New axion misalignment mechanism effect

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History and progress

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

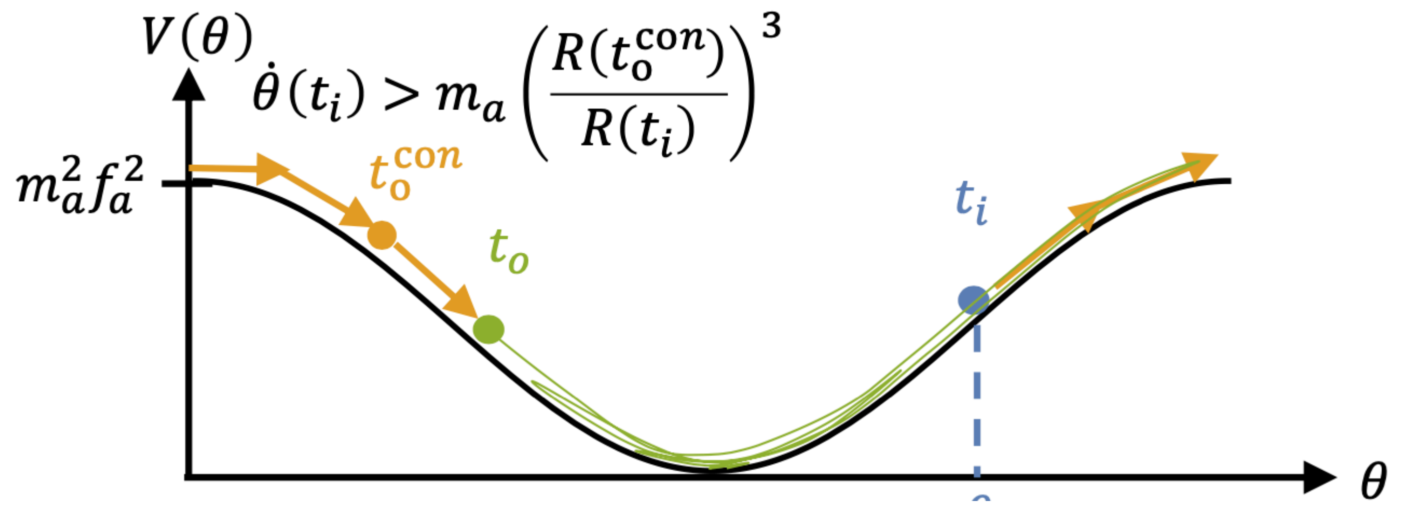
$$\ddot{\phi} + 3H\dot{\phi} + \frac{\Lambda^4(T)}{f^2}\phi = 0$$

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

Kinetic Misalignment mechanism & 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!

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

Strong sphaleron ↓ **Quake chiral asymmetry**

EWsphaleron ↓ **Baryon asymmetry**

Quake chiral asymmetry $\xrightarrow{\text{EWsphaleron}}$ **Baryon asymmetry**

PRL, 124, 111602

History and progress

Trapped Misalignment mechanism : initial $\theta \sim \pi$

- *L. Di Luzio, B. Gavela, P. Quilez, A. Ringwald, JCAP* 10 (2021) 001

Hilltop Misalignment mechanism : initial $\theta \sim \pi$

- *Raymond T. Co, Eric Gonzalez, Keisuke Harigaya，JHEP 05 (2019) 163*

Acoustic Misalignment mechanism: Fluctuations of θ

- *A. Bodas, R.T. Co, A. Ghalsasi, K. Harigaya and L.T. Wang, JHEP 08(2025)131*

Thermal Misalignment mechanism: new thermal potential term

- *B. Batell, A. Ghalsasi, Phys. Rev. D 107(2023)L091701*
- *Y. Zhang, PRL, 132(2024)8, 081003*

Outline

In this talk, we focus on the axion misalignment mechanism in the presence of exotic axion mass generation mechanism, and in the presence of primordial magnetic field.

- **Scenario-2 : Axion misalignment mechanism with specific ALP mass generation mechanism**

  Wei Chao, Mingjie Jin, Hai-jun Li, Ying-quan Peng and Yue Wang, Phys.Rev.D 109(2024)115027

- **Scenario-3 : Axion misalignment mechanism in the presence of primordial magnetic field**

  Wei Chao, Chang-jie Dai, arXiv: 2604.02012

ALP mass via the type-II seesaw mechanism

Type-II seesaw + spontaneous breaking $U(1)_L$ symmetry

LNV term!

$$V(S,\Phi,\Delta) = V(\Phi,\Delta) - \mu_S^2(S^\dagger S) + \lambda_6(S^\dagger S)^2$$

$$+\lambda_7(S^\dagger S)(\Phi^\dagger\Phi) + \lambda_8(S^\dagger S)\mathrm{Tr}(\Delta^\dagger\Delta) + \mu\Phi^T i\tau_2\Delta^\dagger\Phi + \lambda S\Phi^T i\tau_2\Delta^\dagger\Phi + \mathrm{h.c.},$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{v_\phi + \phi + i\chi}{\sqrt{2}} \end{pmatrix} \qquad \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \frac{v_\Delta + \delta + i\xi}{\sqrt{2}} & \frac{\Delta^+}{\sqrt{2}} \end{pmatrix} \qquad S = \frac{v_s + \tilde{s} + i\tilde{a}}{\sqrt{2}}$$

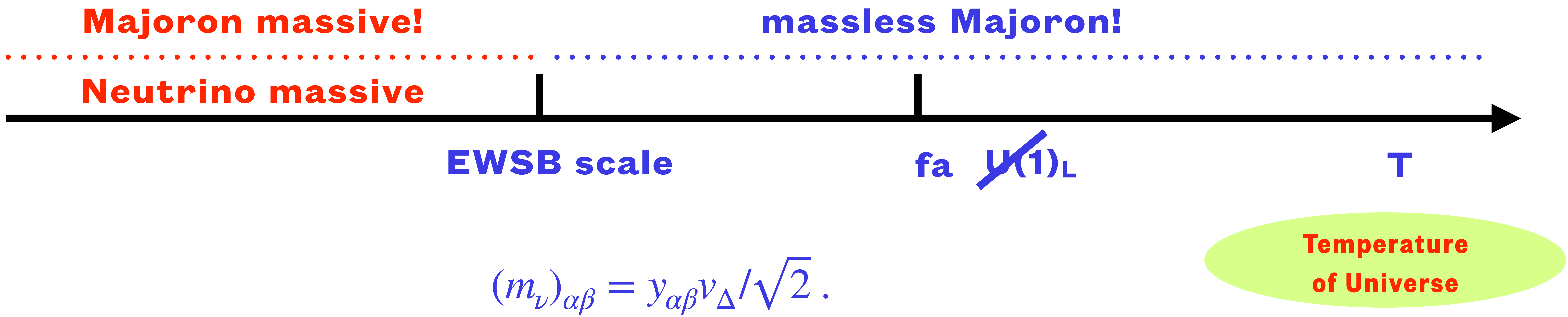
$\tilde{a}$: **Majoron**

Yukawa Interaction $-\mathscr{L}_\Delta = Y_{\alpha\beta}\overline{\ell_L^{\alpha C}} i\sigma^2\Delta\ell_L^\beta + h.c.$

