Recent progress of Leptogenesis mechanism

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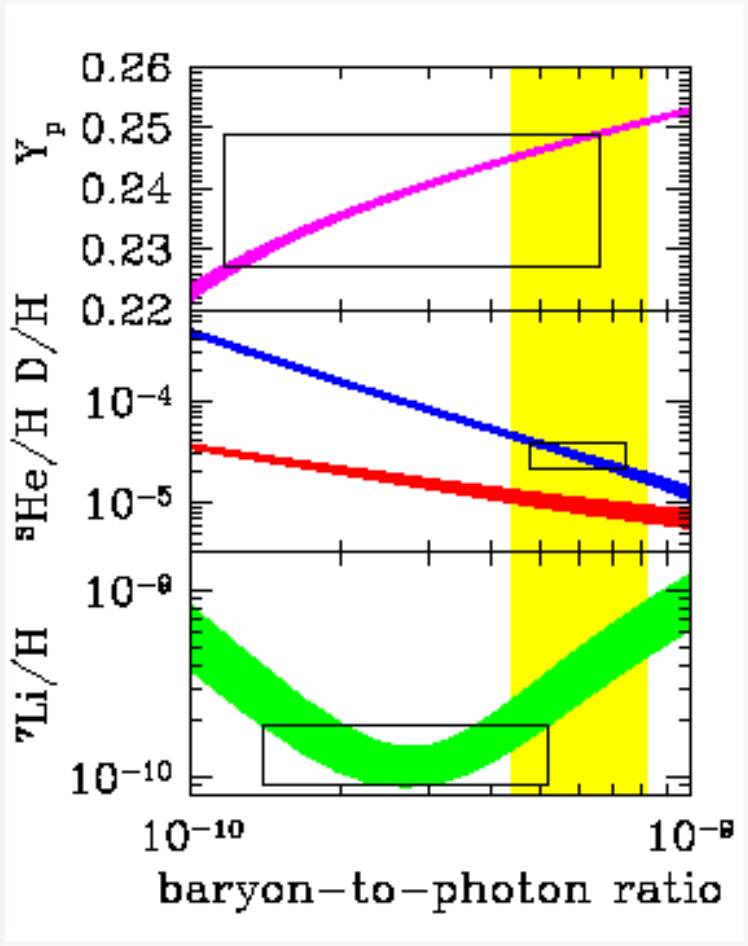
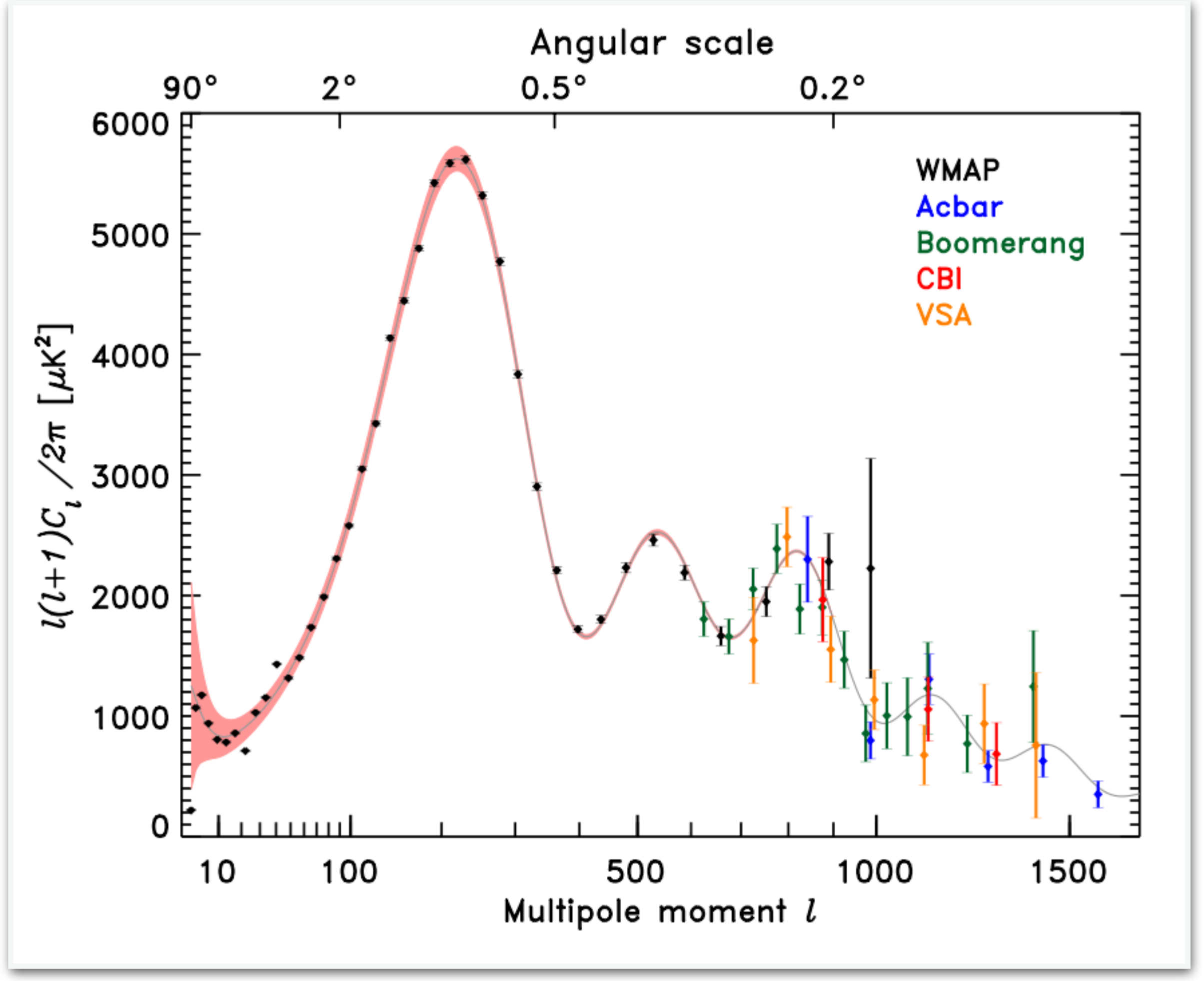
New physics—The Baryon asymmetry

Matter-antimatter asymmetry

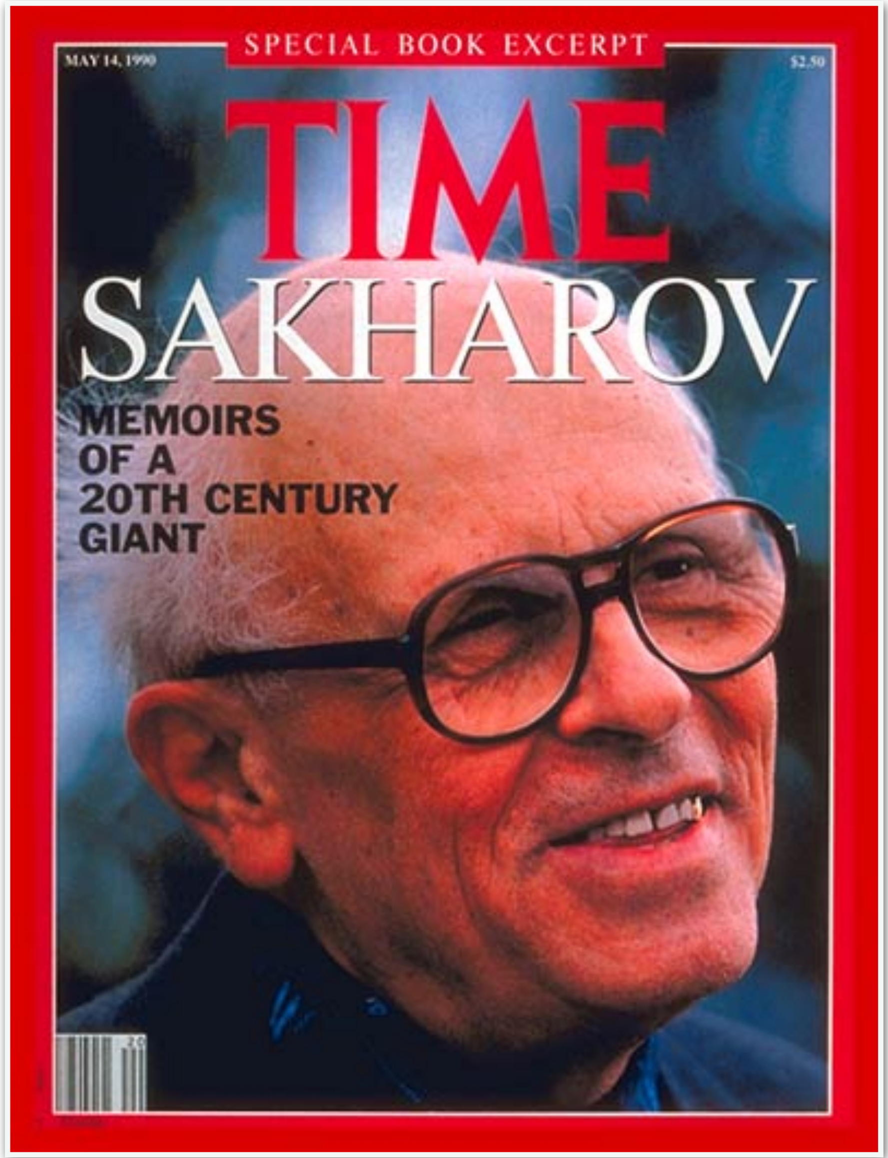
- No galaxy made by ant-baryon is observed
- Baryon asymmetry is measured by the Planck.

