Institute of Physics Publishing
doi:10.1088/1742-6596/33/1/017
Journal of Physics: Conference Series **33** (2006) 191–196
Fourth Meeting on Constrained Dynamics and Quantum Gravity

Instant nonthermal leptogenesis

Eun-Joo Ahn

Department of Astronomy and Astrophysics and Kavli Institute for Cosmological Physics, The University of Chicago, Chicago, IL 60637, USA

E-mail: sein@oddjob.uchicago.edu

Edward W. Kolb

Particle Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA and Department of Astronomy and Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA

E-mail: rocky@fnal.gov

Abstract. We propose an economical model of nonthermal leptogenesis following inflation during "instant" preheating. The model involves only the inflaton field, the standard model Higgs, and the heavy "right-handed" neutrino.

1. Introduction

Leptogenesis [1] is an attractive scenario to account for the observed matter–antimatter asymmetry of the universe. In the scenario, a lepton asymmetry is generated by the decay of massive right-handed (Majorana) neutrinos, N, which are responsible for the (small) masses of left-handed neutrinos via the see-saw mechanism [2]. The lepton asymmetry is then translated to a baryon asymmetry by sphaleron processes [3] around the electroweak era. The Ns must be created after inflation, either nonthermally or thermally during reheating, or thermally during the radiation-dominated era (see e.g. Refs [4, 5]. We discuss a model of nonthermal leptogenesis involving instant preheating [6].

Our model assumes hybrid inflation [7]; thus the properties of the scalar-field potential during reheating may be quite different than the properties of the scalar-field potential during inflation. The scalar-field energy is extracted and thermalised by instant preheating [8]. In instant preheating, the inflaton is strongly coupled to a particle whose mass depends on the value of the inflaton field. As the inflaton oscillates, the coupling of the inflaton to the produced particle results in an increasing mass of the produced particle. As the mass of the produced particle increases, its decay rate will also increase, and decay channels disallowed when the produced particle is at the minimum of its potential may open. We assume this particle is the electroweak Higgs boson h. We will also assume that, as expected, h couples to the N. Normally the mass of the Higgs, m_h, is much, much less than the mass of the N, m_N. However, during instant preheating this need not be the case, and the h may decay directly into N, producing a lepton asymmetry. Later when the inflaton is close to its minimum, the produced Ns become heavier than the h, and they will decay back to the h.

© 2006 IOP Publishing Ltd

The mass of the Higgs will be determined by its coupling to the inflaton ϕ: $m_h \propto |\phi|$. For sufficiently large values of $|\phi|$ during the inflaton oscillations, m_h will be larger than m_N. We will denote the absolute value of ϕ when $m_h(\phi) = m_N$ as ϕ_c. It is useful to imagine a single oscillation of the inflaton field, in particular the first oscillation. As ϕ passes near its minimum, h is effectively massless, and a burst of hs are created. The hs will decay to any kinematically allowed final states. Because of the large h–top-quark coupling, the decay is predominately into top quarks. $h \to N$ becomes kinematically allowed when $|\phi|$ becomes larger than ϕ_c. Therefore, efficient lepton number production happens when ϕ_c is close to the minimum so $h \to N$ process takes place before all the h decays thermally into top quarks. This process is nonthermal, as $m_h > T$ at this time. Eventually ϕ reaches a maximum point ϕ_0^{max} and rolls back down. The decay of the h continues until $\phi < \phi_c$. At this stage, $N \to h$ decay happens, and hs continue to decay into fermions. A lepton asymmetry is generated by both $h \to N$ and $N \to h$ decays. Another burst of hs are produced as ϕ passes again through the nonadiabatic phase at the origin, and the same events occur on the other side of the potential. Since h decays very rapidly, a negligible amount of hs remain when ϕ re-passes through the nonadiabatic regime to produce more hs. This eliminates the influence of the old hs with ϕ during production of new hs, and the backreaction of Higgs in the nonadiabatic region need not be considered. The production and decay of hs siphon away energy from ϕ, and ϕ^{max} decreases for each oscillation. A schematic diagram of the regions of the potential in instant preheating is shown in Fig. 1.

