Chiral asymmetry in the early Universe

Kyohei Mukaida

KEK

Based on **2111.03082, 2208.03237**

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

1.

Introduction

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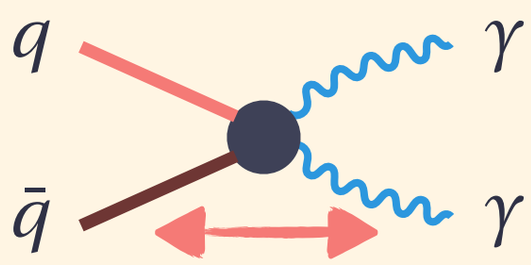
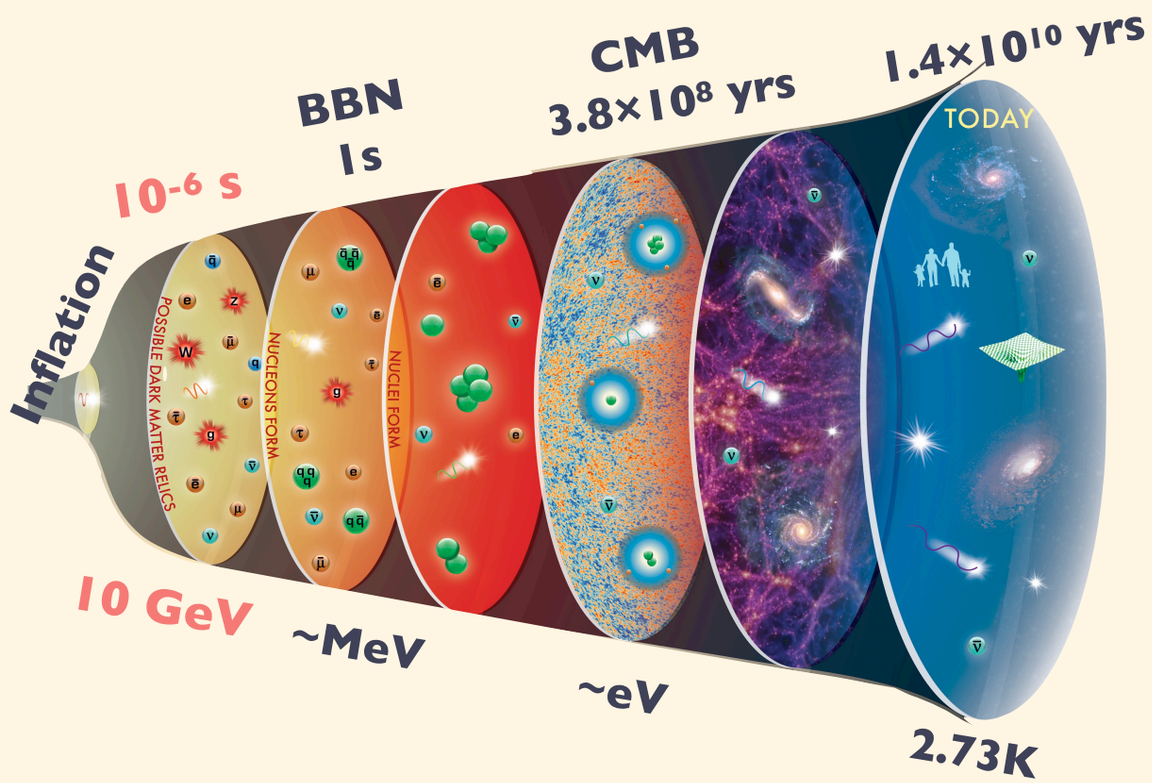
Baryon Asymmetry of Universe

- Need **tiny baryon asymmetry**
  - Pair creation/annihilation in equilibrium



Baryon #		Anti-baryon #		Photon #
n_B	$\sim$	$n_{\bar{B}}$	$\sim$	n_γ



[PDG LBNL]

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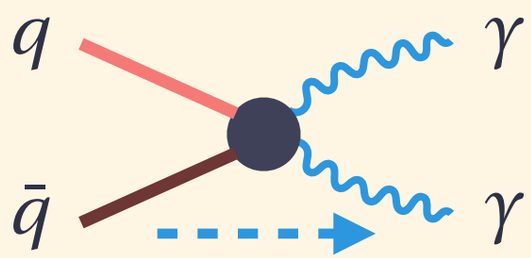

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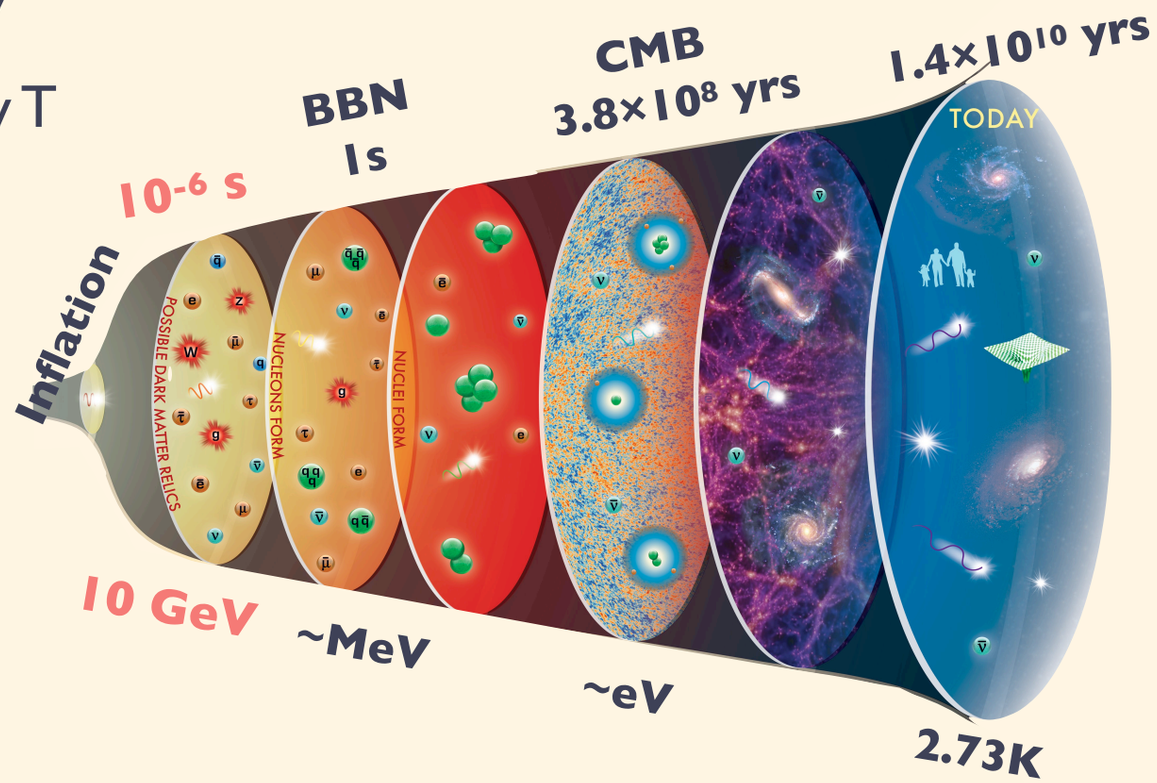

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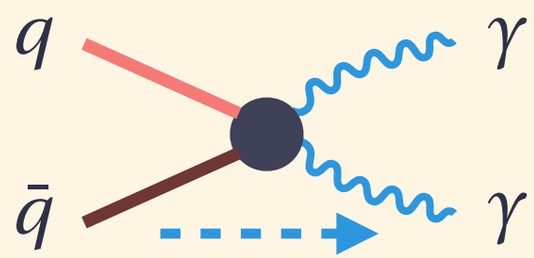

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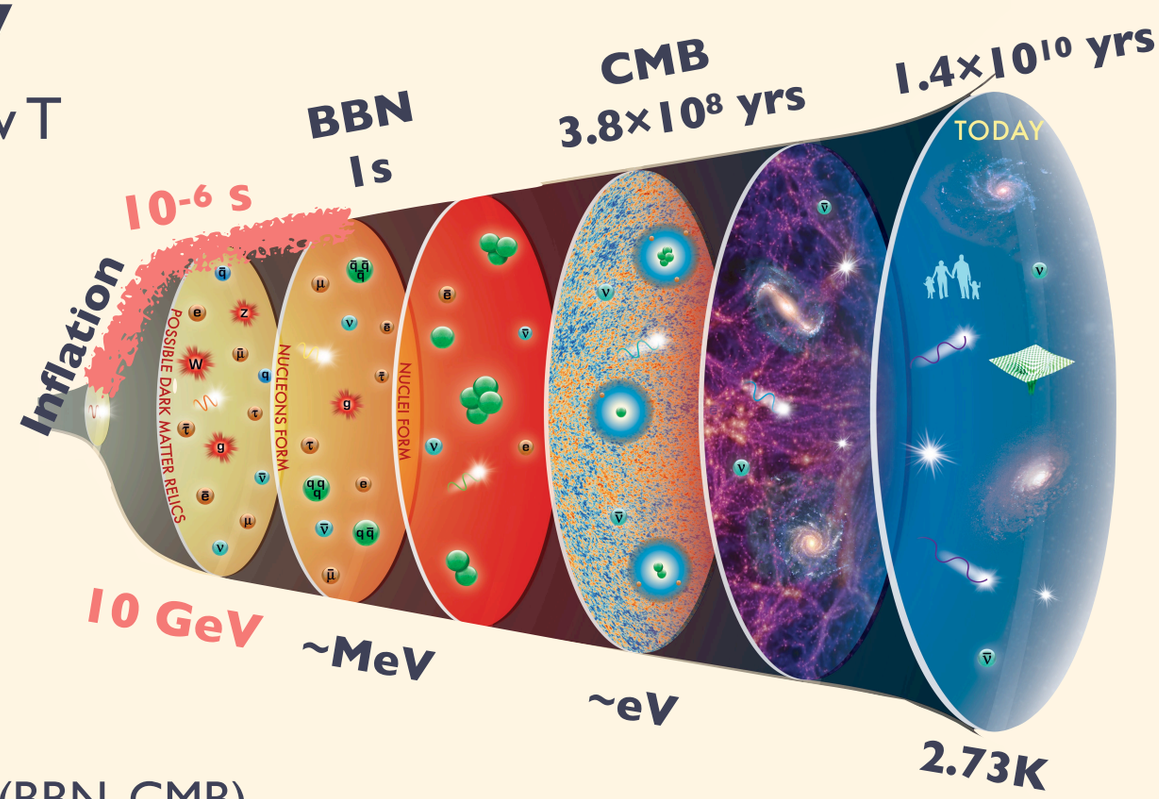
baryon-to-photon ratio: $\eta = \dfrac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$ (BBN, CMB)



