Light Z' and Dark Matter from U(1)x Gauge Symmetry

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Introduction

Dark Matter = One of the most exciting puzzles of cosmology and particle physics

Required properties of DM:
1. electric charge neutral
2. lifetime > age of the Universe
3. cold

There is **NO** dark matter candidate in the Standard Model!

→ Need theories beyond the SM

In this talk, I'll discuss
the minimal U(1)x model with a dark matter candidate

1. U(1)x gauge extension of the SM

Minimal B−L model

J. C. Pati and A. Salam, Phys. Rev. D8 (1973) 1240

A. Davidson, Phys. Rev. D20 (1979) 776

R. N. Mohapatra and R. E. March, Phys. Rev. Lett. 44 (1980) 1316

1. U(1)x gauge extension of the SM

Minimal B−L model

↓ generalization

Minimal U(1)x extended SM

T.Appelquist, et al., Phys. Rev. D68 (2003) 035012

U(1)x charge of a field is given by a linear combination of hypercharge and B−L charge

$$Q_{B-L} \rightarrow Q_X = x_H Q_Y + Q_{B-L}$$

Particle content of the minimal U(1)x model

$$Q_X = x_H Q_Y + Q_{B-L}$$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
$i = 1, 2, 3$ q_L^i	**3**	**2**	$\frac{1}{6}$	$\frac{1}{6}x_H + \frac{1}{3}$
u_R^i	**3**	**1**	$\frac{2}{3}$	$\frac{2}{3}x_H + \frac{1}{3}$
d_R^i	**3**	**1**	$-\frac{1}{3}$	$-\frac{1}{3}x_H + \frac{1}{3}$
ℓ_L^i	**1**	**2**	$-\frac{1}{2}$	$-\frac{1}{2}x_H + (-1)$
e_R^i	**1**	**1**	-1	$-x_H + (-1)$
H	**1**	**2**	$-\frac{1}{2}$	$-\frac{1}{2}x_H$
$j = 1, 2$ N_R^j	**1**	**1**	0	-1
N_R	**1**	**1**	0	-1
Φ	**1**	**1**	0	$+2$

N_R^j, N_R → Anomaly free

$x_H = 0$: minimal B−L model

$|x_H| \gg 1$: hyper-charge oriented U(1)x

N. Okada, SO and D. Raut, Phys. Rev. D95 (2017) 055030

Particle content of the minimal U(1)x model

$$Q_X = x_H Q_Y + Q_{B-L}$$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{1}{6}x_H + \frac{1}{3}$	$+$
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{2}{3}x_H + \frac{1}{3}$	$+$
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$-\frac{1}{3}x_H + \frac{1}{3}$	$+$
ℓ_L^i	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$-\frac{1}{2}x_H + (-1)$	$+$
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	$-x_H + (-1)$	$+$
H	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$-\frac{1}{2}x_H$	$+$
N_R^j	$\mathbf{1}$	$\mathbf{1}$	0	-1	$+$
N_R	$\mathbf{1}$	$\mathbf{1}$	0	-1	$-$
Φ	$\mathbf{1}$	$\mathbf{1}$	0	$+2$	$+$

Z2 parity

Z2-odd for N_R

Z2-even for the other fields

→ Stable

↓

Unique DM candidate

Gauge invariant Yukawa coupling

$$\mathcal{L}_Y \supset -\sum_{i=1}^{3}\sum_{j=1}^{2} Y_D^{ij}\overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{k=1}^{2} Y_N^k \Phi \overline{N_R^{k\;C}} N_R^k - \frac{1}{2} Y_N \Phi \overline{N_R^{\;C}} N_R + \text{h.c.}$$

Dirac Yukawa coupling for RHNs

Majorana Yukawa coupling for RHNs

Gauge invariant Yukawa coupling

$$\mathcal{L}_Y \supset -\sum_{i=1}^{3}\sum_{j=1}^{2} Y_D^{ij}\,\overline{\ell_L^i}\, H N_R^j - \frac{1}{2}\sum_{k=1}^{2} Y_N^k \Phi\, \overline{N_R^{k\,C}} N_R^k - \frac{1}{2} Y_N \Phi\, \overline{N_R^{\,C}} N_R + \text{h.c.}$$

U(1)x symmetry breaking

EW symmetry breaking

Dark Matter

Minimal seesaw

with only two RHNs

P. Minkowski, Phys. Lett. B67 (1977) 421

T. Yanagida, Conf. Proc. C7902131 (1979) 95

2. Freeze-in RHN Dark Matter

DM relic density is evaluated by solving **the Boltzmann equation**

$$\frac{dY}{dx} = -\frac{s(m_{DM})}{H(m_{DM})}\frac{\langle\sigma v_{\rm rel}\rangle}{x^2}\left(Y^2 - Y_{EQ}^2\right)$$

