Leptoflavorgenesis

Kyohei Mukaida

KEK

Based on **2111.03082**, (2208.03237)

Collaboration with V.Domcke, K.Kamada, K. Schmitz, M.Yamada

1.

Introduction

Introduction

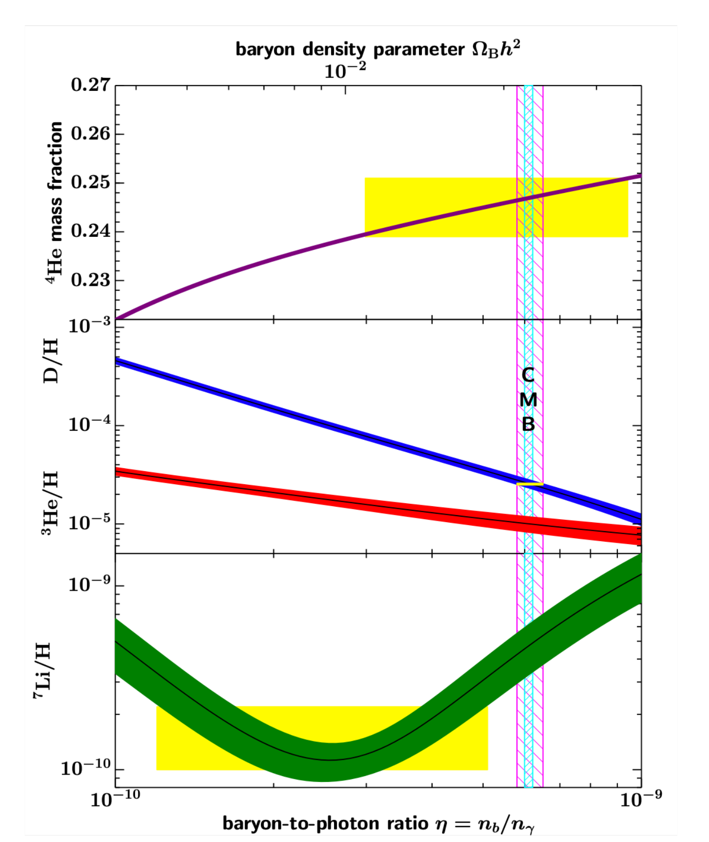
Cosmic Inflation v.s. Baryon Asymmetry

- **Inflation**: accelerated expansion of Universe
  - **Solve** horizon/flatness problems + **Provide** density perturbations.
  - Dilute unwanted relics, **but also baryons**.

- **Baryon asymmetry** of the Universe (BAU)
  - Baryon to photon ratio → $\eta = \frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$
  - Baryon asymmetry

Baryon # Anti-Baryon #

$$10^{10} + 1 \quad - \quad 10^{10} \quad = \quad 1$$



[Particle Data Group]

➡ **Baryogenesis** (i.e., production of BAU) after inflation

Introduction

Sakharov's conditions

- Conditions on Hamiltonian (**H**) and state (**ρ**)

  - Violation of **Baryon charge**

Heisenberg eq. $\dot{Q}_B = i[H, Q_B]$ ⟶ $[H, Q_B] \neq 0$

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  - Violation of **C and CP**

$$\mathrm{Tr}\{\rho \dot{Q}_B\} = i\,\mathrm{Tr}\{\rho[H, Q_B]\}$$
$$= i\,\mathrm{Tr}\{CP\rho CP^{-1}[CPHCP^{-1}, -Q_B]\}$$

→ $[H, CP] \neq 0$ or $[\rho, CP] \neq 0$

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  - Departure from **thermal equilibrium**

$\mathrm{Tr}\{\rho \dot{Q}_B\} = i\,\mathrm{Tr}\{\rho[H, Q_B]\} = i\,\mathrm{Tr}\{Q_B[\rho, H]\}$ → $[H, \rho] \neq 0$

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- **Chiral anomaly**

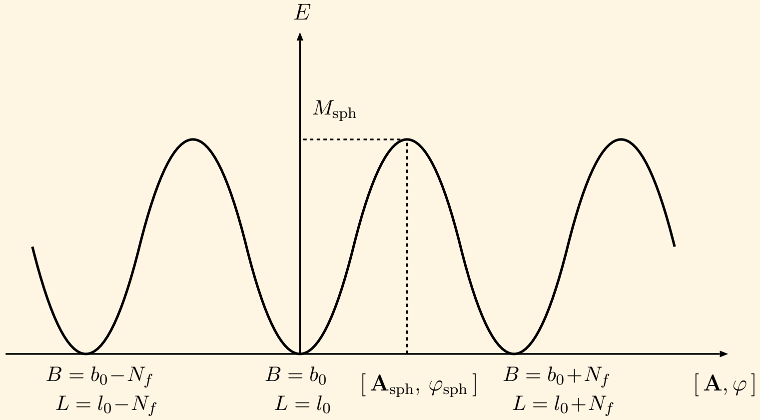
$$\partial_\mu J^\mu_B = \frac{3}{32\pi^2}\left(g_2^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - g_Y^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

