What is ν?
INVISIBLES 12 and Alexei Smirnov Fest
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Leptogenesis confronting neutrino data

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The double side of Leptogenesis

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

- *Cosmological Puzzles* :
  1. Dark matter
  2. $\boxed{\text{Matter - antimatter asymmetry}}$
  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

Can Leptogenesis be useful to overconstrain the seesaw parameter space providing a way to understand the measured values of the neutrino parameters and even to make predictions on future measurements ?

Neutrino mixing parameters

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma} \end{pmatrix}$$

pre-T2K

(Gonzalez-Garcia, Maltoni 2008)

- best-fit point and 1σ (3σ) ranges:

$$\theta_{12} = 34.5 \pm 1.4 \begin{pmatrix} +4.8 \\ -4.0 \end{pmatrix}, \quad \Delta m^2_{21} = 7.67 \,^{+0.22}_{-0.21} \begin{pmatrix} +0.67 \\ -0.60 \end{pmatrix} \times 10^{-5}\ \mathrm{eV}^2,$$

$$\theta_{23} = 43.1 \,^{+4.4}_{-3.5} \begin{pmatrix} +10.1 \\ -8.0 \end{pmatrix}, \quad \Delta m^2_{31} = \begin{cases} -2.39 \pm 0.12 \begin{pmatrix} +0.37 \\ -0.40 \end{pmatrix} \times 10^{-3}\ \mathrm{eV}^2, \\ +2.49 \pm 0.12 \begin{pmatrix} +0.39 \\ -0.36 \end{pmatrix} \times 10^{-3}\ \mathrm{eV}^2, \end{cases}$$

$$\theta_{13} = 3.2^{+4.5} \left(^{+9.6}\right), \qquad \delta_{\mathrm{CP}} \in [0, 360];$$

Nonvanishing θ_{13}

- T2K : $\sin^2 2\theta_{13} = 0.03 - 0.28$ (90% CL NO)
- DAYA BAY: $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$

recent global analyses

$\theta_{13} = 7.7° \div 10.2°$ (95% CL)

$\theta_{23} = 36.3° \div 40.9°$ (95% CL)

$\delta_{\text{best fit}} \sim \pi$

(Normal Ordering)

(Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno 2012)

Analogous results presented by T. Schwetz but $\delta_{\text{best fit}} \sim -\pi/3$

Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: normal or inverted

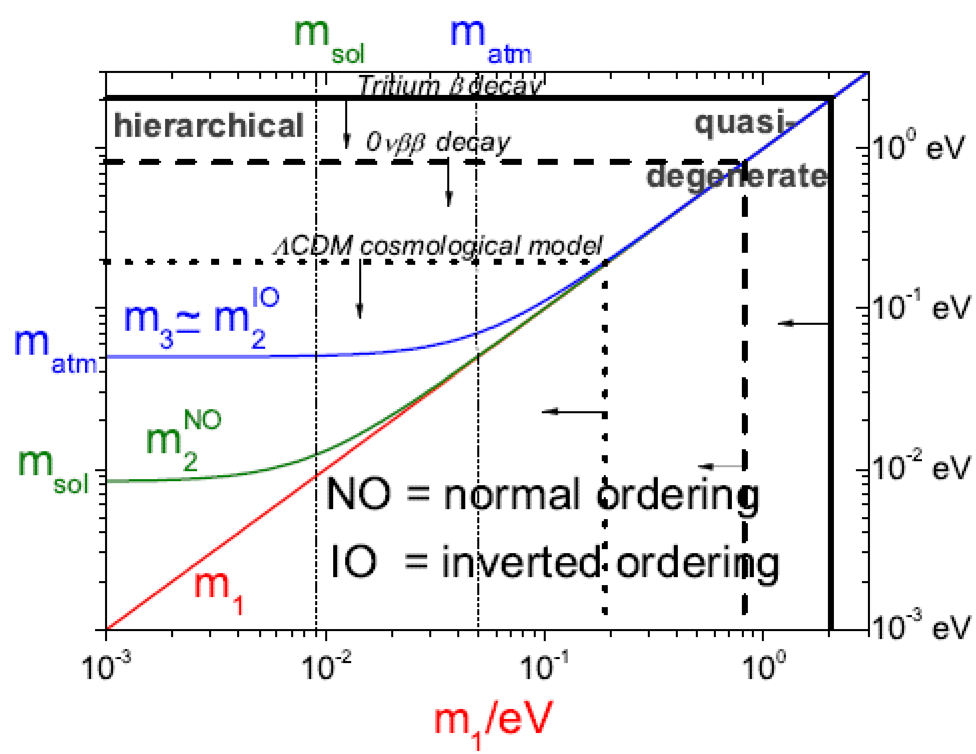
$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

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

Tritium β decay :m_e < 2 eV
(Mainz + Troitzk 95% CL)

$\beta\beta 0\nu$: $m_{\beta\beta}$< 0.34 – 0.78 eV
(CUORICINO 95% CL, similar bound from Heidelberg-Moscow)
NEW! : $m_{\beta\beta}$< 0.14 – 0.38 eV
(EXO-200 90% CL)

CMB+BAO+H0 : $\Sigma\, m_i$ < 0.58 eV
(WMAP7+2dF+SDSS+HST, 95%CL)
CMB+LSS + Lyα :$\Sigma\, m_i$ <0.17 eV
(Seljak et al.)



Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

- Type I seesaw

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

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 $M_3 > M_2 > M_1 \gg m_D$

On average one N_i decay produces a B-L asymmetry given by the

total CP asymmetries

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

- Thermal production of the RH neutrinos $\Rightarrow$ $T_{RH} \gtrsim M_i / (2 \div 10)$

Seesaw parameter space

Imposing $\eta_B = \eta_B^{CMB}$ one would like to get information on U and m_i

Problem: too many parameters

(Casas, Ibarra'01) $m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \boxed{\Omega^T \Omega = I}$ Orthogonal parameterisation

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

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

The **6 parameters in the orthogonal matrix Ω** encode the 3 life times and the 3 total CP asymmetries of the RH neutrinos and is an invariant (King '07)

Parameter reduction from:

- Iso-asymmetry surfaces $\eta_B(U, m_i; \lambda_1, \ldots, \lambda_N) = \eta_B^{CMB}$ (if they "close up" the leptogenesis bound can remove more than one parameter in this case)
- In the asymmetry calculation $\eta_B = \eta_B(U, m_i; \lambda_1, \ldots, \lambda_{M<9})$
- Imposing some (model dependent) conditions on m_D one can reduce the number of parameters and arrive to a new parameterisation where

$$\Omega = \Omega(U, m_i; \lambda_1, \ldots, \lambda_{N<9}) \quad \text{and} \quad M_i = M_i(U, m_i; \lambda_1, \ldots, \lambda_{N\leq M})$$

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

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

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

baryon-to -photon number ratio

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

2) Hierarchical heavy RH neutrino spectrum: $M_2 \gtrsim 3\, M_1$

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

From the last two assumptions

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

4) Barring fine-tuned mass cancellations in the seesaw

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

(Davidson, Ibarra '02)

5) Efficiency factor from simple Boltzmann equations

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

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

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

decays

inverse decays

wash-out

decay parameter

$$\boxed{K_1 \equiv \frac{\Gamma_{N_1}(T=0)}{H(T=M_1)}}$$

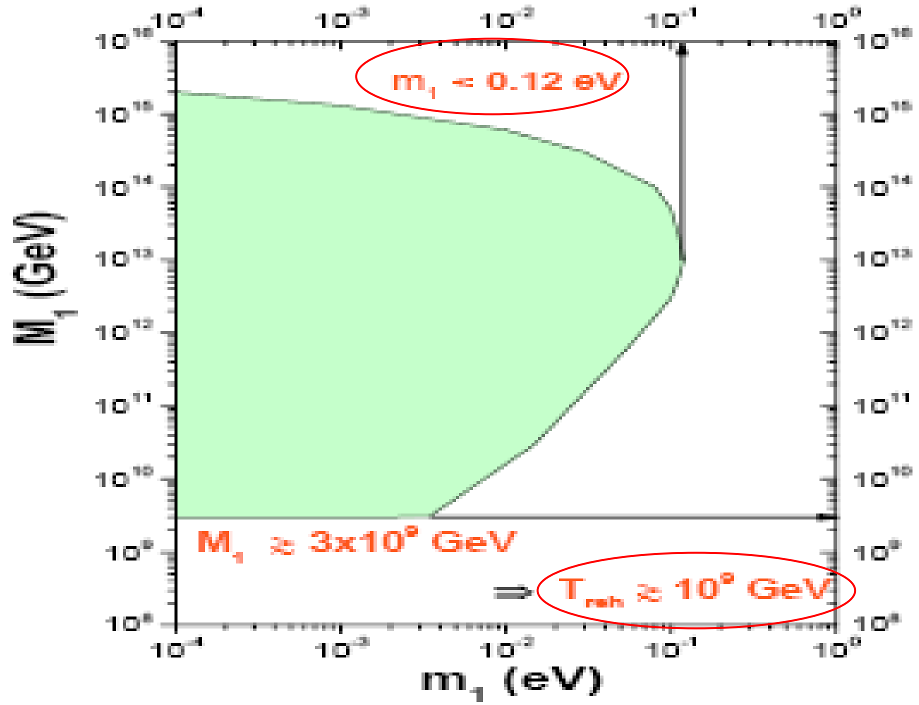
$$\kappa_1(z; K_1, z_{\mathrm{in}}) = -\int_{z_{\mathrm{in}}}^{z} dz' \left[\frac{dN_{N_1}}{dz'}\right] e^{-\int_{z'}^{z} dz''\, W_1(z'')}$$

Neutrino mass bounds in vanilla leptog.

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

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

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



No dipendence on the leptonic mixing matrix U

Independence of the initial conditions

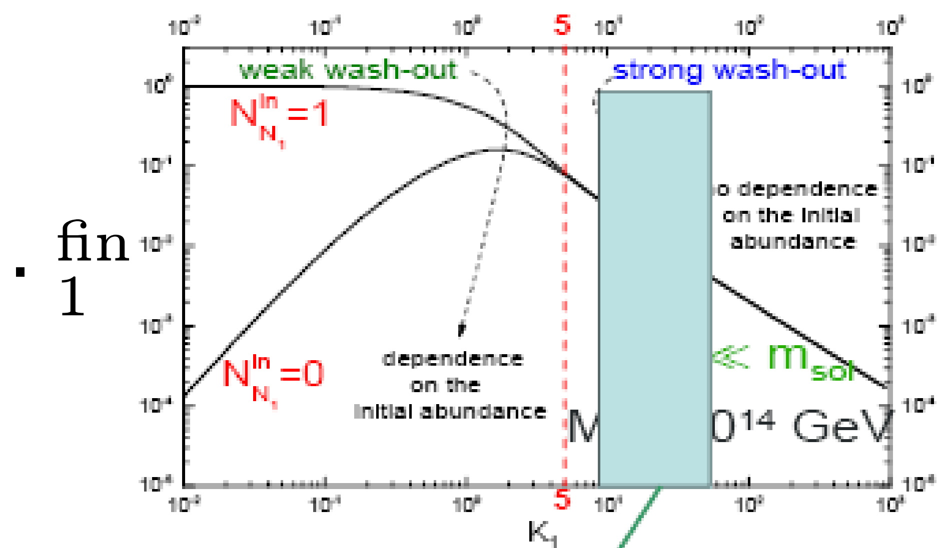
The early Universe „knows" neutrino masses ...

(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

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

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) as:

$$\boxed{m_D = V_L^\dagger \, D_{m_D} \, U_R} \qquad D_{m_D} = \mathrm{diag}\{\lambda_{D1}, \lambda_{D2}, \lambda_{D3}\}$$

SO(10) inspired conditions:

$$\boxed{\lambda_{D1} = \alpha_1 \, m_u \, , \; \lambda_{D2} = \alpha_2 \, m_c \, , \; \lambda_{D3} = \alpha_3 \, m_t \, , \quad (\alpha_i = \mathcal{O}(1))} \qquad \boxed{V_L \simeq V_{CKM} \simeq I}$$

One can express: $\Omega = D_m^{-\frac{1}{2}} \, U^\dagger \, V_L^\dagger \, D_{m_D} \, U_R \, D_M^{-\frac{1}{2}}$

and from the seesaw formula:

$U_R = U_R \, (U, m_i; \alpha_i, V_L)$, $M_i = M_i \, (U, m_i; \alpha_i, V_L) \Longrightarrow \boxed{\eta_B = \eta_B \, (U, m_i; \alpha_i, V_L)}$

one typically obtains (barring fine-tuned 'crossing level' solutions):

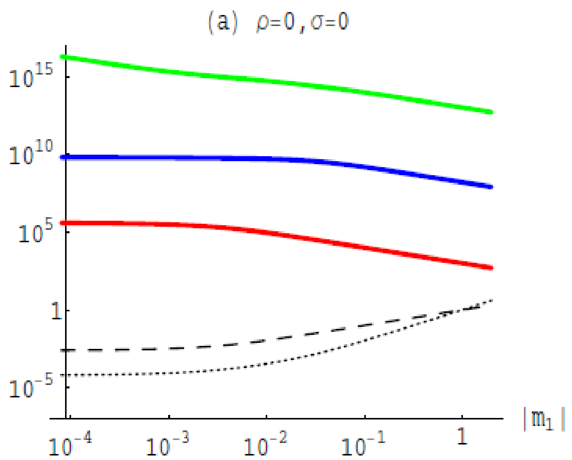
$$\boxed{M_1 \sim \alpha_1^2 \, 10^5 \mathrm{GeV} \, , \;\; M_2 \sim \alpha_2^2 \, 10^{10} \, \mathrm{GeV} \, , \;\; M_3 \sim \alpha_3^2 \, 10^{15} \, \mathrm{GeV}}$$

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

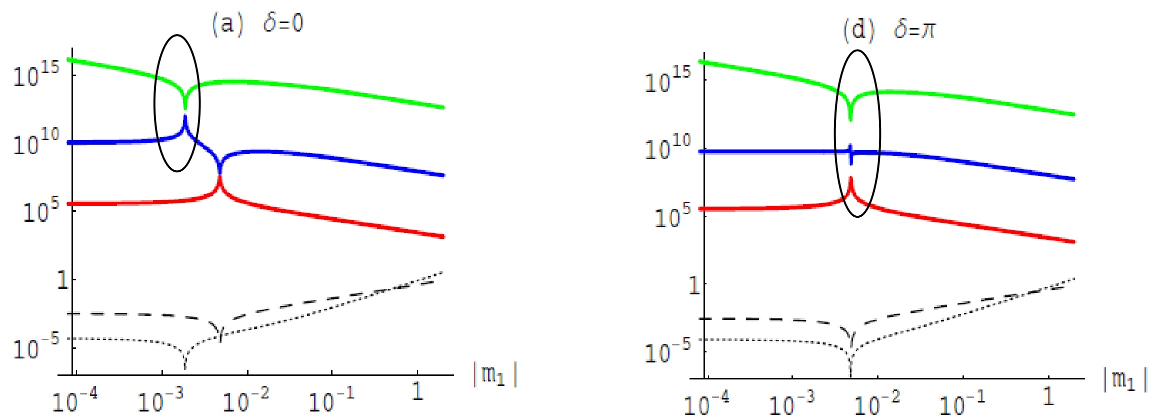
$\Rightarrow$ failure of the N_1-dominated scenario !

Crossing level solutions

(Akhmedov, Frigerio, Smirnov '03)



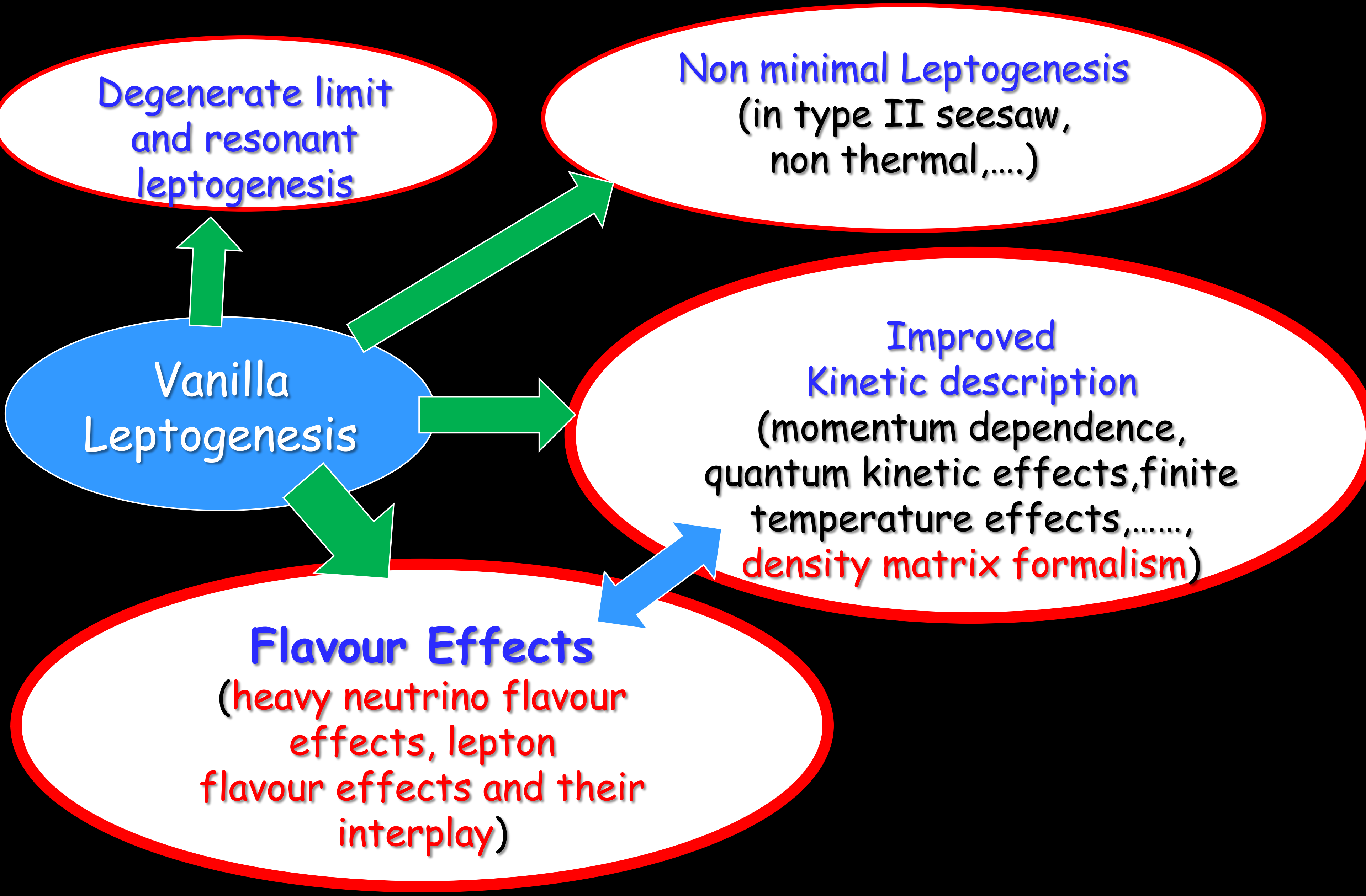
$\rho = \pi/2, \ \sigma = 0, \ s_{13} = 0.1$



At the crossing the CP asymmetries undergo a resonant enhancement (Covi, Roulet, Vissani '96; Pilaftsis '98; Pilaftsis, Underwood '04; ...)

