NNN15/UD2 2015
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LEPTOGENESIS
and
NEUTRINO PARAMETERS

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

- *Cosmological Puzzles :*
  1. Dark matter
  2. Matter - antimatter asymmetry → $\eta_B \simeq 6.1 \times 10^{-10}$
  3. Inflation
  4. Accelerating Universe
- *New stage in early Universe history :*

T

- T_{RH}?? — Inflation
- ↕ 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 underlying the seesaw

Neutrino masses and mixing parameters

PMNS matrix

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

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

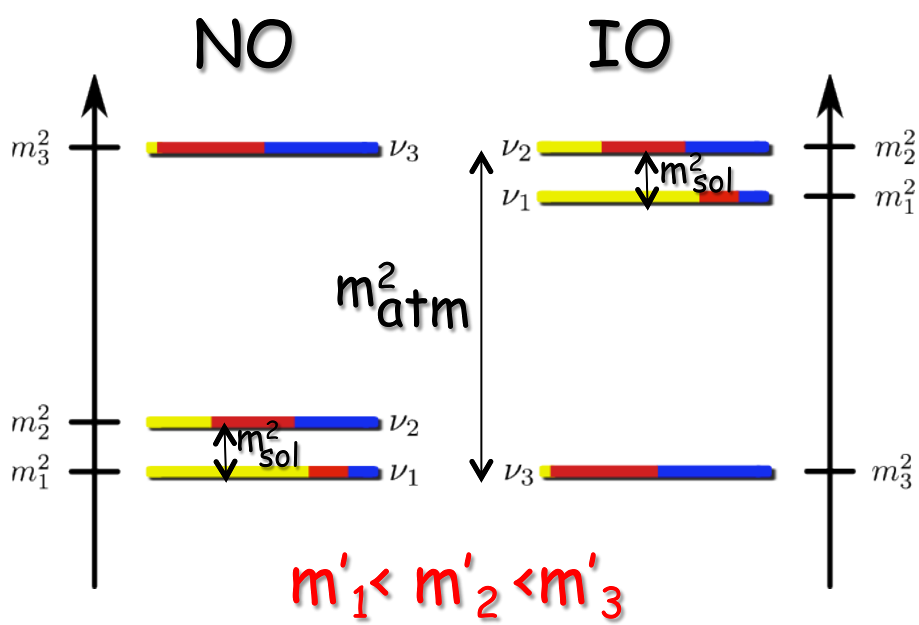
<u>3σ ranges:</u> (NuFIT 2014)

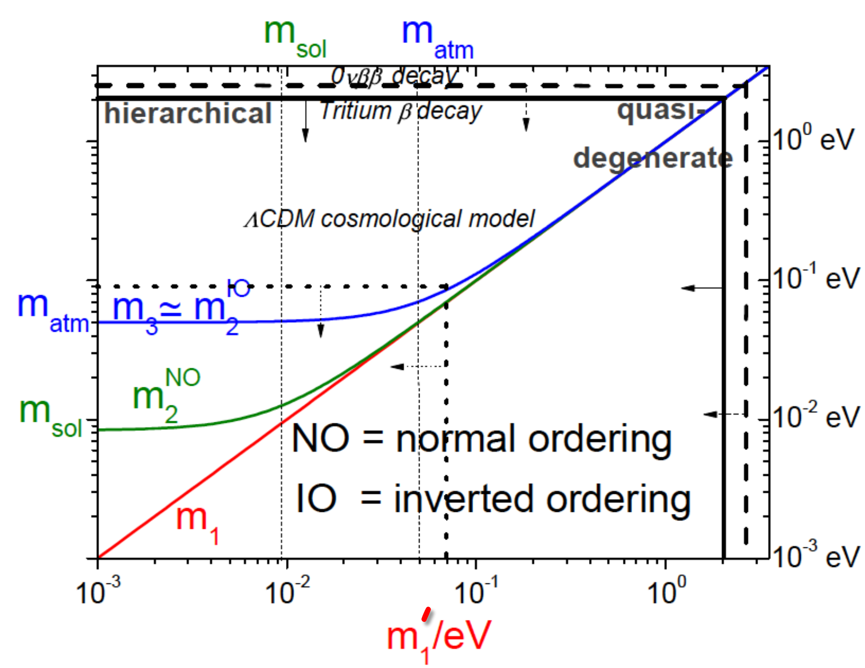
$\theta_{23} \simeq 38^\circ - 53^\circ$ atmospheric mixing angle

$\theta_{12} \simeq 31^\circ - 36^\circ$ solar mixing angle

$\theta_{13} \simeq 7.8^\circ - 9.1^\circ$ reactor mixing angle

$\delta, \rho, \sigma = [-\pi, \pi]$ Dirac and Majorana phases





Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

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

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

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

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

• Thermal production of RH neutrinos

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

(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) $m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \Omega^T \Omega = I$ 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 the flavour basis where charged lepton and Majorana mass matrices are diagonal)

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

Different solutions:

- $\eta_B = \eta_B^{CMB}$ is satisfied only around "peaks"
- some parameters cancel in the asymmetry calculation
- imposing independence of the initial conditions ("strong thermal leptog.")
- theoretical input on m_D
- additional phenomenological constraints (e.g. DM, Inflation, LFV, EDM's,....)

Vanilla leptogenesis

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

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

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 ($M_2 \gtrsim 2M_1$)

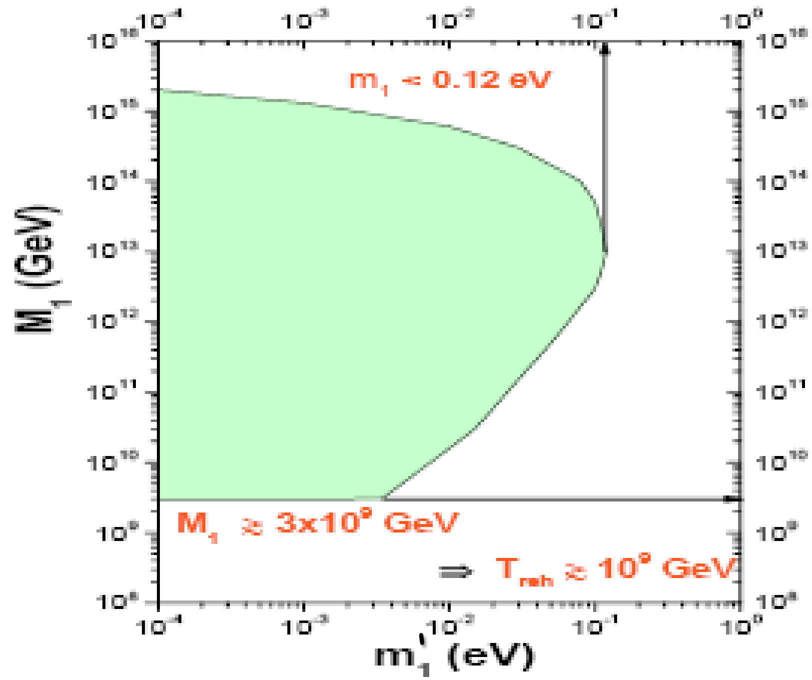
3) Strong lightest RH neutrino wash-out

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

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: it cancels out!

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

Independence of the initial conditions

(Buchmüller, PDB, Plümacher '04)

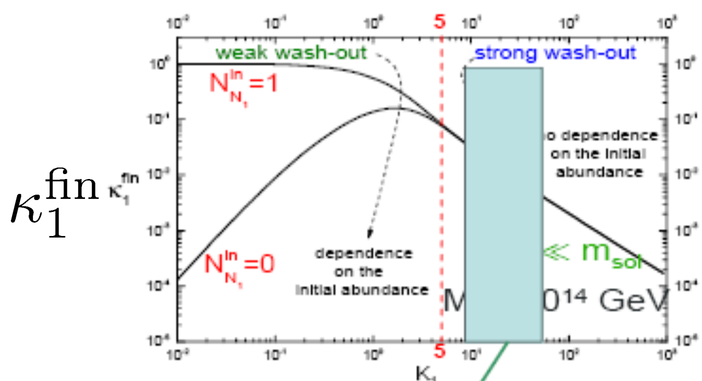
wash-out of a pre-existing asymmetry N_{B-L}^{p}

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

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

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

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

$$D_{m_D} = \mathrm{diag}\{m_{D1}, m_{D2}, m_{D3}\}$$

From the seesaw formula one can express (more details later on):

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

SO(10) inspired conditions*:

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

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

Barring fine-tuned 'crossing level' solutions:

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

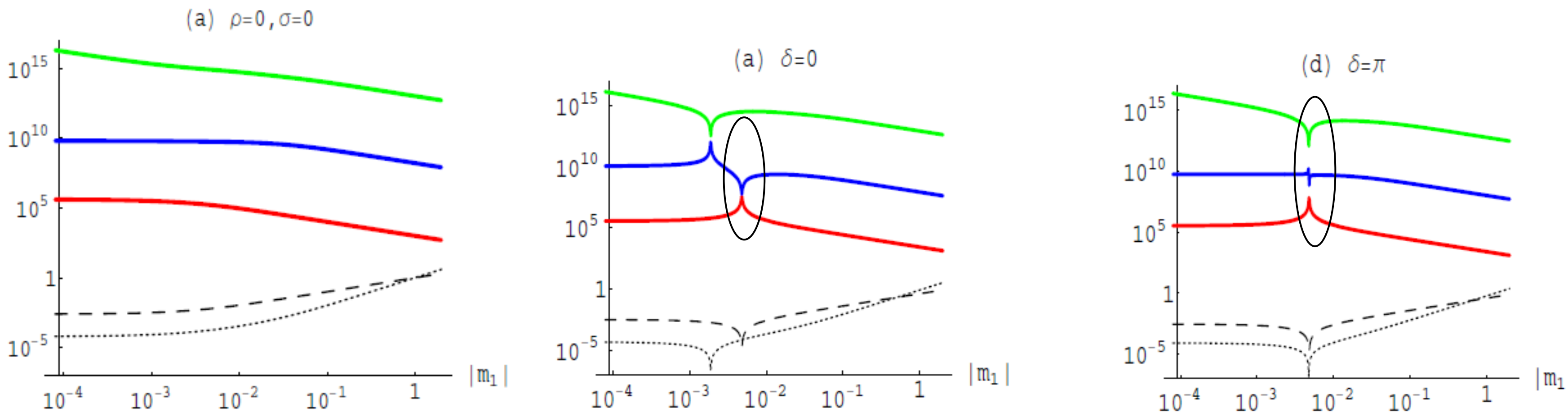
since $M_1 \ll 10^9$ GeV $\Rightarrow \eta_B^{(N1)} \ll \eta_B^{CMB}$

* Note that SO(10)-inspired conditions can be realized beyond SO(10) and even beyond GUT models. The possibility of type II seesaw is neglected.

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:

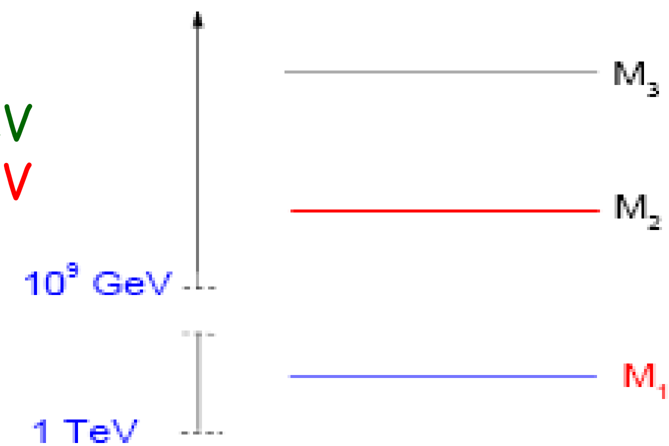
$$N_{B-L}^{\rm f,N_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1} = \varepsilon_1\, \kappa(K_1)$$

...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 $M_2 \gtrsim 4\times10^{10}$ GeV still implying a lower bound $T_{reh} \gtrsim 8\times10^{9}$ GeV

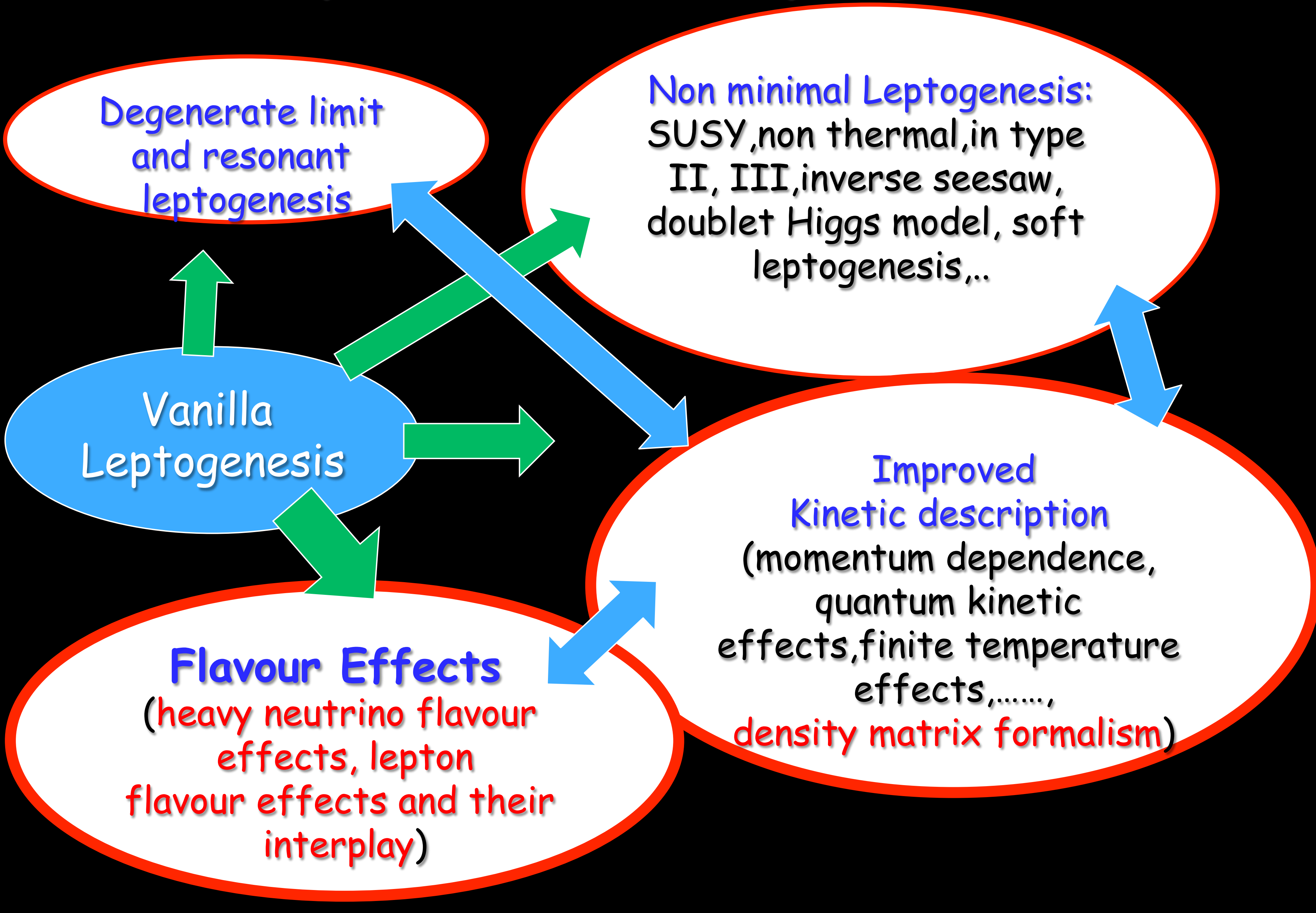


- How special is having $K_1 \lesssim 1$?
  $P(K_1 \lesssim 1) \simeq 0.2\%$ (random scan)

