University of Sussex, 22 September 2014

Decrypting Strong thermal SO(10)-inspired leptogenesis

Pasquale Di Bari
(University of Southampton)

Leptogenesis: a tantalizing opportunity

Cosmology (early Universe) ← → **Neutrino Physics, models of mass**

- *Cosmological Puzzles :*

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

- *New stage in early Universe history :*

T

~10^{16} GeV???	Inflation
$\lesssim 3\times10^{14}$ GeV	QCD freeze-in
	Leptogenesis
100 GeV	EWSSB
0.1- 1 MeV	BBN
0.1- 1 eV	Recombination

Leptogenesis complements low energy neutrino experiments testing the seesaw high energy parameters and providing a guidance toward the model behind the seesaw

Two important questions:

1. Can leptogenesis help to understand neutrino parameters?

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

A common approach in the LHC era: "TeV Leptogenesis"

Is there an alternative approach based on high energy scale leptogenesis? Also considering that:

- No new physics at LHC (not so far);
- New scale ~ 10^{16} GeV (intriguingly close to GUT scale) hinted by BICEP2 (TBC) and typically implying very high reheat temperatures;
- Discovery of a non-vanishing reactor angle opening the door to completing leptonic mixing matrix parameters measurement;
- Cosmological observations start to have the sensitivity to either rule our or discover quasi-degenerate neutrino masses and huge world efforts in improving $0\nu\beta\beta$ sensitivity

Neutrino mixing parameters

Pontecorvo-Maki-Nakagawa-Sakata matrix

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

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

NuFIT 1.3 (2014)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

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

Atmospheric, LB | Reactor, Accel.,LB CP violating phase | Solar,Reactor | bb0ν decay

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

3σ ranges(NO):

$\theta_{23} \simeq 38^\circ - 53^\circ$

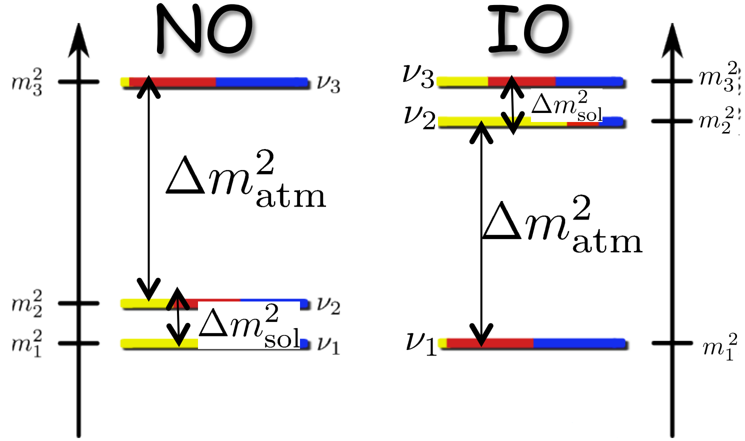
$\theta_{12} \simeq 32^\circ - 38^\circ$

$\theta_{13} \simeq 7.5^\circ - 10^\circ$

$\delta, \rho, \sigma = [-\pi, \pi]$

(Forero, Tortola, Valle '14; Capozzi,Fogli, Lisi,Palazzo '14)

Neutrino masses: $m_1 < m_2 < m_3$



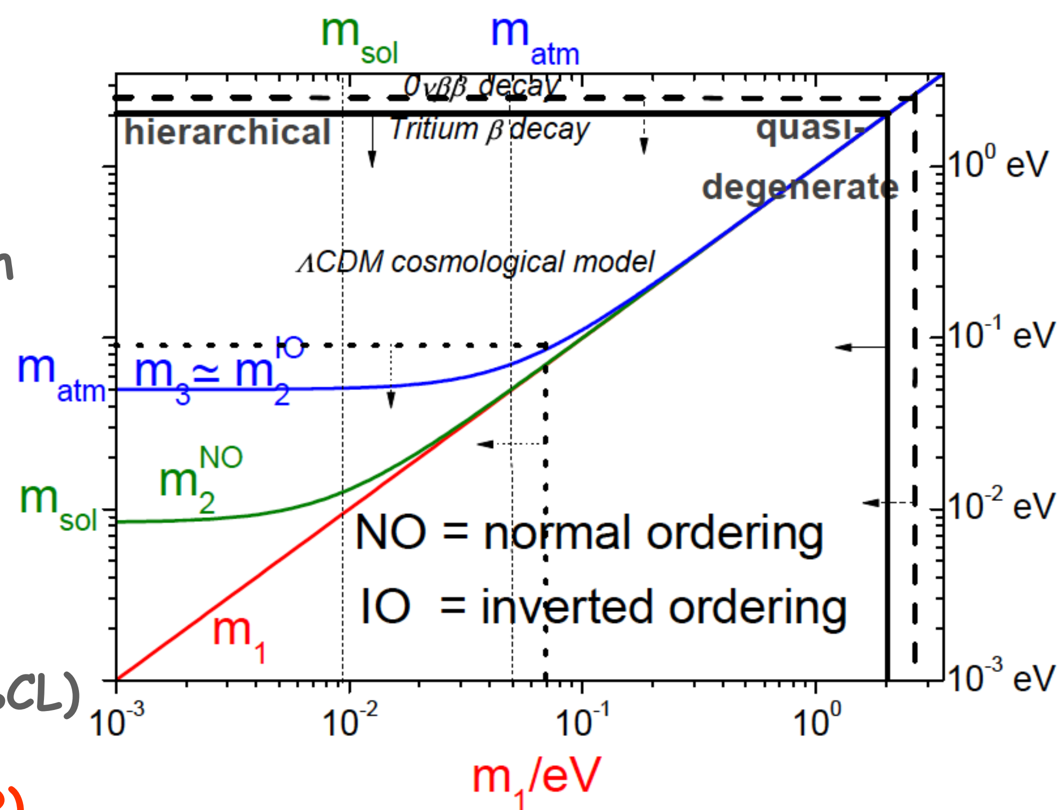
$$m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

$$m_{\rm sol} \equiv \sqrt{\Delta m^2_{\rm sol}} \simeq 0.009\,{\rm eV}$$

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

ββ0ν: $m_{\beta\beta} < 0.34 - 0.78$ eV
(CUORICINO 95% CL, similar from Heidelberg-Moscow)
$m_{\beta\beta} < 0.12 - 0.25$ eV
(EXO-200+Kamland-Zen 90% CL)
$m_{\beta\beta} < 0.2 - 0.4$ eV
(GERDA+IGEX 90% CL)

CMB+BAO+H0 : $\Sigma\, m_i < 0.23$ eV
(Planck+high-l+WMAPpol+BAO 95%CL)
⇒ $m_1 < 0.07$ eV
(some analyses find $m_1 \sim 0.1$eV???)



The minimally extended SM

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}^{\nu}_{\rm mass}$$

$$-\mathcal{L}^{\nu}_{\rm mass} = \bar{\nu}_L\, h\, \nu_R \Rightarrow -\mathcal{L}^{\nu}_{\rm mass} = v\, \bar{\nu}_L\, m_D\, \nu_R$$

Dirac Mass term

Neutrino masses

$$m_D = V_L^{\dagger}\, {\rm diag}(m_{D1}, m_{D2}, m_{D3})\, U_R \;\Rightarrow\; m_i = m_{Di}$$

Neutrino mixing

$$U = V_L^{\ell\dagger}\, V_L$$

<u>Many unanswered questions:</u>

- Why neutrinos are much lighter than all other fermions?
- Why large mixing angles?
- Cosmological puzzles?
- .....why not a Majorana Mass term as well?

Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

• Type I seesaw

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

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

- 3 light Majorana neutrinos with masses

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

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

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

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

total CP asymmetries

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

$$N_{B-L}^{\text{fin}} = \sum_i \varepsilon_i\, \kappa_i^{\text{fin}}$$

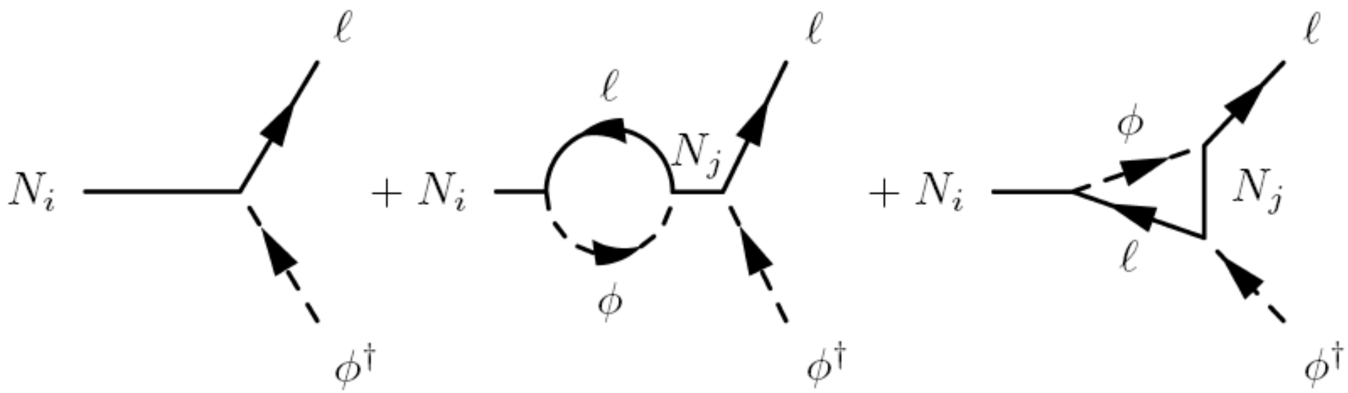
• Thermal production of RH neutrinos (Kuzmin, Rubakov, Shaposhnikov '85)

$T_{RH} \gtrsim M_i / (2 \div 10) \gtrsim T_{sph} \simeq 100$ GeV

$$\Rightarrow \eta_B = a_{\text{sph}} \frac{N_{B-L}^{\text{fin}}}{N_\gamma^{\text{rec}}} = \eta_B^{CMB} = (6.1 \pm 0.1) \times 10^{-10}$$

Total CP asymmetries

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



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

It does not depend on U !

Seesaw parameter space

Imposing $\eta_B = \eta_B^{CMB} \simeq 6 \times 10^{-10} \Rightarrow$ can we test seesaw and leptog.?

Problem: too many parameters

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

$$m_D = U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}$$

(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

A parameter reduction would help and can occur in various ways:

- $\eta_B = \eta_B^{CMB}$ is satisfied around "peaks"
- some parameters cancel in the asymmetry calculation
- imposing independence of the initial conditions
- imposing some condition on m_D
- additional phenomenological constraints (e.g. Dark Matter)

Vanilla leptogenesis

(Buchmüller,PDB,Plümacher '04; Giudice et al. '04; Blanchet, PDB '07)

1) Lepton flavor composition is neglected

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

$$N_{B-L}^{\rm fin} = \sum \varepsilon_i\, \kappa_i^{\rm fin}$$

$$\Rightarrow \eta_B = a_{\rm sph}\,\frac{N_{B-L}^{\rm fin}}{N_\gamma^{\rm rec}} = \eta_B^{CMB} = (6.1 \pm 0.1)\times 10^{-10}$$

2) Hierarchical spectrum ($M_2 \gtrsim 2M_1$)

3) N_3 do not interfere with N_2:

$$(m_D^\dagger\, m_D)_{23} = 0$$

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

4) Barring fine-tuned cancellations

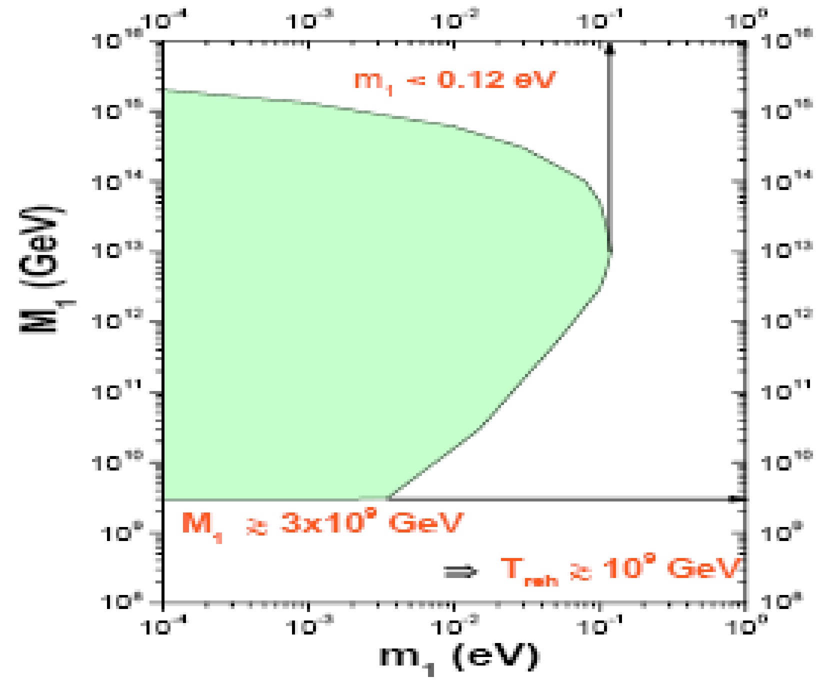
(Davidson, Ibarra '02)

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

5) Efficiency factor from simple Boltzmann equations $\left(z \equiv \frac{M_1}{T}\right)$

$$\kappa_1^{\rm fin}(K_1) = -\int_{z_{\rm in}}^{\infty} dz'\,\frac{dN_1}{dz'}\,e^{-\int_{z'}^{\infty} dz''\,W(z'')}$$

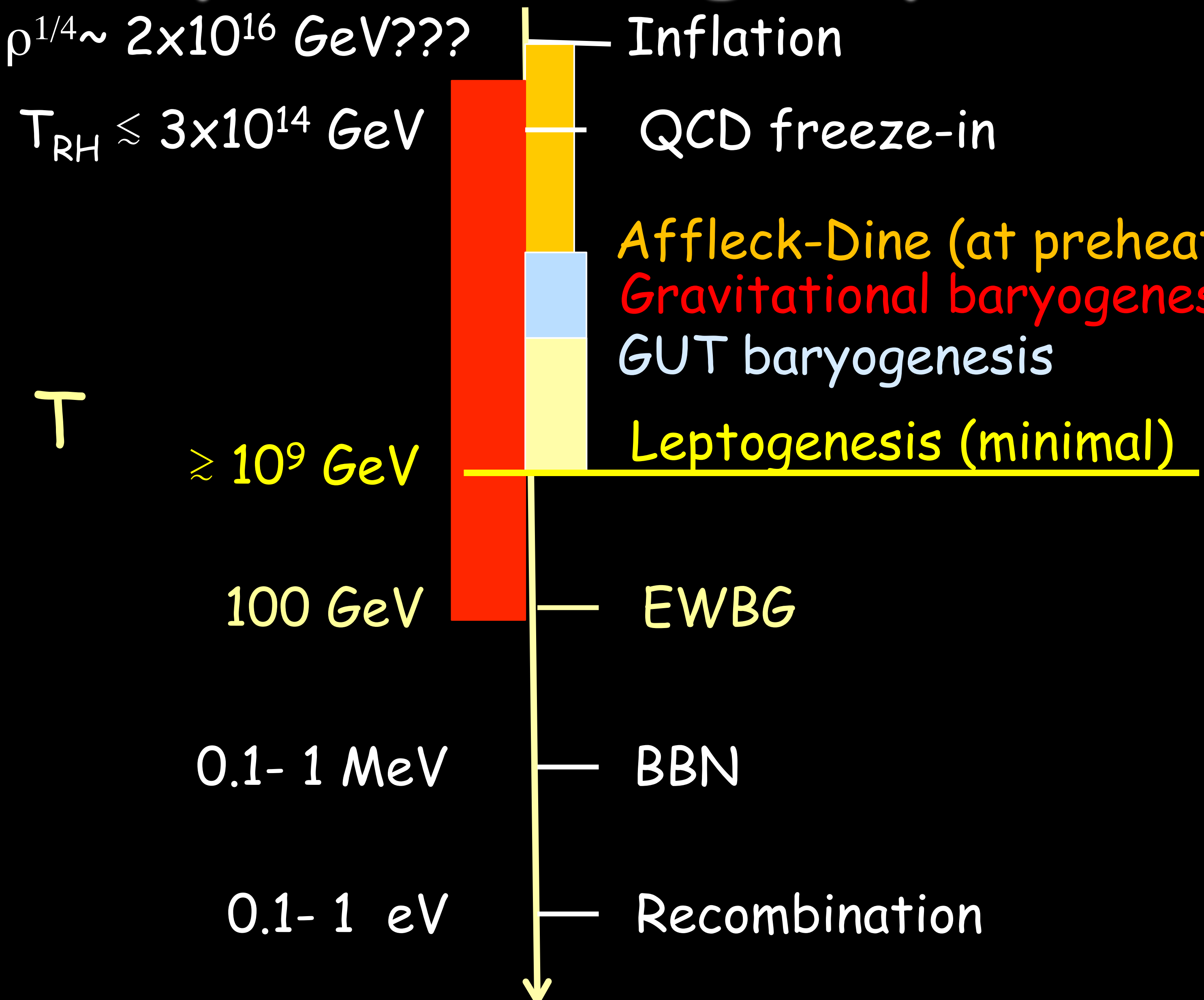
$$\eta_B^{\rm max}(m_1, M_1) \geq \eta_B^{CMB}$$



No dependence on the leptonic mixing matrix U

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

A pre-existing asymmetry?