Baryon # **SU(2)$_w$** Chern-Simons

- Instanton @ vacuum

$$\Gamma_{\text{inst}} \propto e^{-16\pi^2/g^2} \sim \mathcal{O}(10^{-165})$$

No effect within the current age of Universe



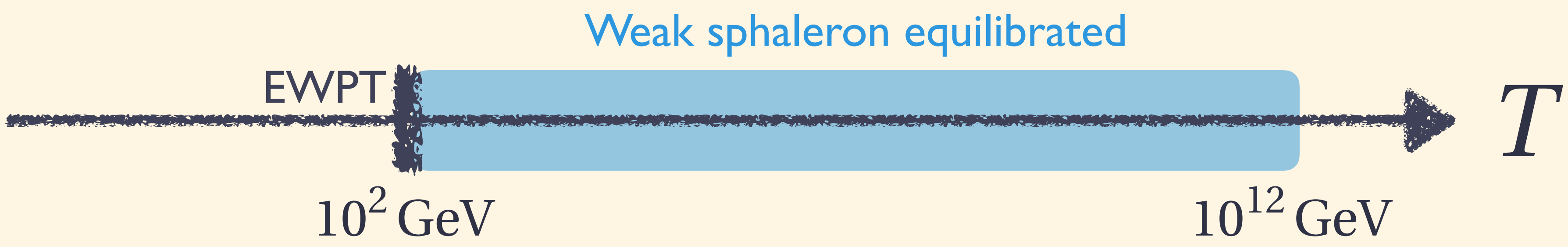
- **Weak sphaleron** at high T

$$\frac{\Gamma_{\text{ws}}}{T^4} = \begin{cases} (8.0 \pm 1.3) \times 10^{-7} & \text{for} \quad T \gtrsim 161\text{GeV} \\ e^{-(147.7\pm1.9)+(0.83\pm0.01)\frac{T}{\text{GeV}}} & \text{for} \quad T \lesssim 161\text{GeV} \end{cases}$$

[See e.g., Boedeker, Buchmuller 2009.07294]

Introduction

Weak sphaleron & Baryogenesis



$\mathrm{U}(1)_B$ | ~~$\mathrm{U}(1)$~~$_B$ →

$$\mathrm{Tr}\left\{e^{-\beta H}Q_B\right\} = \mathrm{Tr}\left\{CPTe^{-\beta H}CPT^{-1}CPTQ_BCPT^{-1}\right\}$$
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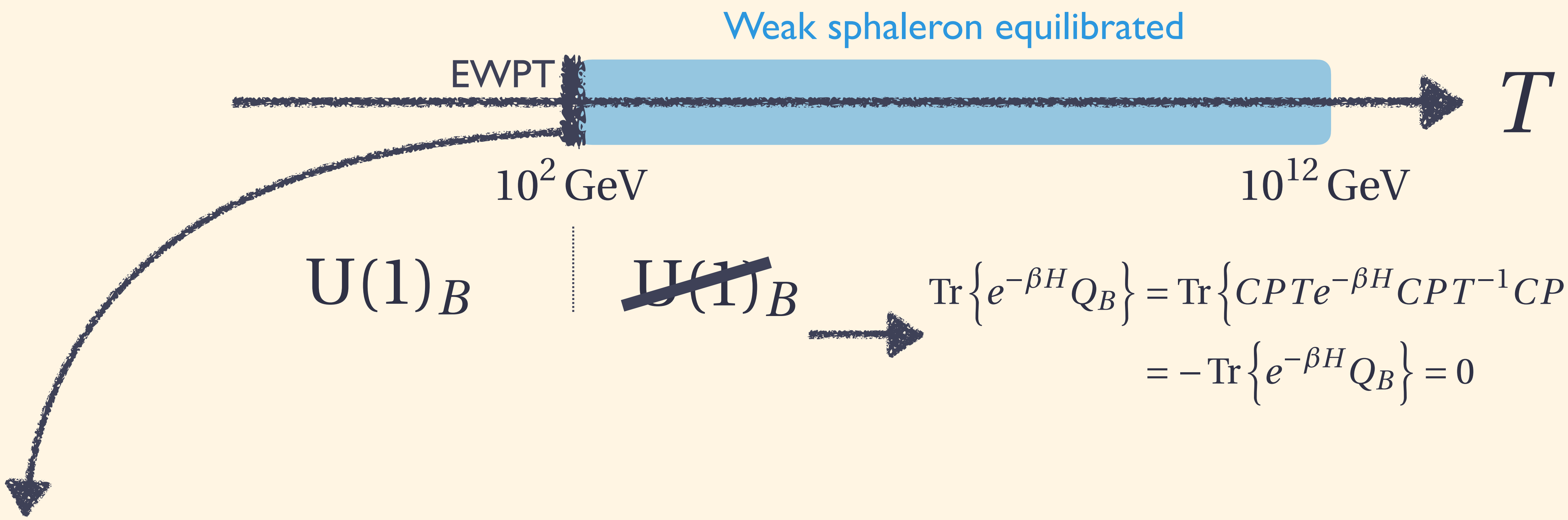

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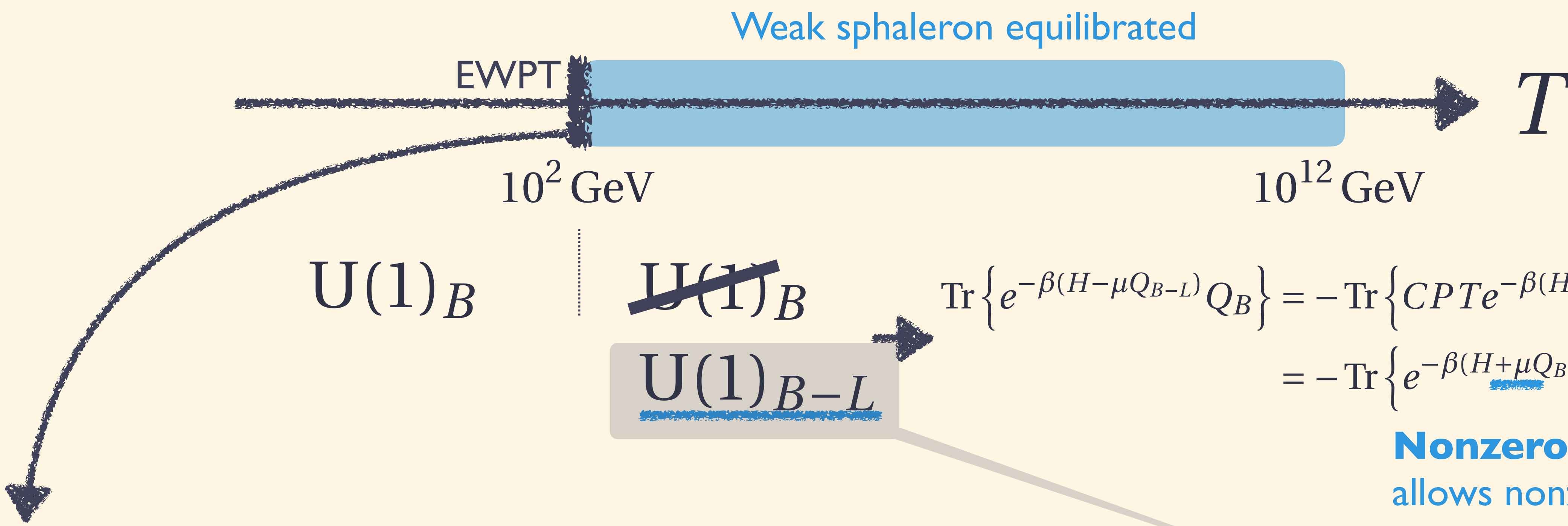
  - We need a new source of CP violation & strong EWPT