- 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 minimal leptogenesis:

Usually 2 motivations:

- Avoiding the reheating temperature lower bound
- In order to get new phenomenological tests….the most typical motivation in this respect is to be able to test the seesaw and leptogenesis at the LHC and/or in LFV processes, ED moments, n-$\bar{n}$-oscillations ⇒ "TeV Leptogenesis"

(talk yesterday by Rabi Mohapatra)

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

- **No new physics at the LHC (not so far, maybe soon?);**
- **Discovery of a non-vanishing reactor angle opened the door to completing leptonic mixing matrix parameters measurement;**
- **Cosmological observations start to have the sensitivity to measure neutrino mass absolute scale (talk by Yvonne Wong) and huge world efforts in improving $0\nu\beta\beta$ sensitivity and by KATRIN in kinematic direct measuerements.**

(charged) lepton flavour effects

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

<u>**Flavor composition of lepton quantum states is important !**</u>

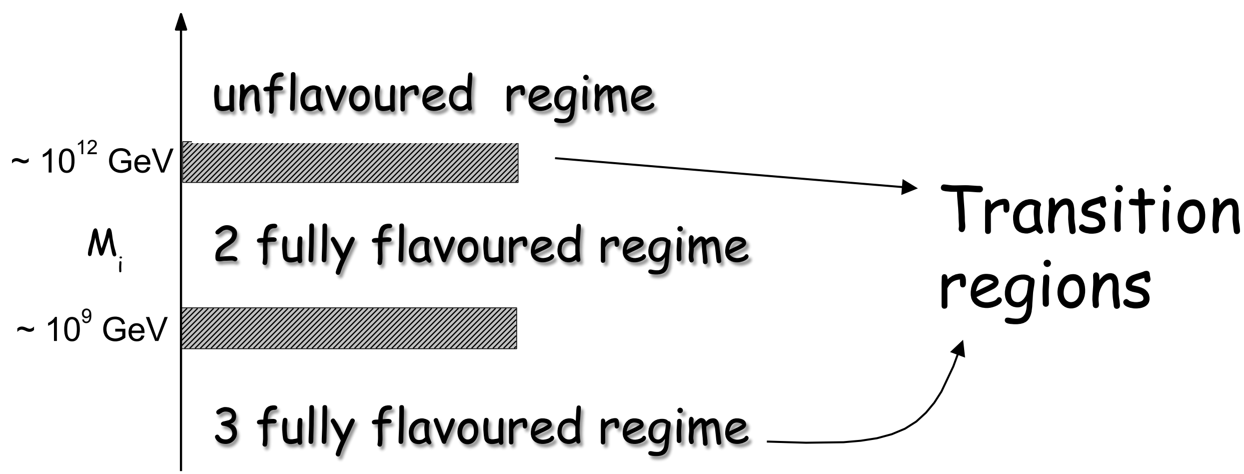
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1 \rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau) \qquad\qquad P_{1\alpha} \equiv |\langle \ell_1 | \alpha \rangle|^2$$

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

For $M_1 \lesssim 5\times10^{11}$ 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 e+μ component

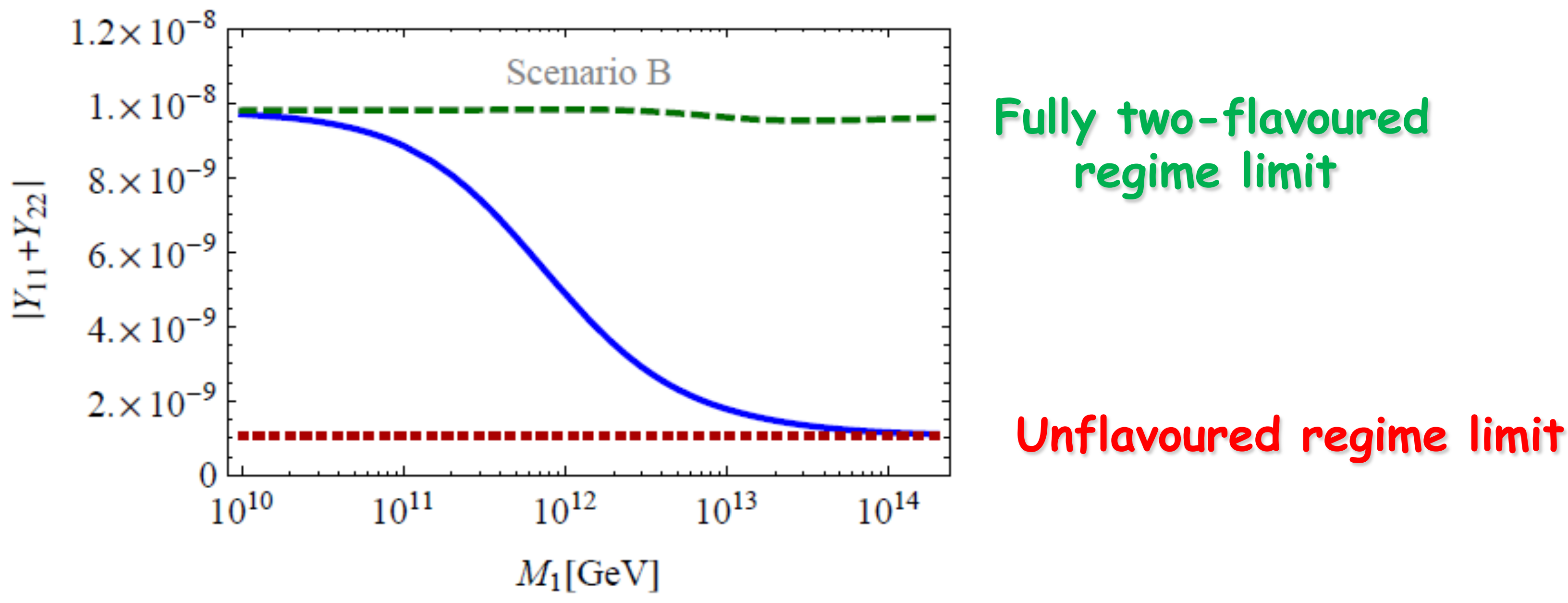
For $M_1 \lesssim 10^9$ GeV then also μ- Yukawas in equilibrium ⇒ 3-flavor regime



Density matrix and CTP formalism to describe the transition regimes

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

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



Two fully flavoured regime

- Classic Kinetic Equations (in their simplest form)

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

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

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

(α = τ, e+μ)

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

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

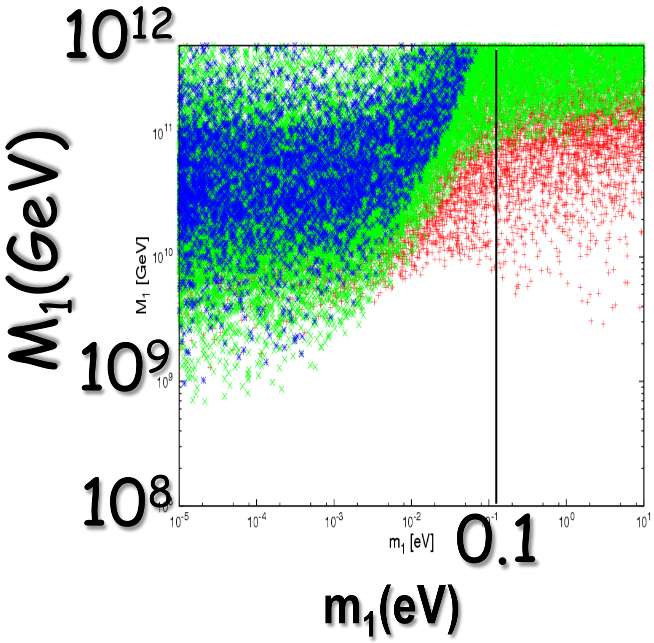
$$\Rightarrow\quad \boxed{\varepsilon_{1\alpha} \equiv -\frac{P_{1\alpha}\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = P^0_{1\alpha}\,\varepsilon_1 + \Delta P_{1\alpha}(\Omega, U)/2}$$

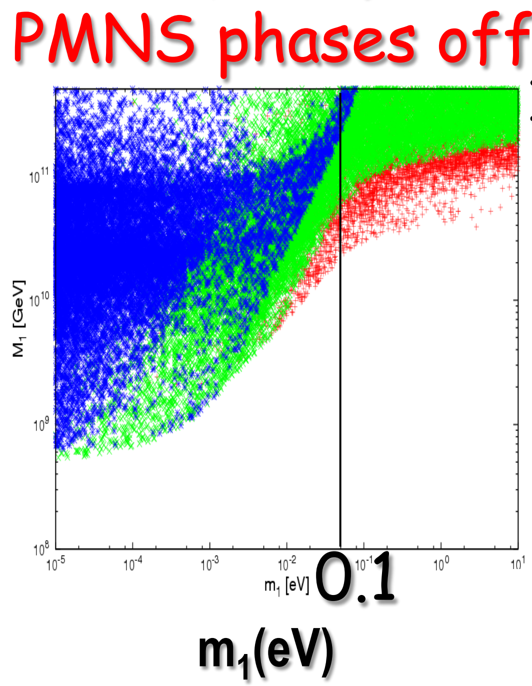
$$\Rightarrow N^{\rm fin}_{B-L} = \sum_\alpha \varepsilon_{1\alpha}\,\kappa^{\rm fin}_{1\alpha} \simeq 2\,\varepsilon_1\,\kappa^{\rm fin}_1 + \frac{\Delta P_{1\alpha}}{2}\left[\kappa^{\rm f}(K_{1\alpha}) - \kappa^{\rm fin}(K_{1\beta})\right]$$

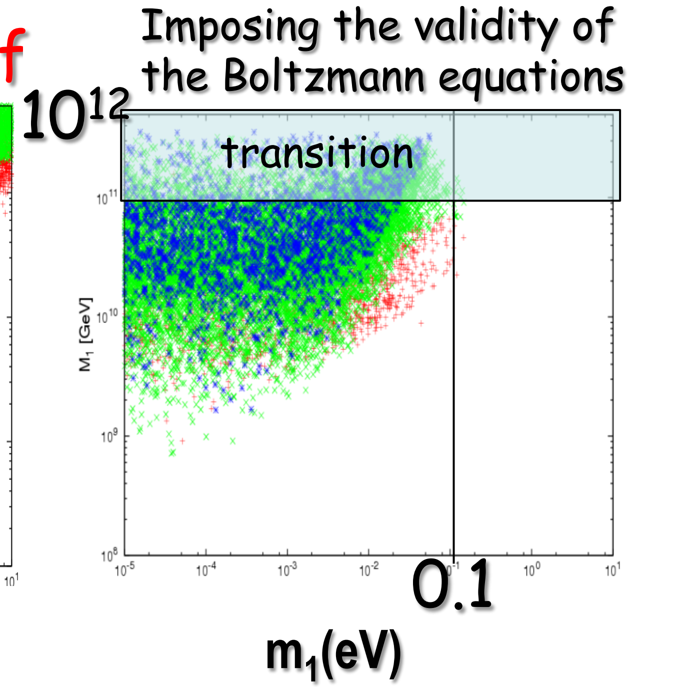
Flavoured decay parameters: $K_{i\alpha} \equiv P^0_{i\alpha}\,K_i = \left|\sum_k \sqrt{\frac{m_k}{m_\star}}\,U_{\alpha k}\,\Omega_{ki}\right|^2$

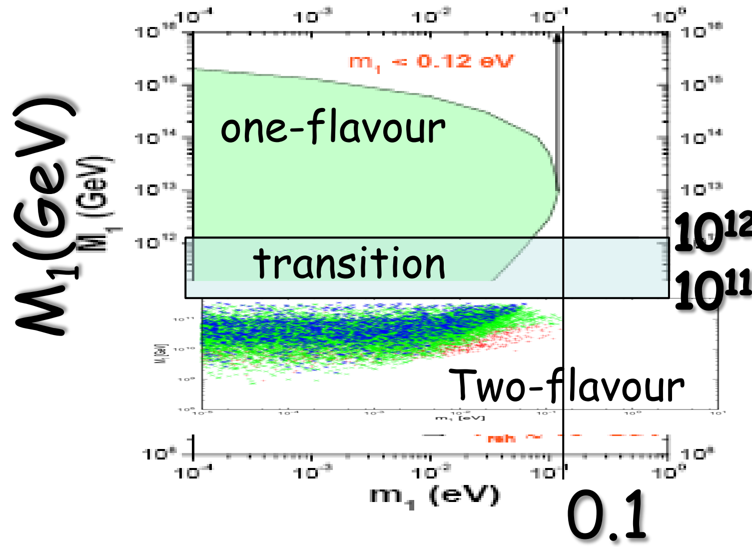
Neutrino mass bounds and role of PMNS phases

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







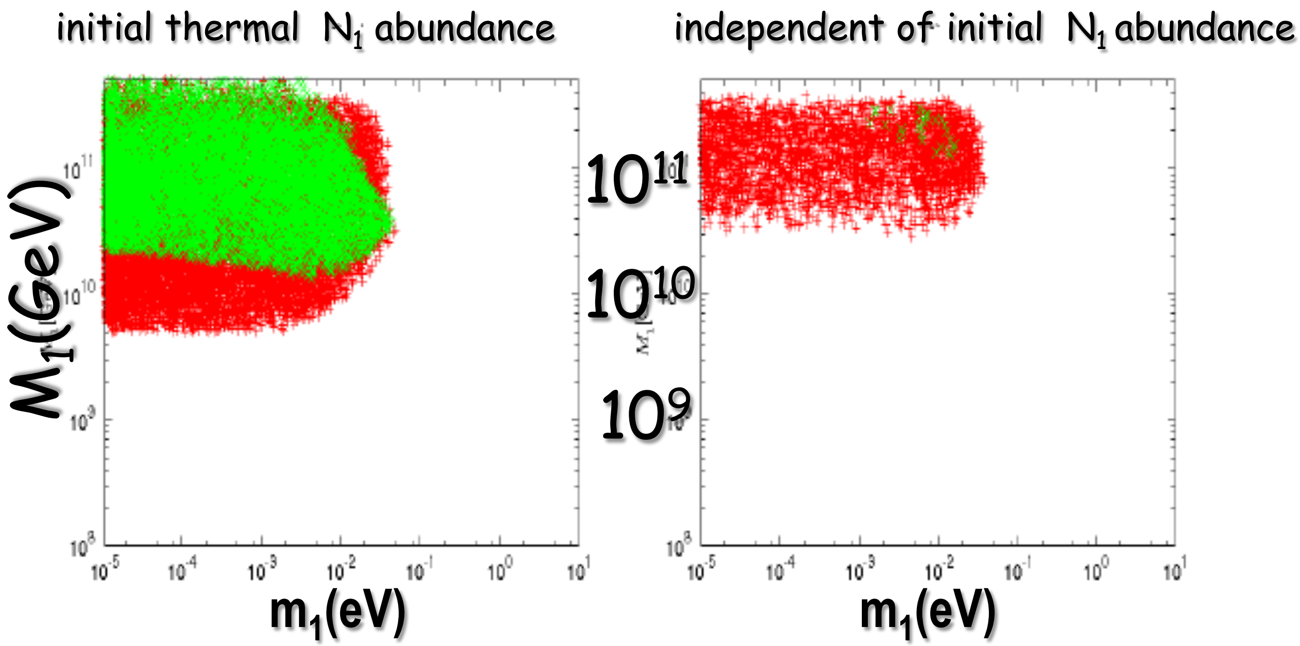


Can the Dirac phase be the only source of CP violation?

