Origin of Mass 2014
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From low energy neutrino data to mass models (and back) with leptogenesis

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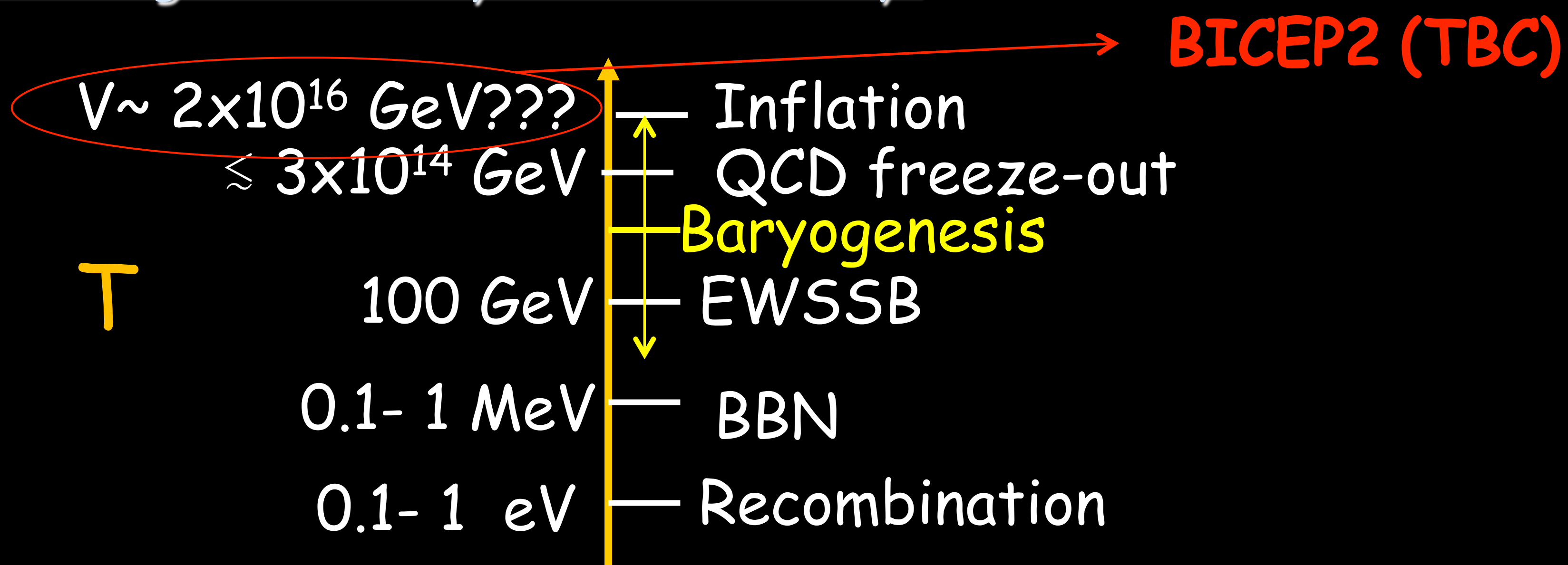
Cosmological puzzles

- *Cosmological Puzzles :*

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

- *New stage in the early Universe history :*



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:</u>

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

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

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

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

Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: normal or inverted

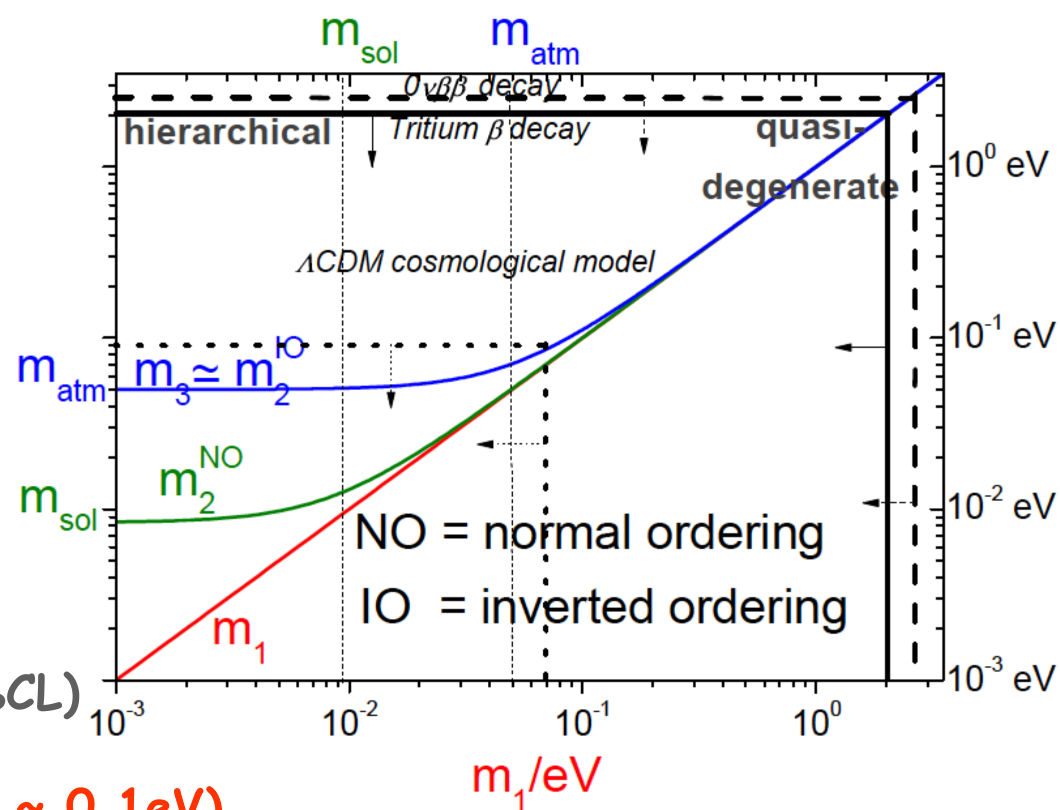
$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

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

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)
$m_{\beta\beta}$< 0.12 – 0.25 eV
(EXO-200+Kamland-Zen 90% CL)
$m_{\beta\beta}$< 0.2 – 0.4 eV
(GERDA+IGEX 90% CL)

CMB+BAO+H0 : Σ m_i < 0.23 eV
(Planck+high-l+WMAPpol+BAO 95%CL)
⇒ m_1 < 0.07 eV
(recent BOSS RESULTS favour m_1 ~ 0.1eV)



Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

- Type I seesaw

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

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

- 3 light neutrinos ν_1, ν_2, ν_3 with masses

$$\mathrm{diag}(m_1, m_2, m_3) = -U^\dagger\, m_D\, \frac{1}{M}\, m_D^T\, U^\star$$

- 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 its

total CP asymmetry

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

- Thermal production of RH neutrinos

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

The double side of Leptogenesis

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

- *Cosmological Puzzles :*

1. Dark matter
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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?

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 (so far);
- BICEP2 (seems to) support the existence of a new scale ~ 2×10^{16} GeV (to be confirmed by Planck);
- The discovery of a non-vanishing reactor angle opens the door to further measurements of mixing parameters (atmospheric angle octant, neutrino mass ordering, Dirac phase)
- cosmological observations start to have the sensitivity to either rule our or discover quasi-degenerate neutrino masses

Seesaw parameter space

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

Problem: too many parameters

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

Orthogonal parameterisation

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

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

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

A parameter reduction would help and can occur 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: $M_2 \gtrsim 2\, M_1$

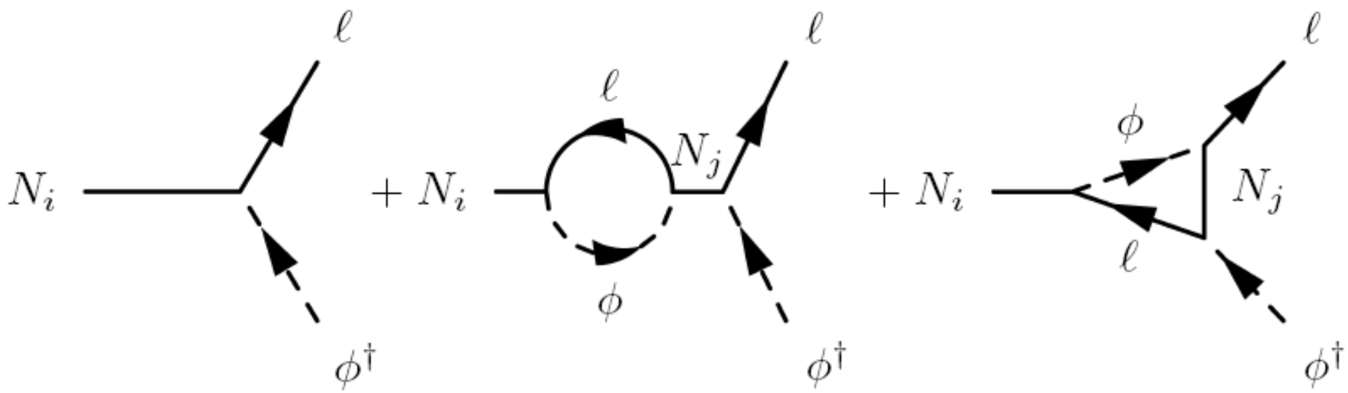
3) N_3 does not interfere with N_2-decays: $(m_D^\dagger\, m_D)_{23} = 0$

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

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

(Davidson, Ibarra '02)

5) Efficiency factor from simple Boltzmann equations

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

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

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

decays

inverse decays

wash-out

decay parameter

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

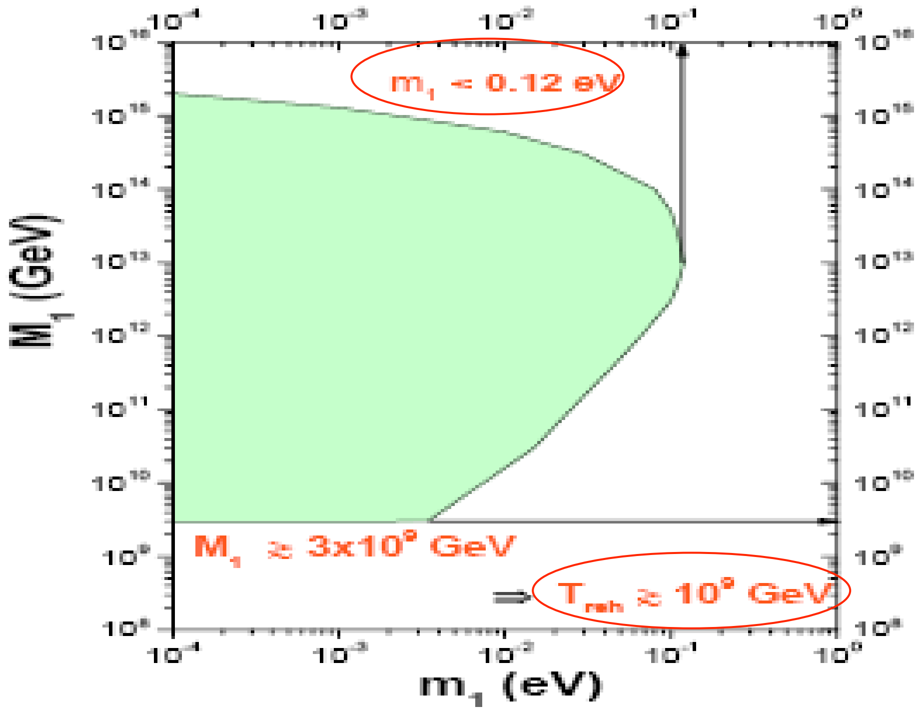
$$\kappa_1(z; K_1, z_{\text{in}}) = -\int_{z_{\text{in}}}^{z} dz' \left[\frac{dN_{N_1}}{dz'}\right] e^{-\int_{z'}^{z} dz''\, W_1(z'')}$$

Neutrino mass bounds in vanilla leptog.

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

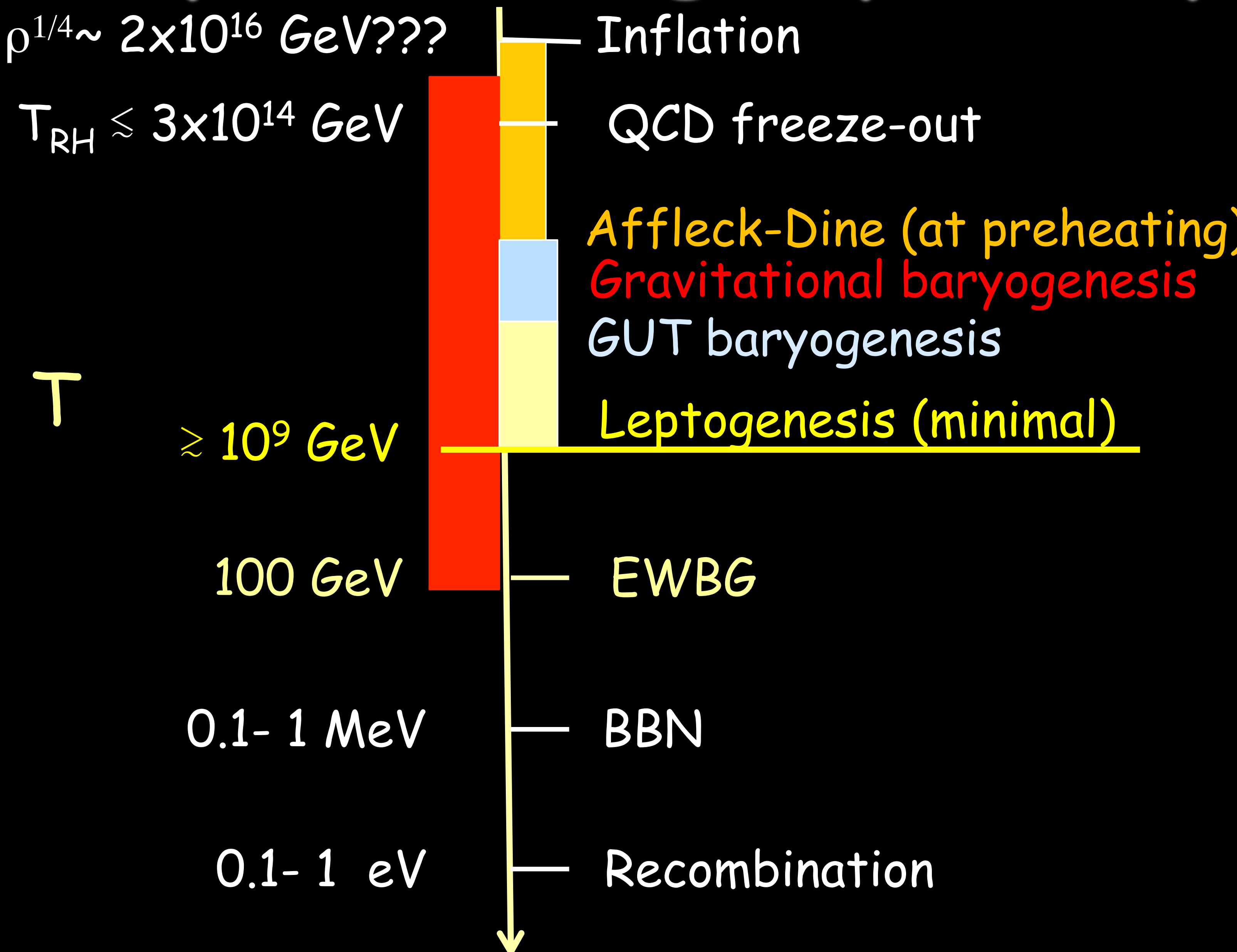
$$\eta_B \simeq 0.01\,\varepsilon_1(m_1, M_1, \Omega)\,\kappa_1^{\rm fin}(K_1) \leq \eta_B^{\rm max} = 0.01\,\varepsilon_1^{\rm max}(m_1, M_1)\,\kappa_1^{\rm fin}(K_1^{\rm max})$$

