Freeze-in sterile neutrino dark matter in the minimal gauge B-L model

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Ref : 2404.00654

Also with Shintaro Eijima and Takashi Shimomura

in PRD **106** 103513 (2022)

§ Introduction

Adding RH neutrinos

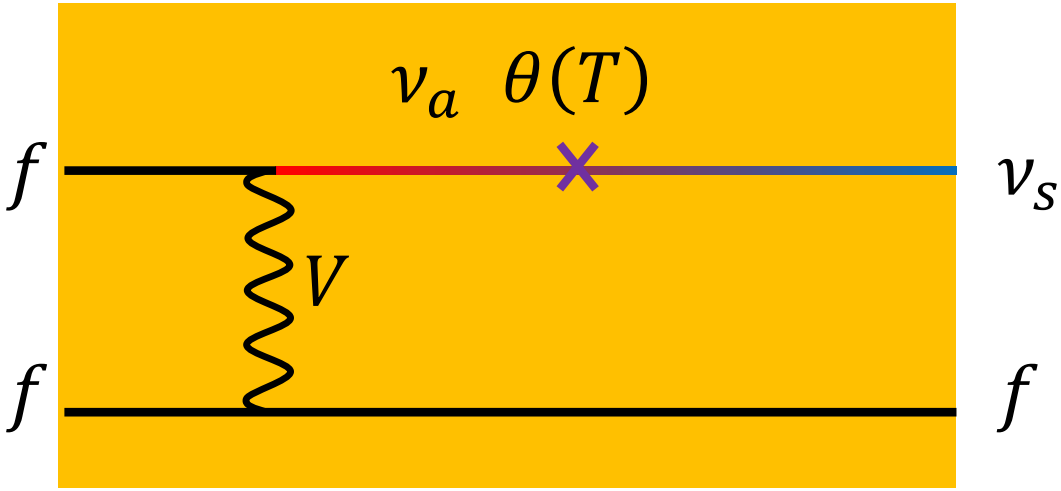
- Adding RH neutrinos

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

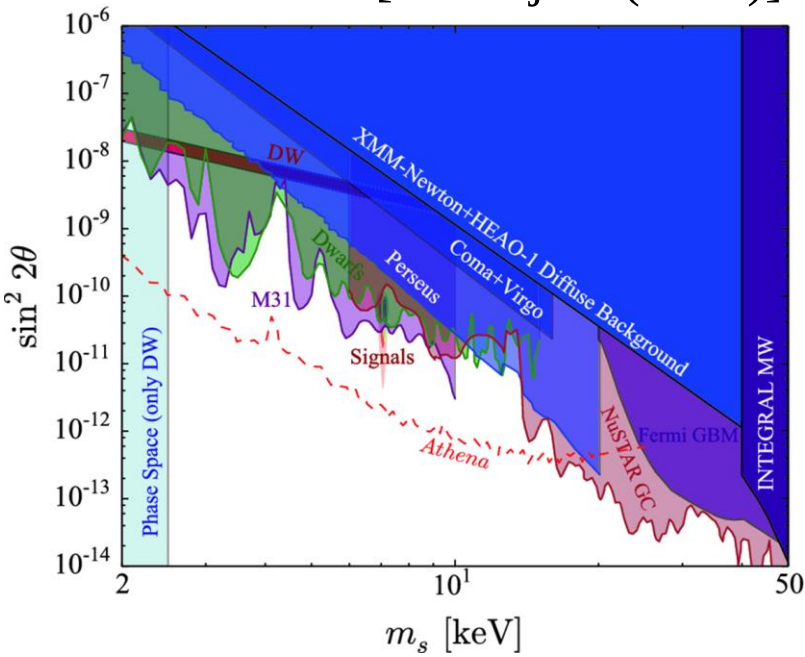
- If Dirac masses $\ll$ Majorana masses, seesaw mechanism works [Minkowski (1977), Yanagida (1979), Gell-Mann et al (1979)]
  - $\begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix} \rightarrow \begin{pmatrix} -m_D^T \frac{1}{M_M} m_D & 0 \\ 0 & M_M \end{pmatrix}$
  - $\nu_a \cong U_{MNS}\nu_L + \theta\nu_R^C$ 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