Key term: $\mu\Phi^T i\sigma^2\Delta\Phi + h.c.$

ALP mass via the type-II seesaw mechanism

Sequential breaking of various symmetries



$$(m_\nu)_{\alpha\beta} = y_{\alpha\beta} v_\Delta/\sqrt{2}\,.$$

$$m_a^2 = \frac{\sqrt{2}\mu v_\phi^2 v_\Delta (v_\phi^2 + 4v_\Delta^2)}{2v_\phi^2(v_\Delta^2 + v_s^2) + 8v_\Delta^2 v_s^2} \simeq \frac{\mu v_\phi^2 v_\Delta}{\sqrt{2} v_s^2}\,,$$

ALP masses

Majoron mass should arise from cosine like potential!

$$\left.\begin{array}{ll} \ell_L \to e^{-\frac{ia}{2f}}\ell_L & S \to e^{+\frac{ia}{f}}S \\ E_R \to e^{-\frac{ia}{2f}}E_R & \Delta \to e^{-\frac{ia}{f}}\Delta \end{array}\right\} \quad -\mathscr{L}_{\rm int} \supset \mu e^{i\frac{a}{f_a}}\Phi^T i\tau_2 \Delta^\dagger \Phi + {\rm h.c..}$$

$$H \to H$$

$$\downarrow$$

After electroweak symmetry breaking

$$-\mathscr{L}_{\rm int} \supset \frac{\mu v_\Phi^2 v_\Delta}{\sqrt{2}}\cos\left(\frac{a}{f_a}\right)$$

$$\downarrow$$

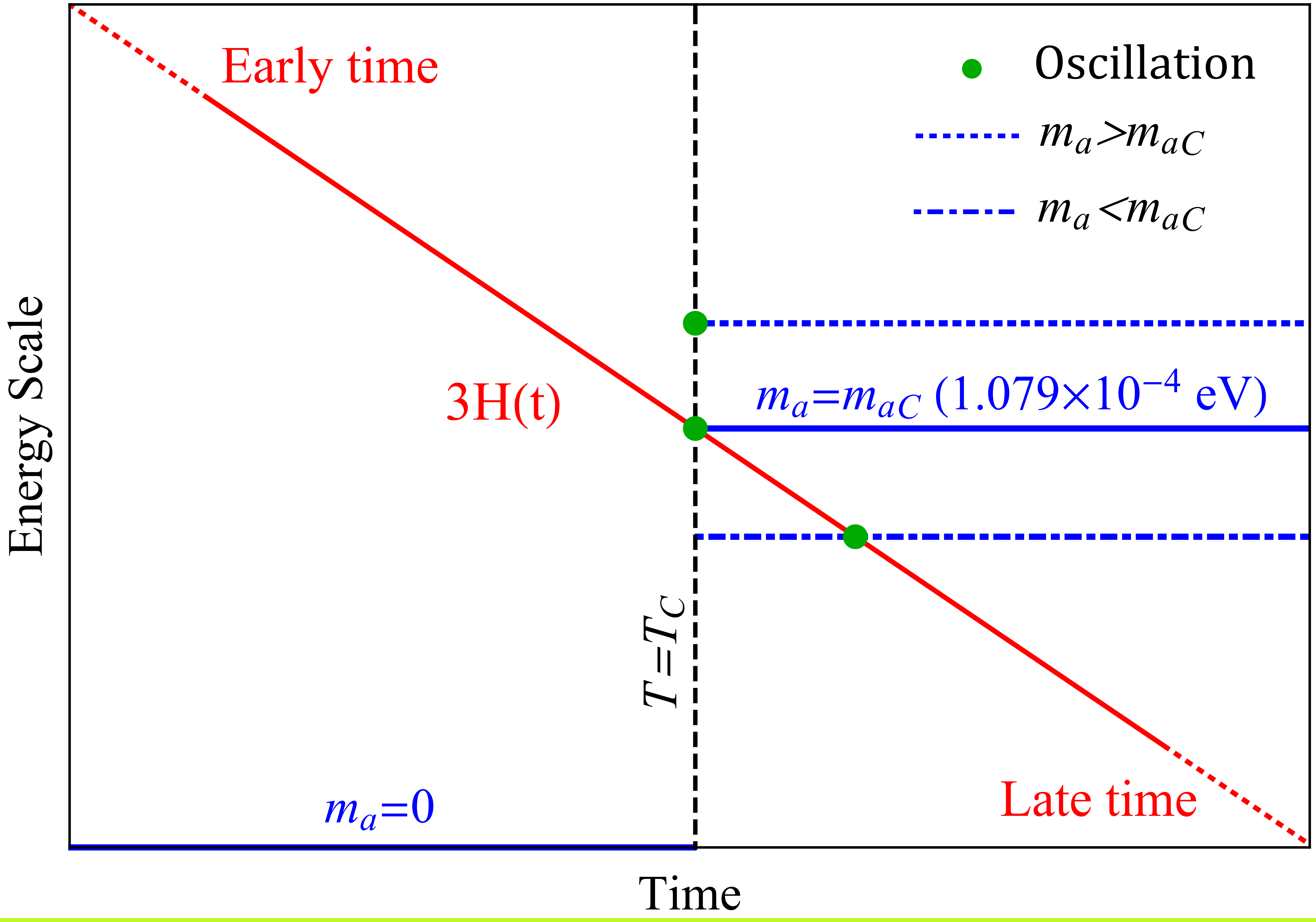
Non-zero Majoron mass

ALP oscillation time is relevant to EW scale !

