PPC 2015 Deadwood, South Dakota, July 2 2015

I) Review and status of Leptogenesis

II) Leptogenesis in action

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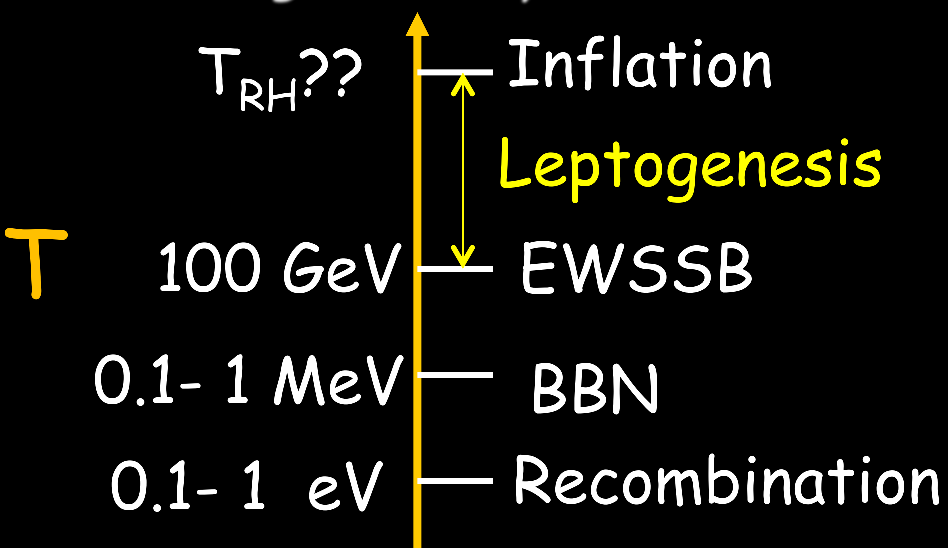
Cosmology (early Universe) ⟵ LEPTOGENESIS ⟶ **Neutrino Physics, models of mass**

- *Cosmological Puzzles :*

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

$\eta_B \simeq 6.1 \times 10^{-10}$

- *New stage in early Universe history :*



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

Neutrino masses and mixing parameters

Pontecorvo-Maki-Nakagawa-Sakata matrix

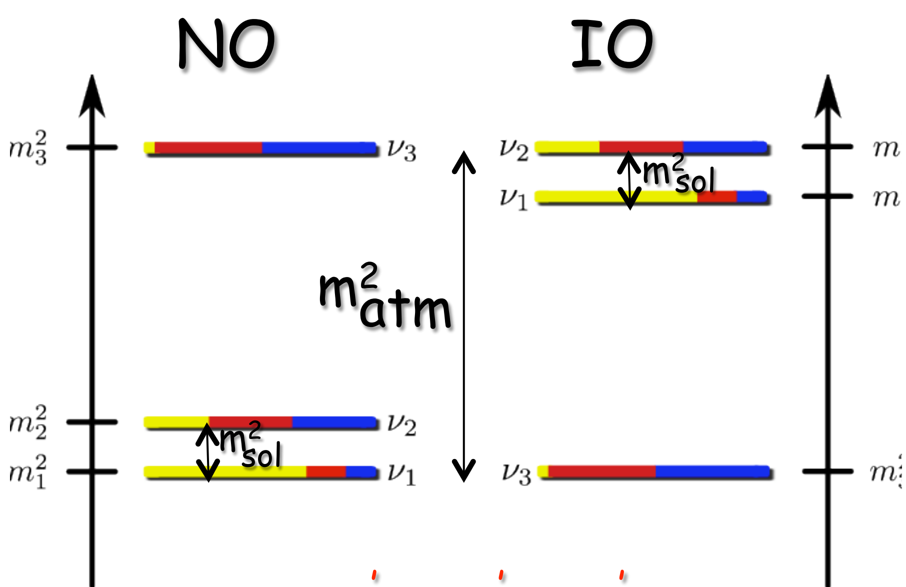
$$|\nu_\alpha\rangle = \sum_i U^\star_{\alpha i}\,|\nu_i\rangle$$

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\,\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\,\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\,\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\,\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\,\delta} & c_{23}\,c_{13} \end{pmatrix} \cdot \mathrm{diag}\left(e^{i\,\rho}, 1, e^{i\,\sigma}\right)$$

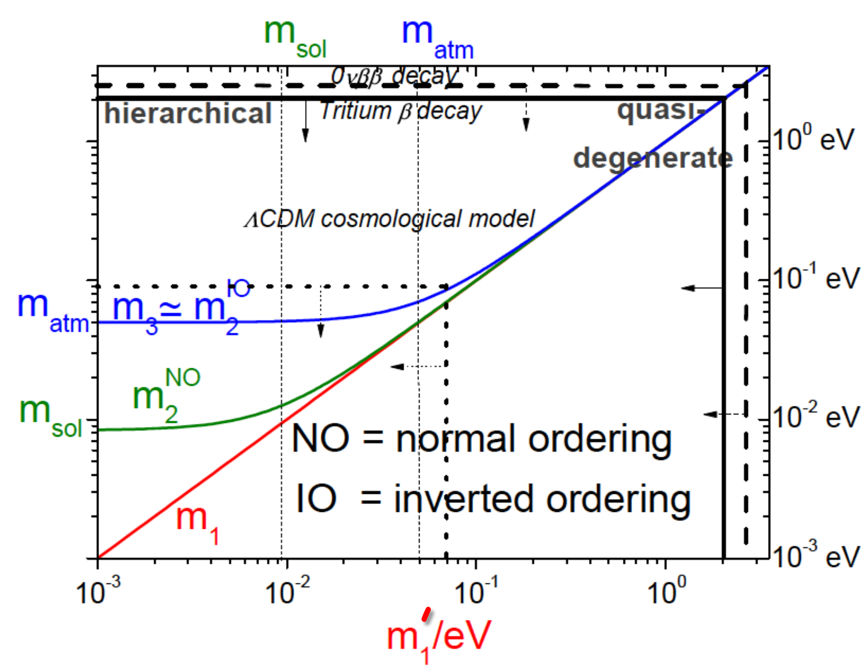
<u>3σ ranges:</u>

(NuFIT 2014)

$\theta_{23} \simeq 38^\circ - 53^\circ$	atmospheric mixing angle
$\theta_{12} \simeq 31^\circ - 36^\circ$	solar mixing angle
$\theta_{13} \simeq 7.8^\circ - 9.1^\circ$	reactor mixing angle
$\delta, \rho, \sigma = [-\pi, \pi]$	Dirac and Majorana phases



$m_1' < m_2' < m_3'$



Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

• Type I seesaw
(talks by L.Everett and M. Peloso)

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

In the see-saw limit ($M \gg m_D$) the 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 $M_3 > M_2 > M_1 \gg m_D$

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

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

total CP asymmetries

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

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

• Thermal production of RH neutrinos

$T_{RH} \gtrsim M_i / (2 \div 10) \gtrsim T_{sph} \simeq 100$ GeV $\Rightarrow \eta_B = a_{sph}\, N_{B-L}^{\rm fin} / N_\gamma^{\rm rec}$

(Kuzmin, Rubakov, Shaposhnikov '85)

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) $m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \boxed{\Omega^T \Omega = I}$ Orthogonal parameterisation

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

(in the flavour 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
- theoretical input on m_D
- additional phenomenological constraints (e.g. Dark Matter)

Vanilla leptogenesis

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

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

1) Lepton flavor composition is neglected

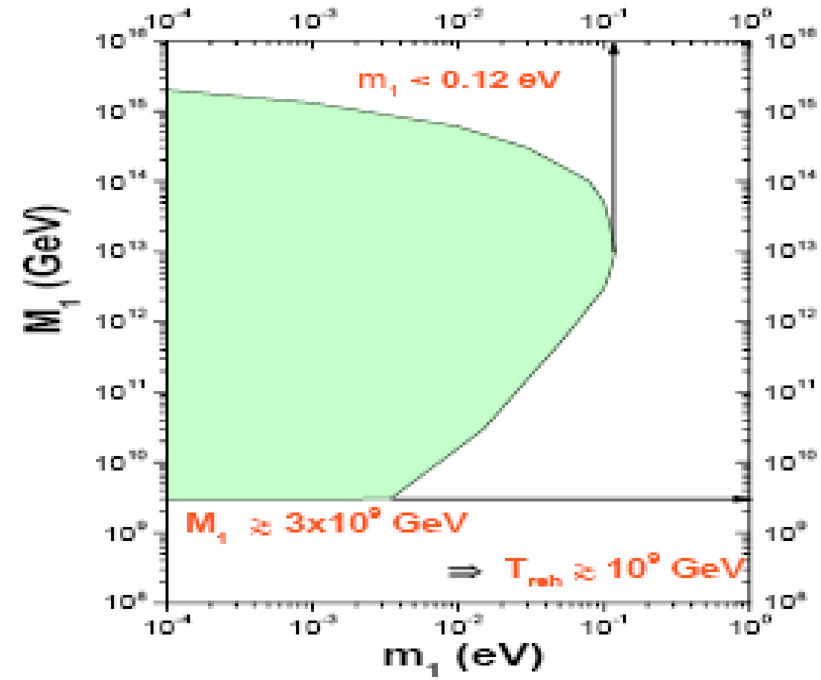
$$N_i \xrightarrow{\Gamma} l_i\, H^\dagger \qquad N_i \xrightarrow{\bar{\Gamma}} \bar{l}_i\, H$$

$$\eta_B \simeq 0.01\, \varepsilon_1\, \kappa^{\rm fin}(K_1)$$

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

3) Strong lightest RH neutrino wash-out

$$\eta_B \simeq 0.01\, \varepsilon_1\, \kappa^{\rm f}(K_1)$$



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

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

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

No dependence on the leptonic mixing matrix U!

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

Independence of the initial conditions

(Buchmüller, PDB, Plümacher '04)

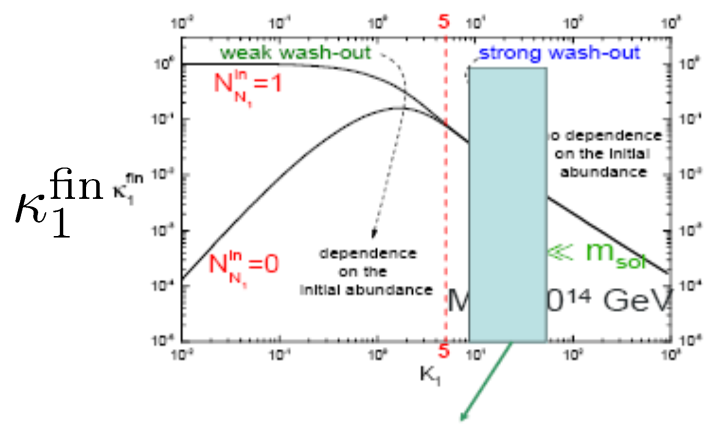
wash-out of a pre-existing asymmetry N_{B-L}^{p}

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

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

equilibrium neutrino mass: $m_* = \dfrac{16\pi^{5/2}\sqrt{g_*}}{3\sqrt{5}}\dfrac{v^2}{M_{\rm Pl}} \simeq 1.08\times 10^{-3}$ eV.

Independence of the initial abundance of N_1 as well



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

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 bi-unitary parameterization:

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

From the seesaw formula one can express:

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

SO(10) inspired conditions*:

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

Barring fine-tuned 'crossing level' solutions:

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

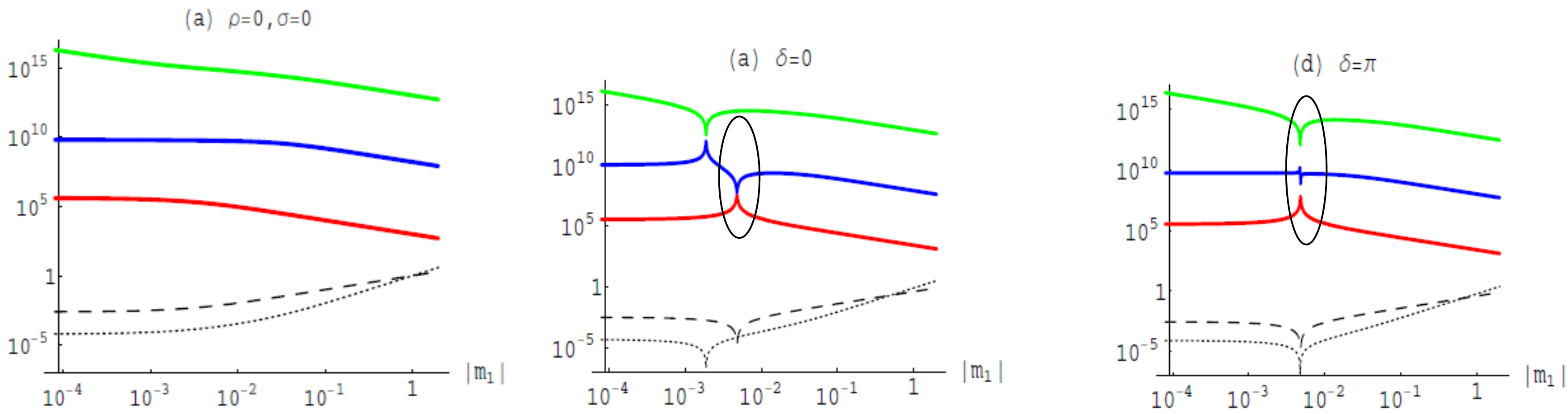
since $M_1 \ll 10^9$ GeV $\Rightarrow \eta_B^{(N1)} \ll \eta_B^{CMB}$

* Note that SO(10)-inspired conditions can be realized beyond SO(10) and even beyond GUT models

Crossing level solutions

(Akhmedov, Frigerio, Smirnov '03; PDB, Fiorentin, Marzola 2014)

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



- **About the crossing levels the N_1 CP asymmetry is enhanced**
- The correct BAU can be attained for a fine tuned choice of parameters: many models have made use of these solutions

(e.g. Ji, Mohapatra,Nasri; Buccella, Falcone, Nardi, '12; Altarelli, Meloni '14, Feng, Meloni, Meroni, Nardi '15)

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:

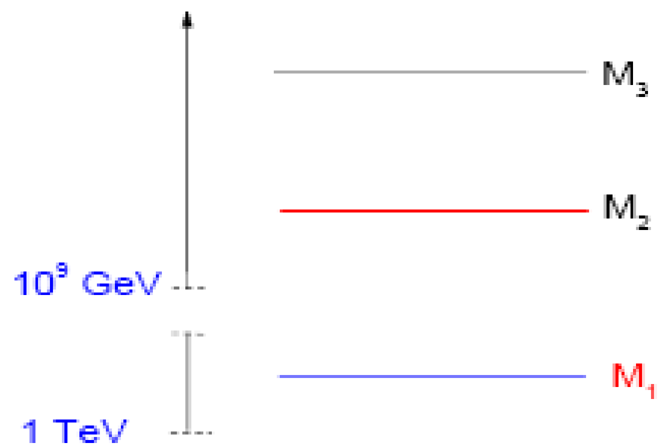
$$N_{B-L}^{\mathrm{f},\mathrm{N}_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\mathrm{f},\mathrm{N}_1} = \varepsilon_1\, \kappa(K_1)$$

