轴子暗物质：理论与观测 2025.05.09~12 山东、青岛

ALP— from Baryogenesis to Direct Detections

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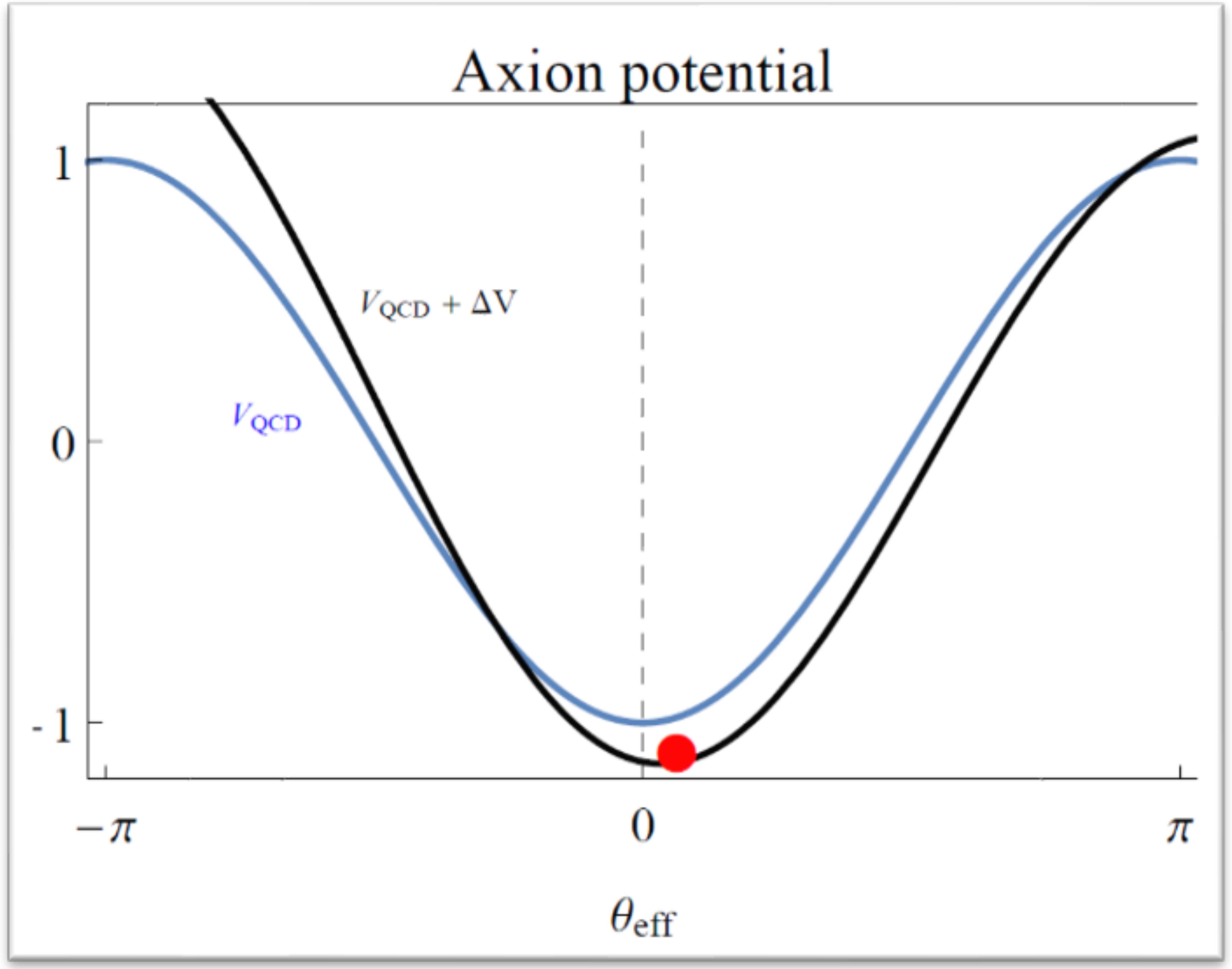
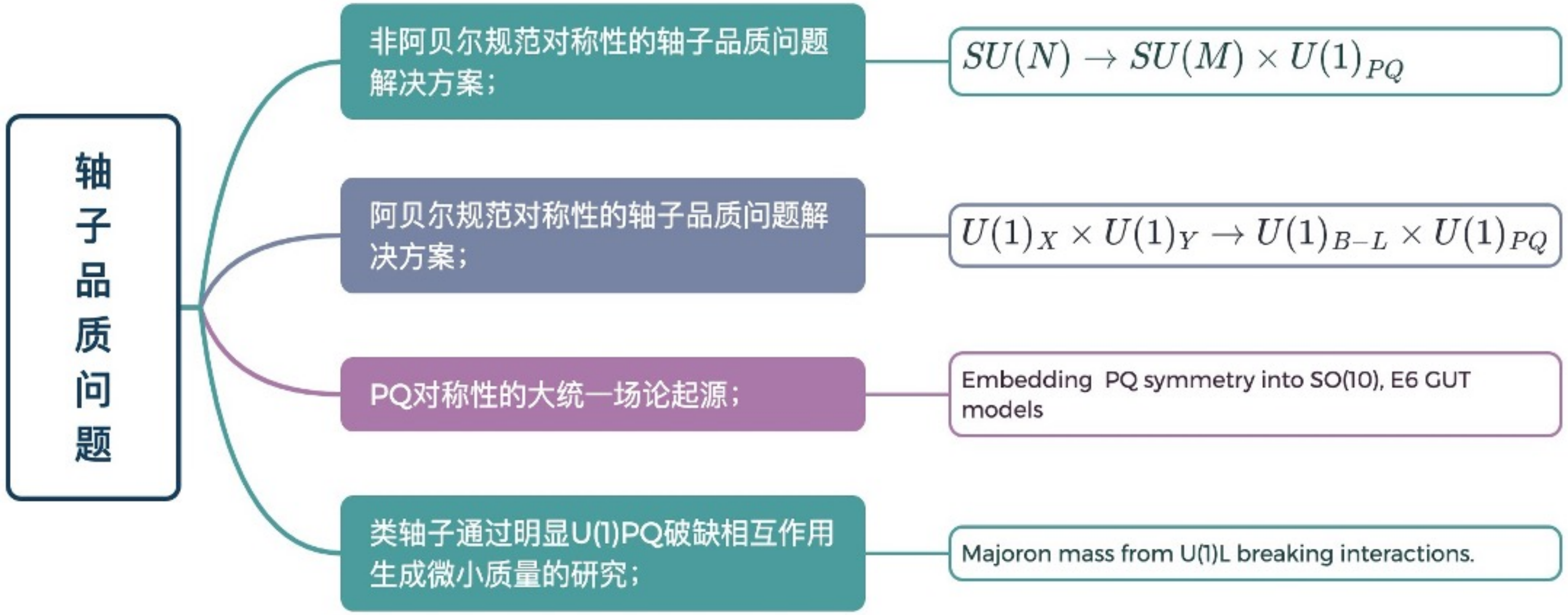
Outline

①Baryogenesis induced by the axion-like particles
✳Majorogenesis (Axiogenesis)
✳Axion-inflation Baryogenesis
②New attempts to the detection of axion-like particle
✳Phonon signal for ALP that has to axion-diphoton coupling
✳Phonon signal for ALP that couples to photon and dark-photon

Quality problem and a chance to the ALP





$$\theta_{eff} \neq 0 \to CPV\ minimum$$

Majoron & neutrino mass via type-I seesaw

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

$$\mathscr{L}_{\rm BSM} = \left(\partial_\mu \Phi\right)^\dagger (\partial^\mu \Phi) + \mu_\Phi^2 \Phi^\dagger \Phi - \lambda_1 (\Phi^\dagger \Phi)^2 - \lambda_2 (\Phi^\dagger \Phi)(H^\dagger H) - \left[Y_{\rm N} \overline{\ell_L} \tilde{H} N_R + \frac{1}{2} \overline{N_R^C} \left(Y_{\rm M} \Phi + m \right) N_R + {\rm h.c.} \right]$$

LNV term!

$$H = \begin{pmatrix} \phi^+ \\ \dfrac{v_\phi + \phi + i\chi}{\sqrt{2}} \end{pmatrix} \qquad \Phi = \frac{v_s + \tilde{s} + i\tilde{a}}{\sqrt{2}}$$

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

Yukawa Interaction $\quad -Y_{\rm N} \overline{\ell_L} \tilde{H} N_R \rightarrow M_D = Y_N v / \sqrt{2}$

Key term: $\quad m \overline{N_R^C} N_R + h.c.$

Quantum Gravity effect!

Majoron interactions and Majoron mass

Field-dependent phase transformation

$$\ell_L \to e^{-\frac{ia}{2f}}\ell_L \qquad S \to e^{+\frac{ia}{f}}S$$

$$E_R \to e^{-\frac{ia}{2f}}E_R \qquad H \to H$$

$$\mathscr{L} \to \mathscr{L} - \frac{a}{2f}\partial_\mu\left(\overline{\ell_L}\gamma^\mu\ell_L + \overline{E_R}\gamma^\mu E_R\right)$$

$$= \mathscr{L} - \frac{a}{2f}\partial_\mu J^L_\mu$$

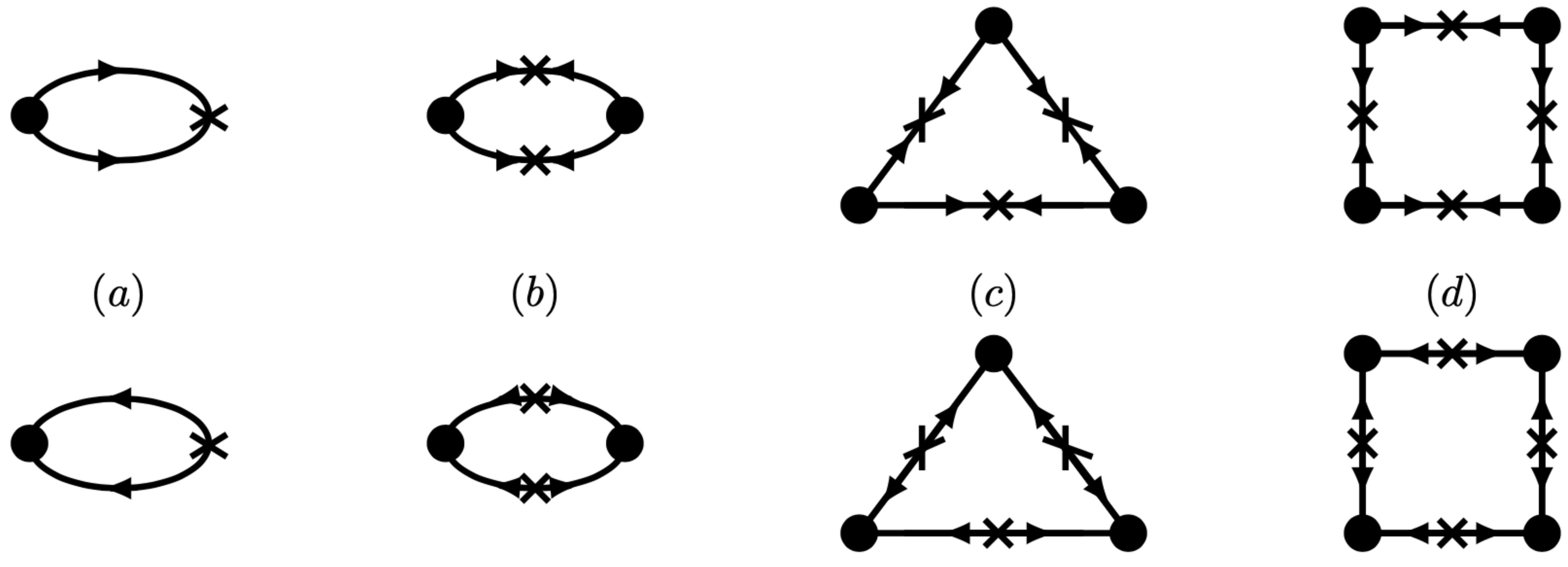
$$= \mathscr{L} + \frac{a}{2f}\frac{N_f}{32\pi^2}\left(g^2 W^a_{\mu\nu}\widetilde{W}^{\mu\nu,a} - g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right)$$

$$N_R \to e^{-\frac{ia}{2f}}N_R \longrightarrow \frac{1}{2}e^{-i\theta}\overline{N_R^C}mN_R + h.c.$$

Majoron interactions and Majoron mass

$$\frac{1}{2}e^{-i\theta}\overline{N_R^C}mN_R + h.c. \longrightarrow$$

Mass insertion of right-handed neutrino masses:



