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Baryogenesis – 40 Years Later[1]

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Abstract. The classical picture of GUT baryogenesis has been strongly modified by theoretical progress concerning two nonperturbative features of the standard model: the phase diagram of the electroweak theory, and baryon and lepton number changing sphaleron processes in the high-temperature symmetric phase of the standard model. We briefly review three viable models, electroweak baryogenesis, the Affleck-Dine mechanism and leptogenesis and discuss the prospects to falsify them. All models are closely tied to the nature of dark matter, especially in supersymmetric theories. In the near future results from LHC and gamma-ray astronomy will shed new light on the origin of the matter-antimatter asymmetry of the universe.

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MATTER-ANTIMATTER ASYMMETRY

The cosmological matter-antimatter asymmetry can be dynamically generated if the particle interactions and the cosmological evolution satisfy Sakharov's conditions [1],

- baryon number violation,
- C and CP violation,
- deviation from thermal equilibrium.

Although the baryon asymmetry is just a single number, it provides an important connection between particle physics and cosmology. In his seminal paper, 40 years ago, Sakharov not only stated the necessary conditions for baryogenesis, he also proposed a specific model. The origin of the baryon asymmetry were CP violating decays of superheavy 'maximons' with mass $\mathcal{O}(M_\mathrm{P})$ at an initial temperature $T_i \sim M_\mathrm{P}$. The CP violation in maximon decays was related to the CP violation observed in K^0-decays, and the violation of baryon number led to a proton lifetime $\tau_p > 10^{50}$ years, much larger than current estimates in grand unified theories.

At present there exist a number of viable scenarios for baryogenesis. They can be classified according to the different ways in which Sakharov's conditions are realized. In grand unified theories baryon number (B) and lepton number (L) are broken by the interactions of gauge bosons and leptoquarks. This is the basis of classical GUT baryogenesis (cf. [2]). In a similar way, lepton number violating decays of heavy Majorana neutrinos lead to leptogenesis [3]. In the simplest version of leptogenesis the initial abundance of the heavy neutrinos is generated by thermal processes. Alternatively, heavy neutrinos

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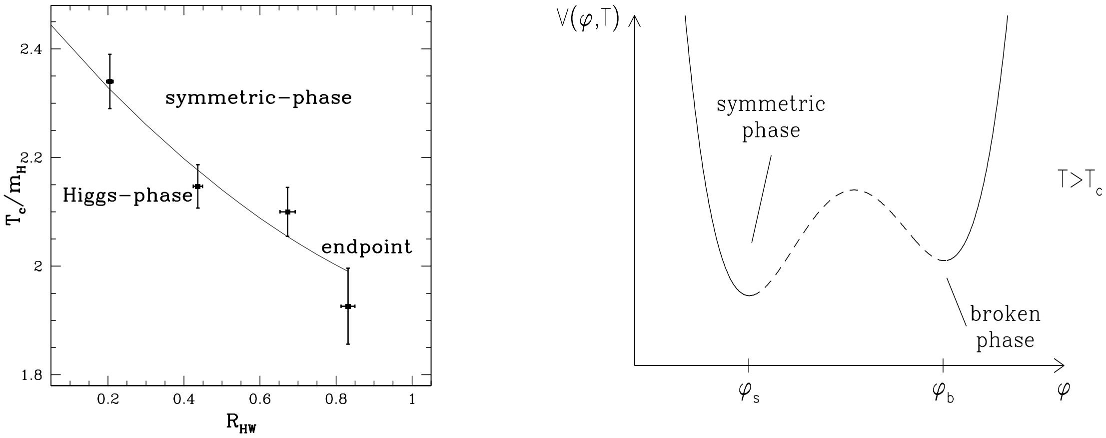

FIGURE 1. *Left:* Critical temperature T_c of the electroweak transition as function of $R_{HW} = m_H/m_W$; from [6]. *Right:* Effective potential of the Higgs field φ at temperature $T > T_c$.

may be produced in inflaton decays or in the reheating process after inflation. Because in the standard model baryon number, C and CP are not conserved, in principle the cosmological baryon asymmetry can also be generated at the electroweak phase transition [4]. A further mechanism of baryogenesis can work in supersymmetric theories where the scalar potential has approximately flat directions. Coherent oscillations of scalar fields can then generate large asymmetries [5].

