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Leptogenesis and low energy neutrino data

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S. Blanchet, PDB, “The minimal model of leptogenesis”, NJP Focus issue on Baryogenesis arXiv 1211.0512 [hep-ph]

PDB and Luca Marzola arXiv 1308.1107

PDB, M.Re Fiorentin, S.King, in preparation (see poster by Michele Re Fiorentin)

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 ↑

T	Event
$< 10^{14}$ 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

In this case one would like to answer.....

...two important questions:

1. Can we get an insight on neutrino parameters from leptogenesis?

In other words: can leptogenesis provide a way to understand current neutrino parameters measurements and even predict future ones?

2. Vice-versa: can we probe leptogenesis with low energy neutrino data?

A common approach in the LHC era: some hopes only by lowering the typical expected scale of leptogenesis ($\sim 10^{10}$ GeV) in order to have additional testable effects (LHC signals, LFV, electric dipole moments, non-unitary leptonic mixing matrix…)

⇒ "TeV Leptogenesis"

Is there an alternative approach based on usual high energy scale leptogenesis and relying just on low energy neutrino data?
After all LHC has not found signals of new physics at the TeV scale (not so far) but our knowledge of the low energy neutrino parameters is experiencing a strong renewed fast progress

Neutrino mixing parameters („pre-T2K")

$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle$$

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

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

Atmospheric | Reactor, Accel., LBL CP violating phase | Solar, Reactor | $\beta\beta 0\nu$ decay

$c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

- best-fit point and 1σ (3σ) ranges:

$\theta_{12} = 34.5 \pm 1.4 \left({}^{+4.8}_{-4.0}\right)$, $\Delta m^2_{21} = 7.67^{+0.22}_{-0.21} \left({}^{+0.67}_{-0.60}\right) \times 10^{-5}\ \text{eV}^2$,

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

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

(Gonzalez-Garcia, Maltoni 08)

Neutrino mixing parameters

Non-vanishing θ_{13}

- T2K : $\sin^2 2\theta_{13} = 0.03 - 0.28$ (90% CL NO)
- DAYA BAY: $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$
- RENO, MINOS, DOUBLE CHOOZ, new T2K data,

Recent global analyses

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

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

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

(Normal Ordering)

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

Analogous results by Gonzalez-Garcia, Maltoni and Schwetz but $\delta_{best\ fit} \sim -\pi/3$ and θ_{23} in first octant favoured only at 1.5 σ for normal order and at 0.9 σ for inverted ordering

Results by Forero, Tortola, Valle neither favour a specific value of δ nor θ_{23} in the first octant

New results presented at this meeting: talks by Suzuki (SK), Malek (T2K),...

Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: normal or inverted

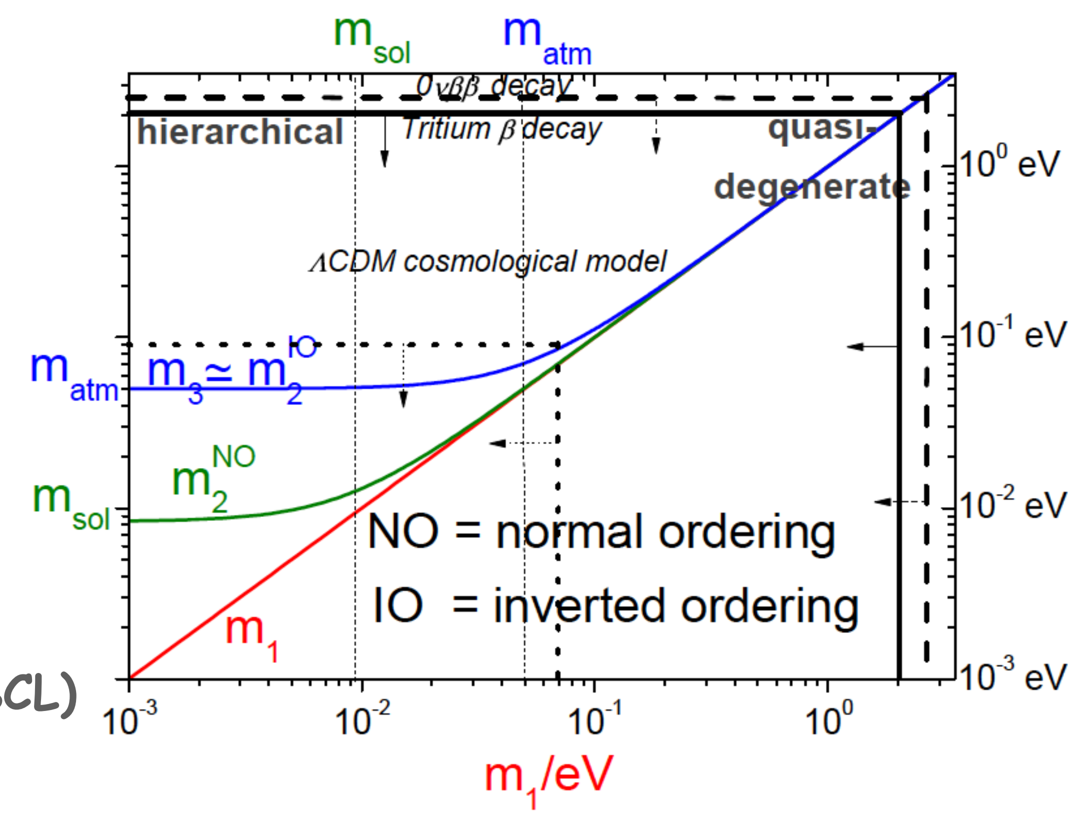
$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

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

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

ββ0ν: $m_{\beta\beta}$< 0.34 – 0.78 eV
(CUORICINO 95% CL, similar bound from Heidelberg-Moscow)
$m_{\beta\beta}$< 0.14 – 0.38 eV
(EXO-200 90% CL)
$m_{\beta\beta}$< 0.2 – 0.4 eV
(GERDA 90% CL)

CMB+BAO+H0 : Σ m_i < 0.23 eV
(Planck+high l+WMAPpol+BAO 95%CL)
⇒ m_1 < 0.07 eV



Minimal scenario of Leptogenesis

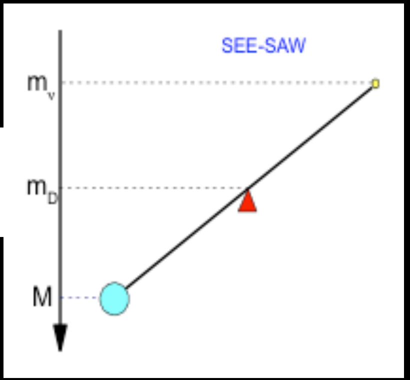
(Fukugita, Yanagida '86)

1. Type I seesaw Lagrangian

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

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

- 3 light neutrinos ν_1, ν_2, ν_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 $M_3 > M_2 > M_1 \gg m_D$



Both light and heavy neutrinos are predicted to be Majorana neutrinos

2. Thermal production of the RH neutrinos $\Rightarrow T_{RH} \gtrsim M_i / (2\div10)$

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

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

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

Predicted baryon-to -photon number ratio

Successful leptogenesis bound : $\eta_B = \eta_B^{CMB} = (6.1 \pm 0.1) \times 10^{-10}$

Seesaw parameter space

Imposing $\eta_B = \eta_B^{CMB}$ one would like to establish links with U and m_i

Problem: too many parameters

Orthogonal parameterisation

(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 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

A parameter reduction would help and can occur if:

- if $\eta_B(U, m_i; \lambda_1, \ldots, \lambda_9) = \eta_B^{CMB}$ is a maximum condition (or close to)
- cancellation in the asymmetry calculation: $\eta_B = \eta_B(U, m_i; \lambda_1, \ldots, \lambda_{M\leq 9})$
- By imposing some (model dependent) conditions on m_D, one can reduce the number of parameters and arrive to a new parameterisation where

$$\Omega = \Omega(U, m_i; \lambda'_1, \ldots, \lambda'_{N\leq M}) \quad \text{and} \quad M_i = M_i(U, m_i; \lambda'_1, \ldots, \lambda'_{N\leq M})$$

Vanilla leptogenesis

1) Flavor composition of final leptons is neglected

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

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

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

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

(Davidson, Ibarra '02)

5) Efficiency factor from simple Boltzmann equations

$$\frac{dN_{N_1}}{dz} = -D_1 \, (N_{N_1} - N_{N_1}^{\rm eq})$$
$$\frac{dN_{B-L}}{dz} = -\varepsilon_1 \, \frac{dN_{N_1}}{dz} - W_1 \, N_{B-L}$$

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

decays

inverse decays

wash-out

decay parameter

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

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

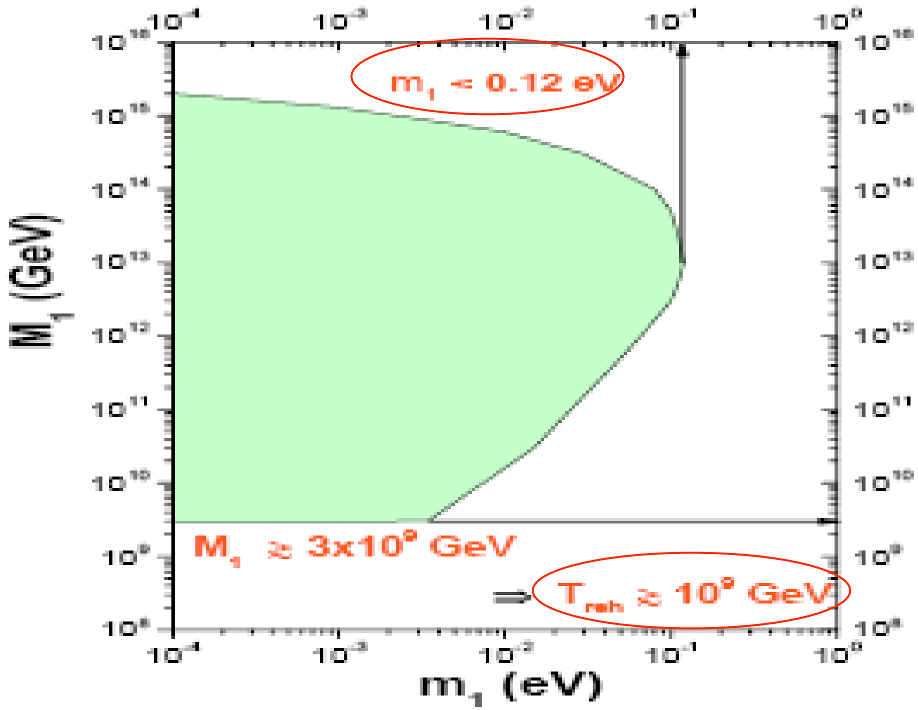
(Buchmuller, PDB, Plumacher '04)

Neutrino mass bounds in vanilla leptogenesis

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

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

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



No dependence on the leptonic mixing matrix U

Independence of the initial conditions

The early Universe „knows" the neutrino masses ...

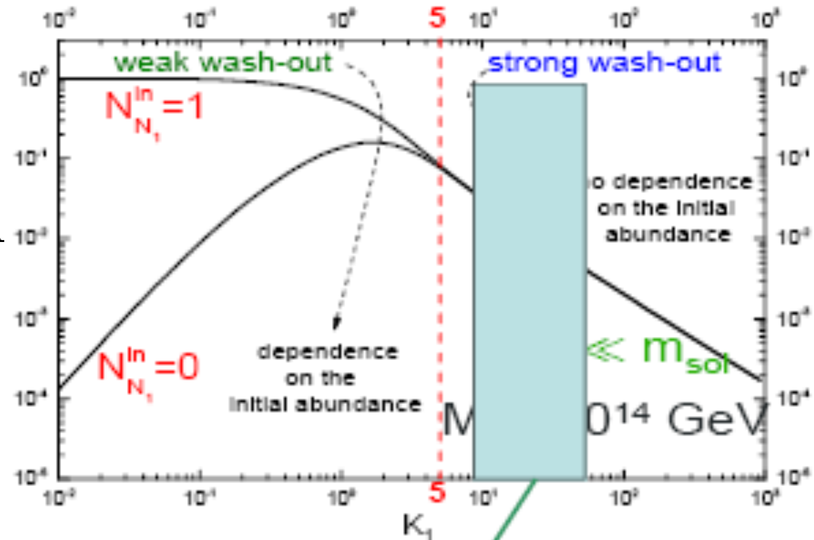
(Fukugita, Yanagida '86
Buchmüller, PDB, Plümacher '04)

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

decay parameter

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

$\kappa_1^{\rm fin}$

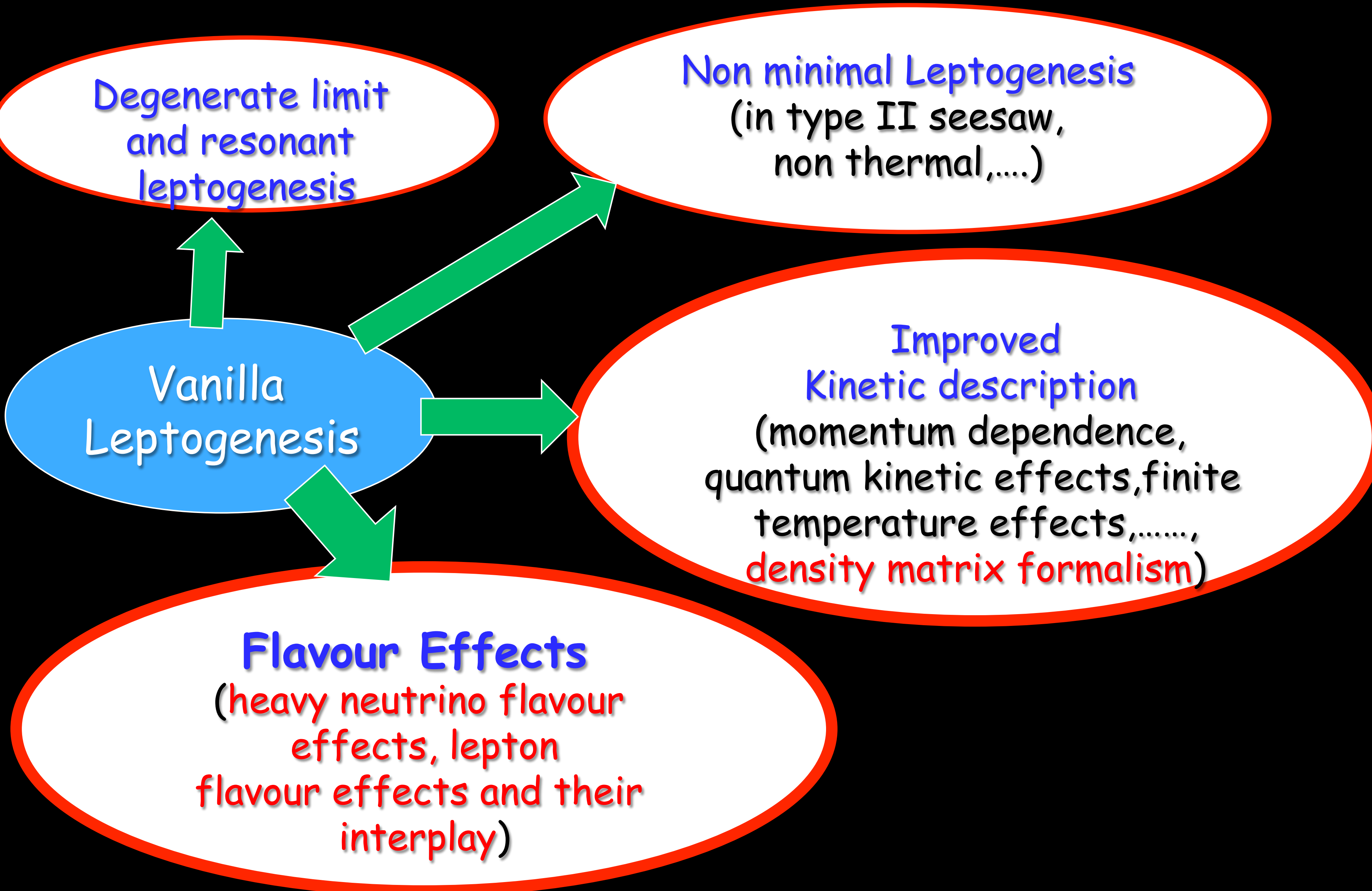


$$K_{\rm sol} \simeq 9 \lesssim K_1 \lesssim 50 \simeq K_{\rm atm}$$

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



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:

