Nordita, Stockholm, 7 April - 2 May 2014

NEWS IN NEUTRINO PHYSICS

Strong thermal Leptogenesis and the absolute neutrino mass scale

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see arXiv:1401.6185 with Sophie E. King & Michele Re Fiorentin

Cosmological puzzles

- *Cosmological Puzzles :*

This talk

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

"RIDE" model see PDB,King,Luhn,Merle, Schmidt'10,'14

- *New stage in early Universe history :*

BICEP2 (TBC)

T

- $V \sim 2\times10^{16}$ GeV? — Inflation
- $\lesssim 3\times10^{14}$ GeV — QCD freeze-out
- Baryogenesis
- 100 GeV — EWSSB
- 0.1- 1 MeV — BBN
- 0.1- 1 eV — Recombination

Neutrino mixing parameters

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

Pontecorvo-Maki-Nakagawa-Sakata matrix

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

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

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

3σ ranges:

$\theta_{23} \simeq 37^\circ - 53^\circ$

$\theta_{12} \simeq 30.5^\circ - 38^\circ$

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

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

Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: normal or inverted

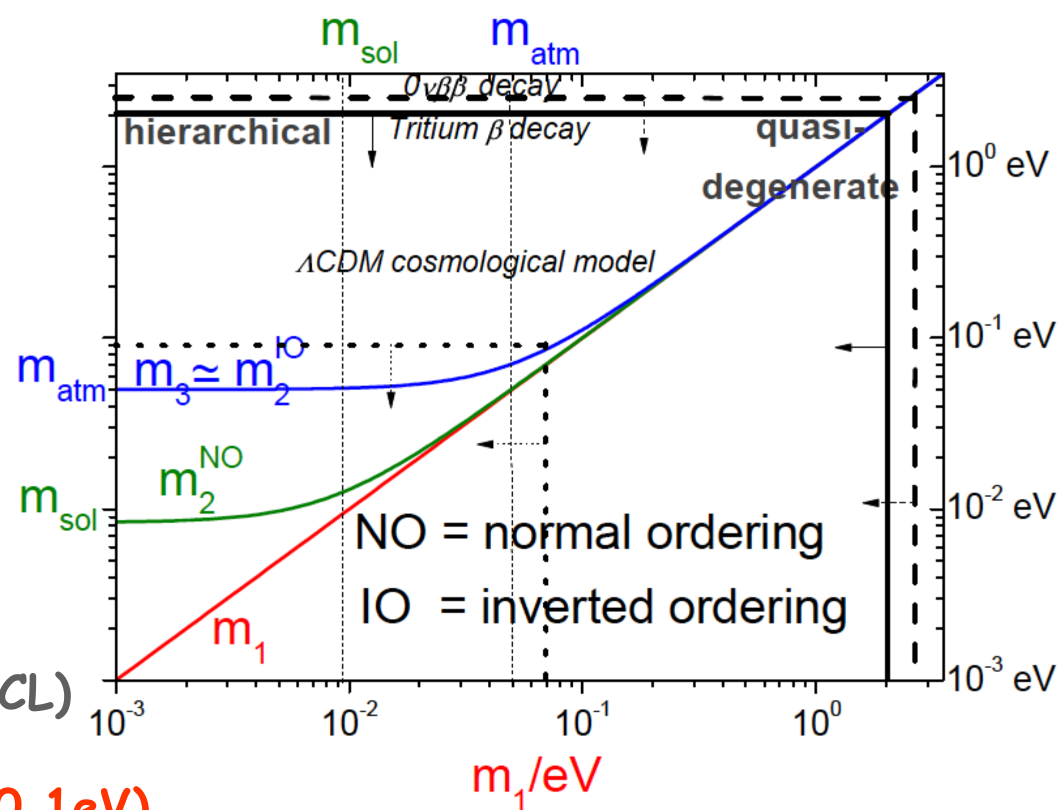
$$m_3^2 - m_2^2 = \Delta m^2_{atm} \text{ or } \Delta m^2_{sol} \qquad m_{atm} \equiv \sqrt{\Delta m^2_{atm} + \Delta m^2_{sol}} \simeq 0.05\,\text{eV}$$

$$m_2^2 - m_1^2 = \Delta m^2_{sol} \text{ or } \Delta m^2_{atm} \qquad m_{sol} \equiv \sqrt{\Delta m^2_{sol}} \simeq 0.009\,\text{eV}$$

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

ββ0ν: $m_{\beta\beta} < 0.34 - 0.78$ eV
(CUORICINO 95% CL, similar bound from Heidelberg-Moscow)
$m_{\beta\beta} < 0.14 - 0.38$ eV
(EXO-200 90% CL)
$m_{\beta\beta} < 0.2 - 0.4$ eV
(GERDA 90% CL)

CMB+BAO+H0 : $\Sigma m_i < 0.23$ eV
(Planck+high l+WMAPpol+BAO 95%CL)
⇒ $m_1 < 0.07$ eV
(but BOSS RESULTS favour $m_1 \sim 0.1$eV)



Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

• Type I seesaw

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

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

- 3 light neutrinos ν_1, ν_2, ν_3 with masses $\text{diag}(m_1, m_2, m_3) = -U^{\dagger}\, m_D\, \frac{1}{M}\, m_D^T\, U^{\star}$
- 3 new heavy RH neutrinos N_1, N_2, N_3 with masses $M_3 > M_2 > M_1 \gg m_D$

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

total CP asymmetries $\varepsilon_i \equiv -\dfrac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i}$

• Thermal production of RH neutrinos

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

The double side of Leptogenesis

Cosmology
(early Universe) ←

→ Neutrino Physics,
New Physics

- *Cosmological Puzzles :*

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

- *New stage in early Universe history :*

T	
~2 x10^{16} GeV?	Inflation
$\lesssim$ 3x10^{14} GeV	QCD freeze-out
	Leptogenesis
100 GeV	EWSSB
0.1- 1 MeV	BBN
0.1- 1 eV	Recombination

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

In this case one would like to answer.....

...two important questions:

1. Can we get an insight on neutrino parameters from leptogenesis?

Can leptogenesis provide a way to understand current neutrino parameters measurements and even predict future ones?

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

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

Is there an alternative approach based on usual high energy scale?

Considering that:

- No new physics at LHC (so far);
- BICEP2 (seems to) supports the existence of a new scale ~ 2×10^{16} GeV;
- The discovery of non-vanishing reactor angle opens the door to further measurements of mixing parameters (atmospheric angle octant, neutrino mass ordering, Dirac phase).

Seesaw parameter space

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

Problem: too many parameters

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

Orthogonal parameterisation

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

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

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

A parameter reduction would help and can occur if:

- $\eta_B = \eta_B^{CMB}$ is satisfied around "peaks"
- some parameters cancel in the asymmetry calculation
- imposing strong thermal leptonesis condition
- by imposing some (model dependent) conditions on m_D

Vanilla leptogenesis

1) Flavor composition of final leptons is neglected

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

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

$$N_{B-L}^{\rm fin} = \sum_i \varepsilon_i\, \kappa_i^{\rm fin} \Rightarrow \eta_B = a_{\rm sph} \frac{N_{B-L}^{\rm fin}}{N_\gamma^{\rm rec}}$$

baryon-to -photon number ratio

Successful leptogenesis bound : $\eta_B = \eta_B^{CMB} = (6.1 \pm 0.1) \times 10^{-10}$

2) Hierarchical heavy RH neutrino spectrum: $M_2 \gtrsim 2\, M_1$

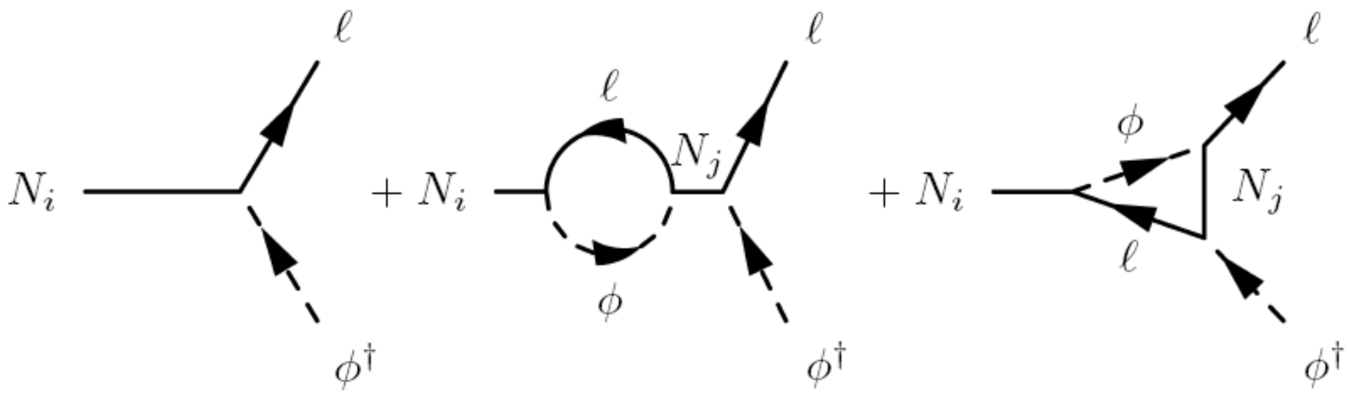
3) N_3 does not interfere with N_2-decays: $(m_D^\dagger\, m_D)_{23} = 0$

From the last two assumptions

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

Total CP asymmetries

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



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

It does not depend on U !

4) Barring fine-tuned mass cancellations in the seesaw

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

(Davidson, Ibarra '02)

5) Efficiency factor from simple Boltzmann equations

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

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

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

decays

inverse decays

wash-out

decay parameter

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

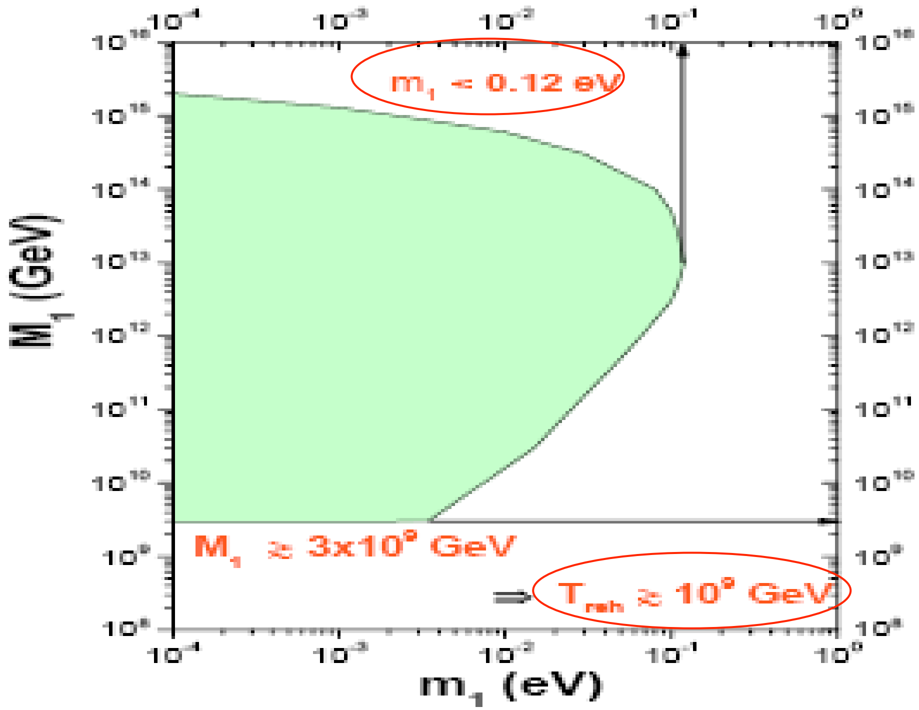
$$\kappa_1(z; K_1, z_{\mathrm{in}}) = -\int_{z_{\mathrm{in}}}^{z} dz' \left[\frac{dN_{N_1}}{dz'}\right] e^{-\int_{z'}^{z} dz''\,W_1(z'')}$$

Neutrino mass bounds in vanilla leptog.

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

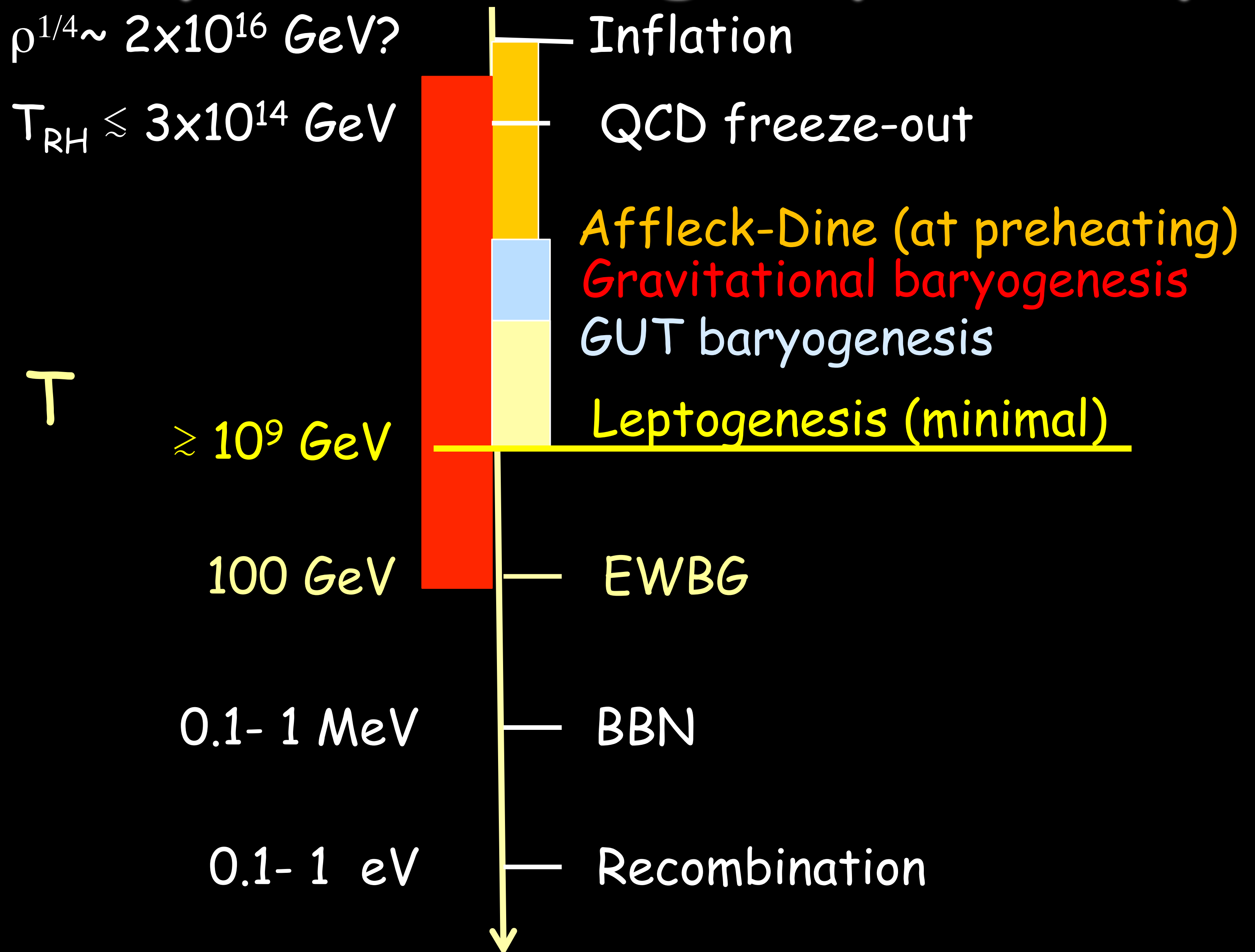
$$\eta_B \simeq 0.01\,\varepsilon_1(m_1, M_1, \Omega)\,\kappa_1^{\rm fin}(K_1) \leq \eta_B^{\rm max} = 0.01\,\varepsilon_1^{\rm max}(m_1, M_1)\,\kappa_1^{\rm fin}(K_1^{\rm max})$$

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



No dipendence on the leptonic mixing matrix U

A pre-existing asymmetry?



