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Baryogenesis from Cosmological CP Violation

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Based on **2504.03506** with **Mateusz Duch** and **Alessandro Strumia**

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PIANO NAZIONALE DI RIPRESA E RESILIENZA

Outline

- Motivation
- Theories for spontaneous CP violation
  - Effective field theory
  - Modular invariance
- Generation of the baryon asymmetry
  - Evolution equations for chemical potentials
  - Lepton-number-violating interactions
  - Solutions to evolution equations
  - Modular baryogenesis

Motivation

What can the modulus scalar τ do in cosmology?

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Be responsible for inflation — τ as the inflaton?

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Ding, Jiang, Zhao, 2405.06497
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Ding, Jiang, Xu, Zhao, 2411.18603
Aoki, Otsuka, Yanagita, 2504.01622

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What about baryogenesis (not via leptogenesis)?

Motivation

CP violation is a necessary ingredient for baryogengesis

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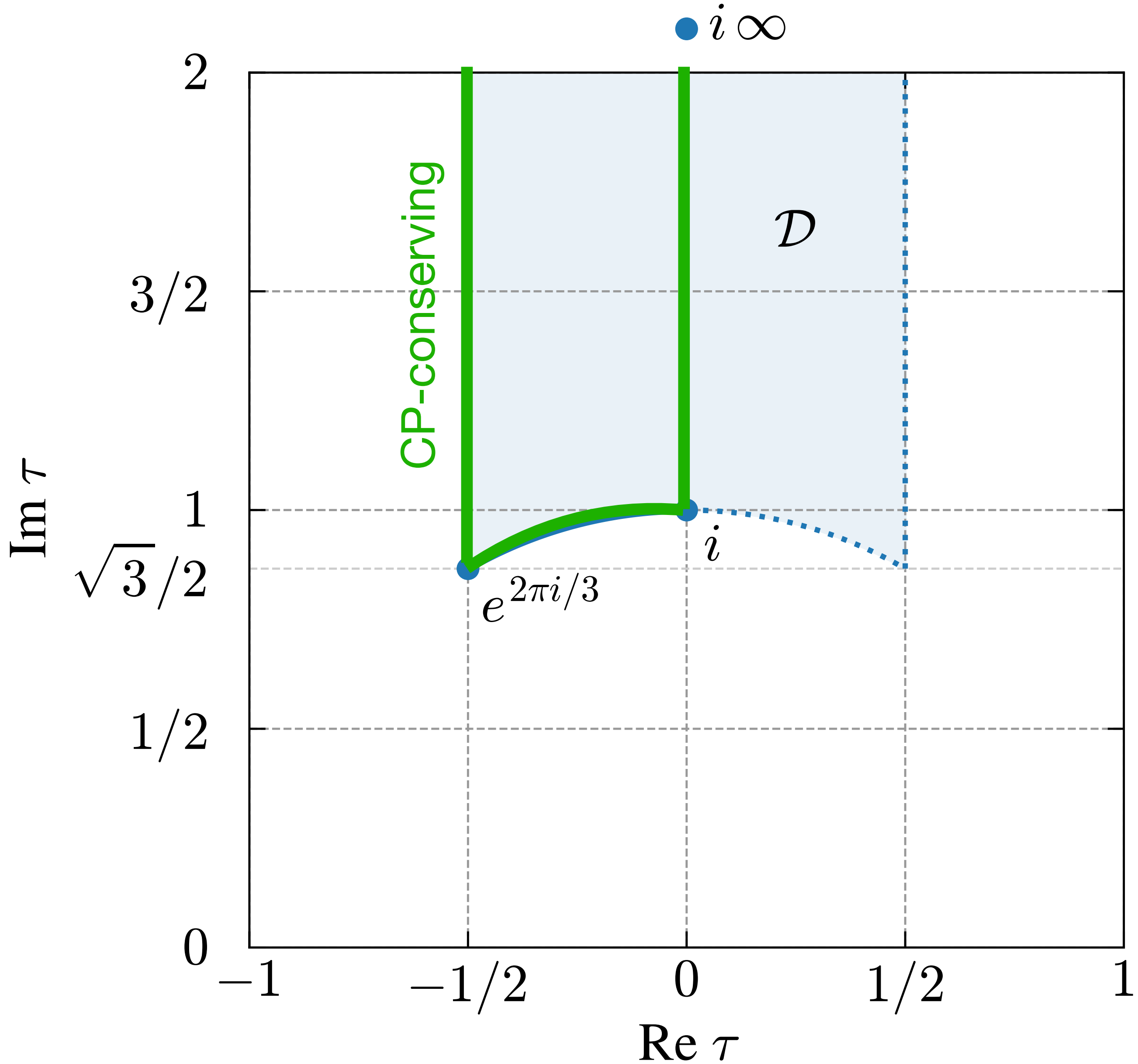

Novichkov, Penedo, Petcov, Titov, 1905.11970
Baur, Nilles, Trautner, Vaudrevange, 1901.03251

CP violation is a necessary ingredient for baryogengesis

$$\tau = \tau_R + i\,\tau_I$$

$$\tau \xrightarrow{\text{CP}} -\tau^* \quad \Leftrightarrow \quad \begin{cases} \tau_R \xrightarrow{\text{CP}} -\tau_R \\ \tau_I \xrightarrow{\text{CP}} \tau_I \end{cases}$$

