Leptogenesis and muon g-2 in gauged $U(1)_{L_\mu - L_\tau}$ extension

Shintaro Eijima (ICRR)

In collaboration with Masahiro Ibe and Kai Murai (ICRR)

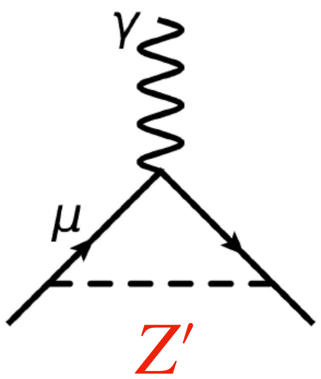
Mar. 7, 2022 @ Exploration of Particle Physics and Cosmology with Neutrinos Workshop 2022

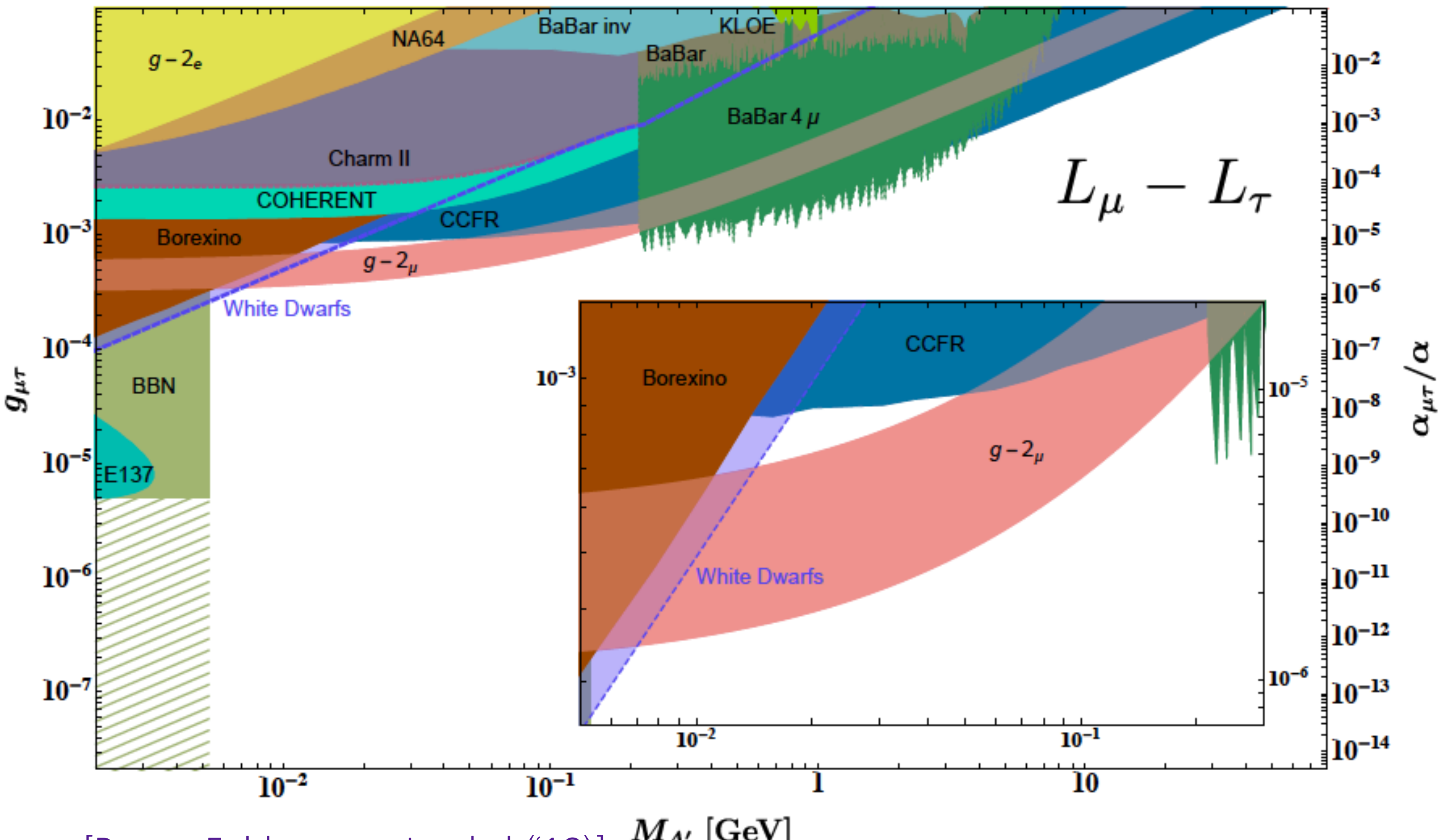
Muon g-2 and gauged $U(1)_{L_\mu - L_\tau}$

