Recent Developments

in

Leptogenesis

Pasquale Di Bari

(Max Planck, Munich)

$$\eta_B^{CMB} = (6.1 \pm 0.2) \times 10^{-10} \gg \eta_{\bar{B}}$$

Matter-antimatter asymmetry

Leptogenesis

Neutrino masses and mixing

B-L violation can solve both problems

A minimal extension of the SM

- Adding right-handed neutrinos with Yukawa couplings h and a Majorana mass term M after spontaneous symmetry breaking $\Rightarrow m_D = v\,h \quad (v \equiv \langle \phi_0 \rangle)$

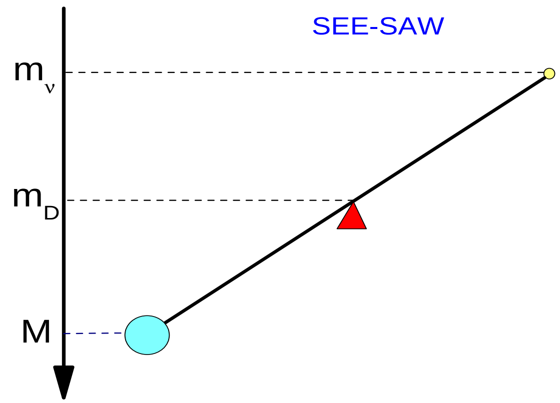
$$\mathcal{L}^{\nu}_{\rm mass} = -\frac{1}{2}\left[(\bar{\nu}_L^c, \bar{\nu}_R)\begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}\right] + h.c.$$

In the see-saw limit ($M \gg m_D$) the spectrum of mass eigenstates splits in 2 sets:

- 3 light neutrinos $\nu_1,\ \nu_2,\ \nu_3$ with masses $m_1 \leq m_2 \leq m_3$ given by:

$$\boxed{\mathrm{diag}(\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3) = -U^{\dagger}\, m_D\, \frac{1}{M}\, m_D^T\, U^{\star}}$$

where U is the mixing matrix

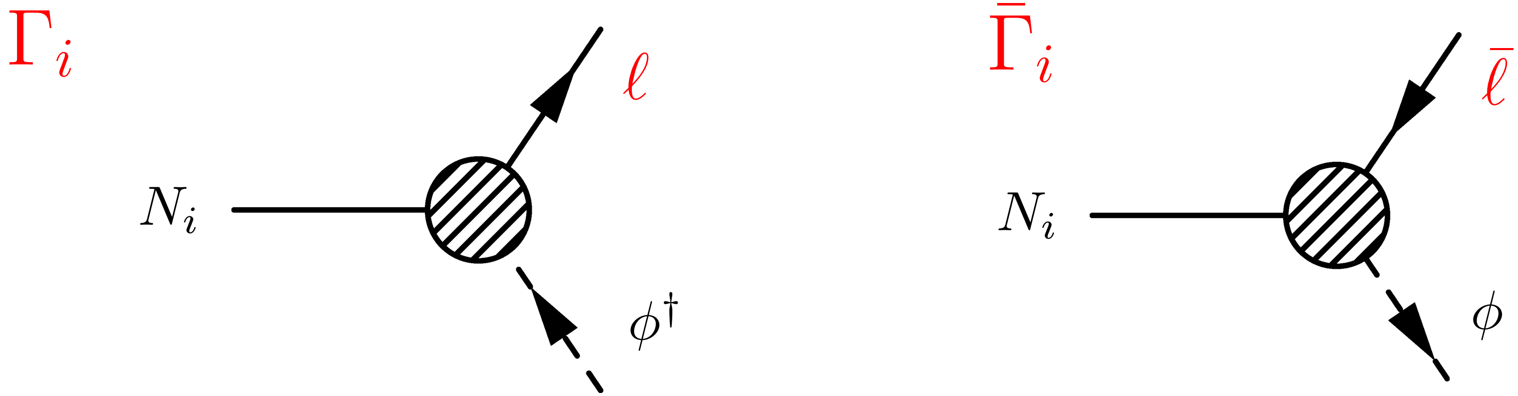


- 3 new heavy RH neutrinos N_1,N_2,N_3 with masses $M_{\rm ew} \ll M_1 \leq M_2 \leq M_3$

Unflavored leptogenesis

(Fukugita, Yanagida '86)

m_D, m_ν and M are complex matrices $\Rightarrow$ natural source of CP violation



- CP asymmetry parameter:

$$\varepsilon_i = -\frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i} \quad \Rightarrow \quad N_{B-L}^{\rm fin} = \sum_i^{1,2,3} \varepsilon_i \, \kappa_i^{\rm fin}$$

efficiency factors $\kappa_i^{\rm fin} \simeq$ # of N_i decaying out-of-equilibrium

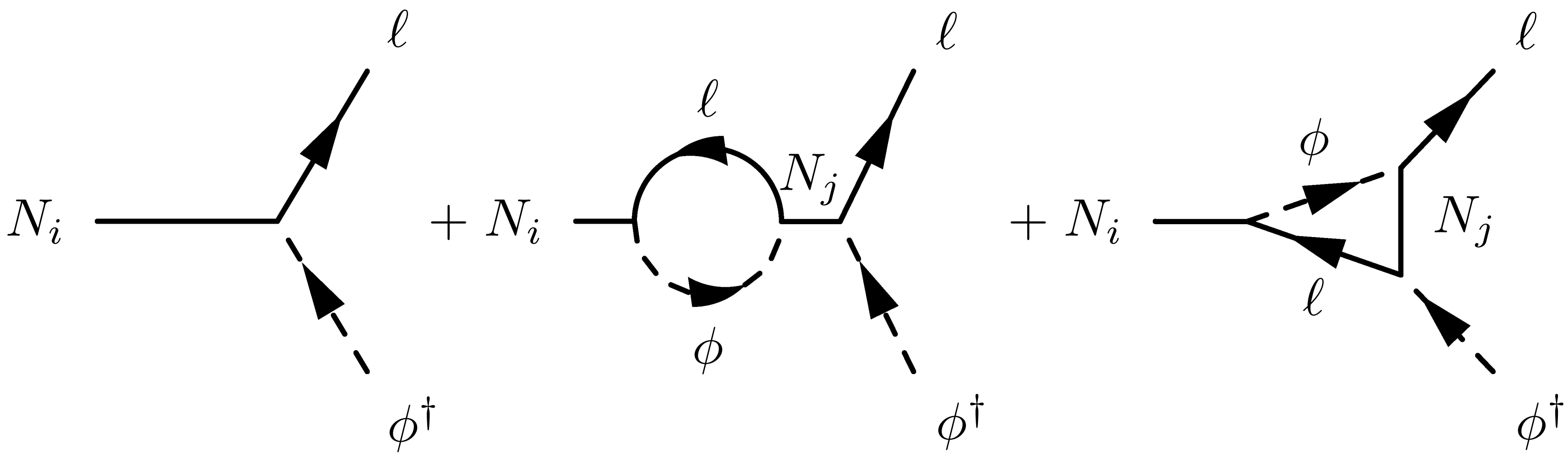
- sphaleron conversion (effective for $10^{12}\,{\rm GeV} \gtrsim T \gtrsim 100\,{\rm GeV}$)

(Kuzmin,Rubakov,Shaposhnikov '85)

$$N_B^{\rm fin} \simeq \frac{1}{3}\,N_{B-L}^{\rm fin} \simeq -\frac{1}{2}\,N_L^{\rm fin} \Rightarrow \boxed{\eta_B \simeq \frac{N_{B-L}^{\rm fin}}{3\,N_\gamma^{\rm rec}} \simeq \; 10^{-2}\,\sum_i \varepsilon_i\,\kappa_i^{\rm fin}}$$

Total CP asymmetries

(Flanz,Paschos,Sarkar'95; Covi,Roulet,Vissani'96; Buchmüller,Plümacher'98)



Assuming $|M_{j\neq i} - M_i| \gg |\Gamma_{j\neq i} - \Gamma_i|$ (off-resonance condition),

the interference between tree level and one-loop diagrams (self energy + vertex) yields:

$$\varepsilon_i \simeq \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j=2,3} \mathrm{Im}\left[(m_D^\dagger\, m_D)^2_{ij}\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

$\Rightarrow$ the ε_i's depend on m_D only through $m_D^\dagger\, m_D \Rightarrow U$ cancels out !

