Right-handed neutrino dark matter under the B-L gauge interaction

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in collaboration with Zhaofeng Kang (KIAS) and Hye-Sung Lee (IBS-CTPU)

Reference: 1606.09317

ILC Summer Camp 2016, July 23-26, 2016, Iwate

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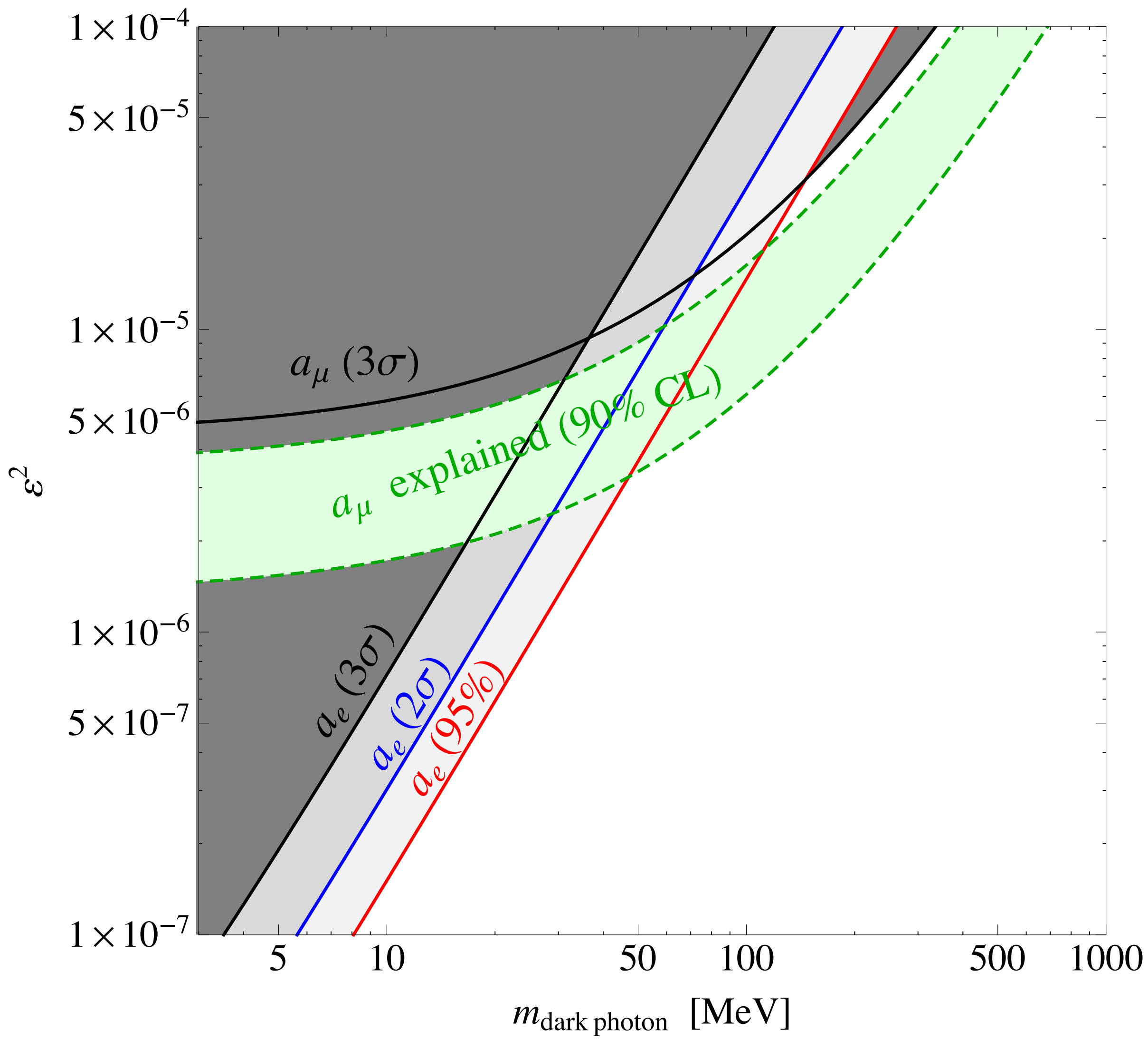
[green band: Pospelov, ’08]



(figure by H.-S. Lee)

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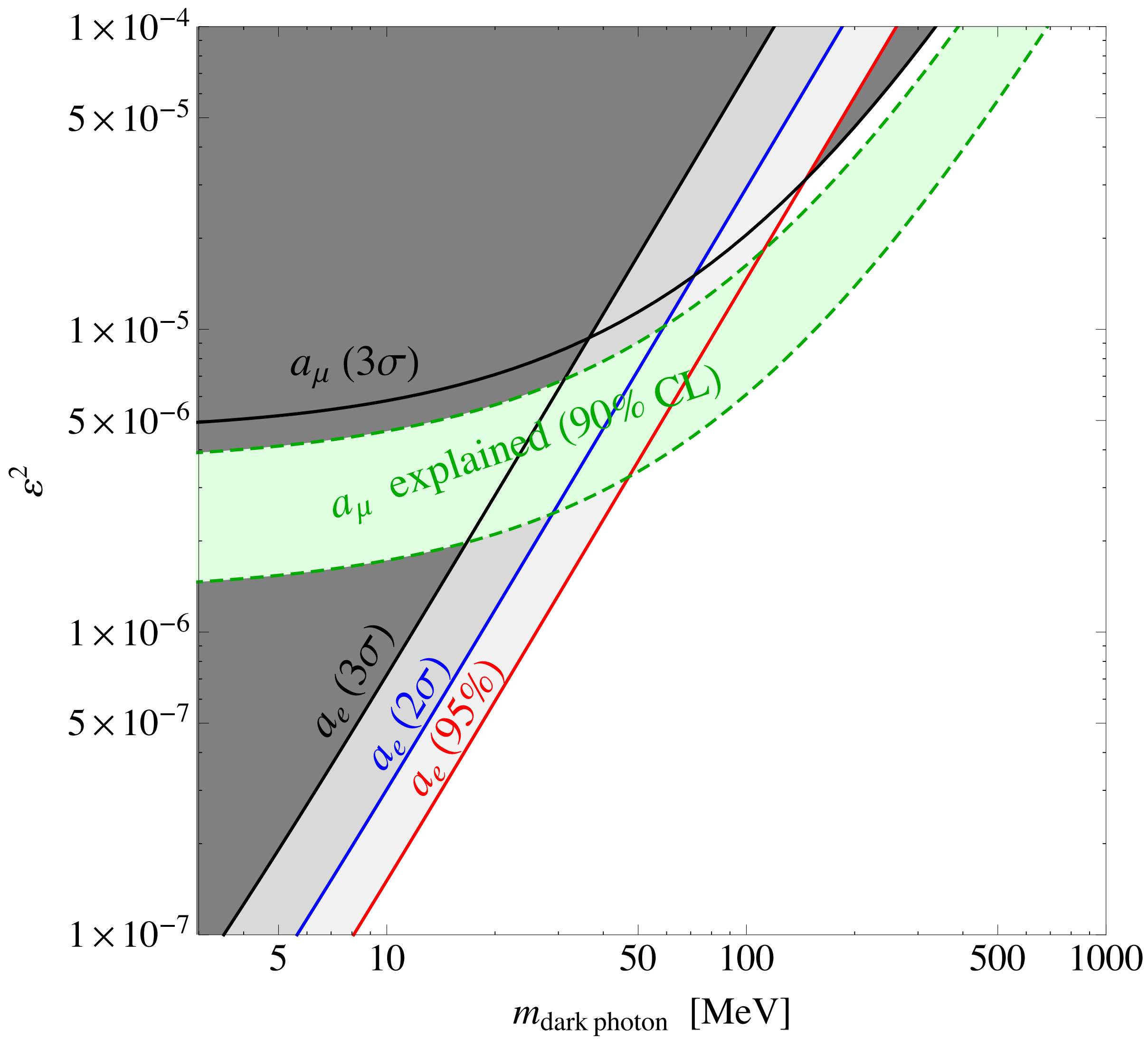
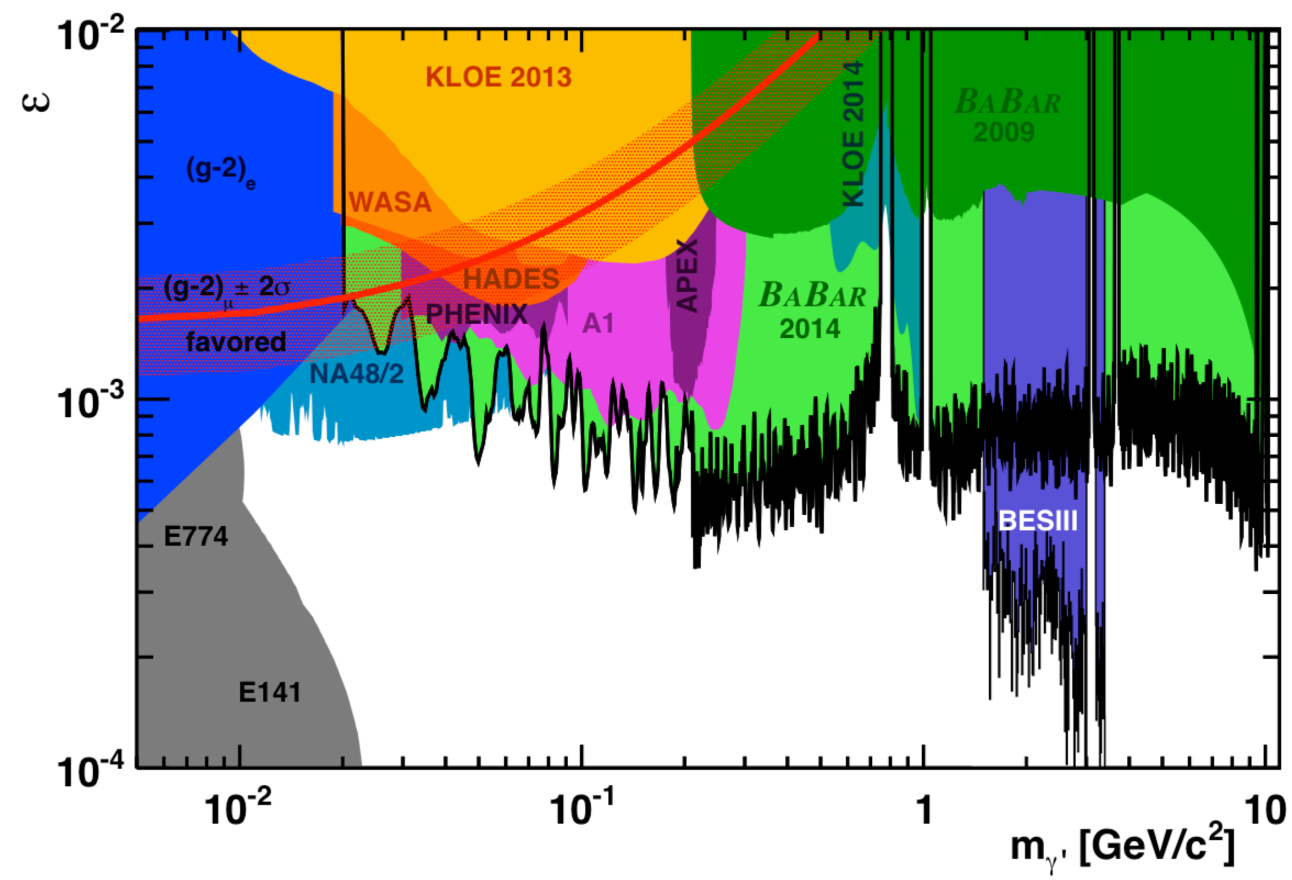


(figure by H.-S. Lee)

[Soffer, '15]



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➢ ***We will try to provide another well-motivated parameter space for Z'.***