$(g-2)_\mu$ anomaly can be explained with Z' in gauged $U(1)_{L_\mu - L_\tau}$ models

Deviation from the Standard Model: 4.2σ

[The Muon g-2 Collaboration ('21)]





[Bauer, Foldenauer, Jaeckel ('18)]

Gauge coupling:

$$g_{Z'} \approx 10^{-4} - 10^{-3}$$

Mass:

$$M_{Z'} \approx 10 - 100\,\mathrm{MeV}$$

↓

Breaking scale:

$$v' = \mathcal{O}(10)\,\mathrm{GeV}$$

Type-I seesaw mechanism under $U(1)_{L_\mu - L_\tau}$ -1-

ν_R's under gauged $U(1)_{L_\mu - L_\tau}$ can reproduce neutrino oscillations

Minimal gauged $U(1)_{L_\mu - L_\tau}$ [Asai, Hamaguchi, Nagata ('17)]

Charge $L_\mu, \nu_{R\mu}$: +1, $L_\tau, \nu_{R\tau}$: -1, Others $(L_e, \nu_{Re}, \cdots)$: 0

$U(1)_{L_\mu - L_\tau}$ breaking scalar σ : +1

Lagrangian of neutrino sector

$\alpha = e, \mu, \tau$

$$\mathcal{L}_\nu = -\lambda_\nu \overline{L_\alpha} \tilde{H} \nu_{R\alpha} - \frac{M_R}{2} \overline{\nu^c_{R\alpha}} \nu_{R\beta}$$

$$- \frac{1}{2} \sum_{\alpha,\beta=e,\mu} h_{\alpha\beta} \sigma^* \overline{\nu^c_{R\alpha}} \nu_{R\beta} - \frac{1}{2} \sum_{\alpha,\beta=e,\tau} h_{\alpha\beta} \sigma \overline{\nu^c_{R\alpha}} \nu_{R\beta} + h.c.$$

$$\lambda_\nu = diag(\lambda_e, \lambda_\mu, \lambda_\tau) \qquad M_R = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau} \\ 0 & M_{\mu\tau} & 0 \end{pmatrix}$$