Independence of the initial conditions

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

(Buchmüller, PDB, Plümacher '04)

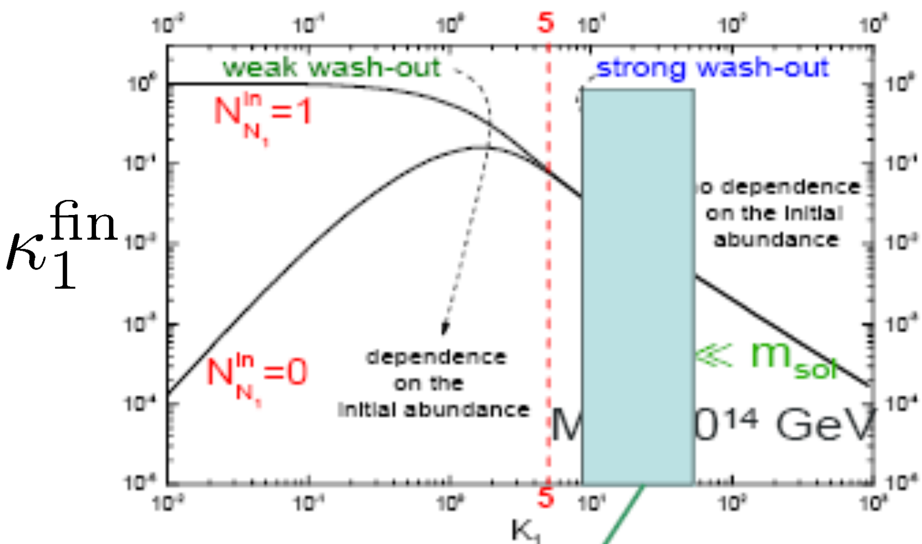
$$\eta_B \simeq 0.01\,\varepsilon_1(m_1, M_1, \Omega)\,\kappa_1^{\rm fin}(K_1)$$

decay parameter

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

Independence of the initial abundance of N_1

wash-out of a pre-existing asymmetry



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

$$K_1 \gtrsim K_{\rm st}(N^{\rm p,i}_{B-L})$$

$$K_{\rm st}(x) \equiv \frac{8}{3\pi}\left[\ln\left(\frac{0.1}{\eta_B^{\rm CMB}}\right) + \ln|x|\right] \simeq 16 + 0.85\,\ln|x|$$

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

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:

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

SO(10) inspired conditions*:

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

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):

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

since $M_1 \ll 10^9$ GeV $\Rightarrow \eta_B^{(N1)} \ll \eta_B^{CMB}$

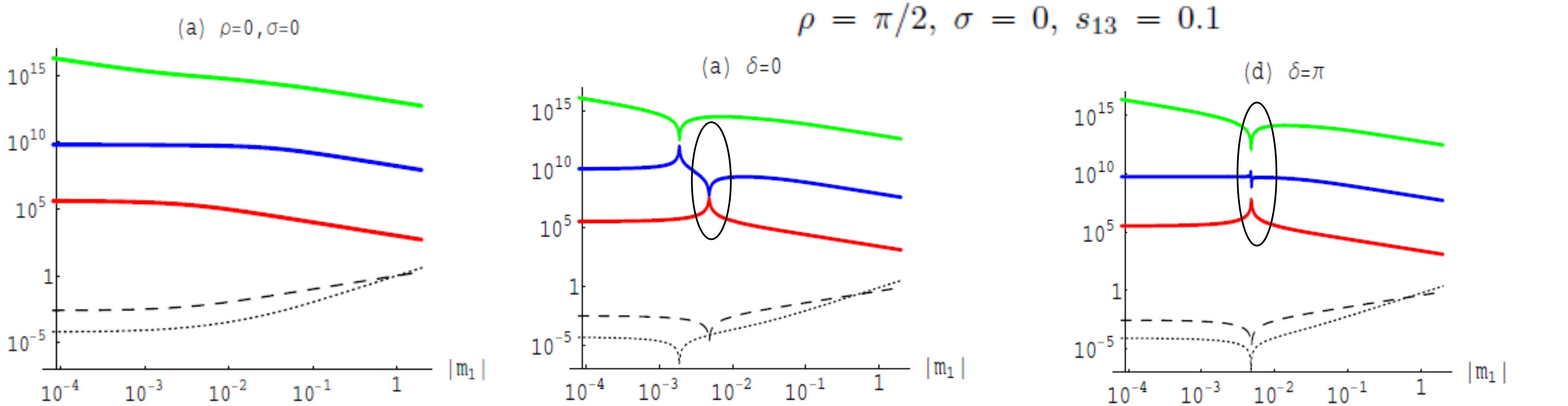
* Note that SO(10)-inspired consditions can be realized also beyond SO(10) and even beyond GUT models (e.g. "Tetraleptogenesis", King '13, Feruglio '14)

Crossing level solutions

(Akhmedov, Frigerio, Smirnov '03; PDB, Fiorentin, Marzola, in preparation)

$$M_1 \simeq \frac{\alpha_1^2\, m_u^2}{|m_{\nu ee}|} \qquad M_2 \simeq \frac{\alpha_2^2\, m_c^2}{m_1\, m_2\, m_3}\,\frac{|m_{\nu ee}|}{|(m_\nu^{-1})_{\tau\tau}|} \qquad M_3 \simeq \alpha_3^2\, m_t^3\,(m_\nu^{-1})_{\tau\tau}$$

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



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

- The correct BAU can be attained for a fine tuned choice of parameters: many models have made use of these solutions (e.g. Buccella, Falcone, Nardi, '12; Altarelli, Meloni '14)
- These, however, have to be strongly fine tuned to reproduce the observed asymmetry. As we will see there is another solution not relying on resonant leptogenesis.

The N_2-dominated scenario

(PDB '05)

What about the asymmetry from the next-to-lightest (N_2) RH neutrinos?
It is typically washed-out:

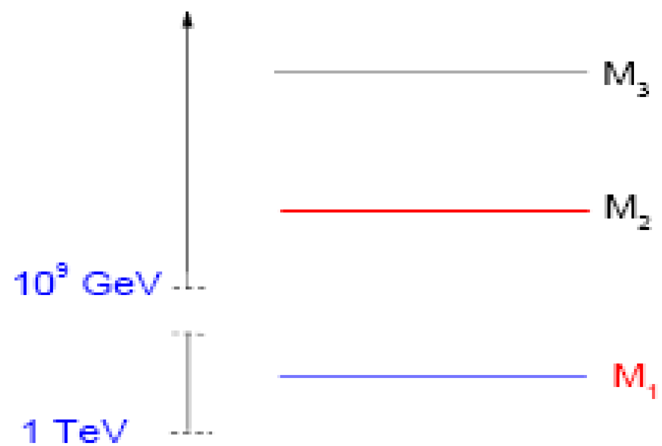
$$N_{B-L}^{\rm f,N_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1} = \varepsilon_1\, \kappa(K_1)$$

...except for a special choice of parameters when $K_1 = m_1/m_* \ll 1$ and $\varepsilon_1 = 0$:

$$\Rightarrow \quad N_{B-L}^{\rm fin} = \sum_i \varepsilon_i\, \kappa_i^{\rm fin} \simeq \varepsilon_2\, \kappa_2^{\rm fin}$$

$$\varepsilon_2 \lesssim 10^{-6} \left(\frac{M_2}{10^{10}\,{\rm GeV}}\right)$$

- 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}



- How special is having $K_1 \lesssim 1$?
  $P(K_1 \lesssim 1) \simeq 0.2\%$ (random scan)

- SO(10)-inspired models do not realise this special corner in the parameter space

since $M_1 \ll 10^9$ GeV and $K_1 \gg 1 \Rightarrow \eta_B^{(N1)}, \eta_B^{(N2)} \ll \eta_B^{CMB}$

Lepton flavour effects

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

Flavor composition of lepton quantum states:

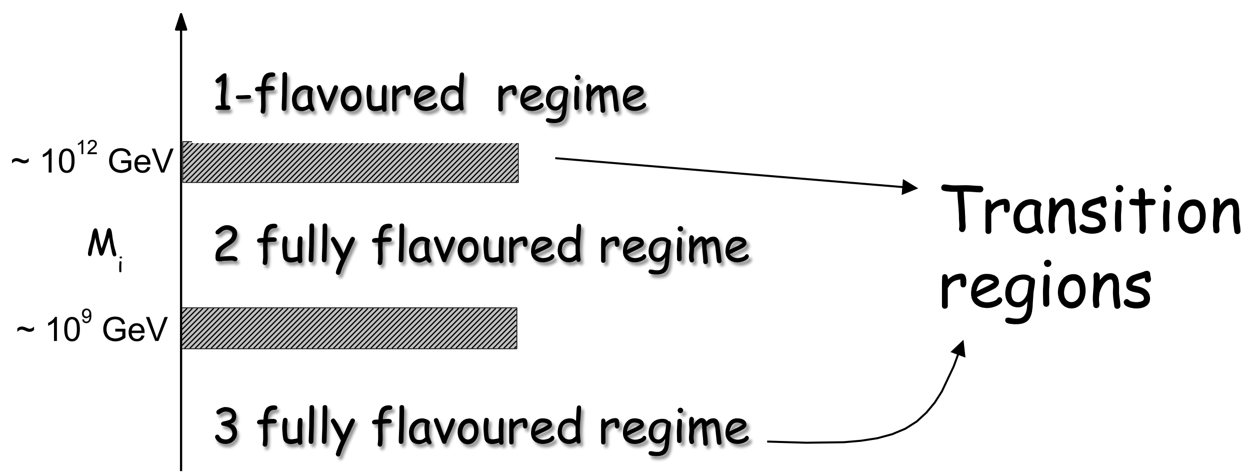
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1\rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau) \qquad\qquad P_{1\alpha} \equiv |\langle \ell_1 | \alpha\rangle|^2$$

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

For $T \gtrsim 10^{12}$ 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 $T \gtrsim 10^9$ GeV then also μ- Yukawas in equilibrium ⇒ 3-flavor regime



Two fully flavoured regime

- Classic Kinetic Equations (in their simplest form)

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

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

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

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

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

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

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

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

Flavoured decay parameters: $K_{i\alpha} \equiv P_{i\alpha}^0\,K_i = \left|\sum_k \sqrt{\frac{m_k}{m_\star}}\,U_{\alpha k}\,\Omega_{ki}\right|^2$

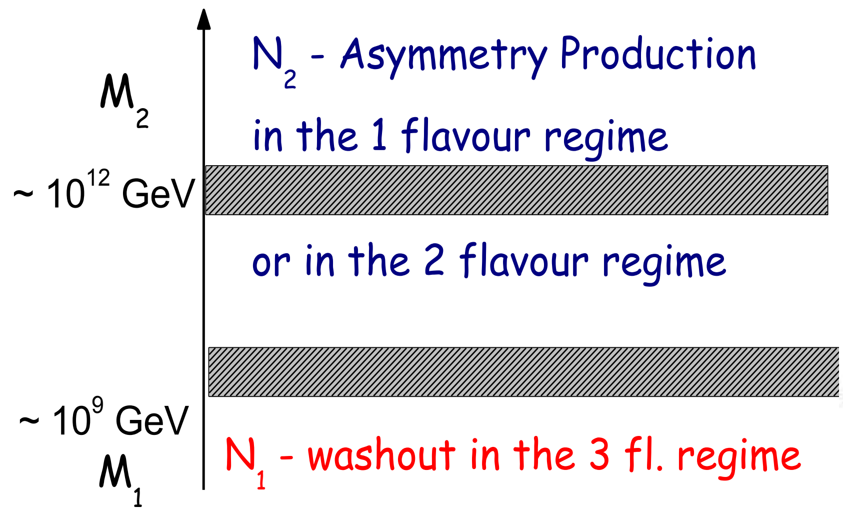
In SO(10)-inspired models this additional CP source is negligible!

