LEPTOGENESIS:

STANDARD MODEL & ALTERNATIVES

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Recent reviews and references:

WB, R. D. Peccei, T. Yanagida, Leptogenesis as the origin of matter, Annu. Rev. Nucl. Part. Sci 2005. 55: 311, hep-ph/0502169

R. N. Mohapatra et al., Theory of neutrinos: A White paper, hep-ph/0510213

WB, P. Di Bari, M. Plümacher, Leptogenesis for pedestrians, Ann. Phys. 315: 303 (2005)

OUTLINE

(1) Matter-Antimatter Asymmetry

(2) Grand Unification & Thermal Leptogenesis

(3) Solving the Kinetic Equations

(4) Bounds on Neutrino Masses

(5) Non-thermal Leptogenesis

(6) Comments on Gravitino Dark Matter

(1) Matter-Antimatter Asymmetry

Observation of acoustic peaks in cosmic microwave background radiation (CMB) has led to precision measurement of the baryon asymmetry $\eta_B \simeq (\eta_B - \eta_{\overline{B}}) = n_B/n_\gamma$ by WMAP collaboration,

$$\eta_B^{CMB} = (6.1^{+0.3}_{-0.2}) \times 10^{-10} \;;$$

'measurement' of η_B at temperature $T_{CMB} \sim 1$ eV, i.e. time $t_{CMB} \sim 3 \times 10^5 y \simeq 10^{13} s$, assumes Friedmann universe.

Second determination of η_B from nucleosynthesis, i.e. abundances of the light elements, D, ^{3}He, ^{4}He, ^{7}Li, yields

$$\eta_B^{BBN} = \frac{n_B}{n_\gamma} = (2.6 - 6.2) \times 10^{-10} \;;$$

'measurement' of η_B at temperature $T_{BBN} \sim 10$ MeV , i.e. time $t_{BBN} \sim 10s$; consistency of η_B^{CMB} and η_B^{BBN} remarkable test of standard cosmological model.

A matter-antimatter asymmetry can be dynamically generated in an expanding universe if the particle interactions and the cosmological evolution satisfy Sakharov's conditions,

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

Baryon asymmetry provides important relationship between the standard model of cosmology and the standard model of particle physics as well as its extensions.

Scenarios for baryogenesis: classical GUT baryogenesis, leptogenesis, electroweak baryogenesis, Affleck-Dine baryogenesis (scalar field dynamics).

Theory of baryogenesis depends crucially on nonperturbative properties of standard model,

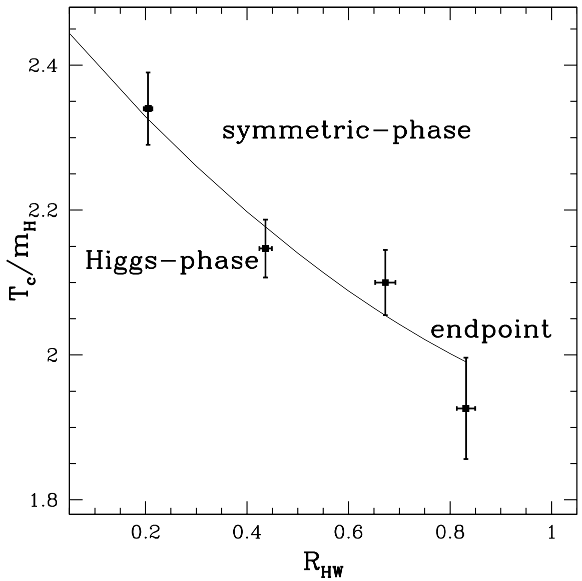
- electroweak phase transition: 'symmetry restoration' at high temperatures, $T > T_{EW} \sim 100$ GeV, smooth transition for large Higgs masses, $m_H > m_H^c \simeq 72$ GeV (LEP bound $m_H > 114$ GeV).

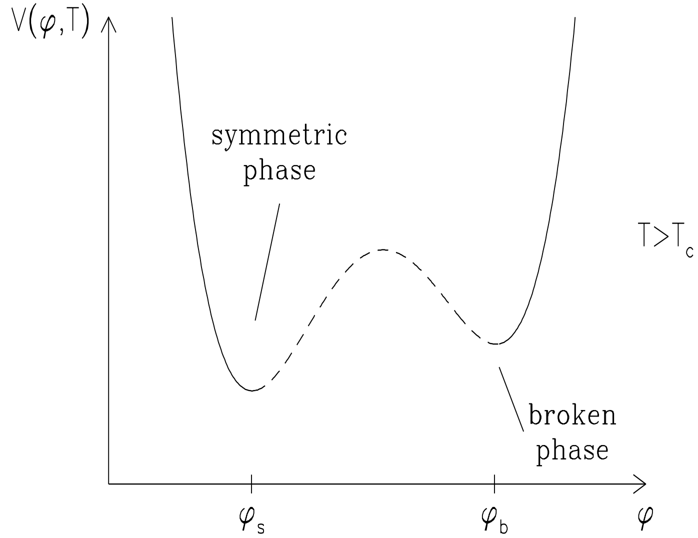
- sphaleron processes: relate baryon and lepton number at high temperatures, in thermal equilibrium in temperature range,

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

Finite temperature potential and phase diagram for electroweak theory:
endpoint of critical line of first-order phase transitions, critical Higgs mass

Csikor, Fodor, Heitger '99





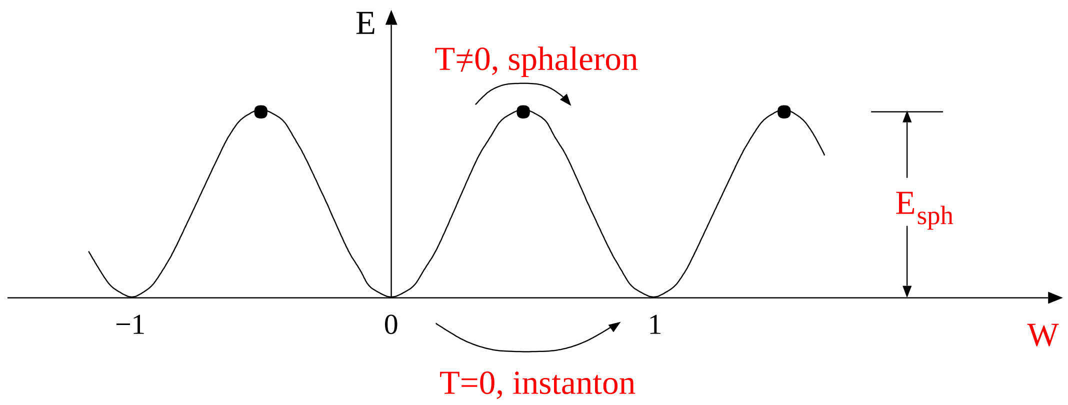
$R_{HW,c} = \frac{m_H^c}{m_W}$, $m_H^c = 72.1 \pm 1.4$ GeV

Baryon and lepton number violating transitions

't Hooft '76; Klinkhammer, Manton '84

Vacuum of SU(2) gauge theory: degeneracy labelled by topological charge

$$N_{CS} = \frac{g^3}{96\pi^2} \int d^3 \epsilon_{ijk} \epsilon^{IJK} W^{Ii} W^{Jj} W^{Kk}$$



crossing of barrier related to change of baryon and lepton number,

$$\Delta B = \Delta L = 3\Delta N_{CS} \, .$$

Baryon and lepton number currents have triangle anomaly,

$$J^B_\mu = \frac{1}{3}\sum_{generations}\left(\overline{q_L}\gamma_\mu q_L + \overline{u_R}\gamma_\mu u_R + \overline{d_R}\gamma_\mu d_R\right) ,$$

$$J^L_\mu = \sum_{generations}\left(\overline{l_L}\gamma_\mu l_L + \overline{e_R}\gamma_\mu e_R\right) ,$$

