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Leptogenesis confronting

neutrino data:

an $SO(10)$ -inspired solution to the problem
of the initial conditions

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The double side of Leptogenesis

**Cosmology
(early Universe)**

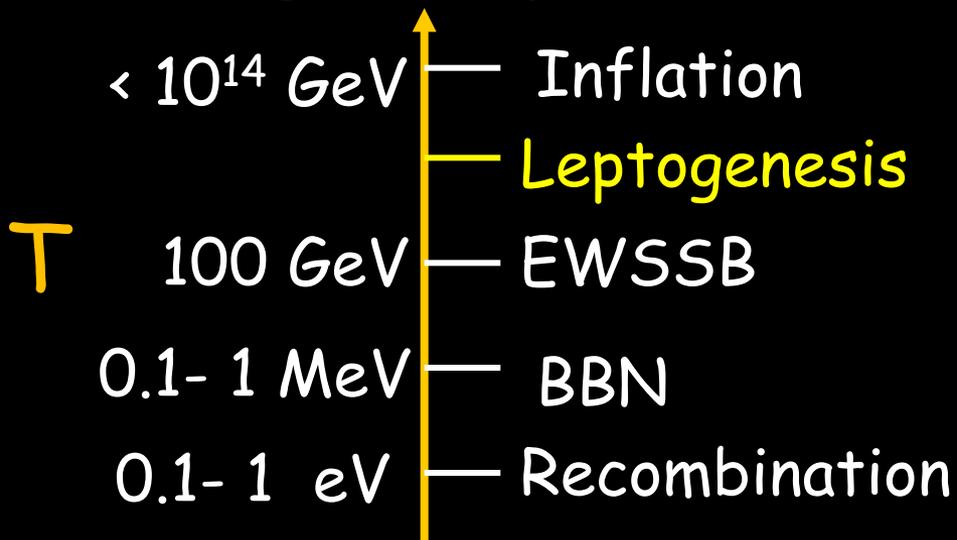


**Neutrino Physics,
New Physics**

• Cosmological Puzzles :

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

• New stage in early Universe history :



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

In this case ...

...two important questions:

1. Can we understand 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?

Typical 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, 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 so far no signals of new physics at the TeV scale but...

Neutrino mixing parameters („pre-T2K“)

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

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{matrix} \Phi \\ \left[\begin{matrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma} \end{matrix} \right] \end{matrix}$$

Atmospheric

**Reactor, Accel., LBL
CP violating phase**

Solar, Reactor

$\beta\beta\nu$ decay

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

- best-fit point and 1σ (3σ) ranges:

$$\theta_{12} = 34.5 \pm 1.4 \begin{matrix} (+4.8) \\ (-4.0) \end{matrix}, \quad \Delta m_{21}^2 = 7.67 \begin{matrix} +0.22 \\ -0.21 \end{matrix} \begin{matrix} (+0.67) \\ (-0.60) \end{matrix} \times 10^{-5} \text{ eV}^2,$$

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

$$\theta_{13} = 3.2 \begin{matrix} +4.5 \\ -3.6 \end{matrix} \begin{matrix} (+9.6) \\ (-8.0) \end{matrix}, \quad \delta_{\text{CP}} \in [0, 360];$$

(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,....

recent
global
analyses

$$\theta_{13} = 7.7^\circ \div 10.2^\circ \text{ (95\% CL)}$$

$$\theta_{23} = 36.3^\circ \div 40.9^\circ \text{ (95\% CL)}$$

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

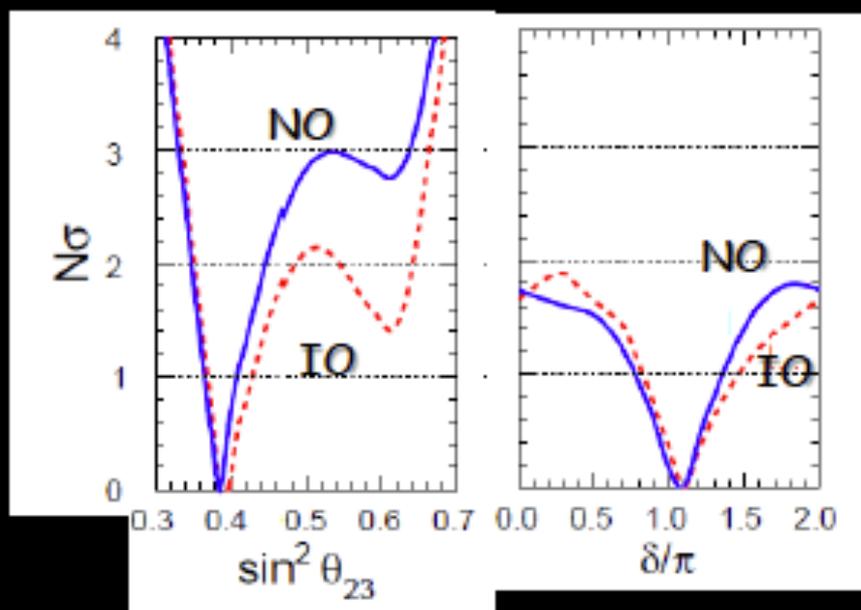
(Normal
Ordering)

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

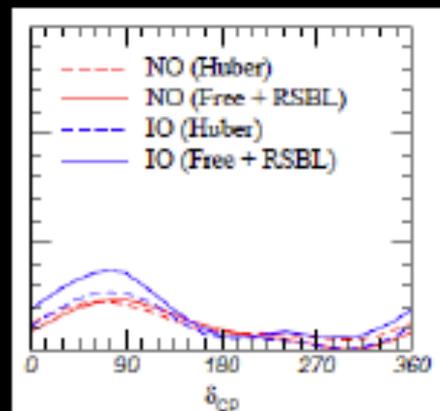
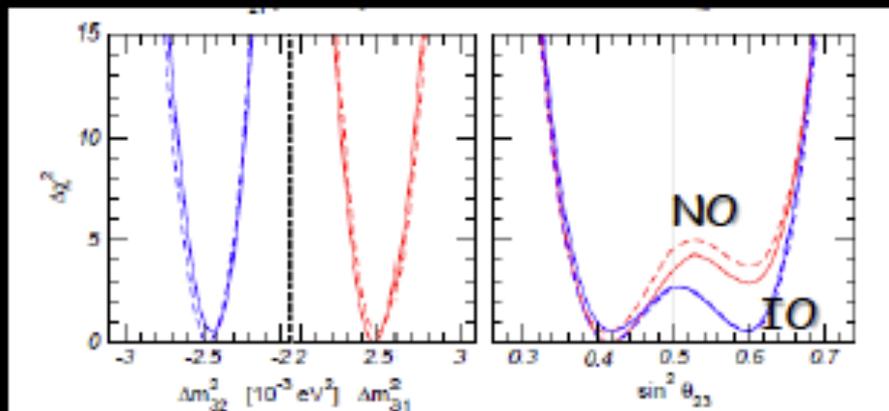
Analogous results by Schwetz et al. but $\delta_{\text{best fit}} \sim -\pi/3$

In more detail:

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



(Gonzalez-Garcia, Maltoni, Salvado, Schwetz 2012)



Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: **normal** or **inverted**

$$m_3^2 - m_2^2 = \Delta m_{\text{atm}}^2 \quad \text{or} \quad \Delta m_{\text{sol}}^2$$

$$m_{\text{atm}} \equiv \sqrt{\Delta m_{\text{atm}}^2 + \Delta m_{\text{sol}}^2} \simeq 0.05 \text{ eV}$$

$$m_2^2 - m_1^2 = \Delta m_{\text{sol}}^2 \quad \text{or} \quad \Delta m_{\text{atm}}^2$$

$$m_{\text{sol}} \equiv \sqrt{\Delta m_{\text{sol}}^2} \simeq 0.009 \text{ eV}$$

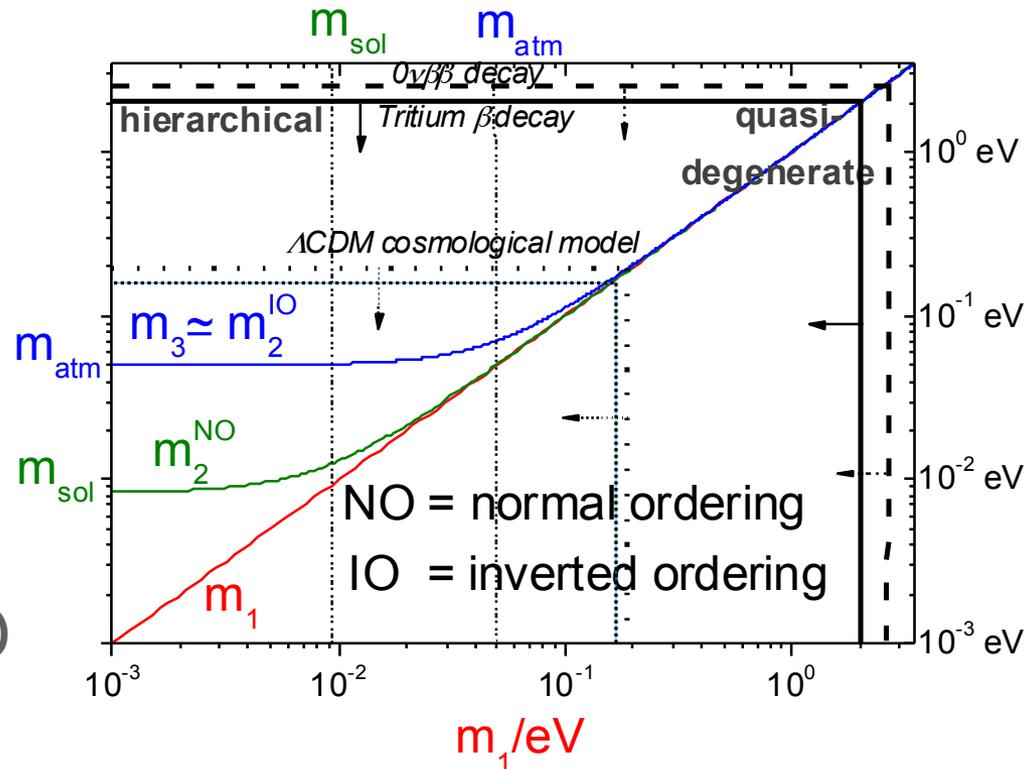
Tritium β decay : $m_e < 2 \text{ eV}$
(Mainz + Troitzk 95% CL)

$\beta\beta 0\nu$: $m_{\beta\beta} < 0.34 - 0.78 \text{ eV}$
(CUORICINO 95% CL, similar bound from Heidelberg-Moscow)

ALSO : $m_{\beta\beta} < 0.14 - 0.38 \text{ eV}$
(EXO-200 90% CL)

CMB+BAO+H0 : $\sum m_i < 0.58 \text{ eV}$
(WMAP7+2dF+SDSS+HST, 95%CL))

Recently : $\sum m_i < 0.44 \text{ eV}$
(WMAP9+BAO+HST)



Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

• Type I seesaw

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

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

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

- 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 $\Rightarrow T_{\text{RH}} \gtrsim M_i / (2 \div 10)$

Seesaw parameter space

Imposing $\eta_B = \eta_B^{\text{CMB}}$ 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**

$$\boxed{m_D} = \boxed{U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}} \left(\begin{array}{l} U^\dagger U = I \\ U^\dagger m_\nu U^* = -D_m \end{array} \right)$$

(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

Parameter reduction from:

(King '07)

- Iso-asymmetry surfaces $\eta_B(U, m_i; \lambda_1, \dots, \lambda_9) = \eta_B^{\text{CMB}}$ (if they "close up" the leptogenesis bound can remove more than one parameter in this case)
- In the asymmetry calculation $\eta_B = \eta_B(U, m_i; \lambda_1, \dots, \lambda_{M \leq 9})$
- By imposing some (model dependent) conditions on m_D , one can reduce the number of parameters and arrive to a new parameterisation where

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

Vanilla leptogenesis

1) Flavor composition of final leptons is neglected



**Total CP
asymmetries**

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

$$N_{B-L}^{\text{fin}} = \sum_i \varepsilon_i \kappa_i^{\text{fin}} \Rightarrow \eta_B = a_{\text{sph}} \frac{N_{B-L}^{\text{fin}}}{N_\gamma^{\text{rec}}} \quad \text{baryon-to-photon number ratio}$$

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

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

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

4) Barring fine-tuned mass cancellations in the seesaw

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

(Davidson, Ibarra '02)

5) Efficiency factor from simple Boltzmann equations

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

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

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

decays

inverse decays

wash-out

decay
parameter

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

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

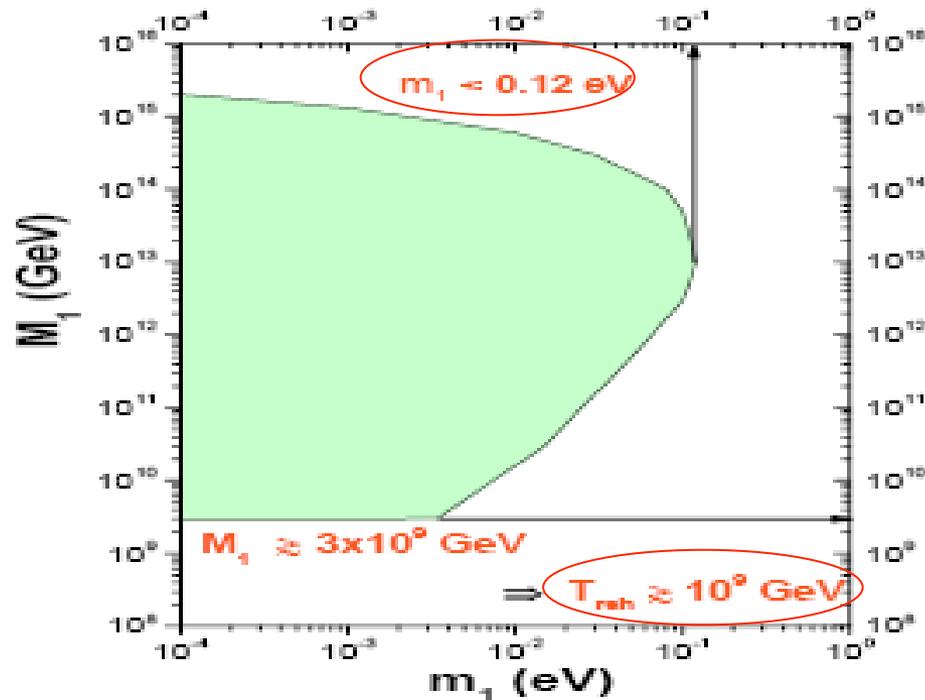
Neutrino mass bounds in vanilla leptog.

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

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

Imposing:

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



No dependence on the leptonic mixing matrix U

Independence of the initial conditions

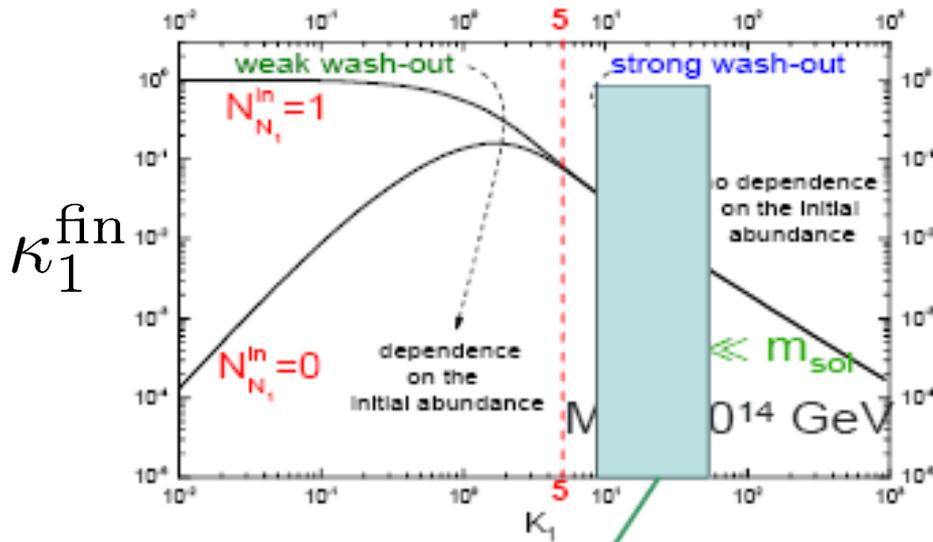
The early Universe „knows“ the neutrino masses ...