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

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

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

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

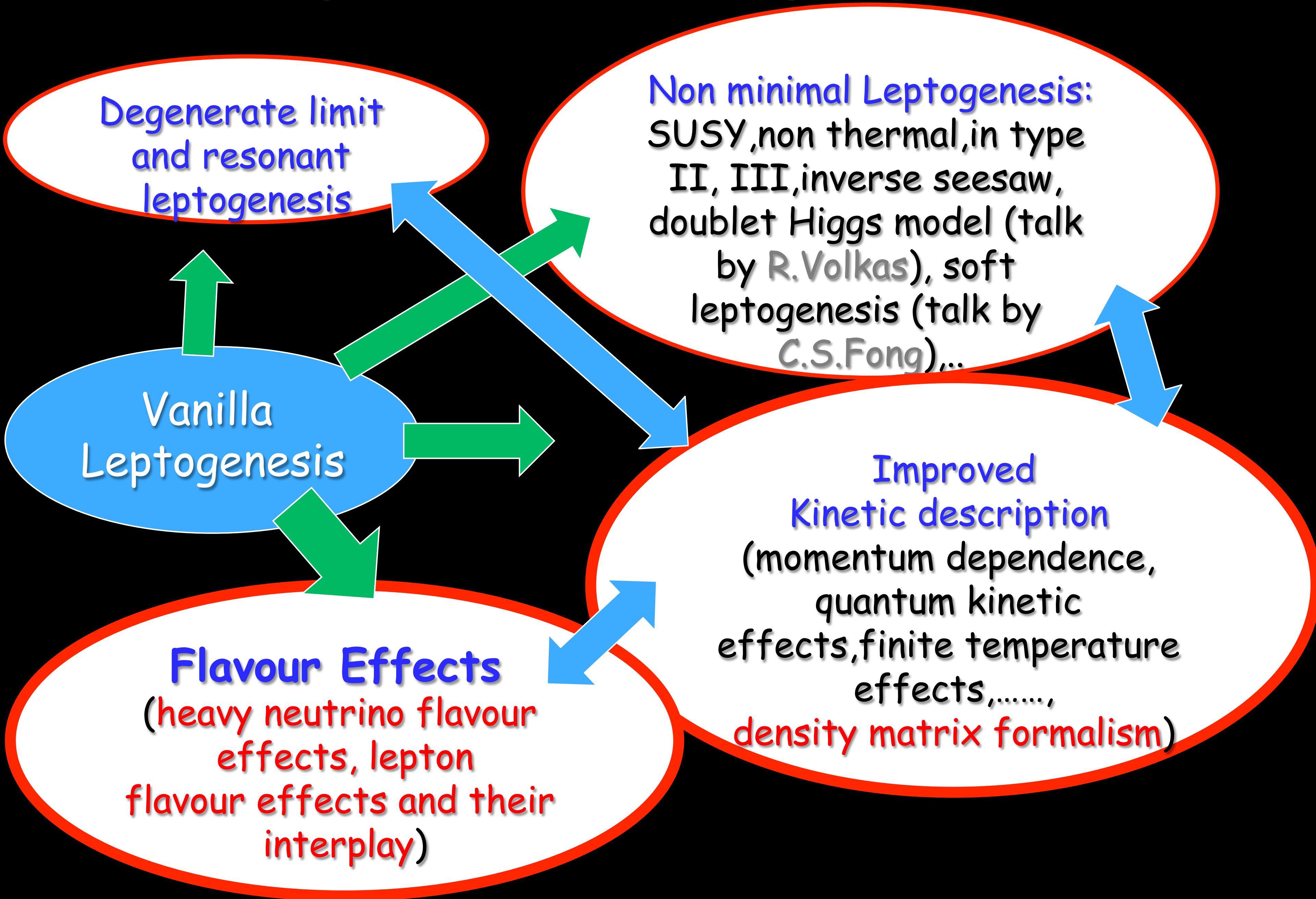


- How special is having $K_1 \lesssim 1$?
  $P(K_1 \lesssim 1) \simeq 0.2\%$ (random scan)

- SO(10)-inspired models do not realise this special choice of parameters!

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

Beyond vanilla Leptogenesis



Beyond the type I seesaw

Usually 2 motivations:

- Avoiding the reheating temperature lower bound
- In order to get new phenomenological tests….the most typical motivation in this respect is quite obviously whether we can test the seesaw and leptogenesis at the LHC and/or in LFV processes, ED moments,…. ⇒ **"TeV Leptogenesis"**

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

- **No new physics at the LHC (at least not so far);**
- **Discovery of a non-vanishing reactor angle opened the door to completing leptonic mixing matrix parameters measurement (talks by P. Coloma, M. Marshakm, V. Paolone, L.M. Magro);**
- **Cosmological observations start to have the sensitivity to measure neutrino masses (talk by J. Hammann) and huge world efforts in improving $0\nu\beta\beta$ sensitivity (talks by M.Lindner, Rielage, V.Wagner) and by KATRIN in kinematic direct measuerements (talk by K. Valerius)**

(charged) 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 is important !

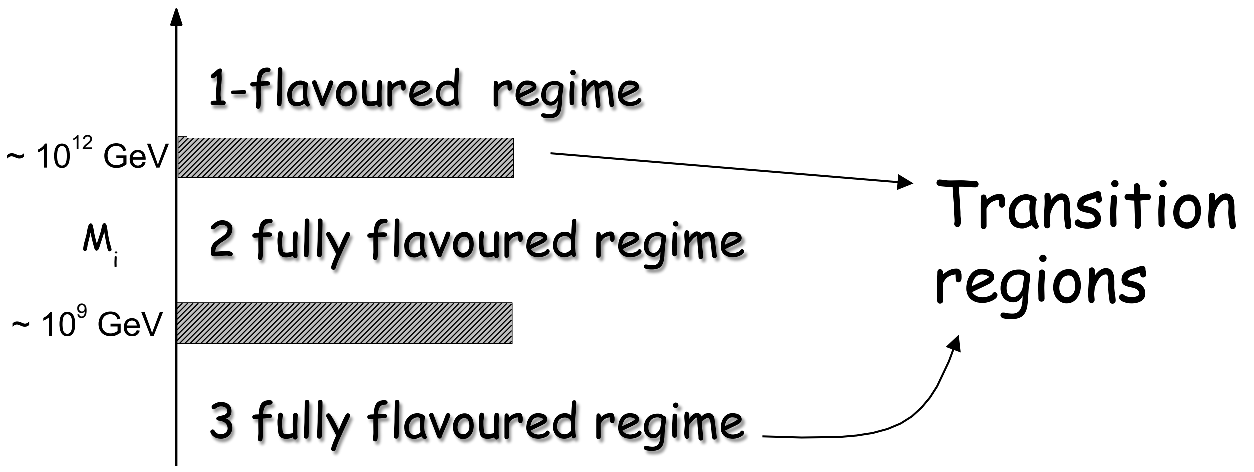
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1 \rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau) \qquad P_{1\alpha} \equiv |\langle \ell_1 | \alpha \rangle|^2$$

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

For $M_1 \lesssim 10^{12}$ 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 $e+\mu$ component

For $M_1 \lesssim 10^9$ GeV then also μ- Yukawas in equilibrium $\Rightarrow$ 3-flavor regime



Two fully flavoured regime

- Classic Kinetic Equations (in their simplest form)

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

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

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

(α = τ, e+μ)

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

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

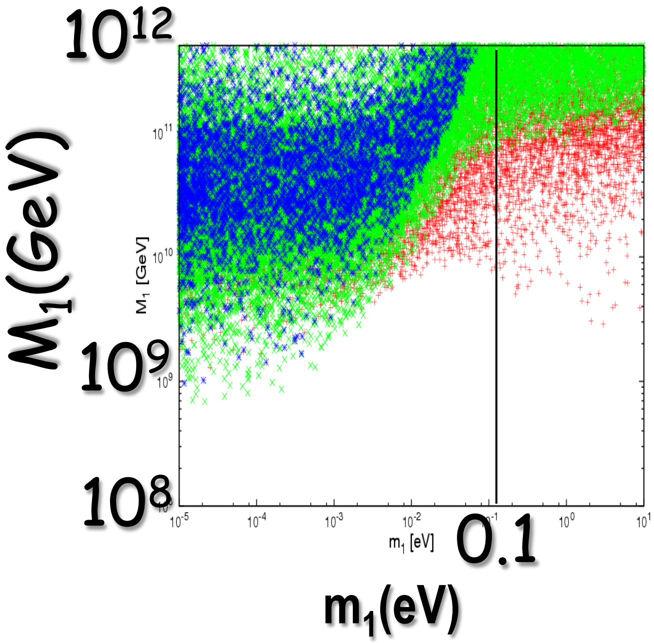
$$\Rightarrow\quad \boxed{\varepsilon_{1\alpha} \equiv -\frac{P_{1\alpha}\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = P_{1\alpha}^0\,\varepsilon_1 + \Delta P_{1\alpha}(\Omega, U)/2}$$

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

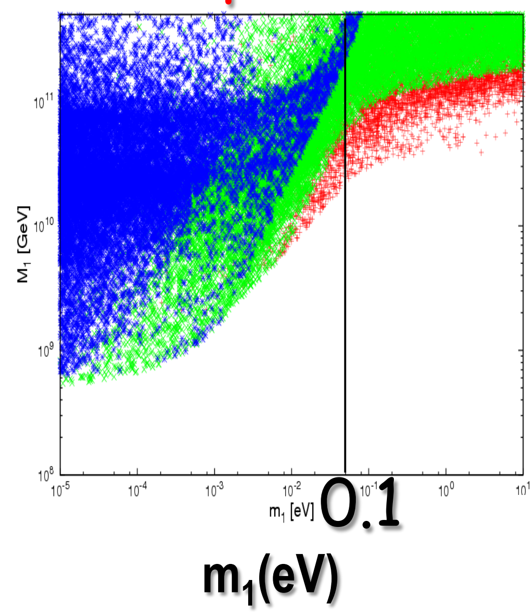
Flavoured decay parameters: $K_{i\alpha} \equiv P_{i\alpha}^0\,K_i = \left|\sum_k \sqrt{\frac{m_k}{m_\star}}\,U_{\alpha k}\,\Omega_{ki}\right|^2$

Neutrino mass bounds and role of PMNS phases

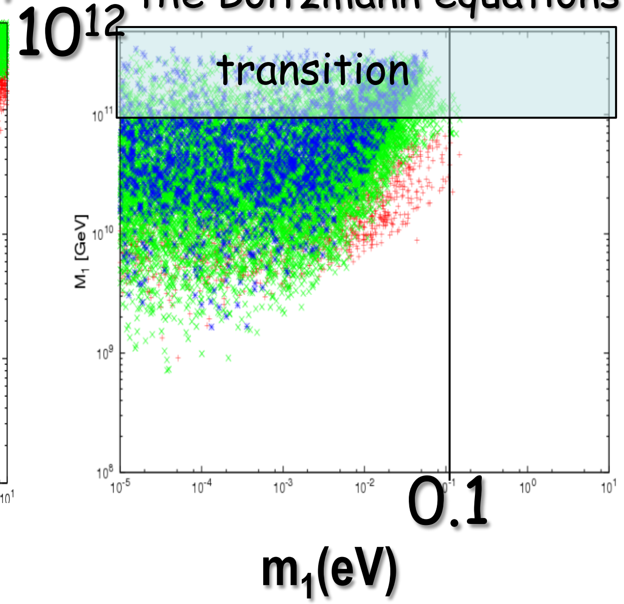
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)

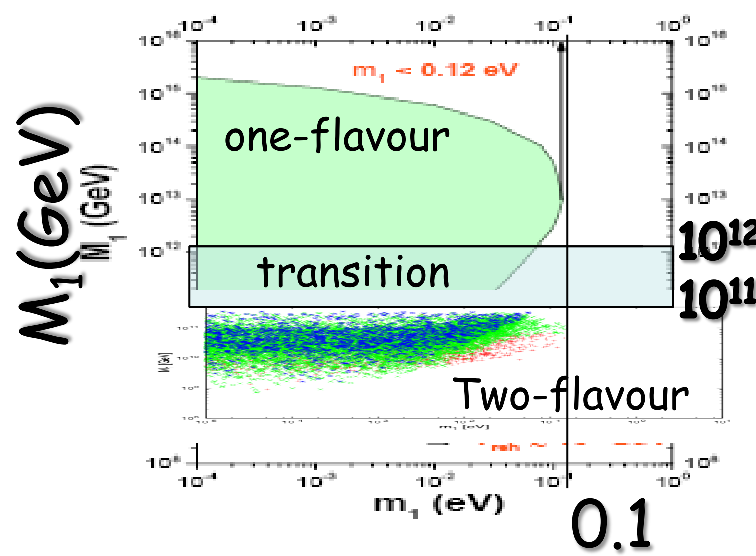


PMNS phases off



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)

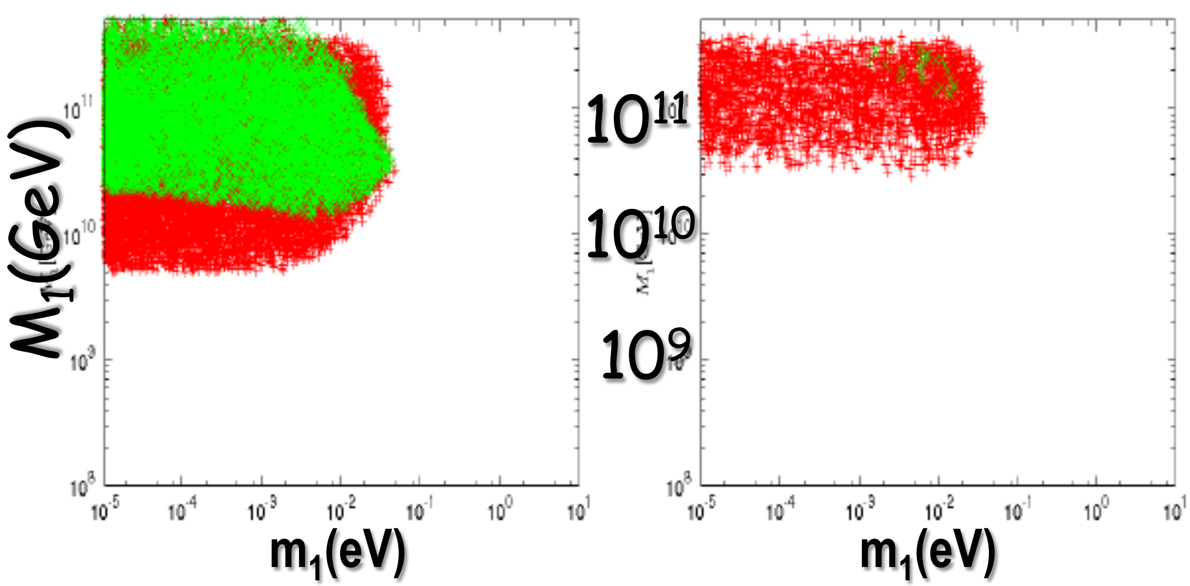
- Assume real $\Omega \Rightarrow \varepsilon_1 = 0 \Rightarrow N_{B-L}^{fin} \Rightarrow \cancel{2\varepsilon_1 \kappa_1^{fin}} + \Delta P_{1\alpha}(\kappa_{1\alpha}^{fin} - \kappa_{1\beta}^{fin})$

- Assume even vanishing Majorana phases ($\alpha = \tau, e+\mu$)