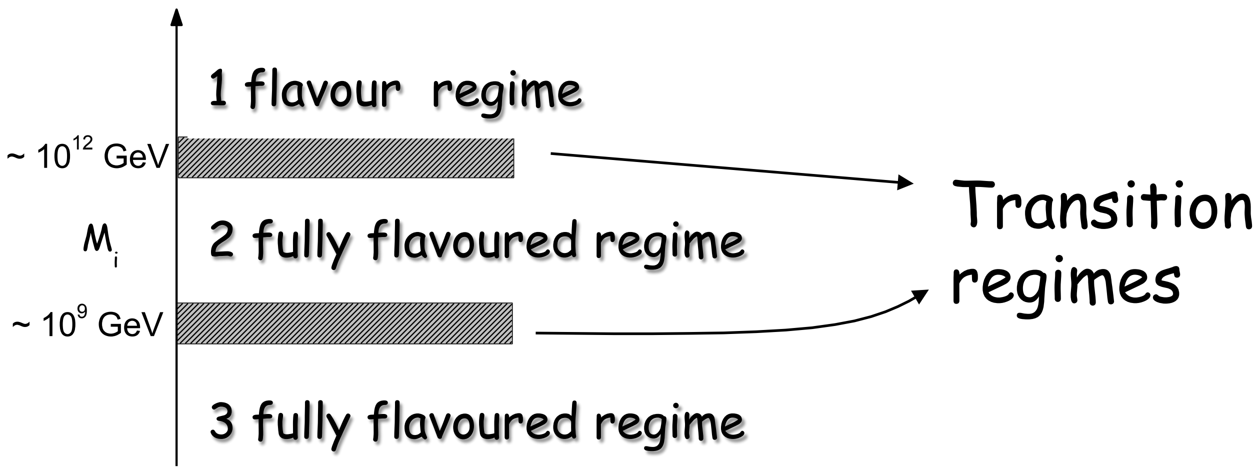
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1 \rangle \, |l_\alpha\rangle \quad (\alpha = e, \mu, \tau) \qquad P_{1\alpha} \equiv |\langle \ell_1 | \alpha \rangle|^2$$

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

For $T \lesssim 10^{12}$ GeV ⇒ 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 $|\bar{l}'_1\rangle$

⇒ they become an incoherent mixture of a τ and of a μ+e component

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



Two fully flavoured regime

- Classic Kinetic Equations (in their simplest form)

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

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

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

(α = τ, e+μ)

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

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

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

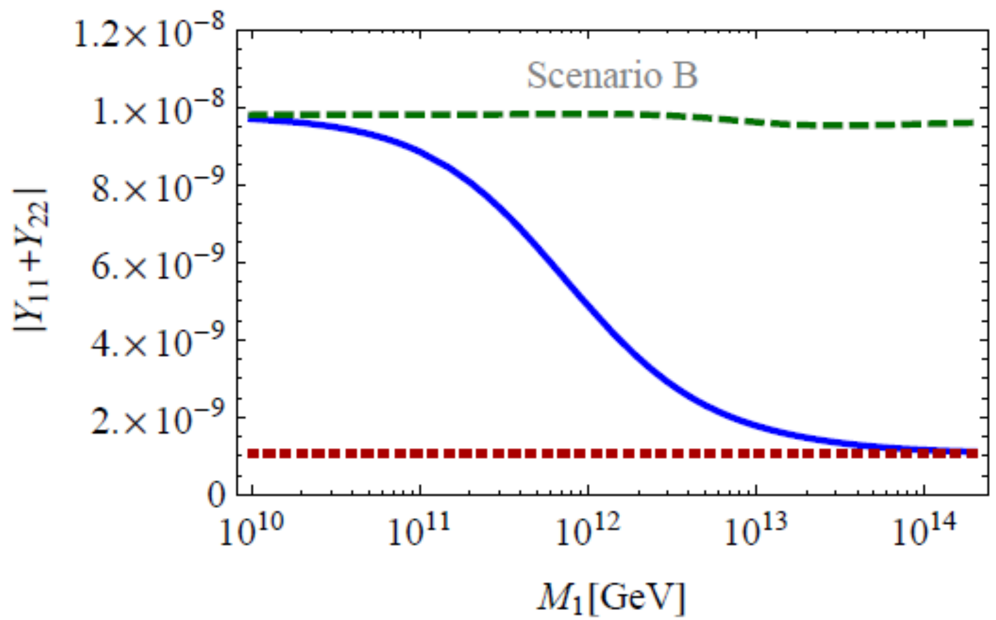
$$\Rightarrow\quad N_{B-L}^{\rm fin} = \sum_\alpha \varepsilon_{1\alpha}\,\kappa_{1\alpha}^{\rm fin} \simeq 2\,\varepsilon_1\,\kappa_1^{\rm fin} + \frac{\Delta P_{1\alpha}}{2}\left[\kappa_{1\alpha}^{\rm fin} - \kappa_{1\beta}^{\rm fin}\right]$$

Vanilla leptogenesis result

Density matrix and CTP formalism to describe the transition regimes

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

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



Fully two-flavoured regime limit

Unflavoured regime limit

Additional contribution to CP violation:

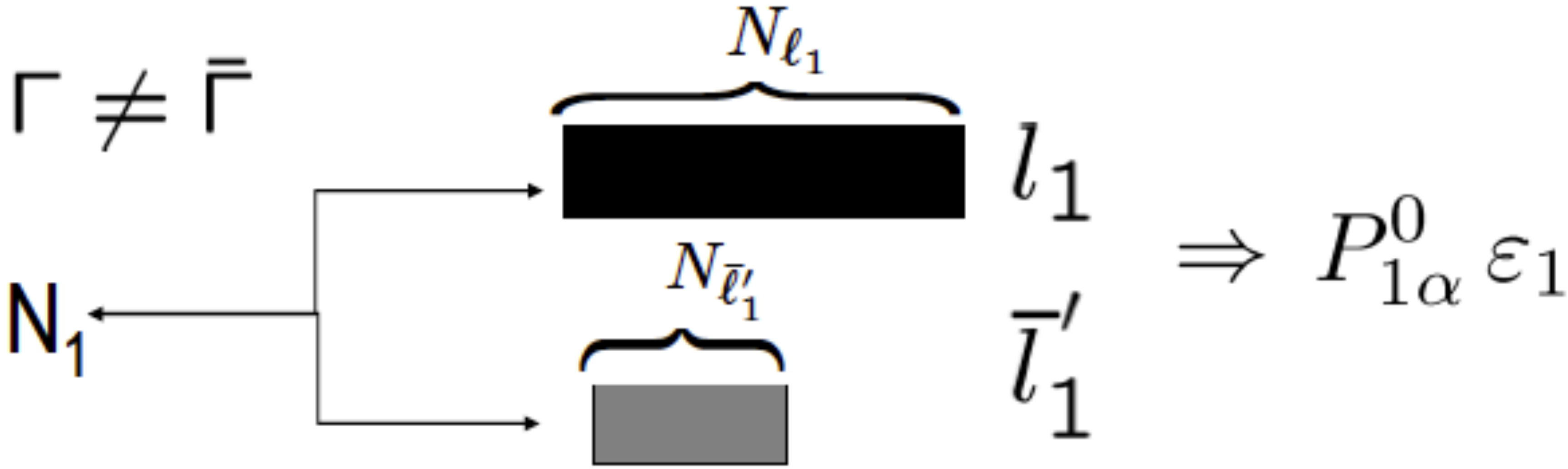
(Nardi, Racker, Roulet '06)

($\alpha = \tau$, e+μ)

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

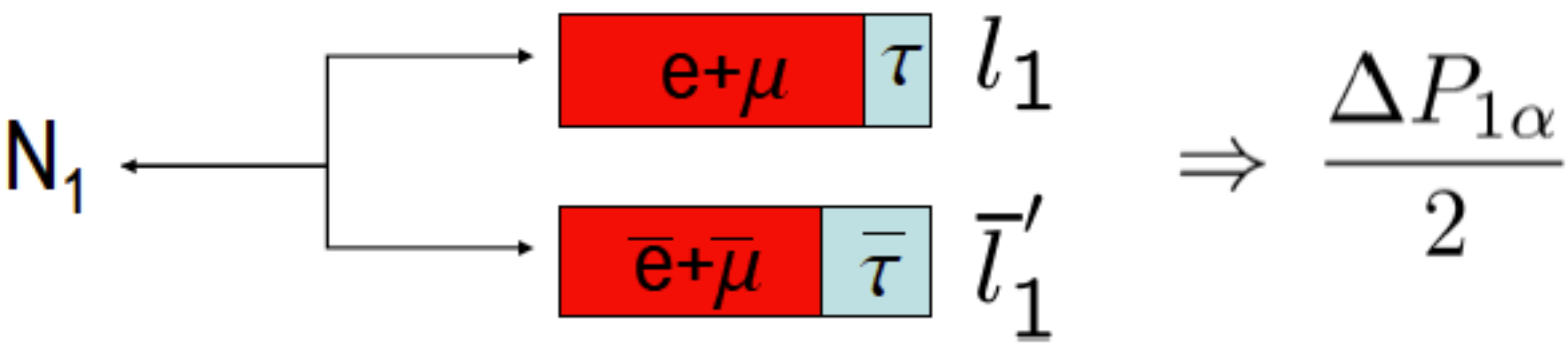
depends on U !

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



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

+



Low energy phases can be the only source of CP violation

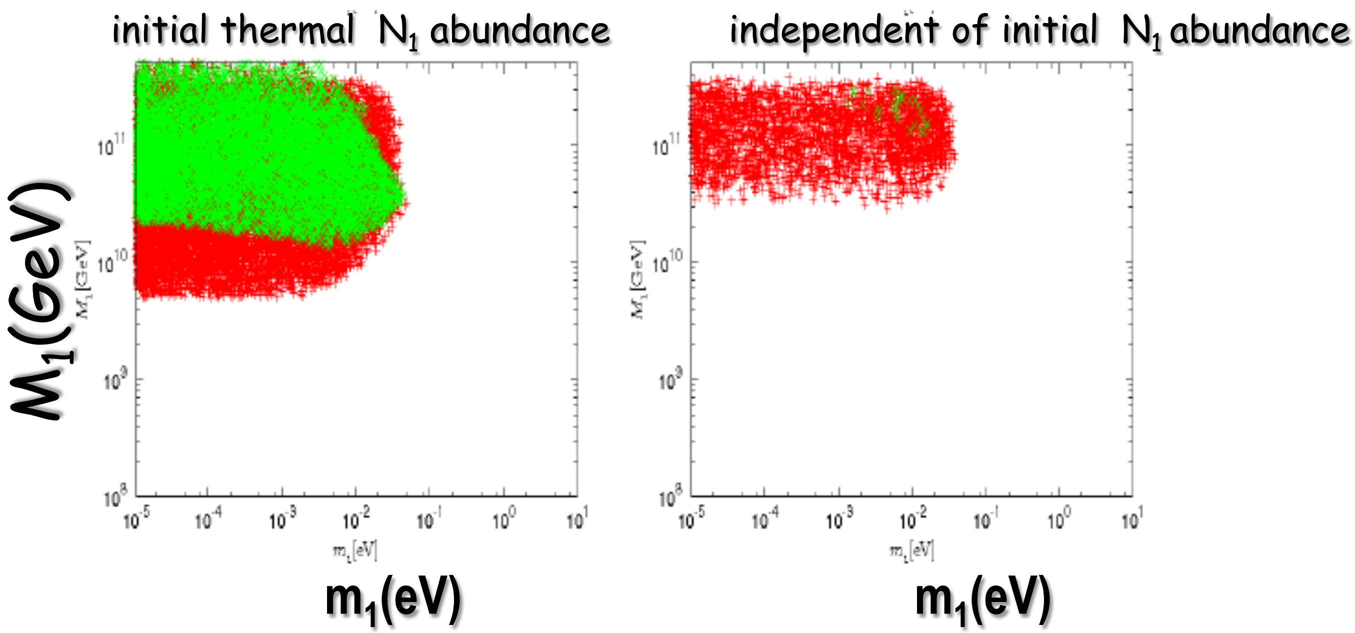
(Nardi et al.'06;Blanchet,PDB'06;Pascoli,Petcov,Riotto '06;Anisimov,Blanchet,PDB '08)

- Assume real $\Omega \Rightarrow \varepsilon_1 = 0 \Rightarrow$ $$\varepsilon_{1\alpha} = P^0_{1\alpha}\,\varepsilon_1 + \frac{\Delta P_{1\alpha}}{2}$$ (with the $P^0_{1\alpha}\,\varepsilon_1$ term crossed out)

$$\Rightarrow N_{B-L} \Rightarrow 2\varepsilon_1\kappa_1^{fin} + \Delta P_{1\alpha}(\kappa_{1\alpha}^{fin} - \kappa_{1\beta}^{fin}) \qquad (\alpha = \tau,\ e+\mu)$$ (with the $2\varepsilon_1\kappa_1^{fin}$ term crossed out)

- Assume even vanishing Majorana phases

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



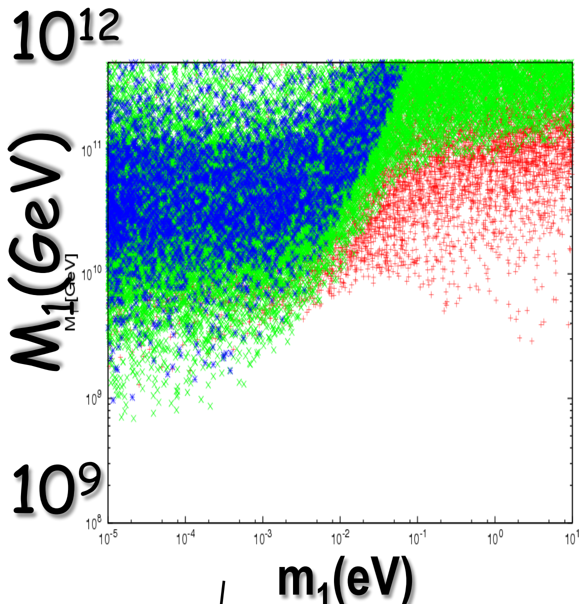
Green points: only Dirac phase with $\sin\theta_{13} = 0.2$, $|\sin\delta| = 1$

Red points: only Majorana phases

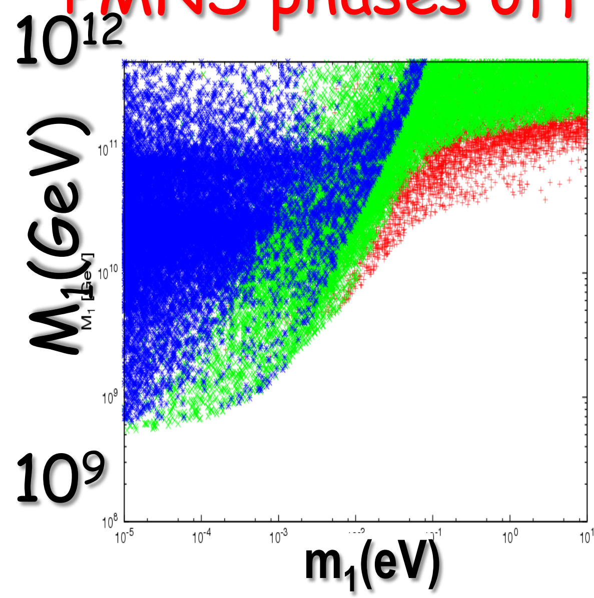
- It is interesting that the same source of CP violation in neutrino oscillations could be the only source successful leptogenesis

Upper bound on m_1 in N_1-dominated leptogenesis

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

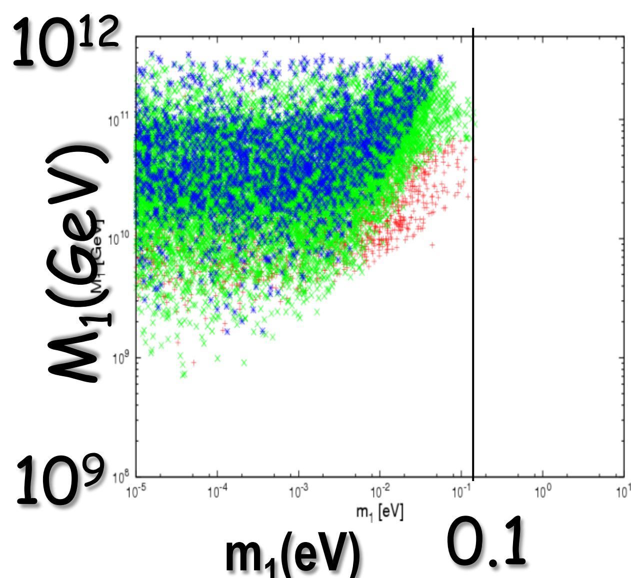


PMNS phases off



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

imposing a condition of validity of Boltzmann equations



Heavy neutrino flavours: the 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:

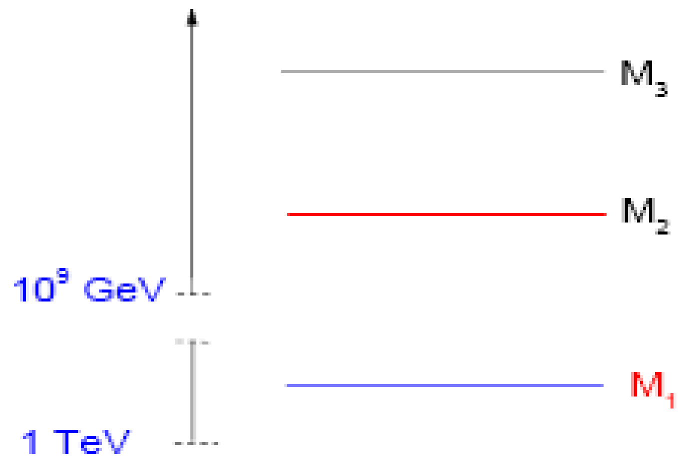
$$N_{B-L}^{\rm f,N_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1} = \varepsilon_1\, \kappa(K_1)$$

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

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

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} !

