Right-handed neutrino dark matter and the B-L gauge boson

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Reference: 1606.09317

Light Dark World 2016, July 11, 2016

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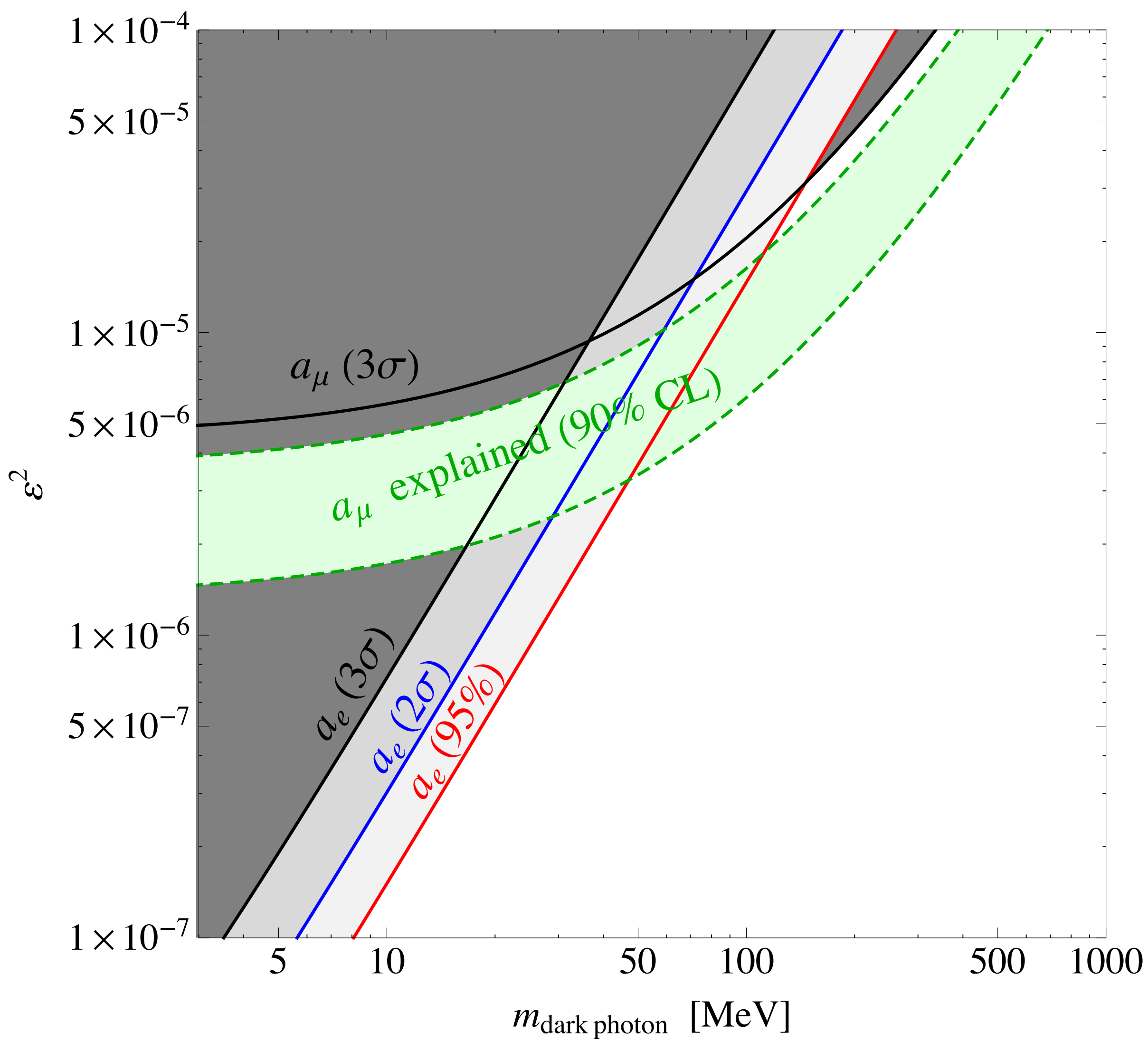
[green band: Pospelov, '08]



(figure by H.-S. Lee)

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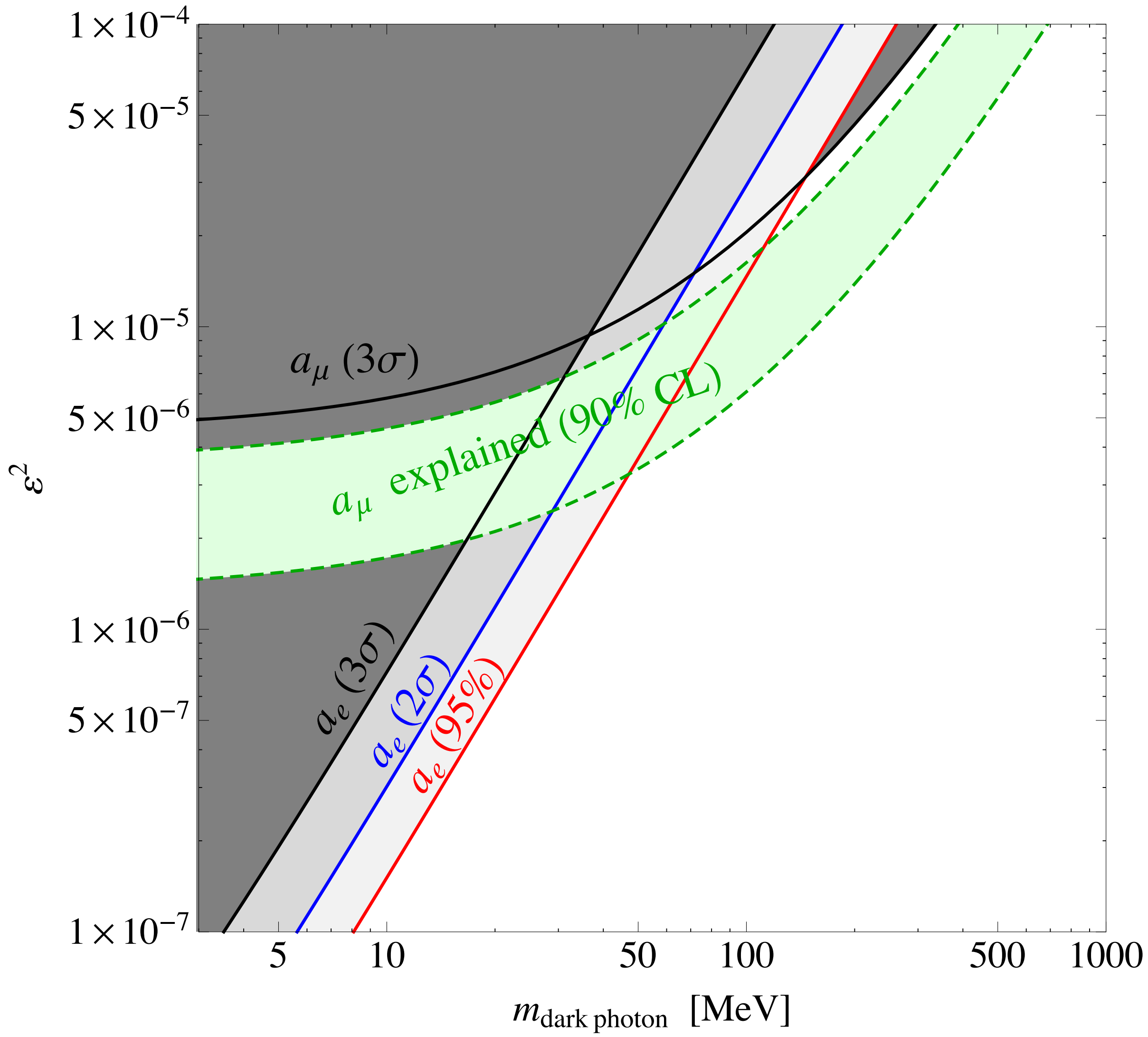
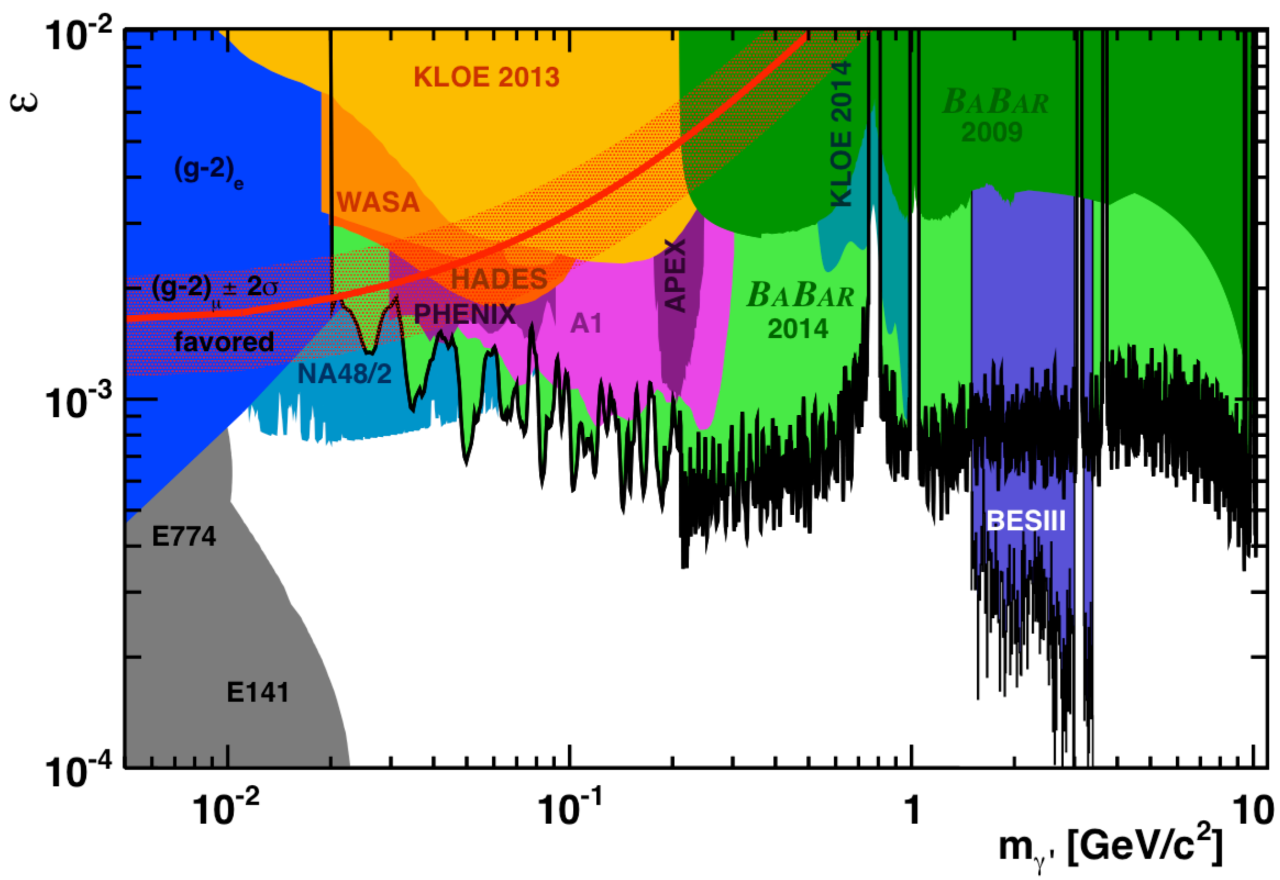


(figure by H.-S. Lee)

[Soffer, '15]



- Until 2015, muon g-2 had provided a strong motivation for the light dark photon.
- However, whole green band is excluded now. (The last small portion is closed by CERN NA48/2)
- ***We will try to provide another well-motivated parameter space for Z'.***

