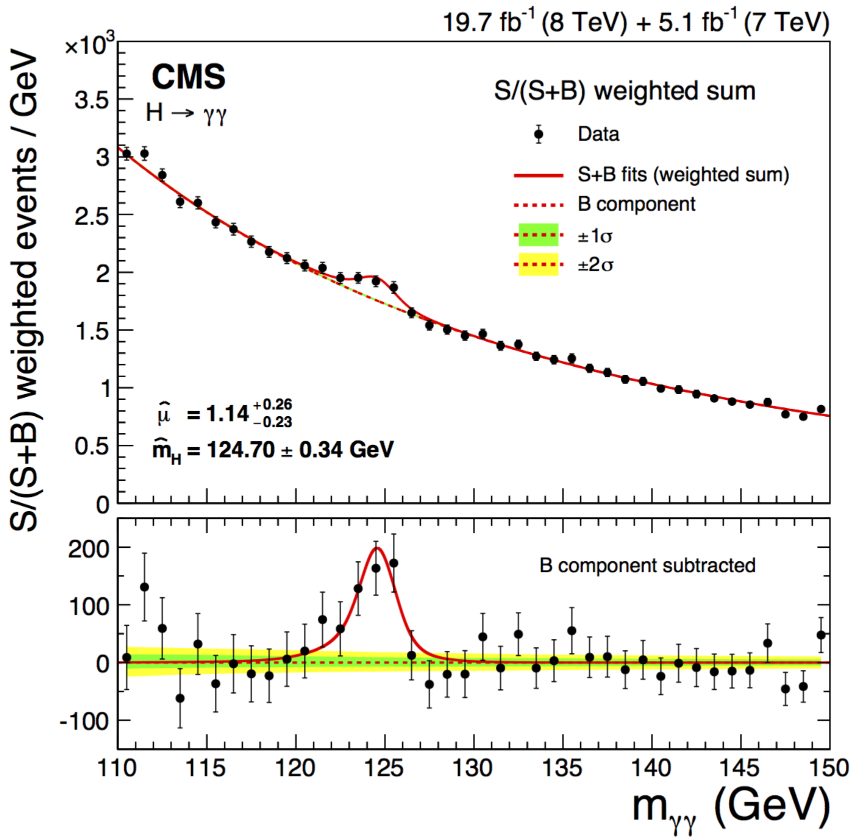
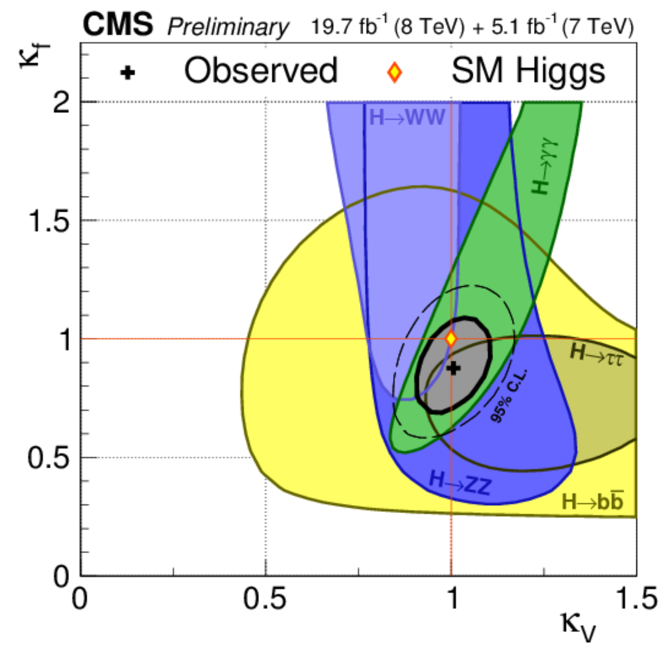
Higgs relaxation and leptogenesis

- The origin of matter-antimatter asymmetry, and the Sakharov's conditions for baryogenesis
- Scalar fields at the end of inflation
- Higgs relaxation: the epoch after inflation implied by the Higgs mass measurement at the LHC
- Higgs relaxation and leptogenesis

Lauren Pearce, Louis Yang, AK, Phys. Rev. Lett. 114 061302 (2015) [arXiv:1410.0722]

Higgs boson discovery





Higgs potential

$$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

where Φ is an SU(2) doublet. $\Phi = (1/\sqrt{2})\{e^{i\theta}\phi, 0\}$, where $\phi(x)$ is real.

