

Nonthermal leptogenesis and Cosmic Inflation

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with Leah Jenks, Edward Kolb, Andrew Long, Evan McDonough

Outline

- Motivation for nonthermal leptogenesis
- Type-I seesaw
- Cosmological gravitational particle production (CGPP)
- Expression for Y_B and kination
- Parameter space for leptogenesis

Motivation

The universe consists of baryons and practically no anti-baryons $Y_B = \frac{n_B}{s} \sim 10^{-10}$

Neutrino oscillation experiments show neutrinos must have a mass – Not captured in the SM

Many well motivated models of inflation have energy scales $H_e \sim 10^{13}$ GeV; also the ones that will be tested by next generation experiments

Seesaw models of leptogenesis propose mass scale for new particle $M_N \sim 10^{13}$ GeV

Type-I Seesaw

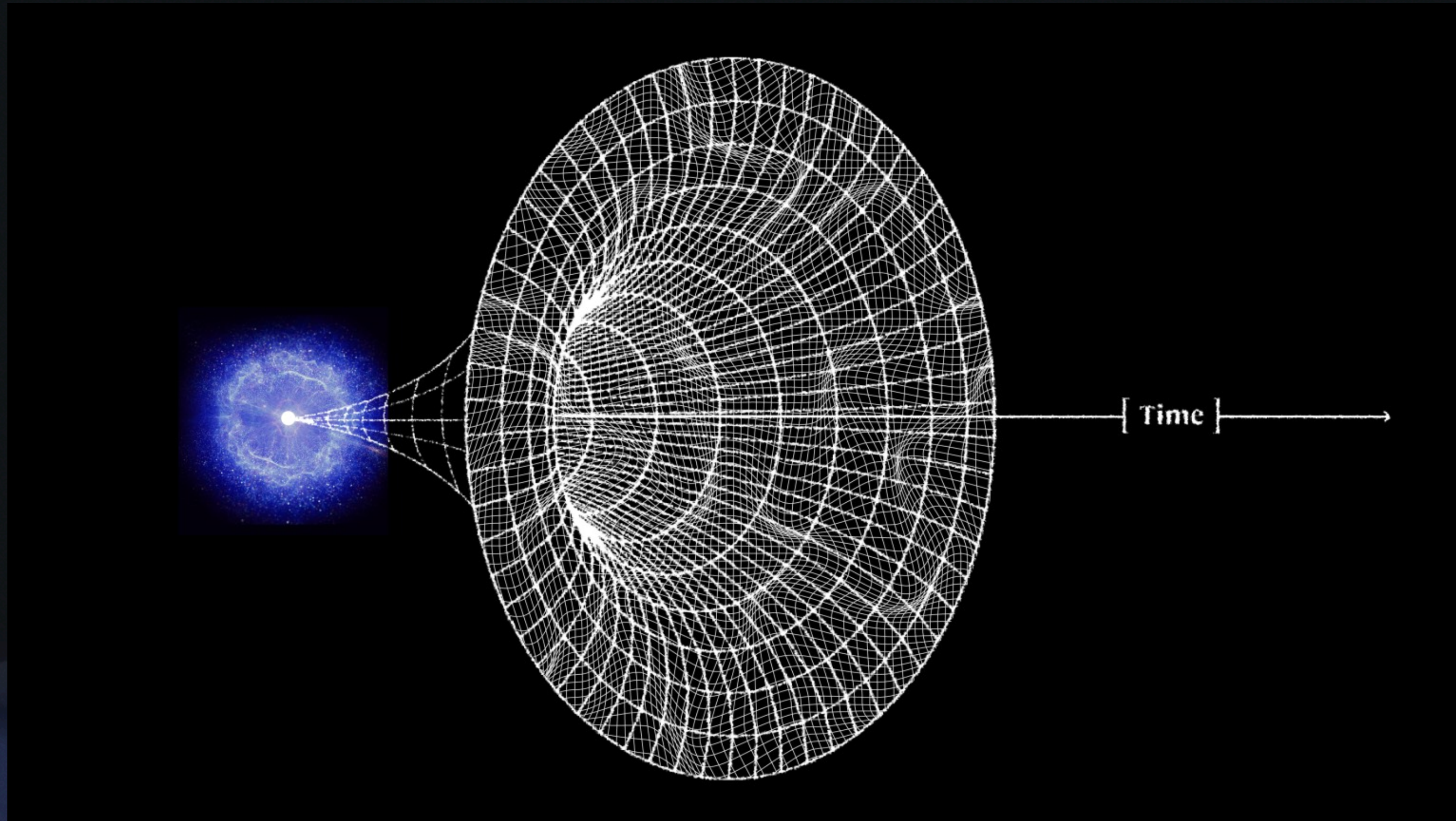
- Introduce 3 heavy right-handed neutrinos N_j , $j = \{1,2,3\}$
- After electroweak symmetry breaking, $\langle \Phi \rangle = (0, v/\sqrt{2})$, $v = 246 \text{ GeV}$
- From this, SM neutrino mass $\mathcal{O}(y^2 v^2 / M_N)$
- For SM neutrino mass $m_\nu \sim 0.1 \text{ eV}$, $M_N \sim 10^{13} \text{ GeV}$

