The Workshop on Grand Unified Theory, Phenomenology and Cosmology (GUTPC 2025)

Leptogenesis via symmetry non-restoration

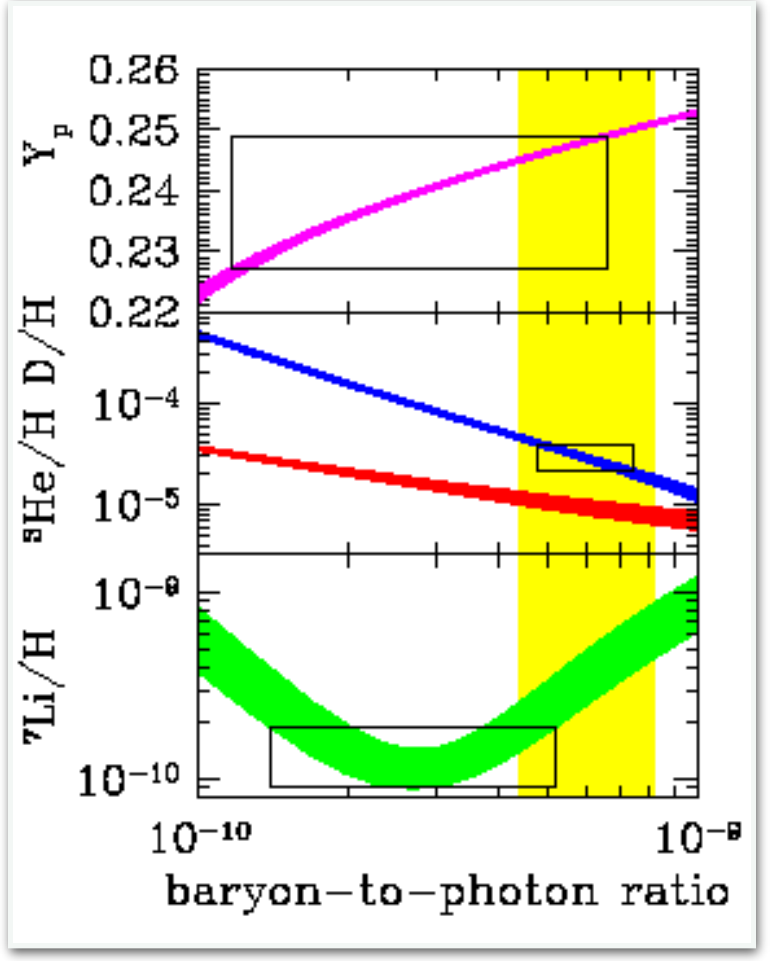
Wei Chao

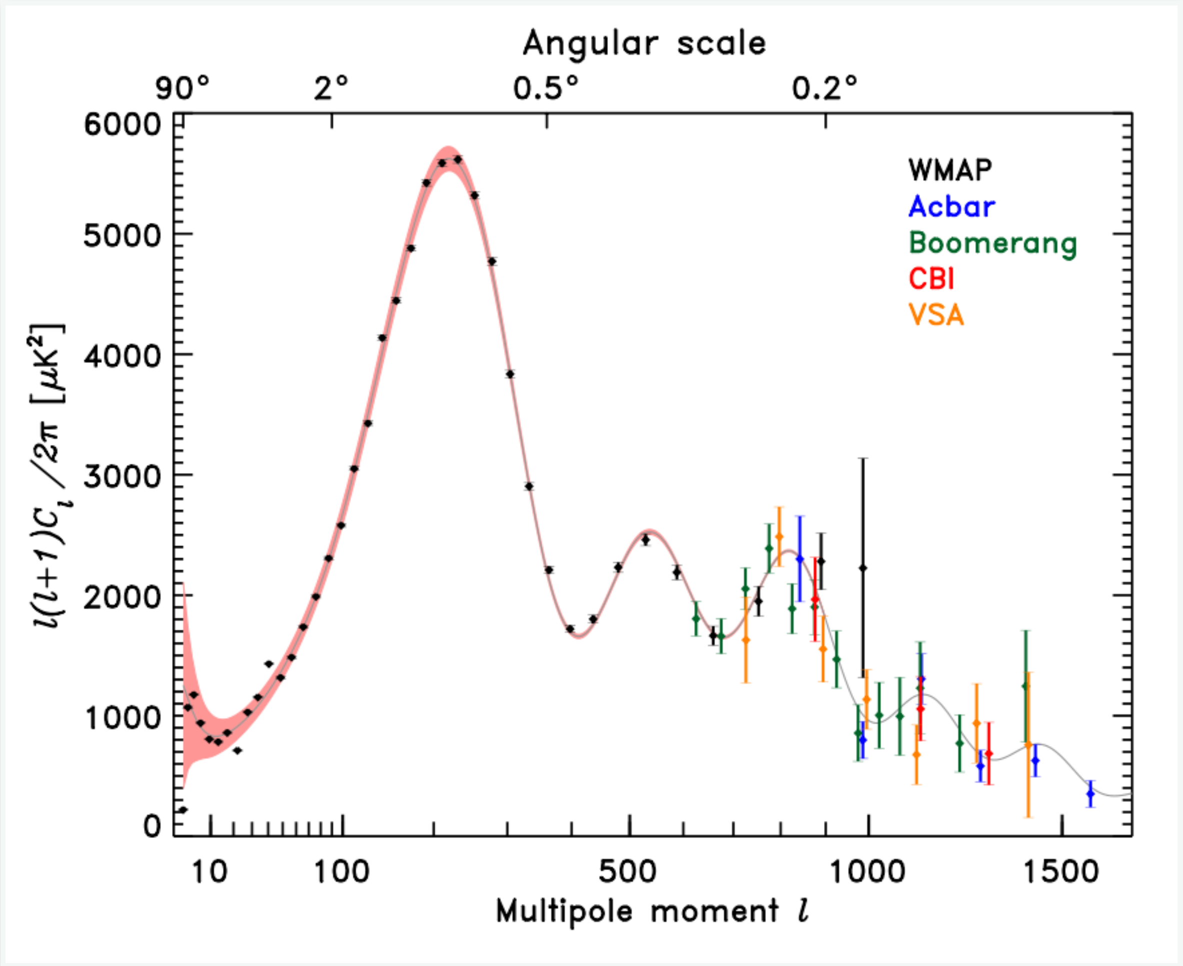
Department of Physics and Astrophysics, Beijing Normal University

New physics—The Baryon asymmetry

Matter-antimatter asymmetry

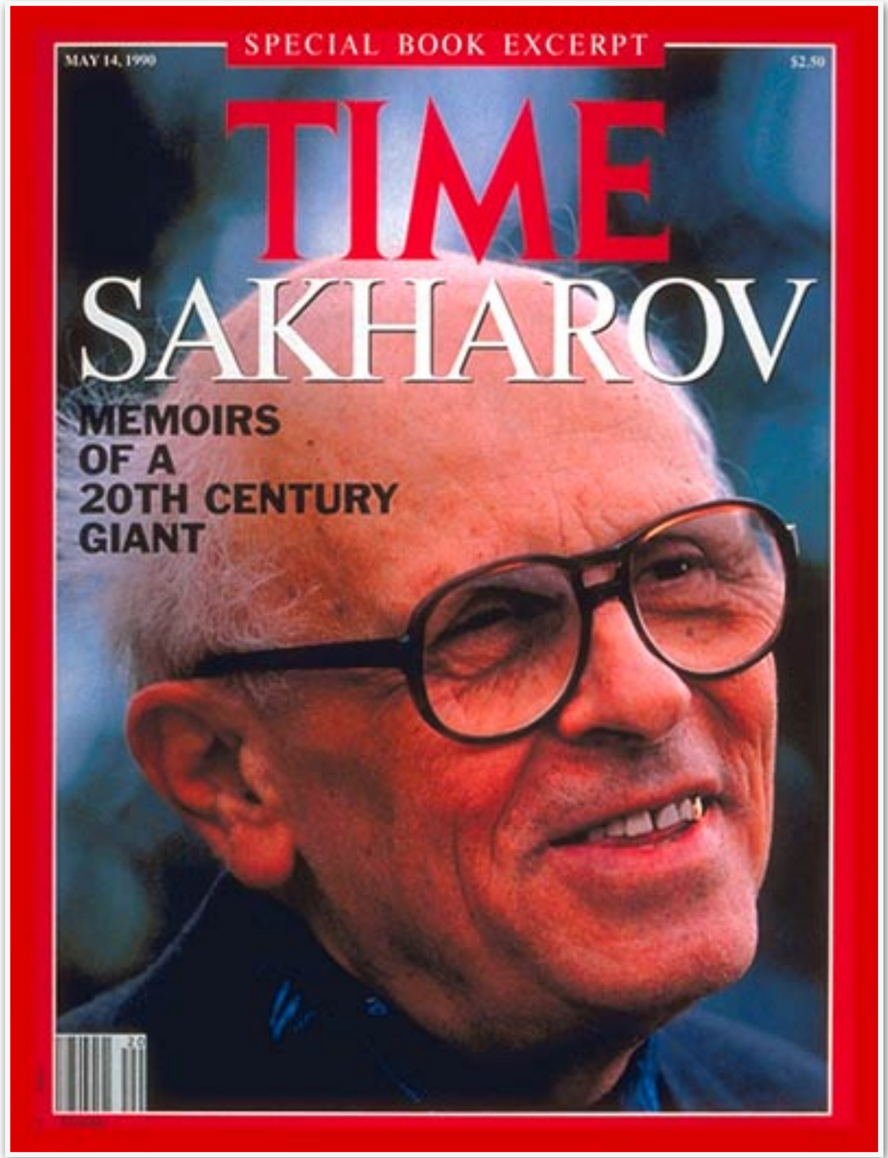
- No galaxy made by ant-baryon is observed
- Baryon asymmetry is measured by the Planck.

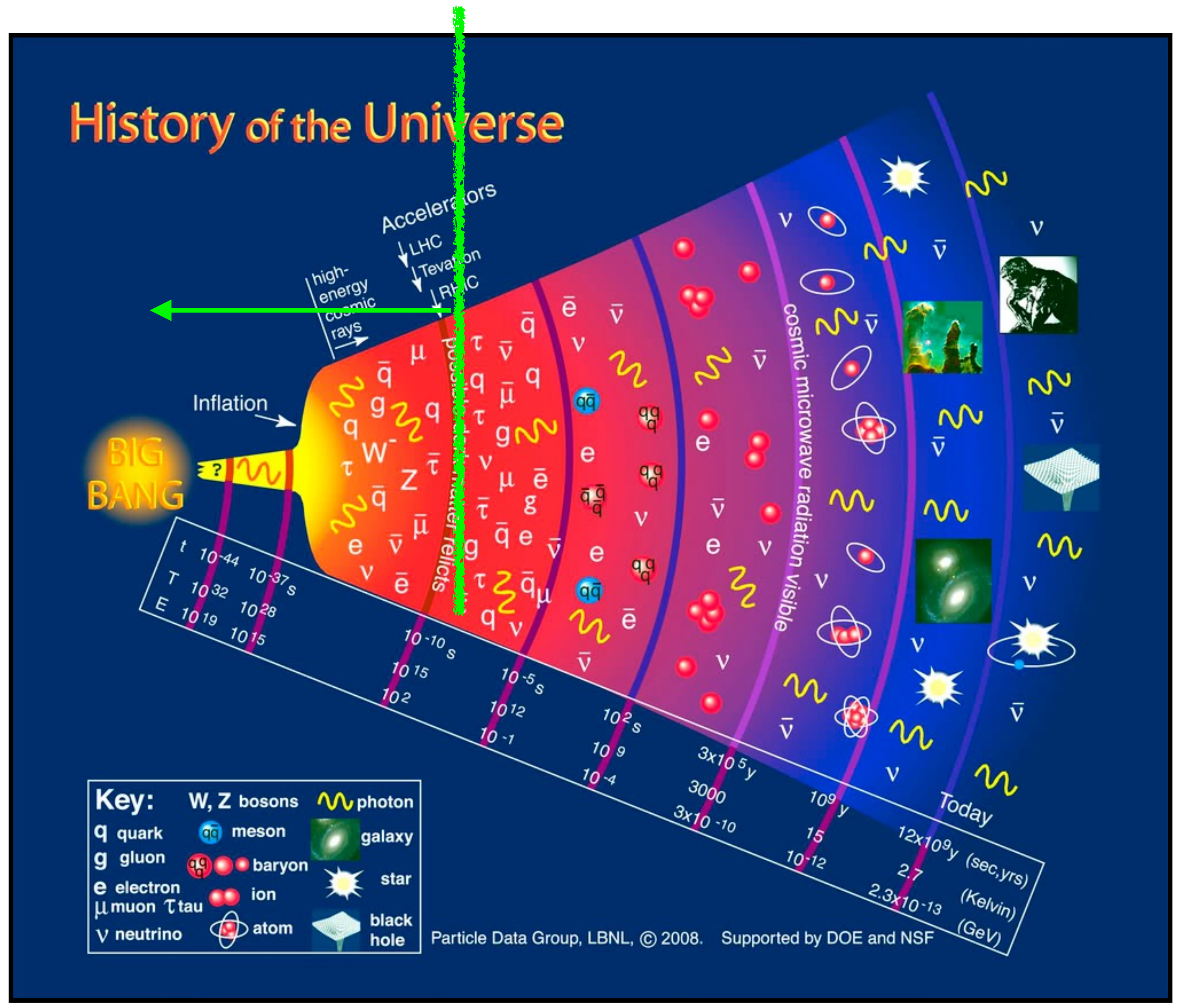




$$\textbf{Baryon asymmetry:} \quad Y_B = \frac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11} \quad \textbf{Planck}$$

Baryogenesis





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

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

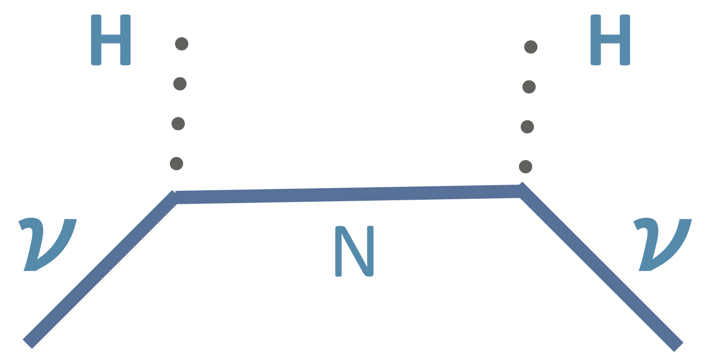
History and development: Leptogenesis

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



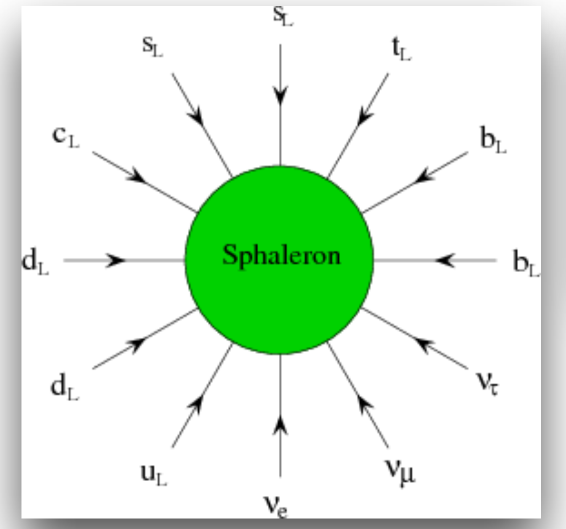
Neutrino mass:

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

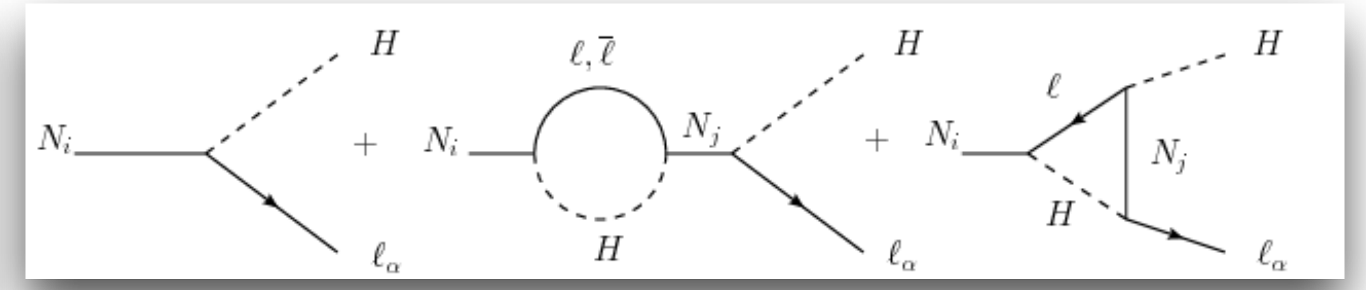
Elegant but losing testability at colliders!

