Leptogenesis & its descendants

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KEK

Based on **2011.09347, 2111.03082**

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

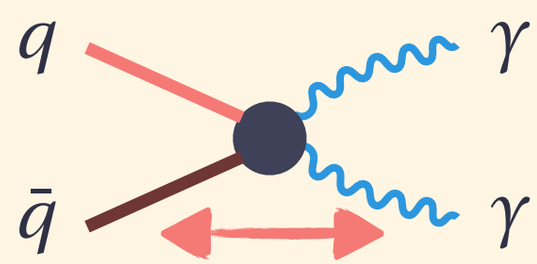
1.

Introduction

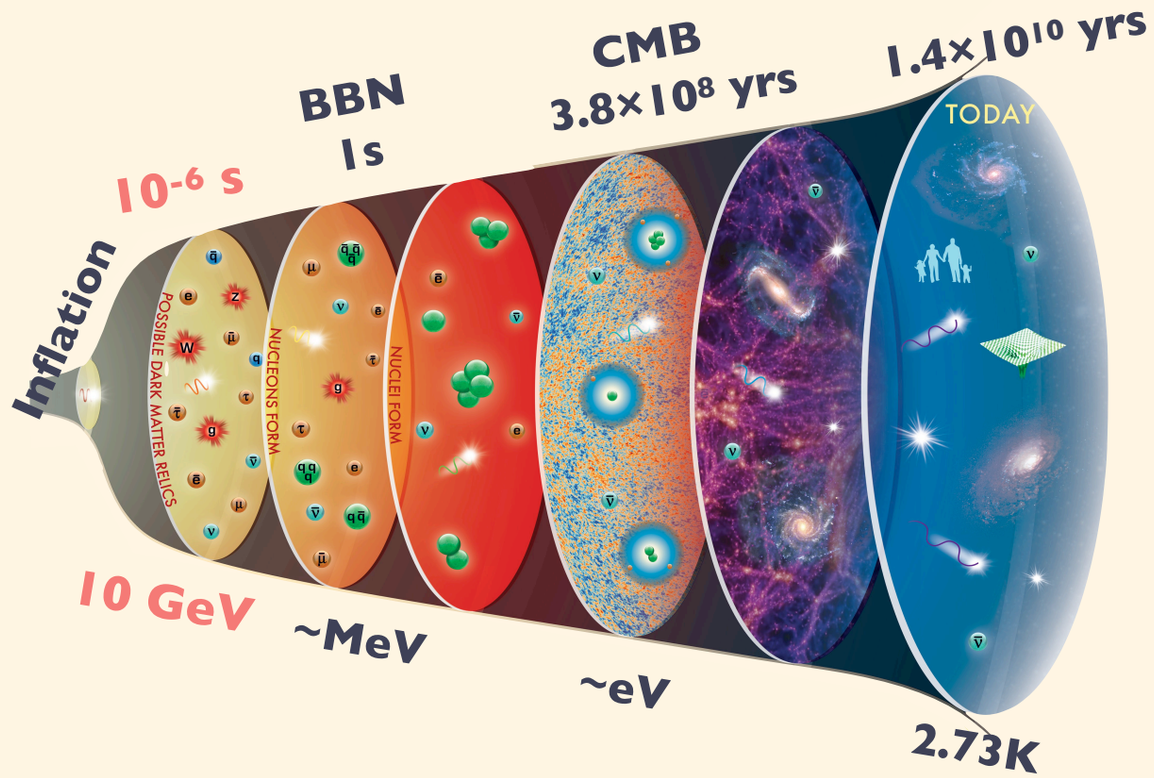
Introduction

Baryon Asymmetry in Inflationary Cosmology

- Need **tiny asymmetry** in the early Universe
  - Pair creation/annihilation in equilibrium



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



[PDG LBNL]

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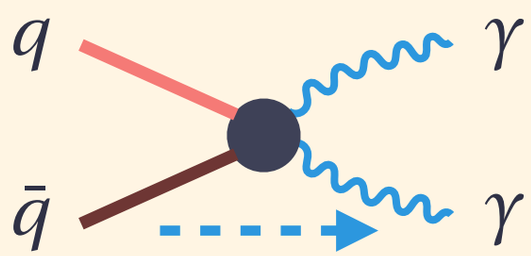

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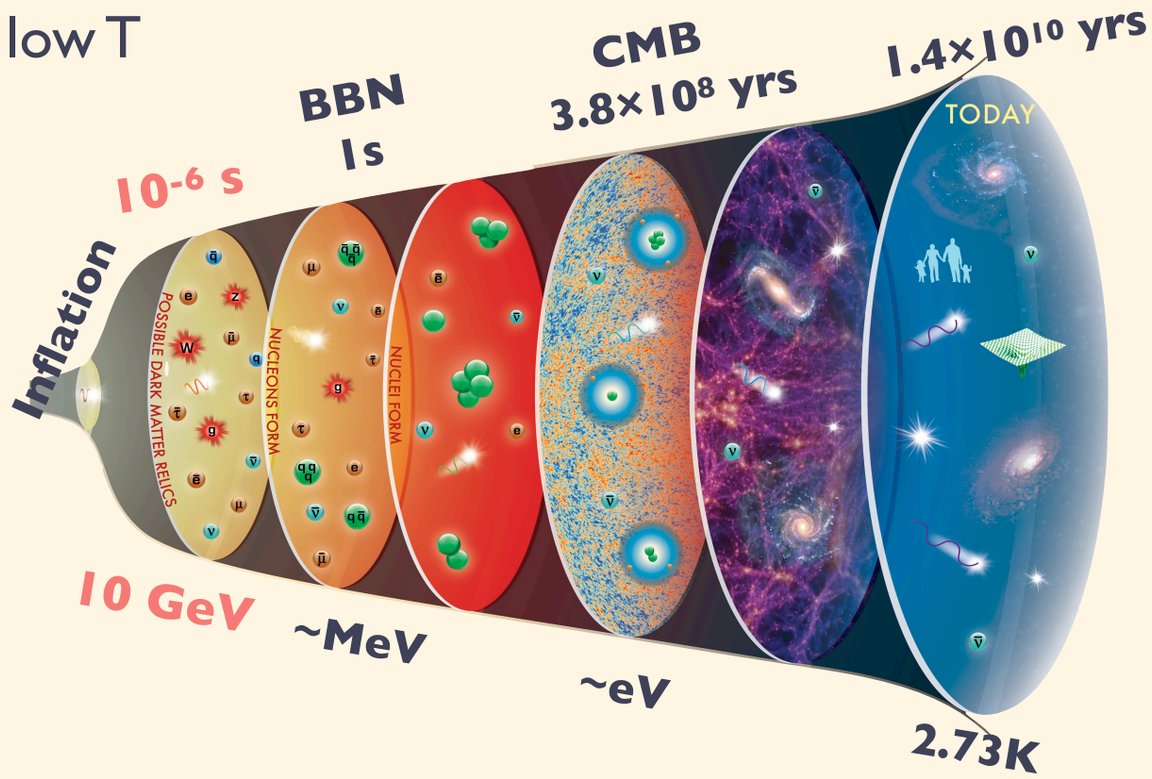

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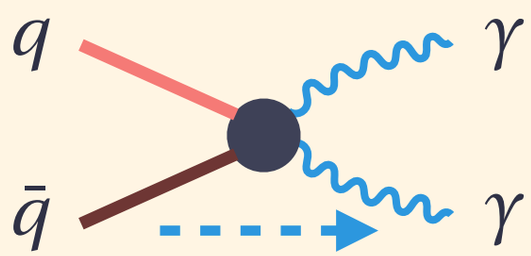

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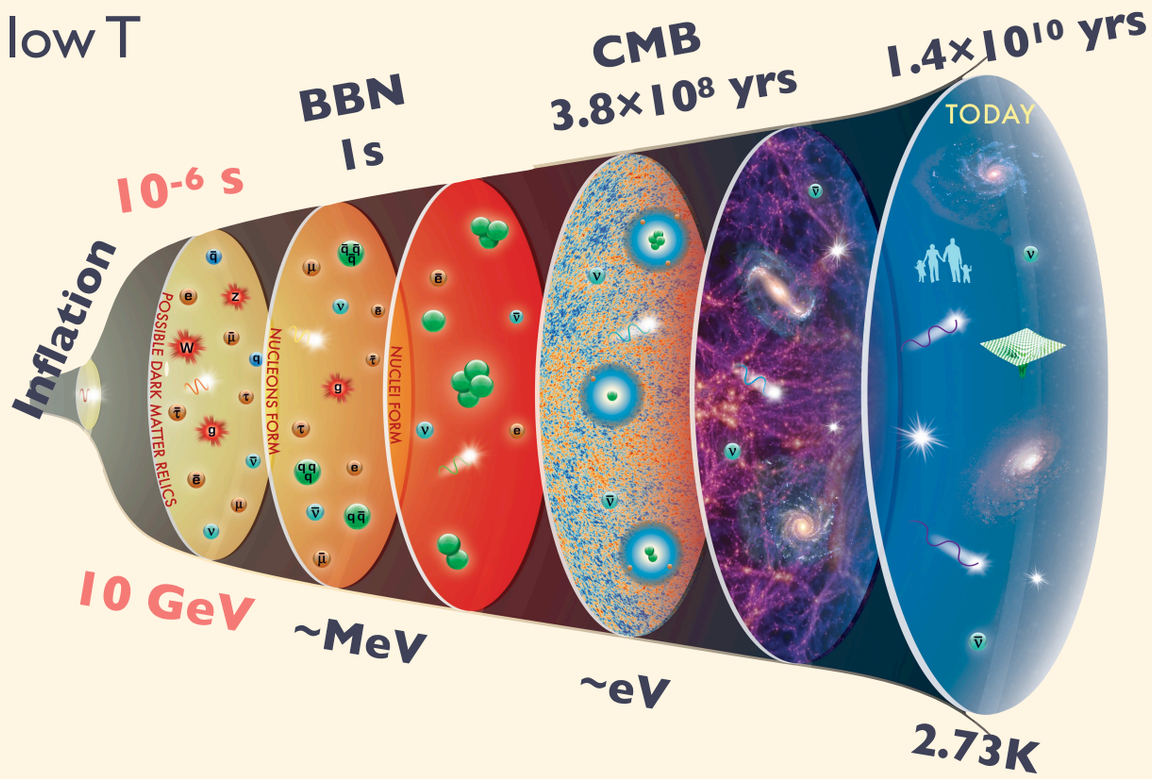