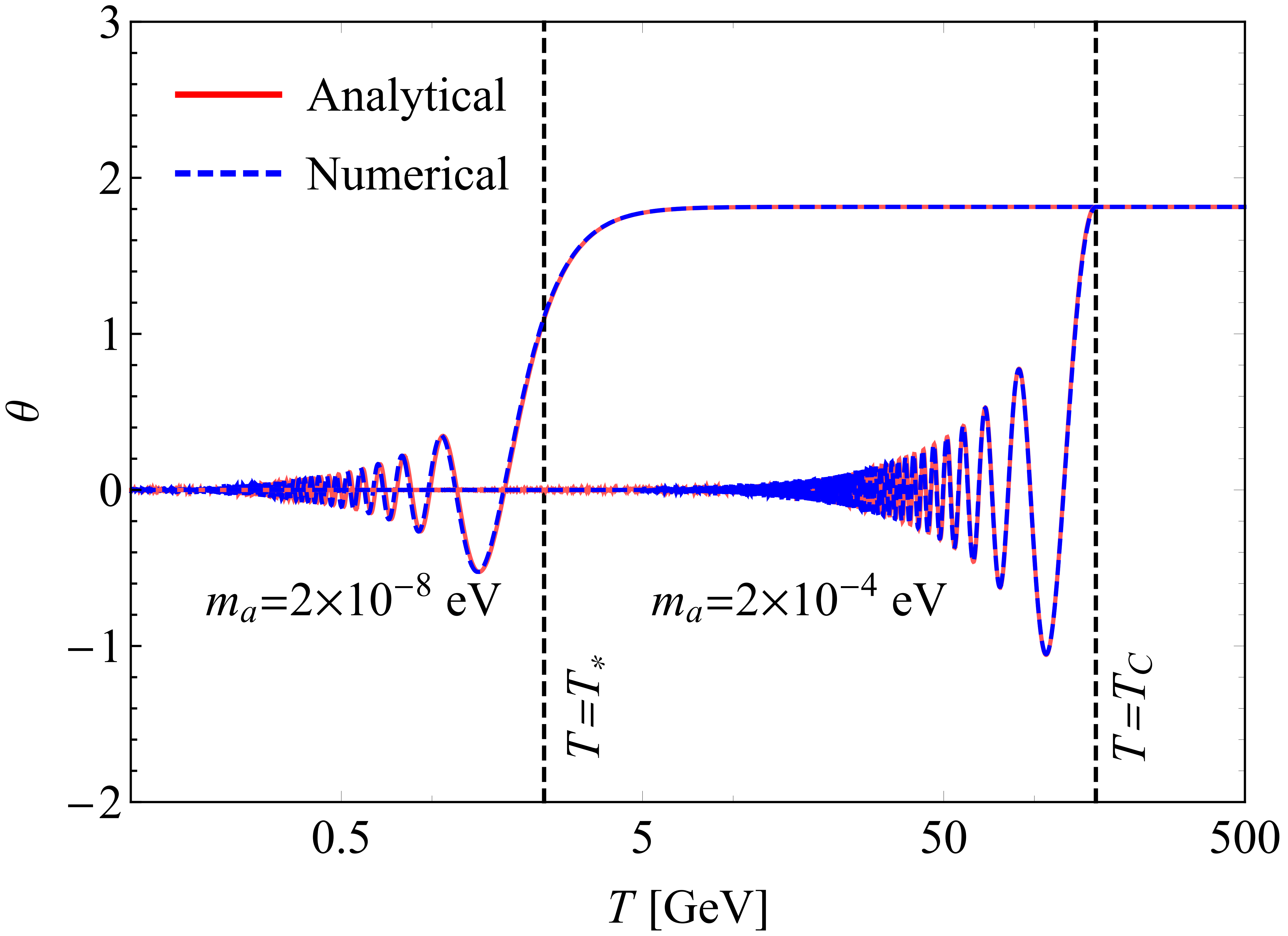
$$m_a^2(T) = \begin{cases} \dfrac{\mu v_\phi^2(T) v_\Delta(T)}{\sqrt{2} f_a^2}, & T \leq T_C \\ 0, & T > T_C \end{cases}$$

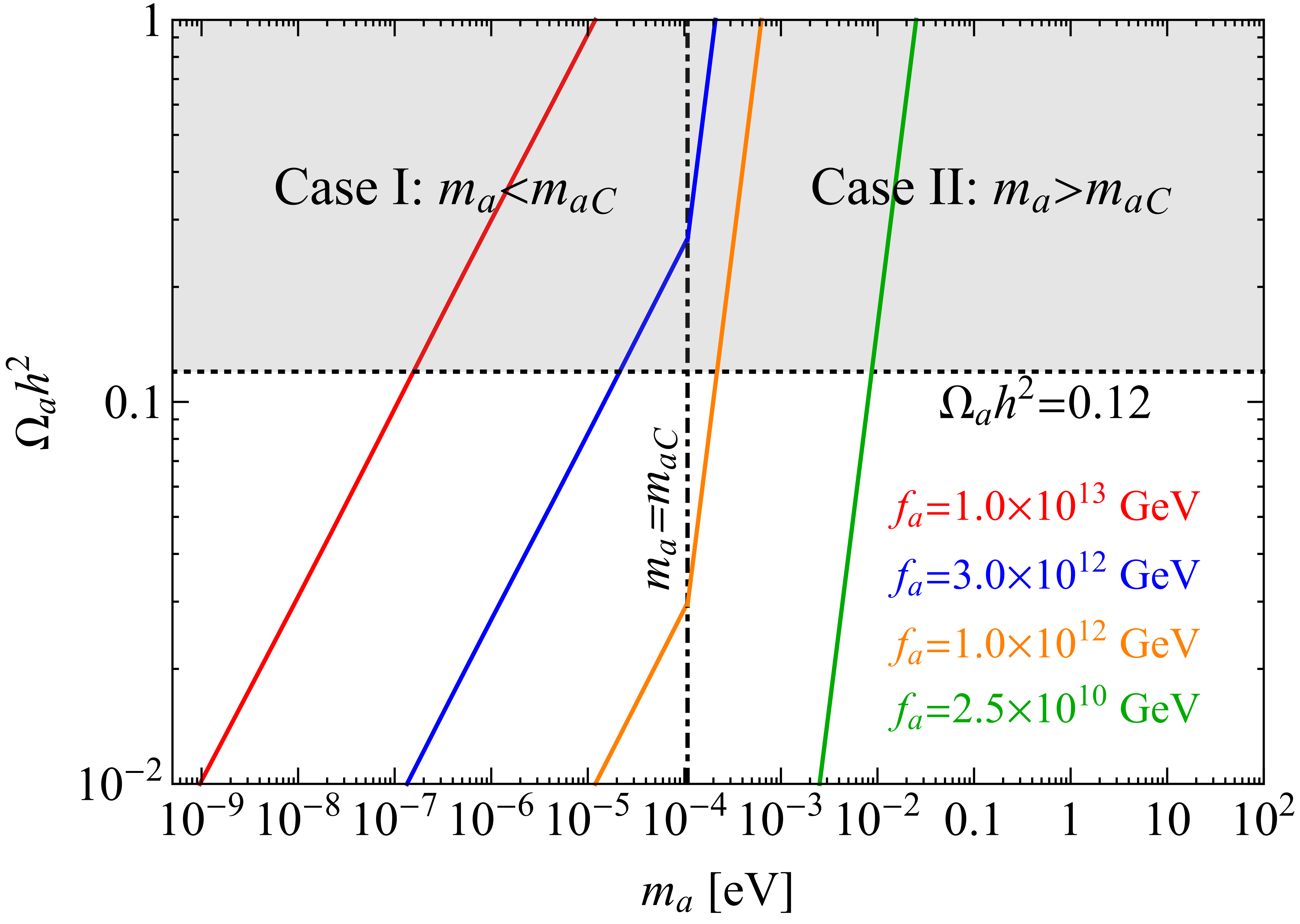
$$T_{\rm osc} = \begin{cases} T_*, & m_a < m_{aC} \\ T_C, & m_a \geq m_{aC} \end{cases}$$