The correct BAU can be attained for a fine tuned choice of parameters: many models have made use of these solutions but as we will see there is another option

Beyond vanilla Leptogenesis



Lepton flavour effects

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

Flavor composition of lepton quantum states:

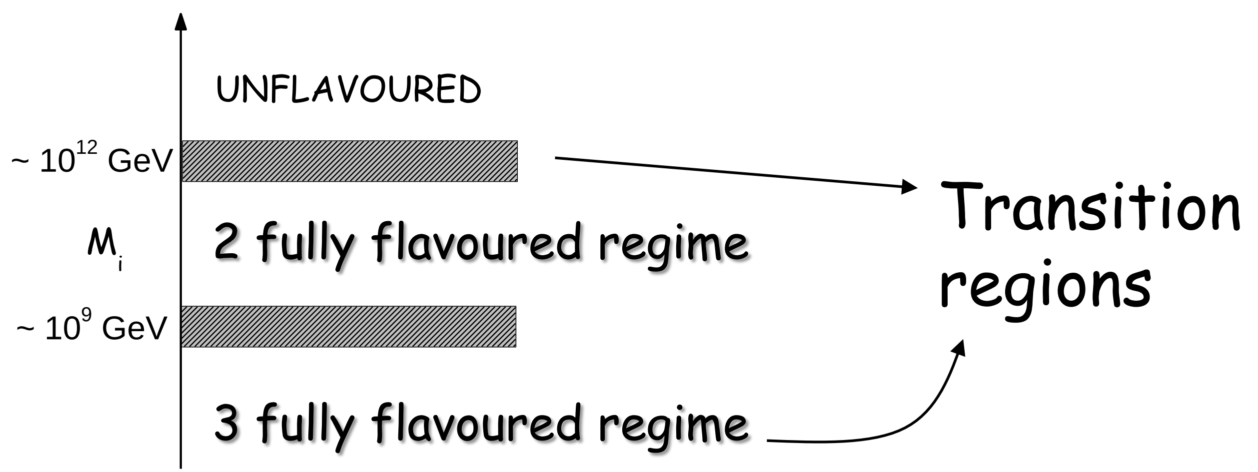
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1\rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau) \qquad P_{1\alpha} \equiv |\langle l_\alpha | l_1\rangle|^2$$

$$|\bar{l}'_1\rangle = \sum_\alpha \langle l_\alpha | \bar{l}'_1\rangle \, |\bar{l}_\alpha\rangle \qquad \bar{P}_{1\alpha} \equiv |\langle \bar{l}_\alpha | \bar{l}'_1\rangle|^2$$

But for $T \lesssim 10^{12}$ 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 a $\mu+e$ component

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



Two fully flavoured regime

(α = τ, e+μ)

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

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

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

- Classic Kinetic Equations (in their simplest form)

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

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

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

$$\Rightarrow N^{\rm fin}_{B-L} = \sum_\alpha \varepsilon_{1\alpha}\,\kappa^{\rm fin}_{1\alpha} \simeq 2\,\varepsilon_1\,\kappa^{\rm fin}_1 + \frac{\Delta P_{1\alpha}}{2}\left[\kappa^{\rm fin}_{1\alpha} - \kappa^{\rm fin}_{1\beta}\right]$$

Additional contribution to CP violation:

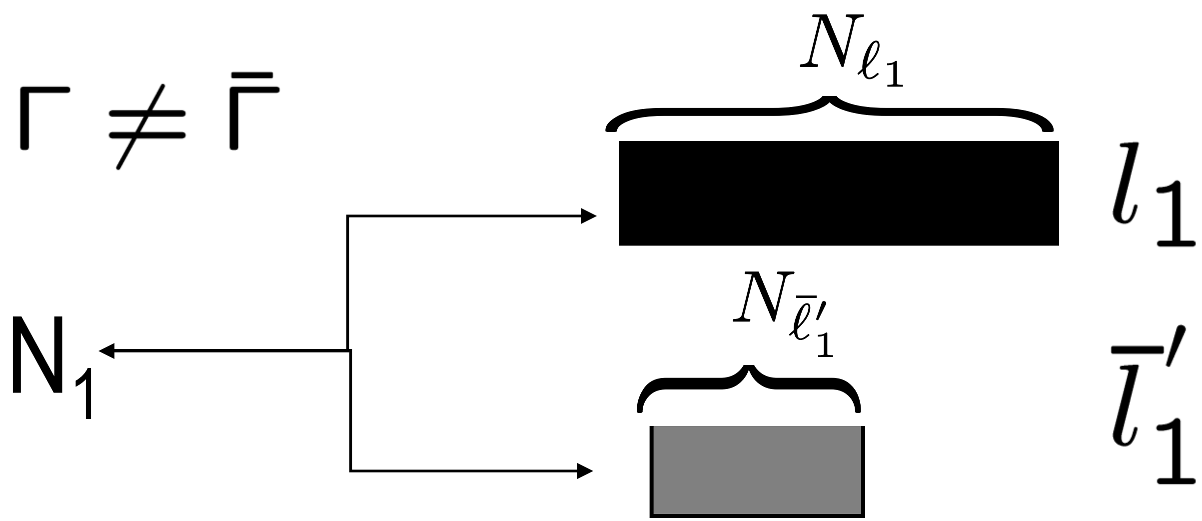
(Nardi, Racker, Roulet '06)

($\alpha = \tau,\ e+\mu$)

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

depends on U !

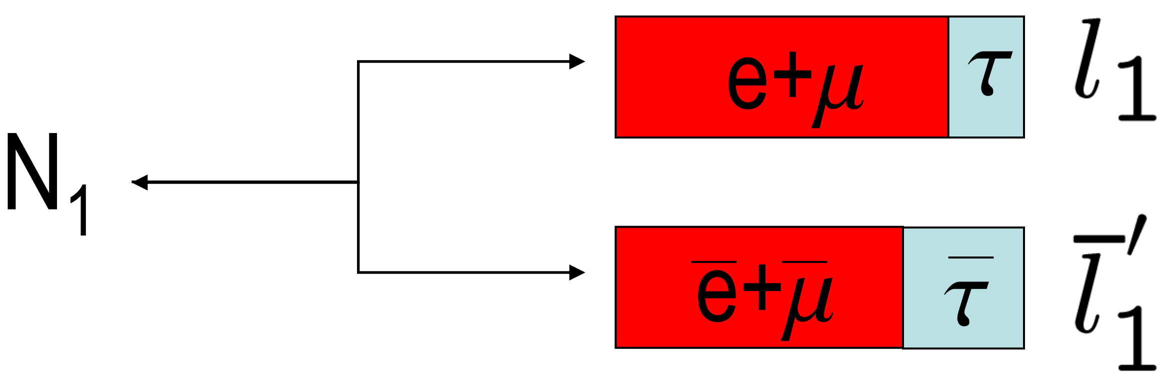
1) $\Gamma \neq \bar{\Gamma}$



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

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

+



$\Rightarrow\ \dfrac{\Delta P_{1\alpha}}{2}$

Low energy phases can be the only source of CP violation

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

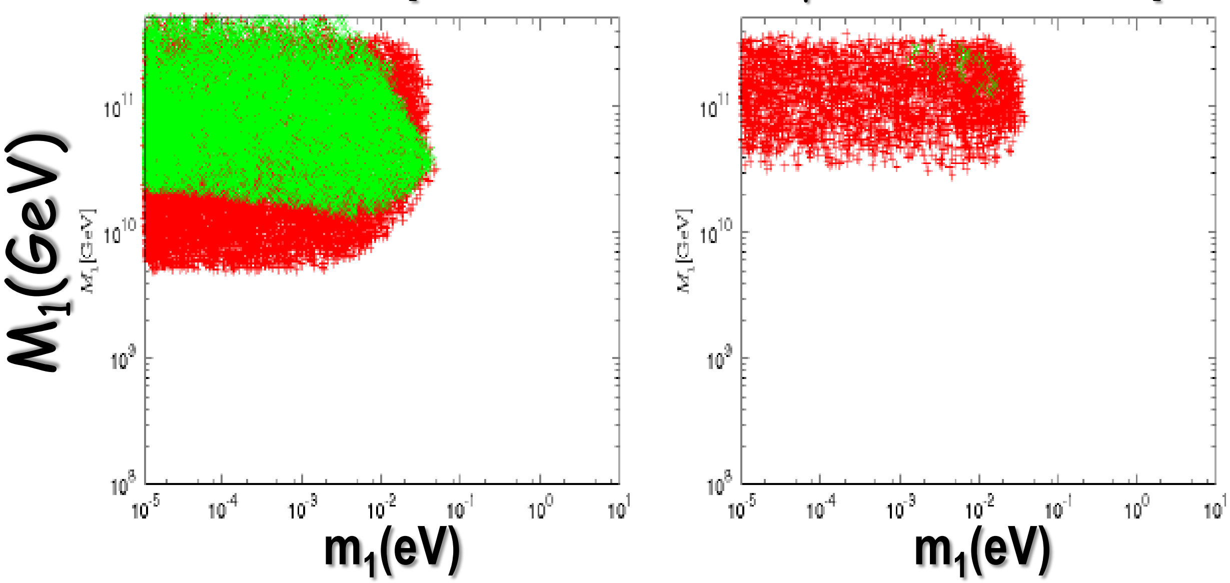
- Assume real $\Omega \Longrightarrow \varepsilon_1 = 0 \Longrightarrow \varepsilon_{1\alpha} = \cancel{P^0_{1\alpha}\,\varepsilon_1} + \dfrac{\Delta P_{1\alpha}}{2}$

$$\Longrightarrow N_{B-L} \simeq \cancel{2\varepsilon_1} K_1^{fin} + \Delta P_{1\alpha}(K_{1\alpha}^{fin} - K_{1\beta}^{fin}) \qquad (\alpha = \tau, e+\mu)$$

- Assume even vanishing Majorana phases

$\Longrightarrow \delta$ with non-vanishing θ_{13} ($J_{CP} \neq 0$) would be the only source of CP violation (testable)

initial thermal N_1 abundance | independent of initial N_1 abundance



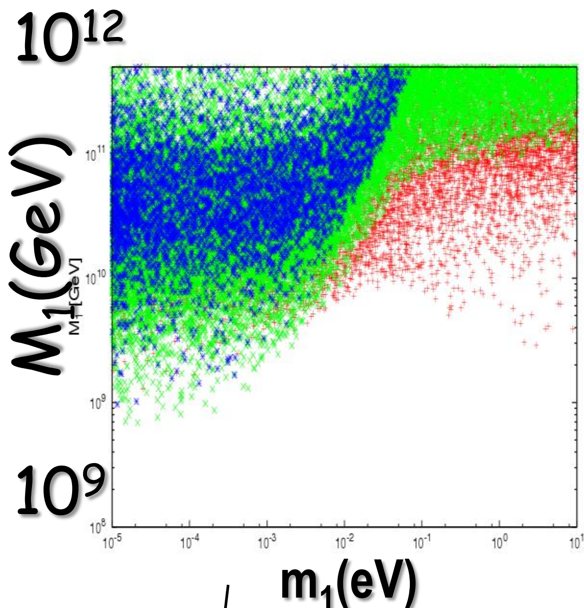
Green points: only Dirac phase with $\sin\theta_{13} = 0.2$, $|\sin\delta| = 1$

Red points: only Majorana phases

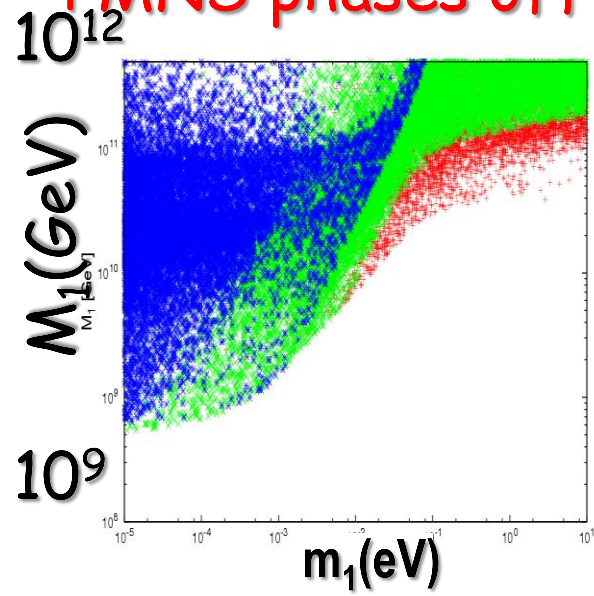
- No reasons for these assumptions to be rigorously satisfied
- In general this contribution is *overwhelmed* by the high energy phases (Davidson, Rius et al.'07)
- But they can be approximately satisfied in specific scenarios for some regions
- It is in any case by itself interesting that CP violation in neutrino mixing could be sufficient to reproduce the observed BAU

Upper bound on m_1

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

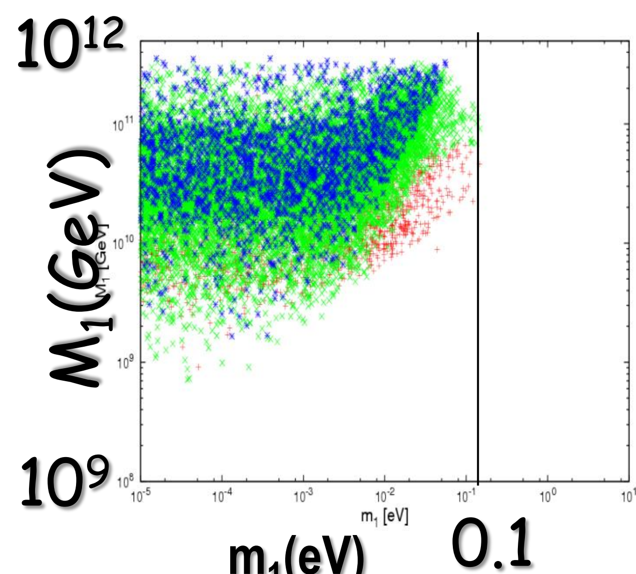


PMNS phases off



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

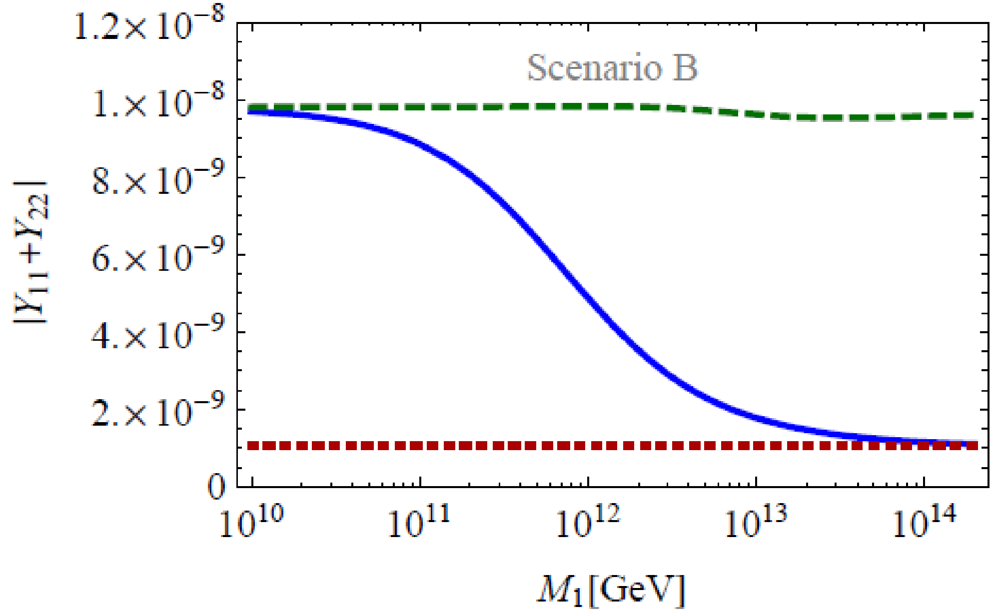
imposing a condition of validity of Boltzmann equations



Density matrix and CTP formalism to describe the transition regimes

(De Simone, Riotto '06; Beneke, Gabrecht, Fidler, Herranen, Schwaller '10)

$$\frac{\mathrm{d}Y_{\alpha\beta}}{\mathrm{d}z} = \frac{1}{szH(z)}\left[(\gamma_D+\gamma_{\Delta L=1})\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}}-1\right)\epsilon_{\alpha\beta}-\frac{1}{2Y_\ell^{\rm eq}}\left\{\gamma_D+\gamma_{\Delta L=1},Y\right\}_{\alpha\beta}\right]-\left[\sigma_2\mathrm{Re}(\Lambda)+\sigma_1|\mathrm{Im}(\Lambda)|\right]Y_{\alpha\beta}$$



Fully two-flavoured regime limit

Unflavoured regime limit

Heavy neutrino flavour effects: N_2-dominated scenario

(PDB '05)

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

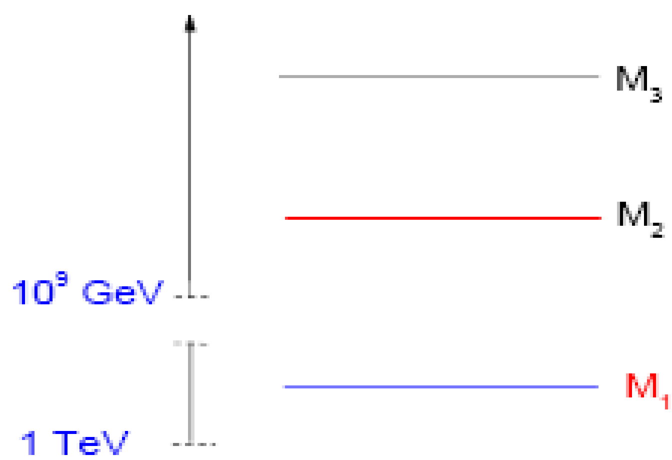
$$N_{B-L}^{f,N_2} = \varepsilon_2 \cdot\, (K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{f,N_1} = \varepsilon_1 \cdot (K_1)$$

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

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

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} !