[PDG LBNL]

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

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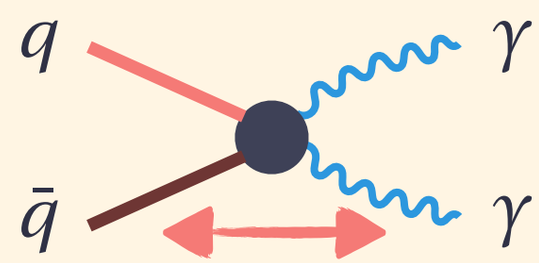

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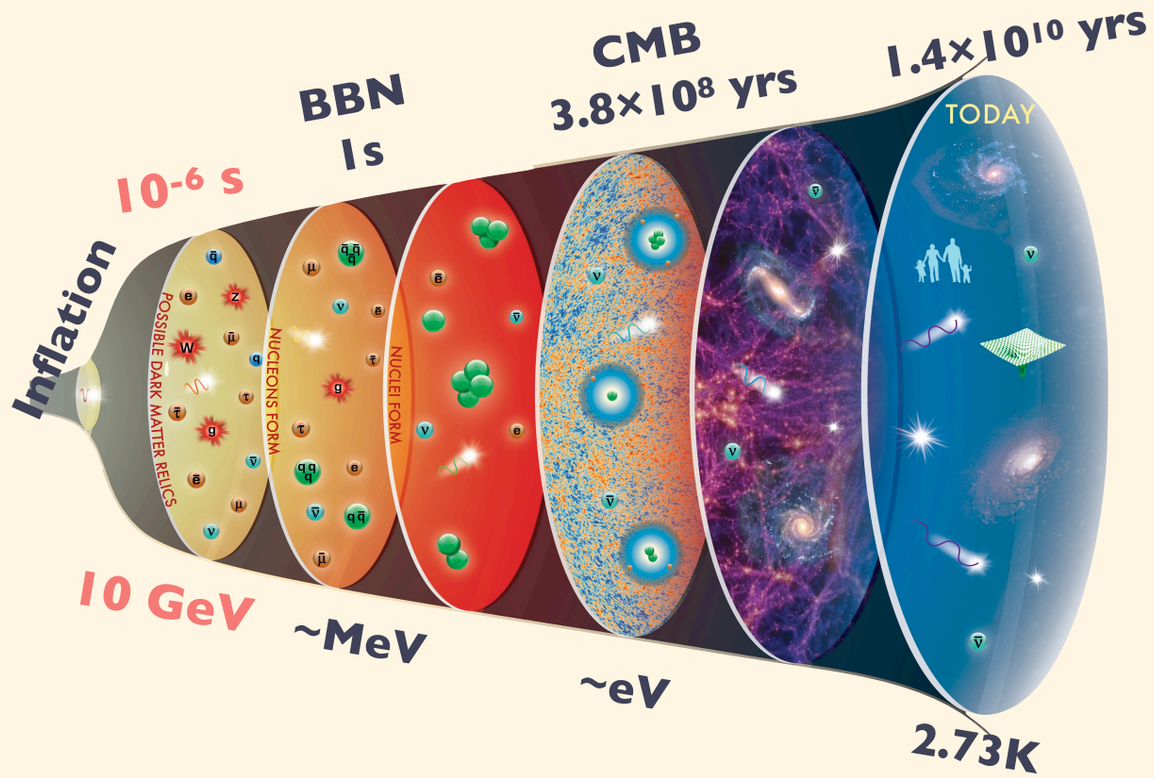

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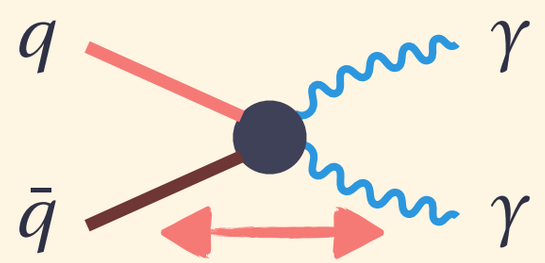

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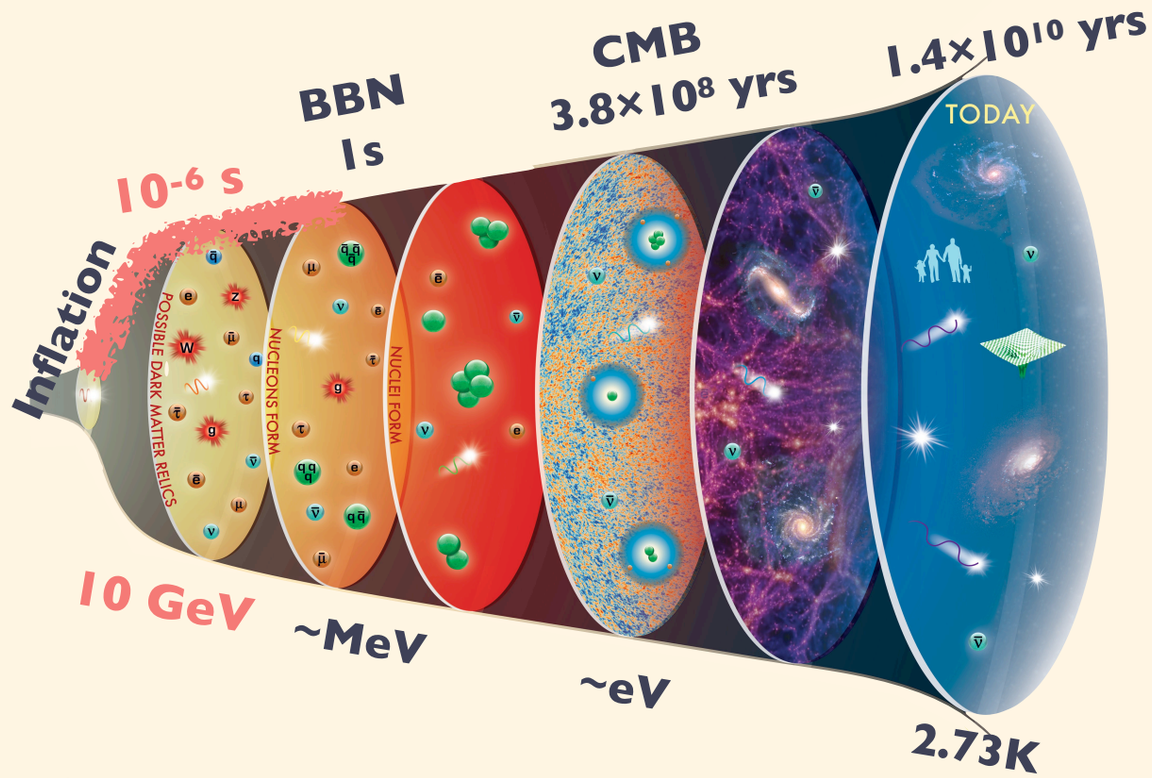

[PDG LBNL]

- Inflation does **NOT** allow us to put it as an initial condition before inflation!

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

2.

Baryogenesis via Leptogenesis

Sakharov's conditions

Recipe for Baryon Asymmetric Universe

- **Sakharov's 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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$$\begin{aligned}\mathrm{Tr}\{\rho \dot{Q}_B\} &= i\,\mathrm{Tr}\{\rho[H, Q_B]\} \\ &= i\,\mathrm{Tr}\{CP\rho CP^{-1}[CPHCP^{-1}, -Q_B]\}\end{aligned}$$

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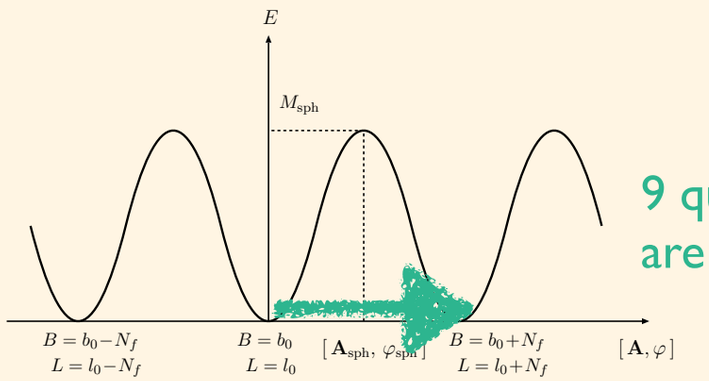
- **Chiral anomaly**