$$m_{aC} = 1.079 \times 10^{-4}\,{\rm eV}$$



ALP Relic Density





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- **Scenario-3 : Axion misalignment mechanism in the presence of primordial magnetic field**

Wei Chao，Chang-jie Dai, arXiv: 2604.02012

Magnetic field in the early universe

Mechanisms for the production of primordial magnetic field

- ○ PMF can be generated during the pseudo-scalar inflation, ϕ, with the Chern-Simons interaction, $\frac{\phi}{4\pi f_a} F\widetilde{F}$.
- ○ PMF can be produced from the axion oscillations.
- ○ PMF can be generated from phase transitions in the early universe.
- ○ PMF can be generated from graviton.

Redshifted as $(1+z)^{-2}$

Axion dynamics in the presence of the PMF

Action

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} (\partial_\mu \phi)(\partial^\mu \phi) - V(\phi) - \frac{g_{\phi\gamma}}{4} \phi F_{\mu\nu} \widetilde{F}^{\mu\nu} \right]$$

Equation of motion

$$\partial_\eta^2 \phi + 2\mathscr{H} \partial_\eta \phi + a^2 m_\phi^2 \phi = g_{\phi\gamma} a^{-2} \mathbf{E}^* \cdot \mathbf{B}^*$$

Helicity

$$h^* = \lim_{V^* \to \infty} \frac{1}{V^*} \int d^3x \mathbf{A}^* \cdot \mathbf{B}^* \ ,$$

Evolution EQ

$$\frac{\partial h^*}{\partial \eta} = \lim_{V^* \to \infty} \frac{1}{V^*} \int d^3x \ (-2\, \mathbf{E}^* \cdot \mathbf{B}^*) \, .$$

Crucial for solving EOM of the axion!

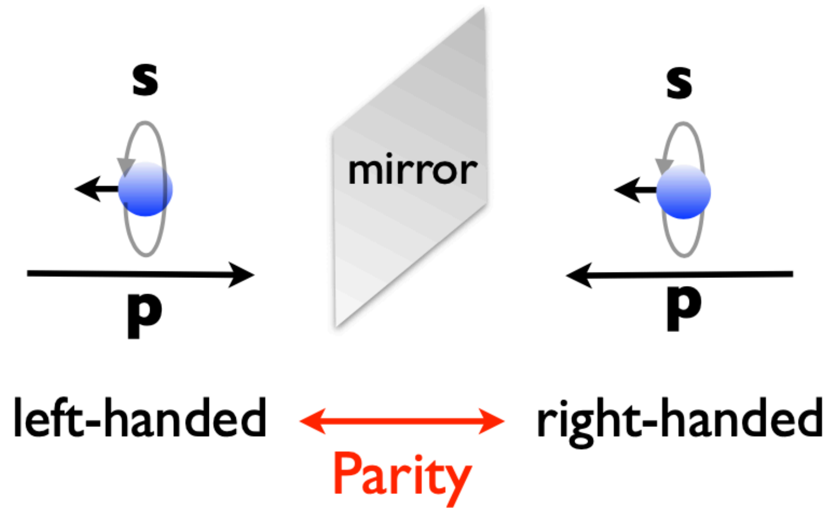
Chiral Magnetic Effect

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

- **Electric current induced by magnetic field in usual media?**

NO!

Chirality of fermions



$$P : j \to -j \quad E \to -E \quad B \to B$$

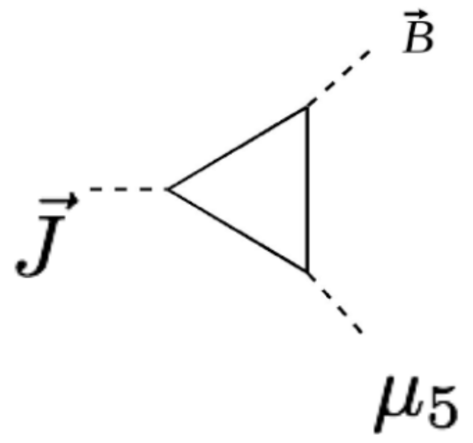
In the presence of a parity odd quantity, electric current can be induced!

