Advances in high energy physics and cosmology
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Leptogenesis and BSM physics

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Why going beyond the SM?

Even without taking into account:

- ❑ (more or less) compelling theoretical motivations (quantum gravity theory, flavour problem, hierarchy problem, naturalness(?),…) and
- ❑ Experimental anomalies in $(g-2)_\mu$, B decays,…

The SM cannot explain:

- *Cosmological Puzzles* :

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

- *Neutrino masses and mixing*

Bridging neutrino physics and cosmology

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

- *Cosmological Puzzles* :

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

$\eta_B \simeq 6.1 \times 10^{-10}$

- *New stage in early Universe history* :

T

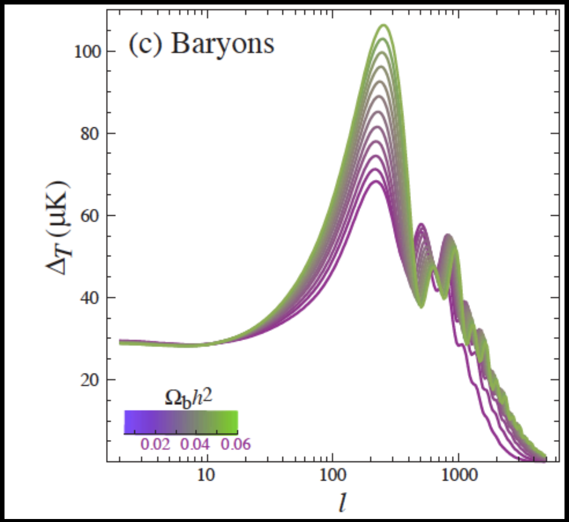
- T_{RH}?? — Inflation
- Leptogenesis
- 100 GeV — EWSSB
- 0.1- 1 MeV — BBN
- 0.1- 1 eV — Recombination

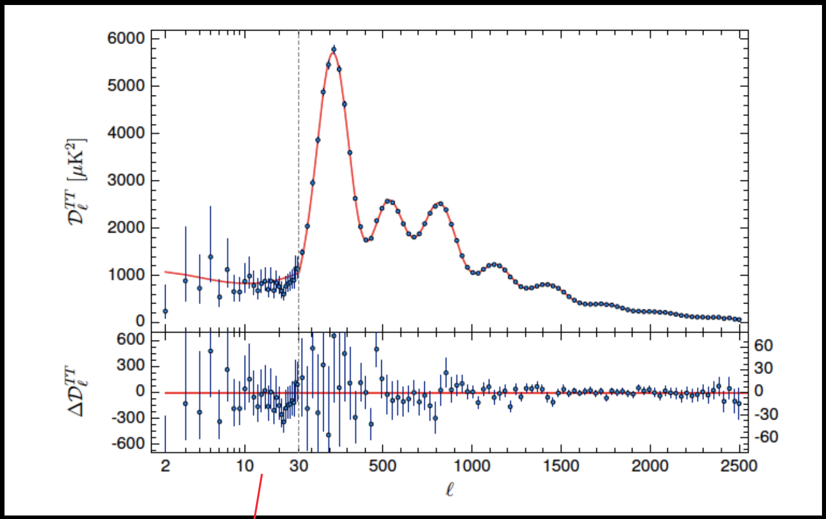
Leptogenesis complements low energy neutrino experiments testing the seesaw high energy parameters and providing a guidance toward the model underlying the seesaw

The baryon asymmetry of the Universe

(Hu, Dodelson, astro-ph/0110414)

(Planck 2015, 1502.10589)



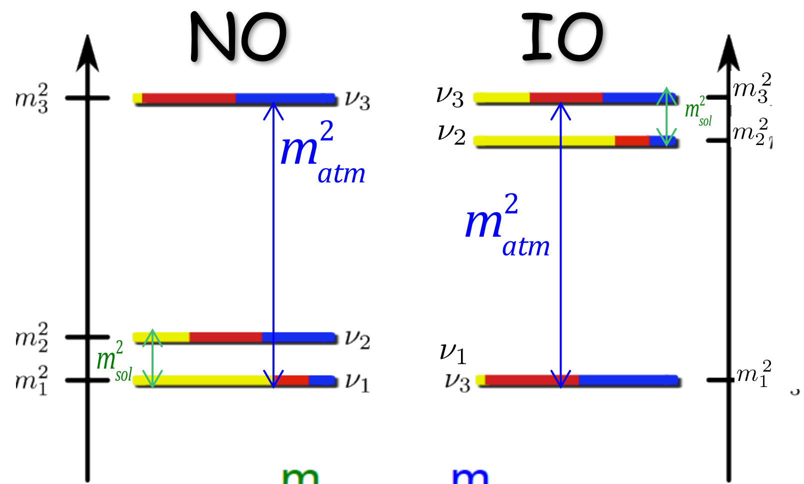


$$\Omega_{B0}h^2 = 0.02222 \pm 0.00023$$

$$\eta_{B0} \equiv \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \simeq \frac{n_{B0}}{n_{\gamma 0}} \simeq 273.5\,\Omega_{B0}h^2 \times 10^{-10} = (6.05 \pm 0.06) \times 10^{-10}$$

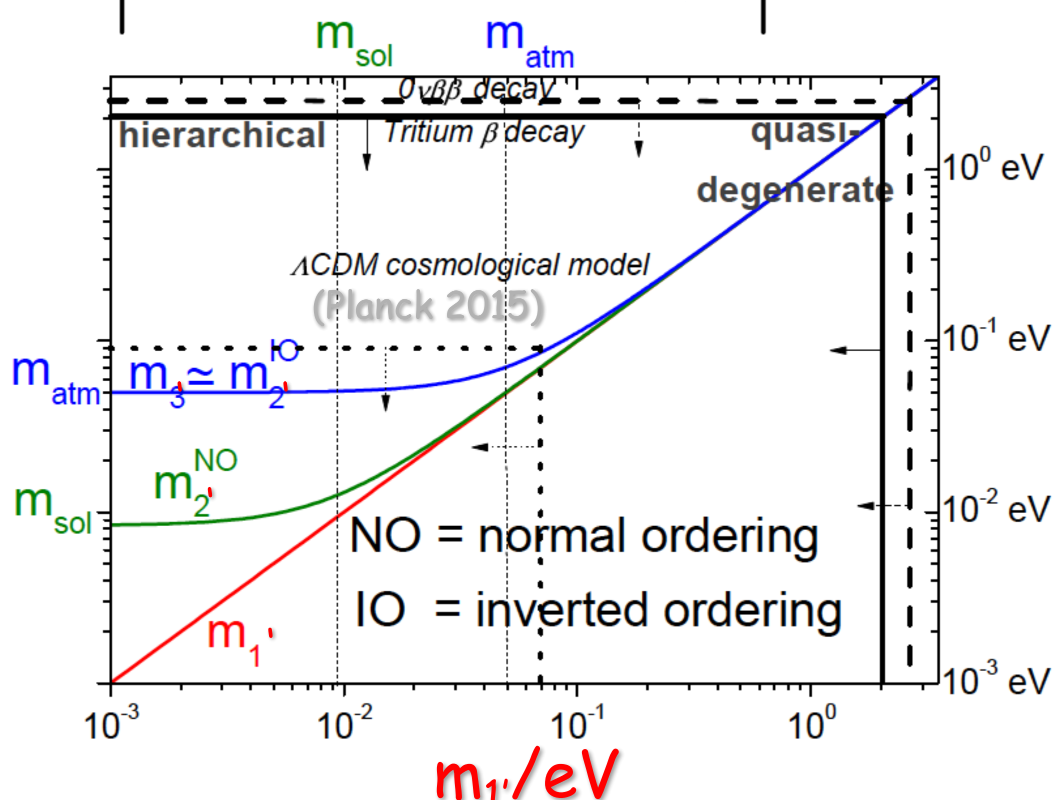
- ❑ Cosmic rays + CMB thermal spectrum fix the sign of η_B
  (Cohen, De Rujula, Glashow astro-ph/9707087)
- ❑ Consistent with (older) BBN determination but more precise and accurate

Neutrino masses: $m_{1'} < m_{2'} < m_{3'}$

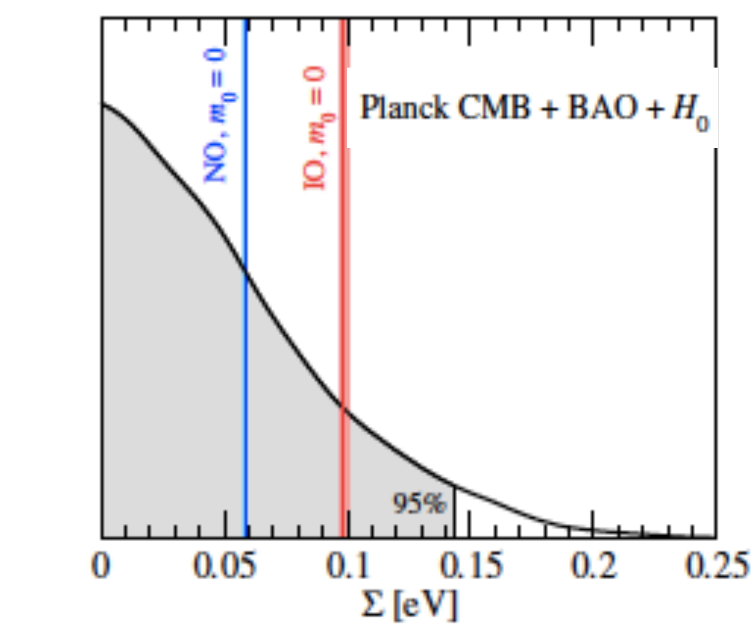


$$NO: m_2^{'} = \sqrt{m_1^{'2} + m^2_{sol}}, \quad m_3^{'} = \sqrt{m_1^{'2} + m^2_{atm}}$$

$$IO: m_2 = \sqrt{m_1^2 + m^2_{atm} - m^2_{sol}}, \quad m_3 = \sqrt{m_1^2 + m^2_{atm}}$$



More aggressively:



(Hannestad,Schwetz,1606.04691)

Neutrino mixing parameters

Pontecorvo-Maki-Nakagawa-Sakata matrix

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

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

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

$$\alpha_{31} = 2(\sigma - \rho)$$
$$\alpha_{21} = -2\rho$$

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

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

(Marrone et al.@ Neutrino 2016)

NO slightly favoured over IO ($\Delta\chi^2$ (IO-NO)=3.1)

3σ ranges(NO):

$\theta_{12} = [30^\circ, 36^\circ]$

$\theta_{13} = [7.8^\circ, 8.9^\circ]$

$\theta_{23} = [38^\circ, 51^\circ]$

$\delta = [-1.15\pi, +0.15\pi]$

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

3σ ranges (IO):

$\theta_{12} = [30^\circ, 36^\circ]$

$\theta_{13} = [7.8^\circ, 8.9^\circ]$

$\theta_{23} = [38^\circ, 53^\circ]$

$\delta = [-1.25\pi, +0.05\pi]$

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

The minimally extended SM

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_Y^\nu$$

$$-\mathcal{L}_Y^\nu = \overline{\nu_L}\, h^\nu\, \nu_R\, \phi \Rightarrow -\mathcal{L}_{\rm mass}^\nu = \overline{\nu_L}\, m_D\, \nu_R$$

Dirac mass term

(in a basis where charged lepton mass matrix is diagonal)

diagonalising m_D :

$$m_D = V_L^\dagger D_{m_D} U_R \qquad D_{m_D} \equiv \begin{pmatrix} m_{D1} & 0 & 0 \\ 0 & m_{D2} & 0 \\ 0 & 0 & m_{D3} \end{pmatrix}$$

$\Rightarrow$

neutrino masses: $m_i = m_{Di}$

leptonic mixing matrix: $U = V_L^\dagger$

Too many unanswered questions:

- Why neutrinos are much lighter than all other fermions?
- Why large mixing angles?
- Cosmological puzzles?
- Why not a Majorana mass term as well?