τ_R can be the only source of (spontaneous) CP violation

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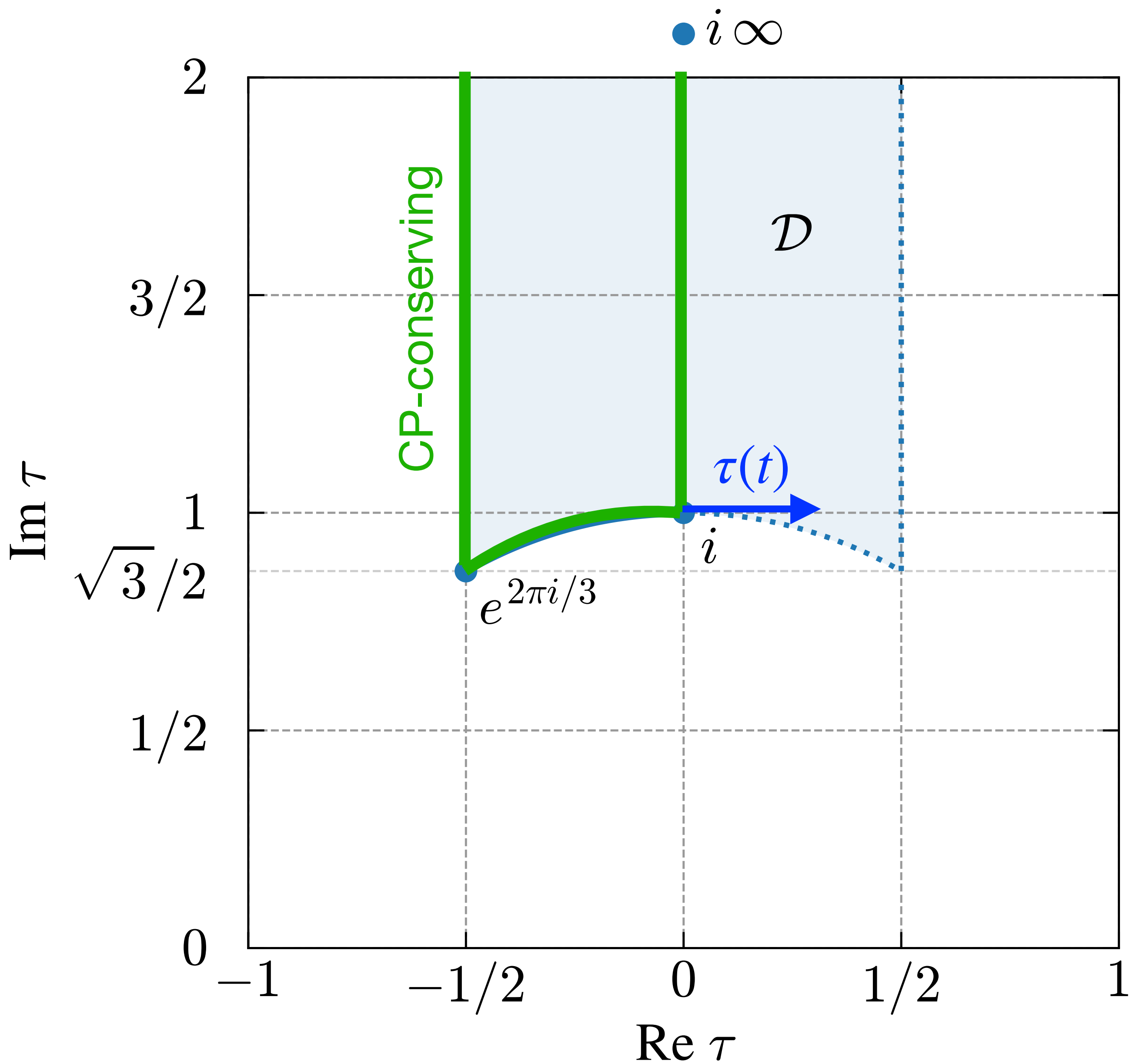

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τ_R can be the only source of (spontaneous) CP violation

Can the cosmological evolution of $\tau(t)$ generate the baryon asymmetry?

EFT for spontaneous CP violation

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{kin}} - V(H,\tau)$$
$$- \left[Y_{\text{u}}(\tau)\, QUH + Y_{\text{d}}(\tau)\, QDH^* + Y_{\text{e}}(\tau)\, LEH^* + Y_{\nu}(\tau)\, LNH + \frac{1}{2} M(\tau)\, NN + \text{h.c.} \right]$$
$$+ \sum_P c_P(\tau)\, \partial_\mu \tau\, J_P^\mu + \theta_3(\tau) \frac{g_3^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \theta_2(\tau) \frac{g_2^2}{32\pi^2} W^a_{\mu\nu} \tilde{W}^{a\mu\nu} + \theta_1(\tau) \frac{g_Y^2}{16\pi^2} Y_{\mu\nu} \tilde{Y}^{\mu\nu}$$

Particle number currents

$$J_\psi = \bar{\psi} \bar{\sigma}^\mu \psi \qquad \psi = \{Q, U, D, L, E, N\}$$
$$J_H = i \left(H^\dagger \partial_\mu H - H \partial_\mu H^\dagger \right)$$

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$c_P(\tau)$ can be removed by τ-dependent field redefinition

$$P \to e^{i\phi_P(\tau)} P \quad \text{with} \quad \phi_P(\tau) = \int^\tau d\tau'\, c_P(\tau')$$

$$Y_{\text{u}}(\tau) \to e^{i(\phi_Q + \phi_U + \phi_H)}\, Y_{\text{u}}(\tau) \qquad Y_{\text{d}}(\tau) \to e^{i(\phi_Q + \phi_D - \phi_H)}\, Y_{\text{d}}(\tau)$$
$$Y_{\text{e}}(\tau) \to e^{i(\phi_L + \phi_E - \phi_H)}\, Y_{\text{e}}(\tau) \qquad Y_{\nu}(\tau) \to e^{i(\phi_L + \phi_N + \phi_H)}\, Y_{\nu}(\tau)$$

$$\theta_3(\tau) \to \theta_3(\tau) - N_{\text{gen}}(2\phi_Q + \phi_U + \phi_D) \qquad \theta_2(\tau) \to \theta_2(\tau) - N_{\text{gen}}(3\phi_Q + \phi_L)$$

Modular invariance

$$\tau \to \frac{a\tau + b}{c\tau + d}\,, \qquad P \to (c\tau + d)^{-k_P} P\,, \qquad Y(\tau) \to (c\tau + d)^{k_Y} Y(\tau)$$

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}(2,\mathbb{Z})$$

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$$\mathscr{L}_{\text{kin}} = h^2 \frac{|\partial_\mu \tau|^2}{(-i\tau + i\bar{\tau})^2} + \left[\frac{i}{2} \frac{\bar{\psi}\bar{\sigma}^\mu D_\mu \psi}{(-i\tau + i\bar{\tau})^{k_\psi}} + \text{h.c.}\right] + \frac{|D_\mu H|^2}{(-i\tau + i\bar{\tau})^{k_H}}$$

$$D_\mu = \partial_\mu + ik_P \frac{\partial_\mu \tau}{-i\tau + i\bar{\tau}}\,, \qquad D_\mu P \to (c\tau + d)^{-k_P} D_\mu P$$

$$\frac{i}{2} \frac{\bar{\psi}\bar{\sigma}^\mu D_\mu \psi}{(-i\tau + i\bar{\tau})^{k_\psi}} + \text{h.c.} = \frac{1}{(2\tau_I)^{k_\psi}} \left[i\bar{\psi}\bar{\sigma}^\mu \partial_\mu \psi \; - \; k_\psi \frac{\partial_\mu \tau_R}{2\tau_I} \bar{\psi}\bar{\sigma}^\mu \psi \right]$$

Each fermion couples to CP-breaking τ_R proportionally to its modular weight k_ψ

Modular invariance and SUSY

Minimal Kähler potential

$$K = -\,h^2 \ln(-i\tau + i\bar{\tau}) + \sum_{\Phi} \frac{\Phi^\dagger \Phi}{(-i\tau + i\bar{\tau})^{k_\Phi}}$$

Superfields τ and $\Phi = Q,\ U,\ D,\ L,\ E,\ N,\ H_u,\ H_d$

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Superfields τ and $\Phi = Q,\ U,\ D,\ L,\ E,\ N,\ H_u,\ H_d$

Going to components…

$$K_i^{\bar{j}} = \frac{\partial^2}{\partial \phi^i \partial \bar{\phi}_{\bar{j}}} K(\phi, \bar{\phi})\,, \quad D_\mu \psi^i = \partial_\mu \psi^i + \Gamma^i_{jk} \partial_\mu \phi^j \psi^k\,, \quad \Gamma^i_{jk} = \left(K^{-1}\right)^i_{\bar{m}} K^{\bar{m}}_{jk}$$

$$\mathscr{L}_{\text{kin}} \supset \frac{i}{2} K_i^{\bar{j}} \bar{\psi}_{\bar{j}} \bar{\sigma}^\mu D_\mu \psi^i + \text{h.c.} = \frac{1}{(2\tau_I)^{k_\psi}} \left[i\bar{\psi}\bar{\sigma}^\mu \partial_\mu \psi - k_\psi \frac{\partial_\mu \tau_R}{2\tau_I} \bar{\psi}\bar{\sigma}^\mu \psi \right]$$

