Freeze-in dark matter from a minimal B – L model and possible grand unification

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Ref: Mohapatra & NO, Phys. Rev. D 101, no.11, 115022 (2020)
[arXiv:2005.00365 [hep-ph]]

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1. Problems of the Standard Model

Although the Standard Model (SM) is the best theory so far, New Physics beyond SM is strongly suggested by various experimental & theoretical points of view

What is missing?

Two major missing pieces

1. Neutrino masses and flavor mixings
2. Dark matter candidate

New Physics must supplement the missing pieces

2. Minimal gauged B-L extension of the SM

Marshak & Mohapatra, PLB 91 (1980) 222;Wetterich, NPB 187 (1981) 343
Masiero, Nieves and Yanagida, PLB 116 (1982) 11 + Others

Based on $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/3$
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$1/3$
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$1/3$
l_L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1
N_R^i	$\mathbf{1}$	$\mathbf{1}$	0	-1
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	-1
H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
Φ	$\mathbf{1}$	$\mathbf{1}$	0	2

3 right-handed neutrinos (RHNs)

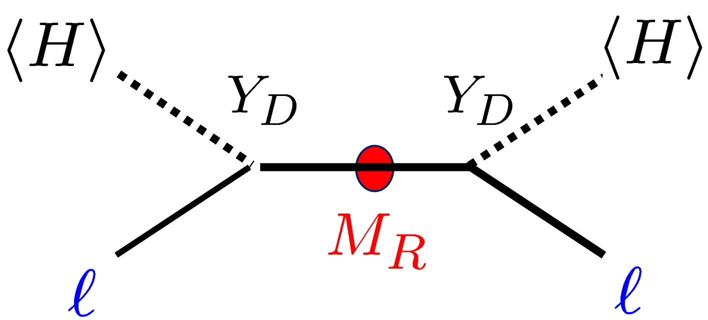
B-L Higgs field for the B-L breaking

Properties of gauged B-L extended SM

- It is easy (well-motivated) to gauge the global B-L symmetry in the SM
- All the gauge anomalies cancel in the presence of 3 RHNs

- New B-L gauge boson mass & RHNs' Majorana masses are generated by the B-L gauge symmetry breaking
- The seesaw mechanism for generating tiny neutrino masses is implemented automatically.

Seesaw mechanism



$$
\begin{aligned}
m_\nu &= \frac{(Y_D\langle H\rangle)^2}{M_R} \\
&= Y_D\langle H\rangle\left(\frac{Y_D\langle H\rangle}{M_R}\right) \ll Y_D\langle H\rangle
\end{aligned}
$$

DM candidate is still missing in the minimal B-L model

Many proposal for introduction of DM particles

Concise model: no extension of the particle content

Example: parity-odd right-handed neutrino DM

RHN DM + Minimal Seesaw

NO & Seto, PRD 82 (2010) 023507

In this talk, we consider another possibility:

the B-L Higgs boson = DM

Mohapatra & NO, PRD 101 (2020) 115022

$$\Phi = \frac{1}{\sqrt{2}}\left(v_{BL} + \boxed{\sigma} + i\chi\right)$$

Challenges to realize the B-L Higgs boson DM

1. Stability & Cosmic Ray constraints: $\tau_\sigma \gtrsim 10^{25}$ sec

Suppression for a single DM coupling & mixing

$\sigma - N_R - N_R$: related to the oscillation data via Seesaw

$\sigma - Z_{BL} - Z_{BL}$: related to g_{BL} & M_{Z_B}

$\sigma - h_{SM}$ mixing : simply dropped

It turns out that the most severe constraint is from the decay mode with off-shell B-L gauge bosons: $\sigma \to Z_{BL} Z_{BL} \to f\bar{f}f\bar{f}$

$$g_{BL} \leq 4.2 \times 10^{-8} \left(\frac{M_{Z_{BL}}}{1\ \mathrm{GeV}}\right) \left(\frac{1\ \mathrm{GeV}}{m_\sigma}\right)^{7/6}$$

