UK HEP FORUM on “Quarks and leptons”
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Baryogenesis

vs.

Leptogenesis

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Puzzles of Modern Cosmology

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

Baryogenesis

$\Rightarrow$ clash between the SM and ΛCDM !

Primordial matter-antimatter asymmetry

- Symmetric Universe with matter- anti matter domains ?

  Excluded by CMB + cosmic rays

  $$\Rightarrow \eta_B^{CMB(Planck)} = (6.1 \pm 0.1) \times 10^{-10} \gg \eta_{\bar{B}}$$

- Pre-existing ? It conflicts with inflation ! (Dolgov '97)

$\Rightarrow$ **dynamical generation (baryogenesis)**

(Sakharov '67)

Models of Baryogenesis

- From phase transitions

  - Electroweak Baryogenesis:

  * in the SM
  * in the MSSM
  * in the nMSSM
  * in the NMSSM
  * in the 2 Higgs model
  * at B-L symmetry breaking
  * in Technicolor
  * ....

- Affleck-Dine:
  - at preheating
  - Q-balls
  - ....

- From Black Hole evaporation
- Spontaneous Baryogenesis
- Gravitational Baryogenesis
- ....
- From heavy particle decays:
  - maximons decays

    (Sakharov '67)
  - GUT Baryogenesis
  - - LEPTOGENESIS (from decays)
- Leptogenesis from RH neutrino oscillations

Baryogenesis in the SM ?

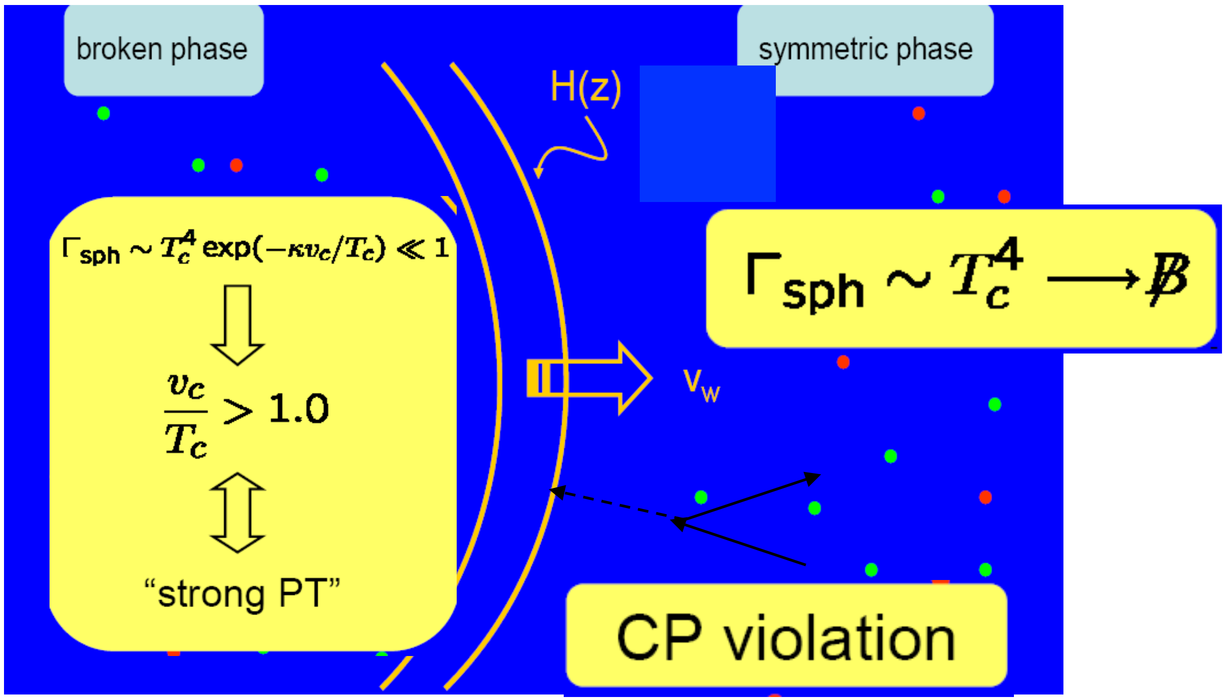
All 3 Sakharov conditions are fulfilled in the SM at some level:

1) Baryon number violation if $T \gtrsim 100$ GeV (sphaleron transitions),
2) CP violation in the quark CKM matrix,
3) Departure from thermal equilibrium (an arrow of time) from the expansion of the Universe

EWBG in the SM

(Kuzmin, Rubakov, Shaposhnikov '85; Kajantie, Laine, Shaposhnikov '97)

If the EW phase transition (PT) is 1st order ⇒ broken phase bubbles nucleate



(Stephan Huber's courtesy)

The ratio v_c/T_c is directly related to the Higgs mass ($\propto 1/M_h^2$) and only for M_h < 40 GeV one can have a strong PT ⇒ EW baryogenesis in the SM is ruled out by the LEP lower bound M_h ⇒ 114 GeV ! (also not enough CP)

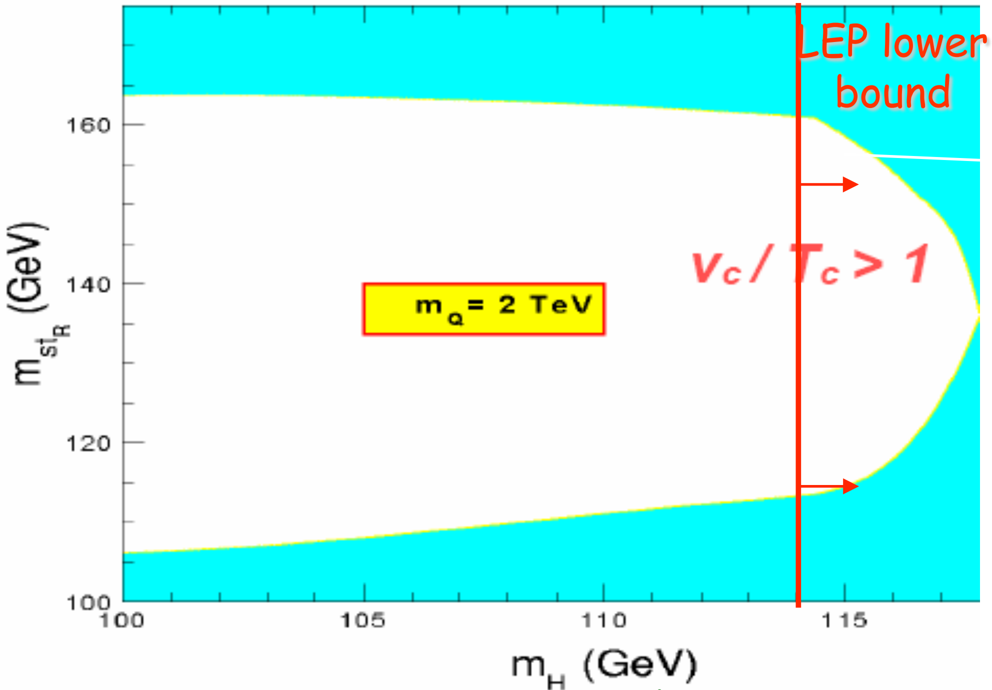
⇒ New Physics is needed!

EWBG in the MSSM: the light stop scenario

(Carena, Quiros, Wagner '98)

•Additional bosonic degrees of freedom (dominantly the light stop contribution) can make the EW phase transition more strongly first order if:

right-handed stop mass (light stop)

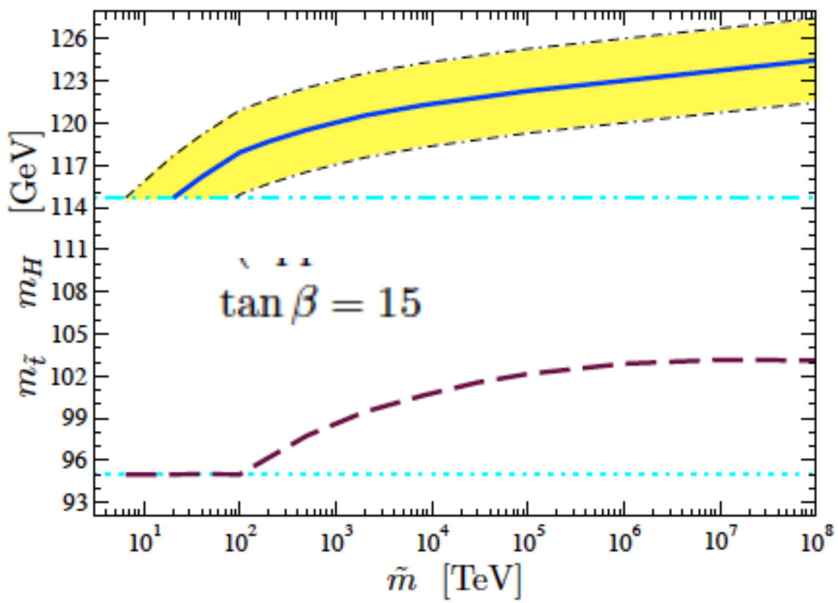


• Notice that there is a tension between the strong PT requirement and the LEP lower bound on M_h and in particular one has to impose $5 \lesssim \tan\beta \lesssim 10$

• In addition there are severe constraints from the simultaneous requirement of CP violation in the bubble walls without generation of too large electric dipole moment of the electron……

EWBG in the MSSM: the light stop scenario

(Carena, Nardini, Quiros, Wagner '09)



common scale for heavy fermion masses

$\tilde{m} > 6.5$ TeV

$m_H \lesssim 127$ GeV

$m_{\tilde{t}} \lesssim 120$ GeV. (light stop)

Light stop scenario after LHC8

- A Higgs mass ~ 125 GeV forces the heavy fermio ns mass scale $\tilde{m}$) to be much above the EW scale but still MSSM EWB seems viable in some region but…

  - A light stop enhances SM-like gluon fusion production rate reducing the decay width into photons incompatibly with LCH8 data

    (Cohen et al '12; Curtin, Jaiswal, Meade '12)

$\Rightarrow$ MSSM EWB ruled out?

  - Tension can be relaxed with a light neutralino with mass lower than about 60 GeV inducing a sizable Higgs invisible decay width

    (Carena Nardini, Quiros, Wagner '12)

- Even though not completely dead, MSSM EWB is strongly cornered and this has induced studies of EWB in other BSM models:
  - in a two-Higgs-doublet model (Dorsch, Huber, No '13)
  - in the NMSSM (Balazs, Mazumdar '13)
  - ….in many more different ways!

EWB, still a "character in search of an author"

Baryogenesis and the early Universe history

T_{RH} = ? ($\lesssim 10^{15}$GeV) — Inflation

T

100 GeV — EWBG

— "Cold" EWBG (Krauss,Trodden'99; Konstandin et al.'10)

0.1- 1 MeV — BBN

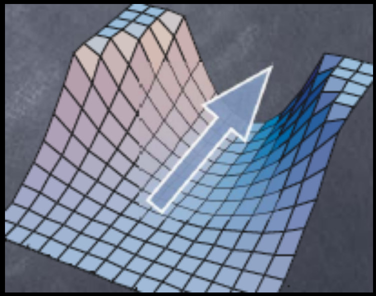
0.1- 1 eV — Recombination

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 !

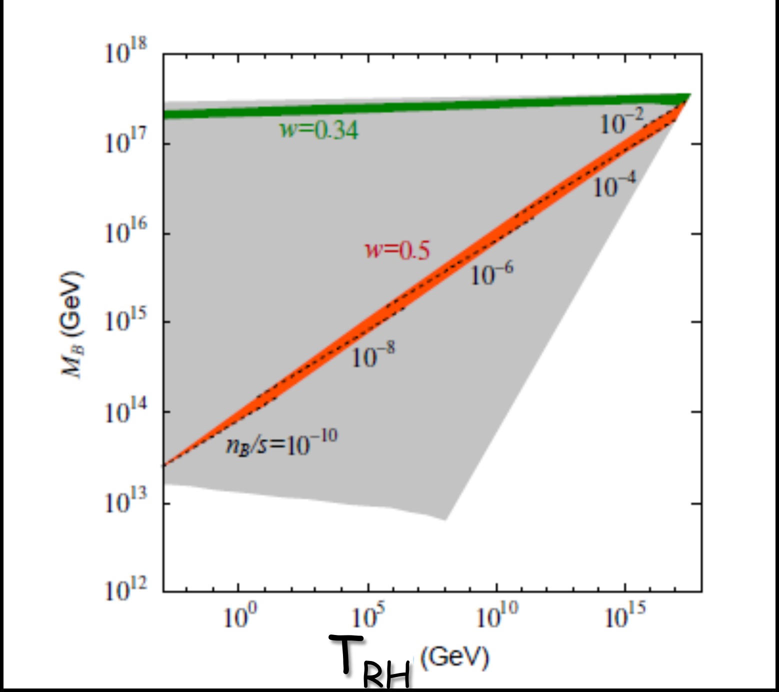
Gravitational Baryogenesis

(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^{μ}:

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

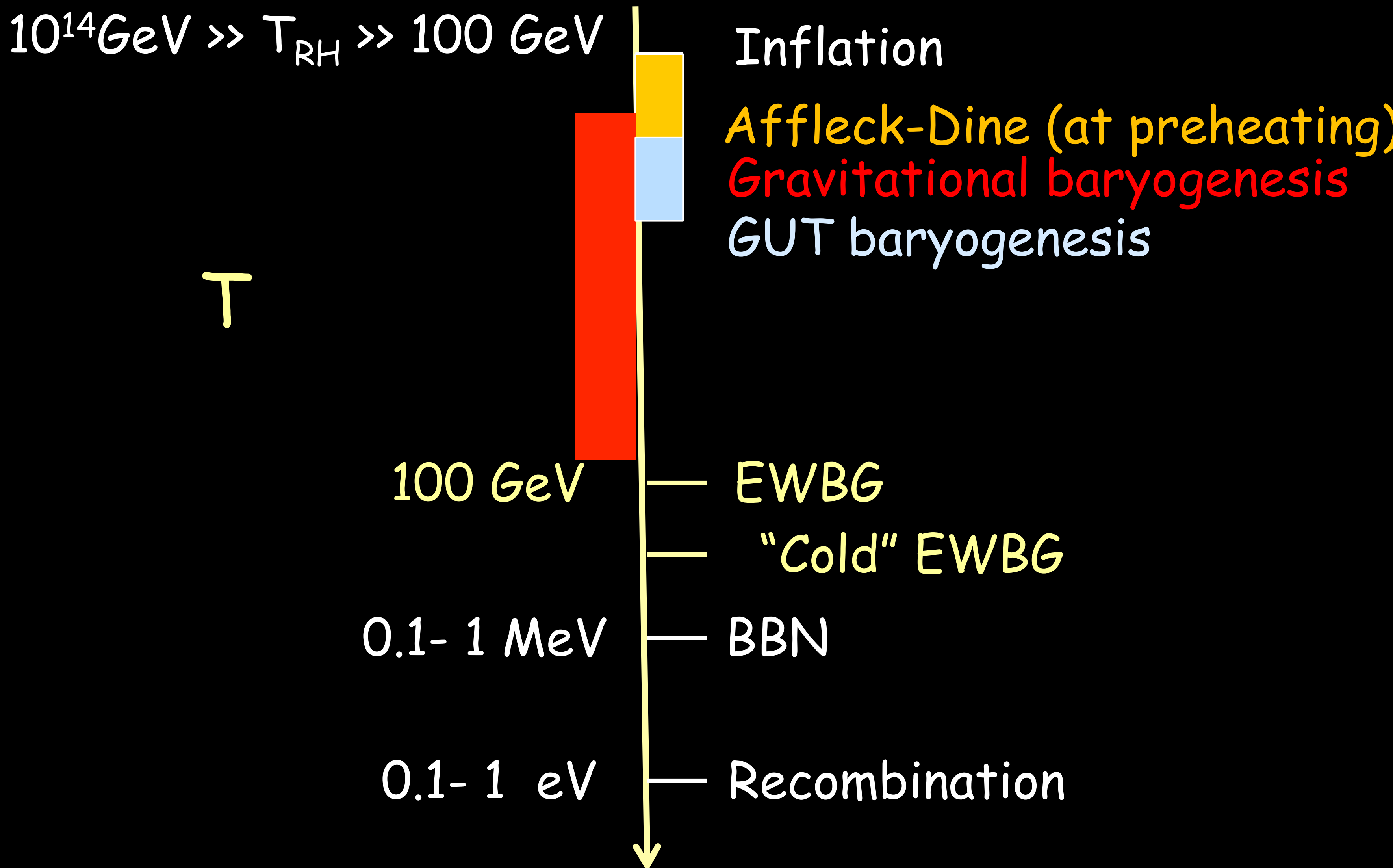
Cutoff scale of the effective theory



It is natural to have this operator in quantum gravity and in supergravity

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

Baryogenesis and the early Universe history



Neutrino mixing parameters („pre-T2K")

$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle$$

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

Maki-Nakagawa-Sakata-Pontecorvo matrix

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

Atmospheric | Reactor, Accel.,LBL CP violating phase | Solar,Reactor | $\beta\beta 0\nu$ decay

