Leptogenesis in the presence of density perturbations

(arXiv: 2501.10148)

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Overview

- The new effect
  —acoustically driven freeze-out
- Motivation
- Enhancement of lepton asymmetry
- Summary

The new effect

—acoustically driven freeze-out—

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The new effect

- We point out a new effect on the freeze-out process of heavy particles induced by density perturbations in the early universe, which we call ``acoustically driven freeze-out.''

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Motivation

Motivation

- In the next 10—20 years,
  we will have the opportunity to test dynamical processes in the high-energy early universe through methods such as gravitational wave observations

- We need to reconsider processes of particle physics in such a situation

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Enhancement of lepton asymmetry

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Intuitive picture

- When right-handed neutrinos disappear from the thermal bath, the number density of right-handed neutrinos
$N_{N_1} \sim \exp(-M_1/T)$

- Roughly we set $T \sim \bar{T}(1+\delta_T)$ where $\bar{T}$ is the spatially averaged temperature of the universe, and δ_T is temperature fluctuations
$\rightarrow N_{N_1} \sim \exp(-M_1/T) \sim \exp(-M_1/\bar{T}) \cdot \exp(M_1\delta_T/\bar{T})$

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Intuitive picture

- So, when $\delta_T \gtrsim \bar{T}/M_1$ is satisfied,

  linear expansion in δ_T cannot be justified

- This condition translates to $\delta_T \gtrsim 0.1$

  because $|N_{B-L}|$ freeze out at $M_1/\bar{T} \sim 10$

Cosmological Perturbations

- Metric perturbations are given by

$$ds^2 = a^2 \left[-(1+2A)\, d\eta^2 - B_{,i}\, d\eta\, dx^i\right] + a^2 \left[(1+2C)\delta_{ij} + 2\left(E_{,ij} - \frac{1}{3}\delta_{ij}\nabla^2 E\right)\right] dx^i\, dx^j$$

- Here, $A, B, C,$ and E are independent functions of time and space

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Boltzmann Equation of N_1

- Boltzmann equation of N_1
  up to the first order of perturbations is

$$\frac{dN_{N_1}(\bar{z})}{d\bar{z}} = -(1+A)K\bar{z}\frac{K_1(z_T)}{K_2(z_T)}\left[N_{N_1}(\bar{z}) - N_{N_1}^{\mathrm{eq}}(z_T)\right]$$

- This equation is invariant under the coordinate transformations

- $N_{N_1} = n_{N_1}(\bar{z})/n_{\gamma}^{\mathrm{eq}}(z_T)$, and K is called decay parameter

Boltzmann Equation of $B-L$

- Boltzmann equation of $B-L$
  up to the first order of perturbations is

$$\frac{dN_{B-L}(\bar{z})}{d\bar{z}} = -\varepsilon_1(1+A)K\bar{z}\frac{K_1(z_T)}{K_2(z_T)}\left[N_{N_1}(\bar{z}) - N_{N_1}^{\mathrm{eq}}(z_T)\right]$$
$$-(1+A)W_{\mathrm{ID}}N_{B-L}$$

- ε_1 is the CP asymmetry, W_{ID} is the washout factor:

$$W_{\mathrm{ID}}(z_T) = \frac{1}{4}K\bar{z}\, z_T^2 K_1(z_T)$$

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Enhancement of lepton asymmetry

- Here, we choose the conformal Newtonian gauge, and assume that the anisotropic stress is negligible

- Then, the line element is

$$ds^2 = [a(\eta)]^2 \left[-(1 + 2\Psi) d\eta^2 + (1 - 2\Psi) \delta_{ij} dx^i dx^j \right]$$

- Temperature fluctuation is as follows:

$$\delta_T = 2 |\mathscr{R}_i| \cos \delta \, \frac{\sin \varphi - \varphi \cos \varphi - \varphi^2 \sin \varphi + \frac{1}{2} \varphi^3 \cos \varphi}{\varphi^3}$$

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Enhancement of lepton asymmetry

- The temperature fluctuation:

$$\delta_T = 2\,|\mathscr{R}_i|\cos\delta\,\frac{\sin\varphi - \varphi\cos\varphi - \varphi^2\sin\varphi + \frac{1}{2}\varphi^3\cos\varphi}{\varphi^3}$$

where $\mathscr{R}_i$ is the curvature perturbation, $\varphi = \dfrac{k\eta}{\sqrt{3}} \equiv \dfrac{\bar{z}}{\bar{z}_H}$

