Freeze-in sterile neutrino dark matter in a feebly gauged $B-L$ model

Yoshiki Uchida[a,b]

[a] South China Normal Univ. (SCNU) [b] Central China Normal Univ. (CCNU)

Based on

- JHEP 05 (2025) 147, [2404.00654]

  Collaborated with **Osamu Seto** (Hokkaido U.) **Takashi Shimomura** (Miyazaki U.)

- [2603.28882], currently under review in JHEP

  Collaborated with **Takeshi Araki** (Koriyama Women's U.) **Kento. Asai** (Kyoto U.) **Yohei Nakashima** (Kyushu U.) **Osamu Seto** (Hokkaido U.) **Takashi Shimomura** (Miyazaki U.)

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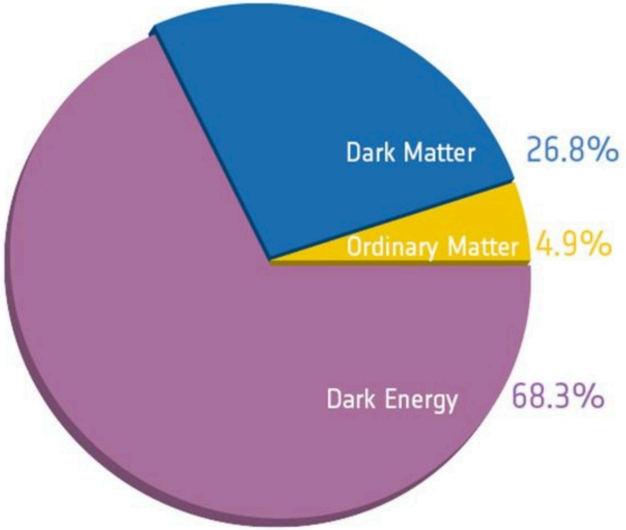
Introduction(2/2)

Dark Matter

✔ Unknown matter (**Dark Matter**) accounts for 26.8% of the total in the universe

✔ Strong evidences supporting the existence of DM
- Galactic rotation curves
- Collision of galaxy clusters

✔ No candidate in the SM



https://www.quora.com/What-is-the-percentage-of-dark-matter-in-the-universe

Neutrino Mass

✔ Observation indicates that at least two neutrinos are massive

✔ Neutrinos are massless in the SM

One of the attractive candidates for addressing both problems is

type-I seesaw model with sterile neutrino DM

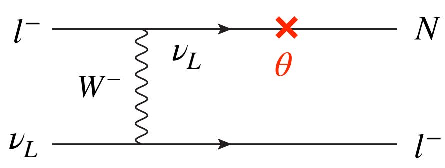
Constraint on sterile neutrino DM

✔ Sterile nutrino DM from Dodelson Widrow mechanism is excluded

Hereafter, N denotes sterile ν DM.

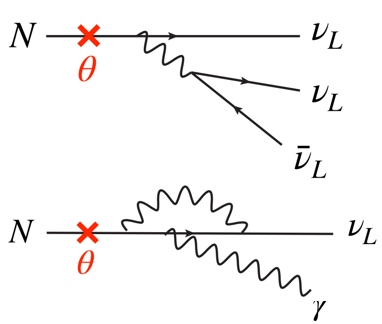
Both production & decay depend on θ

- Freeze-in production of N

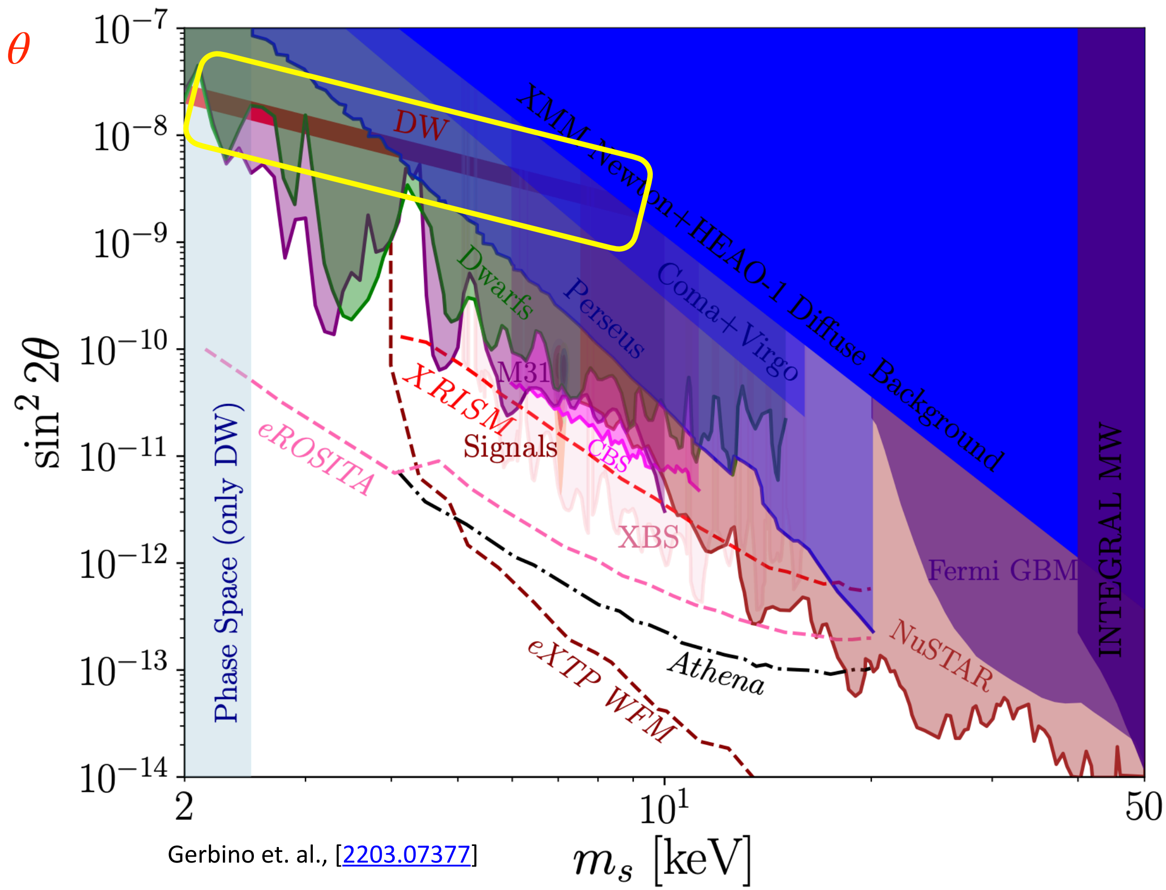


S. Dodelson and L. M. Widrow, [hep-ph/9303287]

- Radiative decay of N



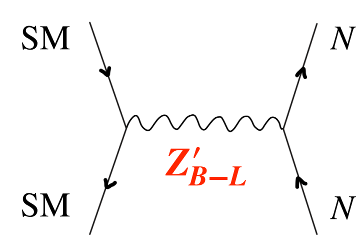
P. B. Pal and L. Wolfenstein, [PhysRevD.25.766]



Gerbino et. al., [2203.07377]

✔ Altanative production mechanism is needed

✔ $\mathrm{SM} - N$ scattering through new mediator: **Gauged $U(1)_{B-L}$ model**



Gauged $B-L$ model w/ sterile ν DM

	Q^i	u^i	d^i	L^i	e_R^i	ν_R^i	H	Φ
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**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

We introduce 3 ν_R

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\nu_R} - V(H,\Phi)$$

*We dropped $\epsilon B_{\mu\nu}X^{\mu\nu}$ for simplicity

$$\mathscr{L}_{\nu_R} = \overline{\nu}_R^i i\gamma^\mu D_\mu \nu_R^i - Y_{\nu ij}\overline{L}^i\tilde{H}\nu_R^j - \frac{1}{2}Y_{\nu_R}\Phi\,\overline{\nu^c}_R^i\nu_R^i + \mathrm{h.c.}$$

$$V(H,\Phi) = \frac{\lambda_1}{2}\left(|H|^2 - \frac{v_H^2}{2}\right)^2 + \frac{\lambda_2}{2}\left(|\Phi|^2 - \frac{v_{B-L}^2}{2}\right)^2 + \lambda_3\left(|H|^2 - \frac{v_H^2}{2}\right)\left(|\Phi|^2 - \frac{v_{B-L}^2}{2}\right)$$

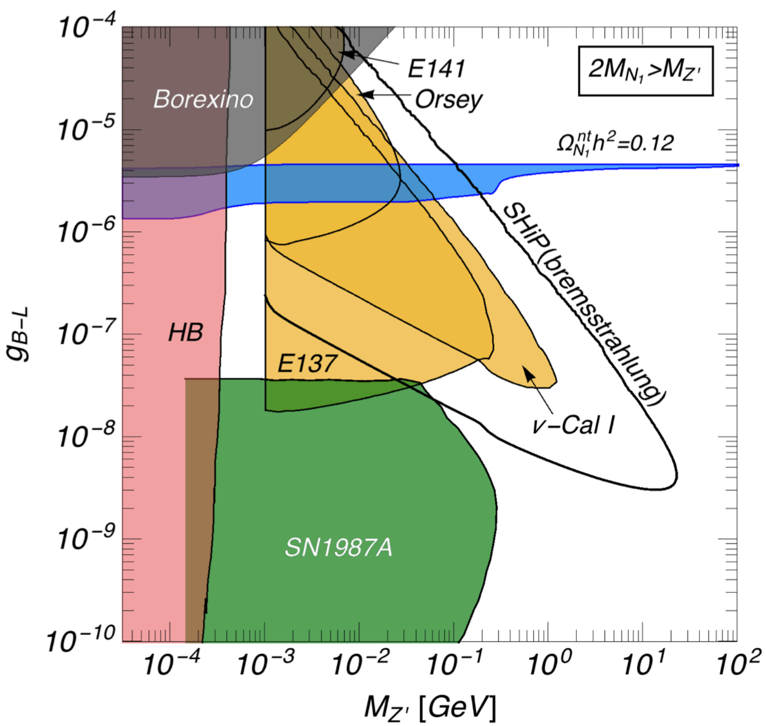
$$H = \frac{1}{\sqrt{2}}(0,\ v_H + \tilde{h})^T \qquad \Phi = \frac{v_{B-L} + \tilde{\phi}}{\sqrt{2}} \qquad \begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \tilde{h} \\ \tilde{\phi} \end{pmatrix}$$

$$m_{N_i} = \frac{1}{\sqrt{2}}Y_{\nu_R}v_{B-L} \qquad m_{Z'} = 2g_{B-L}v_{B-L}$$

Gauged $B-L$ model w/ sterile ν DM

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

We introduce 3 ν_R



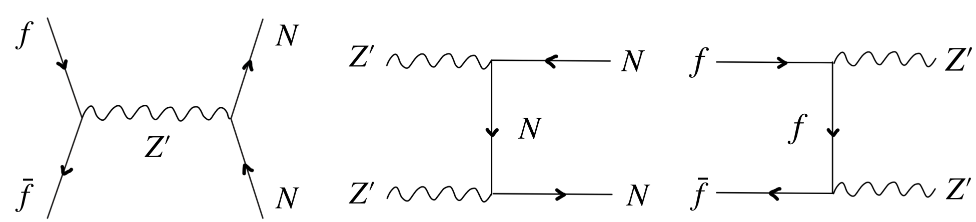
K. Kaneta, Z. F Kang, H. S. Lee, [1606.09317]

✔ Freeze-in sterile ν DM scenario in gauged $U(1)_{B-L}$ is comprehensively studied in Kaneta *et. al.* (2017)

✔ They consider $\lambda_{HS}|H|^2|\Phi|^2$ is vanishingly small

- ϕ does not come into the thermal bath $\quad \Phi = \frac{v_{B-L}+\phi}{\sqrt{2}}$
- Non-thermal production of N through the decay of ϕ is sufficiently small

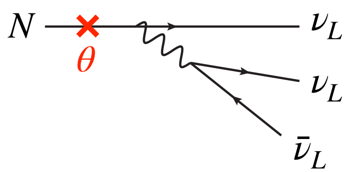
✔ Relevant scattering processes are



✔ What happens if we take ϕ effects into account?

Gauged $B - L$ model w/ sterile ν DM

✔ Dominant decay mode: $N \to 3\nu$



$$\Gamma_{N_1 \to 3\nu} = \frac{1}{13.7 \times 10^9\ \text{years}} \left(\frac{M_N}{\text{GeV}}\right)^3 \left(\frac{\sum_\alpha |Y_{\alpha 1}|}{5.3 \times 10^{-34}}\right)$$

✔ N will be stable as long as the $\sum_\alpha |Y_{\alpha 1}|^2 \simeq 0$

✔ In this limit, the lightest neutrino would be massless ($m_{\nu 1} = 0$) or almost massless, which is still consistent with the experimental constraints

Case A: $m_\phi > 2m_N > m_{Z'}$

○ $\phi \to NN$

✕ $Z' \to NN$

Case B: $2m_N > m_\phi, m_{Z'}$

✕ $\phi \to NN$

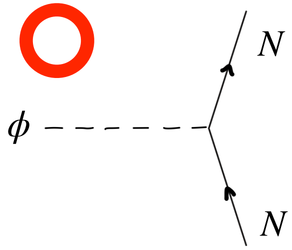
✕ $Z' \to NN$

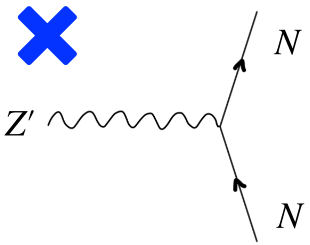
If you want to know the other spectrum, please visit