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

- best-fit point and 1σ (3σ) ranges:

$$\theta_{12} = 34.5 \pm 1.4 \left({}^{+4.8}_{-4.0}\right), \quad \Delta m^2_{21} = 7.67\,^{+0.22}_{-0.21} \left({}^{+0.67}_{-0.60}\right) \times 10^{-5}\ \mathrm{eV}^2,$$

$$\theta_{23} = 43.1\,^{+4.4}_{-3.5} \left({}^{+10.1}_{-8.0}\right), \quad \Delta m^2_{31} = \begin{cases} -2.39 \pm 0.12 \left({}^{+0.37}_{-0.40}\right) \times 10^{-3}\ \mathrm{eV}^2, \\ +2.49 \pm 0.12 \left({}^{+0.39}_{-0.36}\right) \times 10^{-3}\ \mathrm{eV}^2, \end{cases}$$

$$\theta_{13} = 3.2^{+4.5} \left({}^{+9.6}\right), \qquad \delta_{CP} \in [0, 360];$$

(Gonzalez-Garcia, Maltoni 08)

Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: normal or inverted

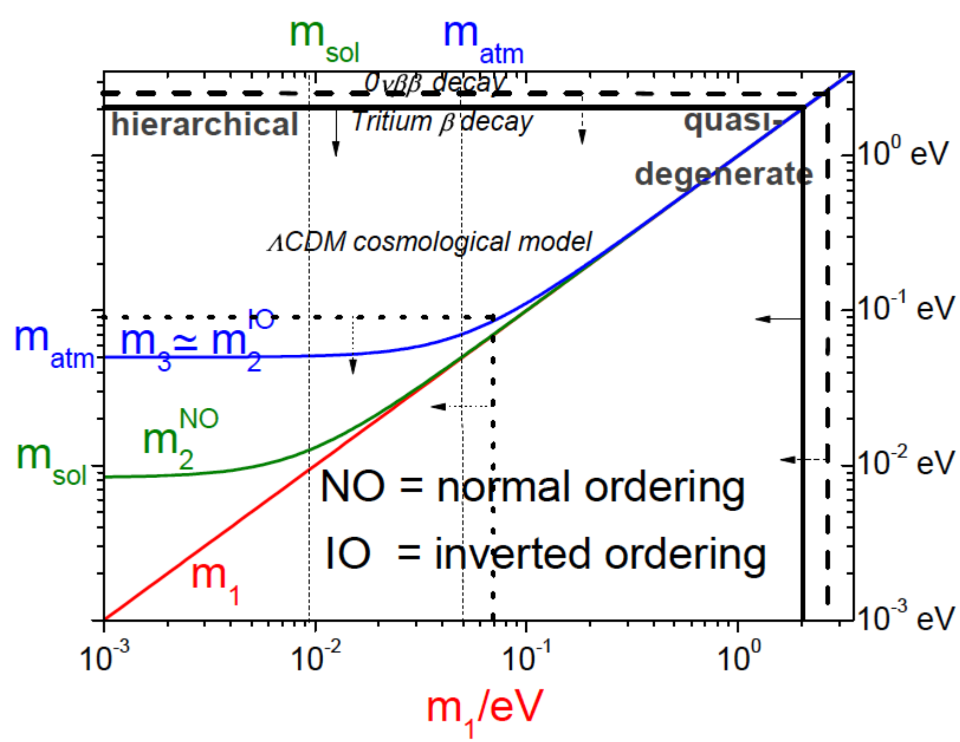
$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,\text{eV}$$

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

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



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 spectrum of mass eigenstates splits in 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 the

total CP asymmetries

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

- Thermal production of the RH neutrinos $\Rightarrow$ $T_{RH} \gtrsim M_i / (2 \div 10)$

...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 or even directly at collliders?

A common approach in the LHC era: by lowering the typical expected scale of leptogenesis (~ 10^{10} GeV) in order to have additional testable effects (LHC signals, LFV,electric dipole moments, non-unitary leptonic mixing matrix…)

⇒ "TeV Leptogenesis"

In light of LHC8 negative data…is there an alternative approach based on usual high energy scale leptogenesis and relying just on low energy neutrino data?

Neutrino mixing parameters

Non-vanishing θ_{13}

- T2K : $\sin^2 2\theta_{13} = 0.03 - 0.28$ (90% CL NO)
- DAYA BAY: $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$
- RENO, MINOS, DOUBLE CHOOZ, new T2K data,

recent global analyses

$\theta_{13} = 7.7° \div 10.2°$ (95% CL)

$\theta_{23} = 36.3° \div 40.9°$ (95% CL)

$\delta_{\text{best fit}} \sim \pi$

(Normal Ordering)

(Fogli, Lisi, Marrone Montanino, Palazzo, Rotunno 2012)

Analogous results by Gonzalez-Garcia, Maltoni and Schwetz but $\delta_{\text{best fit}} \sim -\pi/3$ and θ_{23} in first octant favoured only at 1.5 σ for normal order and at 0.9 σ for inverted ordering

Recent hints (Daya Bay + T2K and SK) seem to support $\delta_{\text{best fit}} \sim -\pi/2$ (talk by F. Di Lodovico)

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 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
- 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: $M_2 \gtrsim 3\, M_1$

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

From the last two assumptions

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

4) Barring fine-tuned mass cancellations in the seesaw

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

(Davidson, Ibarra '02)

5) Efficiency factor from simple Boltzmann equations

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

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

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

decays

inverse decays

wash-out

decay parameter

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

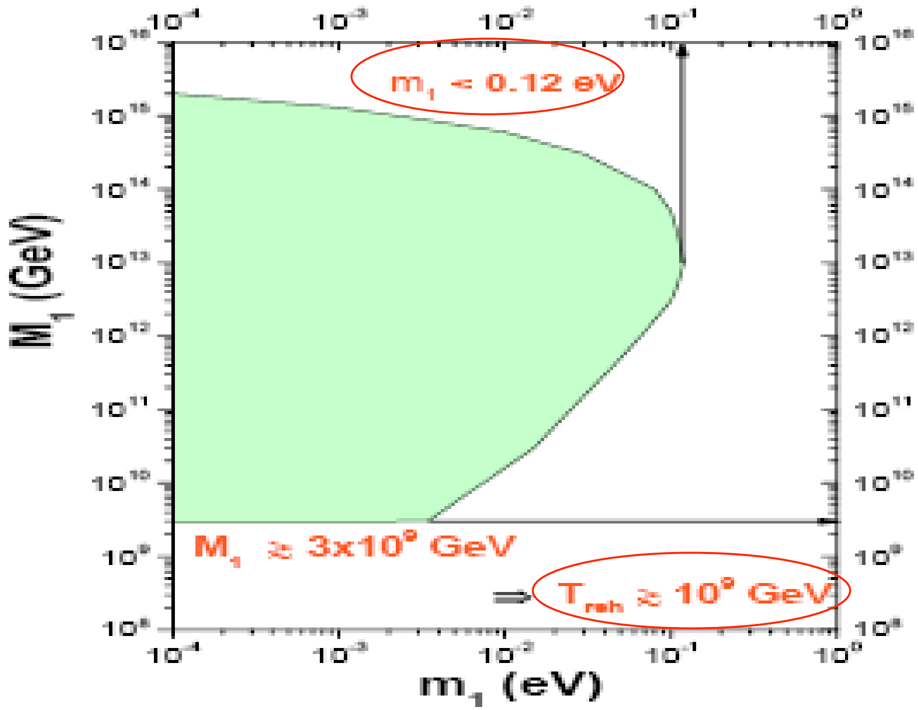
$$\kappa_1(z; K_1, z_{\rm in}) = -\int_{z_{\rm in}}^{z} dz' \left[\frac{dN_{N_1}}{dz'}\right] e^{-\int_{z'}^{z} dz''\, W_1(z'')}$$

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

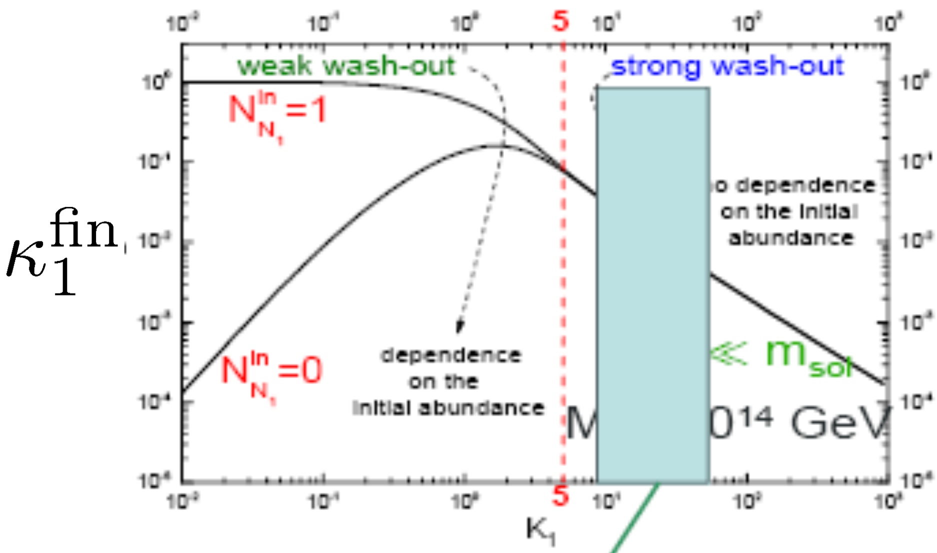
Independence of the initial conditions: strong thermal leptogenesis

(Buchmüller, PDB, Plümacher '04)

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

decay parameter

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



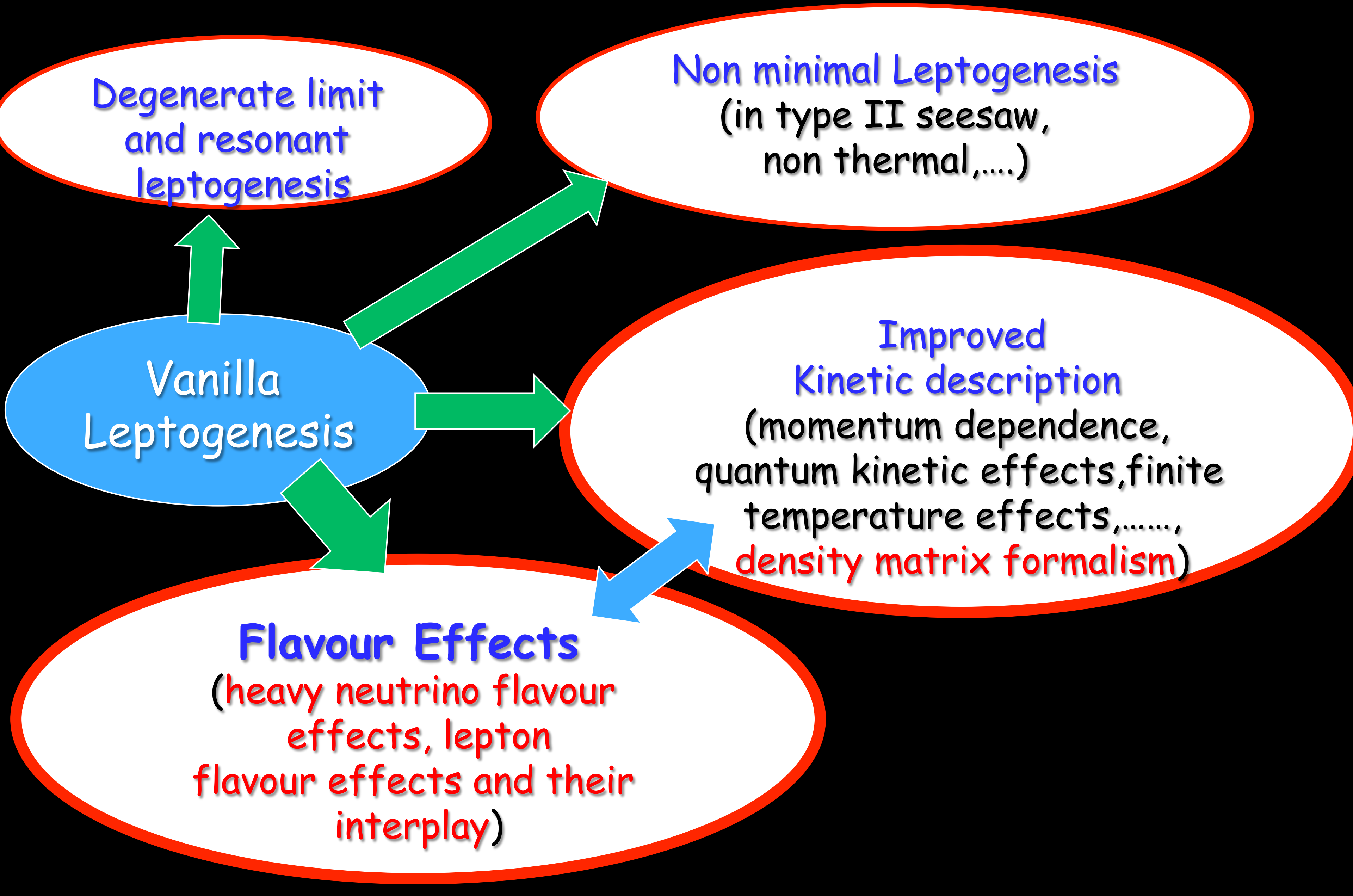
The early Universe seems to „know" the neutrino masses

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

wash-out of a pre-existing asymmetry

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

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:

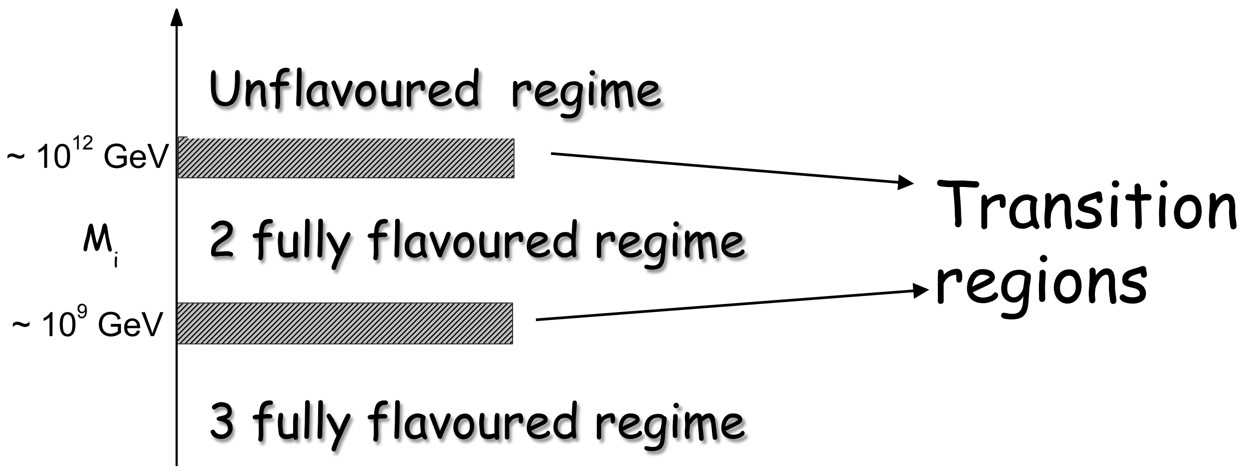
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1 \rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau) \qquad P_{1\alpha} \equiv |\langle \ell_1 | \alpha \rangle|^2$$

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

For $T \gtrsim 10^{12}$ GeV ⇒ 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



Two fully flavoured regime

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

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

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

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

dependence on U

- Classic Kinetic Equations (in their simplest form)

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

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

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

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

Low energy phases can be the only source of CP violation

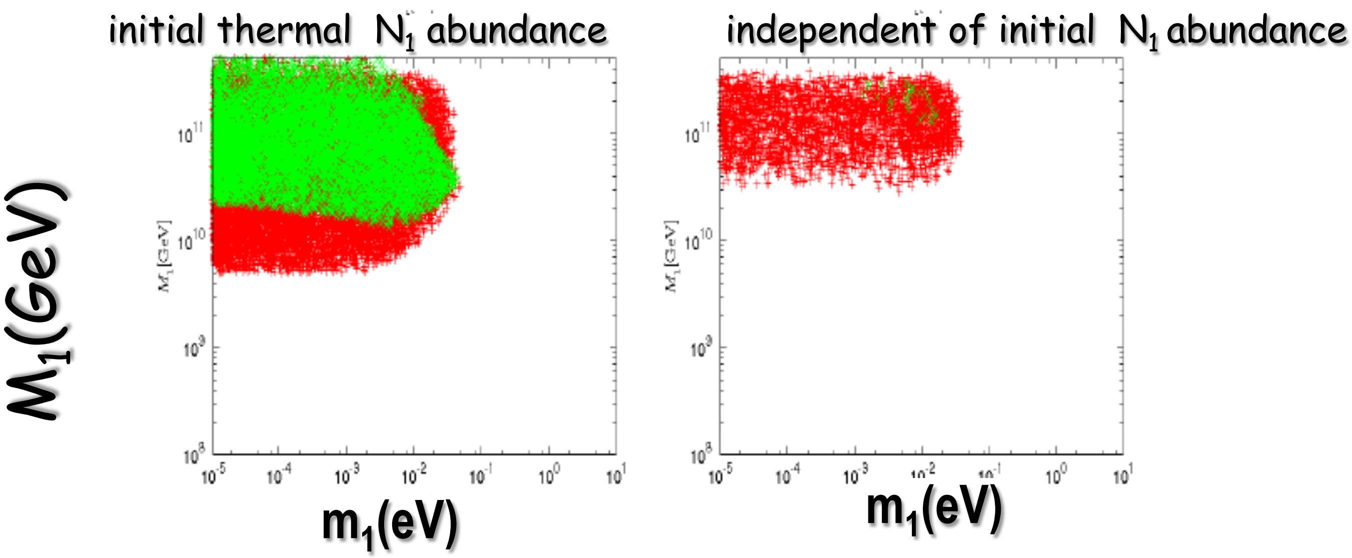
(Nardi et al.'06;Blanchet,PDB'06;Pascoli,Petcov,Riotto '06;Anisimov,Blanchet,PDB '08)