Interplay between lepton and heavy neutrino flavour effects:

- N_2 flavoured leptogenesis

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

- Flavour projection

  (Barbieri,Creminelli,Stumia,Tetradis '00;
  Engelhard, Grossman, Nardi, Nir '07)

- Phantom leptogenesis

  (Antusch, PDB, King, Jones '10;
  Blanchet,PDB, Jones, Marzola '11)

- Flavour coupling

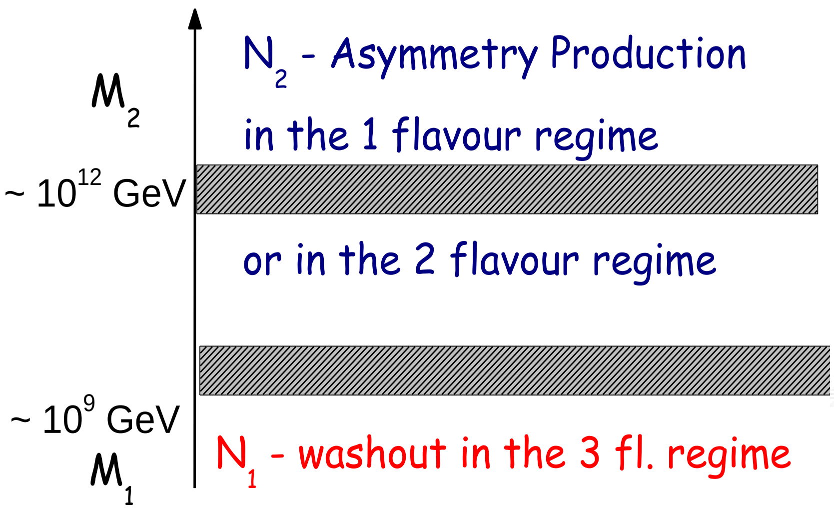
  (Abada,Josse Michaux '07, Antusch, PDB, King, Jones '10)

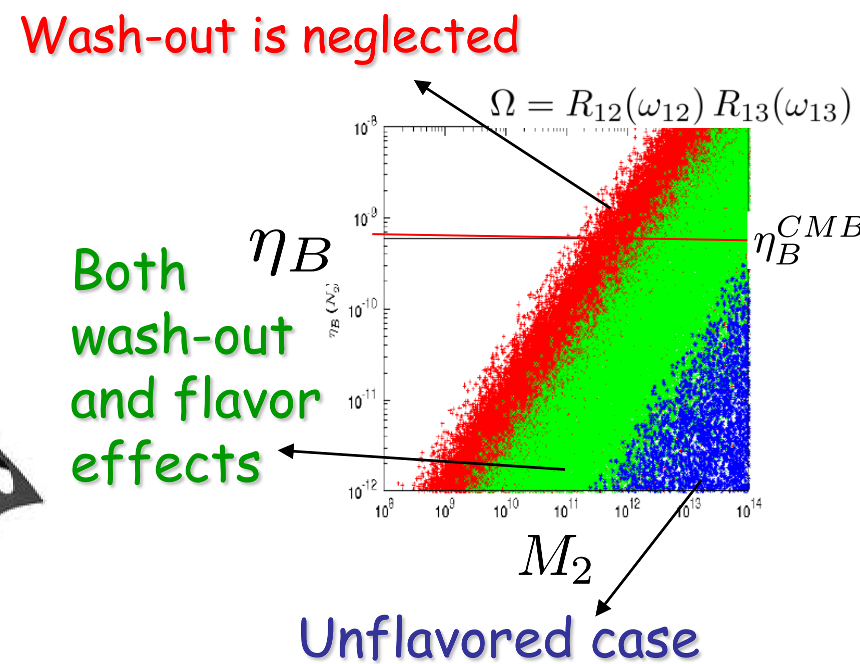
N_2-flavored leptogenesis

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

Combining together lepton and heavy neutrino flavour effects one has

A two stage process:





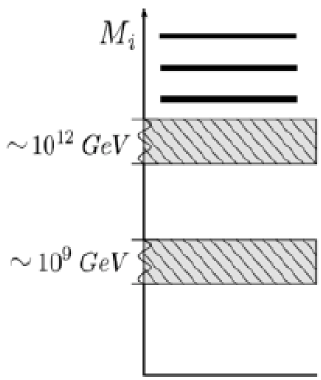
$$N_{B-L}^{\rm f}(N_2) = P_{2e}^0\,\varepsilon_2\cdot(K_2)\,e^{-\frac{3\pi}{8}\,K_{1e}} + P_{2\mu}^0\,\varepsilon_2\cdot(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + P_{2\tau}^0\,\varepsilon_2\cdot(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

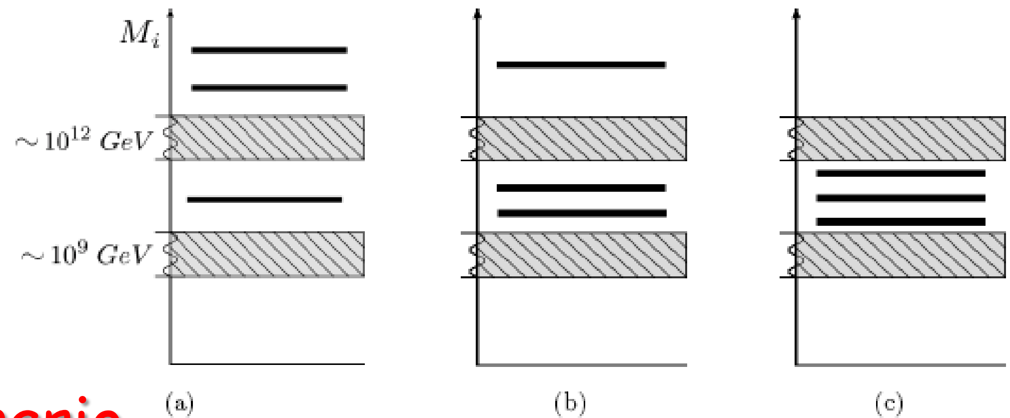
Notice that $K_1 = K_{1e} + K_{1\mu} + K_{1\tau}$

With flavor effects the domain of applicability goes much beyond the choice $\Omega = R_{23}$

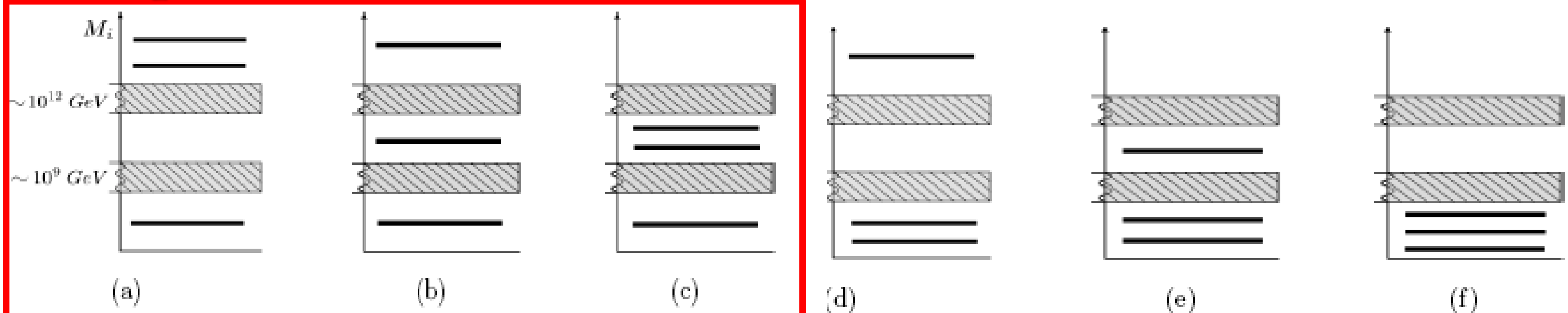
The existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$ not to be negligible !

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





N_2 dominated scenario



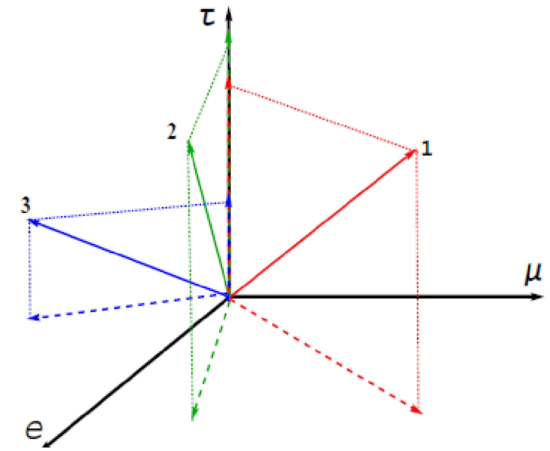
For each pattern a specific set of Boltzmann equations has to be considered !

Density matrix formalism with heavy neutrino flavours

(Blanchet,PDB, Jones, Marzola '11)

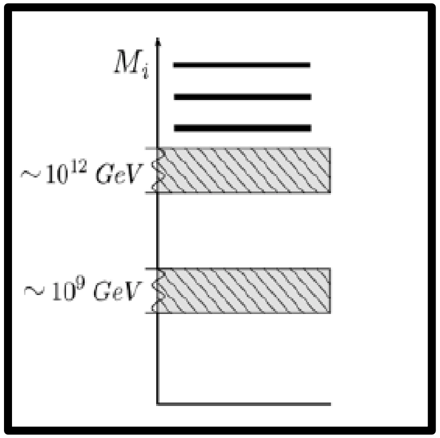
For a thorough description of all neutrino mass patterns including transition regions and all effects (flavour projection, phantom leptogenesis,...) one needs a description in Terms of a density matrix formalism

The result is a "monster" equation:

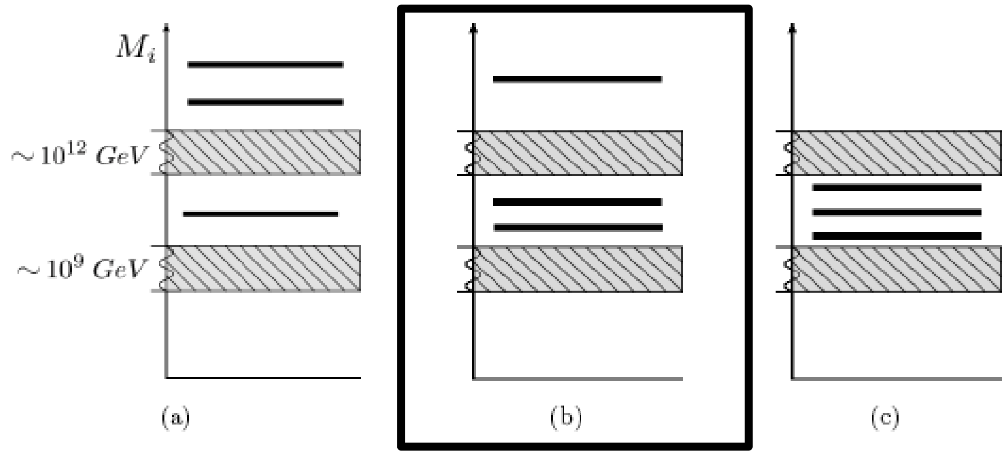


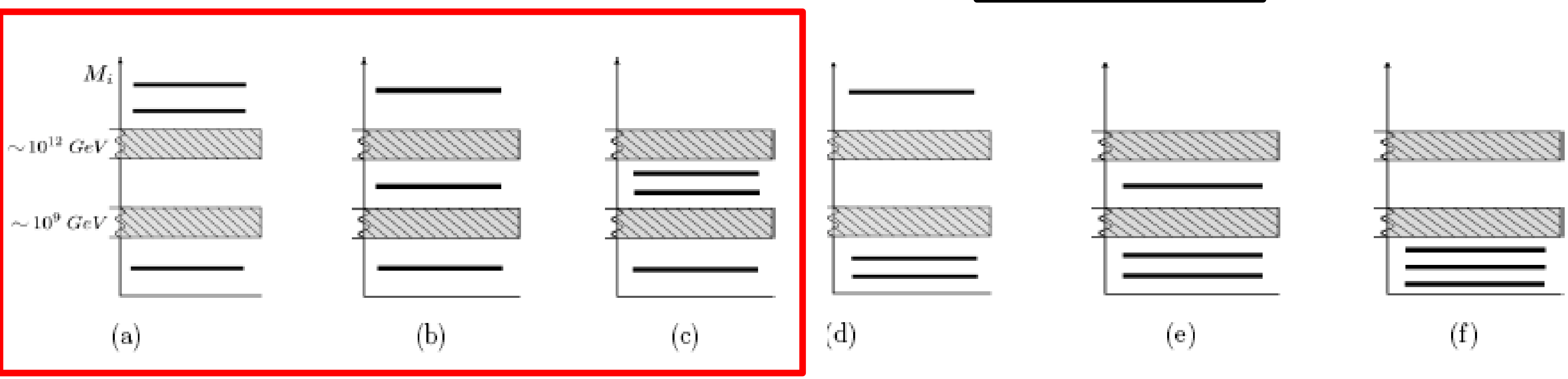
$$
\begin{aligned}
\frac{dN^{B-L}_{\alpha\beta}}{dz} &= \varepsilon^{(1)}_{\alpha\beta}\, D_1\,(N_{N_1}-N_{N_1}^{\rm eq}) - \frac{1}{2}\, W_1\,\{\mathcal{P}^{0(1)}, N^{B-L}\}_{\alpha\beta} \qquad (80)\\
&+ \varepsilon^{(2)}_{\alpha\beta}\, D_2\,(N_{N_2}-N_{N_2}^{\rm eq}) - \frac{1}{2}\, W_2\,\{\mathcal{P}^{0(2)}, N^{B-L}\}_{\alpha\beta}\\
&+ \varepsilon^{(3)}_{\alpha\beta}\, D_3\,(N_{N_3}-N_{N_3}^{\rm eq}) - \frac{1}{2}\, W_3\,\{\mathcal{P}^{0(3)}, N^{B-L}\}_{\alpha\beta}\\
&+ {\rm i}\,{\rm Re}(\Lambda_\tau)\left[\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}, N^{\ell+\bar\ell}\right]_{\alpha\beta} - {\rm Im}(\Lambda_\tau)\left[\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix},\left[\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}, N^{B-L}\right]\right]_{\alpha\beta}\\
&+ {\rm i}\,{\rm Re}(\Lambda_\mu)\left[\begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix}, N^{\ell+\bar\ell}\right]_{\alpha\beta} - {\rm Im}(\Lambda_\mu)\left[\begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix},\left[\begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix}, N^{B-L}\right]\right]_{\alpha\beta}.
\end{aligned}
$$

Heavy neutrino flavored scenario



2 RH neutrino scenario





N_2-dominated scenario → **Particularly attractive for two reasons**

1) It is just that one realised in SO(10) inspired models!

Can they be reconciled with leptogenesis?

The N_2-dominated scenario rescues SO(10) inspired models

(PDB, Riotto '08)

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

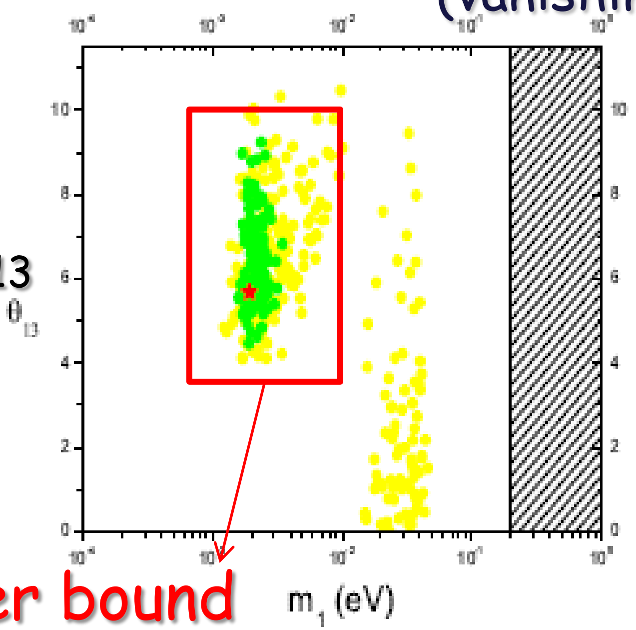
Independent of α_1 and α_3 !

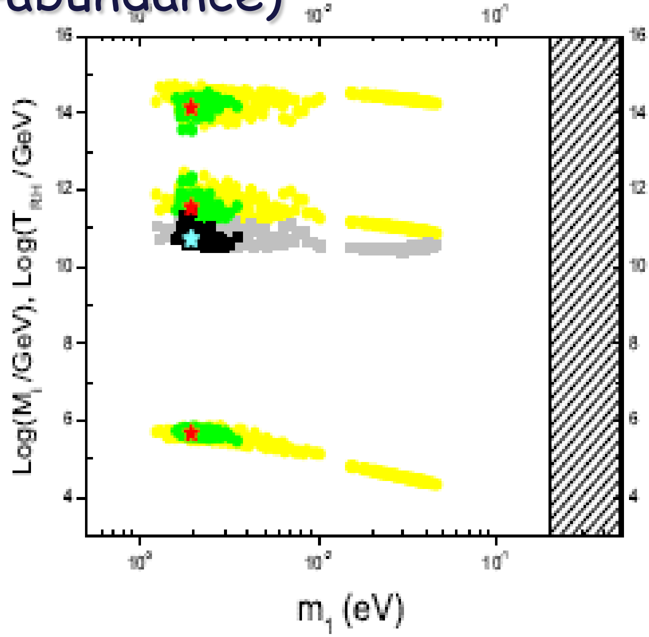
α_2=5 α_2=4 α_2=3

$V_L = I$ Normal ordering

(vanishing initial N_2-abundance)

Θ_{13}





lower bound on Θ_{13} ?

Another way to rescue SO(10) inspired models is by considering a left-right symmetric seesaw (Abada, Hosteins, Josse-Michaux, Lavignac'08)

The model yields constraints on all low energy neutrino observables !

