The 2025 Beijing Particle Physics and Cosmology Symposium (BPCS 2025): early Universe, gravitational-wave templates, collider phenomenology

Spectator processes for Leptogenesis

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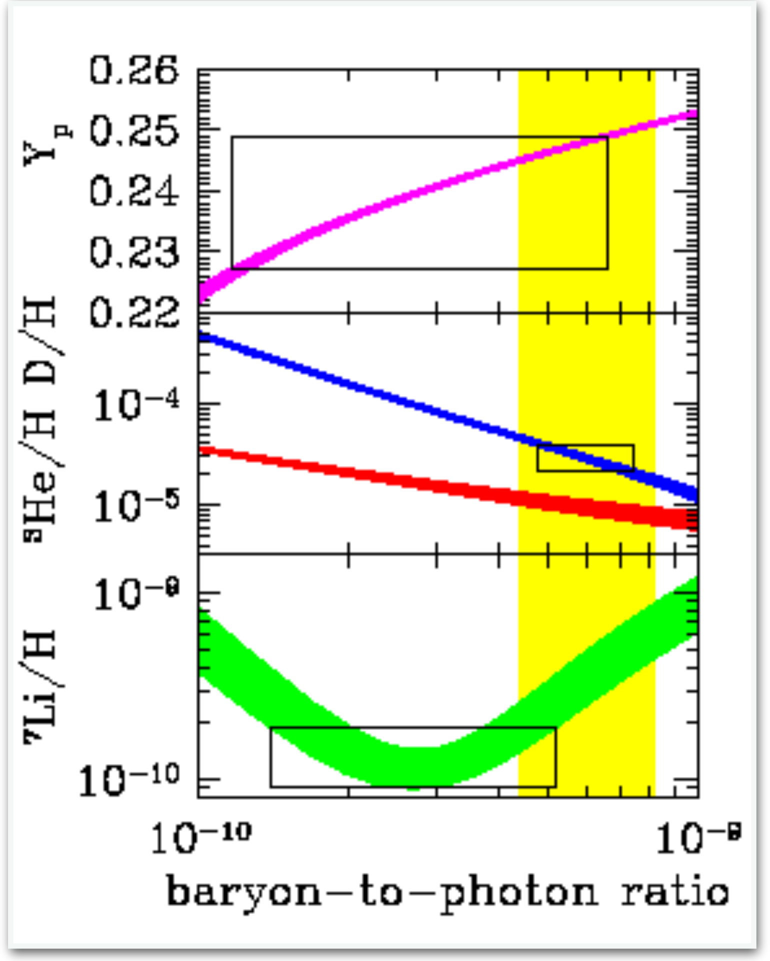
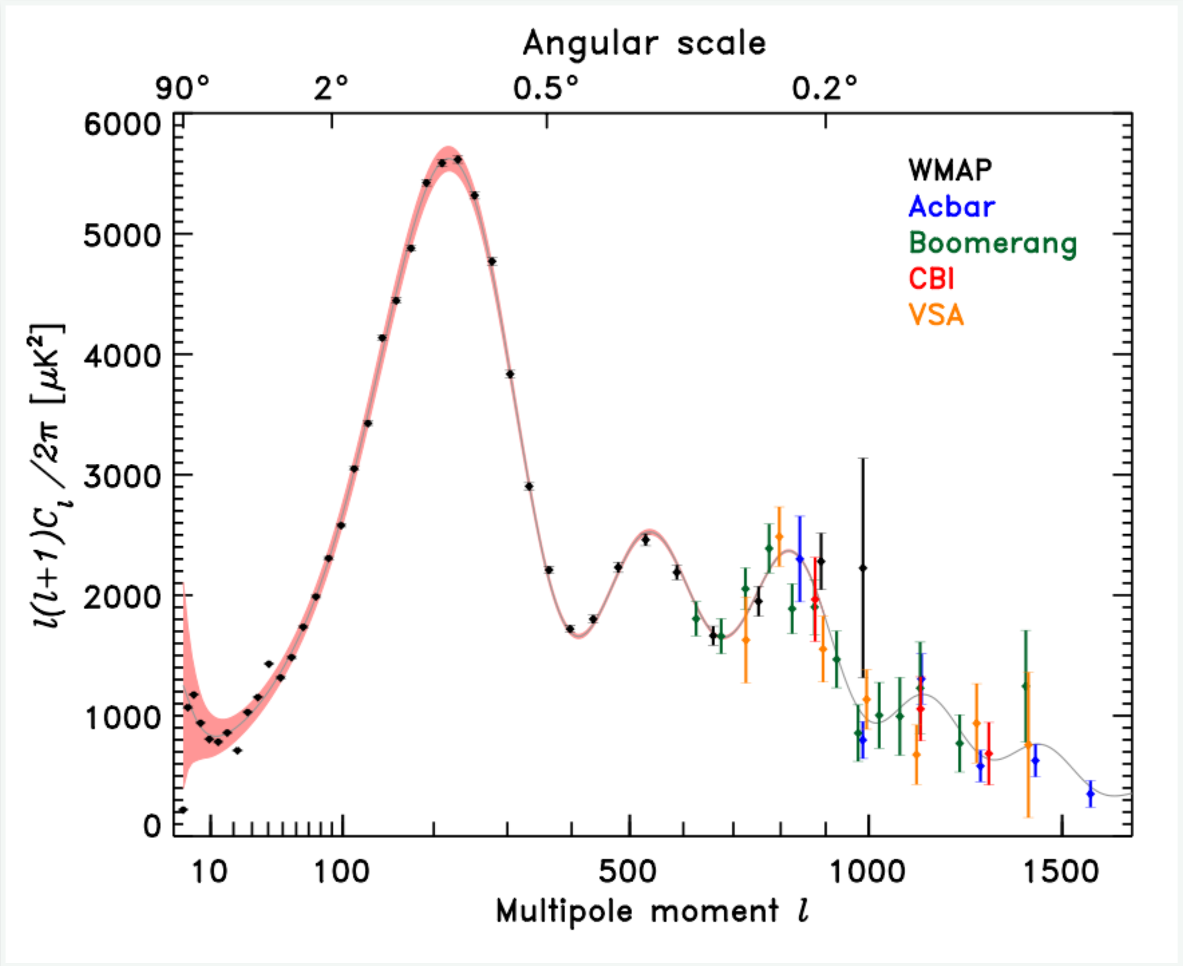
New physics—The Baryon asymmetry

Matter-antimatter asymmetry

❋No galaxy made by ant-baryon is observed

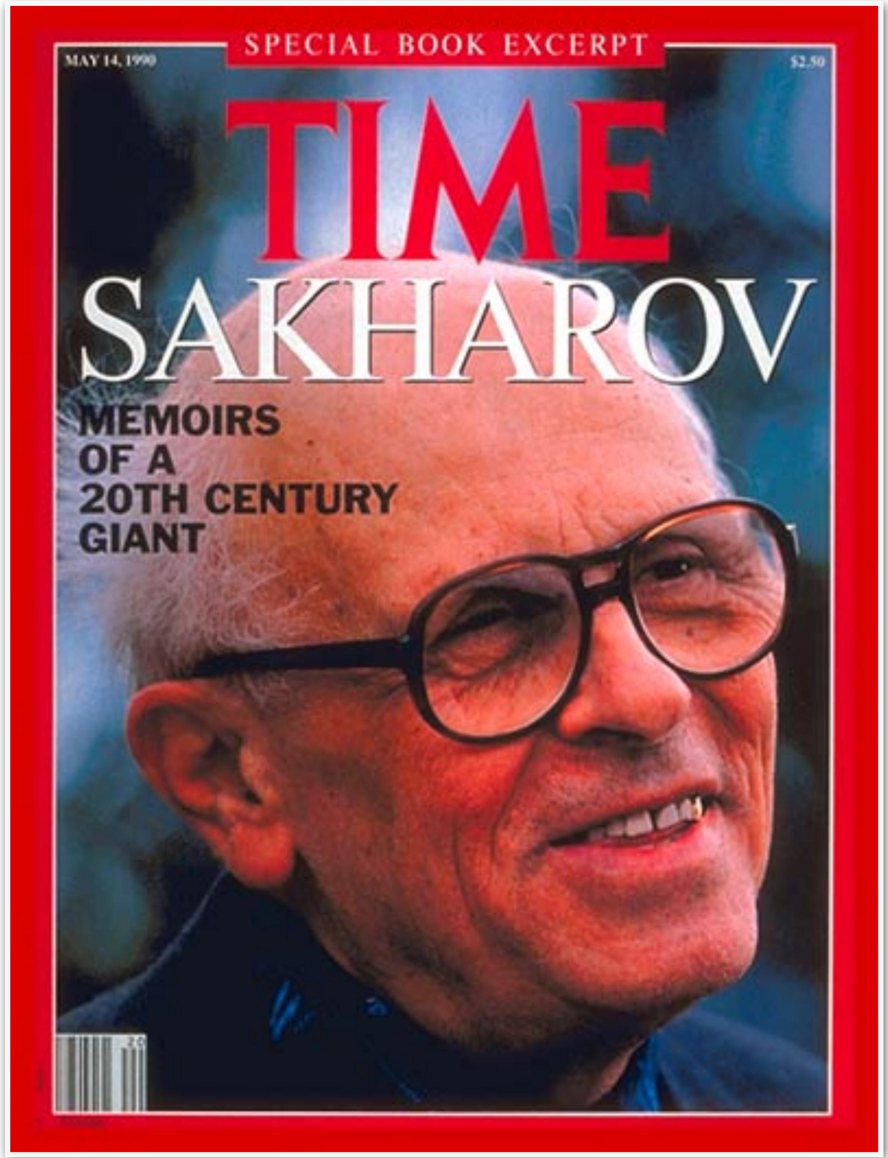
❋Baryon asymmetry is measured by the Planck.

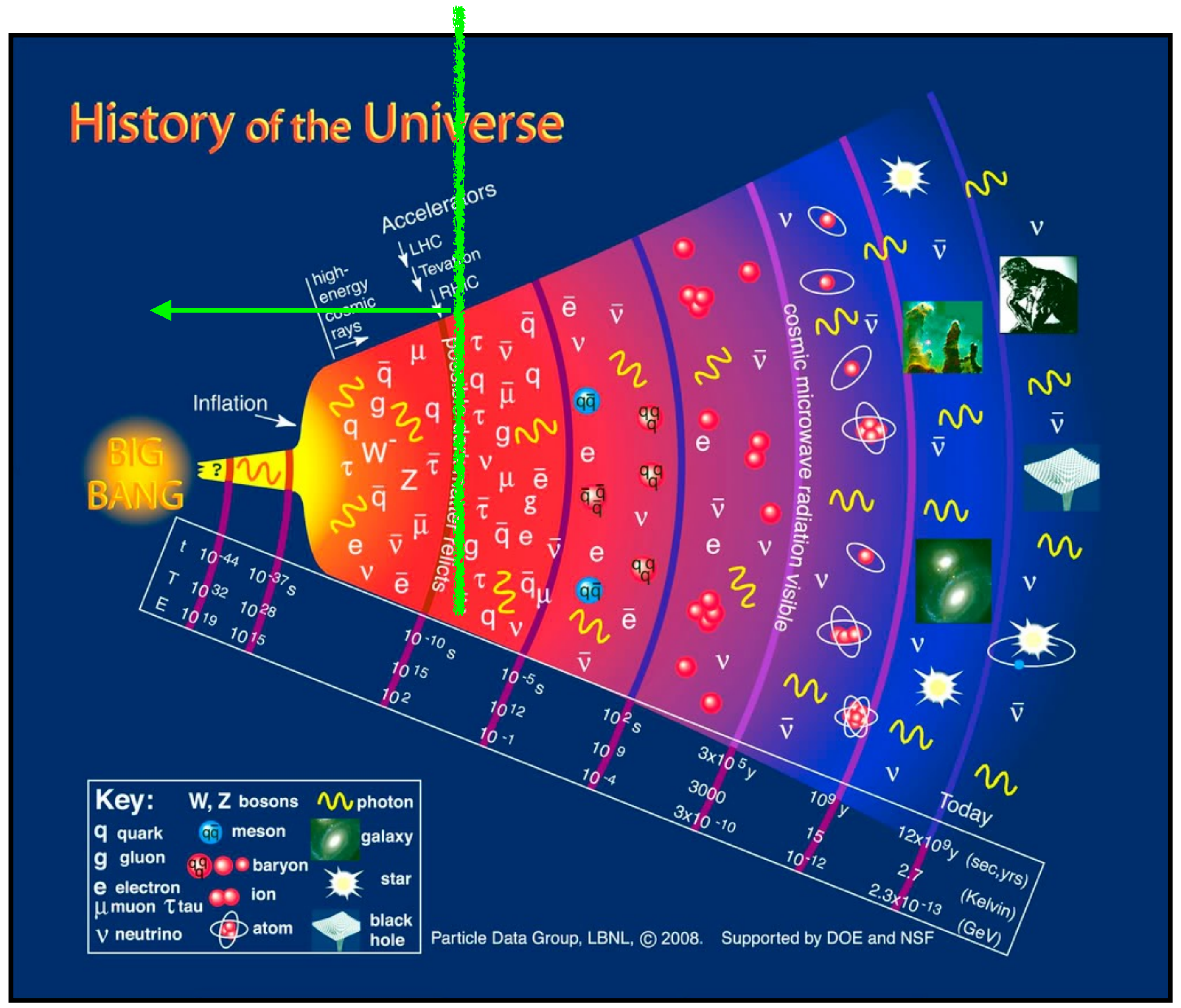




Baryon asymmetry: $Y_B = \frac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$ **Planck**