Strong thermal leptogenesis

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

(Buchmüller, PDB, Plümacher '04)

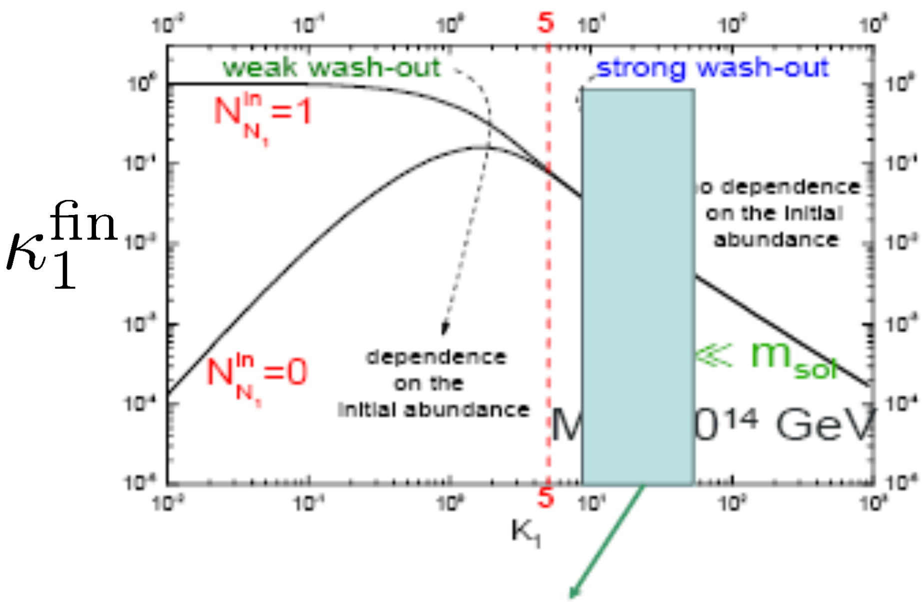
$$\eta_B \simeq 0.01\, \varepsilon_1(m_1, M_1, \Omega)\, \kappa_1^{\rm fin}(K_1)$$

decay parameter

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

Independence of the initial abundance of N_1

wash-out of a pre-existing asymmetry



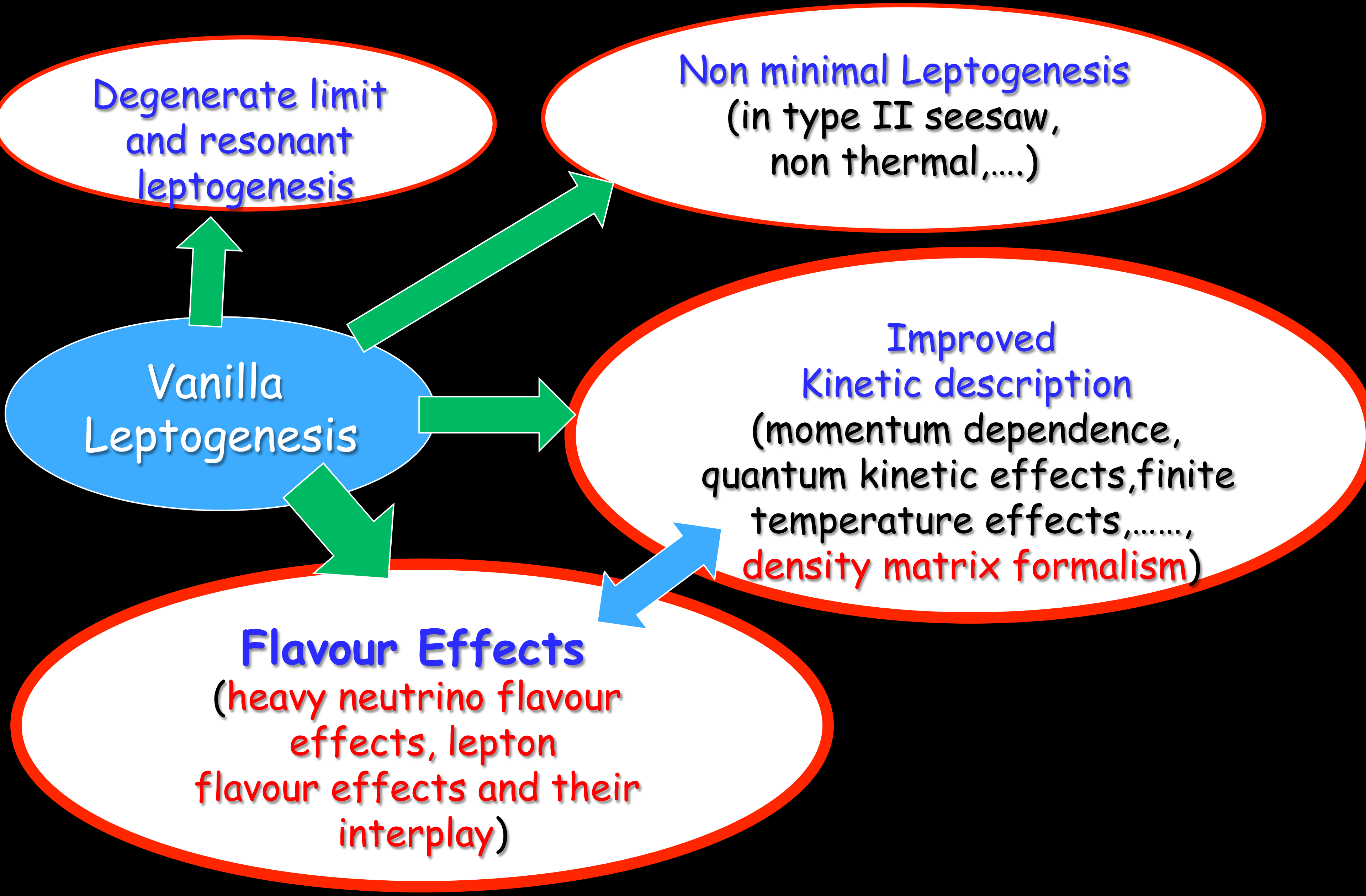
$$N_{B-L}^{\rm p,final} = N_{B-L}^{\rm p,initial}\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1}$$

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

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

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

Beyond vanilla Leptogenesis



Lepton flavour effects

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

Flavor composition of lepton quantum states:

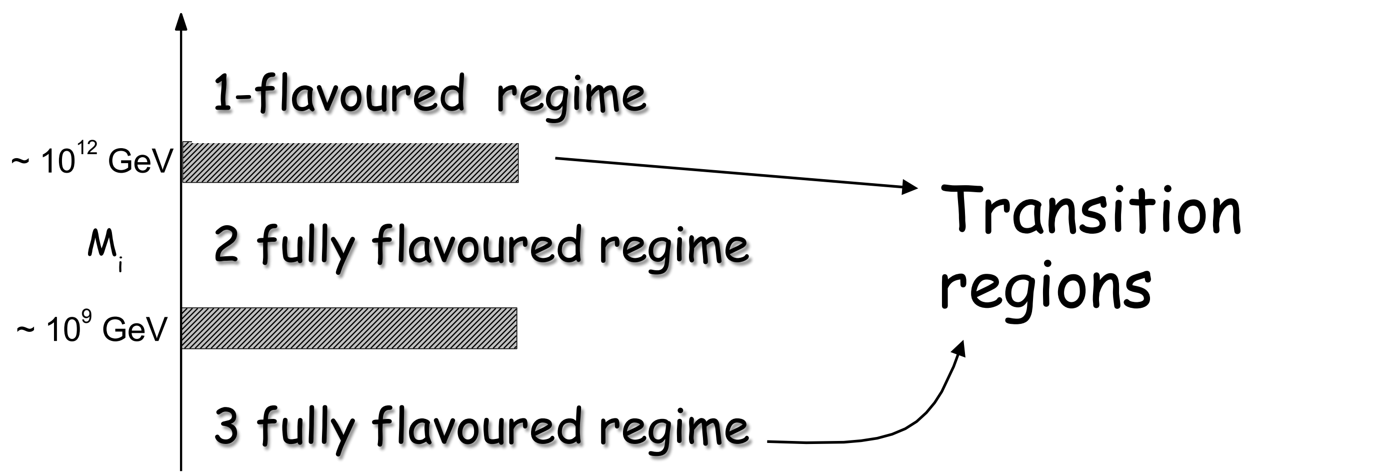
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1 \rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau) \qquad P_{1\alpha} \equiv |\langle \ell_1 | \alpha \rangle|^2$$

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

For $T \gtrsim 10^{12}$ GeV $\Rightarrow$ τ-Yukawa interactions $(\bar{l}_{L\tau}\, \phi\, f_{\tau\tau}\, e_{R\tau})$ are fast enough to break the coherent evolution of $|l_1\rangle$ and $|\bar{l}'_1\rangle$

$\Rightarrow$ they become an incoherent mixture of a τ and of a μ+e component

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



Two fully flavoured regime

(α = τ, e+μ)

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

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

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

- Classic Kinetic Equations (in their simplest form)

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

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

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

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

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

Additional contribution to CP violation:

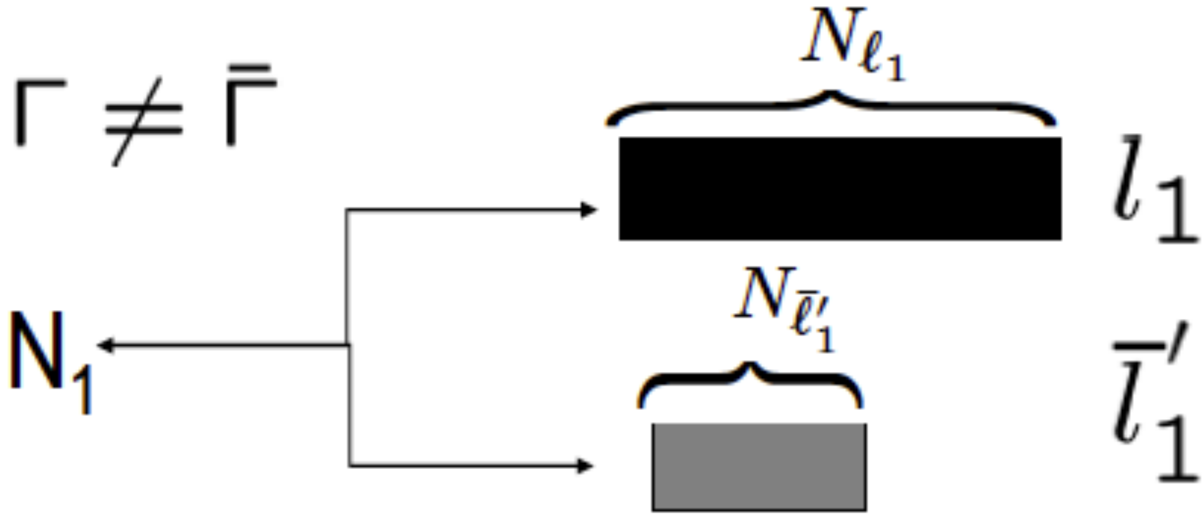
(Nardi, Racker, Roulet '06)

($\alpha = \tau$, e+μ)

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

depends on U !

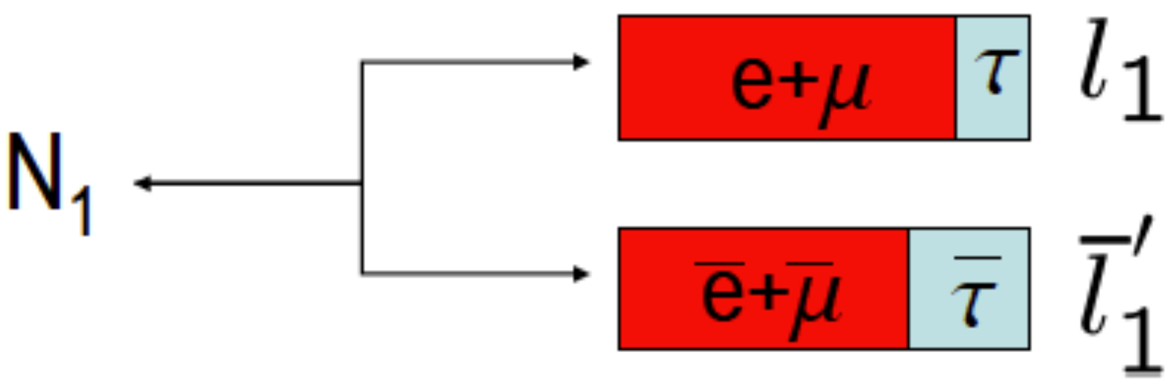
1) $\Gamma \neq \bar{\Gamma}$



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

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

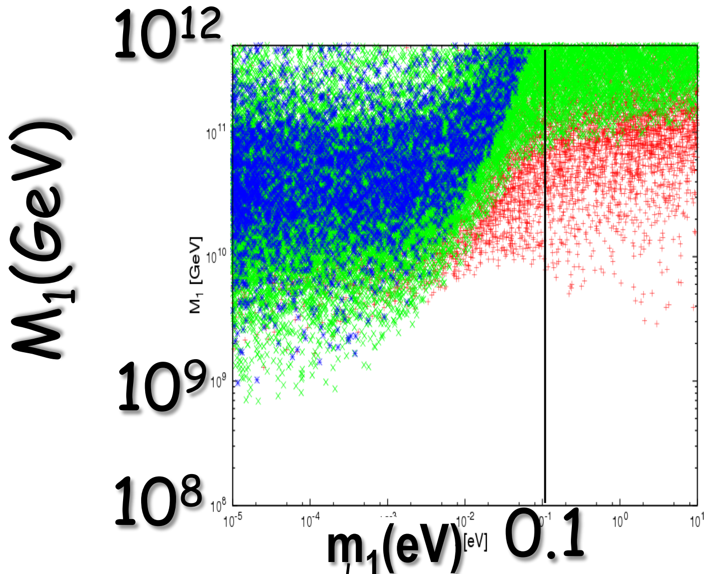
+



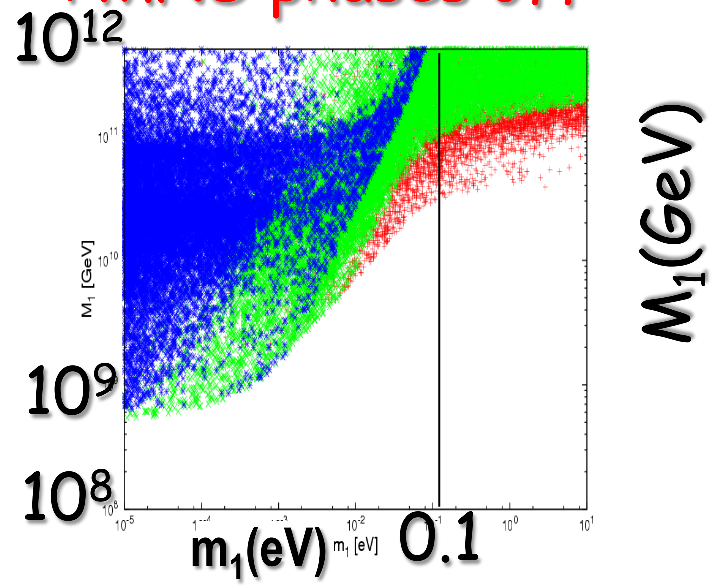
$\Rightarrow \; \frac{\Delta P_{1\alpha}}{2}$