- Assume real $\Omega \Rightarrow \varepsilon_1 = 0 \Rightarrow$ $$\varepsilon_{1\alpha} = P^0_{1\alpha}\,\varepsilon_1 + \frac{\Delta P_{1\alpha}}{2}$$ (the term $P^0_{1\alpha}\varepsilon_1$ struck out)

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

- Assume even vanishing Majorana phases

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



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

Red points: only Majorana phases

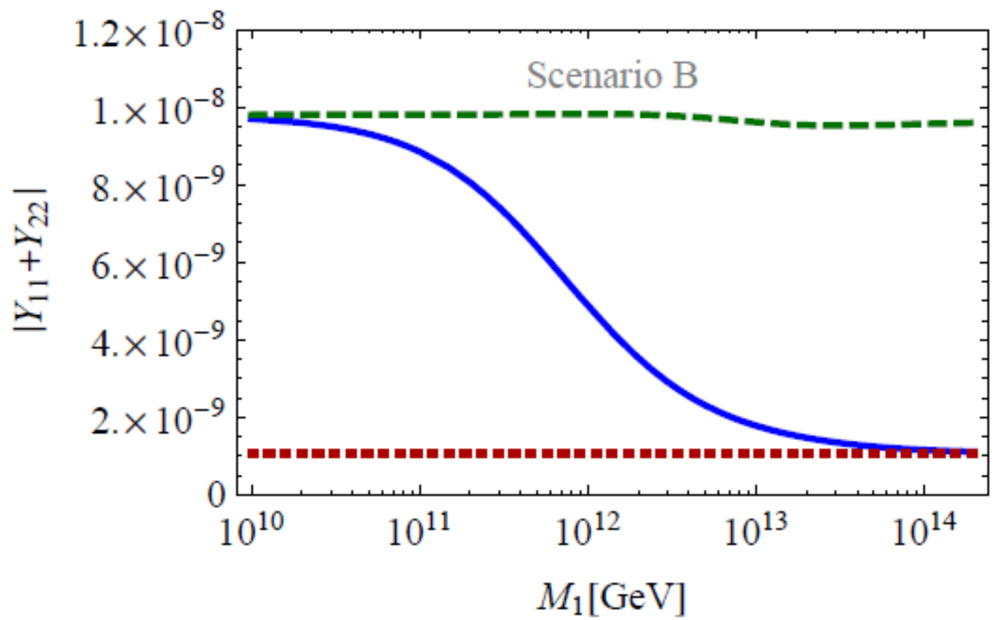
- Though not theoretically motivated, it is interesting that just CP violation in neutrino mixing could be the only source successful leptogenesis and it is approximately realised in some models such as 2RH neutrino model (Antusch, PDB, Jones, King 2010)

In general, however, flavour effects do not open new ways to test leptogenesis in a model independent way: too many parameters!

Density matrix and CTP formalism to describe the transition regimes

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

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



Fully two-flavoured regime limit

Unflavoured regime limit

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:

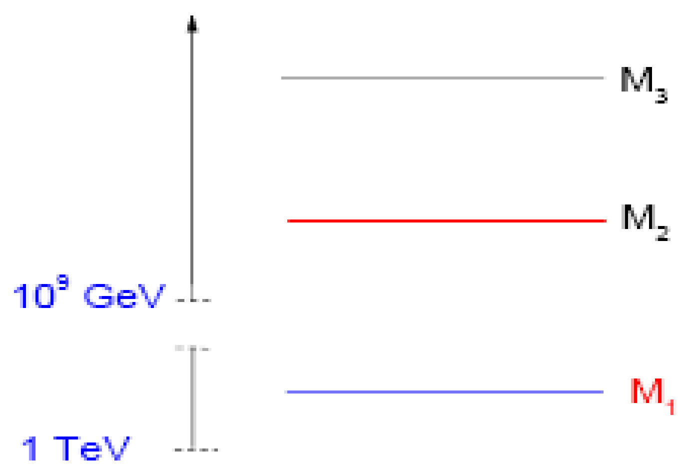
$$N_{B-L}^{\rm f,N_2} = \varepsilon_2 \kappa(K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1} = \varepsilon_1\,\kappa(K_1)$$

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

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

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} !

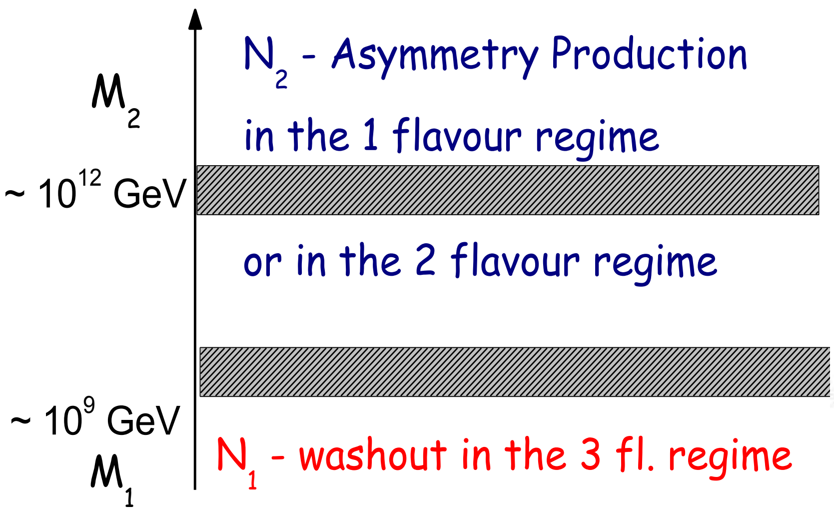


N_2-flavored leptogenesis

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

Combining together lepton and heavy neutrino flavour effects one has

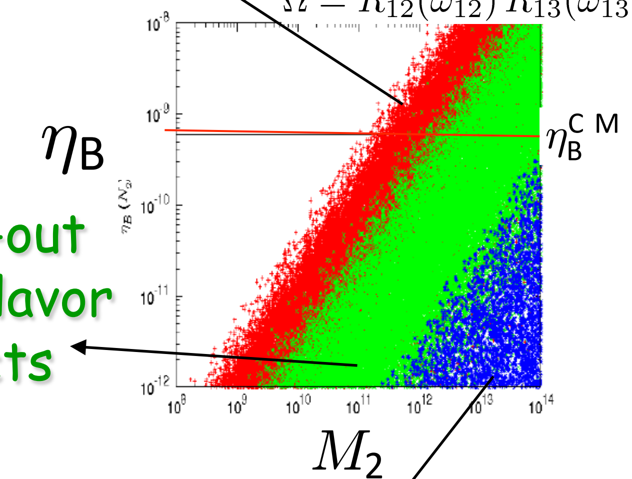
A two stage process:



Wash-out is neglected

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

Both wash-out and flavor effects



Unflavored case

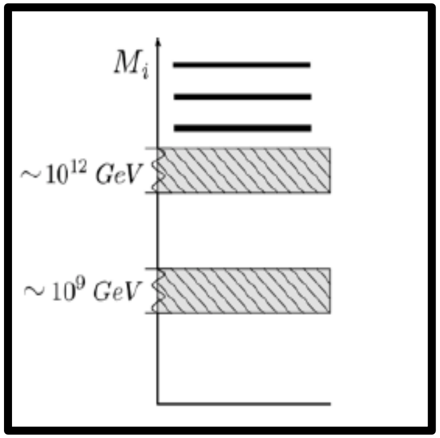
$$N_{B-L}^{\rm f}(N_2) = P_{2e}^0\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_{1e}} + P_{2\mu}^0\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_{1\mu}} + P_{2\tau}^0\, \varepsilon_2\, \kappa(K_2)\, e^{-\frac{3\pi}{8}\, K_{1\tau}}$$

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

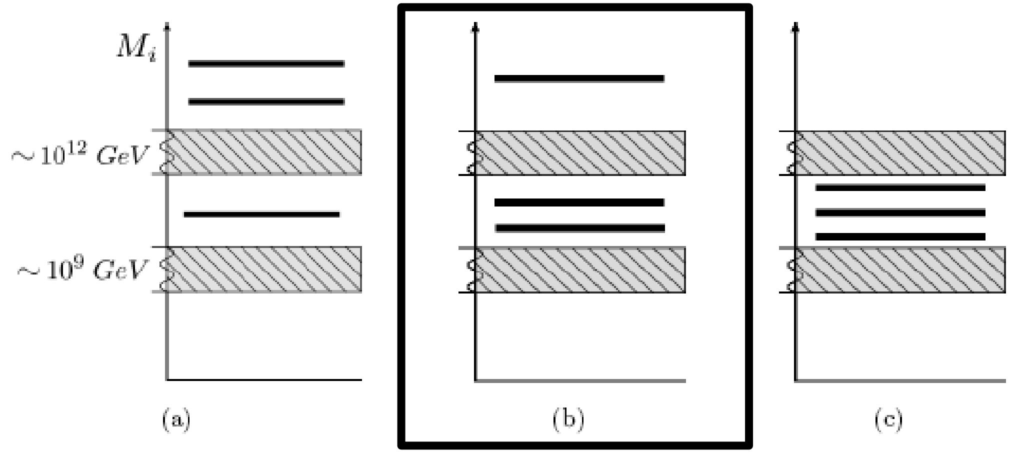
With flavor effects the domain of applicability goes much beyond the choice $\Omega = R_{23}$

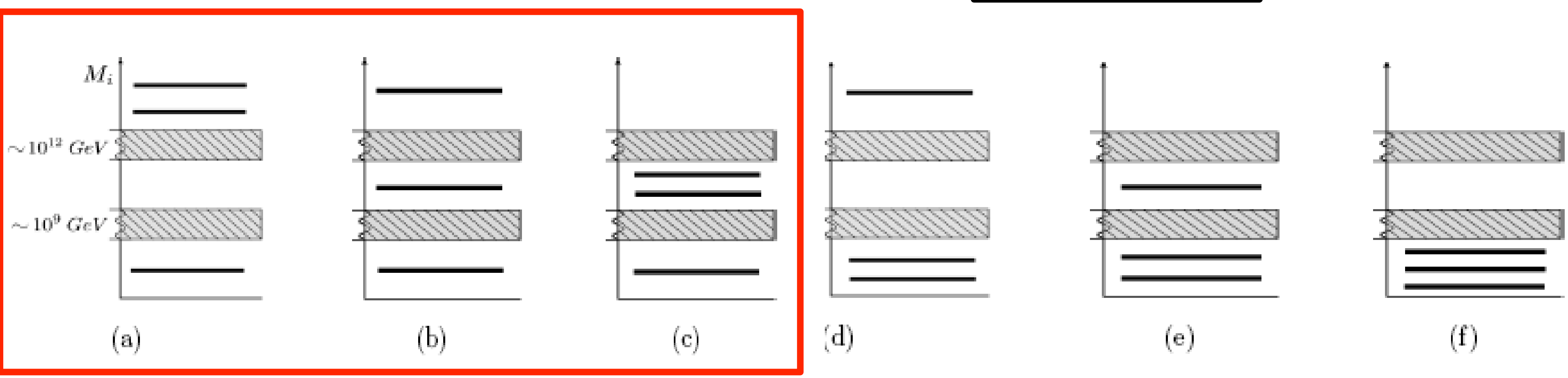
The existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$ not to be negligible !

Heavy neutrino flavored scenario



2 RH neutrino scenario





N_2-dominated scenario → **Particularly attractive for two reasons**

First: It is just that one realised in SO(10) inspired models

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:

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

(not realised just in SO(10) models, see e..g. tetra-model, talk by S. King)

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):

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

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

$\Rightarrow$ failure of the N_1-dominated scenario !

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

(PDB, Riotto '08)

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

Independent of α_1 and α_3 !

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

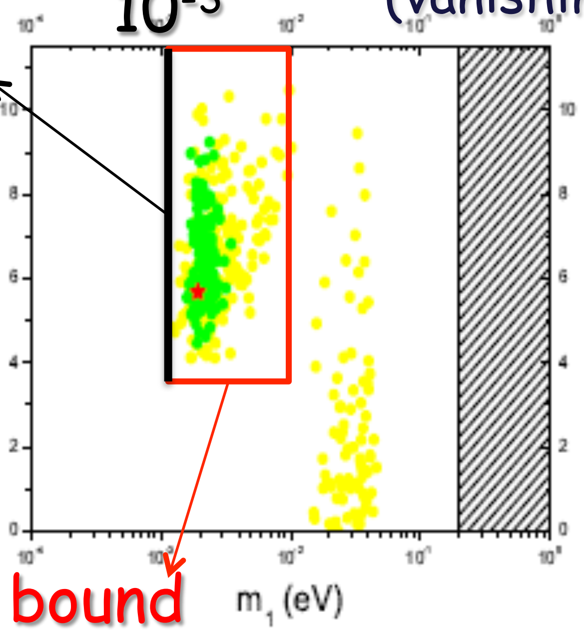
$V_L = I$ Normal ordering

(vanishing initial N_2-abundance)

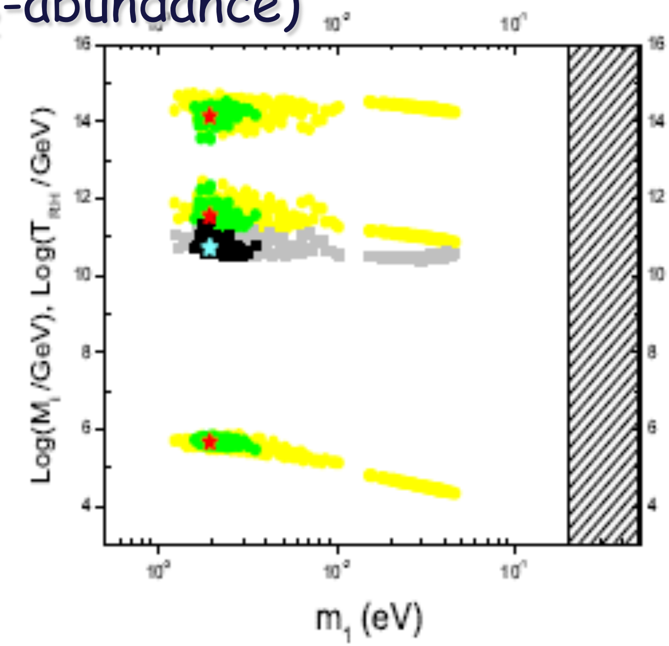
lower bound on m_1

10^{-3}

Θ_{13}



lower bound on Θ_{13} ?

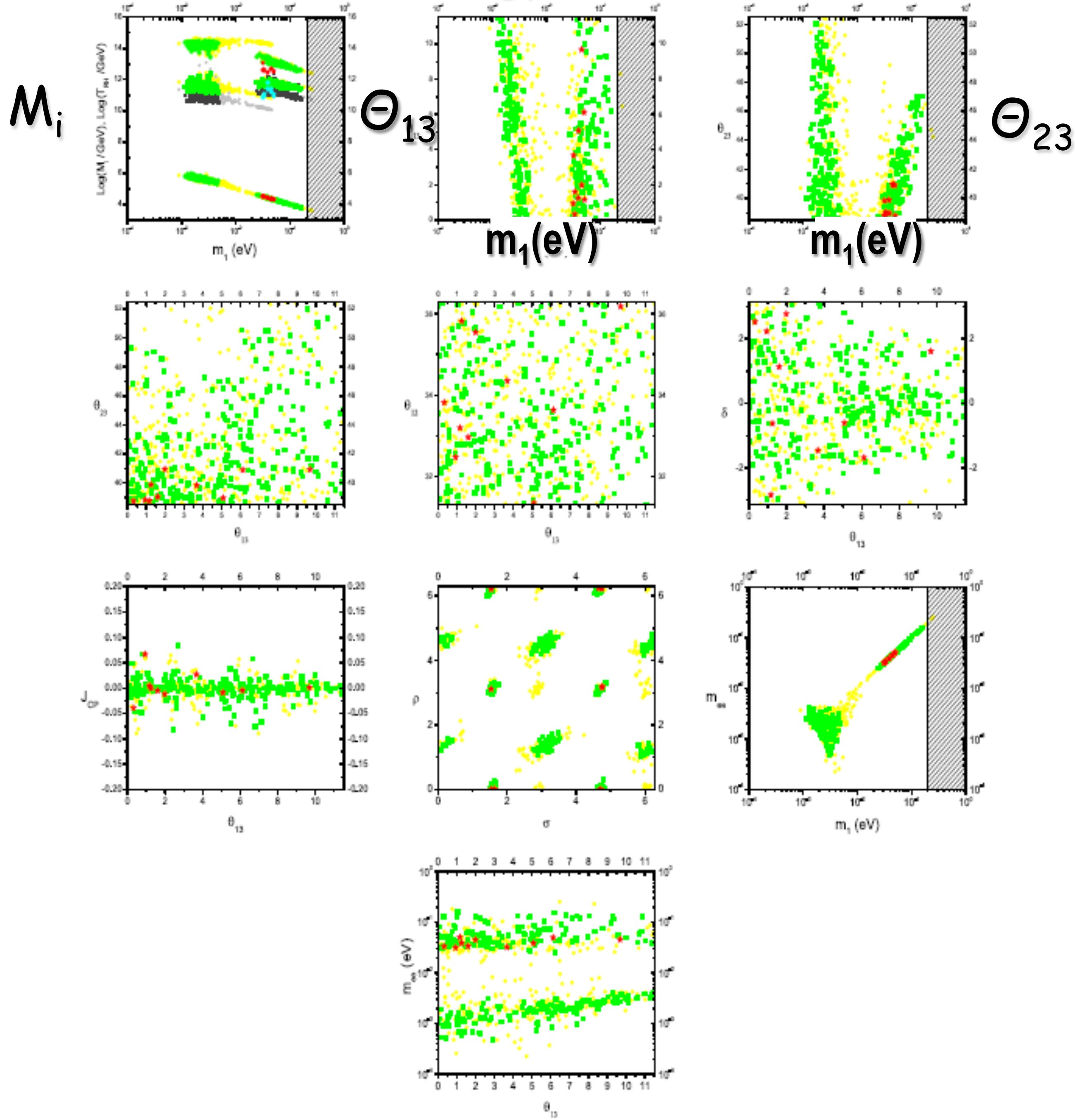


Another way to rescue SO(10) inspired models is by considering a left-right symmetric seesaw (Abada, Hosteins, Josse-Michaux, Lavignac'08)

The model yields constraints on all low energy neutrino observables !