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)

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

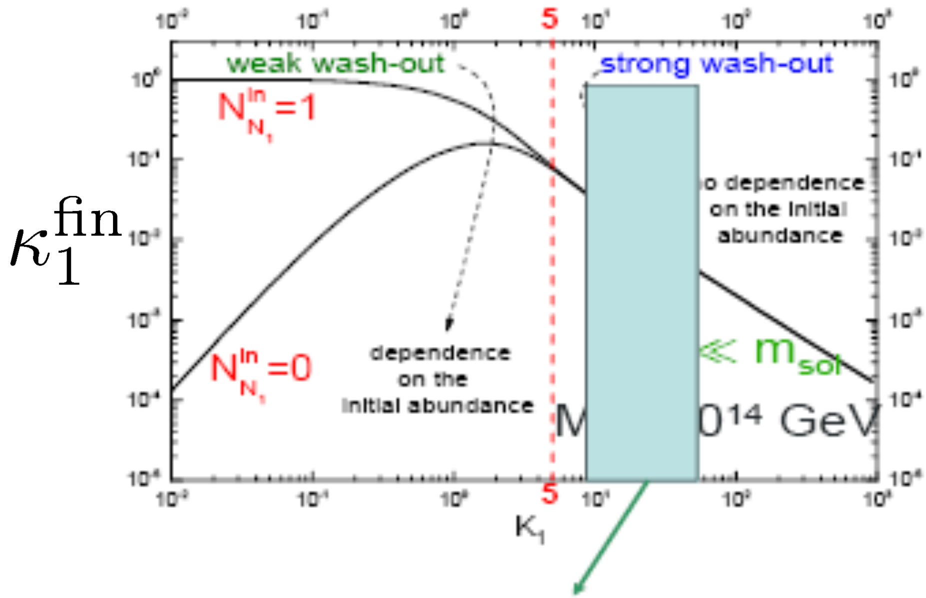
decay parameter

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

Independence of the initial abundance of N_1

wash-out of a pre-existing asymmetry

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

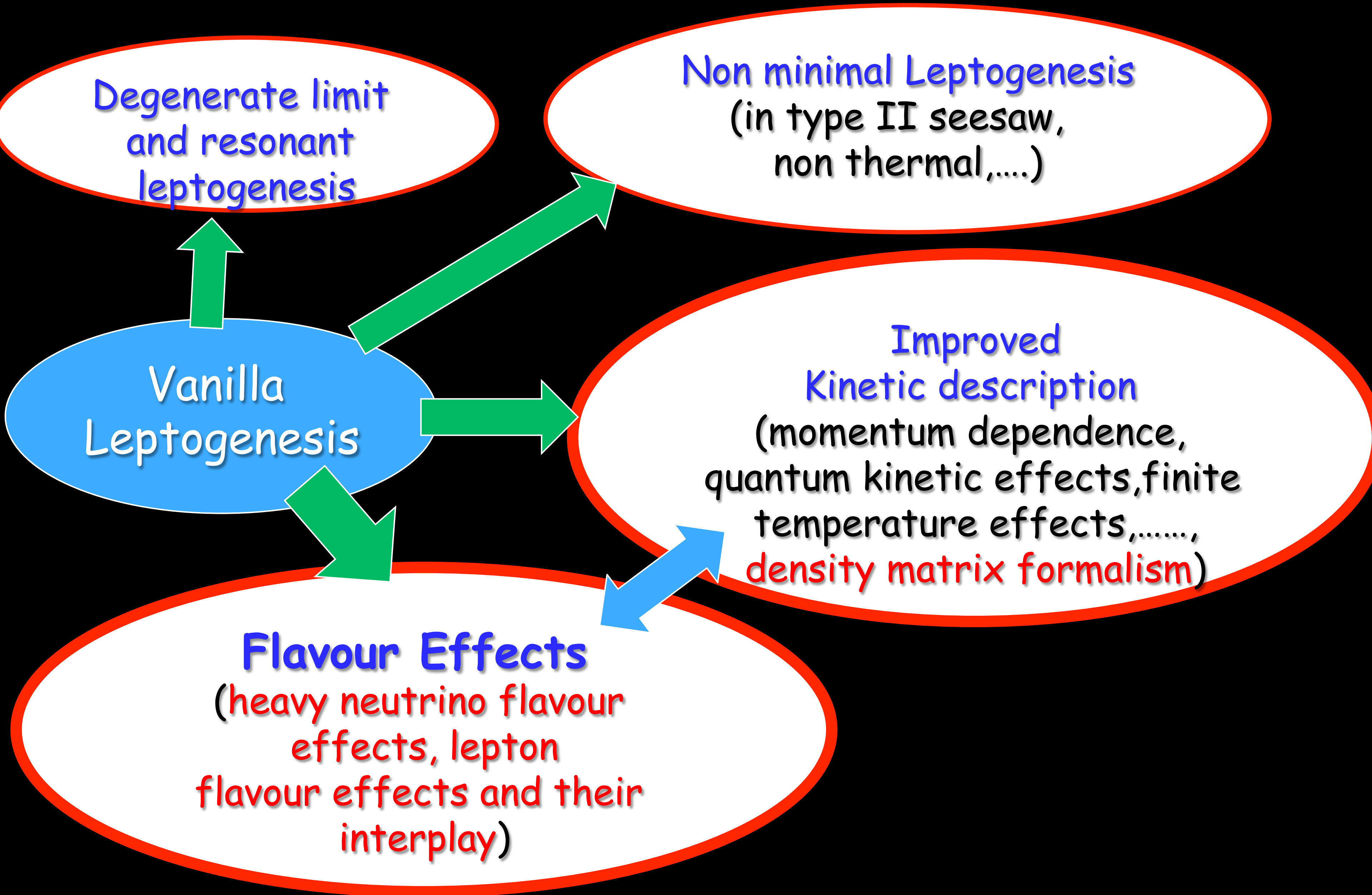


$$K_1 \gtrsim K_{\rm st}(N_{B-L}^{\rm p,i})$$

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

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

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:

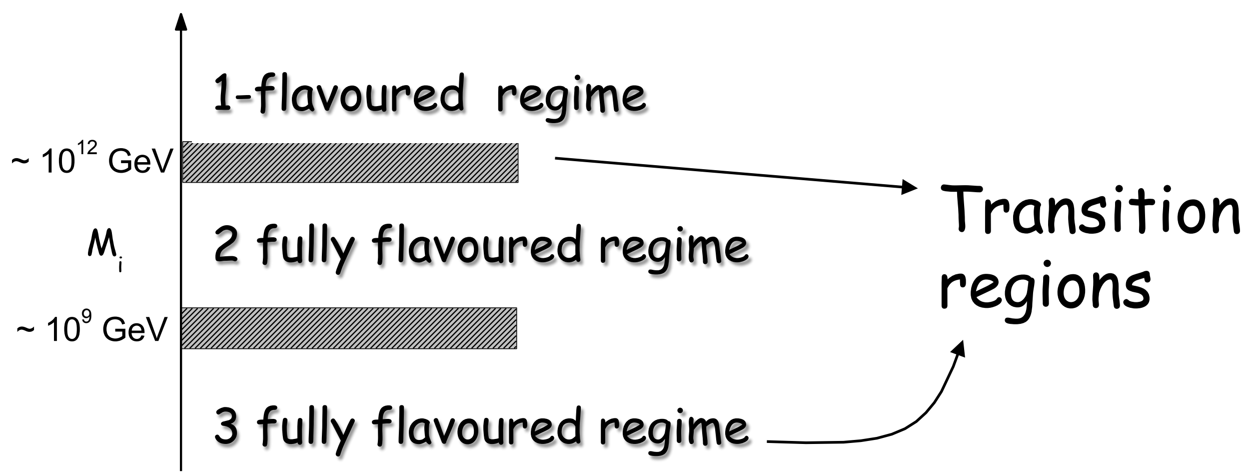
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1 \rangle \, |l_\alpha\rangle \quad (\alpha = e, \mu, \tau) \qquad P_{1\alpha} \equiv |\langle \ell_1 | \alpha \rangle|^2$$

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

For $T \gtrsim 10^{12}$ GeV ⇒ 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 μ+e component

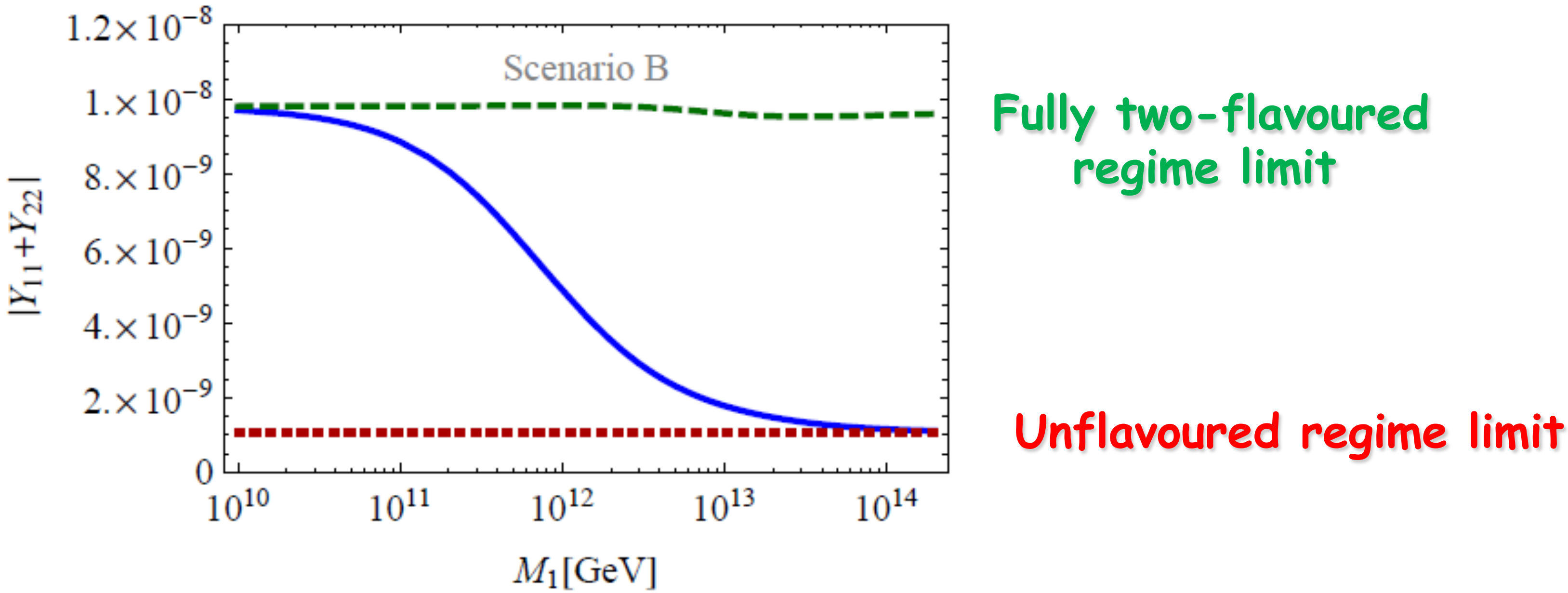
At $T \gtrsim 10^9$ GeV then also μ- Yukawas in equilibrium ⇒ 3-flavor regime



Density matrix and CTP formalism to describe the transition regimes

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

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



Two fully flavoured regime

(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)

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

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

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

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

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

Additional contribution to CP violation:

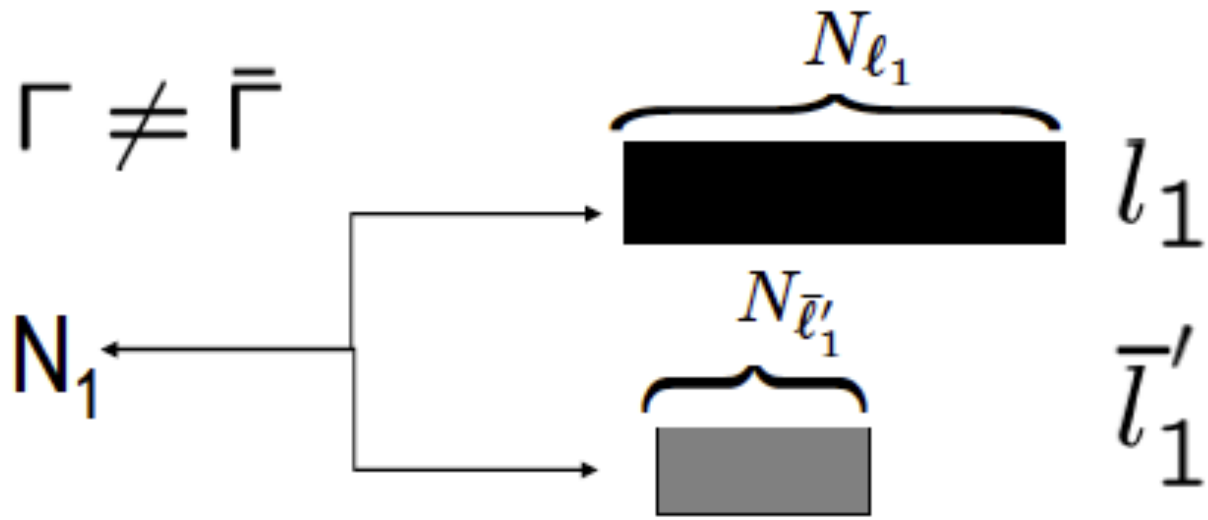
(Nardi, Racker, Roulet '06)

($\alpha = \tau$, e+μ)

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

depends on U !