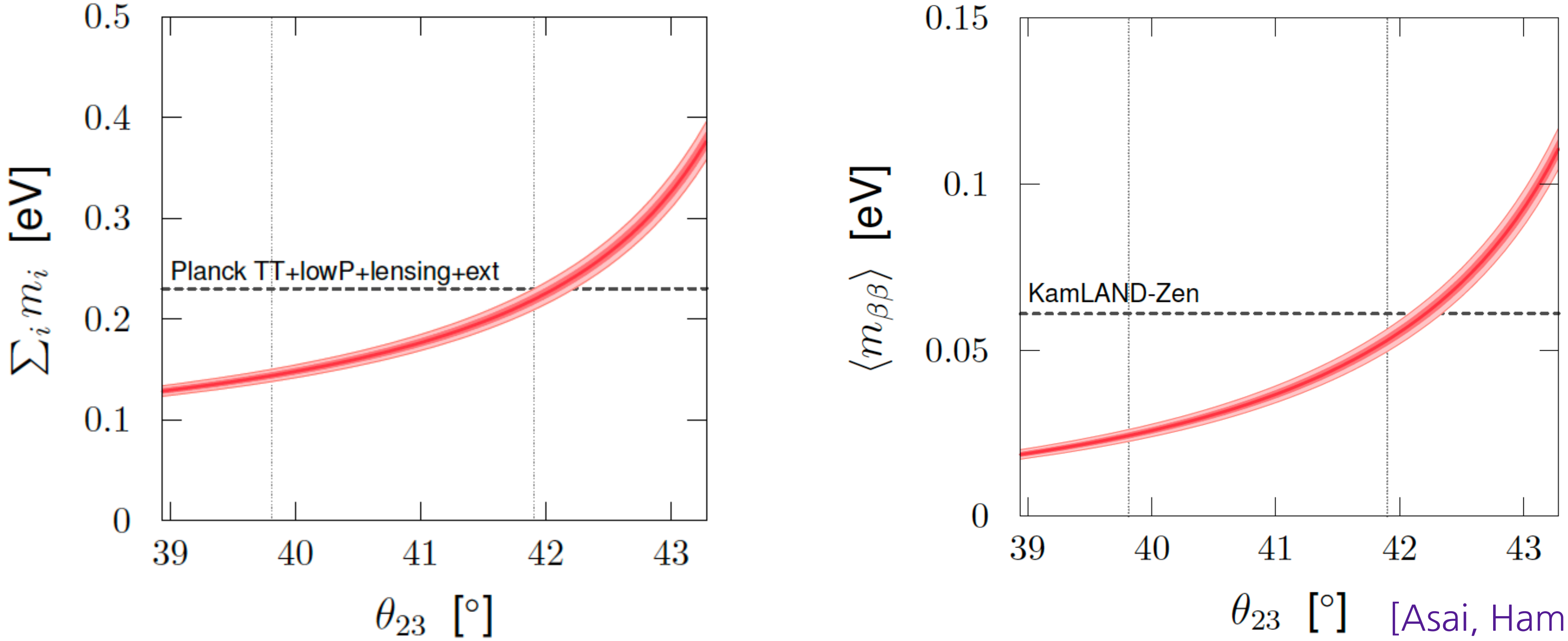
Type-I seesaw mechanism under $U(1)_{L_\mu - L_\tau}$ -2-

ν_R's under gauged $U(1)_{L_\mu - L_\tau}$ can reproduce neutrino oscillations

ν mass matrix: $m_\nu = -\langle H\rangle^2 U^\dagger_{PMNS}[\lambda_\nu M_R^{-1} \lambda_\nu^T] U^*_{PMNS}$

$$M_R = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau} \\ 0 & M_{\mu\tau} & 0 \end{pmatrix} \xrightarrow{\text{Spontaneous breaking of } U(1)_{L_\mu - L_\tau}} \begin{pmatrix} M_{ee} & h_{e\mu}\langle\sigma\rangle & h_{e\tau}\langle\sigma\rangle \\ h_{e\mu}\langle\sigma\rangle & 0 & M_{\mu\tau} \\ h_{e\tau}\langle\sigma\rangle & M_{\mu\tau} & 0 \end{pmatrix} \quad (\langle\sigma\rangle = v'/2)$$

All ν parameters are determined by observed values of oscillations



[Asai, Hamaguchi, Nagata ('17)]

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

How about Leptogenesis??

