# Gauged B-L interacting sterile neutrino dark matter revisited

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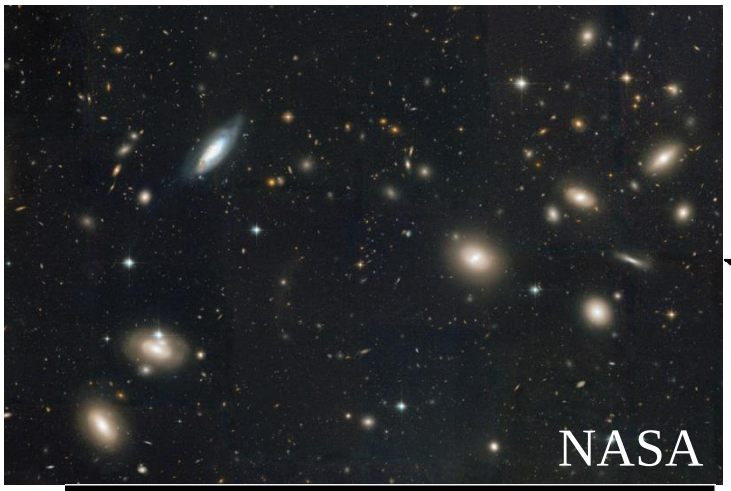
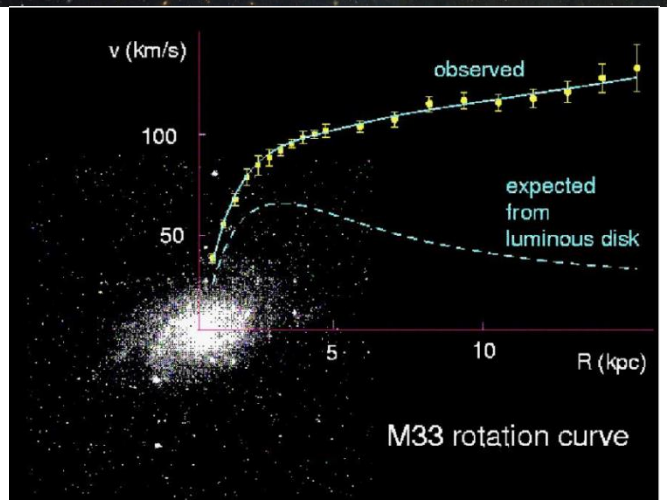
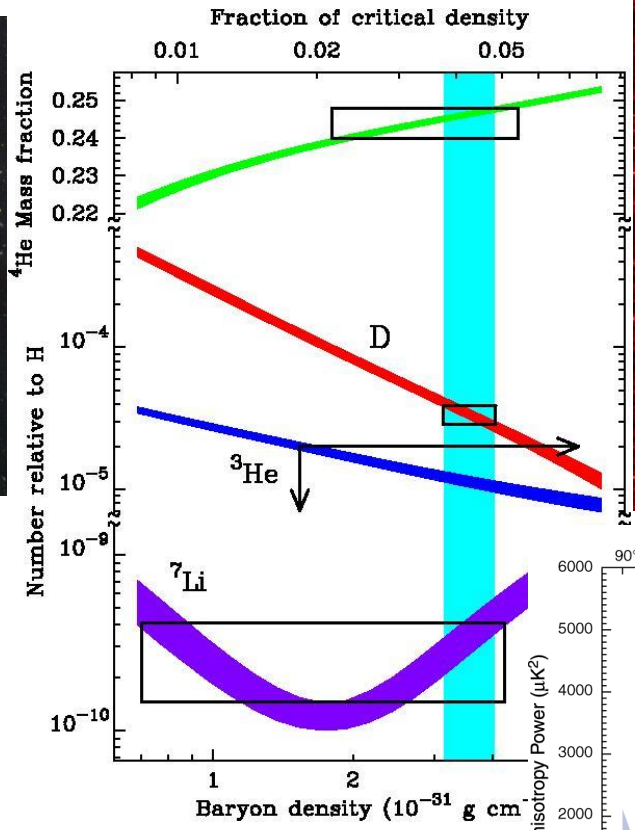
# § Introduction

# Dark matter

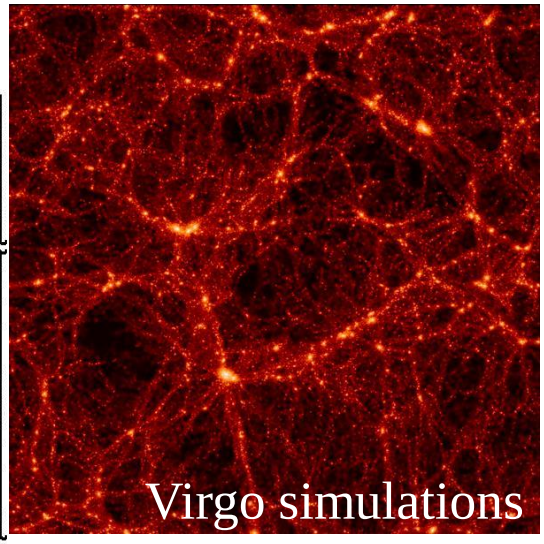
## Convincing evidences

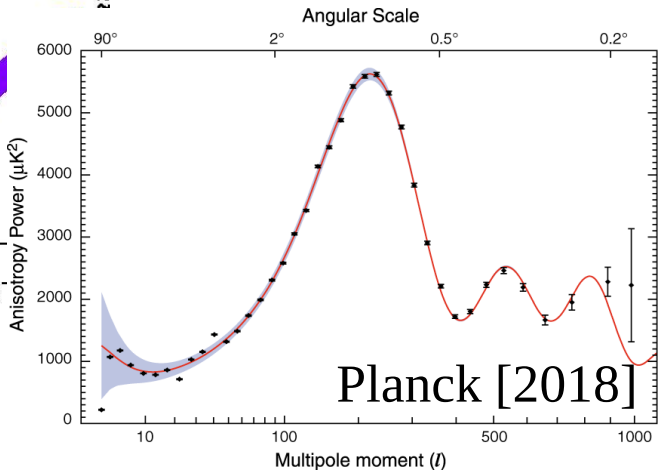



Burles et al [1999]



