XIV International Workshop on Neutrino Telescopes
Venice, 15-18 March 2011

Leptogenesis

and

neutrino masses

Pasquale Di Bari

The double side of Leptogenesis

Cosmology (early Universe) ←  → Neutrino Physics, New Physics

- *Cosmological Puzzles* :

1. Dark matter
2. Matter - antimatter asymmetry
3. Inflation
4. Accelerating Universe

- *New stage in early Universe history* :

T		
< 10^{14} GeV	—	Inflation
	—	Leptogenesis
100 GeV	—	EWSSB
0.1- 1 MeV	—	BBN
0.1- 1 eV	—	Recombination

Leptogenesis complements low energy neutrino experiments testing the seesaw mechanism high energy parameters

⇒ It provides a precious information on the BSM physics responsible for neutrino masses and mixing: a *model builders compass*

Primordial matter-antimatter asymmetry

- Symmetric Universe with matter- anti matter domains ?

  Excluded by CMB + cosmic rays

  $$\Rightarrow \eta_B^{CMB} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.2 \pm 0.15) \times 10^{-10}$$

- Pre-existing ? It conflicts with inflation ! (Dolgov '97)

$\Rightarrow$ **dynamical generation (baryogenesis)**

(Sakharov '67)

Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: normal or inverted

$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

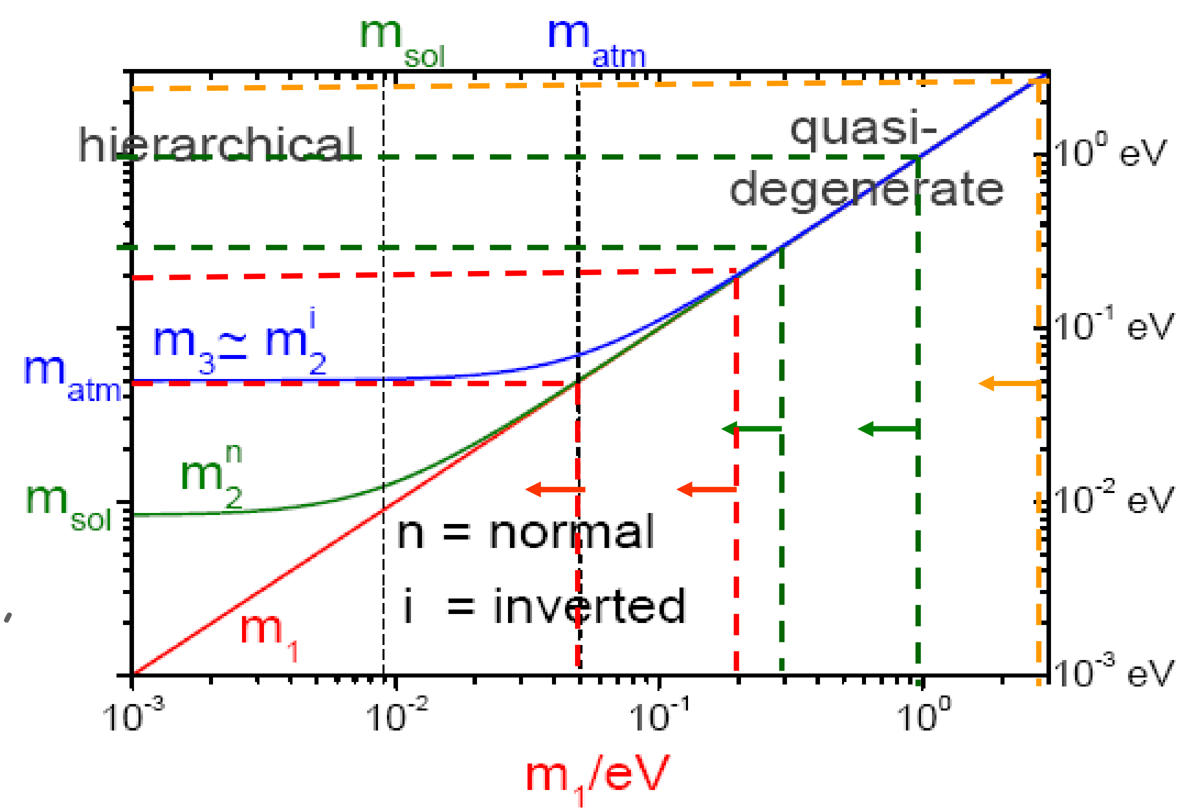
$$m_2^2 - m_1^2 = \Delta m^2_{\rm sol} \text{ or } \Delta m^2_{\rm atm} \qquad m_{\rm sol} \equiv \sqrt{\Delta m^2_{\rm sol}} \simeq 0.009\,{\rm eV}$$

Tritium β decay :m_e<2.3 eV
(Mainz 95% CL)

$\beta\beta 0\nu$:$m_{\beta\beta}$< 0.3 – 1.0 eV
(Heidelberg-Moscow 90% CL, CUORICINO)

Cosmology:

Σ m_i < (0.2-0.6) eV (90% CL),
(Melchiorri, Lisi talk)



Minimal scenario

• Type I seesaw

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

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

$$\mathrm{diag}(m_1, m_2, m_3) = -U^\dagger\, m_D\, \frac{1}{M}\, m_D^T\, U^\star$$

- 3 new heavy RH neutrinos N_1, N_2, N_3 with masses $M_3 > M_2 > M_1 \gg m_D$

• Thermal production of the RH neutrinos $\Rightarrow$ $T_{RH} \gtrsim M_i$

An impossible task ?

Is it possible to reconstruct m_D and M just from low energy neutrino experiments measuring m_i and U_{PMNS} ?

(Casas,Ibarra'01)

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

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

(in the basis where charged lepton and Majorana mass matrices are diagonal)

- parameter counting: 6 + 3 + 6 + 3 = 18

However, hand neutrino experiments give information only on the 9 parameters contained in $m_\nu = -U\, D_m\, U^T$

The **6 parameters in the orthogonal matrix Ω** [it encodes the 3 life times and the 3 total CP asymmetries of the RH neutrinos and it is an invariant (King '07)] **+ the 3 masses M_i** escape the conventional investigation !

Leptogenesis is important to obtain information on the high energy parameters complementing the low energy neutrino experiments

The simplest description: vanilla leptogenesis

1) Flavor composition of final leptons is neglected

$$N_i \xrightarrow{\Gamma} l_i\, H^\dagger \qquad\qquad N_i \xrightarrow{\bar{\Gamma}} \bar{l}_i\, H$$

Total CP asymmetries

$$\varepsilon_i \equiv -\frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i}$$

If $\varepsilon_i \neq 0$ a **lepton asymmetry** is generated from N_i decays and partly converted into a **baryon asymmetry** by sphaleron processes **if $T_{reh} \gtrsim 100$ GeV !** (Kuzmin, Rubakov, Shaposhnikov, '85)

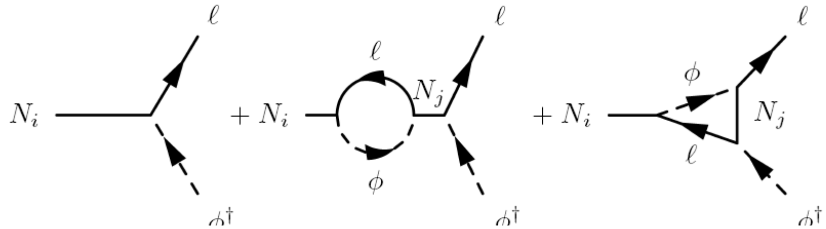
$$N_{B-L}^{\rm fin} = \sum_i \varepsilon_i \kappa_i^{\rm fin} \Rightarrow \eta_B = a_{\rm sph} \frac{N_{B-L}^{\rm fin}}{N_\gamma^{\rm rec}}$$

baryon-to-photon number ratio

efficiency factors $\simeq$ # of N_i decaying out-of-equilibrium

Successful leptogenesis : $\eta_B = \eta_B^{CMB} = (6.2 \pm 0.15) \times 10^{-10}$

The total CP asymmetries can be calculated from :



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

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

It does not depend on U !

2) Strongly hierarchical heavy RH neutrino spectrum $M_2 \gtrsim 100\, M_1$

3) N_3 does not interfere with N_2-decays: $(m_D^\dagger\, m_D)_{23} = 0$

under the last two assumptions $\Rightarrow |\varepsilon_{2,3}|^{\max} \ll |\varepsilon_1|^{\max}$

Imposing $\eta_B=\eta_B^{CMB}$, one obtains a N_1-dominated scenario :

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

efficiency factor

4) Barring fine-tuned mass cancellations

$$|\Omega^2_{ij}| \lesssim 1$$

⇒ Upper bound on ε_1

(Davidson, Ibarra '02)

$$\varepsilon_1 \leq 10^{-6} \left(\frac{M_1}{10^{10}\,\text{GeV}}\right) \frac{m_{\text{atm}}}{m_1 + m_3}$$

5) Classical Kinetic equations integrated on momenta

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

$$\frac{dN_{B-L}}{dz} = -\varepsilon_1 \frac{dN_{N_1}}{dz} - W_1 N_{B-L}$$

decays

inverse decays

wash-out

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

$$\Rightarrow \quad \kappa_1(z; K_1, z_{\text{in}}) = -\int_{z_{\text{in}}}^{z} dz' \left[\frac{dN_{N_1}}{dz'}\right] e^{-\int_{z'}^{z} dz''\, W_1(z'')}$$

Neutrino mass bounds

(Davidson,Ibarra '02;Buchmüller,PDB,Plümacher '02,'03,'04; Giudice et al. '04)

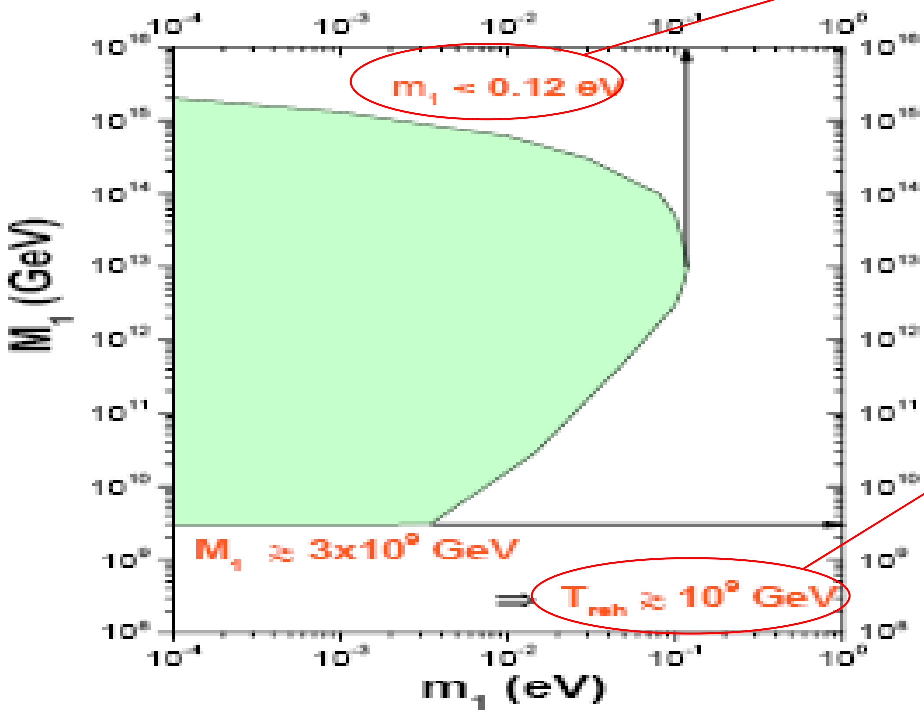
N_1 - dominated scenario

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

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

Vanilla leptogenesis is not compatible with quasi-deg. neutrinos

No constraints on the leptonic mixing matrix U !



These large temperatures in gravity mediated SUSY models suffer from the gravitino problem

An encouraging coincidence

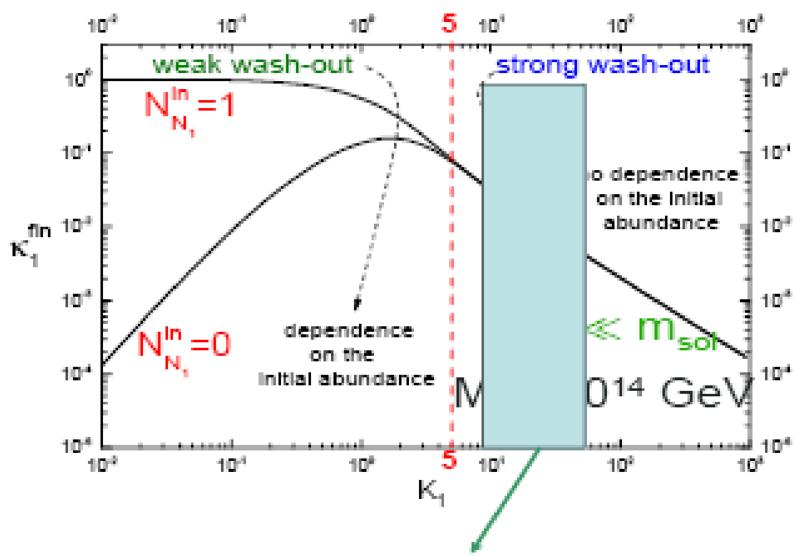
The early Universe „knows" neutrino masses ...

(Buchmüller,PDB,Plümacher '04)

$$\eta_B \simeq 0.01\, \varepsilon_1(m_1, M_1, \Omega)\, \kappa_1^{\rm fin}(K_1)$$

decay parameter

$$K_1 \equiv \frac{\Gamma_{N_1}}{H(T=M_1)} \sim \frac{m_{\rm sol,atm}}{m_\star \sim 10^{-3}\,{\rm eV}} \sim 10 \div 50$$

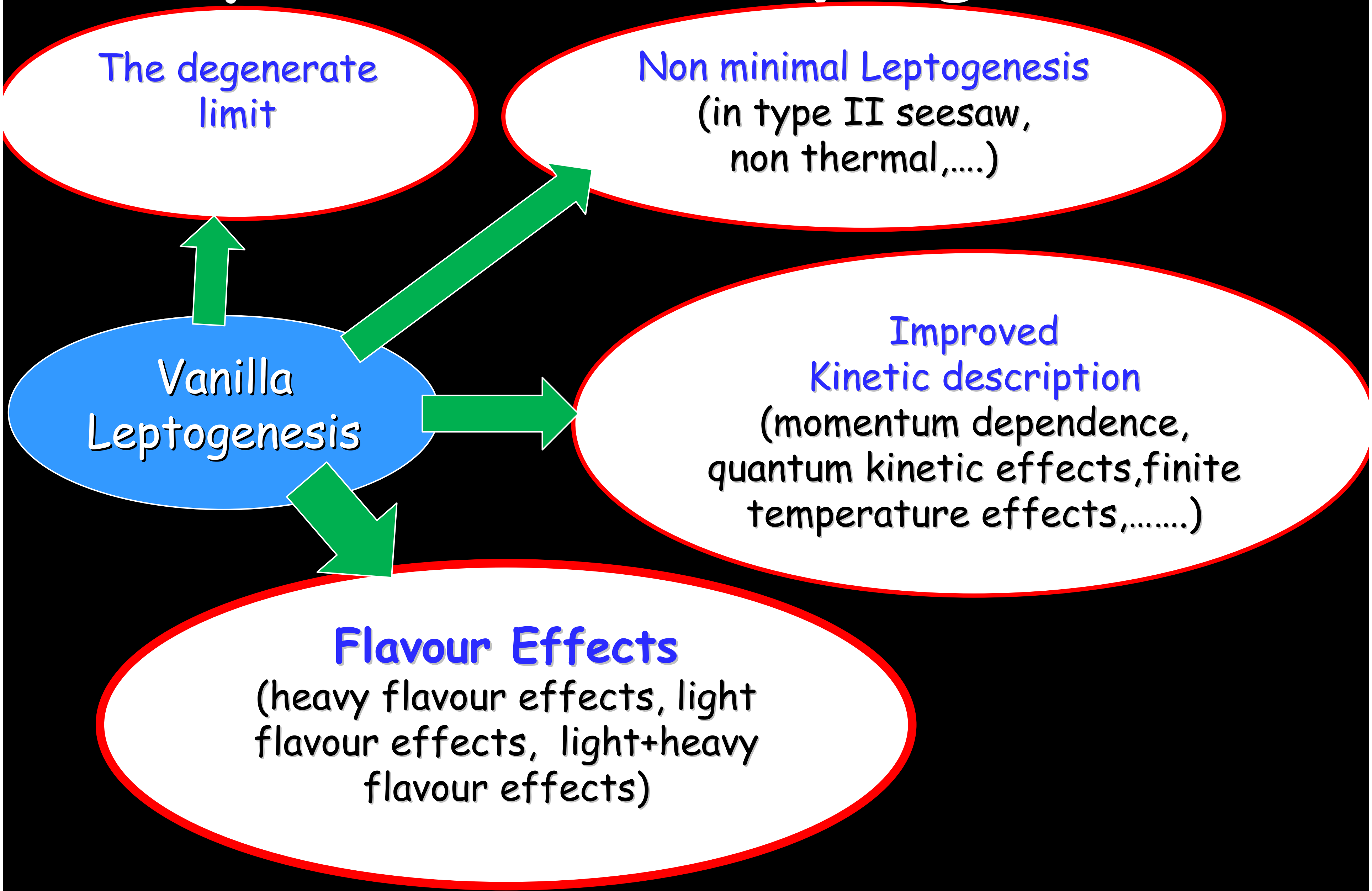


$$K_{\rm sol} \simeq 9 \lesssim K_1 \lesssim 50 \simeq K_{\rm atm}$$

wash-out of a pre-existing asymmetry

$$N_{B-L}^{\rm p,final} = N_{B-L}^{\rm p,initial}\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1}$$

Beyond vanilla Leptogenesis



Improved kinetic description

- **Momentum dependence in Boltzmann equations**
  (Hannestad ' 06; Hahn-Woernle, M. Plümacher, Y.Wong '09; Pastor, Vives'09)
- Kadanoff-Baym equations
  (Buchmüller,Fredenhagen '01; De Simone,Riotto '07; Garny,Hohenegger, Kartavtsev,Lindner '09; Anisimov,Buchmüller,Drewes,Mendizibal '09; Beneke, Garbrecht, Herranen, Schwaller '10)

The asymmetry is directly calculated in terms of Green functions instead than in terms of number densities and they account for off-shell , memory and medium effects in a systematic way

All studies confirm what also happens for other effects (e.g. inclusion of scatterings) and that is expected:
large theoretical uncertainties in the weak wash-out regime, limited O(1) corrections in the strong wash-out regime where the asymmetry is produced in a narrow range of temperatures for $T \ll M_i$ (Buchmüller,PDB,Plümacher)

Light neutrino flavour effects

(Nardi, Nir, Roulet, Racker '06; Abada, Davidson, Losada, Josse-Michaux, Riotto'06; Blanchet, PDB, Raffelt '06; Riotto, De Simone '06)

Flavor composition of lepton quantum states:

$$|l_i\rangle = \sum_\alpha \langle l_\alpha | l_i \rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau)$$

$$|\bar{l}'_i\rangle = \sum_\alpha \langle l_\alpha | \bar{l}'_i \rangle \, |\bar{l}_\alpha\rangle$$

- interactions are flavour blind for $M_i \gtrsim 10^{12}$ GeV
- But for $M_i \lesssim 10^{12}$ GeV $\Longrightarrow$ τ-Yukawa interactions $(\bar{l}_{L\tau}\,\phi\, f_{\tau\tau}\, e_{R\tau})$

are fast enough to break the coherent evolution of $|l_1\rangle$ and $|\bar{l}'_1\rangle$