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

Baryon # **SU(2)w** Chern-Simons



9 quarks + 3 leptons are generated

- Instanton @ vacuum

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

No effect within the current age of Universe

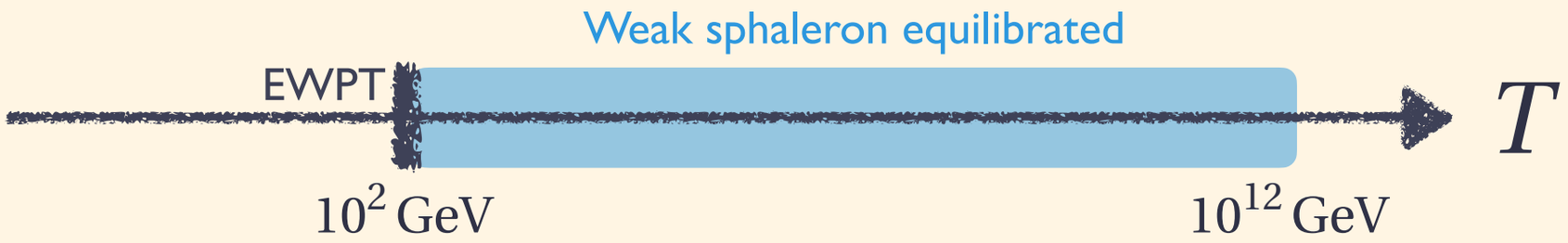
- **Weak sphaleron** at high T

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

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

Chemical transport in SM

Weak sphaleron & Baryogenesis

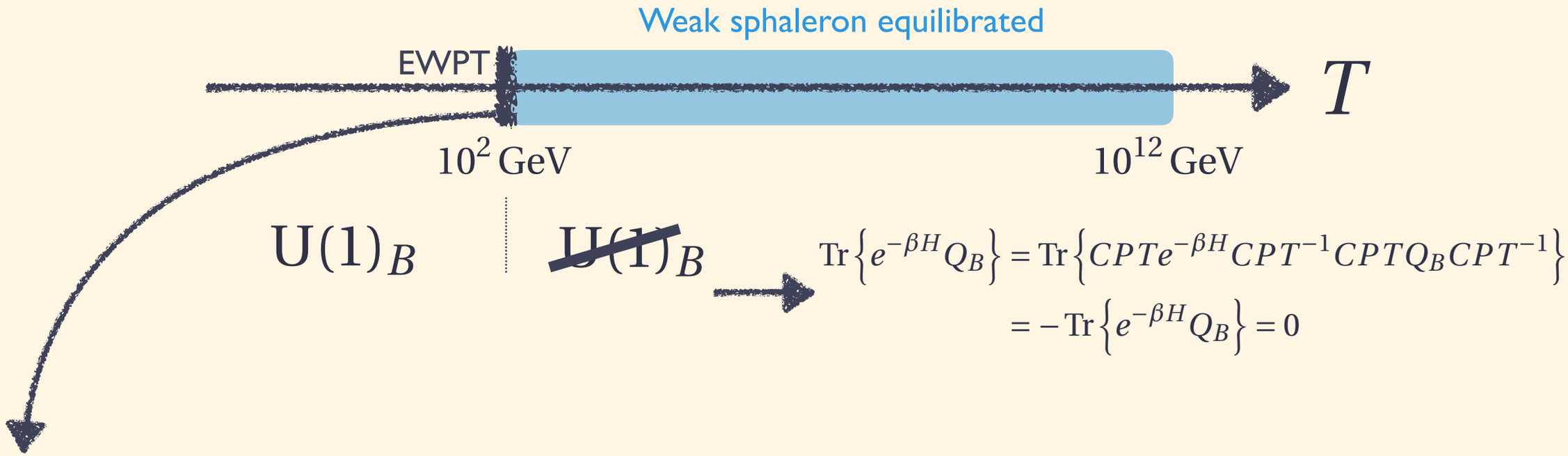


$\mathrm{U}(1)_B$ | ~~$\mathrm{U}(1)_B$~~

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

Chemical transport in SM

Weak sphaleron & Baryogenesis



- Electroweak Baryogenesis [Kuzmin, Rubakov, Shaposhnikov]
  - We need a new source of CP violation & strong EWPT

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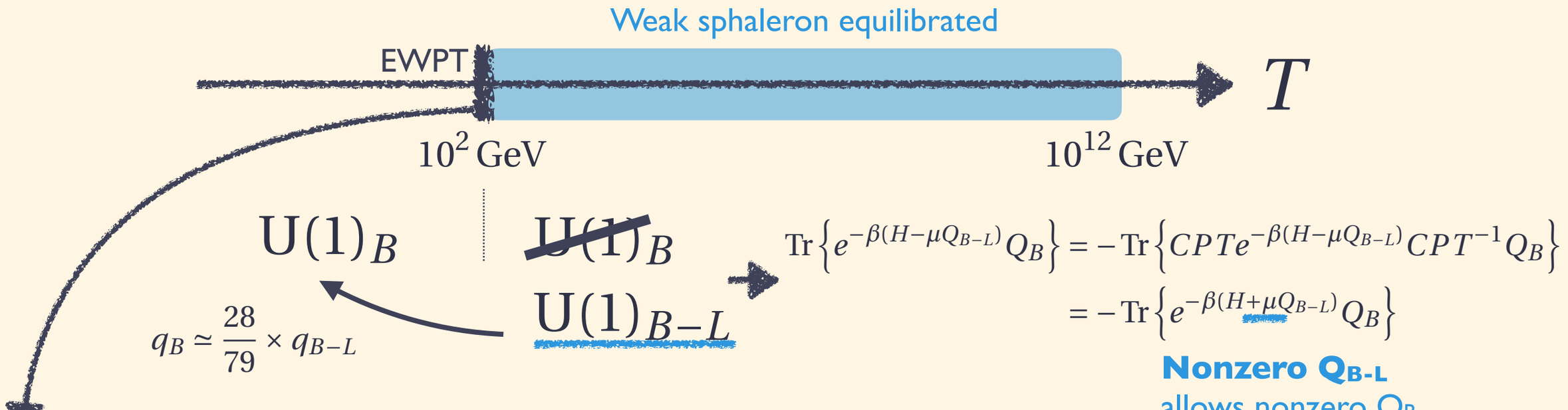

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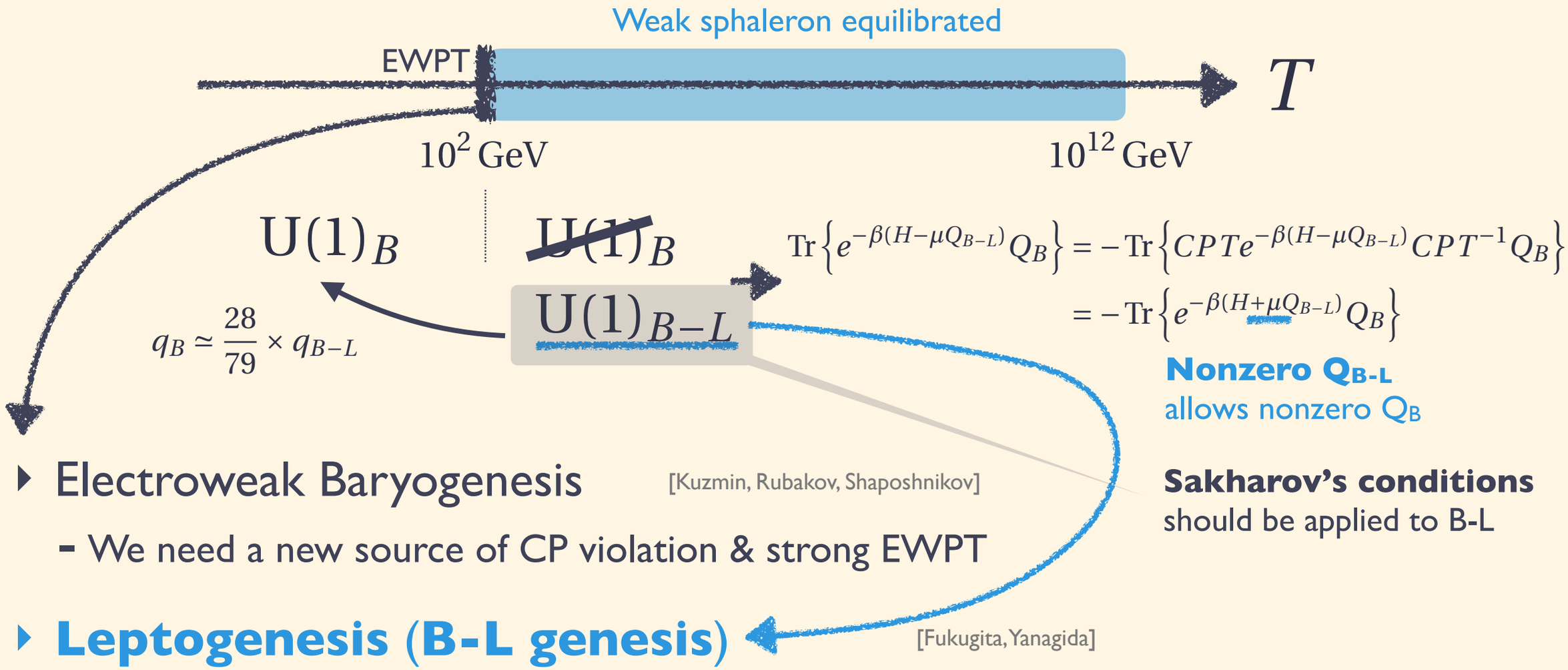


- Electroweak Baryogenesis [Kuzmin, Rubakov, Shaposhnikov]
  - We need a new source of CP violation & strong EWPT
- **Leptogenesis (B-L genesis)** [Fukugita, Yanagida]
  - Two faces of the **dim 5 operator**

$$\frac{c_5^{ff'}}{M}\underset{+1}{(L_{Lf}\cdot H)}\underset{+1}{(L_{Lf'}\cdot H)}$$

