Baryogenesis and Leptogenesis: Some insights and recent developments

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SANGAM@HRI - 2024

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system) contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons."

(from Paul Dirac's Nobel Lecture December 12, 1933)

Plan of the lectures:

- Understanding our universe with Big Bang and indication of baryon asymmetry
- Electroweak baryogenesis
- Leptogenesis
- Some recent developments

References used:

The early Universe by Kolb and Turner

Introduction to Cosmology by Ryden

Neutrinos in particle Physics, Astronomy and Cosmology by Xing

hep-ph/0609145, hep-ph/0406014 ....

Part-1: Understanding our universe with Big Bang and indication of baryon asymmetry

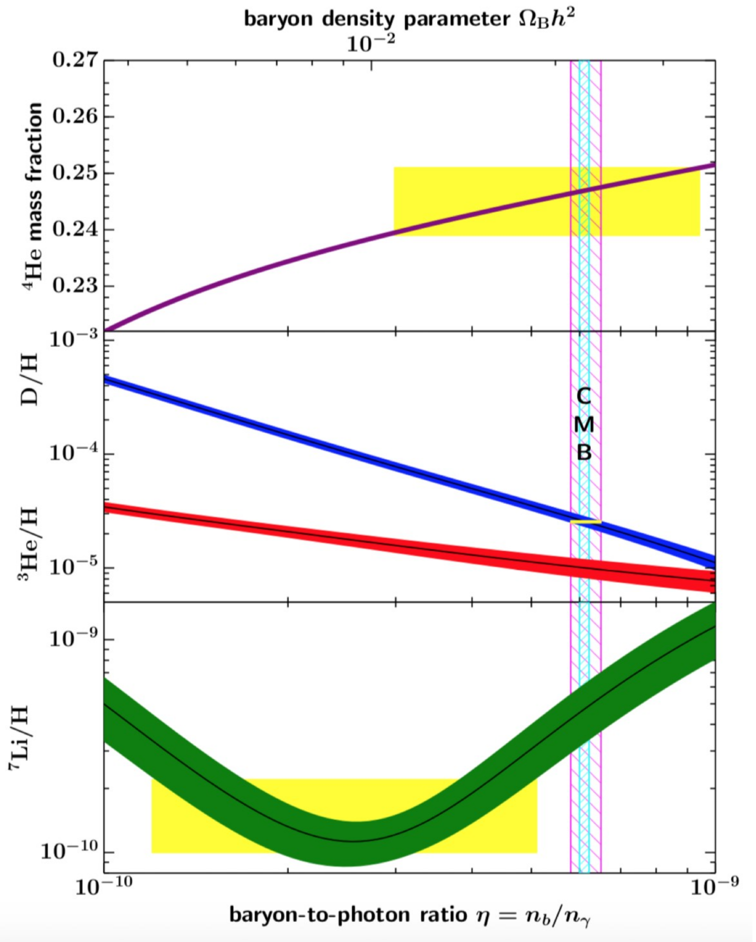
- Our observable Universe is mostly made of matter.
- Antimatter only seen in cosmic rays or produced in the laboratory

Information on baryon asymmetry

Predictions of Big Bang Nucleosynthesis

$$\eta = \frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$$

+ CMB + WMAP Results



Understanding our Universe with Big Bang Model

Fundamental Observations

- At large scale (largen than 100 Mpc): Universe is homogeneous and isotropic
- Redshift $z \equiv \frac{\lambda_{ob} - \lambda_{em}}{\lambda_{em}}$. is proportional to the distance: $z = \frac{H_0}{c} r$, Expanding universe
- Cosmic Microwave Background Radiation: isotropic and characteristic of blackbody temperature ~ T = 2.726 K

Modelling our Universe

On cosmological scales, gravity becomes dominant

Einstein: Mass-energy tells spacetime how to curve and Curved spacetime tells mass-energy how to move.

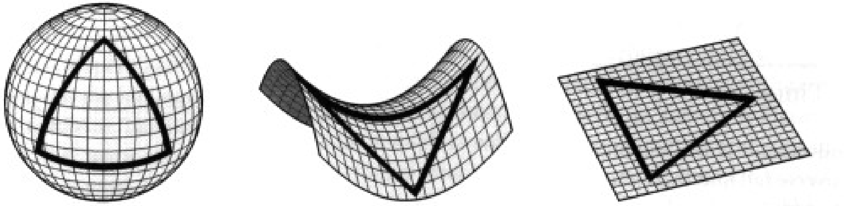
[John Wheeler]

Describing Curvature and expanding universe

According to STR, the spacetime separation between two events (Minkowski metric):

$$ds^2 = -c^2 dt^2 + dr^2 + r^2 d\Omega^2$$

expanding universe



Positive Curvature   Negative Curvature   Flat Curvature

Describing Curvature and expanding universe

According to STR, the spacetime separation between two events (Minkowski metric):

$$ds^2 = -c^2 dt^2 + dr^2 + r^2 d\Omega^2$$

In an expanding universe (FRW metric):

$$ds^2 = -c^2 dt^2 + a^2(t)\left[dr^2 + S_k(r)^2 d\Omega^2\right]$$

$a(t)$: Scale factor — measure of size of the universe

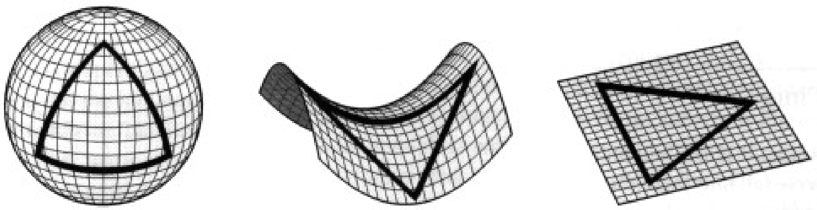
$$S_k(r) = \begin{cases} R \sin \frac{r}{R} & K = +1 \\ r & K = 0 \\ R \sin \frac{r}{R} & K = -1 \end{cases}$$

K: curvature

Light travels along null geodesic:

$$c \frac{dt}{a(t)} = dr.$$

$$1 + z = \frac{a(t_0)}{a(t_e)} = \frac{1}{a(t_e)}.$$



Positive Curvature — Negative Curvature — Flat Curvature

Relations involving energy density (ρ), pressure (p) and scale factor (a): $G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$.

Friedmann equation: $$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{a^2} + \frac{1}{3}\Lambda$$

With $k = \Lambda = 0$

$$a(t) = \left(\frac{t}{t_0}\right)^{\frac{2}{3(1+w)}}$$

Fluid equation: $$\frac{d\rho}{dt} + 3\left(\rho + \frac{p}{c^2}\right)\frac{\dot{a}}{a} = 0$$

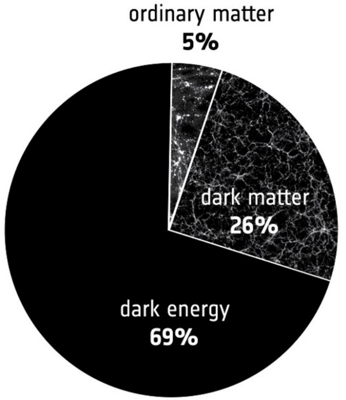
$$\rho(t) = \rho_0 \left[a(t)\right]^{-3(1+w)}$$

$\rho_0 \to \rho(t_0)$ $\qquad a(t_0) = 1$

Equation of state: $$\frac{p}{\rho c^2} = w$$

$w = 0$ pressureless dust (matter)

$w = \frac{1}{3}$ radiation



Our universe today

Origin of CMB: goes back to Recombination and Photon decoupling era

$$p + e^- \to \mathrm{H} + \gamma. \qquad \gamma + e^- \to \gamma + e^-.$$

took place around [$z \sim 1090$ or $T \sim 2970$ K]

Nucleosynthesis and prediction for baryon to photon ratio

Building blocks for nucleosynthesis: neutrons and protons $p + n \rightleftharpoons \mathrm{D} + \gamma.$

n − p inter-conversion: $n + \nu_e \rightleftharpoons p + e^-$ $n + e^+ \rightleftharpoons p + \bar{\nu}_e.$

Around KT ~ 3 MeV, all particles (neutrons, protons, electrons, positrons) were in kinetic equilibrium

$$n_n = g_n \left(\frac{m_n kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{m_n c^2}{kT}\right)$$

n and p were Non-Relativistic by this time

$$n_p = g_p \left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{m_p c^2}{kT}\right)$$

$$\frac{n_n}{n_p} = \exp\left(-\frac{Q_n}{kT}\right)$$

$Q_n = (m_n - m_p)c^2 = 1.29$ MeV

- For $T > Q_n$, $n_n \sim n_p$
- For T drops below Q_n ; n_n/n_p decreases exponentially

These interactions: considered to be in equilibrium [Interaction rate $\Gamma = n\sigma v \simeq 2.1 \left(\frac{KT}{MeV}\right)^5 \; sec^{-1}$]

Hubble parameter (radiation dominated): $H = \frac{\sqrt{g_*}}{4.8}\left(\frac{KT}{MeV}\right)^2 \; sec^{-1}$

$$\frac{\Gamma}{H} \sim \left(\frac{KT}{0.7\,MeV}\right)^3$$

Matter-radiation equality ($KT \sim 3$ eV)

$$\rho_m = \rho_{m,0}\, a^{-3} \qquad \rho_r = \rho_{r,0}\, a^{-4} \quad \Rightarrow \quad \rho_{m,0}(1+z)^3 = \rho_{r,0}(1+z)^4$$

as $\frac{a(t_0)}{a(t)} = 1+z$

$$1+z = \frac{\rho_{m,0}}{\rho_{r,0}} = \left.\frac{\Omega_m}{\Omega_r}\right|_{today} \simeq 3570$$

Freeze out of the n-p interconversion happens around $KT_F \sim 0.7$ MeV (universe was $t_F \sim 1.5$ seconds old)

$n_n/n_p \sim 0.2$

However, neutrons decay having lifetime $\tau_n \sim 880$ sec [$n \to p + e^- + \bar{\nu}_e$]

For times, $t_F < t < \tau_n$; $\frac{n_n}{n_p} \simeq e^{-Q_n/KT_F} \cdot e^{-t/\tau_n}$

BBN proceeds through a series of two-body interactions, building heavy nuclei step by step.

1. Deuterium formation $p + n \rightleftharpoons \mathrm{D} + \gamma.$ $B_{\mathrm{D}} = (m_n + m_p - m_{\mathrm{D}})c^2 = 2.22\,\mathrm{MeV}.$

Assuming chemical equilibrium of p, n, D

$$\frac{n_{\mathrm{D}}}{n_p n_n} = \frac{g_{\mathrm{D}}}{g_p g_n}\left(\frac{m_{\mathrm{D}}}{m_p m_n}\right)^{3/2}\left(\frac{kT}{2\pi\hbar^2}\right)^{-3/2}\exp\left(\frac{[m_p + m_n - m_{\mathrm{D}}]c^2}{kT}\right) = 6\left(\frac{m_n kT}{\pi\hbar^2}\right)^{-3/2}\exp\left(\frac{B_{\mathrm{D}}}{kT}\right)$$

$\eta = \frac{n_b}{n_\gamma}$; $n_\gamma = 0.2436\,(KT)^3$

η does not change much from the onset of nucleosynthesis and today

$n_p \simeq 0.8\, n_b = 0.8\,\eta\, n_\gamma$

$$\frac{n_{\mathrm{D}}}{n_n} \approx 6.5\eta\left(\frac{kT}{m_n c^2}\right)^{3/2}\exp\left(\frac{B_{\mathrm{D}}}{kT}\right)$$

$KT_n \sim 0.07$ MeV

Beyond Deuterium

After a significant formation of deuterium, other reactions became important: ^4He formation (happens pretty fast)

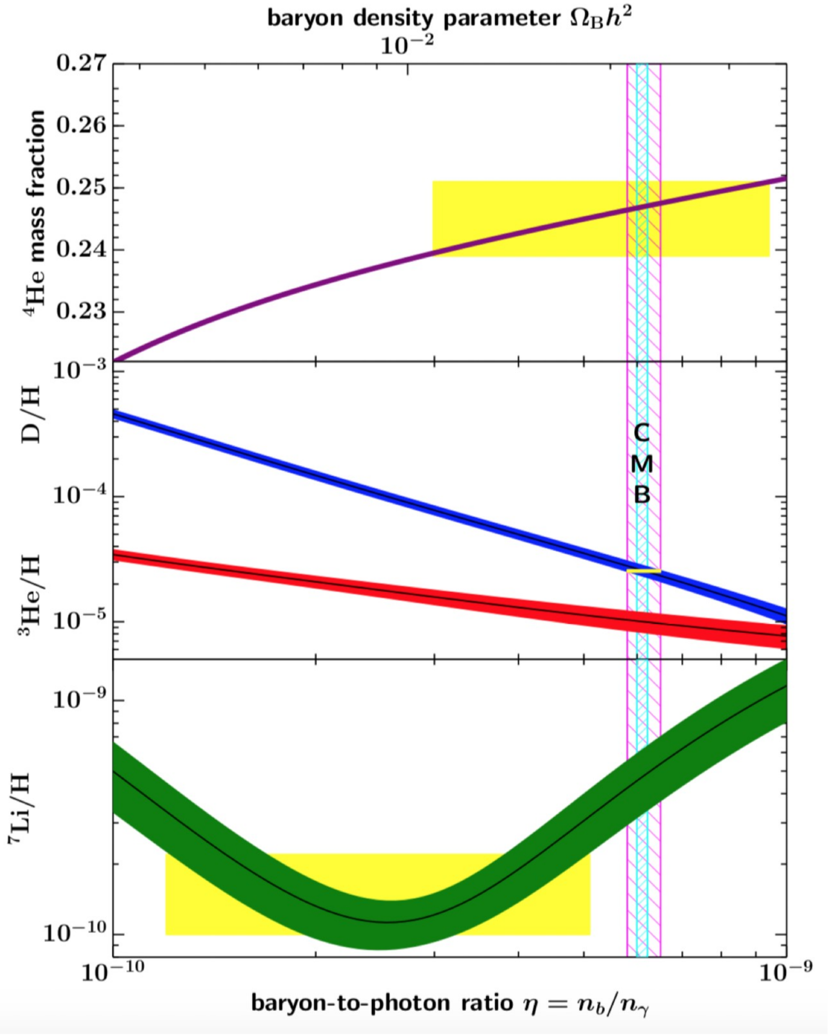
Bottom line: abundance of heavy nuclei (D, ^3He, ^4He, Li) during BBN depends on parameter η

+

Acoustic peaks in angular power spectrum of CMB

$$\eta = \frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$$

- No anti-baryons at the time of BBN...
- Should have its origin at much early universe. How early?



Possible explanation for matter-antimatter asymmetry

Can it be just an initial value for η at the time of Big Bang

(accepting the fine tuning)

No ....

Universe underwent an exponential phase of expansion: **Inflation**

Inflation: erases any pre-existing asymmetry, if any.

Hence, asymmetry must be created only after inflation.

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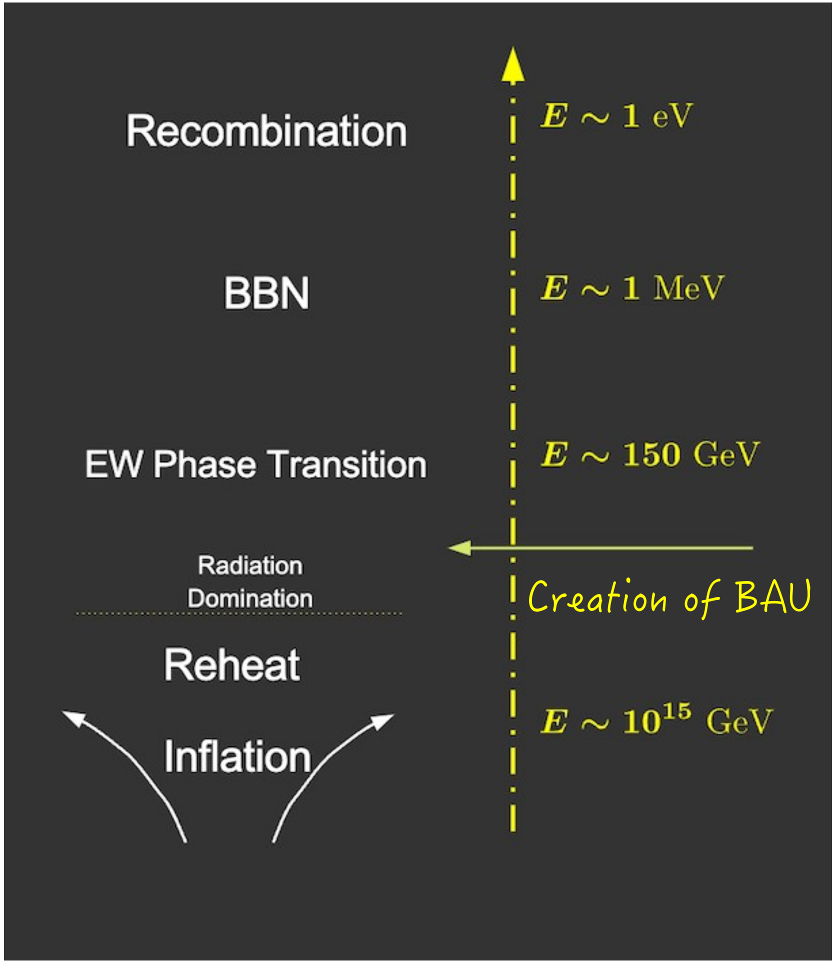


Part-II: Electroweak Baryogenesis

Search for dynamical origin of baryon asymmetry

Sakharov's Conditions

B Violation

C and CP Violation

Departure from Thermal Equilibrium

Sakharov's 1st Condition: obvious

Sakharov's 2nd Condition:

Consider $X \to Y + B$ → C-conjugate process: $\bar{X} \to \bar{Y} + \bar{B}$ | ∴ $\Gamma(X \to Y + B) = \Gamma(\bar{X} \to \bar{Y} + \bar{B})$

If consider C is a sym.

The baryon asymmetry evolution eqn:

$$\frac{dB}{dt} \propto \Gamma(X \to Y + B) - \Gamma(\bar{X} \to \bar{Y} + \bar{B}) \to 0.$$

Now consider, C is violated, but not CP

- $N \to Q_L Q_L$ and $N \to Q_R Q_R$
- For non conservation of C: $\Gamma(N \to Q_L Q_L) \neq \Gamma(\bar{N} \to \bar{Q}_L \bar{Q}_L)$ and $\Gamma(N \to Q_R Q_R) \neq \Gamma(\bar{N} \to \bar{Q}_R \bar{Q}_R)$
- Under CP transformation, $Q_L \to \bar{Q}_R$
- CP conservation implies: $\Gamma(N \to Q_L Q_L) + \Gamma(N \to Q_R Q_R) = \Gamma(\bar{N} \to \bar{Q}_R \bar{Q}_R) + \Gamma(\bar{N} \to \bar{Q}_L \bar{Q}_L)$

So both C and CP violations are required

Sakharov's 3rd Condition:

Artefact of CPT symmetry: for every state with baryon number B and energy E, there exists a state with baryon number −B and identical energy E.

