Summer Institute 'New Trends in Particle Physics & Cosmology' – Sheffield, 21^{st} June 2006

Astroparticle physics I I I

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DESY

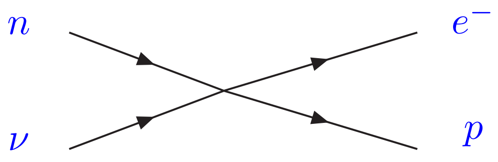
Plan of the Lectures

1. Introduction to Standard Cosmology:
   - GR, particle physics and thermodynamics
   - Present data and open questions
   - A short history of the Early Universe
2. Thermal relics and Dark Matter:
   - The Boltzmann equation in the expanding Universe
   - The number density of a Thermal relic $\longrightarrow$ WIMPs
   - Supersymmetry and the neutralino DM
   - Other SUSY candidates: gravitino & Co
3. The baryon asymmetry:
   - Nucleosynthesis and baryon number of the Universe
   - Sakharov's conditions
   - Sphaleronic transitions and EW baryogenesis
   - Leptogenesis and neutrino masses

Big Bang Nucleosynthesis

After the QCD phase transition at $T \sim 200$ MeV the baryonic matter are $p, n, \pi^0, \pi^\pm, \Lambda, \ldots,$ but at $T \simeq 1$ MeV only the stable one p and the very long-lived n survive. Their number density is not suppressed by $e^{-m/T} \simeq e^{-10^3}$ due to the presence of a chemical potential related to baryon number μ_B. Proton and neutron have the same chemical potential and are still in equilibrium via the reactions

$$n + \nu \leftrightarrow p + e^- \qquad p + \bar{\nu} \leftrightarrow n + e^+$$



$$G_F = \frac{\pi \alpha_w}{\sqrt{2} M_W^2}$$

So the chemical equilibrium gives

$$\frac{n_n^{eq}}{n_p^{eq}} = \exp\left(-\frac{\Delta m + \mu_\nu - \mu_e}{T}\right) \simeq e^{-\frac{\Delta m}{T}} \qquad \text{where} \quad \Delta m \sim 1.29 \text{ MeV}$$

How long do neutrons track equilibrium ??? As long as

$$\langle \sigma(n\nu \to pe) v \rangle \sim \# G_F^2 T^5 \qquad \geq \qquad H = \sqrt{\frac{8\pi G \rho_{rad}}{3}} \sim 1 s^{-1} \left(\frac{T}{1\text{MeV}}\right)^2$$

So freeze-out happens at $T_* \simeq 0.84$ MeV $\qquad \Rightarrow n_n^{eq} \simeq 0.21\, n_p^{eq}$.

Abundances of light elements

After freeze-out the neutrons start to decay with $\tau = 886$ s, i.e. $n_n(t) = n_n(t_*)e^{-t/\tau}$. The lightest composite nucleus is Deuterium, that can be produced in the reaction $p + n \leftrightarrow D + \gamma$

Unfortunately the bounding energy for D is very low $B_D \sim 2.23$ MeV and the number of photons in the Universe above such energy still very large: very easy to dissociate Deuterium !

$$\frac{n_D^{eq}}{n_\gamma} \sim \eta_B X_D \left(\frac{T}{B_D}\right)^2 e^{B_D/T}$$

”Deuterium Bottleneck”

where $\eta_B = n_B/n_\gamma$. So D’s abundance start to grow only after $T \leq 0.06$ MeV, i.e. $t \geq 300$ s.

The equilibrium densities of the other light elements are not reached until after this time, since they are all produced starting from D:

$$D + D \leftrightarrow {}^3He + n \qquad {}^3He + D \leftrightarrow {}^4He + p$$

