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Recent progress in leptogenesis

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The see-saw and leptogenesis

★ There is now compelling evidence that neutrinos have (tiny) masses and (large) mixings. However, the underlying theoretical model is still unkown.

★ One very well-motivated possibility is the see-saw mechanism. In the original form, using very heavy singlet neutrinos, N_i, with a mass of, say, M~10^{10} GeV, naturally small (Majorana) neutrino masses are generated.

★ There is also compelling evidence that a baryon asymmetry must have been produced primordially in order to get [WMAP, 06]

$$\eta_B = n_B/n_\gamma = (6.1 \pm 0.2) \times 10^{-10}$$

★ Baryogenesis via leptogenesis [Fukugita, Yanagida, 86] is the generation of a lepton asymmetry by the out-of-equilibrium and *CP*-violating decay $\Gamma(N_i \rightarrow \ell_i \Phi^\dagger)$ of the heavy neutrinos, and the subsequent conversion into a baryon asymmetry by the anomalous sphaleron processes.

Unflavored leptogenesis

- ★ The flavor composition of the leptons is NOT taken into account:

$$\Gamma(N_i \rightarrow \ell_i \Phi^\dagger) \equiv \sum_\alpha \Gamma(N_i \rightarrow \ell_\alpha \Phi^\dagger)$$

- ★ After solving the relevant Boltzmann equations, in the limit of hierarchical heavy neutrinos, $M_1 \ll M_2 \ll M_3$, implying typically a N_1-dominated scenario, bounds for successful leptogenesis are obtained.
- ★ From the bound on the *CP* asymmetry, one obtains the lower bounds [Davidson, Ibarra, 02; Buchmüller, Di Bari, Plümacher, 02]

$$\boxed{M_1(T_{\mathrm{reh}}) \gtrsim 3(1.5) \times 10^9 \mathrm{GeV}}$$

- ★ There is a suppression of the efficiency for growing absolute neutrino mass scale which leads to the upper bound [Buchmüller, Di Bari, Plümacher, 02]:

$$\boxed{m_1 \lesssim 0.1 \mathrm{eV}}$$

- ★ The final asymmetry is insensitive to the measurable *CP*-violating phases (Dirac or Majorana).

Flavored leptogenesis

- ★ It turns out that the τ charged-lepton Yukawa interactions, $f_{\tau\tau}\bar{\ell}_{\tau}\Phi e_{\tau}$ become important when $T \lesssim 10^{12}\text{GeV}$. The medium distinguishes then two flavors: τ and not τ, i.e. $e+\mu$.
- ★ Flavor effects are important in that:
    - ☐ *They change the washout (typically by a factor 2-3, but can be more)*
    - ☐ *They introduce a new source of CP violation (flavor composition of leptons ≠ flavor composition of antileptons).*
- ★ The lower bound on M_1 do not change [SB, Di Bari, 06] . Concerning the upper bound on m_1, it is not clear whether it is still there or not.
- ★ It is interesting to notice that the Dirac phase, which one hopes to measure in future neutrino oscillation experiments, may provide a sufficient source of *CP* violation to explain the BAU [SB, Di Bari, 06] .

Conclusion

- ★ Baryogenesis via leptogenesis is an attractive mechanism to explain the origin of the BAU.
- ★ Two descriptions coexist: i) when $M_1 \gtrsim 10^{12}\mathrm{GeV}$ the unflavored picture should be correct. ii) when $M_1 \lesssim 10^{12}\mathrm{GeV}$ a flavored treatment is necessary.
- ★ For $M_1 \ll M_2 \ll M_3$, the lower bounds $M_1(T_{\mathrm{reh}}) \gtrsim 3(1.5) \times 10^9\mathrm{GeV}$ hold even accounting for flavor effects. The question about the presence of an upper bound on m_1 is still open.
- ★ Within the flavored regime, the low-energy measurable phases (both Dirac and Majorana) can play an important role.

