第四届高能物理理论与实验融合发展研讨会通知，2025年9月19-23日、辽宁师范大学

手征磁效应与轻子生成机制

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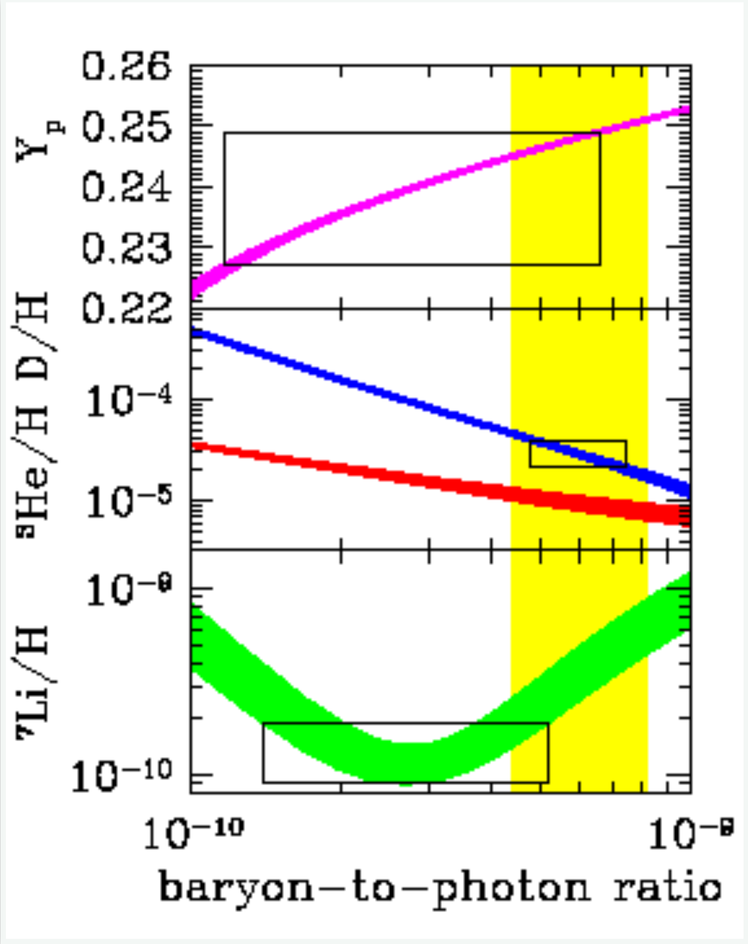
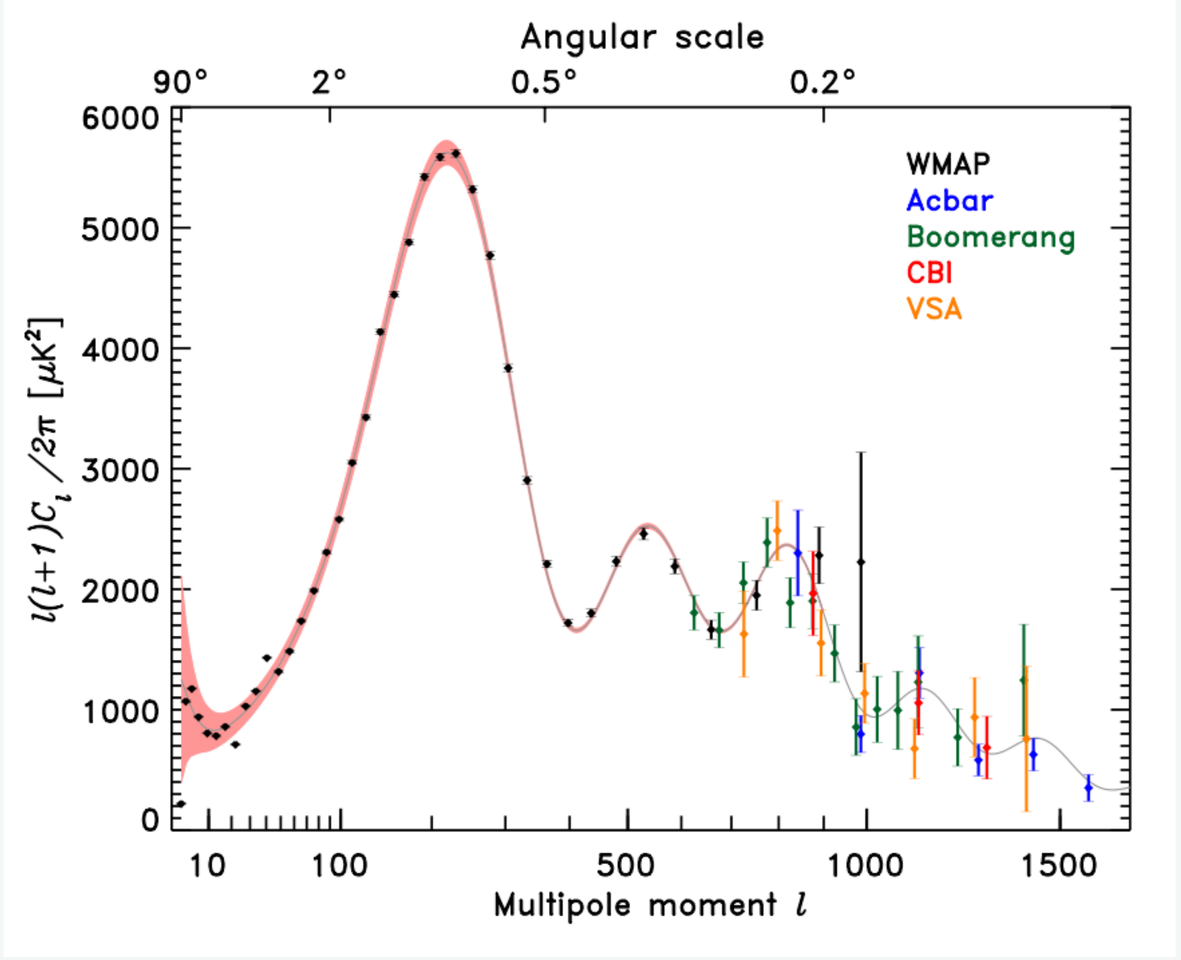
New physics—The Baryon asymmetry

Matter-antimatter asymmetry

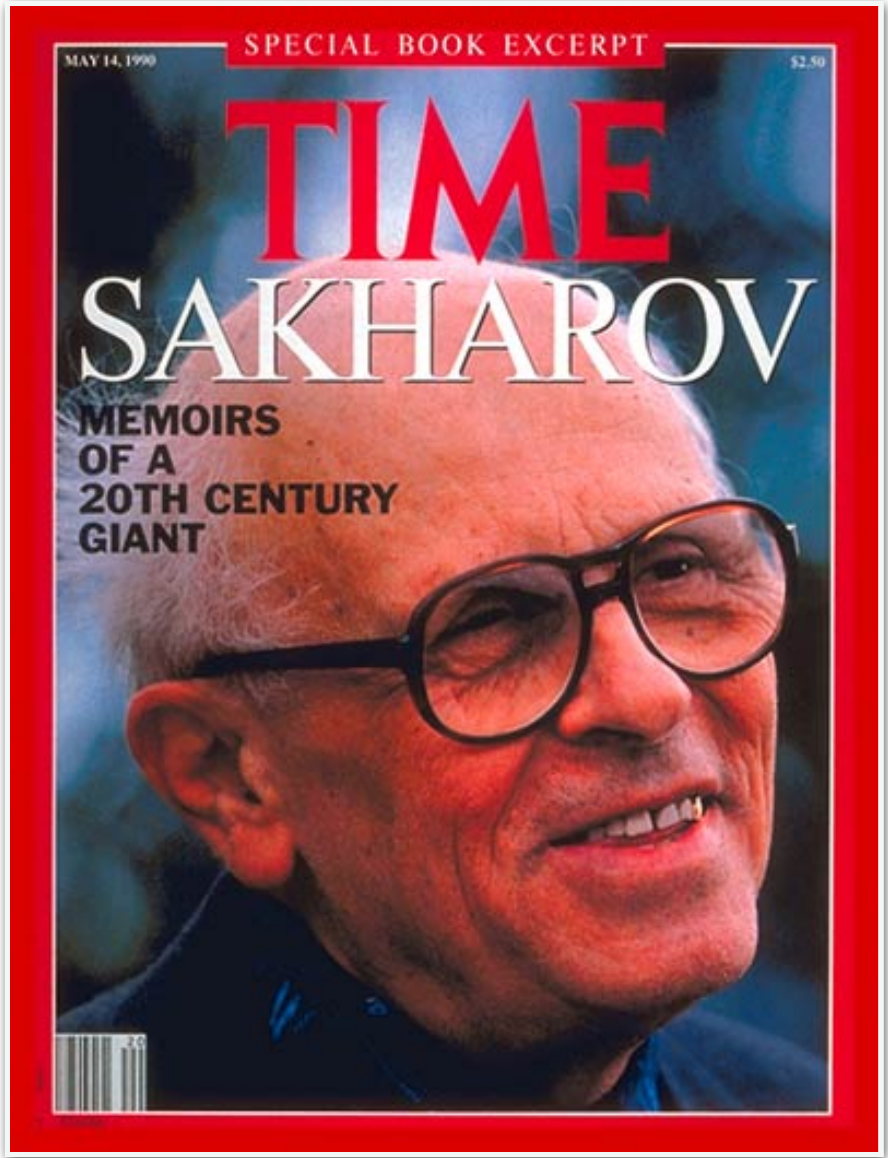
- 没有观测到反物质星系，否则光学望远镜会观测到星系湮灭的射线
- 元素的原初丰度以及CMB功率谱的形状都依赖于重子数与光子数之比