# Dark matter candidates

**Hypothetical candidates**

Sterile neutrino

- $\nu_s \cong \theta\, \nu_L + \nu_R^C$

Almost RH

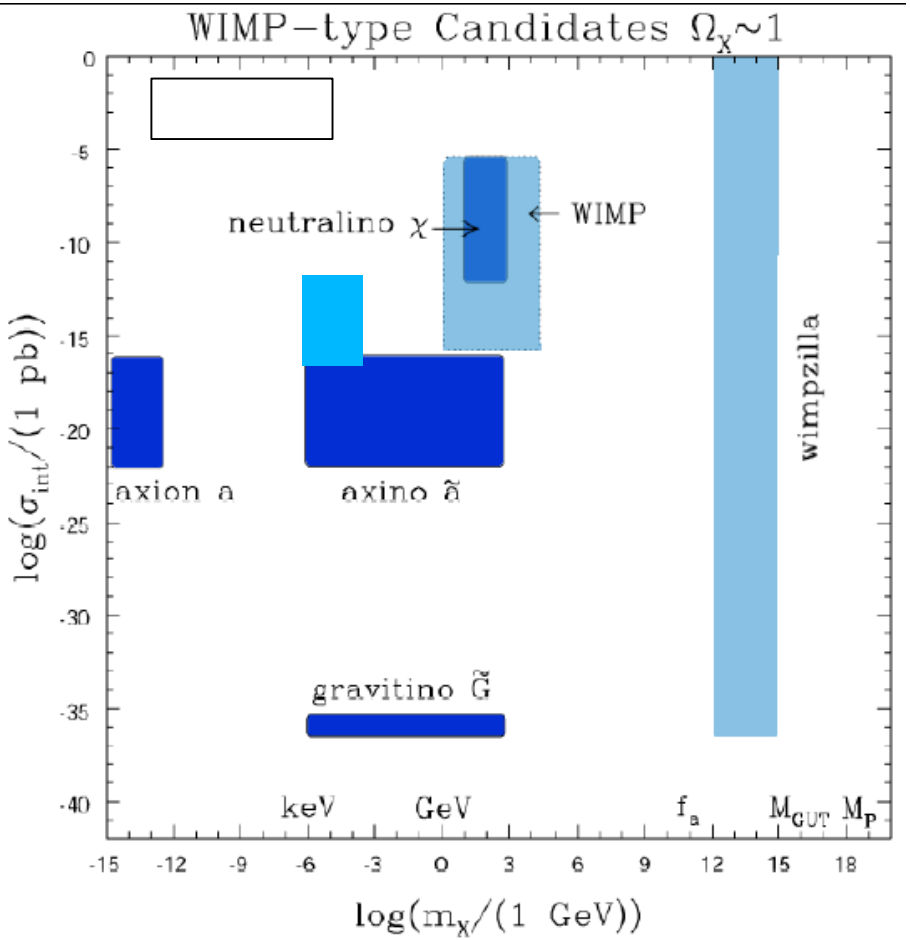
- $\theta = {}^{m_D}/_{M_M} \ll 1$

Tiny active-sterile mixing

Axion

WIMP

**etc**




**modified L. Roszkowski's diagram**

§ SM + RH neutrinos

# Adding RH neutrinos

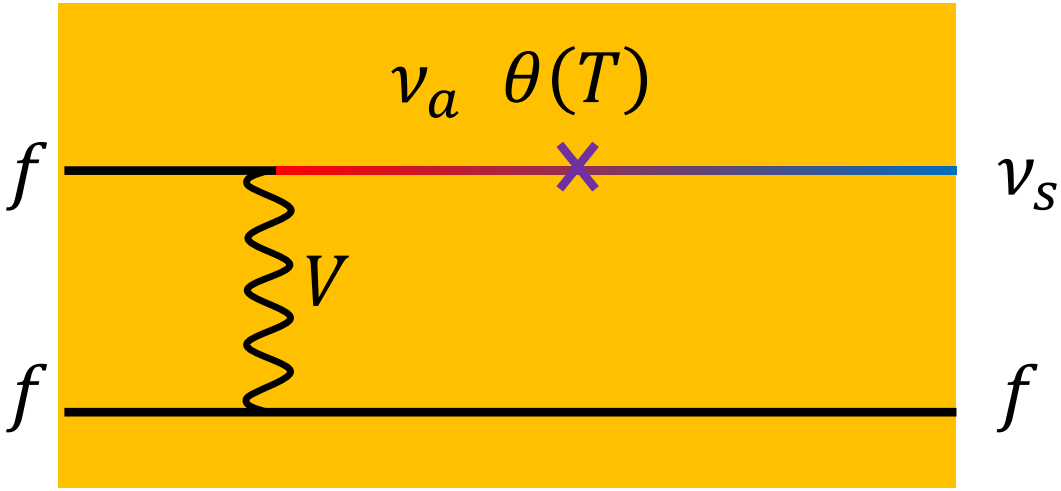
- Adding RH neutrinos

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

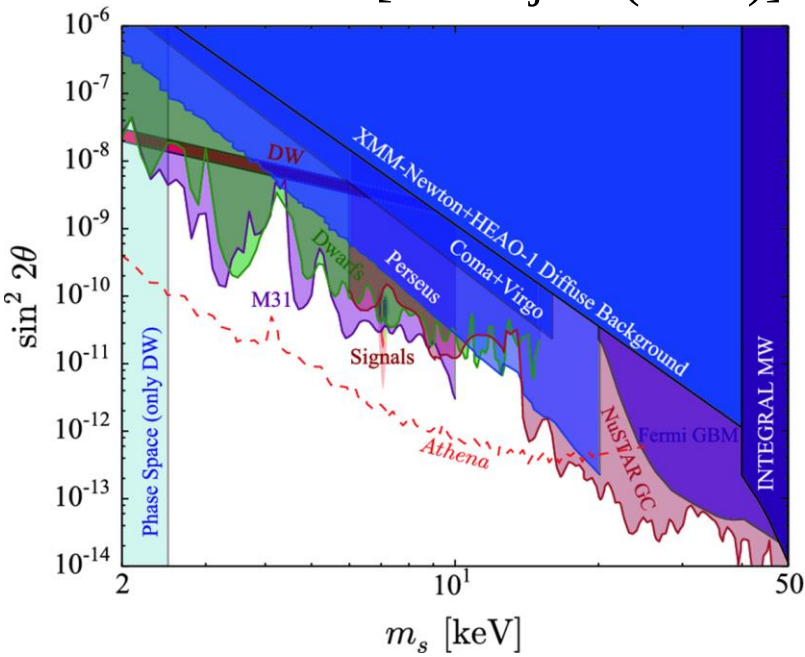
- If Dirac masses $\ll$ Majorana masses, seesaw mechanism works [Minkowski (1977), Yanagida (1979), Gell-Mann et al (1979)]
  - $\begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix} \rightarrow \begin{pmatrix} -m_D^T \frac{1}{M_M} m_D & 0 \\ 0 & M_M \end{pmatrix}$
  - $\nu_a \cong U_{MNS}\nu_L + \theta\nu_R^C$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