K. Kaneta, Z. F Kang, H. S. Lee, [1606.09317]

S. Eijima, O. Seto, T. Shimomura, [2207.01775]

Case A: $m_\phi > 2m_N > m_{Z'}$



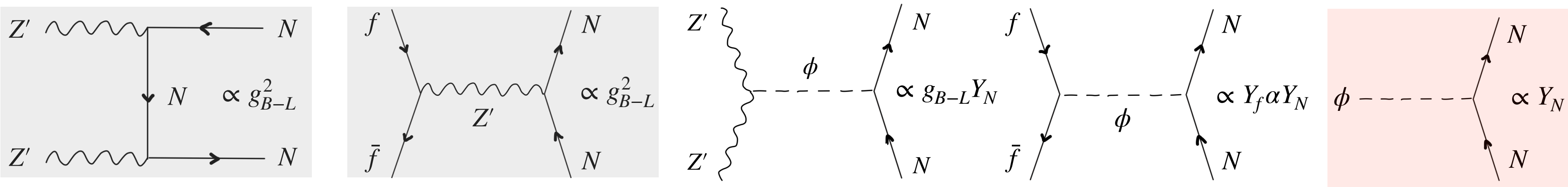


Production Channels

Case A
$m_\phi > 2m_N > m_{Z'}$

N production

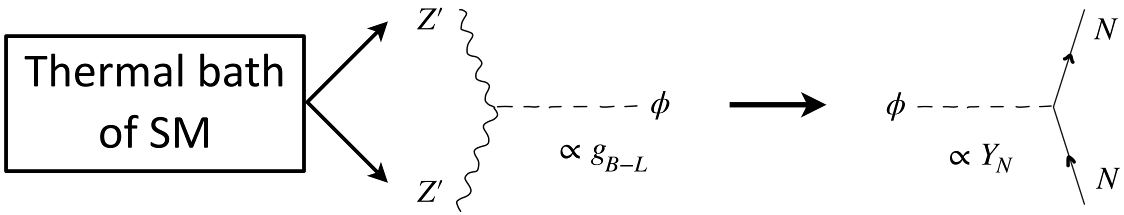
dominant



Kaneta, Kang, Lee

Our work

— Entire production process of N —



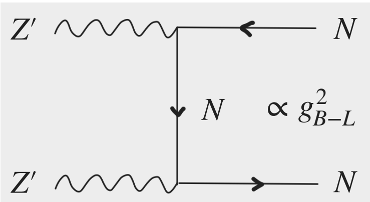
1. $\phi \to NN$ is so effective
2. $Z'Z' \to \phi$ needs to be suppressed to avoid overproduction of N
3. g_{B-L} is shifted to quite a small value
4. Z' is no longer thermalized

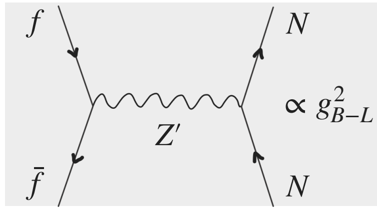
Production Channels

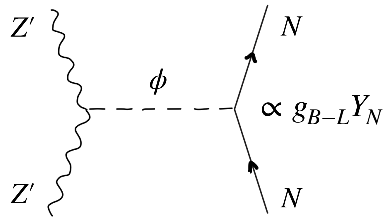
Case A
$m_\phi > 2m_N > m_{Z'}$

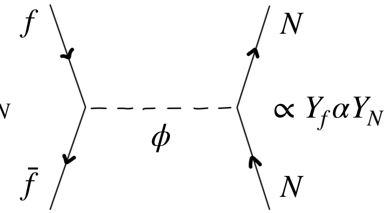
N production

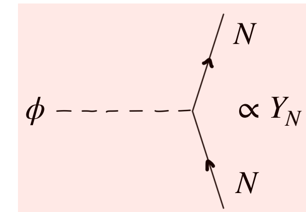
dominant











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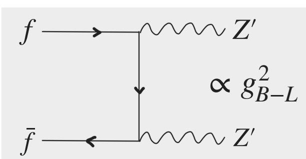
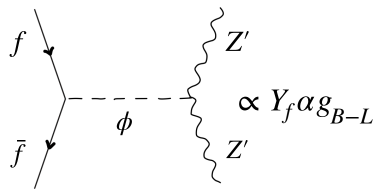
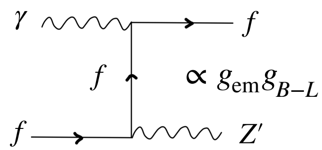
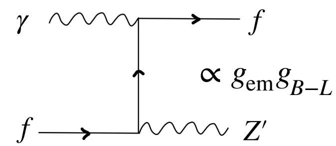
Our work

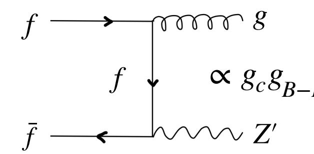
Z' production

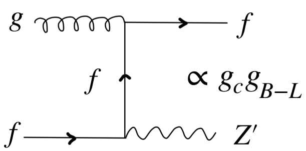


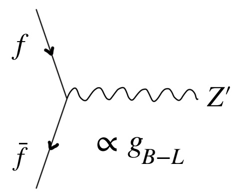


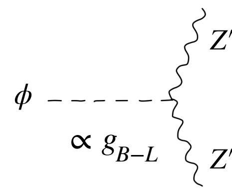




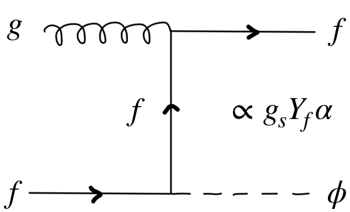


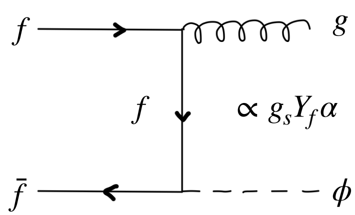


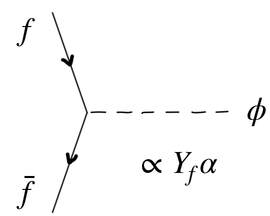


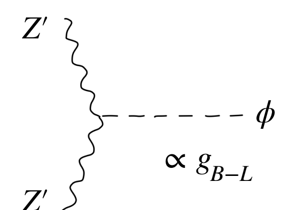


ϕ production









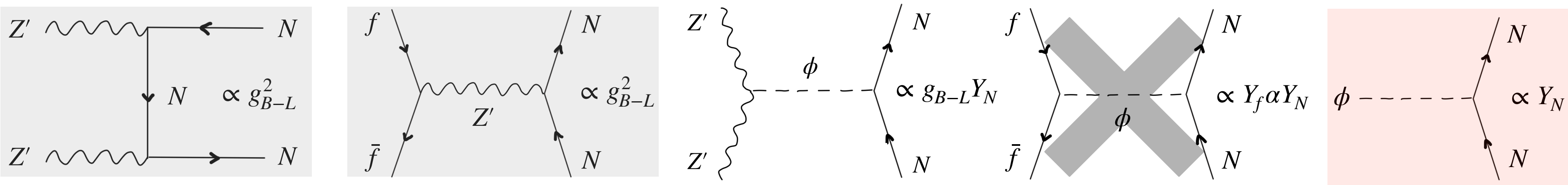
Production Channels

Case A ($\alpha = 0$)
$m_\phi > 2m_N > m_{Z'}$

N production

ϕ-h mixing $\alpha = 0$

dominant



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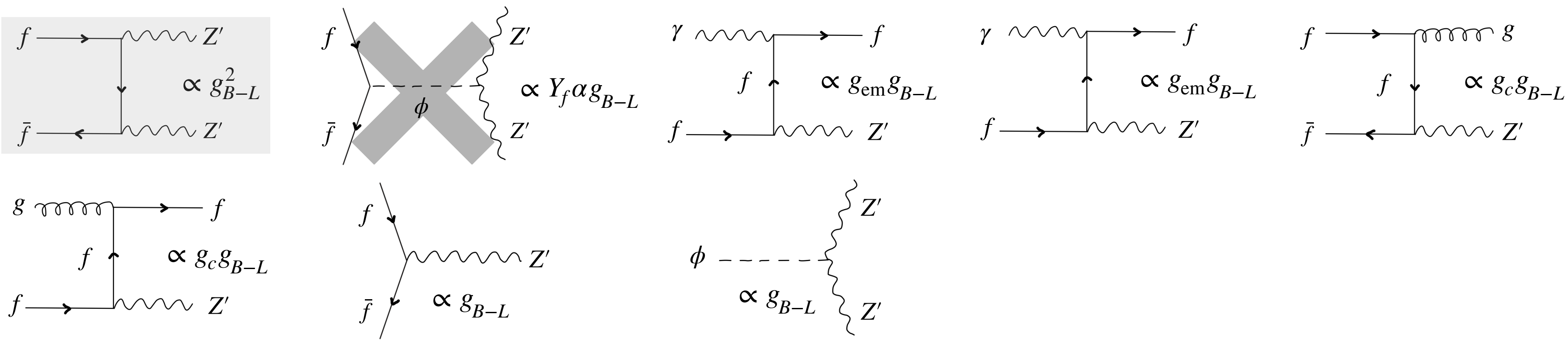
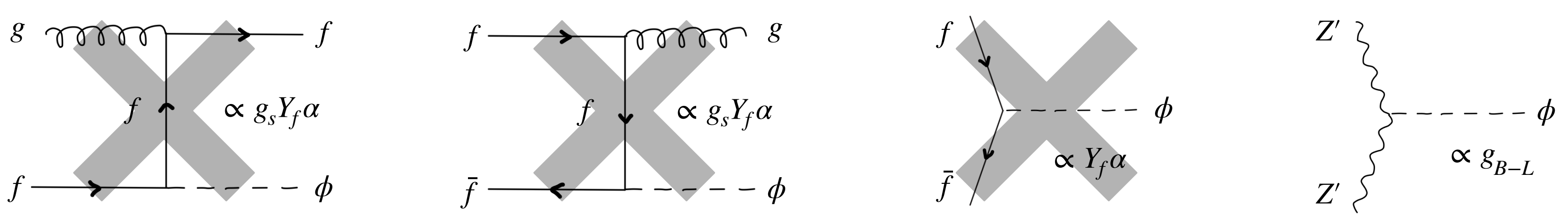
Our work

Z' production



ϕ production



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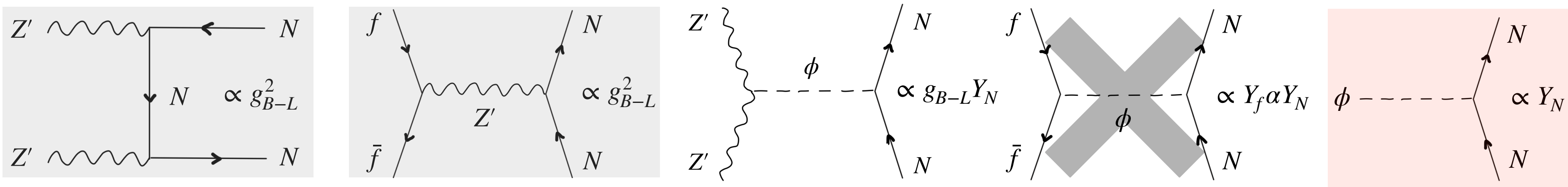

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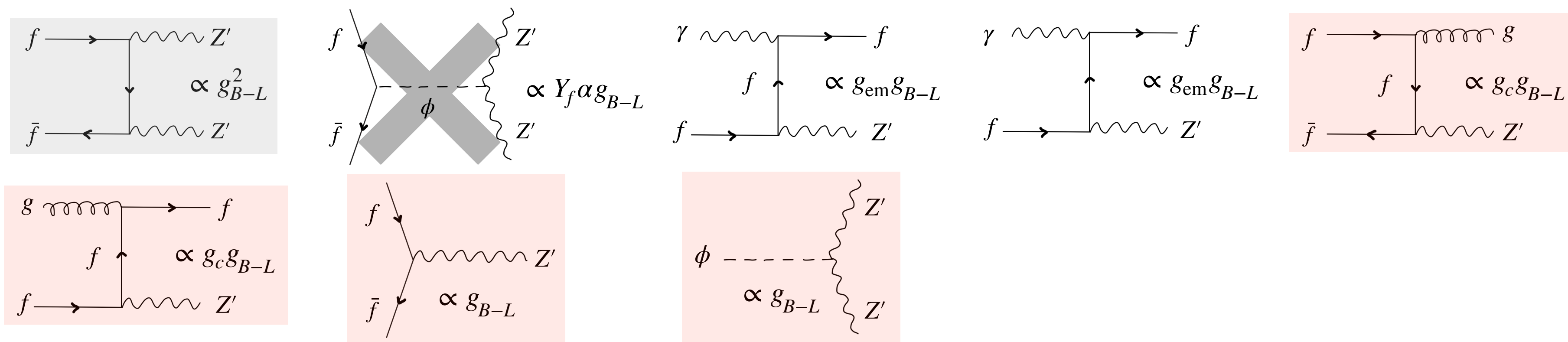
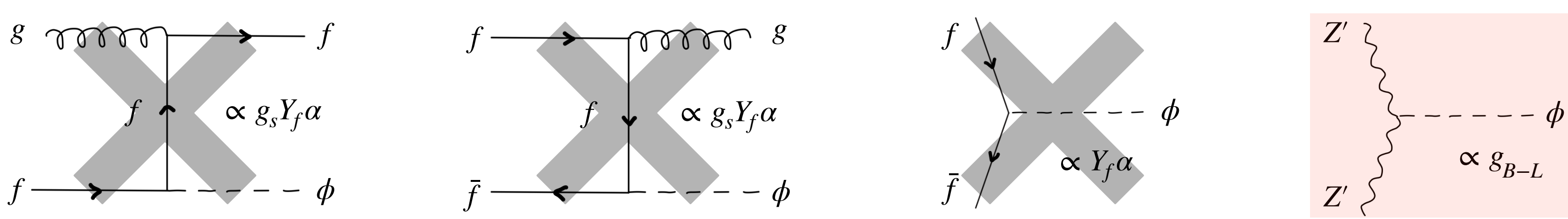
Our work

Z' production



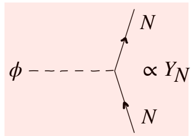
ϕ production



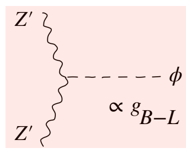
Boltzmann equations

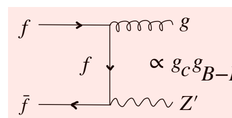
Case A ($\alpha = 0$)
$m_\phi > 2m_N > m_{Z'}$

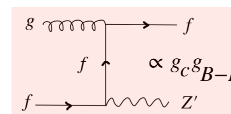
- $$\frac{\mathrm{d}Y_N}{\mathrm{d}t} = \langle \Gamma_{\phi \to NN} \rangle Y_\phi$$ ← N abundance



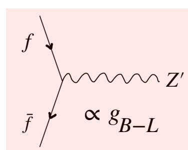
- $$\frac{\mathrm{d}Y_{Z'}}{\mathrm{d}t} = - s\langle \sigma_{Z'Z' \to \phi} v \rangle Y_\phi - \left(\langle \sigma_{f\bar{f} \to gZ'} v n_g \rangle + \langle \sigma_{fg \to fZ'} v n_f \rangle\right)(Y_{Z'} - Y_{Z'}^{\mathrm{eq}})$$ ← Z' abundance