(Buchmüller, PDB, Plümacher '04)

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

decay parameter

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



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

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

wash-out of
a pre-existing
asymmetry

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:

$$m_D = V_L^\dagger D_{m_D} U_R$$

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

SO(10) inspired conditions:

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

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

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:

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

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

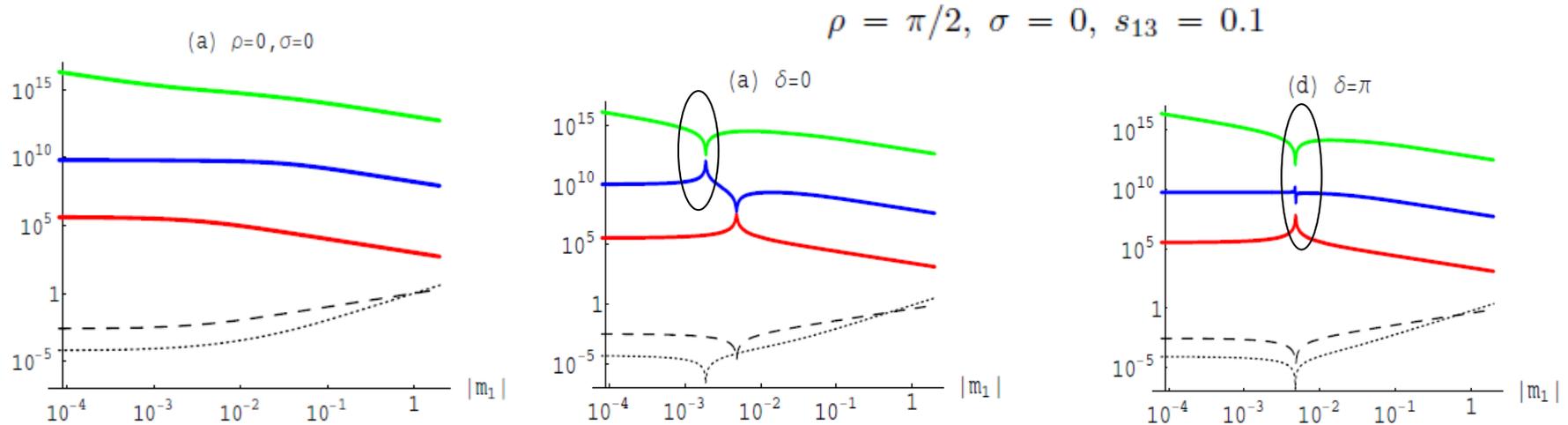
$$M_1 \gg \alpha_1^2 10^5 \text{ GeV}, \quad M_2 \gg \alpha_2^2 10^{10} \text{ GeV}, \quad M_3 \gg \alpha_3^2 10^{15} \text{ GeV}$$

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

\Rightarrow failure of the N_1 -dominated scenario!

Crossing level solutions

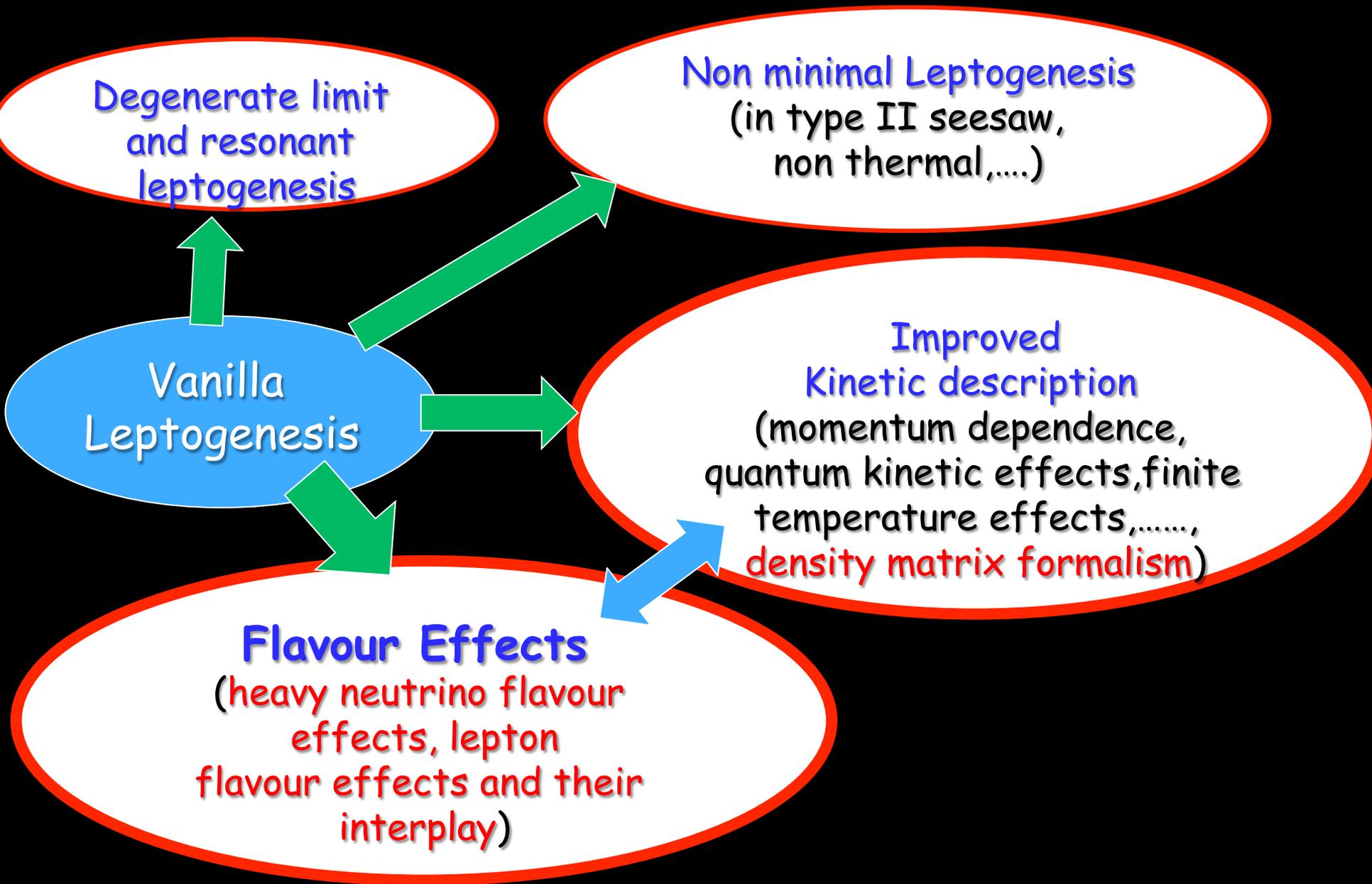
(Akhmedov, Frigerio, Smirnov '03)



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

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)

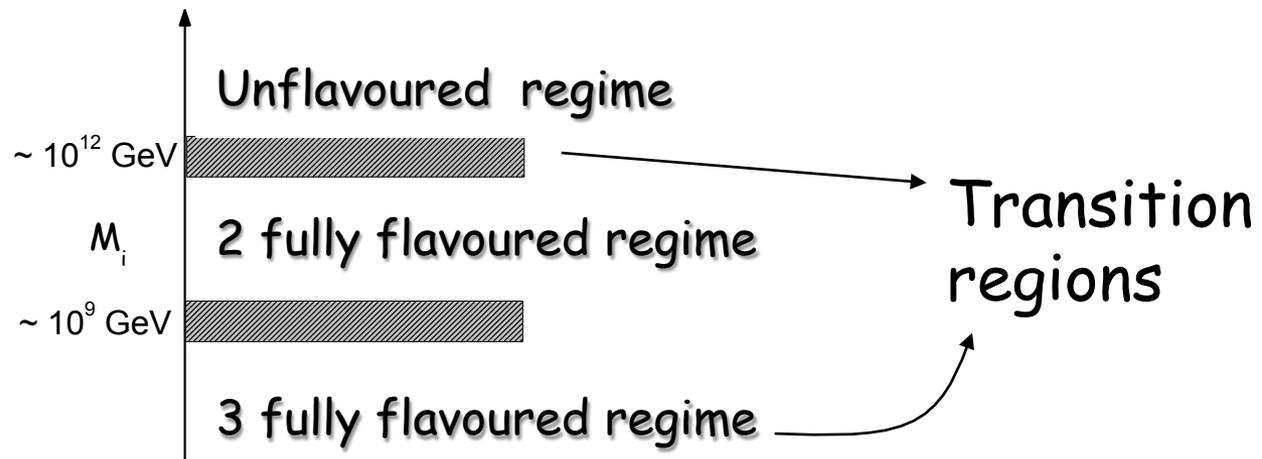
Flavor composition of lepton quantum states:

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

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

But for $T \gtrsim 10^{12} \text{ GeV} \Rightarrow \tau$ -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 $|\bar{l}'_1\rangle \Rightarrow$ they become an incoherent mixture of a τ and of a $\mu+e$ component

At $T \gtrsim 10^9 \text{ GeV}$ then also μ -Yukawas in equilibrium \Rightarrow 3-flavor regime



Two fully flavoured regime

$$\begin{aligned}
 (\alpha = \tau, e+\mu) \quad P_{1\alpha} &\equiv |\langle l_\alpha | l_1 \rangle|^2 = P_{1\alpha}^0 + \Delta P_{1\alpha} / 2 & (\sum_\alpha P_{1\alpha}^0 = 1) \\
 \bar{P}_{1\alpha} &\equiv |\langle \bar{l}_\alpha | \bar{l}_1 \rangle|^2 = P_{1\alpha}^0 - \Delta P_{1\alpha} / 2 & (\sum_\alpha \Delta P_{1\alpha} = 0)
 \end{aligned}$$

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

- Classic Kinetic Equations (in their simplest form)

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

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

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

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

Additional contribution to CP violation:

(Nardi, Racker, Roulet '06)

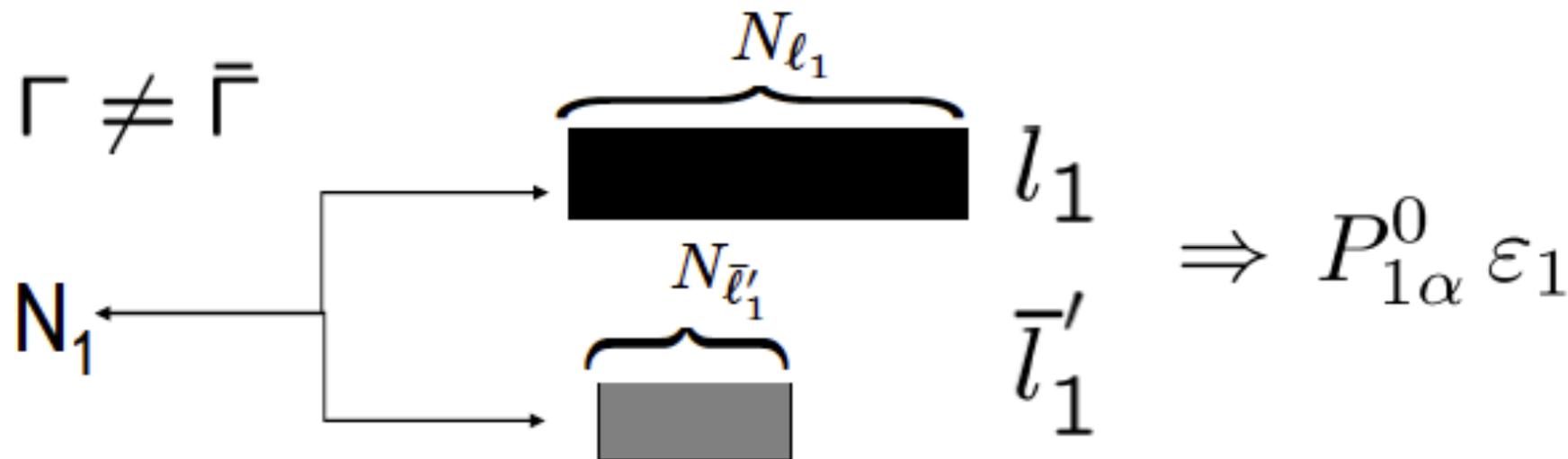
($\alpha = \tau, e+\mu$)

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

depends on U!

1)

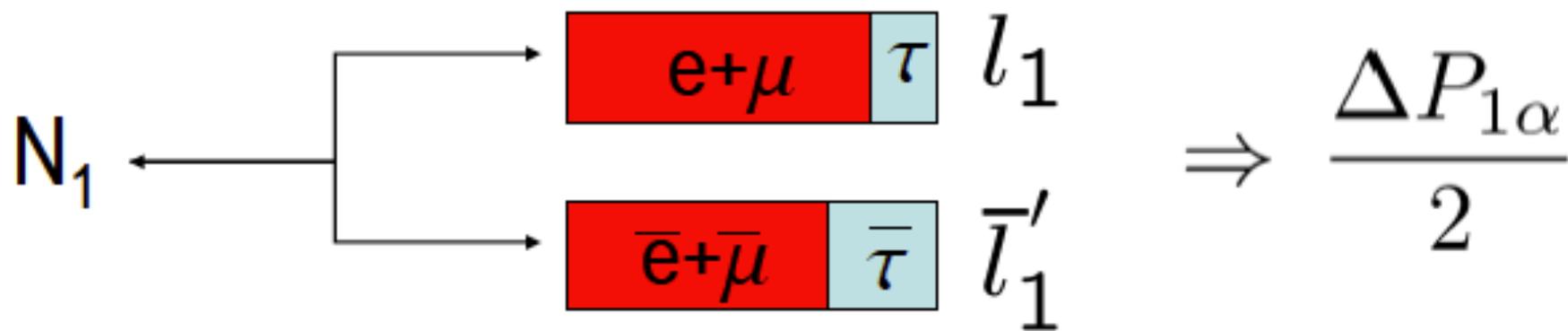
$$\Gamma \neq \bar{\Gamma}$$



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)

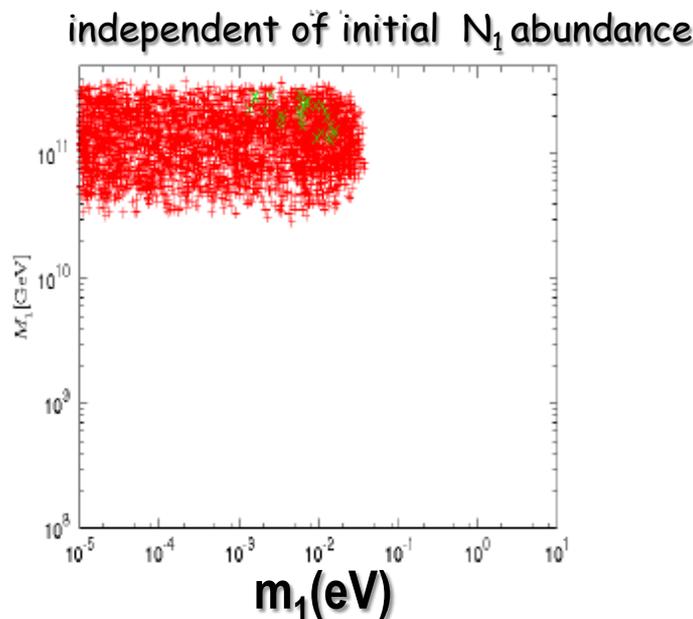
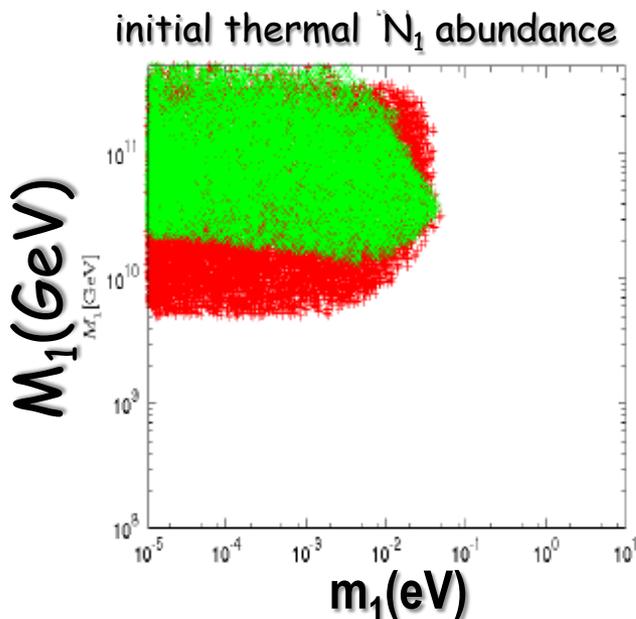
- Assume real $\Omega \Rightarrow \varepsilon_1 = 0 \Rightarrow \varepsilon_{1\alpha} = P_{1\alpha}^0 \varepsilon_1 + \frac{\Delta P_{1\alpha}}{2}$

$\Rightarrow N_{B-L} \Rightarrow \cancel{2\varepsilon_1 k_1^{\text{fin}}} + \Delta P_{1\alpha} (k_{1\alpha}^{\text{fin}} - k_{1\beta}^{\text{fin}}) \quad (\alpha = \tau, e+\mu)$

- 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 $\sin \theta_{13} = 0.2$
 $|\sin \delta| = 1$

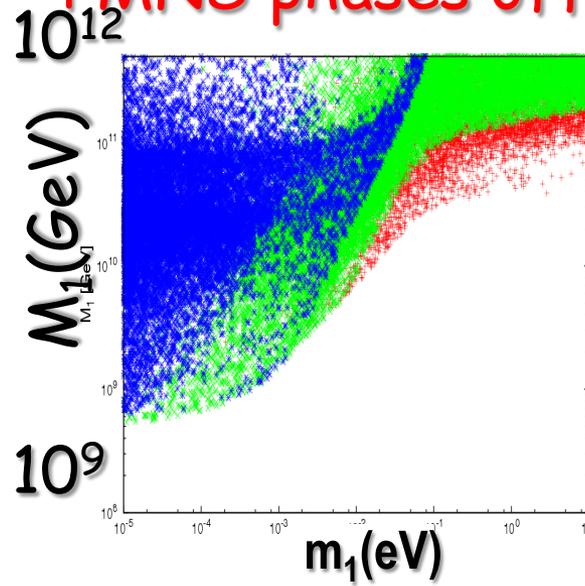
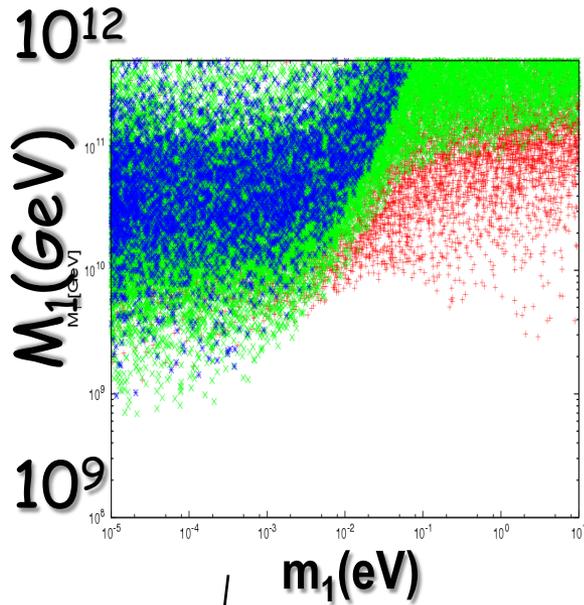
Red points:
only Majorana
phases

