BARYON ASYMMETRY AND THERMAL LEPTOGENESIS*

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Important topics not covered in this talk

During the past two years there has been a boom for leptogenesis, the main topic of this talk, partly because of new results in neutrino physics; huge amount of very interesting work has been done; important topics which cannot be discussed in this talk, include:

- leptogenesis and models of neutrino masses, realizations of the seesaw mechanism in GUT models (→ Feruglio; Petcov; Binétruy, seesaw conference)
- leptogenesis and lepton flavour changing processes, electric dipole moments (→ Savoy; Binétruy, seesaw conference)
- non-thermal leptogenesis and baryogenesis models, e.g., Affleck-Dine type, connection to inflation, ... (→ review Hamaguchi; Binétruy, seesaw conference)

OUTLINE

(1) Elements of Baryogenesis

(2) Thermal Leptogenesis and Neutrino Masses

(3) Alternative Leptogenesis Scenarios

(4) Implications for Dark Matter

(1) Elements of Baryogenesis

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 $T_{BBN} \sim 1$ 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).

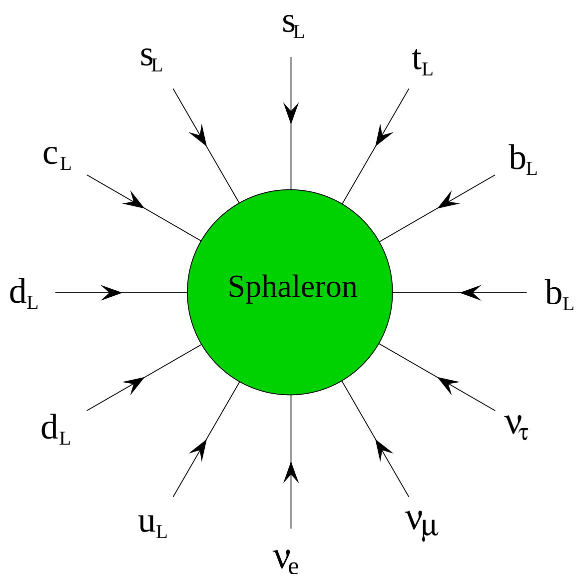
Theory of baryogenesis depends crucially on nonperturbative properties of standard model,

- 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, only $B - L$ conserved; detailed analytical and numerical studies have led to consistent picture for high-temperature phase; $B - L$ violating processes in thermal equilibrium for $T > T_{EW}$.

Baryon and lepton number violating sphaleron processes

't Hooft '76; Klinkhammer, Manton '84, Kuzmin, Rubakov, Shaposhnikov '85



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

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

$B - L$ 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.

Seesaw mechanism and leptogenesis (Fukugita, Yanagida, '86)

explains smallness of the light neutrino masses by largeness of the heavy Majorana masses; predicts six Majorana neutrinos as mass eigenstates,

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

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

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

neutrino mass m_3 is compatible with $(\Delta m^2_{sol})^{1/2} \sim 0.008$ eV and $(\Delta m^2_{atm})^{1/2} \sim 0.05$ eV from neutrino oscillations, i.e. GUT scale physics !!

Ideal candidate for baryogenesis: lightest (heavy) Majorana neutrino, N_1; 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 $\langle B\rangle_T \neq 0$ (much work by many groups since about 1996; expectation $m_i < 1$ eV before experimental results on $\Delta m^2_{\rm atm}$; afterwards leptogenesis boom).

The generated baryon asymmetry is proportional to the CP asymmetry in N_1-decays (simplest case $m_D = h\langle\phi\rangle$, seesaw mass relation),

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

Rough estimate for ε_1 in terms of neutrino masses (example; 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,

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = -d\ \varepsilon_1\ \kappa_f \sim 10^{-9}\ ,$$

with $d \sim 0.01$ dilution factor which accounts for the increase of the number of photons in a comoving volume element between baryogenesis and today; determination of efficiency factor κ_f requires solution of Boltzmann equations (estimate, $\kappa_f \sim 0.1$).

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 important 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 d and κ_f. 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.