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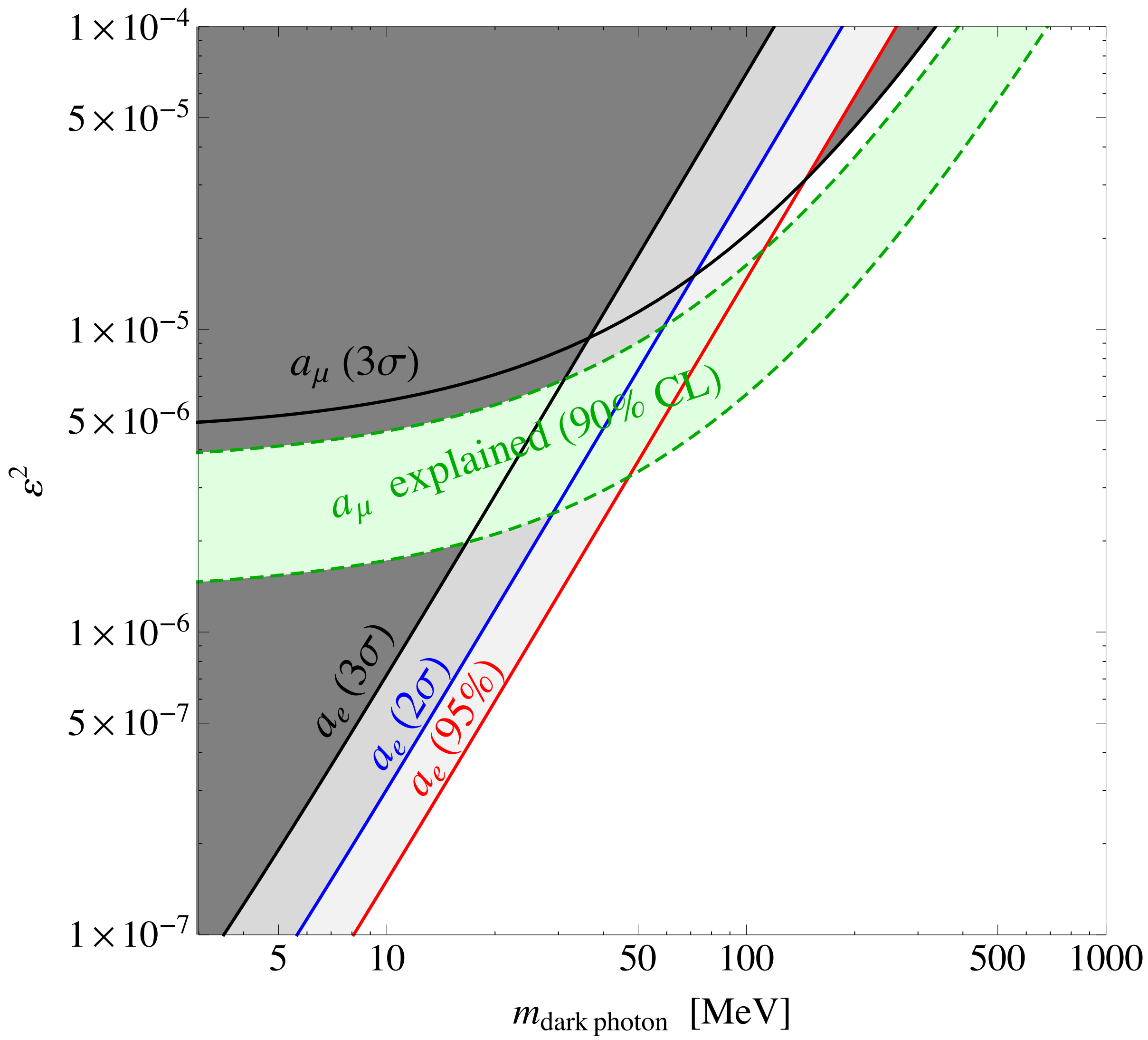

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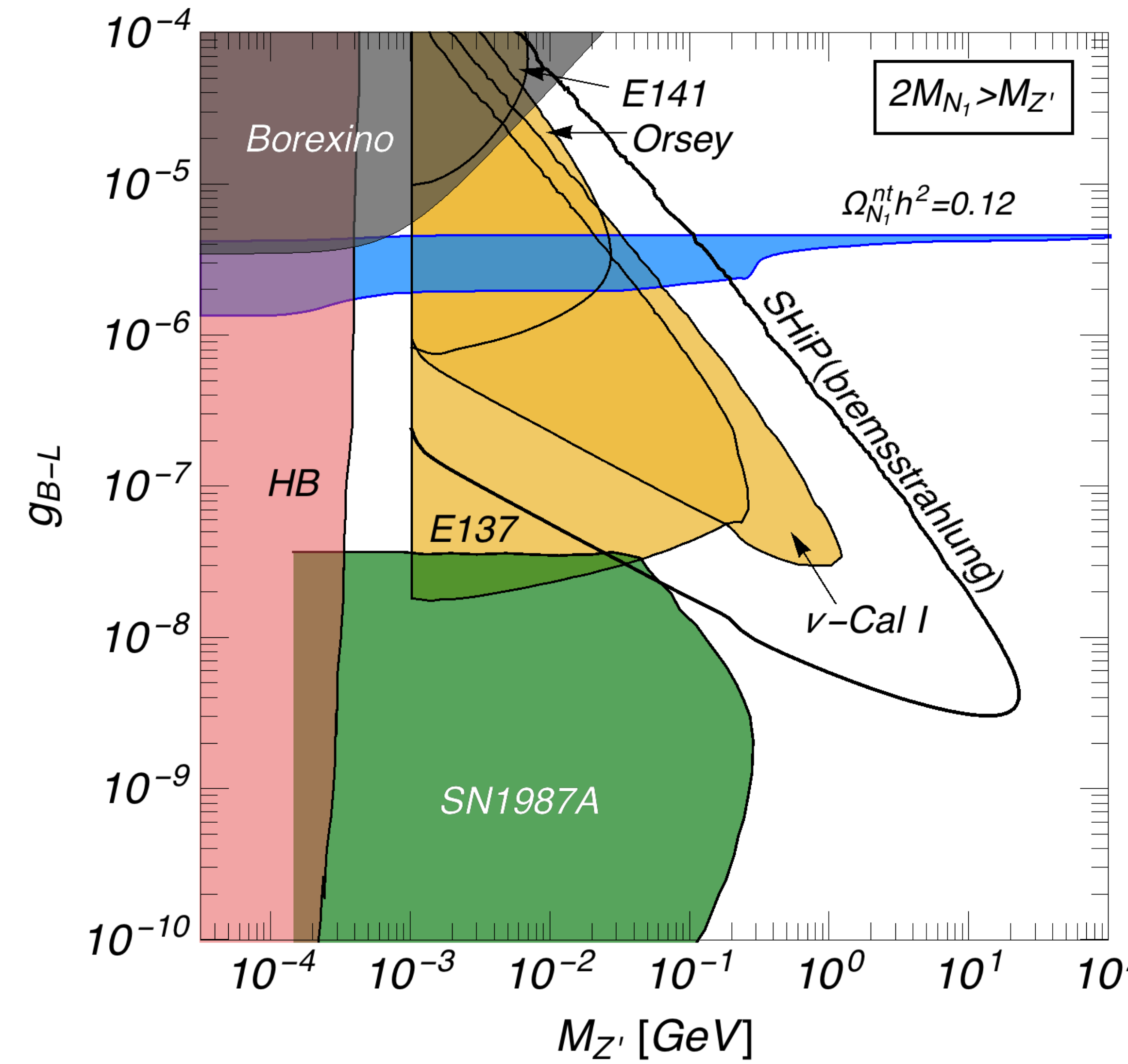

Outline

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

1. Introduction

Where is new physics hiding?

- There are many observations that the SM fails to explain:

  dark matter, neutrino mass, baryon asymmetry of the universe (BAU), …

- Searching for unified description of them is one of the most important tasks in modern particle physics
- It is known that right-handed neutrinos can address these issues

Three right-handed neutrinos?

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

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}_i \partial\!\!\!/ N_i - \left(y_{\alpha i} \overline{L}_\alpha N_i \tilde{H} + \frac{M_i}{2} \overline{N^C}_i N_i + h.c. \right)$$

(known as the νMSM)

[Asaka, Blanchet, Shaposhnikov, '05]
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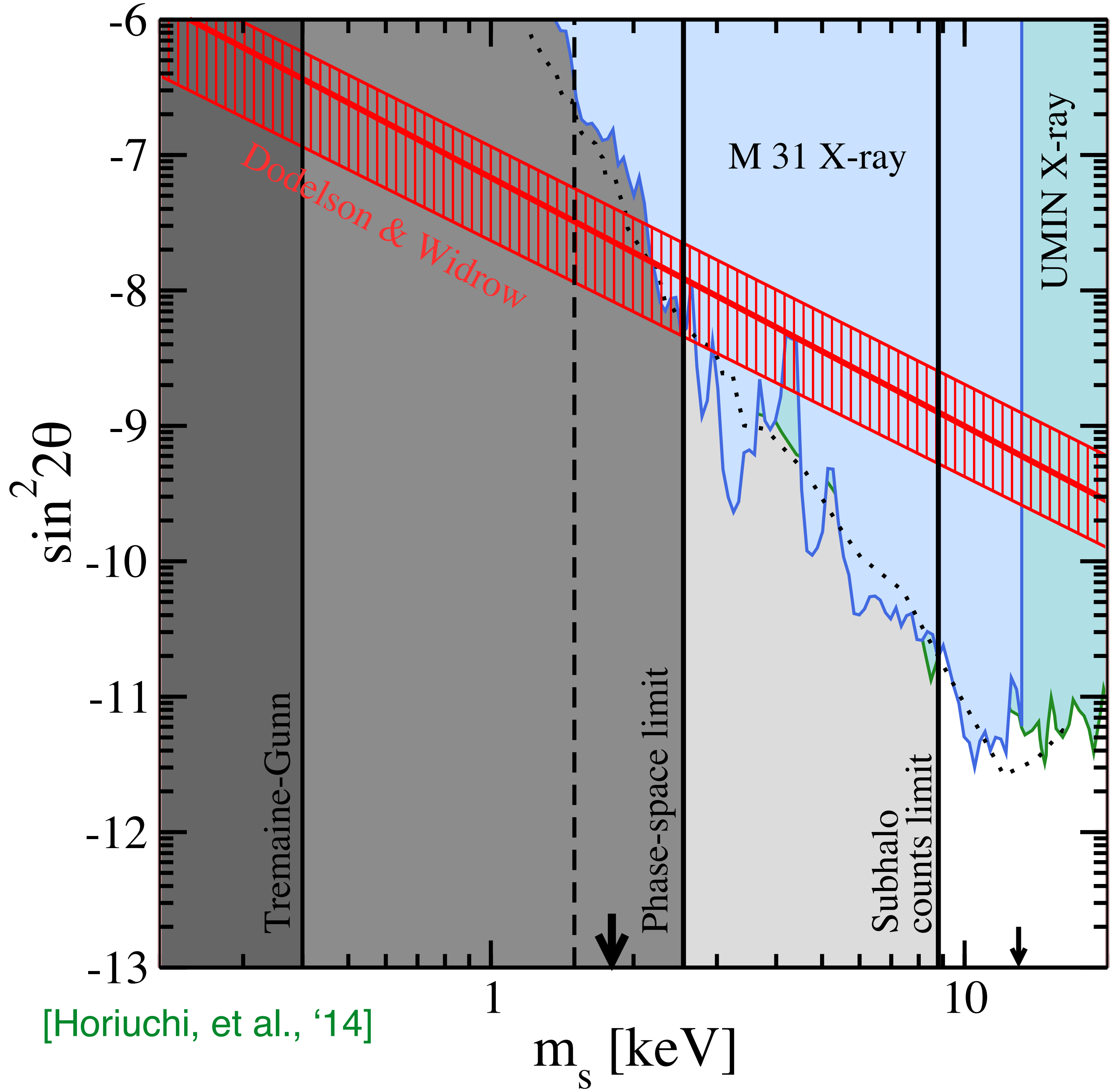
- The lightest right-handed neutrino N_1 can be (keV-scale) dark matter via Dodelson-Widrow mechanism [Dodelson, Widrow, '94]