- No reasons for these assumptions to be rigorously satisfied (Davidson, Rius et al. '07)
- In general this contribution is *overwhelmed* by the high energy phases
- 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 have successful leptogenesis**

Upper bound on m_1

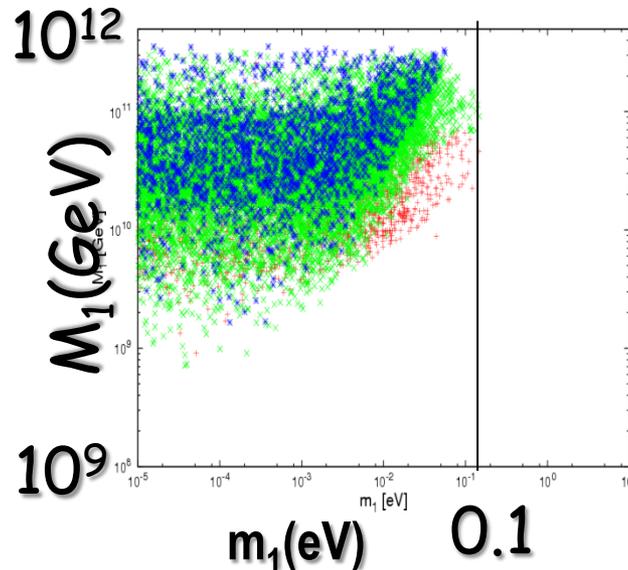
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)

PMNS phases off



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

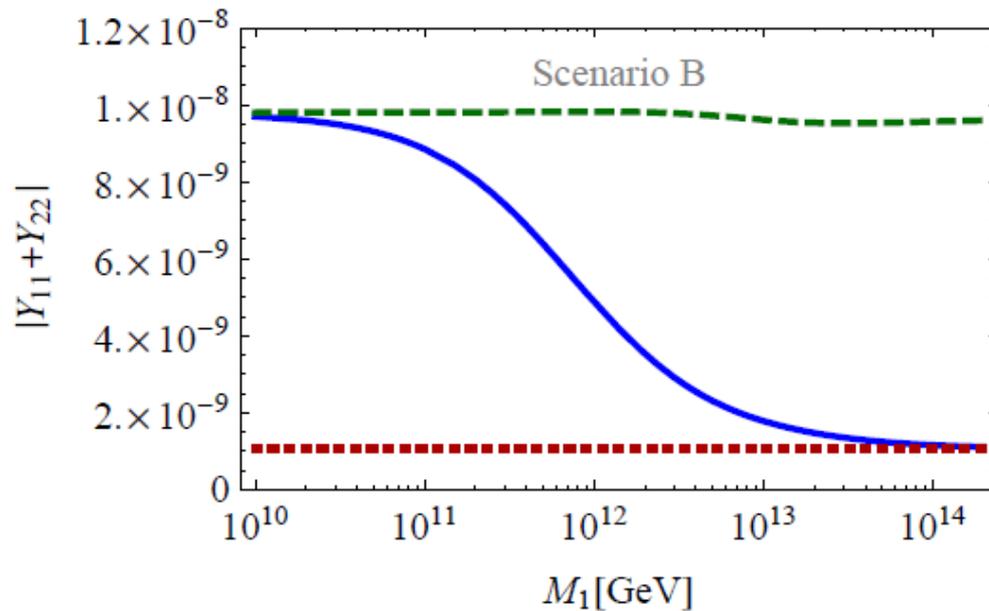
imposing a condition of validity of Boltzmann equations



Density matrix and CTP formalism to describe the transition regimes

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

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



Fully two-flavoured regime limit

Unflavoured regime limit

Heavy neutrino flavour effects:

N_2 -dominated scenario

(PDB '05)

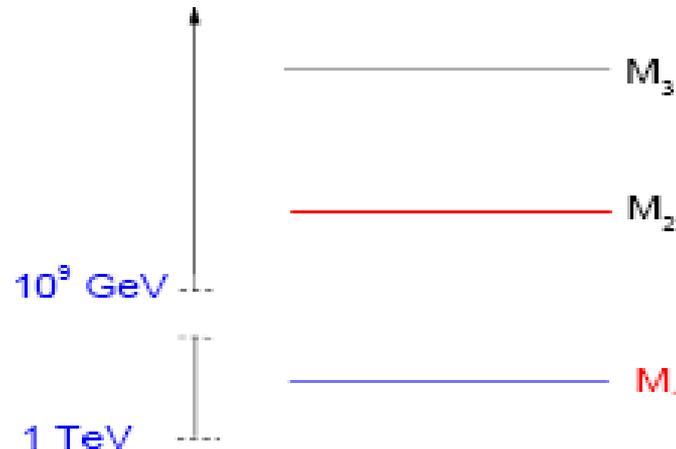
If light flavour effects are neglected the asymmetry from the next-to-lightest (N_2) RH neutrinos is typically negligible:

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

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

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

The lower bound on M_1 disappears and is replaced by a lower bound on M_2 ...
that however still implies a lower bound on T_{reh} !

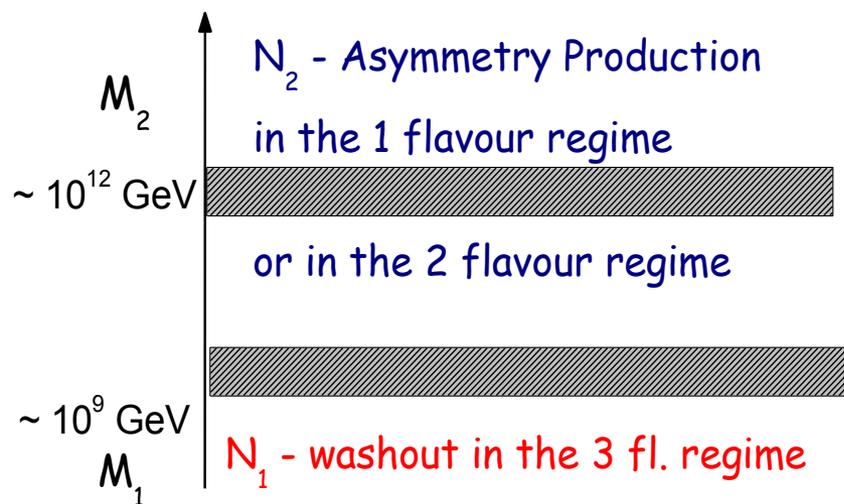


N_2 -flavored leptogenesis

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

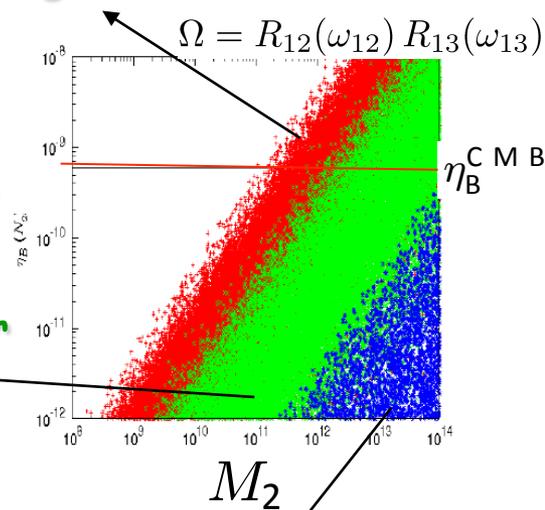
Combining together lepton and heavy neutrino flavour effects one has

A two stage process:



Wash-out is neglected

Both wash-out and flavor effects



Unflavored case

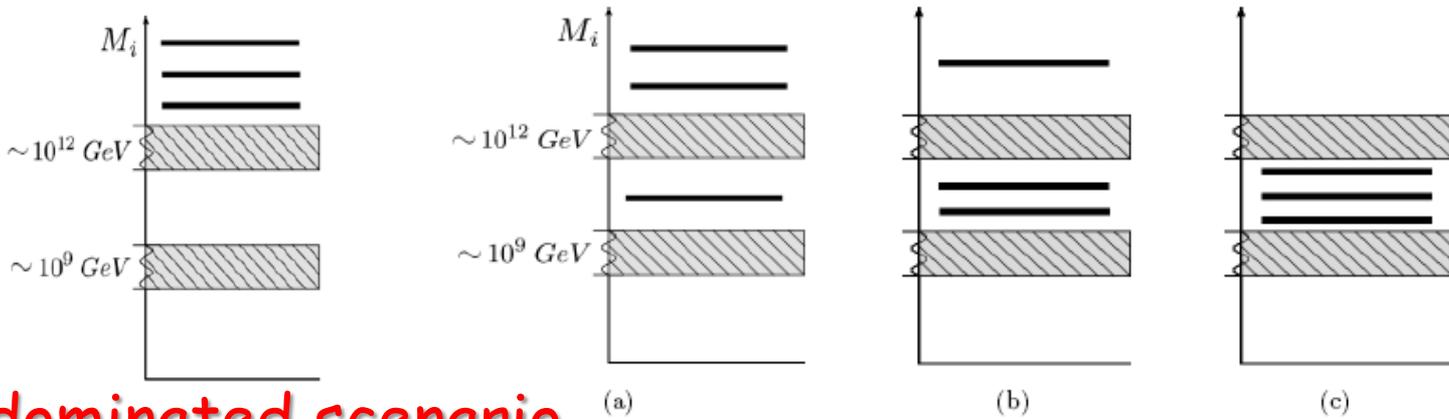
$$N_{B-L}^f(N_2) = P_{2e}^0 \varepsilon_2 \kappa(K_2) e^{-\frac{3\pi}{8} K_{1e}} + P_{2\mu}^0 \varepsilon_2 \kappa(K_2) e^{-\frac{3\pi}{8} K_{1\mu}} + P_{2\tau}^0 \varepsilon_2 \kappa(K_2) e^{-\frac{3\pi}{8} K_{1\tau}}$$

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

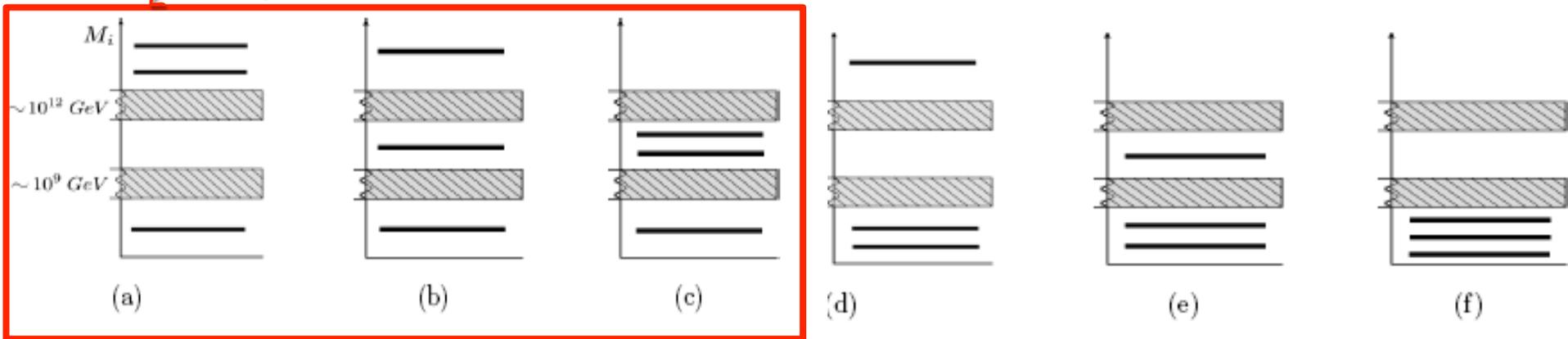
With flavor effects the domain of applicability goes much beyond the choice $\Omega = R_{23}$

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

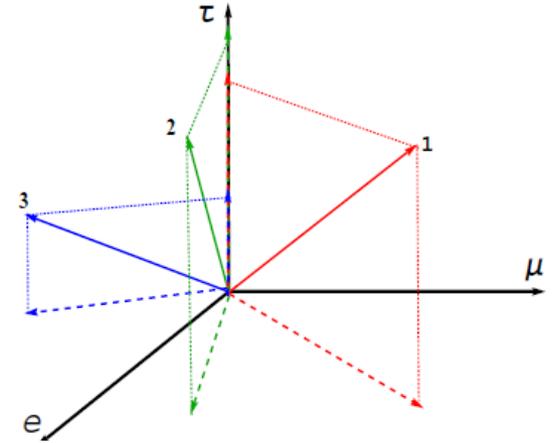


For each pattern a specific set of Boltzmann equations has to be considered

Density matrix formalism with heavy neutrino flavours

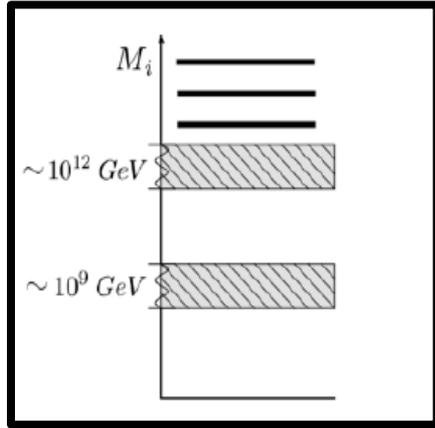
(Blanchet, PDB, Jones, Marzola '11)

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:

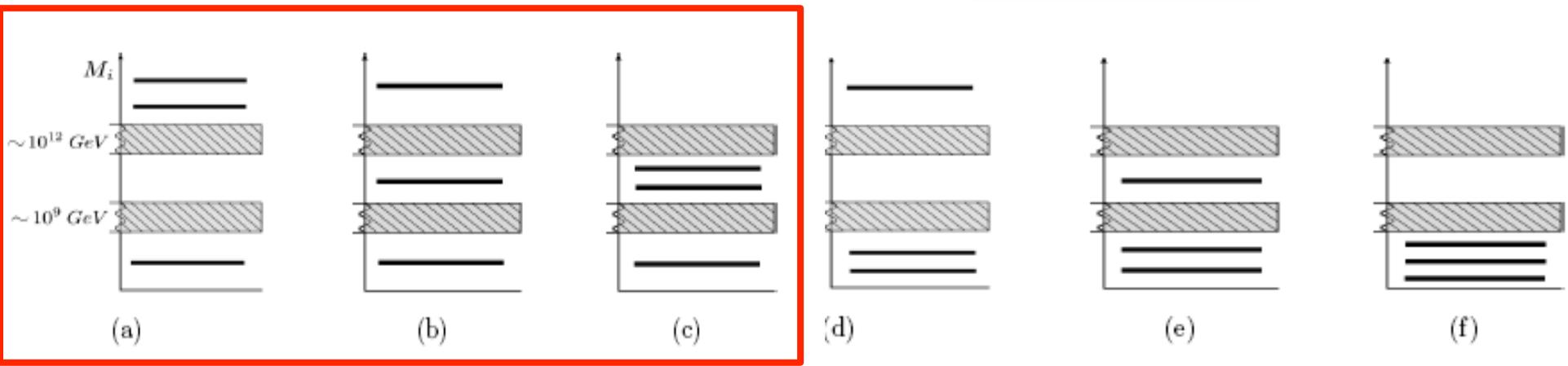
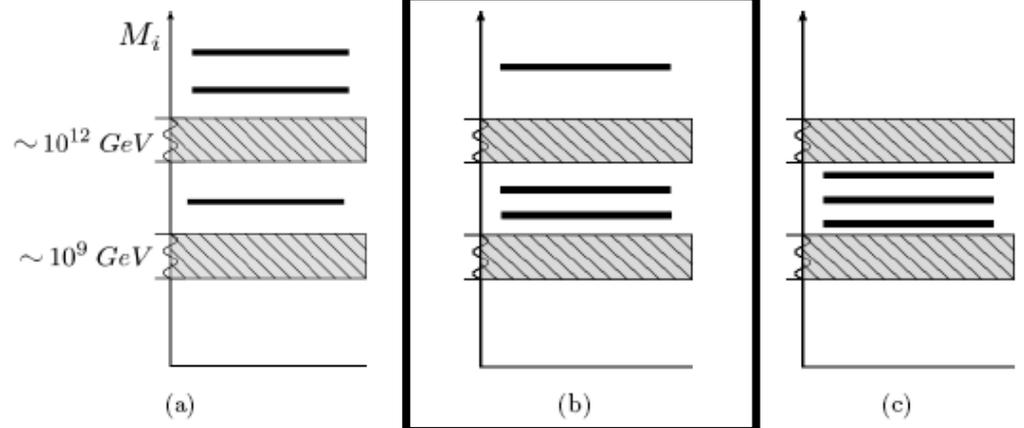


$$\begin{aligned}
 \frac{dN_{\alpha\beta}^{B-L}}{dz} &= \varepsilon_{\alpha\beta}^{(1)} D_1 (N_{N_1} - N_{N_1}^{\text{eq}}) - \frac{1}{2} W_1 \{ \mathcal{P}^{0(1)}, N^{B-L} \}_{\alpha\beta} \\
 &+ \varepsilon_{\alpha\beta}^{(2)} D_2 (N_{N_2} - N_{N_2}^{\text{eq}}) - \frac{1}{2} W_2 \{ \mathcal{P}^{0(2)},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

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)

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

Independent of α_1 and α_3 !

