

Freeze-in production of sterile neutrino dark matter in the gauged B-L model

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Based on

PRD **106** 103513 (2022) with Shintaro Eijima and Takashi Shimomura

JHEP **05** 147 (2025) with Takashi Shimomura and Yoshiki Uchida

§ Introduction

Adding RH neutrinos

- Adding RH neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{i}{2} \overline{\nu_R} \not{\partial} \nu_R - y \bar{L} \Phi \nu_R - \frac{1}{2} \overline{\nu_R^c} M_M \nu_R + h.c.$$

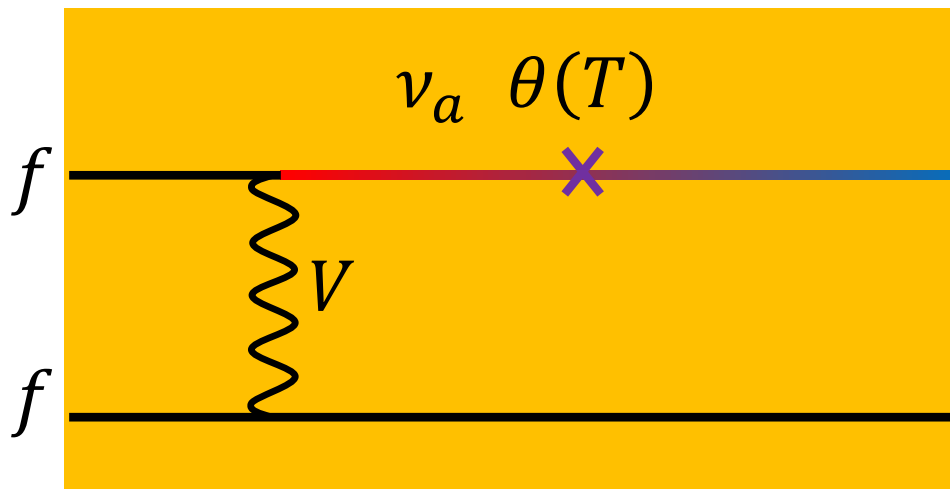
- If Dirac masses $\ll$ Majorana masses, seesaw mechanism works [Minkowski (1977), Yanagida (1979), Gell-Mann et al (1979)]

$$\begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix} \rightarrow \begin{pmatrix} -m_D^T \frac{1}{M_M} m_D & 0 \\ 0 & M_M \end{pmatrix}$$

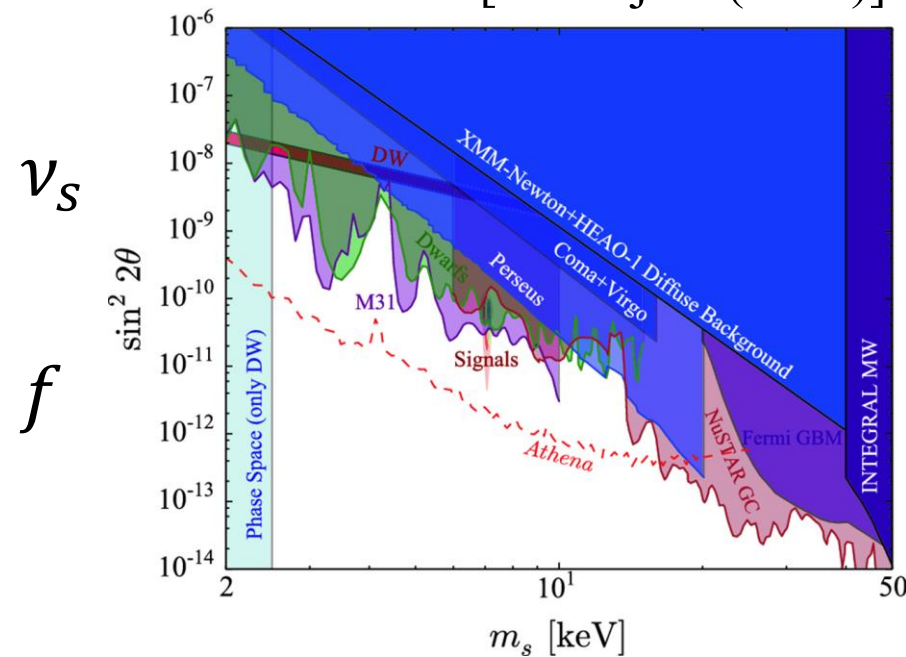
- $\nu_a \cong U_{MNS} \nu_L + \theta \nu_R^c$ Neutrino oscillation
- $\nu_s \cong \theta \nu_L + \nu_R^c$ Sterile neutrino, almost RH
- $\theta = m_D / M_M \ll 1$: active-sterile mixing