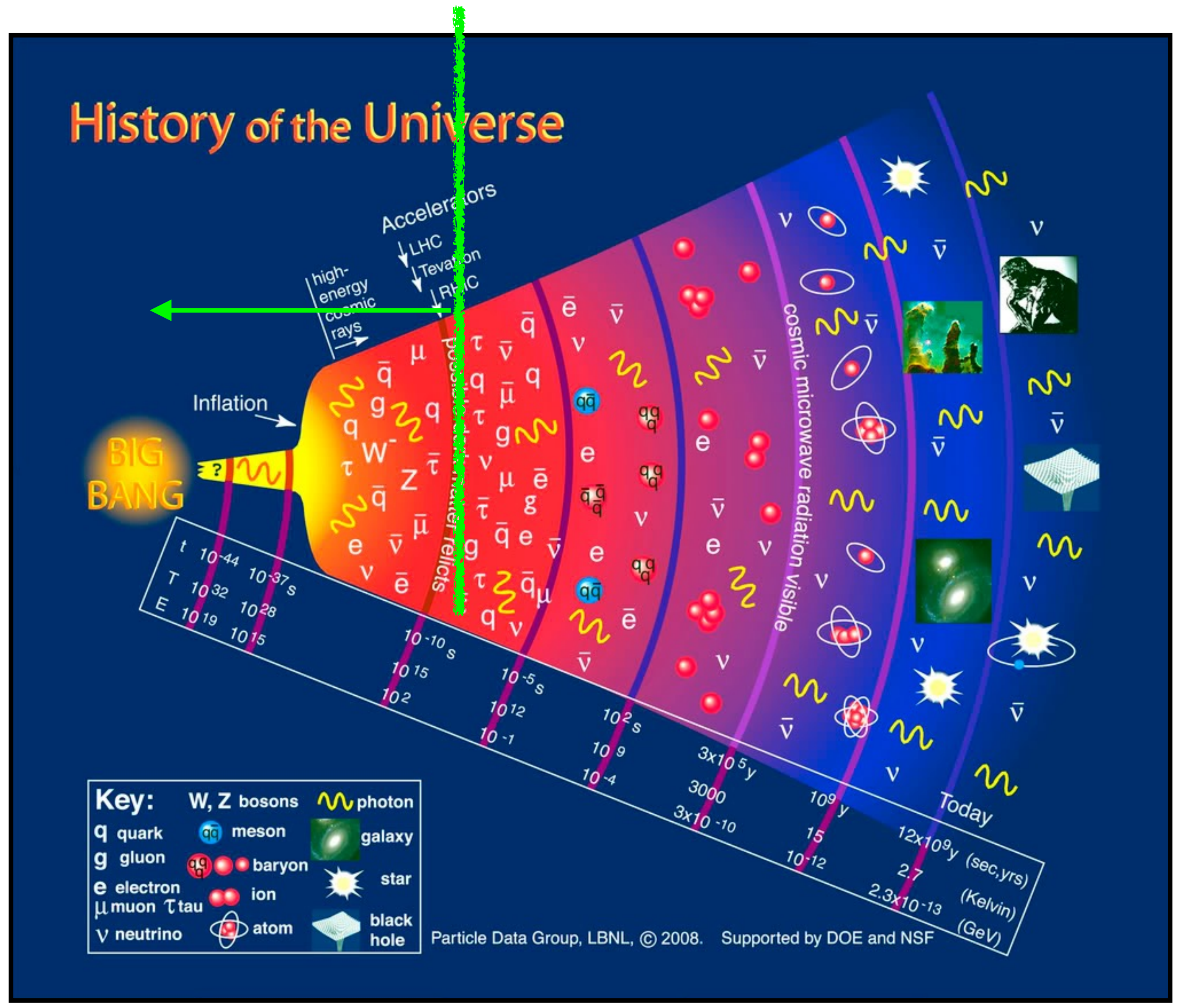




Baryon asymmetry: $Y_B = \dfrac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$ **Planck**

Baryogenesis





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

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

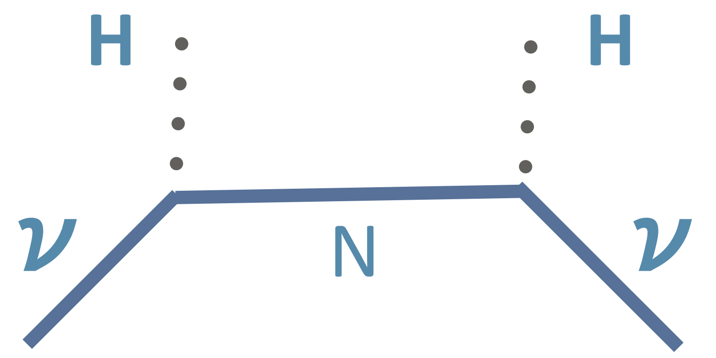
History and development: Leptogenesis

轻子数破坏与 Leptogenesis (type-I seesaw case)

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



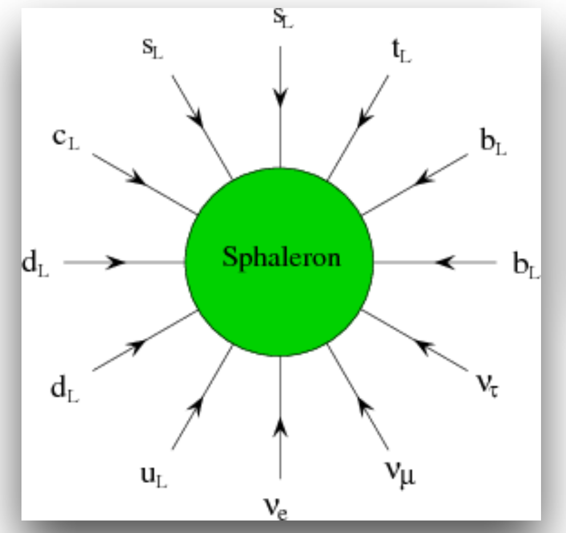
Neutrino mass:

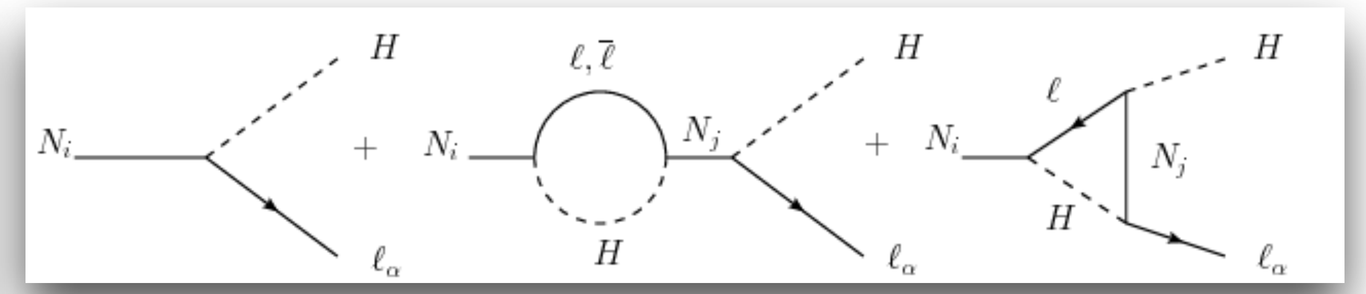
$$M_\nu = -M_D M_R^{-1} M_D^T$$

Elegant but losing testability at colliders!