(a) (b) (c) (d)

(e) (f) (g) (h)

Before symmetry breaking: $M = m$

After symmetry breaking: $M = f_a Y_M/\sqrt{2} + m$

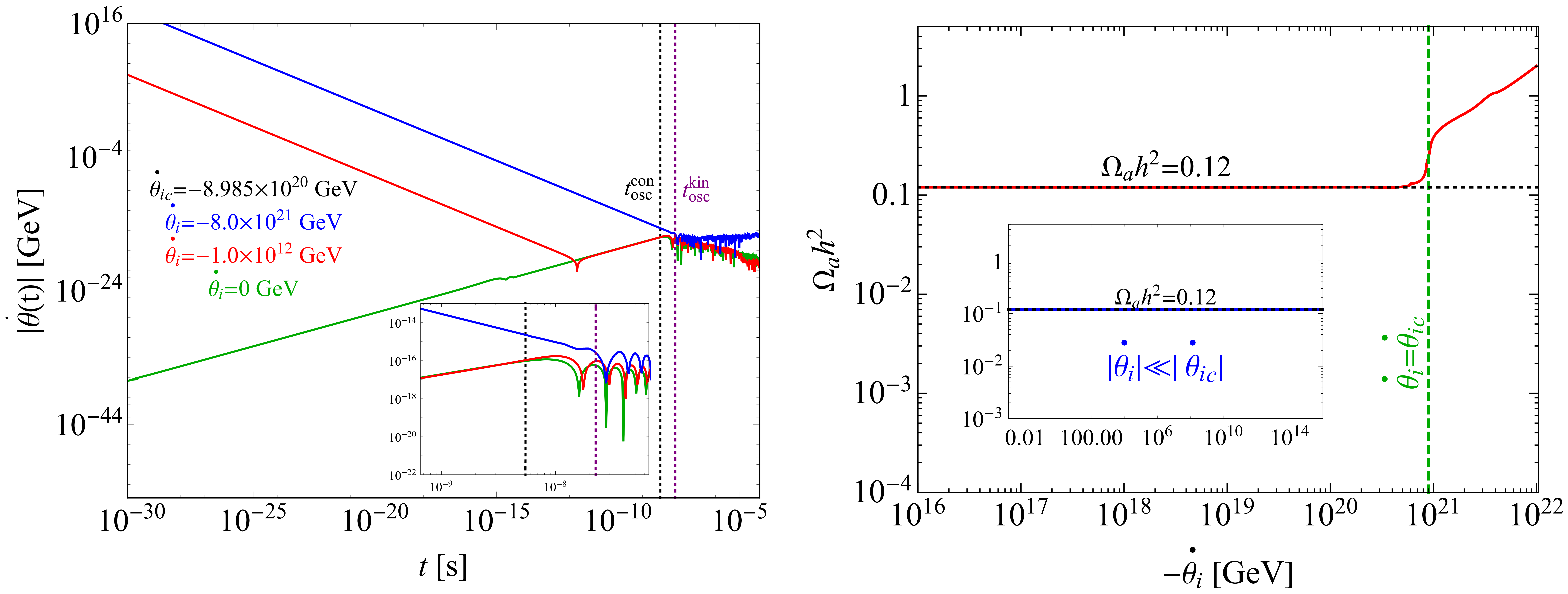
$$V_a \sim -\frac{1}{16\pi^2}\sum_{n=1}^{4} a_n \cos n\theta\,.$$

a_1	a_2	a_3	a_4
$mM^3\left(1+\log\frac{M^2}{M_{pl}^2}\right)$	$2m^2M^2\log\frac{M^2}{M_{pl}^2}$	m^3M	m^4

Majoron mass and its relic density

Majoron mass:	$$m_a^2 = \frac{1}{f_a^2}\frac{d^2V}{d\theta^2} = \frac{1}{16\pi^2 f_a^2}\left\| a_1 + 4a_2 + 9a_3 + 16a_4 \right\| .$$	
Initial velocity: **(Noether theorem)**	*from* $U(1)_L$ (struck through)	**In the traditional misalignment mechanism** $\dot{\theta}_i = 0$
EOM	$$\ddot{\theta} + 3H\dot{\theta} + \frac{1}{f_a^2}\frac{dV_a}{d\theta} = 0,$$	**Different oscillation temperature**

Majoron mass and its relic density



Baryon asymmetry of the universe

LNV → LNV carried by $\dot{\theta}$ → Non-zero B-L

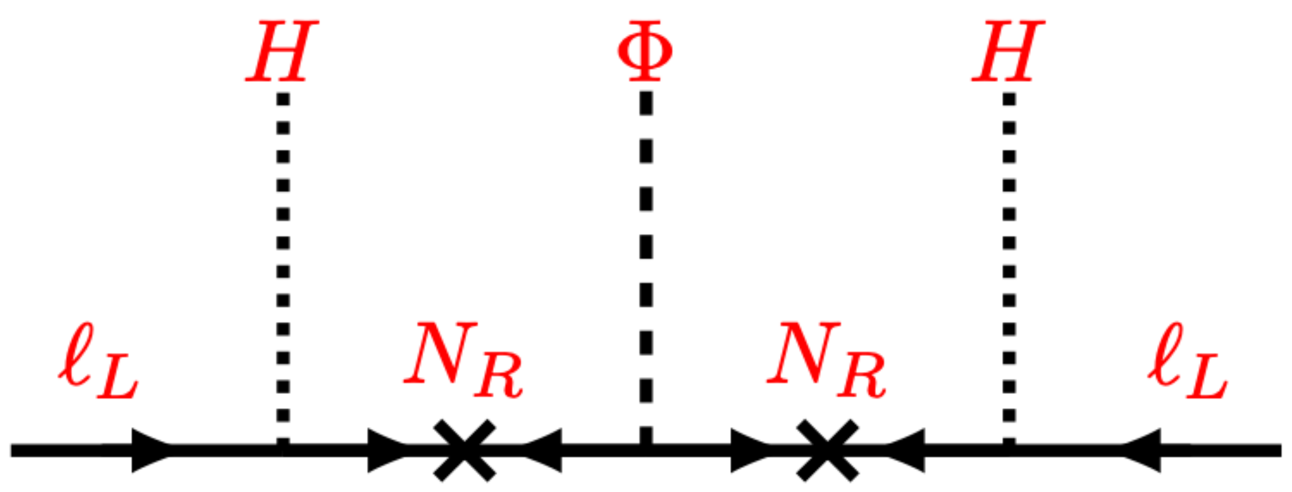
Weinberg operator

Chern-Simons operator

Non-zero B-L → BAU

Sehemas

Key:



$$\mathscr{L}_{\rm int} \supset \frac{1}{2M}\frac{a}{f_a}\ell\ell HH,$$

$$\mathscr{L}_{\rm int} \supset \frac{3g^2}{64\pi^2}\frac{a}{f_a}W\widetilde{W}$$

Baryon asymmetry of the universe

Transport equations:

$$-\frac{d}{d\ln T}\left(\frac{\mu_i}{T}\right) = -\frac{1}{g_i}\sum_{\alpha} n_i^{\alpha}\frac{\gamma_\alpha}{H}\left[\sum_j n_j^{\alpha}\left(\frac{\mu_j}{T}\right) - n_S^{\alpha}\frac{\dot{\theta}(T)}{T}\right],$$

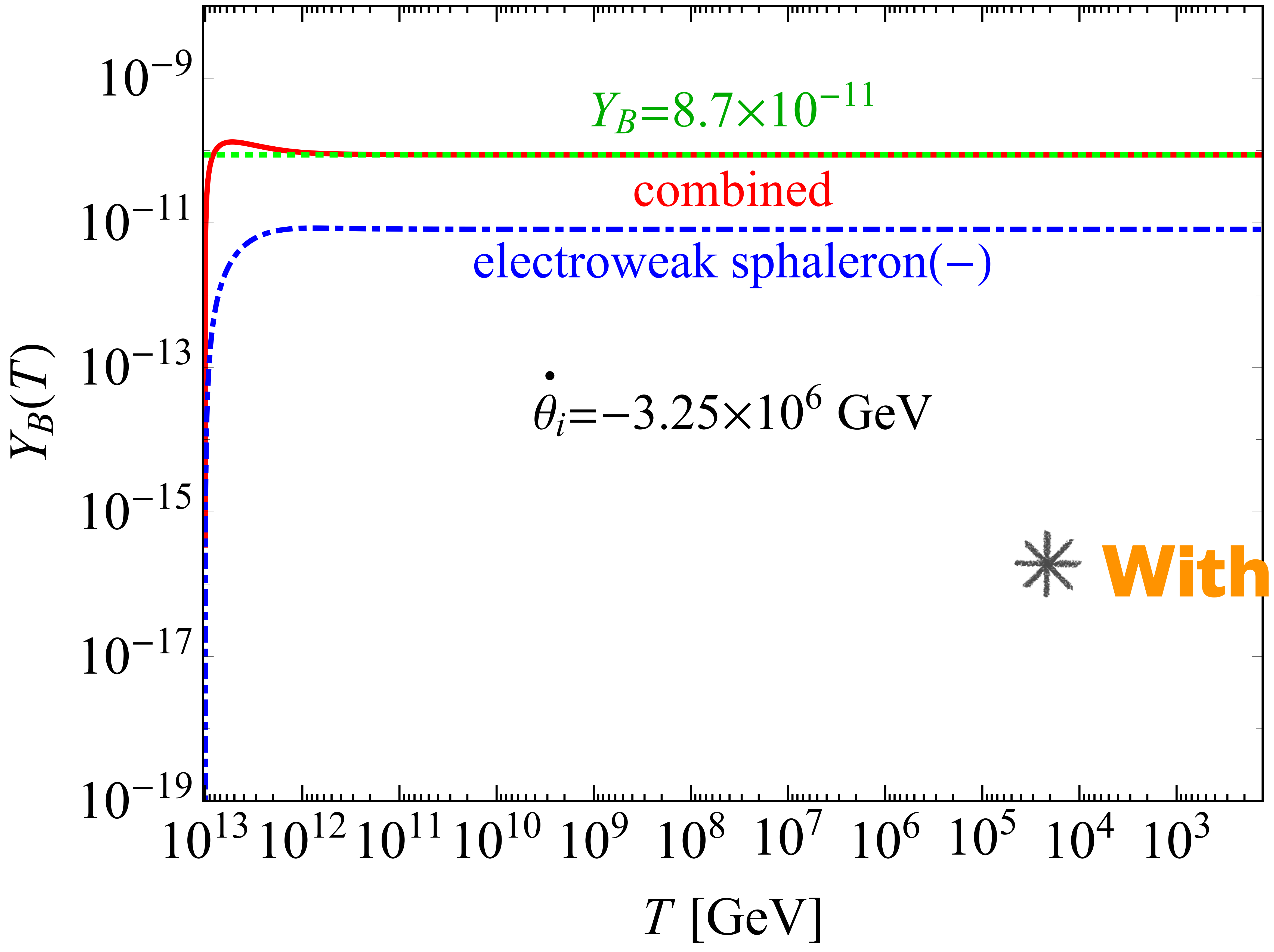
Source term:

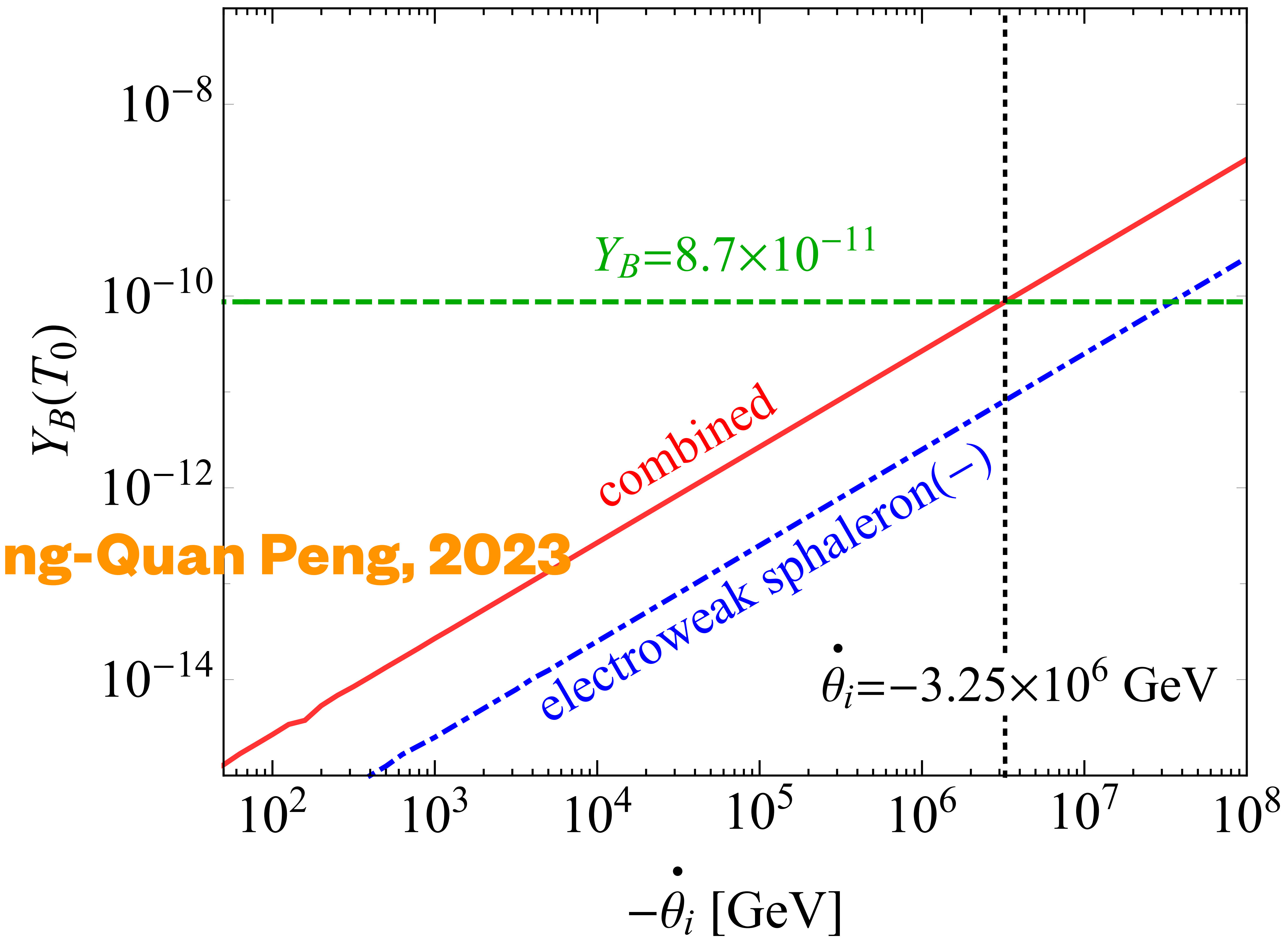
$$\left(n_S^{WS}, n_S^{W_{12}}, n_S^{W_3}, n_S^{SS}, n_S^{Y_\tau}, n_S^{Y_t}, n_S^{Y_b}\right) = \left(\frac{3}{2},1,1,0,0,0,0\right).$$

Weinberg operator decoupling temperature:

$$T_{\rm W} \simeq 6\times 10^{12}\,{\rm GeV}\times\left(\frac{0.05\,{\rm eV}}{m_\nu}\right)^2.$$

Baryon asymmetry of the universe





✳ With Ying-Quan Peng, 2023

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①**Baryogenesis induced by the axion-like particles**
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Axion-inflation triggered baryogensis

- Original idea : Alexander, Peskin, Sheikh-Jabbari, PRL 2004

$$S = \int \sqrt{-g}\left[\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - F(\phi)R\tilde{R}\right]$$

→ **$R\tilde{R}$ production during axion inflation**

+ $$\partial_\mu J_l^\mu = \frac{3}{16\pi^2}R\tilde{R}$$

→ **Net lepton number density after inflation!**

- Net number densities of SM particles can be produced via the axion-inflaton that couples to the Hyper U(1) gauge field via the Chern-Simons interaction, $g(\phi)F\tilde{F}$.
- Hyper-magnetic field may survive to the EWPT, resulting in net BAU (JHEP12(2017)011)

Axion-inflation triggered baryogensis

- **Axion inflation with interactions**

$$\mathscr{L}_{\rm int} = \frac{\alpha}{4\pi}\frac{\phi}{f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

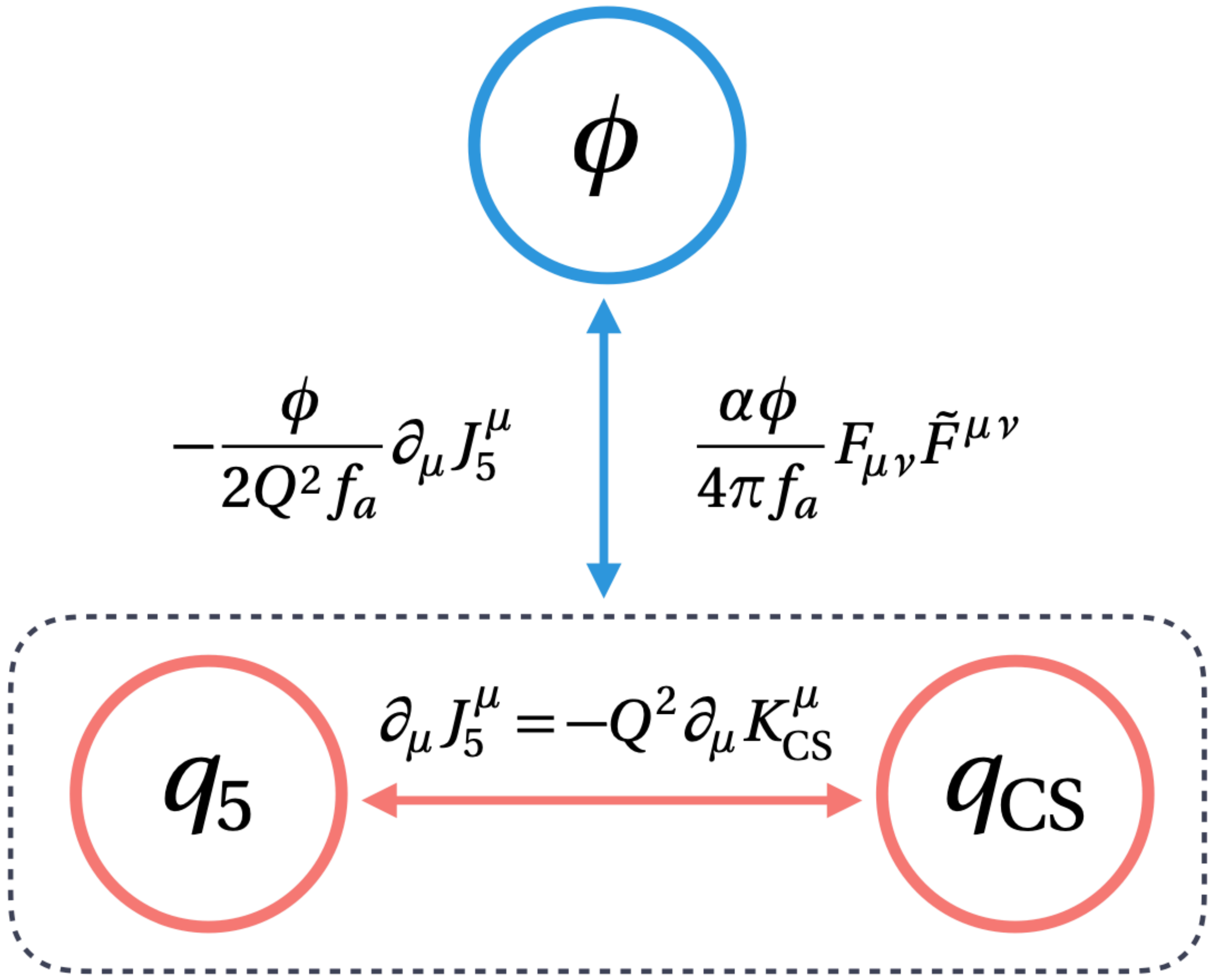
- **Production of gauge fields during inflation:** $\left(\Box\eta^{\mu\nu} - a\frac{\alpha\dot{\phi}}{\pi f_a}\varepsilon^{0\mu\sigma\nu}\partial_\sigma\right)A_\nu = 0$

$$A(\tau, x) = \sum_{\lambda=\pm}\int\frac{d^3k}{(2\pi)^3}\left[A_\lambda(\eta,k)\varepsilon_\lambda(k)a_\lambda(k)e^{ik\cdot x} + \mathrm{h.c.}\right]$$

$$\Rightarrow \left[\frac{\partial^2}{\partial\eta^2} + k(k + 2\lambda\xi aH)\right]A_\lambda(\eta,k) = 0 \Rightarrow A^k_\lambda(\tau) = \frac{e^{\lambda\pi\xi/2}}{\sqrt{2k}}W_{-i\lambda\xi,1/2}(2ik\tau)$$

Axion-inflation triggered baryogensis

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



- **Chern Simons number:**

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

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

- **Chiral fermion asymmetry during reheating**

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

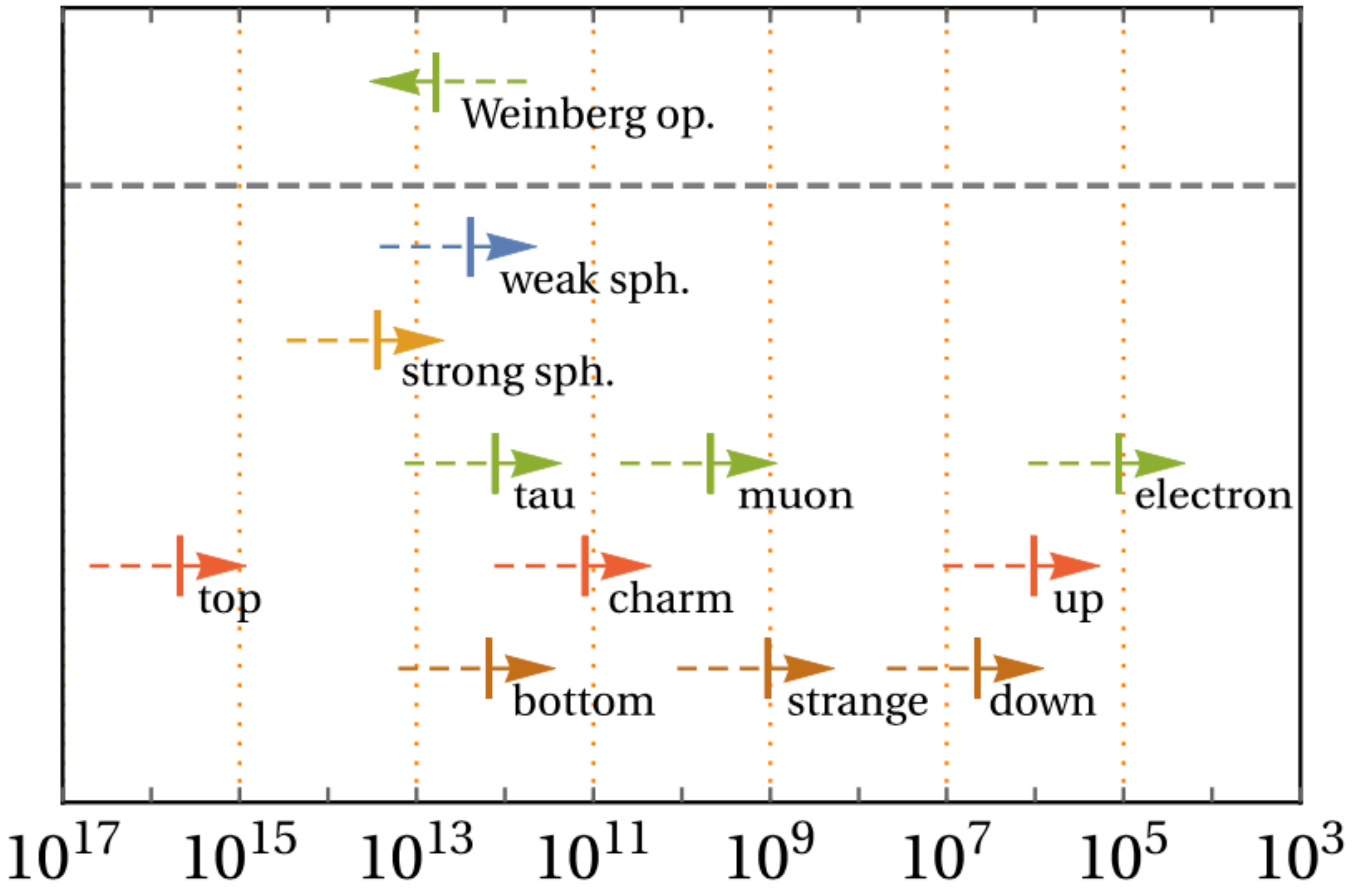
Axion-inflation triggered baryogensis

- **From chiral fermion asymmetries to the BAU**

Transport equations:

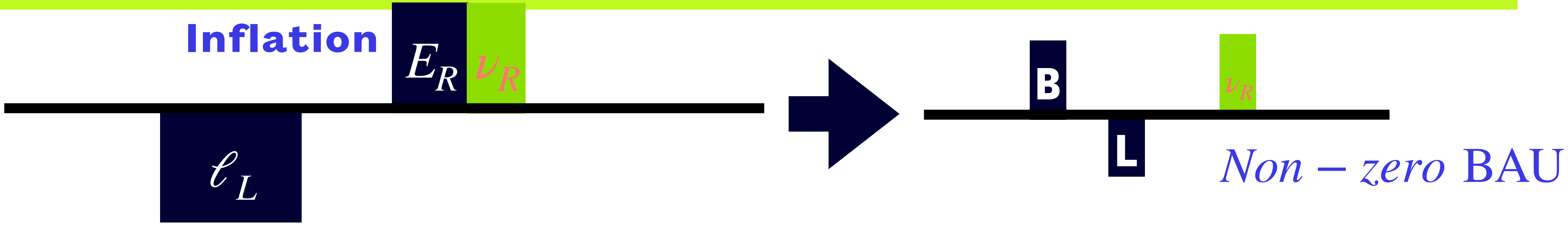
$$-\frac{d}{d\ln T}\left(\frac{\mu_i}{T}\right) = -\frac{1}{g_i}\sum_\alpha n_i^\alpha \frac{\gamma_\alpha}{H}\left[\sum_j n_j^\alpha \left(\frac{\mu_j}{T}\right)\right],$$

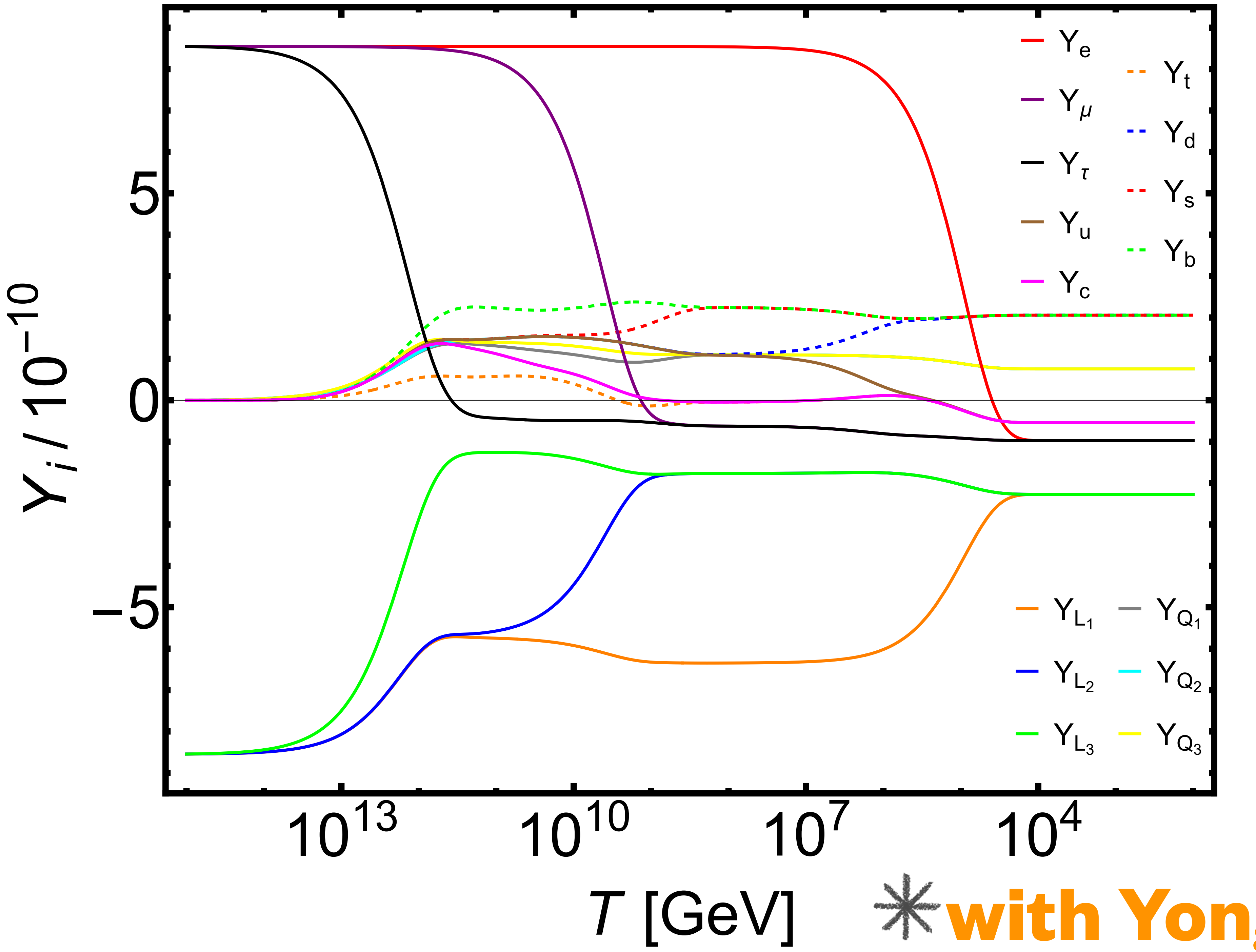
Interaction		WS	SS	Y_e	Y_μ	Y_τ
Γ_α/T^4		$\frac{1}{2}\kappa_{\rm WS}\alpha_2^5$	$\frac{1}{2}\kappa_{\rm SS}\alpha_3^5$	$\kappa_{Y_e}\, y_e^2$	$\kappa_{Y_e}\, y_\mu^2$	$\kappa_{Y_e}\, y_\tau^2$
T_α [GeV]	6.0×10^{12}	2.5×10^{12}	2.8×10^{13}	1.1×10^{5}	4.7×10^{9}	1.3×10^{12}
Interaction	Y_u	Y_c	Y_t	Y_d	Y_s	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}