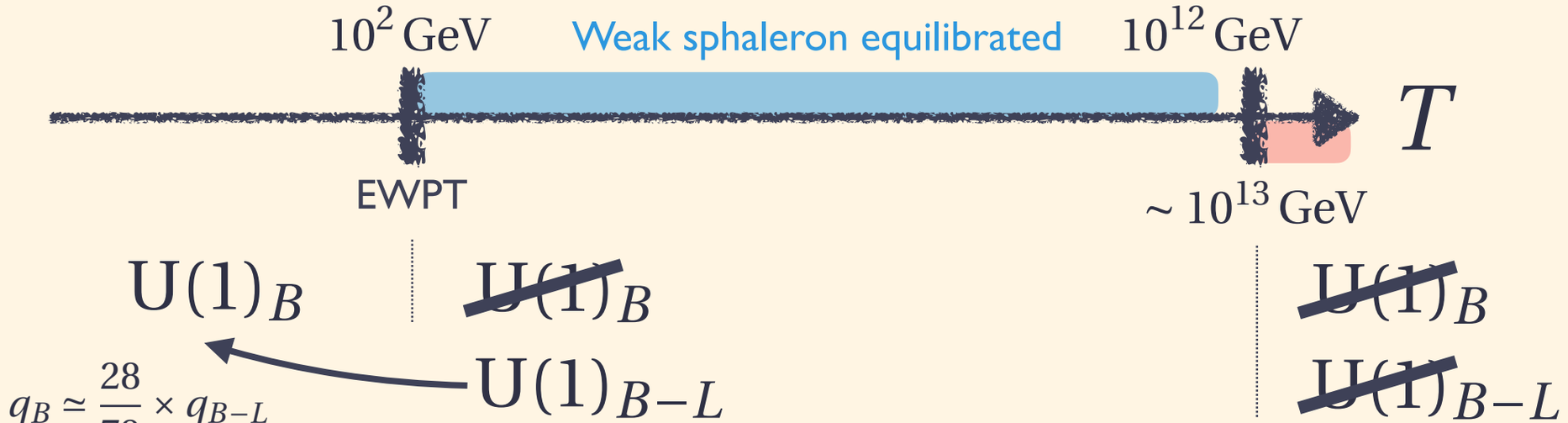
- B-L violation (1st condition)
- neutrino mass

Probed by 0νββ decay!

3.

Leptogenesis & its descendants

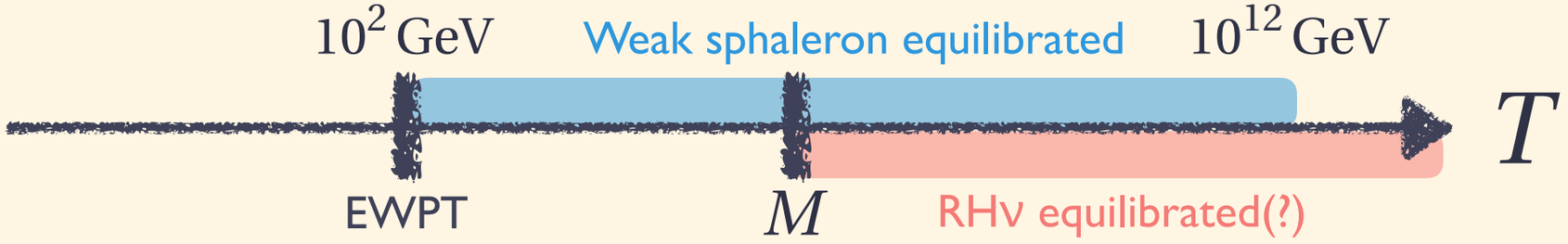
Thermal Leptogenesis



$$\frac{c_5^{ff'}}{M}\left(L_{Lf}\cdot H\right)\left(L_{Lf'}\cdot H\right)$$

Thermal Leptogenesis

Leptogenesis via Majorana RHν



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

$q_B \simeq \frac{28}{79} \times q_{B-L}$ ← $\mathrm{U}(1)_{B-L}$ ~~$\mathrm{U}(1)_{B-L}$~~

$$\mathrm{Tr}\left\{e^{-\beta H} Q_{B-L}\right\} = \mathrm{Tr}\left\{e^{-\beta H} CPT Q_{B-L} CPT^{-1}\right\} = -\mathrm{Tr}\left\{e^{-\beta H} Q_{B-L}\right\} = 0$$

$$\frac{c_5^{ff'}}{M}\left(L_{Lf}\cdot H\right)\left(L_{Lf'}\cdot H\right) \leftarrow h_{\alpha f}\overset{-1\ +1}{\overline{N_{R\alpha}}} L_{Lf} H + \frac{1}{2} M_\alpha \overset{+1\ \ +1}{N_{R\alpha} N_{R\alpha}}$$

RHν thermally populated

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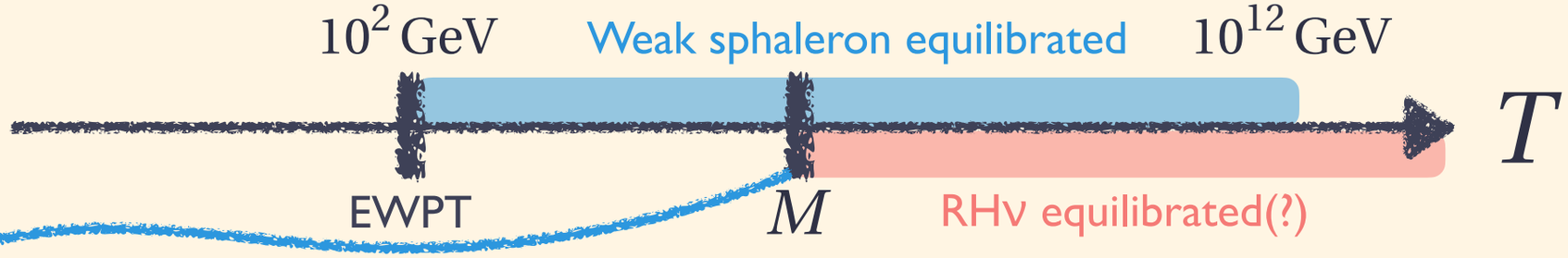

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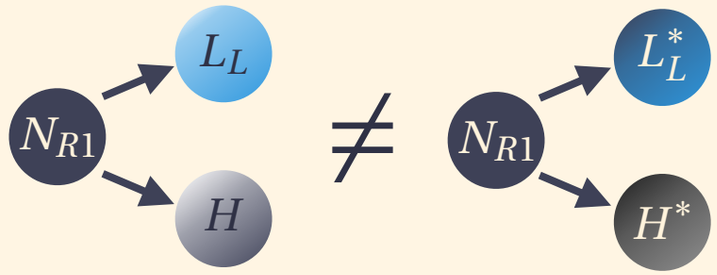
$-1\ +1$ $\qquad$ $+1\ \ +1$ $\qquad$ ① RHν thermally populated

- **Thermal** Leptogenesis [Fukugita, Yanagida Phys.Lett.B 174 (1986)]

  - non-equilibrium + CP-violating decay of Majorana RHν @ T ~ M

Sakharov's conditions



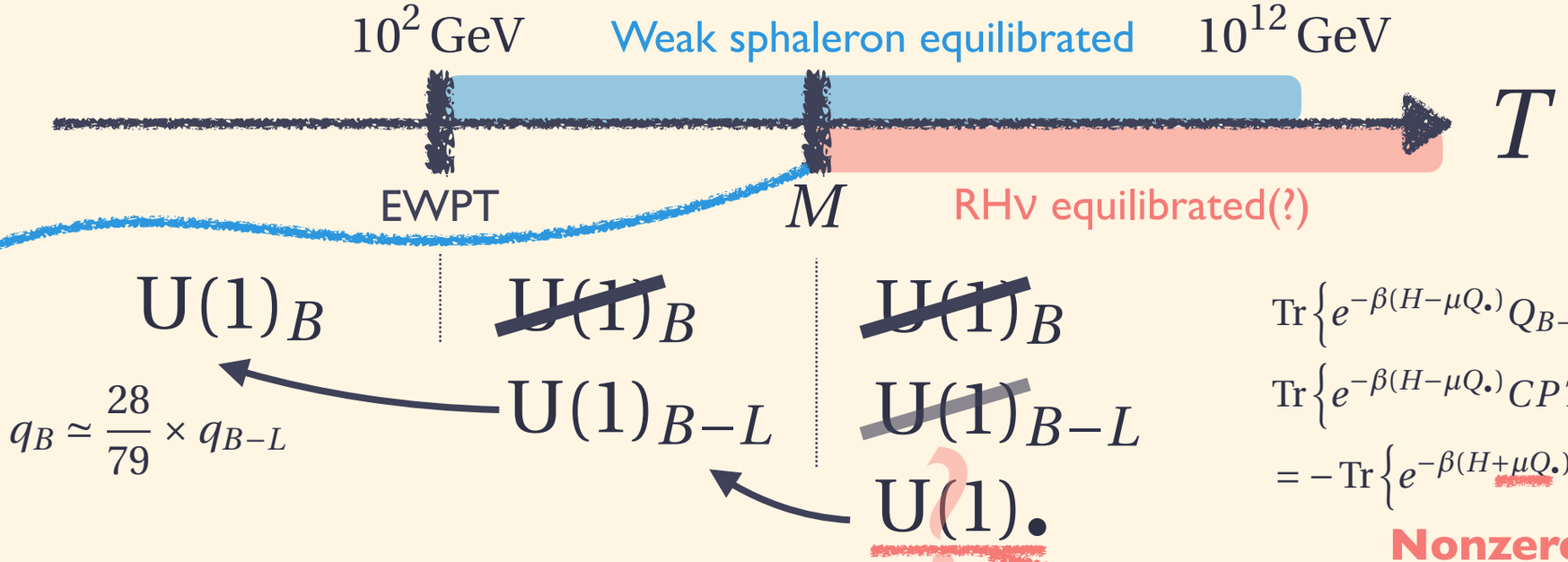
$$\frac{n_B}{s} \simeq 0.3 \times 10^{-10}\left(\frac{\kappa}{0.1}\right)\left(\frac{M_1}{10^9\mathrm{GeV}}\right)\left(\frac{m_{\nu 3}}{0.05\mathrm{eV}}\right)\delta_{\mathrm{eff}}$$

③ **wash-out factor** $\kappa \to 0$ @ thermal eq.