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

- Assume real $\Omega \Rightarrow \varepsilon_1 = 0 \Rightarrow N_{B-L}^{fin} \Rightarrow \cancel{2\varepsilon_1 \kappa_1^{fin}} + \Delta P_{1\alpha}(\kappa_{1\alpha}^{fin} - \kappa_{1\beta}^{fin})$ $(\alpha = \tau, e+\mu)$
- Assume even vanishing Majorana phases

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



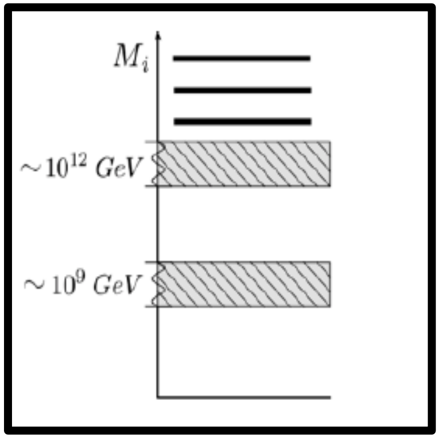
Green points: only Dirac phase with $\sin\theta_{13} = 0.2$ $|\sin\delta| = 1$

Red points: only Majorana phases

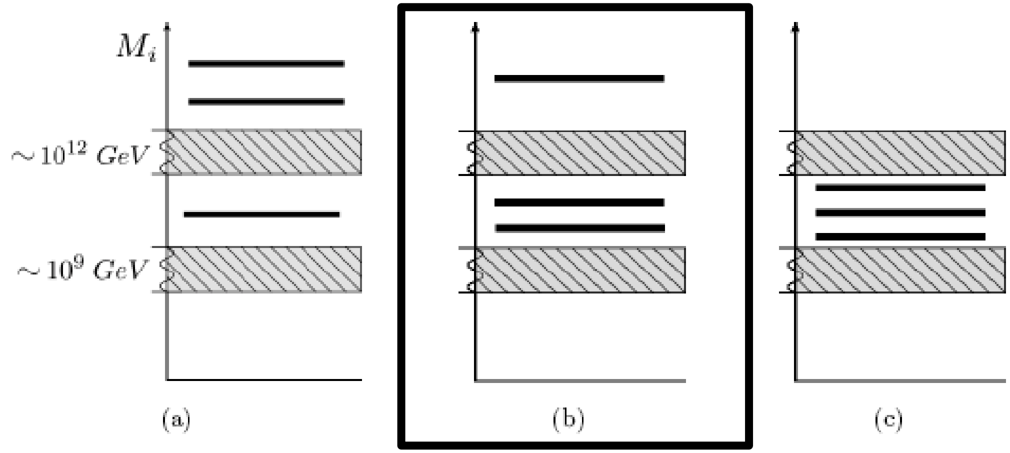
- No reasons for these assumptions to be rigorously satisfied in general this contribution is *overwhelmed* by the high energy phases they could be approximately satisfied in specific scenarios for some regions
- A calculation using full density matrix equation is necessary to confirm!
- DISCOVERY OF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

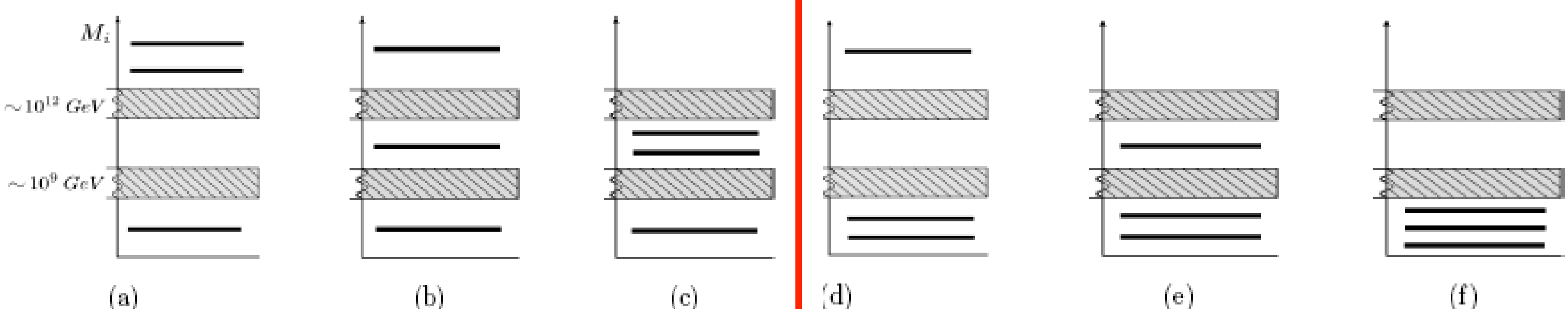
Heavy neutrino lepton flavour effects

Heavy neutrino flavored scenario



2 RH neutrino scenario





N_2 -dominated scenario:
the lightest RH neutrino produces negligible asymmetry

The flavoured N_2-dominated scenario

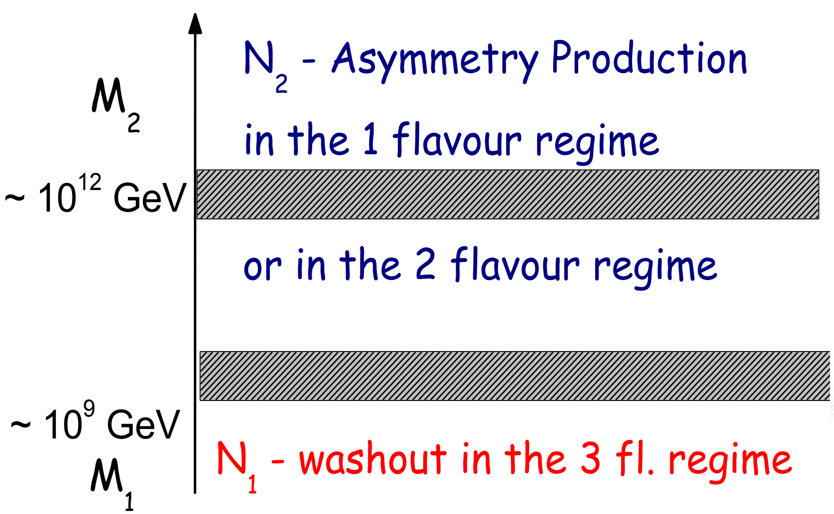
(Vives '05; Blanchet, PDB '06; Blanchet, PDB '08; PDB, Fiorentin '14)

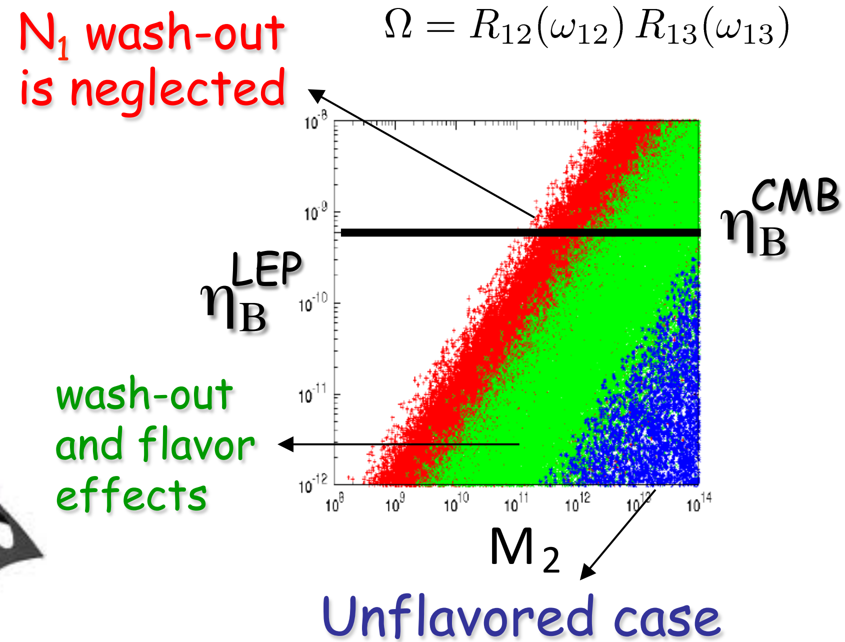
Flavour effects strongly enhance the importance of the N_2-dominated scenario

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

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

A two stage process:





- $K_1 = K_{1e} + K_{1\mu} + K_{1\tau}$; $P(K_1 \lesssim 1) \sim 0.2\%$; $P(K_{1e} \lesssim 1) \sim 2\,P(K_{1\mu,\tau} \lesssim 1) \sim 15\%$ $\Rightarrow \Sigma_\alpha\, P(K_{1\alpha} \lesssim 1) = 30\%$
- 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**

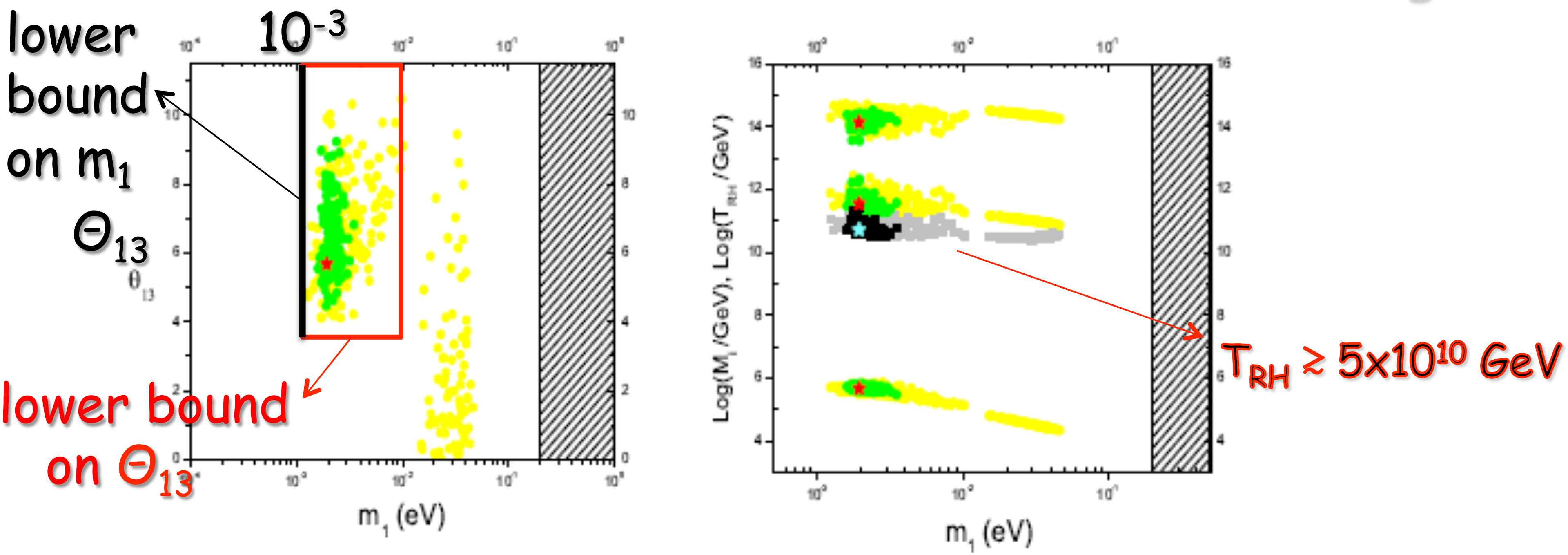
The N_2-dominated scenario rescues SO(10) inspired models

(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



- The solutions are exclusively tauon dominated ($V_L=I$)

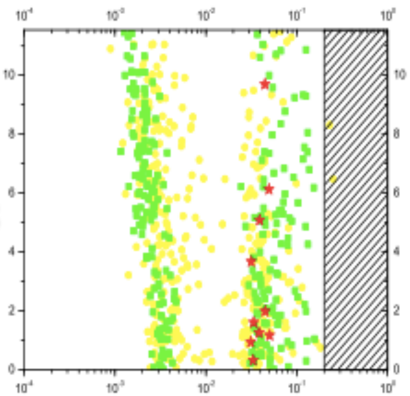
Testing SO(10)-inspired leptogenesis with low energy neutrino data

(PDB, Riotto '10)

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

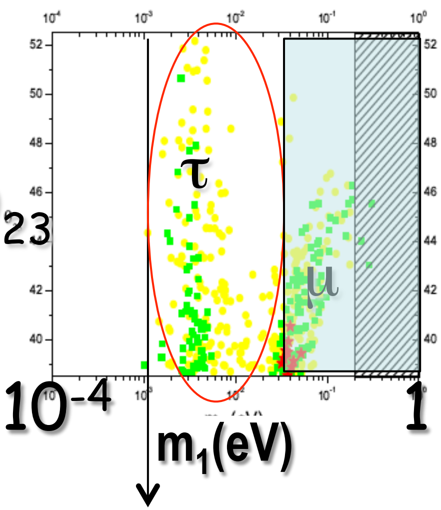
$\alpha_2=5$ $\alpha_2=4$ $\alpha_2=1$ NORMAL ORDERING

Θ_{13}



m_1(eV)

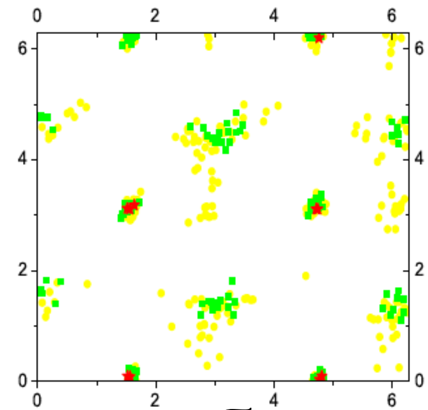
Θ_{23}



m_1(eV)

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

ρ



σ

- Majorana phases constrained about specific values

- The lower bound on θ_{13} at low m_1 disappears
- Muon solutions appear at high m_1 : strongly constrained by Planck
- Marginal allowed regions for INVERTED ORDERING