Y : yield

$$x \equiv \frac{m}{T}$$

Initial condition (freeze-in DM case): $Y(x_{RH}) = 0$

$$x_{RH} = \frac{m_{DM}}{T_{RH}}$$

Reheating temperature T_{RH} after inflation

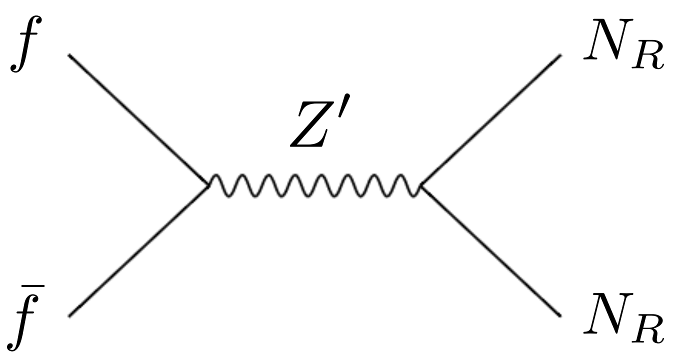
DM relic density at present universe

$$\Omega_{DM}h^2 = \frac{m_{DM}Y(\infty)s_0}{\rho_c/h^2} = 0.12 \text{ (Planck 2018)}$$

2. Freeze-in RHN Dark Matter

$m_{Z'} \ll m_{DM}$ $10 \text{ MeV} \lesssim m_{Z'} \lesssim 1 \text{ GeV}$

Main process for the DM pair creation from the SM thermal plasma



Z'-portal RHN DM

$$\sigma(s) = \frac{g_X^4}{48\pi} \frac{\sqrt{s(s-4m_{DM}^2)}}{(s-m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2} F(x_H)$$