The orthogonal see-saw matrix

(Casas,Ibarra'01)

$$m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \boxed{\Omega^T \Omega = I}$$

$$\boxed{m_D} = \boxed{U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}} \quad \begin{pmatrix} U^\dagger U & = & I \\ U^\dagger m_\nu U^\star & = & -D_m \end{pmatrix}$$

- parameter counting: 6 + 3 + 6 + 3 = 18
  - experiments $\Rightarrow$ information on the 9 'low energy' parameters in $m_\nu = -U\, D_m\, U^T$:
  - the 9 parameters in Ω and in M_i escape conventional investigation: the dark side !
- Ω can be conveniently parameterized in terms of complex rotations:

$$\Omega(\omega_{21}, \omega_{31}, \omega_{32}) = R_{12}(\omega_{21})\; R_{13}(\omega_{31})\; R_{23}(\omega_{32})$$

Unflavored Kinetic equations

$$z \equiv \frac{M_1}{T}$$

$$\begin{aligned}
\frac{dN_{N_i}}{dz} &= -D_i\,(N_{N_i} - N_{N_i}^{\rm eq}) \\
\frac{dN_{B-L}}{dz} &= \sum_i \varepsilon_i\, D_i\,(N_{N_i} - N_{N_i}^{\rm eq}) - N_{B-L}\,\sum_i W_i
\end{aligned}$$

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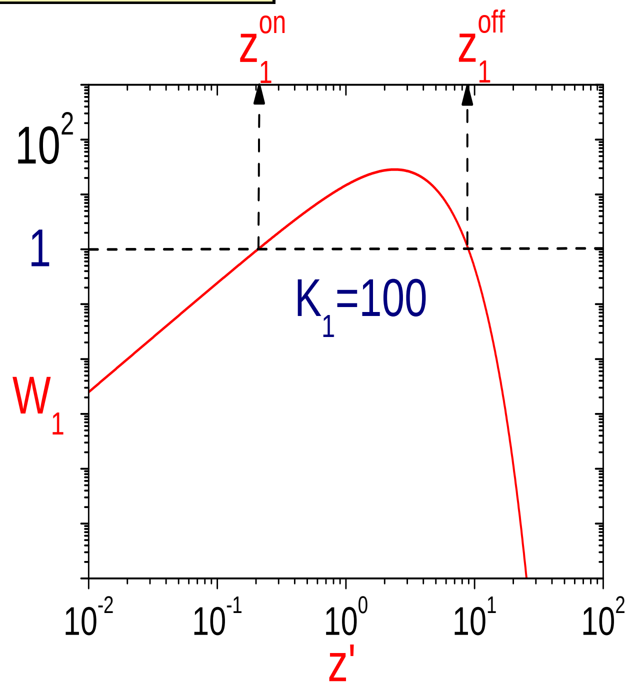
$$N_{B-L}^{\rm fin} = N_{B-L}^{\rm in}\, e^{-\sum_i \int_{z_{\rm in}}^{\infty} dz'\, W_i(z')} + \sum_i \varepsilon_i\, \kappa_i^{\rm fin}$$

$$\kappa_i^{\rm fin} = -\int_{z_{\rm in}}^{\infty} dz'\, \frac{dN_{N_i}}{dz'}\, e^{-\sum_j \int_{z'}^{\infty} dz''\, W_j(z'')}$$



- decay parameters

$$D_i, W_i \propto K_i \equiv \frac{2\,t_U(T=M_i)}{\tau_i} \simeq \frac{\widetilde{m}_i}{m_\star}\,, \quad m_\star \simeq 10^{-3}\,{\rm eV}$$

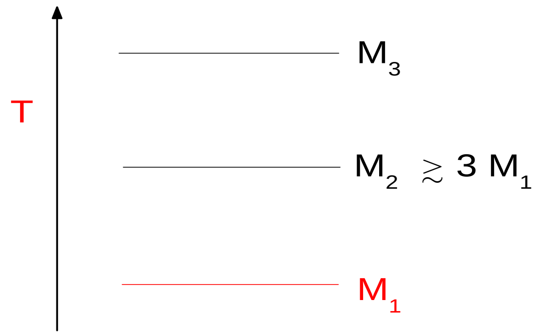
- Weak wash-out regime for $K_j \lesssim 1 \Rightarrow W_j \lesssim 1$ for any z'
- Strong wash-out regime for $K_j \gtrsim 1 \Rightarrow W_j \gtrsim 1$ in some interval $[z_j^{\rm on}, z_j^{\rm off}]$.

Unflavored N_1-dominated scenario

(Davidson, Ibarra '02; Buchmuller,PDB,Plumacher '02; '03; '04; Giudice, Notari, Raidal, Riotto, Strumia, '03)

Assuming:

1. Hierarchical heavy neutrino spectrum



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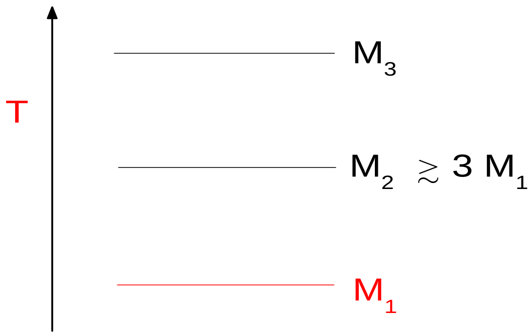

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$$\Rightarrow |\varepsilon_3|, |\varepsilon_2| \ll |\varepsilon_1|$$

$$\Rightarrow \kappa_{j\neq 1}^{\rm fin} \simeq \kappa_{j\neq 1}^{T\sim M_j}\, e^{-K_1}$$

$$\Rightarrow \boxed{N_{B-L}^{\rm fin} = \sum_i \varepsilon_i\, \kappa_i^{\rm fin} \simeq \varepsilon_1\, \kappa_1^{\rm fin}}$$

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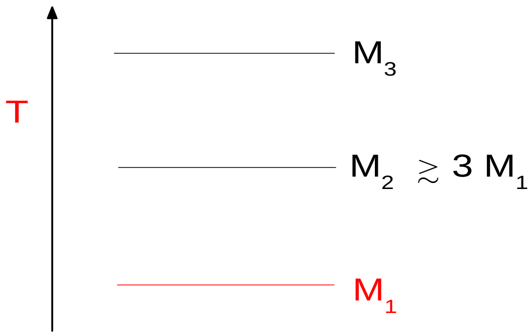
$$\Rightarrow \eta_B \simeq \frac{1}{3}\,\frac{N_{B-L}^{\rm fin}}{N_\gamma^{\rm rec}} = \eta_B^{\rm max}(m_1, M_1)\,\sin\delta_L$$



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$$\varepsilon_1 \simeq \bar{\varepsilon}(M_1)\,\frac{m_{\rm atm}}{m_1+m_3}\,\sin\delta_L(m_1,\Omega)\,,$$

$$\bar{\varepsilon}(M_1) \simeq 10^{-6}\,\left(\frac{M_1}{10^{10}\,{\rm GeV}}\right)$$