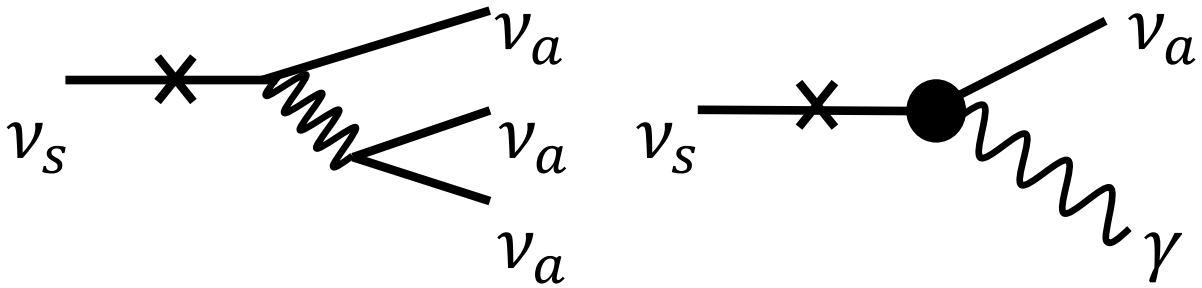
- Production: Dodelson-Widrow mechanism [Dodelson and Widrow (1994)]




[Abazajian (2019)]




- Decay [Pal and Wolfenstein (1982)]



# Sterile neutrino is decaying DM

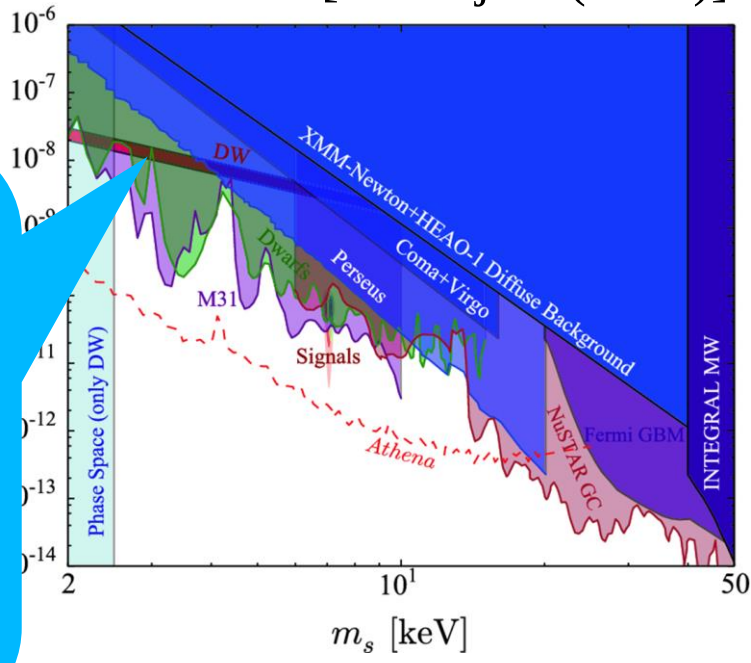
- Production: Dodelson-Widrow mechanism [Dodelson and Widrow (1994)]

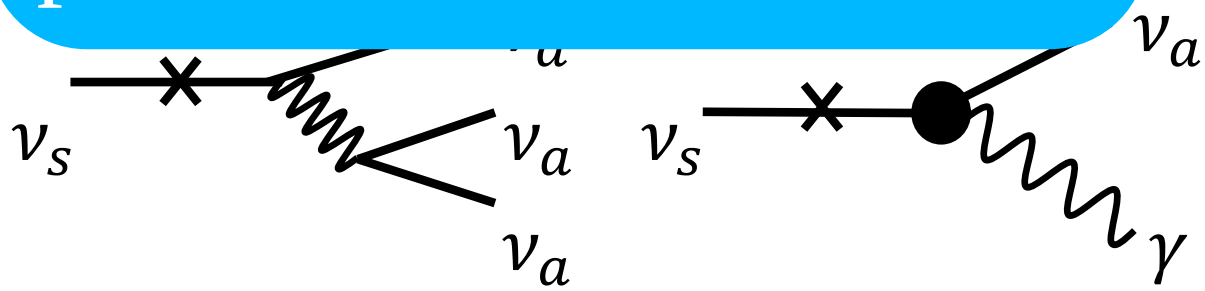
$\nu_a \;\; \theta(T)$

Not compatible

We need an alternative production mechanism

[Abazajian (2019)]



