Sterile neutrino dark matter

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

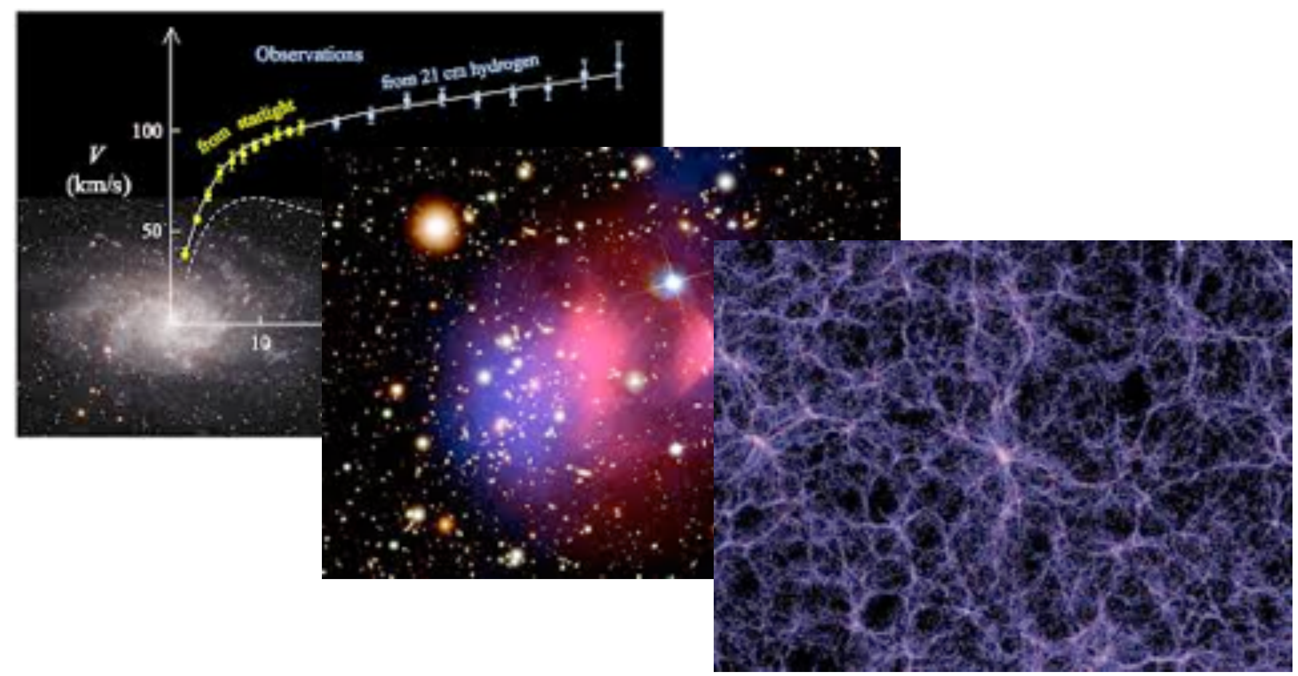
4. Summary

1. Introduction

Dark matter

We empirically know the existence of dark matter:

- ➢ it is hard to explain the rotation curve of the galaxy without dark matter
- ➢ gravitational lens effect of galaxy clusters indicates dark matter
- ➢ observation of the bullet cluster
- ➢ large scaler structure formation
- ➢ WMAP, Planck



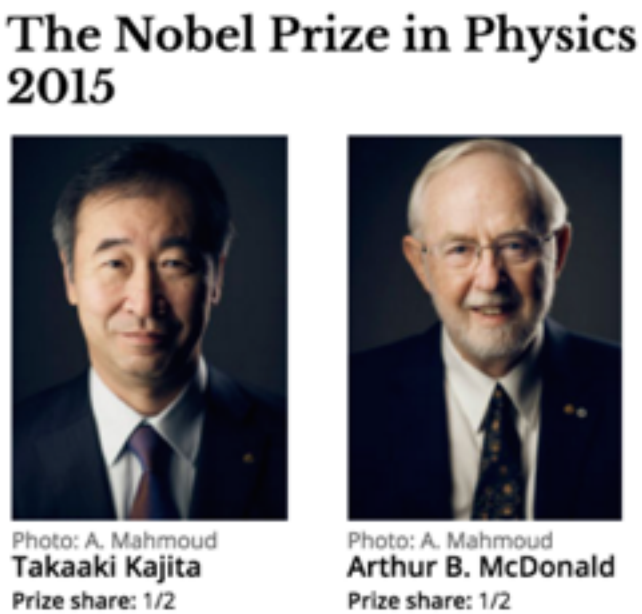
Properties of dark matter

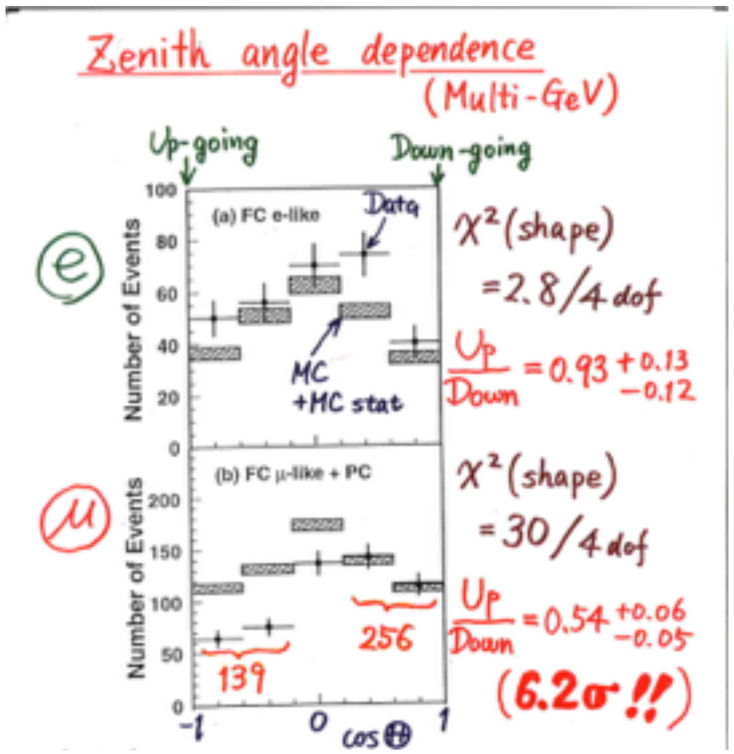
- ➢ Neutral under $SU(3)_C \times U(1)_{EM}$
- ➢ Stable enough
- ➢ Weakly/Feebly interacting

Dark matter is not a part of the standard model

To identify the dark matter is one of the most important tasks in modern particle physics

Neutrino oscillations





(from ICRR's homepage)

- ➢ Neutrinos produced as a flavor state propagate as a mass eigenstate, and are detected as a different flavor state
- ➢ So, neutrino oscillations imply non-zero masses of neutrinos

Right-handed neutrinos as a missing piece to the SM

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

Possible roles of the RHNs in cosmology

➢ RHN as a dark matter candidate:

- production mechanism: non-thermal for $M_N \sim$ keV, thermal for $M_N >$ MeV - GeV
- stability: seesaw for $M_N \sim$ keV, flavor symmetry (?) for $M_N >$ MeV - GeV

➢ RHN as an origin of BAU:

- $M_N \sim O(1\text{-}100)$ GeV: leptogenesis by the active-sterile neutrino oscillation
- $M_N > O(10^9)$ GeV: leptogenesis by the CP violating decay of RHNs

($M_N \sim O(1\text{-}10^{13})$ GeV: resonant leptogenesis)

The neutrino minimal standard model (νMSM)

➢ The νMSM is one of the appealing framework that can address neutrino mass, DM, BAU

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

➢ The Lagrangian of the νMSM is given by

[Asaka, Blanchet, Shaposhnikov, '05]

[Asaka, Shaposhnikov, '05]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_i \partial\!\!\!/ N_i - \left[f_{ai}\bar{L}_a H N_i + \frac{1}{2}\mathcal{M}_{N_i}\overline{N^C}_i N_j + h.c. \right]$$

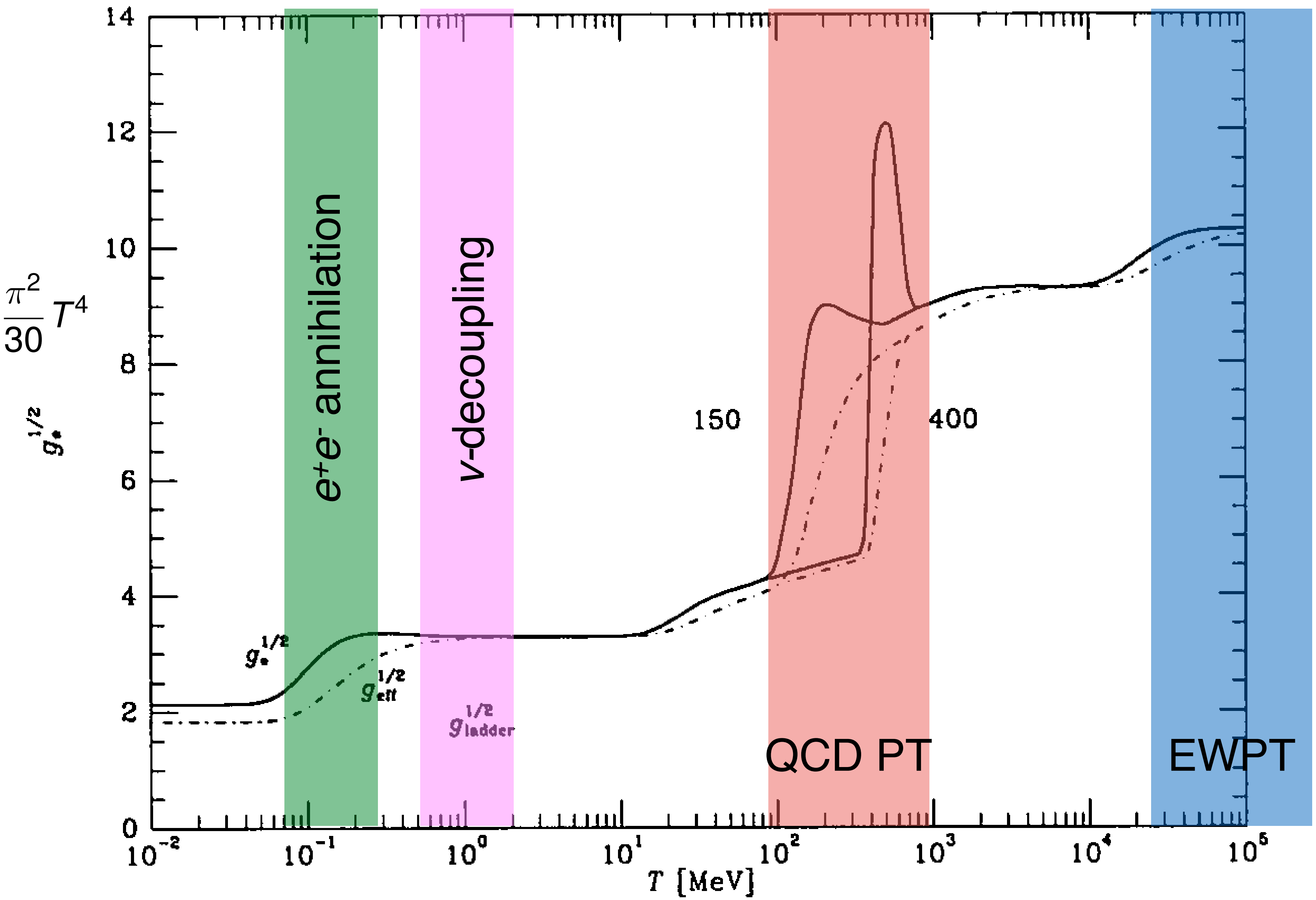
$a = e, \mu, \tau$

- ν_a - N_1 oscillation generates the keV-scale dark matter [Dodelson, Widrow, '94]
- ν_a - $N_{2,3}$ oscillations generate the baryon asymmetry [Akhemedov, Rubakov, Smirnov, '98]

Light sterile neutrino in the early universe

- ➢ Quick look at the thermal history of the universe [Gondolo, Gelmini, '91]

$$\rho_R = g_*(T)\frac{\pi^2}{30}T^4$$



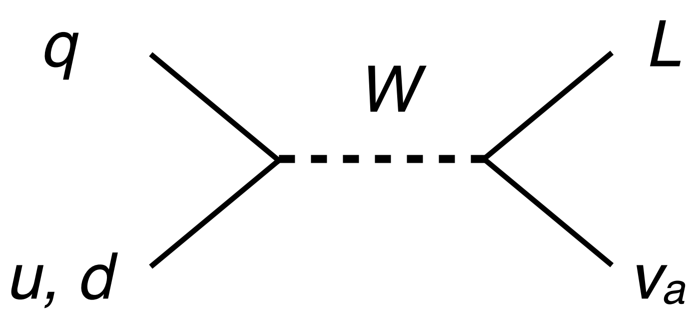
- ➢ Soon after the ν-decoupling, Big Bang Nucleothynsesis (BBN) starts (@ T ~ MeV)
- ➢ Light element observations give a constraint on the number of neutrino species (N_{eff} ~ 3)
- ➢ Sterile neutrino should decouple at T > MeV