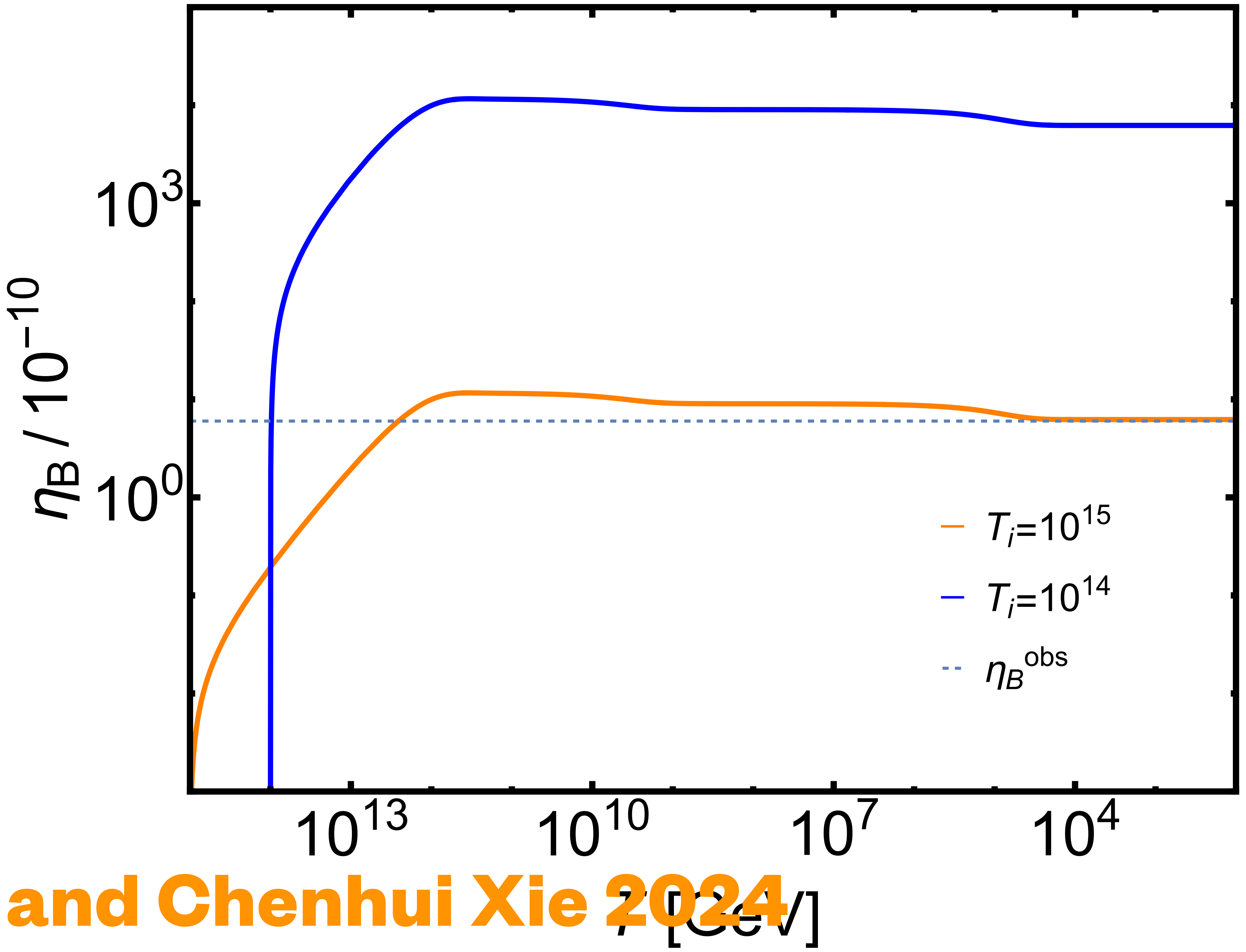


Axion-inflation triggered baryogensis

- $F\tilde{F}$: **U(1)$_L$ gauge field** ✓



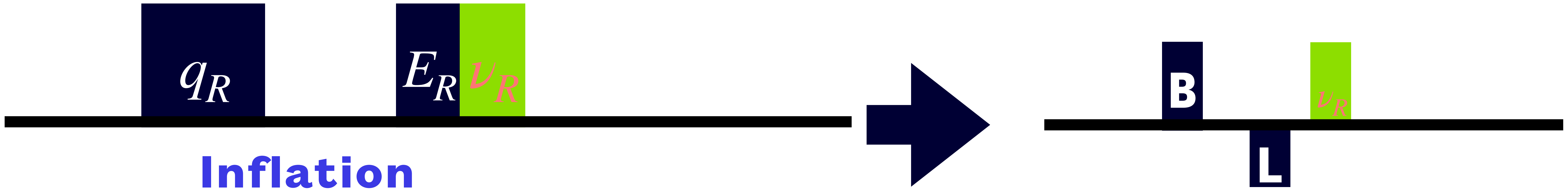


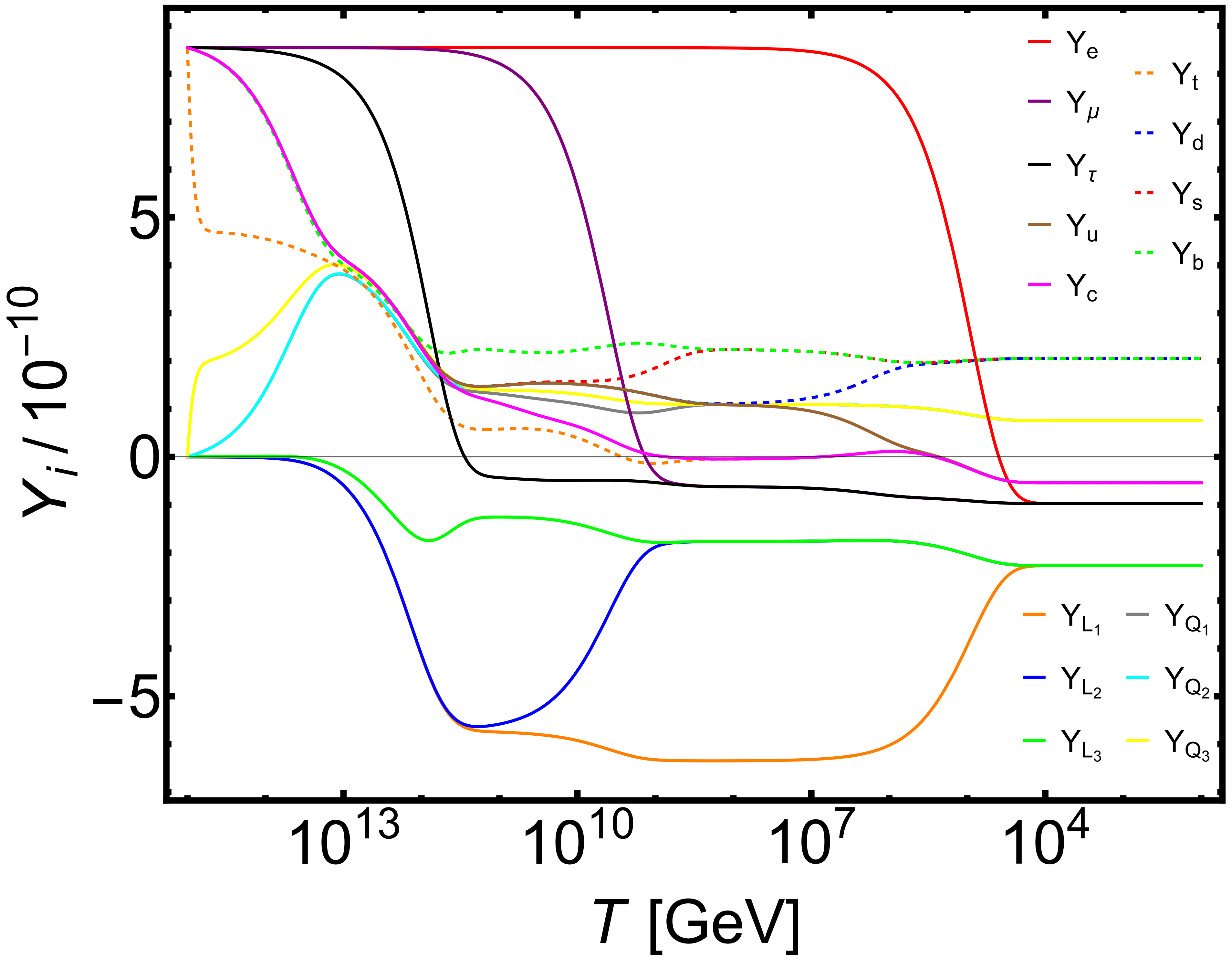


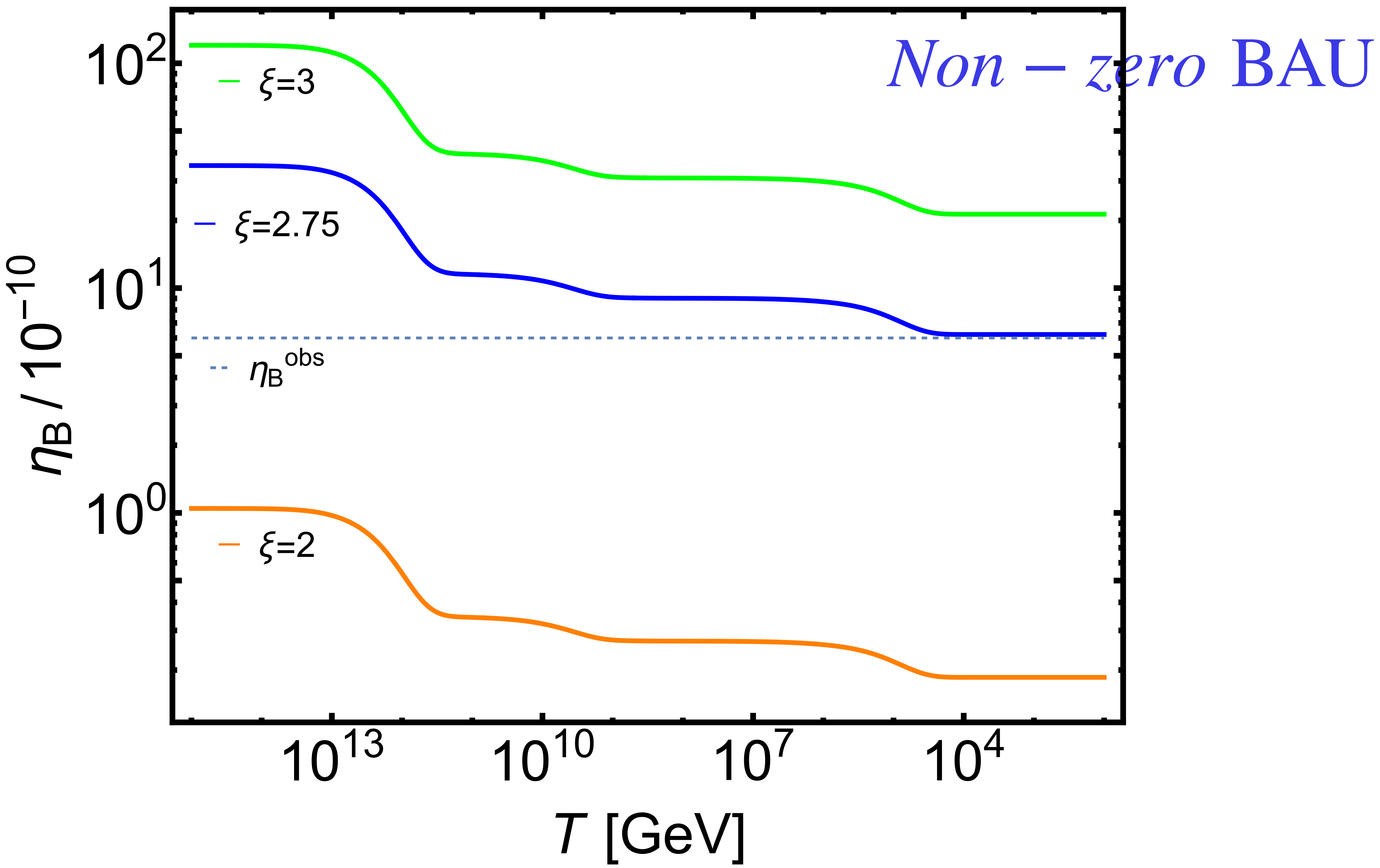
✳**with Yong hua Wang and Chenhui Xie 2024**