Chiral chemical potential can be generated due to topological transition.

$$\mu_5 \neq 0$$

In the presence of magnetic field, electric current is generated

$$\partial_\mu j^\mu = \frac{e^2}{32\pi^2} F\widetilde{F} \to \vec{J} = \frac{e^2}{2\pi^2}\mu_5 \vec{B}$$



Chiral Magnetic Effect

@finite T: Lagrangian/Action for hyper magnetic field in the presence of chemical potential

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

$$\mu_5 \sim \sum_{i=1}^{3} \left[-2\mu_{R_i} + \mu_{L_i} - \frac{2}{3}\mu_{d_i} - \frac{8}{3}\mu_{u_{Ri}} + \frac{1}{3}\mu_{Q_i} \right] \qquad N_{CS}^{Y} = \frac{g'^2}{32\pi^2} 2A \cdot B_Y$$

- **Maxwell equations**

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

$$J = \sigma(E + v \times B) + \frac{2\alpha}{\pi} \mu_5 B - g_{\phi\gamma} B \partial_{\eta} \phi$$

The generalized Ohm’s law

EOM for helicity and the energy density

- **EOM**

$$\frac{\partial h^*}{\partial \eta} = \lim_{V^*\to\infty} \frac{1}{V^*}\int d^3x \frac{2}{\sigma^*}\left(\nabla^2 A^*\right)\cdot B^* + \frac{1}{\sigma^*}\left(\frac{8\alpha}{\pi}\mu_5^* - 4g_{\phi\gamma}\partial_\eta\phi\right)\rho_B^*,$$

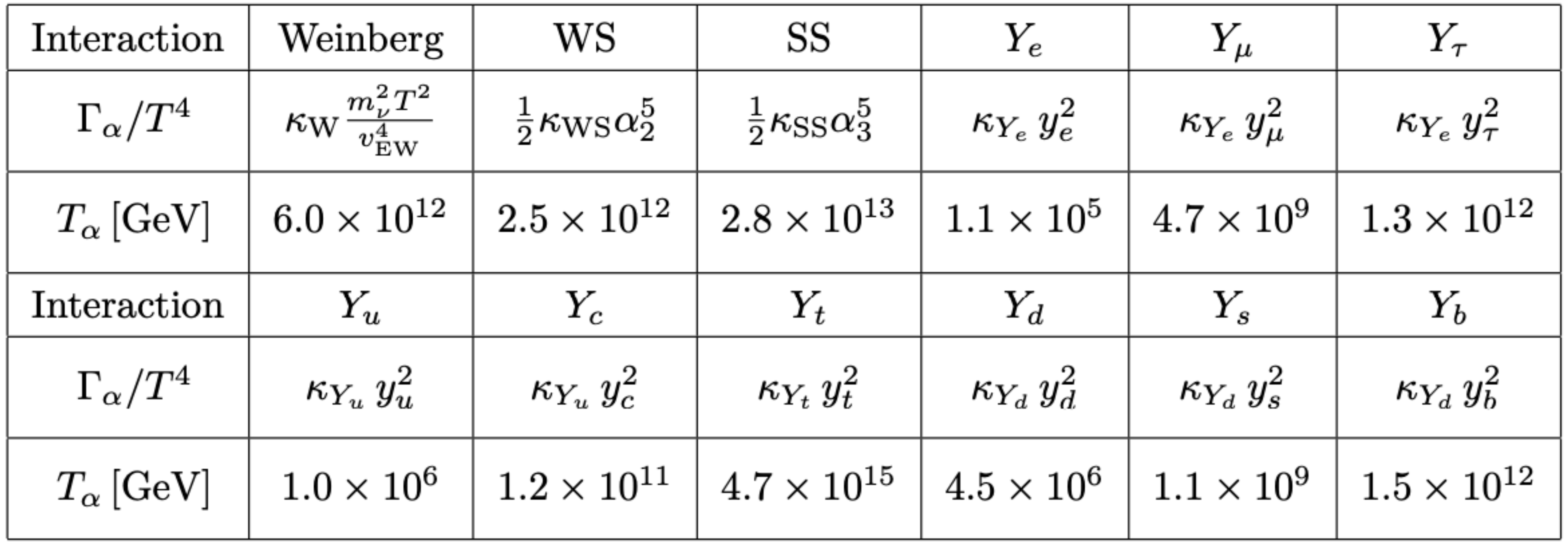
$$\frac{\partial \rho_B^*}{\partial \eta} = \lim_{V^*\to\infty} -\frac{1}{V^*}\frac{1}{\sigma^*}\int d^3x \mathbf{B}^*\cdot\left[\nabla^2\mathbf{B}^* + \nabla\times\left(-\frac{2\alpha}{\pi}\mu_5^*\mathbf{B}^* + g_{\phi\gamma}\mathbf{B}^*\partial_\eta\phi\right)\right]$$