Leotogenesis

BV



CPV



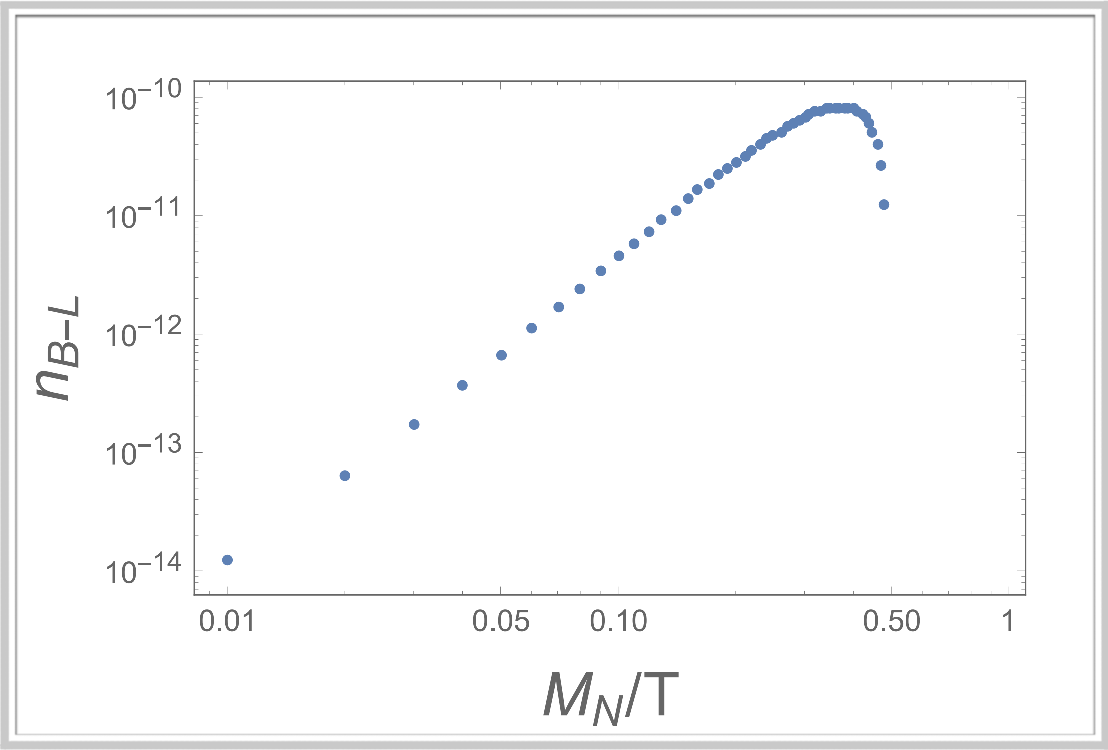
Out of EQ

Heavy neutrinos decouple

Boltzmann EQ

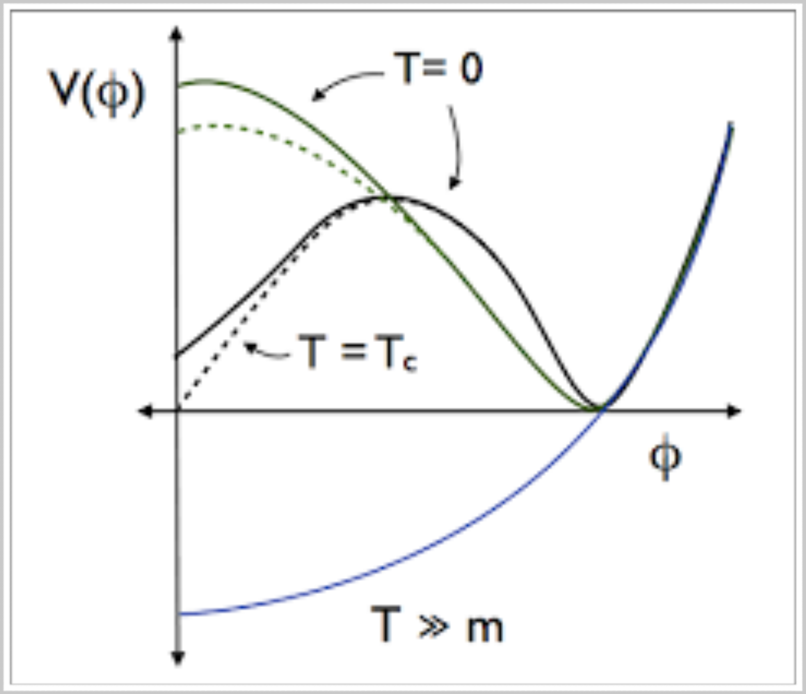
$$\frac{dN}{dz} = -D(N - N^{\rm eq})$$

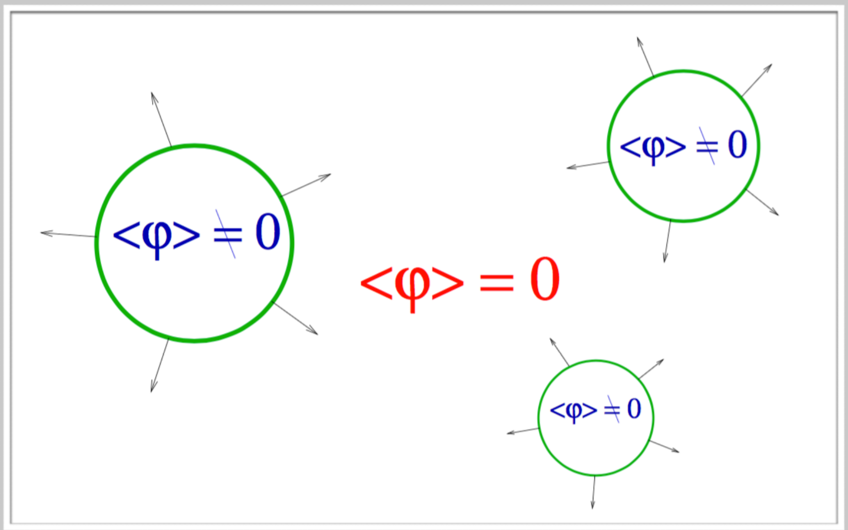
$$\frac{dN_{\rm B-L}}{dz} = -\varepsilon D(N - N^{\rm eq}) + W_{\rm ID} N_{\rm B-L}$$

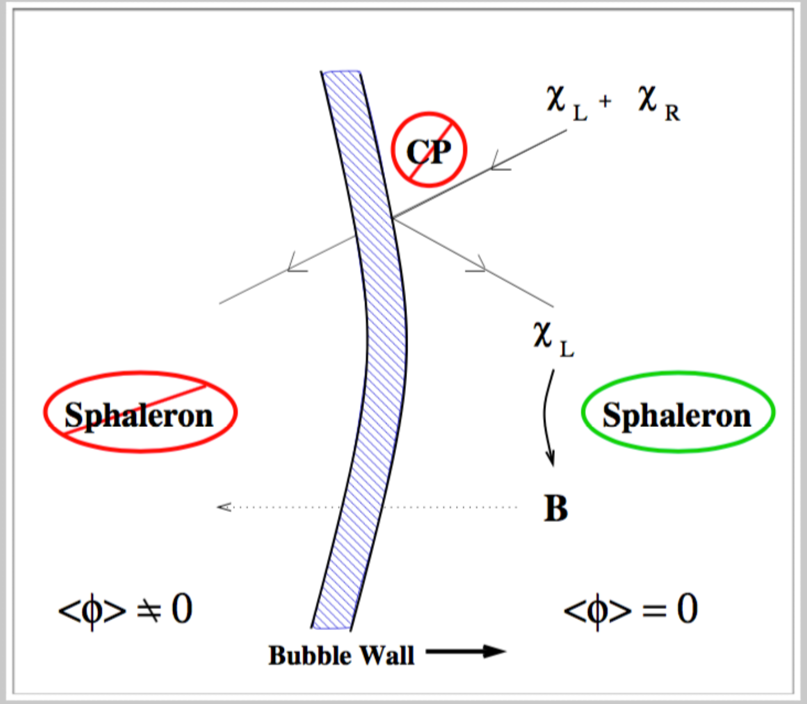


History and development: EW Baryogenesis

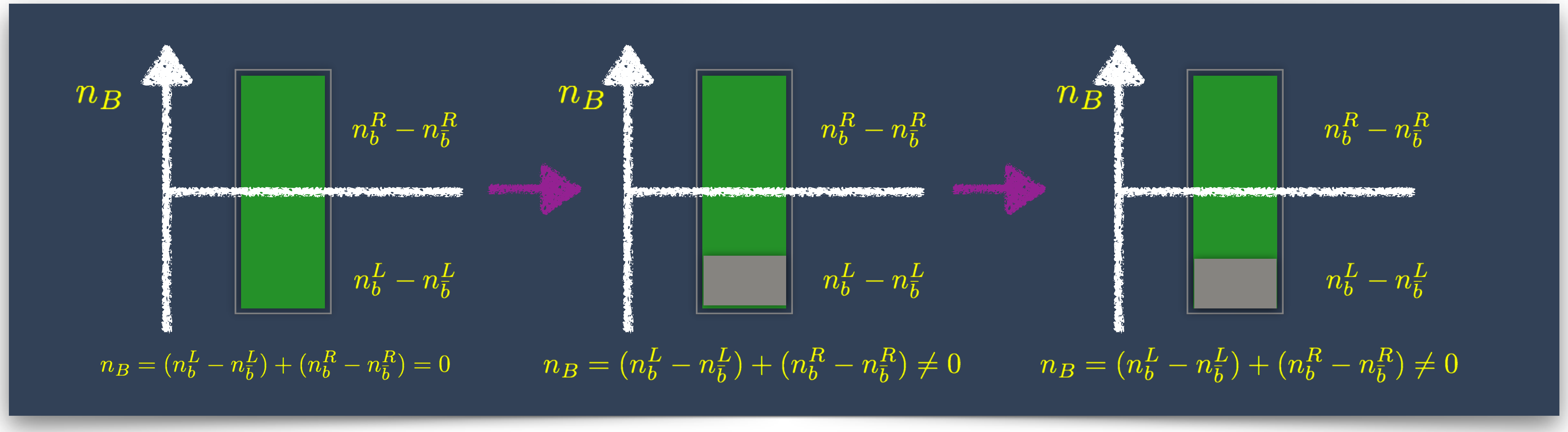
EWBG





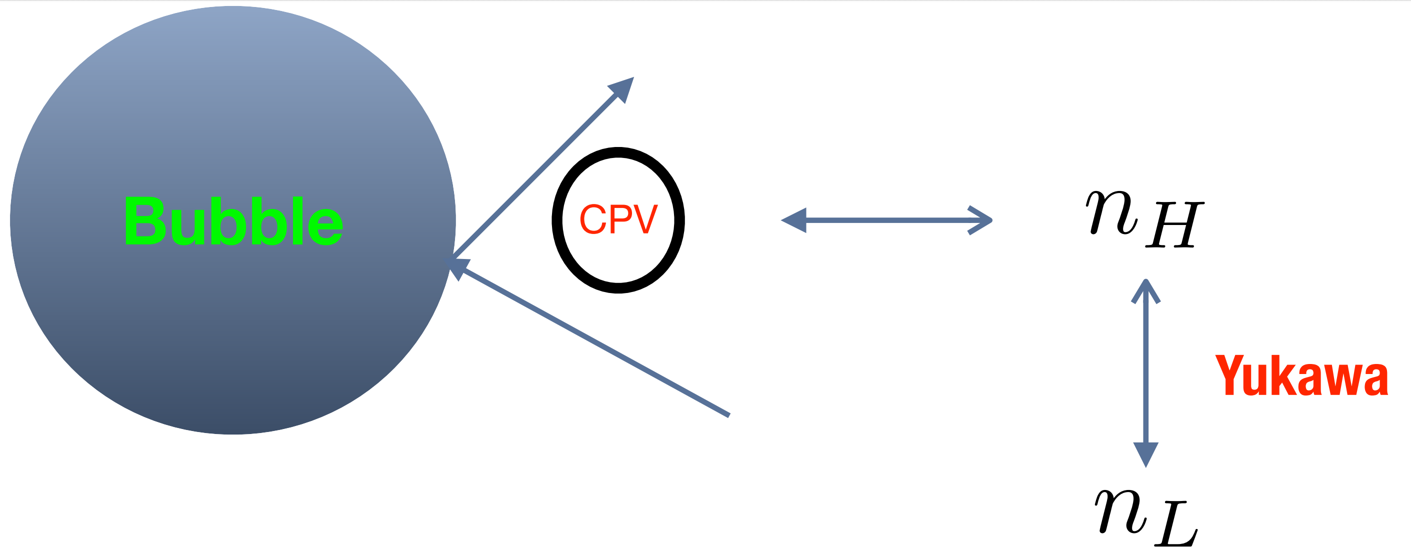


Basic description



Transport equations

$$\frac{\partial n}{\partial t} + \nabla \cdot j(x) = -\int d^3z \int_{-\infty}^{x_0} dz^0 \mathrm{Tr}[\Sigma^>(x,z)S^<(z,x) - S^>(x,z)\Sigma^<(z,x) + S^<(x,z)\Sigma^>(z,x) - \Sigma^<(x,z)S^>(z,x)]$$



$$\partial_\mu \psi_\mu = +\Gamma_\psi^+\left(\frac{\chi}{k_\chi} + \frac{\psi}{k_\psi}\right) + \Gamma_\psi^-\left(\frac{\chi}{k_\chi} - \frac{\psi}{k_\psi}\right) + \left(\sum_i \Gamma_{y_i}\right)\left(\frac{\chi}{k_\chi} - \frac{H}{k_H} - \frac{\psi}{k_\psi}\right) + S_{\rm CP}^\psi$$

$$\partial_\mu \chi_\mu = -\Gamma_\psi^+\left(\frac{\chi}{k_\chi} + \frac{\psi}{k_\psi}\right) - \Gamma_\psi^-\left(\frac{\chi}{k_\chi} - \frac{\psi}{k_\psi}\right) - \left(\sum_i \Gamma_{y_i}\right)\left(\frac{\chi}{k_\chi} - \frac{H}{k_H} - \frac{\psi}{k_\psi}\right) - S_{\rm CP}^\psi$$

$$\partial_\mu H_\mu = \Gamma_{Y_t}\left(\frac{T}{k_T} - \frac{H}{k_H} - \frac{Q}{k_Q}\right) + \left(\sum_i \Gamma_{y_i}\right)\left(\frac{\chi}{k_\chi} - \frac{H}{k_H} - \frac{\psi}{k_\psi}\right) - \Gamma_h \frac{H}{k_H},$$

