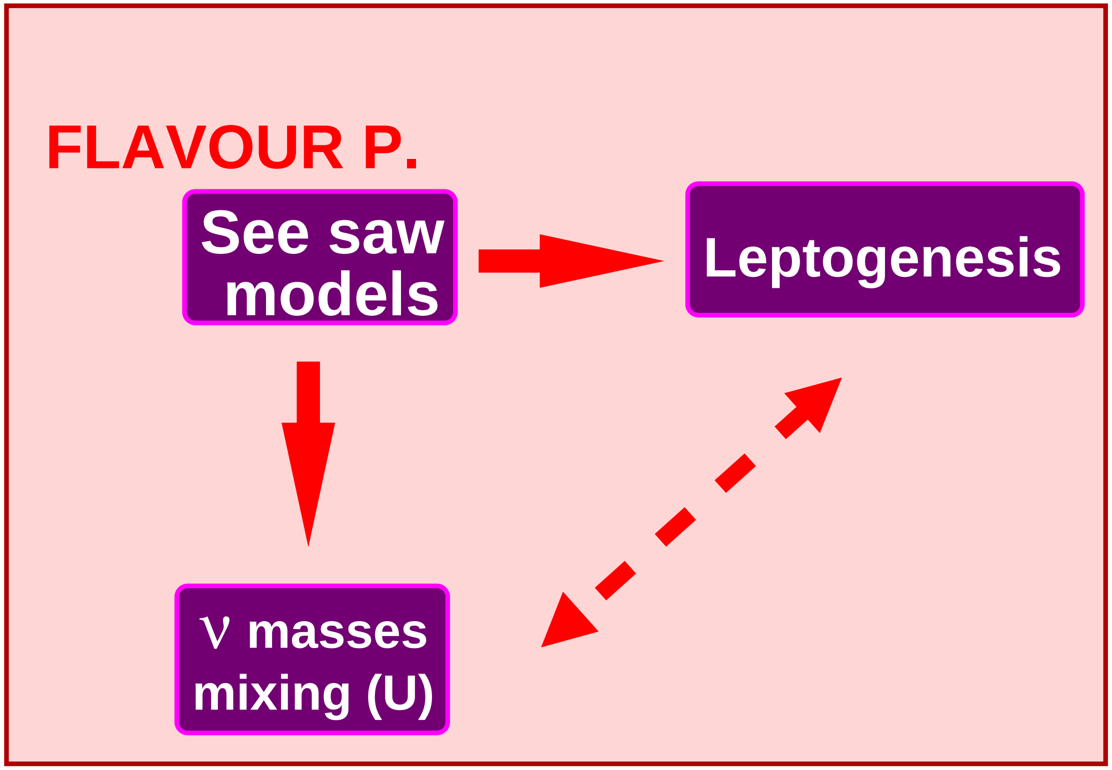
Majorana neutrinos,

neutrinoless double beta-decay

and Leptogenesis

- Discuss in detail leptogenesis in the context of the see-saw mechanism of generation of neutrino masses.

- Study the link between the leptogenesis and low energy physics



1 – Plan of Lecture 2

Leptogenesis and low energy neutrino physics

- 1. Sphaleron processes:

converting L number into B number

- 2. Thermal Leptogenesis:

CP-asymmetry

- 3. Thermal Leptogenesis:

washout factors

- 4. Thermal Leptogenesis:

flavour effects

- 5. Connection between leptogenesis and low energy physics

See-saw mechanism, type I

- We extend the SM by assuming the existence of N_R, singlets with respect to the SM gauge group.
- They have a Majorana mass term. Lepton number is explicitly broken.

$$\boxed{\mathcal{L} = -y_\nu(\bar{N}_R\tilde{\Phi}^\dagger L_L) + \mathrm{h.c.} + \frac{1}{2}M_{MR}(N_R^T C^\dagger N_R + N_R^\dagger C N_R^*)}$$

- M_{MR} is typically at a very heavy scale, TeV–10^{16} GeV.

$$\boxed{\begin{aligned} m_\nu &\simeq -M_D^\dagger \, M_R^{-1} \, M_D^* \, , \\ &= U_{\rm PMNS} \, D_m \, U_{\rm PMNS}^T . \end{aligned}}$$

It is useful to use various parametrizations of $M_D = y_\nu v$:

- Bi–unitary parametrization:

$$\boxed{M_D = U_R^\dagger \, m_D^{diag} \, U_L \, ,}$$

- Orthogonal parametrization.

$$\boxed{M_D \simeq i \sqrt{M_R} \, R \, D_m^{1/2} \, U_{\rm PMNS}^\dagger \, ,}$$

2 – THE FACTS: the baryon asymmetry

There is evidence of the **baryon asymmetry**:

$$\boxed{Y_B \simeq Y_B - Y_{\bar{B}} = n_B/n_\gamma}$$

- Observation of the acoustic peaks in CMB:

$$\boxed{Y_B^{\rm CMB} = \left(6.1^{+0.3}_{-0.2}\right)\ \times 10^{-10}}$$

at $T^{\rm CMB} \sim 1$ eV which corresponds to $t^{\rm CMB} \sim 10^{13}$ s.

- From the abundances of light elements in BBN:

$$\boxed{Y_B^{\rm BBN} = (2.6 - 6.2)\ \times 10^{-10}}$$

at $T^{\rm BBN} \sim 1$ MeV which is $t^{\rm BBN} \sim 10$ s.

Remarkable agreement!

How to explain the existence of the baryon asymmetry?

Sakharov conditions necessary for the dynamical creation of a B-asymmetry in the expanding Early Universe:

- **baryon (lepton) number violation**
- **C and CP violation**
- **deviation from thermal equilibrium**

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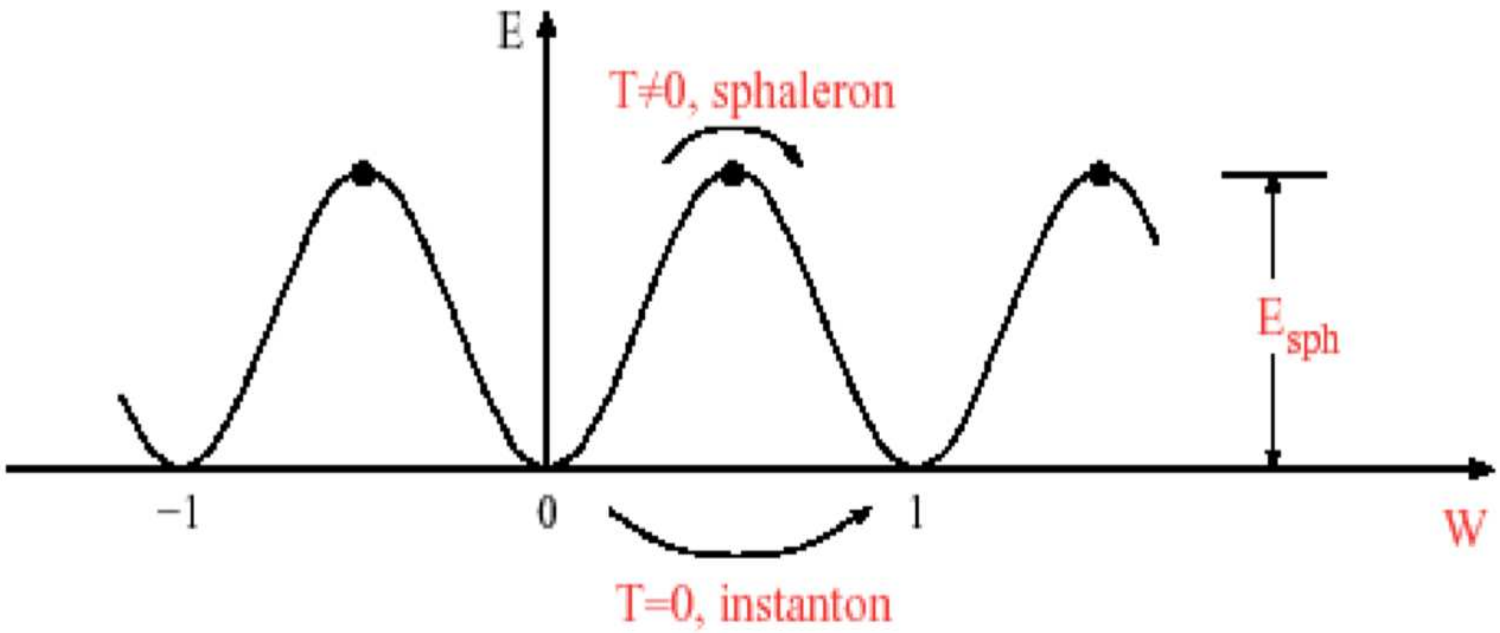
4 – Baryon number violation in the SM