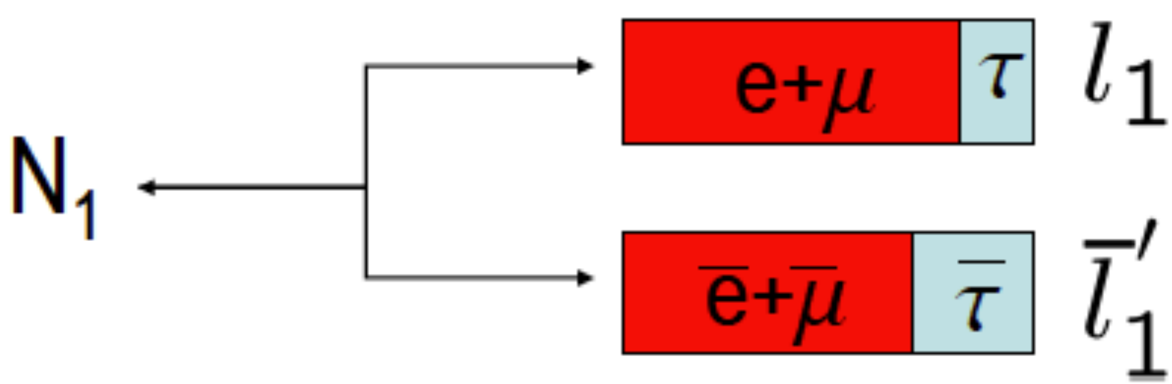
1) $\Gamma \neq \bar{\Gamma}$



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

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

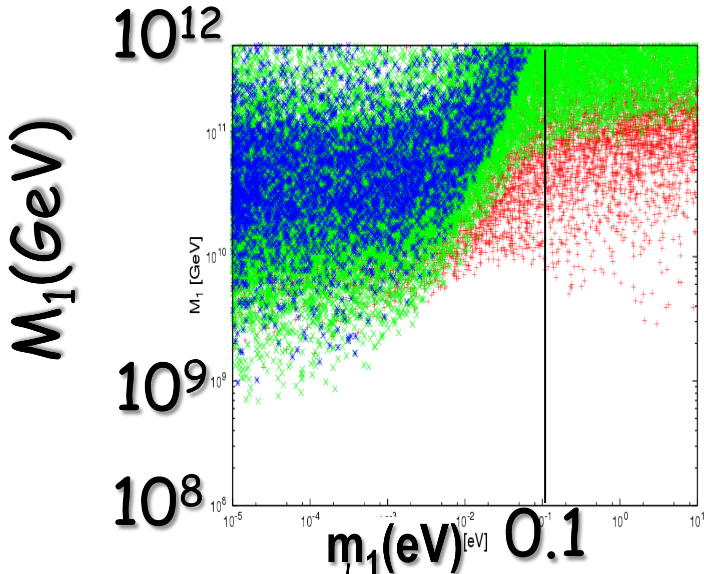
+



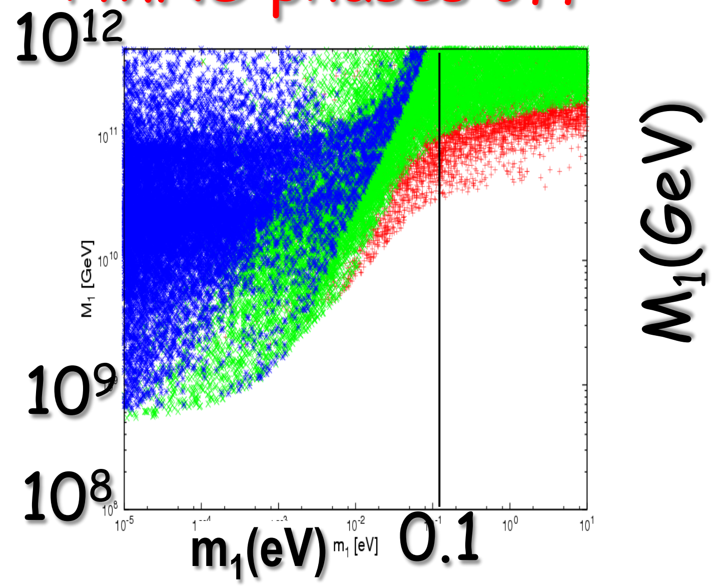
$\Rightarrow \; \frac{\Delta P_{1\alpha}}{2}$

Upper bound on m_1

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

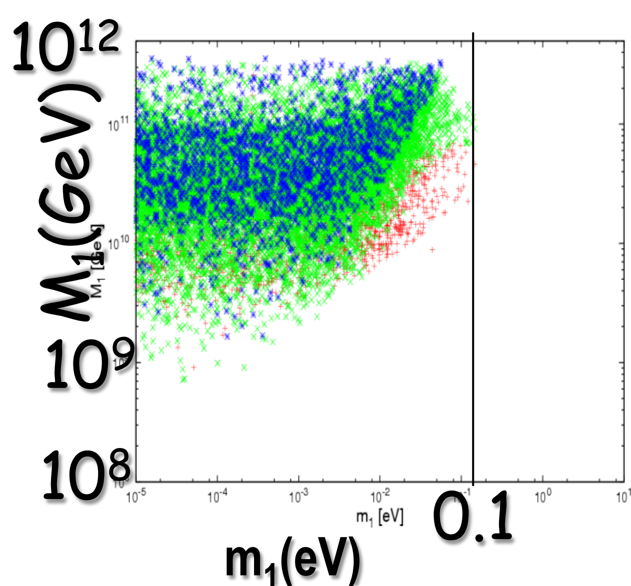


PMNS phases off



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

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:

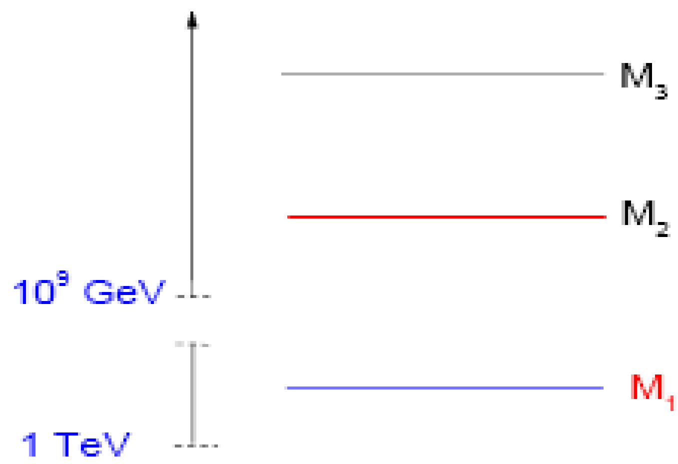
$$N_{B-L}^{f,N_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_1} \ll N_{B-L}^{f,N_1} = \varepsilon_1\, \kappa(K_1)$$

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

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

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} !

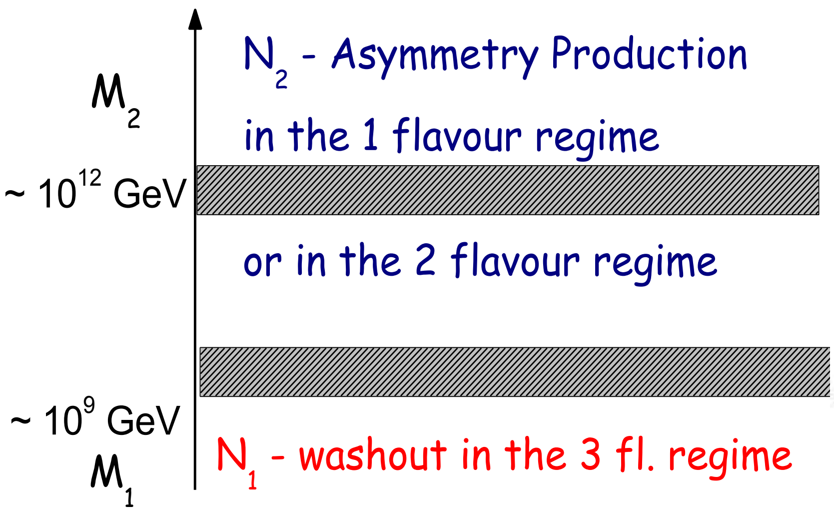


N_2-flavored leptogenesis

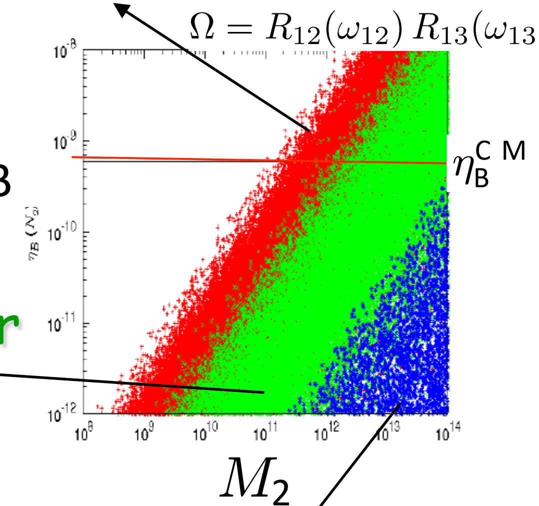
(Vives '05; Blanchet, PDB '06; Blanchet, PDB '08)

Combining together lepton and heavy neutrino flavour effects one has

A two stage process:



Wash-out is neglected



Both wash-out and flavor effects

Unflavored case

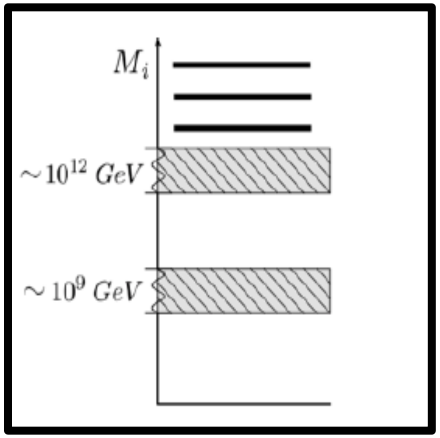
$$N_{B-L}^{\rm f}(N_2) = P^0_{2e}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1e}} + P^0_{2\mu}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + P^0_{2\tau}\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

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

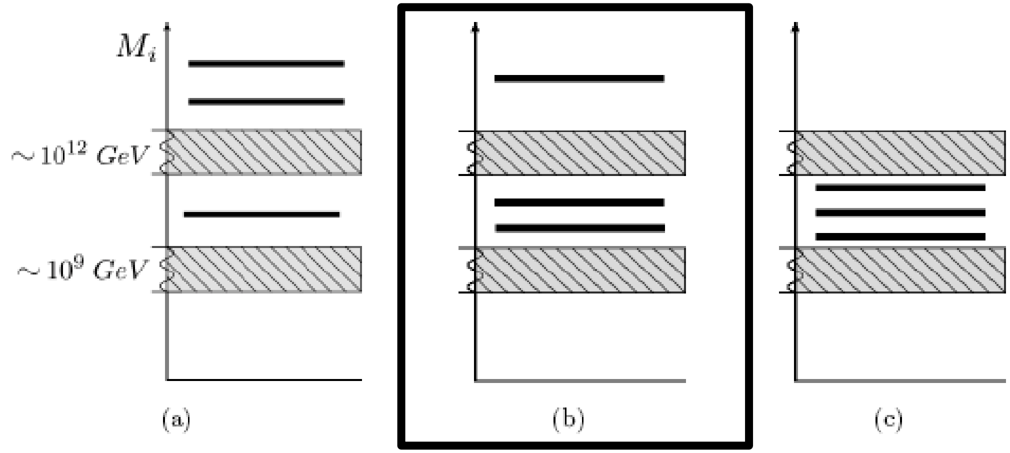
With flavor effects the domain of applicability goes much beyond the choice $\Omega = R_{23}$

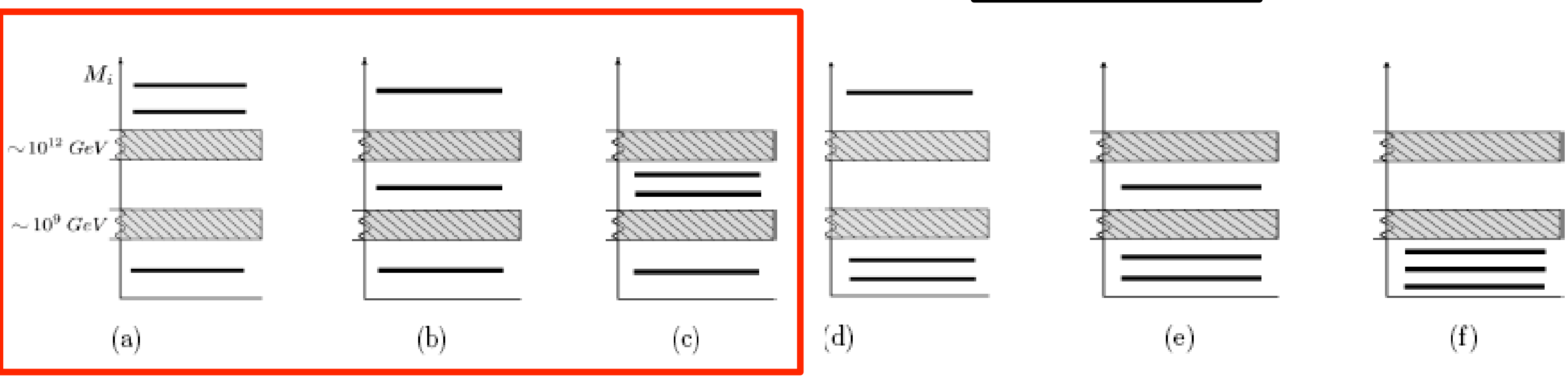
The existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$ not to be negligible!