History and development: Afleck-Dine

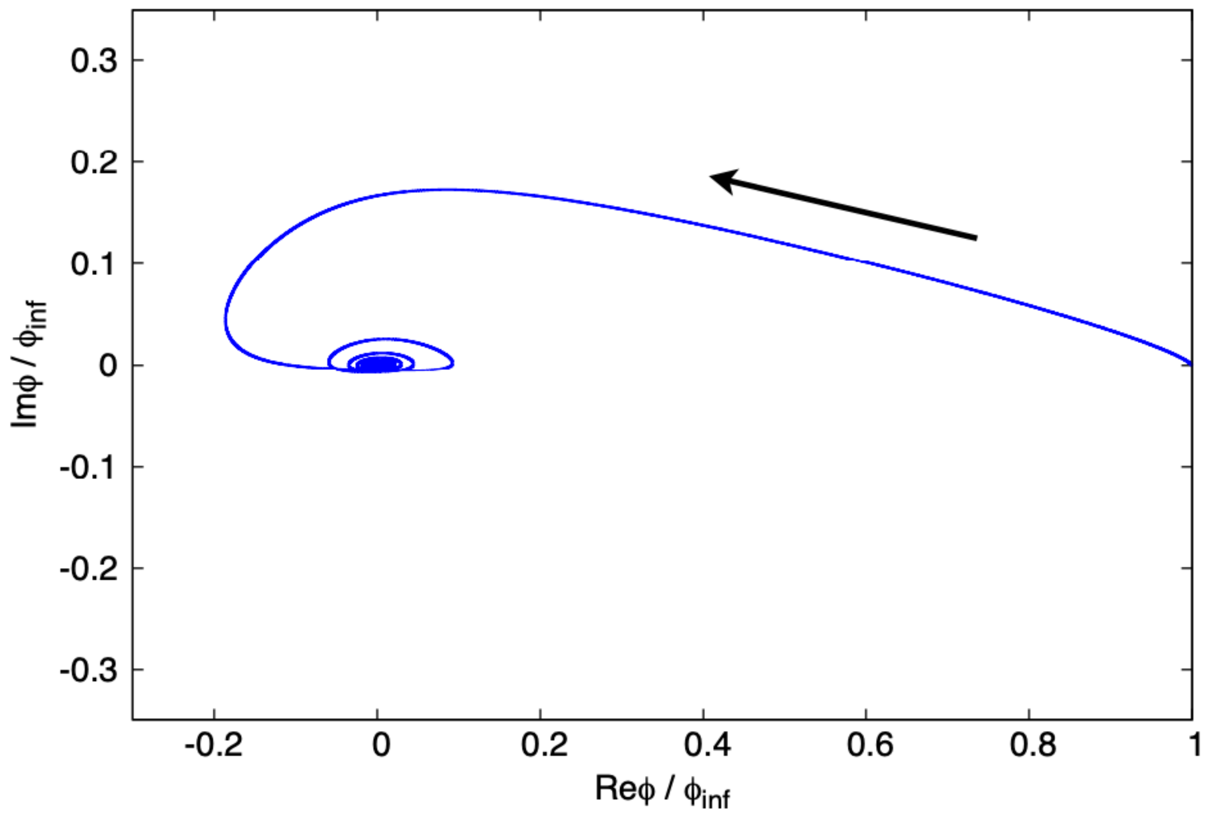
Afleck-Dine Mechanism

Scalars carrying non-zero U(1) charges

Flat directions (AD fields)

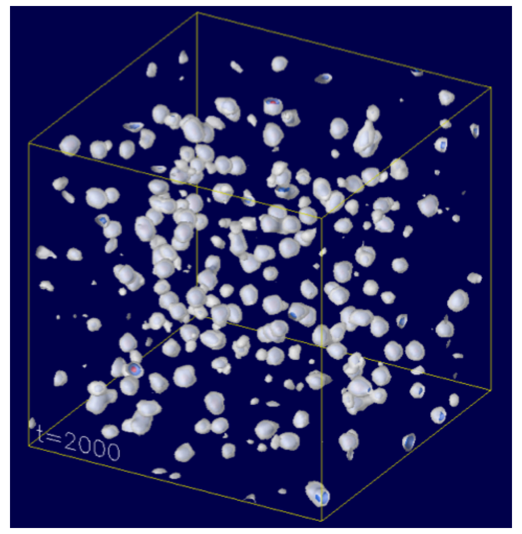
Lifting the potential via B/L violation operators

$$V = (m^2 - cH^2)|\phi|^2 + \lambda|\phi|^4 + \left(\frac{\phi^n}{M^{n-4}} + \mathrm{h.c.}\right)$$



$$\dot{n}_{B,L} + 3Hn_{B,L} = 2\beta \mathrm{Im}\left[\frac{\partial V}{\partial \phi}\phi\right]$$

Q-ball formation (Non-topological soliton in scalar field theory)



Oscillation of AD field → **Q-ball formation**

Q-ball formation → **Long lived Q-ball** → **DM candidate**

Q-ball formation → **Evaporation** → **BAU when sphaleron erase is irrelevant**

History and development: Axiogenesis

QCD Axion

Strong CP problem → **Peccei-Quinn mechanism** → **Axion**

Pseudo-scalar particle

[Preskill, Wise, Wilczek (1983)]
[Abbott, Sikivie (1983)]
[Dine, Fischler (1983)]

$d_n = 5.2 \times 10^{-16} \bar{\theta} \mathrm{e} \cdot \mathrm{cm}$

$d_n \leq 10^{-26} \mathrm{e} \cdot \mathrm{cm}$

Misalignment mechanism : $\phi_0 \neq 0, \quad \dot{\phi} = 0$

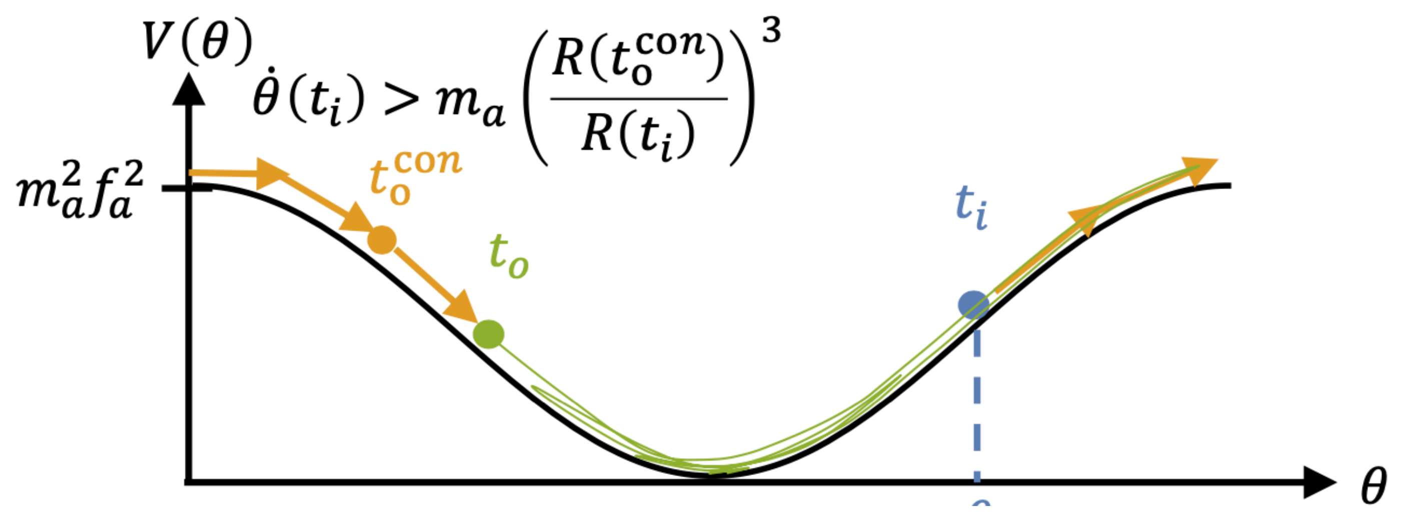
$$\ddot{\phi} + 3H\dot{\phi} + \frac{\Lambda^4(T)}{f^2}\phi = 0$$

$$\rho_{\mathrm{DM}} \sim m_\phi \left[\frac{a(T_{osc})}{a_0}\right]^3 \left[\frac{\Lambda(T_{osc})^4 \theta_i^2}{m_\phi(T_{osc})}\right]$$

Axiogenesis

Kinetic Misalignment mechanism : $\phi_0 \neq 0, \quad \dot{\phi} \neq 0$

[Co, Hall, Harigaya (2019)]
[Chang, Cui (2019)]



Non-zero Peccei-Quinn number→Axiogenesis!

Strong sphaleron → **Quark chiral asymmetry**

$n_{PQ} = S^2 \dot{\phi}$

EWsphaleron

Quark chiral asymmetry → (EWsphaleron; PRL, 124, 111602) → **Baryon asymmetry**

Main point of this talk about Leptogenesis

Traditional Leptogenesis mechanism:

- **There must be primordial B-L violation**
- **There must exist 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

2412.03902

Wei Chao[1,2,*]

[1] *Key Laboratory of Multi-scale Spin Physics, Ministry of Education, Beijing Normal University, Beijing 100875, China*

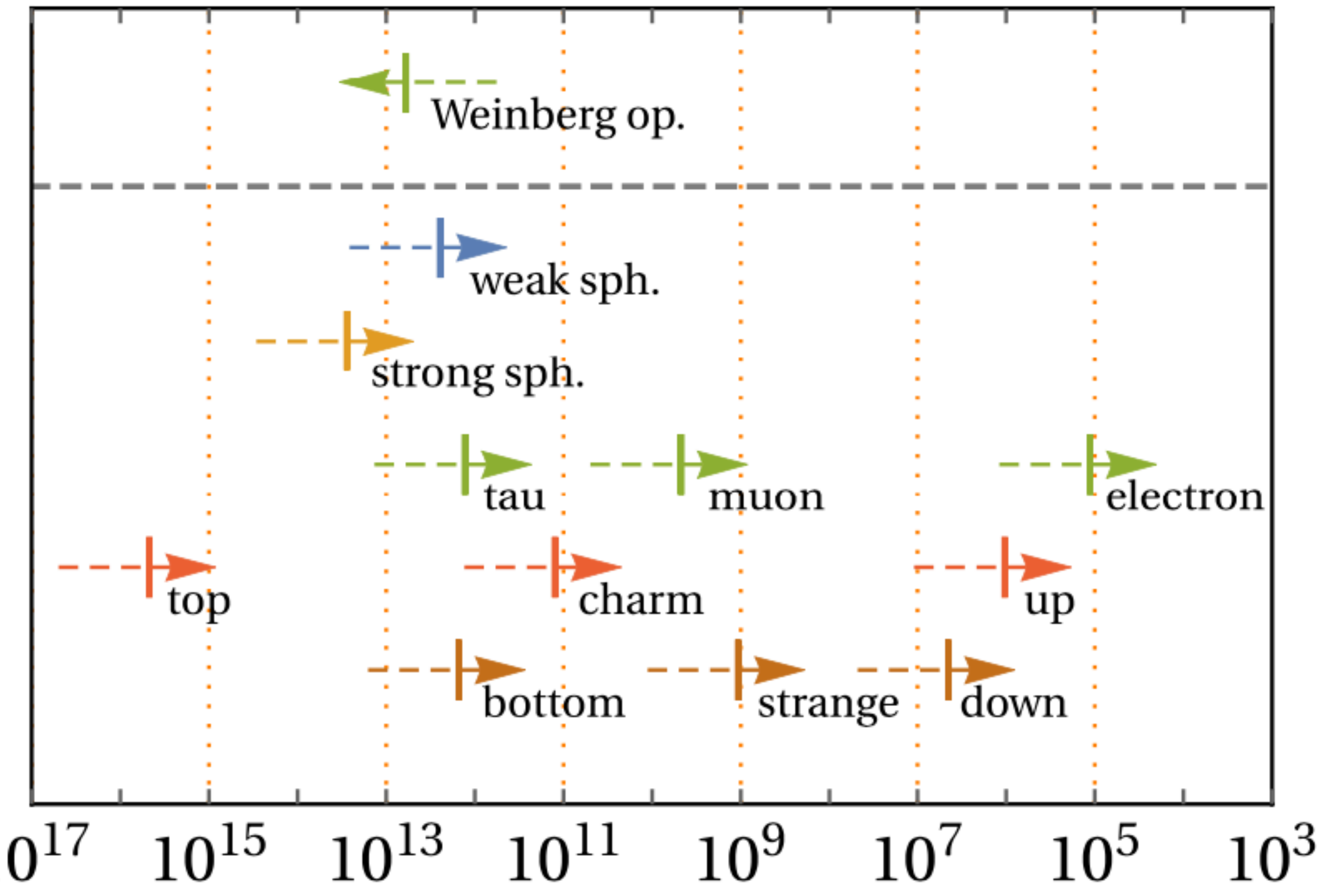
[2] *Center of Advanced Quantum Studies, School of Physics and Astronomy, Beijing Normal University, Beijing, 100875, China*

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}



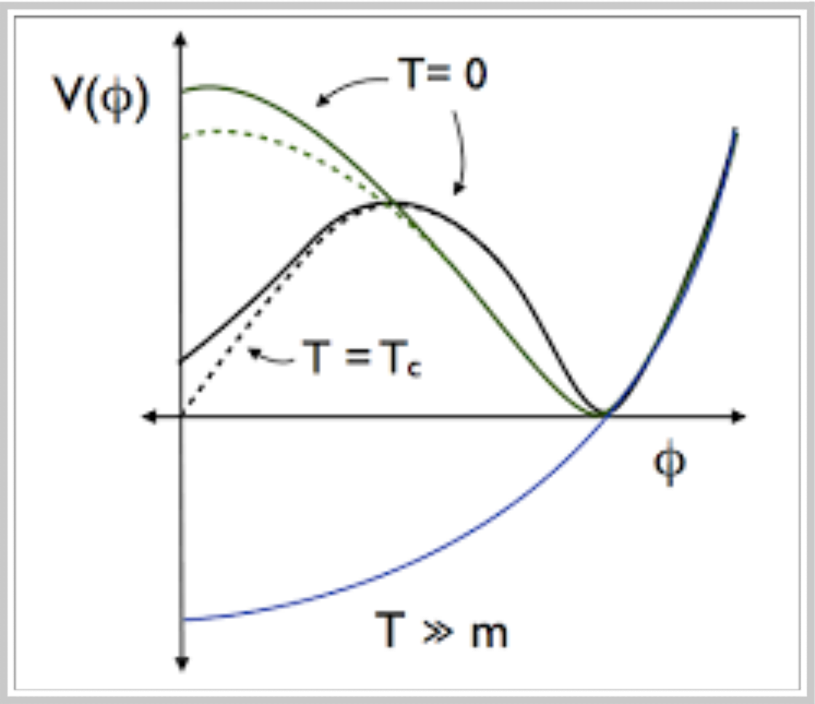
Valerie Domck, Yohei Ema, Kyohei Mukai and Masaki Yamada, JHEP 08(2020)096