$\alpha_2=5$

$\alpha_2=4$

$\alpha_2=3$

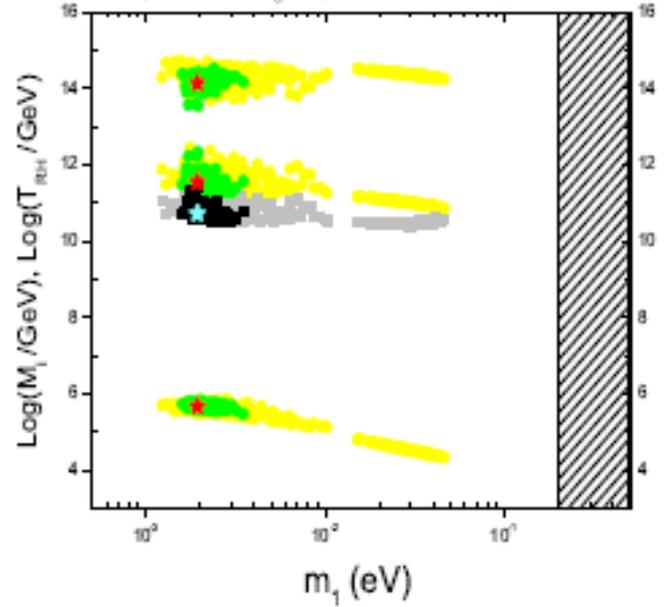
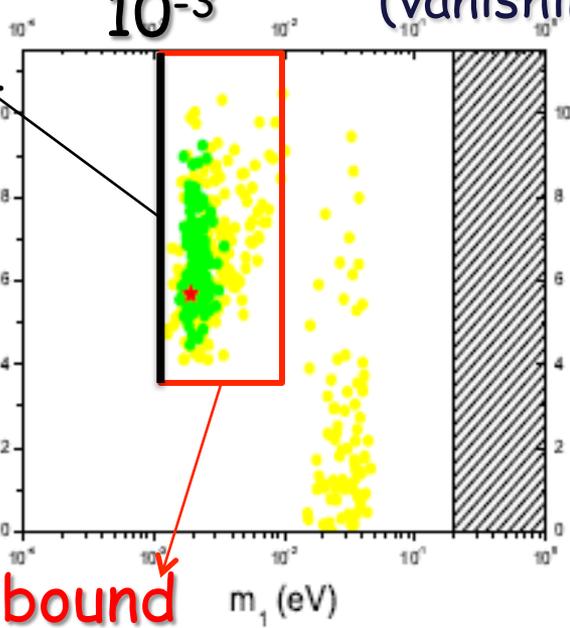
$V_L = I$ Normal ordering

(vanishing initial N_2 -abundance)

lower bound on m_1

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 !

M_i

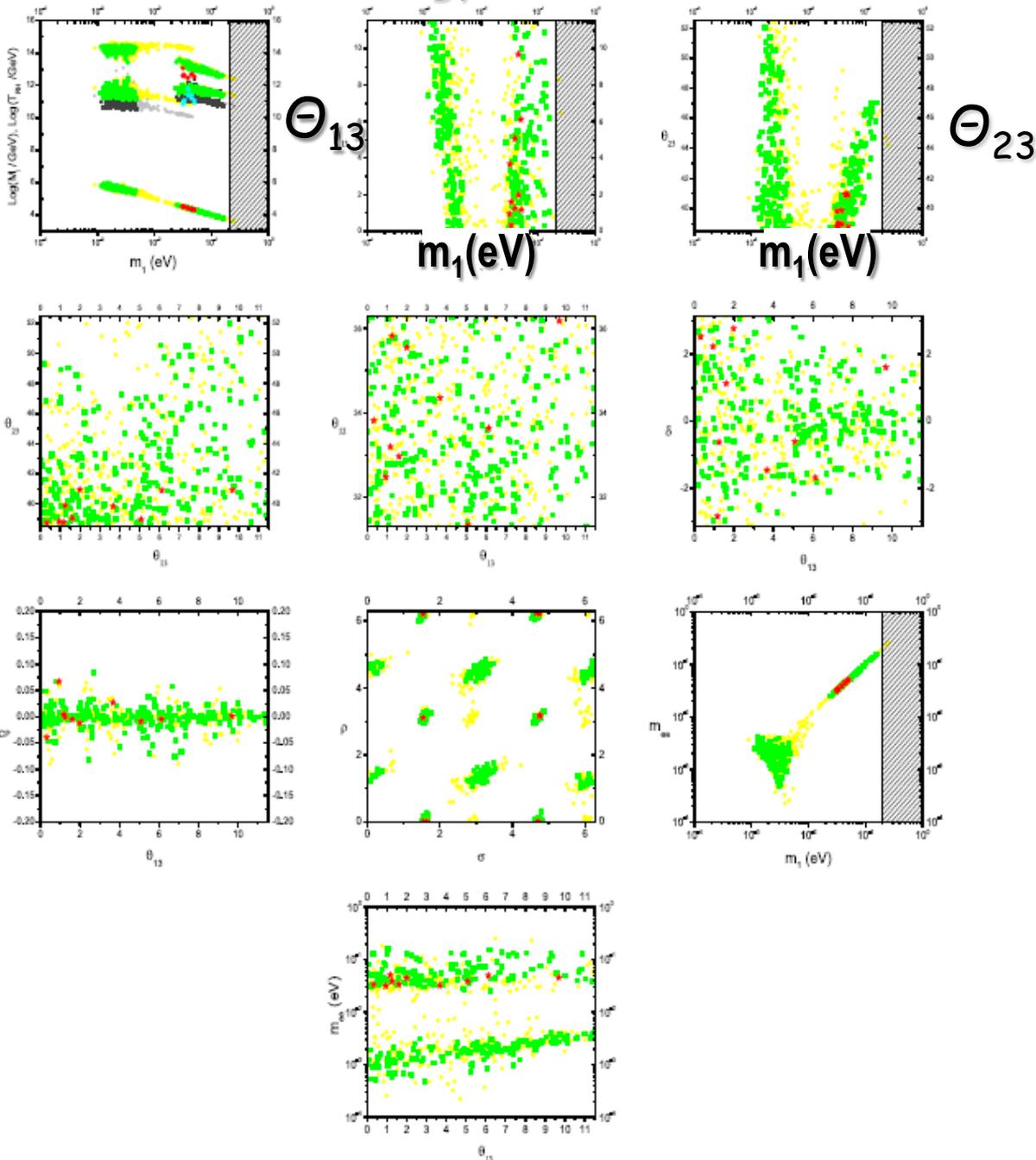
$$I \leq V_L \leq V_{CKM}$$

NORMAL ORDERING

$$\alpha_2 = 5$$

$$\alpha_2 = 4$$

$$\alpha_2 = 1$$



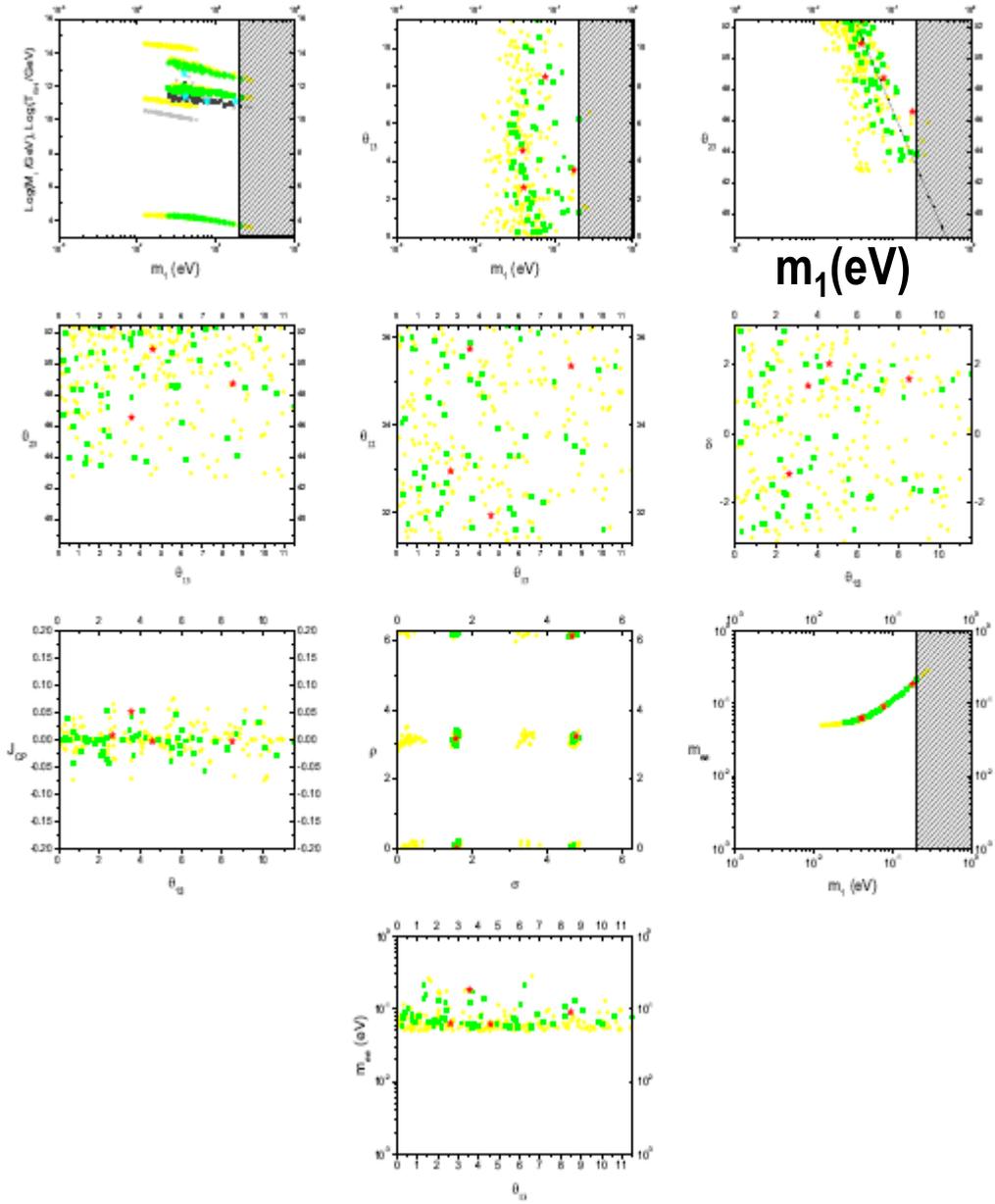
$$I \leq V_L \leq V_{CKM}$$

INVERTED ORDERING

$$\alpha_2 = 5$$

$$\alpha_2 = 4$$

$$\alpha_2 = 1.5$$



Θ_{23}

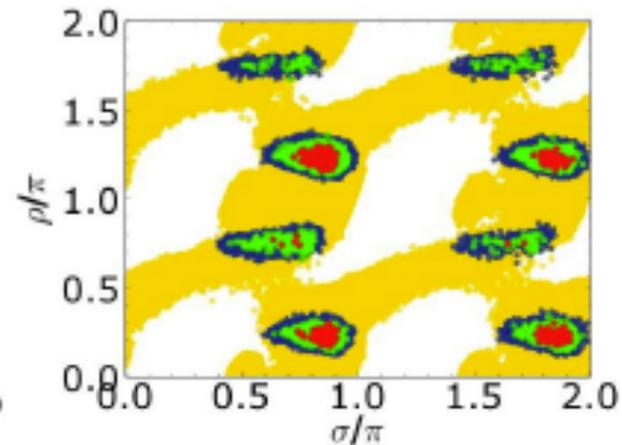
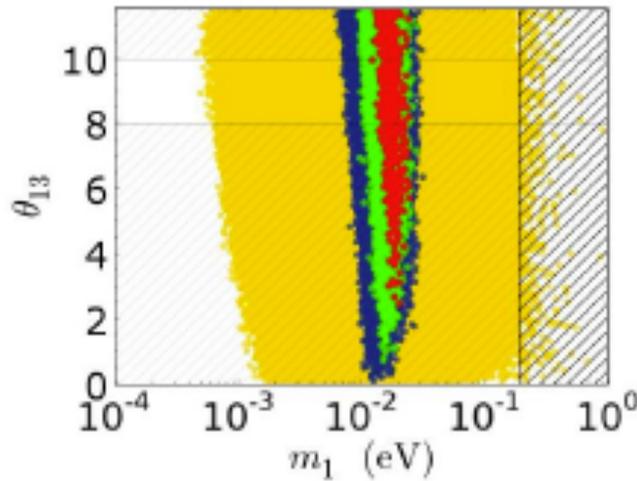
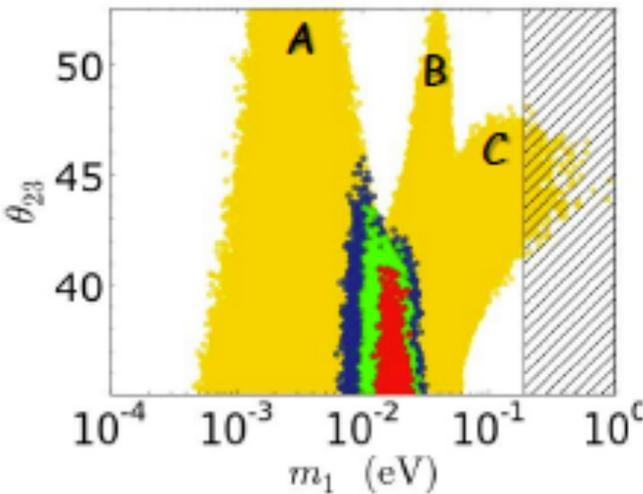
An improved analysis

(PDB, Marzola '11-'12)

We optimised the procedure increasing of two orders of magnitudes the number of solutions (yellow points):

$\alpha_2=5$ NORMAL ORDERING

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



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

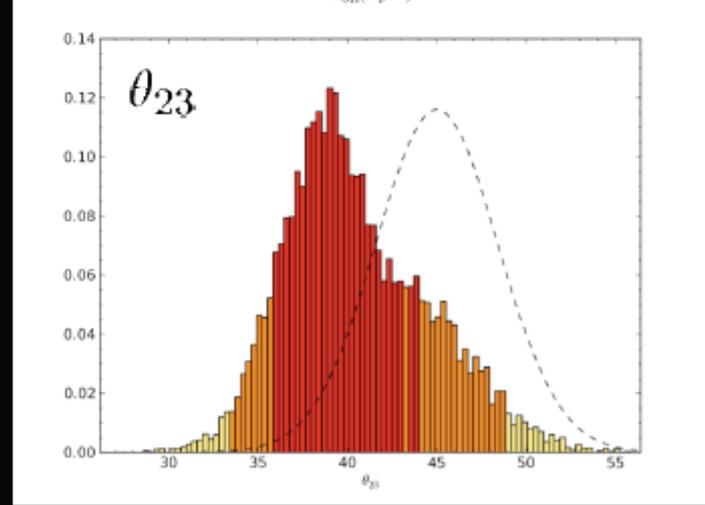
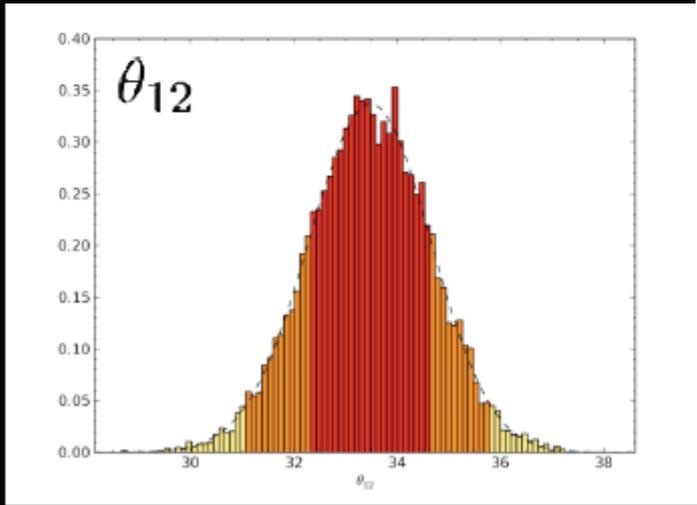
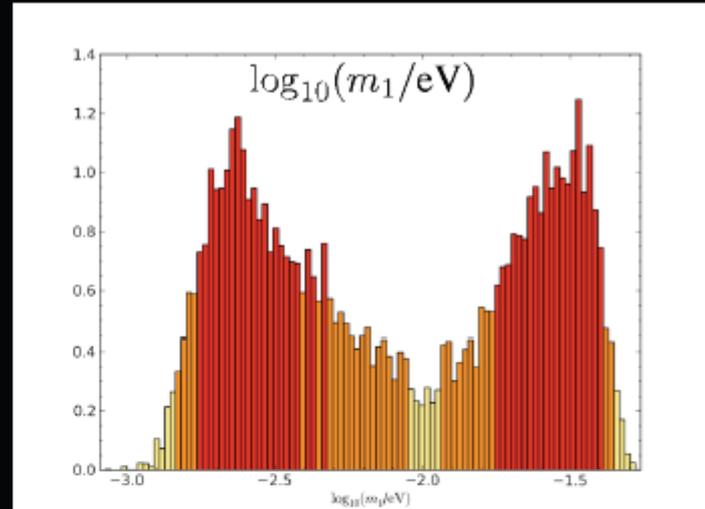
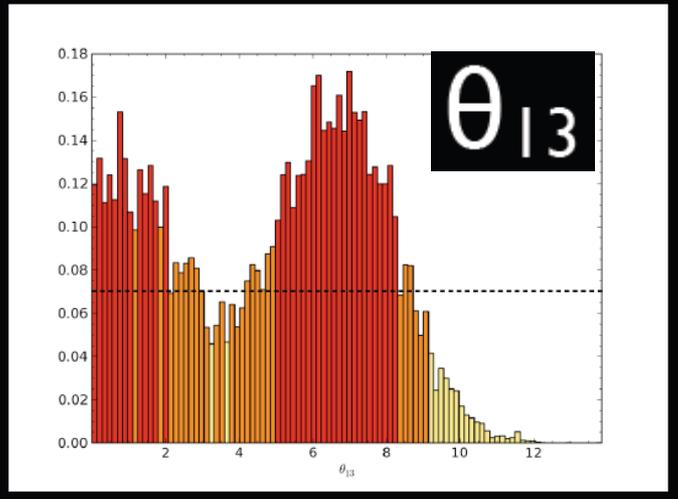
- statistical analysis
- to obtain the blue green and red points

A statistical analysis

P. Di Bari, L. M., S. Huber, S. Peeters - work in progress

68% C.L.

