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

Kunio Kaneta (IBS-CTPU)

기초과학연구원
Institute for Basic Science

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

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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
- Massive neutrinos may indicate the existence of chiral partners: *right-handed neutrinos* (RHNs)
- If there are three RHNs, they can address other important issues, e.g., DM and BAU

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

Success of the SM and the gauge principle

- The gauge principle is one of the successful principles in modern particle physics so far
- The SM gauge symmetry, $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$, regulates not only interactions but also particle content by means of anomaly cancellation

B-L gauge symmetry

- To organize three RHNs under a gauge theory, the $G_{SM} \times U(1)_{B\text{-}L}$ gauge symmetry is one of the simplest extensions of the SM, under which we have the 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'*)

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 is given by

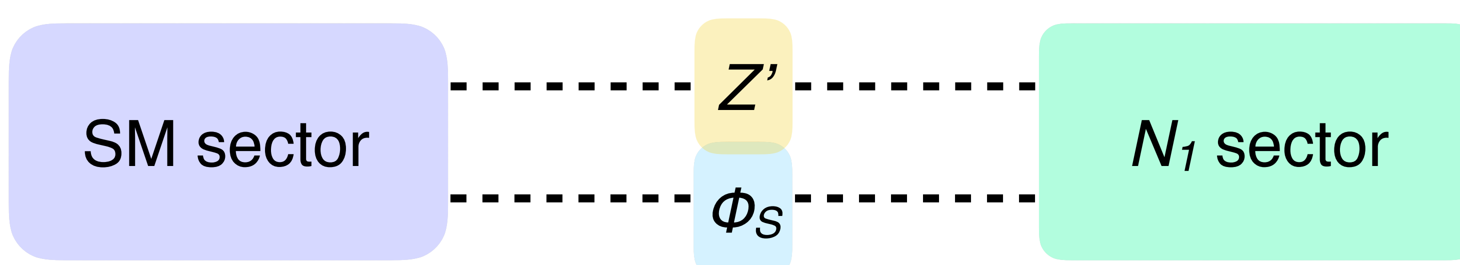
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}_i \not{D} N_i - \left(y_{\alpha i} \overline{L}_\alpha N_i \tilde{\Phi}_H + \frac{\kappa_i}{2} \Phi_S \overline{N_i^C} N_i + h.c. \right) + |D_\mu \Phi_S|^2 - V(\Phi_H, \Phi_S) - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}$$

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

- 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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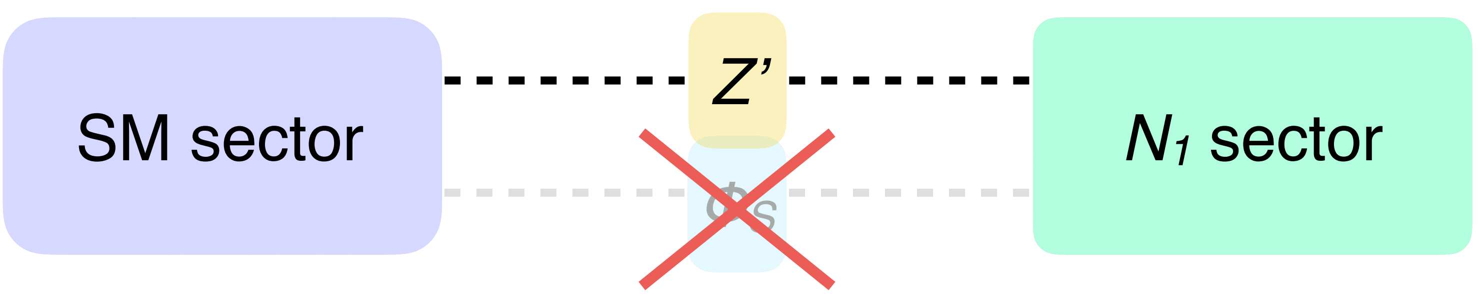


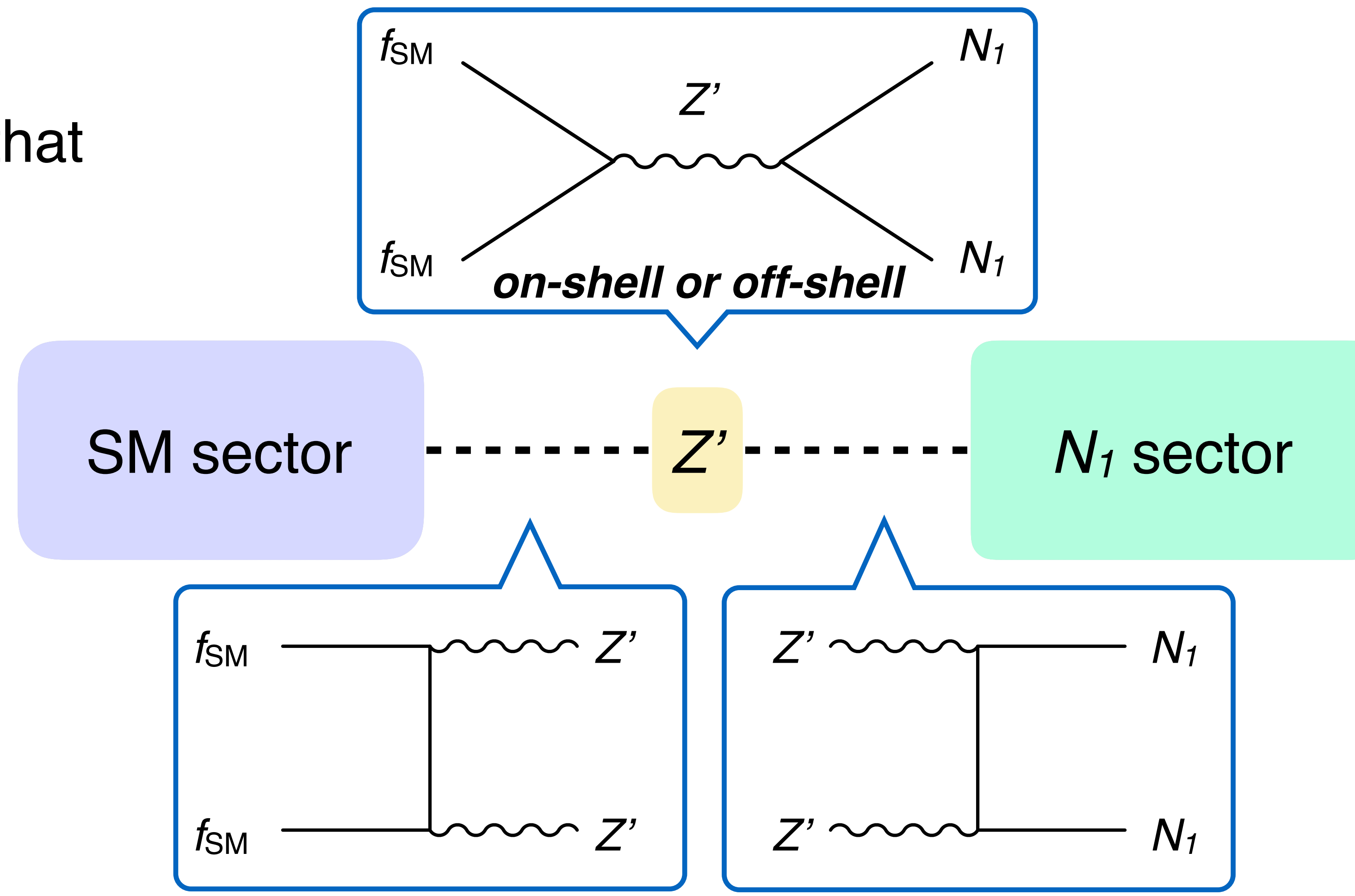
➢ To concentrate on the Z' effect, we turn off the Higgs portal coupling λ_{HS} (→0)