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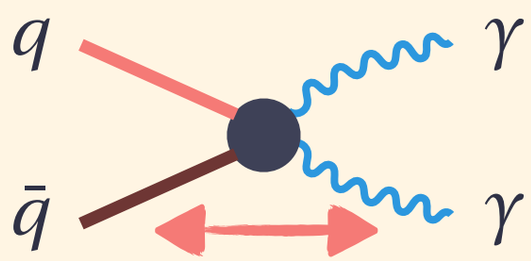

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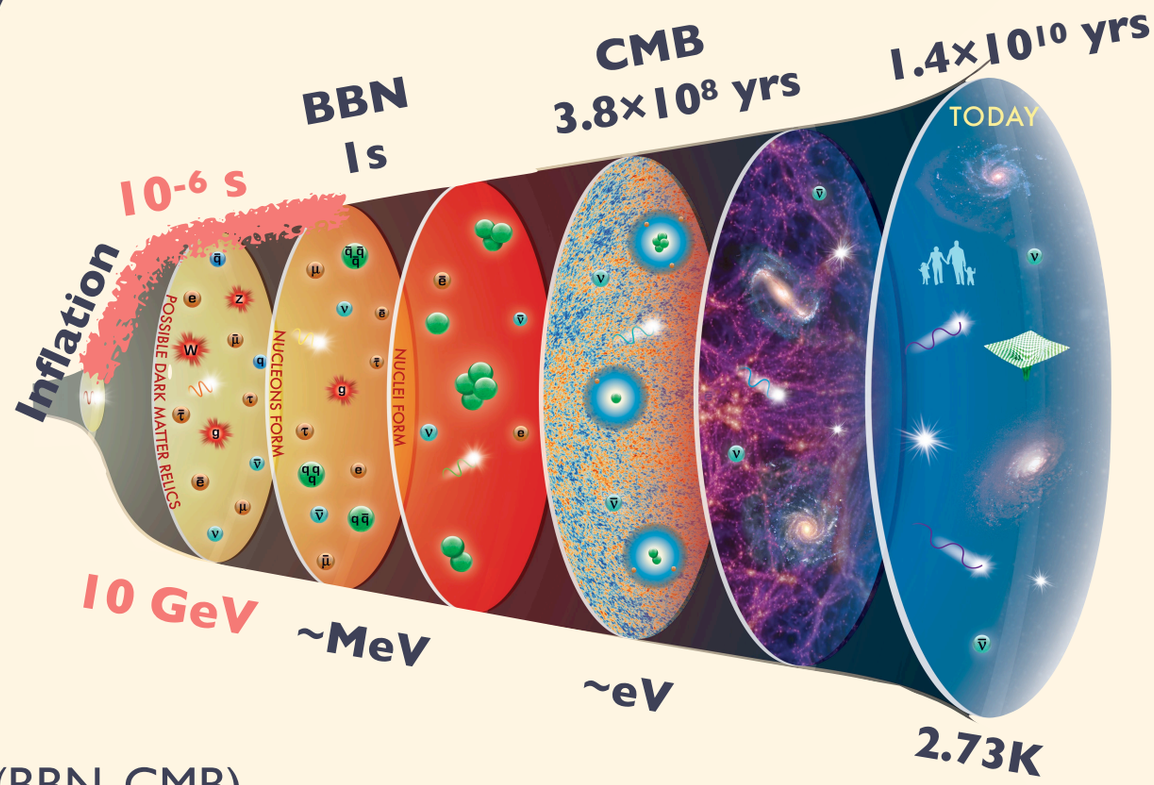

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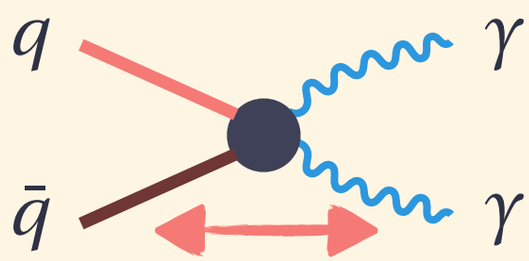

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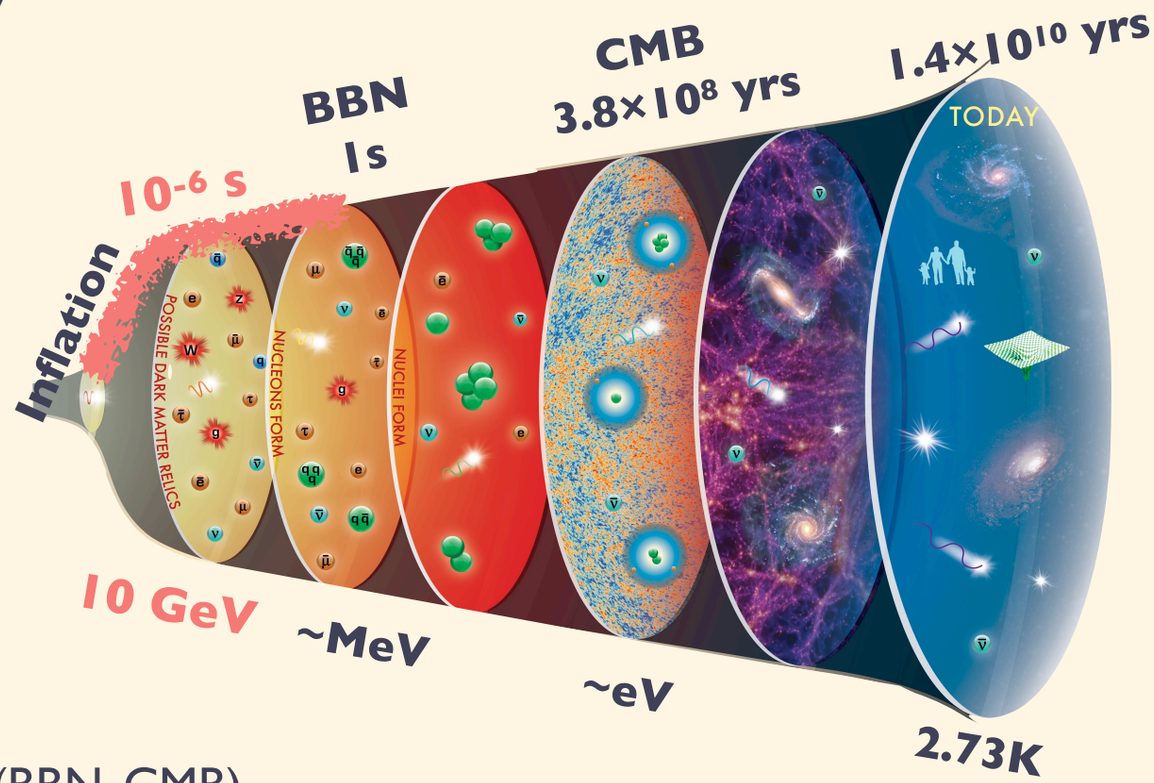

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baryon-to-photon ratio: $\eta = \dfrac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$ (BBN, CMB)

➡ Call for "**baryogenesis" after inflation before BBN**

- Baryon "chemical potential" in the primordial Universe

$$q_B \equiv n_B - n_{\bar{B}} \equiv \frac{1}{6}\mu_B T^2 \longrightarrow \frac{\mu_B}{T} \sim 10^{-10}$$

Introduction

Primordial chiral asymmetries in SM?

- SM → **Chiral** theory under SU(3) x SU(2) x U(1)
  - Generic asymmetries in Matter = Chiral asymmetries!