The N_2-dominated scenario (flavoured)

(Vives '05; Blanchet, PDB '06; Blanchet, PDB '08, PDB, Fiorentin '14)

Flavour effects produce sort of "holes" in the N_1 wash-out

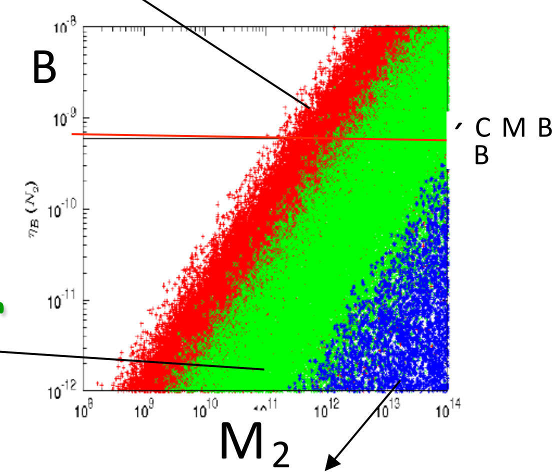
A two stage process:



N_1 wash-out is neglected

Both wash-out and flavor effects

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



Unflavored case

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

- $K_1 = K_{1e} + K_{1\mu} + K_{1\tau}$; $P(K_1 \lesssim 1) \sim 0.2\%$; $P(K_{1e} \lesssim 1) \sim 2\, P(K_{1\mu,\tau} \lesssim 1) \sim 15\%$ $\Rightarrow \Sigma_\alpha P(K_{1\alpha} \lesssim 1) = 30\%$
- With flavor effects the domain of applicability goes much beyond the special choice $\Omega = R_{23}$
- **Existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$'s not to be negligible**

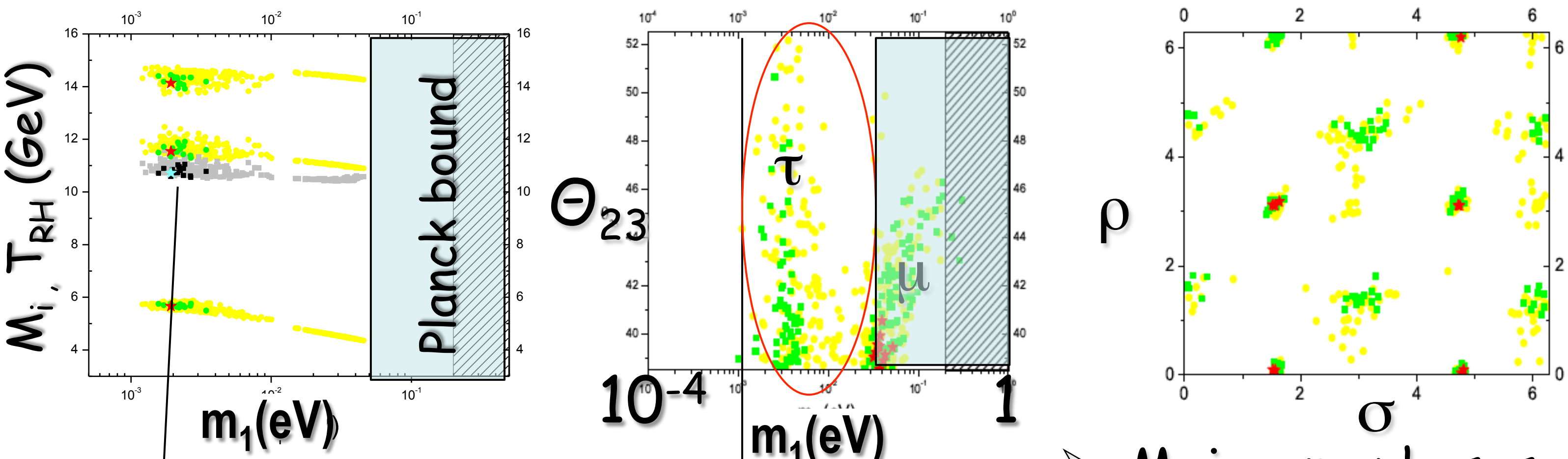
Flavour effects rescue SO(10)-inspired leptogenesis

(PDB, Riotto '08,'10)

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

Independent of $\alpha_1 = m_{D1}/m_u$ and $\alpha_3 = m_{D3}/m_t$

$\alpha_2 = m_{D2}/m_c = 5$ $\alpha_2 = 4$ $\alpha_2 = 3$ NORMAL ORDERING



- $T_{RH} \gtrsim 5\times10^{10}$ GeV
- $m_1 \gtrsim 10^{-3}$ eV
- Majorana phases constrained around specific values

- Very marginal allowed regions for INVERTED ORDERING

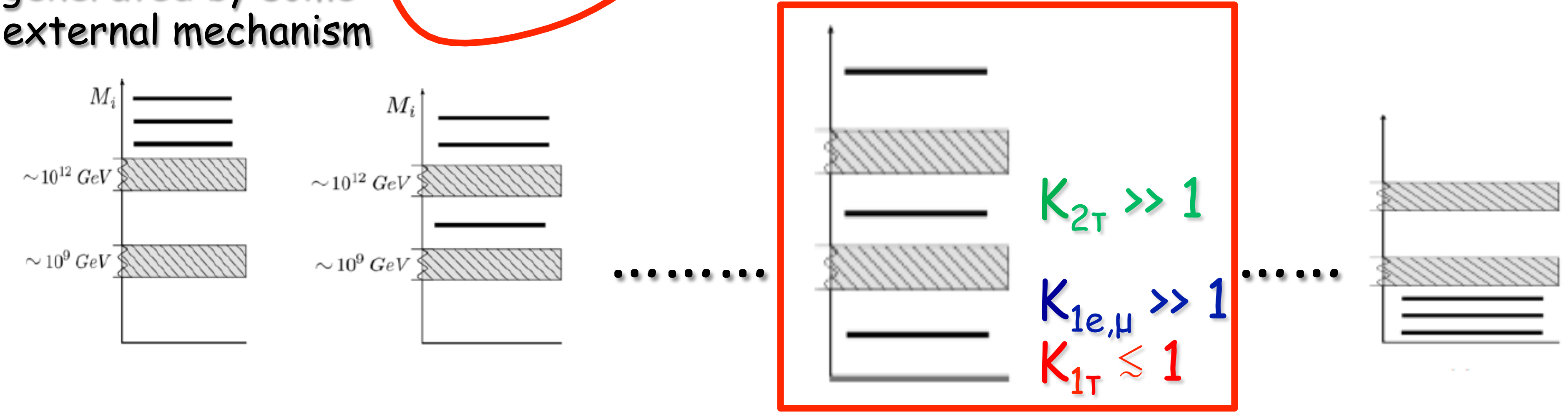
- Most of the solutions are tauon dominated as needed for strong thermal leptogenesis: can SO(10)-inspired thermal leptogenesis be also STRONG?

The problem of the initial conditions in flavoured leptogenesis

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

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

Asymmetry generated from leptogenesis



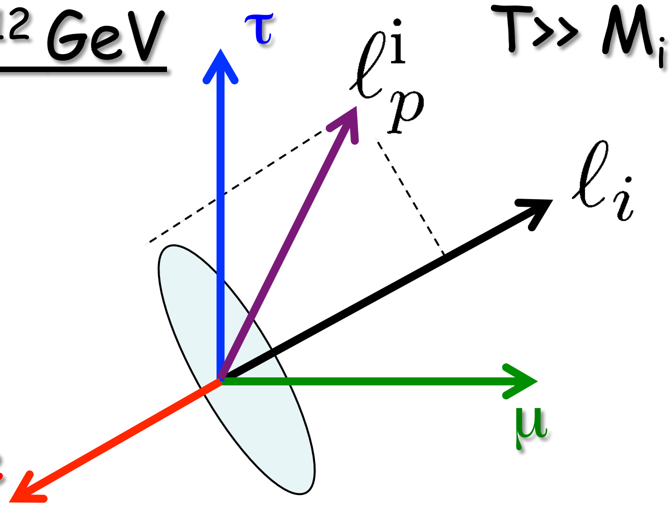
The conditions for the wash-out of a pre-existing asymmetry ('**strong thermal leptogenesis**') can be realised only within a N_2-dominated scenario where the final asymmetry is dominantly produced in the tauon flavour

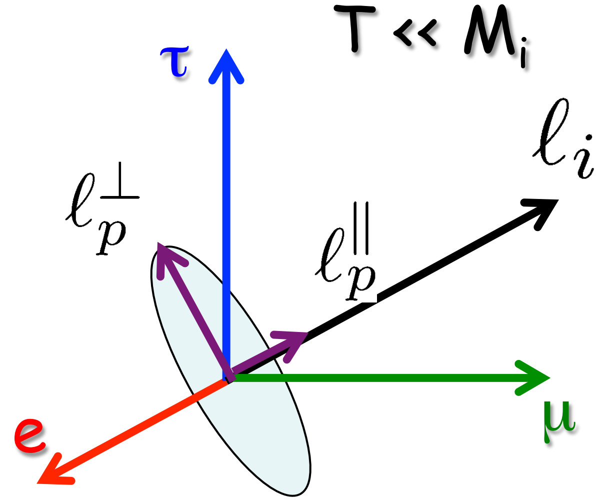
(Bertuzzo,PDB,Marzola '10)

Flavour projection and wash-out of a pre-existing asymmetry

(Barbieri et al. '99; Engelhard, Nir, Nardi '08; Blanchet, PDB, Jones,Marzola '10)

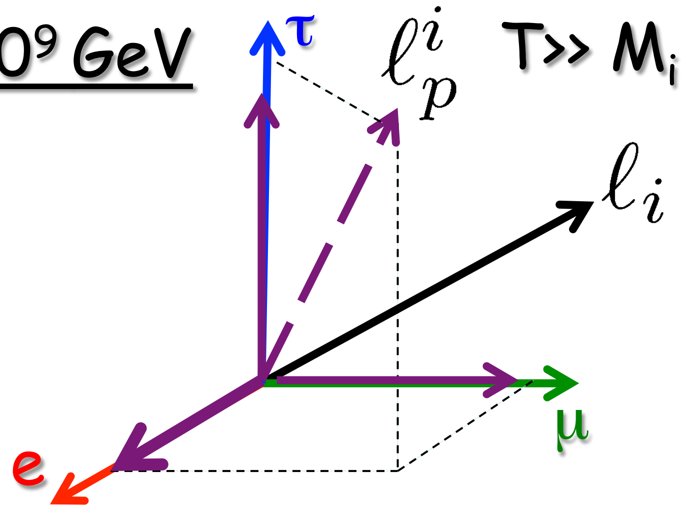
$M_i \gtrsim 10^{12}$ GeV

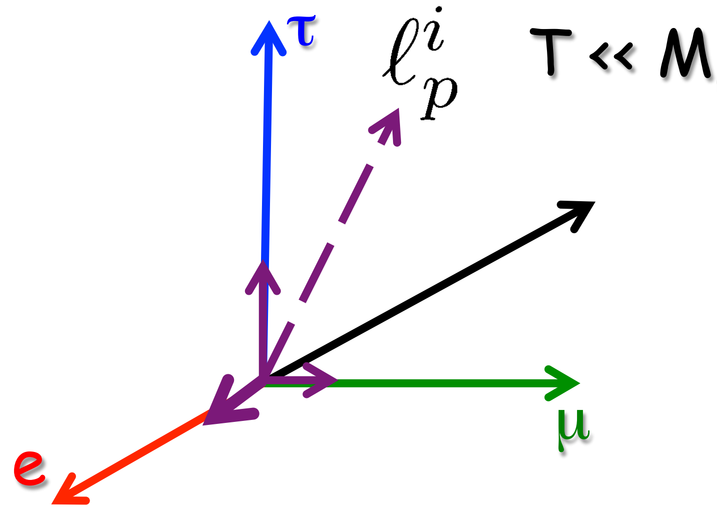




$$N^{\rm p}_{B-L}(T \ll M_i) = (1-P_{{\rm p}i})\, N^{\rm p,i}_{B-L} + P_{{\rm p}i}\, e^{-\frac{3\pi}{8} K_i}\, N^{\rm p,i}_{B-L}$$

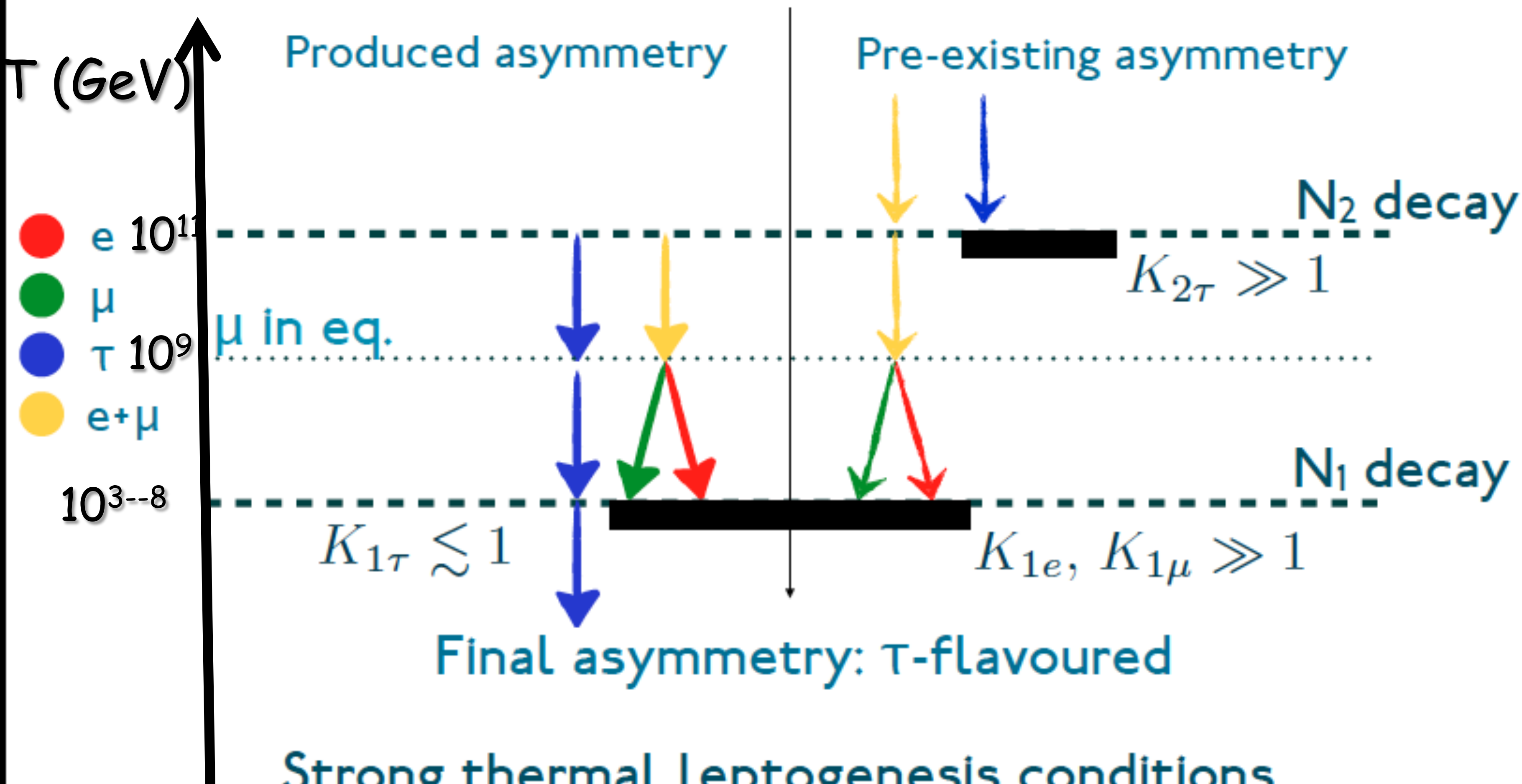
$M_i \ll 10^{9}$ GeV





$$N^{\rm p}_{B-L}(T \ll M_i) = P_{\rm pe}\, e^{-\frac{3\pi}{8} K_{ie}}\, N^{\rm p,i}_{B-L} + P_{{\rm p}\mu}\, e^{-\frac{3\pi}{8} K_{i\mu}}\, N^{\rm p,i}_{B-L} + P_{{\rm p}\tau}\, e^{-\frac{3\pi}{8} K_{i\tau}}\, N^{\rm p,i}_{B-L}$$

How is STL realised? - A cartoon



Strong thermal leptogenesis conditions

$K_{2\tau} \gg 1$	$K_{1e}, K_{1\mu} \gg 1$	$K_{1\tau} \lesssim 1$

Courtesy of Michele Re Fiorentin

A lower bound on neutrino masses (NO)

