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Thermal leptogenesis in the early Universe (and neutrino experiments on the Earth)

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The double side of Leptogenesis

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 hinted by BICEP2 (TBC) and typically implying very high reheat temperatures;

- Discovery of a non-vanishing reactor angle opening the door to further information on mixing parameters;

- Cosmological observations start to have the sensitivity to either rule our or discover quasi-degenerate neutrino masses

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

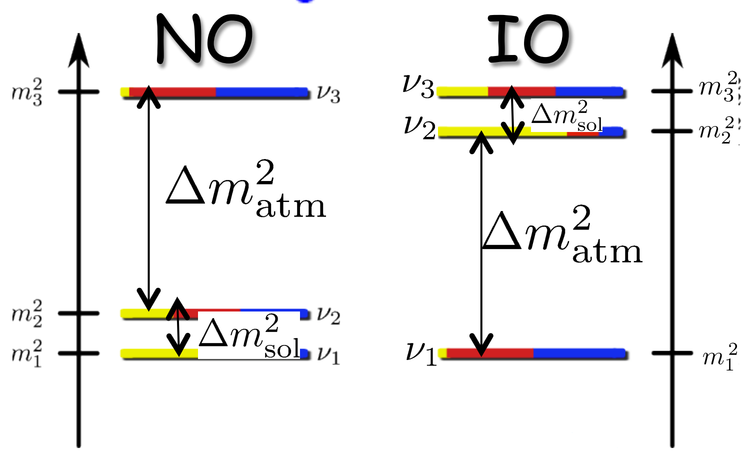
$c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

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: $m_1 < m_2 < m_3$



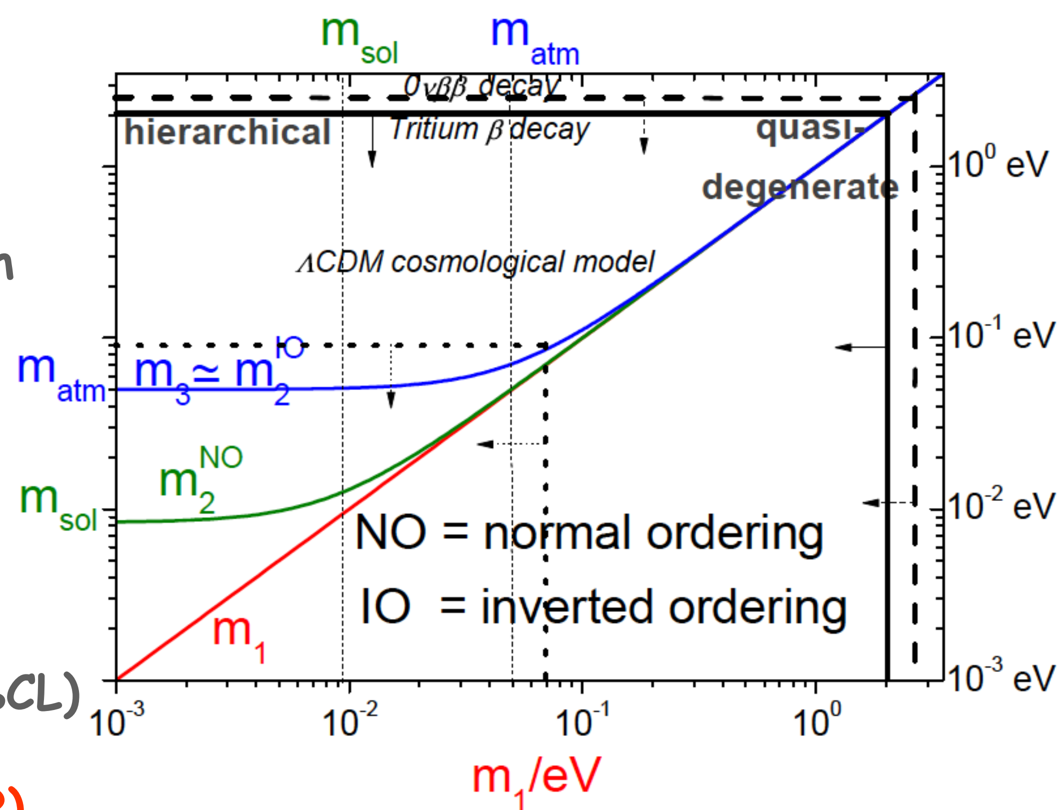
$$m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

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

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???)



Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

- Type I seesaw

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

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

- 3 light Majorana neutrinos with masses $\mathrm{diag}(m_1, m_2, m_3) = -U^\dagger\, m_D\, \frac{1}{M}\, m_D^T\, U^\star$
- 3 very heavy Majorana RH neutrinos N_1, N_2, N_3 with masses $M_3 > M_2 > M_1 \gg m_D$

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

total CP asymmetry

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

- Thermal production of RH neutrinos

$\Rightarrow T_{RH} \gtrsim M_i / (2\div 10) \gtrsim T_{sph} \simeq 100$ GeV (Kuzmin, Rubakov Shaposhnikov '85)

Seesaw parameter space

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

Problem: too many parameters

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

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

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

The **6 parameters in the orthogonal matrix Ω** encode the 3 life times and the 3 total CP asymmetries of the RH neutrinos

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

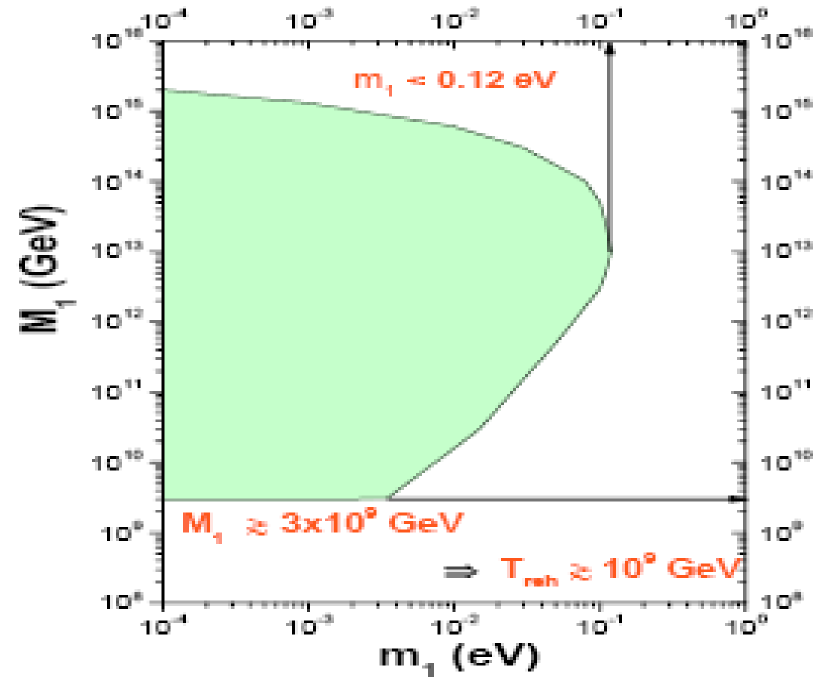
(Davidson, Ibarra '02)

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

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

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

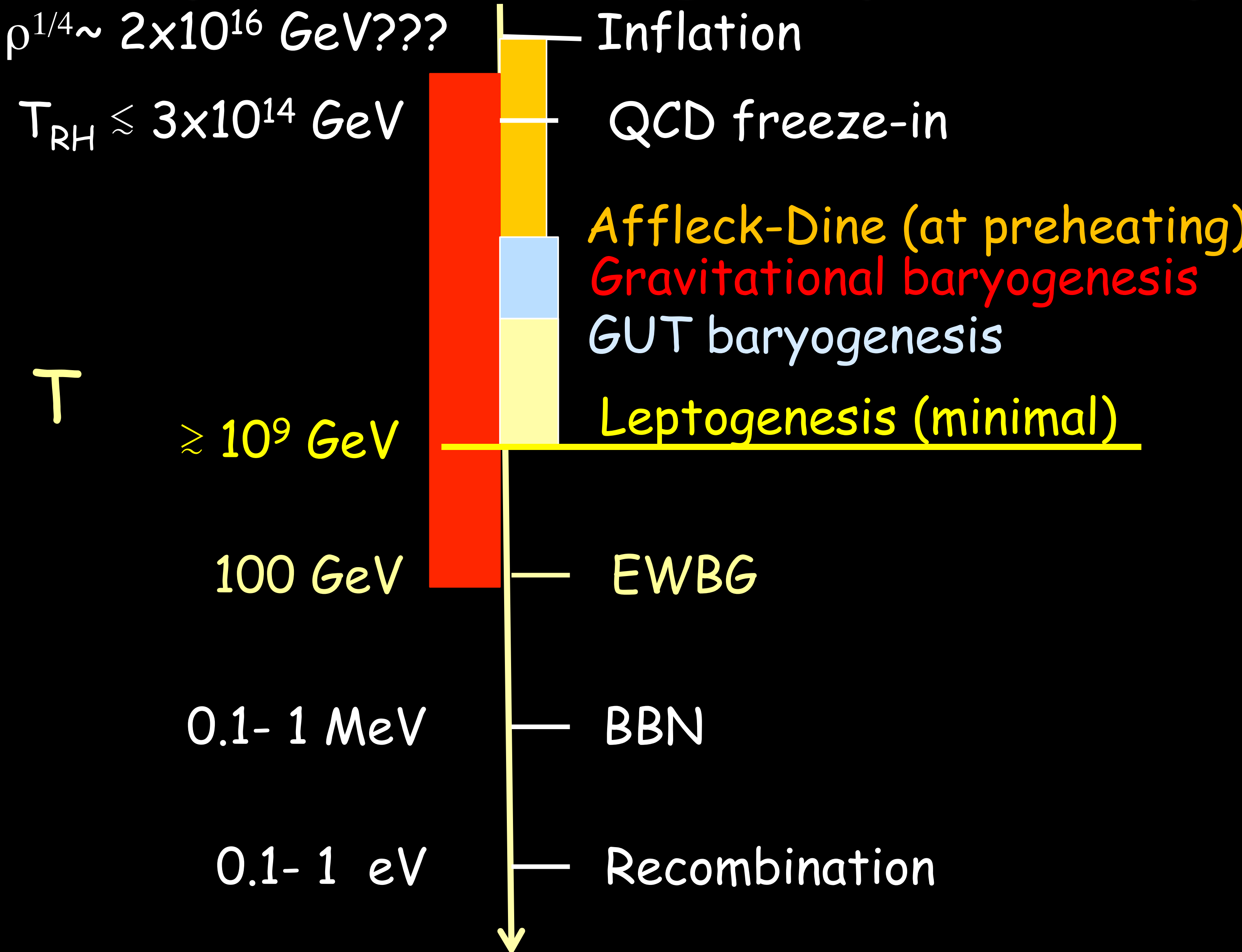
$$\eta_B^{\rm max}(m_1, M_1) \geq \eta_B^{CMB}$$



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)

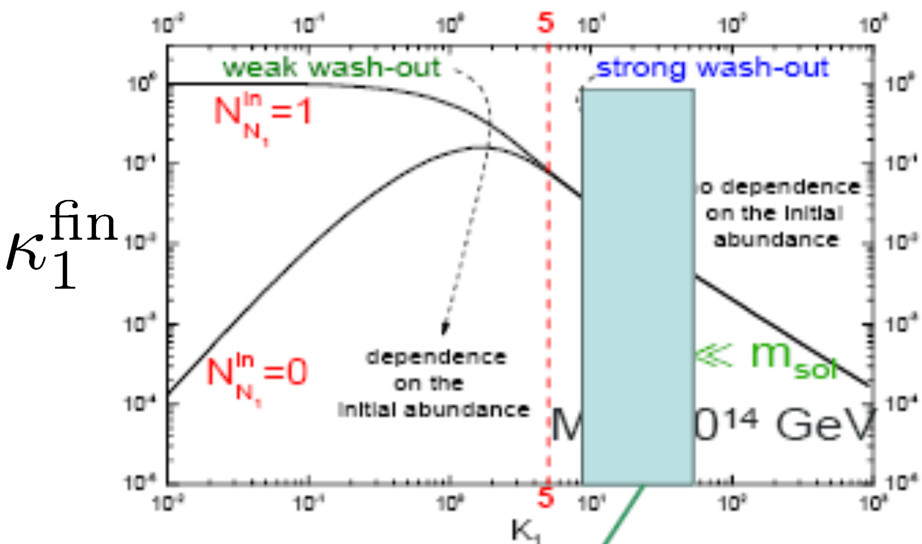
$$\eta_B \simeq 0.01\, \varepsilon_1(m_1, M_1, \Omega)\, \kappa_1^{\rm fin}(K_1)$$

