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

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

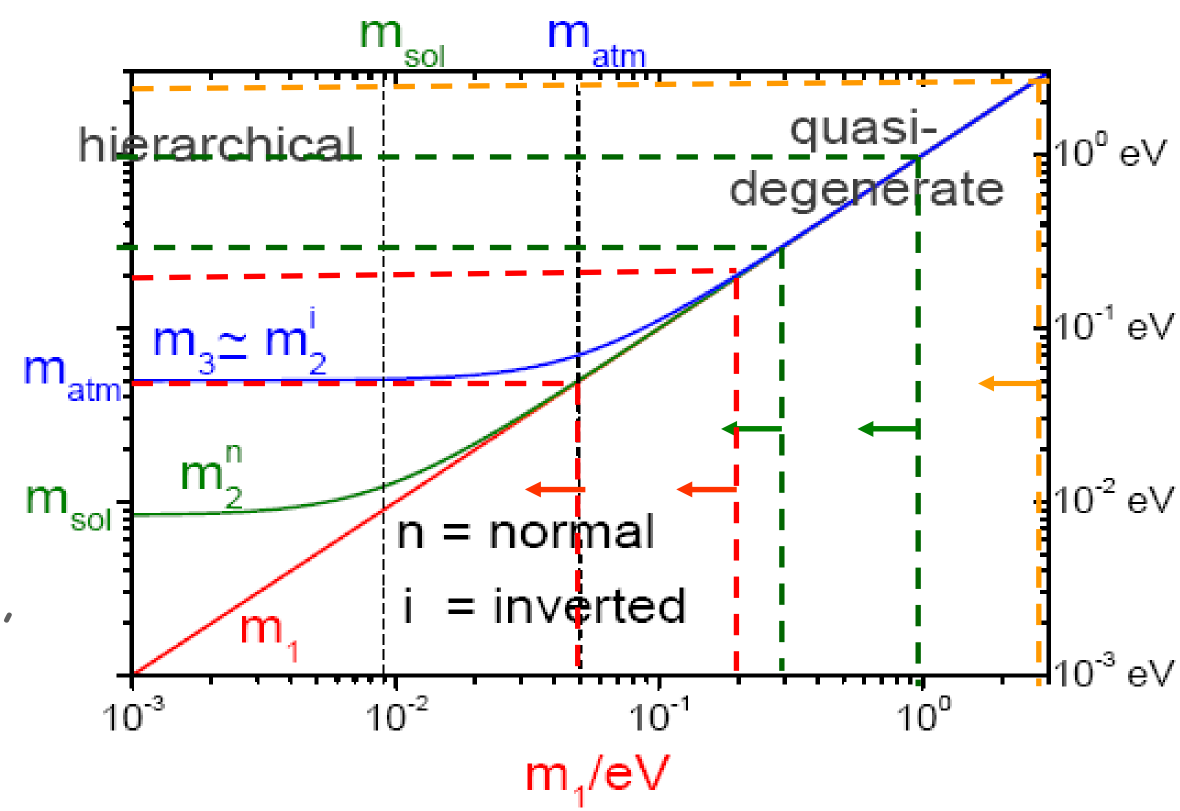
$$m_2^2 - m_1^2 = \Delta m^2_{\rm sol} \text{ or } \Delta m^2_{\rm atm} \qquad m_{\rm sol} \equiv \sqrt{\Delta m^2_{\rm sol}} \simeq 0.009\,{\rm eV}$$

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

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

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

- 3 light neutrinos ν_1, ν_2, ν_3 with masses

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

- 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)

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

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

(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

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

Total CP asymmetries $\qquad \varepsilon_i \equiv -\frac{\Gamma_i - \bar\Gamma_i}{\Gamma_i + \bar\Gamma_i}$

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)

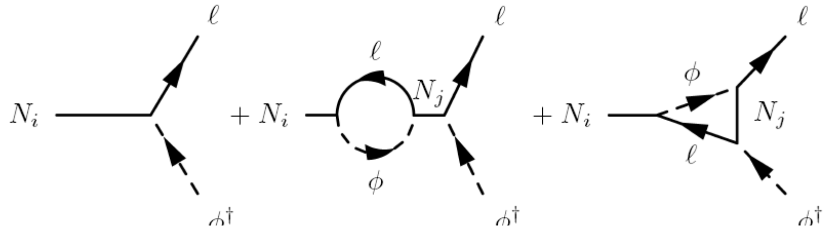
$$N_{B-L}^{\rm fin} = \sum_i \varepsilon_i\, \kappa_i^{\rm fin} \Rightarrow \eta_B = a_{\rm sph}\, \frac{N_{B-L}^{\rm fin}}{N_\gamma^{\rm rec}}$$

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 :

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

efficiency factor

4) Barring fine-tuned mass cancellations

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

$\Rightarrow$ **Upper bound on ε_1**

(Davidson, Ibarra '02)

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

5) Classical Kinetic equations integrated on momenta

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

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

decays

inverse decays

wash-out

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

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

Neutrino mass bounds

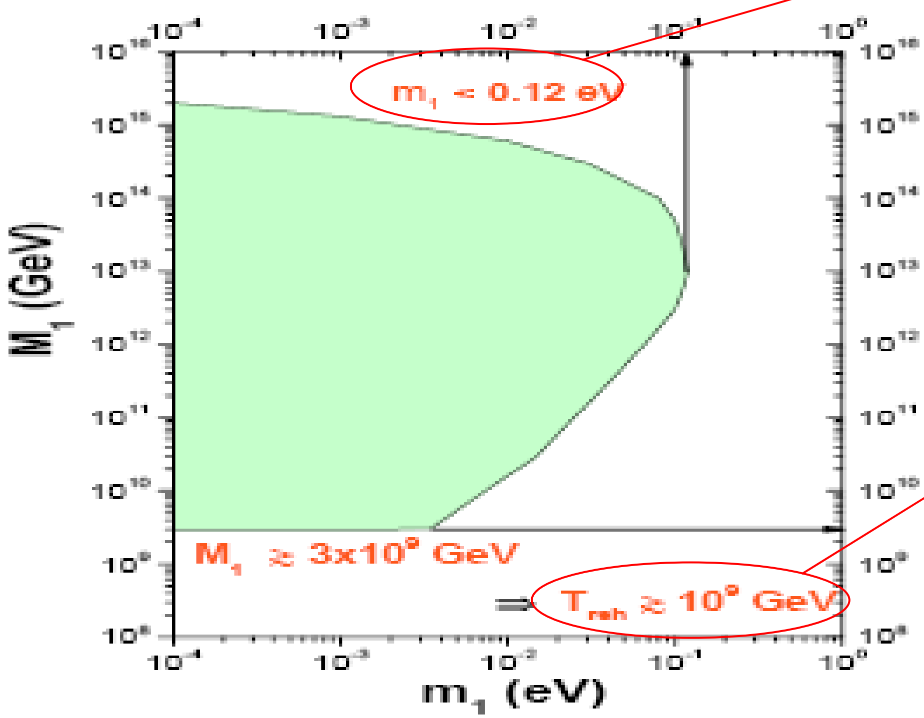
(Davidson,Ibarra '02;Buchmüller,PDB,Plümacher '02,'03,'04; Giudice et al. '04)

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

No constraints on the leptonic mixing matrix U !



Vanilla leptogenesis is not compatible with quasi-deg. neutrinos

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

An encouraging coincidence

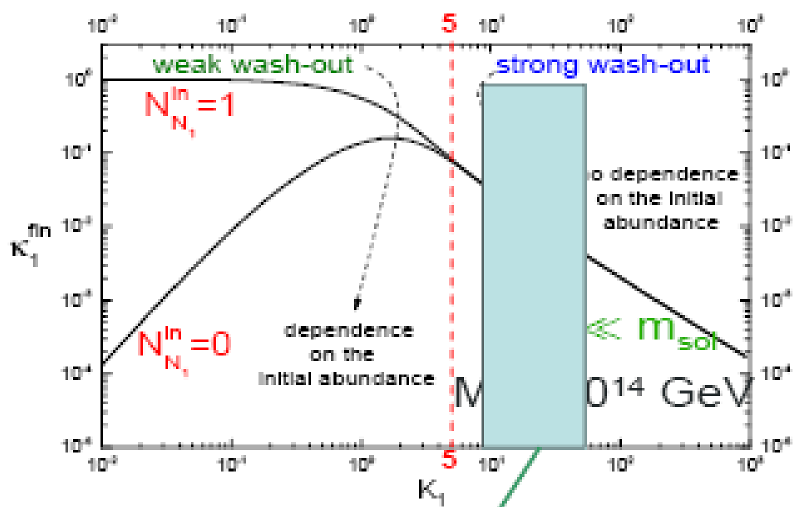
The early Universe „knows" neutrino masses ...

(Buchmüller,PDB,Plümacher '04)