Upper bound on m_1

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

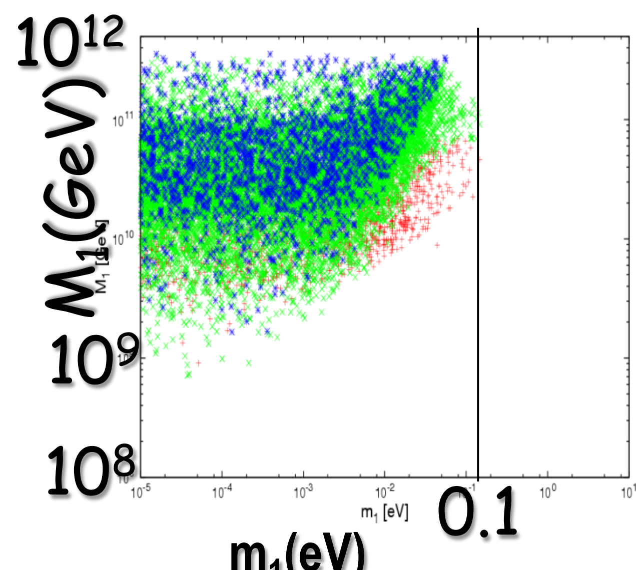


PMNS phases off



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

imposing a condition of validity of Boltzmann equations



Heavy neutrino flavours: the N_2-dominated scenario

(PDB '05)

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

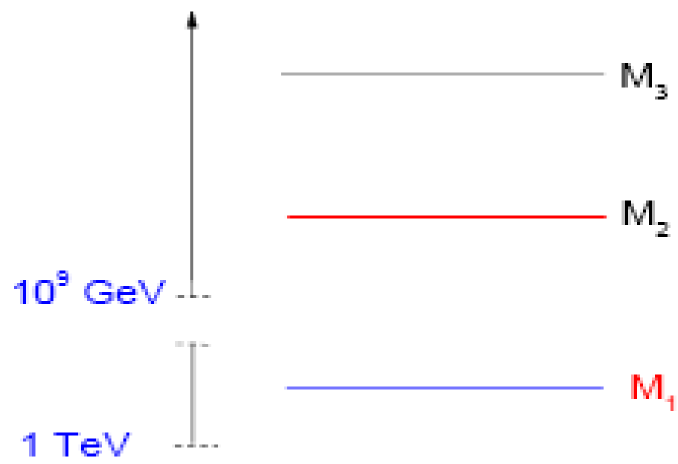
$$N_{B-L}^{f,N_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_1} \ll N_{B-L}^{f,N_1} = \varepsilon_1\, \kappa(K_1)$$

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

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

The lower bound on M_1 disappears and is replaced by a lower bound on M_2 ...

that however still implies a lower bound on T_{reh} !

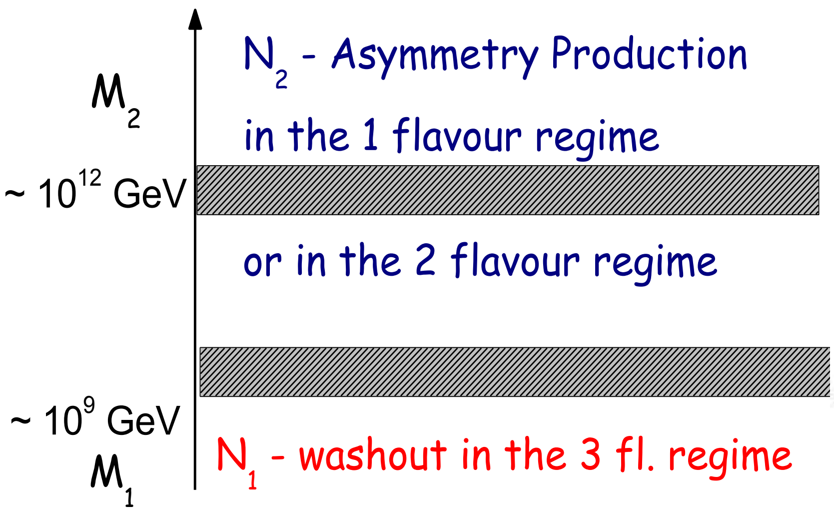


N_2-flavored leptogenesis

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

Combining together lepton and heavy neutrino flavour effects one has

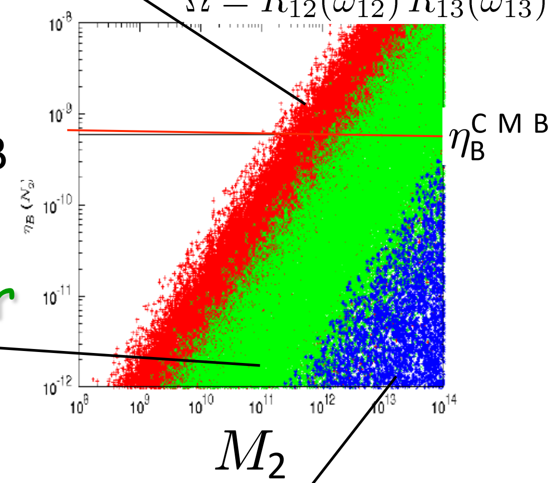
A two stage process:



Wash-out is neglected

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

Both wash-out and flavor effects



Unflavored case

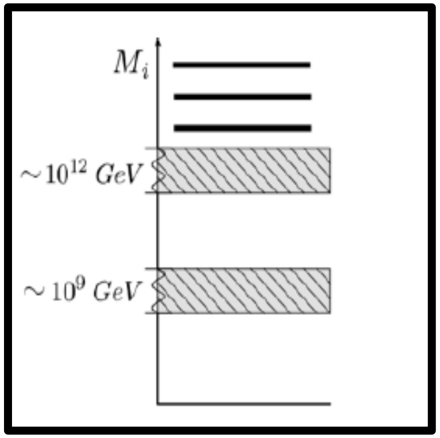
$$N^{\rm f}_{B-L}(N_2) = P^0_{2e}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1e}} + P^0_{2\mu}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + P^0_{2\tau}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

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

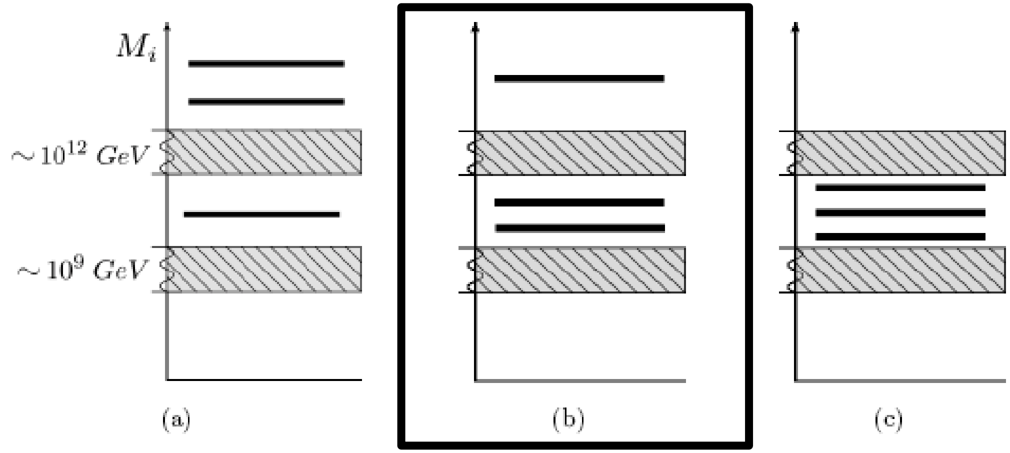
With flavor effects the domain of applicability goes much beyond the choice $\Omega = R_{23}$

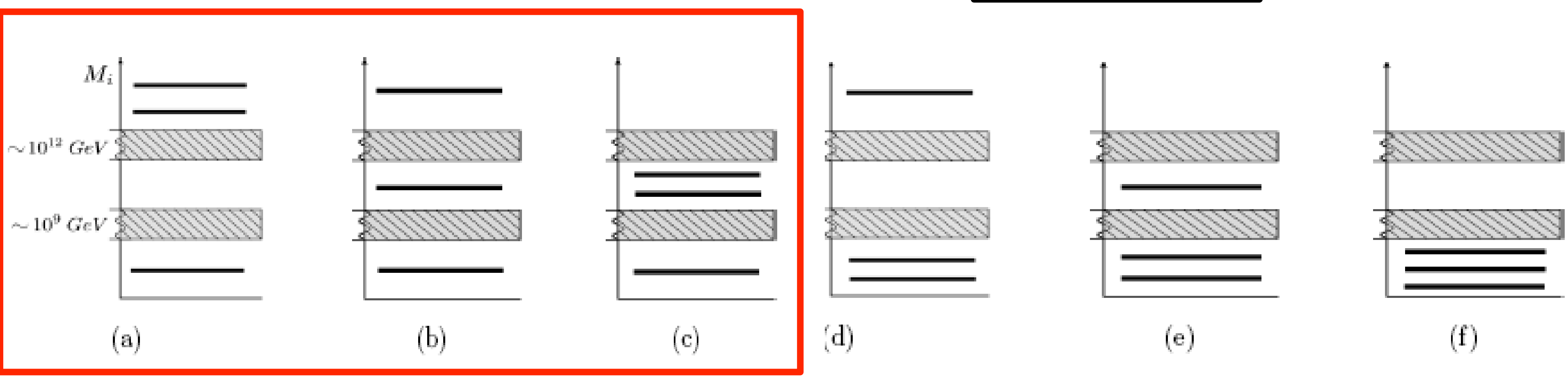
The existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$ not to be negligible!

Heavy neutrino flavored scenario



2 RH neutrino scenario





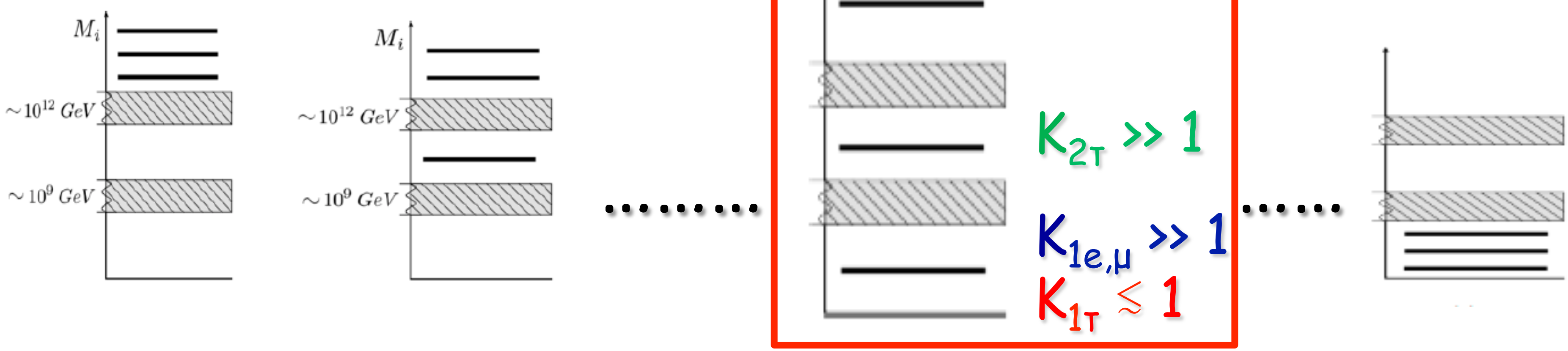
N_2-dominated scenario

(Bertuzzo,PDB,Marzola '10)

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

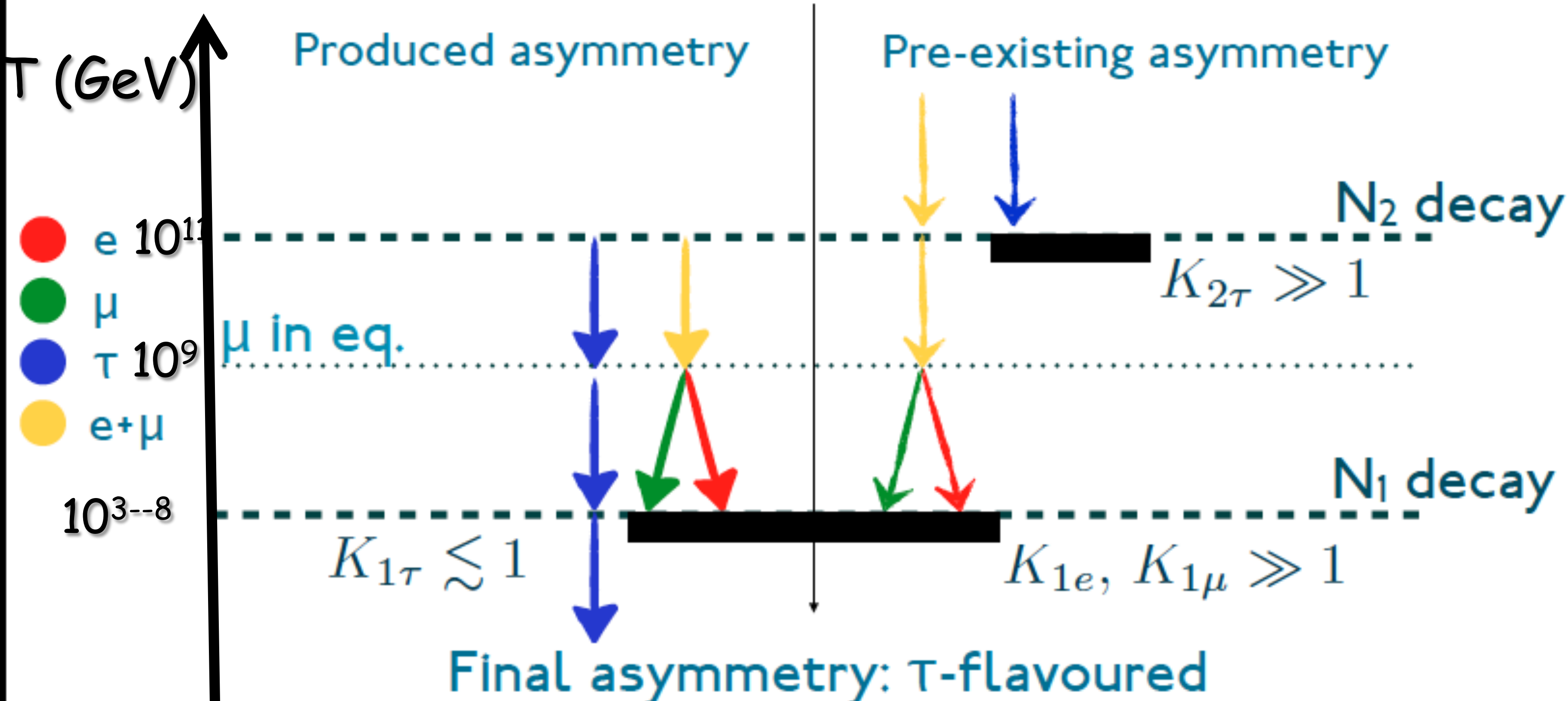
$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p,f} + N_{B-L}^{\rm lep,f}$$

Asymmetry generated from leptogenesis



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

How is STL realised? - A cartoon



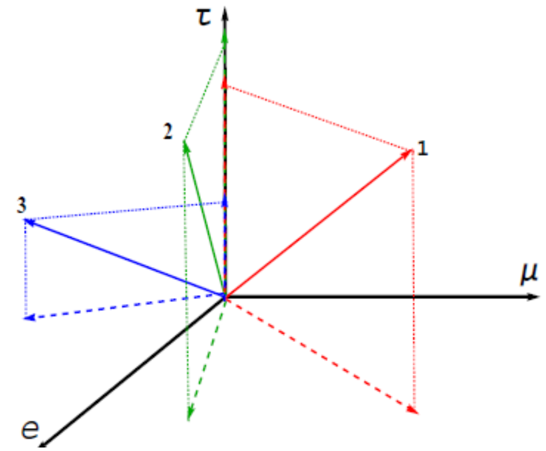
Strong thermal leptogenesis conditions

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

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:

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

Strong thermal leptogenesis and the absolute neutrino mass scale

(PDB, Sophie King, Michele Re Fiorentin 2014)