Relevant reactions for thermalization of N_1

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

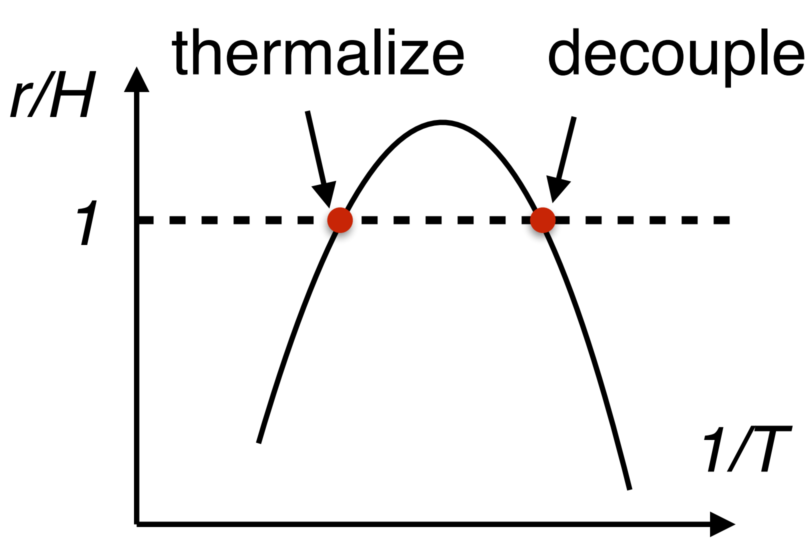
- Reaction rates:

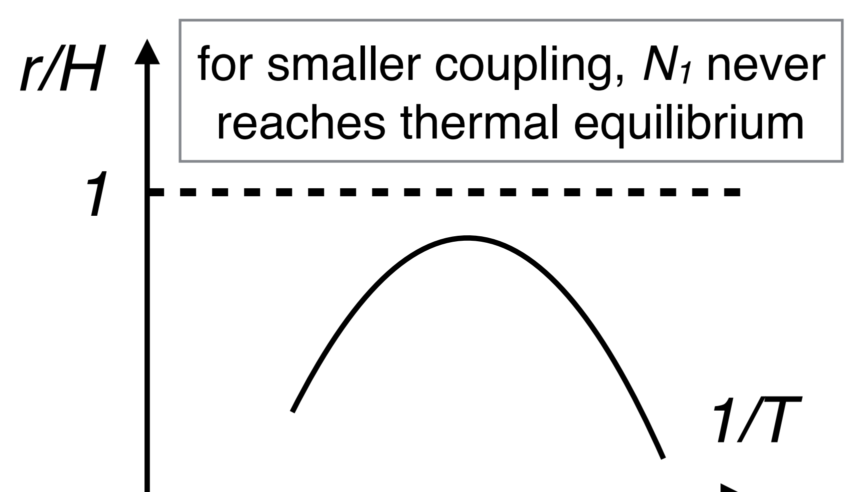
  $r(N_1 \leftrightarrow f_{SM})$, $r(N_1 \leftrightarrow Z')$, $r(Z' \leftrightarrow f_{SM})$



- In most of parameter spaces, $r(N_1 \leftrightarrow f_{SM})$ almost 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*