$$\mathcal{L}_{int} = - y_{ij} \epsilon_{ab} \bar{L}_{a,i} N_j \Phi_h^* + h.c.$$

y_{ij} is 3x3 complex matrix of Yukawa couplings

L is SM lepton doublet, N is heavy neutrino, Φ is SM Higgs

Inflation



- Solves the *flatness problem* and the *horizon problem*

Exponential expansion of space at $t \sim 10^{-30}$ s

Inflation Scale

- Scalar to tensor ratio r set by inflation scale H_e
- CMB temperature anisotropies provide $\Delta_s^2(k_*) \simeq 2.2 \times 10^{-9}$ (Planck)
- $\Delta_t^2(k_*) = \frac{2H_e^2}{\pi^2 M_{\text{Pl}}^2}$, $M_{\text{Pl}} = 2.43 \times 10^{18}$ GeV,
 $H_e \sim 10^{13}$ GeV
- $r \sim 1.6 \times 10^{-3}$, CMB S4 should be able to probe at this precision

$$r = \frac{\Delta_t^2(k_*)}{\Delta_s^2(k_*)}$$

$\Delta_t^2(k_*)$: Primordial power spectrum of gravitational waves

$\Delta_s^2(k_*)$: Curvature given by scalar metric perturbations

Gravitational Production of Heavy Neutrinos

Expanding spacetime naturally provides mechanism for producing particles through gravitational interactions

Heavy neutrinos correspond to spin 1/2 fields given by

$$\Psi(\eta, x) = [a(\eta)]^{-3/2} \int \frac{d^3\mathbf{k}}{2\pi^3} \sum_{\lambda=\pm 1/2} [a_{\mathbf{k},\lambda} U_{\mathbf{k},\lambda}(\eta, x) + a_{\mathbf{k},\lambda}^\dagger V_{\mathbf{k},\lambda}(\eta, x)]$$

Where $U_{k,\lambda}$, $V_{k,\lambda}$ are the mode functions.

Vacuum state defined as:

$\hat{a}_k^{early} |0\rangle = 0$, related to the late time operators:

$$\hat{a}_k^{early} = \alpha_k^* \hat{a}_k^{late} - \beta_k^* \hat{a}_{-k}^{late\dagger}$$

α_k , β_k : Bogoliubov coefficients

Gravitational Production of Heavy Neutrinos

Impose Bunch-Davies initial conditions and find comoving number density, $\beta_{k\pm}$ is the Bogolubov coefficient

$$|\beta_{k,+}|^2 = \lim_{\eta \rightarrow \infty} \left[\frac{\omega_k}{2} |u_{k,+}|^2 + \frac{1}{2\omega_k} |\partial_\eta u_{k,+}|^2 - \frac{1}{2} \right]$$

$$a^3 n_N = \int \frac{d^3 \mathbf{k}}{(2\pi)^3} \left(|\beta_{k,+}|^2 + |\beta_{k,-}|^2 \right)$$