Heavy neutrino flavored scenario



2 RH neutrino scenario





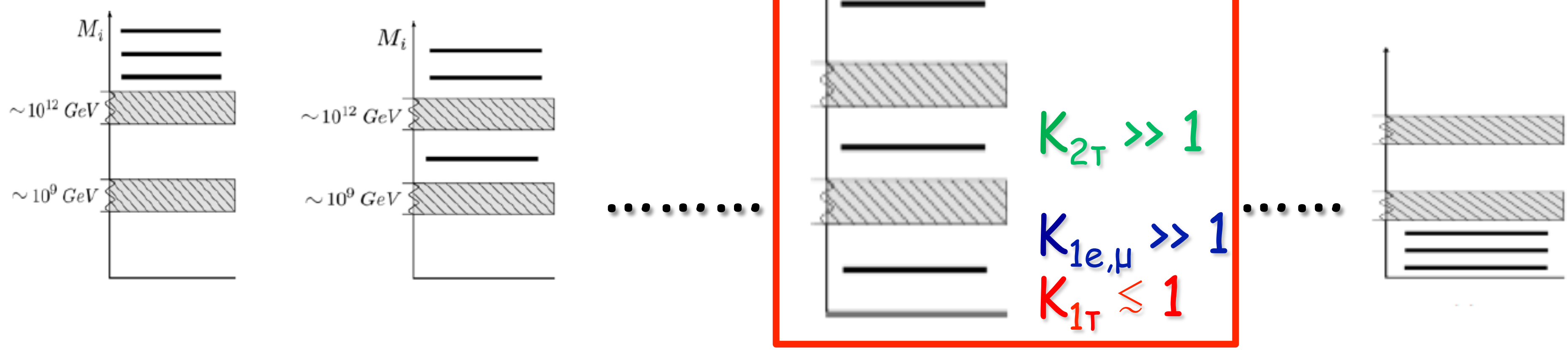
N_2-dominated scenario

(Bertuzzo,PDB,Marzola '10)

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

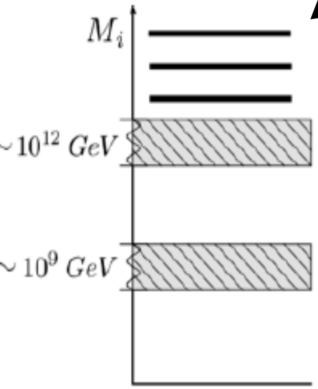
$$N_{B-L}^{\mathrm{f}} = N_{B-L}^{\mathrm{p,f}} + N_{B-L}^{\mathrm{lep,f}}$$

Asymmetry generated from leptogenesis

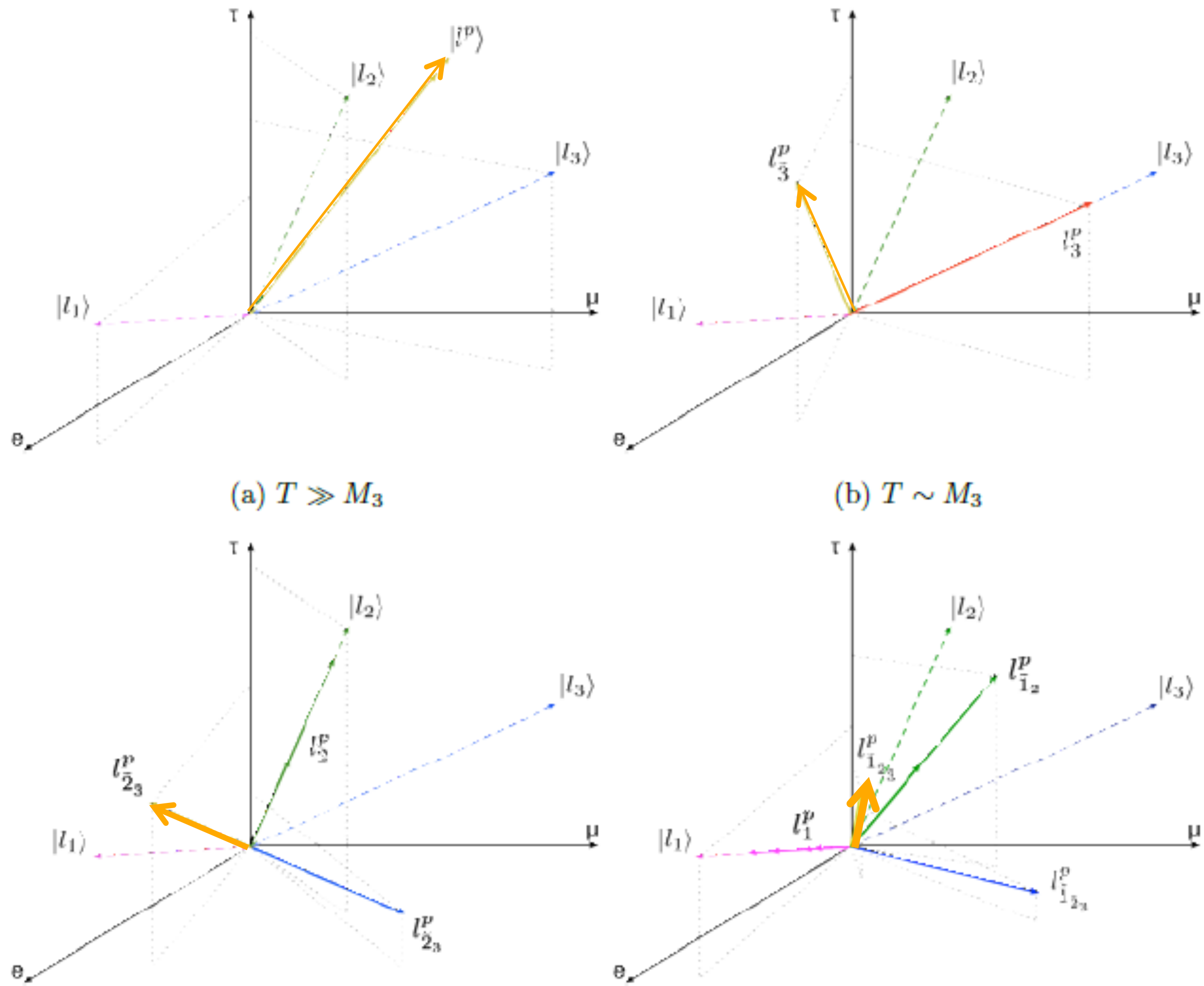


The conditions for the wash-out of a pre-existing asymmetry ('**strong thermal leptogenesis**') can be realised only within a N_2-dominated scenario where the final asymmetry is dominantly produced in the tauon flavour

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



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

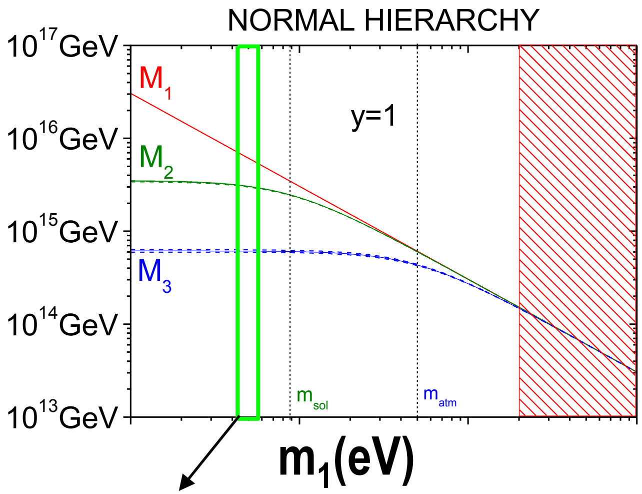


(a) $T \gg M_3$ (b) $T \sim M_3$

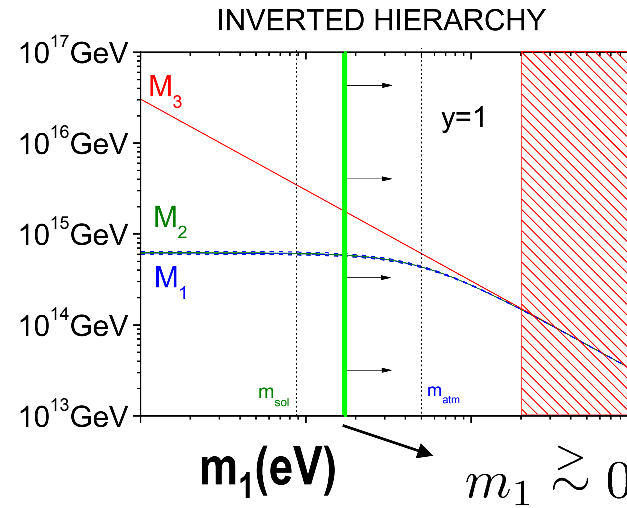
(c) $T \sim M_2$ (d) $T \sim M_1$

Heavy flavoured scenario in models with A4 discrete flavour symmetry

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



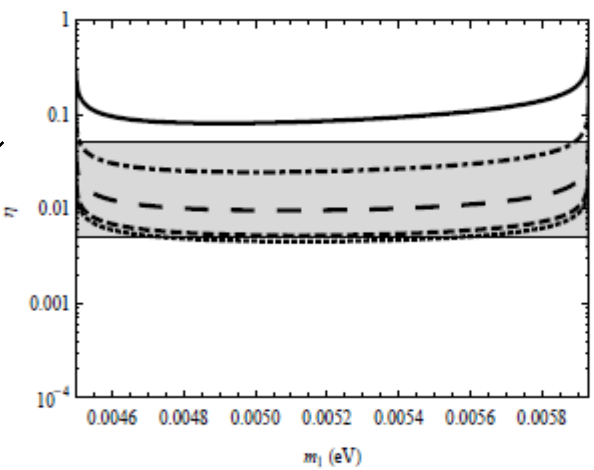
$$m_i = \frac{y^2 \, v_u^2}{M_j}$$



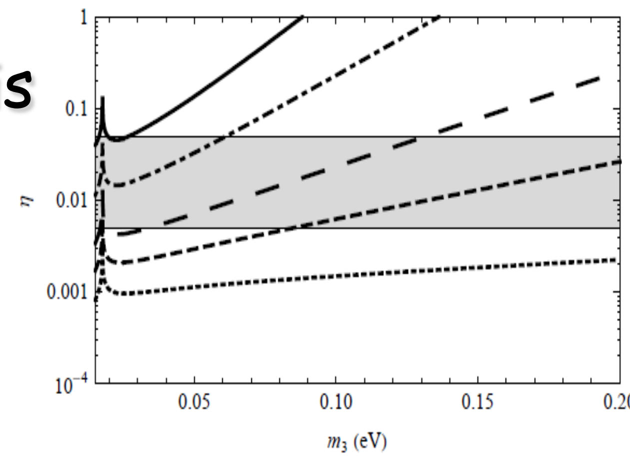
$$m_1 \simeq 5 \times 10^{-3}\,\mathrm{eV}$$

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

imposing successful leptogenesis



η → Symmetry Breaking parameter



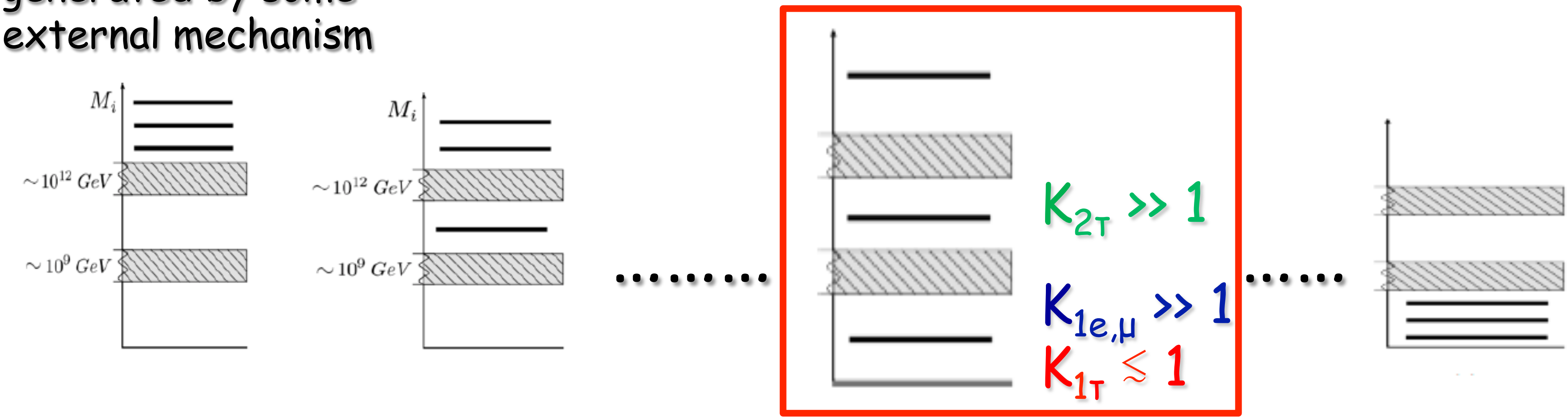
The different lines correspond to values of y between 0.3 and 3

(Bertuzzo,PDB,Marzola '10)