Minimal seesaw mechanism (type I)

• Dirac + (Right-Right) Majorana mass terms

(Minkowski '77; Gell-mann, Ramond, Slansky; Yanagida; Mohapatra, Senjanovic '79)

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

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

- 3 light Majorana neutrinos with masses (seesaw formula):

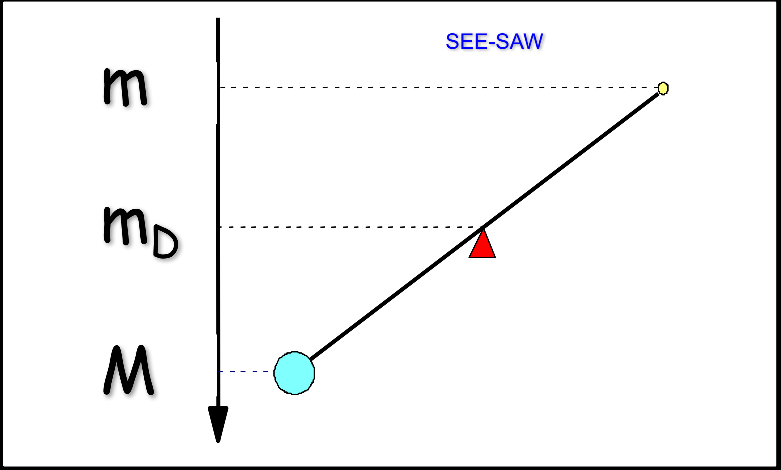
$$\mathrm{diag}(m_1, m_2, m_3) = -U^\dagger\, m_D\, \frac{1}{M}\, m_D^T\, U^\star$$

- 3 very heavy Majorana RH neutrinos N_1, N_2, N_3 with masses $M_3 > M_2 > M_1 \gg m_D$

1 generation toy model (U=1):

$m_D \sim m_{top}$,
$M \sim M_{GUT} \sim 10^{16}$ GeV

$\Rightarrow m \sim m_{atm} \sim 0.05$ eV



Minimal scenario of leptogenesis

(Fukugita, Yanagida '86)

- Thermal production of RH neutrinos

$T_{RH} \gtrsim T_{lep} \simeq M_i / (2 \div 10)$

heavy neutrinos decay $N_i \xrightarrow{\Gamma} L_i + \phi^\dagger \qquad N_i \xrightarrow{\bar{\Gamma}} \bar{L}_i + \phi$

total CP asymmetries $\varepsilon_i \equiv -\frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$ $\Rightarrow N_{B-L}^{fin} = \sum_{i=1,2,3} \varepsilon_i \times \kappa_i^{fin}$

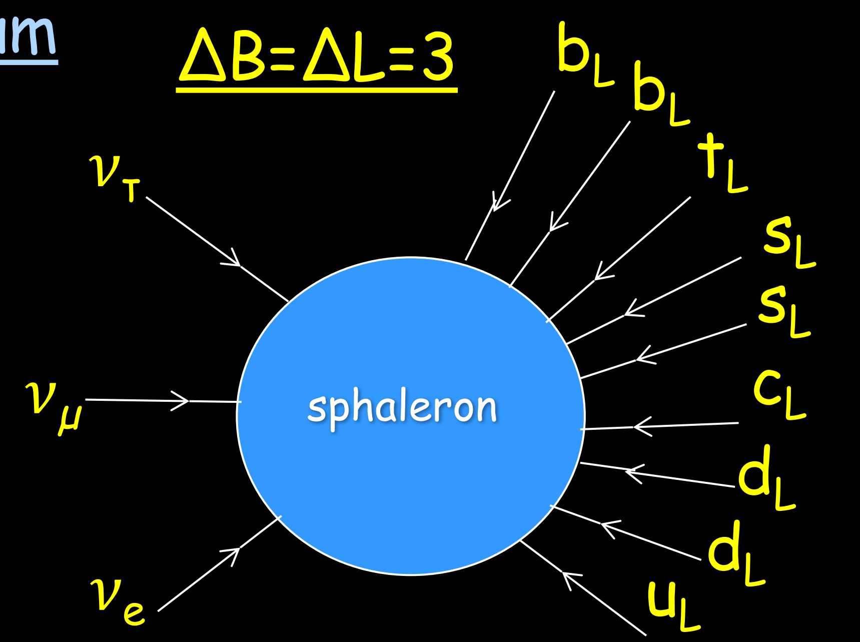
efficiency factors

- Sphaleron processes in equilibrium

$\Rightarrow T_{lep} \gtrsim T_{sphalerons}^{off} \sim 100$ GeV

(Kuzmin, Rubakov, Shaposhnikov '85)

$$\Rightarrow \eta_{B0}^{lep} = \frac{a_{sph} N_{B-L}^{fin}}{N_\gamma^{rec}} \simeq 0.01 N_{B-L}^{fin}$$



Seesaw parameter space

Imposing $\eta_{B0}^{lep} \simeq \eta_{B0}^{CMB} \simeq 6\times 10^{-10}$ $\Rightarrow$ can we test seesaw and leptog.?

Problem: too many parameters

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

Orthogonal parameterisation

$$m_D = U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}$$

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

light neutrino parameters

heavy neutrino parameters escaping experimental information

- Popular solution in the LHC era: TeV Leptogenesis (talk by Ishida in WG5) but no signs so far of new physics at the TeV scale or below able to explain η_{B0} in any baryogenesis model.

- Insisting with high scale leptogenesis is challenging but there are a few strategies able to reduce the number of parameters in order to obtain testable prediction on low energy neutrino parameters

Seesaw parameter space

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

- $n_B = n_B^{CMB}$ is satisfied around "peaks";
- some parameters cancel out in the asymmetry calculation;
- imposing independence of the initial conditions (strong thermal leptog.);
- imposing model dependent conditions on m_D (e.g. SO(10)-inspired)
- 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

$$N_i \xrightarrow{\Gamma} \ell_i + \phi^\dagger \qquad N_i \xrightarrow{\bar\Gamma} \bar\ell_i + \phi$$

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

3) Strong lightest RH neutrino wash-out

$$\eta_{B0} \simeq 0.01 N_{B-L}^{final} \simeq 0.01 \varepsilon_1 \kappa_1^{fin}(K_1, m_1)$$

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

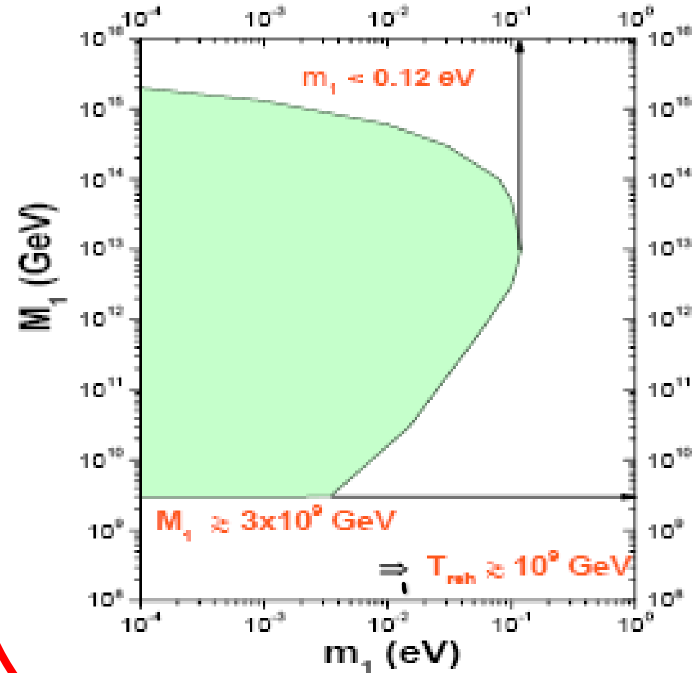
4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

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

5) Efficiency factor from simple Boltzmann equations

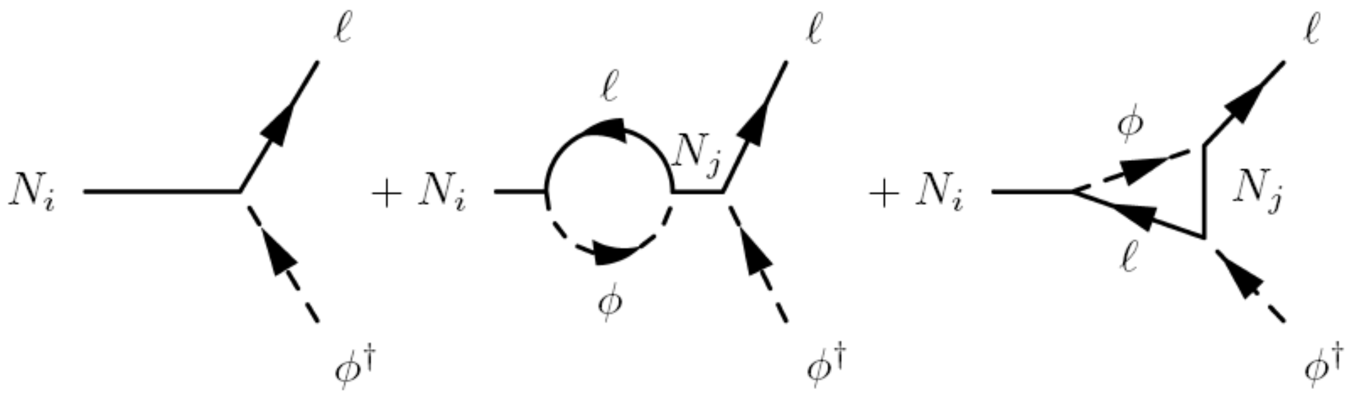
$$\eta_B^{\max}(m_1, M_1) \geq \eta_B^{CMB}$$



No dependence on the leptonic mixing matrix U: it cancels out

Total CP asymmetries

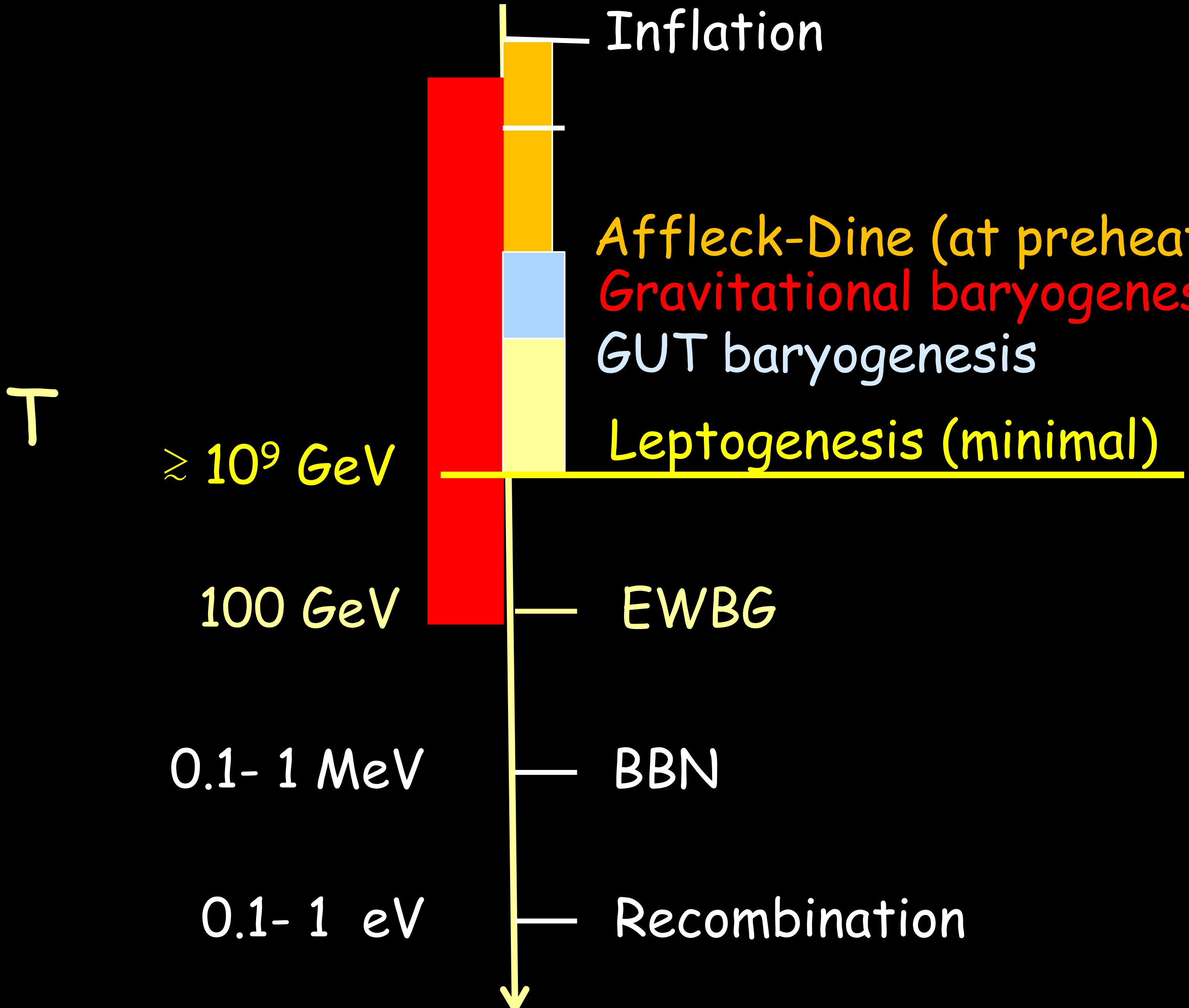
(Flanz,Paschos,Sarkar'95; Covi,Roulet,Vissani'96; Buchmüller,Plümacher'98)



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

It does not depend on U !