- states with baryon number B and −B will be equally populated
- If the system is in thermal equilibrium: $\Gamma(N \to X + Y) = \Gamma(X + Y \to N)$

$$\begin{aligned} \langle B \rangle = \mathrm{Tr}(e^{-\beta H} B) &= \mathrm{Tr}(\Theta\Theta^{-1} e^{-\beta H} B) \\ &= -\mathrm{Tr}(e^{-\beta H} B)\,, \quad \Theta = CPT \end{aligned}$$

Hence, $\langle B \rangle = 0$

Out of thermal equilibrium is required to have $\langle B \rangle \neq 0$

Can the three conditions be met within the Standard Model framework?

Is there Baryon number violation in SM?

Experimentally, baryon number violating events are yet to be observed, proton is stable (proton lifetime > 6.6 x 10^{33} years. This bound is 5x10^{23} times longer than the age of the Universe

Kinetic terms for the fermion fields in the SM: $\mathcal{L}_{\mathrm{F}} = \overline{Q_{\mathrm{L}}}\mathrm{i}\not{D}Q_{\mathrm{L}} + \overline{\ell_{\mathrm{L}}}\mathrm{i}\not{D}\ell_{\mathrm{L}} + \overline{U_{\mathrm{R}}}\mathrm{i}\not{\partial}'U_{\mathrm{R}} + \overline{D_{\mathrm{R}}}\mathrm{i}\not{\partial}'D_{\mathrm{R}} + \overline{E_{\mathrm{R}}}\mathrm{i}\not{\partial}'E_{\mathrm{R}}$

The baryonic current: $J^B_\mu = \frac{1}{3}\sum_{generations}(\overline{q_L}\gamma_\mu q_L + \overline{u_R}\gamma_\mu u_R + \overline{d_R}\gamma_\mu d_R)$

The Leptonic current: $J^L_\mu = \sum_{generations}(\overline{l_L}\gamma_\mu l_L + \overline{e_R}\gamma_\mu e_R)$

Vector like U(1) symmetry

However, only left-chiral components couple to the SU(2) gauge field

Divergence of these currents due to triangle anomaly:

$$\partial_\mu J^\mu_B = i\frac{N_F}{32\pi^2}(-g_2^2 W^{a\mu\nu}\tilde{W}^a_{\mu\nu} + g_1^2 B^{\mu\nu}\tilde{B}_{\mu\nu})$$

$$\partial_\mu J^\mu_L = i\frac{N_F}{32\pi^2}(-g_2^2 W^{a\mu\nu}\tilde{W}^a_{\mu\nu} + g_1^2 B^{\mu\nu}\tilde{B}_{\mu\nu})$$

Violated by the same quantity

$N_F = 3$; Strengths of $SU(2)_L$ and $U(1)_Y$ gauge fields

$$\partial_\mu J^\mu_{B+L} = i\frac{N_F}{16\pi^2}(-g_2^2 W^{a\mu\nu}\tilde{W}^a_{\mu\nu} + g_1^2 B^{\mu\nu}\tilde{B}_{\mu\nu})$$

$$\partial_\mu J^\mu_{B-L} = 0\,,$$

[B-L is conserved, but B+L is violated]

Baryon number violation in SM contd..

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_f}{32\pi^2}\left(-g^2 W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

baryon number $B \equiv \int d^3\mathbf{x}\; J_B^0(x)$

lepton number $L \equiv \int d^3\mathbf{x}\; J_L^0(x)$

are violated

$$B = \frac{(B+L)}{2} + \frac{(B-L)}{2} \qquad \Delta B = \frac{\Delta(B+L)}{2}.$$

Violation of B+L in any physical process (or coupled to it) necessarily **violates B**

r.h.s can be written as total divergence

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_f}{32\pi^2}\left(-g^2 \partial_\mu \mathcal{K}^\mu + g'^2 \partial_\mu K^\mu\right)$$

$$\mathcal{K}^\mu = 2\varepsilon^{\mu\nu\rho\sigma}\left[(\partial_\nu W_\rho^i)W_\sigma^i + \frac{1}{3} g \varepsilon^{ijk} W_\nu^i W_\rho^j W_\sigma^k\right]$$

$$K^\mu = 2\varepsilon^{\mu\nu\rho\sigma}\left[(\partial_\nu B_\rho)B_\sigma\right].$$

related to the vacuum structures of the U(1) and SU(2) sectors

Violation of B in finite time interval:

$$\Delta B = \int_{t_1}^{t_2} dt\, \frac{dB}{dt}$$

$$= \int_{t_1}^{t_2} dt \int d^3x\, \frac{N_f}{32\pi^2}\left(-g^2\partial_\mu \mathcal{K}^\mu + g'^2 \partial_\mu K^\mu\right)$$

$$= \int_{t_1}^{t_2} dt\, N_f \frac{dN_{cs}}{dt} - \int_{t_1}^{t_2} dt\, N_f \frac{dn_{cs}}{dt}$$

$$\Delta B = \Delta L = N_f\left(\Delta N_{CS} - \Delta n_{CS}\right)$$

to generate non-zero baryon number in transitions from t1 → t2, we need fluctuations of the SU(2) gauge that change NCS:

Baryon number violation in SM contd..

$$\Delta B = \Delta L = N_f \left(\Delta N_{\rm CS} - \Delta n_{\rm CS}\right)$$

- The term n_{CS} being gauge invariant, a redefinition of it can be set so as to make it vanishing at the boundary
- The same is not applicable to N_{CS} due to the exotic vacuum structure of SU(2)

Vacuum structure of the non-abelian gauge theories posses an infinite number of topologically distinct vacuum, the field configurations of which are characterised by Chern-Simons numbers.

['t Hooft 1976, Callan et al, 1976, Jackiw and Rebbi, 1976]

Hence, in order to generate non-zero baryon number in transitions over a time interval, we need fluctuations of the SU(2) gauge that change N_{CS}.

Vacuum of SU(2) in R^4

The naive estimate for vacuum does not hold..

$W_{\mu\nu} = 0$ (kinetic term vanishes)

$\rightarrow W_\mu = \frac{1}{2}\sigma^a W_\mu^a = 0$.

Vacuum is not unique.

If $W_{\mu\nu} = 0$, $W_\mu(x)$ can be a pure gauge

$$W_\mu(x) = \frac{i}{g} U(x)\partial_\mu U^\dagger(x)$$

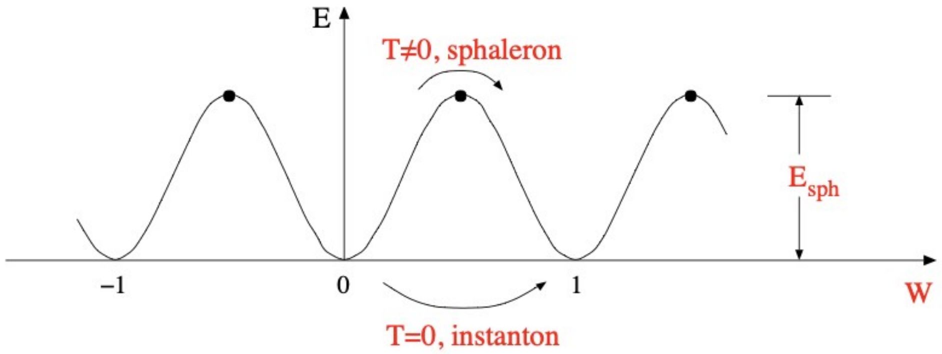
$U(x) \in SU(2)$.

Infinite degenerate ground states: physically identical, distinguishable only by integer-valued winding number of the field

SU(2) is topologically equivalent to S^3 (representative of 3-sphere)

Baryon number violating processes are associated with a transition of the $SU(2)_L$ gauge fields between Topologically different vacua

Each vacuum is defined by a charge $N_{CS} = w$. For a transition between two vacua defined by the classes of mappings $U_n(x)$ and $U_m(x)$, $n \neq m$, arises a change $\Delta N_{CS} = n - m$.



Energy of the gauge field configuration as a function of N_{CS}

Sp. rate: $\Gamma = \lim_{t \to \infty} \frac{\langle |N_{CS}(t) - N_{CS}(0)|^2 \rangle}{t}$

Implication: a transition between vacuum states may lead to an asymmetry in the baryon number which could take part in baryon asymmetry generation (Baryogenesis) in the early universe.

$$\Delta B = \Delta L = N_f (n - m)$$

(i) The quantum mechanical tunneling between two such vacua (the so-called instanton processes in the SU(2) EW sector) is associated with a factor: $e^{-16\pi^2/g^2} \sim 10^{-170}$

Hence, it is heavily suppressed.

(ii) Instead of tunneling through the barrier, the system goes over the barrier (called Sphaleron), a classical thermally aided transition.

Baryon number violation and Sphaleron transition rate (temperature dependent)

In general, the Sphaleron transition rate $\Gamma \propto e^{-E_{sp}/T}$.

- For $T \lesssim T_{EW}$: $\frac{\Gamma}{V} \sim \left(\frac{E_{sp}}{T}\right)^3 \left(\frac{m_W(T)}{T}\right)^4 T^4 e^{-E_{sp}/T}$ [Arnold and McLerran, 1987]

- At very high temperature: EW sym was not broken; VEV vanishes

  No barrier between vac. states

  $\rightarrow$ Sp. transitions were not Boltzmann suppressed.

  $$\frac{\Gamma}{V} \sim \alpha_W^4 T^4 \qquad \alpha_W = \frac{g^2}{4\pi}.$$

The Sphaleron process remains in thermal equilibrium

(compare its interaction rate with the expansion rate of the universe.)

$$T_{EW} \sim 100\ \text{GeV} < T < T_{sp} \sim 10^{12}\ \text{GeV}$$

relevant in the early universe.

C and CP violation in SM

CP violation in SM

Jarlskog invariant quantity:[J.M.Cline,hep-ph/0609145]

$$J = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)K$$

where

$$\begin{aligned} K &= s_1^2 s_2 s_3 c_1 c_2 c_3 sin\delta \\ &= Im(V_{ii} V_{jj} V_{ij}^* V_{ji}^*) \qquad for \quad i \neq j \end{aligned}$$

From the above quantity, CP violation strength be:

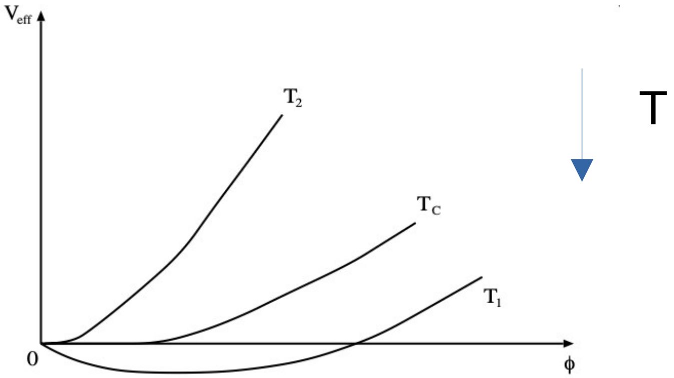
$$\frac{J}{(100GeV)^{12}} \sim 10^{-20}$$

Too small for explaining baryon asymmetry of universe

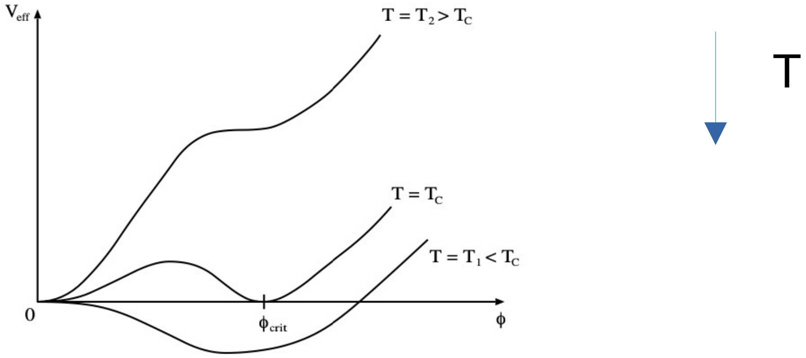
Departure from thermal Equilibrium

Compare interaction rate with the expansion rate of the universe

- Sphaleron enters in thermal equilibrium around $T \sim 10^{12}$ GeV
- After EWPT, its rate is exponentially suppressed implying Sphaleron interaction goes out of equilibrium
- To maximize the asymmetry generation, a First Order Electroweak Phase Transition is required.



2nd order PT (no discontinuity)



1st oder PT (discontinuity prevails)

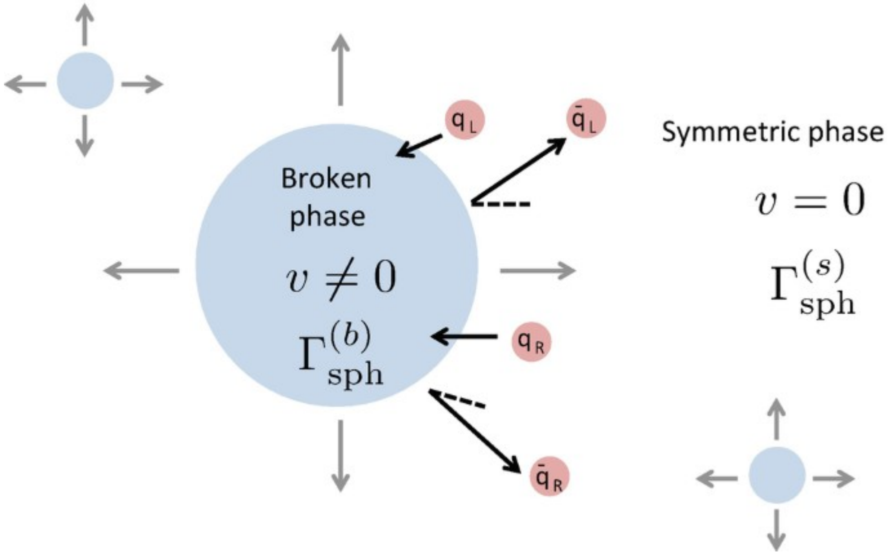
The local and global minima are separated by a barrier

FOPT contd..

- The local and global minima are separated by a barrier

- The FOPT proceeds via bubble nucleation [Inside bubble: symmetry is broken and outside bubble: symmetry unbroken]

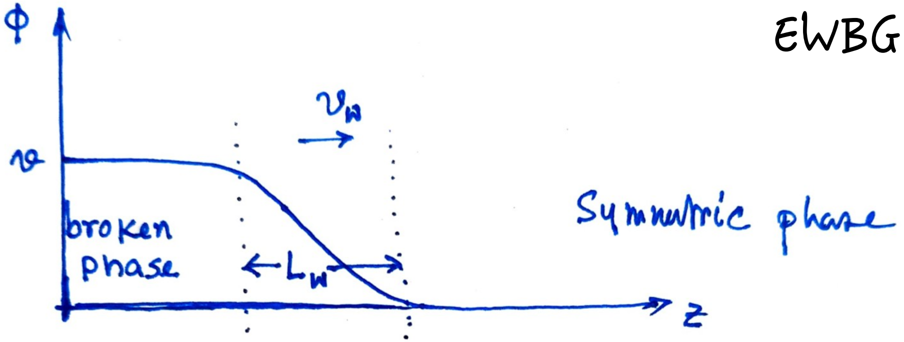
- The bubbles starts to appear randomly throughout the universe, then grow and eventually fill the universe.



Out of equilibrium scenario in the vicinity of bubble nucleation

- sphalerons remain highly active in the symmetric phase, whereas heavily Boltzmann-suppressed inside the bubbles

EWBG in nutshell

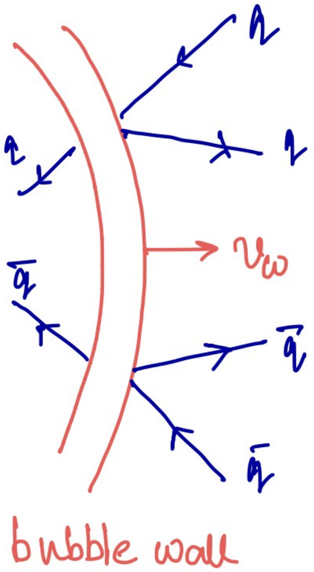


$$\phi(z) = \frac{\rho(z)}{\sqrt{2}} e^{i\theta(z)} \qquad \rho(z) = \frac{v_c}{2}\left(1 - \tanh\frac{z}{L_w}\right)$$

$q_L + \bar{q}_R$ more than $q_R + \bar{q}_L$ } CP violating scattering $\left[\mathcal{L}_f = \sum_\psi y_\psi \bar{\Psi}_L \psi_R H\right]$

$\mu_{q_L}(z)$ generated $\leftrightarrow \left[n_x - n_{\bar{x}} = \frac{g_x}{6}\frac{\mu_x}{T} \cdot T^3\right]$

$\Gamma_{sp} \simeq 0$



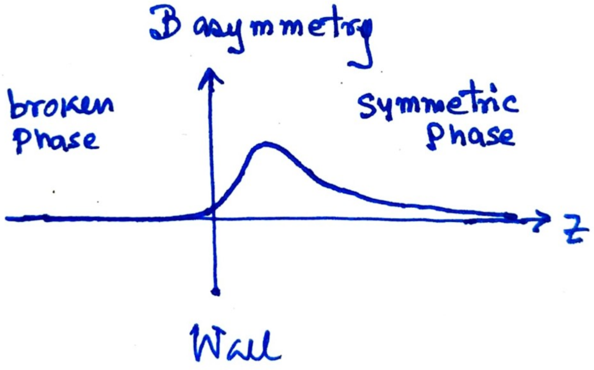
$$v_w \partial_z \mu_i - \sum_j \Gamma_{ij}\mu_j + \cdots = S_i$$

diffusion equation

baryon asym generated near the wall

$$\frac{\partial n_B}{\partial t} = \frac{3}{2}\frac{\Gamma_{sp}}{T}\left(\mu_{q_L} - k_{CS}\frac{n_B}{T^2}\right)$$

$\Gamma_{sp} > H$



Finally as the bubble grows, it captures the asymmetry

Realising First Order EW phase transition in SM

Form of effective potential at high T

Tree level Higgs potential: $V = \lambda \left(|H|^2 - \frac{1}{2} v^2 \right)^2$

1-loop correction at high T: $$V_{1-\text{loop}} = H^2 T^2 \left[\frac{1}{2}\lambda + \frac{3}{16}(3g^2 + g'^2) + \frac{1}{4} y^2 \right] - \frac{TH^3}{12\sqrt{2}\pi} \left(3g^3 + \frac{3}{2}(g^2 + g'^2)^{3/2} + O(\lambda) \right)$$

The effective potential with the **cubic term** (responsible for the barrier) takes the form:

$$V_{\text{tot}} \cong m_H^2(T) H^2 - ETH^3 + \lambda H^4$$

$$m_H^2(T) = -\lambda v^2 + aT^2$$

Realising FOPT in SM contd..