Baryogenesis





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

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

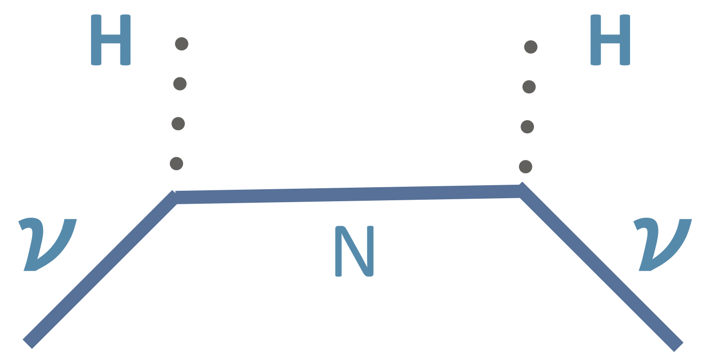
History and development: Leptogenesis

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



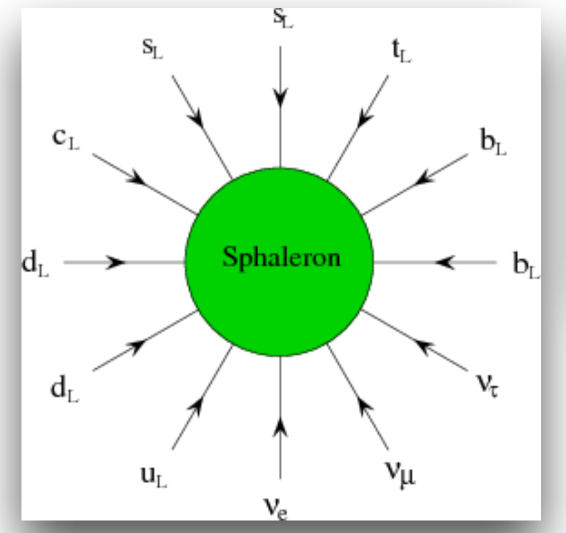
Neutrino mass:

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

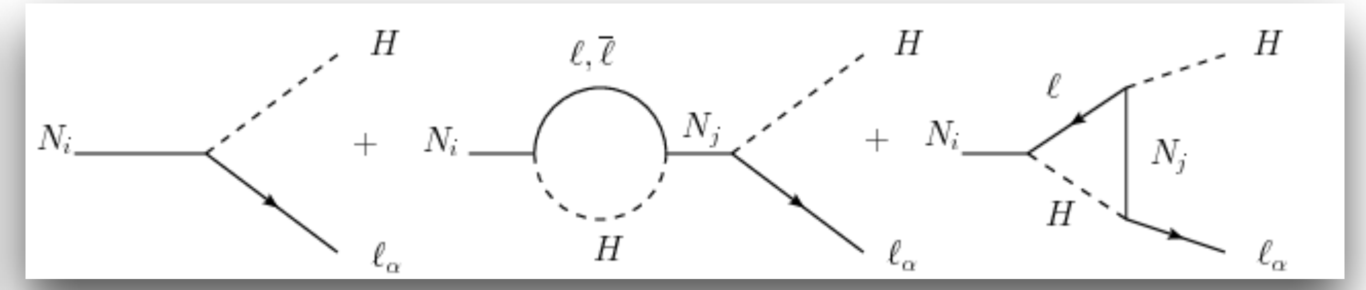
Elegant but losing testability at colliders!

Leotogenesis

BV



CPV



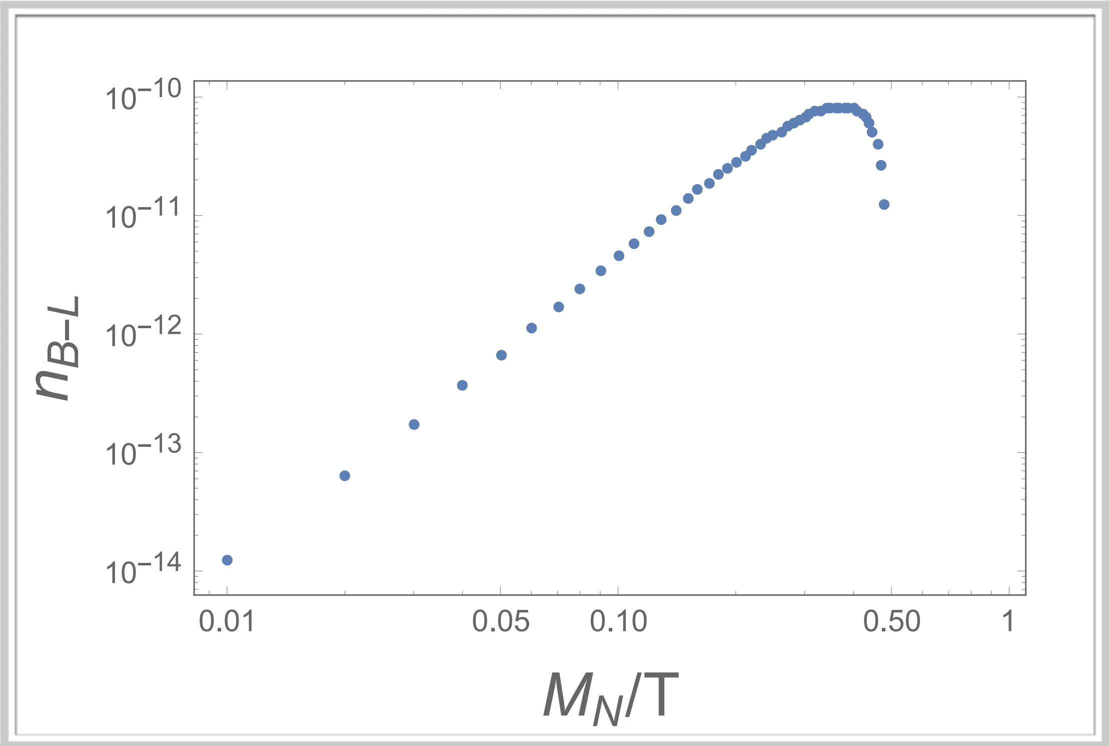
Out of EQ

Heavy neutrinos decouple

Boltzmann EQ

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

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



Outline

This talk focuses on spectator processes of Leptogenesis

- Scenario-1 : Modified spectator process induced by weak sphaleron

- Scenario-2 : Chiral Magnetic effect induced spectator process

Main point： Modified weak sphaleron for leptogenesis

Traditional Leptogenesis mechanism	• There should be primordial B-L violation • There should be right-handed neutrinos

Not necessary!

Sphaleron quenches before electron Yukawa interaction entering thermal equilibrium in the early universe!

Eogenesis via the High-scale Electroweak Symmetry Restoration

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2412.03902

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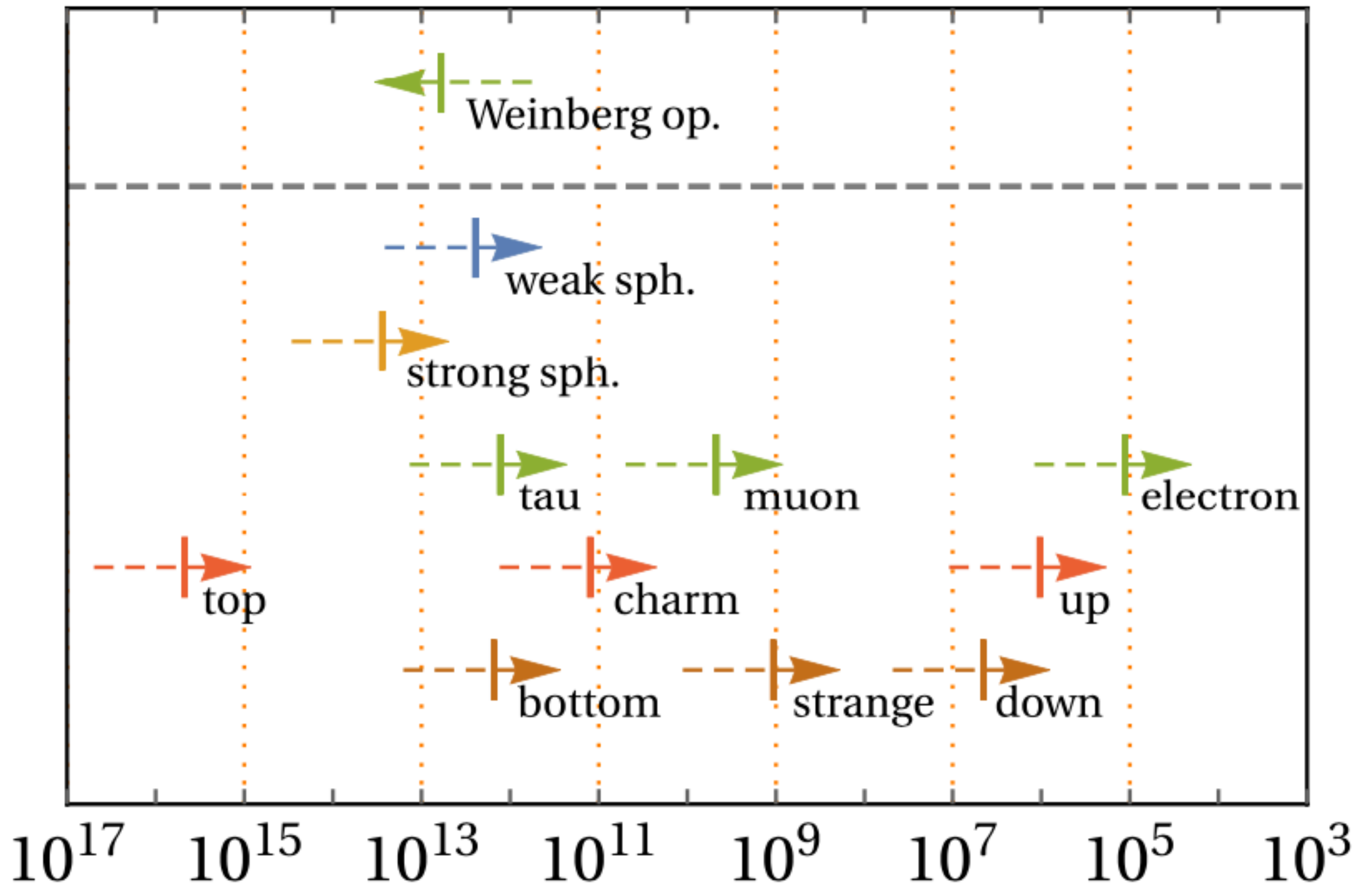
In this paper, we propose a novel electron-assisted Baryogenesis scenario that does not require explicit B-L violation, which is essential for the traditional Leptogenesis mechanism. This scenario

Parameters for various interactions

- **Key Point: Sphaleron may quench before the electron Yukawa interaction entering the equilibrium**

Interaction	Weinberg	WS	SS	Y_e	Y_μ	Y_τ
Γ_α/T^4	$\kappa_W \frac{m_\nu^2 T^2}{v_{EW}^4}$	$\frac{1}{2}\kappa_{WS}\alpha_2^5$	$\frac{1}{2}\kappa_{SS}\alpha_3^5$	$\kappa_{Y_e} y_e^2$	$\kappa_{Y_e} y_\mu^2$	$\kappa_{Y_e} y_\tau^2$
T_α [GeV]	6.0×10^{12}	2.5×10^{12}	2.8×10^{13}	1.1×10^5	4.7×10^9	1.3×10^{12}
Interaction	Y_u	Y_c	Y_t	Y_d	Y_s	Y_b
Γ_α/T^4	$\kappa_{Y_u} y_u^2$	$\kappa_{Y_u} y_c^2$	$\kappa_{Y_t} y_t^2$	$\kappa_{Y_d} y_d^2$	$\kappa_{Y_d} y_s^2$	$\kappa_{Y_d} y_b^2$
T_α [GeV]	1.0×10^6	1.2×10^{11}	4.7×10^{15}	4.5×10^6	1.1×10^9	1.5×10^{12}