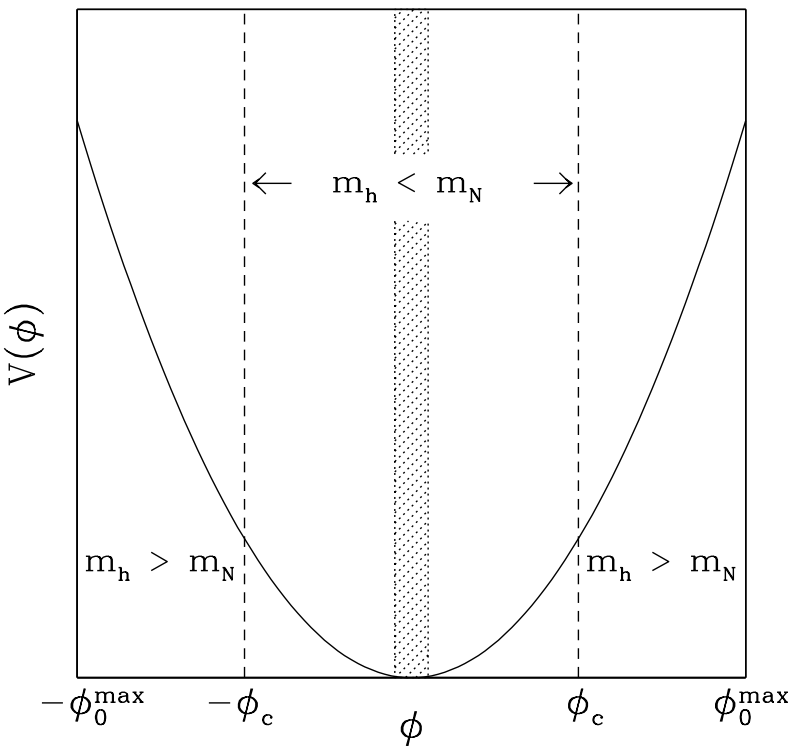

Figure 1. A schematic diagram of regions in the inflaton potential during instant preheating. The shaded column around the minimum illustrates the nonadiabatic region where hs are created. In regions of $|\phi| > \phi_c$, $h \to N$ decay occurs. In regions of $|\phi| < \phi_c$ (modulo the nonadiabatic region), $N \to h$ decay occurs. The regions are not drawn to scale.

2. Instant preheating and the see-saw mechanism

Inflation ends in the hybrid model when ϕ meets a "waterfall" potential in another direction of the scalar field landscape. The ϕ promptly falls into this potential which is responsible for preheating. Hence, ϕ does not carry restrictions on potential parameters (such as the mass) deduced from present cosmological observations. For instance, the mass of the ϕ during the preheating process may be more massive than the mass of the ϕ during inflation.

The interaction Lagrangian of the preheat field is given by

$$\mathcal{L}_{preheat} = -\frac{1}{2} g^2 \phi^2 h^2 \,, \tag{1}$$

where g is the coupling constant. Ignoring its electroweak-scale mass, $m_h = g|\phi|$. We define $\phi_c \equiv g/m_N$. Thus, depending on the initial condition of the ϕ field, m_h may become larger or smaller than m_N as ϕ oscillates about the minimum of its potential. The hs are created when ϕ goes through a nonadiabatic phase, which occurs near the minimum of the potential. This phase is very short and can be treated as instantaneous. A large coupling constant $g \sim 1$ enables a quick and effective thermalisation of the universe within a few oscillations of ϕ.

The see-saw mechanism Lagrangian for three families with Majorana neutrino masses m_{N_i} ($i = 1, 2, 3$) and Yukawa couplings Y^ν_{ij} to the Higgs boson and light neutrinos l is given by

$$\mathcal{L}_{see-saw} = \frac{m_{N_i}}{2} N_i^2 + Y^\nu_{ij} l_i N_j h \,. \tag{2}$$

The left-handed light neutrino masses are $m_\nu = -(vY^\nu)^T m_N^{-1} (vY^\nu)$, where $v = 247$ GeV is the Higgs vacuum expectation value. $\mathcal{L}_{see-saw}$ also generates a dimension-5 effective operator which causes CP violation among the leptons. We consider the case of very hierarchical Majorana neutrinos, $m_{N_1} \ll m_{N_{2,3}}$, which allows us to consider only interactions involving N_1; hence the family subscript is dropped.

A convenient parameter to use is the effective neutrino mass [5]

$$\tilde{m}_1 \equiv (Y_\nu^\dagger Y_\nu)_{11} \frac{v^2}{m_N} \,, \tag{3}$$

which can be seen as the contribution to the neutrino mass mediated by N_1.