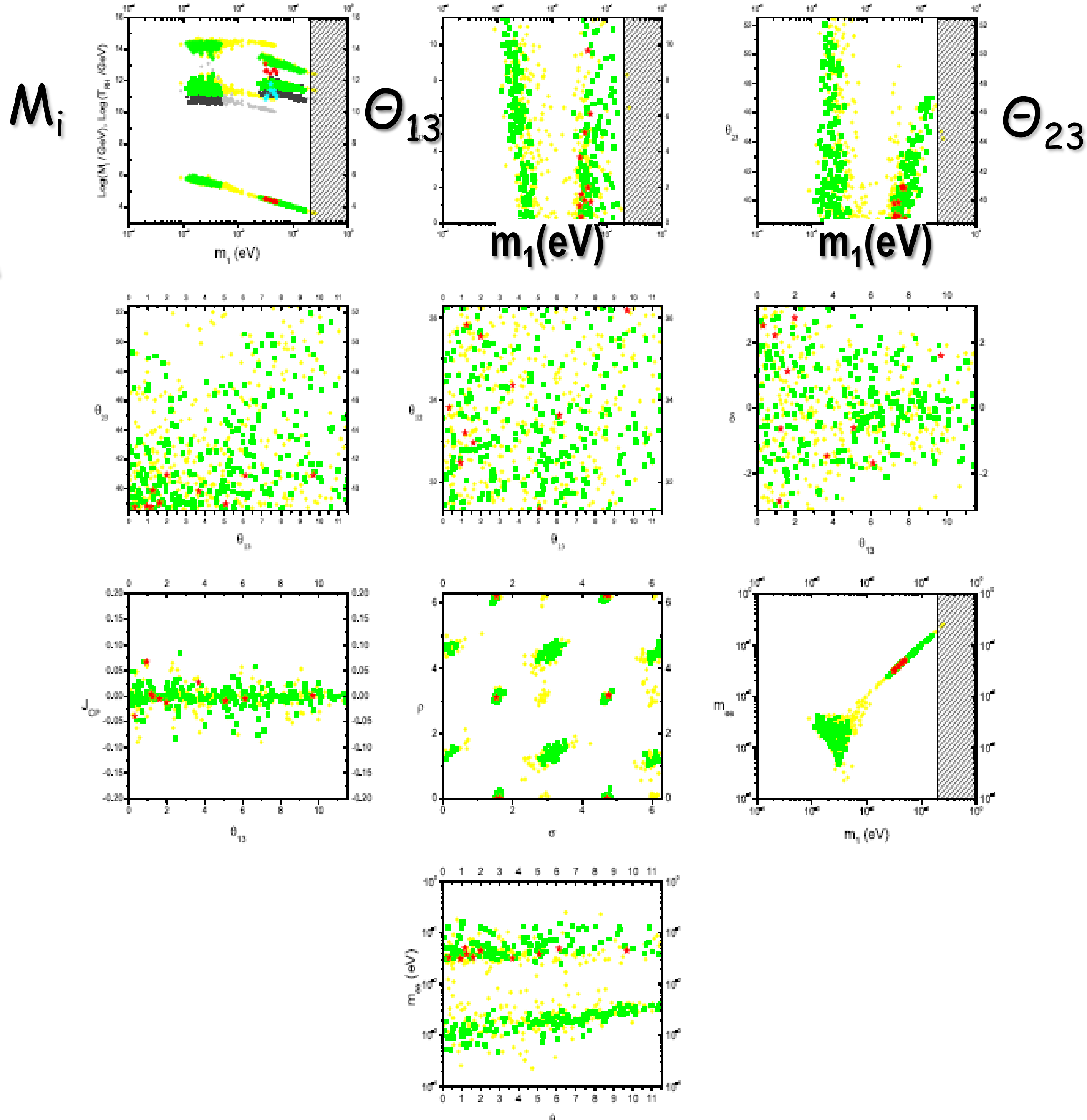
$I < V_L < V_{CKM}$

NORMAL ORDERING

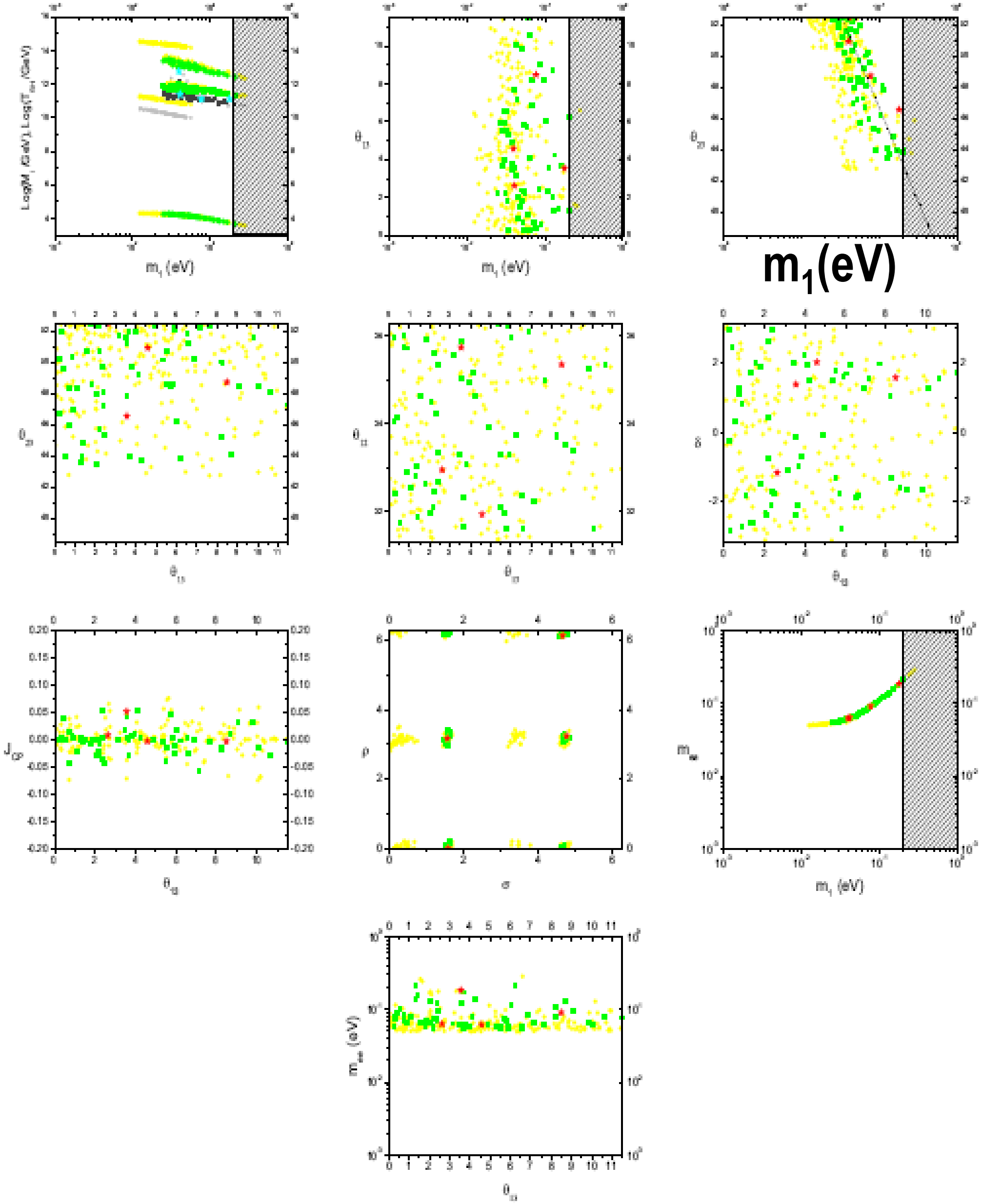
α_2=5

α_2=4

α_2=1



$I < V_L < V_{CKM}$



Θ_{23}

INVERTED ORDERING

α_2=5

α_2=4

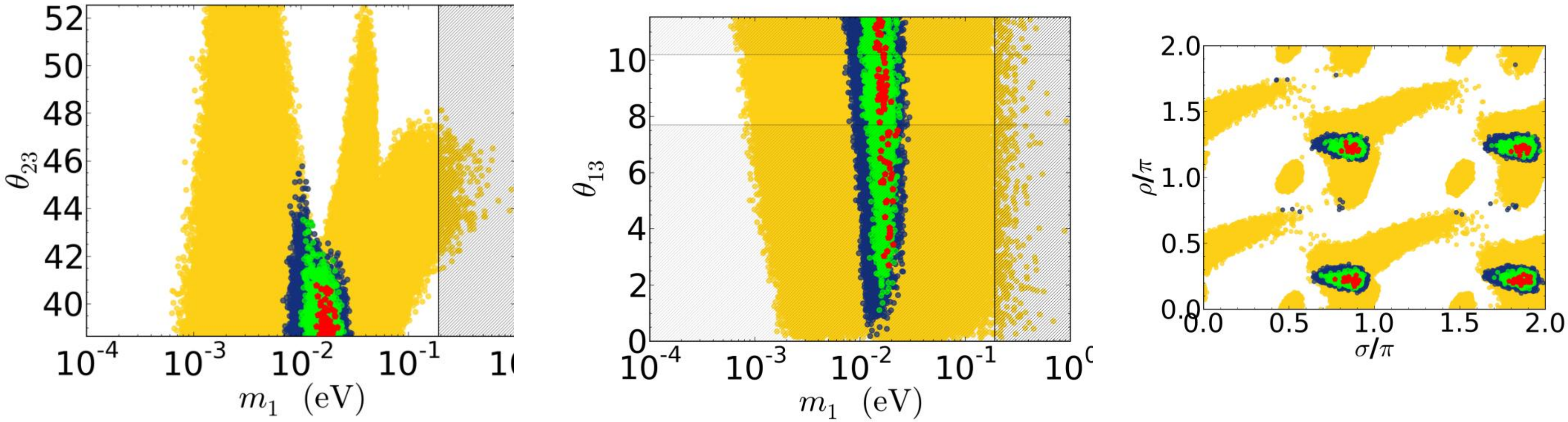
α_2=1.5

An improved analysis

(PDB, Marzola '11-'12)

We optimised the procedure increasing of two orders of magnitudes the number of solutions (focus on yellow points for the time being):

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

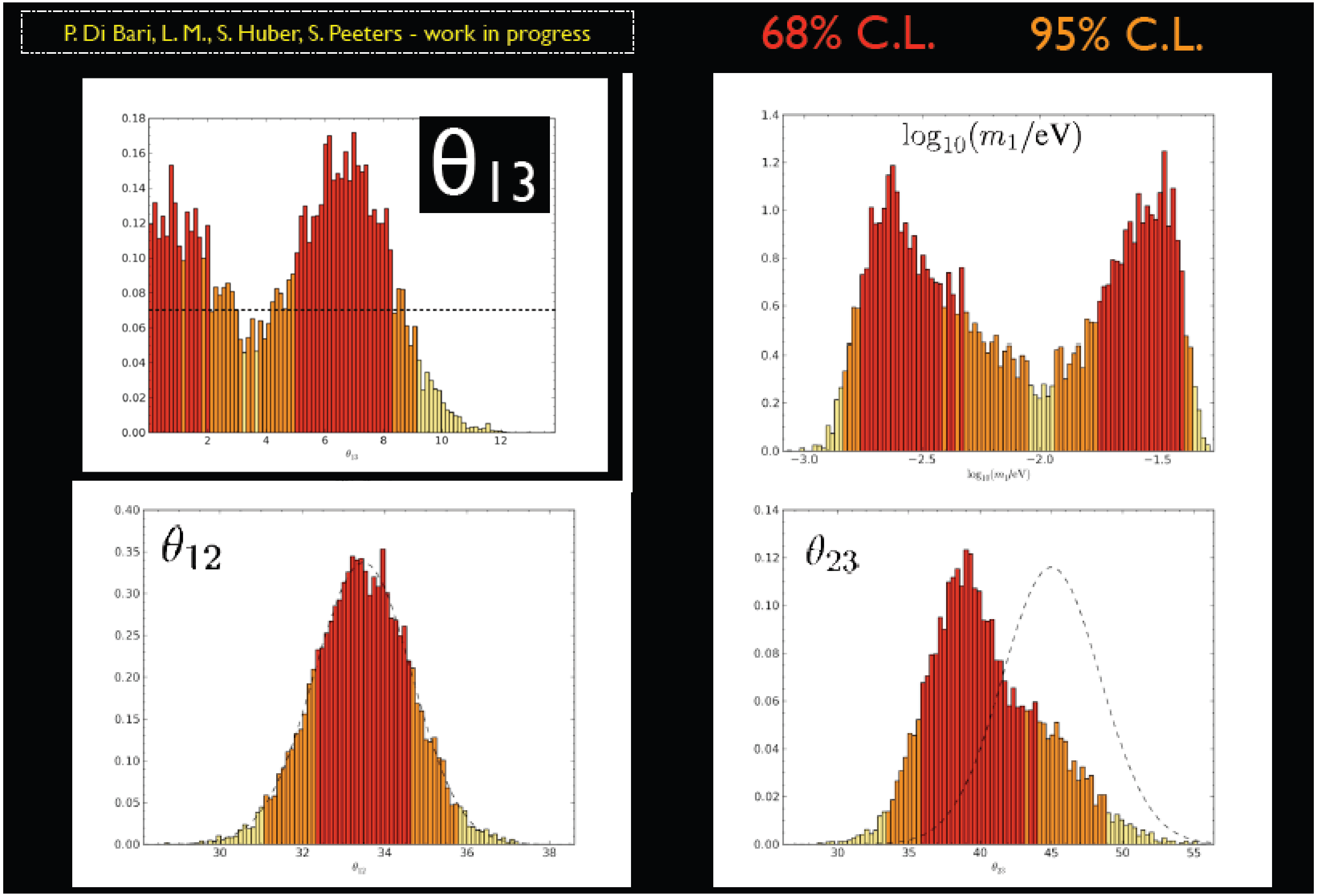


Why? Just to have sharper borders ? NO, two important reasons:

i) statistical analysis

ii) to obtain the blue green and red points

A statistical analysis



Talk by Luca Marzola at the DESY theory workshop 28/9/11

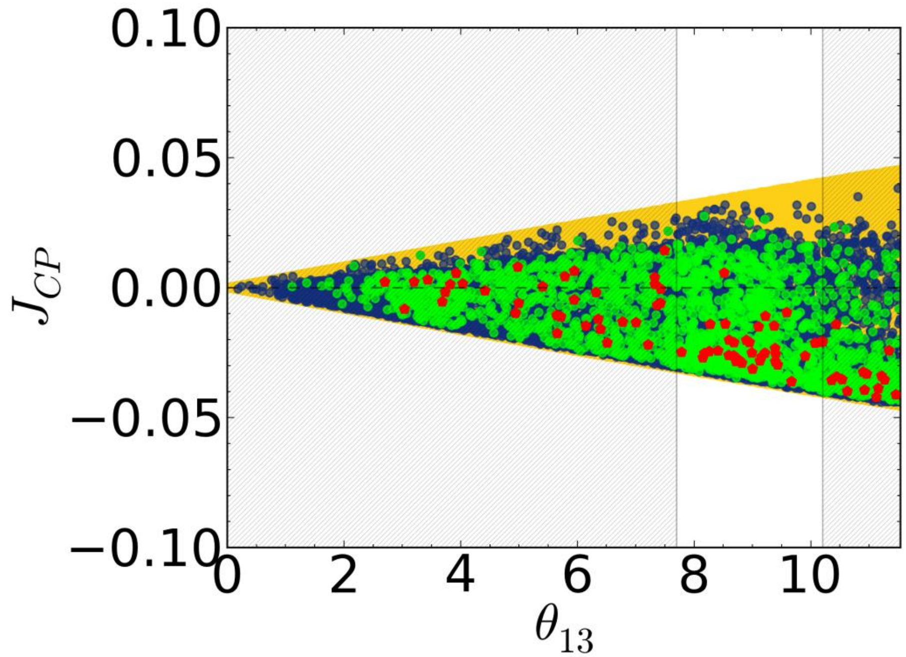
No link between the sign of the asymmetry and J_{CP}

(PDB, Marzola '11-'12)

α_2=5

NORMAL ORDERING

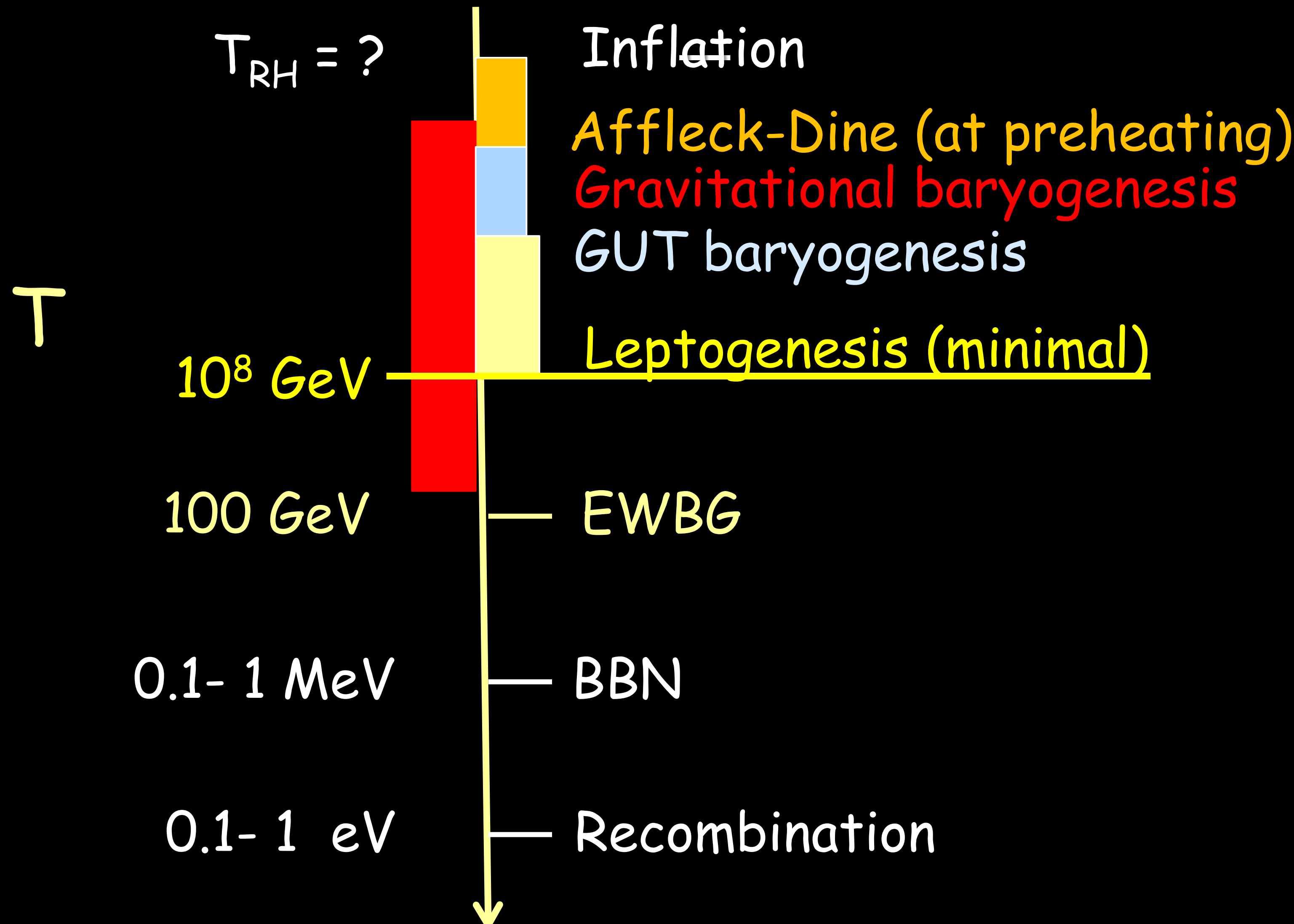
$I < V_L < V_{CKM}$



It is confirmed that there is no link between the matter-antimatter asymmetry and CP violation in neutrino mixing…….for the yellow points

WHAT ARE THEN THE NON-YELLOW POINTS ?