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

decay parameter

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

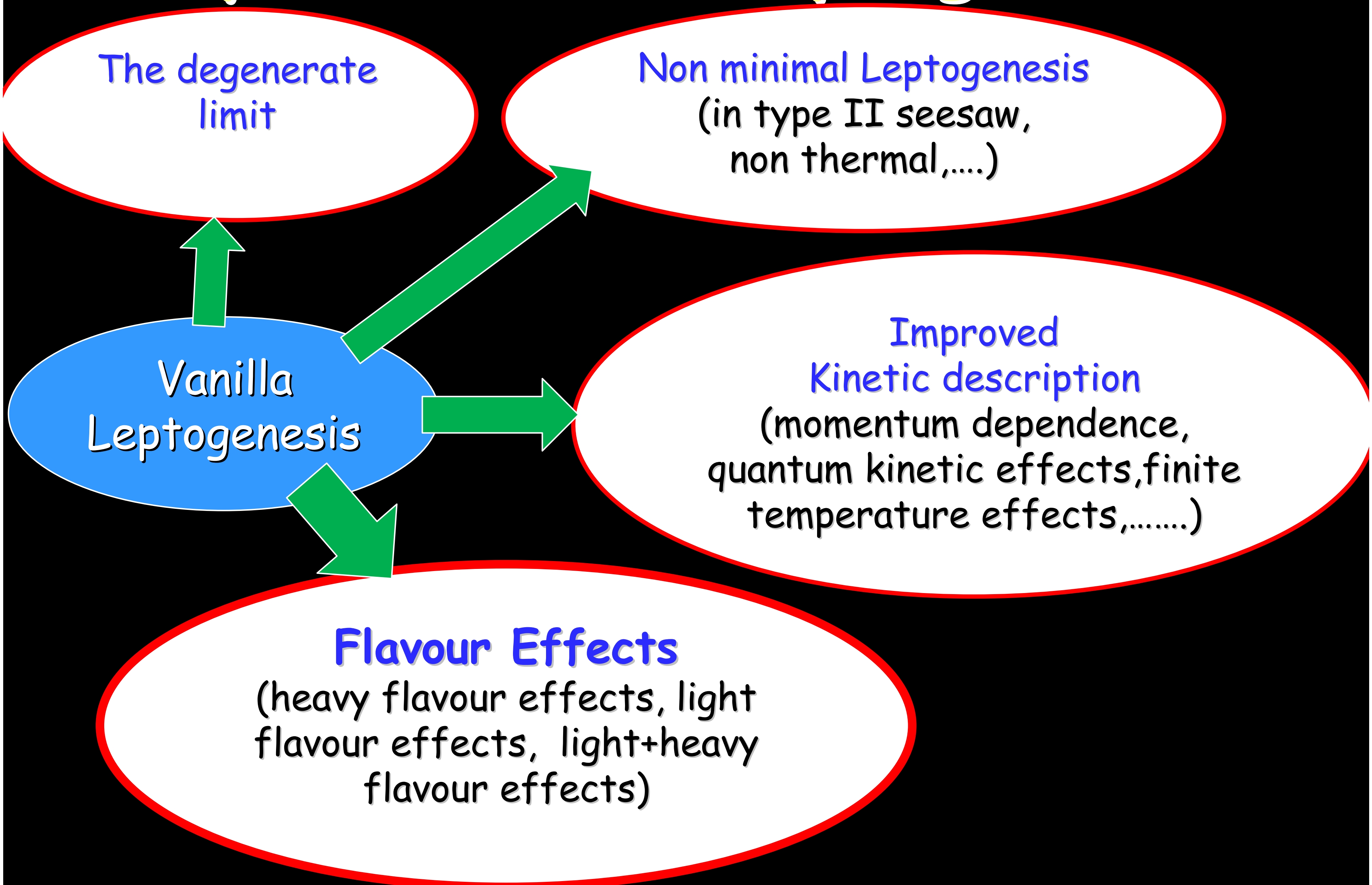


$$K_{\rm sol} \simeq 9 \lesssim K_1 \lesssim 50 \simeq K_{\rm atm}$$

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 $|\bar{l}_1'\rangle$

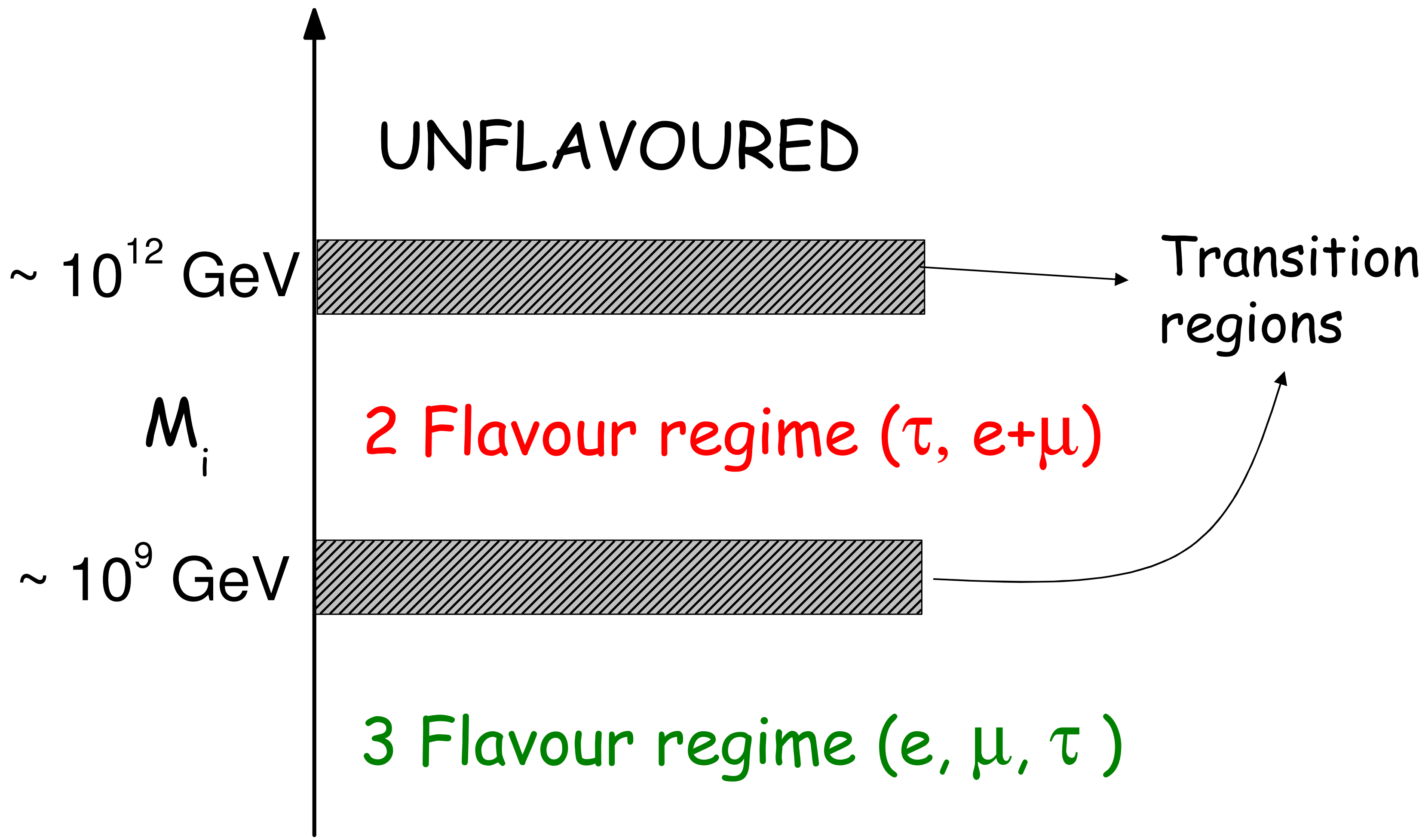
$\Longrightarrow$ they become an incoherent mixture of a τ and of μ+e

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

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

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: $\Rightarrow N_{B-L}^{\rm fin} = \sum_{\alpha=\tau, e+\mu} \varepsilon_{1\alpha}\, \kappa_{1\alpha}^{\rm fin}$

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

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

These 2 terms correspond respectively to 2 different flavor effects:

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

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

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

- Classic Kinetic Equations (in their simplest form)

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

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

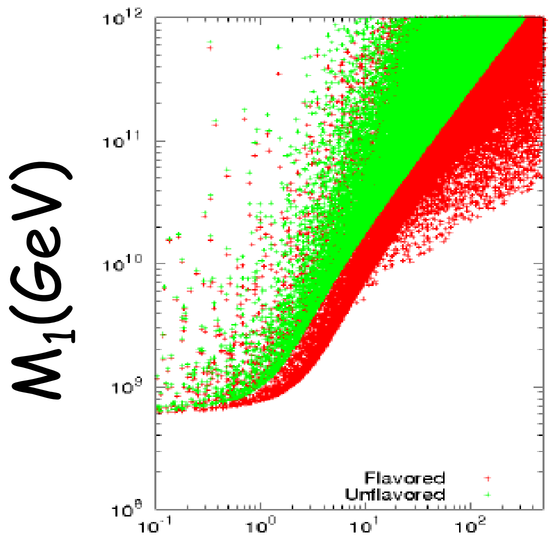
$$\Rightarrow \quad N_{B-L} = \sum_\alpha N_{\Delta_\alpha} \qquad (\Delta_\alpha \equiv B/3 - L_\alpha)$$

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

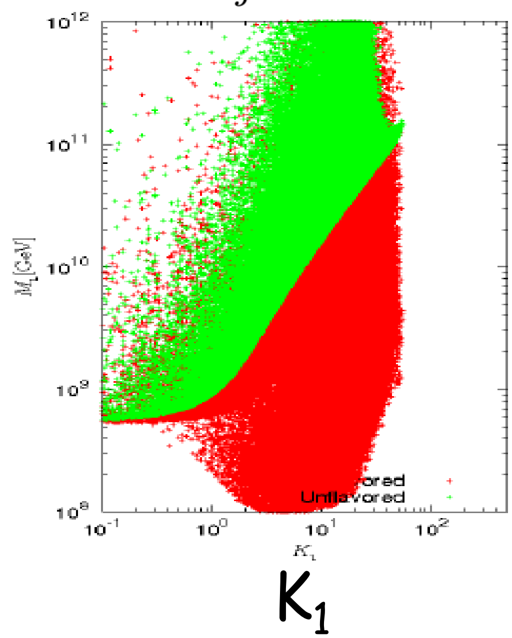
The bounds get relaxed

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

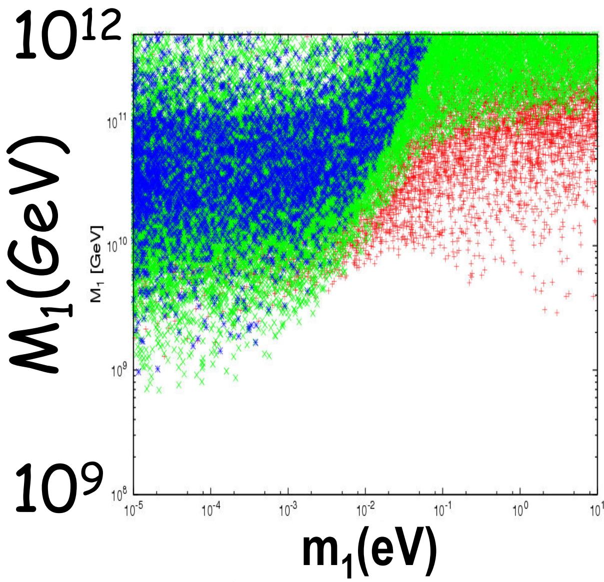
$|\Omega^2_{ij}| \lesssim 1$

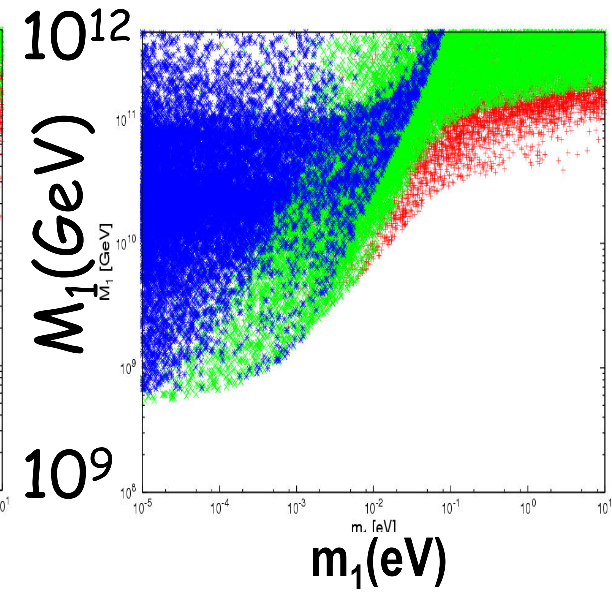


$|\Omega^2_{ij}| \lesssim 10$



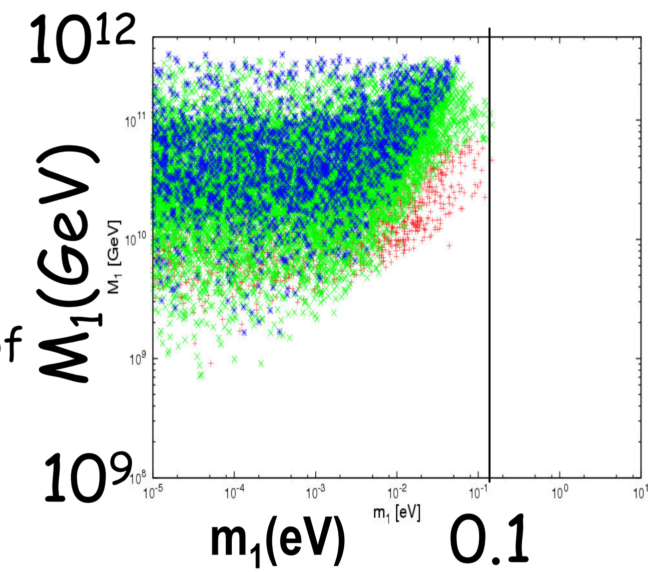
PMNS phases off





imposing a condition of validity of Boltzmann equations

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



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:

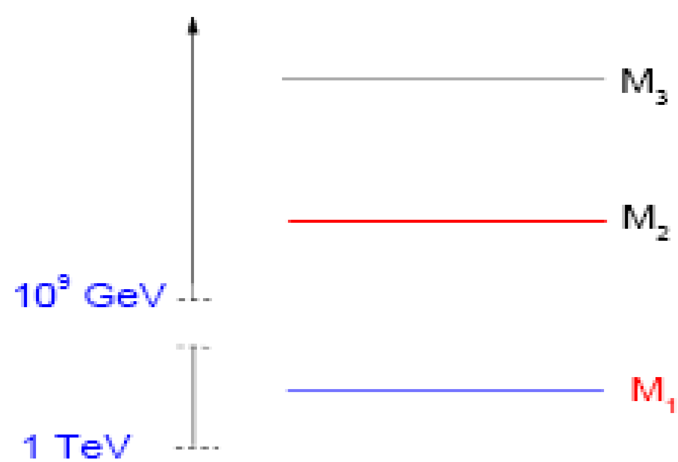
$$N_{B-L}^{\mathrm{f},N_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\mathrm{f},N_1} = \varepsilon_1\, \kappa(K_1)$$

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

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

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} !