$$F(x_H) = 13 + 16x_H + 10x_H^2$$

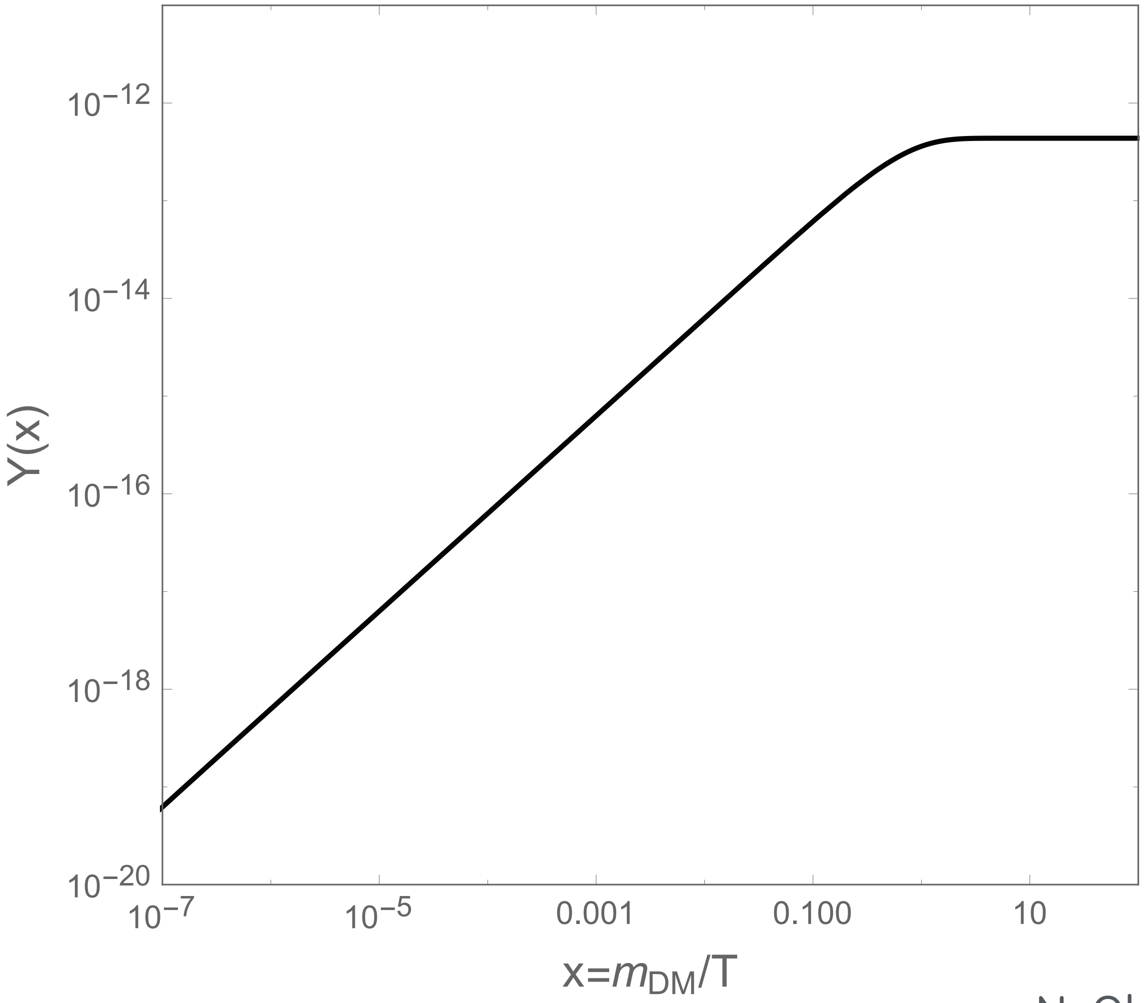
$m_{Z'} \ll m_{DM}$

$$\sigma(s) \simeq \frac{g_X^4}{48\pi} \frac{\sqrt{s(s-4m_{DM}^2)}}{s^2} F(x_H)$$

Result for Y(x)

We numerically solve the Boltzmann equation ($x_{RH} = 10^{-10}$)

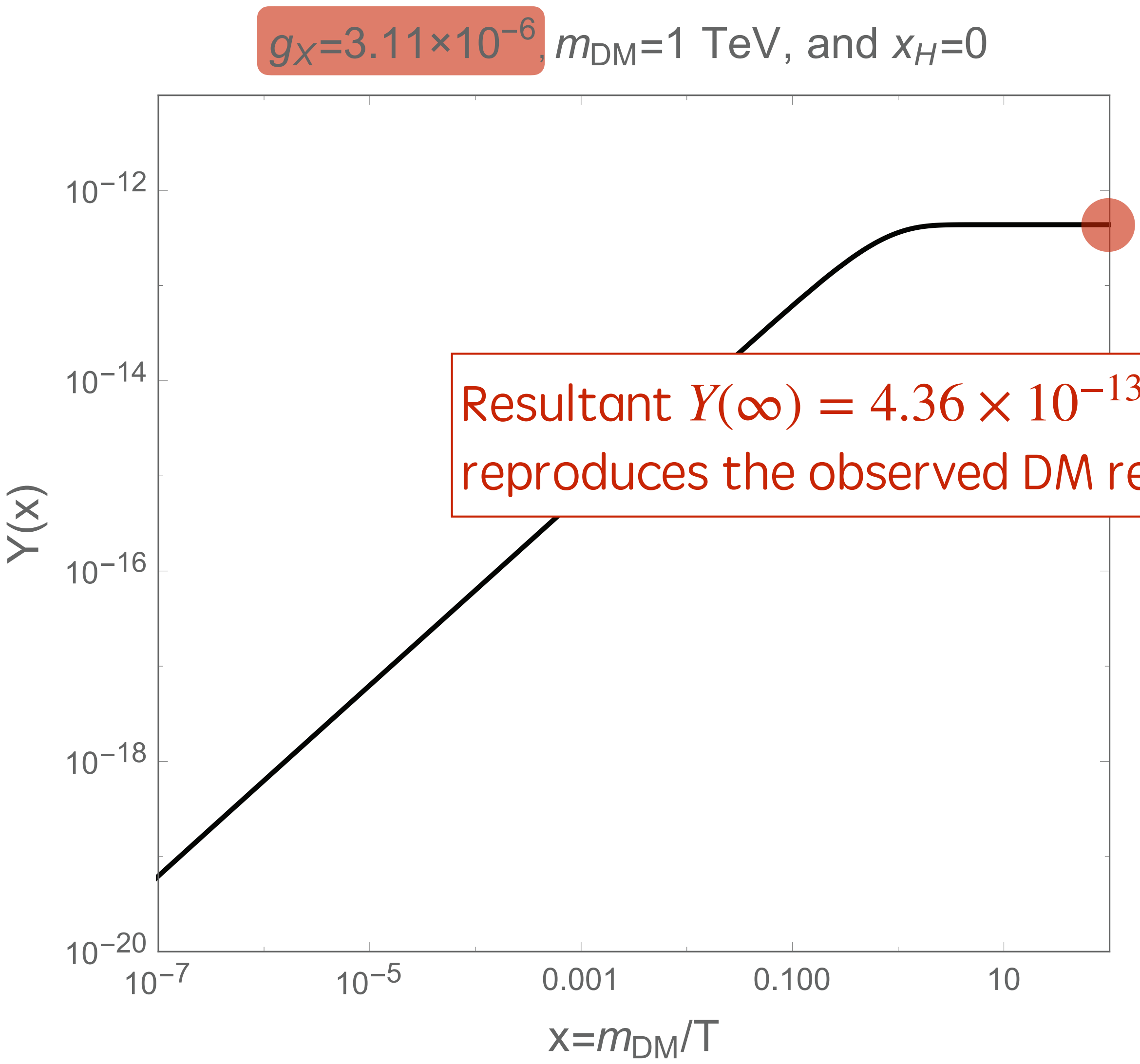
g_X=3.11×10^{-6}, m_{DM}=1 TeV, and x_H=0