A pre-existing asymmetry?



Independence of the initial conditions (strong thermal leptogenesis)

(Buchmüller, PDB, Plümacher '04)

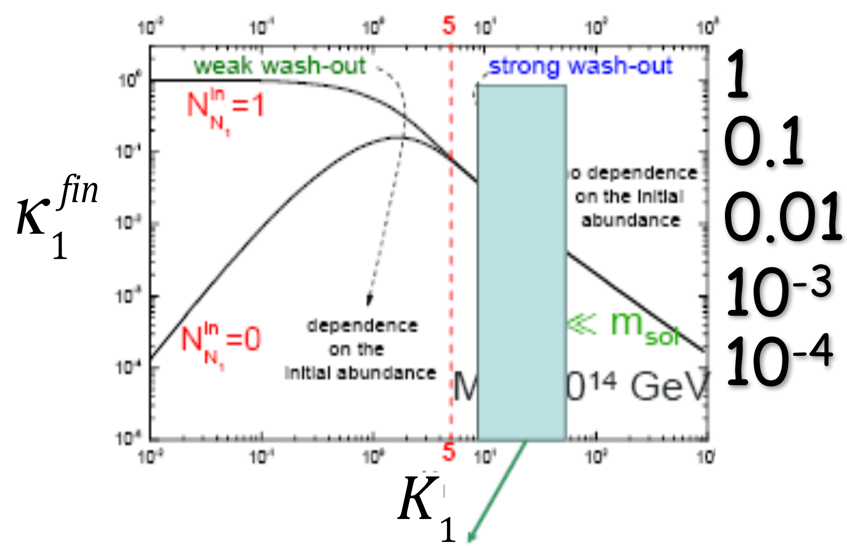
wash-out of a pre-existing asymmetry N^{p}_{B-L}

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

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

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

independence of the initial N_1-abundance as well



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

SO(10)-inspired leptogenesis

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

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

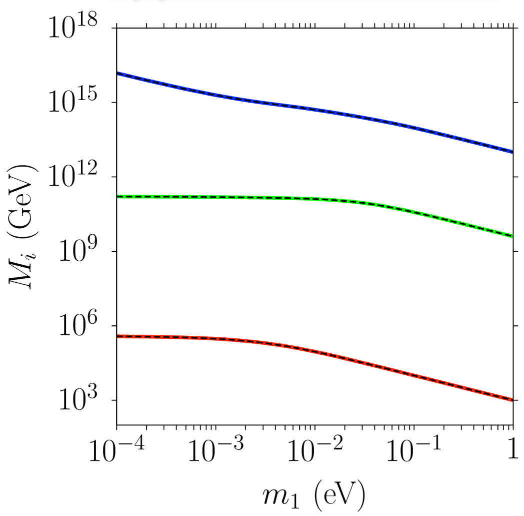
SO(10) inspired conditions:

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

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

From the seesaw formula: $U_R = U_R(U, m_i; \alpha_i, V_L)$, $M_i = M_i(U, m_i; \alpha_i, V_L)$ $\Rightarrow n_{B0} = n_{B0}(U, m_i; \alpha_i, V_L)$

typical solutions



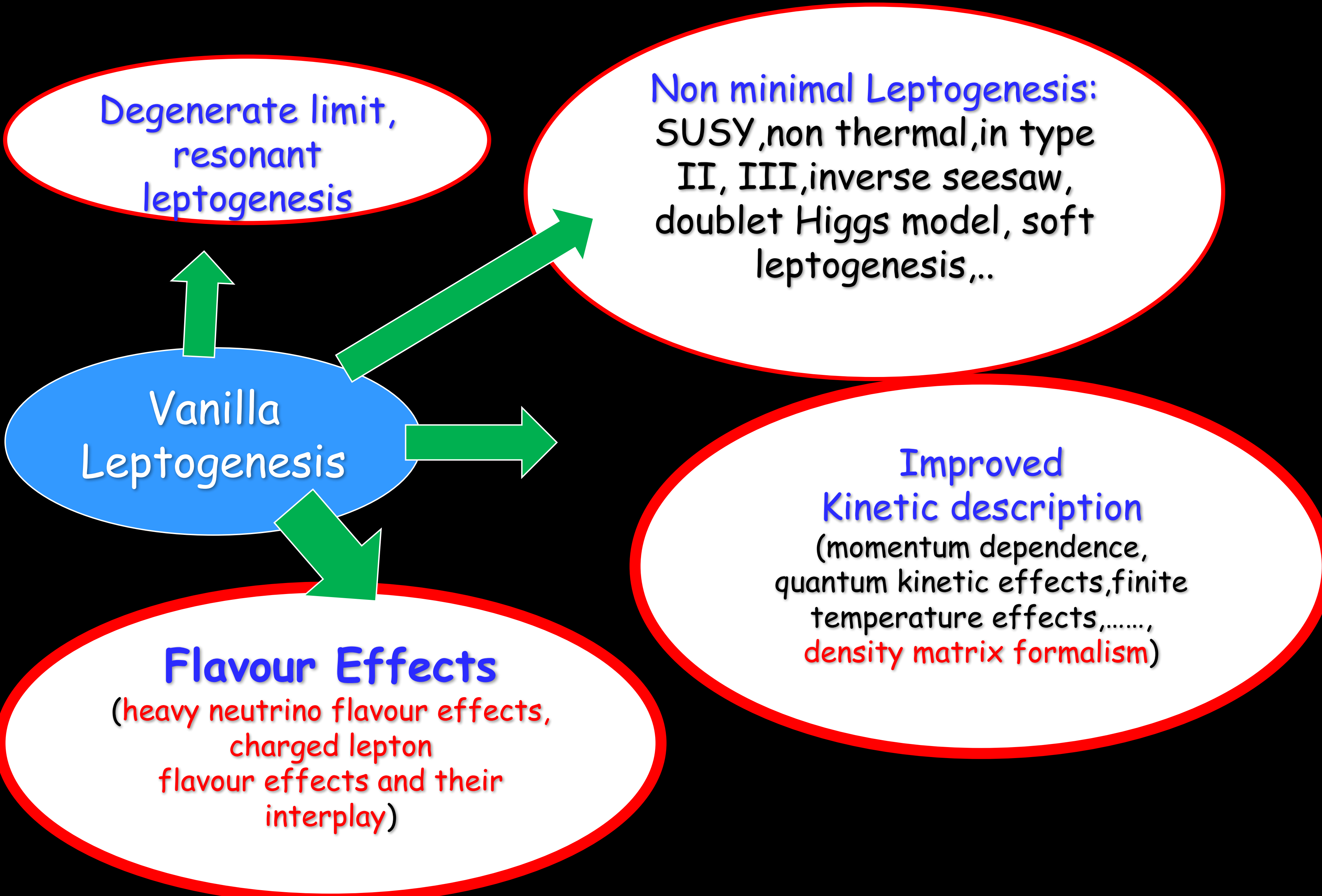
since $M_1 \ll 10^9$ GeV $\Rightarrow n_B^{(N1)} \ll n_B^{CMB}$

RULED OUT ?

Note that high energy CP violating phases are expressed in terms of low energy CP violating phases:

$$\Omega = D_m^{-\frac{1}{2}} \, U^\dagger \, V_L^\dagger \, D_{m_D} \, U_R \, D_M^{-\frac{1}{2}}$$

Beyond vanilla Leptogenesis



Charged lepton flavour effects

(Abada et al '06; Nardi et al. '06; Blanchet, PDB, Raffelt '06; Riotto, De Simone '06)

Flavor composition of lepton quantum states matters!

$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1 \rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau)$$

$$|\bar{l}'_1\rangle = \sum_\alpha \langle l_\alpha | \bar{l}'_1 \rangle \, |\bar{l}_\alpha\rangle$$

- ❑ **T $\lesssim$ 10^{12} GeV** $\Rightarrow$ τ-Yukawa interactions are fast enough break the coherent evolution of $|l_1\rangle$ and $|\bar{l}'_1\rangle$

$\Rightarrow$ incoherent mixture of a τ and of a α+e components $\Rightarrow$ 2-flavour regime

- ❑ T $\lesssim$ 10^9 GeV then also α-Yukawas in equilibrium $\Rightarrow$ **3-flavour regime**

M_1

UNFLAVOURED $\qquad N_{B-L}^{final} = \varepsilon_1 \kappa_1^{fin}$

~ 10^{12} GeV — TRANSITION REGIME: DENSITY MATRIX APPROACH NEEDED

2 Flavour regime (τ, e+μ) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1e+\mu}\kappa_1^{fin}(K_{1e+\mu})$

~ 10^9 GeV — TRANSITION REGIME: DENSITY MATRIX APPROACH NEEDED

3 Flavour regime (e, μ, τ) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1\mu}\kappa_1^{fin}(K_{1\mu}) + \varepsilon_{1e}\kappa_1^{fin}(K_{1e})$

2 fully flavoured regime

Flavoured decay parameters:

$$K_{1\alpha} = P^0_{1\alpha} K_1 = \left| \sum_k \sqrt{\frac{m_k}{m_*}} U_{\alpha k} \Omega_{k1} \right|^2 \leq K_1 \qquad \sum_\alpha K_{1\alpha} = K_1$$

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

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

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

Flavour effects introduce an explicit dependence on U and can in some case greatly enhance the asymmetry compared to the unflavoured case.

3 MAIN APPLICATIONS AND CONSEQUENCES OF FLAVOUR EFFECTS:

- Lower bound on M_1 (an therefore on T_{RH}) is not relaxed
  upper bound on m_1 is slightly relaxed to ~0.2eV but if wash-out is strong then Low energy phases can strongly affect the final asymmetry (second term)

- In the case of real Ω $\Rightarrow$ all CP violation stems from low energy phases;
  if also Majorana phases are CP conserving only δ would be responsible for the asymmetry: $\Rightarrow$ DIRAC PHASE LEPTOGENESIS: $\eta_{B0} \propto |\sin\delta| \sin\theta_{13}$

- Asymmetry produced from heavier RH neutrinos also contributes to the asymmetry and has to be taken into account:
  IT OPENS NEW INTERESTING OPPORTUNITIES

Remarks on the role of δ in leptogenesis

Dirac phase leptogenesis:

- It could work but only for $M_1 \gtrsim 5\times10^{11}$ GeV (plus other conditions on Ω)
  $\Rightarrow$density matrix calculation needed!

- No reasons for Ω to be real except when it is a permutation of identity (from discrete flavour models) but then all CP asymmetries vanish! So one needs quite a a special Ω

- In general the contribution from δ is *overwhelmed* by the high energy phases in Ω

General considerations:

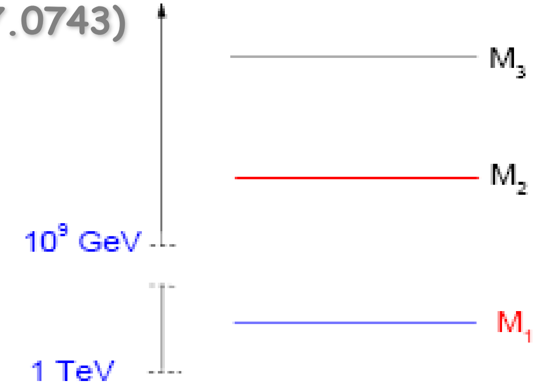
- CP violating value of δ is strictly speaking neither necessary nor sufficient condition for successful leptogenesis and no specific value is favoured model independently but….