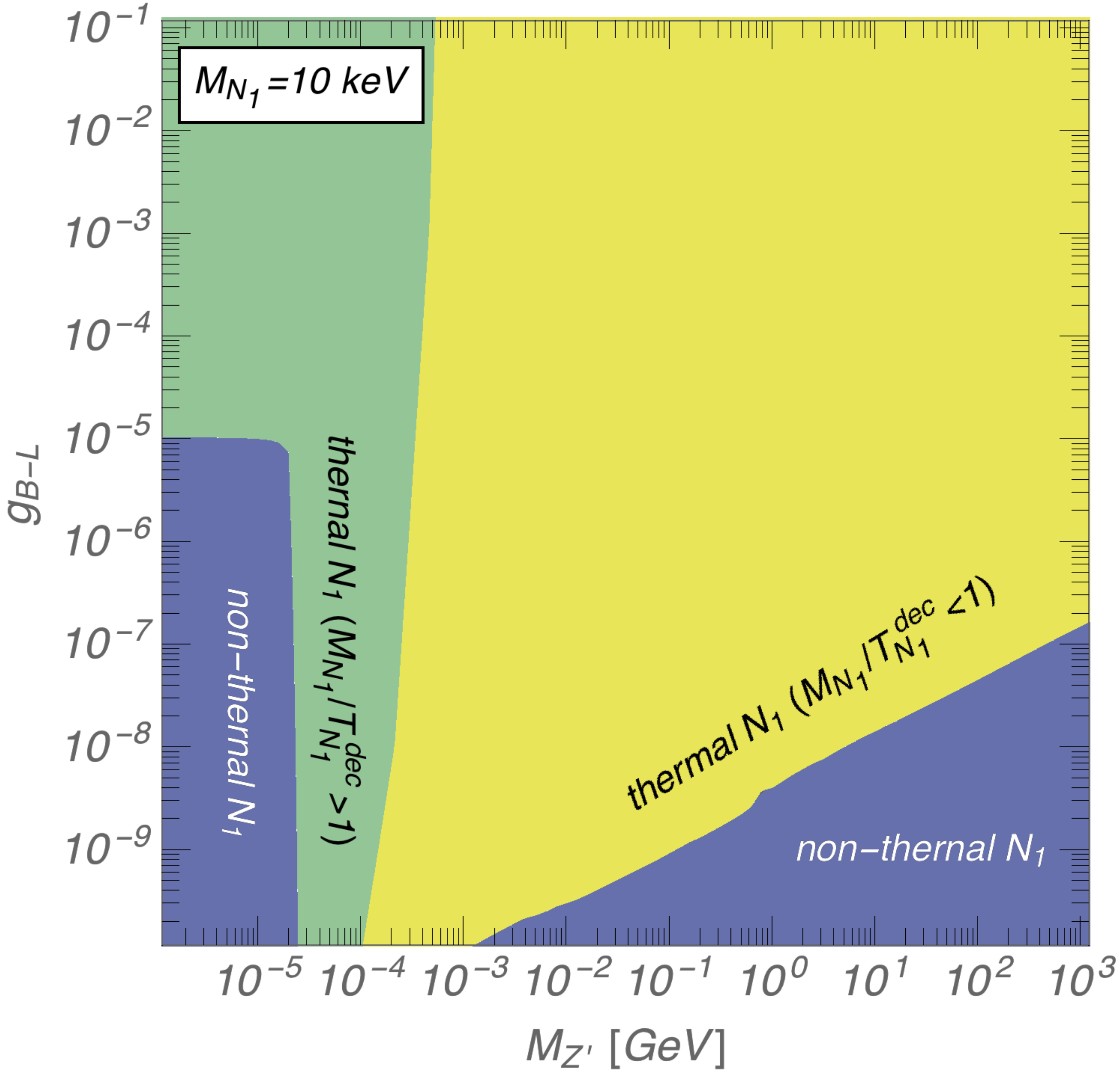




- Dark matter scenario drastically changes, depending on whether N_1 is thermalized or not.

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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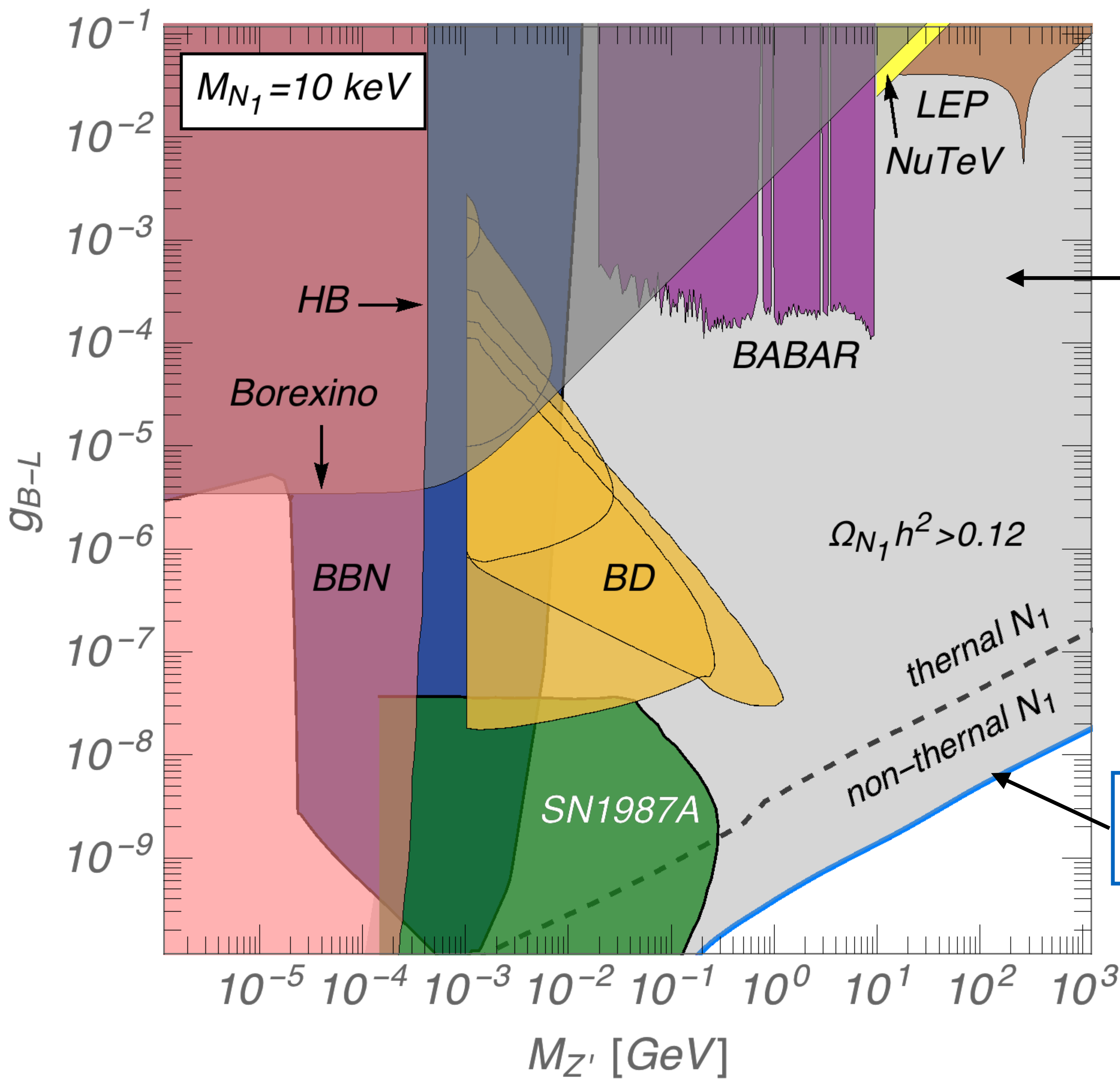