② **CP-violating phase** via ν-Yukawa (h)

Wash-in Leptogenesis

Leptogenesis via Majorana RHν



Other conserved quantities in SM?

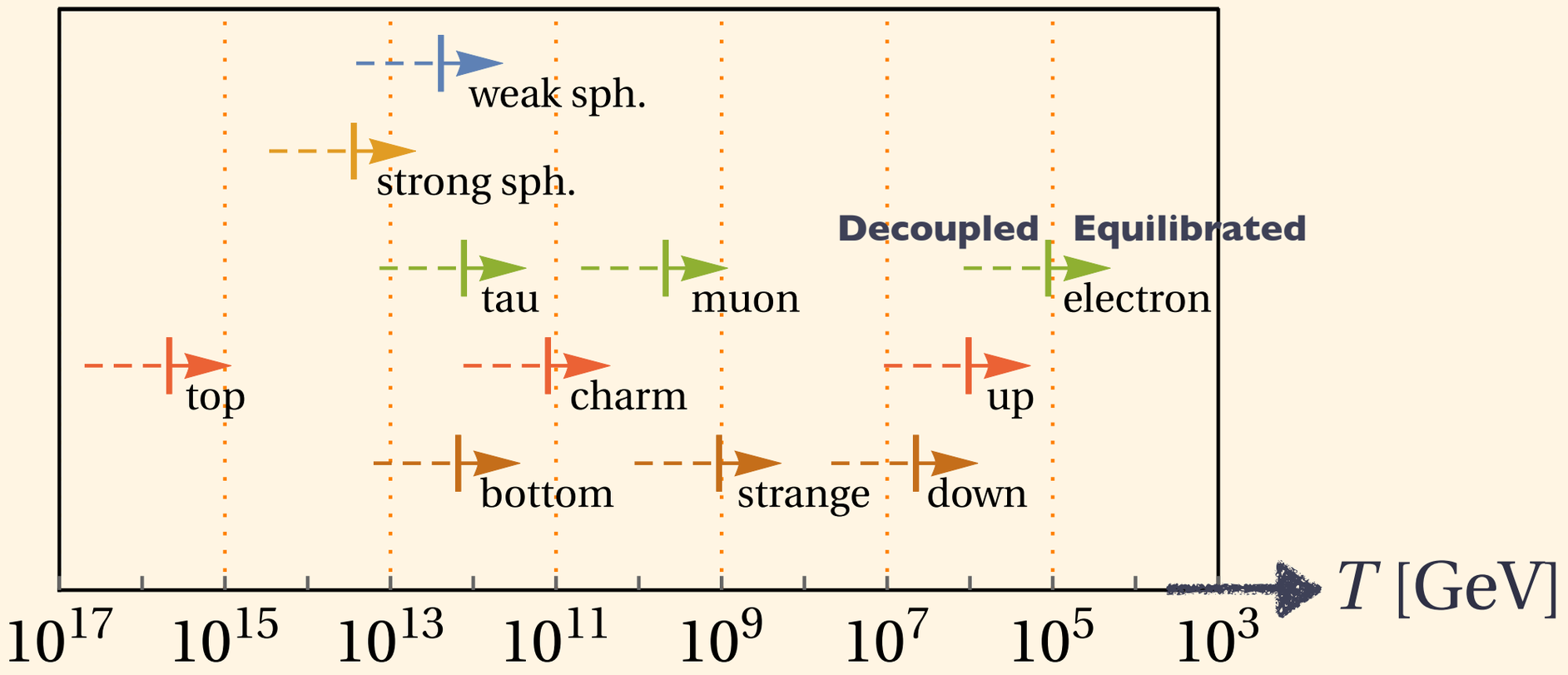
- **Thermal** Leptogenesis [Fukugita, Yanagida Phys.Lett.B 174 (1986)]
  - non-equilibrium + CP-violating decay of Majorana RHν @ T ~ M > 10^9 GeV

- **Wash-in** Leptogenesis [**KM**+ Phys. Rev. Lett. 126, 201802 (2021)]
  - Some conserved (?) charge **q•** is converted to **$q_{B\text{-}L}$**

Conserved charges @ high T

Approximate conserved charges in SM

- **Decoupling** of SM interactions at high T



[B.A.Campbell+ *Phys.Lett.B* 297 (1992) 118-124; **KM**+ JHEP 08 (2020) 096]

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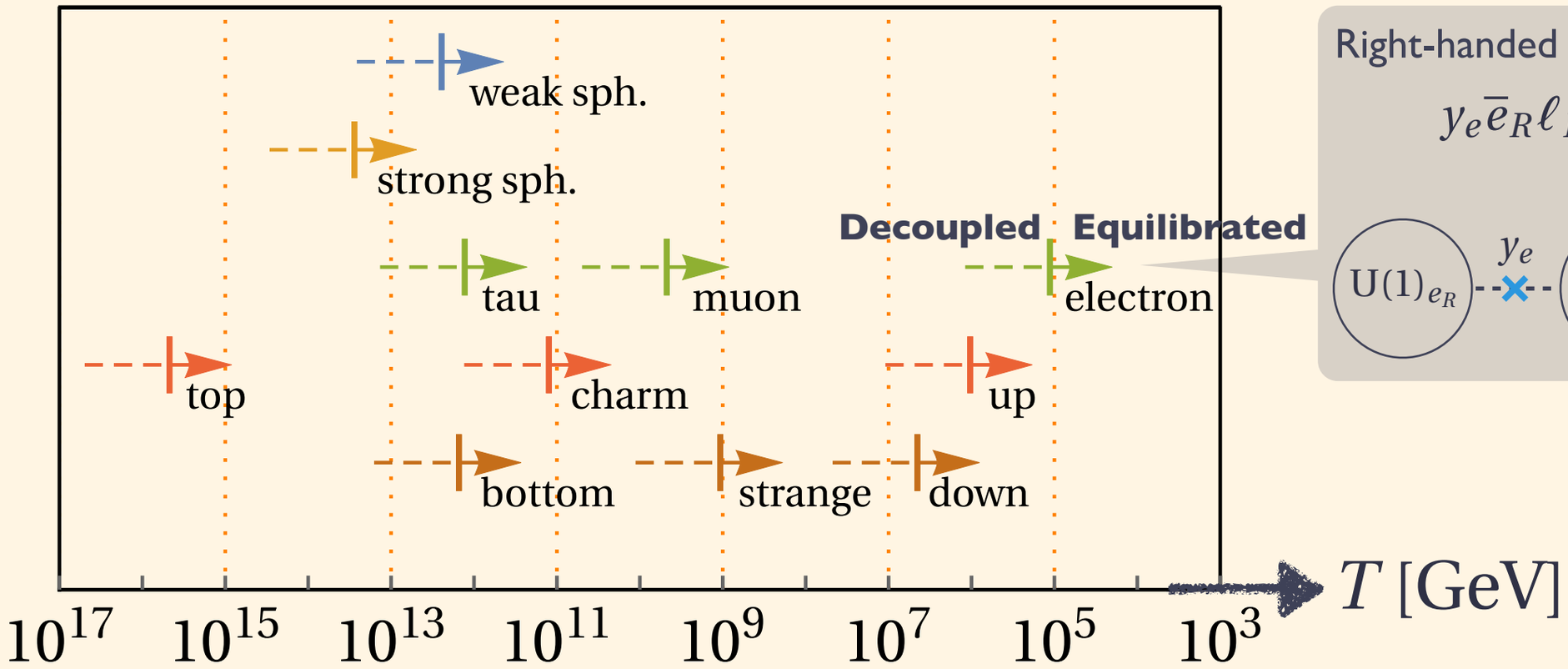

Right-handed **electron Yukawa**

$$y_e \bar{e}_R \ell_{Le} H^\dagger + \text{H.c.}$$

$\mathrm{U}(1)_{e_R}$ --y_e-- $\mathrm{U}(1)_{L_{Le}}$ ▶ **Sphaleron** washout

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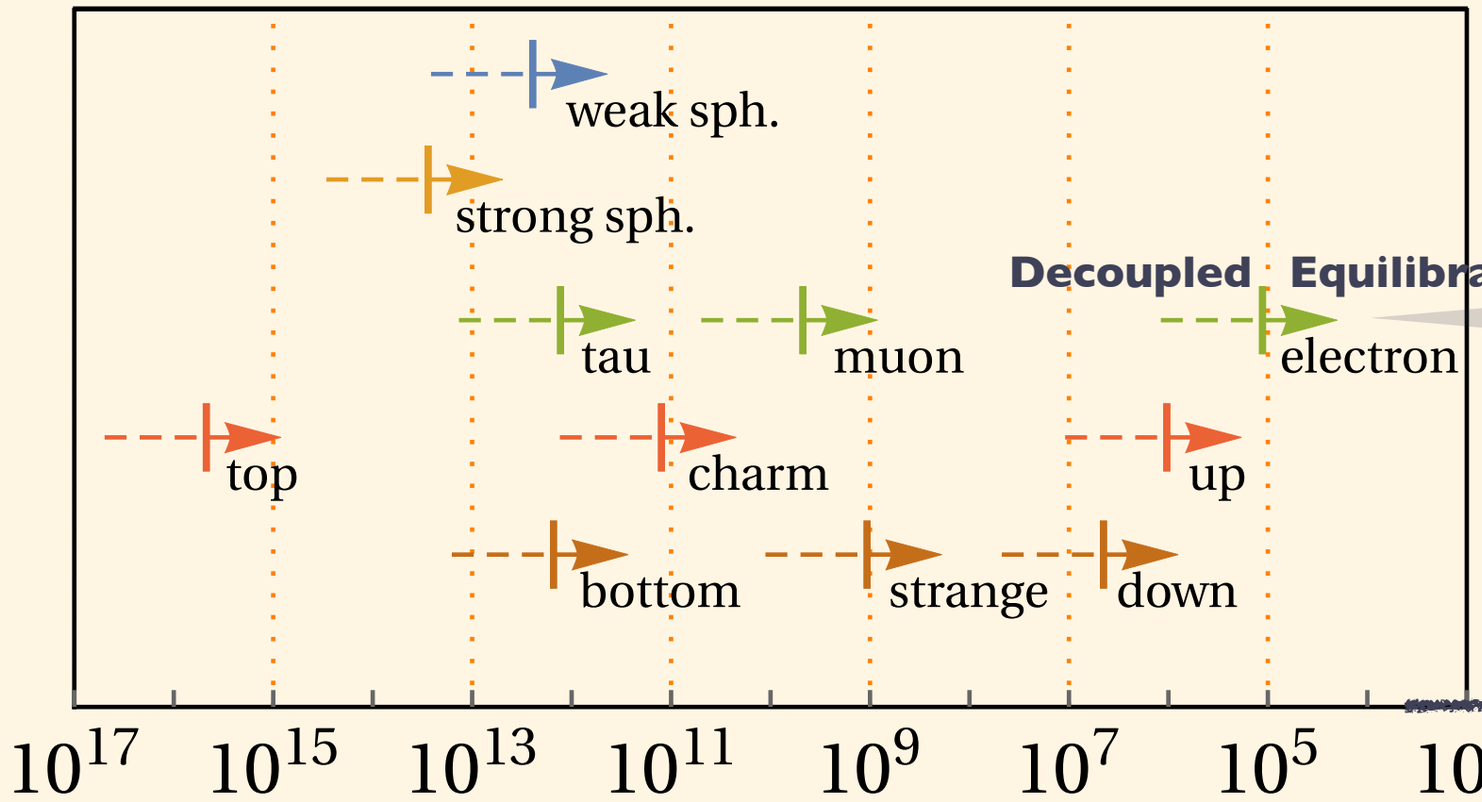