- ….it is important to exclude CP conserving values since from $m_D = U\sqrt{D_m}\,\Omega\,\sqrt{D_M}$ one expects for generic m_D that if there are phases in U then there are also phases in Ω, vice-versa if there are no phases in U one might suspect that also Ω is real (disaster!):

  discovering CP violating value of δ would support a complex m_D

The N_2-dominated scenario

(PDB hep-ph/0502082, Vives hep-ph/0512160;Blanchet,PDB 0807.0743)



- **Unflavoured case:** asymmetry produced from N_2 - RH neutrinos is typically washed-out

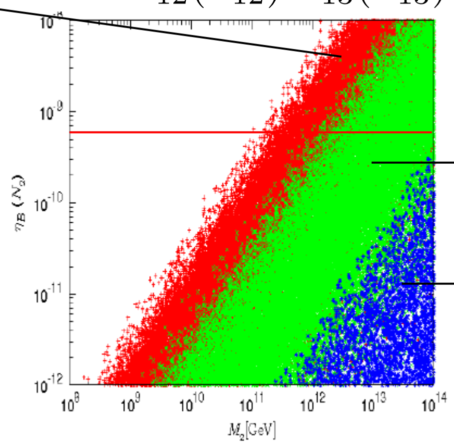
$$\eta_{B0}^{lep(N_2)} \simeq 0.01 \cdot \varepsilon_2 \cdot \kappa^{fin}(K_2) \cdot e^{-\frac{3\pi}{8}K_1} << \eta_{B0}^{CMB}$$

- **Adding flavour effects:** lighest RH neutrino wash-out acts on individual flavour $\Rightarrow$ much weaker

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

no N_1 wash-out for $M_1 \lesssim T_{sph} \simeq 140$ GeV
(PDB,Re Fiorentin 1512.06739)

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



with flavor effects

unflavored case

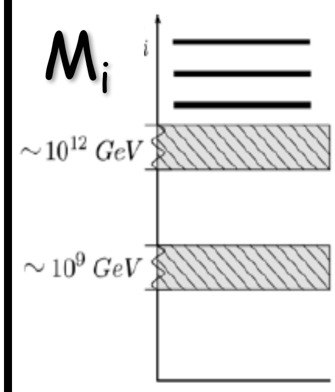
- With flavor effects the domain of successful N_2 dominated leptogenesis greatly enlarges
- **Existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$'s not to be negligible**

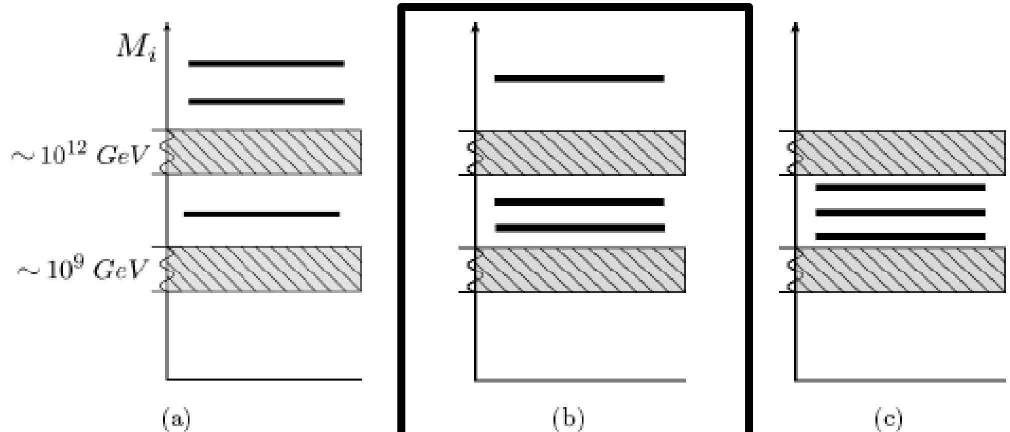
Heavy neutrino lepton flavour effects: 10 hierarchical scenarios

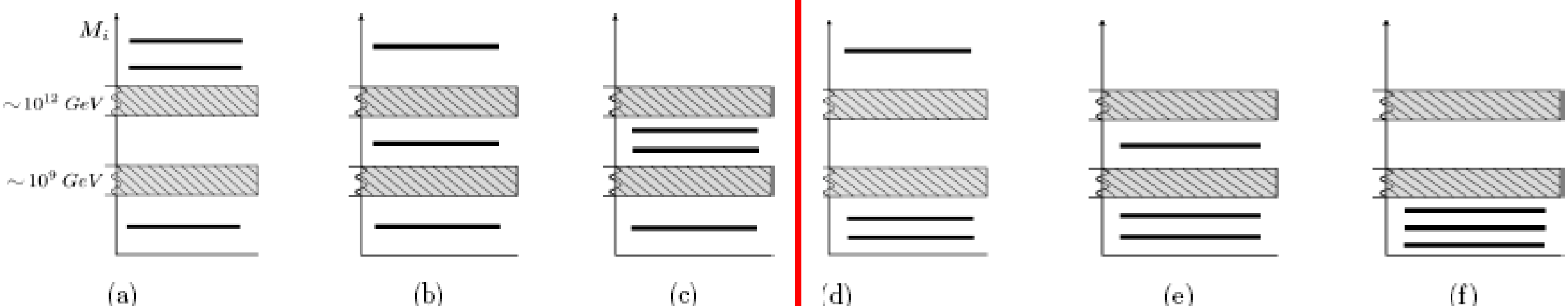
Heavy neutrino flavored scenario

2 RH neutrino scenario

Typically rising in discrete flavour models (talks by DiIura, Shimizu, Titov)







N_2-dominated scenario:

- ☛ N_1 produces negligible asymmetry;
- ☛ It emerges naturally in SO(10)-inspired models;
- ☛ It is the only one that can realise STRONG THERMAL LEPTOGENESIS

SO(10)-inspired leptogenesis

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

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

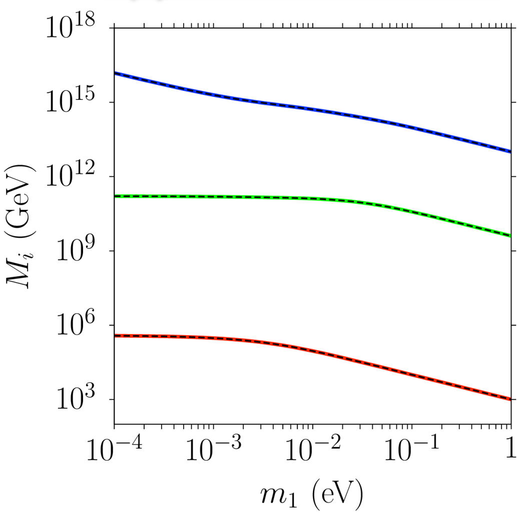
SO(10)-inspired conditions:

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

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

From the seesaw formula: $U_R = U_R\,(U, m_i; \alpha_i, V_L)$, $M_i = M_i\,(U, m_i; \alpha_i, V_L)$ $\Rightarrow \eta_{B0} = \eta_{B0}\,(U, m_i; \alpha_i, V_L)$

typical solutions



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RULED OUT ?

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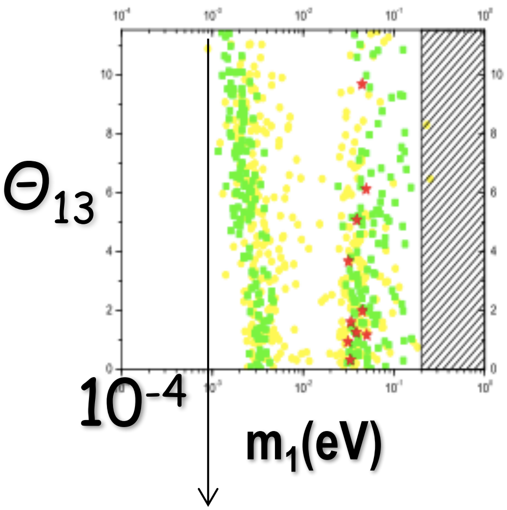
Rescuing SO(10)-inspired leptogenesis

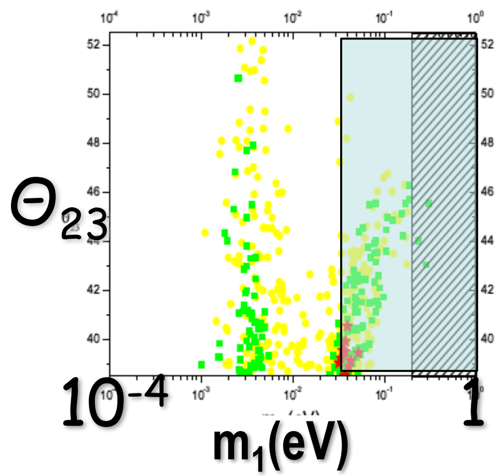
(PDB, Riotto 0809.2285;1012.2343;He,Lew,Volkas 0810.1104)

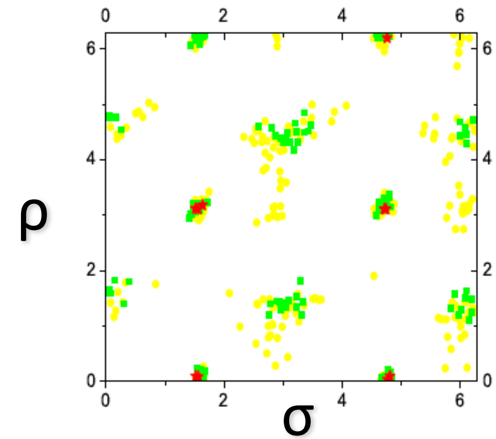
- $I \leq V_L \leq V_{CKM}$
- dependence on α_1 and α_3 cancels out $\Rightarrow$only on $\alpha_2 \equiv m_{D2}/m_{charm}$

$\alpha_2=5$ $\alpha_2=4$ $\alpha_2=1$

NORMAL ORDERING







- ➢ Lower bound $m_1 \gtrsim 10^{-3}$ eV
- ➢ Θ_{23} preferred in the first octant
- ➢ Majorana phases constrained about specific regions

➢ only marginal allowed regions for INVERTED ORDERING

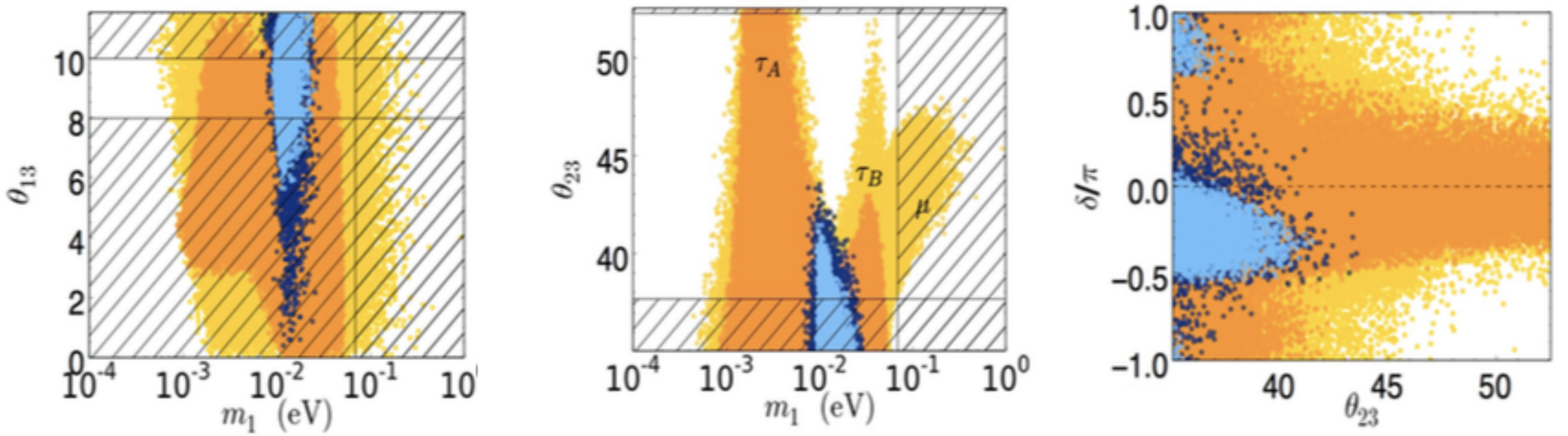
Strong thermal SO(10)-inspired (STSO10) solution

(PDB,Marzola 09/2011,DESY workshop;1308.1107;PDB,Re Fiorentin,Marzola 1411.5478)

- Strong thermal leptonesis condition can be satisfied for a subset of the solutions only for NORMAL ORDERING

$\alpha_2=5$

- yellow regions: $N_{B-L}^{pre-ex}=0$ ($I \leq V_L \leq V_{CKM}$; $V_L = I$)
- blue regions: $N_{B-L}^{pre-ex}=10^{-3}$ ($I \leq V_L \leq V_{CKM}$; $V_L = I$)