The critical temperature is defined when $V_{\text{tot}} = \lambda H^2 \left(H - \frac{v_c}{\sqrt{2}}\right)^2$

Degenerate minima at $H = 0$ and $H = v_c$

comparing with $V_{\text{tot}} \cong m_H^2(T)H^2 - ETH^3 + \lambda H^4$ → $ET_c = \sqrt{2}\lambda v_c$

$$E \simeq \frac{3g^3}{8\sqrt{2}\pi} \qquad \frac{v_c}{T_c} = \frac{E}{2\sqrt{\lambda}} \cong \frac{3g^3}{16\pi\lambda}$$

The ratio is a measure of the strength of the phase transition, determining how strongly the sphalerons are suppressed inside the bubbles.

$$\Gamma_{\text{sph}} \sim e^{-E_{\text{sph}}/T}$$

$$\frac{E_{\text{sph}}}{T} \sim \frac{8\pi}{g}\left(\frac{v}{T}\right)$$

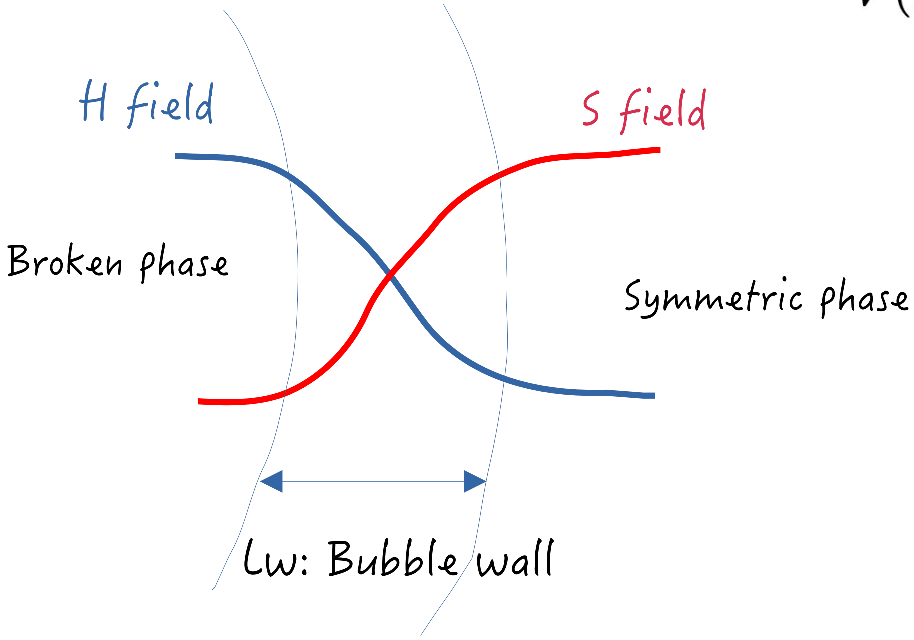
A strong suppression requires

$$\frac{v_c}{T_c} \gtrsim 1 \Rightarrow \lambda < \frac{3g^3}{16\pi} \sim .0164 \rightarrow m_H = \sqrt{\frac{\lambda}{2}}\, v < 32 \text{ GeV}$$

Not possible to have strongly First order EWPT in SM

Realising EWBG in BSM scenarios

Scalar singlet (s) extension



$$V(h,s,T) = \frac{\lambda_h}{4}\left[h^2 - v_c^2 + \frac{v_c^2}{w_c^2}s^2\right]^2 + \frac{\kappa}{4}s^2h^2 + \frac{1}{2}(T^2 - T_c^2)(c_h\,h^2 + c_s\,s^2)$$

- Effectively generates a barrier at tree level (independent of earlier Eh^3 term of the SM alone)
- v_c/T_c can be realised without contradicting the constraints on the SM Higgs mass.

Part-III: Leptogenesis

Leptogenesis and connection to neutrino physics

- Neutrino oscillation --> neutrinos are massive but very light

- In Standard Model, neutrinos are massless --> need to go beyond the SM

One of the most economical extension: Type-I seesaw
[introduce heavy Right Handed Neutrinos (RHN)]

$$-\mathcal{L}_\nu = \overline{\ell_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N^c_{\rm R}} M_{\rm R} N_{\rm R} + {\rm h.c.}$$

- In very early universe with very high temperature, these RHNs can be thermally produced.

- When the temperature of the universe drops below their masses, they decay.

Overview of Type-I seesaw and Neutrino mass

[SM + 3 Right-Handed Neutrinos]

$$\mathcal{L}_{\mathbf{BSM}} = \mathbf{Y}^{\nu}_{\alpha \mathbf{i}} \bar{\ell}_{L_\alpha} \tilde{H} N_i + \frac{M_N}{2} \bar{N_i}^c N_i + h.c$$

After S.S.B.

$$\begin{pmatrix} \bar{\nu}_L & \overline{(N_R)^c} \end{pmatrix} \underbrace{\begin{pmatrix} 0_{3\times3} & m^D_{3\times3} \\ m^{D^T}_{3\times3} & M_{N_{3\times3}} \end{pmatrix}}_{m_{seesaw}} \begin{pmatrix} (\nu_L)^c \\ N_R \end{pmatrix}$$

$$\mathbb{L}^\dagger m_{seesaw} \mathbb{L}^* = m^{block}_{diag}$$

Active-sterile mixing

$$\begin{pmatrix} m_{\nu_{3\times3}} & 0_{3\times3} \\ 0_{3\times3} & M_{N_{3\times3}} \end{pmatrix}$$

$$m_\nu = -m_D M_N^{-1} m_D^T$$

$$\nu_L = U \nu_m + \underbrace{V}_{} N_m$$

$$\mathbf{V = m_D M_N^{-1}}$$

$$U^\dagger m_\nu U^* = D_m$$

$$\begin{pmatrix} D_{m_{3\times3}} & 0_{3\times3} \\ 0_{3\times3} & D_{M_{3\times3}} \end{pmatrix}$$

$$\mathbf{D_m} = \mathrm{diag}(\mathrm{m_1, m_2, m_3})$$

$$D_M = \mathrm{diag}(\mathrm{M_1, M_2, M_3})$$

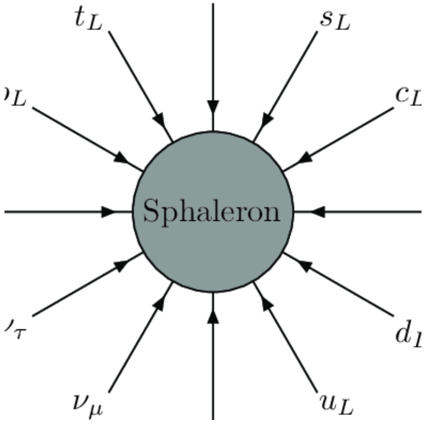
Implications of seesaw in cosmology : Thermal Leptogenesis

Generation of lepton asymmetry via decay of RHN:

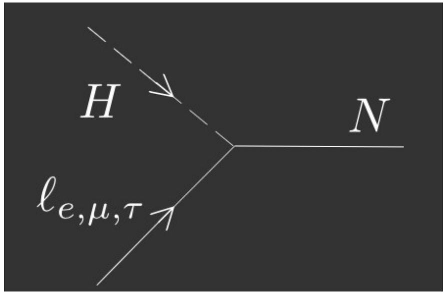
Sakharov conditions can easily be satisfied

- L number violation due to the Majorana nature of heavy RH neutrinos.
- Additional source of CP violation in the leptonic sector via complex Dirac Yukawa couplings (and/or PMNS CP phases).
- Departure from thermal equilibrium when $\Gamma_N < H$

Lepton asymmetry to baryon asymmetry conversion: Sphaleron process



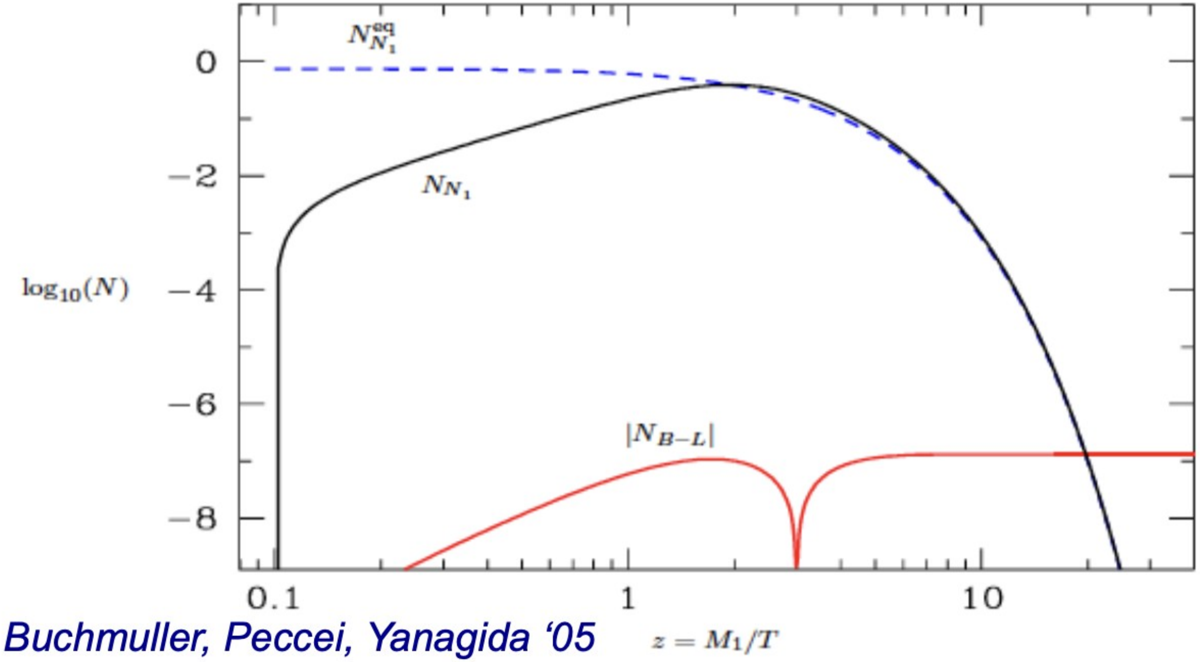
Thermal production of RHN



+scattering

- The story begins right after inflation was over.
- Thermal Production of RHNs: provided $T_{RH} > M_{RHN}$
- attains equilibrium number density :
  [[?] depends on neutrino Yukawa Y_ν]
  $$n_N^{eq} = 2T^3\left[\frac{3}{4}\frac{\zeta(3)}{\pi^2}\right]$$
- At some temperature $T < M_{RHN}$;
  $$n_N^{eq} = 2\left(\frac{M_N T}{2\pi}\right)^{3/2} e^{-M_N/T}$$
- Soon, the heavy neutrinos are not able to follow equilibrium distribution.
  decays out of equilibrium
  [controlled by same Y_ν] $\Gamma_N < H$ [N --> L + H and N --> L* + H*]
- Generation of nonzero CP asymmetry (at one loop) requires at least two RHNs.

Evolution of RHN number density



Buchmuller, Peccei, Yanagida '05

Non-thermal Production of RHN

- With $T_{RH} < M_i$, this is a possibility for producing RHNs.
- In case, RHNs are coupled to the inflaton field (Φ) and $M_\Phi > 2M_i$

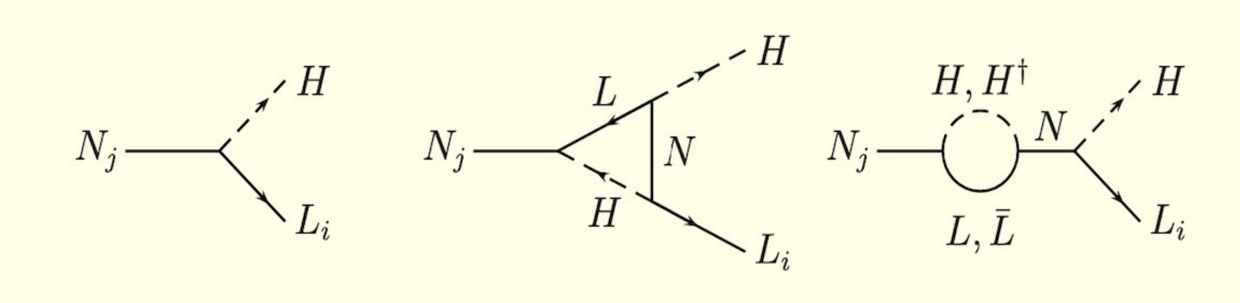
$$\phi \to N_i + N_i$$

With $T_{RH} << M_i$, the produced RHNs would decay immediately: $n_{N_i} \simeq \frac{3}{2} n_{N_i}^{eq} \cdot \frac{T_{RH}}{M_i}$

CP asymmetry calculation (from interference of tree and one loop diagrams)

[Fukugita, Yanagida 1986 Luty, 1992; Flanz et al., 1995; Covi et al., 1996]

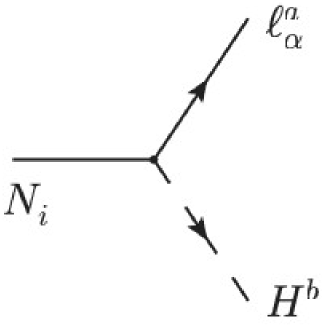
$$\varepsilon_{\ell_\alpha}^{(i)} = \frac{\Gamma(N_i \to \ell_{L_\alpha} + H) - \Gamma(N_i \to \overline{\ell}_{L_\alpha} + \bar{H})}{\sum_\alpha \Gamma(N_i \to \ell_{L_\alpha} + H) + \Gamma(N_i \to \overline{\ell}_{L_\alpha} + \bar{H})}$$



$$\Gamma_{N_i} = \sum_\alpha \Gamma(N_i \to \ell_{L_\alpha} + H) + \Gamma(N_i \to \overline{\ell}_{L_\alpha} + \bar{H})$$
$$= \frac{(Y_\nu^\dagger Y_\nu)_{ii}}{8\pi} M_i.$$

$N^c_i = N_i$

- vanishes at the tree level
- CP violation arises due to the interference between tree and one-loop decay amplitudes [complex Yukawa coupling Y_ν]



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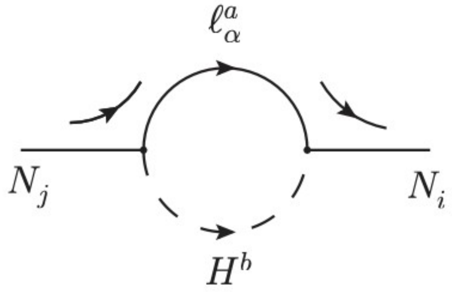


[Dreiner et al., 2010]

$$-\mathcal{L}_\nu = \overline{\ell_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N_{\rm R}^c} M_{\rm R} N_{\rm R} + \text{h.c.}$$

One loop self energy contribution

$$\mathrm{i}\mathcal{M}_{\alpha i}^{\mathrm{s},ab} = -\mathrm{i}\epsilon_{ab}\sum_{j\neq i}\overline{u}(q)P_{\rm R}\left[(Y_\nu)_{\alpha i} + (Y_\nu)_{\alpha j} S(\not{p}, M_j)\Sigma_{ji}(\not{p})\right]u(p)$$

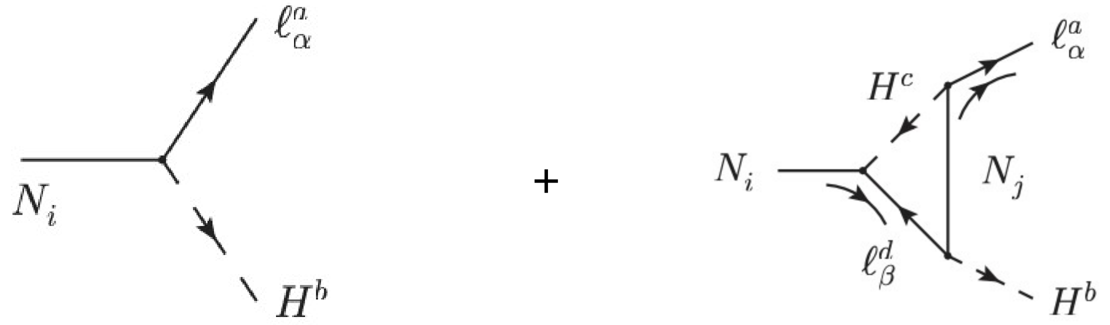
$$K \equiv Y_\nu^\dagger Y_\nu$$

$$\epsilon_{i\alpha}^{s} = \frac{1}{8\pi K_{ii}}\sum_{j\neq i}\frac{M_i}{M_i^2 - M_j^2}\,\mathrm{Im}\left[(Y_\nu^*)_{\alpha i}(Y_\nu)_{\alpha j}\{K_{ji}M_i + K_{ij}M_j\}\right]$$

$$\epsilon_i^s = \sum_\alpha \epsilon_{i\alpha}^s = \frac{1}{8\pi K_{ii}}\sum_{j\neq i}\frac{M_i M_j}{M_i^2 - M_j^2}\,\mathrm{Im}\left[(K_{ij})^2\right]$$

What happens for degenerate RHNs? Enhancement of CP asymmetry!

Resonant Leptogenesis [Pilaftsis, Underwood, 2004/2005]



[Denner et al., 1992]

One loop vertex contribution

$$\epsilon_\alpha^v = \frac{1}{8\pi K_{ii}} \sum_j \mathrm{Im}\left[(Y_\nu^*)_{\alpha i} (Y_\nu)_{\alpha j} K_{ij} \right] f^v\left(\frac{M_j^2}{M_i^2} \right)$$

$$f^v(x) = \sqrt{x}\left[1 + (1+x) \ln\left(\frac{x}{1+x} \right) \right]$$

Unflavoured Estimate of CP asymmetry (with hierarchical RHNs $M_1 \ll M_2 \ll M_3$):

- Lightest RHN (N_1) is the only relevant one for leptogenesis:

$$\varepsilon_{\ell_\alpha} = \frac{1}{8\pi (Y_\nu^\dagger Y_\nu)_{11}} \sum_{j\neq 1} \left\{ \mathrm{Im}[(Y_\nu^*)_{\alpha 1}(Y_\nu)_{\alpha j}(Y_\nu^\dagger Y_\nu)_{1j}]\mathbf{F}\left(\frac{M_j^2}{M_1^2}\right) + \mathrm{Im}[(Y_\nu^*)_{\alpha 1}(Y_\nu)_{\alpha j}(Y_\nu^\dagger Y_\nu)_{j1}]\mathbf{G}\left(\frac{M_j^2}{M_1^2}\right) \right\}$$

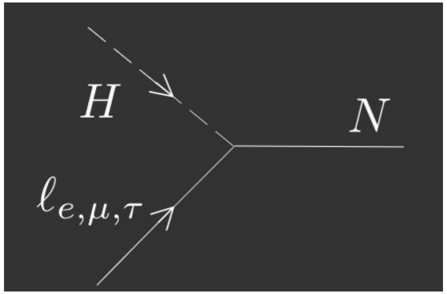
$$\mathbb{F}(x) = \sqrt{x}[1 + \tfrac{1}{1-x} + (1+x)\ln(\tfrac{x}{1+x})] \quad \text{and} \quad \mathbb{G}(x) = 1/(1-x)$$

- Flavour sum: $\varepsilon_\ell = \sum_\alpha \varepsilon_{\ell_\alpha}$ (Vanishing contribution to the second term)

However, both terms remain important for flavoured leptogenesis

Leptogenesis (covered so far...)