Requirements for Leptogenesis

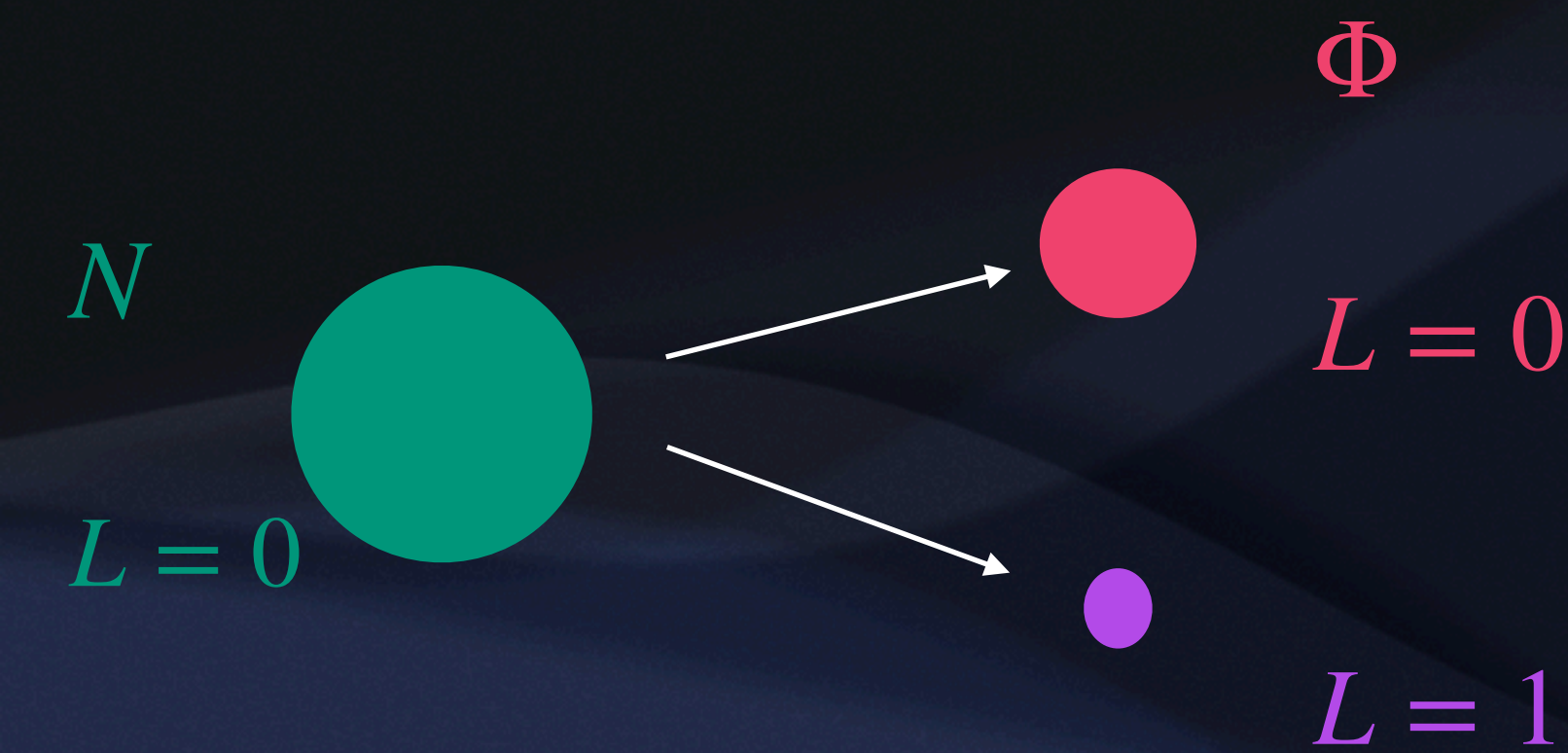
Sakharov Conditions

Baryon (Lepton) number violation

CP-violation

Out of equilibrium conditions

Decays of N 's occur out of thermal equilibrium;
 $T_{RH} \ll M_N$



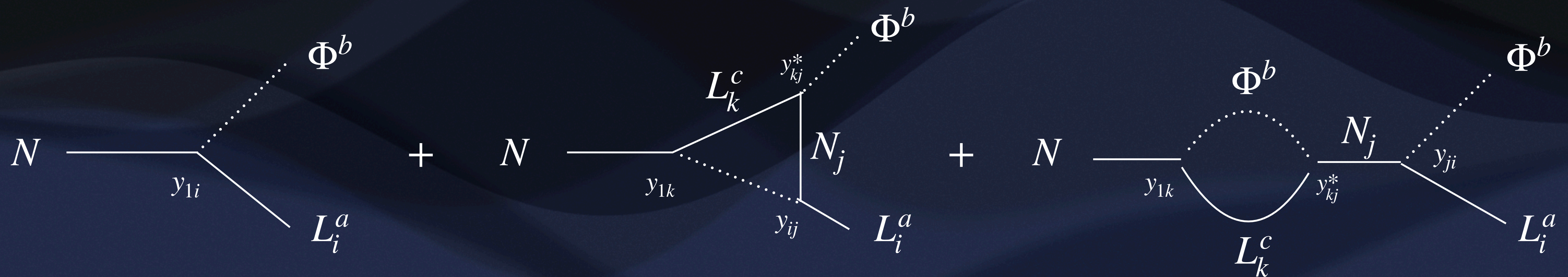
$$\varepsilon_j \equiv \frac{\sum_{ab} \sum_i [\text{Br}(N_j \rightarrow L_{a,i} \Phi_b) - \text{Br}(N_j \rightarrow \bar{L}_{a,i} \bar{\Phi}_b)]}{\sum_{ab} \sum_i [\text{Br}(N_j \rightarrow L_{a,i} \Phi_b) + \text{Br}(N_j \rightarrow \bar{L}_{a,i} \bar{\Phi}_b)]}$$

Davidson-Ibarra Bound

$$|\varepsilon| < \varepsilon_{DI} \equiv \frac{3}{8\pi} \frac{M_N m_\nu}{v^2} \simeq 9.86 \times 10^{-4} \left(\frac{M_N}{10^{13} \text{ GeV}} \right)$$

$m_\nu = 0.05 \text{ eV}$ Atmospheric mass splitting

Amount of CP-violation is constrained by smallness of neutrino masses from neutrino oscillation experiments



Baryon Asymmetry Yield

$$H_{RH} = \left(\frac{a_{RH}}{a_e} \right)^{-3(1+\omega)/2} H_e$$
$$a^3(t)s(t) = a^3(t_{RH})s(t_{RH})$$