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

initial thermal N_1 abundance

independent of initial N_1 abundance



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

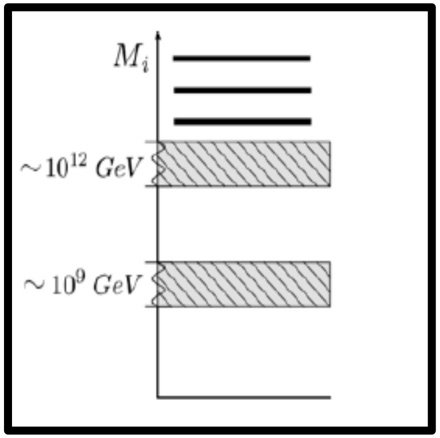
Red points: only Majorana phases

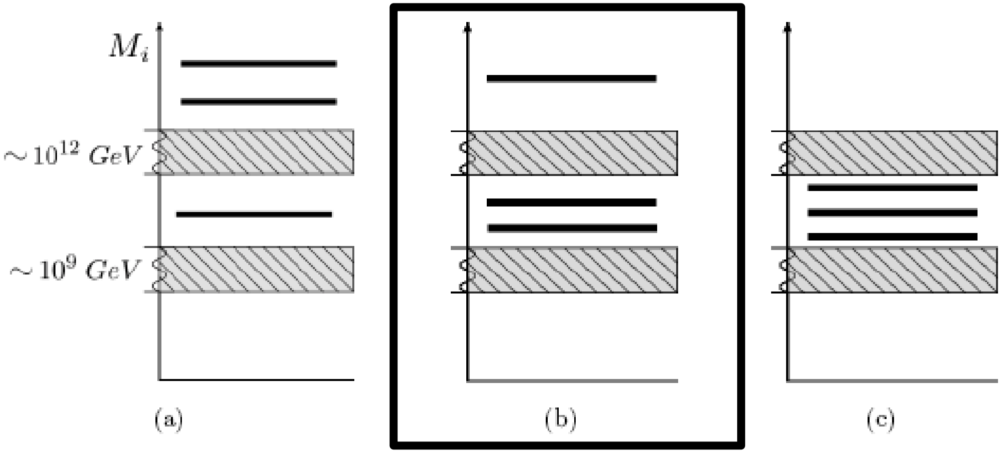
- No reasons for these assumptions to be rigorously satisfied in general this contribution is *overwhelmed* by the high energy phases *they* could be approximately satisfied in specific scenarios for some regions
- A calculation using full density matrix equation is necessary to confirm!
- DISCOVERY OF A CP VIOLATING VALUE OF DIRAC PHASE IS NEITHER NECESSARY NOR SUFFICIENT CONDITION FOR SUCCESSFUL LEPTOGENESIS

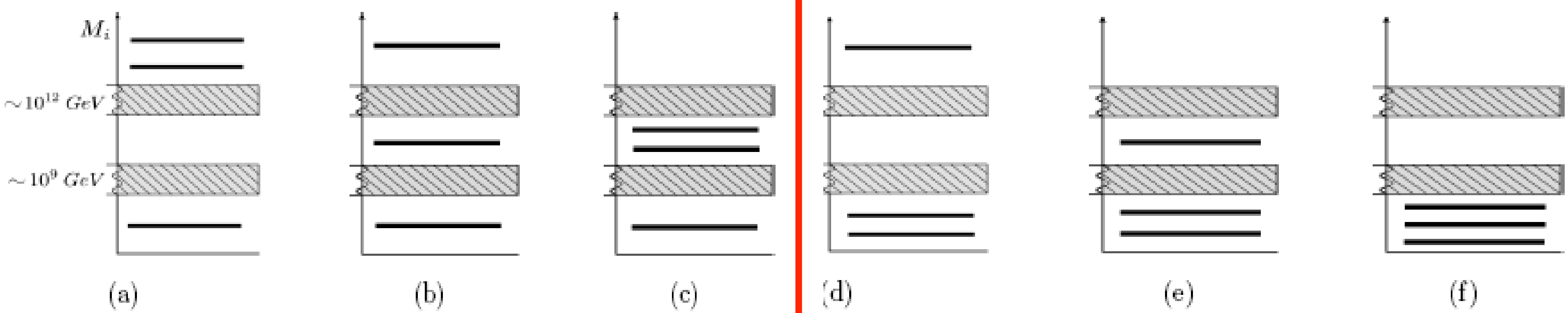
Heavy neutrino lepton flavour effects

Heavy neutrino flavored scenario

2 RH neutrino scenario







N_2-dominated scenario:

the lightest RH neutrino produces negligible asymmetry

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

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

A two stage process:

M_2

N_2 - Asymmetry Production in the 1 flavour regime

~ 10^{12} GeV

or in the 2 flavour regime

~ 10^{9} GeV

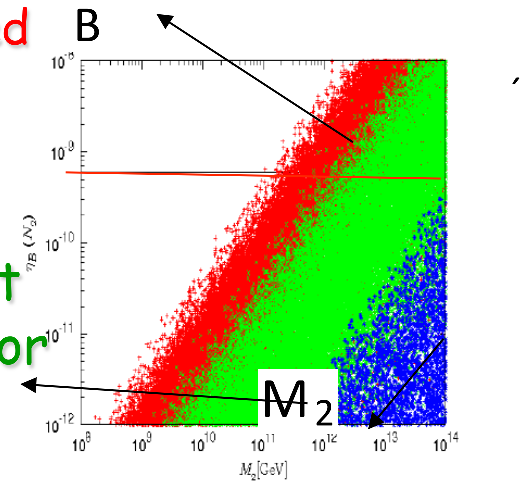
M_1

N_1 - washout in the 3 fl. regime

N_1 wash-out is neglected

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

Both wash-out and flavor effects



C M B

Unflavored case

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

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

(PDB, Riotto '08)

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

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

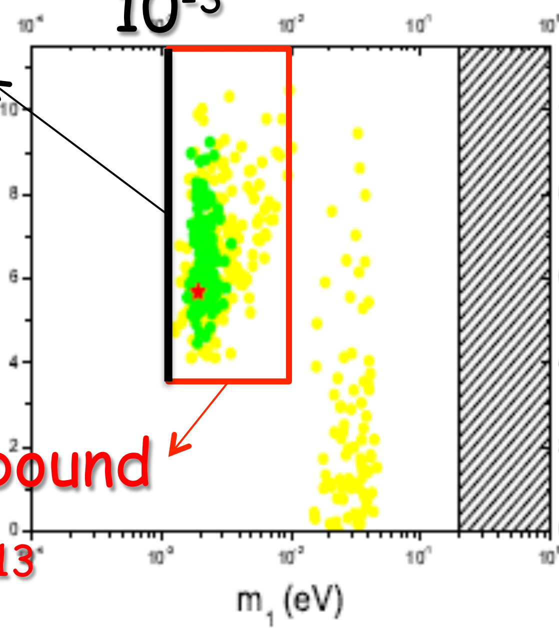
$\alpha_2=5$ $\alpha_2=4$ $\alpha_2=3$

$V_L = I$ Normal ordering

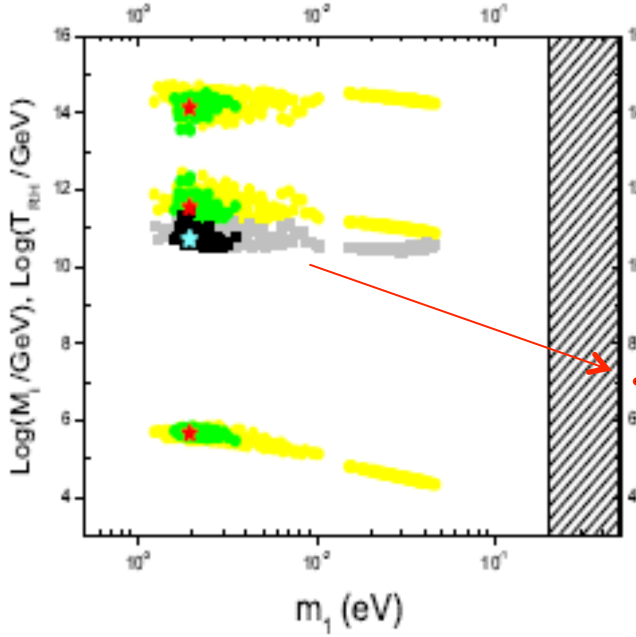
lower bound on m_1

10^{-3}

Θ_{13}



lower bound on Θ_{13}



$T_{RH} \gtrsim 5\times10^{10}$ GeV

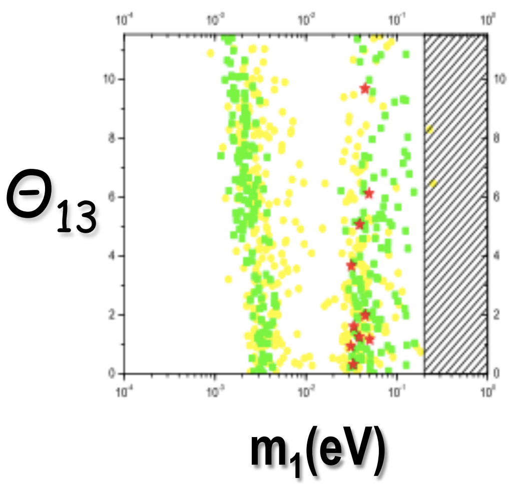
- The solutions are exclusively tauon dominated '

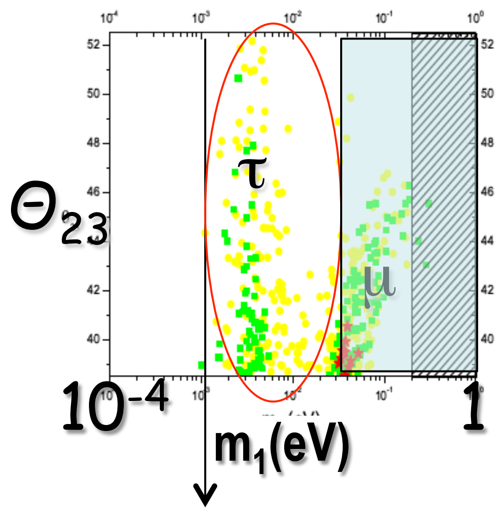
Testing SO(10)-inspired leptogenesis with low energy neutrino data

(PDB, Riotto '10)

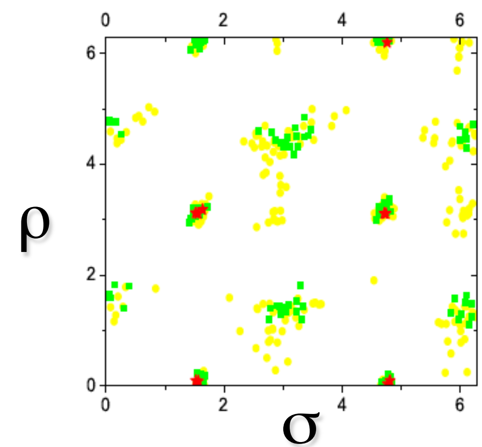
More general calculation with: $I \leq V_L \leq V_{CKM}$

$\alpha_2=5$ $\alpha_2=4$ $\alpha_2=1$ **NORMAL ORDERING**





- $m_1 \gtrsim 10^{-3}$ eV



- Majorana phases constrained about specific values

- The lower bound on θ_{13} at low m_1 disappears
- A muon solution appears at high m_1 : strongly constrained by Planck
- Marginal allowed regions for INVERTED ORDERING

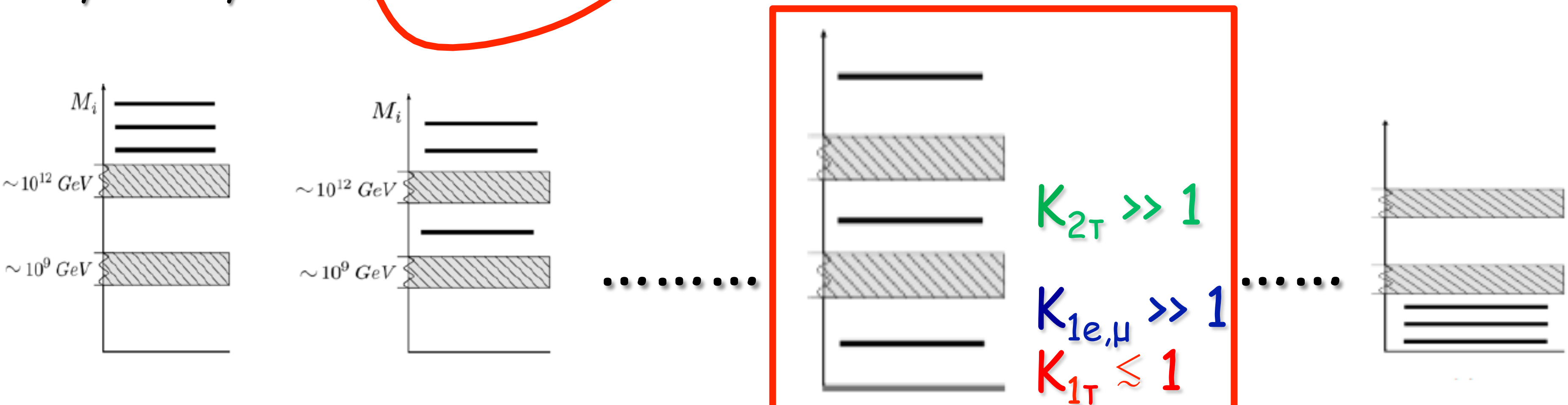
The problem of the initial conditions in flavoured leptogenesis

(Bertuzzo,PDB,Marzola '10)