物理图像

BV | **CPV** | **Out of EQ**



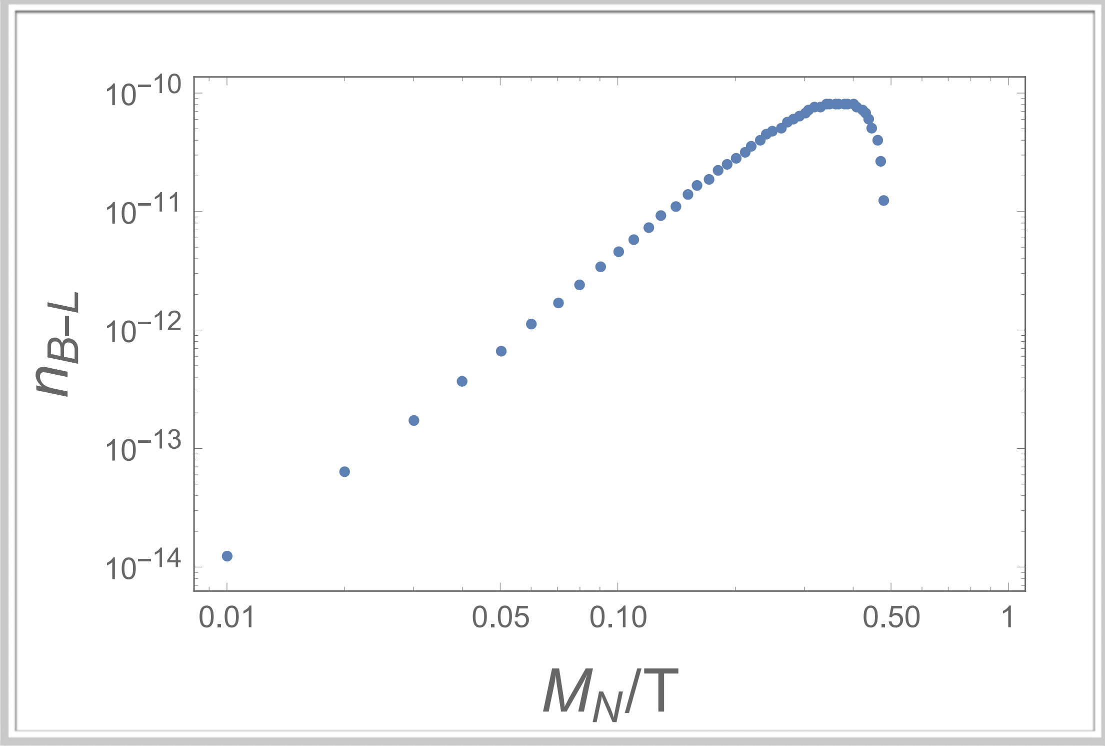


Heavy neutrinos decouple

Boltzmann EQ

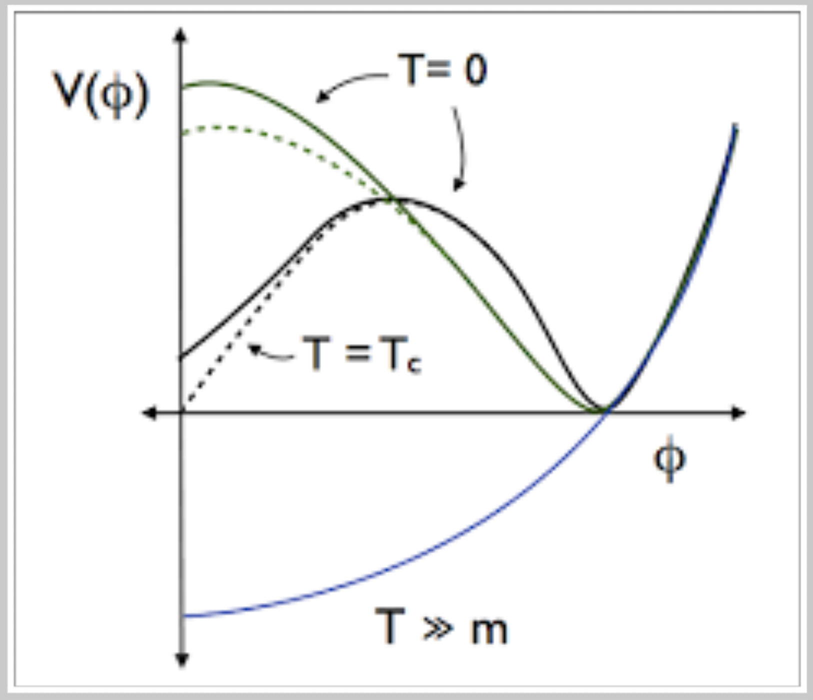
$$\frac{dN}{dz} = -D(N - N^{\rm eq})$$

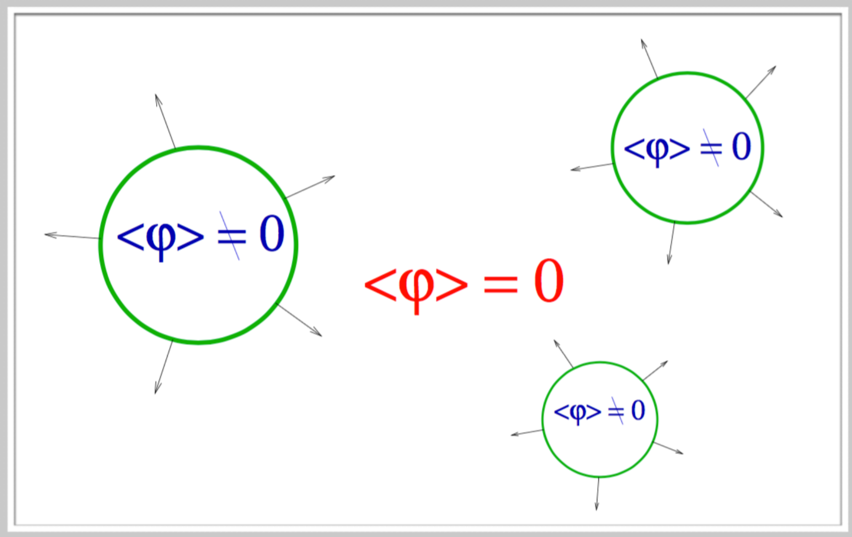
$$\frac{dN_{\rm B-L}}{dz} = -\varepsilon D(N - N^{\rm eq}) + W_{\rm ID} N_{\rm B-L}$$



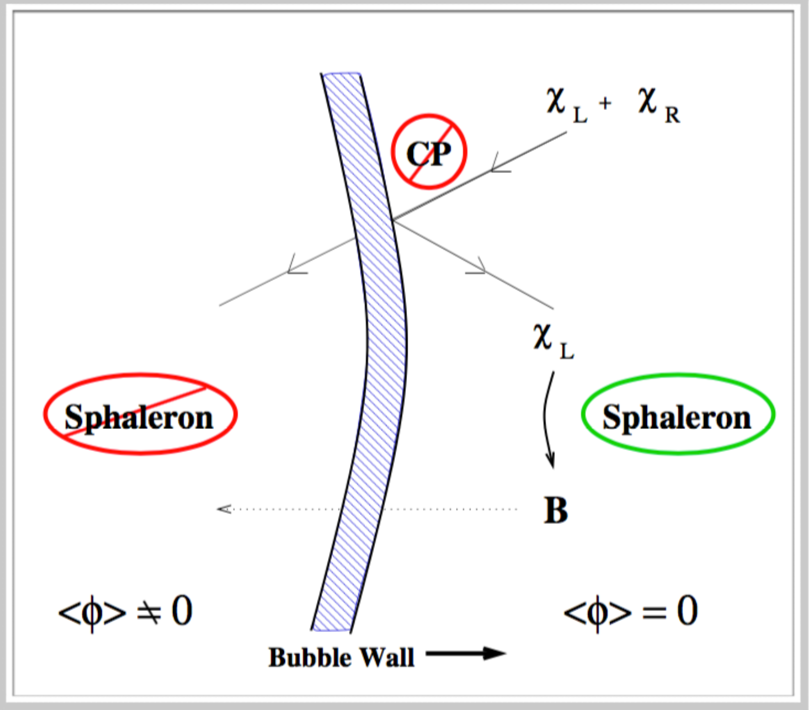
History and development: EW Baryogenesis