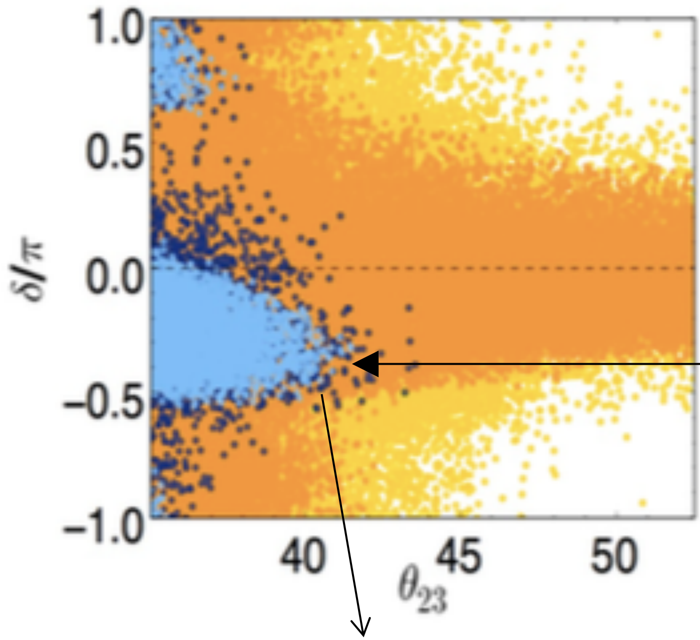
- Absolute neutrino mass scale: $15 \lesssim m_1/\text{meV} \lesssim 25 \Leftrightarrow 85 \lesssim \sum_i m_i/\text{meV} \lesssim 105$
- Non-vanishing Θ_{13} (preliminary results were presented before Daya Bay discovery at the DESY theory workshop, September 2011);
- Θ_{23} strictly in the first octant;

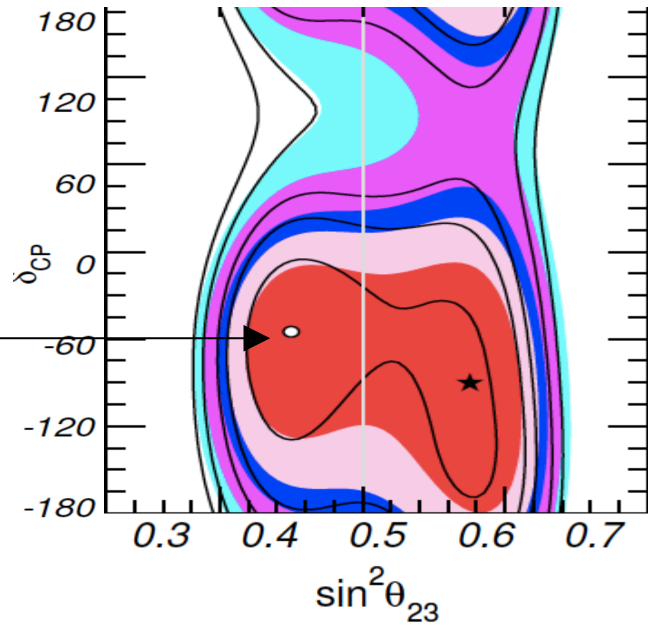
Strong thermal SO(10)-inspired solution : δ vs. θ_{23}

(PDB, Marzola, Invisibles workshop June 2012, arXiv 1308.1107)

http://www.nu-fit.org/?q=node/115

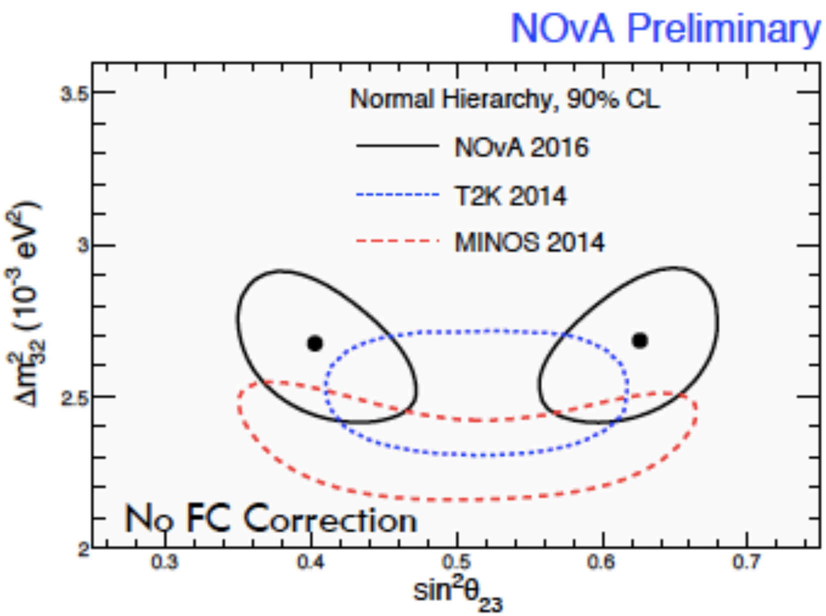
➢ NORMAL ORDERING

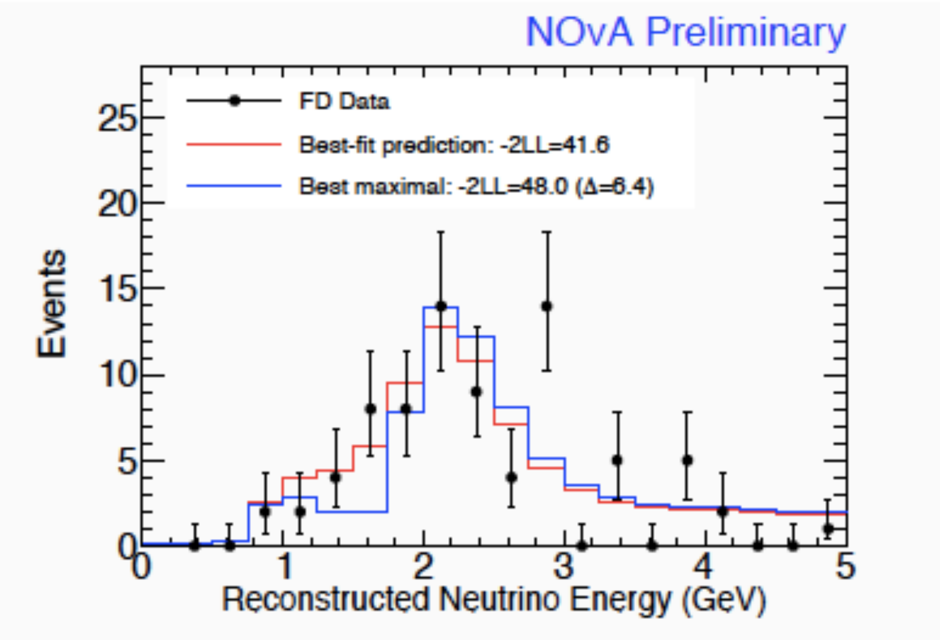




- For values of $\theta_{23} \gtrsim 38^0$ the Dirac phase is predicted to be $\delta \sim -60^0$, the exact range depends on θ_{23} but in any case $\cos\delta > 0$
- It is interesting that low values of the atmospheric mixing angle are also necessary to reproduce b-τ unification in SO(10) models (Bajc, Senjanovic, Vissani '06)
- The new experimental results presented at Neutrino 2016 corroborate this nice agreement between predictions and experiments

New NOvA results (Neutrino 2016)



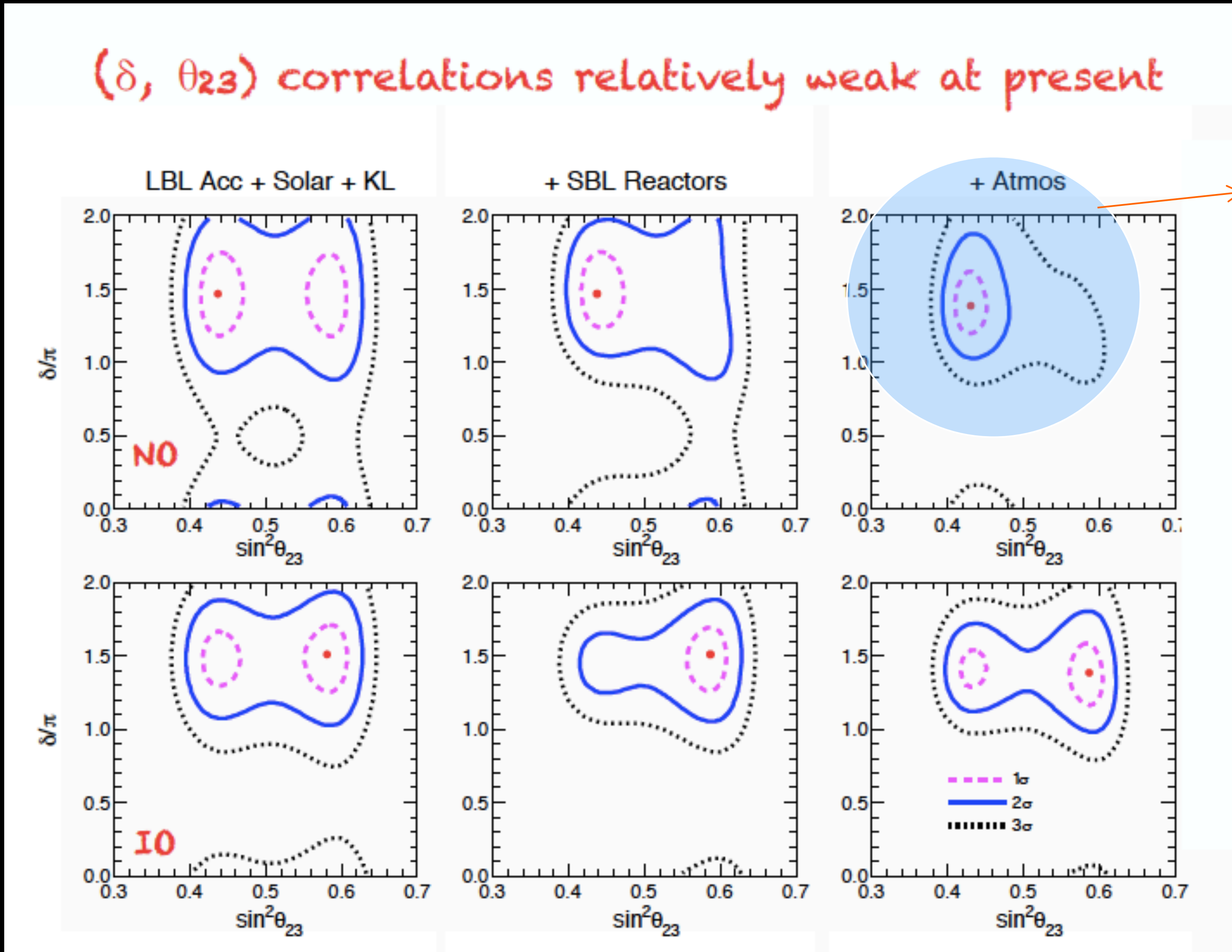


Best Fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\text{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

Preliminary results from global analyses(Marrone at Neutrino 2016)



agrees with STSO10 solution predictions: encouraging

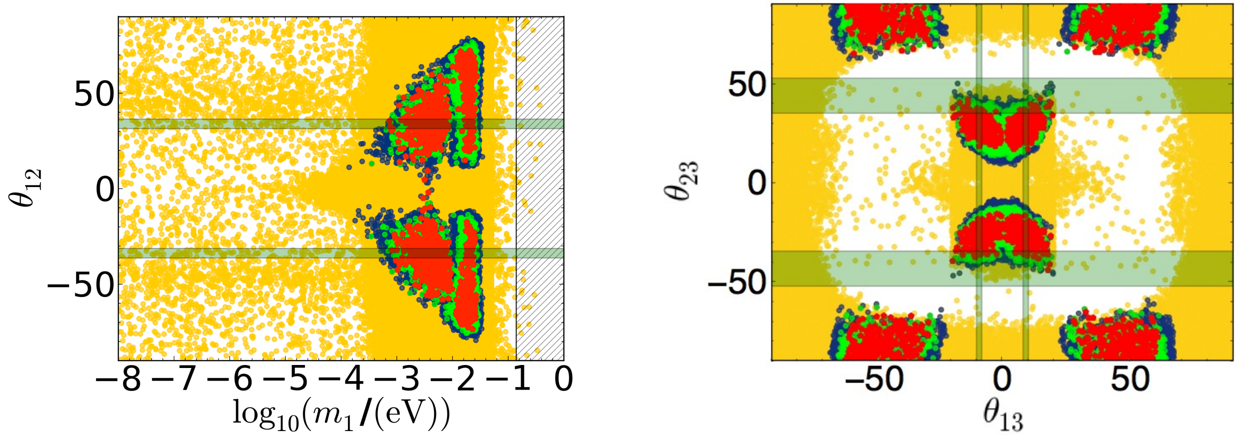
NO slightly favoured over IO ($\Delta\chi^2$ (IO-NO)=3.1) + also cosmology starts preferring NO

STSO10 solution: on the right track?