The theory of baryogenesis crucially depends on nonperturbative properties of the standard model, first of all the nature of the electroweak transition. A first-order phase transition yields a departure from thermal equilibrium. Fig. 1 shows the phase diagram of the electroweak theory, i.e. the critical temperature in units of the Higgs mass, T_c/m_H, as function of the Higgs mass in units of the W-boson mass, $R_{HW} = m_H/m_W$ [6, 7]. For small Higgs masses the phase transition is first-order; above a critical Higgs mass, $m_H > m_H^c \simeq 72$ GeV, it turns into a smooth crossover [8, 9]. This upper bound for a first-order transition has to be compared with the lower bound from LEP, $m_H > 114$ GeV. Hence, there is no departure from thermal equilibrium at the electroweak transition in the standard model.

The second crucial nonperturbative aspect of baryogenesis is the connection between baryon number and lepton number in the high-temperature, symmetric phase of the standard model. Due to the chiral nature of the weak interactions B and L are not conserved [10]. At zero temperature this has no observable effect due to the smallness of the weak coupling. However, as the temperature reaches the critical temperature T_c of the electroweak phase transition, B and L violating processes come into thermal equilibrium [4]. The rate of these processes is related to the free energy of sphaleron-type field configurations which carry topological charge. In the standard model they lead to an effective interaction of all left-handed fermions [10] (cf. Fig. 2),

$$O_{B+L} = \prod_i (q_{Li}q_{Li}q_{Li}l_{Li}) \ , \tag{1}$$

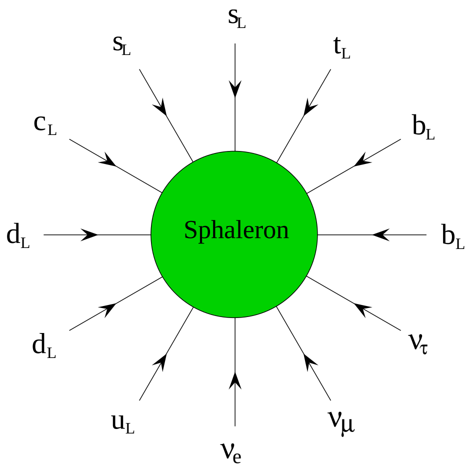

FIGURE 2. One of the 12-fermion processes which are in thermal equilibrium in the high-temperature phase of the standard model.

which violates baryon and lepton number by three units,

$$\Delta B = \Delta L = 3\ . \tag{2}$$

The sphaleron transition rate in the symmetric high-temperature phase has been evaluated by combining an analytical resummation with numerical lattice techniques [11]. The result is, in accord with previous estimates, that B and L violating processes are in thermal equilibrium for temperatures in the range

$$T_{EW} \sim 100\ \text{GeV} < T < T_{SPH} \sim 10^{12}\ \text{GeV}\ . \tag{3}$$

Sphaleron processes have a profound effect on the generation of the cosmological baryon asymmetry. An analysis of the chemical potentials of all particle species in the high-temperature phase yields the following relation between the baryon asymmetry and the corresponding L and $B-L$ asymmetries,

$$\langle B\rangle_T = c_S\langle B-L\rangle_T = \frac{c_S}{c_S-1}\langle L\rangle_T\ . \tag{4}$$

Here c_S is a number $\mathscr{O}(1)$. In the standard model with three generations and one Higgs doublet one has $c_s = 28/79$.