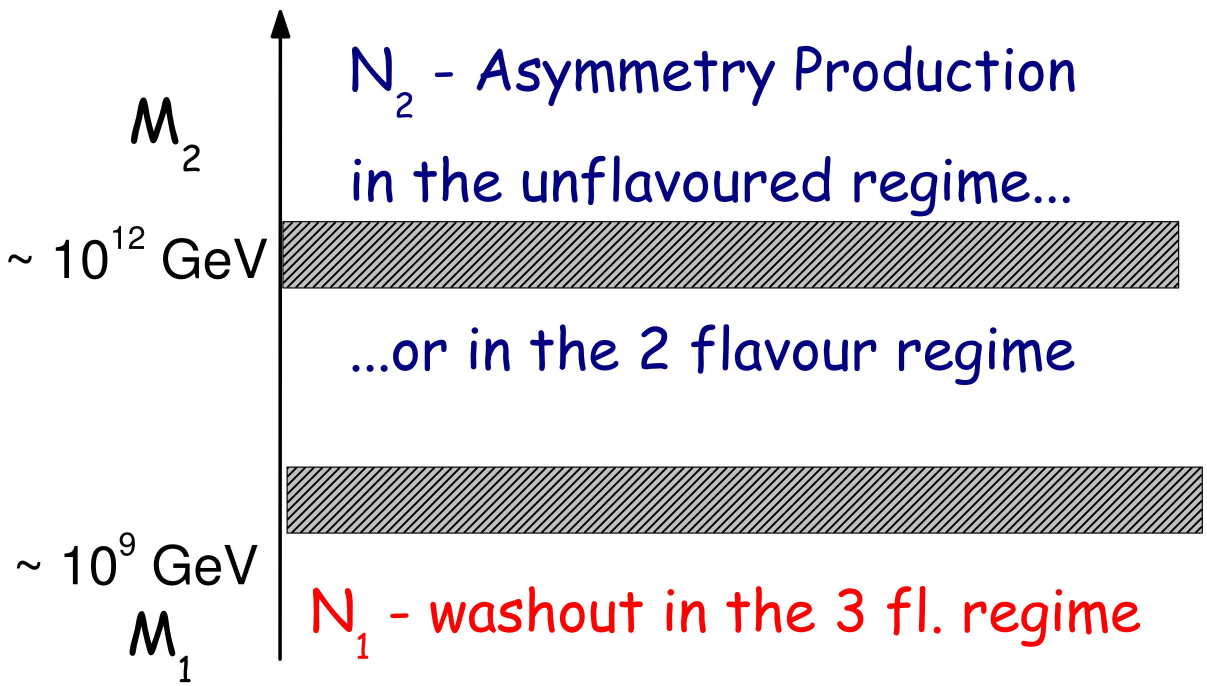


N_2-flavored leptogenesis

(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 $\Rightarrow$

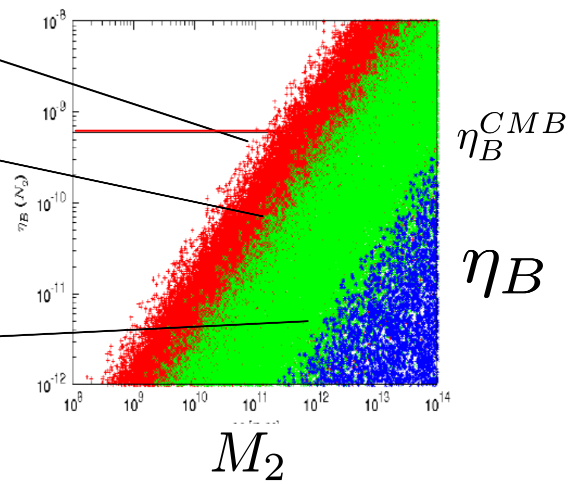
$$N_{B-L}^{\rm f}(N_2) = P_{2e}^{0}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1e}} + P_{2\mu}^{0}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + P_{2\tau}^{0}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

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

Wash-out is neglected

Wash-out and flavor effects are both taken into account

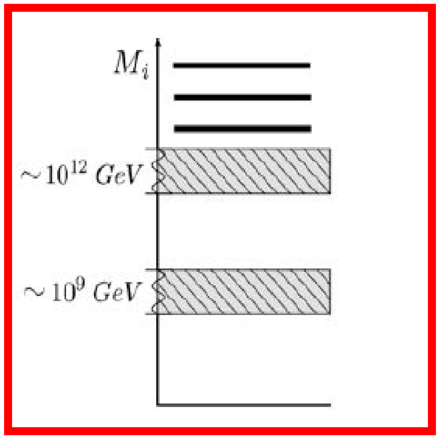
Unflavored case

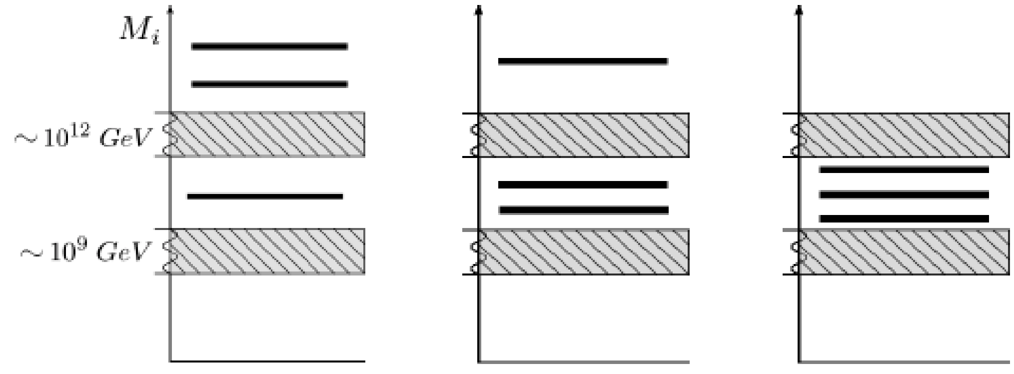


Thanks to flavor effects the domain of applicability extends much beyond the particular choice $\Omega=R_{23}$!

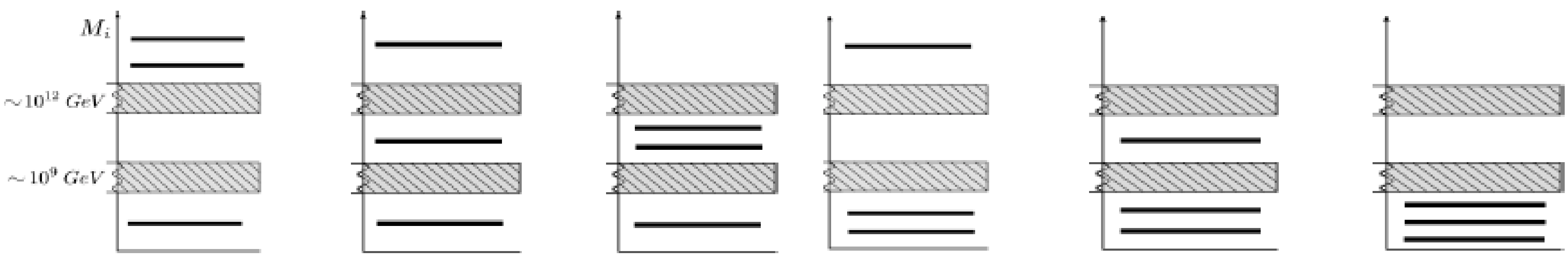
More generally one has to distinguish 10 different RH neutrino mass patterns (Bertuzzo,PDB,Marzola '10)

Heavy flavored scenario





(a) (b) (c)



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

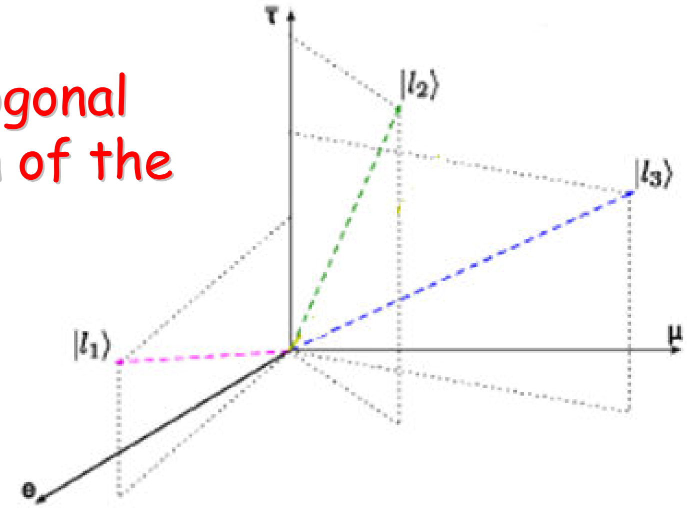
For each pattern a specific set of kinetic equations has to be considered

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



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

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

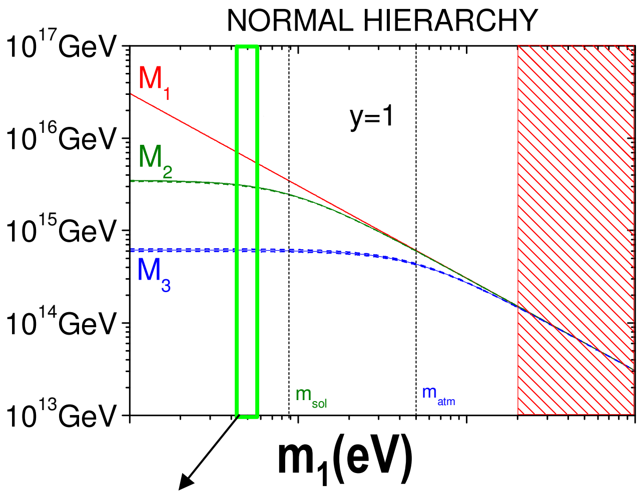
$$\begin{aligned} N^{\rm lep}_{\Delta_1}(T_{B1}) \;=\; & p_{21}\,p_{32}\,\varepsilon_3\,\kappa(K_3)\,e^{-\frac{3\pi}{8}(K_1+K_2)} \\ & + p_{21}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}K_1} \\ & + p_{\tilde 2_3 1}\,(1-p_{32})\,\varepsilon_3\,\kappa(K_3)\,e^{-\frac{3\pi}{8}K_1} \\ & + \varepsilon_1\,\kappa(K_1)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