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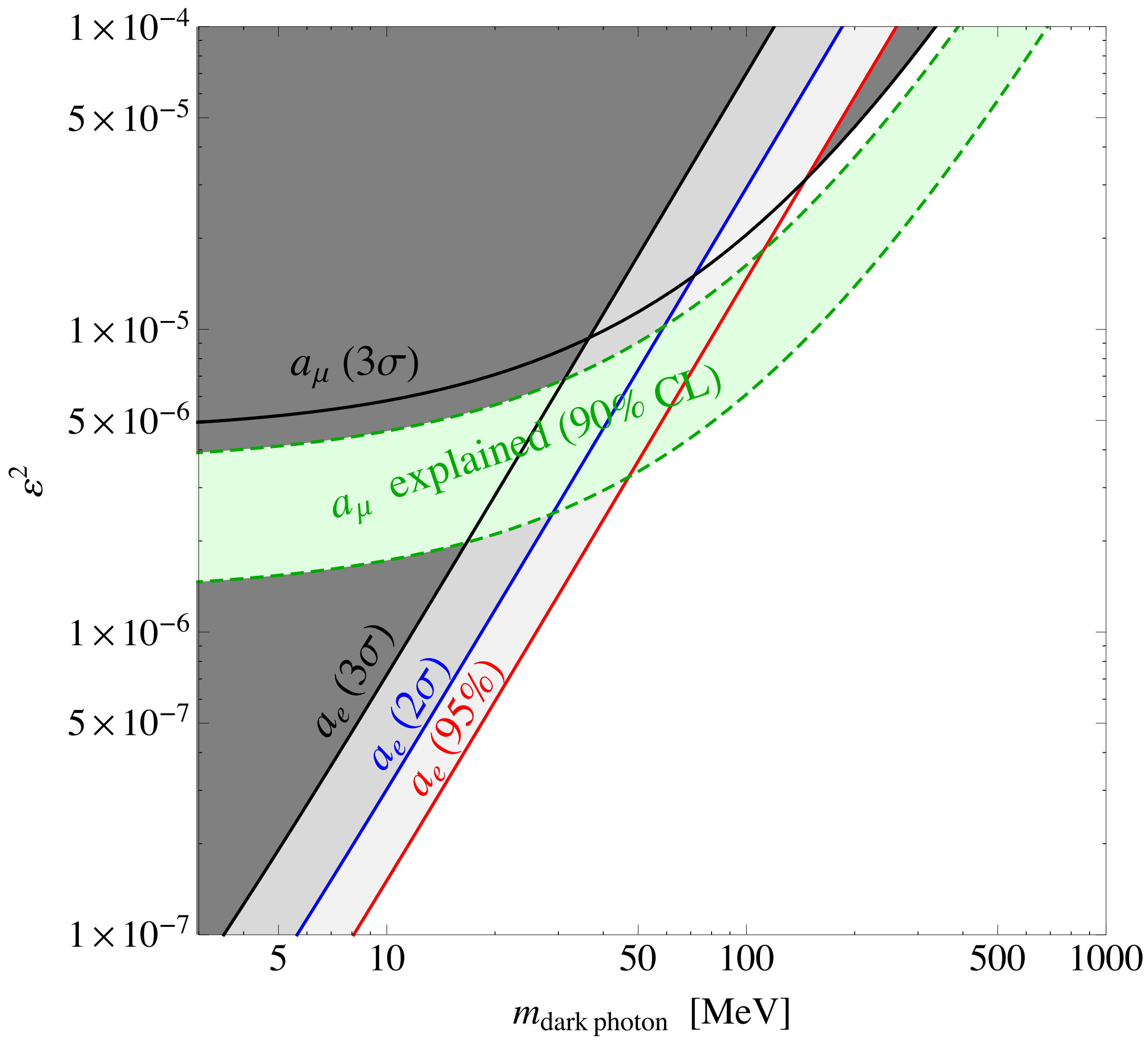

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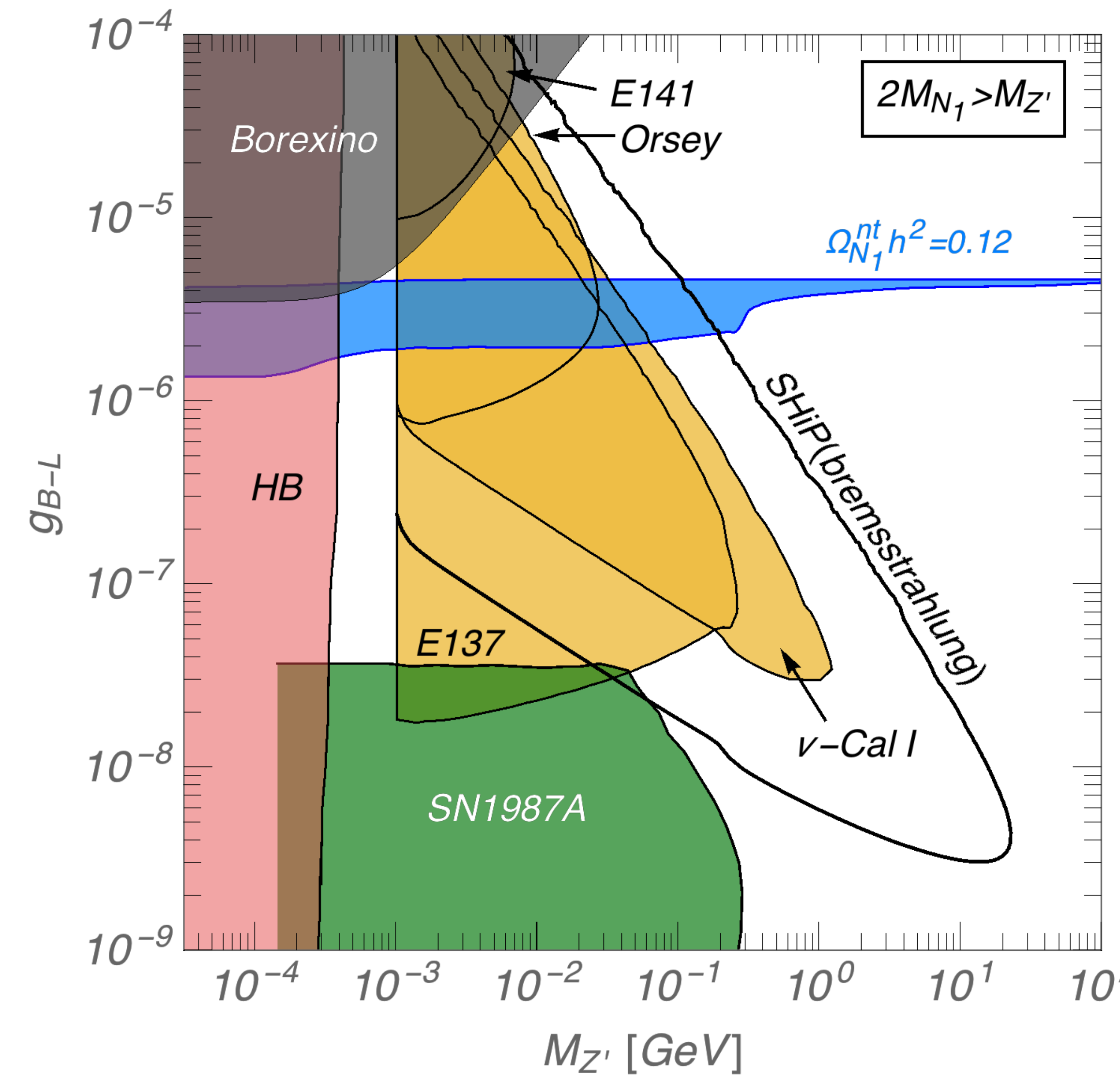


Outline

1. Introduction
2. Dark matter under the *B-L* gauge force
3. Implications
4. Summary

1. Introduction

Right-handed neutrinos as a missing piece to the SM

- Neutrino oscillations imply non-zero masses of neutrinos
- Presumably neutrino masses indicate the existence of chiral partners: right-handed neutrinos
- Right-handed neutrinos also play an important role in addressing other issues, e.g., dark matter and baryon asymmetry of the universe

The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Three right-handed neutrinos?

- A minimal framework is just ***the SM + three right-handed (Majorana) neutrinos***

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}_i \not{\partial} N_i - \left(y_{\alpha i}\overline{L}_\alpha N_i \tilde{H} + \frac{M_i}{2}\overline{N^C}_i N_i + h.c. \right)$$

(νMSM)

[Asaka, Blanchet, Shaposhnikov, ‘05]
[Asaka, Shaposhnikov, ‘05]

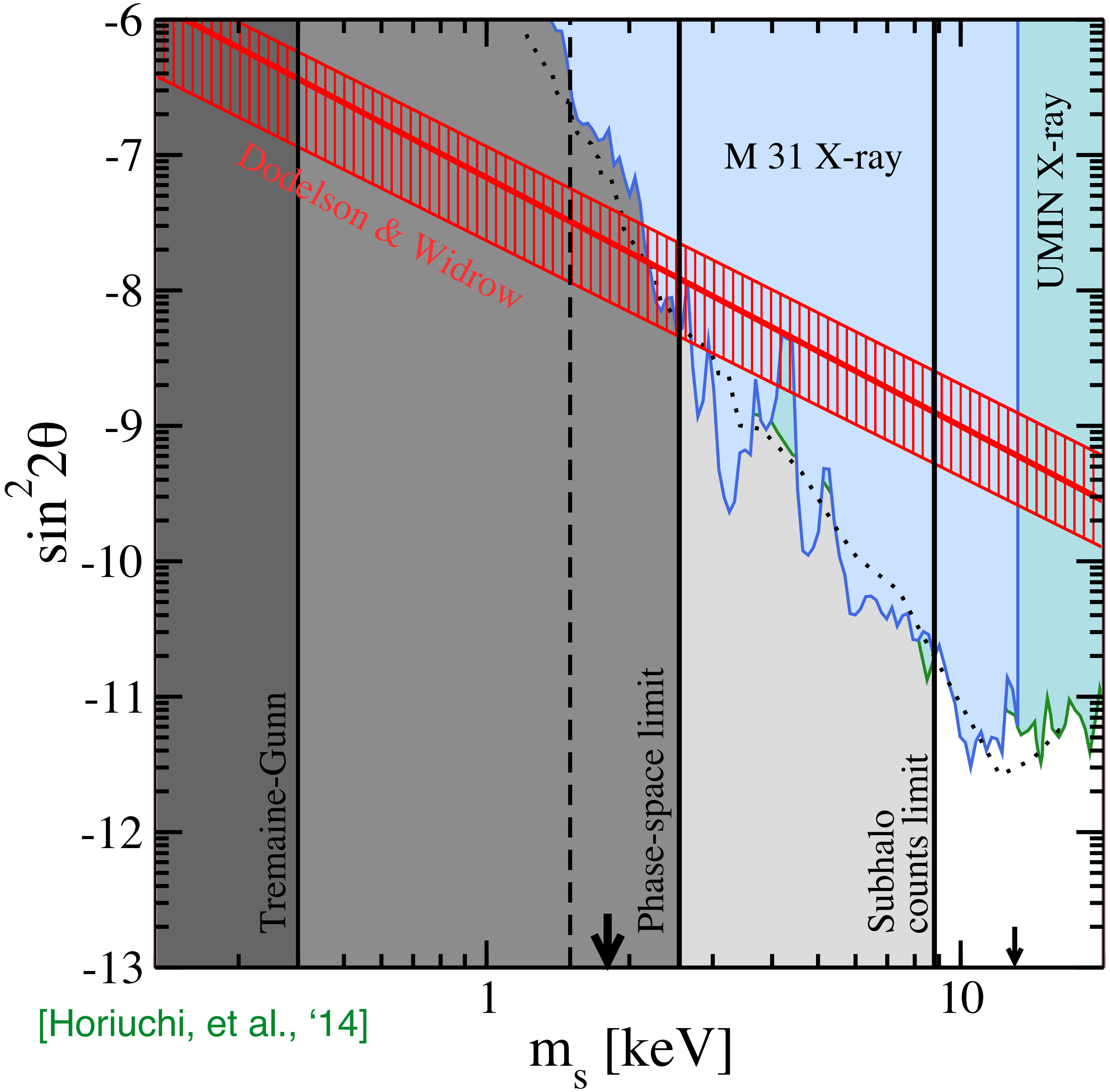
- The lightest right-handed neutrino N_1 can be (keV-scale) dark matter via Dodelson-Widrow mechanism

[Dodelson, Widrow, ‘94]

$$\boldsymbol{\Omega_{N1}h^2 \sim 0.12 \times (\sin^2 2\theta/7\times10^{-8})^{1.23}(M_{N1}/\mathrm{keV})}$$

[K.Abazajian, ‘06]

Constraints on the simplest dark matter production scenario



[Horiuchi, et al., '14]

- Red region: whole amount of dark matter number density is explained by Dodelson-Widrow mechanism

$\Omega_{N1}h^2 \sim 0.12 \times (\sin^2 2\theta / 7\times 10^{-8})^{1.23} (M_{N1}/\mathrm{keV})$

- X-ray observations and phase-space density of dSphs give stringent constraints

- Alternative production mechanism is necessary

(Cf. [R.Adhikari et al, '16])

We discuss a possible scenario for viable production mechanism

Success of the SM and the gauge principle

- ➢ The SM is a phenomenologically successful model so far, and its success is supported by the *gauge principle*: $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$
- ➢ Gauge symmetry plays a role to regulate not only the gauge interactions but also the matter contents by means of the anomaly cancellation

By following this success, the $U(1)_{B\text{-}L}$ gauge symmetry is the most attractive symmetry that offers three right-handed neutrinos

Our framework

- ➢ Under the gauge symmetry $G = G_{SM} \times U(1)_{B\text{-}L}$, we have following new fields:
    - three right-handed neutrinos (N_1, N_2, N_3; *B-L* charge -1)
    - A singlet Higgs field (Φ_S; *B-L* charge -2)
    - *B-L* gauge boson (*Z'*)
- ➢ Our framework ~ the local $U(1)_{B\text{-}L}$ extended version of the νMSM (we call this *UνMSM*)

The B-L gauge interaction can provide viable dark matter production mechanisms;
freeze-in and freeze-out

2. Dark matter under the B-L gauge force

Our setup

➢ Lagrangian of the *UνMSM* is given by

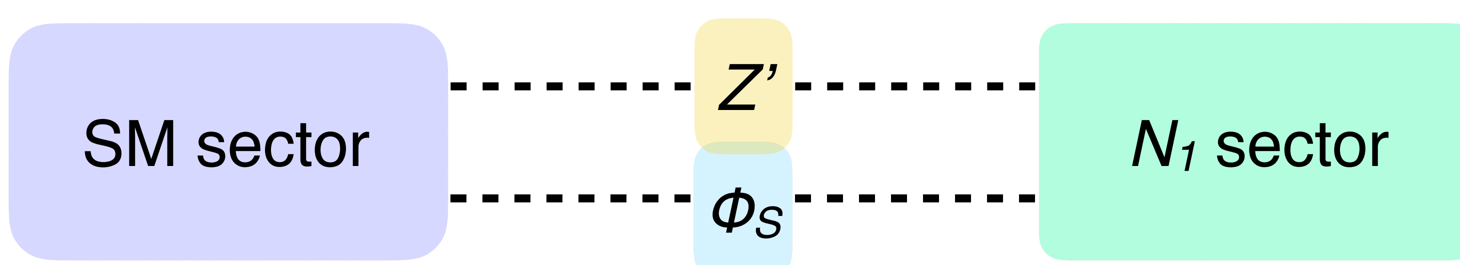
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\overline{N}_i \not{D} N_i - \left(y_{\alpha i} \overline{L}_\alpha N_i \tilde{\Phi}_H + \frac{\kappa_i}{2} \Phi_S \overline{N_i^C} N_i + h.c. \right) + |D_\mu \Phi_S|^2 - V(\Phi_H, \Phi_S) - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}$$

$$V(\Phi_H, \Phi_S) = \frac{\lambda_H}{2}(|\Phi_H|^2 - v_H^2)^2 + \frac{\lambda_S}{2}(|\Phi_S|^2 - v_S^2)^2 + \lambda_{HS}(|\Phi_H|^2 - v_H^2)(|\Phi_S|^2 - v_S^2)$$