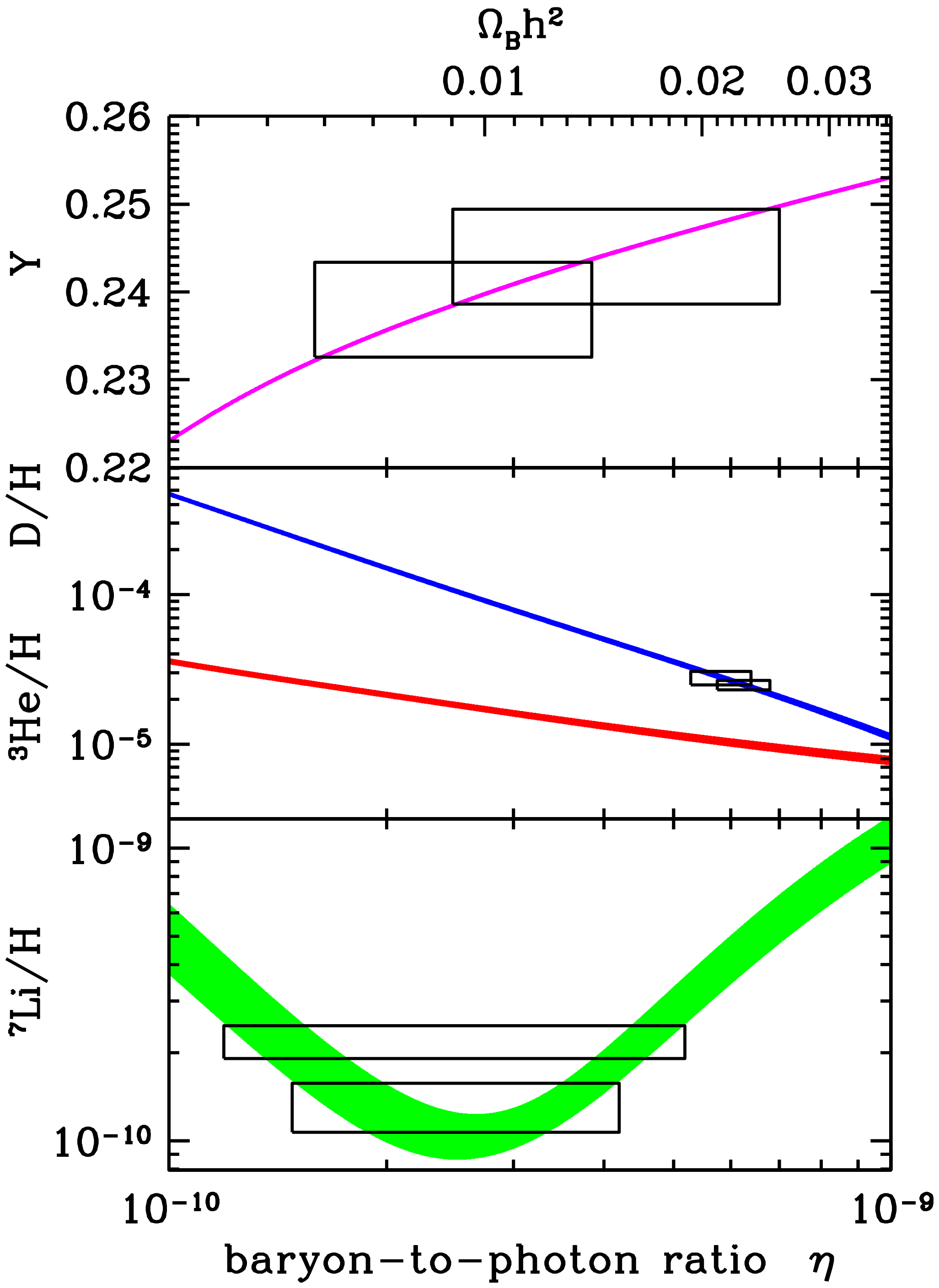
$$D + D \leftrightarrow {}^3H + p \qquad {}^3H + D \leftrightarrow {}^4He + n$$

$$D + D \leftrightarrow {}^4He + \gamma$$

Most of the neutrons end up in ${}^4He$ that is the more strongly bound nucleus, but there remains also a small fraction of Deuterium and ${}^3He$ and some ${}^7Li$ formed from Helium.

BIG BANG NUCLEOSYNTHESIS

[Cyburt '04]