(PDB, Sophie King, Michele Re Fiorentin 2014)

$N^{P,i}_{B-L}$ = 0.001, 0.01, 0.1

max[$|\Omega_{21}|^2$] =2

Starting from the flavoured decay parameters:

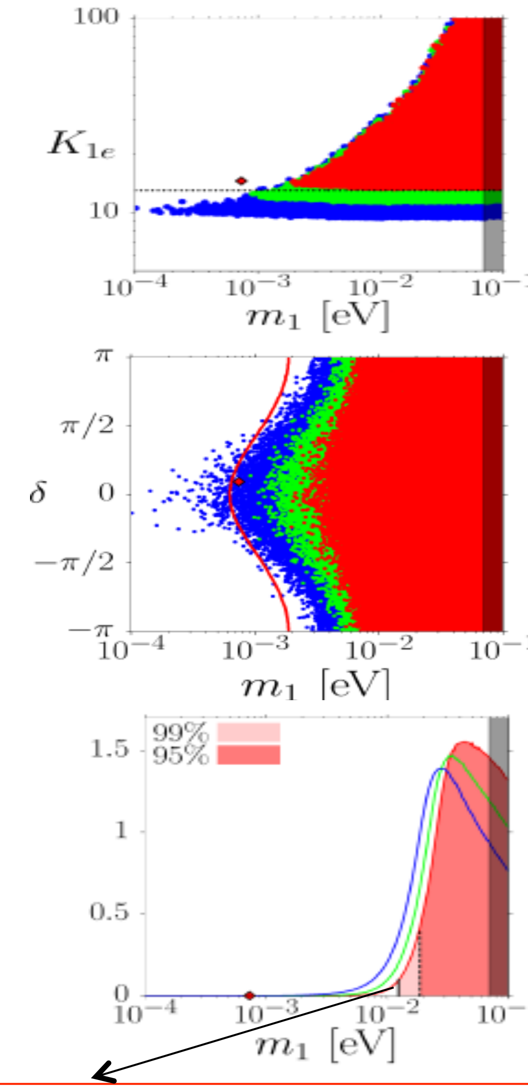
$$K_{i\beta} \equiv p^0_{i\beta}\, K_i = \left|\sum_k \sqrt{\frac{m_k}{m_\star}}\, U_{\beta k}\, \Omega_{ki}\right|^2$$

and imposing $K_{1\tau} \gtrsim 1$ and K_{1e}, $K_{1\mu} \gtrsim K_{st} \simeq 10$ (α=e,μ)

$$m_1 > m_1^{\rm lb} \equiv m_\star\, \max_\alpha \left[\left(\frac{\sqrt{K_{\rm st}} - \sqrt{K^{0,\max}_{1\alpha}}}{\max[|\Omega_{11}|]\,\left|U_{\alpha 1} - \frac{U_{\tau 1}}{U_{\tau 3}}\,U_{\alpha 3}\right|}\right)^2\right]$$

$$K^{0,\max}_{1\alpha} \equiv \left(\max[|\Omega_{21}|]\,\sqrt{\frac{m_{\rm sol}}{m_\star}}\,\left|U_{\alpha 2} - \frac{U_{\tau 2}}{U_{\tau 3}}\,U_{\alpha 3}\right| + \left|\frac{U_{\alpha 3}}{U_{\tau 3}}\right|\,\sqrt{K^{\max}_{1\tau}}\right)^2$$

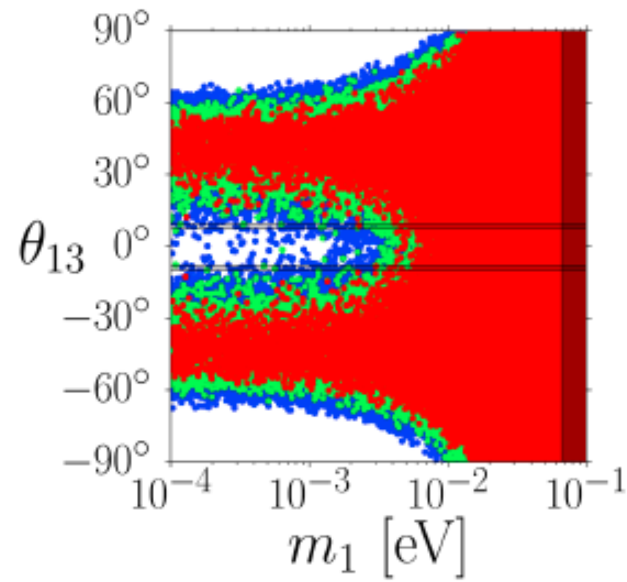
- The lower bound exists if max[$|\Omega_{21}|$] is not too large)



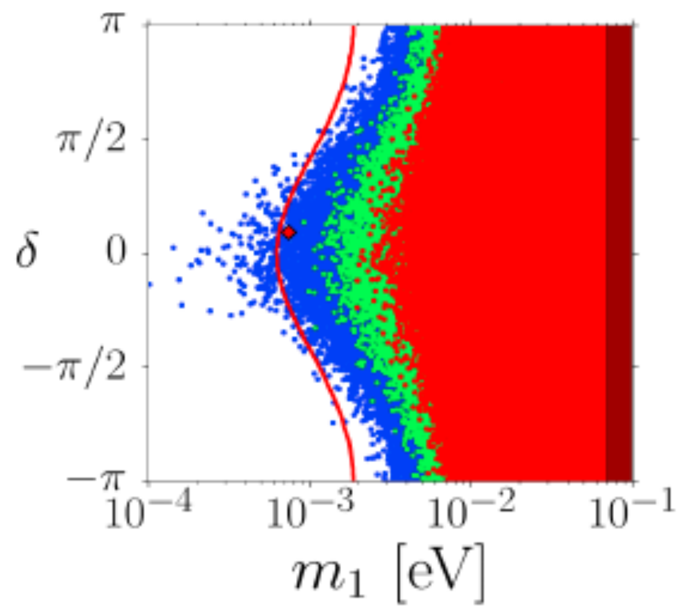
$m_1 \gtrsim$ 10 meV $\Rightarrow \Sigma_i\, m_i \gtrsim$ 75 meV

A lower bound on neutrino masses (NO)

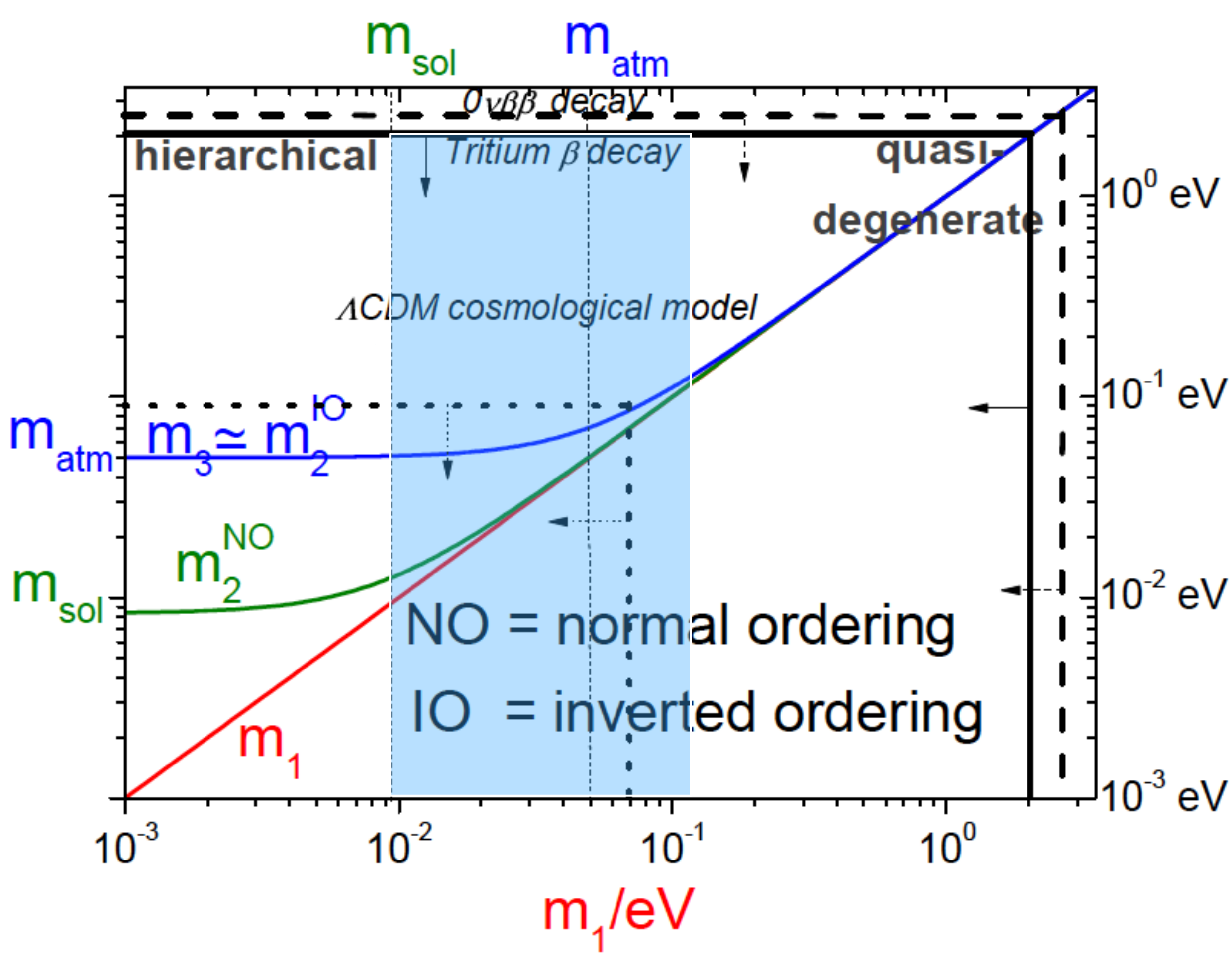
The lower bound would not have existed for large θ_{13} values



It is modulated by the Dirac phase and it could become more stringent when δ will be measured



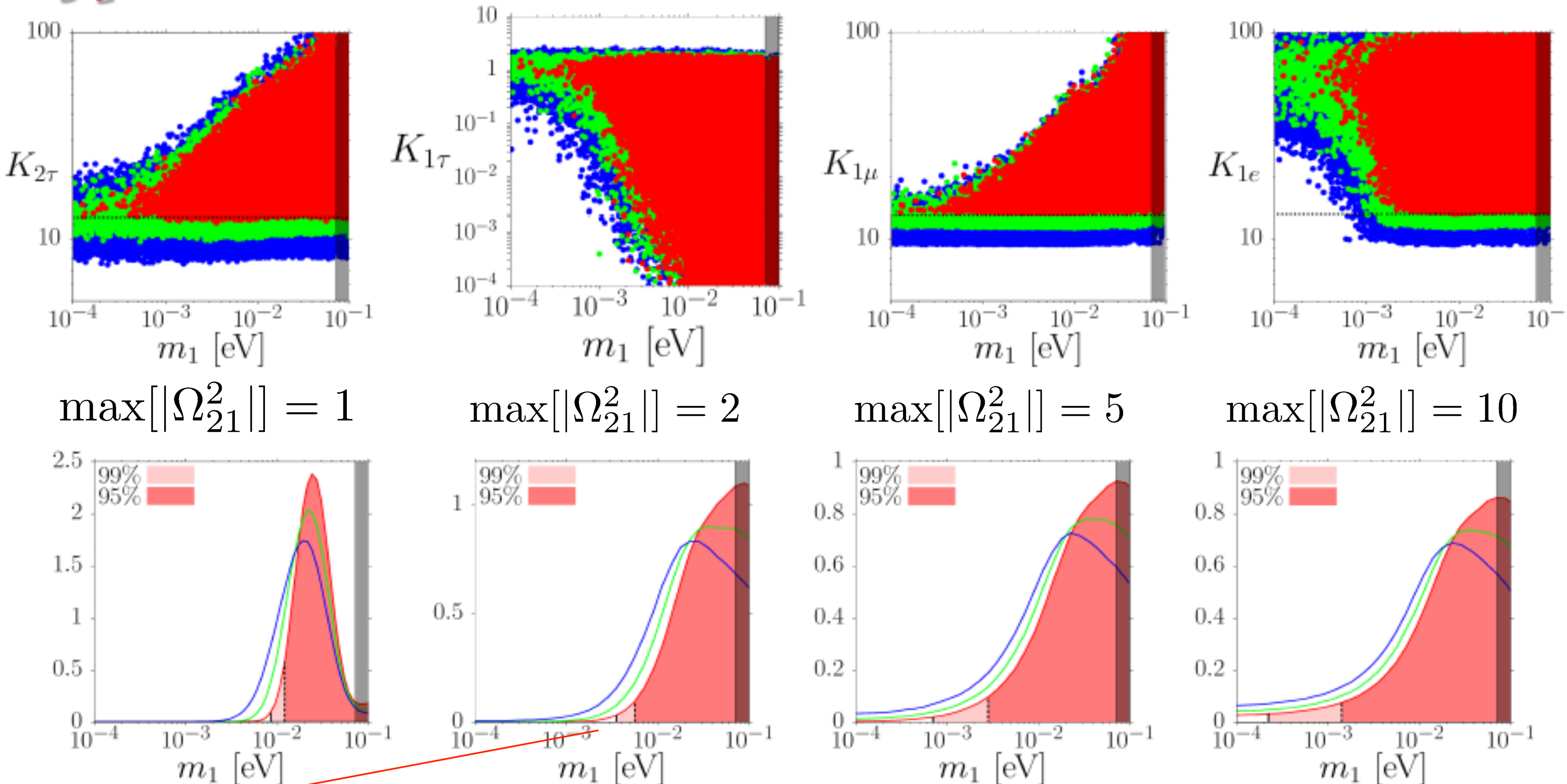
A new neutrino mass window for leptogenesis



$$0.01\ \text{eV} \lesssim m_1 \lesssim 0.1\ \text{eV}$$

A lower bound on neutrino masses (IO)

$N_{B-L}^{P,i}$ = 0.001, 0.01, 0.1 $\max[|\Omega^2_{21}|] = 2$ INVERTED ORDERING



$m_1 \gtrsim 3$ meV $\Rightarrow \Sigma_i\, m_i \gtrsim 100$ meV (not necessarily deviation from HL)