Challenges to realize the B-L Higgs boson DM

2. Observed DM relic density: $\Omega_{DM} h^2 = 0.12$

- Due to the lifetime constraint, the DM particle must be very weakly coupling with the SM sector

- Freeze-out mechanism results in overabundance

- We consider Freeze-in mechanism

Two cases can be considered: for $T \gtrsim M_{Z_{BL}}$,

(i) Z_{BL} was in thermal equilibrium with the SM plasma

$$g_{BL} > 2.7 \times 10^{-8} \left(\frac{M_{Z_{BL}}}{1 \text{ GeV}}\right)^{1/2}$$

(ii) or not

Evaluation of the DM relic density

by solving the Boltzmann equation with DM creation cross section

The main DM creation processes

Case (i): $Z_{BL}Z_{BL} \rightarrow \sigma\sigma$

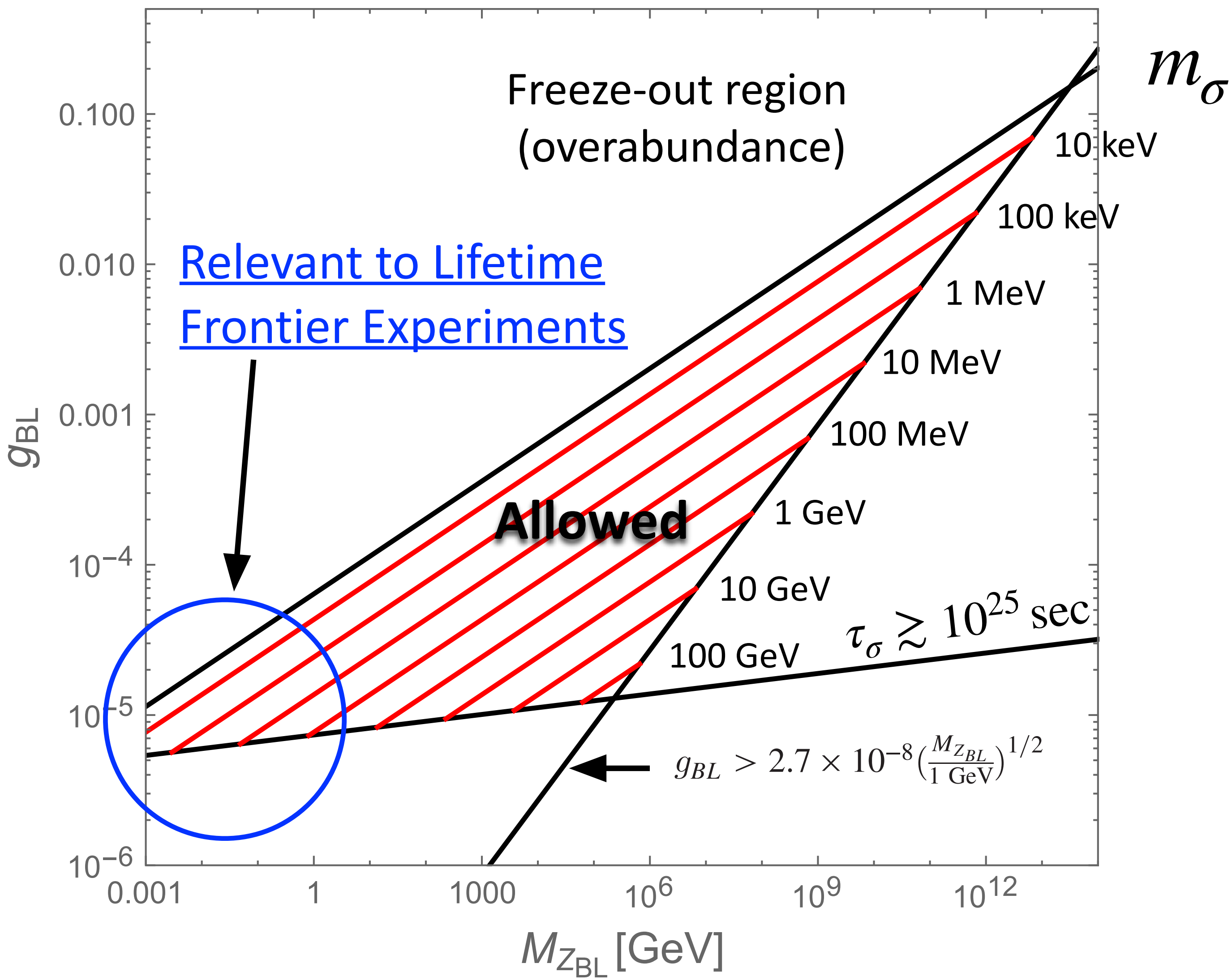
Case (ii): $f\bar{f} \rightarrow Z_{BL}\sigma$