- Production of RHNs in early Universe (thermal and non-thermal)

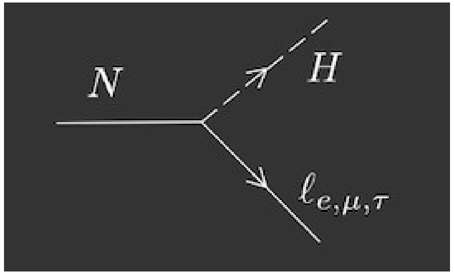


Thermal: $T_{RH} > M_{RHN}$

$$\phi \rightarrow N_i + N_i$$

Non-thermal: $T_{RH} < M_{RHN}$

- Out of equilibrium decay of RHNs



$$\Gamma_N < H$$

- CP asymmetry calculation (flavor dependent)

$$\varepsilon_{\ell_\alpha} = \frac{1}{8\pi (Y_\nu^\dagger Y_\nu)_{11}} \sum_{j\neq 1} \left\{ \mathrm{Im}[(Y_\nu^*)_{\alpha 1}(Y_\nu)_{\alpha j}(Y_\nu^\dagger Y_\nu)_{1j}]\mathbf{F}\left(\frac{M_j^2}{M_1^2}\right) + \mathrm{Im}[(Y_\nu^*)_{\alpha 1}(Y_\nu)_{\alpha j}(Y_\nu^\dagger Y_\nu)_{j1}]\mathbf{G}\left(\frac{M_j^2}{M_1^2}\right) \right\}$$

- Flavour sum: $\varepsilon_\ell = \sum_\alpha \varepsilon_{\ell_\alpha}$

Lepton asymmetry: quantified in terms of number densities of leptons and anti-leptons

$$n_\ell - n_{\bar{\ell}} \propto \varepsilon_i n_{N_i}$$

changes decays + lepton number violating scatterings

Changes due to decay and inverse decays

Exact calculation: Boltzmann equations

Evolution of Lepton asymmetry using Boltzmann equations

$n_a = \frac{N_a}{V}$; N_a : total number of a particles in the physical volume

$V = V_0\, a(t)^3 / a^3(t_0)$

· In absence of any interactions: $\dot{N}_a = 0$

$$\frac{d}{dt}(n_a V) = 0$$

$$\Rightarrow V \dot{n}_a + n_a \frac{V_0}{a(t_0)^3} 3 . a^2(t)\, \dot{a} \times \frac{a}{a} = 0$$

$$\Rightarrow \boxed{V \dot{n}_a + 3H\, n_a V = 0}$$

· In presence of $a + X \rightarrow Y$ and $Y \rightarrow a + X$, change of particles in V per unit time,

$$-V \sum_{X,Y} \int d\Pi_a\, d\Pi_X\, d\Pi_Y\, (2\pi)^4\, \delta^{(4)}(p_a + p_X - p_Y) \Big[f_a f_X (1 \pm f_Y) \times |M|^2_{a+X\rightarrow Y} - f_Y (1 \pm f_a)(1 \pm f_X) |M|^2_{Y\rightarrow a+X} \Big]$$

$f_x \simeq e^{(-E+\mu_x)/T}$

$n_x = e^{\mu_x/T} . n_x^{eq}$

The equation takes the form (with decay + inverse decay)

Assumptions: (i) MB distribution
(ii) $1 \pm f_x \sim 1$

$$\dot{n}_a + 3Hn_a = \sum_{X,Y} \left[\frac{n_Y}{n_Y^{\rm eq}} \gamma(Y \to a + X) - \frac{n_a}{n_a^{\rm eq}} \cdot \frac{n_X}{n_X^{\rm eq}} \gamma(a + X \to Y) \right]$$

$f_x \simeq e^{(-E+\mu_x)/T}$

$n_x = e^{\mu_x/T} \cdot n_x^{eq}$

→

$\gamma(Y \to a+X) = \int d\Pi_Y \, d\Pi_a \, d\Pi_X \, e^{-E_Y/T} |M|^2_{Y\to a+X} (2\pi)^4 \delta^{(4)}(p_Y - p_a - p_X)$

$\gamma(a+X \to Y) = \int d\Pi_a \, d\Pi_X \, d\Pi_Y \, e^{-E_a/T} e^{-E_X/T} |M|^2_{a+X\to Y} (2\pi)^4 (p_a + p_X - p_Y)$

$$\gamma_{(N_i \to \ell_\alpha + H)} = \int d\Pi_{N_i} \, e^{-E_{N_i}/T} \int d\Pi_{\ell_\alpha} \, d\Pi_H \, (2\pi)^4 \, \delta^{(4)}(p_{N_i} - p_{\ell_\alpha} - p_H) \, |M|^2_{N_i \to \ell_\alpha + H}$$

$$= \int d\Pi_{N_i} \, e^{-E_{N_i}/T} \; 2 M_i \Gamma_{N_i} g_{N_i} = n_{N_i}^{eq} \frac{K_1(z)}{K_2(z)} \Gamma_{N_i \to \ell_\alpha + H}$$

K_1, K_2: modified Bessel functions

Consider the decay of the lightest RHN N_1 only (hierarchical RHNs)

$$\gamma_{\rm D} = \sum_\alpha \left[\gamma(N_1 \to \ell_\alpha + H) + \gamma(N_1 \to \bar{\ell}_\alpha + \overline{H}) \right] = n_{N_i}^{\rm eq} \frac{K_1(z)}{K_2(z)} \Gamma_1$$

$z = M_{N_i}/T$

With one loop contribution:

Connected by CPT Symmetry

differ due to CP

$$\gamma(N_1 \to \ell + H) = \gamma(\bar{\ell} + \bar{H} \to N_1) = \frac{1}{2}(1+\epsilon_1)\gamma_D$$

$$\gamma(N_1 \to \bar{\ell} + \bar{H}) = \gamma(\ell + H \to N_1) = \frac{1}{2}(1-\epsilon_1)\gamma_D$$

$$\dot{n}_{N_1} + 3Hn_{N_1} = -\frac{n_{N_1}}{n_{N_1}^{eq}}\gamma(N_1 \to \ell + H) - \frac{n_{N_1}}{n_{N_1}^{eq}}\cdot\gamma(N_1 \to \bar{\ell} + \bar{H})$$

$$+ \frac{n_\ell}{n_\ell^{eq}}\cdot\frac{n_H}{n_H^{eq}}\cdot\gamma(\ell H \to N_1) + \frac{n_{\bar{\ell}}}{n_{\bar{\ell}}^{eq}}\cdot\frac{n_{\bar{H}}}{n_{\bar{H}}^{eq}}\cdot\gamma(\bar{\ell}\bar{H} \to N_1)$$

(each ratio $\frac{n_\ell}{n_\ell^{eq}}, \frac{n_H}{n_H^{eq}}, \frac{n_{\bar{\ell}}}{n_{\bar{\ell}}^{eq}}, \frac{n_{\bar{H}}}{n_{\bar{H}}^{eq}} \to 1$)

$$= -\frac{n_{N_1}}{n_{N_1}^{eq}}\cdot\left[\frac{1}{2}(1+\epsilon_1)\gamma_D + \frac{1}{2}(1-\epsilon_1)\gamma_D\right] + \gamma_{\ell H \to N_1} + \gamma_{\bar{\ell}+\bar{H}\to}$$

$$\boxed{\dot{n}_{N_1} + 3Hn_{N_1} = -\frac{n_{N_1}}{n_{N_1}^{eq}}\cdot\gamma_D + \gamma_D = -\left(\frac{n_{N_1}}{n_{N_1}^{eq}} - 1\right)\gamma_D.}$$

Similarly, for lepton (anti-lepton) densities

$$\dot{n}_\ell + 3Hn_\ell = \sum_\alpha \frac{n_{N_1}}{n^{eq}_{N_1}} \gamma(N_1 \to \ell_\alpha + H) - \frac{n_{\ell_\alpha}}{n^{eq}_{\ell_\alpha}} \cdot \frac{n_H}{n^{eq}_H} \cdot \gamma(\ell_\alpha + H \to N_1)$$

and

$$\dot{n}_{\bar{\ell}} + 3Hn_{\bar{\ell}} = \sum_\alpha \frac{n_{N_1}}{n^{eq}_{N_1}} \cdot \gamma(N_1 \to \bar{\ell}_\alpha + \bar{H}) - \frac{n_{\bar{\ell}_\alpha}}{n^{eq}_{\bar{\ell}_\alpha}} \cdot \frac{n_{\bar{H}}}{n^{eq}_{\bar{H}}} \cdot (\bar{\ell}_\alpha + \bar{H} \to N_1)$$

N --> L + H

and

N --> L* + H*

With, $n_L = n_\ell - n_{\bar{\ell}}$

$$\dot{n}_{B-L} + 3Hn_{B-L} = \left[-\epsilon_1\left(\frac{n_{N_1}}{n^{eq}_{N_1}} + 1\right) - \frac{n_{B-L}}{2n^{eq}_\ell}\right]\gamma_D$$

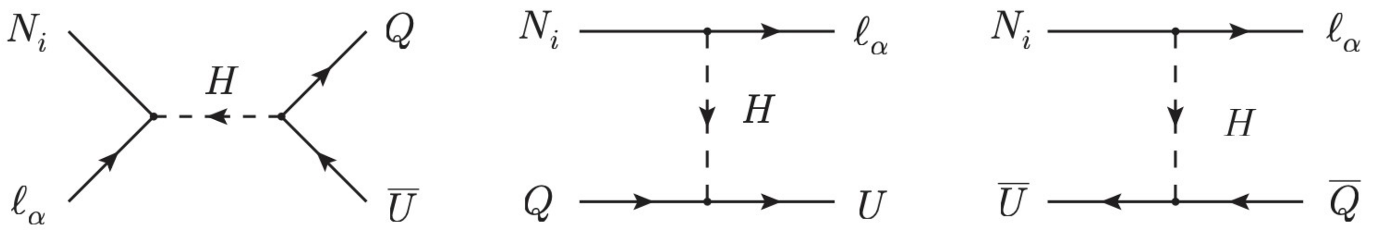
$$\frac{dY_a}{dz} = \frac{dt}{dz} \cdot \frac{d}{dt}\left(\frac{Vn_a}{Vs}\right) = \frac{dt}{dz} \cdot \frac{\dot{n}_a + 3Hn_a}{s}$$

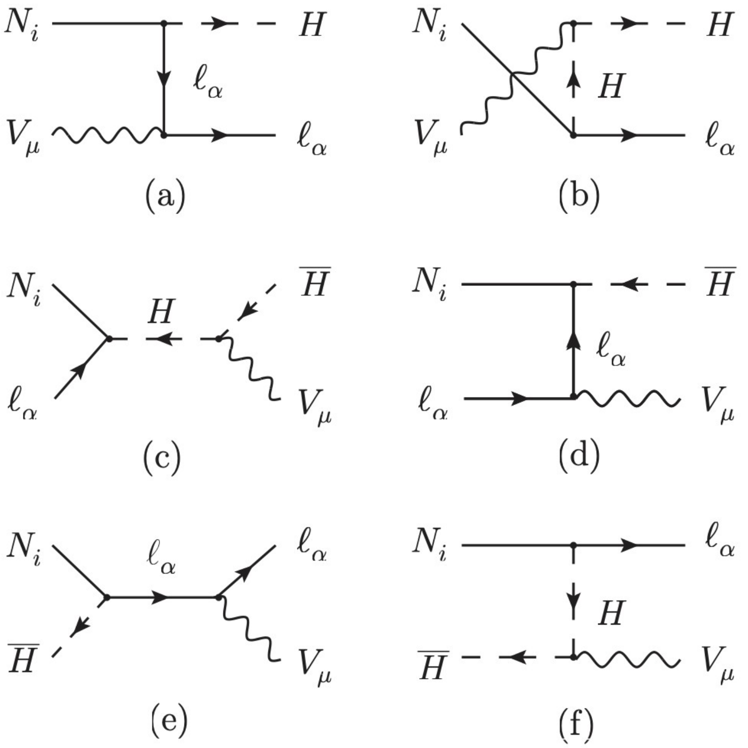
$H(t) = \frac{1}{2t}$ and $t \propto \frac{1}{T^2} = \alpha z^2$

$$\frac{dt}{dz} = 2\alpha z = \frac{2}{z} \cdot t = \frac{1}{Hz}$$

Or in terms of $Y_L = n_L/s$

$$sHz\frac{dY_L}{dz} = D - \overline{D} = \left[\varepsilon_1\left(\frac{Y_{N_1}}{Y^{eq}_{N_1}} + 1\right) - \frac{Y_L}{2Y^{eq}_\ell}\right]\gamma_D$$

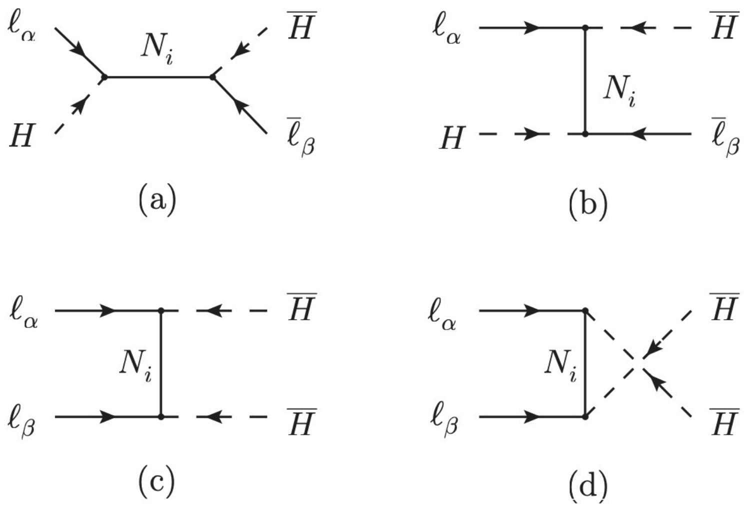




$\Delta L = 1$ scattering:

$\Delta L = 2$ scattering:

On-shell contribution
Needs to be subtracted



On-shell contribution of the $\ell + H \leftrightarrow \overline{\ell} + \overline{H}$ needs to be subtracted to avoid double counting

$$\gamma^{\mathrm{os}}(\ell + H \to \overline{\ell} + \overline{H}) = \gamma(\ell + H \to N_1)\,\mathrm{Br}(N_1 \to \overline{\ell} + \overline{H})$$

$$\gamma'(\ell + H \to \overline{\ell} + \overline{H}) = \gamma_{N_s} - \frac{(1-\varepsilon_1)^2}{4}\gamma_{\mathrm{D}}$$

$$sHz\frac{\mathrm{d}Y_{N_1}}{\mathrm{d}z} = -\left(\frac{Y_{N_1}}{Y_{N_1}^{\mathrm{eq}}} - 1\right)\left(\gamma_{\mathrm{D}} + 2\gamma_{S_s} + 4\gamma_{S_t}\right)$$

$$sHz\frac{dY_{B-L}}{dz} = -\left[\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\epsilon_1 + \frac{Y_{B-L}}{2Y_\ell^{eq}}\right]\gamma_D - \frac{Y_{B-L}}{Y_\ell^{eq}}\cdot\left(2\gamma_N + 2\gamma_{S_t} + \gamma_{S_s}\frac{Y_{N_1}}{Y_N^{eq}}\right)$$

$$\gamma_N \equiv \gamma_{N_s} + \gamma_{N_t}$$

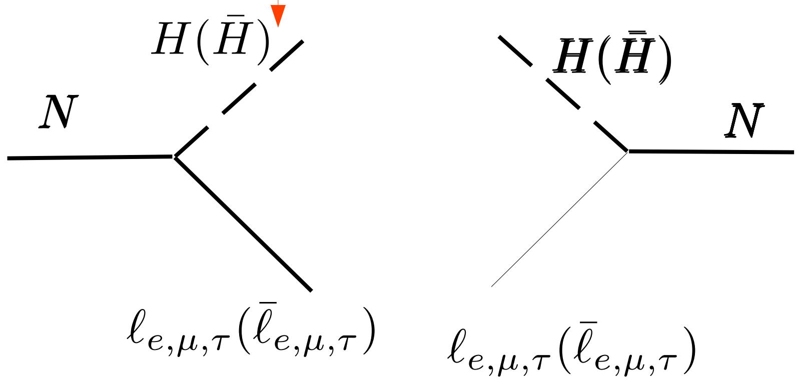
Evolution of asymmetry via Boltzmann equations

$$s\mathcal{H}z\frac{dY_{N_1}}{dz} = \left(\frac{Y_{N_1}}{Y_{N_1}^{\text{eq}}} - 1\right)(\gamma_D + 2\gamma_{S_s} + 4\gamma_{S_t})$$

$$s\mathcal{H}z\frac{dY_{B-L}}{dz} = -\left\{\left(\frac{Y_{N_1}}{Y_{N_1}^{\text{eq}}} - 1\right)\varepsilon_1\gamma_D - \frac{Y_{B-L}}{Y_\ell^{\text{eq}}}\left(2\gamma_N + 2\gamma_{S_t} + \gamma_{S_s}\frac{Y_{N_1}}{Y_{N_1}^{\text{eq}}}\right)\right.$$

$[M_1 << M_2, M_3]$

Washout by 2-2 scattering

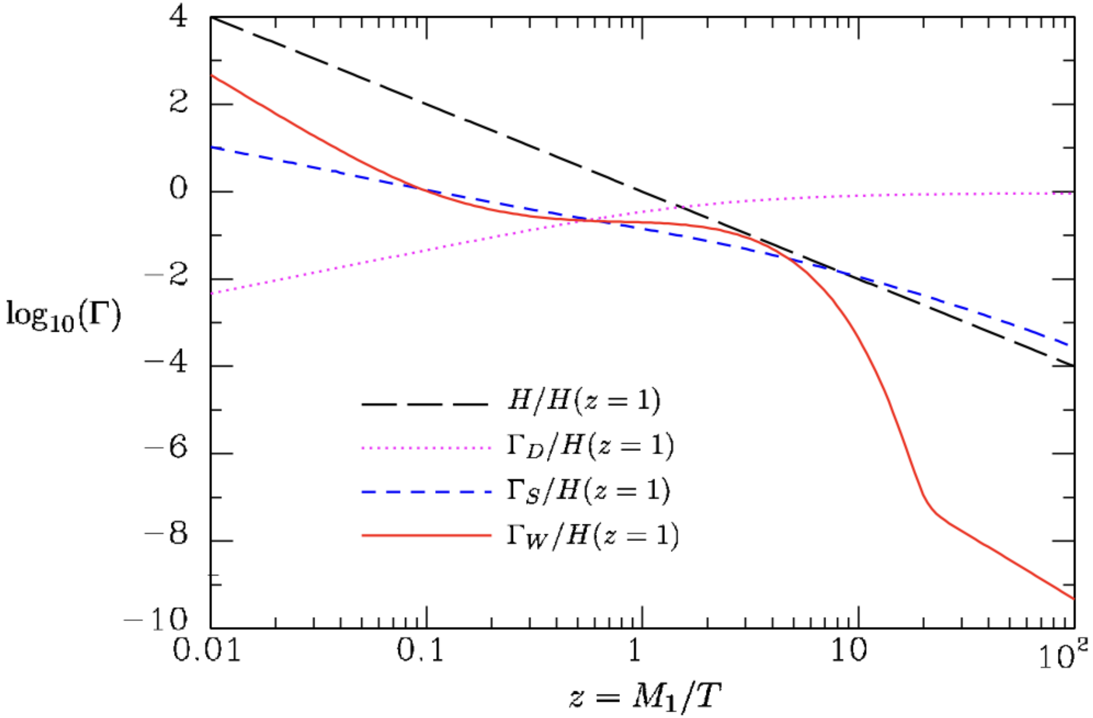


production washout

$$Y_B = \frac{28}{79}Y_{B-L}$$

In sphaleron decoupling limit

- $z = \frac{M_1}{T}$
- $Y_x = \frac{n_x}{s}$
- $\gamma_D = \gamma(N \to \ell H) + \gamma(N \to \bar{\ell}\bar{H})$



4
2
0
−2
−4
−6
−8
−10
$\log_{10}(\Gamma)$
0.01
0.1
1
10
10^2
$z = M_1/T$
$H/H(z=1)$
$\Gamma_D/H(z=1)$
$\Gamma_S/H(z=1)$
$\Gamma_W/H(z=1)$