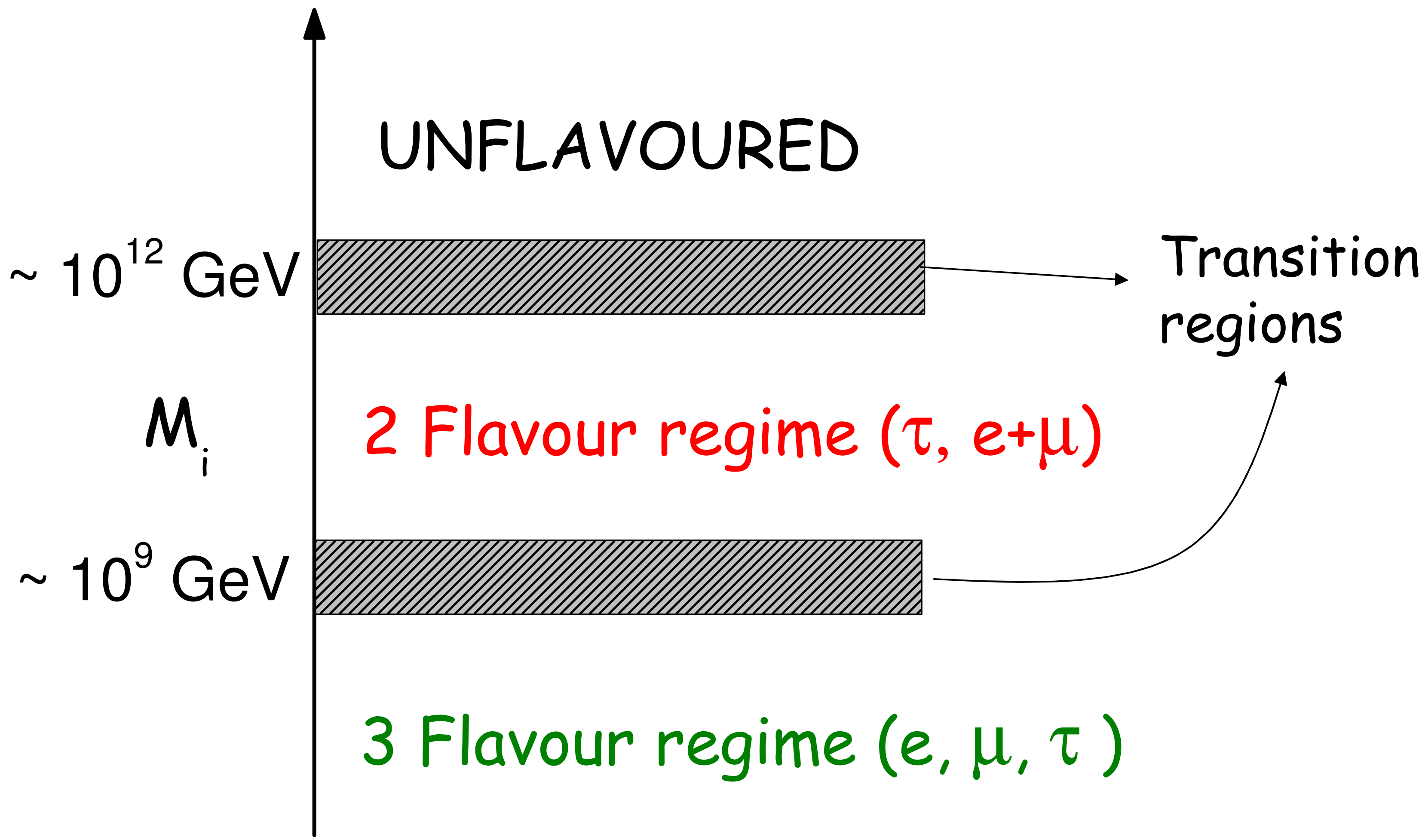
$\Longrightarrow$ they become an incoherent mixture of a τ and of μ+e

If $M_1 \lesssim 10^9$ GeV then also μ- Yukawas in equilibrium $\Longrightarrow$ 3-flavor regime

$$\Rightarrow \quad N_{B-L}^{\rm fin} = \sum_{i,\alpha} \varepsilon_{i\alpha}\, \kappa_{i\alpha}^{\rm fin} \qquad (\alpha = e, \mu, \tau)$$

i: heavy neutrino flavor index

α: lepton flavor index


UNFLAVOURED
~ 10^12 GeV
Transition
regions
M_i
2 Flavour regime (τ, e+μ)
~ 10^9 GeV
3 Flavour regime (e, μ, τ)

Fully two-flavored regime

Let us first insist with a N_1-dominated scenario: $\Rightarrow N_{B-L}^{\rm fin} = \sum_{\alpha=\tau,e+\mu} \varepsilon_{1\alpha}\,\kappa_{1\alpha}^{\rm fin}$

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

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

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

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

- Classic Kinetic Equations (in their simplest form)

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

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

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

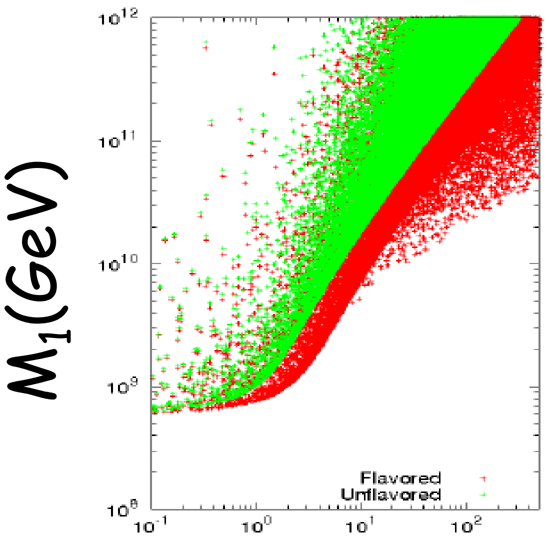
$$\Rightarrow N_{B-L}^{\rm fin} = \sum_\alpha \varepsilon_{1\alpha}\,\kappa_{1\alpha}^{\rm fin} \simeq N_{\rm fl}\,\varepsilon_1\,\kappa_1^{\rm fin} + \frac{\Delta P_{1\alpha}}{2}\,[\kappa_{1\alpha}^{\rm fin} - \kappa_{1\beta}^{\rm fin}]$$

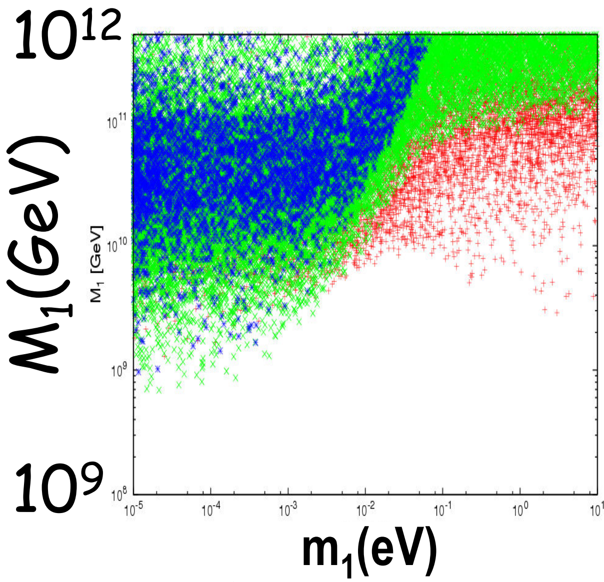
The bounds get relaxed

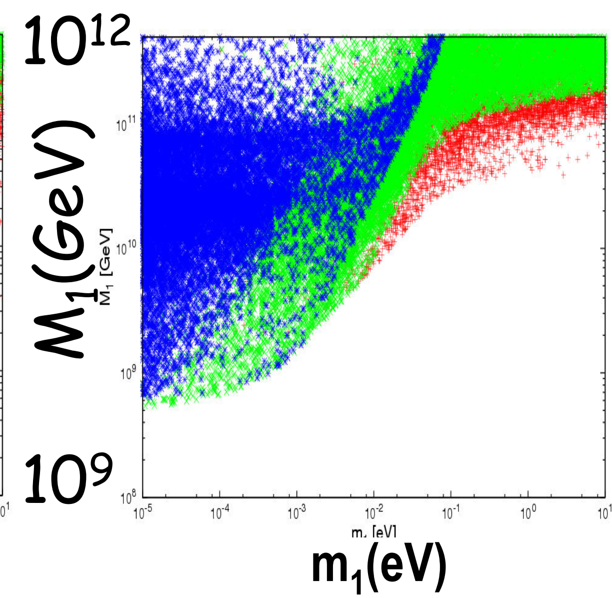
(Abada et al.' 07 Blanchet,PDB '08)

$|\Omega^2_{ij}| \lesssim 1$

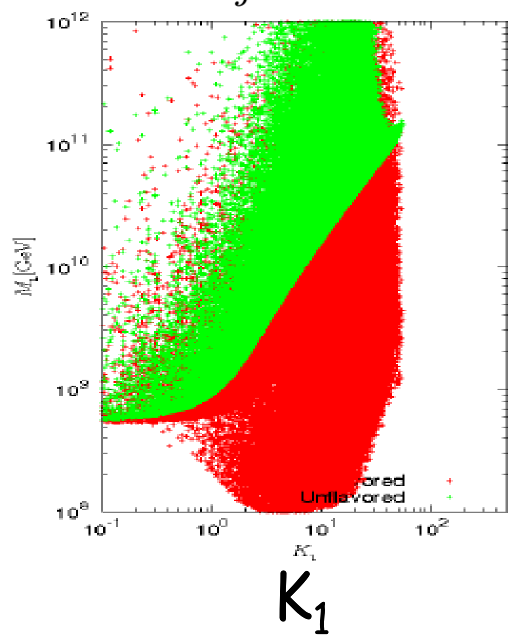
PMNS phases off





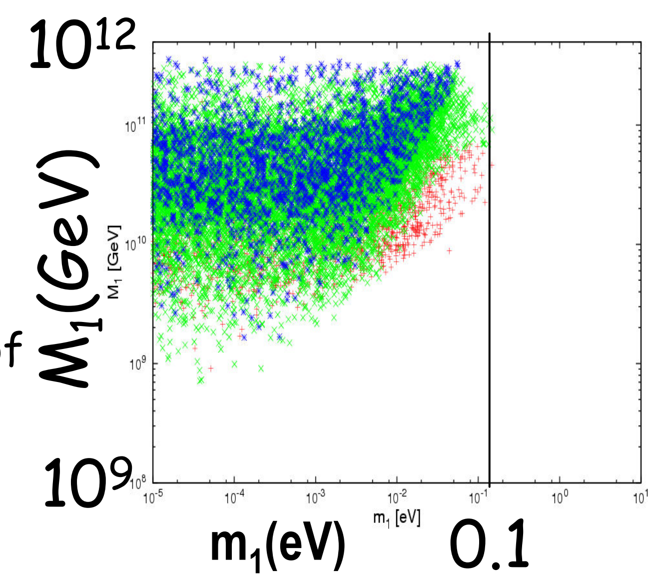


$|\Omega^2_{ij}| \lesssim 10$



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

imposing a condition of validity of Boltzmann equations



Heavy neutrino flavour effects: N_2-dominated scenario

(PDB '05)

If lepton flavour effects are neglected the asymmetry from the next-to-lightest (N_2) RH neutrinos is typically negligible:

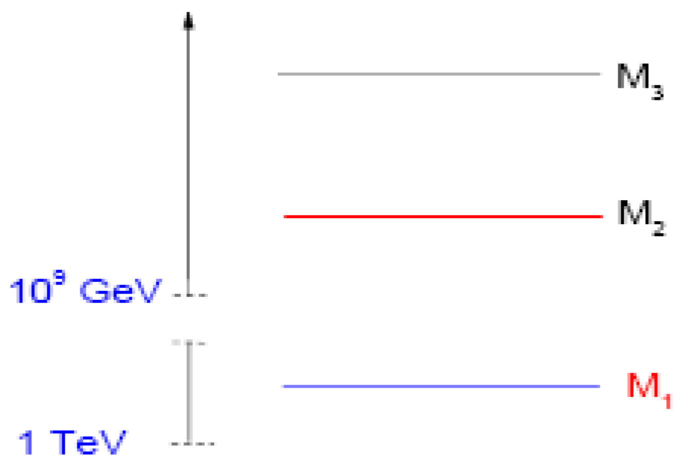
$$N_{B-L}^{f,N_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{f,N_1} = \varepsilon_1\, \kappa(K_1)$$

...except for a special choice of $\Omega=R_{23}$ when $K_1= m_1/m_* \ll 1$ and $\varepsilon_1=0$:

$$\Rightarrow \boxed{N_{B-L}^{\rm fin} = \sum_i \varepsilon_i\, \kappa_i^{\rm fin} \simeq \varepsilon_2\, \kappa_2^{\rm fin}} \qquad \varepsilon_2 \lesssim 10^{-6} \left(\frac{M_2}{10^{10}\,\text{GeV}}\right)$$

The lower bound on M_1 disappears and is replaced by a lower bound on M_2 ...

that however still implies a lower bound on T_{reh} !

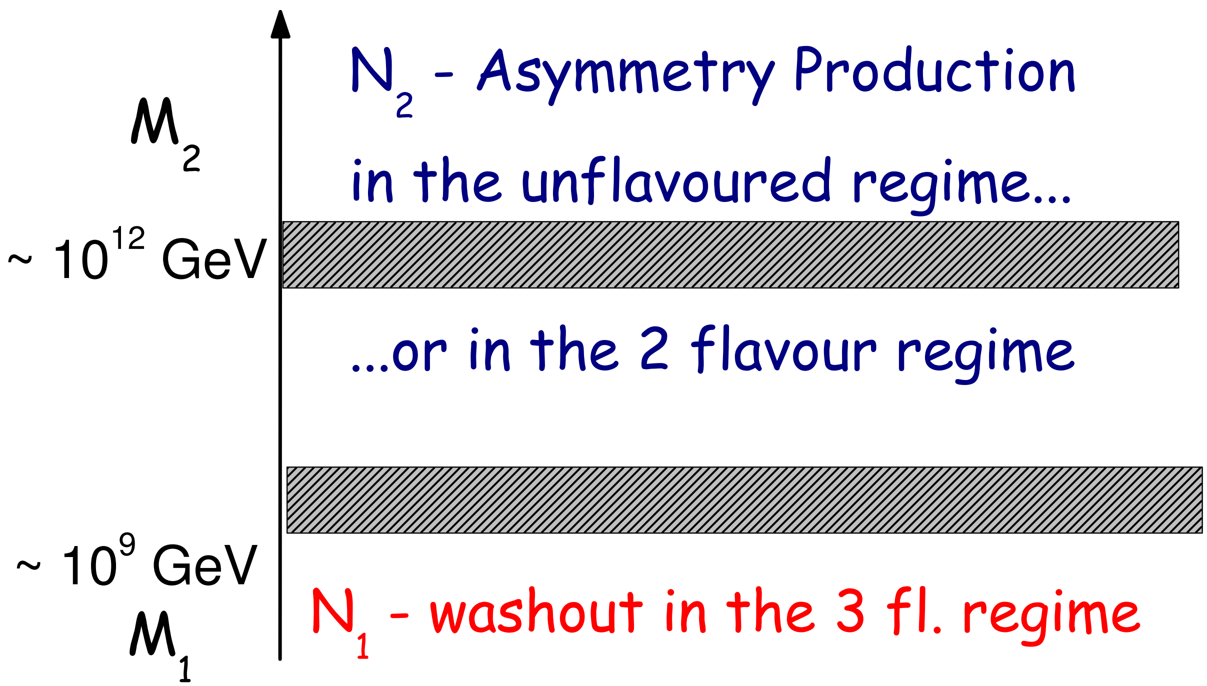


N_2-flavored leptogenesis

(Vives '05; Blanchet, PDB '06; Blanchet, PDB '08)

Combining together lepton and heavy neutrino flavour effects one has

A two stage process:



Notice that the presence of the heaviest RH neutrino N_3 is necessary for the CP asymmetries of N_2 not to be negligible !

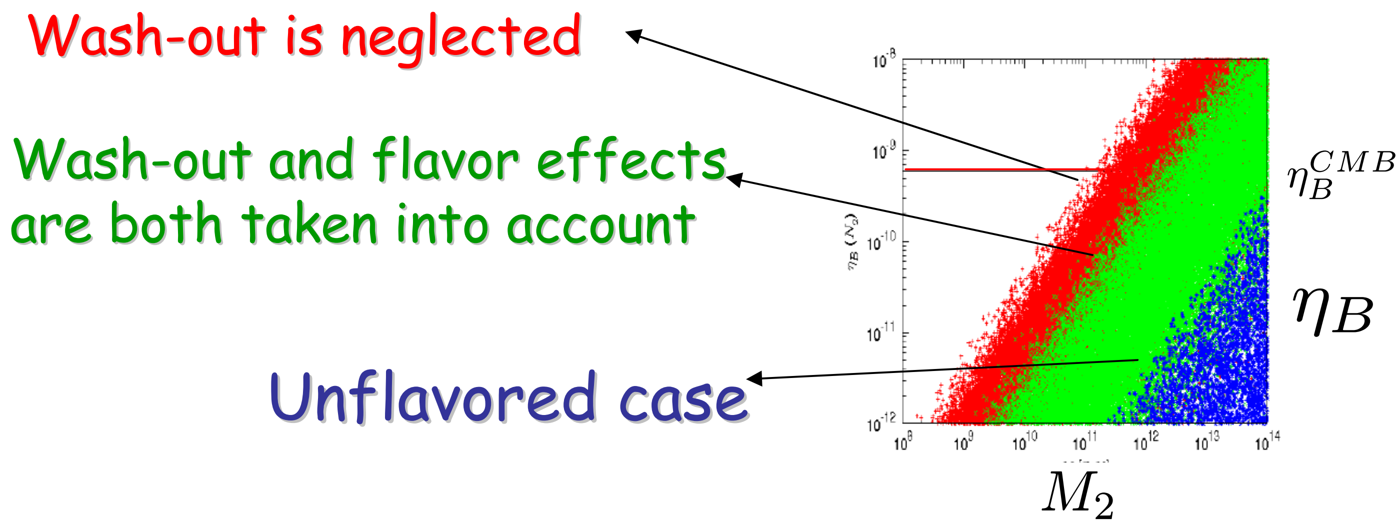
N_2-flavored leptogenesis

(Vives '05; Blanchet, PDB '06; Blanchet, PDB '08)

If (for definiteness) $M_2 \gtrsim 10^{12}$ GeV $\Rightarrow$

$$N_{B-L}^{\rm f}(N_2) = P_{2e}^0\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1e}} + P_{2\mu}^0\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + P_{2\tau}^0\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

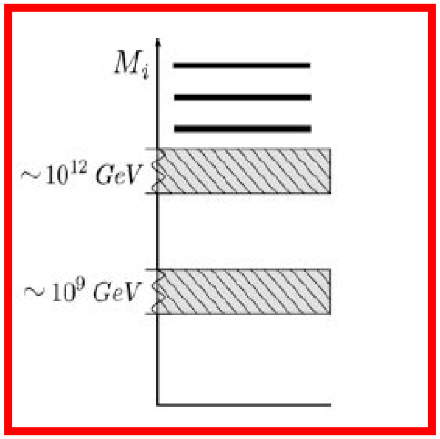
Notice that $K_1 = K_{1e} + K_{1\mu} + K_{1\tau}$

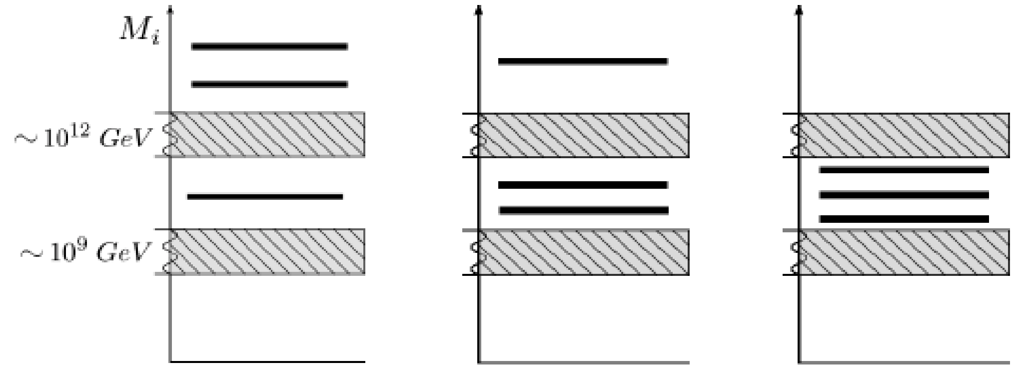


Thanks to flavor effects the domain of applicability extends much beyond the particular choice $\Omega=R_{23}$!