- In the thermal N_1 regions, N_1 is produced as a relativistic particle, so its abundance is overproduced:

$$\Omega^{\rm th}_{N_1} h^2 \simeq 100 \times \left[\frac{M_{N_1}}{10\ \mathrm{keV}}\right]\left[\frac{10.75}{g_*(T^{\rm dec}_{N_1})}\right]$$

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

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

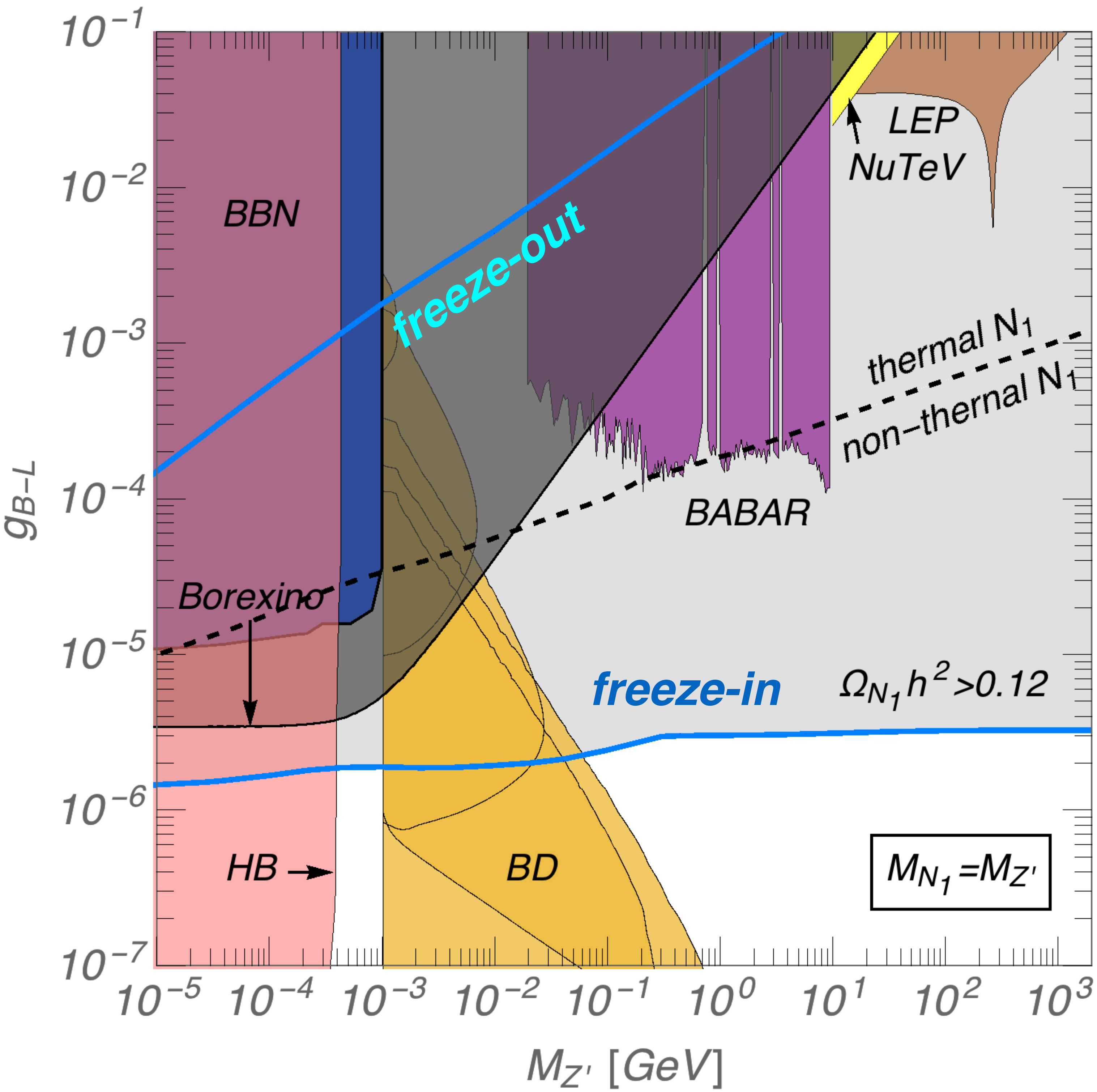
- For $2M_{N1} < M_{Z'}$, the relic abundance of N_1 is roughly given by

$$\Omega^{\rm nt}_{N_1} h^2 \simeq 0.12 \times \left[\frac{100}{g_*}\right]^{3/2}\left[\frac{g_{B-L}}{5.1\times10^{-12}}\right]\left[\frac{7}{C_f}\right]\left[\frac{f(\tau)}{0.19}\right]$$

$$\Gamma_{Z'} \sim C_f \frac{g^2_{B-L}}{12\pi} M_{Z'} \qquad f(\tau) = \tau(1-\tau^2)^{3/2} \qquad (\tau = 2M_{N1}/M_{Z'})$$

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)