Sterile neutrino is decaying DM

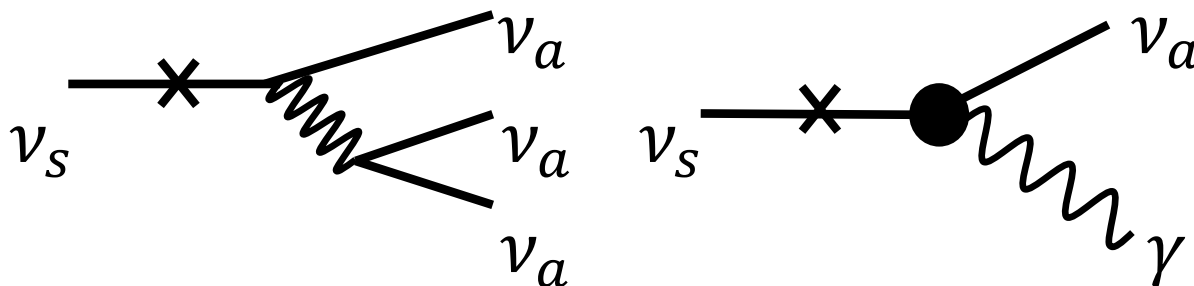
- Production: Dodelson-Widrow mechanism [Dodelson and Widrow (1994)]



[Abazajian (2019)]



- Decay [Pal and Wolfenstein (1982)]