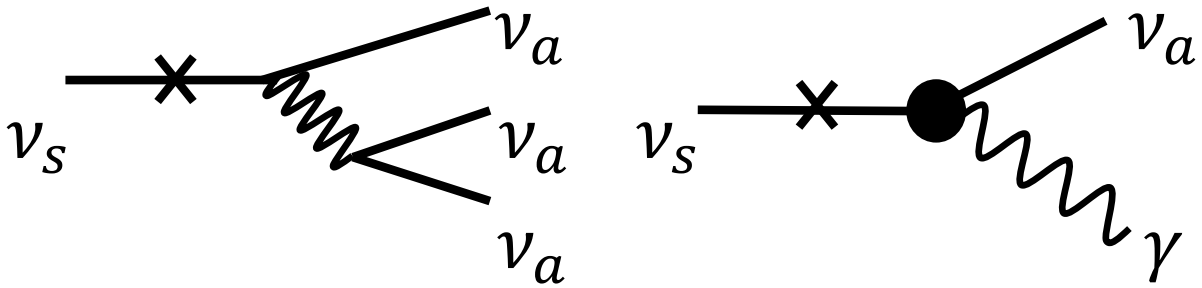
- Production: Dodelson-Widrow mechanism [Dodelson and Widrow (1994)]



[Abazajian (2019)]