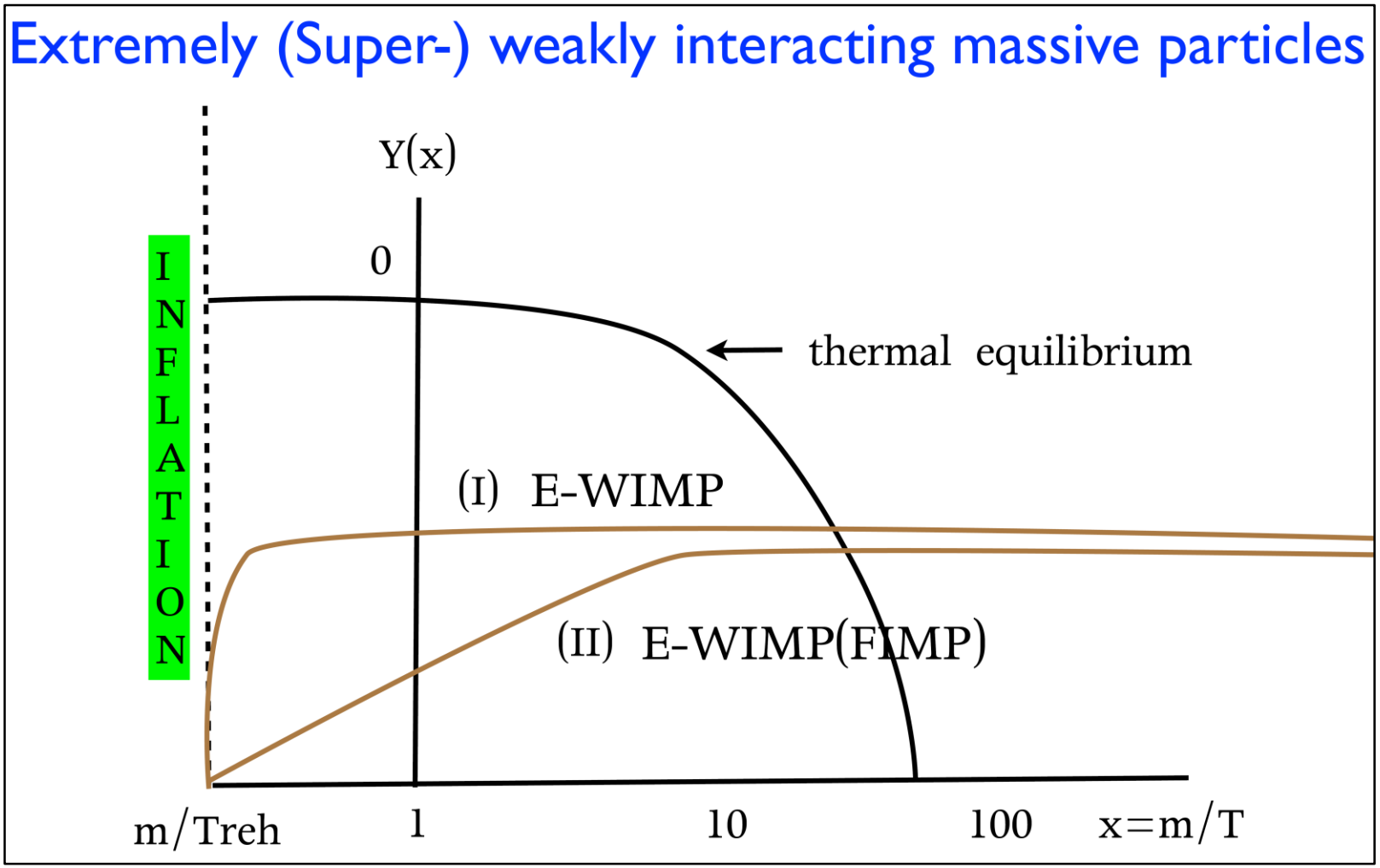
§ Freeze-in production of DM

# Freeze in Production

- UV (in)dependence
  - Depends on Reheating temperature $T_R$
    - E.g., Gravitino, Axino, …
  - Does not depends on $T_R$
    - Renormalizable Op, very weak (feeble) interaction, light mediators
    - Most effective at $T \sim$ DM mass
    - Depends on the cross section only c.f., WIMP
    - E.g., Singlet scalar DM [McDonald (2002)] RH sneutrino DM [Asaka, Ishiwata and Moroi (2006)]
    - Catchy name “Feebly Interacting massive Particle, FIMP” came later [Hall et al (2010)]

# § Freeze in Production

- A kind of non-thermal production




By courtesy of K.Y. Choi

# Freeze in Production

- With equations
- $\frac{d\, n_{\nu_s}}{dt} + 3Hn_{\nu_s} = \langle \sigma v(i\bar{\imath} \rightarrow \nu_s \nu_s) \rangle n_i n_{\bar{\imath}}$
- $\langle \sigma v(i\bar{\imath} \rightarrow \nu_s \nu_s) \rangle \sim \frac{g^4}{T^2}$
- $Y := \frac{n_{\nu_s}}{s} = \int_{T_0}^{T_R} \frac{\langle \sigma v(i\bar{\imath} \rightarrow \nu_s \nu_s) \rangle n_i n_{\bar{\imath}}}{s\, H\, T} dT$

$$\sim \int_{T_0}^{T_R} \frac{M_P\, {g^4}/{T^2}\, T^3 T^3}{s\, T^2\, T} dT \sim \frac{M_P g^4}{m_{\nu_s}}$$

- $\Omega_{\nu_s} h^2 \propto m_{\nu_s} Y \sim M_P g^4$

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

# Extension of the model

- SM+ RH neutrinos
  - Difficulty in Sterile neutrino DM production
  - The number of generation of RH neutrinos?
- Gauged U(1) extension
  - New gauge interactions provide DM production
  - Anomaly free condition
    - $U(1)_{B-L}$ : +1 for baryon, -1 for lepton [Davidson (1979), Mohapatra and Marshak (1980), …]
    - $U(1)_R$ : +1(-1) for RH, 0 for left-handed [Jung et al (2010), Ko, Omura and Yu (2014), …]
  - Various dark photon search in "lifetime frontier"

# Model

- Sterile neutrino DM in feeble gauged U(1) extended model
- Gauged U(1) extension
  - $U(1)_{B-L}$ : +1 for baryon, -1 for lepton [Davidson (1979), Mohapatra and Marshak (1980), …]
  - Particle content

| | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_{B-L}$ |
|---|---|---|---|---|
| $Q^i$ | **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** | $-1$ | $-1$ |
| $\nu_R^i$ | **1** | **1** | 0 | $-1$ |
| $\Phi_H$ | **1** | **2** | $\frac{1}{2}$ | 0 |
| $\Phi_{B-L}$ | **1** | **1** | 0 | 2 |