Valerie Domck, Yohei Ema, Kyohei Mukai and Masaki Yamada, JHEP 08(2020)096

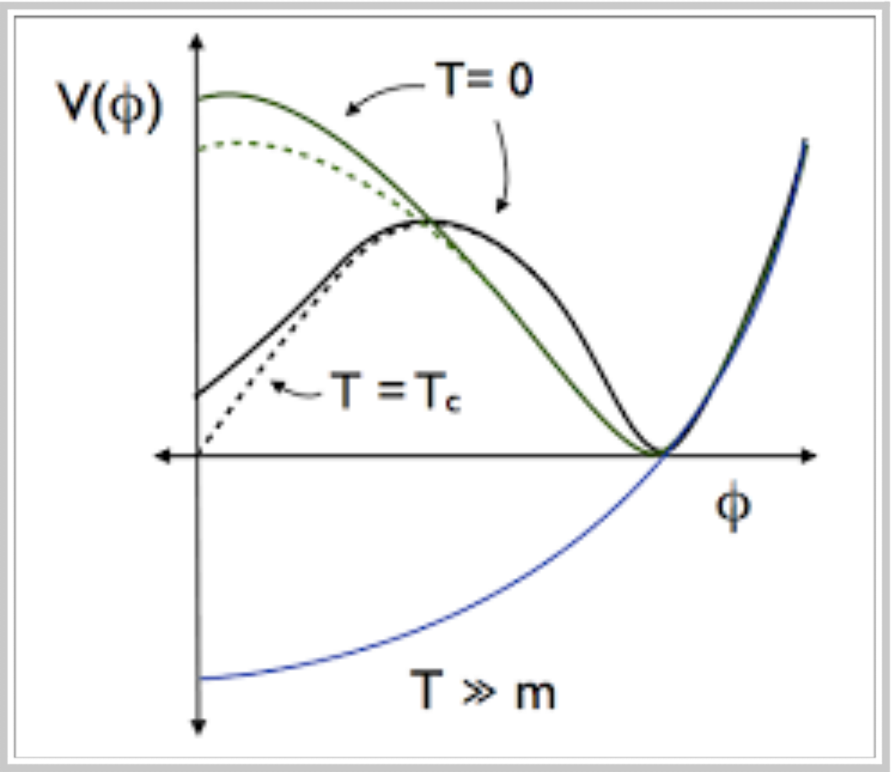


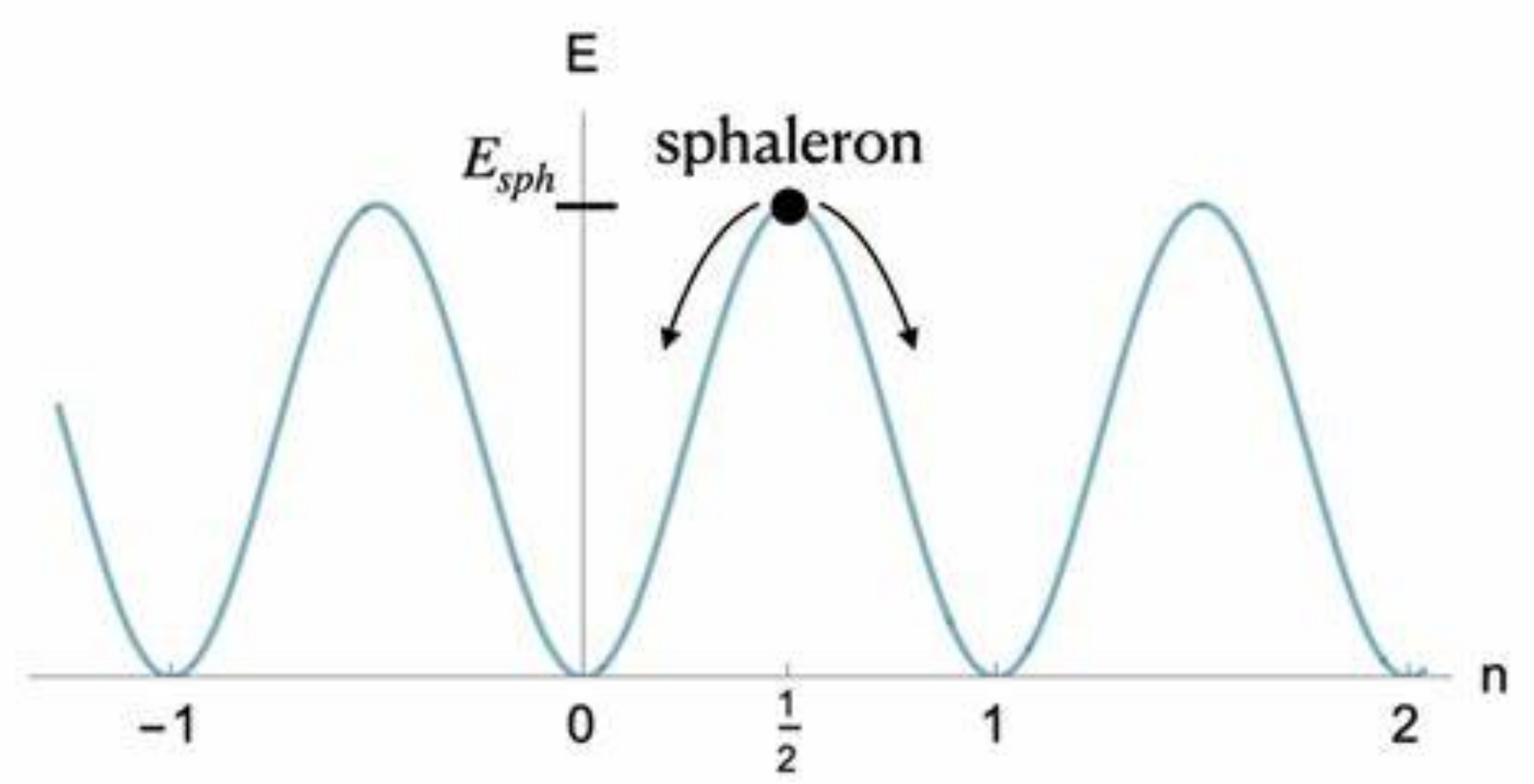
Sphaleron

- **Typical temperature:**

  Sphaleron quench temperature: T≈ 130 GeV

  Electroweak symmetry restored temperature: T≈ 160 GeV





$$\Gamma_{\rm sph}^{\rm brok}(T) = \kappa_{\rm brok}\alpha_W^4 T^4 \exp\left(-\frac{E_{\rm sph}}{T}\right) \quad (4)$$

Symmetry restoration at high T?

Conventional symmetry breaking sequence

The symmetry breaking order according to our imagination!

T — $SO(10), \cdots$

GUT — $SU(5)\times U(1)_X$ — $Pati-Salam$ — $\cdots$

EW — $SU(3)_C\times SU(2)_L\times U(1)_Y\times U(1)_{B-L}$ — $\cdots$

$SU(3)_C\times U(1)_{em}$ — $\cdots$

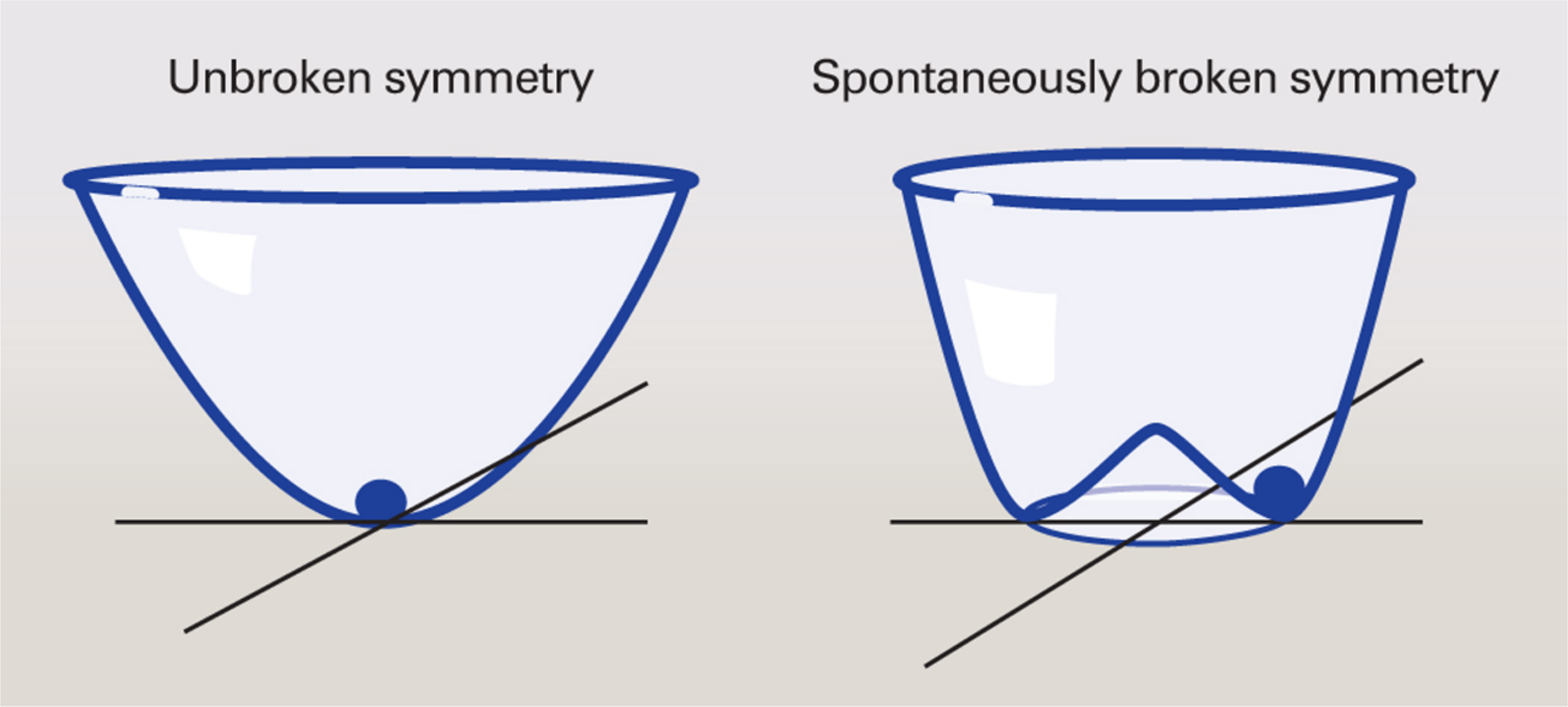
Question: Must all symmetries be restored at high T?

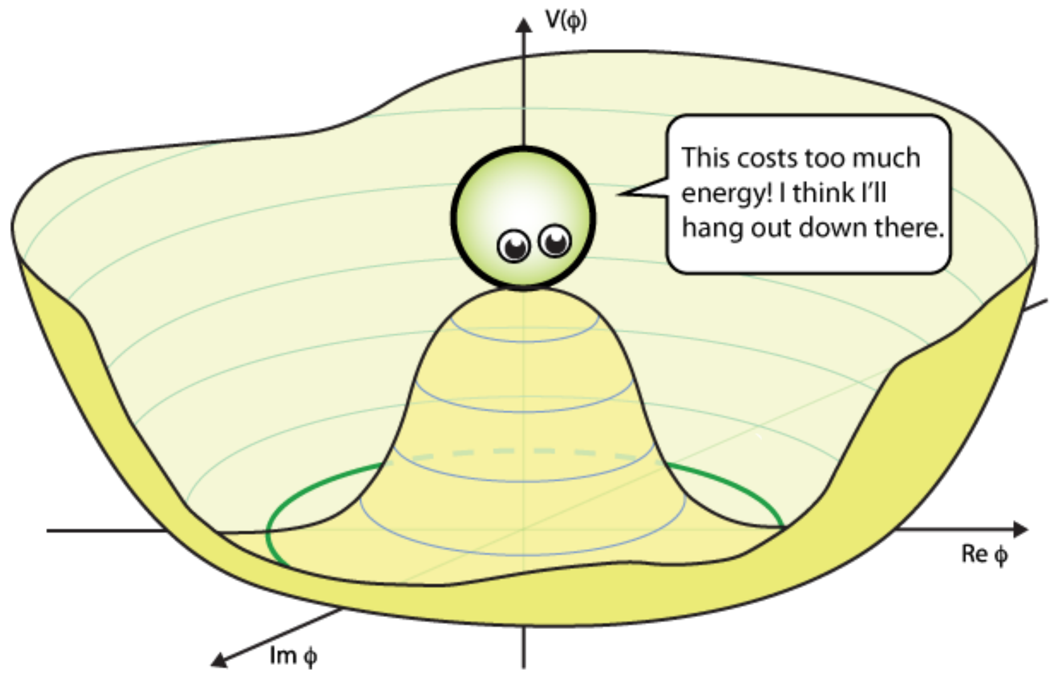
The really maybe not what we have imagined!

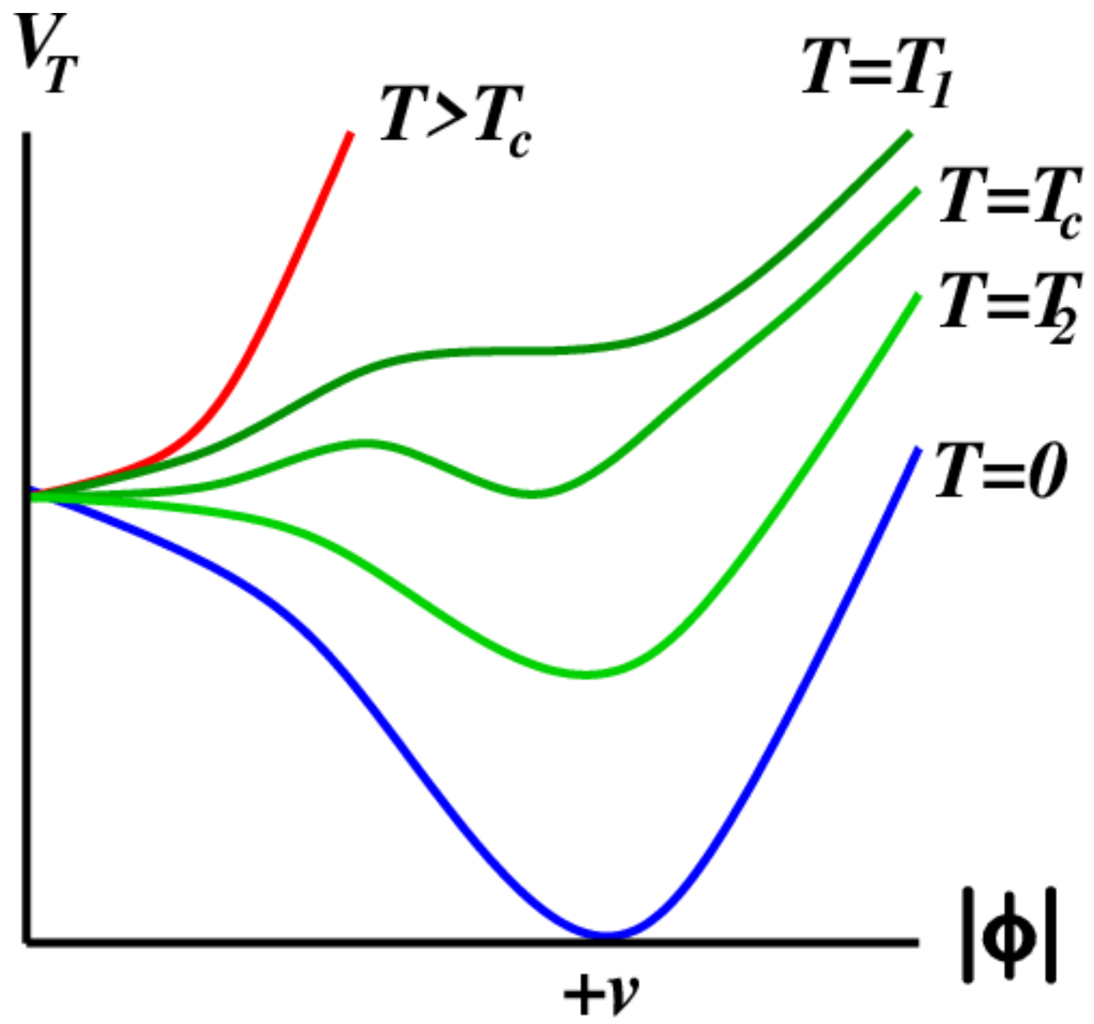
- O(n) x O(n): Weinberg (1974)
- SU(5): Dvali, Mohapatra, Senjanovic ('79, 80'S, 90'S)
- Cline, Moore, Servant et al (1999)
- EM: Langacker & Pi (1980)
- SU(3): Patel, Ramsey-Musolf, Wise (2013)