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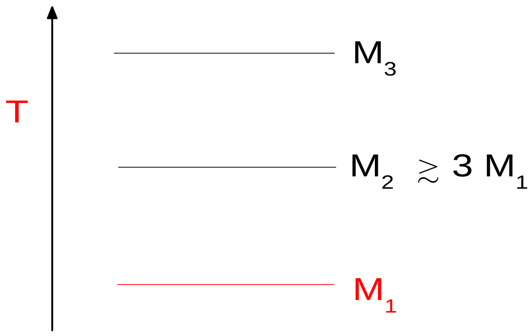

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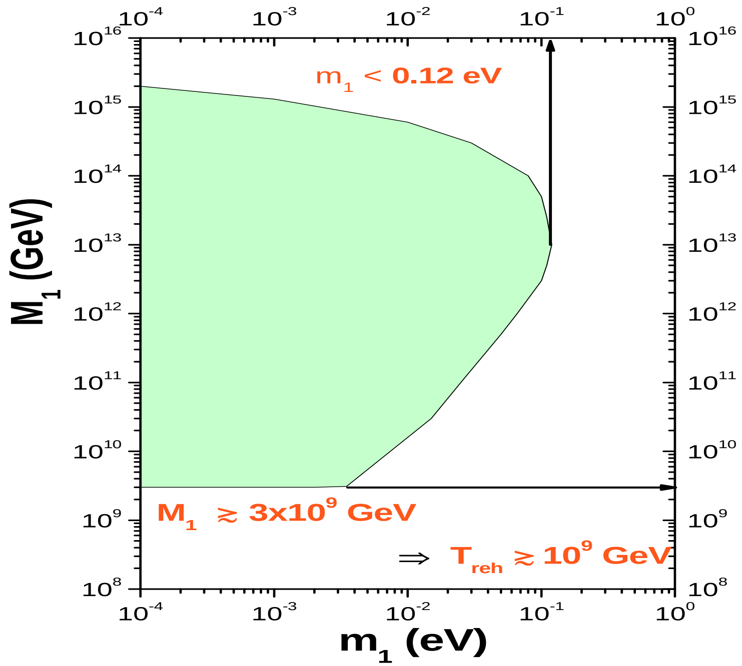
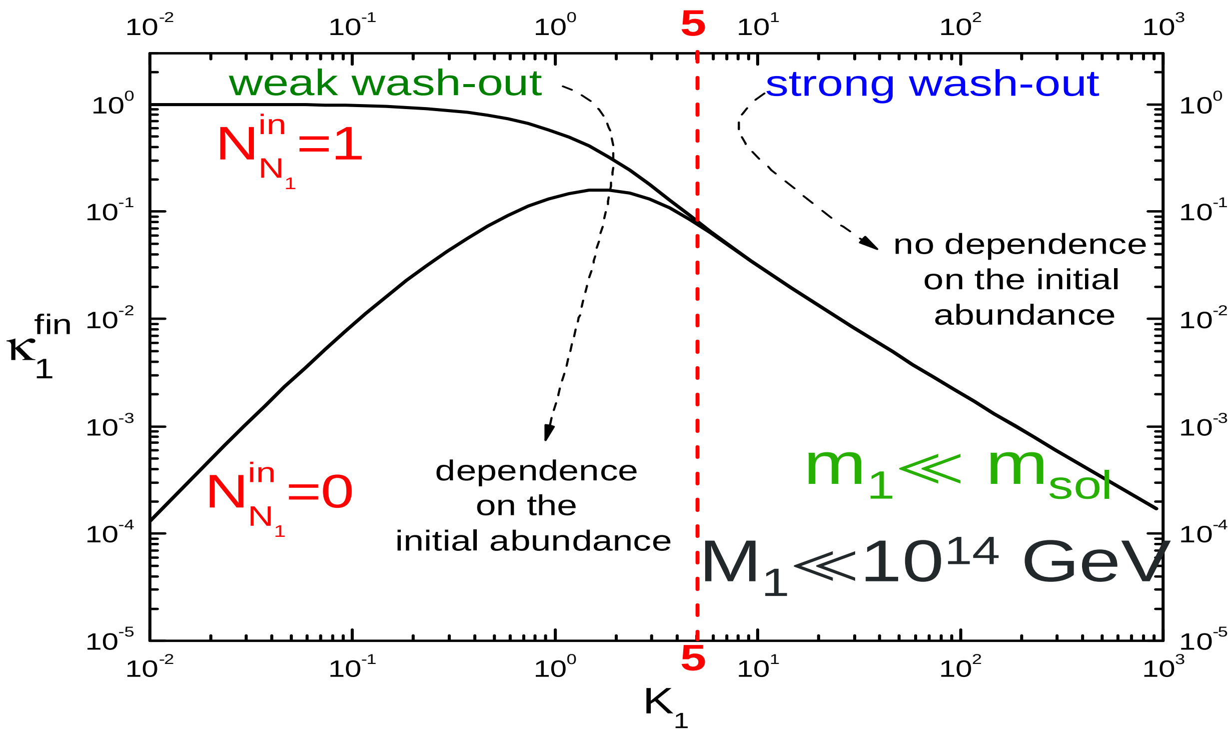
Successful leptogenesis requires:

$$\eta_B^{\rm max}(m_1, M_1) \geq \eta_B^{CMB}$$



Dependence on the initial conditions



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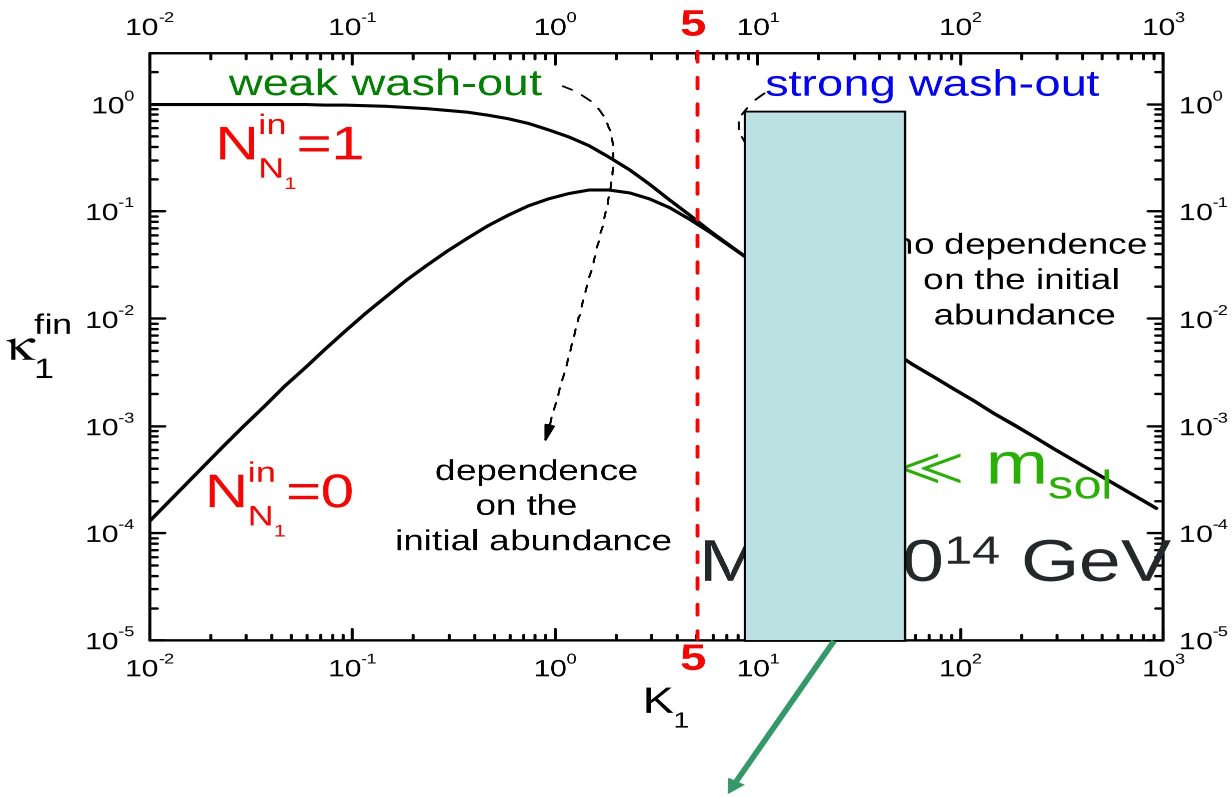
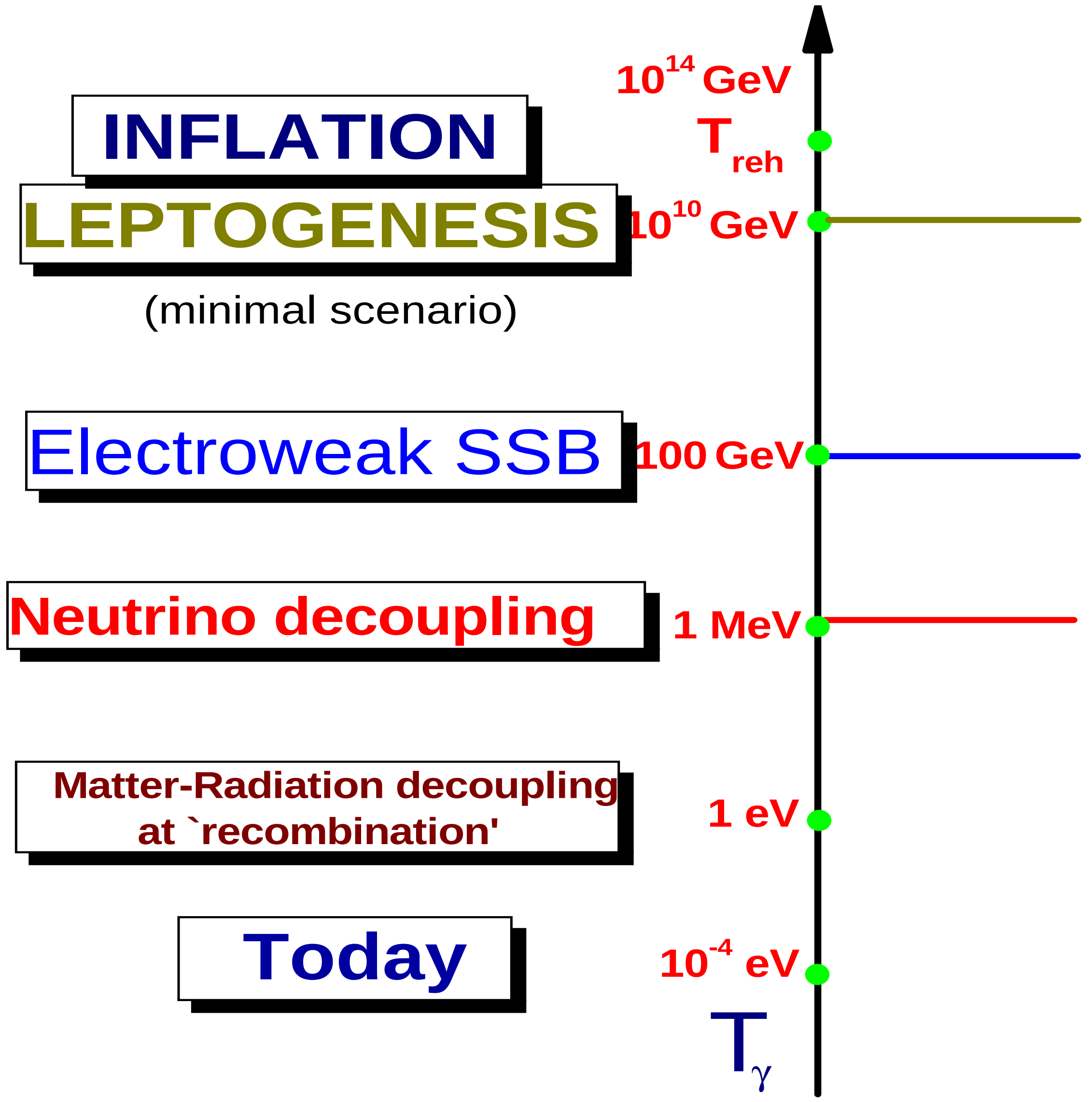


$$K_{\rm sol} \simeq 9 \lesssim K_1 \lesssim 50 \simeq K_{\rm atm}$$

Neutrino mixing data favor the strong wash-out regime !

A very hot Universe for leptogenesis ?



Beyond the unflavored N_1-dominated scenario

- N_2-dominated scenario
- beyond the hierarchical limit
- flavor effects

N_2-dominated scenario

Until now we assumed $\Omega \simeq R_{12}\, R_{13}$, but for:

$$\Omega \simeq R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sqrt{1-\omega_{32}^2} & -\omega_{32} \\ 0 & \omega_{32} & \sqrt{1-\omega_{32}^2} \end{pmatrix} \Longrightarrow$$

- $\varepsilon_1 = 0 \;\Rightarrow$ no asymmetry from N_1-decays
- $\varepsilon_2 \lesssim \varepsilon^{\max}(m_1, M_2)$

  $\Rightarrow$ asymmetry from N_2-decays
- $K_1 = m_1/m_\star$ AND IF $m_1 \lesssim m_\star \simeq 10^{-3}\,\mathrm{eV}$

  $\Rightarrow$ negligible wash-out from N_1-inverse decays

$$\Rightarrow \boxed{N_{B-L}^{\rm fin} = \sum_i \varepsilon_i\, \kappa_i^{\rm fin} \simeq \varepsilon_2\, \kappa_2^{\rm fin}}$$

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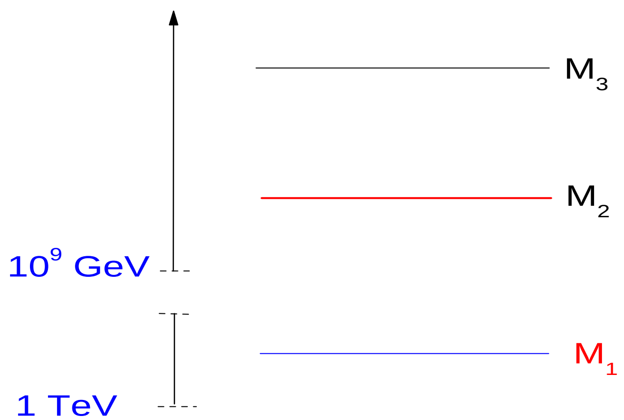
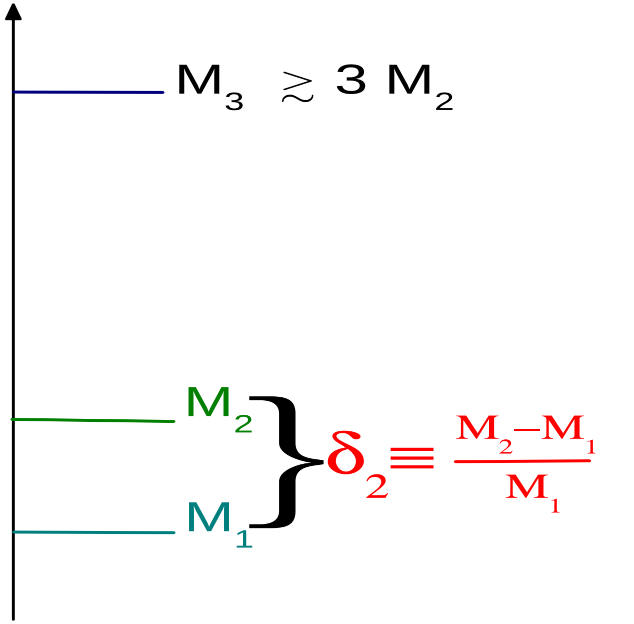


No lower bound on M_1 ! It is replaced by a lower bound on M_2 (still yielding a lower bound on $T_{\rm reh}$) !