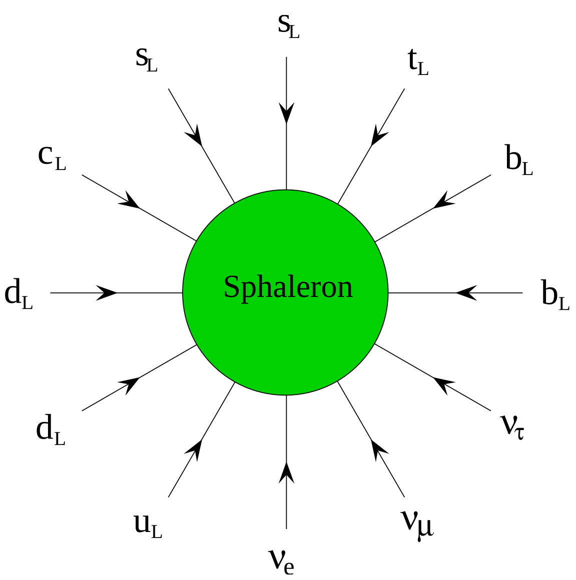
$$\partial^\mu J^B_\mu = \partial^\mu J^L_\mu = \frac{N_f}{32\pi^2}\left(-g^2 W^I_{\mu\nu}\widetilde{W}^{I\mu\nu} + g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right) ,$$

which leads to correlation between change of topological charge and baryon/lepton number,

$$B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3x \partial^\mu J^B_\mu = N_f[N_{cs}(t_f) - N_{cs}(t_i)] .$$

Baryon and lepton number violating sphaleron processes

Kuzmin, Rubakov, Shaposhnikov '85



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

$\Delta B = 3$, $\Delta L = 3$,

$B - L$ conserved

Processes are in thermal equilibrium above electroweak phase transition, for temperatures

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

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

$$\langle B\rangle_T = c_S\langle B-L\rangle_T = \frac{c_S}{c_S-1}\langle L\rangle_T\ ,$$

with c_S number $\mathcal{O}(1)$; in standard model $c_s = 28/79$.

This relation suggests that lepton number violation is needed to explain the cosmological baryon asymmetry. However, it can only be weak, since otherwise any baryon asymmetry would be washed out. The interplay of these conflicting conditions leads to important contraints on neutrino properties and on extensions of the standard model in general.

(2) Grand Unification & Leptogenesis

Lepton number is naturally violated in grand unified theories (GUTs) which extend the SM,

$$G_{SM} = U(1) \times SU(2) \times SU(3) \subset SU(5) \subset SO(10) \ldots \ .$$

Quarks and leptons form SU(5) multiplets (Georgi, Glashow '74),

$$\mathbf{10} = (q_L, u_R^c, e_R^c) \ , \quad \mathbf{5}^* = (d_R^c, l_L) \ , \quad (\mathbf{1} = \nu_R) \ .$$

Unlike gauge fields, quarks and leptons are not unified in a single multiplet; right-handed neutrinos are not needed in SU(5) models; since they are singlets with respect to SU(5), they can have Majorana masses M which are not controlled by the Higgs mechanism.

Three quark-lepton generations have Yukawa interactions with two Higgs fields, $H_1(\mathbf{5})$ and $H_2(\mathbf{5}^*)$,

$$\mathcal{L} = h_{uij}\mathbf{10}_i\mathbf{10}_j H_1(\mathbf{5}) + h_{dij}\mathbf{5^*}_i\mathbf{10}_j H_2(\mathbf{5}^*) + h_{\nu ij}\mathbf{5^*}_i\mathbf{1}_j H_1(\mathbf{5}) + M_{ij}\mathbf{1}_i\mathbf{1}_j \ .$$

Electroweak symmetry breaking yields quark and charged lepton mass matrices and the Dirac neutrino mass matrix $m_D = h_\nu v_1,\ v_1 = \langle H_1 \rangle$. The Majorana mass term ($\Delta L = 2$) can be much larger than the electroweak scale, $M \gg v$.

All quarks and leptons of one generation are unified in a single multiplet in the GUT group SO(10) (Georgi; Fritsch, Minkowski '75),

$$\mathbf{16} = \mathbf{10} + \mathbf{5}^* + \mathbf{1} \ .$$

ν_R's are now required by fundamental gauge symmetry of SO(10).

Seesaw mechanism: explains smallness of the light neutrino masses by largeness of the heavy Majorana masses; predicts six Majorana neutrinos as mass eigenstates, three heavy (N) and three light (ν),

$$\begin{aligned} N &\simeq \nu_R + \nu_R^c : \qquad m_N \simeq M ; \\ \nu &\simeq \nu_L + \nu_L^c : \qquad m_\nu = -m_D^T \frac{1}{M} m_D . \end{aligned}$$

Simplest pattern of SO(10) breaking, Yukawa couplings of third generation $\mathcal{O}(1)$, like the top-quark, yields heavy and light neutrino masses,

$$M_3 \sim \Lambda_{GUT} \sim 10^{15}\ \mathrm{GeV} , \quad m_3 \sim \frac{v^2}{M_3} \sim 0.01\ \mathrm{eV} ;$$

neutrino mass m_3 is compatible with $(\Delta m^2_{sol})^{1/2} \sim 0.009$ eV and $(\Delta m^2_{atm})^{1/2} \sim 0.05$ eV from neutrino oscillations, i.e. GUT scale physics !!

Thermal leptogenesis

Fukugita, Yanagida '86

Lightest (heavy) Majorana neutrino, N_1, is ideal candidate for baryogenesis: no SM gauge interactions, hence out-of-equilibrium condition o.k.; N_1 decays to lepton-Higgs pairs yield lepton asymmetry $\langle L \rangle_T \neq 0$, partially converted to baryon asymmetry $\langle B \rangle_T \neq 0$.

The generated baryon asymmetry is proportional to the CP asymmetry in N_1-decays ($H_1 = H_2^* = \phi$, seesaw relation, ... Flanz et al. '95, Covi et al. '96,...),

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

Rough estimate for ε_1 in terms of neutrino masses (dominance of the largest eigenvalue of m_ν, phases $\mathcal{O}(1)$),

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

order of magnitude of CP asymmetry is given by the mass hierarchy of the heavy Majorana neutrinos, e.g. $\varepsilon_1 \sim 10^{-6}$ for $M_1/M_3 \sim m_u/m_t \sim 10^{-5}$.

Baryon asymmetry for given CP asymmetry ε_1,

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{\kappa}{f} c_S \varepsilon_1 \sim 10^{-10}\dots 10^{-9}\,,$$

with $f \sim 10^2$ dilution factor which accounts for the increase of the number of photons in a comoving volume element between baryogenesis and today; determination of the washout factor κ requires Boltzmann equations (for estimate, $\kappa \sim 0.01\dots 0.1$).

The baryon asymmetry is generated around a temperature

$$T_B \sim M_1 \sim 10^{10} \text{ GeV} ,$$

which is rather large w.r.t gravitino problem in supersymmetric theories; this has possibly interesting implications for the nature of dark matter.