Symmetry at high temperature

- **EW symmetry non-restoration!**







$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4$$

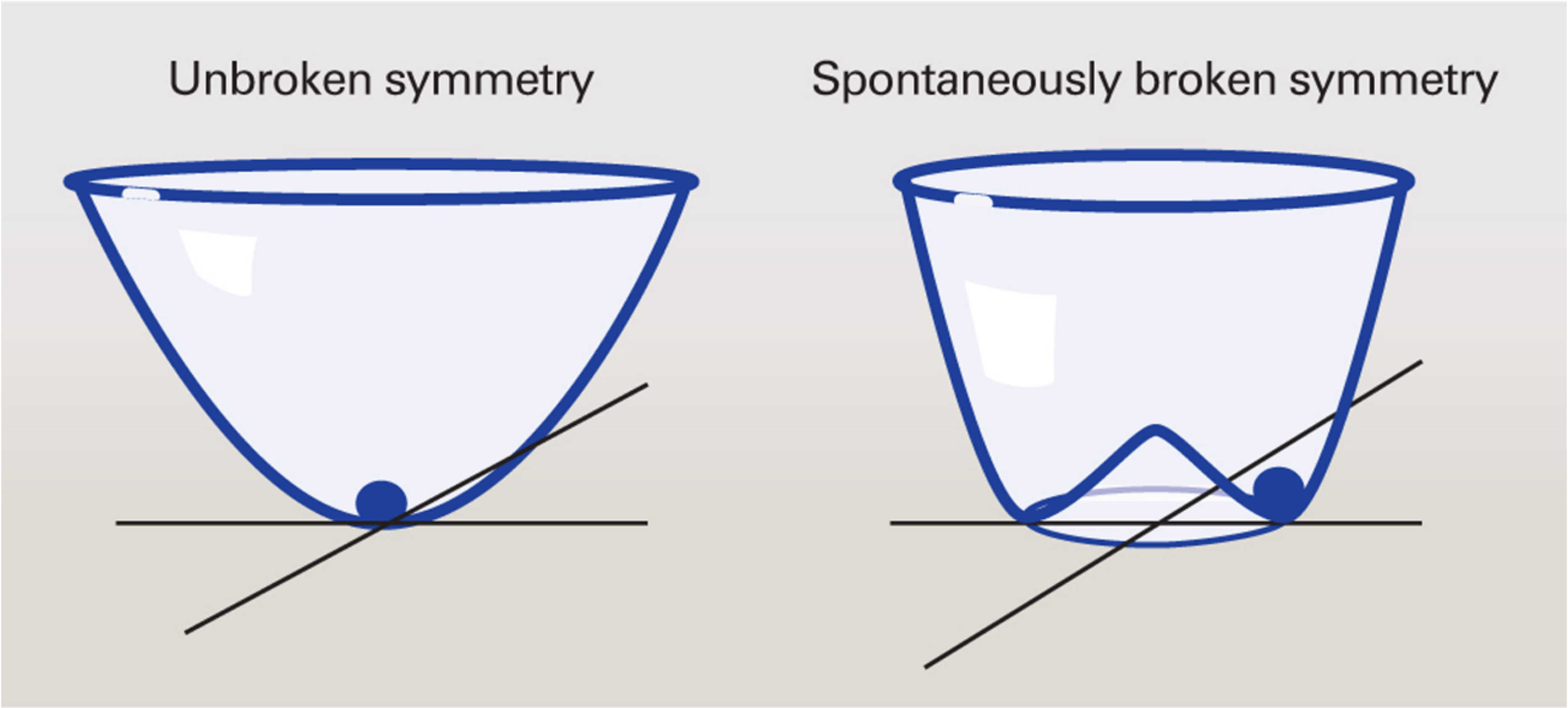
Tree-level

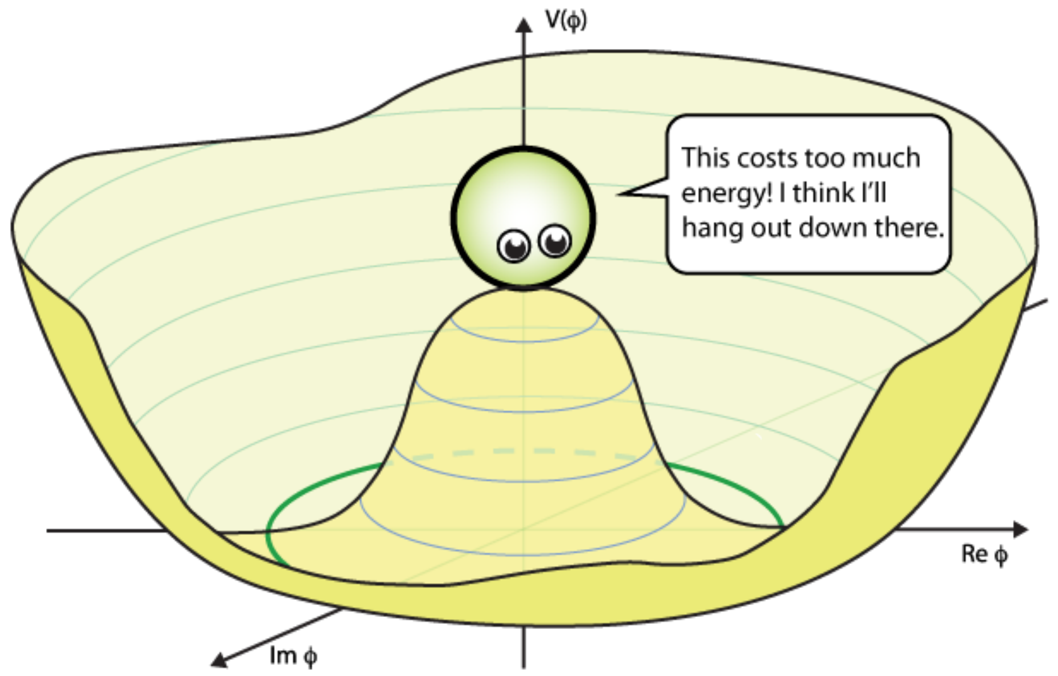
$$\Delta V_1(\phi,T) = \sum_F \frac{g_F T^4}{2\pi^2}\left[\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}(\beta m_F)^2 K_2(\beta m_F n)\right] - \sum_B \frac{g_B T^4}{2\pi^2}\left[\sum_{n=1}^{\infty}\frac{1}{n^2}(\beta m_B)^2 K_2(\beta m_B n)\right].$$

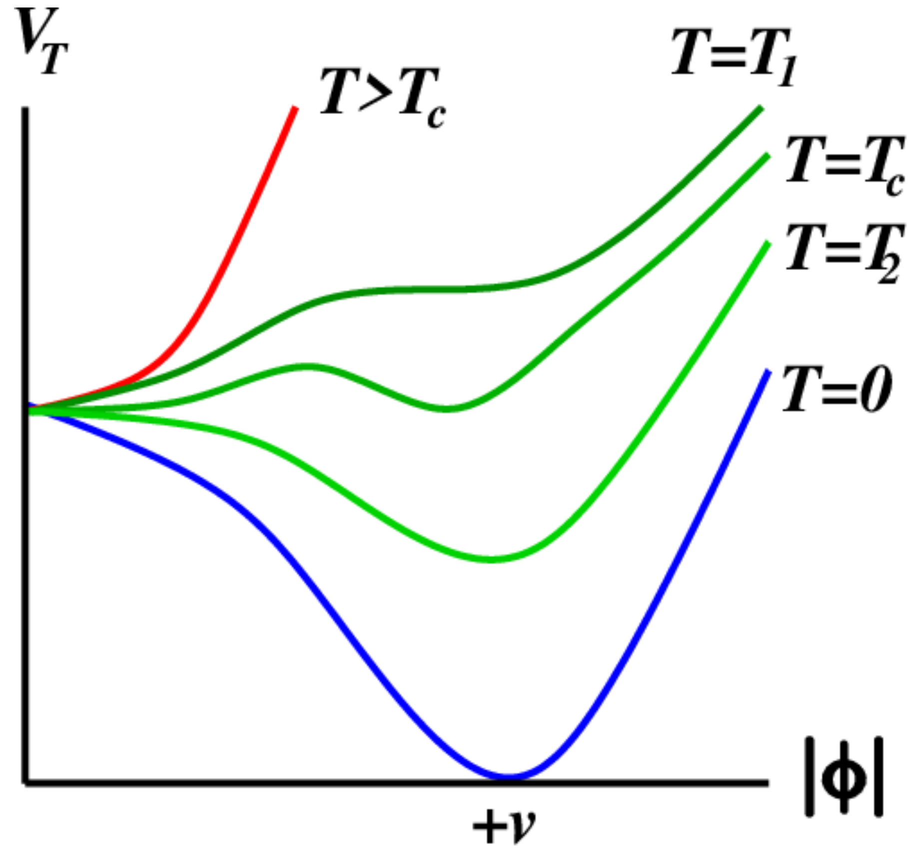
Thermal corrections

Symmetry non-restoration

- **EW symmetry non-restoration?** **Maybe or maybe not!**







$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4$$

$$\Pi_h = T^2\left(\frac{\lambda_t^2}{4} + \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} + N_s\frac{\lambda_{hs}}{12}\right) \qquad (3)$$

Tree-level

BSM corrections can be negative!

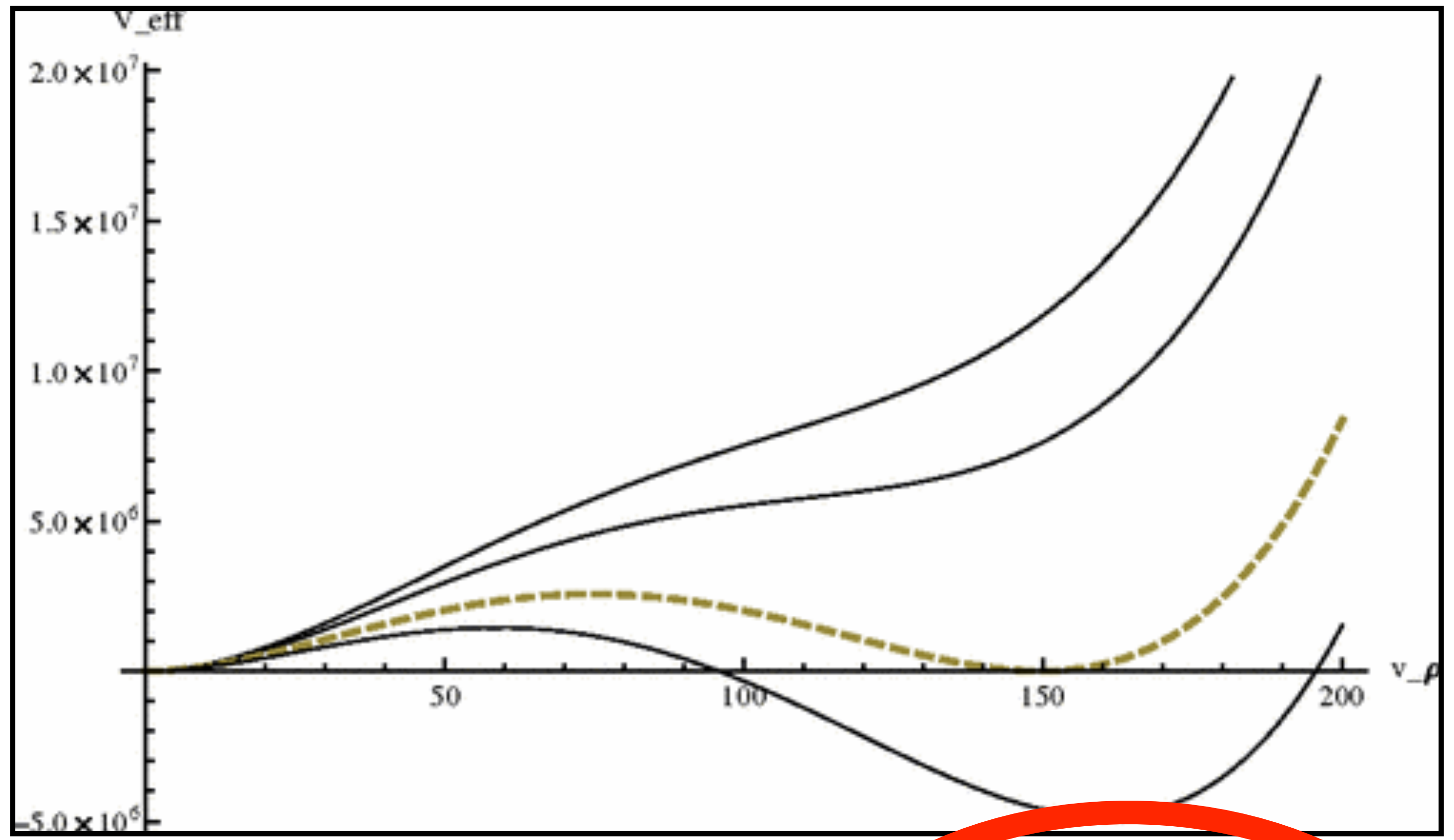
Color symmetry breaking at high T?