➢ As Φ_S develops the vacuum expectation value, $\langle\Phi_S\rangle = v_S$, N_i and Z' acquire the mass:

$$M_{N_i} = \kappa_i v_S, \quad M_{Z'}^2 = 8 g_{B-L}^2 v_S^2$$

➢ We take $M_{N1} < M_{N2}, M_{N3}$, so that N_1 can be a (decaying) dark matter when the Yukawa coupling ($y_{\alpha 1}$) is sufficiently small



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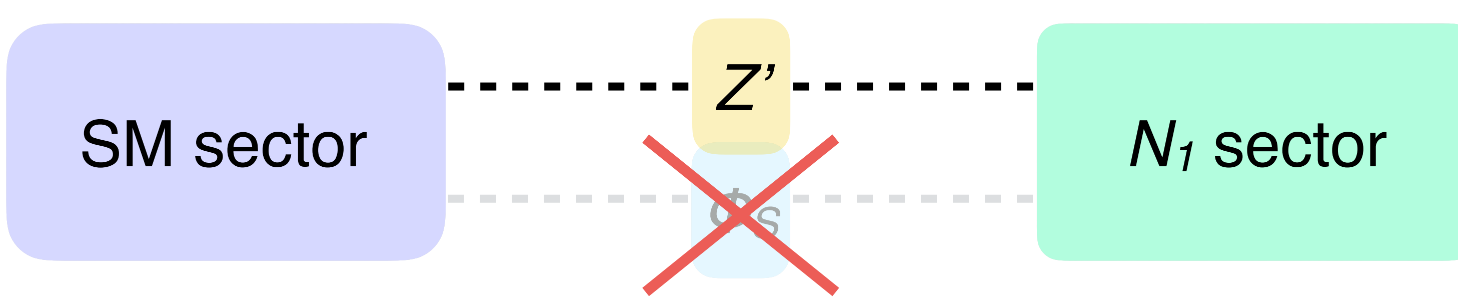


- To concentrate on the Z' effect, we turn off the Higgs portal coupling λ_{HS} ($\rightarrow 0$)

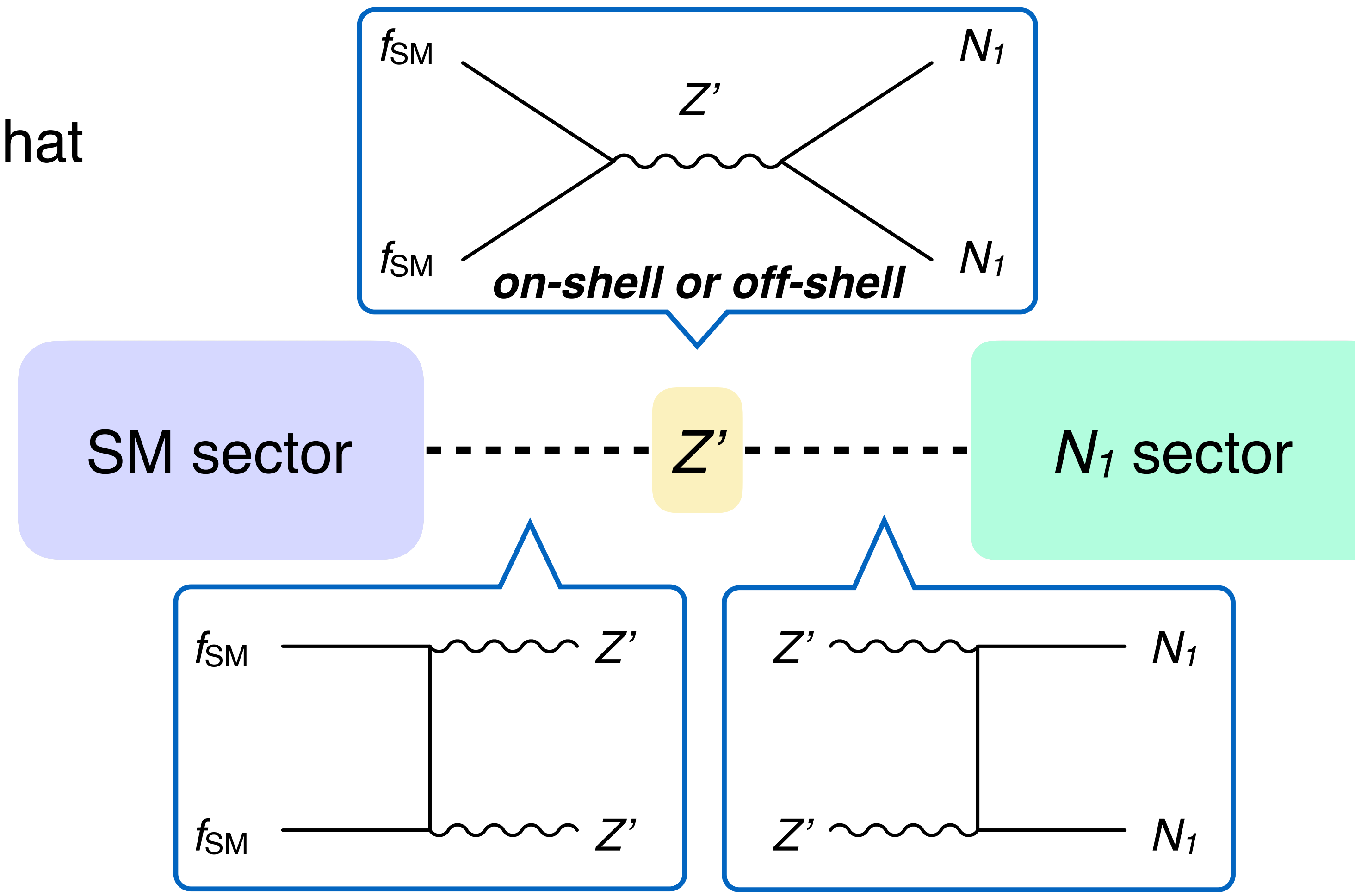
Relevant reactions for thermalization of N_1

➢ There are mainly three processes that can bring N_1 into the thermal bath

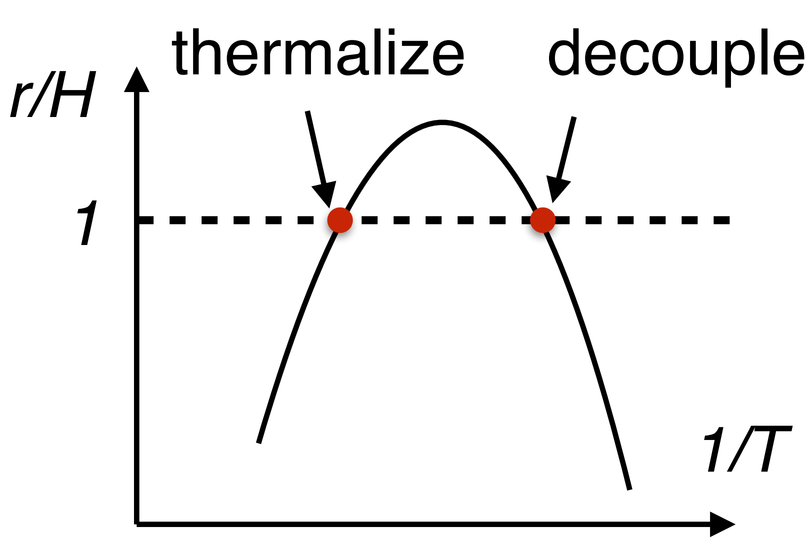
➢ Reaction rates:

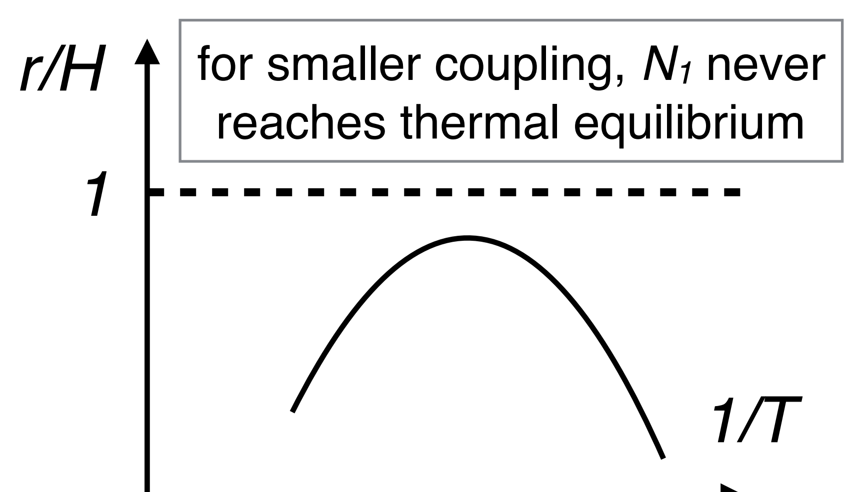
$r(N_1 \leftrightarrow f_{SM}),\ r(N_1 \leftrightarrow Z'),\ r(Z' \leftrightarrow f_{SM})$

➢ In most of parameter spaces, $r(N_1 \leftrightarrow f_{SM})$ determines whether N_1 is thermalized or not



➢ $r(N_1 \leftrightarrow f_{SM})/H \sim 1$ *at the thermalization and the freeze-out temperature*

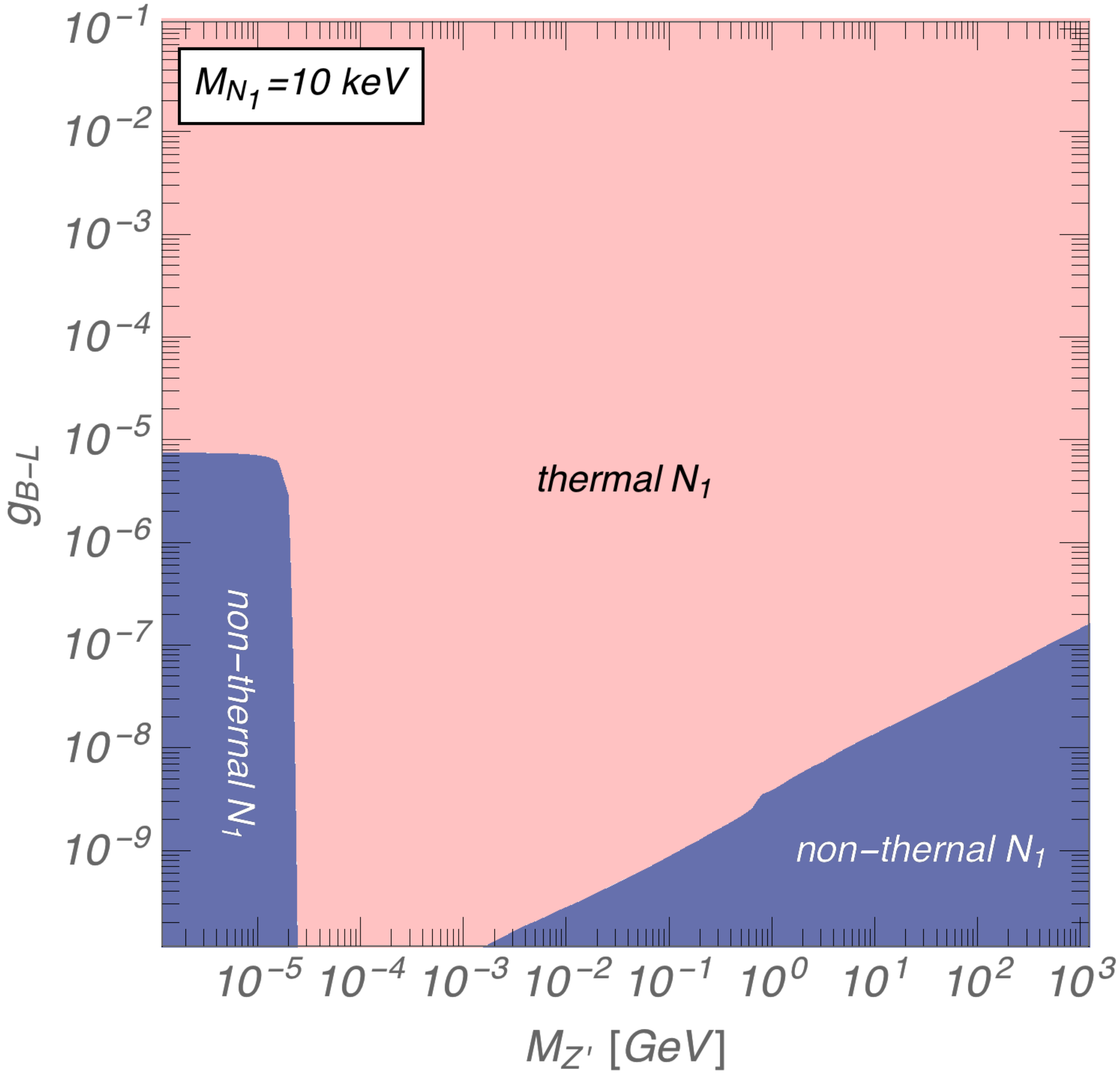




➢ Dark matter scenario drastically changes, depending on whether N_1 is thermalized or not.