N. Okada, SO and Q. Shafi, arXiv: 2003.02667

Result for Y(x)

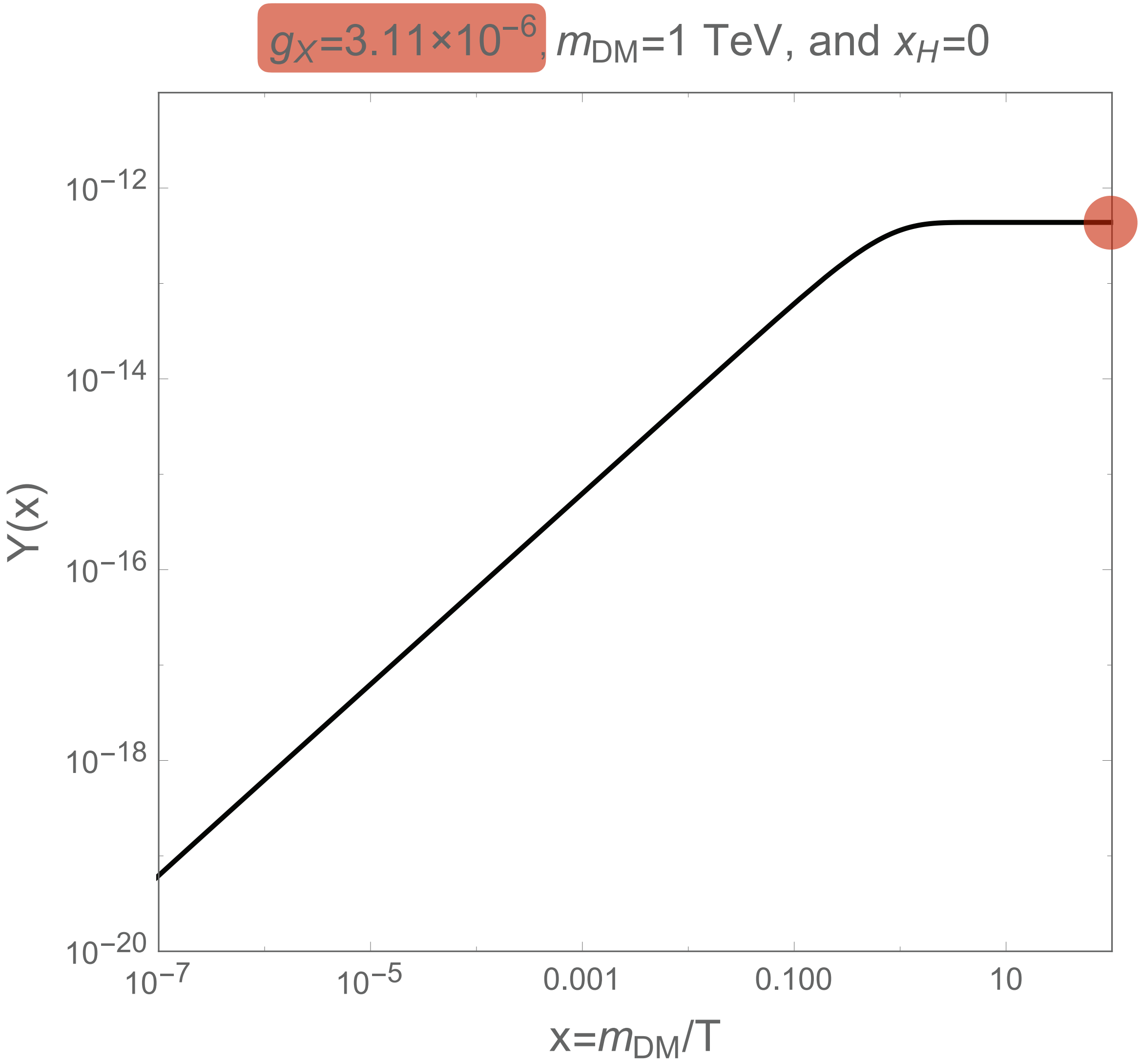
We numerically solve the Boltzmann equation $(x_{RH} = 10^{-10})$



Resultant $Y(\infty) = 4.36 \times 10^{-13}$
reproduces the observed DM relic density $\Omega_{DM}h^2 = 0.12$

Result for Y(x)

