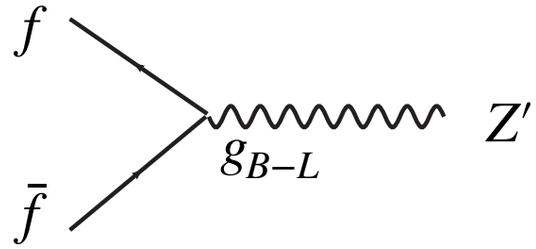
$$\propto -g_{B-L}^4 \frac{s^2}{m_{Z'}^4}$$

$\gamma - Z'$ conversion

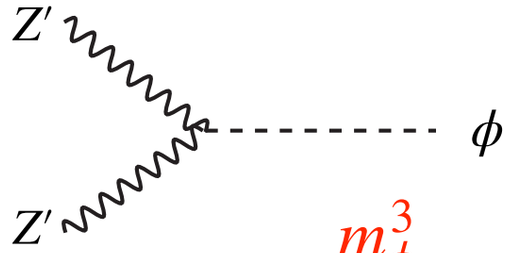


$$\propto e^2 g_{B-L}^2$$

Inverse-decay



$$\propto g_{B-L}^2$$

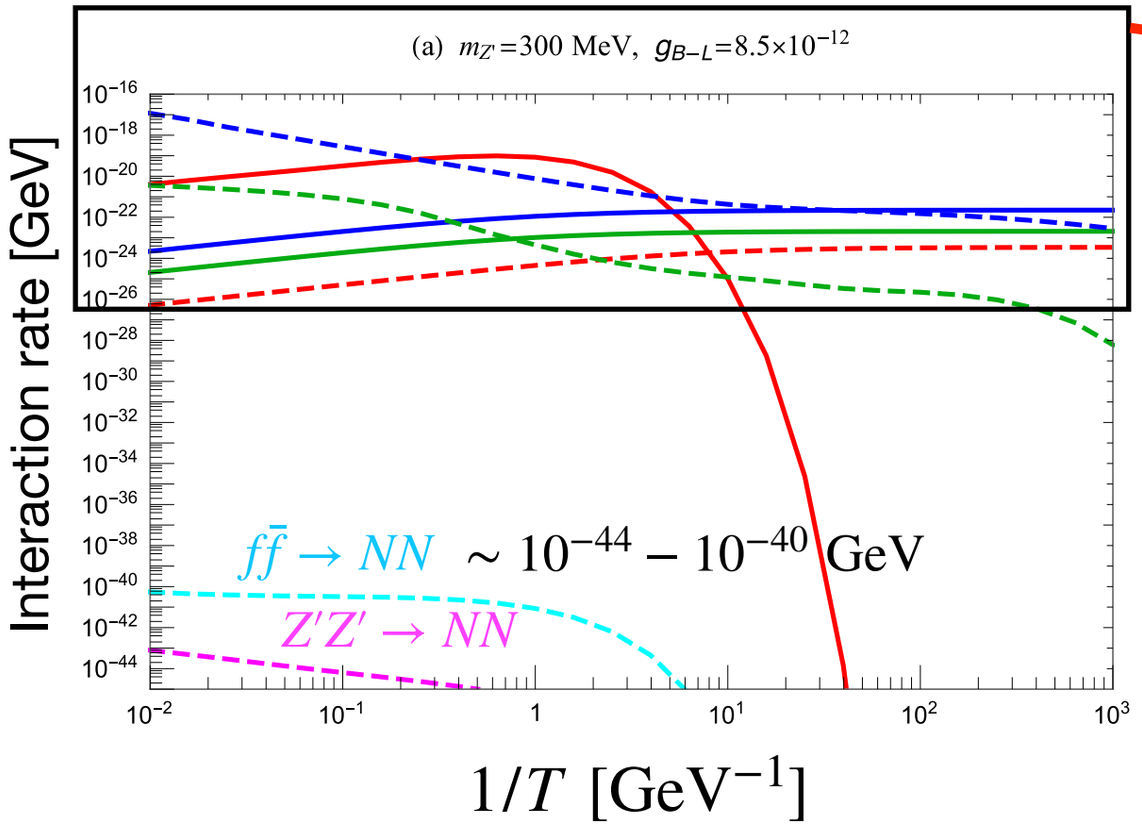


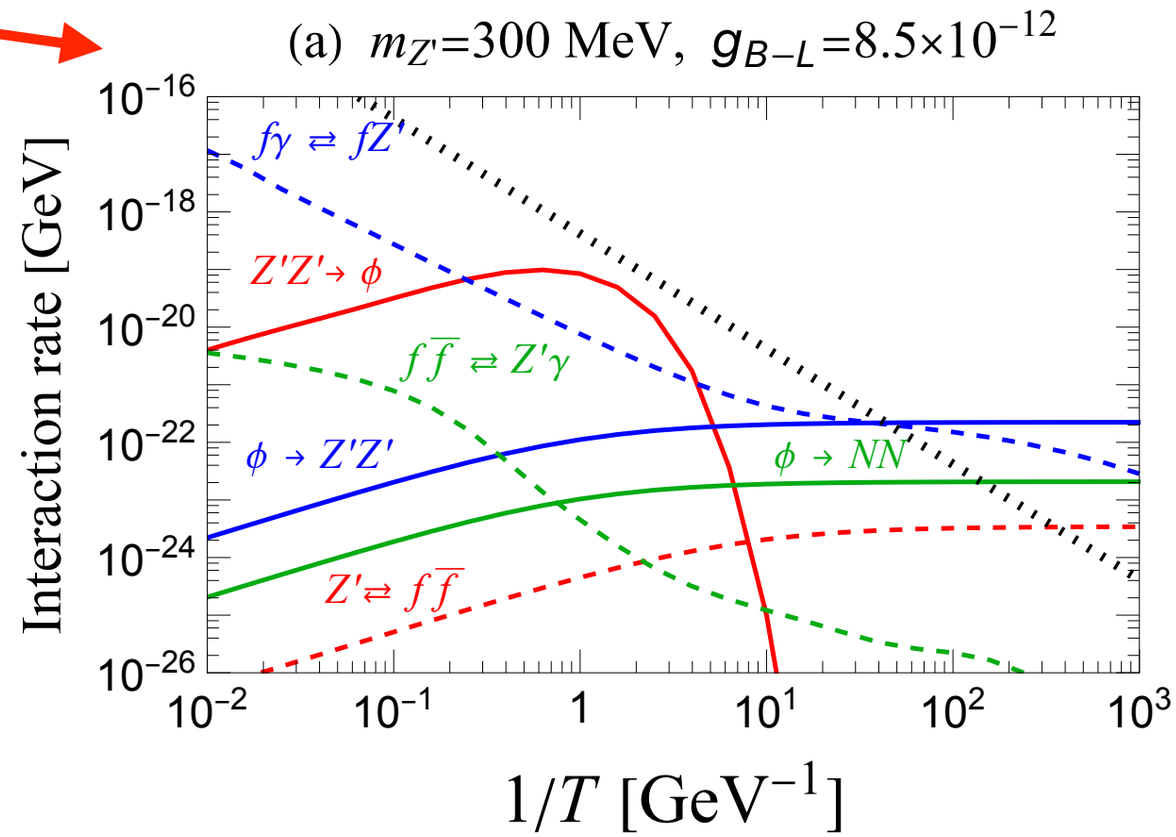
$$\propto g_{B-L}^2 \frac{m_\phi^3}{m_{Z'}^2}$$

Interaction Rate

[Seto, TS, Uchida, arXiv:2404.00654]