95% C.L.



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

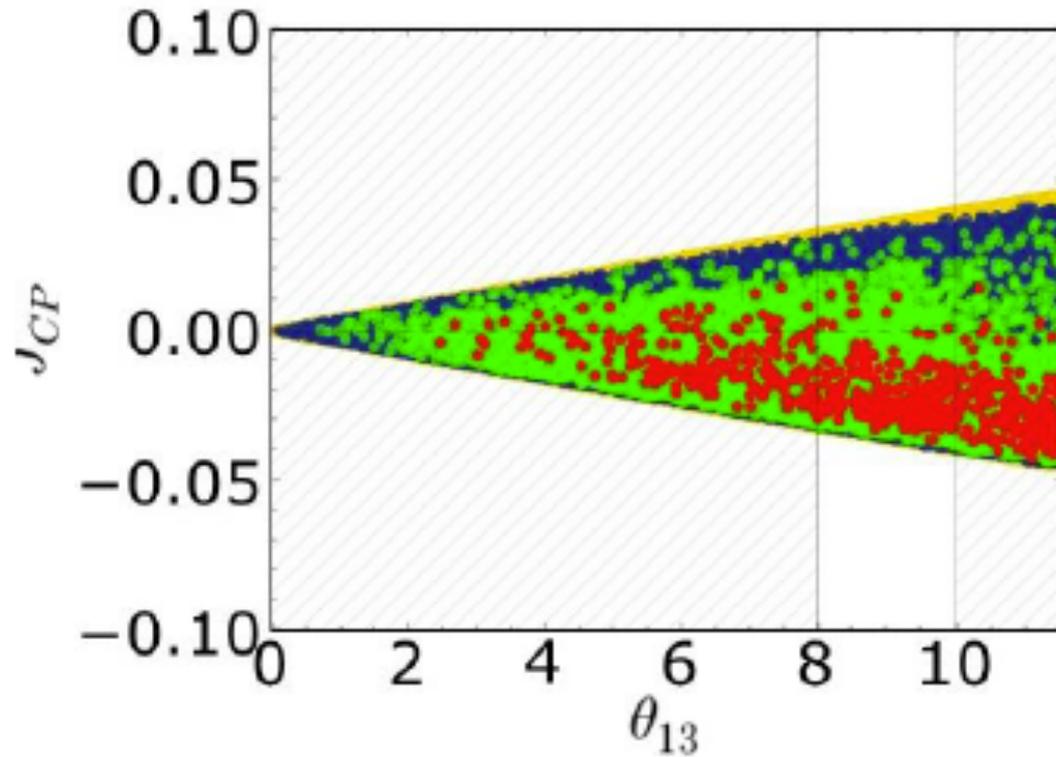
No link between the sign of the asymmetry and J_{CP}

(PDB, Marzola)

$$\alpha_2 = 5$$

NORMAL
ORDERING

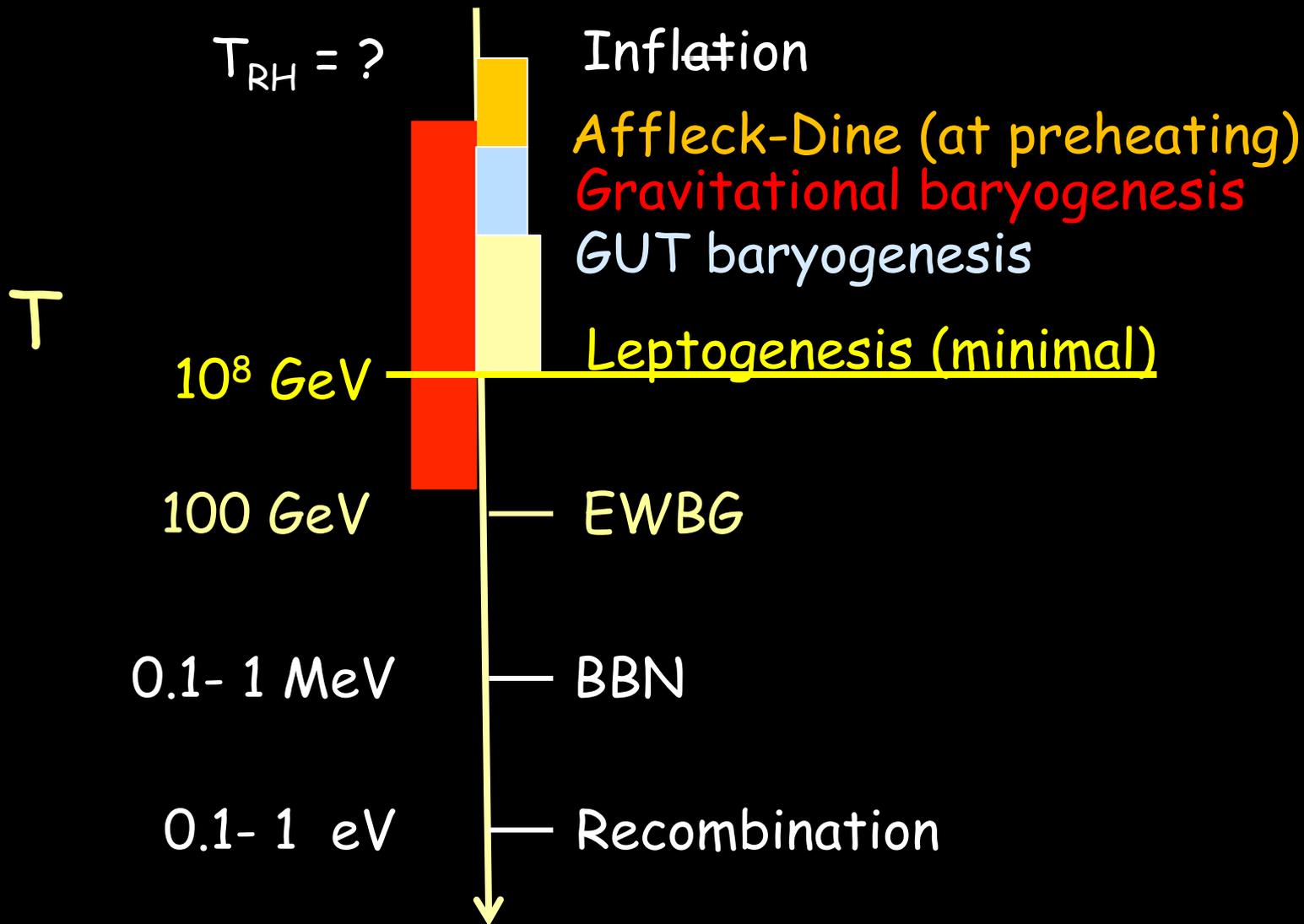
$$I \leq V_L \leq V_{CKM}$$



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 ?

Baryogenesis and the early Universe history

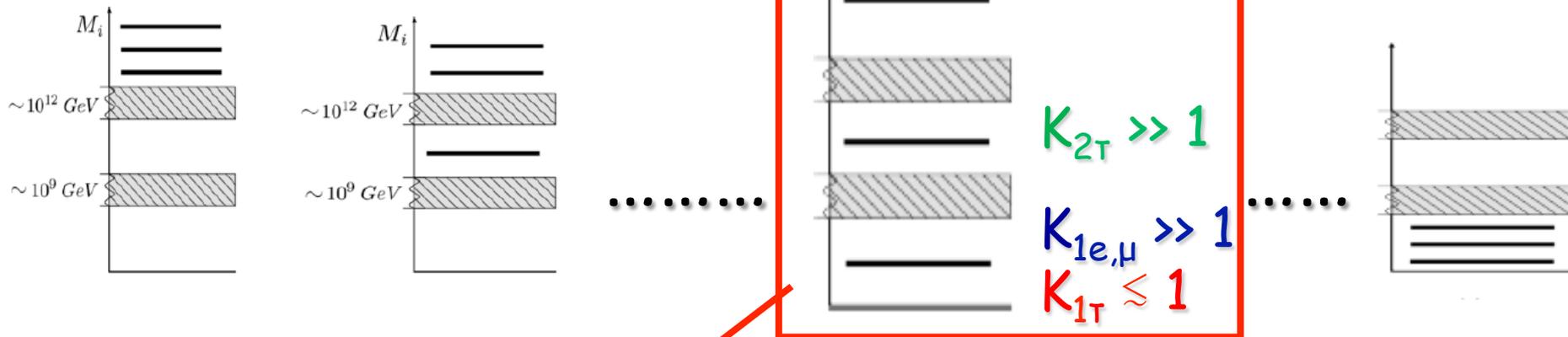


(Bertuzzo, PDB, Marzola '10)

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

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

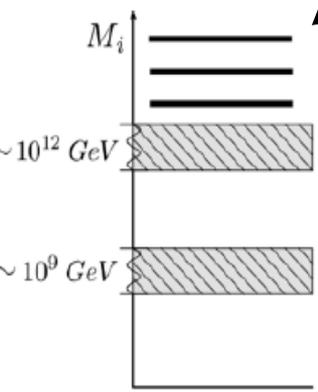
Asymmetry generated from leptogenesis



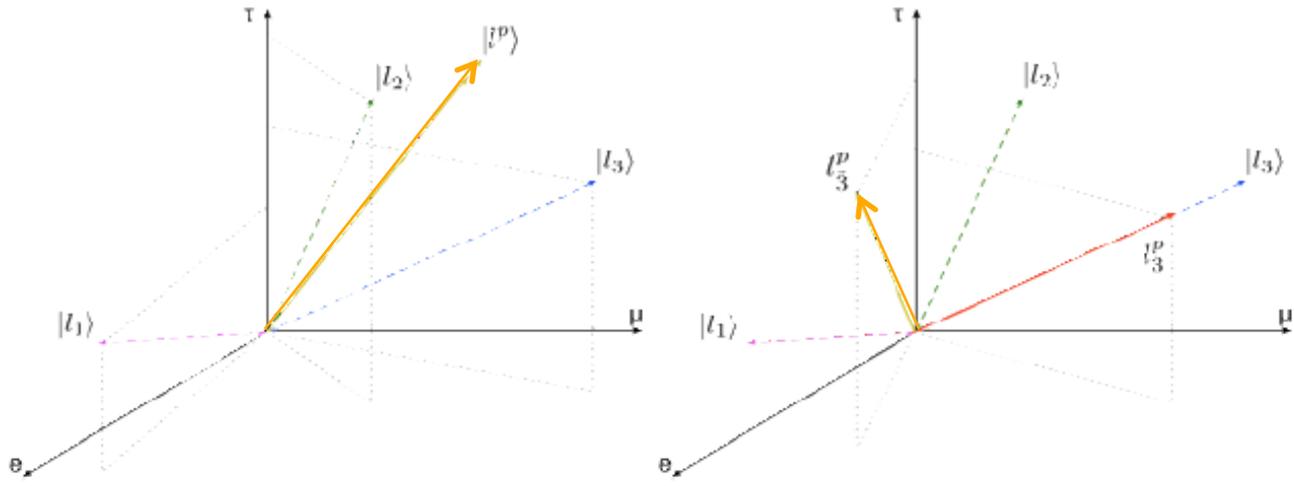
The conditions for the wash-out of a pre-existing asymmetry ('strong thermal leptogenesis') can be realised only within a N_2 -dominated scenario where the final asymmetry is dominantly produced in the tauon flavour

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

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

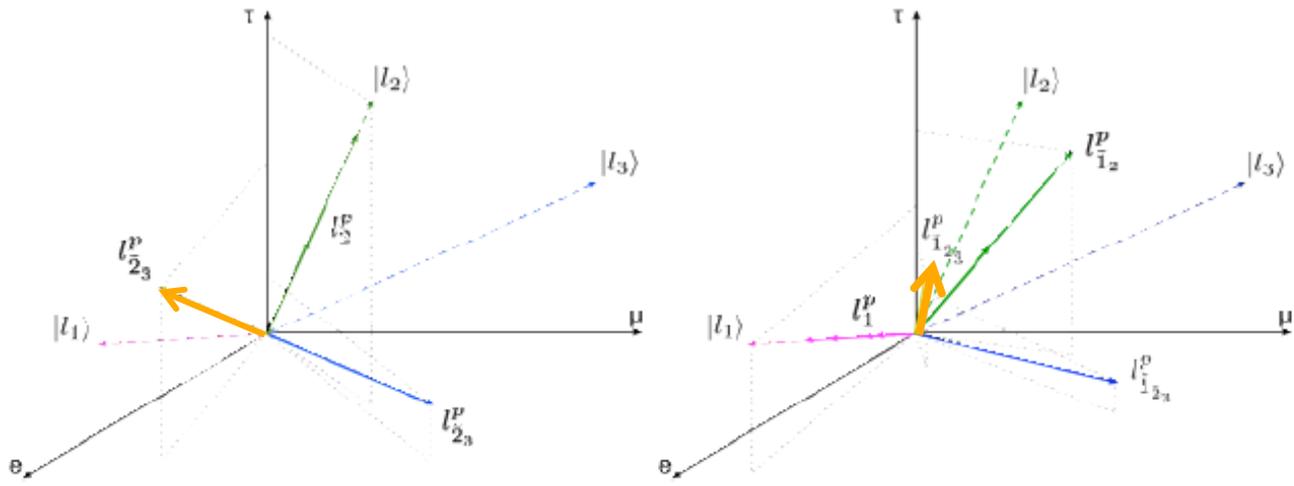


The pre-existing asymmetry (yellow) undergoes a 3 step flavour projection



(a) $T \gg M_3$

(b) $T \sim M_3$



(c) $T \sim M_2$

(d) $T \sim M_1$

Wash-out of a pre-existing asymmetry in $SO(10)$ -inspired leptogenesis

(PDB, Marzola '11)

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

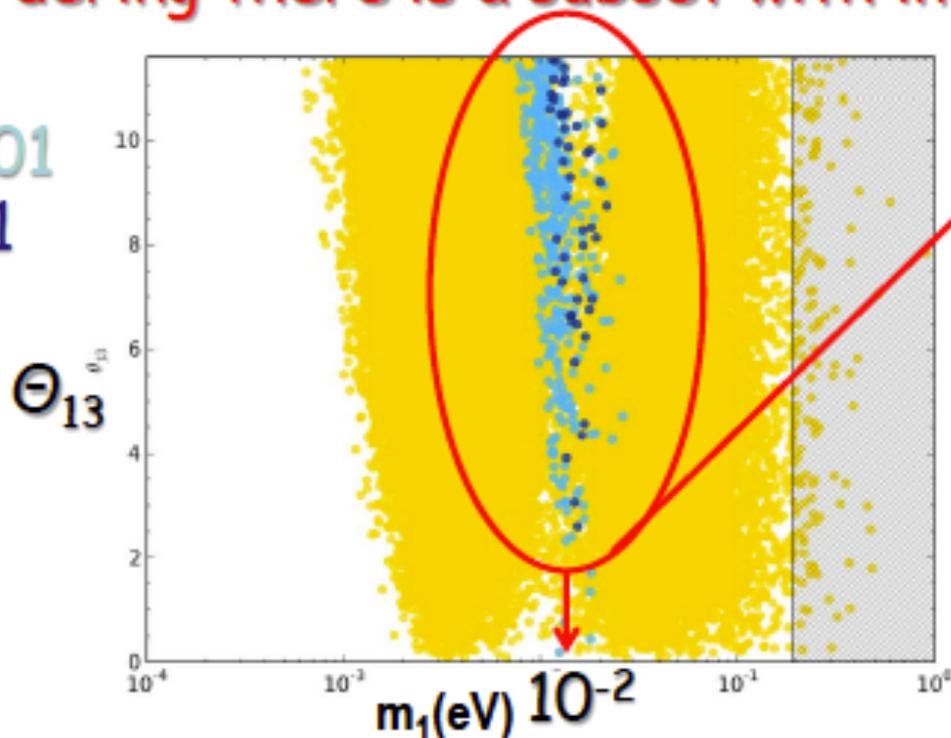
Imposing both successful $SO(10)$ -inspired leptogenesis
 $\eta_B = \eta_B^{CMB} = (6.2 \pm 0.15) \times 10^{-10}$ and $N_{B-L}^{p,f} \ll N_{B-L}^{lep,f}$