LHC Higgs mass measurement $\Rightarrow \lambda$ is smaller than was previously expected. The value of the running coupling

$$\lambda_{\rm eff} \approx \lambda_* + b\ln^2(\phi/\phi_*) \lesssim 10^{-4} \ \text{ for } \ \phi \gtrsim 10^{12}\,\text{GeV}, \ \text{and can be negative.}$$

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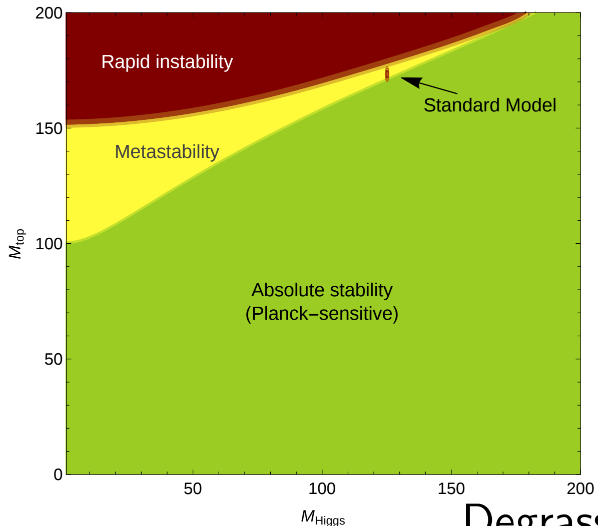

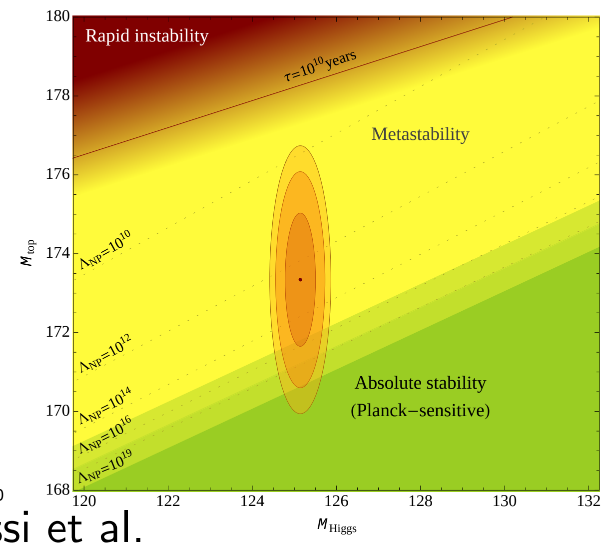

Degrassi et al.

