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Leptogenesis and low energy neutrino data

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The double side of Leptogenesis

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

• *Cosmological Puzzles :*

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

• *New stage in early Universe history :*

T	
?	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 mechanism

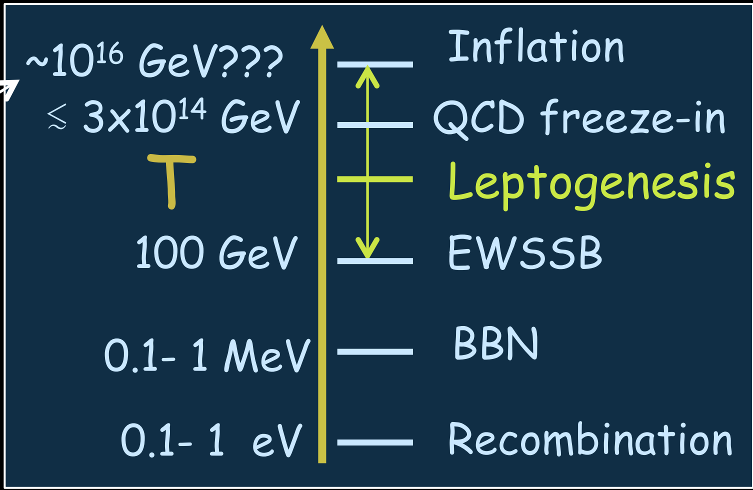
Two important questions:

1. Can leptogenesis help to understand neutrino parameters?

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

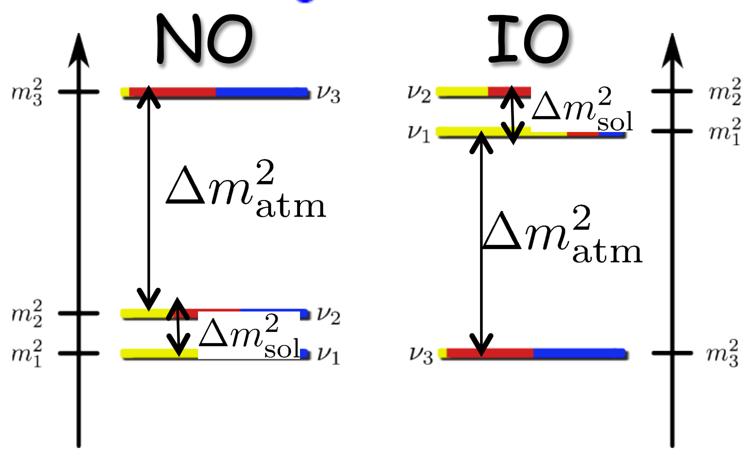
A common approach in the LHC era: "TeV Leptogenesis"

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



- No new physics at LHC (not so far);
- New scale ~ 10^{16} GeV if BICEP2 will be confirmed would typically imply very high reheat temperatures;
- Discovery of a non-vanishing reactor angle opening the door to further information on mixing parameters;
- Cosmological observations start to have the sensitivity to either rule our or discover quasi-degenerate neutrino masses

Neutrino masses: $m_1 < m_2 < m_3$



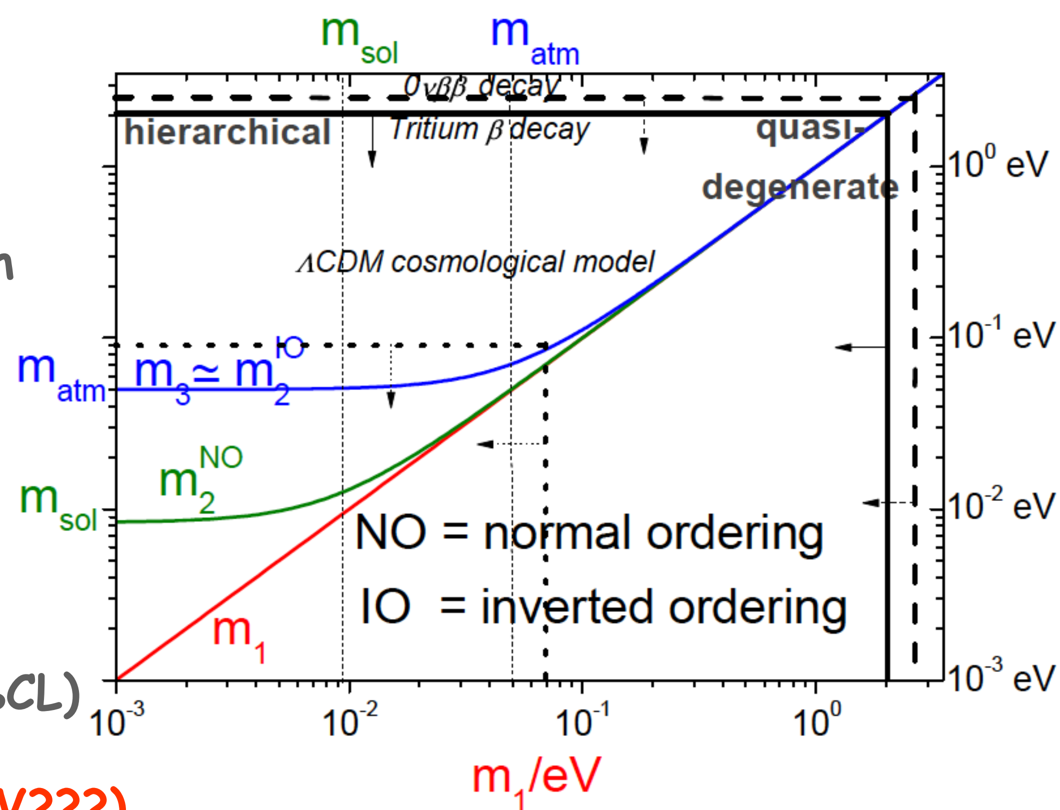
$$m_{atm} \equiv \sqrt{\Delta m^2_{atm} + \Delta m^2_{sol}} \simeq 0.05\,\mathrm{eV}$$

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

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

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

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



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

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

<u>3σ ranges(NO):</u>

$\theta_{23} \simeq 38^\circ - 53^\circ$
$\theta_{12} \simeq 32^\circ - 38^\circ$
$\theta_{13} \simeq 7.5^\circ - 10^\circ$
$\delta, \rho, \sigma = [-\pi,\pi]$

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

Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

• Type I seesaw

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

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

- 3 light neutrinos with masses $\boxed{\mathrm{diag}(m_1, m_2, m_3) = -U^{\dagger}\, m_D\, \frac{1}{M}\, m_D^T\, U^{\star}}$
- 3 very 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 its

total CP asymmetry $\quad \varepsilon_i \equiv -\frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i}$

• Thermal production of RH neutrinos

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

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

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

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

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

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

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

Vanilla leptogenesis

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

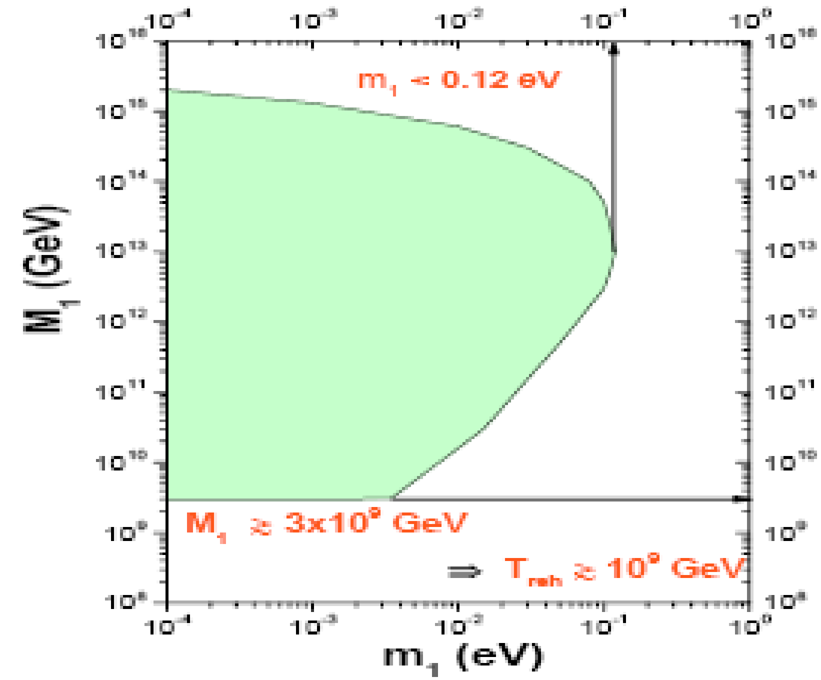
1) Lepton flavor composition is neglected

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

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

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

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



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

3) N_3 do not interfere with N_2:

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

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

4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

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

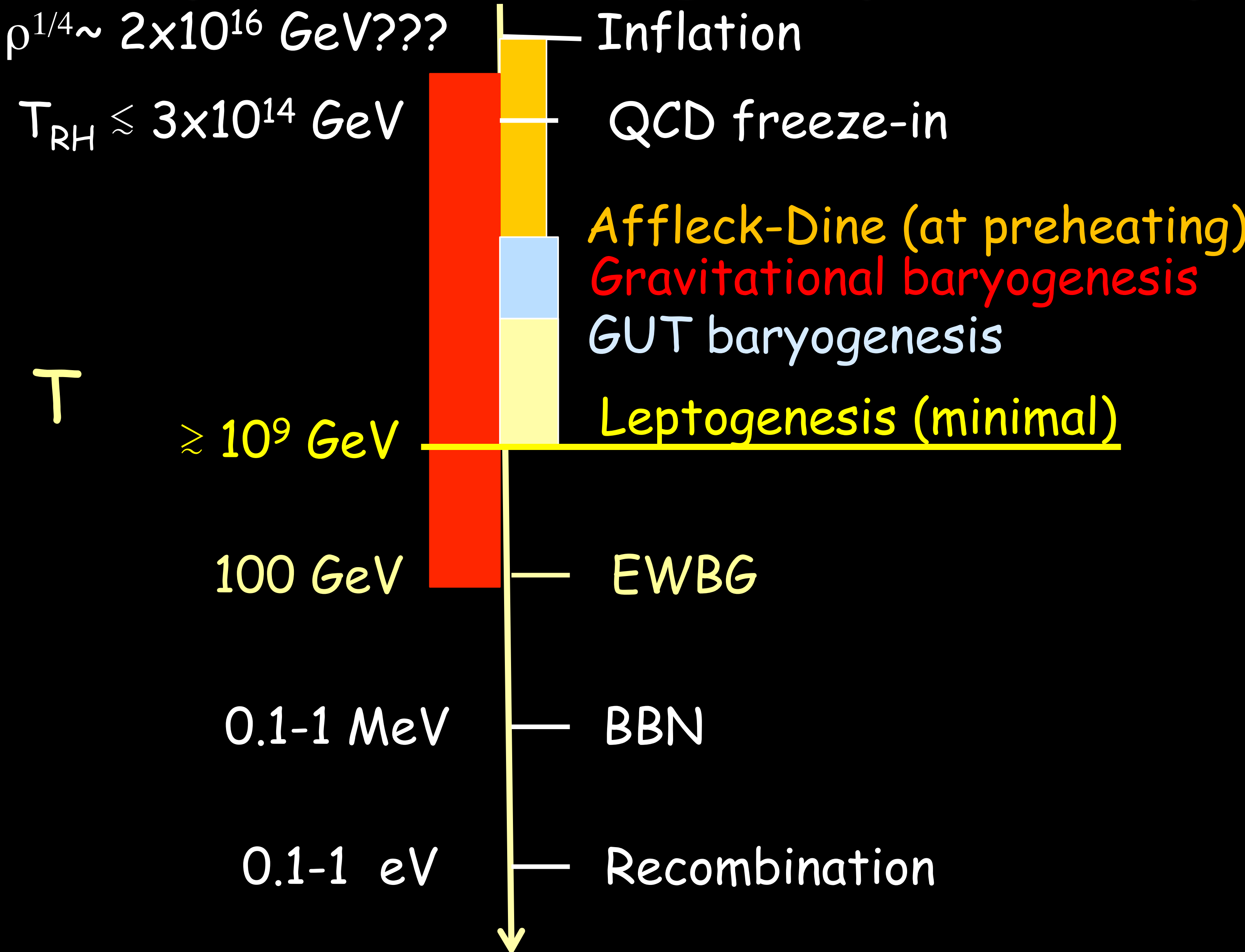
No dependence on the leptonic mixing matrix U

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

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

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

A pre-existing asymmetry?