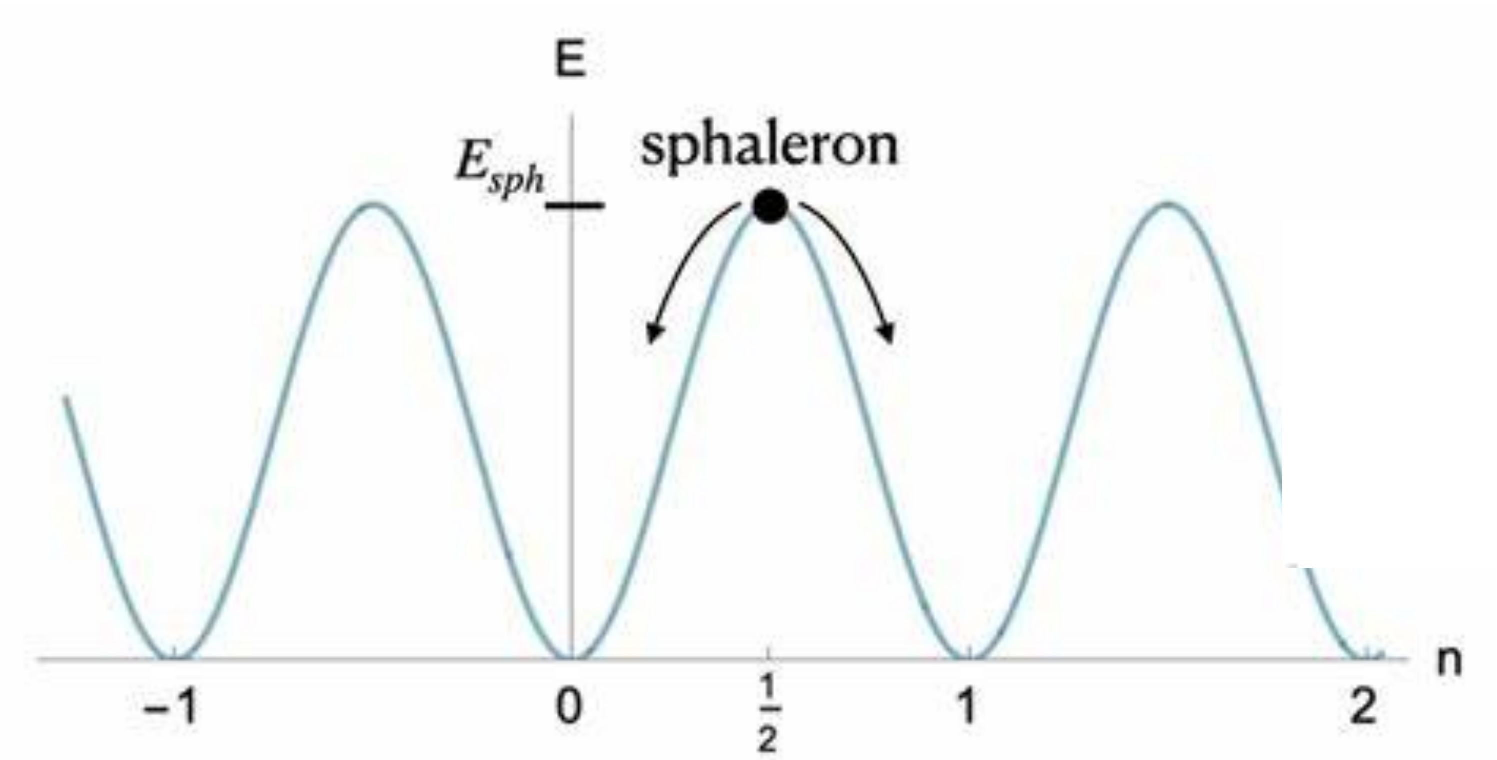
Sphaleron

- **Typical temperature:**

Sphaleron quench temperature: T= 130 GeV

Electroweak symmetry restored temperature: T= 160 GeV

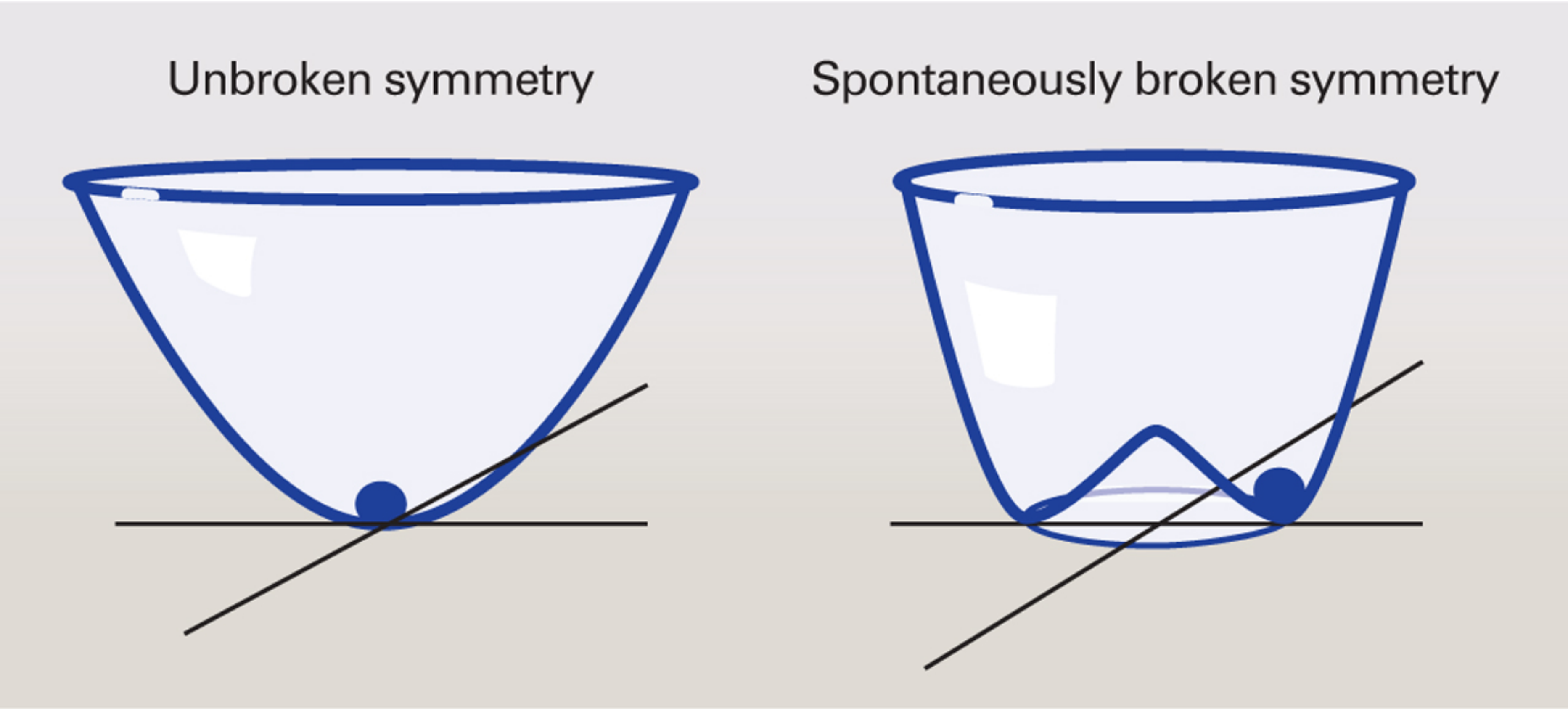


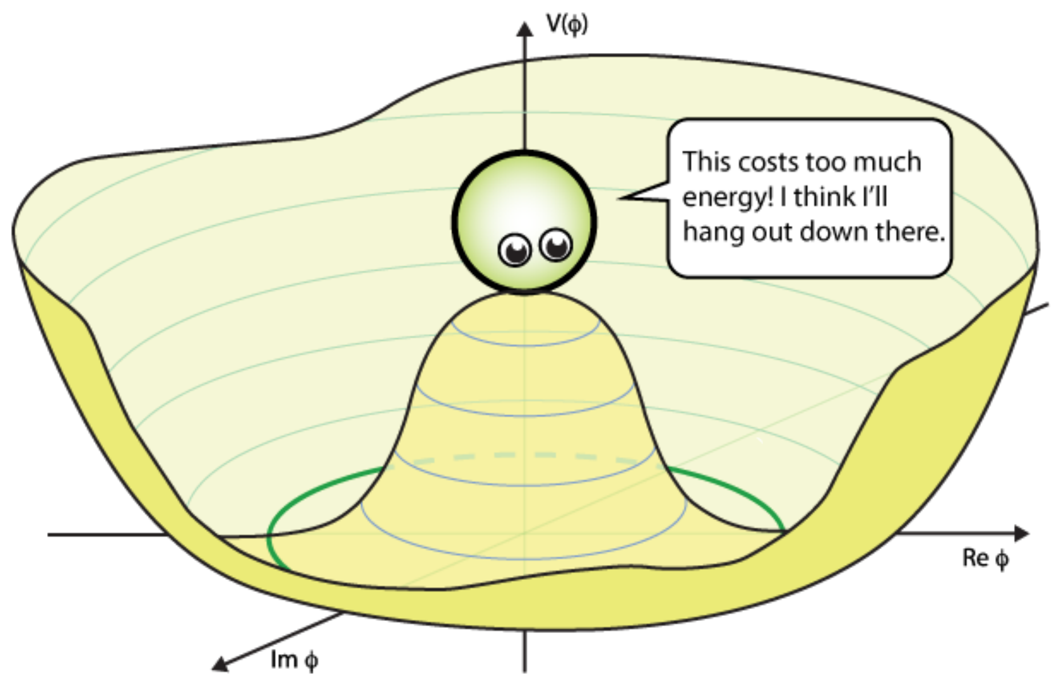


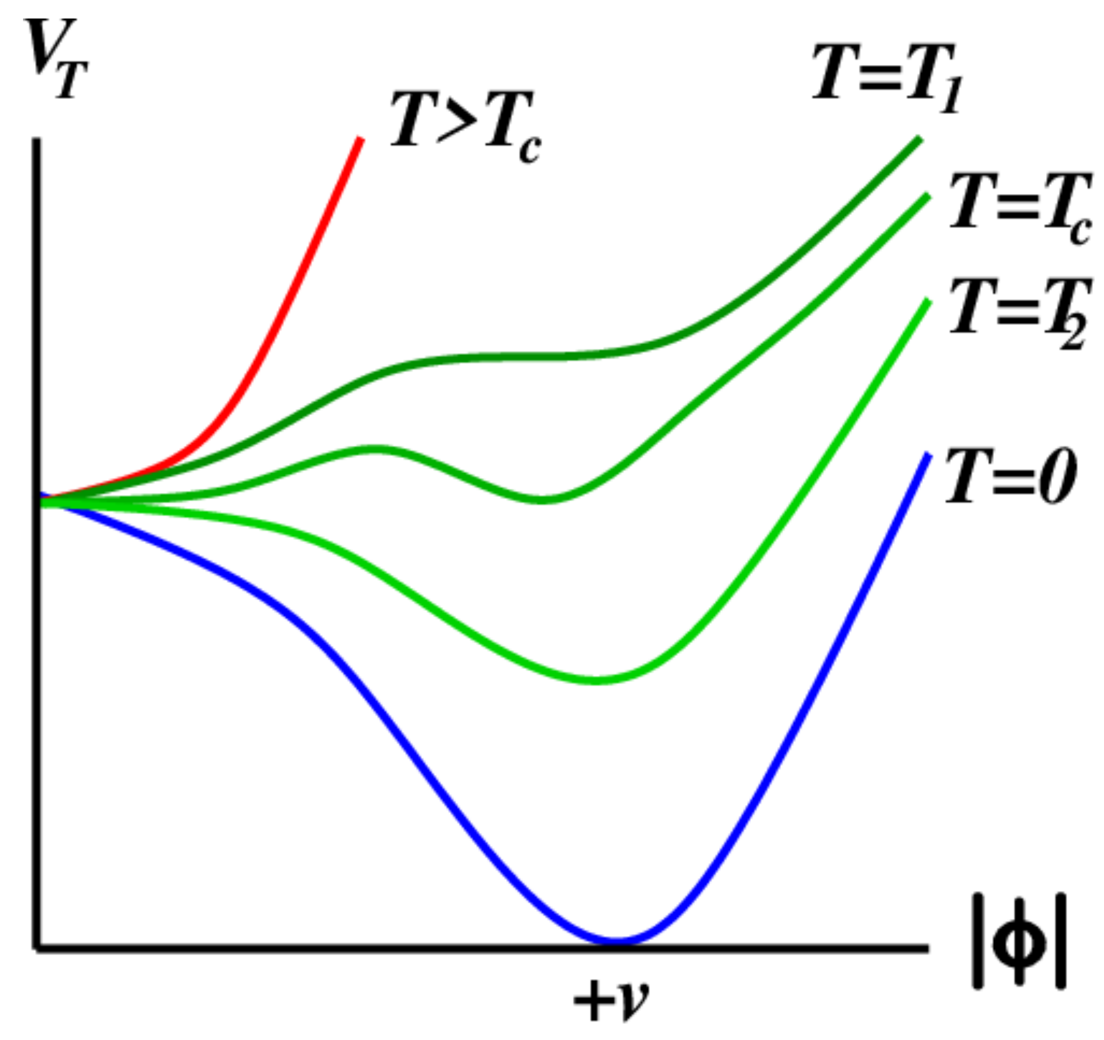
$$\Gamma_{\rm sph}^{\rm brok}(T) = \kappa_{\rm brok}\alpha_W^4 T^4 \exp\left(-\frac{E_{\rm sph}}{T}\right) \qquad (4)$$

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 restoration at high T?

Conventional symmetry breaking sequence	Question: Must all symmetries be restored at high T?