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

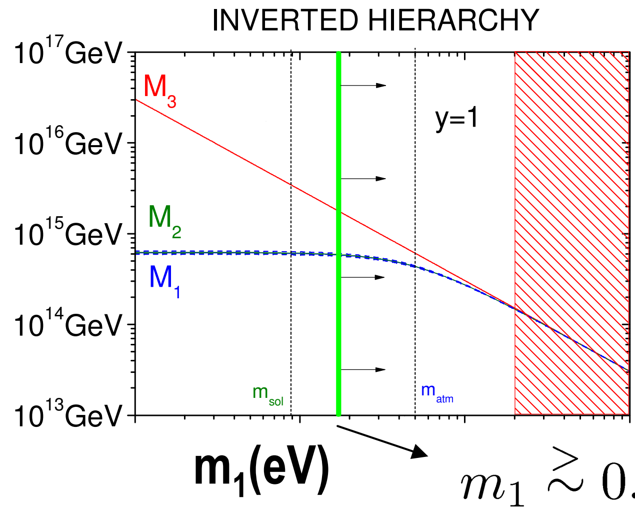
Some deviation from orthogonality (it is realized in form dominance models discussed in King's talk) is typically necessary since otherwise (e.g. with tri-bimaximal mixing) one would have vanishing CP asymmetries and therefore no asymmetry produced from leptogenesis (Antusch, King, Riotto '08; Aristizabal,Bazzocchi,Merlo,Morisi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

Heavy flavoured scenario in models with A4 discrete flavour symmetry

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



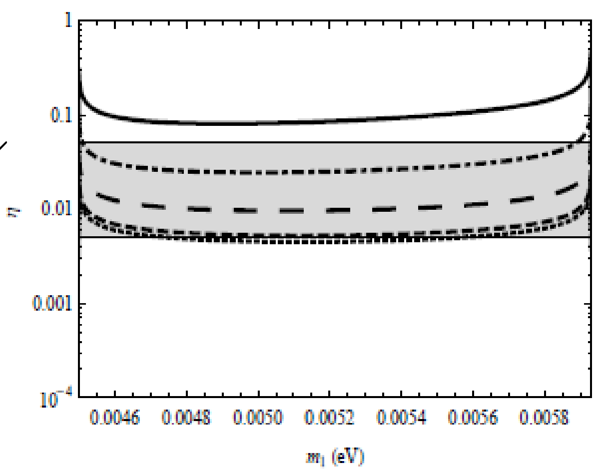
$$m_i = \frac{y^2 \, v_u^2}{M_j}$$



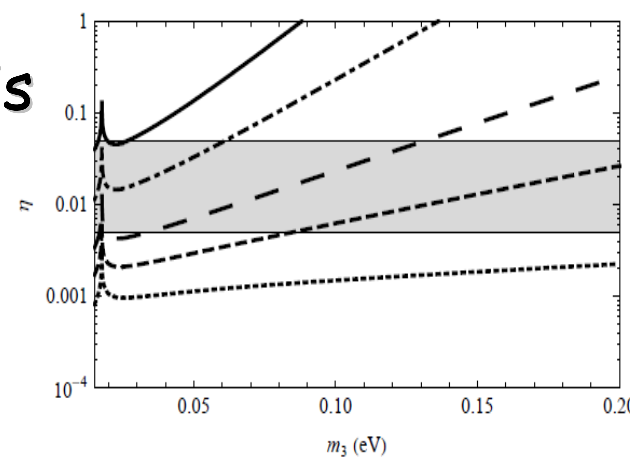
$m_1 \simeq 5 \times 10^{-3}\,\mathrm{eV}$

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

imposing successful leptogenesis

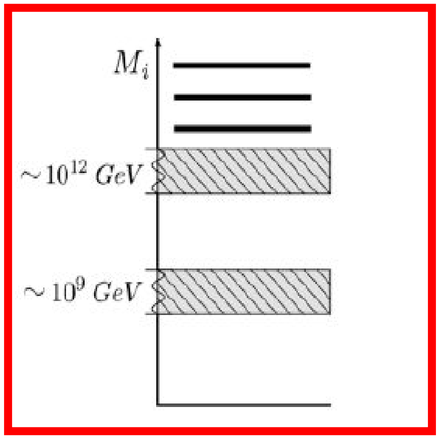


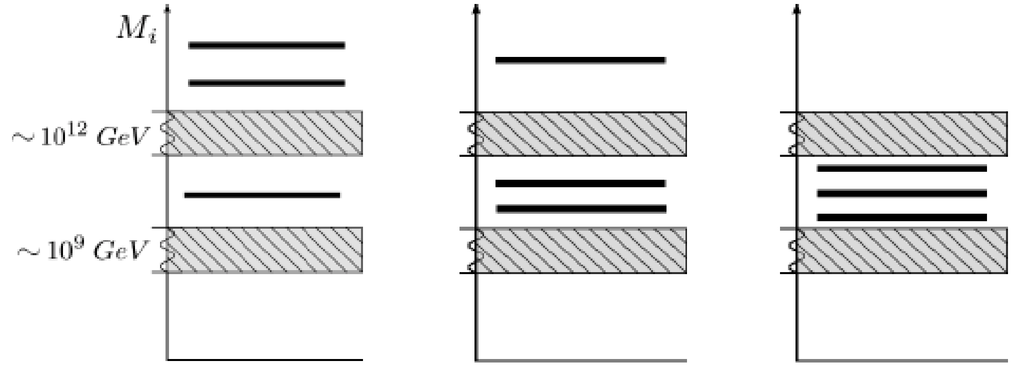
η → Symmetry Breaking parameter



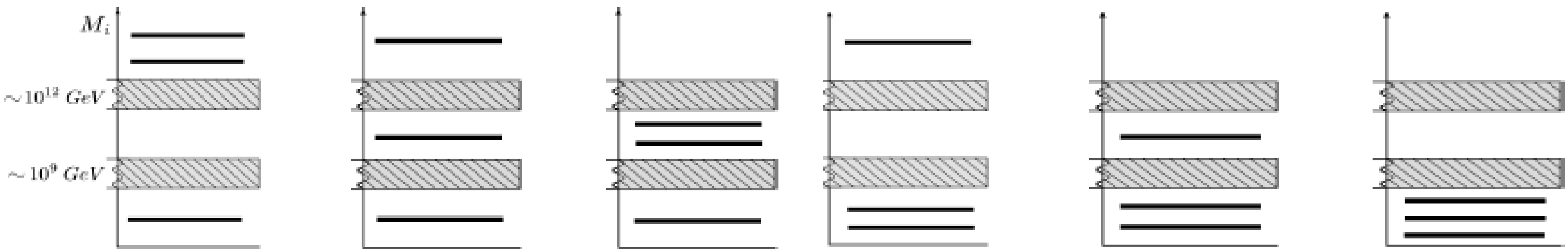
The different lines correspond to values of y between 0.3 and 3

Heavy flavored scenario





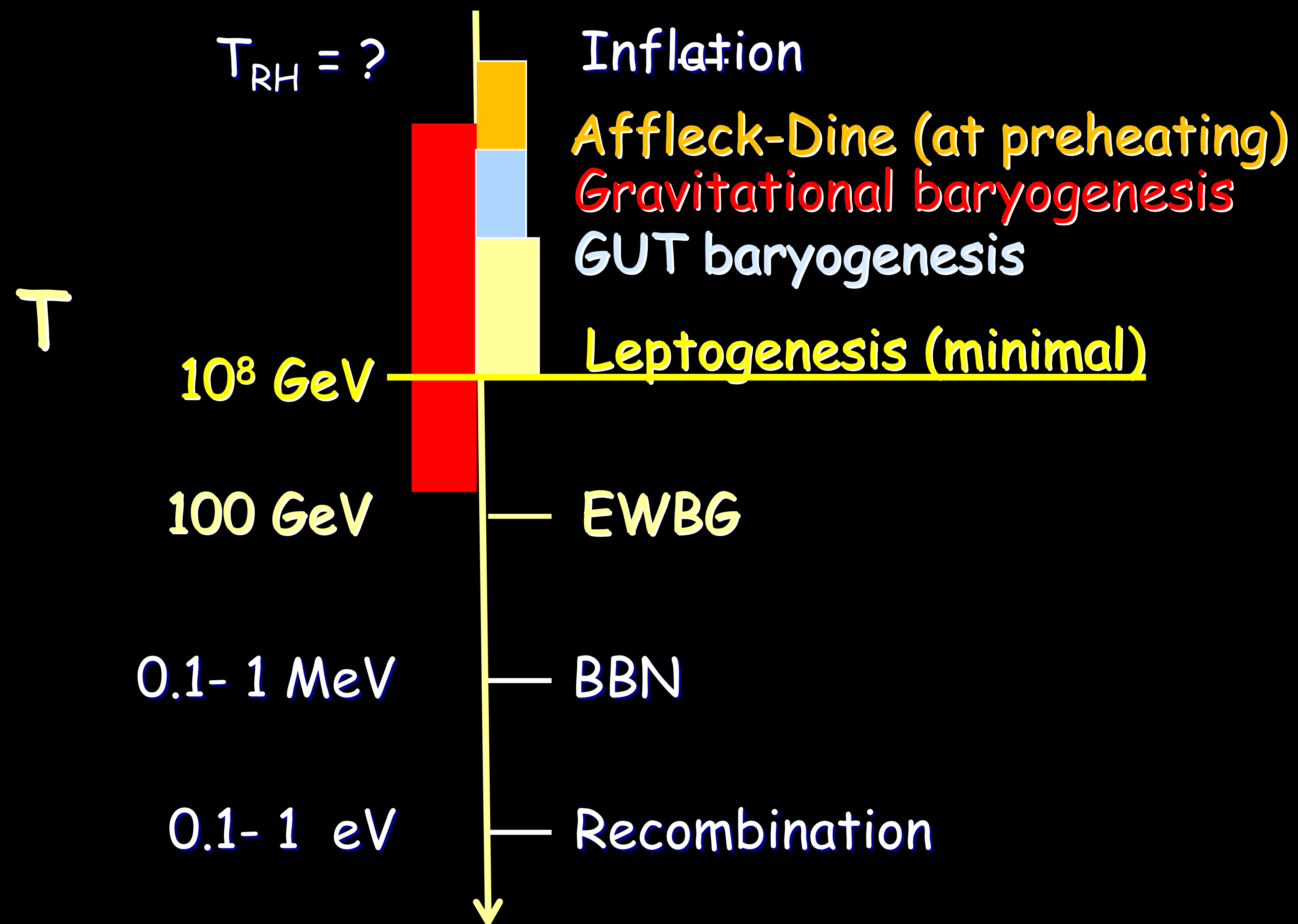
(a) (b) (c)



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

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

Baryogenesis and the early Universe history



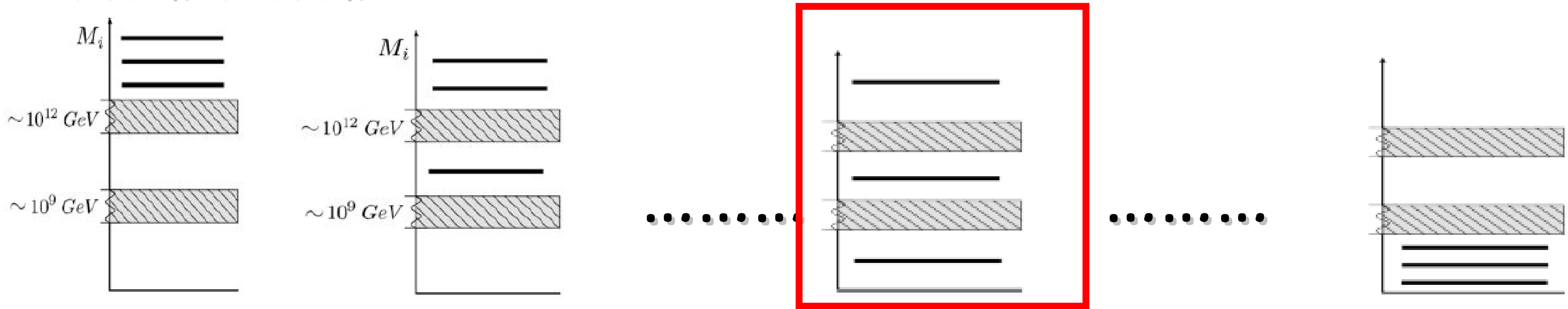
The problem of the initial conditions in flavoured leptogenesis

(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 !