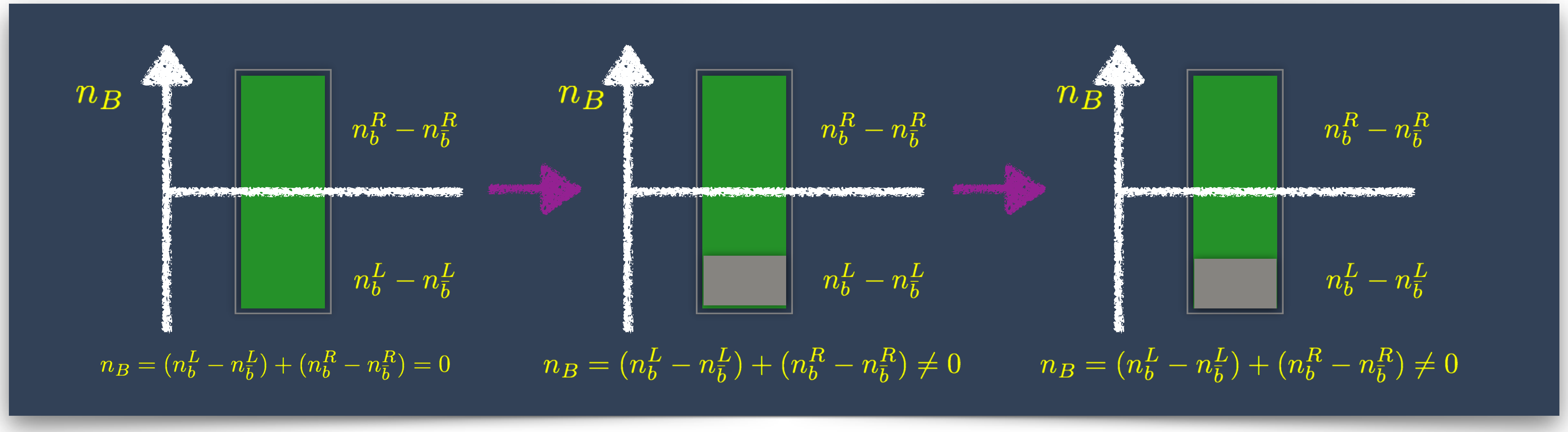
EWBG





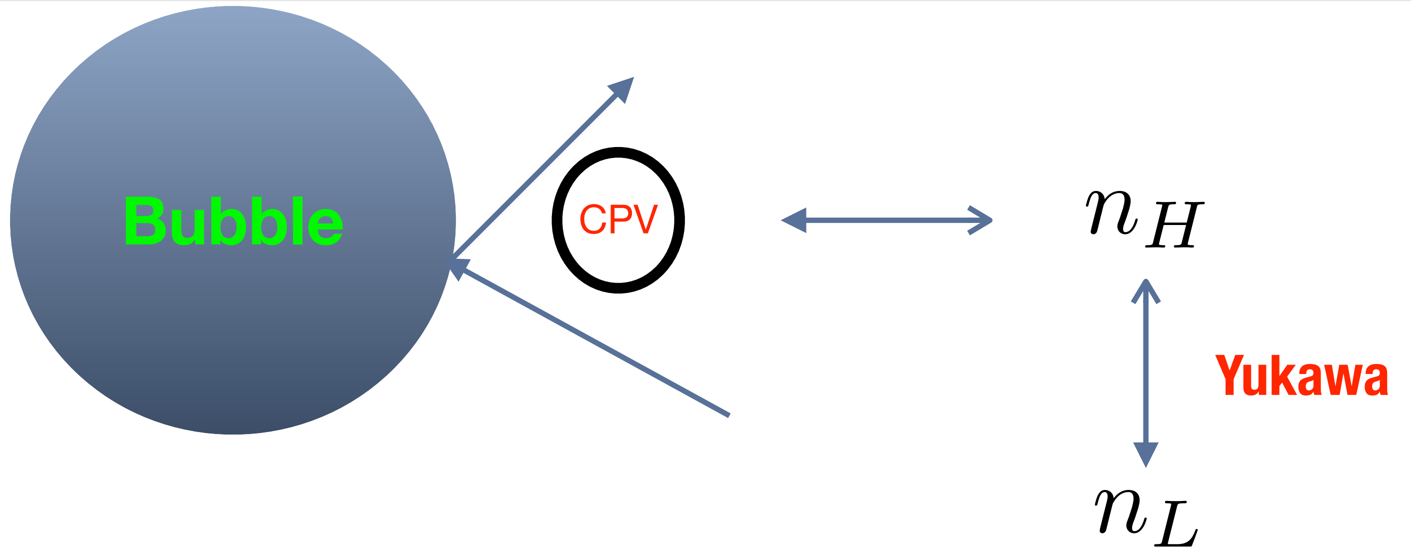
Basic description





输运方程

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



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

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

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

History and development: Affleck-Dine

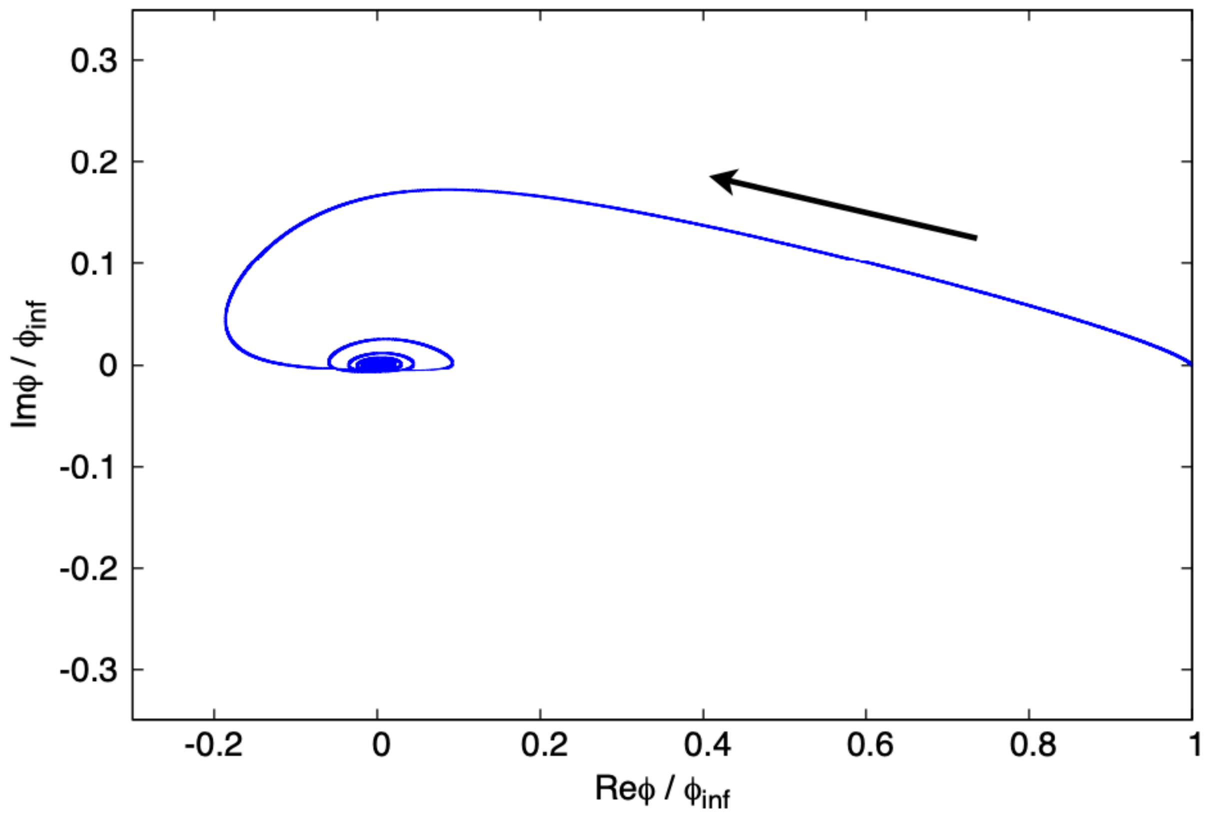
Affleck-Dine Mechanism

Scalars carrying non-zero U(1) charges

Flat directions (AD fields)

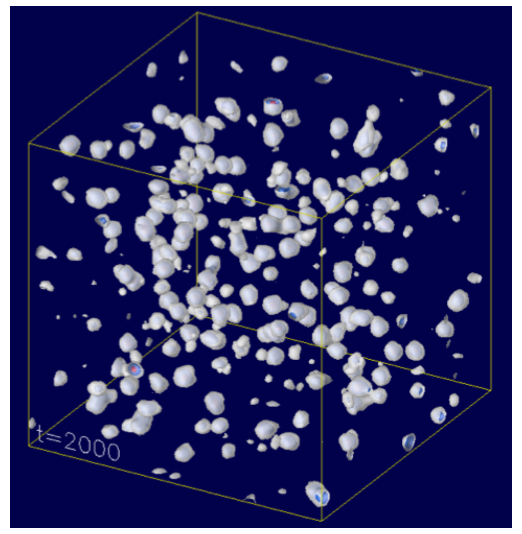
Lifting the potential via B/L violation operators

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



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

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



Oscillation of AD field

↓

Q-ball formation

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

↓ **Evaporation** → **BAU when sphaleron erase is irrelevant**

History and development: Axiogenesis

QCD Axion

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

Pseudo-scalar particle

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

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

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

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

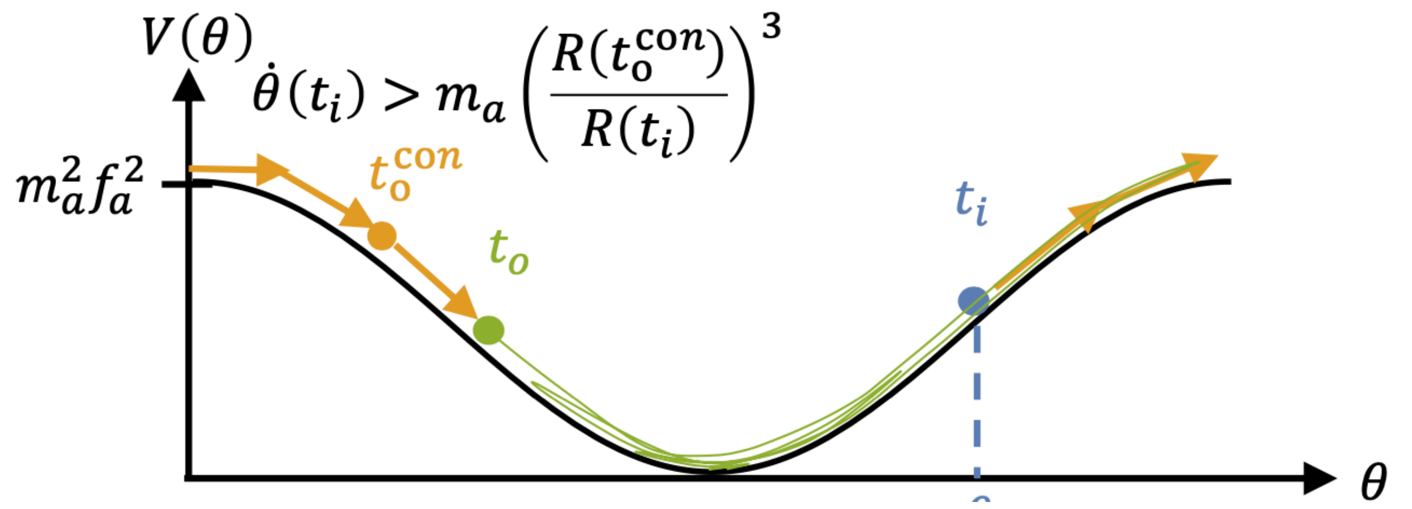
$$\ddot{\phi} + 3H\dot{\phi} + \frac{\Lambda^4(T)}{f^2}\phi = 0$$

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

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

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

EWsphaleron

Quake chiral asymmetry → **Baryon asymmetry**

EWsphaleron

PRL, 124, 111602

Status for Baryogenesis

Primordial B-L Conservation	Electroweak baryogenesis	Bochkarev et al 1990
	Magnetogenesis?	JOYCE et al 1997
	Wash-in Leptogenesis	DOMCKE et al 2021
	Electrogenesis	CHAO, 2024
B-L Violation	Seesaw model	YANAGIDA et al. 1986
	Axion-inflaton Leptogenesis	Alexande et al 2004
	Affleck-Dine field oscillation	Affleck et al 1985
	Axion Baryogenesis	CO et al 2019