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

NORMAL ORDERING



$\alpha_2=5$

$\alpha_2=4$

$\alpha_2=1$

(PDB, Riotto '08)

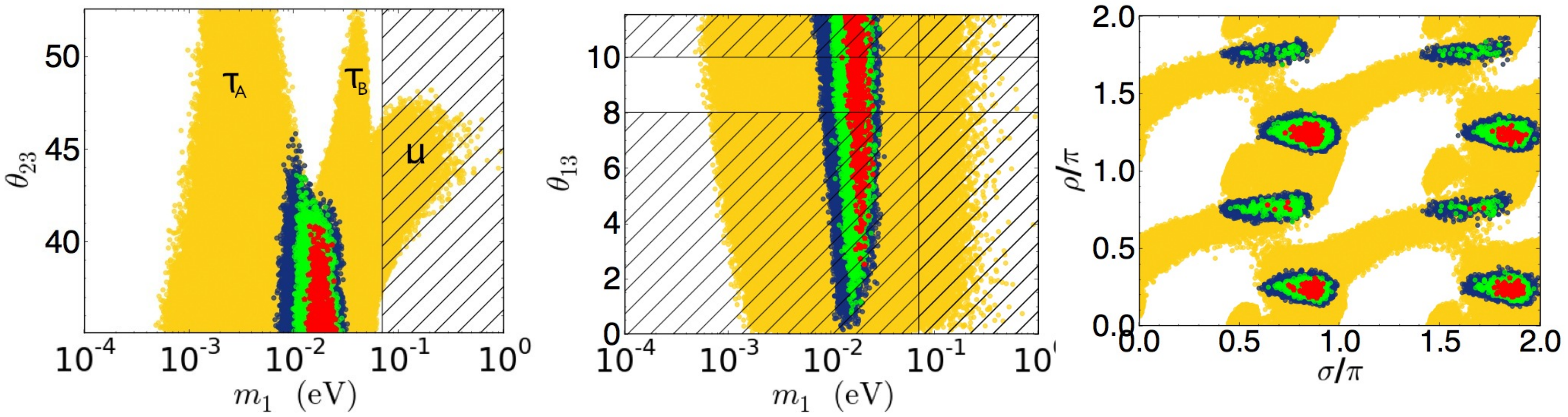
An improved analysis

(PDB, Marzola '11-'12)

We optimised the procedure increasing of two orders of magnitudes the number of solutions (focus on yellow points for the time being):

$\alpha_2=5$ NORMAL ORDERING

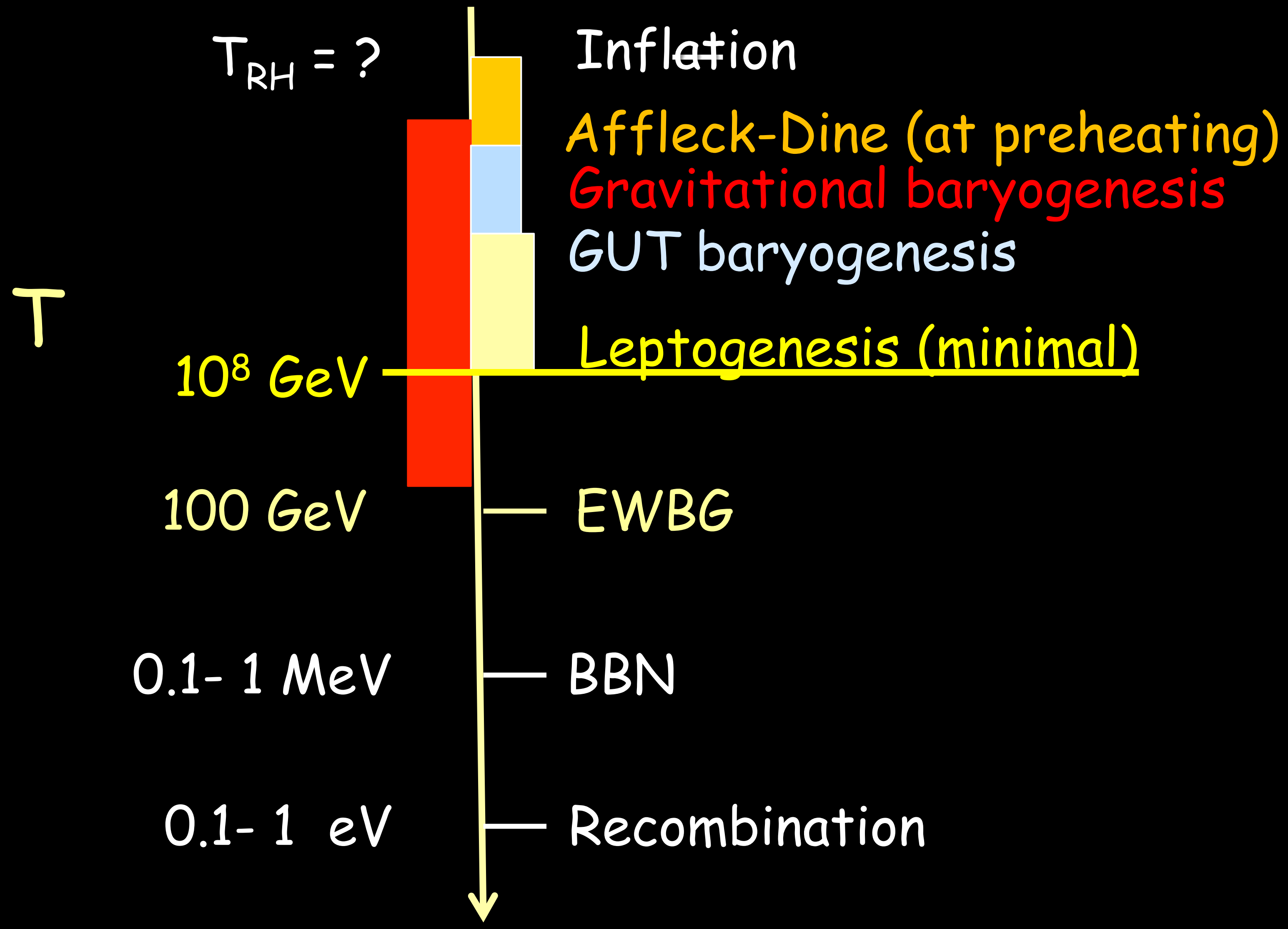
$I \leq V_L \leq V_{CKM}$



What are the blue green and red points?

There is a second reason why the N_2- dominated scenario is important

Baryogenesis and the early Universe history

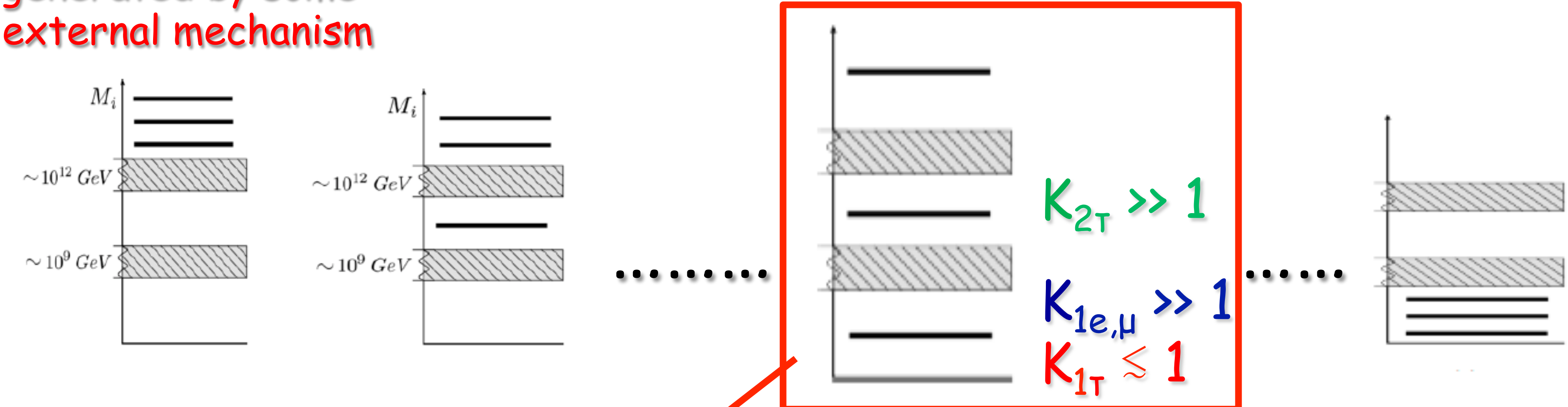


(Bertuzzo,PDB,Marzola '10)

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

This mass pattern is just that one realized in the SO(10) inspired models: can they realise strong thermal leptogenesis?

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '13)

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

Imposing both successful SO(10)-inspired leptogenesis

$\eta_B = \eta_B^{CMB} = (6.2 \pm 0.15) \times 10^{-10}$ and $N^{p,f}_{B-L} \ll N^{lep,f}_{B-L}$

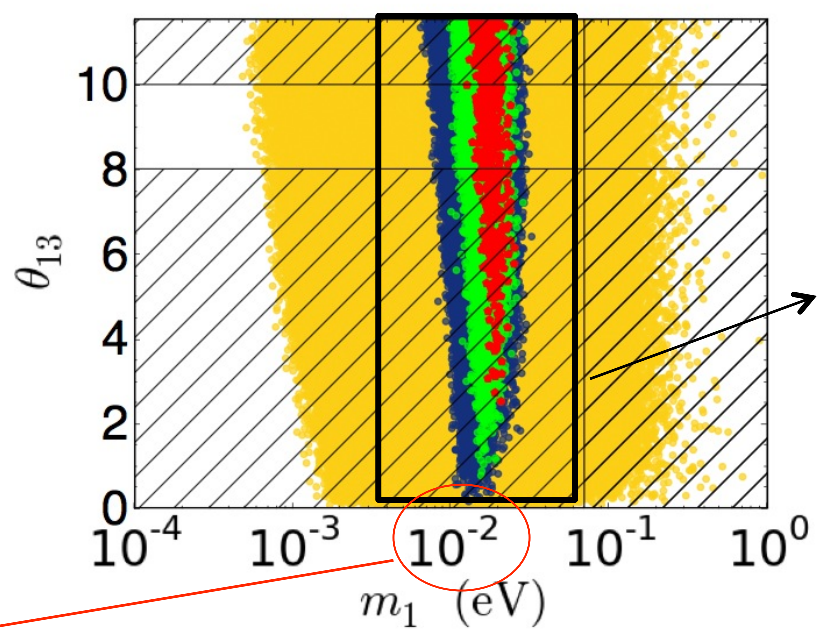
There are NO Solutions for Inverted Ordering !

But for Normal Ordering there is a subset with definite predictions

NON-VANISHING REACTOR MIXING ANGLE

N_{B-L}= 0
0.001
0.01
0.1

α_2=5



non-vanishing Θ_{13} (green and red points)

The lightest neutrino mass is constrained in a narrow range (10-30 meV)

SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11,'12)

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

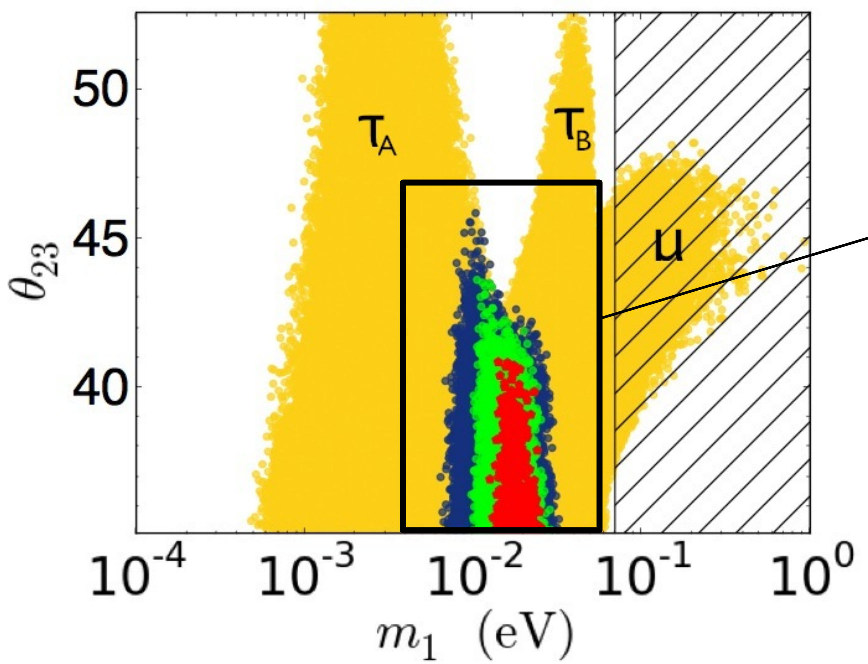
Imposing both successful SO(10)-inspired leptogenesis

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

UPPER BOUND ON THE ATMOSPHERIC MIXING ANGLE

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

$\alpha_2 = 5$



Small atmospheric mixing angle (definitely first octant)

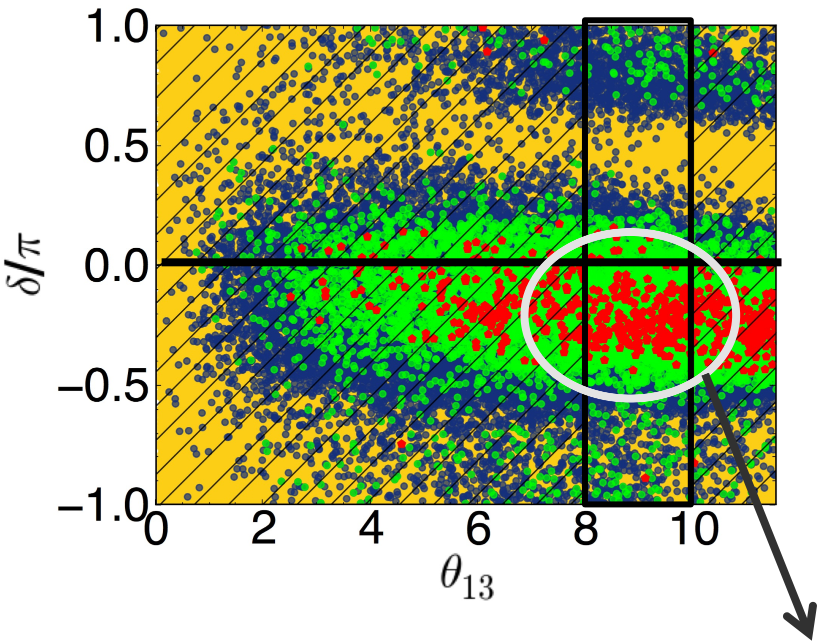
SO(10)-inspired+strong thermal leptogenesis

(PDB, Marzola '11-'12)

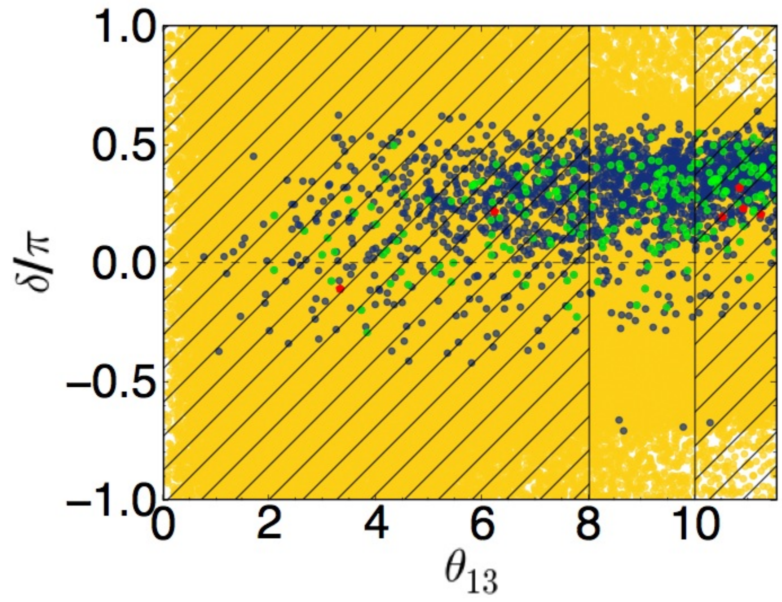
$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p,f} + N_{B-L}^{\rm lep,f}\,,$$