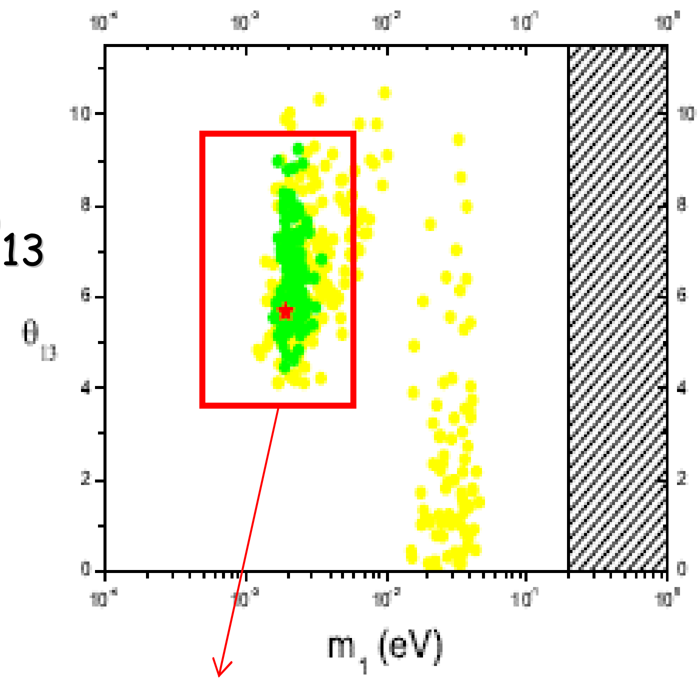
YES: the N_2-dominated scenario rescues SO(10) inspired models ! (PDB, Riotto '08,'10)

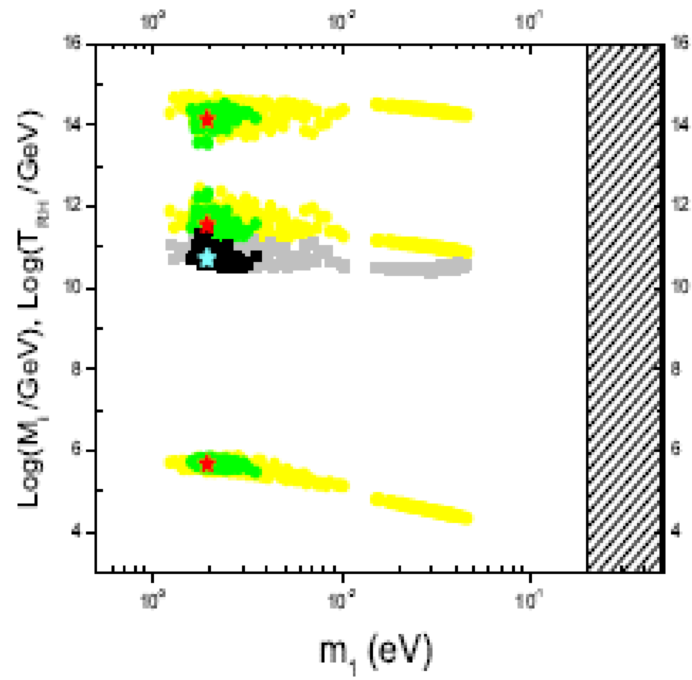
$$N_{B-L}^{\rm f} \simeq \varepsilon_{2e}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1e}} + \varepsilon_{2\mu}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + \varepsilon_{2\tau}\,\kappa(K_{2\tau})\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

Independent of α_1 and α_3 !

$\alpha_2=5$ $\alpha_2=4$ $\alpha_2=3$ $V_L = I$ Normal ordering

Θ_{13}





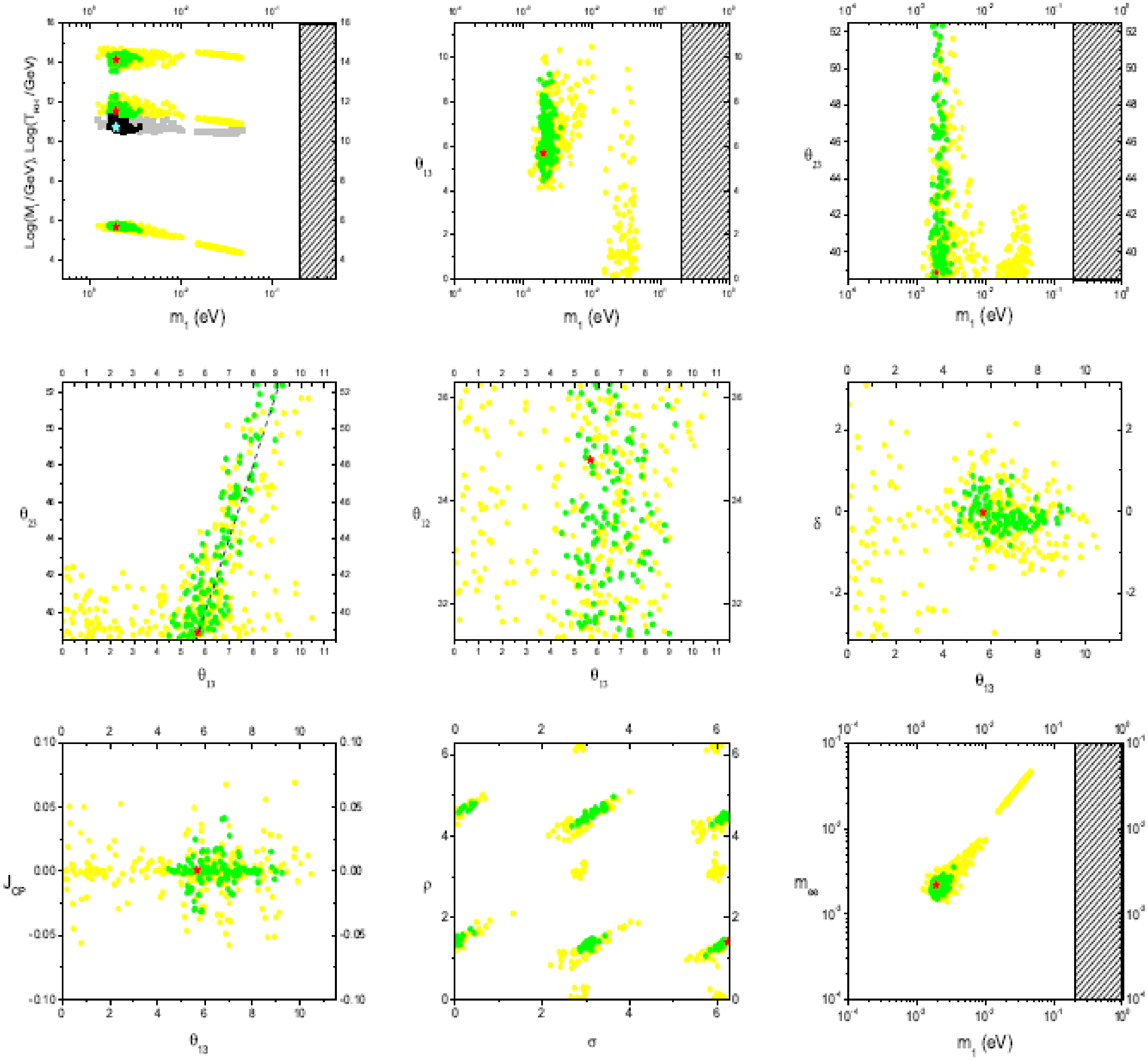
lower bound on Θ_{13}

Vanishing initial N_2 abundance

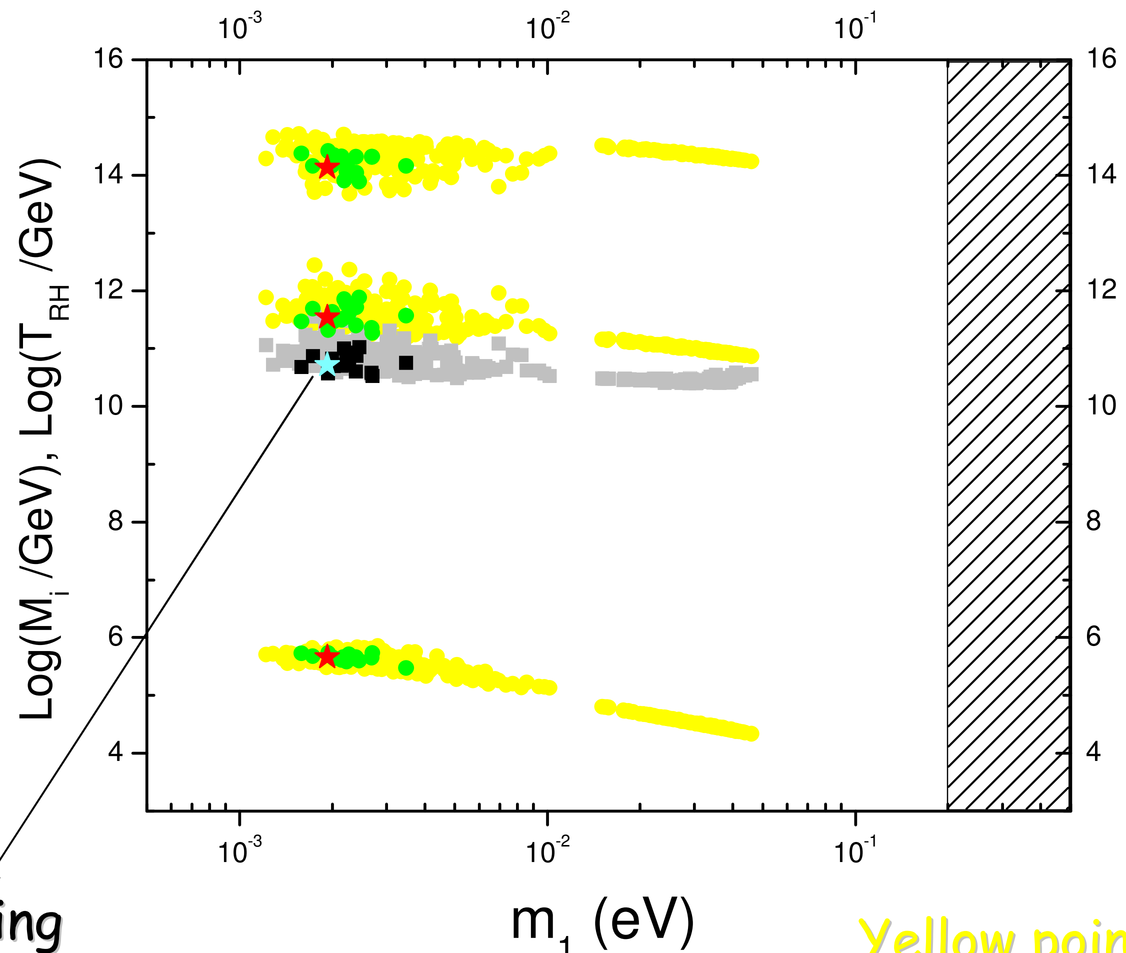
The model yields constraints on all low energy neutrino observables !