(2) Thermal Leptogenesis and Neutrino Masses

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, $g_* = 434/4$),

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

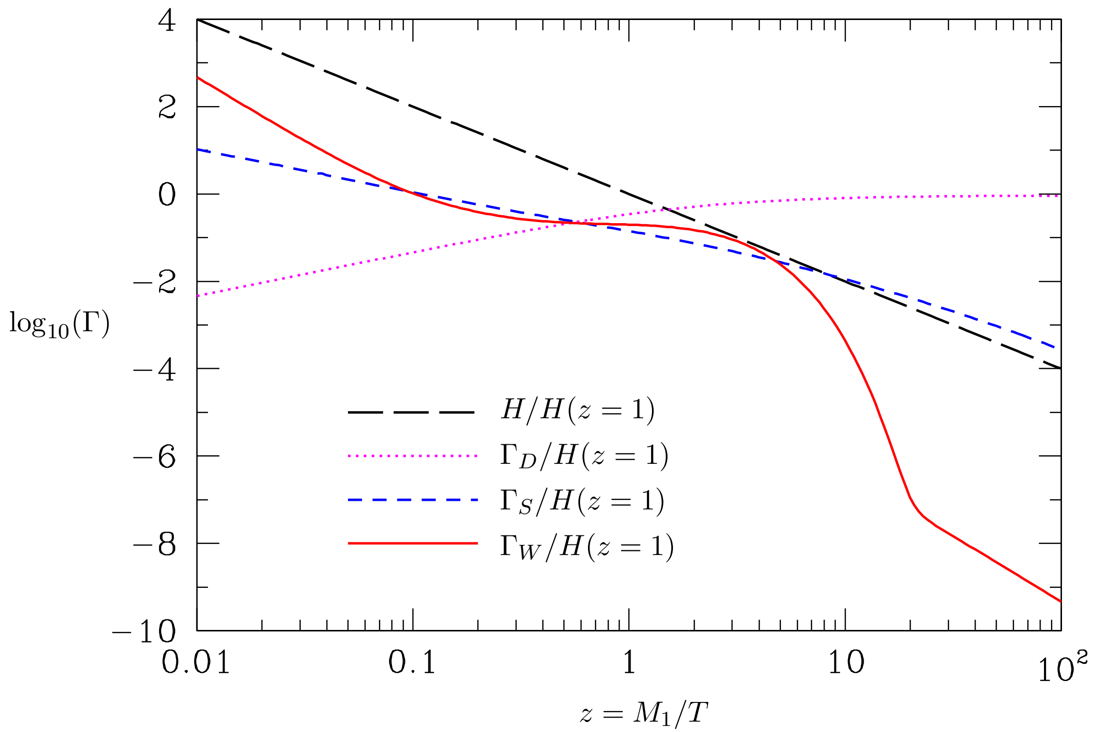
Note: equilibrium neutrino mass m_* close to neutrino masses $\sqrt{\Delta m^2_{\rm sol}} \simeq 8 \times 10^{-3}$ eV and $\sqrt{\Delta m^2_{\rm atm}} \simeq 5 \times 10^{-2}$ eV; hope: baryogenesis via leptogenesis process close to thermal equilibrium ?!

Boltzmann equations for leptogenesis, competition between production and washout,

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

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

Reaction 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 temperature range for baryogenesis: $z = M_1/T = 1 \ldots 8$.

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

Dependence on neutrino parameters: scattering, decay and washout rates depend only on three neutrino masses,