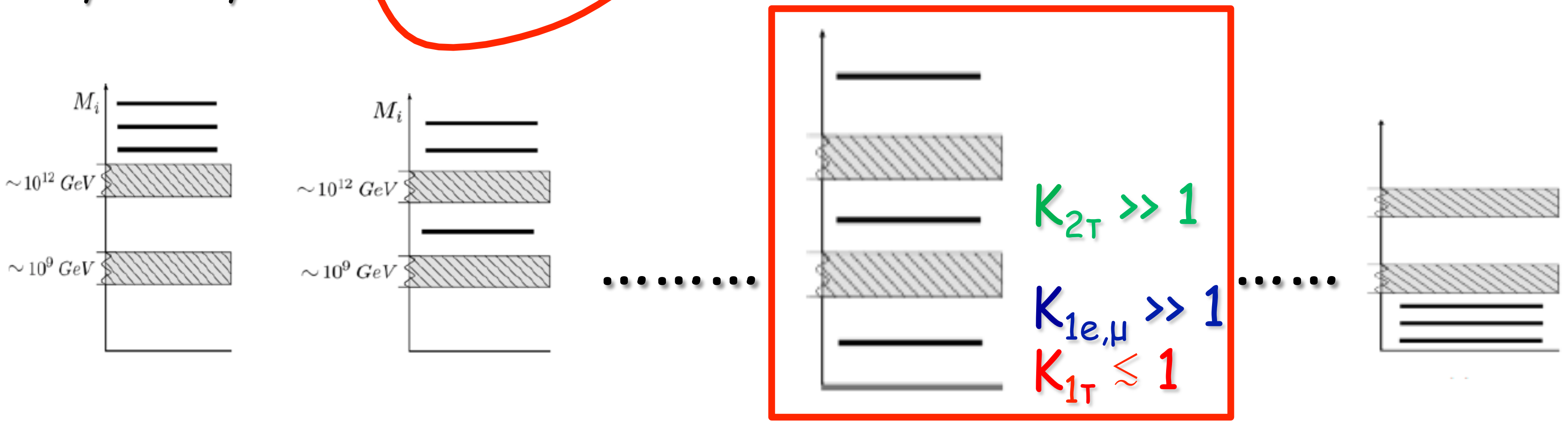
The problem of the initial conditions in flavoured leptogenesis

(Bertuzzo,PDB,Marzola '10)

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

Relic "pre-existing" asymmetry

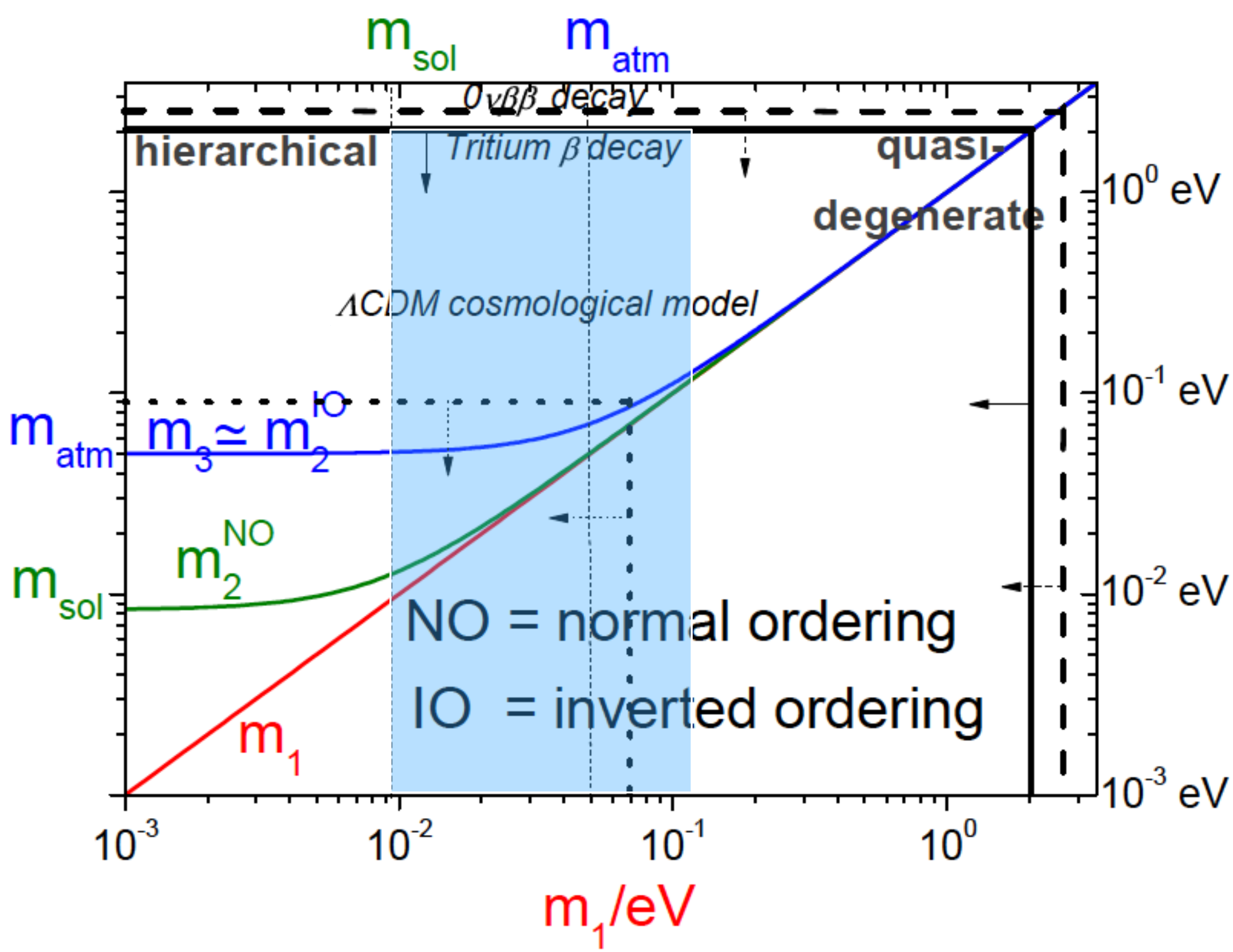
Asymmetry generated from leptogenesis



The conditions for the wash-out of a pre-existing asymmetry, **'strong thermal 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)



$0.01\ \text{eV} \lesssim m_1 \lesssim 0.1\ \text{eV}$ (for NO)

Strong thermal SO(10)-inspired solution

(PDB, Marzola '11; '13; PDB, Fiorentin, Marzola '14)

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

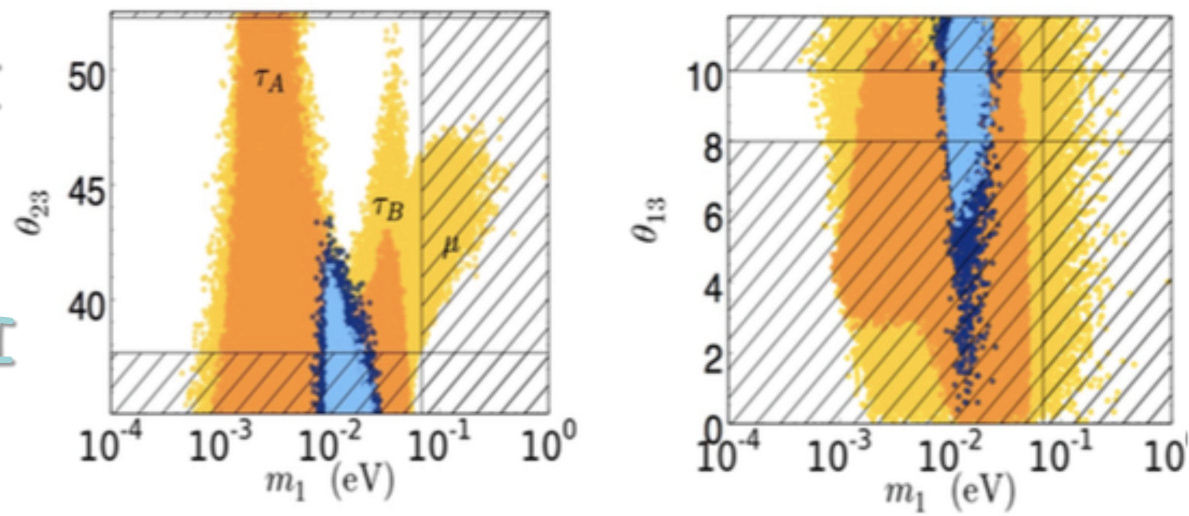
$\alpha_2=5$

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

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

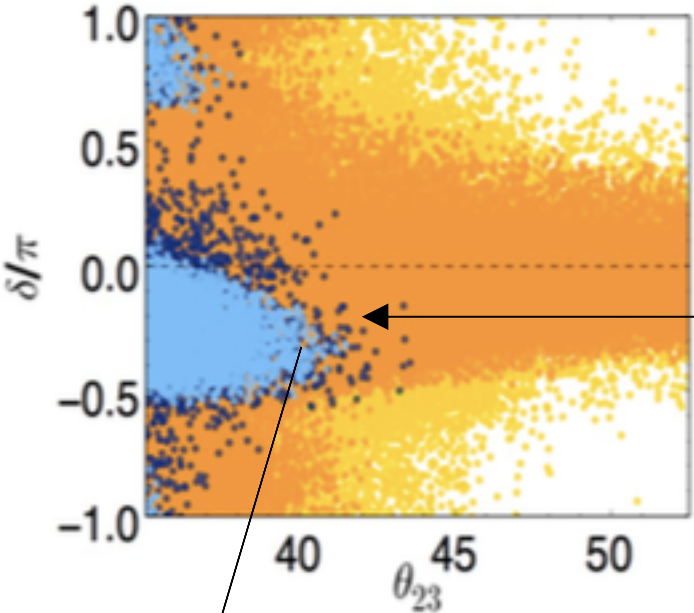
$N^{P,i}_{B-L}=0.001$

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



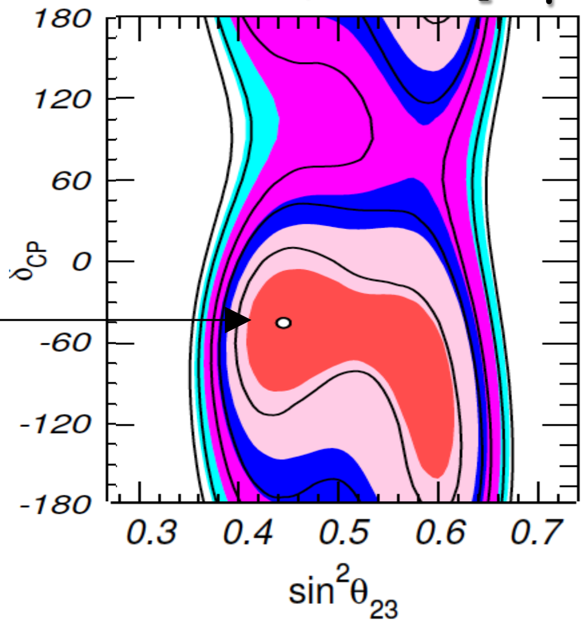
- The lightest neutrino mass respects the general lower bound but is also upper bounded $\Rightarrow$ $15 \lesssim m_1 \lesssim 25$ meV;
- The reactor mixing angle has to be non-vanishing (preliminary results presented before Daya Bay discovery);
- The atmospheric mixing angle falls strictly in the first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

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]



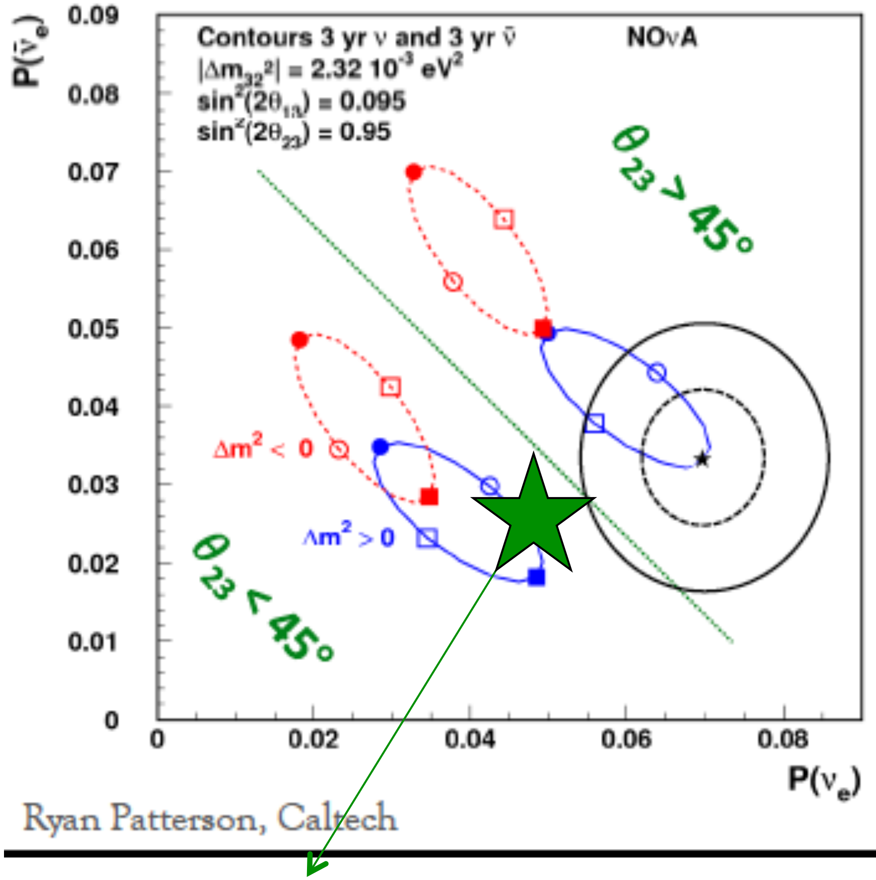
http://www.nu-fit.org/sites/default/files/v12.fig-dlthie-glob.pdf

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 at NOνA

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



Ryan Patterson, Caltech

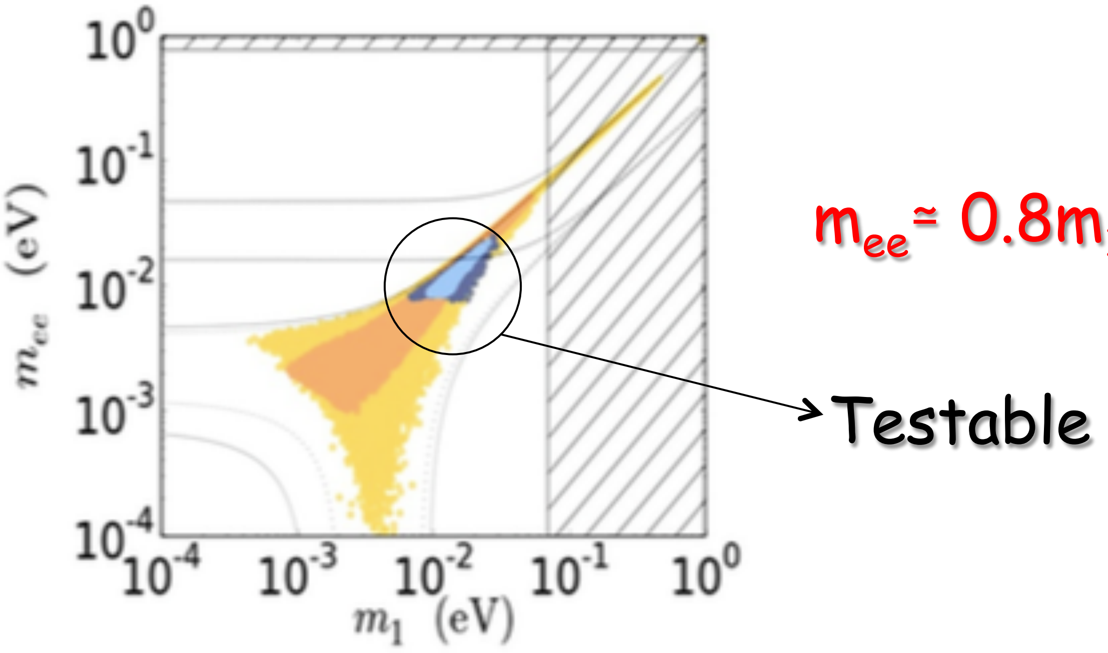
Strong thermal SO(10)-inspired solution

The ultimate test: 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}

$\alpha_2=5$



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

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

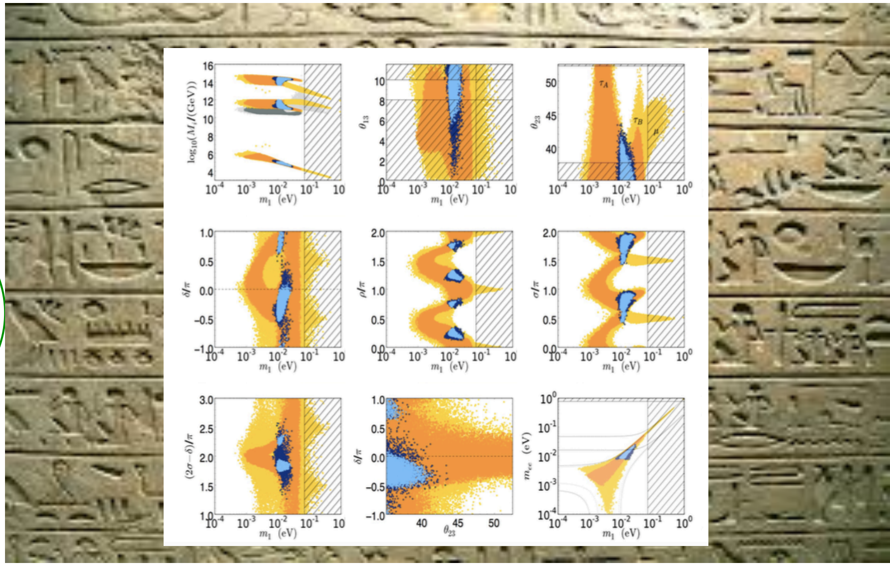
(PDB, Fiorentin, Marzola, 2015)

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

?