Key: symmetry non-storiation

- P. Meade and H. Ramani, Phys. Rev. Lett. 122, 041802 (2018)

$$\delta V_h(T) \sim \frac{1}{2} c_h T^2 h^2 = \frac{1}{2}\left[\frac{3g^2 + g'^2}{16} + \frac{\lambda}{2} + \frac{y_t^2}{4} + \zeta\right] T^2 h^2$$

Higgs gets large VEV at high T

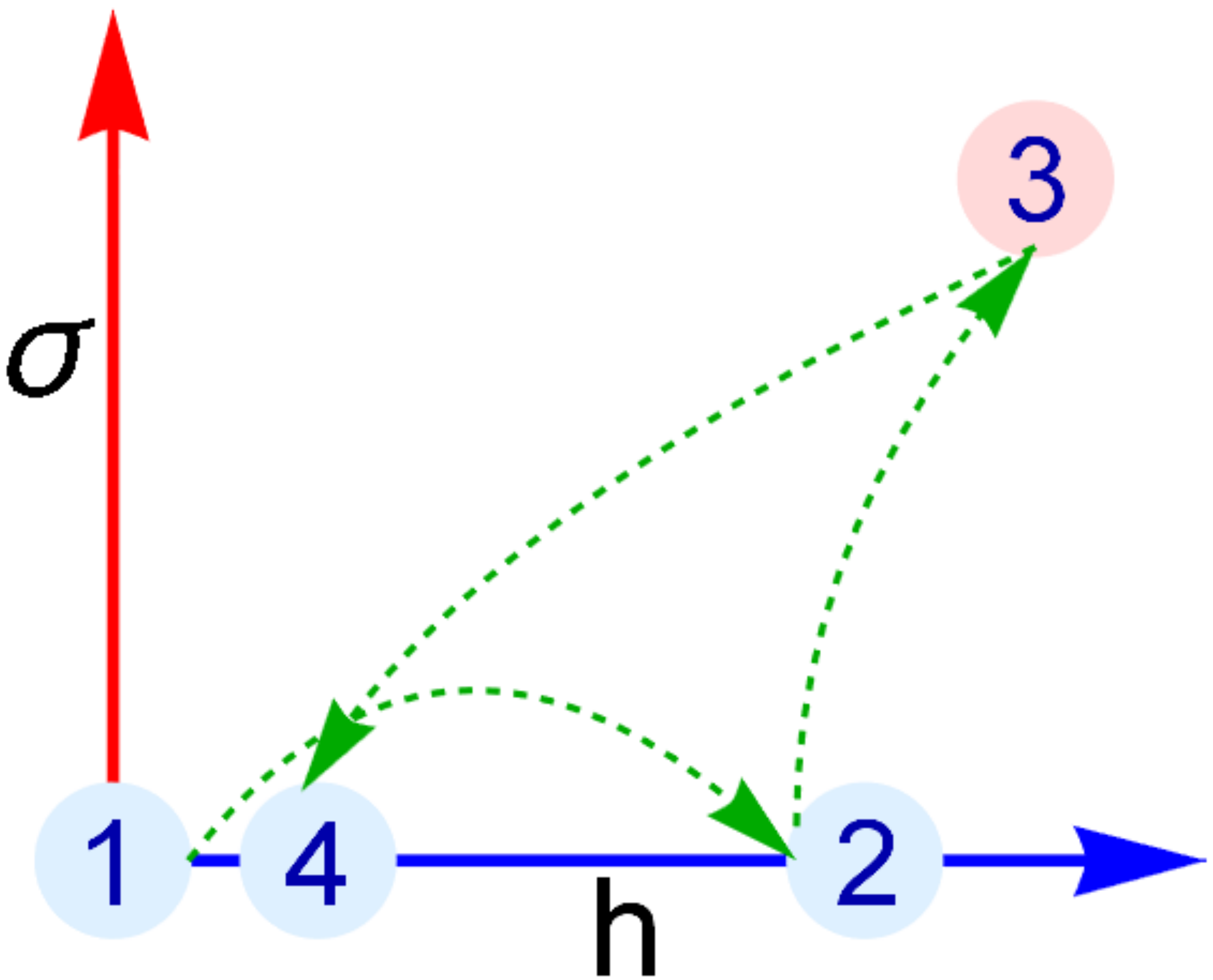


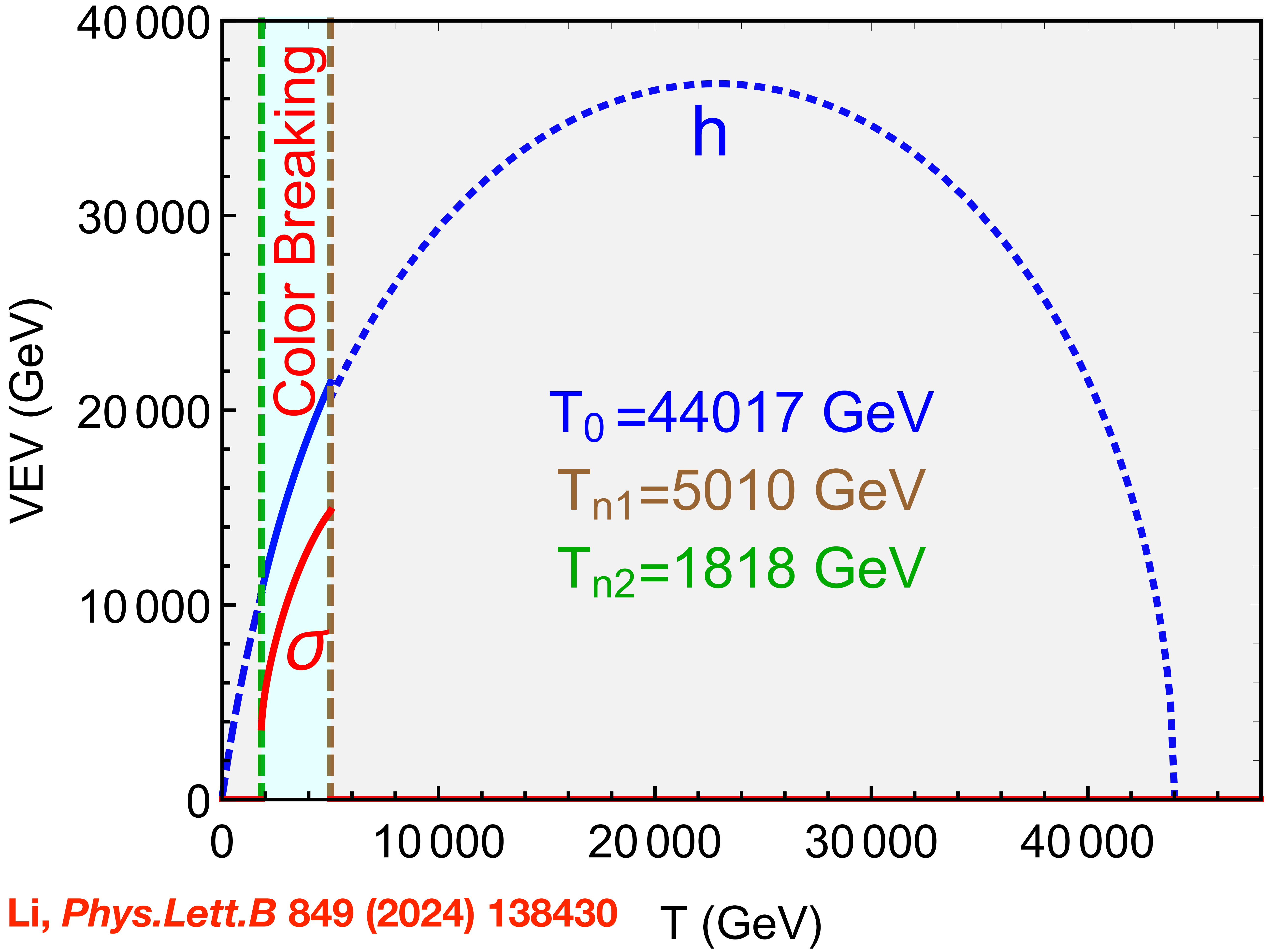
$$V_{\rm eff} = \mu_c^2 \Delta^\dagger \Delta - \lambda_{hc} H^\dagger H \Delta^\dagger \Delta + \lambda_c (\Delta^\dagger \Delta)^2 + V_{\rm SNR}$$

$$V(h, \sigma, T) \supset -\frac{\mu_{hT}^2}{2} h^2 + \frac{\mu_{cT}^2}{2} \sigma^2 - \frac{9 + 2\sqrt{3}}{72\pi} T g_s^3 \sigma^3 + \frac{\lambda_h}{4} h^4 + \frac{\lambda_c}{4} \sigma^4 - \frac{\lambda_{hc}}{4} h^2 \sigma^2,$$

Chao, Huai-ke Guo, Xiu-fei Li, *Phys.Lett.B* 849 (2024) 138430

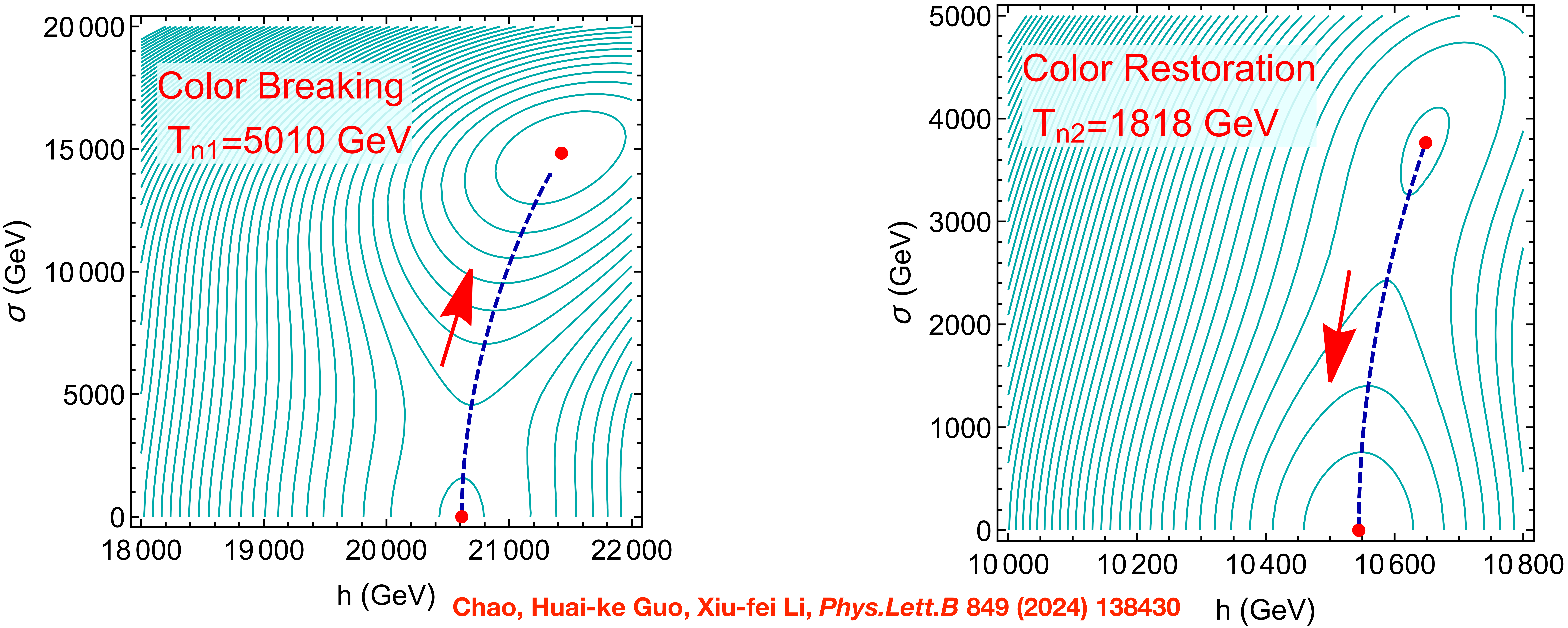
Color symmetry breaking at high T?





Chao, Huai-ke Guo, Xiu-fei Li, *Phys.Lett.B* 849 (2024) 138430

Phase diagrams



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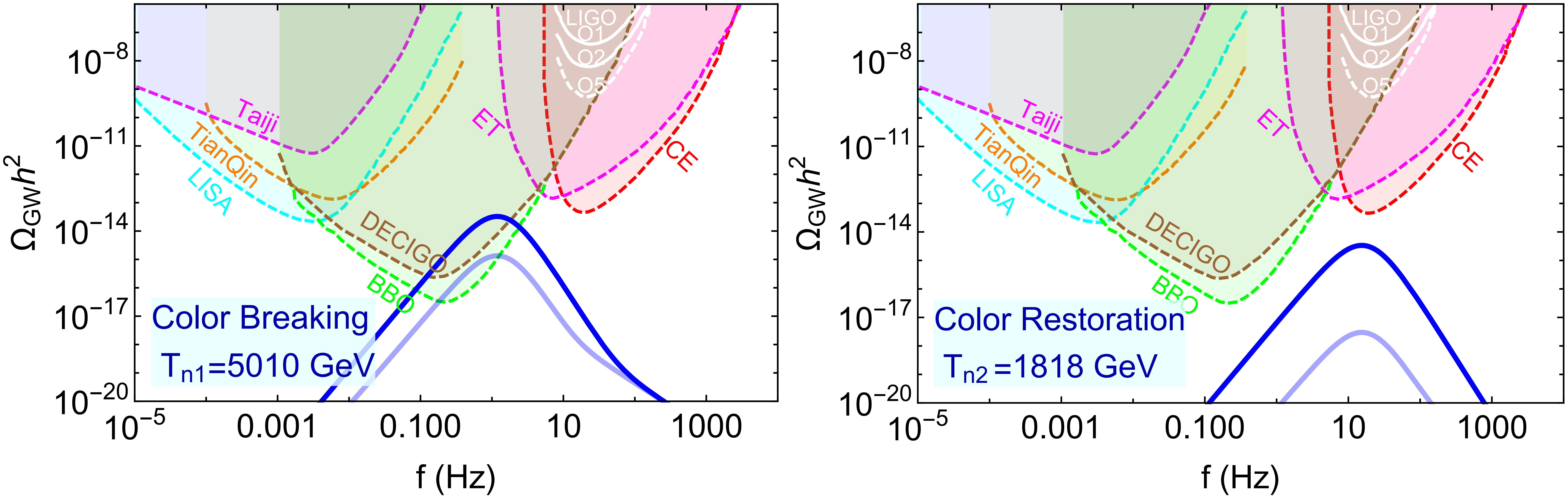
Gravitational waves

Two peak frequencies!