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

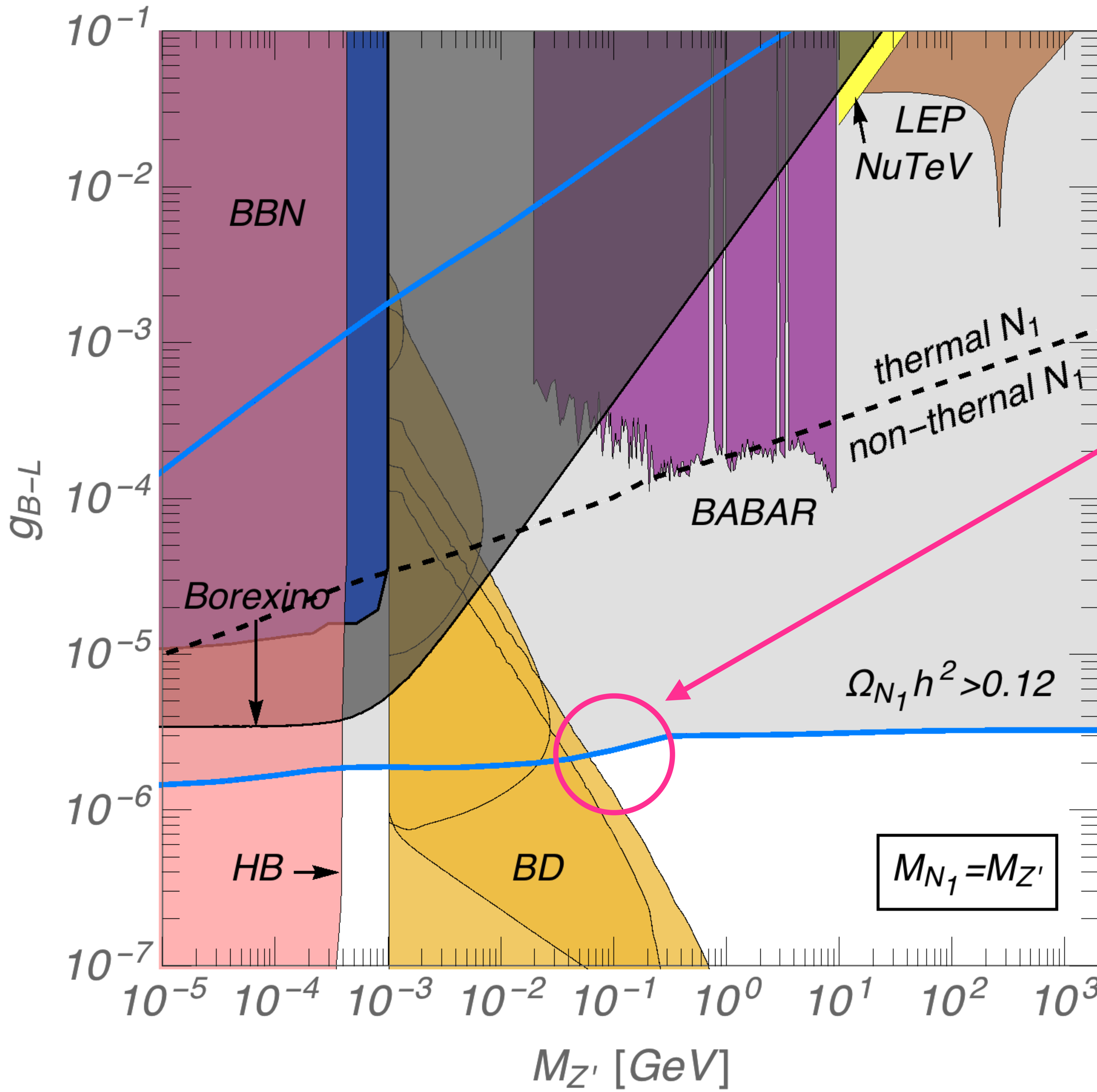
$$\Omega^{\rm th}_{N_1} h^2 = \frac{s_0 M_{N_1} Y^{\rm th}_{N_1}}{\rho_c h^{-2}} \propto \left.\frac{1}{\sigma v}\right|_{T\sim T^{\rm dec}_{N_1}}$$

- 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)