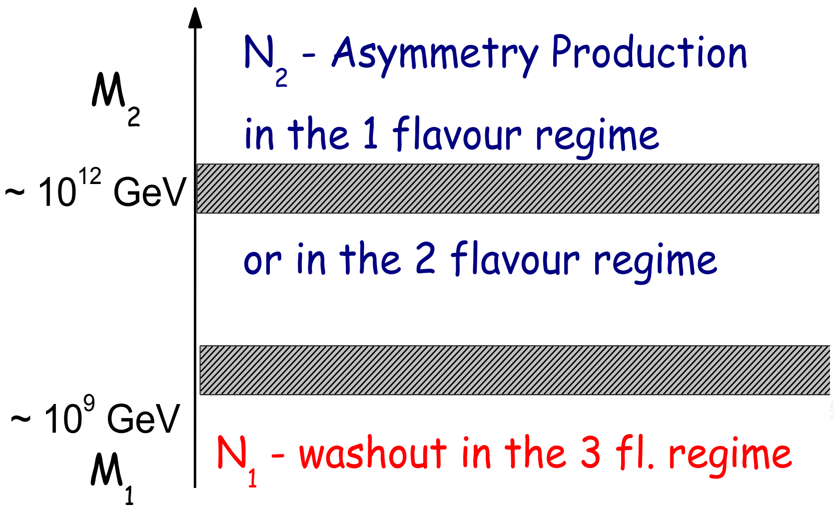


N_2-flavoured leptogenesis

(Vives '05; Blanchet, PDB '06; Blanchet, PDB '08;PDB,M. Re Fiorentin,S. King'13)

Combining together lepton and heavy neutrino flavour effects one has

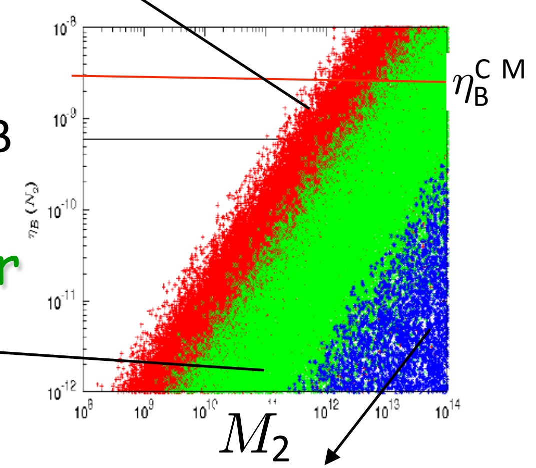
A two stage process:



Wash-out is neglected

$\Omega = R_{12}(\omega_{12})\, R_{13}(\omega_{13})$

Both wash-out and flavor effects



Unflavored case

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

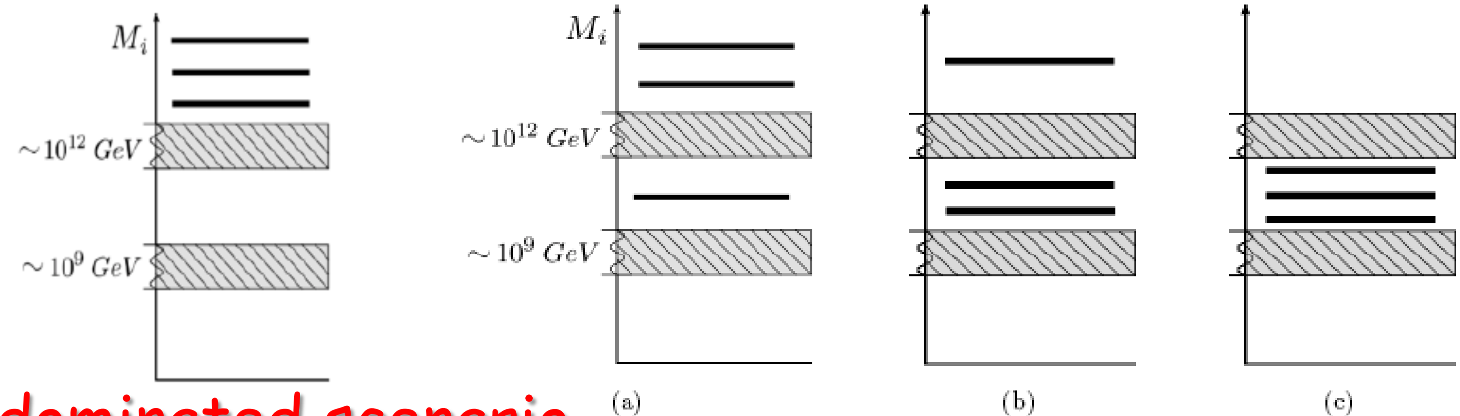
Notice that $K_1 = K_{1e} + K_{1\mu} + K_{1\tau}$

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

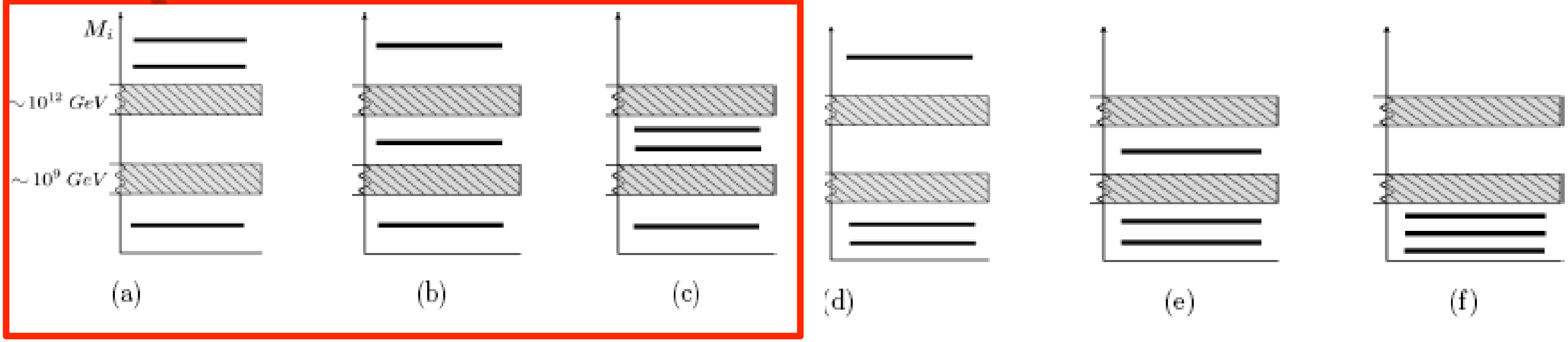
For a preliminary new general analyses see poster by M. Re Fiorentin

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



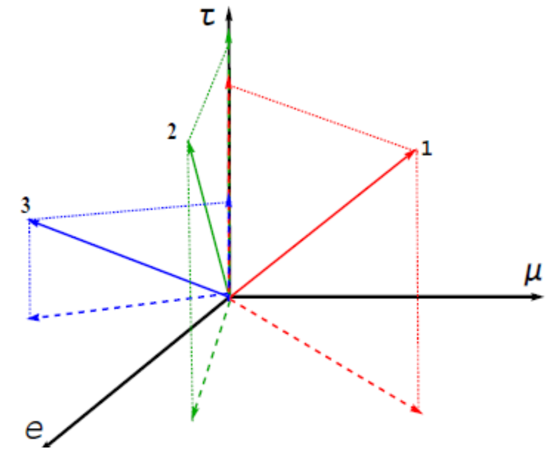
For each pattern a specific set of Boltzmann equations has to be considered but

Density matrix formalism with heavy neutrino flavours

(Blanchet,PDB, Jones, Marzola '11)

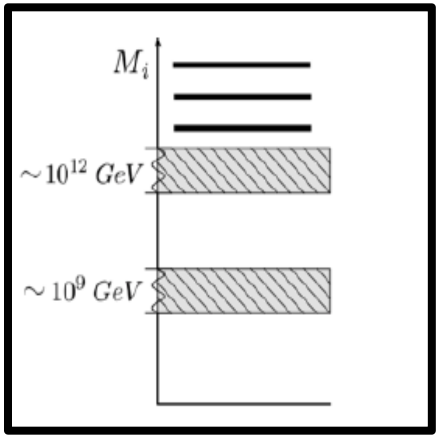
For a thorough description of all neutrino mass patterns including transition regions and all effects (flavour projection, phantom leptogenesis,...) one needs a description in Terms of a density matrix formalism

The result is a "monster" equation:

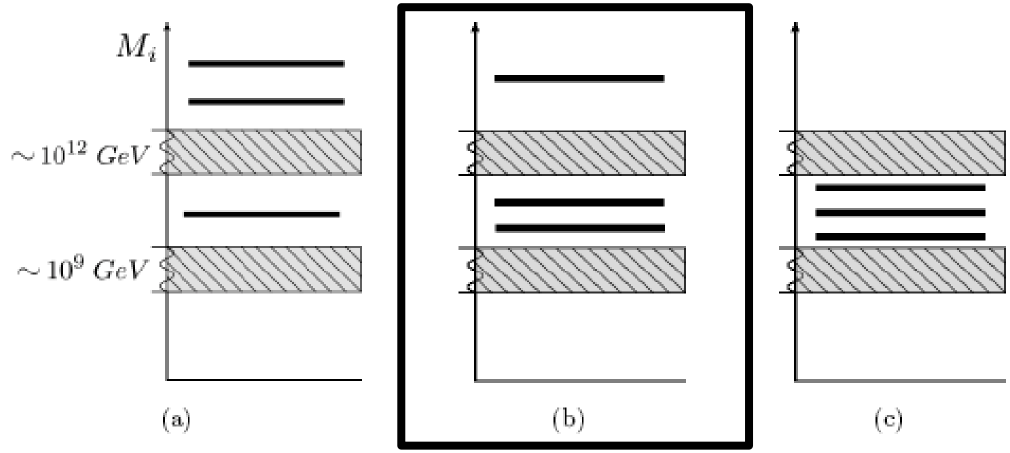


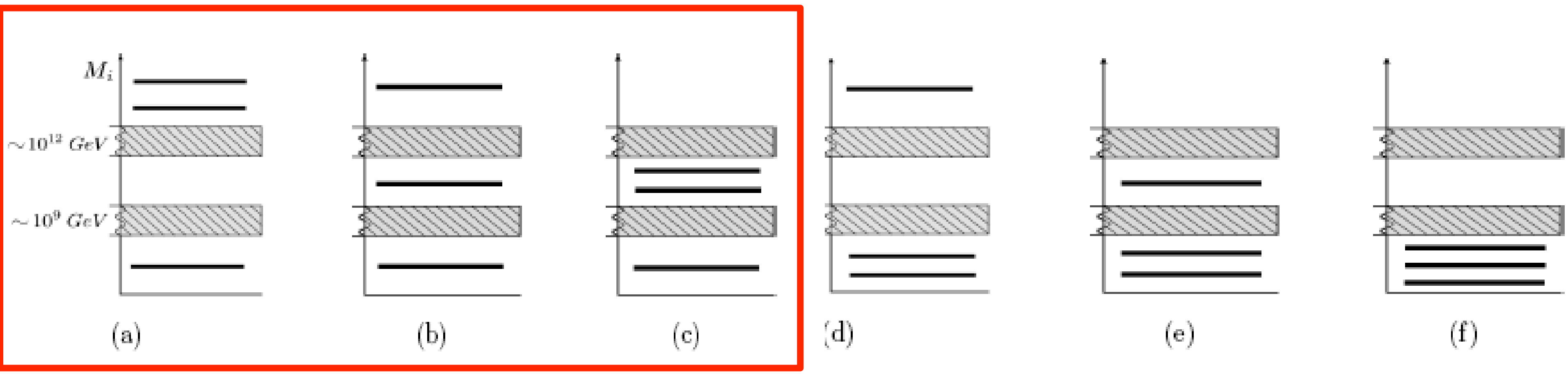
$$\begin{aligned}
\frac{dN^{B-L}_{\alpha\beta}}{dz} &= \varepsilon^{(1)}_{\alpha\beta}\, D_1\,(N_{N_1} - N^{\rm eq}_{N_1}) - \frac{1}{2}\, W_1\, \{\mathcal{P}^{0(1)}, N^{B-L}\}_{\alpha\beta} \qquad (80)\\
&+ \varepsilon^{(2)}_{\alpha\beta}\, D_2\,(N_{N_2} - N^{\rm eq}_{N_2}) - \frac{1}{2}\, W_2\, \{\mathcal{P}^{0(2)},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

Heavy neutrino flavored scenario



2 RH neutrino scenario





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

It is just that one realised in so called SO(10)-inspired models

SO(10)-inspired leptogenesis

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

In general the neutrino Dirac mass matrix m_D can be written (in the basis where the Majorana mass and charged lepton mass matrices are diagonal) as

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

SO(10)-inspired conditions:

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

From the seesaw formula one can express:

$U_R = U_R\,(U, m_i ; \alpha_i, V_L)$, $M_i = M_i\,(U, m_i ; \alpha_i, V_L)$ $\Rightarrow$ $\eta_B = \eta_B\,(U, m_i ; \alpha_i, V_L)$

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

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

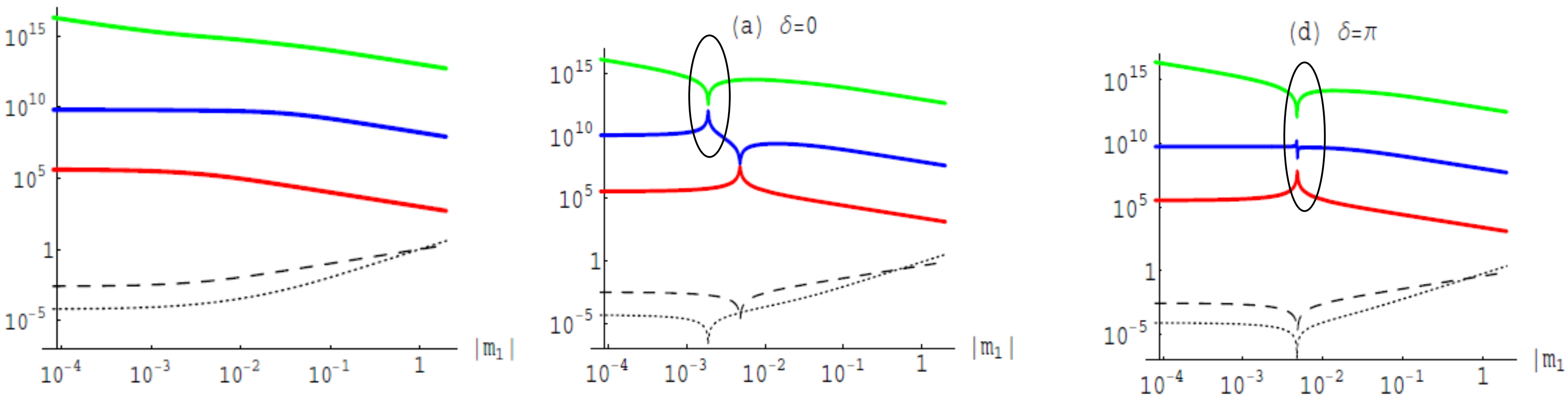
since $M_1 \ll 10^9$ GeV $\Rightarrow \eta_B(N_1) \ll \eta_B^{CMB}$!