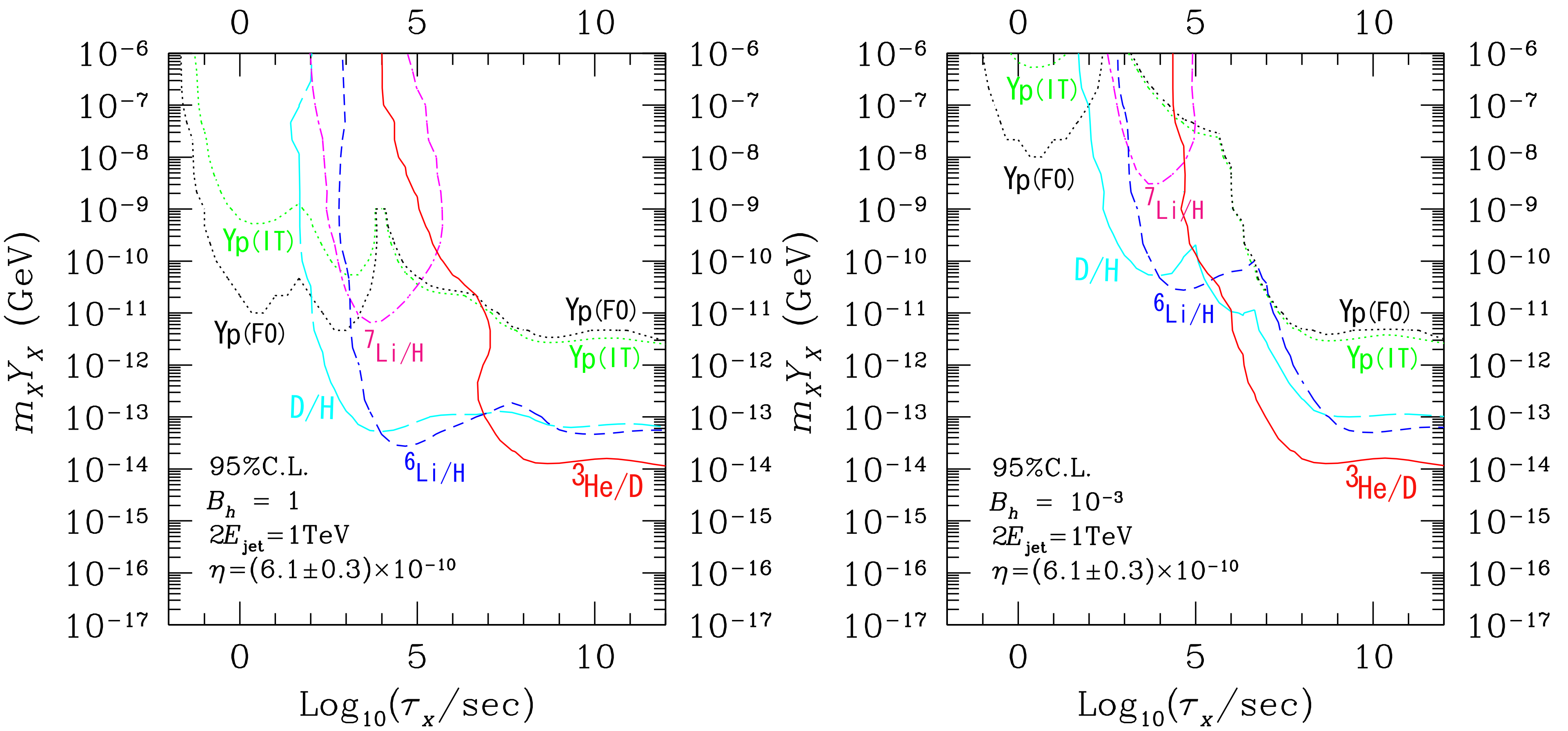


Nucleosynthesis as a probe

The predictions of BBN are very sensitive to changes in the overall picture:

- presence of additional relativistic species: this modifies the expansion rate $H(T)$ and therefore the freeze-out. For example an additional neutrino would make the neutron freeze-out earlier with a larger number density $\longrightarrow$ more ${}^4He$!
- leptonic chemical potential and number density: if the asymmetry in leptons is much larger than the baryonic one, the chemical potential associated to lepton number could be large and affect the rate of interconversion $p \leftrightarrow n \longrightarrow$ change again ${}^4He$!
- the baryonic abundance η_B affects strongly the Deuterium density: the larger η the earlier the burning of D into heavier elements starts and less D remains
- release of energetic particles: they can have different effects depending if they are hadronic or electromagnetic, e.g. change the interconversion $p \leftrightarrow n$, hadro/photodissociate light nuclei after they are formed, etc... Very complex analysis...

BBN bounds on a decaying particle from [Kohri, Kawasaki & Moroi '04]



Strong bounds for the NLSP into gravitino decay scenario, very weak for the axino case, due to the shorter lifetime.

Baryogenesis

So both from BBN and from CMB measurements we obtain $\Omega_B \simeq 0.05$. Is it possible to explain such a number in a symmetric Universe ? Not really: from thermal decoupling 'a la WIMP' we would expect a freeze-out value $\Omega_B \simeq 10^{-10}$ instead... Either need a chemical potential μ_B or a mechanism to separate sufficiently matter and antimatter to avoid annihilation.

Suppose we live in a matter patch in an otherwise symmetric Universe, how large is such a patch ???