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



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

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

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

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

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:

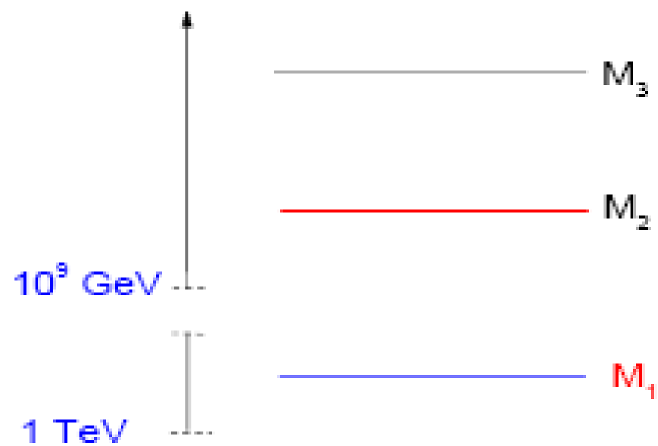
$$N_{B-L}^{\rm f,N_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1} = \varepsilon_1\,\kappa(K_1)$$

...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)

- In the limit $K_1 \to 0$ ($K_1 \lesssim 10^{-30}$!) N_1 is stable on cosmological times and might be the DM particle if one finds a way to produce it (e.g. during or at the end of inflation or from the mixing with N_2) (Anisimov, PDB)

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:

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

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 and $K_1 \gg 1$ ⇒ $\eta_B^{(N1)}, \eta_B^{(N2)} \ll \eta_B^{CMB}$

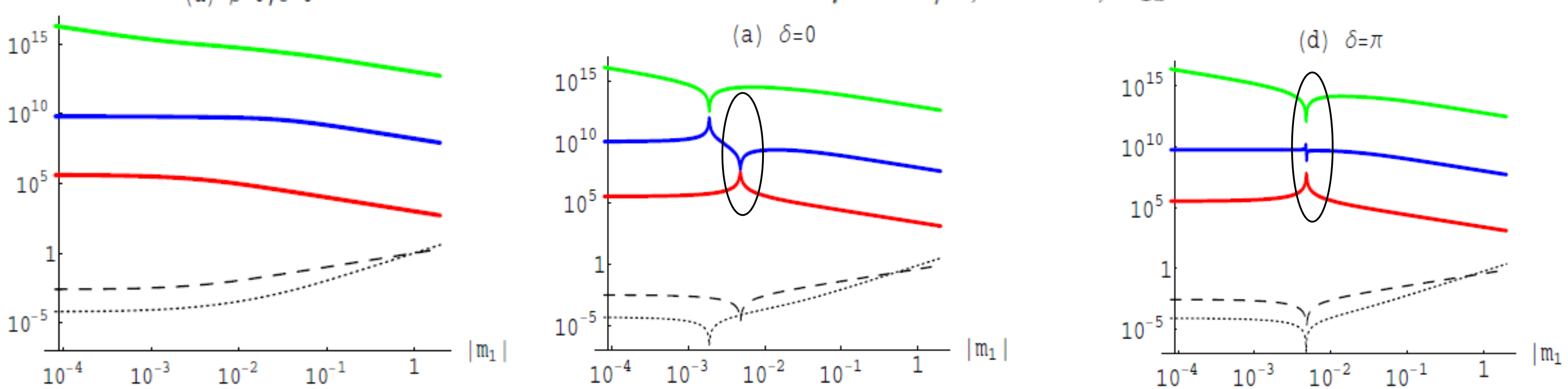
* Note that SO(10)-inspired consditions can be realized also beyond SO(10) and even beyond GUT models (e.g. "Tetraleptogenesis", King '13)

Crossing level solutions

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

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

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



➢ 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.

Lepton flavour effects

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

Flavor composition of lepton quantum states:

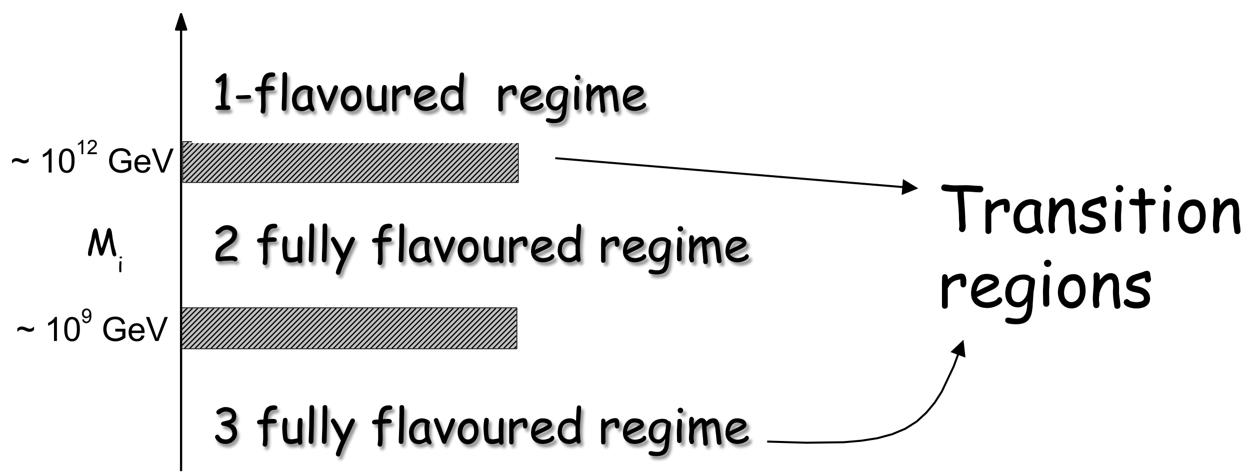
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1\rangle \, |l_\alpha\rangle \quad (\alpha = e, \mu, \tau) \qquad P_{1\alpha} \equiv |\langle \ell_1 | \alpha\rangle|^2$$

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

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

$\Rightarrow$ 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 $\Rightarrow$ 3-flavor regime



Two fully flavoured regime

- Classic Kinetic Equations (in their simplest form)

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

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

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

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

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

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

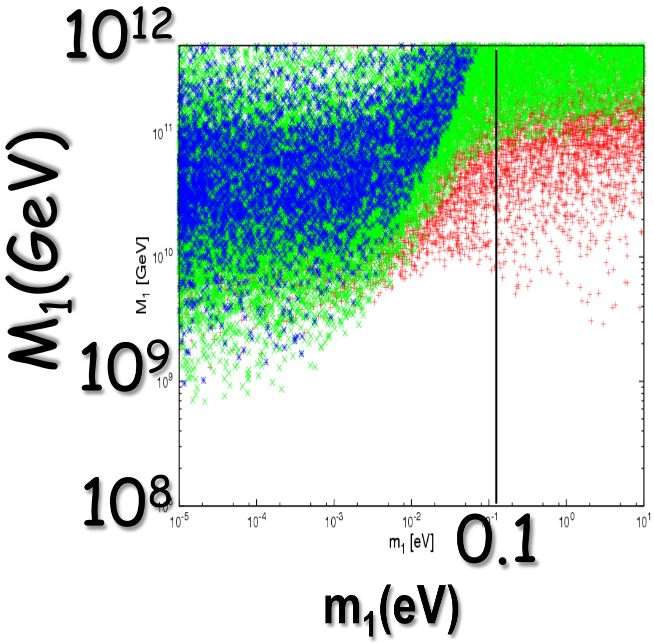
$$\Rightarrow \quad \boxed{\varepsilon_{1\alpha} \equiv -\frac{P_{1\alpha}\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = P_{1\alpha}^0 \, \varepsilon_1 + \Delta P_{1\alpha}(\Omega, U)/2}$$

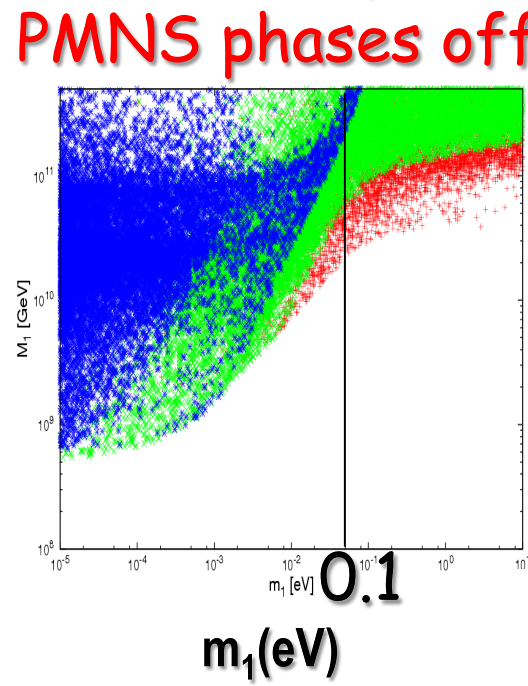
$$\Rightarrow N_{B-L}^{\rm fin} = \sum_\alpha \varepsilon_{1\alpha} \, \kappa_{1\alpha}^{\rm fin} \simeq 2\, \varepsilon_1 \, \kappa_1^{\rm fin} + \frac{\Delta P_{1\alpha}}{2} \left[\kappa^{\rm f}(K_{1\alpha}) - \kappa^{\rm fin}(K_{1\beta})\right]$$

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

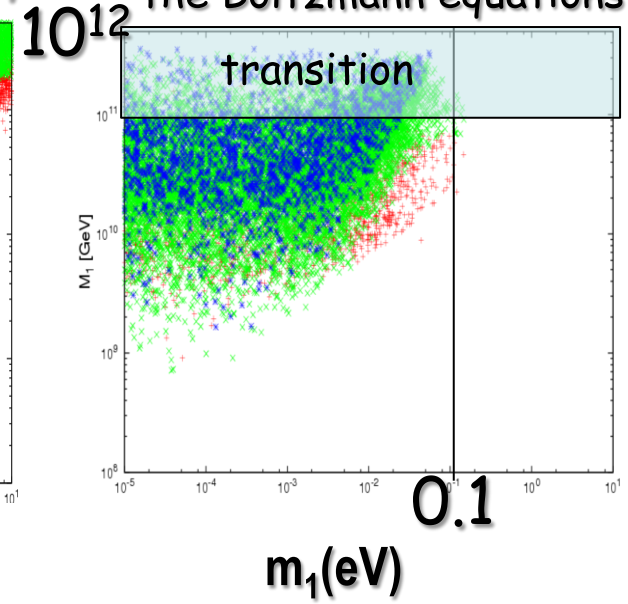
Neutrino mass bounds and role of PMNS phases

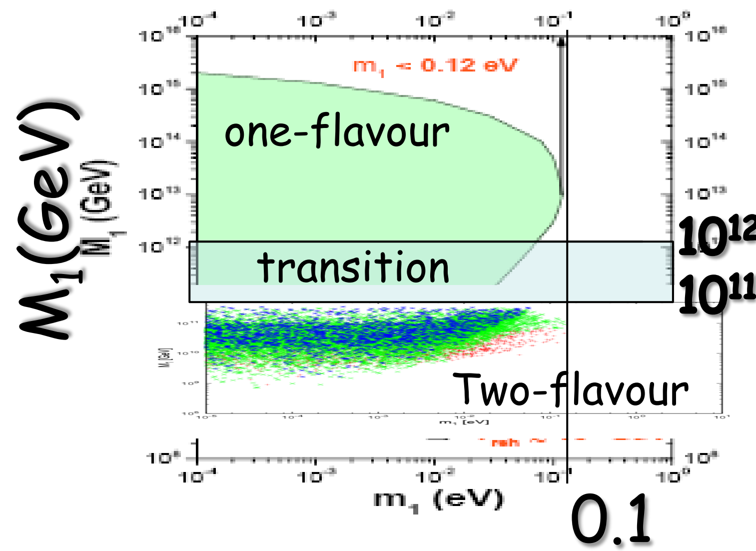
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)