N_1 production and relevant experimental constraints

- For thermal N_1, usual ***freeze-out*** mechanism can work
- For non-thermal N_1, ***freeze-in*** mechanism can work [L.Hall, et al. '09]



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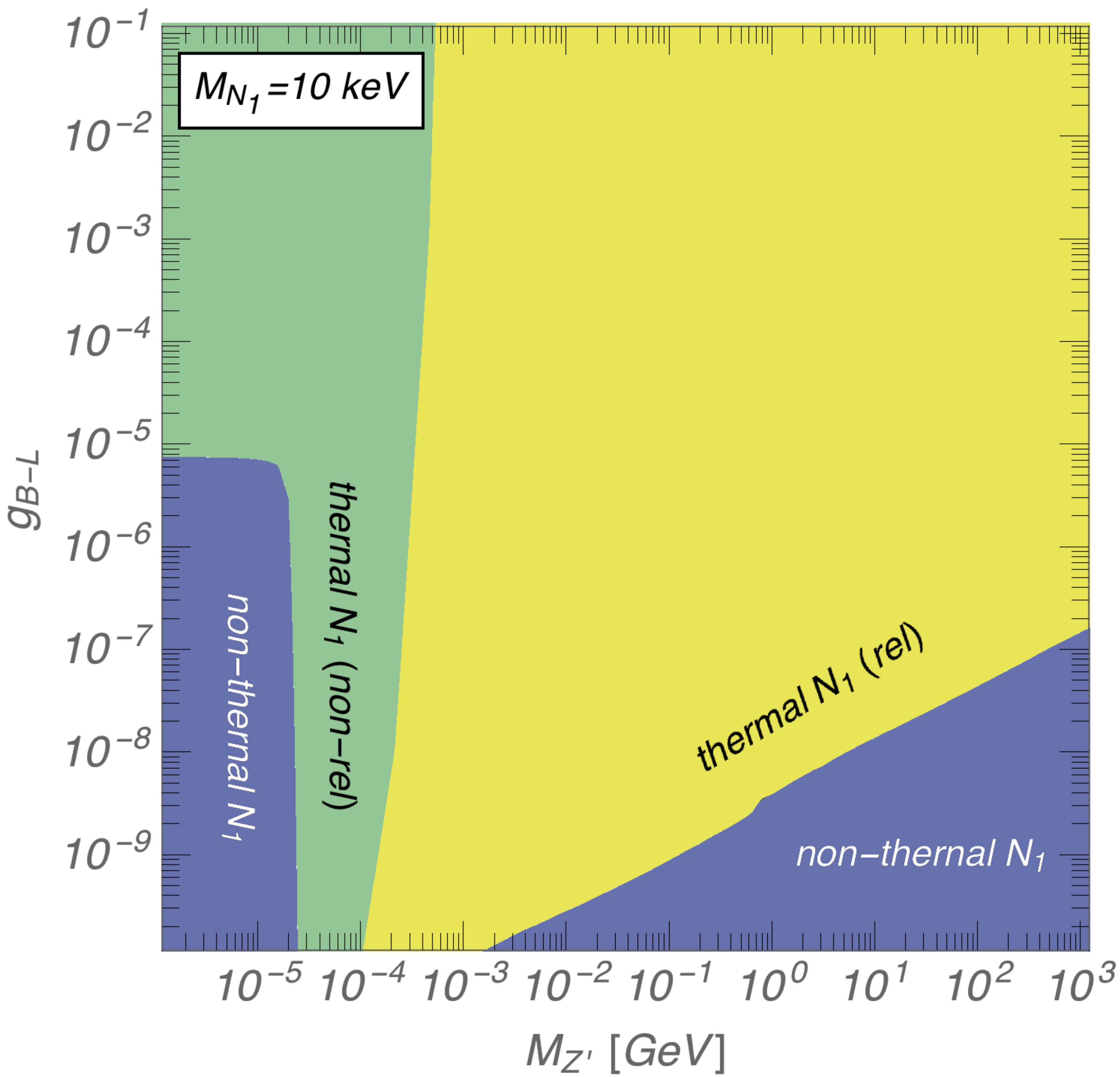

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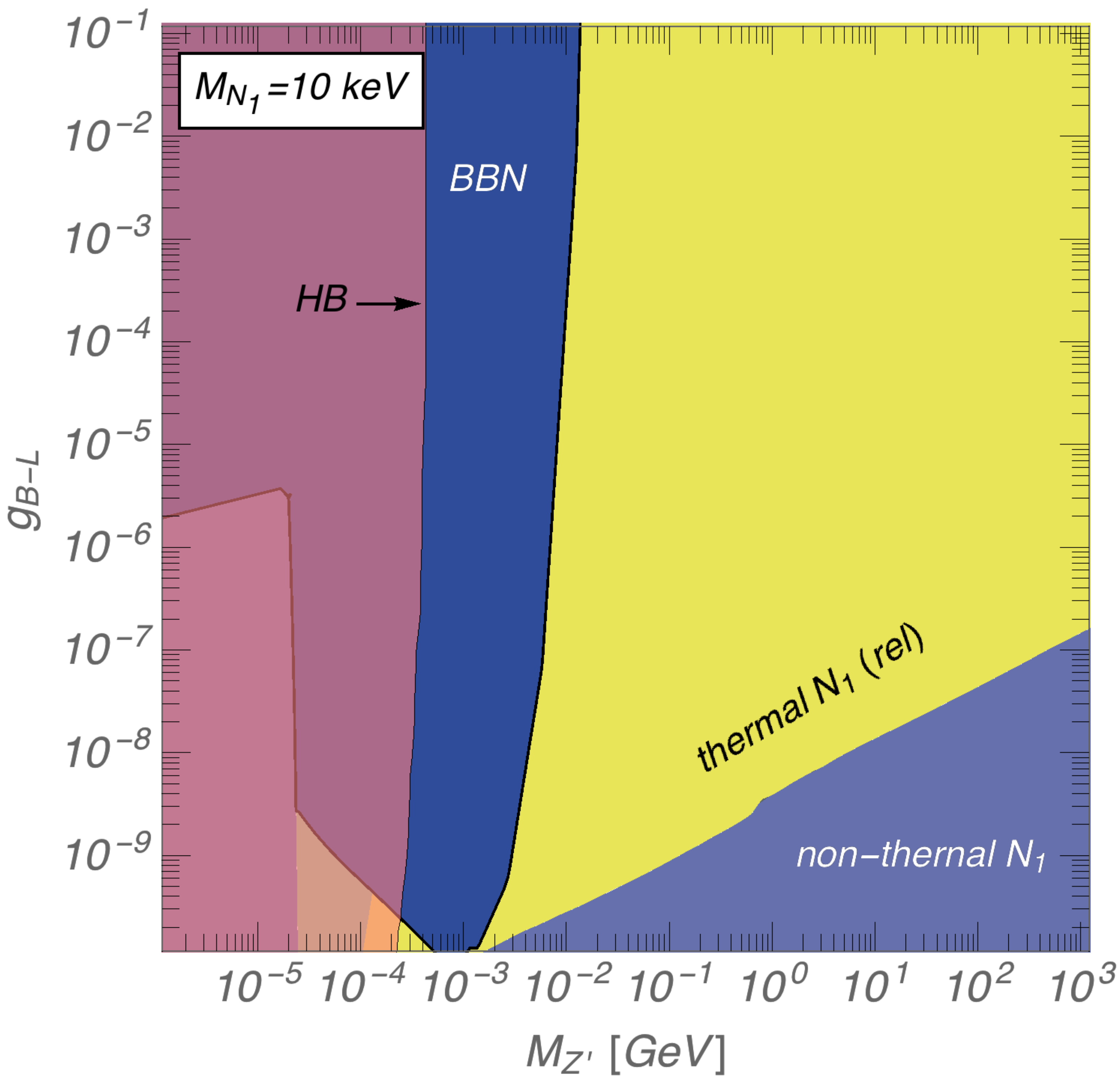

- Constraints from BBN and Horizontal Branch (HB) stars exclude non-rel. N_1
- Rel. N_1 has large number density (due to the lack of Boltzmann suppression)

$$\Omega_{N_1} h^2 = \frac{s_0 M_{N_1}}{\rho_c h^{-2}} \times \left.\frac{n_{N_1}}{s}\right|_{T_{N_1}^{\rm dec}}$$

$$\simeq 110 \times \left[\frac{M_{N_1}}{10\ \mathrm{keV}}\right]\left[\frac{10.75}{g_*(T_{N_1}^{\rm dec})}\right]$$

(over production)

- Some dilution mechanism is necessary (e.g., the late time entropy production by the decay of $N_{2,3}$)

[Bezrukov, et al., '10]

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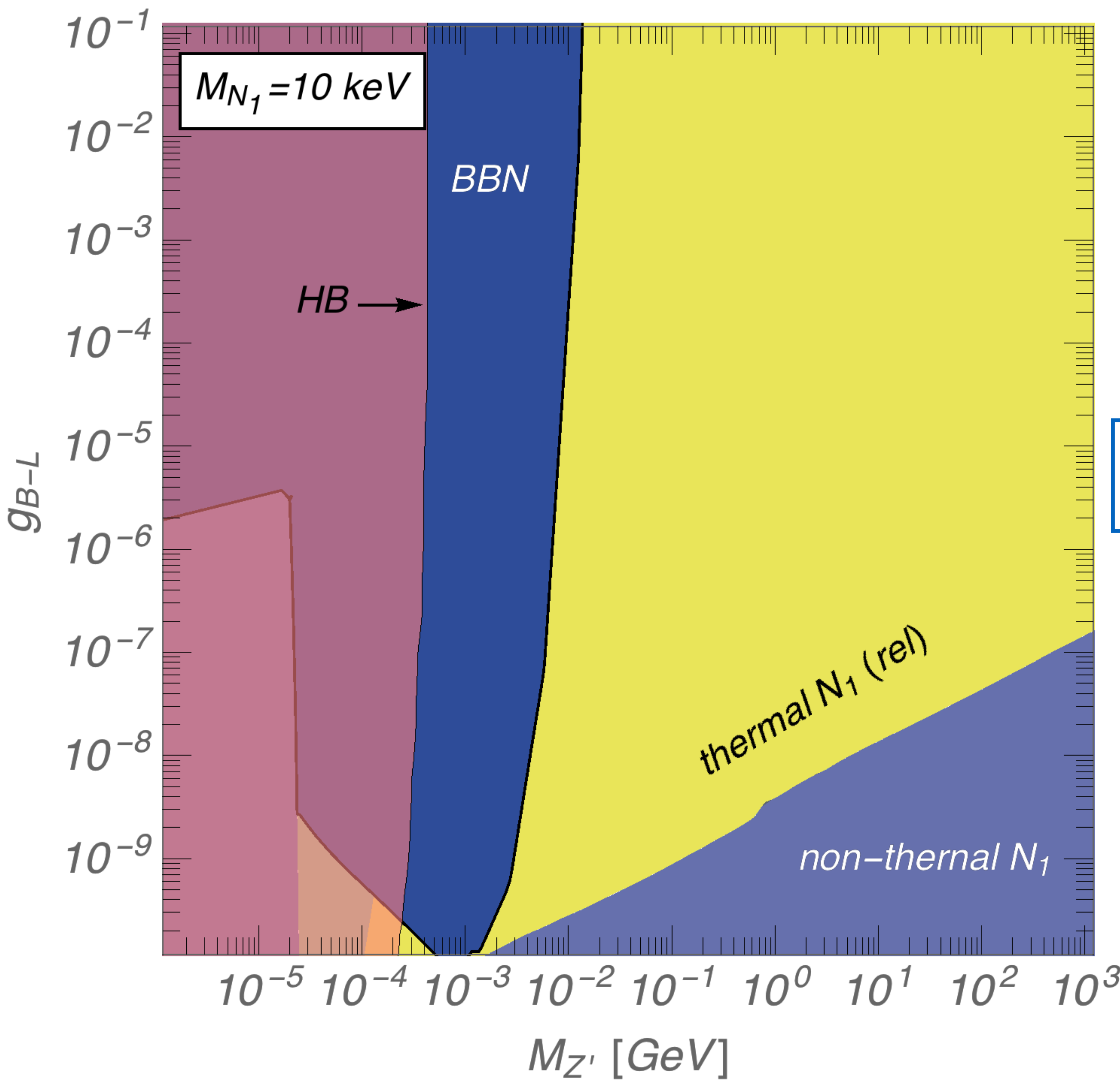