We have no evidence of a boundary, that would give either energetic γ's from π^0 decay and deform the γ rays background, or some antinuclei. We observe antiprotons in cosmic rays, but they are consistent by being produced in spallation processes.

Conclusion: our matter patch is at least as large as the observable Universe ! No causal mechanism can separate particles on scales larger than the horizon so the Universe must be asymmetric !

Sakharov's conditions

Sakharov studied already in 1967 the question of how it is possible to generate a baryon number from an initial symmetric phase ! He found that 3 conditions have to be satisfied:

- B violation: actually need $B-L$ violation since $B+L$ is violated in the SM by the chiral anomaly

$$\partial_\mu J^\mu_{B+L} = 2n_f \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

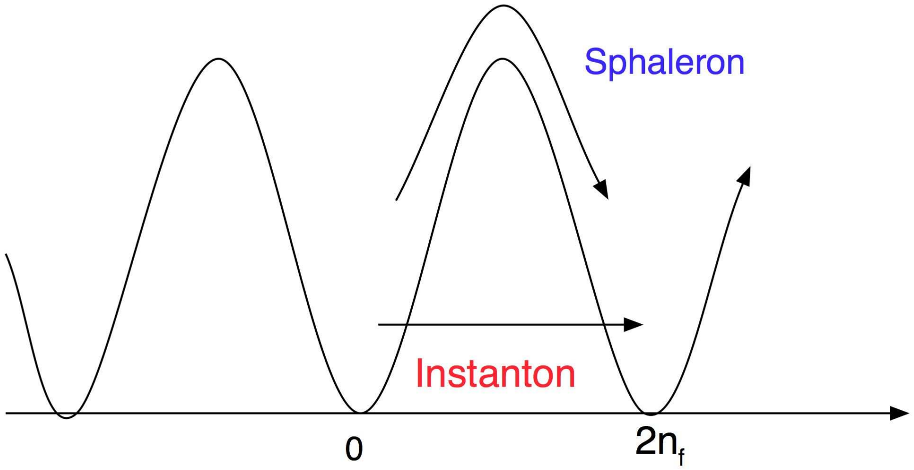
- C and CP violation: otherwise b and $\bar{b}$ would be annihilated/created with the same rate;
- violation of thermal equilibrium: otherwise the maximal entropy state is with $\mu_B = 0$ or

$$\begin{aligned} \langle B\rangle_T &= \mathrm{Tr}(Be^{-\beta H}) = \mathrm{Tr}(CPT(CPT)^{-1}Be^{-\beta H}) \\ &= \mathrm{Tr}((CPT)^{-1}B\,CPT\,e^{-\beta H}) = -\mathrm{Tr}(Be^{-\beta H}) = -\langle B\rangle_T \end{aligned}$$

since $[CPT, H] = 0$, no B generated without a ”time arrow”.

$B+L$ violation in the Standard Model

In the SM the global $U(1)_{B+L}$ is anomalous. This is related to the complex vacuum structure of the theory, which contains vacua with different configurations of the gauge fields and different topological number. Non-perturbative transitions between the vacua change $B+L$ by $2n_f$.



– $T=0$: tunneling and is suppressed by $e^{-\frac{4\pi}{\alpha_W}} \ll 1$

$\rightarrow B$ & L practically conserved!

– $T>0$: the transition can happen via a sphaleron

with rate $\Gamma_{sph}(T) \sim \left(\frac{M_W}{\alpha_W T}\right)^3 M_W^4 e^{-E_{sph}/T}$

So at temperatures $T \leq 100$ GeV sphaleronic transitions are in equilibrium in the Universe $\longrightarrow B+L$ erased if $B-L=0$, otherwise