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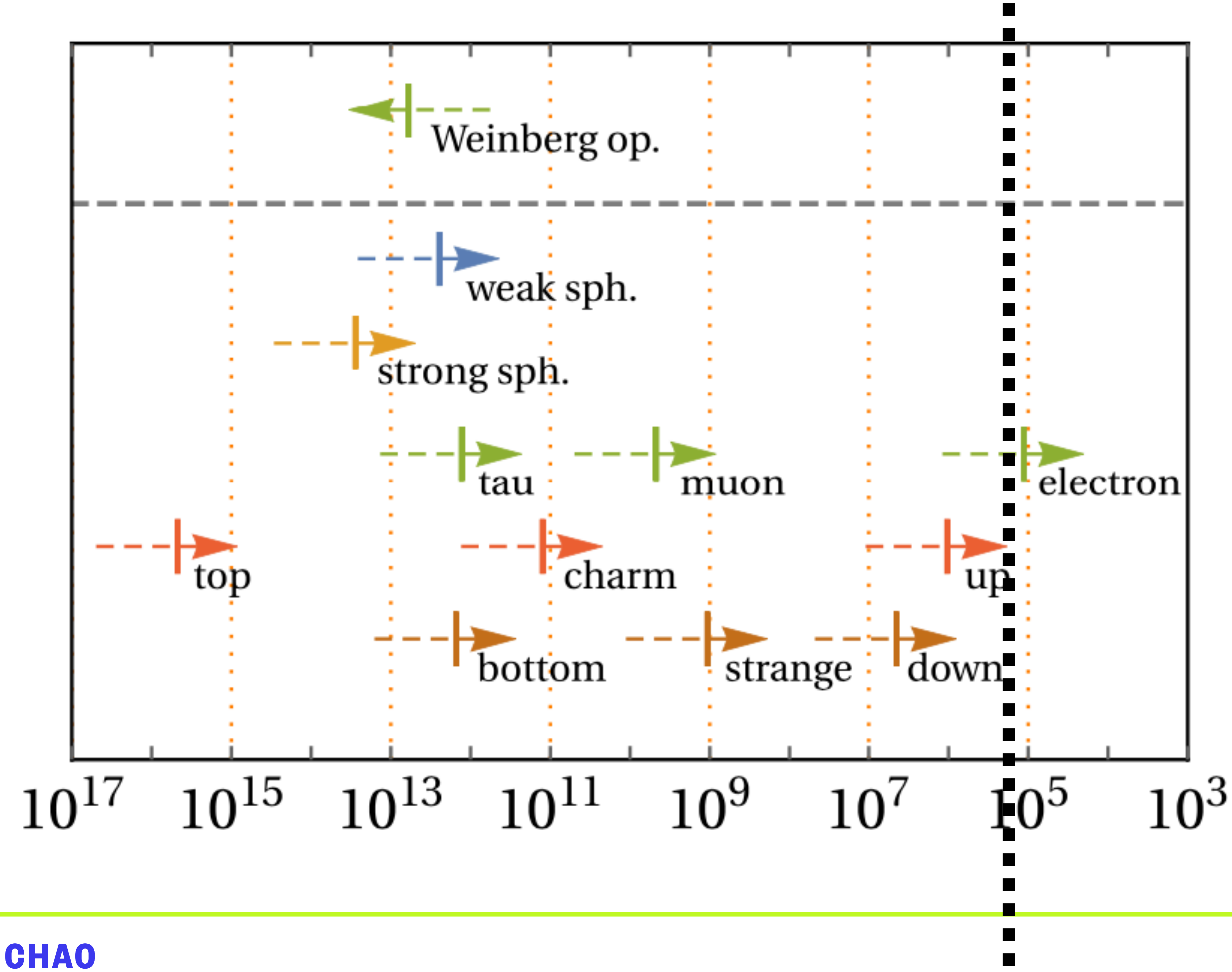
Symmetry non-restoration

- **EW symmetry non-restoration!**



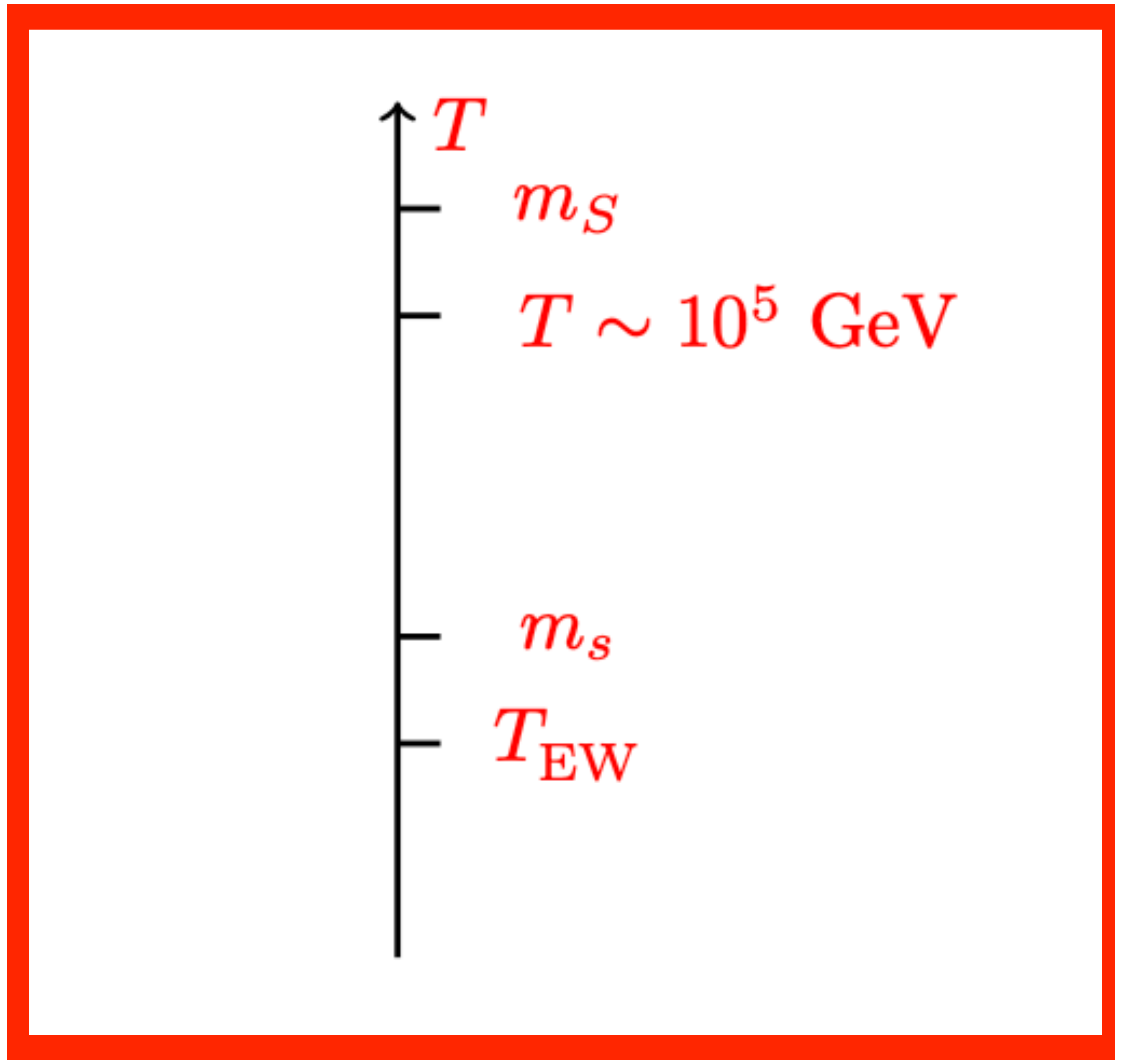
Sphaleron quenches at 10^5 GeV or higher scale.

- Left-handed Electron asymmetry can be transported to the BAU via sphaleron.

- No B-L violation is needed!

Symmetry non-restoration

- **Basic set up: 2HDM or BSM with scalar singlets**



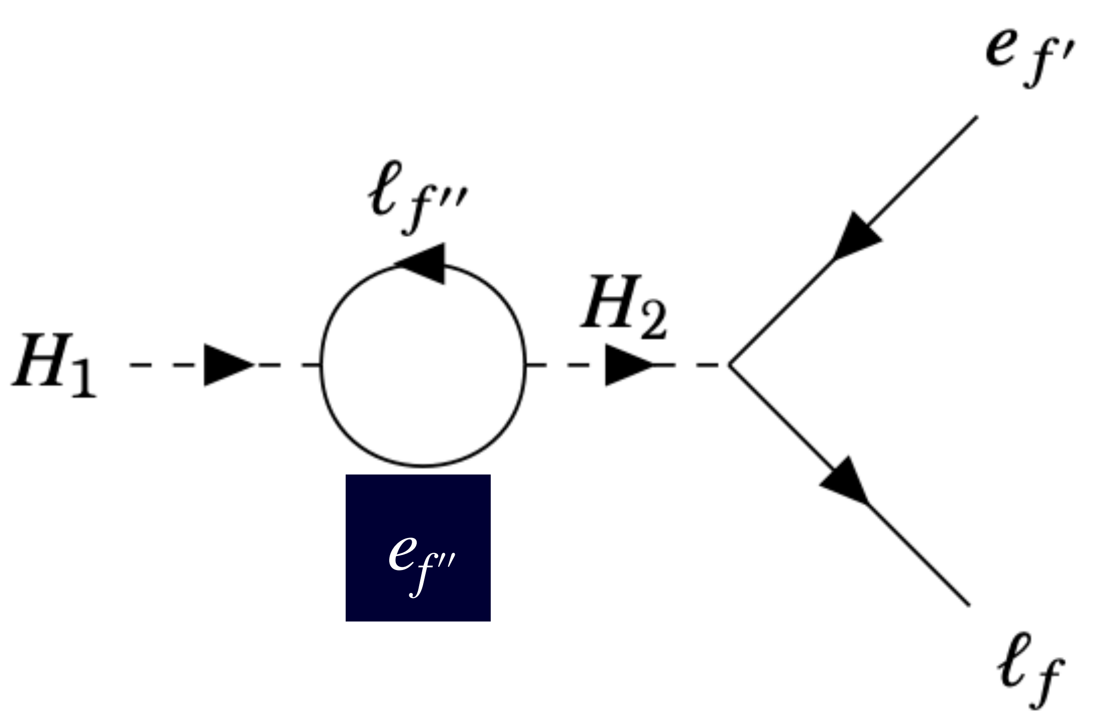
$$\Gamma_{\rm sph}^{\rm brok}(T) = \kappa_{\rm brok}\alpha_W^4 T^4 \exp\left(-\frac{E_{\rm sph}}{T}\right) \qquad E_{\rm sph} > T\log\left(\frac{\kappa_{\rm brok}\alpha_W^4 M_P}{3T}\right)$$

$$E_{\rm sph} = \frac{4\pi v}{g}\int_0^\infty d\xi\left[4(f')^2 + \frac{8}{\xi^2}f^2(1-f)^2 + \frac{\xi^2}{2}(h')^2 + h^2(1-f)^2 + \frac{\xi^2}{16}\sigma^2(h^2-1)^2\right]$$

$$\rightarrow N_s\lambda_{hs} < -4.82$$

Eogenesis

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



$$\varepsilon = \frac{1}{8\pi} \frac{\mathrm{Im}\left[Y^1_{fg} Y^{2\dagger}_{gf} \mathrm{tr}(Y^{1\dagger} Y^2)\right]}{\mathrm{tr}(Y^{1\dagger} Y^1)} f\left(\frac{M_{\Phi_2}}{M_{\Phi_1}}\right)$$

- **Chiral asymmetries are generated in the first generation.**
- **No primordial B-L violation is generated!**
- **No matter right-handed neutrinos exist or not!**