- In the non-thermal N_1 regions, N_1 is produced through

$$f_{SM}\, f_{SM} \to N_1\, N_1$$

- For $2M_{N1} < M_{Z'}$, the relic abundance of N_1 is roughly given by

$$\boxed{\Omega_{N_1} h^2 \simeq 0.12 \times \left(\frac{100}{g_*}\right)^{3/2} \left(\frac{g_{B-L}}{6.3\times 10^{-12}}\right)^2 \left(\frac{43/6}{C_f}\right) f(\tau)}$$

$$\Gamma_{Z'} \sim C_f \frac{g_{B-L}^2}{12\pi} M_{Z'}$$

$$f(\tau) = \tau(2+\tau^2)\sqrt{1-\tau^2} \qquad (\tau = 2M_{N1}/M_{Z'})$$

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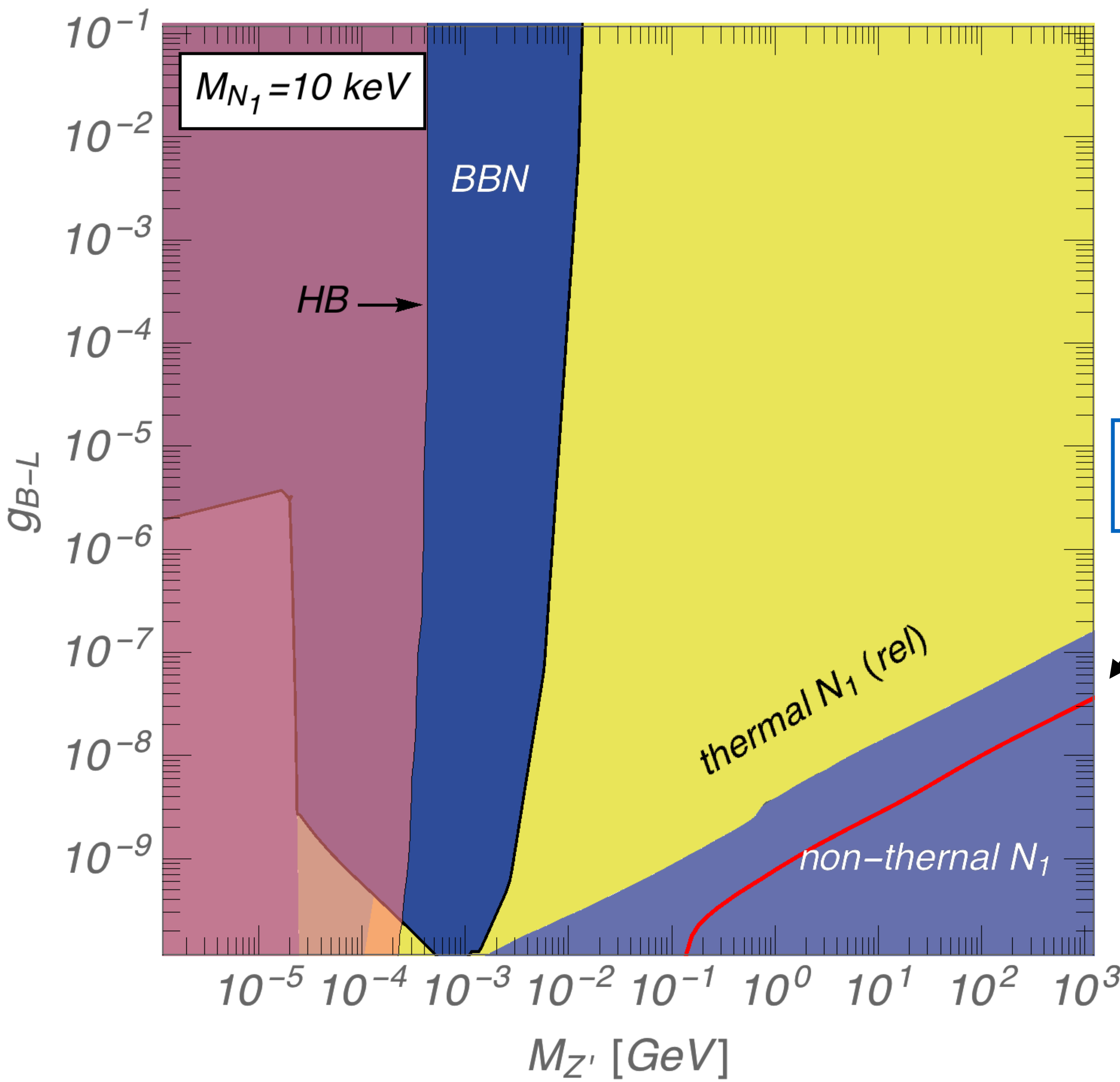

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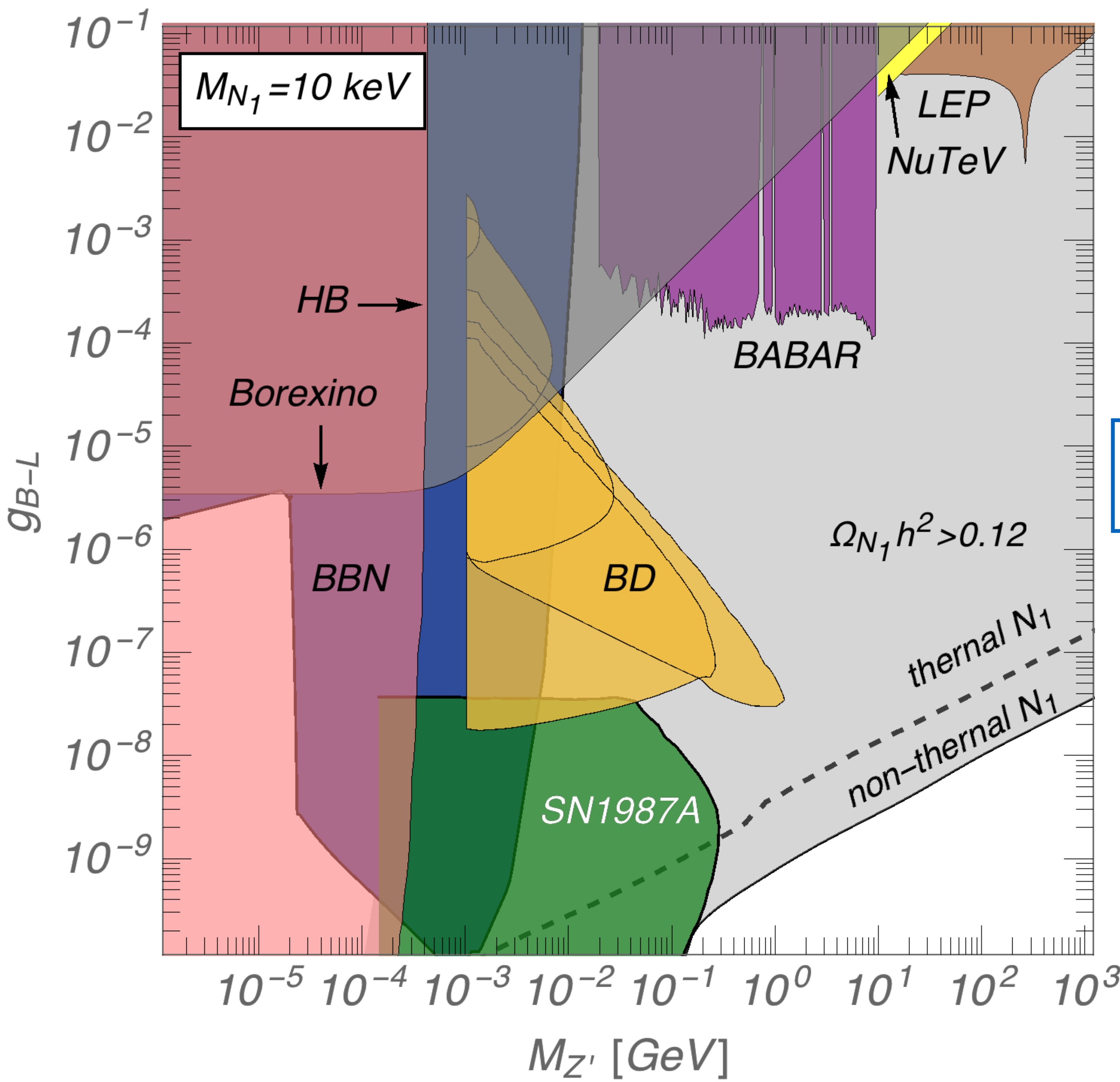

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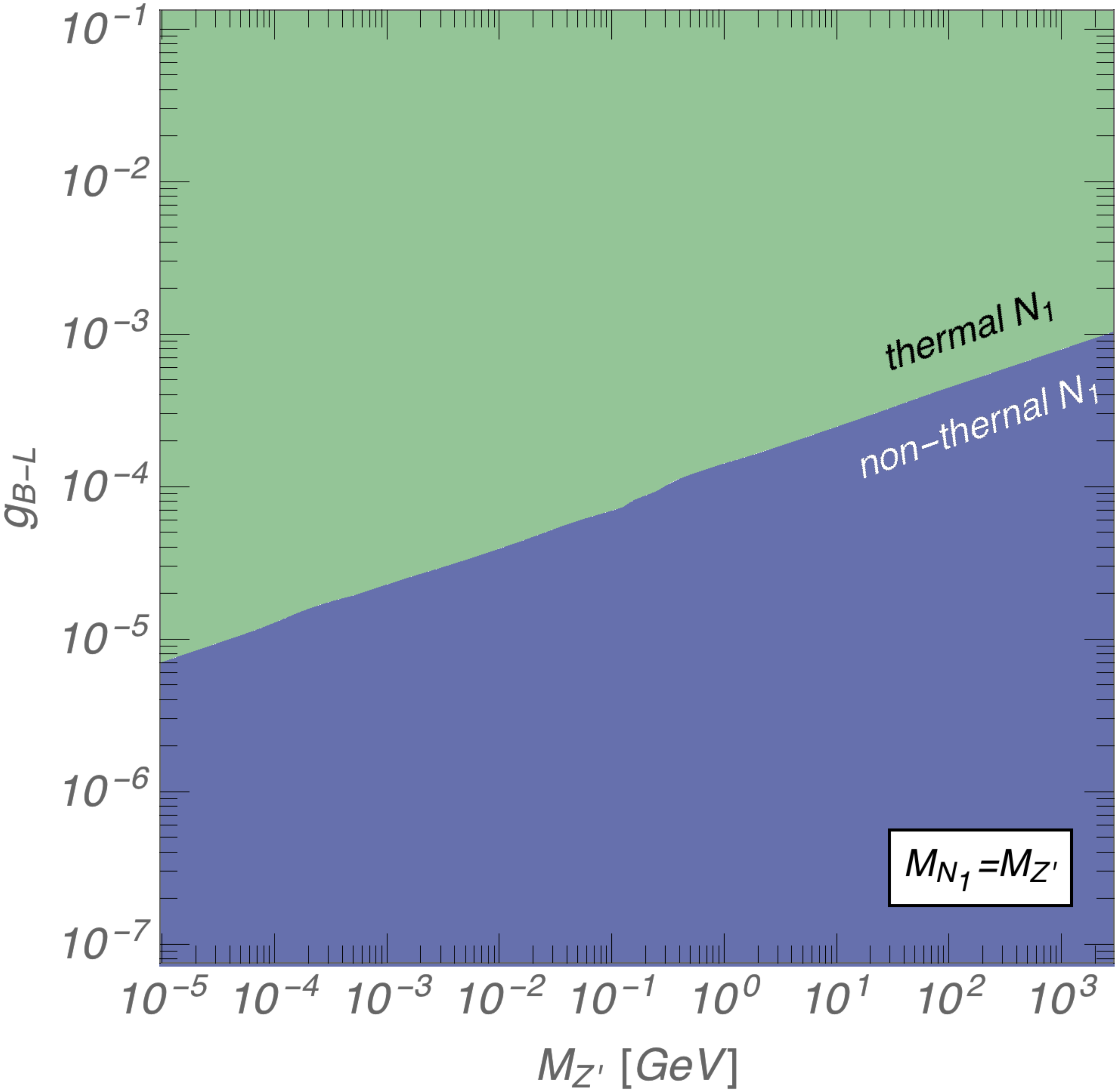
- together with all relevant limits

N_1 production and relevant experimental constraints

- Another interesting case is $2M_{N1} > M_{Z'}$, where Z' can not decay into a pair of N_1
- The reaction rate $r(N_1 \leftrightarrow f_{SM})$ becomes always off-resonant (smaller than on-res. case)



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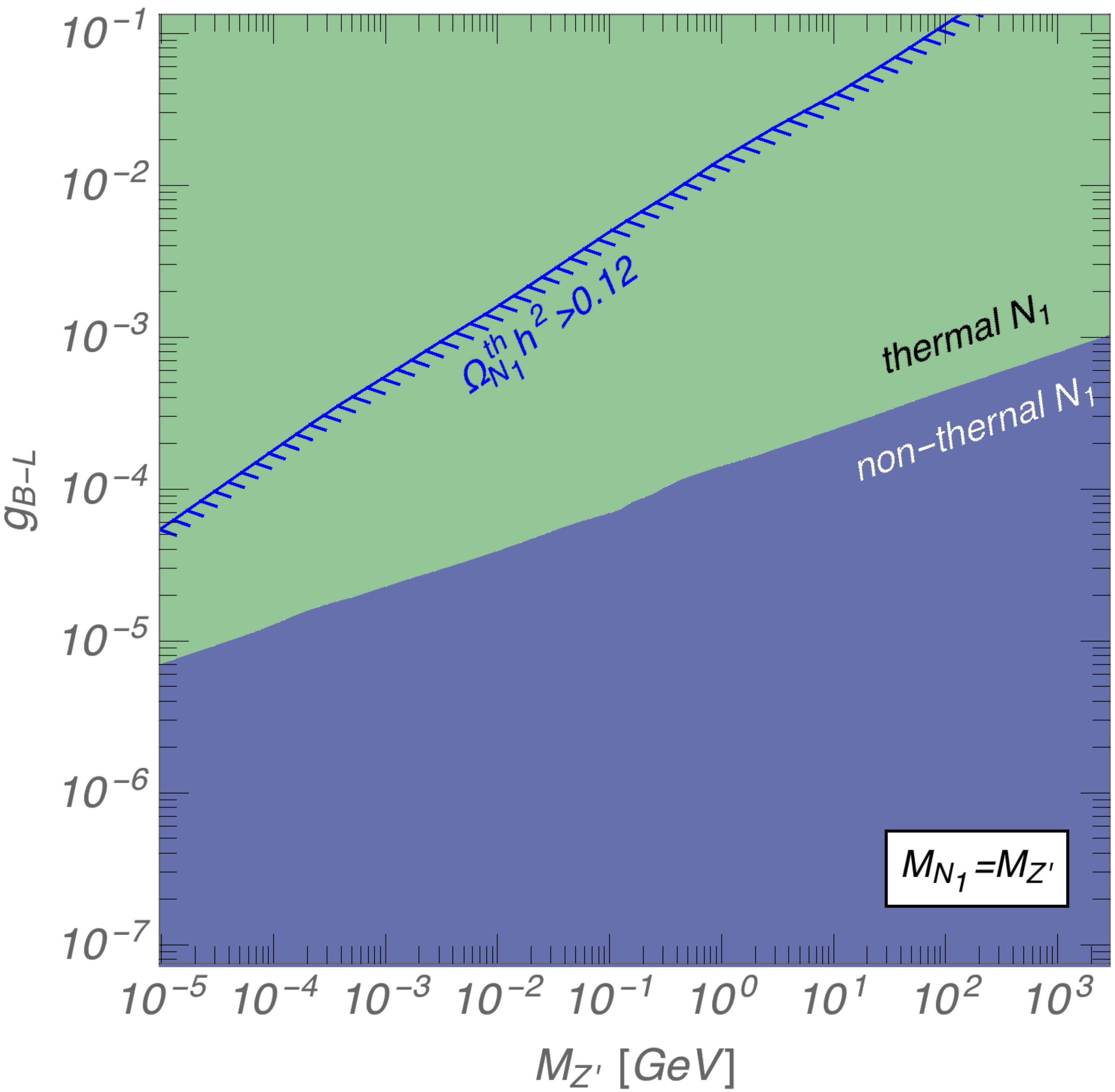