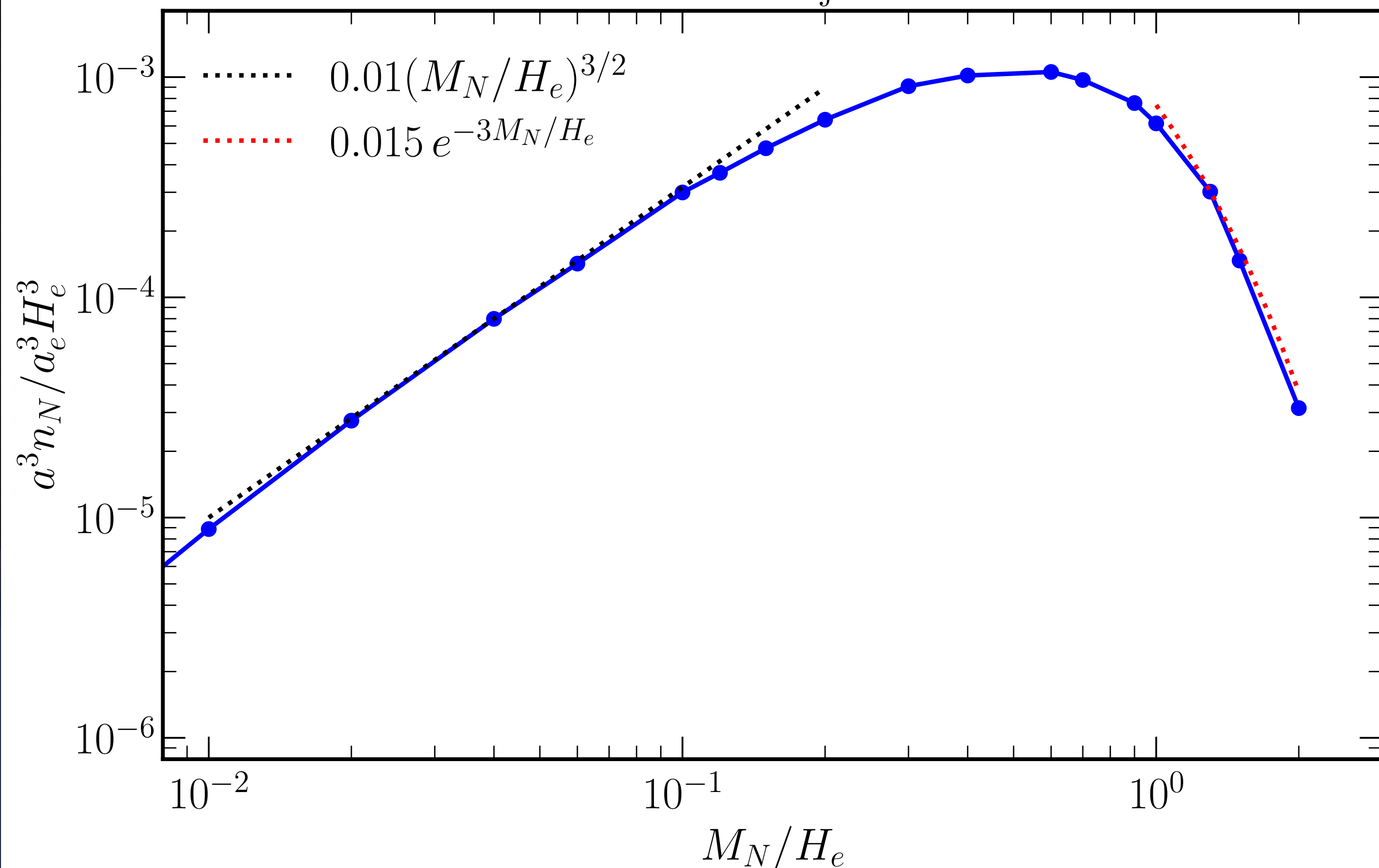
$$Y_B = -\frac{28}{79} \epsilon e^{3N_{RH}\omega} \frac{T_{RH} H_e}{4M_{Pl}^2} \left(\frac{[a^3 n_N]_{init}}{a_e^3 H_e^3} \right)$$

Period of kination, $\omega = 1$ provides exponential growth to the baryon asymmetry yield

$28/79$ is the factor that accounts for the conversion of leptons to baryons through the non-perturbative sphaleron process

Gravitational Production of Heavy Neutrinos

Kination GPP : Majorana Fermion



Production of heavy neutrinos is maximized when $M_N \sim H_e$, for a comoving number density $a^3 n_N \sim 10^{-3}$

Boltzmann Equation

$$\frac{d}{dt}n_N + 3Hn_N = - (n_N - n_N^{eq})[\Gamma + 2n_\gamma^{eq}\langle\sigma v\rangle_1]$$

$$\frac{d}{dt}n_L + 3Hn_L = \epsilon\Gamma(n_N - n_N^{eq}) - n_L\frac{n_L^{eq}\Gamma}{n_l} - 2n_Ln_N\langle\sigma v\rangle_1 - 4n_Ln_\Phi^{eq}\langle\sigma v\rangle_2$$

Reduce to:

$$\frac{d}{dt}(a^3n_N) = -\Gamma(a^3n_N)$$

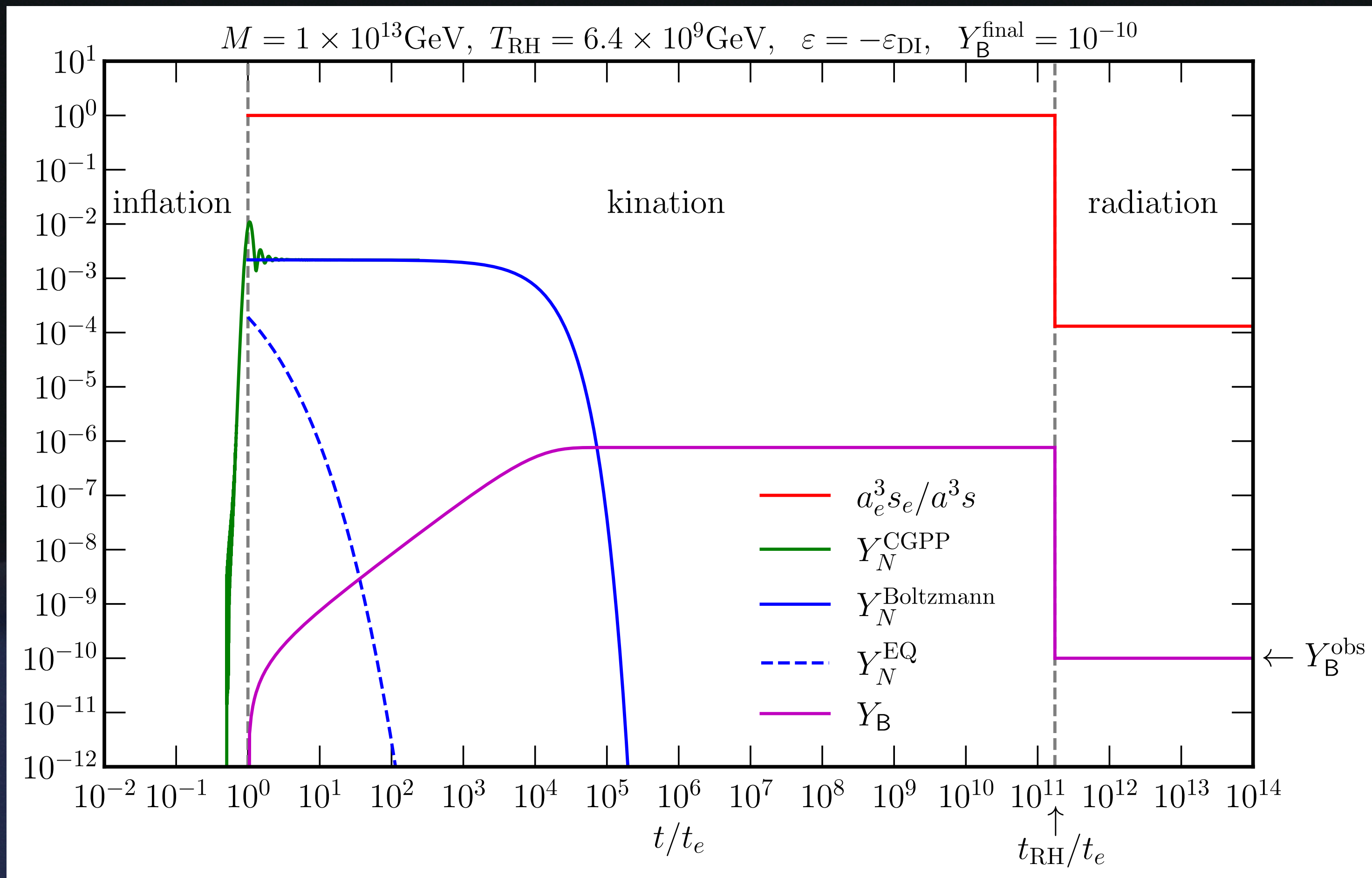
$$\frac{d}{dt}(a^3n_L) = \epsilon\Gamma(a^3n_N)$$