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- Conserved charges **emerge** at high T

E.g., right-handed electron charge $\mathrm{U}(1)_{e_R}$ ~~$\mathrm{U}(1)_{e_R}$~~

Conserved charges @ high T

Approximate conserved charges in SM

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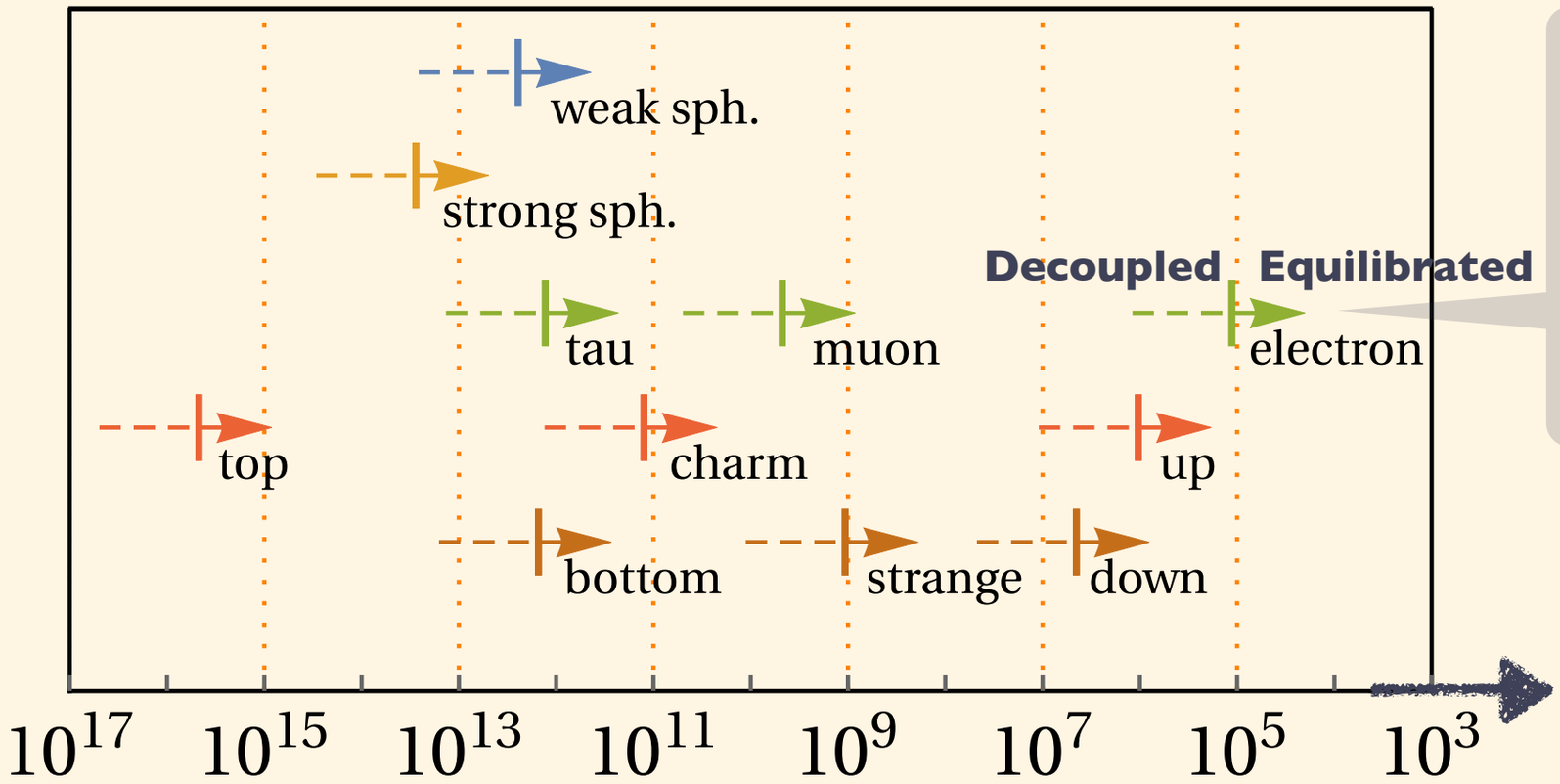

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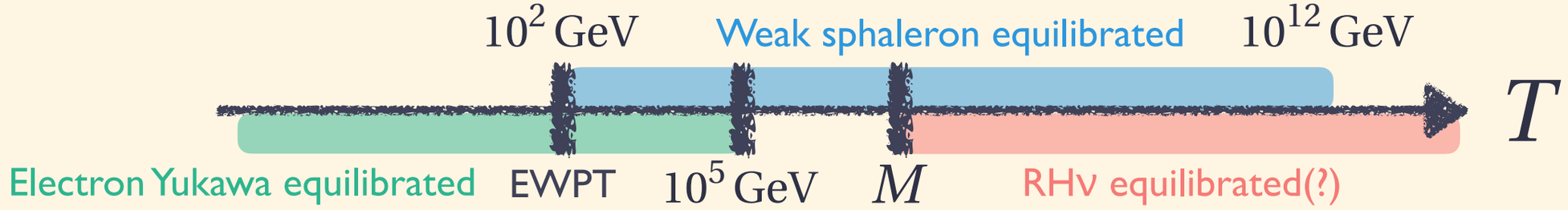
	T [GeV]	y_e	y_{ds}	y_d	y_s	y_{sb}	y_μ	y_c	y_τ	y_b	WS	SS	y_t
(v)	$(10^5, 10^6)$	q_e	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iv)	$(10^6, 10^9)$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iii)	$(10^9, 10^{11-12})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	✓	✓	✓	✓	✓	✓
(ii)	$(10^{11-12}, 10^{13})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	✓	✓
(i)	$(10^{13}, 10^{15})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	q_u	✓

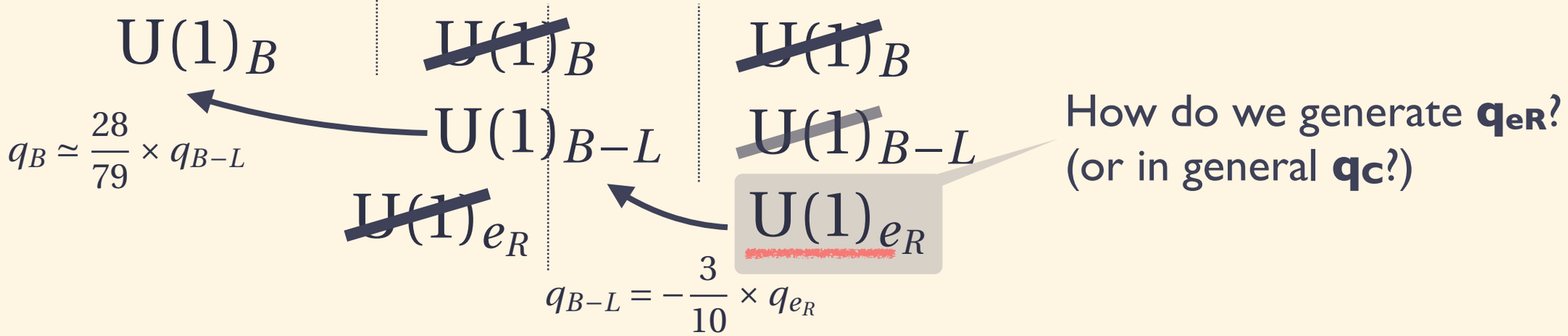
Reprocessed into **B-L charge** via RHν

[**KM**+ Phys.Rev.Lett. 126 (2021) 20, 201802]