Scalars in de Sitter space during inflation

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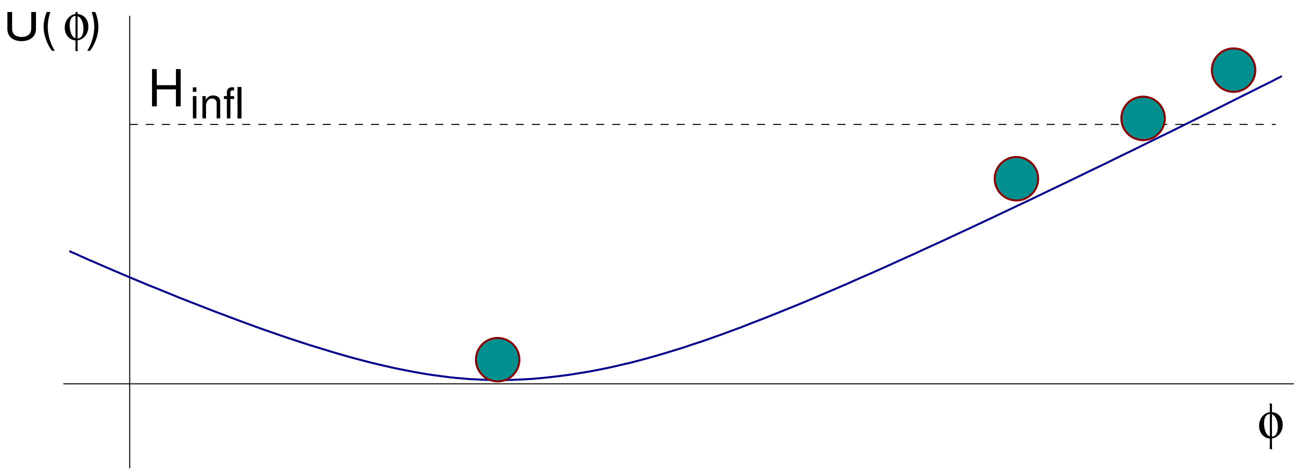

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- For a massive field with $V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4$, the VEV is evolution is given by

$$H\partial_t\langle\phi^2\rangle = \frac{H^4}{4\pi^2} - \frac{2m^2}{3}\langle\phi^2\rangle - 2\lambda\langle\phi^2\rangle^2$$

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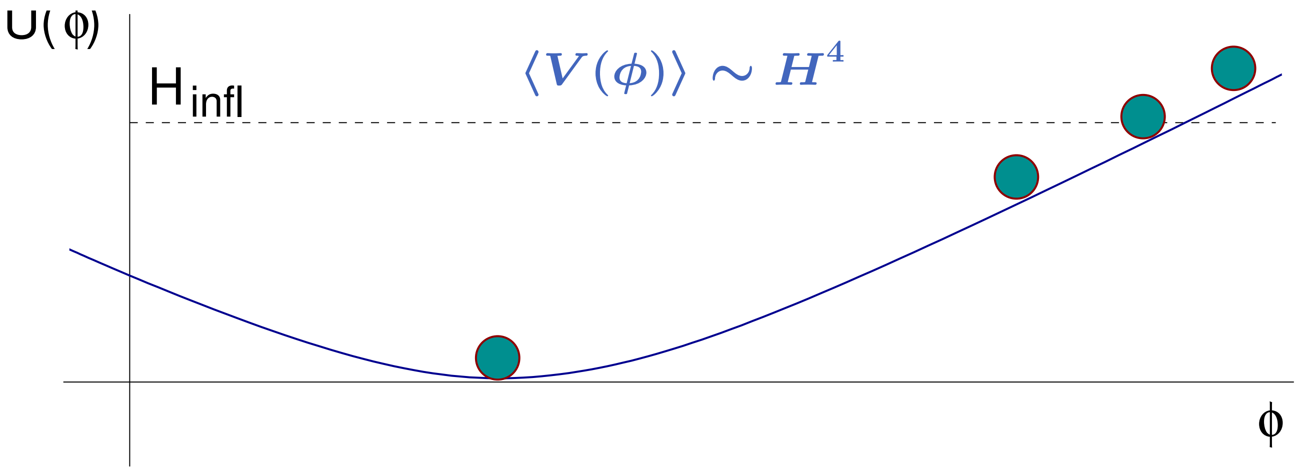
- on average, each degree of freedom carries energy $\sim H^4$ in the de Sitter universe



At the end of inflation, the field is not at the minimum of the effective potential.