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

[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

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

- 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 $U(1)_{B-L}$ gauge symmetry is the most attractive symmetry that offers three right-handed neutrinos

Our framework

- Under the gauge symmetry $G = G_{SM} \times U(1)_{B-L}$, 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 $U(1)_{B-L}$ 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

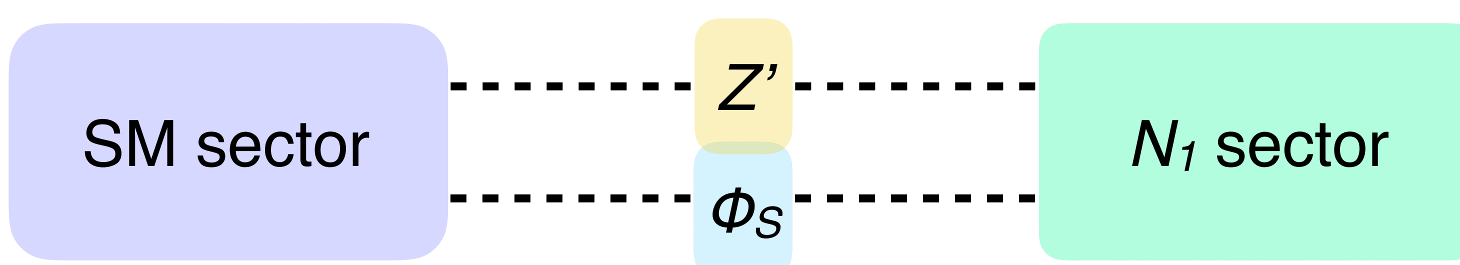
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}_i \not{\partial} N_i - \left(y_{\alpha i} \overline{L}_\alpha N_i \tilde{\Phi}_H + \frac{\kappa_i}{2} \Phi_S \overline{N_i^C} N_i + h.c. \right) + |D_\mu \Phi_S|^2 - V(\Phi_H, \Phi_S) - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}$$

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

- 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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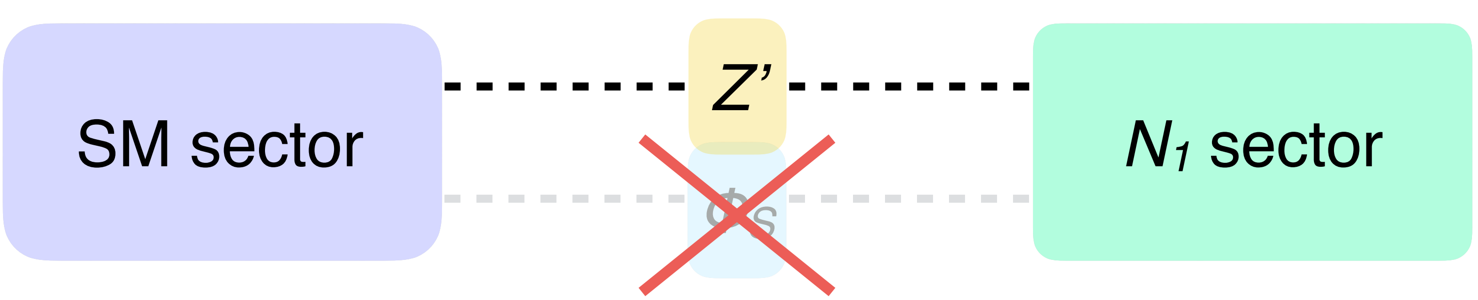


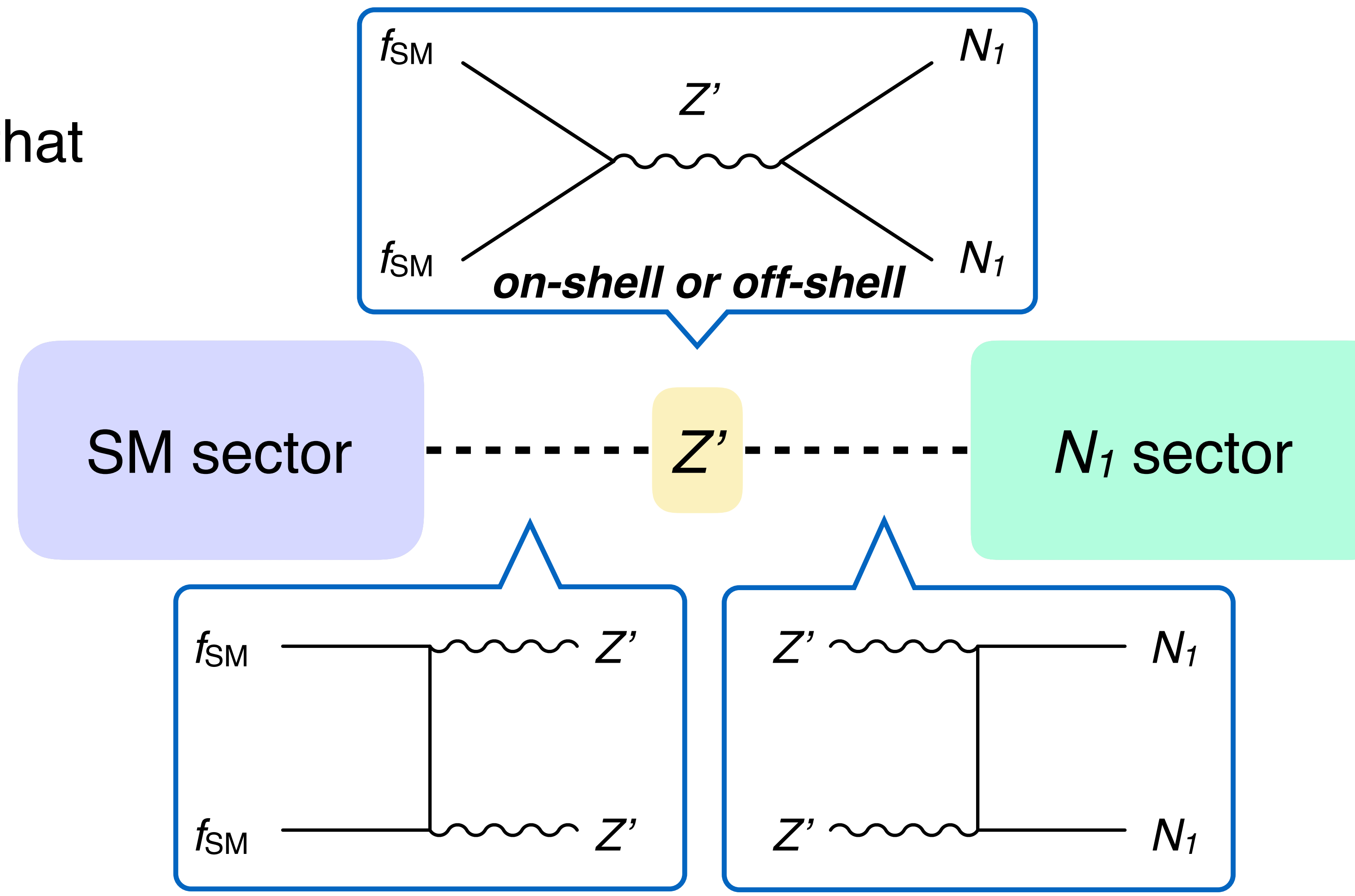
➢ To concentrate on the Z' effect, we turn off the Higgs portal coupling λ_{HS} (→0)

Relevant reactions for thermalization of N_1

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

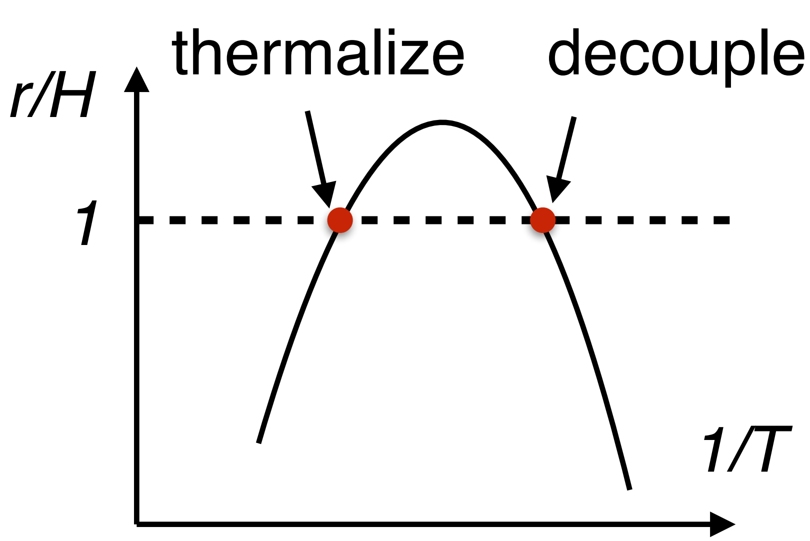
- Reaction rates:

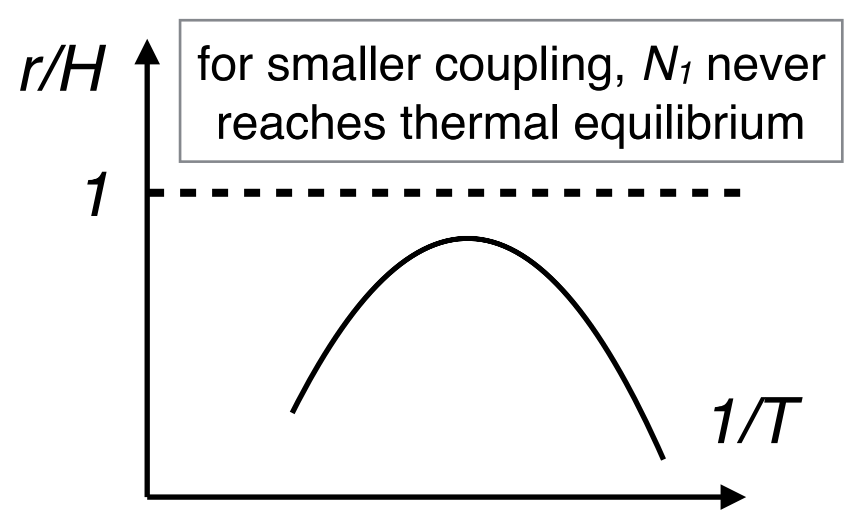
  $r(N_1 \leftrightarrow f_{SM})$, $r(N_1 \leftrightarrow Z')$, $r(Z' \leftrightarrow f_{SM})$