NO Solutions for Inverted Ordering, while for
 Normal Ordering there is a subset with interesting predictions:

$$N_{B-L}^{p,f} = 0$$

0.001

0.01



Non-vanishing θ_{13}

Talk at the DESY
 theory workshop
 28/9/11

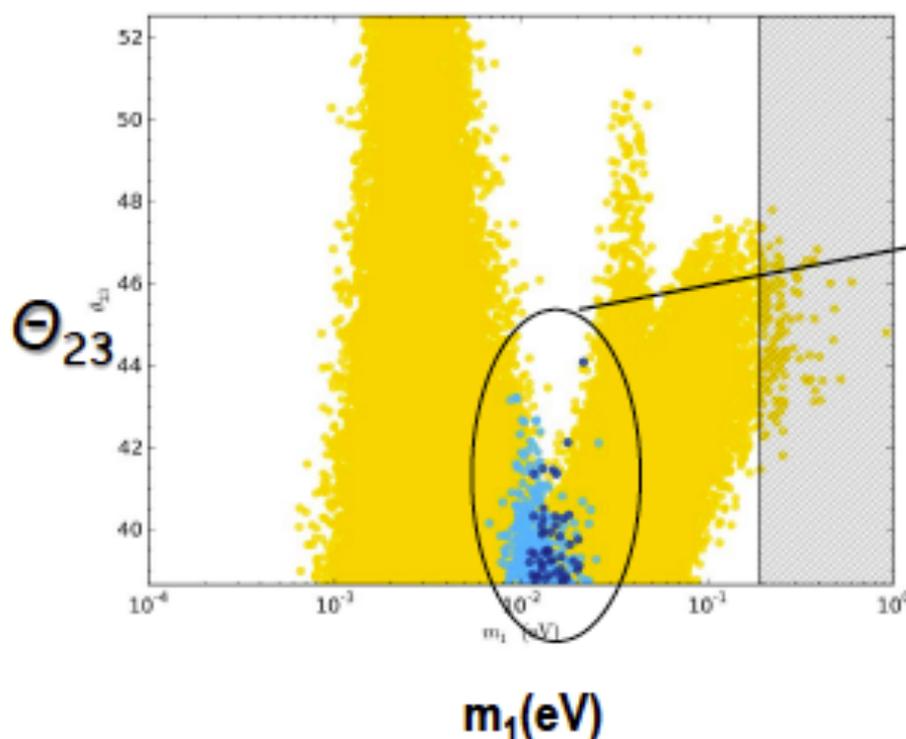
Wash-out of a pre-existing asymmetry

(PDB, Marzola '11)

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

Imposing both successful $SO(10)$ -inspired leptogenesis
 $\eta_B = \eta_B^{\text{CMB}} = (6.2 \pm 0.15) \times 10^{-10}$ and $N_{B-L}^{p,f} \ll N_{B-L}^{\text{lep},f}$

$N_{B-L}^{p,f} = 0$
0.001
0.01



Low values of θ_{23}

Talk at the DESY
theory workshop
28/9/11

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

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

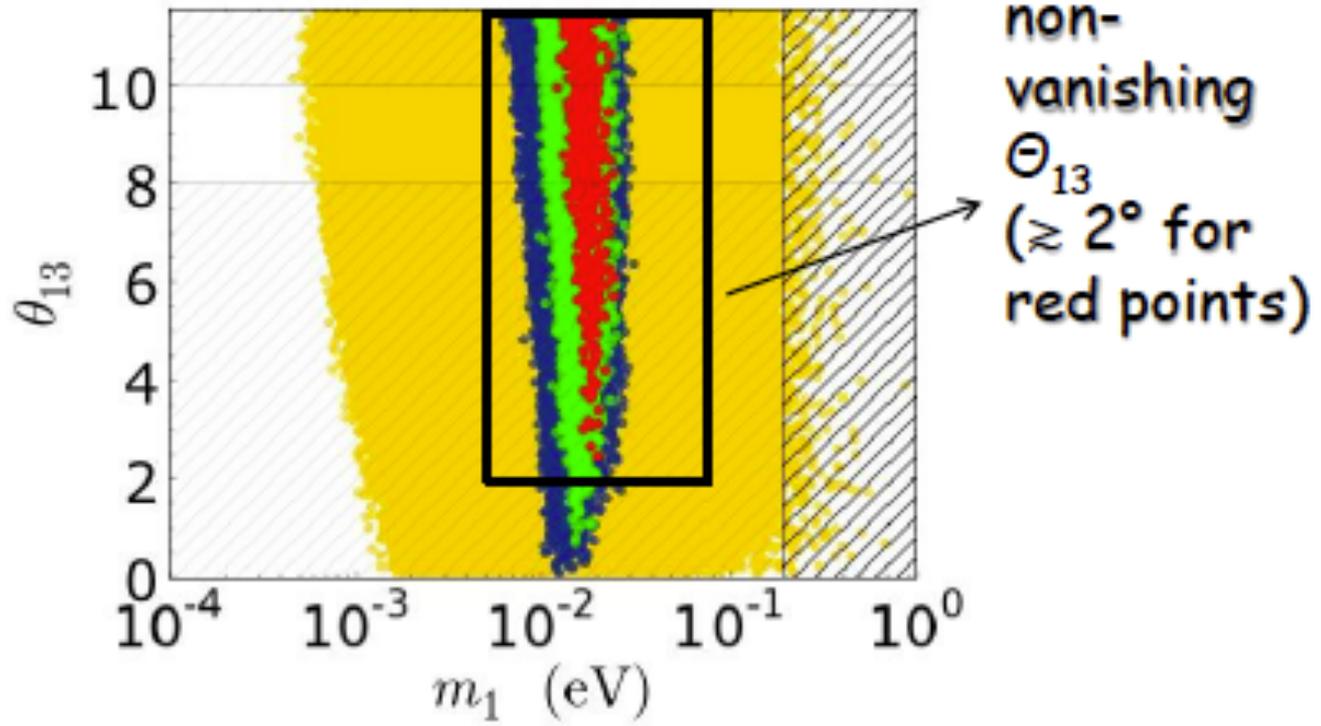
Imposing both successful SO(10)-inspired leptogenesis
 $\eta_B = \eta_B^{\text{CMB}} = (6.2 \pm 0.15) \times 10^{-10}$ and $N_{B-L}^{p,f} \ll N_{B-L}^{\text{lep},f}$

There are NO Solutions for Inverted Ordering !

But for Normal Ordering there is a subset with definite predictions
NON-VANISHING REACTOR MIXING ANGLE

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

$\alpha_2 = 5$



SO(10)-inspired+strong thermal leptogenesis

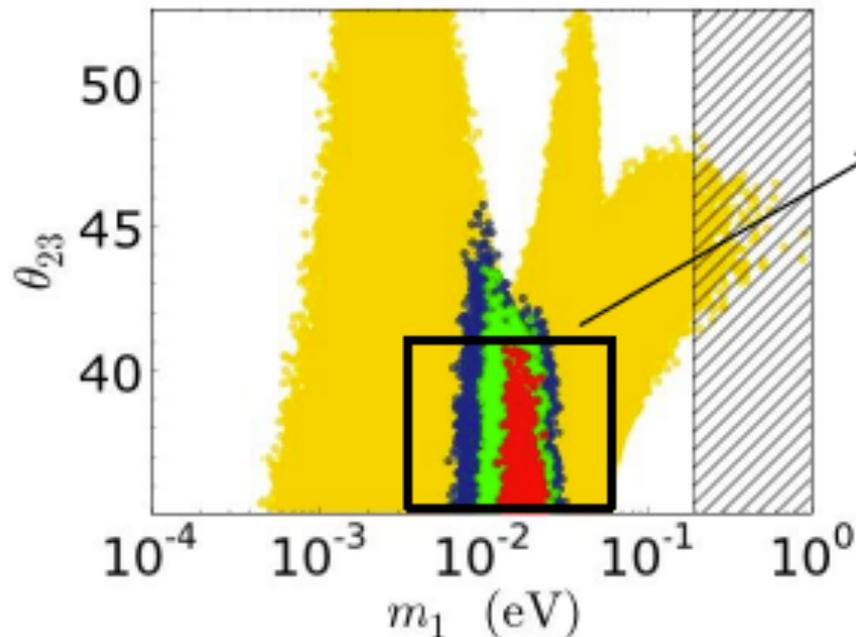
(PDB, Marzola '11,'12) $N_{B-L}^f = N_{B-L}^{p,f} + N_{B-L}^{lep,f}$,

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

UPPER BOUND ON THE ATMOSPHERIC MIXING ANGLE

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

$\alpha_2 = 5$



Small
atmospheric
mixing
Angle ($\approx 41^\circ$)

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

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

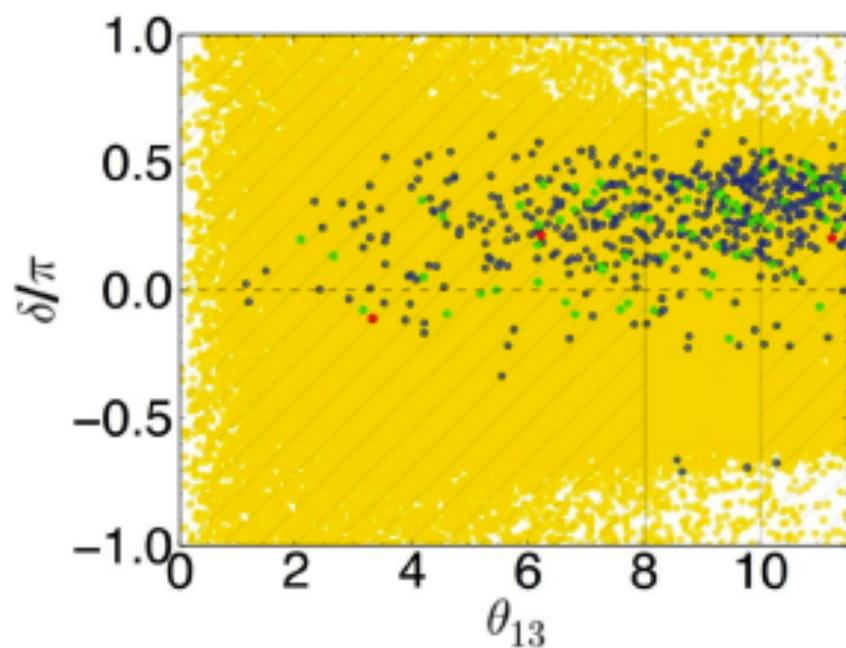
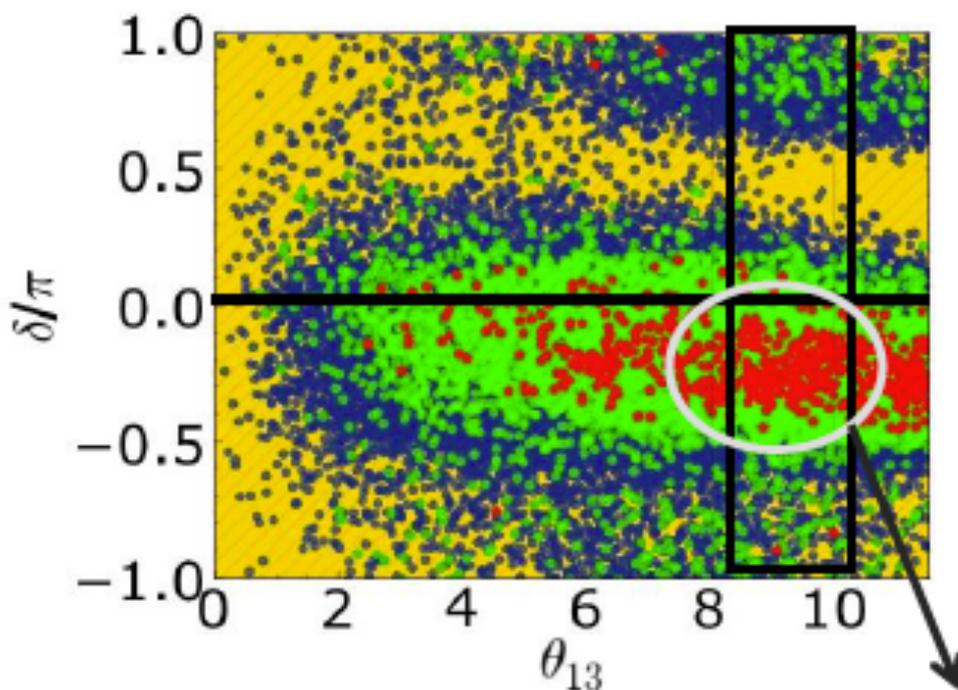
Imposing both successful SO(10)-inspired leptogenesis

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

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

$$\eta_B = \eta_B^{\text{CMB}}$$

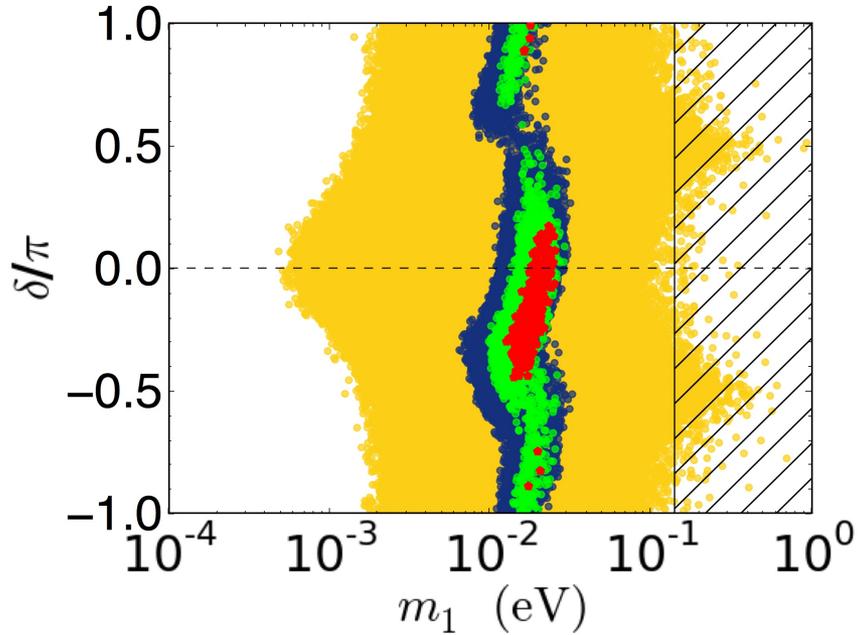
$$\eta_B = -\eta_B^{\text{CMB}}$$



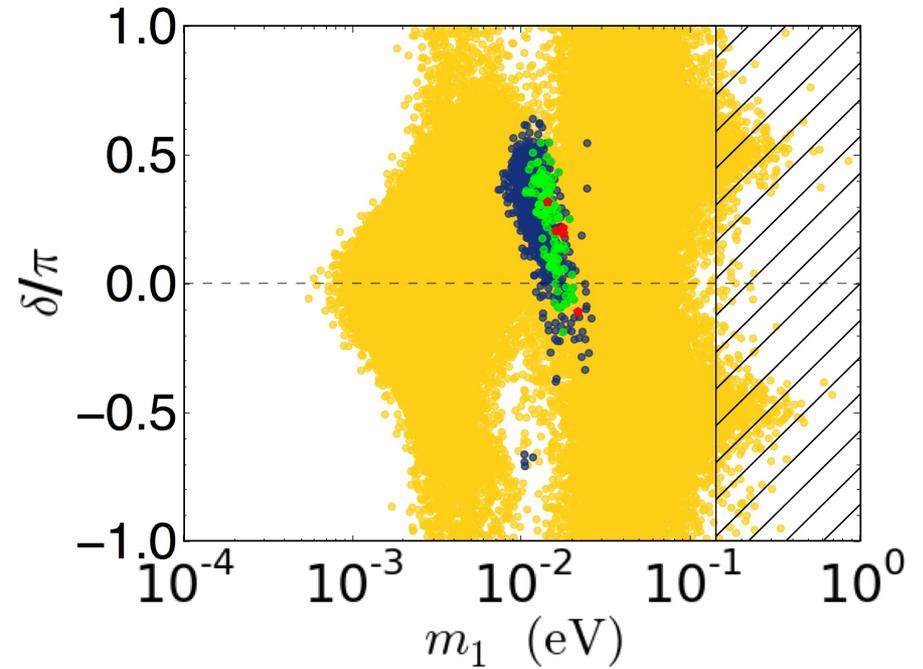
A Dirac phase $\delta \sim -60^\circ$ is favoured for large θ_{13}

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

$$\eta_B = \eta_{B}^{CMB}$$



$$\eta_B = -\eta_{B}^{CMB}$$



SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

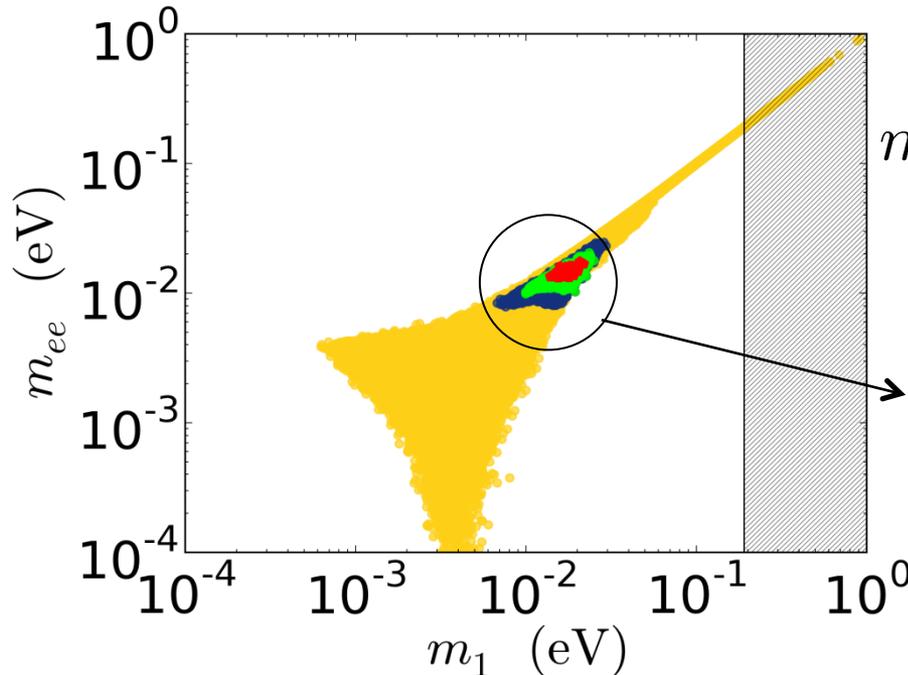
$$N_{B-L}^f = N_{B-L}^{p,f} + N_{B-L}^{\text{lep},f},$$