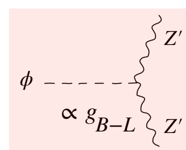




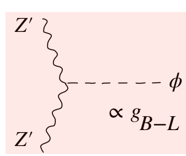


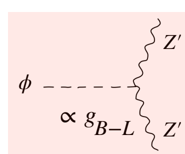
$$+\langle \Gamma_{Z'} \rangle (Y_{Z'} - Y_{Z'}^{\mathrm{eq}}) + \langle \Gamma_{\phi \to Z'Z'} \rangle Y_\phi$$

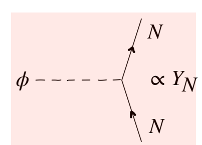




- $$\frac{\mathrm{d}Y_\phi}{\mathrm{d}t} = + s\langle \sigma_{Z'Z' \to \phi} v \rangle Y_{Z'}^2 - \langle \Gamma_{\phi \to Z'Z'} \rangle Y_\phi - \langle \Gamma_{\phi \to NN} \rangle Y_\phi$$ ← ϕ abundance







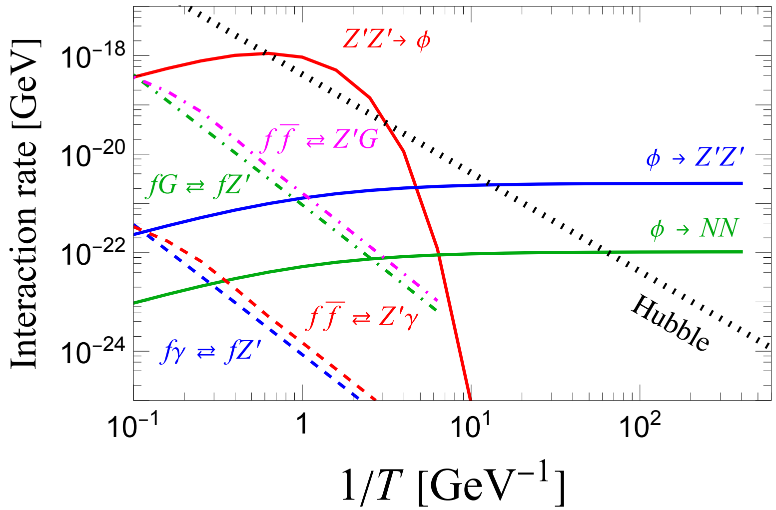
O. Seto, T. Shimomura, **YU**, [2404.00654]

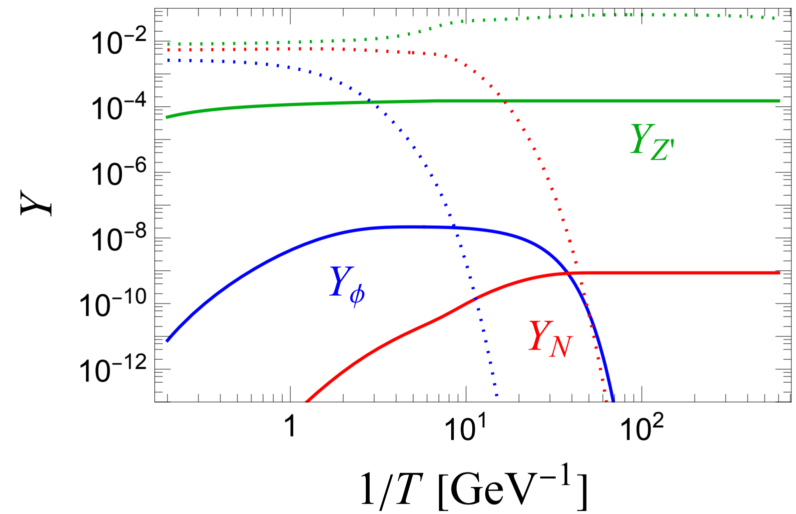
Interaction rate & Yield

Case A ($\alpha = 0$)
$m_\phi > 2m_N > m_{Z'}$

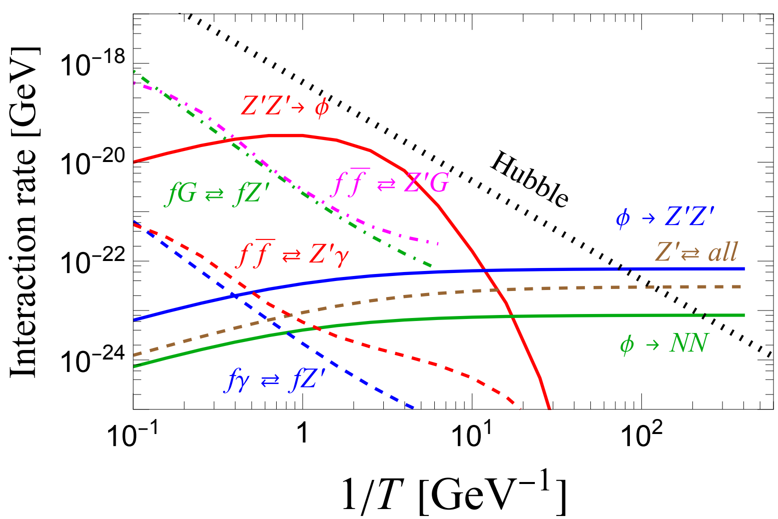
$m_{Z'} = 2$ MeV, $g_{B-L} = 1.3 \times 10^{-13}$

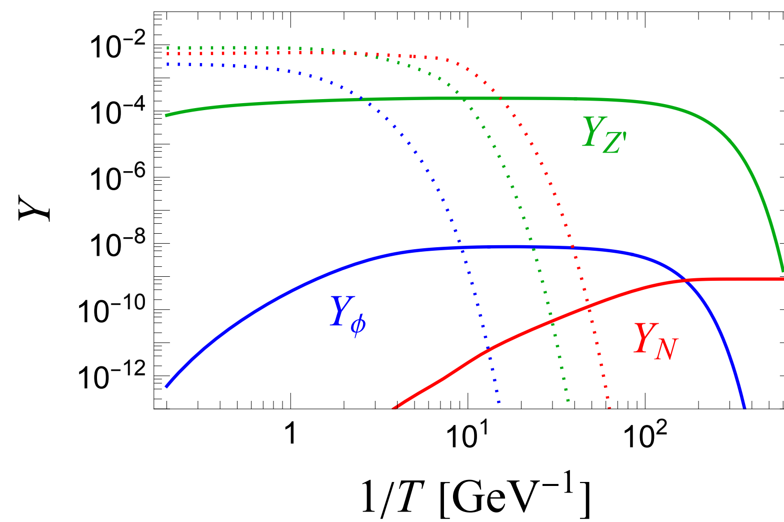
$m_N = 0.5$ GeV, $\Omega h^2 = 0.12$





$m_{Z'} = 850$ MeV, $g_{B-L} = 1.5 \times 10^{-11}$

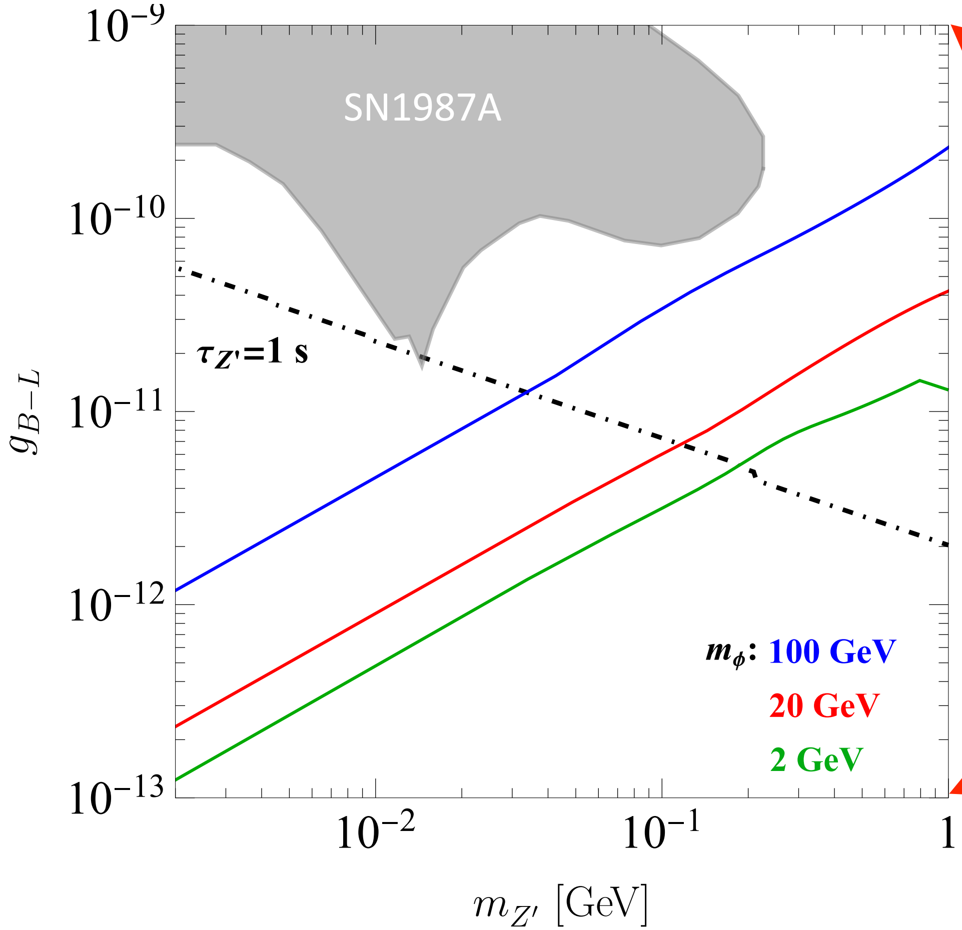




Constraints

Case A ($\alpha = 0$)
$m_\phi > 2m_N > m_{Z'}$

O. Seto, T. Shimomura, **YU**, [2404.00654]



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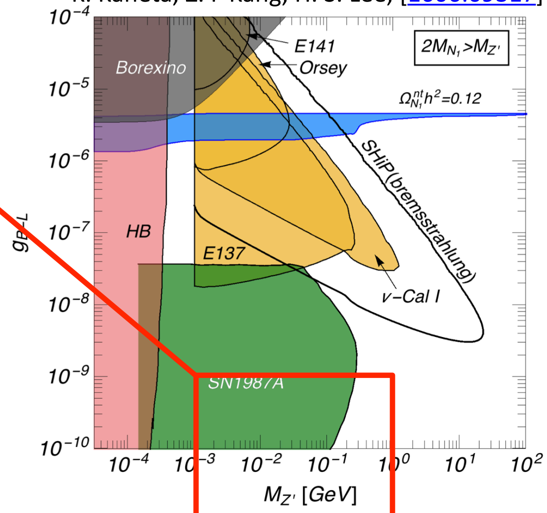
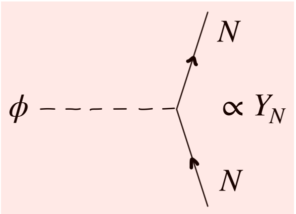


dominant



1. As $\phi \to NN$ is so effective, $\sigma(Z'Z' \to \phi) \propto g_{B-L}^2$ needs to be suppressed to avoid overproduction of N
2. g_{B-L} is shifted to quite a small value
3. Below the dash-dotted line, the Z' boson would decay after the BBN starts