Phantom terms

Final asymmetry from leptogenesis

$$N_{B-L}^{\rm lep,f} \simeq \left[\frac{K_{2e}}{K_{2\tau_2^\perp}}\,\varepsilon_{2\tau_2^\perp}\,\kappa(K_{2\tau_2^\perp}) + \left(\varepsilon_{2e} - \frac{K_{2e}}{K_{2\tau_2^\perp}}\,\varepsilon_{2\tau_2^\perp}\right)\,\kappa(K_{2\tau_2^\perp}/2)\right]\,e^{-\frac{3\pi}{8}\,K_{1e}} + \\ + \left[\frac{K_{2\mu}}{K_{2\tau_2^\perp}}\,\varepsilon_{2\tau_2^\perp}\,\kappa(K_{2\tau_2^\perp}) + \left(\varepsilon_{2\mu} - \frac{K_{2\mu}}{K_{2\tau_2^\perp}}\,\varepsilon_{2\tau_2^\perp}\right)\,\kappa(K_{2\tau_2^\perp}/2)\right]\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + \\ + \varepsilon_{2\tau}\,\kappa(K_{2\tau})\,e^{-\frac{3\pi}{8}\,K_{1\tau}}\,,$$

Relic value of the pre-existing asymmetry:

$$N_{\Delta_\tau}^{\rm p,f} = (p_{\rm p\tau}^0 + \Delta p_{\rm p\tau})\,e^{-\frac{3\pi}{8}\,(K_{1\tau}+K_{2\tau})}\,N_{B-L}^{\rm p,i}\,, \qquad (18)$$

$$N_{\Delta_\mu}^{\rm p,f} = \left\{(1-p_{\rm p\tau}^0)\,\left[p_{\mu\tau_2^\perp}^0\,p_{\rm p\tau_2^\perp}^0\,e^{-\frac{3\pi}{8}\,(K_{2e}+K_{2\mu})} + (1-p_{\mu\tau_2^\perp}^0)\,(1-p_{\rm p\tau_2^\perp}^0)\right] + \Delta p_{\rm p\mu}\right\}\,e^{-\frac{3\pi}{8}\,K_{1\mu}}\,N_{B-L}^{\rm p,i},$$

$$N_{\Delta_e}^{\rm p,f} = \left\{(1-p_{\rm p\tau}^0)\,\left[p_{e\tau_2^\perp}^0\,p_{\rm p\tau_2^\perp}^0\,e^{-\frac{3\pi}{8}\,(K_{2e}+K_{2\mu})} + (1-p_{e\tau_2^\perp}^0)\,(1-p_{\rm p\tau_2^\perp}^0)\right] + \Delta p_{\rm pe}\right\}\,e^{-\frac{3\pi}{8}\,K_{1e}}\,N_{B-L}^{\rm p,i}\,.$$

Successful strong thermal leptogenesis then requires:

$$K_{1e}, K_{1\mu} \gtrsim K_{\rm st}(N_{\Delta_{e,\mu}}^{\rm p,i}),\;\; K_{2\tau} \gtrsim K_{\rm st}(N_{\Delta_\tau}^{\rm p,i}),\;\; K_{1\tau} \lesssim 1\,.$$

A lower bound on neutrino masses

(PDB, Sophie King, Michele Re Fiorentin 2014)

Assume first NORMAL ORDERING

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

$$K_{1\tau} = \left|\sqrt{\frac{m_1}{m_\star}}\,U_{\tau 1}\,\Omega_{11} + \sqrt{\frac{m_2}{m_\star}}\,U_{\tau 2}\,\Omega_{21} + \sqrt{\frac{m_3}{m_\star}}\,U_{\tau 3}\,\Omega_{31}\right|^2 \lesssim 1$$

$m_1 \lesssim m_{sol} \Rightarrow$ $\sqrt{\frac{m_{\rm atm}}{m_\star}}\,U_{\tau 3}\,\Omega_{31} = -\sqrt{\frac{m_1}{m_\star}}\,U_{\tau 1}\,\Omega_{11} - \sqrt{\frac{m_{\rm sol}}{m_\star}}\,U_{\tau 2}\,\Omega_{21} + \sqrt{K_{1\tau}}\,e^{i\varphi}$

Defining: $K^0_{1\alpha} \equiv K_{1\alpha}(m_1 = 0)$ and φ_0 such that

$$\sqrt{K^0_{1\alpha}}\,e^{i\,\varphi_0} \equiv \Omega_{21}\sqrt{\frac{m_{\rm sol}}{m_\star}}\left(U_{\alpha 2} - \frac{U_{\tau 2}}{U_{\tau 3}}\,U_{\alpha 3}\right) + \frac{U_{\alpha 3}}{U_{\tau 3}}\sqrt{K_{1\tau}}\,e^{i\,\varphi}$$

For $\alpha = e, \mu$ we obtain

$$K_{1\alpha} = \left|\Omega_{11}\sqrt{\frac{m_1}{m_\star}}\left(U_{\alpha 1} - \frac{U_{\tau 1}}{U_{\tau 3}}\,U_{\alpha 3}\right) + \sqrt{K^0_{1\alpha}}\,e^{i\,\varphi_0}\right|^2 > K_{\rm st}(N^{\rm p,i}_{\Delta\alpha})$$

A lower bound on neutrino masses

(PDB, Sophie King, Michele Re Fiorentin 2014)

One then easily finds (NO)

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

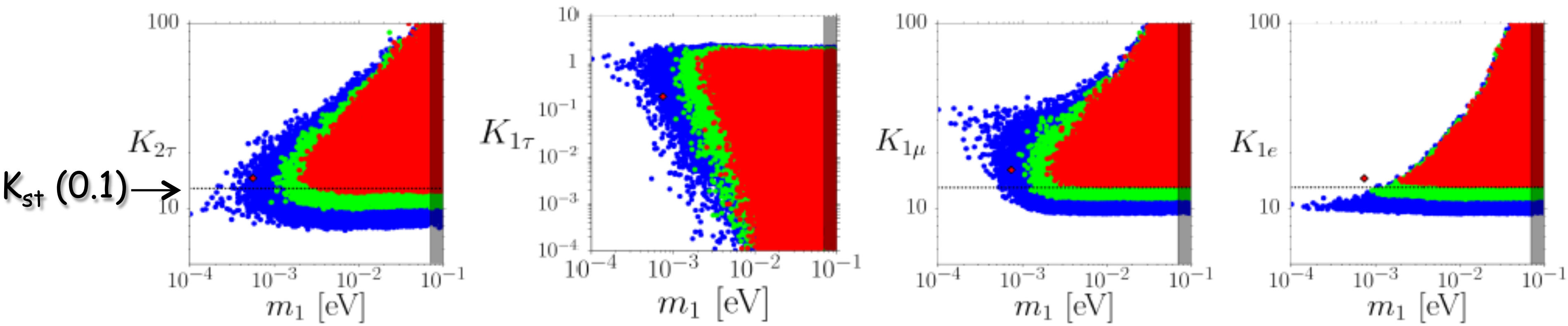
$$K_{1\alpha}^{0,\max} \equiv \left(\max[|\Omega_{21}|] \sqrt{\frac{m_{\rm sol}}{m_\star}} \left| U_{\alpha 2} - \frac{U_{\tau 2}}{U_{\tau 3}} U_{\alpha 3} \right| + \left| \frac{U_{\alpha 3}}{U_{\tau 3}} \right| \sqrt{K_{1\tau}^{\max}} \right)^2$$

The lower bound exists only if either for the muonic flavour or for the electronic (or for both) the value of $K_{1\alpha}^{0,\max}$ is smaller than K_{st} : this indeed happens for the electronic flavour for NO and for the muonic flavour for IO but only if $\max[|\Omega_{21}|]$ is not too large

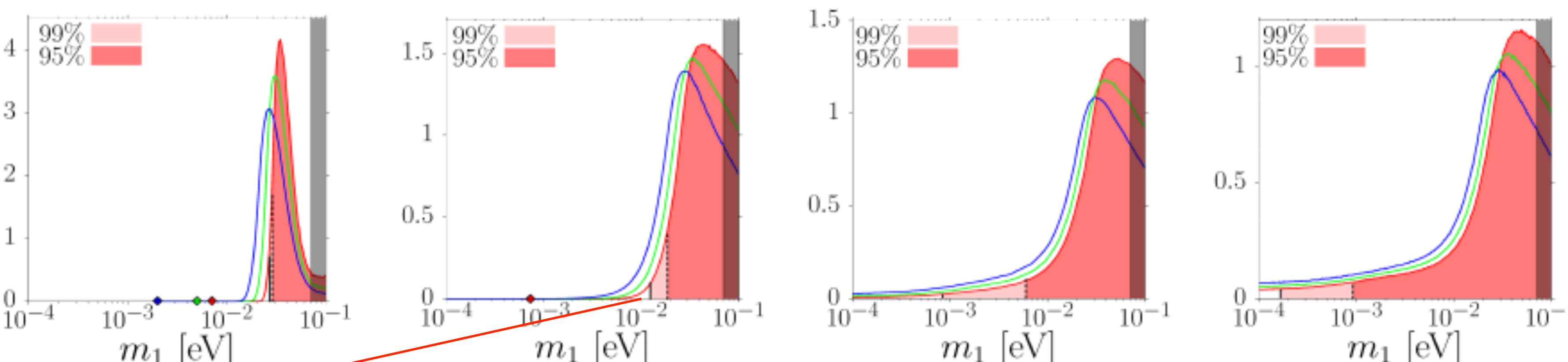
A lower bound on neutrino masses

$N^{p,i}_{B-L}$ = 0.001, 0.01, 0.1 NORMAL ORDERING

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



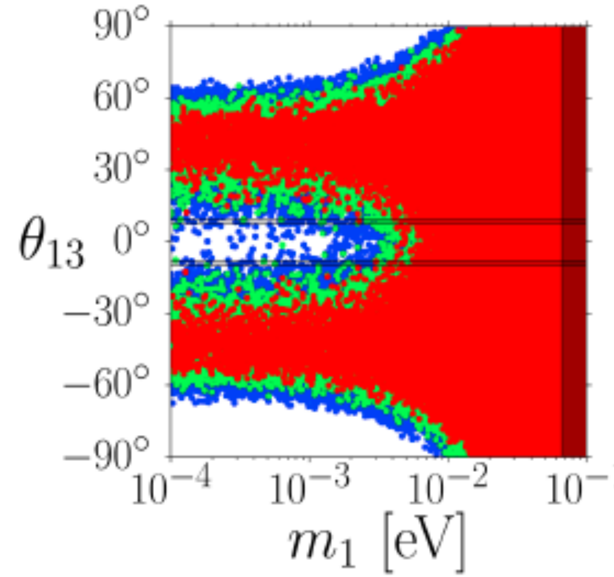
$\max[|\Omega^2_{21}|] = 1$ $\max[|\Omega^2_{21}|] = 2$ $\max[|\Omega^2_{21}|] = 5$ $\max[|\Omega^2_{21}|] = 10$



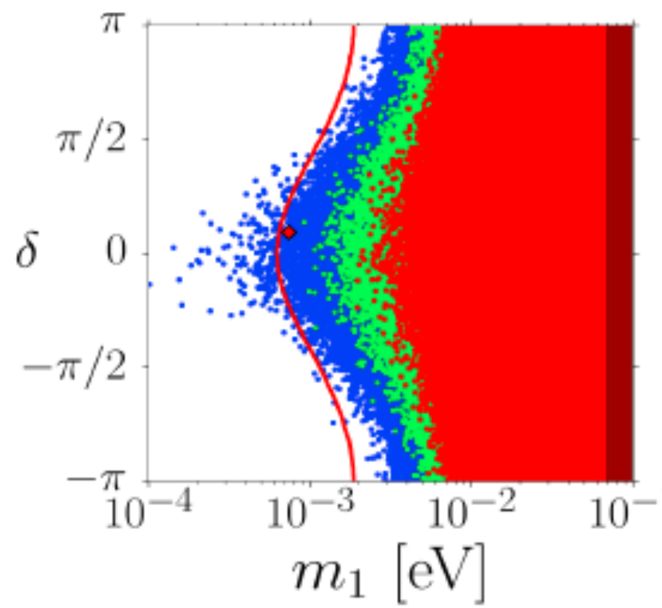
$m_1 \gtrsim 10$ meV $\Rightarrow \Sigma_i m_i \gtrsim 75$ meV (to be compared with 60 meV)

A lower bound on neutrino masses

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



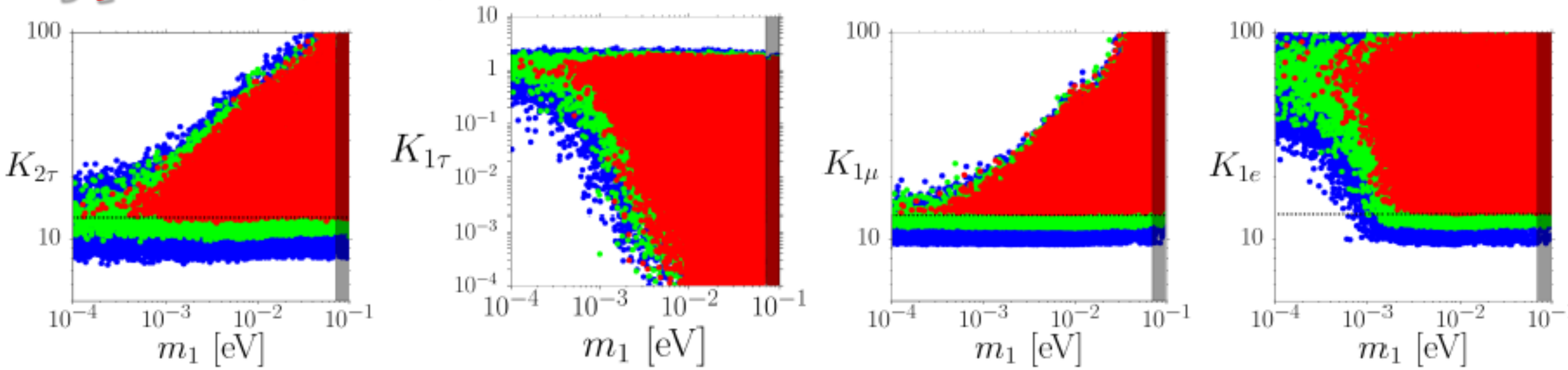
It is modulated by the Dirac phase and it could become more stringent when δ will be measured



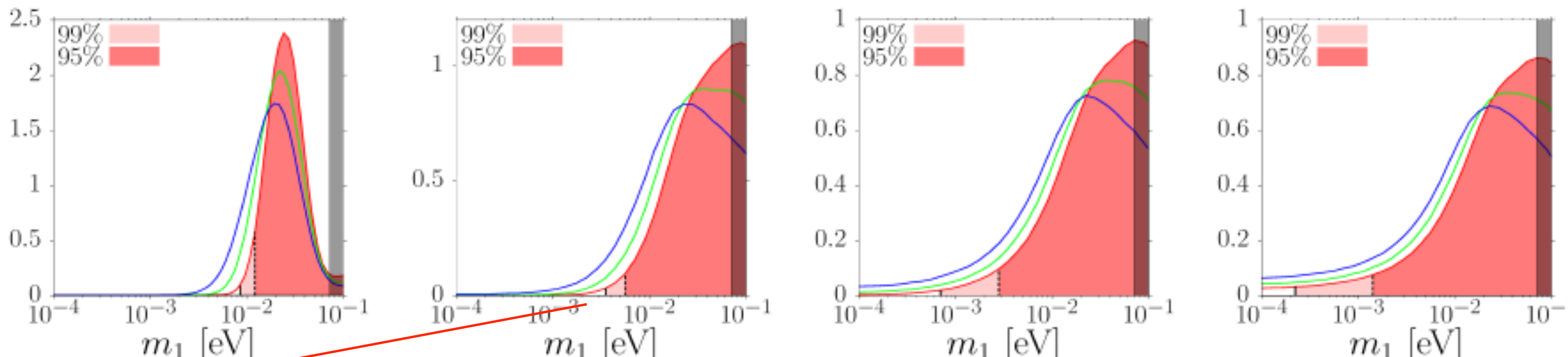
A lower bound on neutrino masses (IO)