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)

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

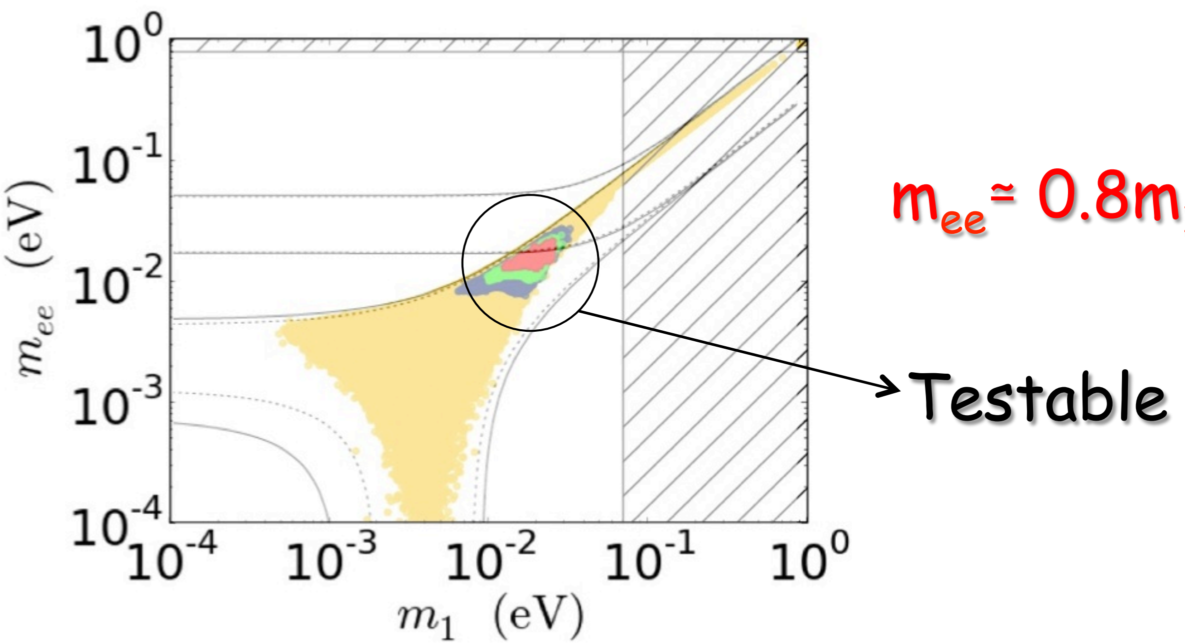
Imposing both successful SO(10)-inspired leptogenesis

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

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

Strong thermal SO(10) inspired leptogenesis: summary

- SO(10)-inspired leptogenesis is not only alive but it contains a subset of solutions able to satisfy quite a tight condition when flavour effects are taken into account: *independence of the initial conditions (strong thermal leptogenesis)*

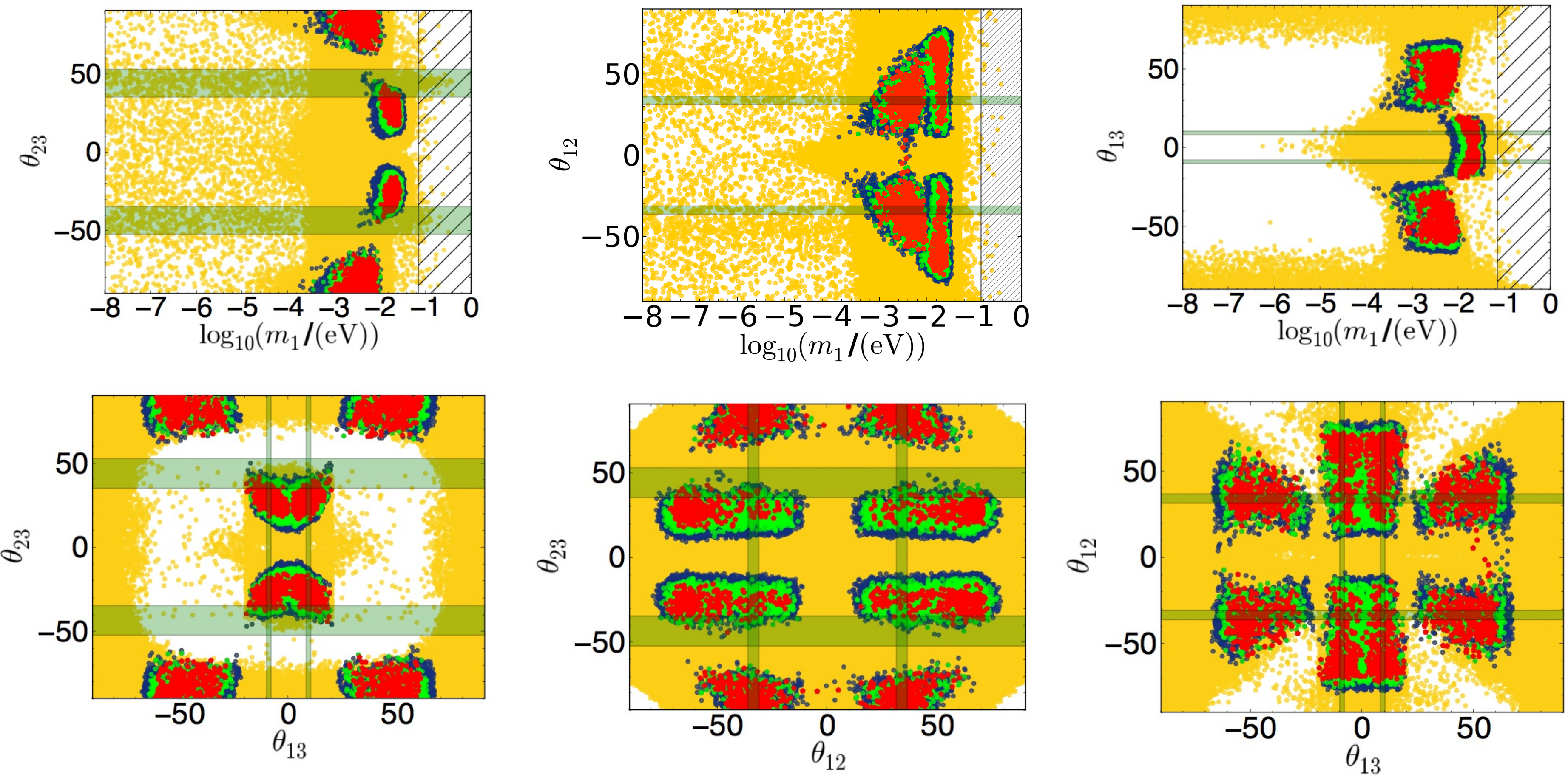
ORDERING	NORMAL
θ_{13}	$\gtrsim 2^\circ$
θ_{23}	$\lesssim 41^\circ$
δ	**$\sim -45^\circ$**
$m_{ee} \simeq 0.8\, m_1$	~ 15 meV

- It provides an example of how (minimal) leptogenesis within a reasonable set of assumptions can yield testable predictions
- Corrections: flavour coupling, RGE effects,...
- Statistical analysis

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

(PDB, Marzola '13)

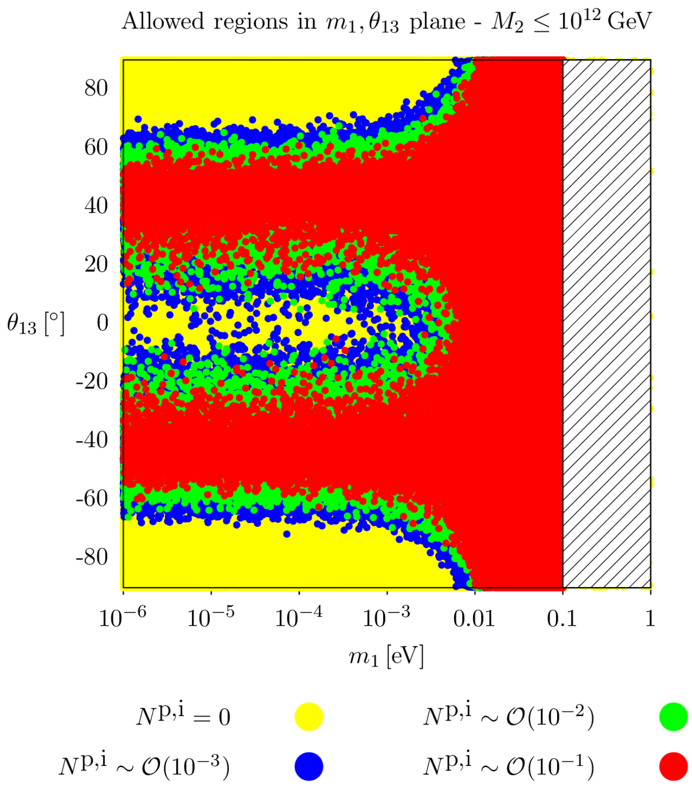
If we do not plug any experimental information (mixing angles left completely free) :

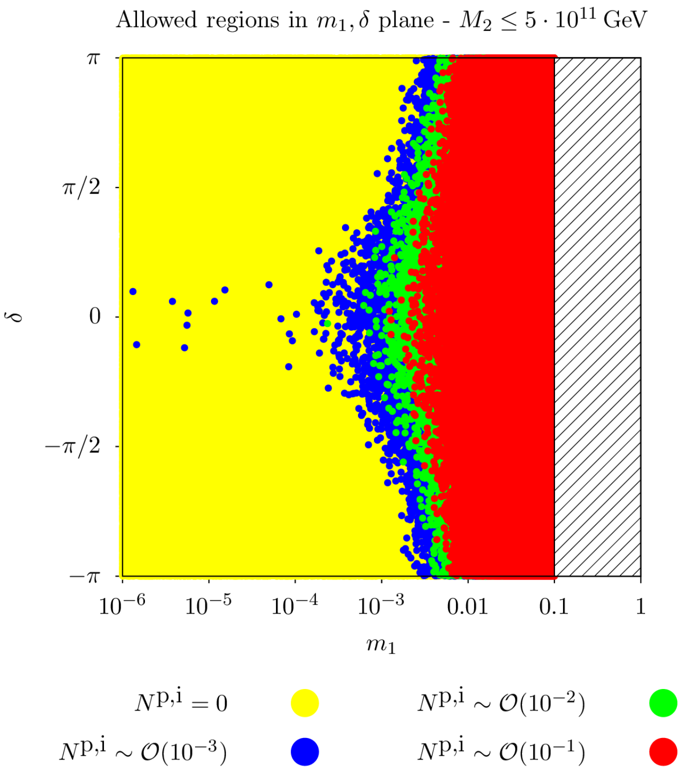


Strong thermal leptogenesis and the absolute neutrino mass scale

(PDB, Sophie King, Michele Re Fiorentin 2013)

$\theta_{13} = 8° \div 10.$





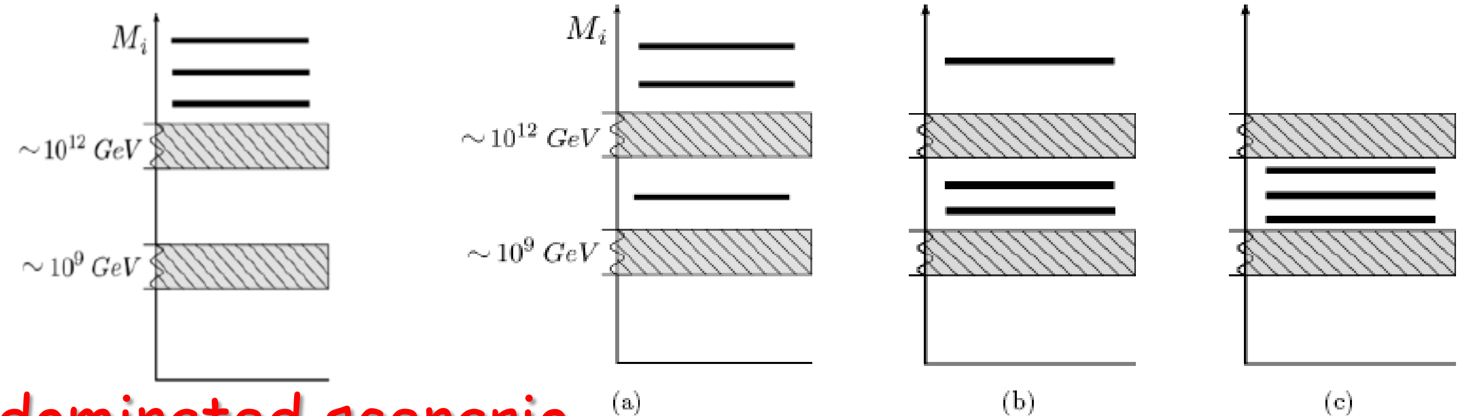
Conclusion

- There is a long list of Baryogenesis models but only a few are testable.
- EWB is cerrtainly one of those but in this moment there is no hint of New Physics able to realise it.
- Other mechanisms could plausibly produce a large asymmetry after inflationary stage especially at large reheat temperatures
- Leptogenesis at TeV scale is also not supported by LHC data so far
- The interplay between heavy neutrino and charged lepton flavour effects introduces many new ingredients in the calculation of the final asymmetry
- Minimal leptogenesis (high scale) is not testable but adding theoretical information one can get nice tests: e.g. SO(10) inspired models
- The strong thermal condition increases predictive power especially on the absolute neutrino mass scale

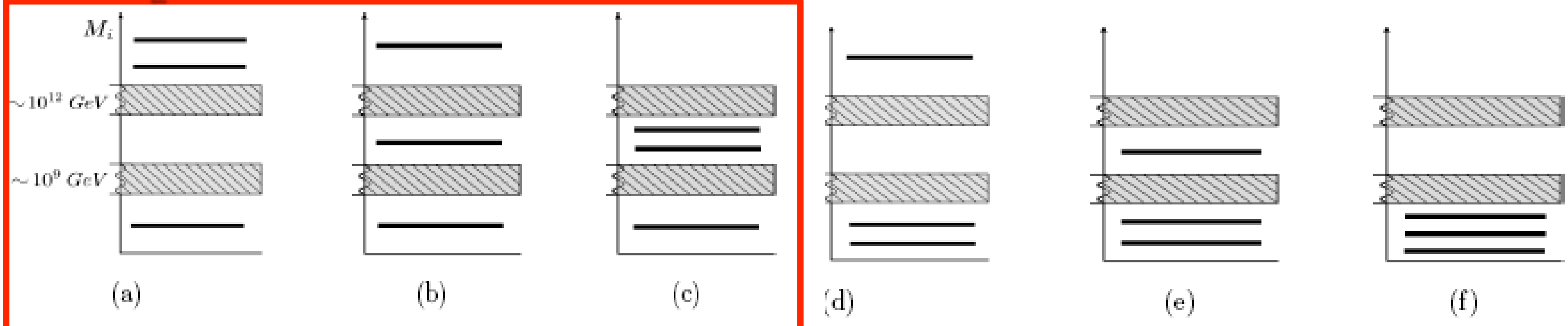
Strong thermal SO(10)-inspired leptogenesis solution

ORDERING	NORMAL
θ_{13}	$\gtrsim 2^\circ$
θ_{23}	$\lesssim 41^\circ$
δ	**$\sim -45^\circ$**
$m_{ee} \simeq 0.8\ m_1$	$\simeq 15$ meV

More generally one has to distinguish 10 different RH neutrino mass patterns (Bertuzzo,PDB,Marzola '10)



N_2 dominated scenario



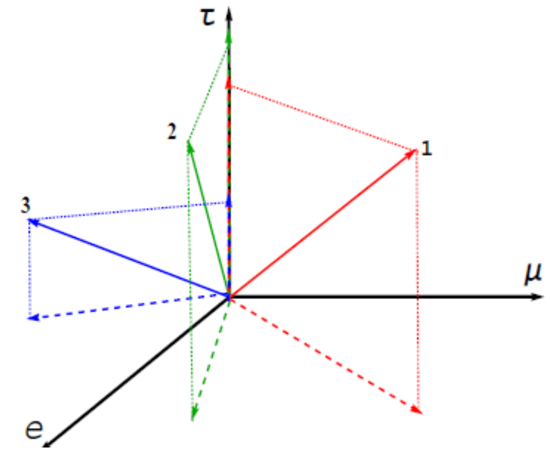
For each pattern a specific set of Boltzmann equations has to be considered

Density matrix formalism with heavy neutrino flavours

(Blanchet, PDB, Jones, Marzola '11)