Wash-in Leptogenesis

Leptogenesis via Majorana RHν





- **Wash-in** Leptogenesis [**KM**+ Phys. Rev. Lett. 126, 201802 (2021)]
  - Approximate conserved charge $\mathbf{q_C}$ at high T is converted to $\mathbf{q_{B\text{-}L}}$

$$q_{B-L} = \sum_C x_C \, q_C\big|_{T\sim M}$$

	T_{B-L} [GeV]	Index α	μ_e	$\mu_{2B_1-B_2-B_3}$	μ_{u-d}	μ_{d-s}	$\mu_{B_1-B_2}$	μ_μ	μ_{u-c}	μ_τ	μ_{d-b}	μ_B	μ_u	$\mu_{\Delta_\perp}$
(v)	$(10^5, 10^6)$	e,μ,τ	$-\frac{3}{10}$	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
(iv)	$(10^6, 10^9)$	e,μ,τ	$-\frac{3}{17}$	0	$-\frac{7}{17}$	✗	✗	✗	✗	✗	✗	✗	✗	✗
(iii)	$(10^9, 10^{11-12})$	$\parallel_\tau,\tau$	$\frac{142-225P_\tau}{247}$	0	$-\frac{123}{247}$	$-\frac{82}{247}$	$\frac{123}{494}$	$\frac{142-225P_\tau}{247}$	✗	✗	✗	✗	✗	$\frac{225}{247}$
(ii)	$(10^{11-12}, 10^{13})$	$\parallel$	$\frac{-23P+7}{30}$	$\frac{1}{5}$	$-\frac{3}{5}$	$-\frac{1}{6}$	$-\frac{3}{10}$	$\frac{-23P+7}{30}$	$\frac{3}{10}$	$\frac{-23P+7}{30}$	$-\frac{4}{15}$	$\frac{23}{90}$	✗	$\frac{23}{30}$
(i)	$(10^{13}, 10^{15})$	$\parallel$	$\frac{-3P+1}{4}$	$\frac{1}{6}$	$-\frac{5}{6}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$\frac{-3P+1}{4}$	$\frac{1}{4}$	$\frac{-3P+1}{4}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{3}$	$\frac{3}{4}$

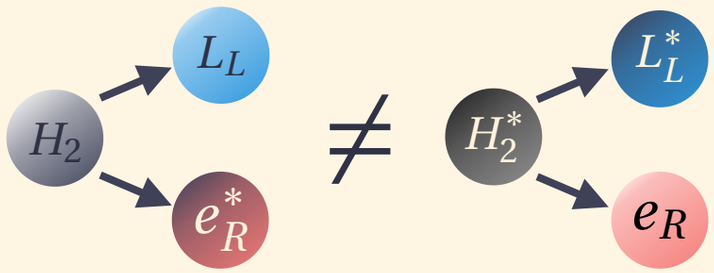
  - It works even if… 1. M > **10^5 GeV**, 2. **No CPV**, 3. **Strong** wath-out

Wash-in Leptogenesis

Examples of q_C asymmetry generation

- Non-equilibrium CPV decay of heavy particle (revival of **GUT baryogenesis?**)

  E.g., $Y^{(e)}_{jff'} H^\dagger_j L_{Lf} \bar{e}_{Rf'}$ Two **heavy** "**Higgs**" H_j (i.e., 3HDM)



$$0 = q_L = q_L\big|_{\text{sphaleron}} + q_{e_R}$$ Sequestered for T > 10^5 GeV

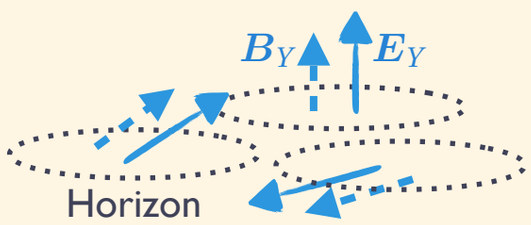
Majorana RHν scatterings $q_{B-L} = -\frac{3}{10} \times q_{e_R}$

- Effective chemical potential from axion inflation

  E.g., $\frac{\phi}{4\Lambda} Y_{\mu\nu} \tilde{Y}^{\mu\nu}$ **axion-like inflaton Φ** w/ Chern-Simons coupling to $U(1)_Y$

  - Simultaneous production of **$U(1)_Y$** gauge field & **q_{eR}** asymmetry during inflation

$$-\langle Y_{\mu\nu} \tilde{Y}^{\mu\nu} \rangle = 4 \langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle \gtrless 0 \quad \text{w/ } \dot{\phi} \gtrless 0$$

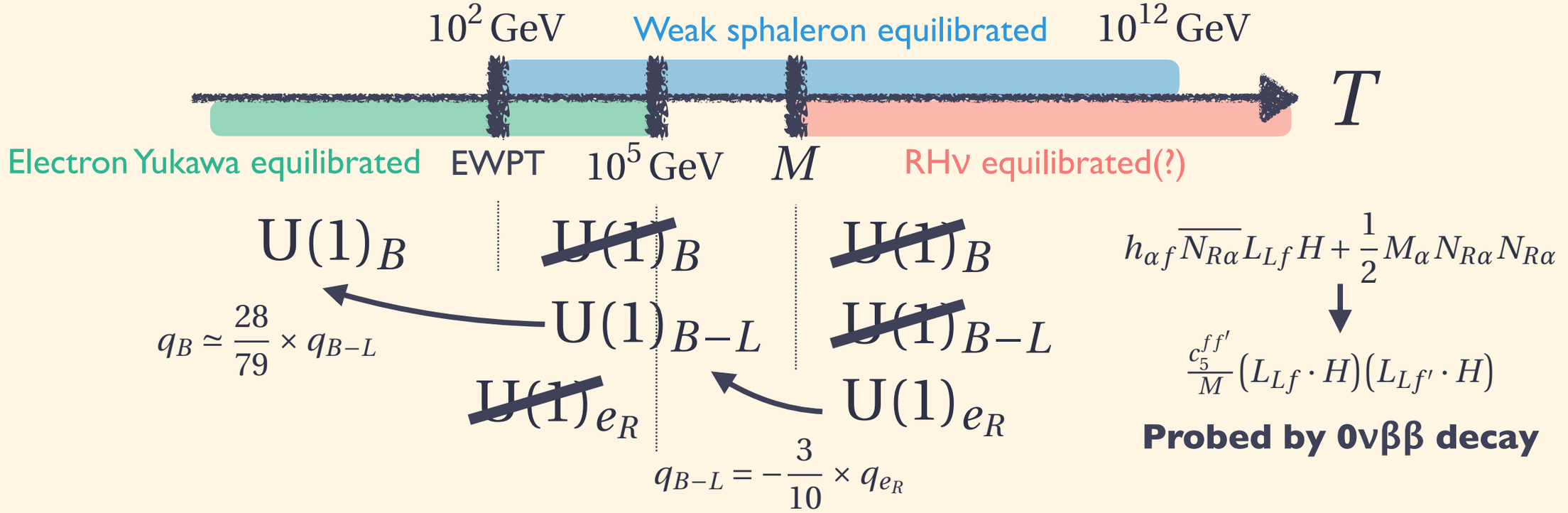


$$\partial_t q_{eR} = \partial_\mu \langle J^\mu_{eR} \rangle = -\frac{g_Y^2}{16\pi^2} \langle Y_{\mu\nu} \tilde{Y}^{\mu\nu} \rangle + \cdots$$

Yukawa interaction negligible for T > 10^5 GeV

Leptoflavorgenesis

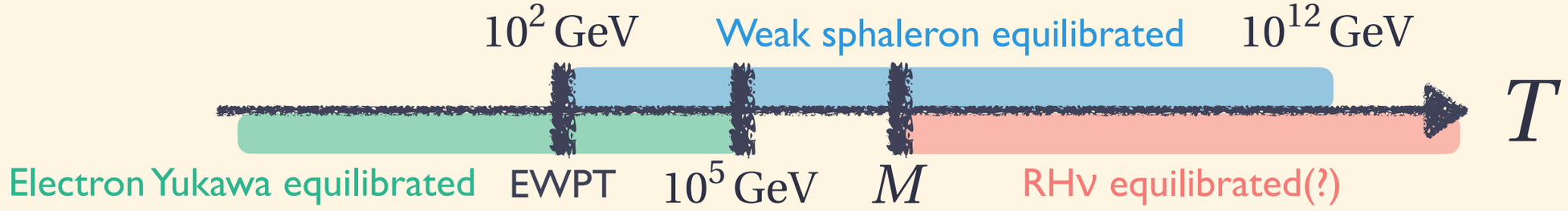
Other options?



- **Thermal** Leptogenesis [Fukugita, Yanagida Phys.Lett.B 174 (1986)]
- **Wash-in** Leptogenesis [**KM**+ Phys. Rev. Lett. 126, 201802 (2021)]

Leptoflavorgenesis

Other options?



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

$\mathrm{U}(1)_{B-L}$ ~~$\mathrm{U}(1)_{B-L}$~~

$q_B \simeq \frac{28}{79} \times q_{B-L}$

~~$\mathrm{U}(1)_{e_R}$~~ $\mathrm{U}(1)_{e_R}$

$q_{B-L} = -\frac{3}{10} \times q_{e_R}$

[Laine, Shaposhnikov 9911473]

$q_B \simeq 0.03 \times \sum_f y_{e_f}^2 q_{\Delta_f}$

lepton Yukawa corrections to ideal gas approx.