We numerically solve the Boltzmann equation $(x_{RH} = 10^{-10})$



$Y(\infty)$ is independent of $x_{RH} \ll 1$

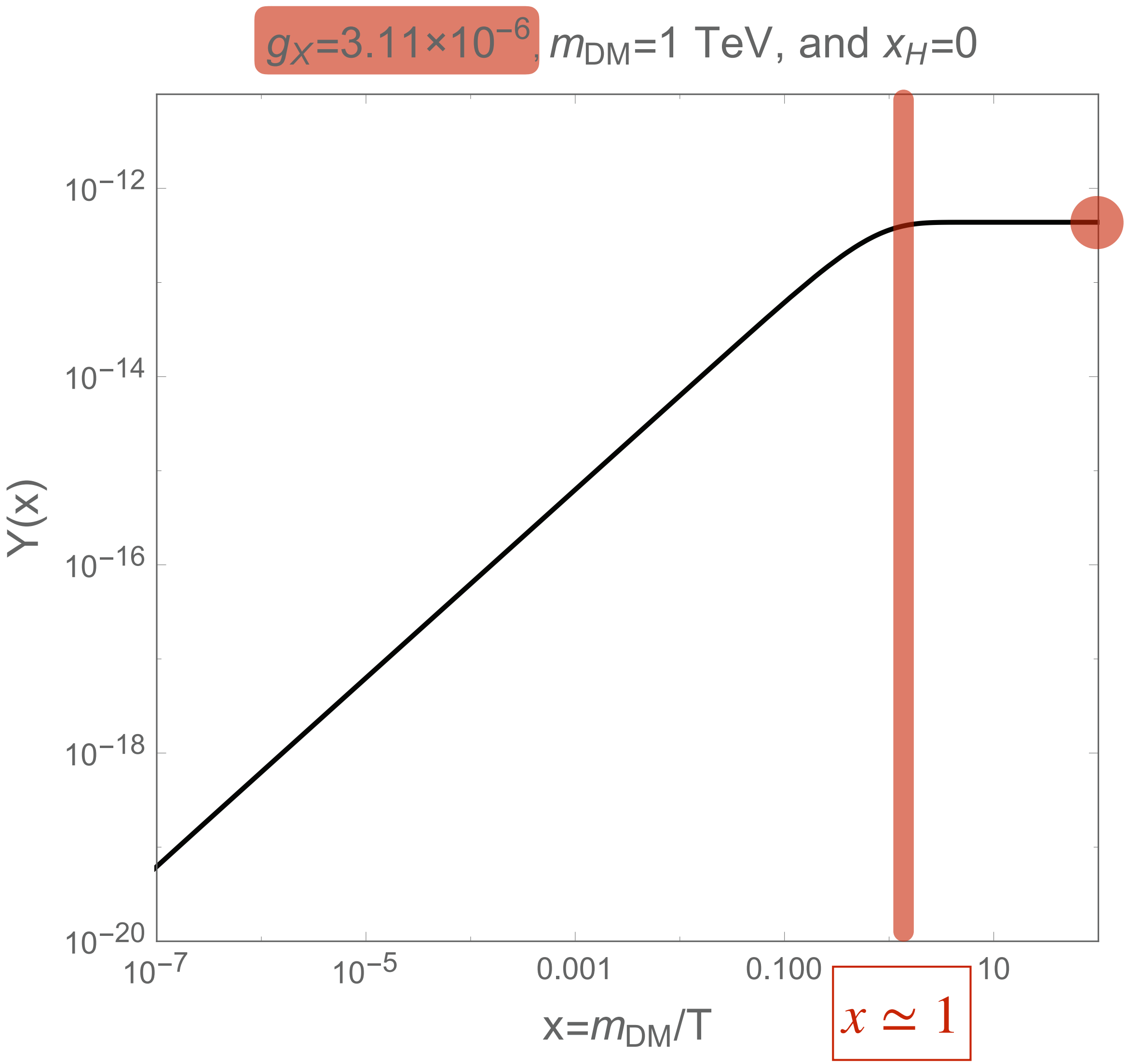
$$Y(\infty) \propto \frac{1}{m_{DM}}$$

↓

$\Omega_{DM}h^2$ is independent of m_{DM}

Result for Y(x)

We numerically solve the Boltzmann equation $(x_{RH} = 10^{-10})$



Resultant $Y(\infty) \simeq Y(x=1)$
since production of DM particles from the thermal plasma stops around $x \sim 1$ $(T \sim m_{DM})$ due to kinematics

g_X to reproduce the observed DM relic density

DM creation cross section:

$$\sigma(x) = \frac{g_X^4}{48\pi} \frac{\sqrt{s(s-4m_{DM}^2)}}{(s-m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2} F(x_H)$$

$$\propto g_X^4 F(x_H)$$

Observed DM relic density is reproduced by

$$g_X = 3.11 \times 10^{-6} \left(\frac{F(0)}{F(x_H)} \right)^{1/4}$$

for a general x_H value

Very small + Z' boson is light

Z' boson is long-lived

3. Future experiments at the Lifetime Frontier

How to test the scenario in the future experiments at the Lifetime Frontier?

