Leptogenesis

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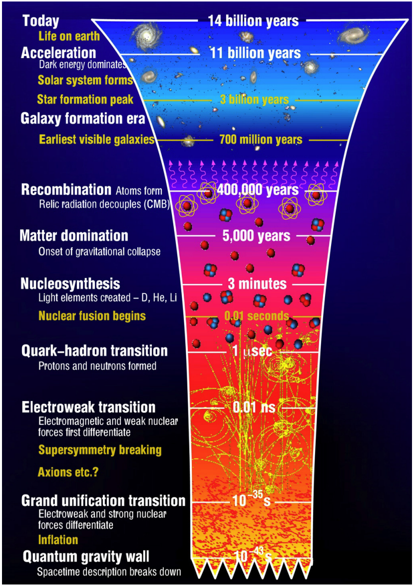
Early Cosmology



The Baryon asymmetry can be parametrized by:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}|_0 = (6.21 \pm 0.16) \times 10^{-10}$$

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s}|_0 = (8.75 \pm 0.23) \times 10^{-11}$$

where $s = g_*(2\pi^2/45)T^3$.
Also

$$\eta = 2.7410^{-8}\Omega_B h^2$$

where $\Omega_B = \rho_B/\rho_{crit}$

Dynamical generation or Initial Condition?

The reasons in favour of dynamics generation:

1. Fine-Tuning

”For every $6,000,000$ $\bar{q}$, there should have been $6,000,001$ $\bar{q}$

2. Inflation!

Experimental Signals of the Asymmetry

1. Big Bang Nucleosynthesis $(D, {}^3He, {}^4He, {}^7Li)$

Synthesis of ${}^4He$: $D(p,\gamma)^3He$ and ${}^3He(D,p)^4He$
$n(D) \propto \eta$, $n({}^3He) \propto \eta^2$.

$$4.7 \times 10^{-10} < \eta < 6.5 \times 10^{-10}, \quad 0.017 < \Omega_B h^2 < 0.024$$

2. CMB Recombination: $\Theta(\hat{n}) = \frac{\Delta T}{T}$

$$0.02149 < \Omega_B h^2 < 0.02397$$

Sakarov Conditions

(1967, Sakarov)

1. Baryon Number Violation: $Y_{\Delta B} = 0 \rightarrow Y_{\Delta B} \neq 0$
2. C and CP violation:
3. Out of equilibrium dynamics: $n_B = \bar{n}_B$

Standard Model?

1. $\Delta B = \Delta L = \pm 3$, this is proportional to $e^{-8\pi^2/g^2}$
2. C and CP violation: due to CKM matrix, $(J \approx \mathcal{O}(10^{-20}))$
3. Out of equilibrium dynamics: ElectroWeak Phase Transition

Possible Solutions

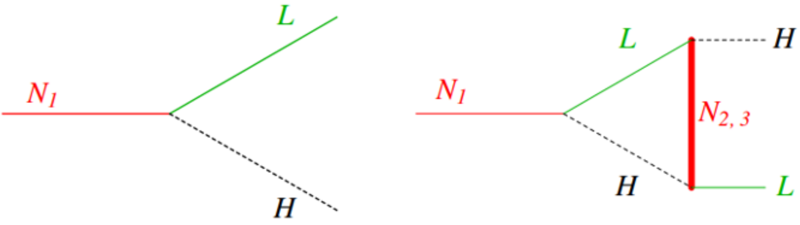
1. GUT Baryogenesis, $X \rightarrow$
2. Leptogenesis
3. Electroweak Baryogenesis (two Higgs Doublet Model)
4. The Affleck-Dine mechanism (ϕ, in SUSY $\phi(sq, H, sL)$)
5. Others...

Thermal Leptogenesis

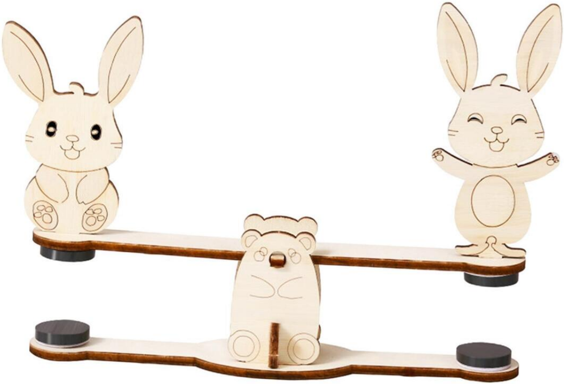
We need a "new" neutrino:

$$\epsilon_{\alpha\alpha} = \frac{\Gamma(\nu_R \to HL) - \Gamma(\nu_R \to \bar{H}\bar{L})}{\Gamma(\nu_R \to HL) + \Gamma(\nu_R \to \bar{H}\bar{L})}$$

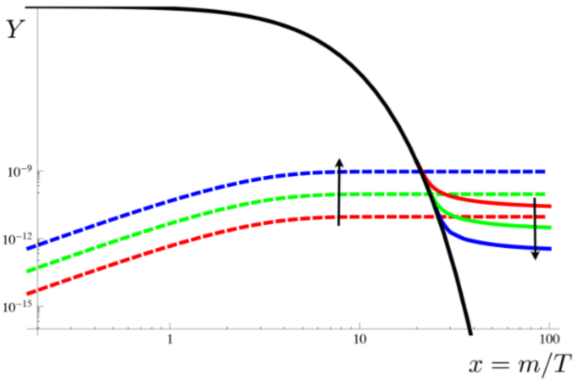
Thermal Leptogenesis



See Saw Models



Freeze-in and Freeze-out



Schematic comparison of the freeze-in (dashed) and freeze-out (solid) scenarios.