Conversion of B-L asymmetry to Baryon asymmetry through Sphalerons

- At very early universe: $\Delta n_x = n_x - n_{\bar{x}} = \begin{cases} \frac{\mu_x}{T} \cdot g_x \frac{T^3}{6} & (f) \\ \frac{\mu_x}{T} g_x \frac{T^3}{3} & (b) \end{cases}$

$\mu_x/T \ll 1$, $m_x/T \ll 1$

- At very high T, EW gauge symmetry was restored (gauge interactions are in thermal equilibrium)

$$n_{\rm B} = \frac{1}{6} T^2 \sum_{i=1}^{N_f} (2\mu_{Q_i} + \mu_{U_i} + \mu_{D_i})$$

$$n_{\rm L} = \frac{1}{6} T^2 \sum_{i=1}^{N_f} (2\mu_{\ell_i} + \mu_{E_i})\ ,$$

[system: N_f generations of fermions, Qi, Ui, Di, li, Ei and N_H generations of Higgs doublets]

$$n_x - n_{\bar{x}} = \frac{g}{2\pi^2} \int \left(\frac{p^2}{e^{(pc-\mu)/T} + 1} - \frac{p^2}{e^{(pc+\mu)/T} + 1} \right) = \frac{g}{6} T^3 \left(\frac{\mu}{T} + \frac{1}{\pi^2} \frac{\mu^3}{T^3} \right)$$

- Below TeV, all the Yukawa interactions are in chemical equilibrium

$$\left.\begin{aligned} \mu_Q + \mu_H - \mu_{u_R} &= 0 \\ \mu_Q - \mu_H - \mu_{d_R} &= 0. \\ \mu_\ell - \mu_H - \mu_{e_R} &= 0. \end{aligned}\right\} \quad \begin{aligned} \mu_{Q_i} &= \mu_Q \\ \mu_{u_{R_i}} &= \mu_U \\ \mu_{d_{R_i}} &= \mu_{d_R} \end{aligned}$$

- Hypercharge conservation: $$N_f(\mu_Q - 2\mu_U - \mu_D) - \sum_i (\mu_{\ell_i} + \mu_{E_i}) + 2N_H\mu_H = 0$$

- Sphaleron process (involving left handed fermions) is in equilibrium $$3N_f\mu_Q + \sum_i \mu_{\ell_i} = 0$$

$$n_{\rm B} = +\frac{1}{6}T^2\frac{8N_f + 4N_H}{2N_f + 3N_H}\sum_i \mu_{E_i}\,,$$

$$n_{\rm L} = -\frac{1}{6}T^2\frac{14N_f + 9N_H}{2N_f + 3N_H}\sum_i \mu_{E_i}$$

translates into

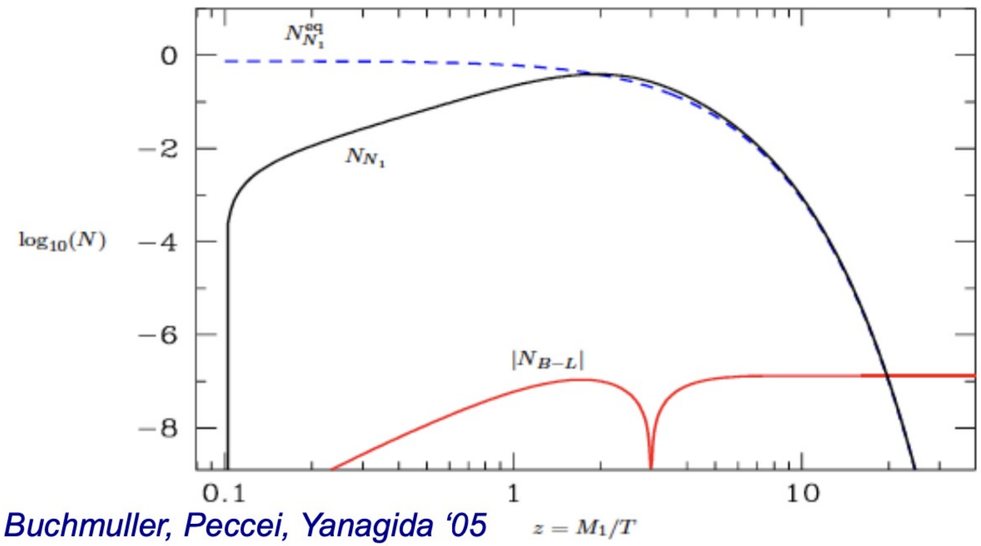
$$n_{\rm B} = \frac{8N_f + 4N_H}{22N_f + 13N_H}(n_{\rm B} - n_{\rm L}) \equiv c\,(n_{\rm B} - n_{\rm L})$$

In SM, $c = 28/79$

- The B-L asymmetry generated during leptogenesis is reprocessed into B asymmetry by sphalerons.

- The Sphaleron process goes out of equilibrium around T* ~ 160 GeV, after which such conversions are not possible.

- Y_B generated around T* remains unchanged thereafter: $\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} = \frac{s}{n_\gamma} Y_B = \frac{\tilde{g}_* \pi^4}{45\zeta(3)} Y_B \approx 1.8 \tilde{g}_* Y_B$



Buchmuller, Peccei, Yanagida '05

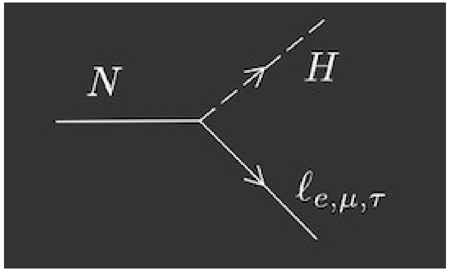
Aspects of flavor in leptogenesis

Barbieria et. al.,2000; Nardi et. al., 2005, 2006; Blanchet, Bari, 2006, 2007; A. Abada et.al.,2007;
,and many more...]

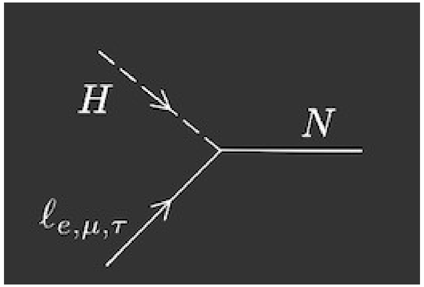
Flavor effects in Leptogenesis

$\mathcal{L} = Y^{\nu}_{\alpha i}\bar{\ell}_{L\alpha}\tilde{H}N_i + Y_\alpha(\bar{\ell}_L)_\alpha H(\ell_R)_\alpha + h.c$

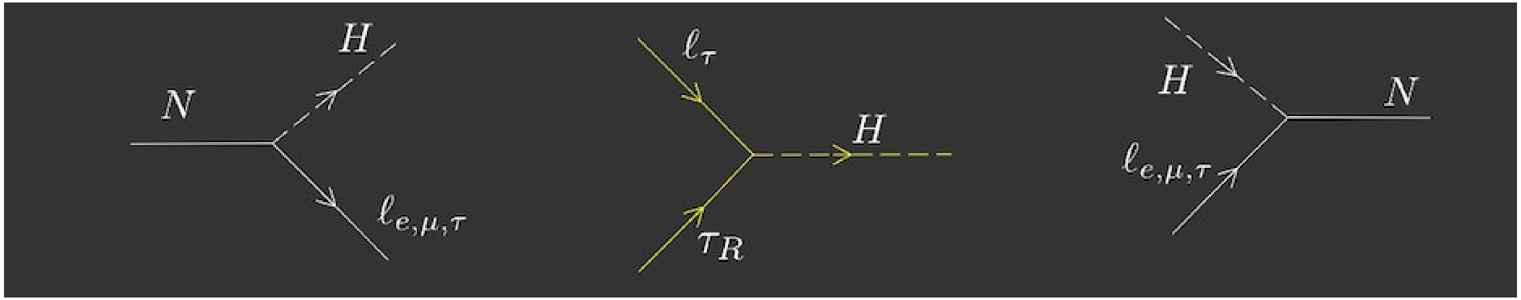
$\Gamma_\alpha < \mathcal{H}$ $(T >> 5 \times 10^{11}\ \mathrm{GeV})$



Production **[Flavor blind]** Washout



$\Gamma_\tau(\propto m_h^2(T)/T) > \mathcal{H}$ [right-handed tau enters equilibrium]



- Washout along individual flavors become different

$$\Gamma_{\tau_R} = \frac{\pi Y_\tau^2}{192\,\zeta(3)} \frac{m_h^2(T)}{T} \quad ; \quad m_h(T) \simeq 0.6\,T$$

(thermal mass)

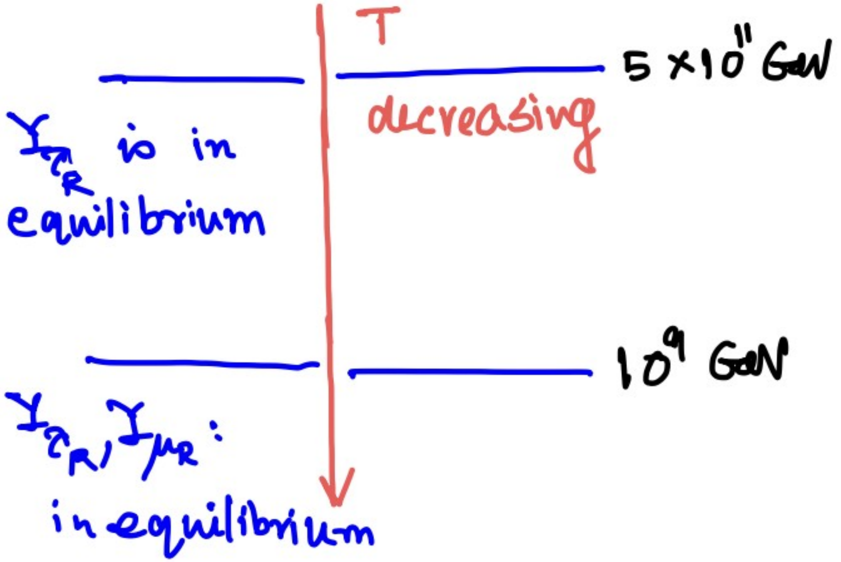
$$H(T) = 0.066\, g_*^{1/2} \frac{T^2}{M_P}$$

$$\Gamma_{\tau_R} \sim H \Rightarrow T_{\tau_R} \simeq 5 \times 10^{11}\ \text{GeV}$$

$Y_\tau, Y_\mu, Y_e \rightarrow$ out of equilibrium

Similarly, $\Gamma_{\mu_R} \sim H \Rightarrow T_{\mu_R} \simeq 10^9\ \text{GeV}$

$$\Gamma_{e_R} \sim H \Rightarrow T_{e_R} \sim 5 \times 10^4\ \text{GeV}.$$



Flavor effects in Leptogenesis

$$\mathcal{L} = Y^{\nu}_{\alpha i}\bar{\ell}_{L\alpha}\tilde{H}N_i + Y_\alpha(\bar{\ell}_L)_\alpha H(\ell_R)_\alpha + h.c$$

T [GeV]

No Flavor effect: $|\ell_1\rangle = \langle \ell_\alpha|\ell_1\rangle|\ell_\alpha\rangle$

$\Gamma_\tau = \mathcal{H}$ $\quad T^0_{\tau_R} \sim [5\times 10^{11}\ \mathrm{GeV}]$

Two Flavor: $|\ell_a\rangle,\ |\ell_\tau\rangle$

$$Y_{B-L} = Y_{B/3-L_a} + Y_{B/3-L_\tau}$$

$\Gamma_\mu = \mathcal{H}$ $\quad T^0_{\mu_R} \sim [10^9\ \mathrm{GeV}]$

Three Flavor: $|\ell_e\rangle,\ |\ell_\mu\rangle,\ |\ell_\tau\rangle$

$$Y_{B-L} = Y_{B/3-L_e} + Y_{B/3-L_\mu} + Y_{B/3-L_\tau}$$

$$s\mathcal{H}z\frac{dY_{B/3-L_\alpha}}{dz} = -\left\{\left(\frac{Y_{N_1}}{Y^{\mathrm{eq}}_{N_1}} - 1\right)\varepsilon_{\ell_\alpha} + \frac{1}{2}K^0_\alpha\sum_\beta (C^\ell_{\alpha\beta} + C^H_\beta)\frac{Y_{B/3-L_\beta}}{Y^{\mathrm{eq}}_\ell}\right\}\gamma_D$$

Flavor effects in Leptogenesis

$$\mathcal{L} = Y^{\nu}_{\alpha i}\bar{\ell}_{L_\alpha}\tilde{H}N_i + Y_\alpha(\bar{\ell}_L)_\alpha H(\ell_R)_\alpha + h.c$$

T [GeV]

No Flavor effect: $|\ell_1\rangle = \langle \ell_\alpha|\ell_1\rangle|\ell_\alpha\rangle$

$\Gamma_\tau = \mathcal{H}$ $\quad T^0_{\tau_R} \sim [5\times 10^{11}\ \mathrm{GeV}]$

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$\Gamma_\mu = \mathcal{H}$ $\quad T^0_{\mu_R} \sim [10^9\ \mathrm{GeV}]$

Three Flavor: $|\ell_e\rangle,\ |\ell_\mu\rangle,\ |\ell_\tau\rangle$

$$Y_{B-L} = Y_{B/3-L_e} + Y_{B/3-L_\mu} + Y_{B/3-L_\tau}$$

$$Y_B = \frac{28}{79}\sum_\alpha Y_{B/3-L_\alpha}$$

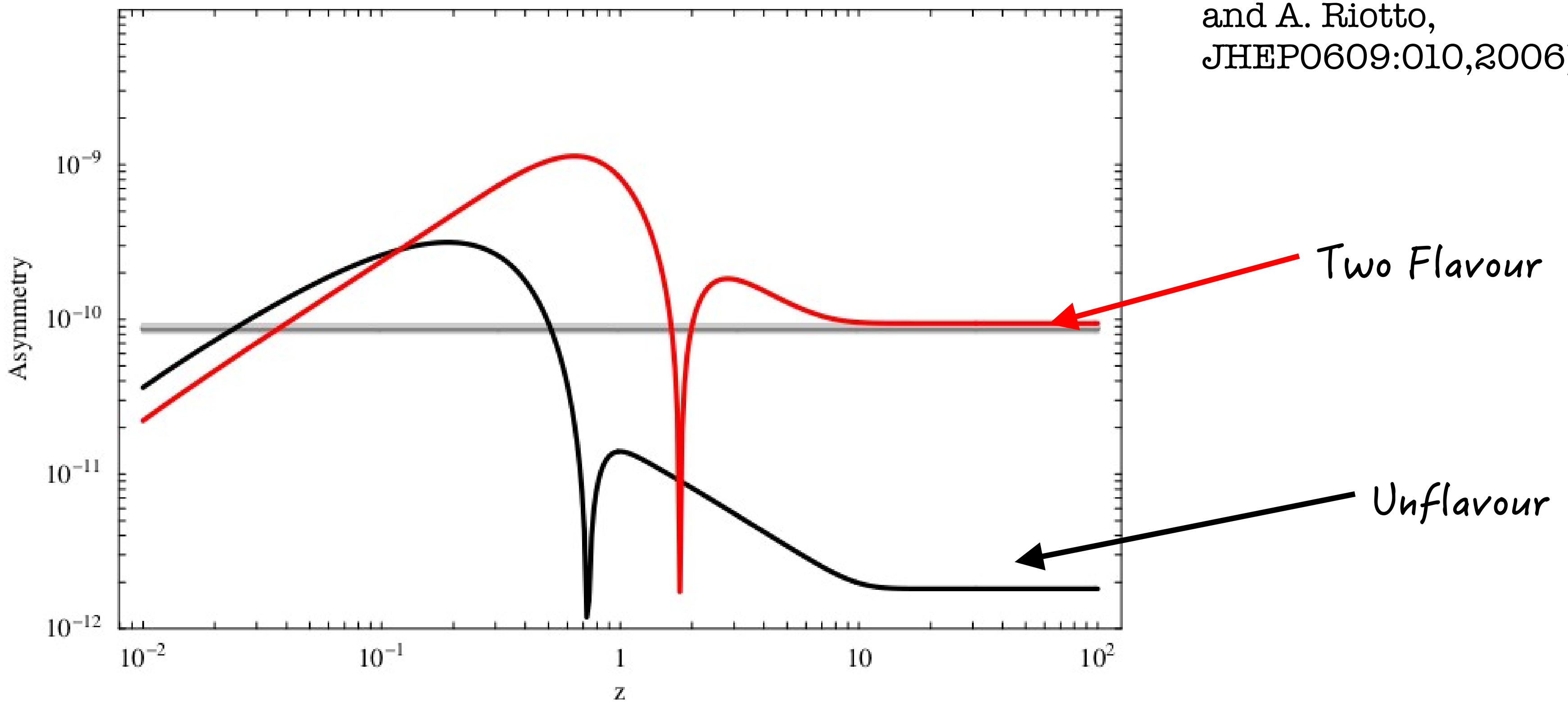
Flavour projector: $|\langle \ell_\alpha|\ell_1\rangle|^2$

Asymmetry converter Matrix

$$s\mathcal{H}z\frac{dY_{B/3-L_\alpha}}{dz} = -\left\{\left(\frac{Y_{N_1}}{Y^{\mathrm{eq}}_{N_1}} - 1\right)\varepsilon_{\ell_\alpha} + \frac{1}{2}K^0_\alpha\sum_\beta (C^\ell_{\alpha\beta} + C^H_\beta)\frac{Y_{B/3-L_\beta}}{Y^{\mathrm{eq}}_\ell}\right\}\gamma_D$$

Importance of flavour effect

[A. Abada, S. Davidson, A. Ibarra, F.-X. Josse-Michaux, M. Losada and A. Riotto, JHEP0609:010,2006]