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

Strong thermal SO(10)-inspired solution



Imposing SO(10)-inspired conditions

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

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

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

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

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

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

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

0ν2β neutrino mass

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

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

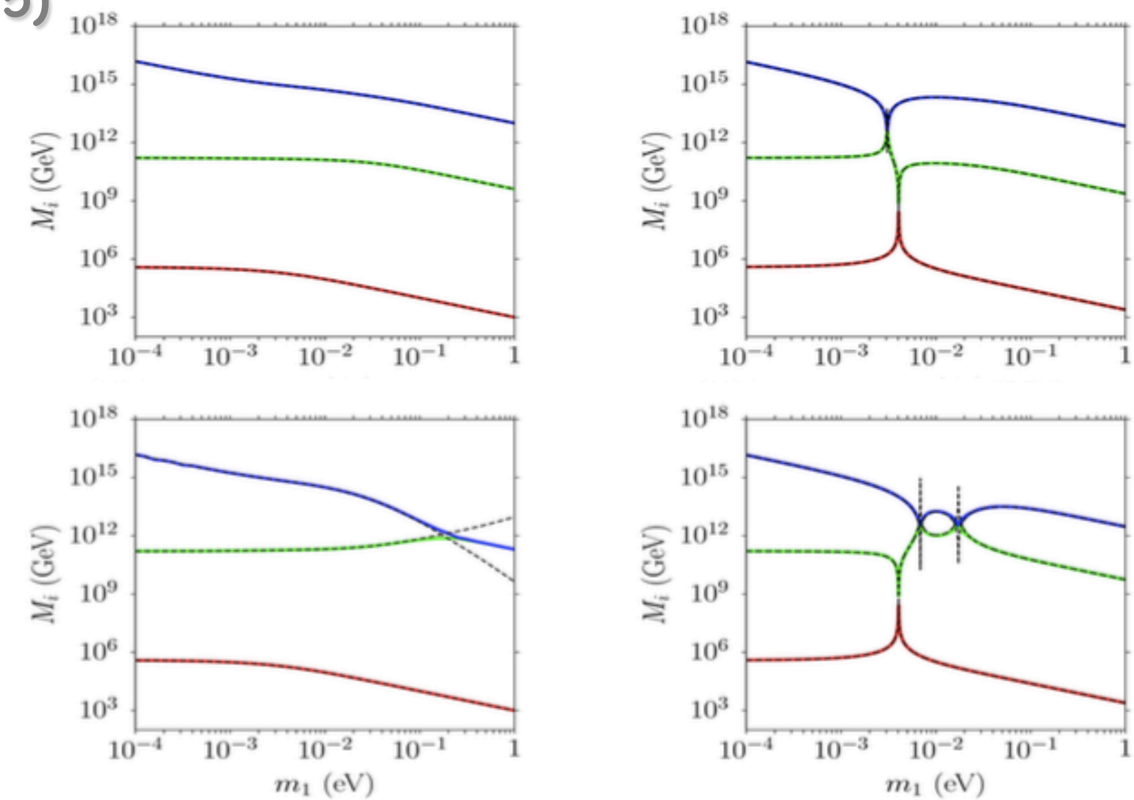
$$M_3 \simeq \alpha_3^2\, m_t^2\, |(m_\nu^{-1})_{\tau\tau}| \simeq \alpha_3^2\, 10^{15}\ \mathrm{GeV}\left(\frac{m_t}{100\mathrm{GeV}}\right)^2\left(\frac{\mathrm{meV}}{m_1}\right)\,.$$

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

RH neutrino masses: analytical vs. num.

(PDB, Fiorentin, Marzola, 2015)

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 $m_{ee} \lll 10$ meV: crossing level solutions typically imply no $0\nu2\beta$ observation! (but this holds for $V_L = I$)

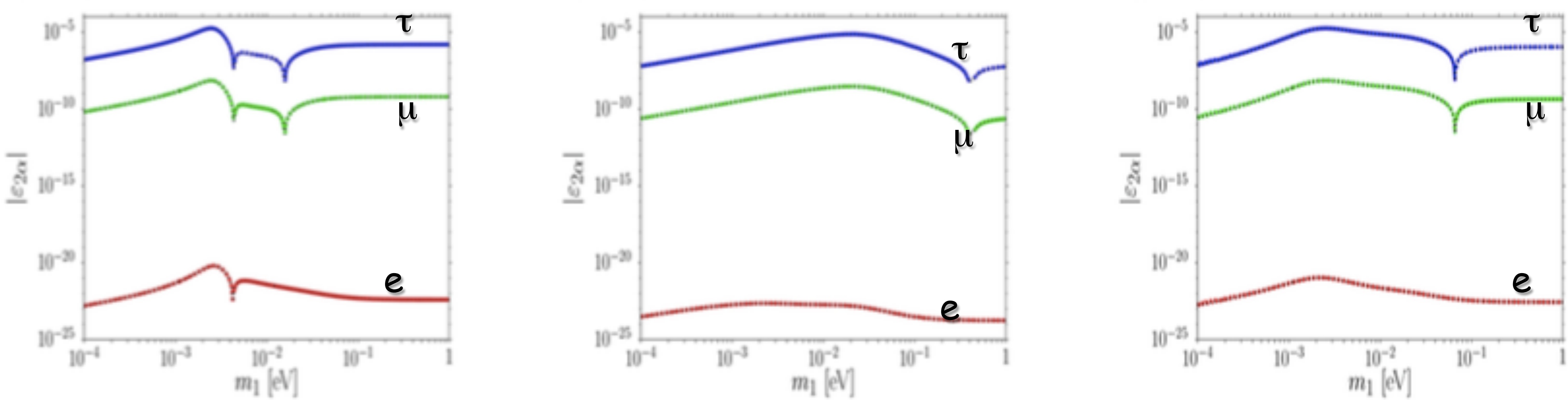
A formula for the final asymmetry for $V_L = I$

CP asymmetries are also reproduced analytically:

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

and this well explains the tau-dominance:

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



Comparison between numerical solutions (solid) and analytical solutions (dashed) :
They reproduce the numerical results so well that they perfectly overlap

A formula for the final asymmetry

(PDB, Fiorentin, Marzola, 2015)

Finally, putting all together, one arrives to an expression for the final asymmetry:

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

Effective (SO10-inspired) leptogenesis phase

$$\alpha_L = {\rm Arg}\,[m_{\nu ee}] - 2\,{\rm Arg}[(m_\nu^{-1})_{\mu\tau}] + \pi - 2\,(\rho+\sigma)\,.$$

<u>This analytical expression for the asymmetry fully reproduces all numerical constraints for V_L=I</u>

These results can be easily generalised to the case $V_L \neq 1$: all given expressions are still valid with the replacement: (Akhmedov, Frigerio, Smirnov, 2005; PDB, King 2015)

$$m_\nu \rightarrow \widetilde{m}_\nu \equiv \widetilde{V}_L\,m_\nu\,\widetilde{V}_L^T$$

An example:leptogenesis in the "A2Z model"

(S.King 2014)

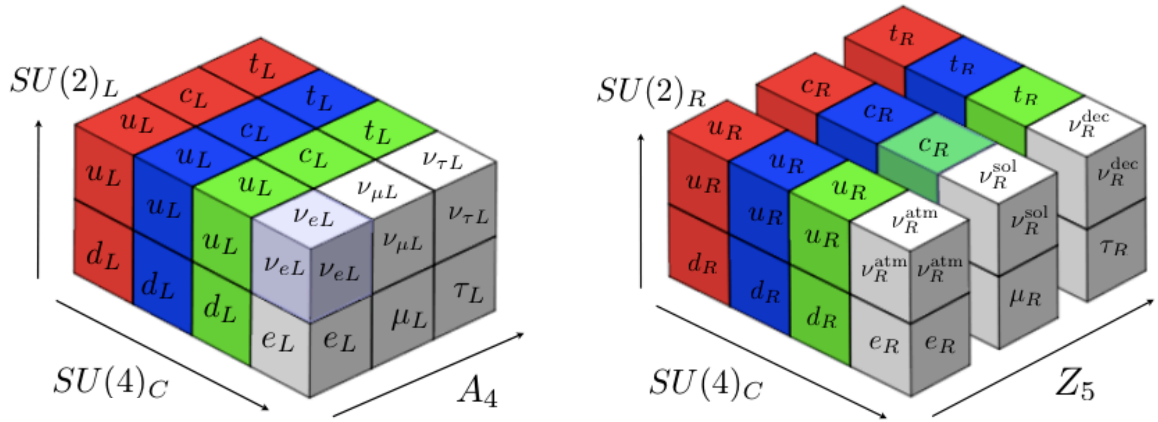


Figure 1: A to Z of flavour with Pati-Salam, where $A \equiv A_4$ and $Z \equiv Z_5$. The left-handed families form a triplet of A_4 and are doublets of $SU(2)_L$. The right-handed families are distinguished by Z_5 and are doublets of $SU(2)_R$. The $SU(4)_C$ unifies the quarks and leptons with leptons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

Neutrino sector:

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

CASE A:

$$m^D_{\nu 1} = m_{\rm up}, \quad m^D_{\nu 2} = m_{\rm charm}, \quad m^D_{\nu 3} = m_{\rm top}$$

CASE B:

$$m^D_{\nu 1} \approx m_{\rm up}, \quad m^D_{\nu 2} \approx 3\, m_{\rm charm}, \quad m^D_{\nu 3} \approx \frac{1}{3}\, m_{\rm top}$$

Leptogenesis in the "A2Z model"

(PDB, S.King 2015)

The only sizeable CP asymmetry is the tauon asymmetry but $K_{1\tau} \gg 1$!

Flavour coupling (mainly due to the hypercharge Higgs asymmetry) 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 are 2 solutions (only for NO)

(PDB, S.King 2015)

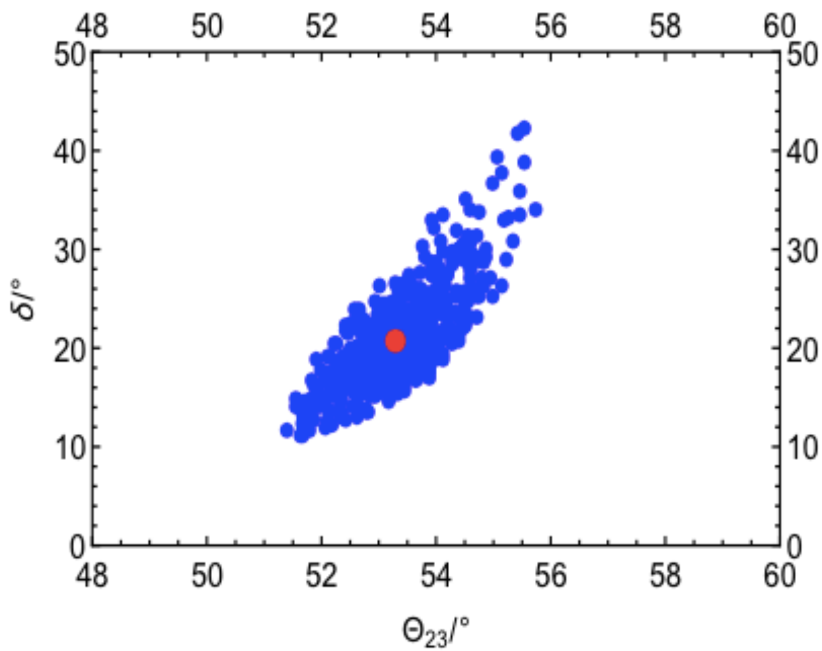
CASE	A	B
ξ	$+4\pi/5$	
$\chi^2_{\rm min}$	5.15	6.1
$M_1/10^7$GeV	15	2.7
$M_2/10^{10}$GeV	0.483	4.35
$M_3/10^{12}$ GeV	2.16	1.31
$\lvert\gamma\rvert$	203	38
m_1/meV	2.3	2.3
m_2/meV ($p_{\Delta m^2_{12}}$)	8.93 (-0.22)	8.94 (-0.25)
m_3/meV ($p_{\Delta m^2_{13}}$)	49.7 (+0.17)	49.7 (+0.21)
$\sum_i m_i$/meV	61	61
m_{ee}/meV	1.95	1.95
$\theta_{12}/^\circ$ ($p_{\theta_{12}}$)	33.0 (-0.58)	33.0 (-0.66)
$\theta_{13}/^\circ$ ($p_{\theta_{13}}$)	8.40 (-0.47)	8.40 (-0.49)
$\theta_{23}/^\circ$ ($p_{\theta_{23}}$)	53.3 (+2.1)	54.0 (+2.3)
$\delta/^\circ$	20.8	23.5
$\eta_B/10^{-10}$ (p_{η_B})	6.101 (+0.01)	6.101 (+0.01)
$\varepsilon_{2\tau}$	-8.1×10^{-6}	-1.3×10^{-5}
$K_{1\mu}$	0.11	0.58
$K_{1\tau}$	4341	800
$K_{2\tau}$	7.3	7.3
$K_{2\mu}$	29.2	29.2
K_{2e}	1.8	1.8

There are 2 solutions (only for NO)

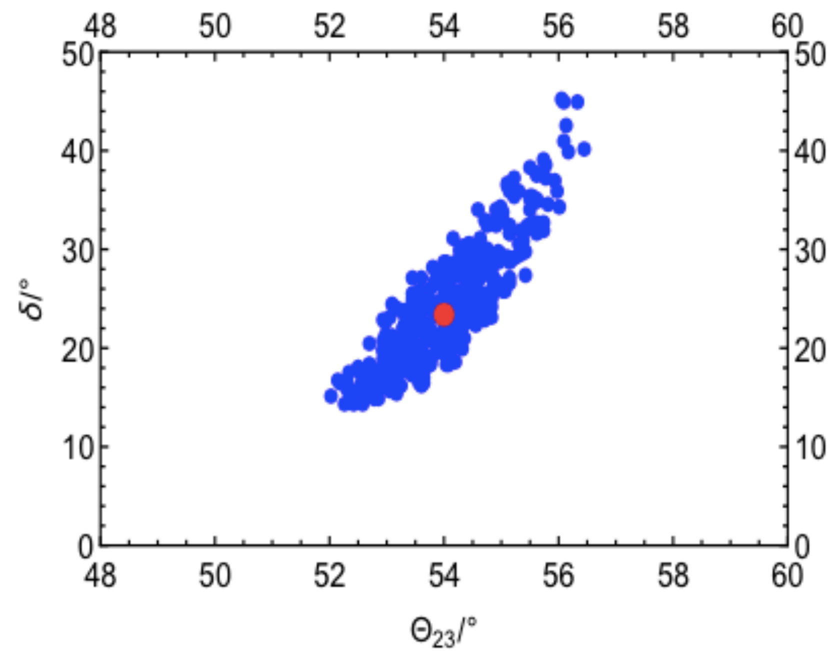
(PDB, S.King 2015)

$\chi^2 < 10$

CASE A



CASE B



These results will be tested quite quickly !