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

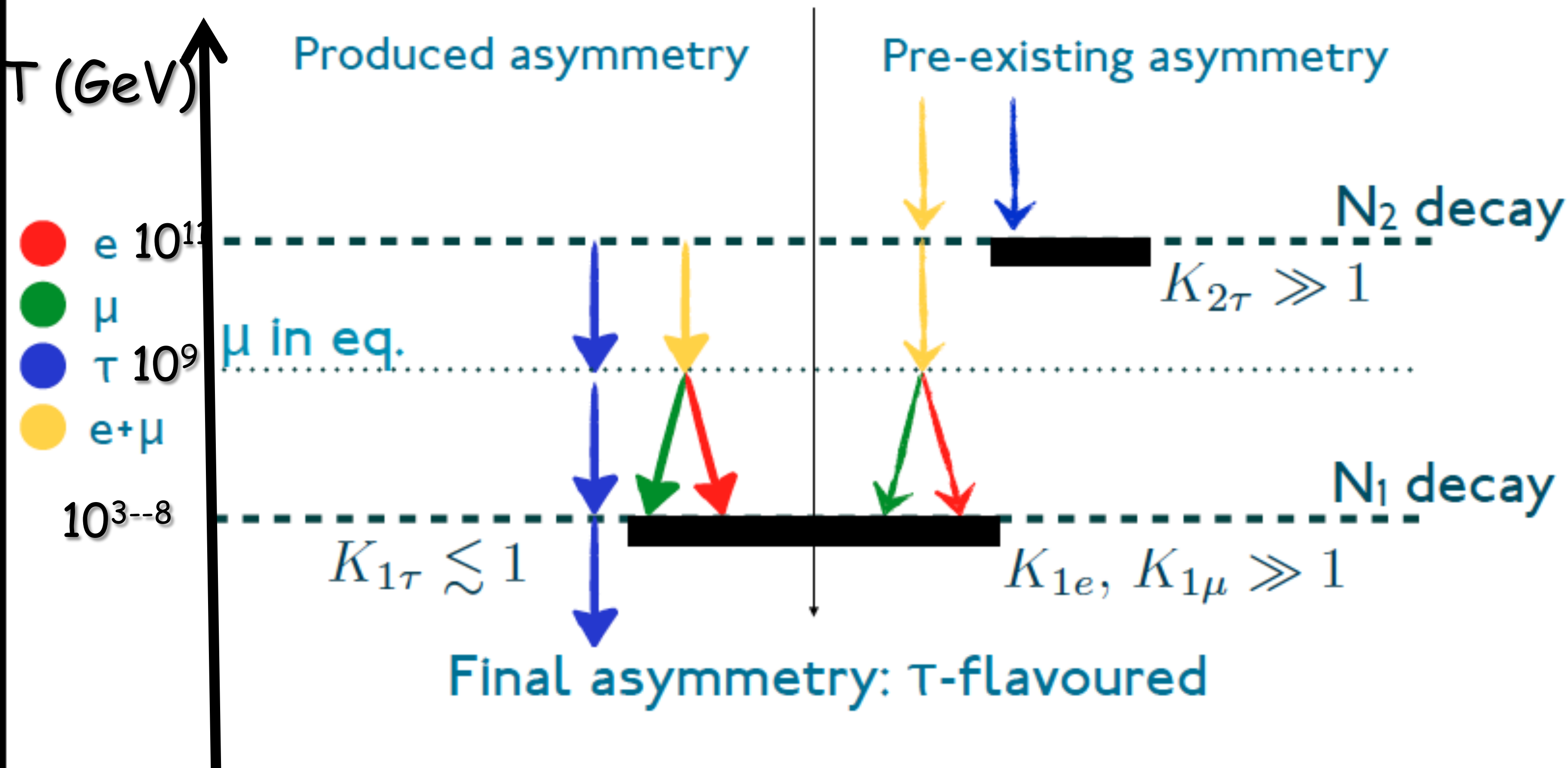
$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p,f} + N_{B-L}^{\rm lep,f}$$

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



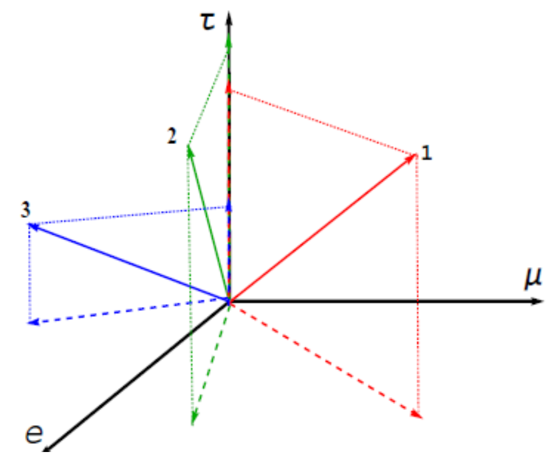
Strong thermal leptogenesis conditions

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

Courtesy of Michele Re Fiorentin

Density matrix formalism with heavy neutrino flavours

(Blanchet, PDB, Jones, Marzola '11)



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

The result is a "monster" equation:

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

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)

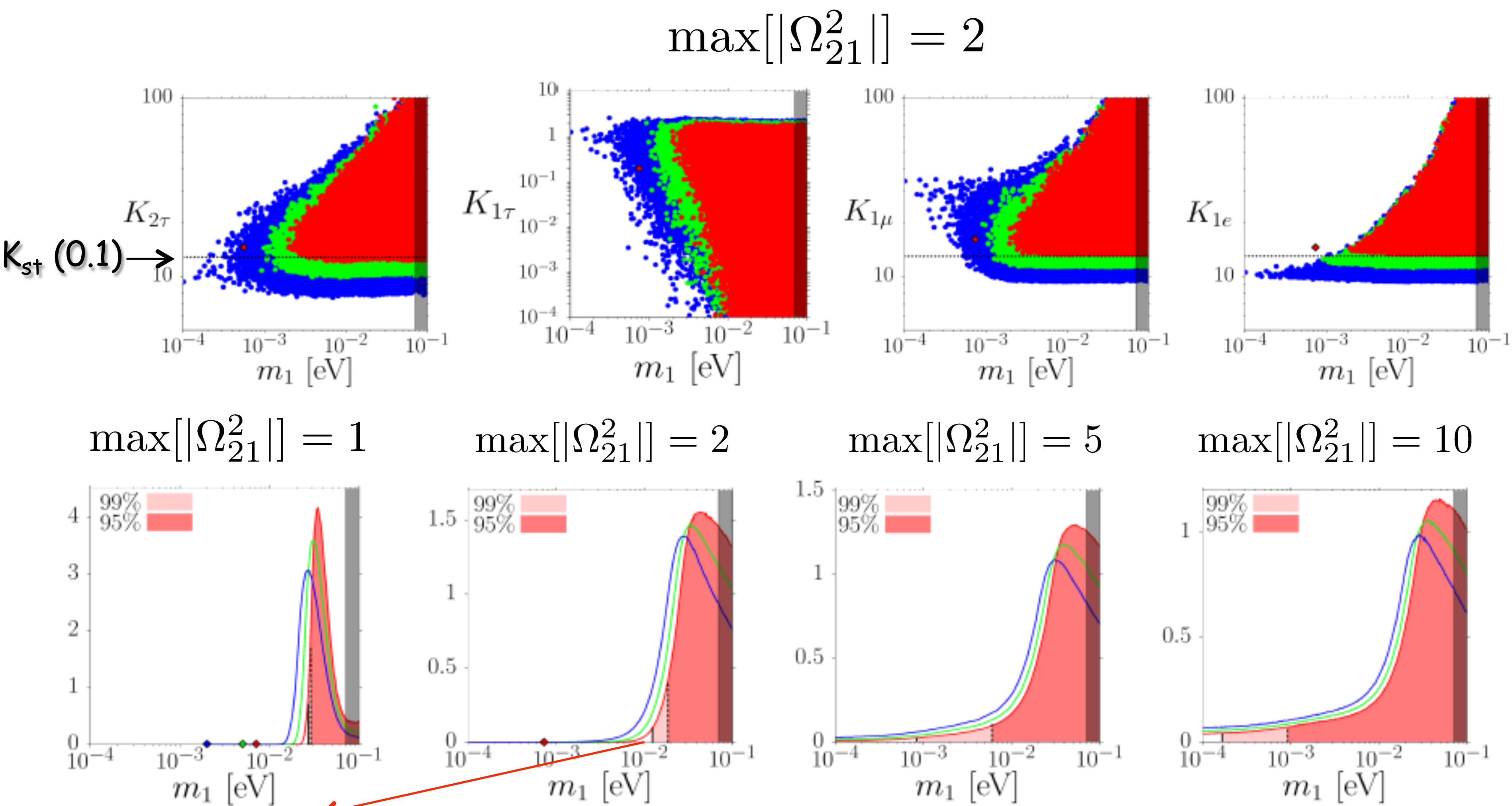
$$m_1 > m_1^{\rm lb} \equiv m_\star \max_\alpha \left[\left(\frac{\sqrt{K_{\rm st}} - \sqrt{K_{1\alpha}^{0,\rm max}}}{\max[||\Omega_{11}||] \left| U_{\alpha 1} - \frac{U_{\tau 1}}{U_{\tau 3}} U_{\alpha 3} \right|} \right)^2 \right]$$

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

The lower bound exists only if either for the muonic flavour or for the electronic (or for both) the value of $K_{1\alpha}^{0,\rm max}$ 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

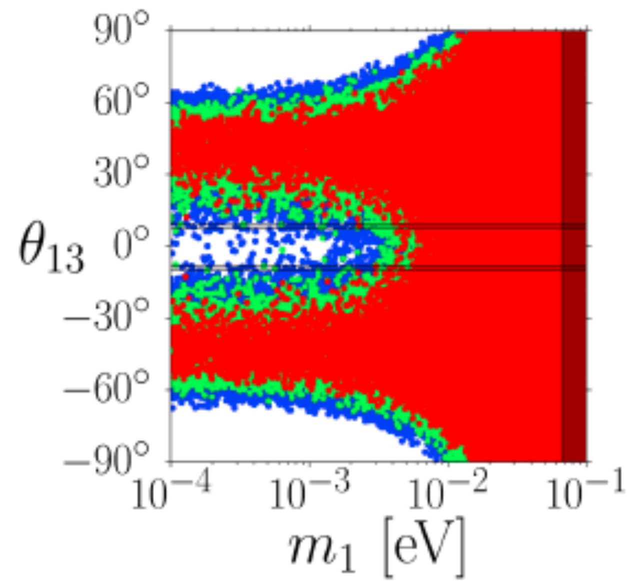
$N^{p,i}_{B-L}$ = 0.001, 0.01, 0.1 NORMAL ORDERING



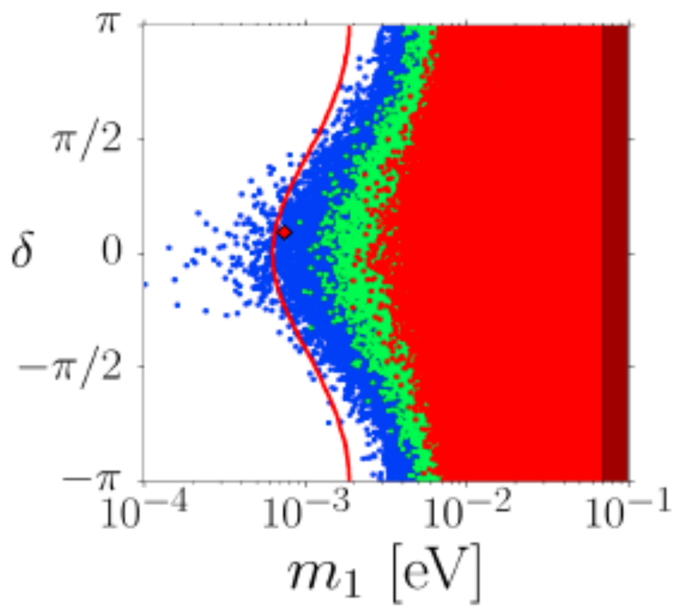
$m_1 \gtrsim 10$ meV $\Rightarrow \Sigma_i\, m_i \gtrsim 75$ meV (to be compared with 60 meV)

A lower bound on neutrino masses

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



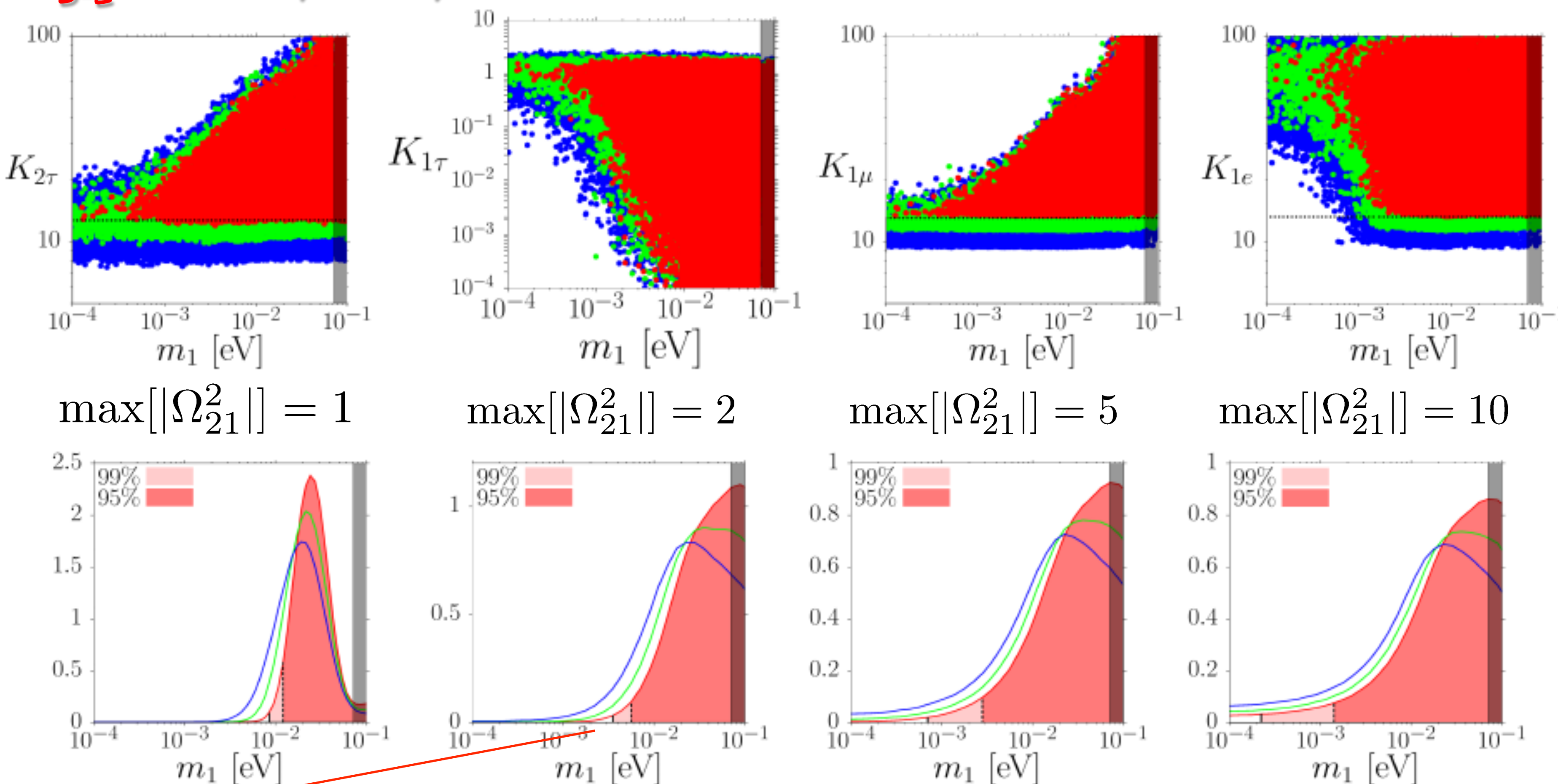
It is modulated by the Dirac phase and it could become more stringent when δ will be measured