The resultant DM relic density is controlled by only three parameters:

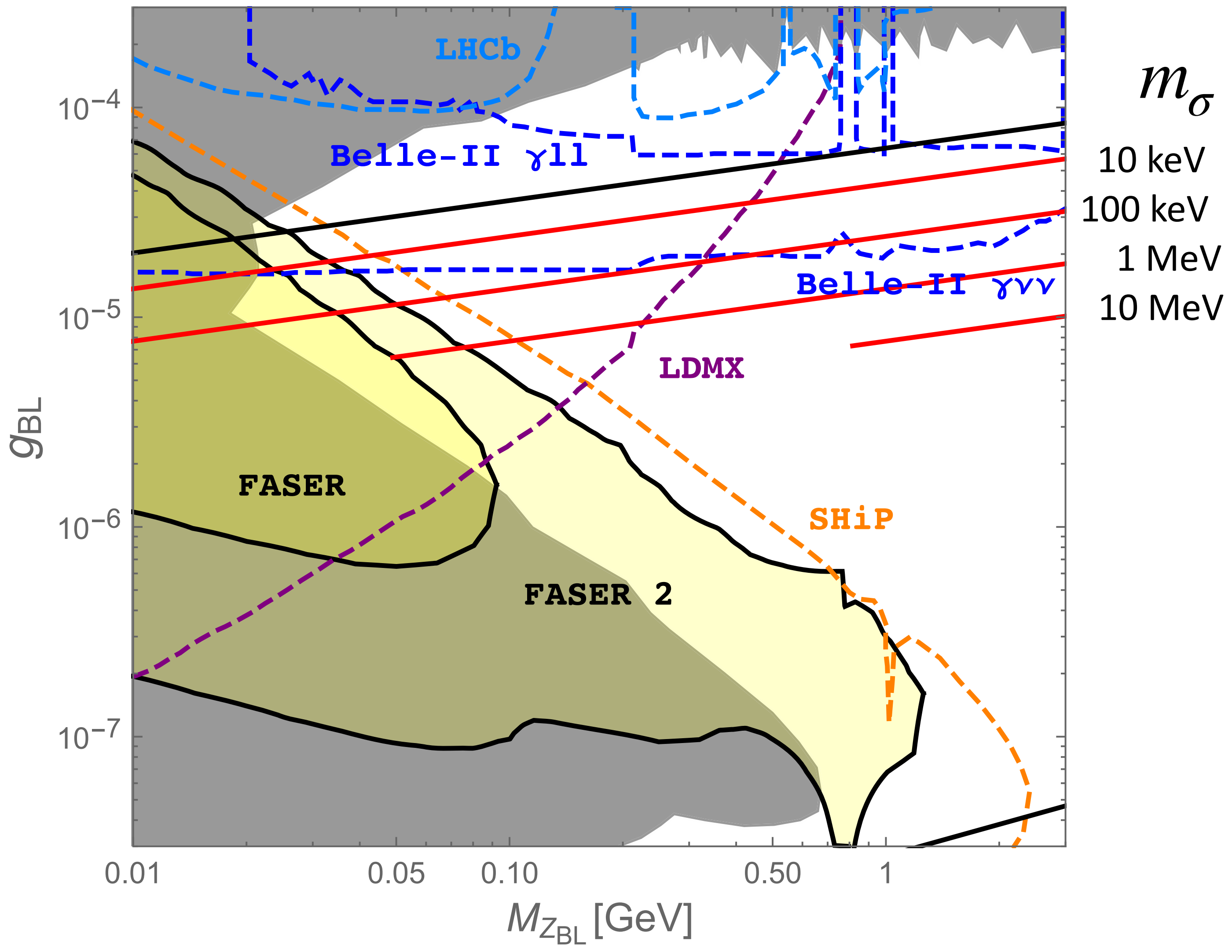
$$g_{BL}, M_{Z_{BL}}, m_\sigma$$

Results for Case (i)