For the Standard Model Higgs,

$$\sqrt{\langle \phi^2 \rangle} = \phi_0 \sim 0.36 \, H_I/\lambda^{1/4},$$

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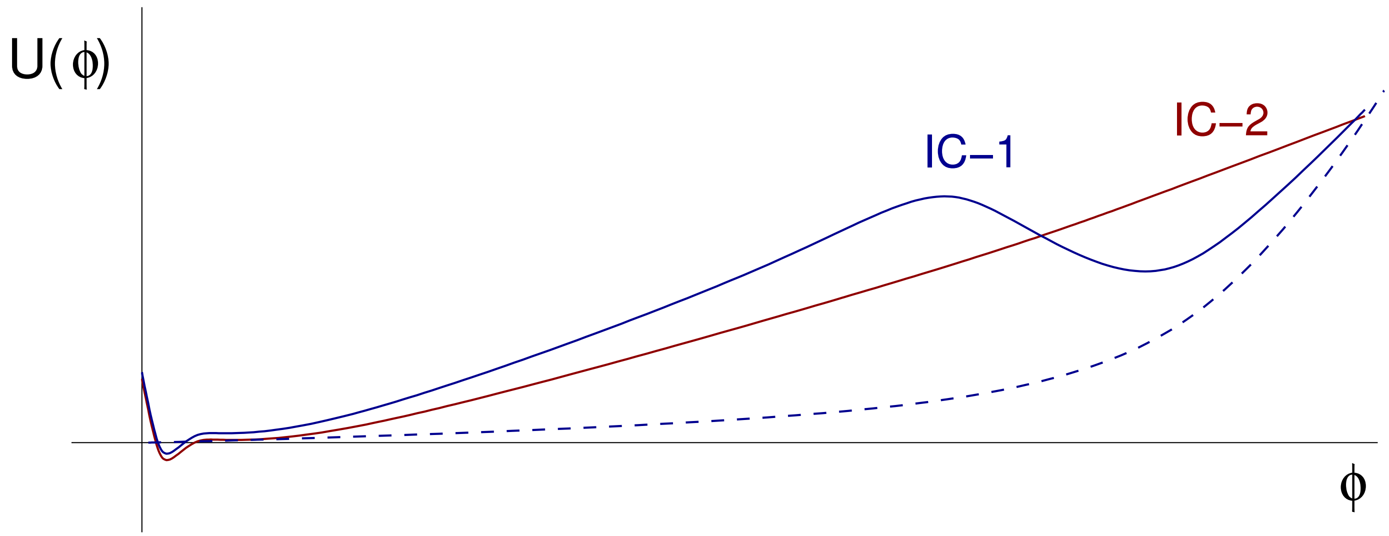
$\Longrightarrow$ Higgs relaxation epoch