Quantifying fine-tuning in SO(10)-inspired models

(PDB, S.King 2015)

Analytical expression also for the orthogonal matrix:

$$\Omega \simeq \begin{pmatrix} -\frac{\sqrt{m_1\,|\widetilde{m}_{\nu 11}|}}{\widetilde{m}_{\nu 11}}\,U_{e1} & \sqrt{\frac{m_2\,m_3\,|(\widetilde{m}_\nu^{-1})_{33}|}{|\widetilde{m}_{\nu 11}|}}\left(U^\star_{\mu 1}-U^\star_{\tau 1}\,\frac{(\widetilde{m}_\nu^{-1})_{23}}{(\widetilde{m}_\nu^{-1})_{33}}\right) & \frac{U^\star_{31}}{\sqrt{m_1\,|(\widetilde{m}_\nu^{-1})_{33}|}} \\ -\frac{\sqrt{m_2\,|\widetilde{m}_{\nu 11}|}}{\widetilde{m}_{\nu 11}}\,U_{e2} & \sqrt{\frac{m_1\,m_3\,|(\widetilde{m}_\nu^{-1})_{33}|}{|\widetilde{m}_{\nu 11}|}}\left(U^\star_{\mu 2}-U^\star_{\tau 2}\,\frac{(\widetilde{m}_\nu^{-1})_{23}}{(\widetilde{m}_\nu^{-1})_{33}}\right) & \frac{U^\star_{32}}{\sqrt{m_2\,|(\widetilde{m}_\nu^{-1})_{33}|}} \\ -\frac{\sqrt{m_3\,|\widetilde{m}_{\nu 11}|}}{\widetilde{m}_{\nu 11}}\,U_{e3} & \sqrt{\frac{m_1\,m_2\,|(\widetilde{m}_\nu^{-1})_{33}|}{|\widetilde{m}_{\nu 11}|}}\left(U^\star_{\mu 3}-U^\star_{\tau 3}\,\frac{(\widetilde{m}_\nu^{-1})_{23}}{(\widetilde{m}_\nu^{-1})_{33}}\right) & \frac{U^\star_{33}}{\sqrt{m_3\,|(\widetilde{m}_\nu^{-1})_{33}|}} \end{pmatrix} D_\Phi ,$$

$$\Omega^{(\mathrm{CASEA})} \simeq \begin{pmatrix} -4.40016 - 15.9889\,i & 0.0930875 - 0.894045\,i & -16.0396 + 4.38107\,i \\ -15.9446 + 3.40333\,i & -1.15394 + 0.0537137\,i & 3.40494 + 15.9553\,i \\ -3.69174 + 4.35811\,i & 0.709793 + 0.204576\,i & 4.37787 + 3.64191\,i \end{pmatrix}$$

$$\Omega^{(CASEB)} \simeq \begin{pmatrix} -1.77835 - 6.85986\,i & 0.108413 - 0.897431\,i & -6.97828 + 1.73423\,i \\ -6.87598 + 1.34103\,i & -1.15331 + 0.0386159\,i & 1.34278 + 6.90018\,i \\ -1.64314 + 1.81259\,i & 0.710523 + 0.199612\,i & 1.85785 + 1.52677\,i \end{pmatrix}$$

Recent fits within SO(10) models

(Joshipura Patel 2011; Rodejohann, Dueck '13)

Minimal Model with $10_H + \overline{126}_H$ (MN, MS)

"full" Higgs Content $10_H + \overline{126}_H + 120_H$ (FN, FS)

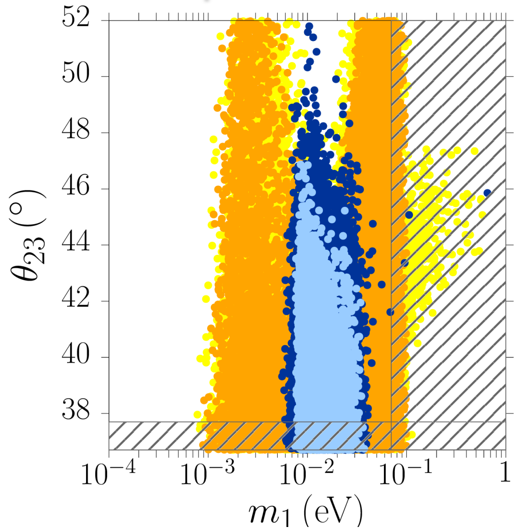
Mod	Comments	$\langle m_\nu \rangle$ [meV]	δ^l_{CP} [rad]	$\sin^2 \theta^l_{23}$	m_0 [meV]	M_3 [GeV]	M_2 [GeV]	M_1 [GeV]	$\chi^2_{\min}$
MN	no RGE, NH	0.35	0.7	0.406	3.03	5.5×10^{12}	7.2×10^{11}	1.5×10^{10}	1.10
MN	RGE, NH	0.49	6.0	0.346	2.40	3.6×10^{12}	2.0×10^{11}	1.2×10^{11}	23.0
MS	no RGE, NH	0.38	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

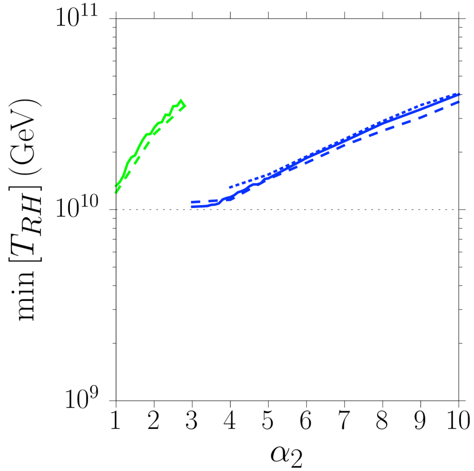
Recently Fong,Meloni,Meroni,Nardi have included leptogenesis for the non SUSY case obtaining that it can give successful leptogenesis (compact RN neutrino spectrum, very small m_{ee}.....huge fine-tuning!).

SUSY SO(10)-inspired leptogenesis

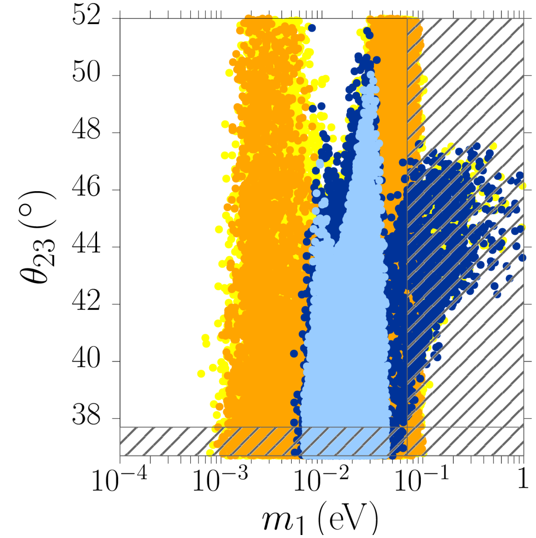
(PDB, Fiorentin, Marzola, preliminary results)

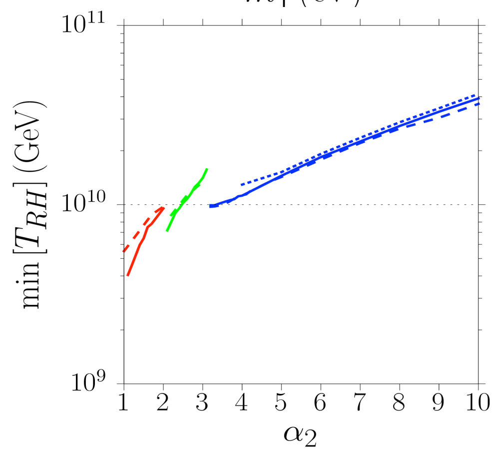
tan β = 5





tan β = 50

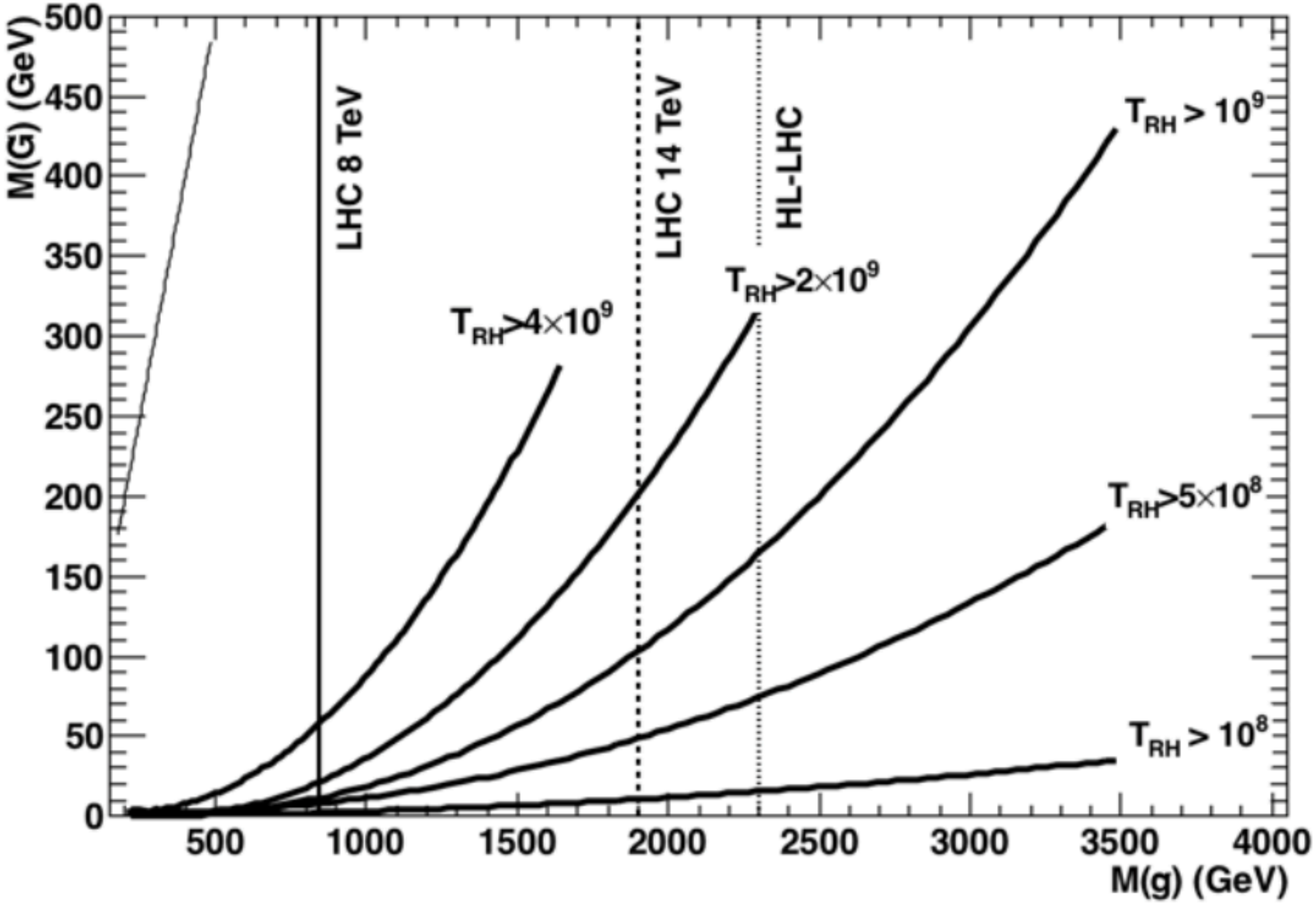




For large values of tan β it seems possible to lower T_{RH} to values consistent with the gravitino problem….more to come soon on this point!

A recent analysis on gravitino DM in pMSSM

(Covi et al 2015)



For large values of tan β it seems possible to lower T_{RH} to values consistent with the gravitino problem….more to come soon on this point!