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

Relic "pre-existing" asymmetry

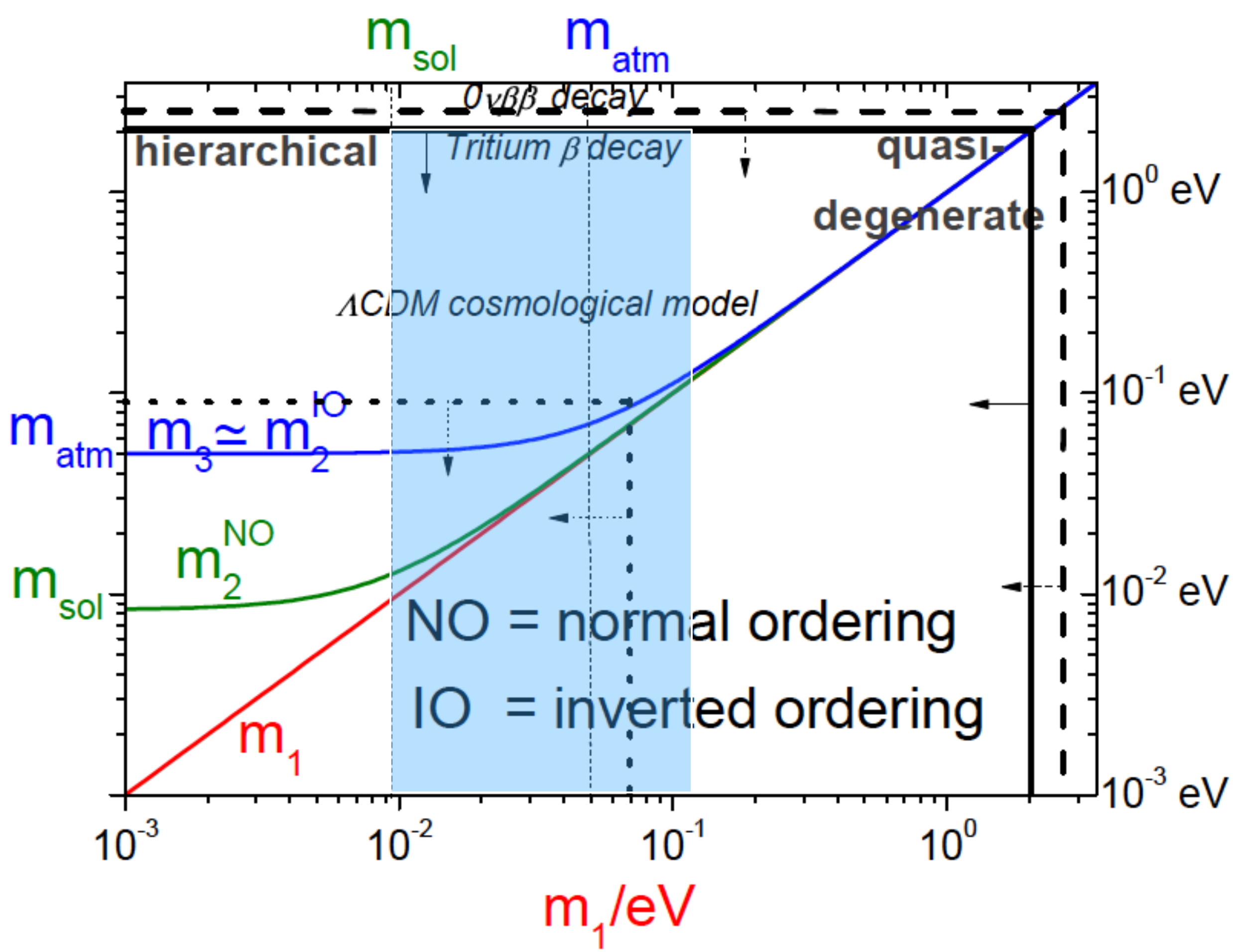
Asymmetry generated from leptogenesis



The conditions for the wash-out of a pre-existing asymmetry, **'strong thermal (ST) leptogenesis'**, can be realised only within a **tauon dominated N_2-dominated scenario!**

Neutrino mass window for ST leptogenesis

(PDB, Sophie King, Michele Re Fiorentin 2014)



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

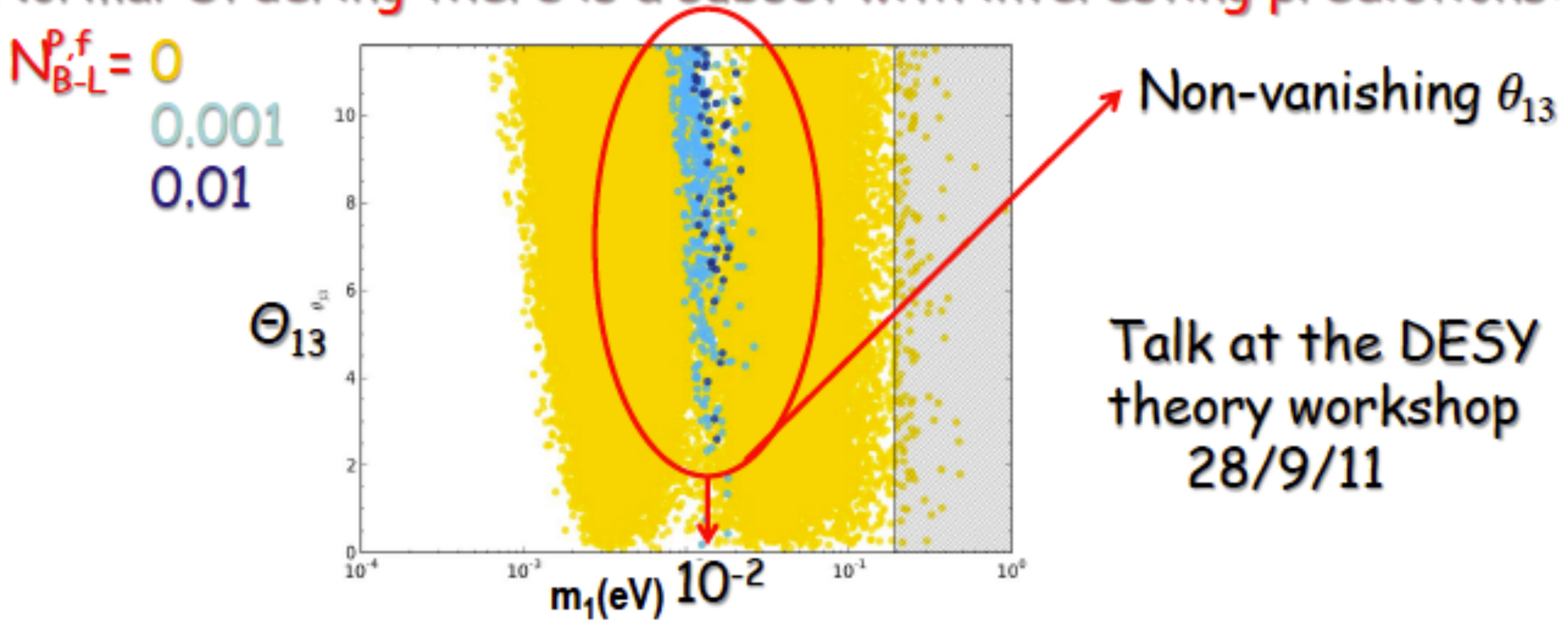
Can SO(10)-inspired leptogenesis realise ST leptogenesis?

(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:

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

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; PDB, Fiorentin, Marzola '14)

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

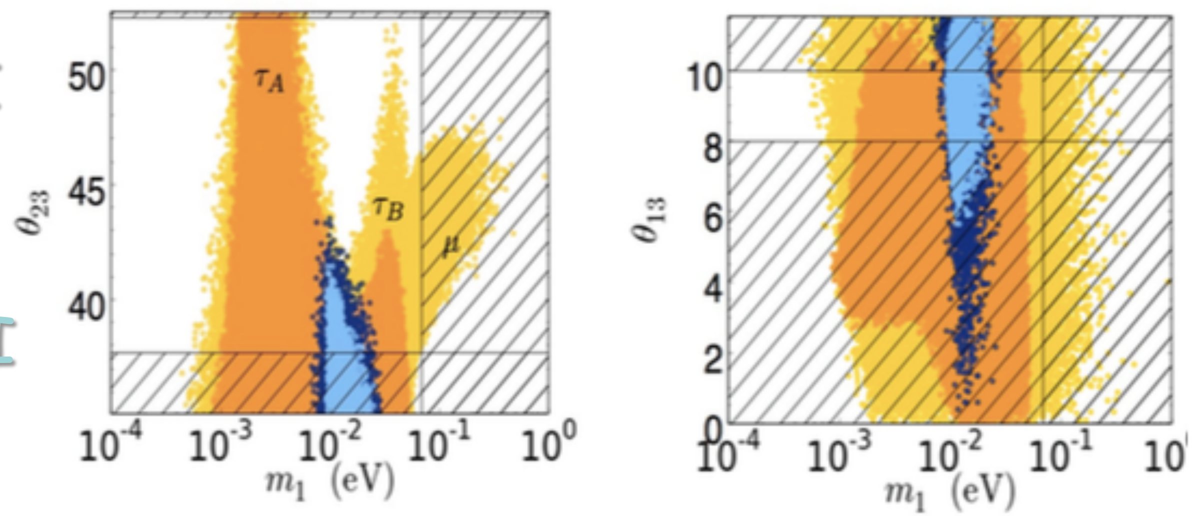
$\alpha_2=5$

$N_{B-L}^{P,i}=0$

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

$N_{B-L}^{P,i}=0.001$

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

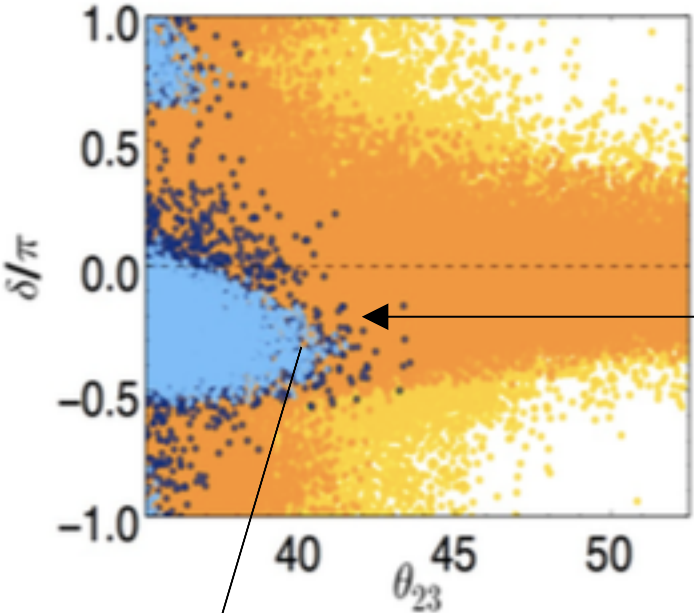


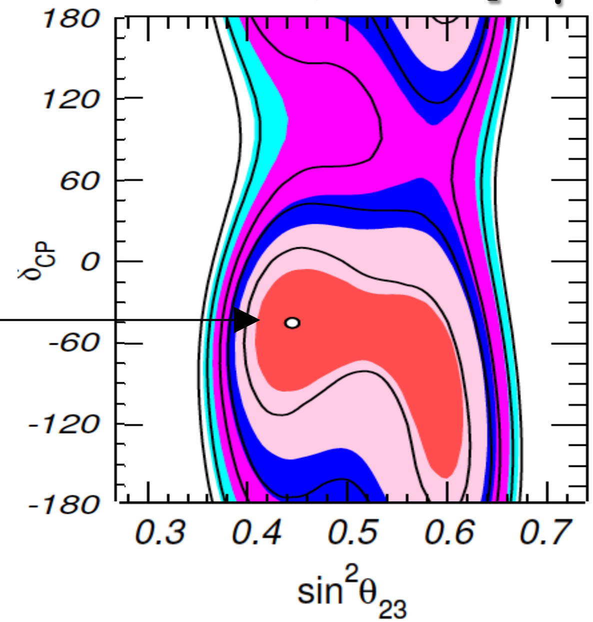
- The lightest neutrino mass respects the general lower bound but is also upper bounded ⇒ $15 \lesssim m_1 \lesssim 25$ meV;
- The reactor mixing angle has to be non-vanishing (preliminary results presented before Daya Bay discovery);
- The atmospheric mixing angle falls strictly in the first octant;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

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

NuFIT 1.2 (2013)