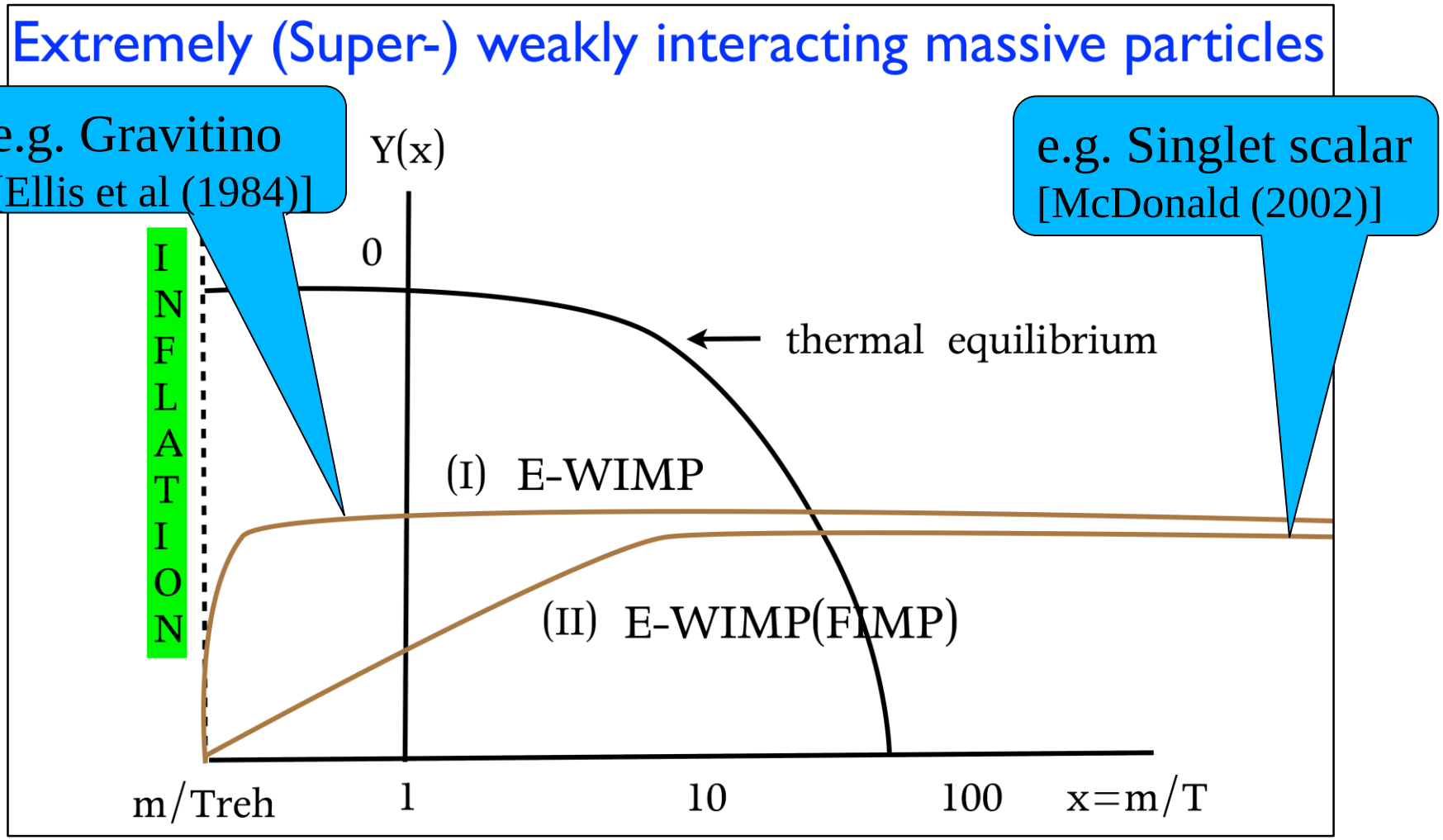


- Decay [Pal and Wolfenstein (1982)]



§ Freeze in Production

- A kind of non-thermal production



By courtesy of K.Y. Choi

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

Model

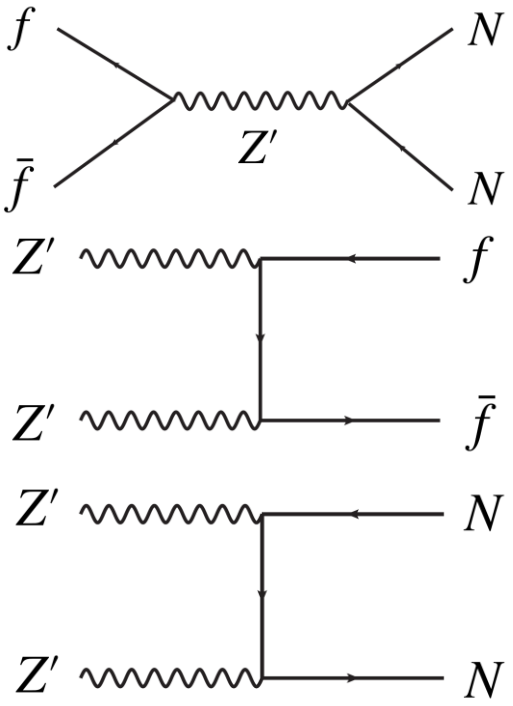
- Gauged U(1) extension
  - $U(1)_{B-L}$: +1 for baryon, -1 for lepton