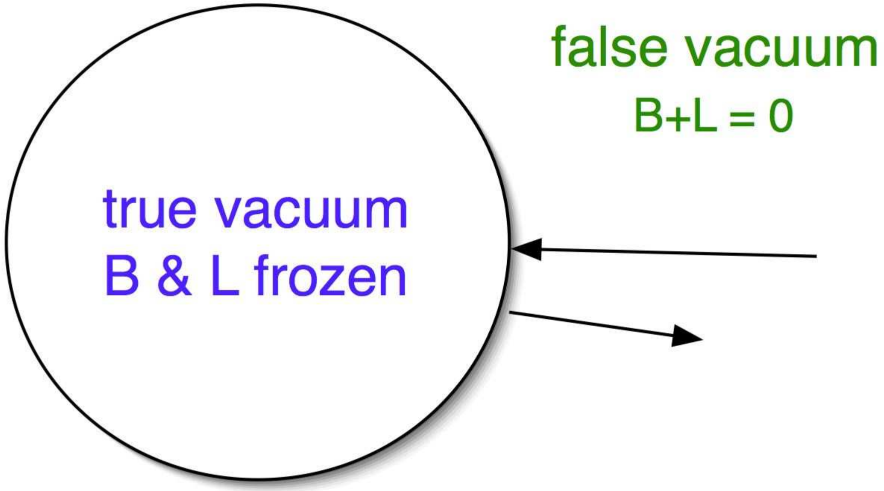
$$B = \frac{8n_f + 4n_H}{22n_f + 13n_H}(B-L)$$

A $B-L$ number is reprocessed into B number !

Is it possible to have baryogenesis in the SM ???

We have B violation via sphalerons, C and CP are present due to the phase in the CKM matrix, what about departure from thermal equilibrium ??? This also happens in the SM if the electroweak phase transition is strongly 1^{st} order. $\longrightarrow$ Bubble nucleation !

Electroweak baryogenesis



The strength of the transition depends on the height of the barrier between the true and false vacua v/T_c and so on the Higgs mass. Lattice studies have shown that the phase transition in the SM is first order only for masses $m_H \leq 40$ GeV, while now we know that $m_H \geq 114$ GeV: the mechanism does not work in the Standard Model !!! Still it could in the MSSM and extended model:

- stronger phase transition: 1^{st} order until $m_H \sim 120$ GeV for one light stop;
- more CP violating phases, while in SM $J \sim 10^{-20}$ perhaps too small.

Baryogenesis via leptogenesis

[Fukugita & Yanagida '86]

Since sphalerons reprocess $B+L$ number, we actually can do baryogenesis even by generating *lepton number* ! Extend the SM to include RH neutrinos with a Majorana mass

$$W = Y_\nu L H_2 N + \frac{1}{2} M_R N N$$

Then after EW symmetry breaking, the mass matrix for neutrinos become

$$M_\nu = \begin{pmatrix} 0 & Y_\nu v_2 \\ Y_\nu^T v_2 & M_R \end{pmatrix} \Rightarrow m_\nu \sim Y_\nu^T M_R^{-1} Y_\nu v_2^2 \ll 1 \text{ for } M_R \gg v_2$$

⟶ seesaw !

This is a good explanation of why the neutrinos are very light ! But note that here we have also L violation due to the Majorana mass term and the RH neutrinos can decay as

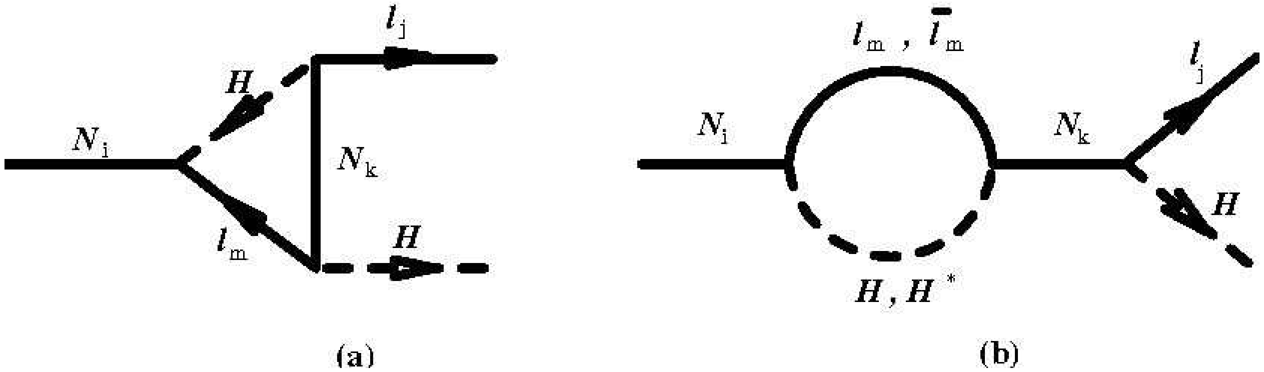
$$N \to L H_2 \qquad N \to \bar{L} \bar{H}_2$$

Possible to exploit N for baryogenesis ?

CP violation in N decay

We have CP in the decay of N if the couplings are complex.