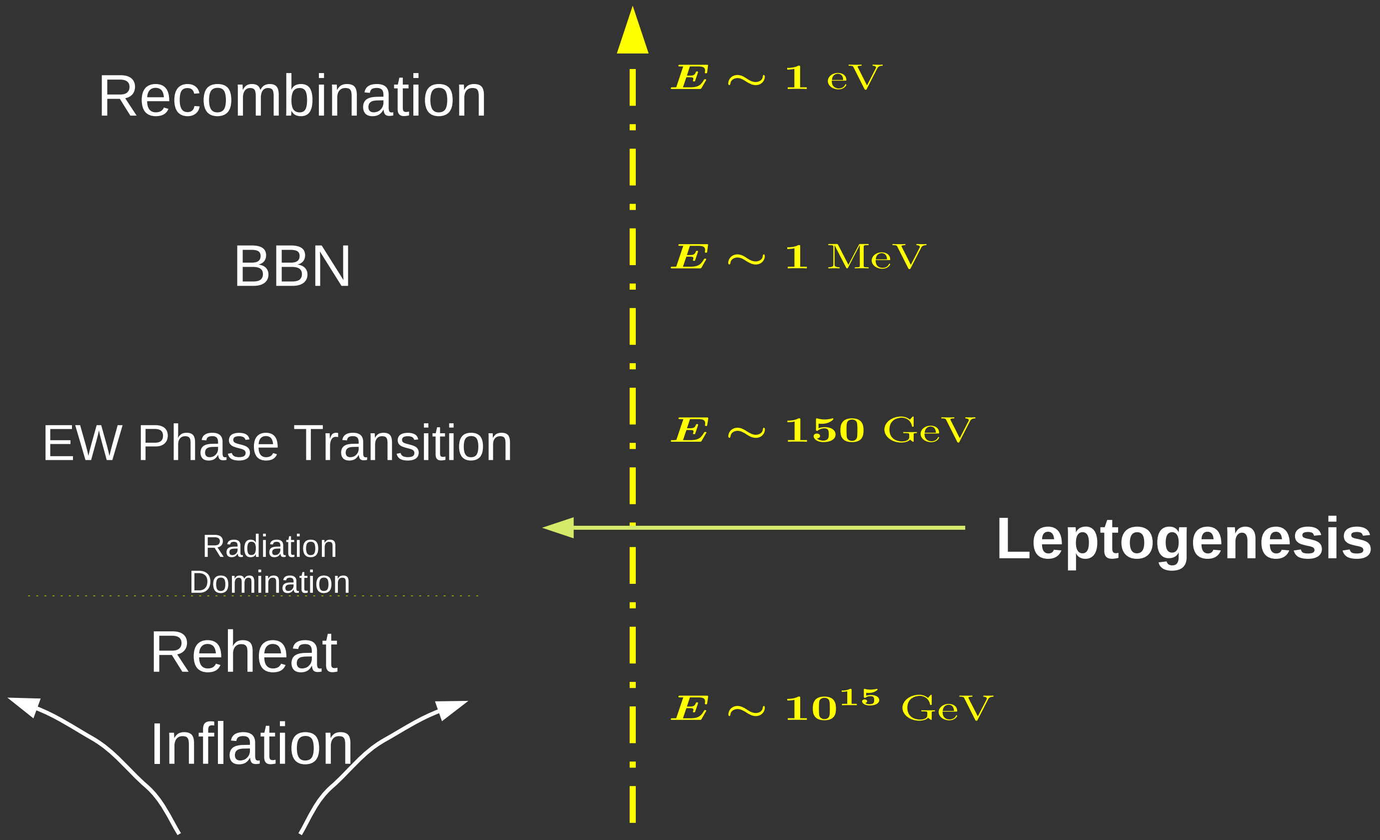
Almost one order shift in produced baryon asymmetry can be achieved

Part-IV: Some recent developments

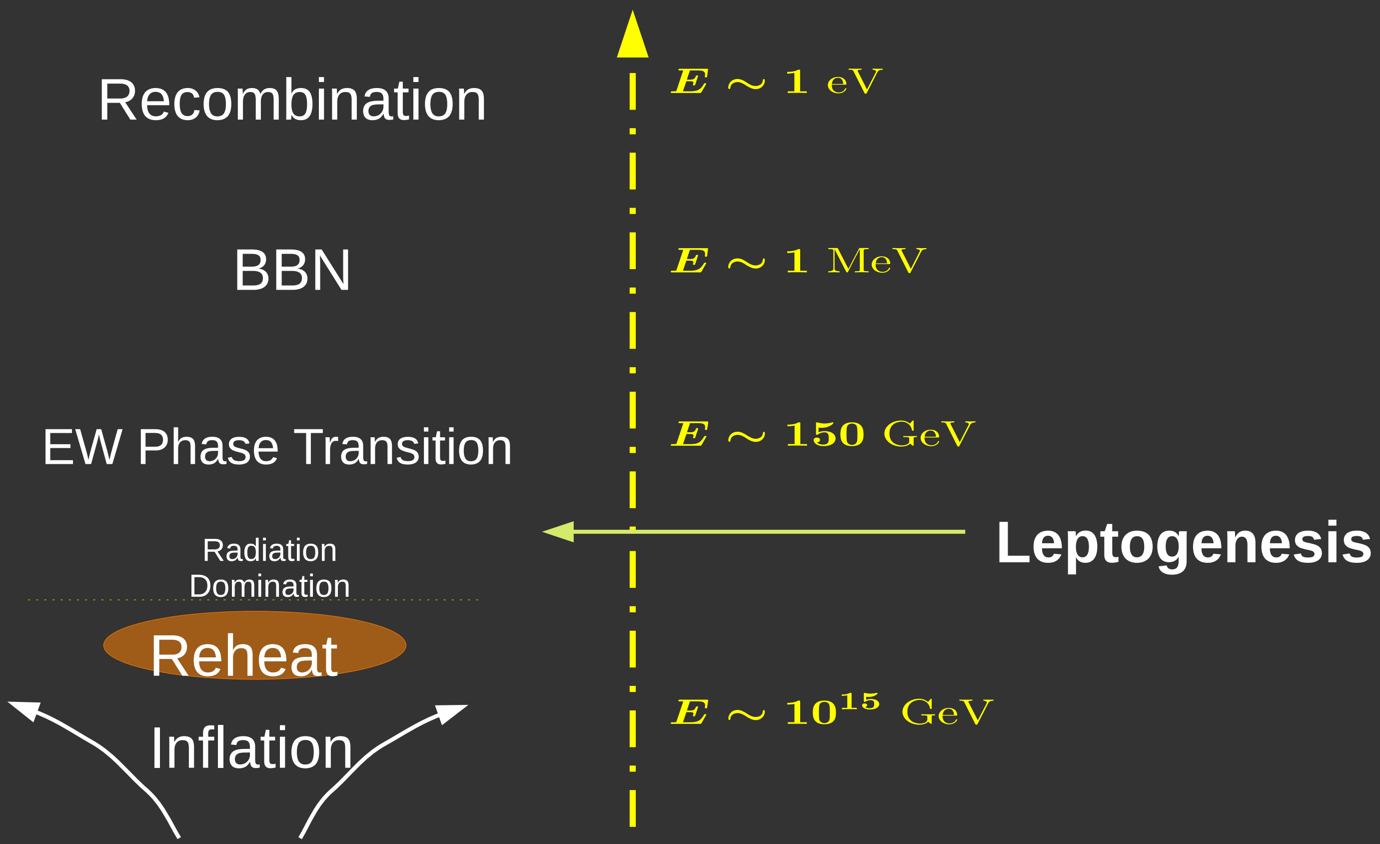
Recent developments on 'Leptogenesis during reheating era'

[A. Datta, R. Roshan and **AS**, 132 **PRL (2024)**]

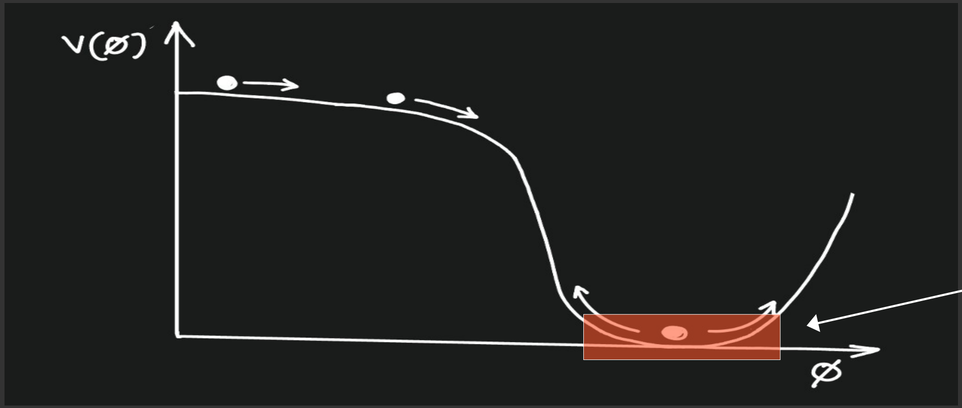
Timeline of Leptogenesis:



Timeline of Leptogenesis:



Inflationary Universe [exponential expansion:] $a \sim e^{Ht}$



Inflaton must decay to radiation

Reheating

- Beginning of the thermal history.
- All elementary particles (of SM) are generated

Era of reheating can be very rich.

Coupling between inflaton and SM

$\mathcal{L} = y_{\phi ff}\phi \bar{f} f$

Produces radiation component ρ_R

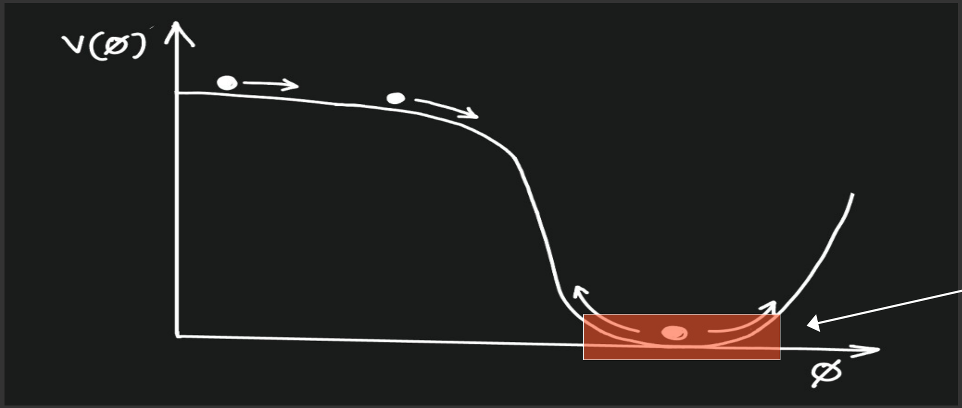
$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}}\rho_\phi a^2$$

$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi \rho_\phi$$

Timeline of the Universe

Recombination	$E \sim 1$ eV
BBN	$E \sim 1$ MeV
EW Phase Transition	$E \sim 150$ GeV
Radiation Domination	
Reheat	
Inflation	$E \sim 10^{15}$ GeV

Inflationary Universe [exponential expansion: $a \sim e^{Ht}$]



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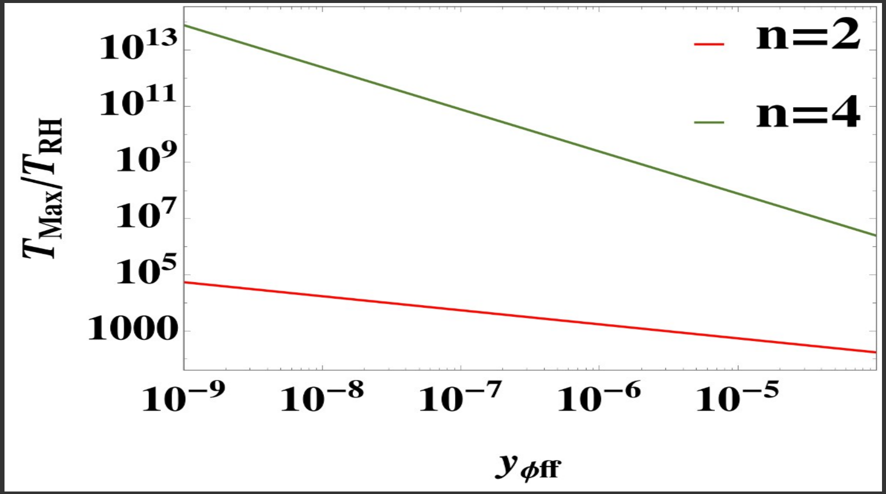
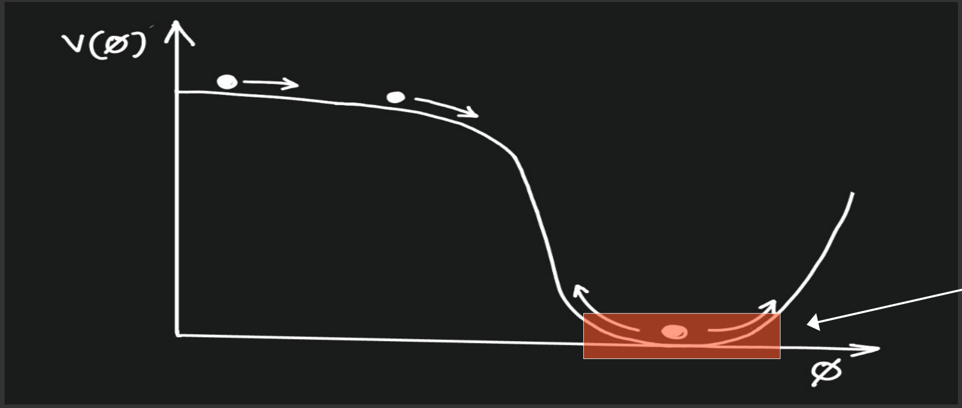


Inflationary Universe [exponential expansion: $a \sim e^{Ht}$]



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- Beginning of the thermal history.
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Era of rehating can be very rich.

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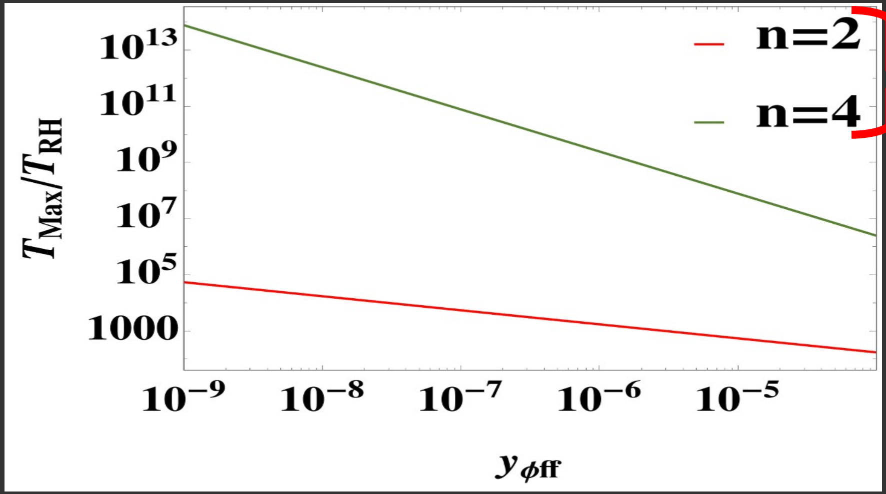
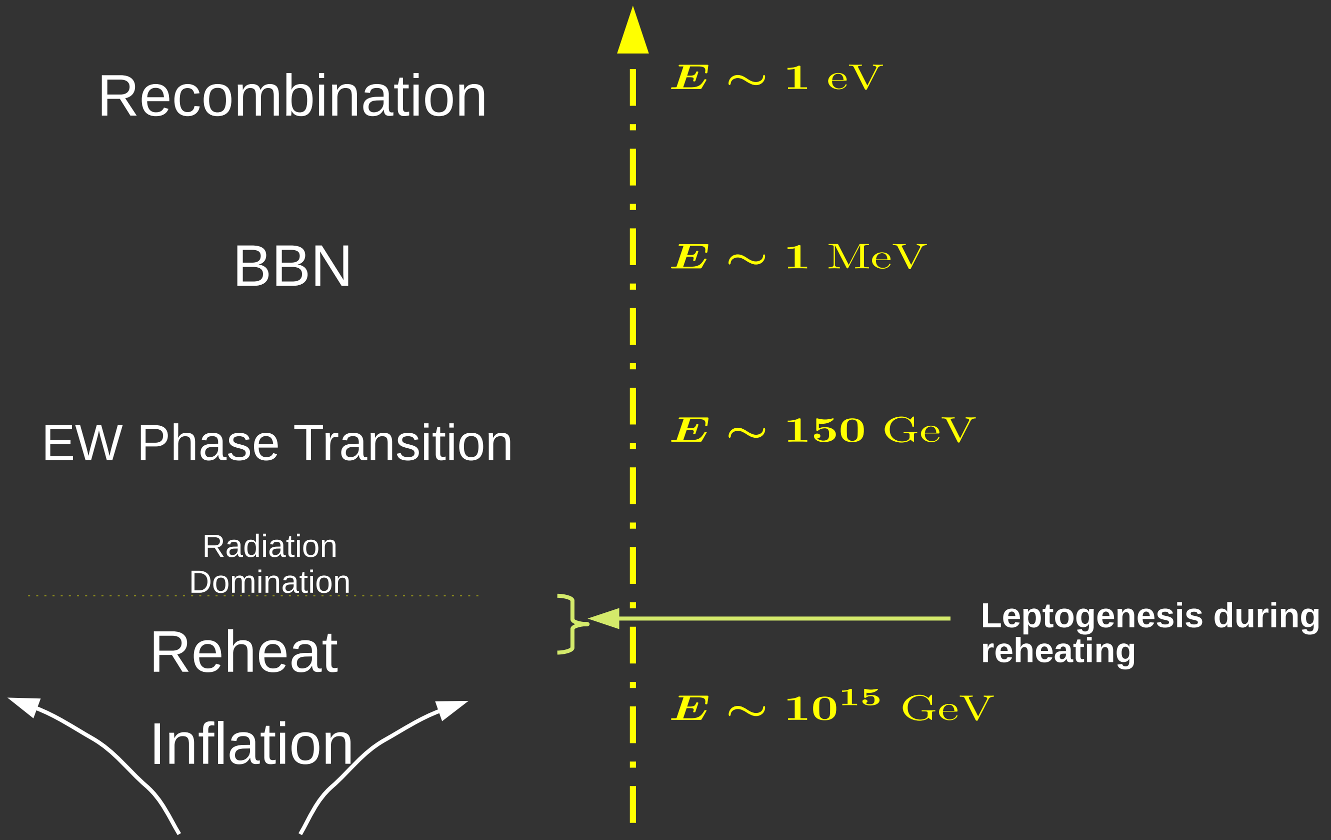
Produces radiation component ρ_R



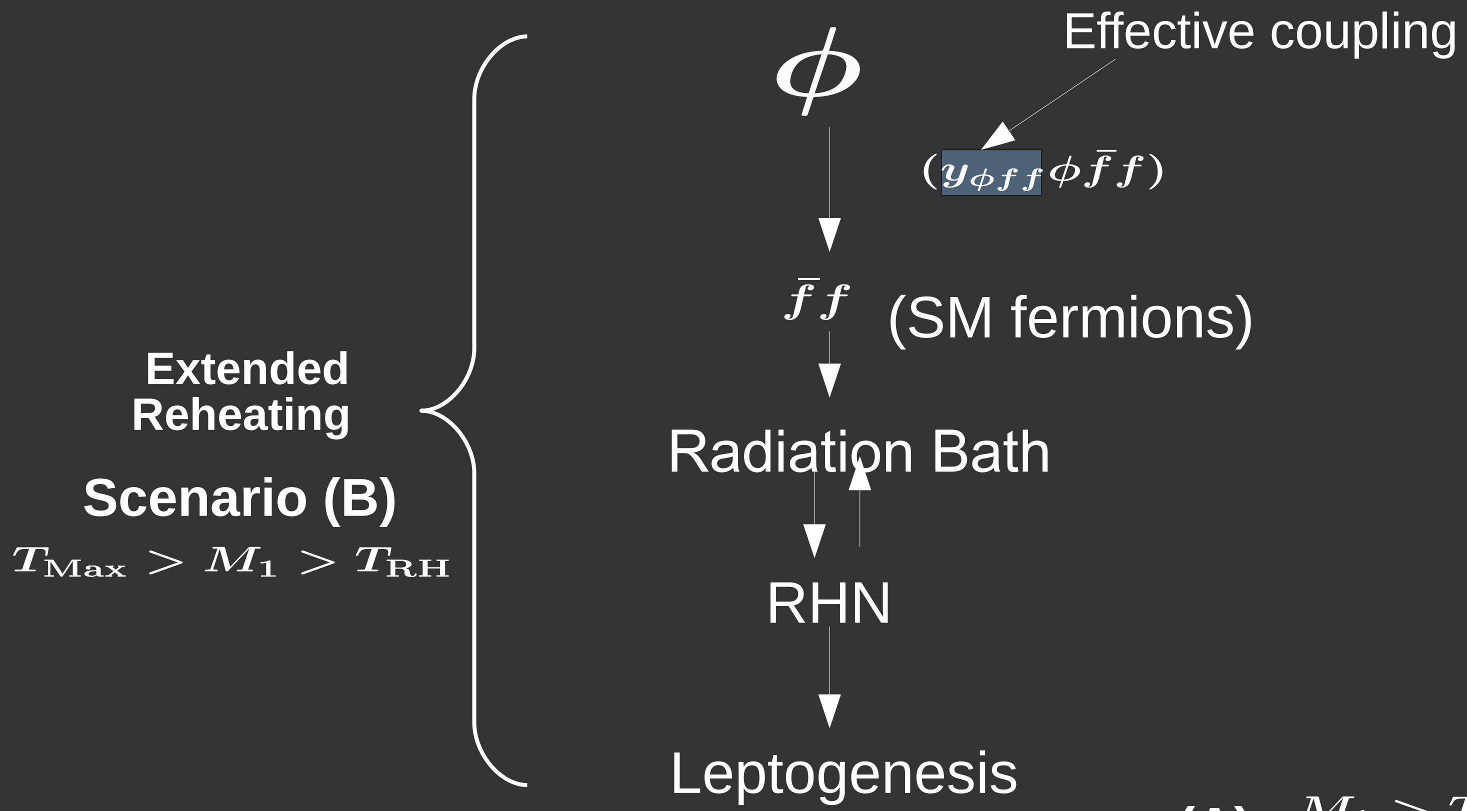
Power in inflaton potential

- **Temperature varies differently.**
- **T_{max} – T_{RH} : depends on effective coupling**