Light sterile neutrino in the early universe

➢ Sterile neutrino reaches the thermal equilibrium through the active-sterile neutrino oscillation:

active neutrino → sterile neutrino → mass eigenstate

$$\begin{bmatrix} \nu_a \\ \nu_s \end{bmatrix} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 \\ \sin\theta_1 & \cos\theta_1 \end{bmatrix} \begin{bmatrix} \nu_i \\ N_1 \end{bmatrix}$$



The weak eigenstate (active neutrino) ν_a is produced in the thermal bath

$\nu_a \sim c_1\, \nu_i + c_2\, N_i$ →

propagate & oscillate as a mass eigenstate (ν_i, N_i)

ν_a component: re-scattering with the SM particles

ν_s component: if $\Gamma_\nu P < H$, ν_s is passing through without re-scattering, otherwise go back to ν_a and re-scattered with the SM particles

reaction rate:

$$\Gamma_\nu \sim G_F^2\, T^5$$

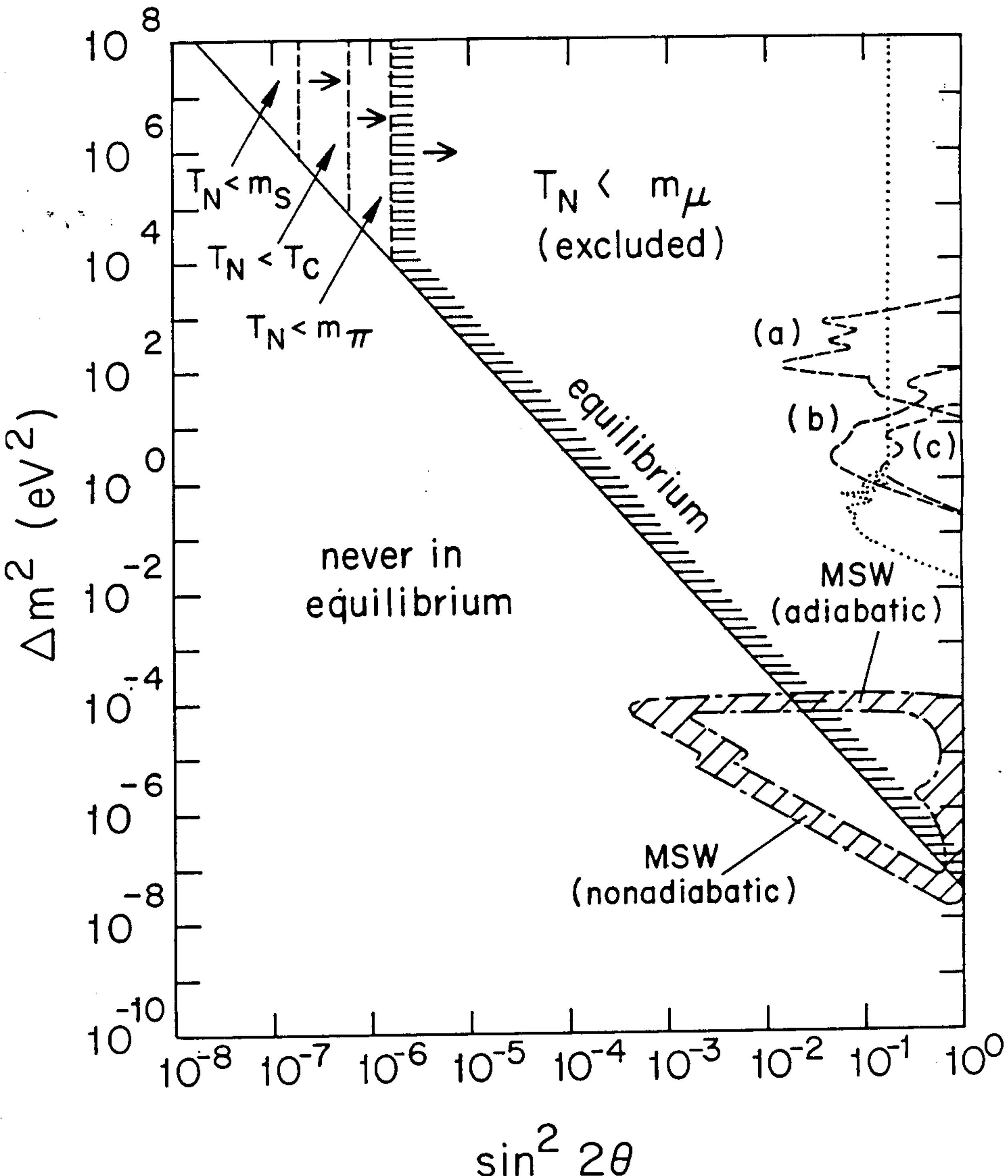
transition rate:

$$P(\nu_a \to \nu_s) = \sin^2 2\theta_1 \sin\left(\frac{\Delta m^2}{4E} t\right)$$

➢ Sufficient condition of time scales for the sterile neutrino to thermalize:

$$t_{\mathrm{oscillation}} \ll t_{\mathrm{scattering}} \ll t_{\mathrm{expansion}}$$

Light sterile neutrino in the early universe



[P.Langacker, '89]

➢ For lage mixing

- ν_s can be thermal, and affects to BBN (N_{eff})
- The life-time of ν_s becomes too short to be dark matter

From cosmological and astrophysical observations, the mixing angle is constrained to be fairly small

The sterile neutrino with small mixing can be a good candidate for dark matter

$\tau_s > \tau_U \sim 13.7\times10^9$ years

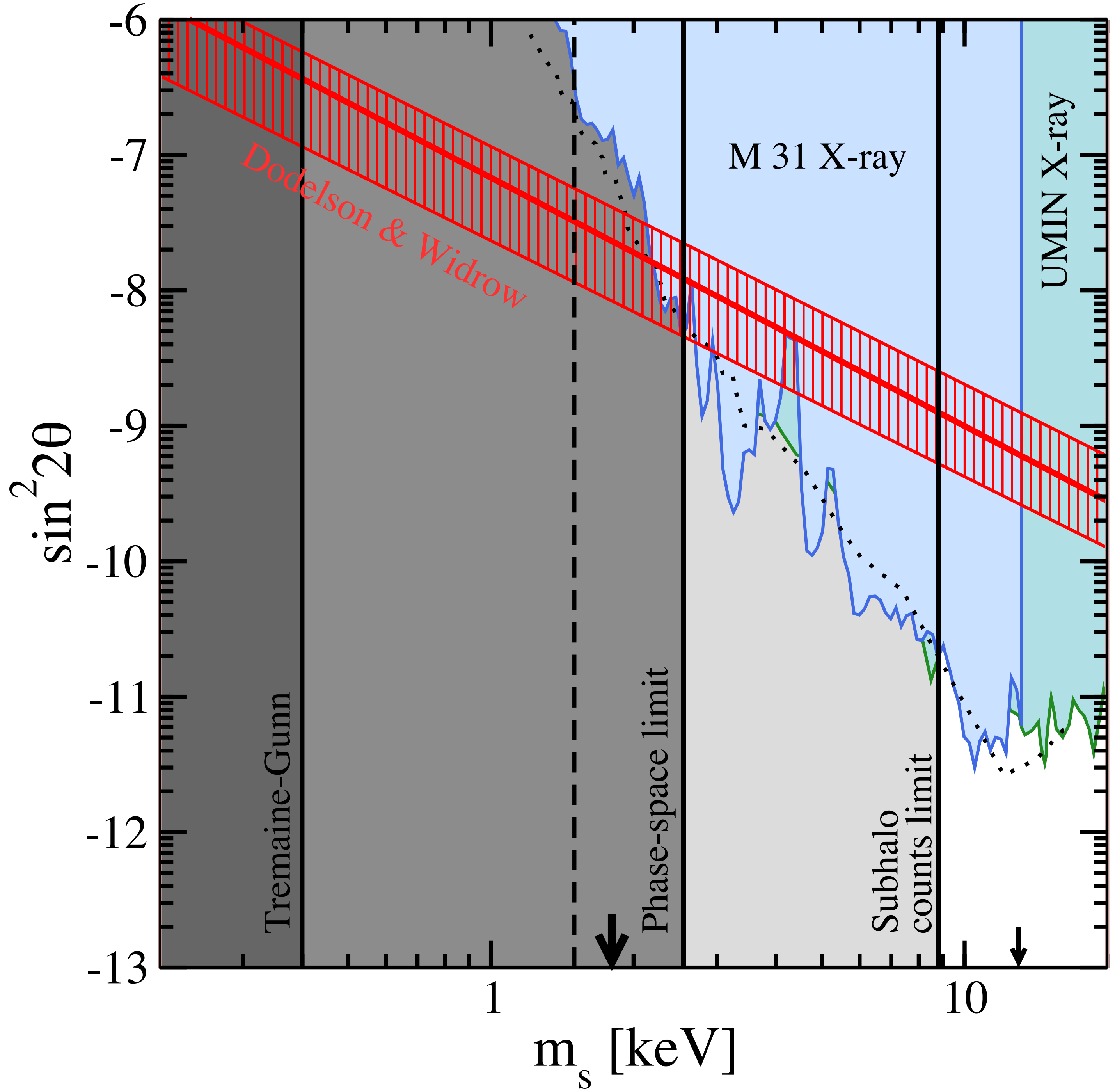
$\longrightarrow \sin^2(2\theta_1)/10^{-6} < (30\mathrm{keV}/M_1)$

For small mixing angle, the dark matter ν_s is non-thermally produced through the ν_a-ν_s oscillation [Dodelson, Widrow, '94]

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

[K.Abazajian, '06]

Astrophysical constraints (X-ray observations)

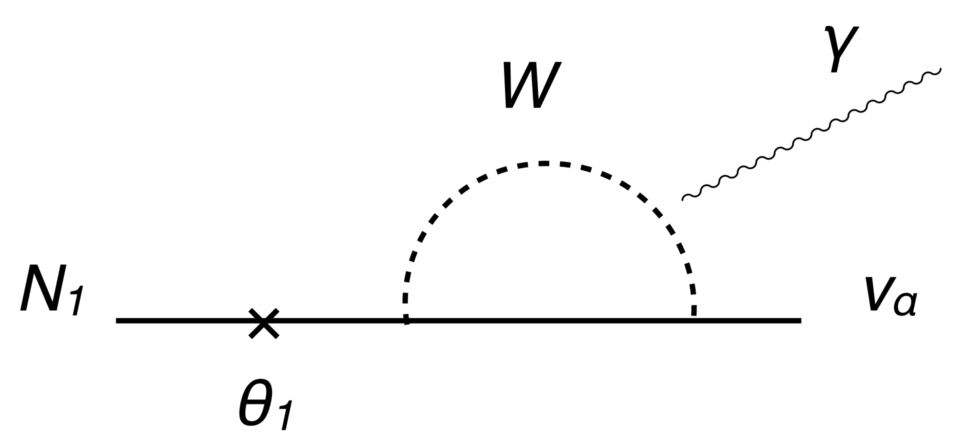


[Horiuchi, et al., '14]

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

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

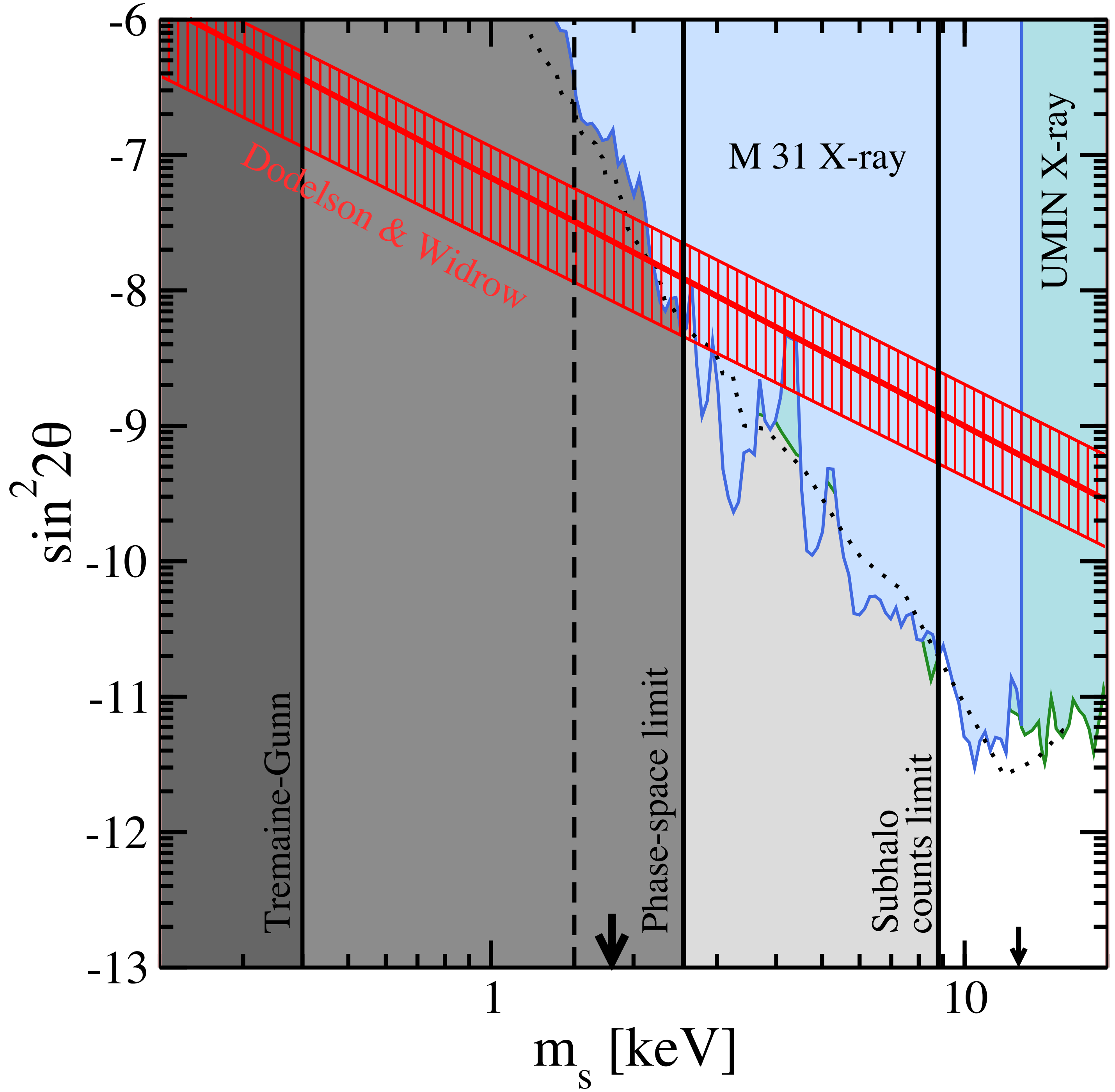
- The sterile neutrino is a long-lived particle, and emitting X-ray



$$\Gamma(N_1 \to \gamma\nu) \sim \theta_1^2 G_F^2 M_{N_1}^5$$

- Non-observation of such X-ray line gives constraints

Astrophysical constraints (phase-space density)