$\Rightarrow$ 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 measured η_B 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

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 !

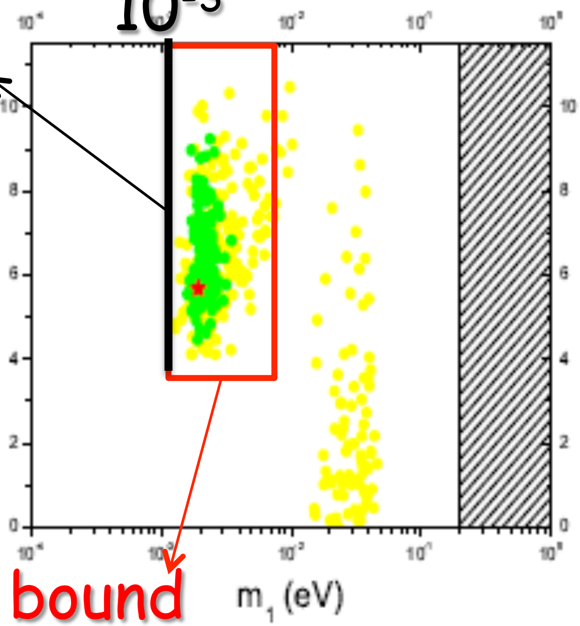
$\alpha_2=5$ $\alpha_2=4$ $\alpha_2=3$ $V_L = I$ Normal ordering

(vanishing initial N_2-abundance)

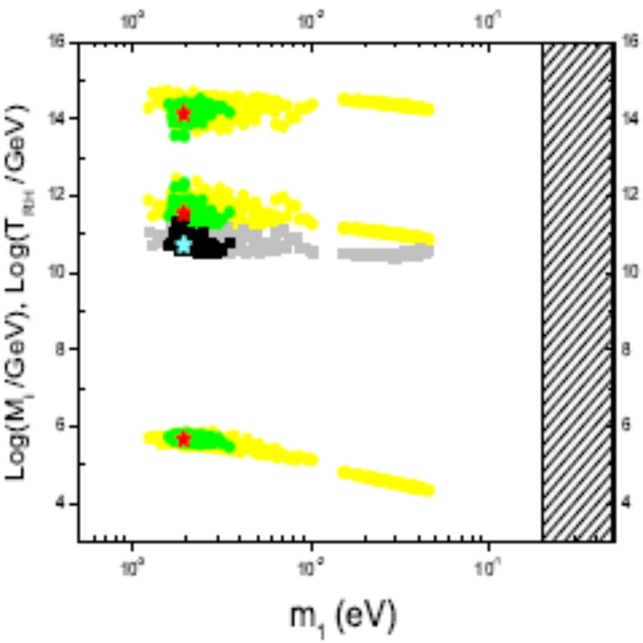
lower bound on m_1

10^{-3}

Θ_{13}



lower bound on Θ_{13} ?

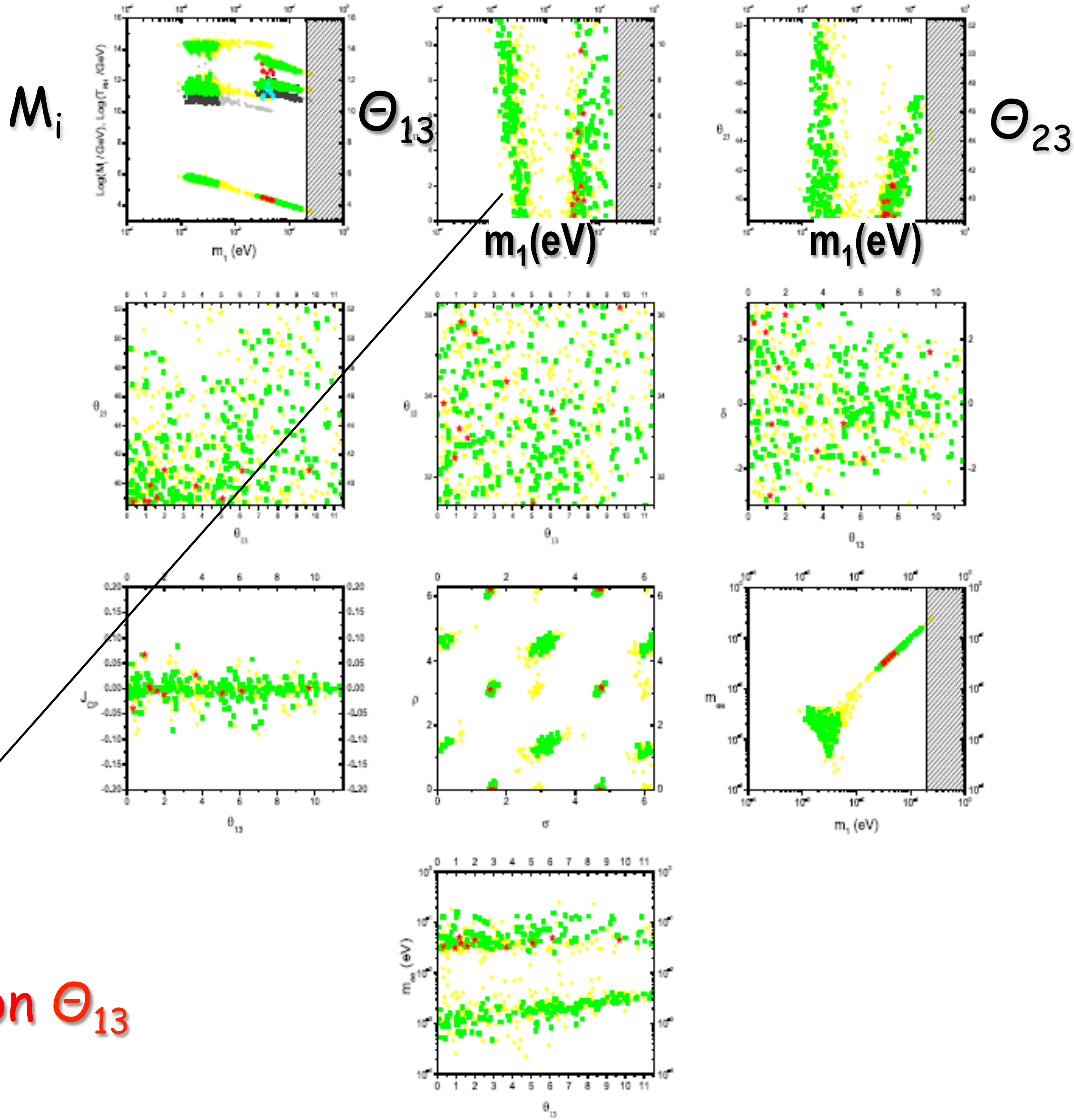


The model yields constraints on all low energy neutrino observables !

(PDB, Riotto '08)

$I \leq V_L \leq V_{CKM}$

NORMAL ORDERING



$\alpha_2=5$

$\alpha_2=4$

$\alpha_2=1$

No lower bound on Θ_{13}

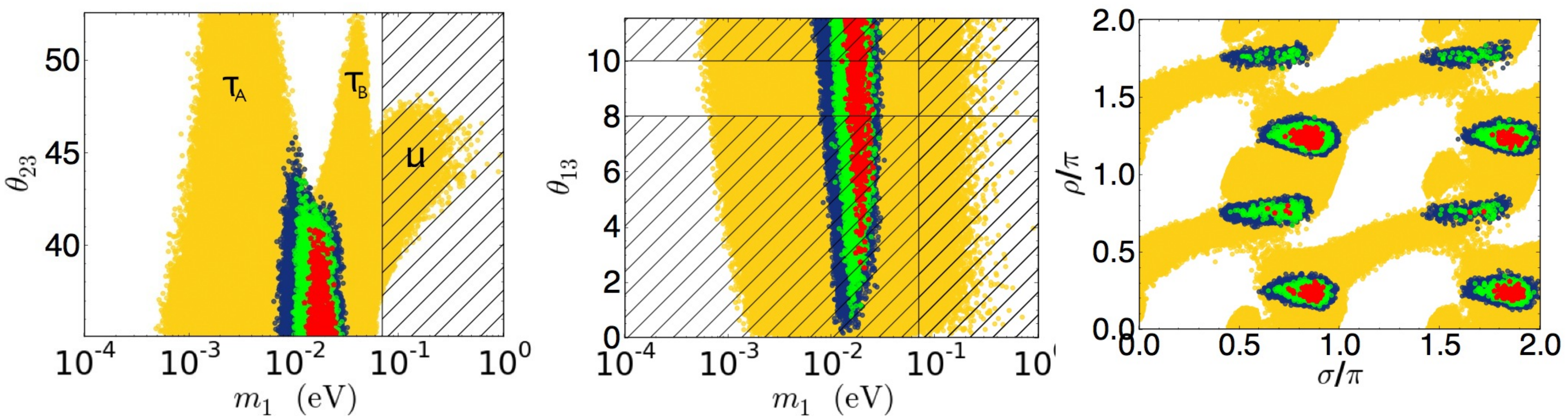
An improved analysis

(PDB, Marzola '13)

We optimised the procedure increasing of two orders of magnitudes the number of solutions (focus on yellow points right now!):

α_2=5 NORMAL ORDERING

$I \le V_L \le V_{CKM}$

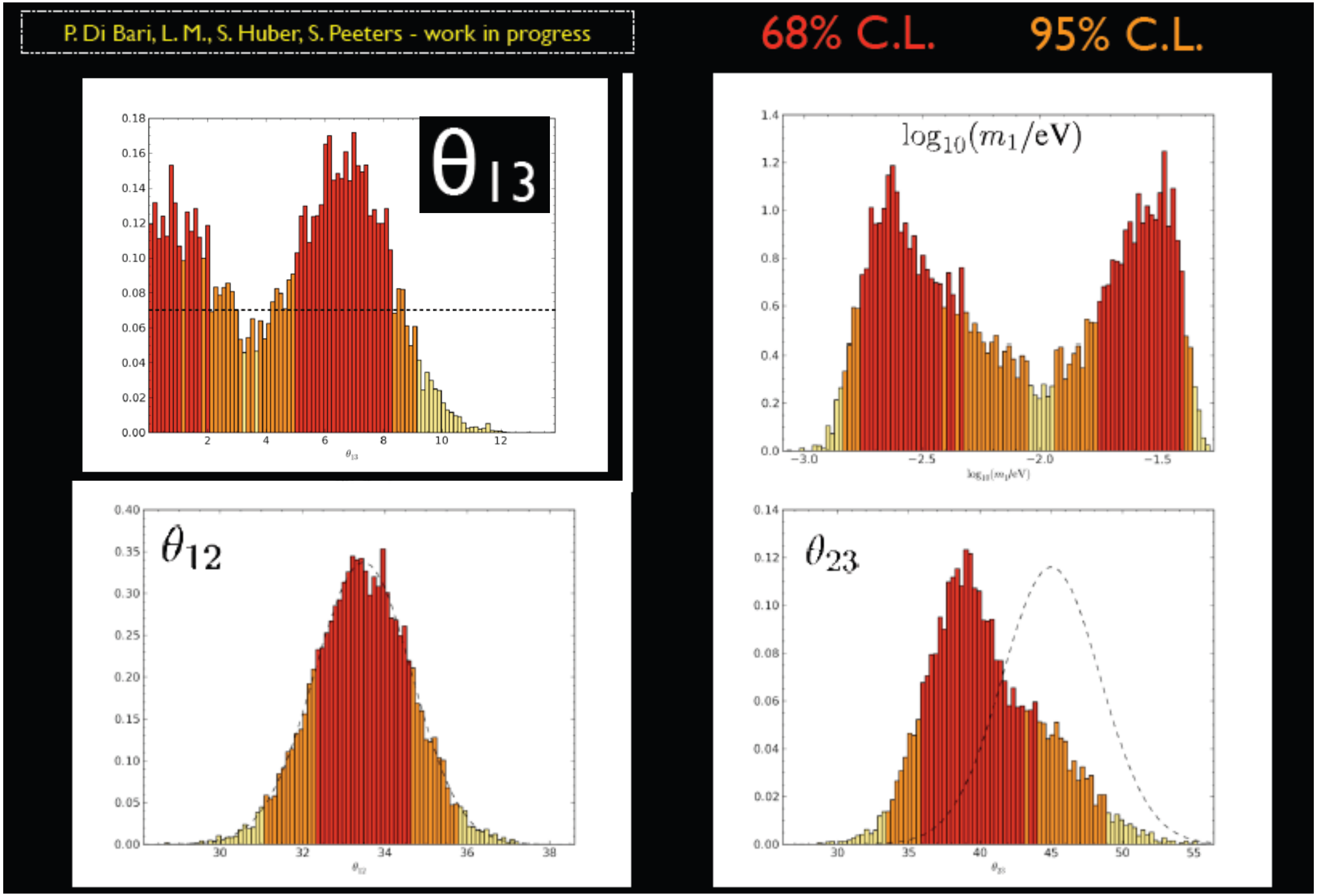


Why? Just to have sharper borders ? NO, two important reasons:

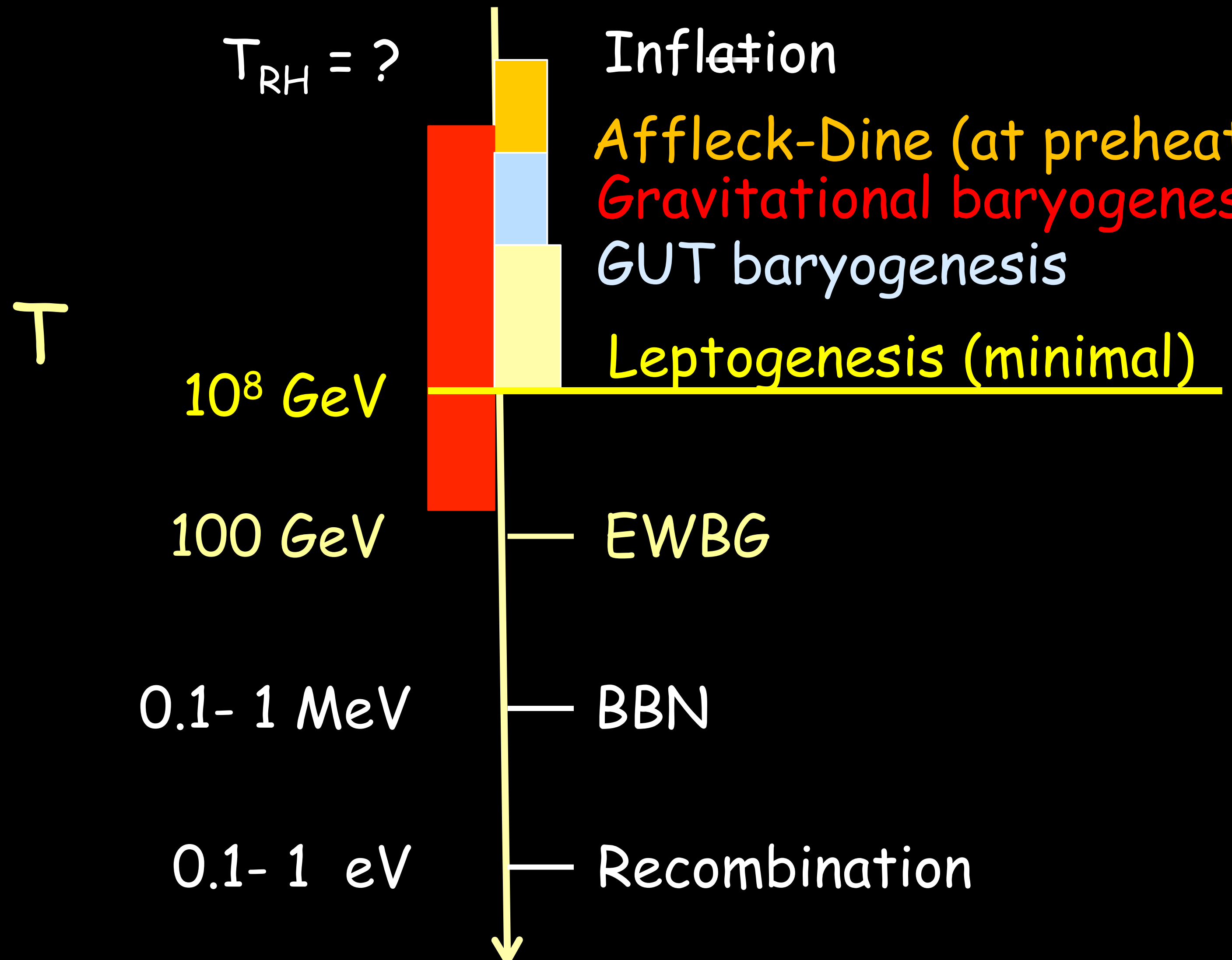
i) statistical analysis

ii) .....to obtain the blue green and red points

Statistical analysis



Baryogenesis and the early Universe history

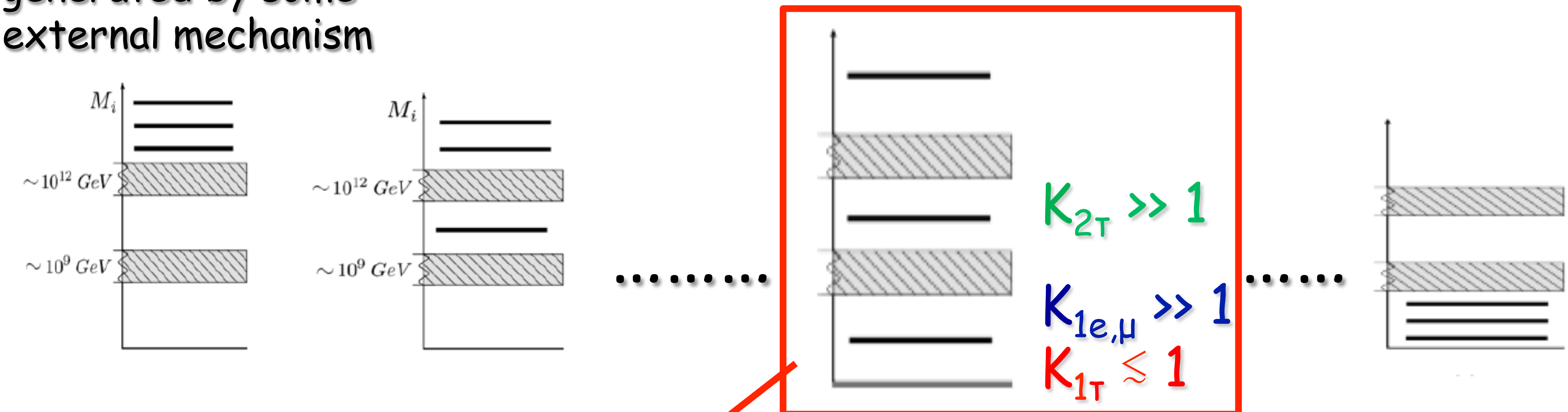


(Bertuzzo,PDB,Marzola '10)

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

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

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 '13)

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

Imposing both successful SO(10)-inspired leptogenesis $\eta_B = \eta_B^{CMB} = (6.1 \pm 0.1) \times 10^{-10}$ and $N_{B-L}^{P,f} \ll N_{B-L}^{leP,f}$

There are NO Solutions for Inverted Ordering !

But for Normal Ordering there is a subset with definite predictions

NON-VANISHING REACTOR MIXING ANGLE

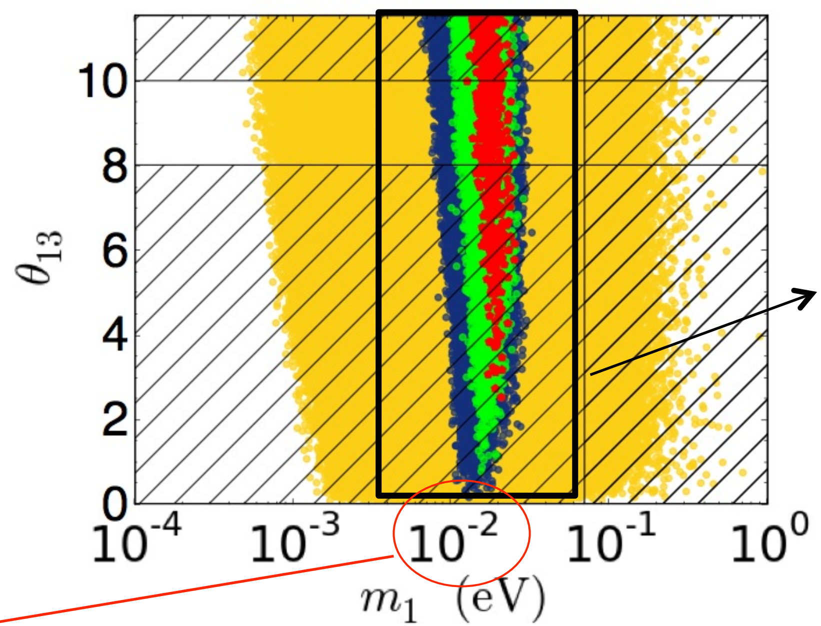
$N^p_{B-L} = 0$

0.001

0.01

0.1

$\alpha_2 = 5$



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

m_1 is constrained in a narrow range (10-30 meV) corresponding to $\sum_i m_i$ = 85

SO(10)-inspired+strong thermal leptogenesis

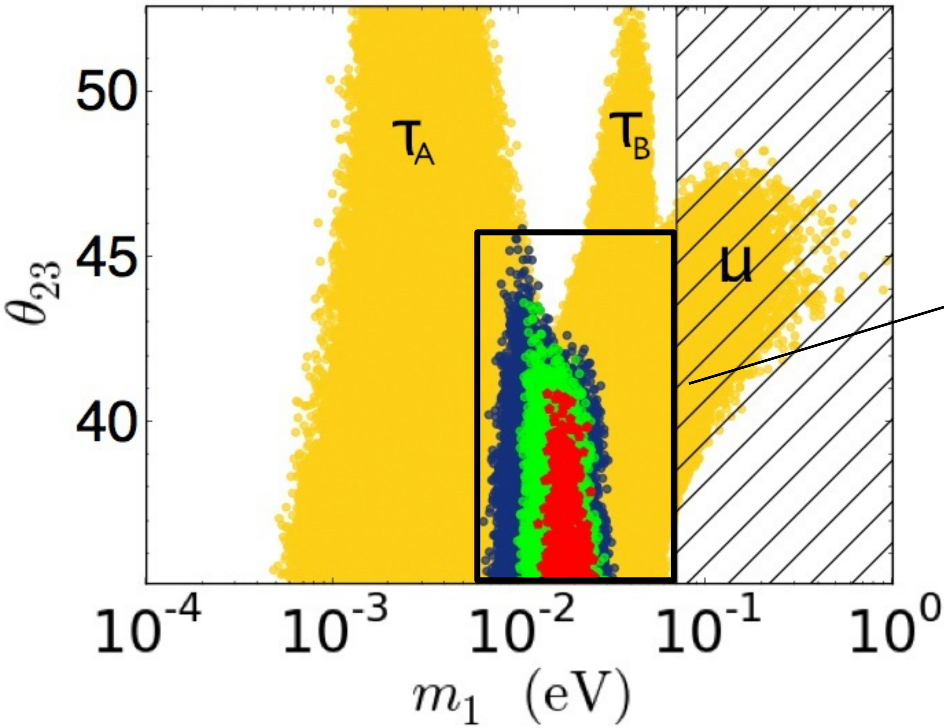
$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p,f} + N_{B-L}^{\rm lep,f}\,,$$

Imposing both successful SO(10)-inspired leptogenesis
$\eta_B = \eta_B^{CMB} = (6.1 \pm 0.1) \times 10^{-10}$ and $N_{B-L}^{P,f} \ll N_{B-L}^{leP,f}$

UPPER BOUND ON THE ATMOSPHERIC MIXING ANGLE

$N^p_{B-L} =$ 0
0.001
0.01
0.1

$\alpha_2 = 5$

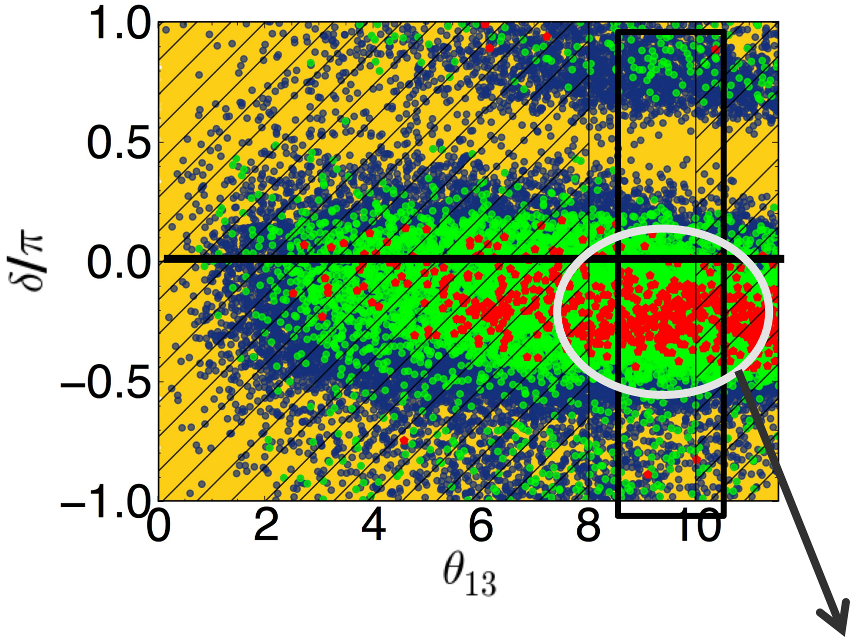


Atmospheric mixing qngle in the first octant

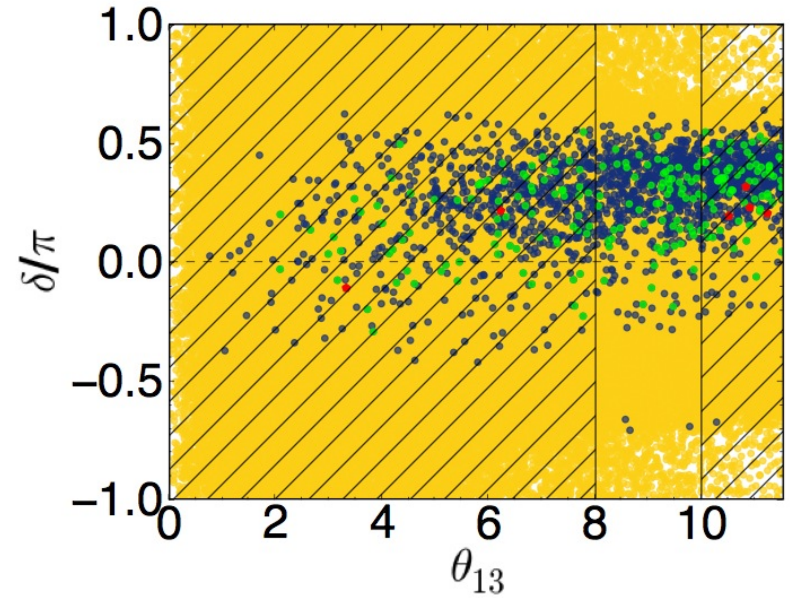
SO(10)-inspired+strong thermal leptogenesis

LINK BETWEEN THE SIGN OF J_{CP} AND THE SIGN OF THE ASYMMETRY

$\eta_B = \eta_B^{CMB}$



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



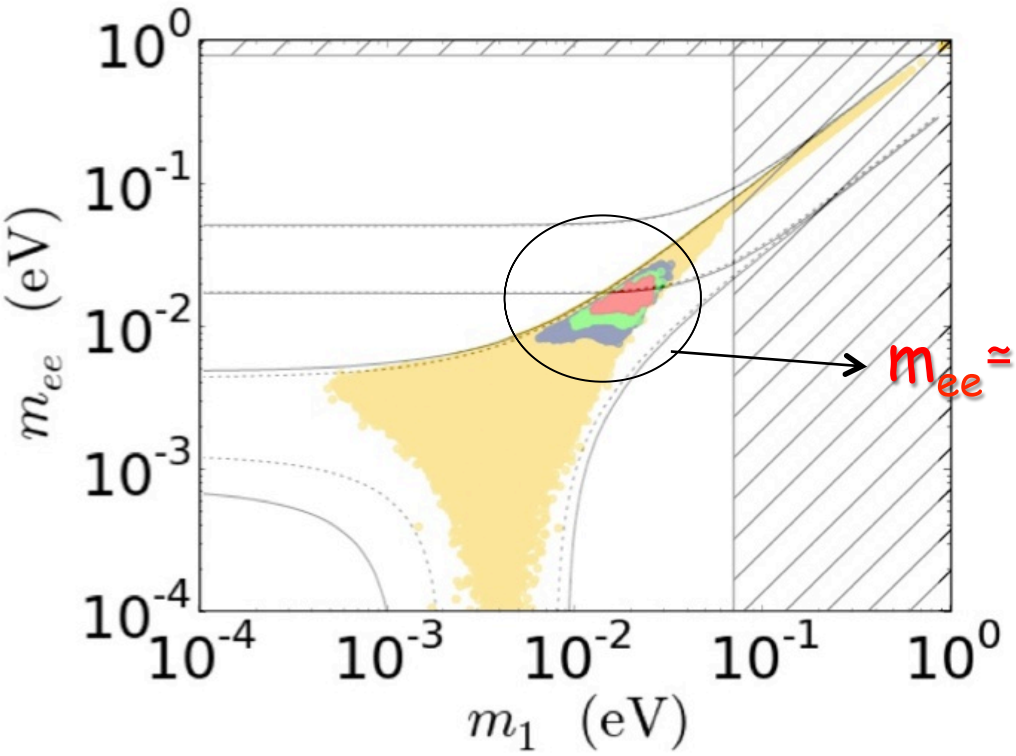
A Dirac phase $\delta \sim -45^\circ$ is favoured for large θ_{13}