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: 带有手征的介质处在磁场中时会有感应电流产生

CME for Leptogenesis

螺旋度密度和磁场能量密度的演化方程

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

- **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

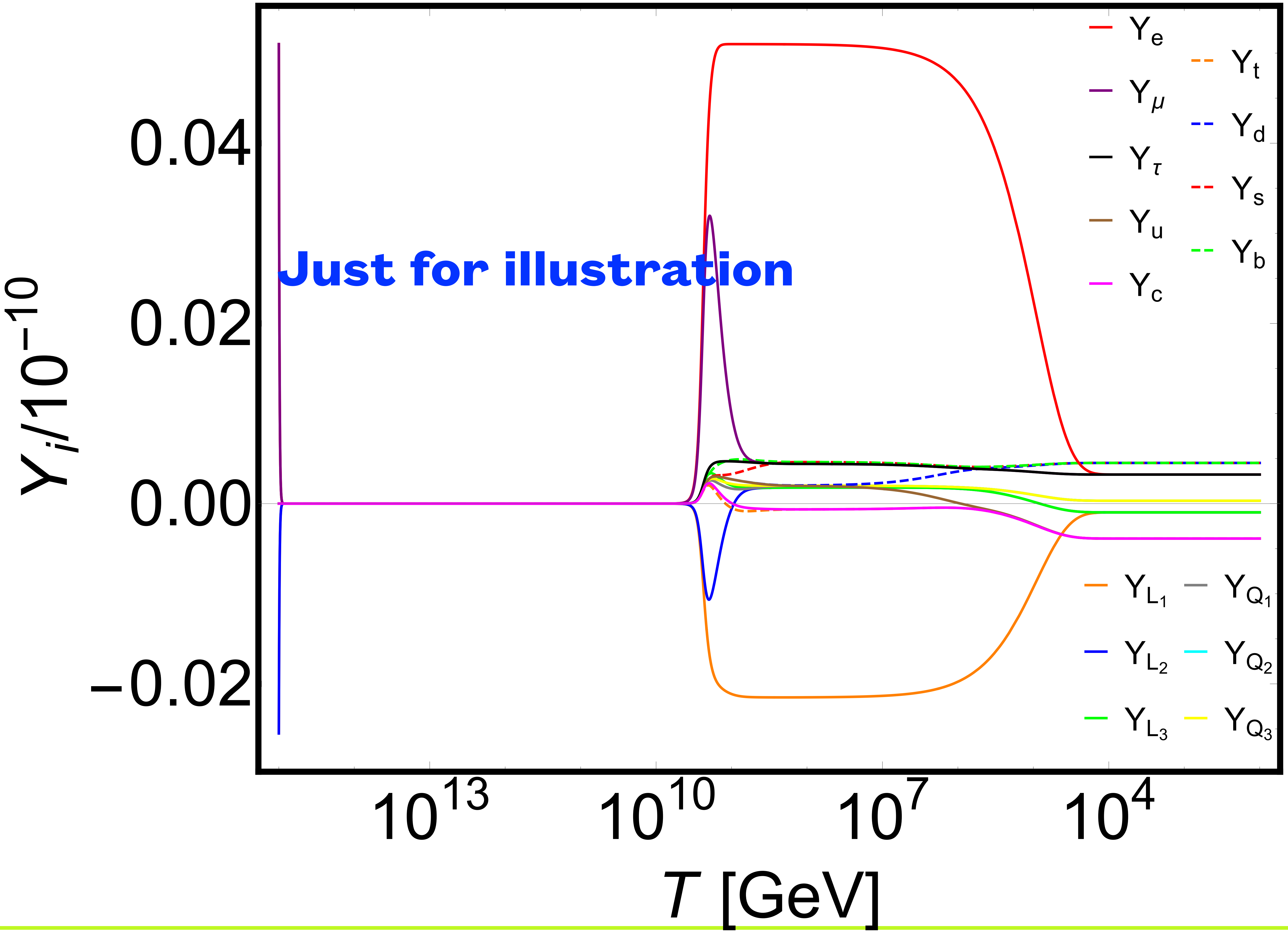
Transport equations

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

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

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

CME for Leptogenesis



U(1) extensions to the minimal SM

（1）手征磁效应可以调节粒子数密度的分配问题，
（2）无法在电弱相变发生之前产生重子数不对称，因为该相互作用保持 B-L守恒
（3）当存在额外的U(1）相互作用，并且中微子为DIRAC粒子的情形，可以借助于反常项来产生重子数不对称！

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

Triangle anomalies(1)

- **U(1)B-L**

$$\partial_\mu \left(j^\mu_{B,Q} \right) = \frac{1}{32\pi^2} \left(g^2 W\widetilde{W} + \frac{1}{9} g'^2 F\widetilde{F} + \frac{4}{9} g^2_{B-L} F'\widetilde{F}' \right)$$

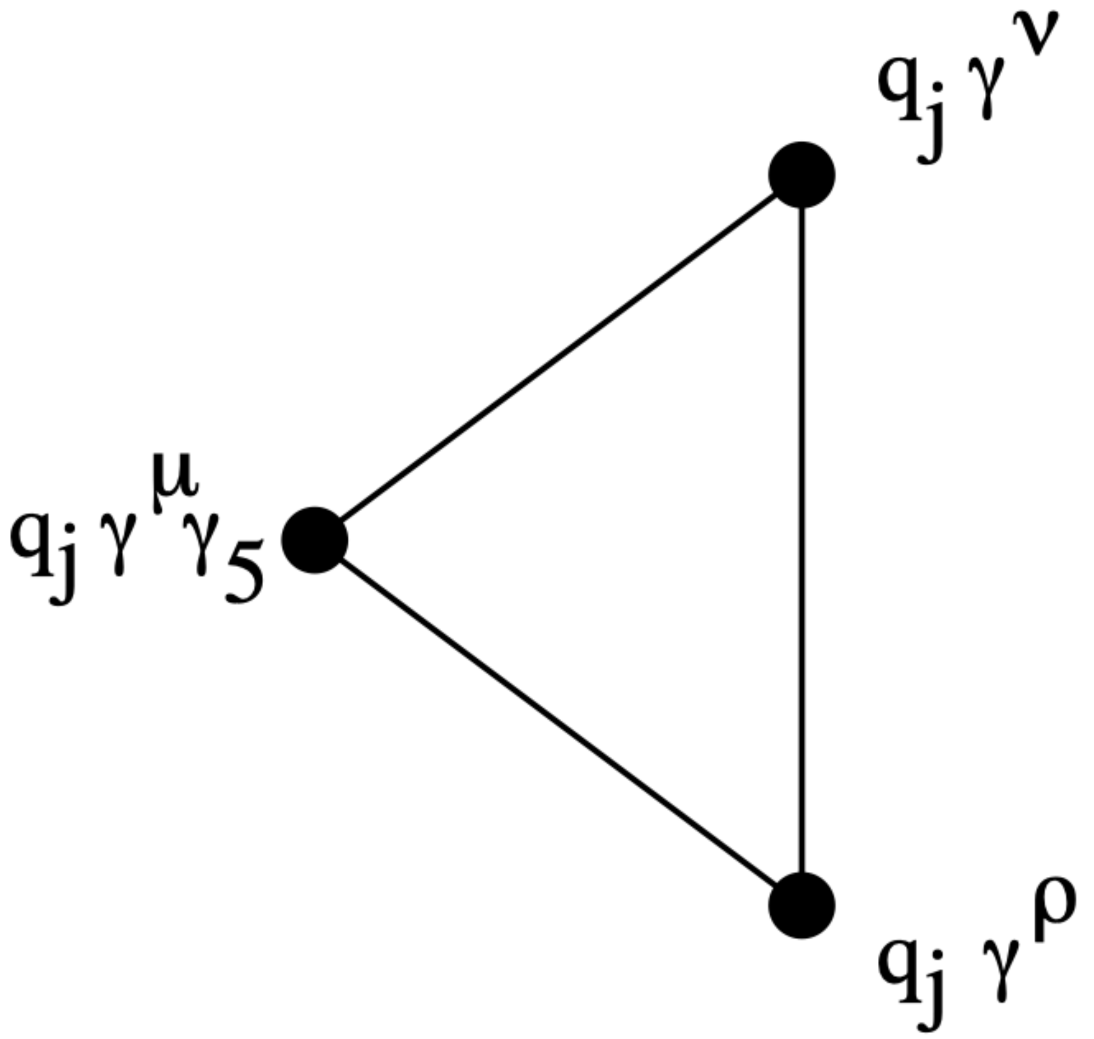
$$\partial_\mu \left(j^\mu_{B,u} \right) = \frac{1}{16\pi^2} \left(-\frac{4}{9} g'^2 F\widetilde{F} - \frac{1}{9} g^2_{B-L} F'\widetilde{F}' \right)$$

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

$$\partial_\mu \left(j^\mu_{L,\ell} \right) = \frac{1}{32\pi^2} \left(g^2 W\widetilde{W} + g'^2 F\widetilde{F} + 4 g^2_{B-L} F'\widetilde{F}' \right)$$

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

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



$$\partial_\mu \left(j^\mu_B - j^\mu_L \right) = 0$$

Triangle anomalies(2)

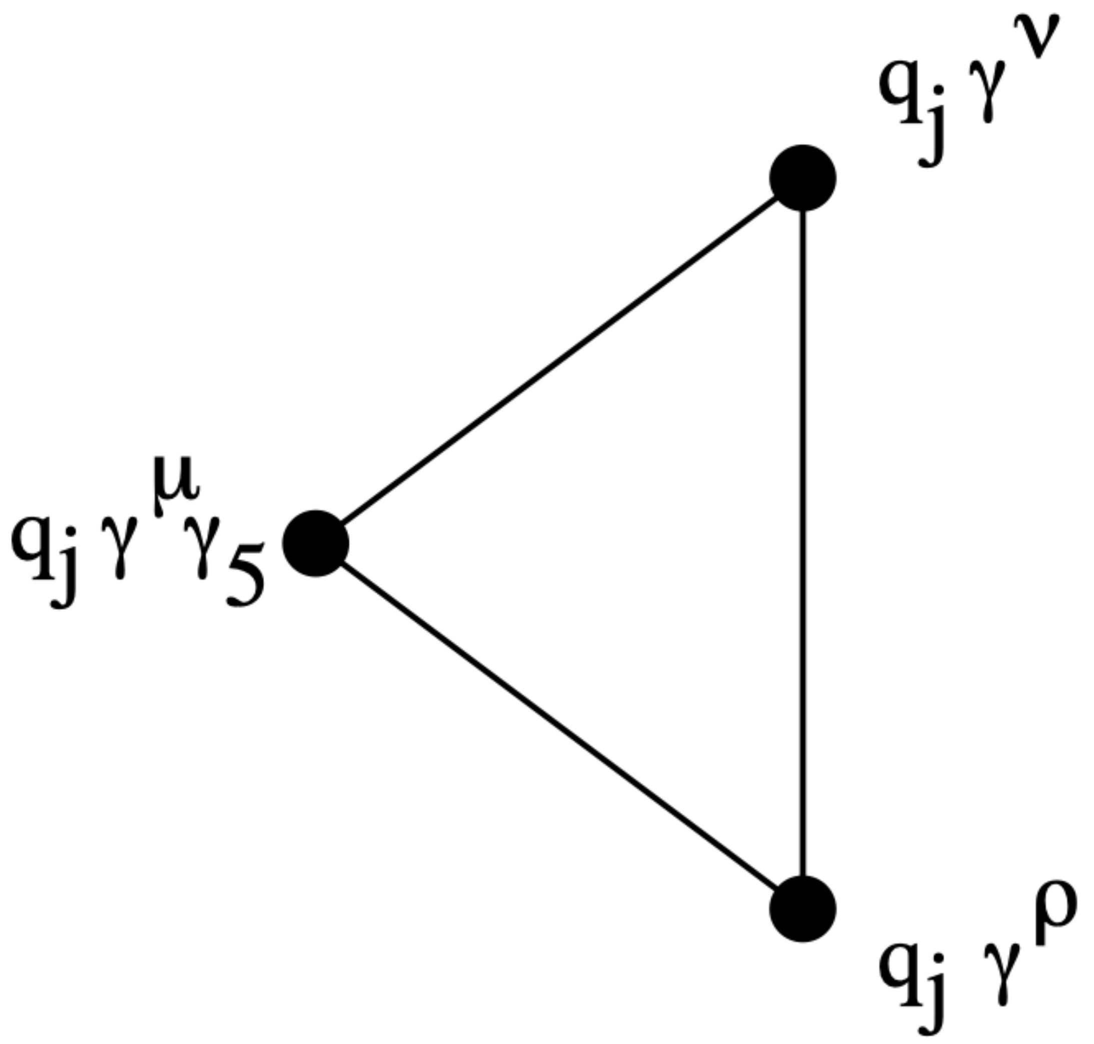
- **U(1)$_R$**

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

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

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

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



$\Rightarrow$

$$\partial_\mu \left(j^\mu_B - j^\mu_L \right) = 0$$

Triangle anomalies(3)