Baryogenesis and the early Universe history

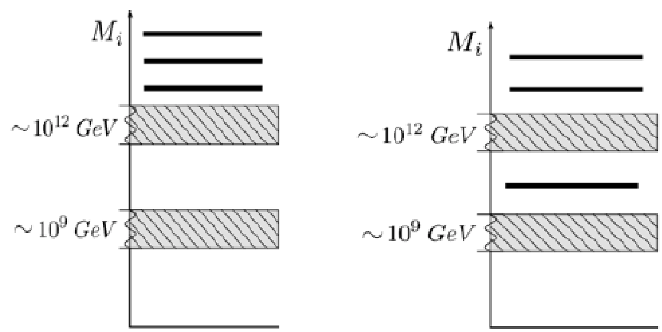


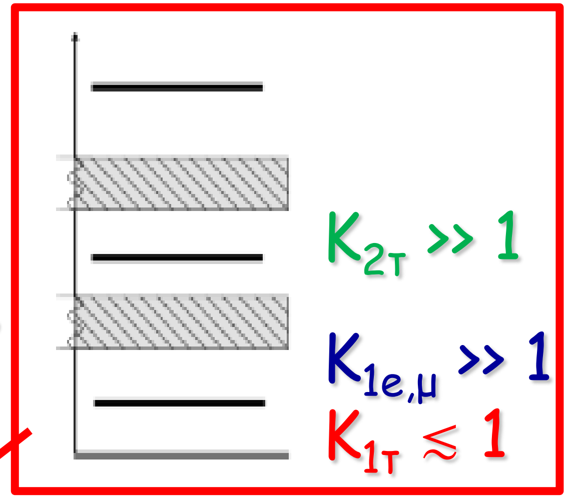
(Bertuzzo,PDB,Marzola '10)

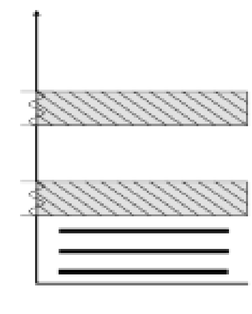
Residual "pre-existing" asymmetry possibly generated by some external mechanism

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

Asymmetry generated from leptogenesis







The conditions for the wash-out of a pre-existing asymmetry ('**strong thermal leptogenesis**') can be realised only within a N_2-dominated scenario where the final asymmetry is dominantly produced in the tauon flavour

This mass pattern is just that one realized in the SO(10) inspired models: can they realise strong thermal leptogenesis?

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

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

Imposing both successful SO(10)-inspired leptogenesis

$\eta_B = \eta_B^{CMB} = (6.2 \pm 0.15) \times 10^{-10}$ and $N_{B-L}^{P,f} \ll N_{B-L}^{leP,f}$

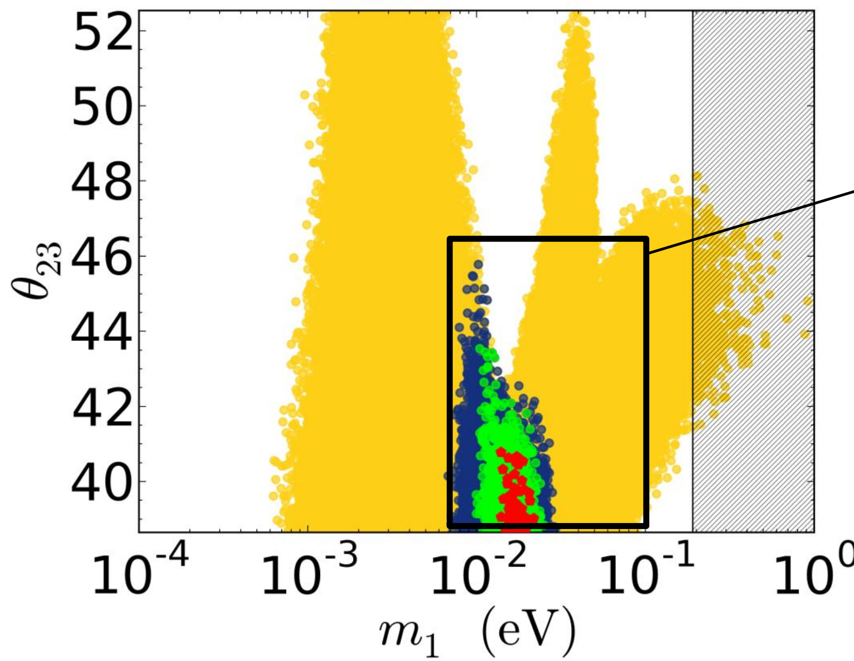
NO Solutions for Inverted Ordering !

But for Normal Ordering there is a subset with definite predictions

UPPER BOUND ON THE ATMOSPHERIC MIXING ANGLE

$N_{B-L} =$ 0
0.001
0.01
0.1

$\alpha_2 = 5$



Small atmospheric mixing angle

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

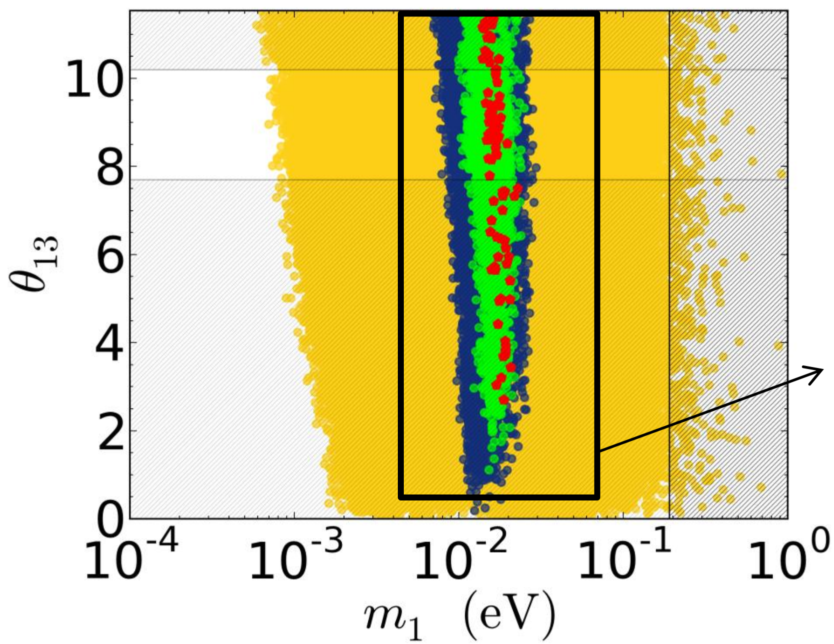
$$N^{\rm f}_{B-L} = N^{\rm p,f}_{B-L} + N^{\rm lep,f}_{B-L}\,,$$

Imposing both successful SO(10)-inspired leptogenesis $\eta_B = \eta_B^{CMB} = (6.2 \pm 0.15) \times 10^{-10}$ and $N^{P,f}_{B-L} \ll N^{leP,f}_{B-L}$

NON-VANISHING REACTOR MIXING ANGLE

N_{B-L} = 0
0.001
0.01
0.1

α_2=5



non-vanishing Θ_{13} (green and red points)

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

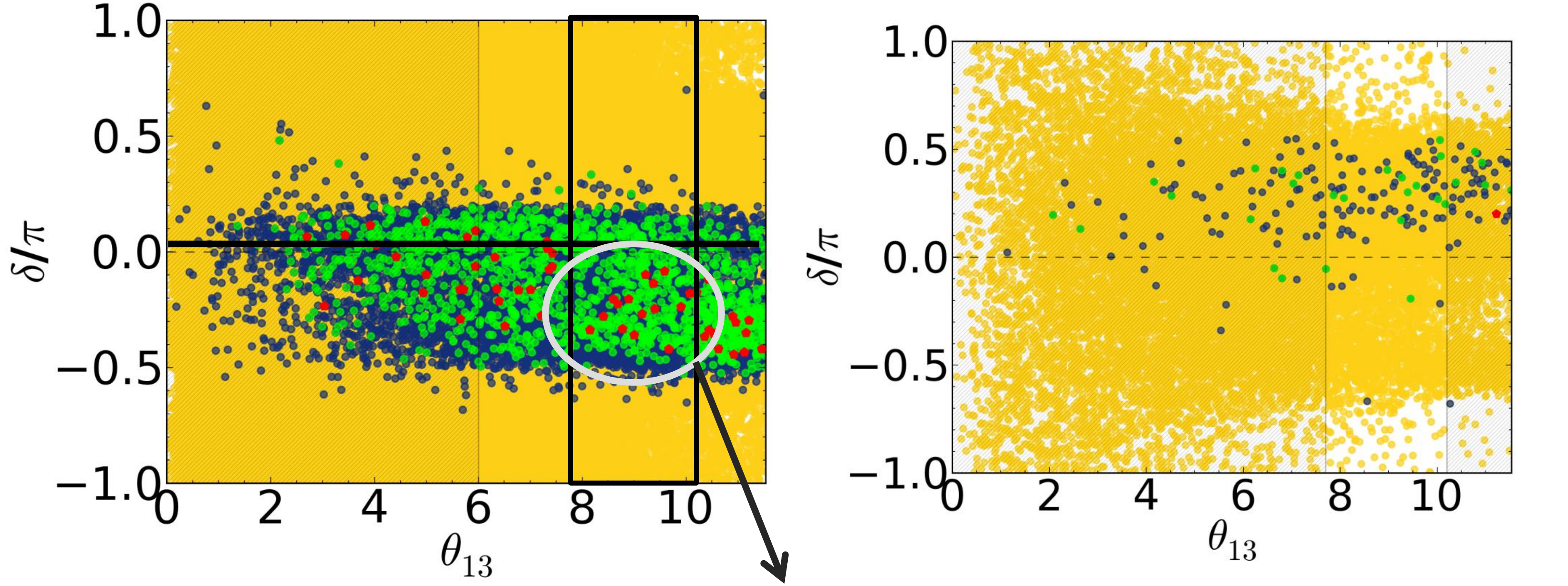
$$N^{\rm f}_{B-L} = N^{\rm p,f}_{B-L} + N^{\rm lep,f}_{B-L} \,,$$

Imposing both successful SO(10)-inspired leptogenesis

$\eta_B = \eta_B^{CMB} = (6.2 \pm 0.15) \times 10^{-10}$ and $N_{B-L}^{P,f} \ll N_{B-L}^{leP,f}$

Link between the sign of J_{CP} and the sign of the asymmetry

$\eta_B = \eta_B^{CMB}$ $\qquad\qquad$ $\eta_B = -\,\eta_B^{CMB}$



A Dirac phase $\delta \sim -60^\circ$ is favoured for large θ_{13}

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

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

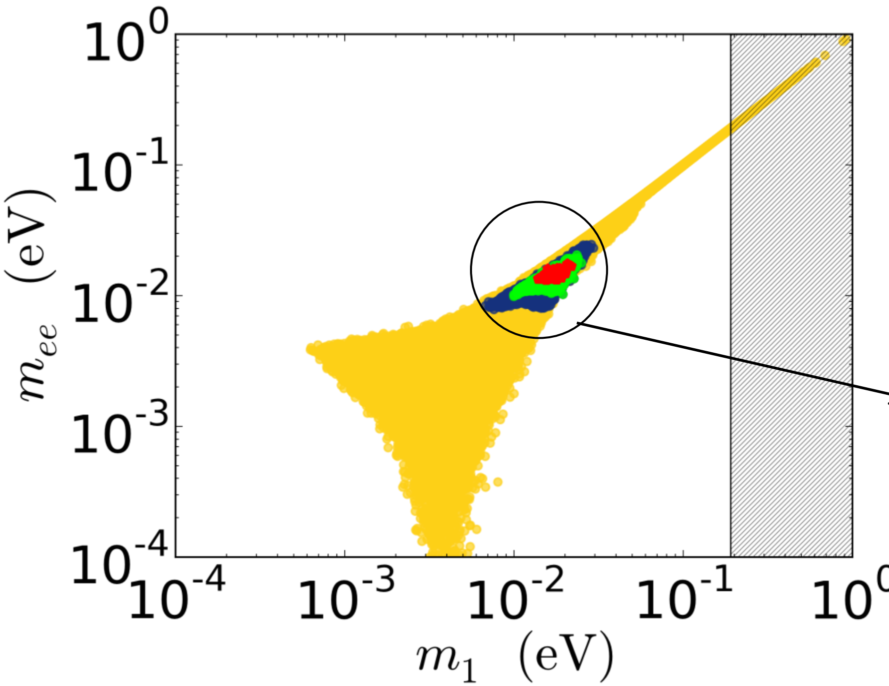
Imposing both successful SO(10)-inspired leptogenesis

$\eta_B = \eta_B^{CMB} = (6.2 \pm 0.15) \times 10^{-10}$ and $N_{B-L}^{P,f} \ll N_{B-L}^{leP,f}$

Sharp prediction on the absolute neutrino mass scales

$N_{B-L} =$ 0
0.001
0.01
0.1

α_2=5



$m_1 \simeq m_{ee} \simeq 20 meV$

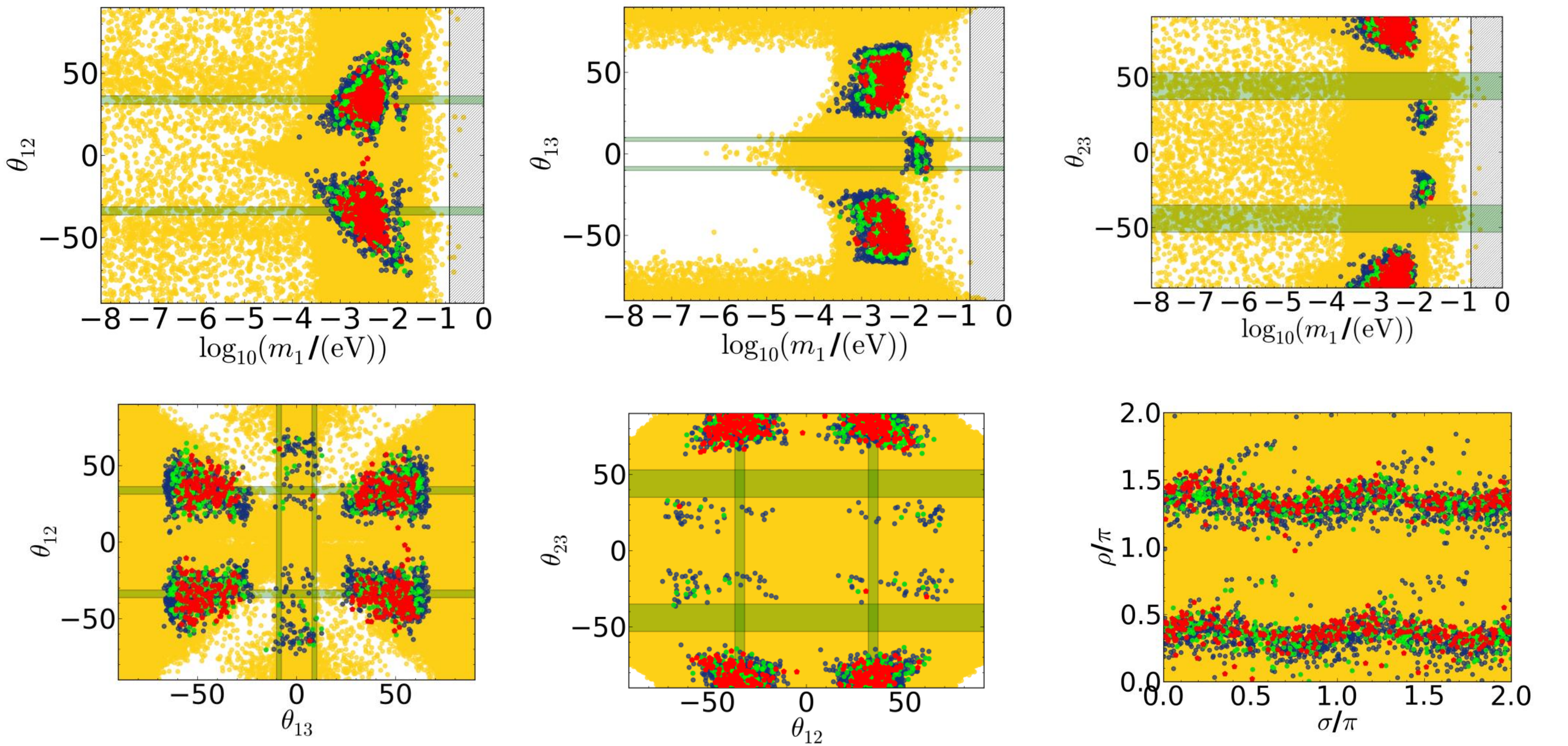
Testable (2020?)
(talks by
Laura Baudis
and Licia Verde)

Strong thermal SO(10)-inspired leptogenesis:

Is it on the right track?