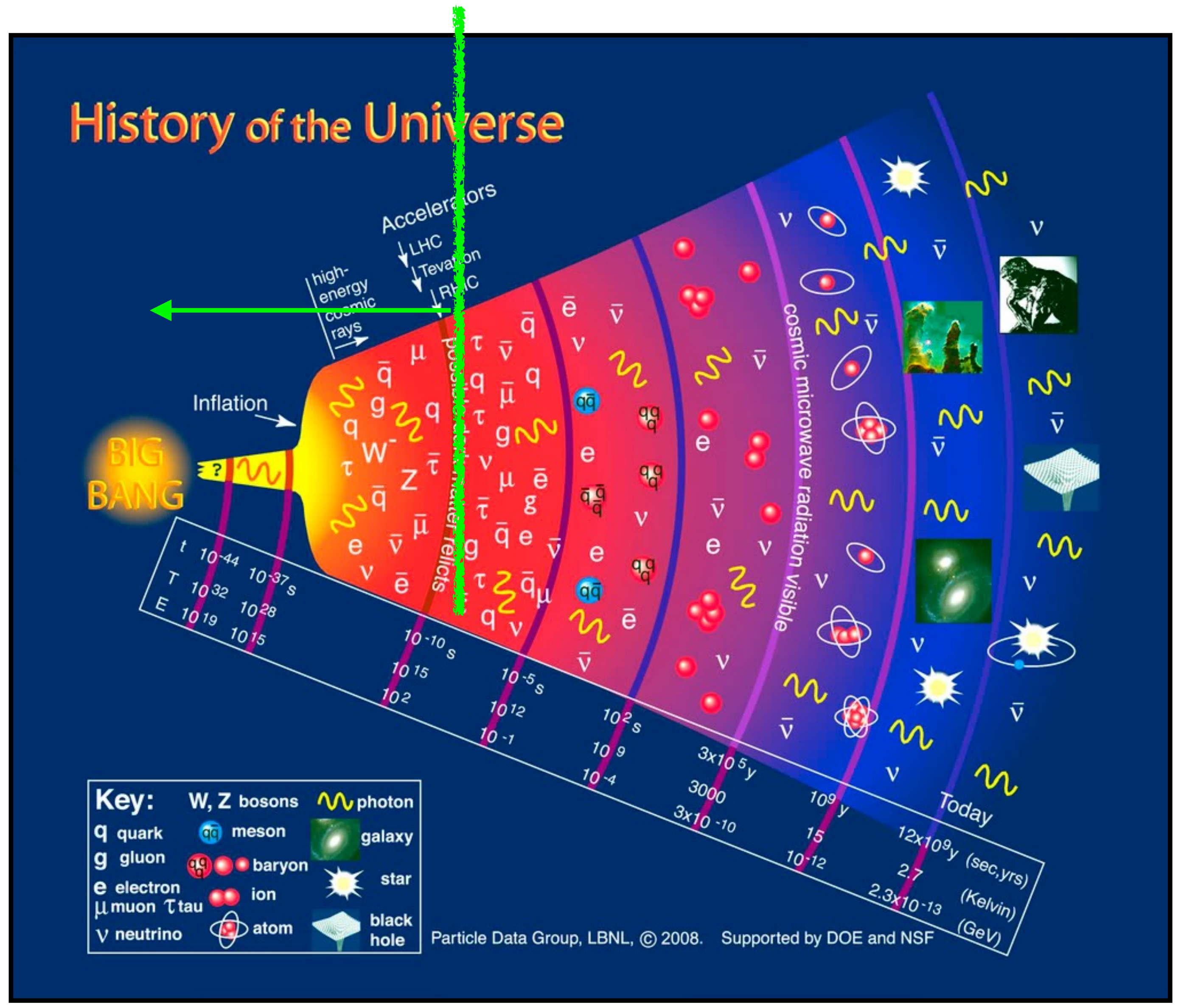




Baryon asymmetry: $Y_B = \dfrac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$ **Planck**

Baryogenesis





★Baryon number violation
★C&CP violation
★Departure from equilibrium

- Leptogenesis
- Electroweak Baryogenesis
- GUT Baryogenesis
- Afleck-Dine Baryogenesis
- Post-sphleron baryogenesis

Status for Baryogenesis

Primordial B-L Conservation

Electroweak baryogenesis	Bochkarev et al 1990
Leptogenesis	YANAGIDA et al. 1986
Wash-in Leptogenesis	DOMCKE et al 2021
Electrogenesis	CHAO, 2024

Primordial B-L Violation

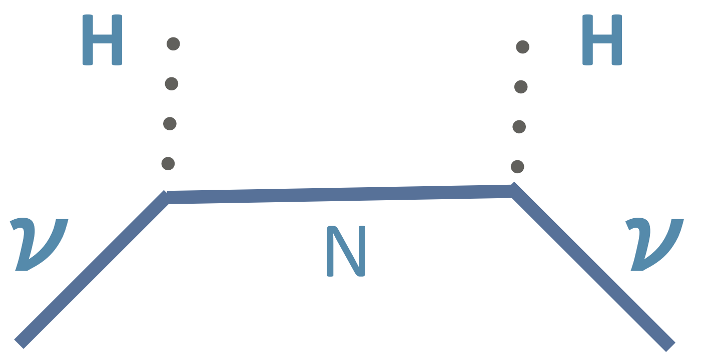
Magnetogenesis	~~CPT~~	JOYCE et al 1997
Axion-inflaton Leptogenesis	~~CPT~~	Alexande et al 2004
Affleck-Dine field oscillation	~~CPT~~	Affleck et al 1985
Axion Baryogenesis	~~CPT~~	CO et al 2019

History and development: Leptogenesis

Type-I seesaw mechanism

Lagrangian: $-\mathcal{L} = Y_\nu \overline{\ell_L} \tilde{H} N_R + \frac{1}{2} \overline{N_R^C} M_R N_R + \text{h.c.}$

Seesaw Mechanism

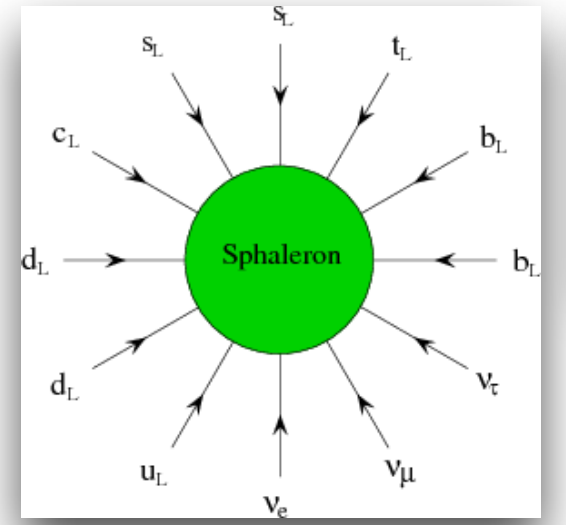


Elegant but losing testability at colliders!

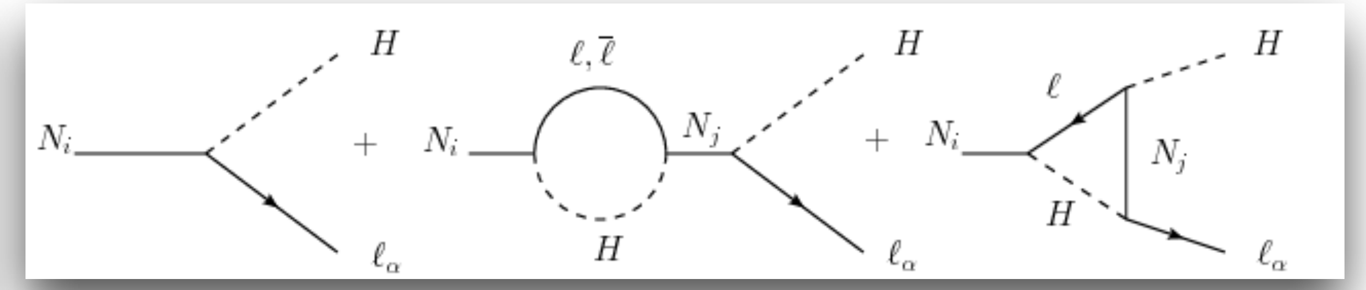
Neutrino mass: $M_\nu = -M_D M_R^{-1} M_D^T$

Leptogenesis (Fukugita&Yanagida 86)

BV



CPV



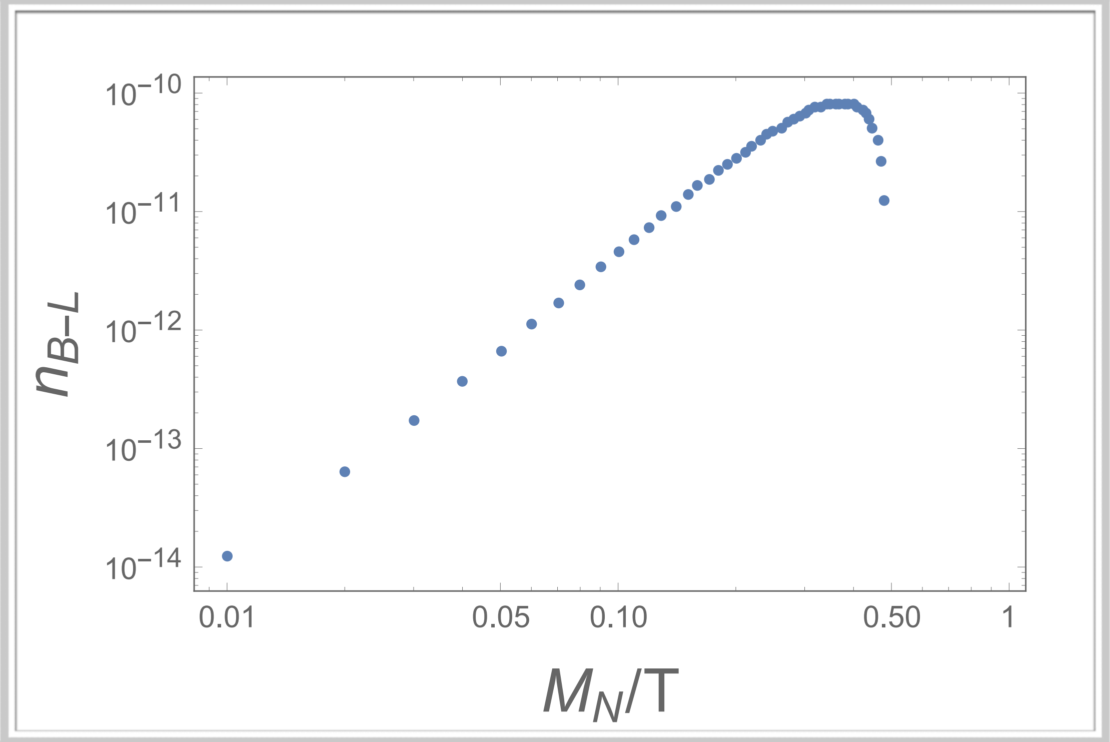
Out of EQ

Heavy neutrinos decouple

Boltzmann EQ

$$\frac{dN}{dz} = -D(N - N^{\mathrm{eq}})$$

$$\frac{dN_{\mathrm{B-L}}}{dz} = -\varepsilon D(N - N^{\mathrm{eq}}) + W_{\mathrm{ID}} N_{\mathrm{B-L}}$$



History and development: Leptogenesis

CTP formalism

Flavor effect

Casas-Ibarra parametrization

Precision BAU

Thermal history

Connection of low-high energy neutrino physics

Leptogenesis (Fukugita&Yanagida 86)

Unification

Testability

GUT model building

Effective field theory

Resonant Leptogenesis

1986~2016

Gravitational Leptogenesis

Framework

- Gravitational chiral anomaly: $\partial_\mu j^\mu_L = \frac{A}{16\pi^2} R\tilde{R}$

A: Counting difference between left-handed and right-handed fermions

- Pseudo-scalar inflation: $\Delta\mathscr{L} = F(\phi)R\tilde{R}$

$$h_{L,R} = \frac{1}{\sqrt{2}}(h_+ \mp i h_\times)$$

$$\Theta = \frac{8}{M_{\rm pl}^2} HF'\dot{\phi}$$

- EOM of Gravitational waves $\Box h_L = -2i\frac{\Theta}{a}\dot{h}'_L$ $\quad \Box h_R = -2i\frac{\Theta}{a}\dot{h}'_R$

- BAU $n = \frac{1}{72\pi^4}\left(\frac{H}{M_{\rm pl}}\right)^2 \Theta H^4 \left(\frac{\mu}{H}\right)^6$

Alexander, Peskin & Sheikh, 0403069 | Maleknejad, 1604.06520 | Adshead, et al., 1711.04800
Kambiase, et al., 0610905 | Kawai and Kim, 1702.07689 | Co, et al., 2205.01689

Leptogenesis via axion oscillation

- **Alexander Kusenko, Kai Schmitz, Tsutomu T. Yanagida, 2014**

❖ **Axion relaxation after inflation** $\ddot{a} + 3H\dot{a} + \partial_a V_{eff}(a) = 0$