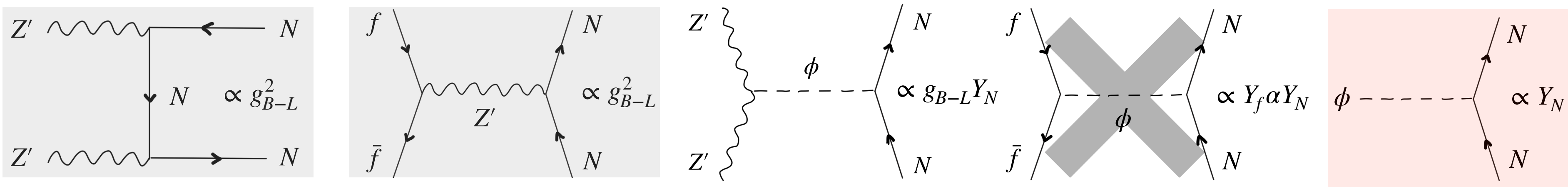
Production Channels

Case A ($\alpha = 0$)
$m_\phi > 2m_N > m_{Z'}$

ϕ-h mixing $\alpha = 0$

N production

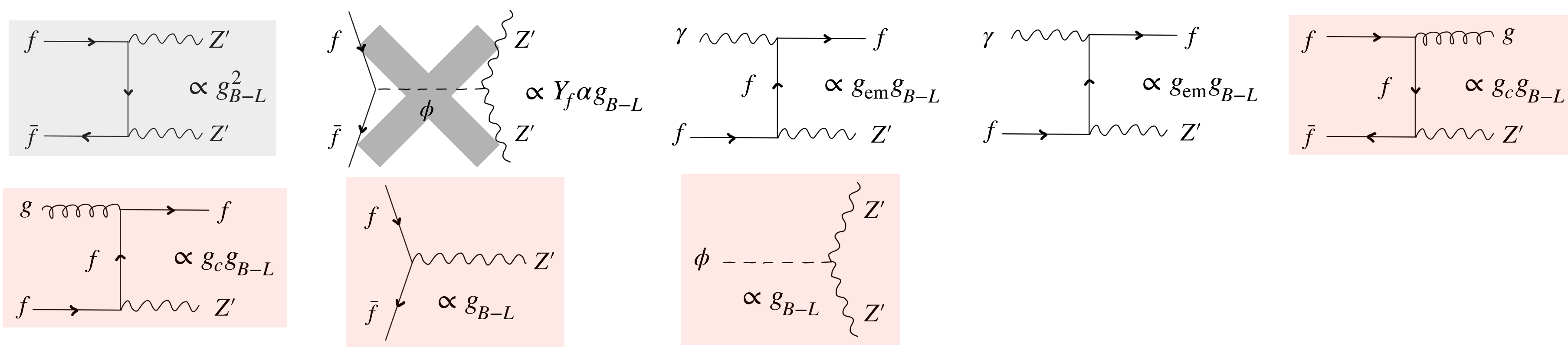
dominant



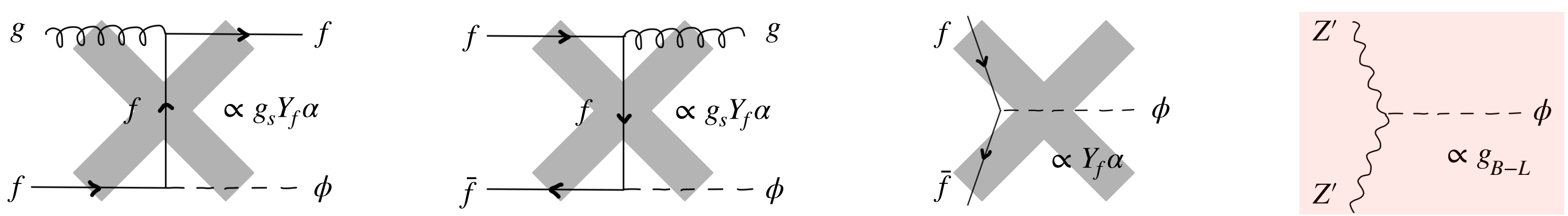
Kaneta, Kang, Lee

Our work

Z' production



ϕ production



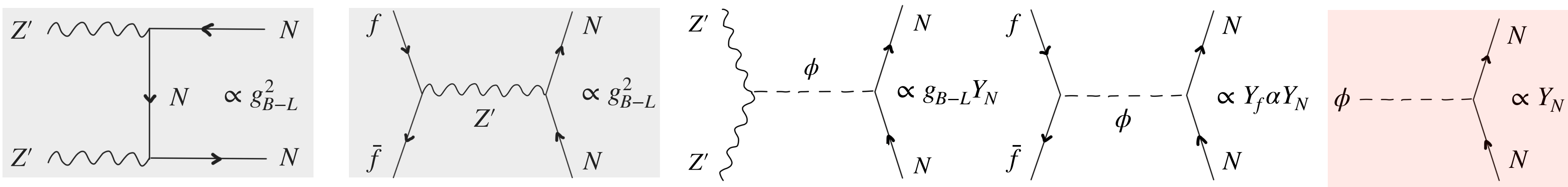
Production Channels

Case A ($\alpha = 10^{-7}$)
$m_\phi > 2m_N > m_{Z'}$

N production

ϕ-h mixing $\alpha = 10^{-7}$

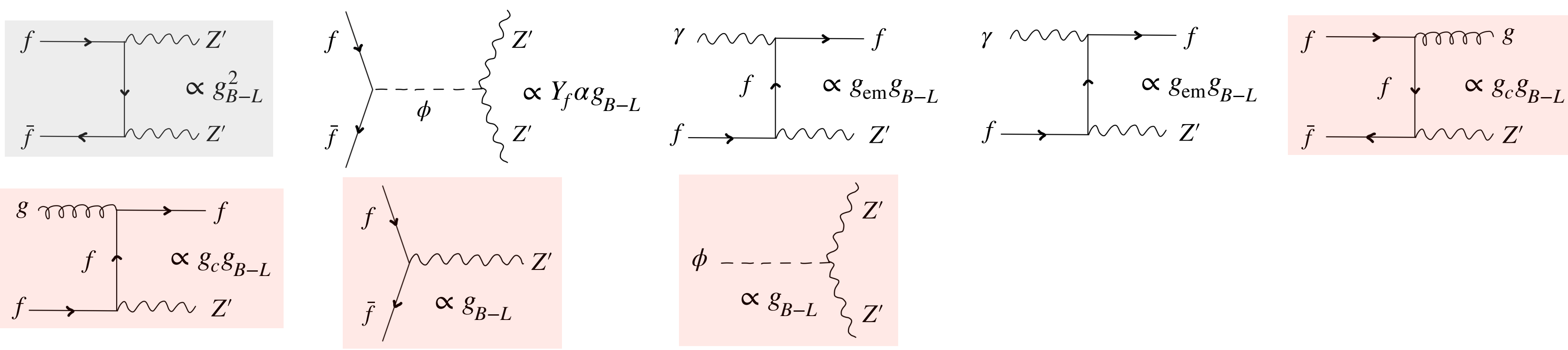
dominant



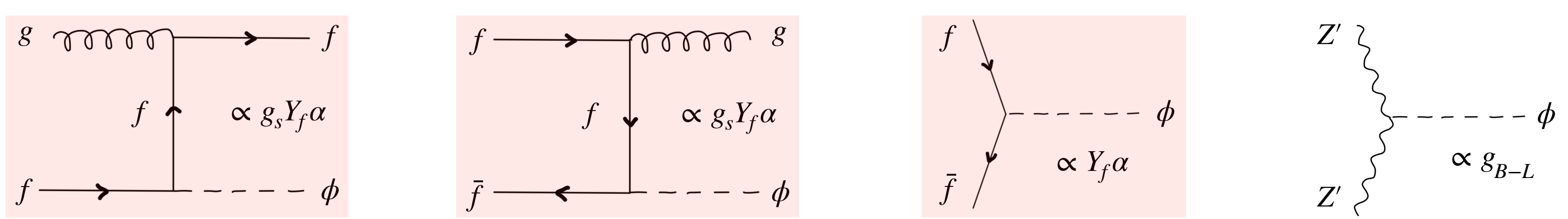
Kaneta, Kang, Lee

Our work

Z' production



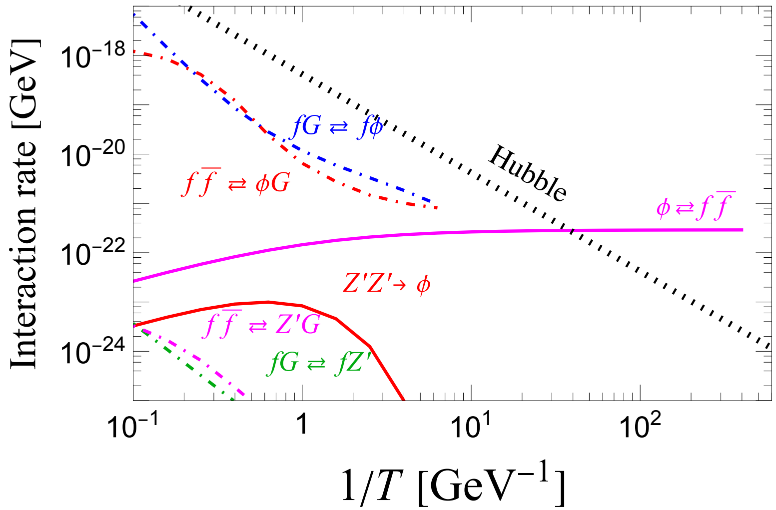
ϕ production

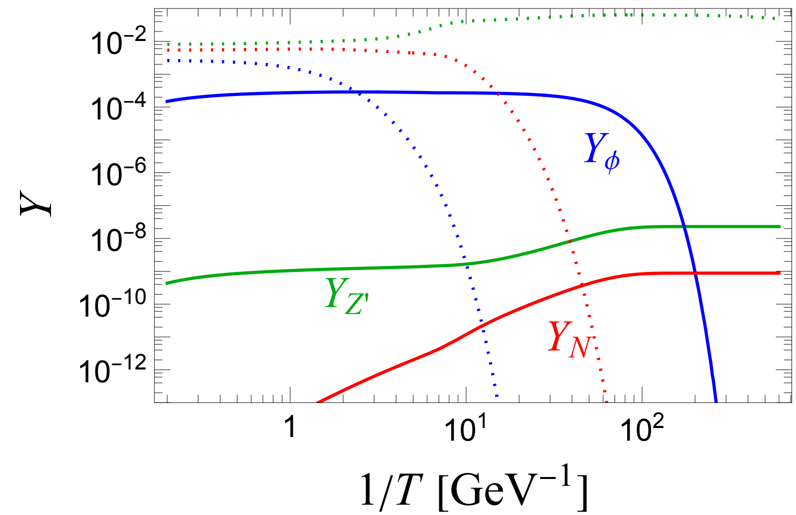


Interaction rate & Yield

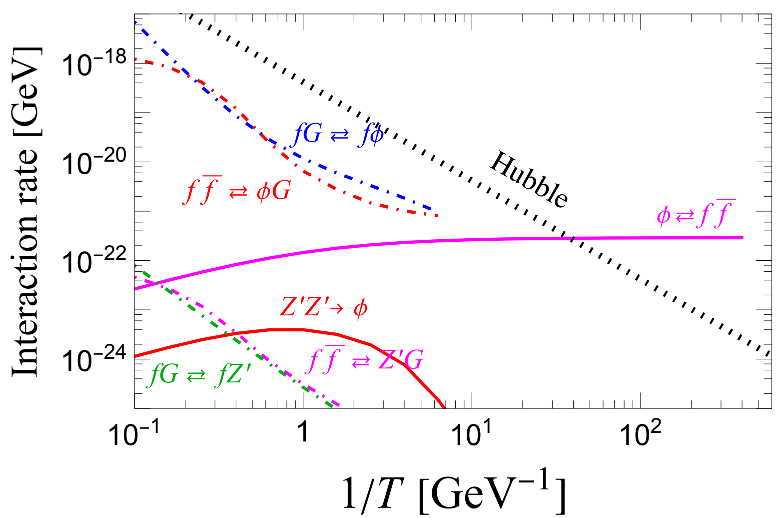
Case A ($\alpha = 10^{-7}$)
$m_\phi > 2m_N > m_{Z'}$

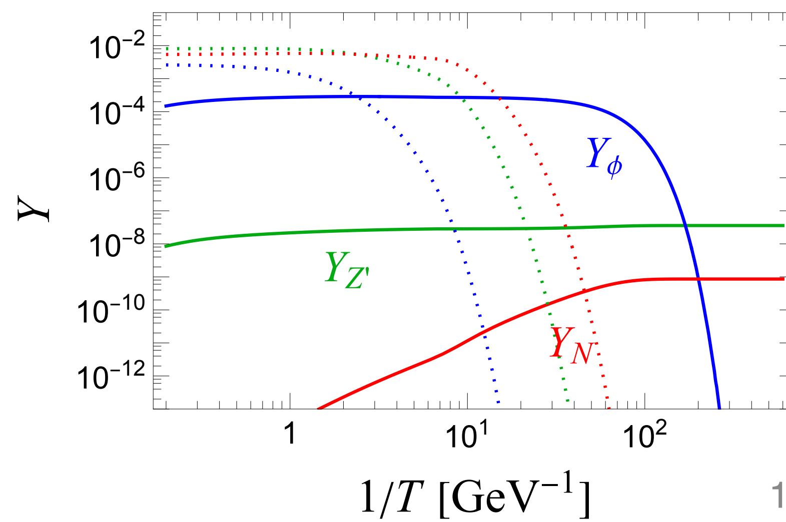
$m_{Z'} = 2$ MeV, $g_{B-L} = 3.8 \times 10^{-16}$, $\Omega h^2 = 0.12$ cf.) $g_{B-L} = 1.3 \times 10^{-13}$ when $\alpha = 0$





$m_{Z'} = 850$ MeV, $g_{B-L} = 1.6 \times 10^{-13}$, $\Omega h^2 = 0.12$ cf.) $g_{B-L} = 1.5 \times 10^{-11}$ when $\alpha = 0$

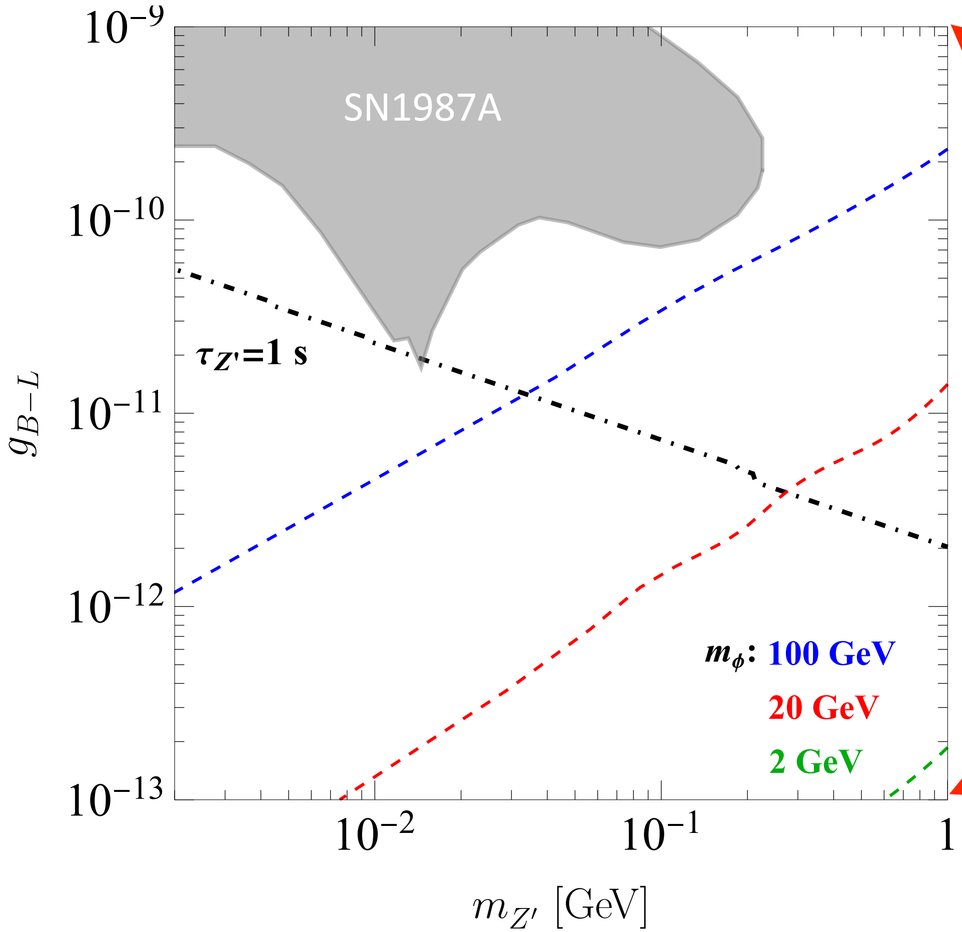




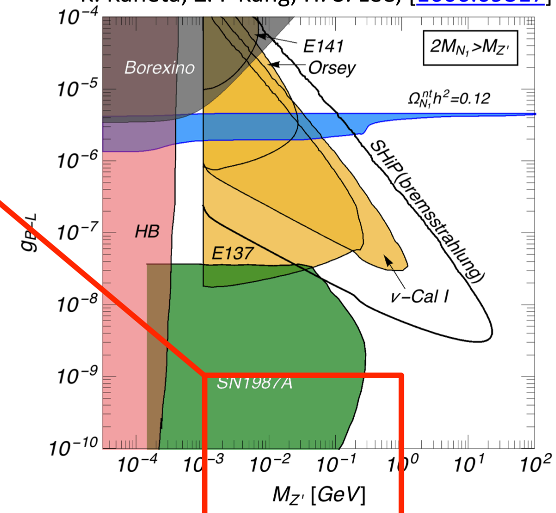
Constraints

Case A ($\alpha = 10^{-7}$)
$m_\phi > 2m_N > m_{Z'}$

O. Seto, T. Shimomura, **YU**, [2404.00654]

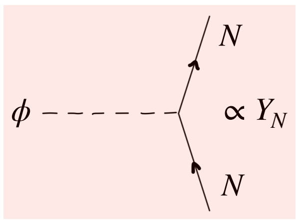


K. Kaneta, Z. F Kang, H. S. Lee, [1606.09317]



1. As $\phi \to NN$ is so effective, $\sigma(Z'Z' \to \phi) \propto g_{B-L}^2$ needs to be suppressed to avoid overproduction of N
2. g_{B-L} is shifted to quite a small value