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



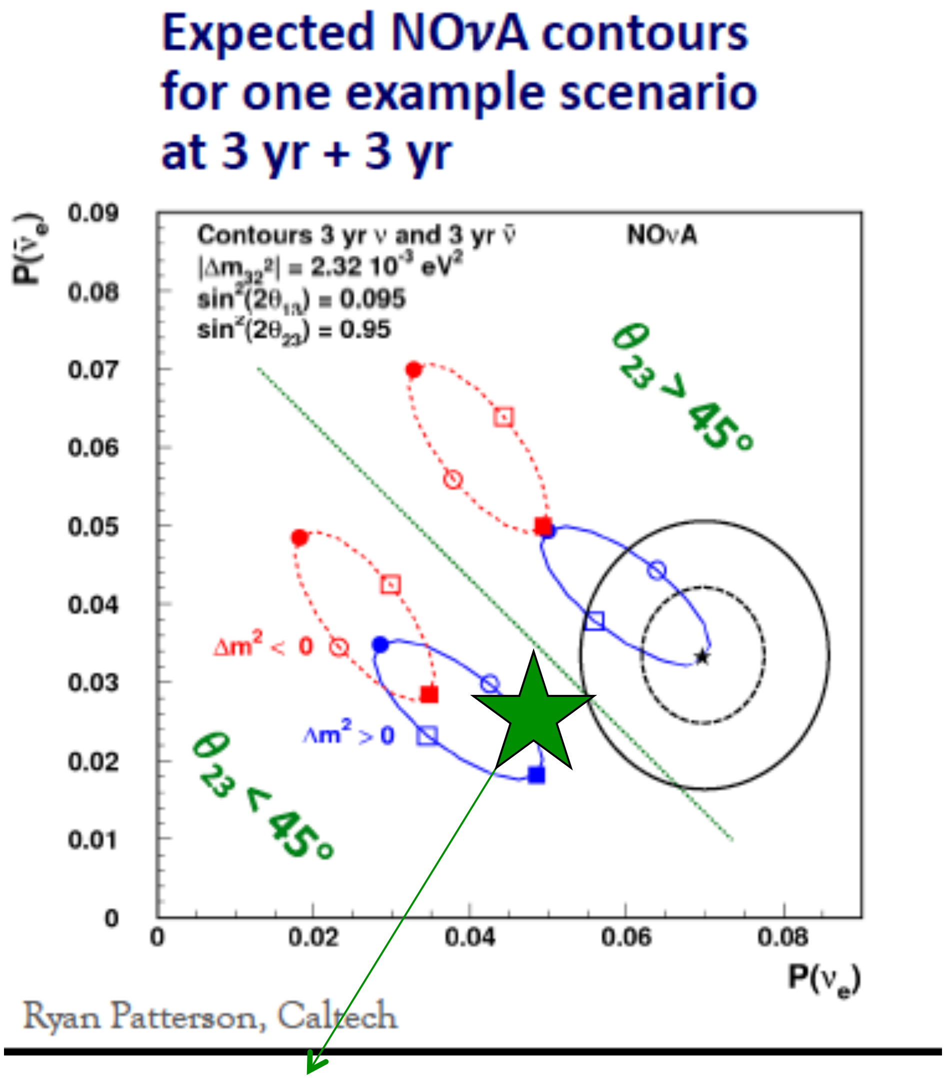


http://www.nu-fit.org/sites/default/files/v12.fig-dlthie-glob.pdf

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



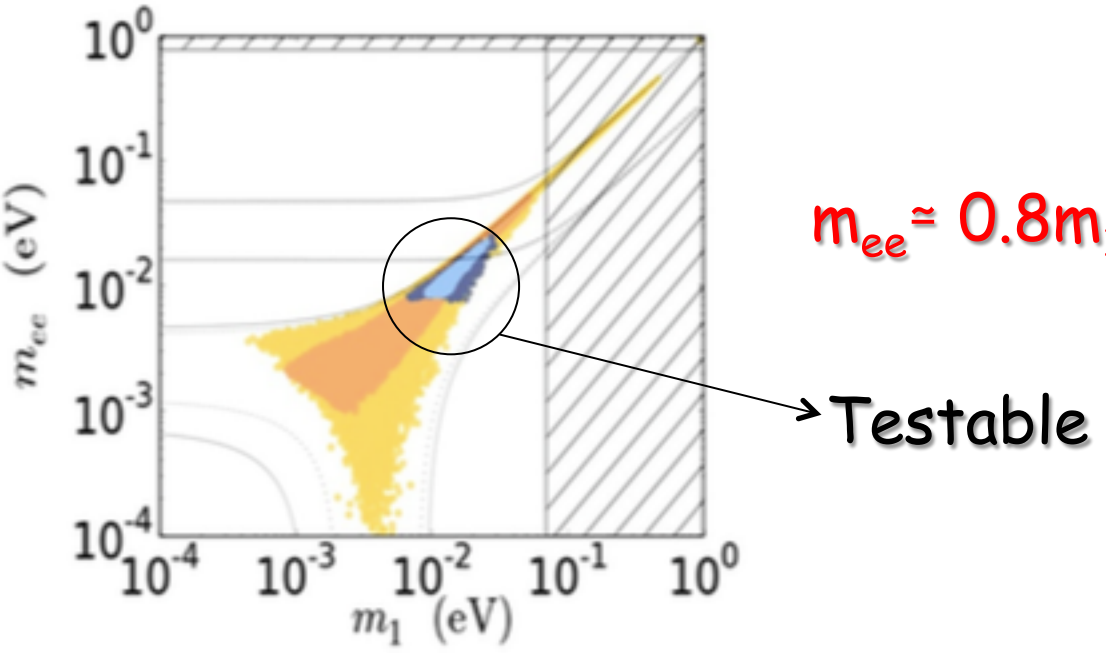
Strong thermal SO(10)-inspired solution

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}

α_2=5



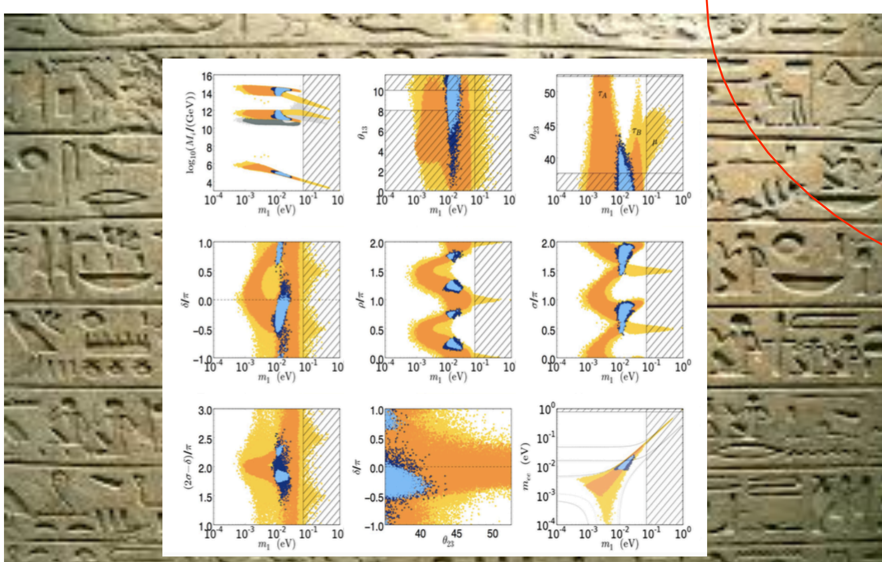
$m_{ee} \simeq 0.8 m_1 \simeq 15$ meV

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

(PDB, Fiorentin, Marzola, 2015)

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

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



?

Strong thermal SO(10)-inspired solution

Imposing SO(10)-inspired conditions

See-saw formula
$$m_\nu = -m_D \, \frac{1}{D_M} \, m_D^T \, . \qquad D_M \equiv \mathrm{diag}(M_1, M_2, M_3),$$

Leptonic mixing matrix
$$U^\dagger \, m_\nu \, U^\star = -D_m \qquad D_m \equiv \mathrm{diag}(m_1, m_2, m_3)$$

Bi-unitary parameterization
$$m_D = V_L^\dagger \, D_{m_D} \, U_R \qquad D_{m_D} \equiv \mathrm{diag}(m_{D1}, m_{D2}, m_{D3})$$

Majorana mass matrix in the Yukawa basis
$$U_R^\star \, D_M \, U_R^\dagger = M = D_{m_D} \, V_L^\star \, U^\star \, D_m^{-1} \, U^\dagger \, V_L^\dagger \, D_{m_D} \simeq -D_{m_D} \, m_\nu^{-1} \, D_{m_D}$$

A diagonalization problem with explicit solution....

SO(10)-inspired conditions
$$m_{D1} = \alpha_1 \, m_u \, , \; m_{D2} = \alpha_2 \, m_c \, , \; m_{D3} = \alpha_3 \, m_t \, , \quad (\alpha_i = \mathcal{O}(1))$$
$$V_L \simeq V_{CKM} \simeq I$$

Full analytical understanding

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

$$M_1 \simeq \frac{m_{D1}^2}{|m_{\nu ee}|} \simeq \frac{\alpha_1^2 m_u^2}{|m_{\nu ee}|} \simeq \alpha_1^2\, 10^5\ \text{GeV} \left(\frac{m_u}{1\text{MeV}}\right)^2 \left(\frac{10\,\text{meV}}{|m_{\nu ee}|}\right)$$

0ν2β neutrino mass

$$\Phi_1 = \text{Arg}[-m^\star_{\nu ee}]\,.$$

$$M_2 \simeq \frac{\alpha_2^2\, m_c^2}{m_1\, m_2\, m_3} \frac{|m_{\nu ee}|}{|(m_\nu^{-1})_{\tau\tau}|} \simeq \alpha_2^2\, 10^{11}\ \text{GeV} \left(\frac{m_c}{400\text{MeV}}\right)^2$$

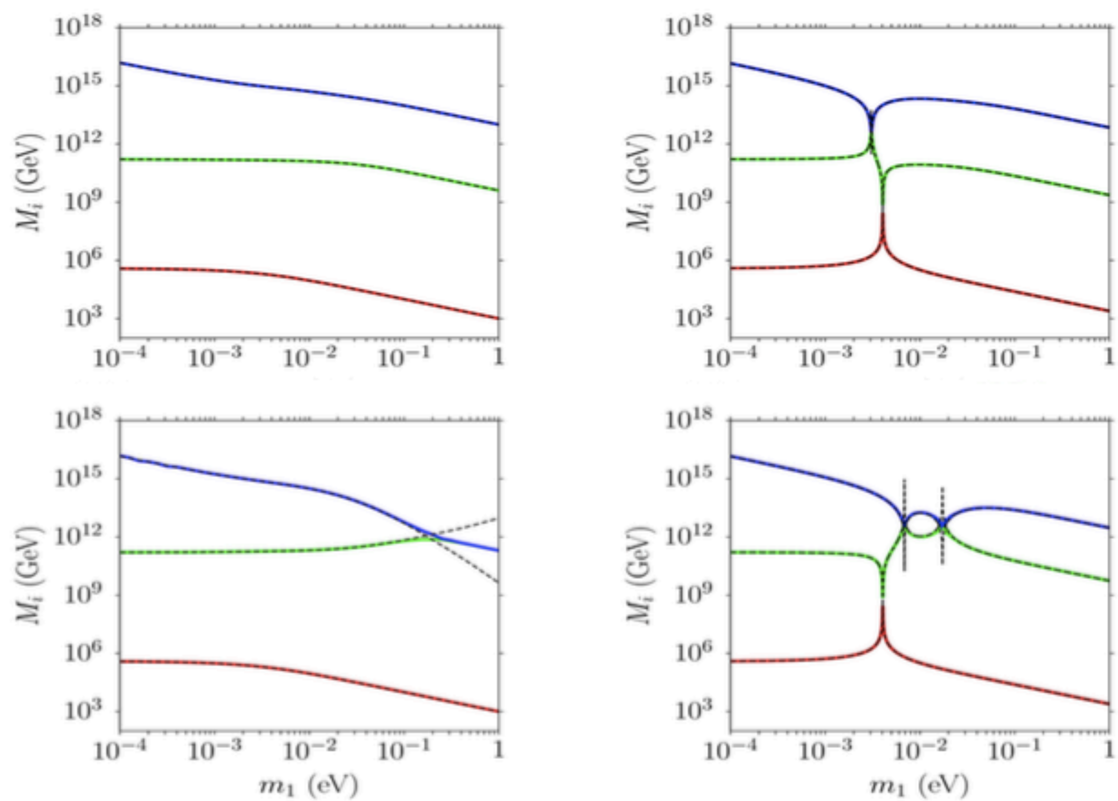
$$\Phi_2 = \text{Arg}\left[\frac{m_{\nu ee}}{(m^{-1})}\right] - 2\,(\rho + \sigma)$$

$$M_3 \simeq \alpha_3^2\, m_t^2\, |(m_\nu^{-1})_{\tau\tau}| \simeq \alpha_3^2\, 10^{15}\ \text{GeV} \left(\frac{m_t}{100\text{GeV}}\right)^2 \left(\frac{\text{meV}}{m_1}\right)\,.$$

$$\Phi_3 = \text{Arg}[-(m_\nu^{-1})_{\tau\tau}]\,.$$

RH neutrino masses: analytical vs. num.

Comparison between numerical solutions (solid) and analytical solutions (dashed)



$$M_1 \simeq \frac{m_{D1}^2}{|m_{\nu ee}|} \simeq \frac{\alpha_1^2\, m_u^2}{|m_{\nu ee}|} \simeq \alpha_1^2\, 10^5\, \mathrm{GeV} \left(\frac{m_u}{1\mathrm{MeV}}\right)^2 \left(\frac{10\,\mathrm{meV}}{|m_{\nu ee}|}\right)$$

Notice that in order to have $M_1 \gtrsim 10^9$ GeV necessarily m_{ee} <<< 10 meV: crossing level solutions typically imply no $0\nu2\beta$ observation! (but this holds for $V_L = I$)

A formula for the final asymmetry (V_L=I)

$$\varepsilon_{2\alpha} \simeq \overline{\varepsilon}(M_2)\,\frac{m_{D\alpha}^2}{m_{D3}^2\,|U_{R32}|^2 + m_{D2}^2}\,\frac{|(m_\nu^{-1})_{\tau\tau}|^{-1}}{m_{\rm atm}}\,{\rm Im}[U_{R\alpha 2}^\star\,U_{R\alpha 3}\,U_{R32}^\star\,U_{R33}]\,.$$

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

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

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

Imposing This epression for the asymmetry fully reproduced all shown constraints for V_L=I

Leptogenesis in the "A2Z model"

(S.King 2014)

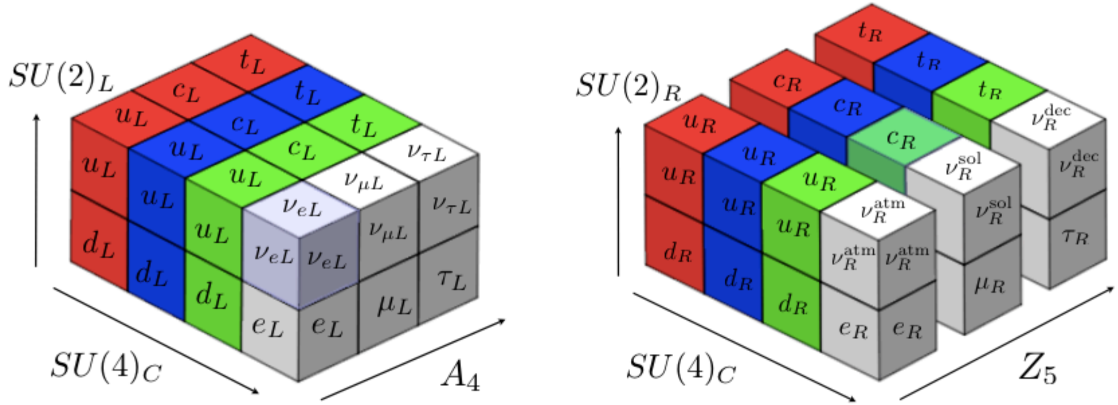


Figure 1: A to Z of flavour with Pati-Salam, where $A \equiv A_4$ and $Z \equiv Z_5$. The left-handed families form a triplet of A_4 and are doublets of $SU(2)_L$. The right-handed families are distinguished by Z_5 and are doublets of $SU(2)_R$. The $SU(4)_C$ unifies the quarks and leptons with leptons as the fourth colour, depicted here as white.

Neutrino sector:

$$Y'^{\nu}_{LR} = \begin{pmatrix} 0 & be^{-i3\pi/5} & 0 \\ ae^{-i3\pi/5} & 4be^{-i3\pi/5} & 0 \\ ae^{-i3\pi/5} & 2be^{-i3\pi/5} & ce^{i\phi} \end{pmatrix}, \quad M'_R = \begin{pmatrix} M'_{11}e^{2i\xi} & 0 & M'_{13}e^{i\xi} \\ 0 & M'_{22}e^{i\xi} & 0 \\ M'_{13}e^{i\xi} & 0 & M'_{33} \end{pmatrix}$$

$$m^D_{\nu 1} \sim m_u, \quad m^D_{\nu 2} \sim 3\, m_c, \quad m^D_{\nu 3} \sim \frac{1}{3}\, m_t$$

Leptogenesis in the "A2Z model"

(PDB S.King 2015)

The only CP asymmetry that is not asymmetrysizeable is the tauon asymmetry but $K_{1\tau} >> 1$!

Flavour coupling is then crucial to produce the correct asymmetry (Antusch,PDB,Jones,King 2011)

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

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

$$\eta_B^{(\mu)} \simeq -\left(\frac{K_{2\mu}}{K_{2e}+K_{2\mu}}\, C^{(2)}_{\tau^{\perp}\tau} - \frac{K_{1\mu}}{K_{1\tau}}\, C^{(3)}_{\mu\tau}\right) e^{-\frac{3\pi}{8}\, K_{1\mu}}\, .$$

There is a solution (NO)!

(PDB S.King 2015)

CASE	B		
ξ	$+4\pi/5$	0	$-4\pi/5$
$\chi^2_{\rm min}$	6.1		
$M'_{11}/{\rm GeV}$	1.33×10^6 GeV		
$M'_{22}/{\rm GeV}$	4.35×10^{10} GeV		
$M'_{33}/{\rm GeV}$	1.31×10^{12} GeV		
$M'_{13}/{\rm GeV}$	6.1×10^9 GeV		
M'_{13}/M'_{22}	0.141		
ϕ/π	0.788		
$M_1/{\rm GeV}$	2.7×10^7 GeV		
$M_2/{\rm GeV}$	4.35×10^{10} GeV		
$M_3/{\rm GeV}$	1.31×10^{12} GeV		
$m_1/{\rm meV}$	2.3		
$m_2/{\rm meV}$ $(p_{\Delta m^2_{21}})$	8.94 (-0.25)		
$m_3/{\rm meV}$ $(p_{\Delta m^2_{31}})$	49.7 (+0.21)		
$m_{ee}/{\rm meV}$	1.95		
$\theta_{12}/^\circ$ $(p_{\theta_{12}})$	33.0 (-0.66)		
$\theta_{13}/^\circ$ $(p_{\theta_{13}})$	8.40 (-0.49)		
$\theta_{23}/^\circ$ $(p_{\theta_{23}})$	54.0 (+2.3)		
$\delta/^\circ$	23.5		
$\beta_1/^\circ$	115		
$\beta_2/^\circ$	278		
$\alpha_{21}/^\circ$	162		
$\alpha_{31}/^\circ$	245		
$\eta_B(p_{\eta_B})/10^{-10}$	6.101 (0.01)		
$\varepsilon_{2\tau}$	1.3×10^{-5}		
$K_{1\mu}$	0.58		
$K_{1\tau}$	800		
$K_{2\tau}$	7.3		
$K_{2\mu}$	29.2		
K_{2e}	1.8		

Table 3: Results for the CASE B (NO) with (flavour coupled) leptogenesis.