We conclude that lepton number violation is necessary in order to generate a cosmological baryon asymmetry[2]. However, it can only be weak, because otherwise any baryon asymmetry would be washed out. The interplay of these conflicting conditions leads to important contraints on neutrino properties and on possible extensions of the standard model in general.

[2] In the case of Dirac neutrinos, which have extremely small Yukawa couplings, one can construct leptogenesis models where an asymmetry of lepton doublets is accompanied by an asymmetry of right-handed neutrinos such that the total lepton number is conserved and $\langle B-L\rangle_T = 0$ [12].

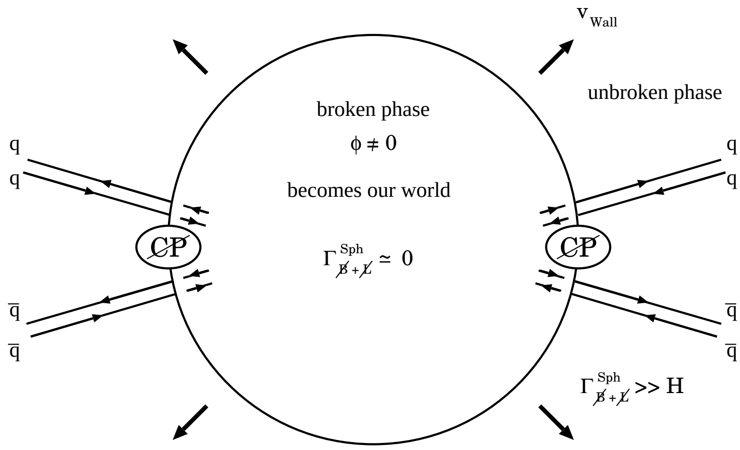

FIGURE 3. Sketch of nonlocal electroweak baryogenesis. From [13].

ELECTROWEAK BARYOGENESIS

A first-order electroweak phase transition proceeds via nucleation and growth of bubbles (cf. [13, 14]). This can provide the departure from thermal equilibrium, which is necessary for electroweak baryogenesis. *CP* violating reflections and transmissions at the bubble surface then generate an asymmetry in baryon number, and for a sufficiently strong phase transition this asymmetry is frozen in the true vacuum inside the bubble (cf. Fig. 3).

As discussed in the previous section, in the standard model the electroweak transition is just a smooth crossover. Hence, there is no departure from thermal equilibrium and baryogenesis cannot take place. The situation changes in two-Higgs doublet models (cf. [14, 15]) and in supersymmetric extensions of the standard model where one can