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

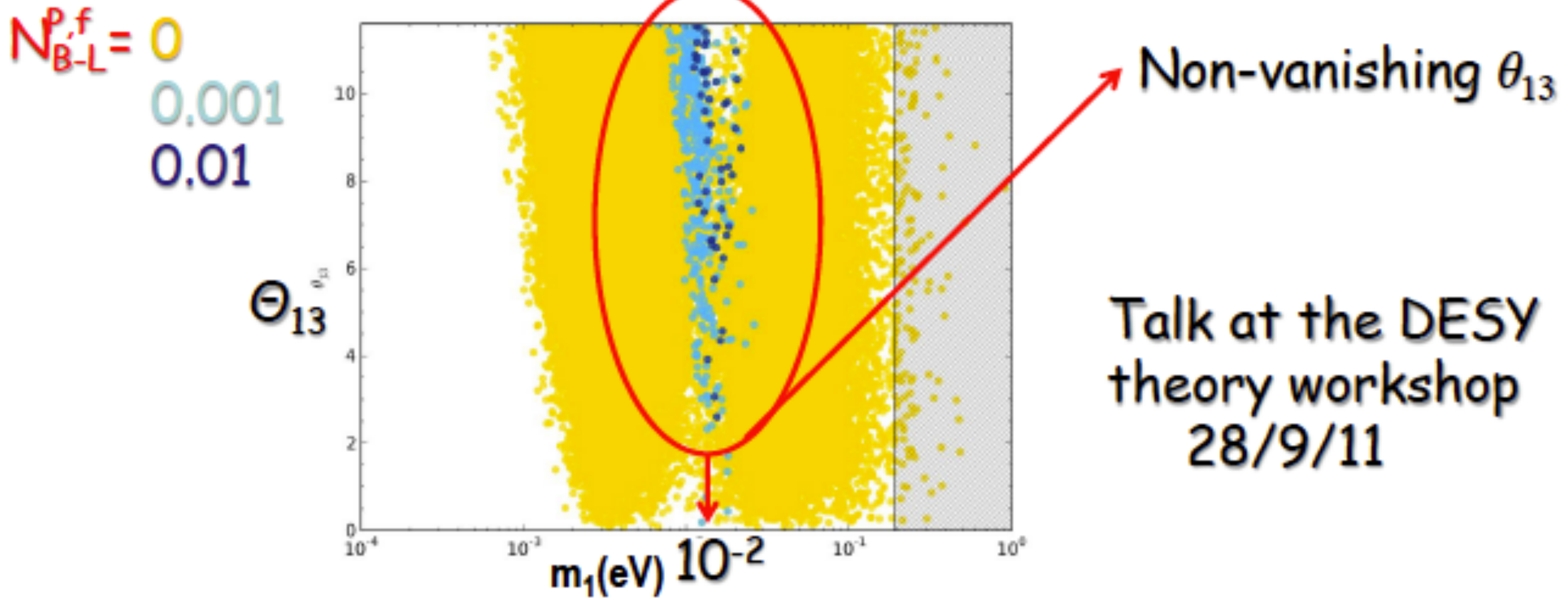
(PDB, Marzola '11)

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

Imposing successful strong thermal leptogenesis condition:

$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p} + N_{B-L}^{\rm lep}, \;\; |N_{B-L}^{\rm p}| \ll N_{B-L}^{\rm lep} \simeq 100\,\eta_B^{CMB}$$

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



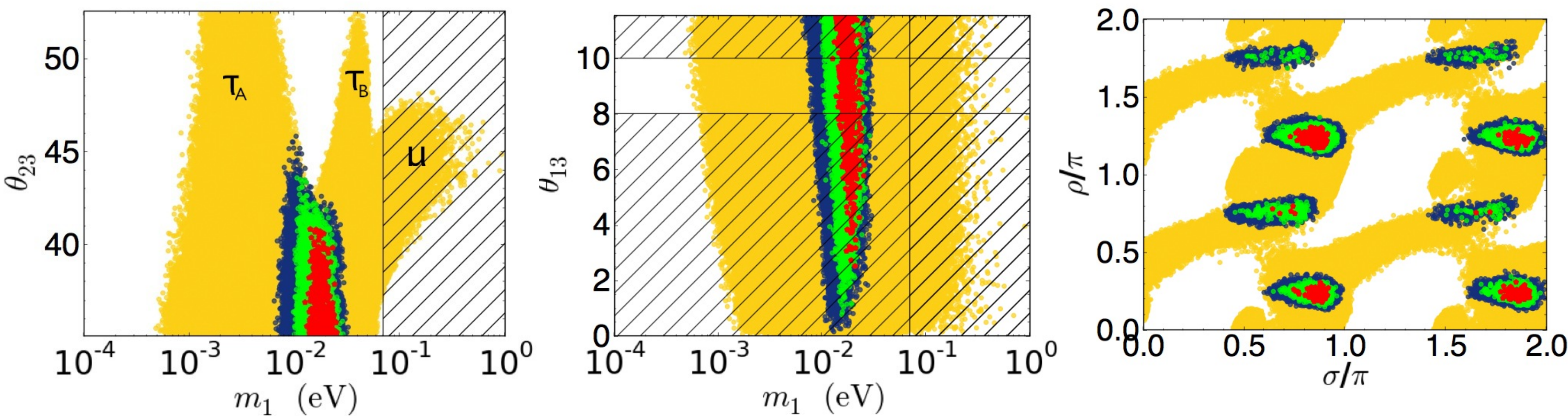
Talk at the DESY theory workshop 28/9/11

Strong thermal SO(10)-inspired solution

(PDB, Marzola '11; '13)

- YES the strong thermal leptonesis condition can be also satisfied for a subset of the solutions (red, green, blue regions) only for NORMAL ORDERING

$\alpha_2=5$ $N^{P,i}_{B-L}$ = 0.001, 0.01, 0.1, 0 $I \leq V_L \leq V_{CKM}$



- The lightest neutrino mass respects the general lower bound but is also upper bounded ⇒ $15 \lesssim m_1 \lesssim 25$ meV;
- The reactor mixing angle has to be non-vanishing (preliminary results presented before Daya Bay discovery);
- The atmospheric mixing angle falls strictly in the first octant;
- The Majorana phases are even more constrained around special values

SO(10)-inspired+strong thermal leptogenesis

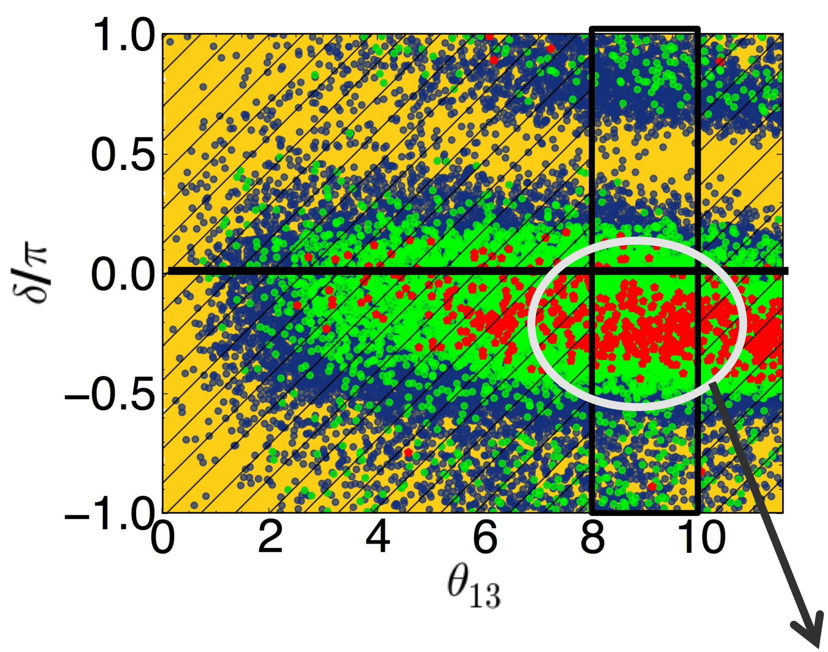
(PDB, Marzola '11-'12)

Imposing successful strong thermal leptogenesis condition:

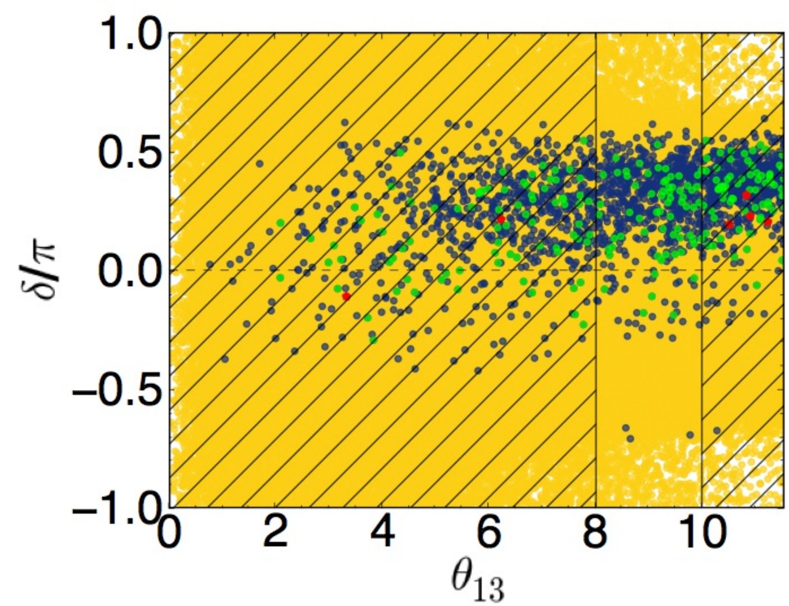
$$N^{\rm f}_{B-L} = N^{\rm p}_{B-L} + N^{\rm lep}_{B-L}, \quad |N^{\rm p}_{B-L}| \ll N^{\rm lep}_{B-L} \simeq 100\, \eta_B^{CMB}$$

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

$\eta_B = \eta_B^{CMB}$



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

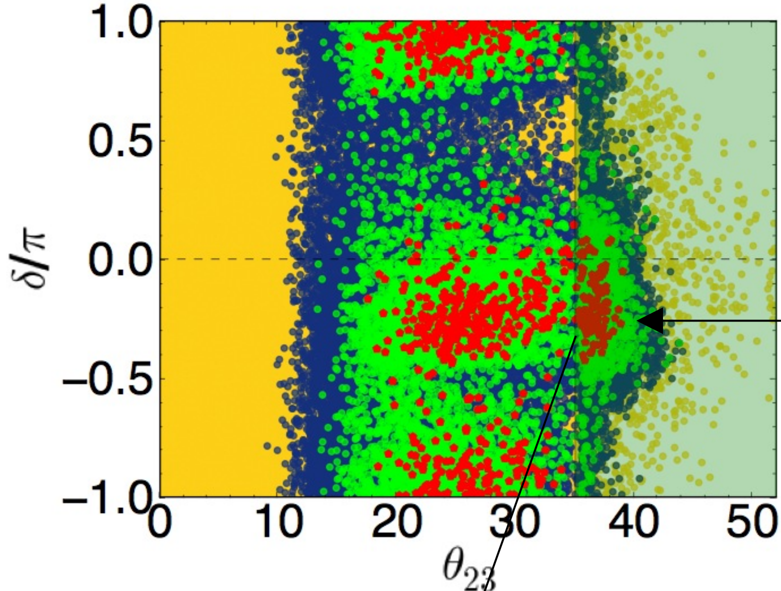


A Dirac phase $\delta \sim -45^\circ$ is favoured: sign matters!

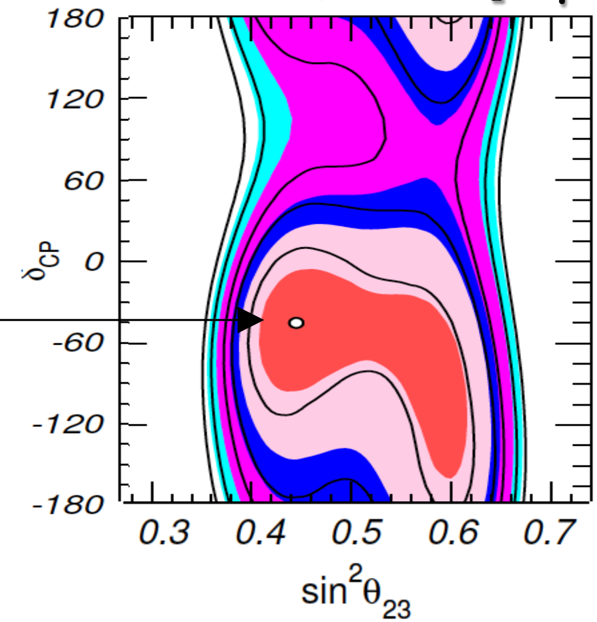
Strong thermal SO(10)-inspired leptogenesis: the atmospheric mixing angle test

NuFIT 1.2 (2013)

arXiv:1308.1107



v1.2: Three-neutrino results after the 'TAUP 2013' conference [September 2013]



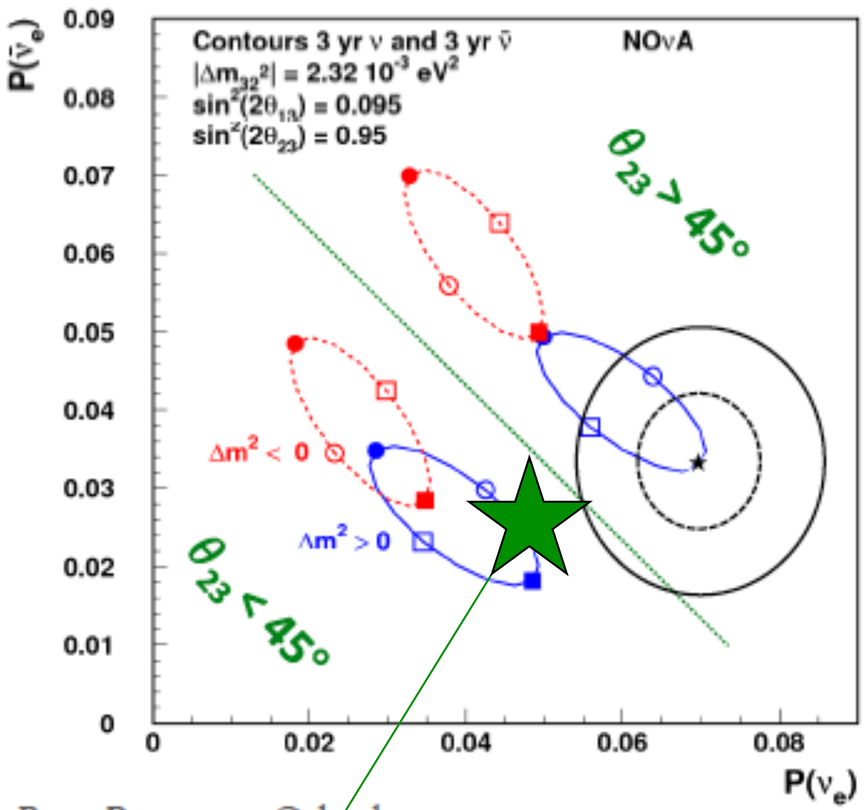
http://www.nu-fit.org/sites/default/files/v12.fig-dlthie-glob.pdf

For values of $\theta_{23} \gtrsim 36^0$ the Dirac phase is predicted to be $\delta \sim -45^0$

It is interesting that low values of the atmospheric mixing angle are also necessary to reproduce b-τ unification in SO(10) models (Bajc, Senjanovic, Vissani '06)