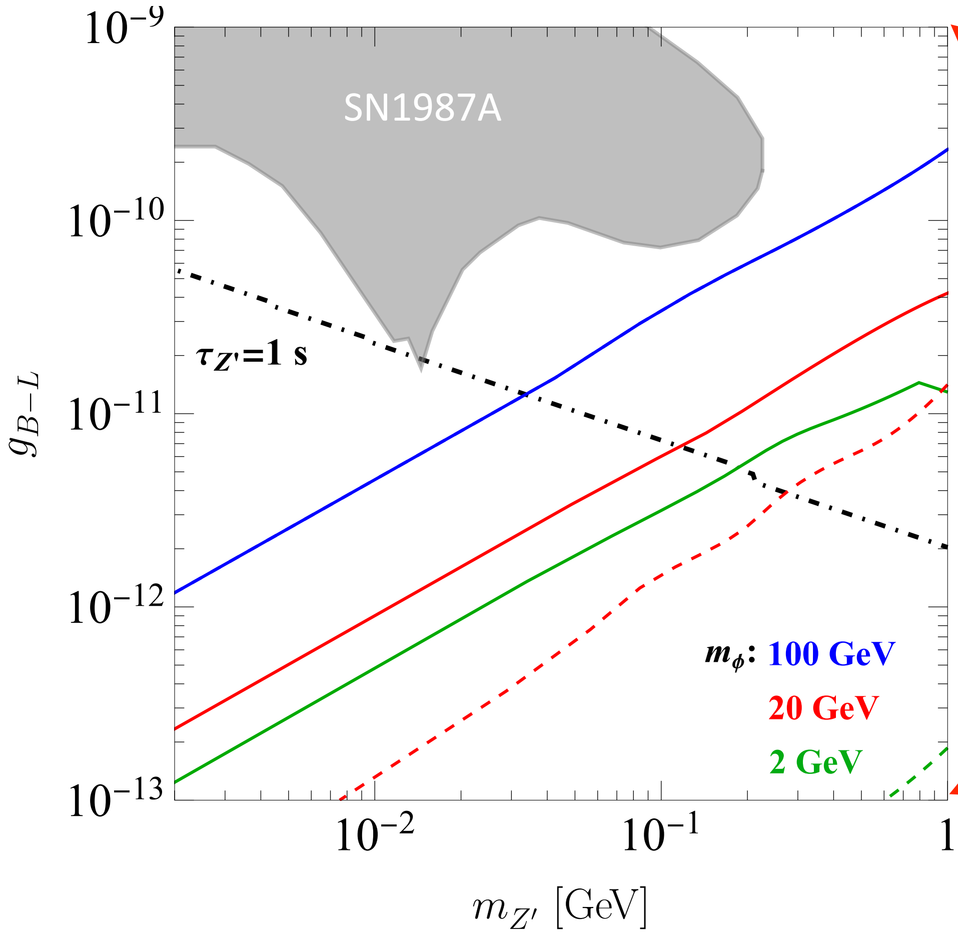
dominant



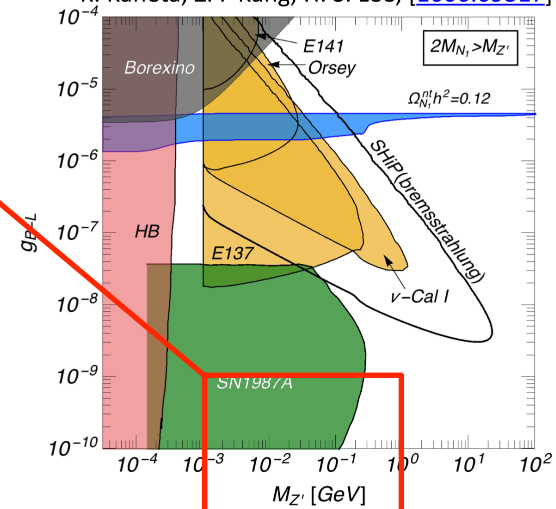
Constraints

Case A ($\alpha = 0,\ 10^{-7}$)
$m_\phi > 2m_N > m_{Z'}$

O. Seto, T. Shimomura, **YU**, [2404.00654]



K. Kaneta, Z. F Kang, H. S. Lee, [1606.09317]



1. As $\phi \to NN$ is so effective, $\sigma(Z'Z' \to \phi) \propto g_{B-L}^2$ needs to be suppressed to avoid overproduction of N
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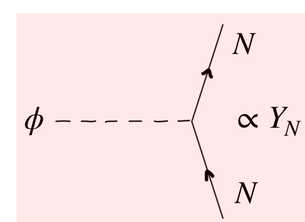
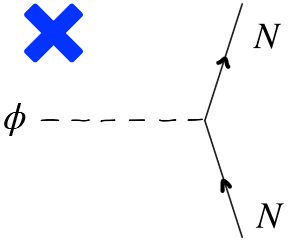
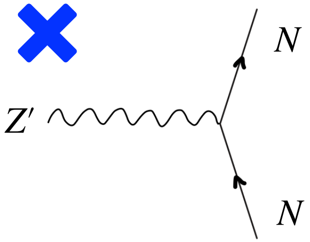
dominant



Case B: $2m_N > m_\phi, m_{Z'}$



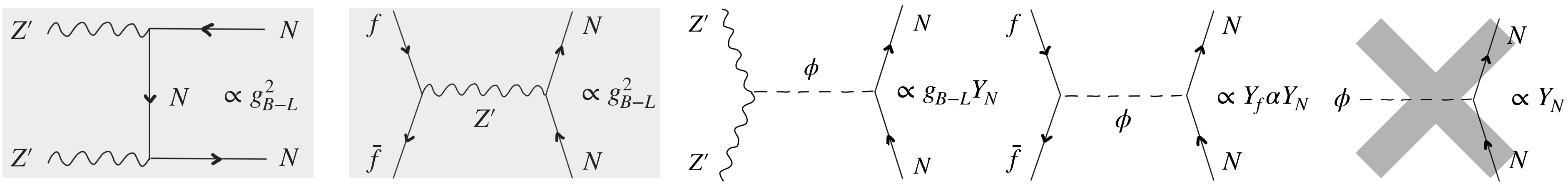


Production Channels

Case B
$2m_N > m_\phi, m_{Z'}$

S. Eijima, O. Seto, T.Shimomura, [2207.01775]

N production

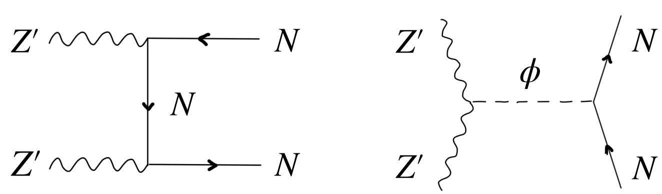


Kaneta, Kang, Lee

Our work

- ✔ Z' is thermalized
- ✔ Yield of N is simply evaluated by $Y_N(t_\mathrm{f}) = \int_{t_\mathrm{i}}^{t_\mathrm{f}} \mathrm{d}t \, \frac{\langle \sigma_{Z'Z' \to NN} v \rangle n_{Z'}^2}{s}$
- ✔ ϕ unitalize the scattering of the longitudinal mode of Z'

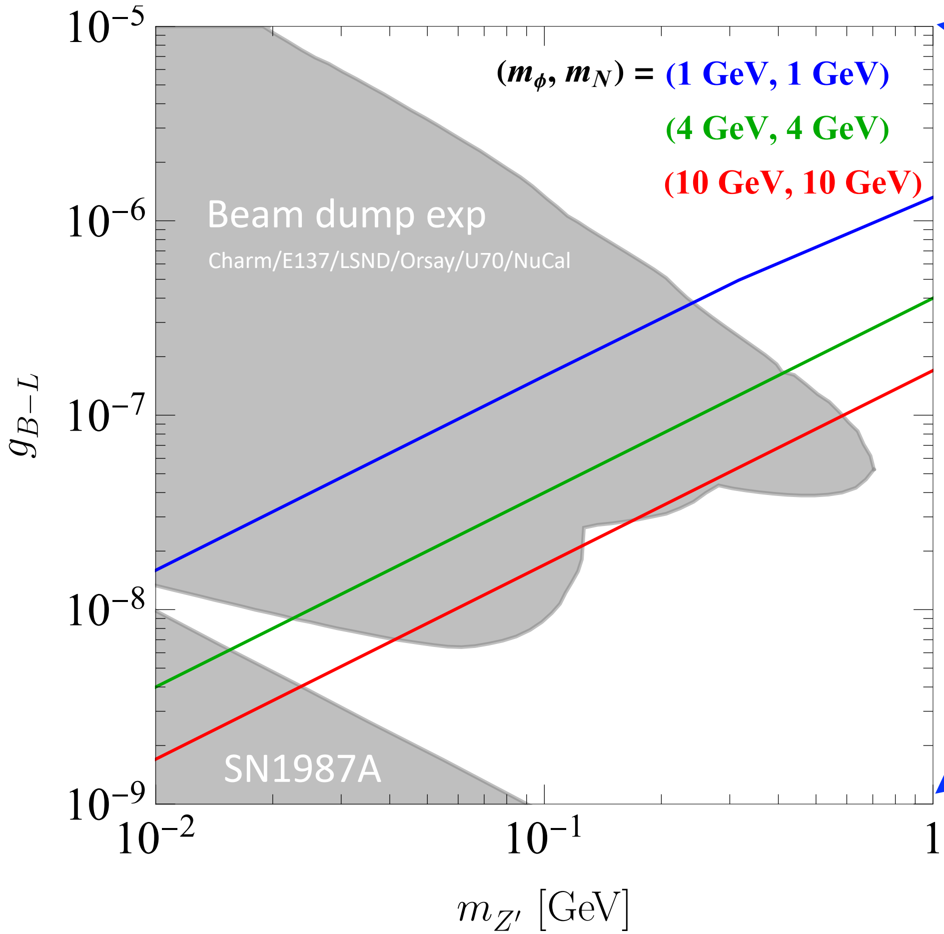
$$\int_0^1 \mathrm{d}\cos\theta \, |\mathscr{M}(Z'Z' \to NN)|^2 \sim \frac{32 g_{B-L}^4}{m_{Z'}^4} \left(\frac{2m_N^4 s^2}{m_N^2(s - 4m_{Z'}^2) + m_{Z'}^4} - \frac{2m_N^2 s^3}{\Gamma_\phi^2 m_\phi^2 + (m_\phi^2 - s)^2} \right) \xrightarrow{s \to \infty} 0$$



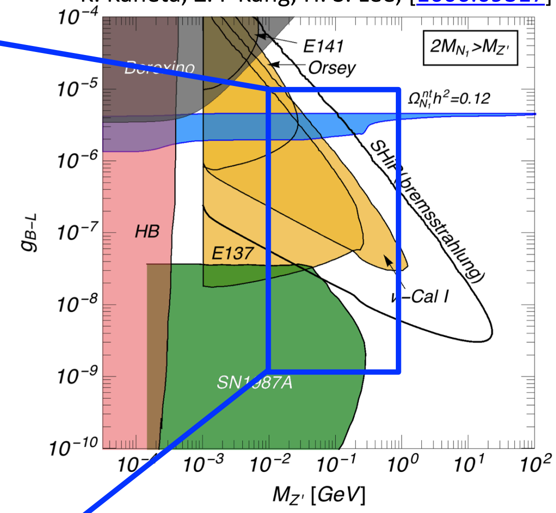
Constraints

S. Eijima, O. Seto, T. Shimomura, [2207.01775]
O. Seto, T. Shimomura, **YU**, [2404.00654]

Case B
$2m_N > m_\phi, m_{Z'}$



K. Kaneta, Z. F Kang, H. S. Lee, [1606.09317]

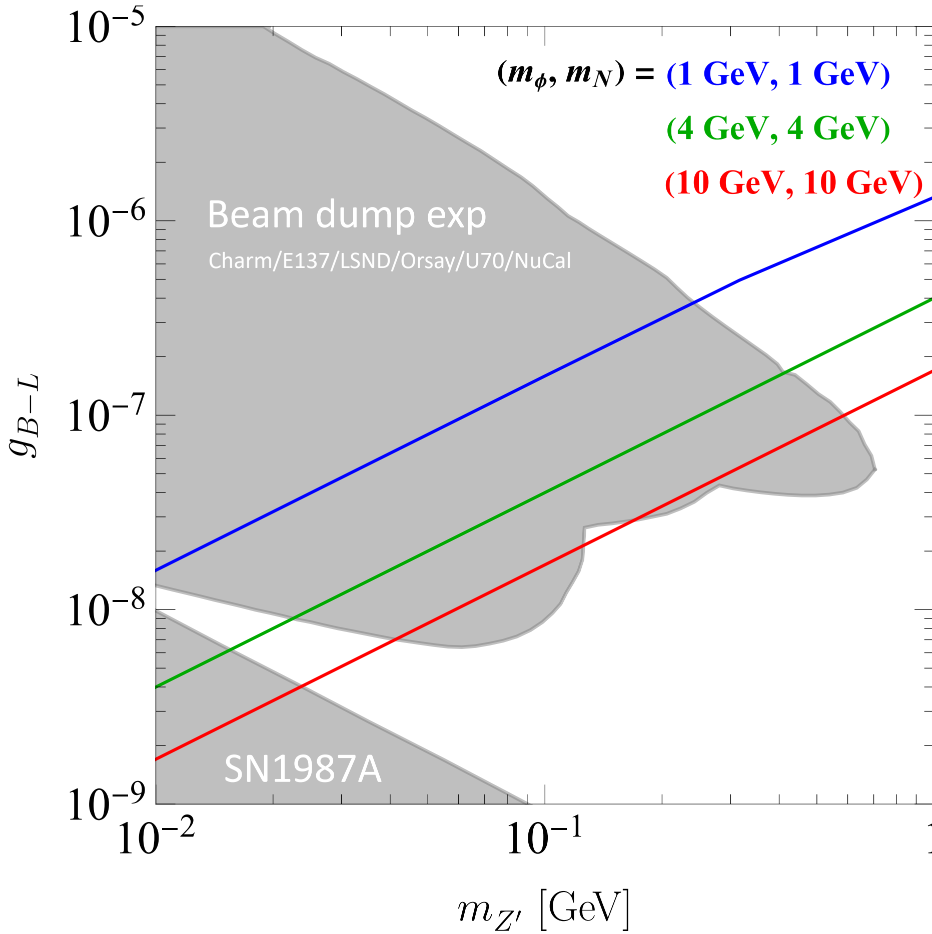


1. Eijima, Seto, Shimomura (2022) found that, if the scattering of the longitudinal mode of Z' is taken into account, effects of ϕ must be included to unitarize this scattering
2. In this case, the main production mode is $Z'Z' \to NN$, not $f\bar{f} \to NN$
3. Ωh^2 depends on both $m_{Z'}$ and m_ϕ