(PDB, Riotto '08; PDB, Marzola '12)

If we do not plug any experimental information (mixing angles left completely free, PRELIMINARY RESULTS) :



Strong thermal SO(10) inspired leptogenesis: summary

- SO(10)-inspired leptogenesis is not only alive but it produces a set of solutions able to satisfy a very difficult condition when flavour effects are taken into account: *independence of the initial conditions (strong thermal leptogenesis)*

ORDERING	NORMAL
θ_{13}	$\gtrsim 3^\circ$
θ_{23}	$\lesssim 41^\circ$
δ	$\sim -60^\circ$
$m_1 \simeq m_{ee}$	~ 20 meV

- It provides an example of how (minimal) leptogenesis within a reasonable set of assumptions can yield testable predictions
- Corrections: flavour coupling, RGE effects,...
- Statistical analysis

Interplay between lepton and heavy neutrino flavour effects:

- N_2 flavoured leptogenesis

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

- Flavour projection

  (Barbieri,Creminelli,Stumia,Tetradis '00;
  Engelhard, Grossman, Nardi, Nir '07)

- Phantom leptogenesis

  (Antusch, PDB, King, Jones '10;
  Blanchet,PDB, Jones, Marzola '11)

- Flavour coupling

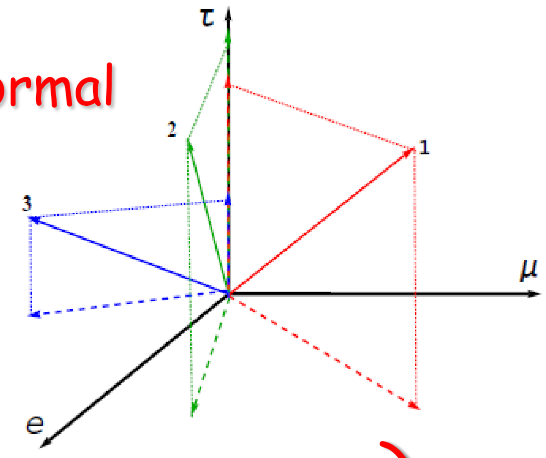
  (Abada,Josse Michaux '07, Antusch, PDB, King, Jones '10)

Flavour projection

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

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

The heavy neutrino flavour basis cannot be orthonormal otherwise the CP asymmetries would vanish: this complicates the calculation of the final asymmetry



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

$\propto p_{12}$ $\qquad \propto (1-p_{12})$

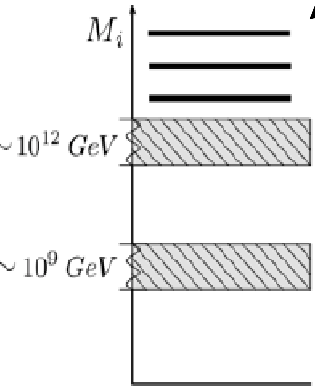
$$N_{B-L}^{(N_2)}(T \ll M_1) = N_{\Delta_1}^{(N_2)}(T \ll M_1) + N_{\Delta_{1\perp}}^{(N_2)}(T \ll M_1)$$

Component from heavier RH neutrinos **parallel** to l_1 and washed-out by N_1 inverse decays

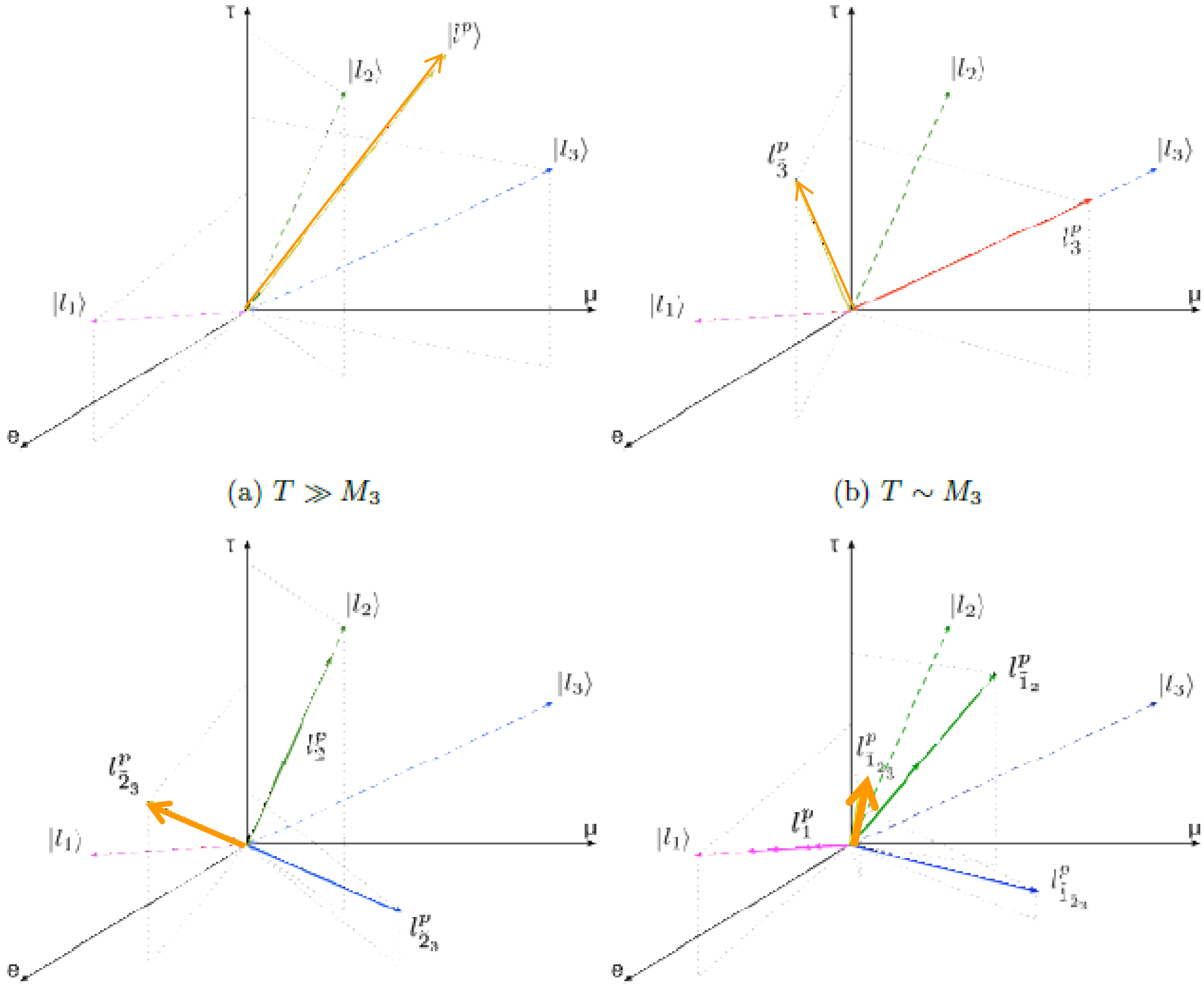
Contribution from heavier RH neutrinos **orthogonal** to l_1 and escaping N_1 wash-out

$$N_{\Delta_1}^{(N_2)}(T \ll M_1) = p_{12}\, e^{-\frac{3\pi}{8}K_1}\, N_{B-L}^{(N_2)}(T \sim M_2)$$

Example: The heavy neutrino flavored scenario cannot satisfy the strong thermal leptogenesis condition



The pre-existing asymmetry (yellow) undergoes a 3 step flavour projection



(a) $T \gg M_3$

(b) $T \sim M_3$

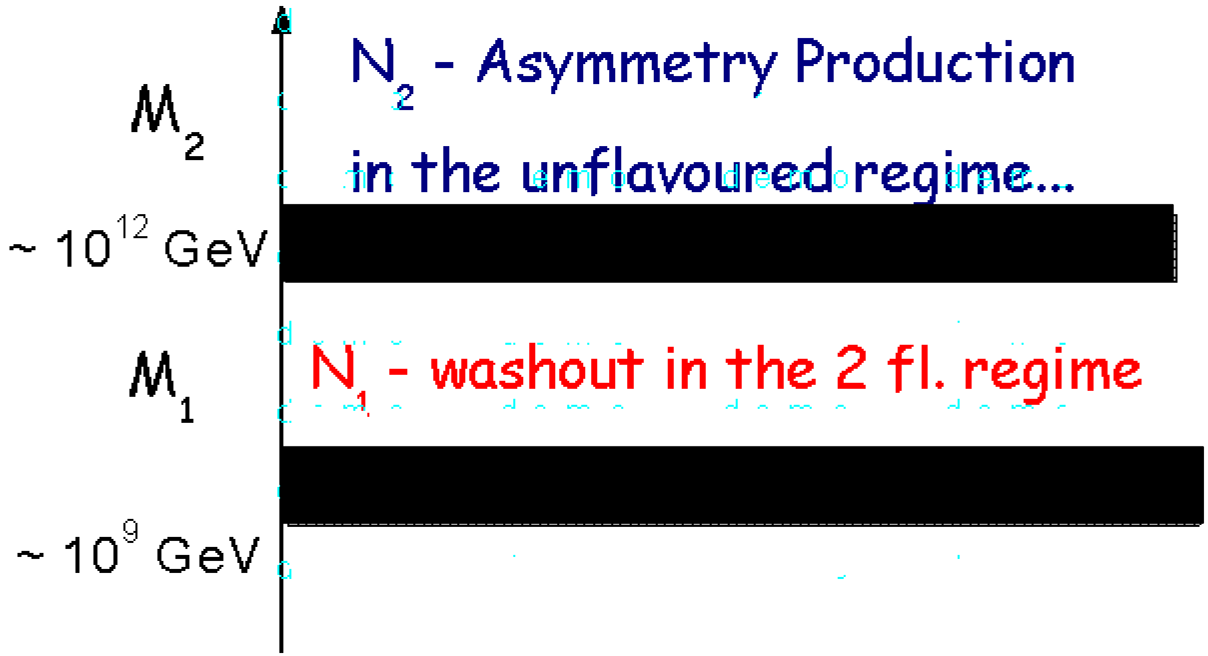
(c) $T \sim M_2$

(d) $T \sim M_1$

Phantom Leptogenesis

(Antusch, PDB, King, Jones '10)

Consider this situation



What happens to N_{B-L} at $T \sim 10^{12}$ GeV?

How does it split into a $N_{\Delta\tau}$ component and into a $N_{\Delta e+\mu}$ component?

One could think:

$$N_{\Delta\tau} = p_{2\tau}\, N_{B-L},$$

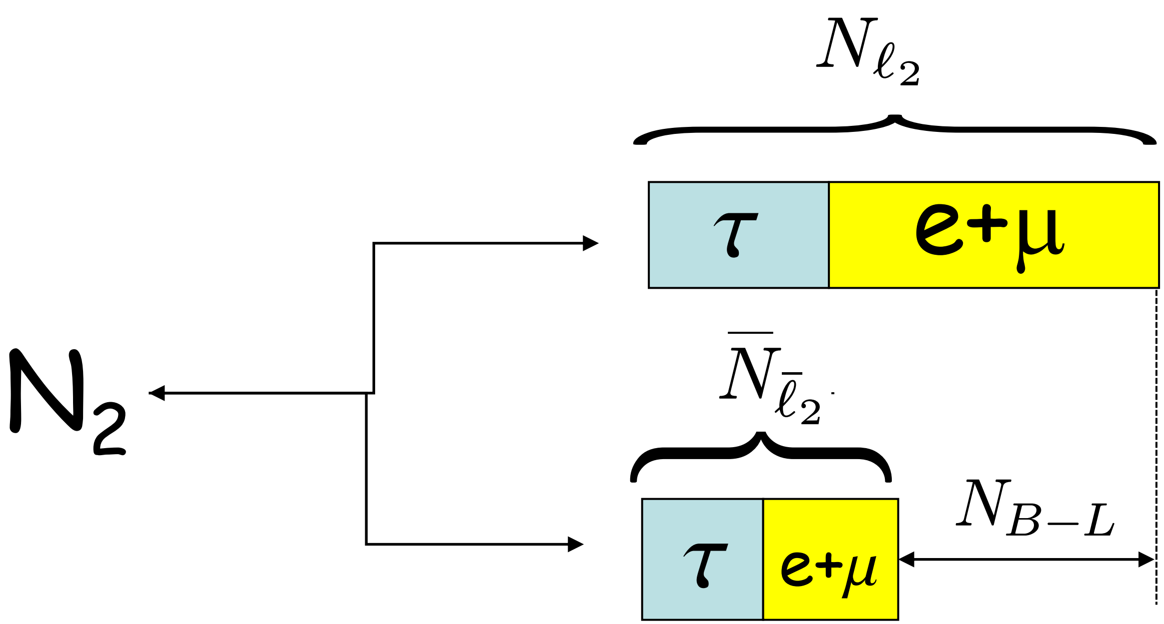
$$N_{\Delta e+\mu} = p_{2\, e+\mu}\, N_{B-L}$$

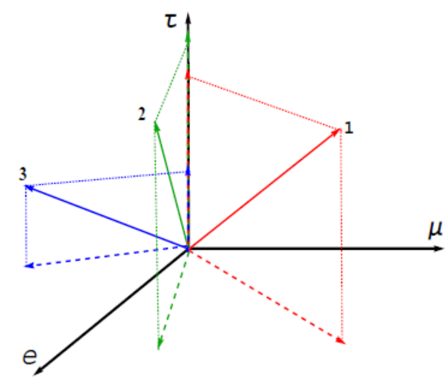
Phantom terms

However one has to consider that in the unflavoured case there are contributions to $N_{\Delta\tau}$ and $N_{\Delta e+\mu}$ that are not just proportional to N_{B-L}

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

Assume an initial thermal N_2-abundance at $T \sim M_2 \gg 10^{12}$ GeV



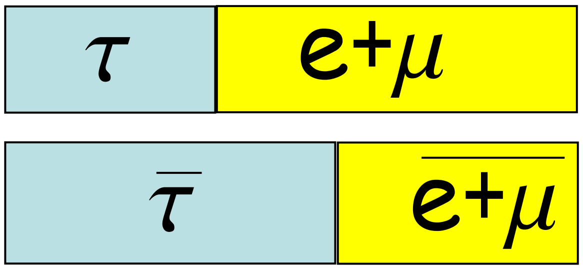


Phantom Leptogenesis

(Antusch, PDB, King, Jones '10)

Let us then consider a situation where $K_2 >> 1$ so that at the end of the N_2 washout the total asymmetry is negligible:

1) $T \sim M_2$: unflavoured regime



$$\Rightarrow \quad N_{B-L}^{T\sim M_2} \simeq 0 \; !$$

2) 10^{12} GeV $\gtrsim T >> M_1$:decoherence $\Longrightarrow$ 2 flavoured regime

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

3) $T \simeq M_1$: asymmetric washout from lightest RH neutrino

Assume $K_{1\tau} \lesssim 1$ and $K_{1e+\mu} >> 1$ $\qquad N_{B-L}^{\rm f} \simeq N_{\Delta_\tau}^{T\sim M_2} \; !$

The N_1 wash-out un-reveal the phantom term and effectively it creates a N_{B-L} asymmetry. Fully confirmed within a density matrix formalism (Blanchet, PDB, Marzola, Jones '11)

Remarks on 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 !

$$N_{\Delta_\tau}^{\rm phantom} = \frac{\Delta p_{2\tau}}{2} N_{N_2}^{\rm in}$$

The reason is that if one starts from a vanishing abundance during the N_2 production one creates a contribution to the phantom term by inverse decays with opposite sign and exactly cancelling with what is created in the decays

In conclusion ....phantom leptogenesis introduces additional strong dependence on the initial conditions

NOTE: in strong thermal leptogenesis phantom terms are also washed out: full independence of the initial conditions!

Phantom terms cannot contribute to the final asymmetry in N_1 leptogenesis but (canceling) flavoured asymmetries can be much bigger than the baryon asymmetry and have implications in active-sterile neutrino oscillations

2 RH neutrino scenario revisited

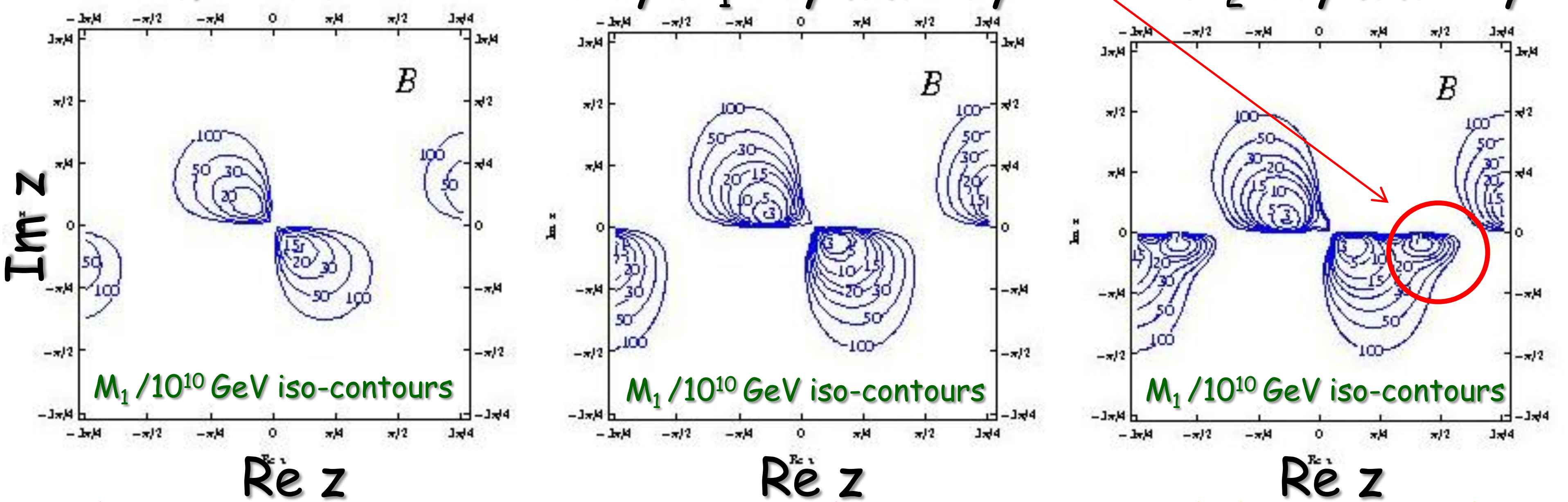
(King 2000;Frampton,Yanagida,Glashow '01,Ibarra, Ross 2003;Antusch, PDB,Jones,King '11)

In the 2 RH neutrino scenario the N_2 production has been so far considered to be safely negligible because $\varepsilon_{2\alpha}$ were supposed to be strongly suppressed and very strong N_1 wash-out. But taking into account:

- the N_2 asymmetry N_1-orthogonal component
- an additional unsuppressed term to $\varepsilon_{2\alpha}$

New allowed N_2 dominated regions appear

Unflavoured | only N_1 asymmetry | + N_2 asymmetry



These regions are interesting because they correspond to light sequential dominated neutrino mass models realized in some grandunified models

Conclusion

The interplay between heavy neutrino and charged lepton flavour effects introduces many new ingredients in the calculation of the final asymmetry and a density matrix formalism becomes much more useful in calculating correctly the final asymmetry

All this finds a nice applications for example
- in a 2 RH neutrino model
- In SO(10) inspired models

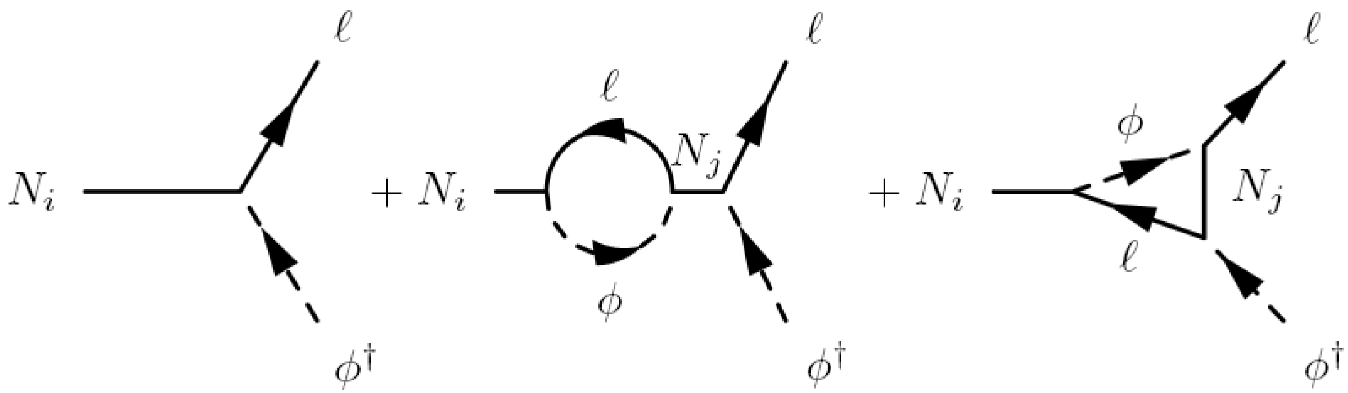
These are able to produce a scenario of leptogenesis with definite predictions on low energy neutrino parameters and with the next experimental developments all this could become extremely exciting

Strong thermal SO(10) inspired leptogenesis solution

ORDERING	NORMAL
θ_{13}	$\gtrsim 3^{\circ}$
θ_{23}	$\lesssim 41^{\circ}$
δ	$\sim -60^{\circ}$
$m_1 \simeq m_{ee}$	~ 20 meV

Total CP asymmetries

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



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

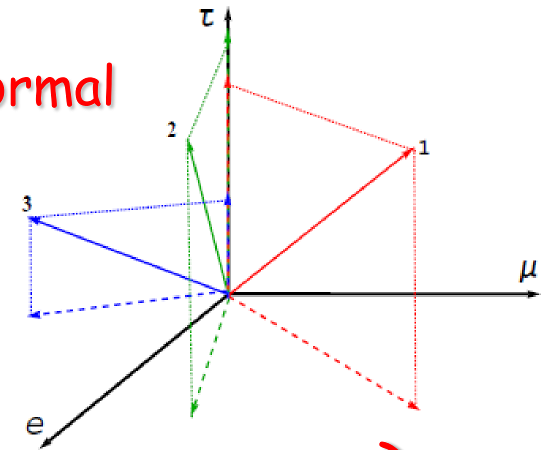
It does not depend on U !