Imposing the validity of the Boltzmann equations





Low energy phases can be the only source of CP violation

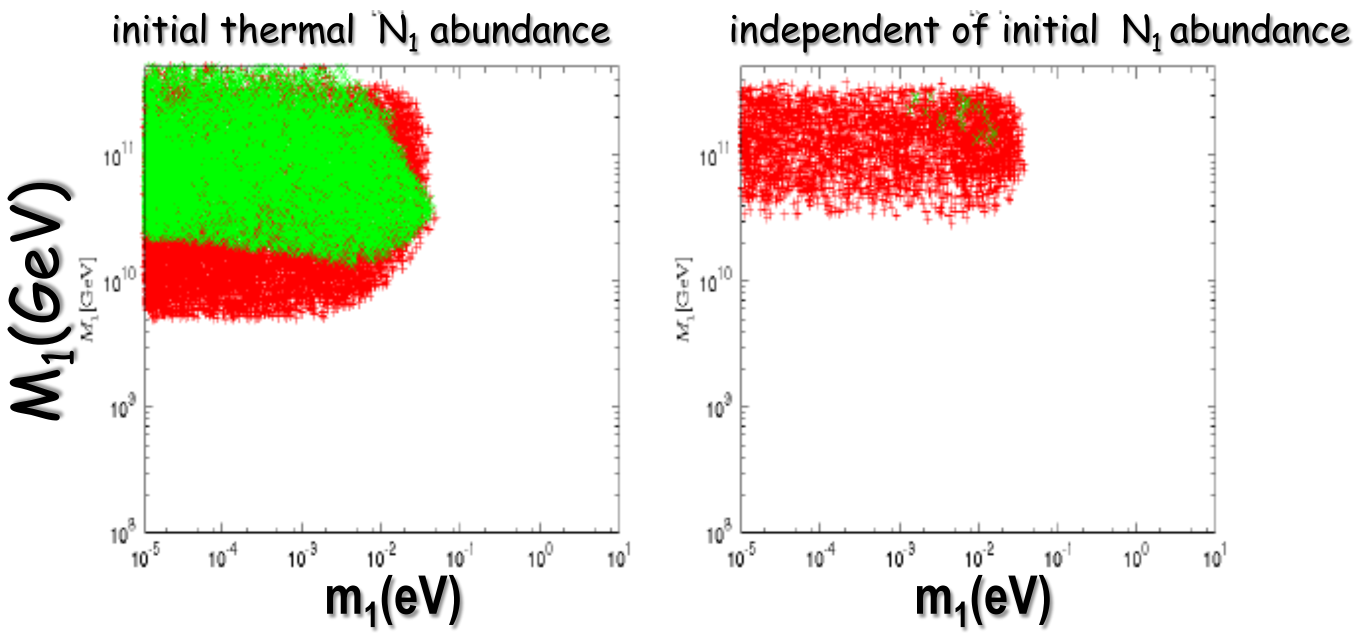
(Nardi et al.'06;Blanchet,PDB'06;Pascoli,Petcov,Riotto '06;Anisimov,Blanchet,PDB '08)

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

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

- 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

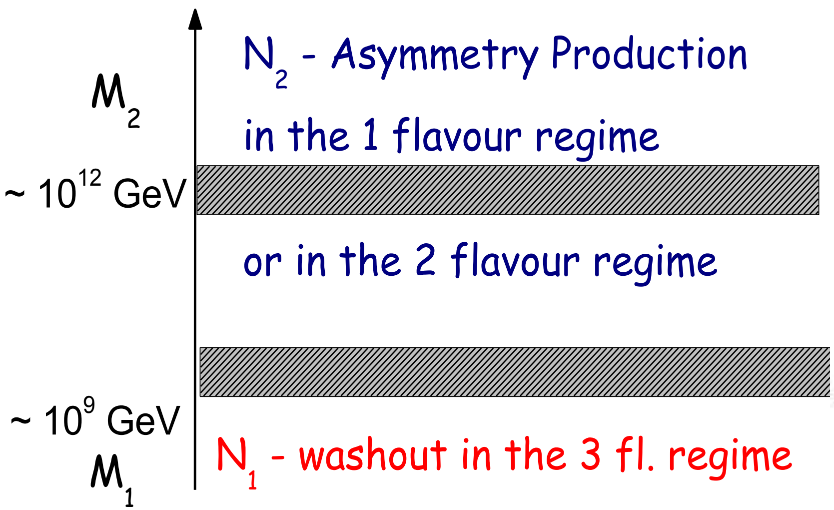
- No reasons for these assumptions to be rigorously satisfied (Davidson, Rius et al.'07)
- In general this contribution is *overwhelmed* by the high energy phases
- But they can be approximately satisfied in specific scenarios for some regions
- It is in any case by itself interesting that CP violation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

The N_2-dominated scenario (flavoured)

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

Flavour effects strongly enhance the importance of the N_2-dominated scenario

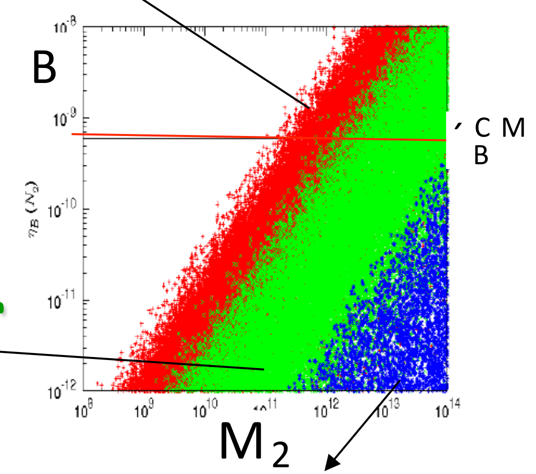
A two stage process:



N_1 wash-out is neglected

Both wash-out and flavor effects

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



Unflavored case

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

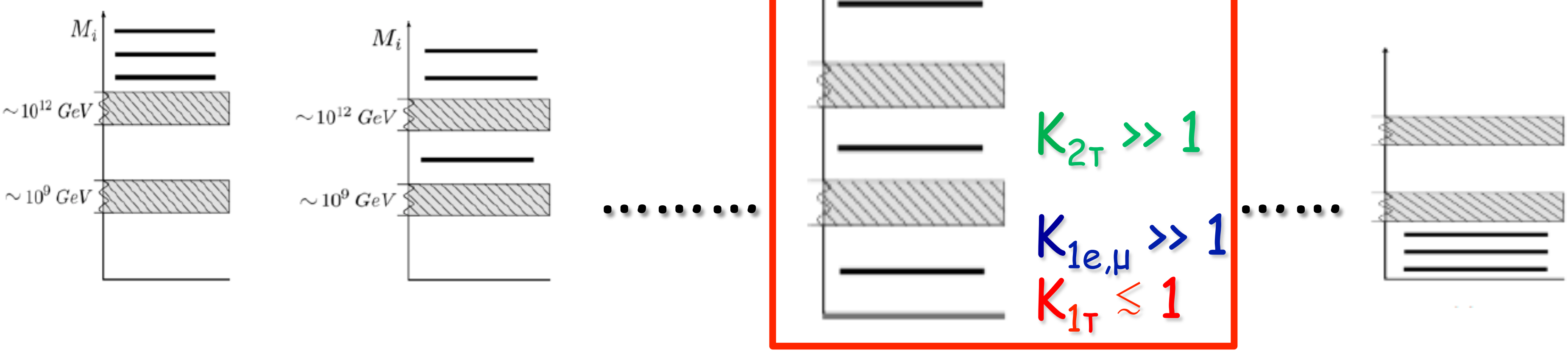
- $K_1 = K_{1e} + K_{1\mu} + K_{1\tau}$; $P(K_1 \lesssim 1) \sim 0.2\%$; $P(K_{1e} \lesssim 1) \sim 2\,P(K_{1\mu,\tau} \lesssim 1) \sim 15\%$ $\Rightarrow \Sigma_\alpha P(K_{1\alpha} \lesssim 1) = 30\%$
- With flavor effects the domain of applicability goes much beyond the special choice $\Omega = R_{23}$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

(Bertuzzo,PDB,Marzola '10)

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

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

Asymmetry generated from leptogenesis



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

A lower bound on neutrino masses (NO)

(PDB, Sophie King, Michele Re Fiorentin 2014)

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)

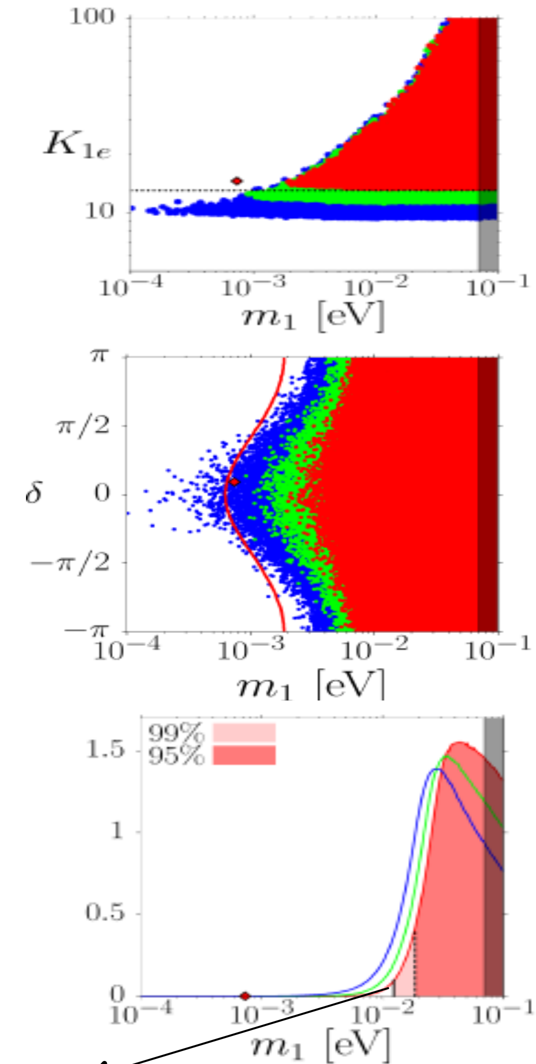
$$m_1 > m_1^{\rm lb} \equiv m_\star \max_\alpha \left[\left(\frac{\sqrt{K_{\rm st}} - \sqrt{K^{0,\max}_{1\alpha}}}{\max[|\Omega_{11}|]\,\left|U_{\alpha 1} - \frac{U_{\tau 1}}{U_{\tau 3}}\,U_{\alpha 3}\right|}\right)^2\right]$$