A lower bound on neutrino masses (IO)

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

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

Neutrino masses: $m_1 < m_2 < m_3$

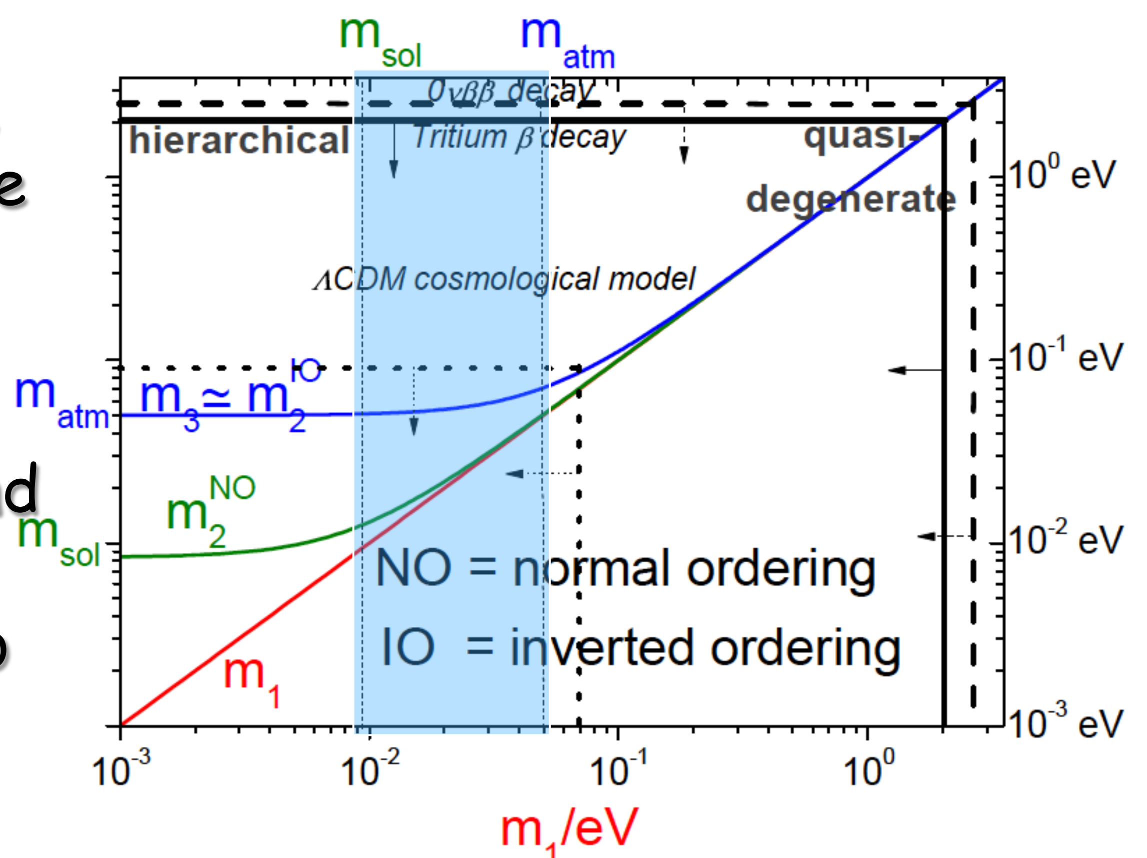
neutrino mixing data

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:

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

SO(10) inspired conditions (also realized beyond SO(10) or GUT models!):

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

From the seesaw formula one can express:

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

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

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

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

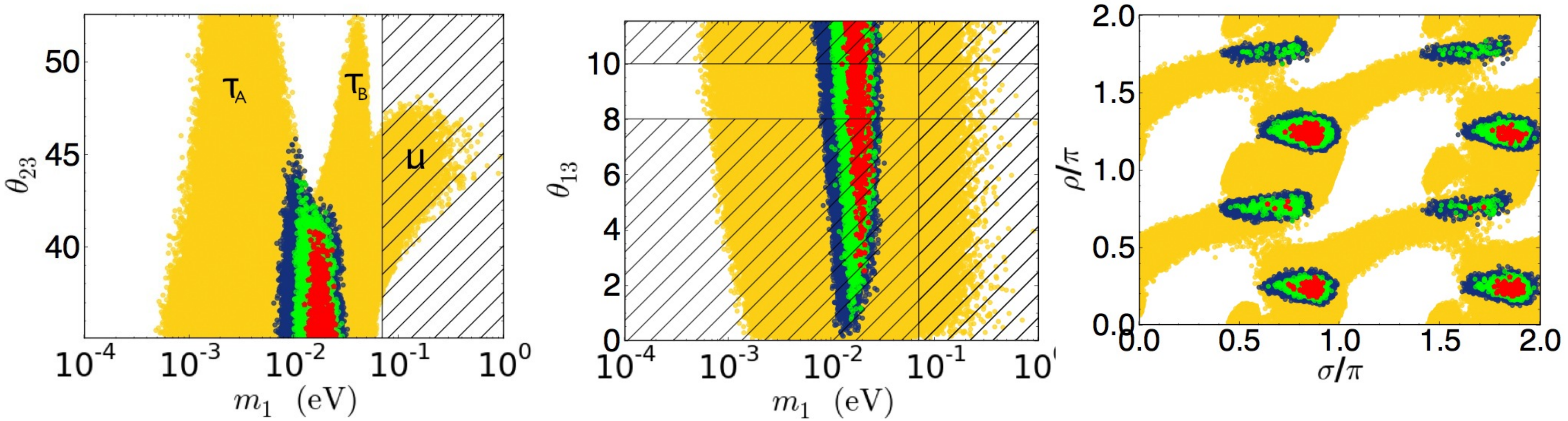
- successful leptogenesis can be attained ($\eta_B = \eta_B^{CMB}$) for some allowed regions in the space of low energy neutrino parameters (see-saw is overconstained!): YELLOW REGIONS. This happens because α_1 and α_3 cancel out in the calculation of the asymmetry

(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

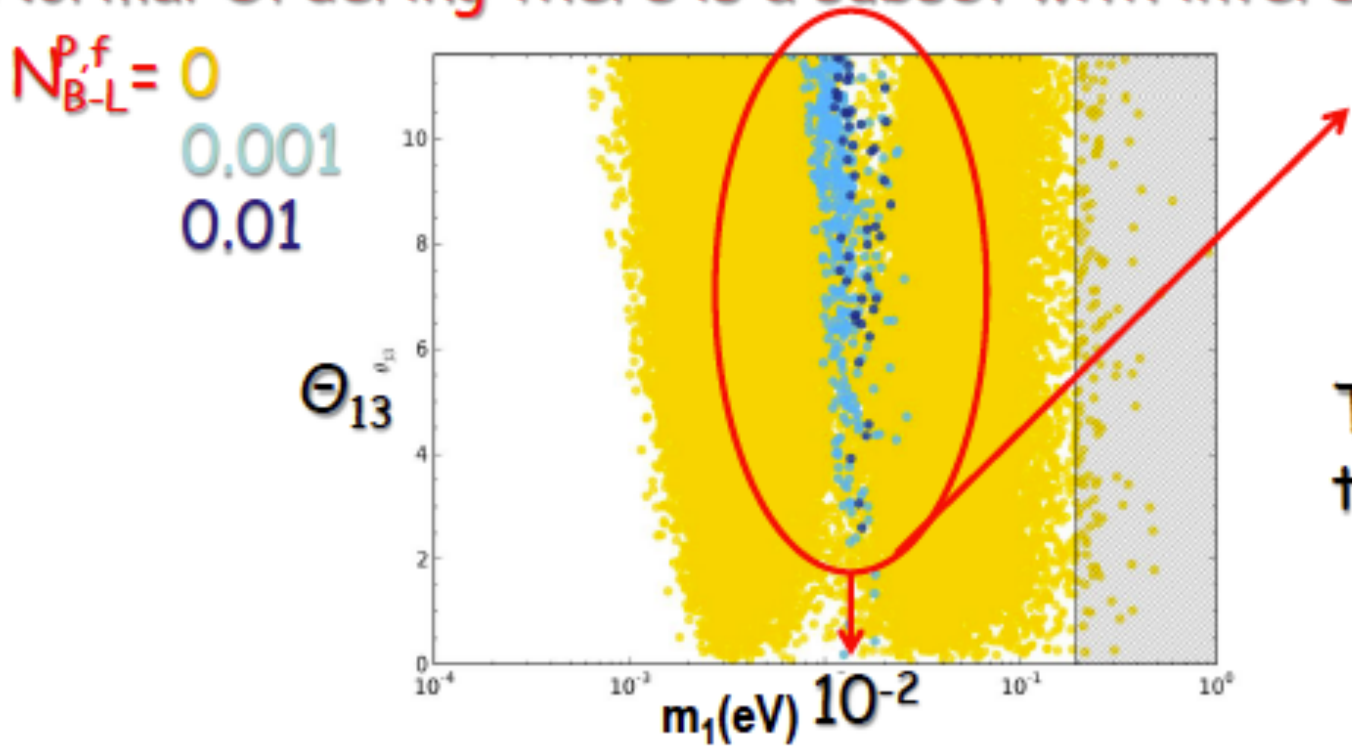
(PDB, Marzola '11)

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

Imposing successful strong thermal leptogenesis condition:

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

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



Talk at the DESY theory workshop 28/9/11

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

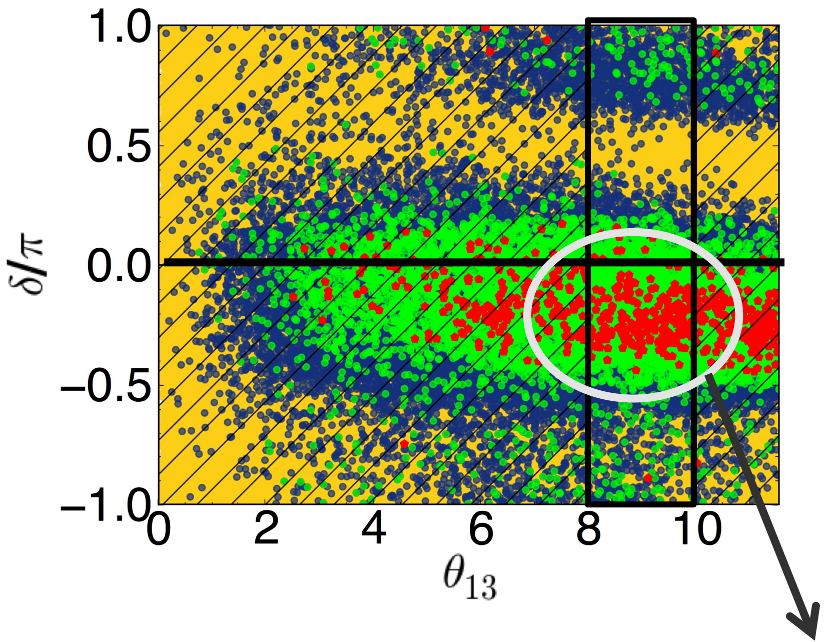
Imposing successful strong thermal leptogenesis condition:

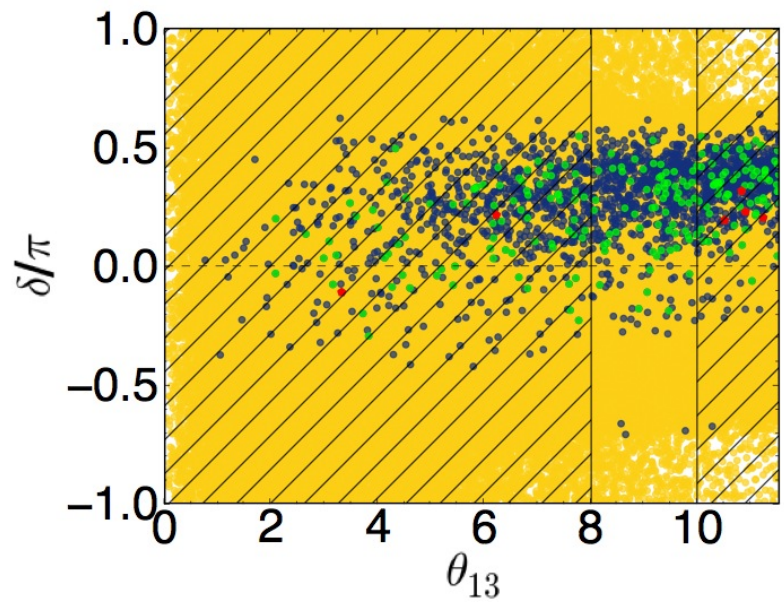
$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p} + N_{B-L}^{\rm lep}, \quad |N_{B-L}^{\rm p}| \ll N_{B-L}^{\rm lep} \simeq 100\,\eta_B^{CMB}$$

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 for large θ_{13}

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

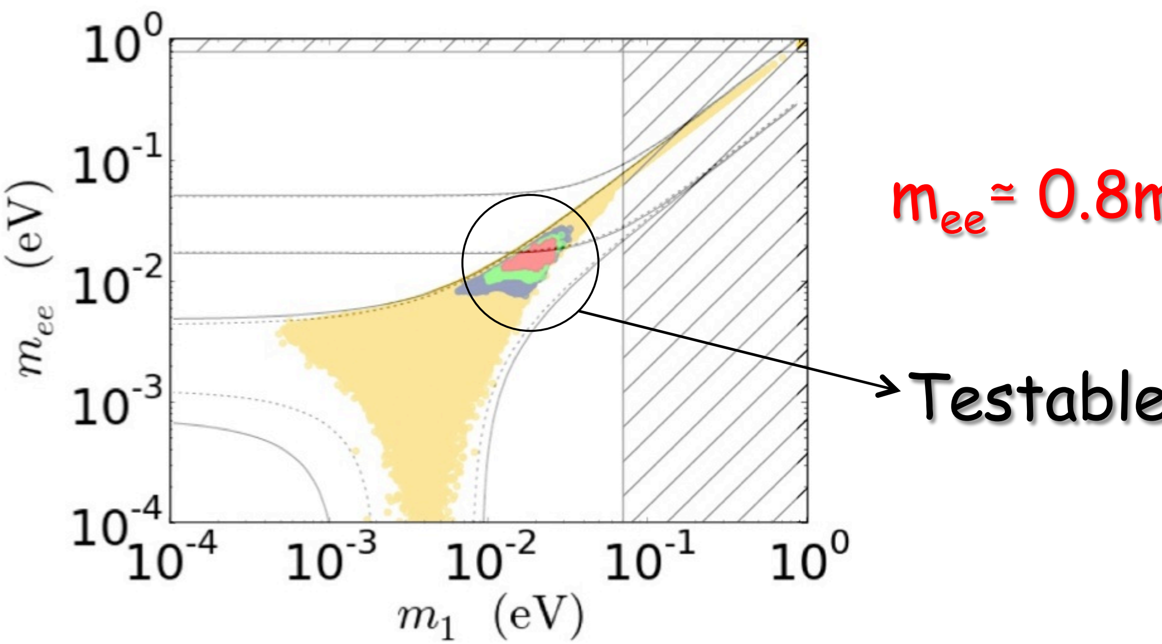
$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p,f} + N_{B-L}^{\rm lep,f} \,,$$