- Global symmetry & **Chiral anomaly**

Classical

$$\underbrace{U(1)_B}_{\frac{\mu_B}{T} \sim 10^{-10}} \times \underbrace{U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}}_{?}$$

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$$\xrightarrow{\cancel{U(1)}_{B+L}}$$

Quantum

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

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

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~~$U(1)_{B+L}$~~

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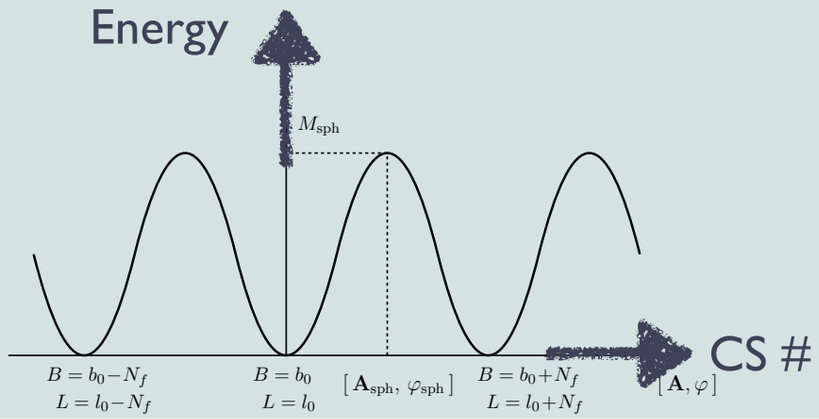

Instanton @ Vacuum $\quad \Gamma_{\rm inst} \propto e^{-16\pi^2/g^2} \sim \mathcal{O}(10^{-165})$

Sphaleron @ high T

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

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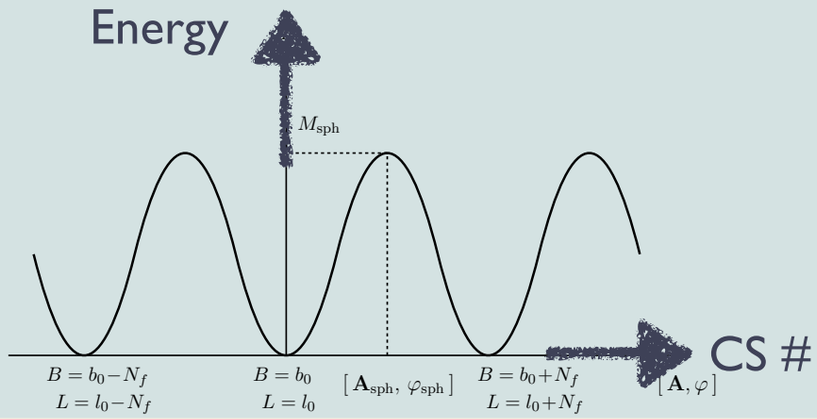

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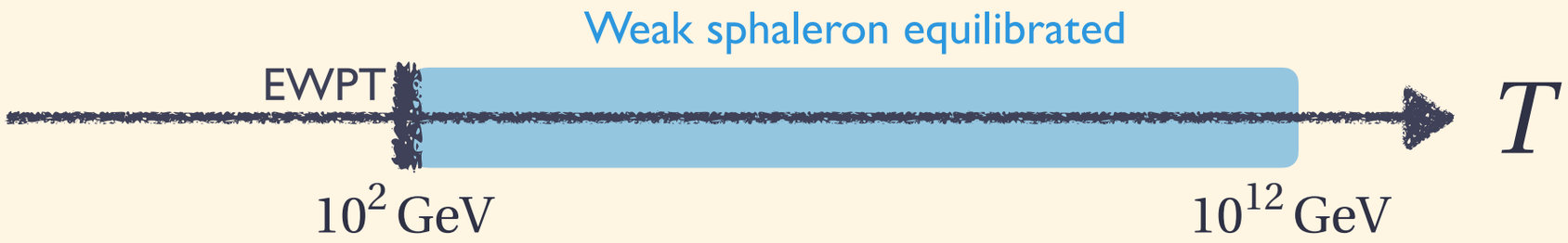

$\mathrm{U}(1)_B$ | ~~$\mathrm{U}(1)_B$~~ →

$$\mathrm{Tr}\left\{e^{-\beta H}Q_B\right\} = \mathrm{Tr}\left\{CPTe^{-\beta H}CPT^{-1}CPTQ_BCPT^{-1}\right\}$$
$$= -\mathrm{Tr}\left\{e^{-\beta H}Q_B\right\} = 0$$

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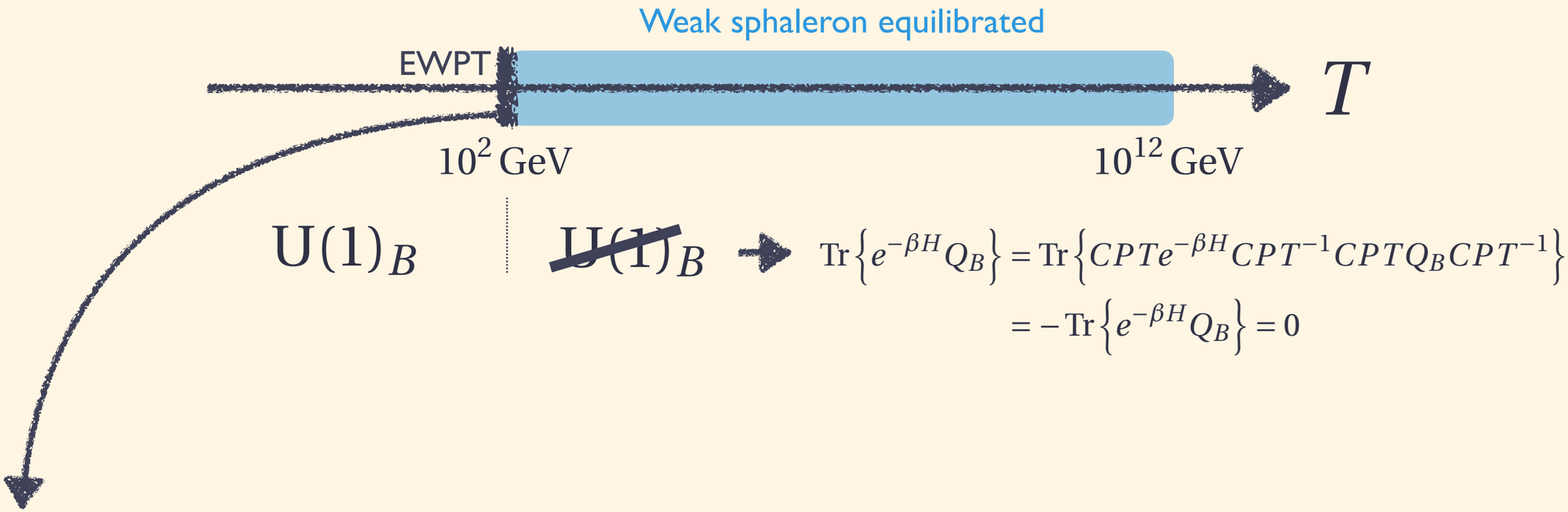

- Electroweak Baryogenesis [Kuzmin, Rubakov, Shaposhnikov]

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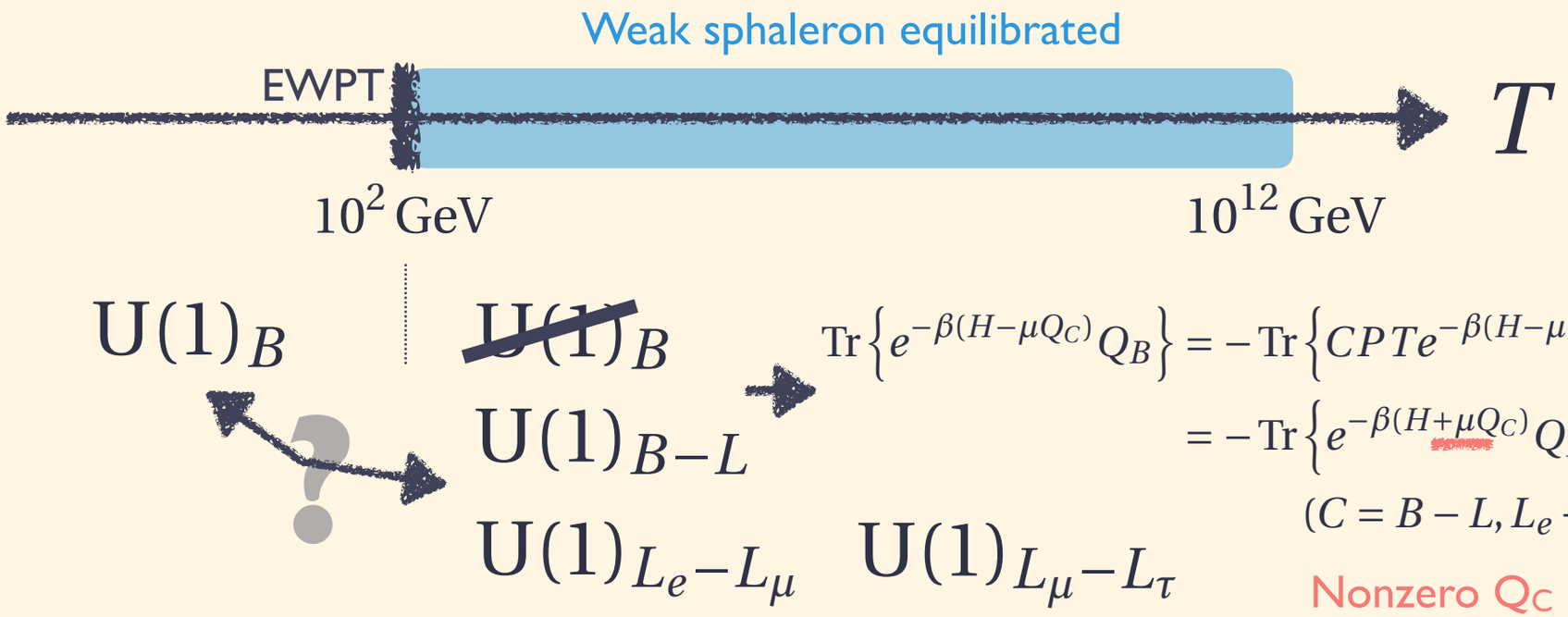

$$\mathrm{Tr}\left\{e^{-\beta(H-\mu Q_C)}Q_B\right\} = -\mathrm{Tr}\left\{CPTe^{-\beta(H-\mu Q_C)}CPT^{-1}Q_B\right\}$$
$$= -\mathrm{Tr}\left\{e^{-\beta(H+\mu Q_C)}Q_B\right\}$$
$$(C = B-L, L_e-L_\mu, L_\mu-L_\tau)$$