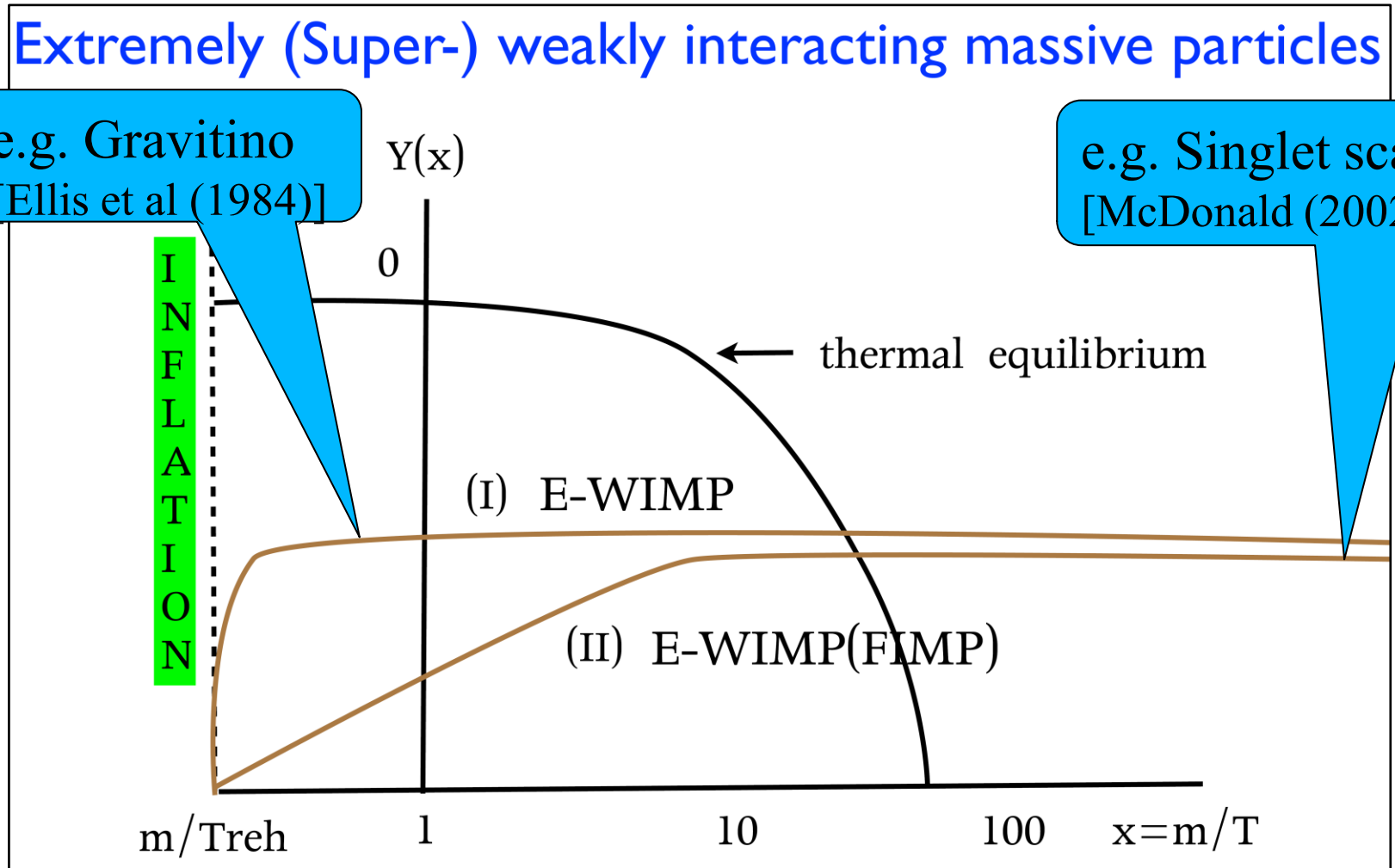
§ Freeze in Production

- A kind of non-thermal production

Extremely (Super-) weakly interacting massive particles

e.g. Gravitino
[Ellis et al (1984)]

e.g. Singlet scalar
[McDonald (2002)]



By courtesy of K.Y. Choi

§ Sterile neutrino DM in feeble gauged $U(1)$ extended model

Model

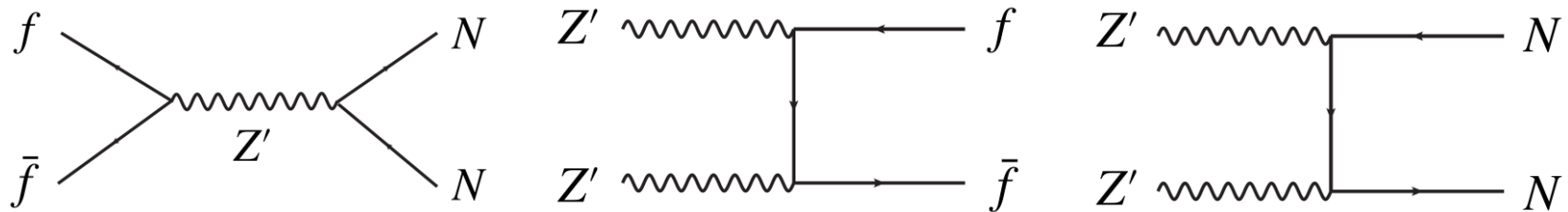
- Gauged U(1) extension
 - $U(1)_{B-L} : +1$ for baryon, -1 for lepton

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
Q^i	3	2	$\frac{1}{6}$	$\frac{1}{3}$
u_R^i	3	1	$\frac{2}{3}$	$\frac{1}{3}$
d_R^i	3	1	$-\frac{1}{3}$	$\frac{1}{3}$
L^i	1	2	$-\frac{1}{2}$	-1
e_R^i	1	1	-1	-1
ν_R^i	1	1	0	-1
Φ_H	1	2	$\frac{1}{2}$	0
Φ_{B-L}	1	1	0	2