Axion-inflation triggered baryogensis

- $F\tilde{F}$: **U(1)$_R$ gauge field** ✓

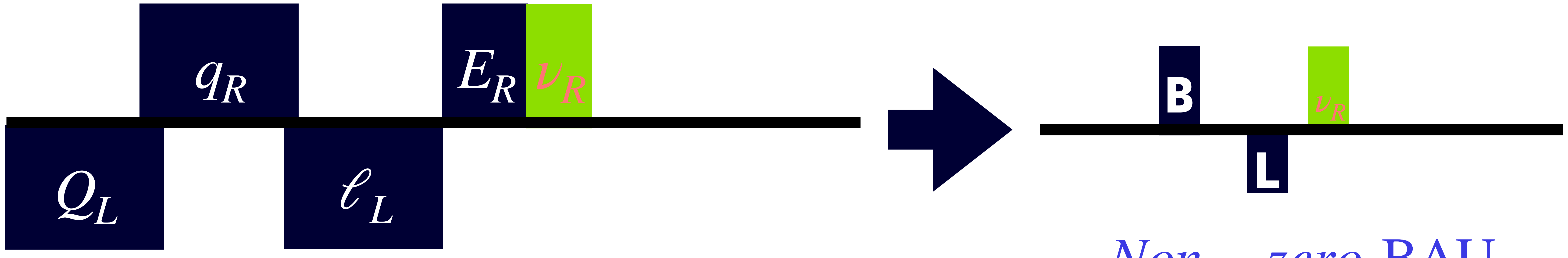






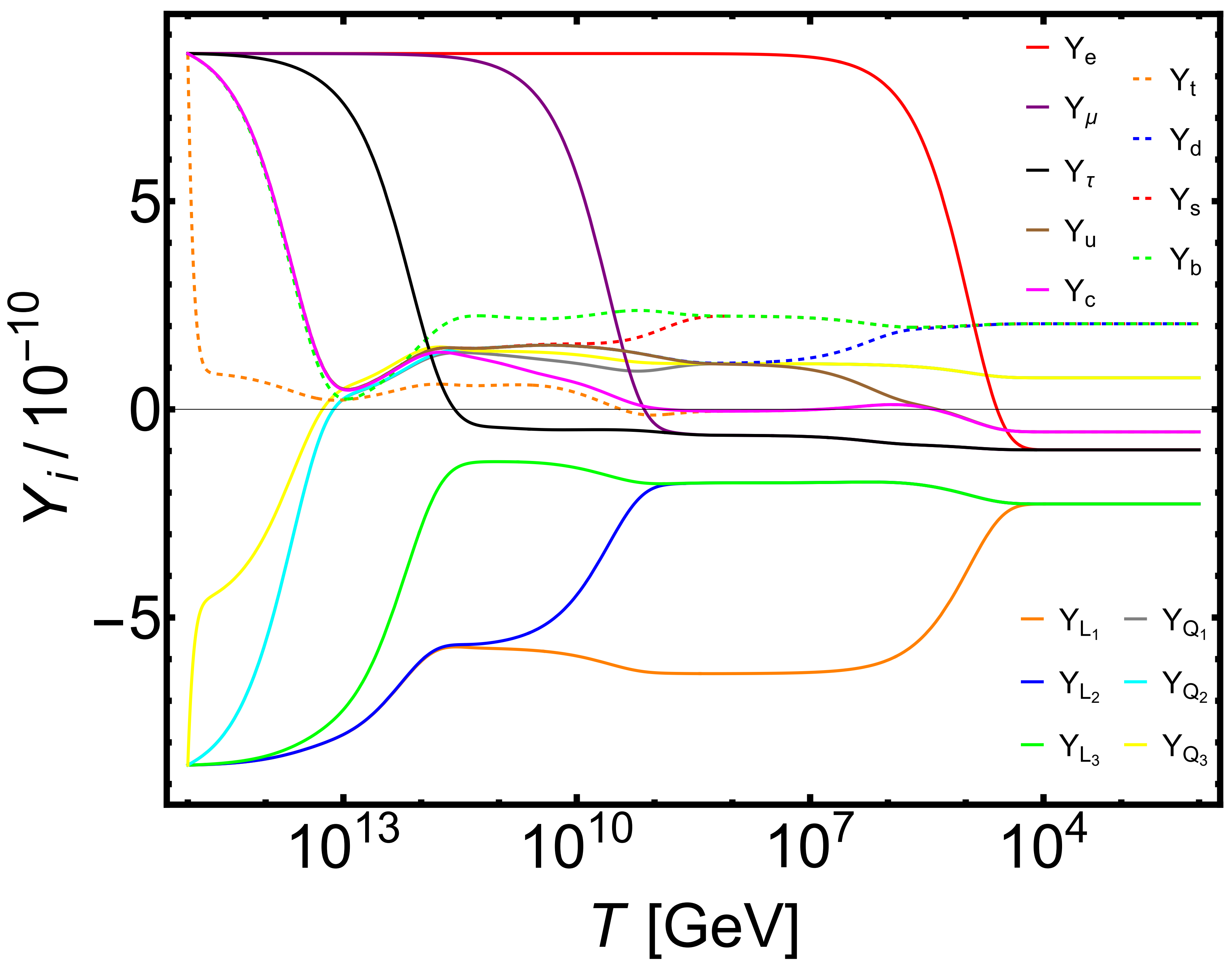
Axion-inflation triggered baryogensis

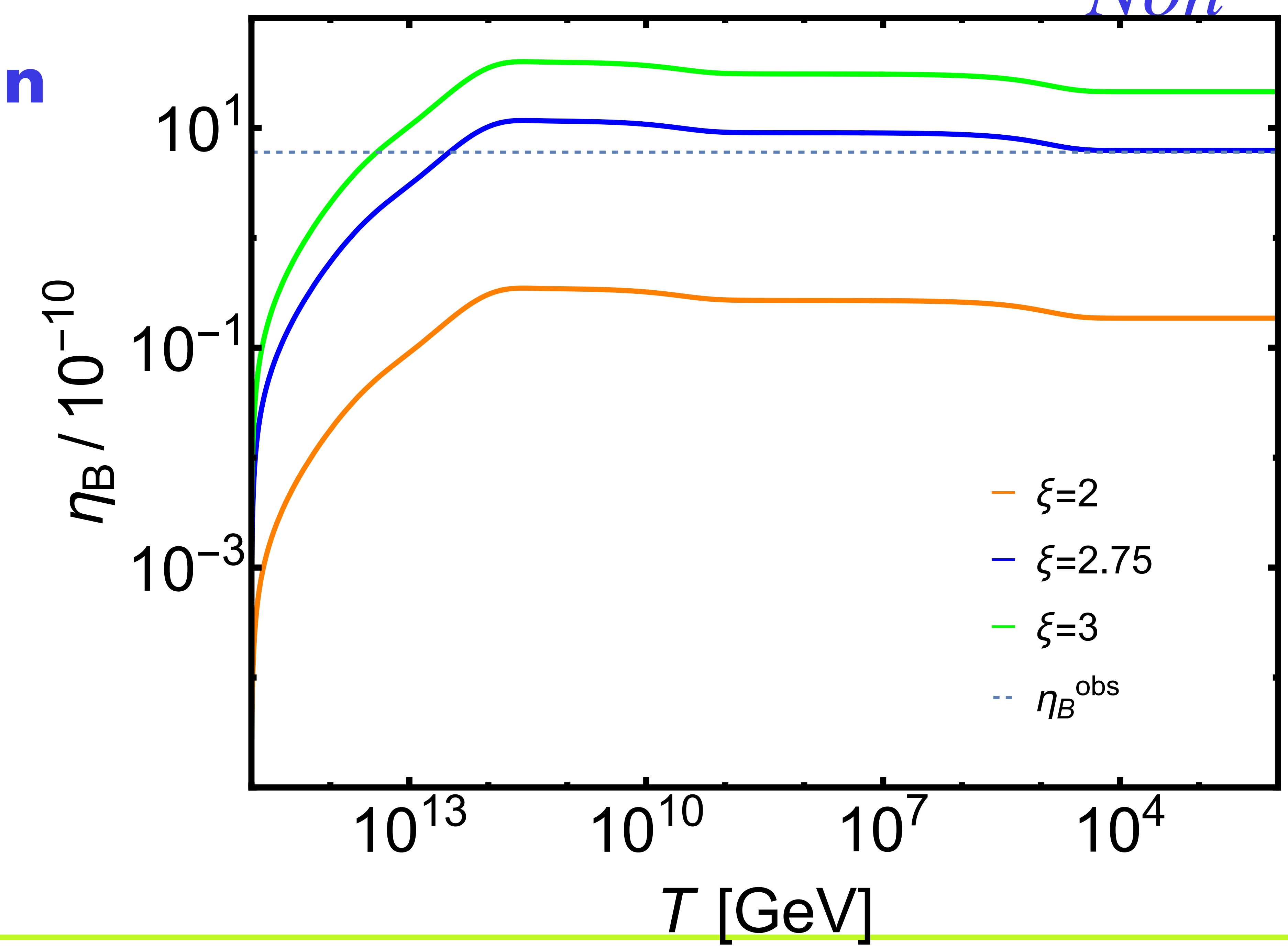
- $F\tilde{F}$: **U(1)$_{B-L}$ gauge field** ✓



$Non-zero$ BAU

Inflation





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Majoron interactions from anomaly

Schemas

$$-\mathcal{L}_{\rm int} \supset \frac{\lambda}{\sqrt{2}} f_a e^{i\frac{a}{f_a}} \Phi^T i\tau_2 \Delta^\dagger \Phi + {\rm h.c..}$$

$$\Delta \to \Delta e^{-i\frac{a}{f_a}}$$

$$-\mathcal{L}_{\rm Yukawa} = y_{\alpha\beta} \overline{\ell_L^{\alpha c}} i\tau_2 \Delta' e^{i\frac{a}{f_a}} \ell_L^\beta + \text{h.c.}$$

$$-\mathcal{L}_{\rm Yukawa} = y^E_{\alpha\beta} \overline{\ell_L^{\alpha'}} H e^{\frac{ia}{2f_A}} E_R^\beta + \text{h.c.}$$

$$\left.\begin{array}{l} \ell_L \to e^{\frac{-ia}{2f}} \ell_L \\ E_R \to e^{\frac{-ia}{2f}} E_R \end{array}\right\} \longrightarrow$$

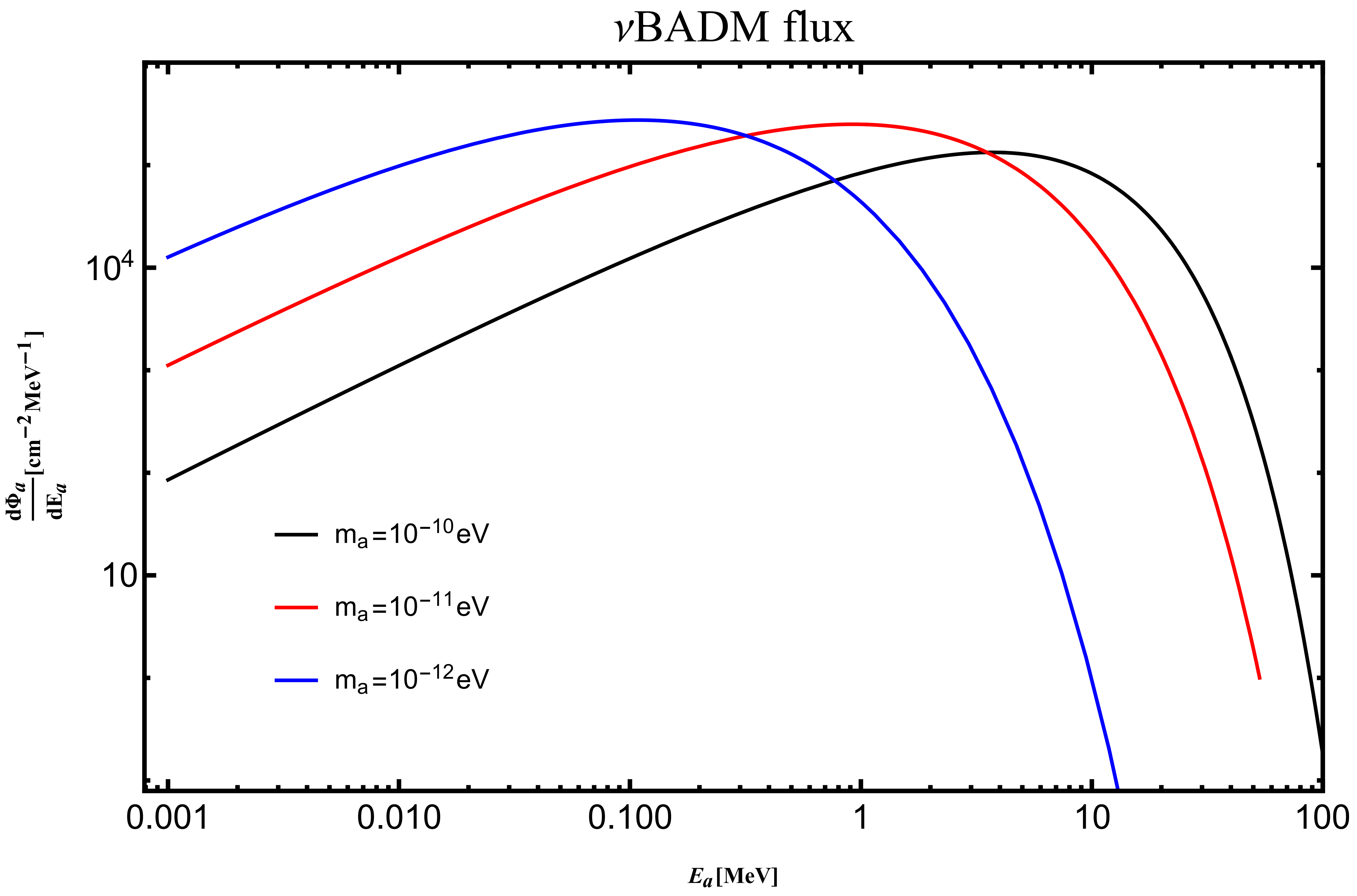
$$\mathcal{L} \to \mathcal{L} - \frac{a}{2f} \partial_\mu \left(\overline{\ell_L} \gamma^\mu \ell_L + \overline{E_R} \gamma^\mu E_R \right)$$

$$= \mathcal{L} - \frac{a}{2f} \partial_\mu J^L_\mu$$

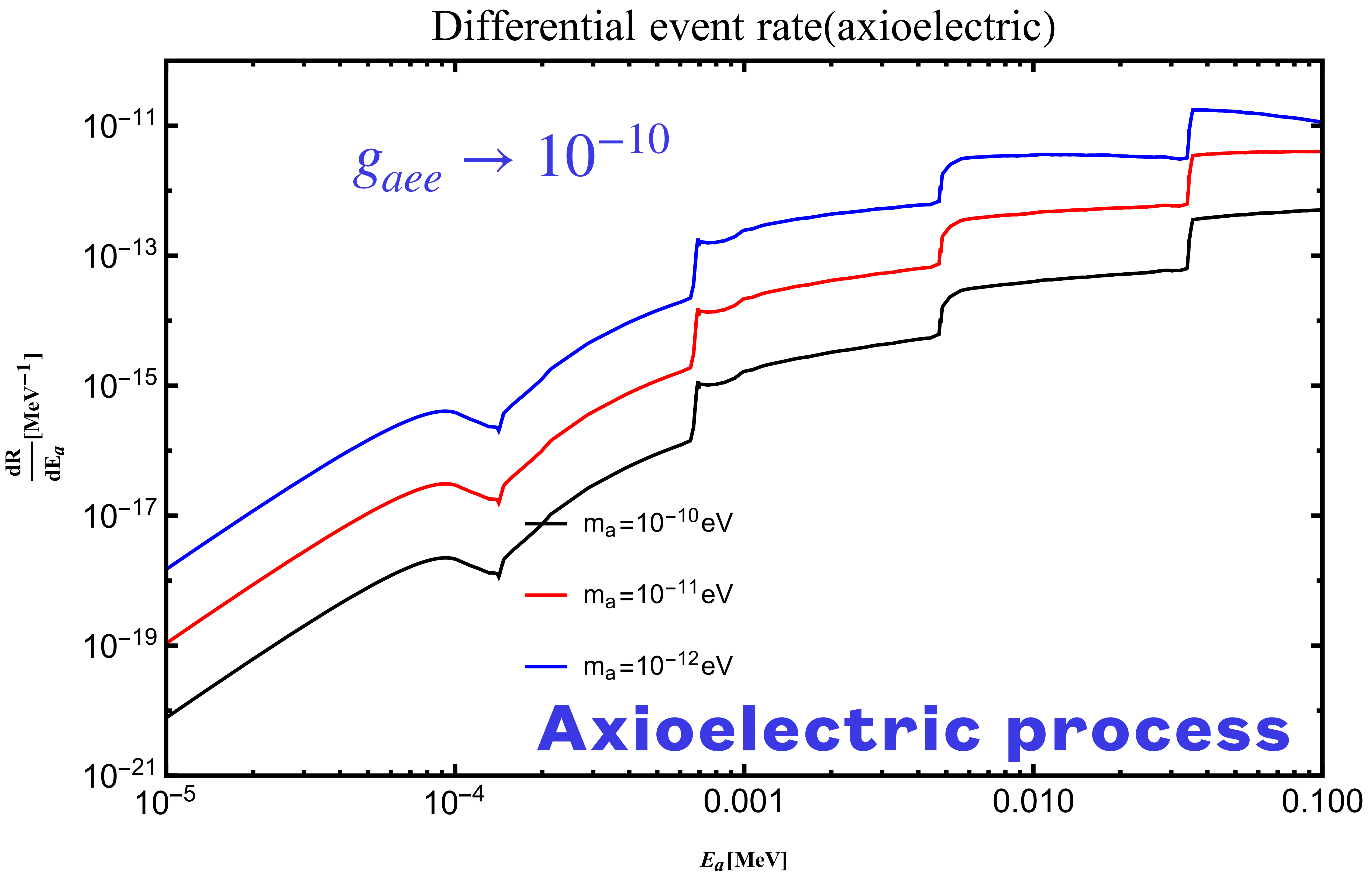
$$= \mathcal{L} + \frac{a}{2f} \frac{N_f}{32\pi^2} \left(g^2 W^a_{\mu\nu} \widetilde{W}^{\mu\nu,a} - g'^2 B_{\mu\nu} \widetilde{B}^{\mu\nu} \right)$$