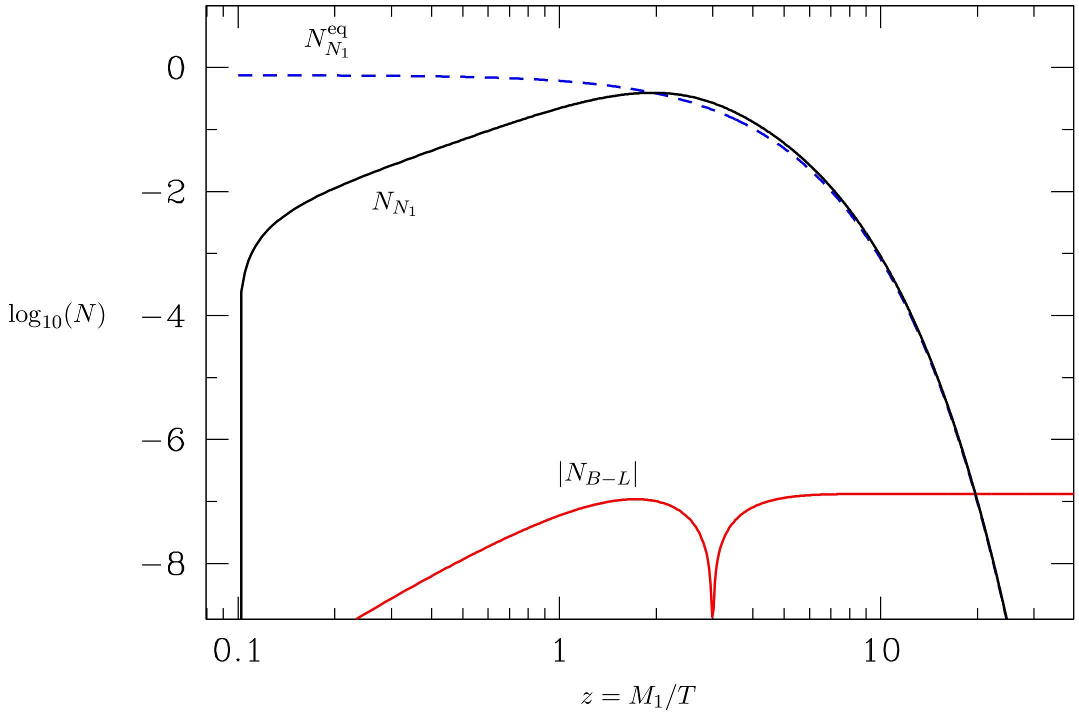
$$D,\ S,\ W-\Delta W\ \propto\ \frac{M_{\rm Pl}\widetilde{m}_1}{v^2}\ ,\quad \Delta W\ \propto\ \frac{M_{\rm Pl}M_1\,\overline{m}^2}{v^4}\ ,$$

with $\widetilde{m}_1$ the effective neutrino mass, and $\overline{m}$ the absolute neutrino mass scale,

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

For quasi-degenerate neutrinos, with increasing $\overline{m}$, the washout rate ΔW becomes important and eventually prevents successful leptogenesis. For typical neutrino parameters the resulting asymmetry is in accord with observation, $\eta_B\sim 0.01\times N_{B-L}\sim 10^{-9}$.

Evolution of number densities and $B - L$ asymmetry



Generation of a $B - L$ asymmetry for zero initial N_1 abundance; Yukawa interactions are strong enough to bring the heavy neutrinos into thermal equilibrium;

generated baryon 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, $|\varepsilon_1| = 10^{-6}$.

Upper bound on CP asymmetry ε_1 (Hamaguchi,Murayama,Yanagida; Davidson, Ibarra;...), $\varepsilon_1 \leq \varepsilon_1^{\max}(M_1, \widetilde{m}_1, \overline{m})$, implies a maximal baryon asymmetry,

$$\eta_B \leq \eta_B^{\max}(\widetilde{m}_1, M_1, \overline{m}) \simeq 0.01\ \varepsilon_1^{\max}(\widetilde{m}_1, M_1, \overline{m})\ \kappa(\widetilde{m}_1, M_1\overline{m}^2)\ .$$

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

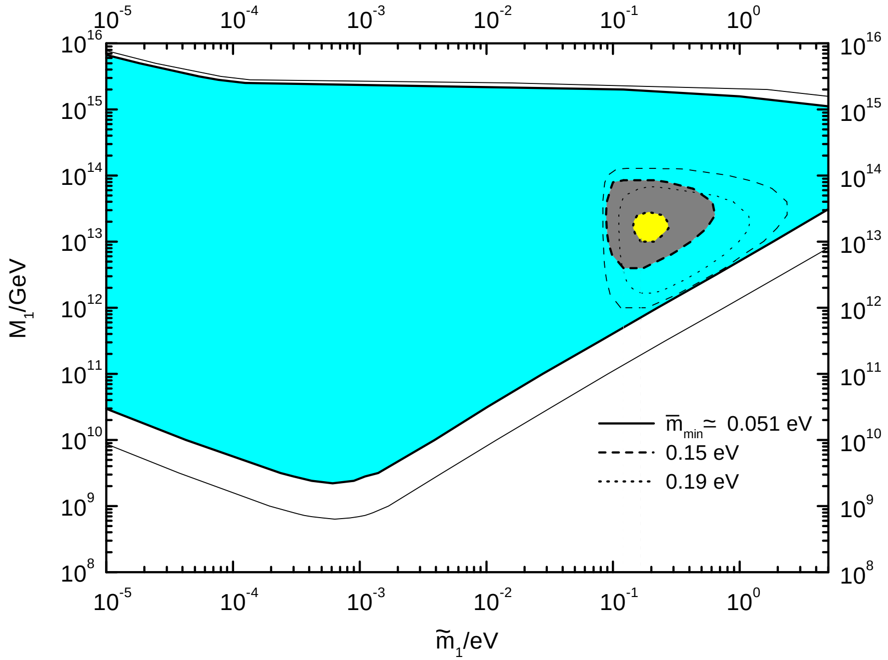
$$\eta_B^{\max}(\widetilde{m}_1, M_1, \overline{m}) \geq \eta_B^{CMB}\ ,$$