[Horiuchi, et al., '14]

- Astrophysical massive objects are surrounded by dark matter
- Fermionic dark matter phase-space density can not exceed the maximal value due to the Pauli principle
- Maximum phase density:

$$f_{\rm FD} = \frac{1}{\exp(-p/T)+1}$$

$$Q_{\rm FD}^{\rm max} \equiv \frac{\bar{\rho}}{\langle v^2 \rangle^{3/2}} \sim \frac{m_s^4}{(2\pi)^3}$$

(except for normalization)

- Demanding the observed phase density should be smaller than Q^{max}, a lower bound on the dark matter mass can be obtained

$$Q^{\rm obs} < Q_{\rm FD}^{\rm max}$$

Alternative DM production mechanism is necessary

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

2. Dark matter under the B-L gauge force

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

Our setup

➢ Lagrangian of the *UνMSM* is given by

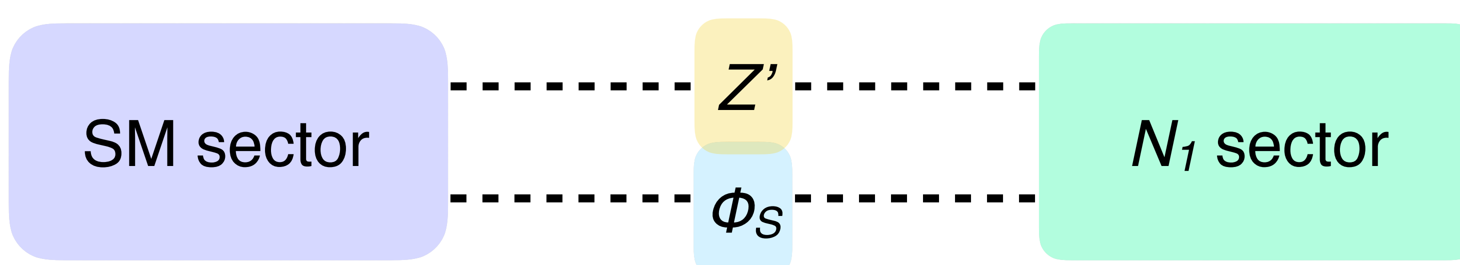
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}_i \not{D} N_i - \left(y_{\alpha i} \overline{L}_\alpha N_i \tilde{\Phi}_H + \frac{\kappa_i}{2} \Phi_S \overline{N_i^C} N_i + h.c. \right) + |D_\mu \Phi_S|^2 - V(\Phi_H, \Phi_S) - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}$$

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

➢ As Φ_S develops the vacuum expectation value, $<\Phi_S>=v_S$, 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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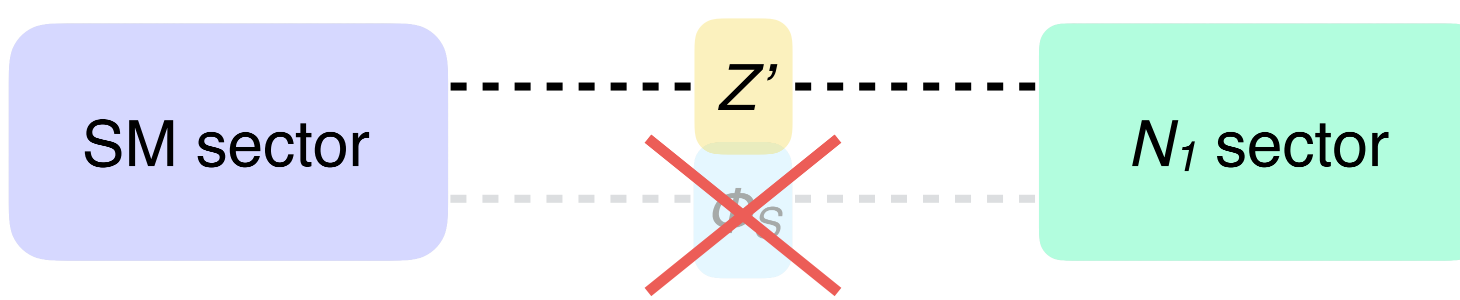


➢ To concentrate on the Z' effect, we turn off the Higgs portal coupling λ_{HS} (→0)

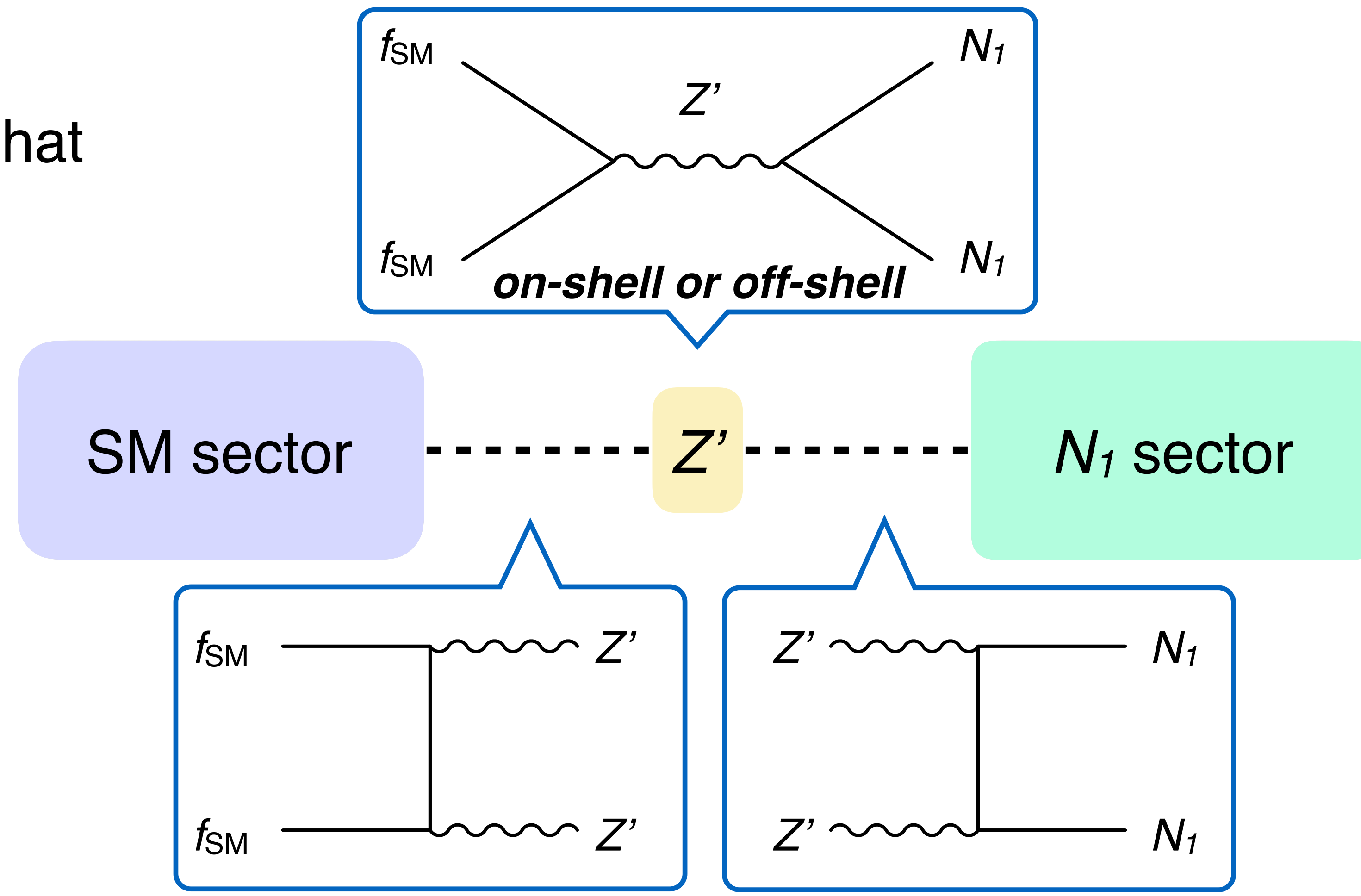
Relevant reactions for thermalization of N_1

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

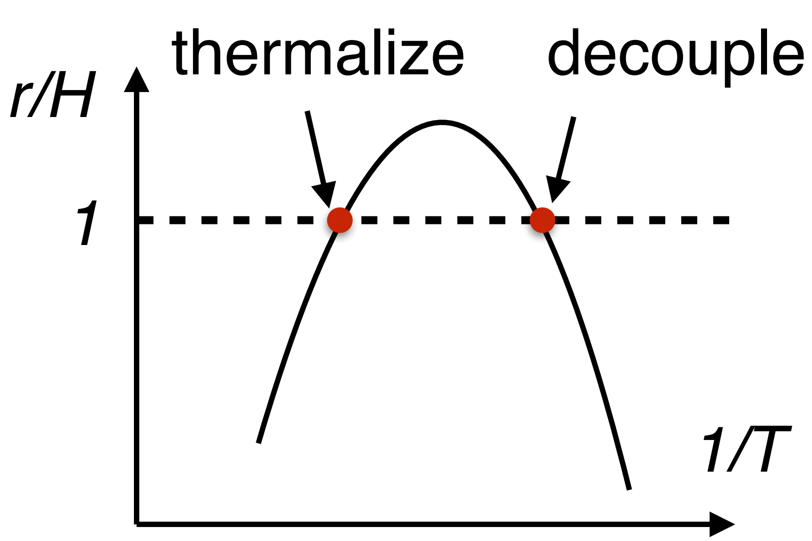
- Reaction rates:

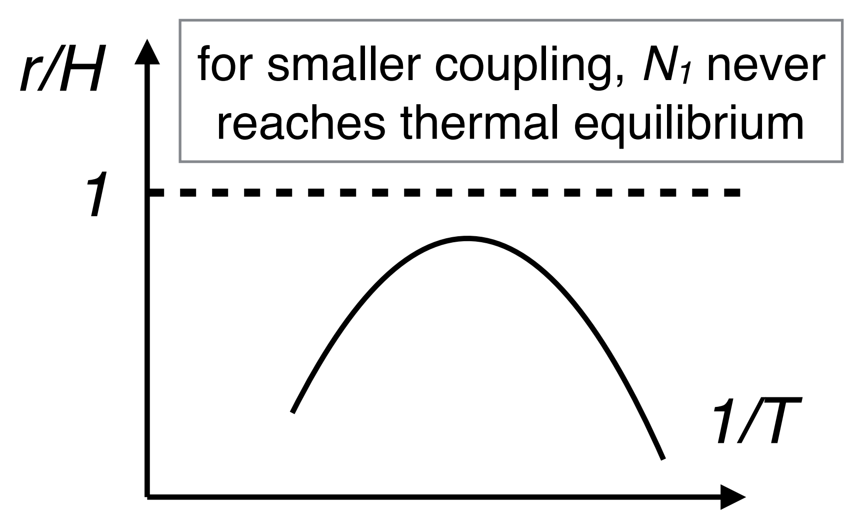
  $r(N_1 \leftrightarrow f_{SM})$, $r(N_1 \leftrightarrow Z')$, $r(Z' \leftrightarrow f_{SM})$