Back-up

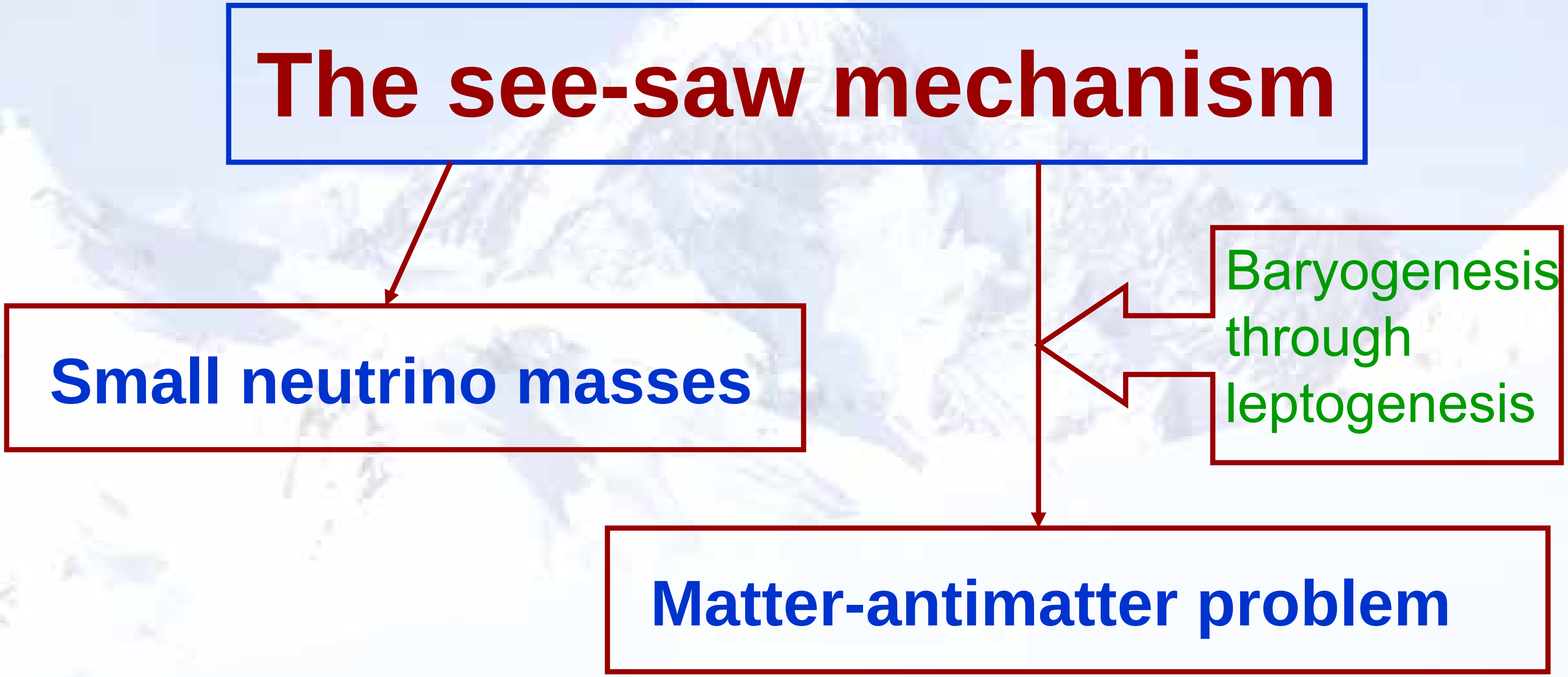
The puzzle of neutrino masses

- ★ The Standard Model of particle physics predicts massless neutrinos.
- ★ Today, after 10 years of great successes in neutrino oscillation experiments, the evidence is overwhelming that neutrinos have masses and mix. One has measured quite precisely two mass-squared differences :

Sol.+ Reac.	$\sqrt{\Delta m^2_{\mathrm{sol}}} \simeq 0.009\ \mathrm{eV}$
Atm.+ Acc.	$\sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.05\ \mathrm{eV}$

- ★ From the the measurement of the Z width at LEP, there should be 3 neutrino flavors, and thus 3 neutrino masses.
- ★ Neutrino oscillation experiments provide no information on the absolute neutrino mass scale! Fortunately, there are other probes possible…

Resolution of the two puzzles



The see-saw mechanism

Small neutrino masses

Baryogenesis through leptogenesis

Matter-antimatter problem

The see-saw mechanism

- ★ The see-saw mechanism originates from the following extension of the SM Lagrangian:

$$\delta L = \overline{N}_i i\partial_\mu\gamma^\mu N_i - \underbrace{h_{i\alpha}\overline{N}_i\Phi L_\alpha}_{\text{Yukawa coupling}} - \underbrace{\frac{1}{2}M_i\overline{N}_i N_i^c}_{\text{Majorana mass term}} + h.c.$$

where $\Phi = (\phi^0, \phi^+)$ and $L_\alpha = (\nu_{L\alpha}, \alpha_L^-)$, $\alpha = e, \mu, \tau$ are the Higgs and left-handed lepton doublets, respectively, and $N_i,\ i = 1, 2, 3$ are RH neutrinos.