yields a constraint on the neutrino mass parameters $\widetilde{m}_1$, M_1 and $\overline{m}$. Detailed analysis leads to upper (lower) bounds on light (heavy) neutrino masses,

$$m_i < 0.12\ \text{eV}\ , \qquad M_1 > 4 \times 10^8\ \text{GeV}\ .$$

Note: these bounds are a factor of two below the recent upper bound of 0.23 eV obtained by WMAP.

Upper bound on neutrino masses from leptogenesis (WB, Di Bari, Plümacher '03)



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; will be tested by forthcoming laboratory experiments, Katrin, Genius, and by cosmology, LSS, WMAP.

Leptogenesis as a problem in statistical mechanics

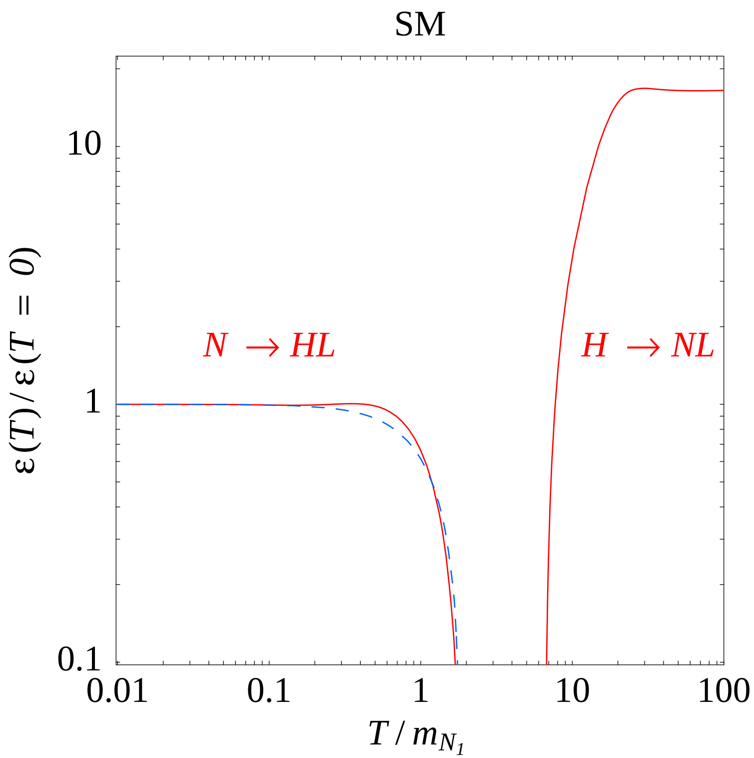
What is the theoretical error of the upper bound on the light neutrino masses? Needed: full quantum mechanical description of non-equilibrium process, a challenging problem! Aspects of a 'theory of leptogenesis':

- quantum mechanical framework, e.g., Kadanoff-Baym equations; present conceptual problem: Boltzmann equations classical, 'collision terms' quantum mechanical;

- wanted: systematic expansion around solution of Boltzmann equations; one expects: relativistic corrections, off-shell effects, 'memory effects', higher order loop corrections etc; much work for the coming years!

- present understanding of high temperature region, $T > M_1$ insufficient; improvement also important for other topics in particle cosmology, like gravitino production, axino production...