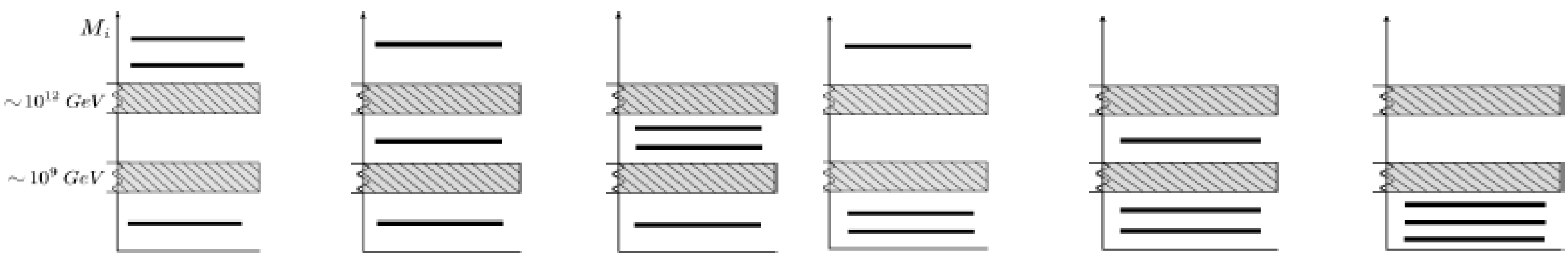
More generally one has to distinguish 10 different RH neutrino mass patterns (Bertuzzo,PDB,Marzola '10)

Heavy flavored scenario





(a) (b) (c)



(a) (b) (c) (d) (e) (f)

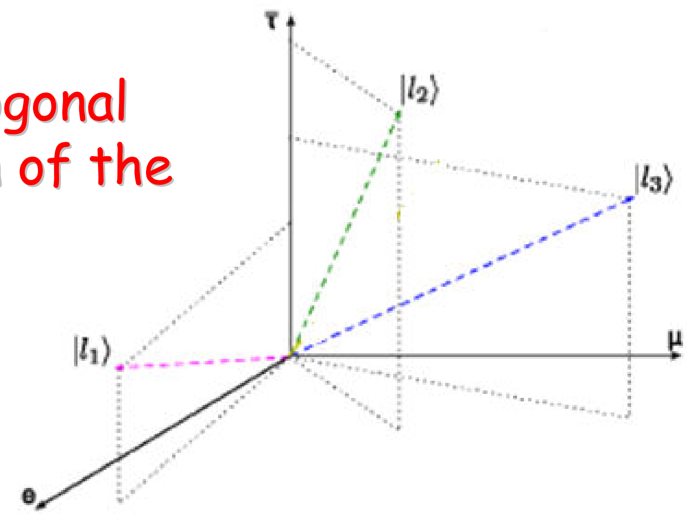
For each pattern a specific set of kinetic equations has to be considered

Heavy flavored scenario

(Engelhard, Nir, Nardi '08 , Bertuzzo,PDB,Marzola '10)

Assume $M_{i+1} > 3M_i$ (i=1,2)

The heavy neutrino flavours basis is not orthogonal in general and this complicates the calculation of the final asymmetry



$$p_{ij} = |\langle \ell_i | \ell_j \rangle|^2 \qquad p_{ij} = \frac{\left|(m_D^\dagger\, m_D)_{ij}\right|^2}{(m_D^\dagger\, m_D)_{ii}\,(m_D^\dagger\, m_D)_{jj}}\,.$$

$$N_{B-L}^{\rm lep}(T_{B1}) = N_{\Delta_1}^{\rm lep}(T_{B1}) + N_{\Delta_{\tilde 1}}^{\rm lep}(T_{B1})\,,$$

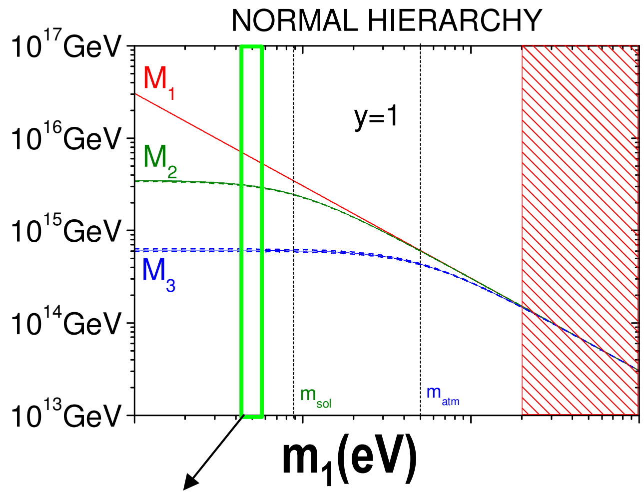
$$\begin{aligned} N_{\Delta_1}^{\rm lep}(T_{B1}) \;=\;& p_{21}\, p_{32}\, \varepsilon_3\, \kappa(K_3)\, e^{-\frac{3\pi}{8}(K_1+K_2)} \\ &+ p_{21}\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}K_1} \\ &+ p_{\tilde{2}_3 1}\,(1-p_{32})\,\varepsilon_3\,\kappa(K_3)\, e^{-\frac{3\pi}{8}K_1} \\ &+ \varepsilon_1\,\kappa(K_1) \end{aligned}$$

$$\begin{aligned} N_{\Delta_{\tilde 1}}^{\rm lep}(T_{B1}) \;=\;& (1-p_{21})\,[p_{32}\,\varepsilon_3\,\kappa(K_3)\, e^{-\frac{3\pi}{8}K_2} + \varepsilon_2\,\kappa(K_2)] \\ &+ (1-p_{\tilde{2}_3 1})\,(1-p_{32})\,\varepsilon_3\,\kappa(K_3)\,. \end{aligned}$$

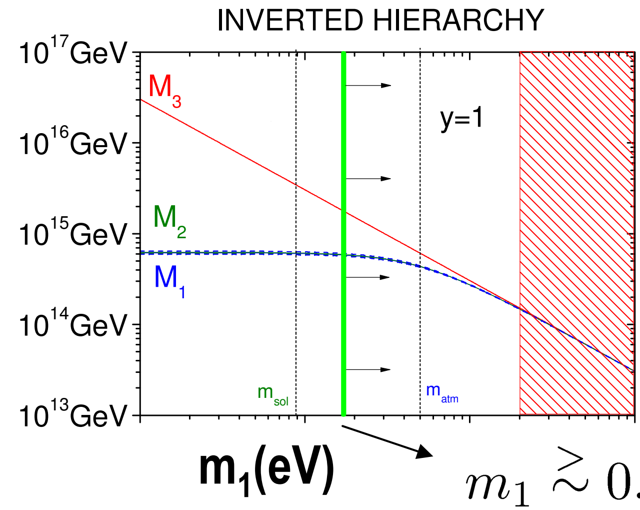
Some deviation from orthogonality (it is realized in form dominance models discussed in King's talk) is typically necessary since otherwise (e.g. with tri-bimaximal mixing) one would have vanishing CP asymmetries and therefore no asymmetry produced from leptogenesis (Antusch, King, Riotto '08; Aristizabal,Bazzocchi,Merlo,Morisi '09)

Heavy flavoured scenario in models with A4 discrete flavour symmetry

(Manohar, Jenkins'08;Bertuzzo,PDB,Feruglio,Nardi '09;Hagedorn,Molinaro,Petcov '09)



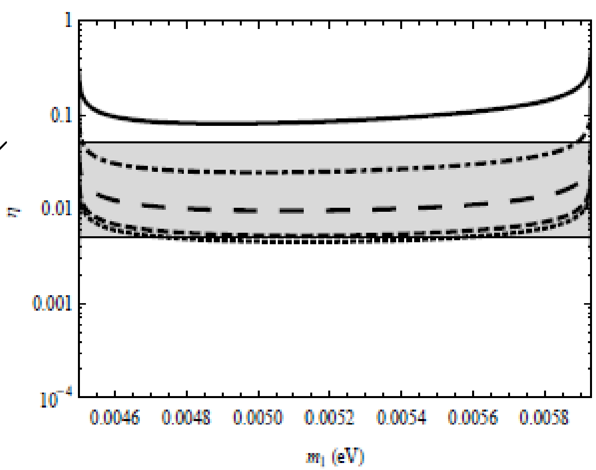
$$m_i = \frac{y^2\, v_u^2}{M_j}$$



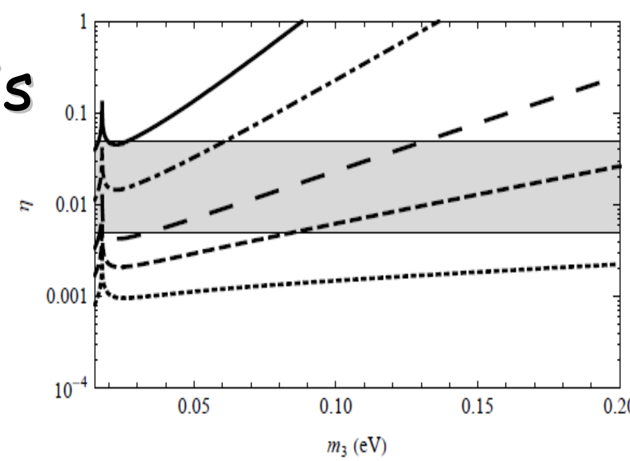
$m_1 \simeq 5 \times 10^{-3}\,\mathrm{eV}$

$m_1 \gtrsim 0.017\,\mathrm{eV}$

imposing successful leptogenesis

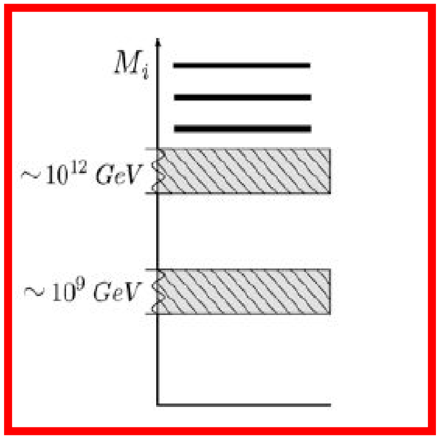


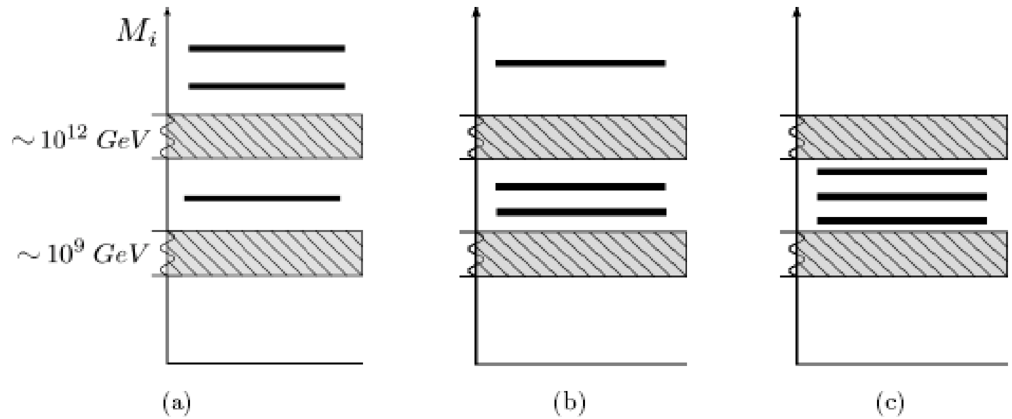
η → Symmetry Breaking parameter

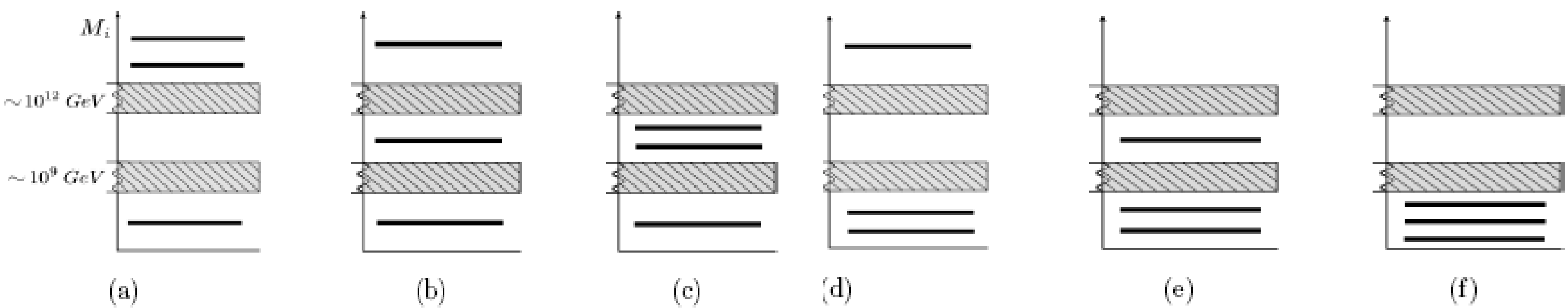


The different lines correspond to values of y between 0.3 and 3

Heavy flavored scenario

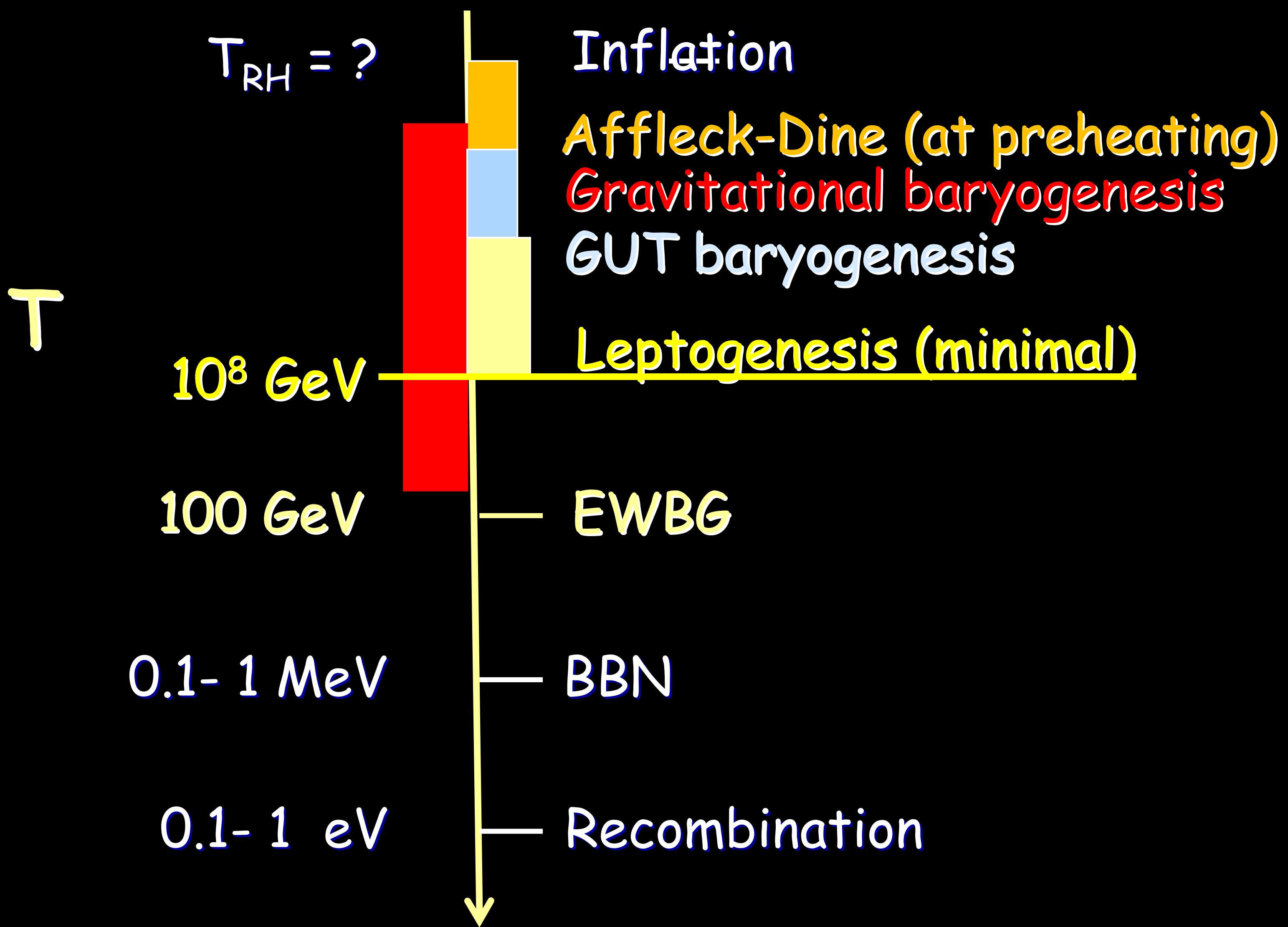






For each pattern a specific set of kinetic equations has to be considered

Baryogenesis and the early Universe history



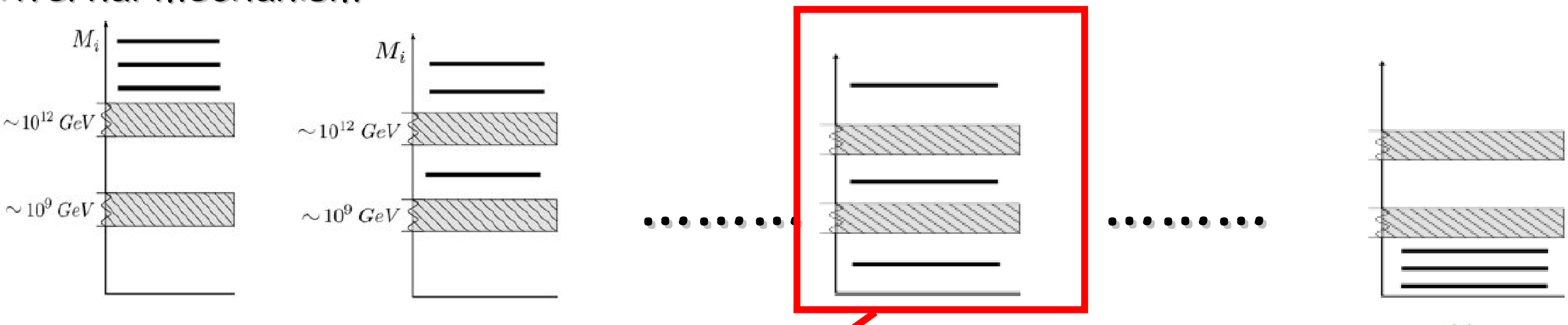
The problem of the initial conditions in flavoured leptogenesi

(Bertuzzo,PDB,Marzola '10)

Residual "pre-existing" asymmetry possibly generated by some external mechanism

$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p,f} + N_{B-L}^{\rm lep,f}$$

Asymmetry generated from leptogenesis



The wash-out of a pre-existing asymmetry is guaranteed only in a N_2-dominated scenario where the final asymmetry is dominantly in the tauon flavour

(loophole:in supersymmetric models(Antusch,King,Riotto'06) also in N_1 dominated scenarios with $\tan^2\beta \gtrsim 20$)

This mass pattern is particularly interesting because it is just that one realized in SO(10) inspired models

SO(10)-inspired leptogenesis

(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03)

Expressing the neutrino Dirac mass matrix m_D (in the basis where the Majorana mass and charged lepton mass matrices are diagonal):

$$m_D = V_L^\dagger \, D_{m_D} \, U_R$$ (bi-unitary parametrization)

where $D_{m_D} = \mathrm{diag}\{\lambda_{D1}, \lambda_{D2}, \lambda_{D3}\}$

and assuming: 1) $\lambda_{D1} = \alpha_1 \, m_u \, , \, \lambda_{D2} = \alpha_2 \, m_c \, , \, \lambda_{D3} = \alpha_3 \, m_t \, , \quad (\alpha_i = \mathcal{O}(1))$

2) $V_L \simeq V_{CKM} \simeq I$

one typically obtains (barring fine-tuned exceptions):

$$M_1 \sim \alpha_1^2 \, 10^5 \mathrm{GeV} \, , \;\; M_2 \sim \alpha_2^2 \, 10^{10} \, \mathrm{GeV} \, , \;\; M_3 \sim \alpha_3^2 \, 10^{15} \, \mathrm{GeV}$$

since $M_1 \ll 10^9$ GeV $\Rightarrow \eta_B(N_1) \ll \eta_B^{CMB}$!

$\Rightarrow$ failure of the N_1-dominated scenario !