Beyond the hierarchical limit

(Pilaftsis '97, Hambye, Lin, Notari, Papucci, Strumia '03; S.Blanchet, PDB '06)



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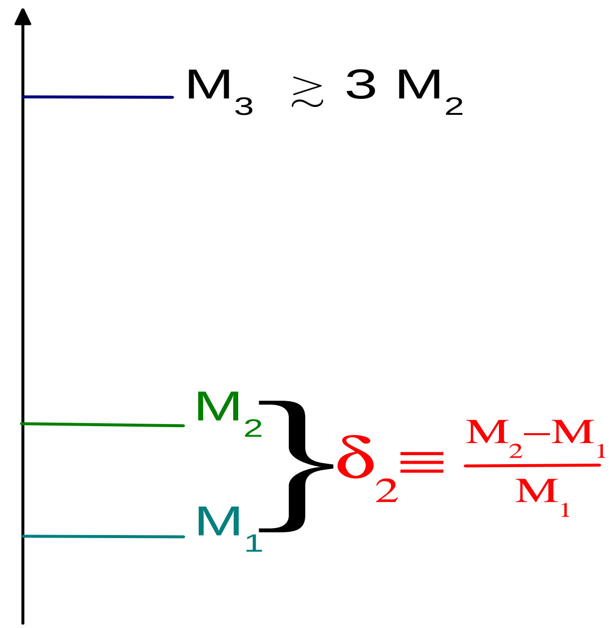

- for $1 \gtrsim \delta_2 \gtrsim 0.01$ three effects play simultaneously a role:

  1. Asymmetries add up:
     $$N_{B-L}^{\rm fin} \simeq \varepsilon_1\, \kappa_1^{\rm fin} + \varepsilon_2\, \kappa_2^{\rm fin} \;\Rightarrow\; N_{B-L}^{\rm fin} \nearrow$$
  2. Wash-out add up as well $\Rightarrow N_{B-L}^{\rm fin} \searrow$
  3. CP asymmetries get enhanced:
     $$\varepsilon_{1,2} \simeq \frac{\varepsilon_{1,2}(M_2 \gg M_1)}{3\, \delta_2} \;\Rightarrow\; N_{B-L}^{\rm fin} \nearrow$$

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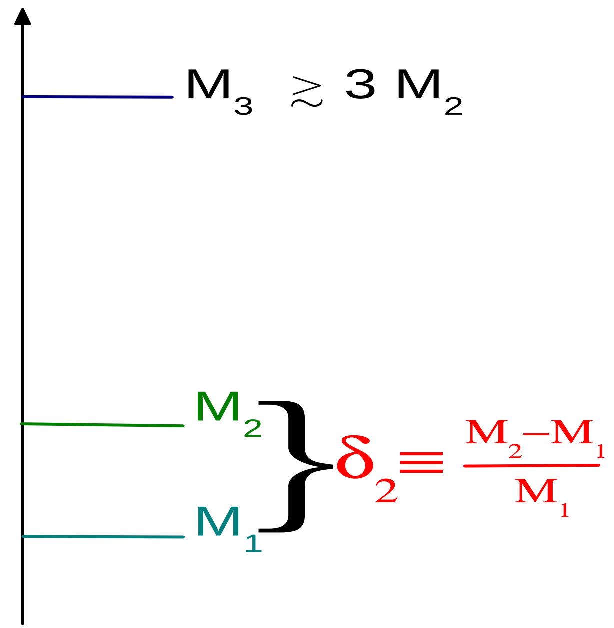

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- for $\delta_2^{\rm res} \ll \delta_2 \lesssim 10^{-2}$ (**degenerate limit**) the first 2 effects saturate $\Rightarrow N_{B-L}^{\rm fin} \propto \delta_2^{-1}$:

$$\boxed{M_1 \gtrsim 4\times 10^9\,{\rm GeV}\,\left(\frac{\delta_2}{0.01}\right) \quad \text{and} \quad T_{\rm reh} \gtrsim 5\times 10^8\,{\rm GeV}\,\left(\frac{\delta_2}{0.01}\right)}$$

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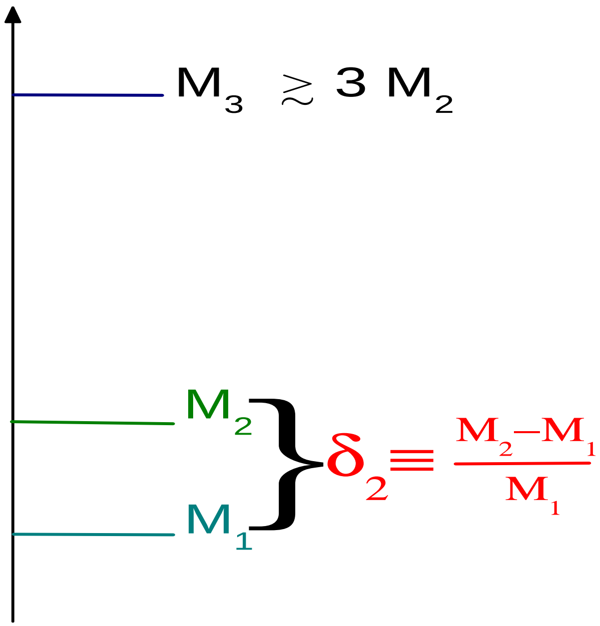

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- for $\delta_2 \sim \delta_2^{\rm res} \sim \bar{\varepsilon}(M_1) \Rightarrow \varepsilon_{1,2} \sim \mathcal{O}(0.1)$ (**resonant leptogenesis**)

  $\Rightarrow$ these lower bounds disappear (but still $T_{\rm reh} \gtrsim 100\,{\rm GeV}$!)

Flavor effects

(Nardi, Nir, Roulet, Racker ’06; Abada et al. ’06; Blanchet, PDB, Raffelt ’06)

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- Flavor composition

$$N_1 \longrightarrow l_1\, H^\dagger\,, \quad |l_1\rangle = \sum_{\alpha=e,\mu,\tau} \langle l_\alpha | l_1\rangle\, |l_\alpha\rangle$$

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- $M_1 \lesssim 10^{12}\,\mathrm{GeV}$ $\Rightarrow$ τ-Yukawa interactions ($f_{\tau\tau}\,\bar{l}_{L\tau}\,\phi\,e_{R\tau}$) are fast enough ($\Gamma_\tau \gtrsim \Gamma_{\mathrm{ID}}$) to break the coherent evolution of the $|l_1\rangle$ and $|\bar{l}'_1\rangle$ quantum states

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- imposing even a more restrictive condition

$$M_1 \lesssim \frac{10^{12}\,\mathrm{GeV}}{2\,W_1(T_B)} \lesssim 10^{12}\,\mathrm{GeV}\,,$$

$\Rightarrow$ $|l_1\rangle$ and $|\bar{l}_1'\rangle$ are projected on the flavor basis and a fully flavored regime holds!