Weak sphaleron & Baryogenesis



$$\mathrm{Tr}\left\{e^{-\beta(H-\mu Q_{B-L})}Q_B\right\} = -\mathrm{Tr}\left\{CPT e^{-\beta(H-\mu Q_{B-L})}CPT^{-1}Q_B\right\}$$
$$= -\mathrm{Tr}\left\{e^{-\beta(H+\mu Q_{B-L})}Q_B\right\}$$

Nonzero Q_{B-L}
allows nonzero Q_B

Sakharov's conditions
should be applied to B-L!

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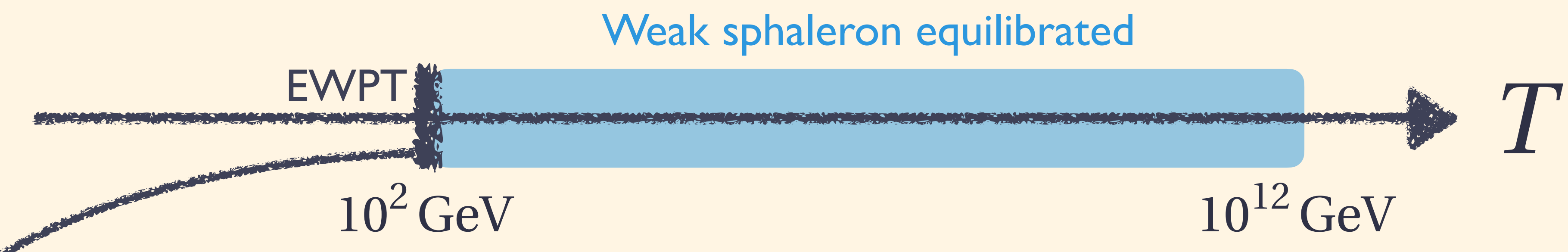

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  - We need a new source of CP violation & strong EWPT
- Leptogenesis (B-L genesis)
  - **Out-of-equil. CPV** decay of the lightest **Majorana** RHν
  - Neutrino mass ← Right-handed Majorana neutrino

[Fukugita, Yanagida Phys.Lett.B 174 (1986)]

ν-Yukawa | Majorana mass

$$h_{\alpha f}\overline{N}_{R\alpha}L_{Lf}\Phi - \frac{1}{2}M_\alpha N_{R\alpha}N_{R\alpha} + \mathrm{H.c.}$$
-1 $+1$

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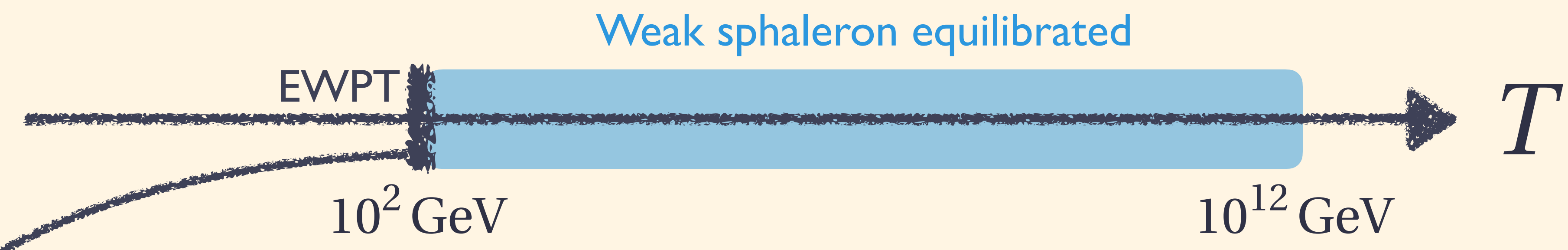

$U(1)_B$ ~~$U(1)_B$~~

$U(1)_{B-L}$

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

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Nonzero leptonflavor Q
allows nonzero Q_B

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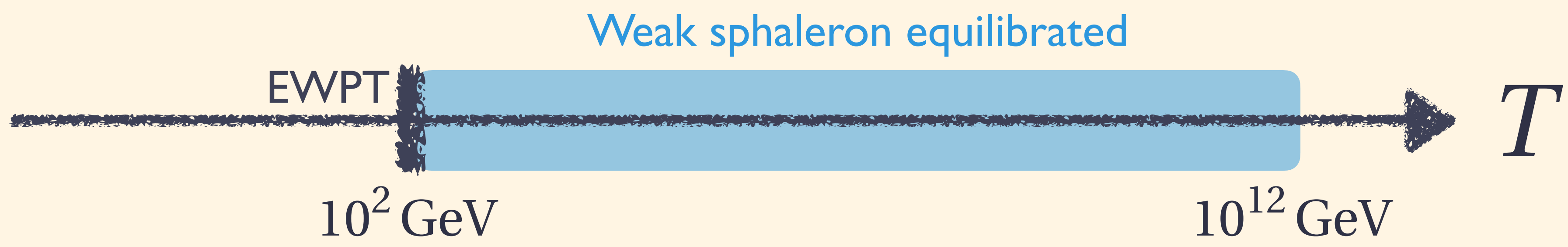
2.