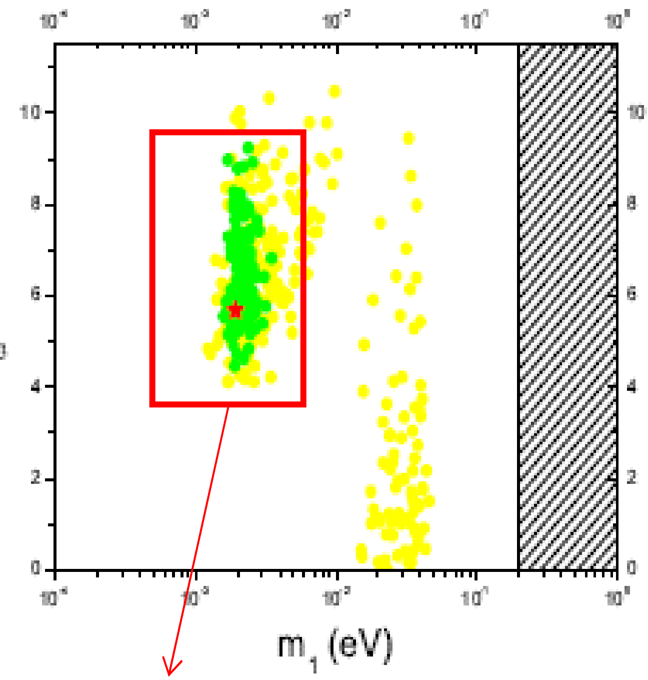
YES: the N_2-dominated scenario rescues SO(10) inspired models ! (PDB, Riotto '08,'10)

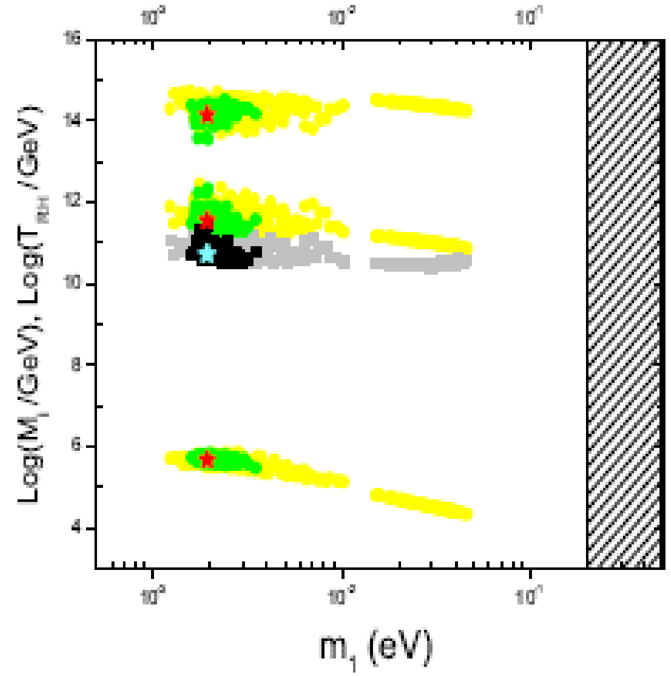
$$N_{B-L}^{\rm f} \simeq \varepsilon_{2e}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1e}} + \varepsilon_{2\mu}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + \varepsilon_{2\tau}\,\kappa(K_{2\tau})\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

Independent of α_1 and α_3 !

α_2=5 α_2=4 α_2=3 $V_L = I$ Normal ordering

Θ_{13}





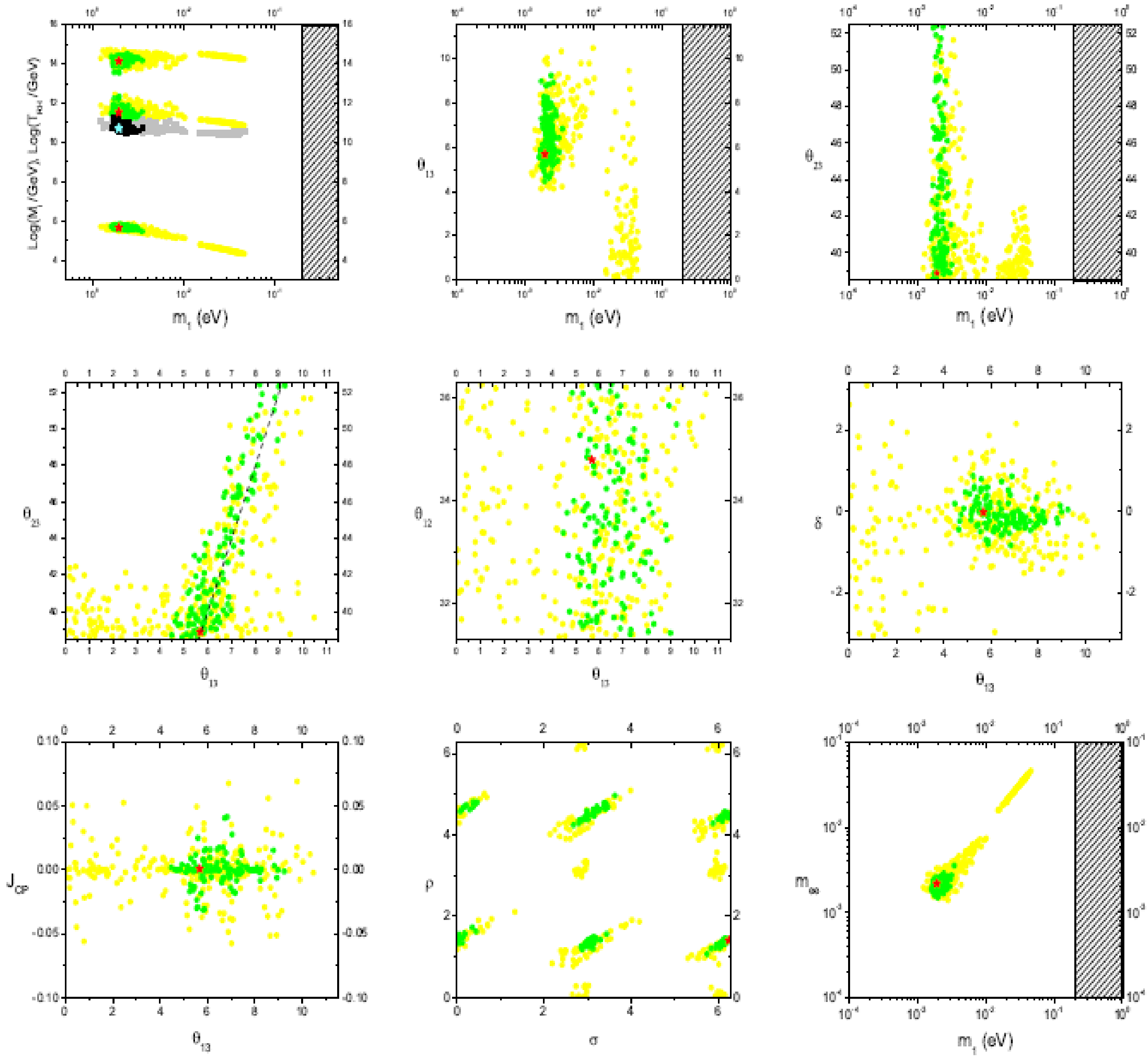
lower bound on Θ_{13}

Vanishing initial N_2 abundance

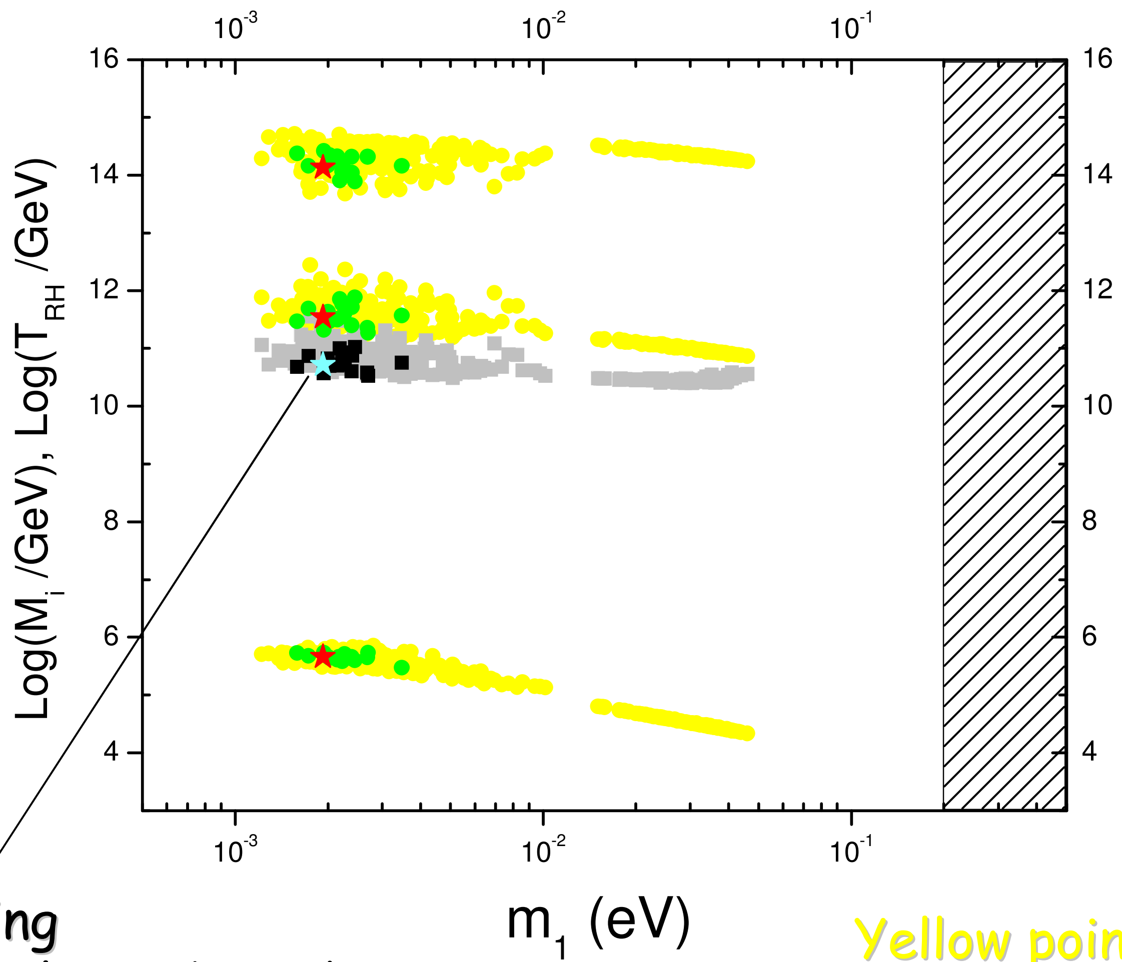
The model yields constraints on all low energy neutrino observables !

$V_L = I$

NORMAL ORDERING



(PDB, Riotto '10)



The reheating temperature lower bound is $\sim 4\mathrm{x}10^{10}$ GeV problem in SUSY

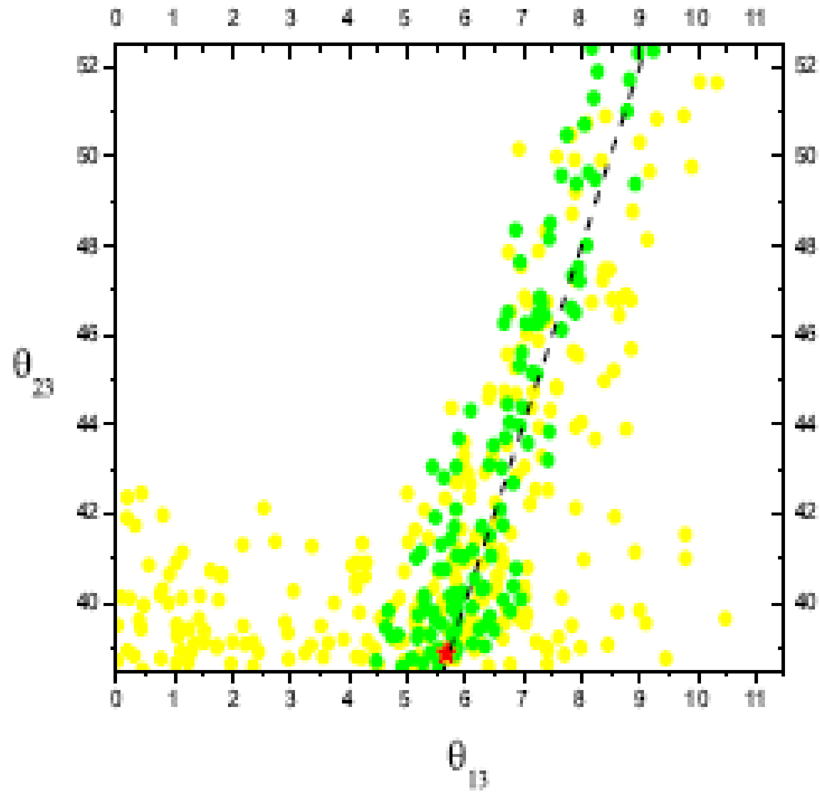
Yellow points: α_2=5

Green points: α_2=4

Red star : α_2=3

(PDB, Riotto '10)

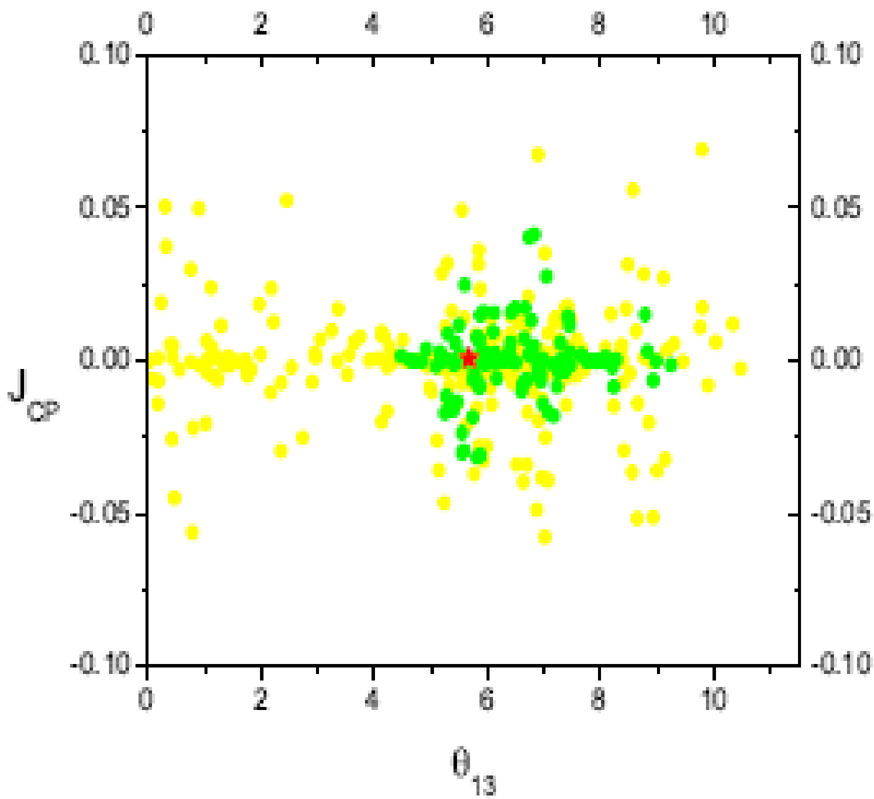
correlation between Θ_{13} and Θ_{23}



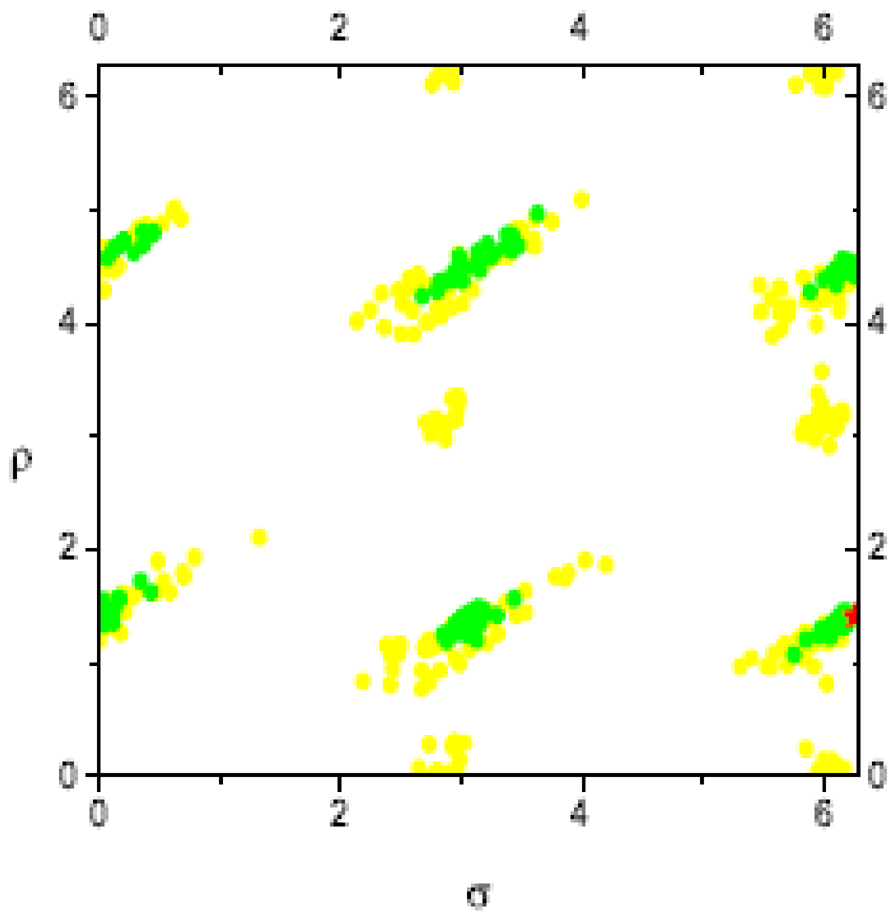
Low values of the atmospheric angle are strongly favoured and maximal mixing is very marginally allowed and excluded for $\Theta_{13} < 6°$

Yellow points: α_2=5
Green points: α_2=4
Red star : α_2=3

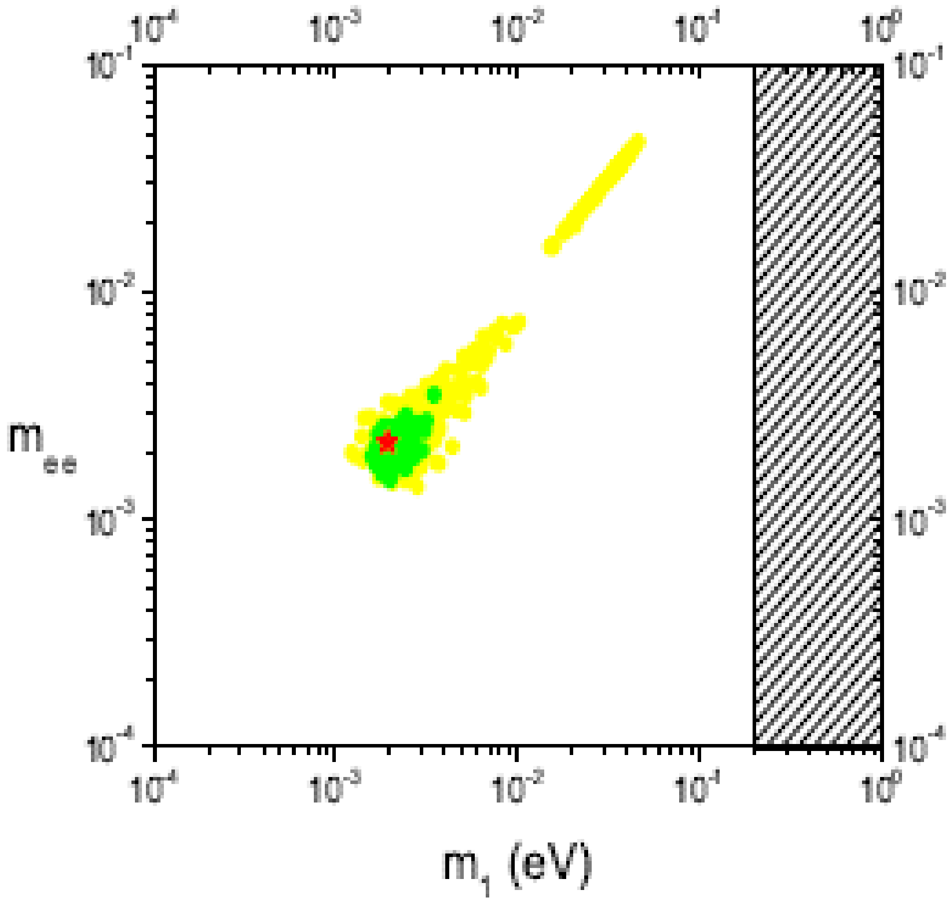
The model does not seem to predict necessarily CP violation in neutrino oscillations