The vacuum structure of a non-abelian ($SU(2)$) gauge theory:



Each minimum is labelled by the topological charge:

$$\boxed{N_{\rm CS} = \frac{g^3}{96\pi^2} \int d^3 \epsilon_{ijk} \epsilon^{IJK} W^{Ii} W^{Jj} W^{Kk} = 0, 1, 2 \ldots}$$

['t Hooft '76; Klinkhammer, Manton '84]

- In the SM, B and L are accidental symmetries, classically conserved.

$$J_\mu^B = \frac{1}{3}\sum_g \left(\bar{q_L}\gamma_\mu q_L + \bar{u_R}\gamma_\mu u_R + \bar{d_R}\gamma_\mu d_R\right) \quad \Rightarrow \quad B = \int d^3x J_0^B(x)$$

$$J_\mu^L = \sum_g \left(\bar{l_L}\gamma_\mu l_L + \bar{e_R}\gamma_\mu e_R\right) \quad \Rightarrow \quad L = \int d^3x J_0^L(x)$$

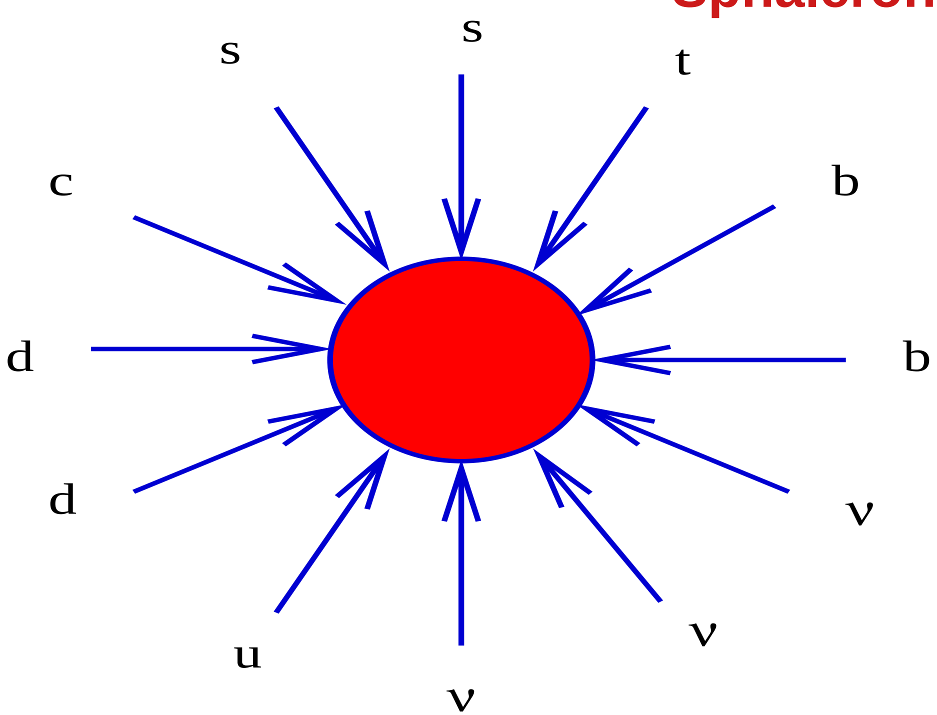
- But at the quantum level, they are anomalous:

$$\partial^\mu J_\mu^B = \partial^\mu J_\mu^L = n_g\left(\frac{g^2}{32\pi^2}W^a_{\mu\nu}\widetilde{W^{a\mu\nu}} - \frac{g'^2}{32\pi^2}F_{\mu\nu}\widetilde{F^{\mu\nu}}\right)$$

- The change in the baryon number is related to the change in the topological charge:

$$\boxed{B_f - B_i = \int_{t_i}^{t_f}\int d^3x\,\partial^\mu J_\mu^B = N_g\Big(N_{cs}(t_f) - N_{cs}(t_i)\Big)}$$

Sphaleron processes



SU(2) instantons lead to

effective 12 fermion interactions:

$\mathcal{O}_{B+L} = \prod_i q_{Li} q_{Li} q_{Li} l_{Li}$

These would induce $\Delta B = \Delta L = 3$.

However, at $T = 0$ the probability to tunnel from one vacuum to the other is:
$\Gamma \sim e^{-4\pi/\alpha} \sim 10^{-165}$.

[Kuzmin, Rubakov, Shaposhnikov ’85]

At finite temperature, the transition proceeds via thermal fluctuations with an unsuppressed probability.

$$\Gamma \sim e^{-\frac{M_W}{\alpha K T}} \; \Gamma = \alpha T^4$$

Sphalerons are efficient in the T range:

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

The generation of a B (L) number becomes possible.

Baryon and Lepton number asymmetries

In a weakly coupled plasma in thermal equilibrium I assign a chemical potential to the particles.

$$n_i - \bar{n}_i = \tfrac{1}{6} g T^3 1(2) \beta\mu_i + \mathcal{O}((\beta\mu_i)^3)$$

- sphaleron processes $\Rightarrow \sum_i (3\mu_{q_i} + \mu_{l_i}) = 0$
- SU(3) QCD instanton processes generate an effective interaction between left-handed and right-handed quarks: $\sum_i (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = 0$
- requiring that the hypercharge of the plasma vanishes $\sum_i (\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{l_i} - \mu_{e_i} + \frac{2}{N_g}\mu_H) = 0$
- Yukawa and gauge interactions in equilibrium:

$$\mu_{q_i} - \mu_H - \mu_{d_j} = 0$$
$$\mu_{q_i} + \mu_H - \mu_{u_j} = 0$$
$$\mu_{l_i} - \mu_H - \mu_{e_j} = 0$$

Resolving for $\mu_{l_i} = \mu_l$, one finds:

$$\mu_e = \frac{2N_g+3}{6N_g+3}\mu_l \qquad \mu_d = -\frac{6N_g+1}{6N_g+3}\mu_l$$

$$\mu_u = \frac{2N_g-1}{6N_f+3}\mu_l \quad \mu_q = -\frac{1}{3}\mu_l \quad \mu_H = \frac{4N_g}{6N_g+3}\mu_l$$

The baryon and lepton numbers can be expressed as

$$B = \sum_i (2\mu_{q_i} + \mu_{u_i} + \mu_{d_i})$$
$$L = \sum_i (2\mu_{l_i} + \mu_{e_i})$$

so that

$$B = -\frac{4}{3}N_g\mu_l \qquad L = \frac{14N_g^2+9N_g}{6N_g+3}\mu_l$$

and

$$\boxed{B = \frac{8N_g+4}{22N_g+13}(B-L) \qquad L = (\frac{8N_g+4}{22N_g+13}-1)(B-L)}$$

Summary: baryon and lepton number violation

While classically in the SM B and L are conserved, they are violated at the quantum level.

At $T > 100$ GeV, sphaleron processes are efficient and a baryon number can be generated via the transition from one gauge vacuum to the other.

The change in baryon and lepton number are related

$$B = \mathcal{O}(1)(B - L)$$

L generated in the Early Universe can be converted in B!

5 – Plan of Lecture 2

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6 – Leptogenesis

- The Majorana right-handed neutrino N_i are in equilibrium in the Early Universe as far as the processes which produce and destroy them are efficient.

- When $T < M_1$, N_1 drops out of equilibrium as it cannot be produced efficiently anymore.

- If Γ for $N_1 \longrightarrow l\Phi$ and $N_1 \longrightarrow \bar{l}\bar{\Phi}$ are different, a lepton asymmetry will be generated.

- This lepton asymmetry is then converted into a baryon asymmetry by sphaleron processes.

[Fukugita, Yanagida]

In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry:

$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to l\Phi) - \Gamma(N_1 \to \bar{l}\bar{\Phi})}{\Gamma(N_1 \to l\Phi) + \Gamma(N_1 \to \bar{l}\bar{\Phi})}$$

2. solve the Boltzmann equation to take into account the wash-out of the asymmetry:

$$Y_L = k\epsilon_1$$

   with k a washout factor.