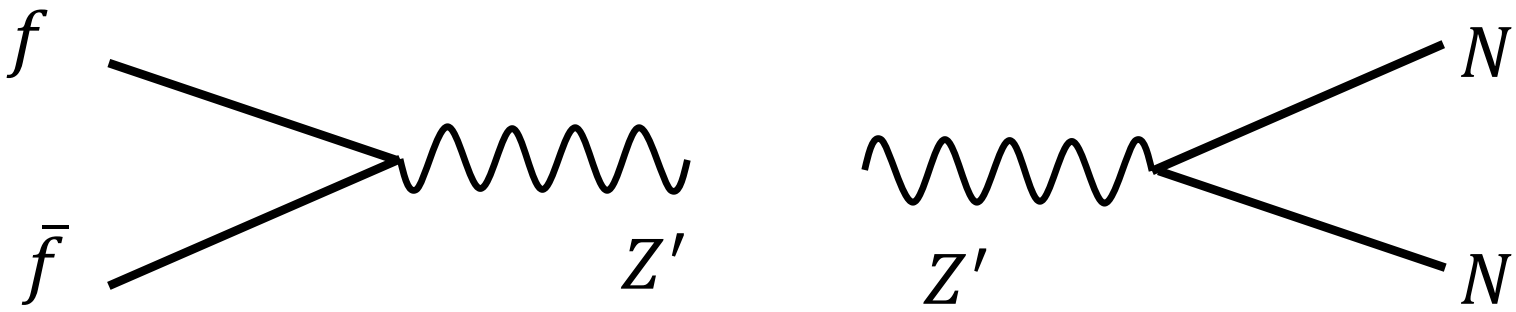
  - Masses
    - $m_{Z'}^2 = 4g_{B-L}^2 v_{B-L}^2$
    - $m_{\nu_R^i} = \frac{y_{\nu_R^i}}{\sqrt{2}} v_{B-L}$
  - Singlet-like $\phi$
  - SM-like $h$
    - The $h - \phi$ mixing $\alpha$

# Mass spectrum

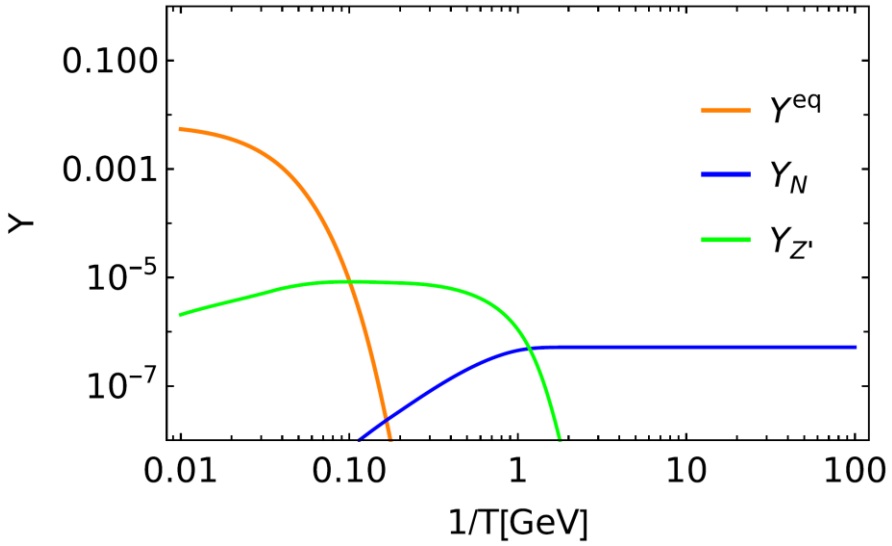
- Dark matter phenomenology depends on the mass spectrum (hereafter $N = \nu_s$)
- $2m_N < m_{Z'}$
  - Decay $Z' \rightarrow NN$ is possible
- $1\mathrm{MeV} < m_{Z'} < 2m_N$
  - Decay $Z' \rightarrow NN$ is not possible
  - $Z'$ is non-relativistic at BBN
- $m_{Z'} < 1\mathrm{MeV} < 2m_N$
  - $Z'$ and ν from $Z'$ are relativistic for BBN and CMB, stellar (RG, HB) constraints [Redondo and Raffelt (2013)], SN1987A constraints [Croon et al (2021), Shin et al (2022),…]

# § § Heavy $Z'$ : $2m_N < m_{Z'}$

- $Z'$ are not thermalized
- Main production mode : $f\bar{f} \to Z' + Z' \to 2N$