The observed value of the baryon asymmetry, $\eta_B \sim 10^{-9}$ is obtained as consequence of a large hierarchy of the heavy neutrino masses, leading to a small CP asymmetry, and the kinematical factors f and κ. The baryogenesis temperature $T_B \sim 10^{10}$ GeV, corresponding to the time $t_B \sim 10^{-26}$ s, characterizes the next relevant epoch before recombination, nucleosynthesis and electroweak transition.

(3) Solving the Kinetic Equations (see WB, Di Bari, Plümacher '04)

Heavy neutrinos are (not) in thermal equilibrium if the decay rate satisfies $\Gamma_1 > H$ ($\Gamma_1 < H$), with $H(T)$ Hubble parameter, i.e.,

$$\widetilde{m}_1 > m_* \quad (\widetilde{m}_1 < m_*) \ ,$$

with 'effective neutrino mass',

$$\widetilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1} \ , \quad m_1 \leq \widetilde{m}_1 \, (<) \, m_3 \ ,$$

and 'equilibrium neutrino mass' ($M_{pl} = 1.2 \times 10^{19}$ GeV, $g_* = 434/4$),

$$m_* = \frac{16\pi^{5/2}}{3\sqrt{5}} g_*^{1/2} \frac{v^2}{M_{pl}} \simeq 10^{-3} \text{ eV} \ .$$

Note: equilibrium neutrino mass m_* close to neutrino masses $\sqrt{\Delta m^2_{\rm sol}} \simeq 8 \times 10^{-3}$ eV and $\sqrt{\Delta m^2_{\rm atm}} \simeq 5 \times 10^{-2}$ eV; hope: baryogenesis via leptogenesis process close to thermal equilibrium ?!

Boltzmann equations for leptogenesis, competition between production and washout,

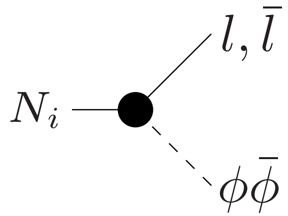
$$
\begin{aligned}
\frac{dN_{N_1}}{dz} &= -(D+S)\,(N_{N_1} - N_{N_1}^{\rm eq})\ , \\
\frac{dN_{B-L}}{dz} &= -\varepsilon_1\, D\,(N_{N_1} - N_{N_1}^{\rm eq}) - W\, N_{B-L}\ .
\end{aligned}
$$

N_i: number densities in comoving volume, $z = M_1/T$, $D = \Gamma_D/(Hz)$: decay rate, $S = \Gamma_S/(Hz)$: scattering rate, $W = \Gamma_W/(Hz)$: washout rate.

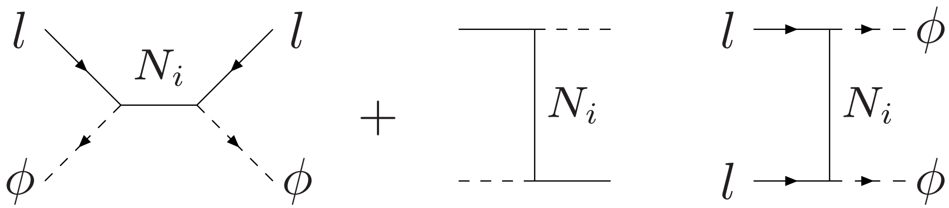
PROCESSES in PLASMA

decays (D), inverse decays (ID)

$$N_i \leftrightarrow l\,\phi\,,\ \bar{l}\,\bar{\phi}$$



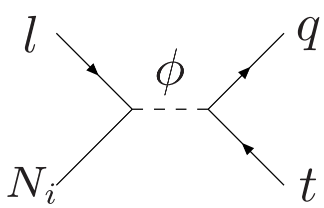
$\Delta L = 2$ processes (N_i virtual)

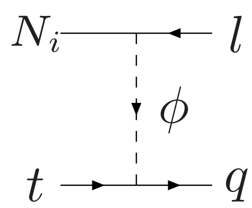


$$l\,\bar{\phi} \leftrightarrow \bar{l}\,\phi\ (N)$$

$$l\,l \leftrightarrow \phi\,\phi$$
$$\bar{l}\,\bar{l} \leftrightarrow \bar{\phi}\,\bar{\phi} \quad (N,\,t)$$

$\Delta L = 1$ processes (N_i real)