The CP violating processes that give rise to lepton asymmetry are

$$h \longrightarrow \begin{cases} Nl \to hll \\ N\bar{l} \to h\bar{l}\bar{l} \end{cases} . \tag{4}$$

The CP parameters in these interactions, ϵ_h for $h \to Nl(\bar{l})$ and ϵ_N for $N \to hl(\bar{l})$, are defined as

$$\epsilon_h \equiv \frac{\Gamma_{h\to Nl} - \Gamma_{h\to N\bar{l}}}{\Gamma_{h\to Nl} + \Gamma_{h\to N\bar{l}}}; \qquad \epsilon_N \equiv \frac{\Gamma_{N\to hl} - \Gamma_{N\to h\bar{l}}}{\Gamma_{N\to hl} + \Gamma_{N\to h\bar{l}}} \,, \tag{5}$$

respectively, where the subscripts of the decay width Γ denotes the decay process concerned. The total CP asymmetry ϵ_{tot} is

$$\epsilon_{\rm tot} \equiv \left(\frac{\Gamma_{h\to Nl}}{\Gamma_{h\to Nl} + \Gamma_{h\to N\bar{l}}} \frac{\Gamma_{N\to hl}}{\Gamma_{N\to hl} + \Gamma_{N\to h\bar{l}}} - \frac{\Gamma_{h\to N\bar{l}}}{\Gamma_{h\to Nl} + \Gamma_{h\to N\bar{l}}} \frac{\Gamma_{N\to h\bar{l}}}{\Gamma_{N\to hl} + \Gamma_{N\to h\bar{l}}} \right) = \frac{1}{2} \left(\epsilon_h + \epsilon_N \right) . \tag{6}$$

The CP parameter is calculated from tree- and one-loop Feynman diagrams. The explicit expression of ϵ_N is [9]

$$|\epsilon_N| \leq \frac{3}{16\,\pi} \frac{m_N\,(m_3 - m_1)}{v^2} \times \begin{cases} 1 - m_1/\tilde{m}_1 & \text{if } m_1 \ll m_3 \\ \sqrt{1 - m_1^2/\tilde{m}_1^2} & \text{if } m_1 \simeq m_3 \end{cases} . \tag{7}$$

3. Leptogenesis

The time evolution of the hs, Ns, and the lepton asymmetry are studied by means of the Boltzmann equations. The following set of Boltzmann equations are used:

$$\begin{aligned}
\dot{n}_h + 3Hn_h + \Gamma_{h\to f\bar{f}}(n_h - n_h^{eq}) + \Gamma_{h\to N}(n_h - n_h^{eq}) - \Gamma_{N\to h}(n_N - n_N^{eq}) &= 0\,, \quad (8)\\
\dot{n}_N + 3Hn_N + \Gamma_{N\to h}(n_N - n_N^{eq}) - \Gamma_{h\to N}(n_h - n_h^{eq}) &= 0\,, \quad (9)\\
\dot{n}_L + 3Hn_L - \frac{\epsilon_h}{2}\Gamma_{h\to N}(n_h - n_h^{eq}) - \frac{\epsilon_N}{2}\Gamma_{N\to h}(n_N - n_N^{eq}) &= 0\,, \quad (10)\\
\dot{\rho}_R + 4H\rho_R - \Gamma_{h\to f\bar{f}}(n_h - n_h^{eq}) - \Gamma_{h\to N}m_h(n_h - n_h^{eq}) - \Gamma_{N\to h}(n_N - n_N^{eq})m_N &= 0\,, \quad (11)
\end{aligned}$$

along with the equation of motion for ϕ,

$$\ddot{\phi} + 3H\dot{\phi} + \mu^2\phi + 2gn_h\phi/|\phi| = 0, \quad (12)$$

where the dot stands for the time derivative and μ is the inflaton mass. n_h and n_N are the number density of h and N, $n_L \equiv n_l - n_{\bar{l}}$ is the lepton number density, and ρ_R is the radiation energy density. It is understood that $\Gamma_{h\to N}$ occurs when $m_h > m_N$, and $\Gamma_{N\to h}$ occurs when $m_h < m_N$. The Hubble expansion rate H is

$$H^2 = \frac{8\pi}{3M_{Pl}^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi) + \rho_h + \rho_N + \rho_R\right), \quad (13)$$

where M_{Pl} is the Planck mass, $V(\phi)$ the inflaton potential, and ρ_h and ρ_N the h and N energy densities density.