❖ **Axion-like field couples to EW gauge field via the Chern-Simons form**

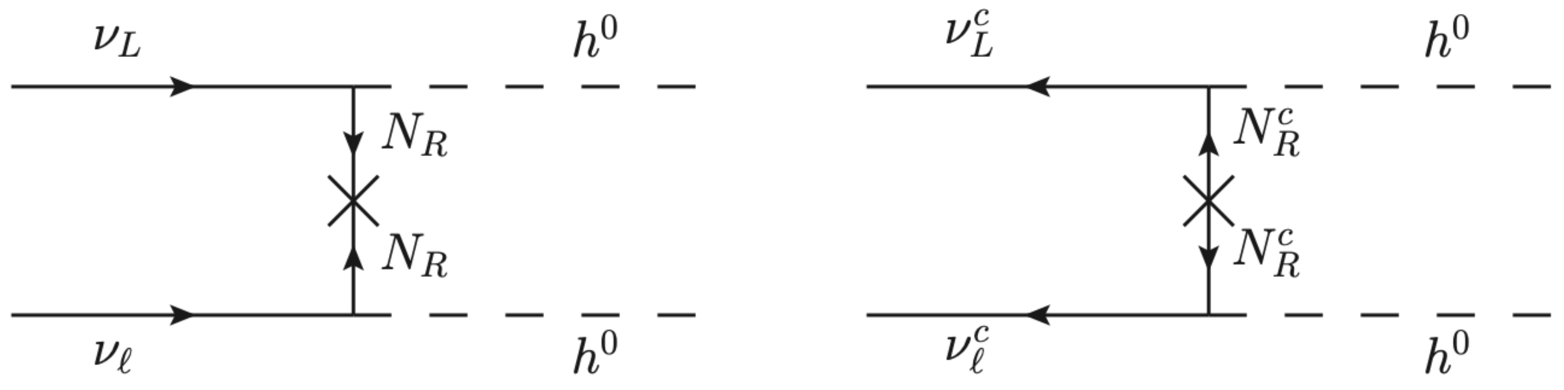
$$\mathscr{L} \sim \frac{a(t)}{f_a}\frac{g_2^2}{32\pi^2}\mathrm{Tr}\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] \rightarrow \frac{\partial_\mu a}{f_a} j_L^\mu \rightarrow \frac{\dot{a}}{f_a} n_L$$

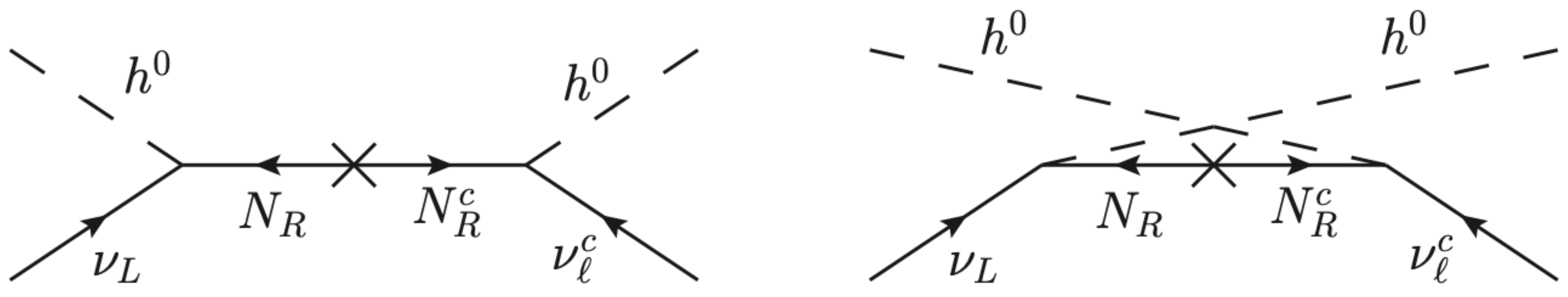
$\dot{a}/f_a$: the effective chemical potential for leptons and anti-leptons

$$n_{\ell,\bar{\ell}}^{\rm eq} \sim T^3\left(1 \pm \frac{\mu_{eff}}{T}\right)$$

$$n_L^{eq} = n_\ell^{eq} - n_{\bar{\ell}}^{eq} \sim \mu_{\rm eff} T^2$$

❖ **LNVs are mediated by the Majorana neutrinos** $\dot{n}_L + 3Hn_L \sim -\Gamma_L(n_L - n_L^{\rm eq})$





Leptogenesis via axion oscillation

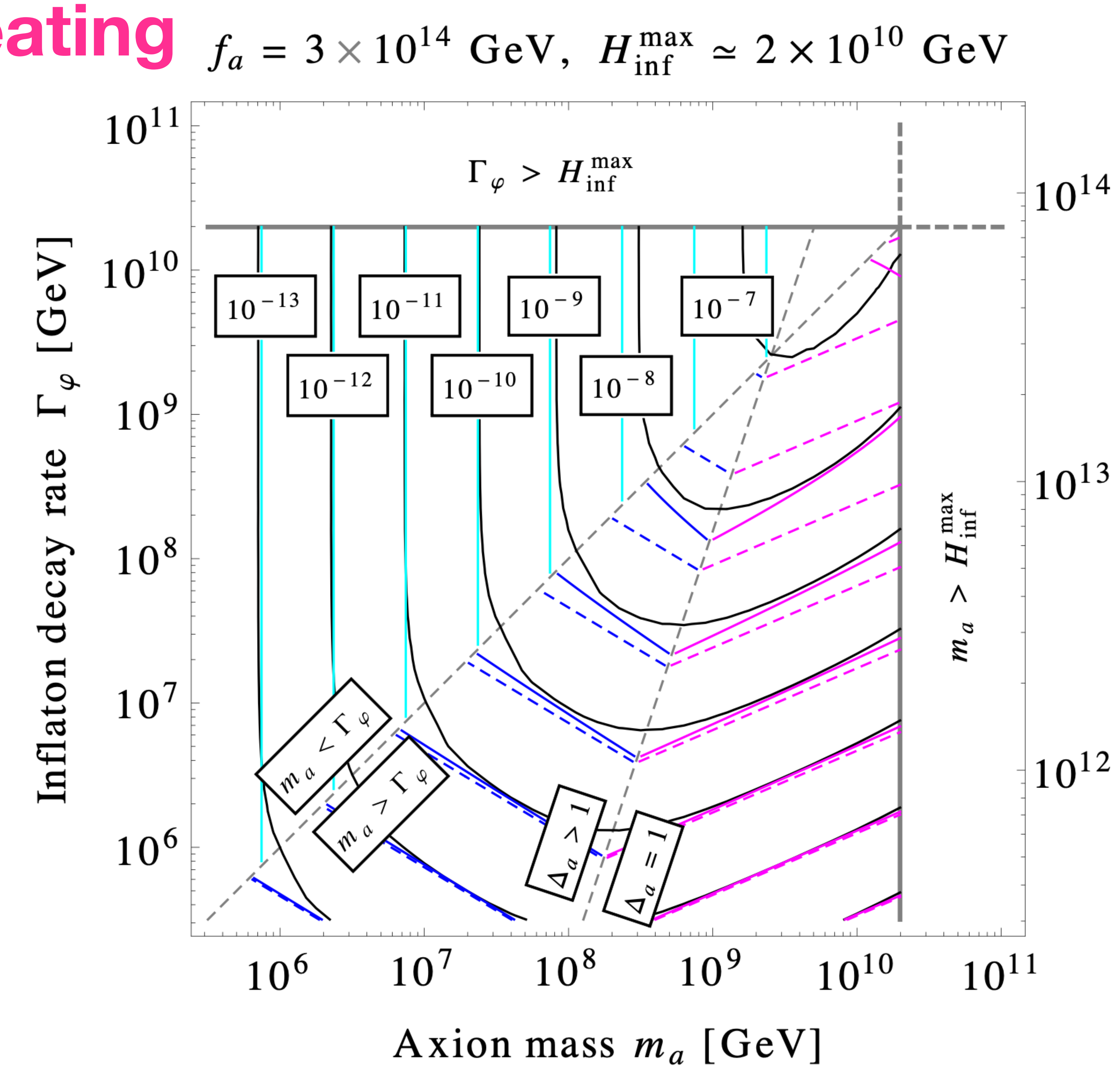
- **Alexander Kusenko, Kai Schmitz, Tsutomu T. Yanagida, 2014**