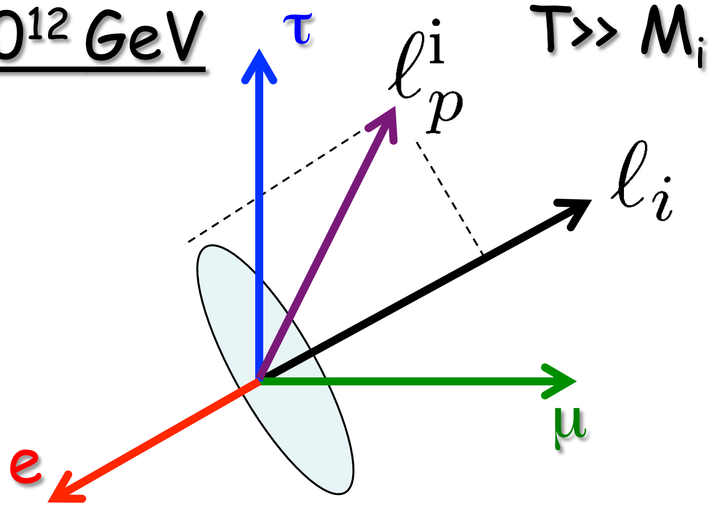
Conclusions:

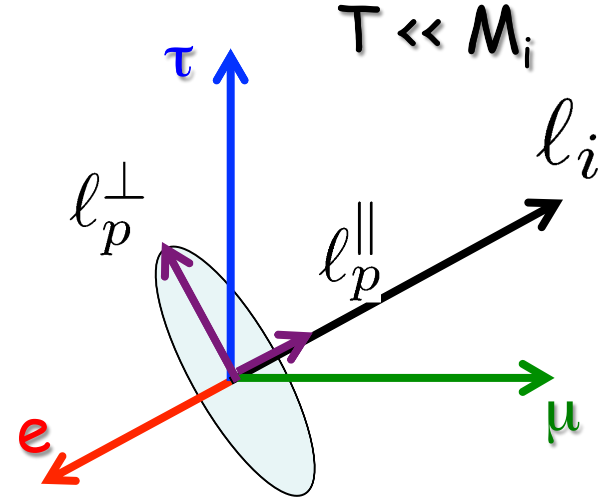
- The importance of discovering CP violation in neutrino oscillations should neither overrated but also not undermined but it should be clear that the `whole package' is important within specific models!
- High scale leptogenesis is difficult to test but maybe not impossible: necessary to work out plausible 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 ca 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 δ, m_{ee}, mass ordering, octant, absolute neutrino mass scale
- SUSY SO(10)-inspired models can be still reconciled with gravitino problem
- WE ARE ENTERING A FASCINATING STAGE: MODELS vs. EXPERIMENTS AND LEPTOGENESIS PLAYS AN IMPORTANT ROLE

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

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

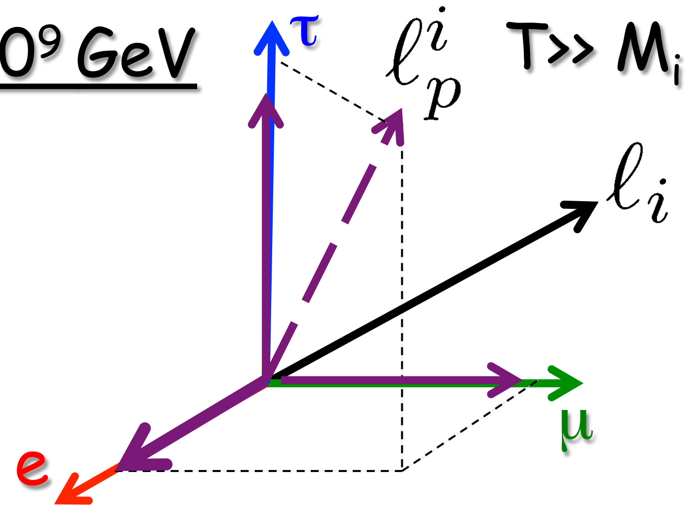
$M_i \gtrsim 10^{12}$ GeV

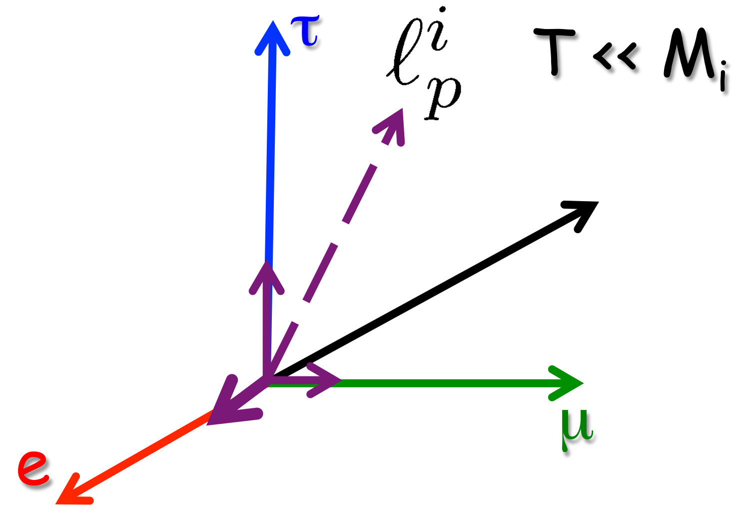




$$N_{B-L}^{\rm p}(T \ll M_i) = (1-P_{{\rm p}i})\,N_{B-L}^{\rm p,i} + P_{{\rm p}i}\,e^{-\frac{3\pi}{8}\,K_i}\,N_{B-L}^{\rm p,i}$$

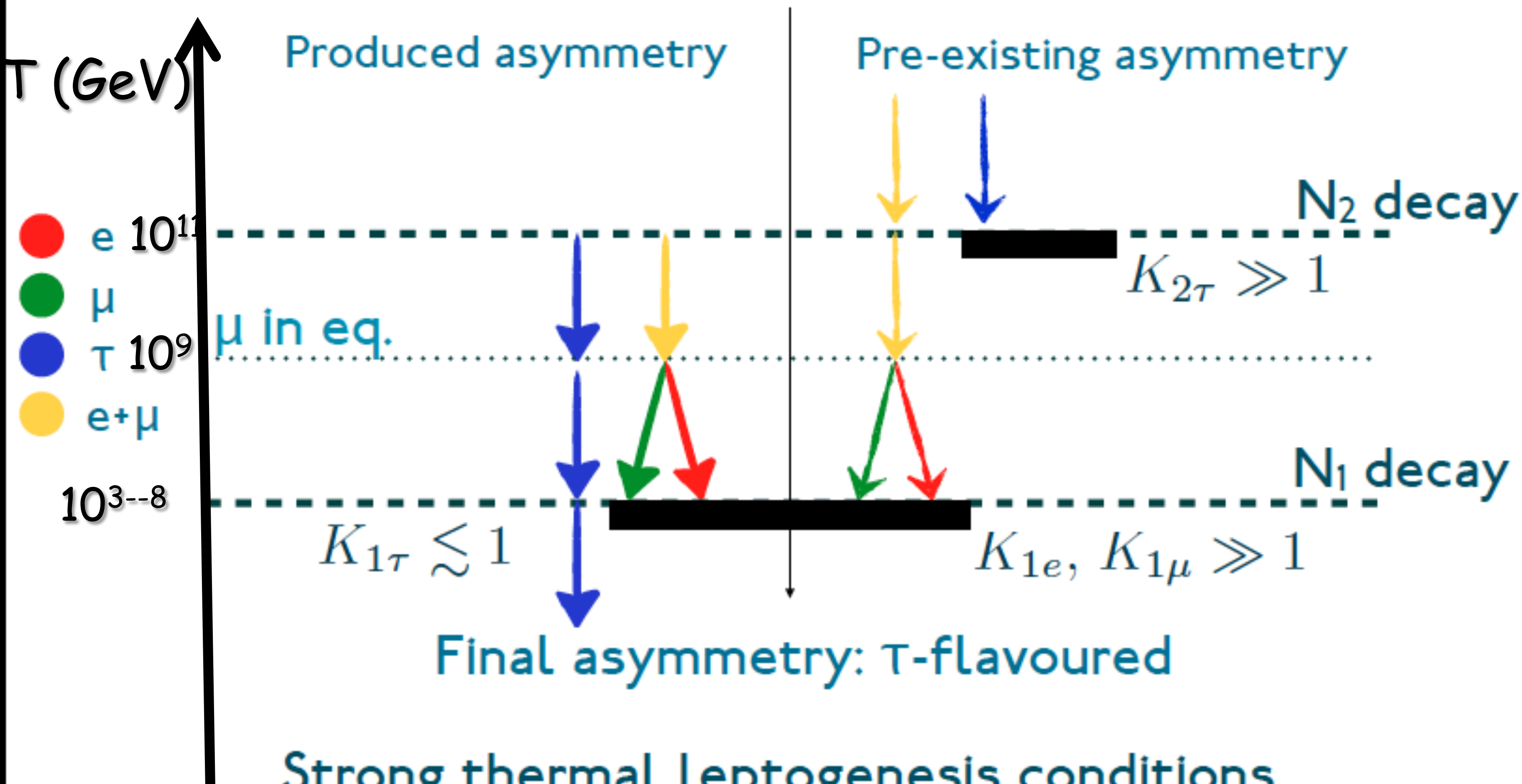
$M_i \ll 10^{9}$ GeV





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

How is STL realised? - A cartoon



Strong thermal leptogenesis conditions

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

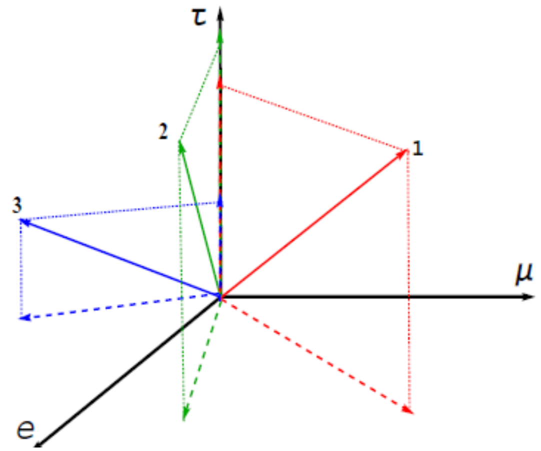
Courtesy of Michele Re Fiorentin

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

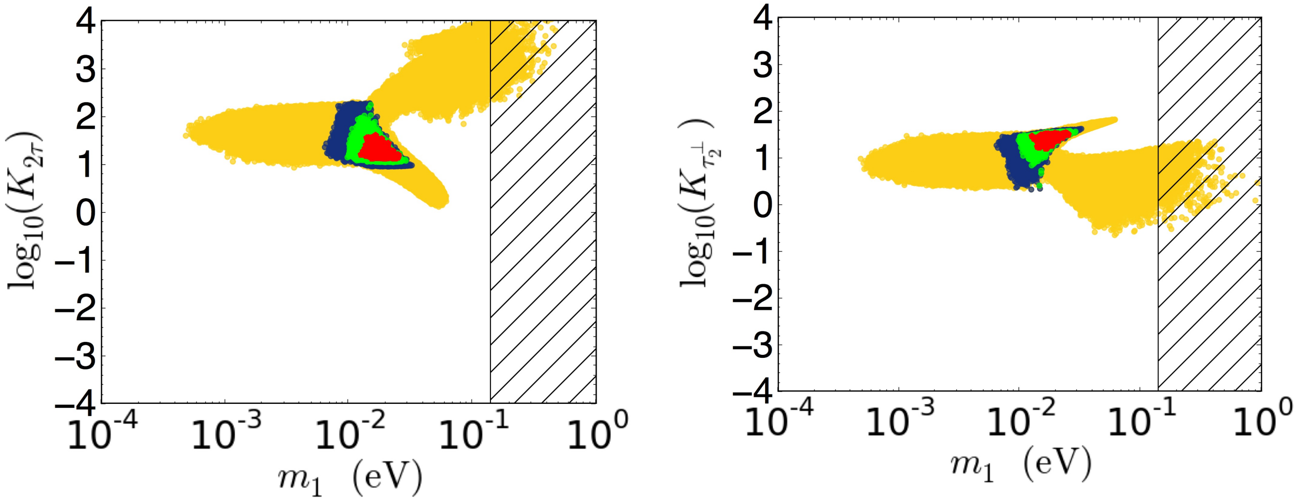
The result is a "monster" equation:



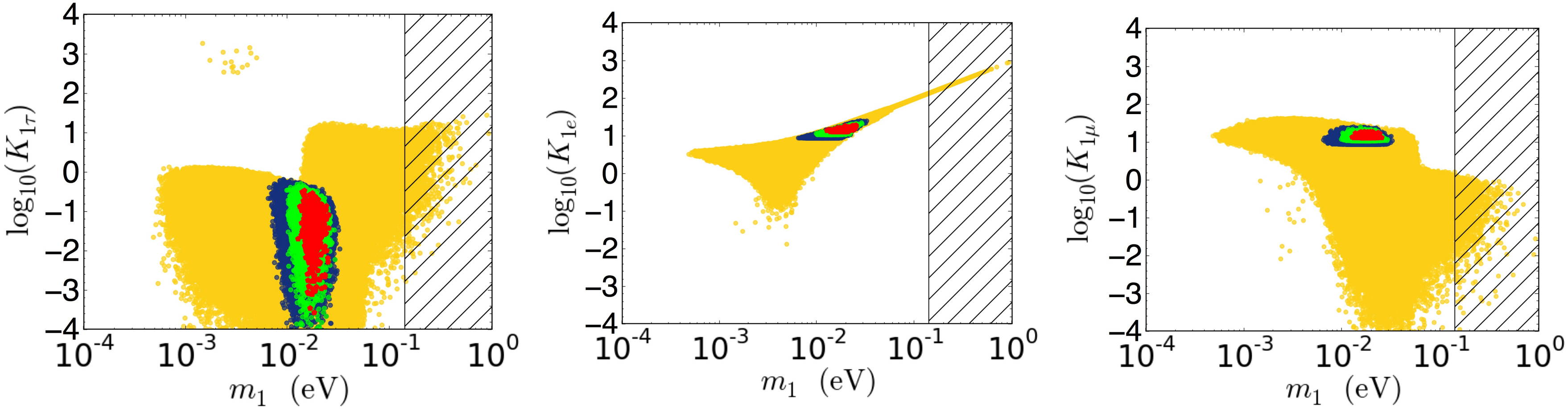
$$
\begin{aligned}
\frac{dN^{B-L}_{\alpha\beta}}{dz} &= \varepsilon^{(1)}_{\alpha\beta}\, D_1\,(N_{N_1} - N^{\rm eq}_{N_1}) - \frac{1}{2}\, W_1\, \{\mathcal{P}^{0(1)}, N^{B-L}\}_{\alpha\beta} \qquad (80)\\
&+ \varepsilon^{(2)}_{\alpha\beta}\, D_2\,(N_{N_2} - N^{\rm eq}_{N_2}) - \frac{1}{2}\, W_2\, \{\mathcal{P}^{0(2)},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

Some insight from the decay parameters

At the production ($T \sim M_2$)



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

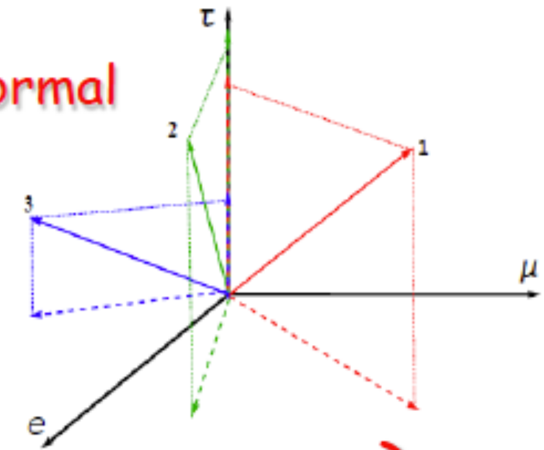


Flavour projection

(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



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

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

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

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

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

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

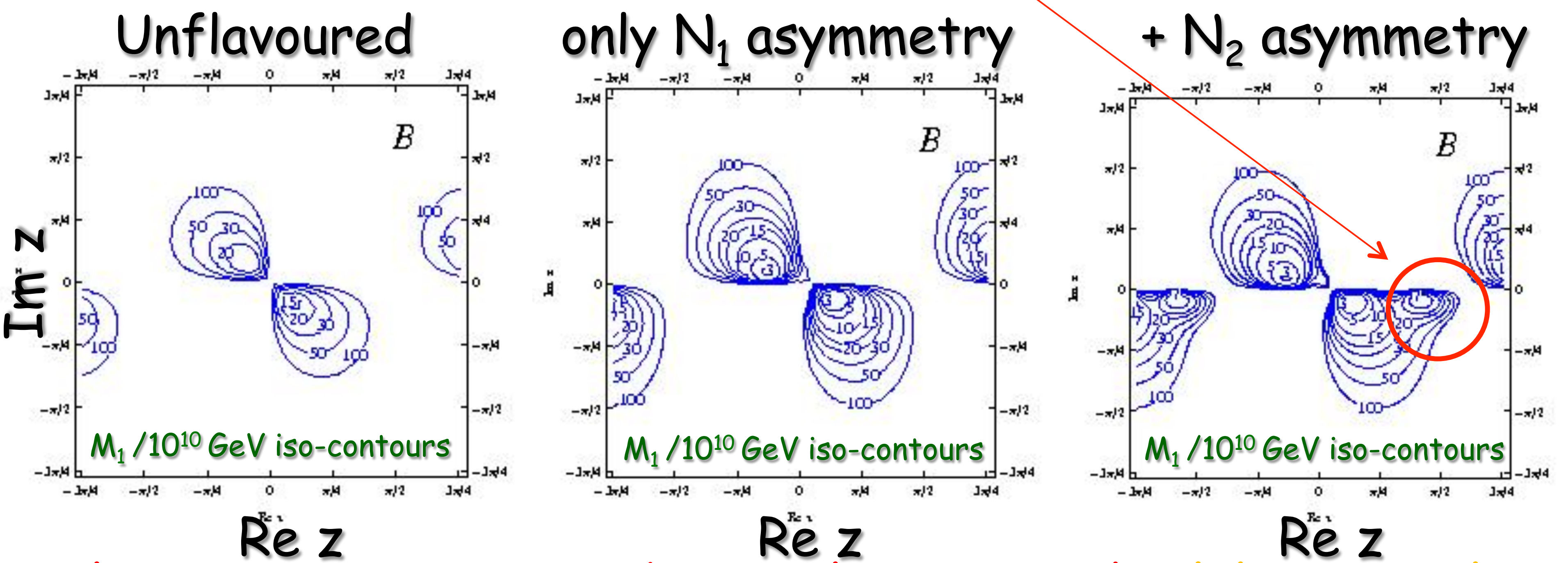
2 RH neutrino scenario revisited

(King 2000;Frampton,Yanagida,Glashow '01,Ibarra, Ross 2003;Antusch, PDB,Jones,King '11)