Direct detections of Majoron DM

Boosted Majoron by supernova ν



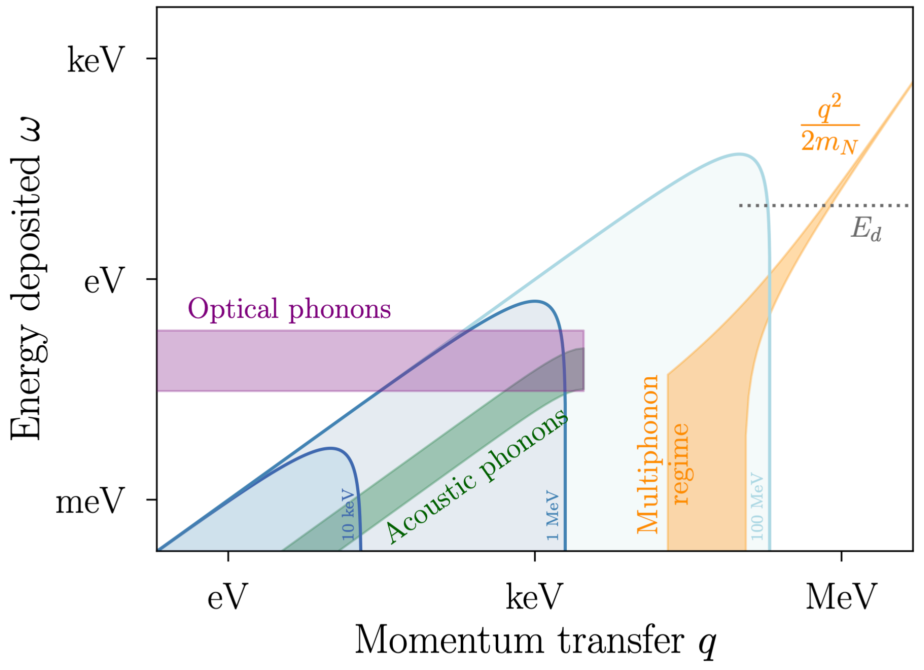
Differential event rate



Direct detections of Majoron DM

Direct detections in condensed matter systems

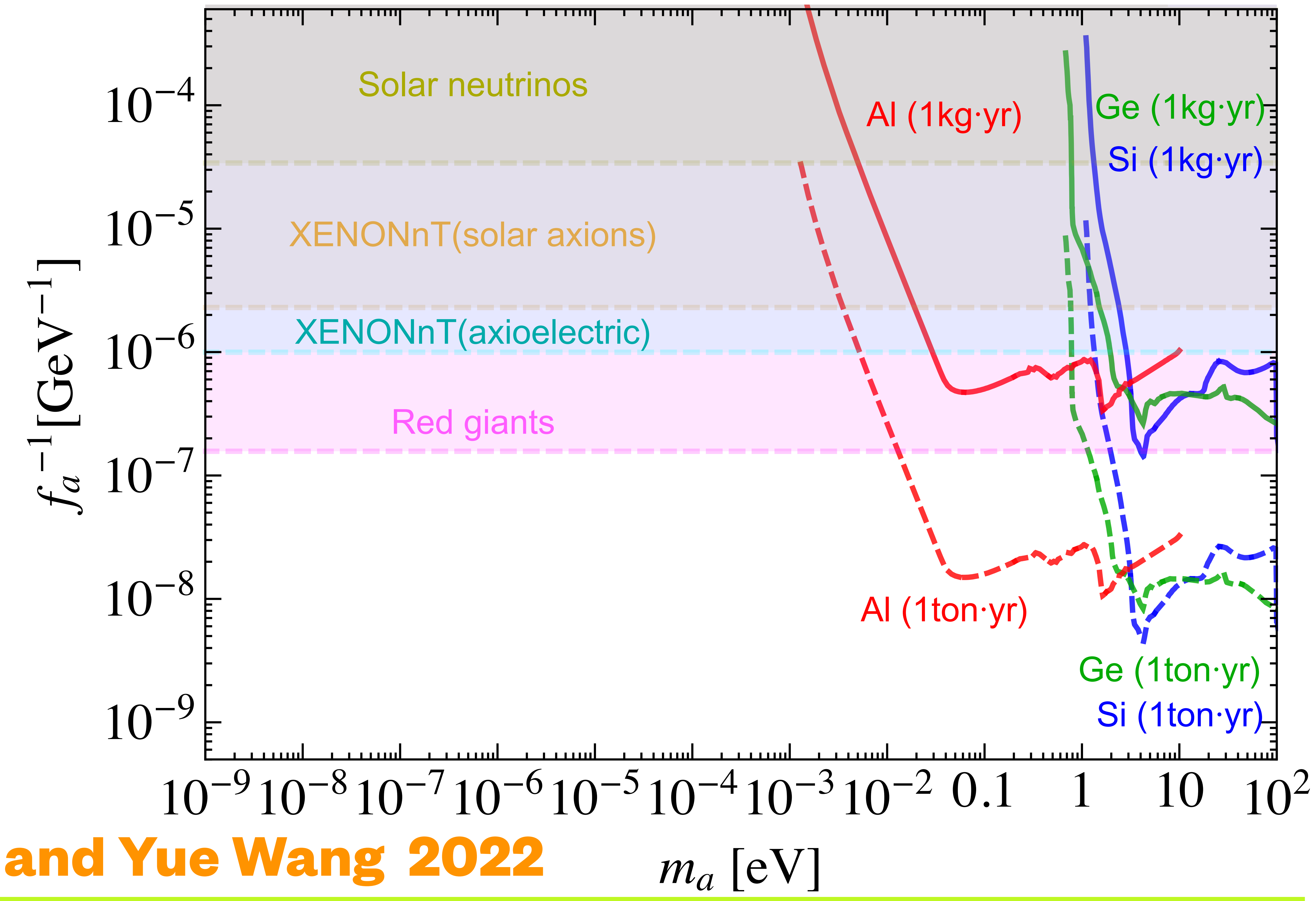
DM mass	DM energy or momentum	CM scale
50 MeV	$p_\chi \sim 50$ keV	zero-point ion momentum in lattice
20 MeV	$E_\chi \sim 10$ eV	atomic ionization energy
2 MeV	$E_\chi \sim 1$ eV	semiconductor band gap
100 keV	$E_\chi \sim 50$ meV	optical phonon energy



$$R \sim \frac{1}{\rho}\frac{\rho_a}{m_a}\frac{3m_a^2}{4m_e^2}\frac{g_{aee}^2}{e^2}\langle n_e \sigma_{abs} v_{rel}\rangle_\gamma$$

$$\langle n_e \sigma_{abs} v_{rel}\rangle_\gamma = -\frac{\mathrm{Im}\Pi(\omega)}{\omega}$$

Combined Constraints



Absorption rate for photon in material

✳with M. Jin, H.J. Li, Y.Q. Peng and Yue Wang 2022

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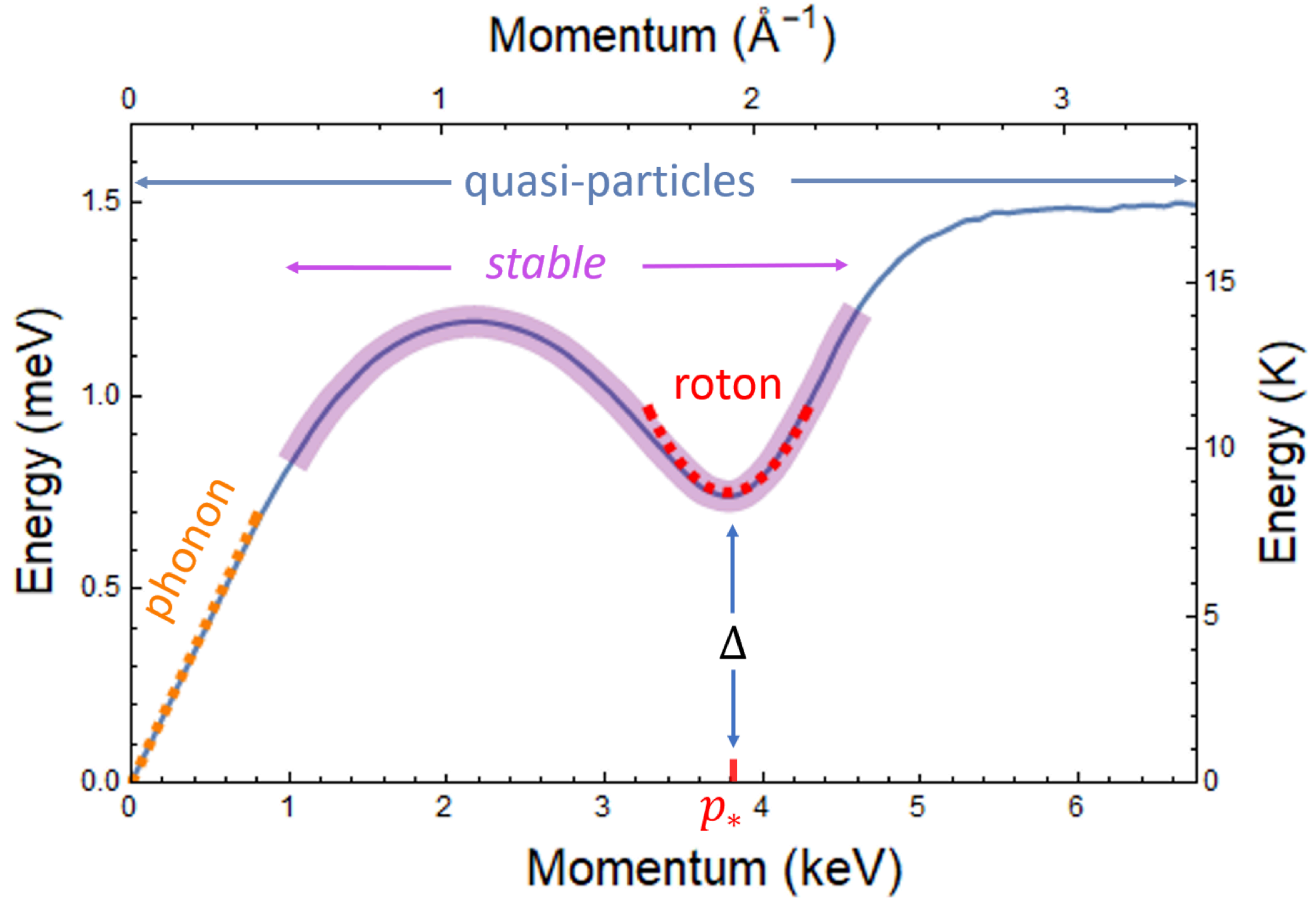
Detecting light DM using superfluid

Phonon (quasiparticle) in Superfluid Helium-4： **A Goldstone-like particle from the spontaneous breaking of the U(1) symmetry as well as the breaking of the boosts and the time translations in the superfluid He-4.**



Action of phonon field

$$S_{int} \sim \int d^4x \sqrt{\frac{\mu}{\bar{n}}} c_s \left[\left(\frac{\mu^2}{2} \frac{db}{d\mu} + \mu b \right) \dot{\pi} F^{0\rho} F^0{}_\rho - \mu b \partial_j \pi F^{ij} F_{0i} + \frac{b}{2} \sqrt{\frac{\mu}{\bar{n}}} c_s \partial_\mu \pi \partial_\nu \pi F^{\mu\rho} F^\nu{}_\rho \right]$$

Phonon-photon conversion in external electric field

- A. Caputo, A. Esposito, E. Geoffray, A. D. Polosa, and S. Sun, Phys. Lett. B 802, 135258 (2020), arXiv:1911.04511 [hep-ph].