We investigated whether leptogenesis can work or not in the gauged $U(1)_{L_\mu - L_\tau}$ model responsible for muon g-2

From ν mass matrix $\langle H \rangle^2 m_\nu^{-1} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} \sim \begin{pmatrix} \frac{M_{ee}}{\lambda_e^2} & \frac{h_{e\mu}\langle\sigma\rangle}{\lambda_e\lambda_\mu} & \frac{h_{e\tau}\langle\sigma\rangle}{\lambda_e\lambda_\tau} \\ \frac{h_{e\mu}\langle\sigma\rangle}{\lambda_e\lambda_\mu} & 0 & \frac{M_{\mu\tau}}{\lambda_\mu\lambda_\tau} \\ \frac{h_{e\tau}\langle\sigma\rangle}{\lambda_e\lambda_\tau} & \frac{M_{\mu\tau}}{\lambda_\mu\lambda_\tau} & 0 \end{pmatrix}$

$\longrightarrow M_{ee} M_{\mu\tau} \sim h_{e\mu} h_{e\tau} \langle\sigma\rangle^2$ $\quad (\langle\sigma\rangle = v'/2)$

i) $M_{ee} \ll M_{\mu\tau}$ (or $M_{ee} \gg M_{\mu\tau}$): Heavier mass $\lesssim 10^{12}$ GeV

$\longrightarrow$ Decaying leptogenesis

[Fukugita, Yanagida ('86)][Pilaftsis ('97)][Pilaftsis, Underwood ('05)]

ii) $M_{ee} \sim M_{\mu\tau}$: Degenerate mass $\leq \langle\sigma\rangle = \mathcal{O}(10)$ GeV

$\longrightarrow$ Oscillating leptogenesis

[Akhmedov, Rubakov, Smirnov ('98)][Asaka, Shaposhnikov ('05)]

Broken or not in cosmological history?

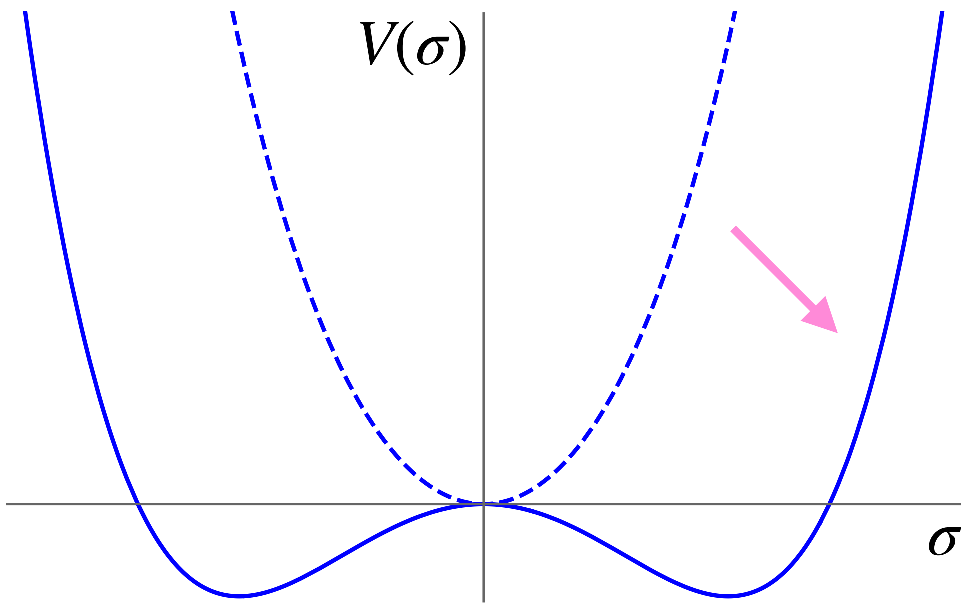
Whether $U(1)_{L_\mu - L_\tau}$ is broken or preserved is important for leptogenesis

