Leptogenesis from magnetic helicity of gauged $U(1)_{B-L}$

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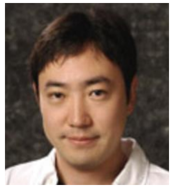


We were invited to Thanksgiving dinner at Hitoshi's house. Unfortunately, nobody can find the photo···

Updated on May 26, 2024

- We had a workshop, ”Berkeley week” at Hongo this March.

- Hitoshi initiated the workshop, and

I was the main local organizer. We worked together for the workshop. It was a great fun and I would like to have the workshop again someday soon.

- After organizing the workshop, I had realized that the success of IPMU is not only attributed to Hitoshi, but also to excellent secretaries. I would like to thank Hitoshi and all those concerned for the success of IPMU!

OK, let’s move on to physics.

My memory on leptogenesis

- When I was a first-year master course student, Fujita-san and Tada-san, together with Namba-san and Takeda-san, offered me to start a collaboration on leptogenesis
- Back then, it was a good practice among Hitoshi's students for senior ones to mentor younger ones
  - I was very well taken care of by the senior students then: Fujita-san, Harigaya-san, Tada-san and Matsuda-san.
  - It was probably due to Hitoshi’s charisma that such excellent senior students had been at IPMU!

Gravi-leptogenesis

Alexander, Peskin, Sheikh-Jabbari, 2006

- Our goal then was to understand the gravi-leptogenesis mechanism
- The standard model $U(1)_{B-L}$ current has a U(1)-gravity-gravity anomaly:

$$\partial J_{B-L} = \frac{3}{16\,\pi^2} R\tilde{R}$$

- Chiral GWs can be produced during axion inflation
- Therefore, the B-L charge is simultaneously produced during axion inflation

Failure of gravi-leptogenesis

- However, Tada-san and Takeda-san had found that this mechanism does not work well with axion inflation
  - The point was,

$$\partial J_{B-L} \sim H_{inf} \Delta n_{B-L}, \qquad R\tilde{R} \sim H_{inf}^4 h^2,$$

  and thus

$$\rho_{\rm grav} \sim M_{Pl}^2 H_{inf}^2 h^2 \sim 100 \left(\frac{n_{B-L}}{s}\right) M_{Pl}^3 T_{Re}$$

  which is too large, unless the reheating temperature is very high.
- We eventually gave up to create leptons in this way.

10 years have passed…

- This February, I was chatting with Kohei and Thanaporn.
- I suddenly recalled that the SM B-L current also has an 't Hooft anomaly:

$$\partial J_{B-L} = \frac{3}{16\,\pi^2} R\tilde{R} - \frac{3\alpha_{B-L}}{4\pi} X\tilde{X},$$

where X is the B-L gauge boson and α is the fine structure constant.

- Then I realized that we can create leptons using the 't Hooft anomaly, assuming that the B-L is gauged

Gauging B-L

- To promote the B-L symmetry to the local symmetry, we have to cancel the anomaly.
- The gravitational and 't Hooft anomaly can be cancelled by adding three generations of right-handed neutrinos:

$$\partial J_N = -\frac{3}{16\,\pi^2} R\tilde{R} + \frac{3\alpha_{B-L}}{4\pi} X\tilde{X} \boxed{+\cdots} \Rightarrow \partial(J_{B-L} + J_N) = 0,$$

Interactions with the SM: we do not specify it for the time being.

- Since there's no long-range force now, the B-L symmetry must be Higgsed at some higher scale.

B-L charge generation

- How does the anomaly generate B-L charges?
- Integrating the anomaly formula over space,

$$\partial J_{B-L} = -\frac{3\alpha_{B-L}}{4\pi} X\tilde{X} \quad \Rightarrow \quad \frac{d}{dt}\left(\int d^3x \; n_{B-L} + \frac{3\alpha}{4\pi}\int d^3x \; X \cdot B_X\right) = 0$$

B-L charge   B-L magnetic helicity

- Therefore, (perturbatively,) the sum of the SM B-L charge and the B-L magnetic helicity is conserved
  - If the helicity is produced, the B-L charge is simultaneously produced

Generation of B-L helicity

- The magnetic helicity is, roughly, the difference of positively and negetively circular-polarized photon amplitude:

$$\int d^3x\ X \cdot B_X \sim \left|\vec{k}\right| \left(|X_+|^2 - |X_-|^2\right)$$