Experimental test on the way: NOνA

Expected NOνA contours for one example scenario at 3 yr + 3 yr



Ryan Patterson, Caltech

Strong thermal SO(10)-inspired solution

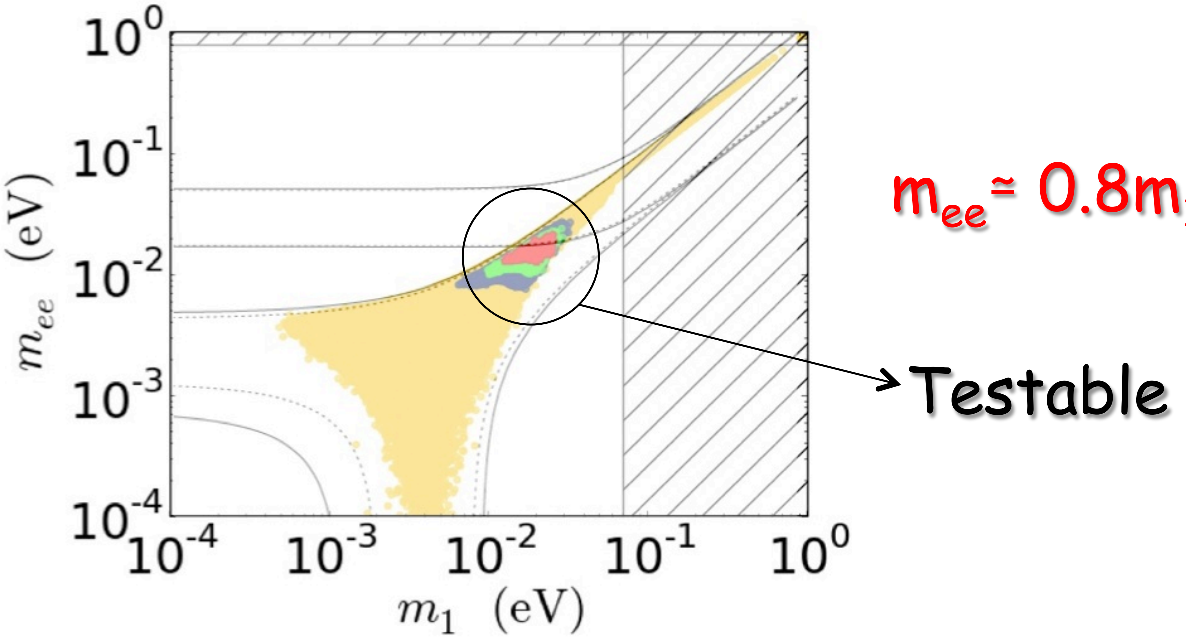
Last brick in the wall: neutrinoless double beta decay

(PDB, Marzola '11-'12)

Sharp predictions on the absolute neutrino mass scale including $0\nu\beta\beta$ effective neutrino mass m_{ee}

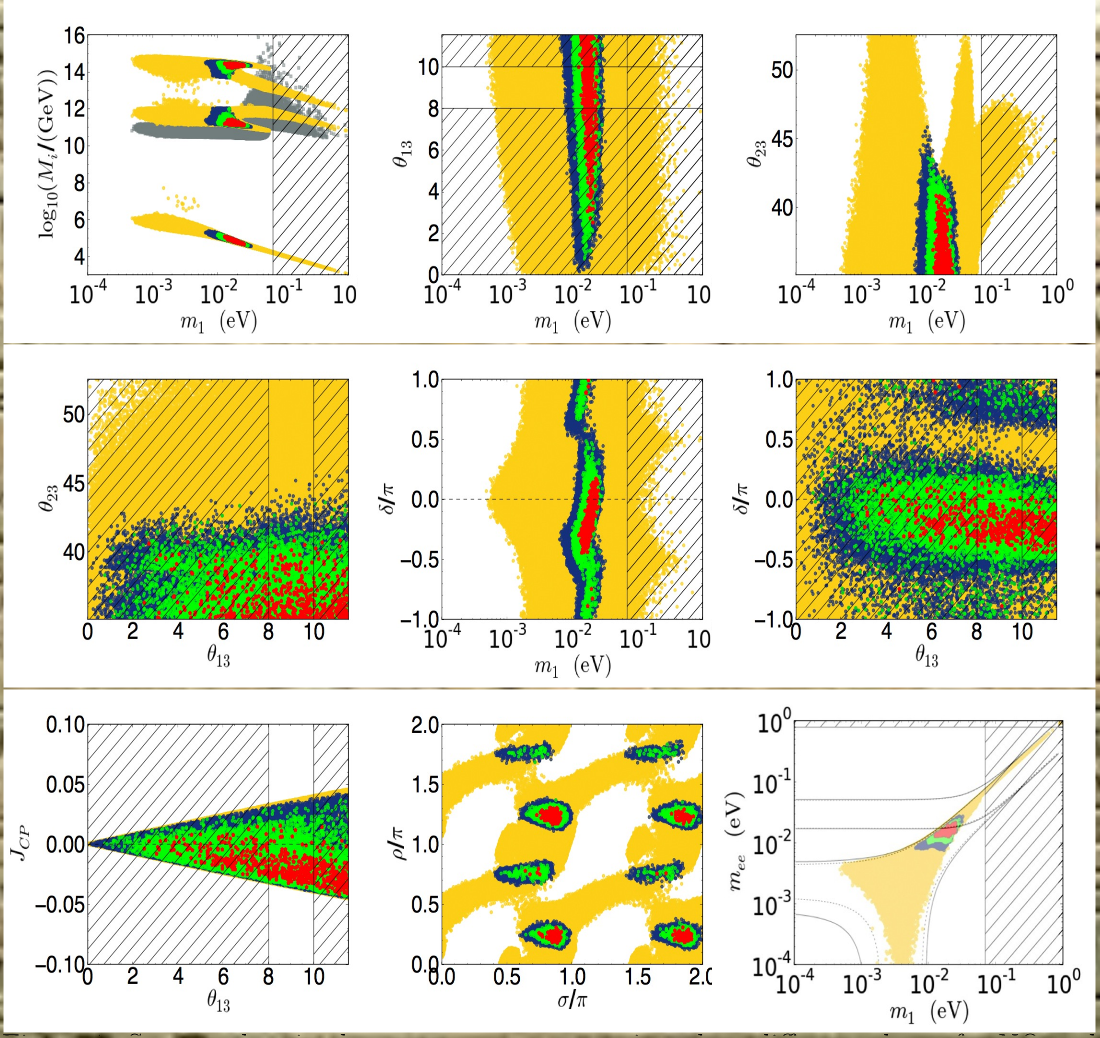
N_{B-L}= 0
0.001
0.01
0.1

α_2=5



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

Decrypting the strong thermal SO(10)-inspired leptogenesis solution

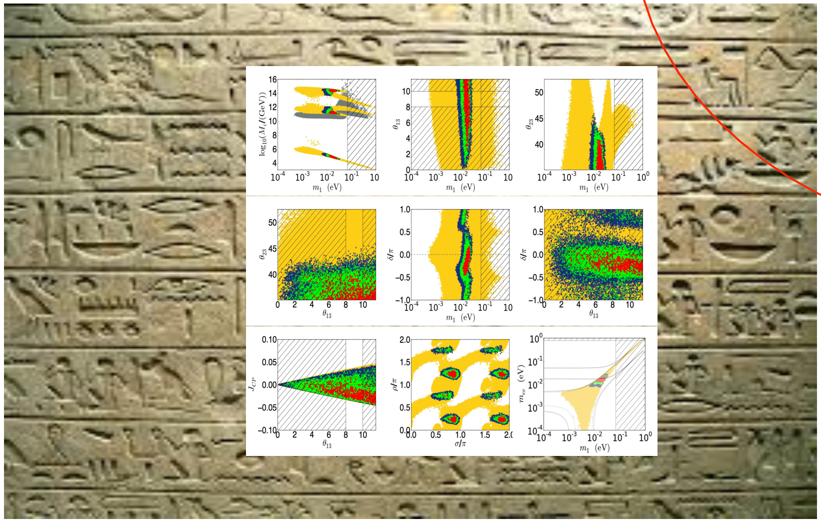


Decrypting the strong thermal SO(10)-inspired leptogenesis solution

(PDB, Fiorentin, Marzola, in preparation)

$$\eta_B \simeq 0.01\, \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, e^{-\frac{3\pi}{8} K_{1\tau}}$$

+ Strong thermal condition
+ SO(10)-inspired conditions



?

Strong thermal SO(10)-inspired solution

Imposing SO(10)-inspired conditions

Seesaw formula

$$m_\nu = -m_D \, \frac{1}{D_M} \, m_D^T \, .$$

Leptonic mixing matrix

$$U^\dagger \, m_\nu \, U^\star = -D_m$$

Bi-unitary parameterisation

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

SO(10)-inspired conditions

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

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

Majorana mass matrix (in the Yukawa basis)

A diagonalization problem:

$$U_R^\star \, D_M \, U_R^\dagger = M = D_{m_D} \, V_L^\star \, U^\star \, D_m^{-1} \, U^\dagger \, V_L^\dagger \, D_{m_D} \simeq -D_{m_D} \, m_\nu^{-1} \, D_{m_D}$$

Diagonalizing the Majorana matrix

$$U_R \simeq \begin{pmatrix} 1 & -\frac{m_{D1}}{m_{D2}} \frac{m^\star_{\nu e\mu}}{m^\star_{\nu ee}} & \frac{m_{D1}}{m_{D3}} \frac{(m_\nu^{-1})^\star_{e\tau}}{(m_\nu^{-1})^\star_{\tau\tau}} \\ \frac{m_{D1}}{m_{D2}} \frac{m_{\nu e\mu}}{m_{\nu ee}} & 1 & \frac{m_{D2}}{m_{D3}} \frac{(m_\nu^{-1})^\star_{\mu\tau}}{(m_\nu^{-1})^\star_{\tau\tau}} \\ \frac{m_{D1}}{m_{D3}} \frac{m_{\nu e\tau}}{m_{\nu ee}} & -\frac{m_{D2}}{m_{D3}} \frac{(m_\nu^{-1})_{\mu\tau}}{(m_\nu^{-1})_{\tau\tau}} & 1 \end{pmatrix} D_\Phi \qquad D_\phi \equiv (e^{-i\,\frac{\Phi_1}{2}}, e^{-i\,\frac{\Phi_2}{2}}, e^{-i\,\frac{\Phi_3}{2}})$$

$$M_3 \simeq m^2_{D3}\,|(m_\nu^{-1})_{\tau\tau}| = m^2_{D3} \left| \frac{(U^\star_{\tau 1})^2}{m_1} + \frac{(U^\star_{\tau 2})^2}{m_2} + \frac{(U^\star_{\tau 3})^2}{m_3} \right| \propto \alpha_3^2\, m_t^2 \qquad \Phi_3 = \mathrm{Arg}[-(m_\nu^{-1})_{\tau\tau}]\,.$$

$$M_1 \simeq \frac{m^2_{D1}}{|m_{\nu ee}|} = \frac{m^2_{D1}}{|m_1\, U^2_{e1} + m_2\, U^2_{e2} + m_3\, U^2_{e3}|} \propto \alpha_1^2\, m_u^2\,. \qquad \Phi_1 = \mathrm{Arg}[-m^\star_{\nu ee}]\,.$$

$$M_2 \simeq \frac{m^2_{D2}}{m_1\, m_2\, m_3} \frac{|m_{\nu ee}|}{|(m_\nu^{-1})_{\tau\tau}|} = m^2_{D2} \frac{|m_1\, U^2_{e1} + m_2\, U^2_{e2} + m_3\, U^2_{e3}|}{|m_2\, m_3\, U^{\star 2}_{\tau 1} + m_1\, m_3\, U^{\star 2}_{\tau 2} + m_1\, m_2\, U^{\star 2}_{\tau 3}|} \propto \alpha_2^2\, m_c^2\,, \qquad \Phi_2 = \mathrm{Arg}\left[\frac{m_{\nu ee}}{(m_\nu^{-1})_{\tau\tau}}\right] - 2\,(\rho + \sigma)$$

A formula for the final asymmetry

$$\varepsilon_{2\alpha} \simeq \overline{\varepsilon}(M_2)\, \frac{m_{D\alpha}^2}{m_{D3}^2\,|U_{R32}|^2 + m_{D2}^2}\, \frac{|(m_\nu^{-1})_{\tau\tau}|^{-1}}{m_{\rm atm}}\, {\rm Im}[U_{R\alpha2}^\star\, U_{R\alpha3}\, U_{R32}^\star\, U_{R33}]\,.$$

Using the approximate expression eq. (31) for U_R and the relations (4), one fin following hierarchical pattern for the $\varepsilon_{2\alpha}$'s:

$$\varepsilon_{2\tau} : \varepsilon_{2\mu} : \varepsilon_{2e} = \alpha_3^2\, m_t^2 : \alpha_2^2\, m_c^2 : \alpha_1^2\, m_u^2\, \frac{\alpha_3 m_t}{a_2\, m_c}\, \frac{\alpha_1^2\, m_u^2}{\alpha_2^2\, m_c^2}\,.$$

$$N_{B-L}^{\rm lep,f} \simeq \frac{3}{16\,\pi}\, \frac{\alpha_2^2\, m_c^2}{v^2}\, \frac{|m_{\nu ee}|\,(|m_{\nu\tau\tau}^{-1}|^2 + |m_{\nu\mu\tau}^{-1}|^2)^{-1}}{m_1\, m_2\, m_3}\, \frac{|m_{\nu\tau\tau}^{-1}|^2}{|m_{\nu\mu\tau}^{-1}|^2}\, \sin\alpha_L$$
$$\times\ \kappa\left(\frac{m_1\, m_2\, m_3}{m_\star}\, \frac{|(m_\nu^{-1})_{\mu\tau}|^2}{|m_{\nu ee}|\,|(m_\nu^{-1})_{\tau\tau}|}\right)$$
$$\times\ e^{-\frac{3\pi}{8}\,\frac{|m_{\nu e\tau}|^2}{m_\star\,|m_{\nu ee}|}}\,.$$

Conclusions:

- The importance of discoverying CP violation in neutrino oscillations should not be be overrated but also not undermined;
- Highs scale leptogenesis is difficult to test but maybe not impossible: necessary to work out plausible scenarios;
- Thermal leptogenesis: problem of the independence of the initial conditions because of flavour effects;
- Solution: N_2-dominated scenario (minimal seesaw, hierarchical N_i)
- Deviations of neutrino masses from the hierarchical limits are expected
- SO(10)-inspired models are rescued by the N_2-dominated scenario and can also realise strong thermal leptogenesis

Strong thermal SO(10)-inspired leptogenesis solution

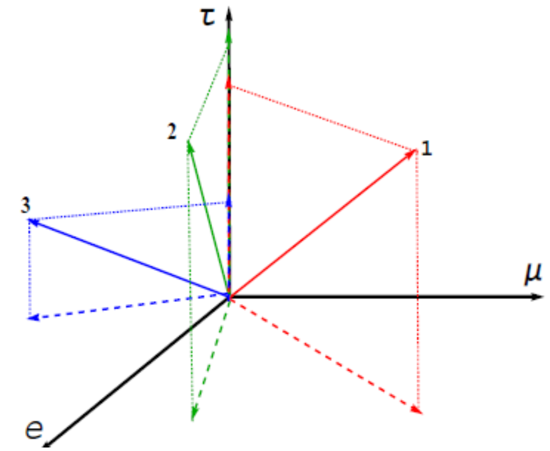
θ_{13}	$\gtrsim 3^\circ$
ORDERING	NORMAL
θ_{23}	$\lesssim 42^\circ$
δ	**$\sim -45^\circ$**
$m_{ee} \simeq 0.8\, m_1$	$\simeq 15$ meV