- 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*

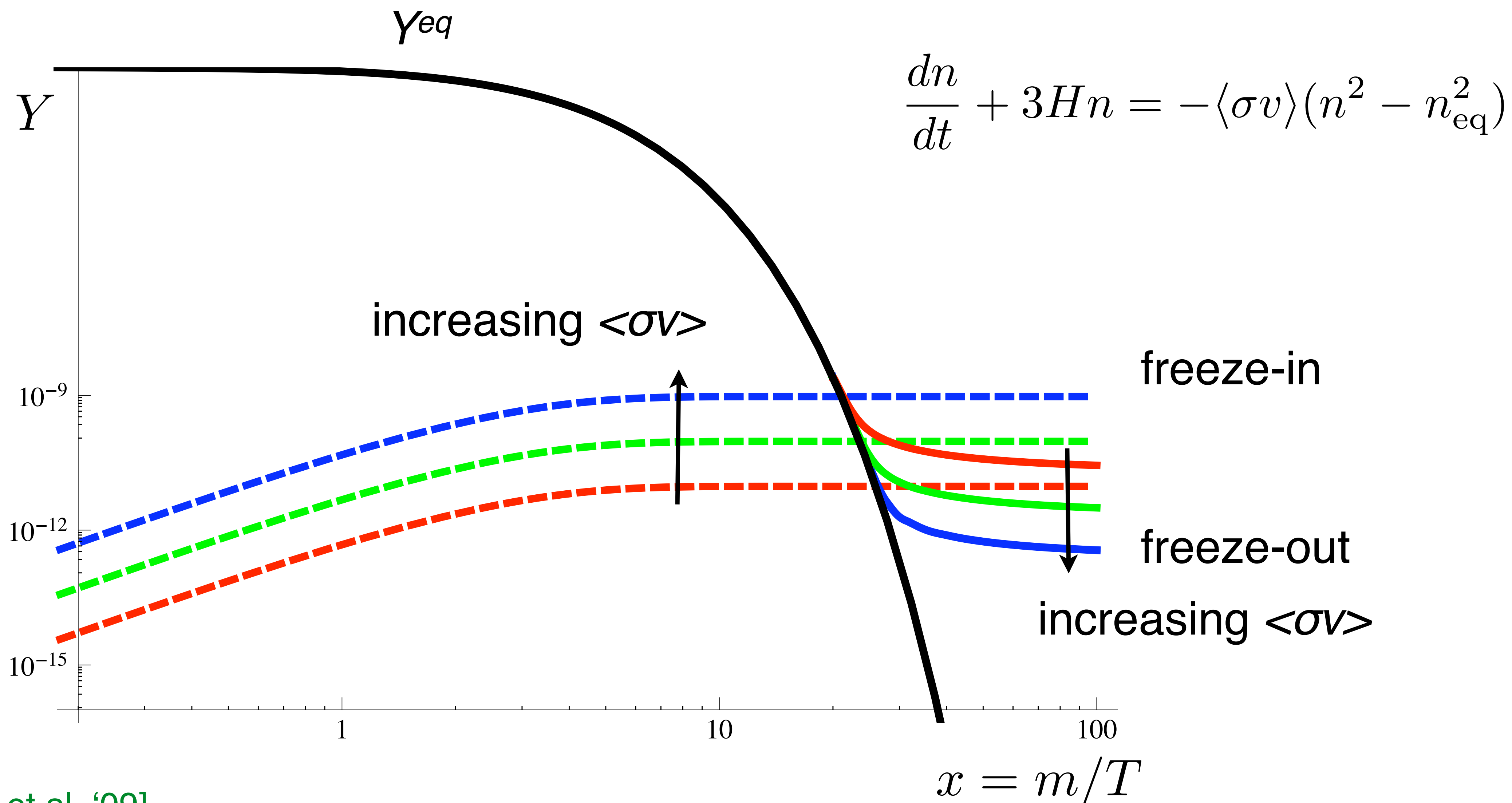




- Dark matter scenario drastically changes, depending on whether N_1 is thermalized or not.

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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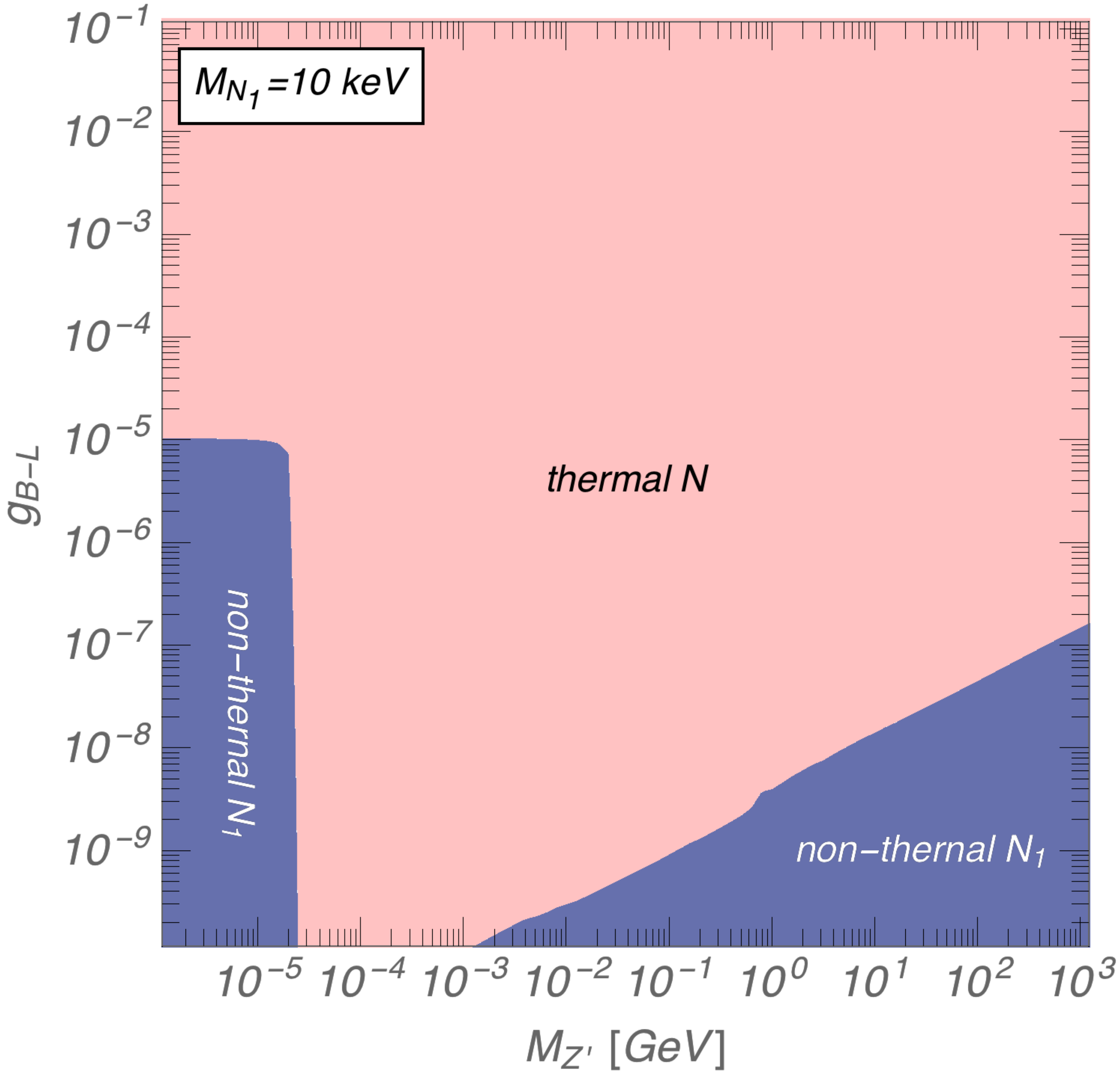

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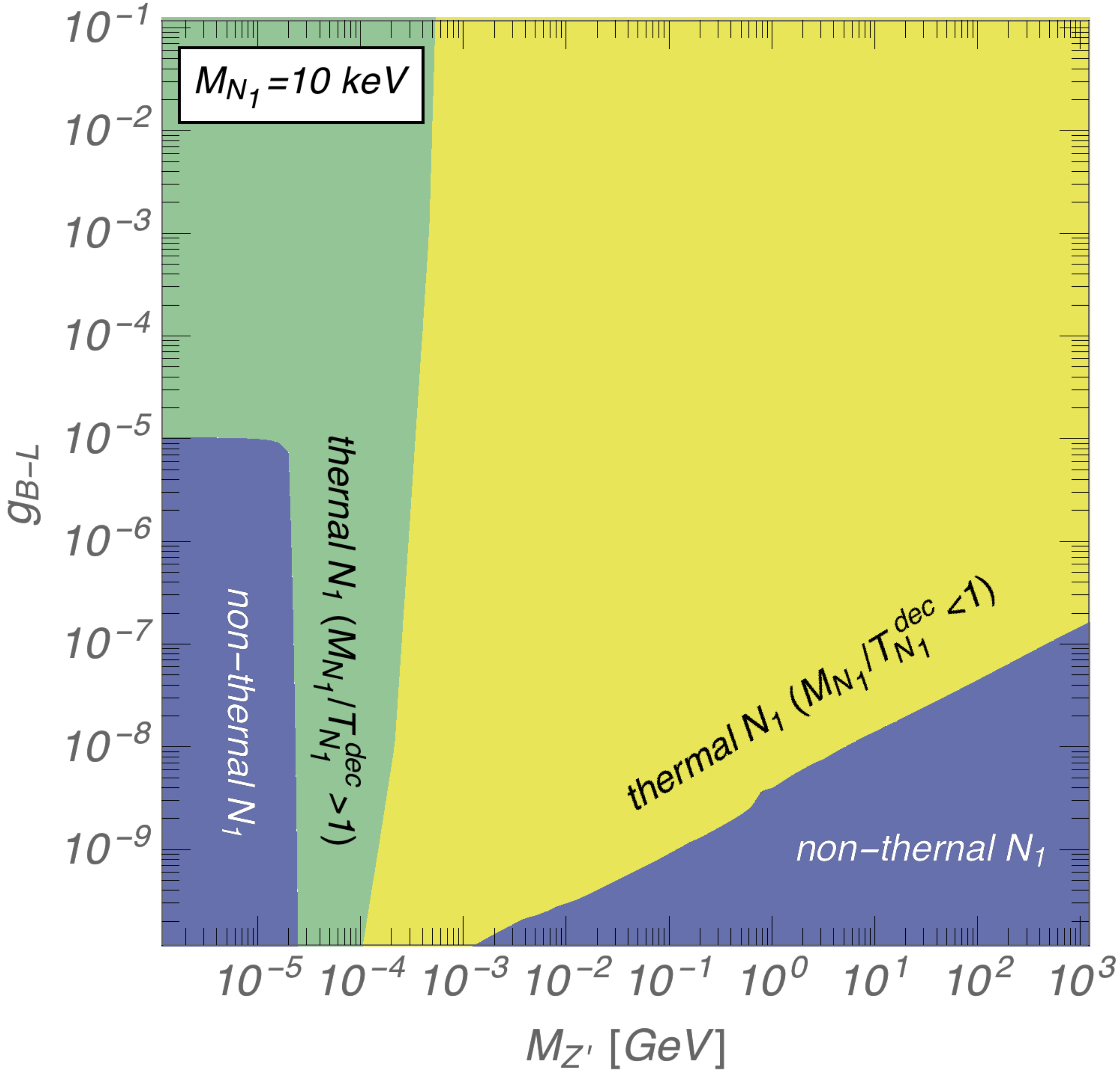

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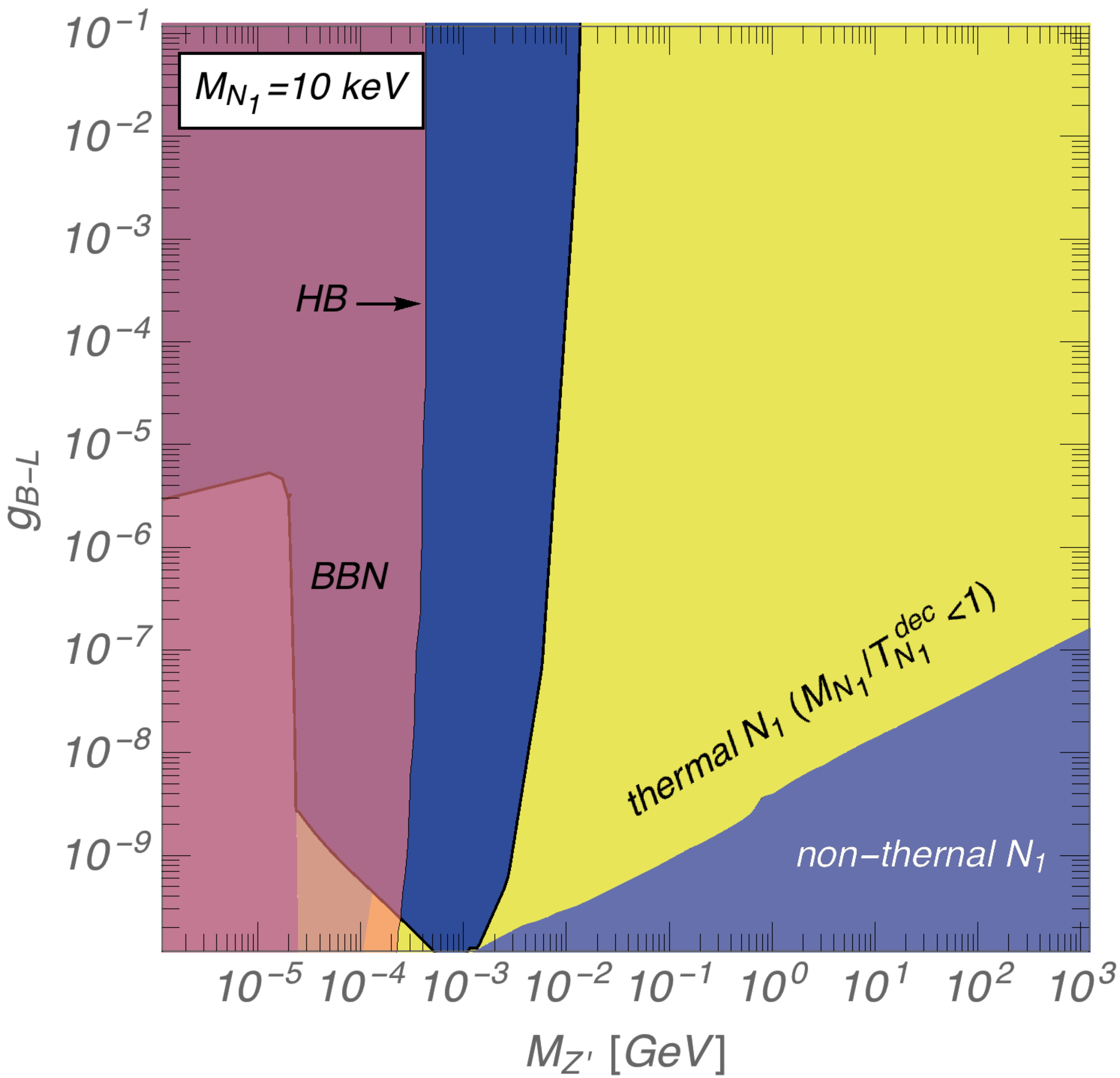