- **Further define**

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

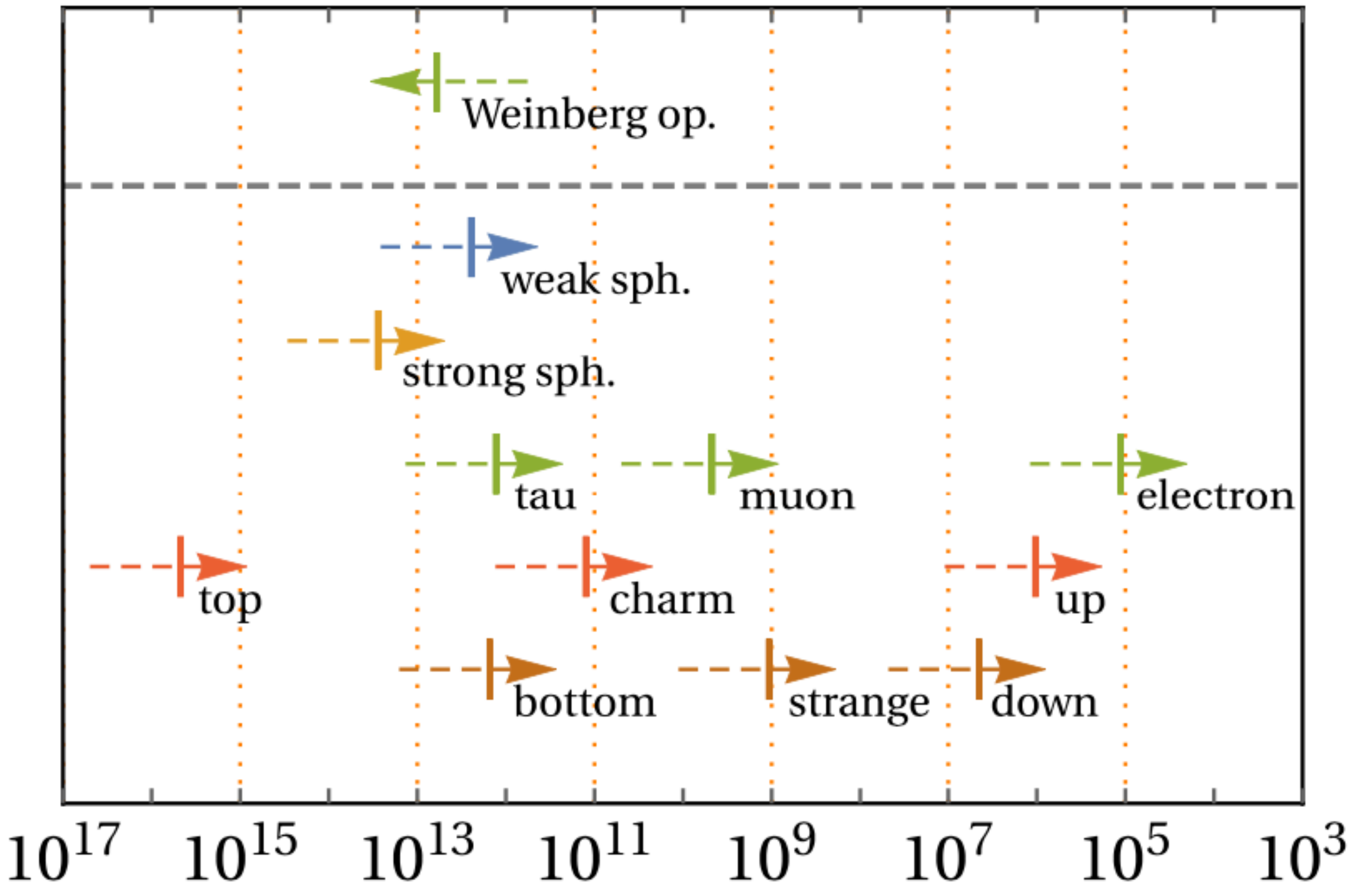
$$\frac{\partial h_k^*}{\partial \eta} = -\frac{2(k^*)^2}{\sigma^*}h_k^* + \frac{1}{\sigma^*}\left(\frac{8\alpha}{\pi}\mu_5^* - 4g_{\phi\gamma}\partial_\eta\phi\right)\rho_{B,k}^* \qquad \frac{\partial \rho_{B,k}^*}{\partial \eta} = -\frac{2(k^*)^2}{\sigma^*}\rho_{B,k}^* + \frac{1}{\sigma^*}\left(\frac{2\alpha}{\pi}\mu_5^* - g_{\phi\gamma}\partial_\eta\phi\right)(k^*)^2h_k^*$$

EOM for chemical potentials



Interaction	Weinberg	WS	SS	Y_e	Y_μ	Y_τ
Γ_α/T^4	$\kappa_{\mathrm{W}} \frac{m_\nu^2 T^2}{v_{\mathrm{EW}}^4}$	$\frac{1}{2}\kappa_{\mathrm{WS}}\alpha_2^5$	$\frac{1}{2}\kappa_{\mathrm{SS}}\alpha_3^5$	$\kappa_{Y_e}\, y_e^2$	$\kappa_{Y_e}\, y_\mu^2$	$\kappa_{Y_e}\, y_\tau^2$
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