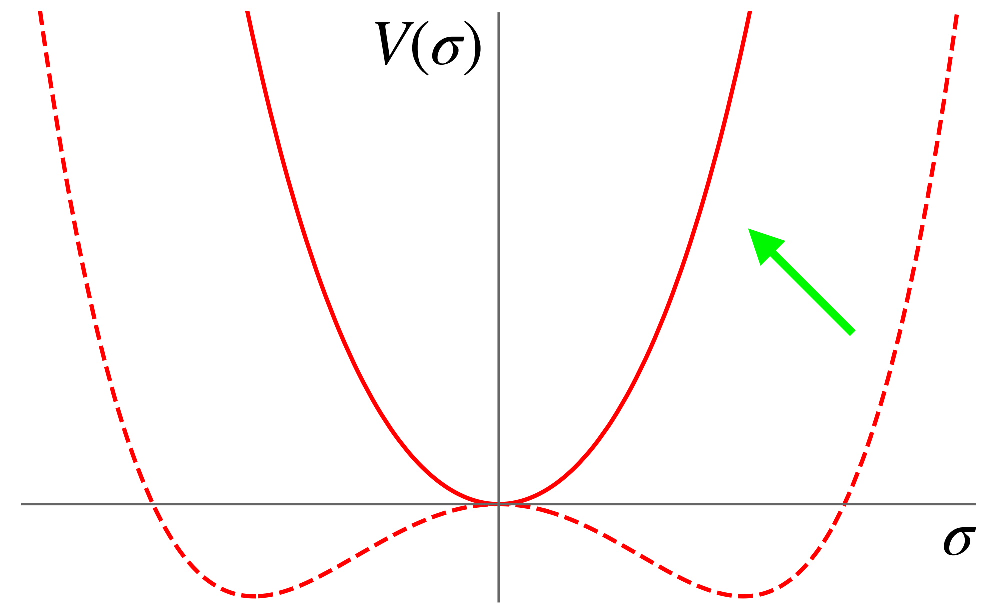
$$V(\sigma) = (-\mu_\sigma^2 + \delta m^2(T))\,|\sigma|^2 + \lambda_\sigma |\sigma|^4$$

: quantum corrections

< 0 → Spontaneous breaking

> 0 → Restoration





Restoration with $g_{Z'}$ is evaluated when $U(1)_{L_\mu - L_\tau}$ is broken and no σ, ν_R and Z' initially

Thermalization

$U(1)_{L_\mu - L_\tau}$ gauge interaction thermalizes σ through $\mu\bar{\mu}(\tau\bar{\tau}) \to \sigma\sigma^*$

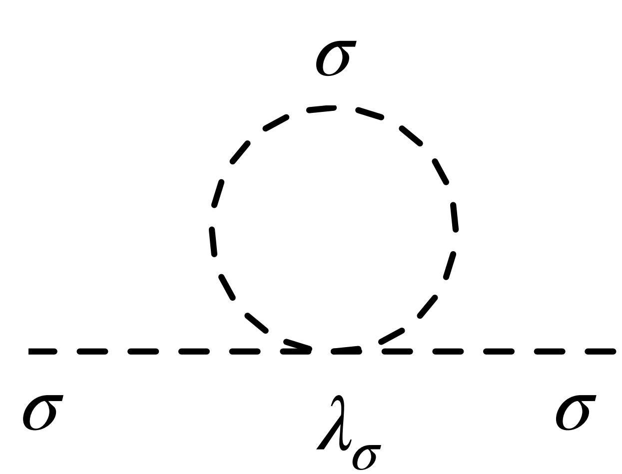
Comparing $\Gamma \approx \frac{g_{Z'}^4}{4\pi} T$ to $H = \left(\frac{\pi^2 g_*}{90}\right)^{\frac{1}{2}} \frac{T^2}{M_p}$ $\quad$ ($M_p = 2.4 \cdot 10^{18}$ GeV)

Thermalization temperature: $T_{th} \sim 4 \cdot 10^3$ GeV $\left(\frac{g_{Z'}}{5 \cdot 10^{-4}}\right)^4$