- k is the wavenumber (we assume a monochromatic wave)

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Enhancement of lepton asymmetry

- The temperature fluctuation:

$$\delta_T = 2|\mathscr{R}_i|\cos\delta\,\frac{\sin\varphi - \varphi\cos\varphi - \varphi^2\sin\varphi + \frac{1}{2}\varphi^3\cos\varphi}{\varphi^3}$$

where $\mathscr{R}_i$ is the curvature perturbation, $\varphi = \frac{k\eta}{\sqrt{3}} \equiv \frac{\bar{z}}{\bar{z}_H}$

- δ is the phase. Each spatial point has a different value of δ
- We choose $|\mathscr{R}_i| = 0.2$ and $\bar{z}_H = 1$

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Enhancement of lepton asymmetry

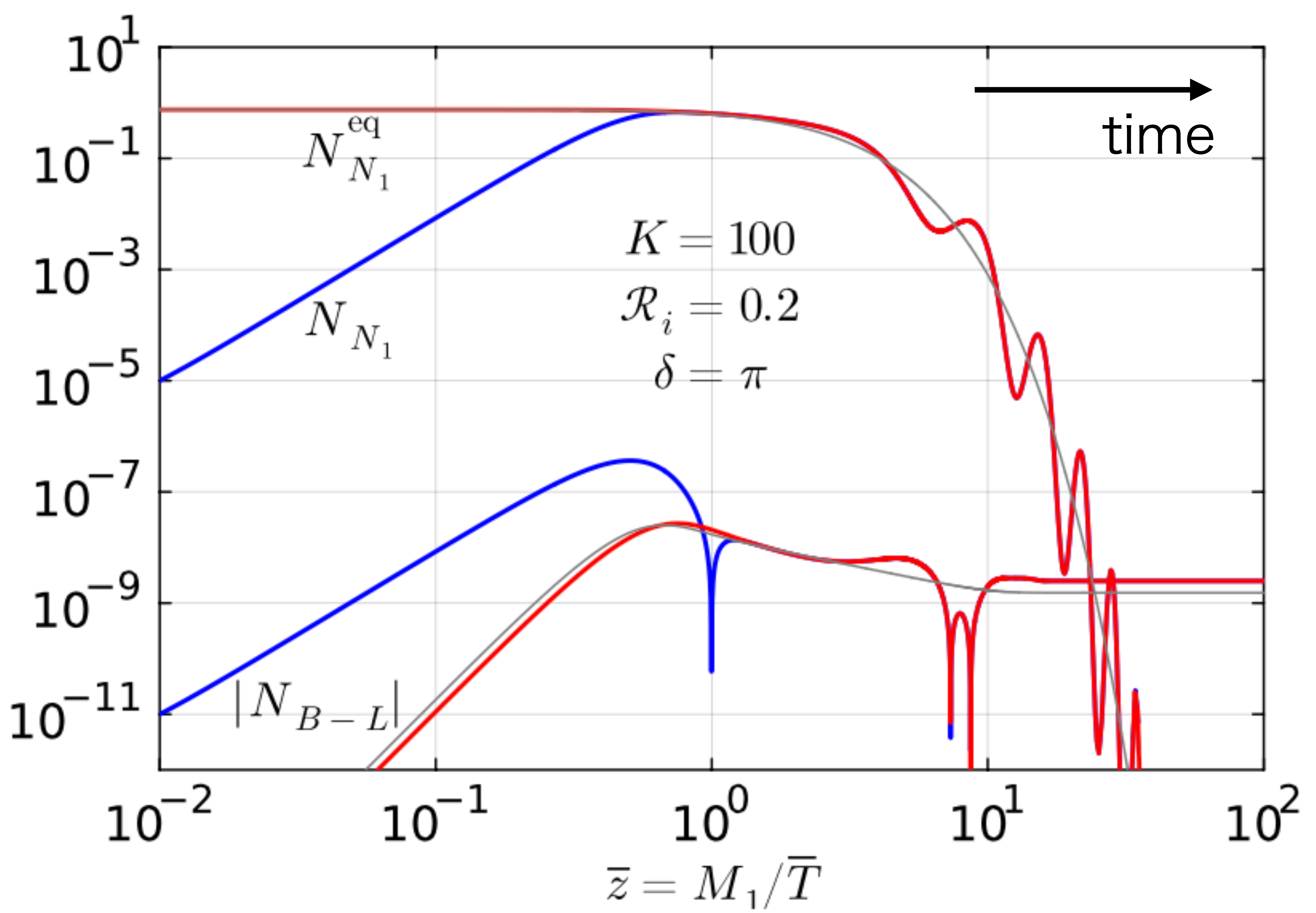
- Comparison between cases with and without temperature fluctuations