Initial conditions

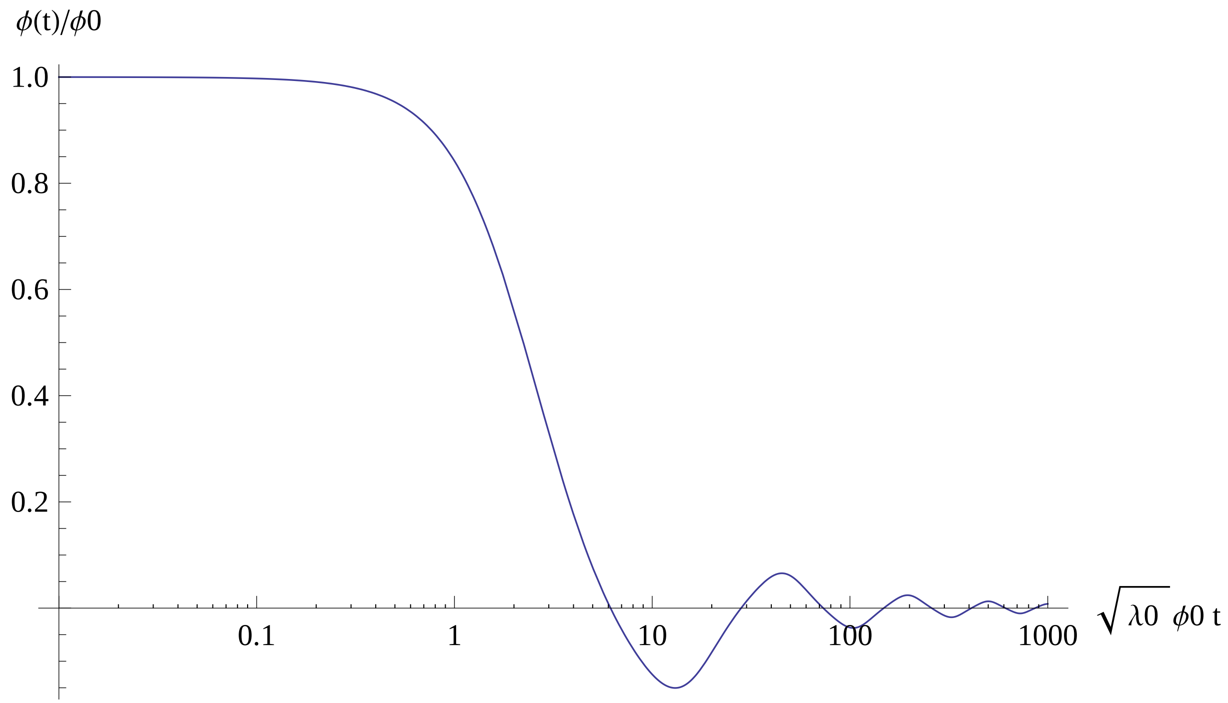
- *IC-1:* Corresponds to the central value of LHC measurement. The instability is cured by a higher-dimensional operator. However, a false vacuum can exist. The Higgs field can start out from a large VEV (similar to the inflaton in the chaotic inflation), and settle in the false vacuum. When reheating begins, the false vacuum is destabilized by the finite-temperature corrections. Baryonic isocurvature perturbations are small if the second derivative in the false vacuum is large in comparison with the Hubble parameter.
- *IC-2:* The self-coupling remains positive, and no false vacuum exist. Baryonic isocurvature perturbations (BIP) can be made small by introducing a coupling to the inflaton via some higher-dimensional operator, which limits the VEV during the initial stages of inflation. Higgs VEV and BIP can develop during the last several e-folds of inflation, which corresponds to the smallest angular scales in the CMB spectrum.

Initial conditions



Two possible shapes of the potential correspond to two types of initial condition.

Higgs field evolution at the end of inflation



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Can the matter-antimatter asymmetry be generated during the Higgs relaxation?

Baryogenesis

$$\eta \equiv \frac{n_B}{n_\gamma} = 10^{-10} \text{(observations, nucleosynthesis, etc.)}$$

Conditions for baryogenesis

Baryogenesis is possible when the following conditions are satisfied [Sakharov '67]:

- **B violation**
  If the baryon number is conserved, there is no way to start from zero and generate a non-zero value
- **C, CP violation**
  B is C-odd, CP-odd, hence C and CP must be broken
- **Universe must be out of thermal equilibrium**
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However, these conditions are **not necessary** if CPT is broken

New physics at a high scale

A number of higher-dimensional operators can play a role. For example, the following operator is unsuppressed for large VEVs:

$$\mathcal{O}_6 = \frac{1}{M_n^2}\partial_\mu(\Phi^\dagger \Phi)\, j^\mu, \quad \text{where} \quad j^\mu = \bar{\psi}\gamma^\mu\psi$$

CP violating diagrams with new physics at a scale M_n yields $\frac{1}{M_n^2}(\Phi^\dagger\Phi)F_{\mu\nu}\tilde{F}^{\mu\nu}$, equivalent to the above after replacing $F_{\mu\nu}\tilde{F}^{\mu\nu}$ with j^μ via anomaly (and integrating by parts):

$$\partial_\mu j^\mu = \frac{1}{32\pi^2}\mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu})$$

Effective chemical potential

Fermion number density and the lepton number density:

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$$\mathcal{O}_6 = \frac{1}{M_n^2}\partial_0(\Phi^\dagger\Phi)\, j^0 = \frac{1}{M_n^2}\partial_0|\phi|^2\, j^0 = \mu_{\rm eff}(t)\, j^0$$

This operator and its effect as a chemical potential have been used extensively in models for electroweak baryogenesis [Dine et al.; Cohen, Kaplan, Nelson].