SO(10)-inspired+strong thermal leptogenesis

NEUTRINOLESS DOUBLE BETA DECAY EFFECTIVE MASS

N_{B-L}= 0
0.001
0.01
0.1

α_2=5

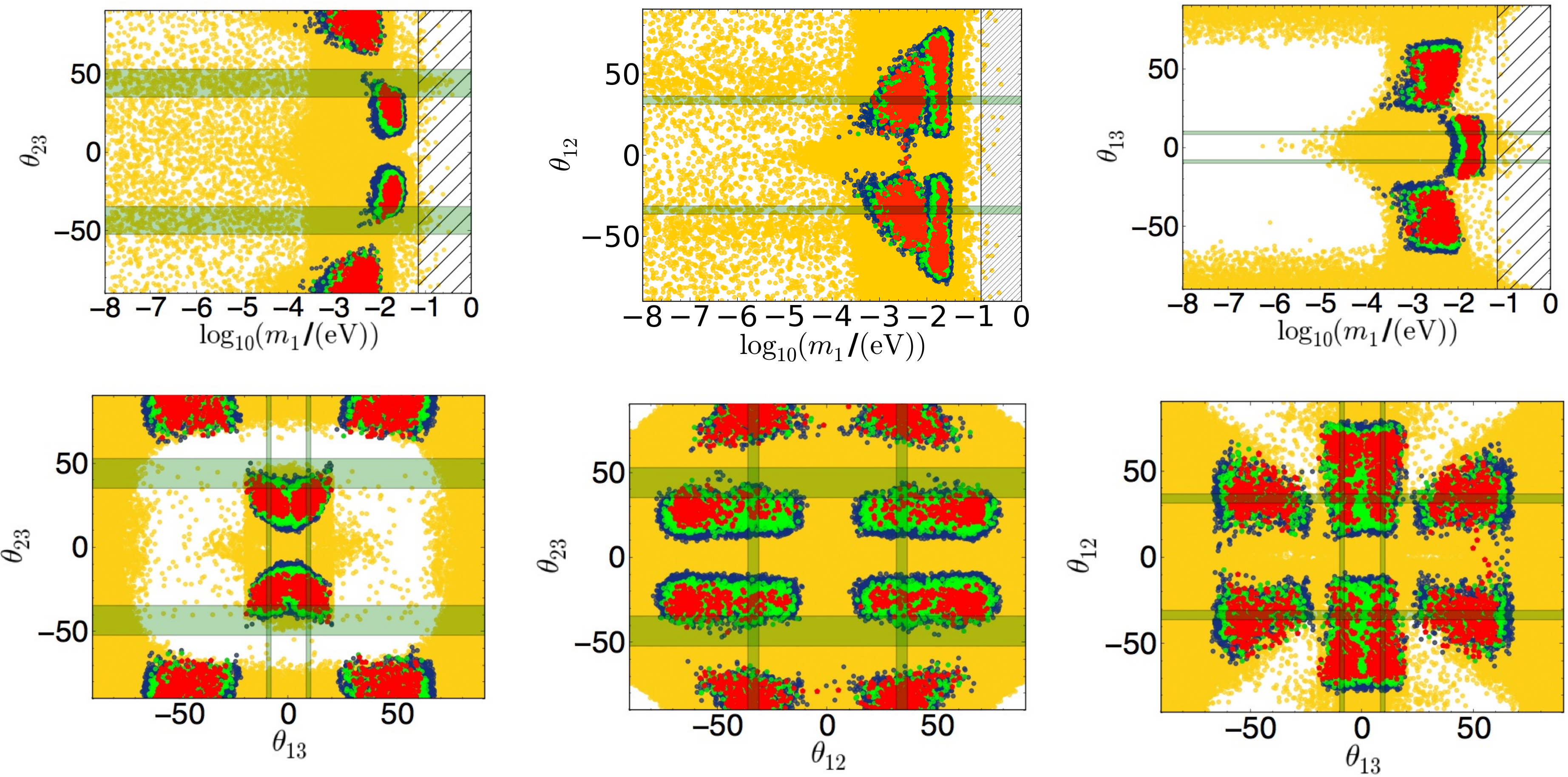


$m_{ee} \simeq 0.8 m_1 \simeq 15$ meV

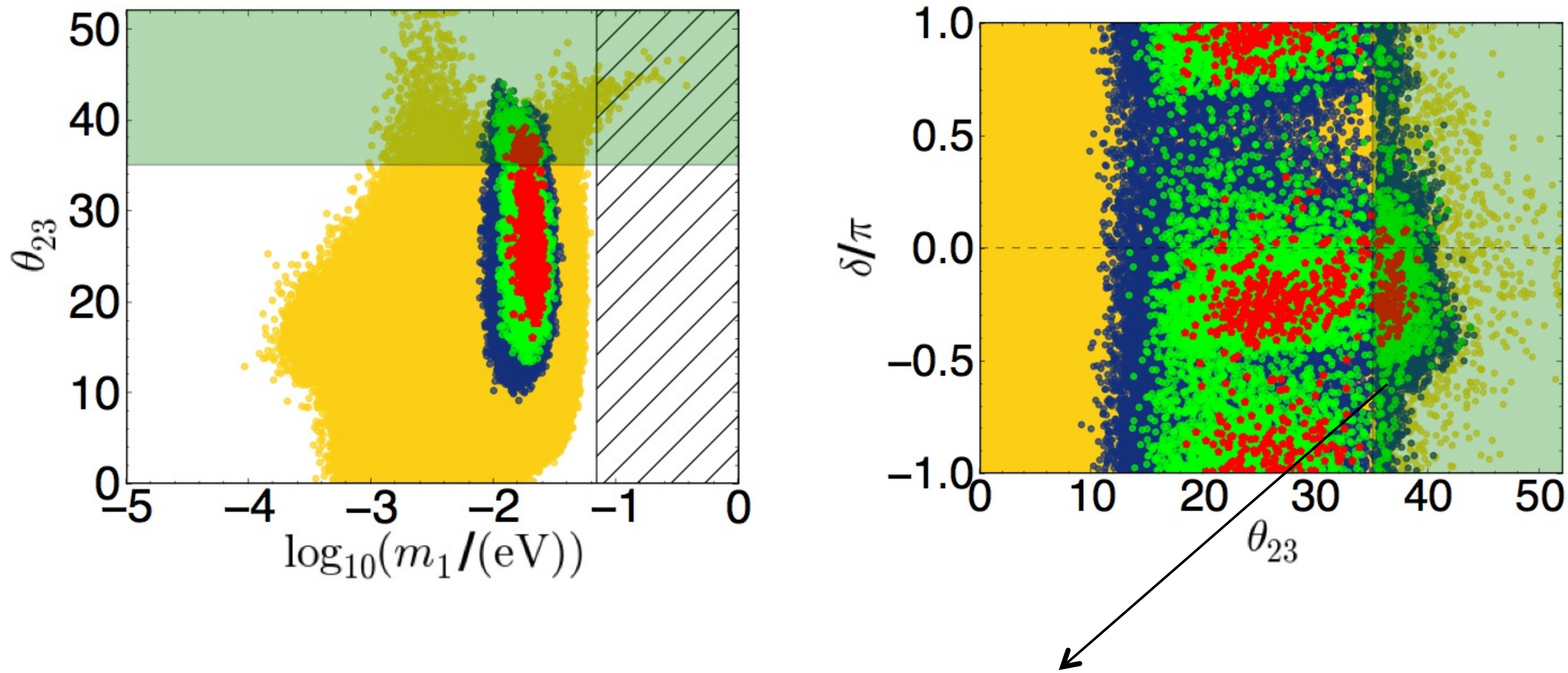
Strong thermal SO(10)-inspired leptogenesis: is it on the right track?

(PDB, Marzola '13)

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



Strong thermal SO(10)-inspired leptogenesis: the atmospheric mixing angle test

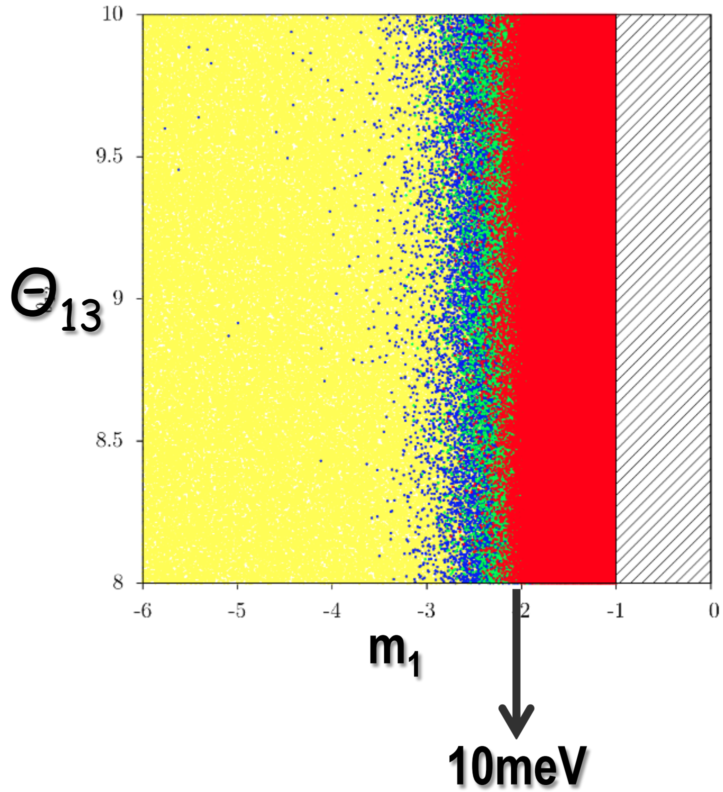


The allowed range for the Dirac phase gets narrower at large values of $\theta_{23} \gtrsim 35^0$

Strong thermal leptogenesis and the absolute neutrino mass scale

(PDB, M. Re Fiorentin, preliminary, see poster by Michele Re Fiorentin)

N^p_{B-L} = 0
0.001
0.01
0.1



Strong thermal (minimal) leptogenesis supports values of neutrino masses that could give a signal during next years in cosmological observations and in 00βν experiments

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 more necessary for a correct calculation of the asymmetry

All this finds a nice application in SO(10)-inspired leptogenesis

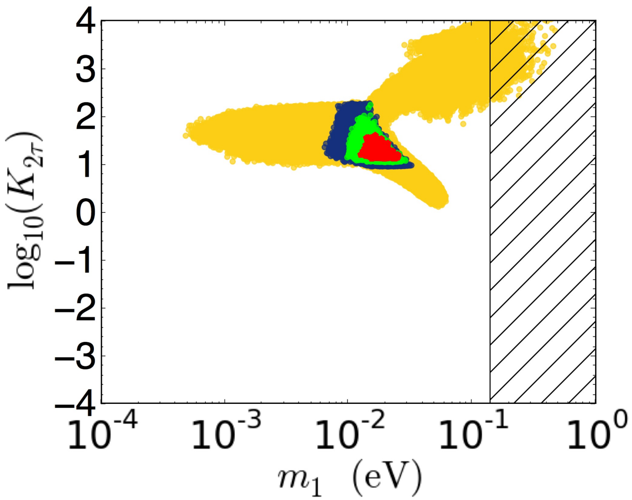
- SO(10)-inspired leptogenesis is not only viable but even a subset of the solutions is able to satisfy quite a tight condition: the *independence of the initial conditions (strong thermal leptogenesis)*

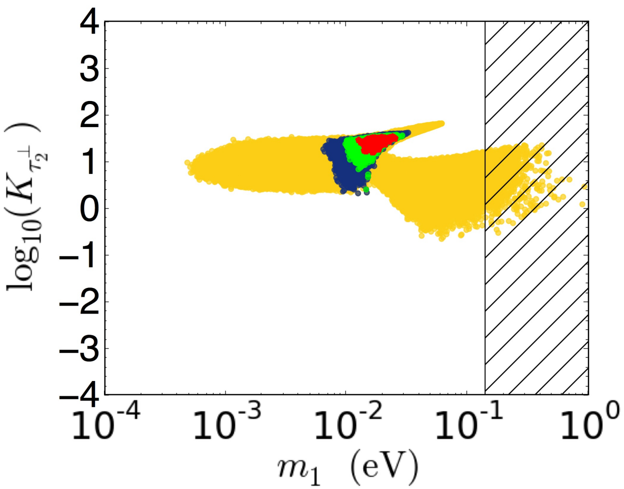
Strong thermal SO(10)-inspired leptogenesis solution

ORDERING	NORMAL
θ_{13}	$\gtrsim 2^\circ$
θ_{23}	$\lesssim 41^\circ$
δ	$\sim -40^\circ$
$m_{ee} \simeq 0.8\, m_1$	$\simeq 15$ meV

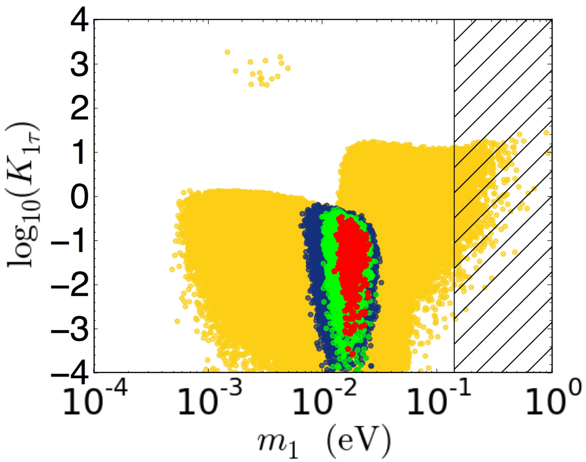
Some insight from the decay parameters

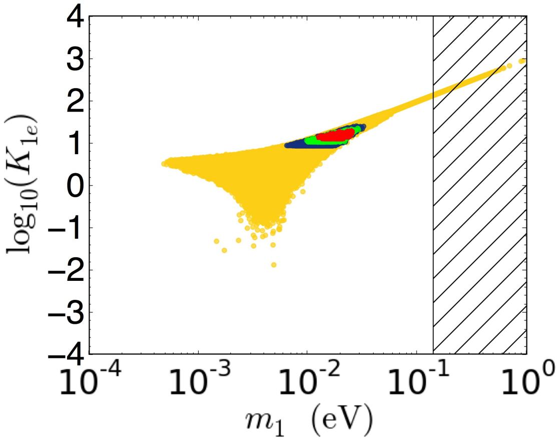
At the production ($T \sim M_2$)

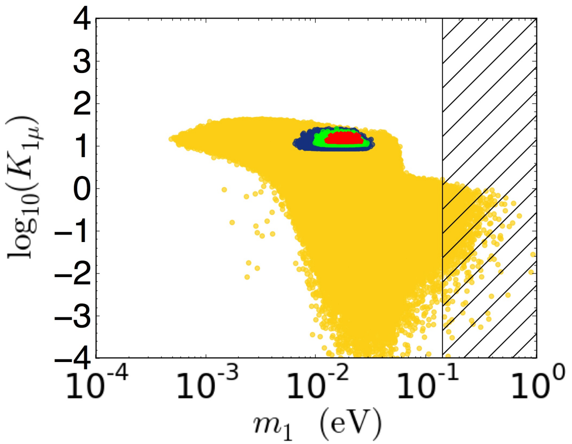




At the wash-out ($T \sim M_1$)







Interplay between lepton and heavy neutrino flavour effects:

- N_2 flavoured leptogenesis
  (Vives '05; Blanchet, PDB '06; Blanchet, PDB '08)