(NO→ IO ⇒ analytically: $m_{sol} \to m_{atm}$, 1→2, 2→3, 3→1)

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



$\max[|\Omega^2_{21}|] = 1$ $\max[|\Omega^2_{21}|] = 2$ $\max[|\Omega^2_{21}|] = 5$ $\max[|\Omega^2_{21}|] = 10$



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

Neutrino masses: $m_1 < m_2 < m_3$

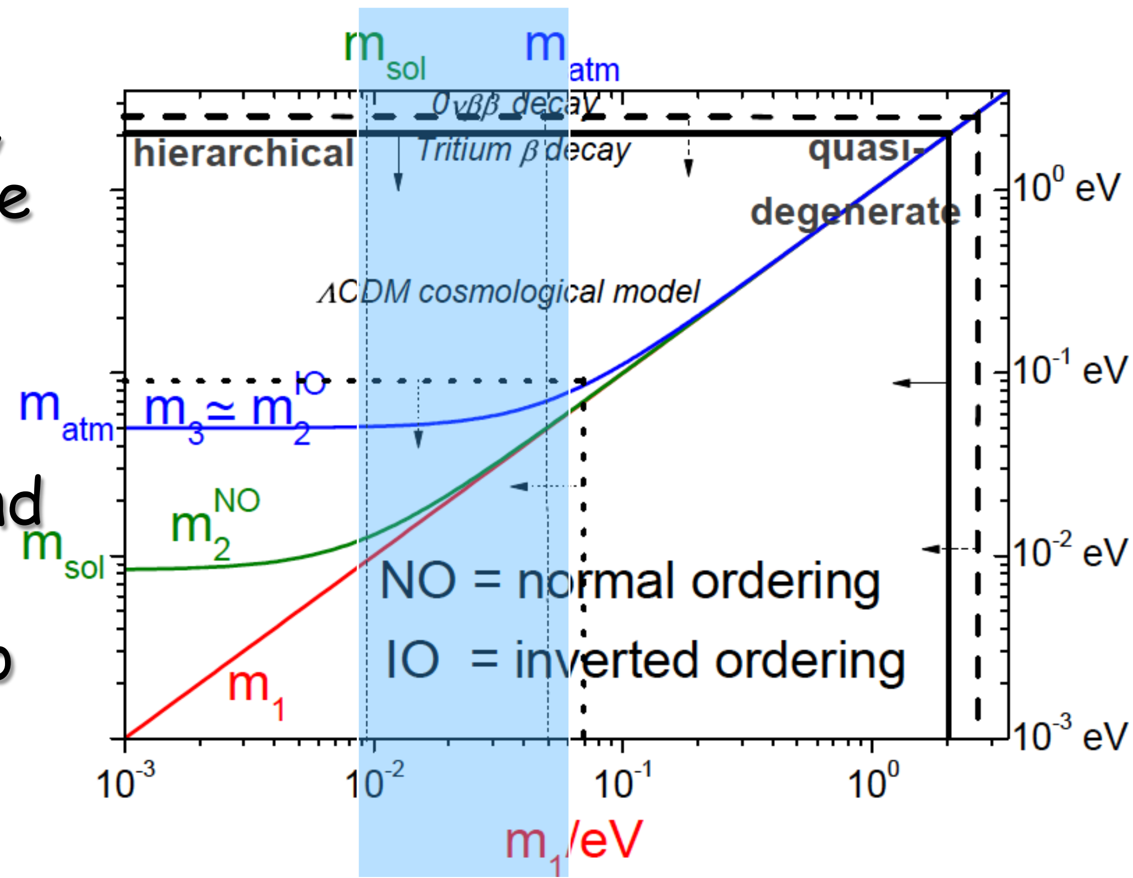
neutrino mixing data

2 possible schemes: normal or inverted

$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

$$m_2^2 - m_1^2 = \Delta m^2_{\rm sol} \text{ or } \Delta m^2_{\rm atm} \qquad m_{\rm sol} \equiv \sqrt{\Delta m^2_{\rm sol}} \simeq 0.009\,{\rm eV}$$

If STL with NO and Planck bound are correct, then neutrino masses have to fall into the "partial hierarchical" window: necessary to solve the ambiguity between NO and IO with neutrino oscillation experiments to extract m_1 and test STL



SO(10)-inspired leptogenesis

(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03)

Expressing the neutrino Dirac mass matrix m_D (in the basis where the Majorana mass and charged lepton mass matrices are diagonal) as:

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

SO(10) inspired conditions:

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

From the seesaw formula one can express:

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

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

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

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

$\Rightarrow$...realizes the N_2-dominated scenario and also...

Strong thermal SO(10)-inspired solution

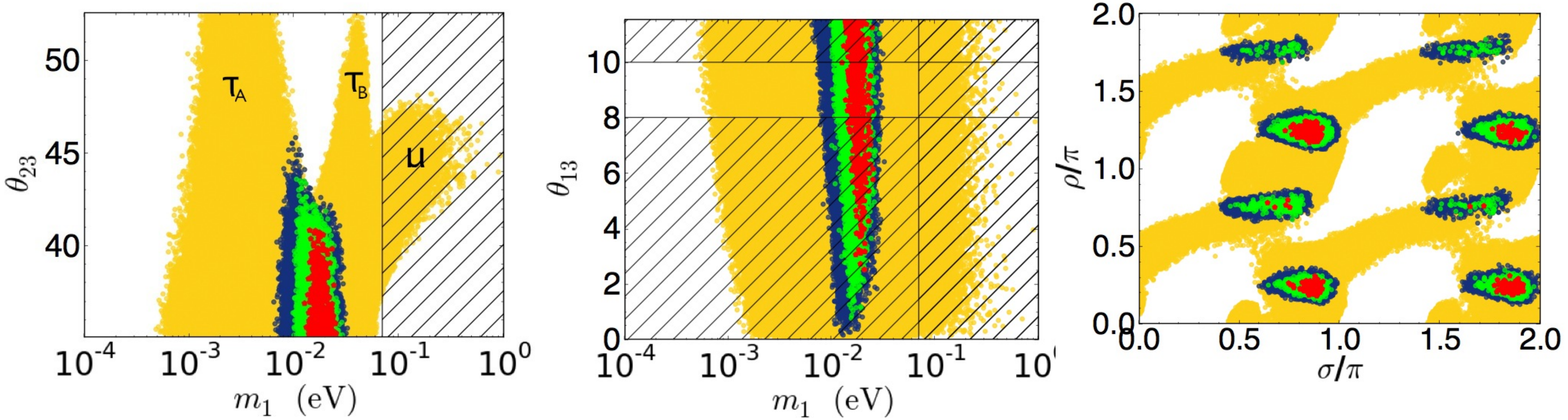
- successful leptogenesis can be attained ($\eta_B = \eta_B^{CMB}$) for some allowed regions in the space of low energy neutrino parameters (see-saw is overconstained!): YELLOW REGIONS. This happens because α_1 and α_3 cancel out in the calculation of the asymmetry

(PDB, Marzola '11-'12)

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

(PDB, Marzola '11-'12)

α_2=5 NORMAL ORDERING $N_{B-L}^{P,i}$= 0.001, 0.01, 0.1 $I \leq V_L \leq V_{CKM}$



For IO marginal allowed solutions but not satisfying strong thermal!

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

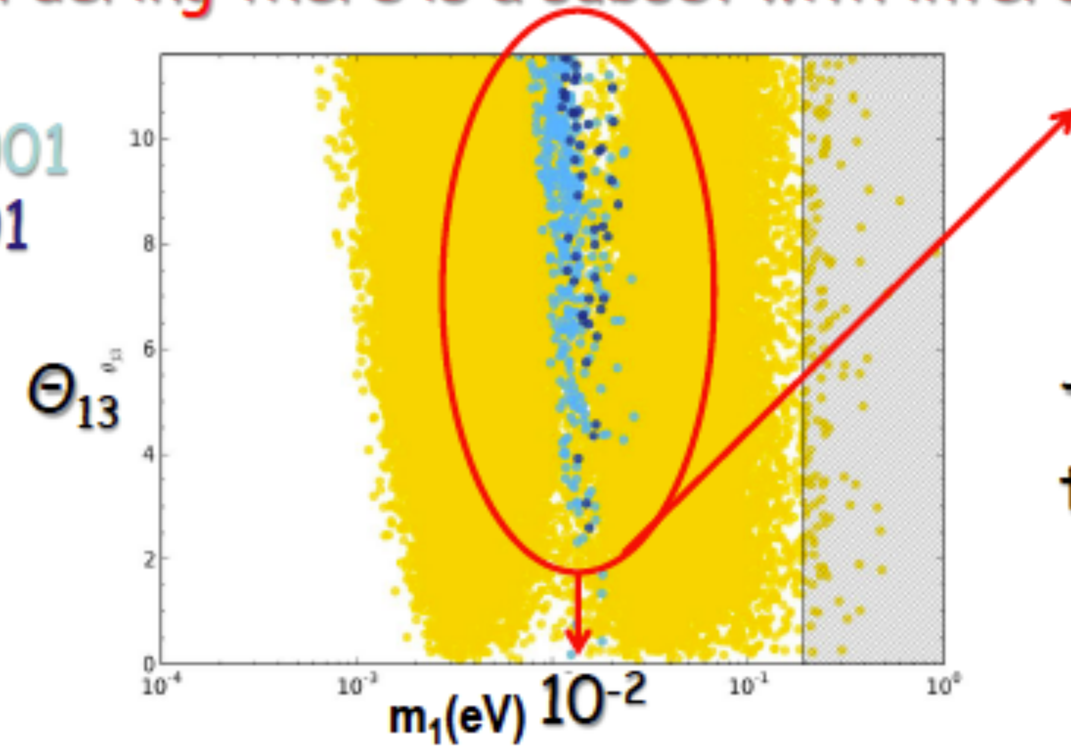
(PDB, Marzola '11)

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

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

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

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



Talk at the DESY theory workshop 28/9/11

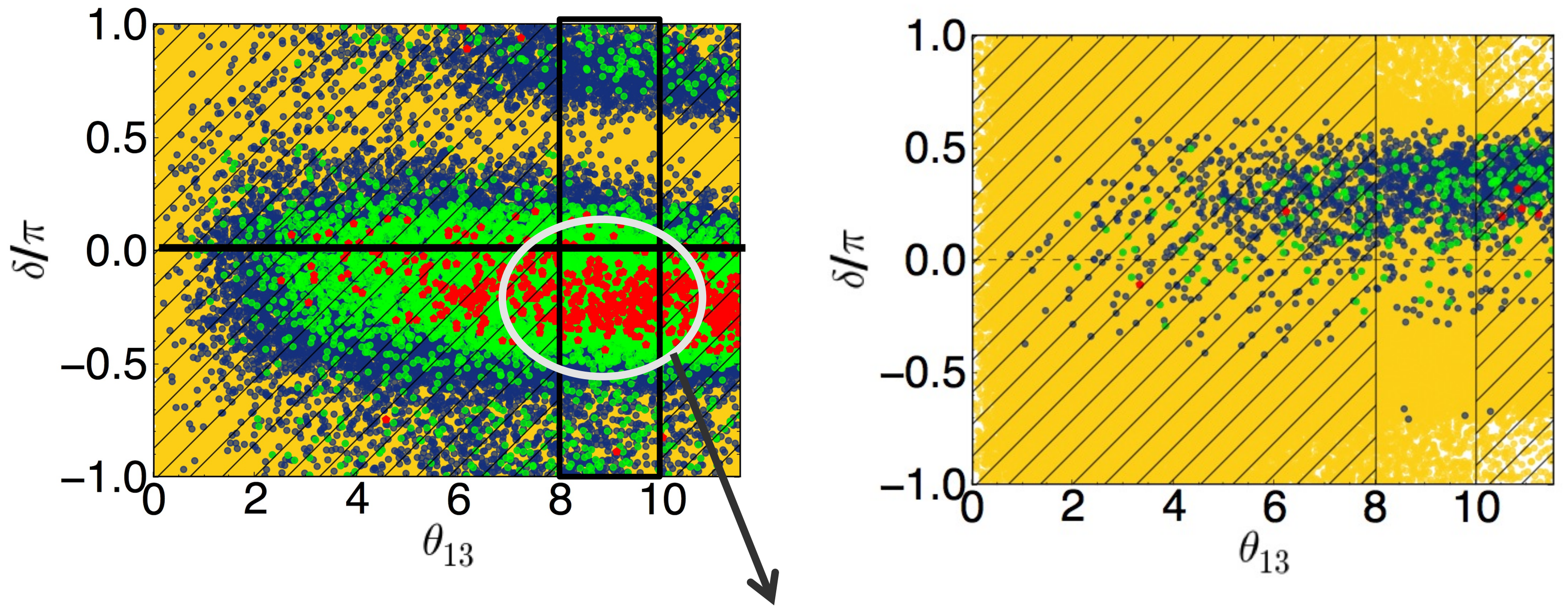
SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

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

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

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



A Dirac phase $\delta \sim -45^\circ$ is favoured for large θ_{13}

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

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

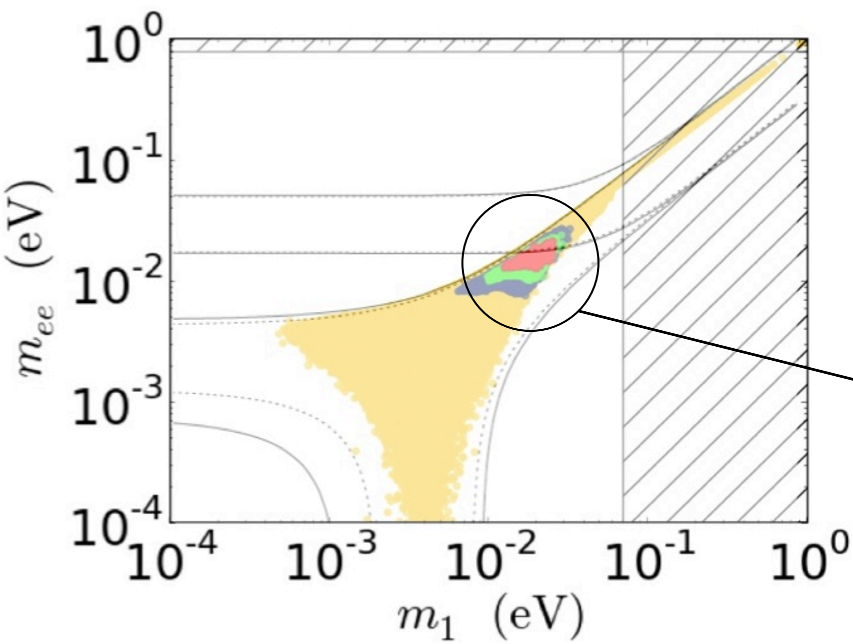
Imposing both successful SO(10)-inspired leptogenesis