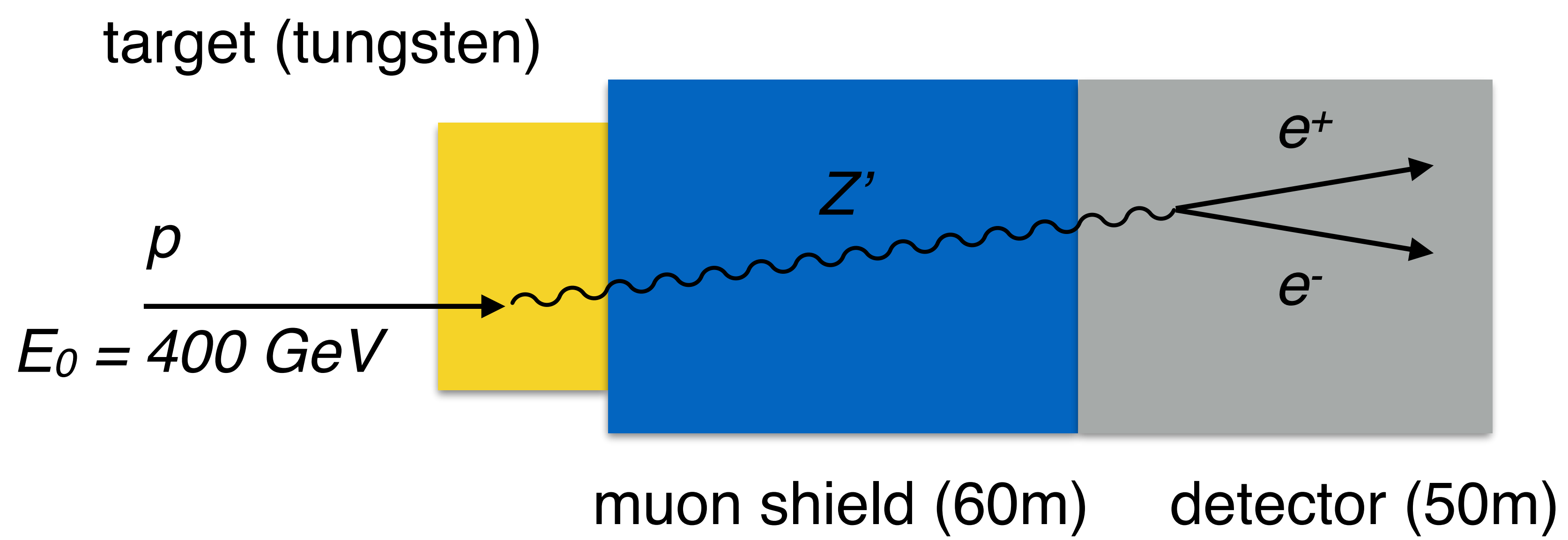
3. Implications



Beam dump experiments can test this region

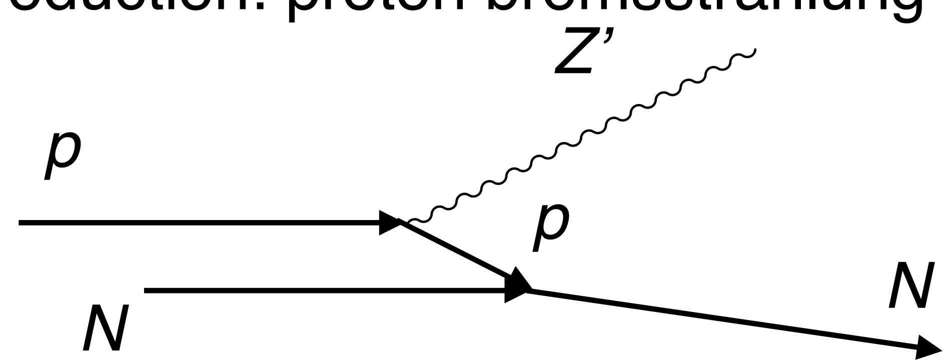
The Search for Hidden Particles (SHiP) experiment

- ➢ 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 lifetime of *Z'* is too short or too long, *Z'* can not be observed

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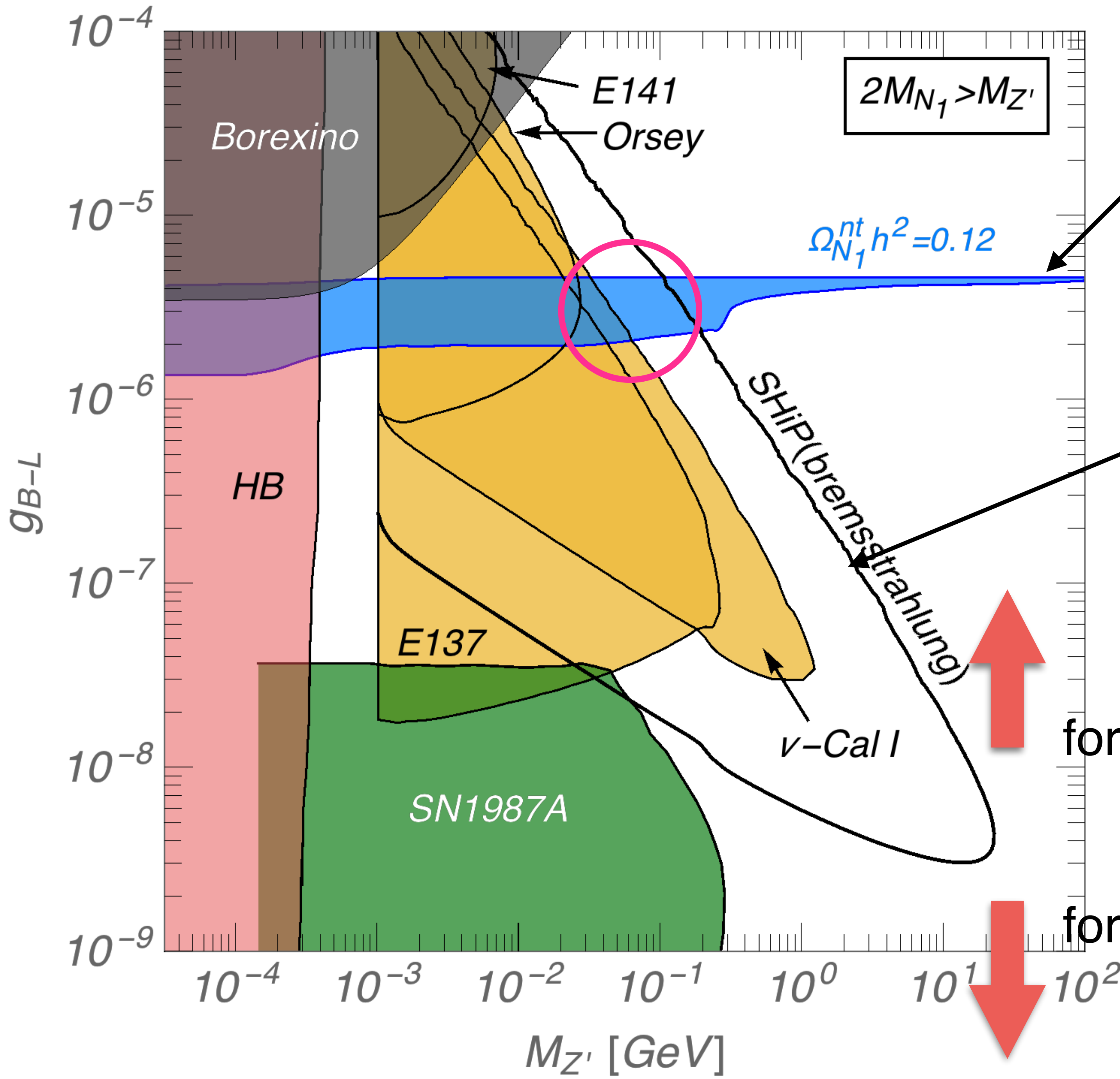