Chemical equilibrium

w/ NLO corrections

Chemical equilibrium in the early Universe



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?

$$\mathrm{Tr}\left\{e^{-\beta(H-\mu Q_C)}Q_B\right\} = -\mathrm{Tr}\left\{CPTe^{-\beta(H-\mu Q_C)}CPT^{-1}Q_B\right\}$$
$$= -\mathrm{Tr}\left\{e^{-\beta(H+\mu Q_C)}Q_B\right\}$$

$(C = B-L, L_e-L_\mu, L_\mu-L_\tau)$

Nonzero Q_C
allows nonzero Q_B

- What is the conversion factors from Q_C to Q_B?
  - **Leptogenesis** ← chemical transport under ideal gas apprx.
  - **Leptoflavorgenesis** ← chemical transport beyond ideal gas apprx.

Chemical equilibrium

SM global symmetry: $U(1)_{B-L} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau} \simeq U(1)_{B/3-L_e} \times U(1)_{B/3-L_\mu} \times U(1)_{B/3-L_\tau}$

$$\rho = \frac{1}{Z} e^{-\beta\left(H - \sum_f \mu_{\Delta_f} Q_{\Delta_f} - \mu_Y Q_Y\right)} \quad \text{w/} \quad Q_{\Delta_f} = \frac{Q_B}{3} - Q_{L_f}$$

Q_Y: hyper charge

Q_B: baryon charge

Q_{L_f}: flavored lepton charge

Chemical equilibrium

Chemical equilibrium @ LO

- The standard conversion factor of B-L into B.

$$\rho = \frac{1}{Z} e^{-\beta\left(H - \sum_f \mu_{\Delta_f} Q_{\Delta_f} - \mu_Y Q_Y\right)}$$ w/ $Q_{\Delta_f} = \frac{Q_B}{3} - Q_{L_f}$

Q_Y: hyper charge; Q_B: baryon charge; Q_{L_f}: flavored lepton charge

- Ideal gas approximation (i.e., LO)

Free Fermi/Bose gas

$$f_\alpha = \frac{g_\alpha}{e^{\beta(p-\mu_\alpha)} \pm 1} \qquad f_{\bar{\alpha}} = \frac{g_\alpha}{e^{\beta(p+\mu_\alpha)} \pm 1} \longrightarrow q_\alpha = n_\alpha - n_{\bar{\alpha}} \simeq \begin{cases} \frac{g_\alpha}{6} \mu_\alpha T^2 \\ \frac{g_\alpha}{3} \mu_\alpha T^2 \end{cases}$$ w/ $q_\alpha \equiv \frac{\langle Q_\alpha \rangle}{\mathrm{vol}(\mathbb{R}^3)}$

e.g., electron $g_e = 1, \; \mu_e = \mu_Y - \mu_{\Delta_1}$

Neutrality condition $\langle Q_Y \rangle = 0$

$$0 = \sum_f \left(\mu_{q_f} + 2\mu_{u_f} - \mu_{d_f} + \mu_{e_f} - \mu_{\ell_f}\right) + 2\mu_H \longrightarrow q_B = \frac{14}{33} \sum_f \frac{\mu_{\Delta_f}}{3} T^2 \qquad q_{B-L} \equiv \sum_f q_{\Delta_f} = \frac{79}{66} \sum_f \frac{\mu_{\Delta_f}}{3} T^2$$

"**The**" conversion factor $$q_B = \frac{28}{79} \sum_f q_{\Delta_f} = \frac{28}{79} q_{B-L}$$

Lepton flavor never contributes to B?

Chemical equilibrium

Chemical equilibrium beyond ideal gas

- The conversion factor into B beyond ideal gas

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Q_Y → hyper charge; Q_B → baryon charge; Q_{L_f} → flavored lepton charge

- **Thermodynamic potential** w/ lepton Yukawa corrections

Pressure as a grand potential

$$p \equiv \frac{T \ln Z}{V} \quad \rightarrow \quad q_\bullet = \frac{\langle Q_\bullet \rangle}{V} = \frac{\partial p}{\partial \mu_\bullet} \quad \longrightarrow \quad q_B = \left.\frac{\partial p}{\partial \mu_B}\right|_{\mu_{B+L}=0, q_Y=0}, \quad q_{\Delta_f} = \left.\frac{\partial p}{\partial \mu_{\Delta_f}}\right|_{\mu_{B+L}=0, q_Y=0}$$

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w/ $\mu_B = \mu_{B+L} + \sum_f \mu_{\Delta_f}/3, \quad \mu_{L_f} = \mu_{B+L} - \mu_{\Delta_f}$

Send $\boldsymbol{\mu_{B+L}}$ **to zero** at the end of computation

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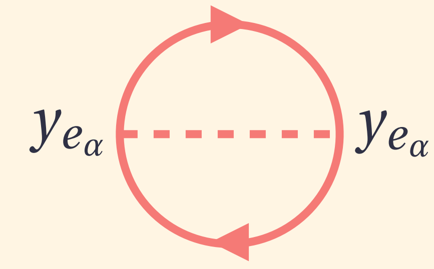
$$p = \frac{1}{3}\mu_B^2 T^2 + \frac{1}{4}\sum_\alpha \mu_{L_\alpha}^2 T^2 + \frac{1}{3}\left(\mu_B - \sum_\alpha \mu_{L_\alpha}\right)\mu_Y T^2 + \frac{11}{12}\mu_Y^2 T^2 - \frac{1}{16\pi^2}\frac{T^2}{2}\sum_\alpha y_{e_\alpha}^2 \left(-3\mu_Y \mu_{L_\alpha} + 2\mu_{L_\alpha}^2\right)$$