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

Sharp prediction on the absolute neutrino mass scales

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

$\alpha_2 = 5$



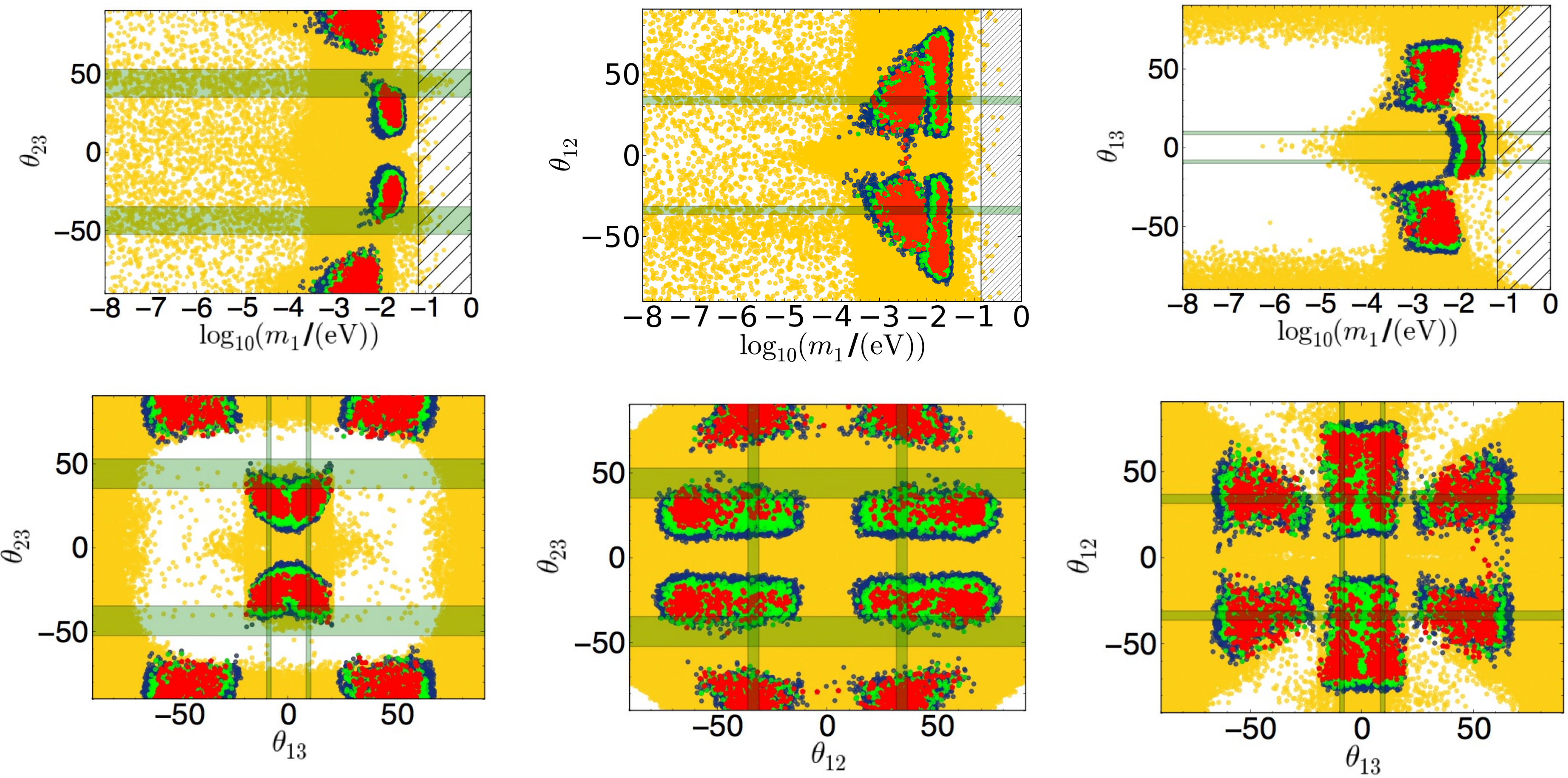
$m_{ee} \simeq 0.8 m_1 \simeq 15$ meV

Testable

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

(PDB, Marzola '13)

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

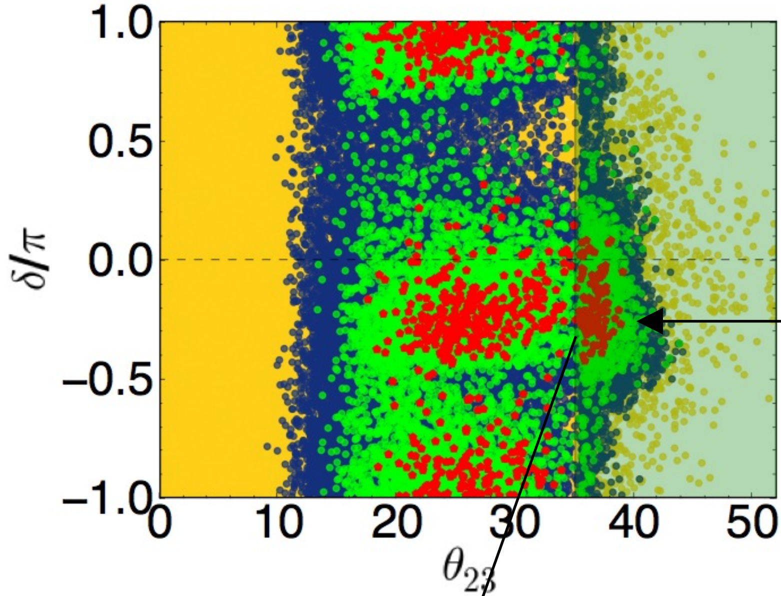


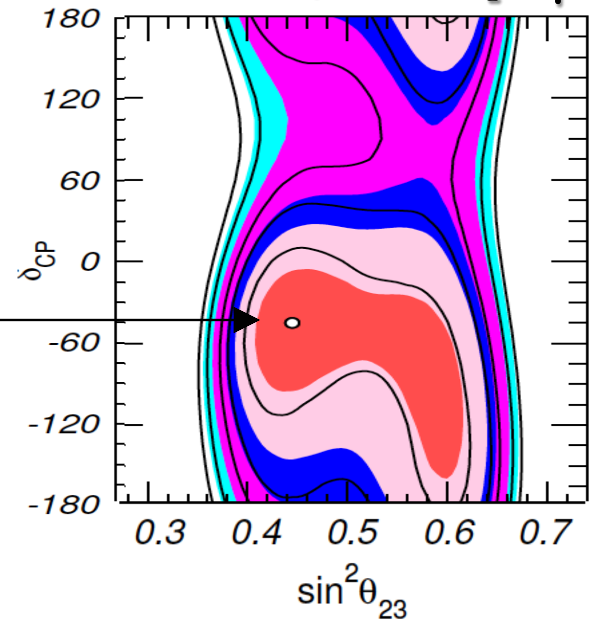
Strong thermal SO(10)-inspired leptogenesis: the atmospheric mixing angle test

NuFIT 1.2 (2013)

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

arXiv:1308.1107





The allowed range for the Dirac phase gets narrower at large values of $\theta_{23} \gtrsim 35^0$

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

Some Final Remarks

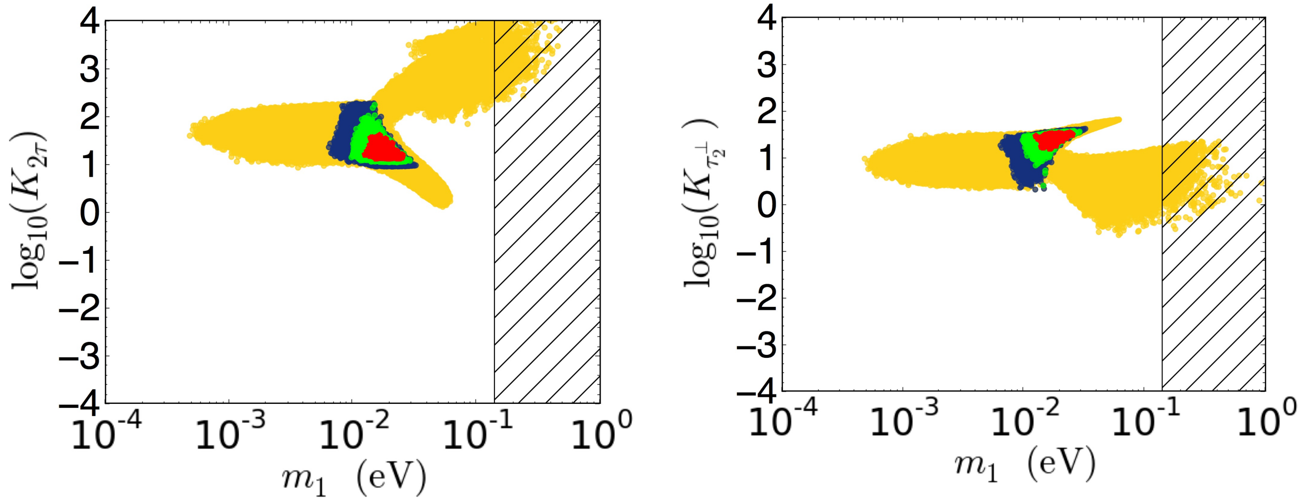
- ✓ If confirmed the BICEP2 signal would support the existence of a very high energy scale (intriguingly close to the grand-unified scale) and likely of very high values of the reheat temperature
- ✓ This would certainly be compatible with a high energy model of baryogenesis such as traditional high scale thermal leptogenesis but it also makes the problem of the initial conditions more compelling
- ✓ With flavour effects the N_2-dominated scenario is the only one able to satisfy strong thermal condition (holds for hierarchical spectrum)
- ✓ But measured values of mixing angles imply a deviation of neutrino masses from the hierarchical limits that might be detected and this is more compelling for NO (BOSS hint as a preliminary hint?)
- ✓ SO(10)-inspired models realise the N_2-dominated scenario and can also realise strong thermal leptogenesis

Strong thermal SO(10)-inspired leptogenesis solution

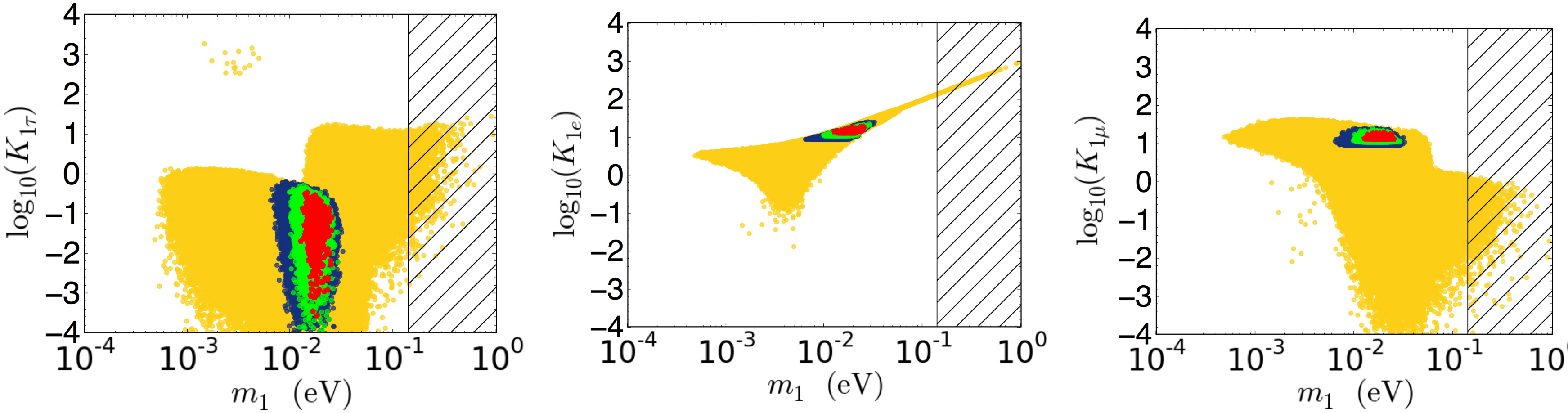
ORDERING	NORMAL
θ_{13}	$\gtrsim 3^\circ$
θ_{23}	$\lesssim 42^\circ$
δ	**$\sim -45^\circ$**
$m_{ee} \simeq 0.8\, m_1$	$\simeq 15$ meV

Some insight from the decay parameters

At the production ($T \sim M_2$)



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



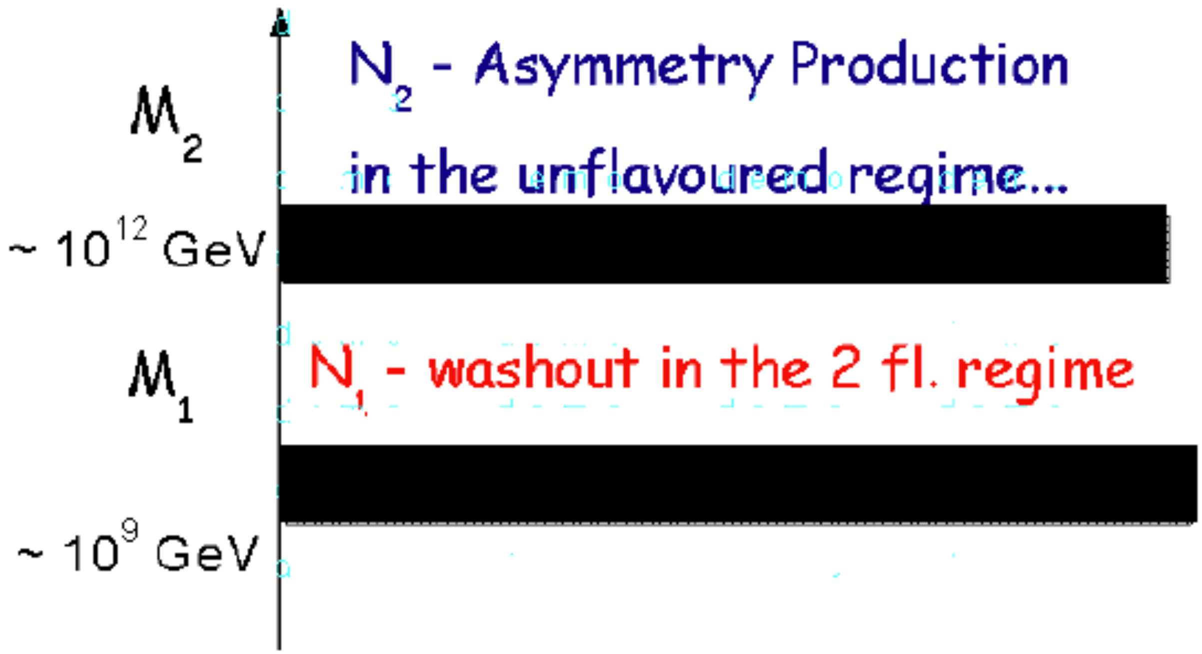
Interplay between lepton and heavy neutrino flavour effects:

- N_2 flavoured leptogenesis
  (Vives '05; Blanchet, PDB '06; Blanchet, PDB '08)
- Phantom leptogenesis
  (Antusch, PDB, King, Jones '10;
  Blanchet,PDB, Jones, Marzola '11)
- Flavour projection
  (Barbieri,Creminelli,Stumia,Tetradis '00;
  Engelhard, Grossman, Nardi, Nir '07)
- Flavour coupling
  (Abada,Josse Michaux '07, Antusch, PDB, King, Jones '10)

Phantom Leptogenesis

(Antusch, PDB, King, Jones '10)

Consider this situation



What happens to $N_{B\text{-}L}$ at $T \sim 10^{12}$ GeV?

How does it split into a $N_{\Delta\tau}$ component and into a $N_{\Delta e+\mu}$ component?