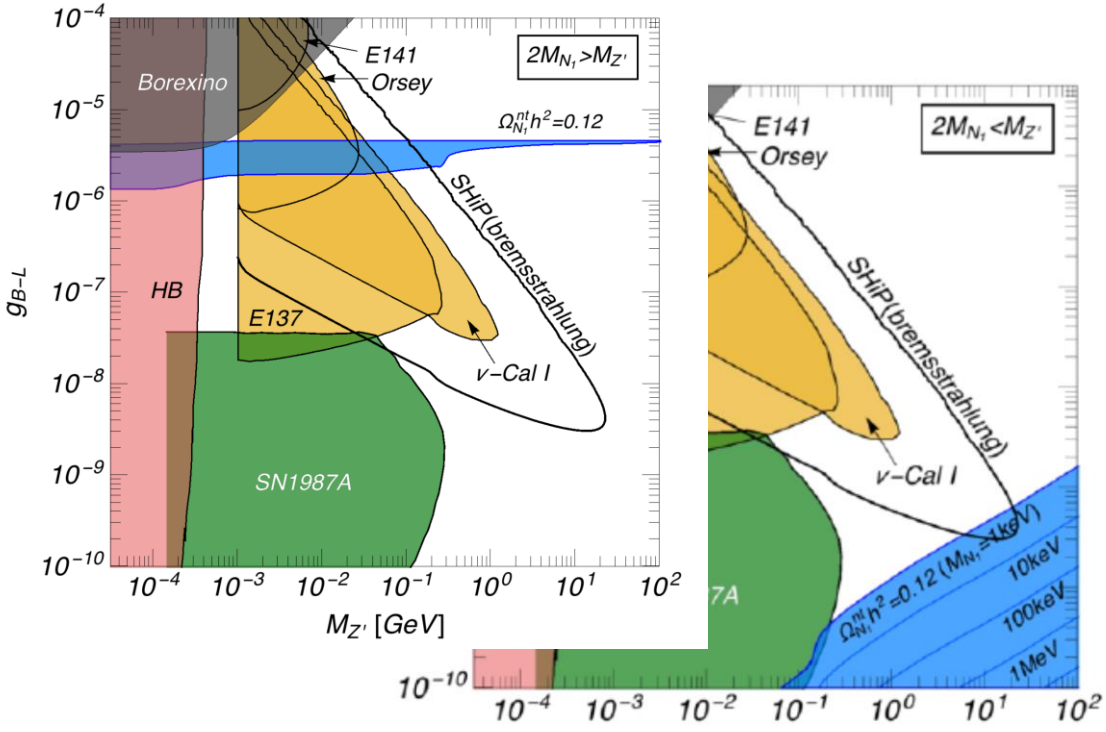
	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
Q^i	**3**	**2**	$\frac{1}{6}$	$\frac{1}{3}$
u_R^i	**3**	**1**	$\frac{2}{3}$	$\frac{1}{3}$
d_R^i	**3**	**1**	$-\frac{1}{3}$	$\frac{1}{3}$
L^i	**1**	**2**	$-\frac{1}{2}$	-1
e_R^i	**1**	**1**	-1	-1
ν_R^i	**1**	**1**	0	-1
Φ_H	**1**	**2**	$\frac{1}{2}$	0
Φ_{B-L}	**1**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





[Kaneta, Kang ane Lee (2017)]

Sterile neutrino DM production

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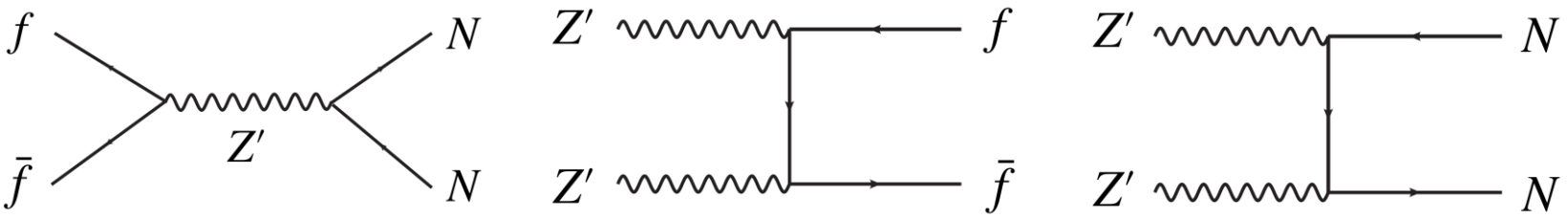
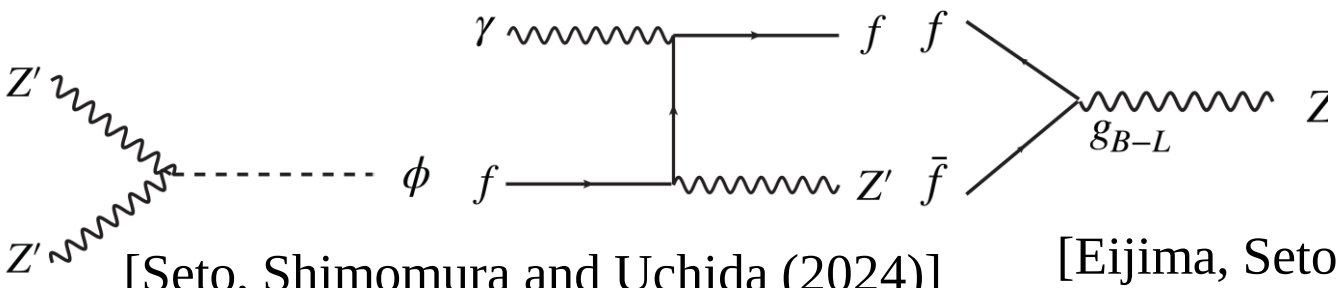
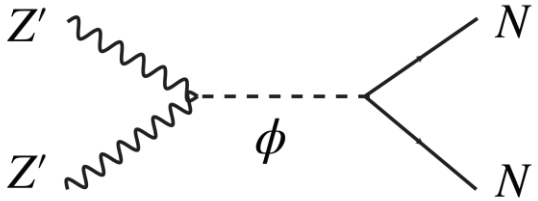