At $T \leq T_{th}$, thermal mass is $\delta m^2(T) = \lambda_\sigma T^2$

$$(-\mu_\sigma^2 + \delta m^2(T)) = (-\lambda_\sigma v'^2 + \delta m^2(T)) > 0$$

down to $T = v'$



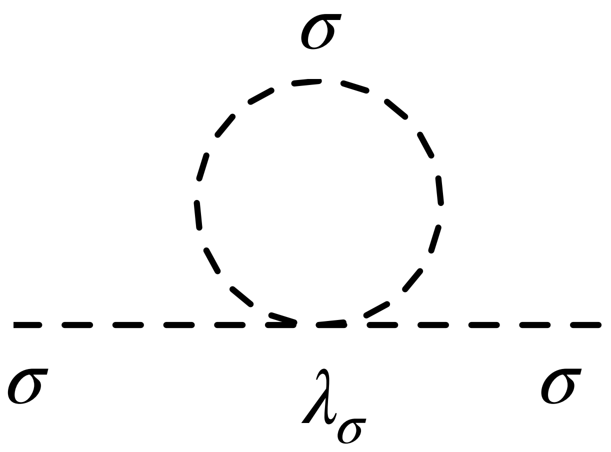
$U(1)_{L_\mu - L_\tau}$ symmetry is restored in $v' \leq T \leq T_{th}$

ν_R and Z' are also thermalized at $T \leq T_{th}$ and contribute to $\delta m^2(T)$

Finite density effect

Even before thermalization particles around σ provide mass correction

$$\delta m^2(T) = \lambda_\sigma \frac{n_\sigma(T)}{\langle 2p^0 \rangle}$$



Solving Boltzmann eq.

$$n_\sigma(T) \approx \frac{g_{Z'}^4}{4\pi} M_p T^2 \quad \text{for} \quad T > T_{th}$$

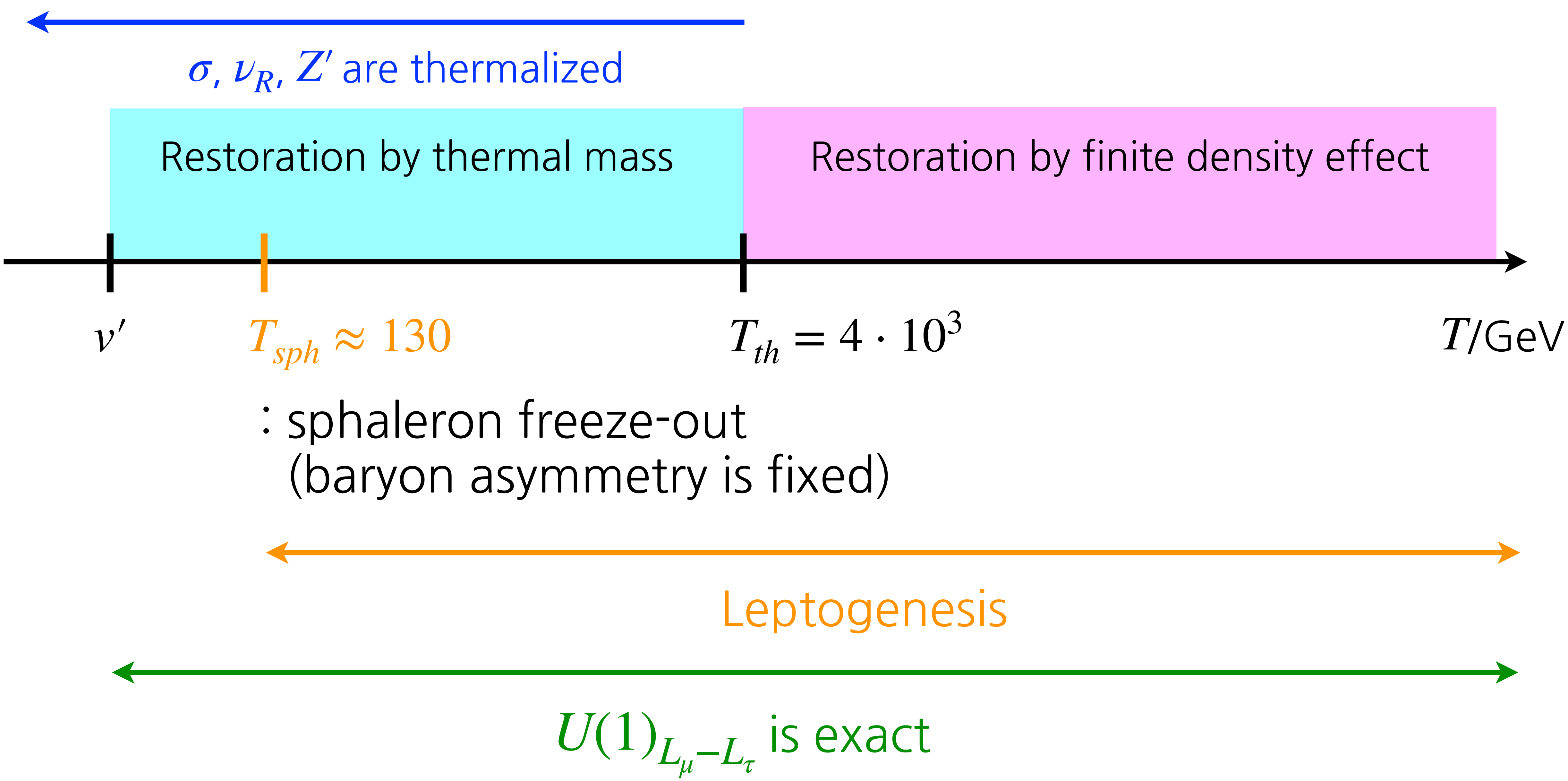
$$\longrightarrow \quad \frac{\delta m^2(T)}{\mu_\sigma^2} \approx 2 \cdot 10^3 \left(\frac{50\,\text{GeV}}{v'} \right)^2 \left(\frac{g_{Z'}}{5 \cdot 10^{-4}} \right)^8 \left(\frac{T}{T_{th}} \right) \quad (\langle 2p^0 \rangle = 2T)$$