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

$h_{\alpha f} \overline{N_{R\alpha}} L_{Lf} H + \frac{1}{2} M_\alpha N_{R\alpha} N_{R\alpha}$

$\downarrow$

$\frac{c_5^{ff'}}{M} (L_{Lf} \cdot H)(L_{Lf'} \cdot H)$

Probed by 0νββ decay

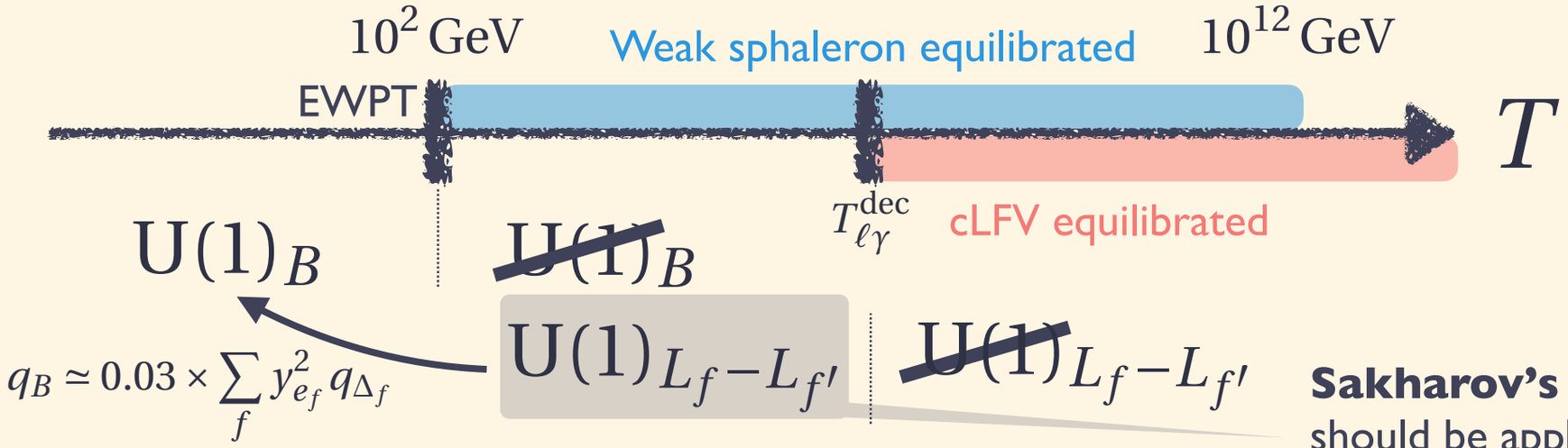
Sakharov's conditions should be applied

- **Thermal** Leptogenesis [Fukugita, Yanagida Phys.Lett.B 174 (1986)]
- **Wash-in** Leptogenesis [**KM**+ Phys. Rev. Lett. 126, 201802 (2021)]
- **Leptoflavorgenesis** [**KM**+ to appear in Phys. Rev. Lett.]

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

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

✓ Current bound [Future prospect]

$$\frac{\Lambda}{\sqrt{C_{\ell\gamma}^{\mu e}}} \gtrsim 6.7\times10^7\ [1.0\times10^8]\ \text{GeV}$$

[MEG / MEG II]

✓ Decoupling temperature of cLFV

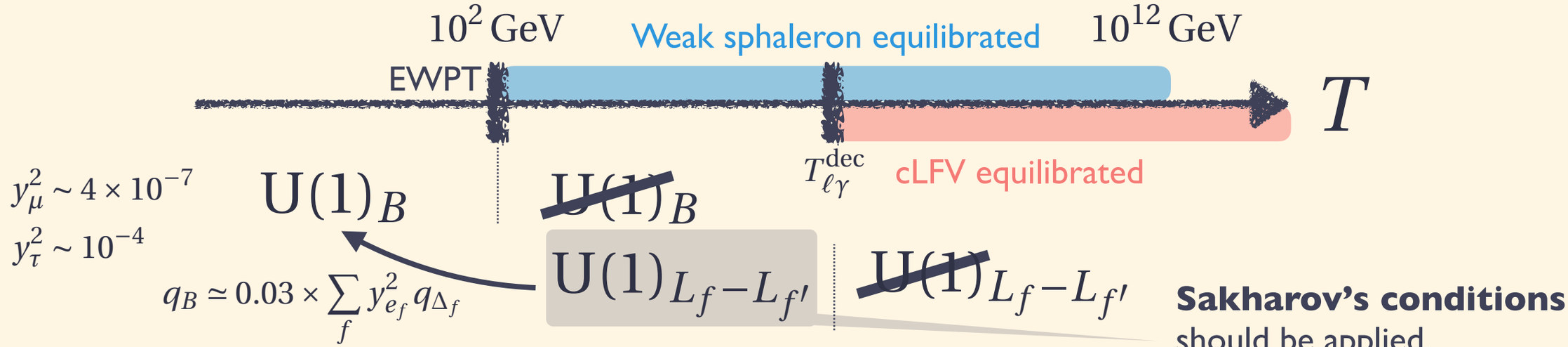
$$T_{\ell\gamma}^{\rm dec} \sim 3\times10^4\,\text{GeV}\left(\frac{\Lambda/\sqrt{C_{\ell\gamma}}}{10^8\,\text{GeV}}\right)^{4/3}$$

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

Leptoflavorgenesis via cLFV

cLFV & Leptoflavorgenesis

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



Sakharov's conditions should be applied.

- **Concrete realization of leptoflavorgenesis via cLFV?**
  - E.g., μ to eγ

$$\frac{2C_{\ell W}^{ff'}}{\Lambda^2} L_{Lf}^\dagger \sigma^{\mu\nu} e_{Rf'} W_{\mu\nu} H \qquad \frac{C_{\ell B}^{ff'}}{\Lambda^2} L_{Lf}^\dagger \sigma^{\mu\nu} e_{Rf'} B_{\mu\nu} H$$

- ✓ Thermal leptoflavorgenesis → However, difficult to generate large asymmetry
- ✓ **Wash-in leptoflavorgenesis** [**KM**, K.Schmitz, M.Yamada 2111.03082]

  Need some mechanism to generate $\mathbf{q_{eR}}$. * Significant suppression if $T_{\ell\gamma}^{\rm dec} \ll T_{y_e}^{\rm dec} \sim 10^5 \mathrm{GeV}$
- ✓ Affleck-Dine leptoflavorgenesis [J.March-Russell+ JHEP 11 (1999) 015]
- ✓ Spontaneous leptoflavorgenesis [**KM**, K.Schmitz, M.Yamada 2111.03082]

…

Summary

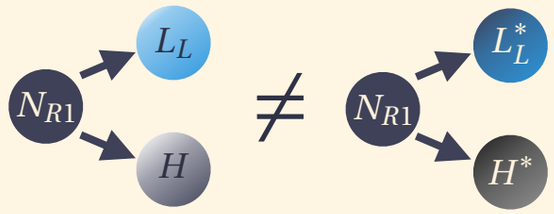
Baryogenesis via Leptogenesis

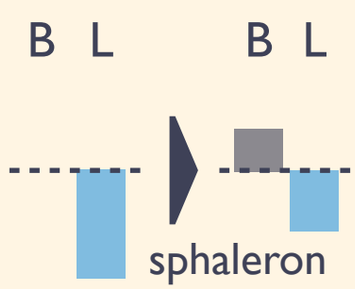
- **B-L genesis** by Majorana RHν (dim 5 op.)

$$h_{\alpha f}\overline{N_{R\alpha}}L_{Lf}H+\frac{1}{2}M_\alpha N_{R\alpha}N_{R\alpha}\longrightarrow\frac{c_5^{ff'}}{M}(L_{Lf}\cdot H)(L_{Lf'}\cdot H)$$

▶ Probed by 0νββ decay!

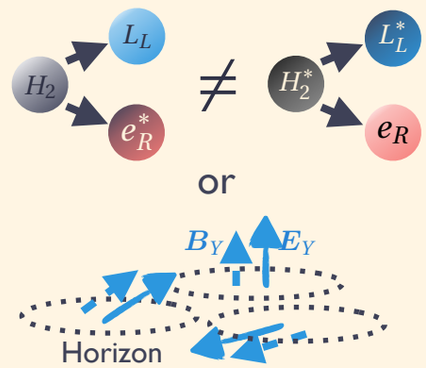
- **Thermal** leptogenesis

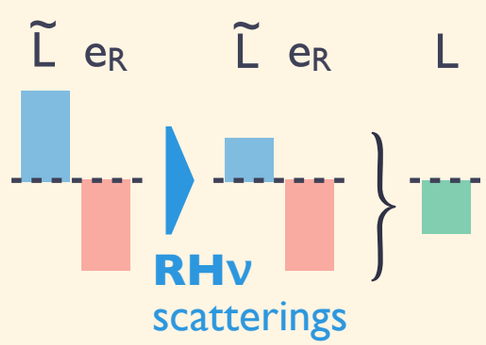




Resonant leptogenesis,
Flavored leptogenesis,…

- **Wash-in** leptogenesis [**KM**+ PRL 126, 201802 (2021)]

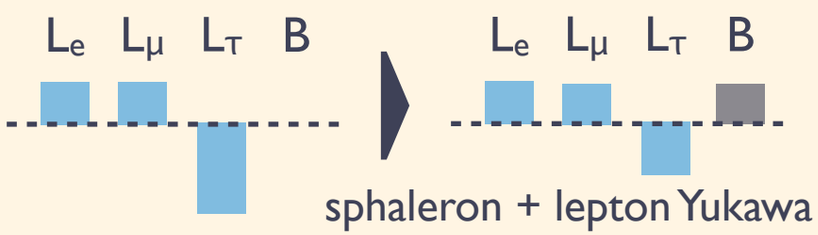




- **Leptoflavorgenesis** via LFV (dim 6 op.) [**KM**, K.Schmitz, M.Yamada 2111.03082]

E.g., $\frac{C_{\ell B}^{ff'}}{\Lambda^2}L_{Lf}^\dagger\sigma^{\mu\nu}e_{Rf'}B_{\mu\nu}H\longrightarrow\frac{C_{\ell\gamma}^{ff'}}{\Lambda^2}\frac{v}{\sqrt{2}}\bar{\ell}_f\sigma^{\mu\nu}P_R\ell_{f'}F_{\mu\nu}$

▶ Probed by μ to eγ!



$$q_B\simeq 0.03\times\sum_f y_{e_f}^2 q_{\Delta_f}$$

[Laine, Shaposhnikov 9911473]

Need **large** lepton asymmetry

1st order QCD PT? [Gao, Oldengott PRL 128 (2022)]

…