- ➢ For thermal N_1, N_1 is ordinary cold dark matter produced by freeze-out mechanism

$$\Omega^{\rm th}_{N_1} h^2 = \frac{s_0 M_{N_1} Y^{\rm th}_{N_1}}{\rho_c h^{-2}} \propto \left.\frac{1}{\sigma v}\right|_{T \sim T^{\rm dec}_{N_1}}$$

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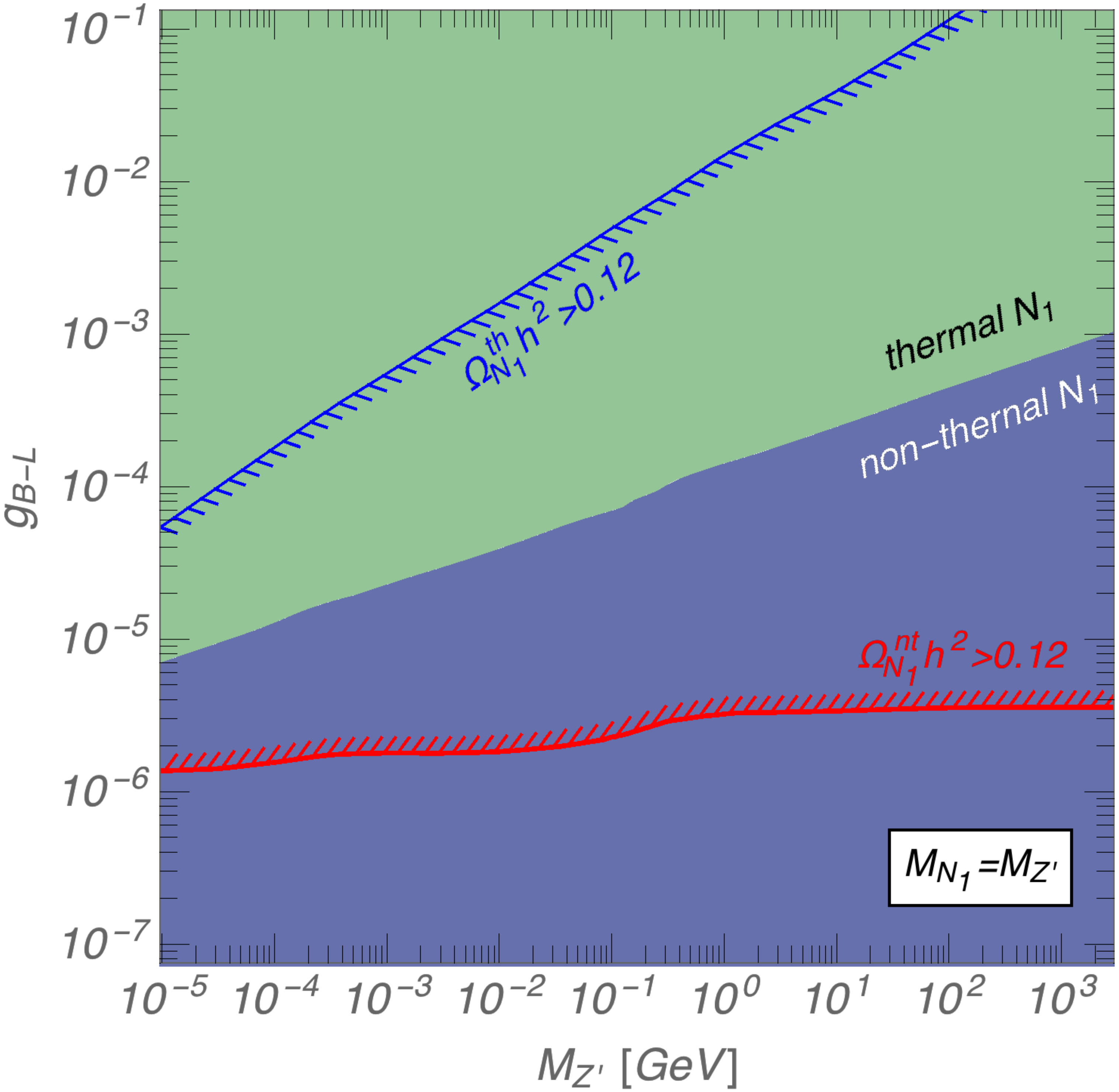

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- For non-thermal N_1, N_1 is produced by freeze-in mechanism

$$\Omega^{\rm nt}_{N_1} h^2 \simeq 0.12 \times \left(\frac{100}{g_*}\right)^{3/2} \left(\frac{g_{B-L}}{4.5 \times 10^{-6}}\right)^4$$

(Since Y_{N1} is proportional to $1/M_{N1}$, its abundance is almost mass independent)

N_1 production and relevant experimental constraints

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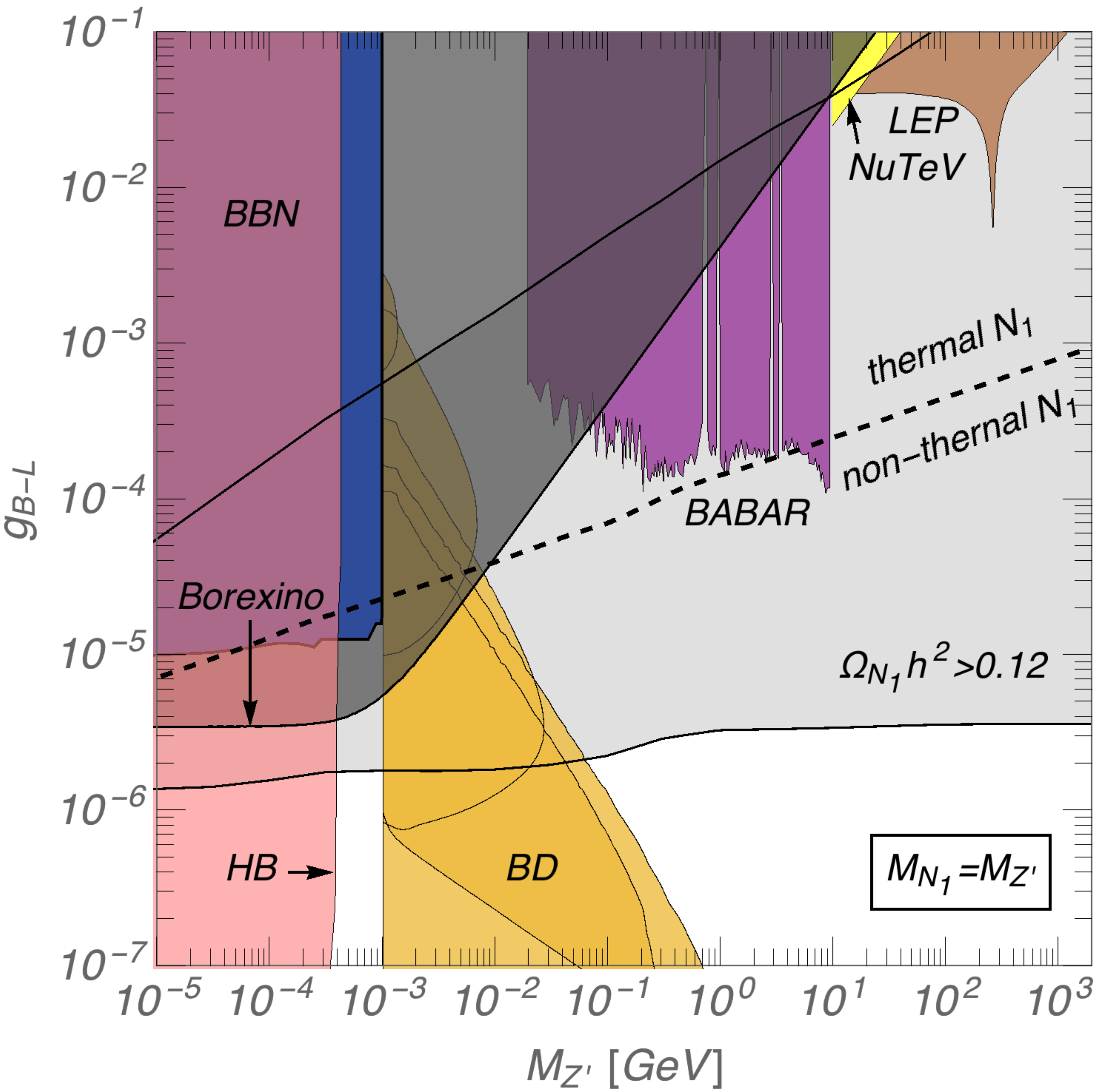

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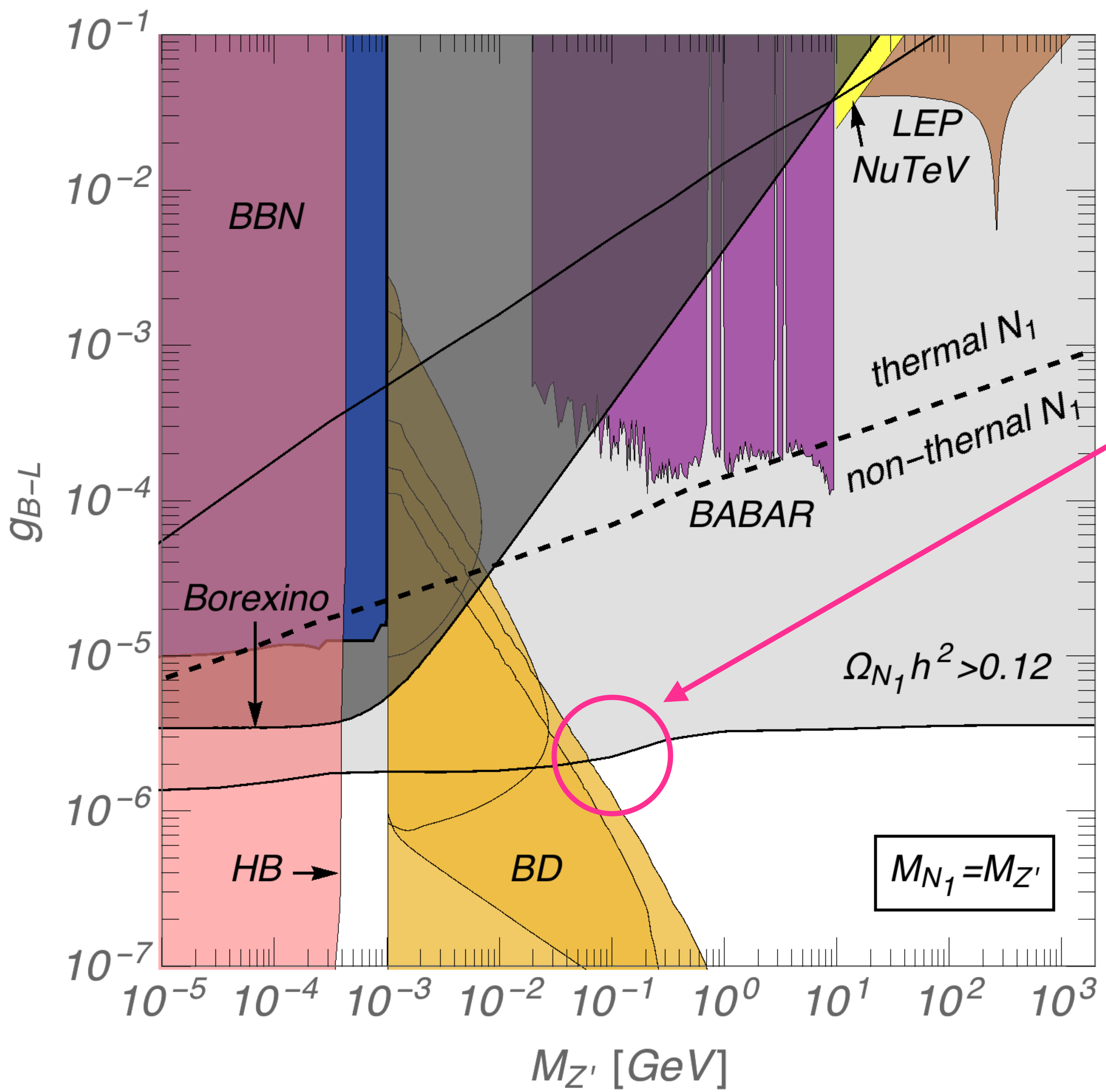
- Relevant constraints