- Constraints from BBN and Horizontal Branch (HB) stars exclude non-rel. N_1

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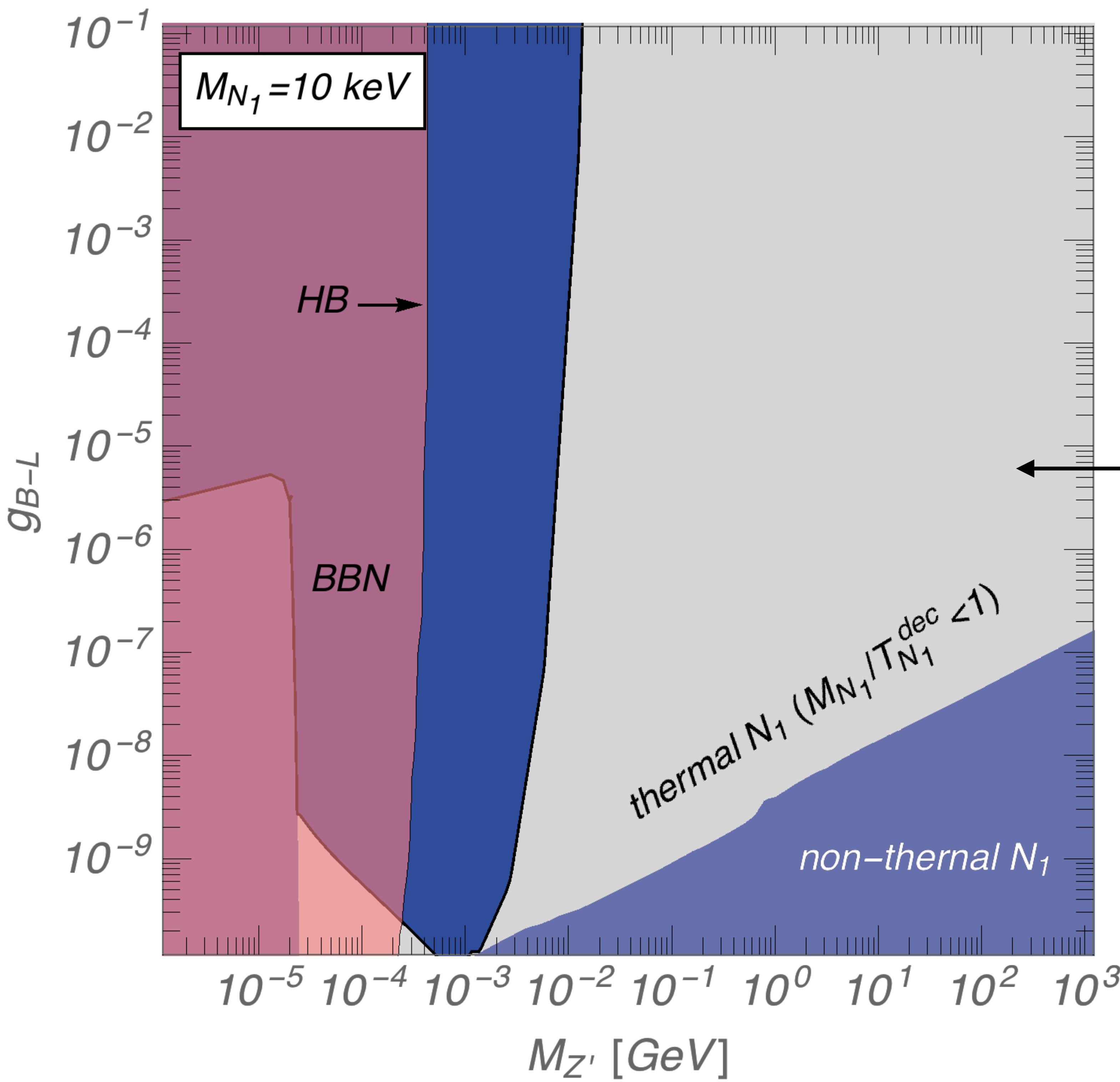

- Constraints from BBN and Horizontal Branch (HB) stars exclude non-rel. N_1
- In the thermal N_1 regions, N_1 is produced as a relativistic particle, so its abundance is overproduced:

$$\Omega_{N_1} h^2 = \frac{s_0 M_{N_1}}{\rho_c h^{-2}} \times \left.\frac{n_{N_1}}{s}\right|_{T_{N_1}^{\rm dec}}$$
$$\simeq 110 \times \left[\frac{M_{N_1}}{10\ \rm keV}\right] \left[\frac{10.75}{g_*(T_{N_1}^{\rm dec})}\right]$$

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

[Bezrukov, et al., '10]

N_1 production and relevant experimental constraints

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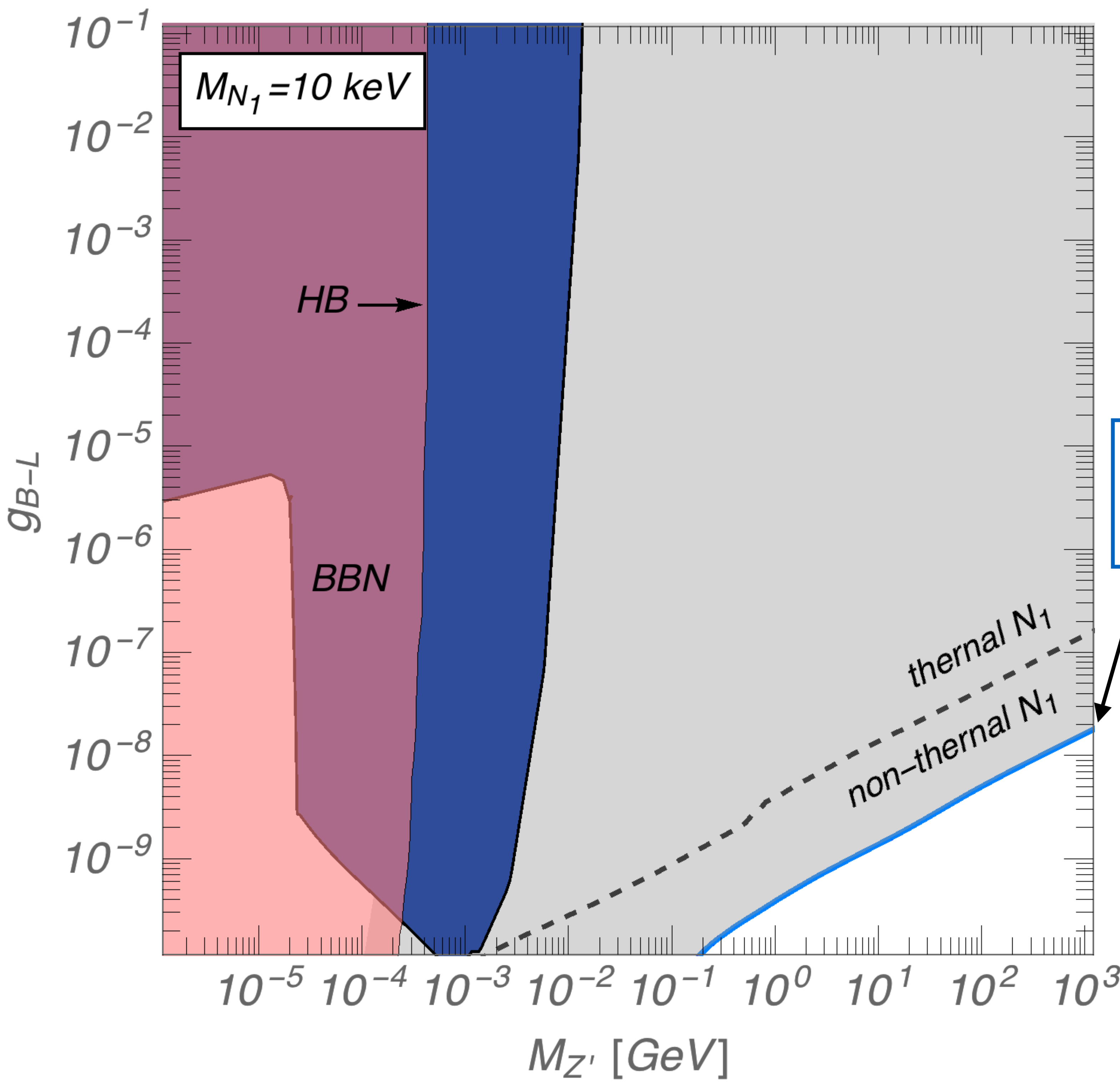

- In the non-thermal N_1 regions, N_1 is produced through

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

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

$$\Omega^{\rm nt}_{N_1} h^2 \simeq 0.12 \times \left[\frac{100}{g_*}\right]^{3/2} \left[\frac{g_{B-L}}{5.1 \times 10^{-12}}\right] \left[\frac{7}{C_f}\right] \left[\frac{f(\tau)}{0.19}\right]$$

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

$$f(\tau) = \tau(1-\tau^2)^{3/2} \qquad (\tau = 2M_{N1}/M_{Z'})$$

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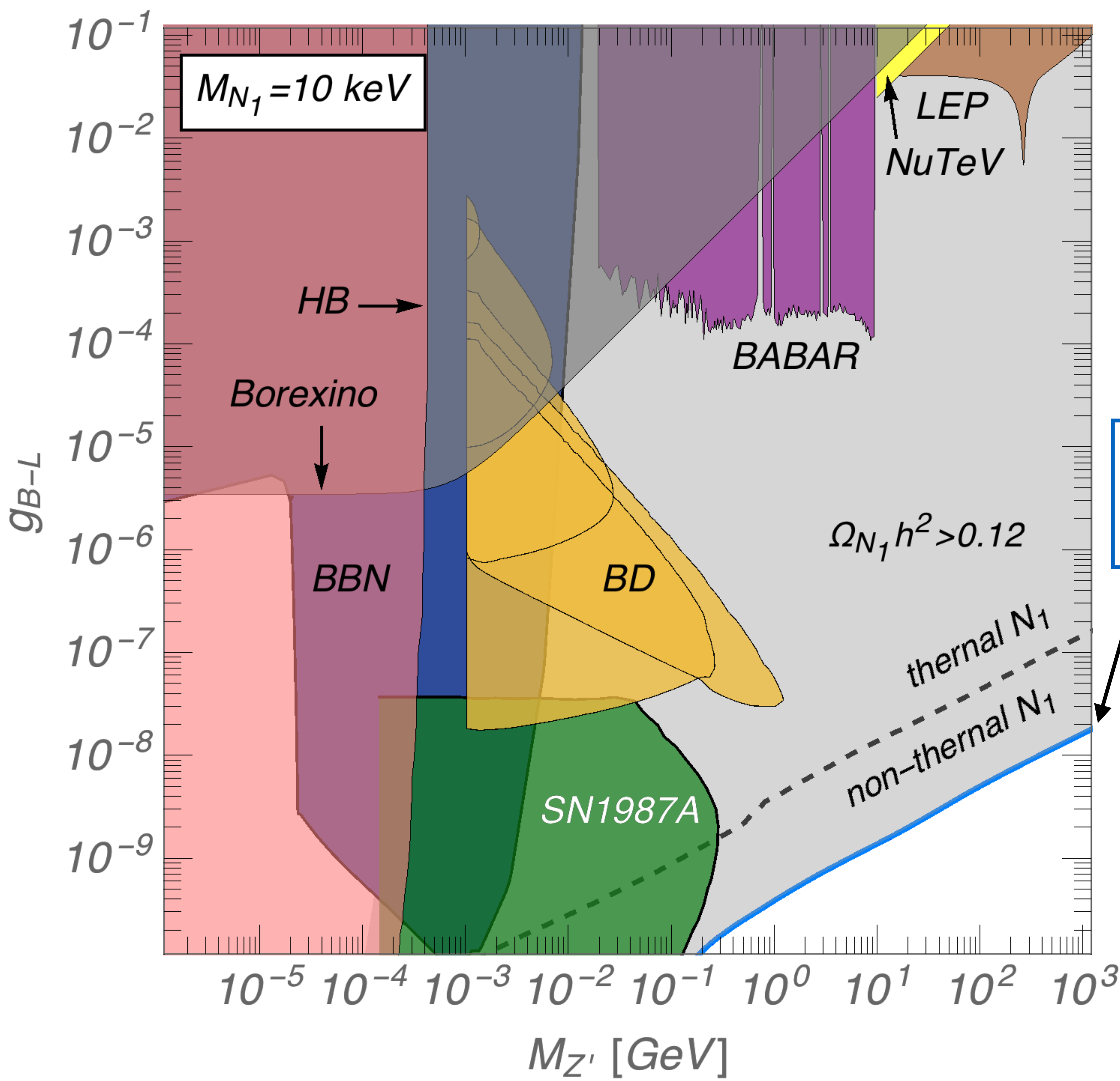