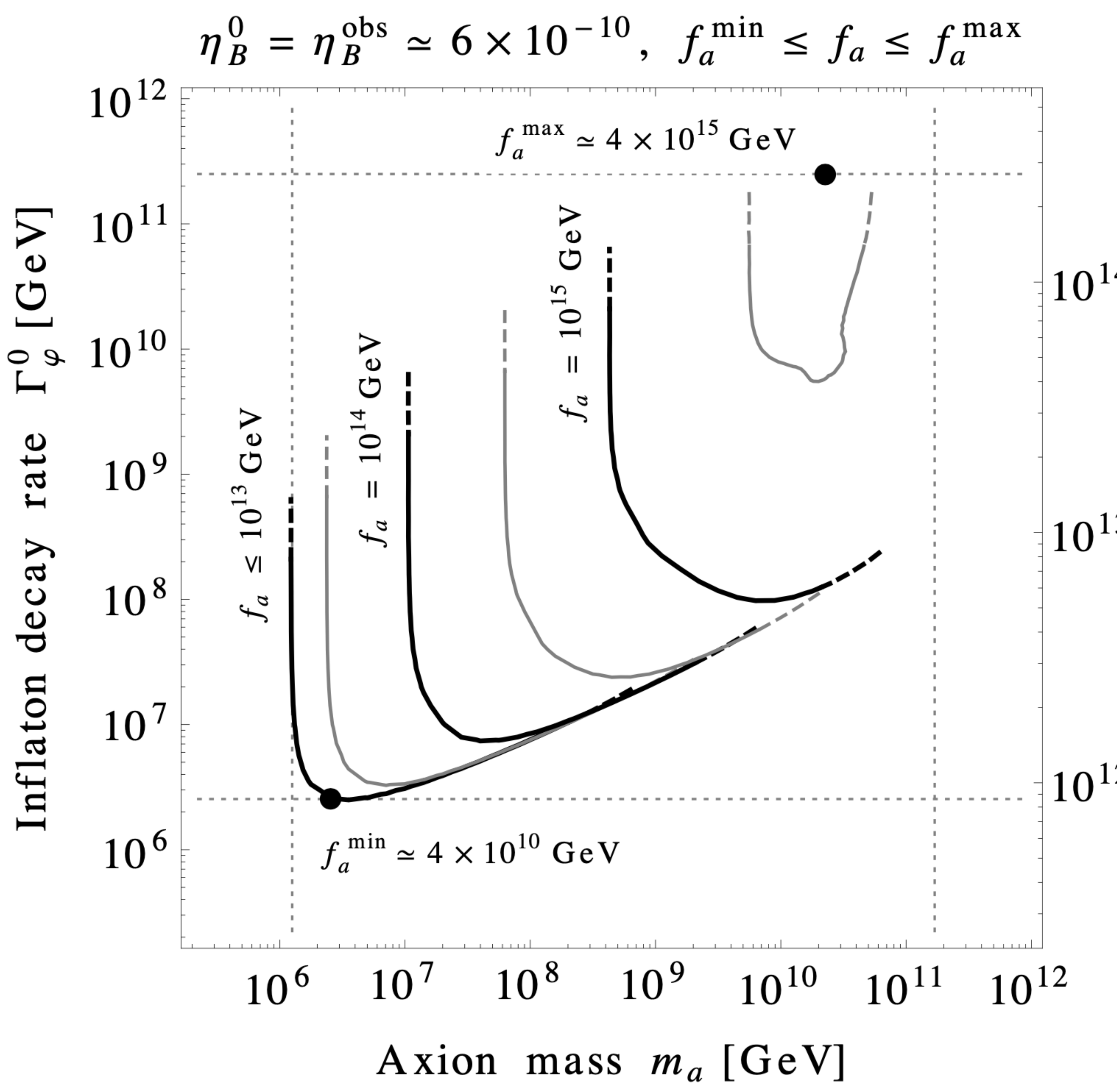
Equations describing the reheating

$$\dot{\rho}_\varphi + 3H\rho_\varphi = -\Gamma_\varphi \rho_\varphi$$

$$\dot{\rho}_R + 4H\rho_R = +\Gamma_\varphi \rho_R$$

$$H^2 = \frac{\rho_\varphi + \rho_R}{3M_{pl}^2}$$





Wash-in Leptogenesis

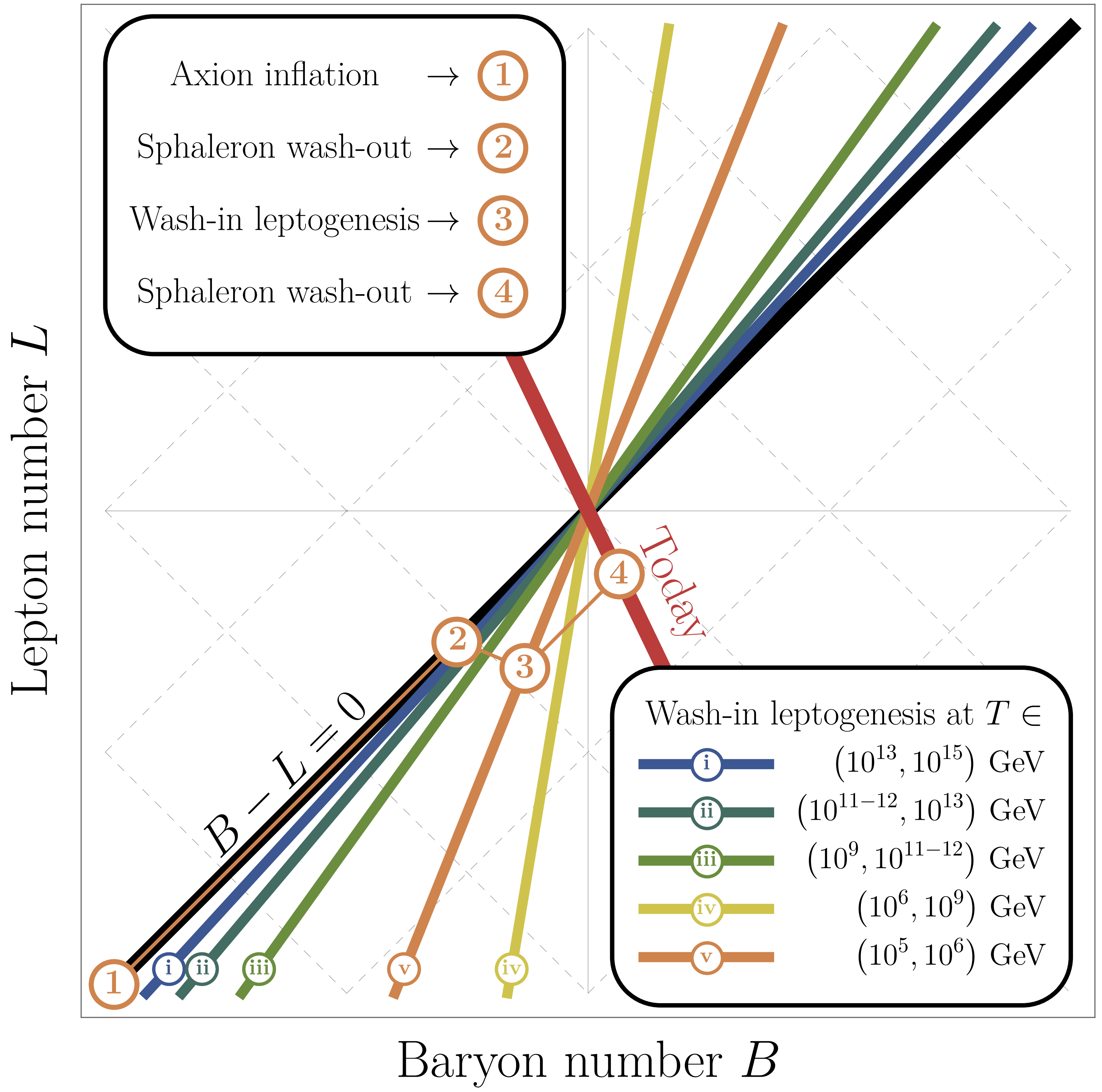
• **Domcke, Kamada, Mukaida, Schmitz and Yamada, 2020**

❖**Lepton flavor asymmetry:** $\Delta_\alpha = \frac{B}{3} - L_\alpha$

❖**Splitting into two parts:** $q_{\Delta_\alpha} = q_{\Delta_\alpha}^{\text{thermal}} + q_{\Delta_\alpha}^{\text{wash-in}}$

❖**Boltzman equation:** $(\partial_t + 3H) q_{\Delta_\alpha}^{\text{wi}} = \sum_\beta \Gamma^w_{\alpha\beta} \left(q^0_\beta - \sum_\sigma C_{\beta\sigma} q^{\text{wi}}_{\Delta_\sigma} \right)$

- Right-handed neutrinos can be as light as several hundreds TeV
- No need for the CP violation in the heavy neutrino sector
- Strong wash-out effect is turned into effective wash-in effect,



Affleck-Dine Leptogenesis

- **N.Barrie, Chengcheng Han, H.Murayama, 2021, PRL**

❖ **Generating the net lepton number during the Higgs inflation in the type-II seesaw framework!**

$$V(h,\Delta^0) = -m_H^2|h|^2 + m_\Delta^2|\Delta^0|^2 + \lambda_H|h|^4 + \lambda_\Delta|\Delta^0|^4 + \lambda_{H\Delta}|h|^2|\Delta^0|^2 + \left(\mu h^2\Delta^{0*} + \frac{\lambda_5}{M_p}|h|^2h^2\Delta^{0*} + \frac{\lambda_5'}{M_p}|\Delta^0|^2h^2\Delta^{0*} + \text{H.c.}\right) + \cdots . \quad (9)$$

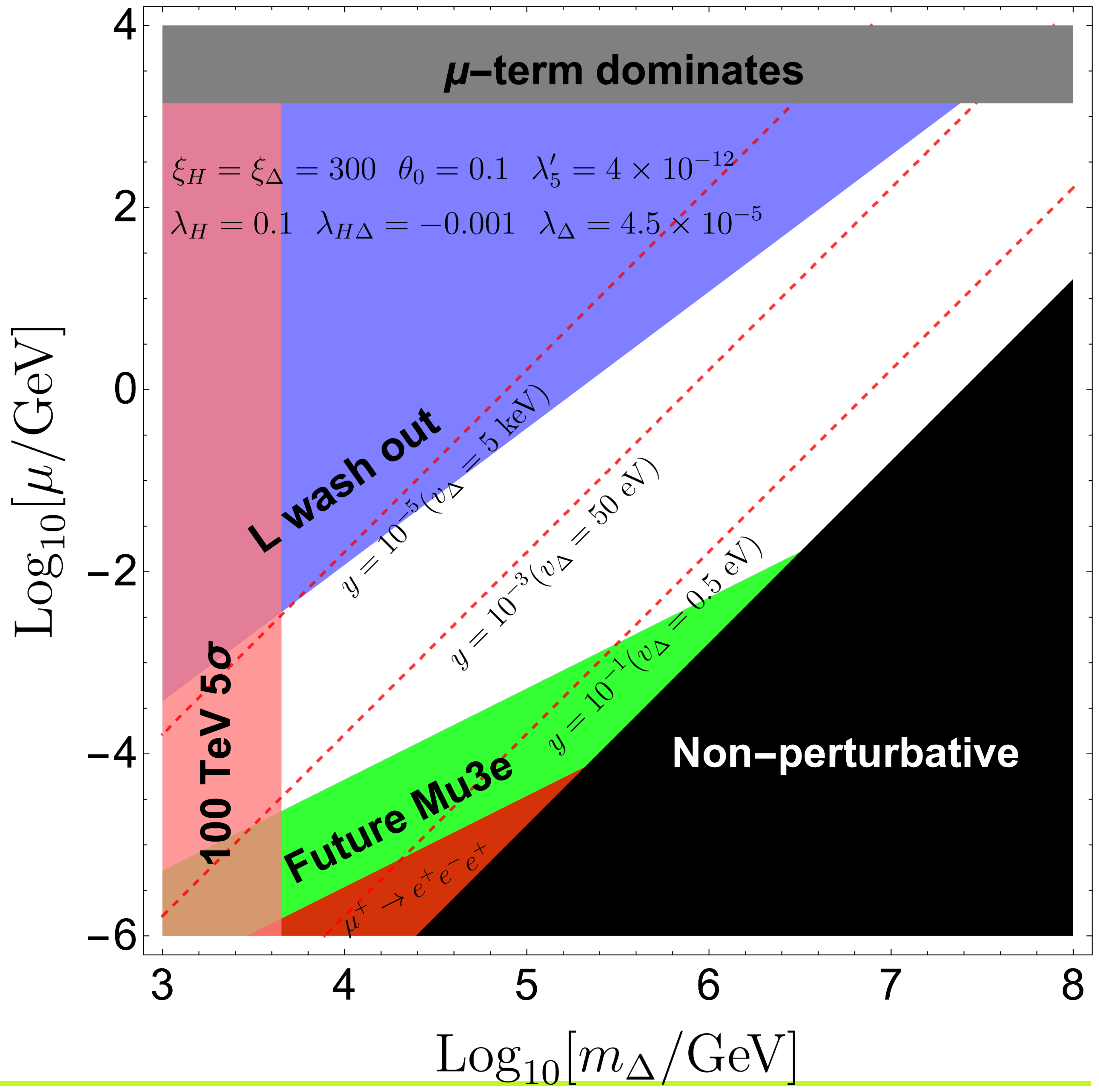
Large LNV

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}M_p^2R - F(H,\Delta)R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H) - g^{\mu\nu}(D_\mu\Delta)^\dagger(D_\nu\Delta) - V(H,\Delta) + \mathcal{L}_{\text{Yukawa}} . \quad (10)$$

Flatten the Potential

$$\eta = \left.\frac{n_B}{s}\right|_{\text{reh}} = \eta_B^{\text{obs}}\left(\frac{|n_{L\text{end}}|/M_p^3}{1.3\times10^{-16}}\right)\left(\frac{g_*}{112.75}\right)^{-1/4},$$

BAU



Leptogenesis via Primordial Black Hole

T. Fujita, et al., 2014

$$(\mathrm{PBH}) \xrightarrow[\times N_\nu]{\text{evaporation}} \begin{pmatrix}\text{right-handed}\\ \text{neutrino}\end{pmatrix} \xrightarrow[\times \epsilon]{\text{decay}} \begin{pmatrix}\text{lepton}\\ \text{number}\end{pmatrix} \xrightarrow[\times \kappa]{\text{sphaleron}} \begin{pmatrix}\text{baryon}\\ \text{number}\end{pmatrix},$$