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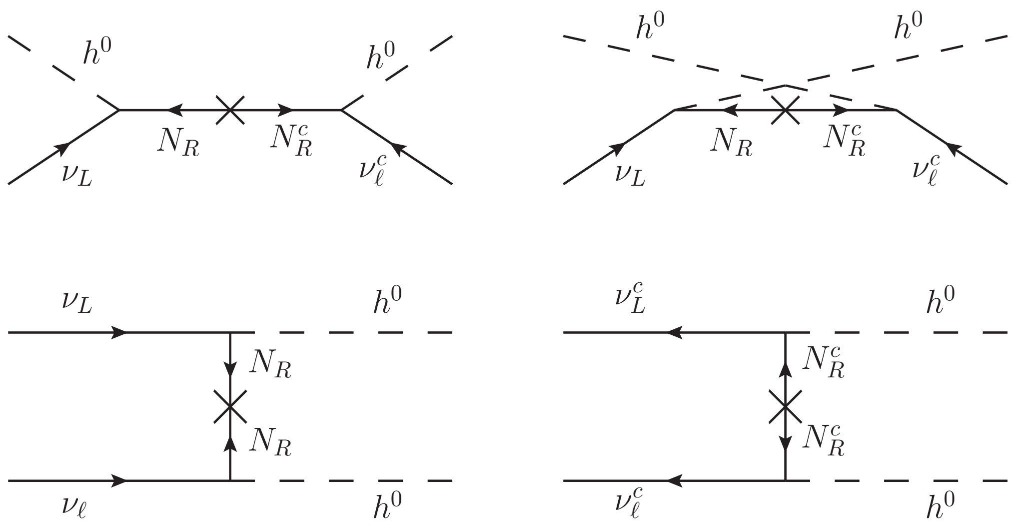
Our case: the "wall" moves in the timelike direction.

Lepton number violation

The term $\boldsymbol{\mu}_{\rm eff}(\boldsymbol{t})\ j^0$ violates CPT and splits the energy levels of leptons and antileptons. No additional source of CP violation is required. In particular, the baryon asymmetry does not depend on the phases in the neutrino mass matrix. If B,L were conserved, this would have no consequence. However, L (and, therefore, $(B+L)$ and $(B-L)$ are violated by the processes involving heavy neutrino lines ($M_R \gg T$):



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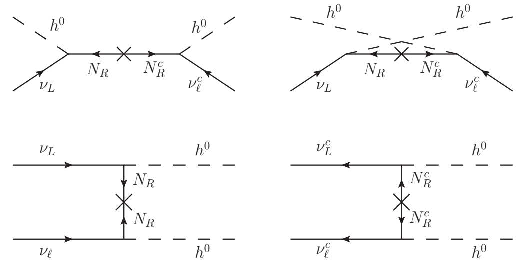


$$\sigma_R \simeq \frac{|(Y^\dagger Y)_{jj}|^2}{16\pi M_{R,j}^2} \simeq \frac{\sum_j m_{\nu,j}^2}{16\pi v_{EM}^4} \sim 10^{-31}\,{\rm GeV}^{-2},$$

where Yukawa couplings are assumed to be ~ 1 in the spirit of the seesaw mechanism.