CP violation always arises from an interference: tree + one-loop diagrams



We can define

$$\epsilon_i = \frac{\Gamma(N_i \to L) - \Gamma(N_i \to \bar{L})}{\Gamma(N_i \to L) + \Gamma(N_i \to \bar{L})} = -\frac{3}{16\pi} \sum_{i \neq j} \frac{M_i}{M_j} \frac{\Im[(Y_\nu^\dagger Y_\nu)^2_{ji}]}{(Y_\nu^\dagger Y_\nu)_{ii}} \text{for} M_i \ll M_j$$

→relation to neutrino masses via Y_ν...

Out of equilibrium decay

To generate the lepton asymmetry we need also departure from thermal equilibrium: out of equilibrium decay of the lightest N. This happens if $\Gamma_1 \leq H$ at $T \sim M_1$.

$$\Gamma_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_1 \leq H = \sqrt{\frac{\pi^2 g_*}{90}} \frac{M_1^2}{M_P}$$

$\Rightarrow M_1 \geq \sqrt{\frac{90}{\pi^2 g_*}} \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_P$, i.e. the RH neutrino have to be sufficiently massive. Or one can refrase it as

$$\tilde{m}_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11} v^2}{M_1} \leq \sqrt{\frac{\pi^2 g_*}{90}} \frac{v^2}{M_P} \sim 10^{-3}\text{eV}$$

If this condition is satisfied, then it is trivial to see that every N gives an ϵ amount of lepton number and the final asymmetry is simply

$$\frac{n_L}{s} = \frac{n_{B-L}}{s} = \frac{135\zeta(3)g}{8\pi^4 g_S}\epsilon_1 \simeq 4 \times 10^{-3}\epsilon_1 \quad \rightarrow \frac{n_B}{s} \sim -1.5 \times 10^{-3}\epsilon_1$$

Otherwise one has to solve a couple of Boltzmann equations...

Boltzmann equation for the $B - L$ number

Remember, yesterday we have taken CP conserved in the Boltzmann equation, but in this case that is not true... We had

$$\dot{n} + 3Hn = \int \frac{d^3p}{2E}\frac{d^3k}{2E_k}....\frac{d^3q}{2E_q}...\delta^4(p+k...-q...)\left(|M(p+k \to q)|^2 f_p f_k ... - |M(q \to p+k)|^2 f_q ...\right)$$

In this case we have to consider that the matrix elements are slightly different:

$$\Gamma(N \to L) \sim \frac{1}{2}\Gamma_N(1+\epsilon) \qquad \Gamma(N \to \bar{L}) \sim \frac{1}{2}\Gamma_N(1-\epsilon)$$

Then we have

$$\begin{aligned} \dot{n}_N + 3Hn_N &= -\int \frac{d^3p}{2E}\frac{d^3k_L}{2E_L}\frac{d^3k_H}{2E_H}\left(f_p - {f_p}^{eq}\right)\frac{1}{2}(1+\epsilon+1-\epsilon)\langle\Gamma_N\rangle + ... \\ \dot{n}_L + 3Hn_L &= \int \frac{d^3p}{2E}\frac{d^3k_L}{2E_L}\frac{d^3k_H}{2E_H}\left(f_p - {f_p}^{eq}\right)\frac{1}{2}(1+\epsilon-1+\epsilon)\langle\Gamma_N\rangle + ... \end{aligned}$$

where we have assumed that the leptons and higgses are in equilibrium.

Taking into account also other processes than the decay we then have

$$\frac{dY_N}{dx} = -\left(\langle\Gamma\rangle + \langle\sigma_{\Delta N=1} v\rangle\right)\left(Y_N - Y_N^{eq}\right)$$

$$\frac{dY_{B-L}}{dx} = -\epsilon_1 \langle\Gamma\rangle (Y_N - Y_N^{eq}) - \langle W\rangle Y_{B-L}$$

If only $\langle\Gamma\rangle$ is important we are way out of equilibrium, but in general the $\Delta N = 1$ scatterings $\langle\sigma v\rangle$ and the wash-out processe $\langle W\rangle$ are non negligible