Fully flavored regime

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- Projectors

$$P_{1\alpha} \equiv |\langle l_\alpha | l_1 \rangle|^2 = P^0_{1\alpha} + \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha P^0_{1\alpha} = 1 \right)$$

$$\bar{P}_{1\alpha} \equiv |\langle \bar{l}_\alpha | \bar{l}'_1 \rangle|^2 = P^0_{1\alpha} - \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha \Delta\, P_{1\alpha} = 0 \right)$$

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These 2 terms correspond respectively to 2 different flavor effects:

1) wash-out is in general reduced: $K_1 \to K_{1\alpha} \equiv K_1 \, P^0_{1\alpha}$

2) additional CP violating contribution $\left(|\bar{l}'_1\rangle \neq CP|l_1\rangle \right)$

$$\Rightarrow \quad \boxed{\varepsilon_{1\alpha} \equiv -\frac{P_{1\alpha}\,\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = P^0_{1\alpha}\,\varepsilon_1 + \Delta P_{1\alpha}(\Omega, U)/2}$$

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- Classic Kinetic Equations (in their simplest form)

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N^{\rm eq}_{N_1} \right)$$

$$\frac{dN_{\Delta_\alpha}}{dz} = -\varepsilon_{1\alpha}\, \frac{dN_{N_1}}{dz} - P^0_{1\alpha}\, W_1\, N_{\Delta_\alpha}$$

$$(\Delta_\alpha \equiv B/3 - L_\alpha)$$

Fully flavored regime

- Projectors

$$P_{1\alpha} \equiv |\langle l_\alpha | l_1 \rangle|^2 = P^0_{1\alpha} + \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha P^0_{1\alpha} = 1 \right)$$

$$\bar{P}_{1\alpha} \equiv |\langle \bar{l}_\alpha | \bar{l}'_1 \rangle|^2 = P^0_{1\alpha} - \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha \Delta P_{1\alpha} = 0 \right)$$

These 2 terms correspond respectively to 2 different flavor effects:

1) wash-out is in general reduced: $K_1 \rightarrow K_{1\alpha} \equiv K_1\, P^0_{1\alpha}$

2) additional CP violating contribution $\left(|\bar{l}'_1\rangle \neq CP|l_1\rangle \right)$

$$\Rightarrow \boxed{\varepsilon_{1\alpha} \equiv -\frac{P_{1\alpha}\,\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = P^0_{1\alpha}\,\varepsilon_1 + \Delta P_{1\alpha}(\Omega, U)/2}$$

- Classic Kinetic Equations (in their simplest form)

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N^{\rm eq}_{N_1} \right)$$

$$\frac{dN_{\Delta_\alpha}}{dz} = -\varepsilon_{1\alpha}\, \frac{dN_{N_1}}{dz} - P^0_{1\alpha}\, W_1\, N_{\Delta_\alpha}$$

$$\Rightarrow \quad N_{B-L} = \sum_\alpha N_{\Delta_\alpha} \qquad (\Delta_\alpha \equiv B/3 - L_\alpha)$$

Are Classic Kinetic Equations enough ?

(Abada et al. '06; Blanchet, PDB, Raffelt '06; De Simone, Riotto '06)

- Unflavored regime holding for $M_1 \gtrsim 10^{12}\,\mathrm{GeV}$

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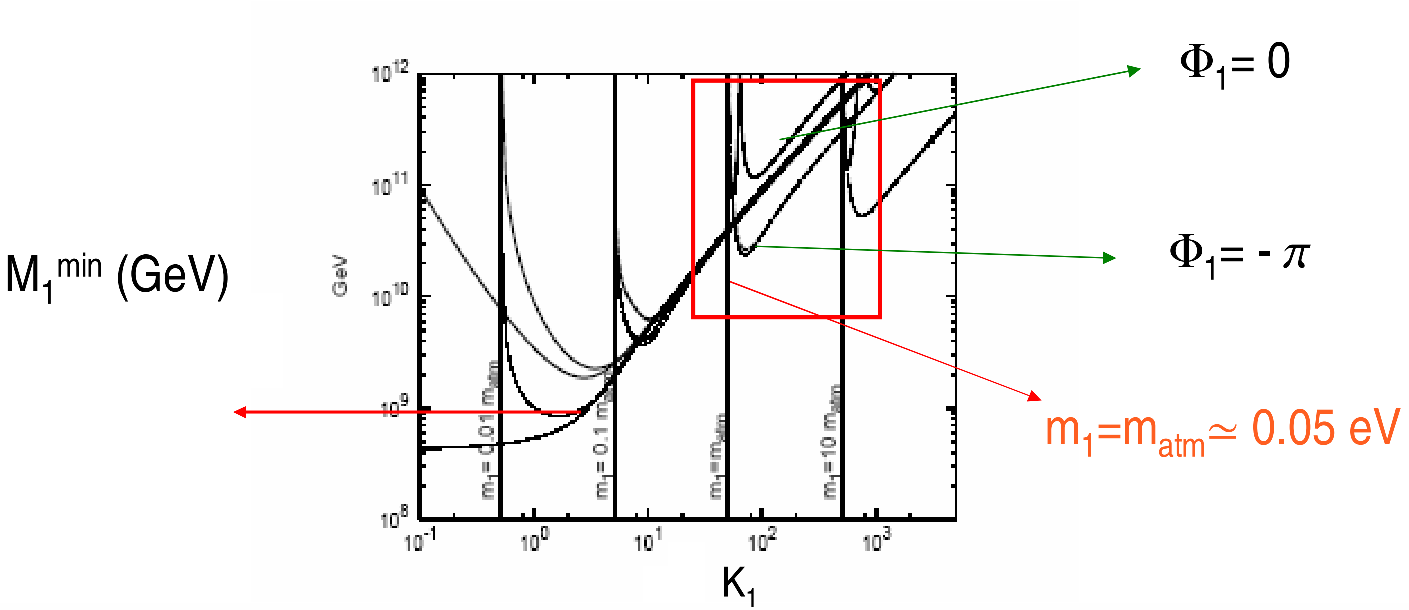
$\Rightarrow$ there is an intermediate regime that requires a (not fully developed !) quantum kinetic treatment in terms of density matrix equations

A description of this intermediate regime is important to answer some questions !

Lower bound on M_1

- The lowest bound on M_1, obtained for $K_1 \to 0$, is the same: $M_1 \gtrsim 10^9\,\mathrm{GeV}$

- For $m_1 \gtrsim 0.1\, m_{\rm atm}$ the lower bound on M_1 gets relaxed by flavor effects at large K_1 especially when Majorana phases are turned on !