- 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*

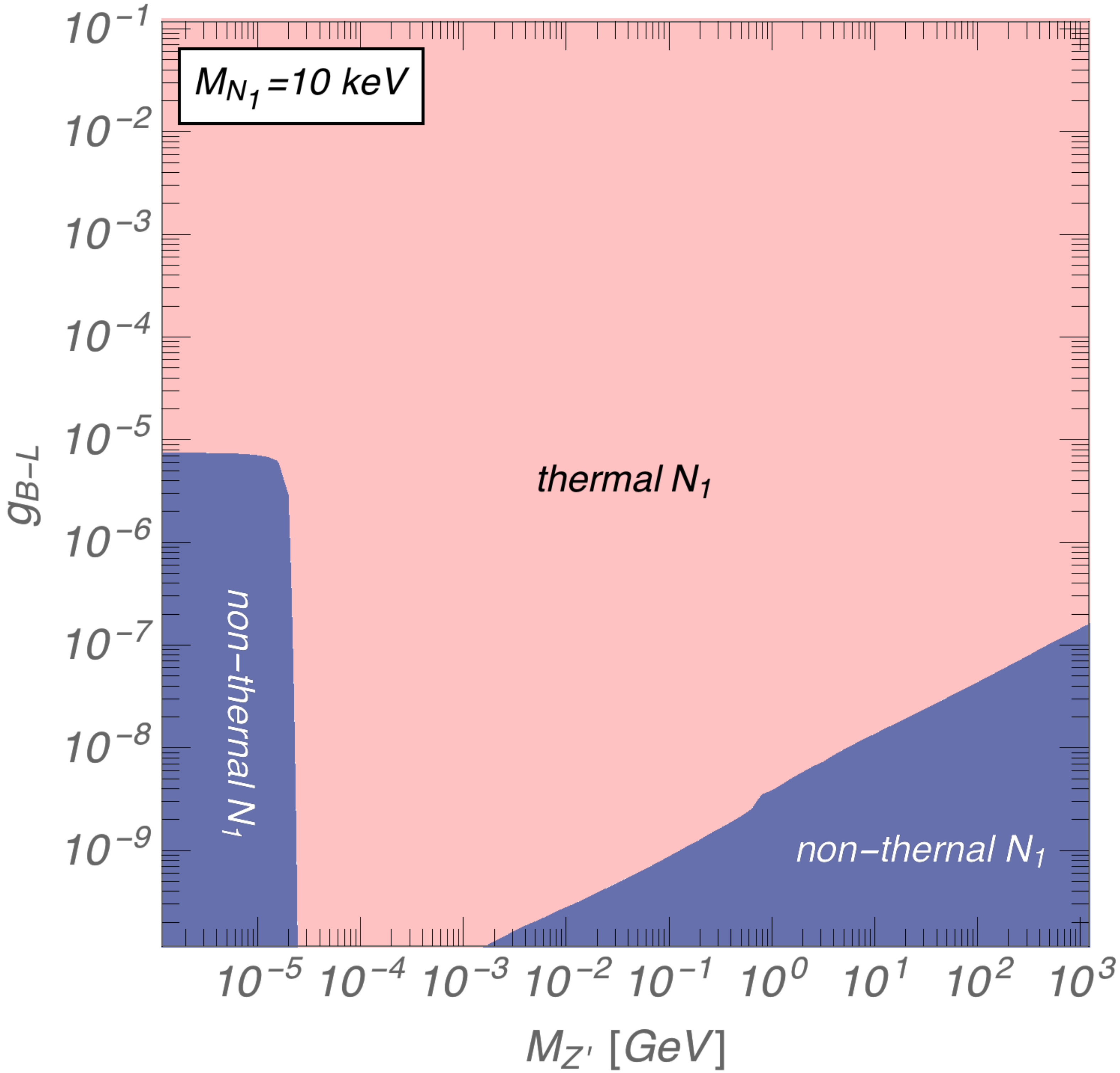




- Dark matter scenario drastically changes, depending on whether N_1 is thermalized or not.

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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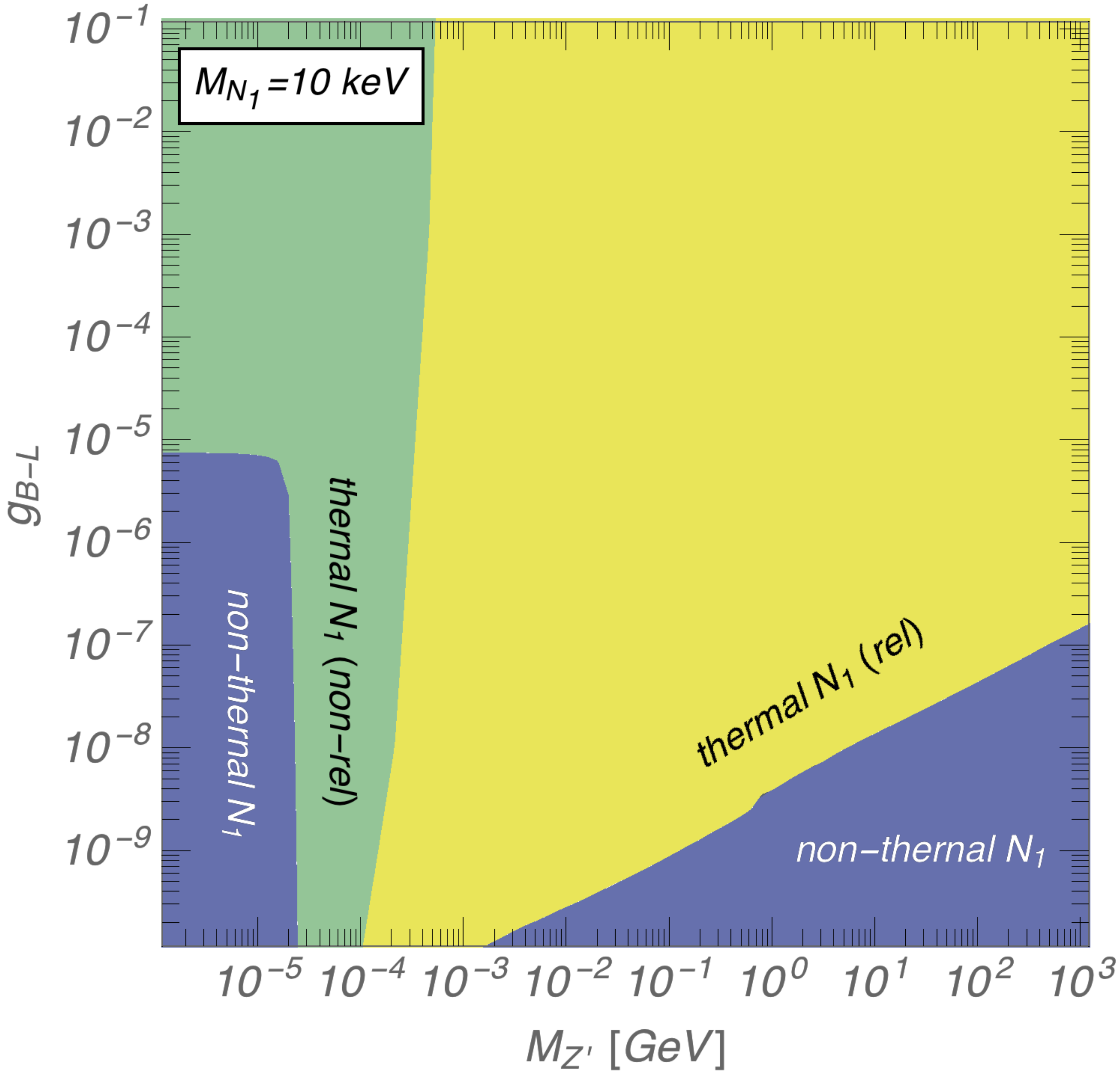

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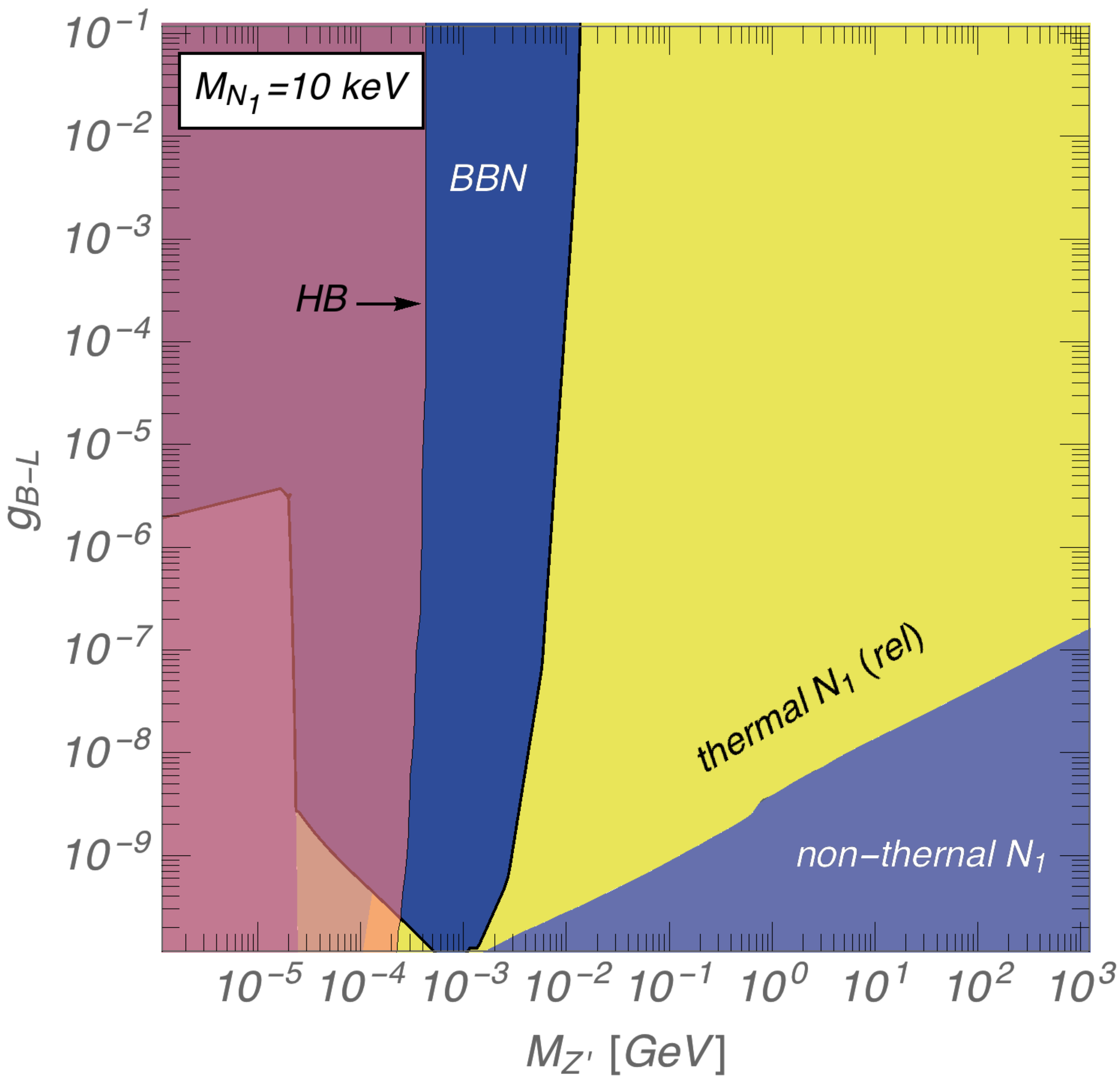

- Constraints from BBN and Horizontal Branch (HB) stars exclude non-rel. N_1
- Rel. N_1 has large number density (due to the lack of Boltzmann suppression)