- $Z' \to NN$ forbidden ($2m_N > m_{Z'}$) case



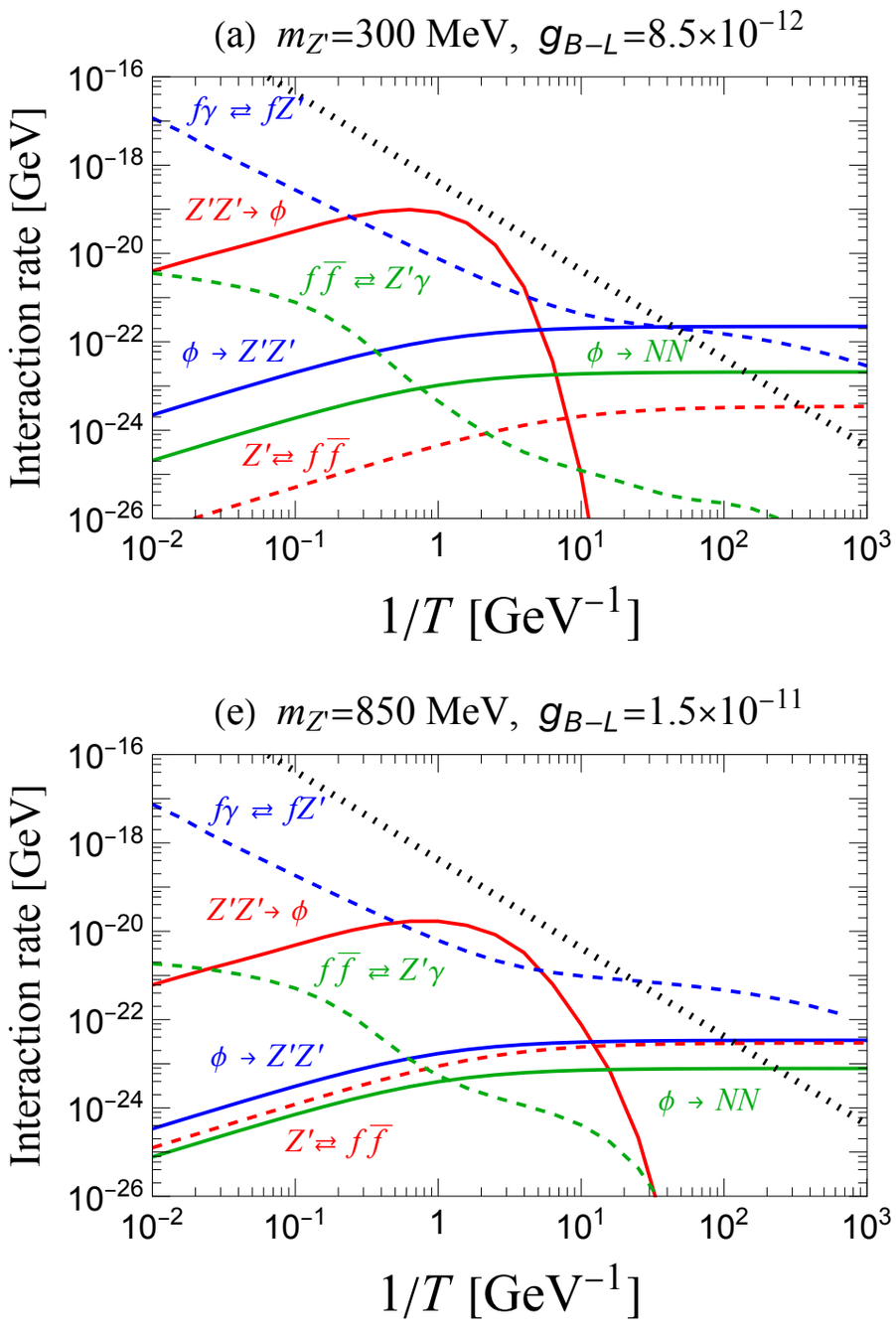


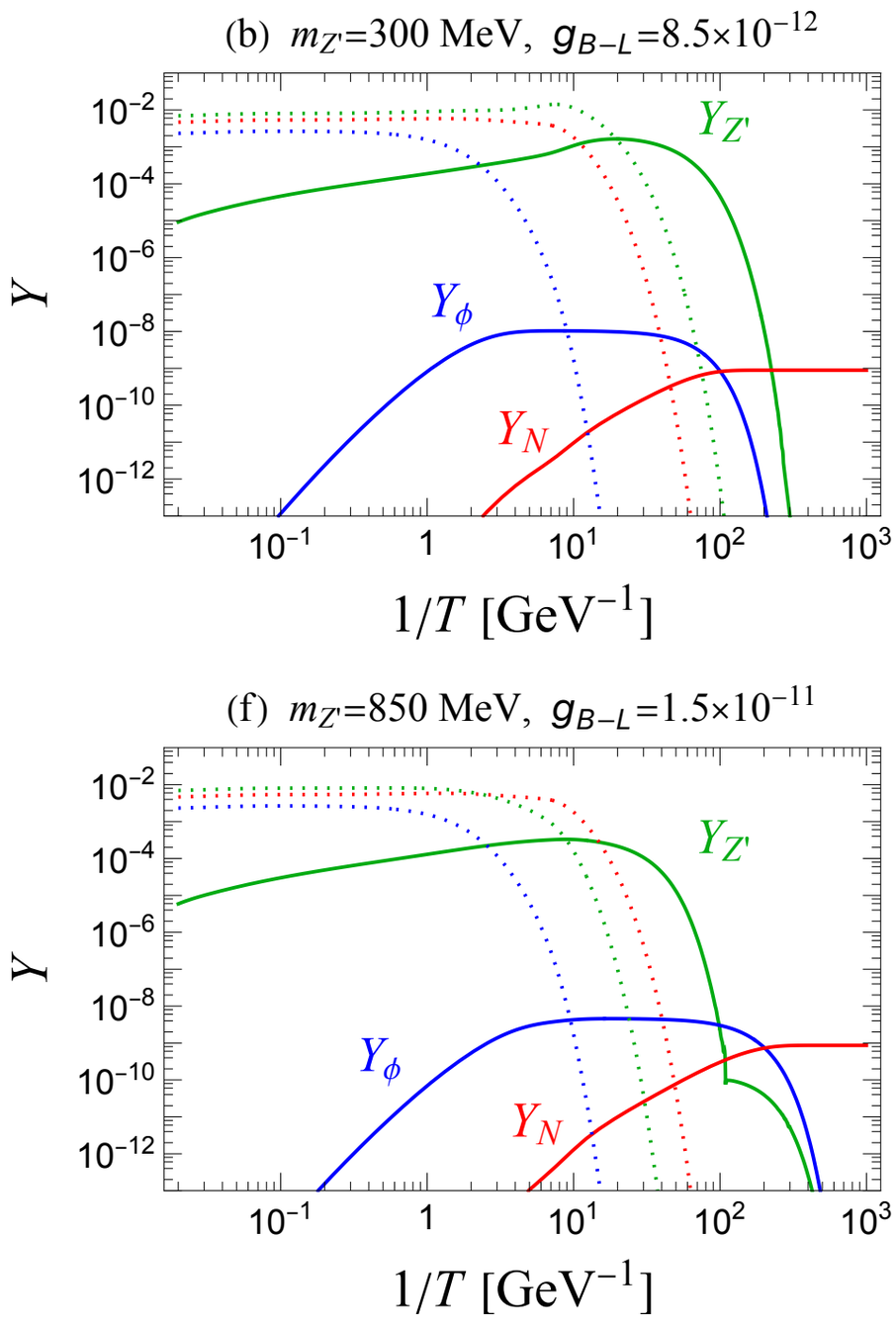
- $f\bar{f} \to NN$, $Z'Z' \to NN$ are suppressed due to $\langle \sigma v \rangle \propto g_{B-L}^4$
- $f\gamma \leftrightarrow fZ'$ is large due to $\propto e^2 g_{B-L}^2$ and abundant f/γ in thermal bath.
- $Z'Z' \to \phi$ is enhanced due to longitudinal mode.
- DM can be produced from $\phi \to NN$ (Ω_{DM} depends on m_ϕ).