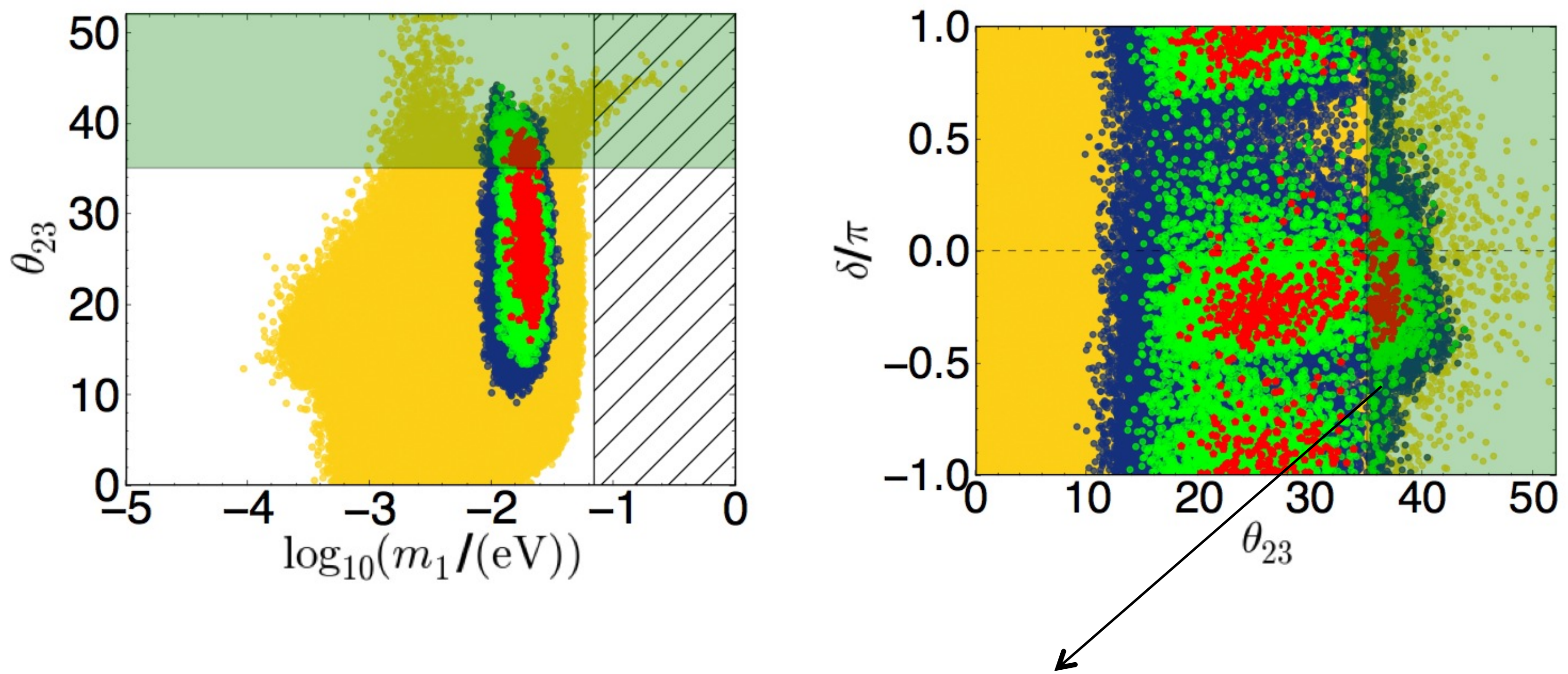
For a thorough description of all neutrino mass patterns including transition regions and all effects (flavour projection, phantom leptogenesis,…) one needs a description in Terms of a density matrix formalism

The result is a "monster" equation:



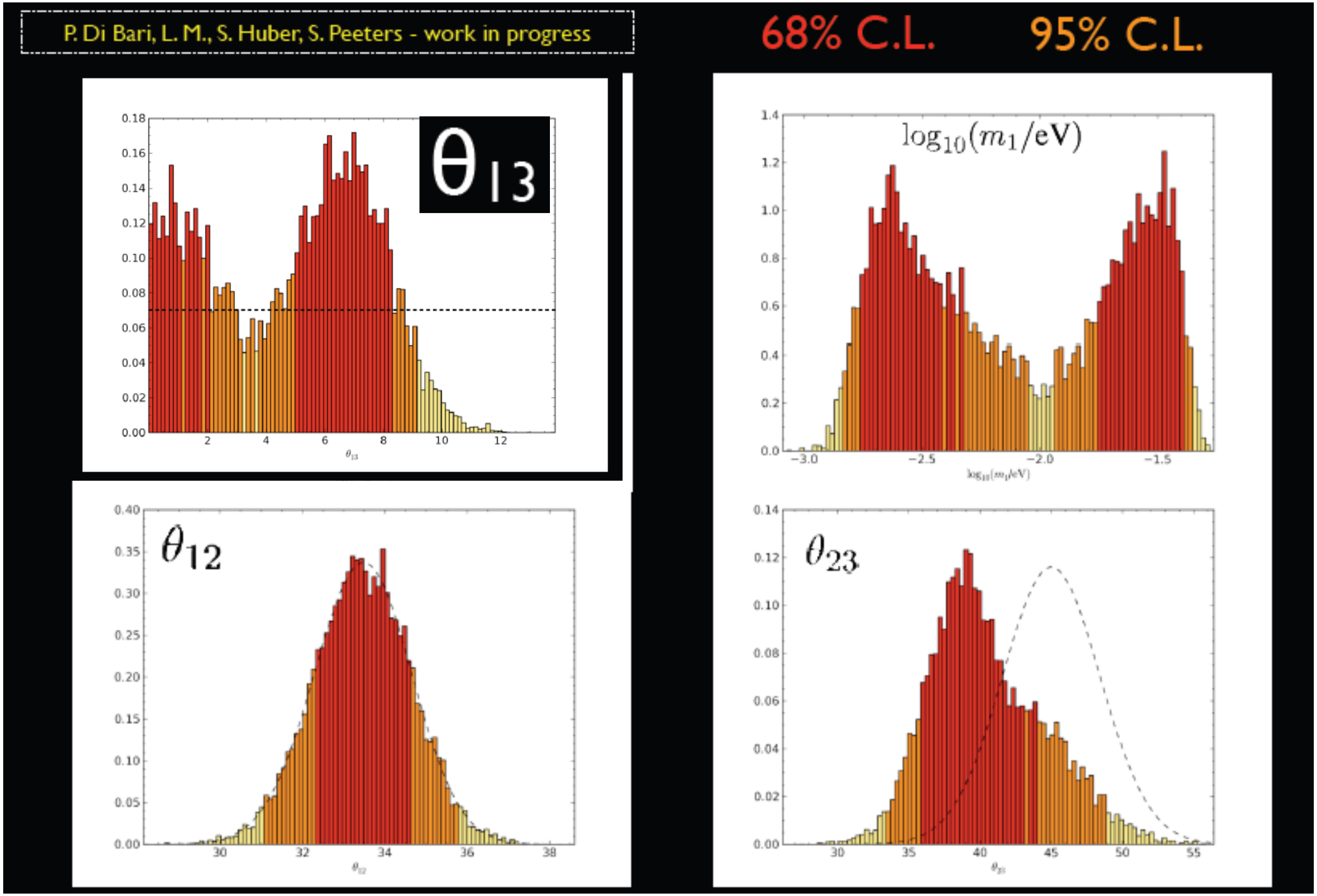
$$\begin{aligned}
\frac{dN^{B-L}_{\alpha\beta}}{dz} &= \varepsilon^{(1)}_{\alpha\beta}\, D_1\,(N_{N_1} - N^{\rm eq}_{N_1}) - \frac{1}{2}\, W_1\, \{\mathcal{P}^{0(1)}, N^{B-L}\}_{\alpha\beta} \qquad (80) \\
&+ \varepsilon^{(2)}_{\alpha\beta}\, D_2\,(N_{N_2} - N^{\rm eq}_{N_2}) - \frac{1}{2}\, W_2\, \{\mathcal{P}^{0(2)},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

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



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

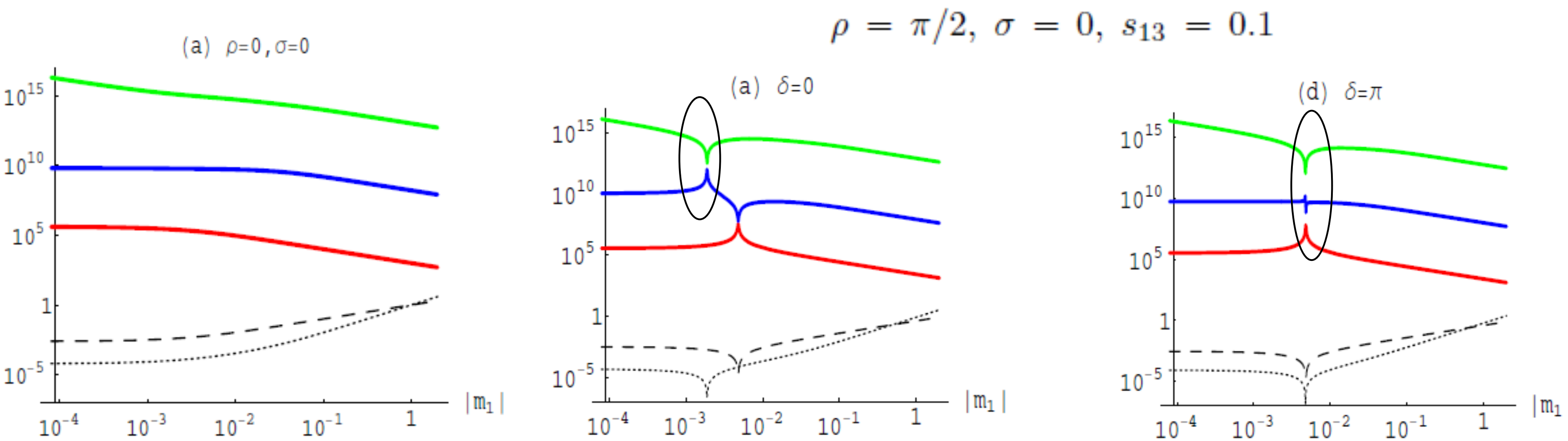
A statistical analysis



Talk by Luca Marzola at the DESY theory workshop 28/9/11

Crossing level solutions

(Akhmedov, Frigerio, Smirnov '03)



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

The measured η_B can be attained for a fine tuned choice of parameters: many models have made use of these solutions but as we will see there is another option

Additional contribution to CP violation:

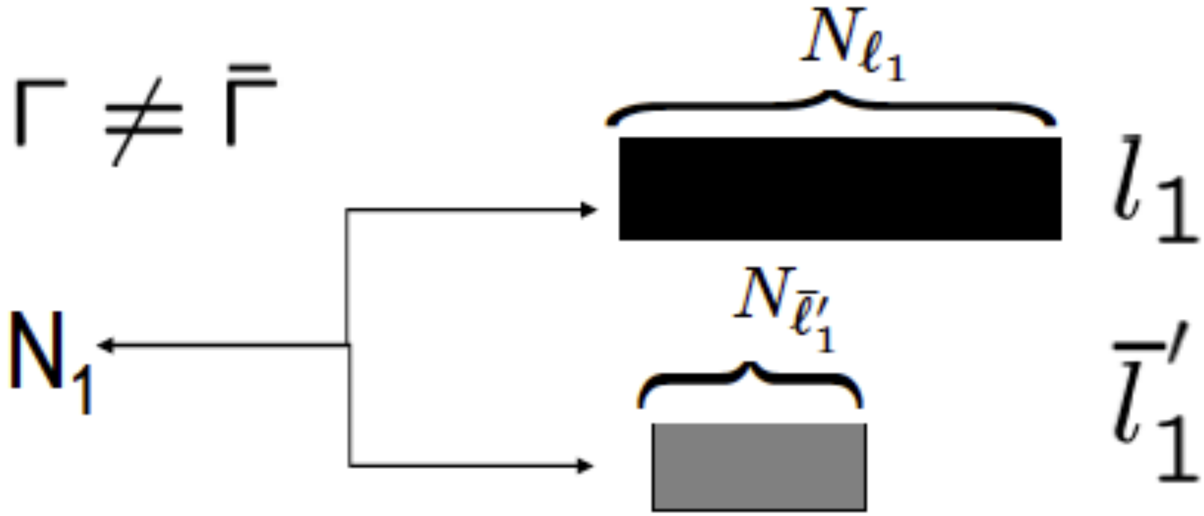
(Nardi,Racker,Roulet '06)

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

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

depends on U !

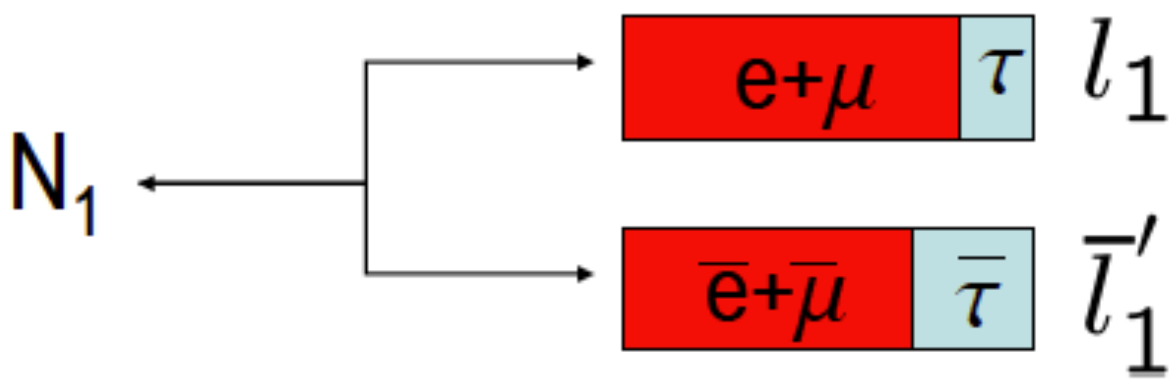
1) $\Gamma \neq \bar{\Gamma}$



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

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

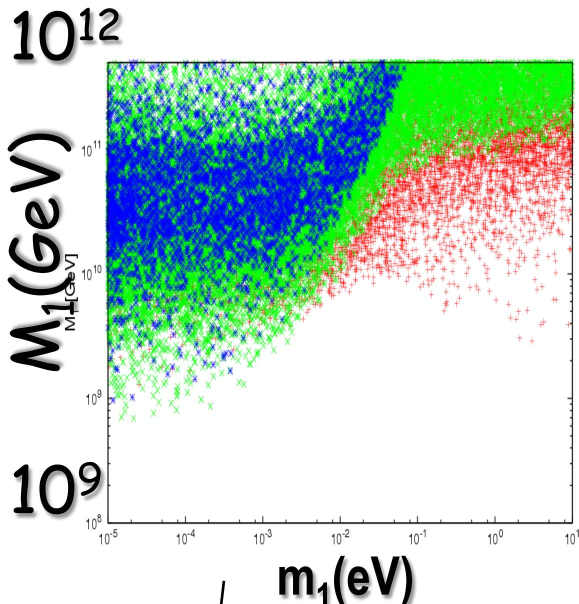
+



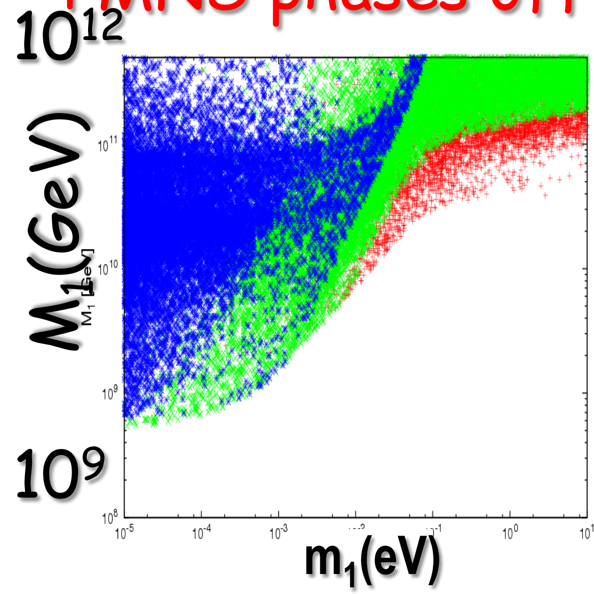
$\Rightarrow \; \frac{\Delta P_{1\alpha}}{2}$