N_ν: The number of neutrino emitted from one PBH

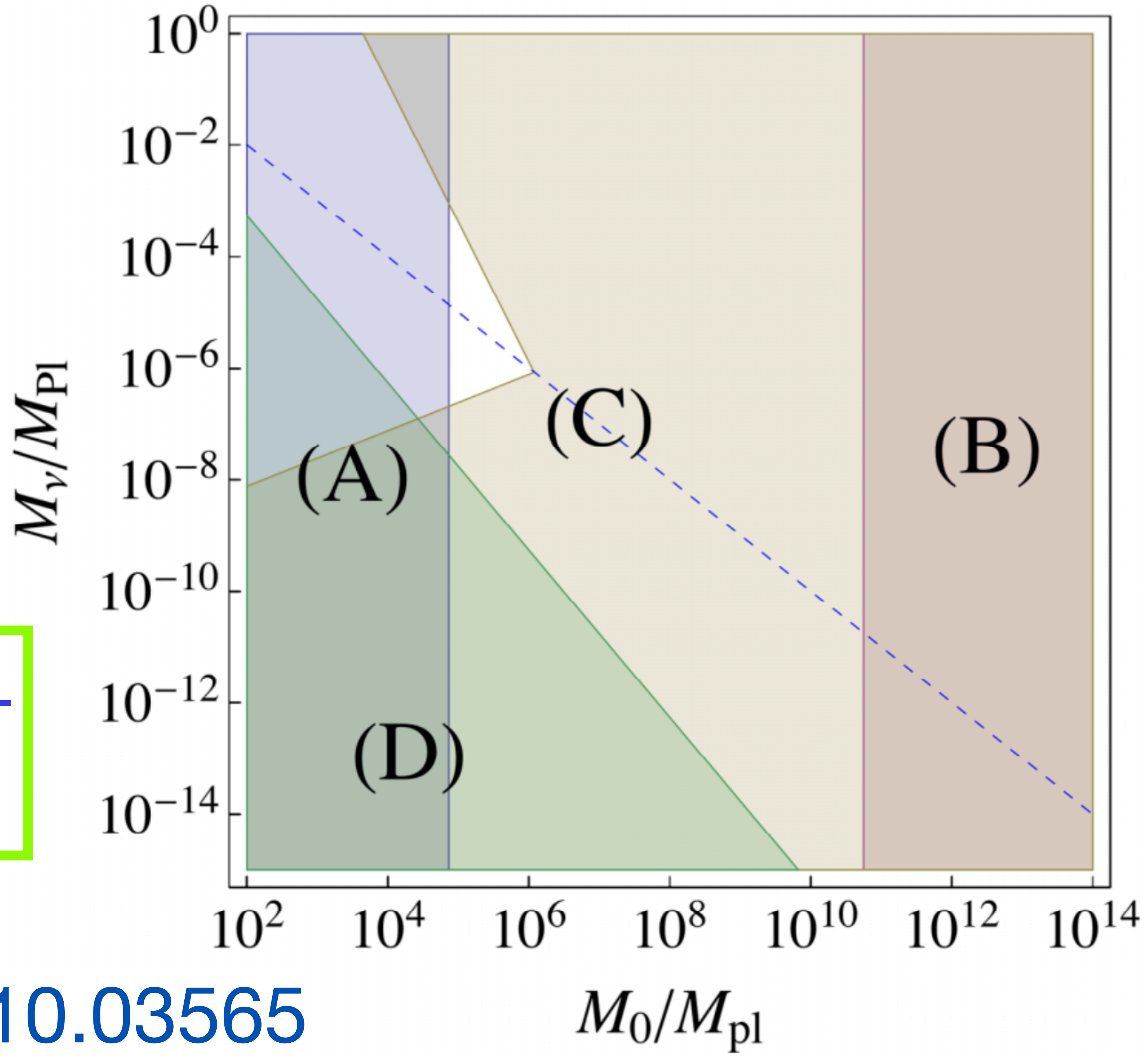
ε: CP asymmetry

κ: efficiency factor

$$\frac{n_B}{s}(t_{\text{now}}) = N_\nu \epsilon \kappa \frac{n_{\text{PBH}}}{s}(t_{\text{evap}})\alpha^{-1}$$

$$\simeq N_\nu \epsilon \kappa \frac{(\pi^2/30) g_* T_{\text{evap}}^4 / M_0}{\alpha (2\pi^2/45) g_* T_{\text{evap}}^3}$$

$$\simeq 0.4 \times \frac{N_\nu \epsilon \kappa}{\alpha}\left(\frac{M_0}{M_{\text{Pl}}}\right)^{-5/2}\left(\frac{g}{100}\right)^{1/2}\left(\frac{g_*}{100}\right)^{-1/4},$$



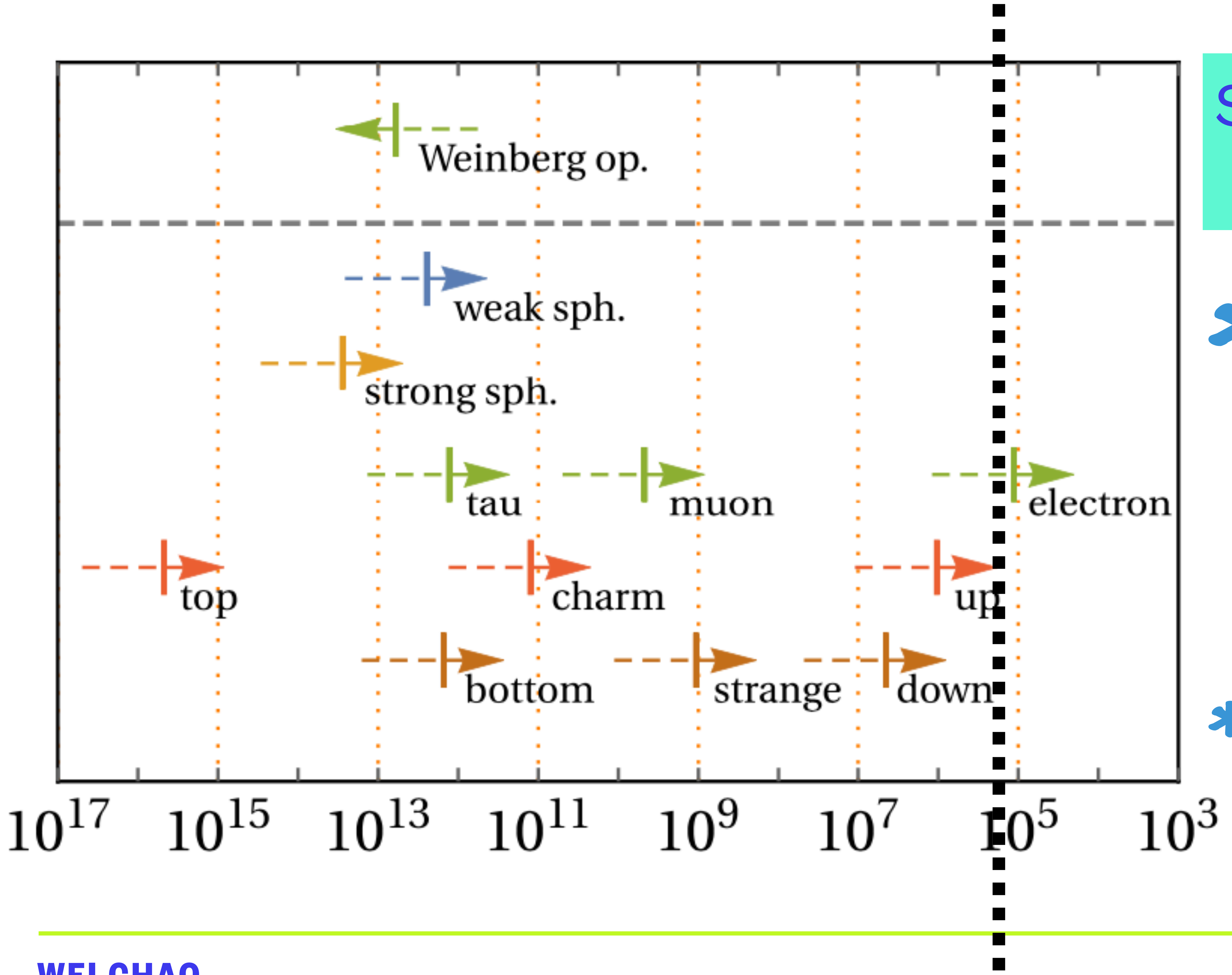
Interplay between thermal right-handed neutrino and non-thermal right-handed neutrinos

$$aH\frac{dn^{\text{B}-\text{L}}}{da} = \varepsilon^1\left[(n_{N_1}^{\text{TH}} - n_{N_1}^{\text{eq}})\Gamma_{N_1}^{T} + n_{N_1}^{\text{BH}}\Gamma_{N_1}^{\text{BH}}\right] + W$$

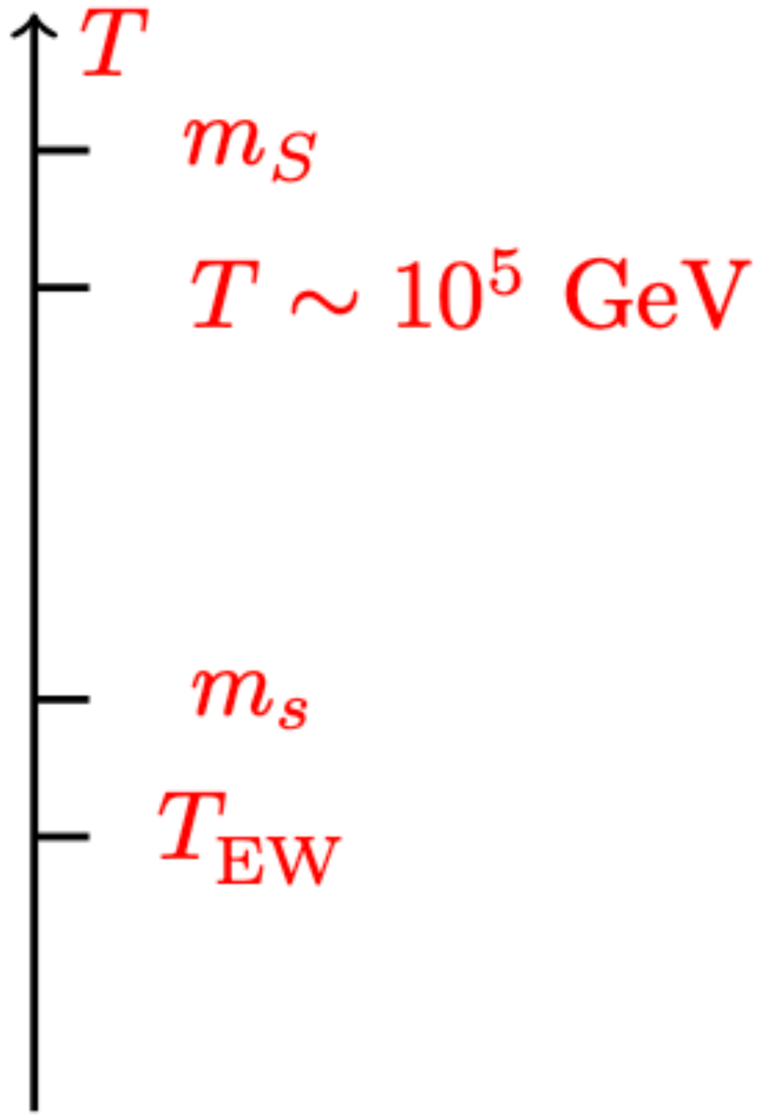
Perez-Gonzalez&Turner, 2010.03565

Leptogenesis via Symmetry Non-Restoration

- **Wei Chao, 2024**



Sphaleron quenches at 10^5 GeV or higher scale.