Ideal gas approximation

lepton Yukawa corrections

Laine, Shaposhnikov 9911473
KM, K.Schmitz, M.Yamada 2111.03082

$$q_B \simeq \left[\frac{28}{79} + \mathcal{O}(y_{e_f}^2)\right]\sum_f q_{\Delta_f} + \frac{47}{632\pi^2}\sum_f y_{e_f}^2 q_{\Delta_f}$$



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w/ $\mu_B = \mu_{B+L} + \sum_f \mu_{\Delta_f}/3, \quad \mu_{L_f} = \mu_{B+L} - \mu_{\Delta_f}$

Send μ_{B+L} **to zero** at the end of computation

- **Baryon charge from lepton-flavor charge** [**KM**, K.Schmitz, M.Yamada 2111.03082]

Corrections from Higgs VEV

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w/ $x_{\rm Sp} \equiv \left.\frac{\phi}{T}\right|_{\text{Sphaleron dec.}} \simeq 1.3$

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0.03

w/ $x_{\rm Sp} \equiv \left.\frac{\phi}{T}\right|_{\rm Sphaleron\ dec.} \simeq 1.3$

Current baryon density w/ B-L = 0

$$\frac{Y_B}{9 \times 10^{-11}} \simeq \frac{y_\tau^2}{10^{-4}} \frac{Y_{L_e + L_\mu - 2L_\tau}}{9 \times 10^{-5}} + \frac{y_\mu^2}{3.7 \times 10^{-7}} \frac{Y_{L_e + L_\tau - 2L_\mu}}{2.4 \times 10^{-2}}$$

➡ Relatively **large asymmetry** is needed to explain BAU.

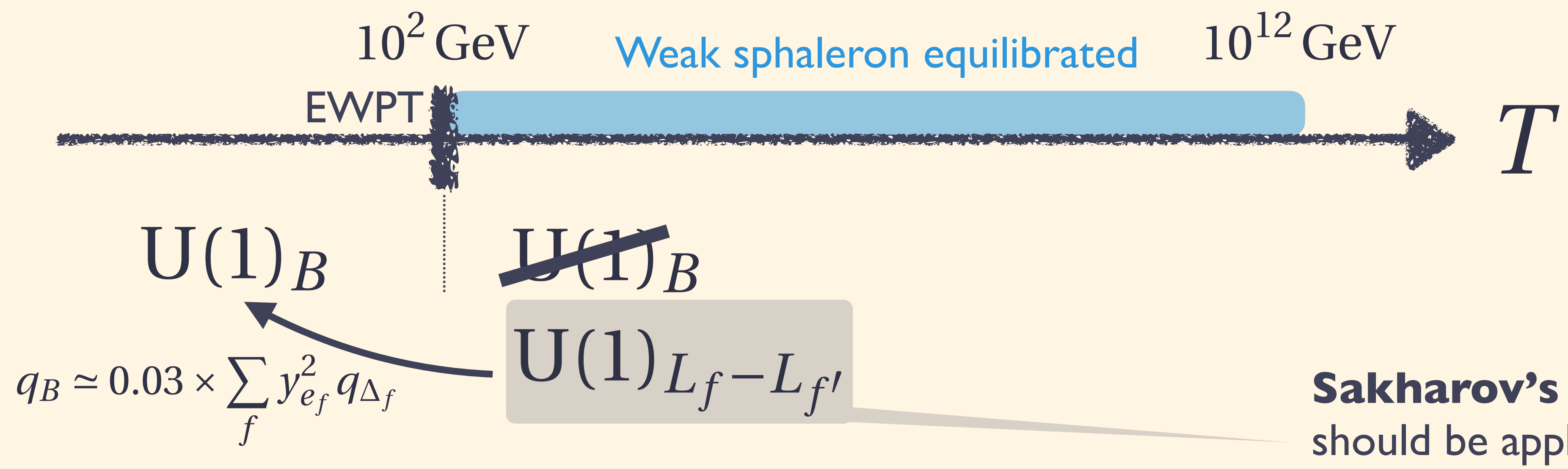
3.

Leptoflavorgenesis via cLFV

Leptoflavorgenesis via cLFV

cLFV & Leptoflavorgenesis

[**KM**, K.Schmitz, M.Yamada 2111.03082]



Sakharov's conditions should be applied.

Leptoflavorgenesis via cLFV

cLFV & Leptoflavorgenesis

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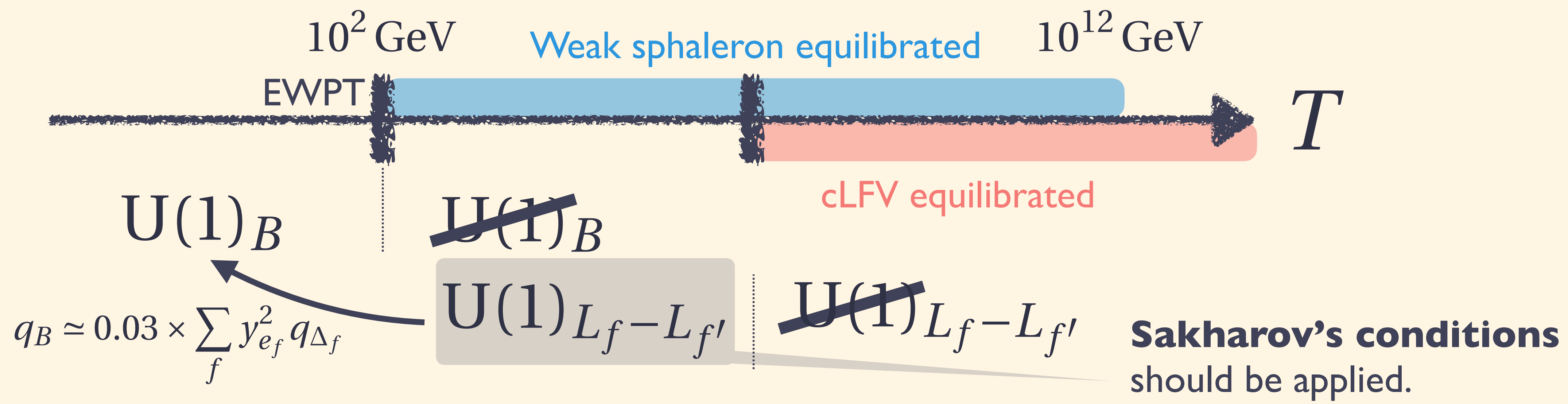