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

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

(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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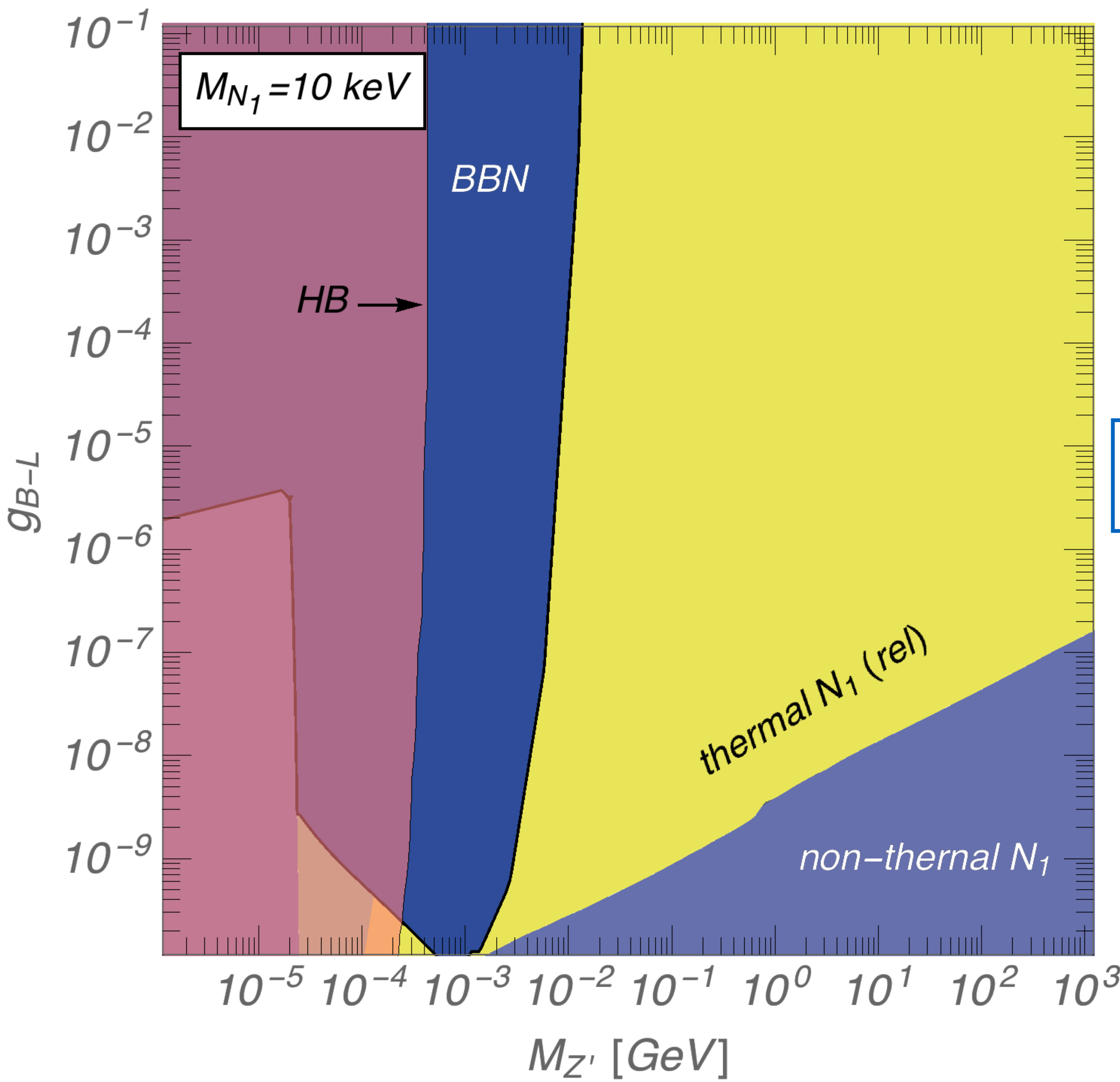

- In the non-thermal N_1 regions, N_1 is produced through

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

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

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

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

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

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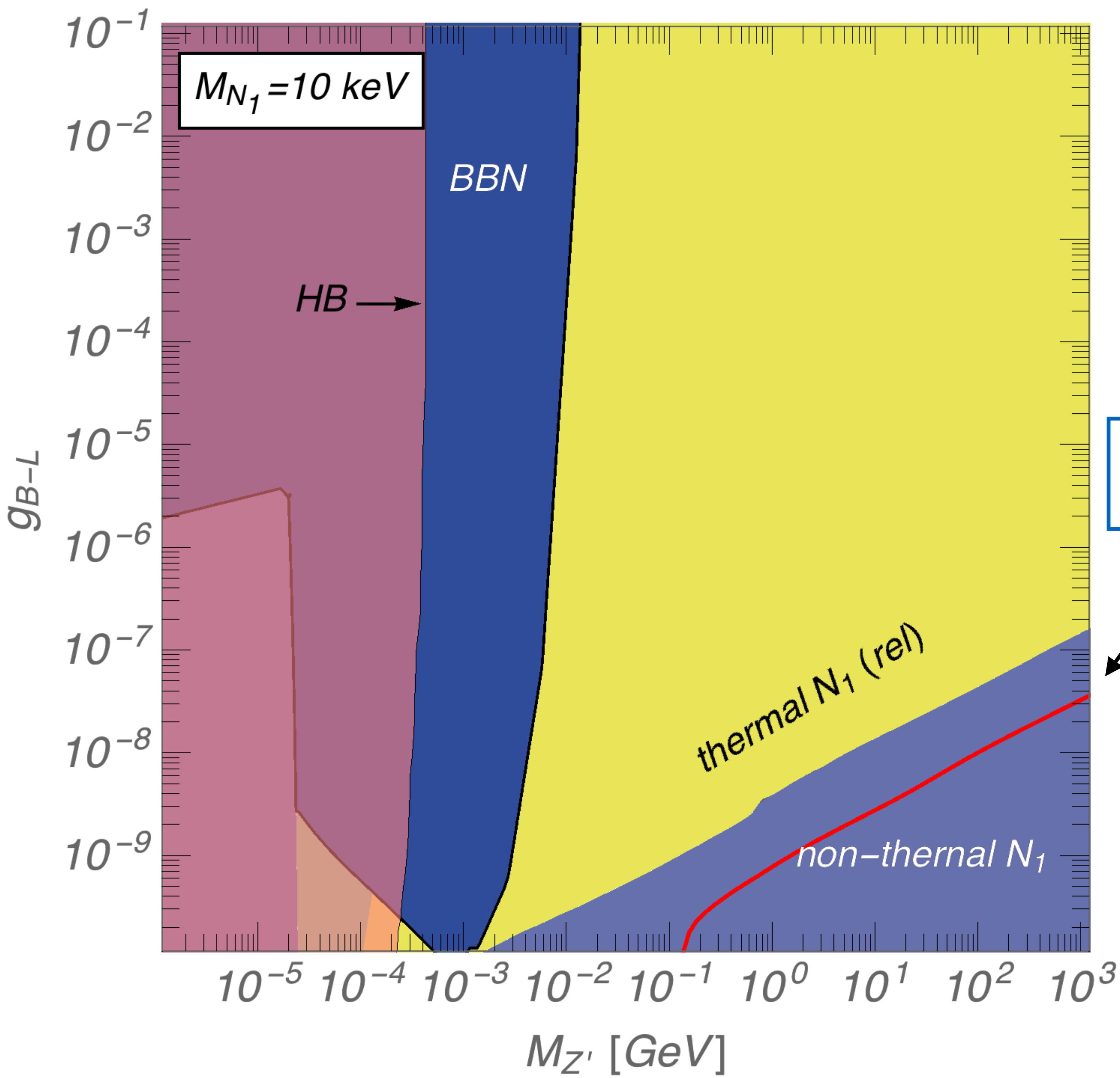

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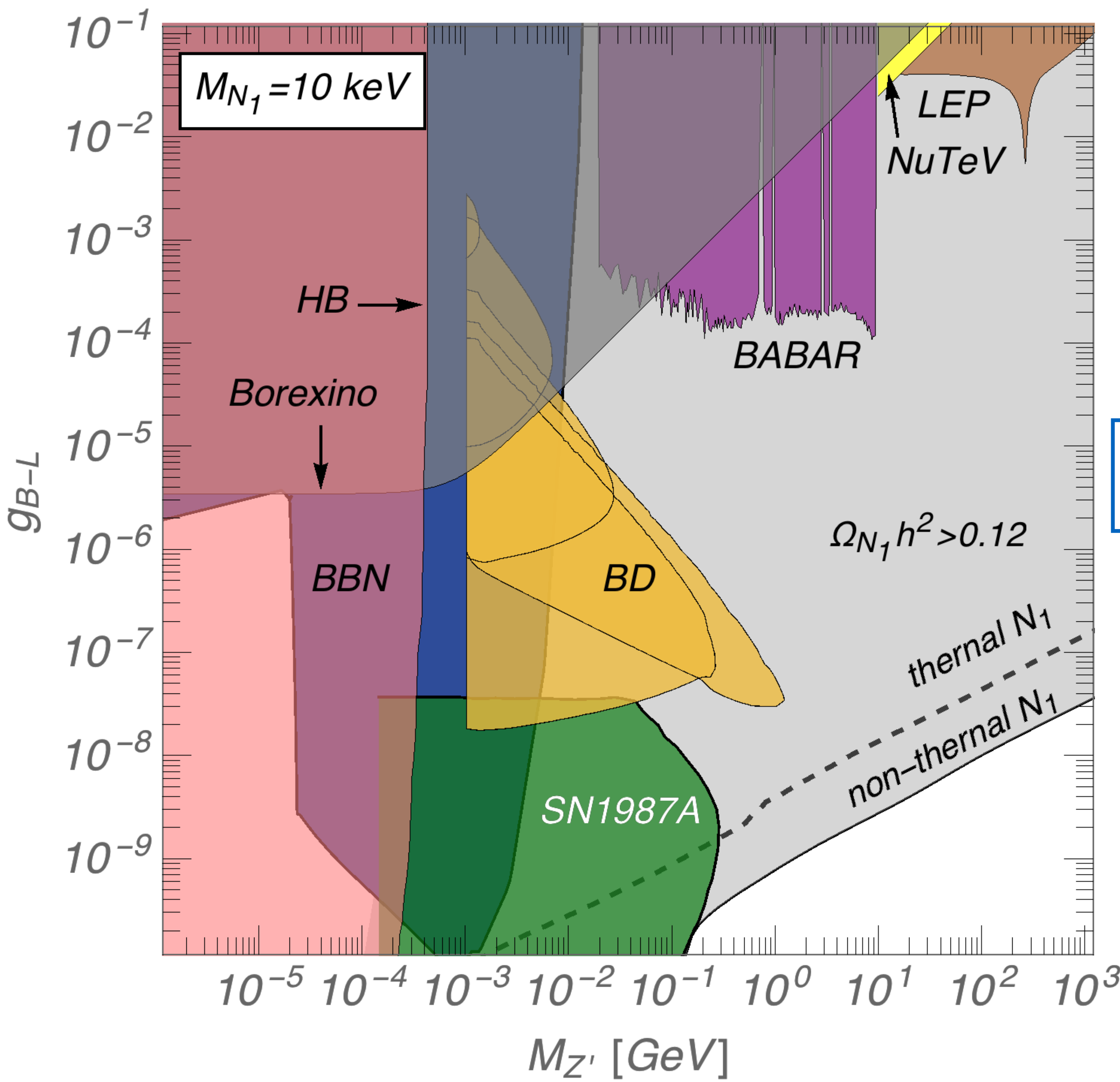