- Thus, it can be created during the axion inflation:

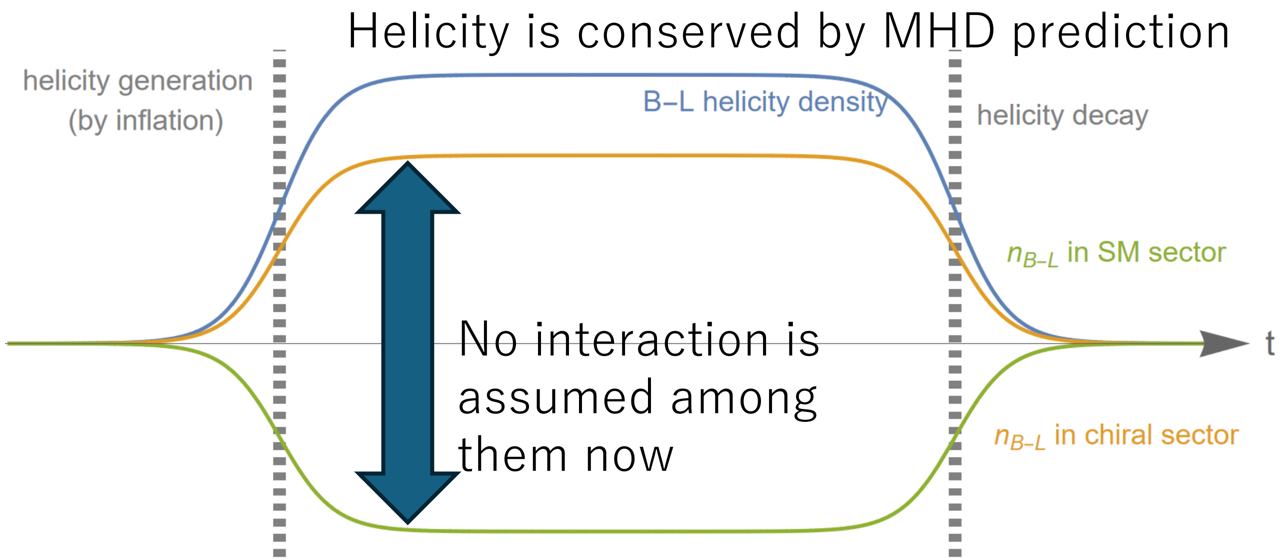
$$\mathcal{L} \sim \frac{1}{2}(\partial a)^2 - \frac{m^2}{2}a^2 - \frac{g_{aXX}}{2}aX\tilde{X}$$

  - X eom has a tachyonic mode with $\dot{a} \neq 0$ and one of the polarization mode is enhanced

Anber, Sorbo 2006

Fate of the B-L helicity

- Let’s assume the sum is initially zero. The RHN B-L charge is then equivalent to the final helicity. The SM B-L charge is just opposite
- As the B-L symmetry is Higgsed now, the B-L helicity is zero today



B-L charges vanish as well

SM-RHN interactions

- SM-RHN Interactions preserves the total B-L charge, but not each B-L charge

$$\partial J_{B-L} = \frac{3}{16\,\pi^2} R\tilde{R} - \frac{3\alpha_{B-L}}{4\pi} X\tilde{X} + \cdots$$

$$\Rightarrow \frac{d}{dt}\left(\int d^3x\ n_{B-L} + \frac{3\alpha}{4\pi}\int d^3x\ X\cdot B_X\right) \neq 0$$

e.g. Weinberg op, which comes from SM-RHN interactions!!