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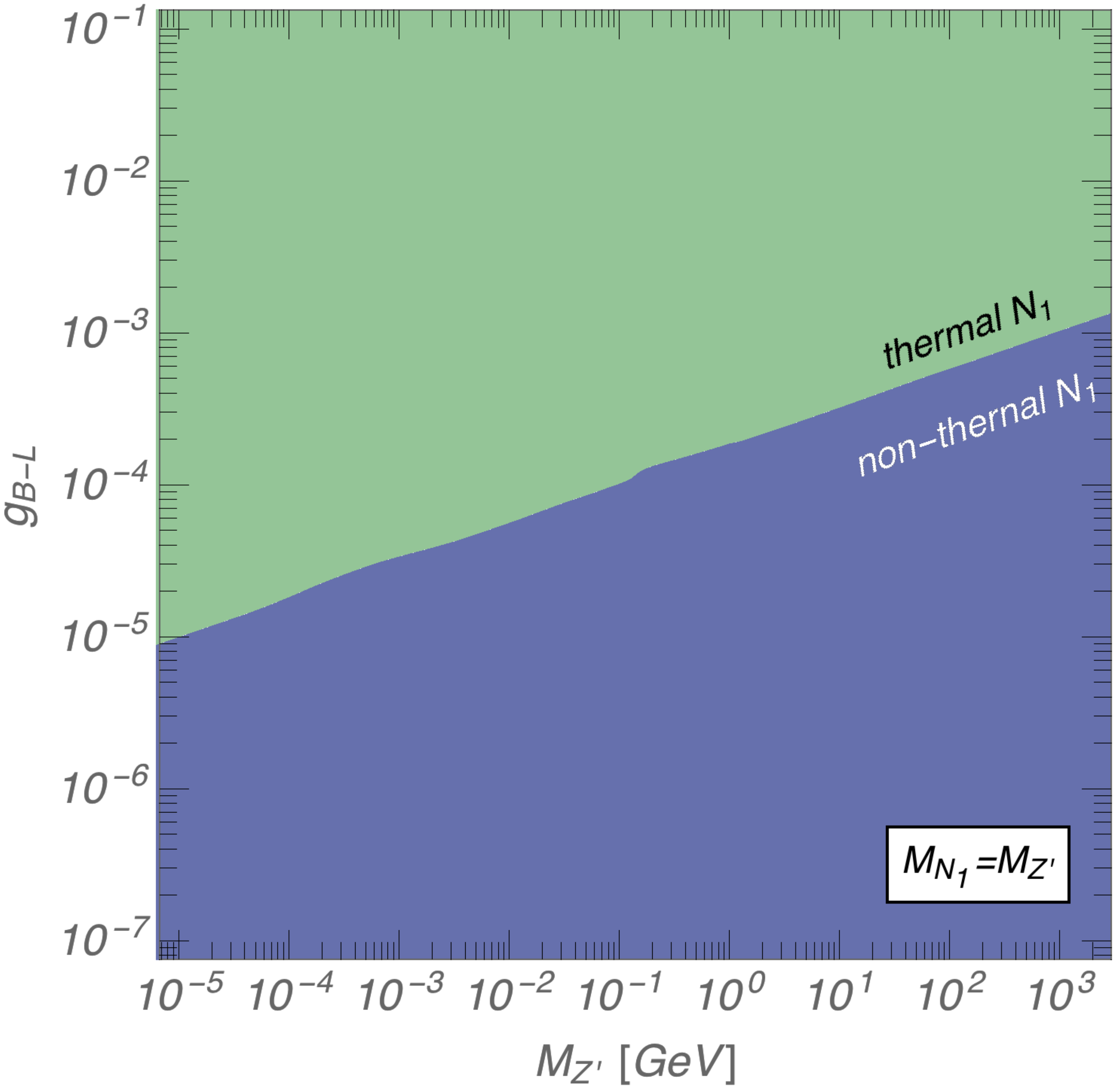
- putting all the relevant constraints

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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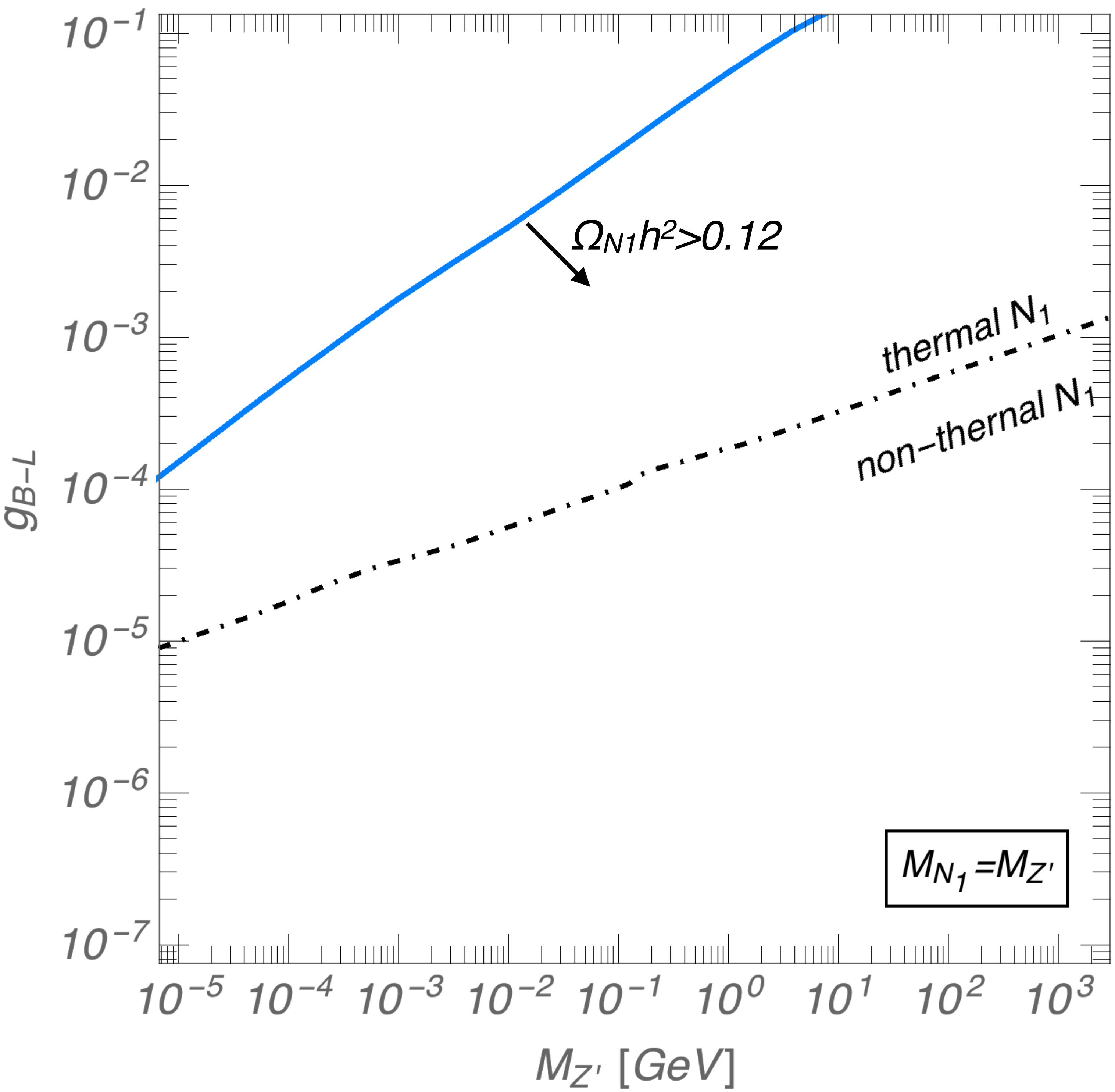

- For thermal N_1, N_1 is usual cold dark matter produced by freeze-out mechanism

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

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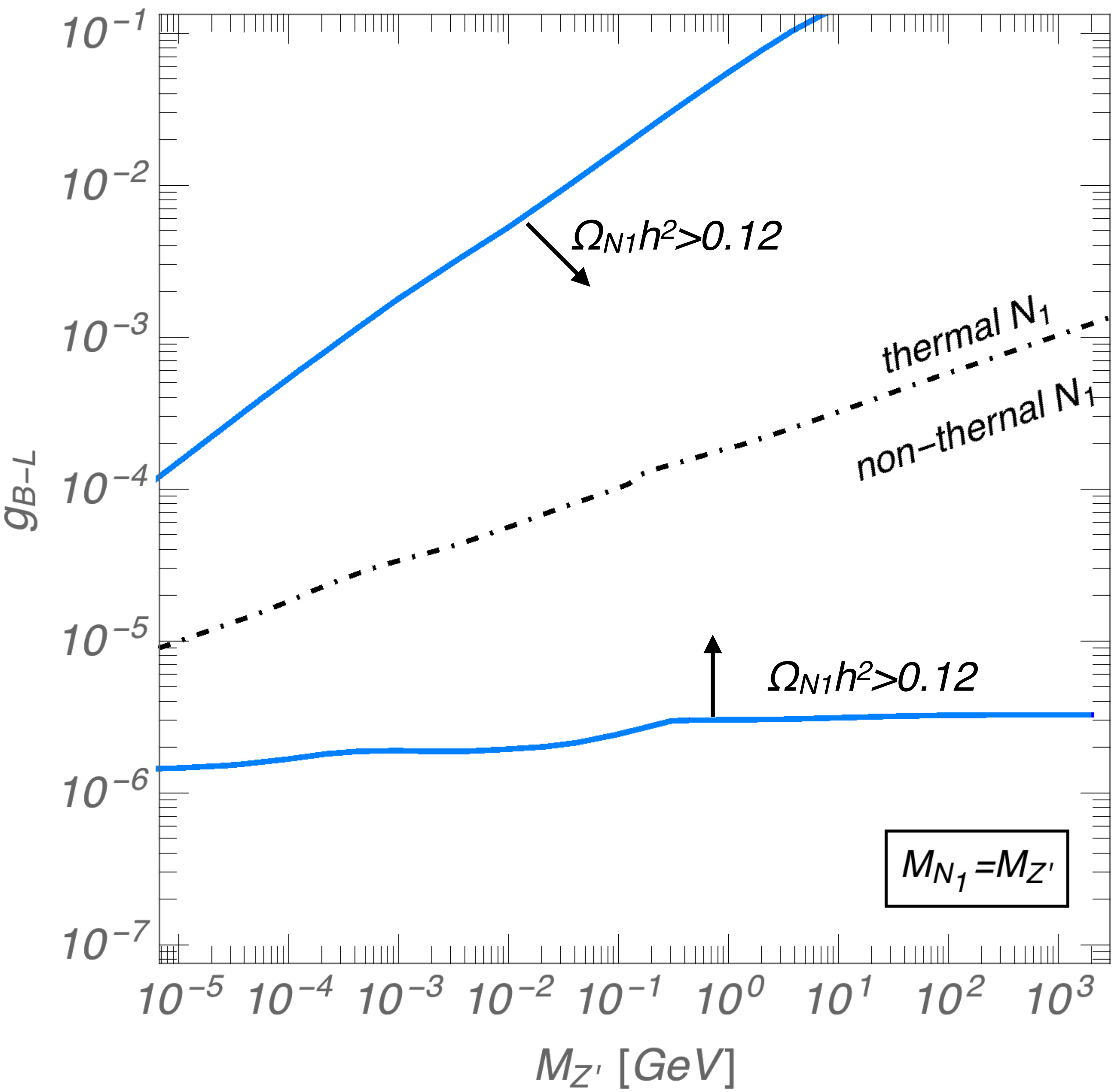

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$$\Omega^{nt}_{N_1} h^2 \simeq 0.12 \times \left(\frac{100}{g_*}\right)^{3/2} \left(\frac{g_{B-L}}{4.5\times 10^{-6}}\right)^4$$