Lepton number generation in the presence of a time-dependent chemical potential

We define an *approximate* lepton number, which becomes exact in the limit $M_R \to 0$.

$$n_L = n_\nu - n_{\bar{\nu}}$$

In equilibrium, n_L would evolve to its equilibrium value $n_L^{\rm eq} \sim \mu_{\rm eff} T^2$. However, the time dependence complicates matter. The time scale for approaching equilibrium is controlled by σ_R. One can use an approximate Boltzmann equation (derived from detailed balance):

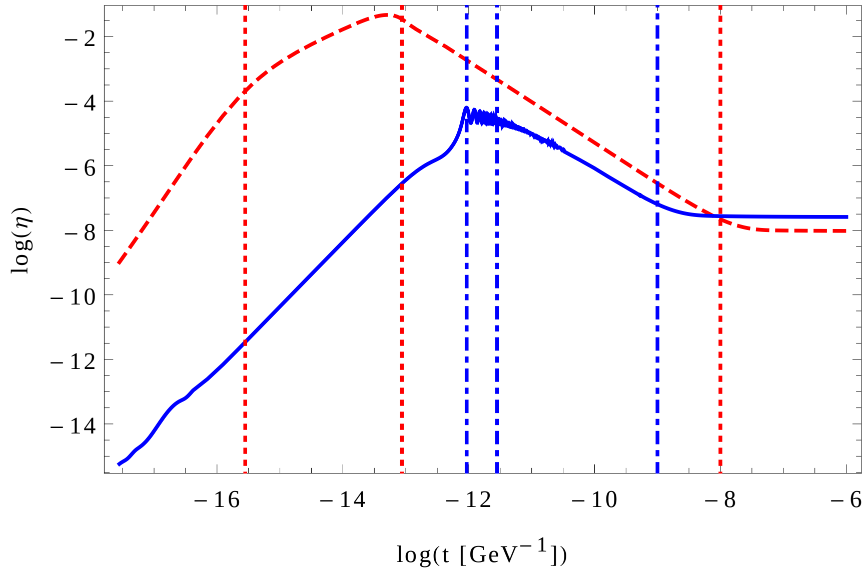
$$\frac{d}{dt} n_L + 3 H n_L \cong -\frac{2}{\pi^2} T^3 \sigma_R \left(n_L - \mu_{\rm eff} T^2 \right).$$

Approximate analytical result

$$
\begin{aligned}
\eta &\equiv \frac{n_L}{(2\pi^2/45)g_* T^3} \\
&= \frac{45}{2\pi^2}\frac{\sqrt{\lambda}\phi_0^3\Lambda_I}{M_n^2 T_R^2}\, t_{\rm rlx}^2\Gamma_I^2 \times \min\left\{1, T_{\rm rlx}^3 t_{\rm rlx}\sigma_R\right\} \\
&\quad \times \exp\left[-\left(\frac{24+3\sqrt{15}}{\sqrt{3g_*\pi^7}}\right)\sigma_R M_P T_R\right]
\end{aligned}
$$

The result is very different from thermal leptogenesis. The asymmetry is independent of CP violation in the neutrino mass matrix. Reheat temperature is lower than the right-handed Majorana mass.

Numerical solution



The IC-1 scenario is shown by the blue solid line for $\Lambda_I = 10^{15}$ GeV, $\Gamma_I = 10^9$ GeV, and $M_R = 9 \times 10^{15}$ GeV, which results in $T_{\rm max} = 6 \times 10^{13}$ GeV, sufficient to destabilize the second minimum. The initial VEV is $\phi_0 = 1 \times 10^{15}$ GeV. The IC-2 case is shown by the red dashed line for $\Lambda_I = 10^{17}$ GeV, $\Gamma_I = 10^8$ GeV, $M_n = 5 \times 10^{12}$ GeV, and $M_R = 10^{16}$ GeV. The maximum temperature during reheating is $T_{\rm max} = 3 \times 10^{14}$ GeV, and $\phi_0 = 1 \times 10^{15}$ GeV.

Conclusion

- LHC measurement of the Higgs boson mass implies that the Higgs field had a large VEV at the end of inflation
- Higgs relaxation should have taken place in the early stages of reheating
- Lepton number asymmetry could be generated during Higgs relaxation epoch; the lepton asymmetry is converted to baryon asymmetry by electroweak processes
- The matter-antimatter asymmetry can be explained by Higgs relaxation leptogenesis
- The parameter space is different from that of thermal leptogenesis
- The baryon asymmetry does not depend on CP violating phases in the neutrino mass matrix.