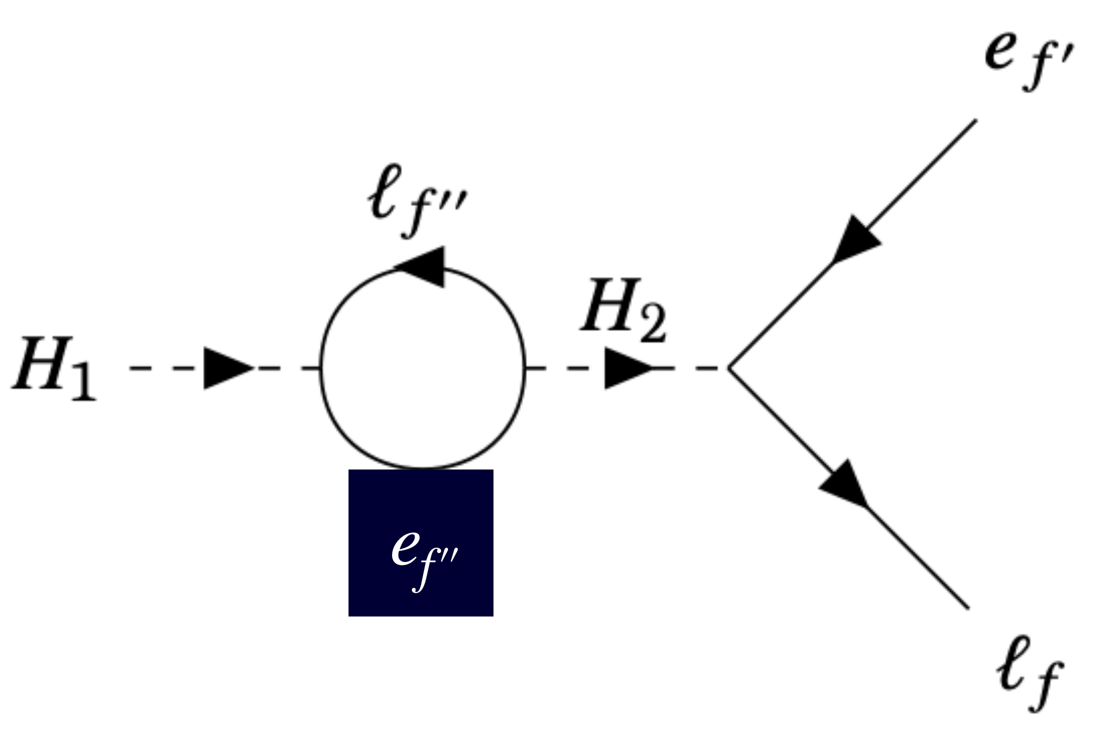


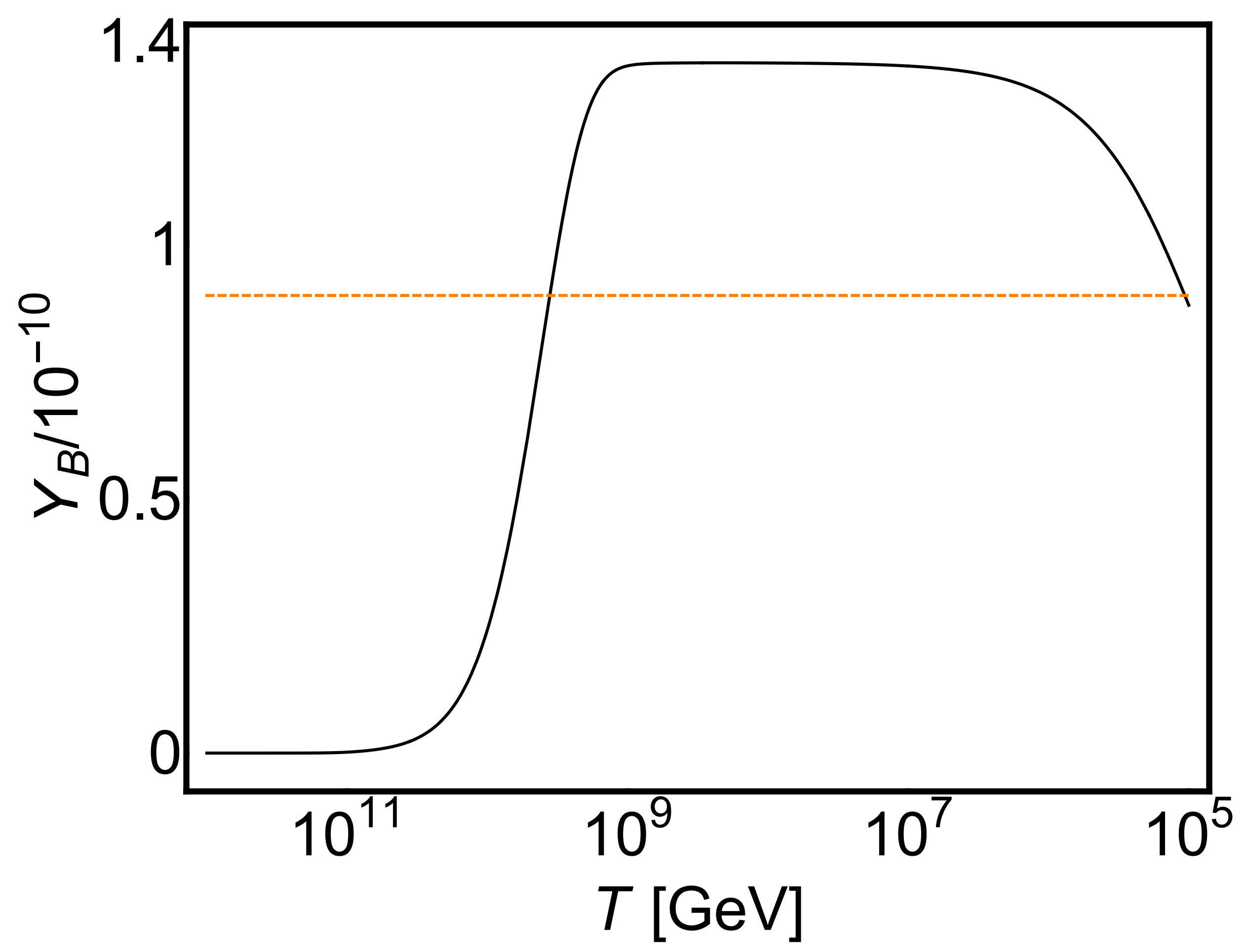
- Left-handed Electron asymmetry can be transported to the BAU via sphaleron.
- No B-L violation is needed!

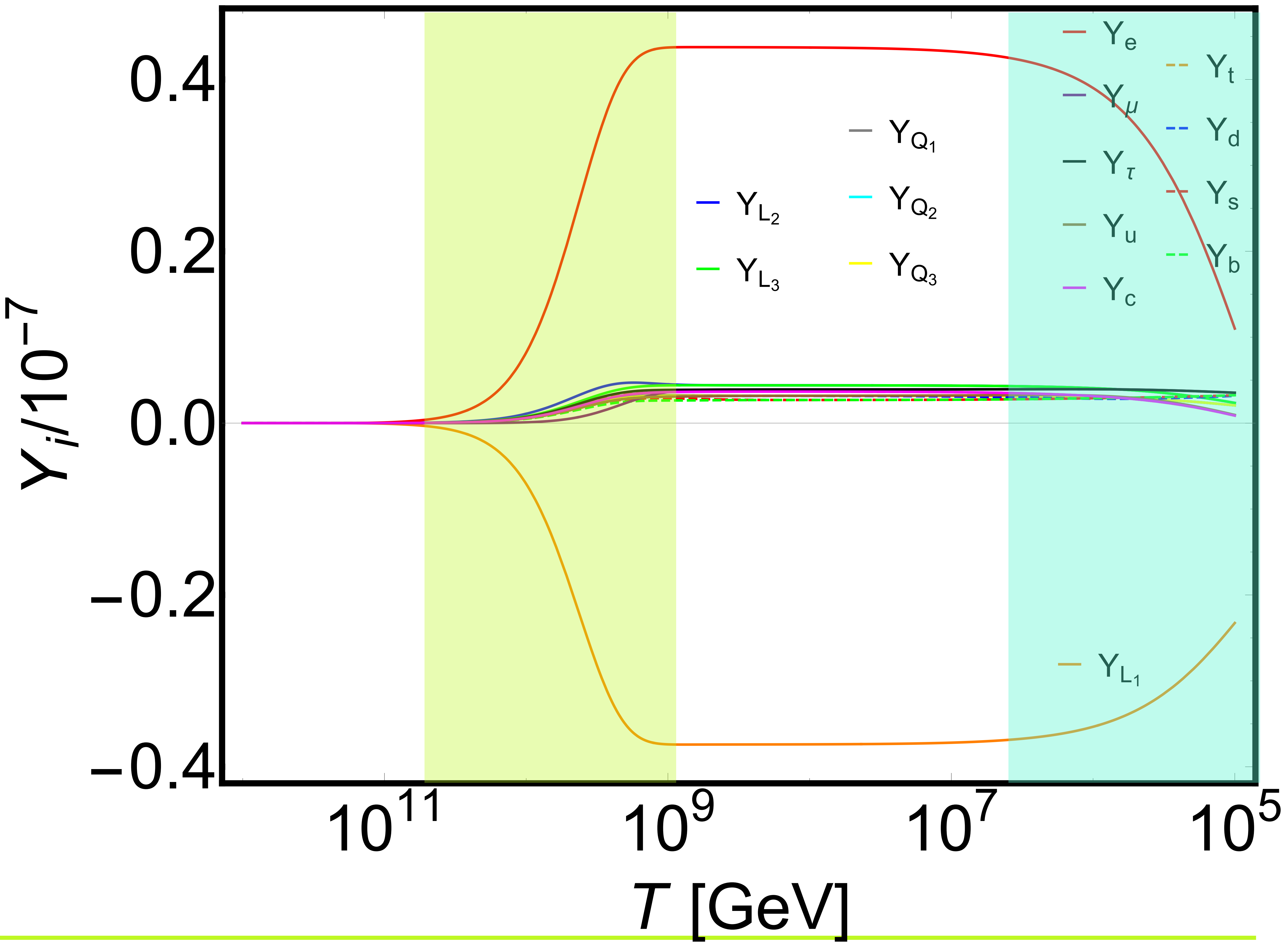
Leptogenesis via Symmetry Non-Restoration

- **Wei Chao, 2024**

- **Higgs doublet decay into chiral electrons with CP violation**







- **Chiral asymmetries are generated in the first generation.**

Leptogenesis Via Chiral Magnetic Effect

- **Wei Chao, 2025**

Lagrangian/Action for hyper magnetic field in the presence of chemical potential

$$-\mathscr{L} \sim \frac{1}{4} Y_{\mu\nu} Y^{\mu\nu} + C_{EW} n_{CS}^{EW} + C_Y N_{CS}^Y + j^\mu Y_\mu + \cdots$$

$$C_Y = \sum_{i=1}^{3} \left[-2\mu_{R_i} + \mu_{L_i} - \frac{2}{3}\mu_{d_i} - \frac{8}{3}\mu_{u_{Ri}} + \frac{1}{3}\mu_{Q_i} \right] \qquad N_{CS}^Y = \frac{g^{'2}}{32\pi^2} 2Y \cdot B_Y$$

- **Maxwell equations**

$$\frac{\partial E}{\partial \eta} - \nabla \times B + J = 0 \qquad \frac{\partial B}{\partial \eta} + \nabla \times E = 0 \qquad \nabla \cdot E = \rho \qquad \nabla \cdot B = 0$$

$$J = \sigma(E + v \times B) + \frac{2\alpha}{\pi} C_Y B$$

CME: When a medium with a chiral asymmetry is exposed to a magnetic field there is an induced electric current