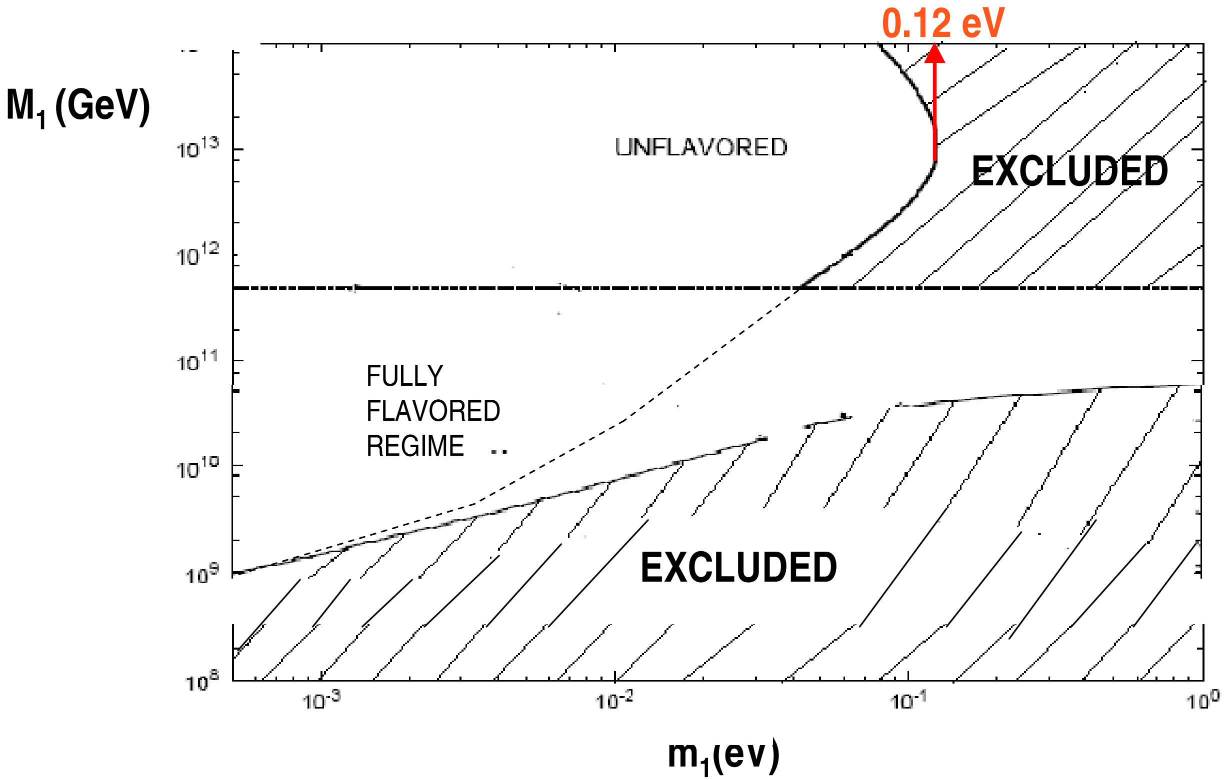


$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\,\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\,\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\,\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\,\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\,\delta} & c_{23}\,c_{13} \end{pmatrix} \times \mathrm{diag}(e^{i\frac{\Phi_1}{2}}, e^{i\frac{\Phi_2}{2}}, 1)\,,$$

Upper bound on m_1

There is no upper bound on m_1 in the fully flavoured regime !

(Abada,Davidson, Losada, Riotto'06; Blanchet, PDB'06)



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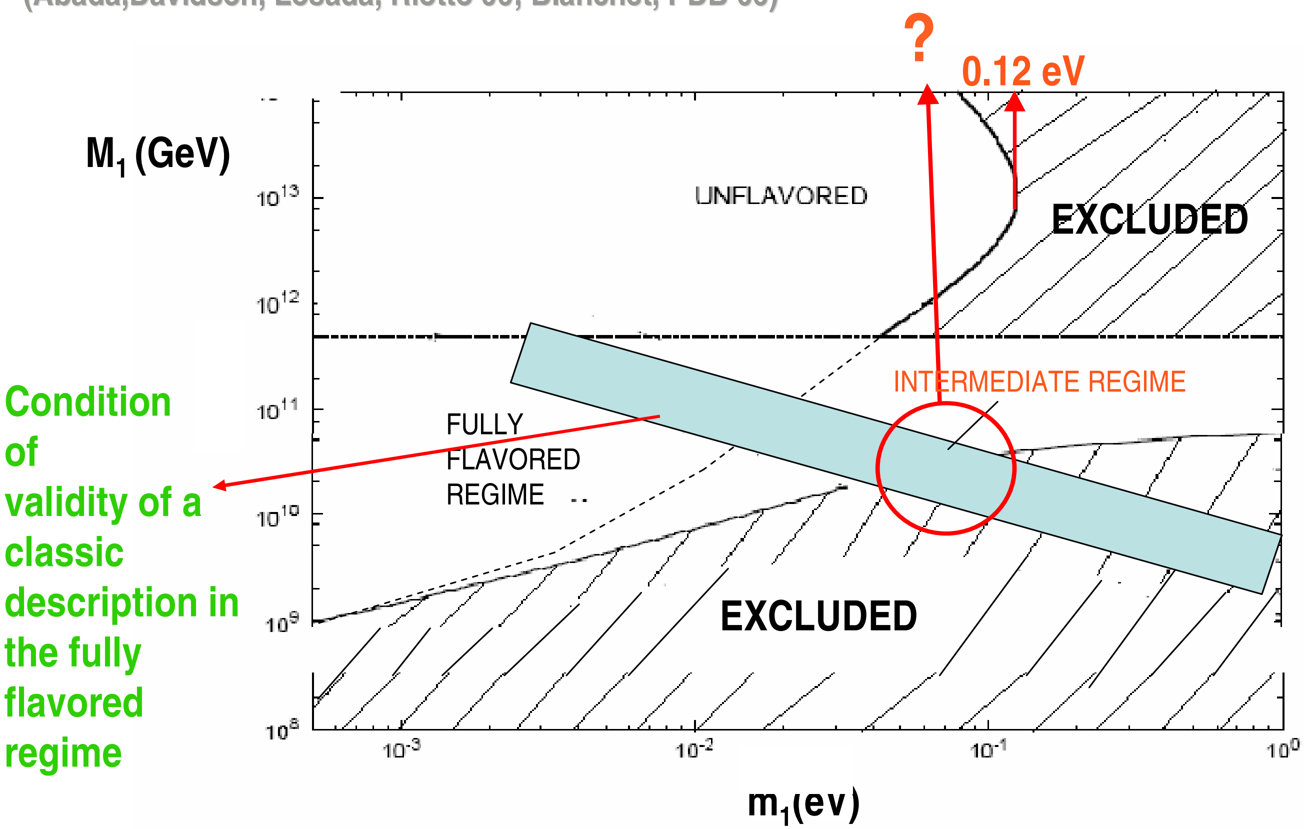

Is the fully flavoured regime suitable to answer the question ?

No ! There is an intermediate regime where a full quantum kinetic description is necessary !

(Blanchet,PDB,Raffelt '06)

An interesting <u>exercise</u>: δ-leptogenesis

(Abada et al. '06; Blanchet, PDB '06; Pascoli, Petcov, Riotto '06; Branco et al. '06; Blanchet, PDB '07)

- Assume Ω matrix real $\Rightarrow \varepsilon_{1\alpha} = \cancel{P^0_{1\alpha}\varepsilon_1} + \Delta P_{1\alpha}/2$
- Assume furthermore $\Phi_1 = \Phi_2 = 0 \;\Rightarrow\; \delta$ is the only source of CP violation !