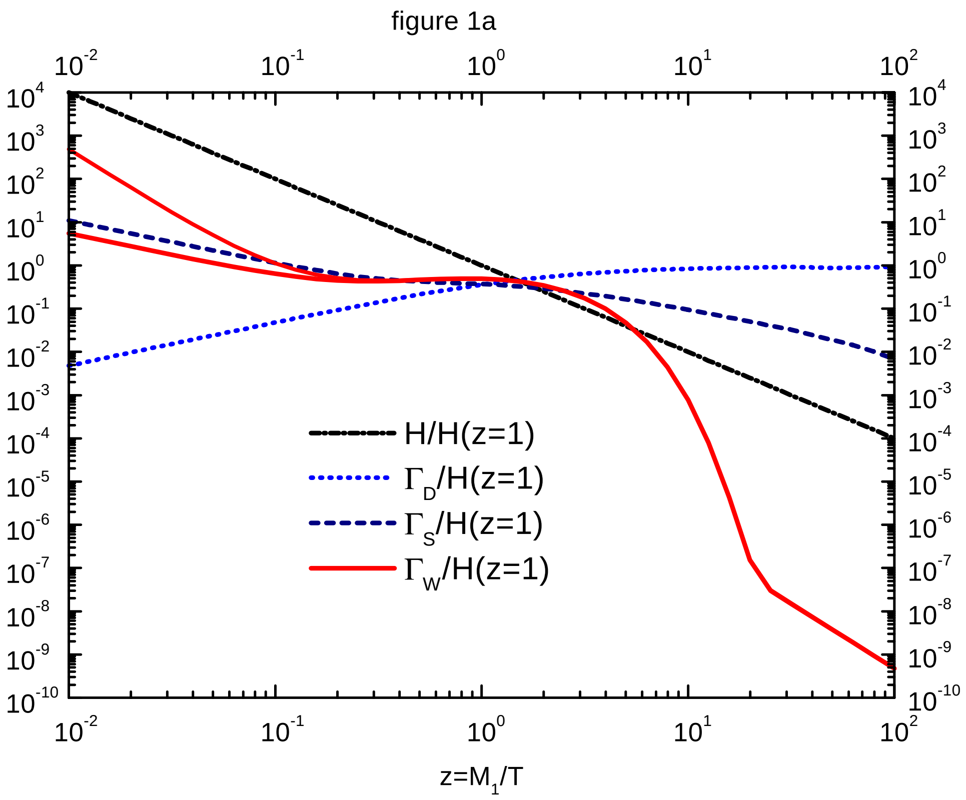




$$N_i\,l \leftrightarrow \bar{t}\,q \quad (\phi,\,s)$$

$$N_i\,t \leftrightarrow \bar{l}\,q \quad (\phi,\,t)$$

Reation rates in a plasma at temperatures $T \sim M_1$

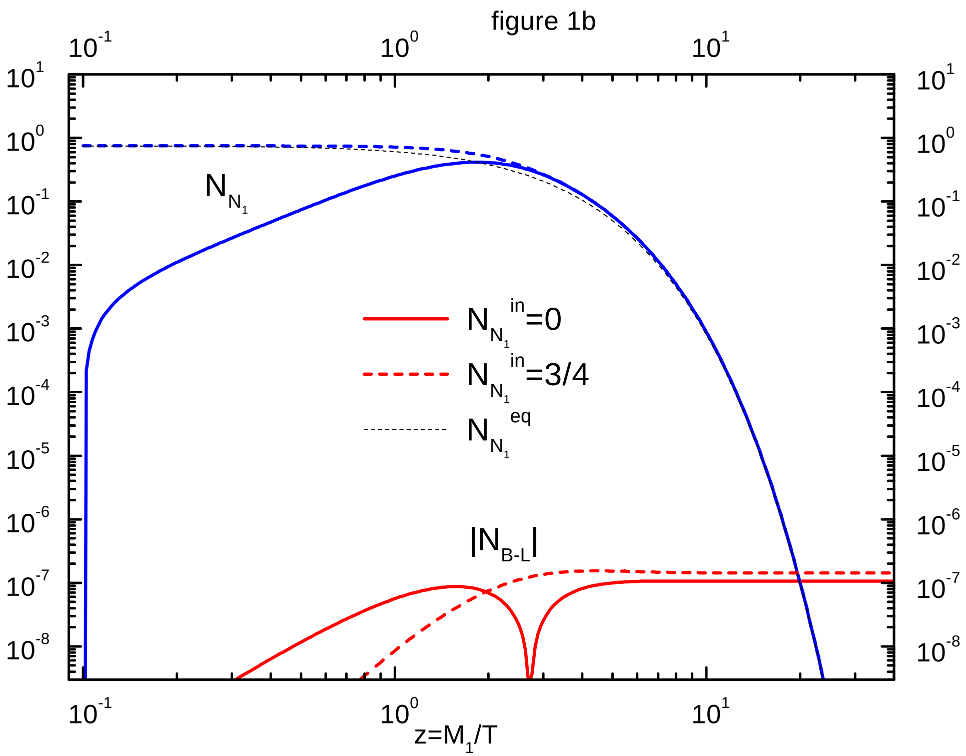


Reaction rates in comparison with the Hubble parameter $H(T) = 1.66\sqrt{g_*}T^2/M_{pl}$ as function of $z = T/M$.

Important temerature range for baryogenesis: $z = 1 \ldots 8$.

Parameters: $M_1 = 10^{10}$ GeV, $\widetilde{m}_1 = 10^{-3}$ eV, $\overline{m} = 0.05$ eV

Evolution of number densities and $B-L$ asymmetry



Generation of a $B-L$ asymmetry for different initial conditions, zero and thermal N_1 abundance; Yukawa interactions are strong enough to bring the heavy neutrinos into thermal equilibrium; observed asymmetry: $\eta_B \simeq 0.01 \times N_{B-L} \sim 10^{-9}$.

Parameters: $M_1 = 10^{10}$ GeV, $\widetilde{m}_1 = 10^{-3}$ eV, $\overline{m} = 0.05$ eV, $|\varepsilon_1| = 10^{-6}$.

Decays and inverse decays

Simplified picture: only decays and inverse decays are effective; for consistency, the real intermediate state contribution to the $2 \to 2$ processes is included. In kinetic equations: $D + S \to D$, $W \to W_{ID}$ (contribution of inverse decays to the washout term). Solution for N_{B-L}:

$$N_{B-L}(z) = N^{\mathrm{i}}_{B-L}\, e^{-\int_{z_{\mathrm{i}}}^{z} dz'\, W_{ID}(z')} - \frac{3}{4}\varepsilon_1\, \kappa(z; \widetilde{m}_1)\;;$$

first term: initial asymmetry, partly reduced by washout, and second term: $B-L$ production from N_1 decays, expressed in terms of the *efficiency factor* κ,

$$\kappa(z) = \frac{4}{3}\int_{z_{\mathrm{i}}}^{z} dz'\, D\left(N_{N_1} - N^{\mathrm{eq}}_{N_1}\right)\, e^{-\int_{z'}^{z} dz''\, W_{ID}(z'')}\;.$$

Note: No generation of baryon asymmetry in thermal equilibrium !!

Limiting cases: the regimes of weak and strong washout, where the decay parameter $K \ll 1$ and $K \gg 1$,

$$K = \frac{\Gamma_D(z=\infty)}{H(z=1)} = \frac{\widetilde{m}_1}{m_*} \, .$$

Insight into the dynamics of the non-equilibrium process in these limiting cases yields analytic description for entire parameter range.

Basic formulae: Decay rate with thermally averaged dilation factor,

$$\Gamma_D(z) = \Gamma_{D1} \left\langle \frac{1}{\gamma} \right\rangle \, , \quad \left\langle \frac{1}{\gamma} \right\rangle = \frac{K_1(z)}{K_2(z)} \, ,$$

depends on the modified Bessel functions K_1 and K_2, and yields the inverse decay rate,

$$\Gamma_{ID}(z) = \Gamma_D(z)\,\frac{N_{N_1}^{\rm eq}(z)}{N_l^{\rm eq}}\;,$$

decay term $D = \Gamma_D/(H z)$ and washout term W_{ID},

$$D(z) = K\,z\,\left\langle\frac{1}{\gamma}\right\rangle\;,\quad W_{ID}(z) = \frac{1}{2}D(z)\,\frac{N_{N_1}^{\rm eq}(z)}{N_l^{\rm eq}}\;.$$

in terms of equilibrium number densities ($g_{N_1} = g_l = 2$),

$$N_{N_1}^{\rm eq}(z) = \frac{3}{8}z^2 K_2(z)\;,\quad N_l^{\rm eq} = \frac{3}{4}\;.$$

(K is only parameter in kinetic equations!)

In the regime *far out of equilibrium, $K \ll 1$*, decays occur at very small temperatures, $z \gg 1$, and the produced $(B-L)$-asymmetry is not reduced by washout effects,

$$\kappa(z) \simeq \frac{4}{3}\left(N^{\rm i}_{N_1} - N_{N_1}(z)\right) \ .$$

The final value of the efficiency factor $\kappa_{\rm f} = \kappa(\infty)$ is proportional to the initial N_1 abundance. If $N_1^{\rm i} = N_1^{\rm eq} = 3/4$, then $\kappa_{\rm f} = 1$; if initial abundance is zero, then $\kappa_{\rm f} = 0$ as well. Hence, the well known problem that one has to invoke some external mechanism to produce the initial abundance of neutrinos. Moreover, an initial (B-L)-asymmetry is not washed out. Thus results strongly depend on initial conditions and there is little predictivity.

To obtain the efficiency factor for *vanishing initial N_1-abundance*, $N_{N_1}(z_{\rm i}) \equiv N^{\rm i}_{N_1} \simeq 0$, one has to calculate how heavy neutrinos are dynamically produced by inverse decays; this requires solving the kinetic equation with the initial condition $N^{\rm i}_{N_1}=0$. Define $z_{\rm eq}$ by the condition

$$N_{N_1}(z_{\rm eq}) = N^{\rm eq}_{N_1}(z_{\rm eq}) \; ,$$

where the number density reaches its maximum. For $z > z_{\rm eq}$ the efficiency factor is the sum of two contributions,

$$\kappa_{\rm f}(z) = \kappa^{-}(z) + \kappa^{+}(z) \; ,$$

for the two integration domains $[z_{\rm i}, z_{\rm eq}]$ and $[z_{\rm eq}, z]$. For *weak washout,* $K \ll 1$, cancellation between κ^{+} and κ^{-}, yields final efficiency factor

$$\kappa_{\rm f}(K) \simeq \frac{9\pi^2}{64} K^2 \; ,$$

which is suppressed w.r.t. the naive expectation $\kappa_{\rm f}(K) \propto K$.