The same structure as in the previous slide

Generation of the baryon asymmetry

Number asymmetry

$$\Delta_P = n_P - n_{\bar{P}} = c_{\rm spin}\, d_P\, T^3 \frac{\mu_P}{T}\,, \qquad c_{\rm spin} = \begin{cases} 1/6 & \text{fermion} \\ 1/3 & \text{boson} \end{cases}$$

μ_P is chemical potential

Baryon asymmetry

$$n_B = \frac{N_{\rm gen}}{3}\left(2\Delta_Q - \Delta_U - \Delta_D\right) = \frac{\mu_B T^2}{6}\,, \quad \mu_B \equiv 3\left(2\mu_Q - \mu_U - \mu_D\right)$$

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Chemical potentials are sourced by

- current couplings $c_P(\tau)$
- Yukawas $Y_P(\tau)$
- theta terms $\theta_{2,3}(\tau)$

Generation of the baryon asymmetry

- Current terms

Cohen, Kaplan, PLB **199** (1987) 251

$$c_P \, \partial_\mu \tau \, J_P^\mu = \mu_P \, J_P^0 \qquad \text{with} \qquad \mu_P = c_P \dot{\tau}$$

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$$c_P\,\partial_\mu\tau\,J_P^\mu = \mu_P\,J_P^0 \qquad \text{with} \qquad \mu_P = c_P\dot{\tau}$$

- Yukawas and Majorana mass

$$Y_P = |\,Y_P\,|\,e^{i\theta_{Y_P}}\,, \qquad M = |\,M\,|\,e^{i\theta_M}$$

Rephasing-invariant combinations:

$$\mu_{Y_\mathrm{u}} \equiv \left(d\theta_{Y_\mathrm{u}}/d\tau + c_Q + c_U + c_H\right)\dot{\tau}\,, \qquad \mu_{Y_\mathrm{d}} \equiv \left(d\theta_{Y_\mathrm{d}}/d\tau + c_Q + c_D - c_H\right)\dot{\tau}$$

$$\mu_{Y_\mathrm{e}} \equiv \left(d\theta_{Y_\mathrm{e}}/d\tau + c_L + c_E - c_H\right)\dot{\tau}\,, \qquad \mu_{Y_\nu} \equiv \left(d\theta_{Y_\nu}/d\tau + c_L + c_N + c_H\right)\dot{\tau}$$

$$\mu_M = \left(d\theta_M/d\tau + 2c_N\right)\dot{\tau}$$

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- Theta terms (weak and strong sphalerons)

$$\mu_{S_2} = \left[-d\theta_2/d\tau + N_\mathrm{gen}\left(3c_Q + c_L\right)\right]\dot{\tau}\,, \qquad \mu_{S_3} = \left[-d\theta_3/d\tau + N_\mathrm{gen}\left(2c_Q + c_U + c_D\right)\right]\dot{\tau}$$

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In the basis where $c_P(\tau) = 0$:

$$\boxed{\mu_{Y_P} = \dot{\theta}_{Y_P}\,, \qquad \mu_{S_i} = -\,\dot{\theta}_i}$$

Evolution equations

Number asymmetries $\Delta_P = n_P - n_{\bar{P}}$ obey the following eqs (assuming $N_{\text{gen}} = 1$)

$$\dot{\Delta}_U + 3H\Delta_U = -S_{Y_u} - S_{S_3}$$
$$\dot{\Delta}_D + 3H\Delta_D = -S_{Y_d} - S_{S_3}$$
$$\dot{\Delta}_Q + 3H\Delta_Q = -S_{Y_u} - S_{Y_d} - 3S_{S_2} - 2S_{S_3}$$
$$\dot{\Delta}_L + 3H\Delta_L = -S_{Y_e} - S_{S_2} - 2S_{\Delta L=2}$$
$$\dot{\Delta}_E + 3H\Delta_E = -S_{Y_e}$$
$$\dot{\Delta}_H + 3H\Delta_H = -S_{Y_u} + S_{Y_d} + S_{Y_e} - 2S_{\Delta L=2}$$

All S_I in the r.h.s. associated to the interaction I (Yukawas, weak/strong sphalerons, or $\Delta L = 2$ interactions) have a common structure:

$$\underbrace{S_I = \gamma_I}_{I \text{ rate per unit volume}} \times \underbrace{\left(\text{combination of } \mu_P \text{ involved in } I \text{ and } \mu_I\right)}_{\text{defined on the previous slide}}/T$$

Evolution equations

- Terms induced by Yukawas

$$S_{Y_\mathrm{u}} = \gamma_{Y_\mathrm{u}} \frac{\mu_Q + \mu_U + \mu_H - \mu_{Y_\mathrm{u}}}{T}\,, \qquad S_{Y_\mathrm{d}} = \gamma_{Y_\mathrm{d}} \frac{\mu_Q + \mu_D - \mu_H - \mu_{Y_\mathrm{d}}}{T}$$

$$S_{Y_\mathrm{e}} = \gamma_{Y_\mathrm{e}} \frac{\mu_L + \mu_E - \mu_H - \mu_{Y_\mathrm{e}}}{T}\,, \qquad S_{Y_\nu} = \gamma_{Y_\nu} \frac{\mu_L + \mu_N + \mu_H - \mu_{Y_\nu}}{T}$$

Neglecting masses, $\gamma_{Y_\mathrm{u}} \approx |Y_\mathrm{u}|^2 T^4$, $\gamma_{Y_\mathrm{e}} \approx |Y_\mathrm{e}|^2 T^4$, etc. $(2 \to 2$ interactions)

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- Terms induced by weak and strong sphalerons

$$S_{S_2} = \gamma_{S_2} \frac{\mu_L + 3\mu_Q - \mu_{S_2}}{T}\,, \qquad S_{S_3} = \gamma_{S_3} \frac{2\mu_Q + \mu_U + \mu_D - \mu_{S_3}}{T}$$

$$\gamma_{S_2} \approx 10\alpha_2^5 T^4\,, \qquad \gamma_{S_3} \approx 100\alpha_3^5 T^4$$

Evolution equations

- Terms induced by Yukawas

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- Terms induced by weak and strong sphalerons

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$$\gamma_{S_2} \approx 10\alpha_2^5 T^4\,, \qquad \gamma_{S_3} \approx 100\alpha_3^5 T^4$$