On the other hand the Majorana phases play a crucial role



Effective Majorana mass small but non vanishing and unambiguosly related to m_1

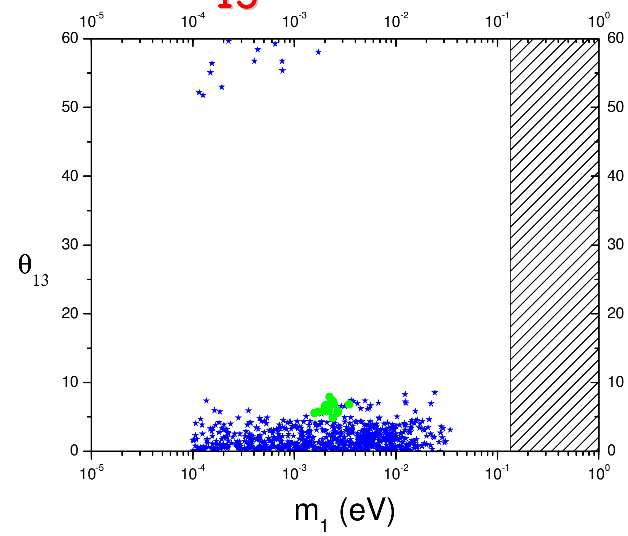


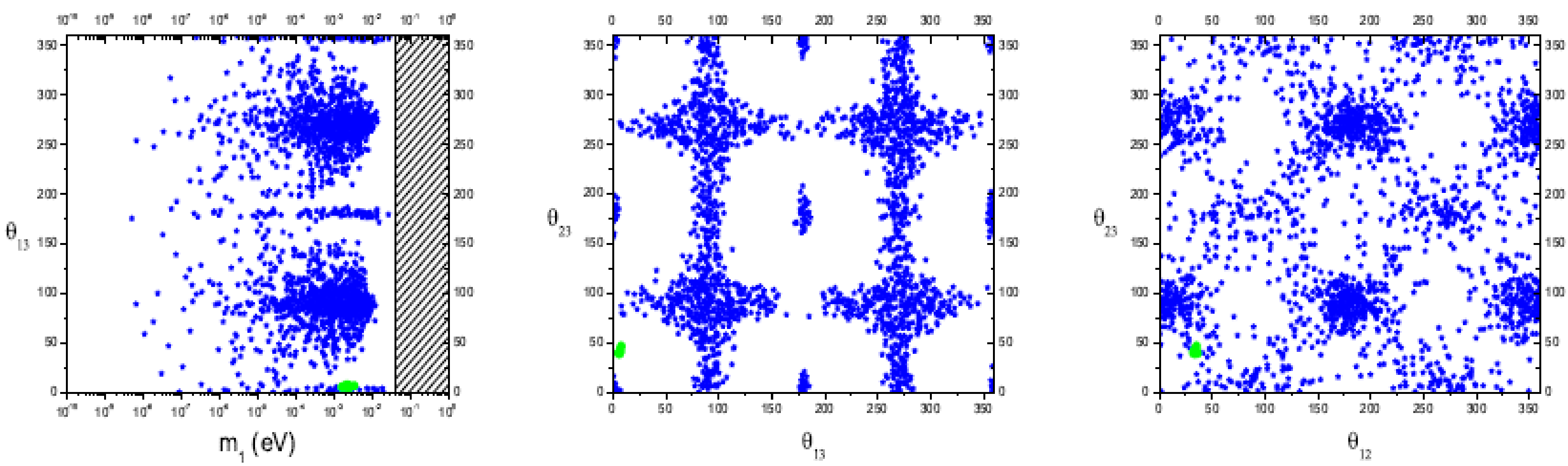
A third encouraging coincidence !

(PDB, Riotto '10)

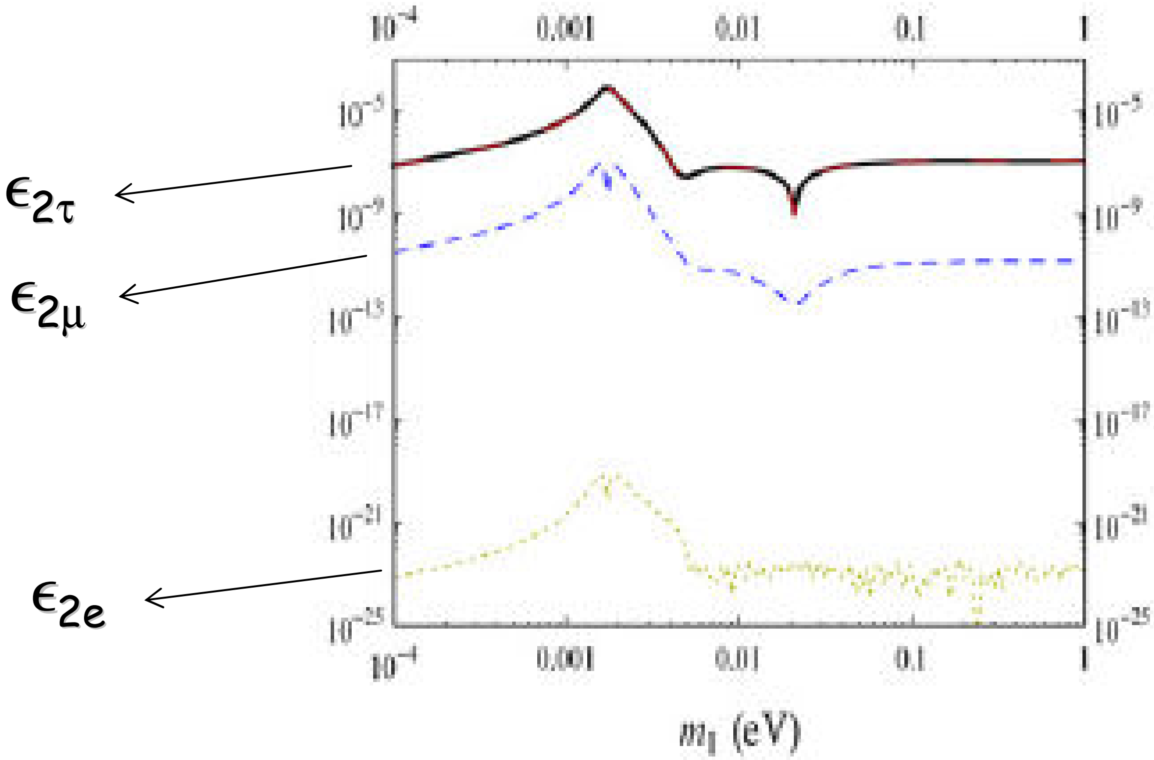
The scenario seems to like $\Theta_{13} < 10°$!

Blue points: α_2=4 and mixing angles let free in (0,60°)
Green points: α_2=4 and current experimental constraints imposed on mixing angles





For the solution with $m_1 \sim 3\times10^{-3}$ eV the asymmetry is dominantly produced in the tauon flavour since $\epsilon_{2\tau,\mu,e} \propto (m_{t,c,u})^2$



For these solutions all conditions for a full independence of the initial confitions are fullfilled !

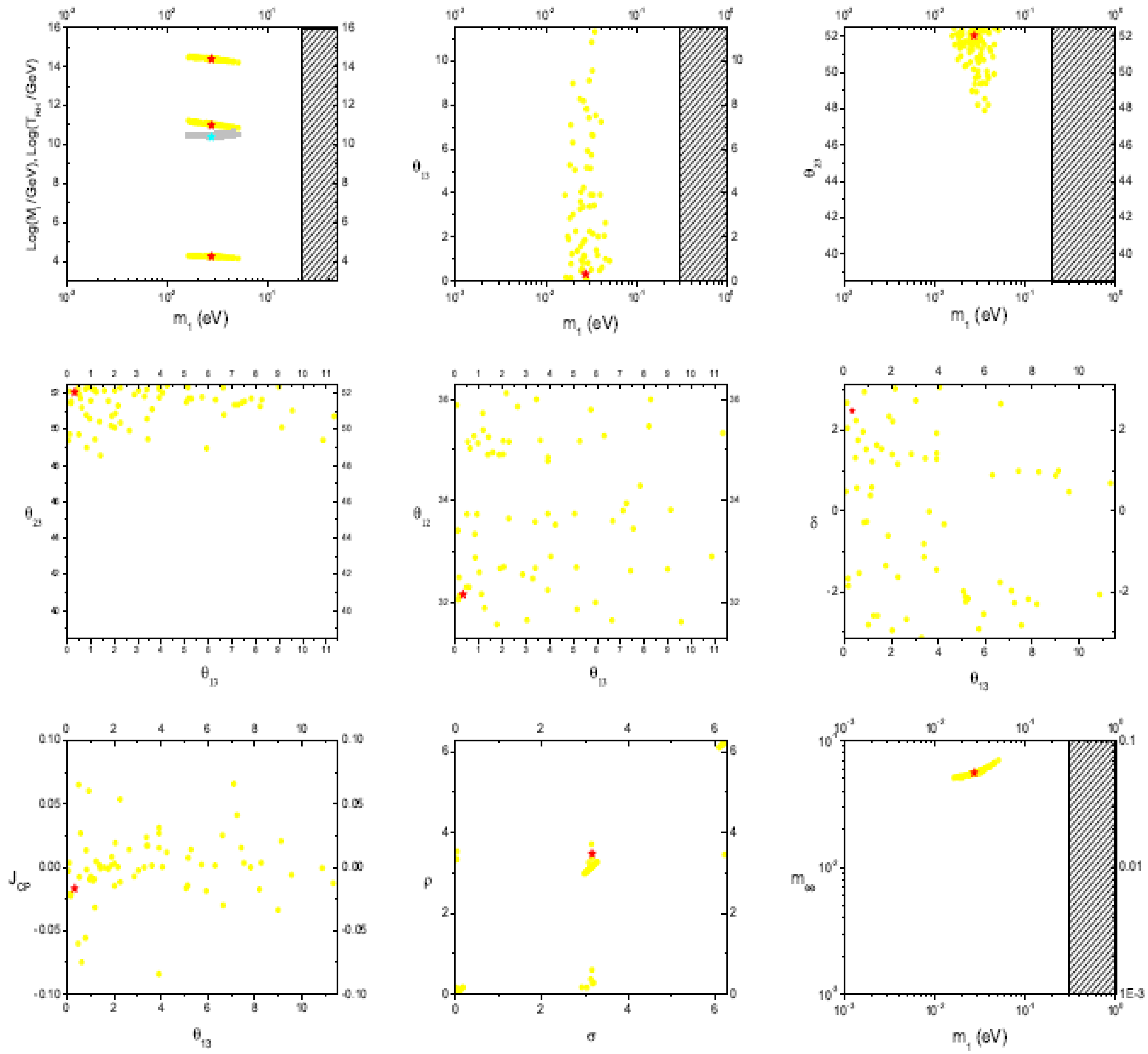
The model yields constraints on all low energy neutrino observables !

$V_L = I$

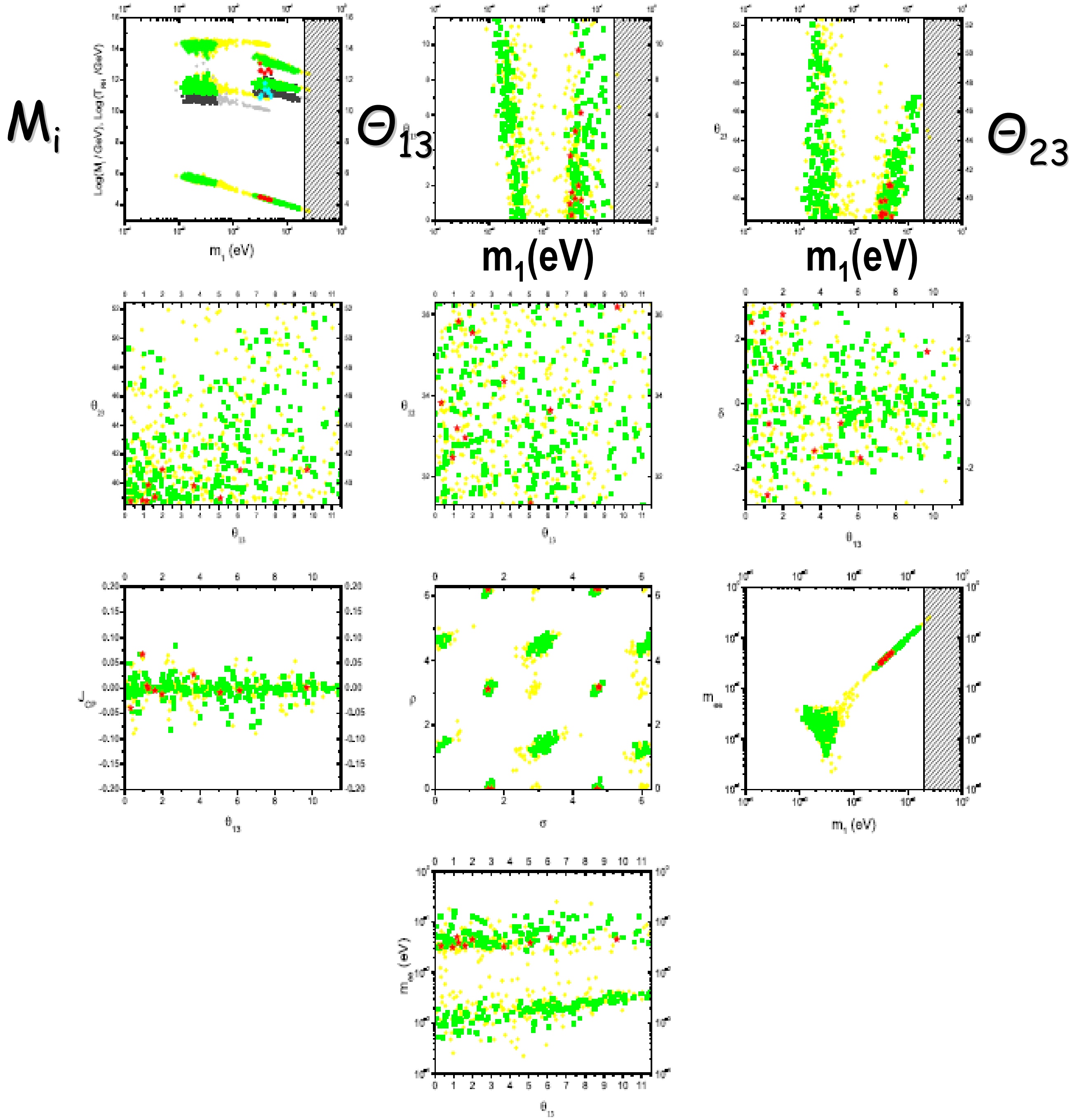
INVERTED ORDERING

α_2=5

α_2=4.7



$I < V_L < V_{CKM}$



NORMAL ORDERING

α_2=5

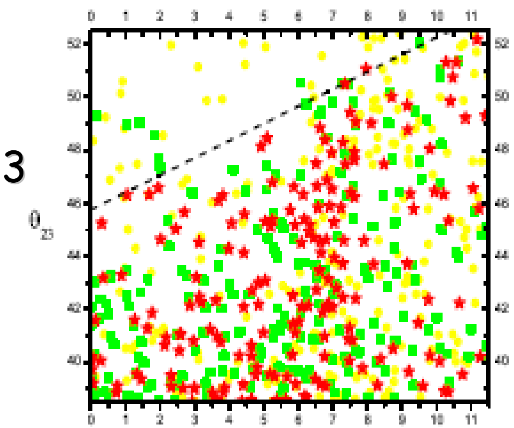
α_2=4

α_2=1

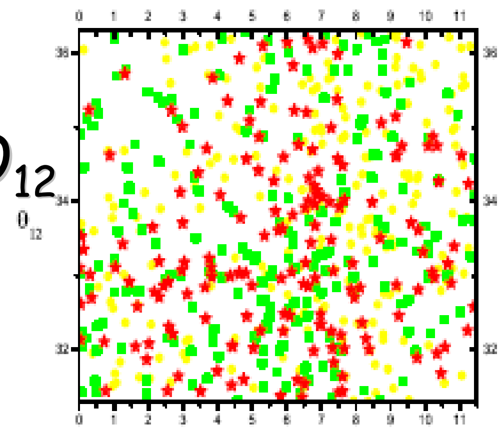
I < V_L < V_{CKM} NORMAL ORDERING α_2=5 α_2=4