$U(1)_{L_\mu - L_\tau}$ **symmetry is also restored at** $T > T_{th}$

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

$U(1)_{L_\mu - L_\tau}$ is exact in temperatures in which leptogenesis can take place

For $g_{Z'} = 5 \cdot 10^{-4}$ and $v' = 50$ GeV from muon g-2,



Right-handed neutrinos under exact $U(1)_{L_\mu - L_\tau}$

There still exist ingredients; CP violation and lepton number violation

- CP violation: at least one physical phase in λ_α, $h_{e\mu}$, $h_{e\tau}$ and M
- Lepton number violation: M_{ee} and $M_{\mu\tau}$

For decays, Pseudo-Dirac representation $\Psi \equiv \begin{pmatrix} \nu_{R\mu}^c \\ \nu_{R\tau} \end{pmatrix}$ for mass basis

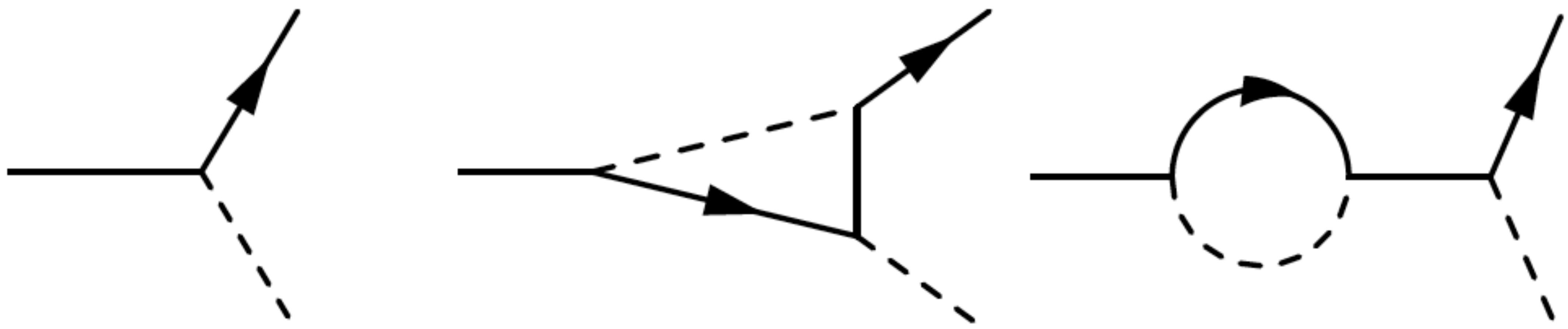
$$\mathcal{L}_{\nu_{Re}} = \overline{\nu_{Re}} i\partial\!\!\!/ \nu_{Re} - \lambda_e \overline{L_e} \tilde{H} \nu_{Re} - \frac{M_{ee}}{2} \overline{\nu_{Re}^c} \nu_{Re} + h.c.,$$