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

Sharp predictions on the absolute neutrino mass scales

N_{B-L}= 0
0.001
0.01
0.1

α_2=5

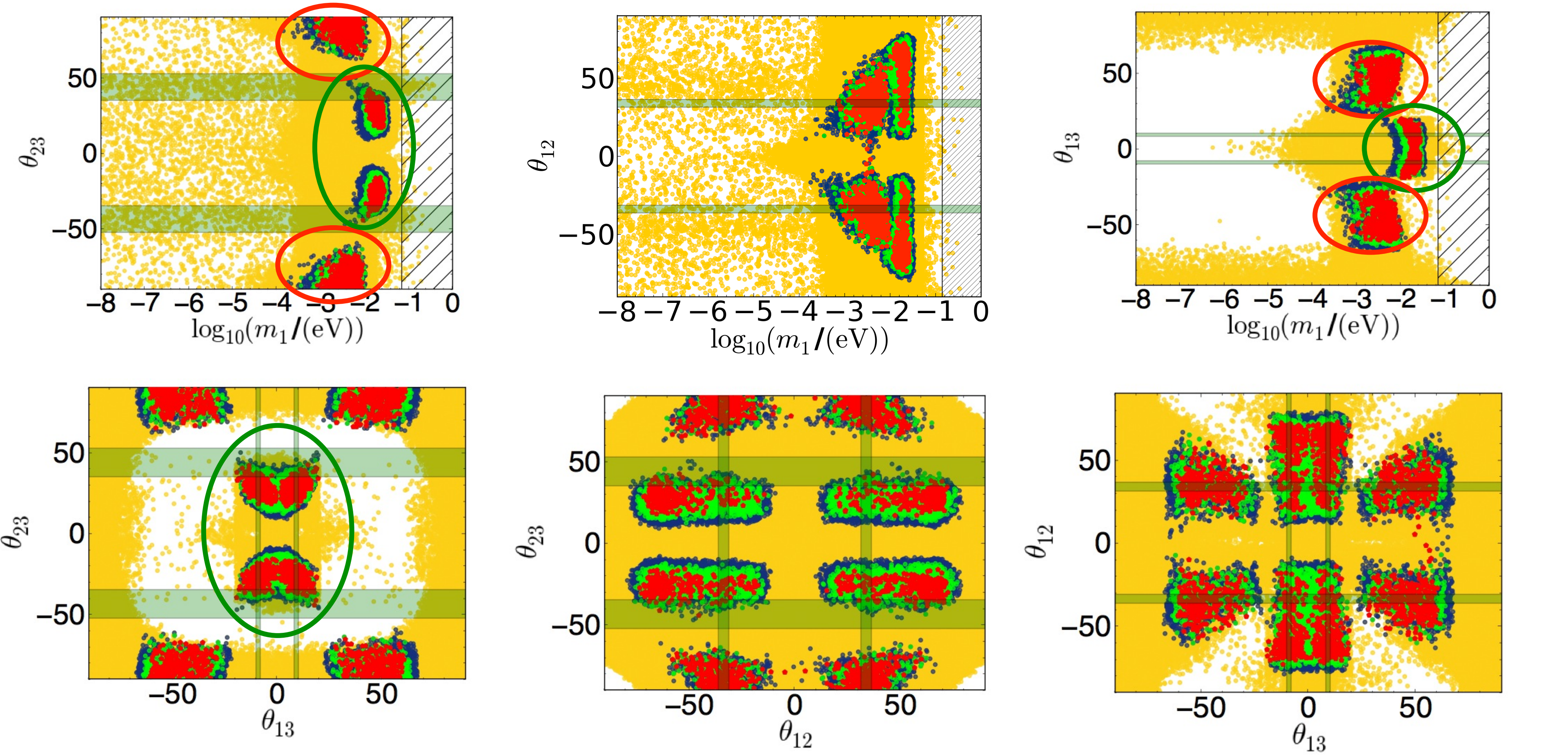


$m_{ee} \simeq 0.8 m_1 \simeq 15$ meV

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

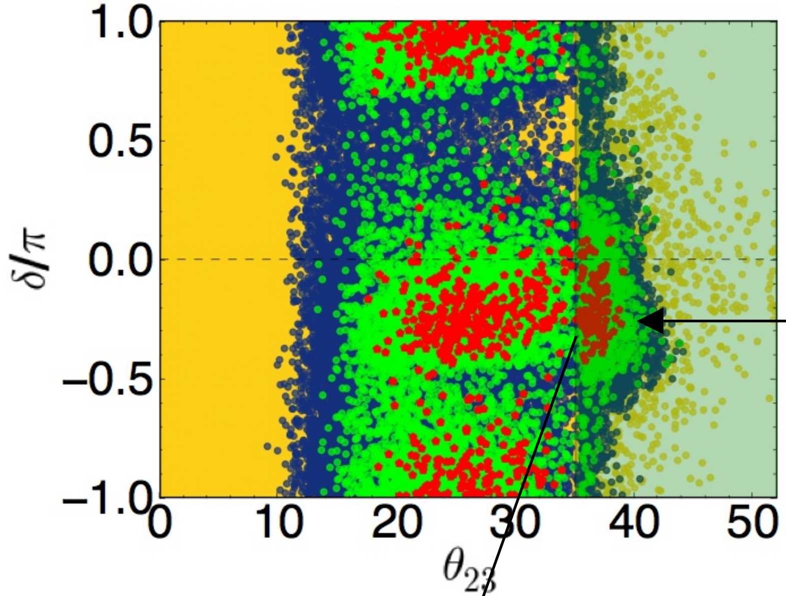
(PDB, Marzola '13)

If we do not plug any experimental information (mixing angles left completely free) : 1 excluded + 1 allowed region



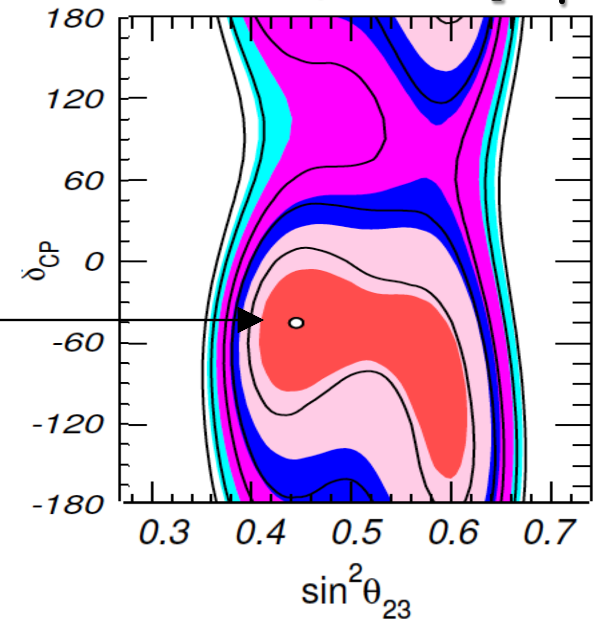
Strong thermal SO(10)-inspired leptogenesis: the atmospheric mixing angle test

arXiv:1308.1107



NuFIT 1.2 (2013)

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

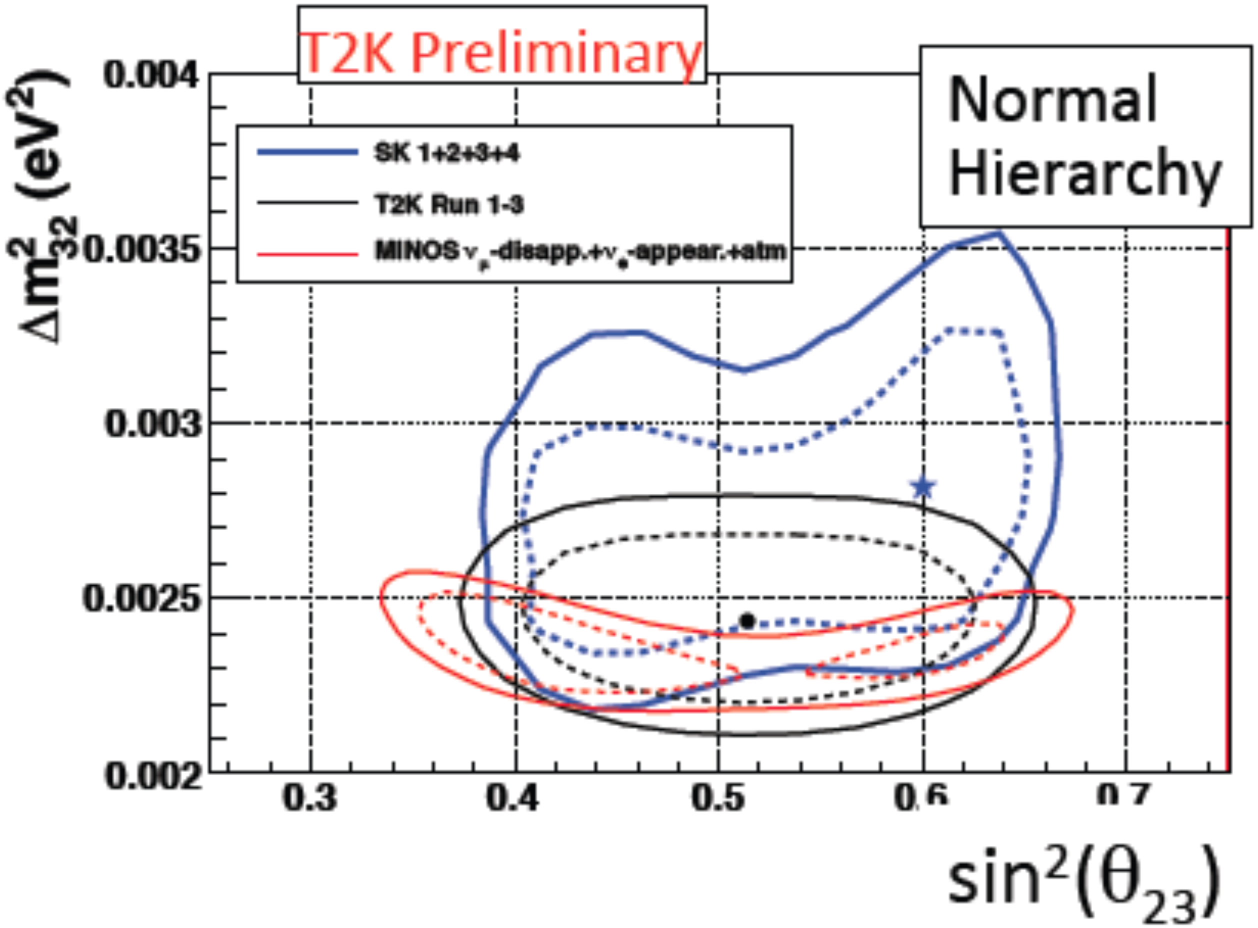


http://www.nu-fit.org/sites/default/files/v12.fig-dlthie-glob.pdf

For large values of $\theta_{23} \gtrsim 35^0$ the Dirac phase is predicted to be $\delta \sim -45^0$

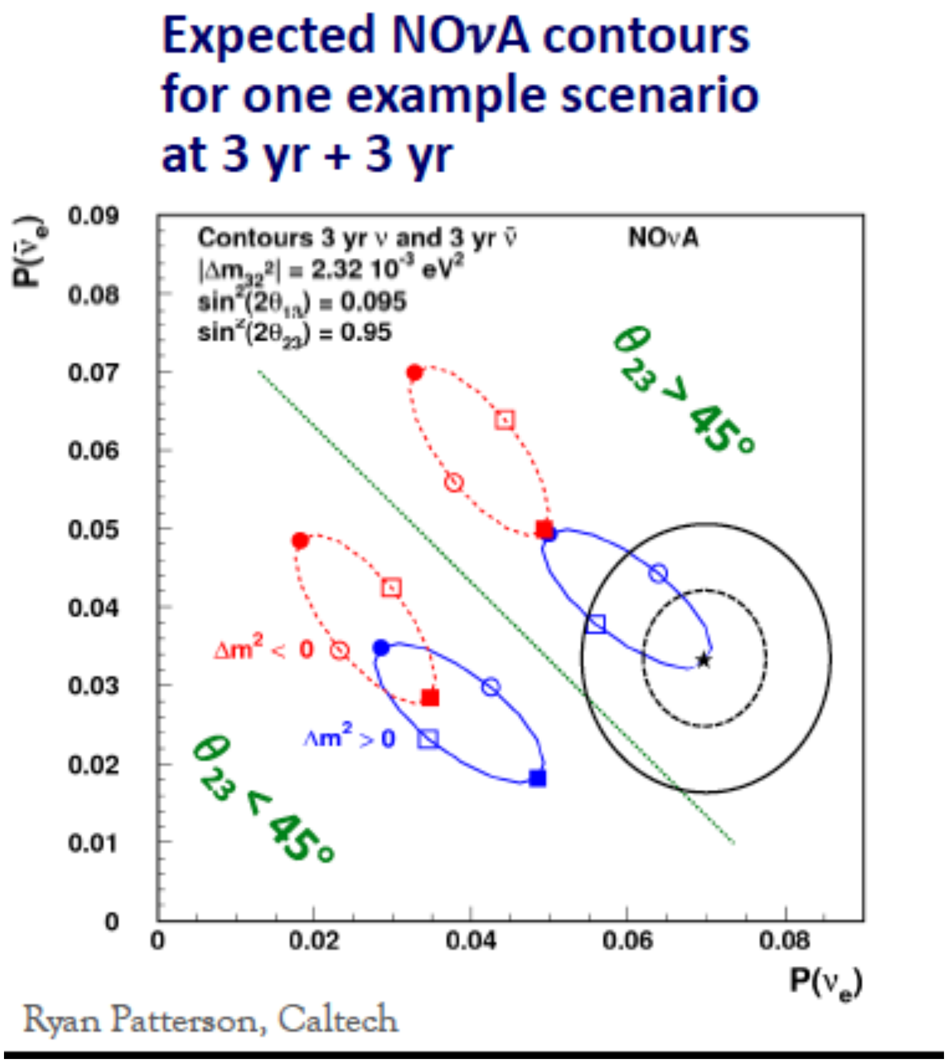
It is interesting that low values of the atmospheric mixing angle are also necessary to reproduce b-τ unification in SO(10) models (Bajc, Senjanovic, Vissani '06)