Nonzero Q_C
allows nonzero Q_B

- Electroweak Baryogenesis [Kuzmin, Rubakov, Shaposhnikov]
- Are there any **connection between Q_C & Q_B**?
  - th-eq Leptogenesis: B-L → B via sphaleron
  - **Leptoflavorgenesis**: L_e - L_μ or L_μ - L_τ → B via sphaleron + lepton Yukawa
  - Non-eq Decaying **helical $U(1)_Y$** field: L_e - L_μ or L_μ - L_τ → B via **chiral plasma inst.**

2.

Chemical equilibrium

in the early Universe

Chemical equilibrium

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

$$\rho = \frac{1}{Z} e^{-\beta\left(H - \Sigma_f \mu_{\Delta_f} Q_{\Delta_f}\right)}$$

w/ $Q_{\Delta_f} = \frac{Q_B}{3} - Q_{L_f}$ → flavored lepton charge

$\frac{Q_B}{3}$ → baryon charge

Chemical equilibrium

Chemical equilibrium of SM

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baryon charge

- Thermodynamic potential

Pressure as a grand potential

$$p \equiv \frac{T \ln Z}{V} \quad \rightarrow \quad q_\bullet = \frac{\langle Q_\bullet \rangle}{V} = \frac{\partial p}{\partial \mu_\bullet}$$

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$$\rho' = \frac{1}{Z} e^{-\beta\left(H - \sum_f \mu_{\Delta_f} Q_{\Delta_f} - \mu_{B+L} Q_{B+L}\right)}$$

$$-\mu_B Q_B - \sum_f \mu_{L_f} Q_{L_f}$$

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

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LO (ideal gas apprx.)

Tr Ln 

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$$p_{\rm LO} \supset \frac{1}{3}\mu_B^2 T^2 + \frac{1}{4}\sum_f \mu_{L_f}^2 T^2 + \frac{1}{3}\left(\mu_B - \sum_f \mu_{L_f}\right) B_0 T^2 + \frac{11}{12} B_0^2 T^2$$

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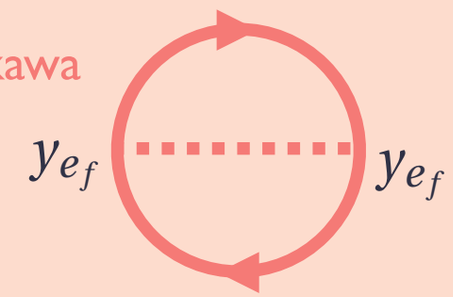
NLO
@ lepton Yukawa



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$$p_{\rm NLO} \supset -\frac{1}{16\pi^2}\frac{T^2}{2}\sum_f y_{e_f}^2 \left(-3B_0 \mu_{L_f} + 2\mu_{L_f}^2\right)$$

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

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

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- Baryon charge & Conserved charges [**KM**, K.Schmitz, M.Yamada 2111.03082]

Corrections from Higgs VEV

$$q_B \simeq \underbrace{\left[\frac{28}{79} + \mathcal{O}(y_{e_f}^2)\right] q_{B-L}}_{\text{ideal gas}} + \underbrace{\frac{47}{632\pi^2} \sum_f y_{e_f}^2 q_{\Delta_f}}_{\text{lepton Yukawa}}$$

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ideal gas — lepton Yukawa

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

Chemical equilibrium

Chemical equilibrium of SM

- The relation between B and Q_C at sphaleron equilibrium

$$\rho' = \frac{1}{Z} e^{-\beta\left(H - \sum_f \mu_{\Delta_f} Q_{\Delta_f} - \mu_{B+L} Q_{B+L} - \mu_B Q_B - \sum_f \mu_{L_f} Q_{L_f}\right)}$$

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 & Conserved charges [**KM**, K.Schmitz, M.Yamada 2111.03082]

Corrections from Higgs VEV

$$q_B \simeq \left[\frac{28}{79} + \mathcal{O}(y_{e_f}^2, x_{\rm Sp}^2)\right] q_{B-L} + \frac{1034 + 2473 x_{\rm Sp}^2 + 792 x_{\rm Sp}^4}{16\pi^2\left(869 + 333 x_{\rm Sp}^2\right)} \sum_f y_{e_f}^2 q_{\Delta_f} \quad \text{w/} \quad x_{\rm Sp} \equiv \left.\frac{\phi}{T}\right|_{\text{Sphaleron dec.}} \simeq 1.3$$

ideal gas — 0.03 — lepton Yukawa

Implications of current baryon density

$$Y_B = \left.\frac{q_B}{s}\right|_{T_{\rm Sp}} = \left.\frac{q_B}{s}\right|_0 \simeq 9 \times 10^{-11} \quad \blacktriangleright \quad Y_{B-L}|_{T \geqslant T_{\rm Sp}} \leqslant 2.5 \times 10^{-10}$$

$$\left(Y_{L_e - L_\tau} + Y_{L_\mu - L_\tau}\right)_{T \geqslant T_{\rm Sp}} \leqslant \frac{9 \times 10^{-5}}{y_\tau^2 / 10^{-4}}$$

$$\left(Y_{L_e - L_\mu} - Y_{L_\mu - L_\tau}\right)_{T \geqslant T_{\rm Sp}} \leqslant \frac{2.4 \times 10^{-2}}{y_\mu^2 / (3.7 \times 10^{-7})}$$

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Leptogenesis
@ saturation
[Fukugita, Yanagida]

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Leptoflavorgenesis
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3.

Chiral plasma instability in the early Universe

Chemical equilibrium

Primordial chiral asymmetries in SM?

- SM → **Chiral** theory under SU(3) x SU(2) x U(1)
  - Generic asymmetries in Matter = Chiral asymmetries!

- Global symmetry & **Chiral anomaly**

Classical

$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} \xrightarrow{\cancel{U(1)}_{B+L}} \textbf{Quantum}\quad U(1)_{B-L} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau}$$

$$\frac{\mu_B}{T} \sim 10^{-10} \longleftrightarrow \frac{\mu_{B-L}}{T} \lesssim 10^{-8} \quad \frac{\mu_{L_\bullet-L_\mu}}{T} \lesssim 1 \quad \frac{\mu_{L_\bullet-L_\tau}}{T} \lesssim 10^{-3} \quad @\ T \geqslant T_{\rm Sp}$$

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

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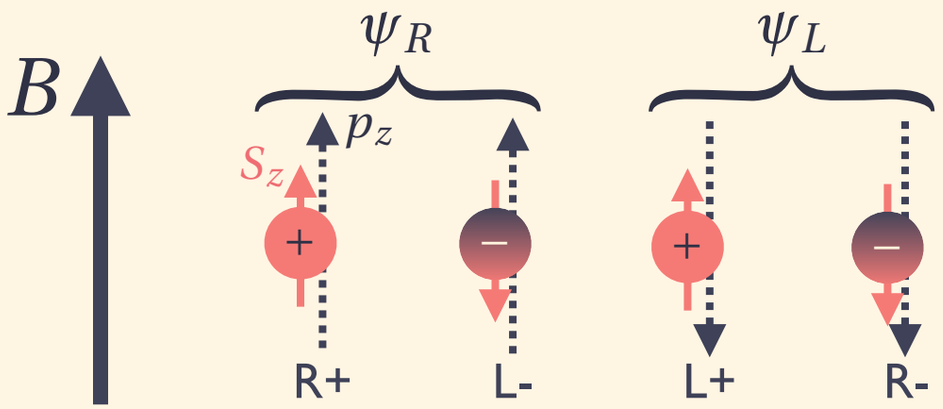
Non-equilibrium chemical transport via **chiral plasma instability**!