We found (sometime more) important modes



[Seto, Shimomura and Uchida (2024)]



[Eijima, Seto and Shimomura (2022)]

Phenomenology depends on 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

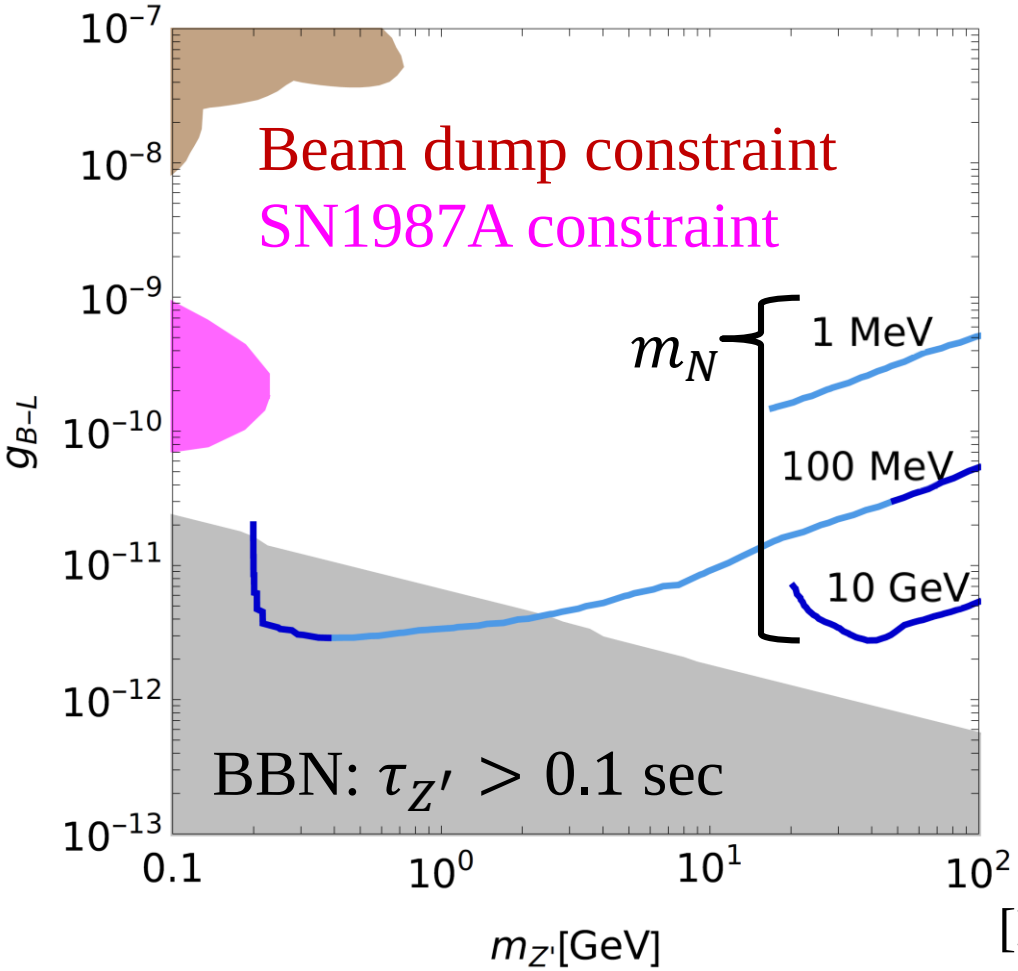
Higgs portal through the mixing
Neither Z' nor ϕ are thermalized