T ↑

$SO(10)$

↓

$SU(5)\times U(1)_X$ $\quad$ $Pati-Salam$

↓ $\qquad$ ↑ $\quad$ …

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

↓ $\qquad$ ↑ $\quad$ …

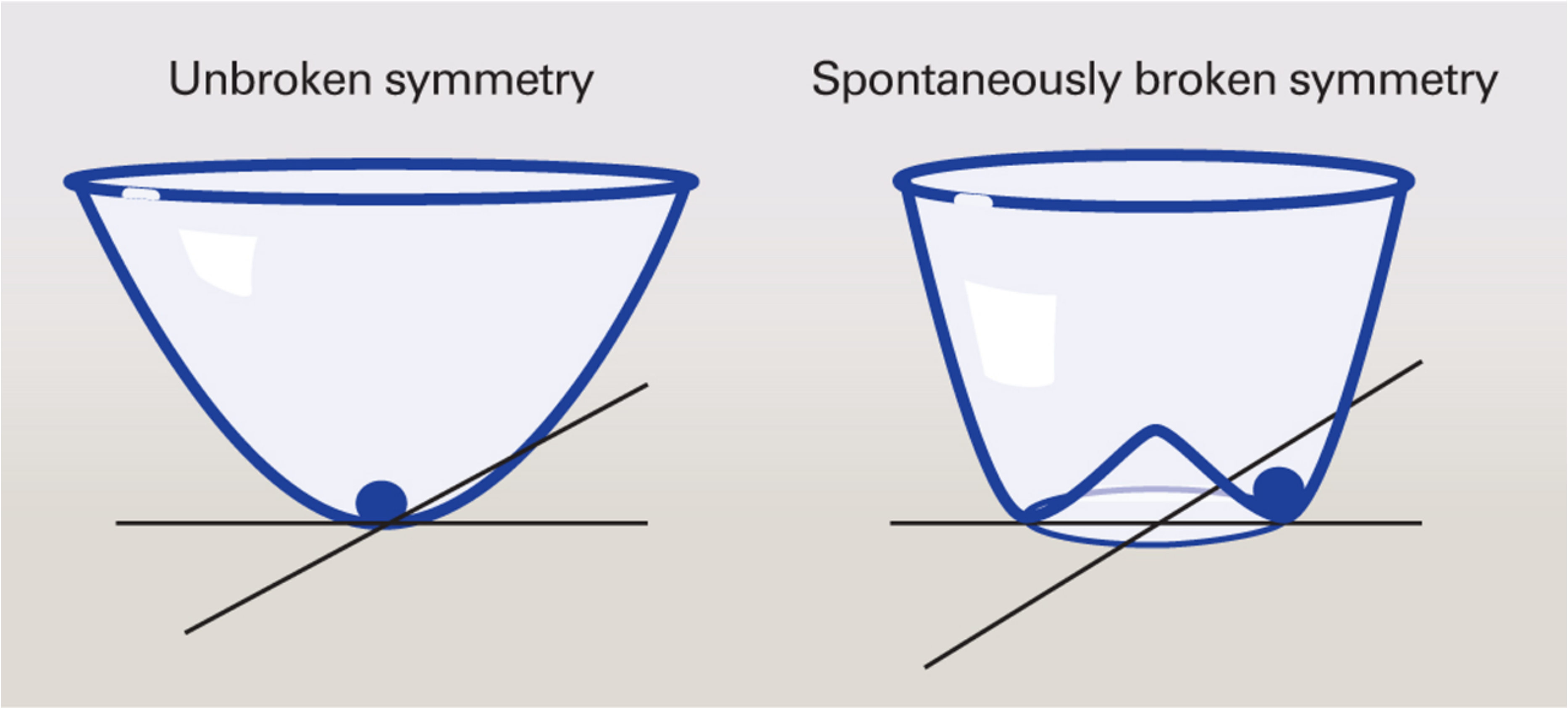
$SU(3)_C\times U(1)_{em}$

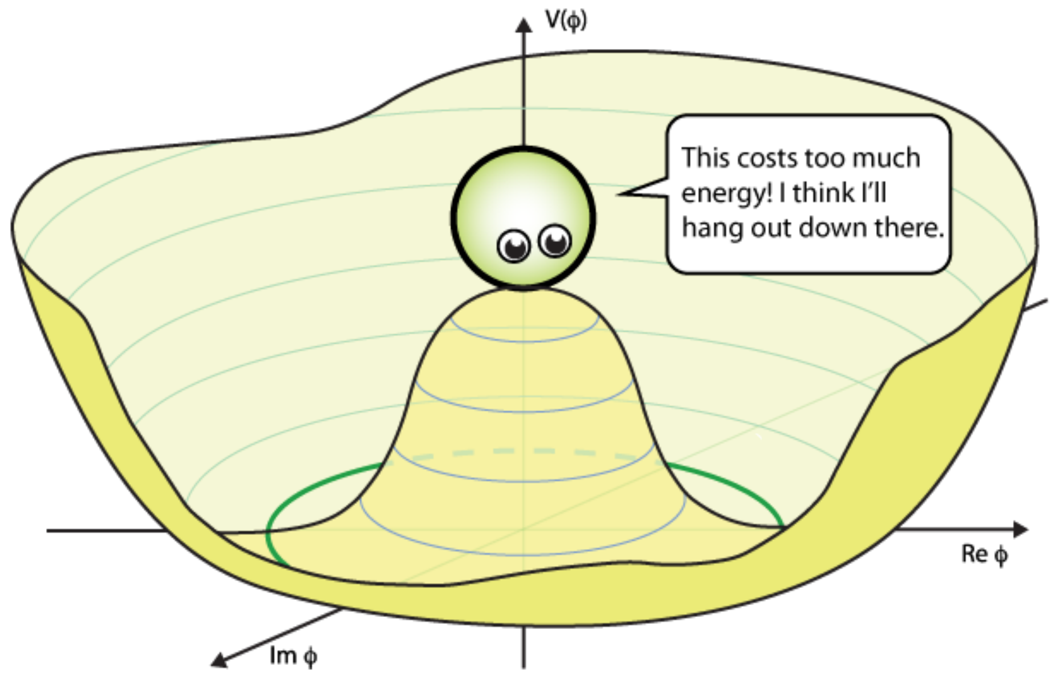
Maybe not!

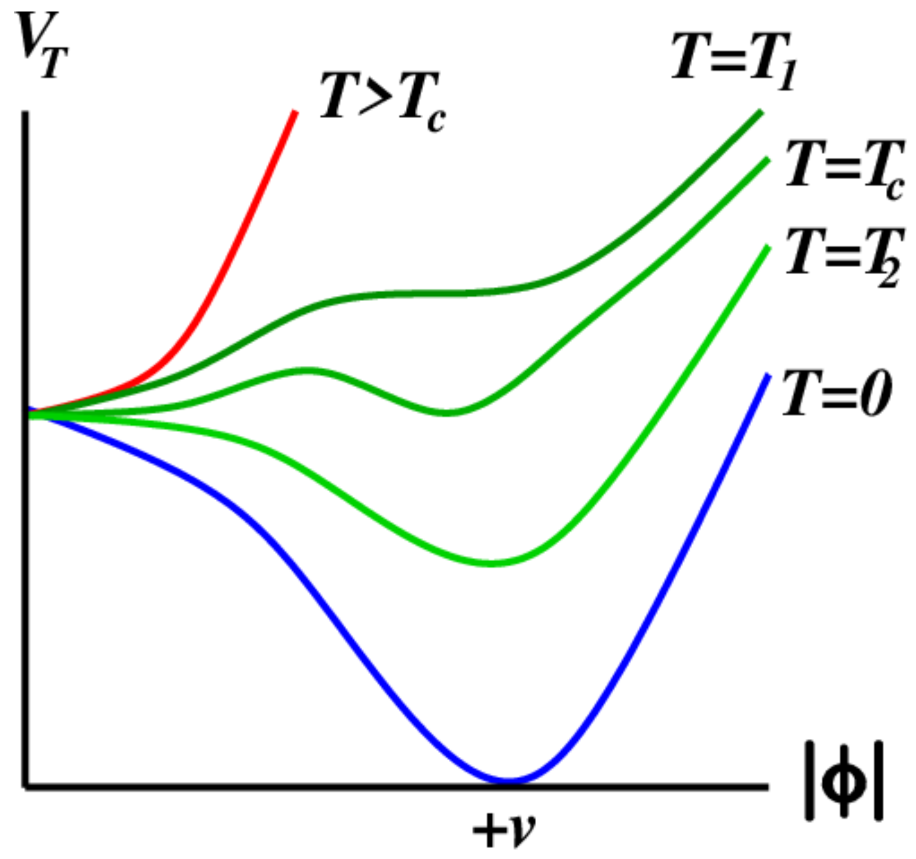
- O(n) x O(n): Weinberg (1974)
- SU(5): Dvali, Mohapatra, Senjanovic ('79, 80'S, 90'S)
- Cline, Moore, Servant et al (1999)
- EM: Langacker & Pi (1980)
- SU(3): Patel, Ramsey-Musolf, Wise (2013)

Symmetry non-restoration

- **EW symmetry non-restoration?** **Maybe!**







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

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

Tree-level

BSM corrections can be negative!

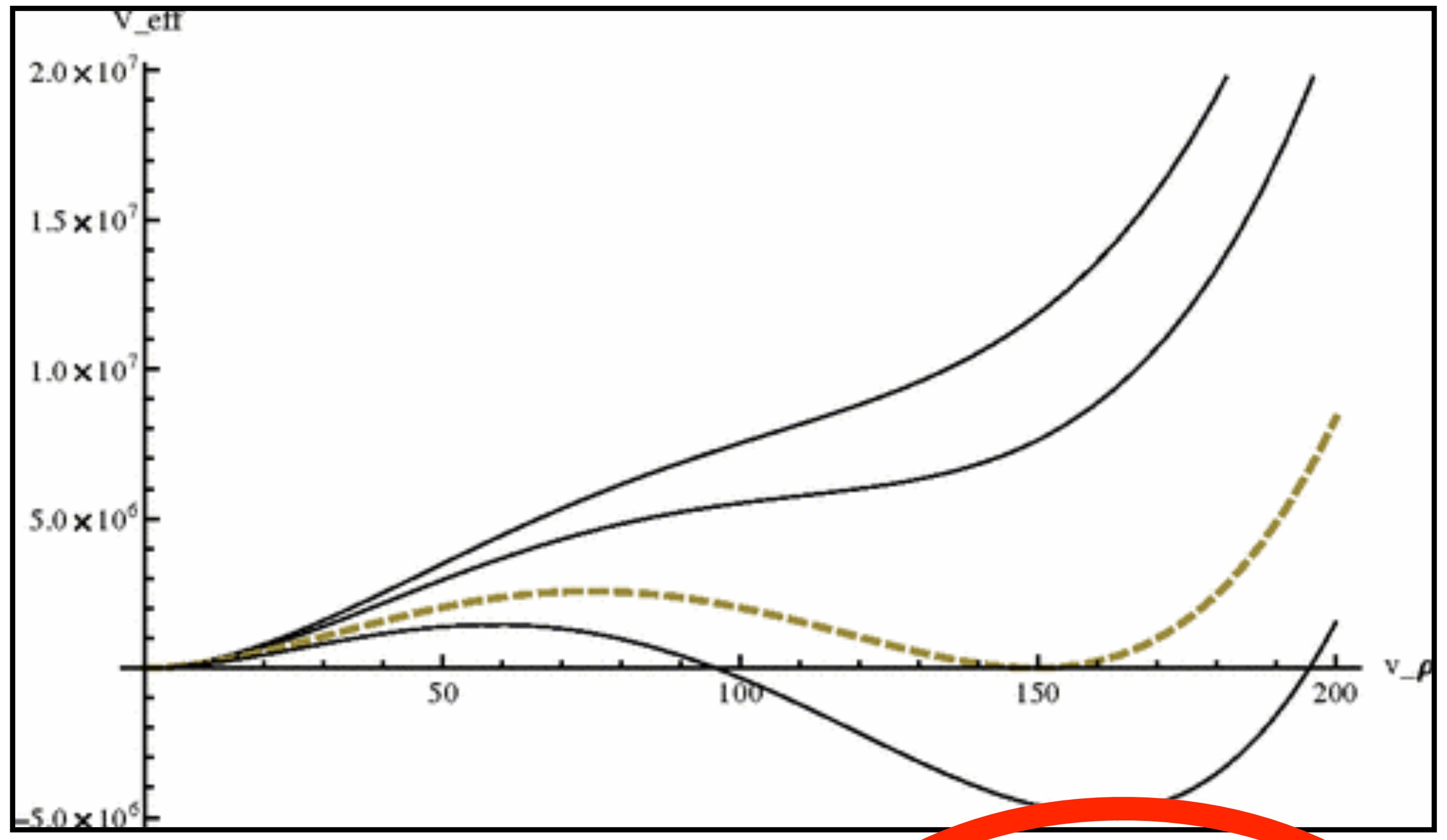
Color symmetry breaking at high T?

Key: symmetry non-storiation

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

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

Higgs gets large VEV at high T

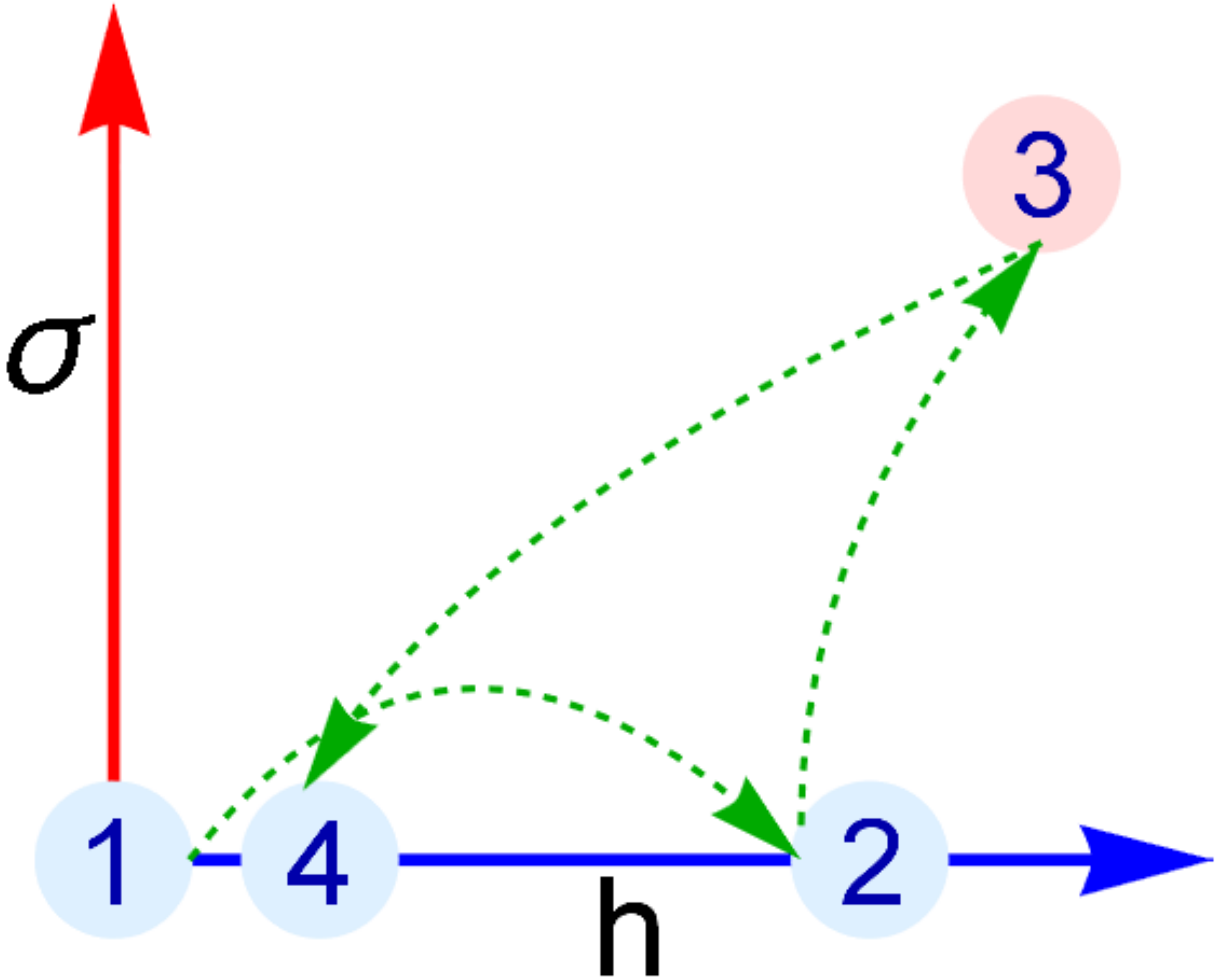


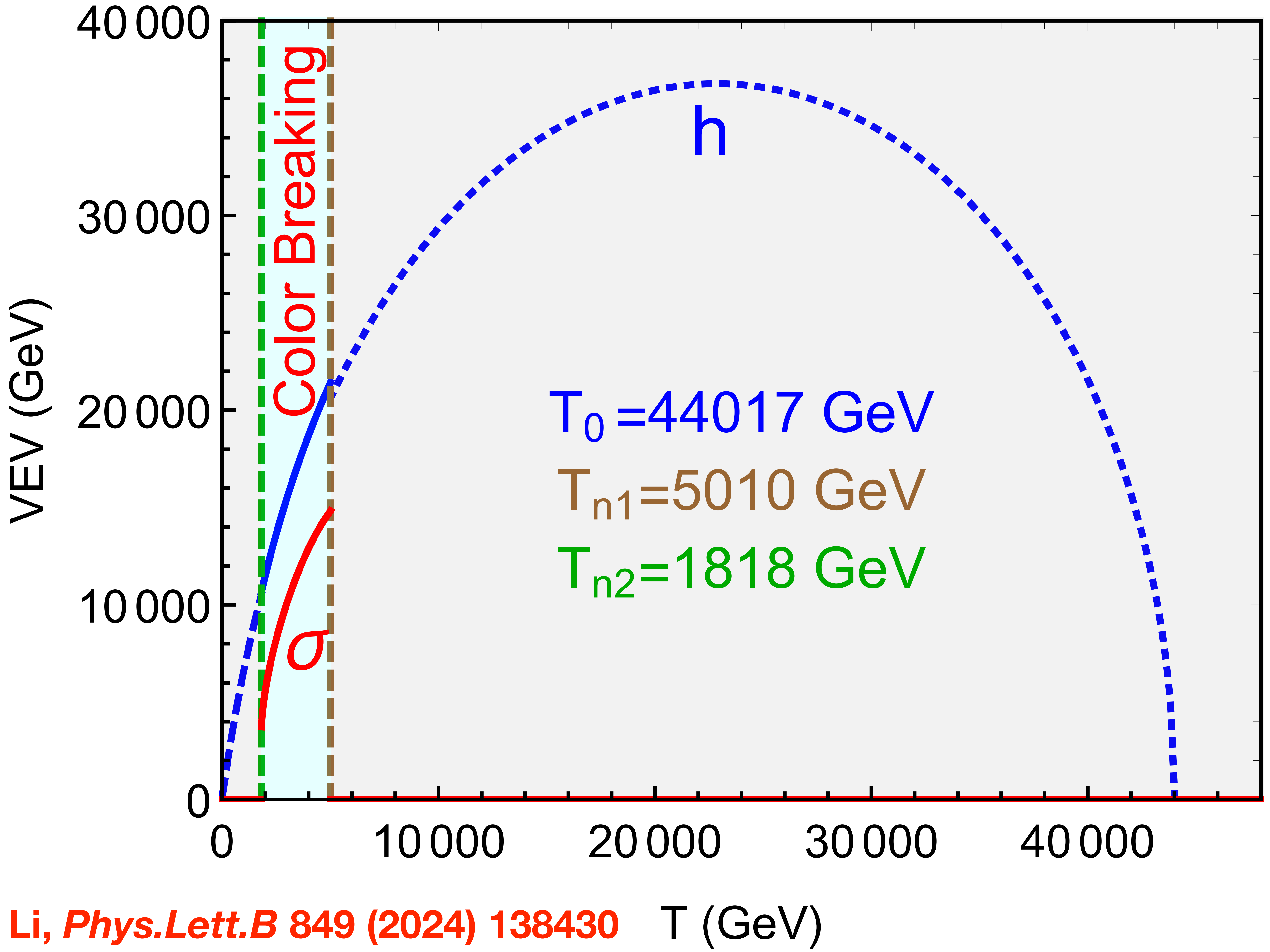
$$V_{\rm eff} = \mu_c^2 \Delta^\dagger \Delta - \lambda_{hc} H^\dagger H \Delta^\dagger \Delta + \lambda_c (\Delta^\dagger \Delta)^2 + V_{\rm SNR}$$