- **U(1)$_B$:**

- **current equations for quarks are the same as these in the U(1)$_{B-L}$**
- **current equations for leptons are the same as these in the SM**

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

$$\partial_\mu\left(j^\mu_{\psi_R}\right) = -\frac{1}{32\pi^2}\left(g^2W\widetilde{W} + g'^2F\widetilde{F} + 16g_B^2F'\widetilde{F}'\right)$$

$$\partial_\mu\left(j^\mu_{\chi_L}\right) = +\frac{1}{16\pi^2}\left(g'^2F\widetilde{F} + 4g_B^2F'\widetilde{F}'\right)$$

$$\partial_\mu\left(j^\mu_{\chi_R}\right) = -\frac{1}{16\pi^2}\left(g'^2F\widetilde{F} + g_B^2F'\widetilde{F}'\right)$$

$$\partial_\mu\left(j^\mu_{\eta_L}\right) = +\frac{1}{4\pi^2}\left(g_B^2F'\widetilde{F}'\right)$$

$$\partial_\mu\left(j^\mu_{\eta_R}\right) = -\frac{1}{16\pi^2}\left(g_B^2F'\widetilde{F}'\right)$$

$$\Rightarrow \quad \partial_\mu\left(j^\mu_{\psi_L} + j^\mu_{\psi_R} + j^\mu_{\chi_L} + j^\mu_{\chi_R} + j^\mu_{\eta_L} + j^\mu_{\eta_R}\right) = 0$$

$$\partial_\mu\left(j^\mu_B - j^\mu_L\right) = 0!$$

Triangle anomalies(4)

- $U(1)_L$:

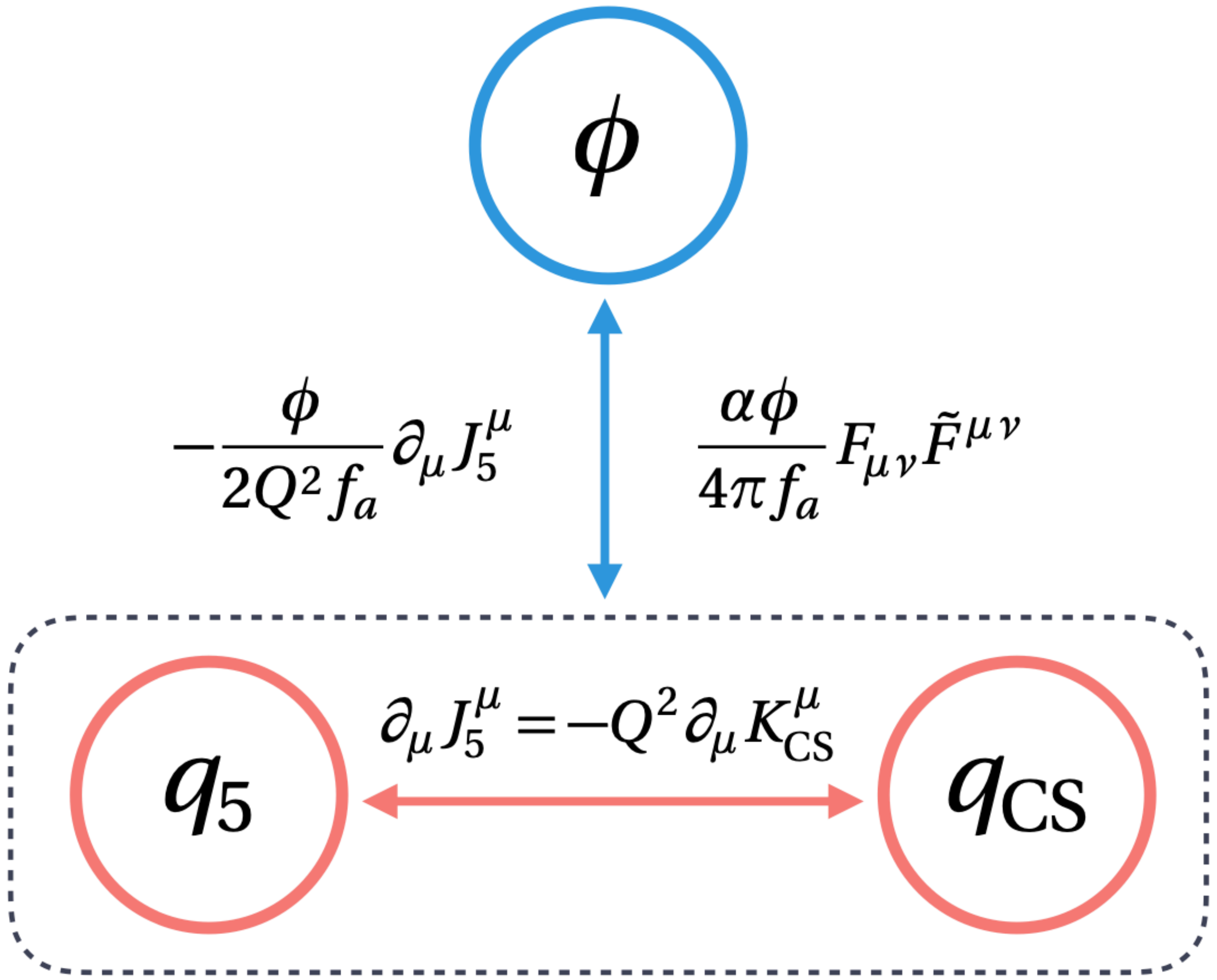
- current equations for quarks are the same as these in the SM
- current equations for leptons are the same as these in the $U(1)_{B-L}$
- current equations for new fermions are the same as these in the $U(1)_B$

$$\partial_\mu \left(j^\mu_{\psi_L} + j^\mu_{\psi_R} + j^\mu_{\chi_L} + j^\mu_{\chi_R} + j^\mu_{\eta_L} + j^\mu_{\eta_R} \right) = 0$$

$$\partial_\mu \left(j^\mu_B - j^\mu_L \right) = 0$$

Axion-inflation triggered leptogenesis

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



- **Chern Simons number:**

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

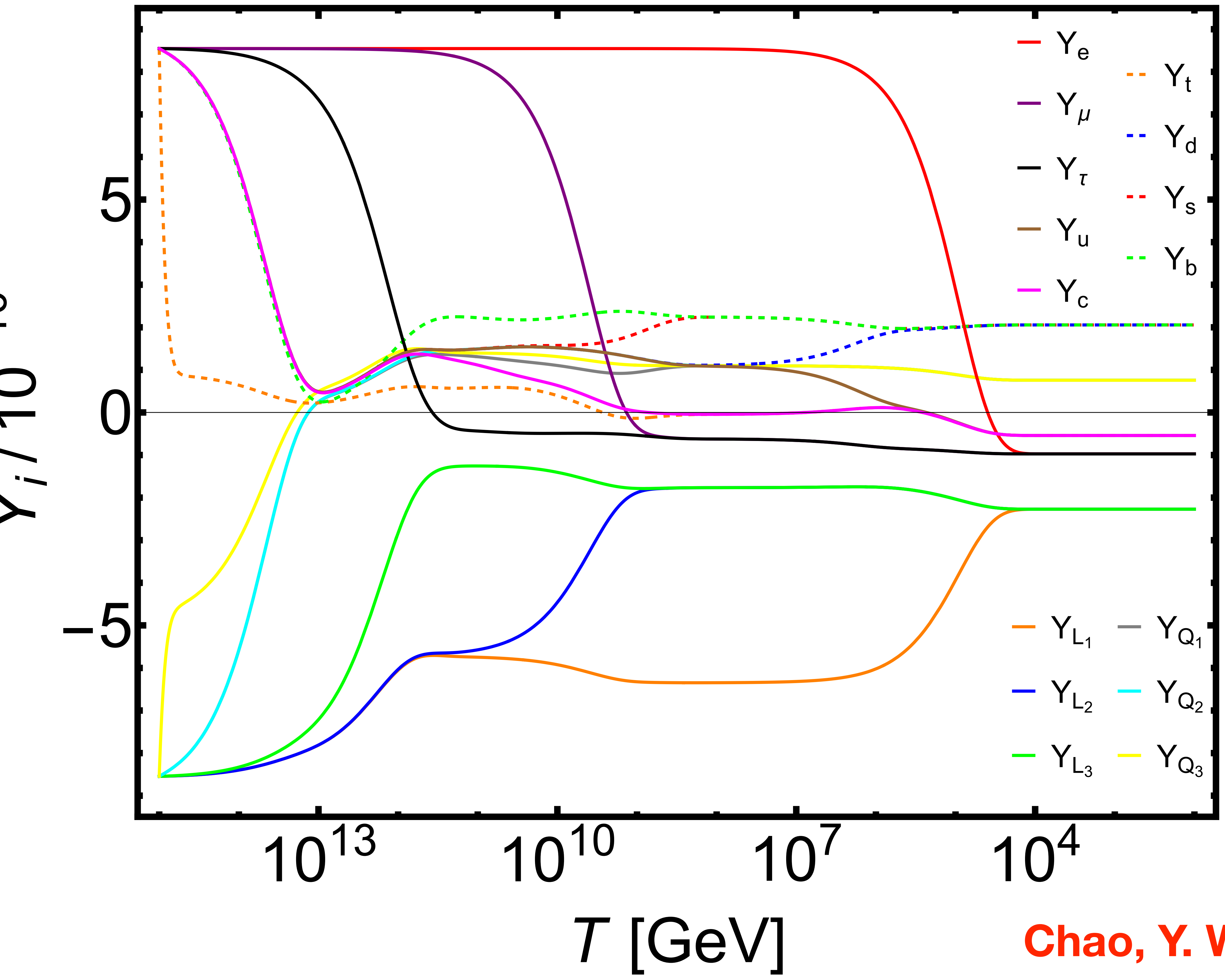
$$= \frac{1}{(2\pi)^2}\sum_{\lambda=\pm}\lambda e^{i\kappa_\lambda\pi}\int \tilde{\tau}^3 d\ln\tilde{\tau}W^*_{\kappa_\lambda,\mu}(-2i\tilde{\tau})W_{\lambda_\sigma,\mu}(-2i\tilde{\tau})a^3H^3$$