Independence of the initial conditions

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

(Buchmüller, PDB, Plümacher '04)

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

decay parameter

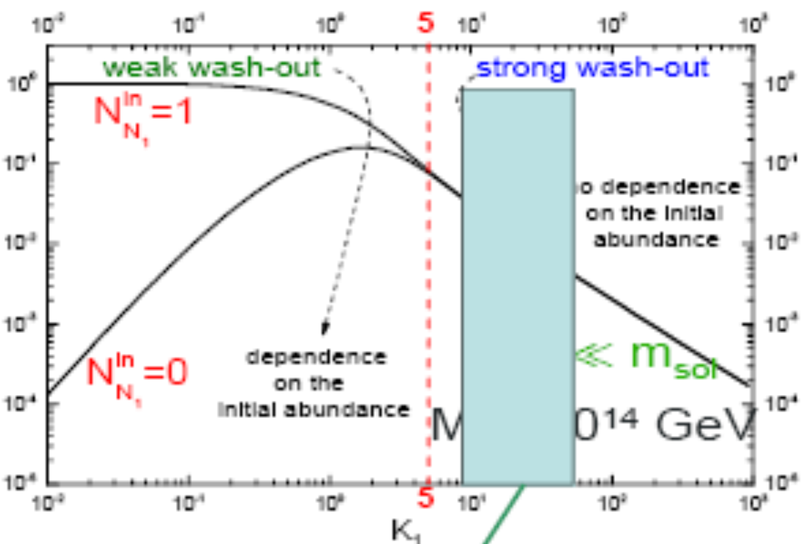
$$K_1 \equiv \frac{\Gamma_{N_1}}{H(T=M_1)} \sim \frac{m_{\rm sol,atm}}{m_\star \sim 10^{-3}\,{\rm eV}} \sim 10 \div 50$$

Independence of the initial abundance of N_1

wash-out of a pre-existing asymmetry

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

$\kappa_1^{\rm fin}$



$$K_1 \gtrsim K_{\rm st}(N^{\rm p,i}_{B-L}) \simeq 16 + 0.85\,\ln(|N^{\rm p,i}_{B-L}|)$$

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

Since $K_1 \gtrsim m_1/10^{-3}$ eV

$\Rightarrow$ optimal neutrino mass window:

$0.1\ {\rm eV} \gtrsim m_1 \gg 10^{-3}{\rm eV}$

The N_2-dominated scenario

(PDB '05)

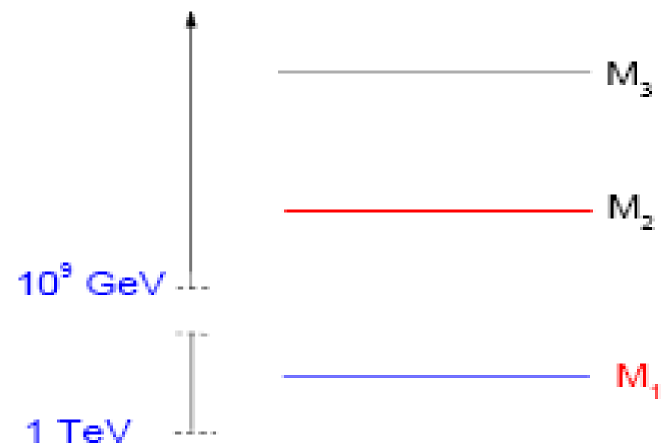
If light flavour effects are neglected the asymmetry from the next-to-lightest (N_2) RH neutrinos is typically washed-out:

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

...except for a special choice of $\Omega = R_{23}$ 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}



- Having $K_1 \lesssim 1$ is a special case. How special? $P(K_1 \lesssim 1) \simeq 0.2\%$ (random scan)

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

SO(10)-inspired leptogenesis

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

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

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

SO(10) inspired conditions*:

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

From the seesaw formula one can express:

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

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

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

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

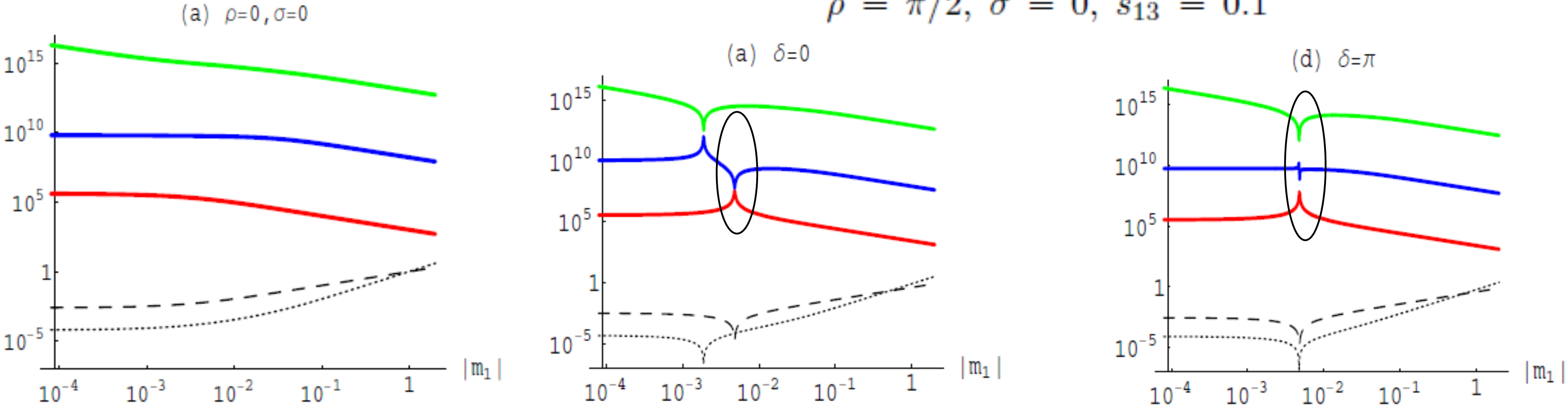
* Note that SO(10)-inspired consditions can be realized also beyond SO(10) and even beyond GUT models (e.g. "Tetraleptogenesis", King '13)

Crossing level solutions

(Akhmedov, Frigerio, Smirnov '03)

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

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



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

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

Lepton flavour effects

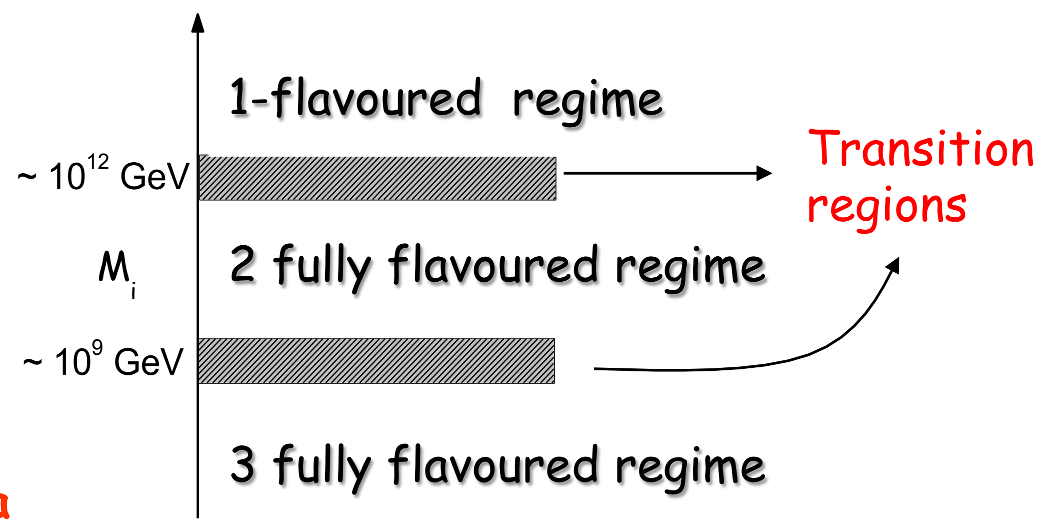
(Abada, Davidson, Losada, Josse-Michaux, Riotto'06; Nardi, Nir, Roulet, Racker '06; Blanchet, PDB, Raffelt '06; Riotto, De Simone '06)

Flavor composition of lepton quantum states:

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

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

- For $M_1 \lesssim 10^{12}$ GeV 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 $|\bar{l}'_1\rangle$ that become a incoherent mixture of a τ and of a μ+e component
  $\Rightarrow$ 2- flavour regime



- For $M_1 \lesssim 10^9$ GeV also μ- Yukawa interactions are fast enough
  $\Rightarrow$ 3-flavor regime

Two fully flavoured regime

- Classic Kinetic Equations (in their simplest form)

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

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

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

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

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

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

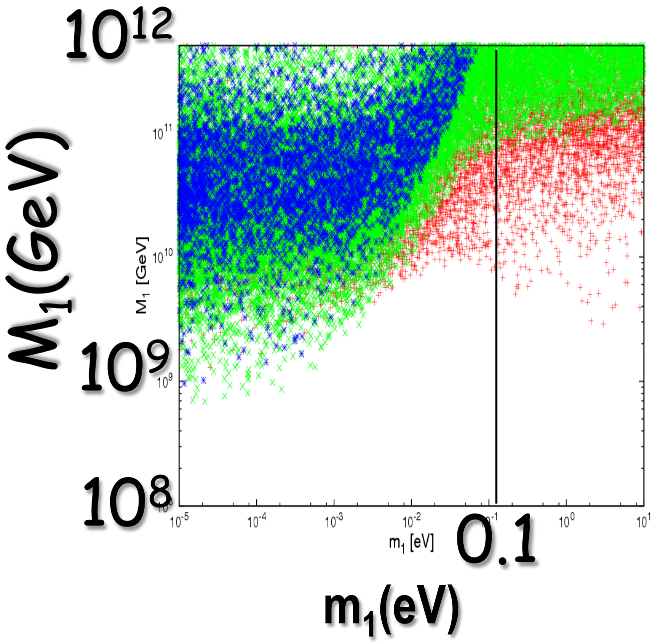
$$\Rightarrow \quad \boxed{\varepsilon_{1\alpha} \equiv -\frac{P_{1\alpha}\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = P_{1\alpha}^0\,\varepsilon_1 + \Delta P_{1\alpha}(\Omega, U)/2}$$

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

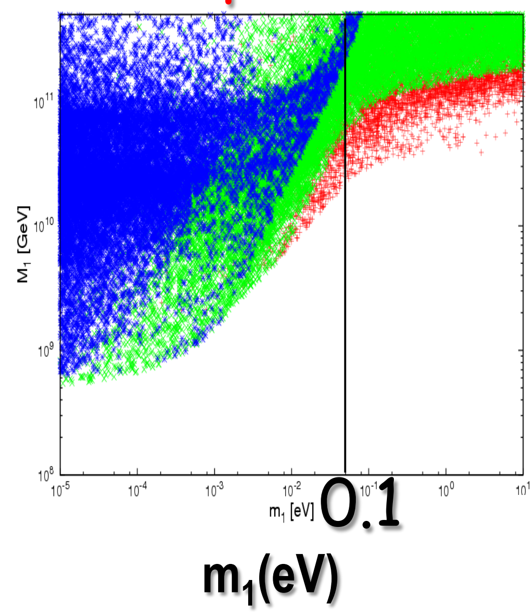
Flavoured decay parameters: $K_{i\alpha} \equiv P_{i\alpha}^0\, K_i = \left|\sum_k \sqrt{\frac{m_k}{m_\star}}\, U_{\alpha k}\,\Omega_{ki}\right|^2$

Neutrino mass bounds and role of PMNS phases

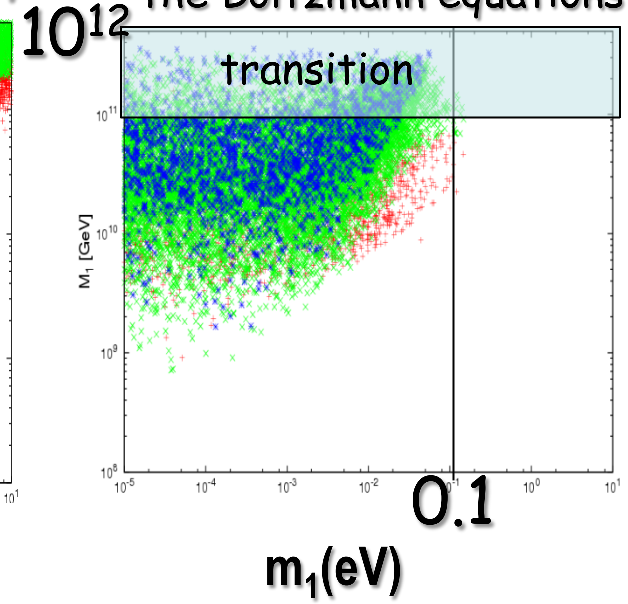
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)

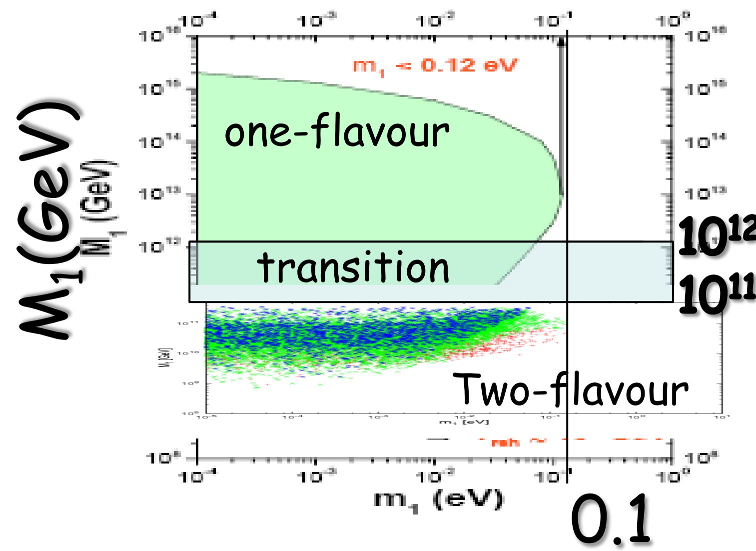


PMNS phases off



Imposing the validity of the Boltzmann equations



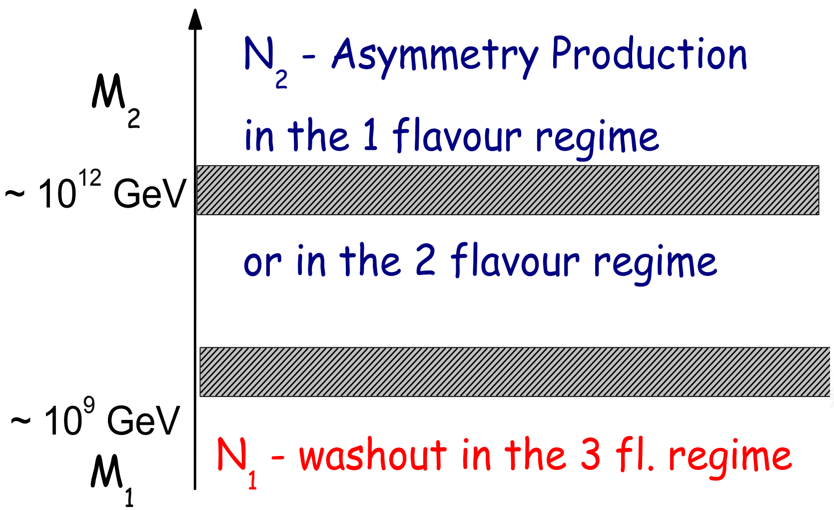


The N_2-dominated scenario (flavoured)