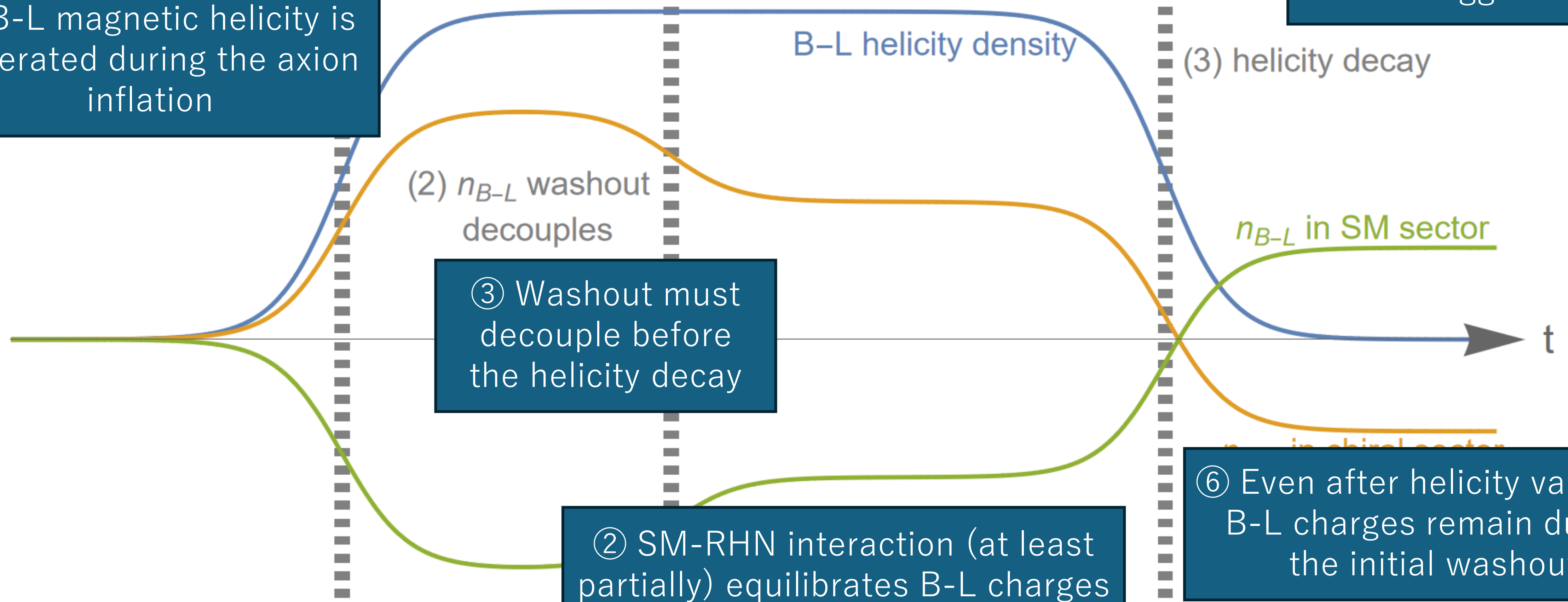
- SM-RHN interactions are nothing but “B-L washout” interactions after B-L breaking