- **Equilibration of cLFV interactions**
  - E.g., μ to eγ

$$\frac{C_{\ell\gamma}^{ff'}}{\Lambda^2} \frac{v}{\sqrt{2}} \bar{\ell}_f \sigma^{\mu\nu} P_R \ell_{f'} F_{\mu\nu}$$

✓ Current bound [Future prospect]

$$\frac{\Lambda}{\sqrt{C_{\ell\gamma}^{\mu e}}} \gtrsim 6.7 \times 10^7 \ [1.0 \times 10^8] \ \mathrm{GeV}$$

Leptoflavorgenesis via cLFV

cLFV & Leptoflavorgenesis

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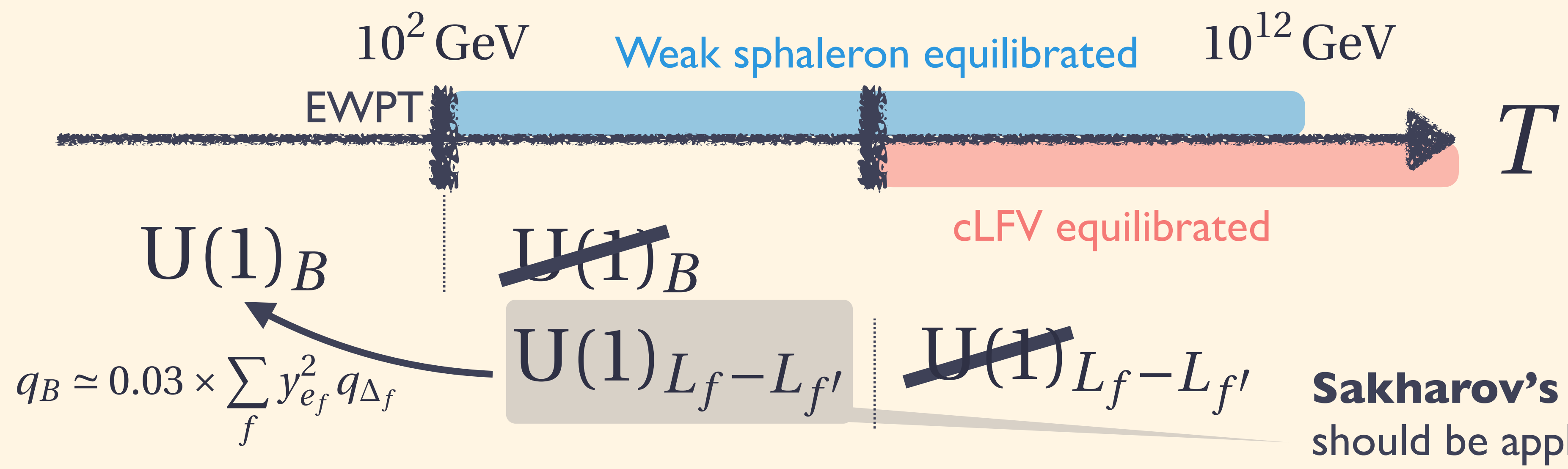

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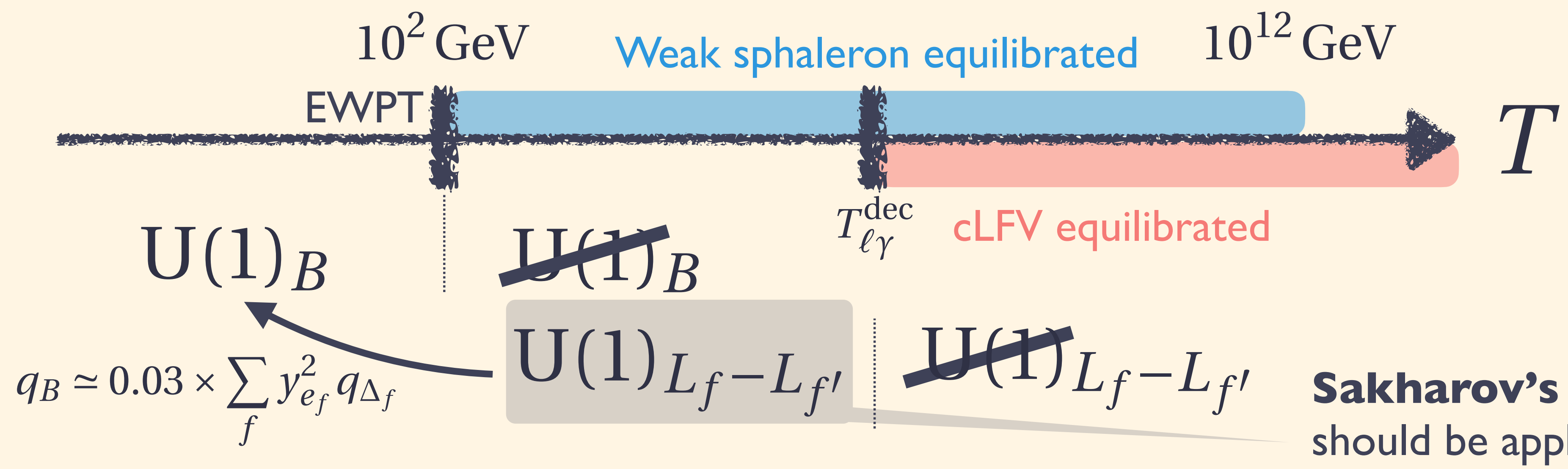