Yield Value

[Seto, TS, Uchida, arXiv:2404.00654]

- Not only the DM but also ϕ and Z' are non-thermally produced.

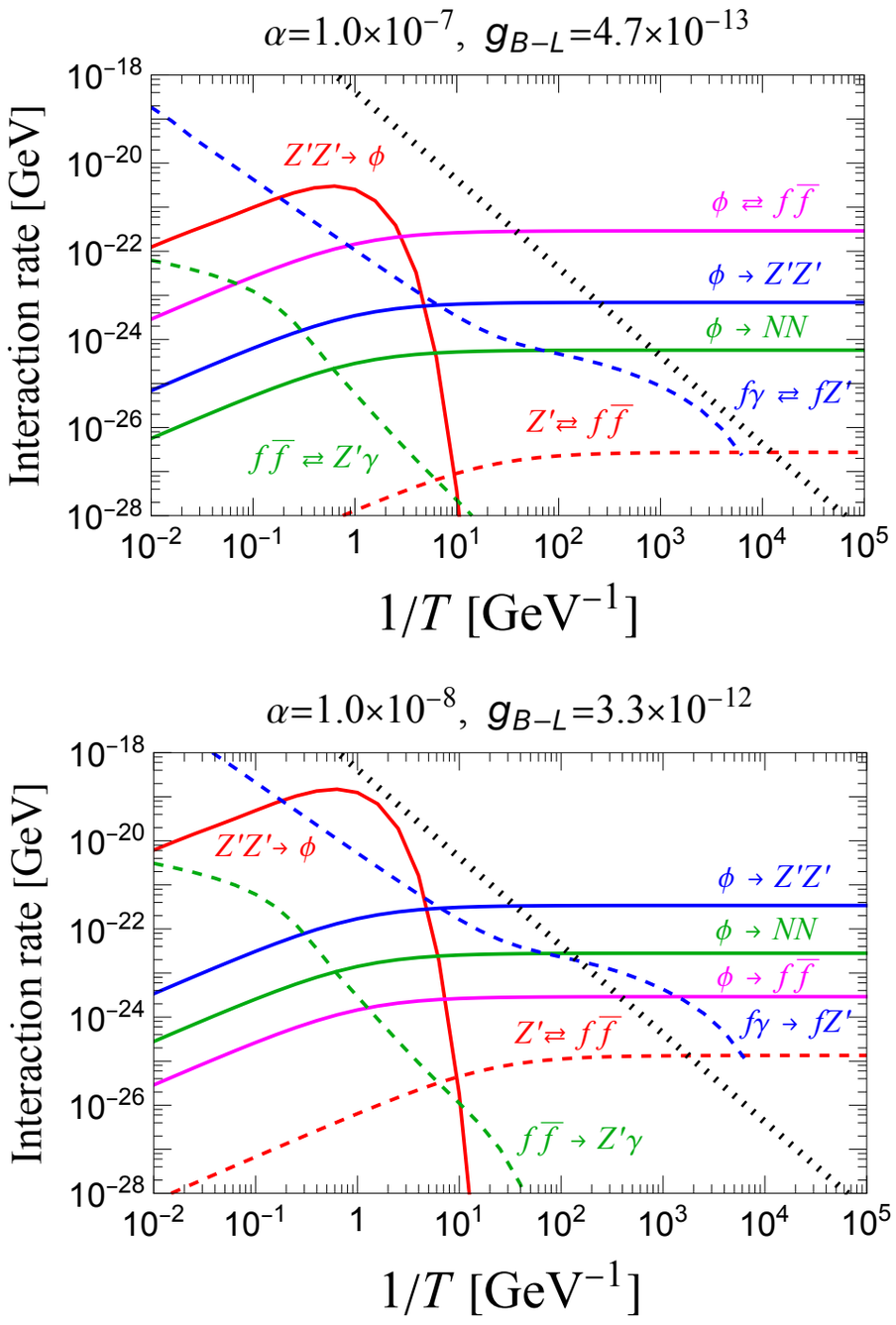


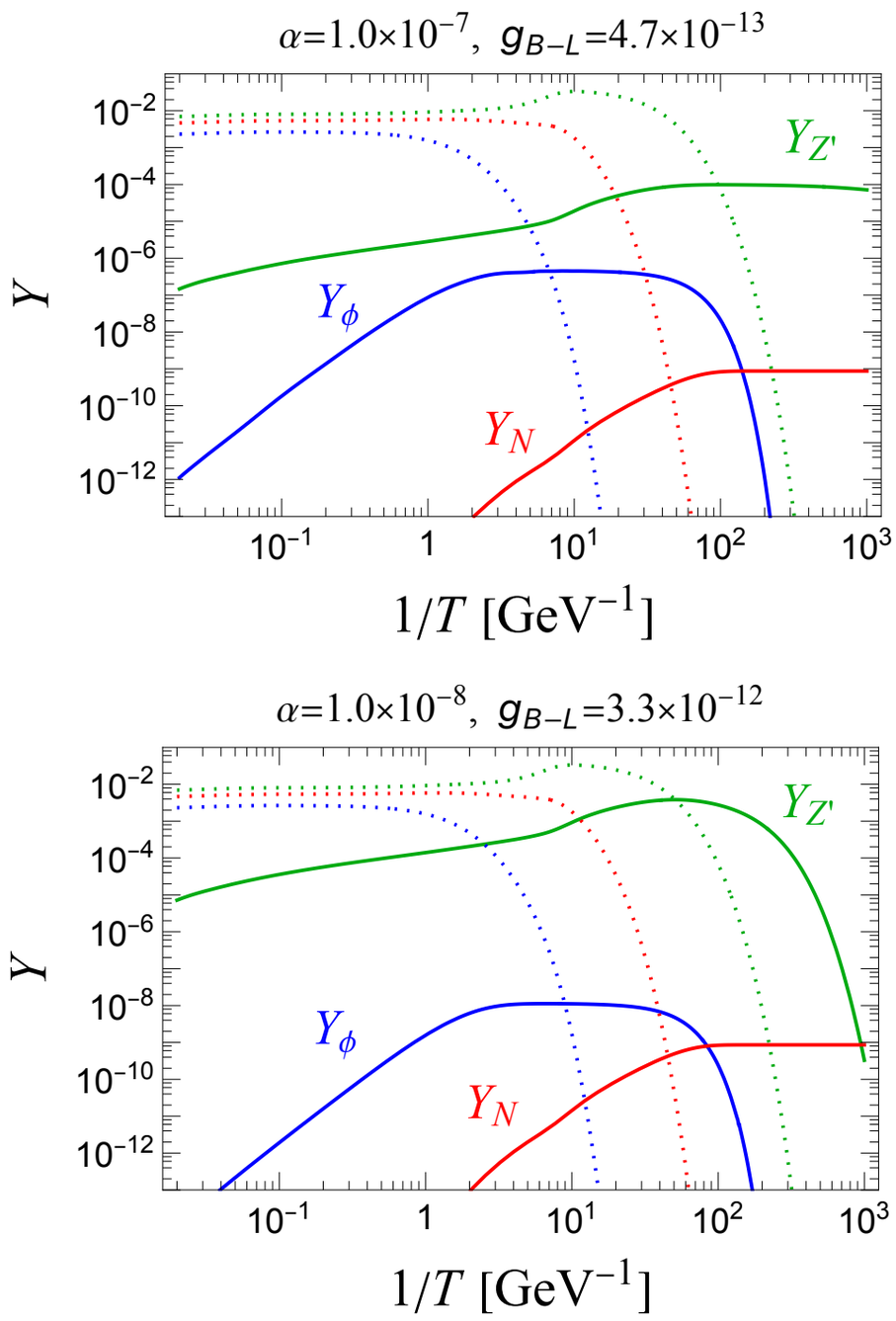


Yield Value

[Seto, TS, Uchida, arXiv:2404.00654]