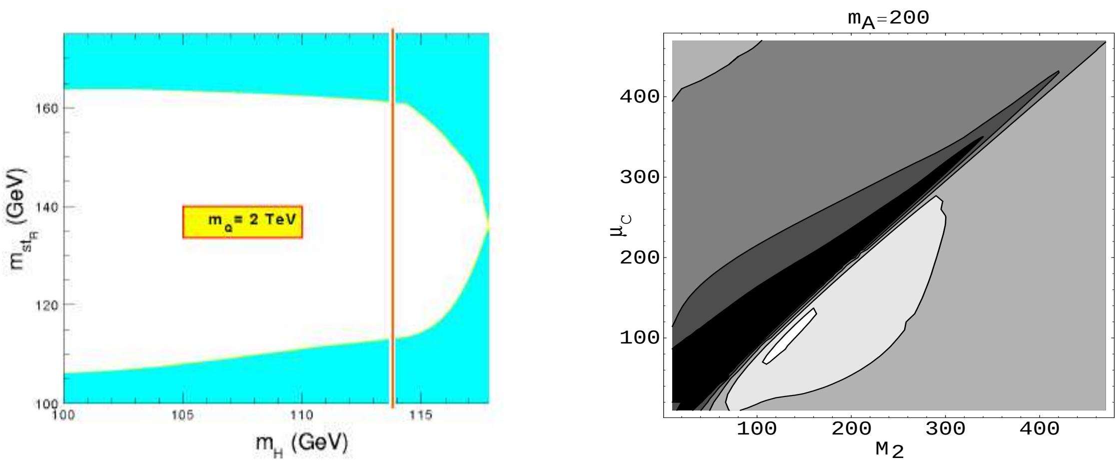

FIGURE 4. *Left:* Upper and lower bounds on the scalar top mass m_{st_R} as function of the Higgs mass m_H. From [16]. *Right:* In the black area of the (μ_c,M_2) plane of μ-parameter and gaugino mass electroweak baryogenesis is viable. From [17].

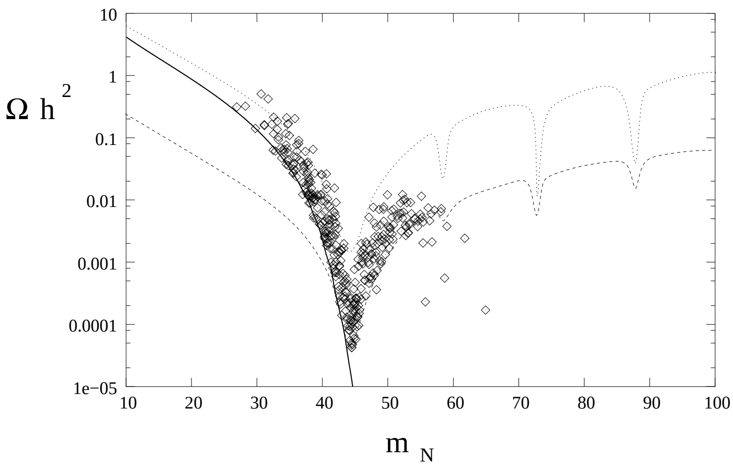

FIGURE 5. Neutralino relic density as function of the neutralino mass in the nMSSM for different parameter sets of the model (scattered points). From [18].

have a sufficiently strong first-order phase transition (cf. [14]). This requires, however, a rather exceptional mass spectrum of superparticles. As the left panel of Fig. 4 shows, one scalar top-quark has to be lighter than the top-quark whereas other scalar quarks are 2 TeV heavy. Also gaugino masses have to be rather small (cf. Fig. 4, right panel).

Even more stringent constraints are obtained if the lightest neutralino is required to be the dominant component of cold dark matter. This case has been studied in detail for the nMSSM, a minimal extension of the MSSM with a singlet field [18]. Fig. 5 shows the neutralino relic density as function of the neutralino mass for various parameter sets of the model represented by the scattered points. It is remarkable that the neutralino has to be very light. This suggests that, should supersymmetry be discovered at the LHC, the consistency of WIMP dark matter and electroweak baryogenesis will be a highly non-trivial test of supersymmetric extensions of the standard model.

AFFLECK-DINE BARYOGENESIS

In general the scalar potential of supersymmetric theories has many flat directions involving scalar fields which carry baryon or lepton number. Typical examples in the MSSM are

$$(LH_u)\ , \quad (U^c D^c D^c)\ , \tag{5}$$

where L, H_u, U^c and D^c denote lepton doublets, one of the Higgs doublets and quark fields, respectively. During inflation these fields generically develop large vacuum expectation values. After inflation these condensates lead to coherent oscillations, which can store large baryon and lepton charge densities. The decay of these condensates eventually converts the scalar charge densities to ordinary fermionic baryon and lepton number.