* **Chiral** asymmetry → **Helical** hyper magnetic fields

Chiral Plasma Instability

Warmup: massless QED

- Chiral magnetic effect



Chiral asymmetry

$Q_5 = Q_R - Q_L, \quad Q_{R/L} = N_{R/L} - \overline{N}_{R/L}$

$$\mu_5 > 0$$

- Chemical transport via chiral plasma instability

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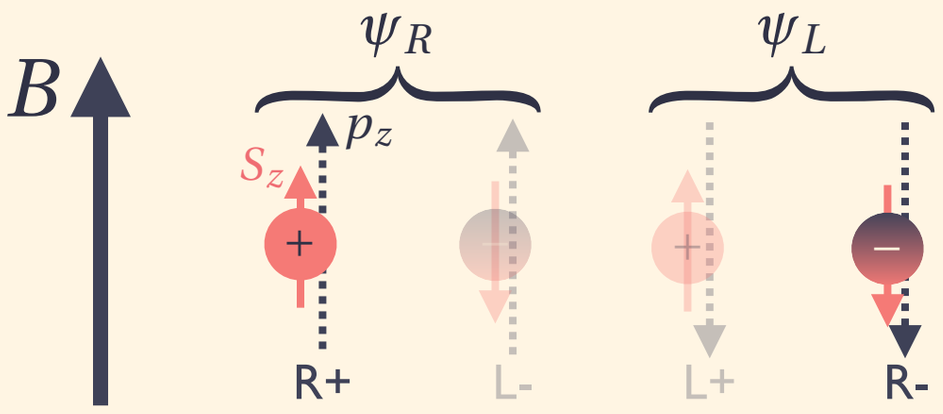

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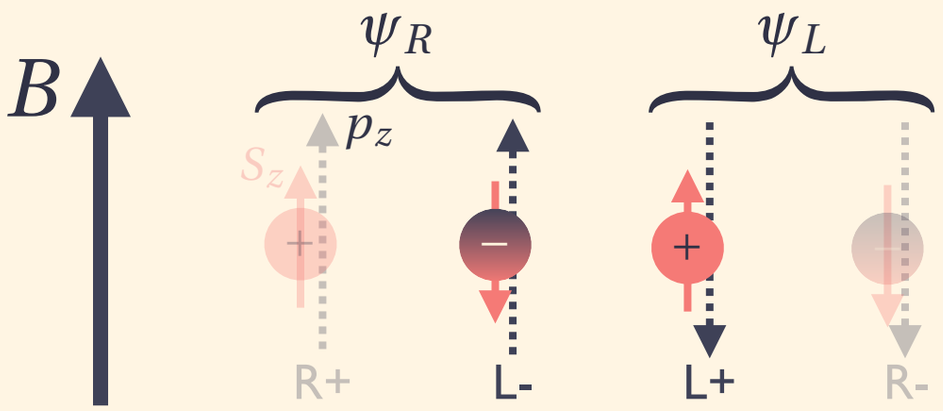

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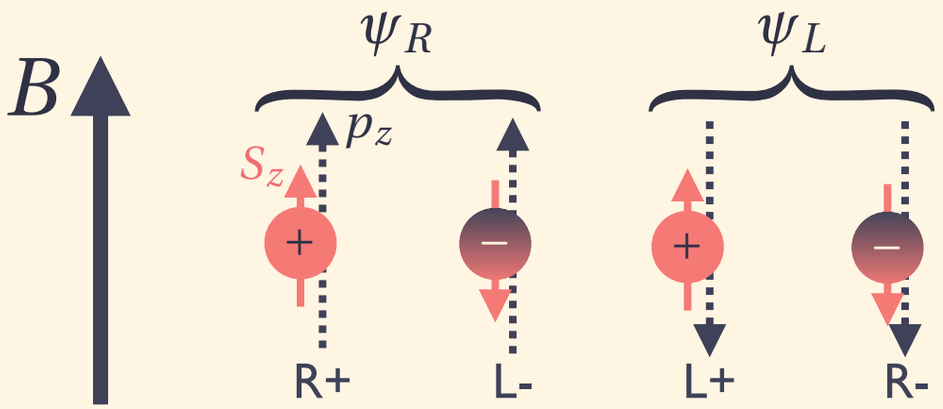

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Electric current along B

$$\boldsymbol{J}_{\rm el} = 2 \times \frac{\alpha}{\pi} \mu_5 \boldsymbol{B}$$ [Vilenken; Alekseev+; Fukushima+]

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$$\partial \cdot J_5 = -\frac{g^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{g^2}{2\pi^2} \boldsymbol{E} \cdot \boldsymbol{B}$$

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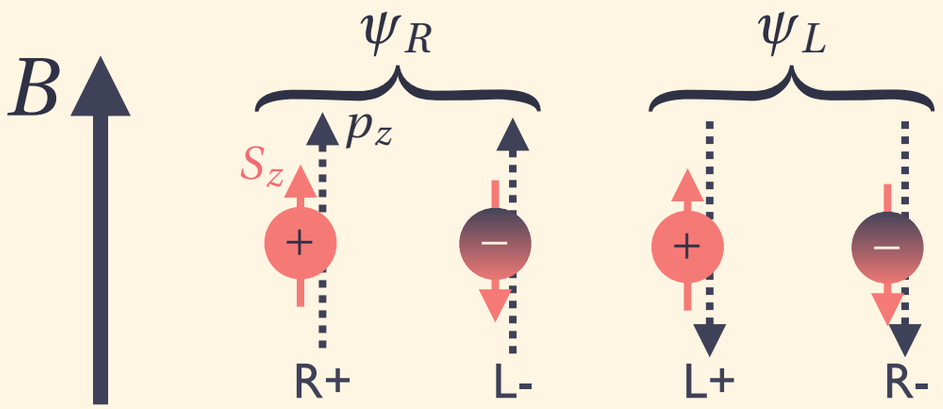

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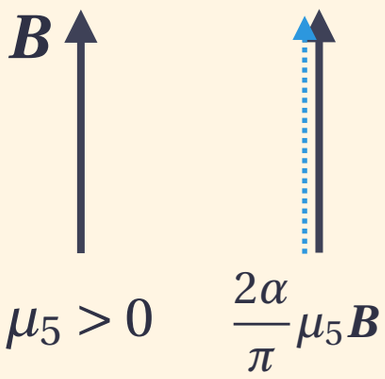

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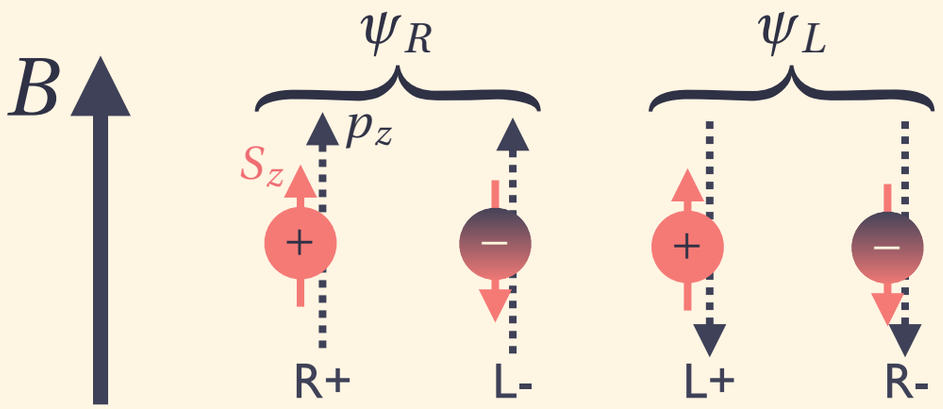

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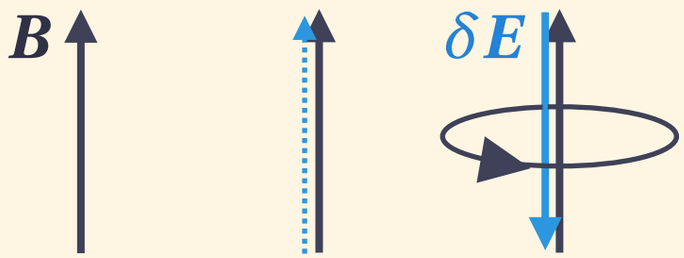

$\mu_5 > 0$ $\quad \frac{2\alpha}{\pi}\mu_5 \boldsymbol{B}$ $\quad \frac{2\alpha}{\pi}\mu_5 \boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{B} - \sigma \boldsymbol{E}$

@ ChMHD

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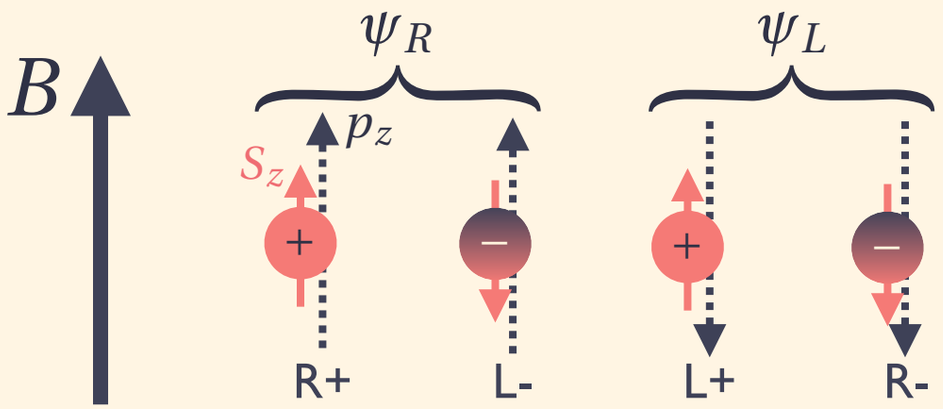

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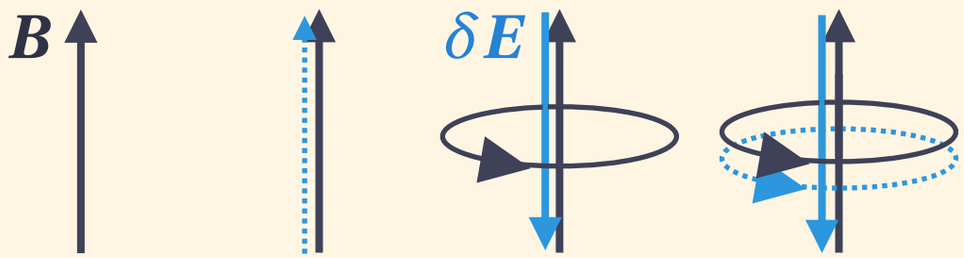