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$$\frac{\Lambda}{\sqrt{C_{\ell\gamma}^{\mu e}}} \gtrsim 6.7\times 10^7 \ [1.0\times 10^8]\ \mathrm{GeV}$$

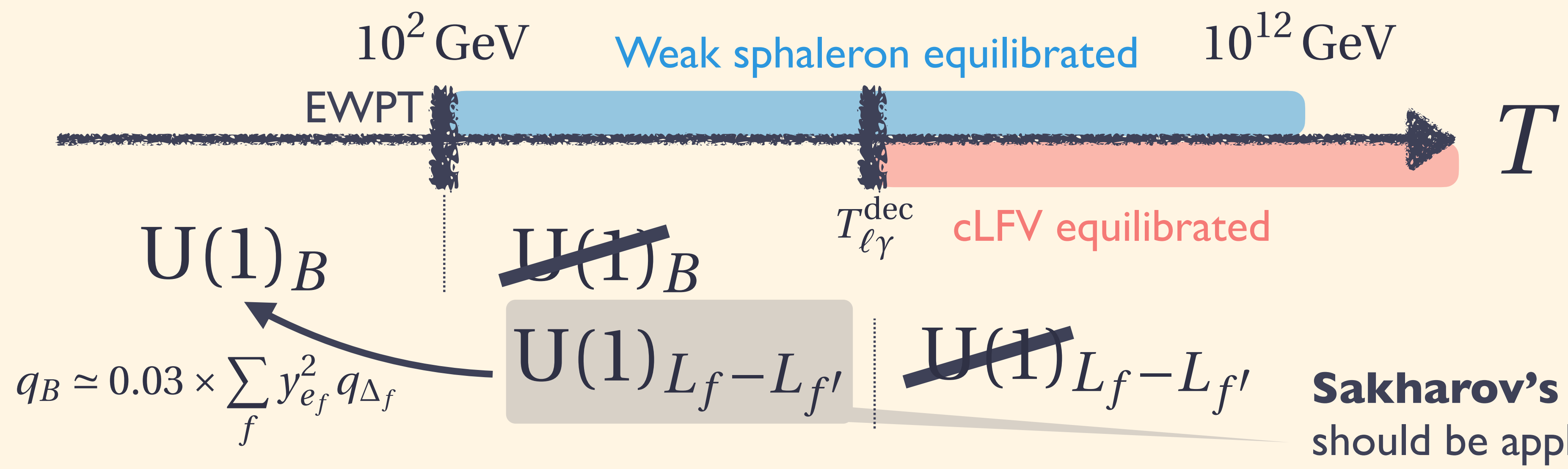
✓ Decoupling temperature of cLFV

$$T_{\ell\gamma}^{\rm dec} \sim 3\times 10^4\,\mathrm{GeV}\left(\frac{\Lambda/\sqrt{C_{\ell\gamma}}}{10^8\,\mathrm{GeV}}\right)^{4/3}$$

Leptoflavorgenesis via cLFV

cLFV & Leptoflavorgenesis

[**KM**, K.Schmitz, M.Yamada 2111.03082]



Sakharov's conditions should be applied.

- **Equilibration of cLFV interactions**
  - E.g., μ to eγ

$$\frac{C_{\ell\gamma}^{ff'}}{\Lambda^2}\frac{v}{\sqrt{2}}\bar{\ell}_f\sigma^{\mu\nu}P_R\ell_{f'}F_{\mu\nu} \xleftarrow{\text{EWPT}} \frac{2C_{\ell W}^{ff'}}{\Lambda^2}L_{Lf}^\dagger\sigma^{\mu\nu}e_{Rf'}W_{\mu\nu}\Phi \quad \frac{C_{\ell B}^{ff'}}{\Lambda^2}L_{Lf}^\dagger\sigma^{\mu\nu}e_{Rf'}B_{\mu\nu}\Phi$$

✓ Current bound [Future prospect]

$$\frac{\Lambda}{\sqrt{C_{\ell\gamma}^{\mu e}}} \gtrsim 6.7\times 10^7\ [1.0\times 10^8]\ \mathrm{GeV}$$

✓ Decoupling temperature of cLFV

$$T_{\ell\gamma}^{\rm dec} \sim 3\times 10^4\,\mathrm{GeV}\left(\frac{\Lambda/\sqrt{C_{\ell\gamma}}}{10^8\,\mathrm{GeV}}\right)^{4/3}$$

Observation of cLFV opens up **new baryogenesis** @T > 10^4 GeV !