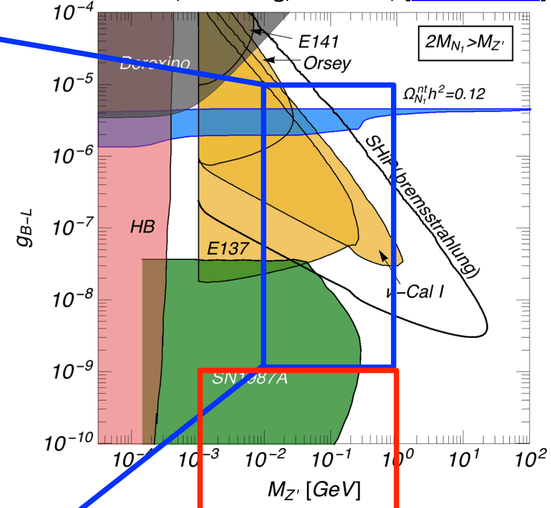
Constraints

S. Eijima, O. Seto, T.Shimomura, [2207.01775]
O. Seto, T. Shimomura, **YU**, [2404.00654]

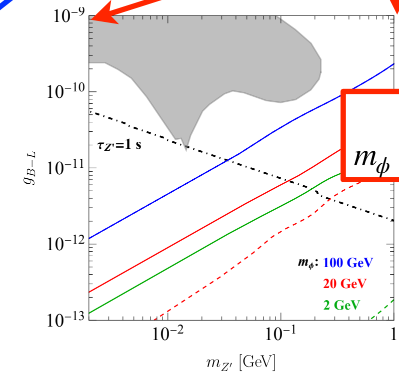
Case B
$2m_N > m_\phi, m_{Z'}$



K. Kaneta, Z. F Kang, H. S. Lee, [1606.09317]



Case A
$m_\phi > 2m_N > m_{Z'}$



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3. Ωh^2 depends on both $m_{Z'}$ and m_ϕ

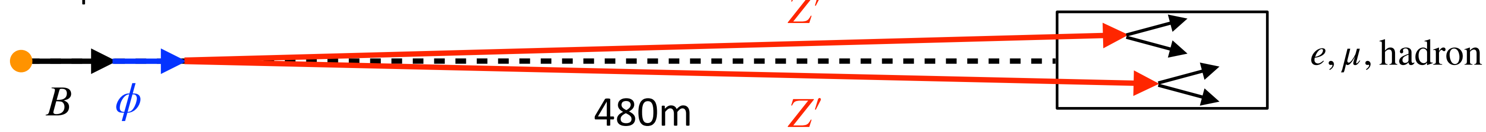
Beam dump experiments (FASER2, SHiP)

Case B
$2m_N > m_\phi, m_{Z'}$

O. Seto, T. Shimomura, **YU**, [2404.00654]

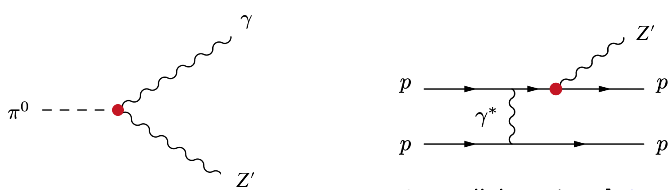
✔ For the small g_{B-L} required to realize freeze-in sterile ν DM, the Z' becomes long-lived

Interaction point   Also see Prof. Shimomura's slide   FASER2 detector → LLP searches

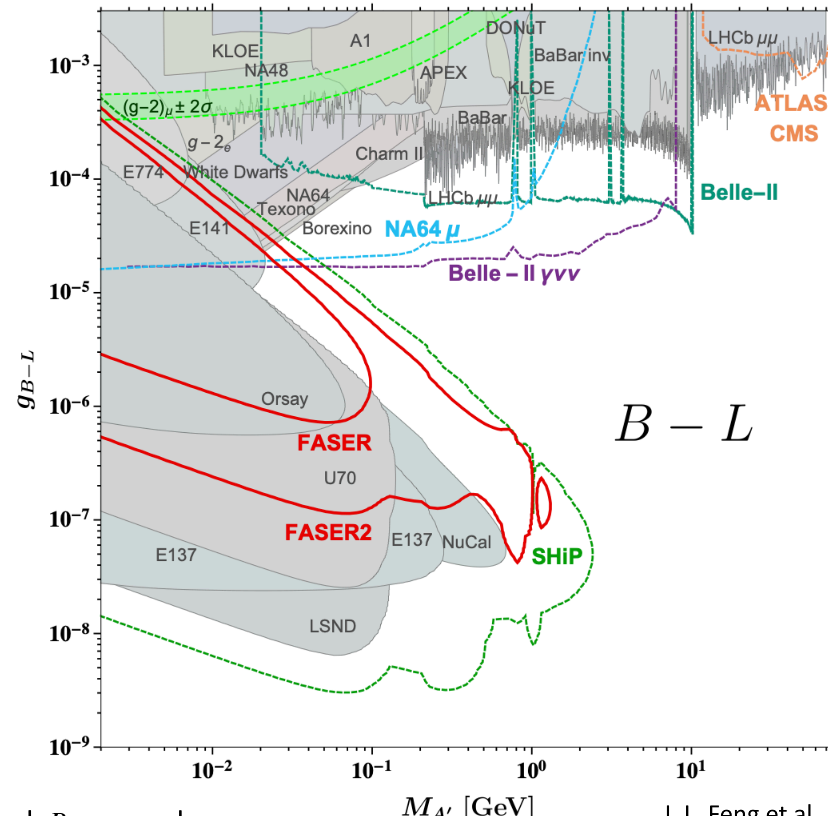


✔ Z' production in beam dump experiments

- Meson decays: $\pi^0 \to \gamma Z'$ $\eta^0 \to \gamma Z'$
- Proton bremsstrahlung: $pp \to ppZ'$

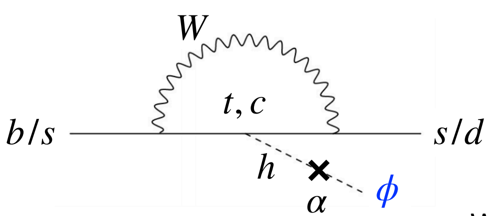


FASER collaboration, [1811.12522]



J. L. Feng et al., [2203.05090]

✔ Dark Higgs ϕ is produced from meson decays



$B \to X_s\, \phi$

$\eta' \to \eta\, \phi$

$K^\pm \to \pi^\pm\, \phi$

$K_L \to \pi^0\, \phi$

$K_S \to \pi^0\, \phi$

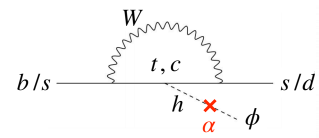
We only focus on main production channel, B meson decay

T. Araki, K. Asai, T. Shimomura, [2107.07487] T. Araki, K. Asai, Y. Nakashima, T. Shimomura, [2008.12765]
T. Araki, K. Asai, Y. Nakashima, T. Shimomura, [2406.17760] T. Araki, K. Asai, H. Otono, T. Shimomura, Y. Takubo, [2210.12730]

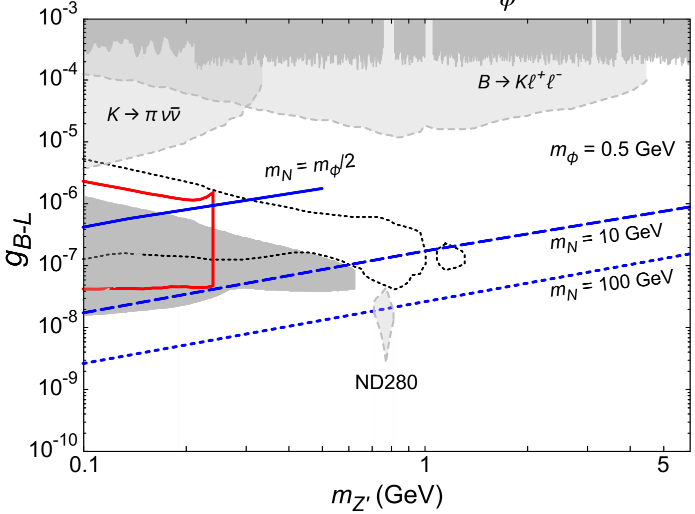
FASER2

Case B
$2m_N > m_\phi, m_{Z'}$

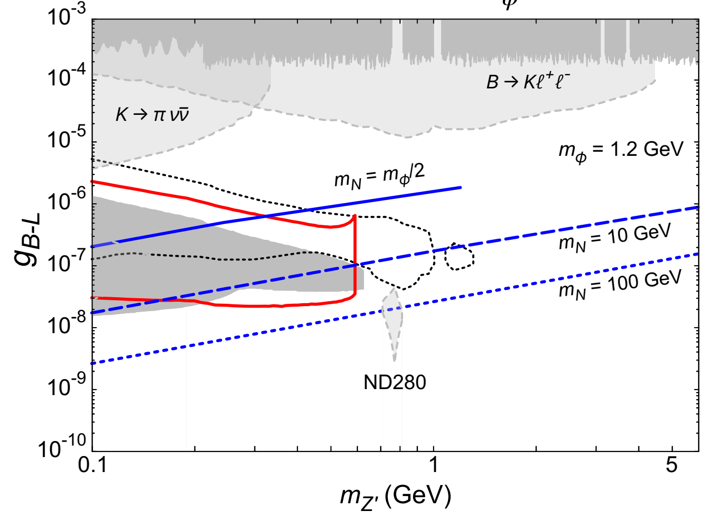
Red contour corresponds to $B \to X_s \phi$ with $\alpha = 10^{-4}$



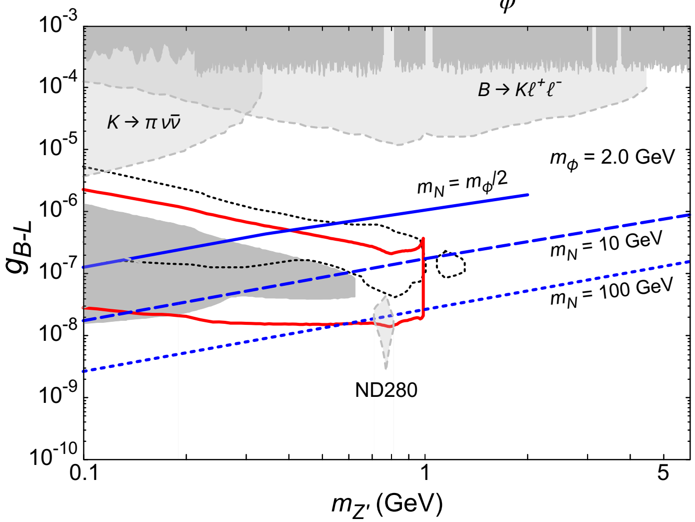
$m_\phi = 0.5$ GeV



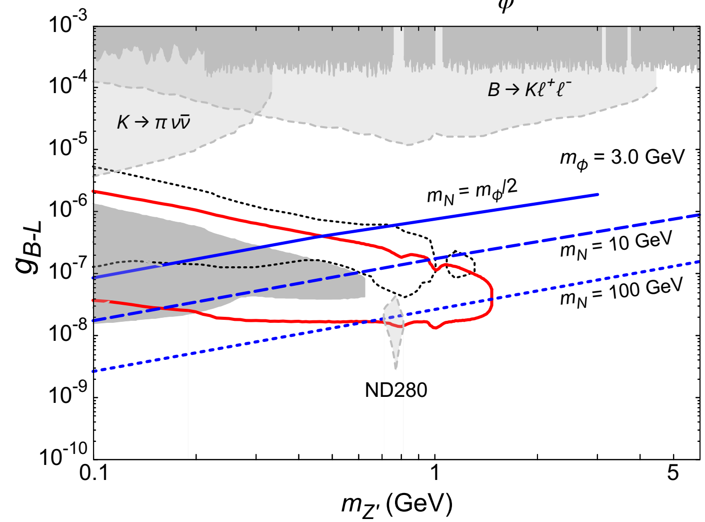
$m_\phi = 1.2$ GeV



$m_\phi = 2.0$ GeV



$m_\phi = 3.0$ GeV

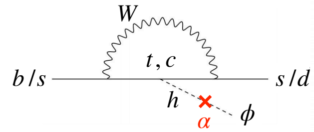


T. Araki, K. Asai, Y. Nakashima, O. Seto, T. Shimomura, **YU** [2603.28882]

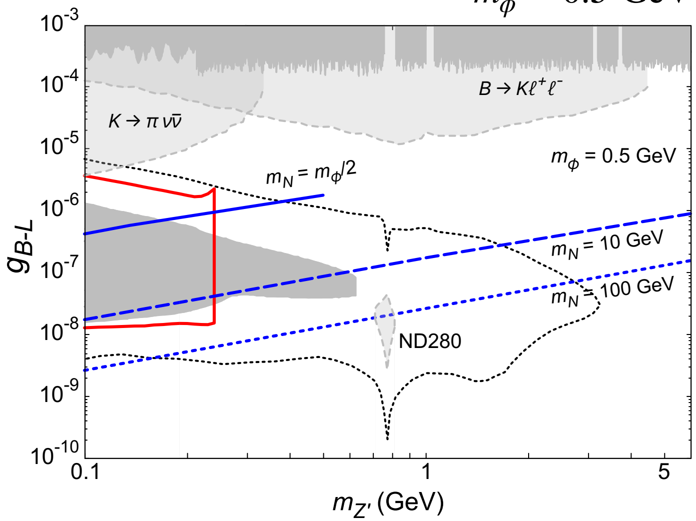
SHiP

Case B
$2m_N > m_\phi, m_{Z'}$

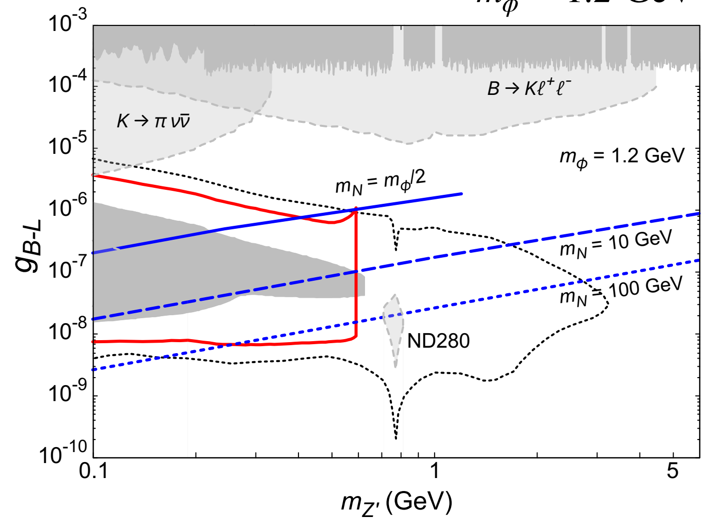
Red contour corresponds to $B \to X_s \phi$ with $\alpha = 10^{-4}$