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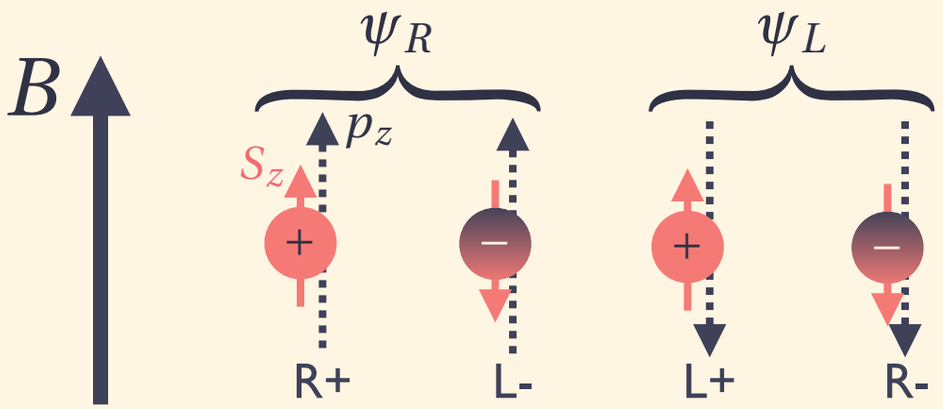

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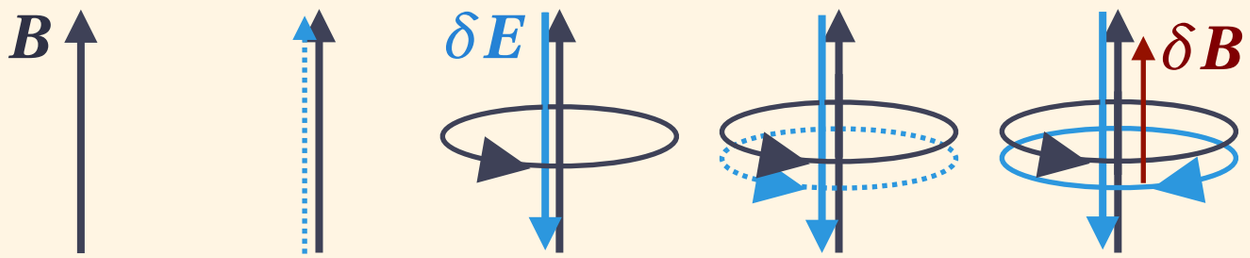

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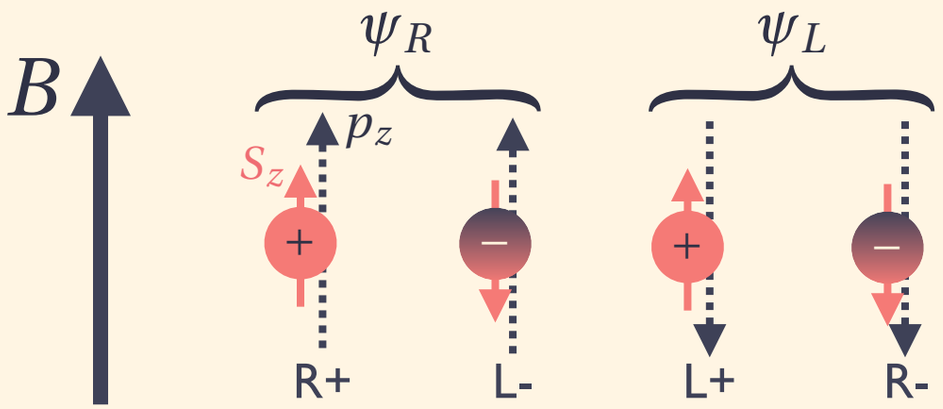

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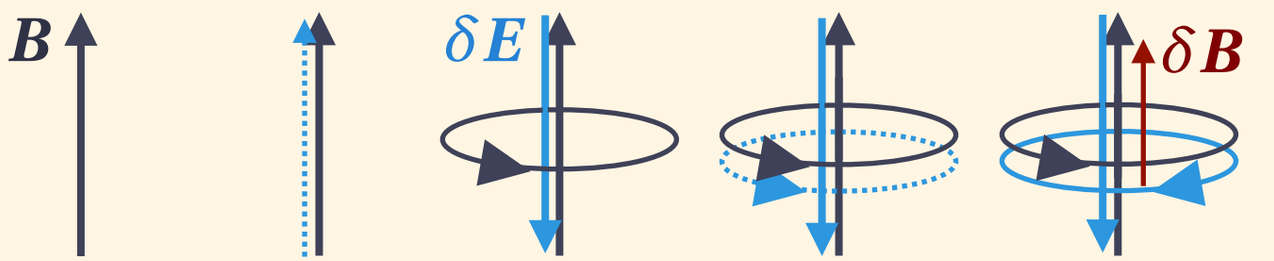

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chiral asym. ▶ **magnetic** helicity

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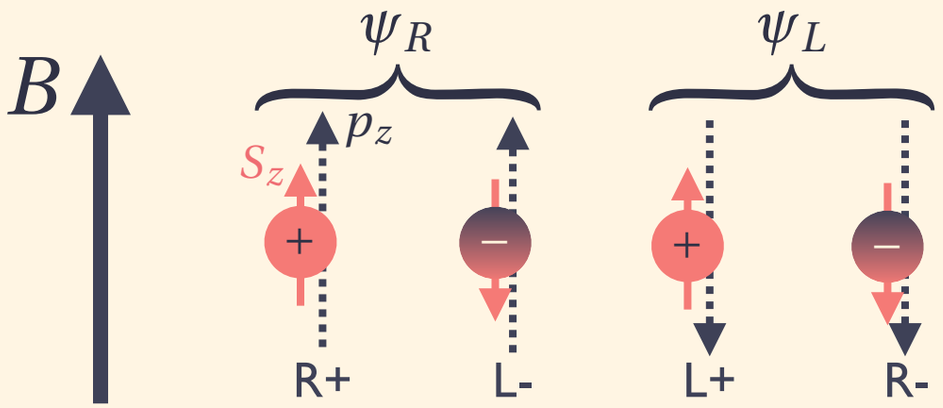

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$$\partial_\eta B_\pm = -\frac{k}{\sigma}\left(k \mp \frac{\alpha}{\pi} 2\mu_5\right) B_\pm + \cdots \quad \text{w/ } i\boldsymbol{k} \times \boldsymbol{e}^\pm_{\boldsymbol{k}} = \pm \boldsymbol{e}^\pm_{\boldsymbol{k}}$$

$$\mu_5 > 0 \longrightarrow \textbf{Tachyonic instability} \quad k < \frac{\alpha}{\pi} 2\mu_5 \quad \text{for} \quad B_+$$

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Time scale [Joyce, Shaposhnikov; Kamada]

$$t_{\rm CPI} \sim \frac{\pi^2 \sigma}{2\alpha^2 \mu_5^2} \longrightarrow T_{\rm CPI} \sim 10^5\,{\rm GeV}\left(\frac{\mu_5/T}{10^{-3}}\right)^2$$

Chiral Plasma Instability

Standard Model & Hyper magnetic fields

- Chiral plasma instability in SM [V.Domcke, K.Kamada, **KM**, K.Schmitz, M.Yamada 2111.03082]

Right-handed

	g_i	Y_i
e_R	1	-1
u_R	3	$2/3$
d_R	3	$-1/3$

Left-handed

	g_i	Y_i
ℓ_L	2	$-1/2$
q_L	6	$1/6$

Hyper electric current along B_Y

$$\boldsymbol{J}_Y = \frac{\alpha_Y}{\pi}\mu_{5Y}\boldsymbol{B}_Y$$

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Depends on T!