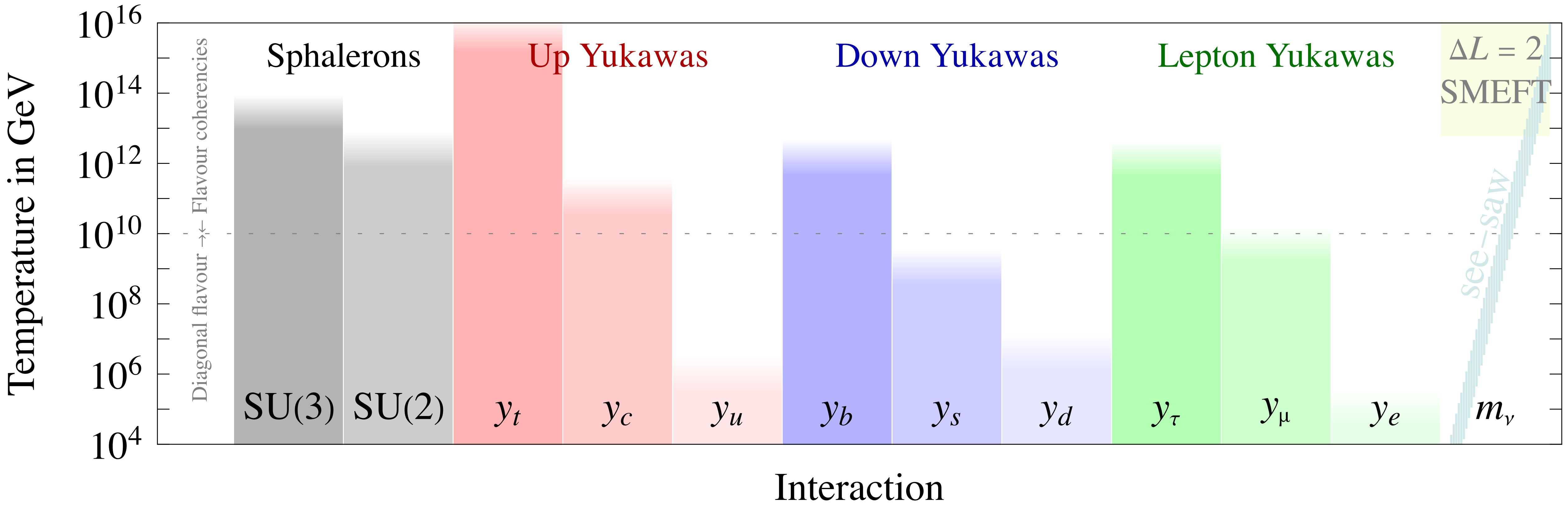
- Term induced by $\Delta L = 2$ interactions

$$S_{\Delta L=2} = \gamma_{\Delta L=2} \frac{2\left(\mu_L + \mu_H\right) - \mu_{LLHH}}{T} \qquad \text{where} \qquad \mu_{LLHH} = 2\mu_{Y_\nu} - \mu_M$$

This term requires a dedicated discussion

Thermal equilibrium for different interactions

$$\Gamma_I(T_{\rm dec}) = \frac{\gamma_I(T_{\rm dec})}{T^3_{\rm dec}} \sim H(T_{\rm dec}) \approx \frac{T^2_{\rm dec}}{M_{\rm Pl}}$$



Lepton-number-violating interactions

- Weinberg operator

$$\frac{1}{2\Lambda}(LH)^2 \quad \text{with} \quad \Lambda = \frac{v^2}{m_\nu} \approx 6 \times 10^{14}\ \text{GeV} \quad \text{for} \quad m_\nu = m_{\text{atm}} = 0.05\ \text{eV}$$

$$\gamma_W \approx T^6/\Lambda^2 \quad \Rightarrow \quad T \gtrsim \Lambda^2/M_{\text{Pl}} \approx 10^{12}\ \text{GeV}$$

Lepton-number-violating interactions

- Heavy Majorana neutrino

$$\frac{1}{\Lambda} = \frac{Y_\nu^2}{M}$$

γ_{Y_ν} dominated by on-shell $N \leftrightarrow LH, \bar{L}H^*$ decays with $\Gamma_N = \dfrac{|Y_\nu|^2 M}{8\pi}$

$$\dot{\Delta}_N + 3H\Delta_N = -S_{Y_\nu} - 2S_M, \qquad S_M = \gamma_M \frac{2\mu_N - \mu_M}{T}$$

NO with $m_{\nu_1} \ll m_{\nu_2} = m_{\rm sun} = \sqrt{\Delta m_{21}^2} \ll m_{\nu_3} = m_{\rm atm} = \sqrt{|\Delta m_{32}^2|}$

$$\frac{\Gamma_N}{H} \approx \frac{\tilde{m}}{m_*}, \qquad m_* = \frac{256\sqrt{d_{\rm SM}}v^2}{3M_{\rm Pl}} \approx 23\,{\rm meV}$$

- $N_{\rm atm}$ that mediates $m_{\rm atm} \gtrsim m_*$ is in thermal equilibrium for $0.1\,M \lesssim T \lesssim 10\,M$
- $N_{\rm sol}$ that mediates $m_{\rm sun} \lesssim m_*$ is out of equilibrium for any T

Equilibrium solutions

$\dot{\Delta}_P = 0$ and $H = 0$ almost equivalent to $S_I = 0$ separately

Lepton Yukawa $EL\bar{H}$:	$\mu_{Y_e} = \mu_E + \mu_L - \mu_H$
Down-quark Yukawa $DQ\bar{H}$:	$\mu_{Y_d} = \mu_D + \mu_Q - \mu_H$
Up-quark Yukawa UQH :	$\mu_{Y_u} = \mu_U + \mu_Q + \mu_H$
$SU(3)_c$ sphalerons :	$\mu_{S_3} = N_{\text{gen}}(2\mu_Q + \mu_U + \mu_D)$
$SU(2)_L$ sphalerons :	$\mu_{S_2} = N_{\text{gen}}(3\mu_Q + \mu_L)$
$\Delta L = 2$ interactions:	$\mu_{LLHH} = 2\mu_L + 2\mu_H$
$U(1)_Y$ conservation :	$0 = N_{\text{gen}}(\mu_Q - 2\mu_U + \mu_D - \mu_L + \mu_E) + 2\mu_H$

Neglecting $\gamma_{Y_d} \ll \gamma_{S_3}, \gamma_{Y_u}$, we get a good approximation:

$$\boxed{\mu_{B-L}^{\text{eq}} \simeq \frac{72\mu_{Y_u} + 9\mu_{Y_e}}{11} - \frac{79}{22}\mu_{LLHH} + \frac{28}{33}\mu_{S_2} - \frac{19}{11}\mu_{S_3}}$$

Baryon asymmetry is sourced by a time dependence of the phases of Yukawas (even of the lepton Yukawa only) and of the sphalerons

Solving the evolution equations

$$\frac{d}{d\ln T}\frac{\mu_{B-L}}{T} = -\frac{66}{237}\frac{\gamma_{\Delta L=2}}{HT^3}\frac{\mu_{B-L}-\mu_{B-L}^{\mathrm{eq}}}{T}$$

- μ_{B-L} freezes at a value $\mu_{B-L}^{\mathrm{dec}} \sim \mu_{B-L}^{\mathrm{eq}}(T_{\mathrm{dec}})$, where T_{dec} is the decoupling temperature of $\Delta L = 2$ interactions