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

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

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

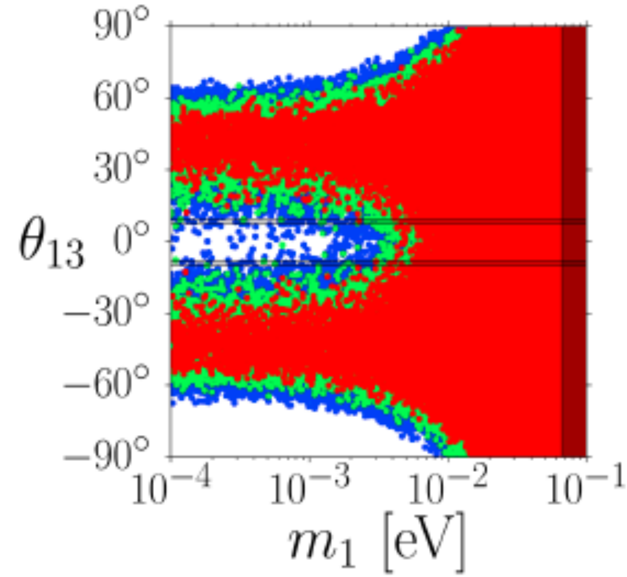
max[$|\Omega_{21}|^2$] = 2



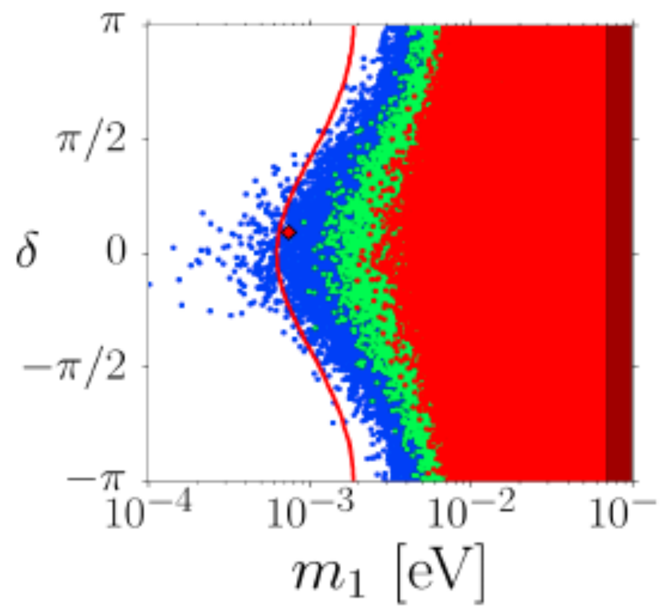
$m_1 \gtrsim$ 10 meV $\Rightarrow \Sigma_i\, m_i \gtrsim$ 75 meV

A lower bound on neutrino masses (NO)

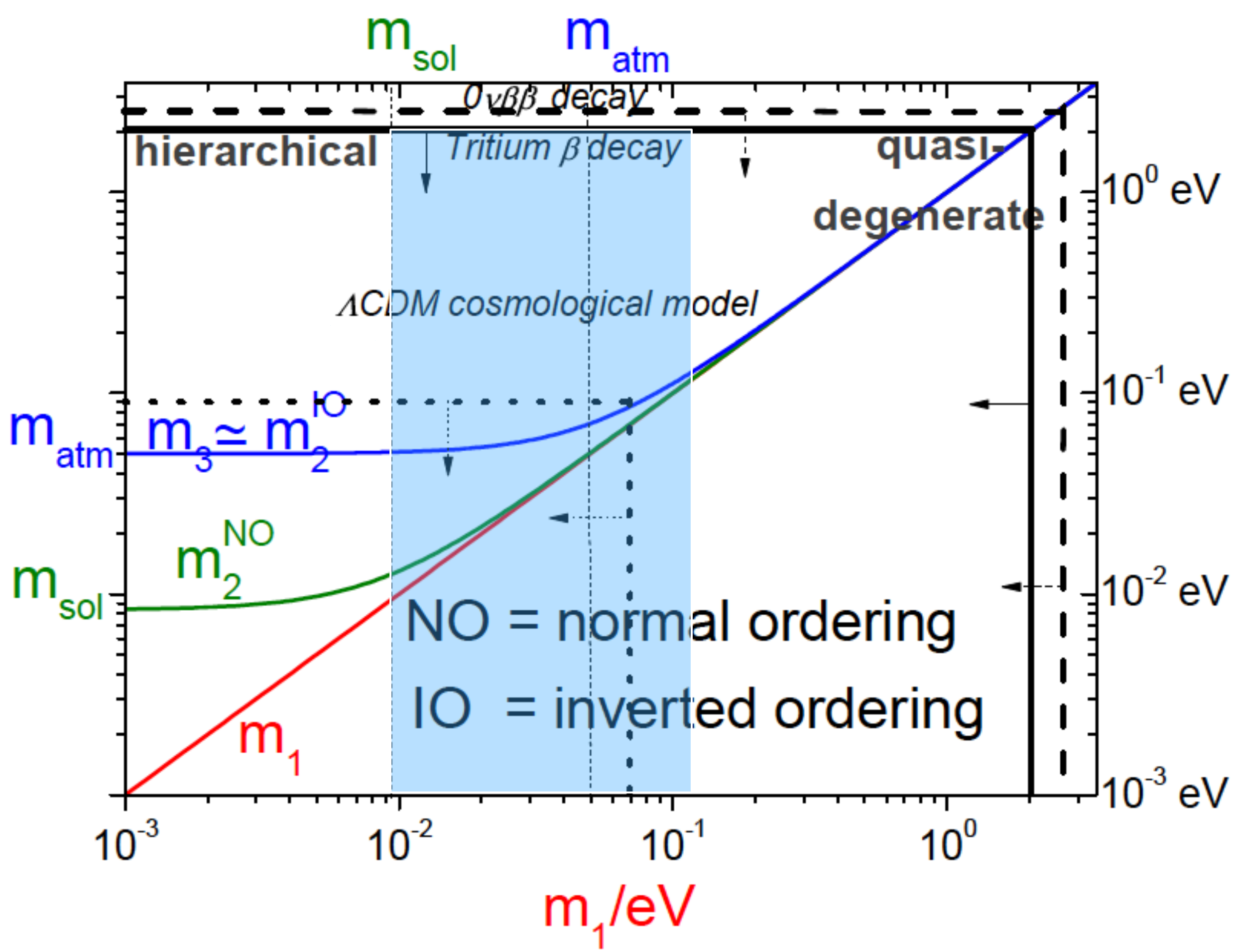
The lower bound would not have existed for large θ_{13} values



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



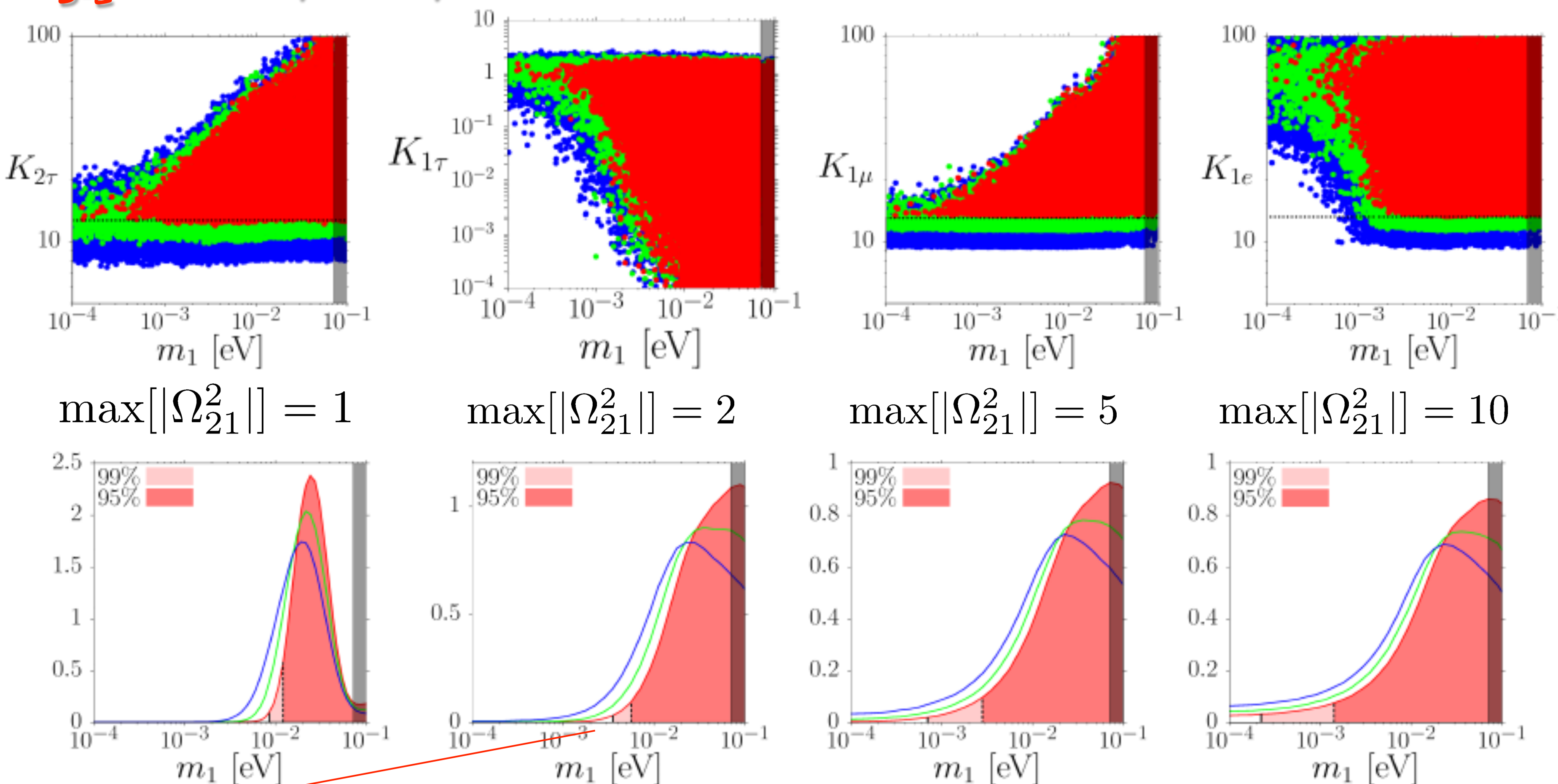
A new neutrino mass window for leptogenesis



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

A lower bound on neutrino masses (IO)

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



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

Flavour effects rescue SO(10)-inspired leptogenesis

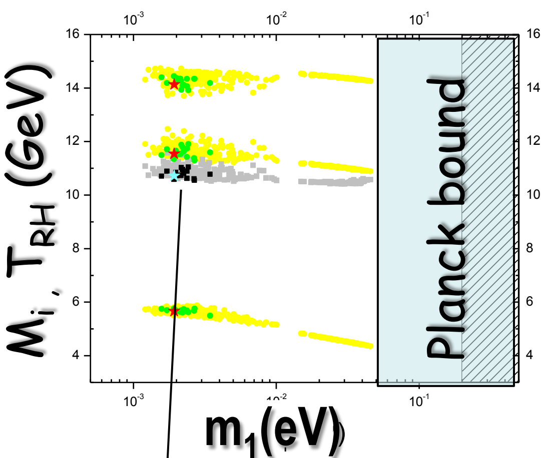
(PDB, Riotto '08,'10)

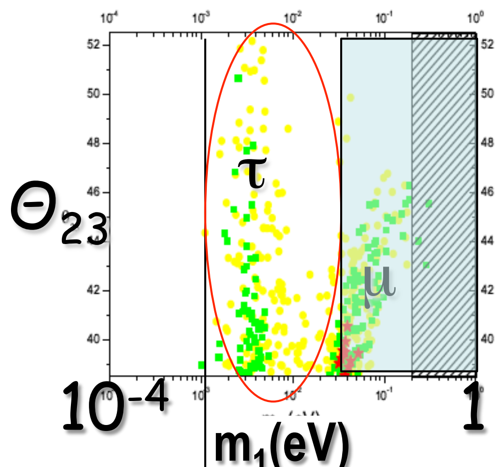
$$N_{B-L}^{\rm f} \simeq \varepsilon_{2e}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1e}} + \varepsilon_{2\mu}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + \varepsilon_{2\tau}\,\kappa(K_{2\tau})\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

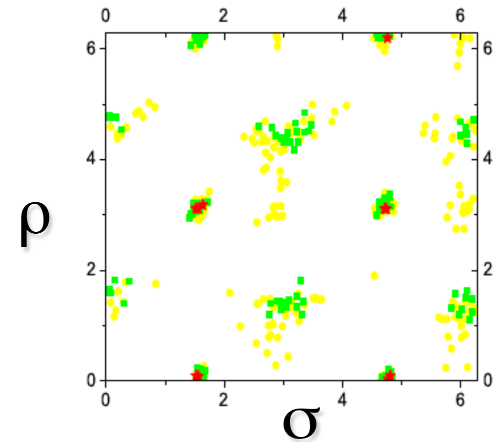
Independent of $\alpha_1 = m_{D1}/m_u$ and $\alpha_3 = m_{D3}/m_t$

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

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?