Flavour projection

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

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

The heavy neutrino flavour basis cannot be orthonormal otherwise the CP asymmetries would vanish: this complicates the calculation of the final asymmetry



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

$\propto p_{12}$ $\qquad \propto (1-p_{12})$

$$N_{B-L}^{(N_2)}(T \ll M_1) = N_{\Delta_1}^{(N_2)}(T \ll M_1) + N_{\Delta_{1\perp}}^{(N_2)}(T \ll M_1)$$

Component from heavier RH neutrinos **parallel** to l_1 and washed-out by N_1 inverse decays

Contribution from heavier RH neutrinos **orthogonal** to l_1 and escaping N_1 wash-out

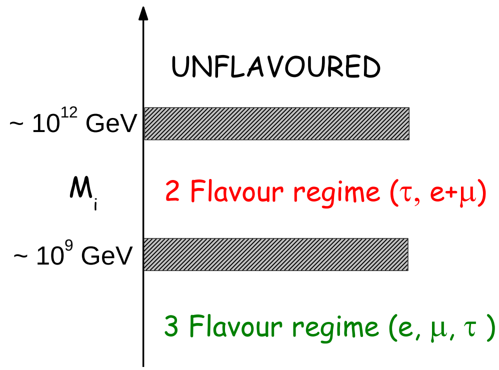
$$N_{\Delta_1}^{(N_2)}(T \ll M_1) = p_{12}\, e^{-\frac{3\pi}{8}K_1}\, N_{B-L}^{(N_2)}(T \sim M_2)$$

?

Limitations of Boltzmann equations

All results have been obtained within Boltzmann kinetic formalism assuming that leptons are either pure states or a full incoherent admixture of lepton flavour eigenstates (mixed states)

Limitations:



- Asymmetry cannot be calculated when masses fall in transition regions

- Even in the fully flavoured regimes, the simultaneous occurrence of many effects makes the calculation quite contrived and one should worry whether everything is consistently taken into account

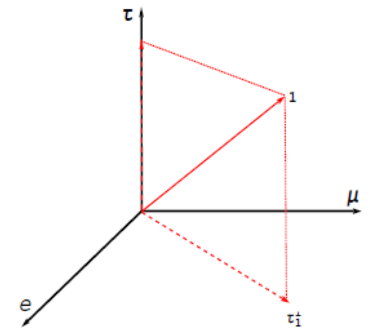
- More insight is certainly needed!

Density matrix formalism

Within a density matrix formalism it is possible to describe consistently a system that is a statistical ensemble of several elementary quantum states that are either pure states or mixed states.

Consider our leptons ℓ_1 produced by the decays of N_1

$$|1\rangle = \mathcal{C}_{1\tau}\,|\tau\rangle + \mathcal{C}_{1\tau_1^\perp}\,|\tau_1^\perp\rangle\,, \quad \mathcal{C}_{1\alpha} \equiv \langle\alpha|1\rangle$$
$$(\alpha = \tau, \tau_1^\perp)$$



Density operator

$$\hat{\rho}^{\ell_1} \equiv |1\rangle\langle 1| = \sum_{\alpha,\beta} \rho_{\alpha\beta}|\alpha\rangle\langle\beta|$$

For a pure state $\hat{\rho}^2 = \hat{\rho}$ Moreover since $\rho = \rho^\dagger$ there is always a basis where is diagonal, in this case the basis is simply $|1\rangle,\ |1^\perp\rangle$

$$\rho_{ij} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \qquad (i,j = 1, 1^\perp)$$

Density matrix formalism

When the ℓ_1 start to interact with the thermal bath, there will be

the early Universe starts to be populated both with pure states $|1\rangle$ and with mixed states $|\tau\rangle, |\tau_1^\perp\rangle$

I can still find a basis $|A\rangle, |B\rangle$ where the density matrix is diagonal:

$$\rho_{AB} = \mathrm{diag}(p_A, p_B), \quad \text{where } p_A + p_B = 1 \quad \text{but now } \rho \neq \rho^2$$

- When all states are pure simply $|A\rangle = |1\rangle, |B\rangle = |1^\perp\rangle$

- When all states are mixed $|A\rangle = |\tau\rangle, |B\rangle = |\tau_1^\perp\rangle$ but this time

$$\rho_{\tau\tau_1^\perp} = \mathrm{diag}(p_{1\tau}, 1 - p_{1\tau})$$

We can also introduce the lepton number density matrix simply as

$$N_{ij}^{\ell} = N_{\ell_1}\, \rho_{ij}^{\ell}$$

Density matrix formalism

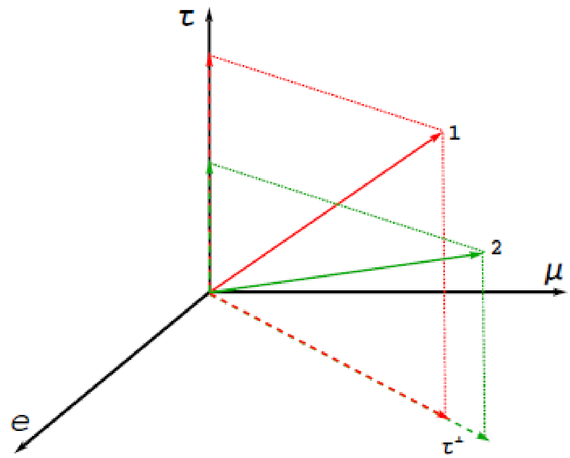
In the charged lepton flavour basis $|\tau\rangle, |\tau_1^\perp\rangle$ one has a transition from a matrix with off-diaagonal elements to a diagonal matrix. This evolution can be described with kinetic equations introducing decoherence due to the scatterings with the thermal bath

The result (subtracting density matrix for leptons and anti-leptons) for the B-L asymmetry matrix is

$$
\begin{aligned}
\frac{dN_{\alpha\beta}^{B-L}}{dz} &= \varepsilon_{\alpha\beta}^{(1)}\, D_1\,(N_{N_1} - N_{N_1}^{\rm eq}) - \frac{1}{2}\, W_1\, \left\{\mathcal{P}^{0(1)}, N^{B-L}\right\}_{\alpha\beta} \\
&+ \; {\rm i}\, \frac{{\rm Re}(\Lambda_\tau)}{H\, z} \left[\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, N^{\ell+\bar\ell}\right]_{\alpha\beta} - \frac{{\rm Im}(\Lambda_\tau)}{H\, z} \left[\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, N^{B-L}\right]\right]_{\alpha\beta},
\end{aligned}
\tag{45}
$$

Density matrix formalism

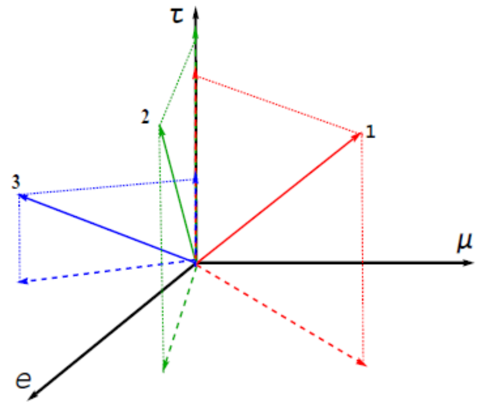
When more than 1 heavy neutrino flavour is included but still one has only 2 lepton flavours $|\tau\rangle, |\tau_1^{\perp}\rangle$
The equation includes 2 source terms for the asymmetry



$$
\begin{aligned}
\frac{dN^{B-L}_{\alpha\beta}}{dz} &= \varepsilon^{(1)}_{\alpha\beta}\, D_1\, (N_{N_1} - N^{\rm eq}_{N_1}) - \frac{1}{2} W_1 \left\{\mathcal{P}^{0(1)}, N^{B-L}\right\}_{\alpha\beta} \qquad (50) \\
&+ \varepsilon^{(2)}_{\alpha\beta}\, D_2\, (N_{N_2} - N^{\rm eq}_{N_2}) - \frac{1}{2} W_2 \left\{\mathcal{P}^{0(2)}, N^{B-L}\right\}_{\alpha\beta} \\
&+ i\,{\rm Re}(\Lambda_\tau) \left[\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, N^{\ell+\bar\ell}\right]_{\alpha\beta} - {\rm Im}(\Lambda_\tau) \left[\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, N^{B-L}\right]\right]_{\alpha\beta} .
\end{aligned}
$$

Density matrix formalism

When the whole 3 flavour structure is taken into account

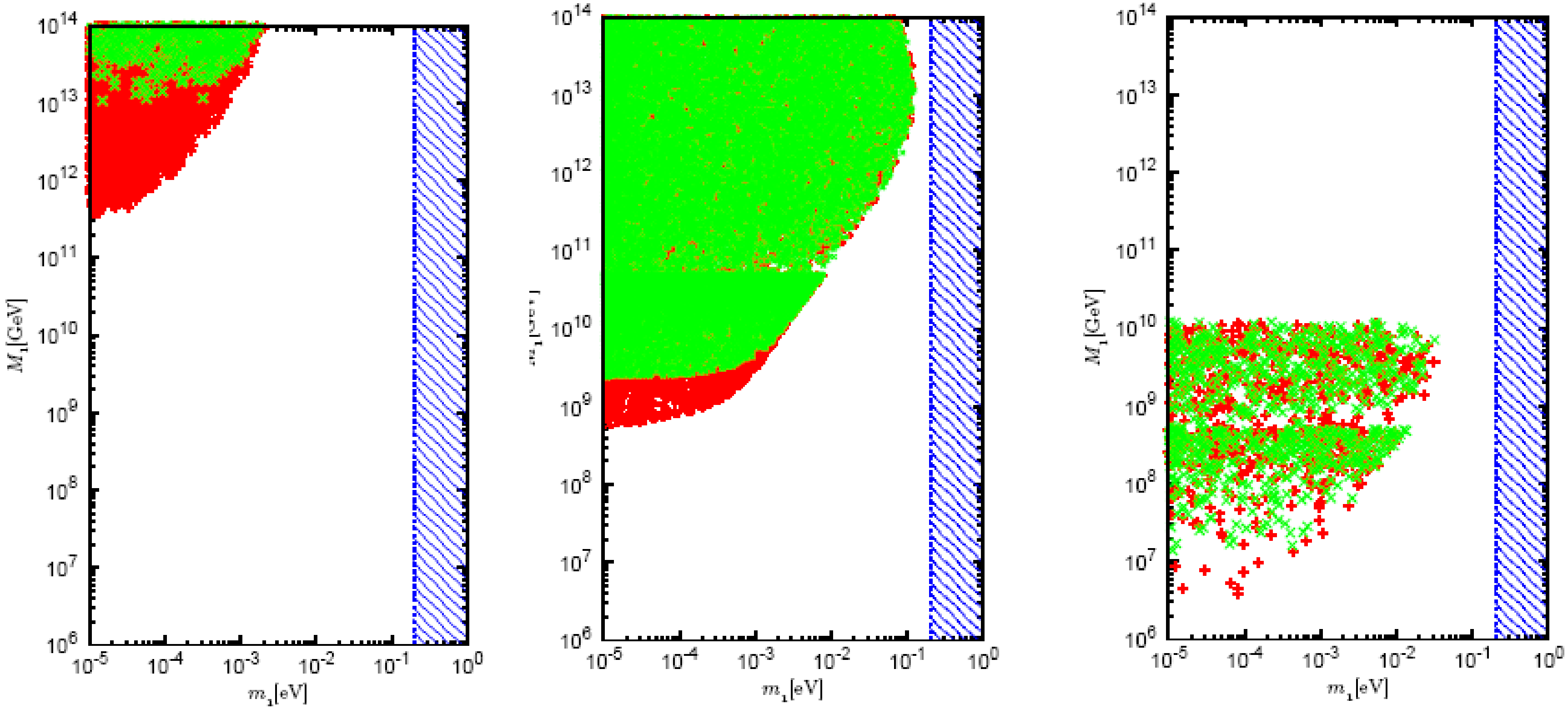


The result is a monster equation:

$$
\begin{aligned}
\frac{dN^{B-L}_{\alpha\beta}}{dz} &= \varepsilon^{(1)}_{\alpha\beta}\, D_1\, (N_{N_1} - N^{\rm eq}_{N_1}) - \frac{1}{2}\, W_1\, \left\{\mathcal{P}^{0(1)}, N^{B-L}\right\}_{\alpha\beta} \\
&+ \varepsilon^{(2)}_{\alpha\beta}\, D_2\, (N_{N_2} - N^{\rm eq}_{N_2}) - \frac{1}{2}\, W_2\, \left\{\mathcal{P}^{0(2)}, N^{B-L}\right\}_{\alpha\beta} \\
&+ \varepsilon^{(3)}_{\alpha\beta}\, D_3\, (N_{N_3} - N^{\rm eq}_{N_3}) - \frac{1}{2}\, W_3\, \left\{\mathcal{P}^{0(3)}, N^{B-L}\right\}_{\alpha\beta} \\
&+ {\rm i}\,{\rm Re}(\Lambda_\tau) \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, N^{\ell+\bar{\ell}}\right]_{\alpha\beta} - {\rm Im}(\Lambda_\tau) \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, N^{B-L}\right]\right]_{\alpha\beta} \\
&+ {\rm i}\,{\rm Re}(\Lambda_\mu) \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, N^{\ell+\bar{\ell}}\right]_{\alpha\beta} - {\rm Im}(\Lambda_\mu) \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, N^{B-L}\right]\right]_{\alpha\beta} .
\end{aligned}
\qquad (80)
$$

A first encouraging coincidence

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



Green points: Unflavored

Red points: Flavored

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):

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

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

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

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

one typically obtains (barring fine-tuned exceptions):

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

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

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

---

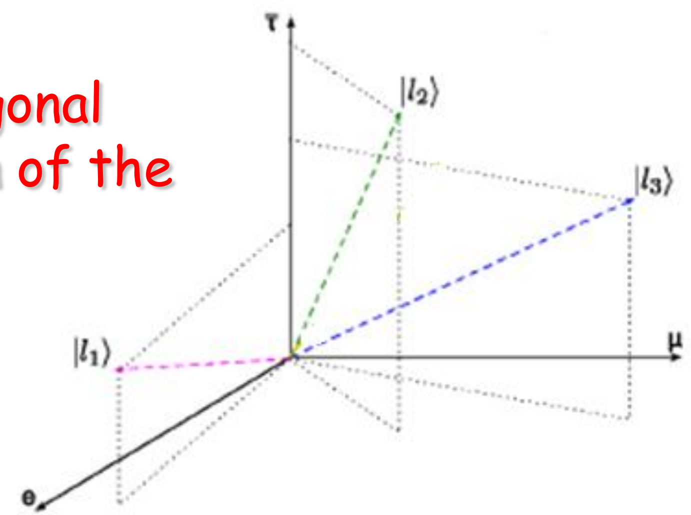
* Note that: $\Omega = D_m^{-\frac{1}{2}} \, U^\dagger \, V_L^\dagger \, D_{m_D} \, U_R \, D_M^{-\frac{1}{2}}$

Heavy neutrino flavored scenario

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

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

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



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

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

$$\begin{aligned} N_{\Delta_1}^{\rm lep}(T_{B1}) &= p_{21}\,p_{32}\,\varepsilon_3\,\kappa(K_3)\,e^{-\frac{3\pi}{8}\,(K_1+K_2)} \\ &+ p_{21}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_1} \\ &+ p_{\tilde 3_2 1}\,(1-p_{32})\,\varepsilon_3\,\kappa(K_3)\,e^{-\frac{3\pi}{8}\,K_1} \\ &+ \varepsilon_1\,\kappa(K_1) \end{aligned}$$

$$\boxed{\begin{aligned} N_{\Delta_{\tilde 1}}^{\rm lep}(T_{B1}) &= (1-p_{21})\,[p_{32}\,\varepsilon_3\,\kappa(K_3)\,e^{-\frac{3\pi}{8}\,K_2} + \varepsilon_2\,\kappa(K_2)] \\ &+ (1-p_{\tilde 3_2 1})\,(1-p_{32})\,\varepsilon_3\,\kappa(K_3)\,. \end{aligned}}$$