Imposing both successful SO(10)-inspired leptogenesis
 $\eta_B = \eta_B^{\text{CMB}} = (6.2 \pm 0.15) \times 10^{-10}$ and $N_{B-L}^{p,f} \ll N_{B-L}^{\text{lep},f}$

Sharp prediction on the absolute neutrino mass scale

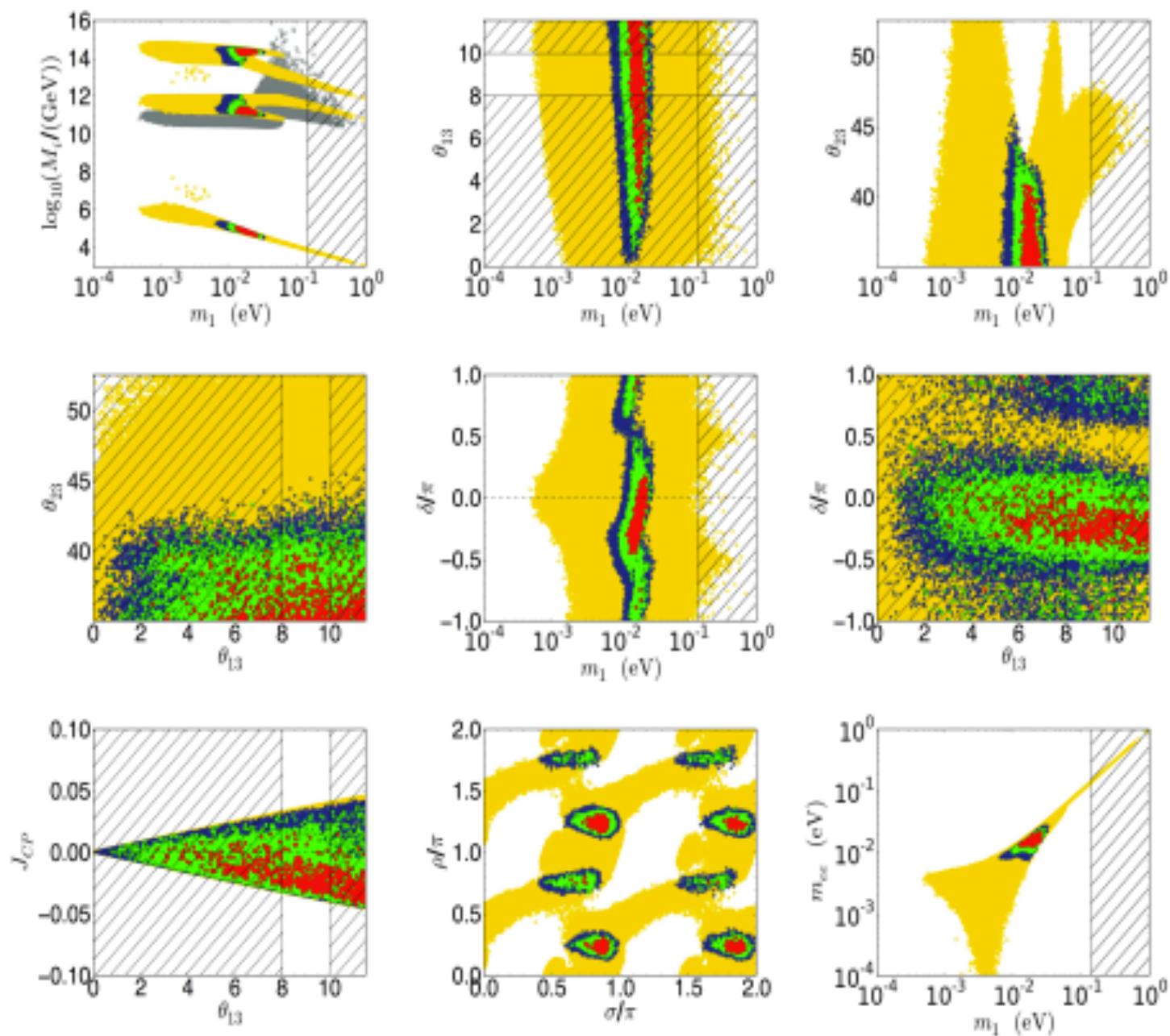
$N_{B-L} =$
0
0.001
0.01
0.1

$\alpha_2 = 5$



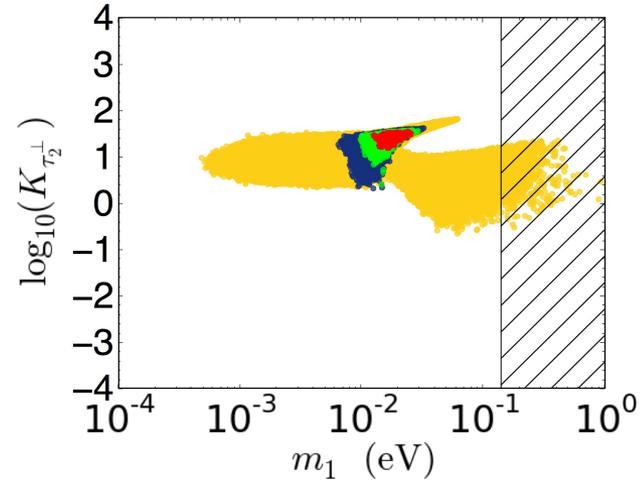
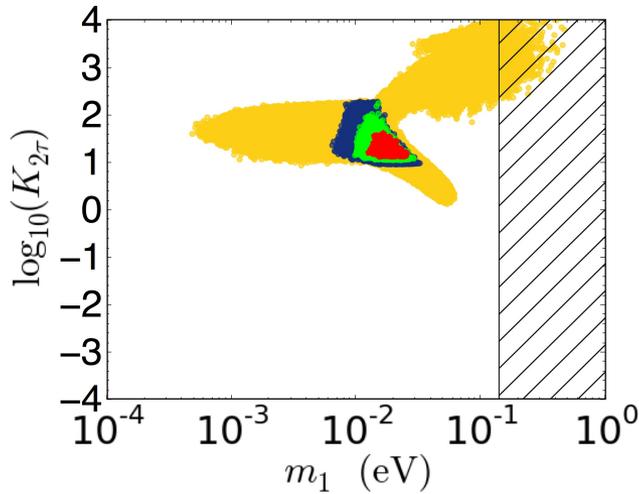
$m_1 \simeq m_{ee} \simeq 20 \text{meV}$

→ Testable (<2020?)

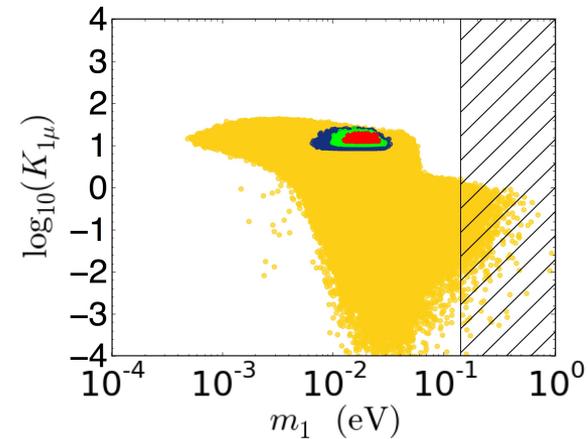
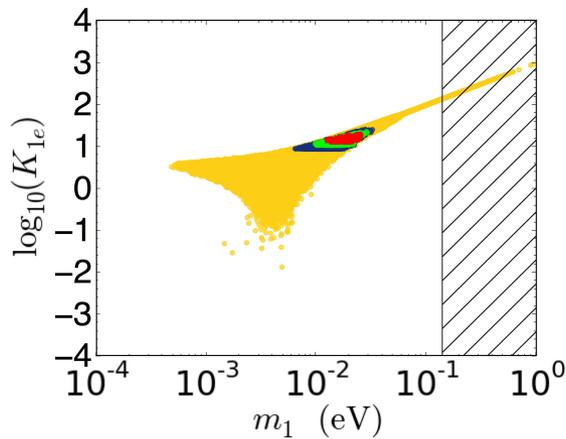
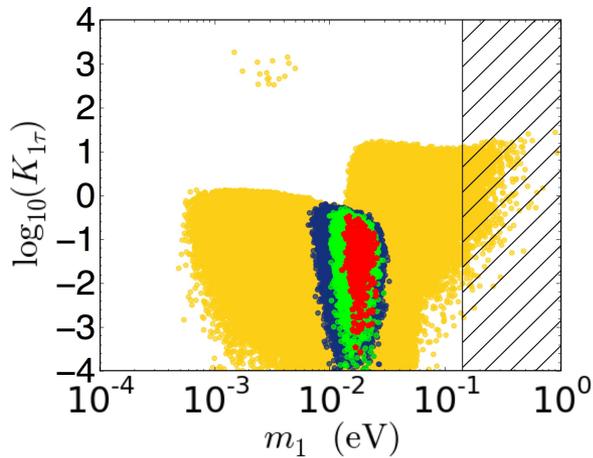


Some insight from the decay parameters

At the production
($T \sim M_2$)



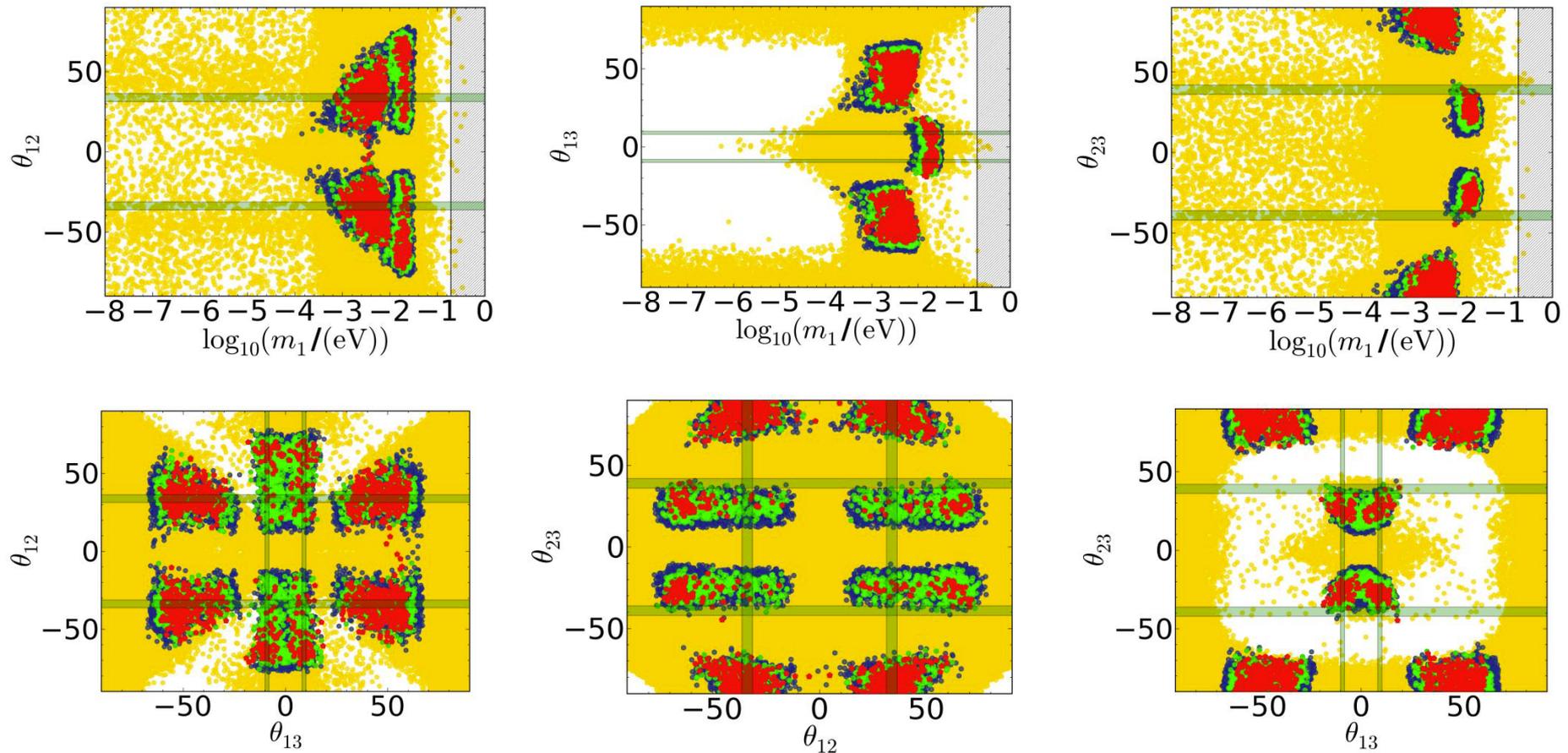
At the wash-out ($T \sim M_1$)



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

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

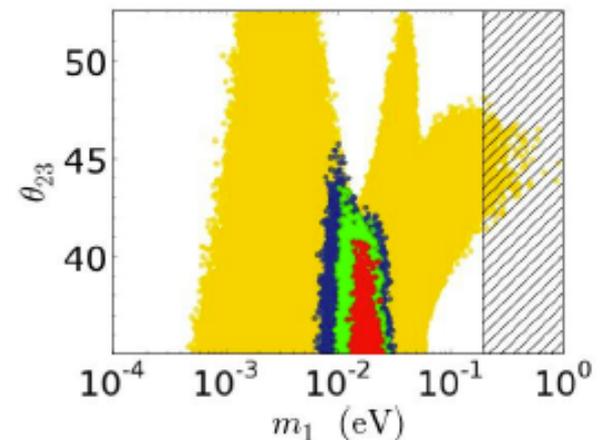
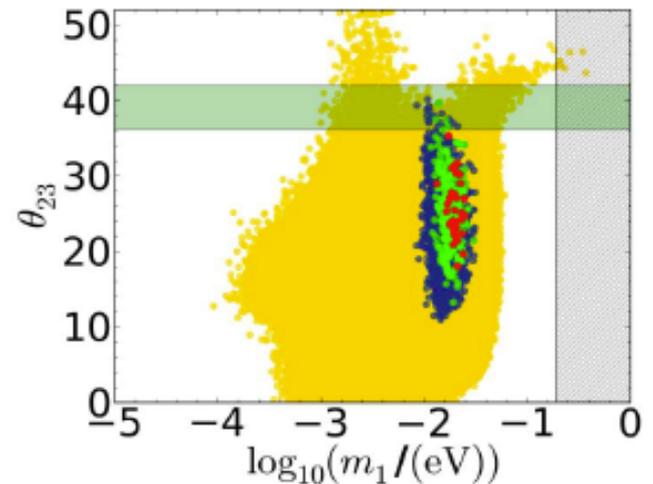
If we do not plug any experimental information (mixing angles left completely free, PRELIMINARY RESULTS):



Strong thermal $SO(10)$ -inspired leptogenesis: Full allowed range for the atmospheric angle

Another interesting exercise:
we imposed the experimental
information on all parameters
but on the atmospheric mixing angle:

This result clearly shows that data
are already testing now crucially the
prediction on the atmospheric mixing
angle that should be as low as possible
and certainly lower than about 41°
(red points)



Strong thermal SO(10) inspired leptogenesis: summary

- SO(10)-inspired leptogenesis is not only alive but it contains a subset of solutions able to satisfy quite a tight 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	$\sim -60^\circ$
$m_1 \approx m_{ee}$	$\sim 20 \text{ meV}$

- 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

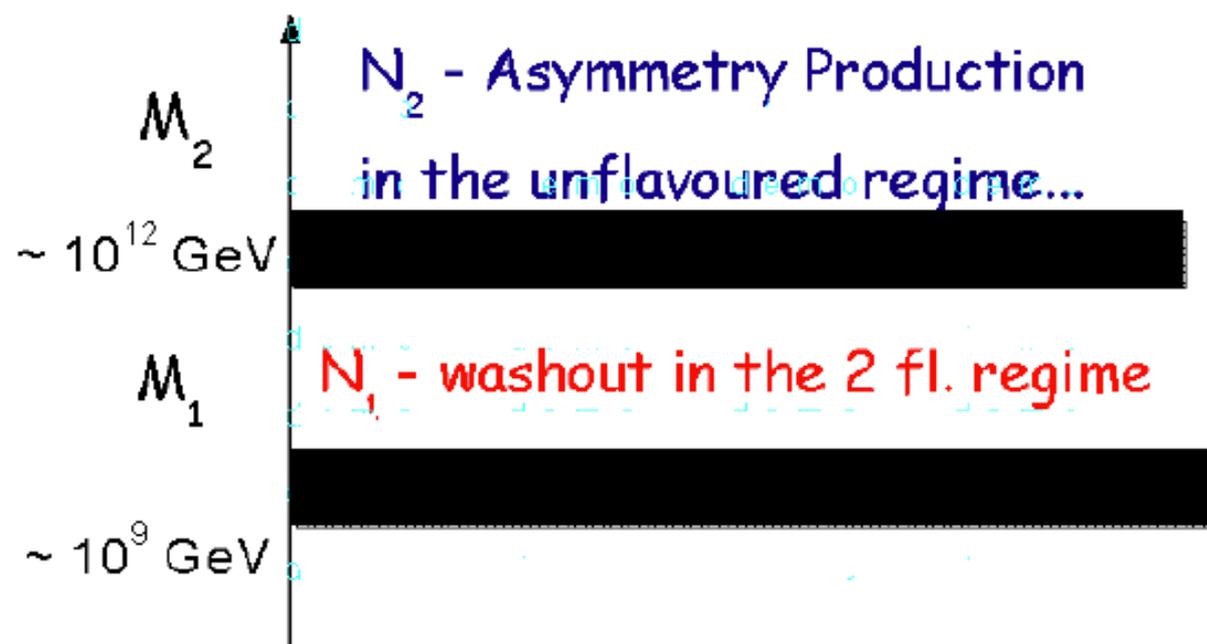
Interplay between lepton and heavy neutrino flavour effects:

- **N_2 flavoured leptogenesis**
(Vives '05; Blanchet, PDB '06; Blanchet, PDB '08)
- **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 $N_{\Delta T}$ component and into a $N_{\Delta e+\mu}$ component?