- FASER
- FASER 2
- Belle II
- LHCb
- SHiP
- LDMX

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We need to interpret the analysis result for the B−L gauge boson to the U(1)x model case

Results for the $|x_H| \lesssim 1$ are expected to be similar to the one for the B−L case

→ Hyper−charge oriented case in $|x_H| \gg 1$

B−L case — Z' boson coupling with the SM fermions is controlled by g_{BL}

Hyper−charge oriented case — controlled by $g_X |x_H|$

↓

$$g_{BL} \longleftrightarrow g_X |x_H|$$

3. Future experiments at the Lifetime Frontier

Gauge coupling to reproduce the observed DM relic density $\Omega_{DM}h^2 = 0.12$

$$g_X = 3.11 \times 10^{-6} \left(\frac{F(0)}{F(x_H)} \right)^{1/4}$$

$$\downarrow$$

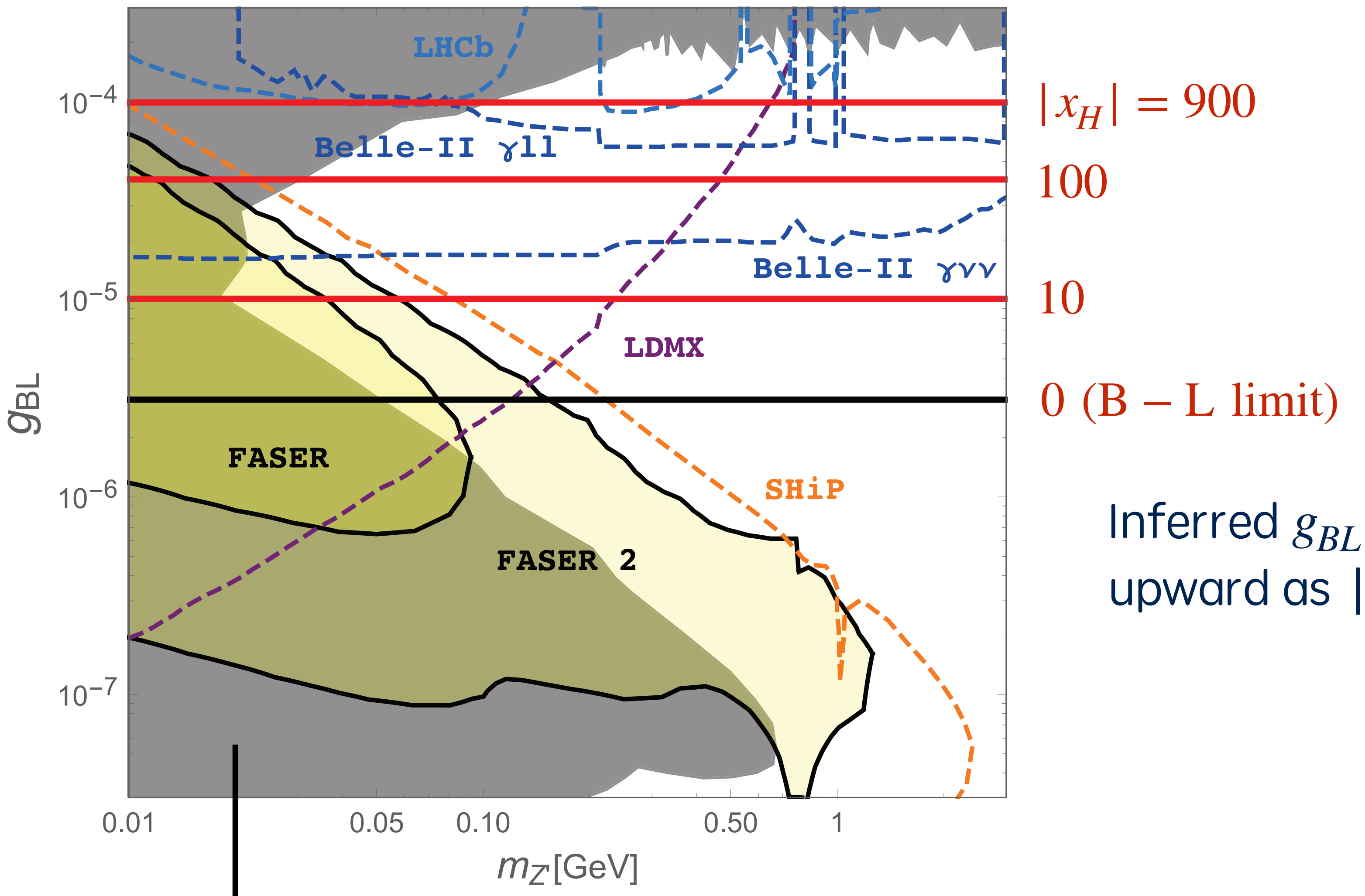
$$g_X \simeq \frac{3.32 \times 10^{-6}}{\sqrt{|x_H|}} \quad \text{for } |x_H| \gg 1$$

g_{BL} value in the analysis of the prospective search for the B−L gauge boson can be inferred to be

Inferred g_{BL} : $\quad g_{BL} \longrightarrow g_X |x_H| \simeq 3.32 \times 10^{-6} \sqrt{|x_H|}$

Inferred g_{BL} to reproduce DM relic abundance

N. Okada, SO and Q. Shafi, arXiv: 2003.02667



Inferred g_{BL} value shifts upward as $|x_H|$ increases

Current excluded region

- Searches for long-lived particle
- Anomalous neutrino interactions

If a long-lived Z’ boson is observed in the future,

we can determine $|x_H|$ and **Z’**!!