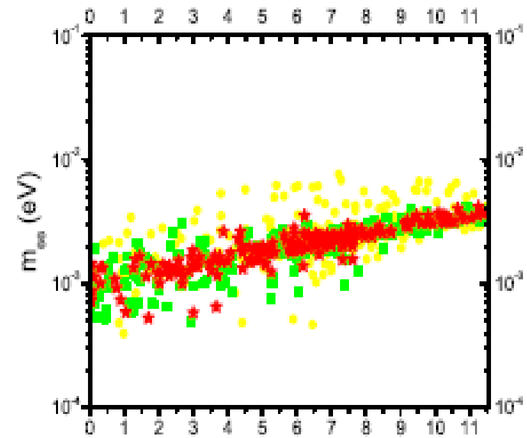
α_2=3.7 m_1 < 0.01 eV

Θ_{23}



Θ_{12}

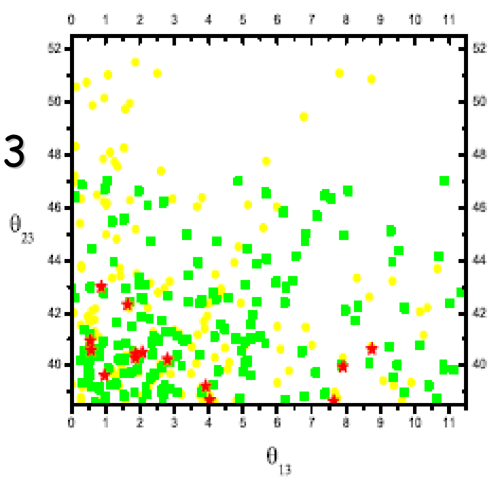




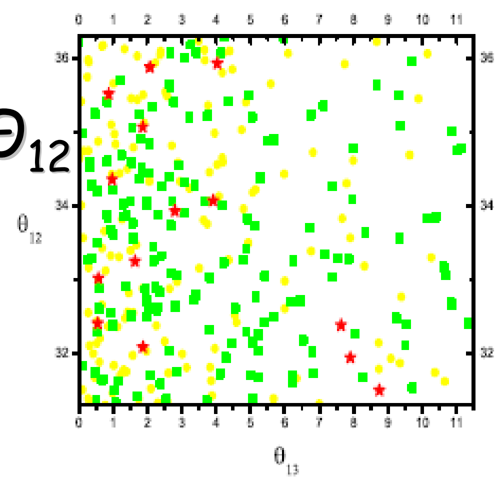
Θ_{13} Θ_{13} Θ_{13}

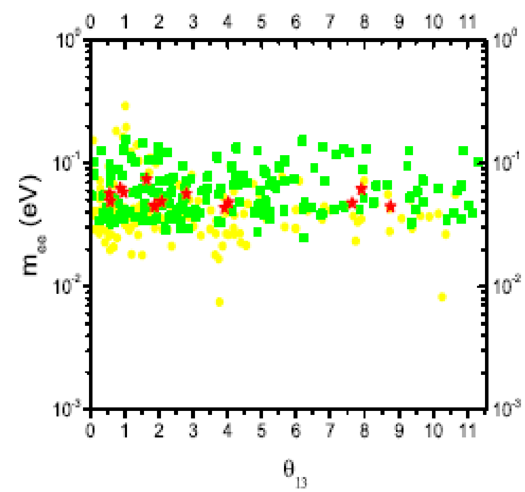
α_2=1 m_1 > 0.01 eV

Θ_{23}



Θ_{12}





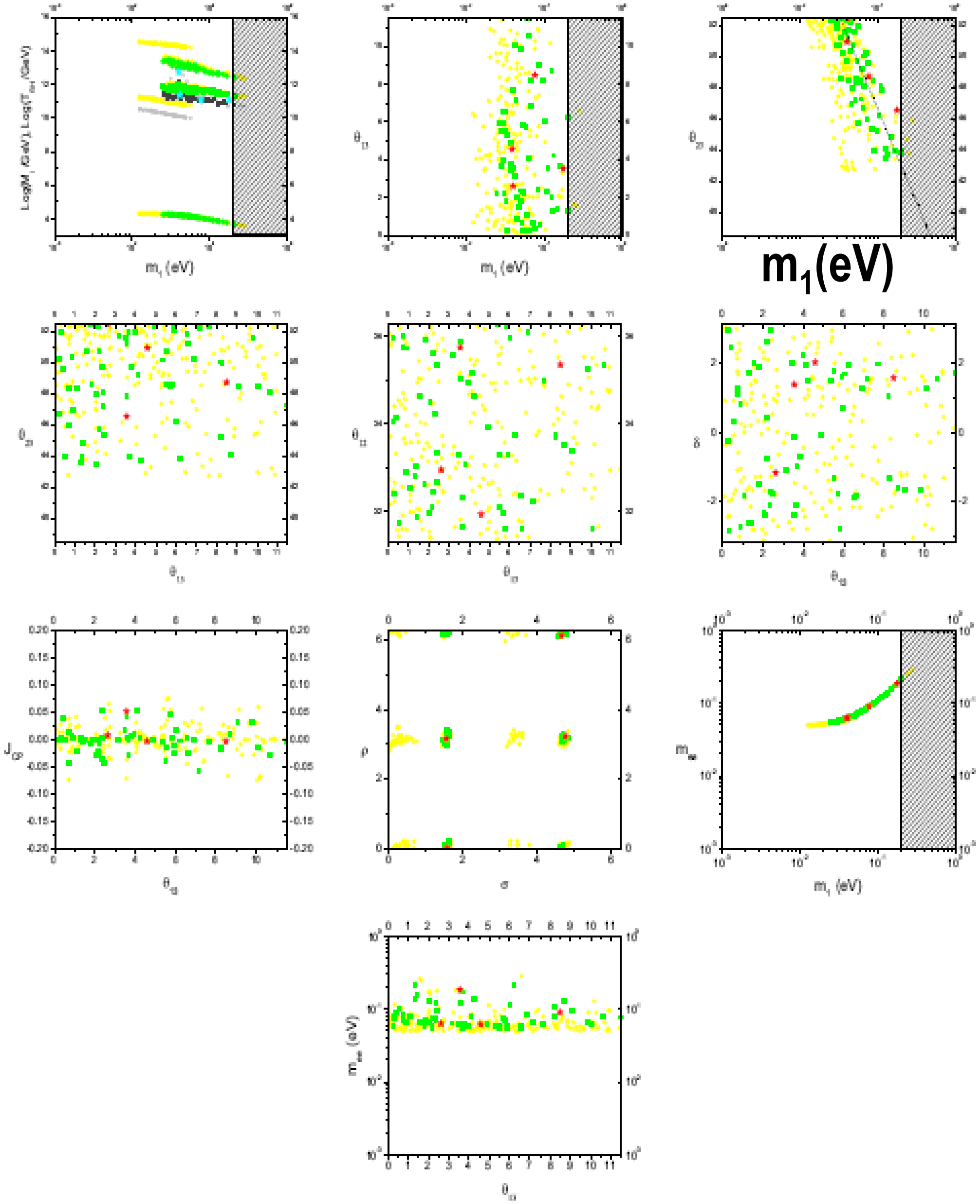
$I < V_L < V_{CKM}$

INVERTED ORDERING

α_2=5

α_2=4

α_2=1.5



Θ_{23}

Conclusions

Leptogenesis is an important way to complement low energy neutrino experiments to test the see-saw mechanism since the high energy parameters are involved as well.

Leptogenesis+low energy neutrino experiments are still not sufficient to over-constraint the see-saw parameter space in a general case and ine has

i)either to look for additional phenomenologies (LFV processes ? EDM's ?, collider physics ?)

or

ii) Restrict the parameter space imposing some assumption

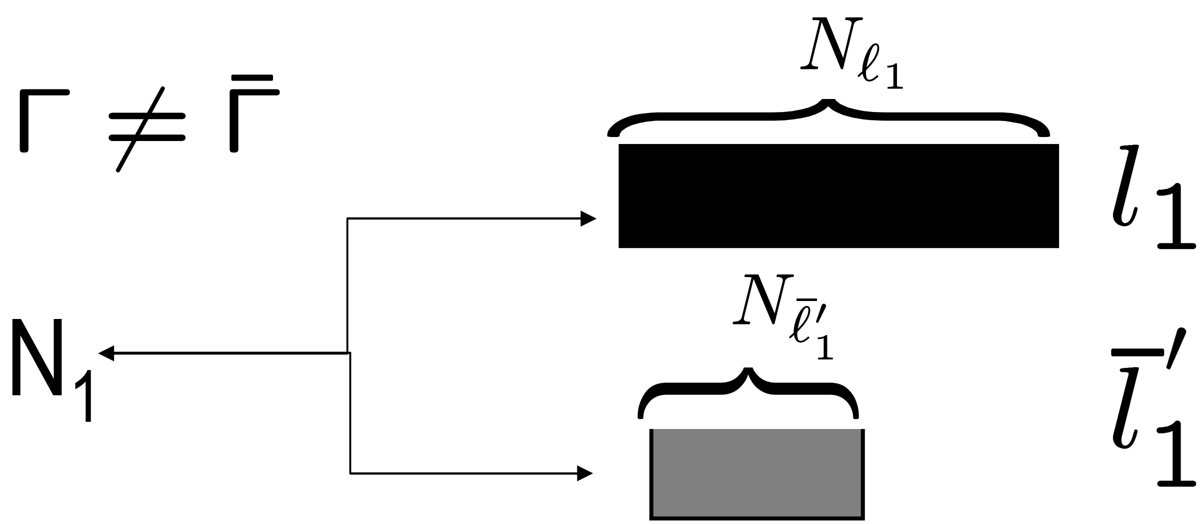
For example SO(10)-inspired models are potentially predictive. They Are ruled out in a traditional N_1-dom scenario but when production from N_2 neutrinos is taken into account they are viable and produce interesting constraints on the light neutrino mass matrix parameters

Additional contribution to CP violation:

$$\varepsilon_{1\alpha} = P^0_{1\alpha}\,\varepsilon_1 + \frac{\Delta P_{1\alpha}}{2}$$

depends on U !

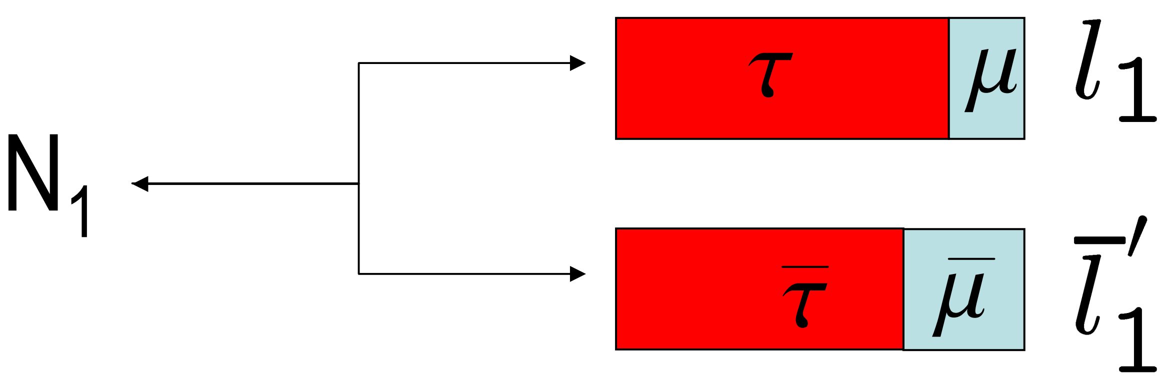
1) $\Gamma \neq \bar{\Gamma}$



$\Rightarrow \; P^0_{1\alpha}\,\varepsilon_1$

2) $|\bar{l}'_1\rangle \neq CP|l_1\rangle$

+



$\Rightarrow \; \frac{\Delta P_{1\alpha}}{2}$

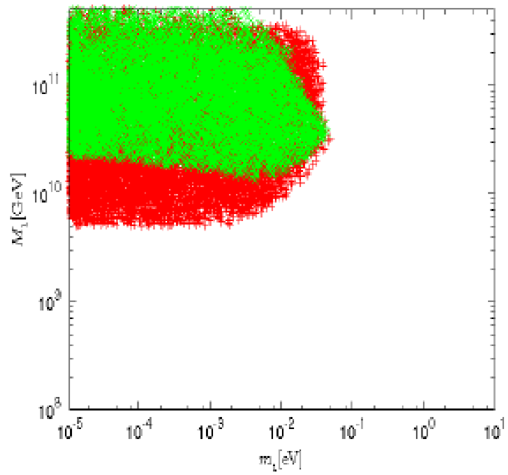
Low energy phases as the only source of CP violation

(Nardi et al; Blanchet,PDB, '06; Pascoli, Petcov, Riotto; Anisimov, Blanchet, PDB '08)

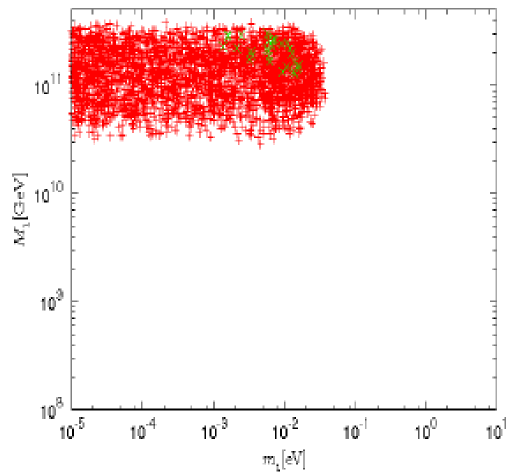
The whole CP violation can stems just from low energy phases (Dirac, Majorana phases) and still it is possible to have successful leptogenesis !

(Blanchet, PDB '09)

initial thermal N_1 abundance



independent of initial N_1 abundance



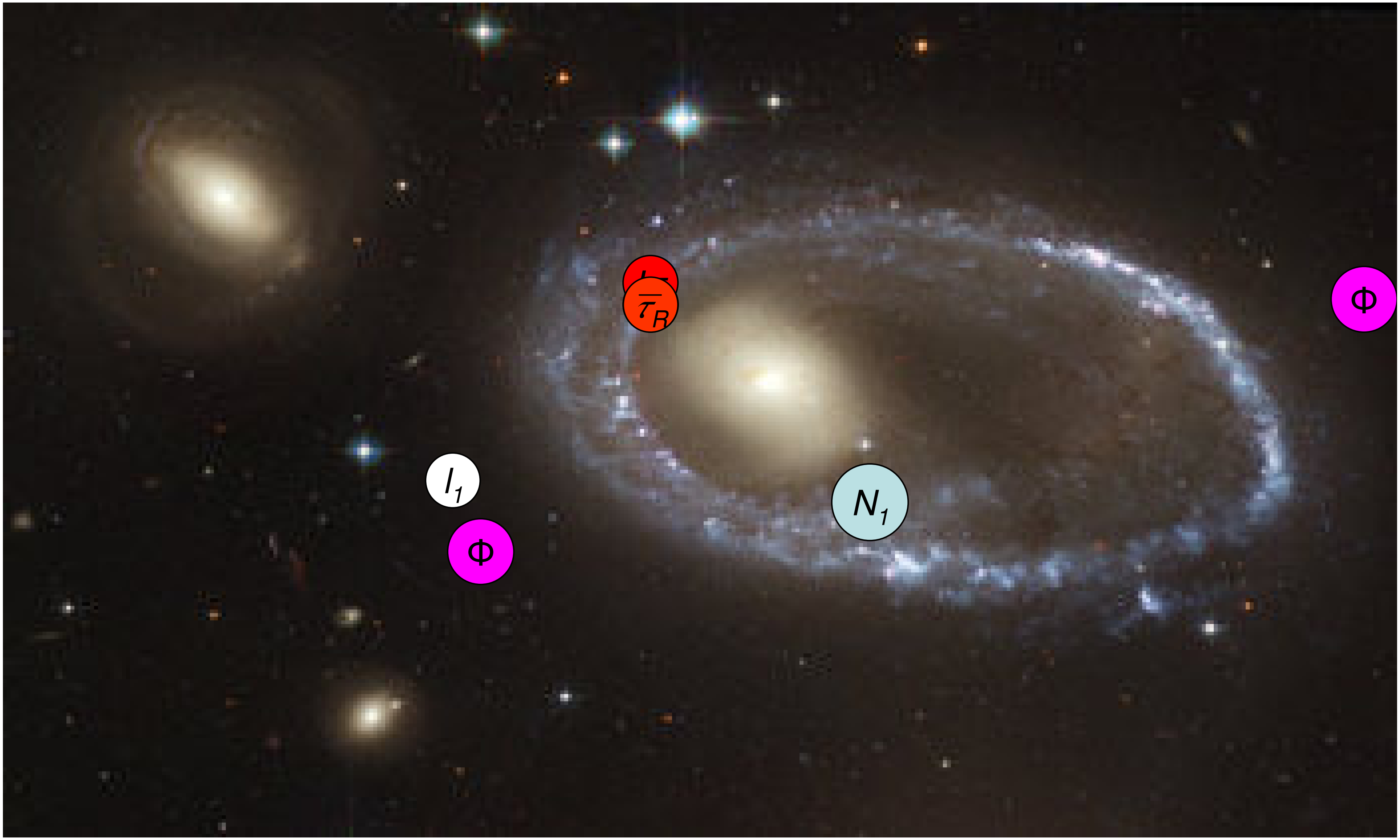
Green points: only Dirac phase with $\sin\theta_{13} = 0.2$

Red points: only Majorana phases

However, in general, we cannot constraint the low energy phases with leptogenesis and viceversa we cannot test leptogenesis just measuring CP violation at low energies: we need to add some further condition !

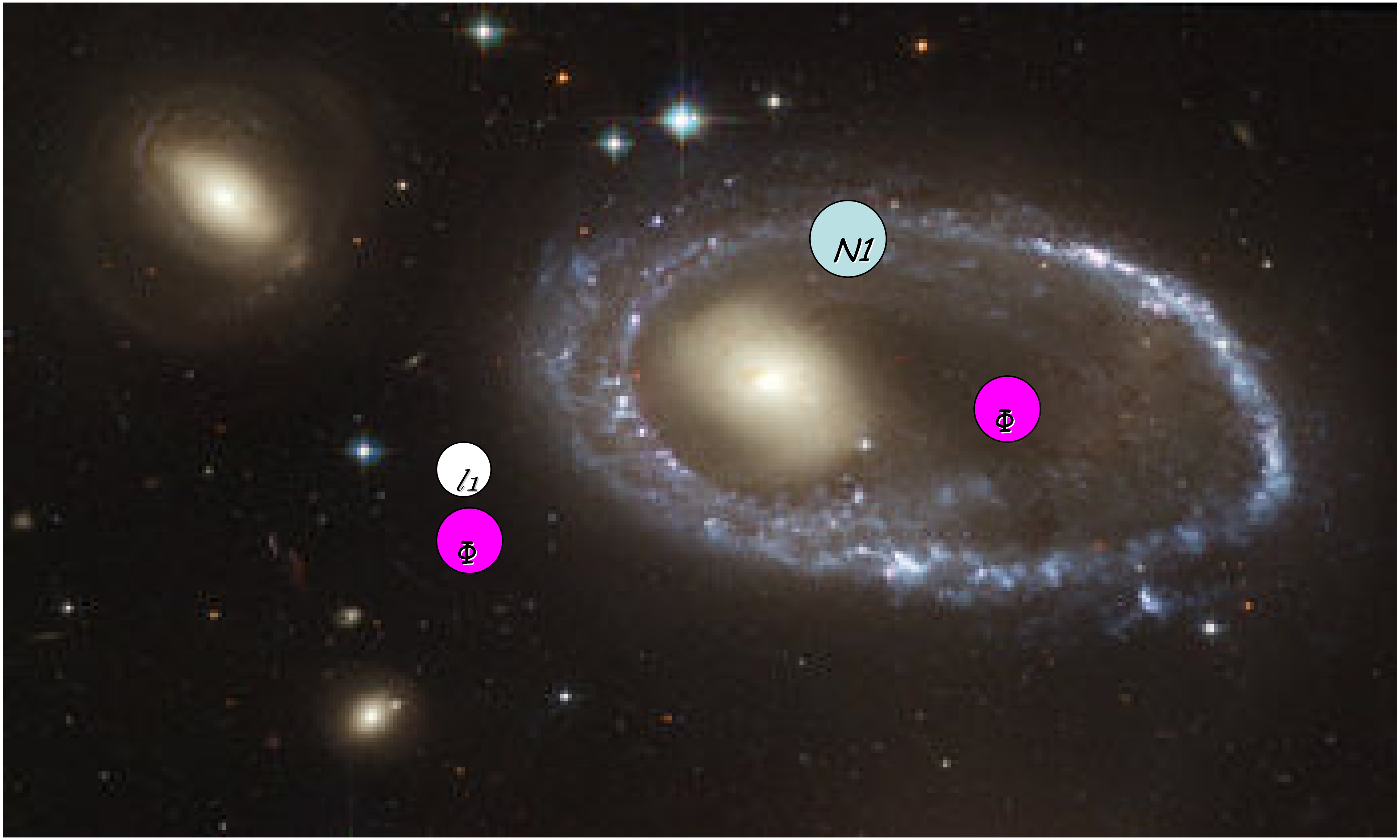
(Blanchet, PDB '06)

FULLY TWO-FLAVORED REGIME



(Blanchet, PDB '06)

NO FLAVOR



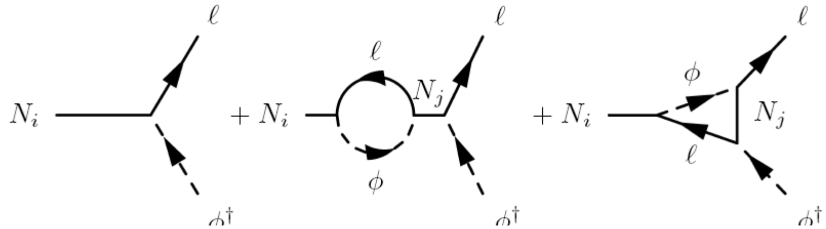
Puzzles of Modern Cosmology

1. Dark matter
2. Matter - antimatter asymmetry
3. Inflation
4. Accelerating Universe
5. Extra ultrarelativistic degrees of freedom ? $N_\nu^{\mathrm{eff}} = 4.3 \pm 0.85$ (WMAP 7 '10)

Baryogenesis

$\Longrightarrow$ clash between the SM and ΛCDM !

The total CP asymmetries can be calculated from :



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

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

It does not depend on U !