$\Omega_{DM} h^2 = 0.12$ along the red lines

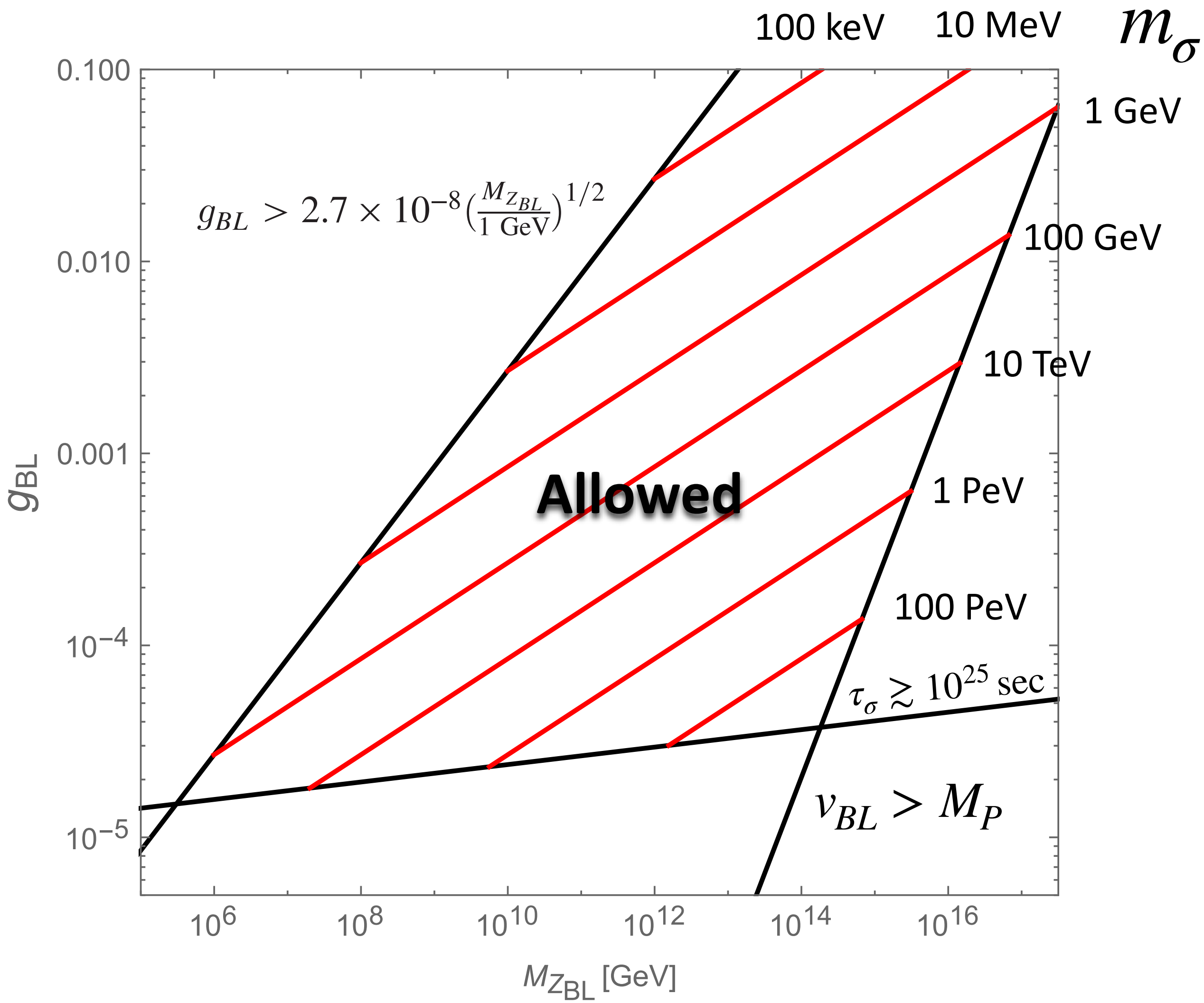


Long-lived B-L gauge boson search in the future



Results for Case (ii)

$\Omega_{DM}h^2 = 0.12$ along the red lines



Prospects for SO(10) embedding

Generalization of the minimal B-L model:
the minimal U(1)_X model

- The structure of the model is essentially the same
- SU(5)xU(1) GUT embedding is possible
- Then, SO(10) embedding

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$SU(5)$	SO(10)
q_L	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/5$		
u_L^c	$\mathbf{3}^*$	$\mathbf{1}$	$2/3$	$1/5$	**10**	
e_L^c	$\mathbf{1}$	$\mathbf{1}$	$+1$	$1/5$		**16**