Our scenario

④ By the MHD prediction, the helicity can be conserved in the early universe

⑤ We found helicity decays just after B-L is Higgsed

① B-L magnetic helicity is generated during the axion inflation



③ Washout must decouple before the helicity decay

② SM-RHN interaction (at least partially) equilibrates B-L charges

⑥ Even after helicity vanishes, B-L charges remain due to the initial washout

HF, Kamada, Sichanugrist, 2024

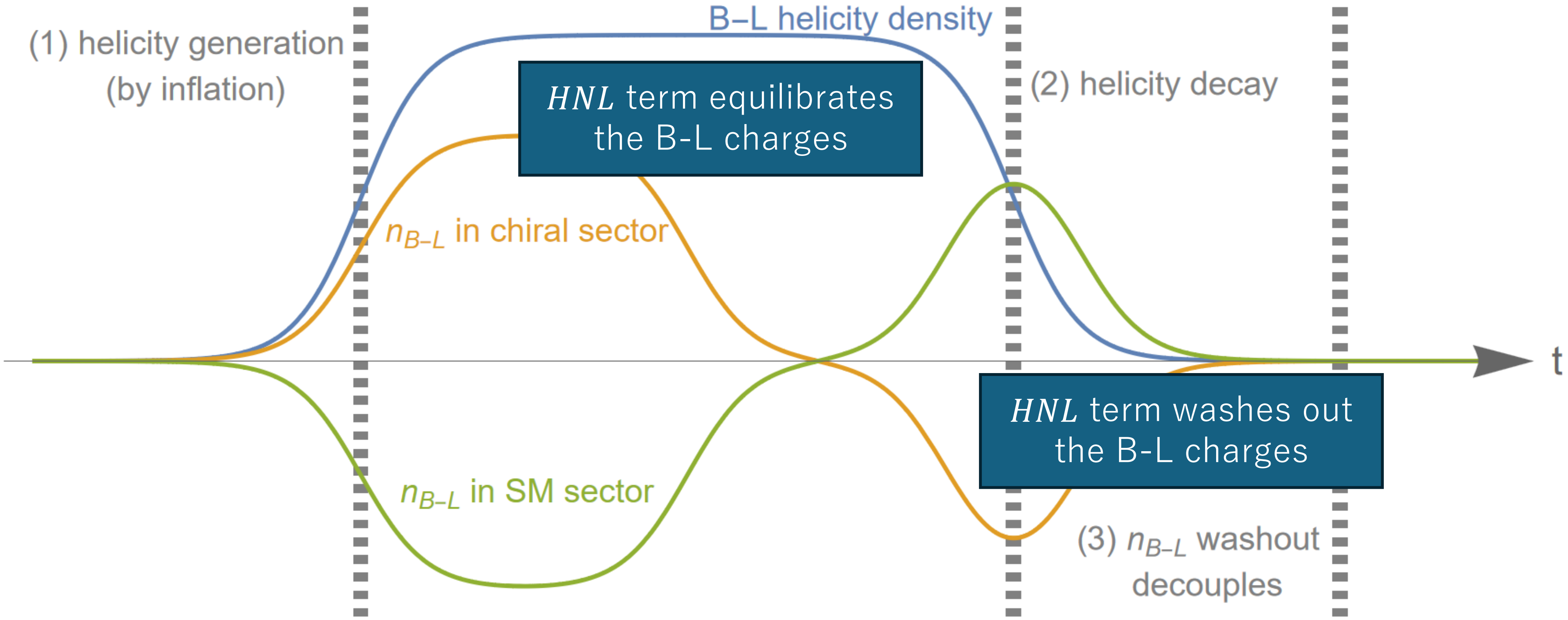
Right-handed neutrino interactions

- Now we would like to check if the previous scenario works for models of right-handed neutrino interaction
- As examples, we consider following cases:
  - SM neutrinos have Majorana masses:
    - $\Delta\mathcal{L} \sim y_S HNL + \frac{1}{2} y_N \Phi N^2, \quad y_s \sim 10^{-3}$
  - SM neutrinos have Dirac masses:
    - $\Delta\mathcal{L} \sim y_S HNL, \quad y_s \lesssim 10^{-12}$

Case 1: Majorana neutrino

- $\Delta\mathcal{L} \sim y_S HNL + \frac{1}{2} y_N \Phi N^2,\ y_s \sim 10^{-3}$
- Interactions are so large that B-L charges in the SM and RHN sectors can be completely equilibrated
- The question is whether the equilibrating interaction decouples before the helicity decays
- We evaluated the MHD equations and found that helicity decays much before the right-handed neutrinos decouple if the B-L phase transition is of 2nd order
- The B-L charge is thus rapidly washed out

Case 1: Majorana neutrino

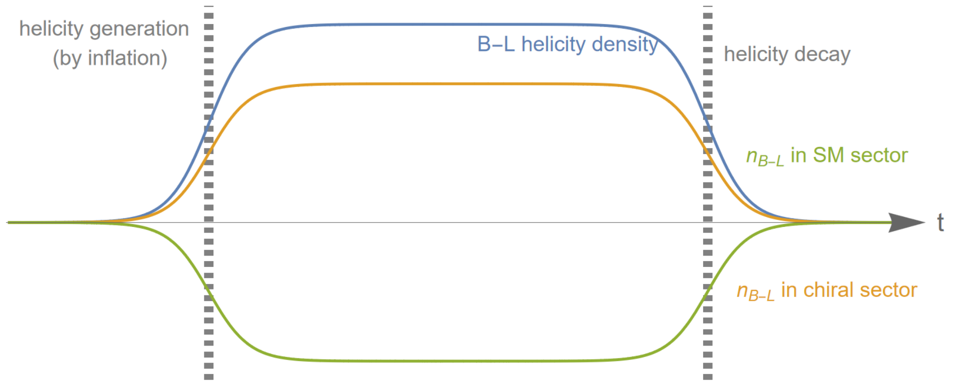


Case 2: Dirac neutrino

- $\Delta\mathcal{L} \sim y_s H N L, \quad y_s \lesssim 10^{-12}$
- The SM sector and the RHN sector are completely decoupled
- Thus, the model does not work by itself
- However, higher dimensional operators such as