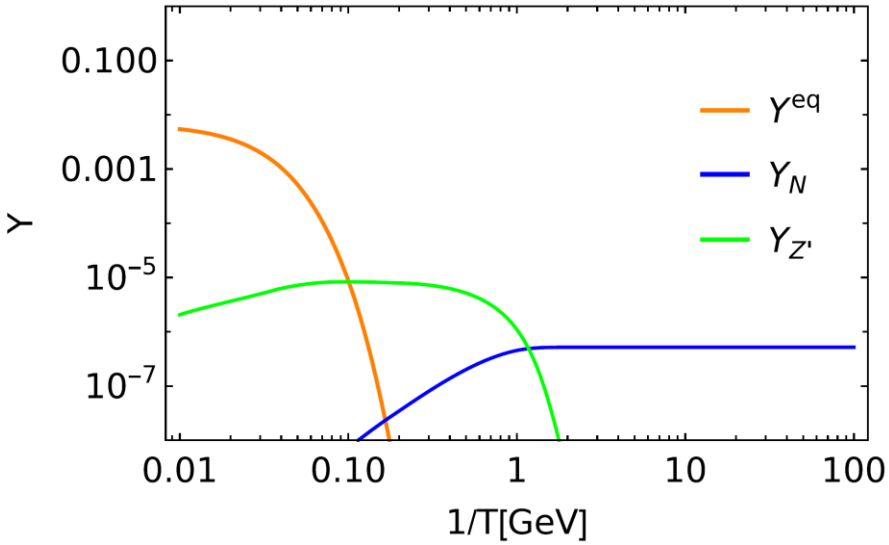
§ § $2m_N < m_{Z'}$

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

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

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