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

(PDB, Marzola '11)

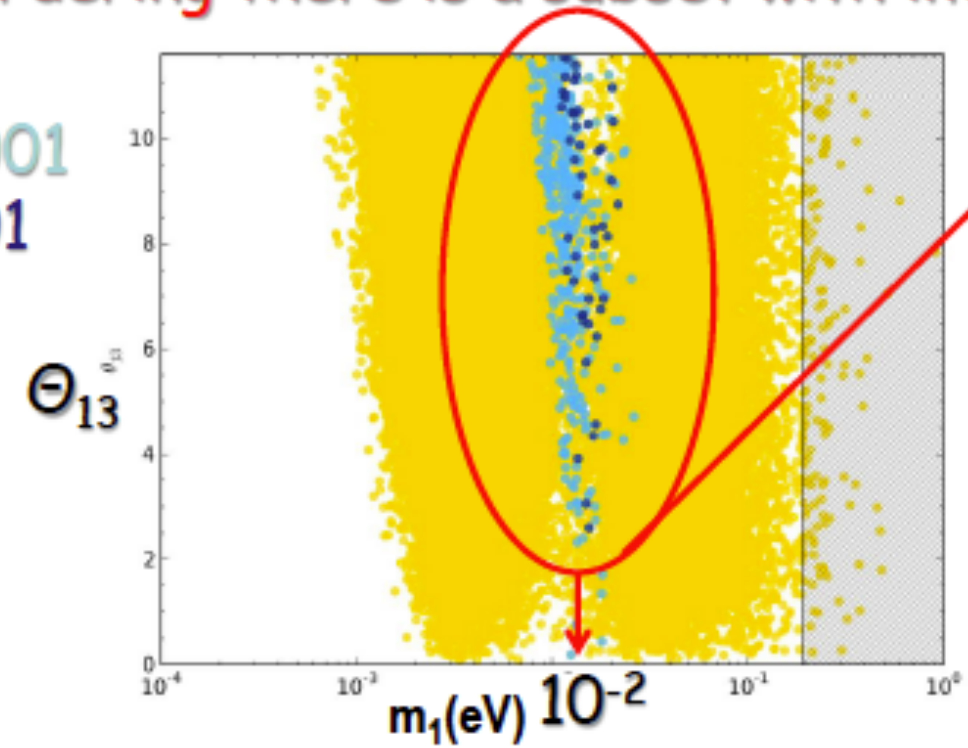
$$N^{\rm f}_{B-L} = N^{\rm p,f}_{B-L} + N^{\rm lep,f}_{B-L}\,,$$

Imposing successful strong thermal leptogenesis condition:

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

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

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



Non-vanishing θ_{13}

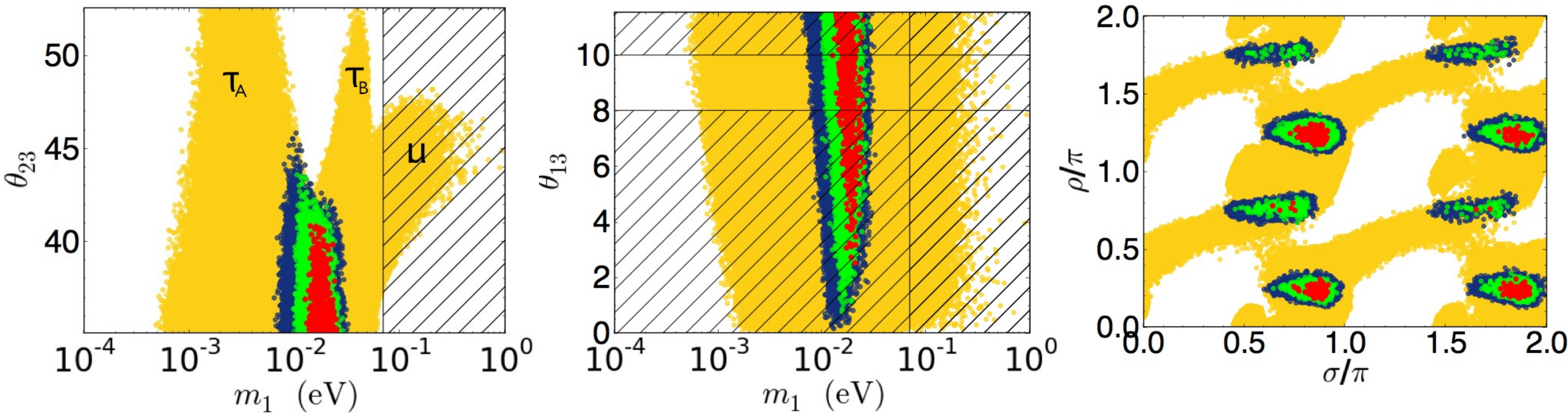
Talk at the DESY theory workshop 28/9/11

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 $\Rightarrow$ $15 \lesssim m_1 \lesssim 25$ 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

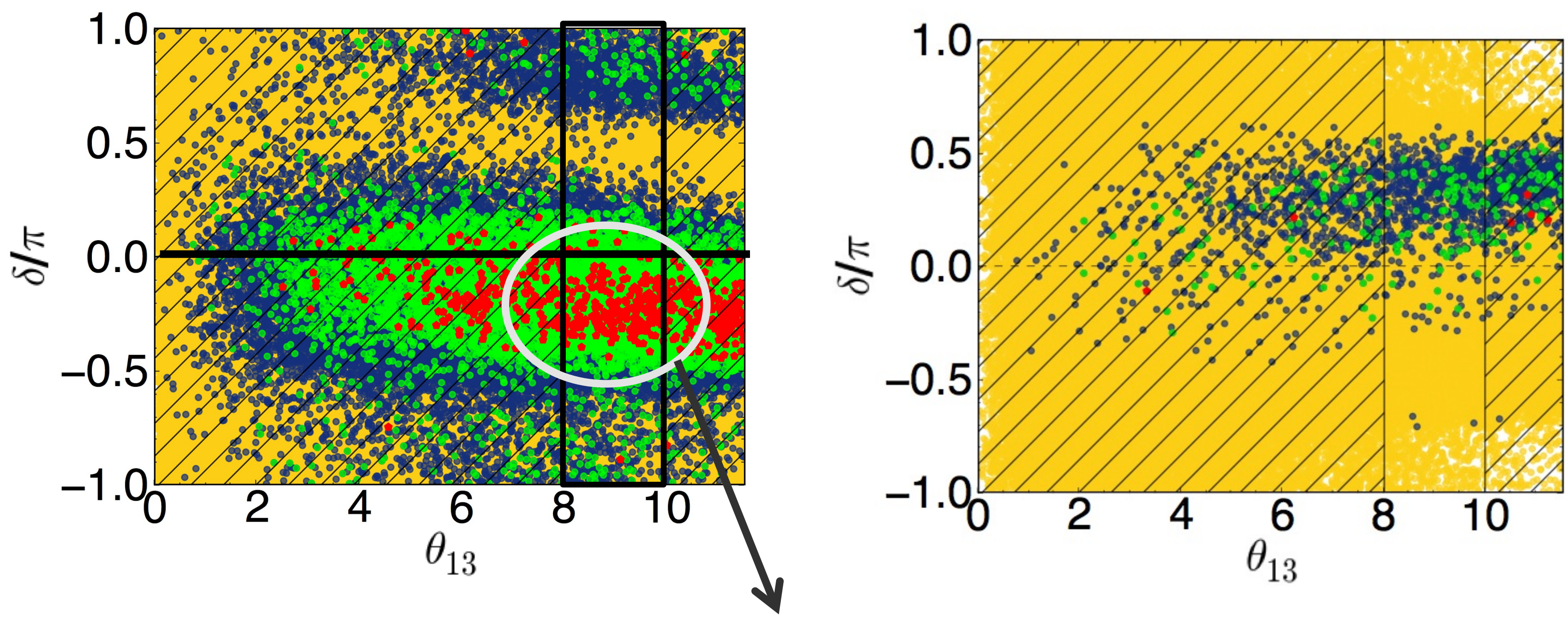
(PDB, Marzola '11-'12)

Imposing successful strong thermal leptogenesis condition:

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

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

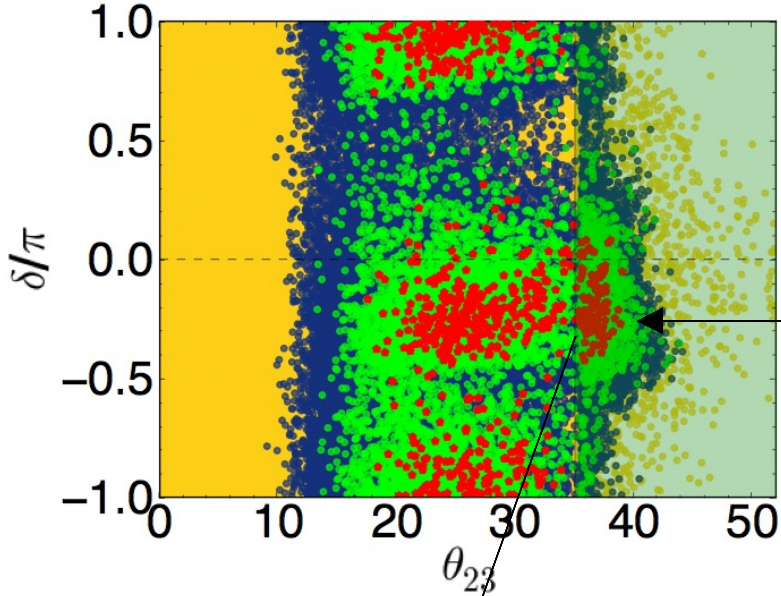
$\eta_B = \eta_B^{CMB}$ $\qquad\qquad$ $\eta_B = -\,\eta_B^{CMB}$



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

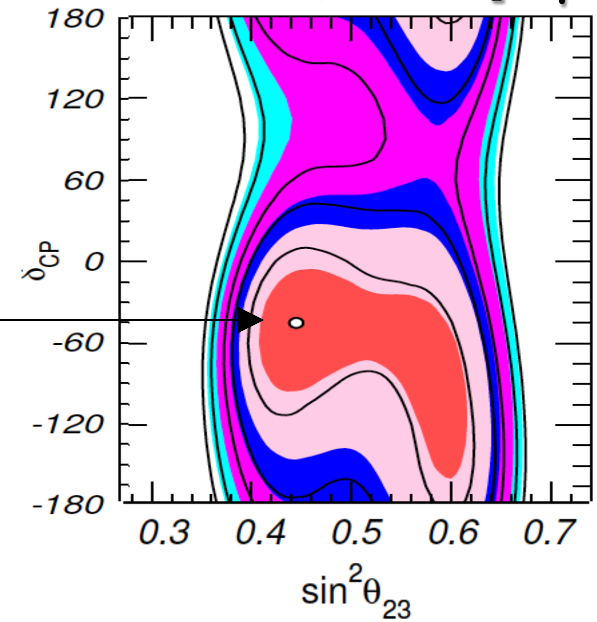
Strong thermal SO(10)-inspired leptogenesis: the atmospheric mixing angle test

arXiv:1308.1107



NuFIT 1.2 (2013)