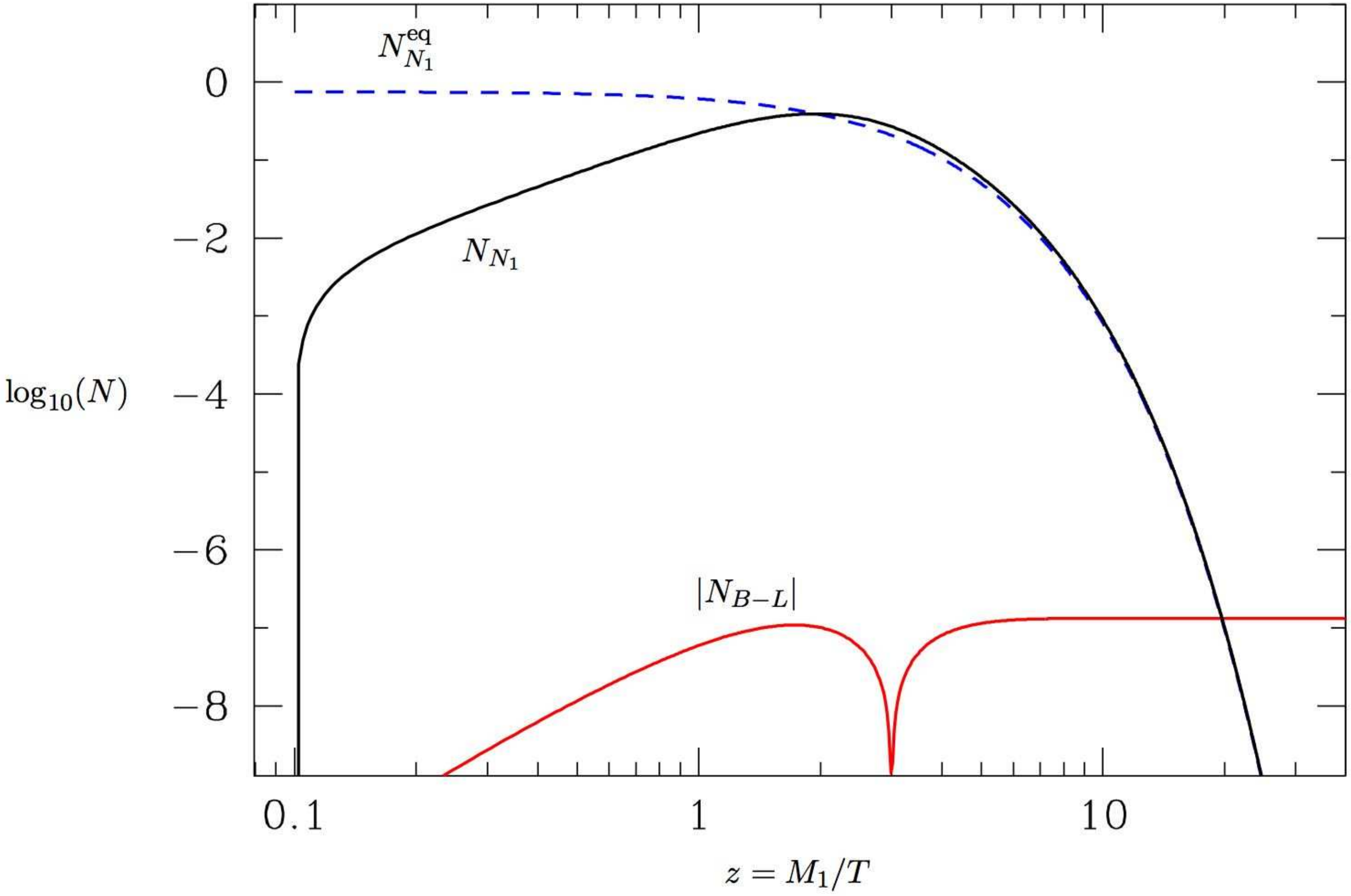
$$\langle\Gamma\rangle, \langle\sigma_{\Delta N=1} v\rangle, \langle W(N\text{exch.})\rangle \propto \frac{\tilde{m}_1 M_P}{v^2}$$

$$\langle\Delta W\rangle \propto \frac{\bar{m} M_1 M_P}{v^4}$$

The most important parameter is $\tilde{m}_1$ and the average neutrino mass scale $\bar{m}$.