Eogenesis

- **Transport equations**

$$-\frac{dY_\Sigma}{d\ln T} = -\frac{\gamma_D}{H}\left[Y_\Sigma - Y_\Sigma^{\rm EQ}\right]$$

$$-\frac{d}{d\ln T}\left(\frac{\mu_\Phi}{T}\right) = -2\frac{\gamma_D}{H}\left(\frac{\mu_\Phi}{T} - \frac{4}{3}\frac{\mu_{L_k}}{T}\right)$$

$$\gamma_D = \frac{K_1(z)}{K_2(z)}\Gamma_\Phi$$

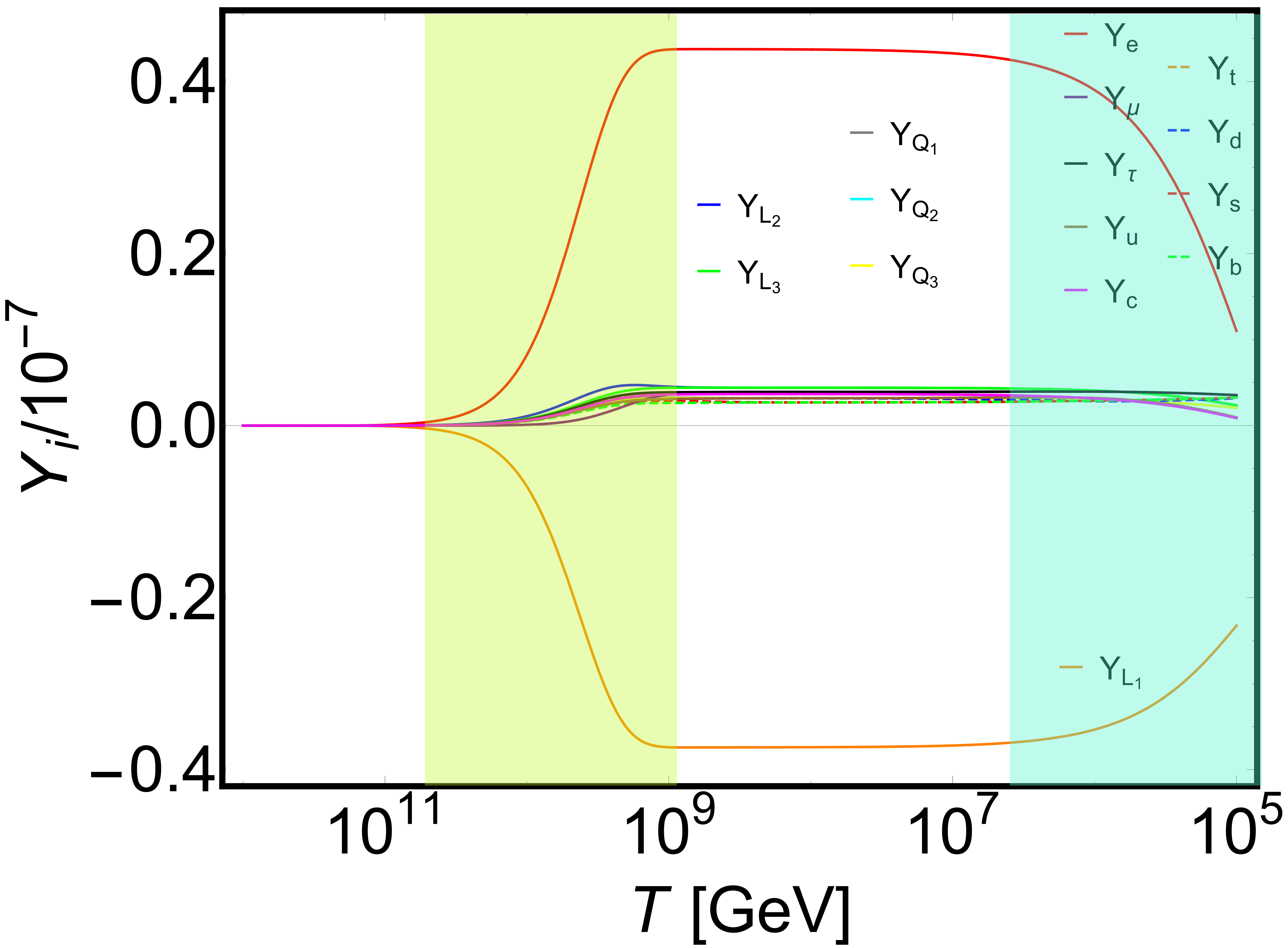
$$-\frac{d}{d\ln T}\left(\frac{\mu_{L_k}}{T}\right) = -\frac{1}{g_{L_k}}\frac{\gamma_{WS}}{H}\left[\sum_{i=1}^{3}\left(\frac{\mu_{L_i}}{T} + 3\frac{\mu_{Q_i}}{T}\right)\right]$$

$$-\frac{1}{g_{L_k}}\frac{\gamma_{Y_{E_k}}}{H}\left(-\frac{\mu_{E_k}}{T} + \frac{\mu_{L_k}}{T} - \frac{\mu_H}{T}\right)$$

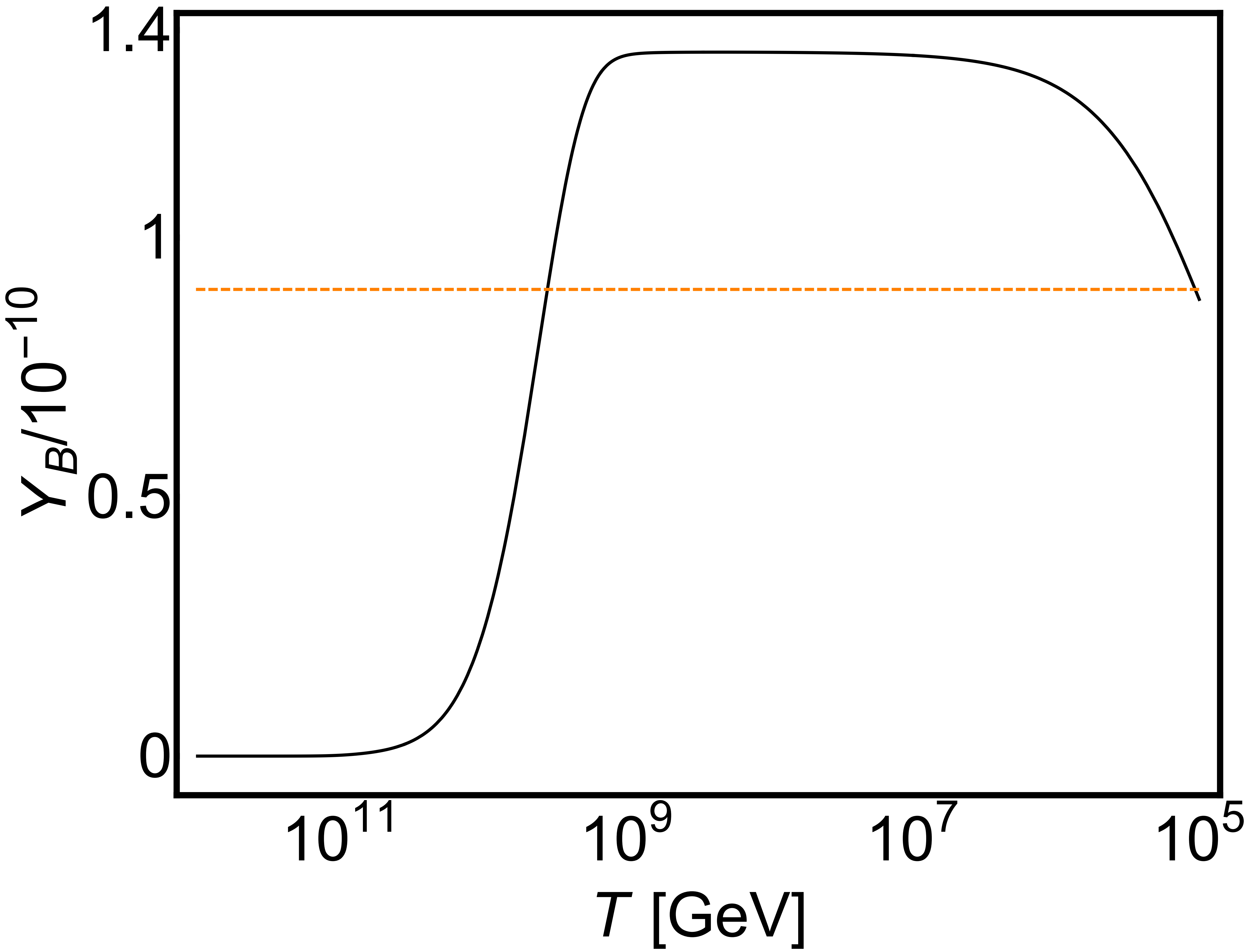
$$+\frac{1}{g_{L_k}}\frac{\gamma_D}{H}\varepsilon\left[\frac{4\pi^2 g_*^S}{15}Y_\Sigma - \frac{48\zeta(3)}{\pi^2}\right]$$

$$-\frac{2}{g_{L_k}}g_\Phi\frac{\gamma_D}{H}\left(\frac{4}{3}\frac{\mu_{L_k}}{T} - \frac{\mu_\Phi}{T}\right)$$

Eogenesis



0.4
0.2
0.0
−0.2
−0.4
$Y_i/10^{-7}$
10^{11}
10^9
10^7
10^5
T [GeV]
Y_e
Y_μ
Y_τ
Y_u
Y_c
Y_t
Y_d
Y_s
Y_b
Y_{Q_1}
Y_{Q_2}
Y_{Q_3}
Y_{L_2}
Y_{L_3}
Y_{L_1}



1.4
1
0.5
0
$Y_B/10^{-10}$
10^{11}
10^9
10^7
10^5
T [GeV]

Outline

- Scenario-1 : Modified spectator process induced by weak sphaleron
- Scenario-2 : Chiral Magnetic effect induced spectator process

CME for Leptogenesis

Starting point

$$\Delta B = \Delta L = N_g(\Delta N_{CS}^W - \Delta N_{CS}^Y) \qquad \Delta N_{CS}^Y = \frac{g_Y^2}{16\pi^2}\Delta H$$

- **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.**

CME for Leptogenesis

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

CME for Leptogenesis

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**

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

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

CME for Leptogenesis

Transport equations

$$-\frac{d}{d\ln T}\left(\frac{\mu_{E_i}}{T}\right) = -\frac{1}{g_{E_i}}\frac{\gamma_{E_i}}{H}\left(\frac{\mu_{E_i}}{T} - \frac{\mu_{L_i}}{T} + \frac{\mu_H}{T}\right) + \frac{6}{g_E}\frac{\alpha}{2\pi}\frac{\partial h}{\partial \ln T}$$

$$\frac{d}{d\ln T}\left(\frac{\mu_{L_i}}{T}\right) = +\frac{1}{g_{L_i}}\frac{\gamma_{E_i}}{H}\left(\frac{\mu_{E_i}}{T} - \frac{\mu_{L_i}}{T} + \frac{\mu_H}{T}\right) - \frac{1}{g_{L_i}}\frac{2\gamma_{WS}}{H}\left[\sum_i \frac{\mu_{L_i}}{T} + 3\sum_i \frac{\mu_{Q_i}}{T}\right] - \frac{6}{g_{L_i}}\frac{\alpha}{2\pi}\frac{\partial h}{\partial \ln T}$$

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

CME for Leptogenesis in U(1)$_{\text{Li-Lj}}$

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

Triangle anomalies

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

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

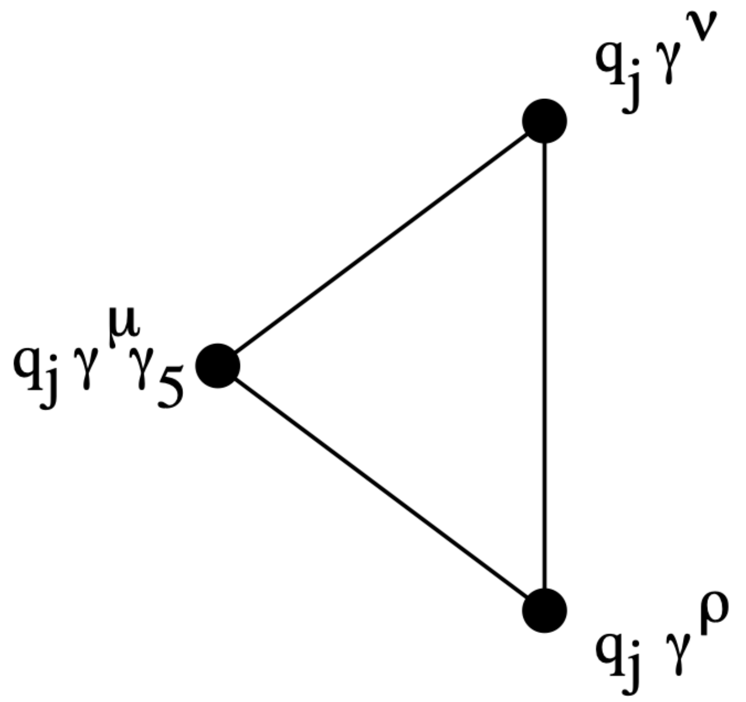
$$\partial_\mu\left(j^\mu_{L_\tau}\right) = \frac{1}{32\pi^2}\left(g^2 W\widetilde{W} + g'^2 F\widetilde{F}\right) \quad (4)$$

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

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

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

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

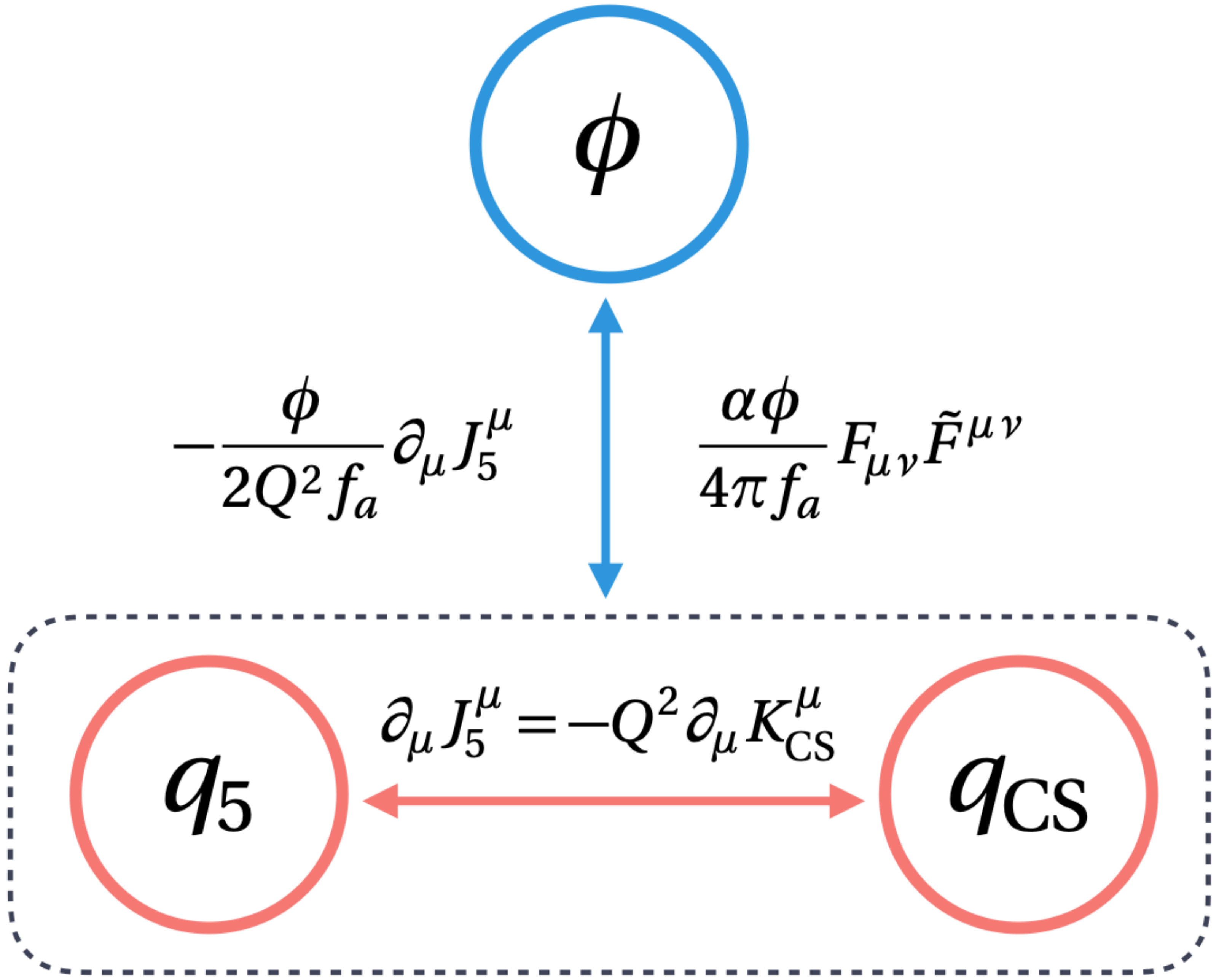


$$\partial_\mu\left(j^\mu_B - j^\mu_L\right) = -\frac{g_X^2}{8\pi^2}F'\widetilde{F}' \neq 0$$