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

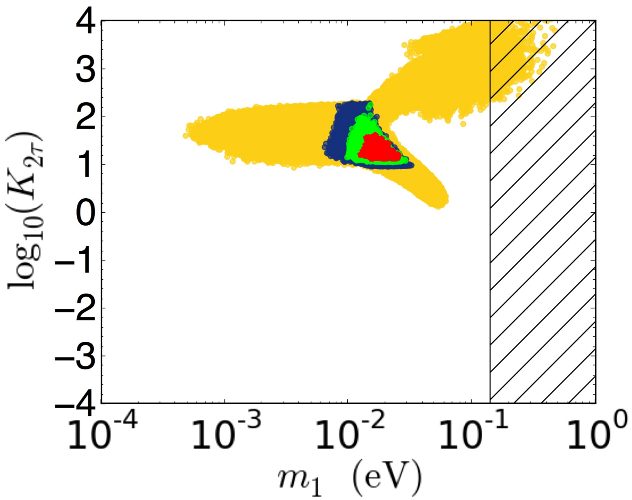
The result is a "monster" equation:

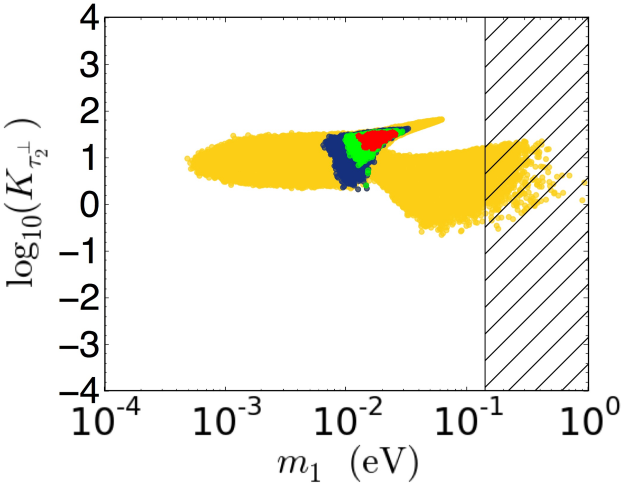


$$
\begin{aligned}
\frac{dN^{B-L}_{\alpha\beta}}{dz} = \; & \varepsilon^{(1)}_{\alpha\beta}\, D_1\, (N_{N_1} - N^{\rm eq}_{N_1}) - \frac{1}{2} W_1 \left\{\mathcal{P}^{0(1)}, N^{B-L}\right\}_{\alpha\beta} \\
+ \; & \varepsilon^{(2)}_{\alpha\beta}\, D_2\, (N_{N_2} - N^{\rm eq}_{N_2}) - \frac{1}{2} W_2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

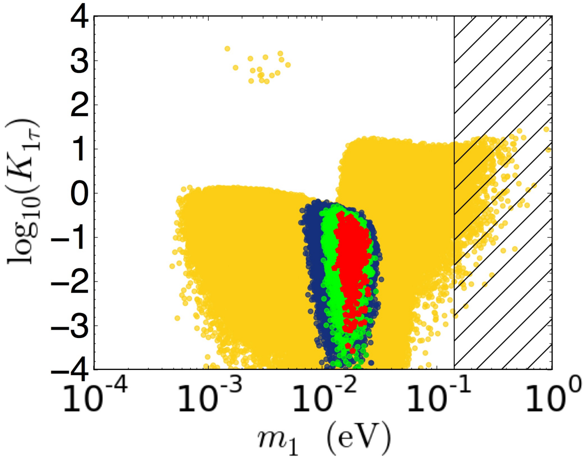
Some insight from the decay parameters

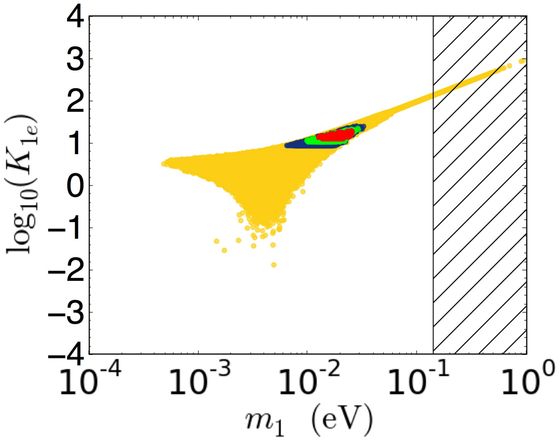
At the production ($T \sim M_2$)

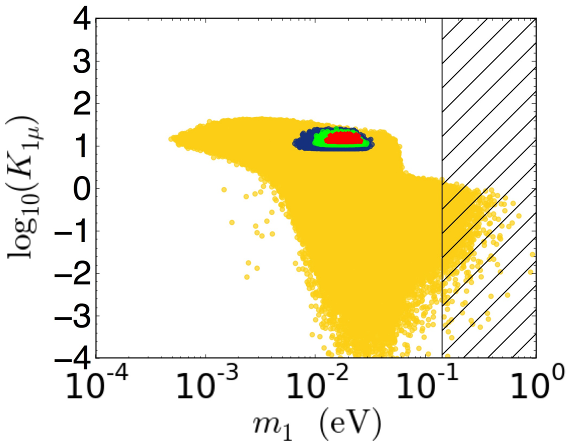




At the wash-out ($T \sim M_1$)





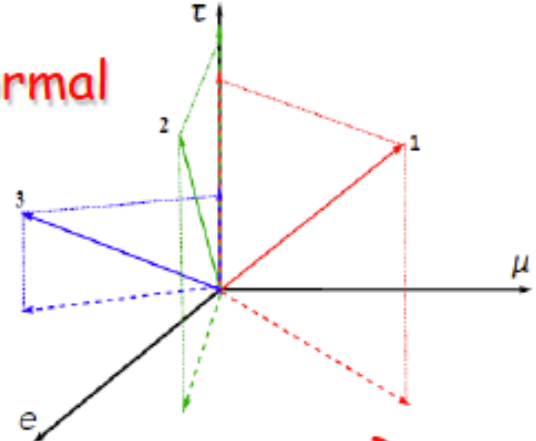


Flavour projection

(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



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

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

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

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

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

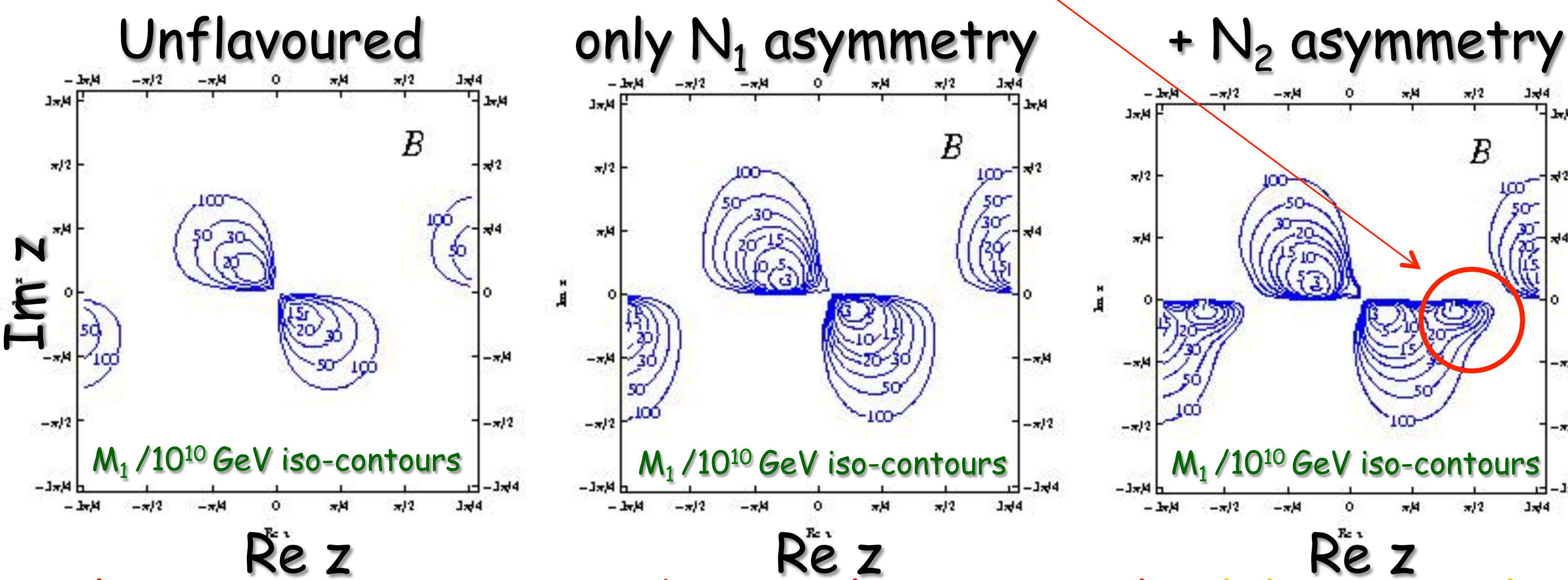
2 RH neutrino scenario revisited

(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

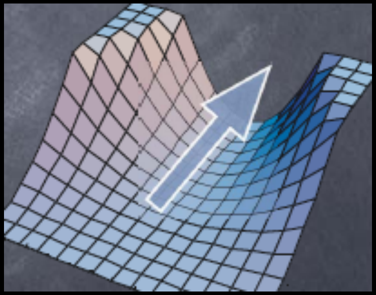
Affleck-Dine Baryogenesis

(Affleck, Dine '85)

In the Supersymmetric SM there are many "flat directions" in the space of a field composed of squarks and/or sleptons

$$V(\phi) = \sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2 + \frac{1}{2}\sum_A \left(\sum_{ij} \phi_i^* (t_A)_{ij} \phi_j\right)^2$$

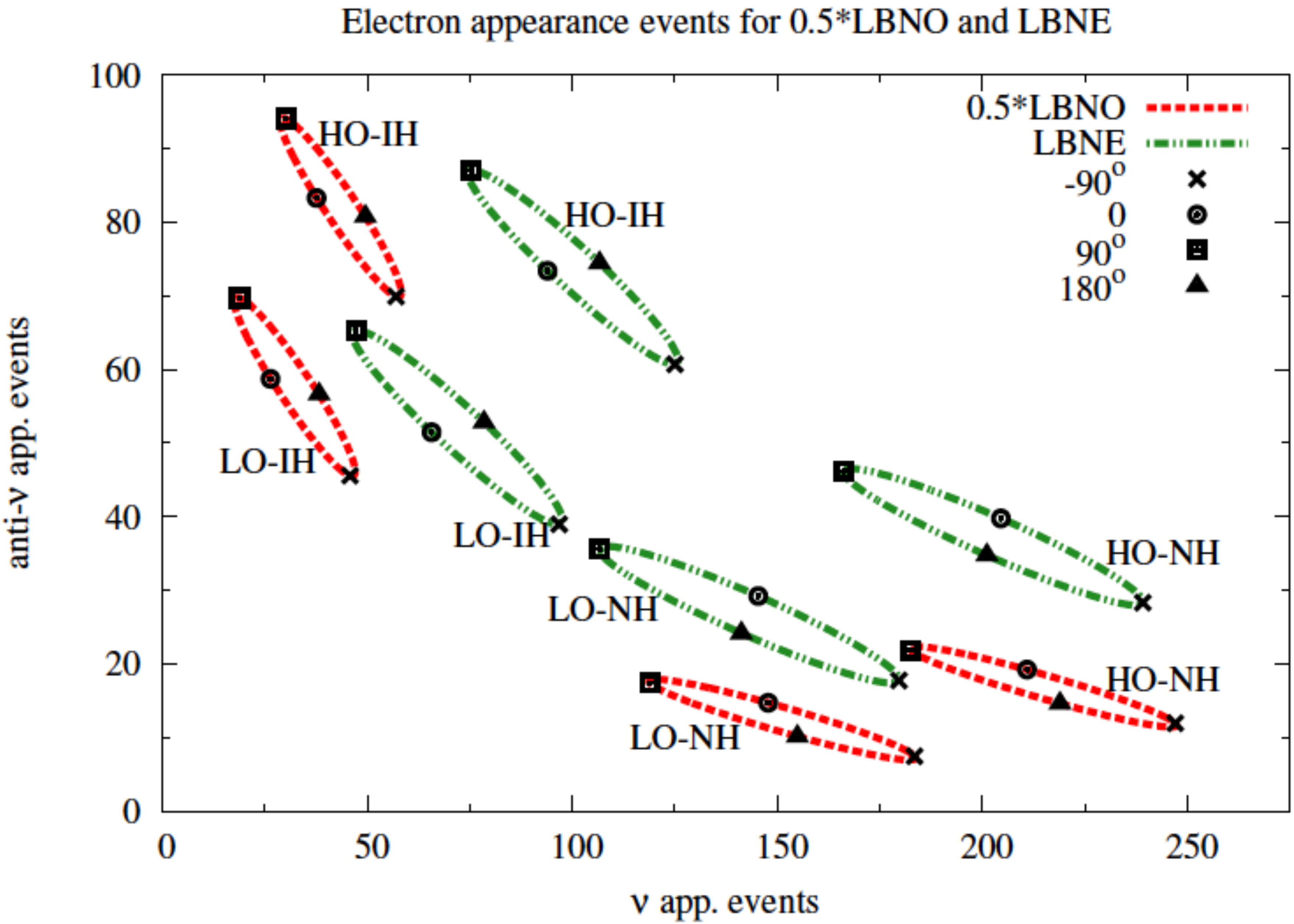
F term D term



A flat direction can be parametrized in terms of a complex field (AD field) that carries a baryon number that is violated dynamically during inflation

$$\frac{n_B}{s} \sim 10^{-10} \left(\frac{m_{3/2}}{m_\Phi}\right) \left(\frac{m_\Phi}{\mathrm{TeV}}\right)^{-\frac{1}{2}} \left(\frac{M}{M_P}\right)^{\frac{3}{2}} \left(\frac{T_R}{10\,\mathrm{GeV}}\right)$$

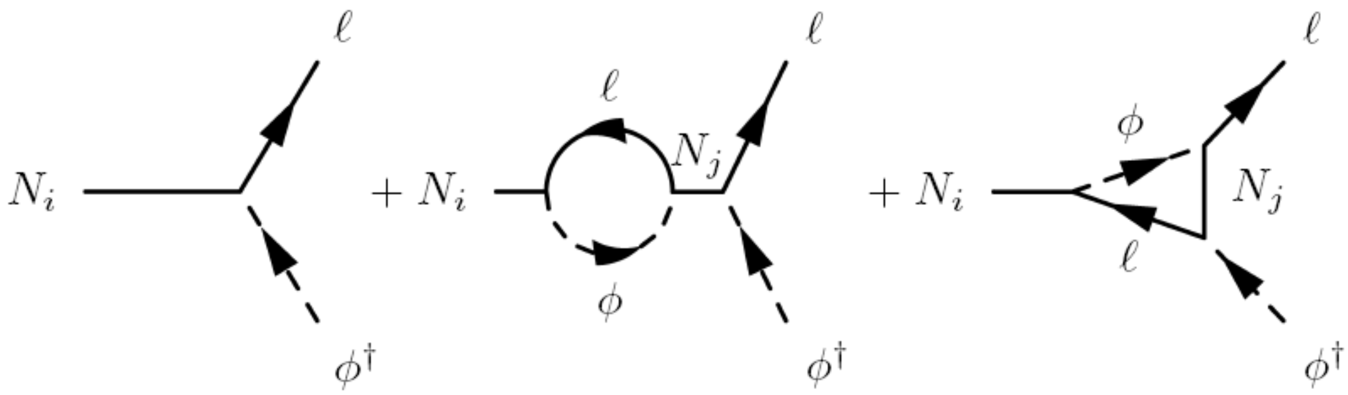
The final asymmetry is $\propto T_{RH}$ and the observed one can be reproduced for low values $T_{RH} \sim 10$ GeV !