➢ Freeze-in N_1

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

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

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 $g_{B\text{-}L}$, Z' lifetime becomes shorter

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

➢ SHiP will be able to cover:

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

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➢ $2M_{N1} > M_{Z'}$

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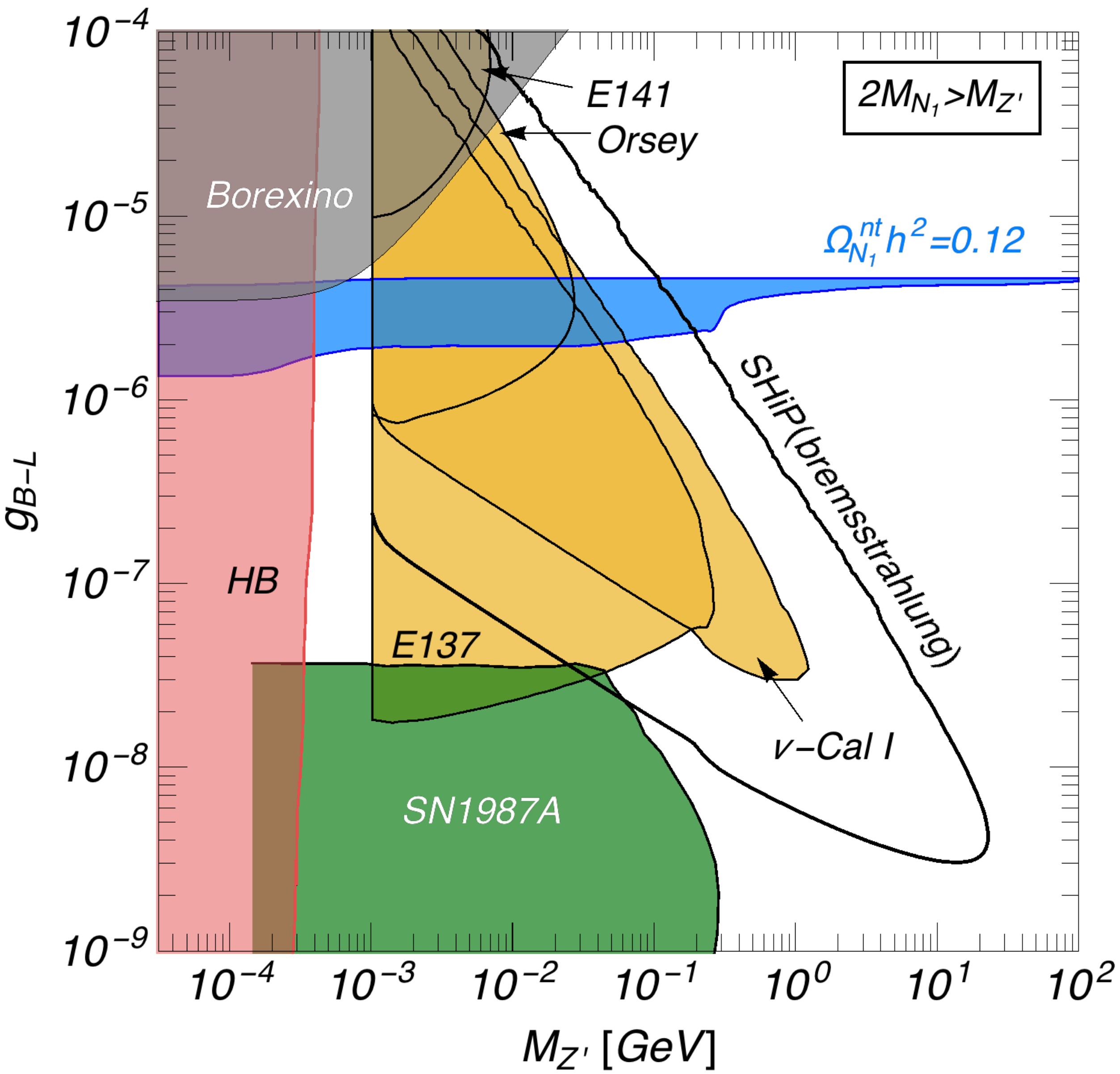