- ★ This extension is clearly acceptable on grounds of gauge invariance and renormalizability, and is minimal in its particle content (here: 3 new particles).

The see-saw mechanism

- ★ The masses of the singlet neutrinos are essentially free parameters, and thus can be taken to be very large ($\gg 100\ \mathrm{GeV}$).

⇒ See-saw mechanism! [Minkowski, 77]

- ★ After spontaneous symmetry breaking, the vev $\langle\Phi\rangle$ of the Higgs leads to a Dirac mass term $m_\mathrm{D} = h\langle\Phi\rangle$. The see-saw assumes $M \gg m_\mathrm{D}$ so that the neutrino mass term can be block-diagonalized as:

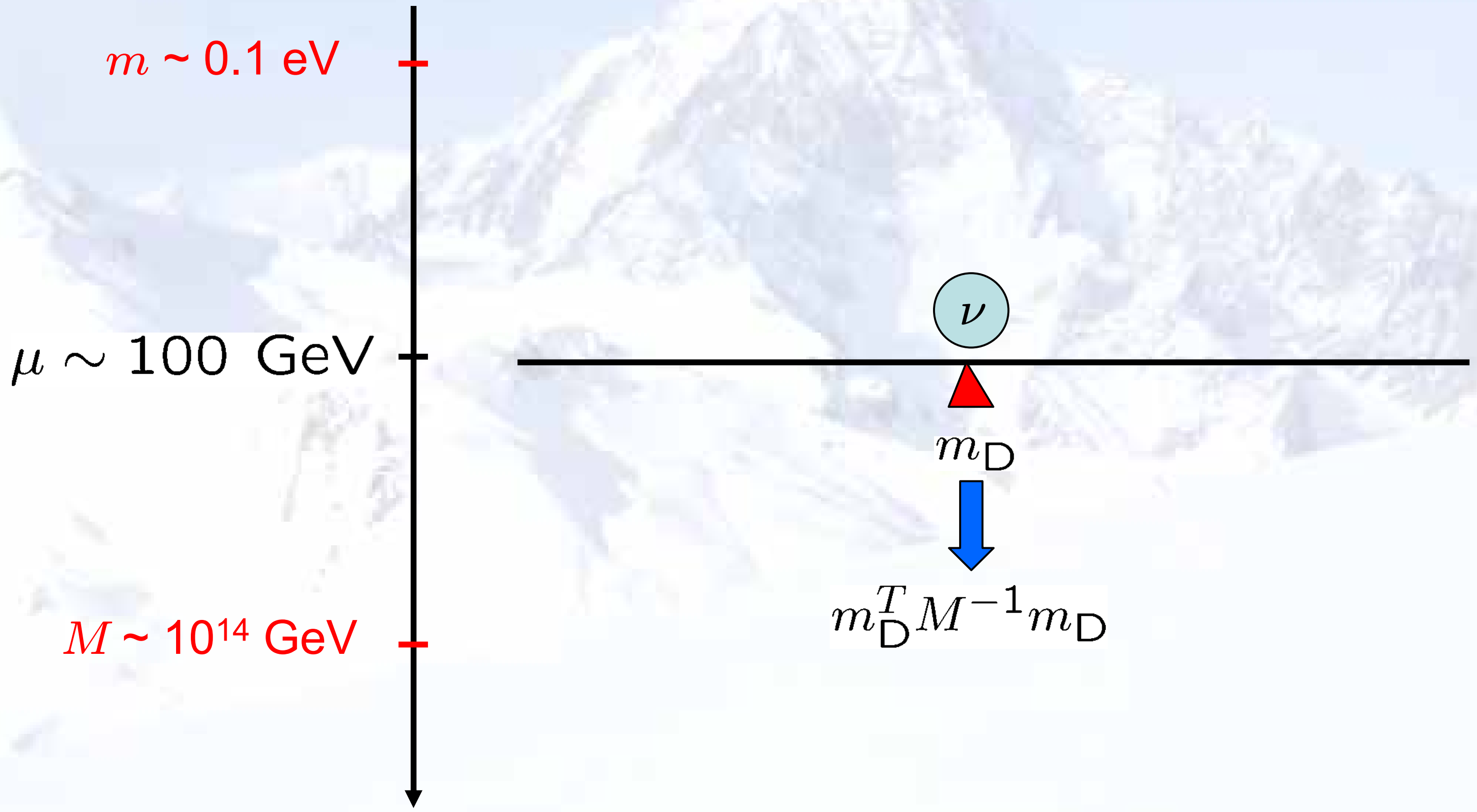
$$\begin{pmatrix} 0 & m_\mathrm{D}^T \\ m_\mathrm{D} & M \end{pmatrix} \xrightarrow{\text{1st order}} \begin{pmatrix} m_\mathrm{D}^T M^{-1} m_\mathrm{D} & 0 \\ 0 & M \end{pmatrix}$$