d_L^c	$\mathbf{3}^*$	$\mathbf{1}$	$-1/3$	$-3/5$	$\mathbf{5}^*$	
ℓ_L	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$-3/5$		
N_L^c	$\mathbf{1}$	$\mathbf{1}$	0	$+1$	$\mathbf{1}$	
H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$2/5$		**10**
Φ	$\mathbf{1}$	$\mathbf{1}$	0	$+2$		**126**

Successful gauge coupling unification?

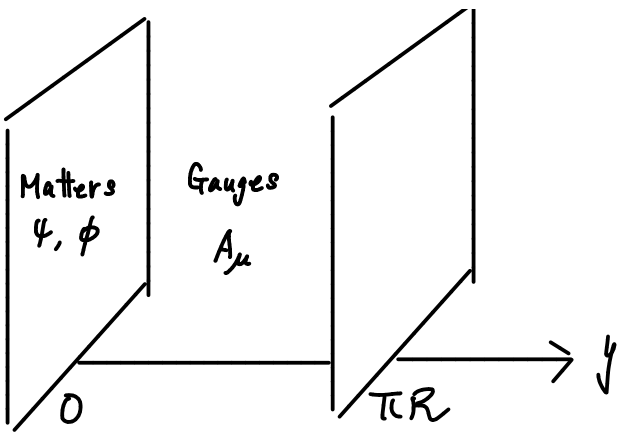
➢ With a suitable set of extra matters, SU(5) gauge coupling unification is possible

➢ But, the U(1) gauge coupling is much smaller than the SM ones in our Freeze-In DM scenario

How can we realize the successful gauge coupling unification?