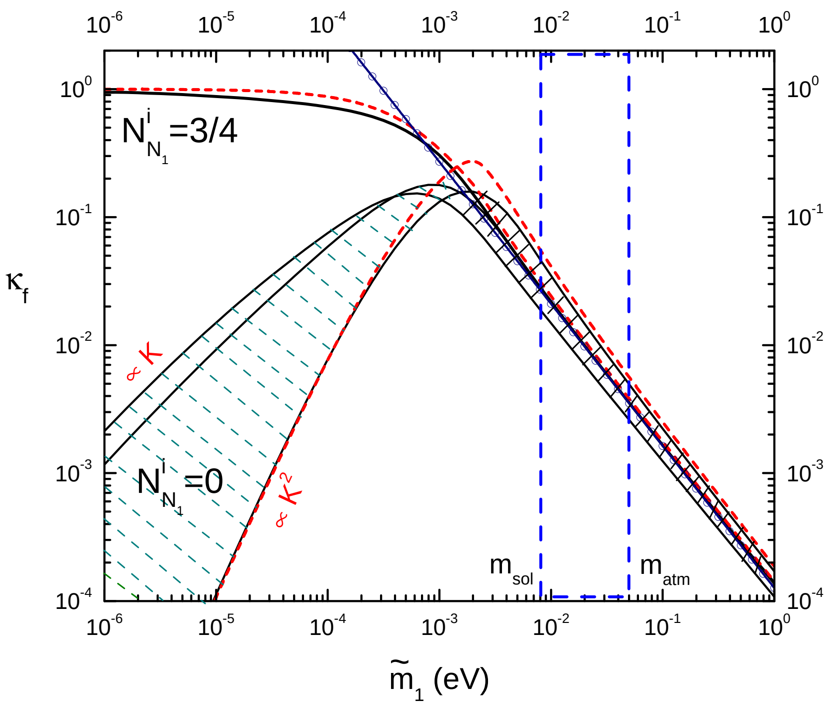
Large thermal corrections (Giudice, Notari, Raidal, Riotto, Strumia '03)



resummation of thermal masses leads to qualitative change of leptogenesis picture at temperatures $T > M_1$, where Higgs decay, $H \to NL$, is dominant.

Detailed analysis, including also models of non-thermal leptogenesis; for SM upper bound on light neutrino masses, $m_i < 0.15$ eV.

Analytical solution of Boltzmann equations (WB, Di Bari, Plümacher '04)



baryon asymmetry:

$\eta_B \simeq 0.01\, \varepsilon_1\, \kappa_f$,

final efficiency factor:

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

estimate of theoretical uncertainties

Detailed study yields, analytically, for SM the bound $m_i < 0.12\ eV$; note that $m_{\rm sol}$ and $m_{\rm atm}$ are in 'safe region' of strong washout, where $\widetilde{m}_1 > m_* \simeq 10^{-3}$ eV.

What have we learnt from leptogenesis about the absolute neutrino mass scales? Successful leptogenesis yields the upper and lower bounds

$$m_i < 0.1 \text{ eV} , \quad M_1 > 2 \times 10^9 \text{ GeV} ,$$

with an error on the light neutrino bound of about 0.03 eV (?) (uncertainty due to 'spectator processes' is ~ -0.02 eV). Ten years ago the masses

$$m_3 \sim 10 \text{ keV} , \quad M_1 \sim 1 \text{ TeV} ,$$

were believed to be compatible with leptogenesis. Without knowledge of $\Delta m^2_{\rm atm}$ one finds $m_i < 250$ eV, $M_1 > 2 \times 10^6$ GeV; hence progress equally shared between experiment and theory. Successful leptogenesis, independent of initial conditions, suggests the neutrino mass window

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

(3) Alternative leptogenesis mechanisms

Discovery of quasi-degenerate neutrino masses would require significant modifications of 'minimal' leptogenesis and/or seesaw mechanism. Possible way out: contributions from Higgs triplets to neutrino masses, theoretically well motivated (Hambye, Senjanovic; Rodejohann; P. Gu, X.-J. Bi; Strumia et al.;...); no bound on light neutrino mass scale, bound on heavy neutrino mass scale relaxed, e.g. $m_i \sim 0.35 \text{ eV}$, $M_1 > 4 \times 10^8 \text{ GeV}$ (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.,

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

Interesting realizations in supersymmetric models (Giudice et al., Grossman et al., Hambye et al., Boubekeur et al.,...)

(4) Implications for Dark Matter

Large baryogenesis temperature, $T_B > 10^9$ GeV, potentially in conflict with thermal production of gravitinos, due to BBN constraints (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, $m_{\widetilde{g}} < 2$ TeV (Bolz et al.; Fujii et al.; WB, Hamaguchi, Ratz;...). 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 et al.). 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 $10^{-3}\ \mathrm{eV} \leq m_i \leq 0.1\ \mathrm{eV}$, 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.