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

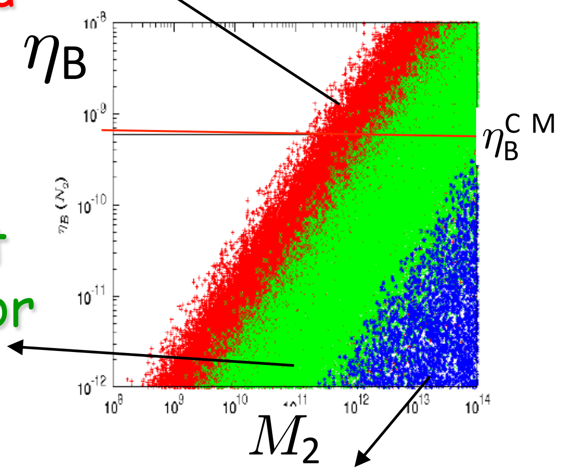
Flavour effects strongly enhance the importance of the N_2-dominated scenario

A two stage process:



N_1 wash-out is neglected

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



Both wash-out and flavor effects

Unflavored case

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

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

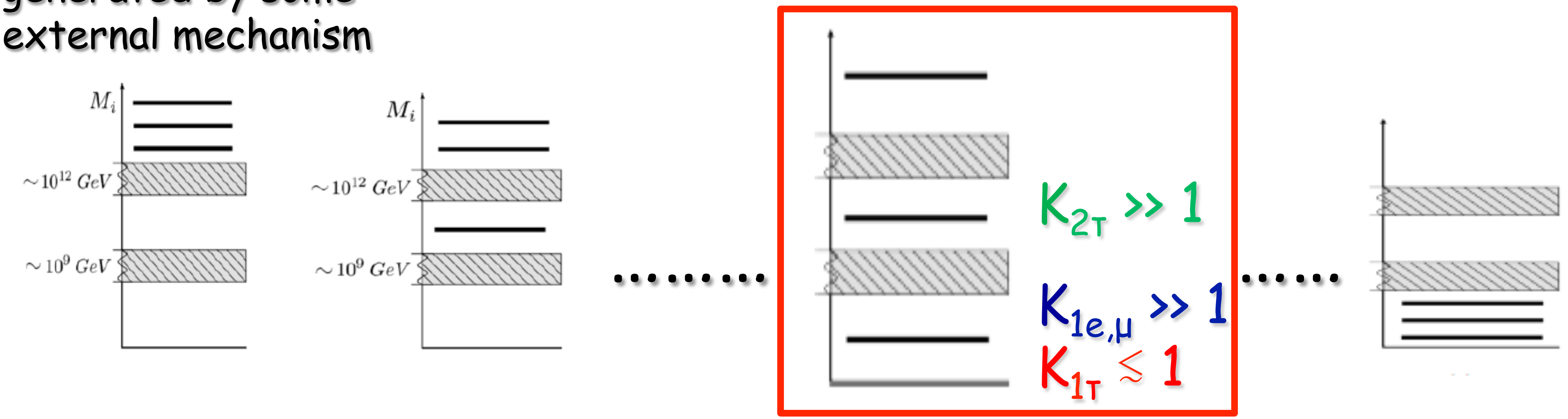
The problem of the initial conditions in flavoured leptogenesis

(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

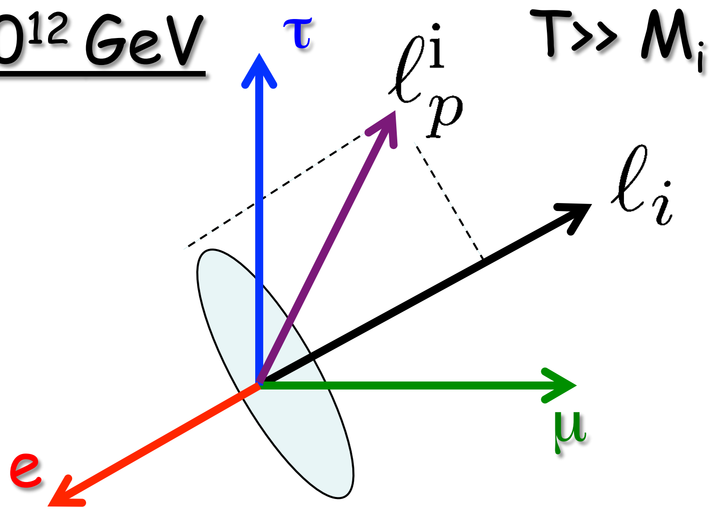


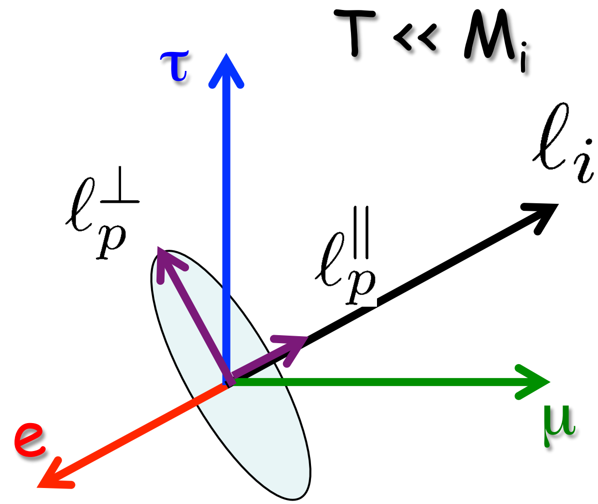
The conditions for the wash-out of a pre-existing asymmetry ('**strong thermal leptogenesis**') can be realised only within a N_2-dominated scenario where the final asymmetry is dominantly produced in the tauon flavour

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

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

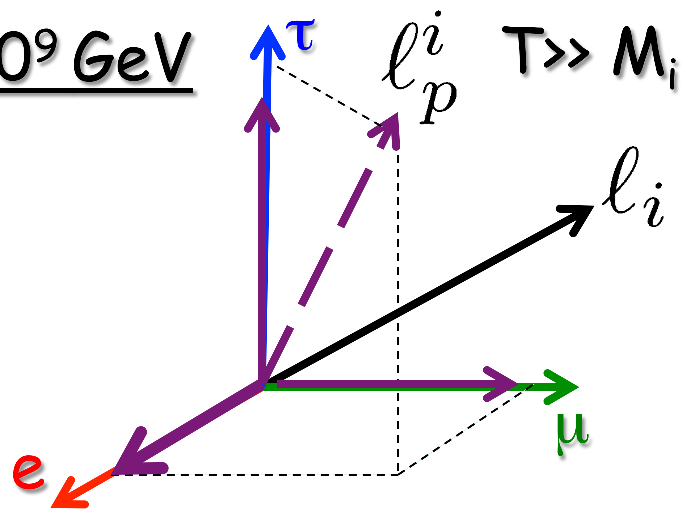
$M_i \gtrsim 10^{12}$ GeV

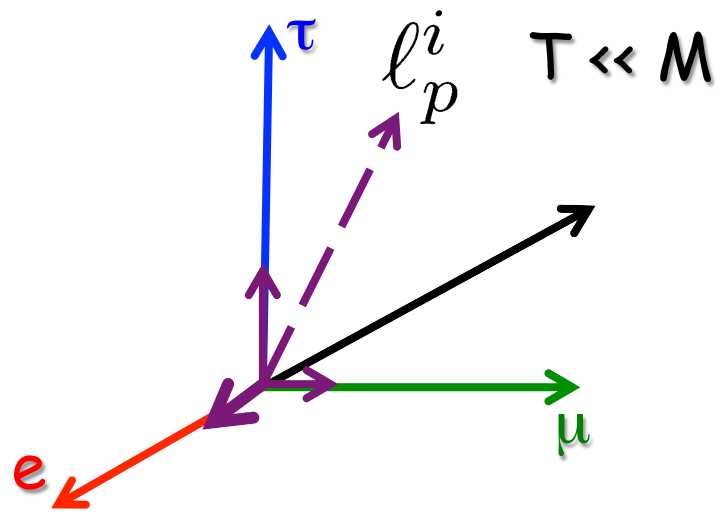




$$N_{B-L}^{\rm p}(T \ll M_i) = (1 - P_{{\rm p}i}) N_{B-L}^{\rm p,i} + P_{{\rm p}i}\, e^{-\frac{3\pi}{8}\,K_i}\, N_{B-L}^{\rm p,i}$$

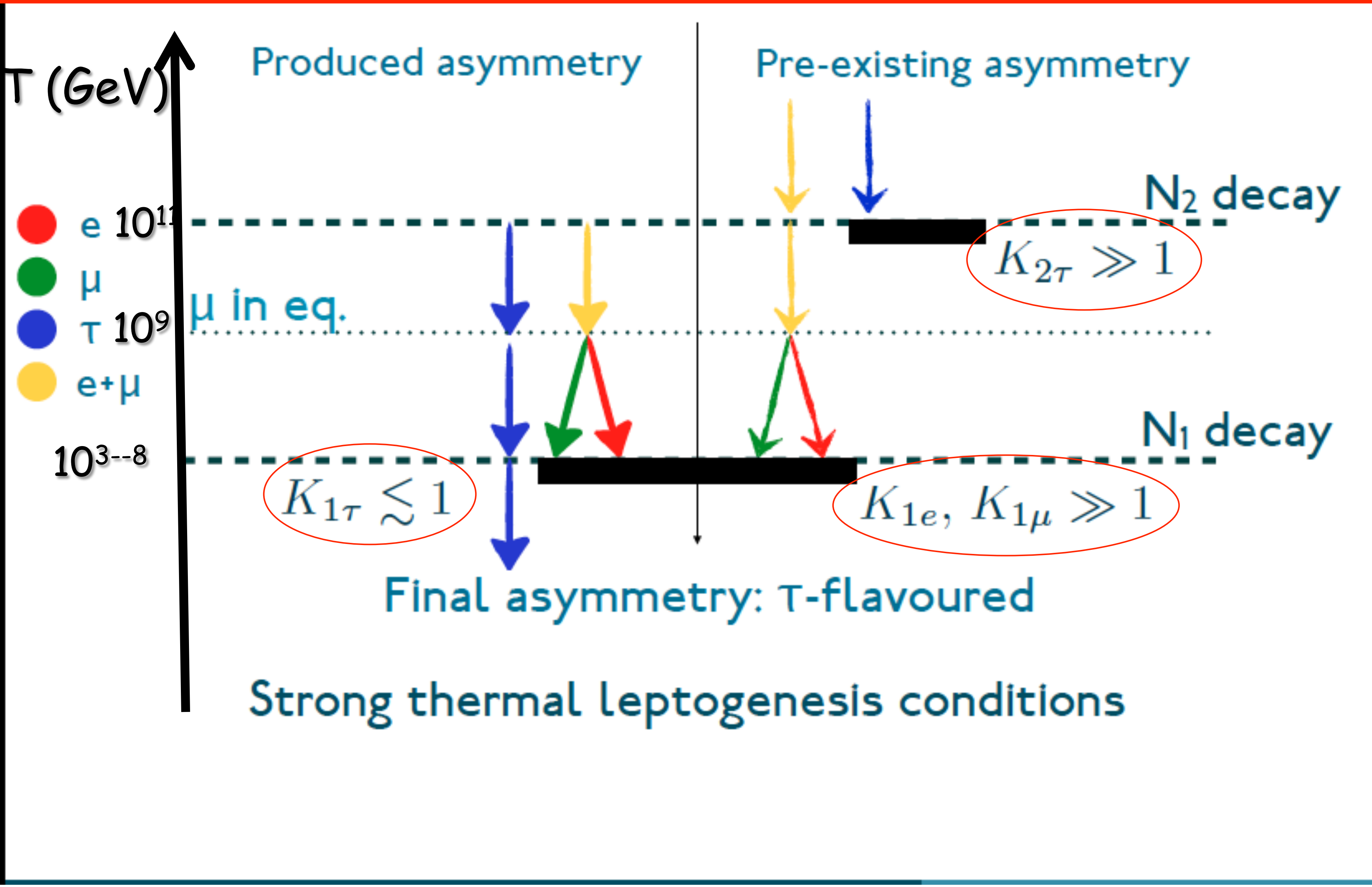
$M_i \ll 10^9$ GeV





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

Successful strong thermal leptogenesis



Courtesy of Michele Re Fiorentin

A lower bound on neutrino masses

(PDB, Sophie King, Michele Re Fiorentin 2014)

Starting from the flavoured decay parameters:

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

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

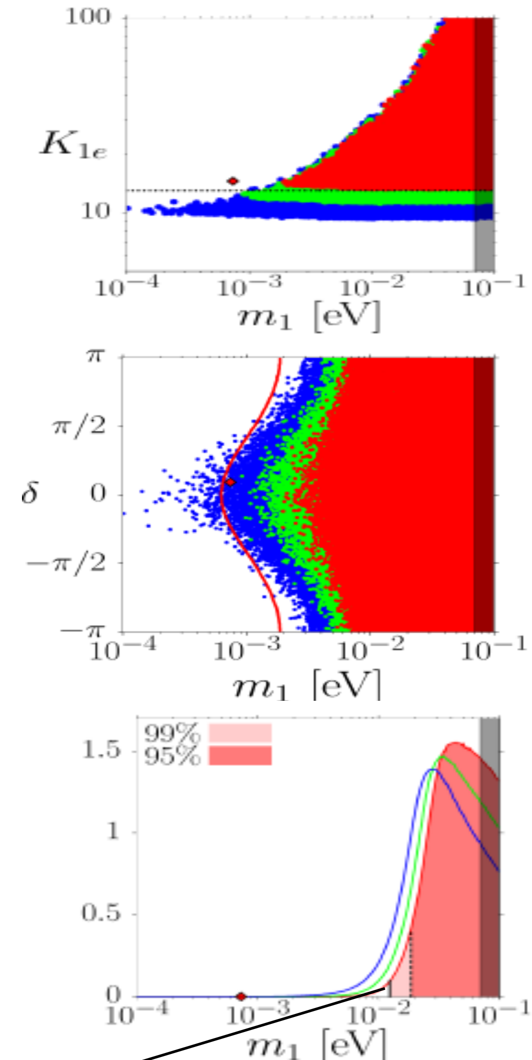
$$\boxed{m_1 > m_1^{\rm lb} \equiv m_\star \max_\alpha \left[\left(\frac{\sqrt{K_{\rm st}} - \sqrt{K^{0,\max}_{1\alpha}}}{\max[|\Omega_{11}|]\, \left|U_{\alpha 1} - \frac{U_{\tau 1}}{U_{\tau 3}}\, U_{\alpha 3}\right|}\right)^2\right]}$$

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

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

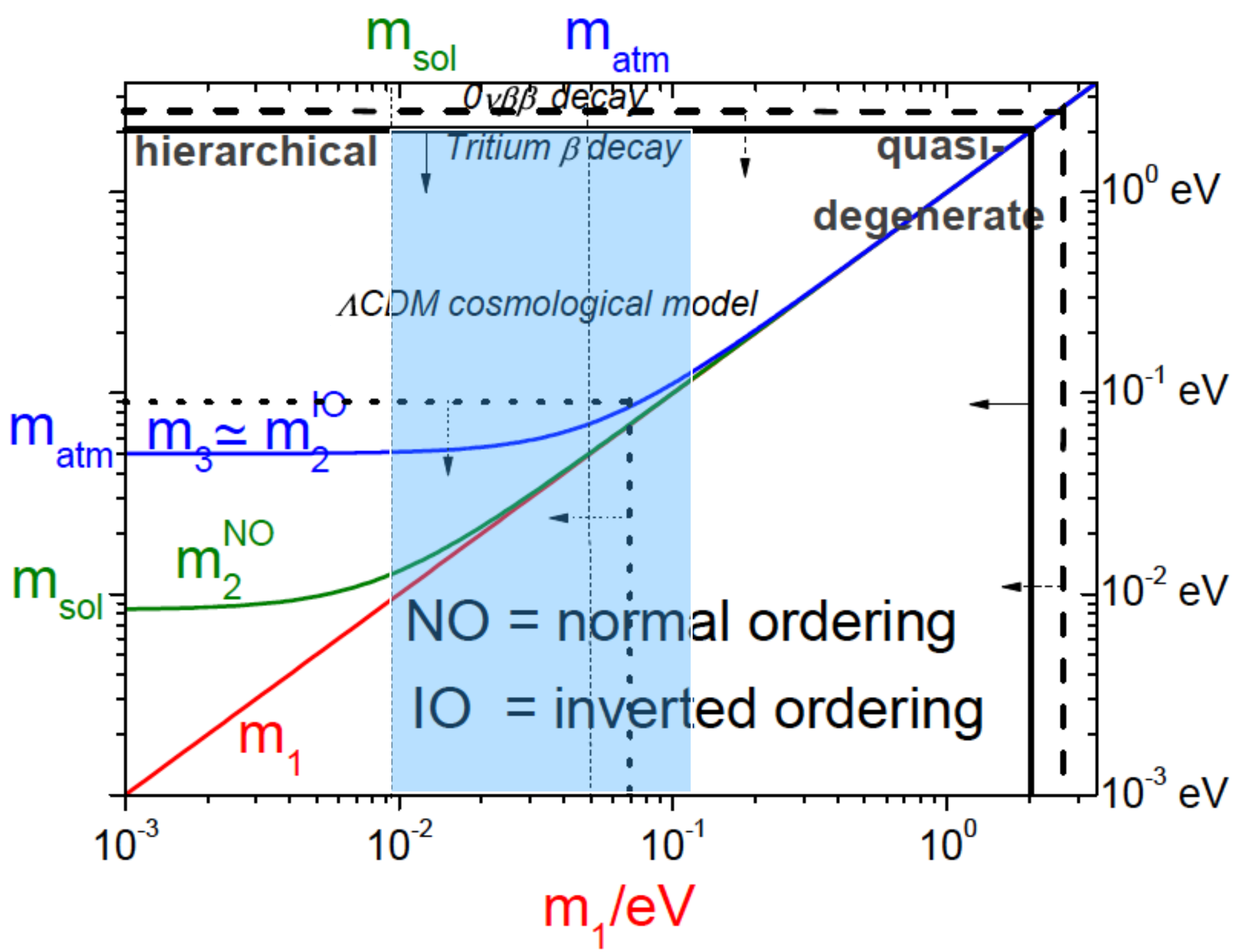
$N^{P,i}_{B-L}$ = 0.001, 0.01, 0.1

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



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

A new neutrino mass window for leptogenesis



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

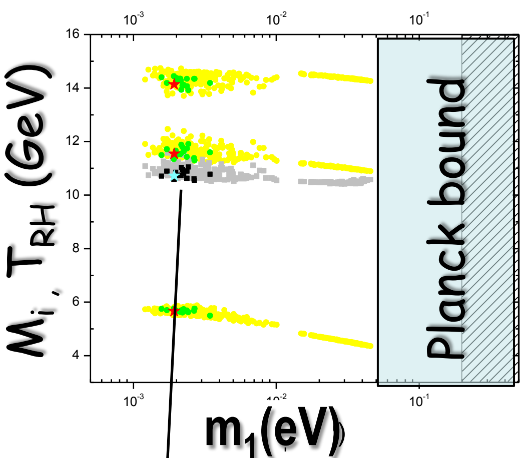
N_2-dominated scenario rescues SO(10)-inspired leptogenesis

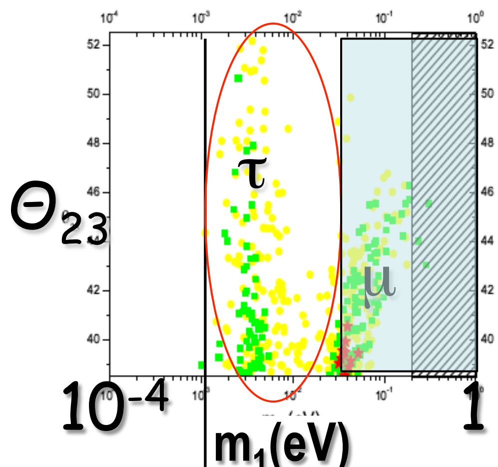
(PDB, Riotto '08,'10)

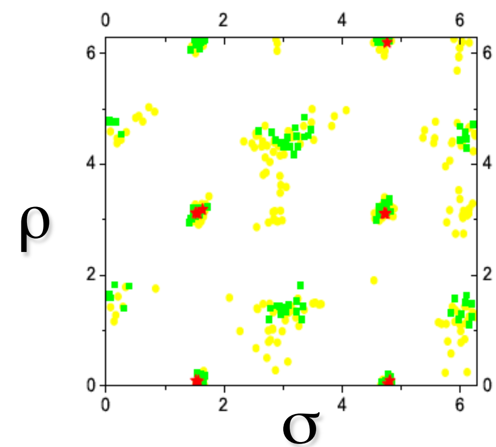
$$N^{\rm f}_{B-L} \simeq \varepsilon_{2e}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1e}} + \varepsilon_{2\mu}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + \varepsilon_{2\tau}\,\kappa(K_{2\tau})\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

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

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







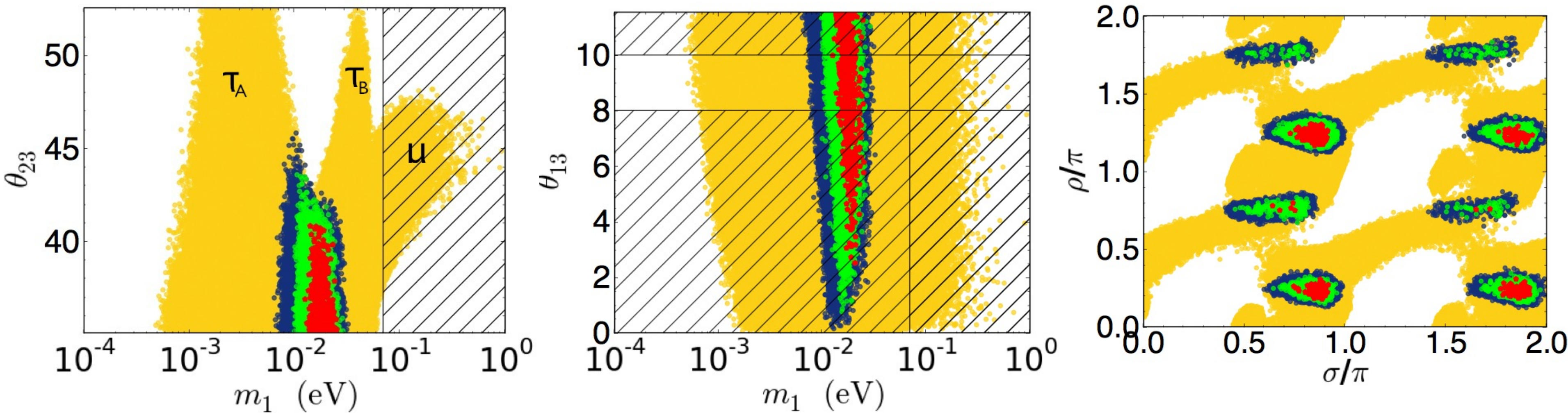
- $T_{RH} \gtrsim 5\times10^{10}$ GeV
- $m_1 \gtrsim 10^{-3}$ eV
- Majorana phases constrained around specific values
- Very marginal allowed regions for INVERTED ORDERING
- Alternative way to rescue SO(10) inspired models is by considering a left-right symmetric seesaw (Abada, Hosteins, Josse-Michaux, Lavignac'08)
- Most of the solutions are tauon dominated as needed for strong thermal leptogenesis: can SO(10)-inspired thermal leptogenesis be also STRONG?

Strong thermal SO(10)-inspired solution

(PDB, Marzola '11; '13)

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

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



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

SO(10)-inspired+strong thermal leptogenesis

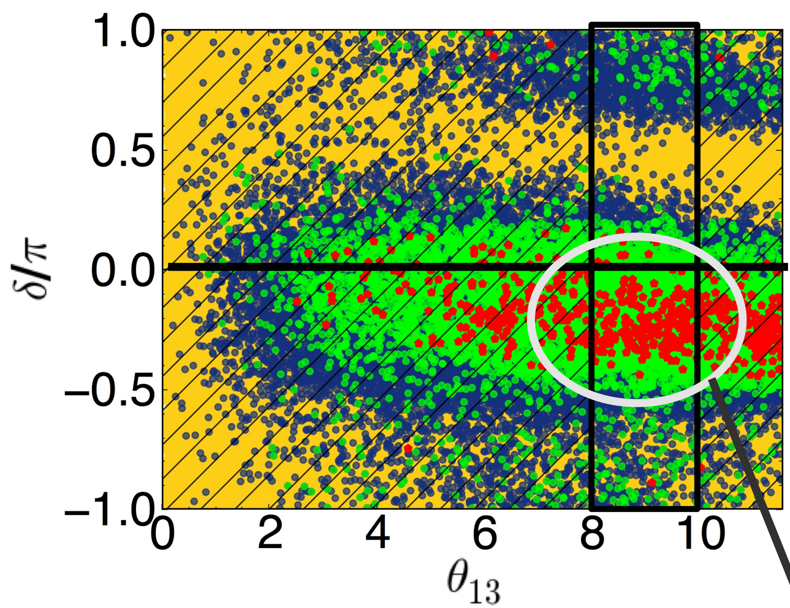
(PDB, Marzola '11-'12)

Imposing successful strong thermal leptogenesis condition:

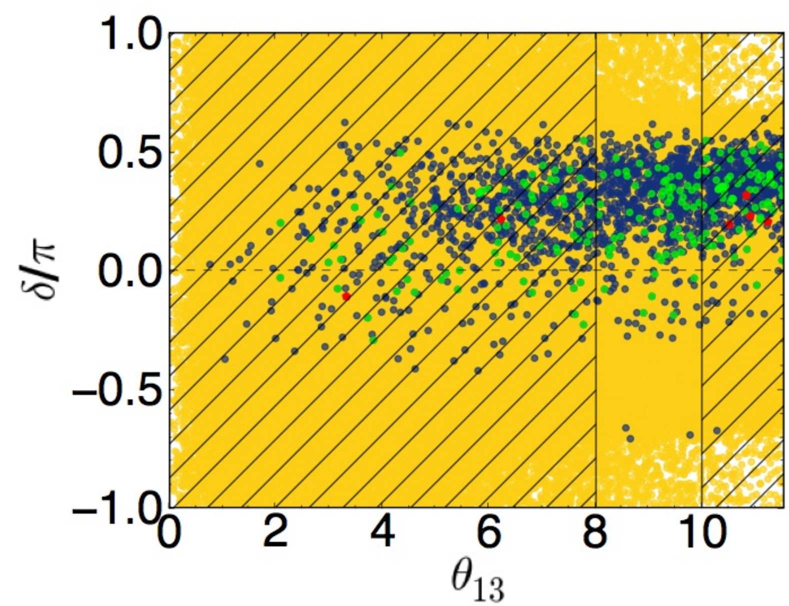
$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p} + N_{B-L}^{\rm lep}, \quad |N_{B-L}^{\rm p}| \ll N_{B-L}^{\rm lep} \simeq 100\, \eta_B^{CMB}$$