Contribution from heavier RH neutrinos orthogonal to l_1 and escaping N_1 wash-out

Notice that some deviation from orthogonality 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)

A recent global analysis

Global analysis of neutrino masses, mixings and phases: entering the era of leptonic CP violation searches

G.L. Fogli,[1,2] E. Lisi,[2] A. Marrone,[1,2] D. Montanino,[3,4] A. Palazzo,[5] and A.M. Rotunno[1]

arXiv:1205.5254v2 [hep-ph] 25 May 2012

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.34 – 2.50	2.26 – 2.58	2.15 – 2.66
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.32 – 2.49	2.25 – 2.56	2.14 – 2.65
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.45	2.14 – 2.79	1.81 – 3.11	1.49 – 3.44
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.46	2.15 – 2.80	1.83 – 3.13	1.50 – 3.47
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.98	3.72 – 4.28	3.50 – 4.75	3.30 – 6.38
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.08	3.78 – 4.43	3.55 – 6.27	3.35 – 6.58
δ/π (NH)	0.89	0.45 – 1.18	—	—
δ/π (IH)	0.90	0.47 – 1.22	—	—

2) The lower bounds on M_1 and on T_{reh} get relaxed:

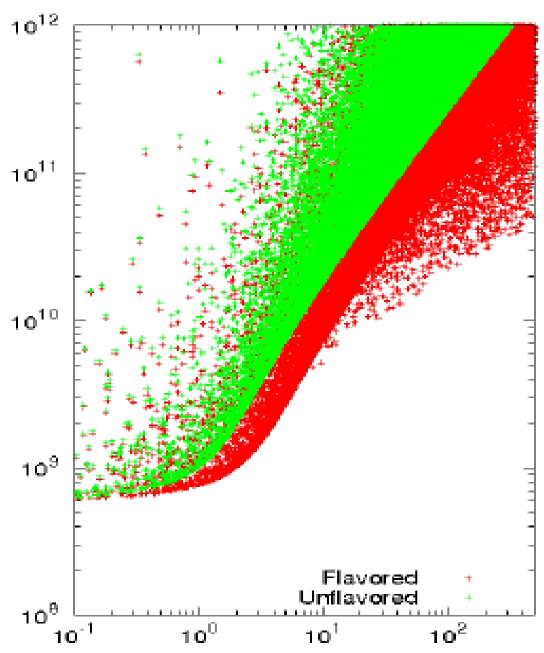
(Blanchet, PDB '08)

$$\frac{\Delta P_{i\alpha}}{2} \simeq \frac{1}{8\,\pi\,(h^\dagger\,h)_{ii}} \sum_{j\neq i} \left\{ \mathrm{Im}\left[h^\star_{\alpha i}\, h_{\alpha j} \left(\frac{3}{2\,\sqrt{x_j}} (h^\dagger h)_{ij} + \left(\qquad \right) \right] \right\} \qquad \boxed{x_j = \frac{M_j^2}{M_1^2}}$$

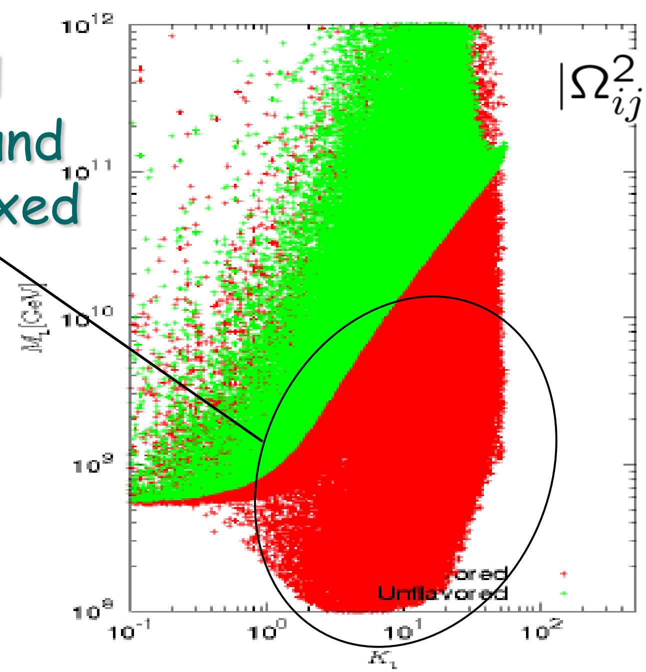
It dominates for $|\Omega_{ij}| \lesssim 1$ but is upper bounded because of Ω orthogonality:

$$\left| \frac{\Delta P_{1\alpha}}{2} \right| < \bar{\varepsilon}(M_1)\,\sqrt{P^0_{1\alpha}}$$

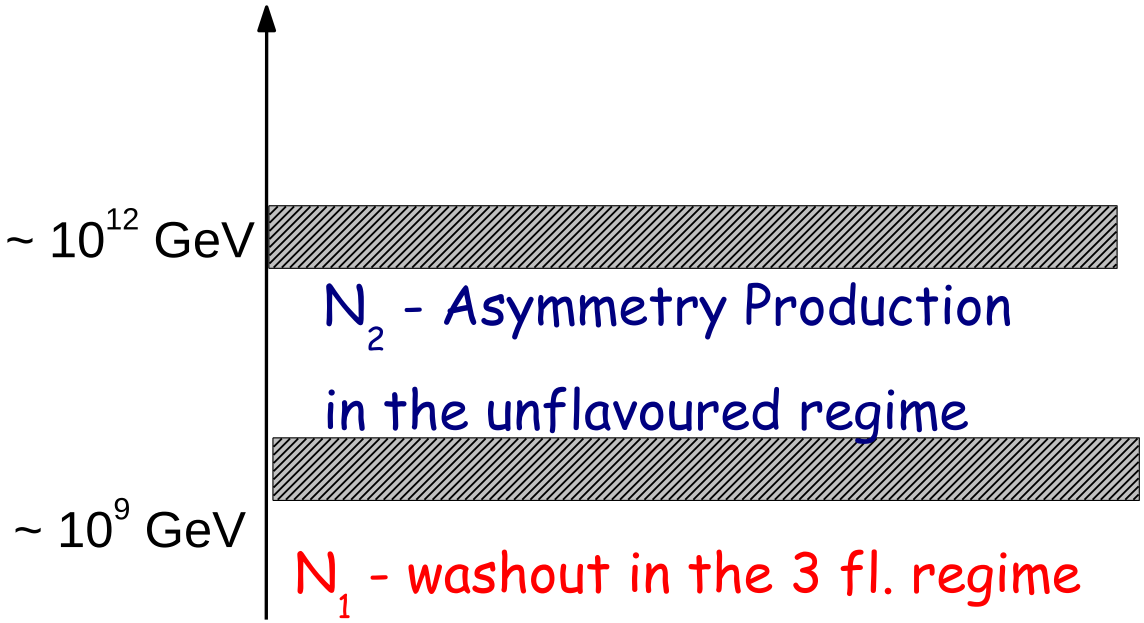
It is usually neglected but since it is not upper bounded by orthogonality, for $|\Omega_{ij}| \gtrsim 1$ it can be important



The usual lower bound gets relaxed



Analogous results hold in the case when the production occurs in the 2 flavour regime for 10^{12} GeV $\gtrsim M_2 \gtrsim 10^{9}$ GeV:

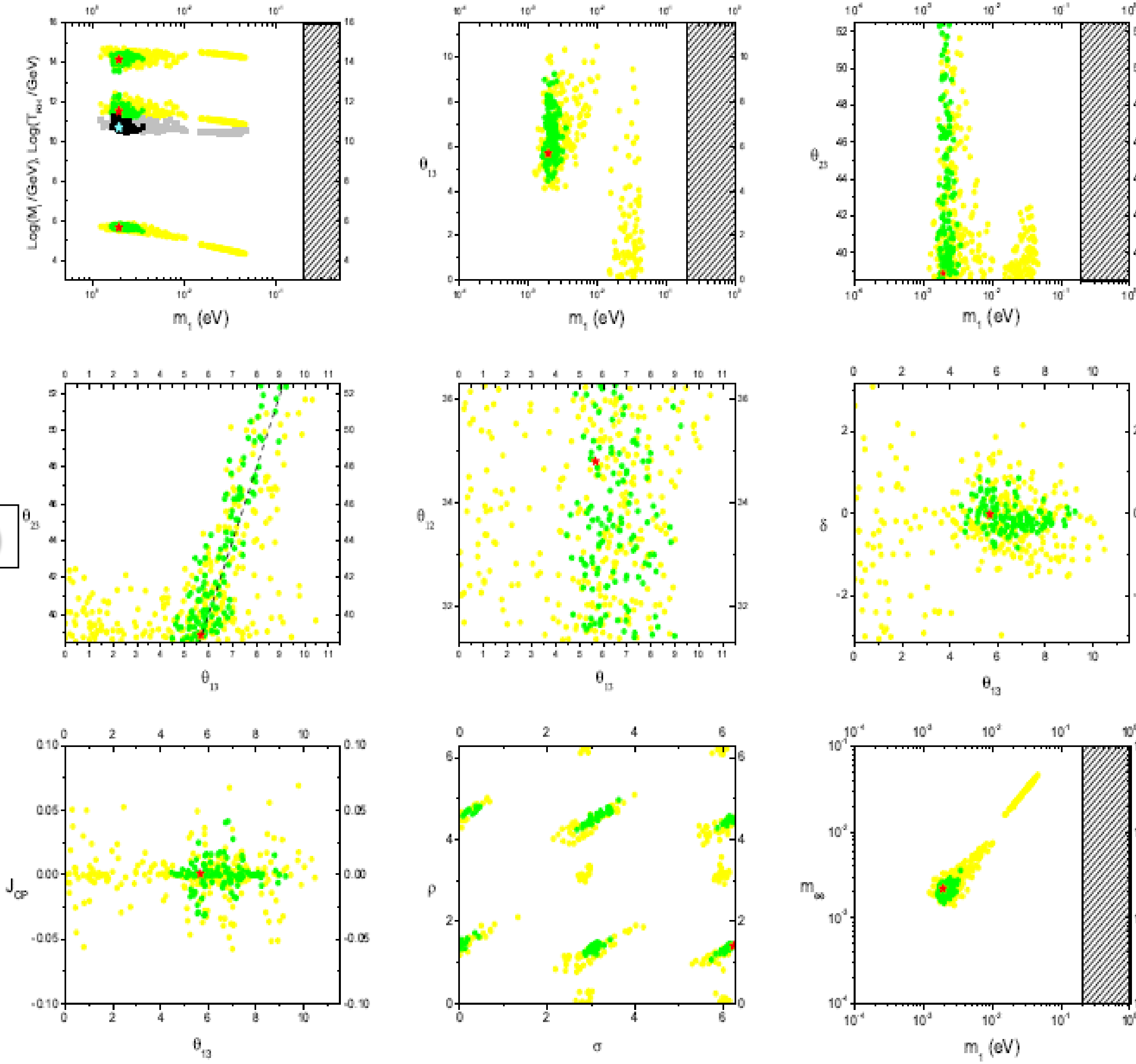


$$N^{\rm f}_{B-L} \simeq \varepsilon_{2e}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1e}} + \varepsilon_{2\mu}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + \varepsilon_{2\tau}\,\kappa(K_{2\tau})\,e^{-\frac{3\pi}{8}\,K_{1\tau}} \,.$$

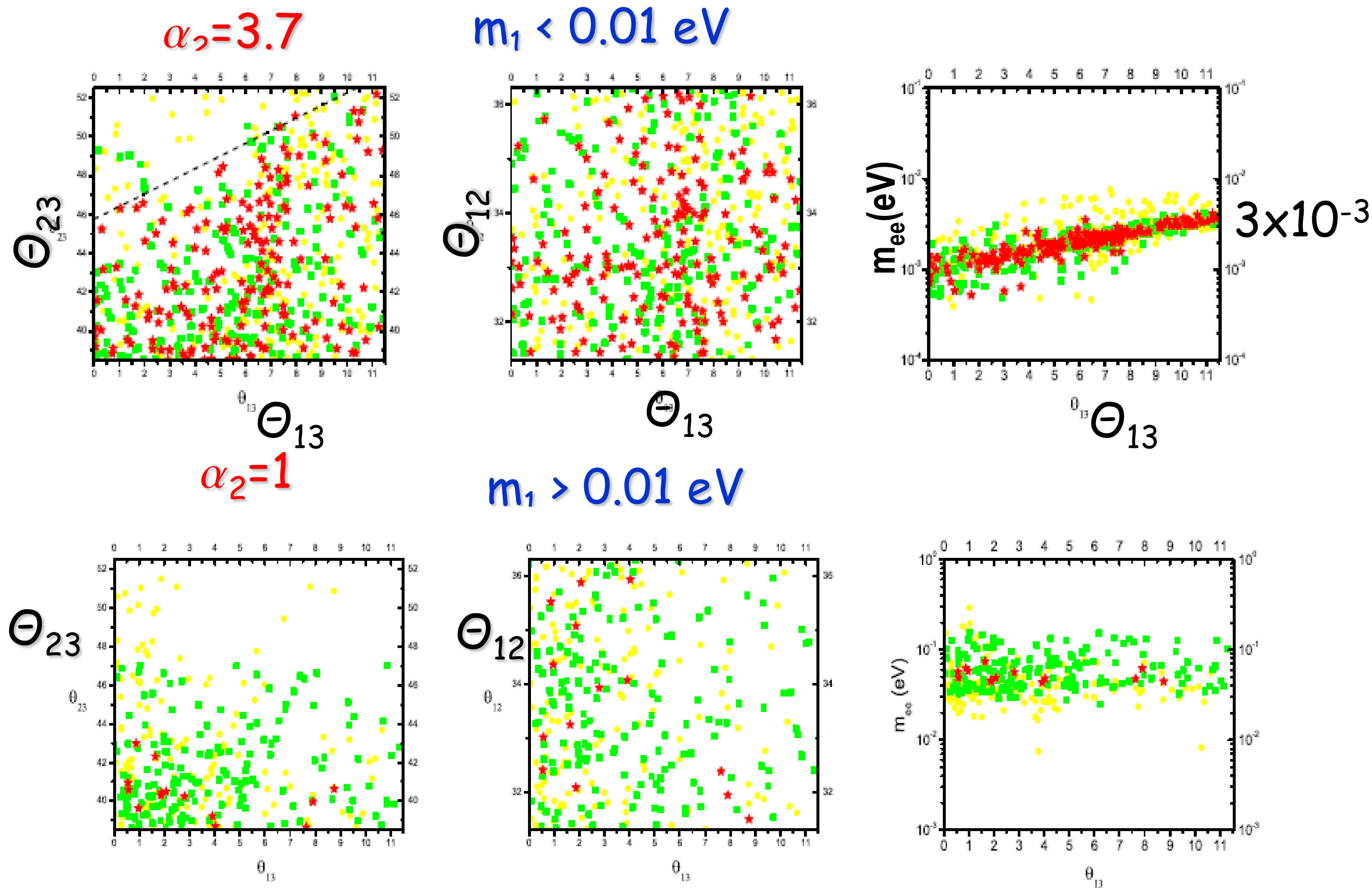
$V_L = I$

NORMAL ORDERING

(PDB, Riotto '10)



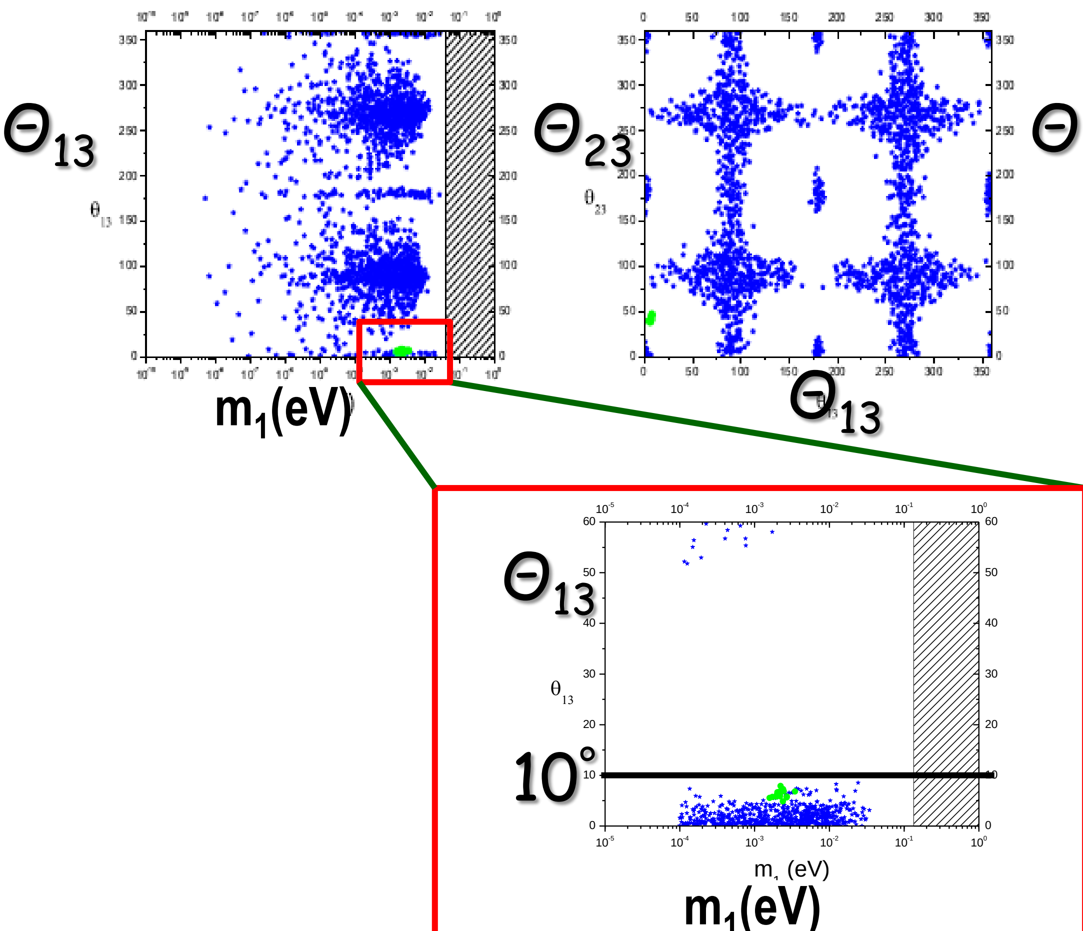
$I < V_L < V_{CKM}$ NORMAL ORDERING $\alpha_2=5$ $\alpha_2=4$



Are the data pointing in the right direction?

(PDB, Riotto '10)

Blue points: α_2=4 and mixing angles let free in (0,180°)
Green points: α_2=4 and current experimental constraints imposed on mixing angles



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