4. Conclusion and discussion

We consider a $U(1)_X$ gauge symmetry extension of the SM with a Z'-portal Majorana fermion DM that allowed for a relatively light gauge boson Z' with mass of 10 MeV–a few GeV and a much heavier DM through the freeze-in mechanism.

Motivated by the future Lifetime Frontier experiments,
we have focused on the parameter space where the DM particle very weakly couples to the light Z' boson.
In this case, the Z' boson is long-lived.

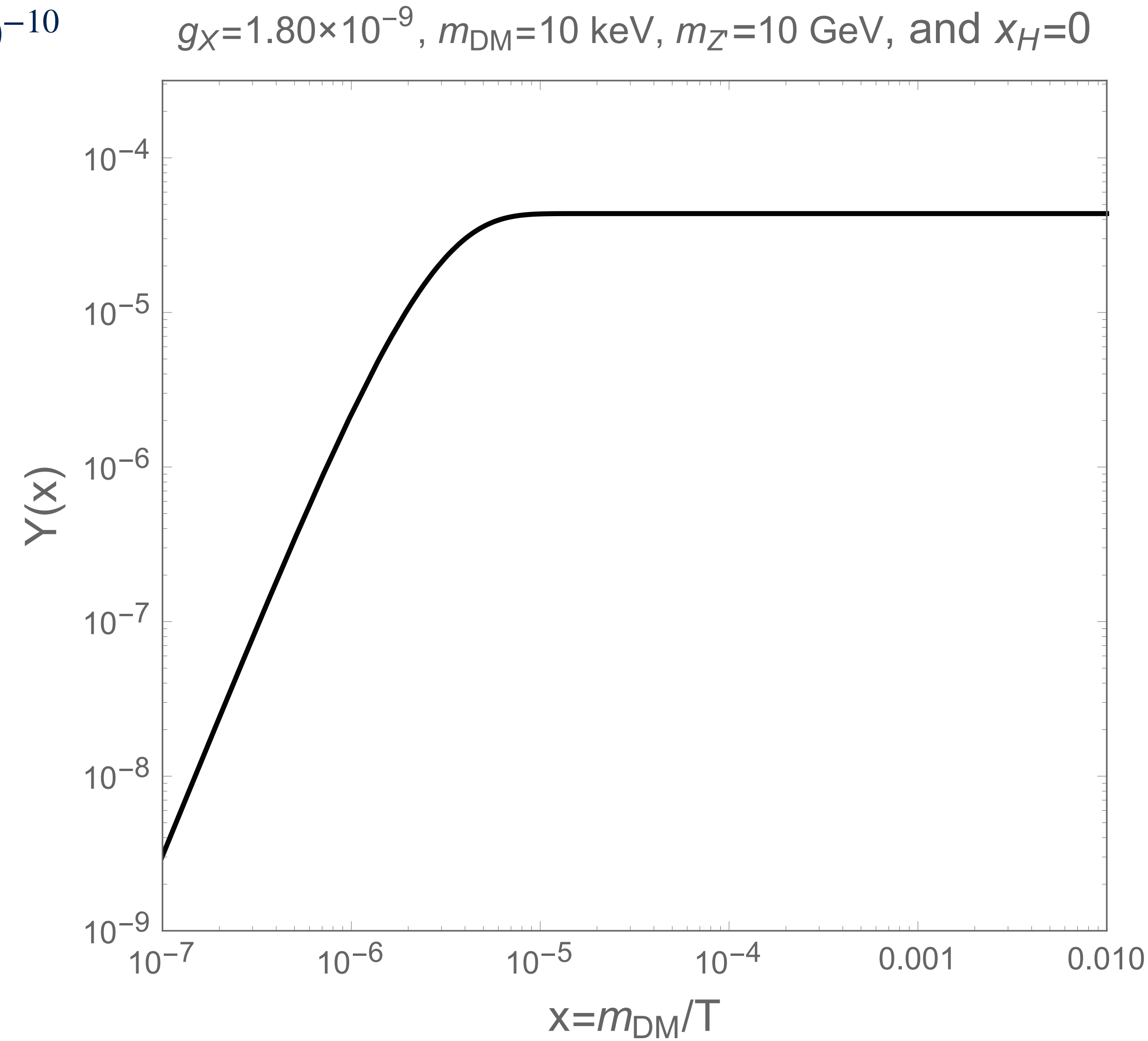
For $m_{Z'} \ll m_{DM}$ case, we have identified the model parameter regions to reproduce the observed DM relic density $\Omega_{DM}h^2 = 0.12$.