This ‘AD mechanism’ is a prominent example of nonthermal baryogenesis. So far no ‘standard model’ of AD baryogenesis has emerged, and it appears difficult to falsify this

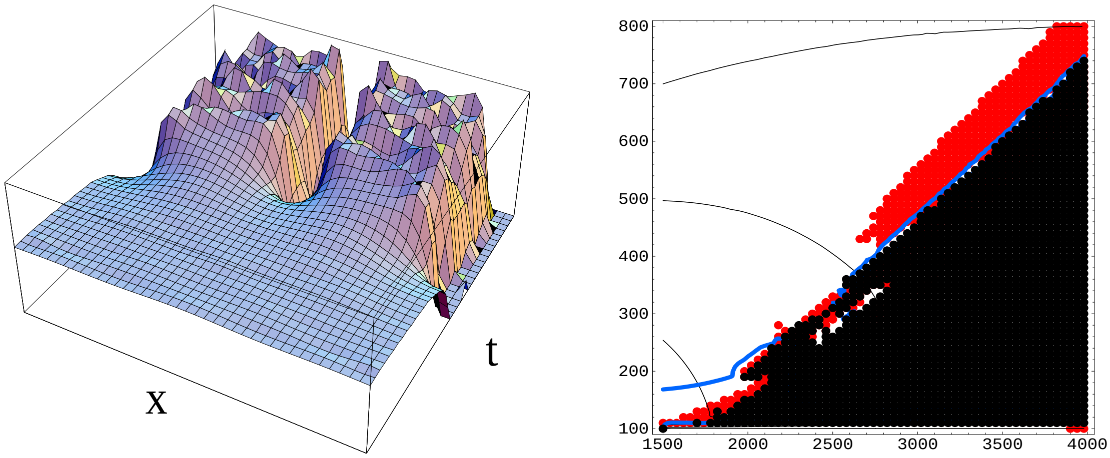

FIGURE 6. *Left:* The charge density per comoving unit volume in (1+1) dimensions for a sample potential during the period when the spatially homogeneous condensate breaks up into high- and low-density domains which are expected to form Q-balls. From [19]. *Right:* Allowed domains (red) of m_0 [GeV] (horizontal axis) and $M_{1/2}$ [GeV] (vertical axis) in an mSUGRA model for nonthermally produced higgsino dark matter; the thin black contours correspond to different Higgs masses. From [20].

scenario. On the other hand, certain types of dark matter would strongly support the AD mechanism.

In the case of the $U^cD^cD^c$ flat direction, the decay of the condensate can lead to the formation of Q-balls as illustrated in the left panel of Fig. 6 (cf. [19]). These macroscopic objects with large baryon number and mass,

$$B_Q \sim 10^{26}\,, \quad M_Q \sim 10^{24}\ \mathrm{GeV}\,, \tag{6}$$

can lead to striking signatures at Super-Kamiokande and ICECUBE. Alternatively, the decay of unstable Q-balls can nonthermally produce higgsinos which, for the parameters shown in Fig. 6, yield the observed cold dark matter density. The identification of a neutralino LSP as higgsino at LHC would be inconsistent with thermally produced WIMP dark matter. A discovery of higgsino dark matter in direct search experiments could then be a hint for Q-balls as a possible nonthermal production mechanism. In this way, as in the case of electroweak baryogenesis, the nature of dark matter would provide a clue also for the origin of ordinary matter.

THERMAL LEPTOGENESIS

About 20 years ago, leptogenesis was suggested as the origin of matter by Fukugita and Yanagida [3]. The basis of this proposal is the seesaw mechanism which explains the smallness of the light neutrino masses by mixing with heavy Majorana neutrinos. The theory predicts six Majorana neutrinos as mass eigenstates, three heavy (N) and three light (ν),

$$m_N \simeq M\,, \quad m_\nu = -m_D^T\frac{1}{M}m_D\,. \tag{7}$$

Here the Dirac neutrino mass matrix $m_D = hv$ is the product of the matrix h of Yukawa couplings and the expectation value v of the Higgs field ϕ, which breaks the electroweak symmetry. If Yukawa couplings of the third generation are $\mathscr{O}(1)$, as it is the case for the top-quark, the corresponding heavy and light neutrino masses are

$$M_3 \sim \Lambda_{GUT} \sim 10^{15}\ \text{GeV} , \quad m_3 \sim \frac{v^2}{M_3} \sim\ 0.01\ \text{eV} . \tag{8}$$