Upper bound on m_1

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

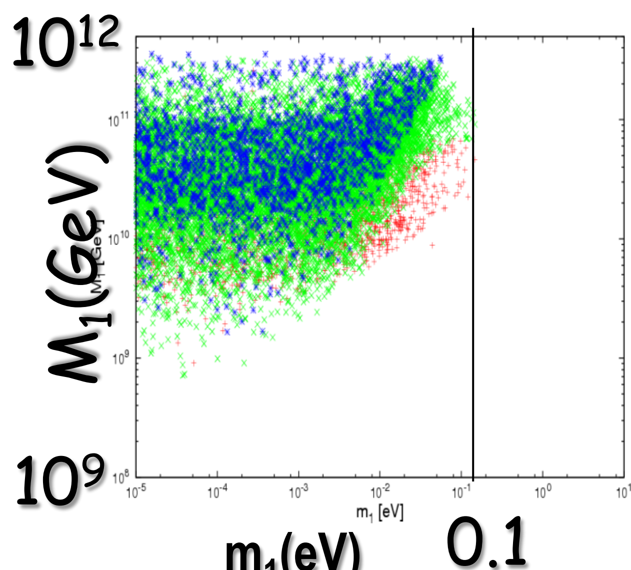


PMNS phases off



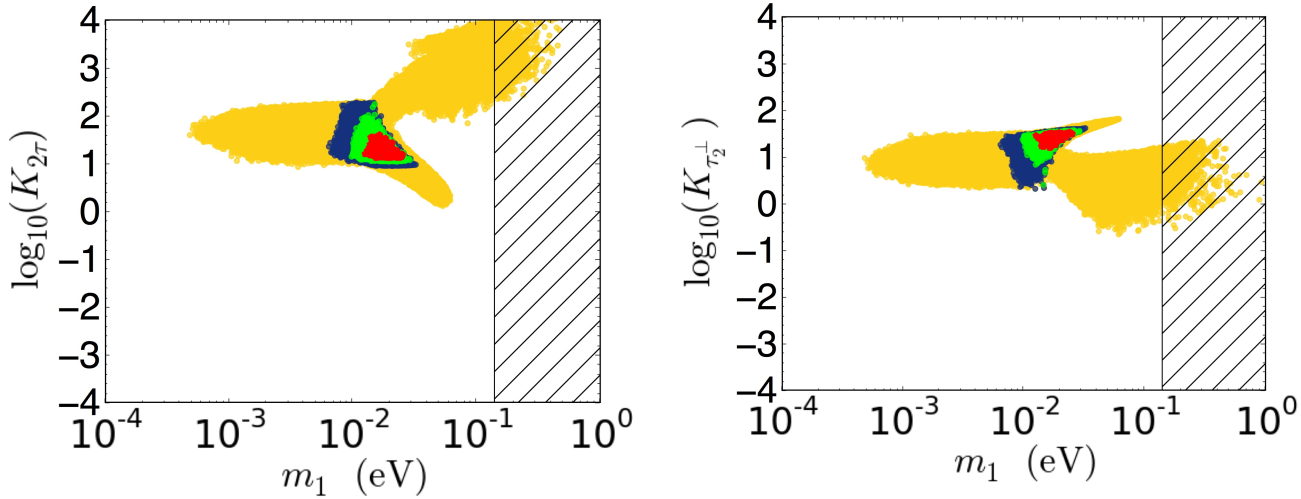
$M_1 \lesssim 10^{12}\,\mathrm{GeV}/W_1(T_B)$

imposing a condition of validity of Boltzmann equations

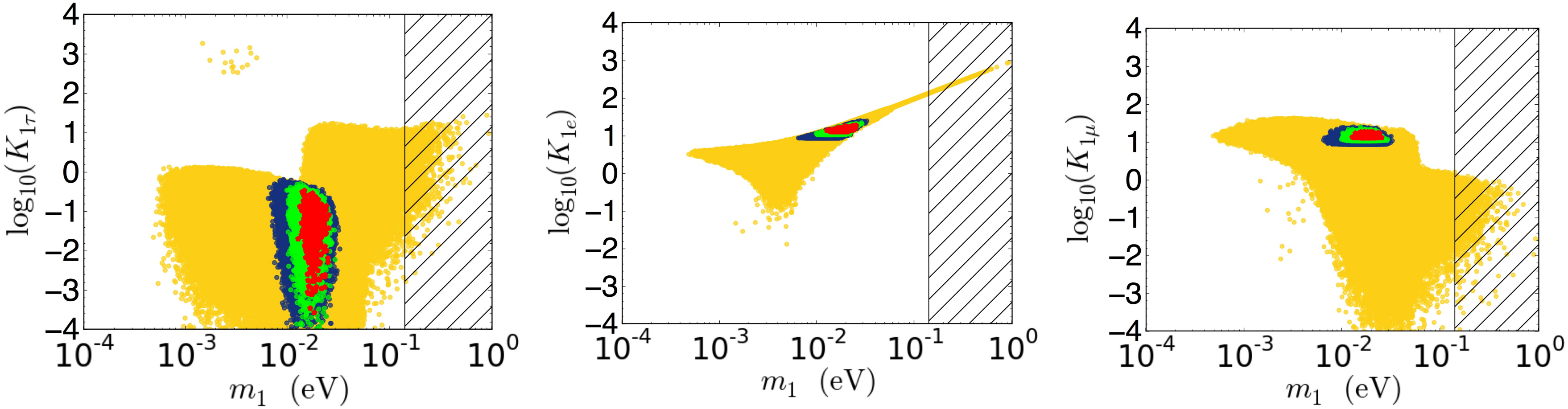


Some insight from the decay parameters

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)

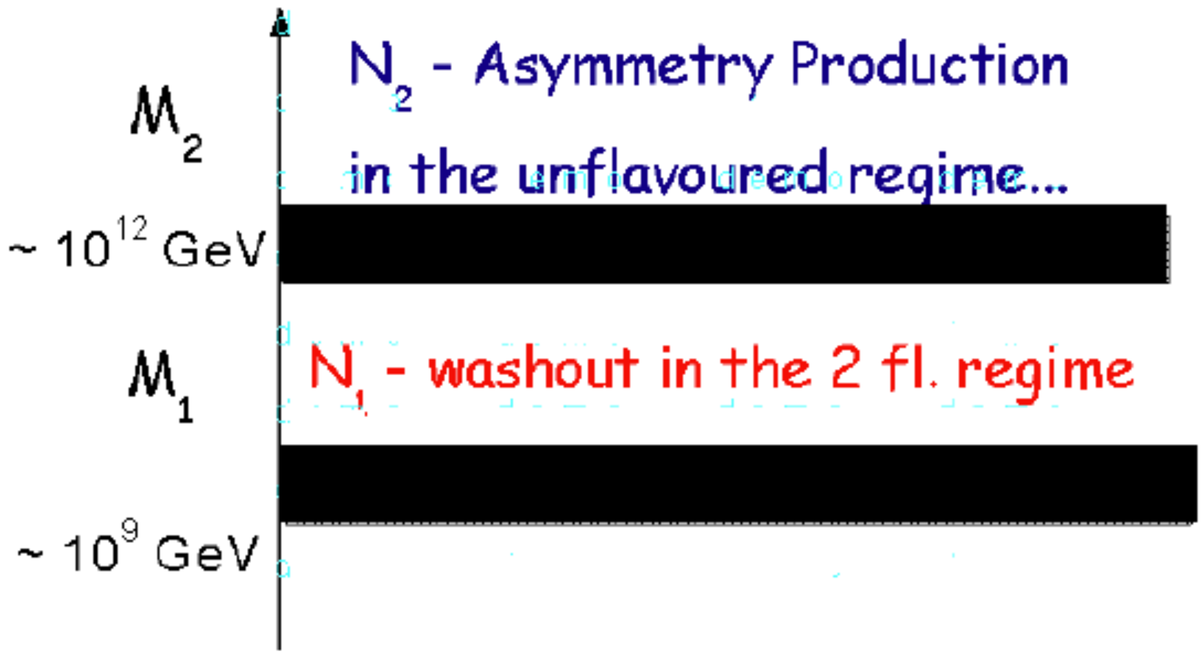
- Flavour projection
  (Barbieri,Creminelli,Stumia,Tetradis '00;
  Engelhard, Grossman, Nardi, Nir '07)

- 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-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:

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

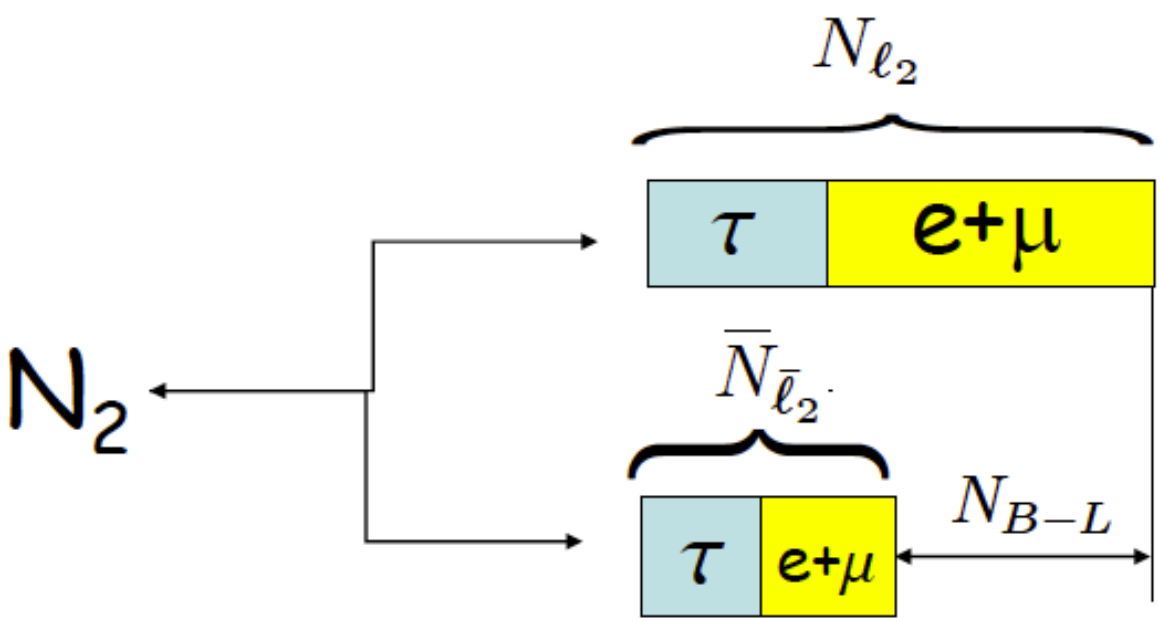
$$N_{\Delta e+\mu} = p_{2\,e+\mu}\, N_{B-L}$$

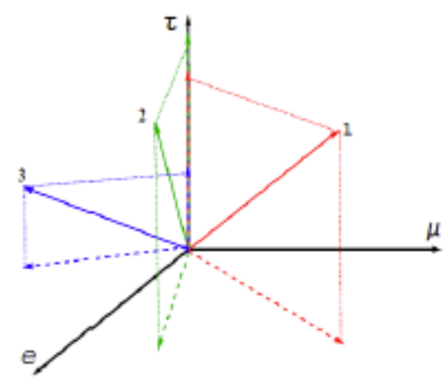
Phantom terms

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



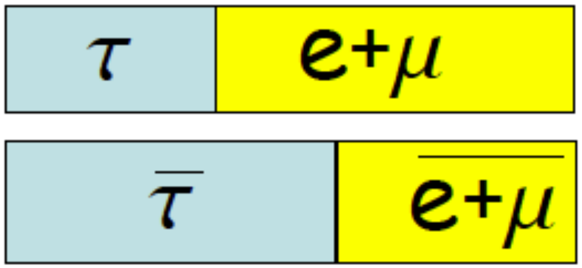


Phantom Leptogenesis

(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 $\gtrsim T \gg M_1$: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 $K_{1e+\mu} \gg 1$

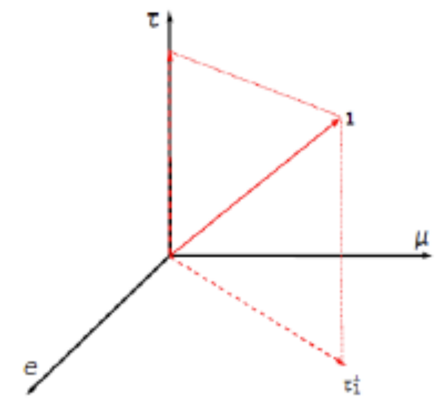
$$N_{B-L}^{\rm f} \simeq N_{\Delta_\tau}^{T\sim M_2}\ !$$

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:

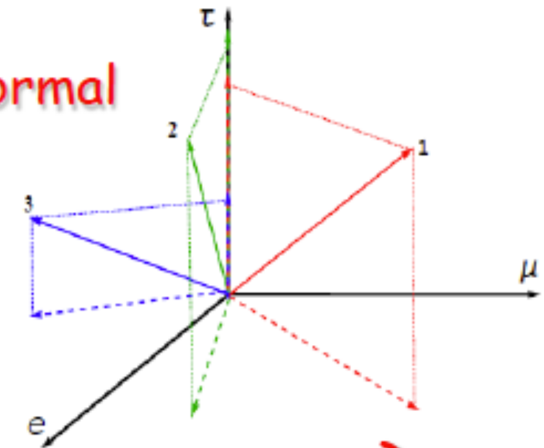
$$N_{\tau\tau}^{B-L,{\rm f}} \simeq p^0_{2\tau}\, N^{\rm f}_{B-L} - \frac{\Delta p_{2\tau}}{2}\,\kappa(K_2/2),$$

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



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

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

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

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

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

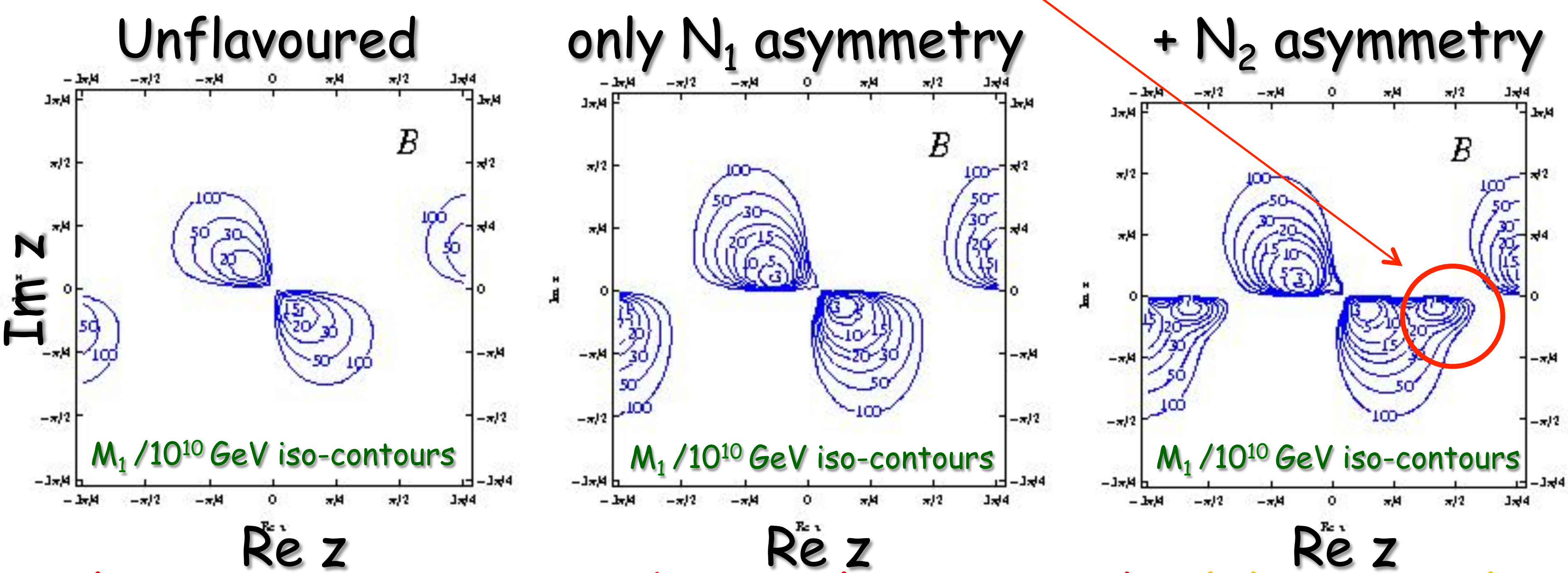
2 RH neutrino scenario revisited

(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

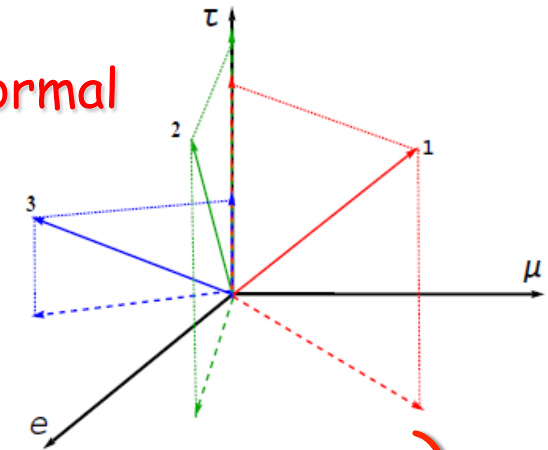
Flavour projection

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

Assume M_{i+1} [illegible] $3M_i$ (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} $(1-p_{12})$