Leptogenesis Via Chiral Magnetic Effect

EOM for helicity and the energy density of magnetic field

$$h = \int \frac{d^3x}{V} A \cdot B = \int dk h_k \qquad \rho_B = \int \frac{d^3x}{V} \frac{1}{2} B^2 = \int dk \rho_k$$

- **EOM**

$$\frac{\partial h}{\partial \eta} = \lim_{V \to \infty} \int \frac{d^3x}{V} \left(2B \cdot \nabla^2 A \frac{1}{\sigma} + \frac{4\alpha}{\pi} \frac{C_{CS}}{\sigma} B_Y^2 \right)$$

$$\boxed{-T\frac{\partial h_k}{\partial T} = -\frac{2k^2}{\sigma_0}\frac{T}{H} h_k + \frac{8\alpha}{\pi\sigma_0}\left(\frac{C_{CS}^Y}{T}\right)\frac{T}{H}\rho_k \qquad -T\frac{\partial \rho_k}{\partial T} = -\frac{2k^2}{\sigma_0}\frac{T}{H}\rho_k + \frac{2\alpha k^2}{\pi\sigma_0}\left(\frac{C_{CS}^Y}{T}\right)\frac{T}{H} h_k}$$

Leptogenesis Via Chiral Magnetic Effect

- **Wei Chao, 2025**

B&L violations via Triangle anomalies

$$\partial_\mu j_L^\mu = \frac{N_f}{32\pi^2}(-g^2 W\widetilde{W} + g'^2 B\widetilde{B}) \qquad \Delta B = \Delta L = N_g(\Delta N_{CS}^W - \Delta N_{CS}^Y) \qquad \Delta N_{CS}^Y = \frac{g_Y^2}{16\pi^2}\Delta H$$

- **Traditional Leptogenesis:** $\Delta N_{CS}^Y = 0$ — **Source term comes from the LNV decay of seesaw particles**

- **Magnetogenesis:** $\Delta N_{CS}^Y \neq 0$ — **No other source term**

- **What we focus on:** $\Delta N_{CS}^Y = 0 \;\&\; B \neq 0$ — **There might be non-helical magnetic field in the early universe.**

Leptogenesis Via Chiral Magnetic Effect

- $U(1)_{L_e-L_\mu}$

Triangle anomalies

$$\partial_\mu\left(j^\mu_{L_{e/\mu}}\right) = \frac{1}{32\pi^2}\left(g^2W\widetilde{W}+g'^2F\widetilde{F}+4g_X^2F'\widetilde{F'}\right) \quad (2)$$

$$\partial_\mu\left(j^\mu_{E_{e/\mu}}\right) = \frac{1}{16\pi^2}\left(-g'^2F\widetilde{F}-g_X^2F'\widetilde{F'}\right) \quad (3)$$

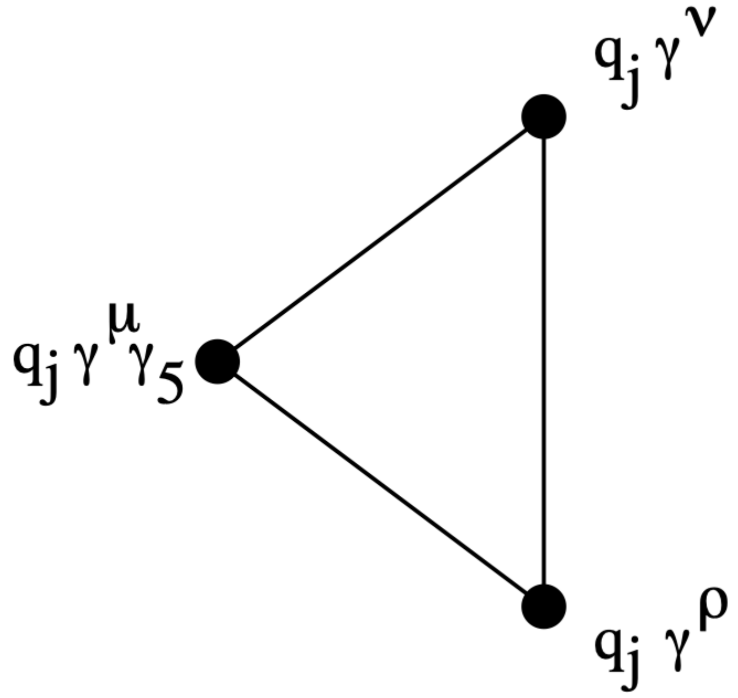
$$\partial_\mu\left(j^\mu_{L_\tau}\right) = \frac{1}{32\pi^2}\left(g^2W\widetilde{W}+g'^2F\widetilde{F}\right) \quad (4)$$

$$\partial_\mu\left(j^\mu_{E_\tau}\right) = \frac{1}{16\pi^2}\left(-g'^2F\widetilde{F}\right) \quad (5)$$

$$\partial_\mu\left(j^\mu_{B,Q}\right) = \frac{1}{32\pi^2}\left(g^2W\widetilde{W}+\frac{1}{9}g'^2F\widetilde{F}\right) \quad (6)$$

$$\partial_\mu\left(j^\mu_{B,u}\right) = \frac{1}{16\pi^2}\left(-\frac{4}{9}g'^2F\widetilde{F}\right) \quad (7)$$

$$\partial_\mu\left(j^\mu_{B,d}\right) = \frac{1}{16\pi^2}\left(-\frac{1}{9}g'^2F\widetilde{F}\right) \quad (8)$$

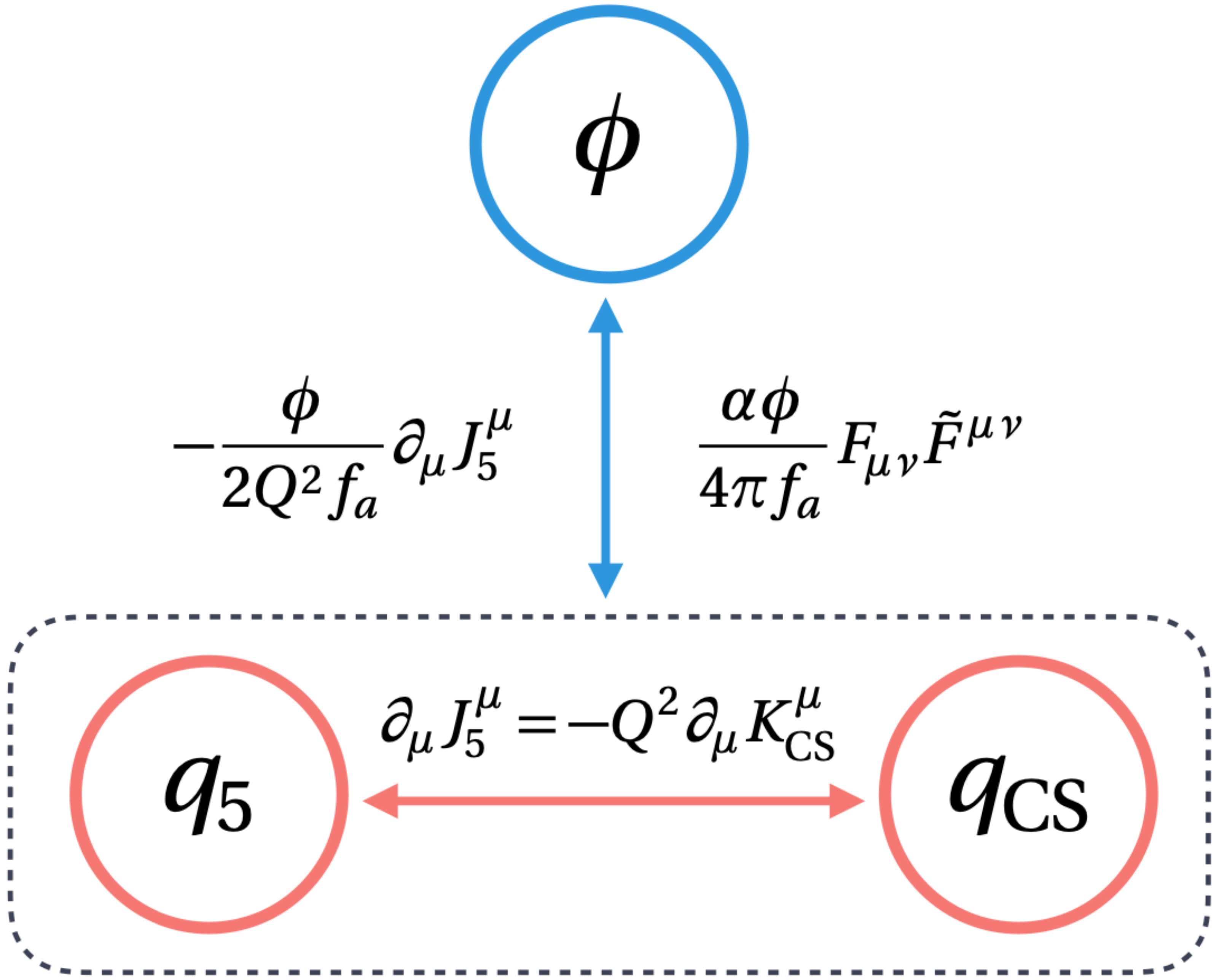


$$\boxed{\partial_\mu\left(j^\mu_B-j^\mu_L\right) = -\frac{g_X^2}{8\pi^2}F'\widetilde{F}' \neq 0}$$

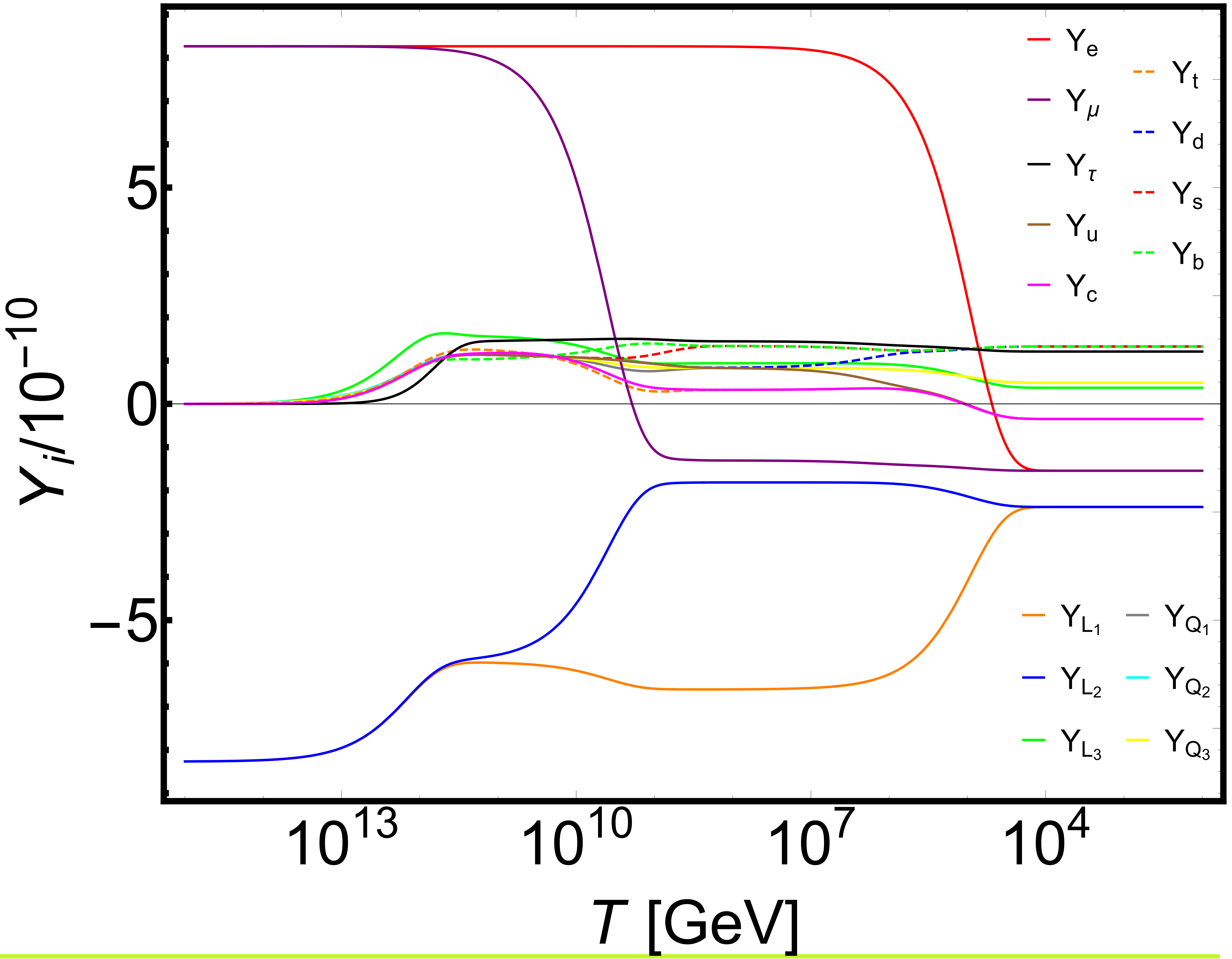
Leptogenesis Via Chiral Magnetic Effect

- **Case I: New gauge field carry non-zero helicity and the symmetry is broken at high scale**