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



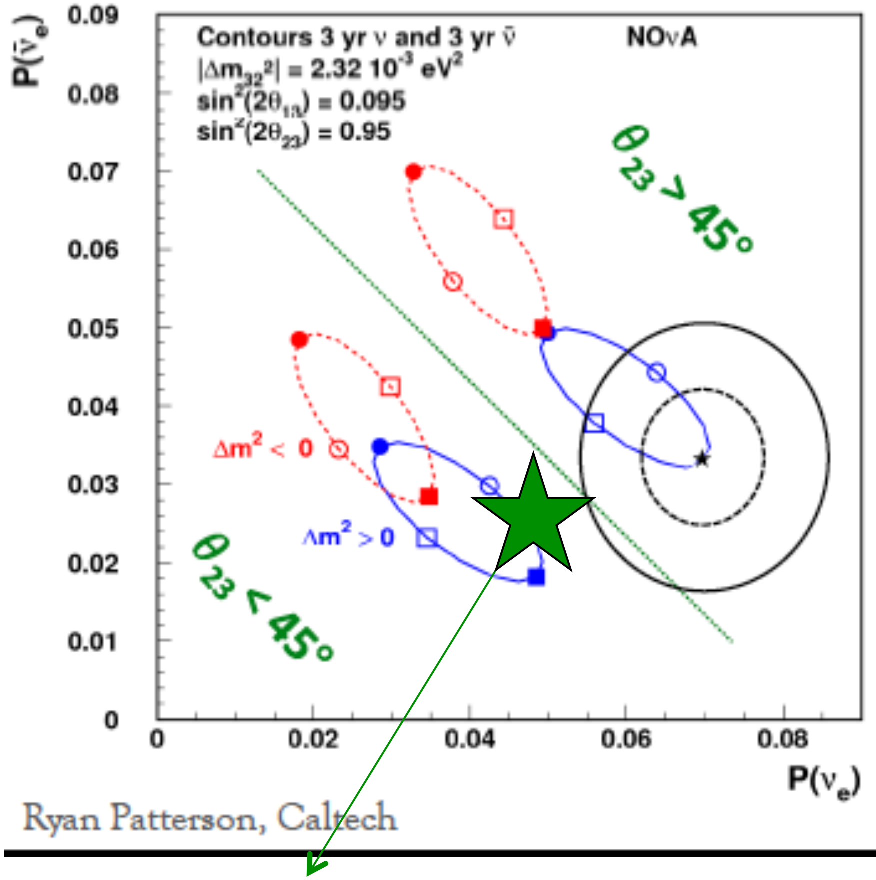
http://www.nu-fit.org/sites/default/files/v12.fig-dlthie-glob.pdf

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

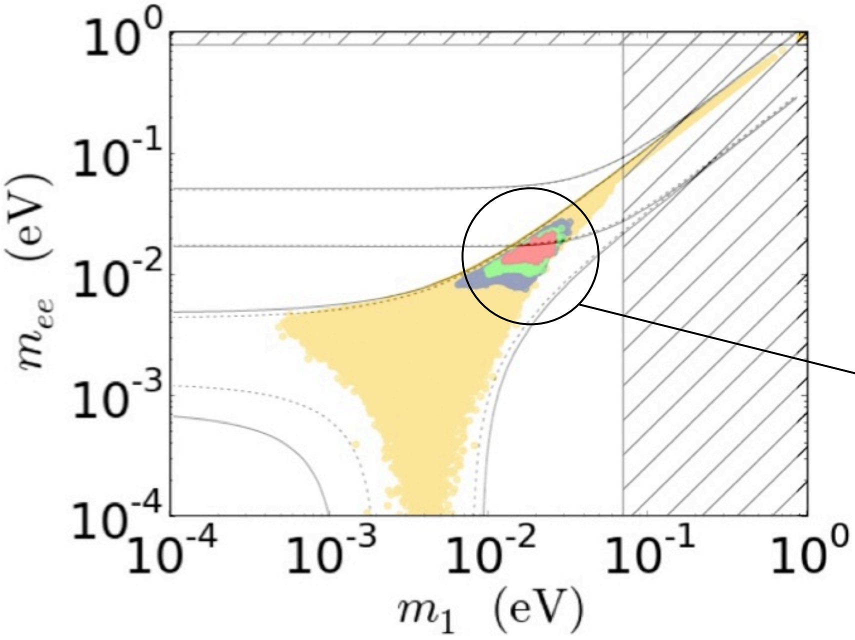
Last brick in the wall: neutrinoless double beta decay

(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

Testable

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

(Not so) subliminal messages:

- 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

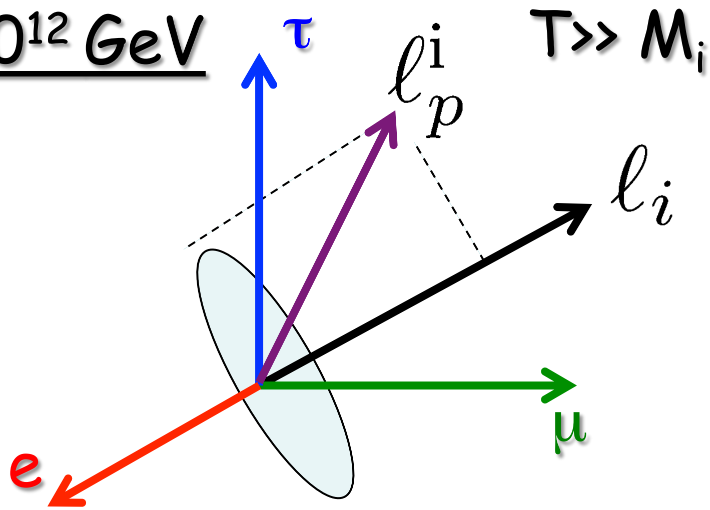
Strong thermal SO(10)-inspired leptogenesis solution

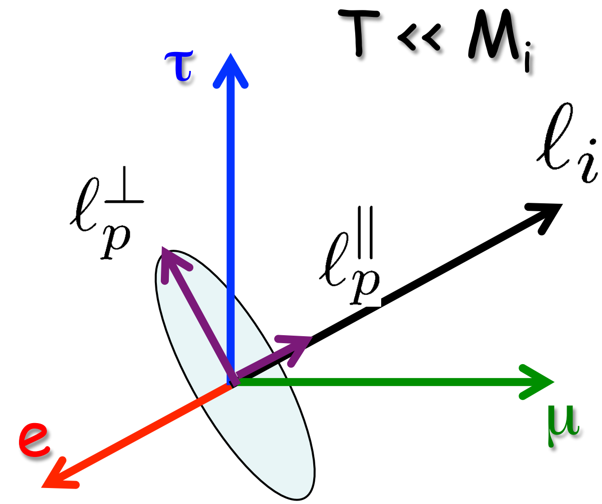
θ_{13}	$\gtrsim 3^\circ$
ORDERING	NORMAL
θ_{23}	$\lesssim 42^\circ$
δ	**$\sim -45^\circ$**
$m_{ee} \simeq 0.8\, m_1$	$\simeq 15$ meV

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

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

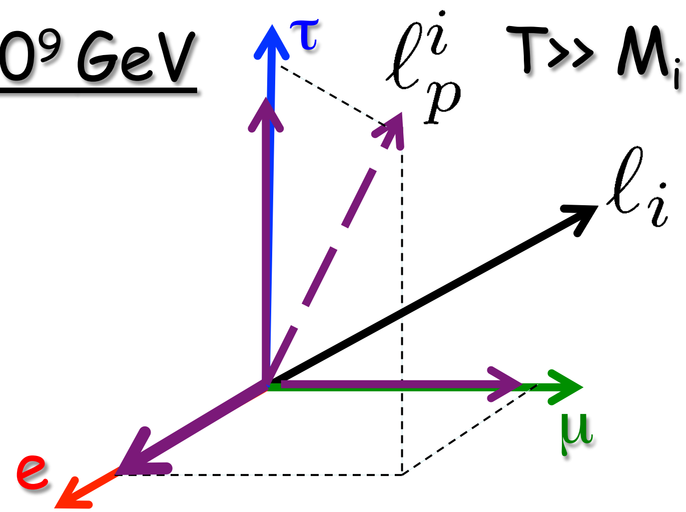
$M_i \gtrsim 10^{12}$ GeV

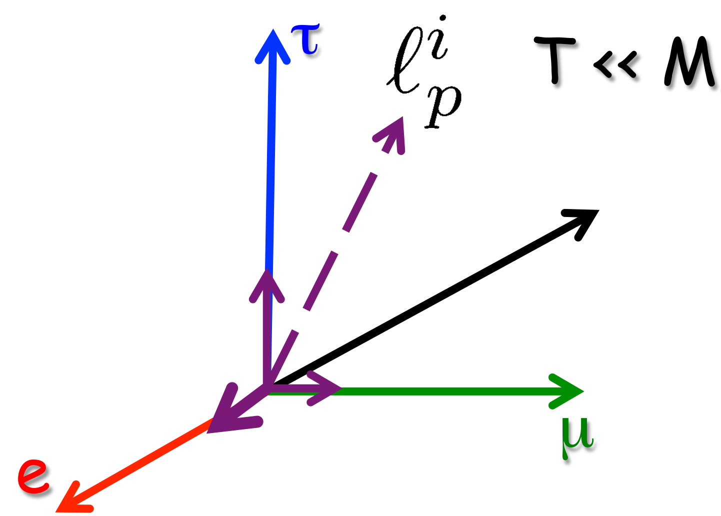




$$N^{\rm p}_{B-L}(T \ll M_i) = (1-P_{{\rm p}i})N^{\rm p,i}_{B-L} + P_{{\rm p}i}\, e^{-\frac{3\pi}{8}K_i}\, N^{\rm p,i}_{B-L}$$