After diagonalization: 3 light Majorana neutrinos, mass $m_1 \leq m_2 \leq m_3$

3 heavy Majorana neutrinos, mass $M_1 \leq M_2 \leq M_3$

The see-saw mechanism

- ★ Conventional picture



m ~ 0.1 eV

$\mu \sim 100$ GeV

M ~ 10^{14} GeV

ν

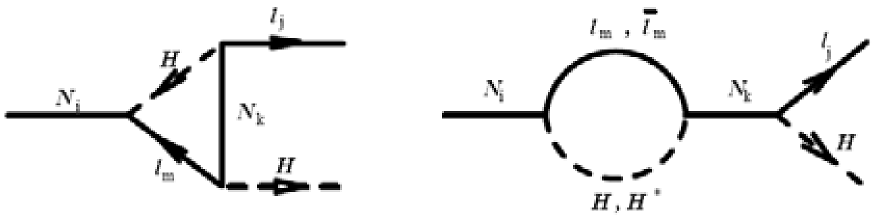
m_D

$m_\text{D}^T M^{-1} m_\text{D}$

Baryogenesis through leptogenesis

- Baryogenesis through leptogenesis [Fukugita, Yanagida, 86] is the generation of a lepton asymmetry by the decay of heavy right-handed neutrinos, and the subsequent conversion into a baryon asymmetry by the anomalous sphaleron processes.

- The three Sakharov conditions are fulfilled :
  - Baryon number is violated in anomalous processes
  - *CP* is violated in the decay of the heavy neutrinos: interference between tree level and 1-loop diagrams



$$\varepsilon_i = -\frac{\Gamma(N_i \to L_i\Phi^\dagger) - \Gamma(N_i \to \bar{L}_i\Phi)}{\Gamma(N_i \to L_i\Phi^\dagger) + \Gamma(N_i \to \bar{L}_i\Phi)}$$

CP asymmetry parameter

  - Decays are out of equilibrium at some point, parametrized by

$$K_i \equiv \frac{\Gamma(N_i \to L_i\Phi^\dagger)|_{T\to 0}}{H(T=M_i)}$$

``decay parameter´´

Baryogenesis through leptogenesis

- ★ In practice, in order to estimate the baryon asymmetry produced in leptogenesis, one has to solve coupled Boltzmann equations.

- ★ In most cases where $M_1 \ll M_2 \ll M_3$, it is enough to consider the decay of the lightest RH neutrino:

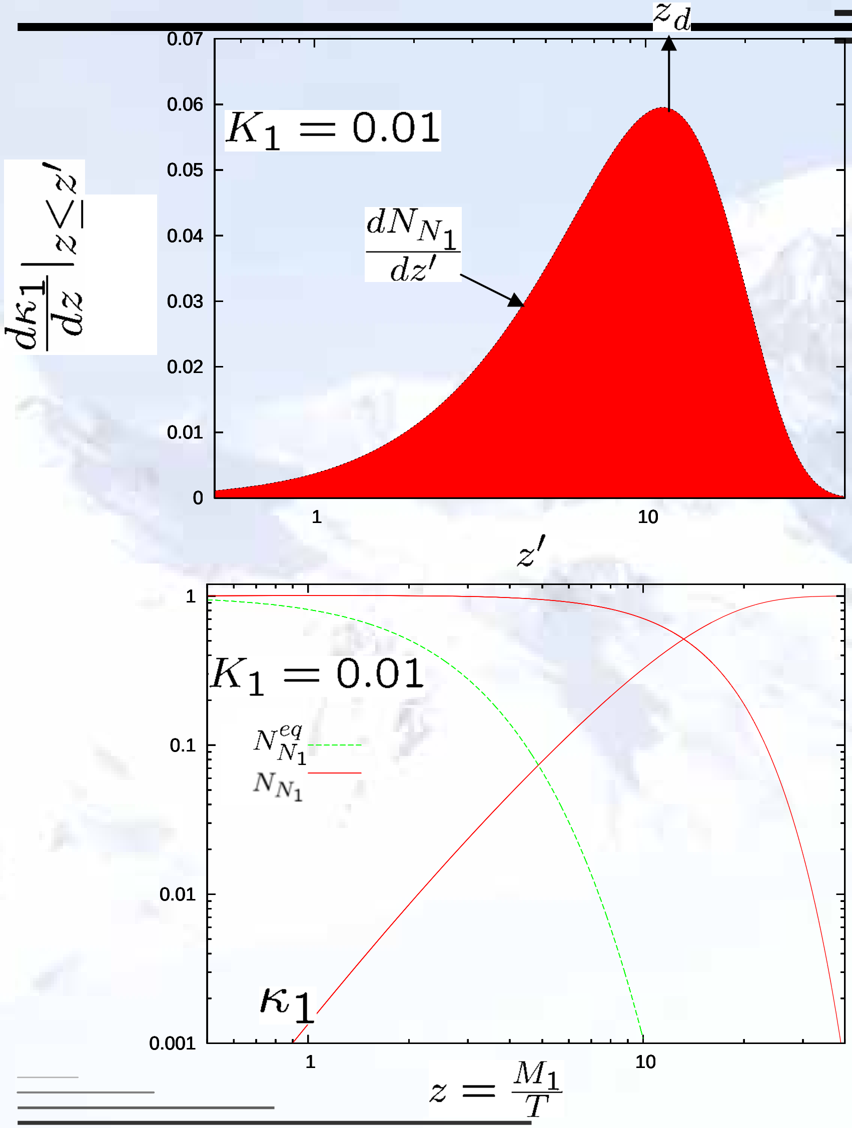
$$\boxed{\eta_B \propto \varepsilon_1 \kappa_1^{\mathrm{fin}}}$$

where κ_1^{fin} is the final efficiency factor, which depends mainly on K_1.

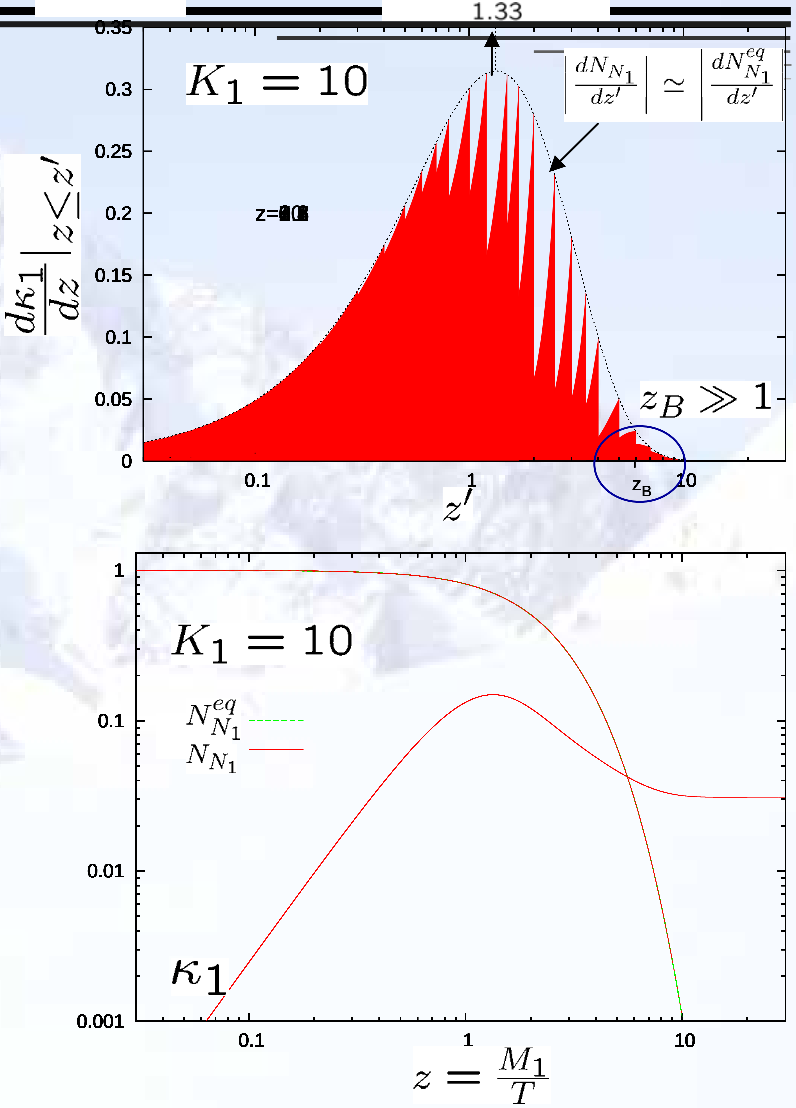
- ★ When the decay parameter $K_1 \gtrsim 1$ one talks about the strong wash-out. Conversely, when $K_1 \lesssim 1$ one has a weak wash-out.