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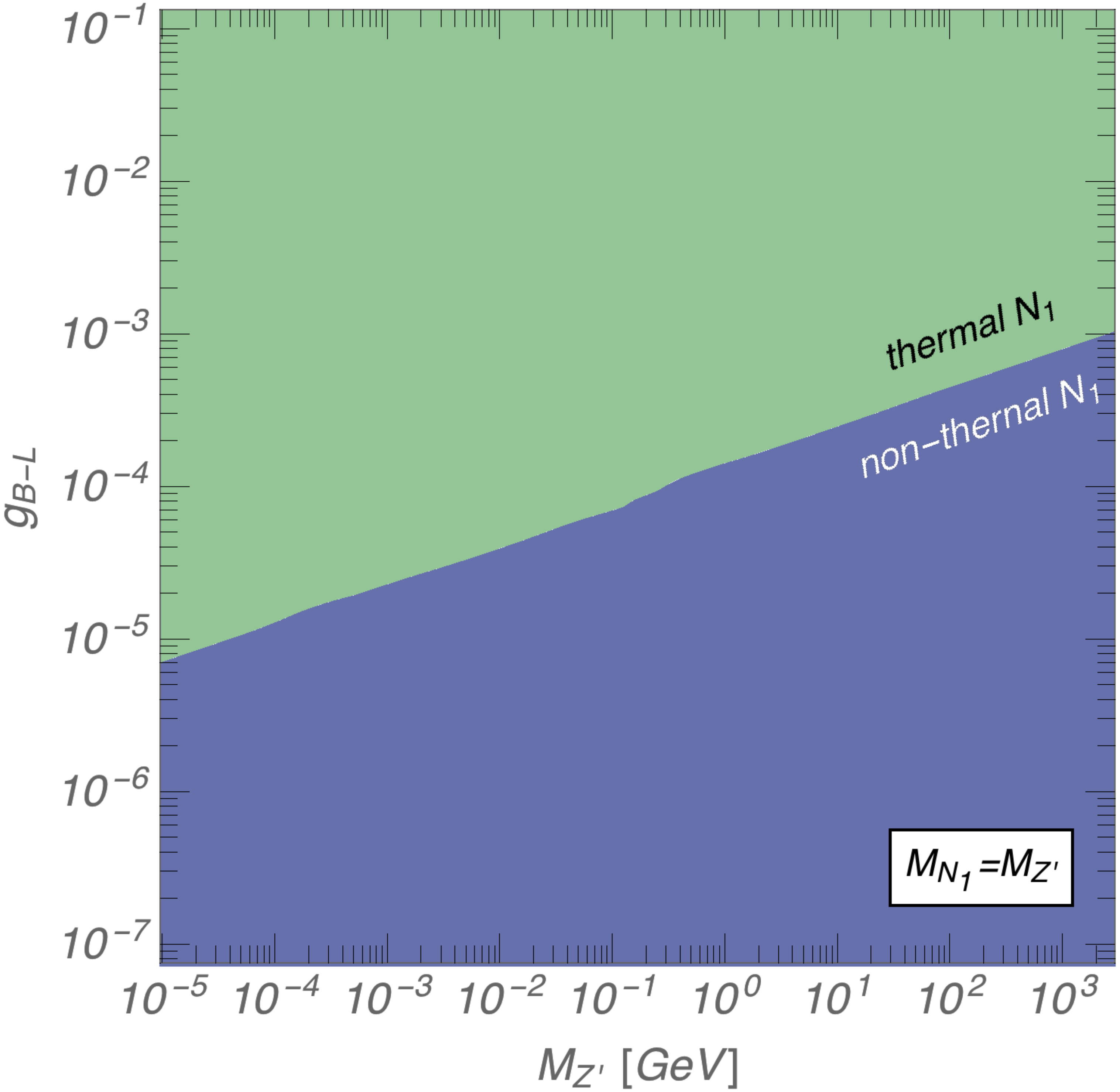
- together with all relevant limits

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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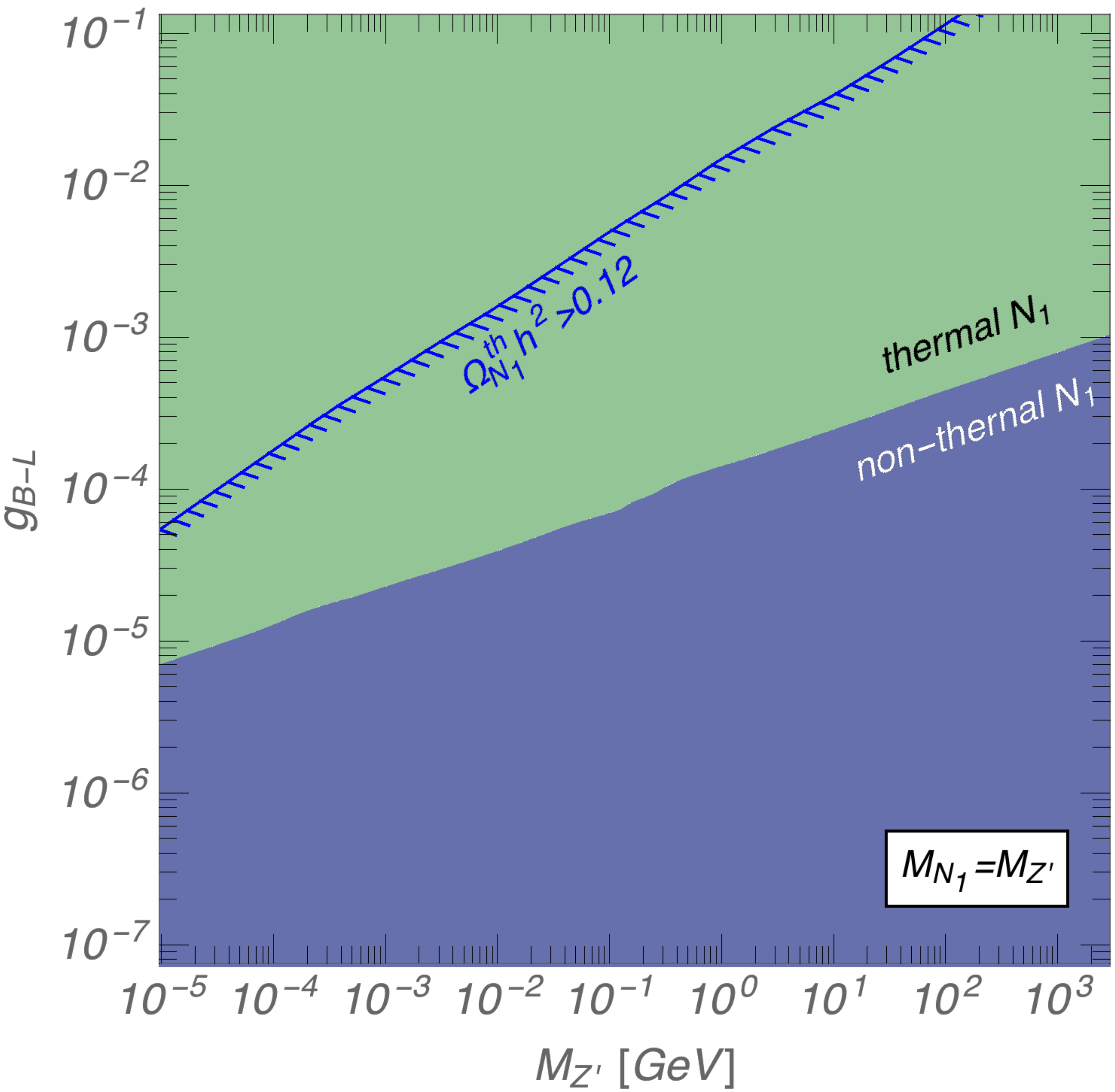

- For thermal N_1, N_1 is ordinary cold dark matter produced by freeze-out mechanism

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

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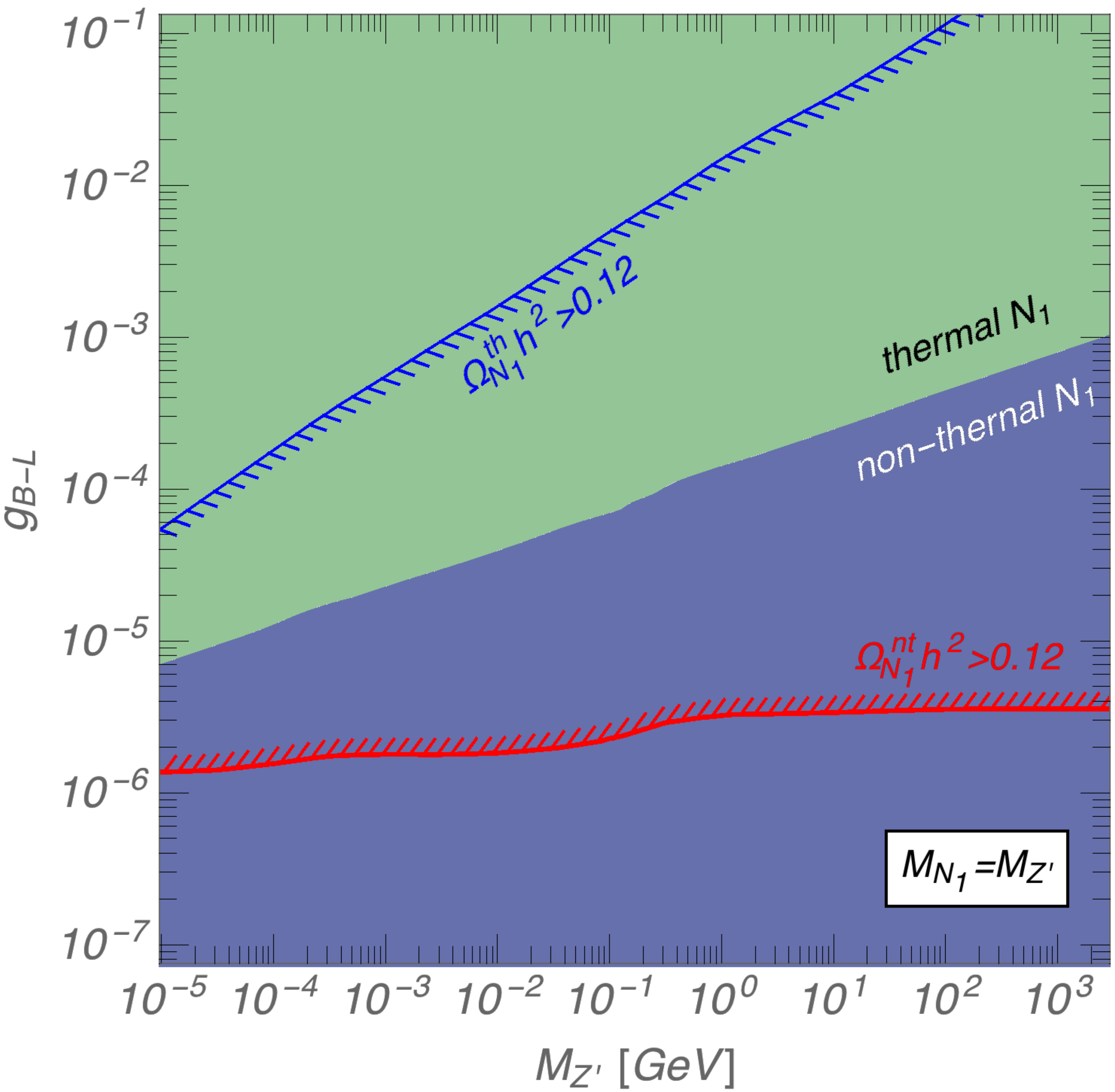

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- For non-thermal N_1, N_1 is produced by freeze-in mechanism