- **Axion inflation** $\rightarrow q_{CS} \rightarrow q_5$



V. Domcke and K. Mukaida, JCAP 2018



Leptogenesis Via Chiral Magnetic Effect

- **Case II: No primordial B-L asymmetry and no primordial helical magnetic field**

$$-\frac{d}{d\ln T}\left(\frac{\mu_{E_i}}{T}\right) = -\frac{1}{g_{E_i}}\frac{\gamma_{E_i}}{H}\left(\frac{\mu_{E_i}}{T}-\frac{\mu_{L_i}}{T}+\frac{\mu_H}{T}\right) + q_e^2\gamma_y + q_l^2\gamma_l \quad (6)$$

$$-\frac{d}{d\ln T}\left(\frac{\mu_{L_i}}{T}\right) = +\frac{1}{g_{E_i}}\frac{\gamma_{E_i}}{H}\left(\frac{\mu_{E_i}}{T}-\frac{\mu_{L_i}}{T}+\frac{\mu_H}{T}\right) - \frac{1}{g_{L_i}}\frac{\gamma_{WS}}{H}\left[\sum_i \frac{\mu_{L_i}}{T} + 3\sum_i \frac{\mu_{Q_i}}{T}\right] - q_L^2\gamma_y - q_l^2\gamma_l \quad (7)$$

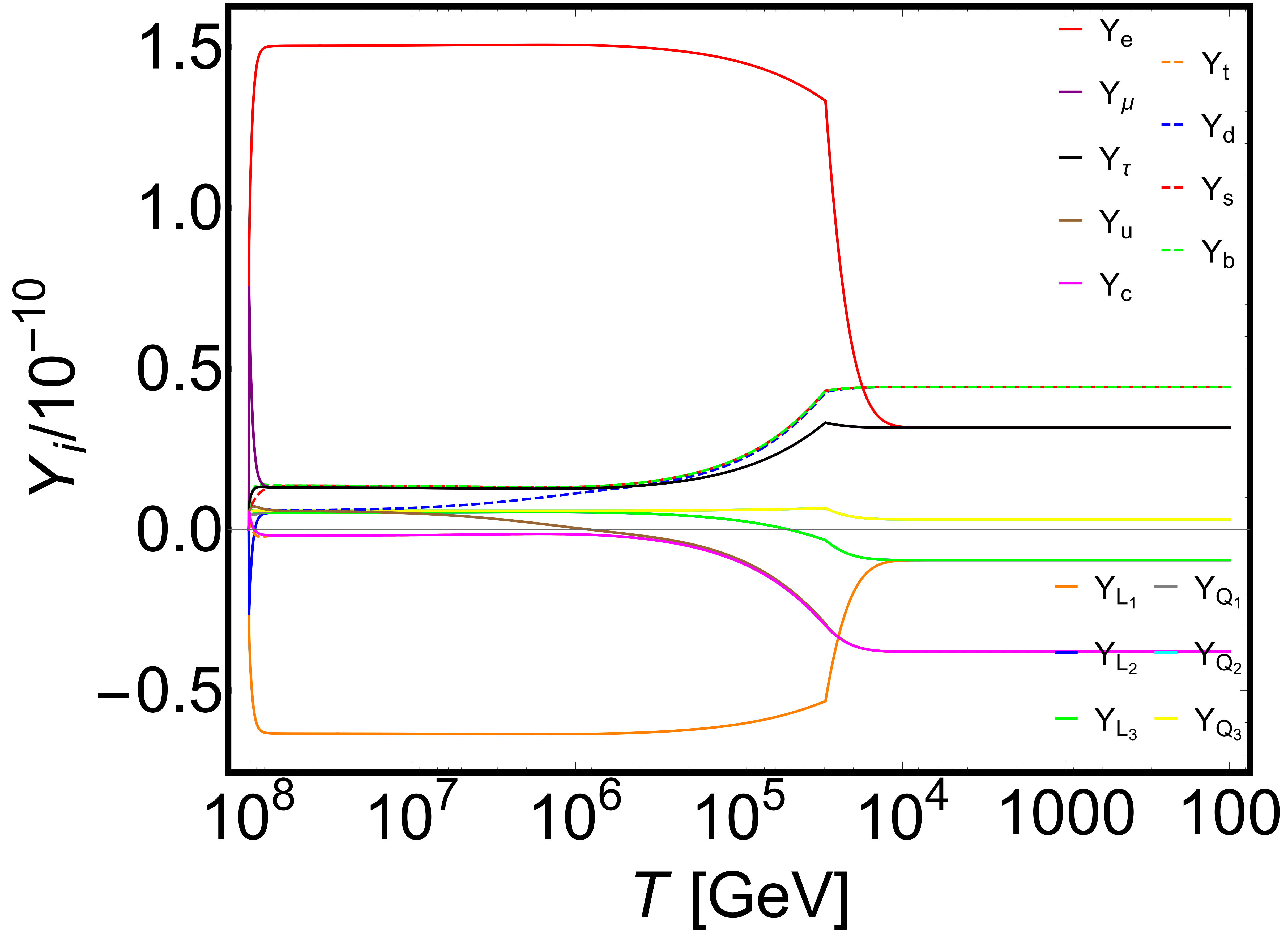
$$-\frac{\partial h_k}{\partial \ln T} = -\frac{2k^2}{\sigma_0}\frac{T}{H}h_k + \frac{8\alpha'}{\pi\sigma_0}\frac{T}{H}\frac{\mu_X}{T}\rho_k$$

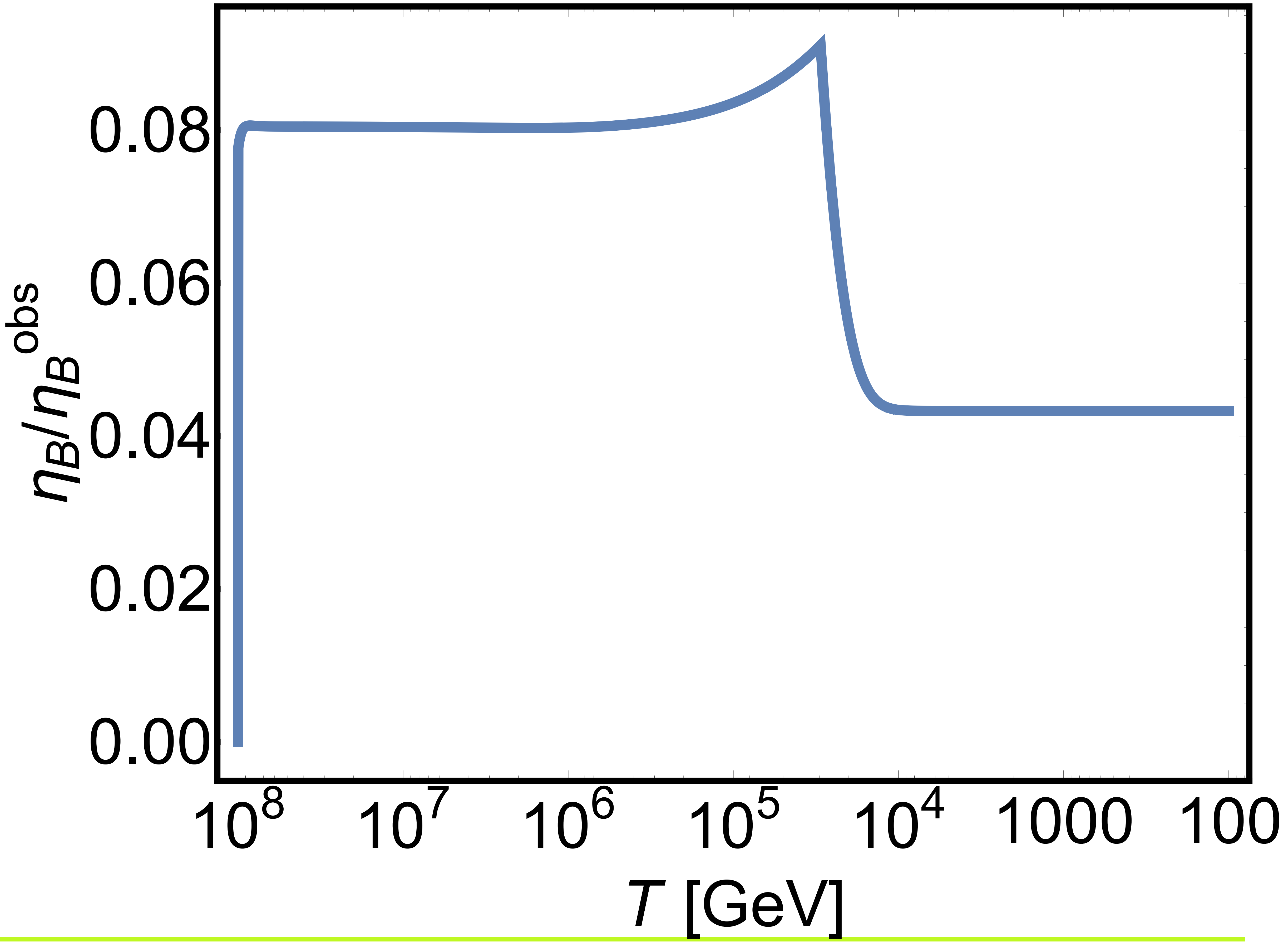
$$-\frac{\partial \rho_k}{\partial \ln T} = -\frac{2k^2}{\sigma_0}\frac{T}{H}\rho_k + \frac{2\alpha' k^2}{\pi\sigma_0}\frac{T}{H}\frac{\mu_X}{T}h_k$$

$$\frac{\mu_X}{a} = -2\mu_{L_1} - 2\mu_{L_2} + \mu_{e_1} + \mu_{e_2} \,.$$

Leptogenesis Via Chiral Magnetic Effect

- **Case II: No primordial B-L asymmetry and no primordial helical magnetic field**





Conclusion

问题本身十分重要，值得持续深入的探索

CTP formalism

Flavor effect

Casas-Ibarra parametrization

Effective field theory

Resonant Leptogenesis

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Thank you for your attention!