For *strong washout*, $K \gg 1$, one can neglect negative contribution κ^-. Now the neutrino abundance tracks closely the equilibrium behavior,

$$\kappa(z) = \frac{2}{K}\int_{z_{\rm eq}}^{z} dz' \, \frac{1}{z'} W_{ID}(z') \, e^{-\int_{z'}^{z} dz'' \, W_{ID}(z'')} \; .$$

Integral is dominated by contribution around $z_{\rm B}$ where $W_{ID}(z_{\rm B}) \simeq 1$, with $W_{ID}(z) > 1$ for $z < z_{\rm B}$ and $W_{ID}(z) < 1$ for $z > z_{\rm B}$. Hence, the asymmetry produced for $z < z_{\rm B}$ is essentially erased, whereas for $z > z_{\rm B}$, washout is negligible. Explicit calculation yields

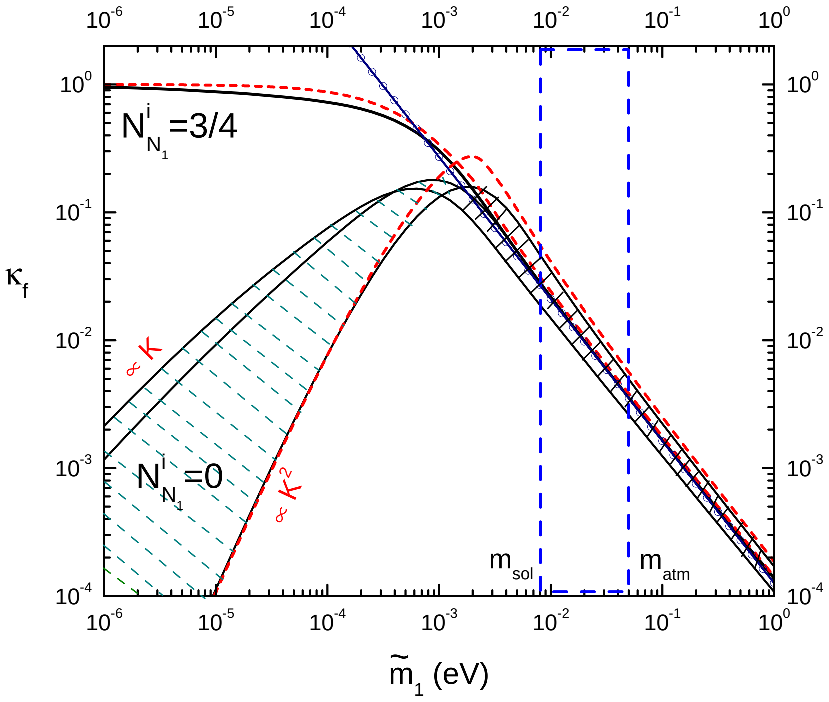
$$z_B(K) \simeq 1 + \frac{1}{2}\ln\left(1 + \frac{\pi K^2}{1024}\left[\ln\left(\frac{3125\pi K^2}{1024}\right)\right]^5\right) \; > \; 1 \; ,$$

and final efficiency factor in terms of $z_B(K)$,

$$\kappa_{\rm f}(K) \simeq \frac{2}{z_{\rm B}(K)K}\left(1 - e^{-\frac{1}{2}z_{\rm B}(K)K}\right) \ .$$

Extrapolation to regime of weak washout, $K \ll 1$, rather accurate, where $\kappa_{\rm f} = 1$ corresponding to thermal initial abundance, $N^{\rm i}_{N_1} = N^{\rm eq}_{N_1} = 3/4$; at $K \simeq 3$ rapid transition from strong to weak washout.

The discussion of decays and inverse decays can be extended to include $\Delta L = 1$ and $\Delta L = 2$ scattering and washout processes. For weak washout, $K \ll 1$, the main effect is the enhancement $\kappa_{\rm f} \propto K$. Relevant effects include scattering processes involving gauge bosons and thermal corrections to the decay and scattering rates (Pilaftsis, Underwood '03; Giudice et al. '03) (see hatched region in figure). Additional uncertainty is due to dependence on initial N_1 abundance and possible initial asymmetry created before onset of leptogenesis.



Strong washout regime, $K \gg 1$: efficiency factor not sensitive to initial N_1 production, thermal abundance always reached; $\Delta L = 1$ washout processes small $\longrightarrow$ reliable prediction

Note: $\sqrt{\Delta m^2_{\rm sol}}$ and $\sqrt{\Delta m^2_{\rm atm}}$ in strong washout regime !!

$$\kappa_f = (2 \pm 1) \times 10^{-2} \times \left(\frac{0.01\ \text{eV}}{\widetilde{m}_1}\right)^{1.1\pm0.1}$$

(4) Bounds on Neutrino Masses

Scattering, decay and washout rates depend only on three neutrino masses,

$$D,\ S,\ W - \Delta W \ \propto \ \frac{M_{\rm Pl}\widetilde{m}_1}{v^2}\,, \quad \Delta W \ \propto \ \frac{M_{\rm Pl} M_1\, \overline{m}^2}{v^4}\,,$$

with $\widetilde{m}_1$ the effective neutrino mass, and $\overline{m}$ the quadratic mean,

$$\overline{m}^2 = {\rm tr}\left(m_\nu^\dagger m_\nu\right) = m_1^2 + m_2^2 + m_3^2\,.$$

For quasi-degenerate neutrinos, with increasing $\overline{m}$, the washout rate ΔW becomes important and eventually prevents leptogenesis ($\omega \simeq 0.19$),

$$\kappa_f \simeq \kappa_f(\widetilde{m}_1)\,\exp\left[-\frac{\omega}{z_B}\left(\frac{M_1}{10^{10}{\rm GeV}}\right)\left(\frac{\overline{m}}{\rm eV}\right)^2\right]\,.$$

Upper bound on CP asymmetry ε_1 (Hamaguchi et al. '02; Davidson, Ibarra '02),

$$\varepsilon_1 \leq \varepsilon_1^{\max}(M_1, \widetilde{m}_1, \overline{m}) = \frac{3}{16\pi}\frac{M_1}{v^2}(m_3 - m_1)(1 + \ldots)\ ,$$