It is very remarkable that the light neutrino mass m_3 is of the same order as the mass differences $(\Delta m^2_{sol})^{1/2}$ and $(\Delta m^2_{atm})^{1/2}$ inferred from neutrino oscillations. This suggests that, via the seesaw mechanism, neutrino masses indeed probe the grand unification scale! The difference of the observed mixing patterns of quarks and leptons is a puzzle whose solution has to be provided by the correct GUT model. Like for quarks and charged leptons one expects a mass hierarchy also for the right-handed neutrinos. For instance, if their masses scale like the up-quark masses one has $M_1 \sim 10^{-5} M_3 \sim 10^{10}$ GeV.

The lightest of the heavy Majorana neutrinos, N_1, is ideally suited to generate the cosmological baryon asymmetry. Since it has no standard model gauge interactions it can naturally satisfy the out-of-equilibrium condition. N_1 decays to lepton-Higgs pairs then yield a lepton asymmetry $\langle L \rangle_T \neq 0$, which is partially converted to a baryon asymmetry $\langle B \rangle_T \neq 0$. The generated asymmetry is proportional to the *CP* asymmetry [21] in N_1-decays which is conveniently expressed in the following form,

$$\varepsilon_1 = \frac{\Gamma(N_1 \to l\phi) - \Gamma(N_1 \to \overline{l\phi})}{\Gamma(N_1 \to l\phi) + \Gamma(N_1 \to l\phi)} \simeq -\frac{3}{16\pi} \frac{M_1}{(hh^\dagger)_{11} v^2} \text{Im} \left(h^* m_\nu h^\dagger \right)_{11} , \tag{9}$$

where the seesaw mass relation (7) has been used. From the expression (9) one easily obtains a rough estimate for ε_1 in terms of neutrino masses. Assuming dominance of the largest eigenvalue of m_ν, phases $\mathscr{O}(1)$ and approximate cancellation of Yukawa couplings in numerator and denominator one finds,

$$\varepsilon_1 \sim \frac{3}{16\pi} \frac{M_1 m_3}{v^2} \sim\ 0.1\ \frac{M_1}{M_3} , \tag{10}$$

where we have again used the seesaw relation. Hence, the order of magnitude of the *CP* asymmetry is approximately given by the mass hierarchy of the heavy Majorana neutrinos. For $M_1/M_3 \sim m_u/m_t \sim 10^{-5}$ one has $\varepsilon_1 \sim 10^{-6}$.

Given the *CP* asymmetry ε_1 one obtains for the baryon asymmetry,

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = -d \varepsilon_1 \kappa_f \sim 10^{-10} . \tag{11}$$

Here the dilution factor $d \simeq 10^{-2}$ accounts for the increase of the number of photons in a comoving volume element between baryogenesis and today, and the efficiency factor κ_f represents the effect of washout processes in the plasma. In the estimate (11) we have assumed a typical value, $\kappa_f \sim 10^{-2}$. Thus the correct value of the baryon asymmetry is obtained as consequence of a large hierarchy of the heavy neutrino masses, which leads