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

(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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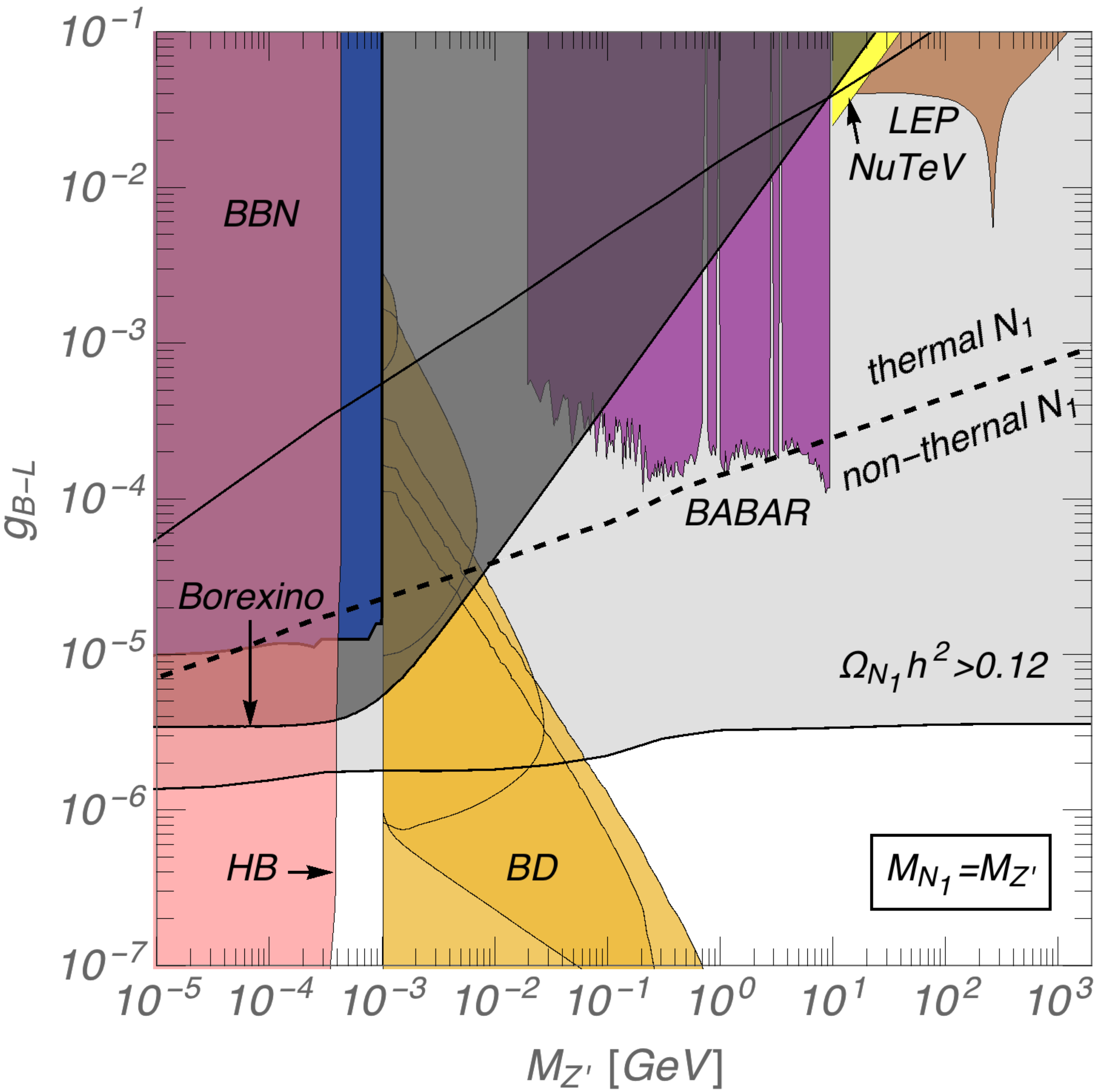

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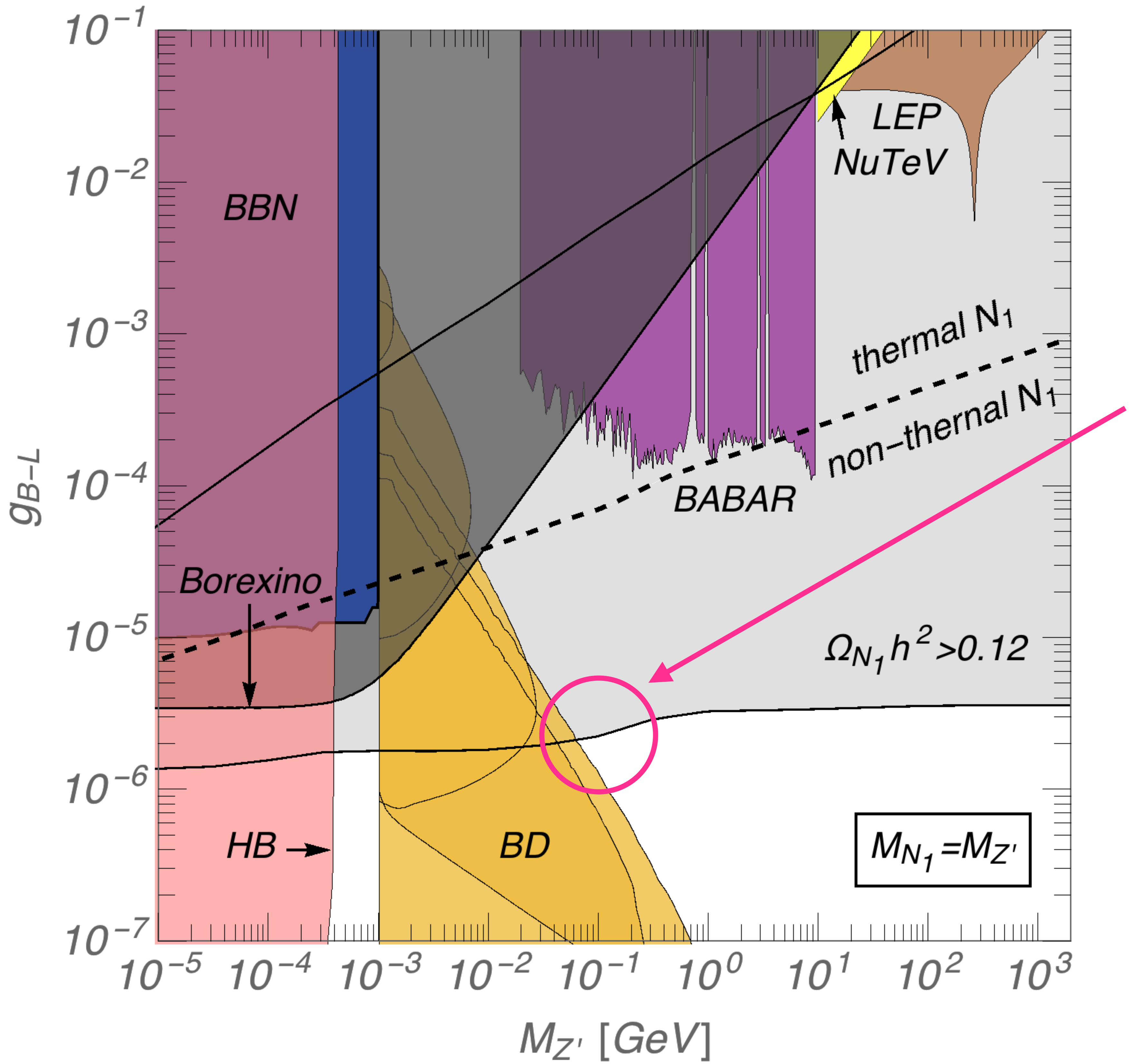
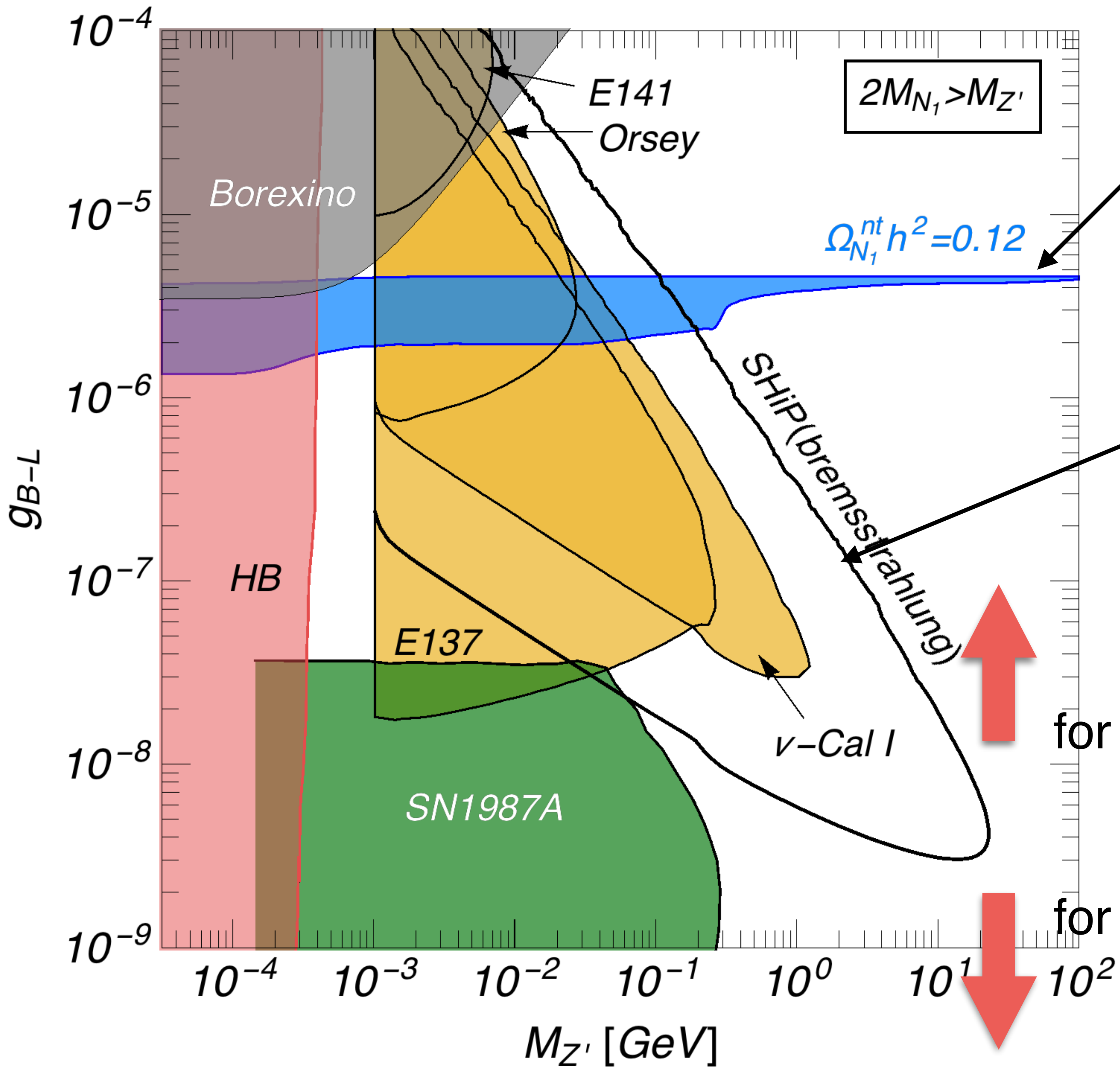
- Relevant constraints

3. Implications



The SHiP experiment can test this region

The Search for Hidden Particles (SHiP) experiment



➢ Freeze-in N_1

$$\Omega^{\rm nt}_{N_1}h^2 \simeq 0.12 \times \left(\frac{100}{g_*}\right)^{3/2}\left(\frac{g_{B-L}}{4.5\times10^{-6}}\right)^4$$

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

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-L}, Z' life-time becomes shorter