implies a maximal baryon asymmetry,

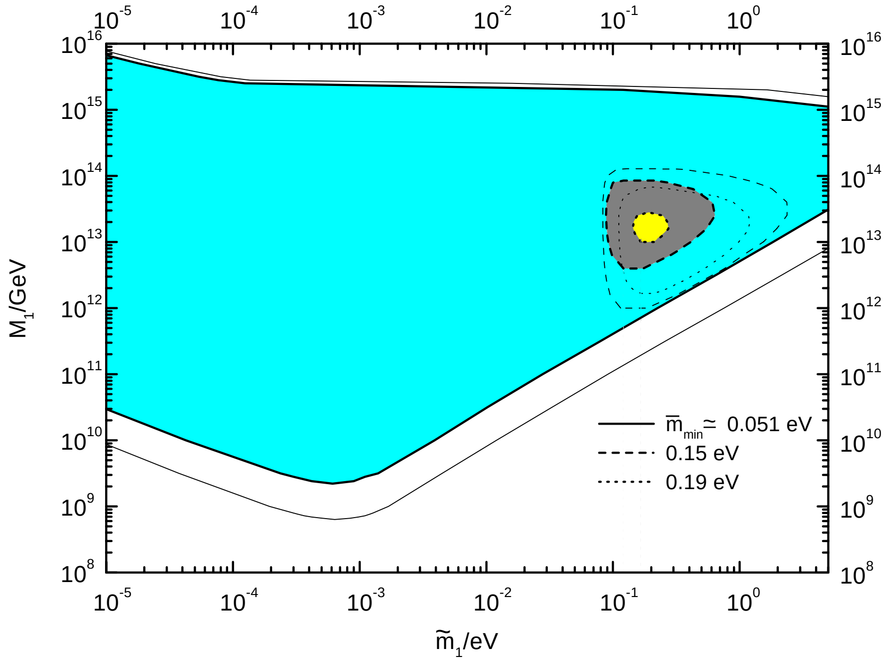
$$\eta_B \leq \eta_B^{\max}(\widetilde{m}_1, M_1, \overline{m}) \simeq 0.01 \varepsilon_1^{\max}(\widetilde{m}_1, M_1, \overline{m}) \kappa(\widetilde{m}_1, M_1, \overline{m})\ .$$

Requiring the maximal asymmetry to be larger than the observed one,

$$\eta_B^{\max}(\widetilde{m}_1, M_1, \overline{m}) \geq \eta_B^{CMB}\ ,$$

yields a constraint on the neutrino mass parameters $\widetilde{m}_1$, M_1 and $\overline{m}$; lower bound on heavy neutrino mass: $M_1 > 4 \times 10^8\ (2 \times 10^9)\ \mathrm{GeV}$.

Upper bound on neutrino masses from leptogenesis



neutrino masses:

$$m_3^2 = \frac{1}{3}\left(\overline{m}^2 + 2\Delta m_{atm}^2 + \Delta m_{sol}^2\right),$$

$$m_2^2 = \frac{1}{3}\left(\overline{m}^2 - \Delta m_{atm}^2 + \Delta m_{sol}^2\right),$$

$$m_1^2 = \frac{1}{3}\left(\overline{m}^2 - \Delta m_{atm}^2 - 2\Delta m_{sol}^2\right).$$

bound $\overline{m} < 0.20$ eV yields $m_i < 0.12$ eV (0.15 eV, Giudice et at. '03); will be tested by laboratory experiments, Katrin, Gerda,..., and by cosmology, LSS, WMAP.

Dependence on initial conditions is of crucial importance for baryogenesis in general. Boltzmann equation for washout of large initial asymmetry ($\varepsilon_1 = 0$),

$$\frac{dN_{B-L}}{dz} = -W\, N_{B-L}\ ;$$

corresponding $B-L$ asymmetry,

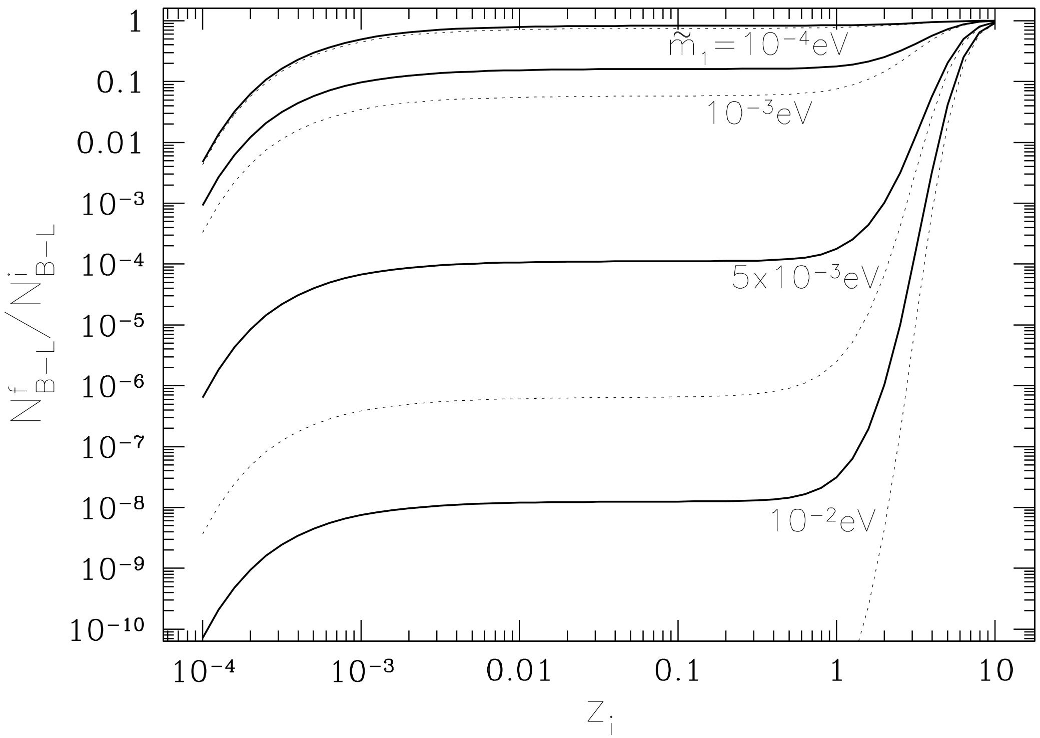
$$N^{\rm f}_{B-L} = \omega(z_{\rm i}) N^{\rm i}_{B-L}\ , \qquad \omega(z_{\rm i}) = e^{-\int_{z_{\rm i}}^{\infty} dz\, W(z)}\ ;$$

washout becomes very efficient for $\widetilde{m}_1 > m_* \simeq 10^{-3}$ eV.

Conclusion: leptogenesis is successful for neutrino masses in the range

$$10^{-3}\ \text{eV} \leq m_i \leq 0.1\ \text{eV}\ .$$

Washout of large initial $B-L$ asymmetry



Washout of an initial asymmetry at $z_i \sim 1$, i.e. $T_i \sim M_1$, becomes efficient for $\widetilde{m}_1 \geq m_* \sim 10^{-3}$ eV; the efficiency increases exponentially with $\widetilde{m}_1$.

Washout factors as function of $z_i = M_1/T_i$ without (full line) and with (dashed line) N_1-top scatterings; $M_1 = 10^{10}$ GeV.

Current research on thermal leptogenesis:

Important recent development: dependence on lepton flavour in strong washout regime Abada et al. hep-ph/0601083, hep-ph/0605281; Nardi, Nir, Roulet, Racker, hep-ph/0601084; Blanchet, Di Bari, hep-ph/0607330; can upper bound on light neutrino masses be circumvented by special flavour structures ?!

In general, neutrino mass matrix has contribution from $SU(2)$ triplet fields (Lazarides, Shafi, Wetterich; Mohapatra, Senjanović), in addition to the seesaw term of $SU(2)$ singlet heavy Majorana neutrinos,

$$m_\nu = -m_D^T \frac{1}{M} m_D + m_\nu^{\text{triplet}} \ .$$

So far, the minimal case, $m_\nu^{\text{triplet}} = 0$, has been assumed; 'natural' in GUTs, but not necessarily true! A dominant triplet contribution destroys the connection between leptogenesis and low energy neutrino physics.