(PDB, Marzola '13)

What is the probability that the agreement is due to a coincidence?
This sets the statistical significance of the agreement

(N^p_{B-L}= 0, 0.001, 0.01, 0.1)



If the first octant is found then $p \lesssim 10\%$

If NO is found then $p \lesssim 5\%$

If $\sin\delta < 0$ is confirmed then $p \lesssim 2\%$

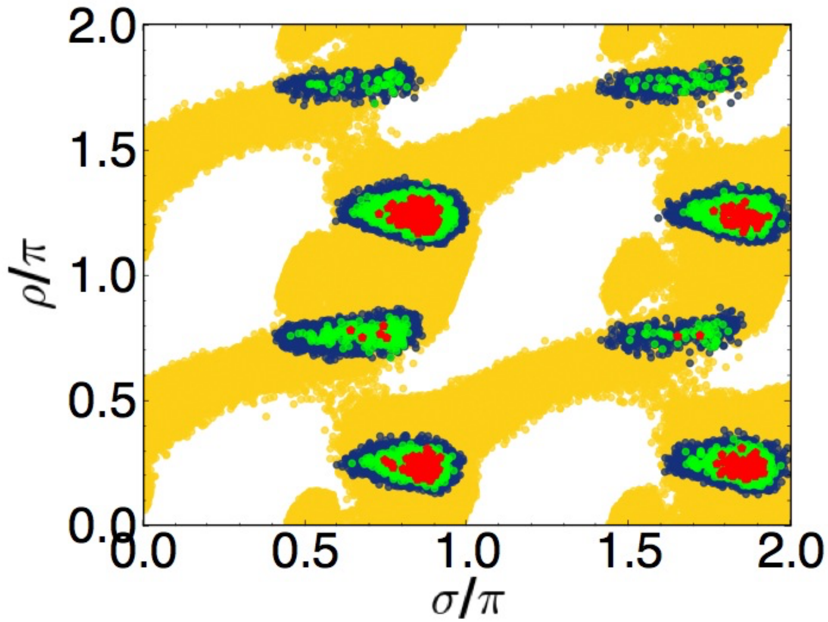
If $\cos\delta < 0$ is found then $p \lesssim 1\%$ and then?

STSO10: Majorana phases and neutrinoless double beta decay

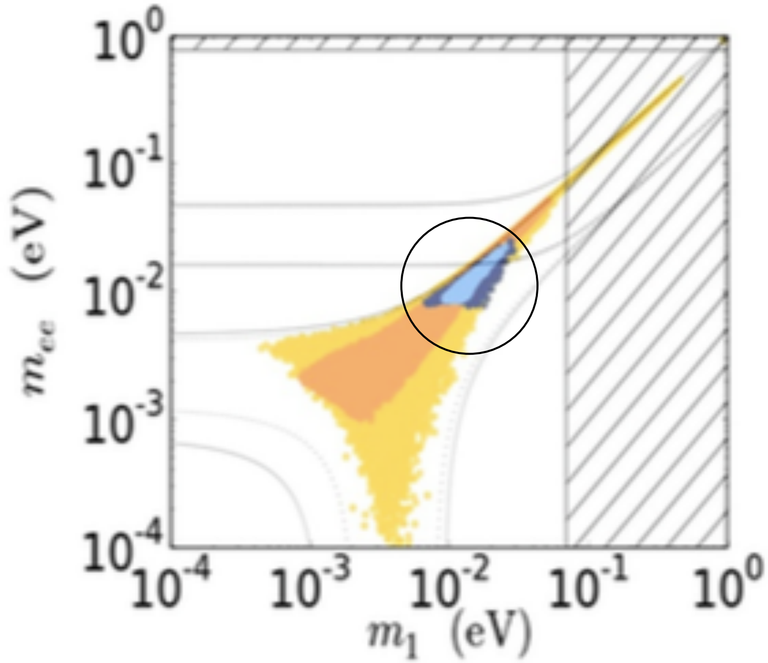
(PDB,Marzola1308.1107;PDB,Re Fiorentin,Marzola 1411.5478)

α_2=5 ➢ NORMAL ORDERING

Majorana phases



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



- Majorana phases are constrained around definite values
- Sharp prediction on the absolute neutrino mass scale: both on m_1 and m_{ee}
- Despite one has normal ordering, m_{ee} value might be within exp. Reach
- If also these predictions are satisfied exp, then p $\lesssim$ 0.01% (conservative)

Decrypting SO(10)-inspired models

(Akhmedov, Frigerio, Smirnov, 2005; PDB, Re Fiorentin, Marzola, 1411.5478)

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

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

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

0νββ neutrino mass

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

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

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

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

Decrypting SO(10)-inspired leptogenesis

(PDB, Re Fiorentin, Marzola, 1411.5478)

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

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

Effective SO(10)-inspired leptogenesis phase

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

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

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

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

An example of realistic model:

SO(10)-inspired leptogenesis in the "A2Z model"

(S.F. King 2014)

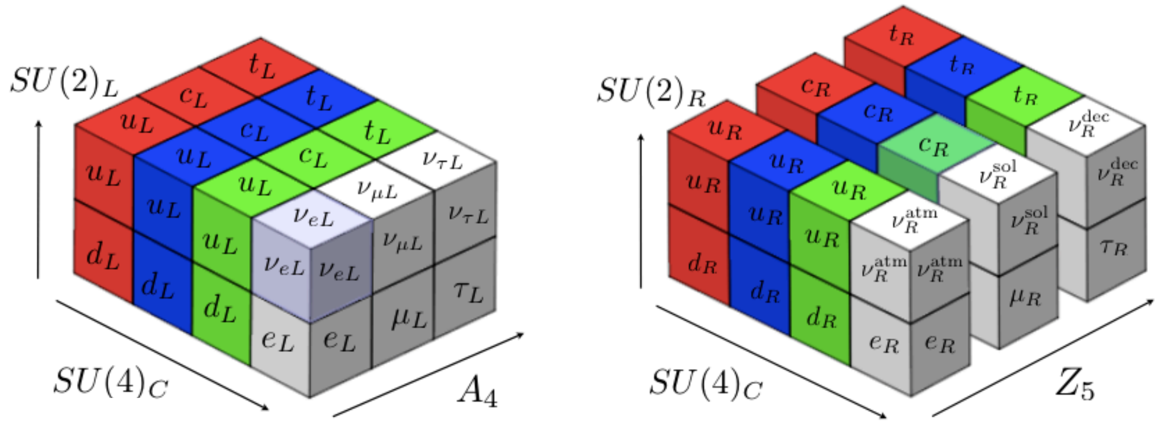


Figure 1: A to Z of flavour with Pati-Salam, where $A \equiv A_4$ and $Z \equiv Z_5$. The left-handed families form a triplet of A_4 and are doublets of $SU(2)_L$. The right-handed families are distinguished by Z_5 and are doublets of $SU(2)_R$. The $SU(4)_C$ unifies the quarks and leptons with leptons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

Neutrino sector:

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

CASE A:

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

CASE B:

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

There are 2 solutions (only for NO)

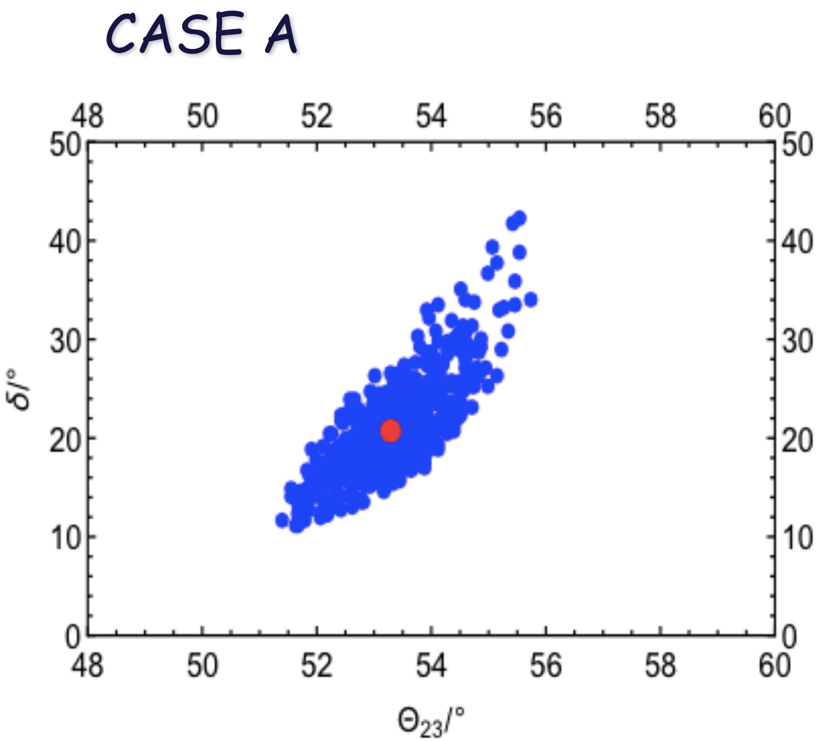
(PDB, S.King 1507.06431)

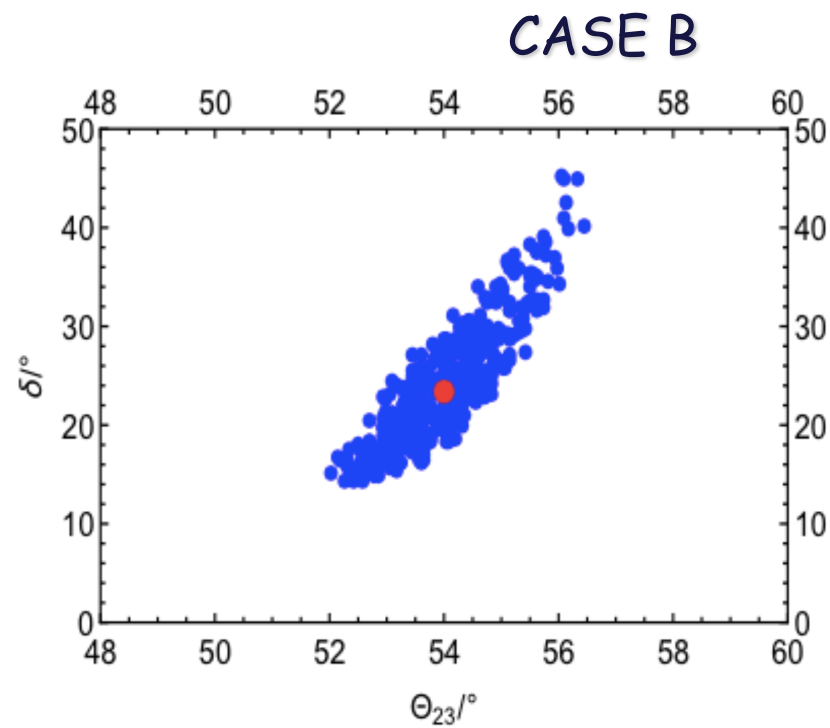
The spectrum is not so strongly hierarchical: it is in the proximity of crossing level solutions

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

There are 2 solutions (only for NO)

(PDB, S.F. King 1507.06431)





This region will be tested relatively quickly

Quantifying the fine-tuning

(PDB, S.King 2015)

Analytical expression also for the orthogonal matrix:

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

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

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

- Fine tuned cancellations in the see-saw formula at the level of $|\Omega_{ij}|^{-2}$ this seems to be quite a recurrent issue in fits.....