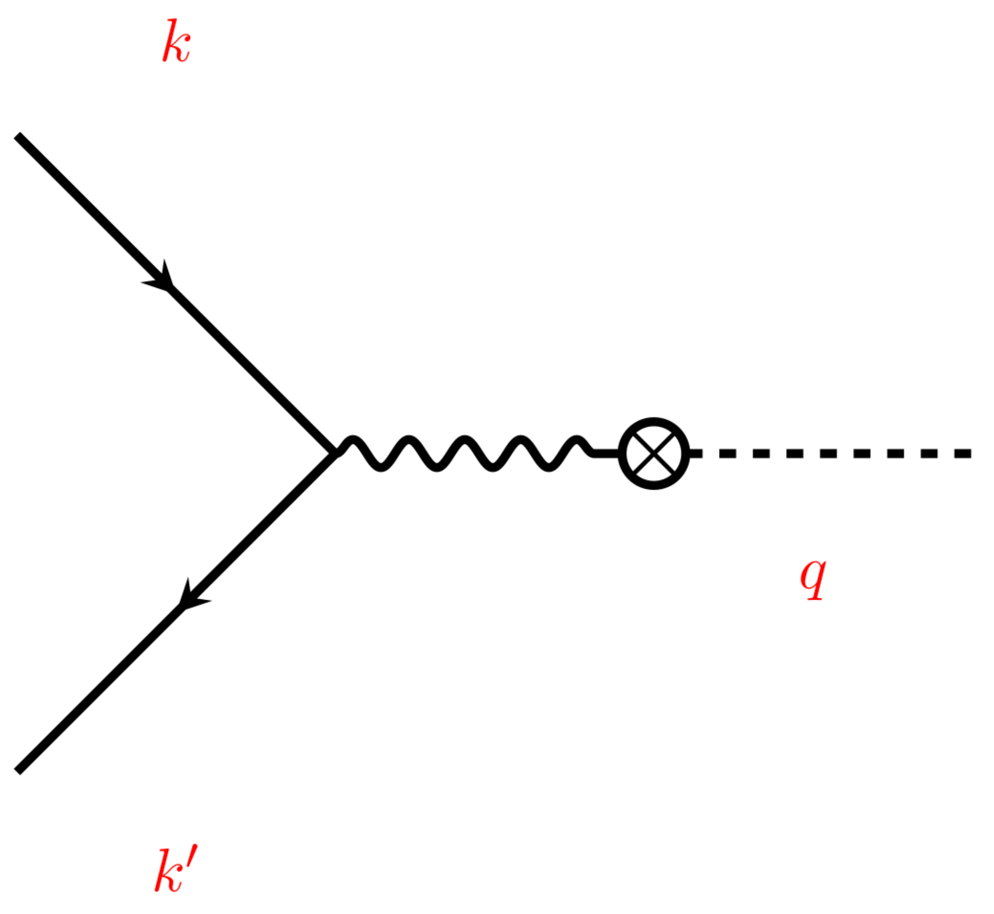
DM electromagnetic form factors in superfluid

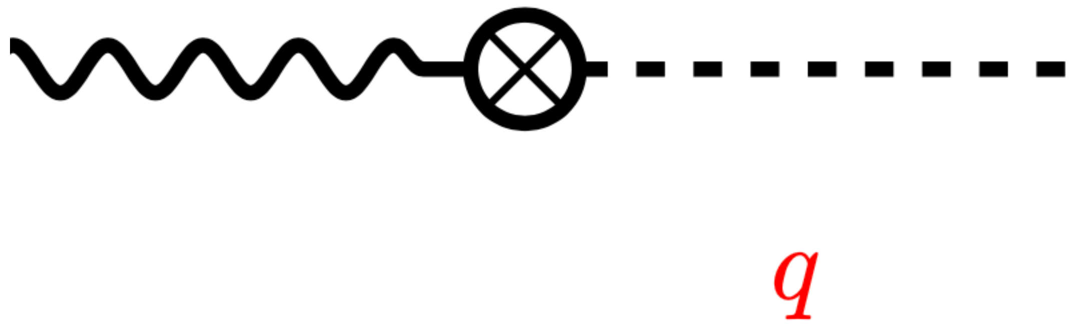
Lagrangian:

$$S_{\rm eff} = \int d^4x \Big[\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - \alpha\bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu} - \beta\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} - \frac{\lambda}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} - \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}g_{a\gamma\gamma'}aF_{\mu\nu}\tilde{F}'^{\mu\nu} + {\rm H.c.}$$
$$+\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}a(X)F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}b(X)F^{\mu\rho}F^{\nu}_{\rho}\partial_\mu\phi\partial_\nu\phi\Big],$$

α: charge radius; β: Anapole moment; λ: magnetic moment.

Feynman diagram for DM-Helium scattering:



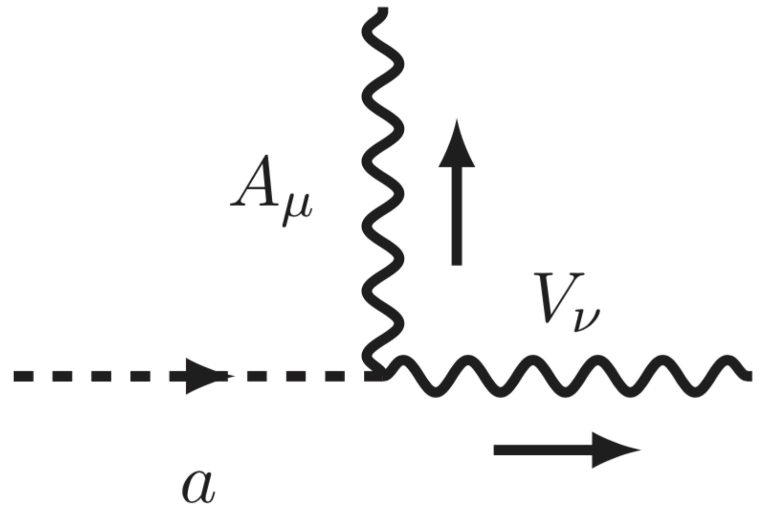


$$= i\frac{\alpha_E\bar{n}}{m_{He}c_s}\sqrt{\frac{m_{He}}{\bar{n}}}E_i\omega_q(\omega_q\delta_i^\mu + q_i\delta_0^\mu),$$

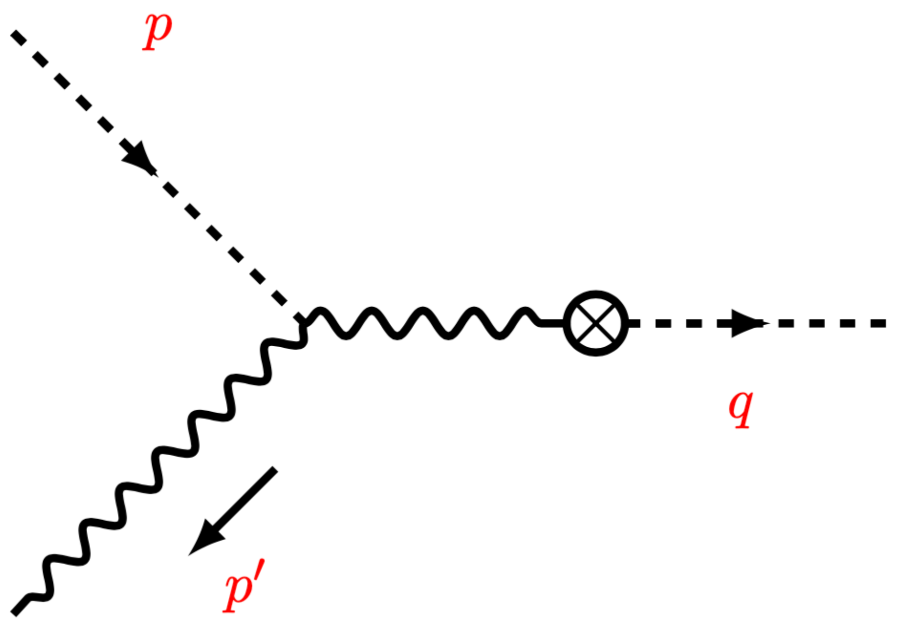
Detecting ALP using superfluid

$a\gamma\gamma'$ **coupling: (1) No DD constraint on this coupling ; (2) There are already strong constraint on** $g_{a\gamma\gamma}$.

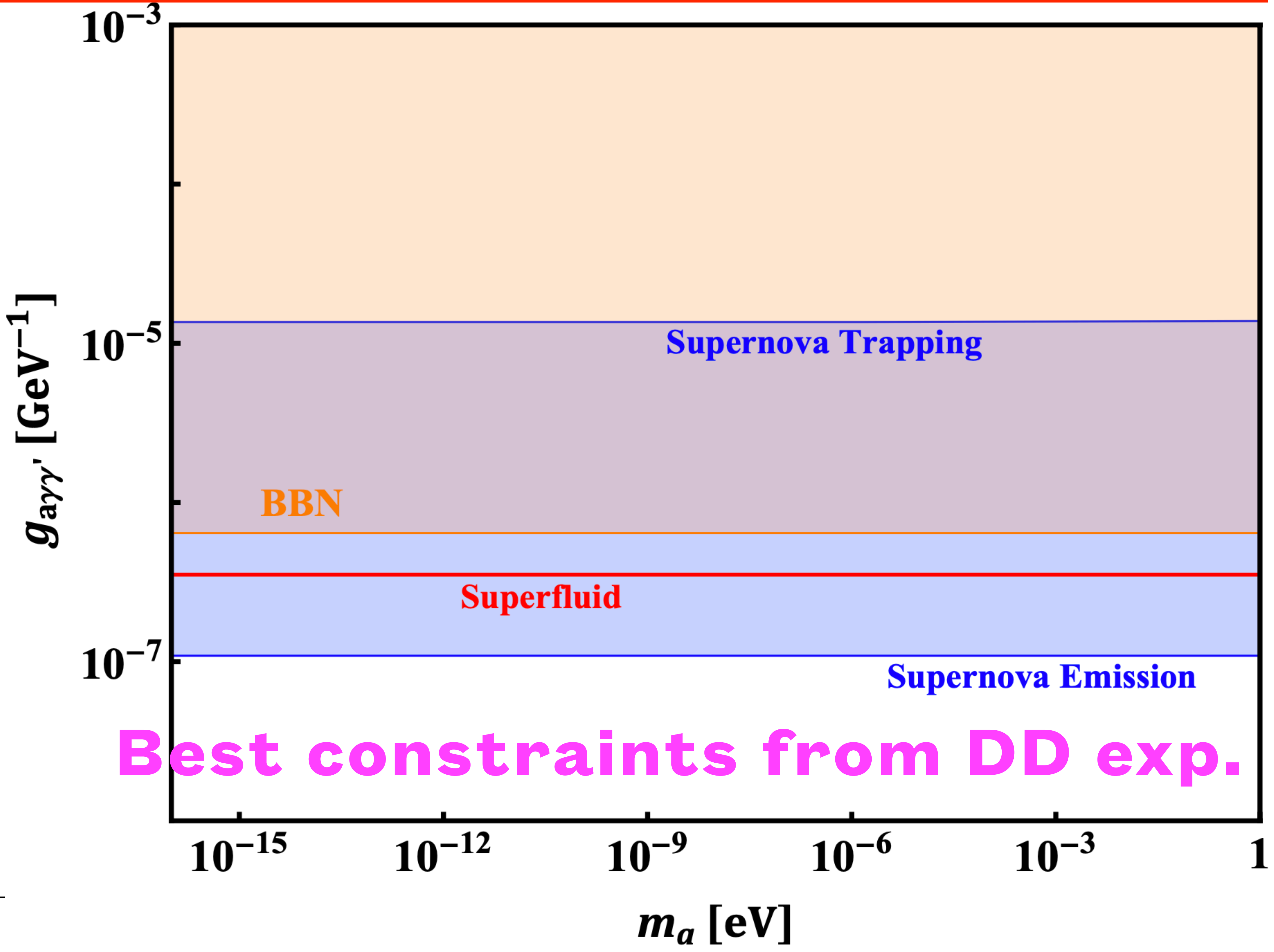
With S. Sun, X. Wang, and C.H. Xie, 2024



$$= g_{a\gamma\gamma'}\epsilon^{\mu\alpha\nu\beta}q_\mu p'_\nu,$$



$$\frac{d\Gamma}{d\omega} = \frac{g^2_{a\gamma\gamma'}\bar{n}\alpha_E^2}{16\pi m_a \omega^2 m_{He} E v_a}\frac{|\mathbf{E}|^2\omega^2}{c_s^2}\Bigg\{(\cos^2\theta_E - c_s^2)\omega^2\left(1-\frac{1}{c_s^2}\right)\Bigg[E^2(1-v_a^2) + 2E\omega\left(\frac{v_a}{c_s}\cos\theta - 1\right) + \omega^2\left(1-\frac{1}{c_s^2}\right)\Bigg] - \omega^2\left(1-\frac{1}{c_s^2}\right)(E\cos\theta_E - |\mathbf{p}|^2 c_s\cos\theta_a)^2 - (\cos^2\theta_E - c_s^2)\left[\omega\left(E - \frac{|\mathbf{p}|}{c_s}\cos\theta\right) - \omega^2\left(1-\frac{1}{c_s^2}\right)\right]^2\Bigg\}.$$



Summary

Issue-I:

Interesting phenomenologies can be induced by axion-like particles, such as dark matter and the baryon asymmetry of the universe.

Issue-II

How to directly detection axion-like particles is an open question. In addition to the traditional cavity experiment, we explore possible strategy that may detect exotic ALP interactions.

Thank you for your attention!