$$\Delta\mathcal{L} \sim \frac{1}{\Lambda^2}(NL)^2$$

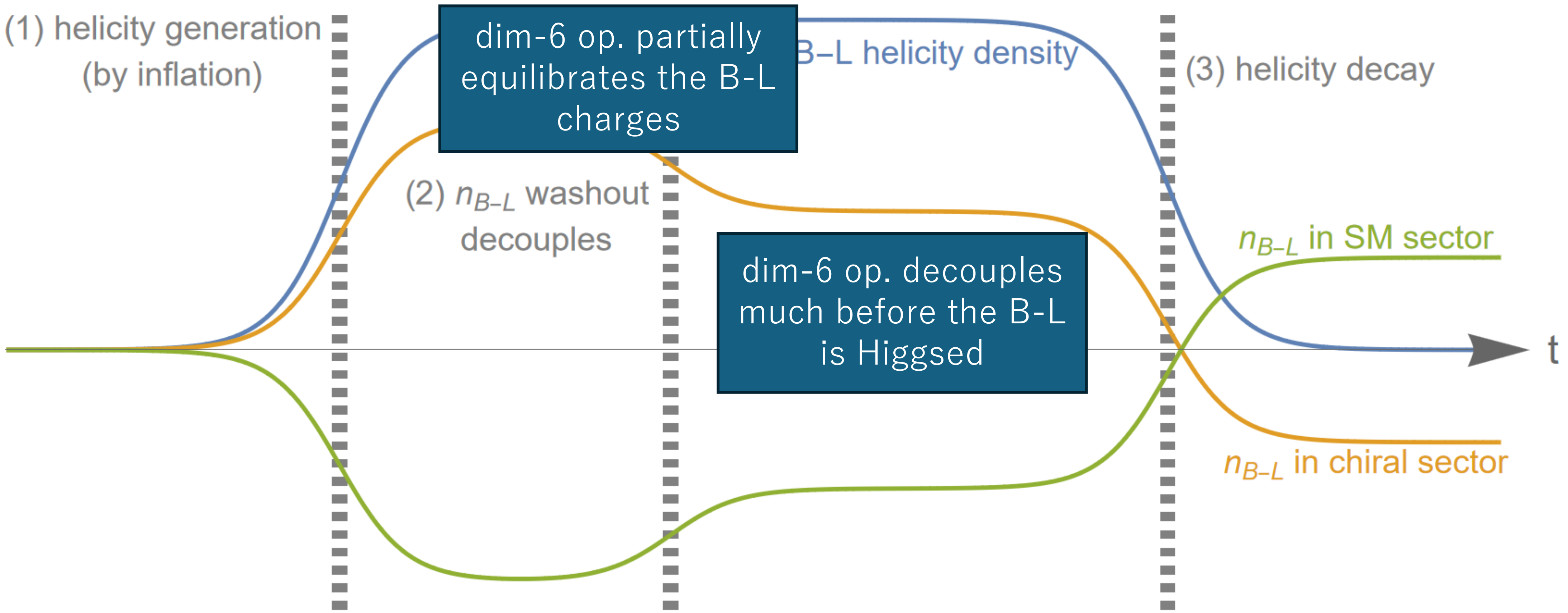
may connect the SM and RHN sector



Dirac neutrino and higher dim. operators

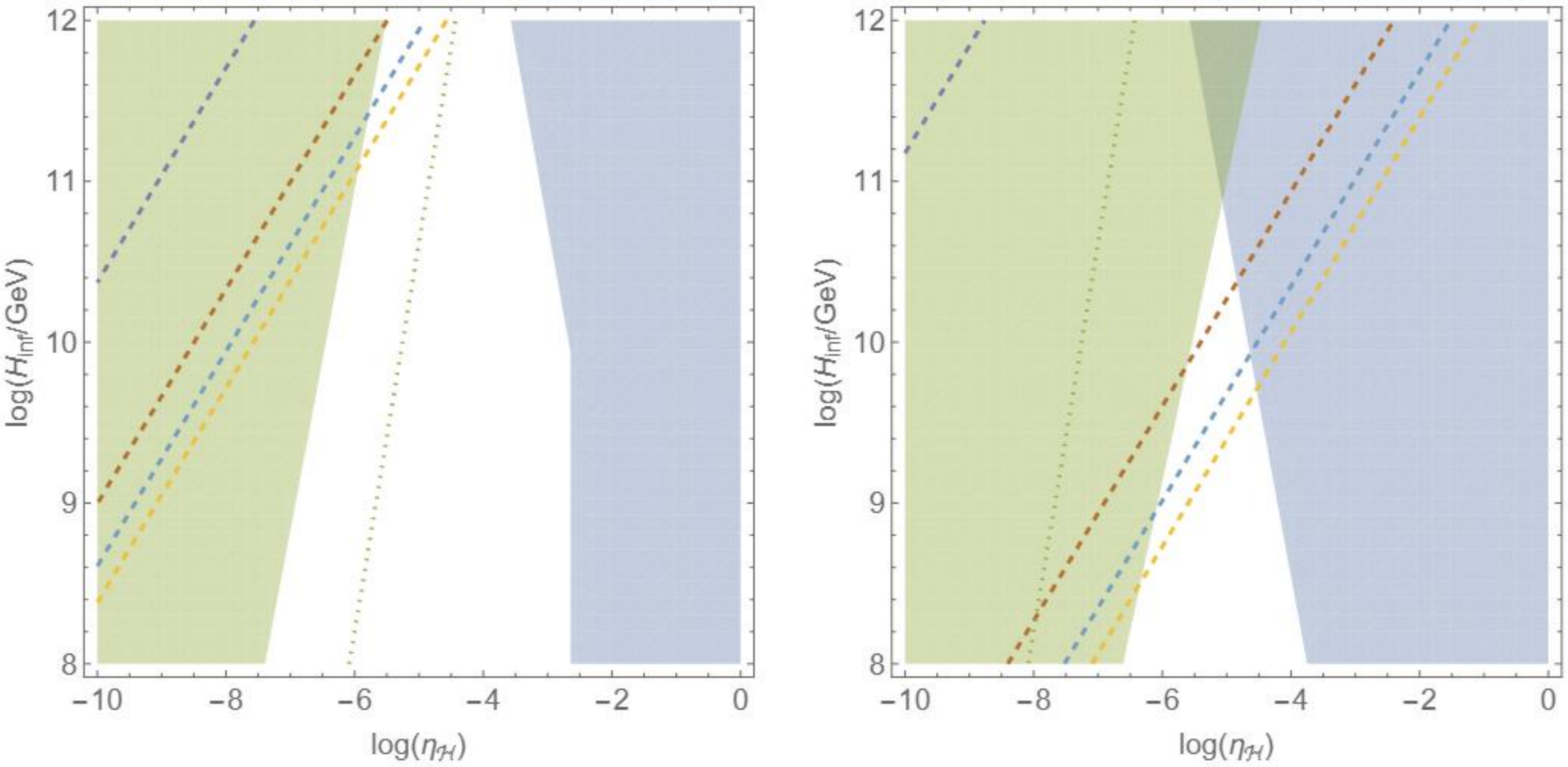
- Does such a higher dimensional operator exist naturally?
- Yes, it’s possible.
    - Some models try to explain the smallness of the Dirac Yukawa. Such models are called “Dirac seesaw” models e.g. M. Roncadelli, D. Wyler, 1983
    - These models typically add additional heavy particle, just like the usual seesaw models, to generate small Yukawas
    - The heavy particles also generates the higher dimensional operator.

Case 2: Dirac neutrino



Result

$g_{B\text{-}L} = 0.01$ $g_{B\text{-}L} = 0.1$



Green: too small magnetic helicity; the helicity dissipates.
Green dotted: more conservative estimation

Blue: too large abundance of the helicity & generated fermions.

η: helicity-to-entropy ratio
(If all the helicity is washed out, we get too many baryons)

Summary

- If B-L symmetry is gauged with right-handed neutrinos, the SM B-L charge can be generated together with the B-L magnetic helicity and the RHN B-L charge.
- For the Dirac neutrino case, we found that we can have a successful leptogenesis scenario
    - Our model is one of the realization of “Dirac leptogenesis” models
    - I personally found this viewpoint is interesting. Although I did not know such an idea before finising our paper, but…

(Well, I guess that for any topic in hep-ph, there exists a corresponding paper by Hitoshi. Hopefully, someone proves this conjecture.)

Realistic Dirac Leptogenesis

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