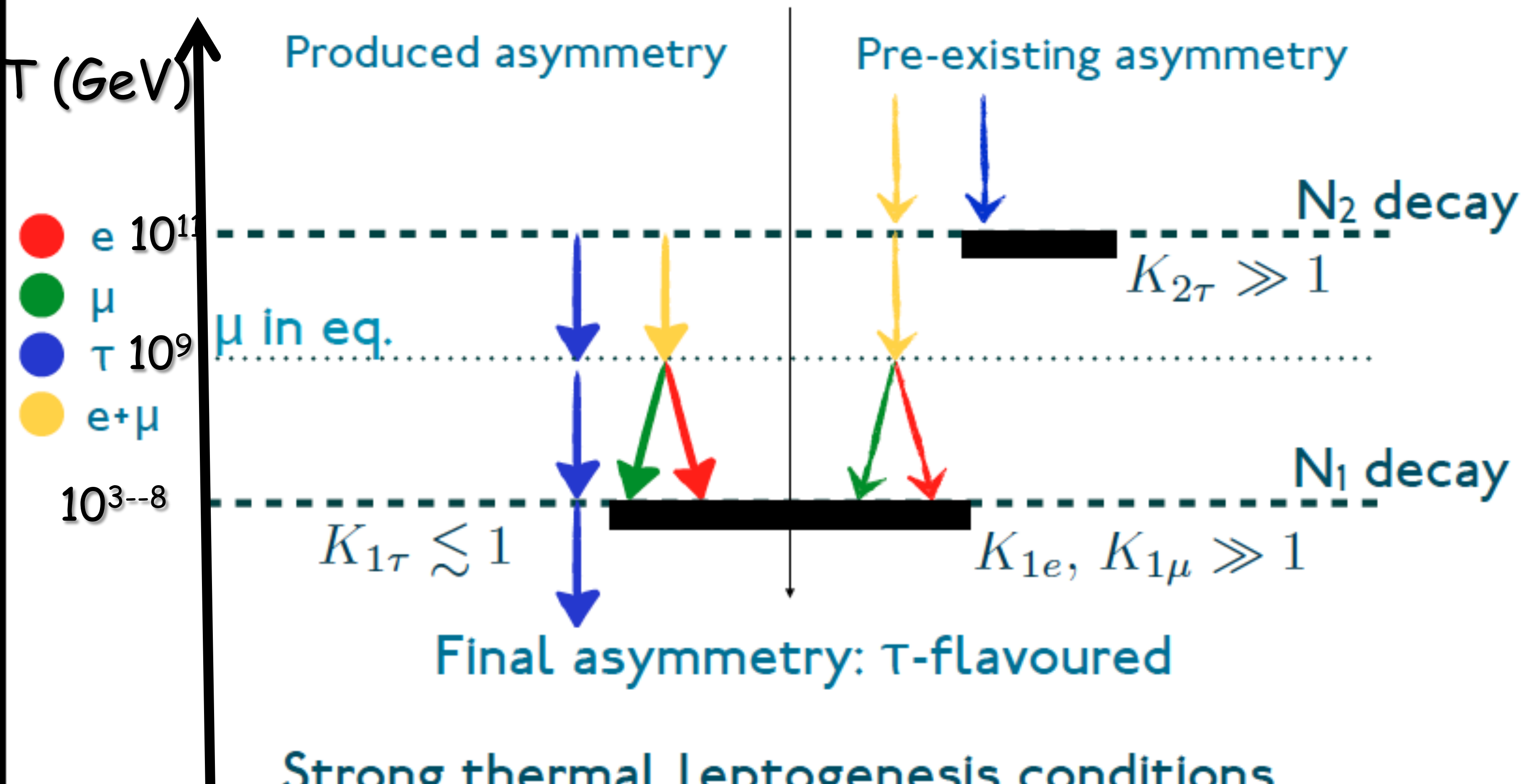
M_i << 10^9 GeV





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

How is STL realised? - A cartoon



Strong thermal leptogenesis conditions

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

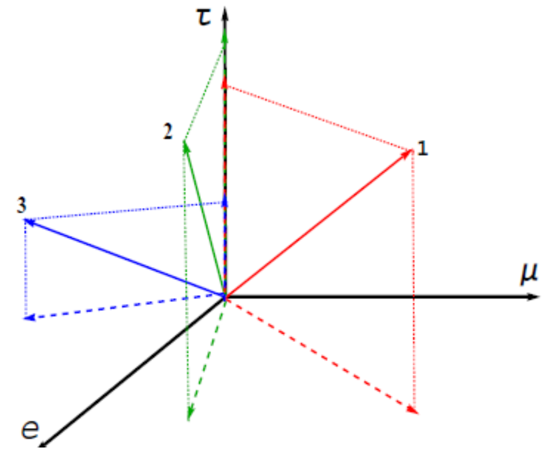
Courtesy of Michele Re Fiorentin

Density matrix formalism with heavy neutrino flavours

(Blanchet, PDB, Jones, Marzola '11)

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

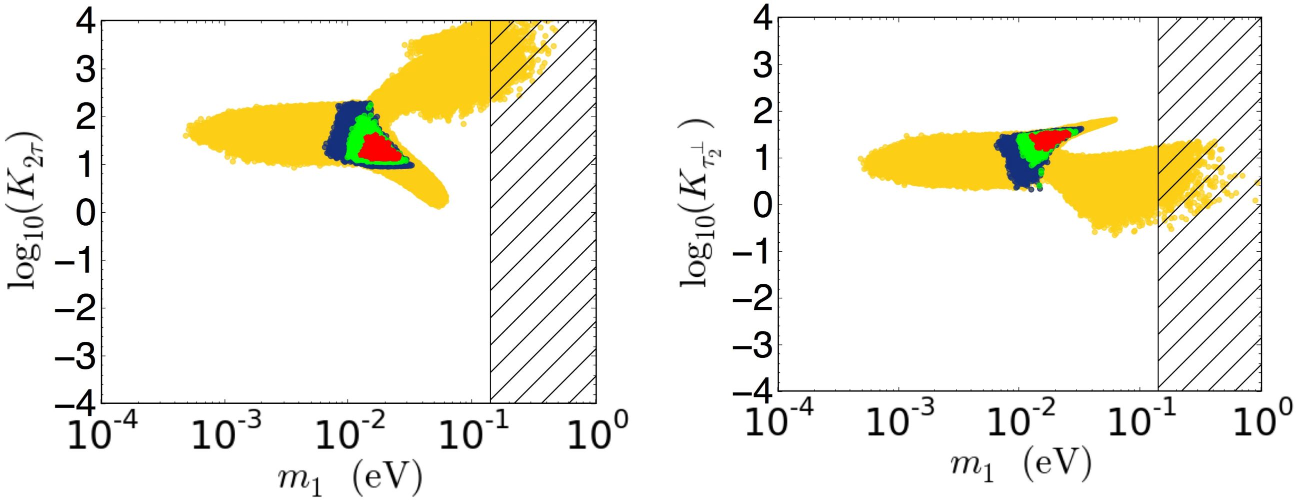
The result is a "monster" equation:



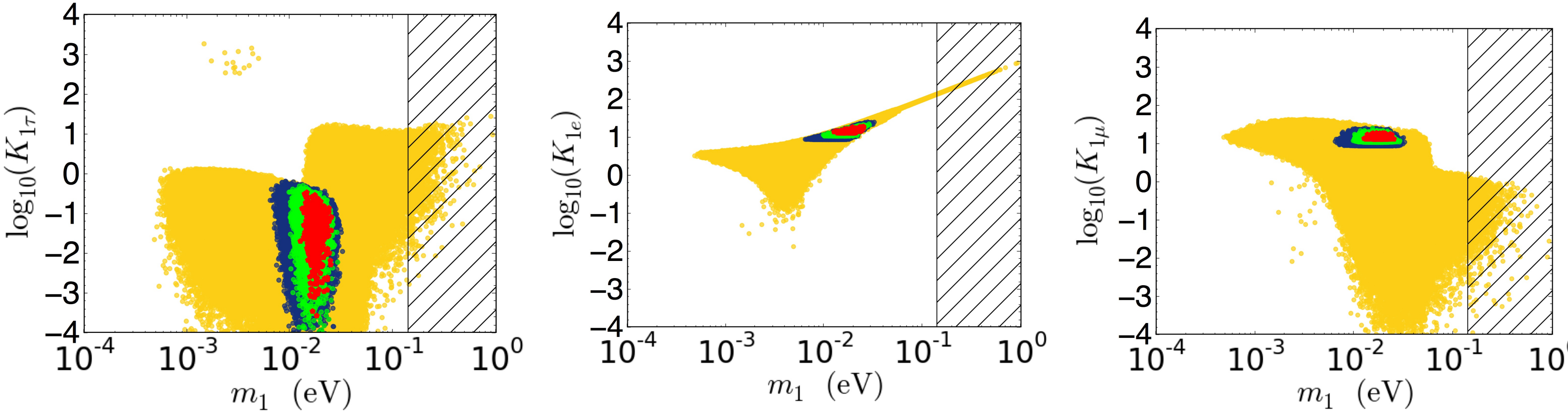
$$
\begin{aligned}
\frac{dN^{B-L}_{\alpha\beta}}{dz} &= \varepsilon^{(1)}_{\alpha\beta}\, D_1\,(N_{N_1} - N^{\rm eq}_{N_1}) - \frac{1}{2}\, W_1\,\{\mathcal{P}^{0(1)}, N^{B-L}\}_{\alpha\beta} \\
&+ \varepsilon^{(2)}_{\alpha\beta}\, D_2\,(N_{N_2} - N^{\rm eq}_{N_2}) - \frac{1}{2}\, W_2\,\{\mathcal{P}^{0(2)},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

Some insight from the decay parameters

At the production ($T \sim M_2$)



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

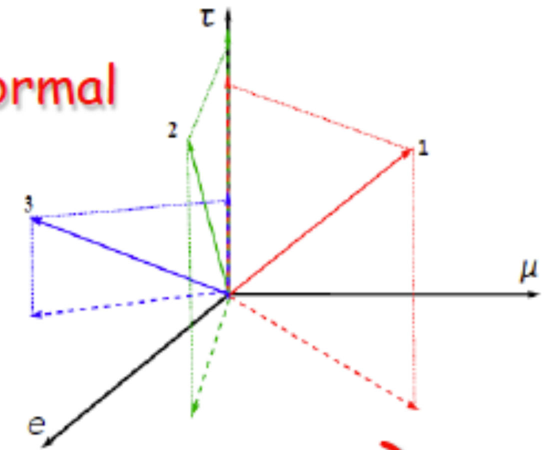


Flavour projection

(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



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

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

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

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

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

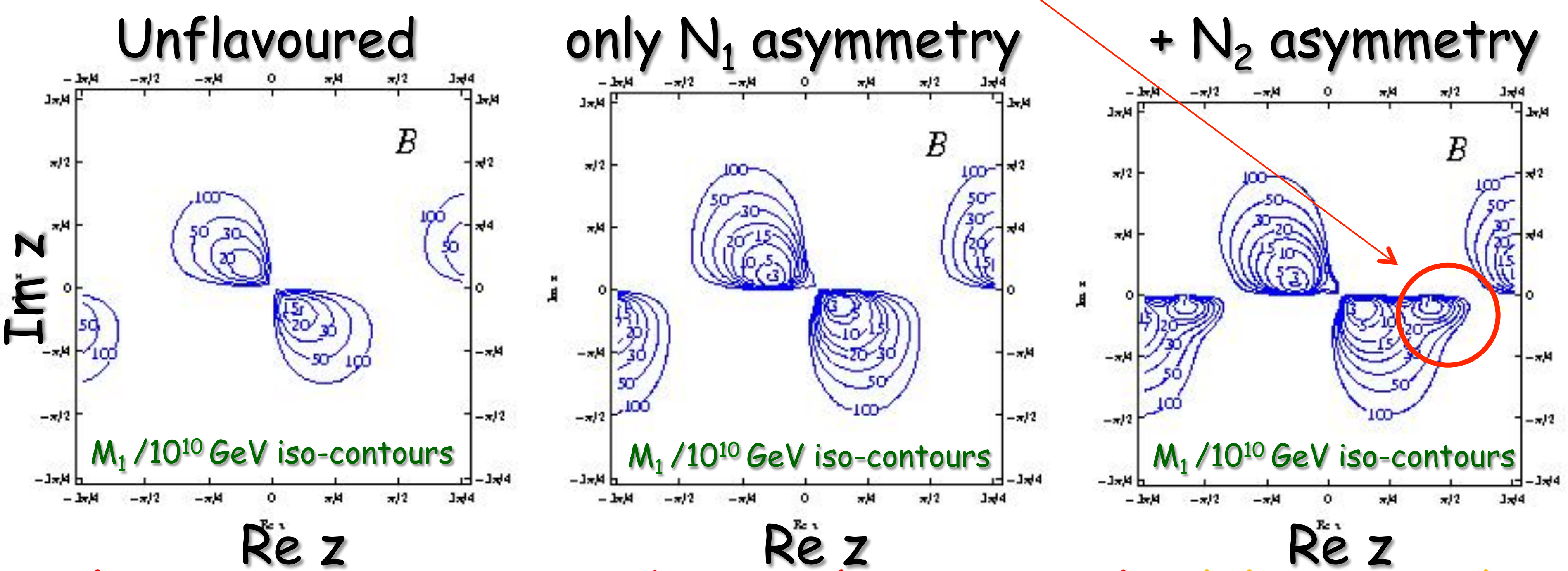
2 RH neutrino scenario revisited

(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



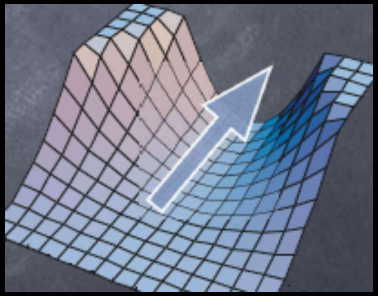
These regions are interesting because they correspond to light sequential dominated neutrino mass models realized in some grandunified models