Take a specific value

$K = 100$ and $\delta = \pi$

Blue lines correspond to $N_{N_1}^{\text{initial}} = 0$, Red lines to

$N_{N_1}^{\text{initial}} = N_{N_1}^{\text{eq}} = 3/4$



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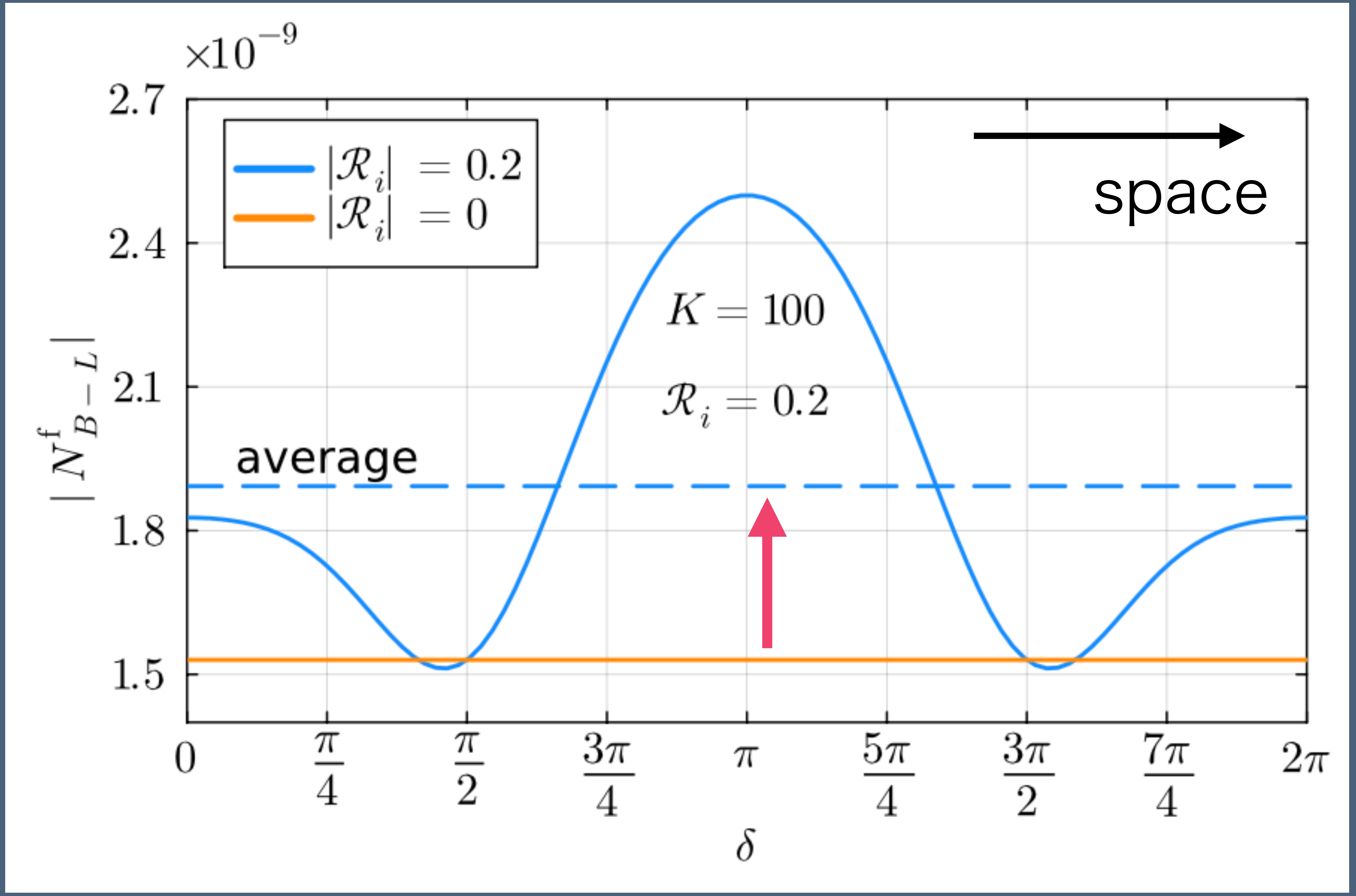
Enhancement of baryon asymmetry