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

$\eta_B = \eta_B^{CMB}$



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



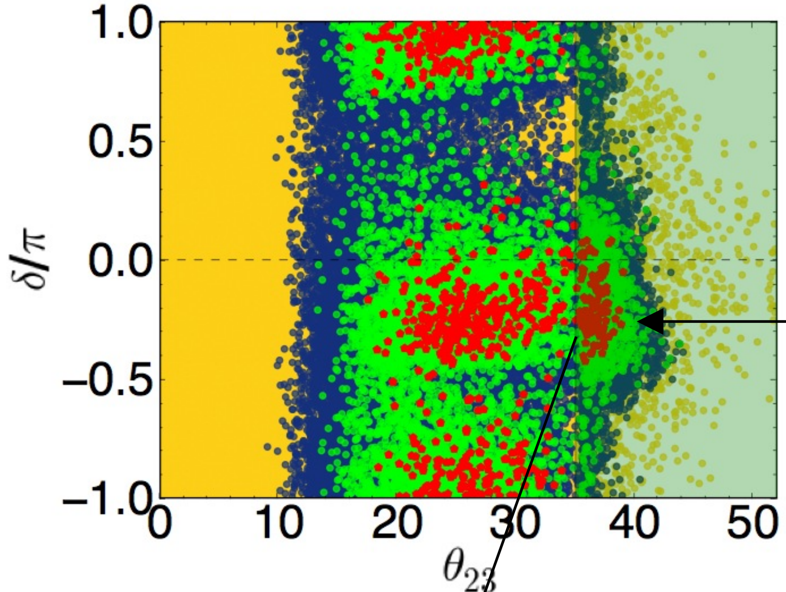
A Dirac phase $\delta \sim -45^\circ$ is favoured: sign matters!

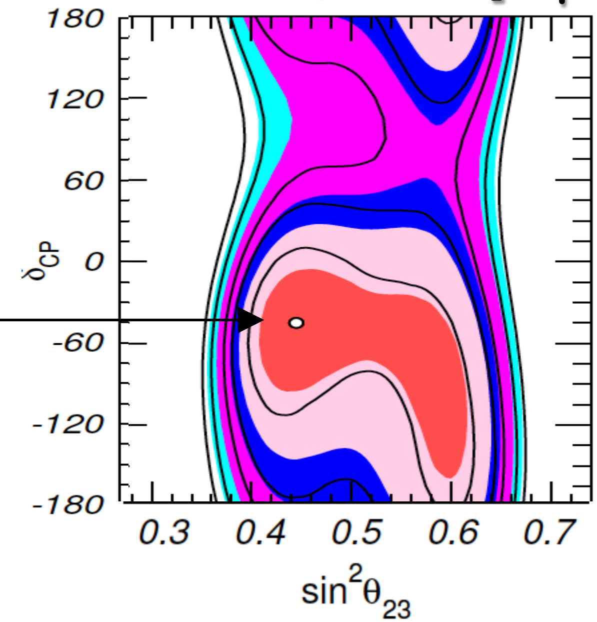
Strong thermal SO(10)-inspired leptogenesis: the atmospheric mixing angle test

NuFIT 1.2 (2013)

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

arXiv:1308.1107



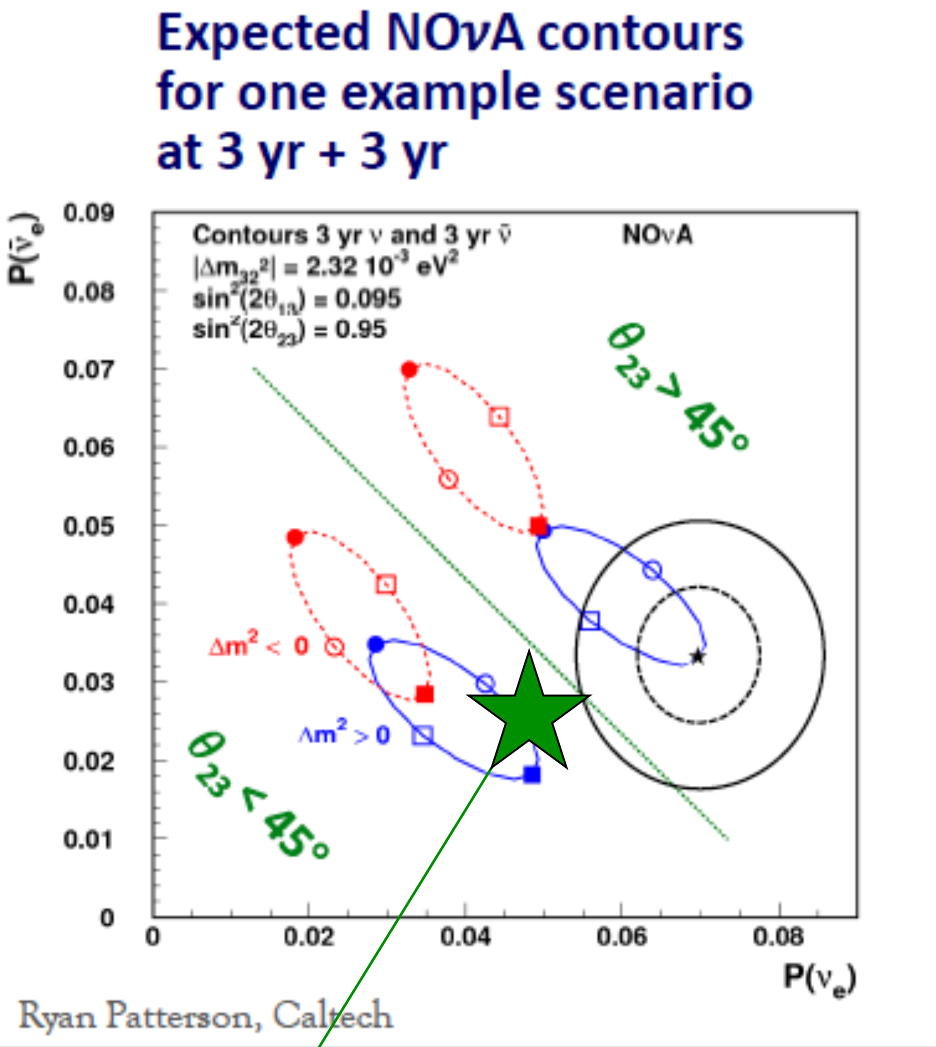


http://www.nu-fit.org/sites/default/files/v12.fig-dlthie-glob.pdf

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

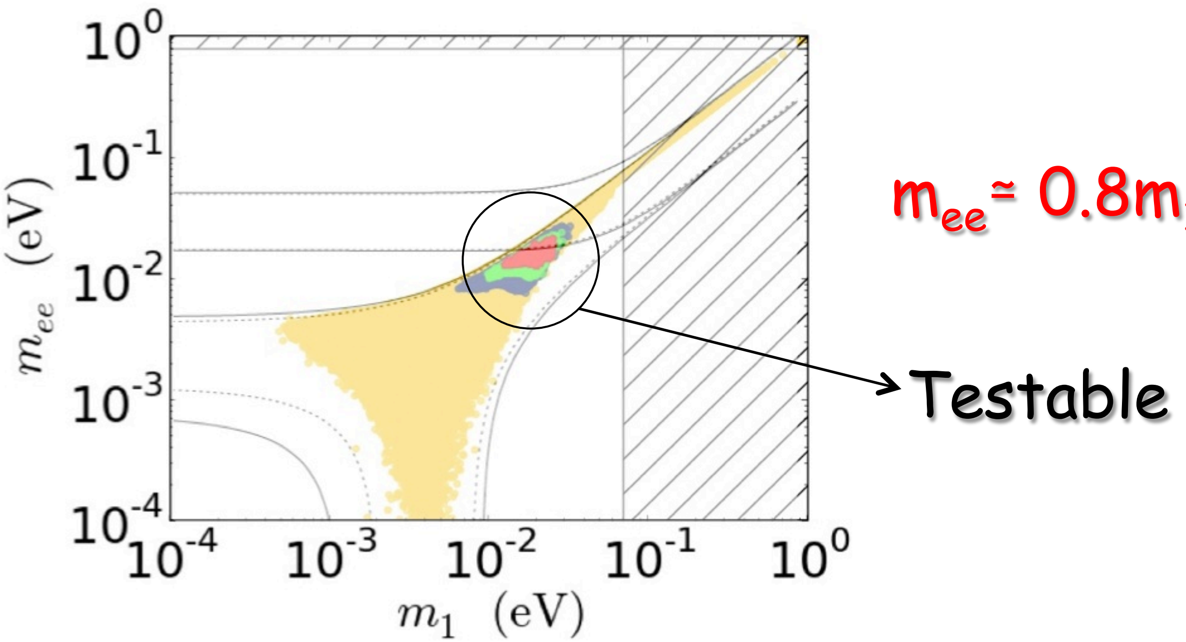
SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

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

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

$\alpha_2 = 5$



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

Final Remarks

- BICEP2: existence of a very high energy scale ~ 10^{16} GeV???
- Thermal leptogenesis: problem of the initial conditions more compelling;
- Solution: N_2-dominated scenario (minimal seesaw, hierarchical N_i)
- Deviations of neutrino masses from the hierarchical limits are expected SO(10)-inspired models are rescued by the N_2-dominated scenario and can also realise strong thermal leptogenesis

Strong thermal SO(10)-inspired leptogenesis solution

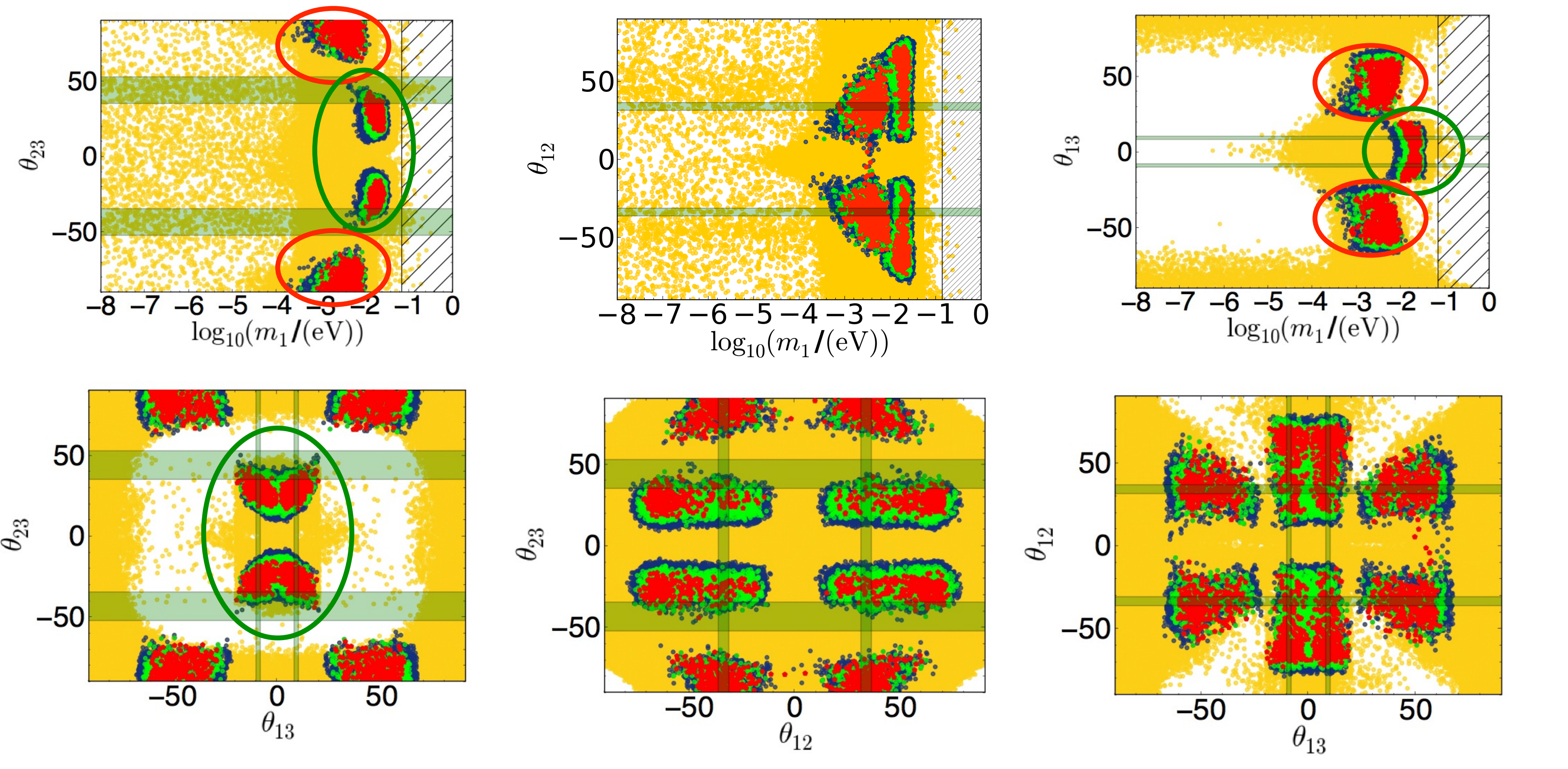
ORDERING	NORMAL
θ_{13}	$\gtrsim 3^\circ$
θ_{23}	$\lesssim 42^\circ$
δ	**~ -45°**
$m_{ee} \simeq 0.8\, m_1$	$\simeq 15$ meV