- ★ There are different reasons why the strong wash-out is favored, the most prominent one being that there the resulting is independent of the initial conditions in this case.

WEAK WASHOUT



STRONG WASHOUT



Implications of leptogenesis

- ★ There is an upper bound on the *CP* asymmetry [Asaka et al., 01; Davidson, Ibarra, 02]

$$\varepsilon_1 \leq \overline{\varepsilon}(M_1) \simeq 10^{-6}\left(\frac{M_1}{10^{10}\,\mathrm{GeV}}\right)$$

  one obtains a lower bound on M_1 and on the reheating temperature [Davidson, Ibarra, 02; Buchmüller, Di Bari, Plümacher, 02] :

$$\boxed{M_1(T_{\mathrm{reh}}) \gtrsim 3(1.5)\times 10^9\,\mathrm{GeV}}$$

- ★ There is a suppression of the efficiency for growing absolute neutrino mass scale leads to a stringent upper bound [Buchmüller, Di Bari, Plümacher, 02] :

$$\boxed{m_1 \lesssim 0.1\,\mathrm{eV}}$$

Recent development: flavor effects

- ★ Recently, it was realized that the flavor structure of the leptons should be taken into account.
- ★ The reason is that when $T \lesssim 10^{12}\text{GeV}$, the τ-lepton Yukawa interaction $f_{\tau\tau}\overline{L}_\tau \Phi E_\tau$ is in equilibrium, i.e. $\Gamma_\tau \gtrsim H$.
- ★ These interactions are then fast enough to 'measure' if the flavor of the state produced in the decay of the heavy neutrino is τ or not; a 2-flavor basis ('τ' and '$e\mu$') is defined. [Abada, Davidson, Josse-Michaux, Losada, Riotto, 06 ; Nardi, Nir, Racker, Roulet, 06]
- ★ These considerations can affect the resulting asymmetry by large factors in special cases. In particular, the upper bound on m_1 will be very affected, if not removed. Note that the important lower bound on M_1 is not changed by flavor effects!!
- ★ Interestingly, flavor effects introduce a dependence of the final asymmetry on the lepton mixing matrix.

Conclusions

- ★ The see-saw mechanism allows the resolution of two important puzzles of modern physics: the smallness of neutrino masses and the origin of matter.
- ★ Baryogenesis through leptogenesis is an elegant solution to the matter-antimatter problem and implies a link between neutrino masses and a cosmological parameter, the baryon-to-photon ratio.
- ★ In this scenario, one of the largest energy scales in cosmology is related to the particles with the tiniest mass!
- ★ Recent developments (flavor effects) have shown that the link with neutrino physics is tighter than previously thought.
- ★ In particular, the Dirac phase in the lepton mixing matrix, which one hopes to measure in future neutrino experiments, could be the unique source of *CP* violation required to explain the origin of matter.