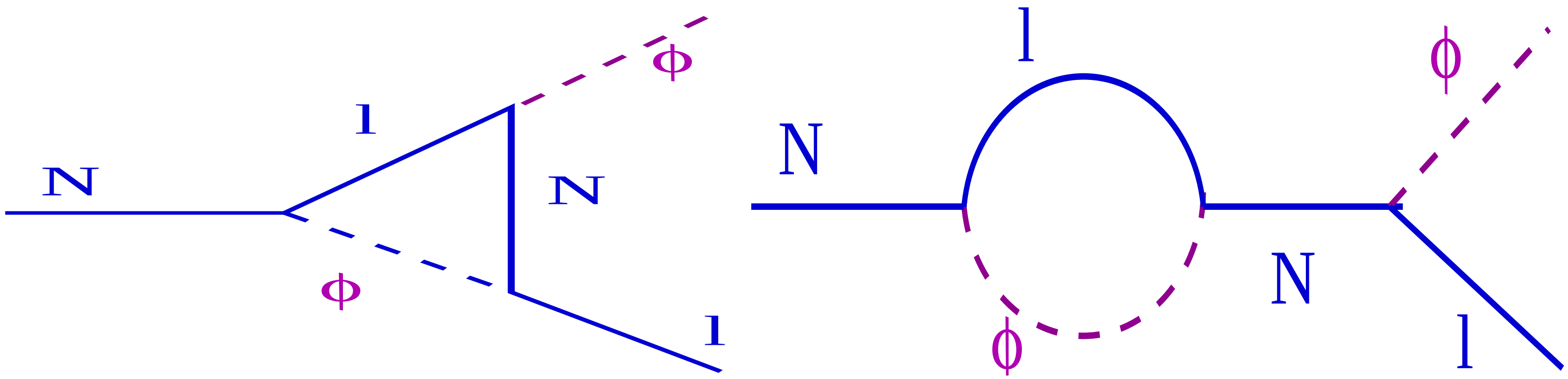
3. convert the lepton asymmetry into baryon asymmetry

$$Y_B = \frac{k}{g^*} c_s \epsilon_1 \sim 10^{-3} - 10^{-4}\epsilon_1$$

7 – CP-asymmetry: 1 flavour approximation

At tree level Γ is real: $\Gamma_{\rm tree}(N_1 \longrightarrow l\Phi) = \Gamma_{\rm tree}(N_1 \longrightarrow \bar{l}\bar{\Phi}) \; = |y|^2 m_N$

The CP-asymmetry arises from the interference between tree level and one-loop graphs [Flanz; Covi, Roulet, Vissani...]:



$$\epsilon_1 = \frac{1}{8\pi}\frac{1}{|yy^\dagger|_{11}} \sum_{i=2,3} \mathrm{Im}\Big((yy^\dagger)^2_{1i}\Big) \left(f(\frac{M_i^2}{M_1^2}) + g(\frac{M_i^2}{M_1^2})\right)$$

where $f(x) = \sqrt{x}\Big(1 - (1+x)\log\left(\frac{1+x}{x}\right)\Big)$ and $g(x) = \frac{\sqrt{x}}{1-x}$.

- For hierarchical RH neutrino, $M_1 \ll M_2 \ll M_3$,

$$\epsilon_1 = -\frac{3}{8\pi}\frac{1}{|yy^\dagger|_{11}} \sum_{i=2,3} \mathrm{Im}\Big((yy^\dagger)^2_{1i}\Big) \frac{M_1}{M_i}$$

We will assume hierarchical RH neutrinos.

- If N_1 and N_2 are nearly degenerate, there is a resonant enhancement of the lepton asymmetry: resonant leptogenesis. [Pilaftsis, Underwood]

$$\epsilon_j = -\frac{3}{8\pi}\frac{\sum_j \mathrm{Im}\Big((yy^\dagger)^2_{ij}\Big)}{|yy^\dagger|_{ii}|yy^\dagger|_{jj}} \Big(\frac{(M_i^2 - M_j^2)M_i\Gamma_{N_j}}{(M_i^2 - M_j^2)^2 + M_i^2\Gamma^2_{N_j}}\Big)$$

The required RH neutrino mass scale can be significantly smaller, as small as TeV.

Departure from equilibrium

[A detailed discussion in W. Buchmuller, Lectures at St. Andrews]

In equilibrium, no net lepton asymmetry can be generated.

The equilibrium distribution of N is maintained as far as the processes which create and destroy N ($N \leftrightarrow \Phi l$, $Nl \leftrightarrow qt$, $ll \leftrightarrow \Phi\Phi$, ...) are efficient.

The N number density is:

$$\mathcal{N}_N^{\mathrm{eq}} = \frac{g_N^2}{(2\pi)^3} \int \frac{1}{e^{\frac{E - m u_N}{T}} + 1} \, d^3p$$

- Relativistic limit:

$$\mathcal{N}_N^{\mathrm{eq}} \simeq \frac{3\zeta(3)}{4\pi^2} g_N T^3$$

- Non-relativistic limit:

$$\mathcal{N}_N^{\mathrm{eq}} \simeq g_N \left(\frac{M_N T}{2\pi}\right)^{3/2} e^{-\frac{M_N - \mu_N}{T}}$$

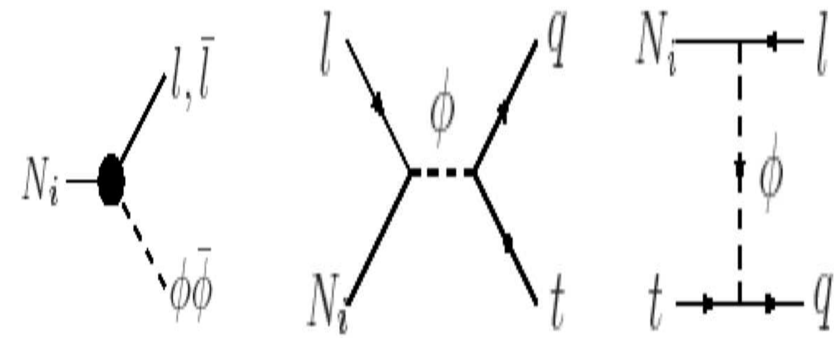
N go out of equilibrium when:

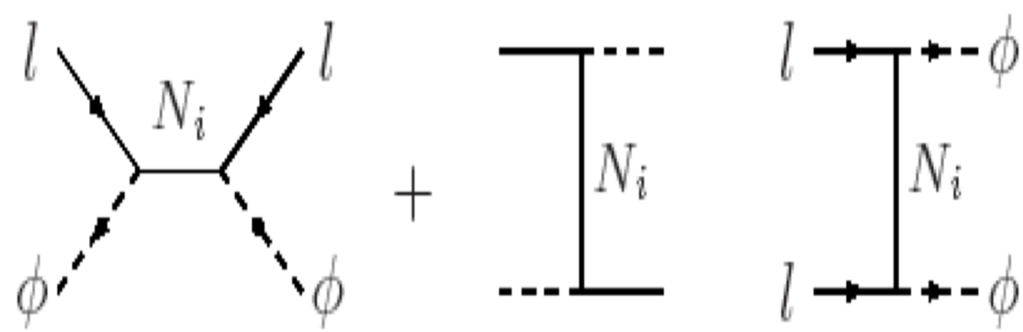
$$\Gamma \sim H$$

Γ is the production rate and H is the expansion rate of the Universe.

The processes relevant for Γ are:

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





Let's compare the various processes:

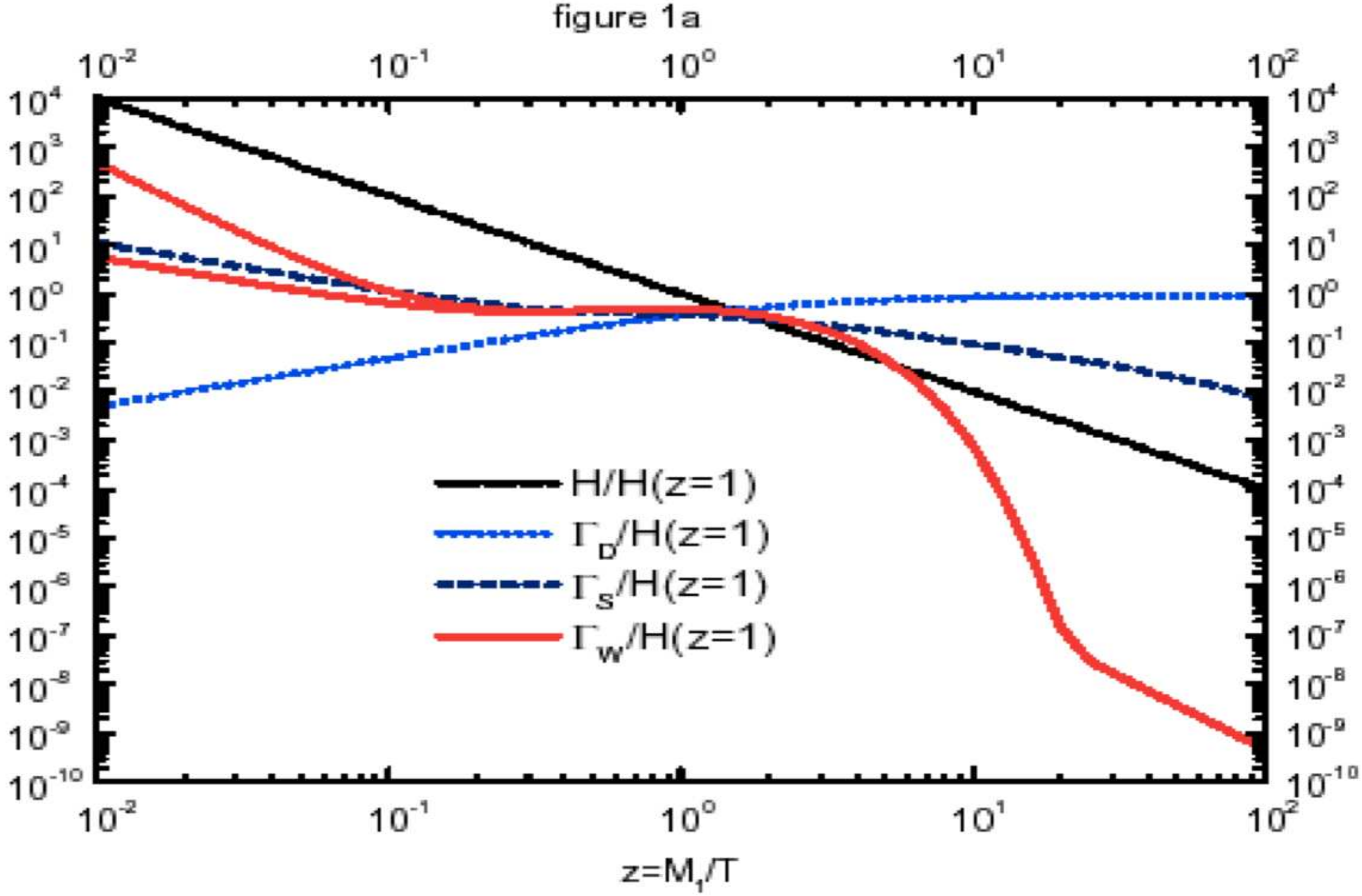
- the N decay rate: $\Gamma_{\rm D} \sim \frac{y^2}{4\pi} M_1 \left[\begin{array}{ll} M_1/T & T > M_1 \\ 1 & T \leq M_1 \end{array} \right.$

- the inverse decay rate: $\Gamma_{\rm ID} \sim \Gamma_{\rm D} \left[\begin{array}{ll} 1 & T > M_1 \\ (M_1/T)^{3/2} \exp^{-M_1/T} & T \leq M_1 \end{array} \right.$

- the $\Delta L = 1$ scatterings: $\Gamma \simeq n\sigma \sim T^3 y^4 \frac{T^2}{(T^2+M_1^2)^2}$

- the expansions rate: $H \simeq \sqrt{g^*}\frac{T^2}{M_{\rm Pl}}$

7 – CP-asymmetry: 1 flavour approximation



[Buchmuller, Di Bari, Plumacher]

In order to evaluate the washout processes it is necessary to solve the Boltzmann equations:

$$\frac{d\mathcal{N}_{N_1}}{dz} = -(\frac{\Gamma_D}{Hz} + \frac{\Gamma_S}{Hz})(\mathcal{N}_{N_1} - \mathcal{N}_{N_1}^{\rm eq})$$

$$\frac{d\mathcal{N}_{B-L}}{dz} = -\epsilon_1 \frac{\Gamma_D}{Hz}(\mathcal{N}_{N_1} - \mathcal{N}_{N_1}^{\rm eq}) - \frac{\Gamma_W}{Hz}\mathcal{N}_{B-L}$$

with $\mathcal{N}$ the number density per comoving volume and $z = M_1/T$.

New developments: consider quantum Boltzmann equations.

[Buchmuller, Di Bari, Plumacher, Riotto, De Simone, Giudice, Strumia, Notari, Raidal]

Limiting cases.

The dominant process which controls the N number is the decay whose rate depends on y^2/M. We define:

$$\widetilde{m_1} \equiv \frac{M_D^\dagger M_D}{M_1}$$
$$m_* = \frac{16\pi^{5/2}}{3\sqrt{5}}\sqrt{g^*}\frac{v^2}{M_{\mathrm{Pl}}} \simeq 10^{-3}\ \mathrm{eV}$$

The amount of washout can be estimated with:

$$K \equiv \frac{\Gamma_D(z \to \inf)}{H(z=1)} = \frac{\widetilde{m_1}}{m_*}$$

- $K \gg 1$: strong washout
- $K \ll 1$: weak washout

Strong washout ($K \gg 1$)

The N abundance tracks the equilibrium one.

Any asymmetry produced early on is washout out $\Rightarrow$ no dependence on the initial conditions.

The washout effects can be approximated as:

$$\eta(\widetilde{m_1}) \sim \left(\frac{\widetilde{m_1}}{0.2\times 10^{-3}\ \mathrm{eV}}\right)^{-1.16}$$

Weak washout ($K \ll 1$)

Decays occur at very low T and washout effects are negligible.

An initial asymmetry is not washout out significantly.

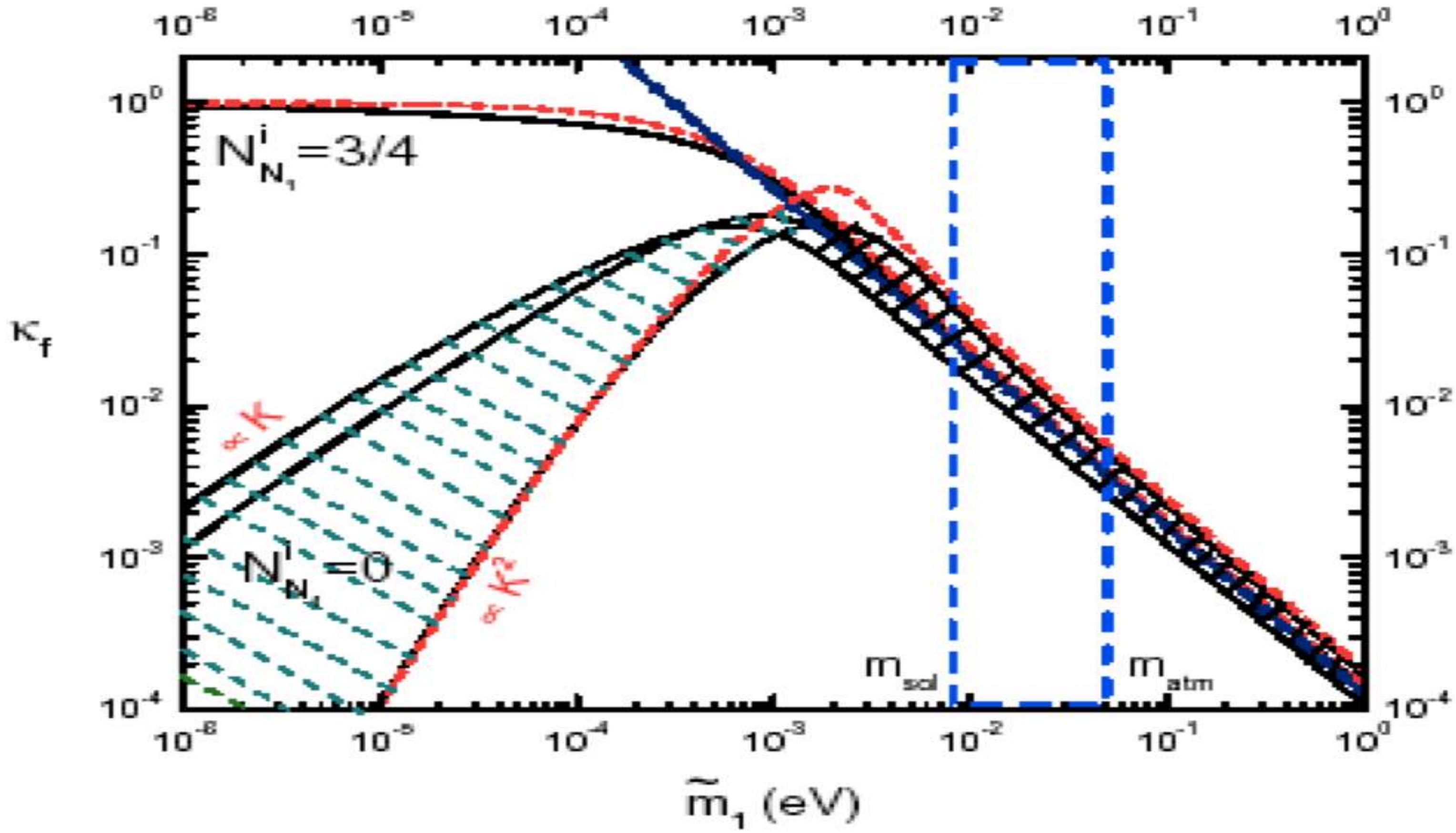
If initially $\eta_L \sim 0$, the final baryon asymmetry is suppressed.