Still many stages to come but in good shape so far

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) : 1 excluded + 1 allowed region



Gravitational Baryogenesis

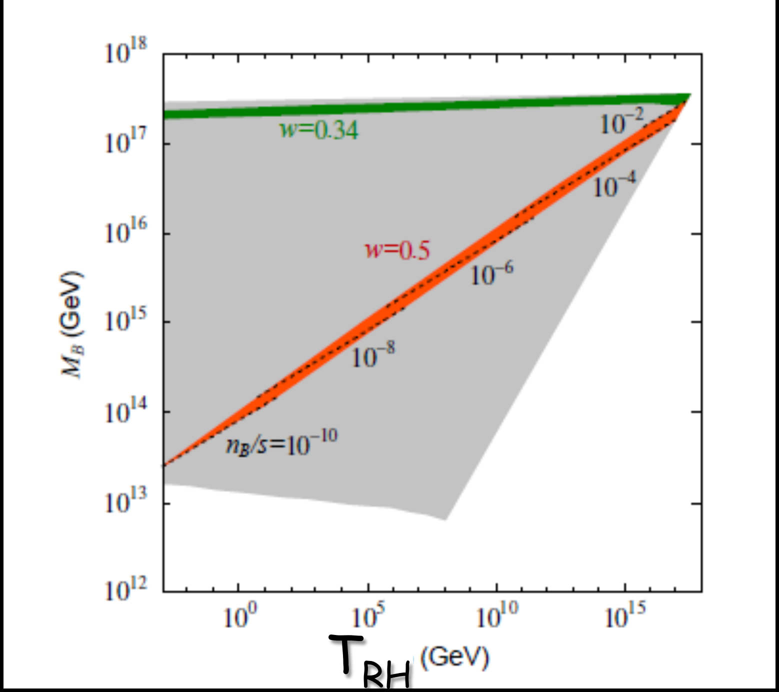
(Davoudiasl, Kribs, Kitano, Murayama, Steinhardt '04)

The key ingredient is a CP violating interaction between the derivative of the Ricci scalar curvature $\mathcal{R}$ and the baryon number current J^m:

$$\frac{1}{M_*^2}\int d^4x\sqrt{-g}(\partial_\mu \mathcal{R})J^\mu$$

Cutoff scale of the effective theory

This operator emerges naturally in quantum gravity and in supergravity



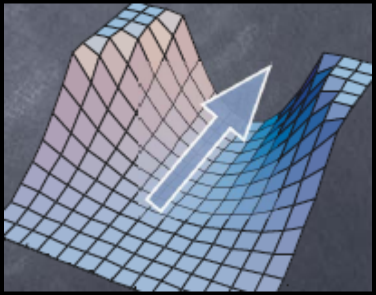
It works efficiently and asymmetries even much larger than the observed one are generated for $T_{RH} \gg 100$ GeV

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

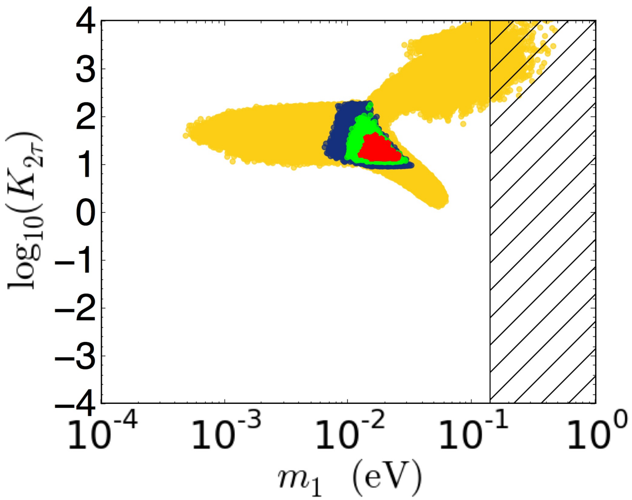
A flat direction can be parametrized in terms of a complex field (AD field) that carries a baryon number that is violated dynamically during inflation

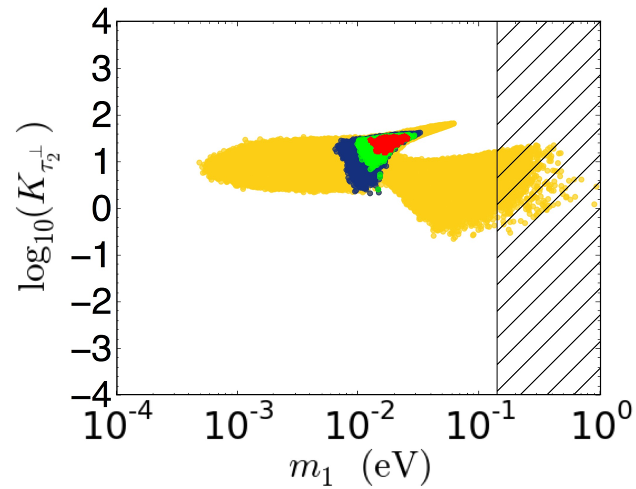
$$\frac{n_B}{s} \sim 10^{-10}\left(\frac{m_{3/2}}{m_\Phi}\right)\left(\frac{m_\Phi}{\mathrm{TeV}}\right)^{-\frac{1}{2}}\left(\frac{M}{M_P}\right)^{\frac{3}{2}}\left(\frac{T_R}{10\,\mathrm{GeV}}\right)$$

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

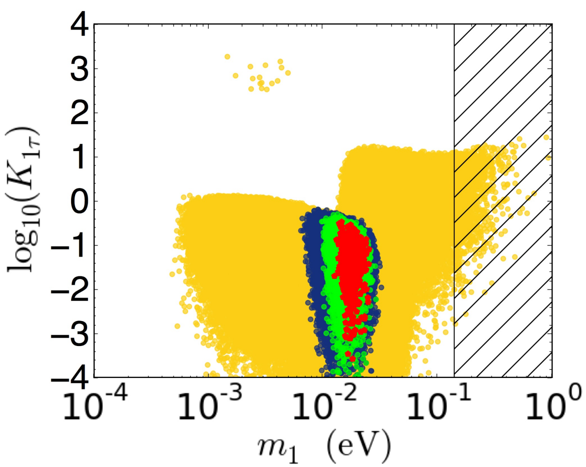
Some insight from the decay parameters

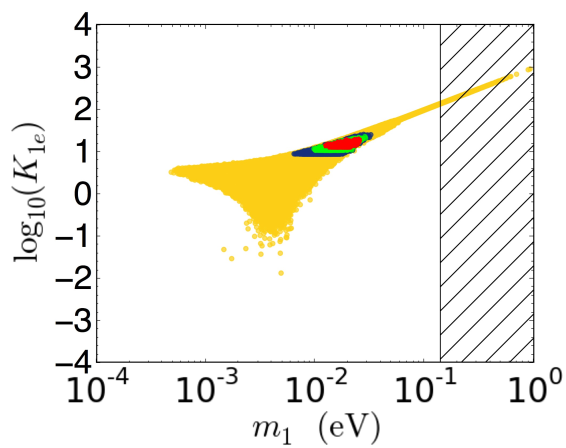
At the production ($T \sim M_2$)

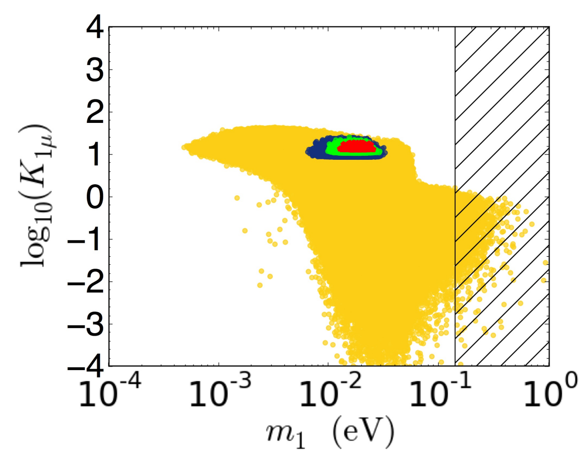




At the wash-out ($T \sim M_1$)







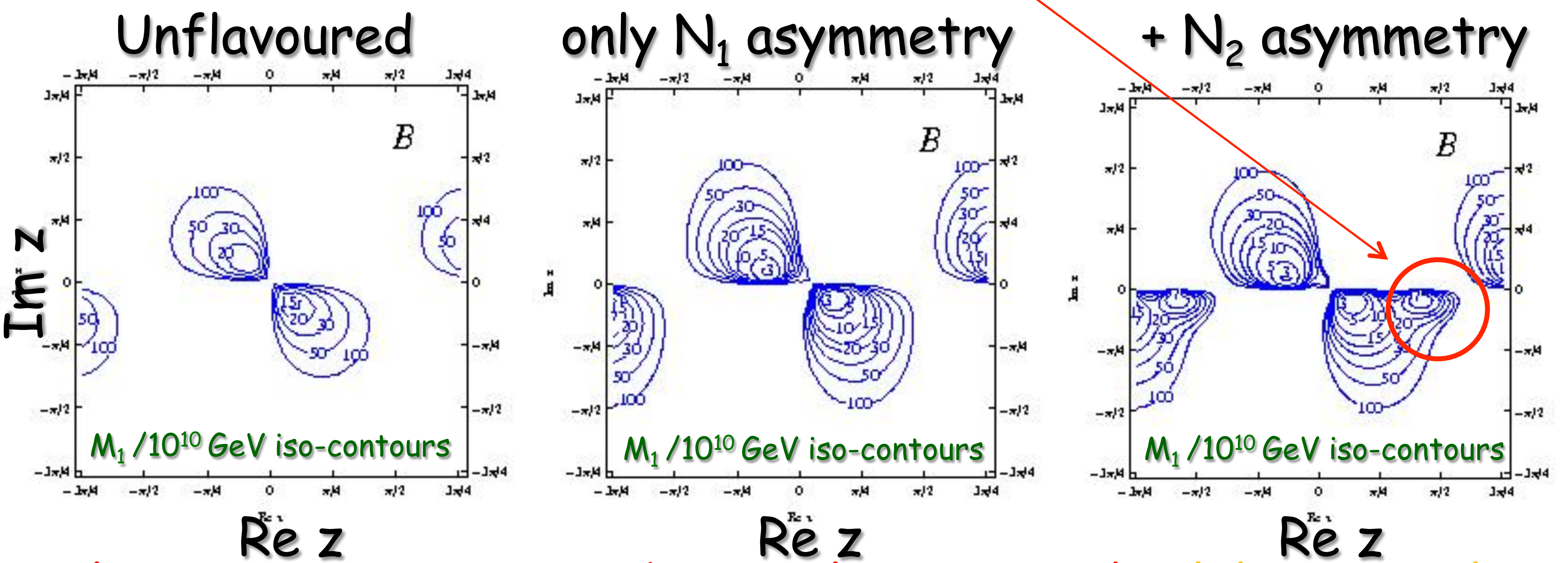
2 RH neutrino scenario revisited

(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:

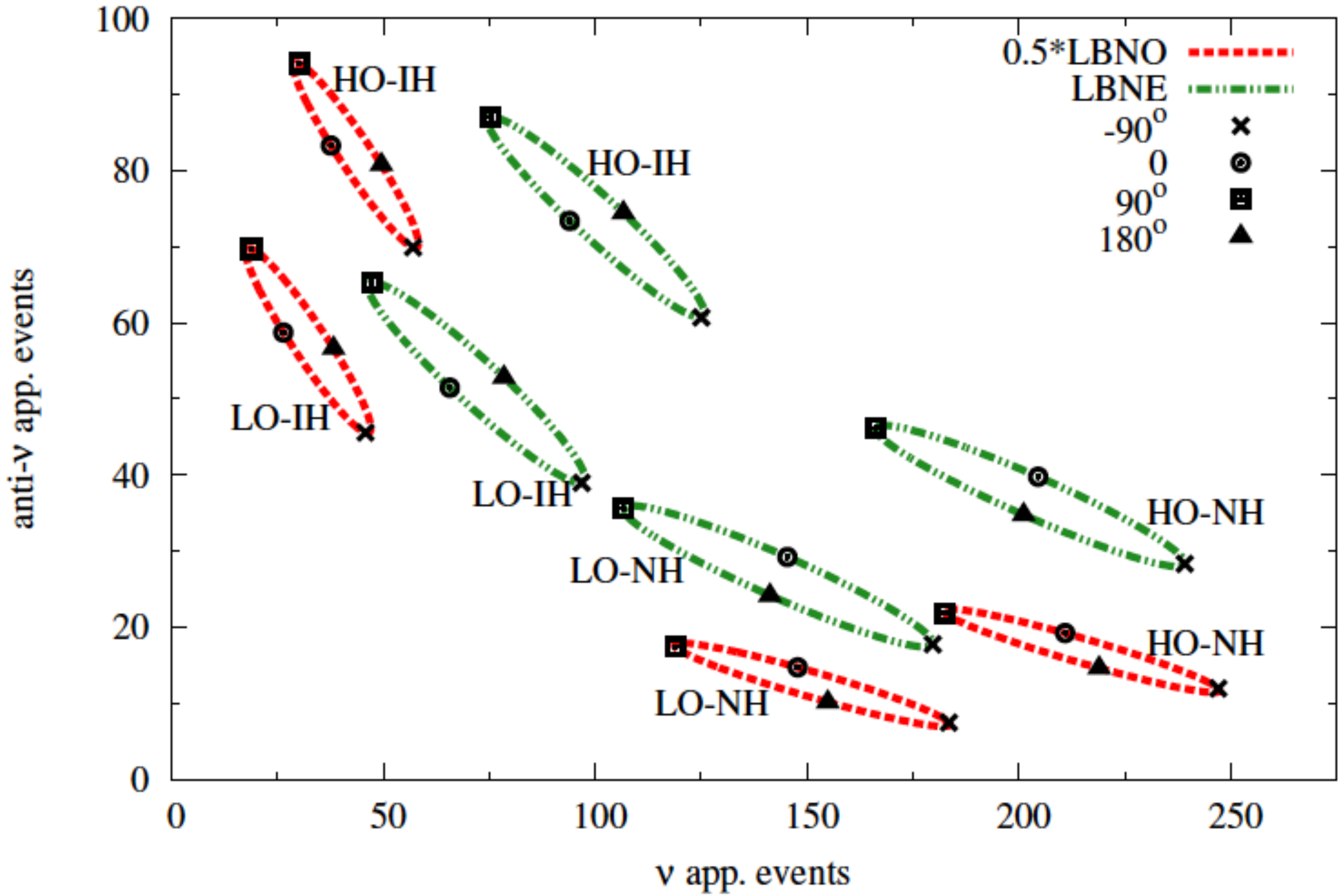
- the N_2 asymmetry N_1-orthogonal component
- an additional unsuppressed term to $\varepsilon_{2\alpha}$