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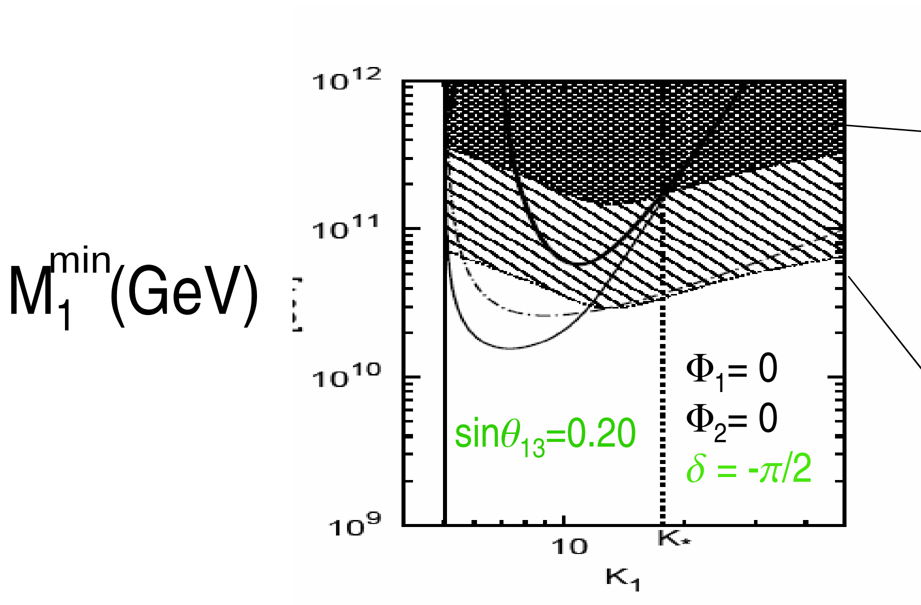

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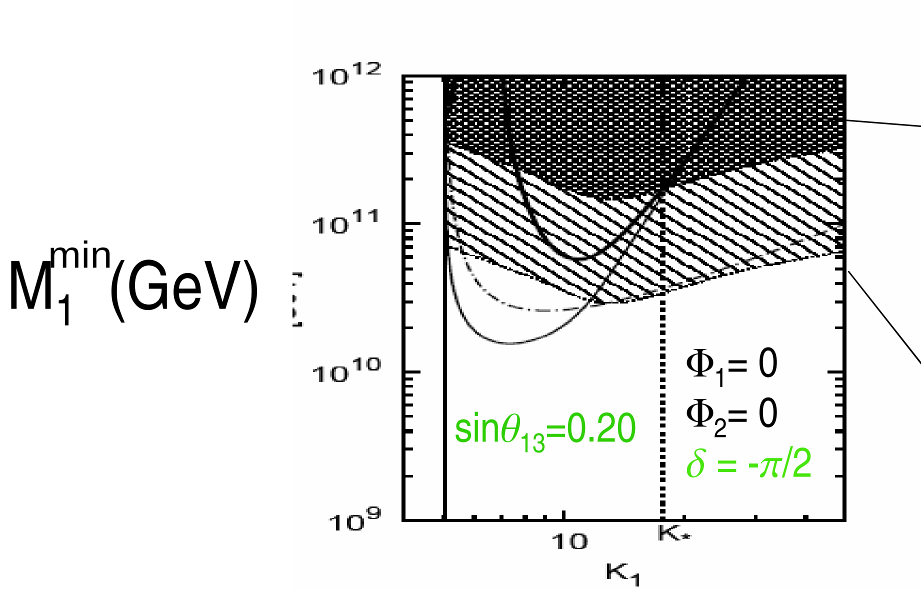

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Here some minor corrections are also expected

- a quantum kinetic description is strongly required
- only a marginally allowed region with strong dependence on initial conditions

Full degenerate limit: $M_1 \simeq M_2 \simeq M_3$

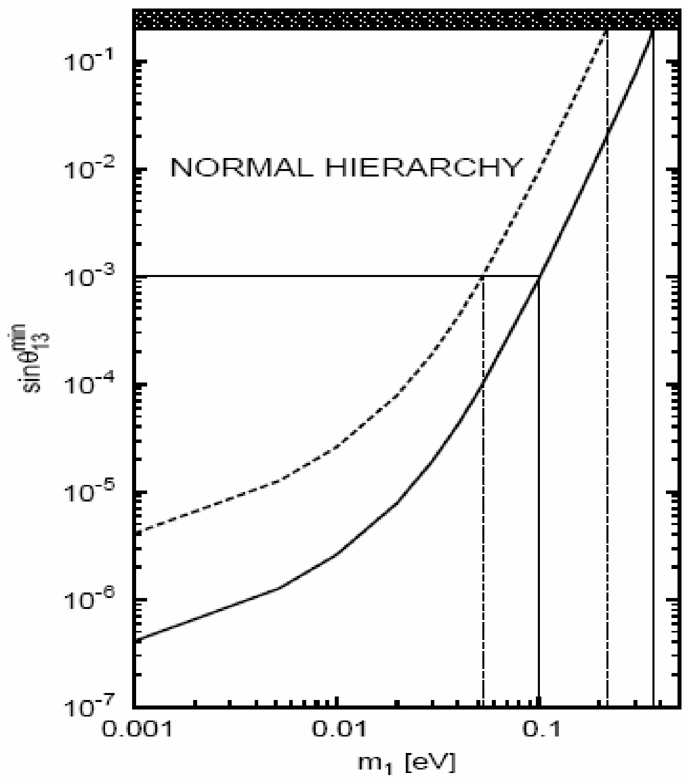
$$\delta_{31} \equiv \frac{M_3 - M_1}{M_1}$$

$$M_1 \gtrsim 5 \times 10^9\ \mathrm{GeV}\ \frac{\delta_{31}}{|\sin\theta_{13}\ \sin\delta|} \qquad (\delta_{31} \lesssim 0.01)$$

The **maximum enhancement of the CP asymmetries** is obtained in so called **resonant leptogenesis**

$$\delta_{31}^{\mathrm{res}} \simeq (1 \div 10)\, \frac{\overline{\varepsilon}(M_1)}{3}$$

$\Longrightarrow$ lower bound on **sin θ_{13}** and upper bound on **m_1**



- Some remarks on δ-leptogenesis

- **negative**: δ-leptogenesis is currently missing a theoretical motivation, this is why it has to be regarded at the moment as an exercise, but . . .

- **positive**: it is an interesting exercise, since if CP violation in neutrino mixing is discovered it is nice to know that, under some conditions (degenerate RH neutrino spectrum !), a known phase can act as the only source of CP violation

- **neutral** if CP violation is not discovered it does not mean that leptogenesis is ruled out, on the other hand if it is discovered the picture is certainly strengthened !

Summary of present results and ...

- Unflavored N_1-leptogenesis $\Rightarrow$ nice ‘conspiracy’ with ν-mixing data and important neutrino mass bounds: $M_1, T_{\rm reh} \gtrsim 10^9\,{\rm GeV}$, $m_1 \lesssim 0.12\,{\rm eV}$;
- N_2-leptogenesis: minimal way to evade the M_1-lower bound; while degenerate limit is necessary to allow low $T_{\rm reh}$;
- Flavor effects: important recent development but not a revolution ! They have to be taken into account since $[N_{B-L}^{\rm fin}]_{\rm fl}/[N_{B-L}^{\rm fin}]_{\rm unfl} \gg 1$ in some cases;
- The most extreme case is leptogenesis stemming only from low energy phases: $[N_{B-L}^{\rm fin}]_{\rm fl}/[N_{B-L}^{\rm fin}]_{\rm unfl} = \infty$. In particular δ-leptogenesis is an interesting exercise because δ can be realistically measured in next years and it is nice to know that it can be the only source of CP violation for successful leptogenesis.
- A full quantum kinetic treatment is highly desirable: urgent goal in future research activity in leptogenesis.

...a wish-list for future

- $T_{\rm reh} \gtrsim 100\,{\rm GeV}$
- non viable Electro-weak Baryogenesis
- CP violation in neutrino mixing
- $\beta\beta 0\nu$ decay
- SUSY discovery with the right features:
  - non viable electro-weak baryogenesis
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- the dream: production of heavy RH neutrinos at LHC

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