$$\eta(\widetilde{m_1}) = \tfrac{4}{3}(\mathcal{N}^i - \mathcal{N}(z))$$

- If there is an initial asymmetry $\mathcal{N} = 3/4$:
$$\eta(\widetilde{m_1}) \sim 1$$

- For vanishing initial asymmetry, the washout effects can be expressed as:
$$\eta(\widetilde{m_1}) \sim \left(\frac{\widetilde{m_1}}{8.25\times 10^{-3}\ \mathrm{eV}}\right)$$

7 – CP-asymmetry: 1 flavour approximation



[Buchmuller et al.]

8 – Plan of Lecture 2

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9 – Flavour effects in leptogenesis

New development

At high T GeV, the Yukawa interactions for l are out of equilibrium and effectively e, μ and τ are indistinguishable. They enter in equilibrium when $\Gamma \sim H$.

$$\tau : \quad y_\tau^2 T/(4\pi) \sim g_*^{1/2} T^2/M_{\rm Pl} \quad T \sim 10^{12}\ \text{GeV}$$

$$\mu : \quad y_\mu^2 T/(4\pi) \sim g_*^{1/2} T^2/M_{\rm Pl} \quad T \sim 10^{9}\ \text{GeV}$$

At $T < 10^{12}$ GeV, flavour effects need to be taken into account: the lepton asymmetry in each flavour is computed by looking at the flavour CP-asymmetry and the flavour washout effects.

[Abada et al.; Nardi et al.; Di Bari et al.; See also Antush, Barbieri et al., Pilaftsis and Underwood; Anisimov et al., Endoh et al., Fujihara et al., Vives]

For each flavour one evaluates:

- $\epsilon_\alpha = \frac{1}{8\pi\ (yy^\dagger)_{11}} \sum_j \mathrm{Im}\Big(y_{1\alpha}(yy^\dagger)_{1j} y^*_{j\alpha}\Big)\Big(f(\frac{M_i^2}{M_1^2}) + g(\frac{M_i^2}{M_1^2})\Big)$

- $\widetilde{m_l} \equiv \frac{|\lambda_{1l}|^2\, v^2}{M_1}, \quad l = e, \mu, \tau\ .$

- $\boxed{Y_B \simeq -\frac{12}{37 g_*}\left(\epsilon_2\, \eta\left(\frac{417}{589}\,\widetilde{m_2}\right) + \epsilon_\tau\, \eta\left(\frac{390}{589}\,\widetilde{m_\tau}\right)\right)\ ,}$

where $\epsilon_2 = \epsilon_e + \epsilon_\mu$, $\widetilde{m_2} = \widetilde{m_e} + \widetilde{m_\mu}$ and

$$\eta\left(\widetilde{m_l}\right) \simeq \left(\left(\frac{\widetilde{m_l}}{8.25\times10^{-3}\,\mathrm{eV}}\right)^{-1} + \left(\frac{0.2\times10^{-3}\,\mathrm{eV}}{\widetilde{m_l}}\right)^{-1.16}\right)^{-1}\ .$$

- In some cases the results differ significantly from the ”one-flavor” approximation.

For ex., let’s consider the case of no CPV in the right-handed sector:

- biunitary parametrisation: V_R real.
- orthogonal parametrisation: R real.

In the one-flavour approximation,

$\epsilon_1 \propto \mathrm{Im}(M_D M_D^\dagger)_{1j} \propto \mathrm{Im}(U_R^\dagger M_D^2 U_R) = 0.$

No leptogenesis.

In presence of flavour, using $\epsilon_\tau = -\epsilon_2$:

$$Y_B \simeq \frac{12}{37 g_*} \epsilon_\tau \, \left(\eta \left(\frac{417}{589} \widetilde{m_2} \right) - \eta \left(\frac{390}{589} \widetilde{m_\tau} \right) \right) \ ,$$

In general, this is different from 0.

[Abada et al.; SP, Petcov, Riotto]

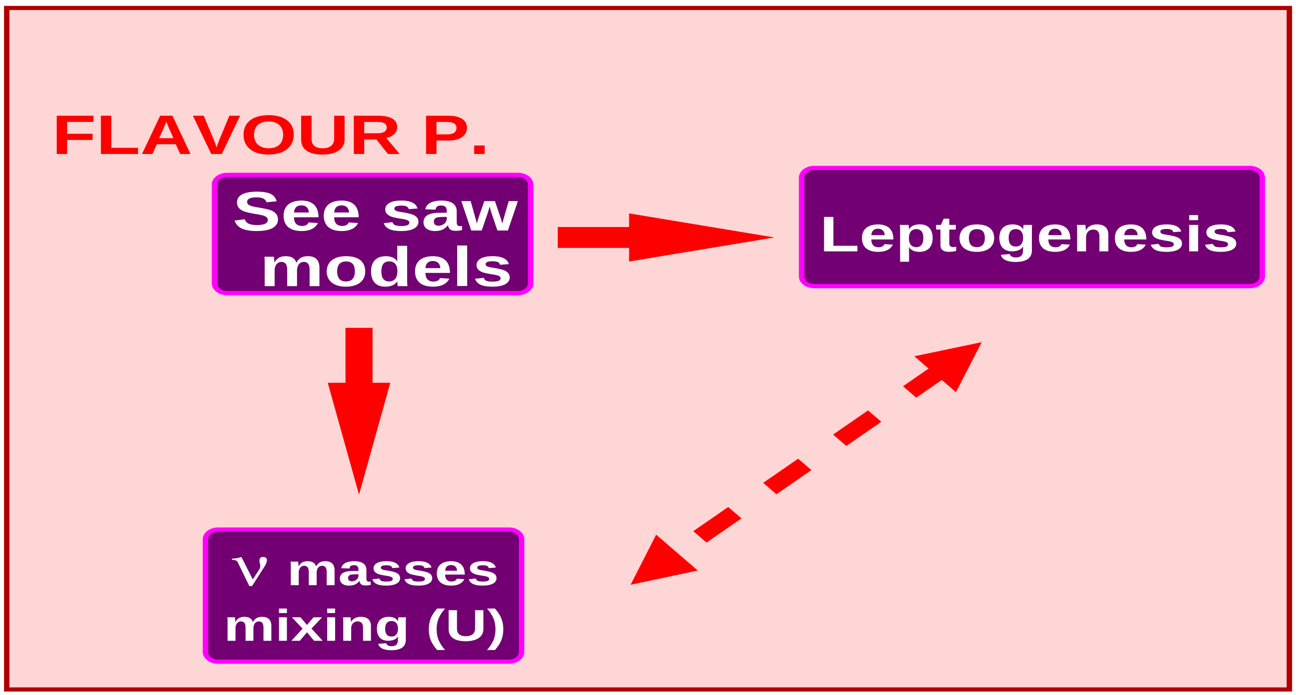
Summary of leptogenesis

- Leptogenesis takes place in the context of see-saw models.

- The CP-violating N_1 decays produce a baryon asymmetry

which is then converted into a baryon asymmetry.

- Leptogenesis can reproduce the observed baryon asymmetry.