$V_L = I$

NORMAL ORDERING



(PDB, Riotto '10)



The reheating temperature lower bound is $\sim 4\times10^{10}$ GeV problem in SUSY

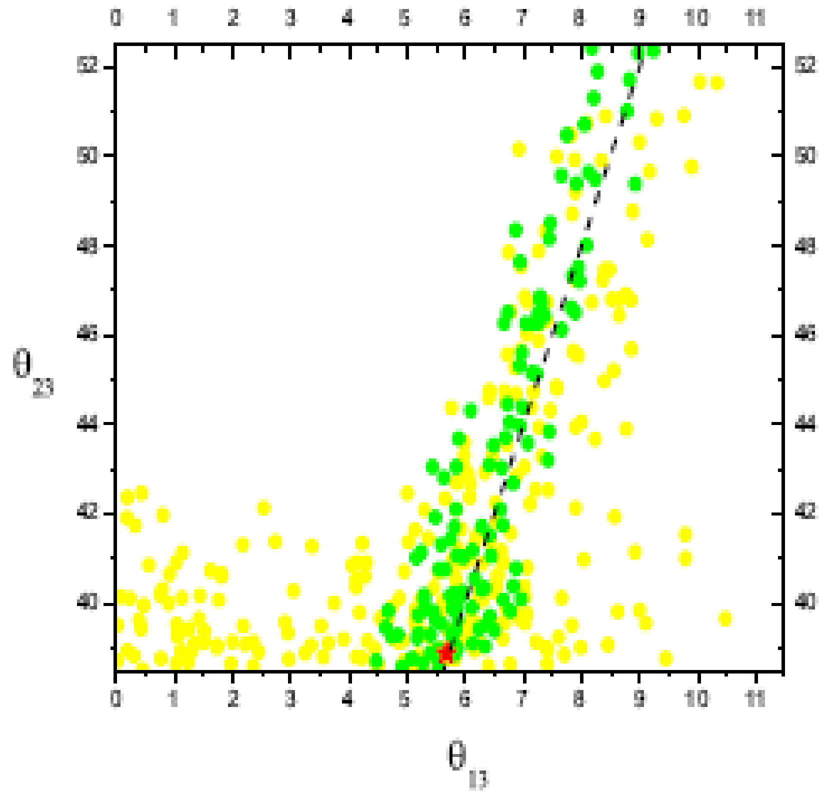
Yellow points: α_2=5

Green points: α_2=4

Red star : α_2=3

(PDB, Riotto '10)

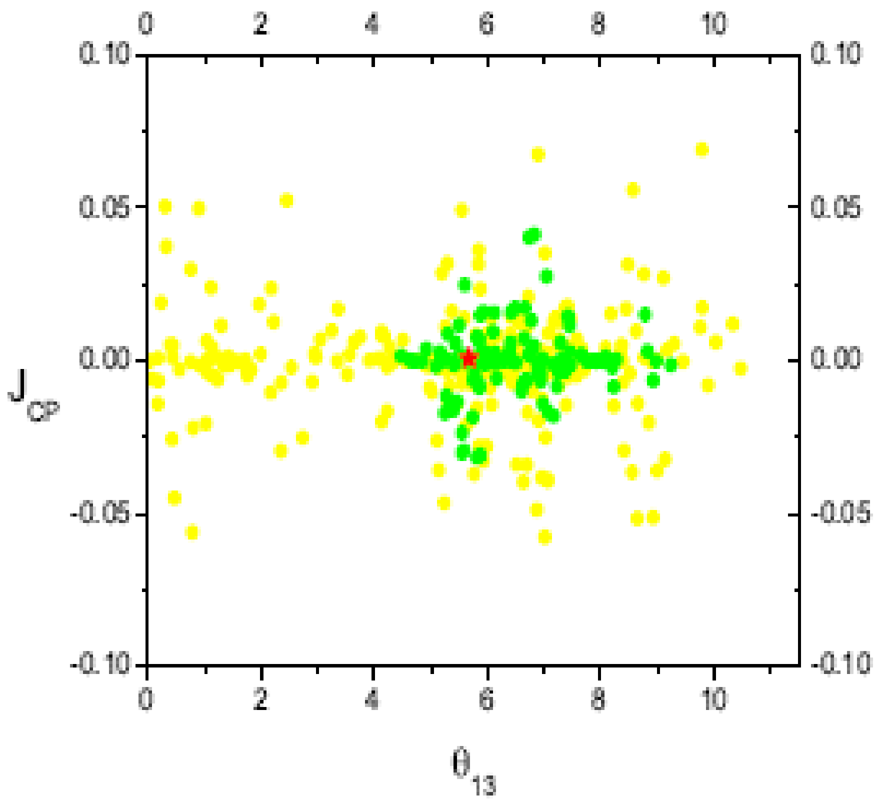
correlation between Θ_{13} and Θ_{23}



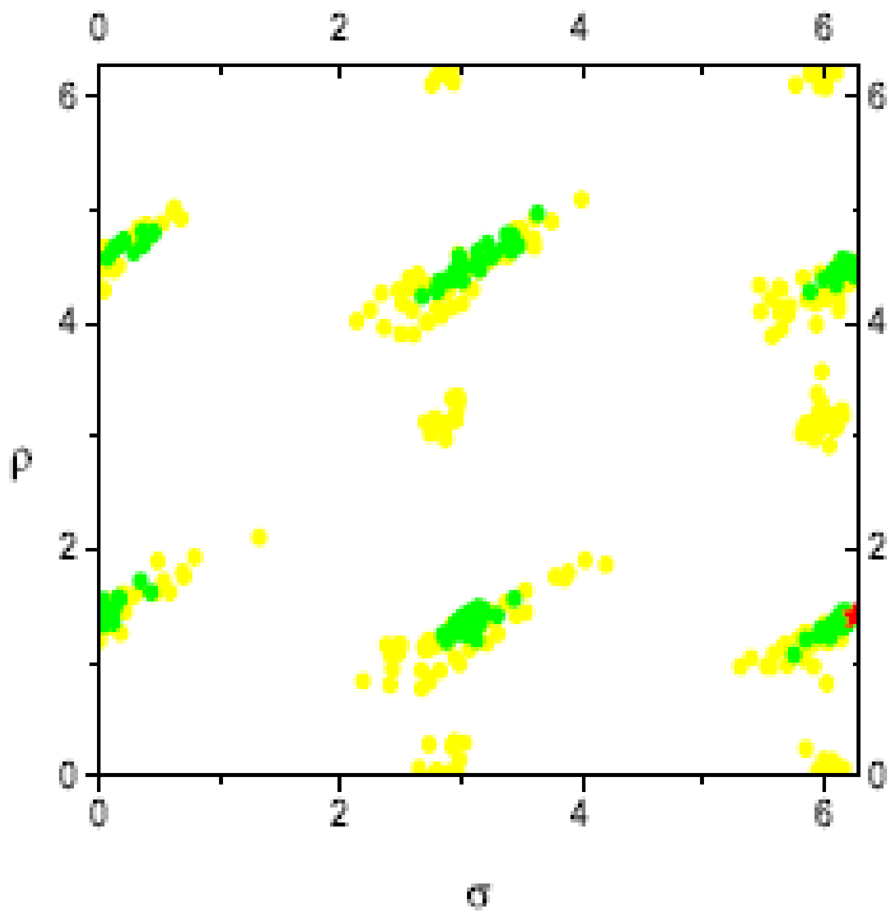
Low values of the atmospheric angle are strongly favoured and maximal mixing is very marginally allowed and excluded for $\Theta_{13} < 6^\circ$

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

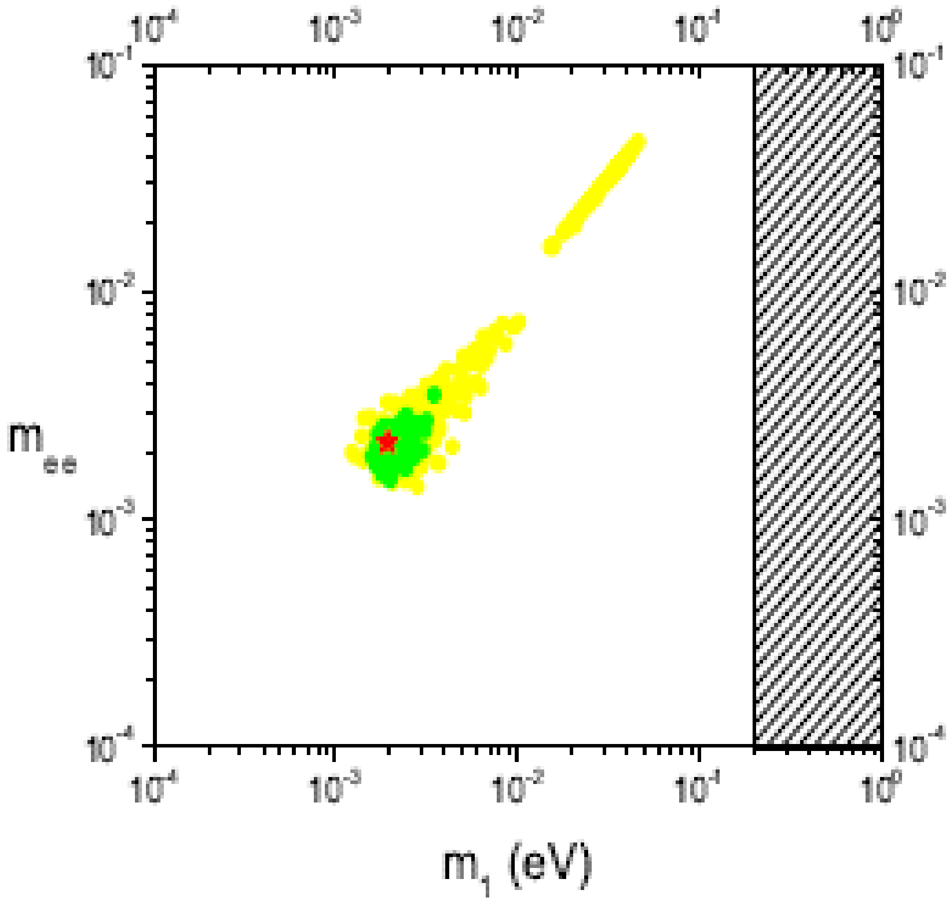
The model does not seem to predict necessarily CP violation in neutrino oscillations



On the other hand the Majorana phases play a crucial role



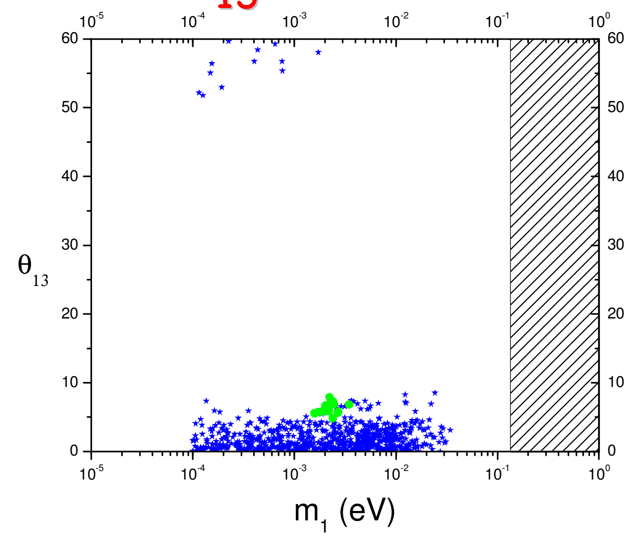
Effective Majorana mass small but non vanishing and unambiguosly related to m_1



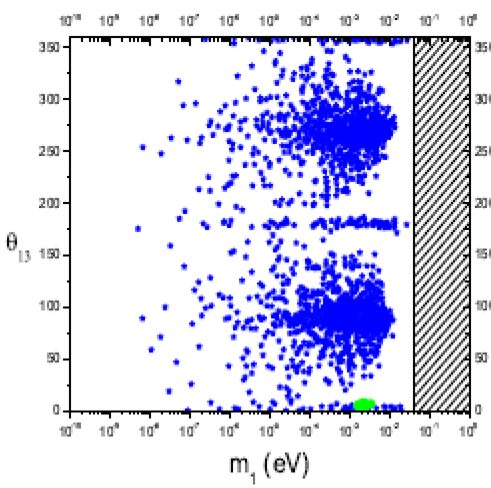
A third encouraging coincidence !