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

N_1 production and relevant experimental constraints

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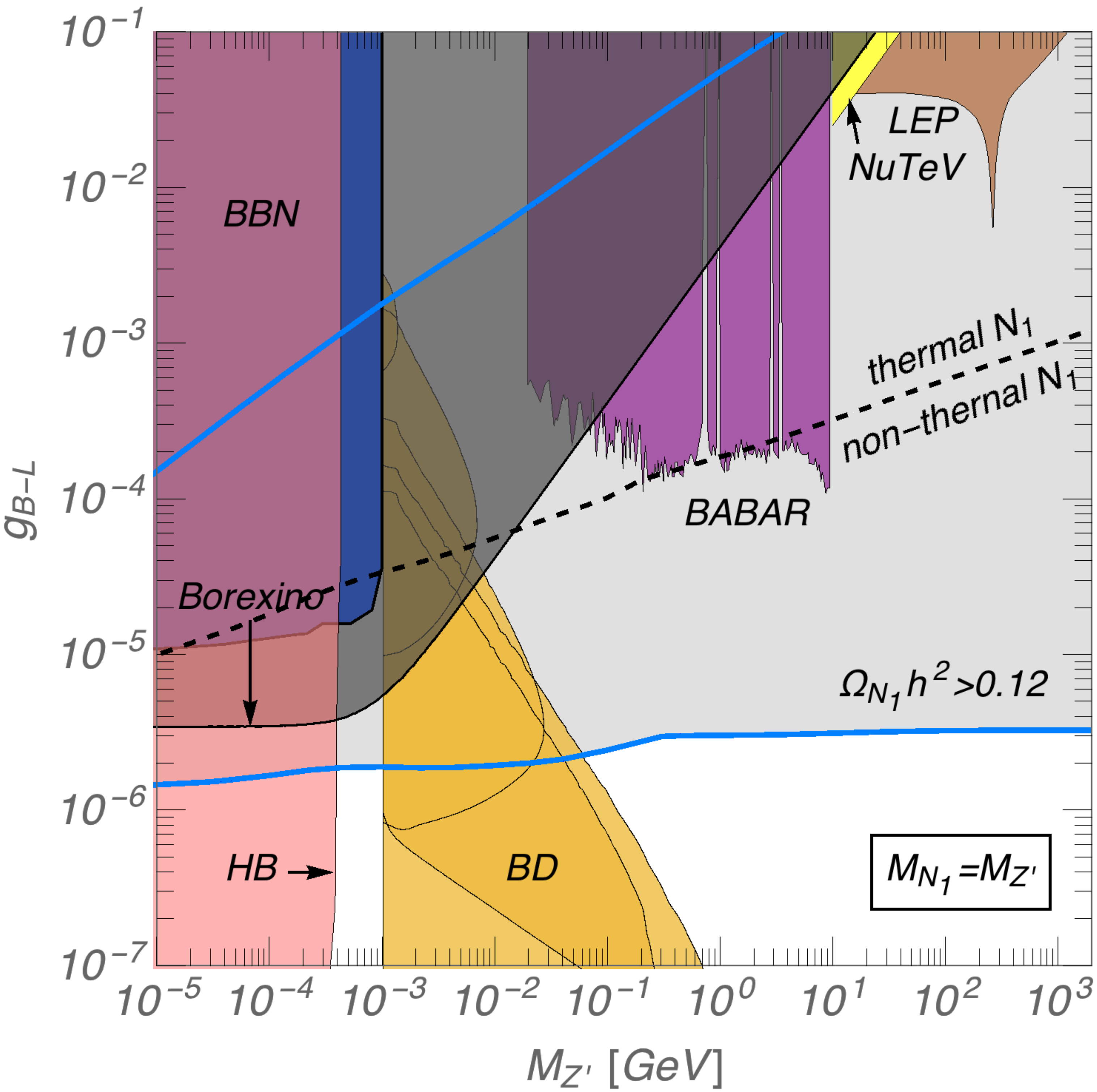

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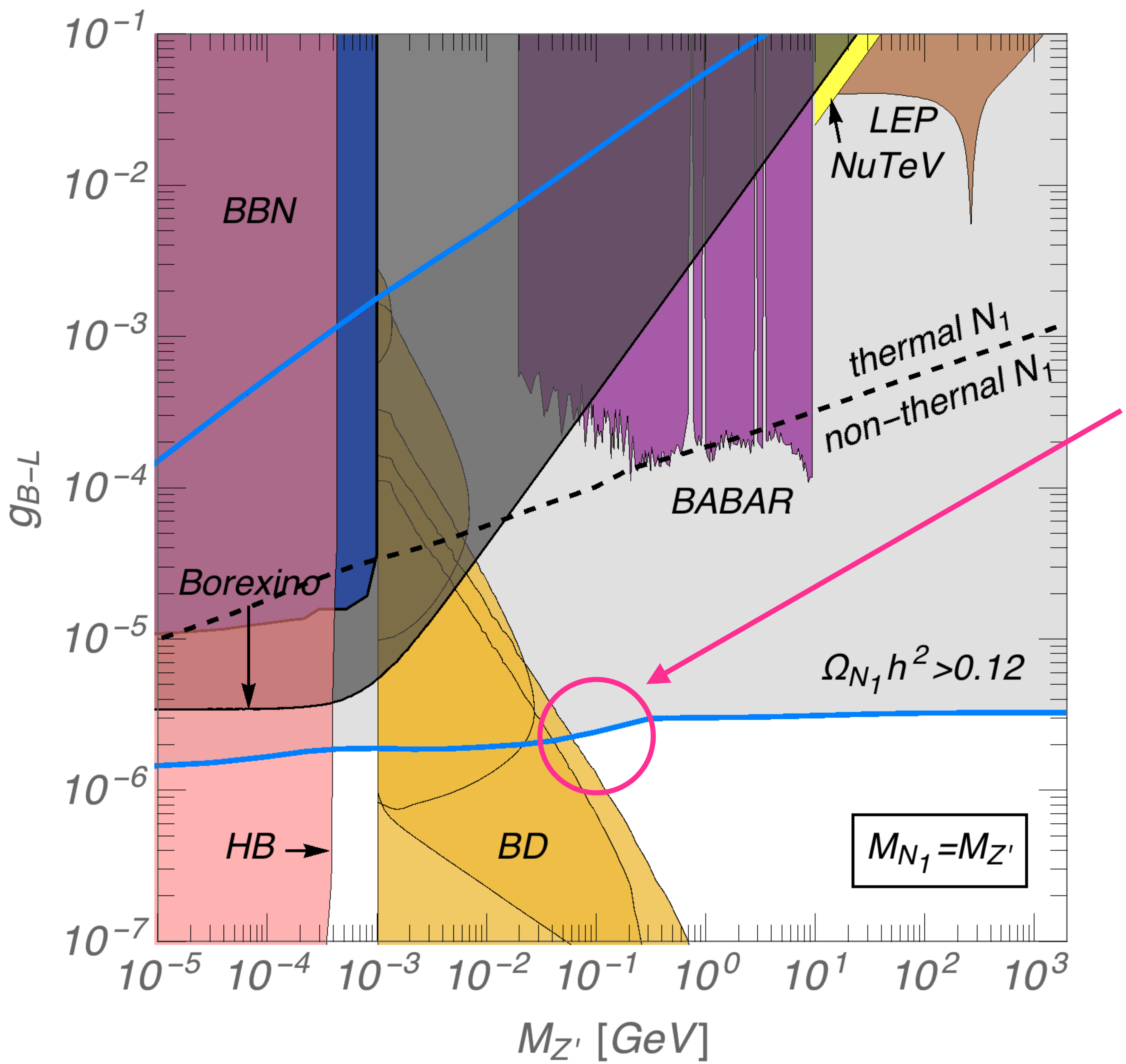
- Relevant experimental constraints

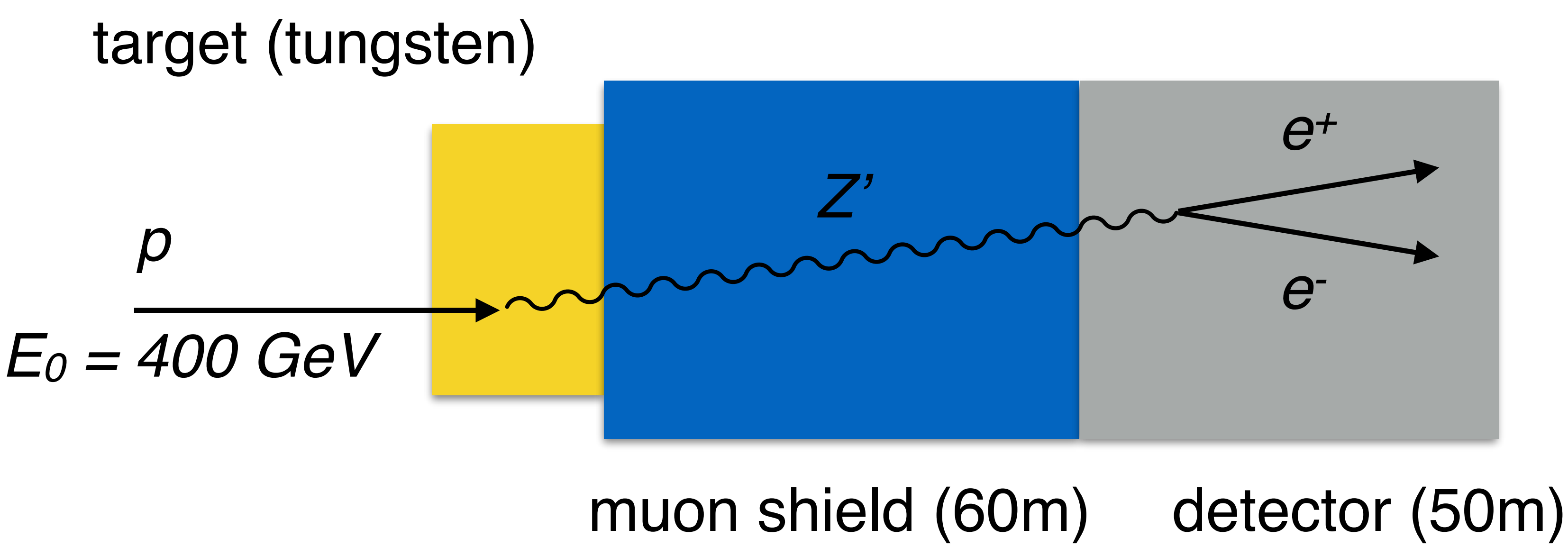
3. Implications



Beam dump experiments can test this region

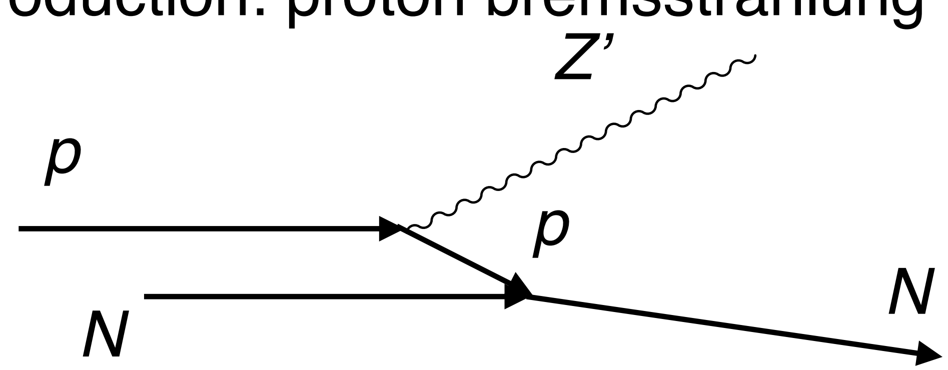
The Search for Hidden Particles (SHiP) experiment

- 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: $N_{sig} \sim N_{POT} \times R_{prod} \times P_{det}$

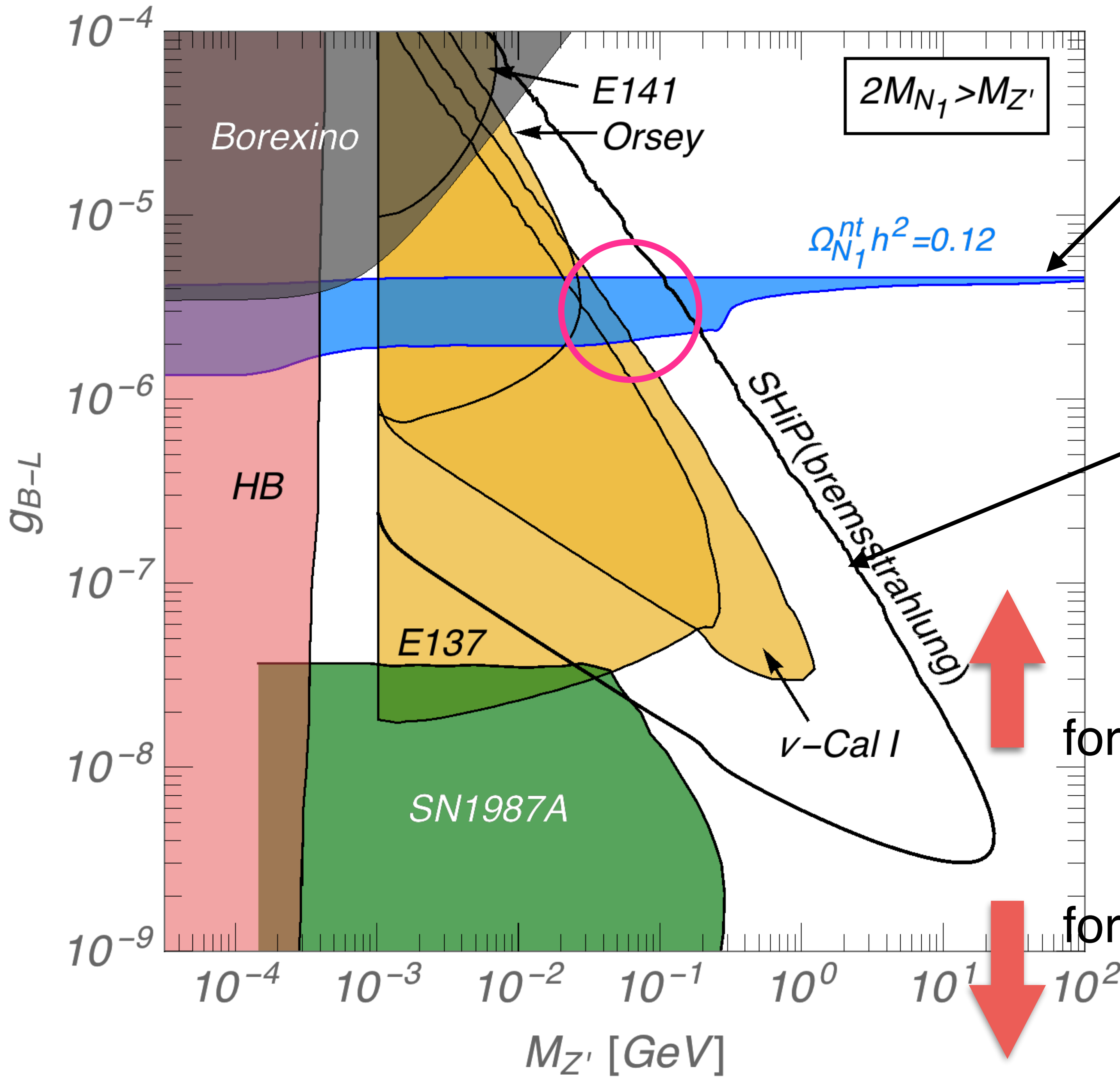
  - *Z'* production: proton bremsstrahlung