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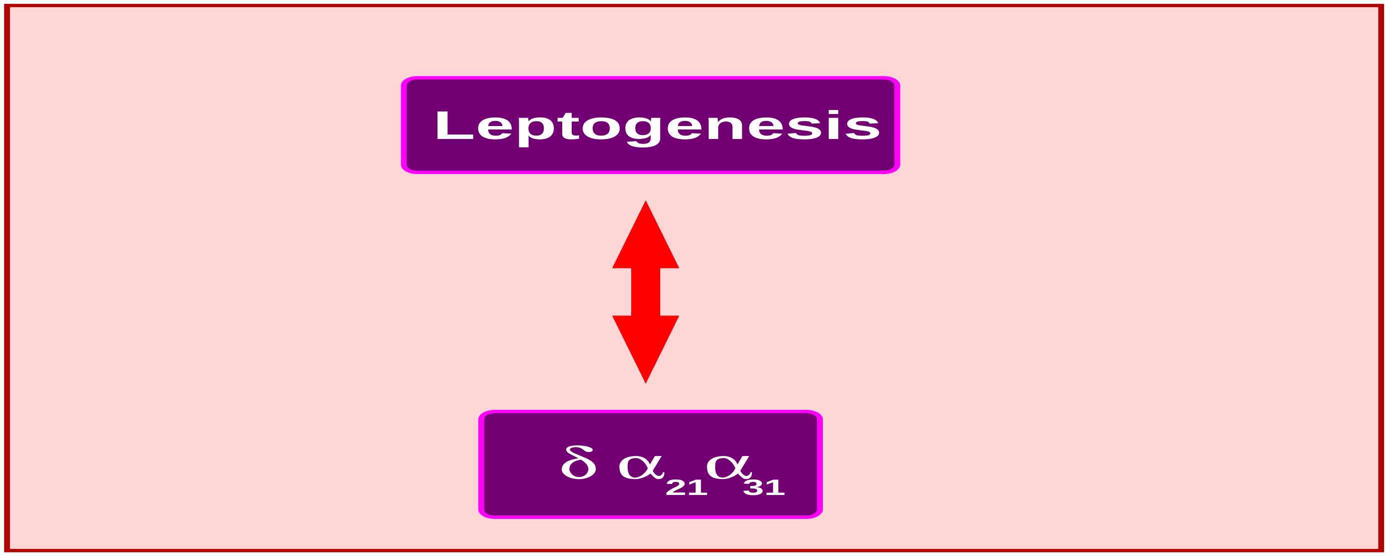
11 – Is there a connection between CP-V at low energy and in leptogenesis?



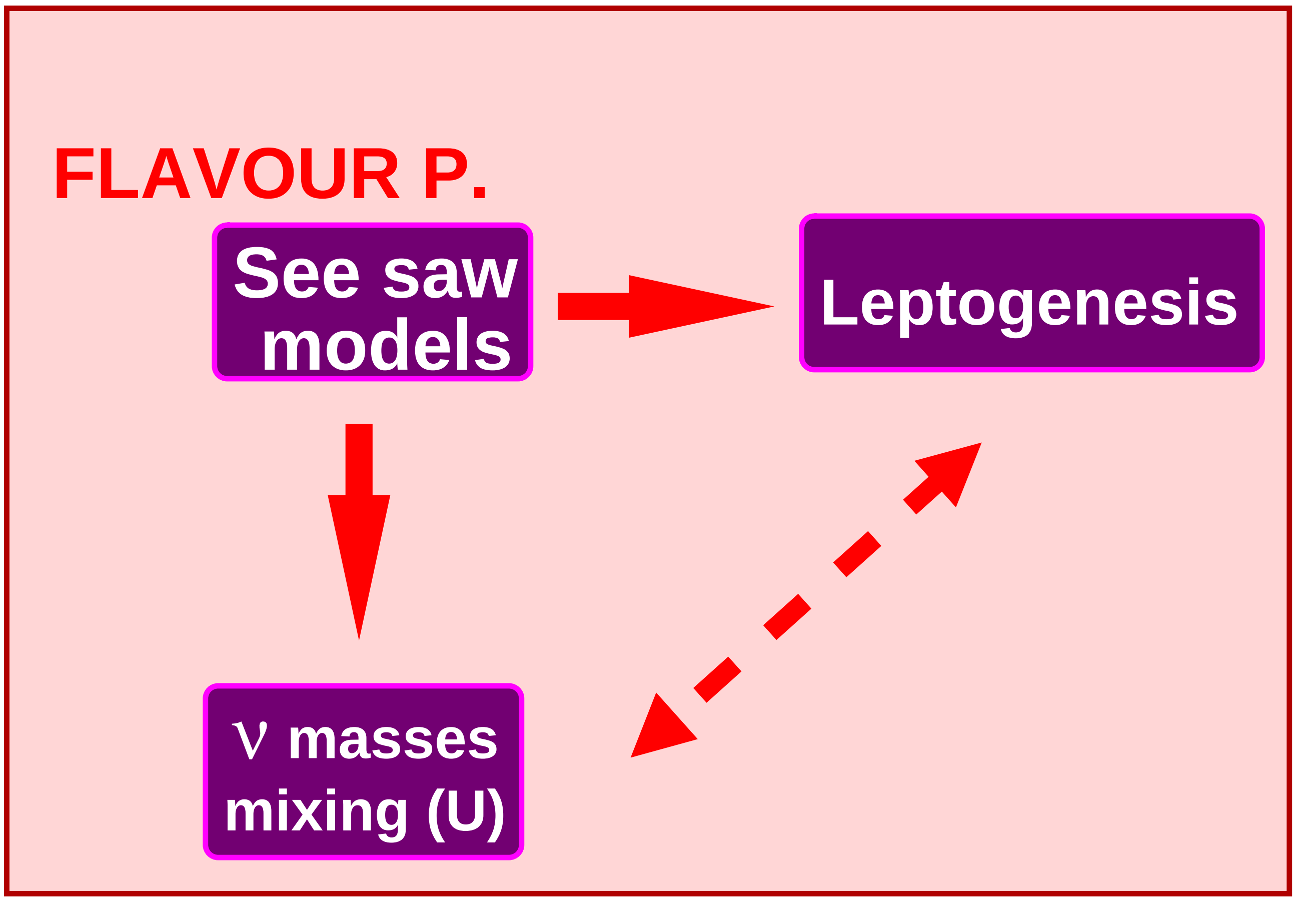
High energy parameters			Low energy parameters		
M_R	3	0	d_m	3	0
λ	9	6	U	3	3

9 parameters are lost, of which 3 phases. In a model-independent way there is **no one-to-one connection** between the low-energy phases and the ones entering leptogenesis. [see, e.g., S.P., MPLA]

In understanding the origin of the flavour structure, the see-saw models have a reduced number of parameters, with no independent R. In some cases,

it is possible to predict

the baryon asymmetry from the Dirac and/or Majorana phases.



An example: 2 RH neutrinos.

$$\mathcal{L} = \frac{1}{2}(N_1 N_2)\begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \end{pmatrix} + (N_1 N_2)\begin{pmatrix} a & a' & 0 \\ 0 & b & b' \end{pmatrix}\begin{pmatrix} L_1 \\ L_2 \\ L_3 \end{pmatrix} \cdot H + \mathrm{h.c.}$$

In order to reproduce ν data, we can take: $a' = \sqrt{2}a$, $b = b'$, $a^2/M_1 \ll b^2/M_2$.

We get: $m_1 = 0$, $m_2 = 2a^2/M_1$, $m_3 = 2b^2/M_2$.

- The baryon asymmetry and the low-energy CP-violation are related:

$$\sin\delta \propto -\frac{a^4 b^4}{M_1^3 M_2^3}\epsilon_1$$

12 – Observing low-energy CPV implies leptogenesis?

We use the orthogonal parametrization: $\lambda = 1/v \sqrt{M}\, R \sqrt{m} U^\dagger$

with $R_{1i} R_{1j}$ real. [Abada et al., Nardi et al., SP, Petcov, Riotto]

one-flavour
$$\boxed{\epsilon_1 = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_\rho m_\rho^2 R_{1\rho}^2\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2} = 0}$$

with flavour
$$\boxed{\epsilon_l = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U_{l\beta}^* U_{l\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}}$$

ϵ_l depends on the mixing matrix U directly (NEW!).

NH spectrum

Let's consider $m_1 \ll m_2 \simeq \sqrt{\Delta m^2_\odot} \ll m_3 \simeq \sqrt{\Delta m^2_{\rm atm}}$.

[SP, Petcov, Riotto]

1. $\epsilon_\tau \propto$

$$M_1 f(R_{ij}) \left[c_{23}s_{23}c_{12}\sin\left(\frac{\alpha_{32}}{2}\right) - c_{23}^2 s_{12} s_{13}\sin\left(\delta - \left(\frac{\alpha_{32}}{2}\right)\right)\right]$$

Direct dependence on the Majorana and Dirac phases.