- $f\bar{f} \to \phi$ is possible when ϕ has the mixing with the SM higgs

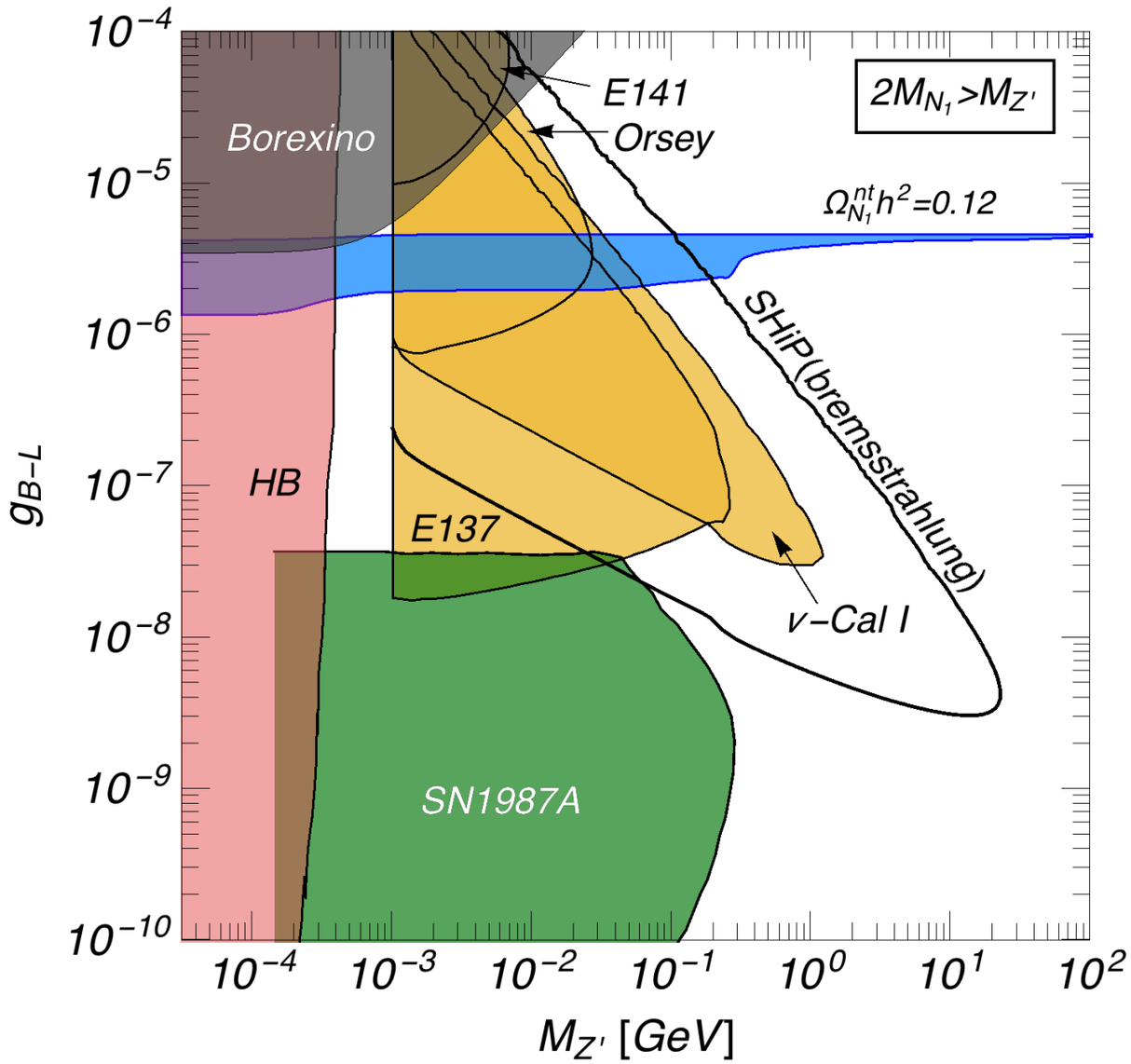


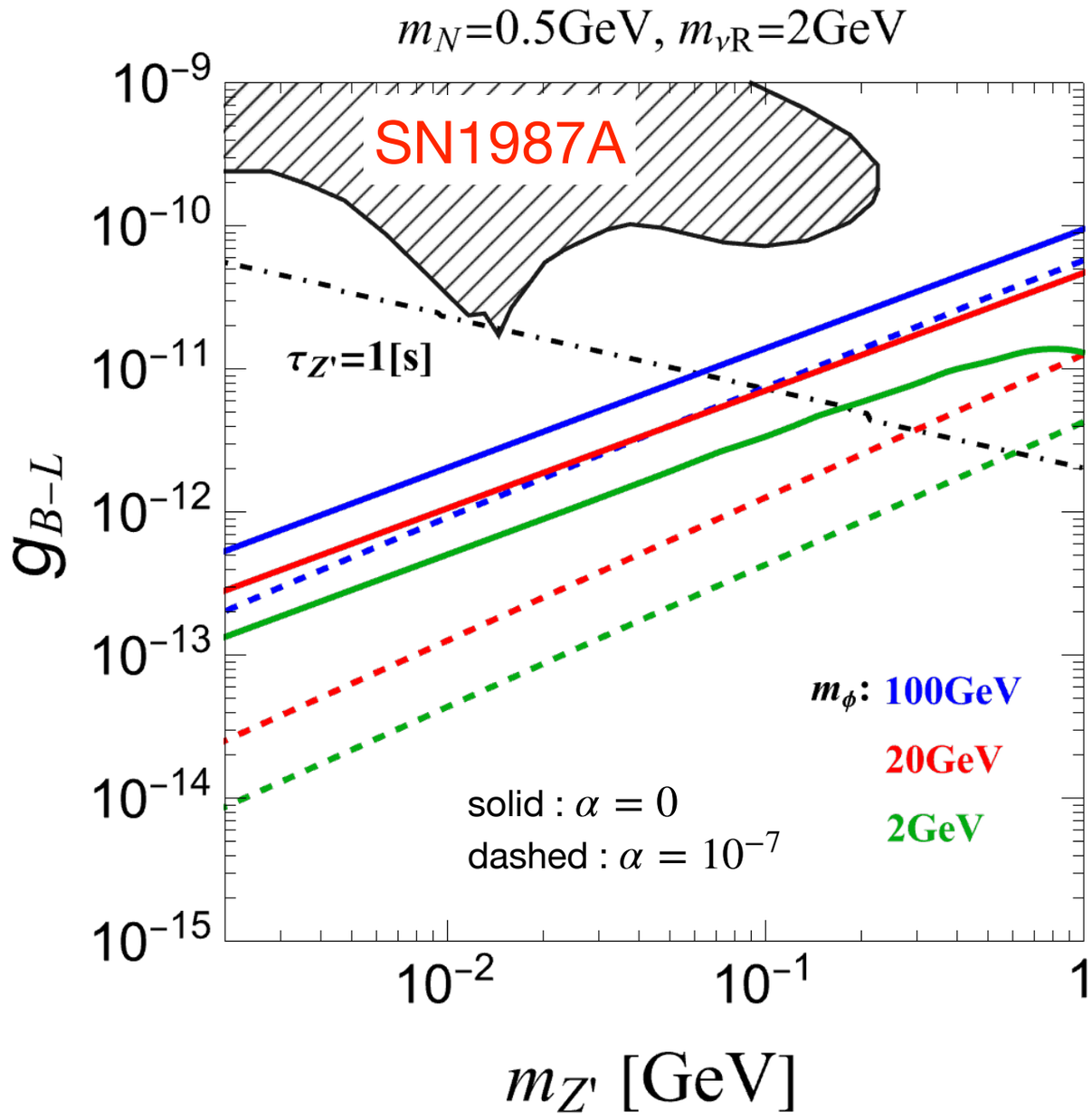