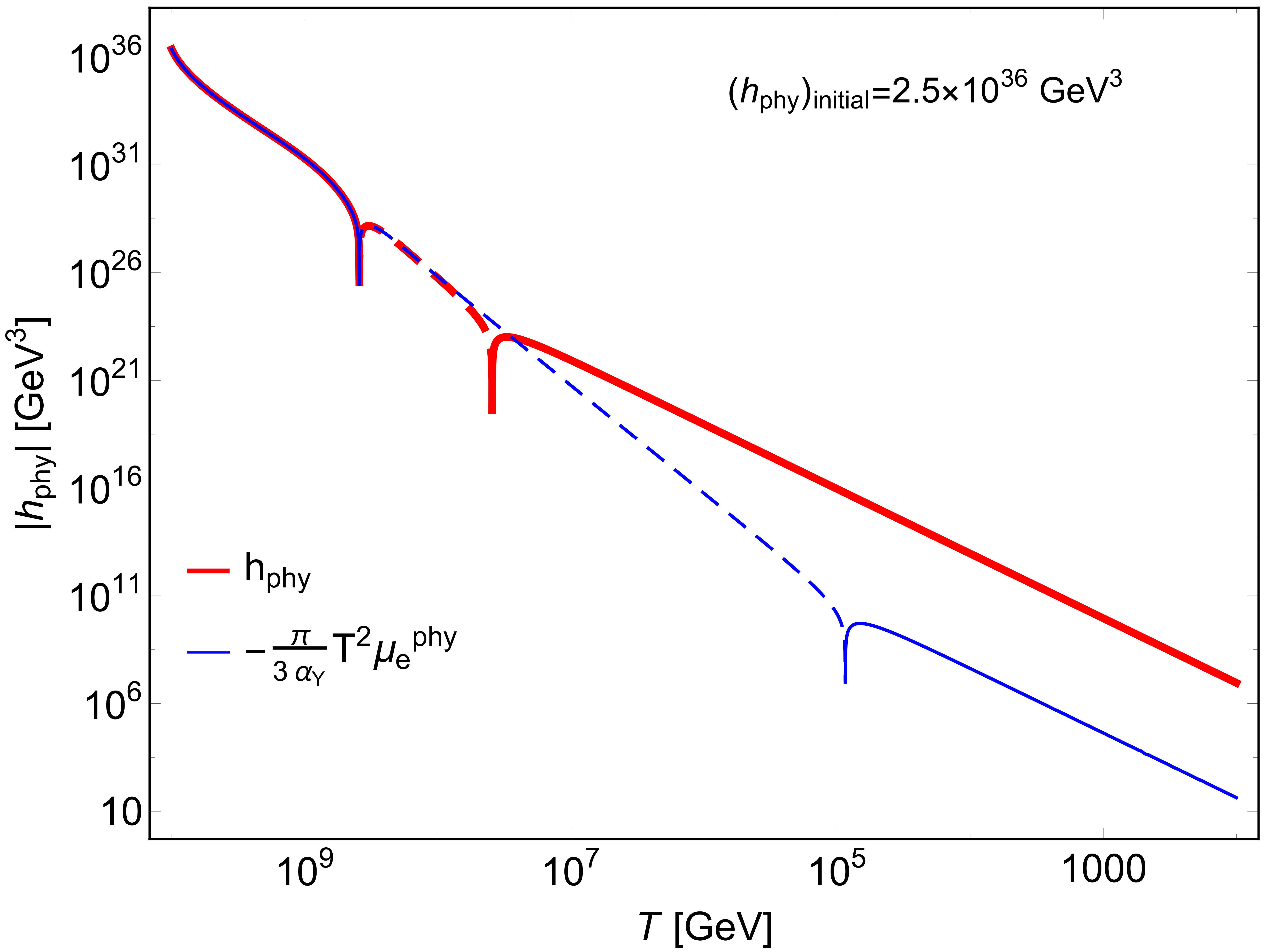


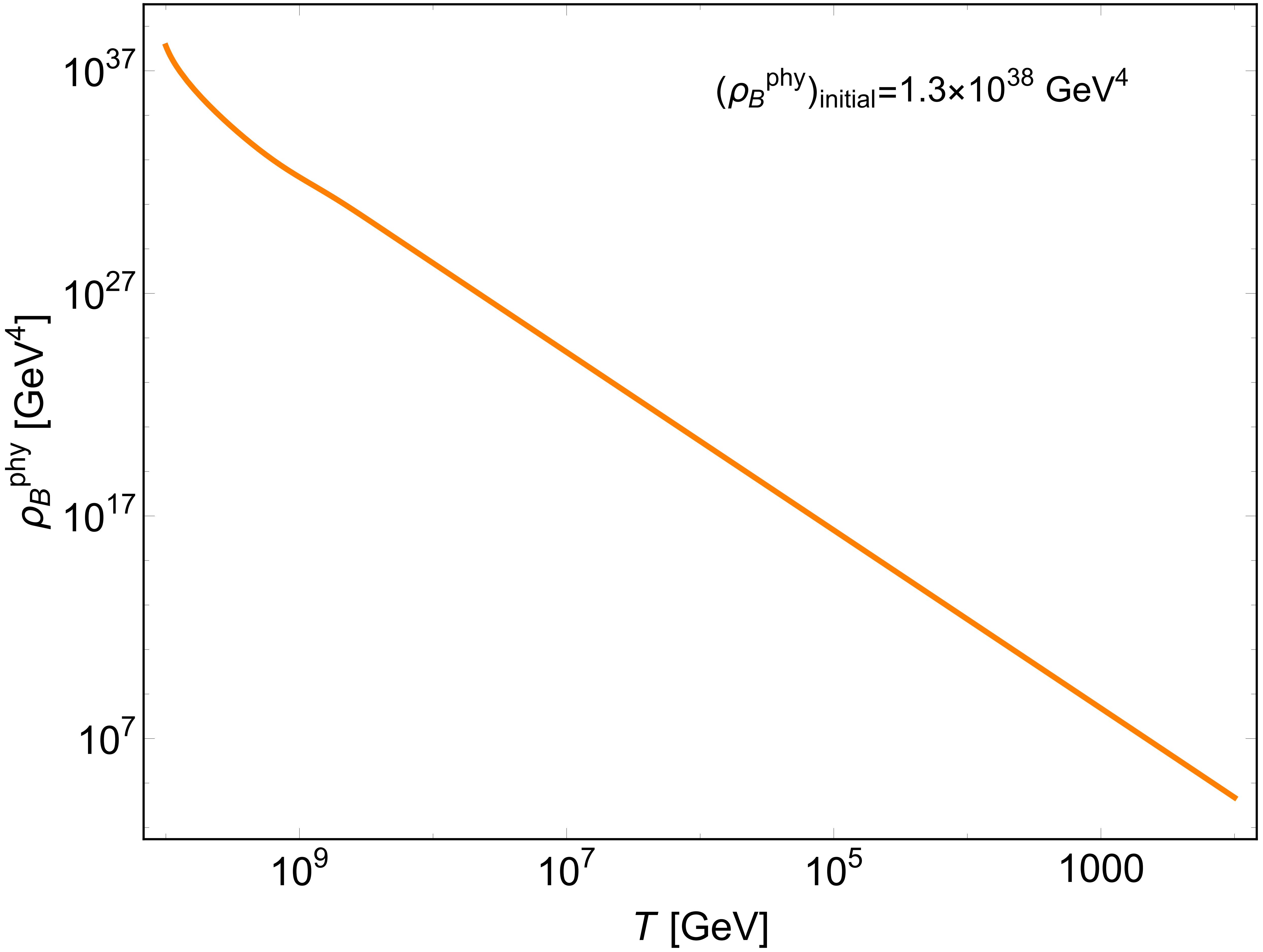
- **Toy scenario: Assuming all interactions except right-handed electron are in thermal equilibrium**