Recent fits within SO(10) models

(Joshipura Patel 2011; Rodejohann, Dueck '13)

Mod	Comments	$\langle m_\nu \rangle$ [meV]	δ^l_{CP} [rad]	$\sin^2 \theta^l_{23}$	m_0 [meV]	M_3 [GeV]	M_2 [GeV]	M_1 [GeV]	$\chi^2_{\min}$
MN	no RGE, NH	0.35	0.7	0.406	3.03	5.5×10^{12}	7.2×10^{11}	1.5×10^{10}	1.10
MN	RGE, NH	0.49	6.0	0.346	2.40	3.6×10^{12}	2.0×10^{11}	1.2×10^{11}	23.0
MS	no RGE, NH	0.38	0.27	0.387	2.58	3.9×10^{12}	7.2×10^{11}	1.6×10^{10}	9.41
MS	RGE, NH	0.44	2.8	0.410	6.83	1.1×10^{12}	5.7×10^{10}	1.5×10^{10}	3.29
FN	no RGE, NH	4.96	1.7	0.410	8.8	1.9×10^{13}	2.8×10^{12}	2.2×10^{10}	6.6×10^{-5}
FN	RGE, NH	2.87	5.0	0.410	1.54	9.9×10^{14}	7.3×10^{13}	1.2×10^{13}	11.2
FS	no RGE, NH	0.75	0.5	0.410	1.16	1.5×10^{13}	5.3×10^{11}	5.7×10^{10}	9.0×10^{-10}
FS	RGE, NH	0.78	5.4	0.410	3.17	4.2×10^{13}	4.9×10^{11}	4.9×10^{11}	6.9×10^{-6}
FN	no RGE, IH	35.37	5.4	0.590	35.85	2.2×10^{13}	4.9×10^{12}	9.2×10^{11}	2.5×10^{-4}
FN	RGE, IH	35.52	4.7	0.590	30.24	1.1×10^{13}	3.5×10^{12}	5.5×10^{11}	13.3
FS	no RGE, IH	44.21	0.3	0.590	6.27	1.2×10^{13}	4.2×10^{11}	3.5×10^{7}	3.9×10^{-8}
FS	RGE, IH	24.22	3.6	0.590	11.97	1.2×10^{13}	3.1×10^{11}	2.0×10^{3}	0.602

Recently Fong,Meloni,Meroni,Nardi have included leptogenesis for the Non SUSY case obtaining that it can giv successful leptogenesis (compact RN neutrino spectrum, very small m_{ee})

Conclusions:

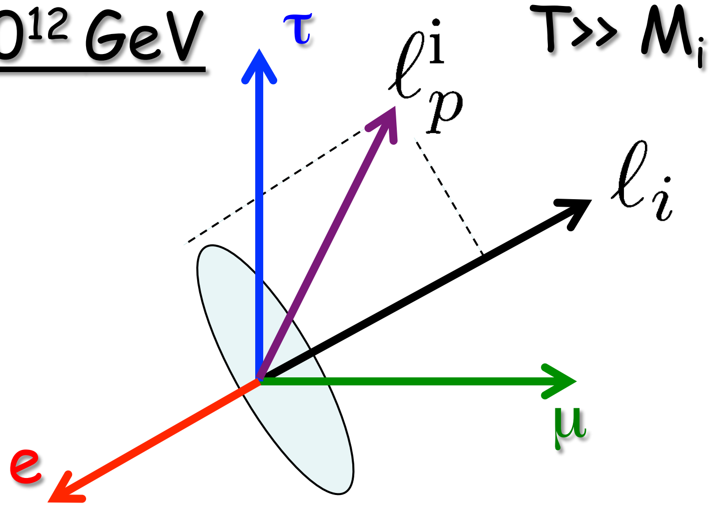
- The importance of discoverying CP violation in neutrino oscillations should not be be overrated but also not undermined;
- High scale leptogenesis is difficult to test but maybe not impossible: necessary to work out plausible scenarios;
- Thermal leptogenesis: problem of the independence of the initial 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
- Study of realistic models incorporating leptogenesis started but there is still quite a lot of work to be done.....different solutions migth emerge but typically they make sharp predictions on delta, m_{ee}, ordering

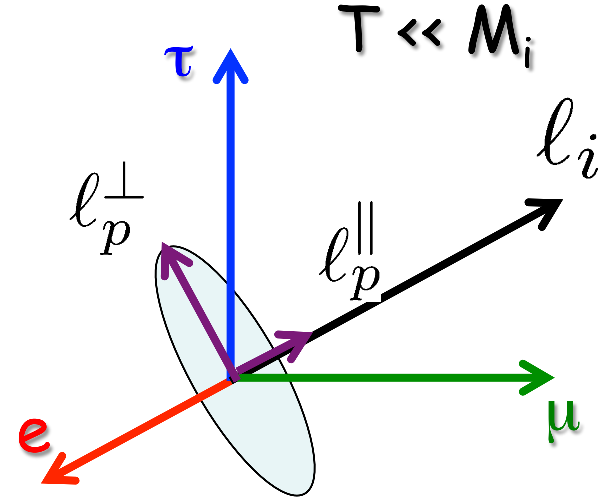
We are entering an interesting stage where leptogenesis can really give an important guidance among models and increase the predictive power in light of next measurements from low energy neutrino experiments

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

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

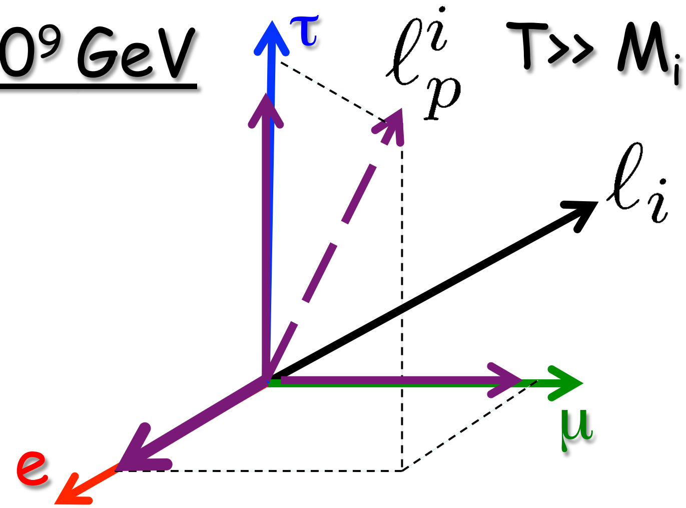
$M_i \gtrsim 10^{12}$ GeV

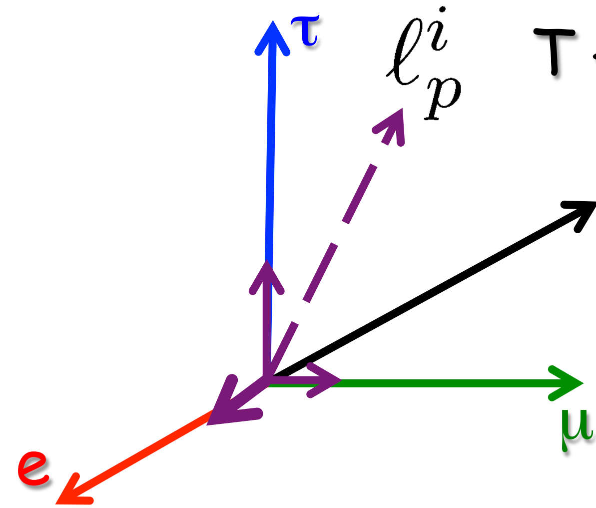




$$N_{B-L}^{\rm p}(T \ll M_i) = (1 - P_{{\rm p}i})N_{B-L}^{\rm p,i} + P_{{\rm p}i}\, e^{-\frac{3\pi}{8}\,K_i}\, N_{B-L}^{\rm p,i}$$

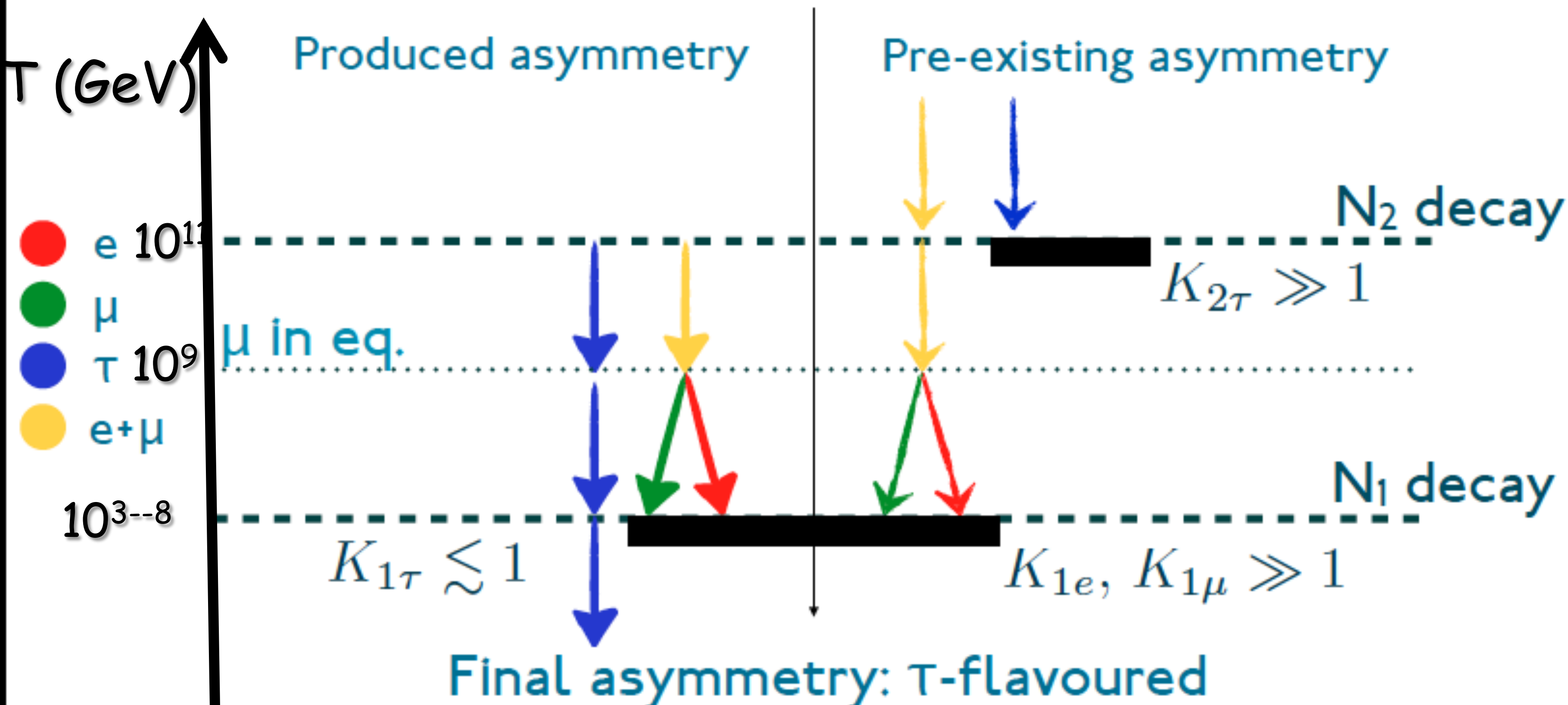
M_i << 10^9 GeV





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

How is STL realised? - A cartoon



Strong thermal leptogenesis conditions

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

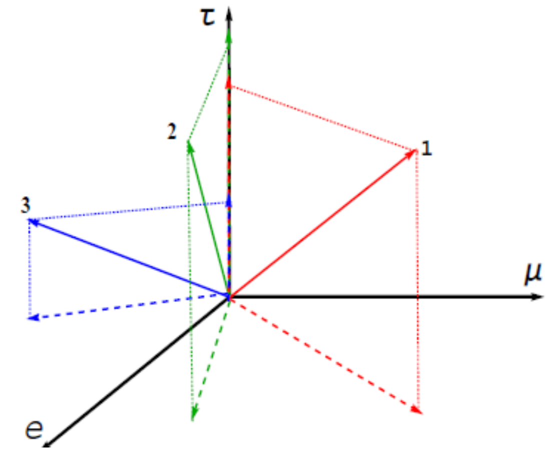
Courtesy of Michele Re Fiorentin

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:



$$\frac{dN^{B-L}_{\alpha\beta}}{dz} = \varepsilon^{(1)}_{\alpha\beta}\,D_1\,(N_{N_1}-N^{\rm eq}_{N_1}) - \frac{1}{2}\,W_1\,\{\mathcal{P}^{0(1)}, N^{B-L}\}_{\alpha\beta} \quad (80)$$

$$+ \; \varepsilon^{(2)}_{\alpha\beta}\,D_2\,(N_{N_2}-N^{\rm eq}_{N_2}) - \frac{1}{2}\,W_2\,\{\mathcal{P}^{0(2)}, N^{B-L}\}_{\alpha\beta}$$

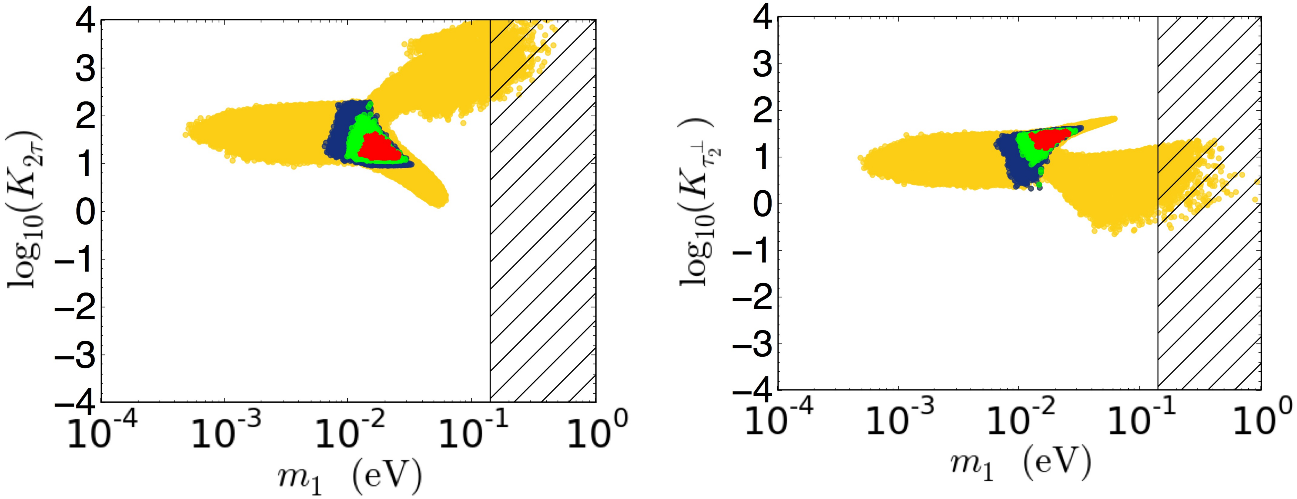
$$+ \; \varepsilon^{(3)}_{\alpha\beta}\,D_3\,(N_{N_3}-N^{\rm eq}_{N_3}) - \frac{1}{2}\,W_3\,\{\mathcal{P}^{0(3)}, N^{B-L}\}_{\alpha\beta}$$

$$+ \; {\rm i}\,{\rm Re}(\Lambda_\tau)\left[\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}, N^{\ell+\bar\ell}\right]_{\alpha\beta} - {\rm Im}(\Lambda_\tau)\left[\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix},\left[\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}, N^{B-L}\right]\right]_{\alpha\beta}$$