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

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

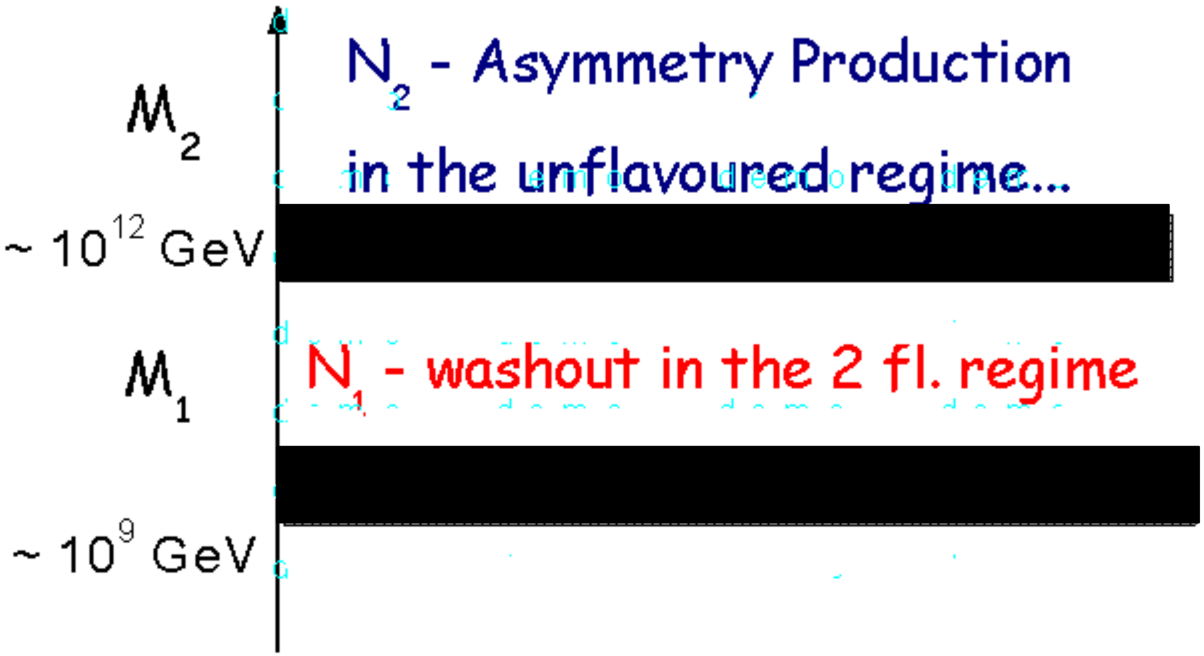
Contribution from heavier RH neutrinos **orthogonal** to l_1 and escaping N_1 wash-out

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

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:

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

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

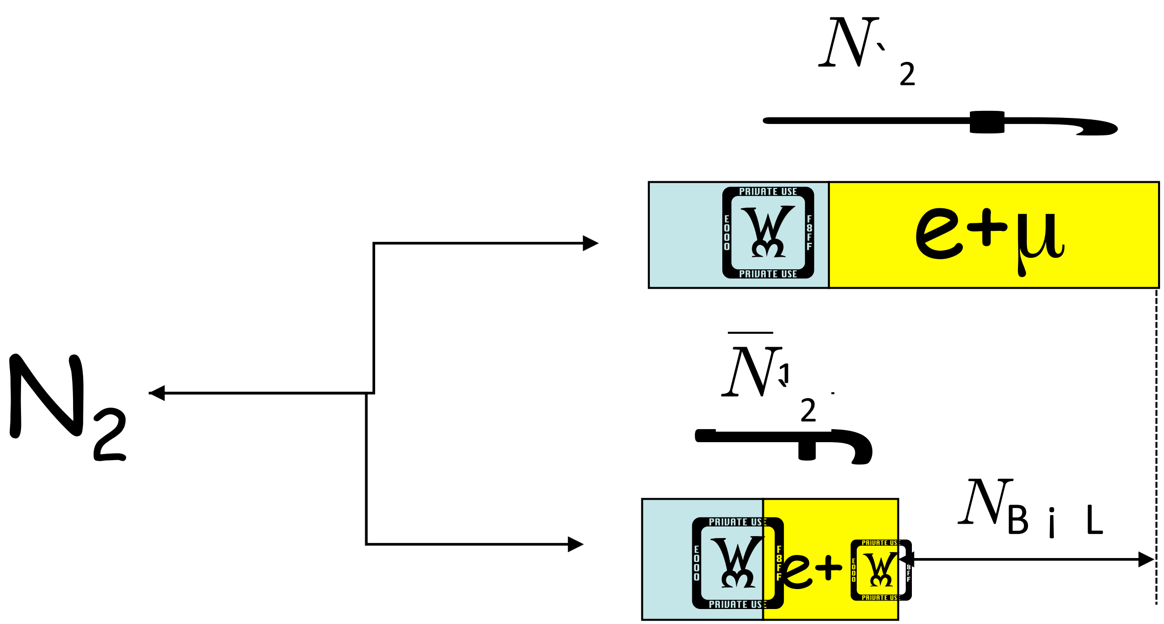
Phantom terms

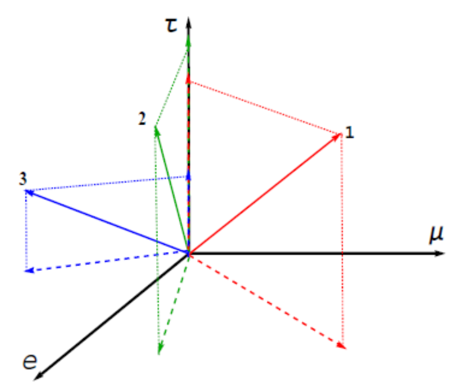
However one has to consider that in the unflavoured case there are contributions to $N_{\Delta\tau}$ and $N_{\Delta e+\mu}$ that are not just proportional to N_{B-L}

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



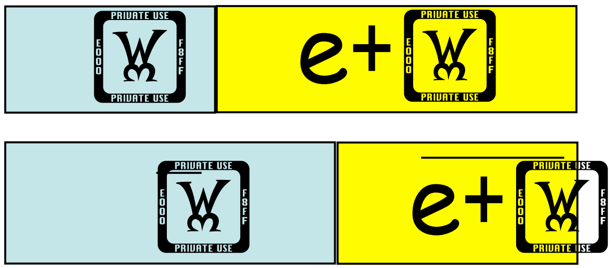


Phantom Leptogenesis

(Antusch, PDB, King, Jones '10)

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

1) $T \sim M_2$: unflavoured regime



$) \quad N_{B \,¡\, L}^{T \,»\, M_2} \;'\; 0 \;!$

2) 10^{12} GeV [illegible] T >> M_1 :decoherence [illegible] 2 flavoured regime

$$N_{B \,¡\, L}^{T \,»\, M_2} = N_{¢ \,¿}^{T \,»\, M_2} + N_{¢ \; e+1}^{T \,»\, M_2} \;'\; 0 \;!$$

3) T [illegible] M_1: asymmetric washout from lightest RH neutrino

Assume $K_{1\tau}$ [illegible] 1 and $K_{1e+\mu} >> 1$ $\quad N_{B \,¡\, L}^{f} \;'\; N_{¢ \,¿}^{T \,»\, M_2} \;!$

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 !

$$N_{\text{¢}\ \text{¿}}^{\text{phantom}} = \frac{\text{¢}\ p_{2\text{¿}}}{2} N_{N_2}^{\text{in}}$$

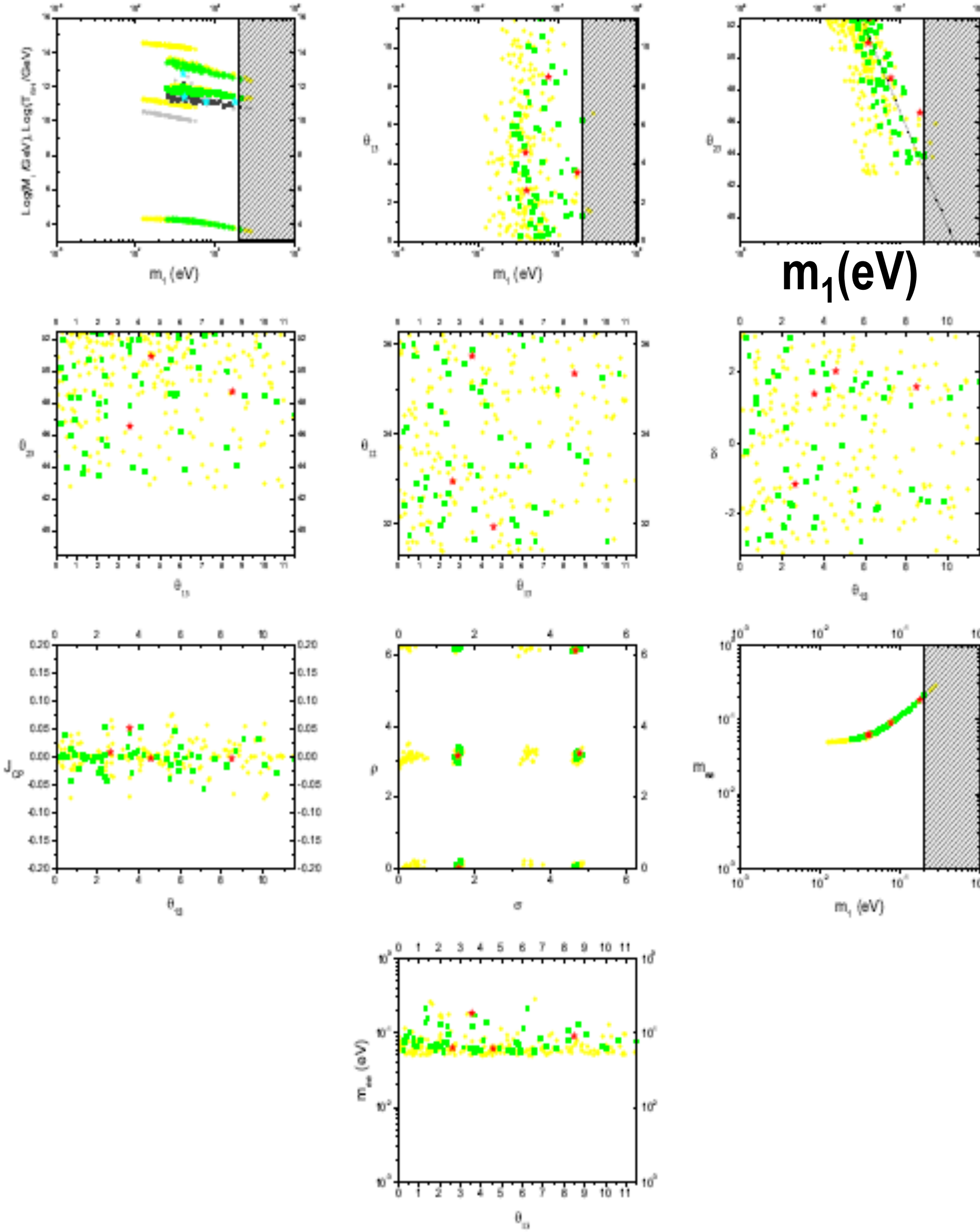
The reason is that if one starts from a vanishing abundance during the N_2 production one creates a contribution to the phantom term by inverse decays with opposite sign and exactly cancelling with what is created in the decays

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

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



Θ_{23}

INVERTED ORDERING

$\alpha_2=5$

$\alpha_2=4$

$\alpha_2=1.5$

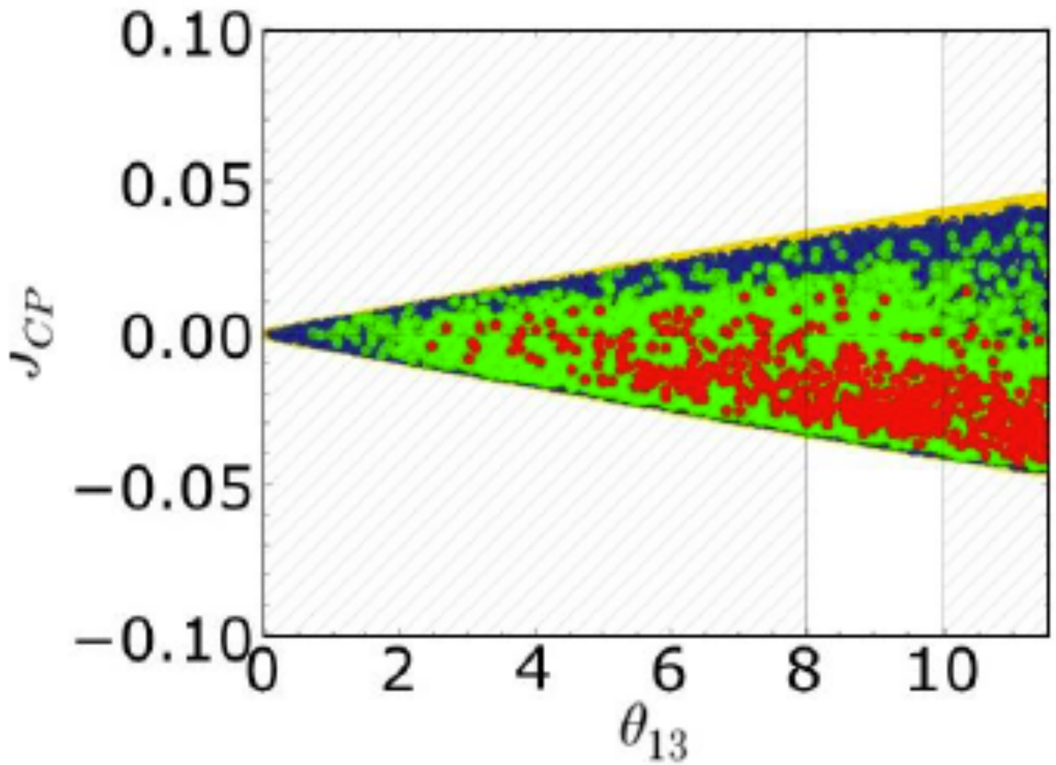
No link between the sign of the asymmetry and J_{CP}

(PDB, Marzola)

$\alpha_2=5$

NORMAL ORDERING

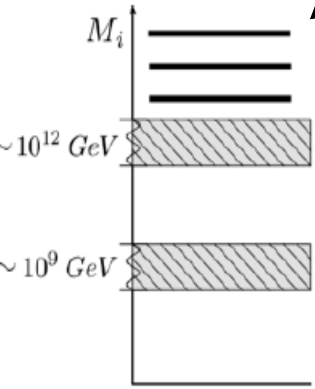
$I \leq V_L \leq V_{CKM}$



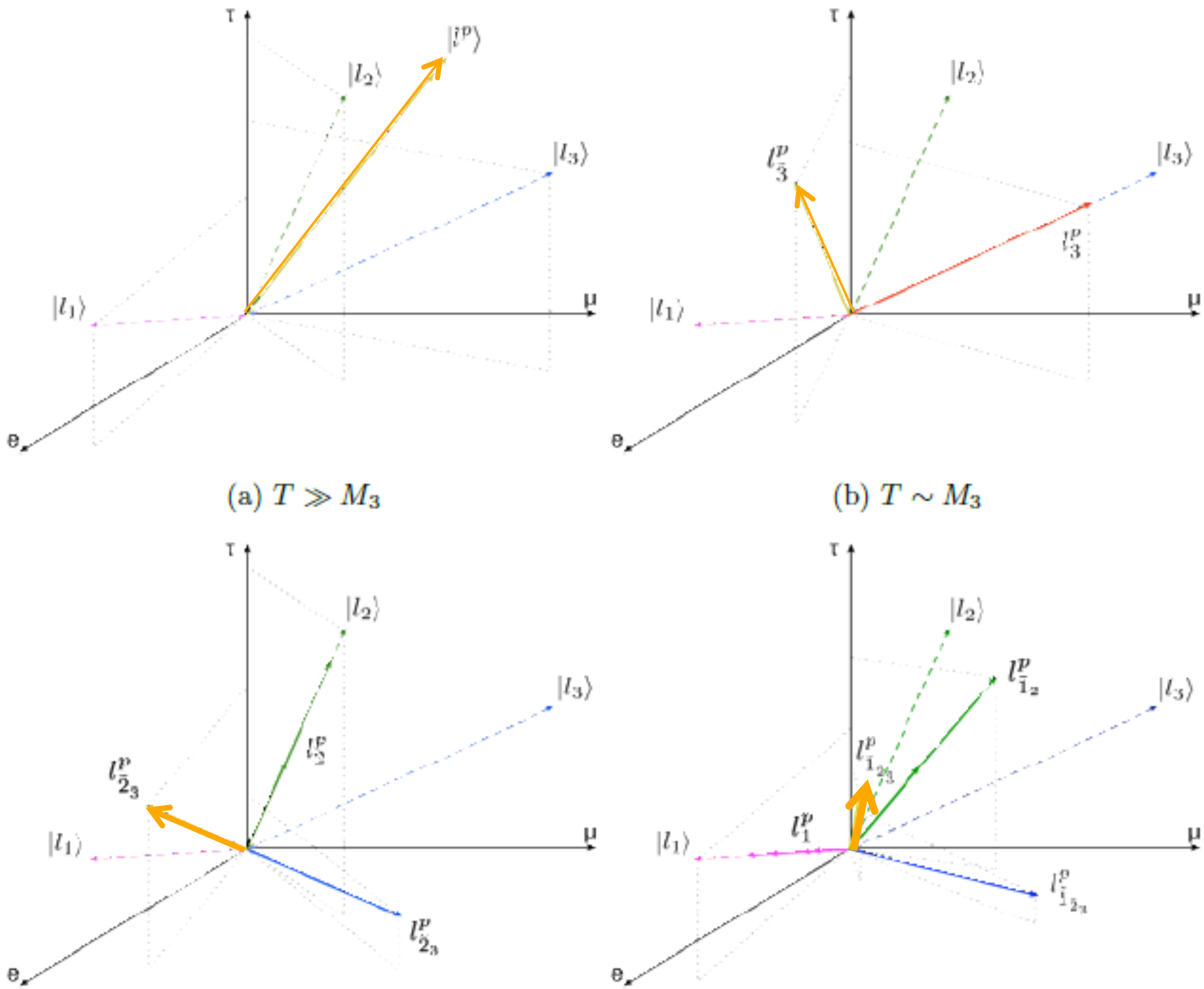
It is confirmed that there is no link between the matter-antimatter asymmetry and CP violation in neutrino mixing…….for the yellow points

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

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

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