Discovery of quasi-degenerate neutrino masses would require significant modifications of 'minimal' leptogenesis and/or seesaw mechanism. Higgs triplet contribution to neutrino masses is possible way out (Hambye, Senjanovic; Rodejohann; P. Gu, X.-J. Bi; Strumia et al.; D'Ambrosio et al.,...); no upper bound on light neutrino mass scale, bound on heavy neutrino mass scale relaxed, e.g. $m_i \sim 0.35\ \mathrm{eV}\ ,\ M_1 > 4 \times 10^8\ \mathrm{GeV}$ (Antusch, King).

More dramatic solution: 'resonant leptogenesis', maximal enhancement of CP asymmetry through degeneracy of heavy neutrinos, $(M_2 - M_1)/M_1 \sim 10^{-10}$ (Pilaftsis, Underwood; Hambye;...); then low scale leptogenesis possible, e.g.,

$$m_3 \sim 0.1\ \mathrm{eV}\ , \quad M_1 \sim 1\ \mathrm{TeV}\ ,$$

with observable consequences at colliders; near degeneracy via approximate flavour symmetry (West). Interesting realizations in supersymmetric models (Giudice et al.; Grossman et al.; Hambye et al.; Boubekeur et al.; Allahverdi, Drees;...)

(4) Nonthermal Leptogenesis

Thermal leptogenesis requires a large reheating temperature in the early universe, $T_R \sim M_1 > 10^9$ GeV. Potential problem for supersymmetry, which is of central importance for extensions of the standard model (gravitino problem: overproduction of gravitinos at T_R; causes problems with BBN (unstable gravitino) or overclosure of universe (stable gravitino)).

Possible way out: nonthermal production of heavy Majorana neutrinos, where one does not have a strong constraint on the reheating temperature $\rightarrow$ extensive literature. Two interesting examples, with many variations until today: Nonthermal leptogenesis via inflaton decay (Lazarides, Shafi '91) (yields lower bound on heaviest light neutrino, $m_3 > 0.01 \ldots 0.1\mathrm{eV}$), and AD leptogenesis (Affleck, Dine '85) (yields upper bound on lightest light neutrino, $m_1 < 10^{-9}\mathrm{eV}$).

Nonthermal Leptogenesis via Inflaton Decay (see Asaka et al. '00)

Inflation is attractive hypothesis in modern cosmology, because it solves the horizon and flatness problems, and also accounts for the origin of density fluctuations. Hypothesis: Inflaton Φ decays dominantly into a pair of the lightest heavy Majorana neutrinos, $\Phi \to N_1 + N_1$. Assume, for simplicity, that other decay modes including those into pairs of N_2 and N_3 are energetically forbidden. The N_1 neutrinos decay subsequently into $H + \ell_L$ or $H^\dagger + \ell_L^\dagger$. For reheating temperatures T_R lower than the mass M_1 of N_1, the out-of-equilibrium condition is automatically satisfied.

The two channels for N_1 decay have different branching ratios when CP conservation is violated. Interference between tree-level and one-loop diagrams generates lepton-number asymmetry as usual, with lepton asymmetry parameter ε and effective CP-violating phase $\delta_{\rm eff}$,

$$\varepsilon = -\frac{3}{8\pi}\frac{M_1}{\langle H\rangle^2}m_3\delta_{\rm eff}\ , \quad \delta_{\rm eff} = \frac{\mathrm{Im}\left[h_{13}^2 + \frac{m_2}{m_3}h_{12}^2 + \frac{m_1}{m_3}h_{11}^2\right]}{|h_{13}|^2 + |h_{12}|^2 + |h_{11}|^2}\ ,$$

which yields numerically,

$$\varepsilon \simeq -2\times 10^{-6}\left(\frac{M_1}{10^{10}\mathrm{GeV}}\right)\left(\frac{m_3}{0.05\mathrm{eV}}\right)\delta_{\rm eff}\ .$$

Chain decays $\Phi \to N_1 + N_1$, $N_1 \to H + \ell_L$ or $H^\dagger + \ell_L^\dagger$ reheat the universe producing also entropy for the thermal bath. Ratio of lepton number to entropy density after reheating (inflaton mass m_Φ, $\delta_{\rm eff} = 1$),

$$\frac{n_L}{s} \simeq -\frac{3}{2}\varepsilon\frac{T_R}{m_\Phi} \simeq 3\times 10^{-10}\left(\frac{T_R}{10^6\mathrm{GeV}}\right)\left(\frac{M_1}{m_\Phi}\right)\left(\frac{m_3}{0.05\mathrm{eV}}\right)\ .$$

Baryon-number asymmetry is generated through sphaleron effects,

$$\frac{n_B}{s} \simeq -\frac{8}{23}\frac{n_L}{s} \, .$$

Important merit of inflaton-decay scenario: no lower bound on reheating temperature $T_R \sim M_1$, only requirement $m_\Phi > 2M_1$.

For reheating temperatures $T_R < 10^7 \; (10^6) \; \mathrm{GeV}$, which satisfy the cosmological constraint on the gravitino abundance, and using $m_\Phi > 2M_1$, observed baryon number to entropy ratio gives a constraint on the heaviest light neutrino:

$$m_3 > 0.01 \; (0.1) \; \mathrm{eV} \; ,$$

consistent with atmospheric neutrino mass $\sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.05$ eV. (Recall: branching ratio 100 $\%$ into a pair of N_1s assumed!)

Affleck-Dine Leptogenesis

(see Asaka et al. '00)

In the SUSY Standard Model, for unbroken supersymmetry, some combinations of scalar fields do not enter the potential, constituting so-called flat directions. Since the potential is (almost) independent of these fields, they may have large initial values in the early universe. Such flat directions receive soft masses in the SUSY-breaking vacuum. When the expansion rate $H_{\rm exp}$ of the universe becomes comparable to their masses, the flat directions begin to oscillate around the minimum of the potential. If the flat directions carry baryon or lepton number, this can lead to (AD) baryogenesis.

(Most) interesting candidate for a flat direction is

$$\phi_i = (2H\ell_i)^{1/2},$$

where ℓ_i is lepton doublet field of the i-th family; H and ℓ_i are scalar components of chiral multiplets. Because this flat direction carries lepton number, a lepton asymmetry can be created during the coherent oscillation (AD leptogenesis). Sphaleron processes then transmute this lepton asymmetry into a baryon asymmetry.

The seesaw mechanism induces dimension-five operator in the superpotential,

$$W = \frac{m_\nu}{2|\langle H \rangle|^2}(\ell H)^2 \, .$$

(basis in which neutrino mass matrix is diagonal; drop subscript i.) This superpotential leads to scalar potential for flat direction ϕ,

$$V_{\rm SUSY} = \frac{m_\nu^2}{4|\langle H \rangle|^4}|\phi|^6 \, .$$

In addition, there is a SUSY-breaking potential,

$$\delta V = m_\phi^2|\phi|^2 + \frac{m_{\rm SUSY} m_\nu}{8|\langle H\rangle|^2}(a_m \phi^4 + {\rm h.c.}) ,$$

where a_m is complex; typical values: $m_\phi \simeq m_{\rm SUSY} \simeq 1$ TeV, $|a_m| \sim 1$. Complex a_m can lead to lepton-number generation.