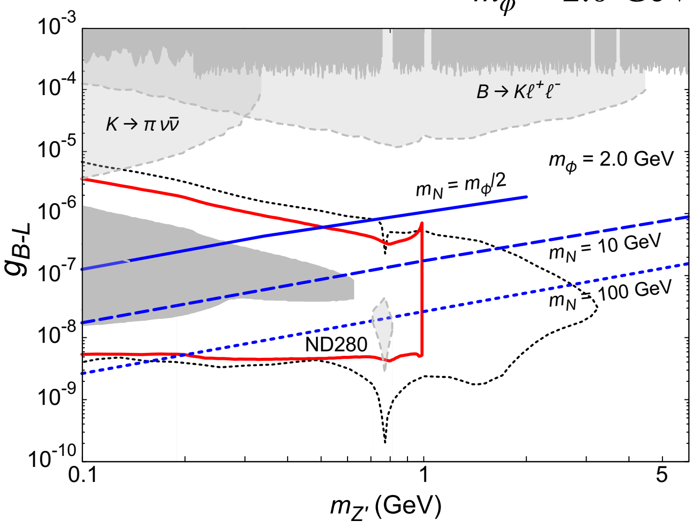
$m_\phi = 0.5$ GeV



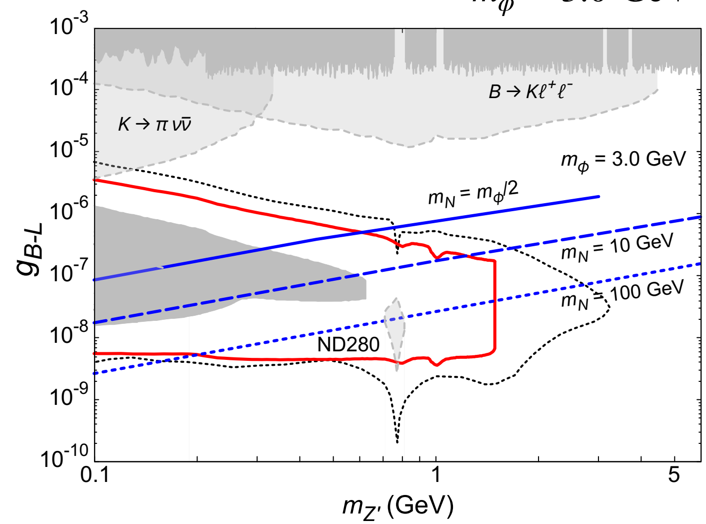
$m_\phi = 1.2$ GeV



$m_\phi = 2.0$ GeV



$m_\phi = 3.0$ GeV



T. Araki, K. Asai, Y. Nakashima, O. Seto, T. Shimomura, **YU** [2603.28882]

Summary

1. We reexamine gauged $U(1)_{B-L}$ model, including $U(1)_{B-L}$ breaking scalar ϕ

Case A
$m_\phi > 2m_N > m_{Z'}$

○ $\phi \to NN$ ✕ $Z' \to NN$

2. $\phi \to NN$ is the main production channel for N

3. As $\phi \to NN$ is so effective, $\sigma(Z'Z' \to \phi) \propto g_{B-L}^2$ needs to be suppressed to avoid overproduction of N, resulting in non-thermalization of Z'

4. $g_{B-L} \simeq 10^{-13} - 10^{-9}$ to reproduce the DM relic abundance.

5. If we turn on the scalar mixing α, g_{B-L} must be even smaller

Case B
$2m_N > m_\phi, m_{Z'}$

✕ $\phi \to NN$ ✕ $Z' \to NN$

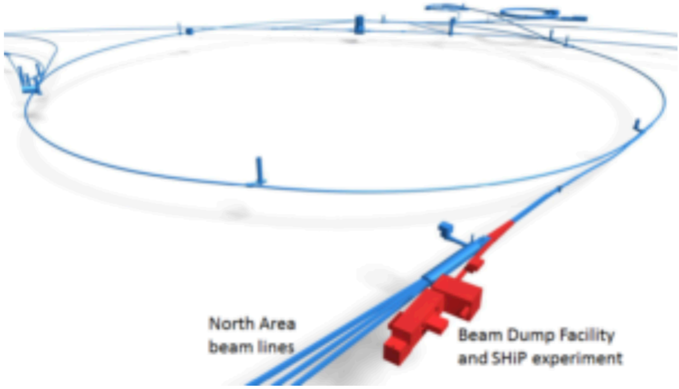
6. $Z'Z' \to NN$ is the main production channel for N

7. $g_{B-L} \simeq 10^{-9} - 10^{-6}$ to reproduce the DM relic abundance, can be searched for by FASER, FASER2, and SHiP experiments

8. We take into account $\phi \to Z'Z'$, which enlarge the sensitivity of FASER2 and SHiP

Back up

Search for Hidden Particles (SHiP)



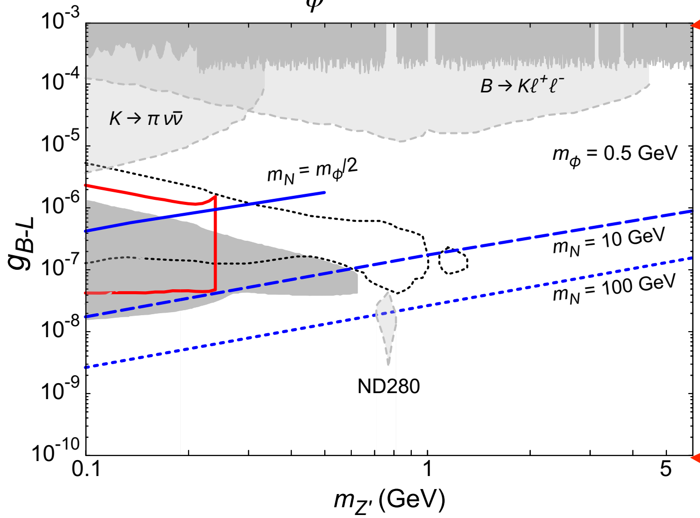
https://www.bo.infn.it/gruppo1/en/ship-experiment/

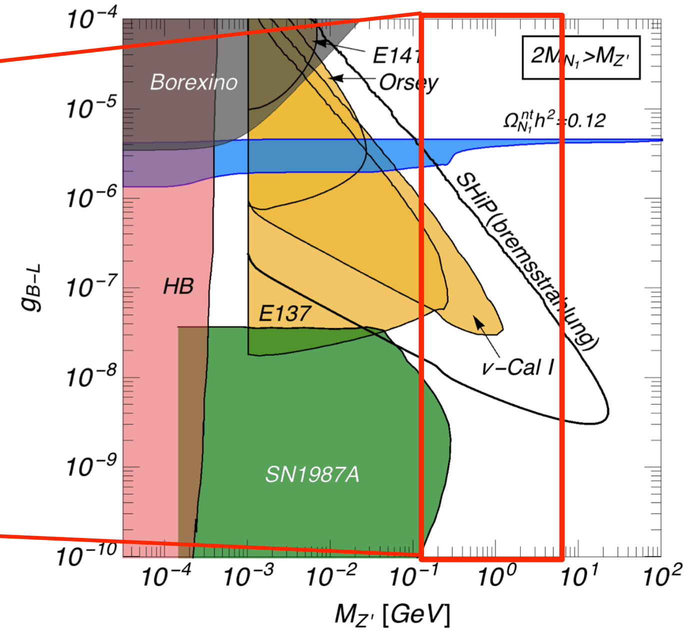
FASER2

Case B
$2m_N > m_\phi, m_{Z'}$

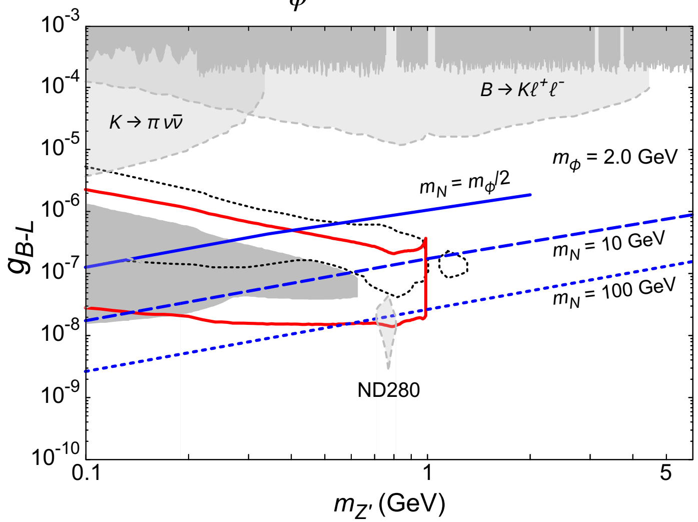
Red contour corresponds to $B \to X_s \phi$ with $\alpha = 10^{-4}$

$m_\phi = 0.5$ GeV

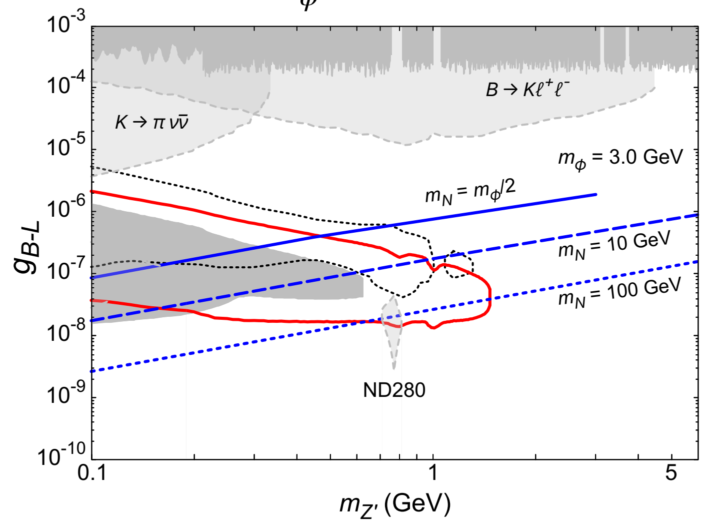




$m_\phi = 2.0$ GeV



$m_\phi = 3.0$ GeV



T. Araki, K. Asai, Y. Nakashima, O. Seto, T. Shimomura, **YU** [2603.28882]

SHiP

Case B
$2m_N > m_\phi, m_{Z'}$

Red contour corresponds to $B \to X_s \phi$ with $\alpha = 10^{-4}$

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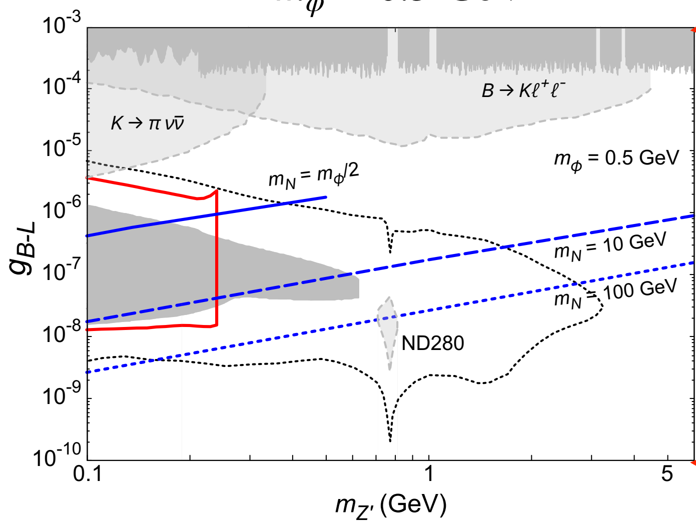
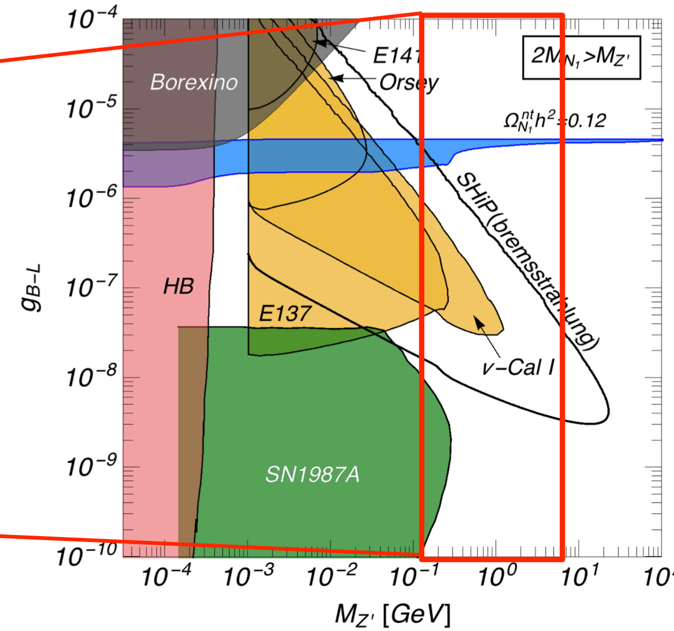
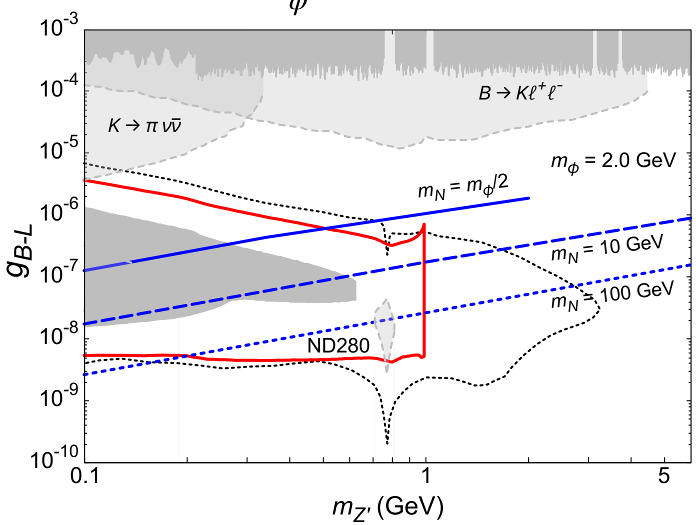
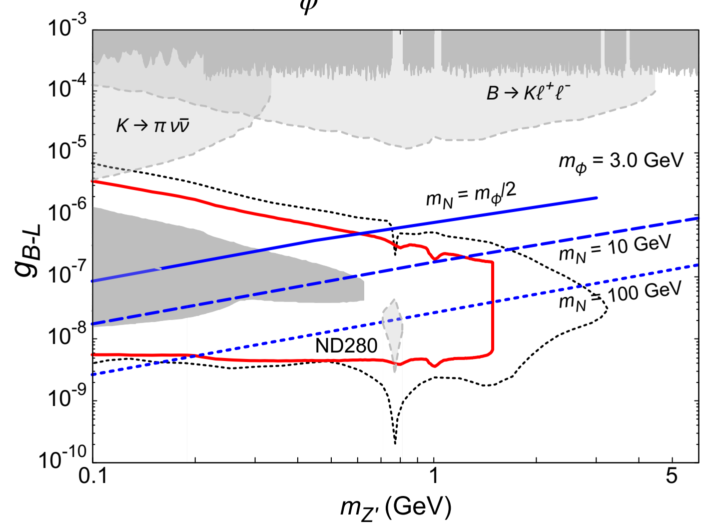