2. Washout factor: $\eta\left(\frac{390}{589}\widetilde{m_\tau}\right) - \eta\left(\frac{417}{589}\widetilde{m_2}\right)$.

$$\widetilde{m_2} \simeq \sqrt{\Delta m^2_{\rm atm}}\,\Big(\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}}|R_{12}|^2(1-c_{12}^2 s_{23}^2) + |R_{13}|^2 s_{23}^2\Big)\,,$$

$$\widetilde{m_\tau} \simeq \sqrt{\Delta m^2_{\rm atm}}\,\Big(\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}}|R_{12}|^2 c_{12}^2 s_{23}^2 + |R_{13}|^2 c_{23}^2\Big)\,.$$

- $Y_B = 0$ if $\eta\left(\frac{390}{589}\widetilde{m_\tau}\right) = \eta\left(\frac{417}{589}\widetilde{m_2}\right)$.

- Strong washout in τ and 2: $\widetilde{m_{2,\tau}} \gg 2 \times 10^{-3}$ eV.

$$\eta\left(\widetilde{m_l}\right) \propto \widetilde{m_l}^{-1.16}.$$

- Weak washout in τ and 2: $\widetilde{m_{2,\tau}} \ll 2 \times 10^{-3}$ eV.

$$\eta\left(\widetilde{m_l}\right) \propto \ \widetilde{m_l}\,\Sigma_l(\widetilde{m_l}).$$

- Strong washout in α and strong-mild washout in β:

$$\eta\left(\widetilde{m_\beta}\right) \propto \left(\left(\frac{\widetilde{m_\beta}}{8.25\times10^{-3}\ \mathrm{eV}}\right)^{-1} + \left(\frac{0.2\times10^{-3}\ \mathrm{eV}}{\widetilde{m_\beta}}\right)^{-1.16}\right)^{-1}.$$

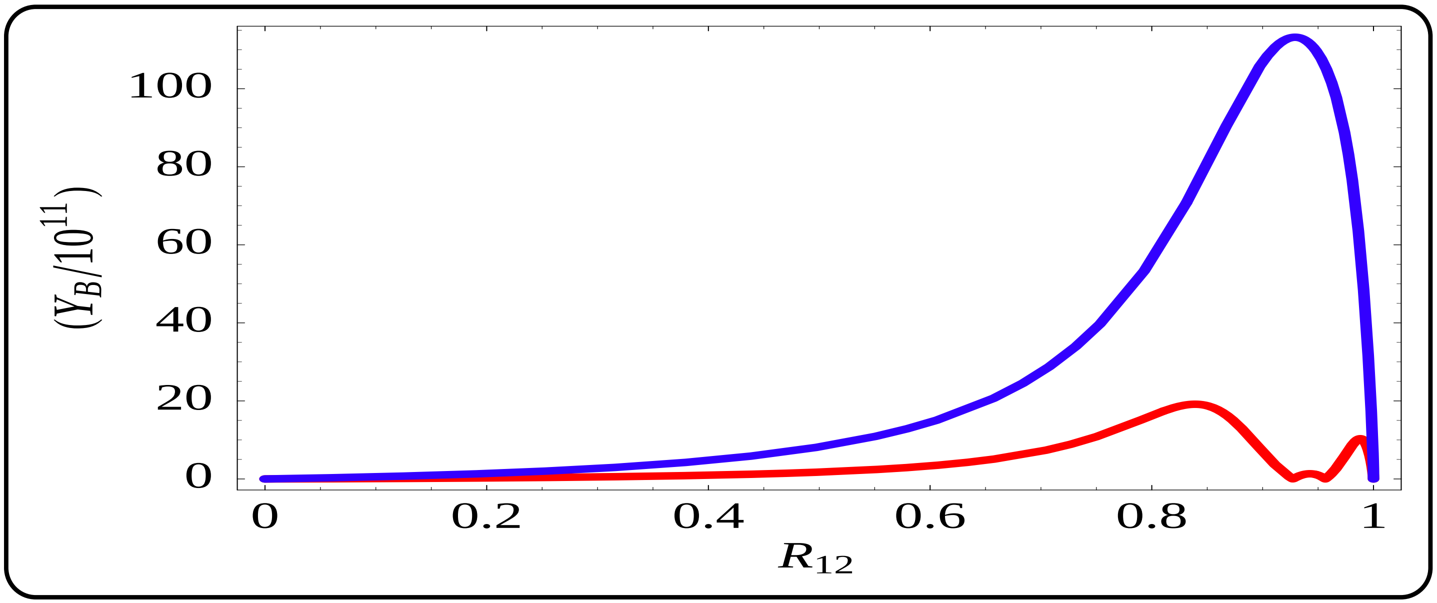
- Maximal asymmetry is obtained in the intermediate regime.

[Abada et al.]

Dependence on R

$$|Y_B| \sim 10^{-8} \frac{M_1}{10^{11}\ \text{GeV}} \frac{|R_{12}||R_{13}|}{\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\text{atm}}}\right)^{\frac{1}{2}} |R_{12}|^2+|R_{13}|^2} \left|\eta\left(\frac{390}{589}\widetilde{m_\tau}\right) - \eta\left(\frac{417}{589}\widetilde{m_2}\right)\right|$$

$$\sim \begin{cases} 2.9\times 10^{-11} \frac{|R_{12}|}{|R_{13}|^{3.32} c_{23}^{2.32}} \left|1 - \left(\frac{390}{417}\ \frac{c_{23}^2}{s_{23}^2}\right)^{1.16}\right| & \text{Strong washout} \\ 1.5\times 10^{-9}\, |R_{12}||R_{13}| & \text{Weak washout} \end{cases}$$

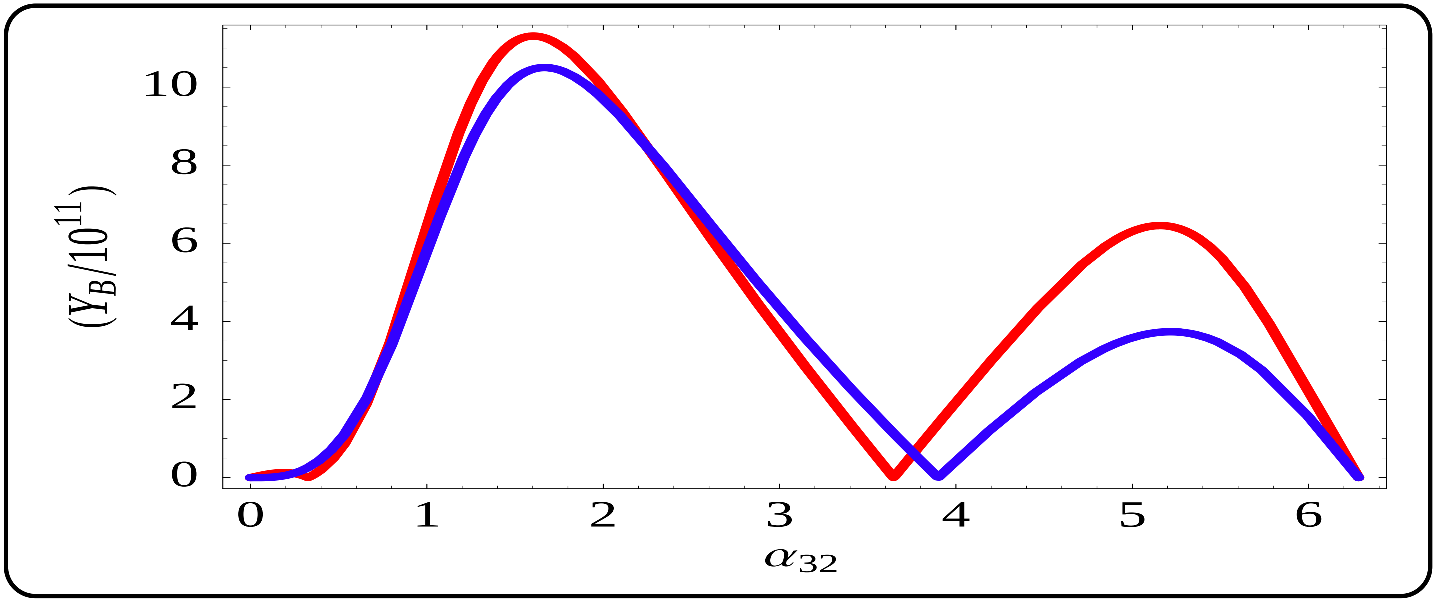


Leptogenesis due to the Majorana phase.

$$\boxed{|Y_B| \propto c_{23}\, c_{13}\, \left(s_{23} c_{12} + c_{23} s_{12} s_{13}\right) \left|\sin \frac{\alpha_{32}}{2}\right|.}$$

Taking $R_{12}^2 = 0.85$, $R_{13}^2 = 0.15$, we get

$$|Y_B| \cong 2.0\,(2.2) \times 10^{-10} \left(\frac{\sqrt{\Delta m^2_{\rm atm}}}{0.05~{\rm eV}}\right) \left(\frac{M_1}{10^{11}~{\rm GeV}}\right)$$



Leptogenesis due uniquely to the Dirac phase.