One could think:

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

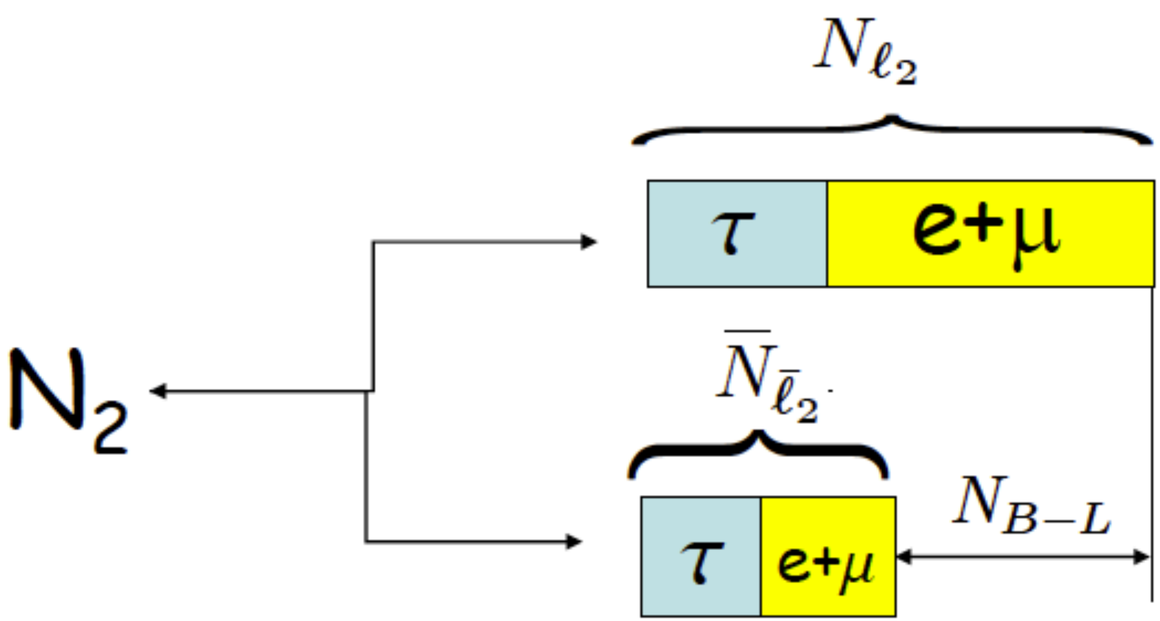
$$N_{\Delta e+\mu} = p_{2\, e+\mu}\, N_{B\text{-}L}$$

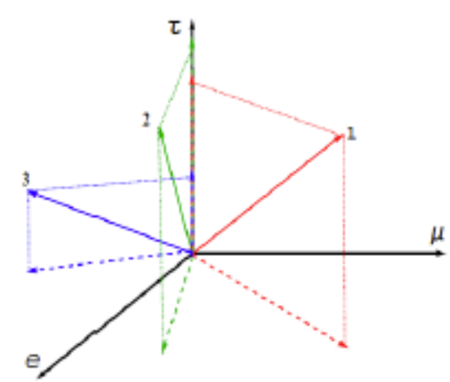
Phantom terms

However one has to consider that in the unflavoured case there are contributions to $N_{\Delta\tau}$ and $N_{\Delta e+\mu}$ that are not just proportional to N_{B-L}

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

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



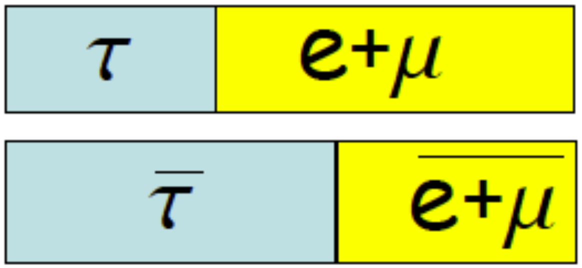


Phantom Leptogenesis

(Antusch, PDB, King, Jones '10)

Let us then consider a situation where $K_2 \gg 1$ so that at the end of the N_2 washout the total asymmetry is negligible:

1) $T \sim M_2$: unflavoured regime



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

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

$$N_{B-L}^{T\sim M_2} = N_{\Delta\tau}^{T\sim M_2} + N_{\Delta_{e+\mu}}^{T\sim M_2} \simeq 0\,!$$

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

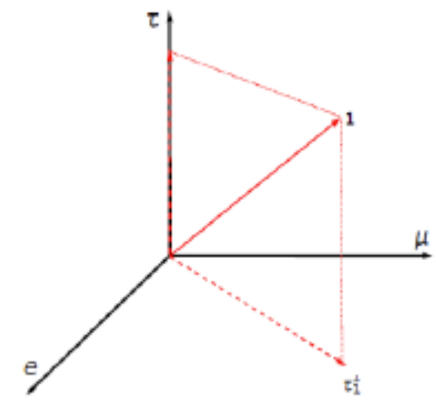
Assume $K_{1\tau} \lesssim 1$ and $K_{1e+\mu} \gg 1$ $\qquad N_{B-L}^{\rm f} \simeq N_{\Delta_\tau}^{T\sim M_2}\,!$

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

Phantom Leptogenesis within a density matrix formalism

(Blanchet, PDB, Marzola, Jones '11-12')

In a picture where the gauge interactions are neglected the lepton and anti-leptons density matrices can be written as:



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

There is a recent update (see 1112.4528 v2 to appear in JCAP)

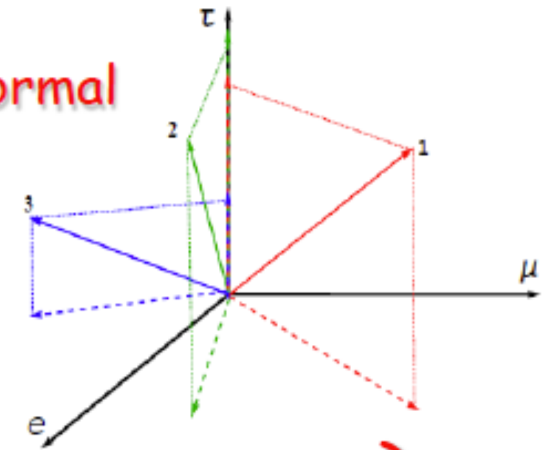
Because of the presence of gauge interactions, the difference
of flavour composition between lepton and anti-leptons is measured and this induces a wash-ou
the phantom terms from Yukawa interactions though with halved wash-out rate compared to t
one acting on the total asymmetry and in the end:

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

Flavour projection

(Engelhard, Nir, Nardi '08 , Bertuzzo,PDB,Marzola '10)

Assume $M_{i+1} \gtrsim 3M_i$ (i=1,2)



The heavy neutrino flavour basis cannot be orthonormal otherwise the CP asymmetries would vanish: this complicates the calculation of the final asymmetry

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

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

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

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

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

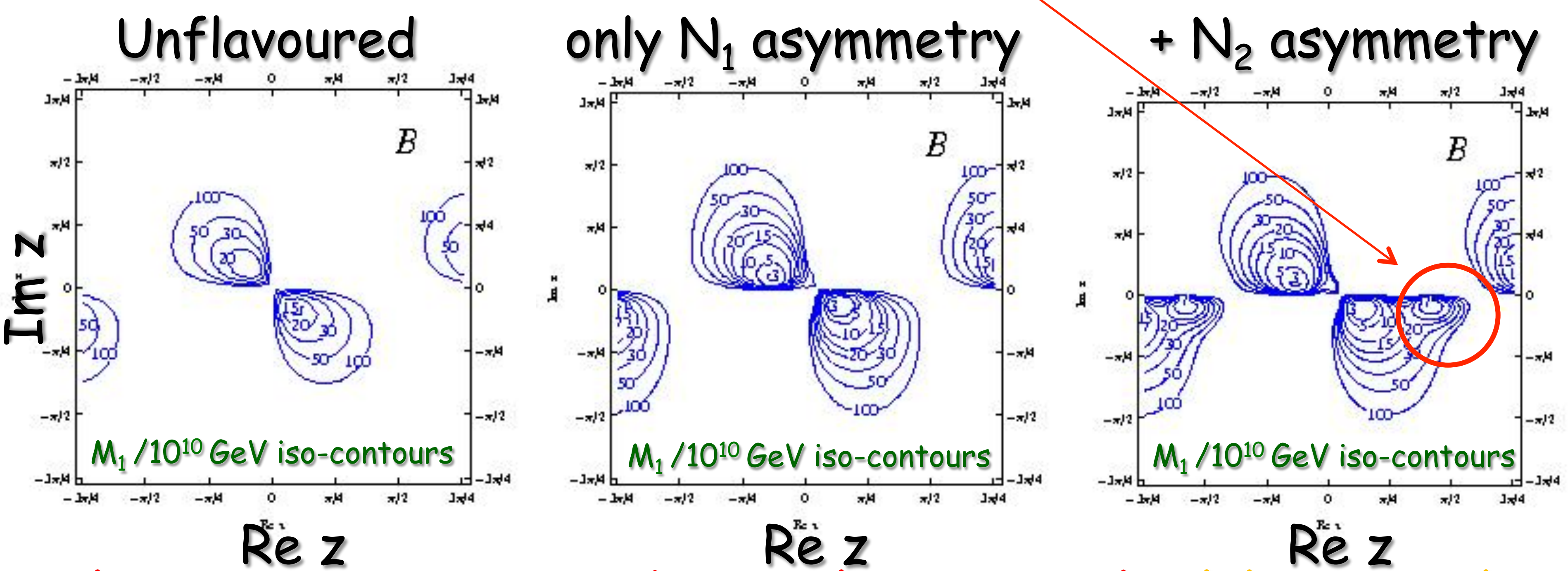
2 RH neutrino scenario revisited

(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

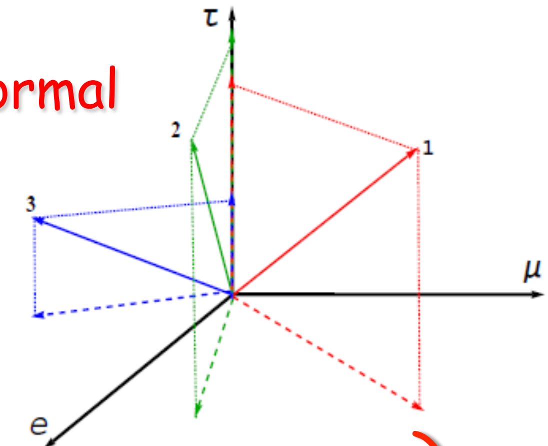
Flavour projection

(Engelhard, Nir, Nardi '08 , Bertuzzo,PDB,Marzola '10)

Assume M_{i+1} [symbol] $3M_i$ (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

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



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

$$N_{B\,¡\,L}^{(N_2)}(T\ ¿\ M_1) = N_{¢\,1}^{(N_2)}(T\ ¿\ M_1) + N_{¢\,1?}^{(N_2)}(T\ ¿\ M_1)$$

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

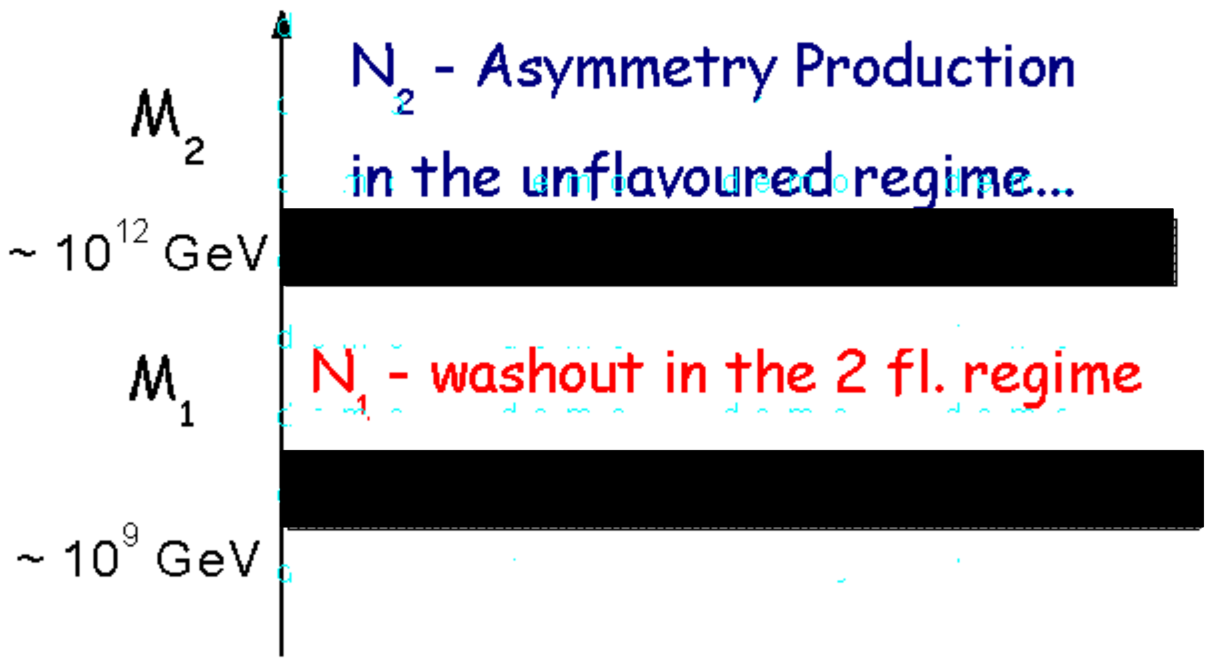
Contribution from heavier RH neutrinos **orthogonal** to l_1 and escaping N_1 wash-out

$$N_{¢\,1}^{(N_2)}(T\ ¿\ M_1) = p_{12}\, e^{¡\,\frac{3¼}{8} K_1}\, N_{B\,¡\,L}^{(N_2)}(T\ »\ M_2)$$

Phantom Leptogenesis

(Antusch, PDB, King, Jones '10)

Consider this situation



What happens to N_{B-L} at $T \sim 10^{12}$ GeV?

How does it split into a $N_{\Delta\tau}$ component and into a $N_{\Delta e+\mu}$ component?

One could think:

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

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

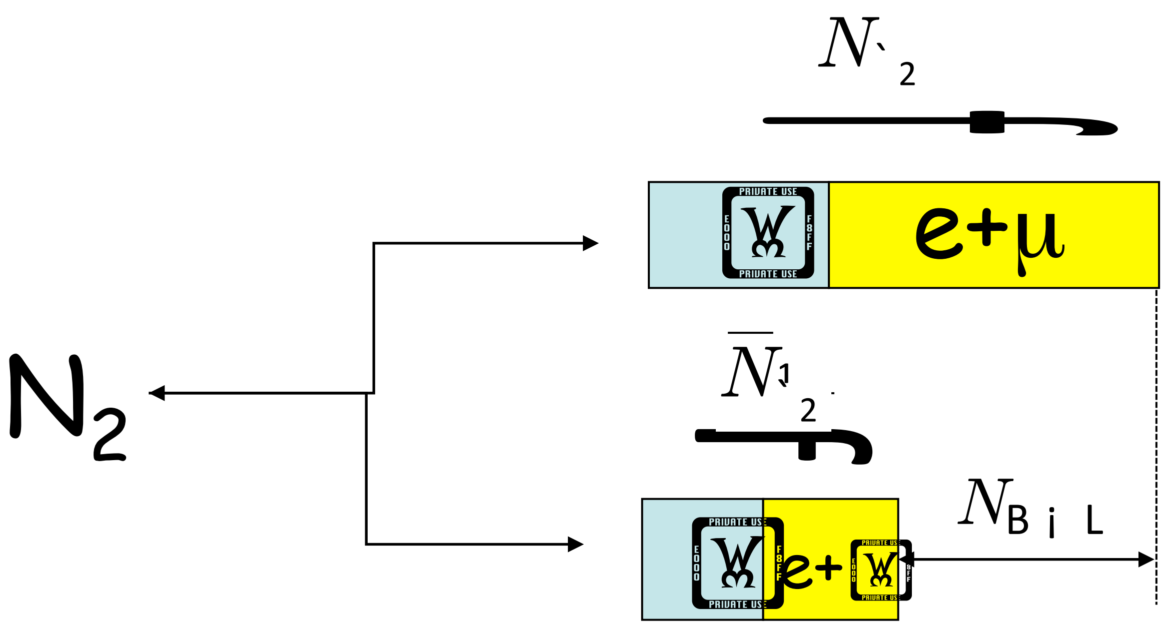
Phantom terms

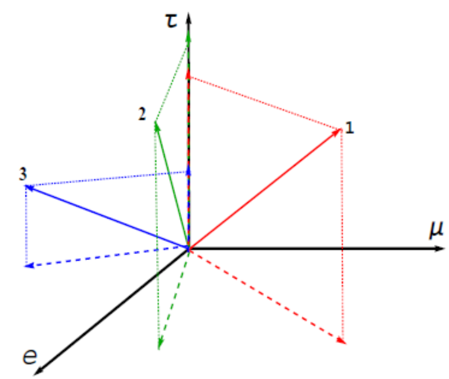
However one has to consider that in the unflavoured case there are contributions to $N_{\Delta\tau}$ and $N_{\Delta e+\mu}$ that are not just proportional to N_{B-L}

Remember that:

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

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



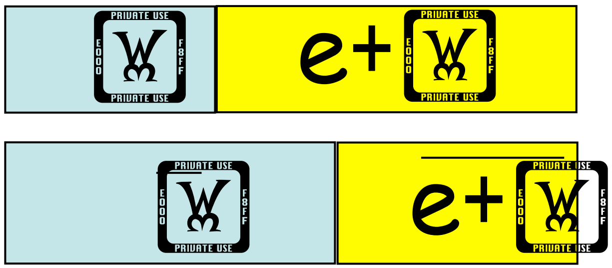


Phantom Leptogenesis

(Antusch, PDB, King, Jones '10)

Let us then consider a situation where $K_2 \gg 1$ so that at the end of the N_2 washout the total asymmetry is negligible:

1) $T \sim M_2$: unflavoured regime



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

2) 10^{12} GeV $\gtrsim$ T >> M_1 :decoherence $\Rightarrow$ 2 flavoured regime

$$N_{B-L}^{T\sim M_2} = N_{\Delta_\tau}^{T\sim M_2} + N_{\Delta_{e+\mu}}^{T\sim M_2} \simeq 0 \ !$$

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

Assume $K_{1\tau} \lesssim 1$ and $K_{1e+\mu} \gg 1$ $\qquad N_{B-L}^{f} \simeq N_{\Delta_\tau}^{T\sim M_2}$!