- SM equilibration conditions imply

$$\mu_B = \frac{28}{79}\mu_{B-L}^{\mathrm{dec}}$$

$$\boxed{\frac{n_B}{s} = \frac{15}{4\pi^2 d_{\mathrm{SM}}}\frac{\mu_B}{T}}$$

This ratio remains constant and the current entropy density is $s \approx 7.04\, n_\gamma$

$$\boxed{\mu_B \sim \dot{\tau} \text{ at decoupling}}$$

Time evolution of τ

$$\ddot{\tau} + 3H\dot{\tau} = -m_\tau^2\left(\tau - \tau_f\right)$$

$$\dot{\tau}/\tau \simeq -m_\tau^2/3H \quad \text{if} \quad H(T) \gg m_\tau$$

Maximal $\dot{\tau} \sim m_\tau$ when $H \sim m_\tau$

$$\boxed{\frac{n_B}{n_\gamma} \lesssim \frac{\mu_{B-L}^{\text{dec}}}{T_{\text{dec}}} \lesssim \frac{T_{\text{dec}}}{M_{\text{Pl}}}}$$

$T_{\text{dec}} \gtrsim 10^{10}$ GeV Similarly to Cohen, Kaplan, PLB **199** (1987) 251

Assuming $\dot{\tau}_i = 0$, $\quad \tau(T) = \tau_f + (\tau_i - \tau_f)\sqrt{\frac{T}{T_i}}\,\frac{J_{1/4}\left(\frac{m_\tau}{2H(T)}\right)}{J_{1/4}\left(\frac{m_\tau}{2H(T_i)}\right)}$

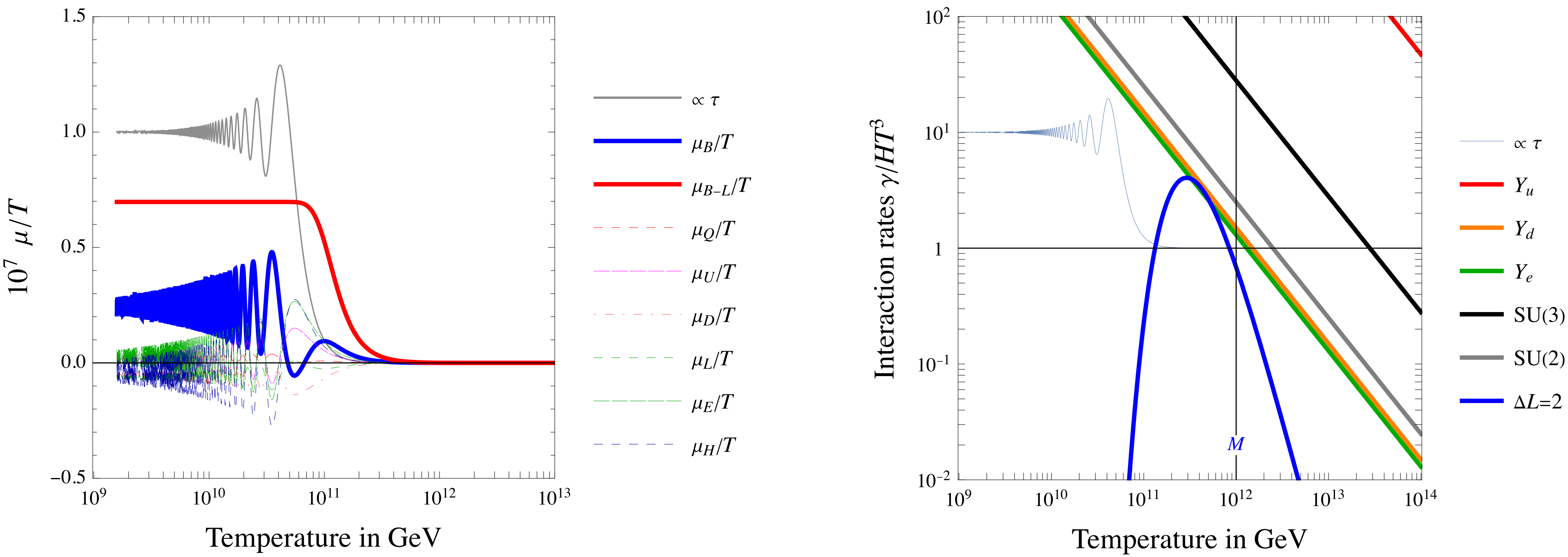
Modular baryogenesis at $T \sim 10^{11}$ GeV

$\Delta L = 2$ interactions decouple at $T_{\rm dec} \sim 10^{11}$ GeV

$$m_\tau \sim H \sim T_{\rm dec}^2 / M_{\rm Pl} \sim 10 \text{ TeV}$$

$$\tau_i = i \;\rightarrow\; \tau_f = \frac{1}{4} + i$$

$m_\tau = 10^{4.3}$ GeV , $M = 10^{12}$ GeV, $Y_u \propto E_4(\tau)$, $\tilde m = m_{\rm atm}$



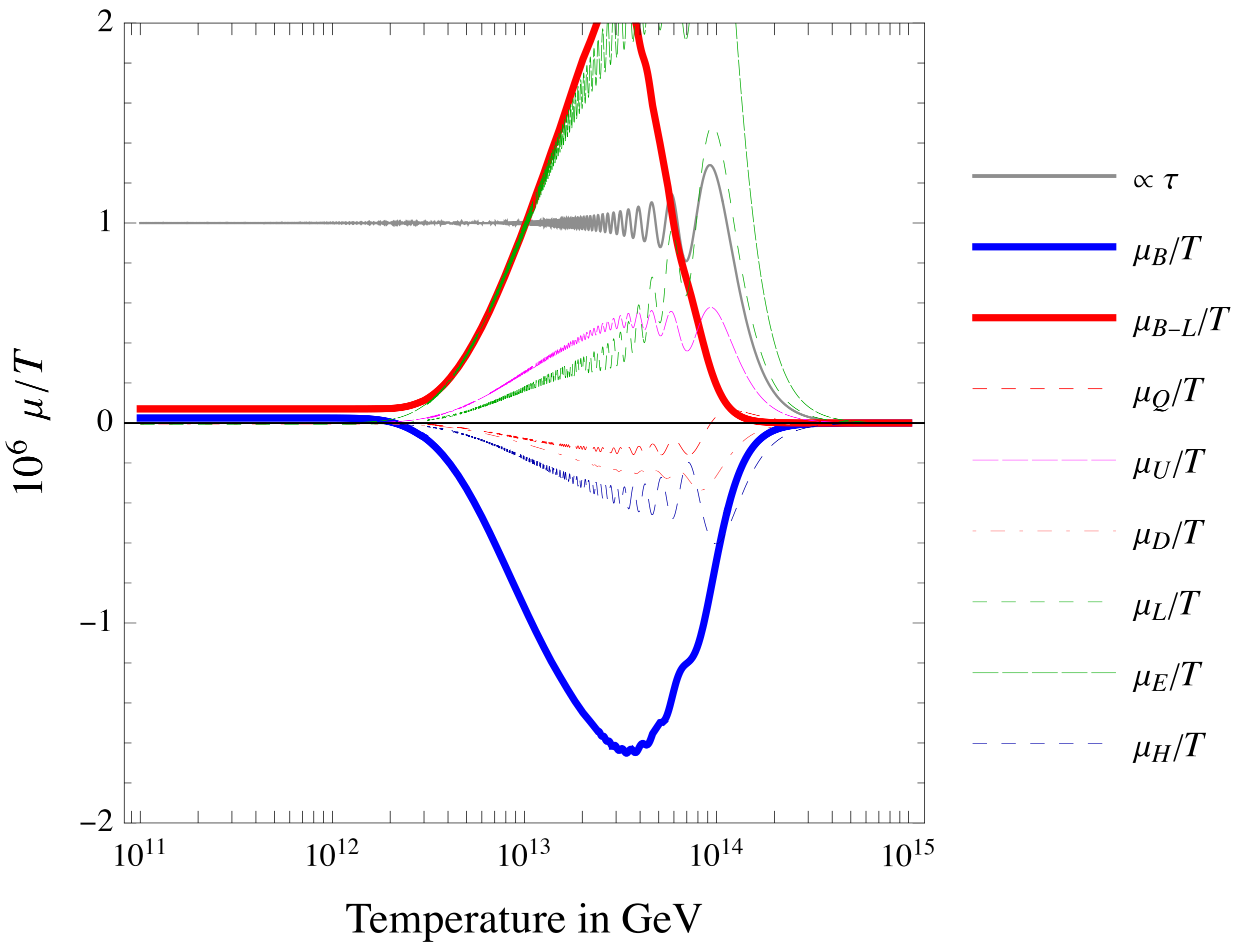
Modular baryogenesis at $T \gg 10^{11}$ GeV