$$\begin{aligned}\mathcal{L}_\Psi &= \overline{\Psi} i D\!\!\!\!/\, \Psi - M_{\mu\tau} \overline{\Psi}\Psi \\ &- \left(\lambda_\mu \overline{L_\mu} \tilde{H} P_R \Psi^c + \lambda_\tau \overline{L_\tau} \tilde{H} P_R \Psi - \frac{1}{2} h_{e\mu} \sigma^* \overline{\nu_{Re}^c} P_R \Psi^c - \frac{1}{2} h_{e\tau} \sigma \overline{\nu_{Re}^c} P_R \Psi + h.c. \right)\end{aligned}$$

Leptogenesis with either ν_{Re} or Ψ decay can be considered

Decaying Leptogenesis

CP violation arises interference between tree and loop diagrams



Vertex diagram — Product of Yukawa couplings in interference term

ν_{Re} decay: $|\lambda_e|^4$

Ψ decay: $|\lambda_\mu|^2 |\lambda_\tau|^2$

Real

Self-energy diagram — Not exists. Just self-energy of incoming ν_R

Restricted flavor structure forbids to provide CP violation

No leptogenesis from decays

Oscillating Leptogenesis

CP violating ν_R oscillations are source of lepton asymmetry

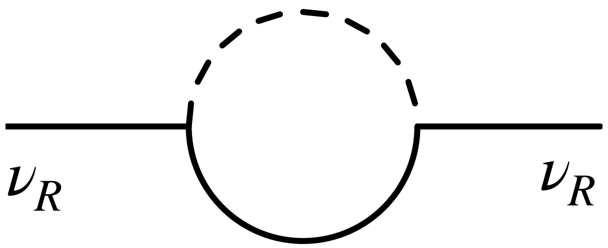
Density matrix formalizm

Density matrix of ν_R : $\rho_{\nu_R} = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$

- $\rho_{\alpha\alpha}$: occupation number
- $\rho_{\alpha\beta}$: correlation among flavors

Oscillations are described by commutator with effective Hamiltonian

$$\frac{d\rho_{\nu_R}}{dt} \supset -i[H_{\nu_R}, \rho_{\nu_R}] \qquad \text{(3x3)}$$



$$H_{\nu_R} = H_0 + H_I$$

H_I: Diagonal from λ_α, $h_{e\mu}$, and $h_{e\tau}$

$$H_0 = p\,\mathbf{1} + \frac{1}{2p} M_R^\dagger M_R = p\,\mathbf{1} + \frac{1}{2p} \begin{pmatrix} M^2_{ee} & 0 & 0 \\ 0 & M^2_{\mu\tau} & 0 \\ 0 & 0 & M^2_{\mu\tau} \end{pmatrix}$$ Diagonal

Restricted flavor structure forbids to give rise ν_R oscillations

No leptogenesis from oscillations too

Summary

We found incompatibility of leptogenesis with the gauged $U(1)_{L_\mu - L_\tau}$ extension responsible for muon g-2

Contrary to optimistic expectation, the minimal extension fails to explain the muon g-2 anomaly, neutrino masses, and the baryon asymmetry of the Universe at the same time

Other approaches or further extensions compatible with $U(1)_{L_\mu - L_\tau}$ are necessary to construct theory for such phenomena beyond the Standard Model