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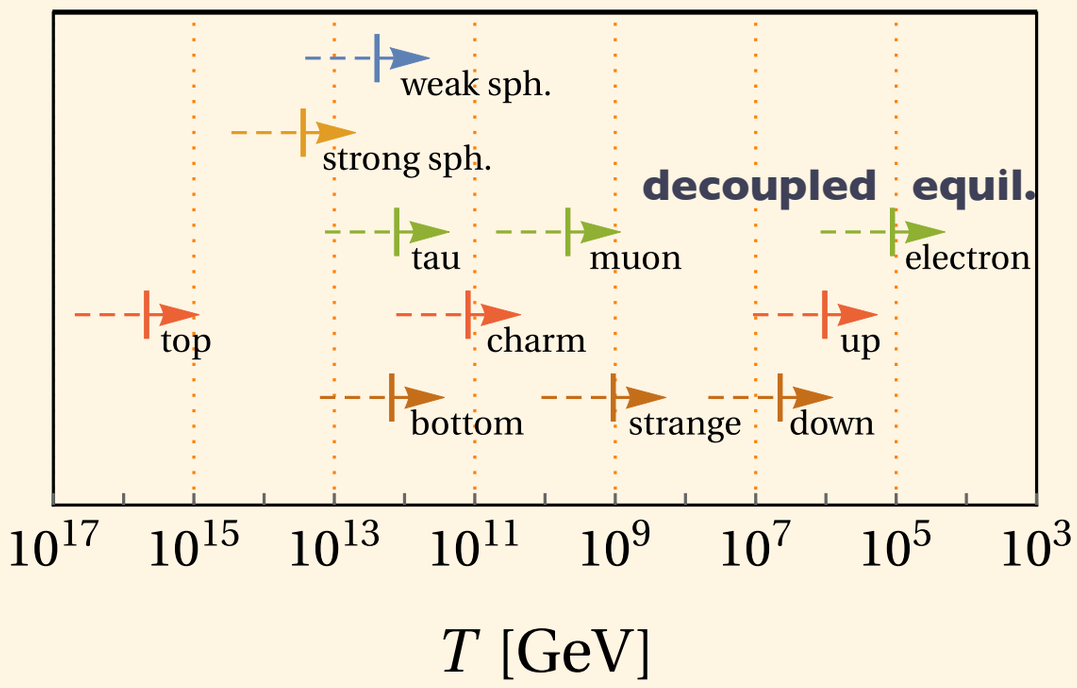
Approximate conserved charges in SM



- $T \lesssim 10^5\,\mathrm{GeV}$ $\quad \mu_{5Y} = 0 \rightarrow$ **no instability!**

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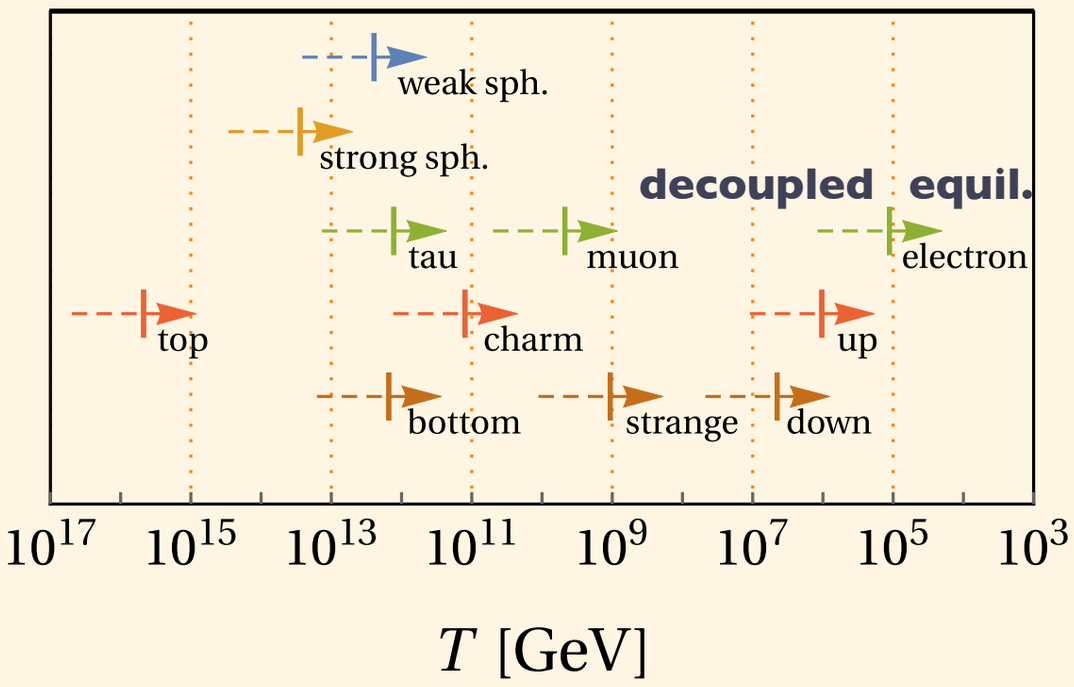

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- $10^5\,\text{GeV} \lesssim T \lesssim 10^6\,\text{GeV}$ electron Yukawa **decoupled**

$$\mu_{5Y} = \frac{711\mu_e + 237\mu_{\Delta_e} - 52\mu_{B-L}}{481}$$

$$\partial \cdot J_{e_R} = -\frac{g_Y^2}{16\pi^2} B_{\mu\nu}\tilde{B}^{\mu\nu}$$

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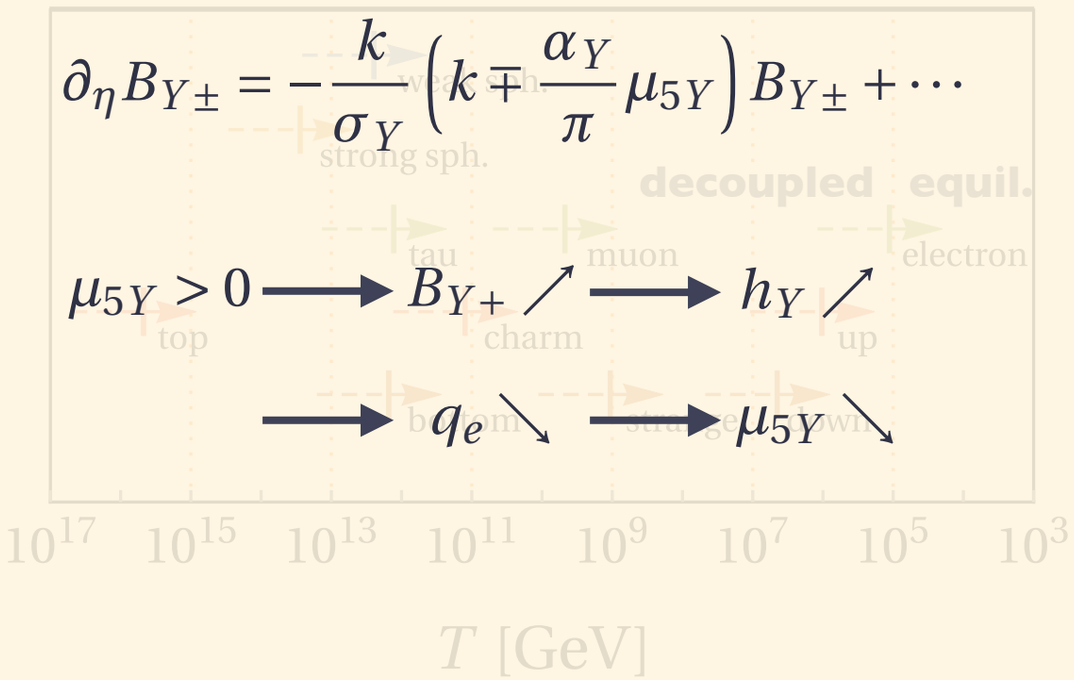
Depends on T!

Approximate conserved charges in SM

$$\partial_\eta B_{Y\pm} = -\frac{k}{\sigma_Y}\left(k \mp \frac{\alpha_Y}{\pi}\mu_{5Y}\right)B_{Y\pm} + \cdots$$

$$\mu_{5Y} > 0 \longrightarrow B_{Y+} \nearrow \longrightarrow h_Y \nearrow$$

$$\longrightarrow q_e \searrow \longrightarrow \mu_{5Y} \searrow$$



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- $10^5\,\text{GeV} \lesssim T \lesssim 10^6\,\text{GeV}$ electron Yukawa **decoupled**

$$\mu_{5Y} = \frac{711\mu_e + 237\mu_{\Delta_e} - 52\mu_{B-L}}{481}$$ chiral plasma inst. → **0**

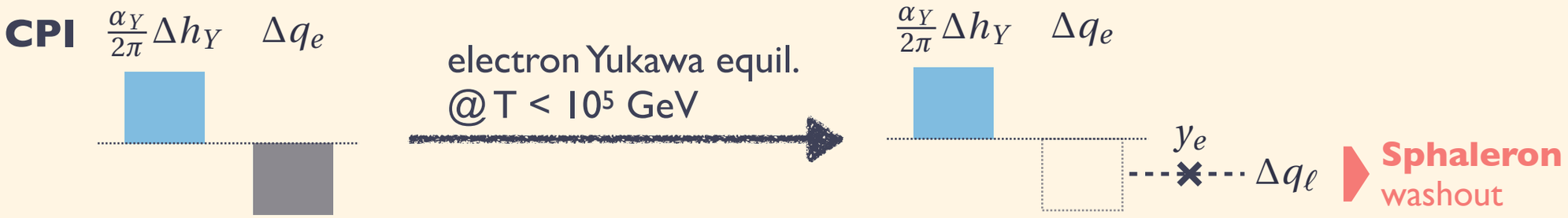
$$\partial \cdot J_{e_R} = -\frac{g_Y^2}{16\pi^2}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

$$\Delta h_Y = -\frac{2\pi}{\alpha_Y}\Delta q_e \simeq \frac{\pi T^2}{3\alpha_Y}\frac{237\mu_{\Delta_e} - 52\mu_{B-L}}{711}$$