We have discussed how our scenario can be tested by various future Lifetime Frontier experiments.
We found that the $U(1)_X$ model with a large $|x_H|$ (hyper-charge oriented case) dramatically alters the parameter region to be explored by the future experiments compared to that for B–L mode.

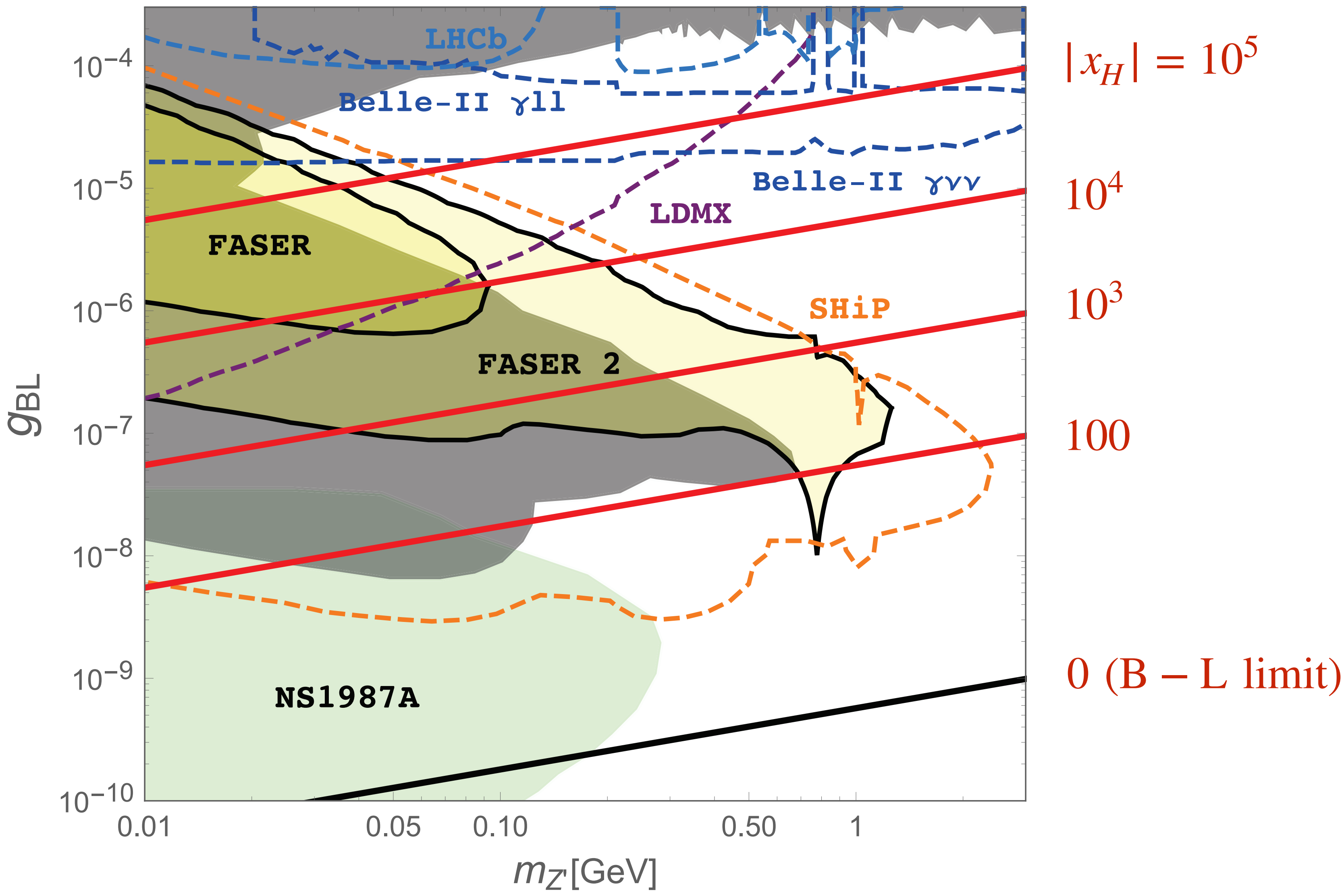
Back Up

$m_{Z'} >> m_{DM}$ case

$x_{RH} = 10^{-10}$



mZ' >> mDM case



LHCb
Belle-II γll
Belle-II γνν
LDMX
FASER
FASER 2
SHiP
NS1987A
$|x_H| = 10^5$
10^4
10^3
100
0 (B – L limit)
g_{BL}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.01
0.05
0.10
0.50
1
$m_{Z'}$[GeV]