$$\mu_5^* = \frac{711}{481}\mu_e^* \ ,$$

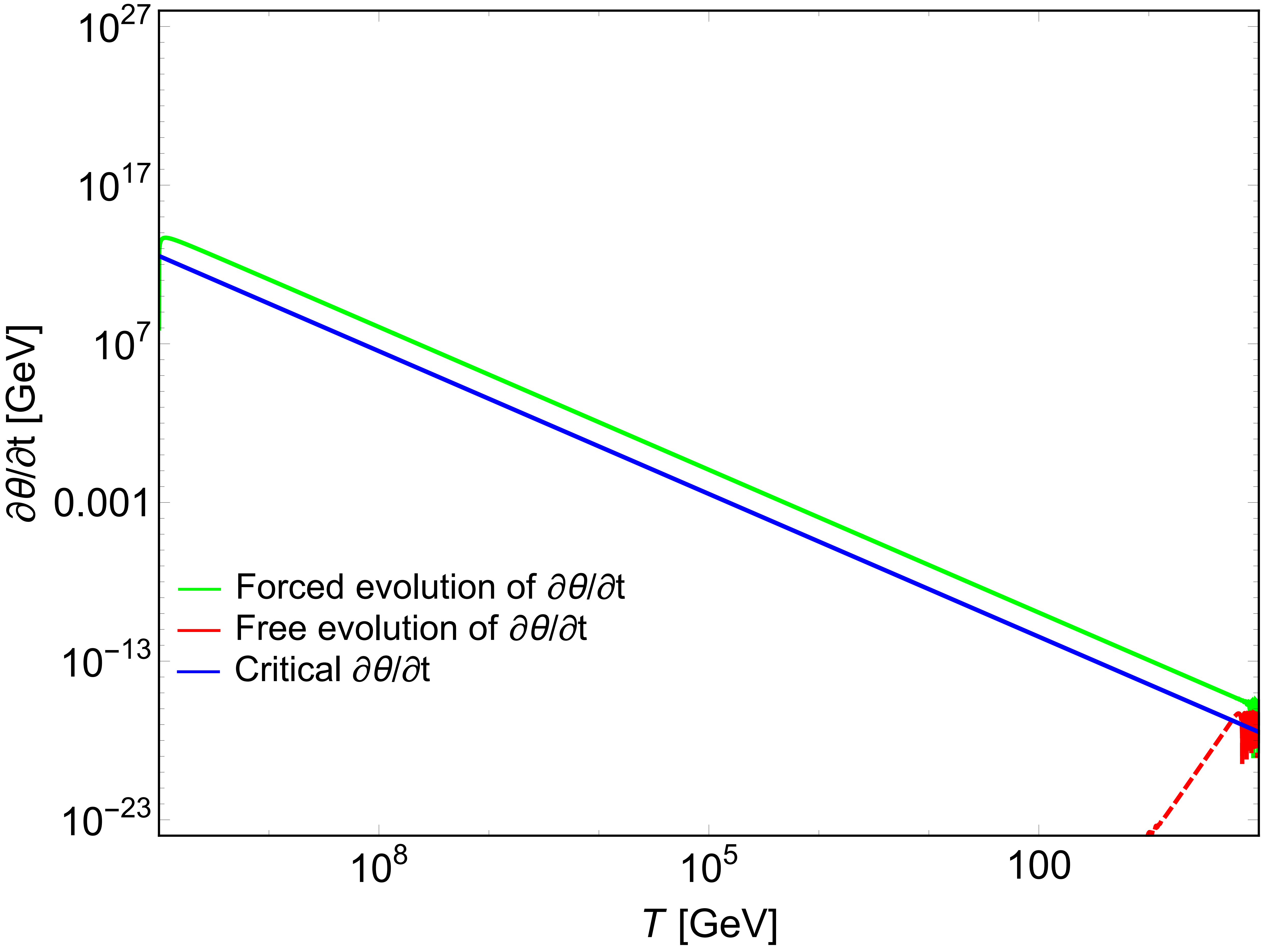
$$\frac{\partial \mu_e^*}{\partial \eta} = -\frac{3}{(T^*)^2}\frac{\alpha}{\pi}\frac{\partial h}{\partial \eta} - \Gamma_{\mathrm{Y_e}}\frac{711}{481}\mu_e^*$$

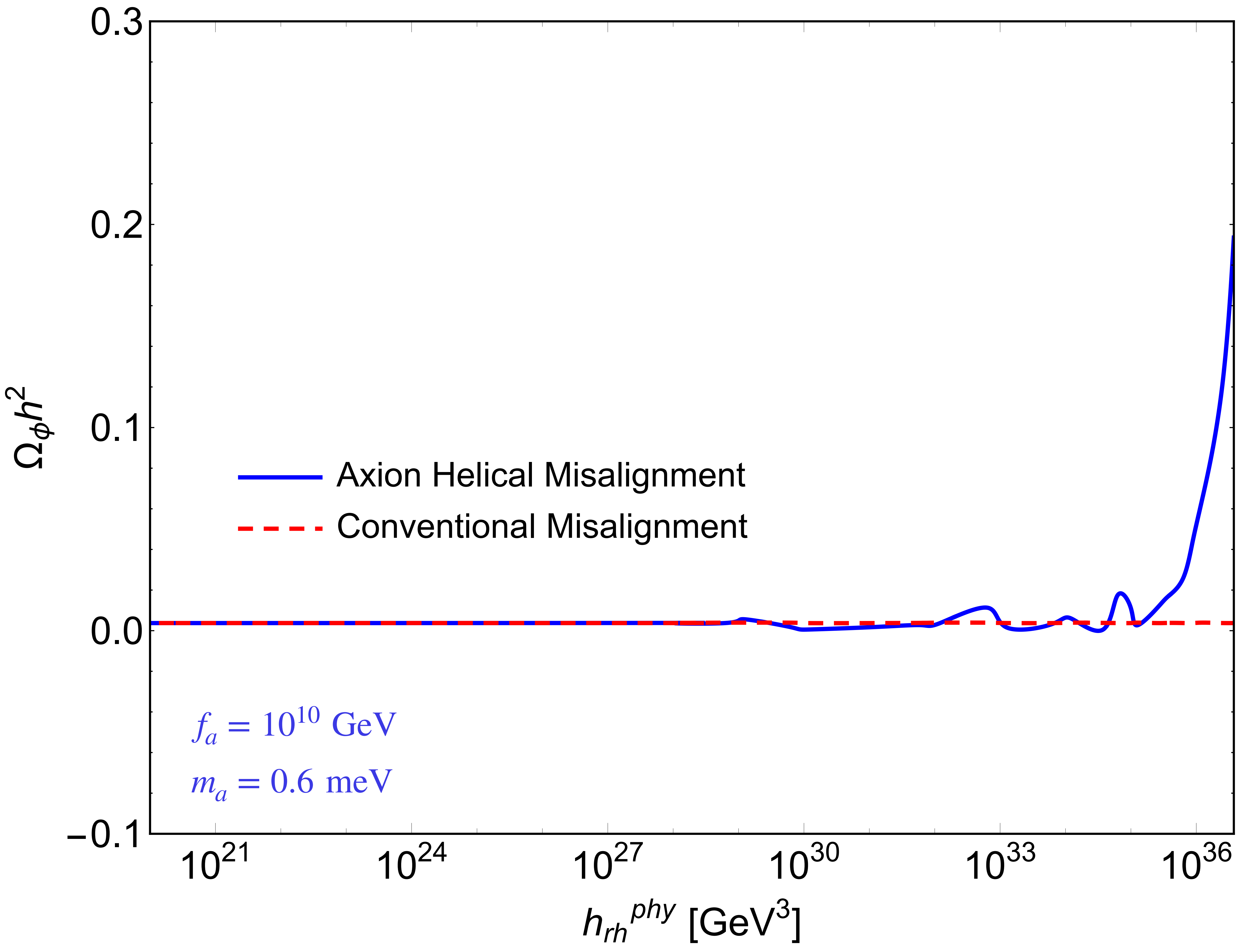
Numerical results





Numerical results





Conclusion

Axion misalignment mechanism is curial for evaluation of the axion relic abundance. There are still several effects need to be clarified for this mechanism:

■ Axion misalignment mechanism is relevant to mass generation mechanism of the axion.

■ Axion misalignment mechanism is relevant to the evolution of the PMF and Chiral asymmetries.

Thank you for your attention!