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

Wei Chao, H. Guo, X. F. Li, *Phys. Lett.B* 849 (2024) 138430

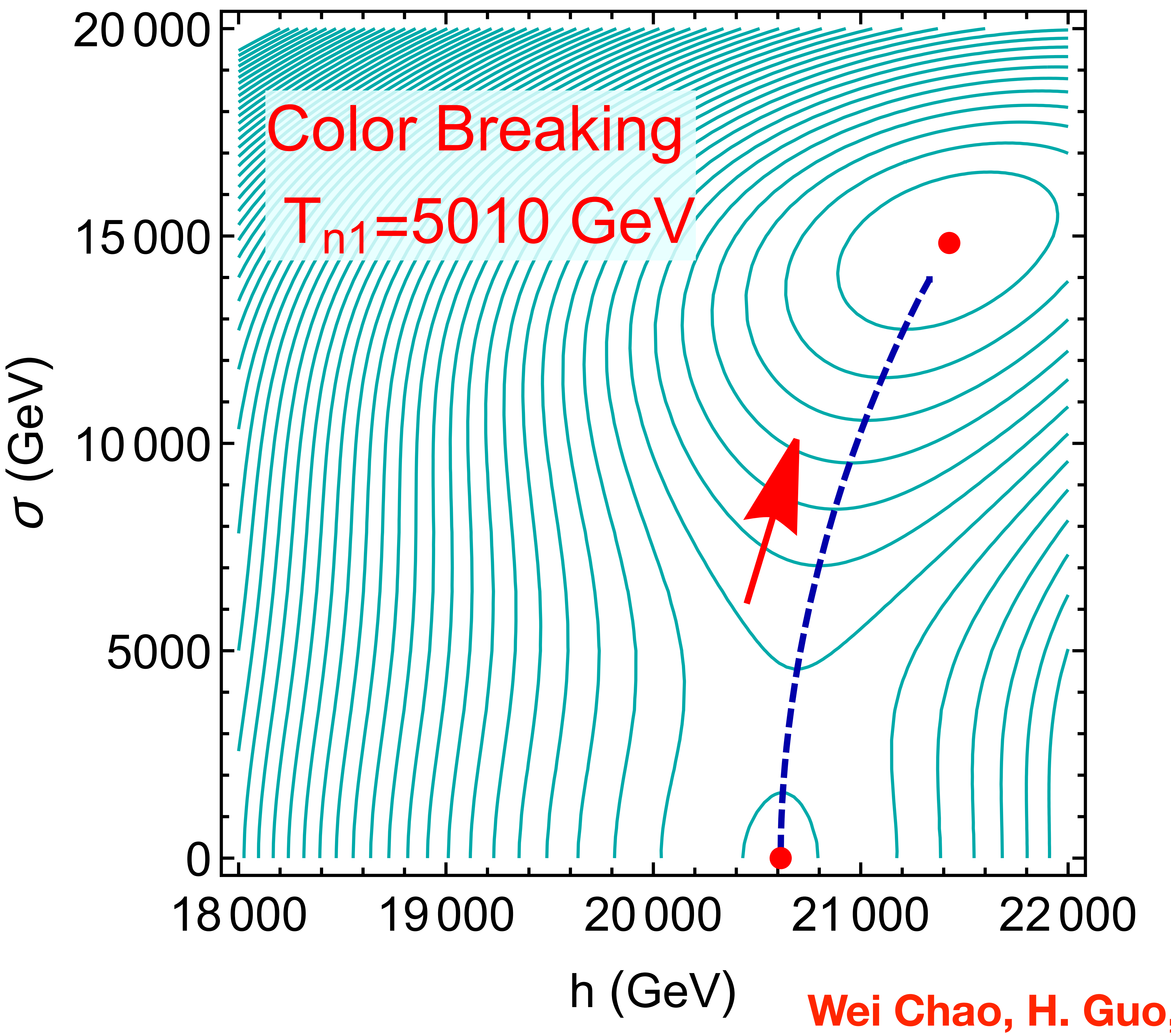
Color symmetry breaking at high T?

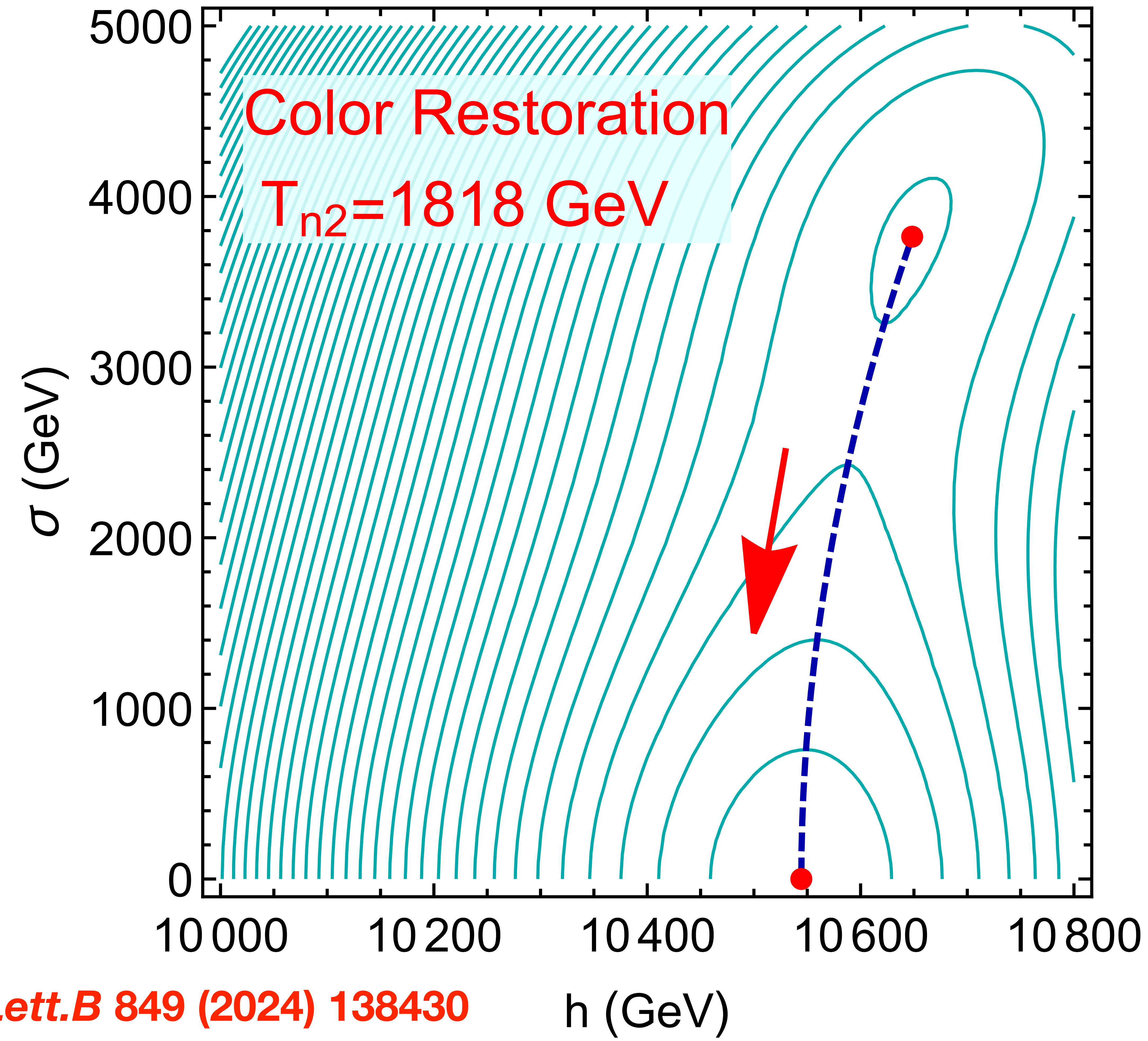




Wei Chao, H. Guo, X. F. Li, *Phys.Lett.B* 849 (2024) 138430

Phase diagrams





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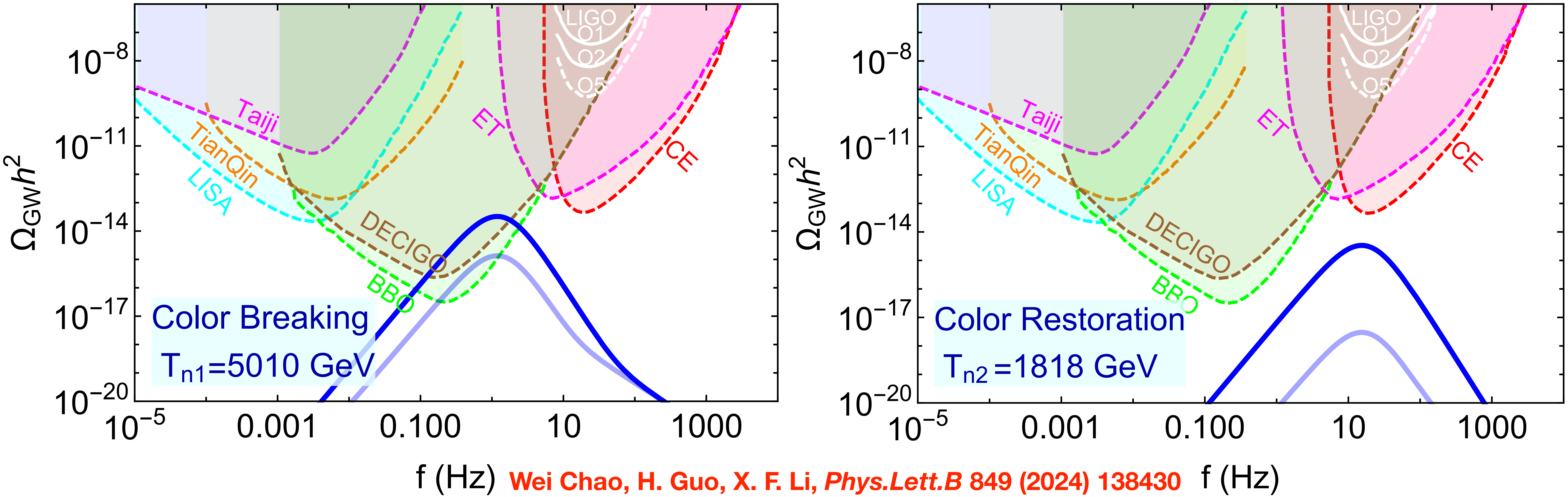
Gravitational waves

Two peak frequencies!



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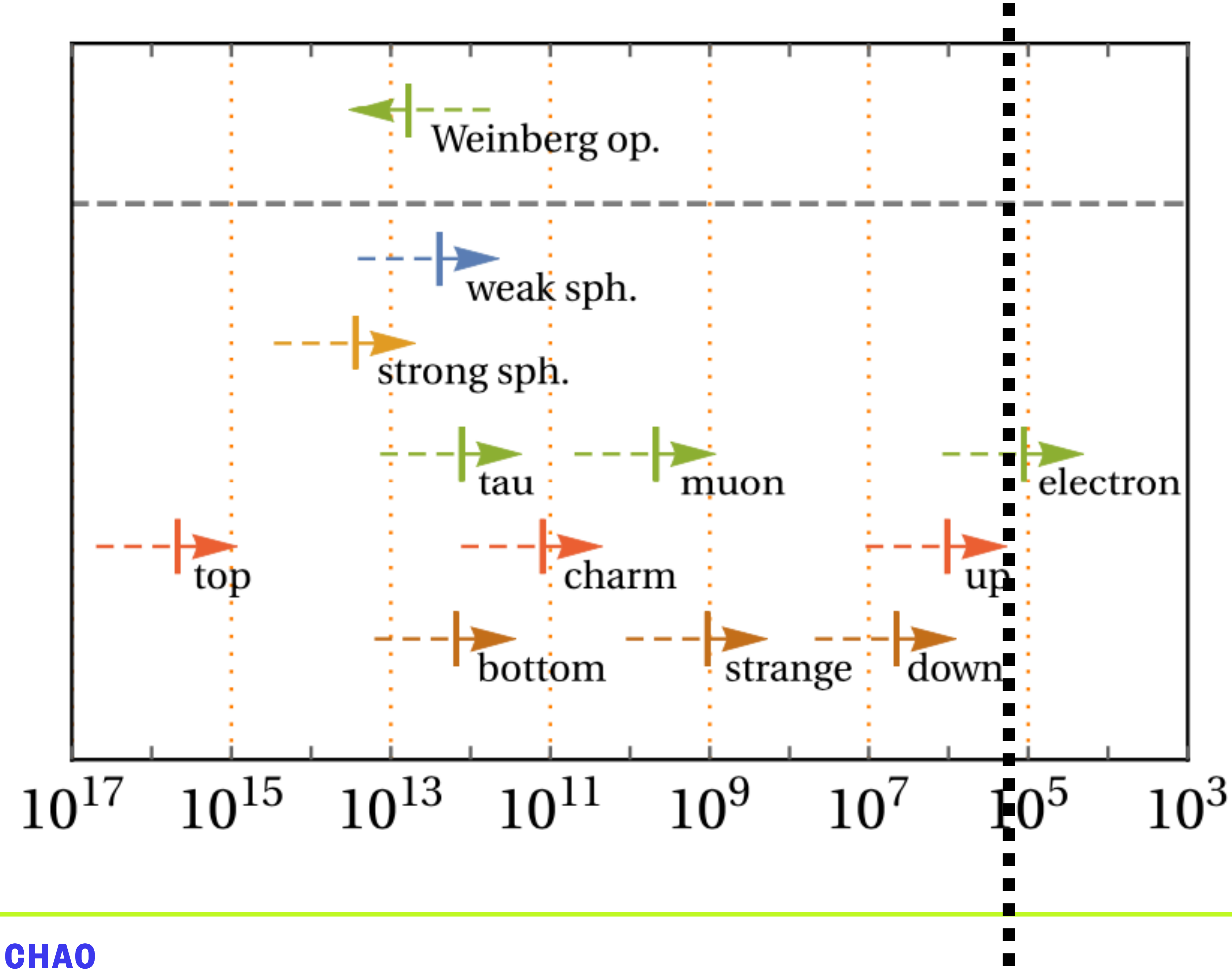
Symmetry non-restoration