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

➢ SHiP will be able to cover:

$$1\ \mathrm{MeV} \lesssim M_{Z'} \lesssim 200\ \mathrm{MeV}$$

The Search for Hidden Particles (SHiP) experiment

➢ $2M_{N1} > M_{Z'}$

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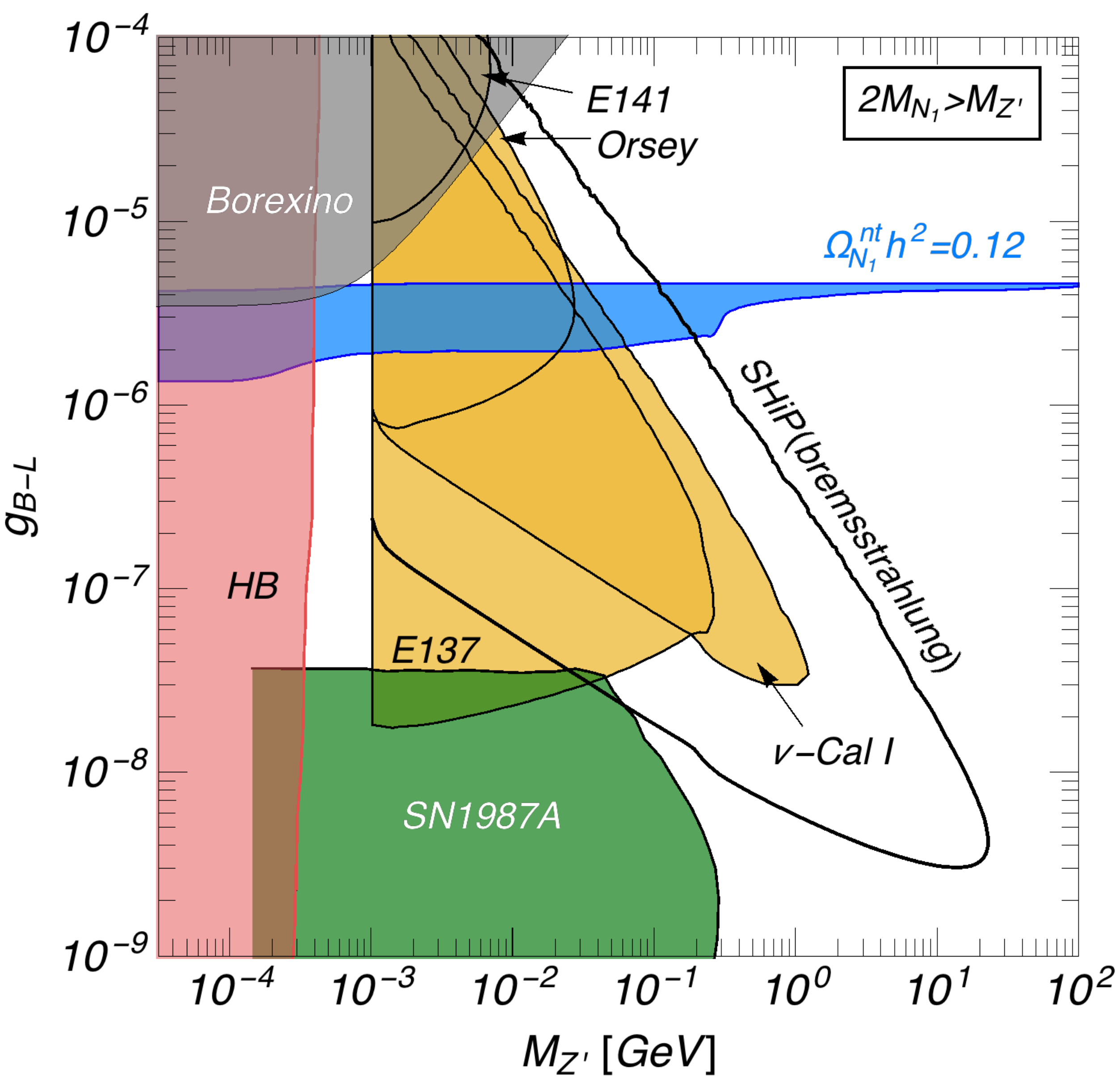

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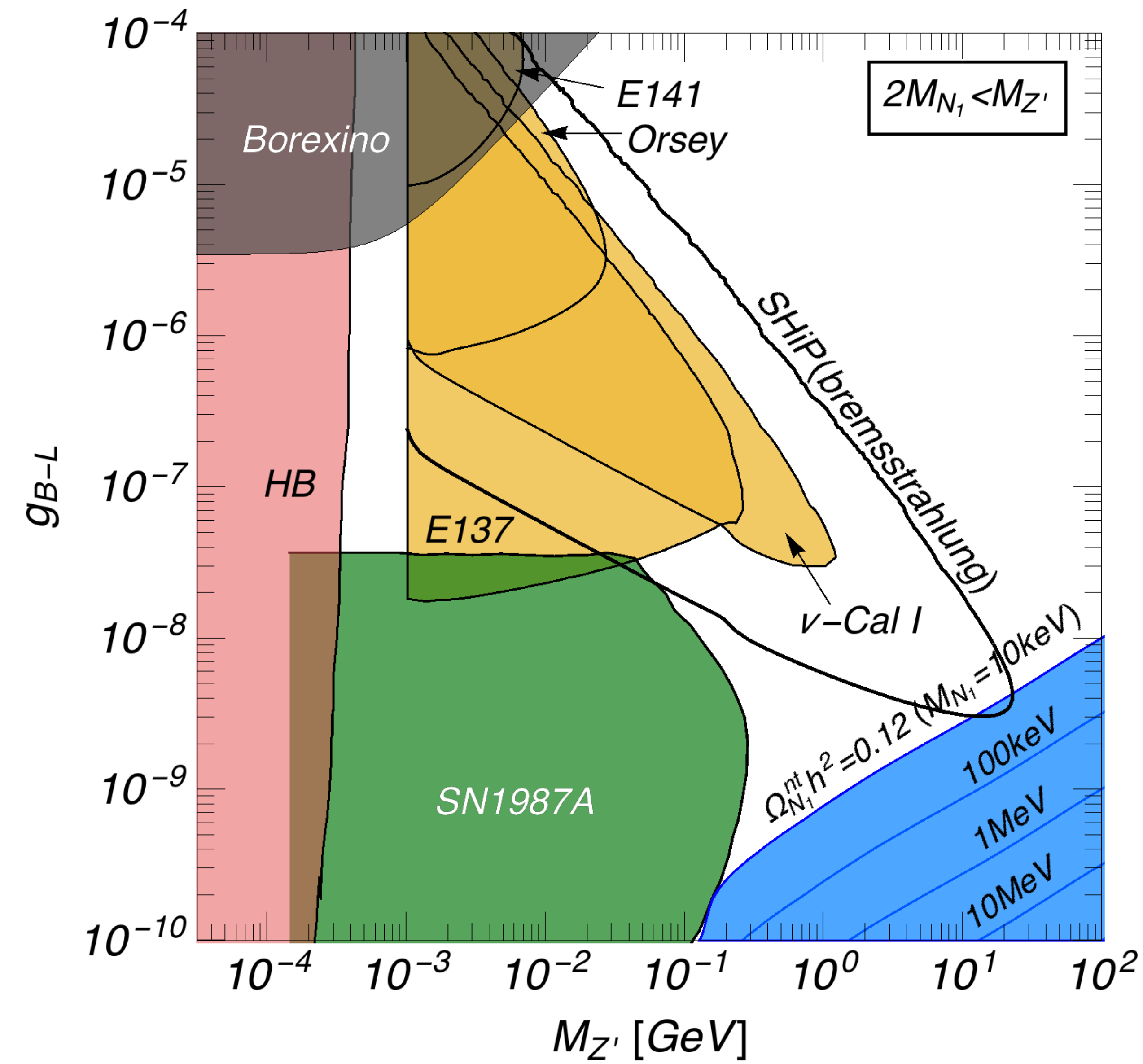


SHiP can be a powerful tool for searching the freeze-in scenario

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

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

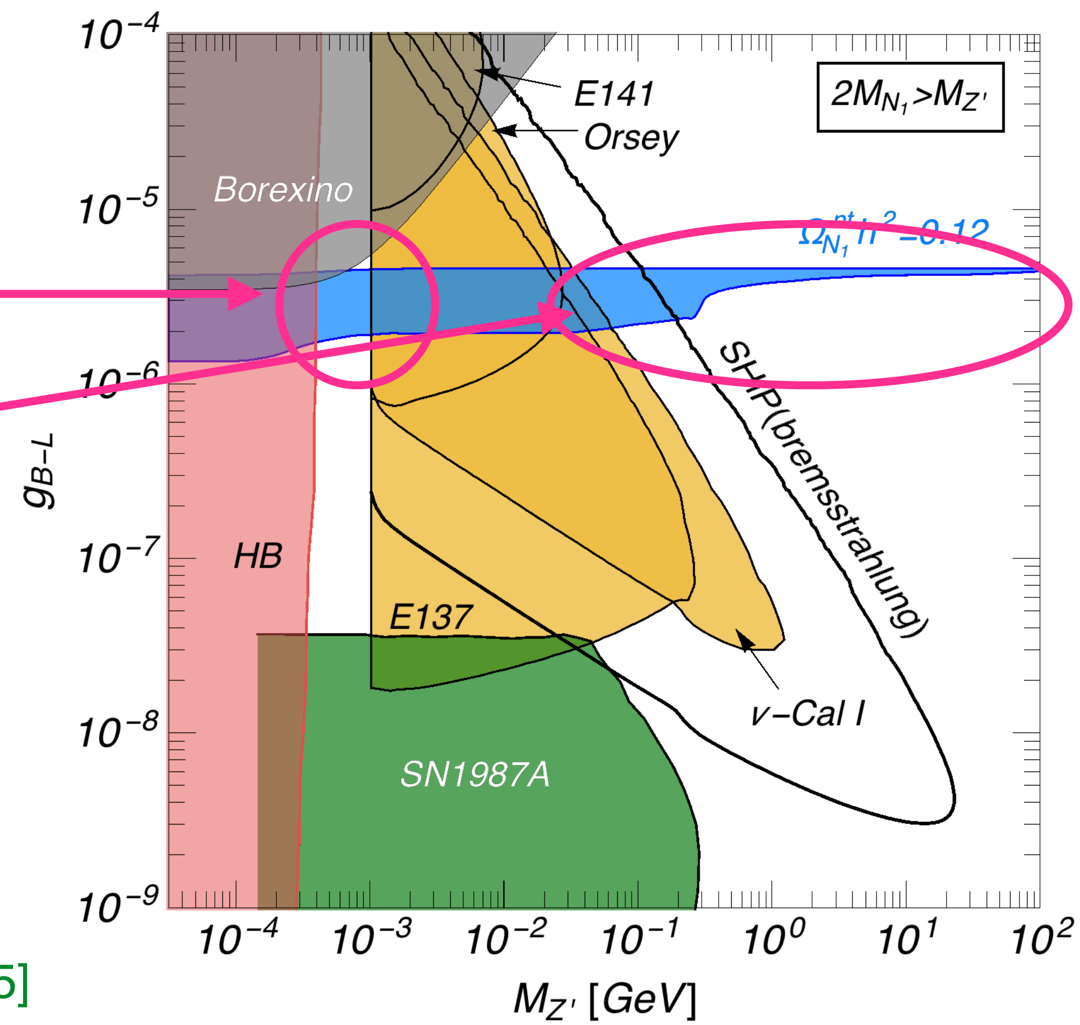
- This leads to

(taking $\lambda_S = 4\pi$)

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

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

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



- $M_s \sim 750$ *GeV* may be responsible for the diphoton excess at the LHC Run 2

[KK, S.Kang, H.-S.Lee, '15]

Summary

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