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

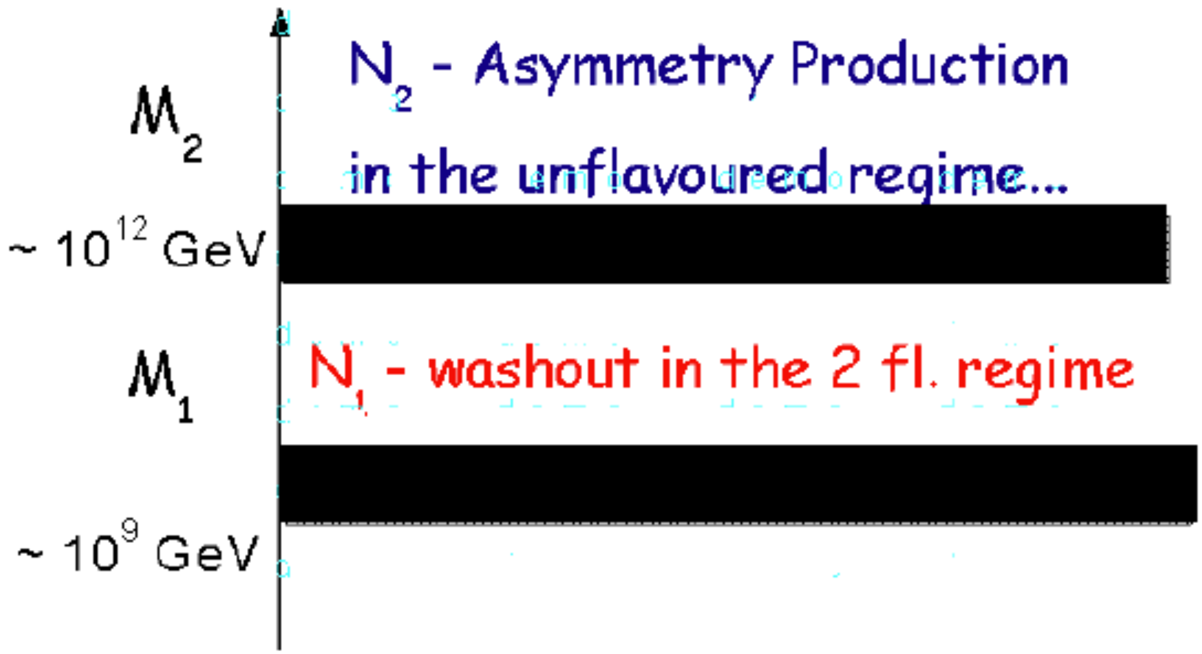
- Flavour projection
  (Barbieri,Creminelli,Stumia,Tetradis '00;
  Engelhard, Grossman, Nardi, Nir '07)

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

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:

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

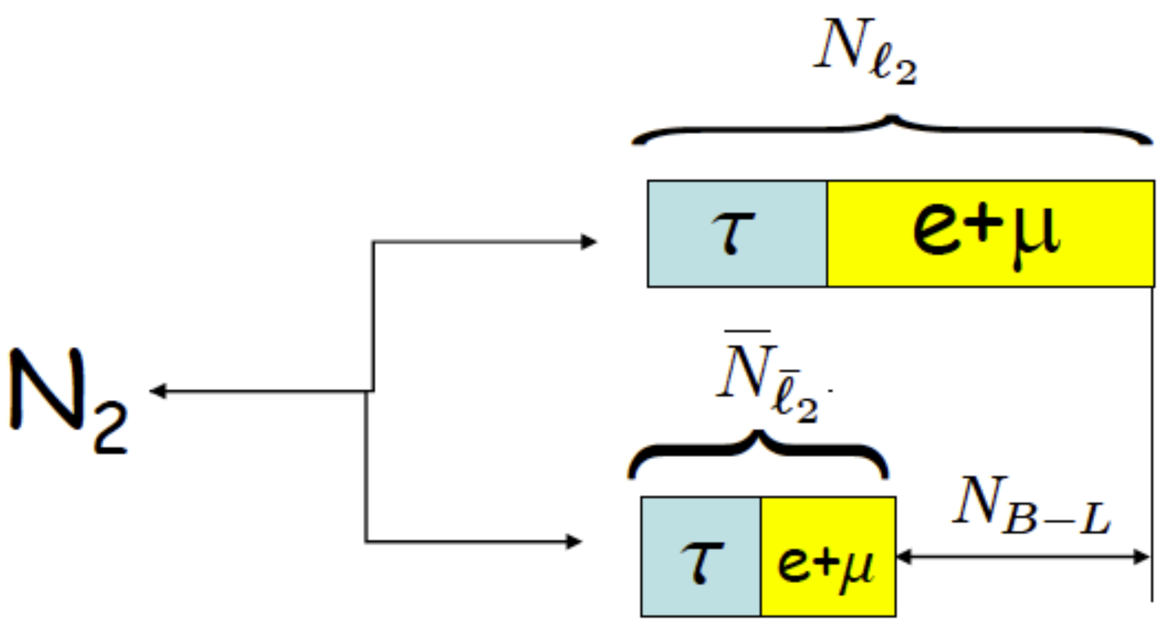
$$N_{\Delta e+\mu} = p_{2\, e+\mu}\, N_{B-L}$$

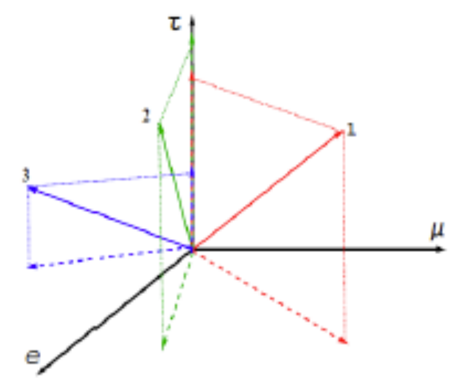
Phantom terms

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 $T \sim M_2 >> 10^{12}$ GeV



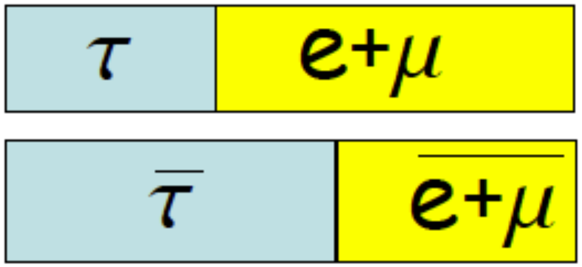


Phantom Leptogenesis

(Antusch, PDB, King, Jones '10)

Let us then consider a situation where $K_2 \gg 1$ 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 $\gtrsim T \gg M_1$: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

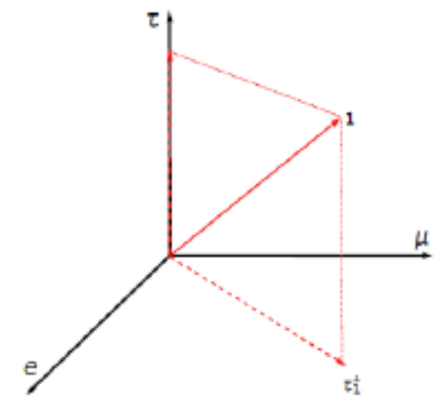
Assume $K_{1\tau} \lesssim 1$ and $K_{1e+\mu} \gg 1$ $\qquad N_{B-L}^{\rm f} \simeq N_{\Delta_\tau}^{T\sim M_2}\ !$

The N_1 wash-out un-reveal the phantom term and effectively it creates a N_{B-L} asymmetry.

Phantom Leptogenesis within a density matrix formalism

(Blanchet, PDB, Marzola, Jones '11-12')

In a picture where the gauge interactions are neglected the lepton and anti-leptons density matrices can be written as:



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

There is a recent update (see 1112.4528 v2 to appear in JCAP)

Because of the presence of gauge interactions, the difference of flavour composition between lepton and anti-leptons is measured and this induces a wash-ou the phantom terms from Yukawa interactions though with halved wash-out rate compared to t one acting on the total asymmetry and in the end:

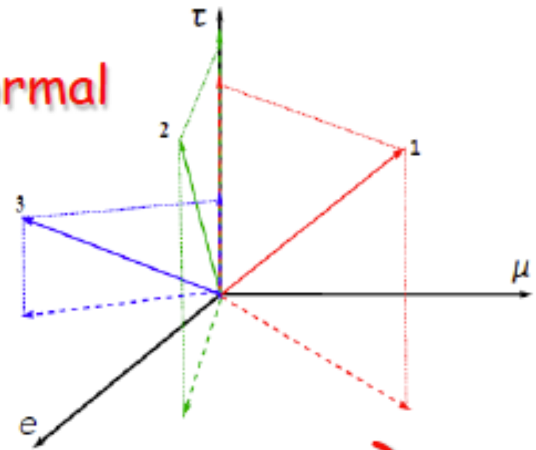
$$N_{\tau\tau}^{B-L,{\rm f}} \simeq p^0_{2\tau}\, N^{\rm f}_{B-L} - \frac{\Delta p_{2\tau}}{2}\,\kappa(K_2/2),$$

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

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

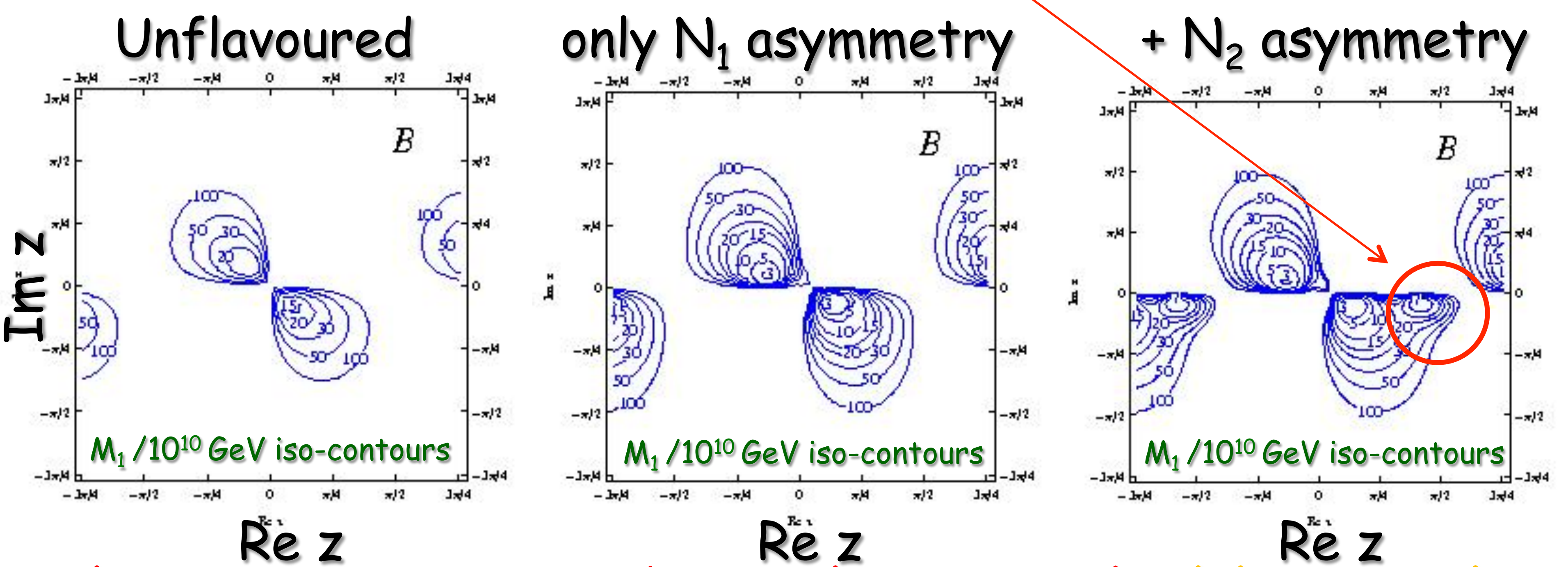
2 RH neutrino scenario revisited

(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



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

Flavour projection

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

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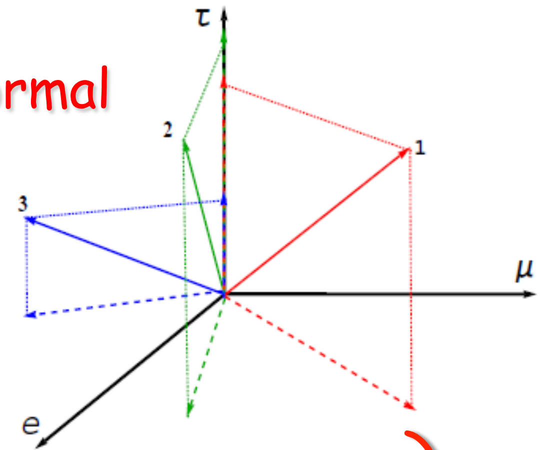

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p_{12} $\qquad$ $(1-p_{12})$

$$N^{(N_2)}_{B\,¡\,L}(T\ ¿\ M_1) = N^{(N_2)}_{¢\,1}(T\ ¿\ M_1) + N^{(N_2)}_{¢\,1?}(T\ ¿\ M_1)$$

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

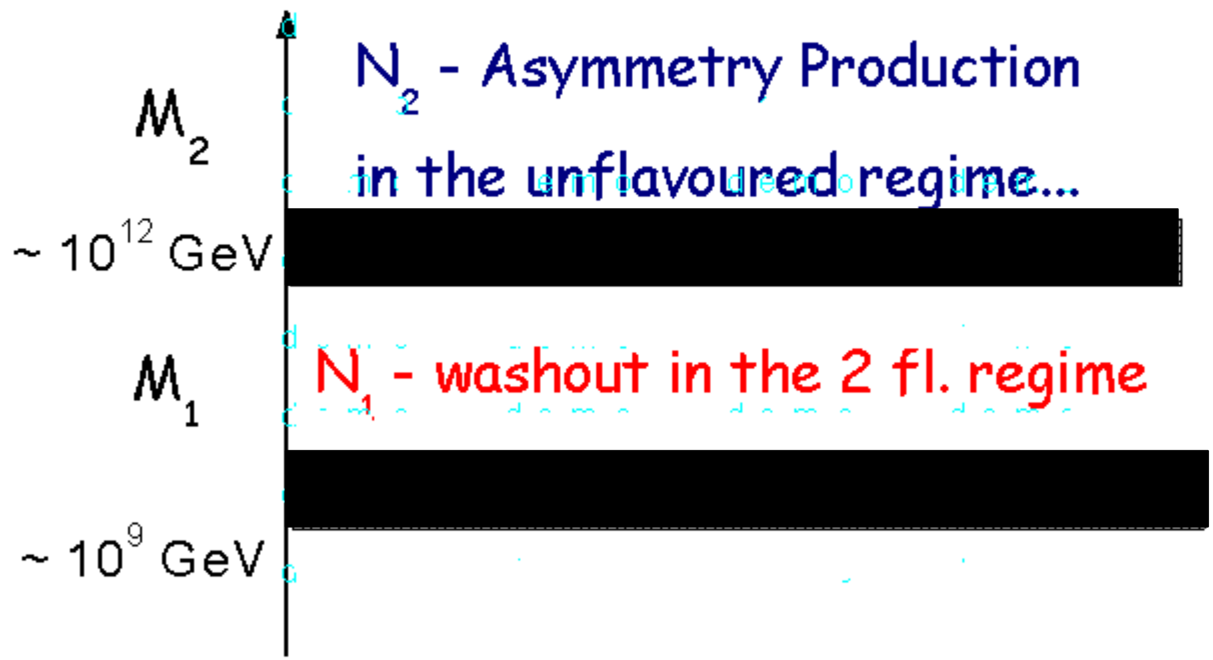
Contribution from heavier RH neutrinos **orthogonal** to l_1 and escaping N_1 wash-out

$$N^{(N_2)}_{¢\,1}(T\ ¿\ M_1) = p_{12}\, e^{¡\,\frac{3¼}{8}\,K_1}\, N^{(N_2)}_{B\,¡\,L}(T\ »\ M_2)$$

Phantom Leptogenesis

(Antusch, PDB, King, Jones '10)