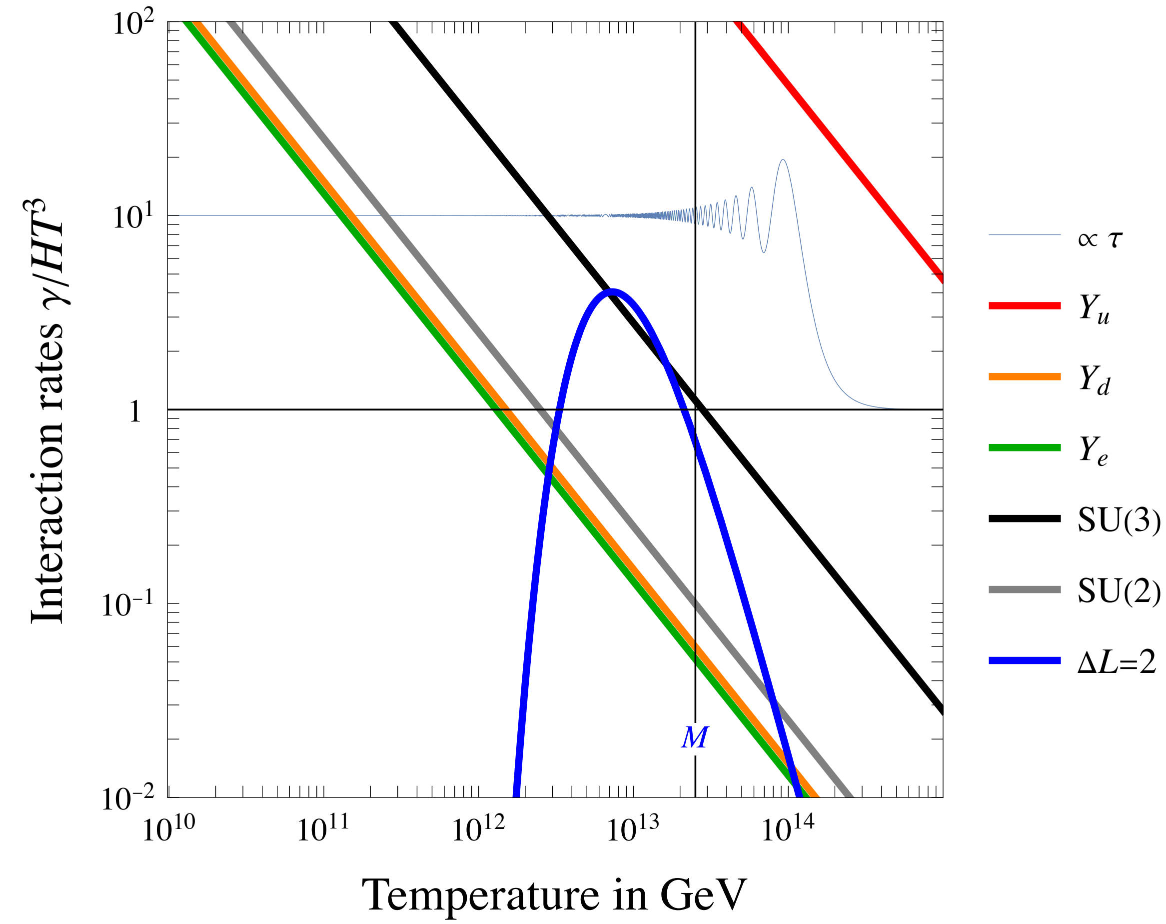
$T_{\rm RH} \lesssim 0.003\, M_{\rm Pl}$ $\quad$ $m_\tau \lesssim T_{\rm RH}^2/M_{\rm Pl} \sim 10^{13}$ GeV $\quad$ $n_B/n_\gamma \sim T_{\rm RH}/M_{\rm Pl} \sim 10^{-3}$

Fast $\Delta L = 2$ interactions can partially wash-out the baryon asymmetry

$$\tau_i = i \;\to\; \tau_f = \frac{1}{4} + i$$

$m_\tau = 10^{11}$ GeV , $M = 10^{13.4}$ GeV, $Y_e \propto E_4(\tau)$, $\tilde{m} = m_{\rm atm}$