$$\Gamma = (yy^\dagger)_{11}\frac{M_N}{8\pi}$$

Decays of N's

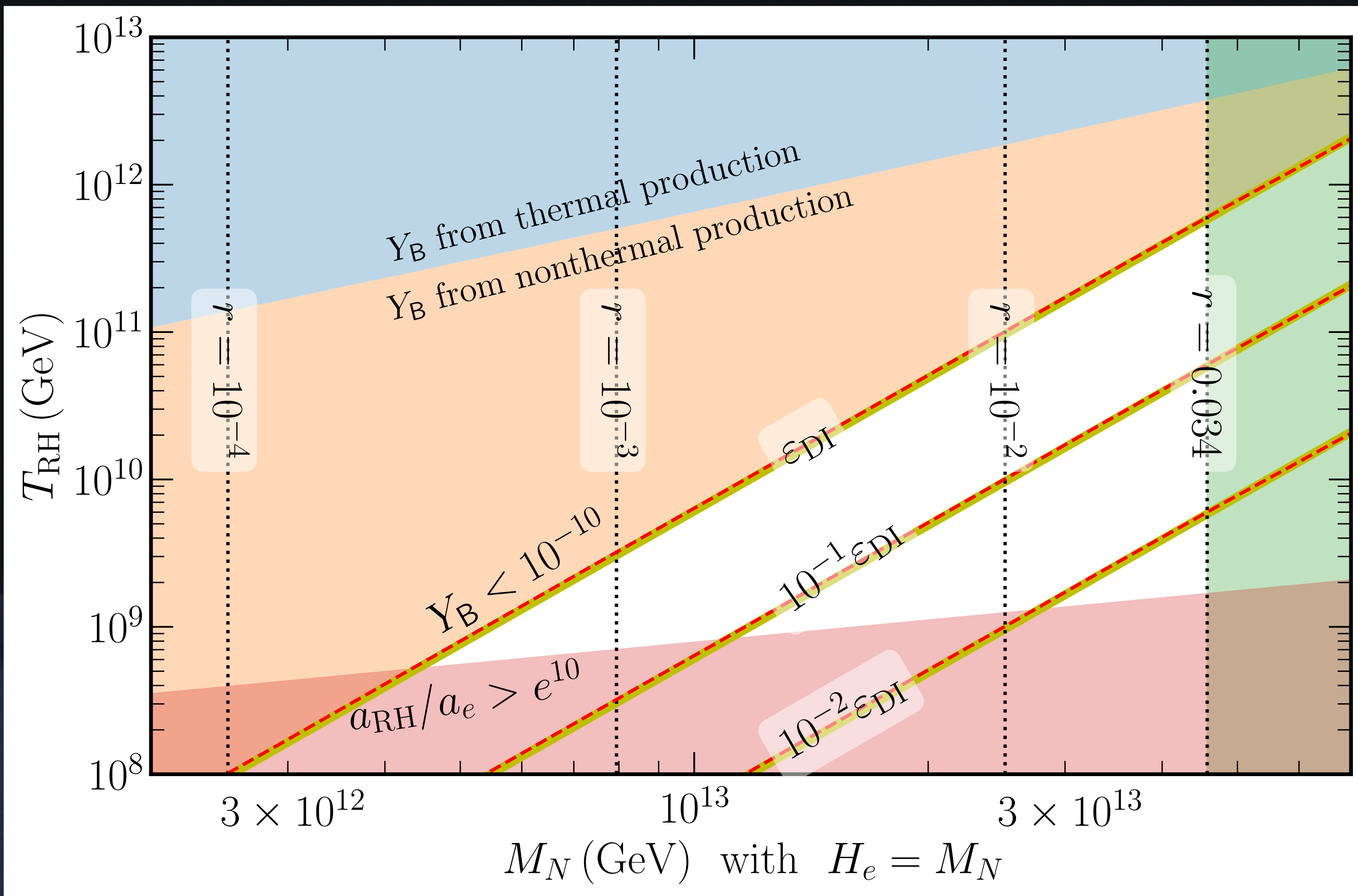
$\langle\sigma v\rangle_1$, $\langle\sigma v\rangle_2$ are lepton violating scattering cross-sections that may result in washout

Evolution of Baryon Asymmetry



- Solid blue curve shows decays of heavy neutrinos
- Produces the generated baryon asymmetry in purple
- Dashed blue curve shows the thermal density of N 's is always smaller than those produced gravitationally

Leptogenesis Parameter Space



- White is allowed parameter space for nonthermal leptogenesis
- Dashed red lines for Davidson-Ibarra bound
- Green is excluded from CMB
- Red is excluded from max. Duration of kination

Summary

Nonthermal production of heavy neutrinos allows for testable parameter space for the baryon asymmetry through future CMB experiments!