A popular class of SO(10) models

(Fritzsch, Minkowski, Annals Phys. 93 (1975) 193-266; R.Slansky, Phys.Rept. 79 (1981) 1-128; G.G. Ross, GUTs, 1985; Dutta, Mimura, Mohapatra, hep-ph/0507319; G. Senjanovic hep-ph/0612312)

In SO(10) models each SM particles generation + 1 RH neutrino are assigned to a single 16-dim representation. Masses of fermions arise from Yukawa interactions of two 16s with vevs of suitable Higgs fields. Since:

$$16 \otimes 16 = 10_{\rm S} \oplus \overline{126}_{\rm S} \oplus 120_{\rm A};$$

The Higgs fields of renormalizable SO(10) models can belong to 10-, 126-,120-dim representations yielding Yukawa part of the Lagrangian

$$\mathcal{L}_Y = 16\,(Y_{10} 10_H + Y_{126}\overline{126}_H + Y_{120} 120_H)\,16\,.$$

After SSB of the fermions at M_{GUT}=2x10^{16} GeV one obtains the masses:

up-quark mass matrix	$M_u = v_{10}^u Y_{10} + v_{126}^u Y_{126} + v_{120}^u Y_{120}\,,$
down-quark mass matrix	$M_d = v_{10}^d Y_{10} + v_{126}^d Y_{126} + v_{120}^d Y_{120}\,,$
neutrino mass matrix	$M_D = v_{10}^u Y_{10} - 3 v_{126}^u Y_{126} + v_{120}^D Y_{120}\,,$
charged lepton mass matrix	$M_l = v_{10}^d Y_{10} - 3 v_{126}^d Y_{126} + v_{120}^l Y_{120}\,,$
RH neutrino mass matrix	$M_R = v_{126}^R Y_{126}\,,$
LH neutrino mass matrix	$M_L = v_{126}^L Y_{126}\,,$

Simplest case but clearly non-realistic: it predicts no mixing at all (both in quark and lepton Sectors). For realistic models one has to add at least the 126 contribution

NOTE: these models do respect SO(10)-inspired conditions

Recent fits within SO(10) models

(Joshipura Patel 2011; Rodejohann, Dueck '13)

No type II seesaw contribution: it does not seem to help the fits

Minimal Model with $10_H + \overline{126}_H$ (MN, MS)
"full" Higgs Content $10_H + \overline{126}_H + 120_H$ (FN, FS)

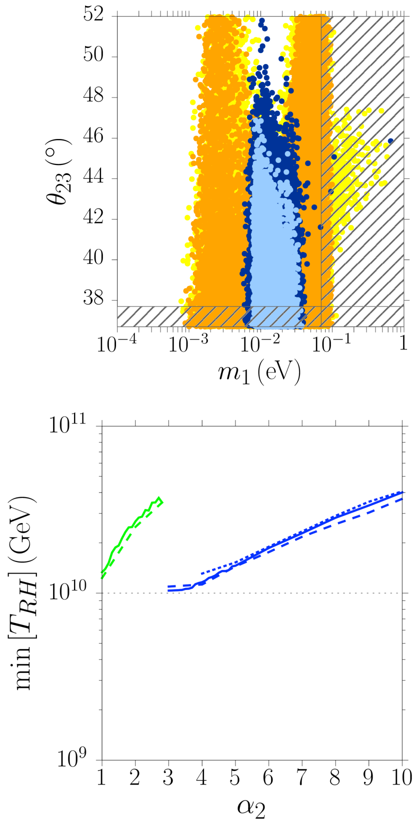
Mod	Comments	$\langle m_\nu \rangle$ [meV]	δ^l_{CP} [rad]	$\sin^2 \theta^l_{23}$	m_0 [meV]	M_3 [GeV]	M_2 [GeV]	M_1 [GeV]	$\chi^2_{\min}$
MN	no RGE, NH	0.35	0.7	0.406	3.03	5.5×10^{12}	7.2×10^{11}	1.5×10^{10}	1.10
MN	RGE, NH	0.49	6.0	0.346	2.40	3.6×10^{12}	2.0×10^{11}	1.2×10^{11}	23.0
MS	no RGE, NH	0.38	0.27	0.387	2.58	3.9×10^{12}	7.2×10^{11}	1.6×10^{10}	9.41
MS	RGE, NH	0.44	2.8	0.410	6.83	1.1×10^{12}	5.7×10^{10}	1.5×10^{10}	3.29
FN	no RGE, NH	4.96	1.7	0.410	8.8	1.9×10^{13}	2.8×10^{12}	2.2×10^{10}	6.6×10^{-5}
FN	RGE, NH	2.87	5.0	0.410	1.54	9.9×10^{14}	7.3×10^{13}	1.2×10^{13}	11.2
FS	no RGE, NH	0.75	0.5	0.410	1.16	1.5×10^{13}	5.3×10^{11}	5.7×10^{10}	9.0×10^{-10}
FS	RGE, NH	0.78	5.4	0.410	3.17	4.2×10^{13}	4.9×10^{11}	4.9×10^{11}	6.9×10^{-6}
FN	no RGE, IH	35.37	5.4	0.590	35.85	2.2×10^{13}	4.9×10^{12}	9.2×10^{11}	2.5×10^{-4}
FN	RGE, IH	35.52	4.7	0.590	30.24	1.1×10^{13}	3.5×10^{12}	5.5×10^{11}	13.3
FS	no RGE, IH	44.21	0.3	0.590	6.27	1.2×10^{13}	4.2×10^{11}	3.5×10^{7}	3.9×10^{-8}
FS	RGE, IH	24.22	3.6	0.590	11.97	1.2×10^{13}	3.1×10^{11}	2.0×10^{3}	0.602

Recently Fong,Meloni,Meroni,Nardi(1412.4776) have included leptogenesis for the non-SUSY case obtaining successful leptogenesis: but such a compact RN neutrino spectrum implies huge fine-tuning. Too simplistic models? What solution: non renormalizable terms? Type II seesaw term? SUSY seems to improve the fits and also give 1 hier. solution

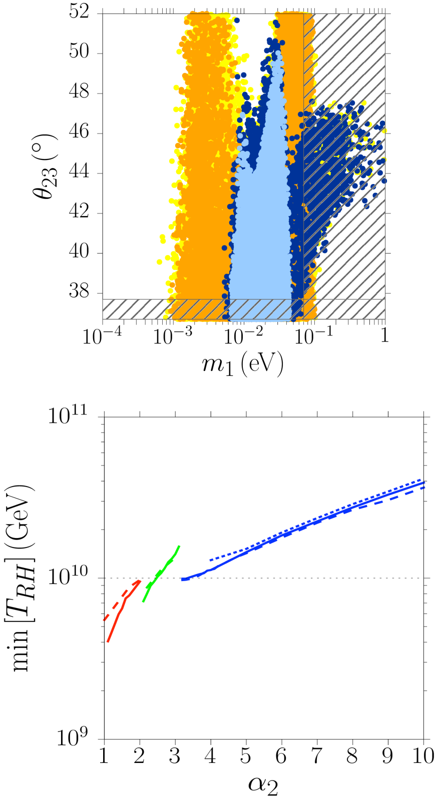
SUSY SO(10)-inspired leptogenesis

(PDB, Re Fiorentin, Marzola, 1512.06739)

$\tan\beta = 5$



$\tan\beta = 50$



It is possible to lower T_{RH} to values consistent with the gravitino problem for $m_g \gtrsim 30$ TeV

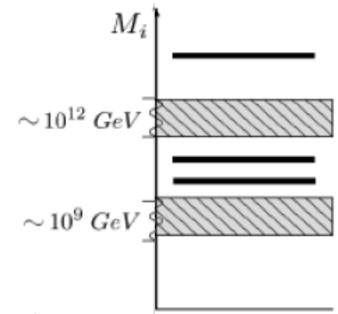
(Kawasaki, Kohri, Moroi, 0804.3745)

Alternatively, for lower gravitino masses, one has to consider non-thermal SO(10)-inspired leptogenesis

(Blanchet, Marfatia 1006.2857)

2 RH neutrino models

(PDB, NOW 2006;Anisimov,PDB 0812.5085;PDB, P.Ludl,S. Palomarez-Ruiz 1606.06238)
(S.F. King hep-ph/9912492;Frampton,Glashow,Yanagida hep-ph/0208157;Ibarra,Ross2003;
Antusch, PDB,Jones,King '11)



- They can be obtained from 3 RH neutrino models in the limit $M_3 \to \infty$
- Number of parameters get reduced to 11
- Contribution to asymmetry from both 2 RH neutrinos.

The contribution from the lightest (N_1) typically dominates but the contribution from next-to-lightest (N_2) opens new regions that correspons to light sequential dominated neutrino mass models realised in some GUT models. In any case there is still a lower bound

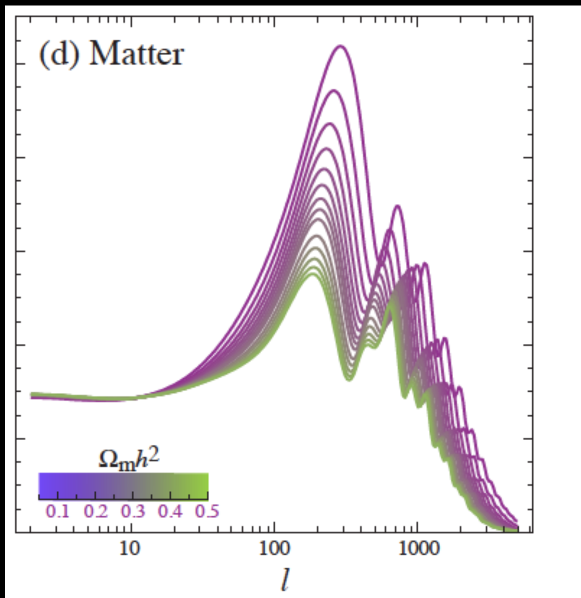
$$M_1 \gtrsim 2\text{x } 10^{10}\,\text{GeV} \Rightarrow T_{RH} \gtrsim 6 \times 10^9\,\text{GeV}$$

- Recently 2 RH neutrino model realised in A4 x SU(5) SUSY GUT model with interesting link between "leptogenesis phase" and Dirac phase
(F, Bjorkeroth, S.F. King 1505.05504)
- 2 RH neutrino model can be also obtained from 3 RH neutrino models with 1 vanishing Yukawa eigenvalue ⇒ potential DM candidate

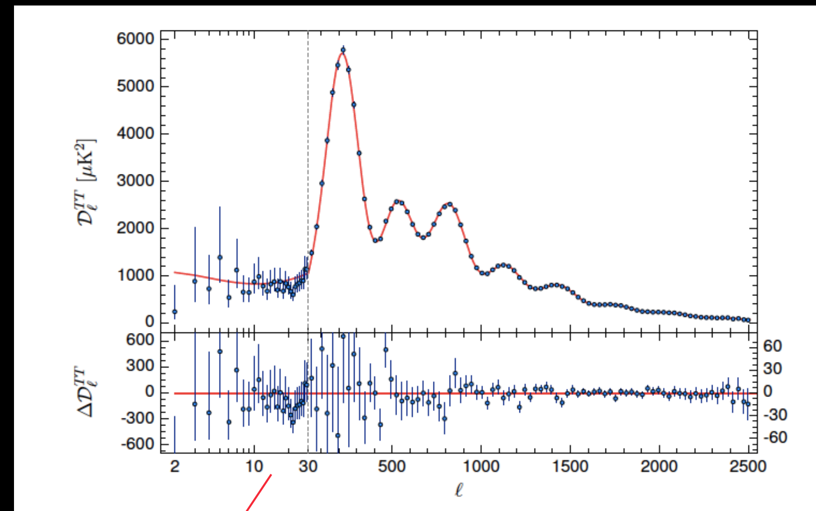
(A.Anisimov, PDB hep-ph/0812.5085)

The Dark Matter of the Universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2015, 1502.10589)



CMB +"ext"

$$\Omega_{CDM,0}h^2 = 0.1188 \pm 0.0010 \sim 5\Omega_{B,0}h^2$$

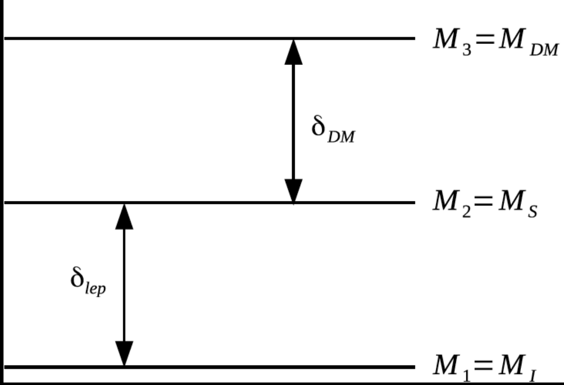
Unifying Leptogenesis and Dark Matter

(PDB, NOW 2006;Anisimov,PDB,0812.5085;PDB, P.Ludl,S. Palomarez-Ruiz 1606.06238)

1 RH neutrino has vanishing Yukawa couplings

$$m_D \simeq \begin{pmatrix} m_{De1} & m_{De2} & 0 \\ m_{D\mu 1} & m_{D\mu 2} & 0 \\ m_{D\tau 1} & m_{D\tau 2} & 0 \end{pmatrix}$$

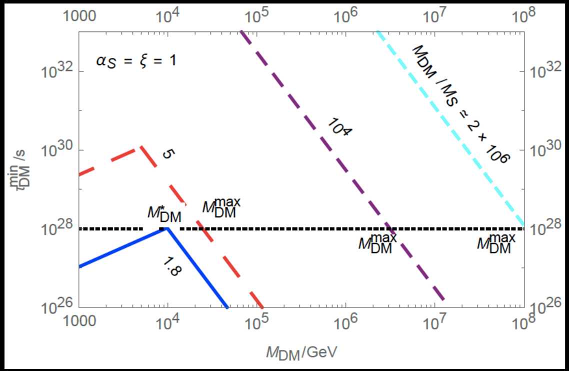
$\Rightarrow$ 2 RH neutrino seesaw model