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

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

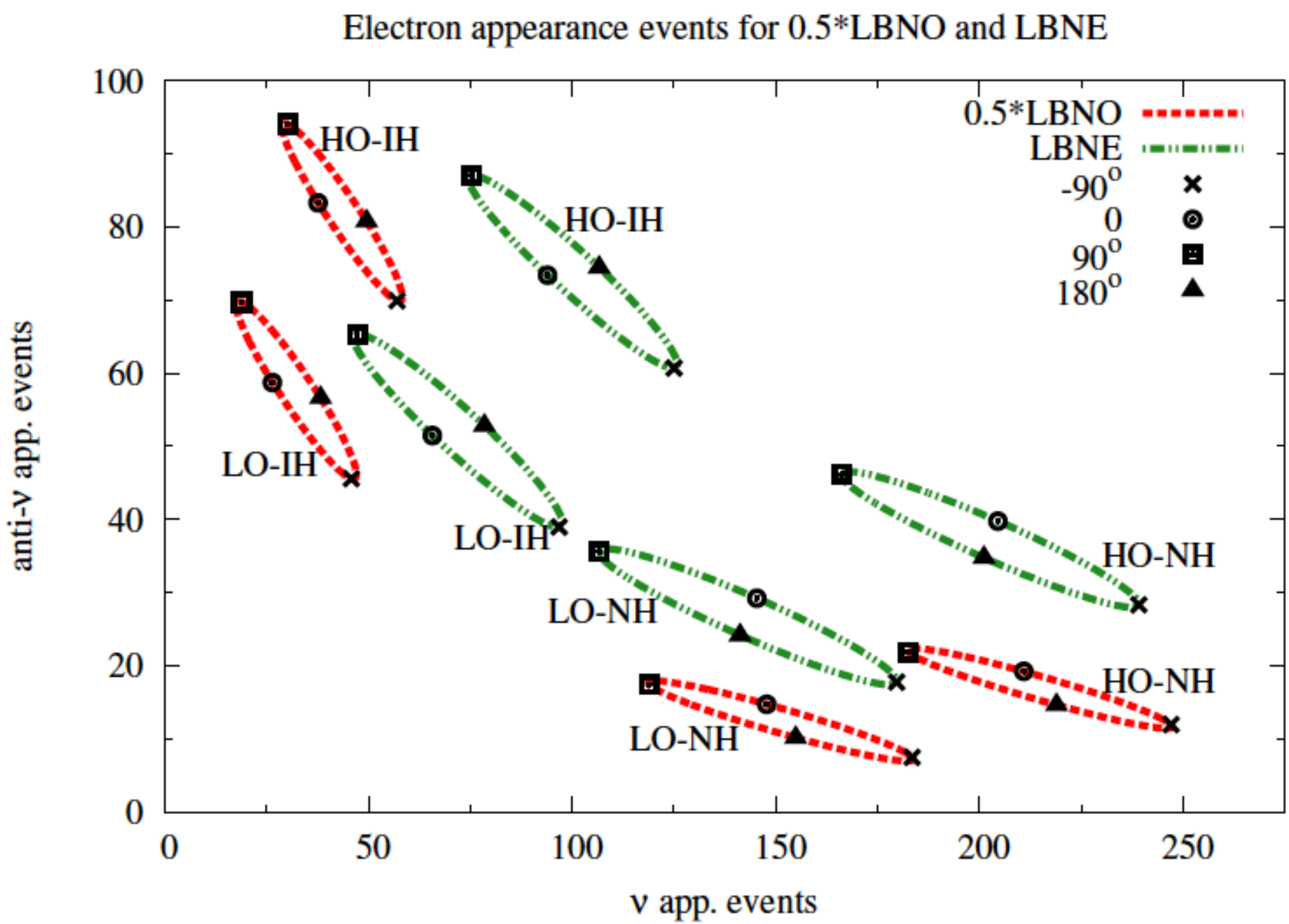


F term D term

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

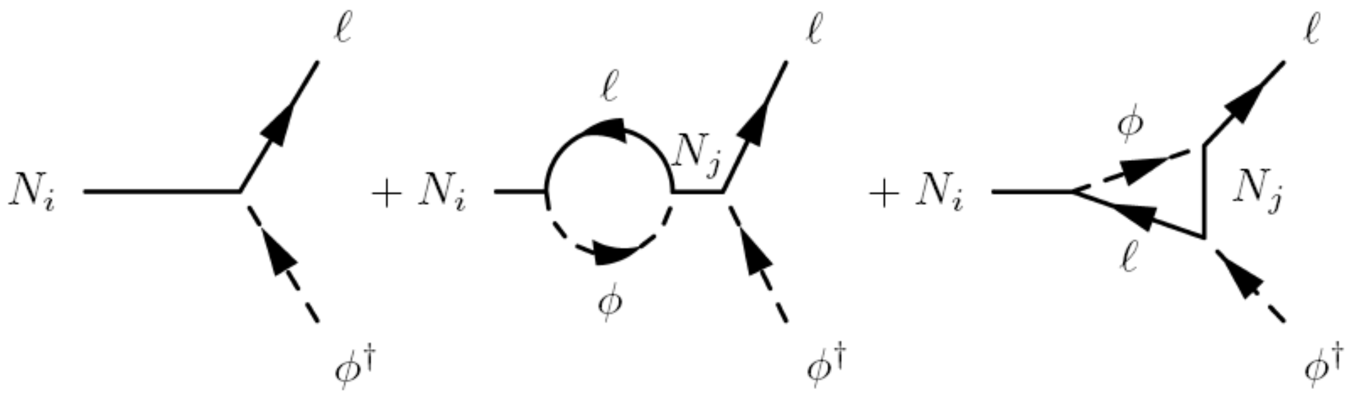
$$\frac{n_B}{s} \sim 10^{-10}\left(\frac{m_{3/2}}{m_\Phi}\right)\left(\frac{m_\Phi}{\mathrm{TeV}}\right)^{-\frac{1}{2}}\left(\frac{M}{M_P}\right)^{\frac{3}{2}}\left(\frac{T_R}{10\,\mathrm{GeV}}\right)$$

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
0
20
40
60
80
100
0
50
100
150
200
250

Total CP asymmetries

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



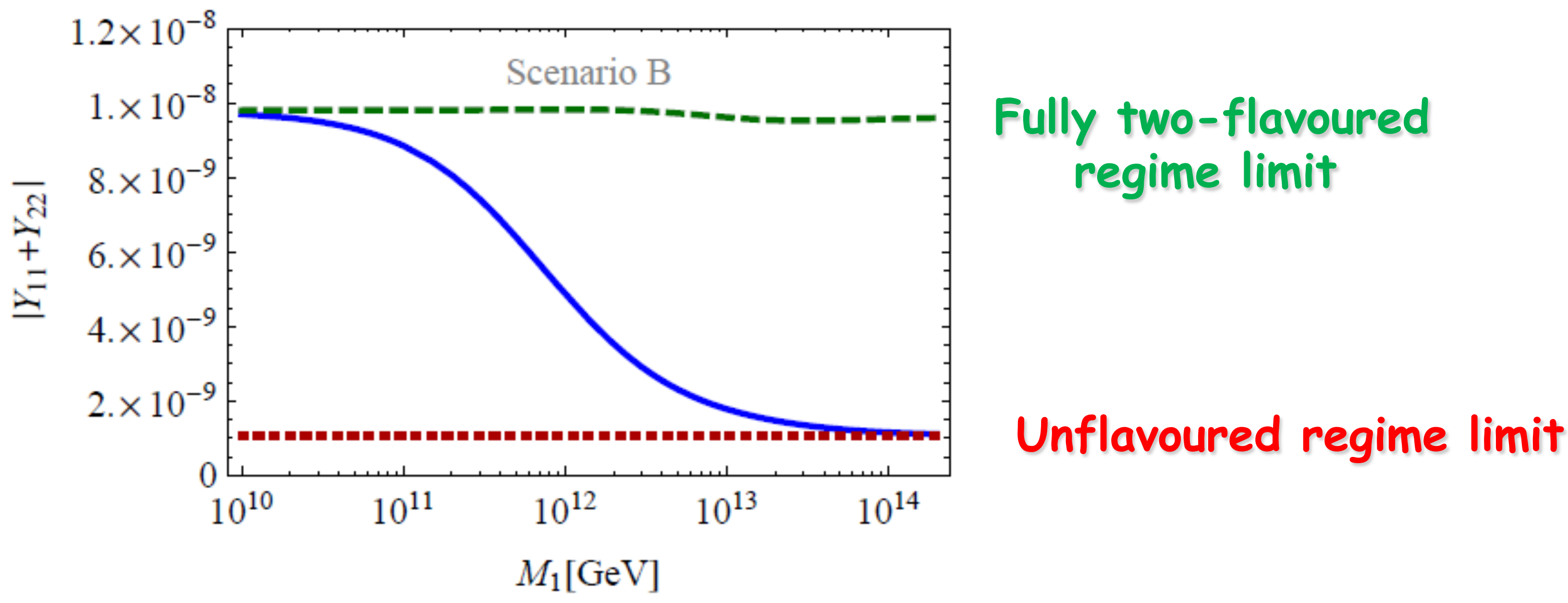
$$\varepsilon_i \simeq \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(m_D^\dagger\, m_D)^2_{ij}\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

It does not depend on U !

Density matrix and CTP formalism to describe the transition regimes

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

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



Additional contribution to CP violation:

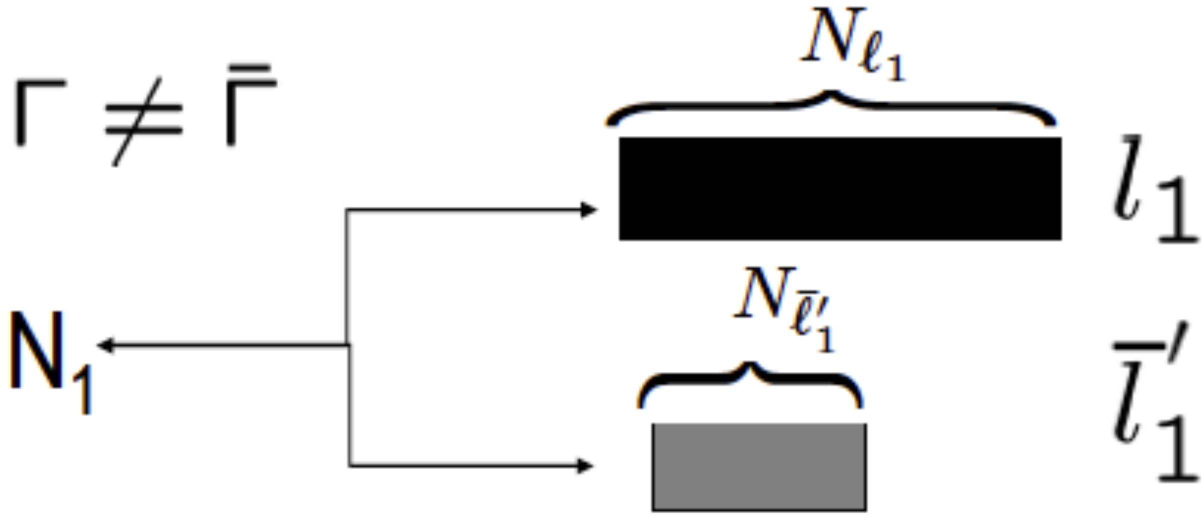
(Nardi, Racker, Roulet '06)

(α = τ, e+μ)

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

depends on U !

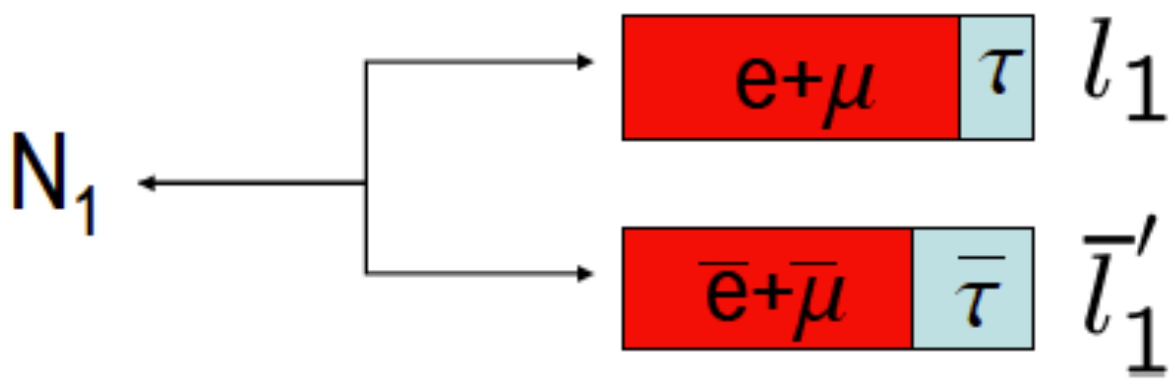
1) $\Gamma \neq \bar{\Gamma}$



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

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

+



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