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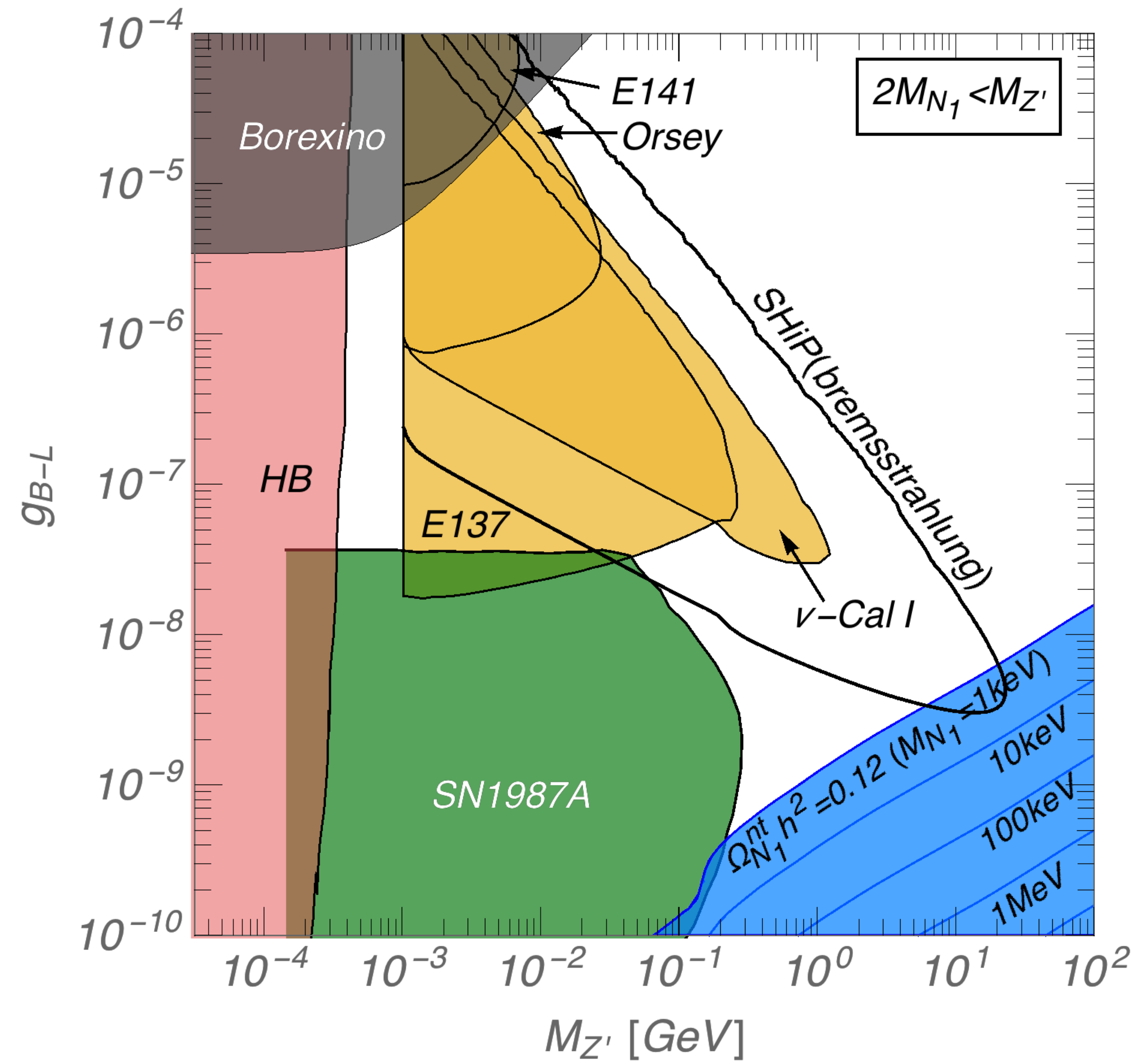


SHiP can be a powerful tool for searching the freeze-in scenario

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

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

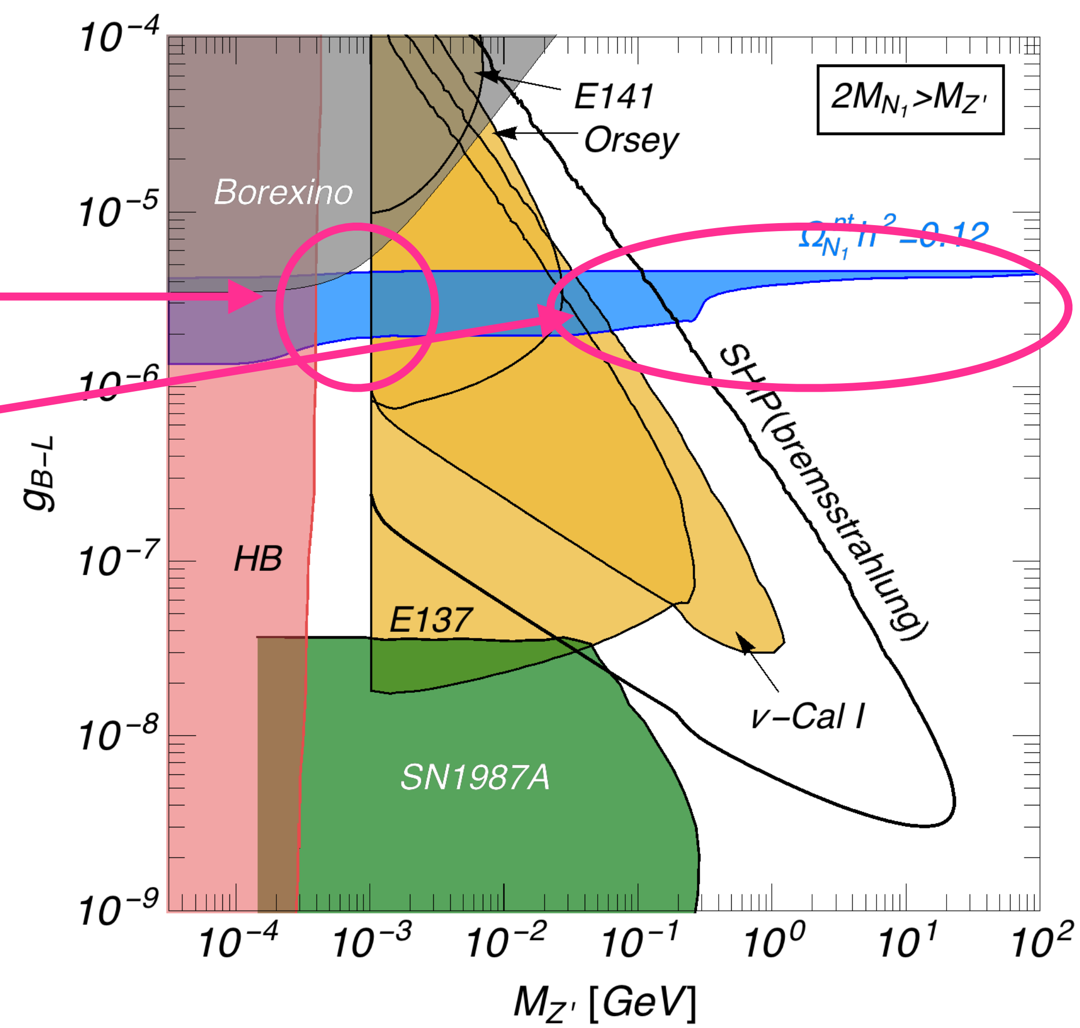
- This leads to

(taking $\lambda_S = 4\pi$)

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

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

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



Summary

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