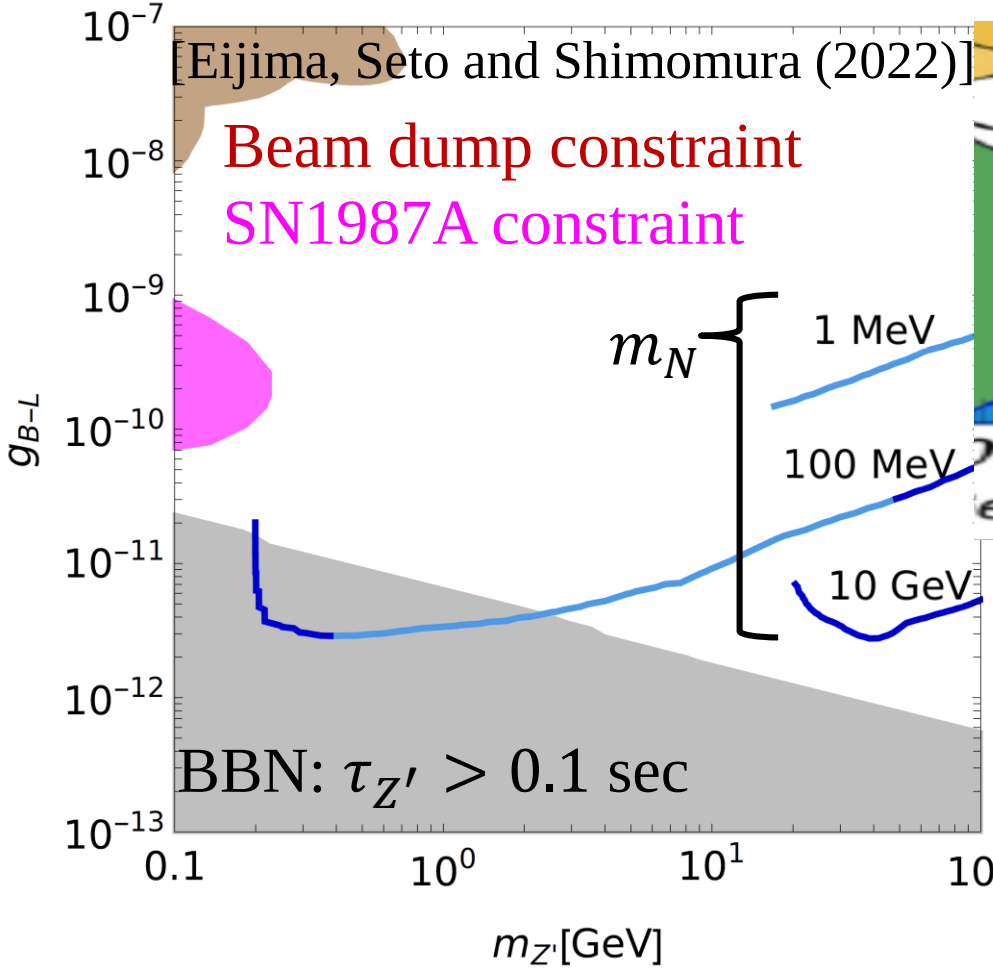


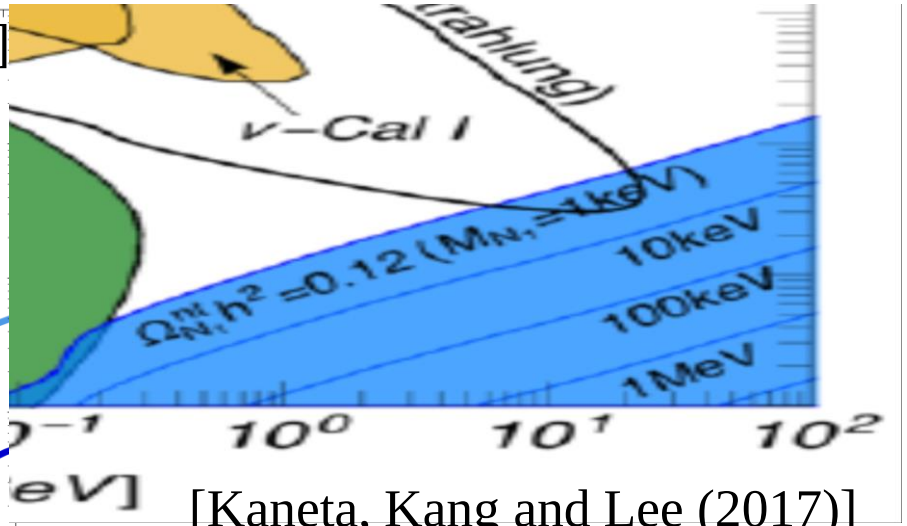

- At the production
  - $p_N \cong \frac{1}{2} m_{Z'}$ could be relativistic.
  - Warm DM?



# § § Heavy $Z'$ : $2m_N < m_{Z'}$

- Production by decay: $Z' \to 2N$ (hereafter $N = \nu_s$)
- The free streaming length $\lambda_{\rm fs}$ bound [Irsic et al (2017)]



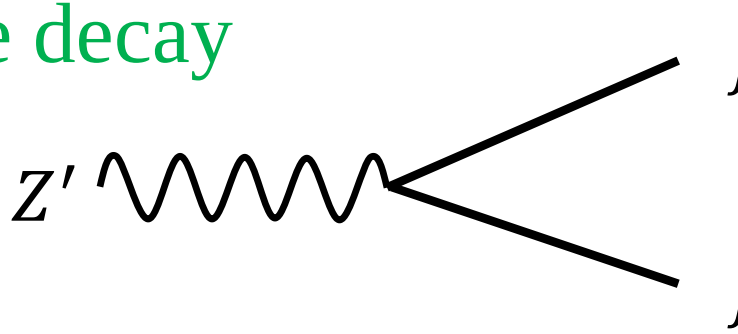

[Kaneta, Kang and Lee (2017)]