Electron appearance events for 0.5*LBNO and LBNE
0.5*LBNO
LBNE
-90°
0
90°
180°
HO-IH
HO-IH
LO-IH
LO-IH
LO-NH
LO-NH
HO-NH
HO-NH
anti-ν app. events
ν app. events

Total CP asymmetries

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



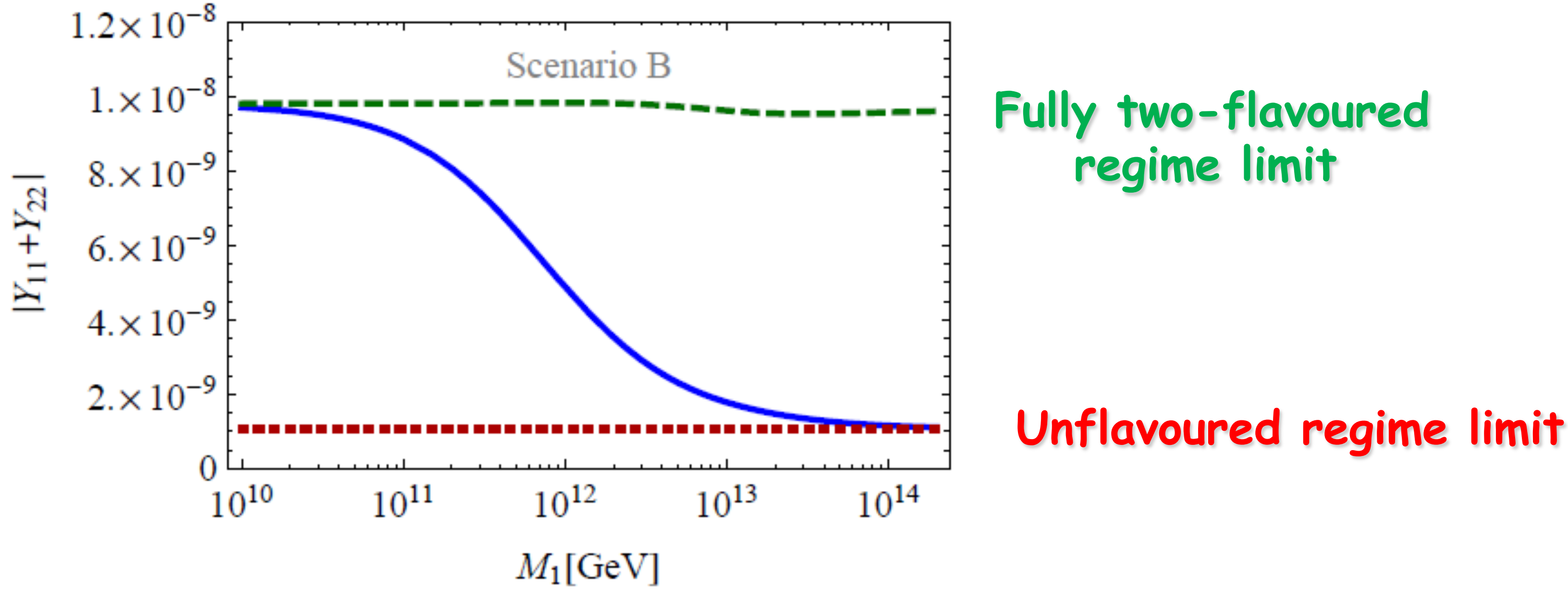
$$\varepsilon_i \simeq \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(m_D^\dagger\, m_D)_{ij}^2\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

It does not depend on U !

Density matrix and CTP formalism to describe the transition regimes

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

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



Additional contribution to CP violation:

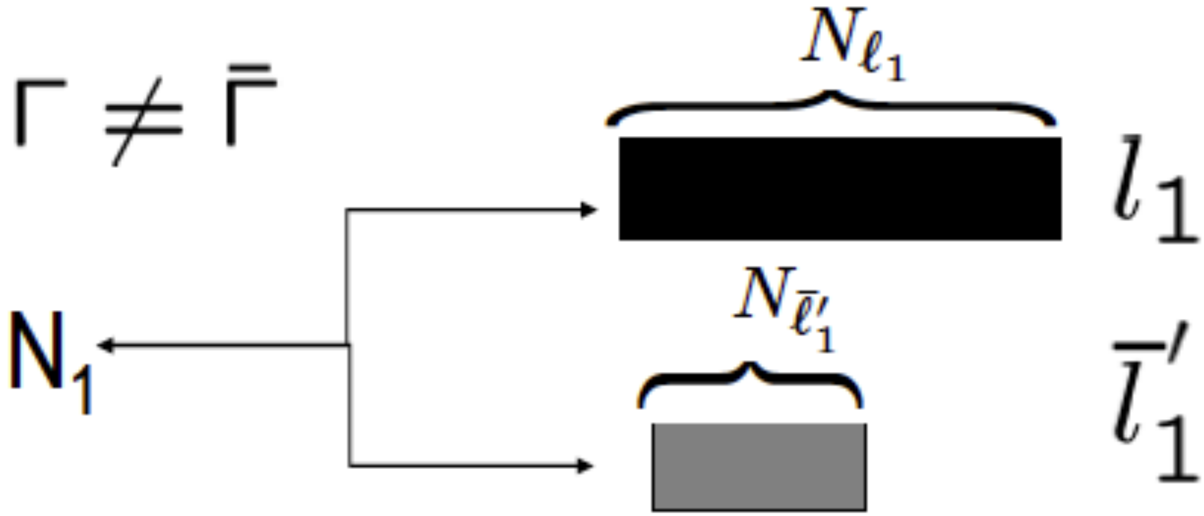
(Nardi, Racker, Roulet '06)

(α = τ, e+μ)

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

depends on U !

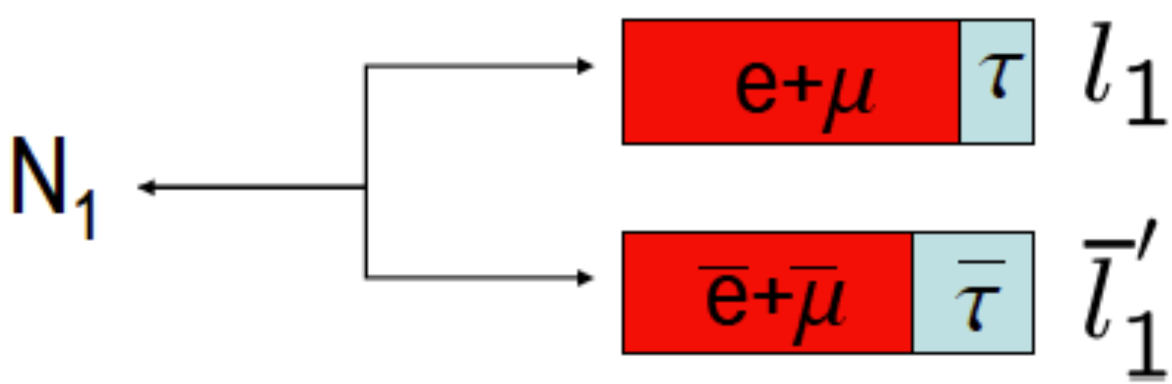
1) $\Gamma \neq \bar{\Gamma}$



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

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

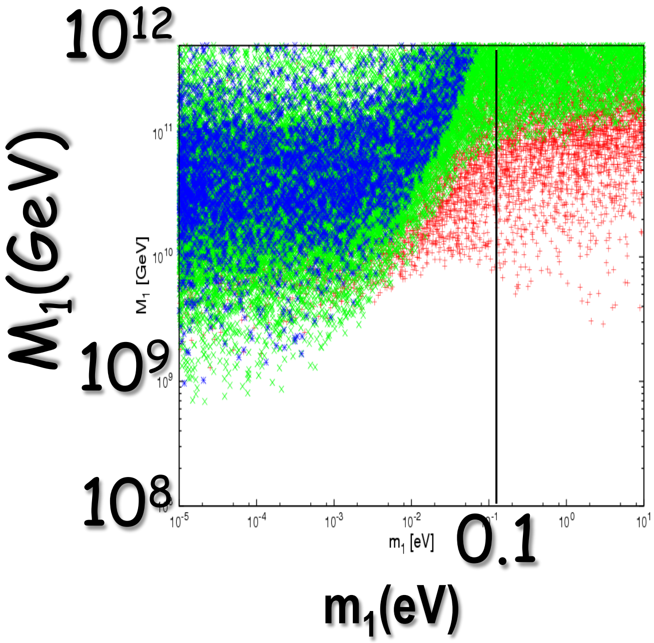
+



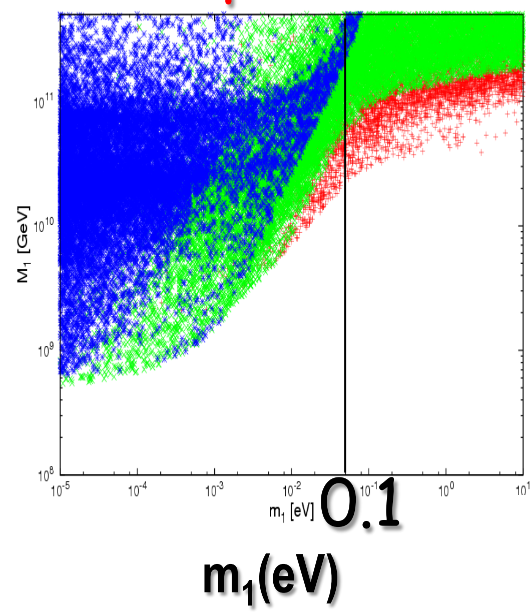
$\Rightarrow \; \frac{\Delta P_{1\alpha}}{2}$

Neutrino mass bounds and role of PMNS phases

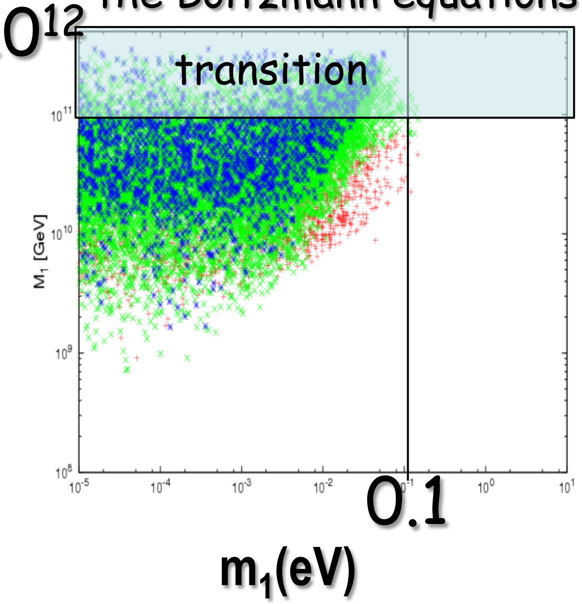
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)

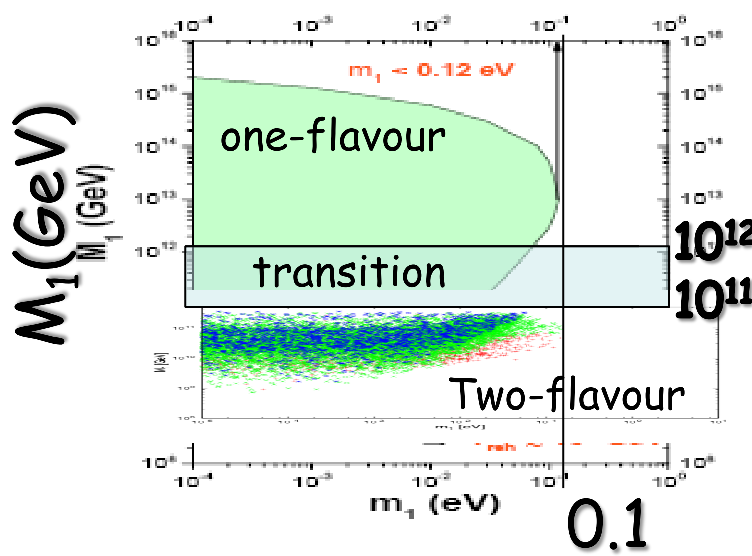


PMNS phases off



Imposing the validity of the Boltzmann equations





Low energy phases can be the only source of CP violation

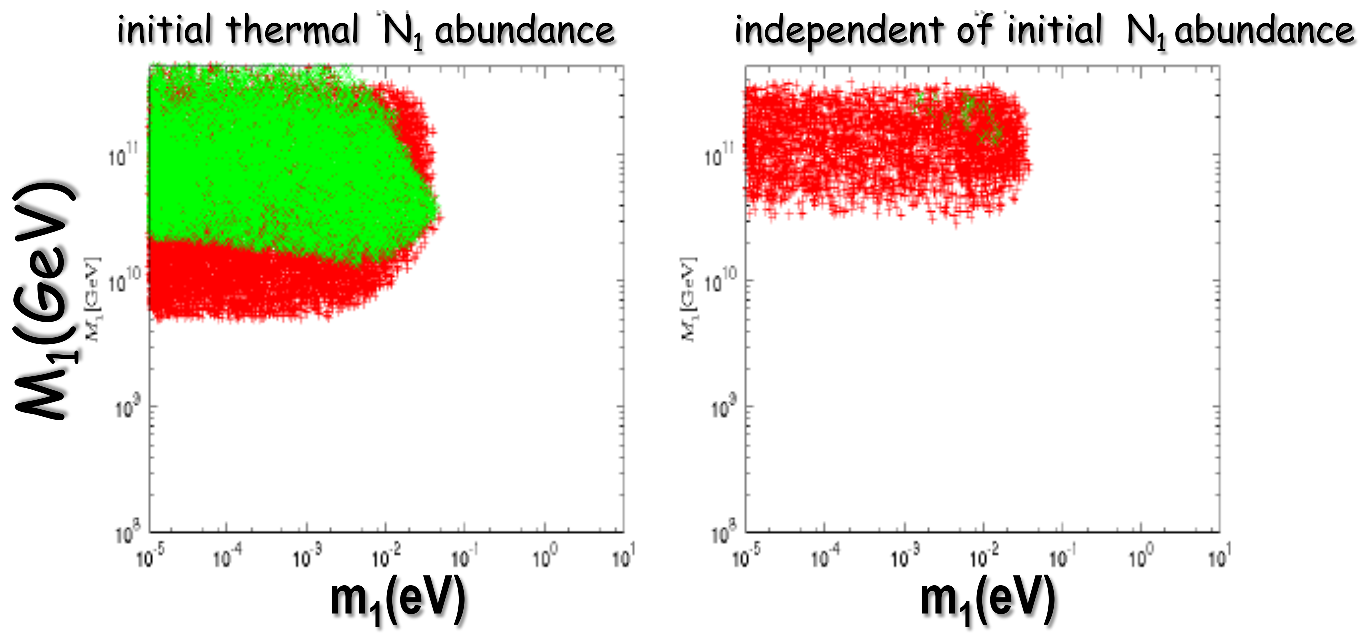
(Nardi et al.'06;Blanchet,PDB'06;Pascoli,Petcov,Riotto '06;Anisimov,Blanchet,PDB '08)

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

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

- Assume even vanishing Majorana phases

$\Rightarrow$ δ 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