See Saw Models

$$\mathcal{L} = m\nu_R\nu_L + M\nu_R\nu_R + h.c.$$

Mass Matrix:

$$\mathcal{L} = \begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

so the eigenvalues are:

$$\lambda_1 \approx \frac{m^2}{M}, \qquad \lambda_2 \approx M$$

Thermal Leptogenesis

Again...

$$\epsilon_{\alpha\alpha} = \frac{\Gamma(\nu_R \to HL) - \Gamma(\nu_R \to \bar{H}\bar{L})}{\Gamma(\nu_R \to HL) + \Gamma(\nu_R \to \bar{H}\bar{L})}$$

Then, via the sphaleron process:

$$Y_{\Delta B} \approx 10^{-3} \epsilon_{\alpha\alpha} \eta_{\alpha}$$

Thermal Leptogenesis

Using:

$$\mathcal{L} = yLH\nu_R + h.c.$$

We get:

$$\epsilon = \frac{1}{8\pi}\sum_{j=2} \frac{Im([(y\dagger y)_{j1}]^2)}{(y\dagger y)_{11}} g(M_j^2/M_1^2)$$

$g(x) = \sqrt{x}((1-x)^{-1} + 1 - (1+x)\ln(1+1/x))$, and $x_2 = M_2^2/M_1^2$

Thermal Leptogenesis

We expect to find:

$$\epsilon \approx 10^{-6}$$

Thermal Leptogenesis

$$Y_{\Delta B} \approx 10^{-3} \epsilon \eta,$$

where η gives the efficiency of this process! And... How can we calculate η?

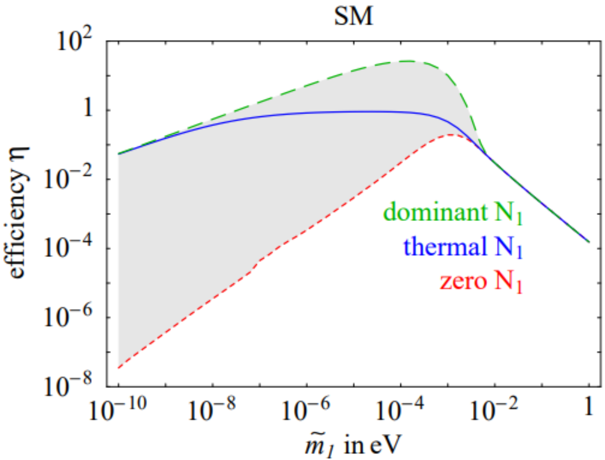
Boltzmann Equations

$$\dot{n}_N + 3Hn_N = -\sum_{a,i,j}[Na... \leftrightarrow ij...],$$

where $H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi\rho}{M_p^2}}$.

$$[Na... \leftrightarrow ij...] = \frac{n_N n_a \dots}{n_N^{eq} n_a^{eq} \dots}\gamma^{eq} - \frac{n_i n_j \dots}{n_i^{eq} n_j^{eq} \dots}\gamma^{eq}$$

Boltzmann Equations

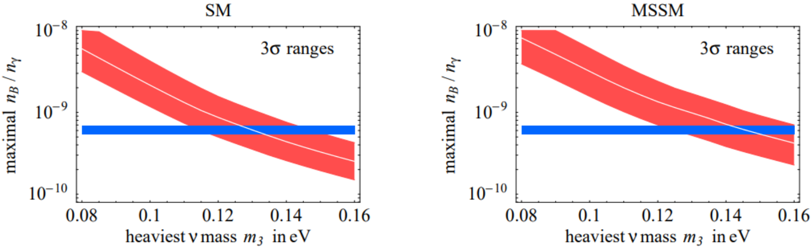


Wash-Out Coefficient

For case 0: (zero initial N_1 population)

$$\frac{1}{\eta} \approx \frac{3.3 \times 10^{-3} eV}{m} + (\frac{m1}{0.55 \times 10^{-3} eV})^{1.16}$$

Leptogenesis Bound on Neutrino Masses



where, $m_3^2 = m_1^2 + \Delta m_{atm}^2 + \Delta m_{sun}^2$. The lower bound for the right-handed neutrinos is given by:

$$m_{N_1} > \frac{4.5 \times 10^8 \mathrm{GeV}}{\eta}$$

Finally

Thank you!