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

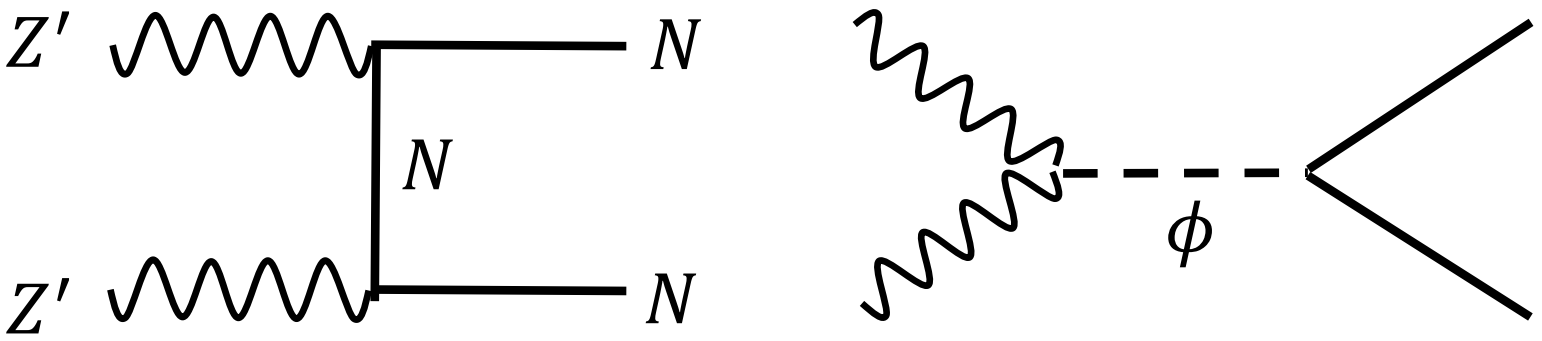
$\lambda_{\rm fs} < 0.01\ \text{Mpc}$

# §§ Light $Z'$ : $1\text{MeV} < m_{Z'} < 2m_N$

- $Z'$ can be thermalized by the decay and the inverse decay



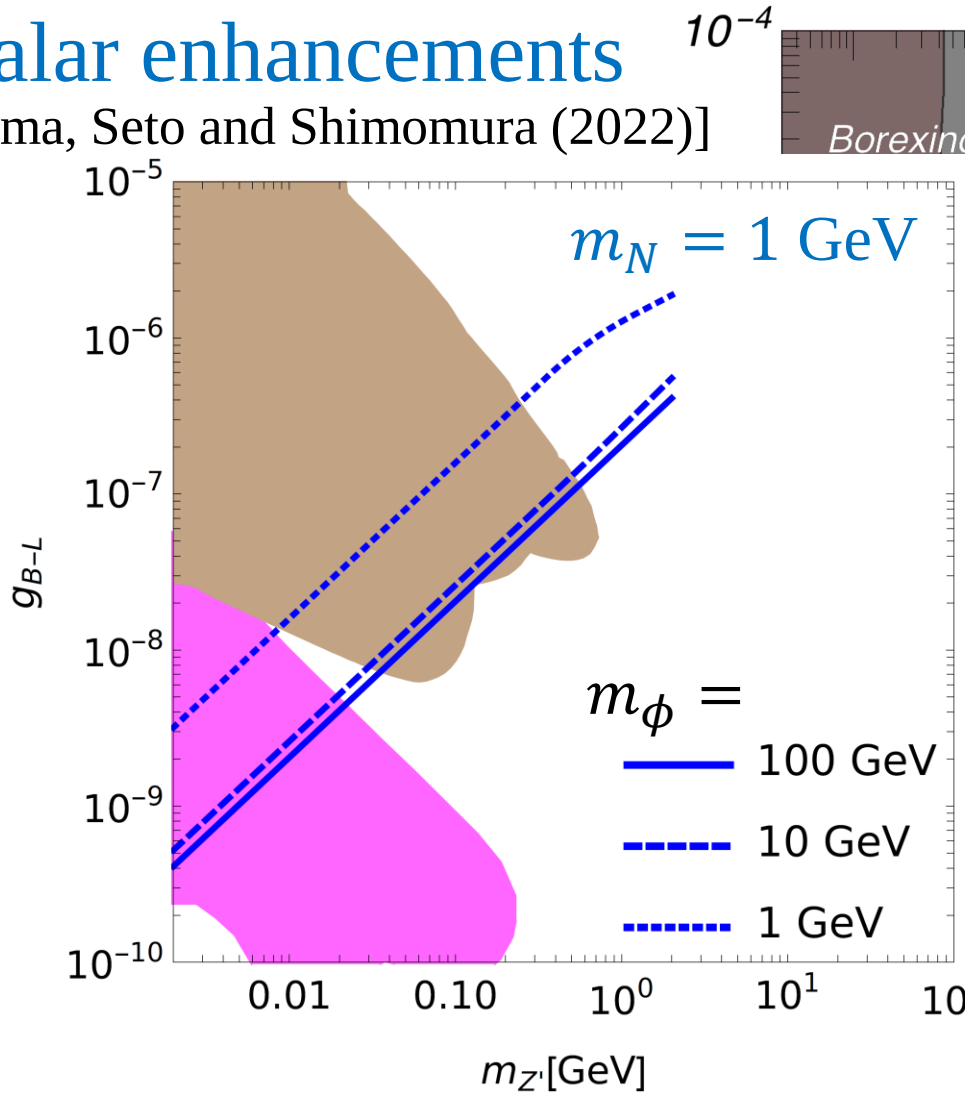

- The dominant production mode from $Z'$

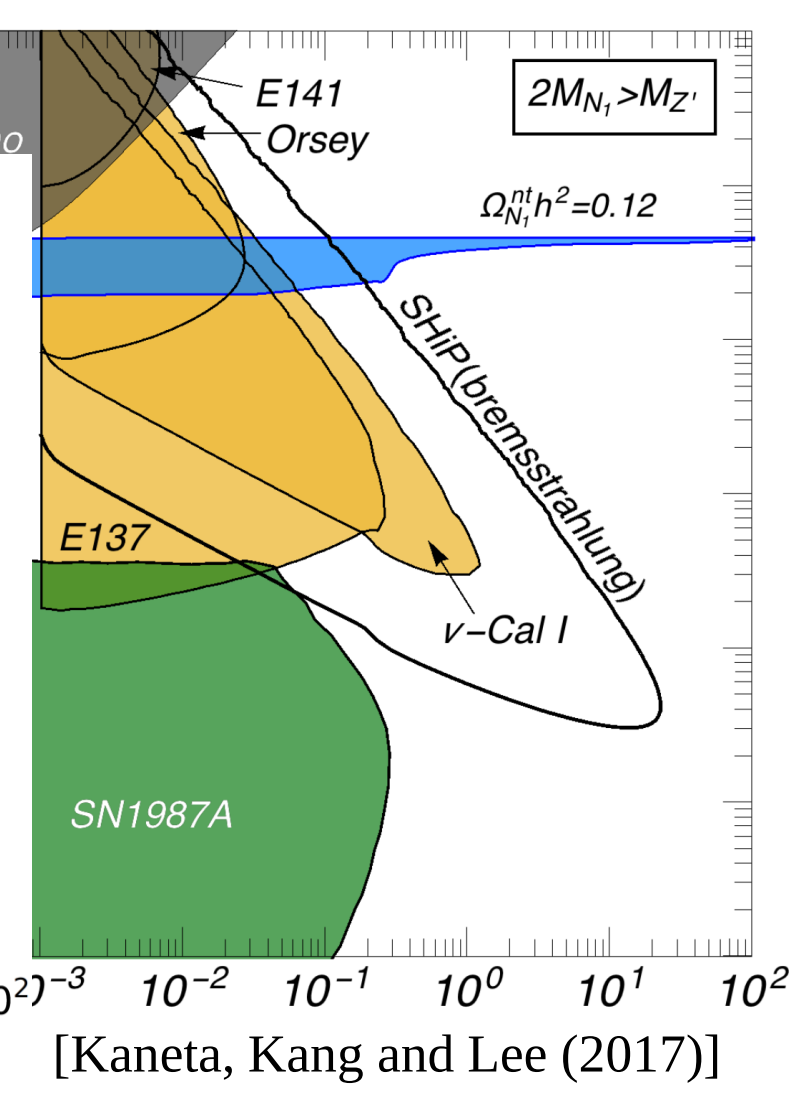


# § § Light $Z'$ : $1\mathrm{MeV} < m_{Z'} < 2m_N$

longitudinal mode and scalar enhancements

[Eijima, Seto and Shimomura (2022)]