Baryogenesis at EWPT

Baryogenesis from Decaying Helicity

- Chemical transport @ 10^5 GeV > T > 10^2 GeV



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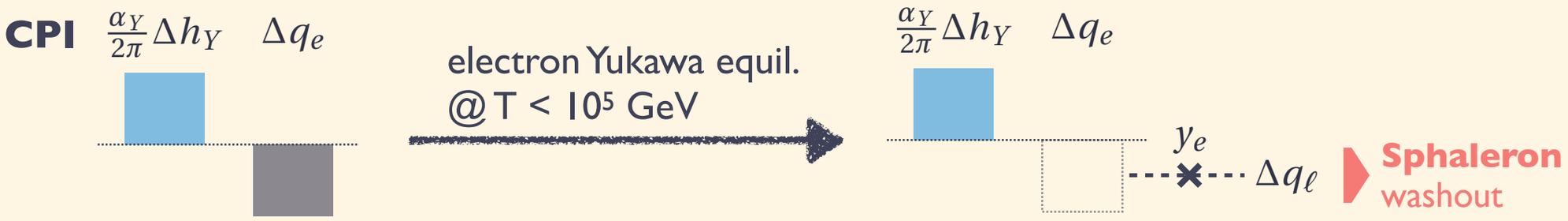


- Chemical transport @ **electroweak crossover**

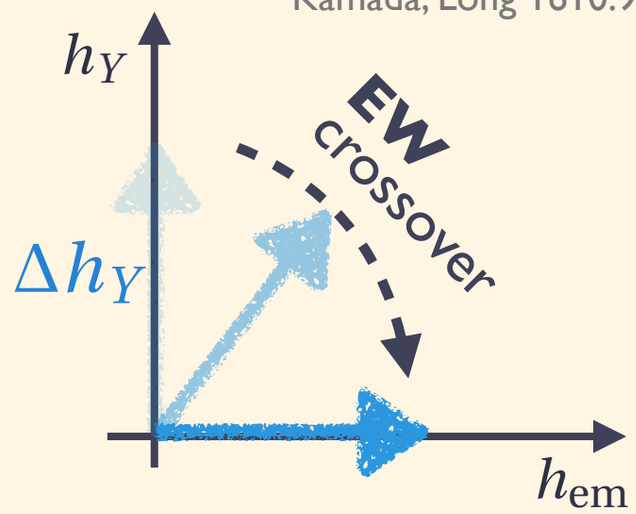
Fujita, Kamada 1602.02109
Kamada, Long 1610.93974

- **Sphaleron washout** v.s. **Decaying helicity**

$$\partial_\eta q_B = -\frac{111}{34}\Gamma_{\rm ws} q_B + \frac{3}{2}\left(g_2^2 + g_Y^2\right)\sin(2\theta)\left(\partial_\eta\theta\right)\frac{\Delta h_Y}{8\pi^2}$$

$$\propto \partial_\eta h_Y$$

$$\Gamma_{\rm ws} \propto e^{-\frac{M_{\rm sph}(T)}{T}} \quad \text{w/ } M_{\rm sph}(T) \propto v(T)$$



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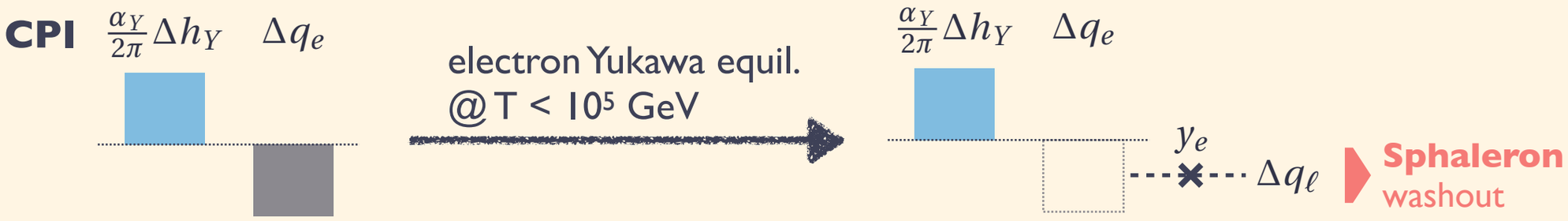

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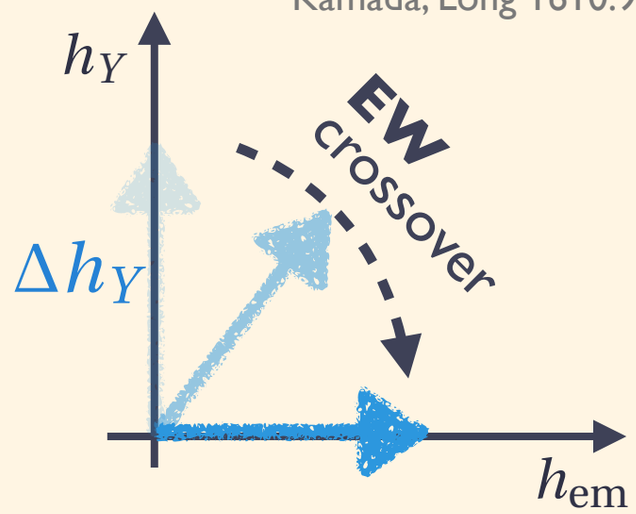


Baryon overproduction!

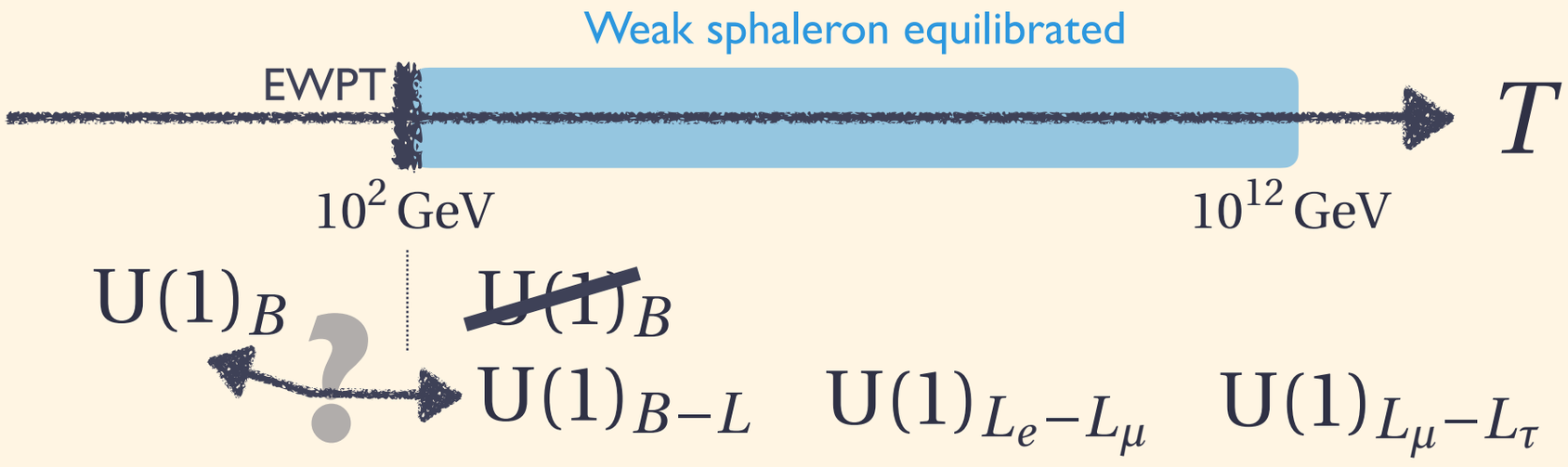
$$Y_B = \left.\frac{q_B}{s}\right|_0 = \left.\frac{q_B}{s}\right|_{T_{\rm Sp}} = \epsilon \times \frac{3\alpha_Y}{4\pi}\left.\frac{\Delta h_Y}{s}\right|_{T_{\rm CPI}} \sim 10^{-7}\left(\frac{\epsilon}{0.05}\right)\left(\frac{\mu_{\Delta_e}/T}{10^{-3}}\right)$$

Sphaleron washout factor

*** no CPI for** $\frac{\mu_{\Delta_e}}{T} < 10^{-3}$

Summary

Primordial chiral asymmetries in SM?



- **Conserved charges & Observed baryon asymmetry?**
  - Leptogenesis (th-eq) $Y_B \simeq \frac{28}{79} Y_{B-L}$ (Ideal gas) $\longrightarrow$ $Y_{B-L}|_{T\geqslant T_{\rm Sp}} \leqslant 2.5\times10^{-10}$
  - Leptoflavorgenesis $Y_B \simeq 0.03 \sum_f y_{e_f}^2 Y_{\Delta_f}$ (loop) $\longrightarrow$ $\left(Y_{L_e-L_\tau}+Y_{L_\mu-L_\tau}\right)_{T\geqslant T_{\rm Sp}} \leqslant 9\times10^{-5}$, $\left(Y_{L_e-L_\mu}-Y_{L_\mu-L_\tau}\right)_{T\geqslant T_{\rm Sp}} \leqslant 2.4\times10^{-2}$
  - (Non-eq) Hyper magnetogenesis via **chiral plasma inst.**

$$Y_B = \epsilon \frac{3\alpha_Y}{4\pi}\frac{\Delta h_Y}{s}\bigg|_{T_{\rm Sp}} = -\epsilon\,\frac{3Y_e}{2}\bigg|_{T_{\rm CPI}>10^5\,\mathrm{GeV}} \sim \epsilon\,\frac{Y_{\Delta_e}}{2}\bigg|_{T_{\rm CPI}>10^5\,\mathrm{GeV}} \longrightarrow \frac{\mu_{\Delta_e}}{T}\bigg|_{T\sim10^5\,\mathrm{GeV}} < 10^{-3}$$

Decaying h_Y — chiral anomaly of e_R — **chiral plasma instability** — To avoid baryon overproduction!