Timeline of Leptogenesis:



Setup:



(A) $M_1 > T_{\rm Max}$

(B) $T_{\rm Max} > M_1 > T_{\rm RH}$

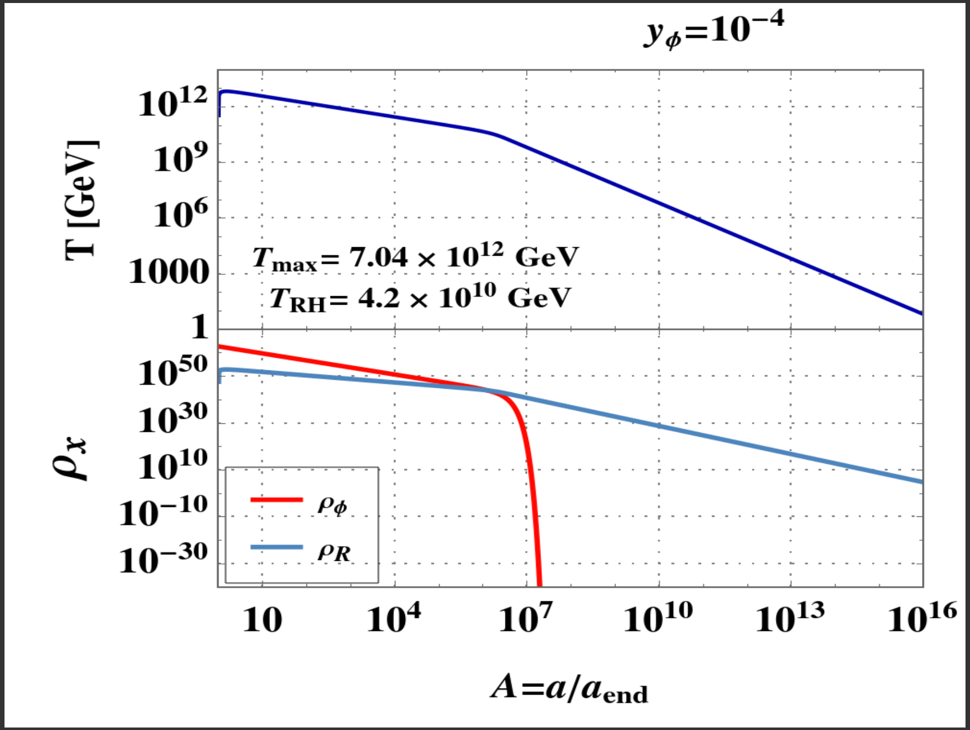
(C) $M_1 < T_{\rm RH}$

Bolzmann Equation and Temperature:

$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}} \rho_\phi a^2$$

$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}} \Gamma_\phi \rho_\phi$$

$$\mathcal{H}^2 = \frac{\rho_\phi + \rho_R}{3M_P^2}$$

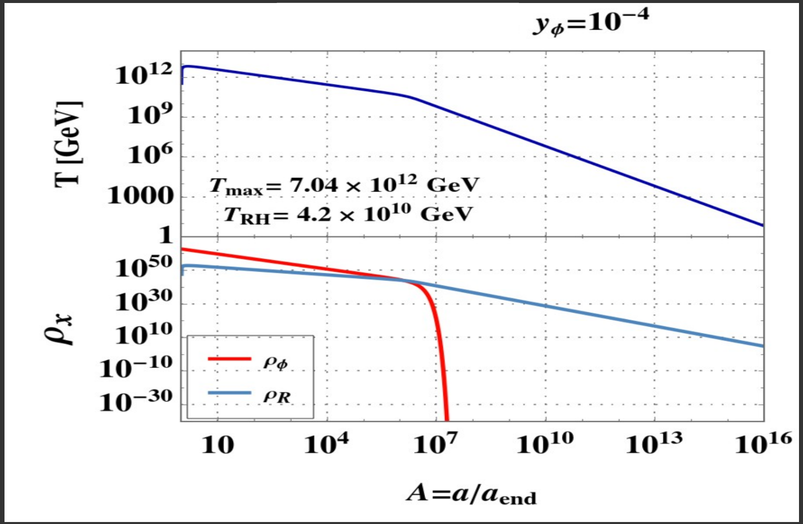


Equilibration of Charged lepton Yukawa:

$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}}\rho_\phi a^2$$

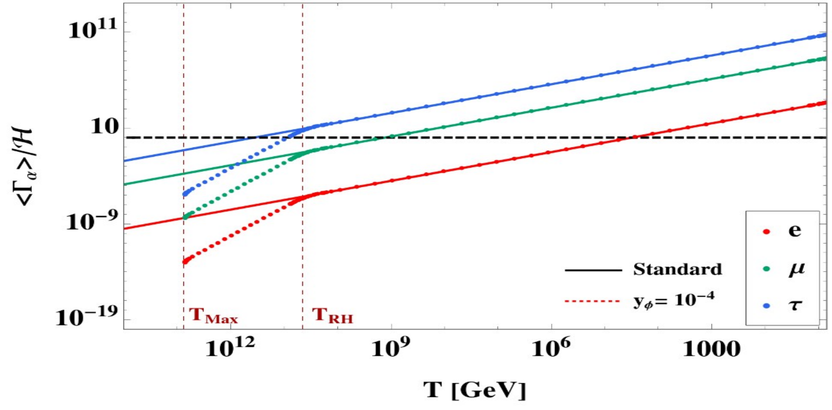
$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi\rho_\phi$$

$$\mathcal{H}^2 = \frac{\rho_\phi + \rho_R}{3M_P^2}$$



Thermal Mass of Higgs

$$\langle\Gamma_\alpha\rangle = \frac{\pi Y_\alpha^2}{192\zeta(3)}\frac{m_h^2(T)}{T} = \mathcal{H}$$

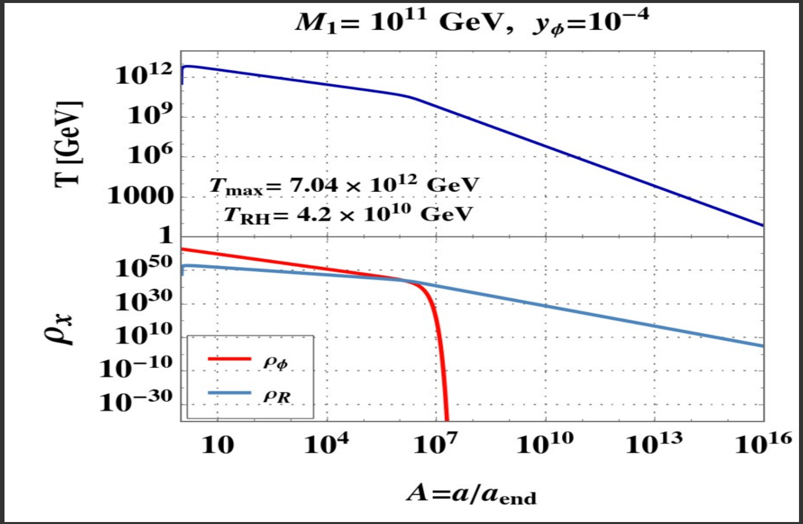


Equilibration of Charged lepton Yukawa:

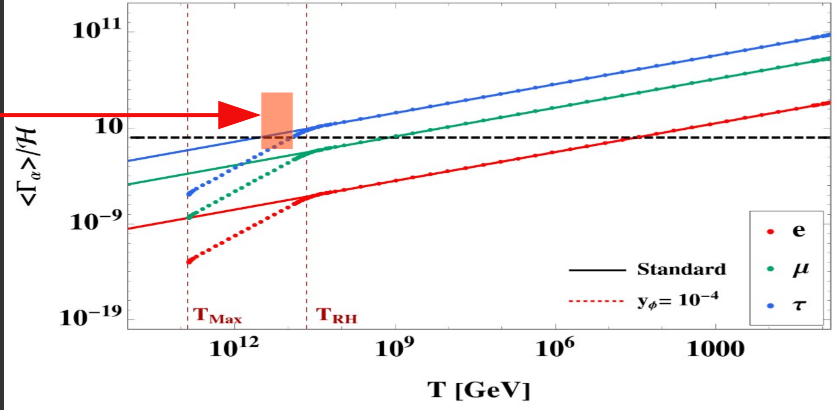
$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}}\rho_\phi a^2$$

$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi \rho_\phi$$

$$\mathcal{H}^2 = \frac{\rho_\phi + \rho_R}{3M_P^2}$$



- **Delayed equilibration of charged lepton Yukawa interactions**



Shift in ET and effect on flavor leptogenesis

$$T_{max} > M_1 > T_{RH}$$

- Decay of N_1 would produce lepton asymmetry
- **However,** flavor regimes are shifted

Need to relook into flavor leptogenesis

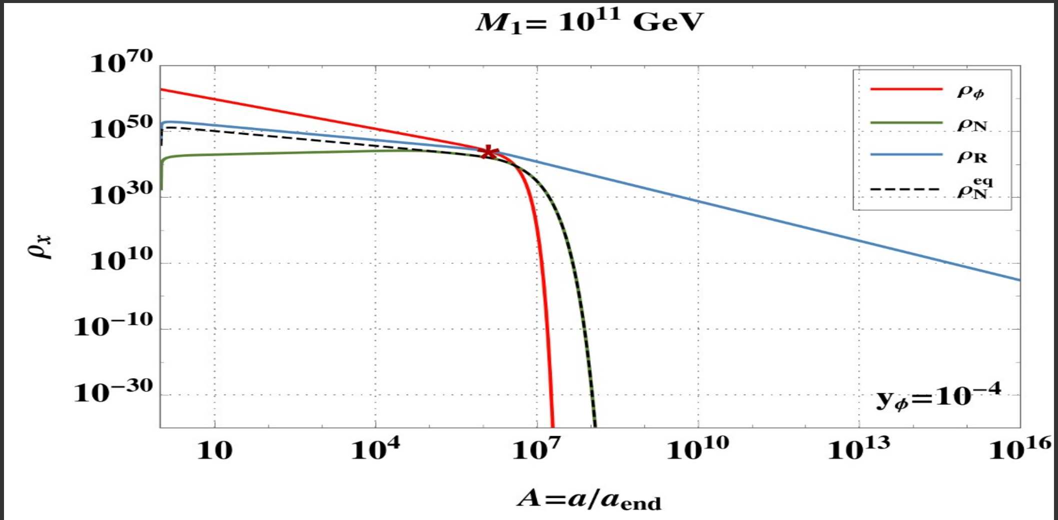
Bolzmann Equation and Temperature:

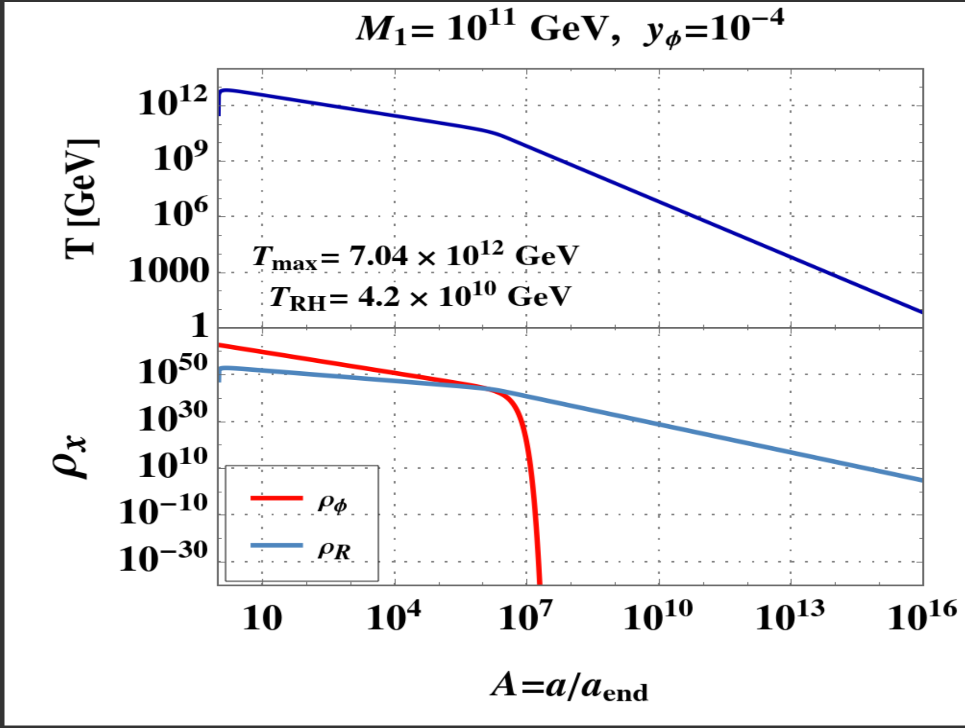
$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}}\rho_\phi a^2$$

$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi\rho_\phi + \frac{a^3}{H}\langle\Gamma_{N_1}\rangle(\rho_{N_1} - \rho_{N_1}^{\rm eq})$$

$$\frac{d(\rho_{N_1} a^3)}{da} = -\frac{\langle\Gamma_{N_1}\rangle a^2}{\mathcal{H}}(\rho_{N_1} - \rho_{N_1}^{\rm eq})$$

$$\mathcal{H}^2 = \frac{\rho_\phi + \rho_R + \rho_{N_1}}{3M_P^2}$$





Modification of Flavor effect

$$\mathcal{L} = Y^{\nu}_{\alpha i}\bar{\ell}_{L_\alpha}\tilde{H}N_i + Y_\alpha(\bar{\ell}_L)_\alpha H(\ell_R)_\alpha + h.c$$

T [GeV]

No Flavor effect: $|\ell_1\rangle = \langle\ell_\alpha|\ell_1\rangle|\ell_\alpha\rangle$

$T^0_{\tau_R} \sim [5\times 10^{11}]$ — $\Gamma_\tau = \mathcal{H}$

Two Flavor: $|\ell_a\rangle,\ |\ell_\tau\rangle$

$$Y_{B-L} = Y_{B/3-L_a} + Y_{B/3-L_\tau}$$

$T^0_{\mu_R} \sim [10^9]$ — $\Gamma_\mu = \mathcal{H}$

Three Flavor: $|\ell_e\rangle,\ |\ell_\mu\rangle,\ |\ell_\tau\rangle$

$$Y_{B-L} = Y_{B/3-L_e} + Y_{B/3-L_\mu} + Y_{B/3-L_\tau}$$

Modification of Flavor effect

$$\mathcal{L} = Y^{\nu}_{\alpha i}\bar{\ell}_{L_\alpha}\tilde{H}N_i + Y_\alpha(\bar{\ell}_L)_\alpha H(\ell_R)_\alpha + h.c$$

$y_\phi = 10^{-4}$

T [GeV]

No Flavor effect: $|\ell_1\rangle = \langle \ell_\alpha | \ell_1 \rangle | \ell_\alpha \rangle$

$T^0_{\tau_R} \sim [5 \times 10^{11}]$

$T_{\tau_R} \sim [7.5 \times 10^{10}]$ $\Gamma_\tau = \mathcal{H}$

Leptogenesis

No Flavor effect

Two Flavor: $|\ell_a\rangle, \; |\ell_\tau\rangle$

$$Y_{B-L} = Y_{B/3-L_a} + Y_{B/3-L_\tau}$$

$T^0_{\mu_R} \sim [10^9]$ $\Gamma_\mu = \mathcal{H}$

Three Flavor: $|\ell_e\rangle, \; |\ell_\mu\rangle, \; |\ell_\tau\rangle$

$$Y_{B-L} = Y_{B/3-L_e} + Y_{B/3-L_\mu} + Y_{B/3-L_\tau}$$

Modification of Baryon asymmetry

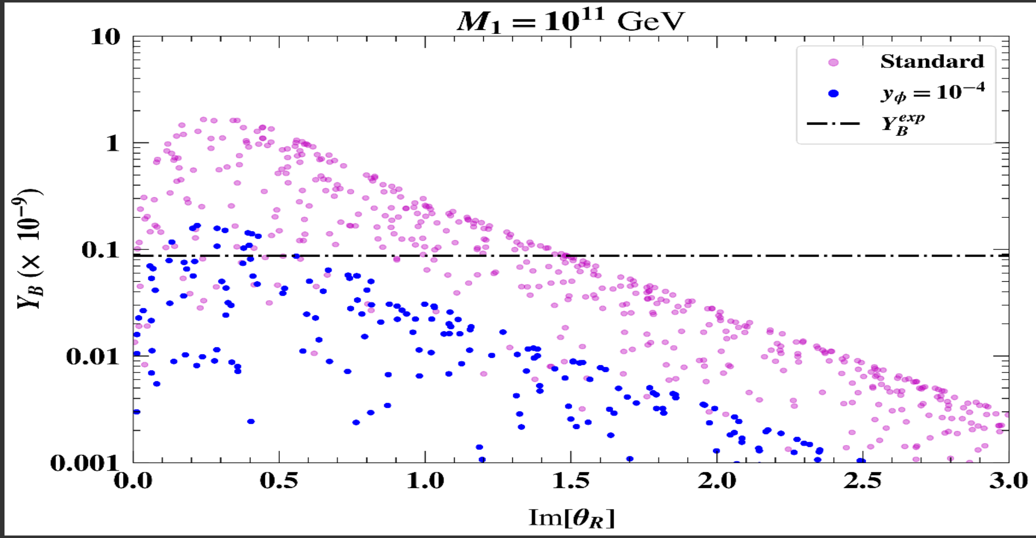
$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}}\rho_\phi a^2$$

$$\frac{d\,(\rho_R a^4)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi \rho_\phi + \frac{a^3}{H}\langle\Gamma_{N_1}\rangle(\rho_{N_1} - \rho_{N_1}^{\rm eq})$$

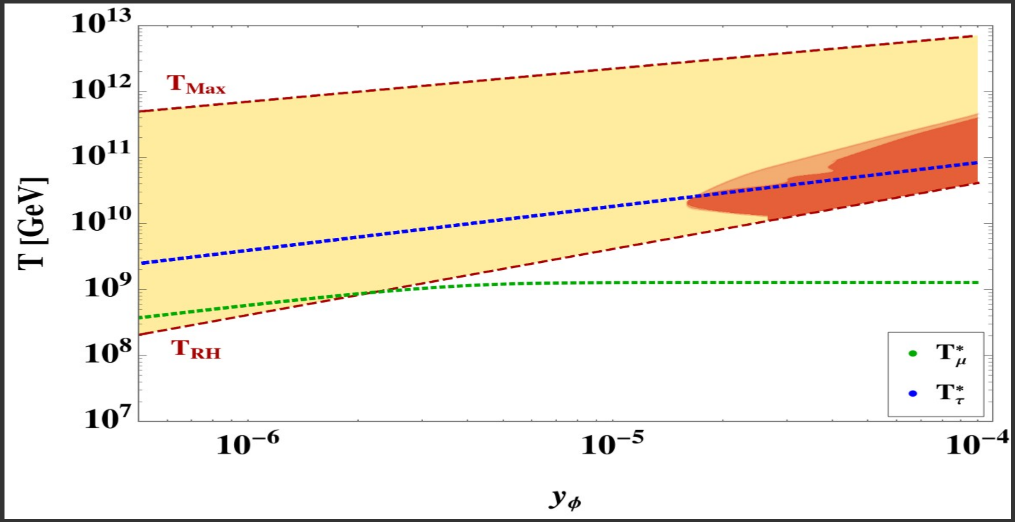
$$\frac{d(\rho_{N_1} a^3)}{da} = -\frac{\langle\Gamma_{N_1}\rangle a^2}{\mathcal{H}}(\rho_{N_1} - \rho_{N_1}^{\rm eq})$$

$+$

$$\frac{d(n_{B-L}a^3)}{da} = -\frac{\langle\Gamma_{N_1}\rangle a^2}{\mathcal{H}}\left[\frac{\varepsilon_\ell}{M_1}(\rho_{N_1} - \rho_{N_1}^{\rm eq}) + \frac{n_{N_1}^{\rm eq}}{2n_\ell^{\rm eq}} n_{B-L}\right]$$



Modification of Baryon asymmetry



- **Prolonged Reheating** was achived by varying the inflaton-SM fermion coupling.
- Due to the **nontrivial behaviour of Temperature** in between T_{max} and T_{RH}, **equilibration temperature of charged lepton Yukawa interactions shift** from their standard thermal value.
- **More stringent parameter space** satisfying correct baryon asymmetry is observed due to the **modifed flavor effect** as well as **dilution of baryon asymmetry** due to **entropy injection** from inflaton decay.