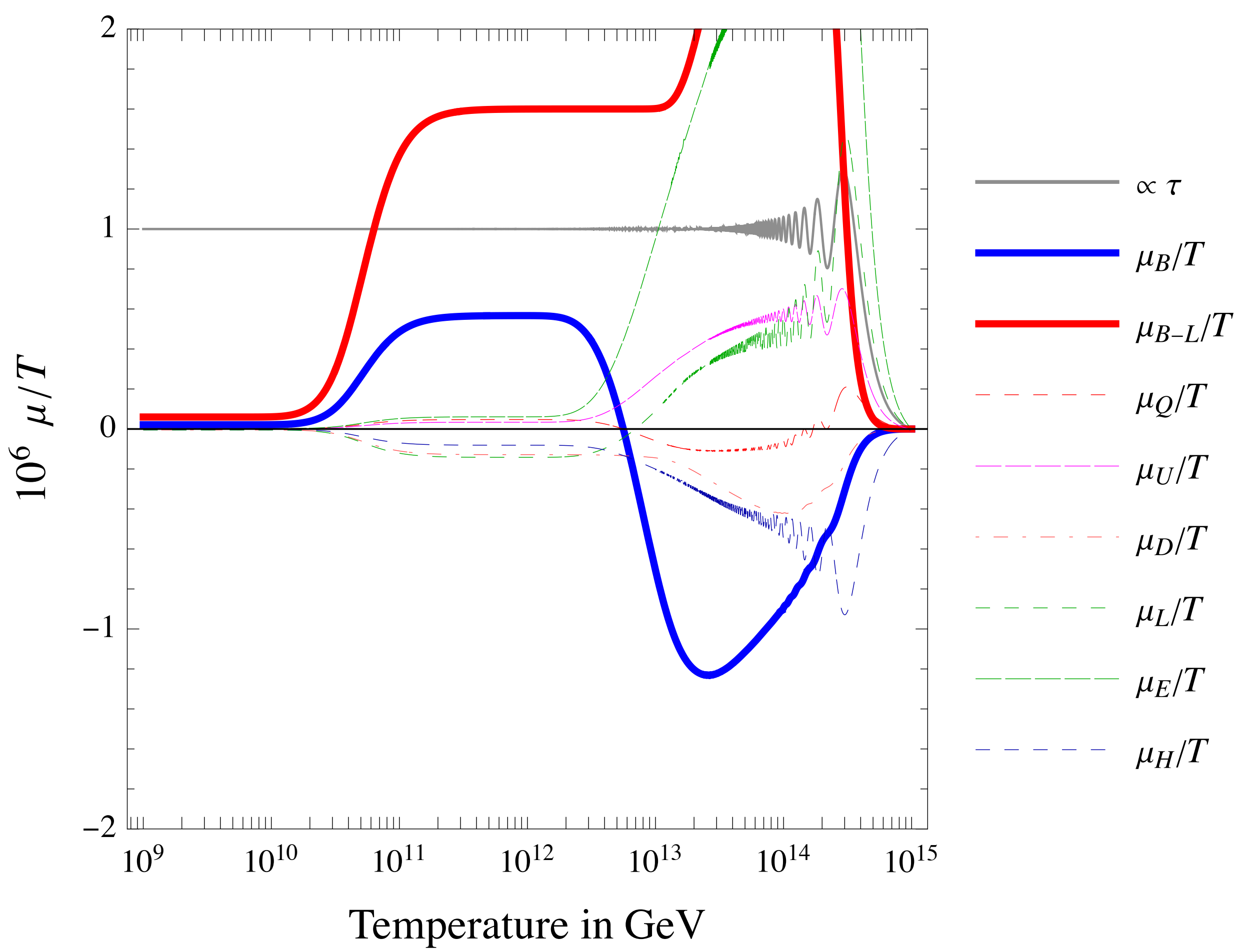
Modular baryogenesis at $T \gg 10^{11}$ GeV

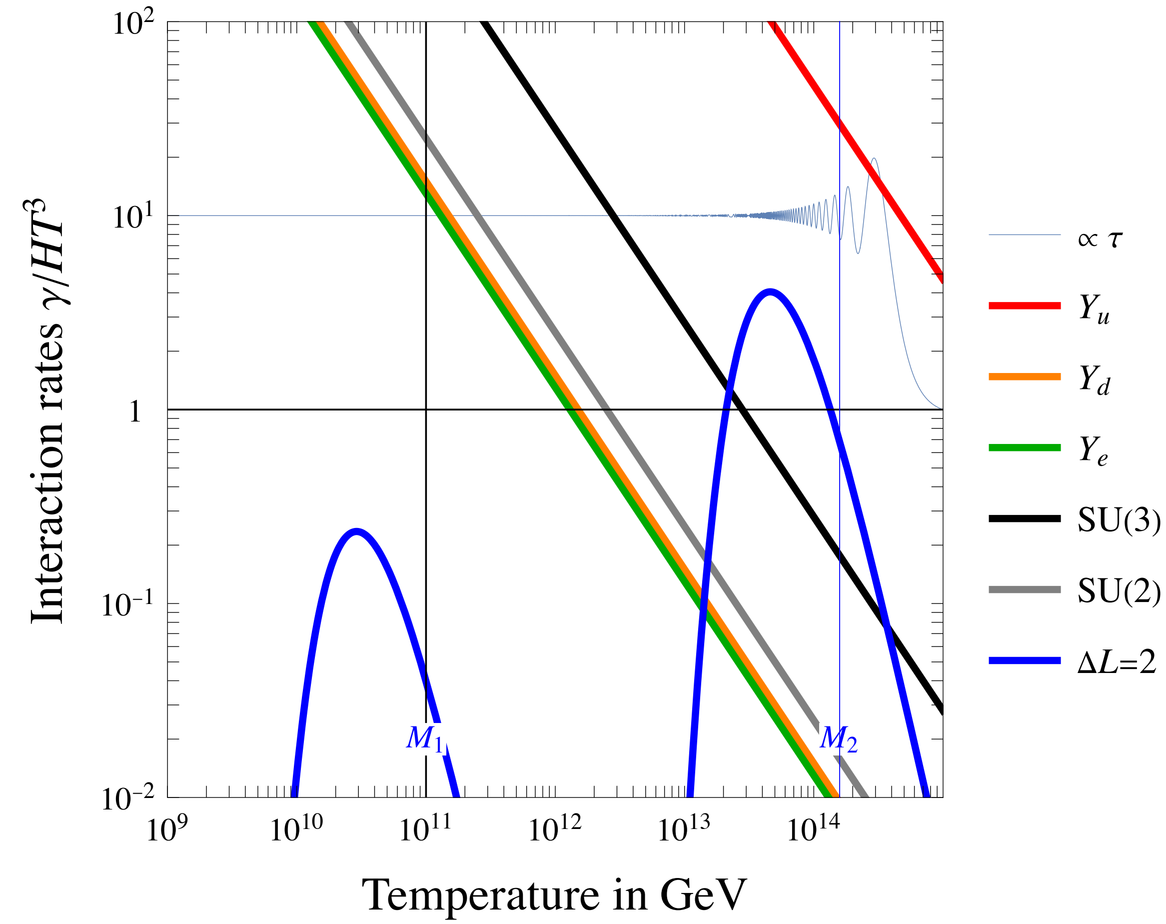
$T_{\rm RH} \lesssim 0.003\, M_{\rm Pl}$ $\quad$ $m_\tau \lesssim T_{\rm RH}^2/M_{\rm Pl} \sim 10^{13}$ GeV $\quad$ $n_B/n_\gamma \sim T_{\rm RH}/M_{\rm Pl} \sim 10^{-3}$

Fast $\Delta L = 2$ interactions can partially wash-out the baryon asymmetry

$$\tau_i = i \;\rightarrow\; \tau_f = \frac{1}{4} + i$$

$m_\tau = 10^{12}$ GeV , $M_1 = 10^{11}$ GeV, $M_2 = 10^{14.2}$ GeV, $\tilde{m}_1 = m_{\rm sun}$, $\tilde{m}_2 = m_{\rm atm}$, $Y_e \propto E_4(\tau)$





Summary and conclusions

Baryogenesis can arise from the cosmological evolution of a CP-breaking modulus scalar τ, either during the Big Bang or around the end of inflation

- EFT with Yukawas $Y(\tau)$, theta terms $\theta_{2,3}(\tau)$ and derivative current couplings $c_P(\tau)$
- Majorana mass M of N breaks L, while weak sphalerons break $B + L$
- Cosmological evolution of τ (possibly from a CP-conserving point to a CP-violating minimum of its potential) induces time variation of θ_{Y_P} and $\theta_{2,3}$ which source chemical potentials
- Chemical potentials obey time evolution equations

Summary and conclusions

Two regimes of modular baryogenesis

- τ evolves at $T_{\rm dec} \sim 10^{11}$ GeV when $\Delta L = 2$ interactions go out of equilibrium

$$m_\tau \sim H \sim T_{\rm dec}^2/M_{\rm Pl} \sim 10 \text{ TeV} \qquad \text{and} \qquad n_B/n_\gamma \sim T_{\rm dec}/M_{\rm Pl} \sim 10^{-10}$$