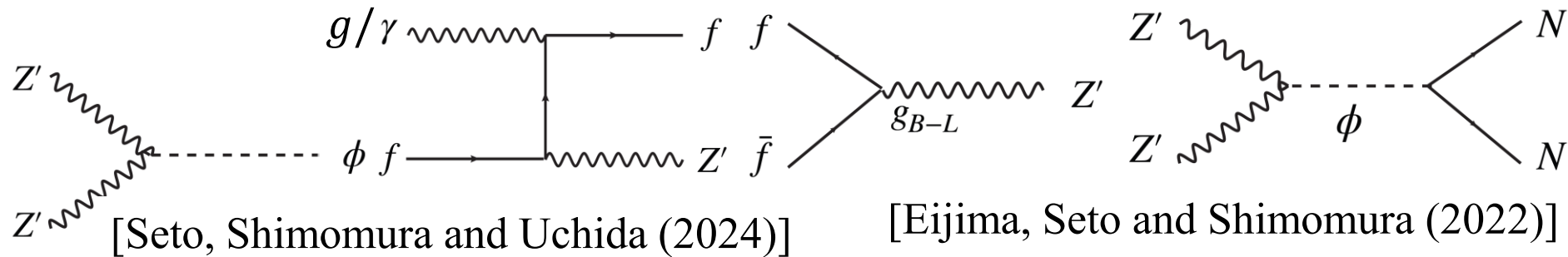
- Masses
 - $m_{Z'}^2 = 4g_{B-L}^2 v_{B-L}^2$
 - $m_{\nu_R^i} = \frac{y_{\nu_R^i}}{\sqrt{2}} v_{B-L}$
- Singlet-like ϕ
- SM-like h
 - The $h - \phi$ mixing α

Sterile neutrino DM production

- ν_s DM by Z' mediated non-thermal production
[Khalil and Seto (2008), Kaneta, Kang and Lee (2017), Biswas and Gupta (2017), ...] (hereafter, N instead of ν_s)
- Processes considered in previous works



We found (sometime more) important modes

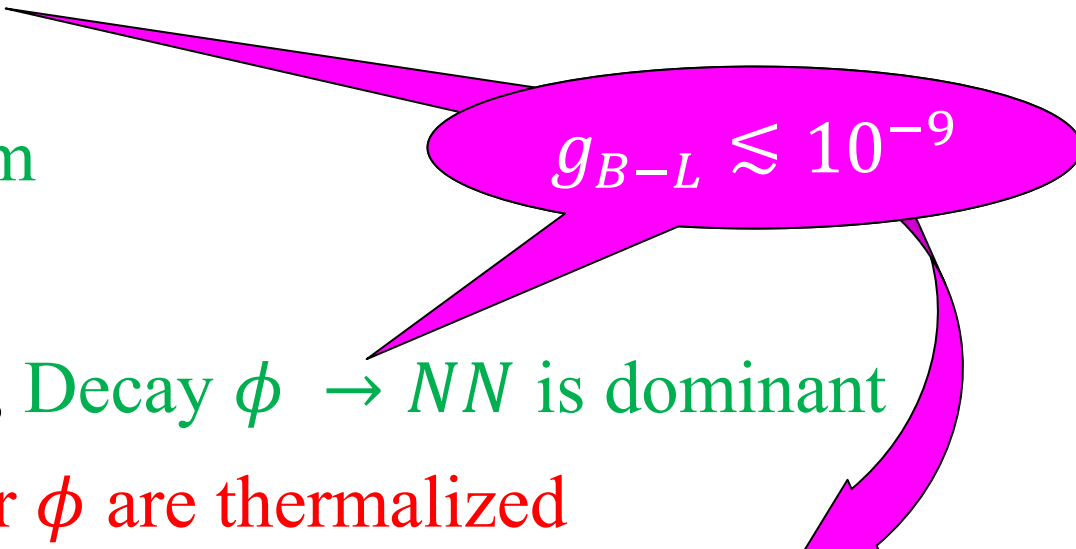


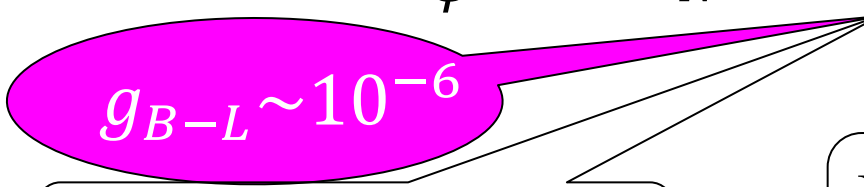
[Seto, Shimomura and Uchida (2024)]

[Eijima, Seto and Shimomura (2022)]