The range of value used for the parameters during the numerical integration are as follows: $3\times10^{-5}\,\mathrm{eV} < \tilde{m}_1 < 1$ eV; $10^9\,\mathrm{GeV} < m_N < 10^{15}$ GeV; $\mu > 10^{13}$ GeV; $\dot{\phi}_0 < (10^{16}\,\mathrm{GeV})^2$; and $g \sim 1$. The upper limit to $\tilde{m}_1$ comes from the sum of the three lefthanded neutrino mass combining neutrino oscillation data with constraints from the cosmic microwave background and large scale structure observations, under the assumption that $\tilde{m}_1 \leq \sum m_\nu$ with a hierarchical left handed neutrino spectrum [10]. The lower limit has been arbitrarily set. The Yukawa coupling must be neither too small nor too large for the see-saw mechanism to be compelling. The upper bound of m_N is derived by setting $(Y_\nu^\dagger Y_\nu)_{11} \sim 100$. The inflation parameters μ and $\dot{\phi}_0$ are derived from observation [11]. In the preheating model we consider, the mass of the inflaton during preheating must be larger or equal to the mass of the inflaton during inflation. Hence we consider $\mu > 10^{13}$ GeV. We stress that the bounds of all the parameters are approximate and not very stringent. Preheating is terminated when $\rho_R/\rho_\phi \geq 10$, deeming this to be sufficient that the radiation energy dominates over the scalar energy density.

The lepton number n_L/s, where s is the entropy, gets translated to a baryon number n_b/s via sphaleron process. Sphalerons transfer a lepton asymmetry to a baryon asymmetry by reactions conserving n_{B-L} but violating n_{B+L}.

Figure 2 shows the region of m_N and $\tilde{m}_1$ where n_B/s is higher than observation. The lower limit of $\tilde{m}_1$ is due to the bound of 3×10^{-5} eV we used in our calculations; if the bound is lowered, the contour simply continues downward. The slant shape on the left hand boarder of the shaded area is not a simple slope relation; this comes from the combined restriction of $n_B/s \geq 9\times10^{-11}$ and the nonthermal condition of $m_N > T$. The preheat field parameters μ and $\dot{\phi}_0$ are not very sensitive in determining n_B/s.

The reheat temperature T_{RH} is greater than 10^{10} GeV in most of these regions. In supersymmetric models, this leads to overproduction of gravitinos which causes incompatibility with BBN observations [12]. Some models of supersymmetry have a larger mass to the gravitino [13], which can relax the constraint on T_{RH}. As we do not explicitly consider supersymmetry in our calculations above, our model agrees with all observations.

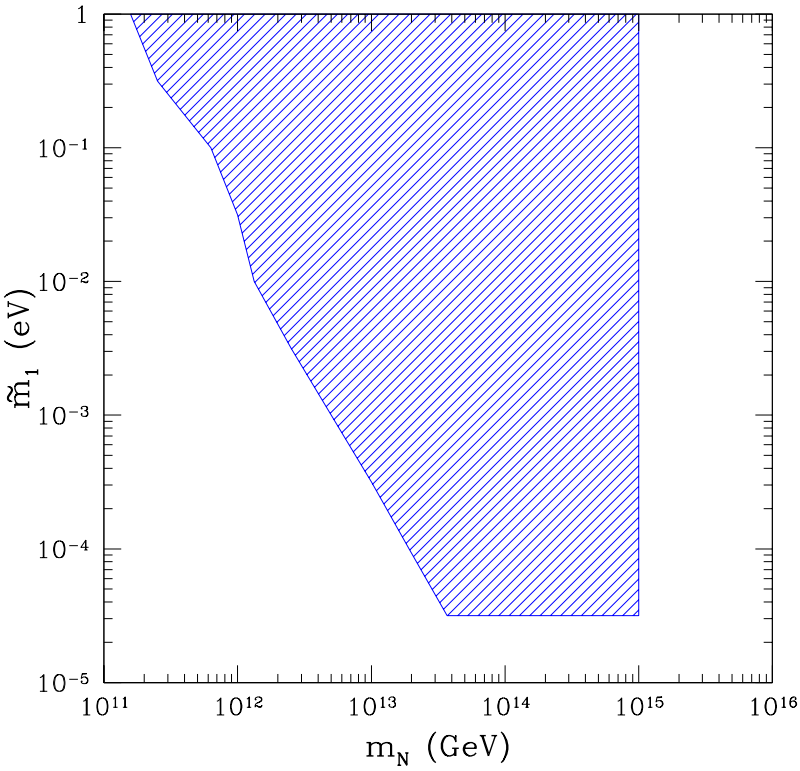

Figure 2. Regions of m_N and $\tilde{m}_1$ which satisfies the observed n_B/s value.

4. Conclusion

We have proposed a simple, economical model of nonthermal leptogenesis during instant preheating in the context of standard model and its extension to include Majorana partners. A hybrid inflation is employed, which allows us to evade the constraints on the properties of the inflaton potential from observations. If the electroweak Higgs is coupled to the inflaton, then one can expect instant preheating where the inflaton energy is extracted by resonant Higgs production as the inflaton passes through $\phi = 0$. As the inflaton grows during an oscillation, the effective mass of the Higgs may become large enough such that it can decay to the right-handed Majorana neutrino N, even if the mass of the N is as large as 10^{11} to 10^{16} GeV. A lepton number may be produced in this phase. Later, when the value of the inflaton field decreases, the Higgs mass will fall below the N mass, and the N will decay to Higgs, also producing a lepton number.