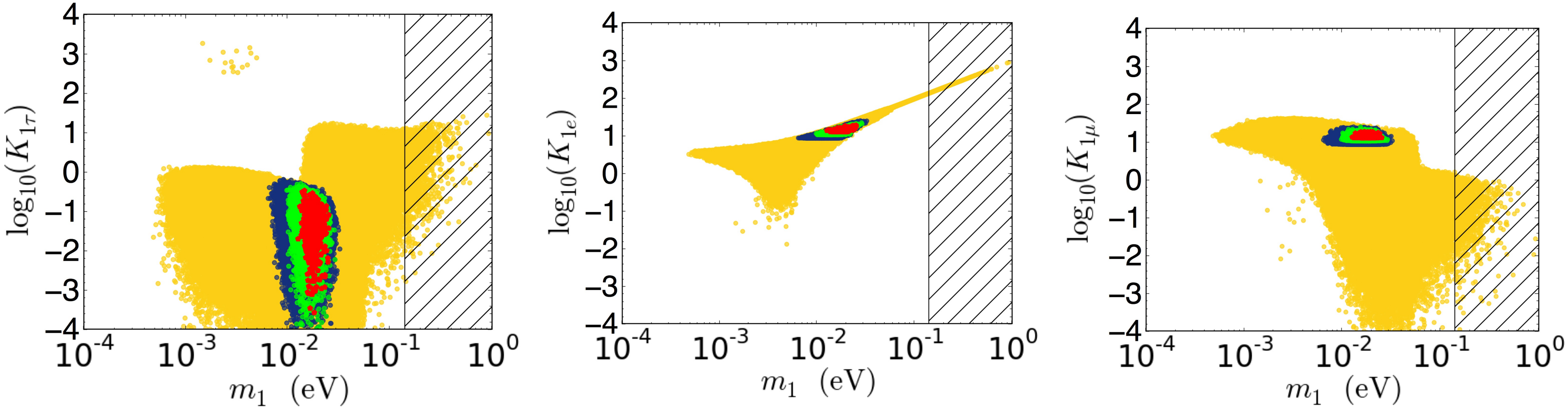
$$+ \; {\rm i}\,{\rm Re}(\Lambda_\mu)\left[\begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix}, N^{\ell+\bar\ell}\right]_{\alpha\beta} - {\rm Im}(\Lambda_\mu)\left[\begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix},\left[\begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix}, N^{B-L}\right]\right]_{\alpha\beta}.$$

Some insight from the decay parameters

At the production ($T \sim M_2$)



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

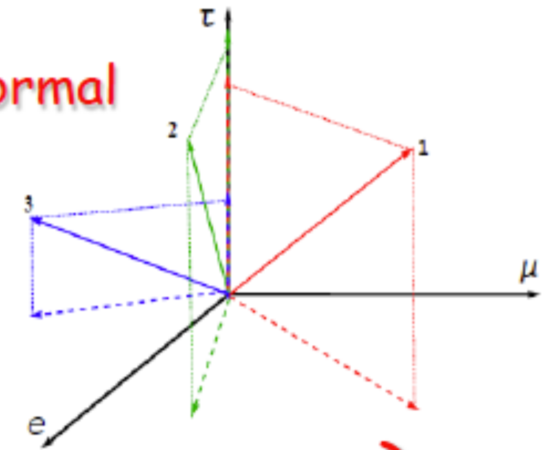


Flavour projection

(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

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

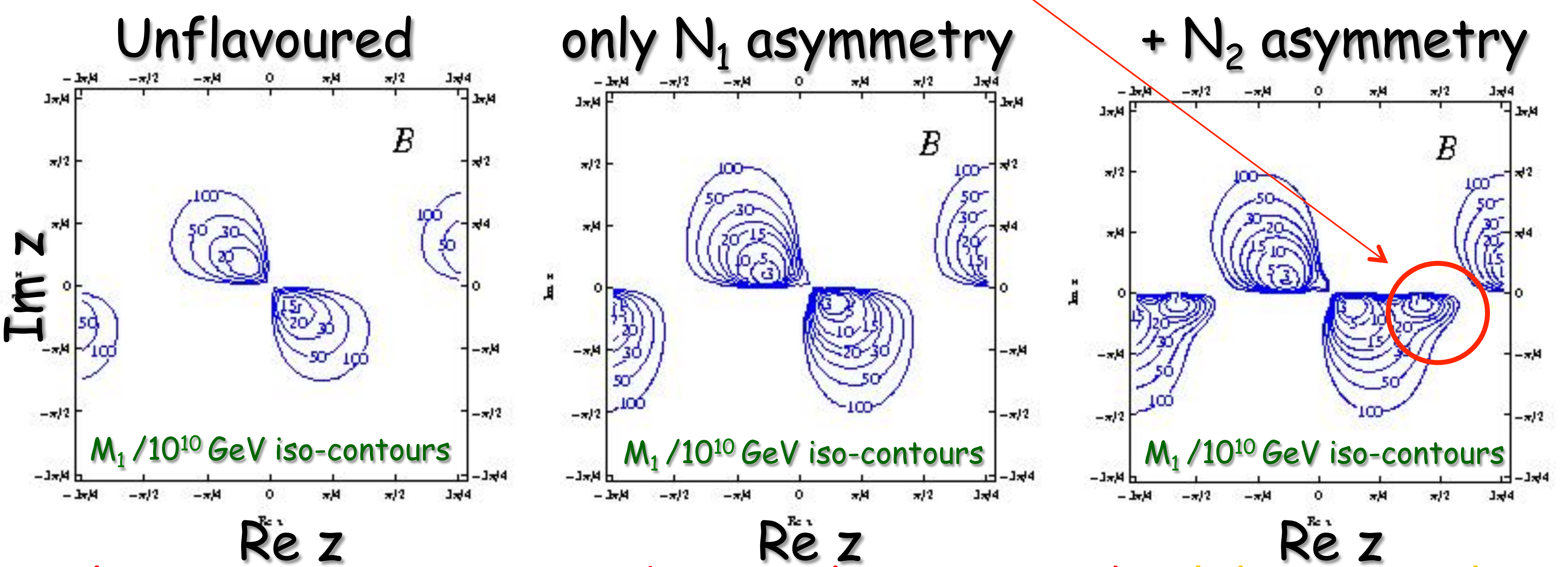
2 RH neutrino scenario revisited

(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



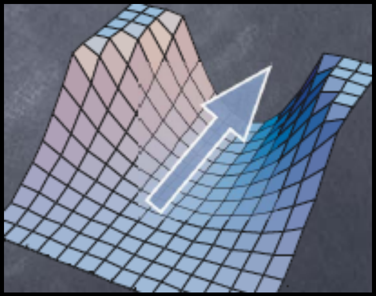
These regions are interesting because they correspond to light sequential dominated neutrino mass models realized in some grandunified models

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

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

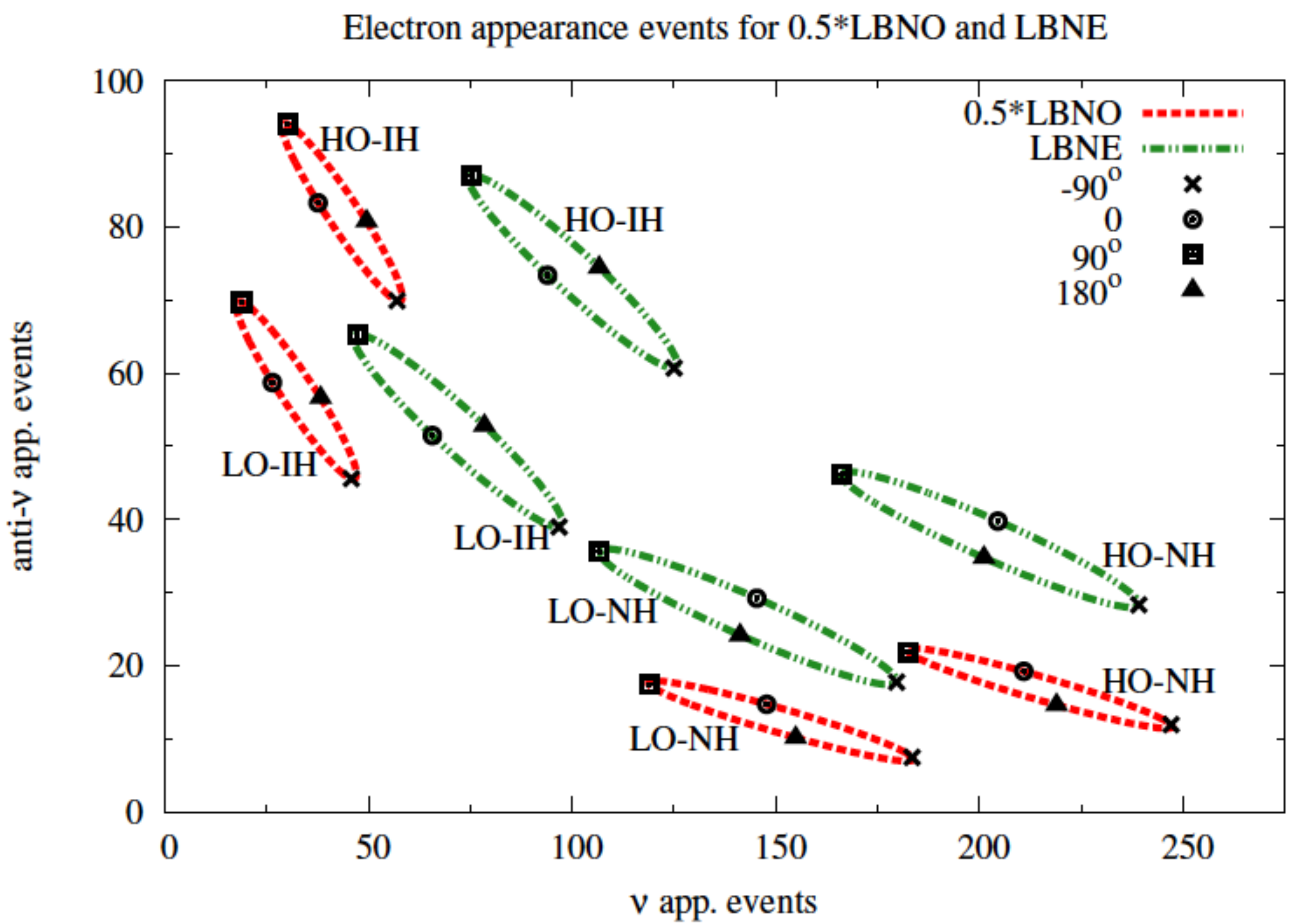


F term D term

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

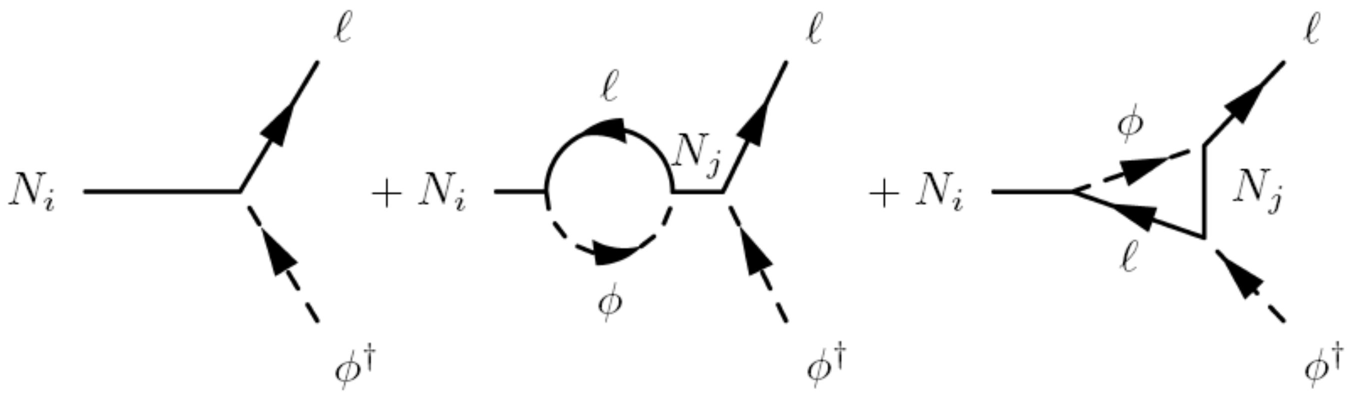
$$\frac{n_B}{s} \sim 10^{-10} \left(\frac{m_{3/2}}{m_\Phi}\right) \left(\frac{m_\Phi}{\mathrm{TeV}}\right)^{-\frac{1}{2}} \left(\frac{M}{M_P}\right)^{\frac{3}{2}} \left(\frac{T_R}{10\,\mathrm{GeV}}\right)$$

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)



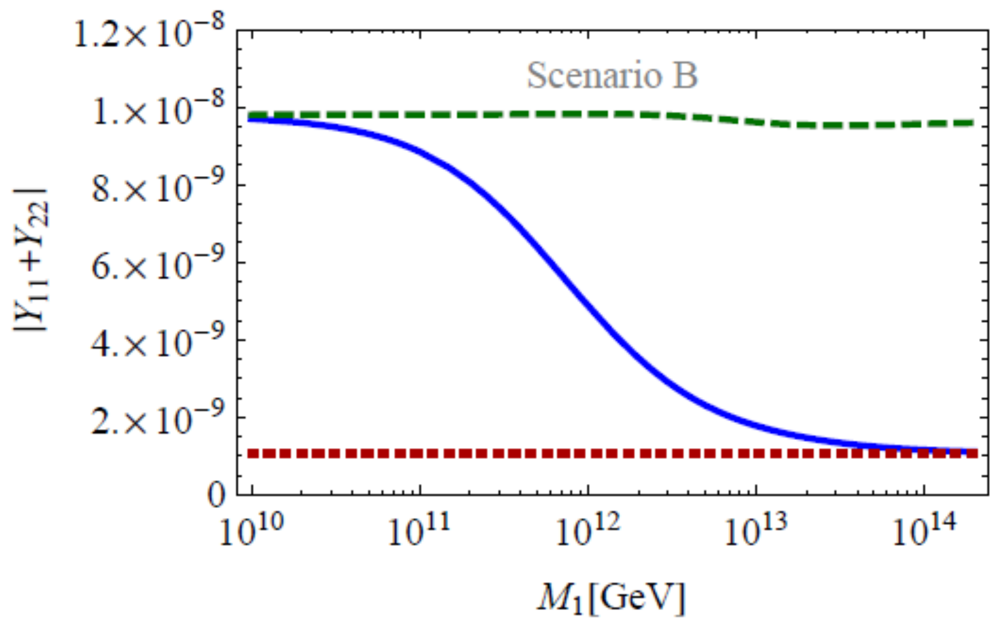
$$\varepsilon_i \simeq \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(m_D^\dagger\, m_D)^2_{ij}\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

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)

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



Fully two-flavoured regime limit

Unflavoured regime limit

Additional contribution to CP violation:

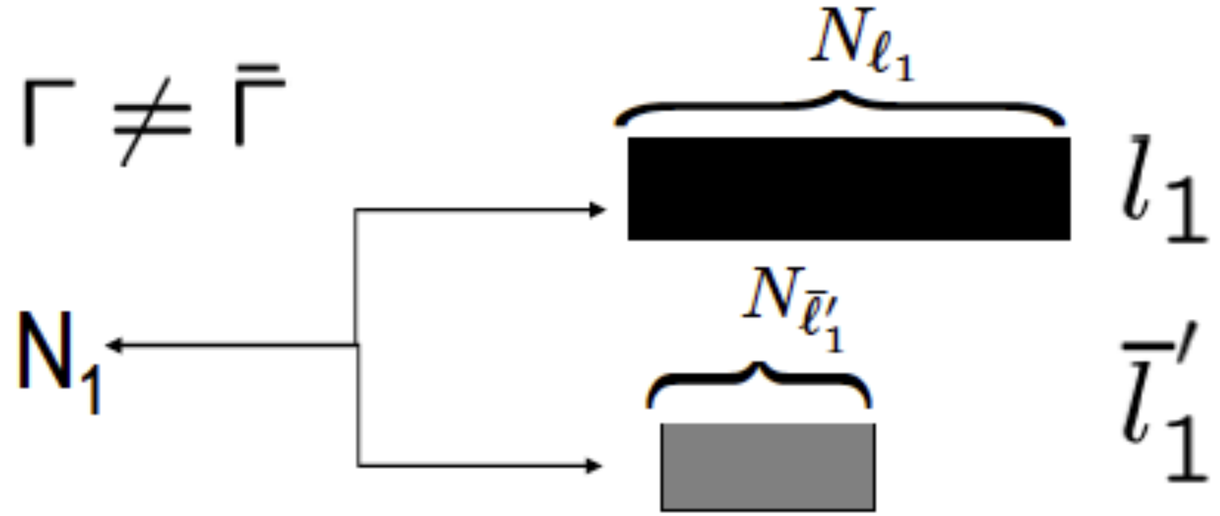
(Nardi, Racker, Roulet '06)

($\alpha = \tau$, e+μ)

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

depends on U !