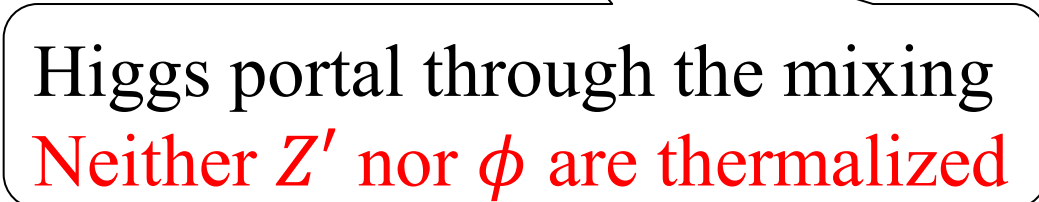
Phenomenology depends on the spectrum

- $2m_N < m_{Z'}$
 - Decay $Z' \rightarrow NN$ is dominant
 - Non-thermal Z'
 - May be too warm
- $m_{Z'} < 2m_N$
 - For $m_\phi > 2m_N$, Decay $\phi \rightarrow NN$ is dominant
 - Neither Z' nor ϕ are thermalized
 - For $m_\phi < 2m_N$, $Z'Z' \rightarrow NN$ or $f\bar{f} \rightarrow NN$ dominant


$$g_{B-L} \lesssim 10^{-9}$$


$$g_{B-L} \sim 10^{-6}$$

Z' are thermalized



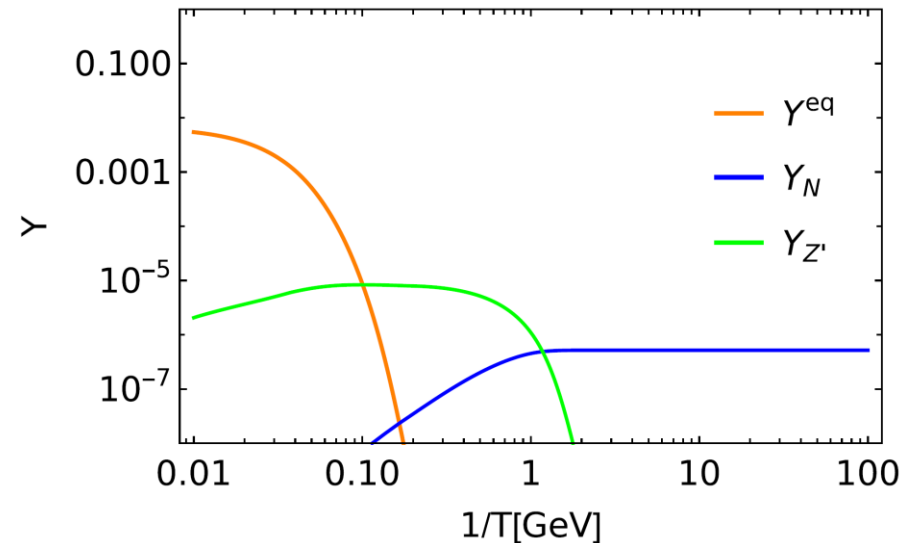
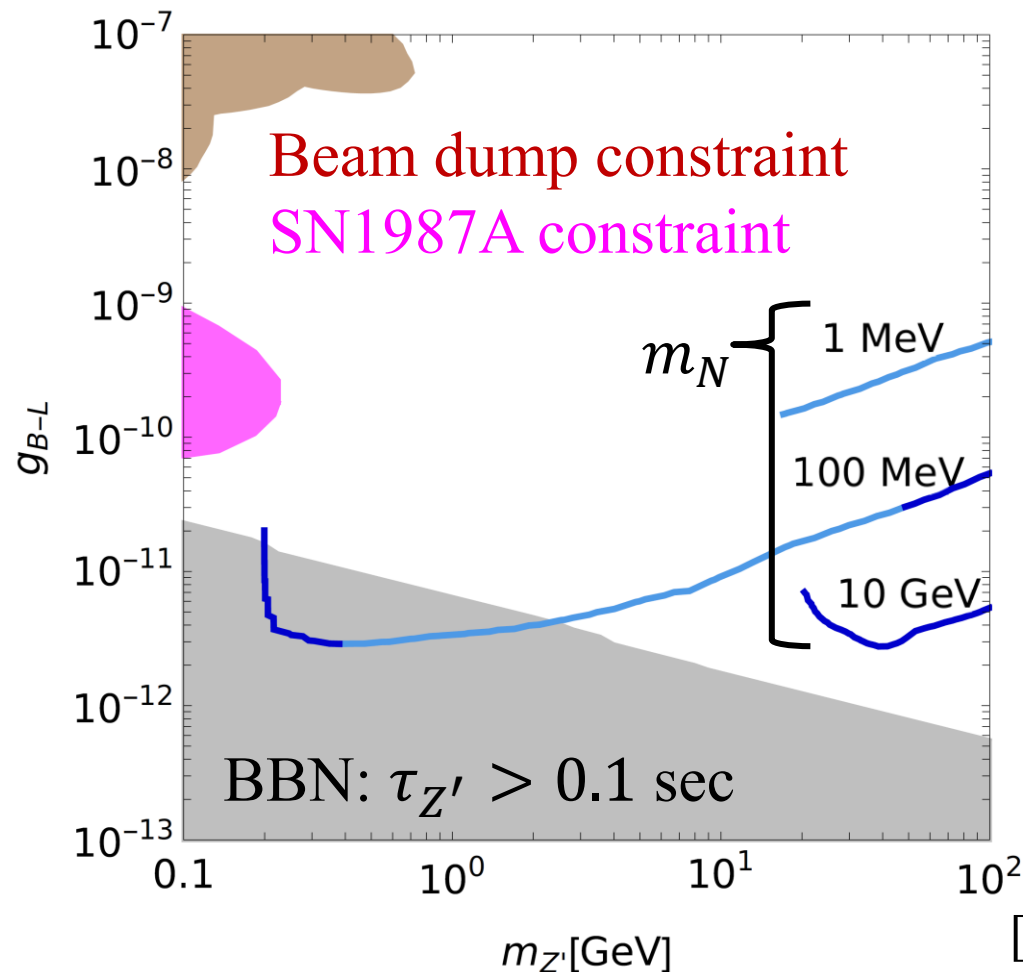
Higgs portal through the mixing
Neither Z' nor ϕ are thermalized