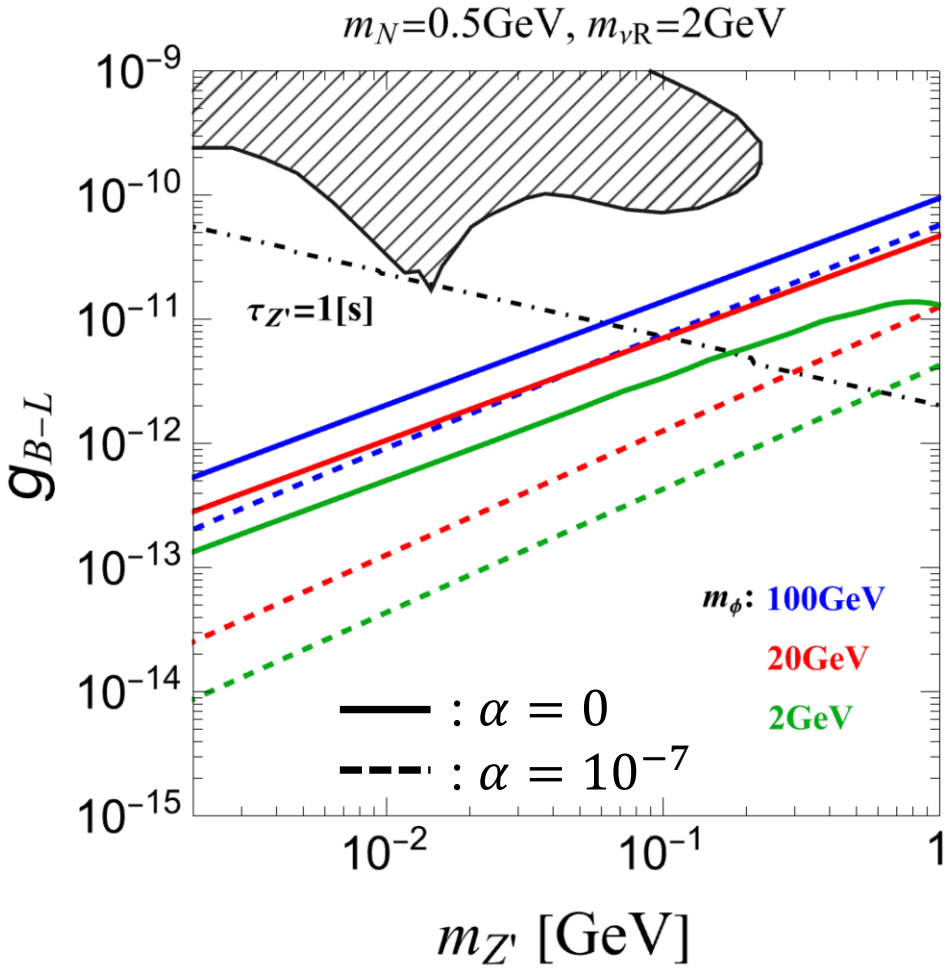


[Eijima, Seto and Shimomura (2022)]

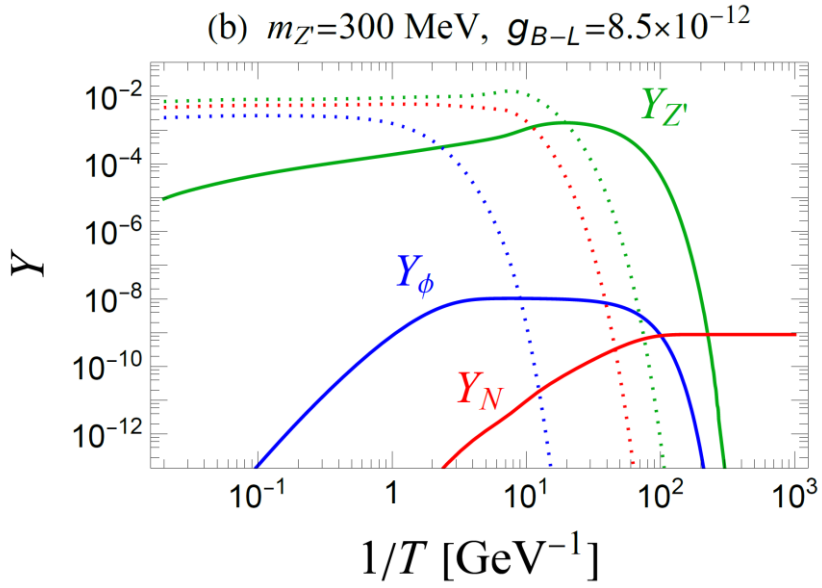
§ § $m_{Z'} < 2m_N < m_\phi$

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

[Seto, Shimomura and Uchida (2024)]