Solutions of the Boltzmann equation

[Buchmüller, Di Bari & Plümacher '04]



General solution of the Boltzmann equation

[Buchmüller, Di Bari & Plümacher ’04]

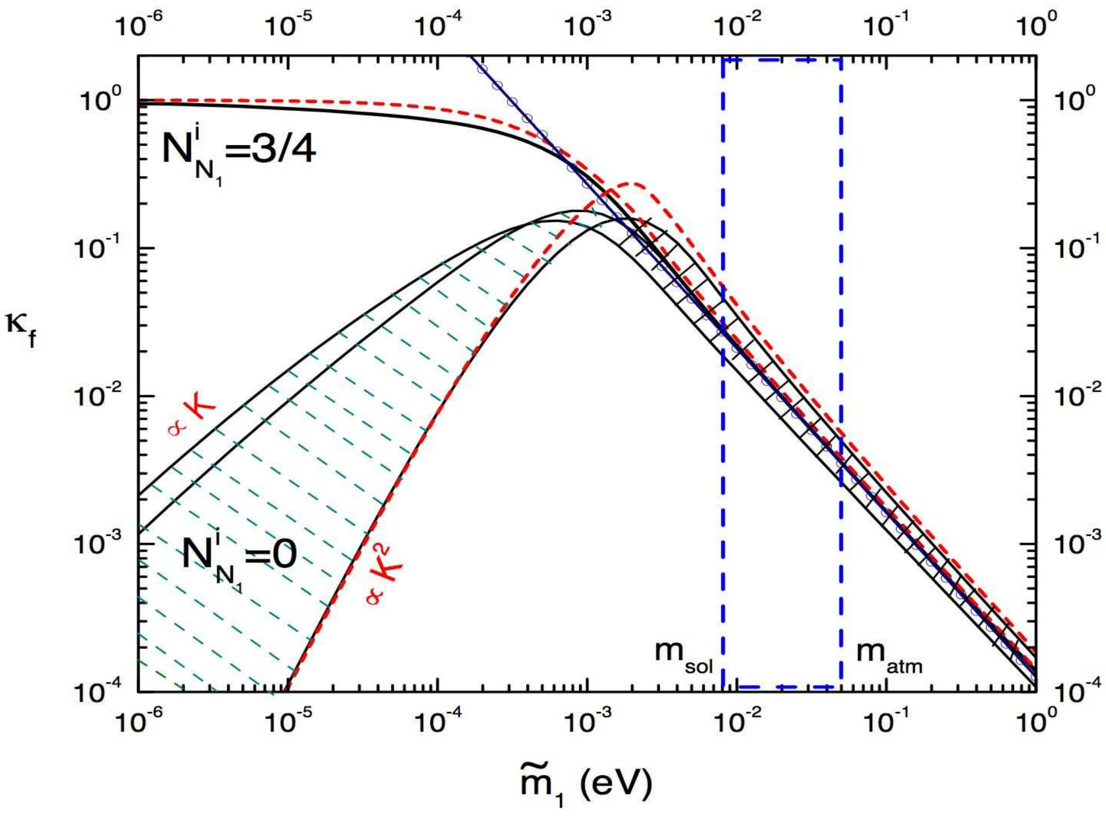
A general solution for the baryon number from leptogenesis can be given in the form

$$\eta_B \simeq 10^{-2} \epsilon_1 \kappa_f$$

where the efficiency factor κ_f comes from the solution of the Boltzmann equation.

→ light neutrino mass window

$$10^{-3}\text{eV} \leq m_1 \leq 0.1\text{eV}$$



Final remarks on leptogenesis

- possible also to realize the scenario in SUSY, but then some conflict with the limits on T_{RH} from gravitinos since one needs $T_{RH} \sim 10^9$ GeV ;
- such bounds can be relaxed in ”resonant” leptogenesis, that shows an enhanced ϵ due to nearly degenerate RH Majorana masses;
- possible also to have non-thermal leptogenesis, but then one is more sensitive to the initial conditions;
- the CP violation in leptogenesis is in general uncorrelated with the low energy CP asymmetry in the leptonic sector; only in specific mass models it is possible to relate the two, e.g. the sign or even more;
- leptogenesis can be used to test and constrain specific neutrino mass models ;
- still, baryogenesis could also be due to some other mechanism apart from the one covered in this lecture...

To finish a list of references...

- Books:

  The Early Universe by E.W. Kolb and M.S. Turner by Addison-Wesley 1990

- Reviews:

  Particle Data Group on Astrophysics and Cosmology on the web at `http://pdg.lbl.gov/`

  Particle Dark Matter:Evidence, Candidates and Constraints by

  G. Bertone, D. Hooper and J. Silk, arXiv:hep-ph/0404175

  Primordial Nucleosynthesis: Successes and Challenges by

  G. Steigman, arXiv:astro-ph/0511534

  Baryogenesis and leptogenesis by

  M. Trodden, arXiv:hep-ph/0411301

  Leptogenesis for pedestrians by

  W. Buchmüller, P. Di Bari and M. Plümacher, arXiv:hep-ph/0401240