- We want to know the spatial average of final values of baryon number

  spatial average

  = average over δ

  The effects of temperature fluctuations $\delta_T = \delta T/\bar{T}$ increases the spatial average of final baryon number (red arrow)



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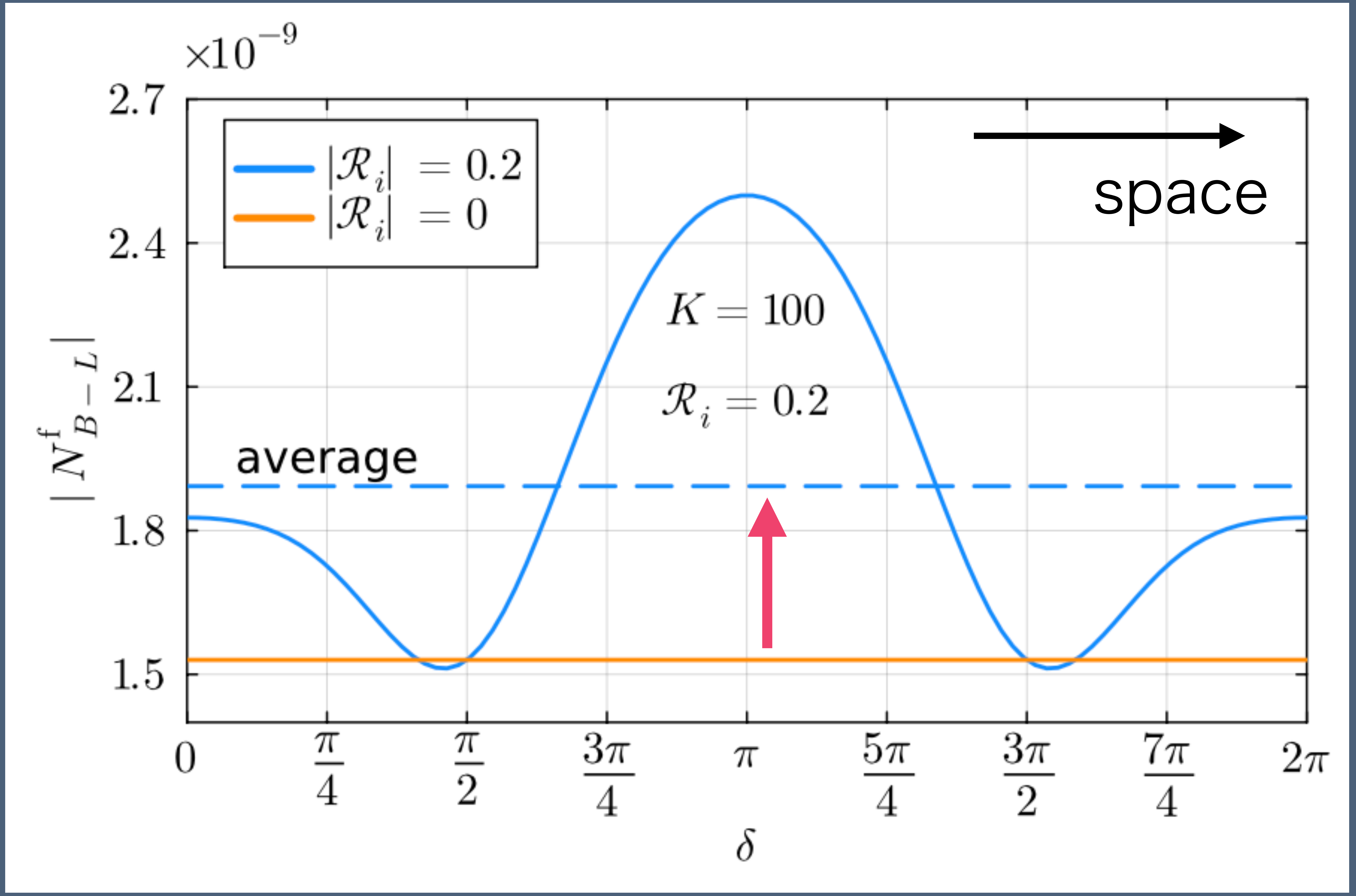
Enhancement of baryon asymmetry

- If we linearise with respect to δ_T, the baryon number will not increase because increases of positive δ_T and decreases of negative δ_T cancel out each other
- Therefore, increases of baryon number represents beyond-linear effects of δ_T!