The N_1 wash-out un-reveal the phantom term and effectively it creates a N_{B-L} asymmetry. Fully confirmed within a density matrix formalism (Blanchet, PDB, Marzola, Jones '11)

Remarks on phantom Leptogenesis

We assumed an initial N_2 thermal abundance but if we were assuming
An initial vanishing N_2 abundance the phantom terms were just zero !

$$N^{\mathrm{phantom}}_{\text{¢ ¿}} = \frac{\text{¢ } p_{2\text{¿}}}{2} N^{\mathrm{in}}_{N_2}$$

The reason is that if one starts from a vanishing abundance during the N_2 production one creates a contribution to the phantom term by inverse decays with opposite sign and exactly cancelling with what is created in the decays

In conclusion ....phantom leptogenesis introduces additional strong dependence on the initial conditions

NOTE: in strong thermal leptogenesis phantom terms are also washed out: full independence of the initial conditions!

Phantom terms cannot contribute to the final asymmetry in N_1 leptogenesis but (canceling) flavoured asymmetries can be much bigger than the baryon asymmetry and have implications in active-sterile neutrino oscillations

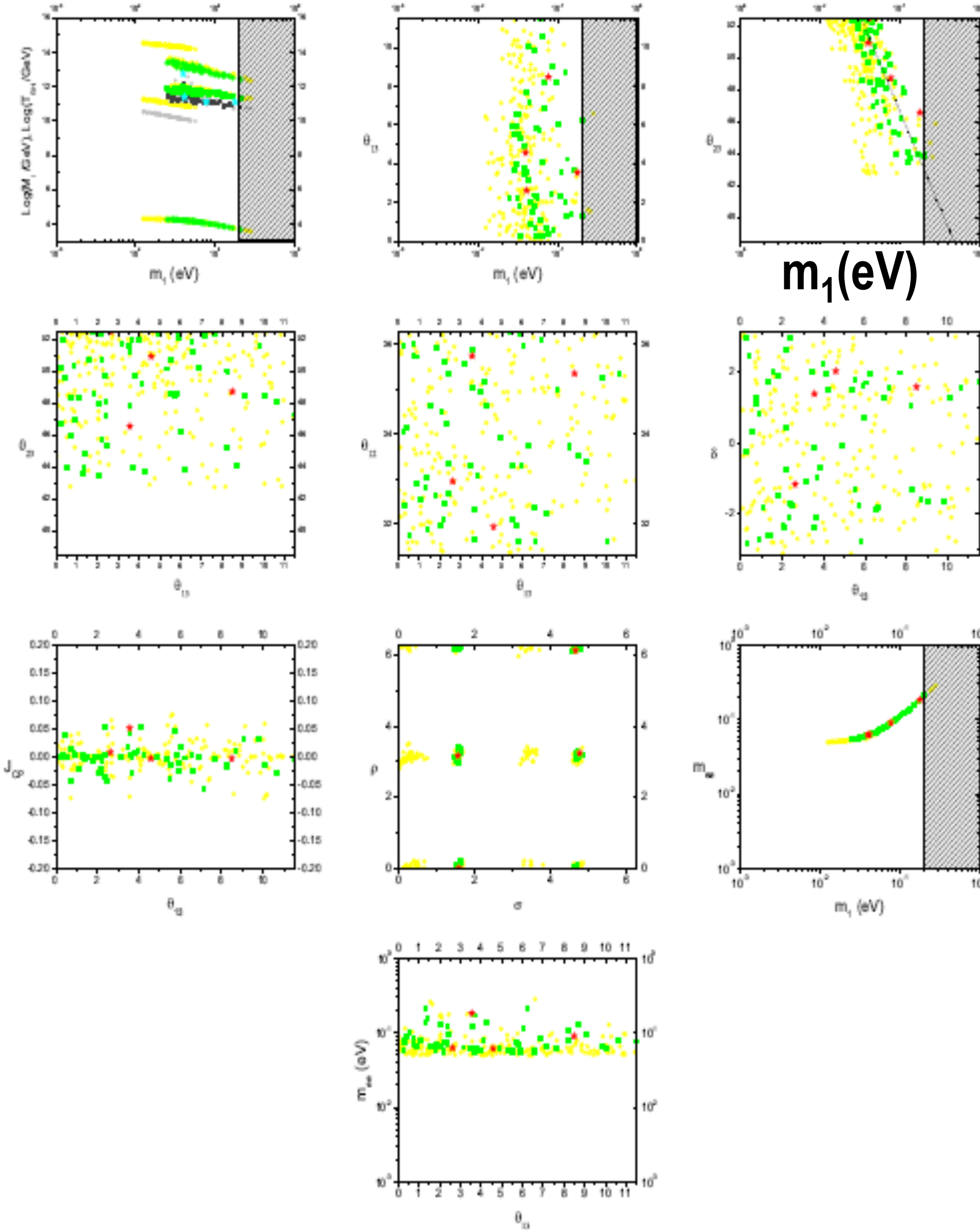
$I \leq V_L \leq V_{CKM}$

INVERTED ORDERING

$\alpha_2 = 5$

$\alpha_2 = 4$

$\alpha_2 = 1.5$



Θ_{23}

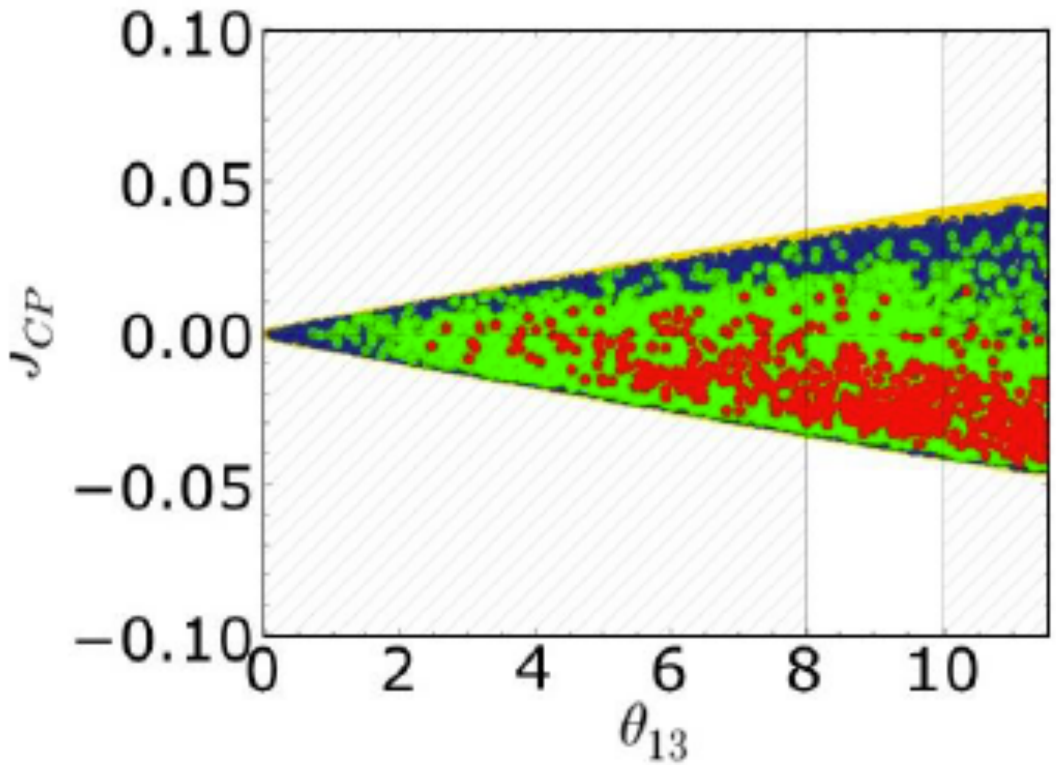
No link between the sign of the asymmetry and J_{CP}

(PDB, Marzola)

α_2=5

NORMAL ORDERING

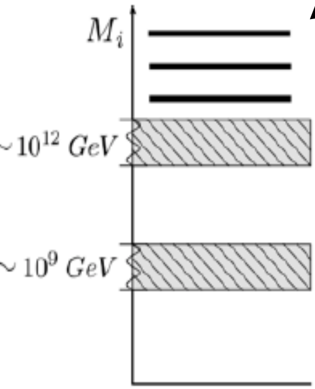
$I \leq V_L \leq V_{CKM}$



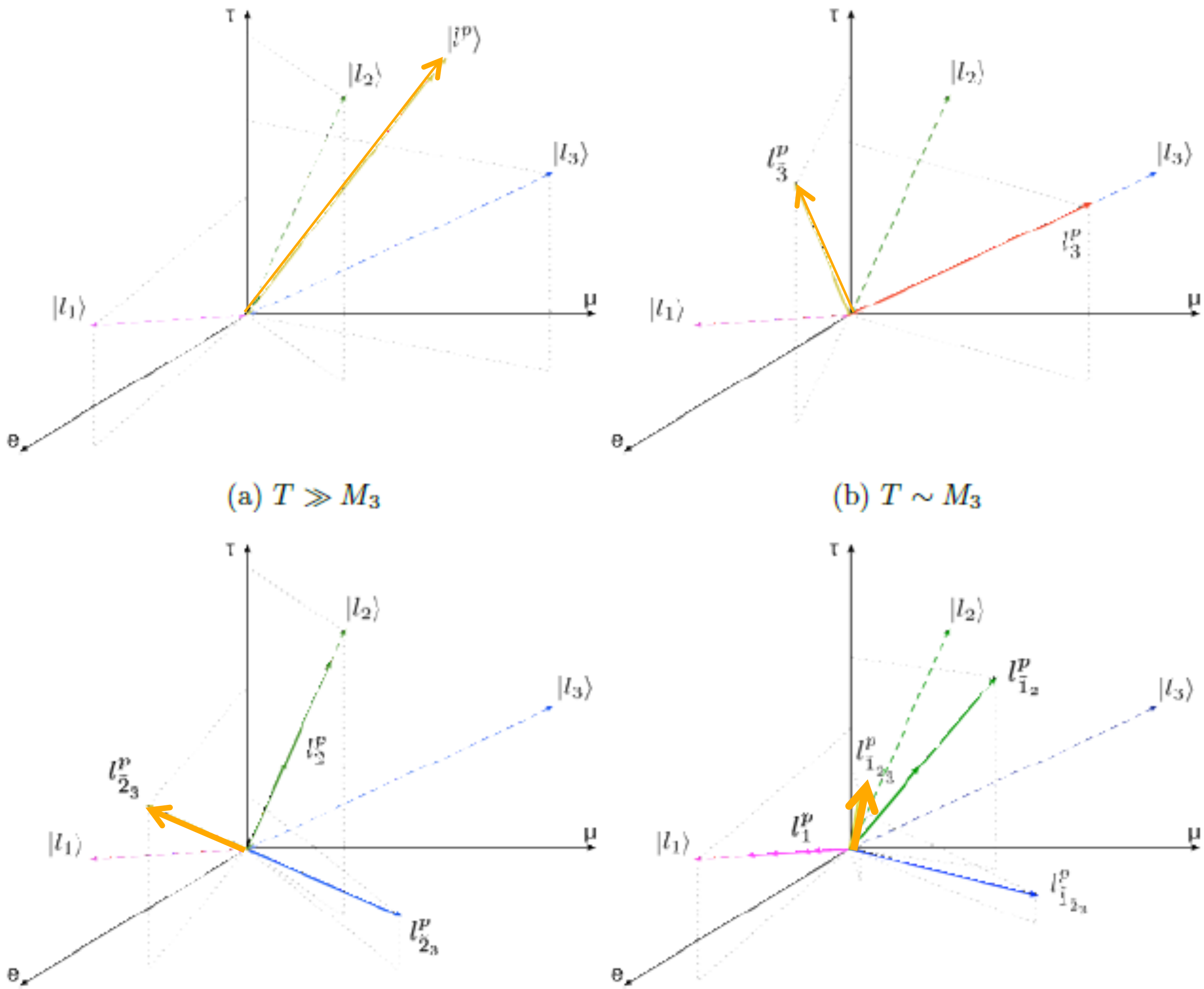
It is confirmed that there is no link between the matter-antimatter asymmetry and CP violation in neutrino mixing…….for the yellow points

WHAT ARE THE NON-YELLOW POINTS ?

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



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



(a) $T \gg M_3$

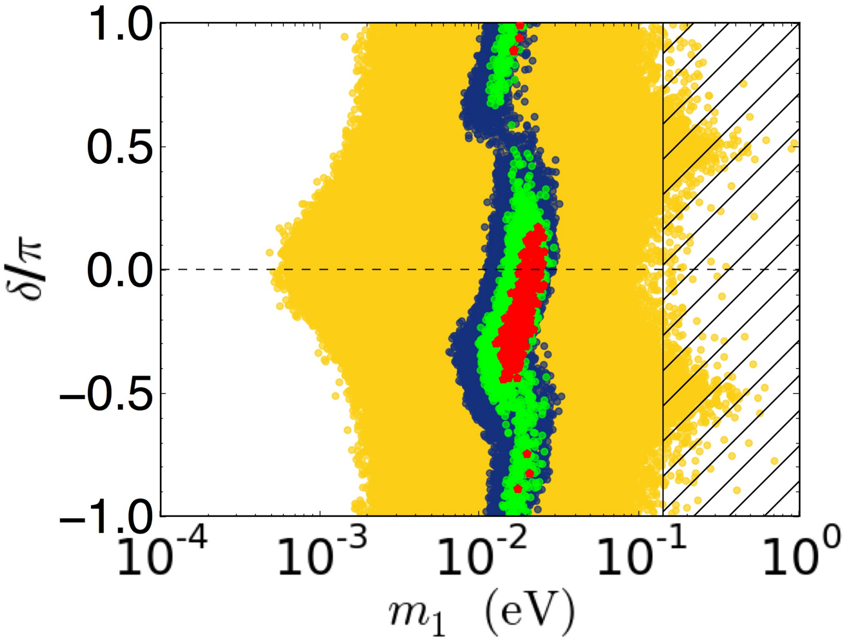
(b) $T \sim M_3$

(c) $T \sim M_2$

(d) $T \sim M_1$

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

$\eta_B = \eta^{CMB}_B$



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