New allowed N_2 dominated regions appear



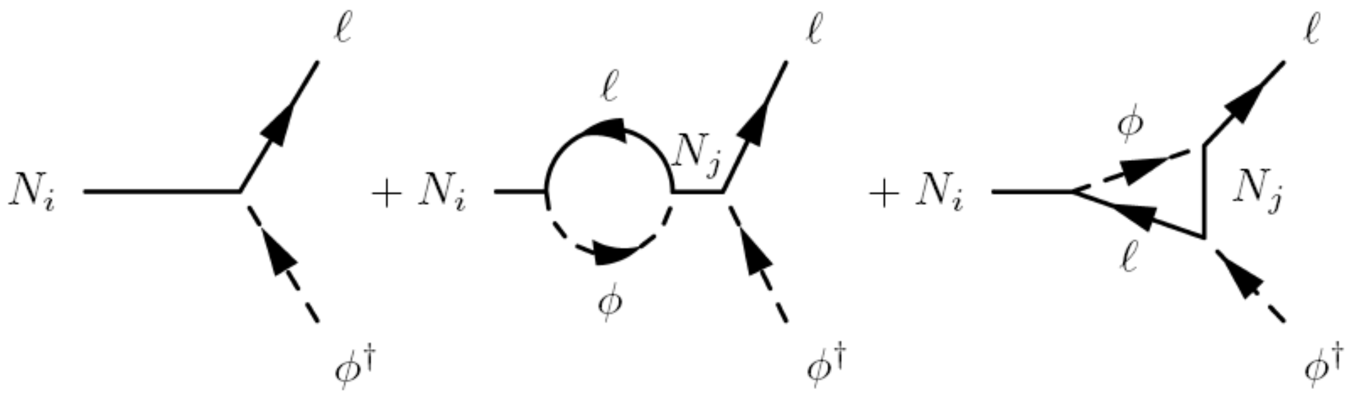
These regions are interesting because they correspond to light sequential dominated neutrino mass models realized in some grandunified models

Electron appearance events for 0.5*LBNO and LBNE



Total CP asymmetries

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



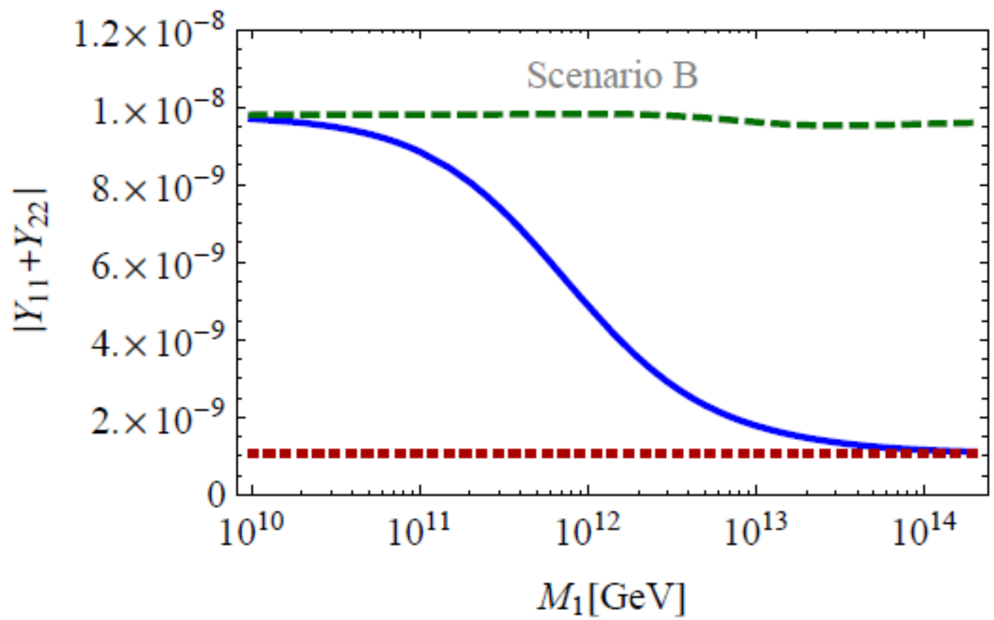
$$\varepsilon_i \simeq \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(m_D^\dagger\, m_D)^2_{ij}\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

It does not depend on U !

Density matrix and CTP formalism to describe the transition regimes

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

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



Fully two-flavoured regime limit

Unflavoured regime limit

Additional contribution to CP violation:

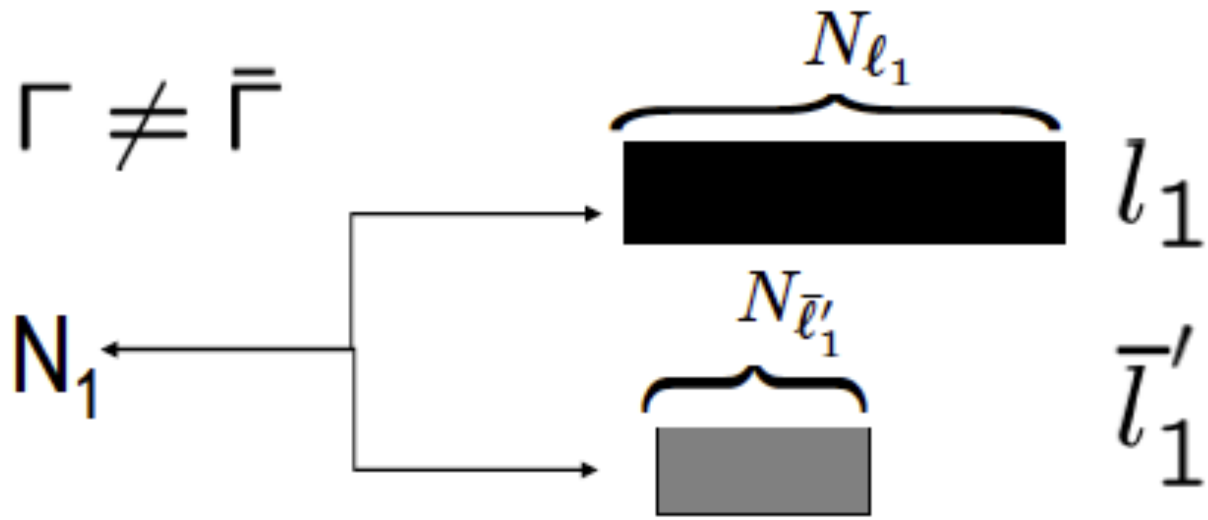
(Nardi, Racker, Roulet '06)

(α = τ, e+μ)

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

depends on U !

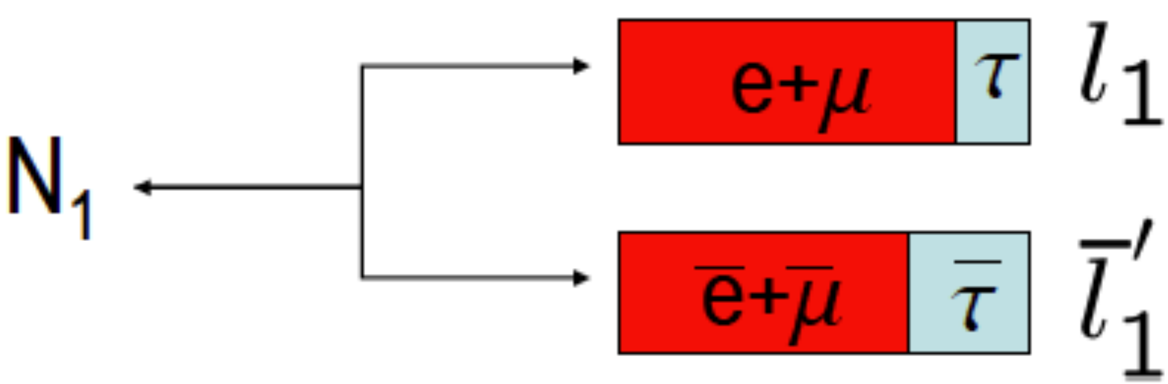
1) $\Gamma \neq \bar{\Gamma}$



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

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

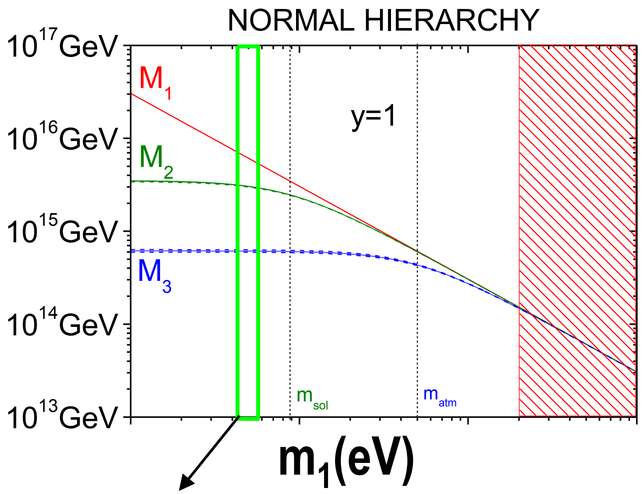
+



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

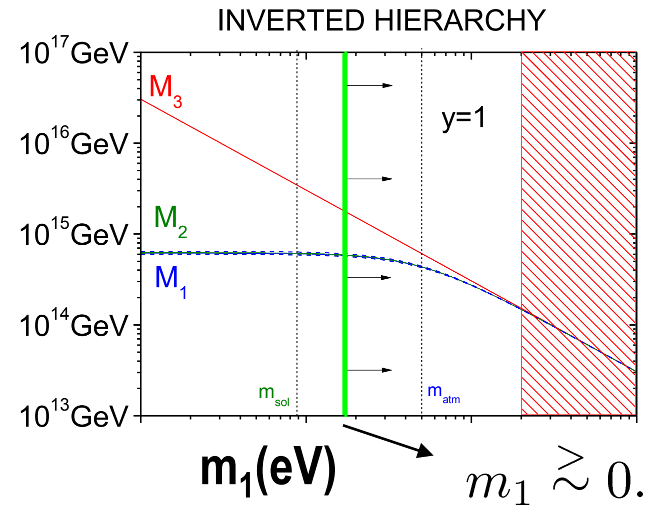
Heavy flavoured scenario in models with A4 discrete flavour symmetry

(Manohar, Jenkins'08; Bertuzzo, PDB, Feruglio, Nardi '09; Hagedorn, Molinaro, Petcov '09)