Leptoflavorgenesis via cLFV

cLFV & Leptoflavorgenesis

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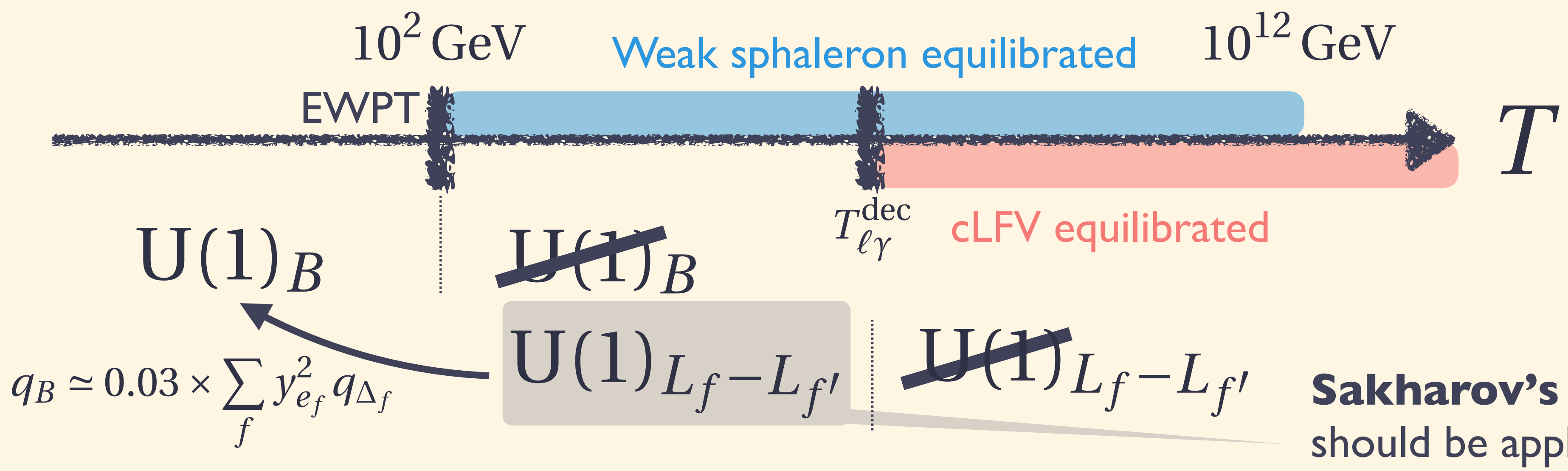


Sakharov's conditions should be applied.

- **Concrete realization of leptoflavorgenesis via cLFV?**
  - E.g., μ to eγ $\quad \frac{2C_{\ell W}^{ff'}}{\Lambda^2} L_{Lf}^{\dagger} \sigma^{\mu\nu} e_{Rf'} W_{\mu\nu} \Phi \quad \frac{C_{\ell B}^{ff'}}{\Lambda^2} L_{Lf}^{\dagger} \sigma^{\mu\nu} e_{Rf'} B_{\mu\nu} \Phi$

✓ Thermal leptoflavorgenesis → but, difficult to generate large asym.

✓ **Spontaneous leptoflavorgenesis**

(Almost) any shift symmetric coupling can do the job! E.g., $\theta_{\rm ALP}\,\partial \cdot J_{e_R}, \quad \theta_{\rm ALP}\, G_{\mu\nu}\tilde{G}^{\mu\nu}, \cdots$

✓ Affleck-Dine leptoflavorgenesis [J.March-Russell, H.Murayama, A.Riotto JHEP 11 (1999) 015]

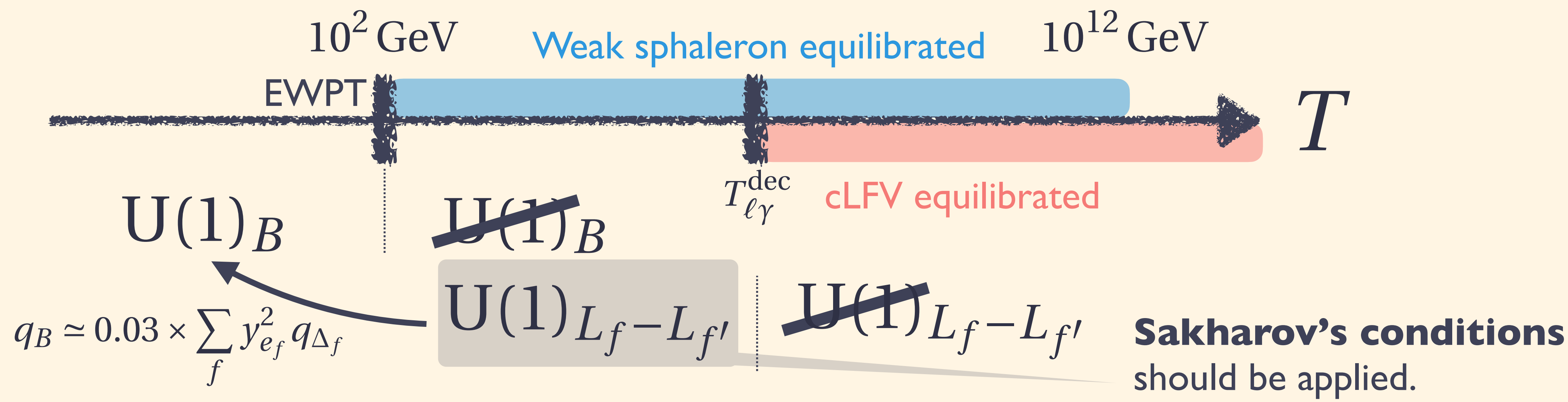
✓ **Wash-in leptoflavorgenesis**

…

Conclusions

Leptoflavorgenesis via cLFV

[**KM**, K.Schmitz, M.Yamada 2111.03082]



- Observation of cLFV → leptoflavorgenesis @ decoupling $T_{\rm cLFV}$
  - ✓ It can be effective at relative low T such as 10^4 GeV.
- Lepton-flavor asymmetry is enough (no need for B-L).
- **Large lepton-flavor asymmetry** is required.
  - ✓ QCD PT becomes the first order ? → gravitational wave? [Gao, Oldengott Phys.Rev.Lett. 128 (2022)]
  - ✓ Chiral plasma instabilities put constraints on τ-phobic case. [V.Domcke, K.Kamada, **KM**, K.Schmitz, M.Yamada 2208.03237]