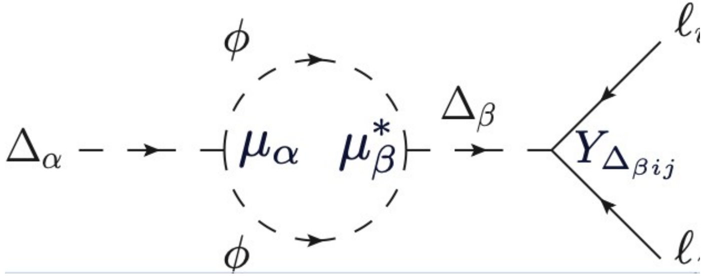
Some other possibilities

- Resonant Leptogenesis [Pilaftsis, Underwood, (2004/2005)]
- Triplet leptogenesis [Ma, Sarkar 1998, Hambye, Ma, Sarkar 2002, Hambye, Senjanovic (2003)]
- Spontaneous baryogenesis and leptogenesis [Cohen, Kaplan 1987, Li, Wang, Feng, Zhang (2002), Kusenko, Schmitz, Yanagida (2014)]
- Leptogenesis with sub-electroweak scale RHNs [Bhandari, Datta, Sil (2024)]
- Leptogenesis from Higgs decay [Hambye, Teresi (2016)]

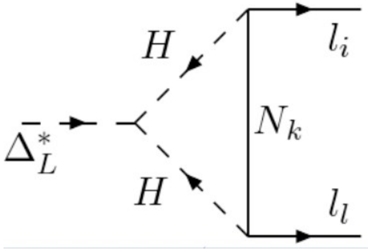
Triplet Leptogenesis

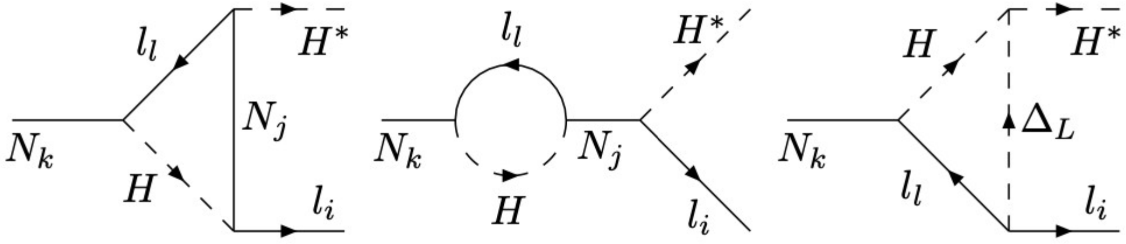
A single triplet can't produce lepton asymmetry

With two triplets
[Type-II seesaw]



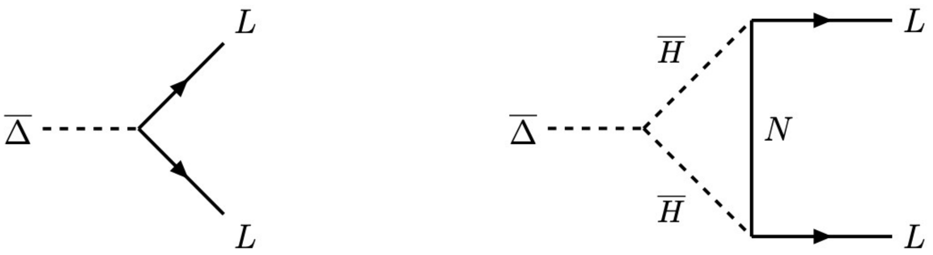
With triplets and RHNs
[Type-I + II seesaw]





Leptogenesis dominated by lightest seesaw state hybrid situation (minimal): 1 RHN + 1 Triplet

[type-I + II seesaw]



As the mass scales approach each other, certain (often neglected) scattering processes involving both the states become numerically significant. [Pramanick, Ray, Sil; arXiv: 2401.12189]

Spontaneous Baryogenesis

- Fermion coupling with a homogeneous scalar field (e.g. Axion-like particle, a)

$$\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\psi \supset \frac{\dot{a}}{f_a}(n_b - n_{\bar{b}}) \equiv \mu_{\rm eff} n_B$$

Cohen, Kaplan '87

ALP Derivative coupling

Baryon Current

Spontaneous CPT breaking!

- $\mu_{\rm eff} \equiv \dot{\theta} = \dot{a}/f_a$ → ***Effective chemical potential***

Induces an **asymmetry** between baryon and anti-baryon in equilibrium

$$n_B^{\rm eq} = n_b^{\rm eq} - n_{\bar{b}}^{\rm eq} \approx \frac{1}{6}\mu_{\rm eff} T^2$$

- Need ***B violation***: Asymmetry in equilibrium → **Violation of Sakharov's 3rd Condition!**

Baryon asymmetry freezes out as ***B violation*** drops out of equilibrium!

- If ψ are SM leptons → Generation of lepton asymmetry → **Spontaneous Leptogenesis**

Spontaneous Leptogenesis

- Source of ***L violation*** → **Weinberg Operator**, $\mathcal{L}_{\not{L}} \supset -\frac{(LH)^2}{\Lambda_W}$

↓

- $\Lambda_W \simeq 6 \times 10^{14}$ GeV → set by neutrino mass, $m_\nu = \frac{v^2}{2\Lambda_W}$
- $T_{\rm Dec} \simeq 10^{14}$ GeV → set by $\mathcal{H}(T_{\rm Dec}) = \Gamma_{\not{L}}(T_{\rm Dec})$, where $\Gamma_{\not{L}} \sim \frac{(\sum m_\nu^2)T^3}{16\pi v^2}$

↳ **Scale of spontaneous leptogenesis** (must not exceed $T_{\rm RH}^{\rm max}$)

- Source of ***chemical potential*** (or, non zero $\dot{\theta}$) ?

↳ Onset of ALP oscillation ($T_{\rm osc}$) → set by $3\mathcal{H}(T_{\rm osc}) \approx m_a$

ALP Misalignment mechanism

$T_{\rm osc} > T_{\rm Dec}$ (or, $m_a \gtrsim 10^5$ GeV) is required

- Tracking of ***L asymmetry:*** $\dot{n}_L + 3\mathcal{H}n_L = -\Gamma_{\not{L}}\left(n_L - n_L^{\rm eq}\right)$ —Electroweak Sphaleron→ $n_B = \frac{28}{79}n_L$

Leptogenesis in a dynamical vacuum

Bhandari, Datta, AS, arXiv:2312.13157

- RHN mass can be generated through the coupling $\frac{1}{2}\alpha_i \phi \overline{N_i^c} N_i$ → $U(1)_{B-L}$ Symmetric term
- A $U(1)_{B-L}$ symmetry breaking phase transition occurs at T_* → ϕ acquires a vev → RHN becomes massive

Suppose Φ acquires a temperature dependent vev at T*
(EW symmetry is still unbroken at this stage)

$$v_\phi(T) \simeq \begin{cases} 0 & ; \quad T > T_*, \\ AT^2 & ; \quad T_c < T \leq T_*, \\ AT^2 + Bv^2(T) & ; \quad T \leq T_c, \end{cases}$$

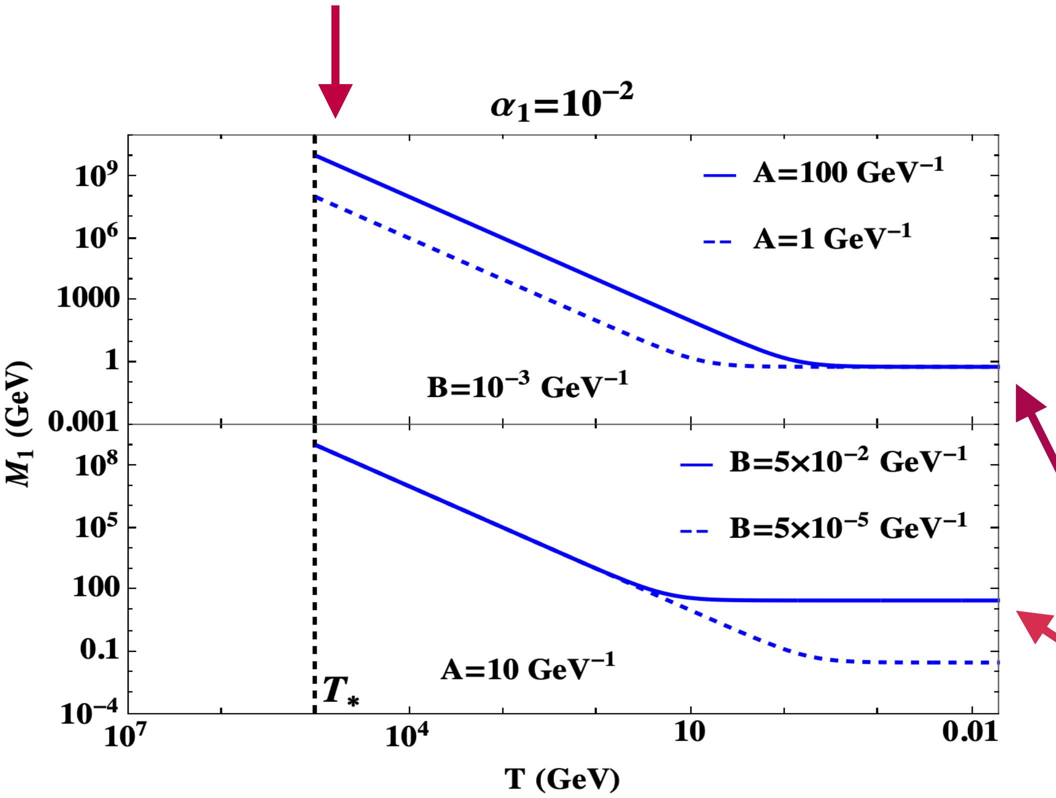
RHN mass can be parametrised as:

$$M_i(T) = \begin{cases} 0 & ; \quad T > T_* \\ \alpha_i(AT^2) & ; \quad T_c < T \leq T_* \\ \alpha_i(AT^2 + Bv^2(T)) & ; \quad T \leq T_c \end{cases}$$

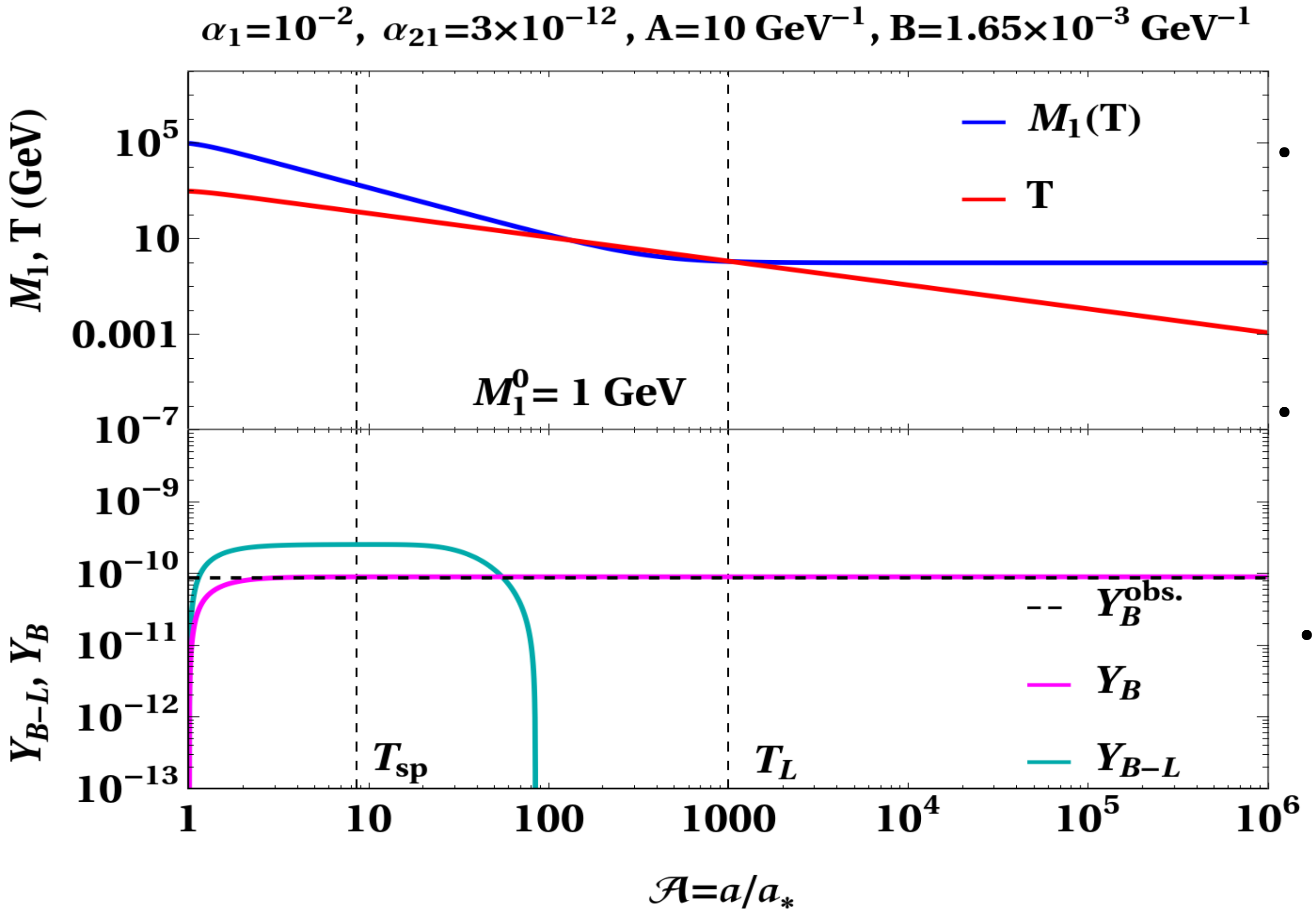
Due to an effective $\phi H^\dagger H$ coupling, the term $Bv^2(T)$ is generated below Tc (onset of EWSB)

Zero-temperature RHN mass can even be smaller Than EW scale

Thermal Leptogenesis (resonant) can be realised at high temperature



Zero-temperature RHN mass can even be smaller Than EW scale



May resolve the Helium Anomaly [PRL 130 (2023)]

- Above the temp. T_L, RHN mass becomes smaller than the surrounding temperature, causing a new phase of RHN production through inverse decay.
- Again below the temp. T_L, at some point the RHN mass becomes larger than T of the surrounding.
- If $M_i^0 > m_h + m_\ell$ (the other two say) RHNs will decay into SM Higgs and lepton, producing a late lepton asymmetry below the EW scale.


ANTIMATTER'S GONE MISSING...
WHEN DID THIS HAPPEN, SIR?
ABOUT 15 BILLION YEARS AGO...
LOST-PROPERTY OFFICE
CERN

Thank you

Limit on Maximum CP asymmetry and Davidson-Ibarra bound

$$|\varepsilon_\ell| \lesssim \frac{3}{8\pi}\frac{M_1}{v^2}(m_3 - m_1) = \varepsilon_\ell^{\mathrm{Max}}$$

Number density to entropy density ratio $Y_{B-L} \equiv n_{B-L}/s = -\frac{1}{7.04}\frac{3}{4}\varepsilon_\ell \kappa_f$

κ_f : efficiency factor

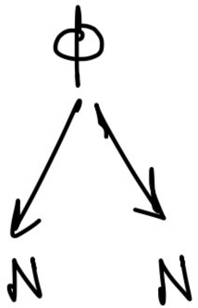
Precise estimate requires solution of **Boltzmann equation**

$Y_B^{Max} > Y_B^{exp} = 8.72 \times 10^{-11}$ introduces

Lower limit on lightest RHN mass

$$M_1 \gtrsim \frac{7.04}{0.96 \times 10^{-2}}\frac{8\pi v^2}{3m_3}\frac{Y_B^{\mathrm{exp}}}{\kappa_f}$$

$$\approx \frac{6 \times 10^8\ \mathrm{GeV}}{\kappa_f}\left(\frac{Y_B^{\mathrm{exp}}}{8.718 \times 10^{-11}}\right)\left(\frac{0.05\ \mathrm{eV}}{m_3}\right)$$



At T_{RH}, $\rho_\phi = \rho_R \rightarrow \frac{\pi^2 g_*}{30} T_{RH}^4$

$\rho_\phi \leftrightarrow m_\phi n_\phi$

$$\Rightarrow \quad n_\phi(T_{RH}) = \frac{\pi^2 g_*}{30 m_\phi} T_{RH}^4$$

$$s = \frac{2\pi^2}{45} g_{*s} T^3$$

1 ϕ produces 2 N.

$$\Rightarrow \quad n_N = 2 n_\phi = \frac{\pi^2 g_*}{15 m_\phi} T_{RH}^4$$

$$\frac{n_N}{s} = \frac{\pi^2 g_* T_{RH}^4}{15\, m_\phi} \times \frac{45}{2\pi^2 g_{*s} T_{RH}^3}$$

$$\boxed{\frac{n_N}{s} = \frac{3}{2} \cdot \frac{g_*}{g_{*s}} \frac{T_{RH}}{m_\phi}.}$$