$$\S \S \quad 2m_N < m_{Z'}$$

- Main production mode : $f\bar{f} \rightarrow Z' + Z' \rightarrow 2N$
- The free streaming length λ_{fs} bound [Irsic et al (2017)]

$$0.01 \text{ Mpc} < \lambda_{fs} < 0.1 \text{ Mpc}$$

$$\lambda_{fs} < 0.01 \text{ Mpc}$$

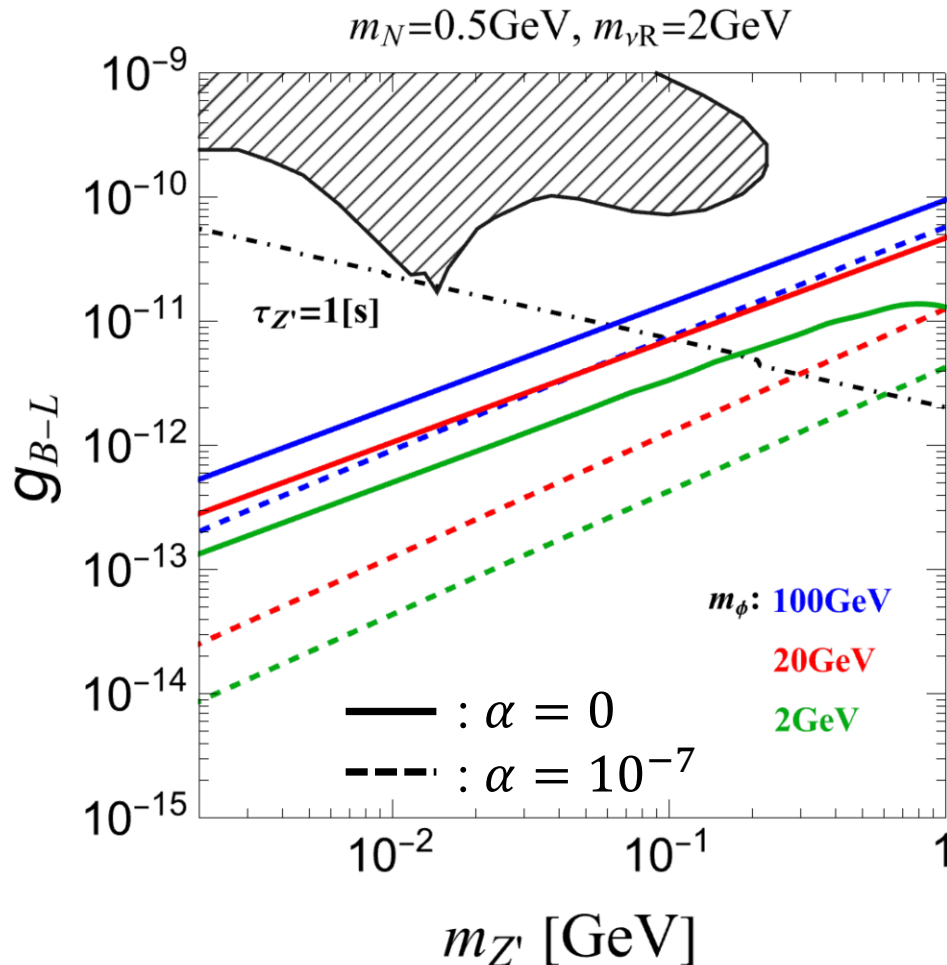


[Eijima, Seto and Shimomura (2022)]

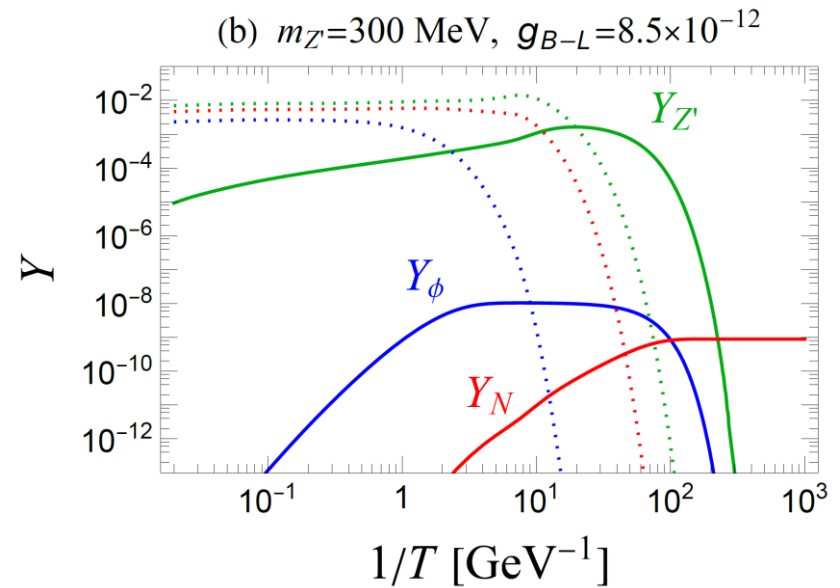
$$\S \S \quad m_{Z'} < 2m_N < m_\phi$$

- Main modes : $f\gamma \rightarrow fZ' + Z'Z' \rightarrow \phi + \phi \rightarrow 2N$

[Seto, Shimomura and Uchida (2025)]