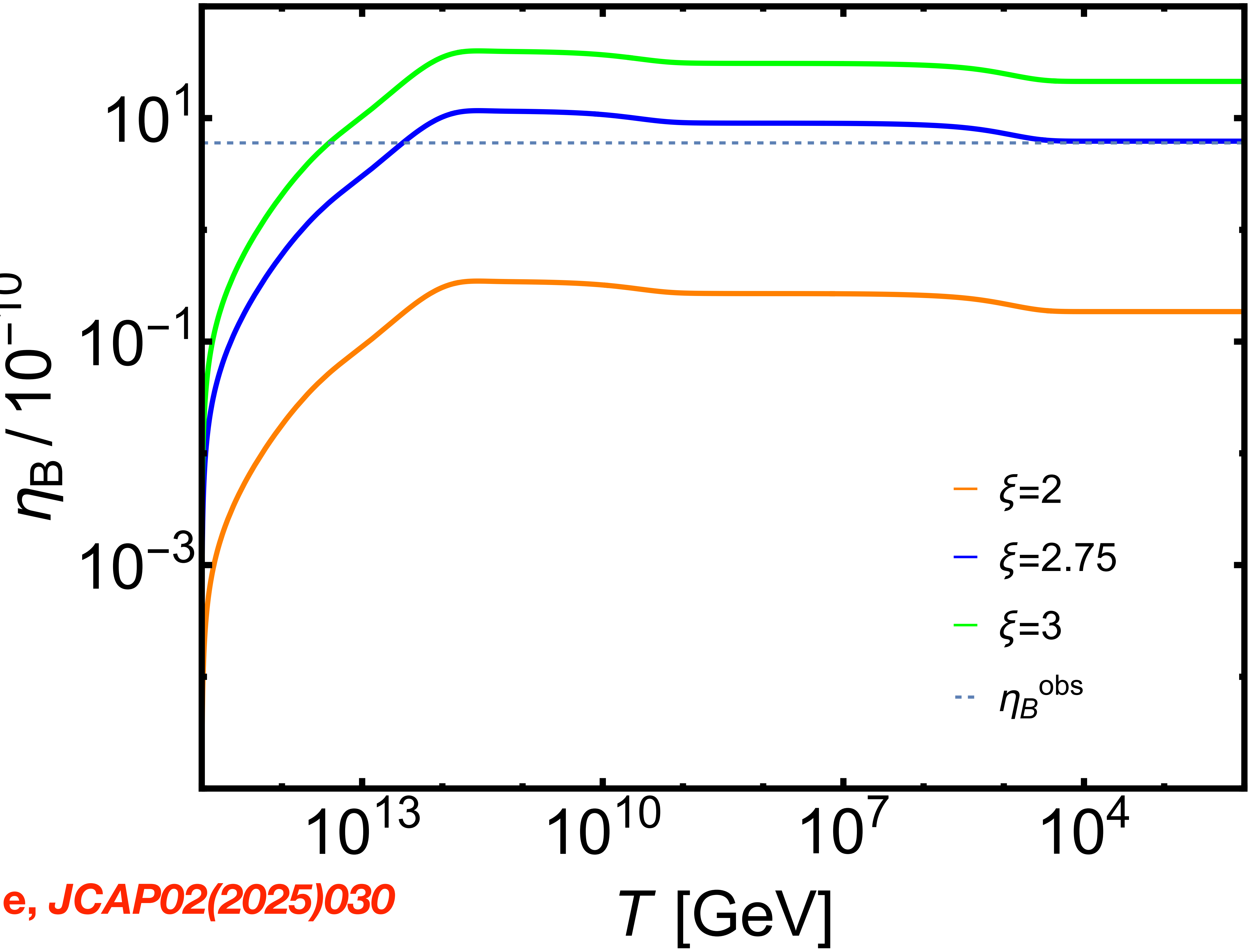
- **Chiral fermion asymmetry during reheating**