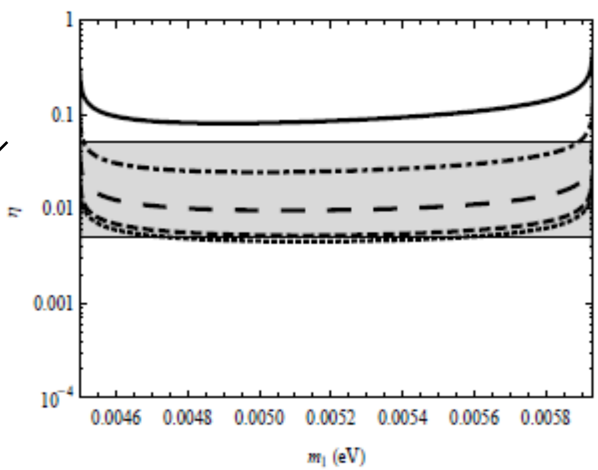
$m_1 \simeq 5 \times 10^{-3}\,\mathrm{eV}$

$$m_i = \frac{y^2\, v_u^2}{M_j}$$



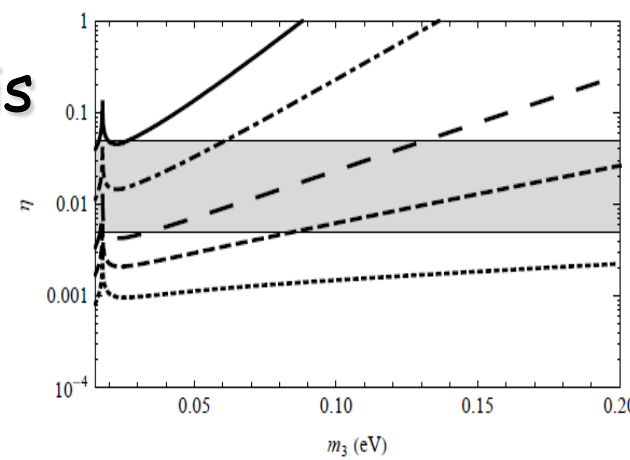
$m_1 \gtrsim 0.017\,\mathrm{eV}$

imposing successful leptogenesis



η

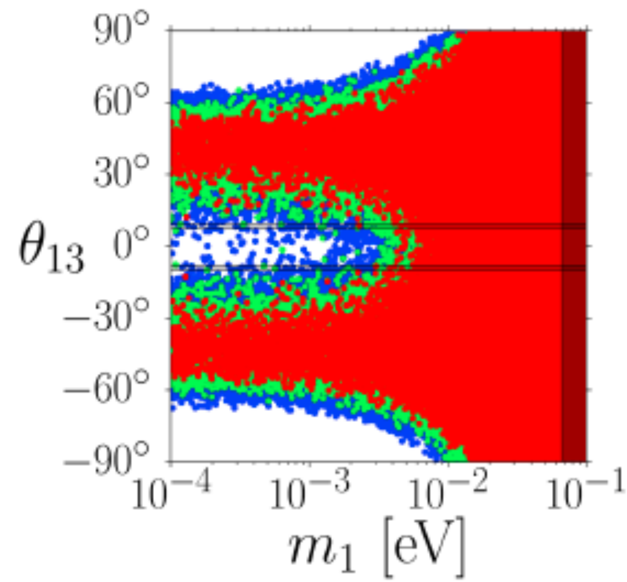
Symmetry Breaking parameter



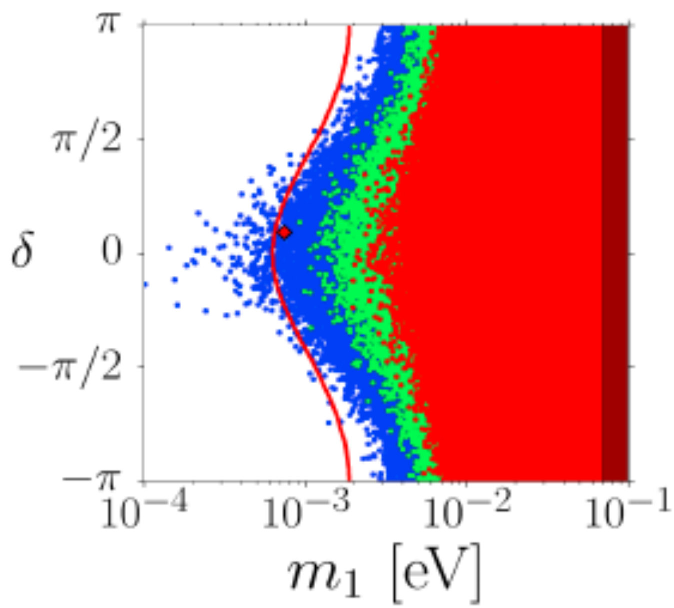
The different lines correspond to values of y between 0.3 and 3

A lower bound on neutrino masses

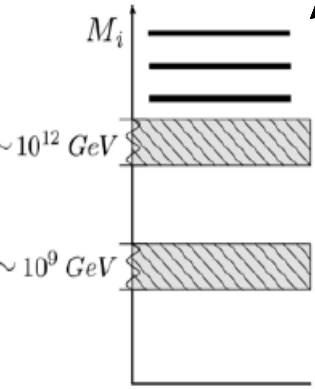
The lower bound would not have existed for large θ_{13} values



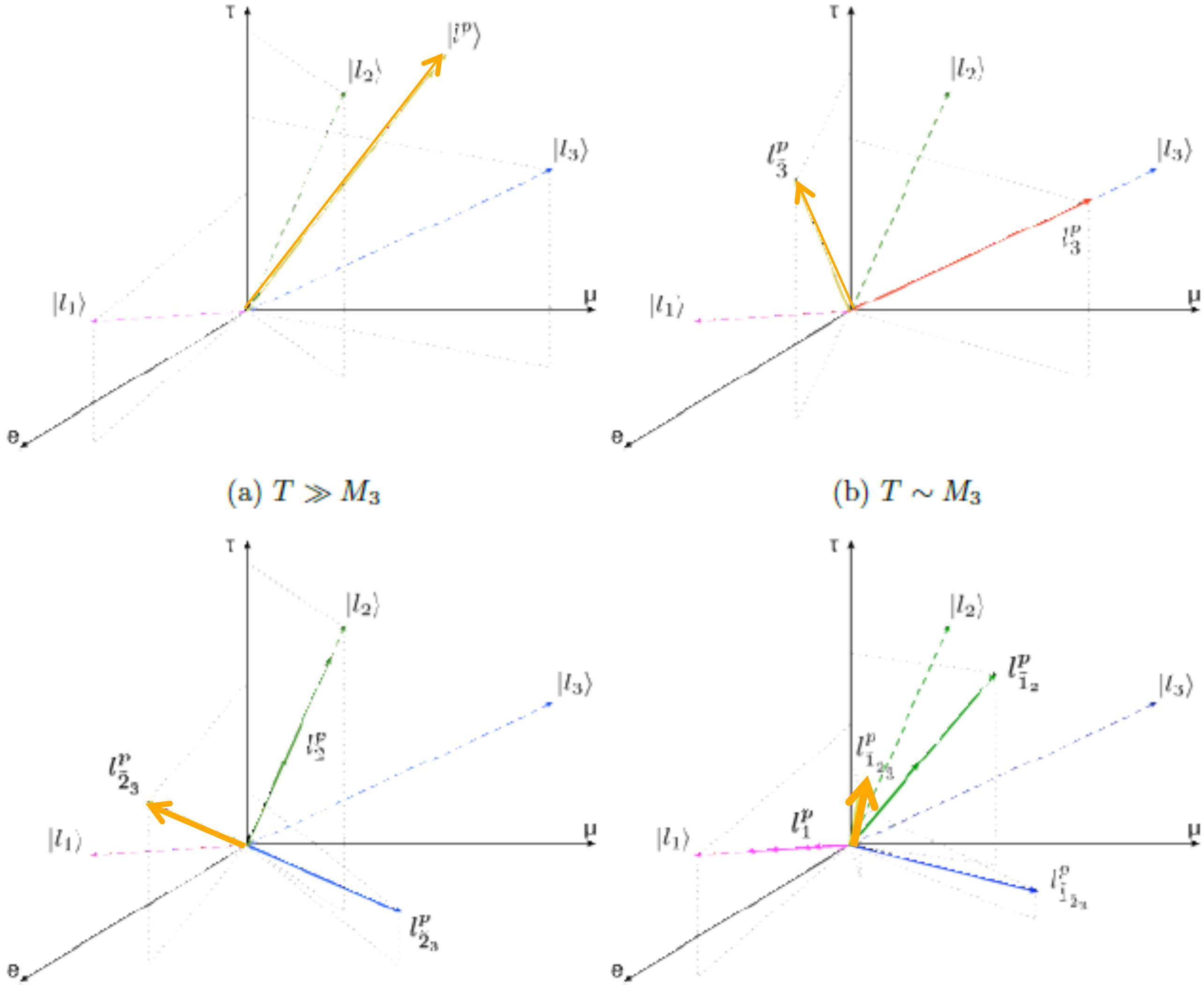
It is modulated by the Dirac phase and it could become more stringent when δ will be measured



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



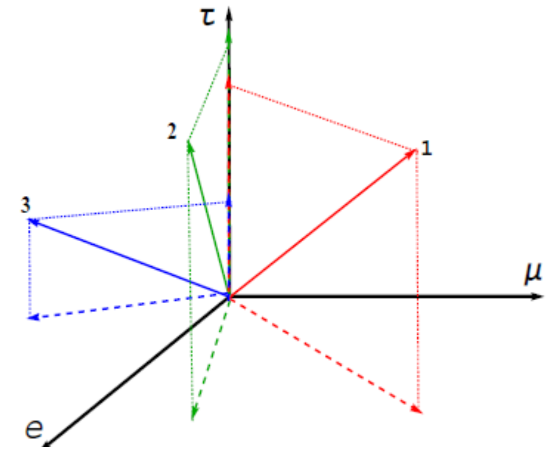
The pre-existing asymmetry (yellow) undergoes a 3 step flavour projection



(a) $T \gg M_3$ (b) $T \sim M_3$ (c) $T \sim M_2$ (d) $T \sim M_1$

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:

$$N_{\Delta_\tau}^{\rm p,f} = (p_{\rm p\tau}^0 + \Delta p_{\rm p\tau})\,e^{-\frac{3\pi}{8}\,(K_{1\tau}+K_{2\tau})}\,N_{B-L}^{\rm p,i}\,, \qquad (18)$$
$$N_{\Delta_\mu}^{\rm p,f} = \left\{(1-p_{\rm p\tau}^0)\,\left[p_{\mu\tau_2^\perp}^0\,p_{\rm p\tau_2^\perp}^0\,e^{-\frac{3\pi}{8}\,(K_{2e}+K_{2\mu})} + (1-p_{\mu\tau_2^\perp}^0)\,(1-p_{\rm p\tau_2^\perp}^0)\right] + \Delta p_{\rm p\mu}\right\}\,e^{-\frac{3\pi}{8}\,K_{1\mu}}\,N_{B-L}^{\rm p,i},$$
$$N_{\Delta_e}^{\rm p,f} = \left\{(1-p_{\rm p\tau}^0)\,\left[p_{e\tau_2^\perp}^0\,p_{\rm p\tau_2^\perp}^0\,e^{-\frac{3\pi}{8}\,(K_{2e}+K_{2\mu})} + (1-p_{e\tau_2^\perp}^0)\,(1-p_{\rm p\tau_2^\perp}^0)\right] + \Delta p_{\rm pe}\right\}\,e^{-\frac{3\pi}{8}\,K_{1e}}\,N_{B-L}^{\rm p,i}\,.$$

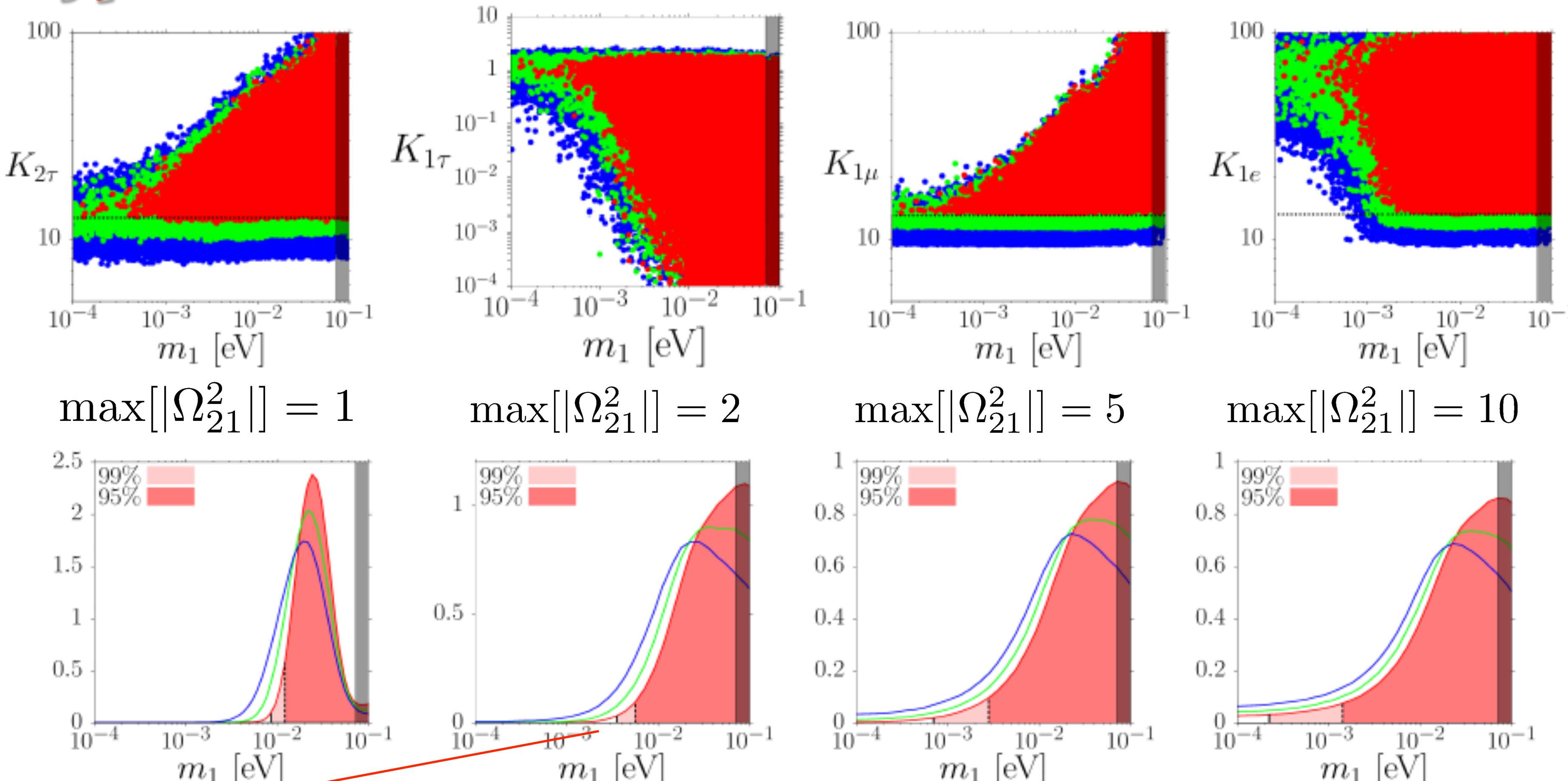
Successful strong thermal leptogenesis then requires:

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

A lower bound on neutrino masses (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



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