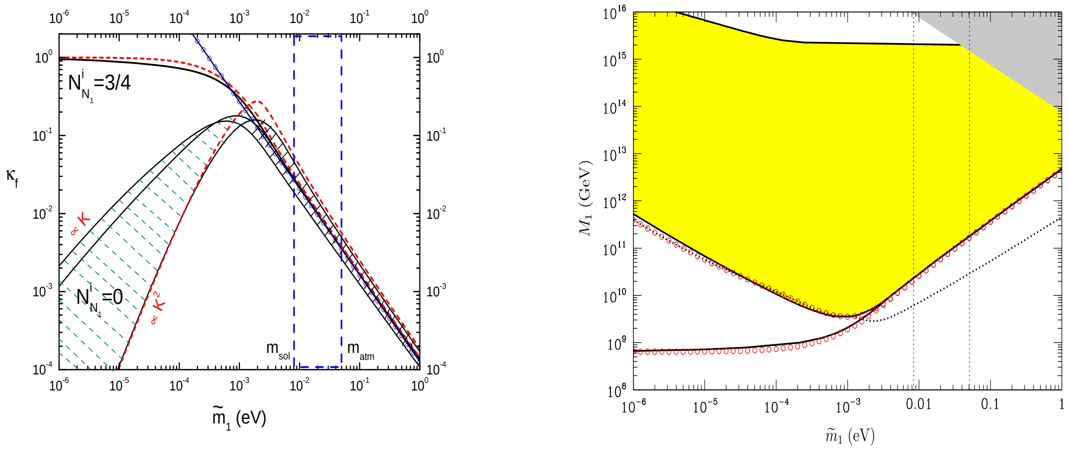

FIGURE 7. *Left:* Final efficiency factor κ_f as function of the effective neutrino mass $\widetilde{m}_1$. *Right:* Lower bounds on M_1 (analytical: circles) and the initial temperature T_i (dotted line) as functions of $\widetilde{m}_1$. Upper and lower curves correspond to zero and thermal initial N_1 abundance, respectively. In both panels the vertical dashed lines indicate the range (m_{sol},m_{atm}). From [29].

to a small *CP* asymmetry, and the kinematical factors d and κ_f [22]. The baryogenesis temperature,

$$T_B \sim M_1 \sim 10^{10}\ \mathrm{GeV}\,, \tag{12}$$

corresponds to the time $t_B \sim 10^{-26}$ s, which characterizes the next relevant epoch before electroweak transition, nucleosynthesis and recombination.

During the past years the quantitative connection between thermal leptogenesis and neutrino masses has been studied in great detail, in particular in the simplest case of hierarchical heavy Majorana neutrinos. The crucial ingredients are the upper bound on the *CP* asymmetry ε_1 [23, 24] and the analysis of the various production and washout processes in the thermal plasma [25, 26, 27, 28, 29]. One finds that successful leptogenesis favours the light neutrino mass window [26]

$$10^{-3}\ \mathrm{eV} < m_i < 0.1\ \mathrm{eV}\,. \tag{13}$$

For $m_i > 10^{-3}$, the efficiency factor κ_f, and therefore the baryon asymmetry η_B, is independent of the initial N_1 abundance; furthermore, the final baryon asymmetry does not depend on the value of an initial baryon asymmetry generated by some other mechanism (cf. Fig. 7). Hence, the value of η_B is entirely determined by neutrino properties. For neutrino masses $m_i > 0.1$ eV the *CP* asymmetry ε_1 becomes too small and washout processes are too strong such that the generated baryon asymmetry is too small. A second important result is a lower bound on the baryogenesis temperature T_B [24, 29] of about 10^9 GeV, depending on $\widetilde{m}_1$ and the initial N_1 abundance.

An important recent development in the theory of leptogenesis concerns the effect of the flavour composition of heavy neutrino decays on the generated lepton asymmetry [30]. Particularly interesting is the possible connection between the baryon asymmetry