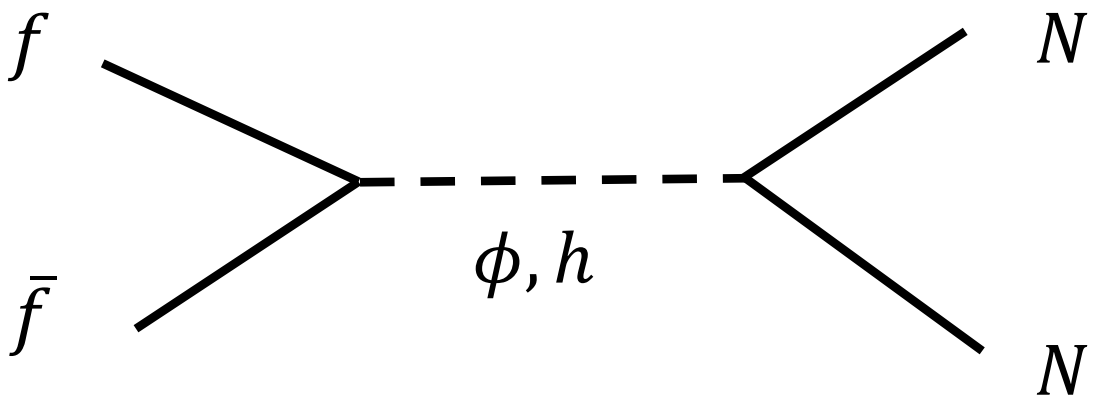




[Kaneta, Kang and Lee (2017)]

# §§ Very light $Z'$:

# $m_{Z'} < 1\mathrm{MeV} < 2m_N$

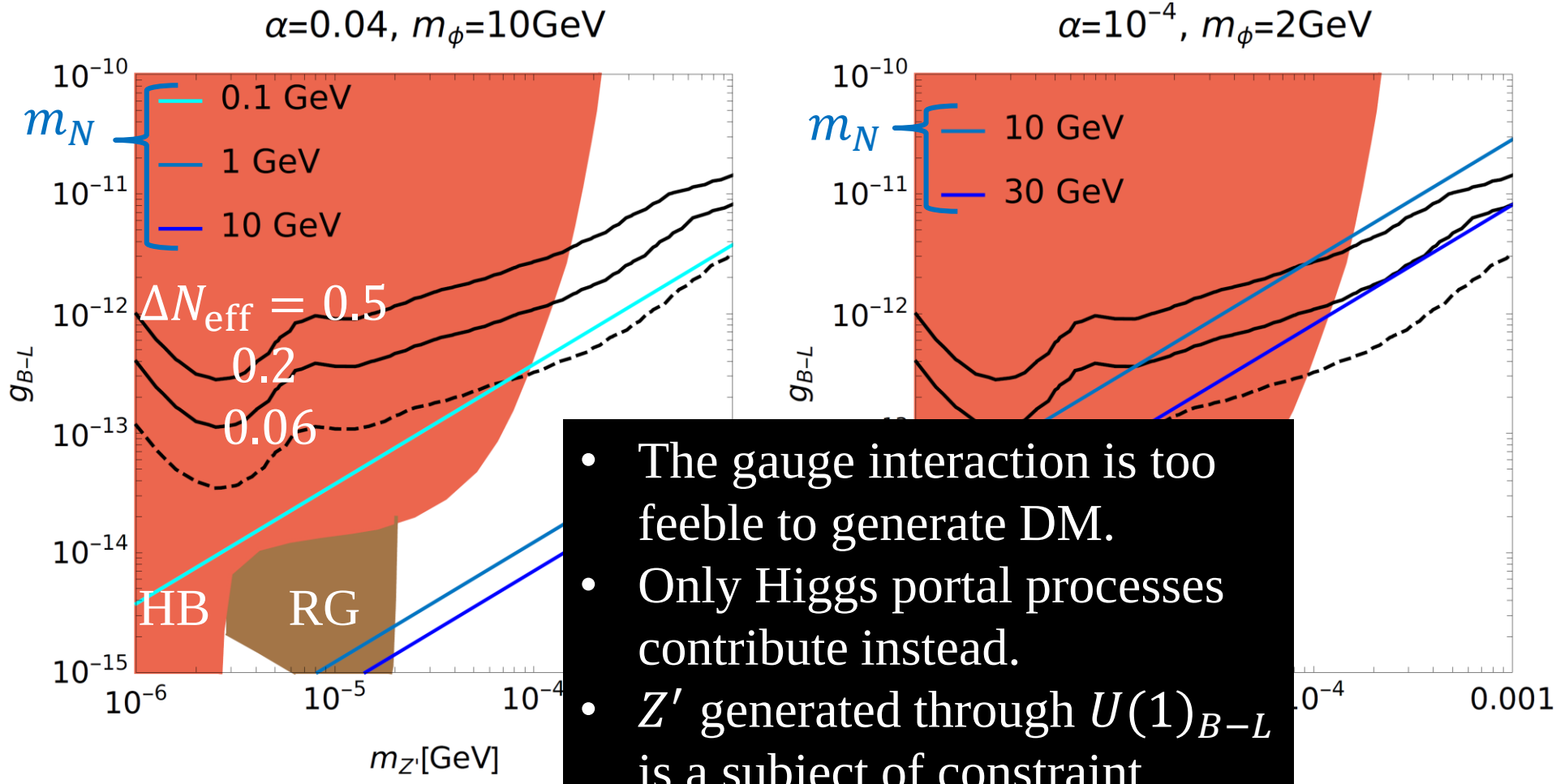
- Little $Z'$ could be produced.
  - If not, too much dark radiation
  - Gauge coupling must be very small
- Main production mode : $f\bar{f} \to (\phi, h) \to 2N$
  - Though Higgs mixing, not gauge interaction



# §§ Very light $Z'$:

# $m_{Z'} < 1\text{MeV} < 2m_N$

- $Z'$ and the decay products become dark radiation




- The gauge interaction is too feeble to generate DM.
- Only Higgs portal processes contribute instead.
- $Z'$ generated through $U(1)_{B-L}$ is a subject of constraint

# § Summary

- We reinvestigated sterile neutrino DM in gauged B-L model
- Production
  - Heavy $Z'$: free streaming constraints
  - Light $Z'$: longitudinal mode and scalar enhancements
  - Very light $Z'$: only Higgs portal viable
- Mass
  - $\gtrsim$ 1 MeV
  - $\nu_s \to \nu_a l\bar{l}$, hadronic modes
    - ✓ c.f. X-ray from radiative decay for keV $\nu_s$