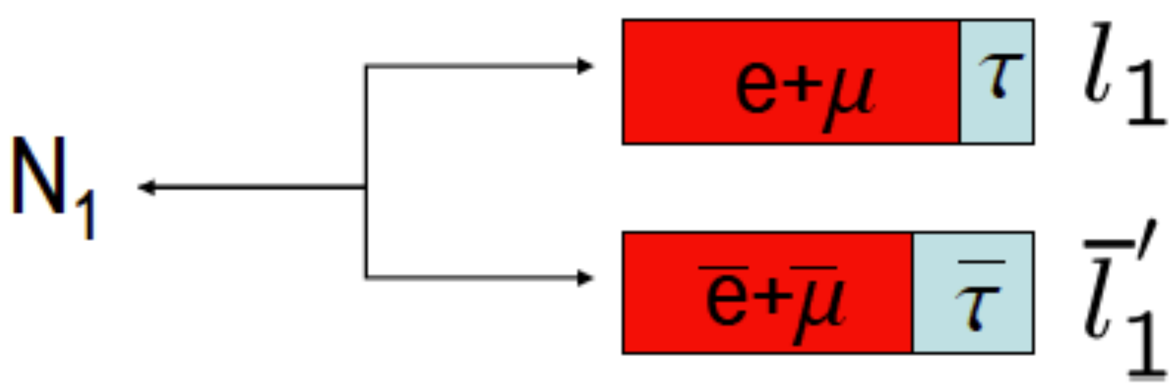
1) $\Gamma \neq \bar{\Gamma}$



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

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

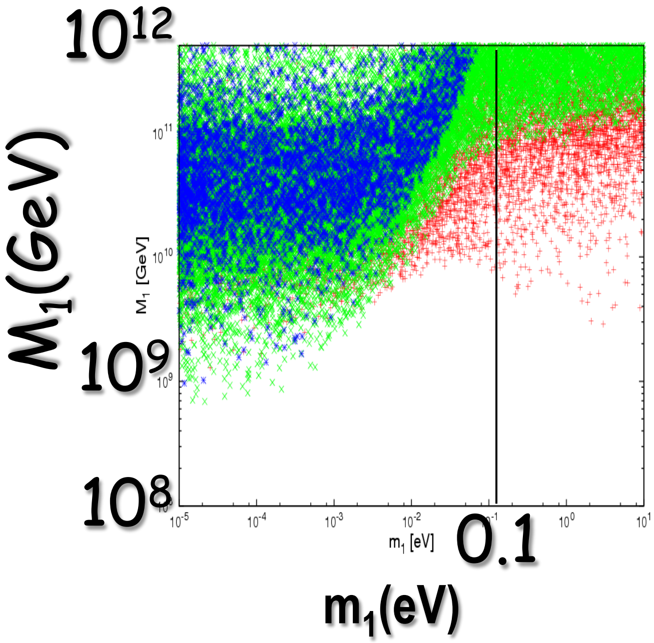
+



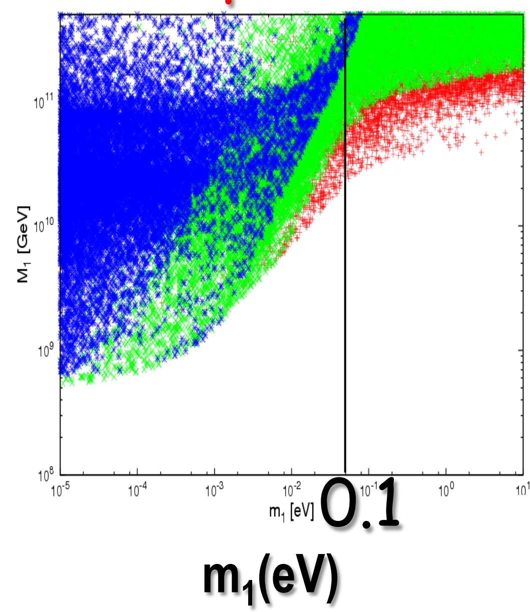
$$\Rightarrow \; \frac{\Delta P_{1\alpha}}{2}$$

Neutrino mass bounds and role of PMNS phases

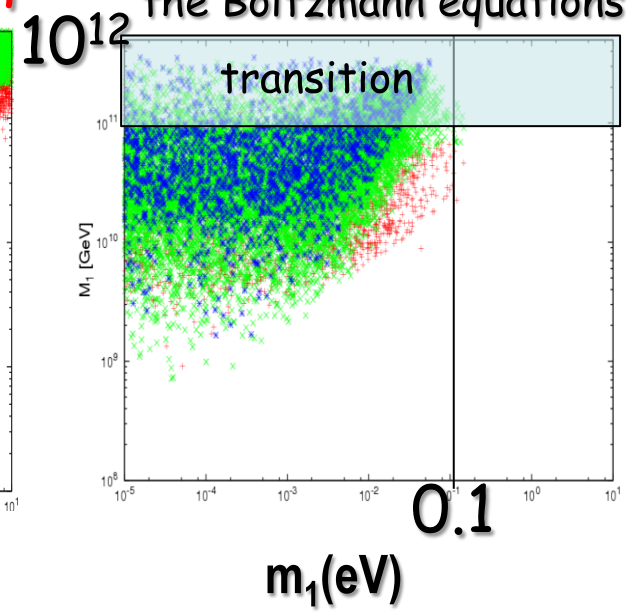
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)

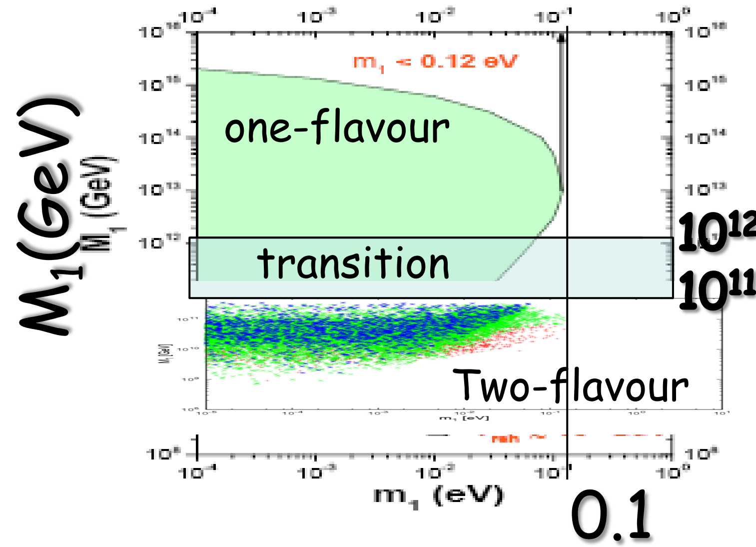


PMNS phases off



Imposing the validity of the Boltzmann equations





Low energy phases can be the only source of CP violation

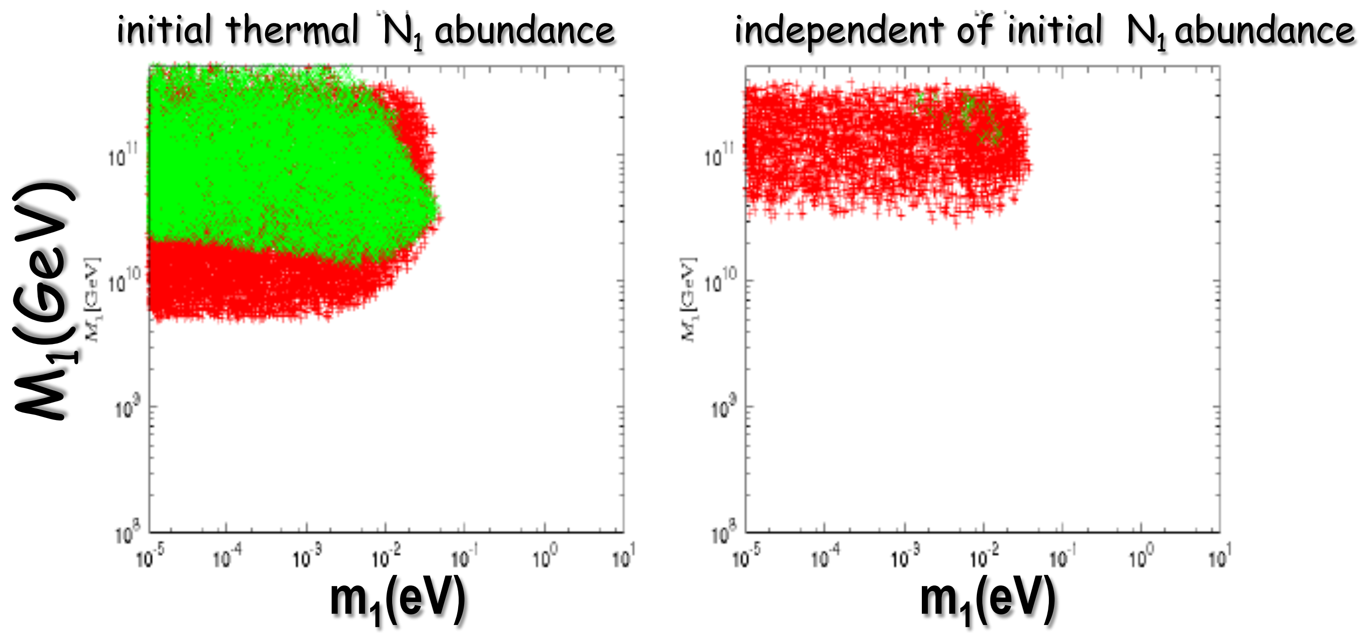
(Nardi et al.'06;Blanchet,PDB'06;Pascoli,Petcov,Riotto '06;Anisimov,Blanchet,PDB '08)

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

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

- 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)



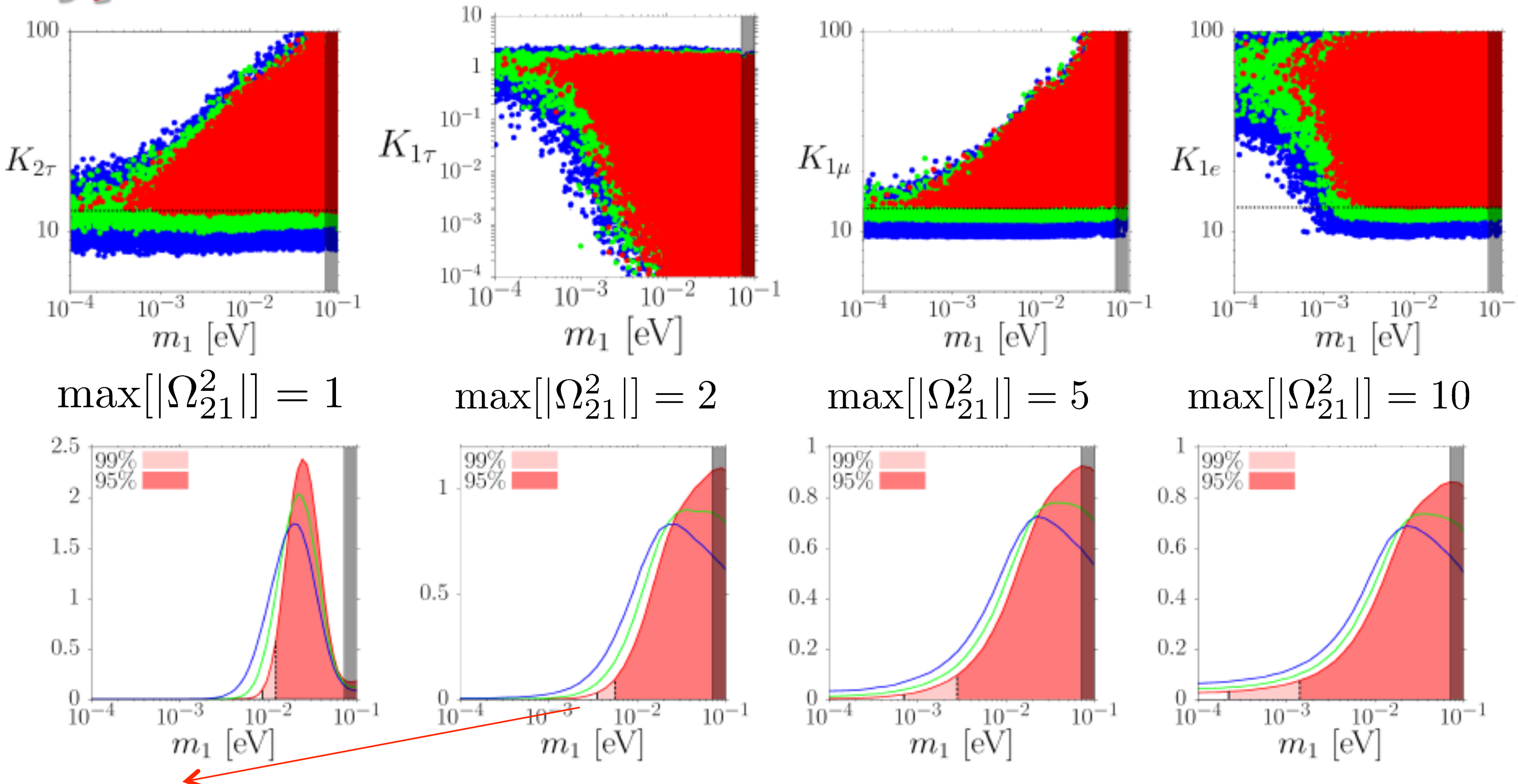
Green points: only Dirac phase with $\sin\theta_{13} = 0.2$, $|\sin\delta| = 1$

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

A lower bound on neutrino masses (IO)

$N^{P,i}_{B-L}$ = 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)