The atmospheric mixing angle test



MINOS: taken from DPF 2013 (Alexander Radovic)

Experimentl test on the way: NOνA



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

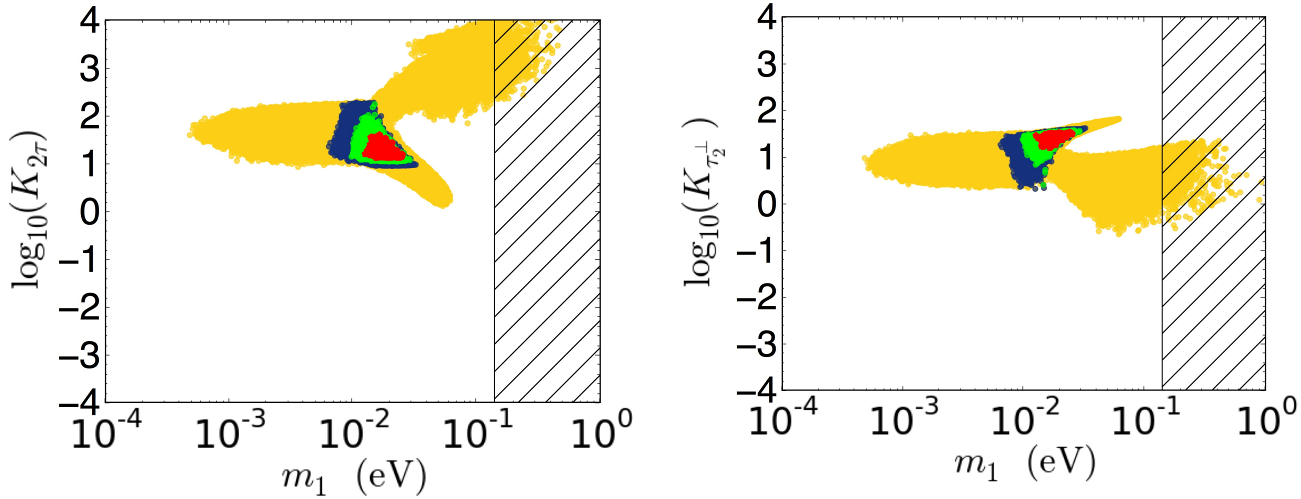
ORDERING	NORMAL
θ_{13}	$\gtrsim 3^\circ$
θ_{23}	$\lesssim 42^\circ$
δ	**$\sim -45^\circ$**
$m_{ee} \simeq 0.8\, m_1$	$\simeq 15$ meV

A (truly) final remark

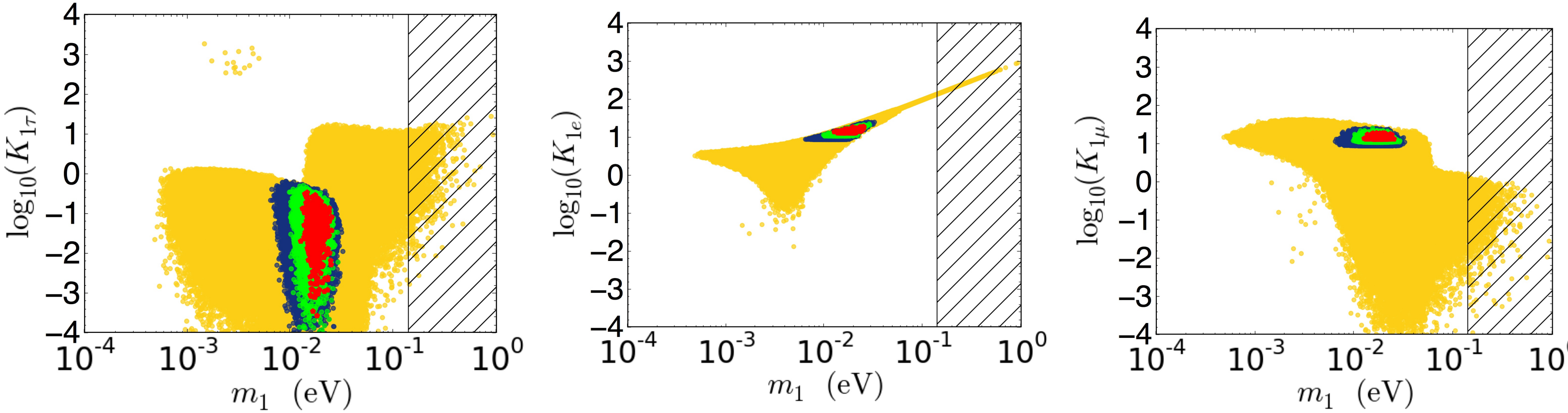
"A hypothesis has to take a risk, has
to stick is neck out. If a theory does not take a risk at all
Because it is compatible with every possible observation
that it is not scientific" (K. Popper)

Some insight from the decay parameters

At the production ($T \sim M_2$)



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

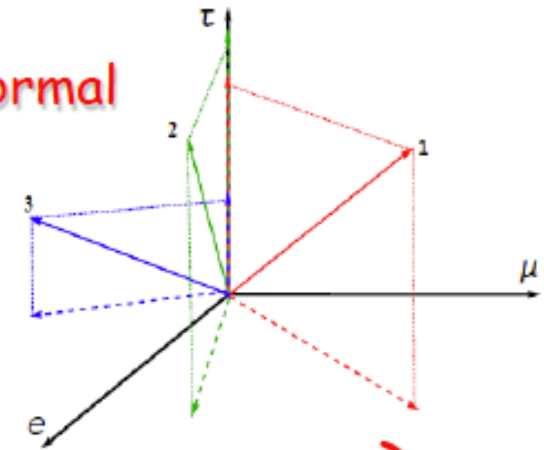


Flavour projection

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

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

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



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

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

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

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

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

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

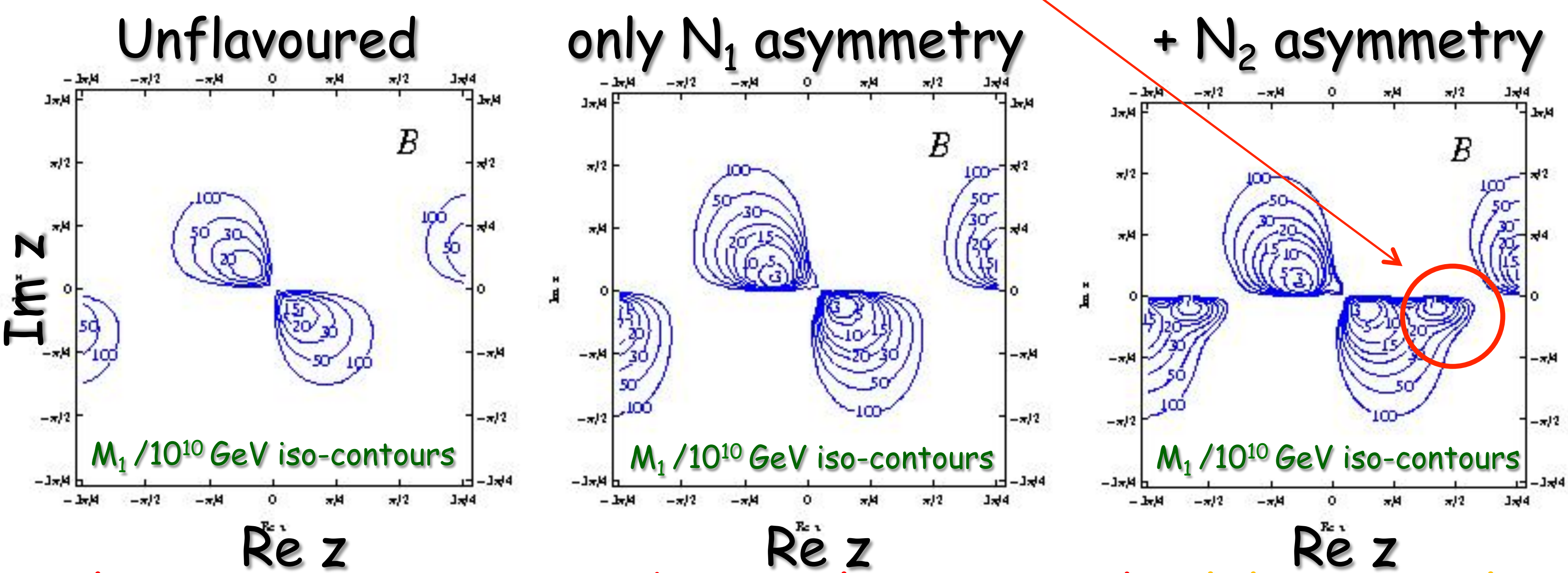
2 RH neutrino scenario revisited

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

In the 2 RH neutrino scenario the N_2 production has been so far considered to be safely negligible because $\varepsilon_{2\alpha}$ were supposed to be strongly suppressed and very strong N_1 wash-out. But taking into account:

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

New allowed N_2 dominated regions appear



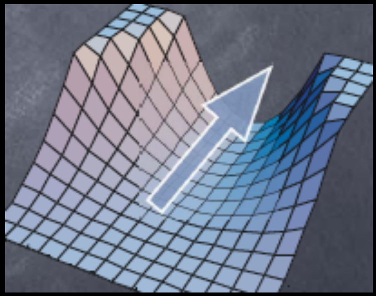
These regions are interesting because they correspond to light sequential dominated neutrino mass models realized in some grandunified models

Affleck-Dine Baryogenesis

(Affleck, Dine '85)

In the Supersymmetric SM there are many "flat directions" in the space of a field composed of squarks and/or sleptons

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

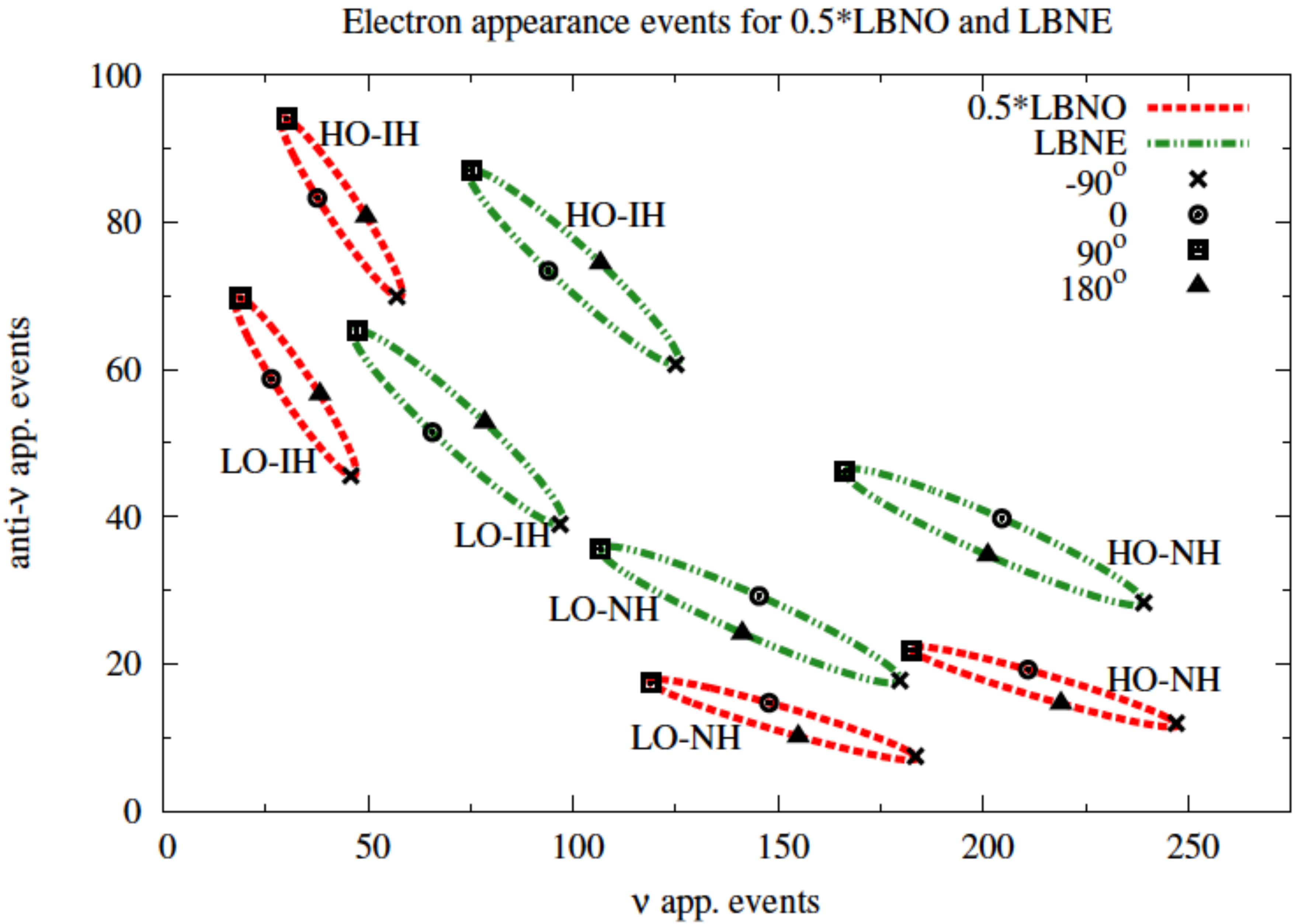


F term D term

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

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

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


Electron appearance events for 0.5*LBNO and LBNE
0.5*LBNO
LBNE
-90°
0
90°
180°
HO-IH
HO-IH
LO-IH
LO-IH
LO-NH
LO-NH
HO-NH
HO-NH
anti-ν app. events
ν app. events
0
20
40
60
80
100
0
50
100
150
200
250