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

Axion-inflation Leptogensis

U(1)_{B-L}

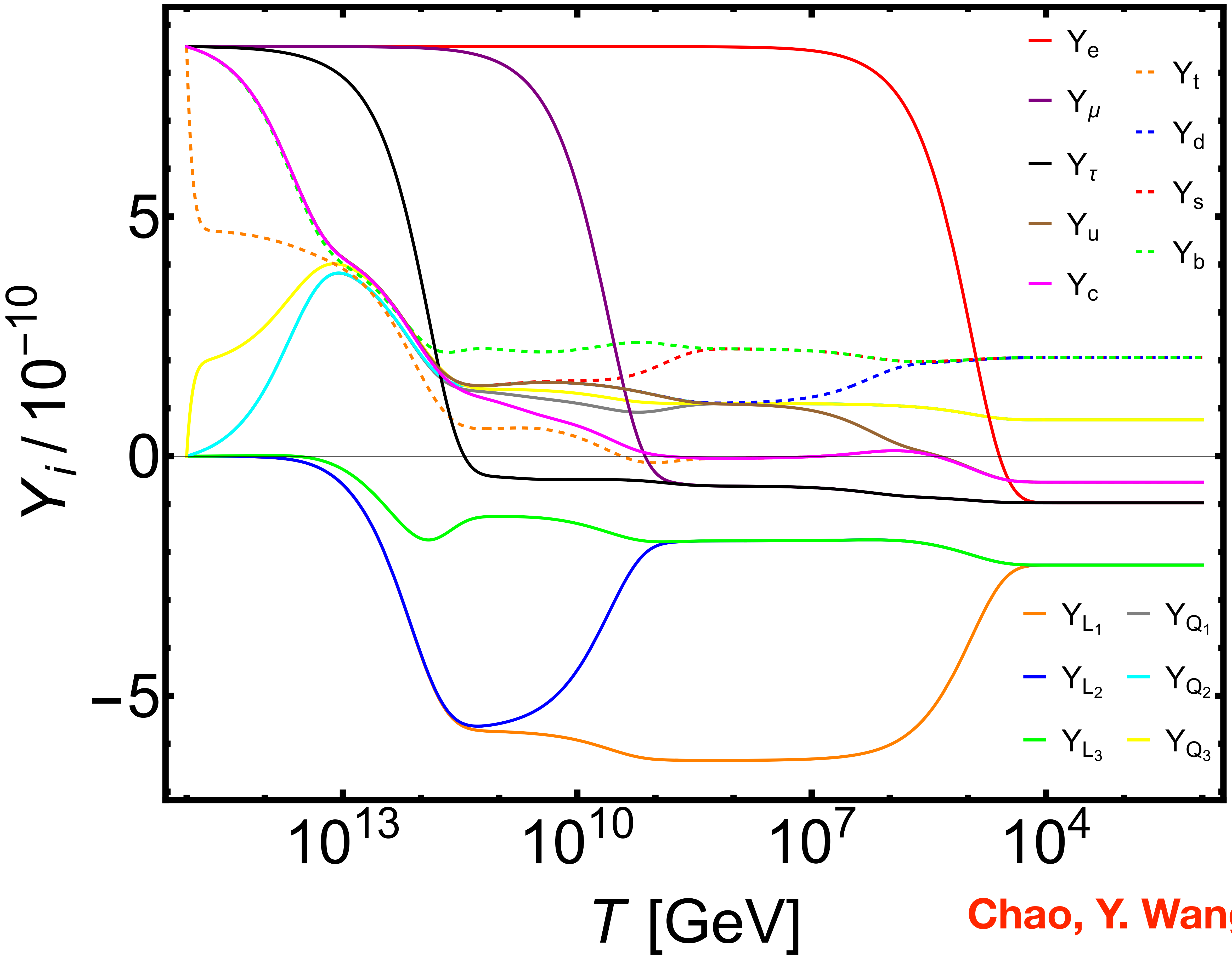


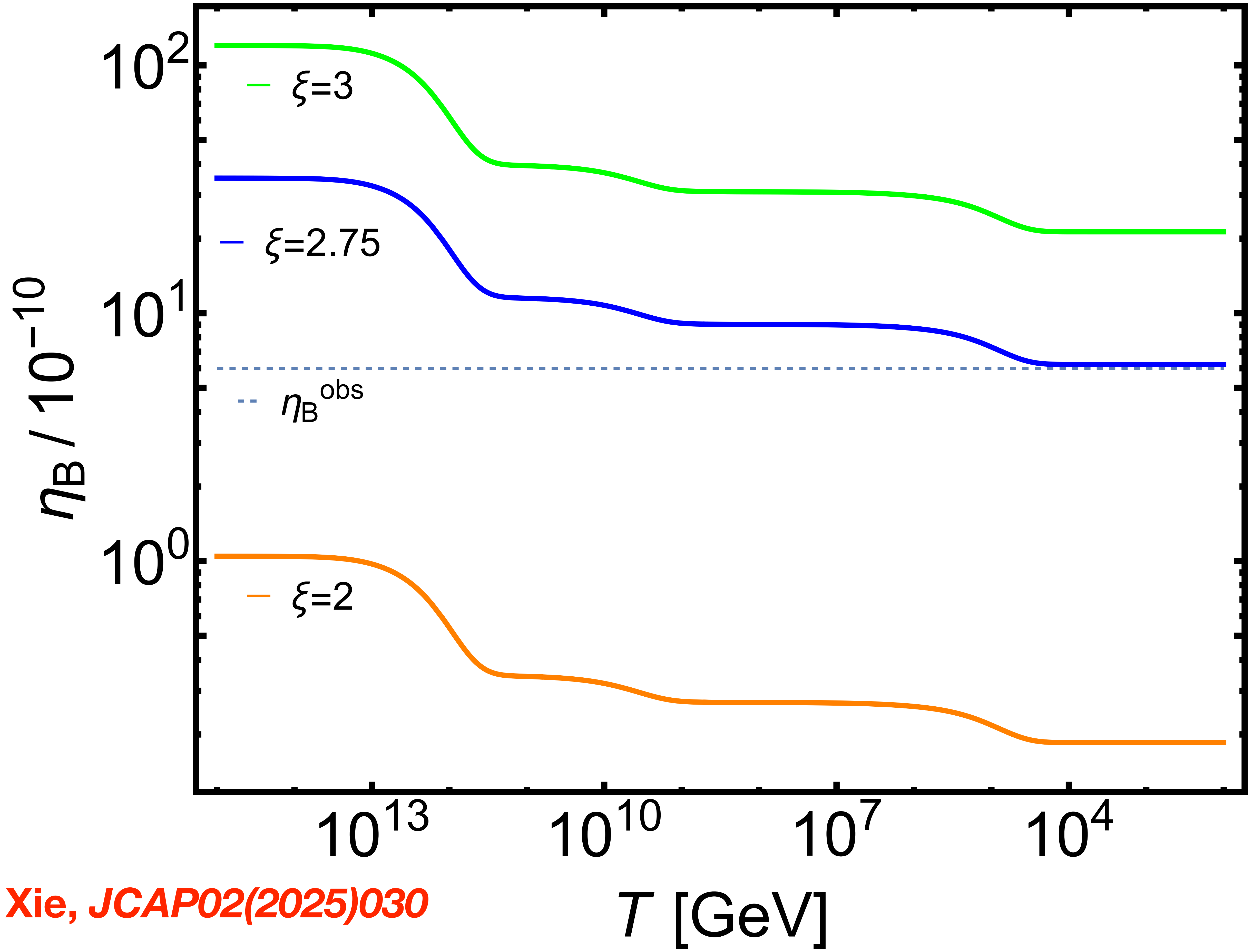


Chao, Y. Wang, C. Xie, *JCAP02(2025)030*

Axion-inflation Leptogensis

U(1)_{R}





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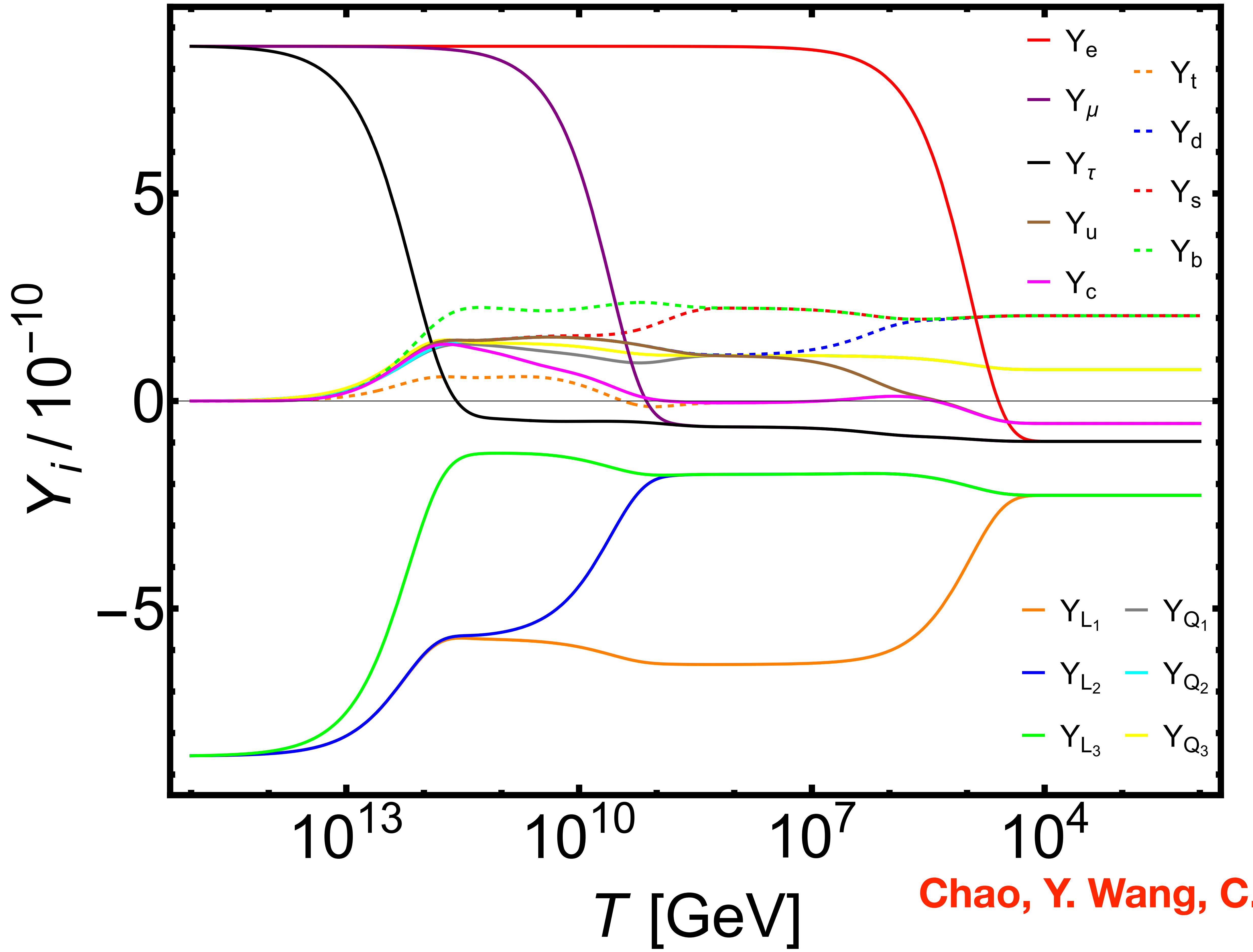
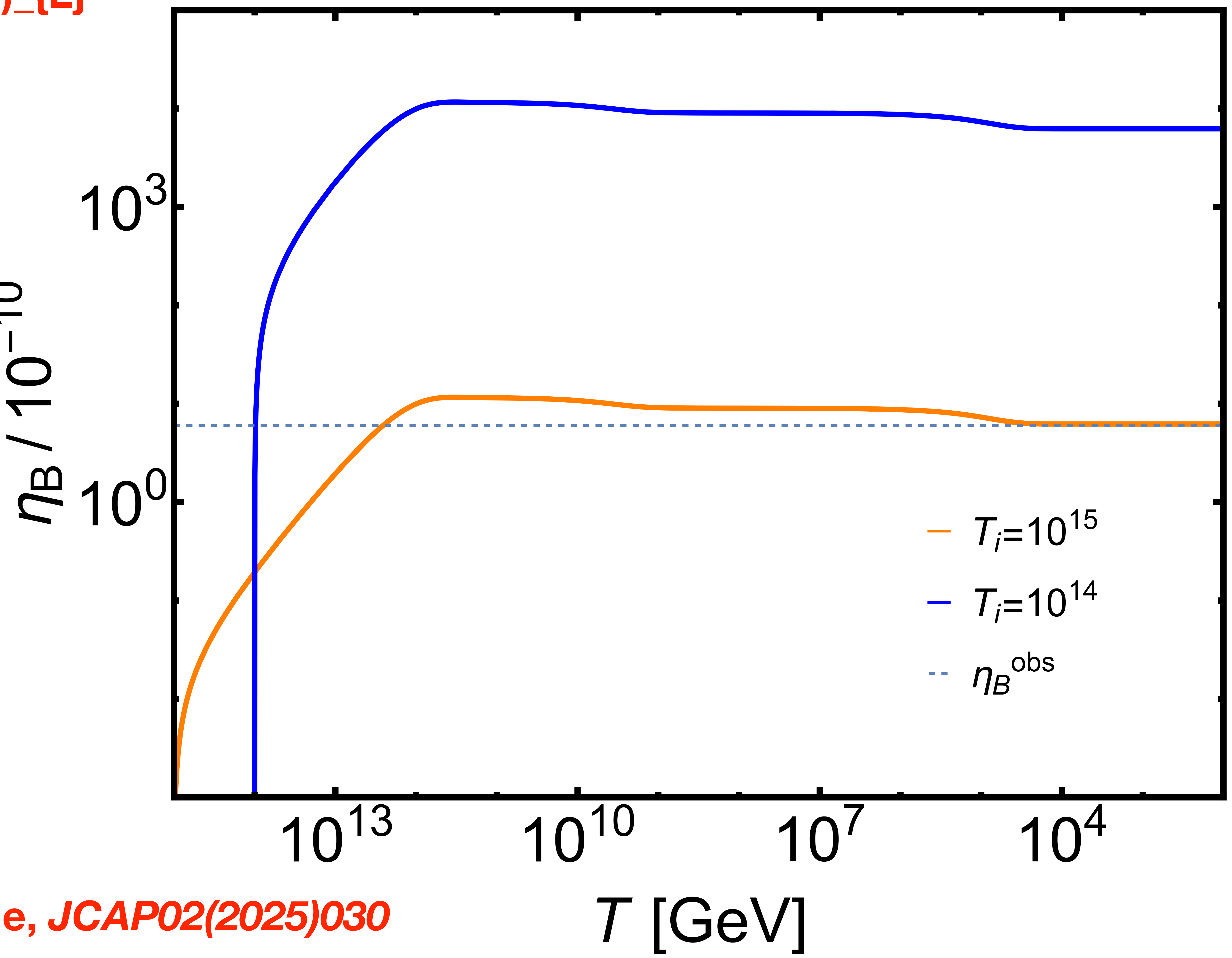
Axion-inflation Leptogensis

U(1)_{L}





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Summary

Leptogenesis mechanism is an elegant mechanism deserving dedicate study in many aspects. We work on the impact of U(1) gauge interactions to the Leptogenesis mechanism and presented the following two results:

- The spectator process induced by the chiral magnetic effect is explicitly derived .
- A workable Dirac Leptogenesis scenario is presented.

Thank you for your attention!