The parameter space

[Seto, TS, Uchida, arXiv:2404.00654]

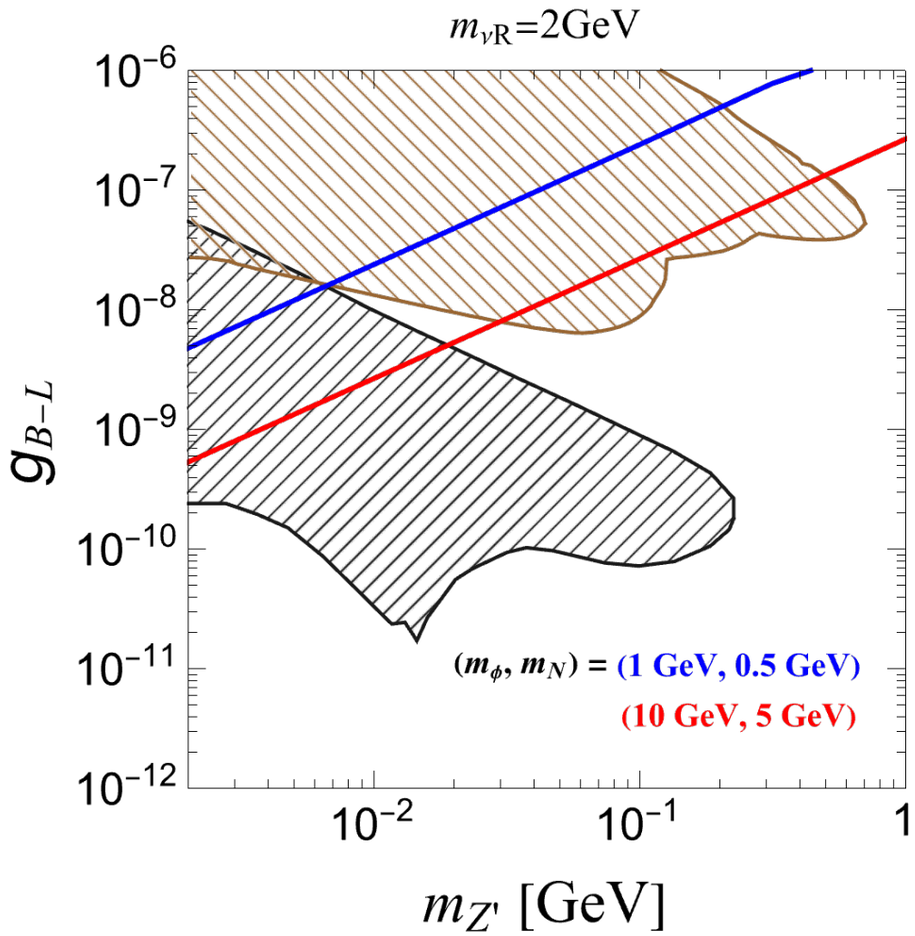
- The gauge coupling must be much smaller due to the new processes.