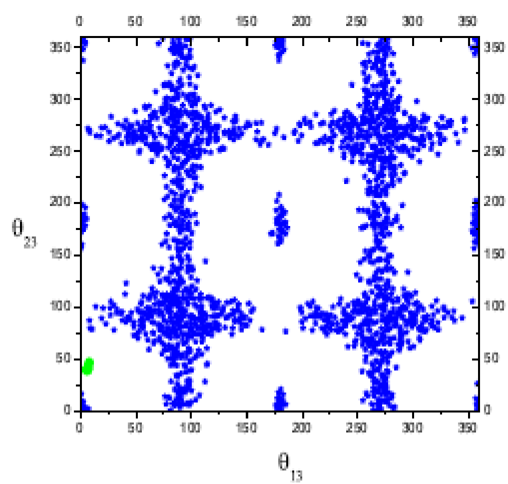
(PDB, Riotto '10)

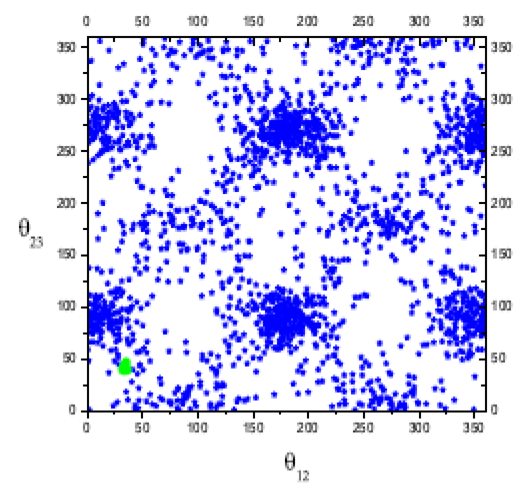
The scenario seems to like $\Theta_{13} < 10°$!



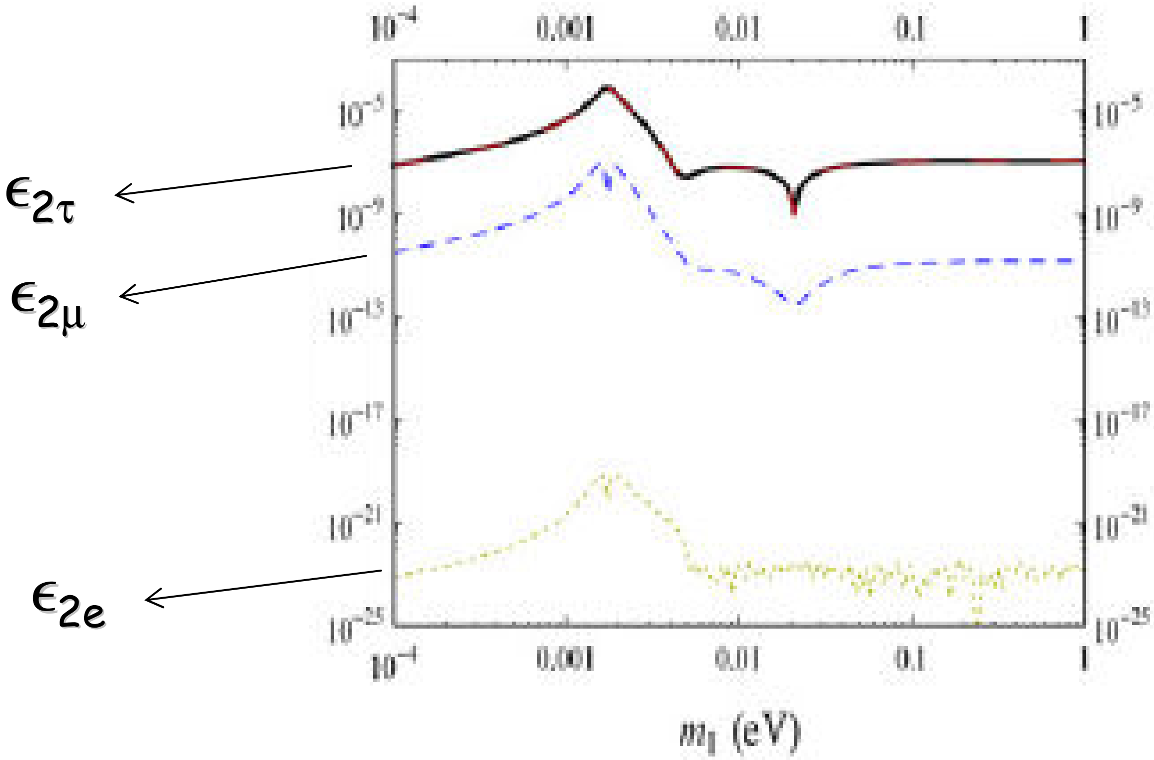
Blue points: α_2=4 and mixing angles let free in (0,60°)
Green points: α_2=4 and current experimental constraints imposed on mixing angles







For the solution with $m_1 \sim 3 \times 10^{-3}$ 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 !

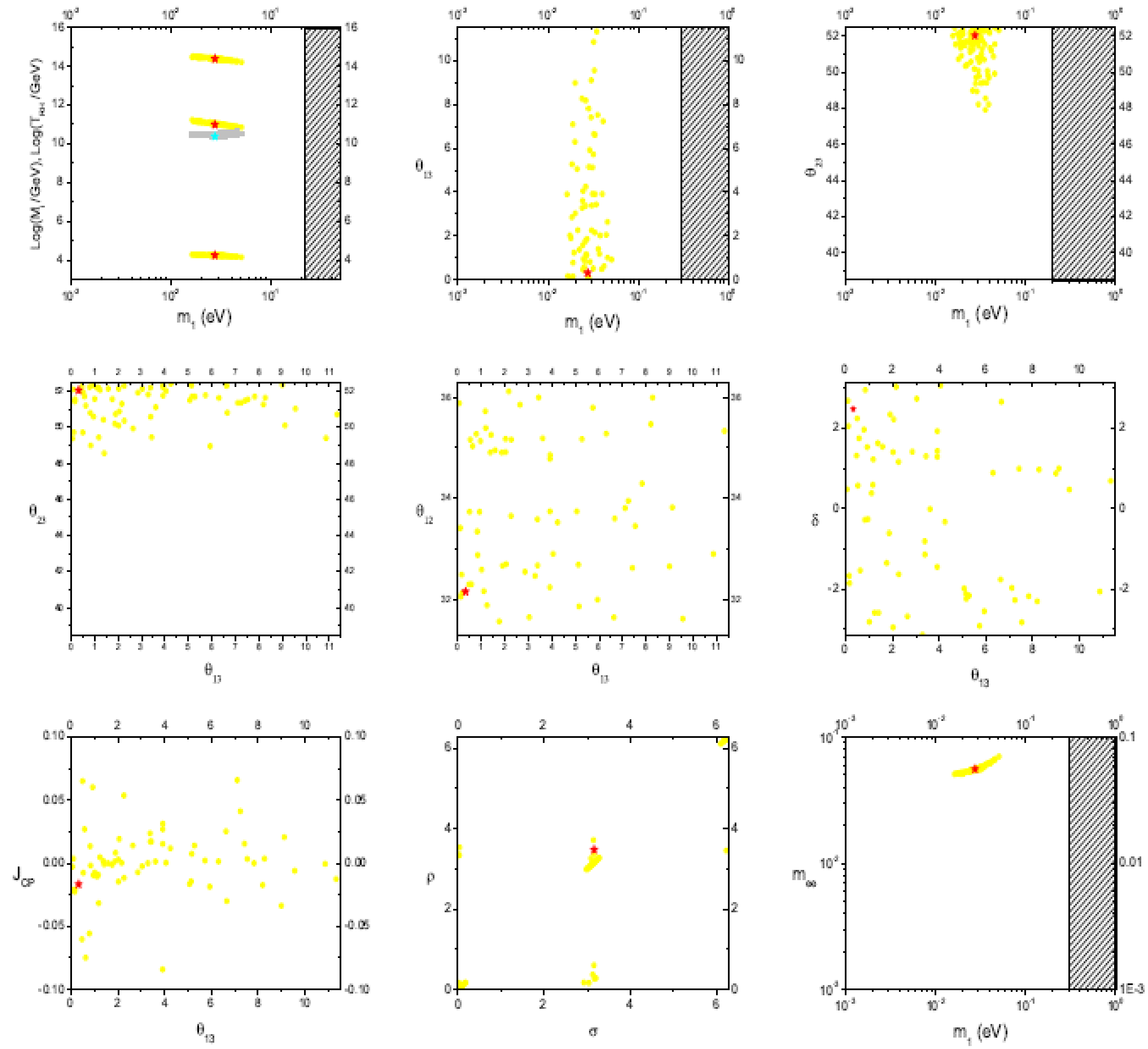
The model yields constraints on all low energy neutrino observables !