  (a heavier τ is expected, since its mass is not protected by a shift symmetry)

- τ evolves at higher $T \sim T_{\rm RH} \lesssim 0.003\, M_{\rm Pl}$ GeV

$$m_\tau \sim H \sim T_{\rm RH}^2/M_{\rm Pl} \sim 10^{12} \text{ GeV}$$

$$n_B/n_\gamma \sim T_{\rm RH}/M_{\rm Pl} \sim 10^{-3} \text{ is partially washed-out by } \Delta L = 2 \text{ interactions}$$

Backup slides

Baryon asymmetry of the Universe

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \left(6.15 \pm 0.15\right) \times 10^{-10}$$

Sakharov conditions (assume CPT invariance) Sakharov, JETP Lett. **5** (1967) 24

1. Baryon number B violation
2. C and CP violation
3. Interactions out of thermal equilibrium

Spontaneous baryogenesis (CPT violation at finite T) Cohen, Kaplan, PLB **199** (1987) 251; NPB **308** (1988) 913

1. B violation
2. Spontaneous CP violation
3. Interactions in thermal equilibrium

Spontaneous baryogenesis and axiogenesis

- Spontaneous baryogenesis — Cohen, Kaplan, PLB **199** (1987) 251; NPB **308** (1988) 913

$$\mathscr{L} \supset \partial_\mu \phi \, J_B^\mu \qquad \text{spontaneously and softly broken } \mathrm{U}(1)_B$$

- Axion baryogenesis ("axiogenesis") — Co, Harigaya, 1910.02080

$$\mathscr{L} \supset \partial_\mu a \, J_{\mathrm{PQ}}^\mu \qquad \text{spontaneously and explicitly broken } \mathrm{U}(1)_{\mathrm{PQ}}$$

m_a is protected by a shift symmetry, and axion baryogenesis is operative at

$$T \sim \sqrt{m_a M_{\mathrm{Pl}}} \sim 100 \text{ GeV}$$

$$n_B / n_\gamma \sim T/M_{\mathrm{Pl}} \text{ is too small}$$

Unlike a pseudo-Goldstone boson, τ can be arbitrarily heavy and features well-motivated CP-violating couplings that break shift symmetry and contribute to baryogenesis

Fields and their quantum numbers

Fields	spin	$\mathrm{U}(1)_Y$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(3)_c$	L	B	d
$U = u_R$	$1/2$	$-\frac{2}{3}$	1	$\bar{3}$	0	$-\frac{1}{3}$	3
$D = d_R$	$1/2$	$\frac{1}{3}$	1	$\bar{3}$	0	$-\frac{1}{3}$	3
$Q = (u_L, d_L)$	$1/2$	$\frac{1}{6}$	2	3	0	$\frac{1}{3}$	6
$E = e_R$	$1/2$	1	1	1	-1	0	1
$N = \nu_R$	$1/2$	0	1	1	-1	0	1
$L = (\nu_L, e_L)$	$1/2$	$-\frac{1}{2}$	2	1	1	0	2
$H = (0, v + h/\sqrt{2})$	0	$\frac{1}{2}$	2	1	0	0	2

Global U(1)

Particles P carry U(1) charges q_P

The VEV f of complex scalar $S = \frac{f}{\sqrt{2}} e^{i\frac{a}{f}}$ with charge q_S breaks U(1) spontaneously

$a = a(x)$ is a Nambu-Goldstone boson (pseudo-NGb because of anomalies)

$$Y_u(a) QUH = c S^{-q_{QUH}/q_S} QUH \qquad \text{with} \qquad q_{QUH} = q_Q + q_U + q_H$$

We can make Yukawas real by $P \to e^{i\frac{q_P}{q_S}\frac{a}{f}} P \;\Rightarrow\; \sum_P \frac{q_P}{q_S} \frac{\partial_\mu a}{f} J_P^\mu$ and no CP violation

Alternatively, we can introduce a covariant-like derivative:

$$\partial_\mu P \to D_\mu P = \partial_\mu P + i \frac{q_P}{q_S} \frac{\partial_\mu a}{f}$$

- At least two complex scalars are needed to break CP spontaneously
- Global symmetries are expected to be broken by quantum gravity

Local U(1)

Two complex scalars $S_1 = \frac{f_1}{\sqrt{2}} e^{i\frac{a_1}{f_1}}$ and $S_2 = \frac{f_2}{\sqrt{2}} e^{i\frac{a_2}{f_2}}$ with charges q_1 and q_2

$$Y(S_1, S_2)\, QUH = \left(c_1 S_1^{-q_{QUH}/q_{S_1}} + c_2 S_2^{-q_{QUH}/q_{S_2}} \right) QUH$$

Gauge transformation $S_i \to e^{iq_{S_i}\alpha} S_i$ with $\alpha = -\frac{a}{f}$ removes a, but leaves τ

$$a = \frac{q_{S_1} f_1 a_1 + q_{S_2} f_2 a_2}{f} \qquad \tau = \frac{q_{S_2} f_2 a_1 - q_{S_1} f_1 a_2}{f} \qquad f = \sqrt{q_{S_1}^2 f_1^2 + q_{S_2}^2 f_2^2}$$

$$\mathscr{L}_{\text{eff}} = \left[y_1 \exp\left(-iq_{QUH} \frac{q_{S_2} f_2}{q_{S_1} f_1} \frac{\tau}{f} \right) + y_2 \exp\left(iq_{QUH} \frac{q_{S_1} f_1}{q_{S_2} f_2} \frac{\tau}{f} \right) \right] QUH - \frac{m_\tau^2}{2} \tau^2 + \ldots$$

Solving the evolution equations

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi\,, \qquad \frac{d\rho_{\rm SM}}{dt} + 4H\rho_{\rm SM} = \Gamma_\phi \rho_\phi$$

$$H^2 = \frac{\rho_{\rm SM} + \rho_\phi}{3M_{\rm Pl}^2}\,, \qquad \rho_{\rm SM} = \frac{\pi^2}{30} d_{\rm SM}(T) T^4$$

$$\frac{d}{dt} = H \frac{d}{d\ln a} = -H \frac{d}{d\ln T}$$

$$\dot{\Delta}_P + 3H\Delta_P = -c_{\rm spin} d_P T^3 H \frac{d}{d\ln T}\frac{\mu_P}{T}$$

$$\frac{d_E}{6}\frac{d}{d\ln T}\frac{\mu_E}{T} = \frac{\gamma_{Y_e}}{HT^3}\frac{\mu_L + \mu_E - \mu_H - \mu_{Y_e}}{T}$$

$$\frac{d}{d\ln T}\frac{\mu_{B-L}}{T} = -\frac{66}{237}\frac{\gamma_{\Delta L=2}}{HT^3}\frac{\mu_{B-L} - \mu_{B-L}^{\rm eq}}{T}$$

$$\mu_B = \frac{28}{79}\mu_{B-L}^{\rm dec}\,, \qquad \frac{n_B}{s} = \frac{15}{4\pi^2 d_{\rm SM}}\frac{\mu_B}{T}$$