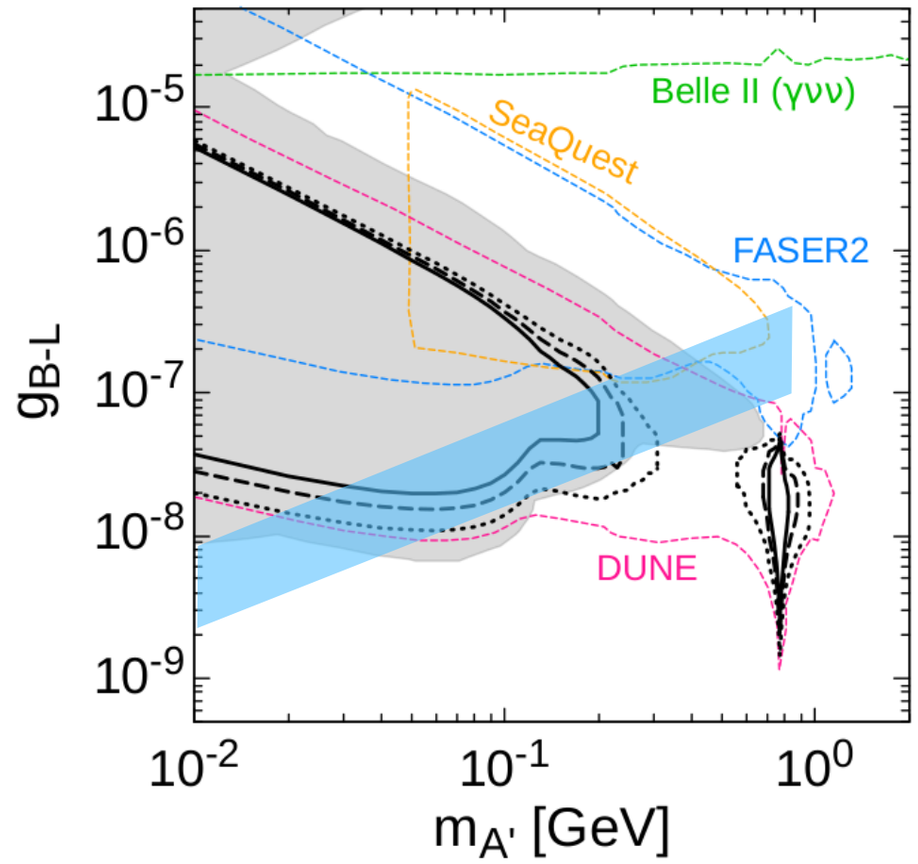


$\phi \to NN$ forbbiden case

- $2m_N > m_{Z'}, m_\phi$
  - DM cannot be produced from ϕ decay.
  - Scattering of $Z'Z' \to NN$ is only way for the DM production.



[Araki, Asai, Iizawa, Otono, TS, Takubo, 2308.01565]



Sensitivity region to $Z' \to \mathrm{viz}$.

- Such a region can be searched by the FASER experiment.

[Seto, Shimomura, Uchida, on-going]

Summary

We have reexamined the freeze-in production of the sterile neutrino dark matter in gauged *B*-*L* model.

- $Z' \to NN$ forbidden ($2m_N > m_{Z'}$) case
  - $f\gamma \to fZ'$, $Z'Z' \to \phi$ are dominant processes of the production.
  - The new particles N, Z', ϕ are produced by freeze-in mechanism.
  - DM can be produced from ϕ decay when kinematically allowed.
  - The gauge coupling must be $10^{-14} - 10^{-10}$.

- $Z', \phi \to NN$ forbidden ($2m_N > m_{Z'}, m_\phi$)
  - Scattering of $Z'Z' \to NN$ is only way for the DM production.
  - The gauge coupling can be large, $10^{-9} - 10^{-6}$.
  - Z' can be searched at future FASER 2 experiment.