- **EW symmetry non-restoration? The answer is Yes!**



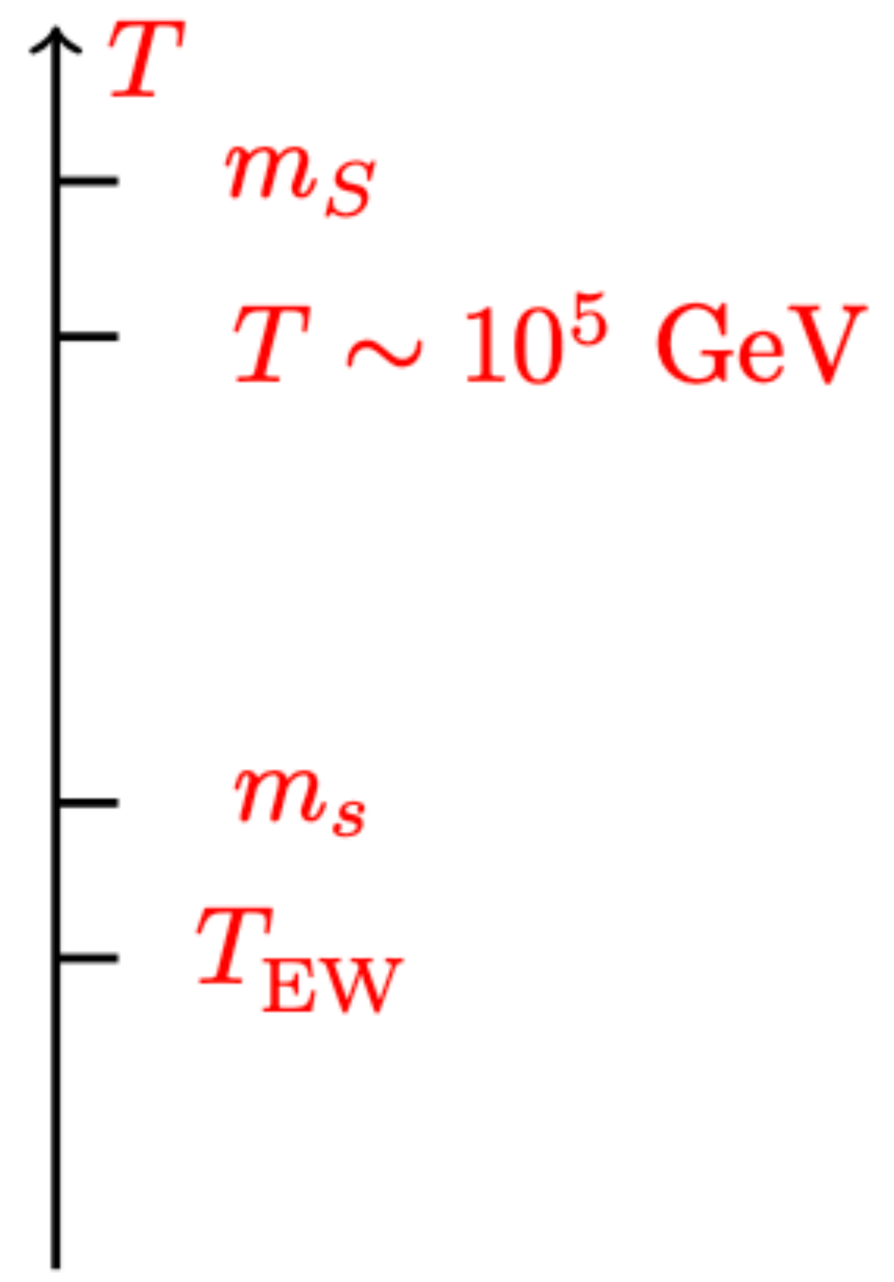
Sphaleron quenches at 10^5 GeV.

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

* No B-L violation is needed!

Symmetry non-restoration

- **Basic set up**



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

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

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

Leptogenesis

- Scenario-1 : Axion inflation Leptogenesis

- Scenario-2 : Eogenesis

Axion-inflation baryogensis

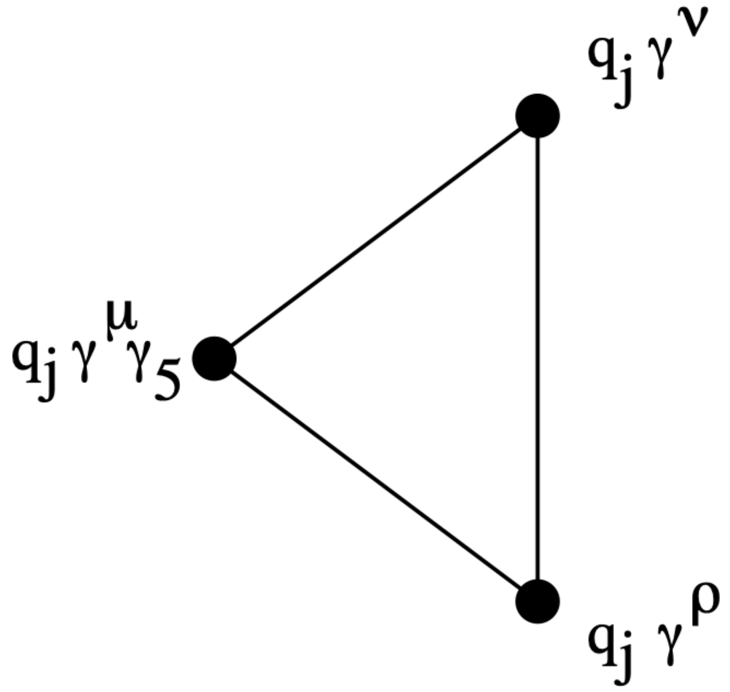
- **$U(1)_R$: Gauged U(1) symmetry for right-handed fermions**

scenario	symmetries	Q_L	ℓ_L	U_R	D_R	E_R	N_R	H	ψ_L	ψ_R	χ_L	χ_R	η_L	η_R
(i)	$U(1)_{\mathbf{B-L}}$	$+\frac{1}{3}$	-1	$+\frac{1}{3}$	$+\frac{1}{3}$	-1	-1	0	×	×	×	×	×	×
(ii)	$U(1)_{\mathbf{R}}$	0	0	-1	$+1$	-1	$+1$	1	×	×	×	×	×	×
(iii)	$U(1)_{\mathbf{B}}$	$+\frac{1}{3}$	0	$+\frac{1}{3}$	$+\frac{1}{3}$	0	0	0	-1	$+2$	$+2$	-1	$+2$	-1
(iv)	$U(1)_{\mathbf{L}}$	0	$+1$	0	0	$+1$	$+1$	0	-1	$+2$	$+2$	-1	$+2$	-1

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

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

$$\partial_\mu \left(j^\mu_{L,N} \right) = \frac{1}{16\pi^2} \left(-g_R^2 F'\widetilde{F}' \right)$$

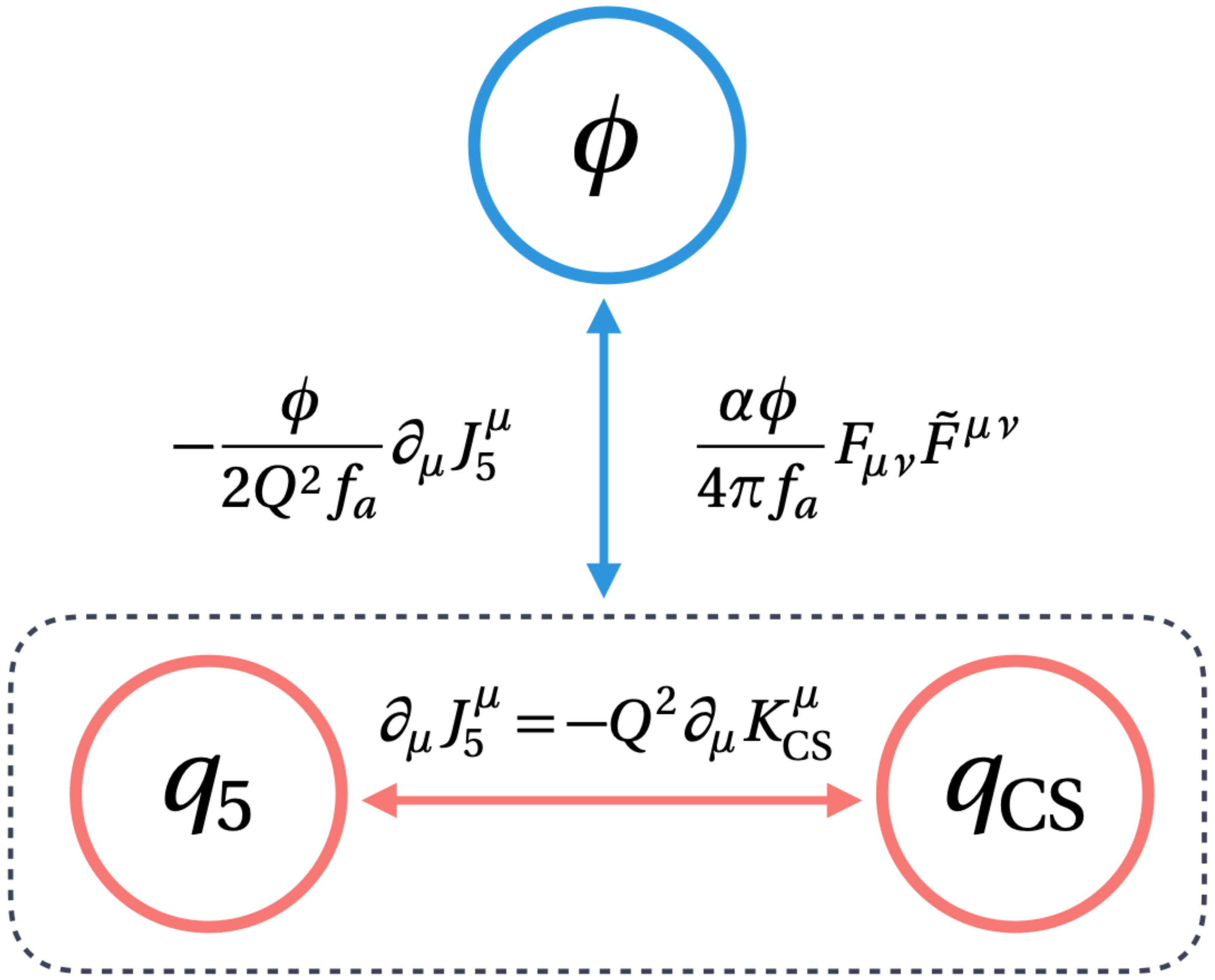


$$\partial_\mu \left(j^\mu_{L,E} \right) = \frac{1}{16\pi^2} \left(-g'^2 F\widetilde{F} - g_R^2 F'\widetilde{F}' \right)$$

$$\Rightarrow \quad \partial_\mu \left(j^\mu_B - j^\mu_{L'} - j^\mu_N - j^\mu_e \right) = 0$$

Axion-inflation baryogensis

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



- **Chern Simons number:**

$$n_{CS} \equiv \frac{1}{(2\pi)^2}\mathscr{K}(\xi)a^3H^3$$

$$= \frac{1}{(2\pi)^2}\sum_{\lambda=\pm}\lambda e^{i\kappa_\lambda \pi}\int \tilde{\tau}^3 d\ln\tilde{\tau}W^*_{\kappa_\lambda,\mu}(-2i\tilde{\tau})W_{\lambda_\sigma,\mu}(-2i\tilde{\tau})a^3H^3$$

- **Chiral fermion asymmetry during reheating**

$$n_{f,\sigma} = -\epsilon_\sigma N_{f,\sigma}\frac{g_X^2}{8\pi^2 a^3}n_{CS} = -\epsilon_i N_i \frac{g_X^2}{2(2\pi)^4}H^3\mathscr{K}(\xi)$$

Axion-inflation baryogensis

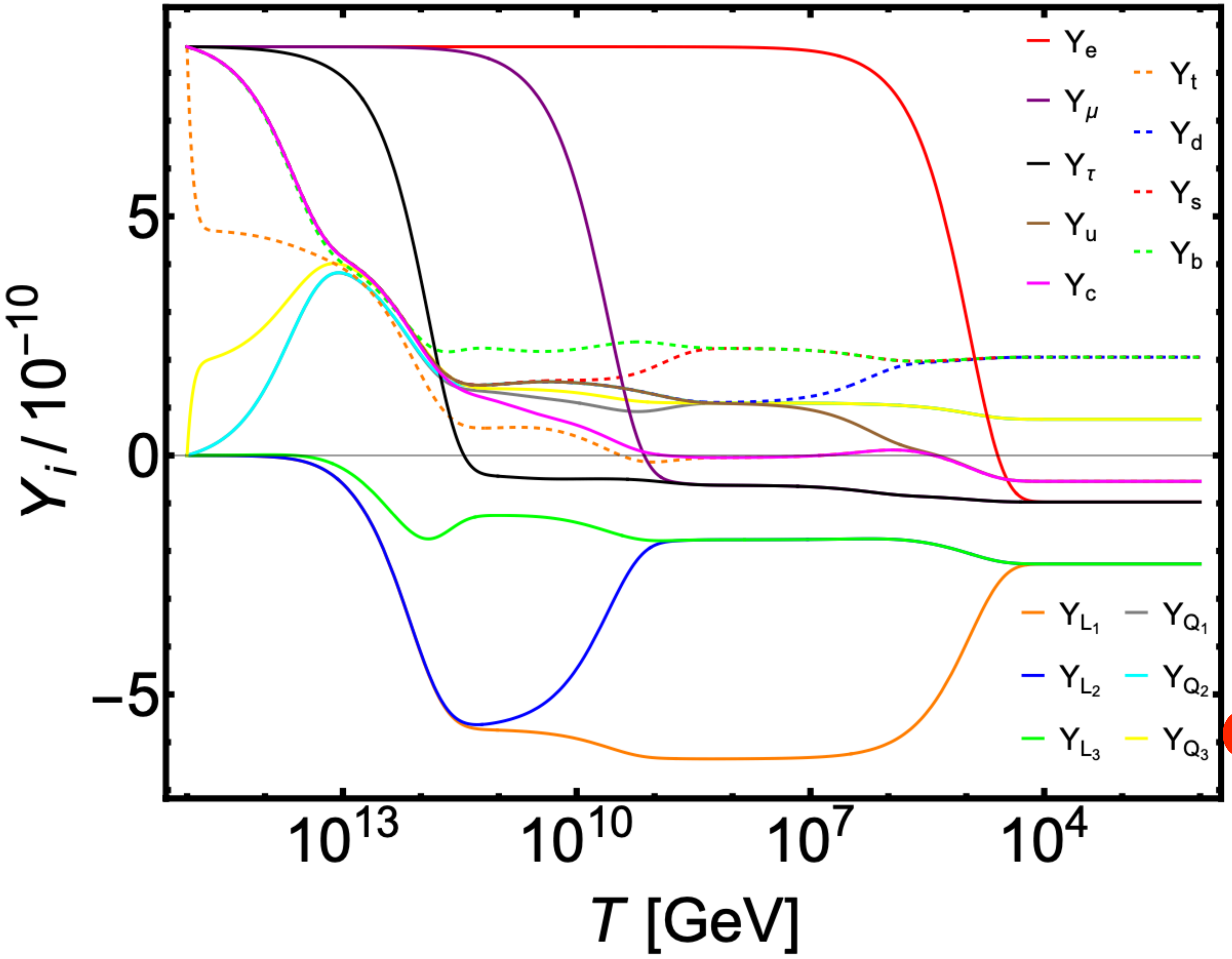
For the case in which neutrinos are Majorana particle