In the 2 RH neutrino scenario the N_2 production has been so far considered to be safely negligible because $\varepsilon_{2\alpha}$ 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



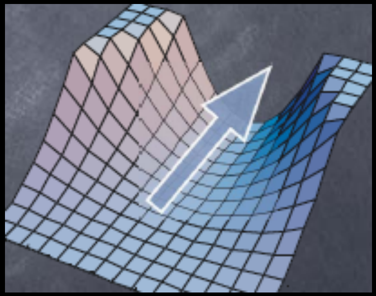
These regions are interesting because they correspond to light sequential dominated neutrino mass models realized in some grandunified models

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

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



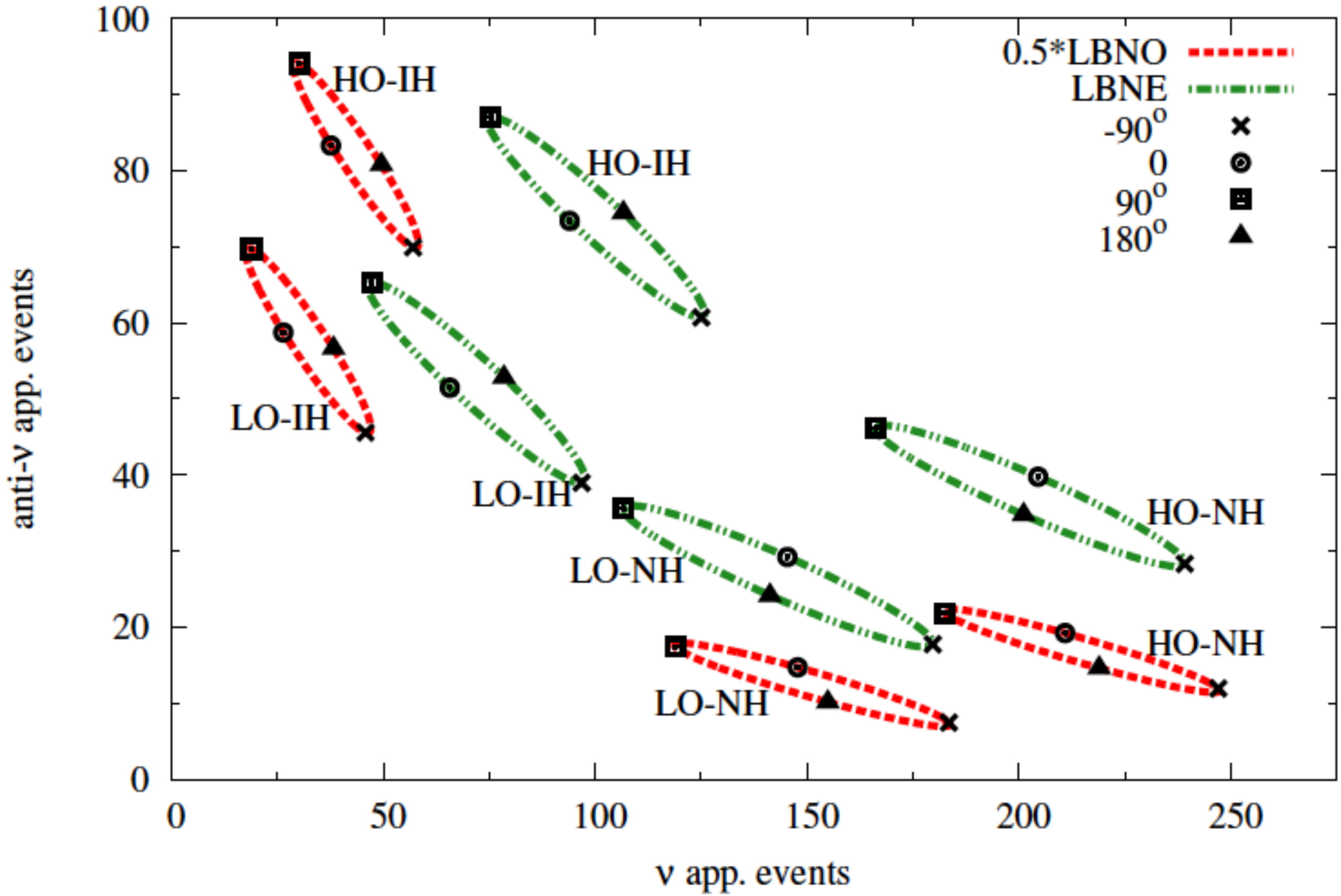
F term D term

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

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

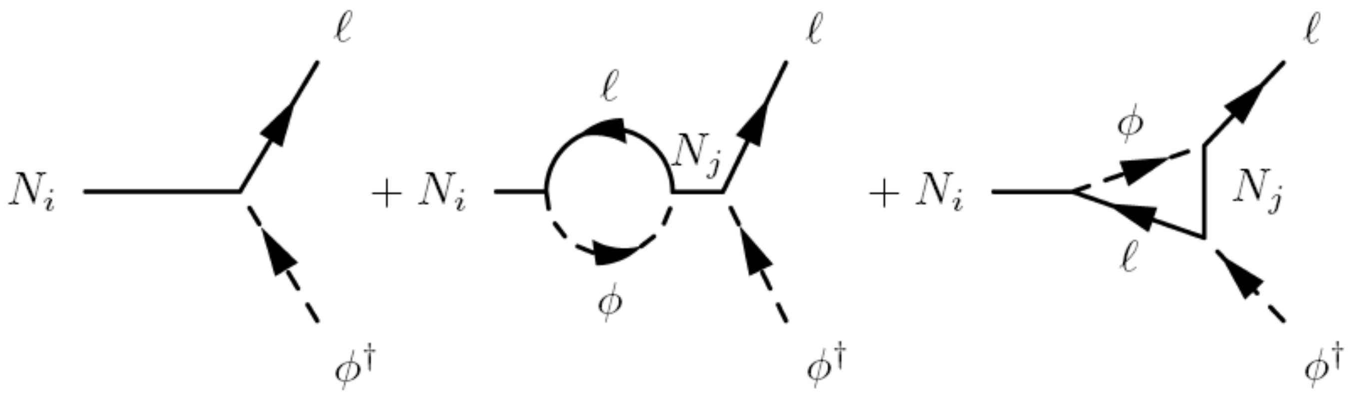
The final asymmetry is $\propto T_{RH}$ and the observed one can be reproduced for low values $T_{RH} \sim 10$ GeV !

Electron appearance events for 0.5*LBNO and LBNE



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 !

Additional contribution to CP violation:

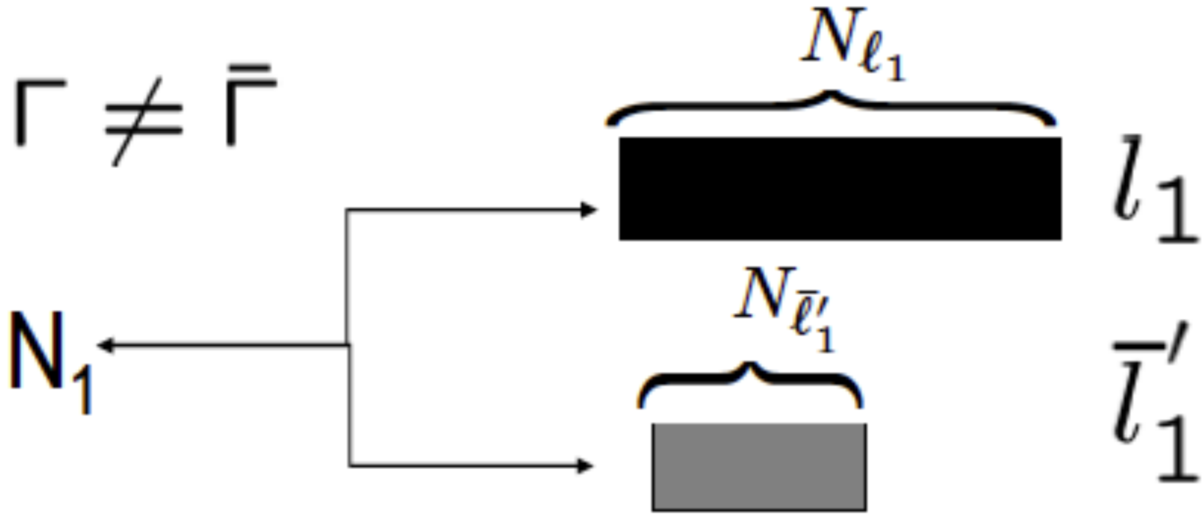
(Nardi,Racker,Roulet '06)

(α = τ, e+μ)

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

depends on U !

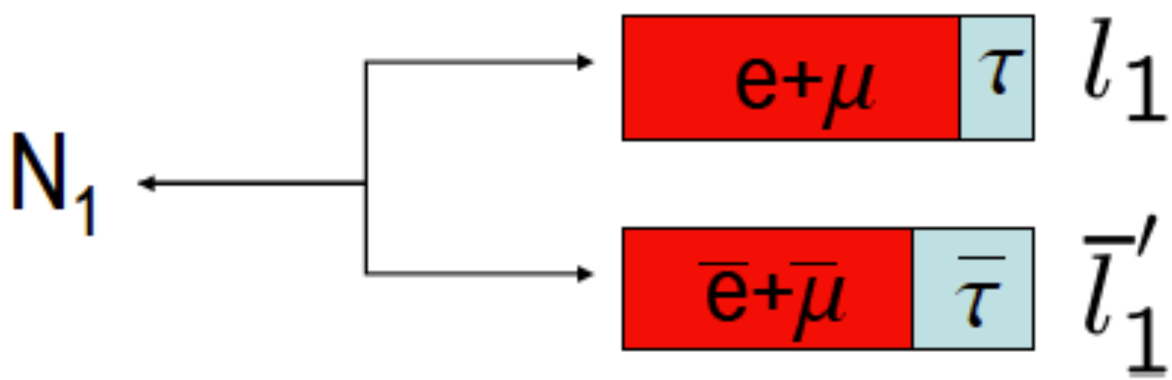
1) $\Gamma \neq \bar{\Gamma}$



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

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

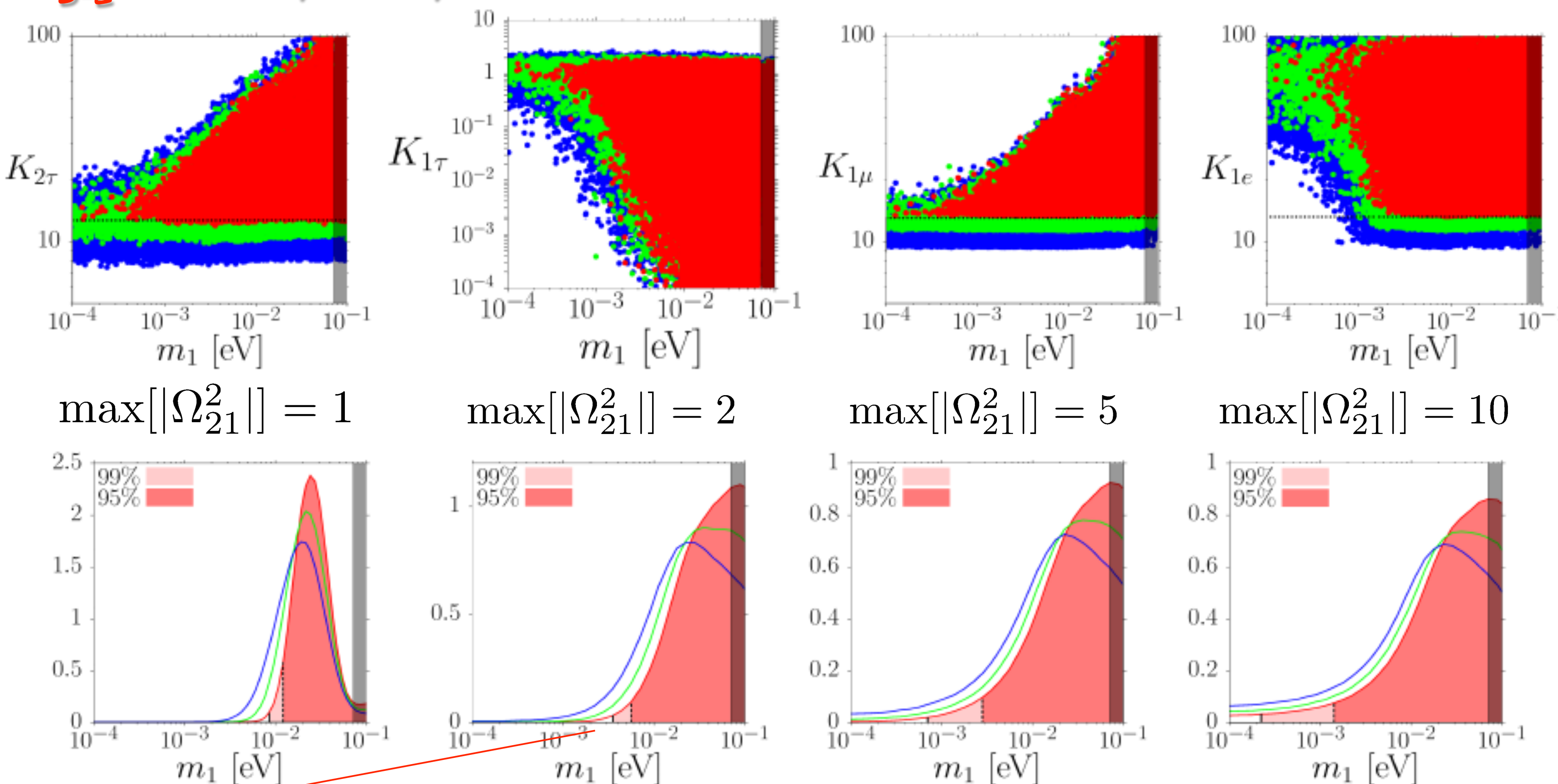
+



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

A lower bound on neutrino masses (IO)

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



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