One could think:

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

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

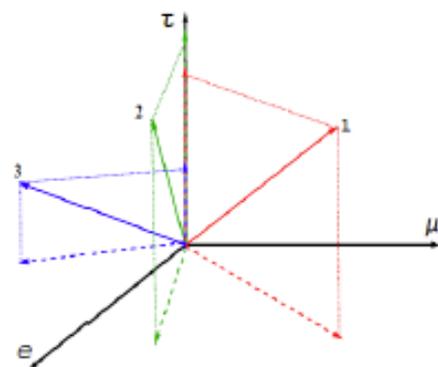
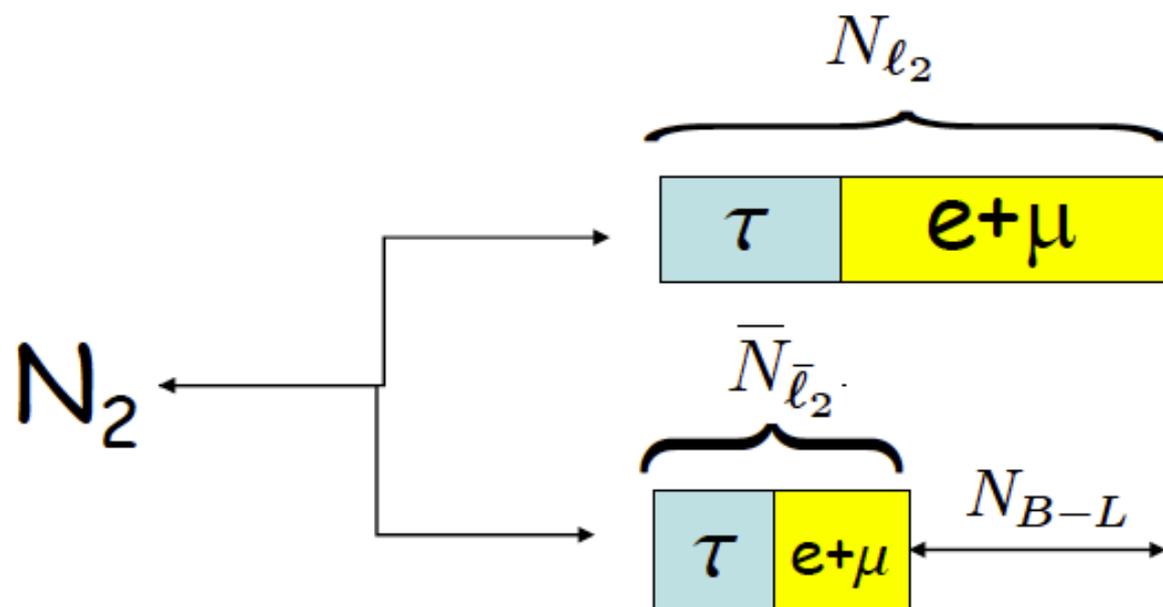
Phantom terms

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:

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

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

τ	$e+\mu$
$\bar{\tau}$	$\overline{e+\mu}$

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

2) $10^{12} \text{ GeV} \gtrsim T \gg M_1$: decoherence \Rightarrow 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 $K_{1e+\mu} \gg 1$

$$N_{B-L}^f \simeq N_{\Delta\tau}^{T \sim M_2} !$$

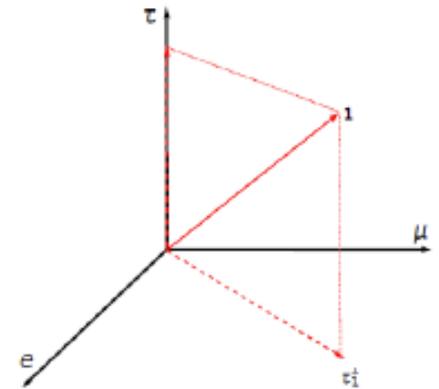
The N_1 wash-out un-reveal the phantom term and effectively it creates a N_{B-L} asymmetry.

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:

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



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-out of the phantom terms from Yukawa interactions though with halved wash-out rate compared to the one acting on the total asymmetry and in the end:

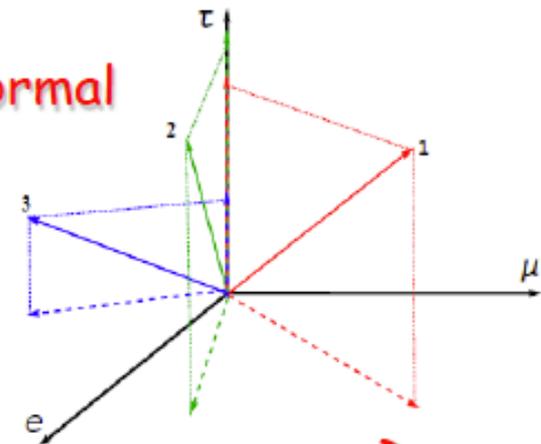
$$N_{\tau\tau}^{B-L,f} \simeq p_{2\tau}^0 N_{B-L}^f - \frac{\Delta p_{2\tau}}{2} \kappa(K_2/2),$$

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



$$p_{ij} = |\langle l_i | l_j \rangle|^2 \quad p_{ij} = \frac{|(m_D^\dagger m_D)_{ij}|^2}{(m_D^\dagger m_D)_{ii} (m_D^\dagger m_D)_{jj}}$$

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

$\propto p_{12}$

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

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

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

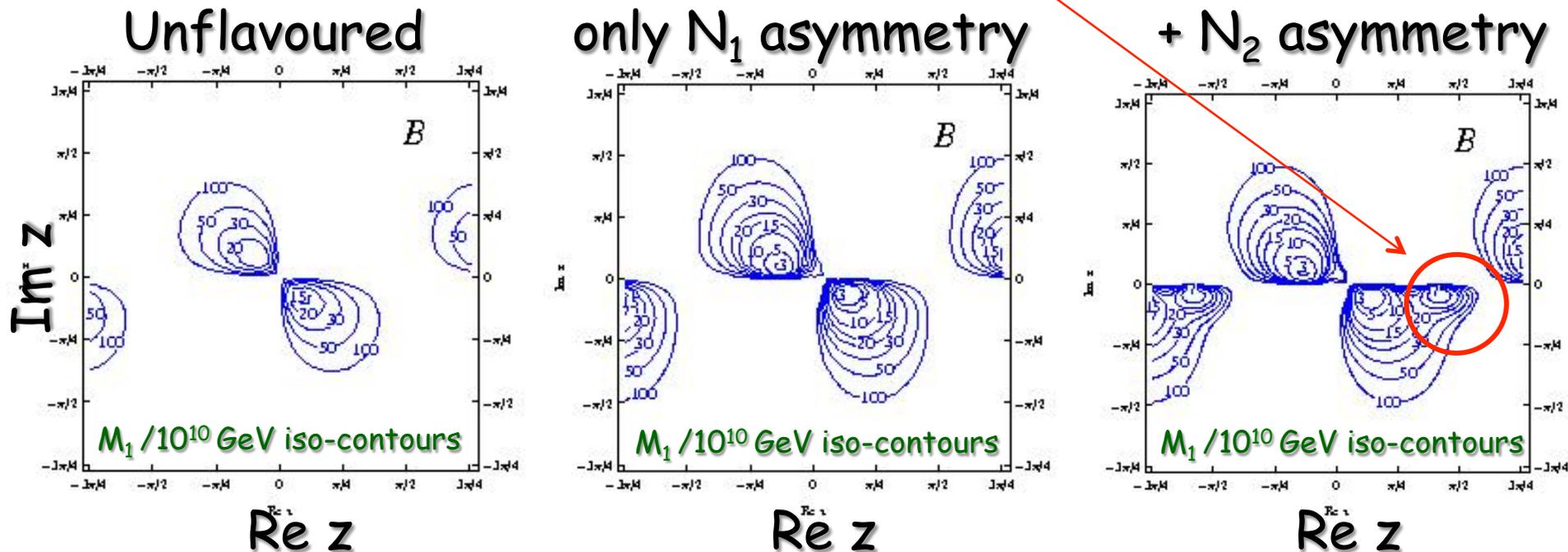
2 RH neutrino scenario revisited

(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 $\epsilon_{2\alpha}$ 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 $\epsilon_{2\alpha}$

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

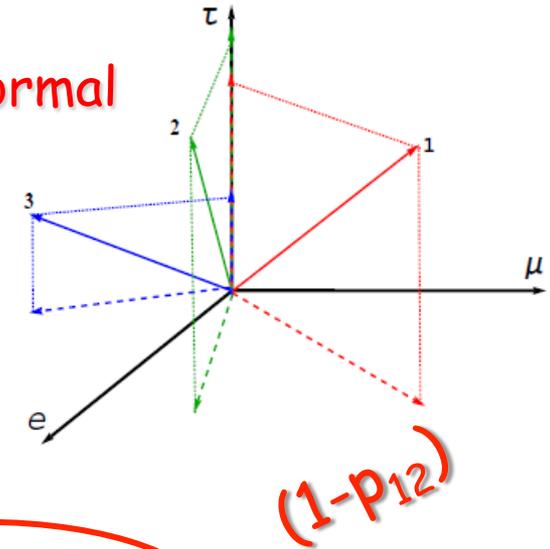
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$$N_{B i L}^{(N_2)}(T \dot{c} M_1) = N_{\dot{c} 1}^{(N_2)}(T \dot{c} M_1) + N_{\dot{c} 1?}^{(N_2)}(T \dot{c} M_1)$$

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

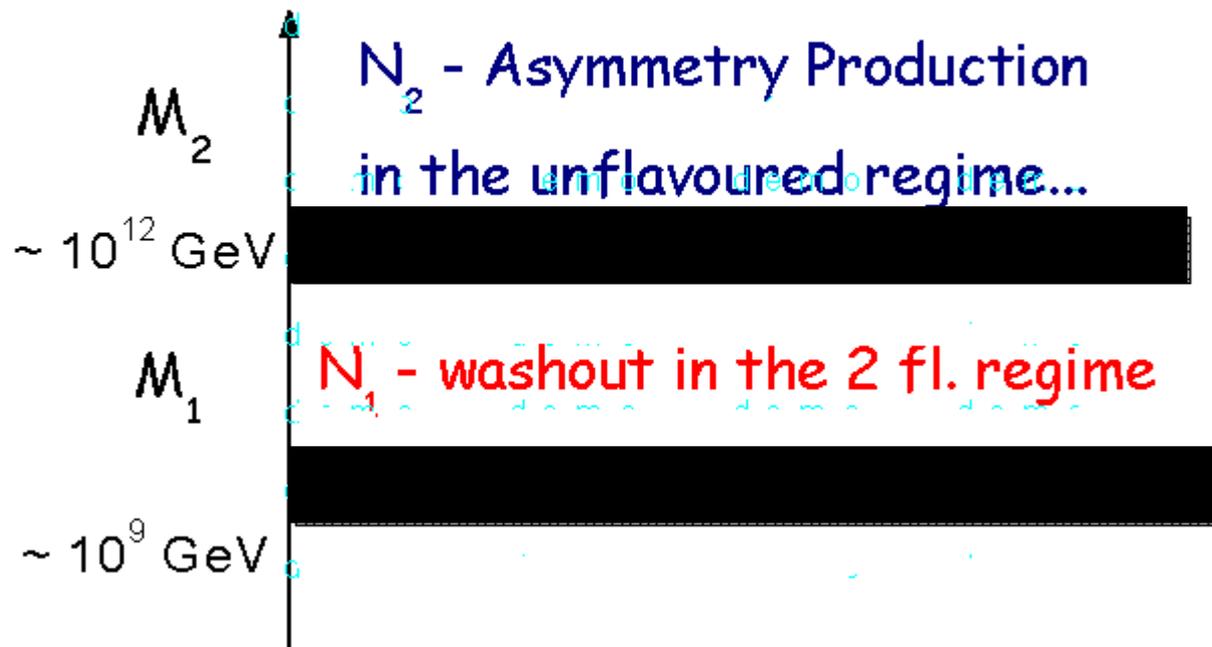
Contribution from heavier RH neutrinos orthogonal to l_1 and escaping N_1 wash-out

$$N_{\dot{c} 1}^{(N_2)}(T \dot{c} M_1) = p_{12} e^{i \frac{3\pi}{8} K_1} N_{B i L}^{(N_2)}(T \gg M_2)$$

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 $N_{\Delta T}$ component and into a $N_{\Delta e+\mu}$ component?

One could think:

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

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

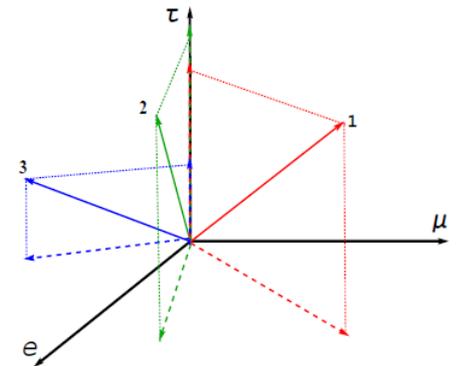
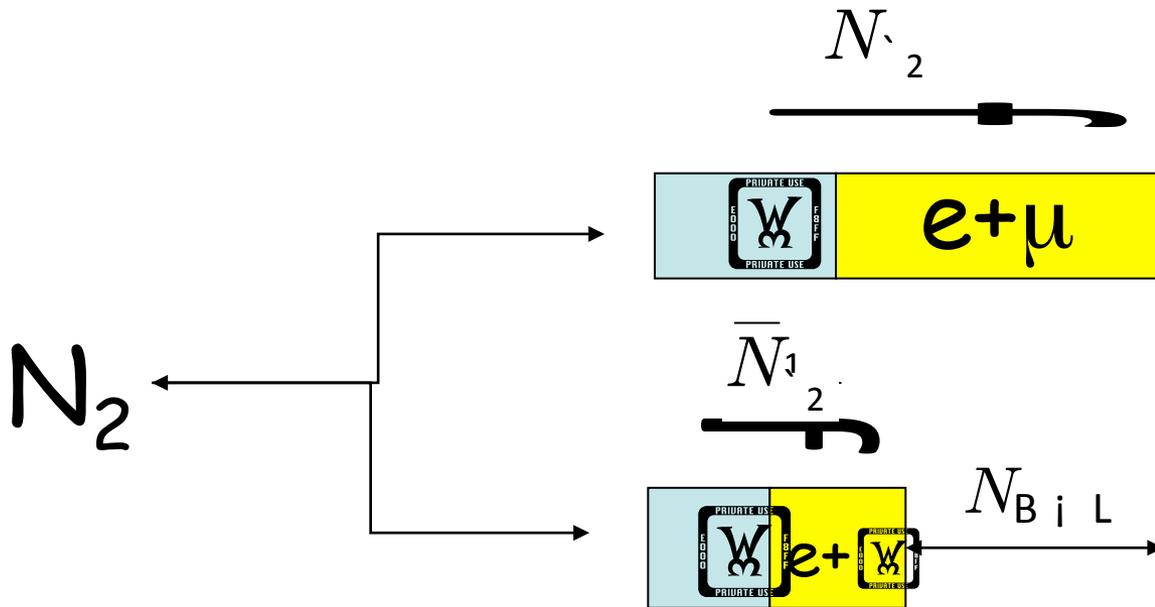
Phantom terms

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:

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

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

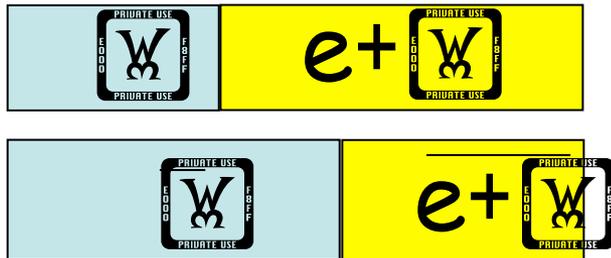


Phantom Leptogenesis

(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



$$) \quad N_{B-L}^T \gg M_2 \quad , \quad 0 !$$

2) $10^{12} \text{ GeV} \quad T \gg M_1$: decoherence 2 flavoured regime

$$N_{B-L}^T \gg M_2 = N_{\check{c}}^T \gg M_2 + N_{e^+}^T \gg M_2 \quad , \quad 0 !$$

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

Assume $K_{1T} \ll 1$ and $K_{1e+\mu} \gg 1$

$$N_{B-L}^f \quad , \quad N_{\check{c}}^T \gg M_2 !$$

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 !

$$N_{\zeta_i}^{\text{phantom}} = \frac{\zeta_{p_{2i}}}{2} N_{N_2}^{\text{in}}$$

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

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

ORDERING	NORMAL
θ_{13}	$\approx 3^\circ$
θ_{23}	$\approx 41^\circ$
δ	$\sim -60^\circ$
$m_1 \approx m_{ee}$	$\sim 20 \text{ meV}$

Strong thermal
 $SO(10)$ inspired
leptogenesis
solution