  - 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

The Search for Hidden Particles (SHiP) experiment



- Freeze-in N_1

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

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

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' lifetime becomes shorter

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

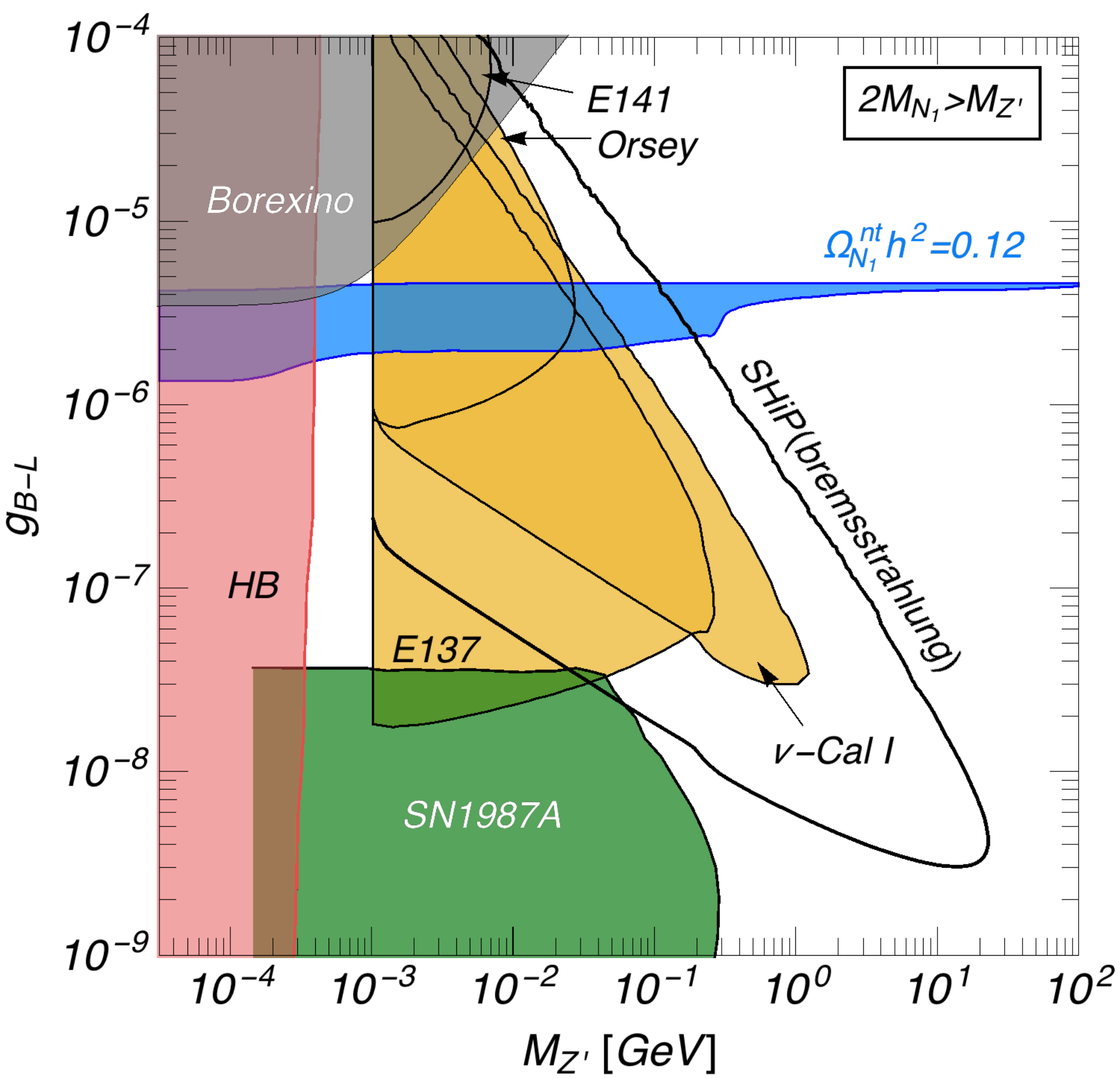
- SHiP will be able to cover:

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

The Search for Hidden Particles (SHiP) experiment

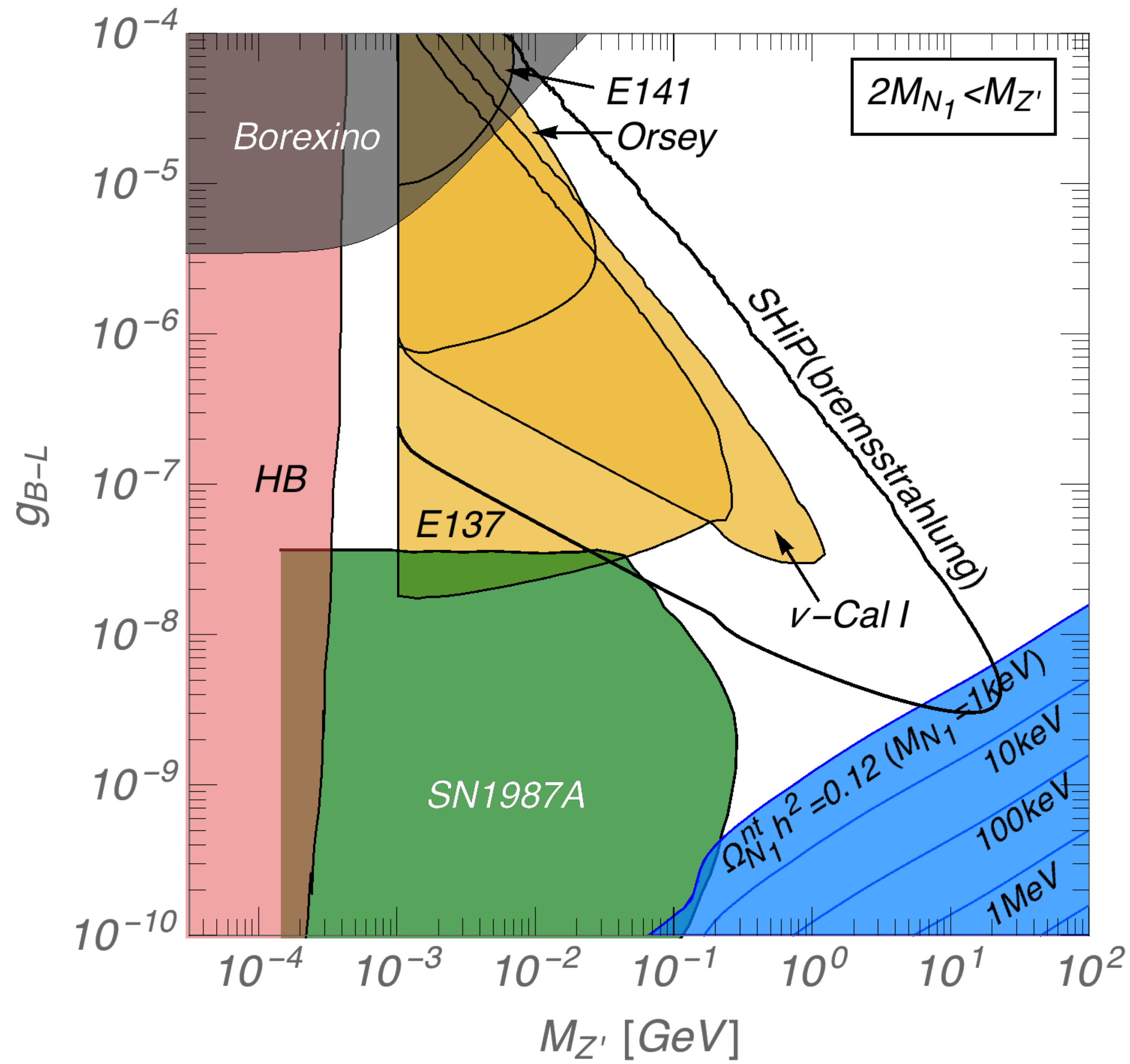
➢ $2M_{N1} > M_{Z'}$

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



➢ $2M_{N1} < M_{Z'}$

$$\Omega^{\rm nt}_{N_1} h^2 \simeq 0.12 \times \left[\frac{100}{g_*}\right]^{3/2} \left[\frac{g_{B-L}}{5.1\times 10^{-12}}\right] \left[\frac{7}{C_f}\right] \left[\frac{f(\tau)}{0.19}\right]$$



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

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

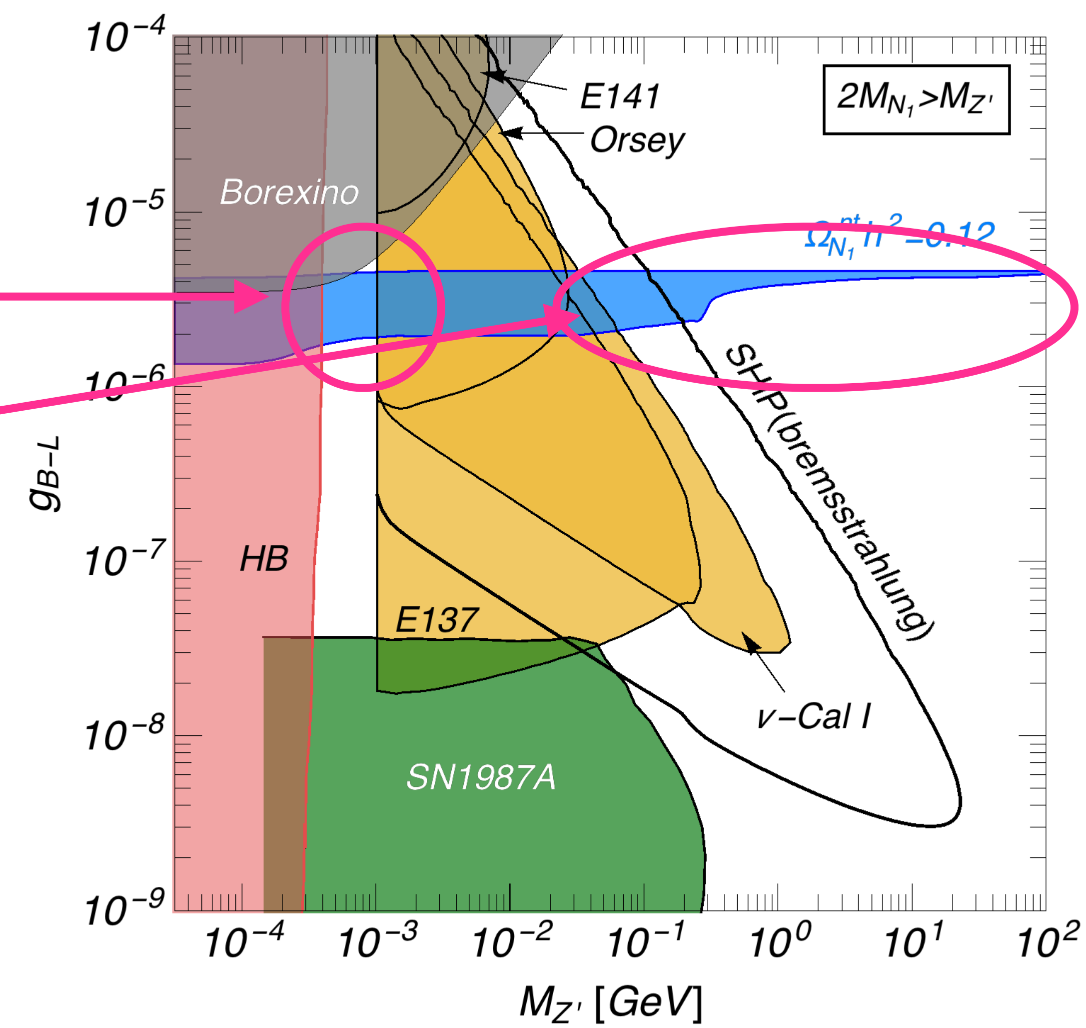
➢ This leads to

(taking $\lambda_S = 4\pi$)

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

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

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



Summary

- ➤Recent observations disfavor the simple production mechanism for sterile neutrino dark matter (DW mech.) in the νMSM.

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

- ➤ Forthcoming beam dump experiment can (partly) test the freeze-in scenario.