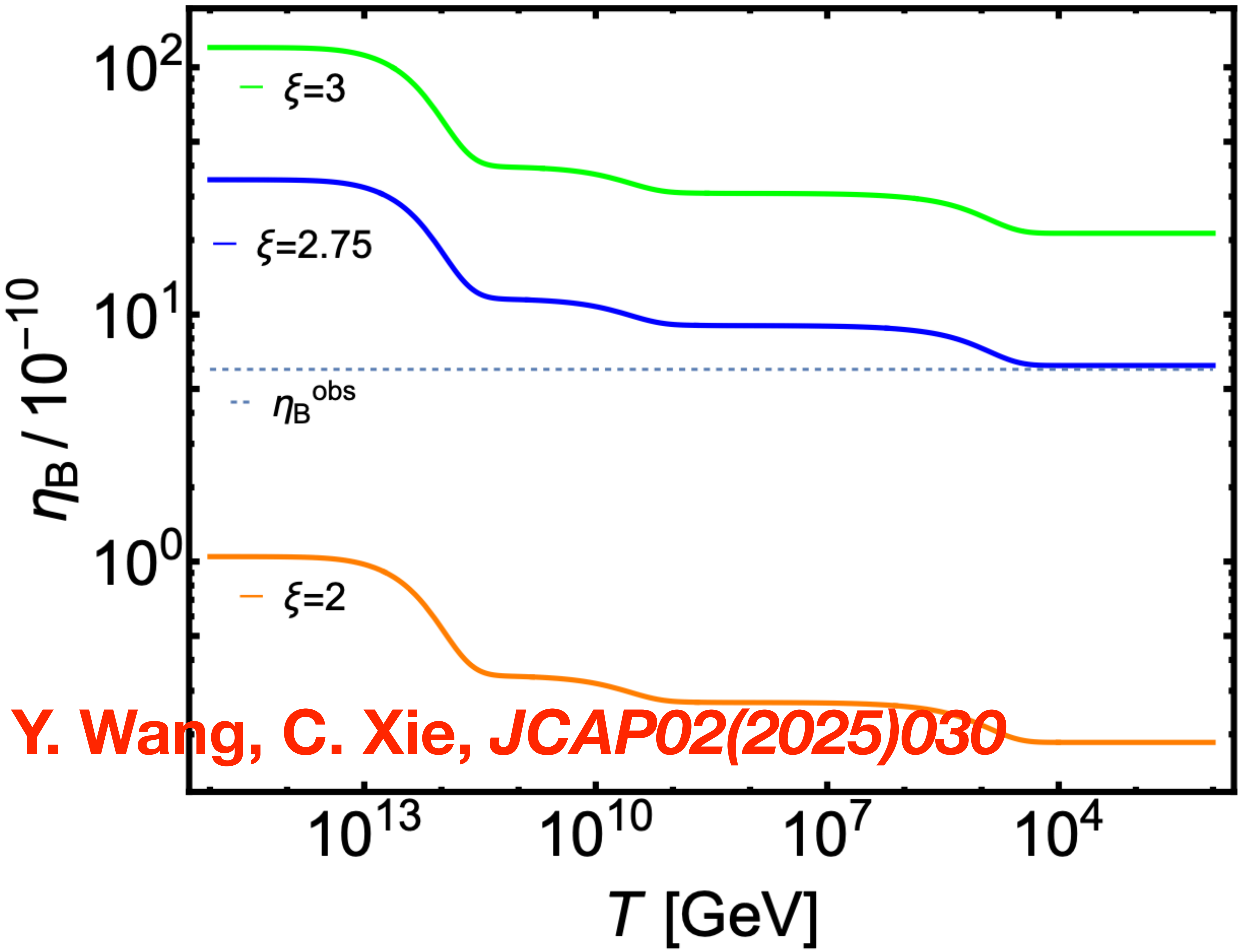
$$Y_B = \frac{28}{79} Y_{B-L'} = \frac{28}{79} \frac{n_e}{s}\Big|_{T=T_{\rm FO}}$$

- **Concrete value depends on the input of the axion inflation parameters!**

Axion-inflation baryogensis

If neutrinos are Dirac particles!





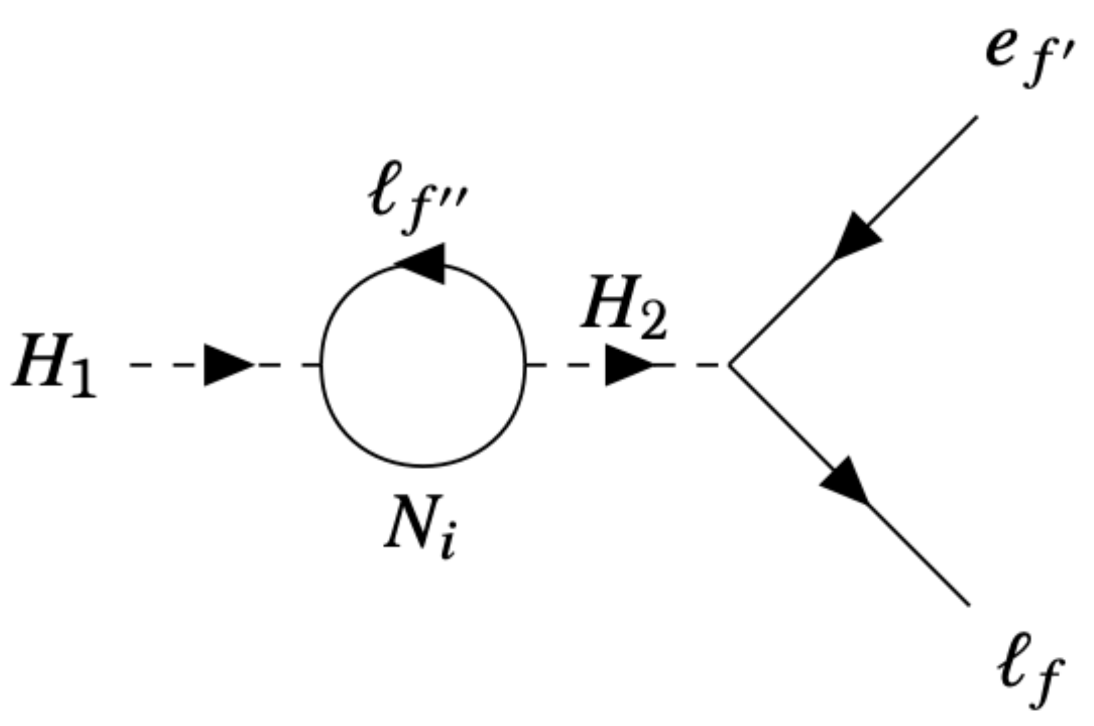
Chao, Y. Wang, C. Xie, *JCAP02(2025)030*

Leptogenesis

- Scenario-1 : Axion inflation Leptogenesis
- Scenario-2 : Eogenesis

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**

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

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

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

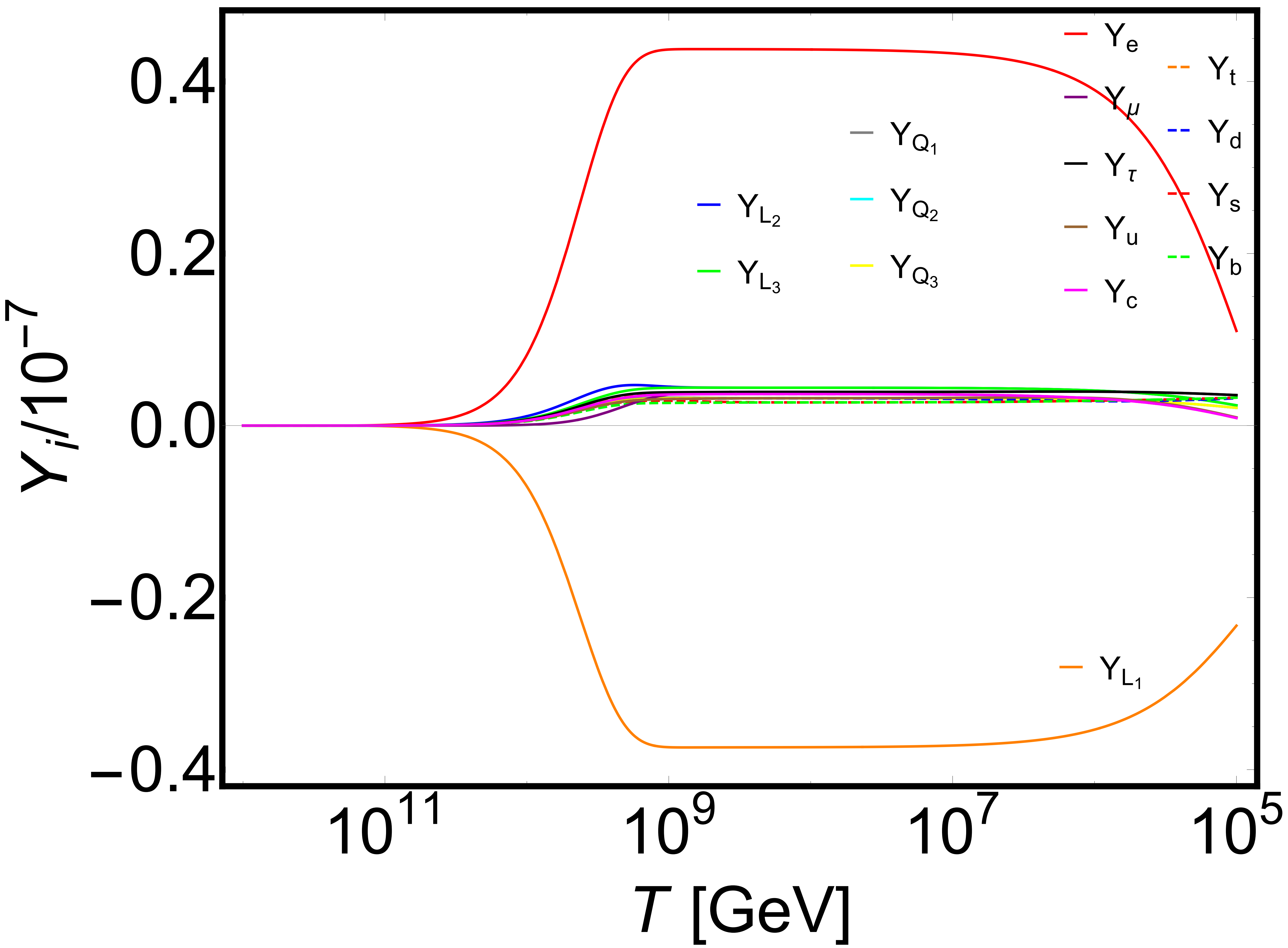
$$-\frac{d}{d\ln T}\left(\frac{\mu_{L_k}}{T}\right) = -\frac{1}{g_{L_k}}\frac{\gamma_{WS}}{H}\left[\sum_{i=1}^{3}\left(\frac{\mu_{L_i}}{T} + 3\frac{\mu_{Q_i}}{T}\right)\right]$$

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

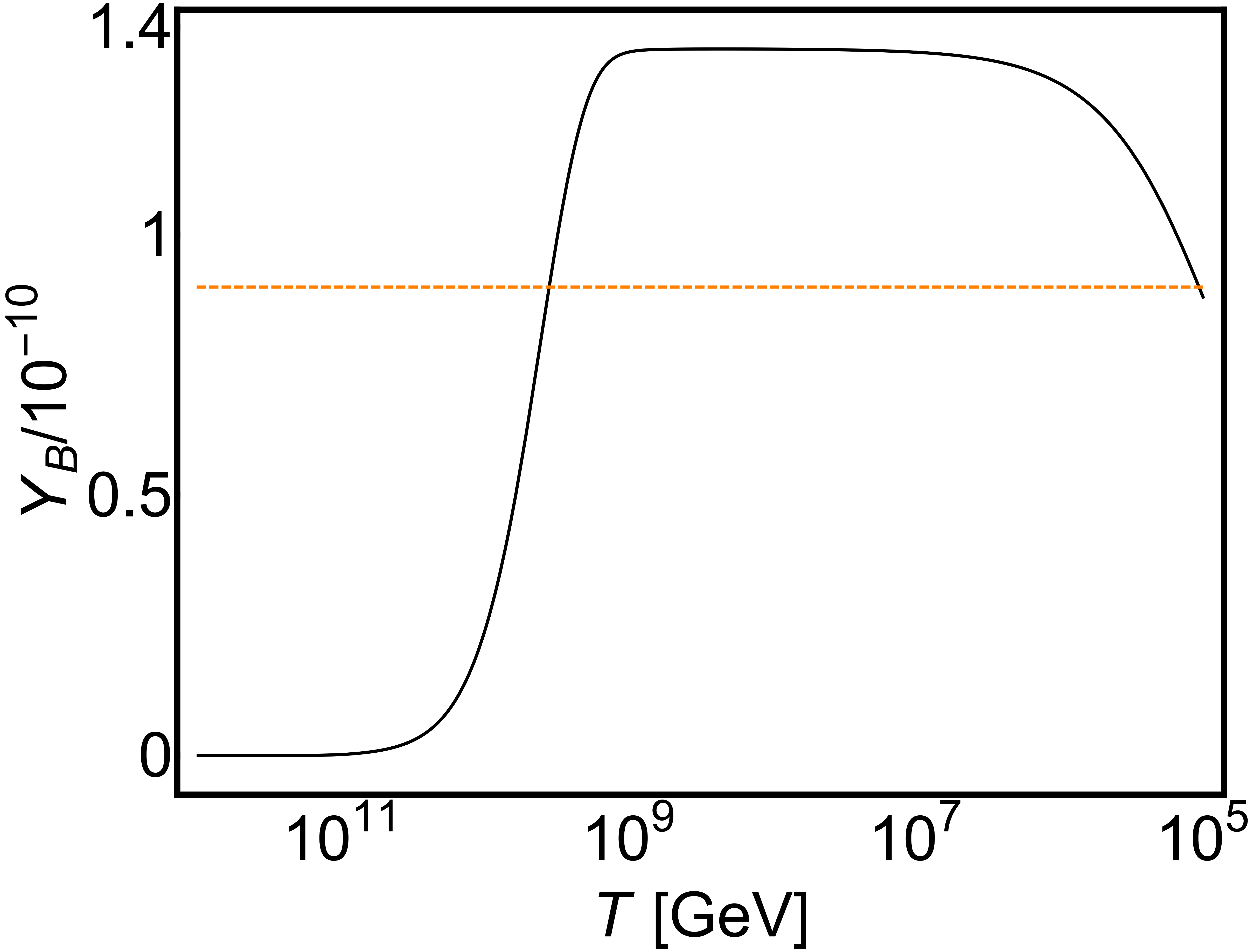
$$+\frac{1}{g_{L_k}}\frac{\gamma_D}{H}\varepsilon\left[\frac{4\pi^2 g_*^S}{15}Y_\Sigma - \frac{48\zeta(3)}{\pi^2}\right]$$

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

Eogenesis



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



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

Conclusion

A new type of Leptogenesis is proposed, which is dubbed as **Eogenesis**

- No primordial B-L is needed
- No dependence on the nature of neutrinos

Thank you for your attention!