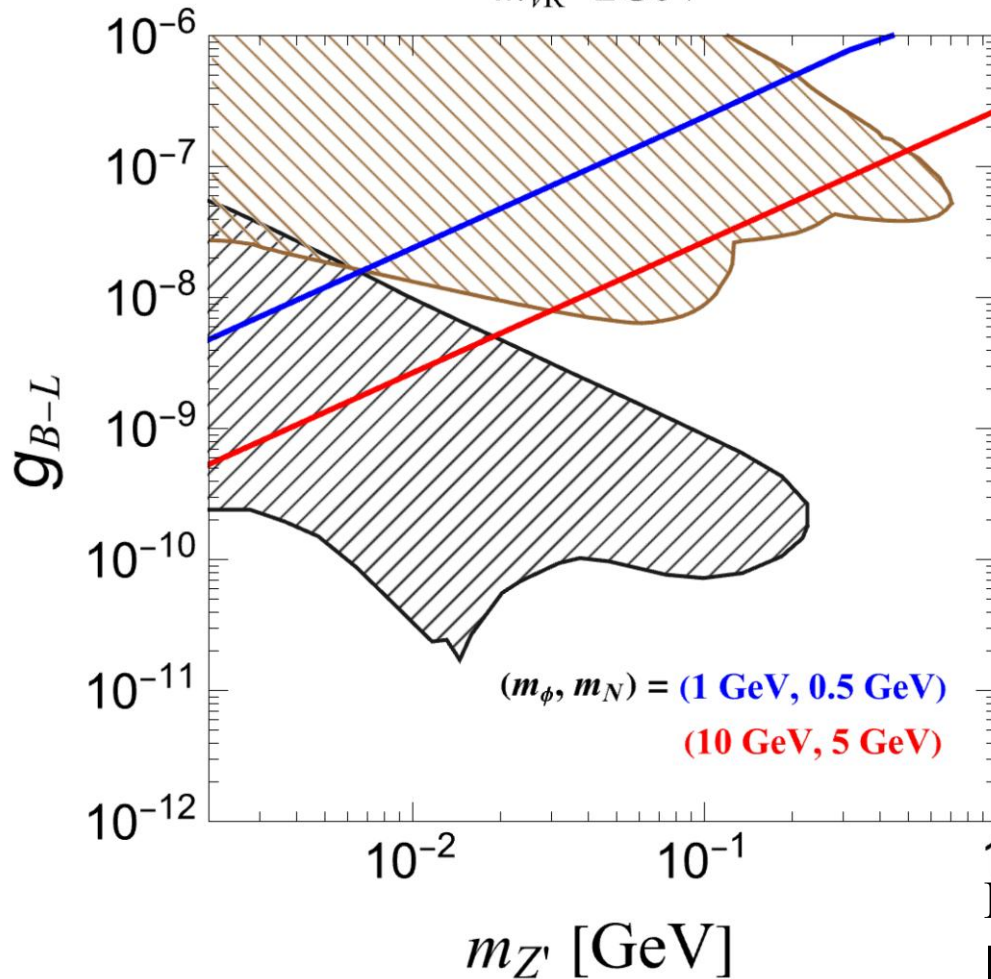
Typical yield evolution



$$\S \S \quad m_{Z'}, m_\phi < 2m_N$$

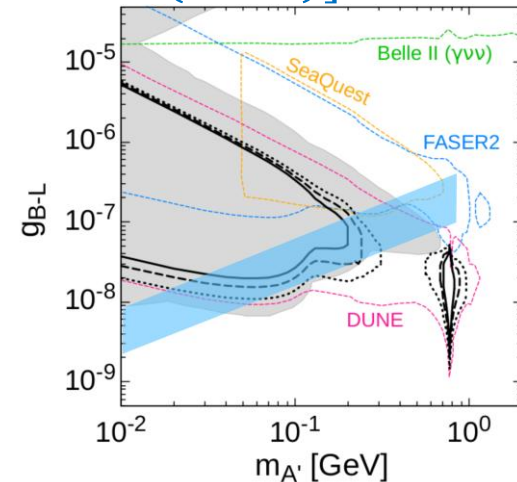
- $Z'Z' \rightarrow NN$ dominant case

$m_{\nu R}=2\text{GeV}$ [Seto, Shimomura and Uchida (2025)]



The parameter region can be probed by future long-lived particle searches

c.f. e.g. [Araki et al (2023)]



Dedicated study to our model is ongoing
 [Asai, ..., Seto, ...]

§ Summary

- We reexamined sterile neutrino DM in $U(1)_{B-L}$.
- Solving the Boltzmann eq. for N is not enough.
- $2m_N < m_{Z'}$ case and $m_{Z'} < 2m_N < m_\phi$ case
 - All Z' , ϕ and N are non-thermal.
 - $g_{B-L} \lesssim 10^{-9}$
- $m_{Z'}, m_\phi < 2m_N$ case
 - $g_{B-L} \lesssim 10^{-6}$
 - Z' may be found in long-lived particle search such as FASER2