Allowed areas of RHnu mass

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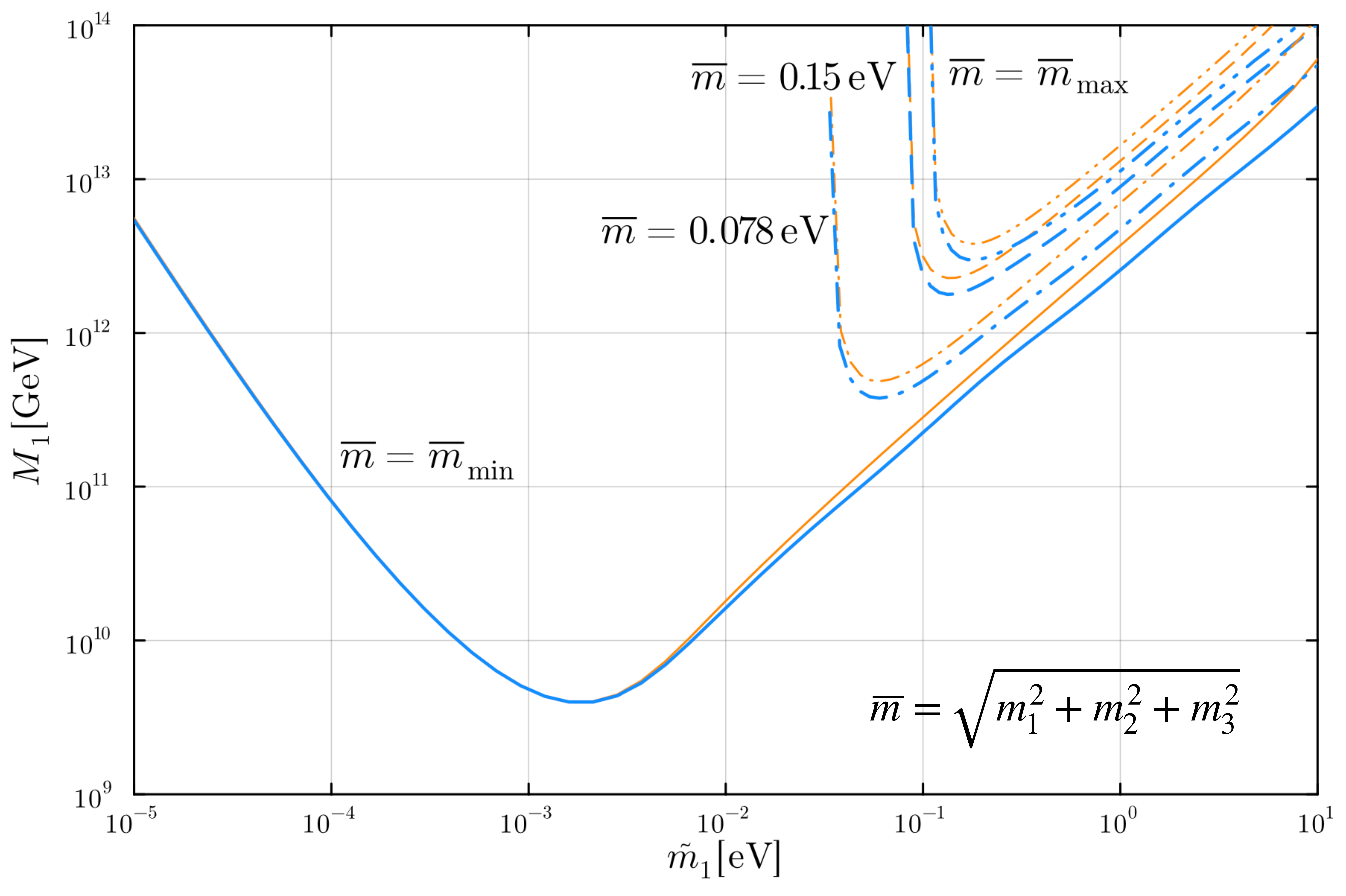
- The existence of area in which leptogenesis succeed is supported by CMB
- With fluctuations, allowed areas become broad



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Summary

Summary

- We investigate the effects of small-scale density perturbations on leptogenesis

- We point out a new effect which we call
``acoustically driven freeze-out”.
It cannot be captured with linear expansion in the temperature fluctuation. This effect comes from the exponential disappearance of RHnu from the thermal bath,
and we found that it enhances
the final lepton (and thus the final baryon) asymmetry

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