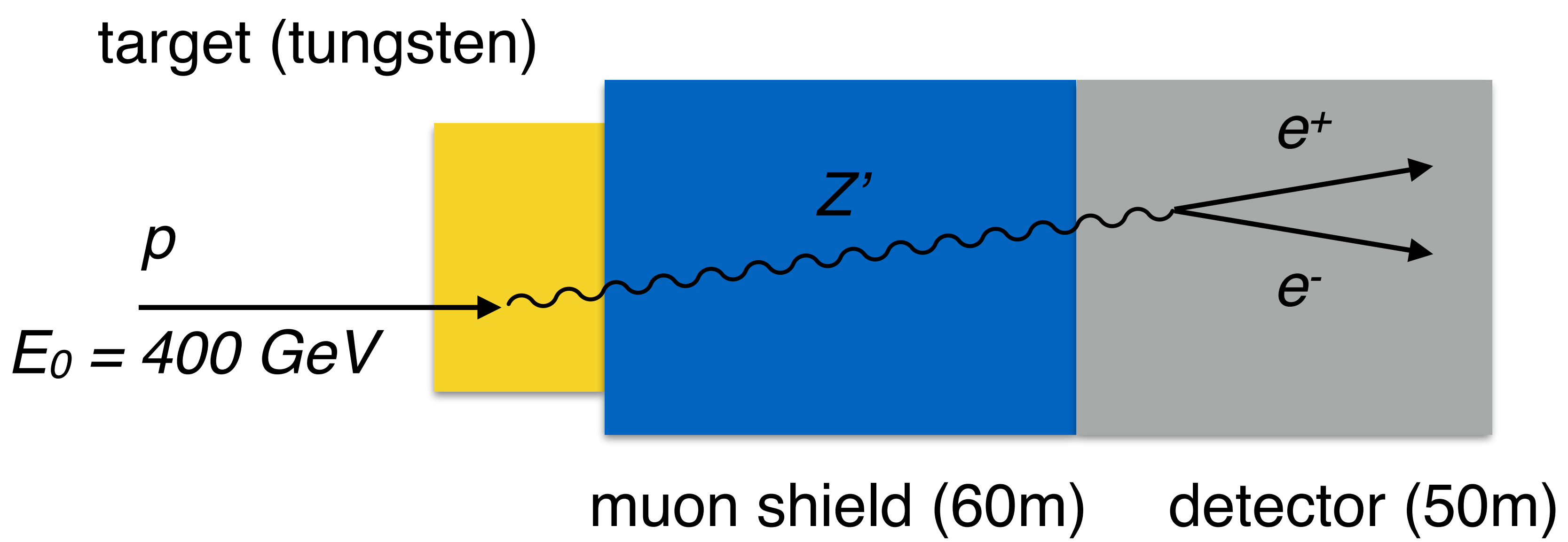
3. Implications



Beam dump experiments can test this region

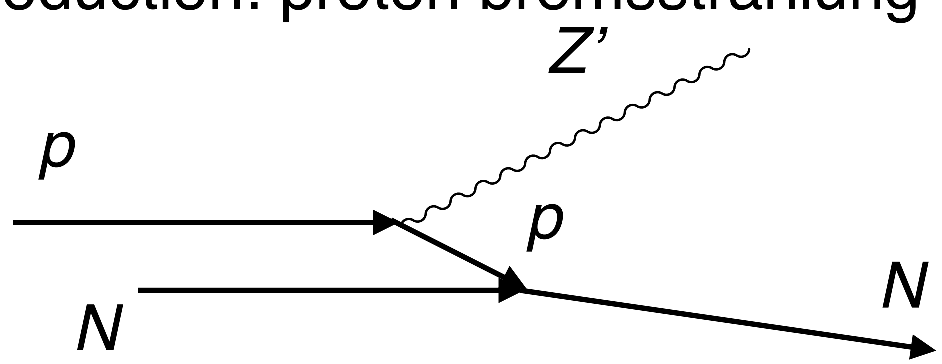
The Search for Hidden Particles (SHiP) experiment

- SHiP: A new proton beam dump experiment at CERN
- The SHiP utilizes 400 GeV proton beam from the SPS with ~10^{20} protons on target



- The number of signal events: $N_{sig} \sim N_{POT} \times R_{prod} \times P_{det}$

  - *Z'* production: proton bremsstrahlung



  - P_{det}: probability that *Z'* decays inside the detector

  If the life-time of *Z'* is too short or too long, *Z'* can not be observed

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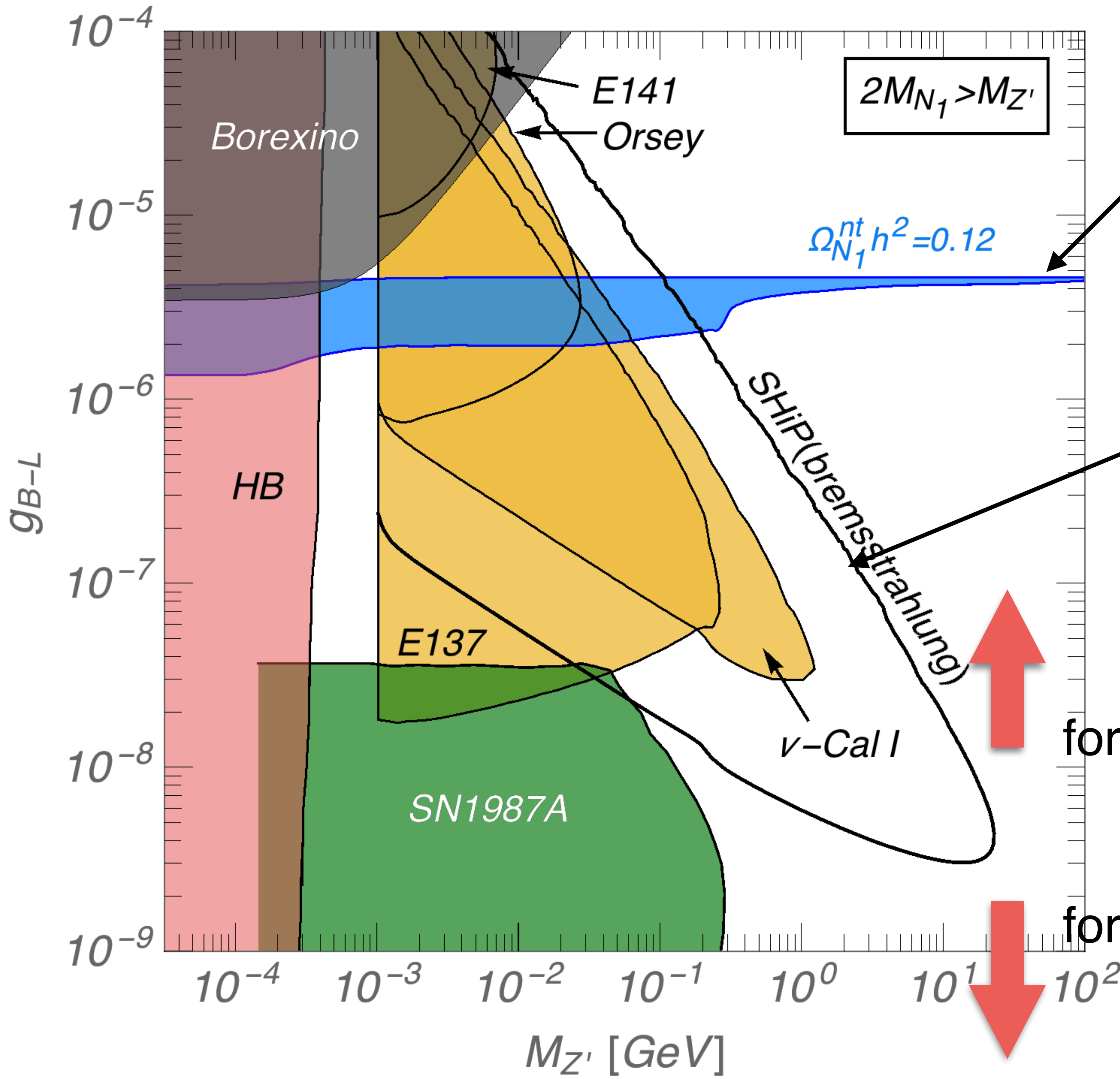

➢ Freeze-in N_1

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$$g_* \sim g_*(M_{N_1})$$

SHiP parameters:
E_{beam} = 400GeV, $N_{POT} = 10^{20}$
shield length: 50m
detector length: 60m
$N_{sig} > 3$ (assuming no-background)

[Gorbunov, et al., '15]

for larger $g_{B\text{-}L}$, Z' life-time becomes shorter

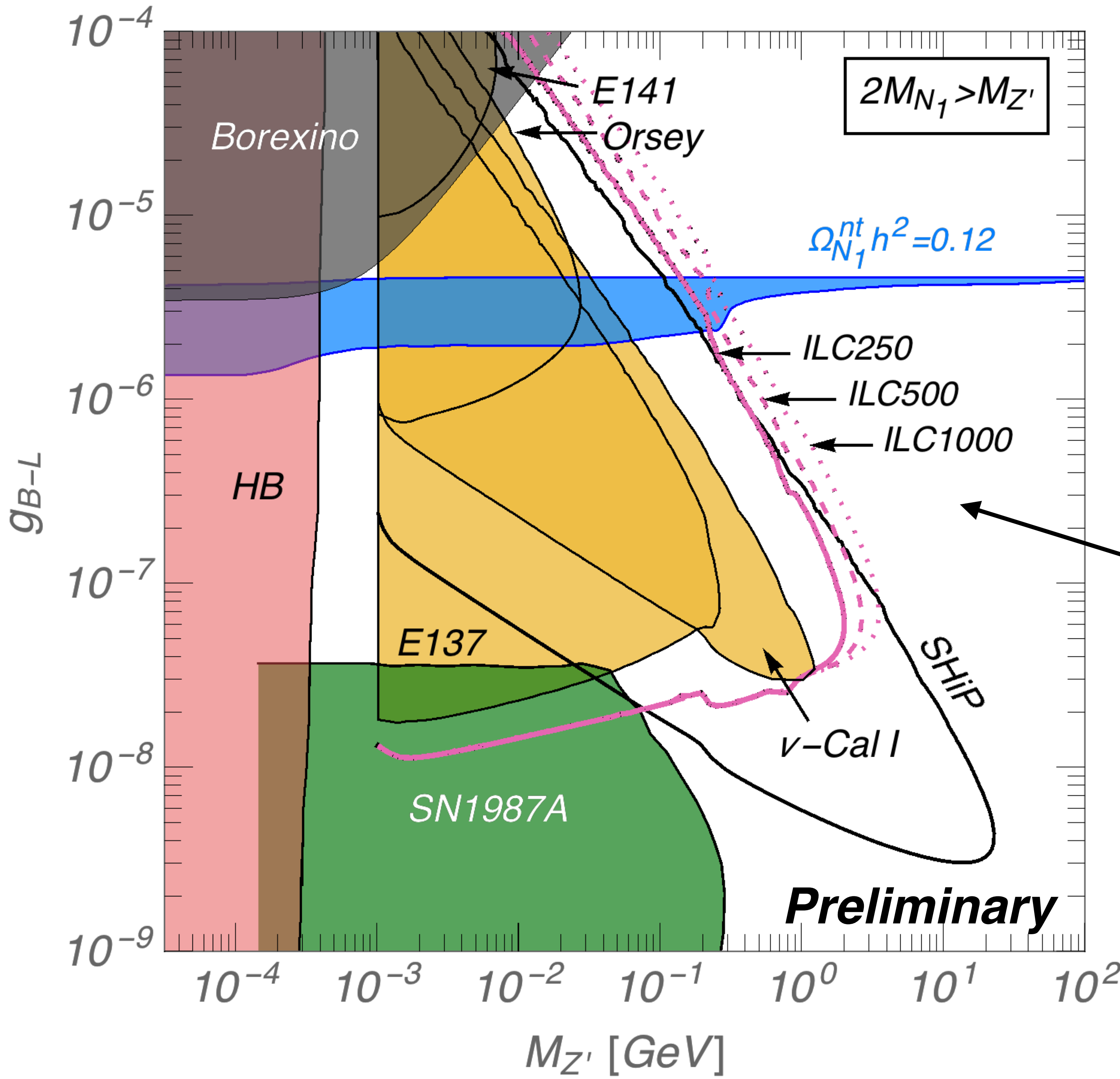
for smaller $g_{B\text{-}L}$, Z' life-time becomes longer

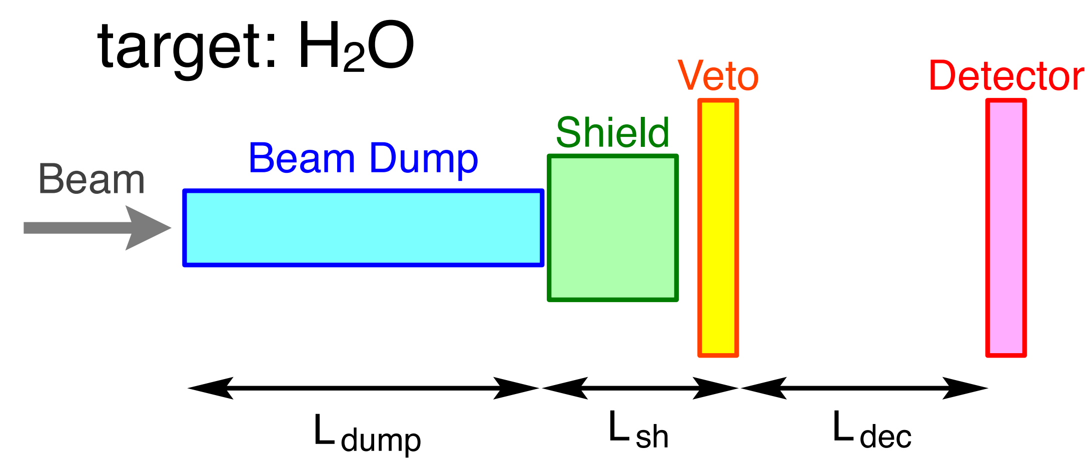
➢ SHiP will be able to cover:

$1\ MeV < M_{Z'} < 200\ MeV$ (blue region)

Beam dump experiment at the ILC (BDeeLC)

[Kanemura, Moroi, Tanabe, '15]





BDeeLC setup:
E_{beam} = 250GeV, 500GeV, 1TeV
$N_e = 4 \times 10^{21}$ (one-year operation)
L_{dump} = 11m
L_{sh} = 50 m
L_{dec} = 50m
$N_{sig} > 3$ (assuming no-background)

➢ BDeeLC will be able to cover:

1 MeV < $M_{Z'}$ < 300 MeV ~ 400 MeV
(blue region)

Discovery reach of the SHiP and BDeeLC

➢ $2M_{N1} > M_{Z'}$

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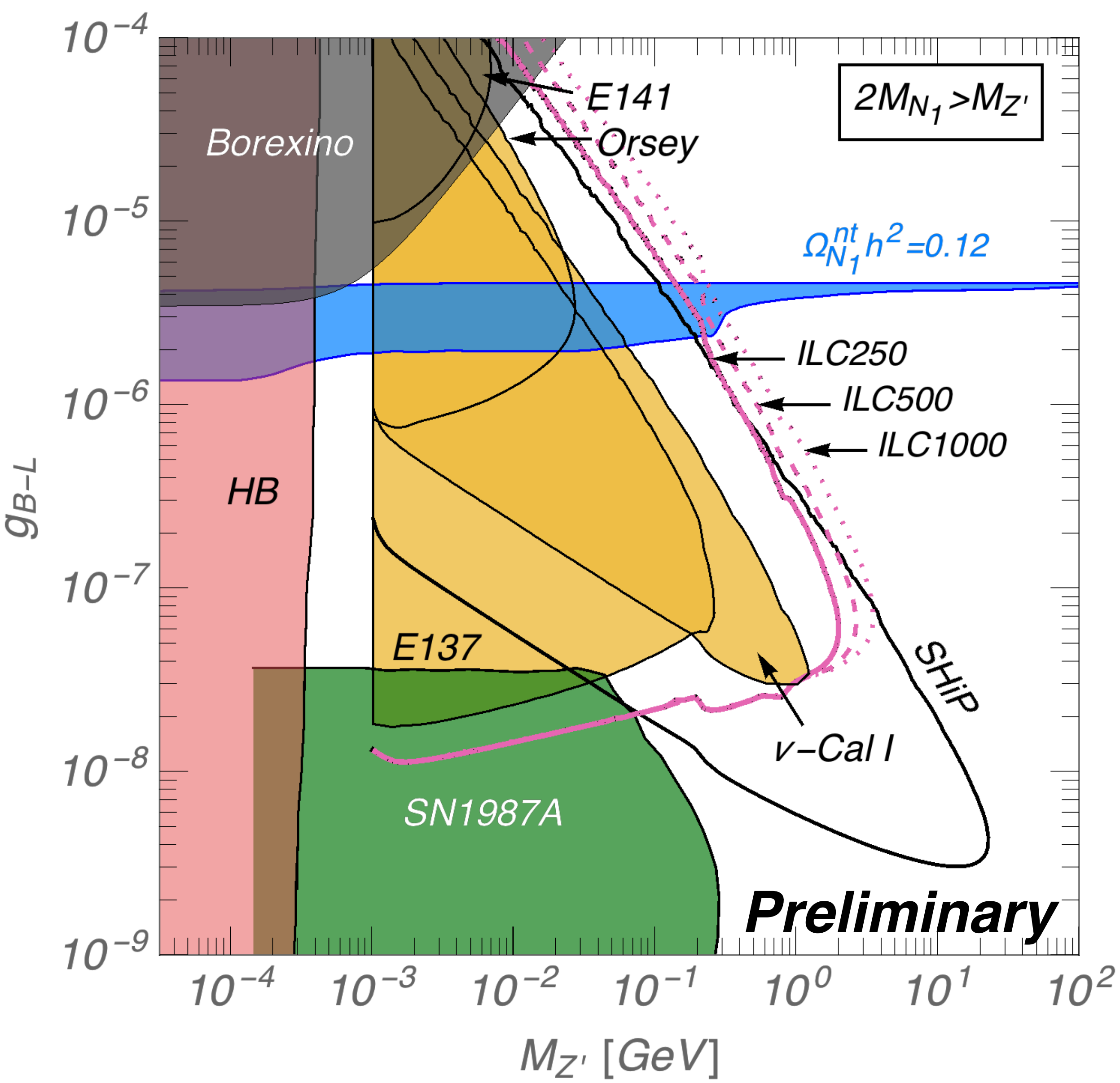

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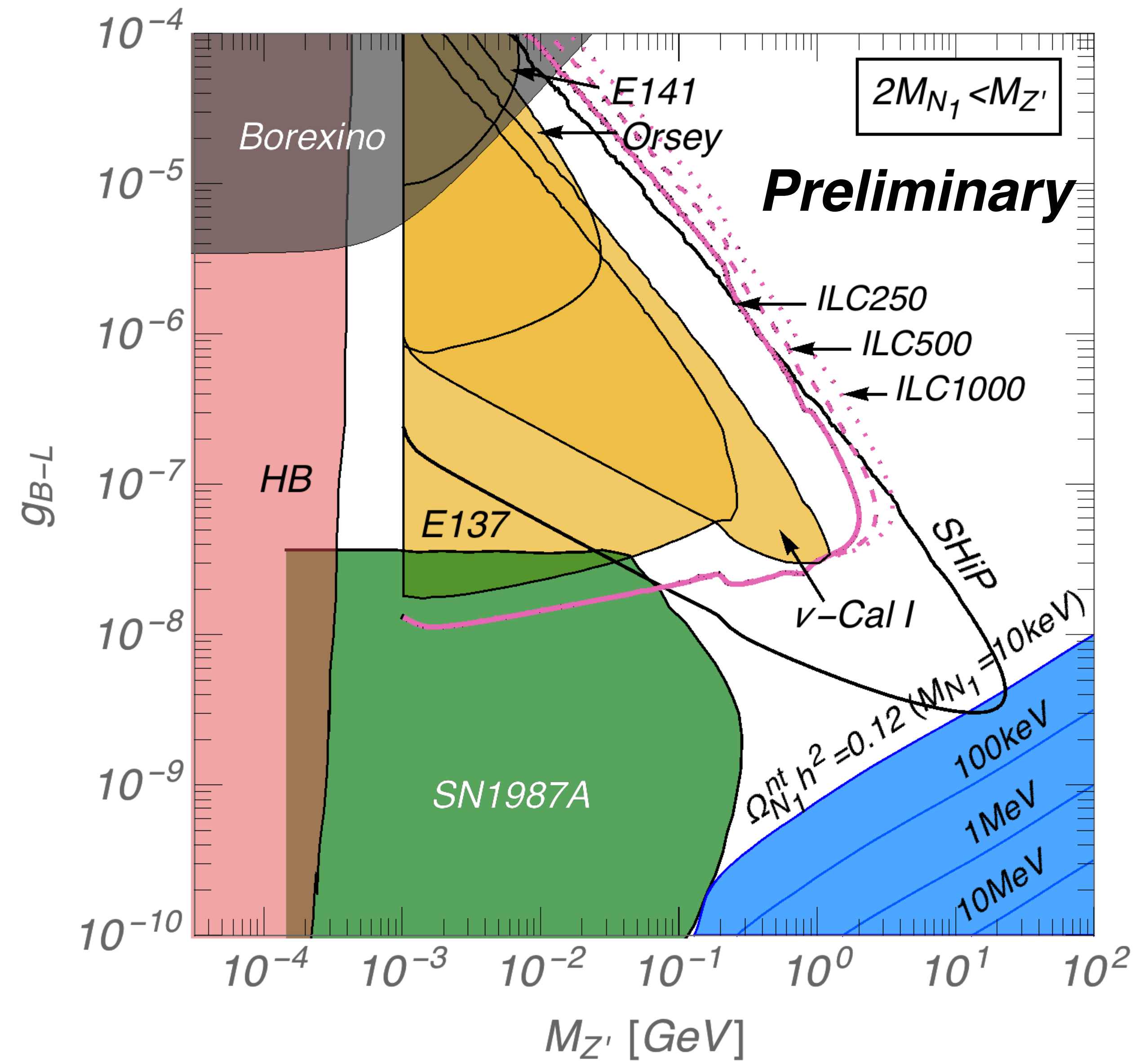


SHiP and BDeeLC can be a powerful tool for searching the freeze-in scenario

B-L breaking scale

- Dark matter abundance is determined by $g_{B\text{-}L}$ and $M_{Z'}$, which implies v_S through

$$M_{Z'}^2 = 8 g_{B-L}^2 v_S^2$$

- In the freeze-in region for off-resonance case ($2M_{N1}>M_{Z'}$), we obtain

$$v_S^2 \simeq (7.9\times 10^4 M_{Z'})^2 \left(\frac{0.12}{\Omega^{\rm nt}_{N_1} h^2}\right)^{1/2} \left(\frac{100}{g_*}\right)^{3/4}$$

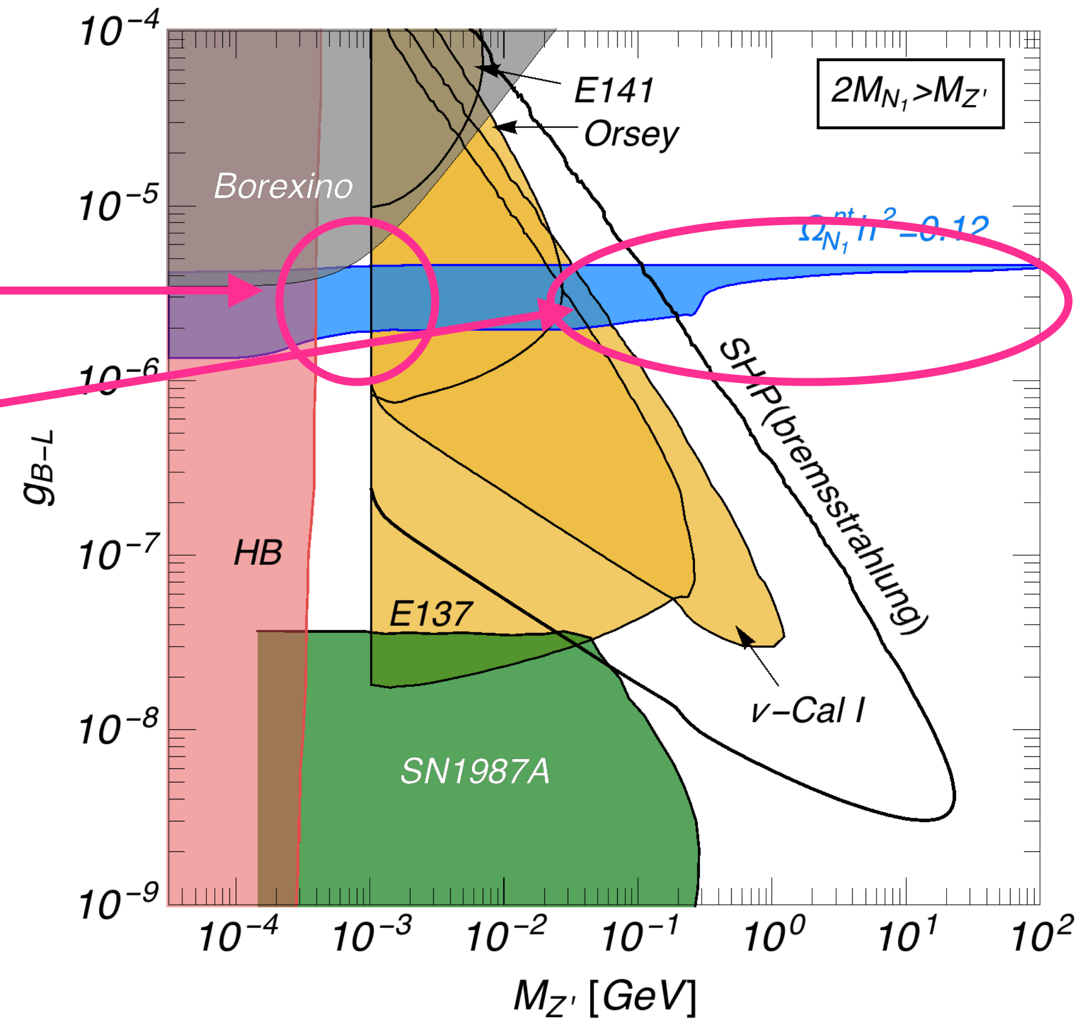
- This leads to

(taking $\lambda_S = 4\pi$)

$$200\ \text{GeV} \lesssim M_s \lesssim 400\ \text{GeV}$$

$$M_s \gtrsim 4\ \text{TeV}$$

$$(M_S^2 \simeq 2\lambda_S v_S^2)$$



Summary

- We discussed various right-handed neutrino dark matter scenarios in the UνMSM: $U(1)_{B\text{-}L}$ gauge extension of the νMSM.

- The *B-L* gauge interaction can open new windows for right-handed neutrino dark matter.

- Forthcoming fixed target experiment can test the freeze-in scenario.