It holds if:

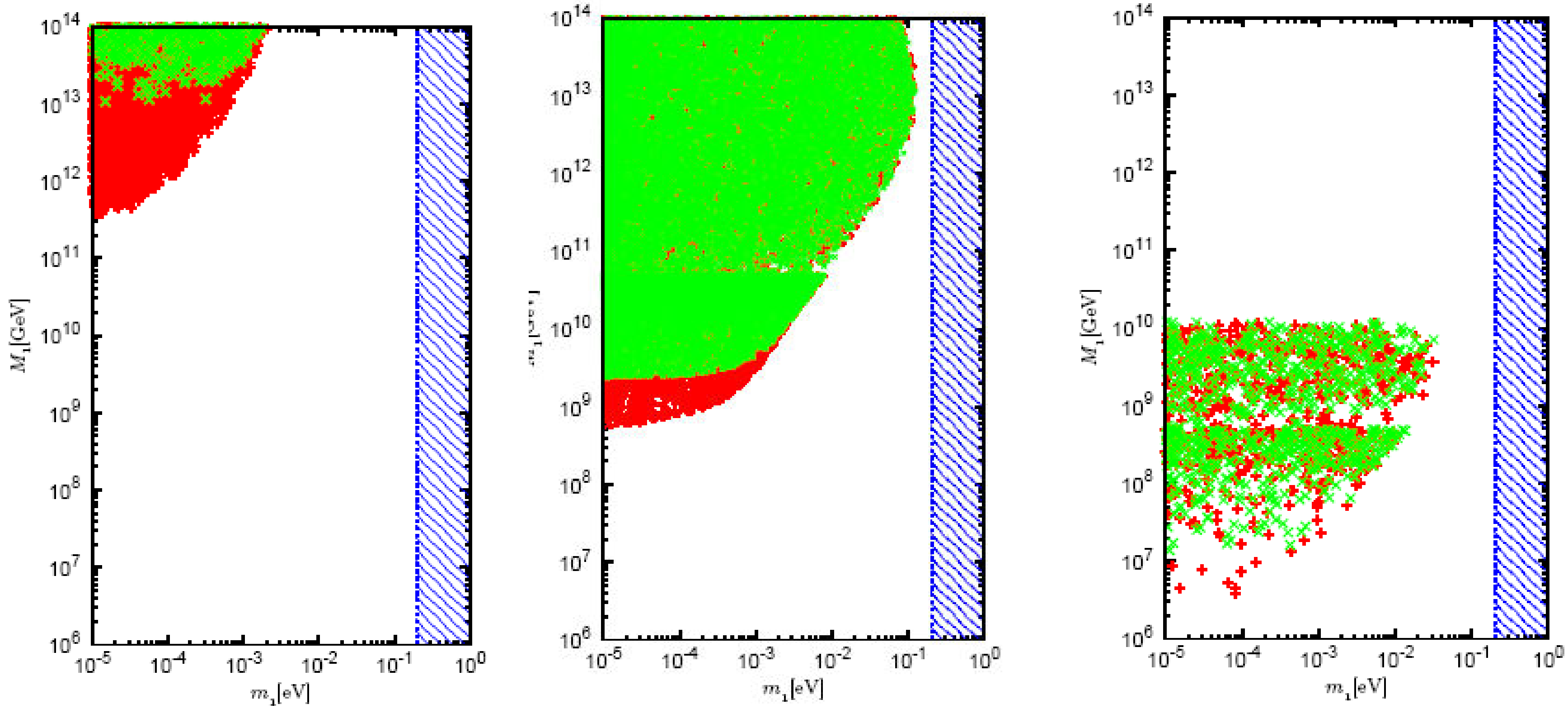
Hierarchical RH neutrino spectrum $\quad M_2 \gtrsim 100\, M_1$

N_3 does not interfere with N_2-decays: $\quad (m_D^\dagger\, m_D)_{23} = 0$ (PDB '05)

under these two conditions $\quad \Rightarrow |\varepsilon_{2,3}|^{max} \ll |\varepsilon_1|^{max}$

Leptogenesis “conspiracy“ (2)

$m_{atm} = 10^{-5}\ eV$ $\qquad m_{atm} = 0.05\, eV$ $\qquad m_{atm} = 10\, eV$

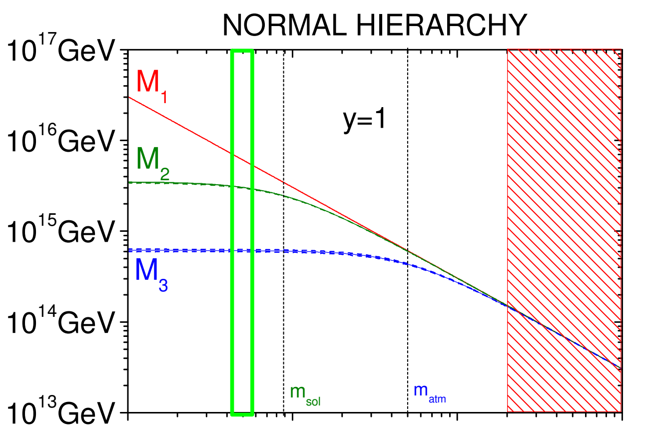


Green points: Unflavored

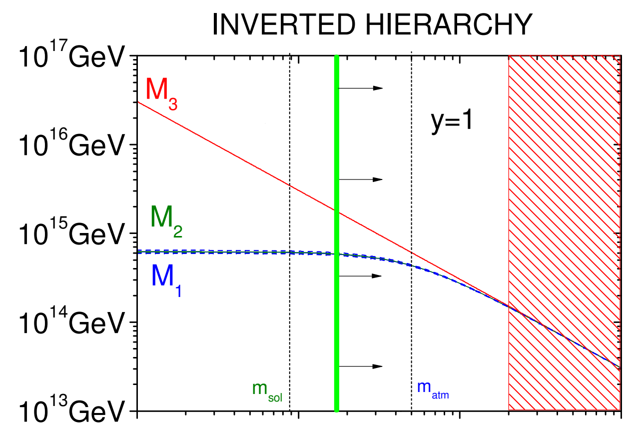
Red points: Flavored

Leptogenesis and discrete flavour symmetries: A4

(Ma '04; Altarelli, Feruglio '05; Bertuzzo, Di Bari, Feruglio, Nardi '09;Hagedorn,Molinaro,Petcov '09)

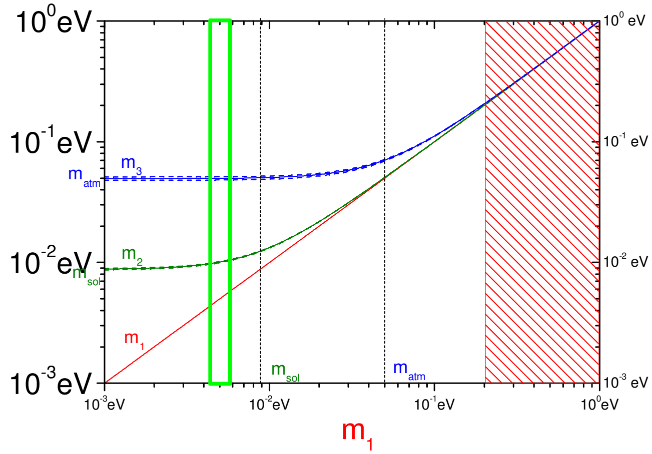


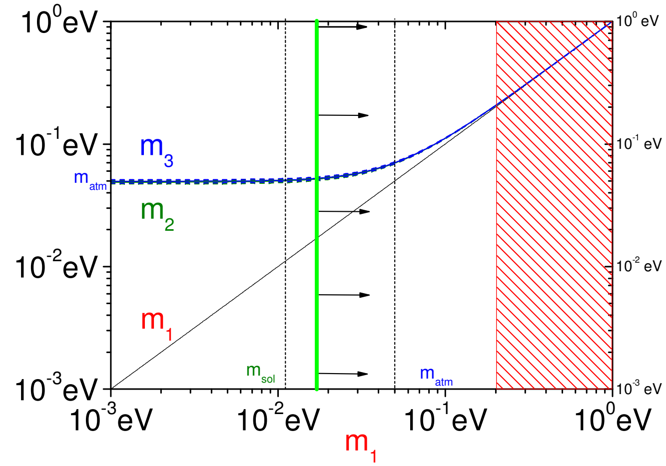
$$m_i = \frac{y^2\, v_u^2}{M_j}$$



$$m_1 \simeq 5\times 10^{-3}\,\mathrm{eV}$$

$$m_1 \gtrsim 0.017\,\mathrm{eV}$$





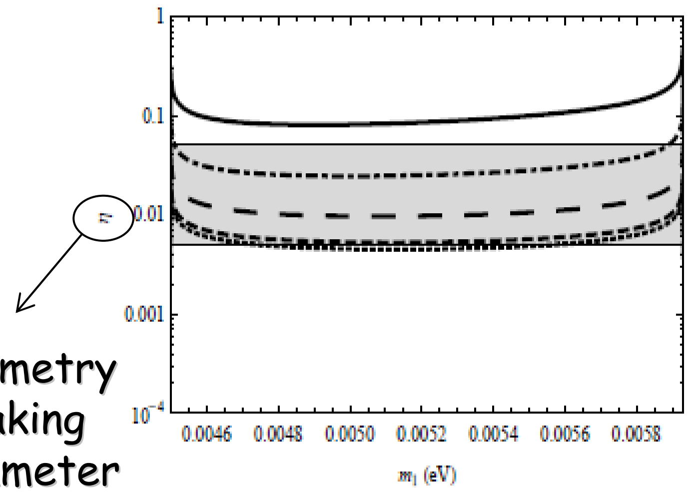
The situation is less attractive than in SO(10) inspired models because the RH neutrino mass spectrum first requires very high temperatures, second it does not allow a wash-out of a pre-existing asymmetry

Leptogenesis in A4 models

(Ma '04; Altarelli, Feruglio '05; Bertuzzo, Di Bari, Feruglio, Nardi '09)

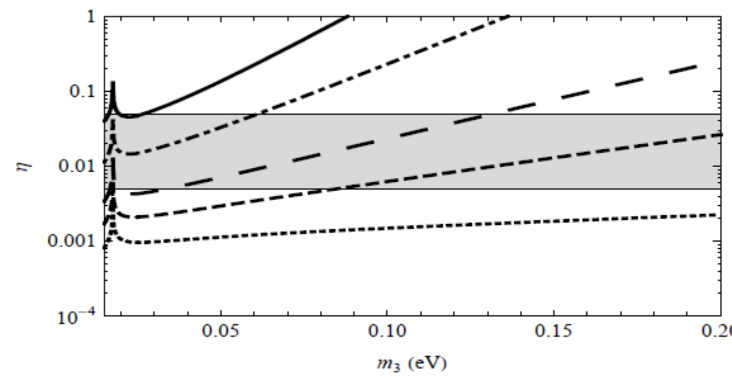
However successful leptogenesis seems to be possible (better in the normal hierarchical case) just for the best values of the symmetry breaking parameters

Normal ordering



Symmetry Breaking parameter

Inverted ordering



The different lines correspond to values of y between 0.3 and 3

Flavoured Boltzmann equations

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

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

These 2 terms correspond respectively to 2 different flavor effects:

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

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

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

- Classic Kinetic Equations (in their simplest form)

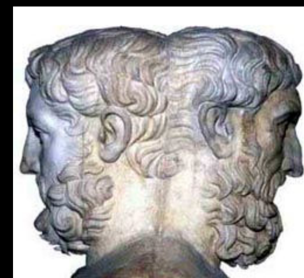
$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N^{\rm eq}_{N_1} \right)$$

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

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

The double side of Leptogenesis

Cosmology (early Universe)



Neutrino Physics, New Physics

- *Cosmological Puzzles* :

1. Dark matter
2. Matter - antimatter asymmetry
3. Inflation
4. Accelerating Universe

- *New stage in early Universe history* :

T

< 10^{14} GeV — Inflation

— Leptogenesis

100 GeV — EWSSB

0.1- 1 MeV — BBN

0.1- 1 eV — Recombination

Leptogenesis complements
low energy neutrino experiments
testing the
high energy parameters
of the seesaw mechanism

⇒ It provides a precious guidance to try to understand what kind of new physics is responsible for the neutrino masses and mixing

Beyond the type I seesaw

It is motivated typically by two reasons:

- Again avoid the reheating temperature lower bound
- In order to get new phenomenological tests….the most typical motivation in this respect is quite obviously whether we can test the seesaw and leptogenesis at the LHC

Typically lowering the RH neutrino scale at TeV , the RH neutrinos decouple and they cannot be efficiently produced in colliders

Many different proposals to circumvent the problem:

- additional gauged $U(1)_{B-L}$ (King,Yanagida '04)
- leptogenesis with Higgs triplet (type II seesaw mechanism)

(Ma,Sarkar '00 ; Hambye,Senjanovic '03; Rodejohann'04; Hambye,Strumia '05; Antusch '07)

- leptogenesis with three body decays (Hambye '01)
- see-saw with vector fields (Losada,Nardi '07)
- inverse seesaw mechanism and leptogenesis

(talk by R. Mohapatra)

Non minimal leptogenesis

Non thermal leptogenesis

The RH neutrino production is non-thermal and typically associated to inflation. They are often motivated in order to obtain successful leptogenesis with low reheating temperature.

- RH neutrino production from inflaton decays (Shafi,Lazarides' 91)

- Leptogenesis from RH sneutrinos decays (Murayama,Yanagida ' 93)

- RH neutrinos can also be produced at the end of inflation during the pre-heating stage (Giudice,Peloso,Riotto,Tkachev99)

-The connections with low energy neutrino experiments become even looser in these scenarios, while they can be made with properties of CMBR anisotropies (Asaka, Hamaguchi,Yanagida '99)

Improved kinetic description

- **Momentum dependence in Boltzmann equations**

  (Hannestad ' 06; Hahn-Woernle, M. Plümacher, Y.Wong '09; Pastor, Vives'09)

- **Kadanoff-Baym equations**

  (Buchmüller,Fredenhagen '01; De Simone,Riotto '07; Garny,Hohenegger, Kartavtsev,Lindner '09; Anisimov,Buchmüller,Drewes,Mendizibal '09; Beneke, Garbrecht, Herranen, Schwaller '10)

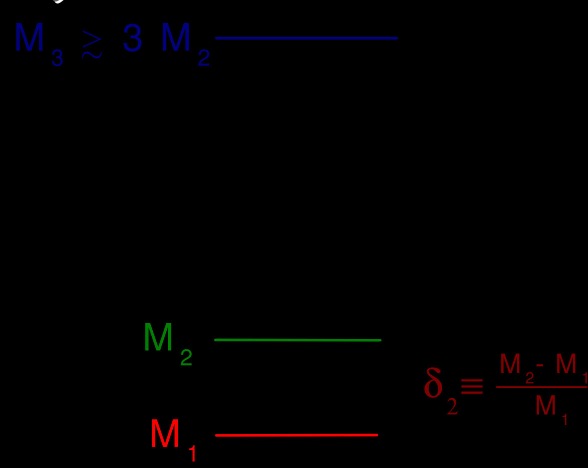
  The asymmetry is directly calculated in terms of Green functions instead than in terms of number densities and they account for off-shell , memory and medium effects in a systematic way

At the moment all these analyses confirm what also happens for other effects (e.g. inclusion of scatterings) and that is expected: **large theoretical uncertainties in the weak wash-out regime, limited corrections ($\mathcal{O}(1)$) in the strong wash-out regime** where the asymmetry is produced in a narrow range of temperatures for T << M_i (Buchmüller,PDB,Plümacher

The degenerate limit

(Covi, Roulet, Vissani '96; Pilaftsis ' 97; Blanchet, PDB '06)

Different possibilities, for example: :



- partial hierarchy: $M_3 \gg M_2$, M_1

$$\Rightarrow \quad |\varepsilon_3| \ll |\varepsilon_2|, |\varepsilon_1| \quad \text{and} \quad \kappa_3^{\rm fin} \ll \kappa_2^{\rm fin}, \kappa_1^{\rm fin}$$

CP asymmetries get enhanced $\propto 1/\delta_2$

$$\Rightarrow N_{B-L}^{\rm fin} \nearrow$$

For $\delta_2 \lesssim 0.01$ (degenerate limit) :

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

The reheating temperature lower bound is relaxed

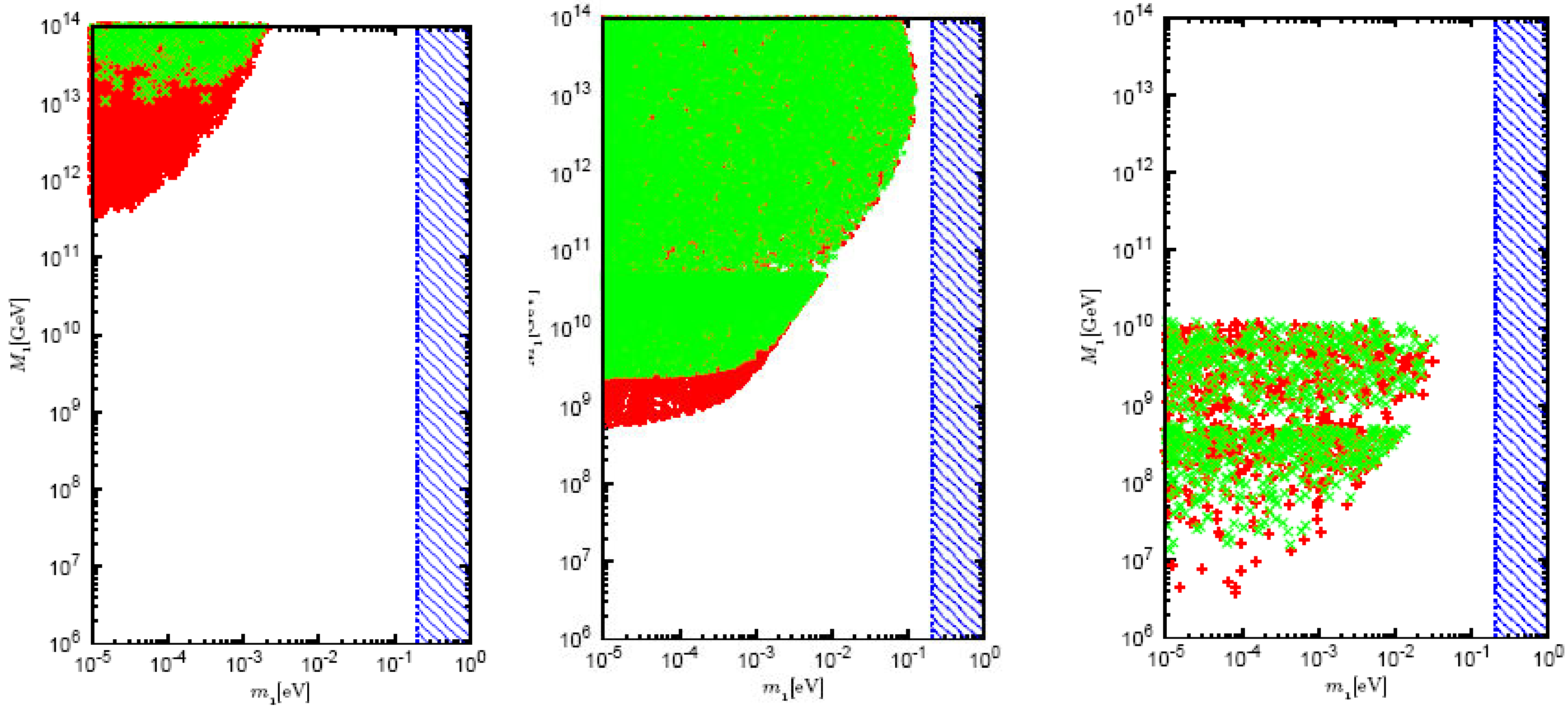
The required tiny value of δ_2 can be obtained e.g. in *radiative leptogenesis* (Branco, Gonzalez, Joaquim, Nobre'04,'05)

Flavor effects do not spoil the conspiracy

Green points: Unflavored

Red points: Flavored

$m_{atm} = 10^{-5}\, eV$ $m_{atm} = 0.05\, eV$ $m_{atm} = 10\, eV$

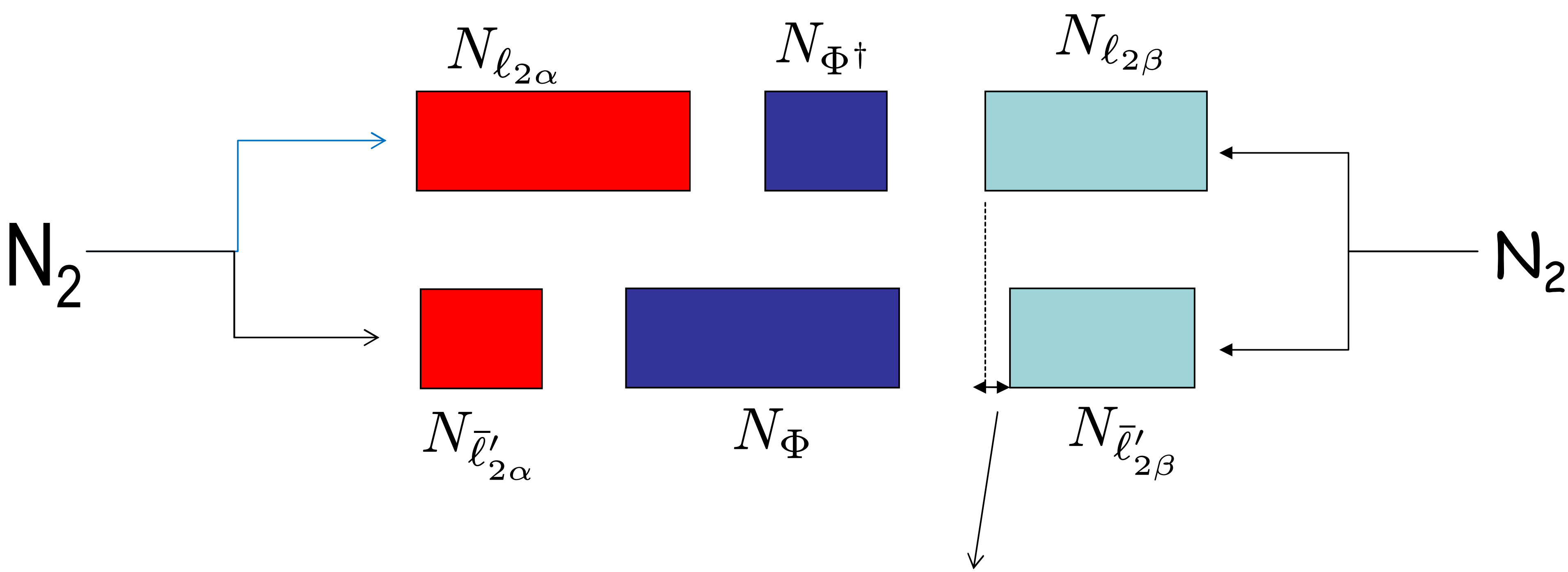


….but they yield two interesting results:

A pictorial representation

Let us give a pictorial description focusing on the dominant Higgs asymmetry and disregarding the asymmetries in quarks and charged lepton singlets

Assume $K_{2\alpha} \lesssim 1$ while $K_{2\beta} \gg 1$



This β-asymmetry is induced by the "thermal contact" with the α-leptons via the Higgs

Production stage

We have to solve :

$$\frac{dN_{N_2}}{dz_2} = -D_2\,(N_{N_2} - N_{N_2}^{\rm eq})\,,$$
$$\frac{dN_{\Delta_\gamma}}{dz_2} = \varepsilon_{2\gamma}\,D_2\,(N_{N_2} - N_{N_2}^{\rm eq}) - P_{2\gamma}^0\,W_2\,\sum_{\alpha=\gamma,\tau} C_{\gamma\alpha}^{(2)}\,N_{\Delta_\alpha}\,,$$
$$\frac{dN_{\Delta_\tau}}{dz_2} = \varepsilon_{2\tau}\,\Delta_2\,(N_{N_2} - N_{N_2}^{\rm eq}) - P_{2\tau}^0\,W_2\,\sum_{\alpha=\gamma,\tau} C_{\tau\alpha}^{(2)}\,N_{\Delta_\alpha}\,.$$

Defining U as the matrix that diagonalizes: $P_2^0 \equiv \begin{pmatrix} P_{2\gamma}^0\,C_{\gamma\gamma}^{(2)} & P_{2\gamma}^0\,C_{\gamma\tau}^{(2)} \\ P_{2\tau}^0\,C_{\tau\gamma}^{(2)} & P_{2\tau}^0\,C_{\tau\tau}^{(2)} \end{pmatrix}$

$$U\,P_2^0\,U^{-1} = {\rm diag}(P_{2\gamma'}^0, P_{2\tau'}^0)$$

The asymmetry at T ~ M_2 is then given by :

$$N_{\Delta_\gamma}^{T\sim M_2} = U_{\gamma\gamma'}^{-1}\,[U_{\gamma'\gamma}\,\varepsilon_{2\gamma} + U_{\gamma'\tau}\,\varepsilon_{2\tau}]\;\kappa(K_{2\gamma}) + U_{\gamma\tau'}^{-1}\,[U_{\tau'\gamma}\,\varepsilon_{2\gamma} + U_{\tau'\tau}\,\varepsilon_{2\tau}]\;\kappa(K_{2\tau})\,,$$
$$N_{\Delta_\tau}^{T\sim M_2} = U_{\tau\gamma'}^{-1}\,[U_{\gamma'\gamma}\,\varepsilon_{2\gamma} + U_{\gamma'\tau}\,\varepsilon_{2\tau}]\;\kappa(K_{2\gamma}) + U_{\tau\tau'}^{-1}\,[U_{\tau'\gamma}\,\varepsilon_{2\gamma} + U_{\tau'\tau}\,\varepsilon_{2\tau}]\;\kappa(K_{2\tau})\,,$$
$$N_{B-L}^{T\sim M_2} = N_{\Delta_\gamma}^{T\sim M_2} + N_{\Delta_\tau}^{T\sim M_2}\,.$$

Flavour coupling in the N_2-dom.scenario

(Antusch, PDB, Jones, King '10)

Flavor coupling does not relevantly affect the final asymmetry In N_1-leptogenesis (Abada, Josse-Michaux '07) but a strong enhancement is possible in N_2-leptogenesis because here now there are three stages to be taken into account:

1) Production at 10^{12} GeV >> T ~ $M_2 \gtrsim 10^9$ GeV (2-flavour regime):

$$
\begin{aligned}
\frac{dN_{N_2}}{dz_2} &= -D_2\,(N_{N_2} - N_{N_2}^{\rm eq})\,, \\
\frac{dN_{\Delta_\gamma}}{dz_2} &= \varepsilon_{2\gamma}\,D_2\,(N_{N_2} - N_{N_2}^{\rm eq}) - P_{2\gamma}^0\,W_2 \sum_{\alpha=\gamma,\tau} C_{\gamma\alpha}^{(2)}\,N_{\Delta_\alpha}\,,\ (\gamma \equiv e+\mu) \\
\frac{dN_{\Delta_\tau}}{dz_2} &= \varepsilon_{2\tau}\,\Delta_2\,(N_{N_2} - N_{N_2}^{\rm eq}) - P_{2\tau}^0\,W_2 \sum_{\alpha=\gamma,\tau} C_{\tau\alpha}^{(2)}\,N_{\Delta_\alpha}\,.
\end{aligned}
$$

2) Decoherence at T ~ 10^9 GeV : $N_{\Delta_\gamma}^{T\sim M_2}$ splits into $N_{\Delta_\mu}^{T\sim M_2}$ and $N_{\Delta_e}^{T\sim M_2}$

3) Lightest RH neutrino wash-out at T ~ M_1 << 10^9 GeV (3-fl. regime):

$$
\frac{dN_{\Delta_\alpha}}{dz_1} = -P_{1\alpha}^0\,\sum_\beta C_{\alpha\beta}^{(3)}\,W_1\,N_{\Delta_\beta}\,, \qquad (\alpha,\beta = e,\mu,\tau)
$$

Lightest RH neutrino wash-out

We have to solve

$$\frac{dN_{\Delta_\alpha}}{dz_1} = -P^0_{1\alpha}\,\sum_\beta\, C^{(3)}_{\alpha\beta}\, W_1\, N_{\Delta_\beta}\,, \qquad (\alpha,\beta = e,\mu,\tau)$$

using as initial conditions $N^{\rm in}_{\Delta\beta} = N^{T\sim M_2}_{\Delta\beta}$

If we first neglect the flavour coupling using the approximation $C^{(3)} = I$, then

$$\frac{dN_{\Delta_\alpha}}{dz_1} = -P^0_{1\alpha}\, W_1\, N_{\Delta_\alpha}\,, \qquad (\alpha,\beta = e,\mu,\tau)$$

This can be straightforwardly solved finding:

$$N^{\rm f}_{B-L} = N^{T\sim T_{M_2}}_{\Delta_e}\, e^{-\frac{3\pi}{8}\,K_{1e}} + N^{T\sim M_2}_{\Delta_\mu}\, e^{-\frac{3\pi}{8}\,K_{1\mu}} + N^{T\sim M_2}_{\Delta_\tau}\, e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

Flavor swap scenario

(Antusch, PDB, Jones, King '10)

Suppose that at the production the e+μ (γ) flavour component of the asymmetry is weakly washed-out while the τ component is strongly washed-out. Then the latter can be considerably enhanced by flavor coupling:

$$N_{\Delta_\tau}^{T\sim M_2} \simeq \varepsilon_{2\tau}\,\kappa(K_{2\tau}) - C^{(2)}_{\tau\gamma}\,\varepsilon_{2\gamma}\,\kappa(K_{2\gamma}) \simeq C^{(2)}_{\tau\gamma}\,\varepsilon_{2\gamma}\,\kappa(K_{2\gamma})\,,$$

$$N_{\Delta_\gamma}^{T\sim M_2} \simeq \varepsilon_{2\gamma}\,\kappa(K_{2\gamma})\,,$$

At the production the total asymmetry does not relevantly change (Abada, Josse-Michaux '07) but... a "flavor-swap" can be induced at the N_1 wash-out if $K_{1e}, K_{1\mu} \gg 1\,, K_{1\tau} \ll 1$

$$\Rightarrow N_{B-L}^{\rm f} = N_{\Delta_e}^{T\sim T_{M_2}}\, e^{-\frac{3\pi}{8}\,K_{1e}} + N_{\Delta_\mu}^{T\sim M_2}\, e^{-\frac{3\pi}{8}\,K_{1\mu}} + N_{\Delta_\tau}^{T\sim M_2}\, e^{-\frac{3\pi}{8}\,K_{1\tau}} \simeq N_{\Delta_\tau}^{T\sim M_2} \simeq C^{(2)}_{\tau\gamma}\,\varepsilon_{2\gamma}\,\kappa(K_{2\gamma})$$

In this way the strong enhancement of the τ-asymmetry at the production translates into a strong enhancement of the final asymmetry

Flavour coupling at the N_1 wash-out

Let us now take into account flavour coupling at the N_1-wash-out as well:

$$\frac{dN_{\Delta_\alpha}}{dz_1} = -P^0_{1\alpha}\,\sum_\beta\, C^{(3)}_{\alpha\beta}\,W_1\,N_{\Delta_\beta}\,, \qquad\qquad (\alpha,\beta = e,\mu,\tau)$$

using as initial conditions $N^{\rm in}_{\Delta\beta} = N^{T\sim M_2}_{\Delta\beta}$

We can repeat the same trick as before, i.e. introducing a matrix V that diagonalizes:

$$P^0_1 \equiv \begin{pmatrix} P^0_{1e}\,C^{(3)}_{ee} & P^0_{1e}\,C^{(3)}_{e\mu} & P^0_{1e}\,C^{(3)}_{e\tau} \\ P^0_{1\mu}\,C^{(3)}_{\mu e} & P^0_{1\mu}\,C^{(3)}_{\mu\mu} & P^0_{1\mu}\,C^{(3)}_{\mu\tau} \\ P^0_{1\tau}\,C^{(3)}_{\tau e} & P^0_{1\tau}\,C^{(3)}_{\tau\mu} & P^0_{1\tau}\,C^{(3)}_{\tau\tau} \end{pmatrix}$$

One finally finds the general solution :

$$N^{\rm f}_{\Delta_\alpha} = \sum_{\alpha''} V^{-1}_{\alpha\alpha''}\, e^{-\frac{3\pi}{8}\,K_{1\alpha''}} \left[\sum_\beta V_{\alpha''\beta}\,N^{T\sim M_2}_{\Delta_\beta}\right]\,, \qquad N^f_{B-L} = \sum_\alpha N^{\rm f}_{\Delta_\alpha}$$

with $K_{1\alpha''} \simeq K_{1\alpha}$

Circumventing the N_1 wash-out

Because of flavour coupling at the N_1 wash-out there is another interesting effect. Let us "unpack" the previous general expression for example for the τ-asymmetry:

$$
\begin{aligned}
N^{\rm f}_{\Delta_\tau} \;\simeq\;& V^{-1}_{\tau e''}\left[\sum_\beta V_{e''\beta}\, N^{T\sim M_2}_{\Delta_\beta}\right] e^{-\frac{3\pi}{8}\,K_{1e}} \\
&+ V^{-1}_{\tau\mu''}\left[\sum_\beta V_{\mu''\beta}\, N^{T\sim M_2}_{\Delta_\beta}\right] e^{-\frac{3\pi}{8}\,K_{1\mu}} \\
&+ V^{-1}_{\tau\tau''}\left[\sum_\beta V_{\tau''\beta}\, N^{T\sim M_2}_{\Delta_\beta}\right] e^{-\frac{3\pi}{8}\,K_{1\tau}}
\end{aligned}
$$

Now even though one has $K_{1\tau} \gg 1$, there is still a final τ asymmetry that manages to escape the N_1 wash-out. Why ? Again because of the Higgs asymmetry present in the thermal bath that is not exactly that one needed for a complete wash-out of the τ asymmetry

⇒ the lightest RH neutrino wash-out becomes less efficient !

Phantom terms

We have now to answer: how at the decoherence, at T ~ 10^9 GeV,

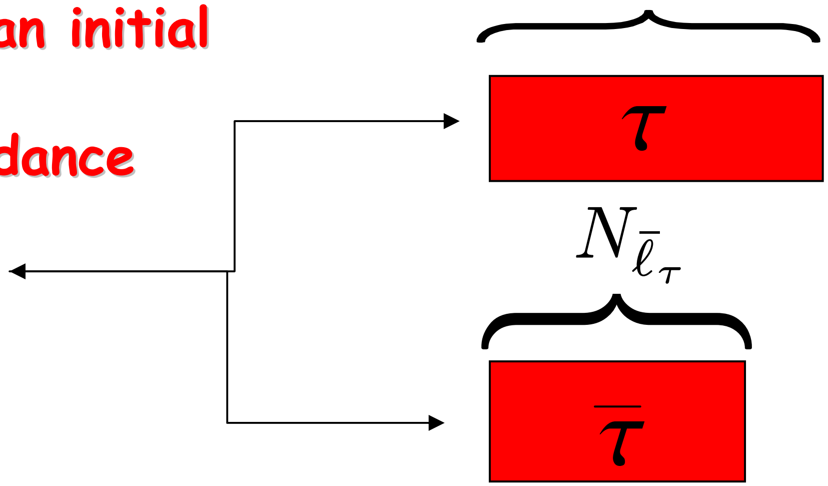
$$N_{\Delta_\gamma}^{T\sim M_2} \text{ splits into } N_{\Delta_\mu}^{T\sim M_2} \text{ and } N_{\Delta_e}^{T\sim M_2}?$$

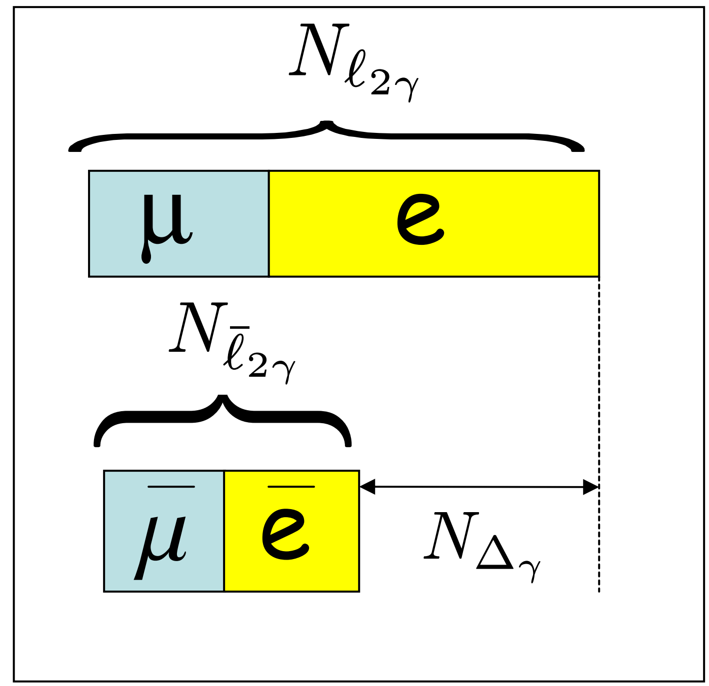
First stage: T ≳ M_2 (decays)

N_{ℓ_τ}

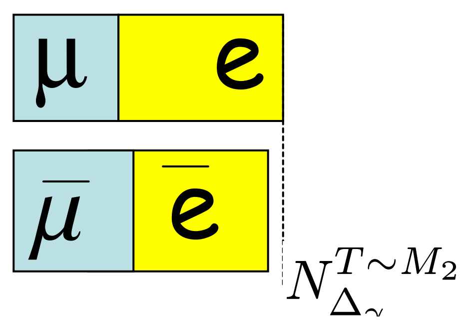
Assume an initial thermal N_2-abundance

N_2





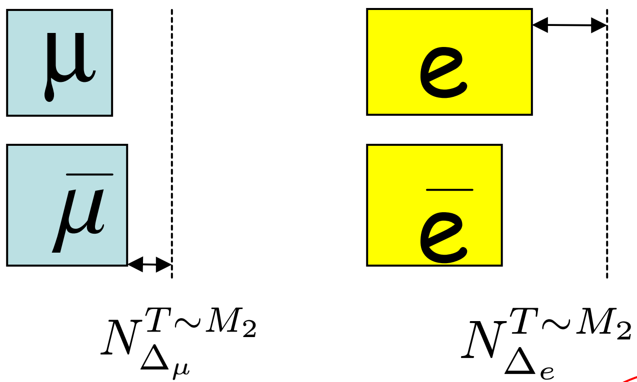
Second stage: T ~ M_2 (N_2 - washout)



The N_2 wash-out can only suppress the γ-asymmetry but it cannot change the flavour compositions of $\ell_{2\gamma}$ and $\bar{\ell}'_{2\gamma}$

Phantom terms

Third stage: 10^9 GeV ≳ T' >> M_1 (3-flavour regime)



$$f_{2\alpha} \equiv \frac{|\langle \ell_\alpha | \ell_{2\gamma}\rangle|^2 + |\langle \bar{\ell}_\alpha | \bar{\ell}'_{2\gamma}\rangle|^2}{2}$$

$$N_{\Delta_e}(T') = p_e + \frac{f_{2e}}{f_{2e}+f_{2\mu}} N_{\Delta_\gamma}^{T\sim M_2}, \quad N_{\Delta_\mu}(T') = p_\mu + \frac{f_{2\mu}}{f_{2e}+f_{2\mu}} N_{\Delta_\gamma}^{T\sim M_2}$$

$$\simeq \kappa(K_{2\gamma})\,\varepsilon_{2\gamma} \quad \text{(neglecting flavour coupling !)}$$

Phantom terms

$$p_e = \varepsilon_{2e} - \frac{f_{2e}}{f_{2e}+f_{2\mu}}\,\varepsilon_2$$

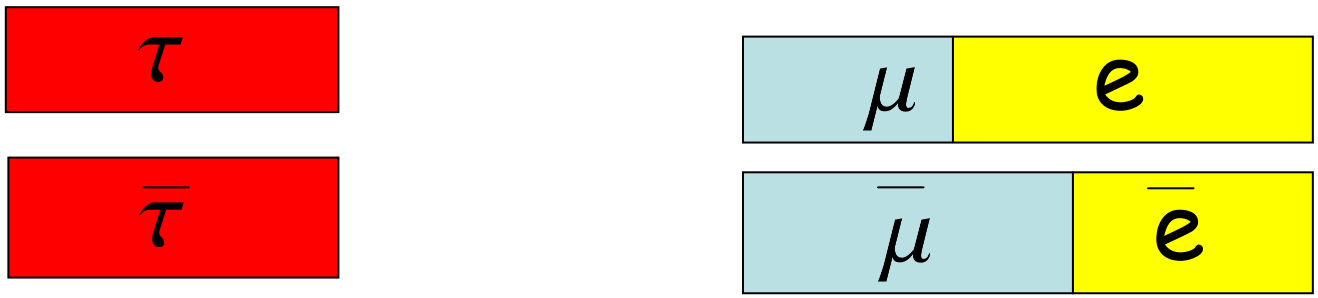
$$p_\mu = \varepsilon_{2\mu} - \frac{f_{2\mu}}{f_{2e}+f_{2\mu}}\,\varepsilon_2 = -p_e$$

Notice that phantom terms are not suppressed by N_2 wash-out !

Phantom Leptogenesis

We can have then a situation where $K_{2\gamma}$, $K_{2\tau} \gg 1$ so that at the End of the N_2 washout the total asymmetry is negligible:

$T \sim M_2$



$$N_{B-L}^{T\sim M_2} = N_{\Delta\tau}^{T\sim M_2} + N_{\Delta\gamma}^{T\sim M_2} \simeq 0\ !$$

10^9 GeV $\gtrsim T \gg M_1$

$$N_{B-L}^{T\sim M_2} = N_{\Delta\tau}^{T\sim M_2} + N_{\Delta e}^{T\sim M_2} + N_{\Delta\mu}^{T\sim M_2} \simeq 0\ !$$

$T \simeq M_1$

Assume $K_{1e} \lesssim 1$ and $K_{1\mu} \gg 1$

$$N_{B-L}^{\rm f} = N_{\Delta e}^{T\sim M_2} \simeq p_e\ !$$

The N_1 wash-out un-reveal the phantom term and effectively it create a N_{B-L} asymmetry ! There is nothing esoteric but there is a...

Drawback of phantom Leptogenesis

We assumed an initial N_2 thermal abundance but if we were assuming An initial vanishing N_2 abundance the phantom terms were just zero !

Therefore, more generally :

$$p_e = \left(\varepsilon_{2e} - \frac{f_{2e}}{f_{2e}+f_{2\mu}}\,\varepsilon_2\right) N_{N_2}^{\rm in}$$

The reason is that phantom terms with opposite sign would be created during the N_2 production by inverse decays and exactly cancelling with the contribution generated from decays ! More generally

In conclusion ....phantom leptogenesis is more a problem for the N_2 dominated scenario since it introduces a strong dependence on the initial conditions !!