$m_\phi = 2.0$ GeV

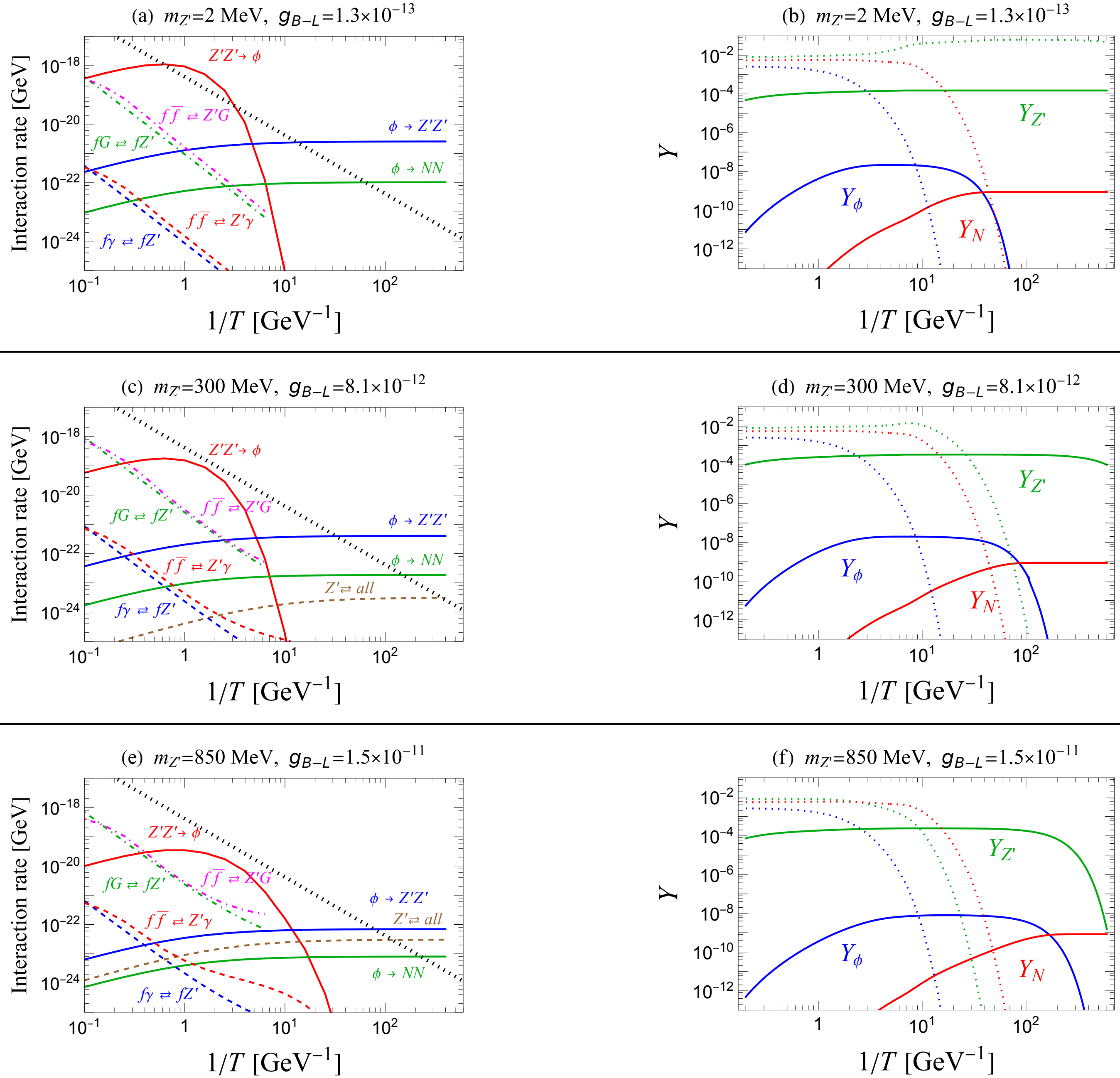


$m_\phi = 3.0$ GeV



Interaction rate & Yield

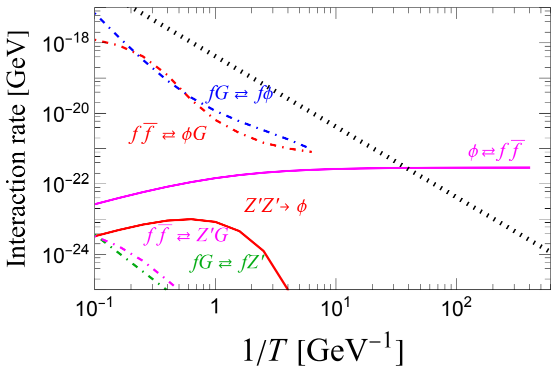
Case A ($\alpha = 0$)
$m_\phi > 2m_N > m_{Z'}$



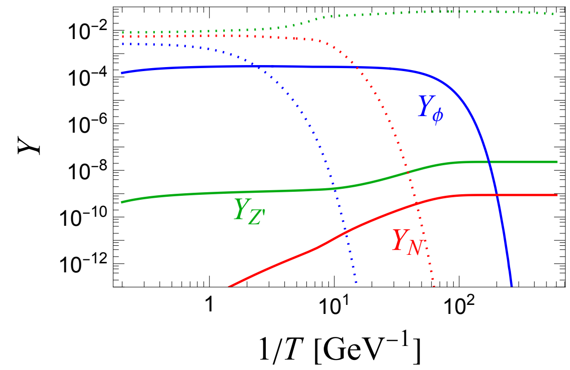
Interaction rate & Yield

Case A ($\alpha = 10^{-7}$)
$m_\phi > 2m_N > m_{Z'}$

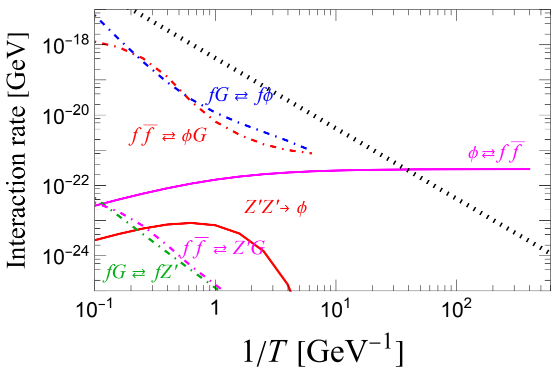
(a) $m_{Z'}$=2 MeV, g_{B-L}=3.8×10^{-16}



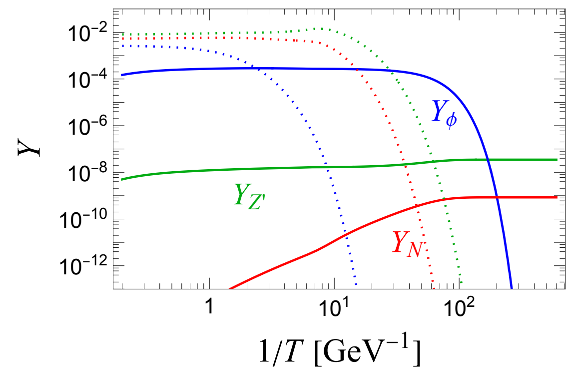
(b) $m_{Z'}$=2 MeV, g_{B-L}=3.8×10^{-16}



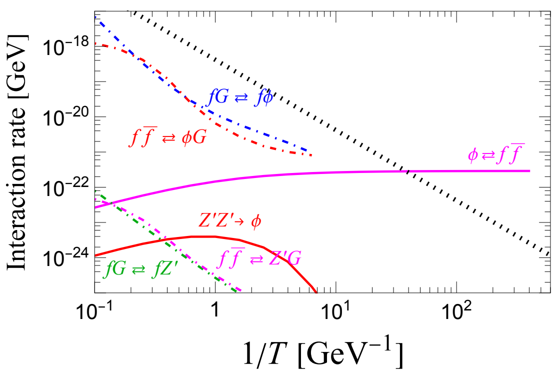
(c) $m_{Z'}$=300 MeV, g_{B-L}=5.6×10^{-14}



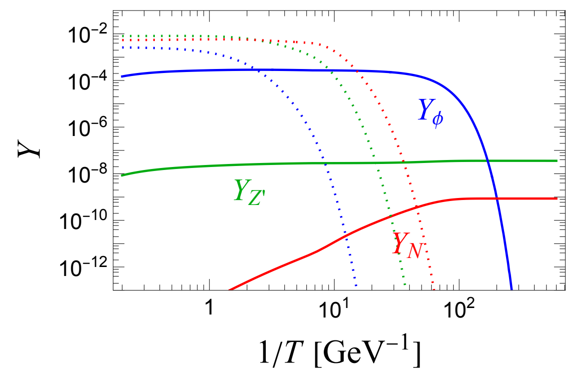
(d) $m_{Z'}$=300 MeV, g_{B-L}=5.6×10^{-14}



(e) $m_{Z'}$=850 MeV, g_{B-L}=1.6×10^{-13}



(f) $m_{Z'}$=850 MeV, g_{B-L}=1.6×10^{-13}



Gauged $B-L$ model w/ sterile ν DM

	Q^i	u^i	d^i	L^i	e^i_R	ν^i_R	H	Φ
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**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

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\nu_R} - V(H,\Phi)$$

*We dropped $\epsilon B_{\mu\nu}X^{\mu\nu}$ for simplicity

$$\mathscr{L}_{\nu_R} = \overline{\nu}^i_R i\gamma^\mu D_\mu \nu^i_R - Y_{\nu ij}\overline{L}^i\tilde{H}\nu^j_R - \frac{1}{2}Y_{\nu_R}\Phi\,\overline{\nu^c}^i_R\nu^i_R + \mathrm{h.c.}$$

$$V(H,\Phi) = \frac{\lambda_1}{2}\left(|H|^2 - \frac{v_H^2}{2}\right)^2 + \frac{\lambda_2}{2}\left(|\Phi|^2 - \frac{v_{B-L}^2}{2}\right)^2 + \lambda_3\left(|H|^2 - \frac{v_H^2}{2}\right)\left(|\Phi|^2 - \frac{v_{B-L}^2}{2}\right)$$

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \tilde{h} \\ \tilde{\phi} \end{pmatrix}$$

$$H = \frac{1}{\sqrt{2}}(0,\ v_H + \tilde{h})^T \qquad \Phi = \frac{v_{B-L} + \tilde{\phi}}{\sqrt{2}}$$

$$m_{N_i} = \frac{1}{\sqrt{2}}Y_{\nu_R}v_{B-L} \qquad m_{Z'} = 2g_{B-L}v_{B-L}$$

Case A: $m_\phi > 2m_N > m_{Z'}$

○ $\phi \to NN$

✕ $Z' \to NN$

Case B: $2m_N > m_\phi, m_{Z'}$

✕ $\phi \to NN$

✕ $Z' \to NN$

Gauged $B-L$ model w/ sterile ν DM

$$\Gamma_{N_1\to 3\nu} = \frac{G_F^2 M_{N_1}^5}{96\pi^3}\sin^2\theta_1 = \frac{G_F^2 M_N^3}{96\pi^3}\sum_\alpha |Y_{\alpha 1}|^2 v_H^2$$

$$= \frac{G_F M_N^3}{96\sqrt{2}\pi^3}\sum_\alpha |Y_{\alpha 1}|^2$$

$$= 2.9\times 10^{-9}\ \mathrm{GeV}^{-2} M_N^3 \sum_\alpha |Y_{\alpha 1}|^2$$

$$= 2.9\times 10^{-9}\ \mathrm{GeV}^{-2}\frac{6.5\times 10^{41}\ \mathrm{GeV}^{-1}}{13.7\times 10^9\ \mathrm{year}} M_N^3 \sum_\alpha |Y_{\alpha 1}|^2$$

$$= \frac{1}{13.7\times 10^9\,\mathrm{years}}\left(\frac{M_N}{\mathrm{GeV}}\right)^3\left(\frac{\sum_\alpha |Y_{\alpha 1}|}{5.3\times 10^{-34}}\right)$$

$$G_F = 1.2\times 10^{-5}\ \mathrm{GeV}^{-2}$$

$$\hbar = 6.6\times 10^{-25}\ \mathrm{GeV\ s} = 2.1\times 10^{-32}\ \mathrm{GeV\ year}$$

$$1\ \mathrm{year} = 1/(2.1\times 10^{-32})\ \mathrm{GeV}^{-1}$$

$$13.7\times 10^9\ \mathrm{year} = \frac{13.7\times 10^9}{2.1\times 10^{-32}}\ \mathrm{GeV}^{-1} = \frac{13.7\times 10^9}{2.1\times 10^{-32}}\ \mathrm{GeV}^{-1} = 6.5\times 10^{41}\ \mathrm{GeV}^{-1}$$