$V_L = I$

INVERTED ORDERING

$\alpha_2=5$

$\alpha_2=4.7$



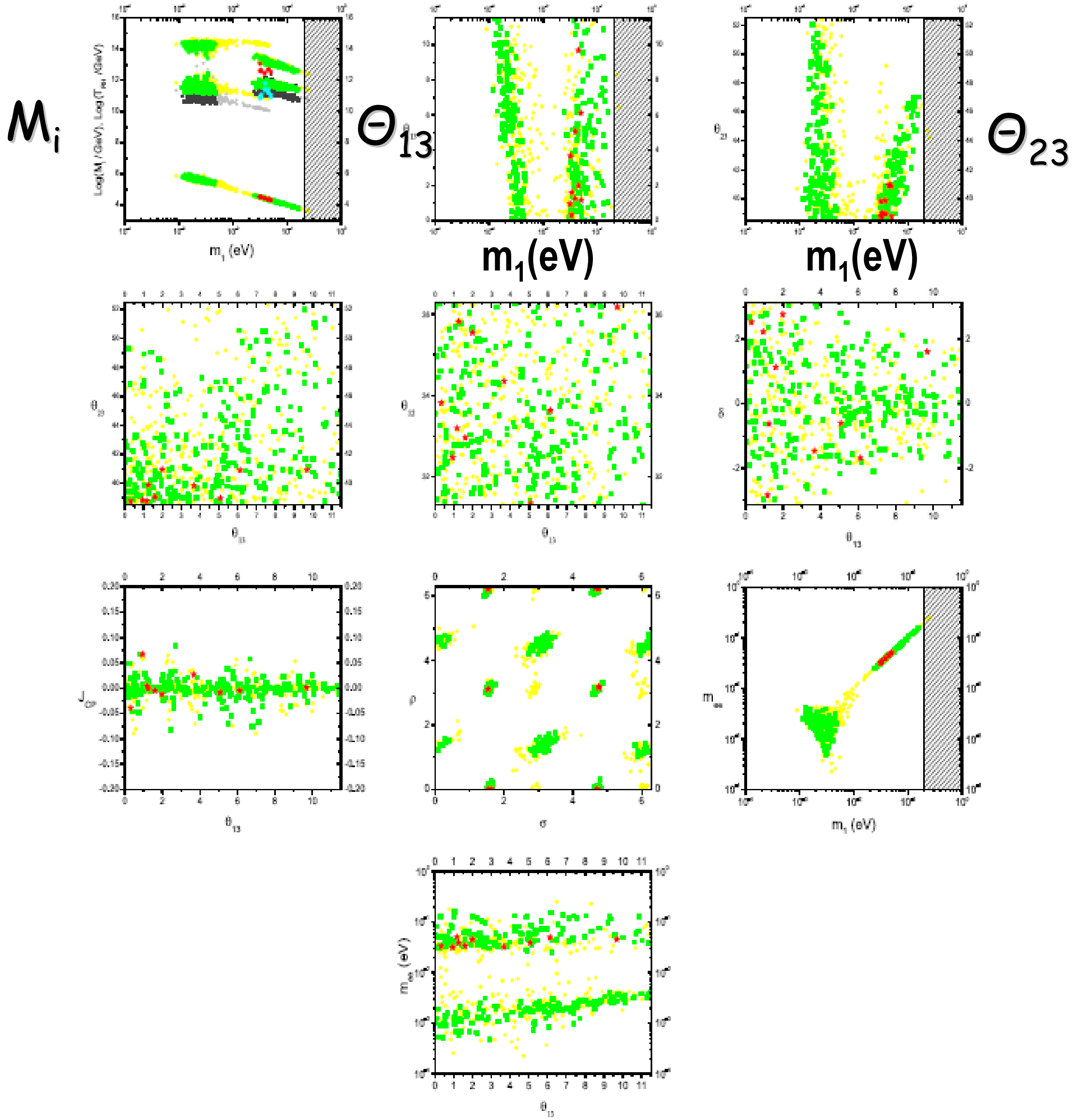
$I < V_L < V_{CKM}$

NORMAL ORDERING

α_2=5

α_2=4

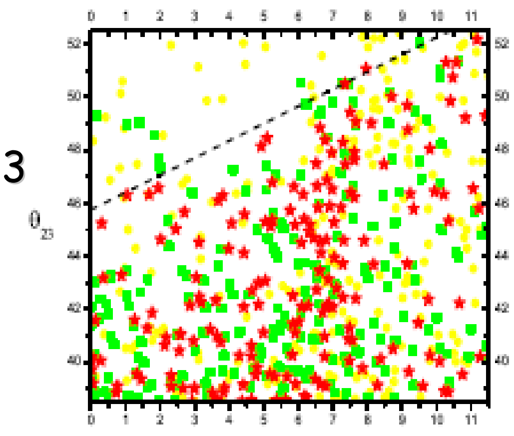
α_2=1



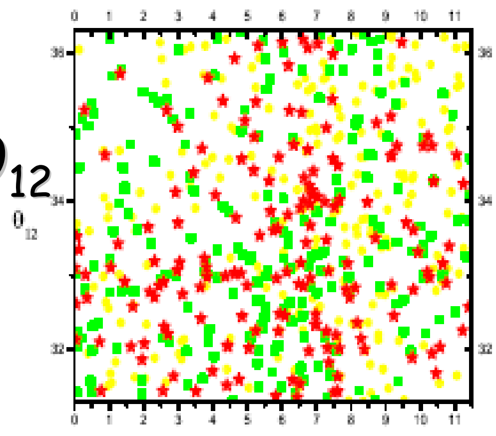
$I < V_L < V_{CKM}$ NORMAL ORDERING $\alpha_2=5$ $\alpha_2=4$

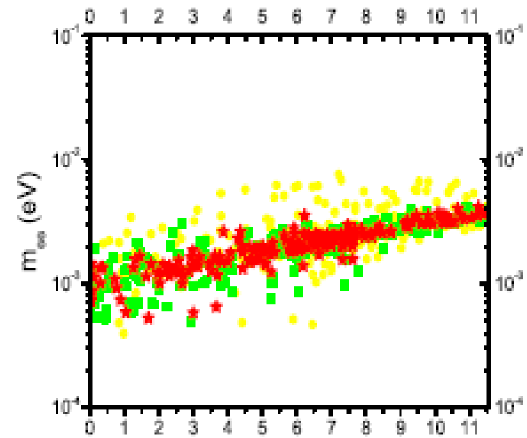
$\alpha_2=3.7$ $m_1 < 0.01$ eV

Θ_{23}



Θ_{12}

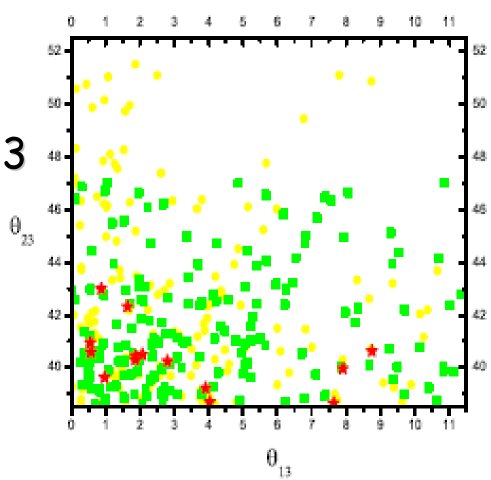




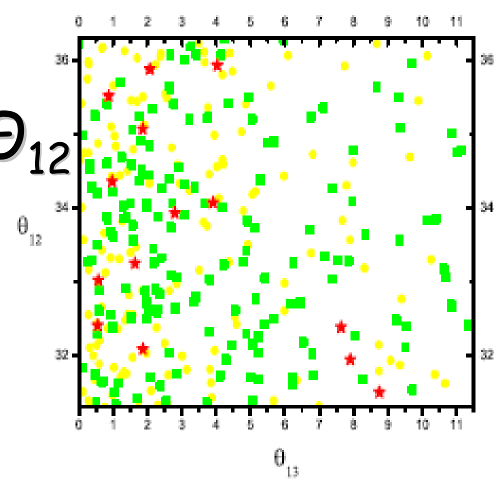
Θ_{13} Θ_{13} Θ_{13}

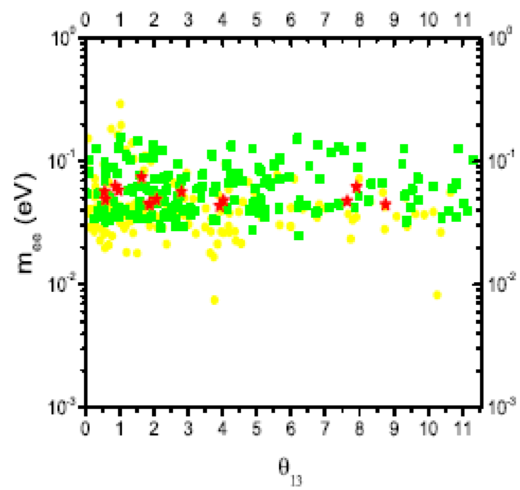
$\alpha_2=1$ $m_1 > 0.01$ eV

Θ_{23}

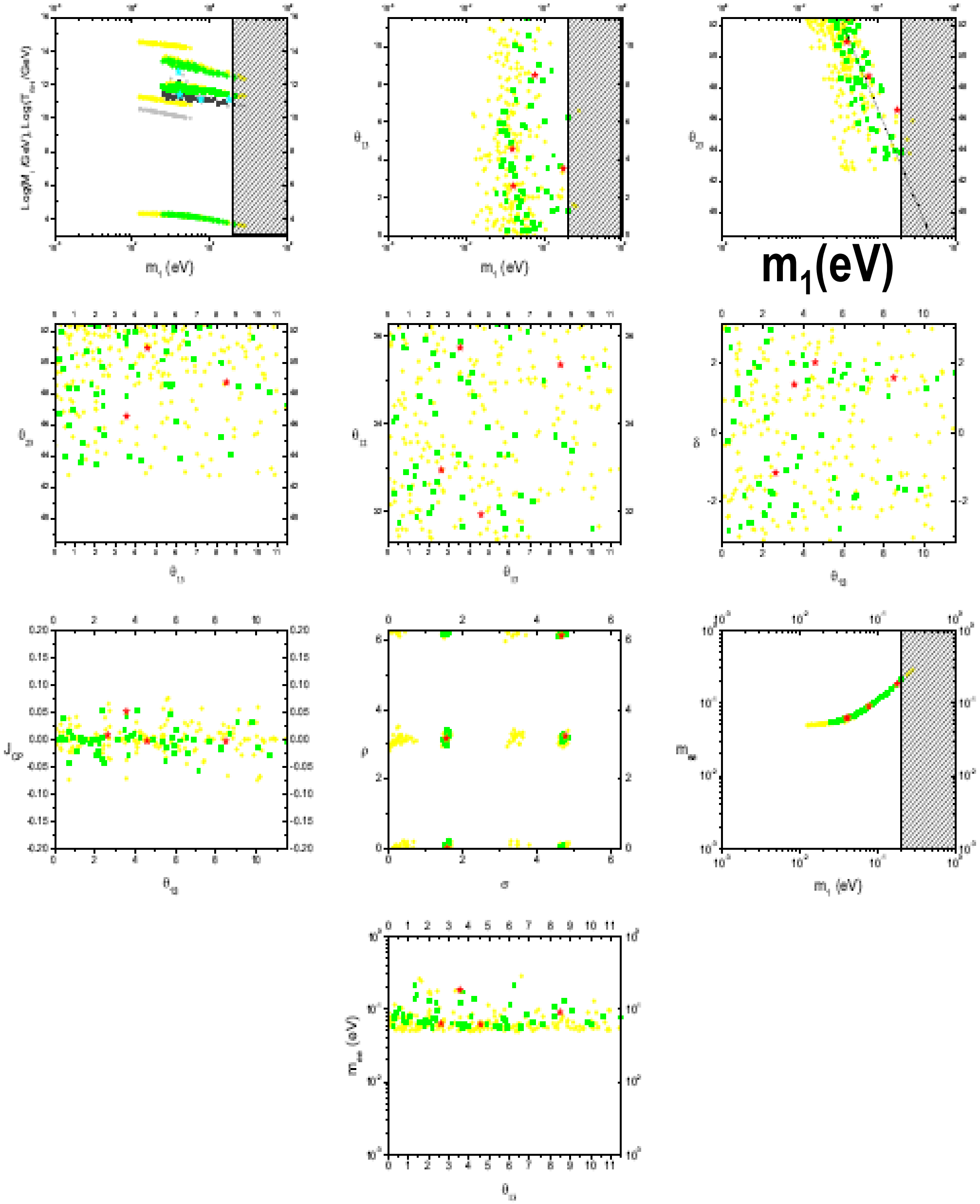


Θ_{12}





$I < V_L < V_{CKM}$



Θ_{23}

INVERTED ORDERING

α_2=5

α_2=4

α_2=1.5

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