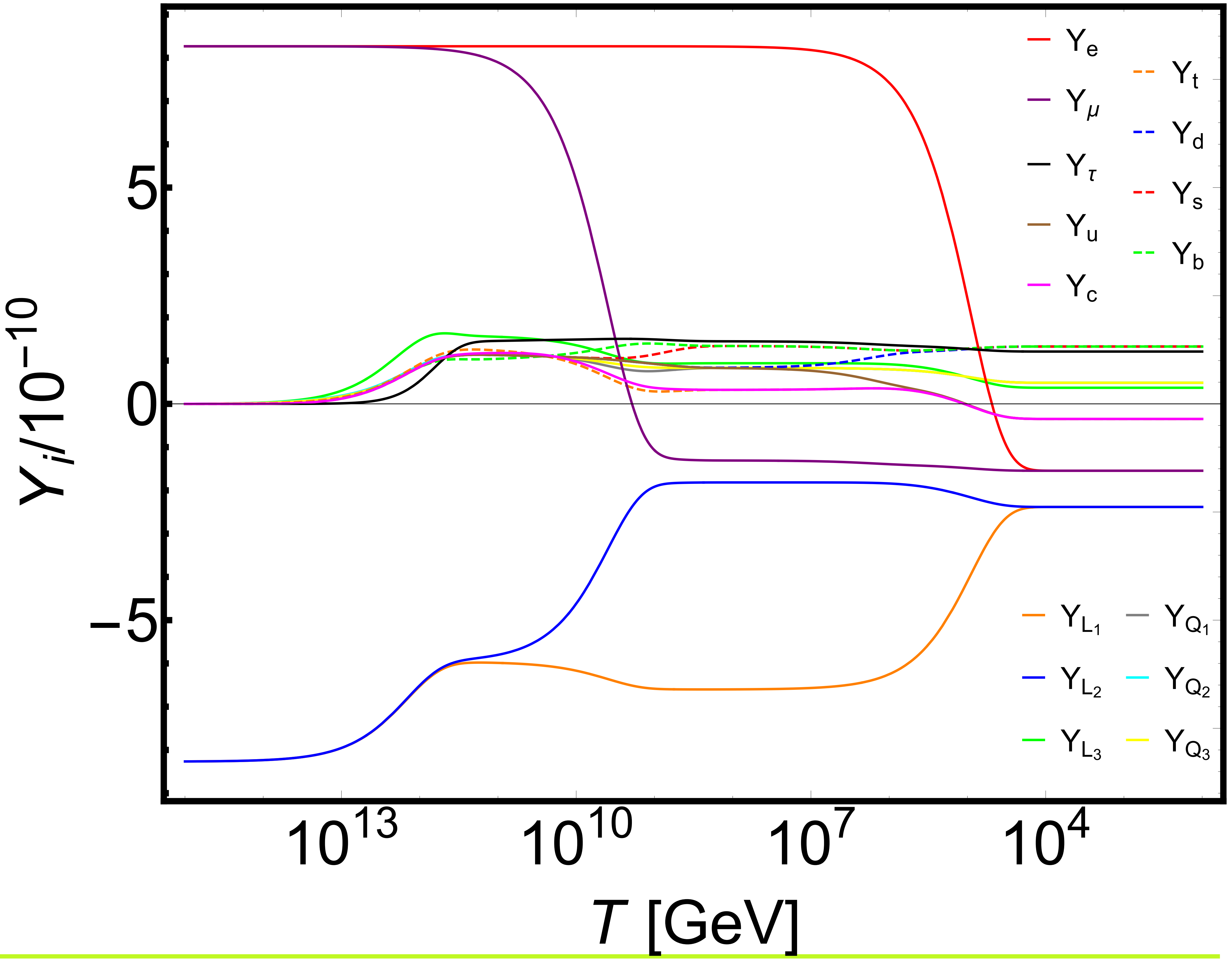
CME for Leptogenesis in U(1)$_{Li-Lj}$

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

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

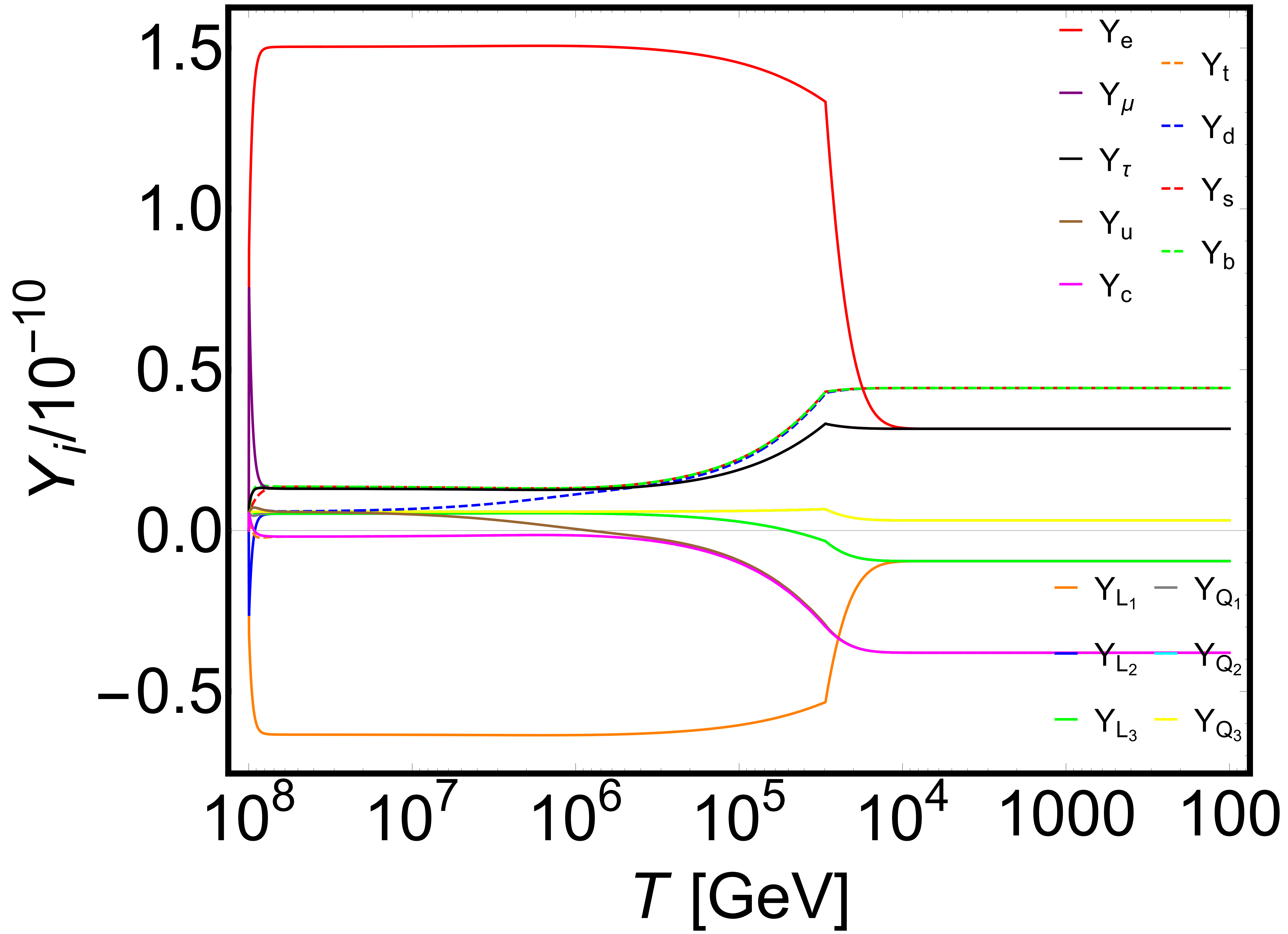


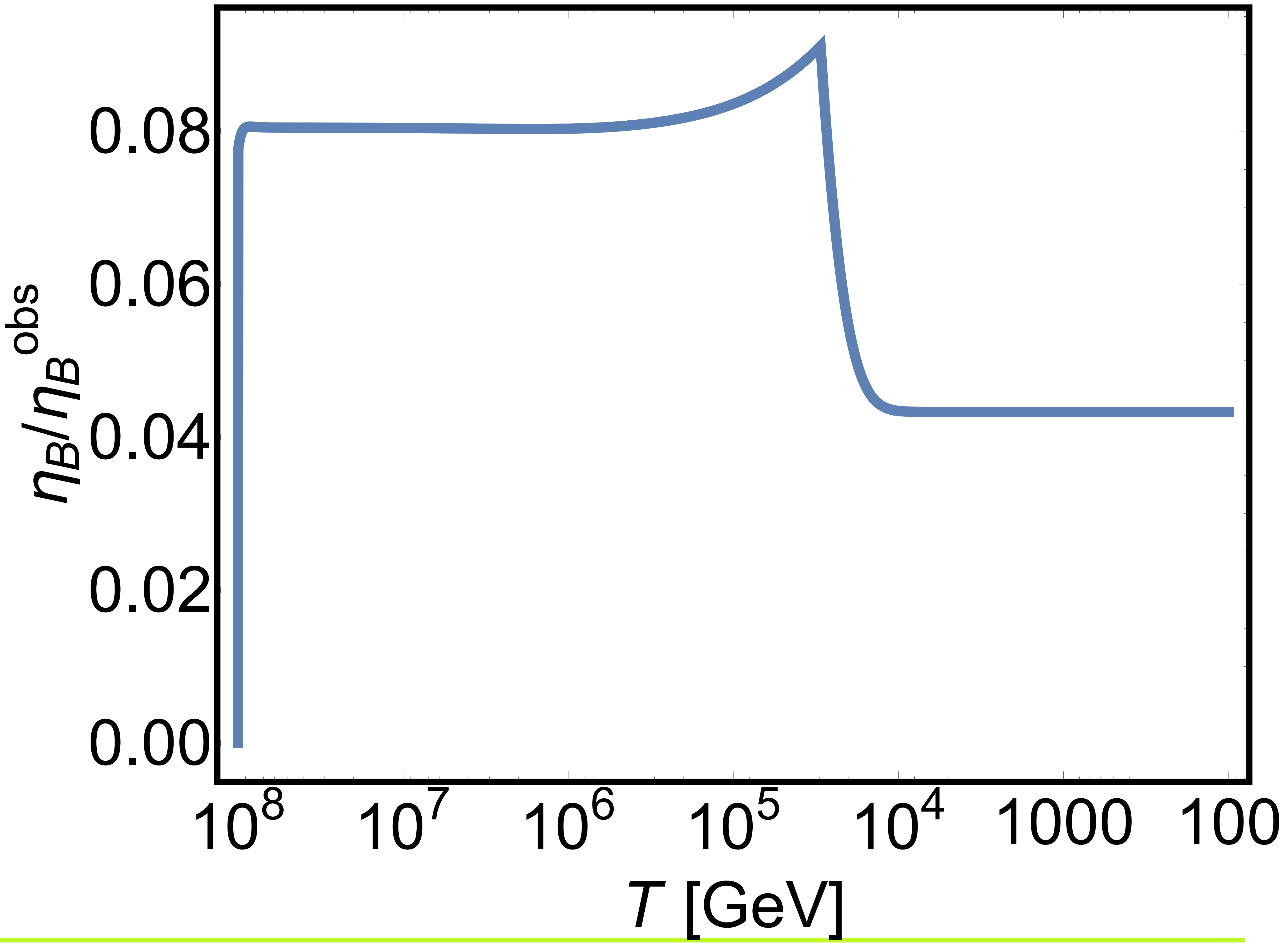
V. Domcke and K. Mukaida, JCAP 2018



CME for Leptogenesis in U(1)$_{Li\text{-}Lj}$

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





Conclusion

Leptogenesis is a beautiful mechanism for BAU, triggering many model building in recent years. We find possible connections between Leptogenesis and phase transition as well as CME effect.

- Primordial B-L charge is not necessary in Leptogenesis.
- Spectator process induced by the gauge sector deserve further investigation.

Thank you for your attention!