Hypothesis: flat direction ϕ acquires negative $({\rm mass})^2$ during inflationary phase and rolls down to the point balanced by the potential $V_{\rm SUSY}$. Thus, the AD field ϕ has initial value $\sqrt{H_{\rm inf}|\langle H\rangle|^2/m_\nu}$, where $H_{\rm inf}$ is the Hubble parameter during inflation. ϕ decreases in amplitude gradually after inflation, and begins to oscillate around the potential minimum when the Hubble parameter $H_{\rm exp}$ becomes comparable to SUSY-breaking mass m_ϕ. At the beginning of oscillation, AD field has value $|\phi_0| \simeq \sqrt{m_\phi|\langle H\rangle|^2/m_\nu}$ which becomes an effective initial value for leptogenesis.

The time evolution of the AD field ϕ is given by

$$\frac{\partial^2\phi}{\partial t^2} + 3H_{\rm exp}\frac{\partial\phi}{\partial t} + \frac{\partial V}{\partial\phi^*} = 0 \ ,$$

where $V = V_{\rm SUSY} + \delta V$. With the lepton number

$$n_{\rm L} = i\left(\frac{\partial\phi^*}{\partial t}\phi - \phi^*\frac{\partial\phi}{\partial t}\right) \ ,$$

the evolution of $n_{\rm L}$ is

$$\frac{\partial n_{\rm L}}{\partial t} + 3H_{\rm exp}n_{\rm L} = \frac{m_{\rm SUSY}m_\nu}{2|\langle H\rangle|^2}{\rm Im}(a_m^*\phi^{*4}) \ .$$

The motion of ϕ in the phase direction generates lepton number, predominantly during time $t_{\rm osc} \simeq 1/H_{\rm osc} \simeq 1/m_\phi$ after beginning of oscillation,

$$n_{\rm L} \simeq \frac{m_{\rm SUSY} m_\nu}{2|\langle H \rangle|^2} \delta_{\rm eff} |a_m \phi_0^4| \times t_{\rm osc} \; ,$$

with $\delta_{\rm eff} = \sin(4{\rm arg}\phi + {\rm arg}a_m)$ as effective CP-violating phase. After entropy production, final result for baryon-number asymmetry,

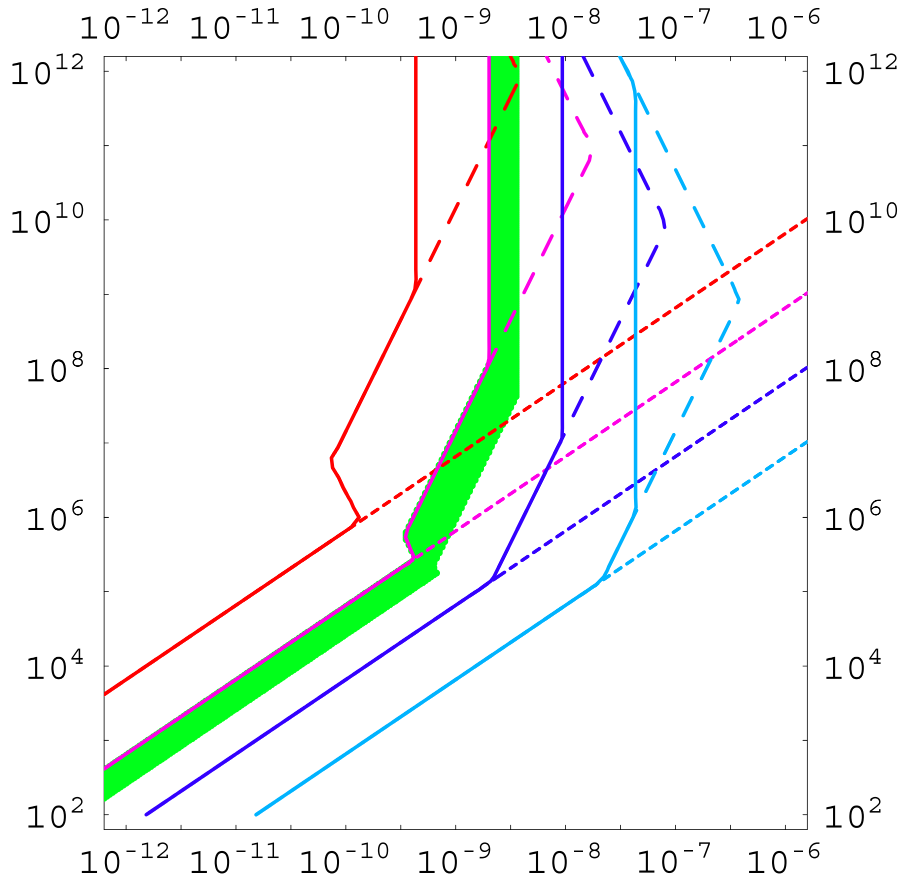
$$\frac{n_{\rm B}}{s} \simeq \frac{1}{23} \frac{|\langle H \rangle|^2 T_R}{m_\nu M_G^2} \; .$$

The observed ratio $n_{\rm B}/s \simeq 0.9 \times 10^{-10}$ implies

$$m_\nu < 10^{-9} \; {\rm eV}$$

for $T_R < 10^6$ GeV, i.e., upper bound on the mass of the lightest neutrino.

Upper bound on lightest neutrino mass in AD leptogenesis



Contour plot for baryon asymmetry $Y_B = n_B/s$ in the m_1 [eV] (horizontal) - T_R [GeV] plane. The full lines correspond to $Y_B = 10^{-9}, 10^{-10}, 10^{-11}, 10^{-12}$ from left to right. (Asaka et al. '00).

(6) Comments on Gravitino Dark Matter

Large baryogenesis temperature, $T_B > 10^9$ GeV, potentially in conflict with thermal production of gravitinos, due to BBN constraints (Weinberg '82; Khlopov, Linde; Ellis, Kim, Nanopoulos; '84).

Possible solution: gravitino lightest superparticle (LSP), main constituent of cold dark matter, $m_{3/2} \sim 10 \ldots 100$ GeV, thermal production after inflation; implies upper bound on gluino mass, $m_{\tilde{g}} < 2$ TeV (Bolz et al., Fujii et al., WB, Hamaguchi, Ratz; Ellis et al., Roszkowski et al., Kawasaki et al.;...). Gravitino dark matter could also be produced in NSP (WIMP) decays (Feng, Rajaraman, Takayama;...).

Alternatively, unstable gravitino can be very heavy, $m_{3/2} \sim 100$ TeV, as in anomaly mediation; then superparticle spectrum strongly restricted (Luty, Sundrum; Ibe, Kitano, Murayama, Yanagida). In any case, close connection between leptogenesis and superparticle mass spectrum.

SUMMARY

Theoretical developments over almost two decades concerning electroweak phase transition and sphaleron processes have established connection between baryon and lepton number in high-temperature phase of the SM.

Decays of heavy Majorana neutrinos (N_1) at temperatures $T \sim 10^{10}$ GeV ($t \sim 10^{-26} s$) provide natural explanation of origin of matter; leptogenesis is successful for neutrino mass window $10^{-3}\ \mathrm{eV} < m_i < 0.1\ \mathrm{eV}$, consistent with neutrino oscillations.

Discovery of quasi-degenerate neutrinos would require major modifications of 'minimal' leptogenesis and/or seesaw mechanism, e.g. contributions from Higgs triplets, 'resonant leptogenesis' or non-thermal leptogenesis.

Leptogenesis strongly supports gravitino dark matter; discovery of dark matter will also shed light on origin of 'visible' matter.