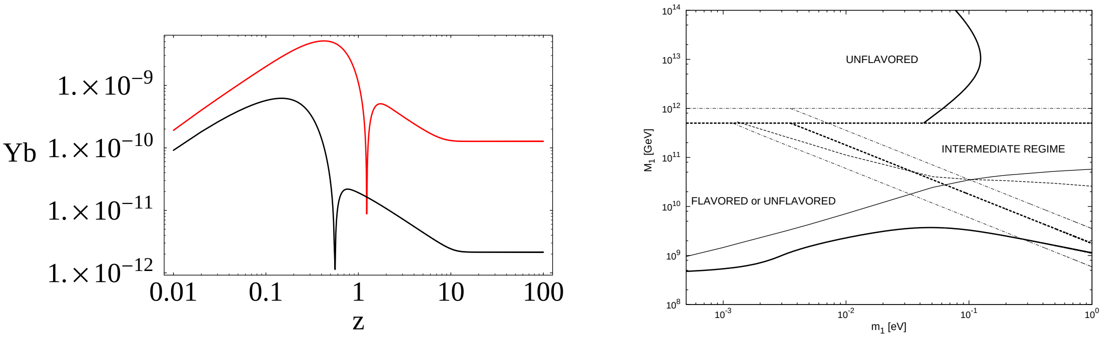

FIGURE 8. *Left:* Baryon asymmetry for specific lepton mass matrices including flavour effects (upper) and without flavour effect (lower). From Abada et al. [31]. *Right:* Domains of the (M_1-m_1) plane with different relevance of flavour effects; the two thick solid lines border the region where successful leptogenesis is possible. From [32].

and *CP* violation at low energies [31]. Flavour effects can significantly enhance the generated baryon asymmetry (cf. Fig. 8) and therefore relax the upper bound on the light neutrino masses given in (13). To quantify this effect which strongly depends on the neutrino mass parameters (cf. Fig. 8), a full quantum kinetic description of the leptogenesis process is required [32]. Several groups have started to study leptogenesis on the basis of Kadanoff-Baym equations [33].

Over the years much work has also be done on the connection between leptogenesis and neutrino mass matrices which can account for low-energy neutrino data. Many interesting models, some also very different from the scenario considered above, have been discussed in the literature [34]. Of particular interest is the connection with *CP* violation in other low energy processes [35]. Together with leptogenesis, improved measurements of neutrino parameters will have strong implications for the structure of grand unified theories.

An alternative to thermal leptogenesis is nonthermal leptogenesis [36] where the heavy Majorana neutrinos are not produced by thermal processes. These models are less predictive but arise naturally in many extensions of the standard model.

An intriguing aspect of thermal leptogenesis is its incompatibility with the most popular supersymmetric extensions of the standard model where the lightest neutralino is the dominant component of cold dark matter and a heavy gravitino, decaying after nucleosynthesis, requires a reheating temperature in the early universe much below the temperature needed for leptogenesis. This clash has triggered much work on alternatives to WIMP dark matter. An attractive possibility is gravitino dark matter (cf. [36, 37, 38]) which can have striking effects at the LHC as well as in gamma-ray astronomy.

CONCLUSIONS

40 years after Sakharov's work on the cosmological matter-antimatter asymmetry we have several viable models of baryogenesis, the most predictive ones being electroweak baryogenesis and leptogenesis. In fact, based on our theoretical understanding of the electroweak phase diagram, electroweak baryogenesis in the standard model has already

been excluded by the LEP bound on the Higgs mass. Supersymmetric electroweak baryogenesis will soon be tested at the LHC.

Detailed studies of the nonequilibrium leptogenesis process have led to the preferred neutrino mass window 10^{-3} eV $< m_i <$ 0.1 eV in the simplest scenario with hierarchical heavy neutrinos. The consistency with the experimental evidence for neutrino masses has dramatically increased the popularity of the leptogenesis mechanism. It is exciting that new experiments and cosmological observations will probe the absolute neutrino mass scale in the coming years. However, more work is needed on the full quantum mechanical treatment of leptogenesis, in particular the flavour dependence.

All baryogenesis mechanisms are closely related to the nature of dark matter. A discovery of the standard supergravity scenario at LHC could be consistent with electroweak baryogenesis but would rule out the simplest version of thermal leptogenesis. On the other hand, evidence for gravitino dark matter can be consistent with leptogenesis. Finally, the discovery of macroscopic dark matter like Q-balls would point towards nonperturbative dynamics of scalar fields in the early universe and therefore favour Affleck-Dine baryogenesis.

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