5D extension of the model

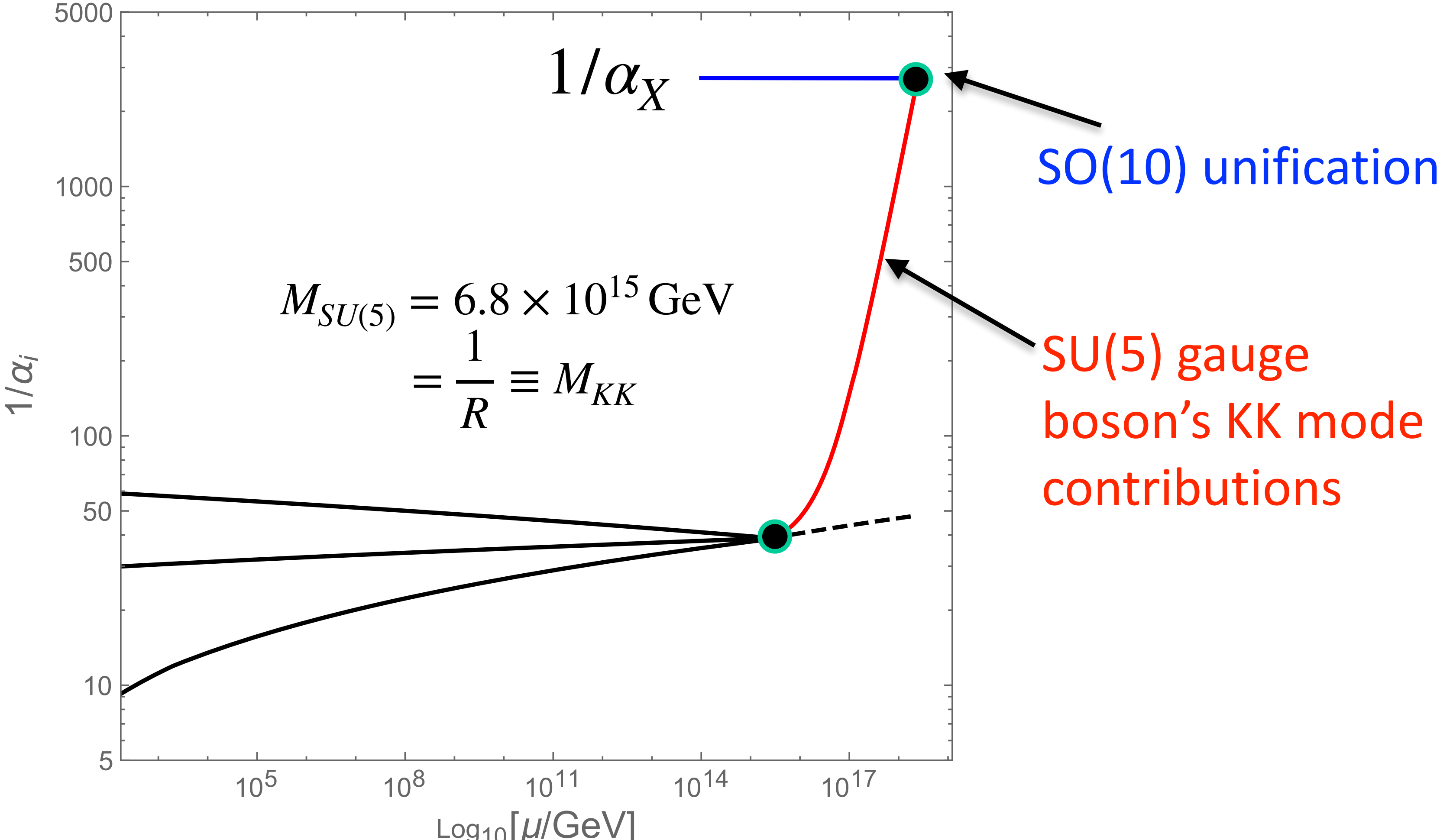
- S^1/Z_2 compactification with a brane at y=0
- 1/R= SU(5) GUT scale



5D SO(10) GUT

Extra matters (color adjoint + SU(2) adjoint scalars) @ 5 TeV

SM gauge group —> SU(5) x U(1) —> SO(10) in 5D



5. Summary

- We have considered the minimal B-L model where the B-L Higgs boson play the role of a decaying DM
- Lifetime & observed relic density constraints require freeze-in DM scenario
- We have identified the allowed parameter region
- For a low DM mass region, the long-lived B-L gauge boson can be explored by FASER etc in the future
- SO(10) GUT embedding has been considered in 5D