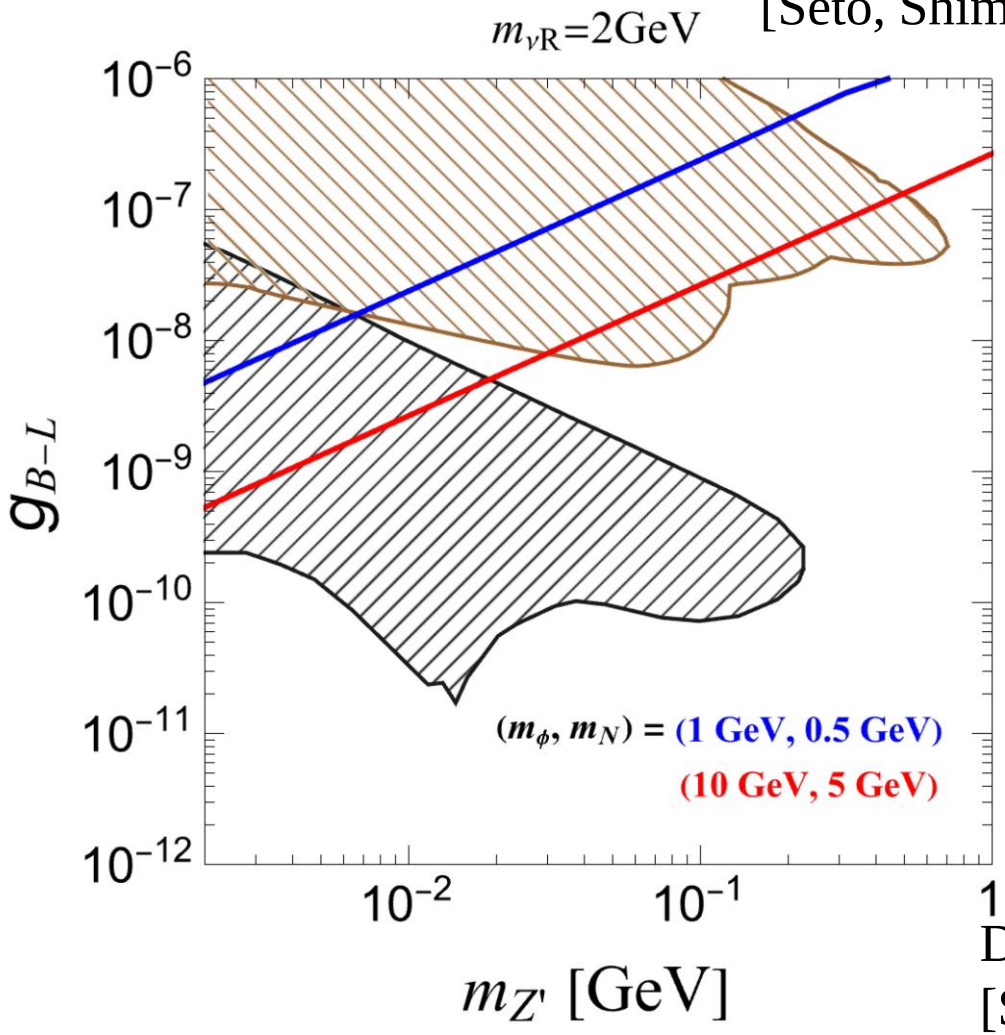
Typical yield evolution



§ § $m_{Z'}, m_\phi < 2m_N$

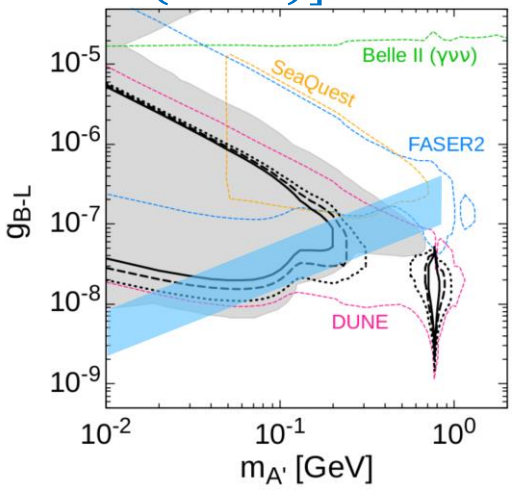
- $Z'Z' \to NN$ dominant case

[Seto, Shimomura and Uchida (2024)]



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 [Seto, Shimomura and Uchida]

§ 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
  - Free streaming constraints
- $m_{Z'} < 2m_N < m_\phi$ case
  - $f\gamma \to fZ'$, $Z'Z' \to \phi$ and $\phi \to NN$ are main modes.
  - $g_{B-L} \lesssim 10^{-9}$
- $m_{Z'}, m_\phi < 2m_N$ case
  - $g_{B-L} \lesssim 10^{-6}$
  - Z' may be found in long-lived particle search such as FASER2