For a successful leptogenesis to happen in our model, we require $m_N > 10^{11}$ GeV. For most of the parameter space we find $T_{RH} > 10^{10}$ GeV, which may cause incompatibility with BBN observations in some SUSY models. The resulting lepton number only weakly depends on inflation parameters, is rather more sensitive to two neutrino mass parameters from the neutrino sector, and depends on the CP-phase in the heavy neutrino sector.

Acknowledgments

E J Ahn warmly thanks the conference organisers and Luigi for providing a wonderful meeting. This research was carried out at Fermilab, The University of Chicago, and the Kavli Institute for Cosmological Physics and was supported (in part) by NASA grant NAG5-10842 and NSF PHY-0114422. KICP is a NSF Physics Frontier Center.

References

[1] Fukugita M and Yanagida T 1986 *Phys. Lett. B* **174**, 45.

[2] Gell-Mann M, Ramond P and Slansky R 1979 *Proceedings of the Supergravity Stony Brook Workshop*, New York, eds. Van Nieuwenhuizen P and Freedman D; Yanagida T 1979 *Proceedinds of the Workshop on Unified Theories and Baryon Number in the Universe*, Tsukuba, Japan, eds. Sawada A and Sugamoto A; Mohapatra R N and Senjanovic G, 1980 *Phys. Rev. Lett.* **44**, 912; *ibid.* 1981 *Phys.Rev. D* **23**, 165.

[3] Kuzmin V A, Rubakov V A and Shaposhnikov M E 1985 *Phys. Lett. B* **155**, 36.

[4] Luty M A 1992 *Phys. Rev. D* **45**, 455; Buchmuller W and Plumacher M 2000 *Int. J. Mod. Phys. A* **15**, 5047; Hambye T, Ma E and Sarkar U 2000 *Nucl. Phys. B* **590**, 429; Davidson S and Ibarra A 2001 *JHEP* **0109**, 013; Branco G C, Morozumi T, Nobre B M and Rebelo M N 2001 *Nucl. Phys. B* **617**, 475; Ellis J R and Raidal M 2002 *Nucl. Phys. B* **643**, 229; Branco G C, Gonzalez Felipe R, Joaquim F R, Masina I, Rebelo M N, and Savoy C A 2003 *Phys. Rev. D* **67**, 073025; King S F 2003 *Phys. Rev. D* **67**, 113010; Pascoli S, Petcov S T and Yaguna C E 2003 *Phys. Lett. B* **564**, 241; Davidson S 2003 *JHEP* **0303**, 037; Akhmedov E K, Frigerio M and Smirnov A Y 2003 *JHEP* **0309**, 021; Allahverdi R and Mazumdar A 2003 *Phys. Rev. D* **67**, 023509; Fukuyama T, Kikuchi T, Osaka T 2005 *JCAP* **0506** 005.

[5] Plumacher M, Z. 1997 *Phys. C* **74**, 549; Giudice G F ,Notari A, Raidal M, Riotto A and Strumia A 2004 *Nucl. Phys. B* **685**, 89.

[6] Ahn E and Kolb E W 2005 Nonthermal instant leptogenesis (*Preprint* astro-ph/0508399)

[7] Linde A D 1994 *Phys. Rev. D* **49**, 748.

[8] Kofman L, Linde A D and Starobinsky A A 1997 *Phys. Rev. D* **56**, 3258; Felder G N, Kofman L and Linde A D 1999 it Phys. Rev. D **59**, 123523.

[9] Davidson S and Ibarra A 2002 *Phys. Lett. B* **535**, 25.

[10] Fogli G L, Lisi E, Marrone A, Melchiorri A , Palazzo A, Serra P and Silk J 2004 *Phys. Rev. D* **70**, 113003.

[11] Peiris H V *et al.* 2003 *Astrophys. J. Suppl.* **148**, 213.

[12] Cyburt R H, Fields B D and Olive K A 2003 *Phys. Lett. B* **567**, 227; Cyburt R H, Fields B D and Olive K A and Skillman E 2005 *Astropart. Phys.* **23**, 313.

[13] Arkani-Hamed N and Dimopoulos S 2005 JHEP **0506**, 073; Giudice G F and Romanino A 2004 *Nucl. Phys. B* **699**, 65 [Erratum-ibid. B **706**, 65 (2005)].