Consider this situation



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

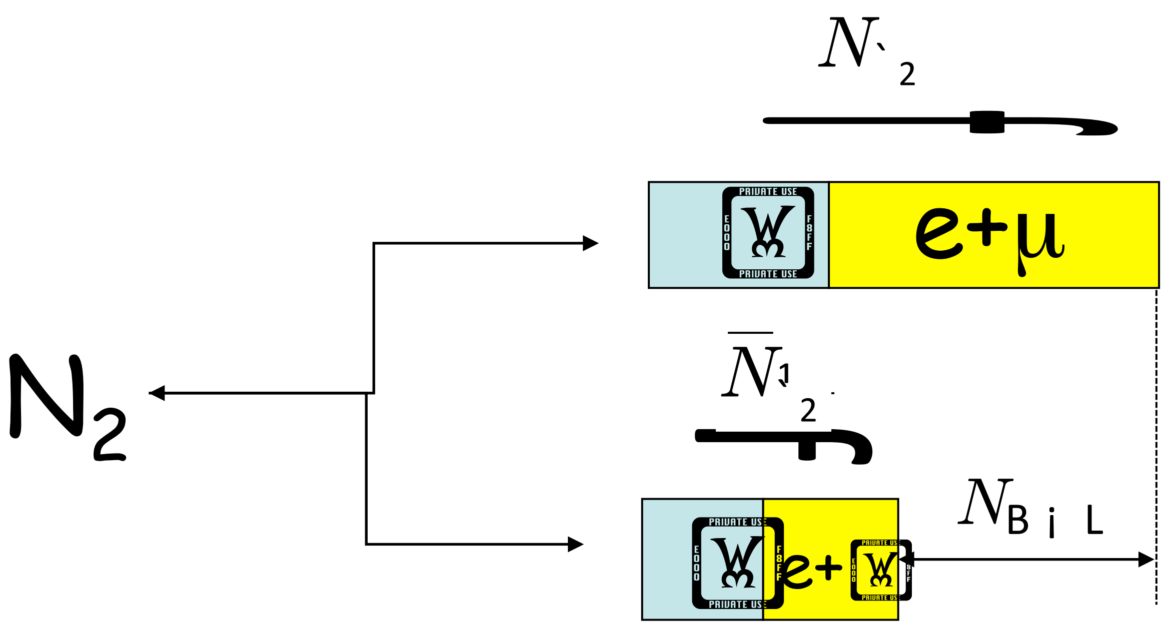
Phantom terms

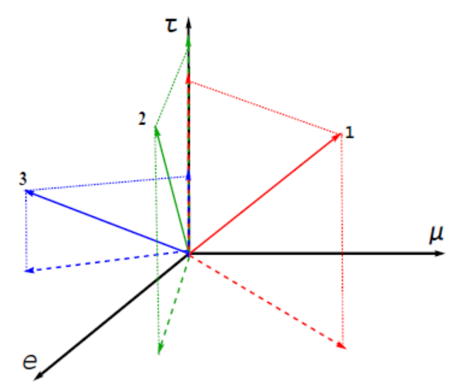
However one has to consider that in the unflavoured case there are contributions to $N_{\Delta\tau}$ and $N_{\Delta e+\mu}$ that are not just proportional to N_{B-L}

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 $K_2 \gg 1$ so that at the end of the N_2 washout the total asymmetry is negligible:

1) $T \sim M_2$: unflavoured regime

[illegible]	$e+$[illegible]
[illegible]	$\overline{e+}$[illegible]

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

2) 10^{12} GeV [illegible] $T \gg M_1$:decoherence [illegible] 2 flavoured regime

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

3) T [illegible] M_1: asymmetric washout from lightest RH neutrino

Assume $K_{1\tau}$ [illegible] 1 and $K_{1e+\mu} \gg 1$ $\quad N_{B-L}^{f} \simeq N_{\Delta\tau}^{T \sim M_2} \rightarrow$

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 !

$$N^{\rm phantom}_{¢\ ¿} = \frac{¢\ p_{2¿}}{2} N^{\rm in}_{N_2}$$

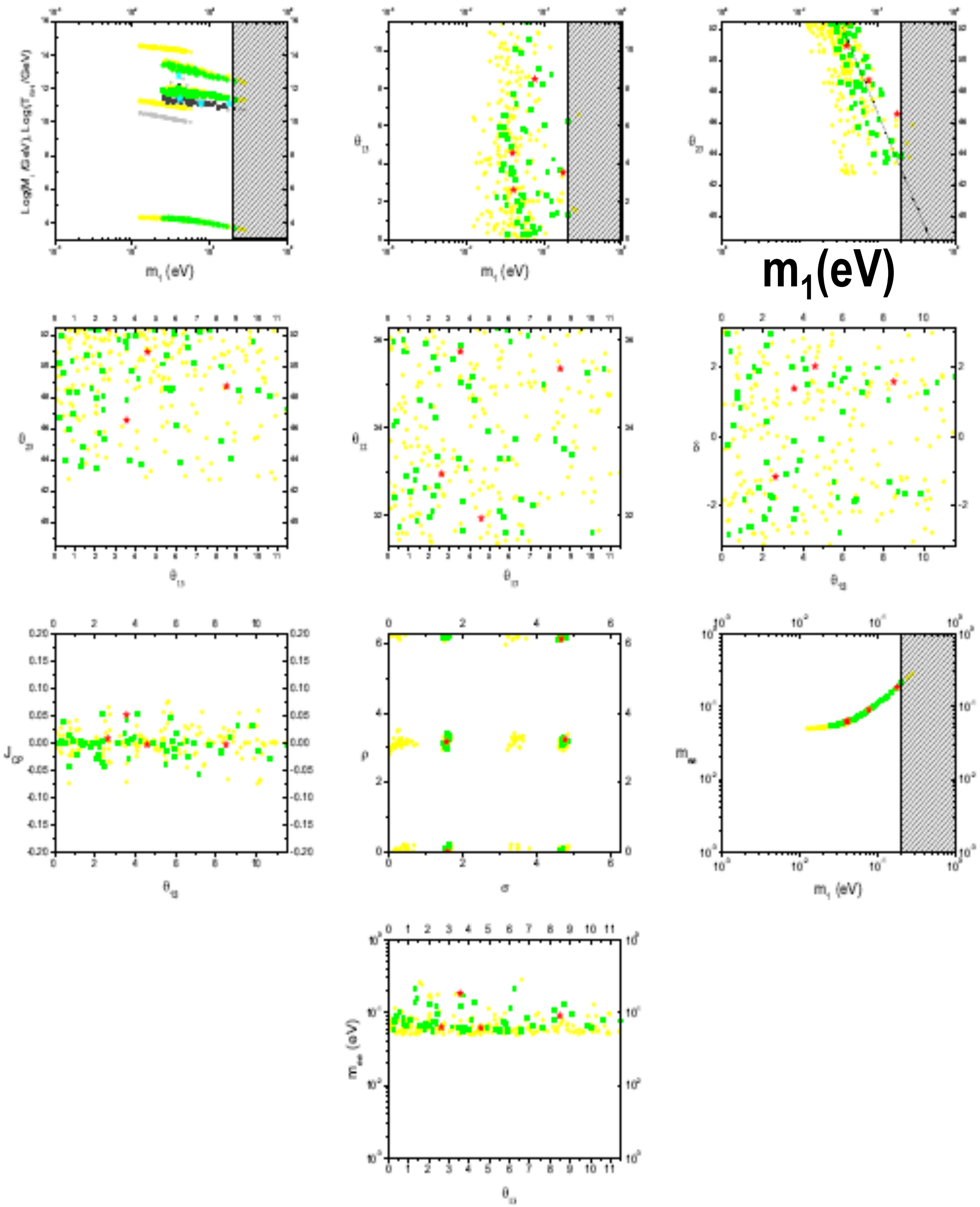
The reason is that if one starts from a vanishing abundance during the N_2 production one creates a contribution to the phantom term by inverse decays with opposite sign and exactly cancelling with what is created in the decays

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

$I \leq V_L \leq V_{CKM}$



Θ_{23}

INVERTED ORDERING

α_2=5

α_2=4

α_2=1.5

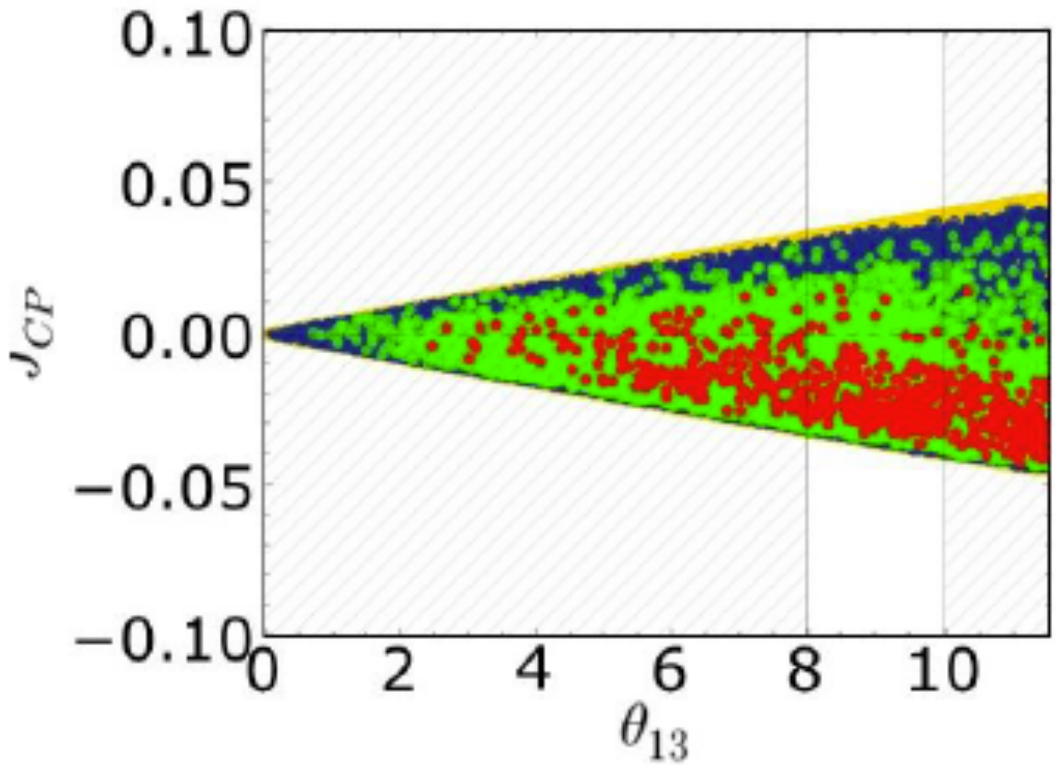
No link between the sign of the asymmetry and J_{CP}

(PDB, Marzola)

$\alpha_2=5$

NORMAL ORDERING

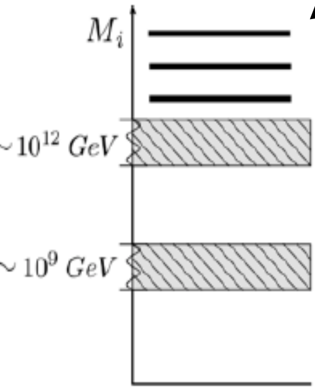
$I \leq V_L \leq V_{CKM}$



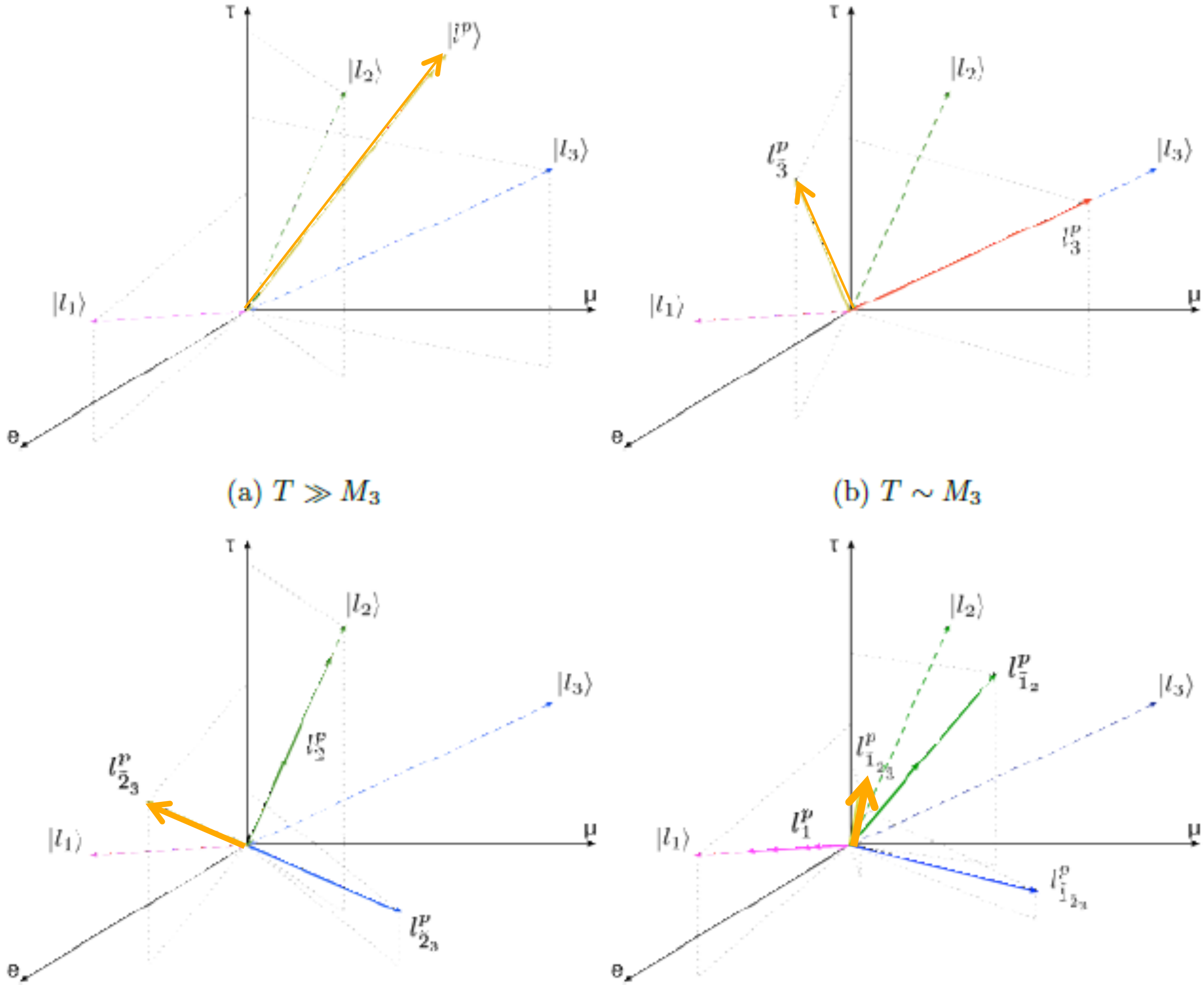
It is confirmed that there is no link between the matter-antimatter asymmetry and CP violation in neutrino mixing…….for the yellow points

WHAT ARE THE NON-YELLOW POINTS ?

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



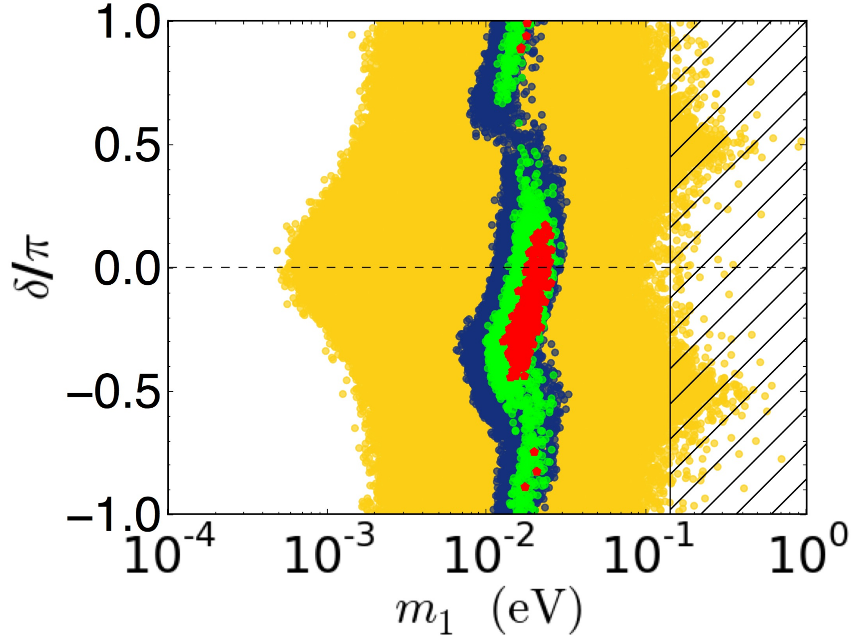
The pre-existing asymmetry (yellow) undergoes a 3 step flavour projection



(a) $T \gg M_3$ (b) $T \sim M_3$ (c) $T \sim M_2$ (d) $T \sim M_1$

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

$\eta_B = \eta^{CMB}_B$



$\eta_B = - \eta^{CMB}_B$