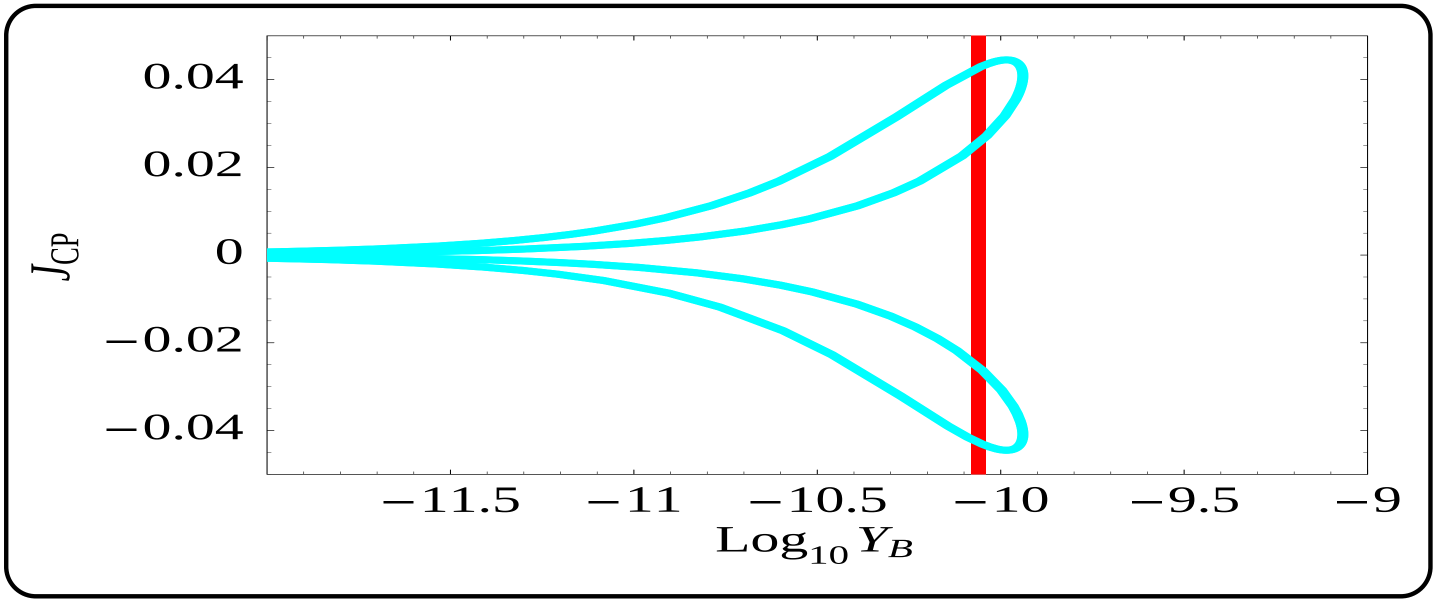
$$\boxed{|Y_B| \propto c_{23}^2 \, s_{12} \, s_{13} \; |\sin\delta| .}$$

For $R_{12}^2 = 0.85$, $R_{13}^2 = 0.15$, we get

$$|Y_B| \cong 2.8 \times 10^{-11} \, |\sin\delta| \, \left(\frac{s_{13}}{0.2}\right) \left(\frac{M_1}{10^{11} \text{ GeV}}\right) \; .$$

Imposing $M_1 < 5 \times 10^{11}$ GeV for flavour effects to be important, we find

$$\boxed{|\sin\theta_{13} \, \sin\delta| \gtrsim 0.11 \, , \quad \sin\theta_{13} \gtrsim 0.11 \, .}$$

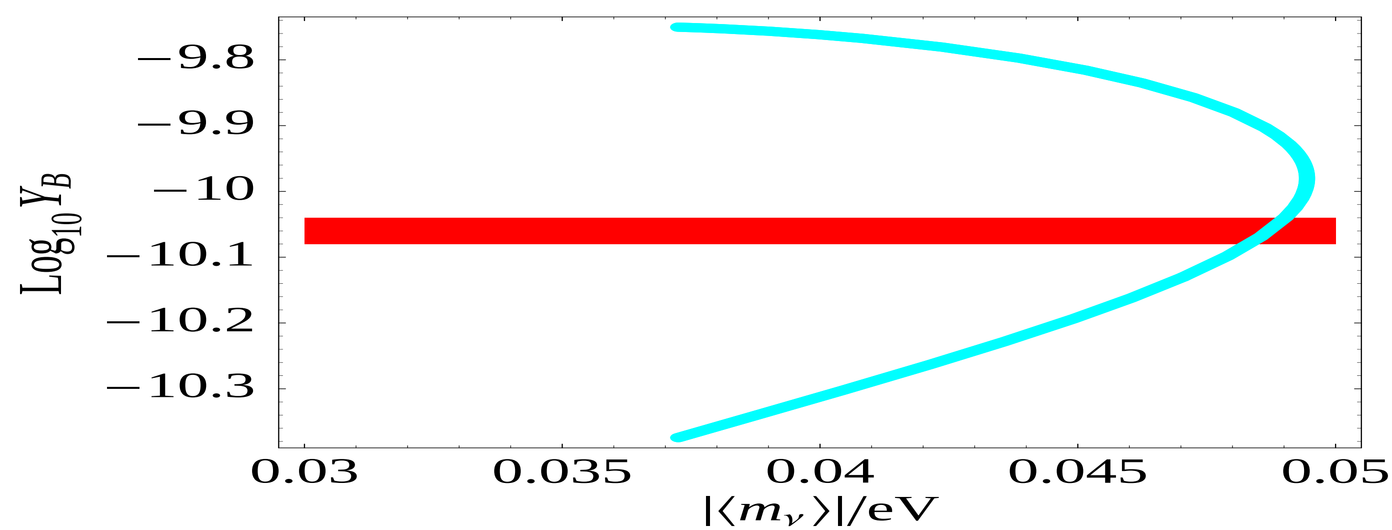


IH spectrum

$$\epsilon_l \simeq \frac{3M_1\sqrt{\Delta m^2_{\rm atm}}}{32\pi v^2}\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}\right)\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}\right)^{\frac{1}{4}}\frac{|R_{11}R_{12}|}{|R_{11}|^2+|R_{12}|^2}\,\mathrm{Im}\,\left(U^*_{l1}U_{l2}\right).$$

$$|Y_B| \cong 2.2\times 10^{-12}\left(\frac{\sqrt{\Delta m^2_{\rm atm}}}{0.05\ \mathrm{eV}}\right)\left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right).$$

In order to have Y_B compatible with observations, $R_{11}R_{12}$ purely imaginary:



The gravitino problem and non-thermal leptogenesis

- Hierarchical leptogenesis requires $M_1 > 2 \times 10^9$ GeV. The reheating temperature $T_{RH} > M_1$.

- In supersymmetric models, high T_{RH} leads to an overproduction of gravitinos. If stable, they typically would overclose the universe. If unstable and decay during and after BBN, they can affect the light elements abundance. These constraints lead to $T_{RH} < 10^9$ GeV.

- Ways out: consider non SUSY models

consider gravitinos in specific mass ranges

enhance asymmetry via resonance

produce N non-thermally (non-thermal leptogenesis): for ex. from inflaton decays.

Current lines of research

- Quantum Boltzmann equations
- Leptogenesis in Type-II see-saw
- Flavour symmetries and leptogenesis
- Non-thermal leptogenesis

13 – Conclusions and outlook

- The evidence of neutrino oscillations implies neutrino masses and mixing.
- The see-saw mechanism provides an elegant explanation for the smallness of neutrino masses. It predicts Majorana neutrinos.
- Leptogenesis takes place in the context of see-saw models and can successfully explain the baryon asymmetry of the Universe.

The observation of L violation ($(\beta\beta)_{0\nu}$-decay)

and of CPV in the lepton sector (neutrino oscillations and/or $(\beta\beta)_{0\nu}$-decay)

would be a strong indication, even if not a proof, of leptogenesis.