…but couples to one "source" RH neutrino N_S via Higgs portal-type interactions

$$\mathcal{L} = \frac{\lambda_{IJ}}{\Lambda}\, \phi^\dagger \phi\, \overline{N_I^c}\, N_J$$

These are responsible both for production via RH neutrino mixing (non-adiabatic conversions) and for decays $\Rightarrow$decays are unavoidable $\Rightarrow$it predicts some contribution to high energy neutrino flux potentially testable with neutrino telescopes (IceCube,Km^3,……)



Correct DM abundance and life time for $\Lambda/\lambda \sim 10^{25}$ GeV

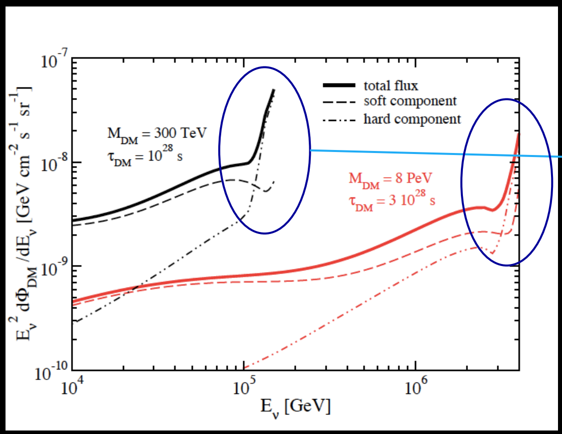
Interference of N_S with the third RH neutrino $\Rightarrow$ (1-100) TeV leptogenesis

Nicely predicted a signal at IceCube

(Anisimov,PDB,0812.5085;PDB, P.Ludl,S. Palomarez-Ruiz 1606.06238)

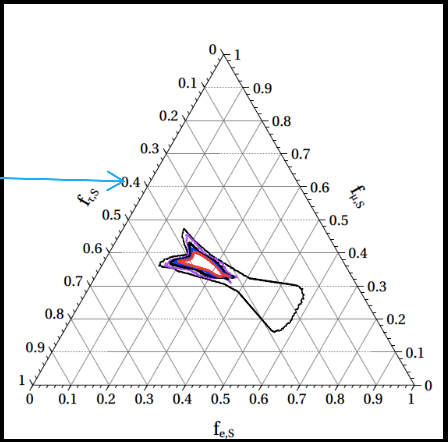
- DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe
- Potentially testable high energy neutrino contribution

Energy neutrino flux



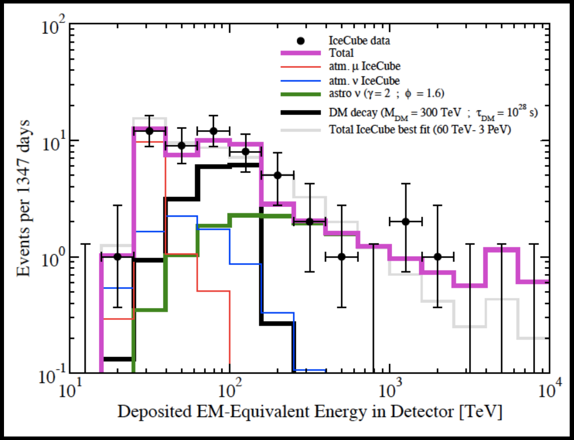
Hard component

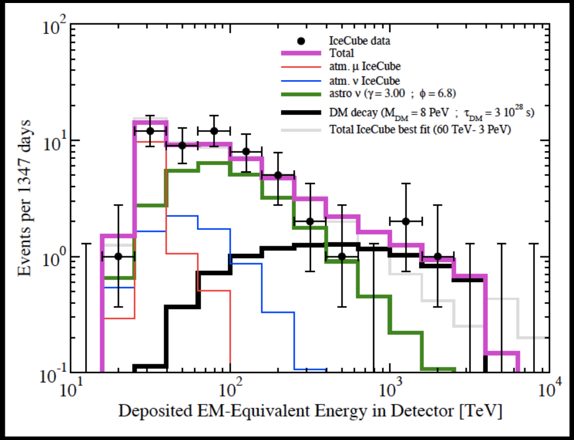
Flavour composition at the detector



Neutrino events at IceCube: 2 examples

M_{DM}=300TeV





M_{DM}=8 PeV

Summary

- High energy scale leptogenesis is the most attractive scenario of baryogenesis if absence of new physics at TeV scale of below will persist

- N_2-dominated scenario provides is naturally realised in SO(10)-inspired models and also to satisfy STRONG THERMAL LEPTOGENESIS

- STRONG SO(10) thermal solution has strong predictive power and current data are in line. Deviation of neutrino masses from the hierarchical limits is expected; despite normal ordering, m_{ee} ~ 15meV might be still within reach; Despite NO neutrinoless double beta decay signal also within reach

- Study of realistic models incorporating leptogenesis started but there is still not a satisfactory model able to fit everything

- SUSY SO(10)-inspired models can be still reconciled with gravitino problem and improve of quark+lepton sectors parameters;

- A unified scenario of DM and resonant leptogenesis can be tested with IceCube high energy neutrino data.

Leptogenesis in the "A2Z model"

(PDB, S.King 2015)

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

Flavour coupling (mainly due to the hypercharge Higgs asymmetry) is then crucial to produce the correct asymmetry:
(Antusch,PDB,Jones,King 2011)

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

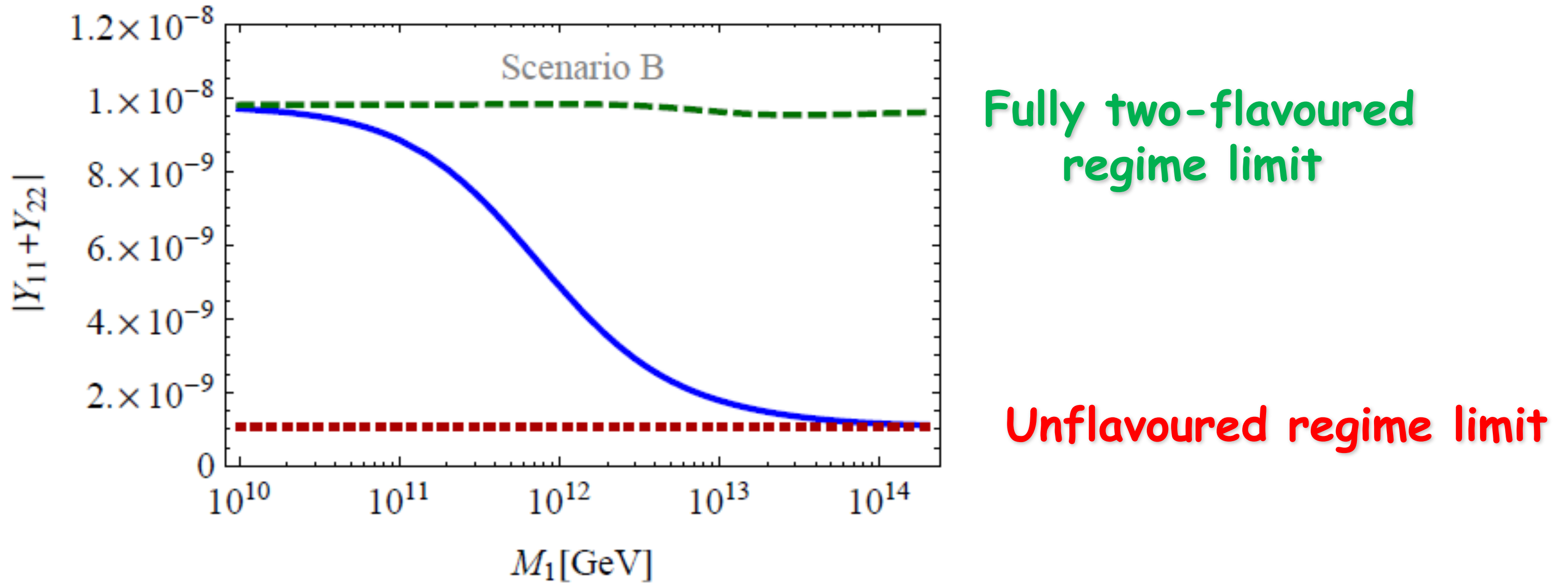
$$\eta_B^{(e)} \simeq -0.01\, \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, \frac{K_{2e}}{K_{2e}+K_{2\mu}}\, C^{(2)}_{\tau^{\perp}\tau}\, e^{-\frac{3\pi}{8}\, K_{1e}}$$

$$\eta_B^{(\mu)} \simeq -\left(\frac{K_{2\mu}}{K_{2e}+K_{2\mu}}\, C^{(2)}_{\tau^{\perp}\tau} - \frac{K_{1\mu}}{K_{1\tau}}\, C^{(3)}_{\mu\tau}\right) e^{-\frac{3\pi}{8}\, K_{1\mu}} .$$

Density matrix and CTP formalism to describe the transition regimes

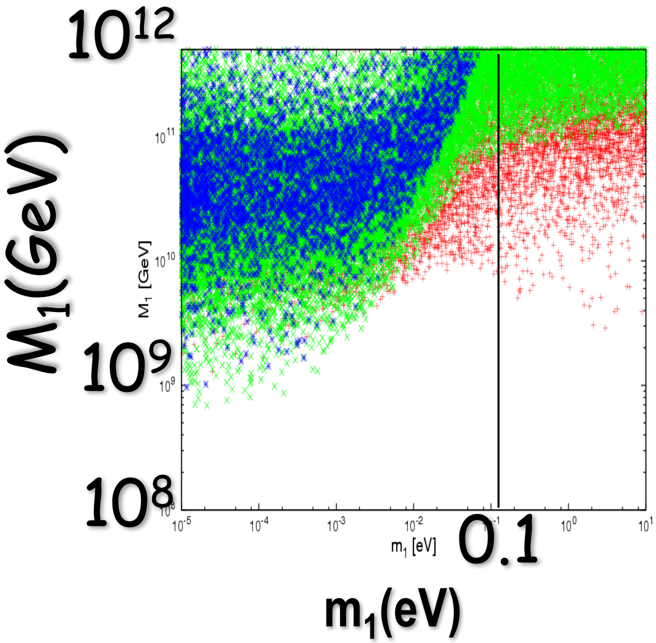
(De Simone, Riotto '06; Beneke, Gabrecht, Fidler, Herranen, Schwaller '10)

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

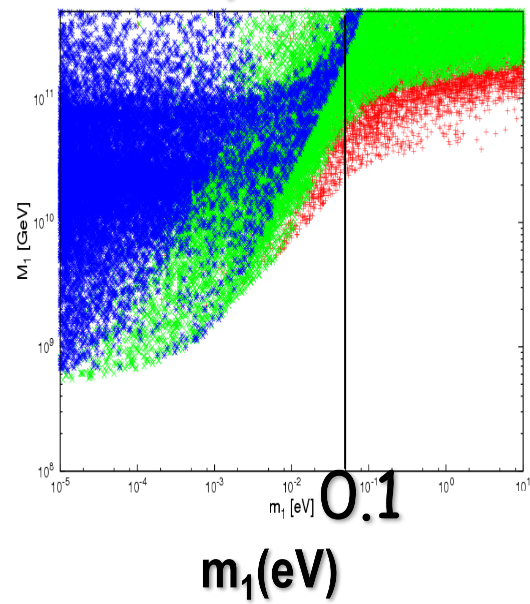


Neutrino mass bounds and role of PMNS phases

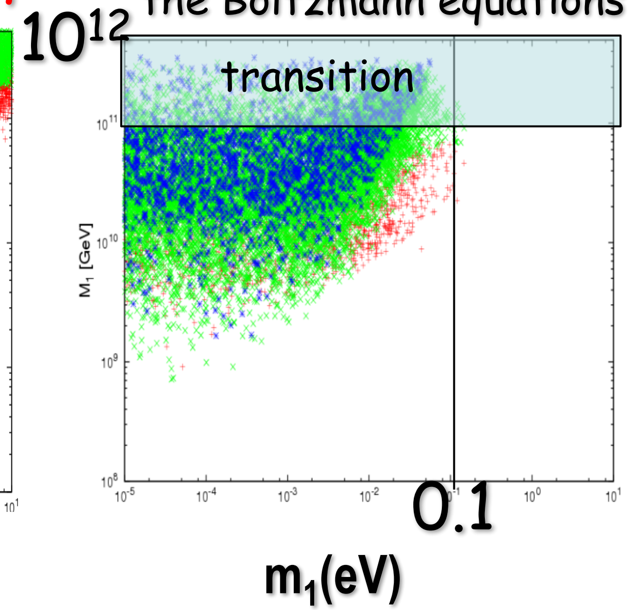
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)

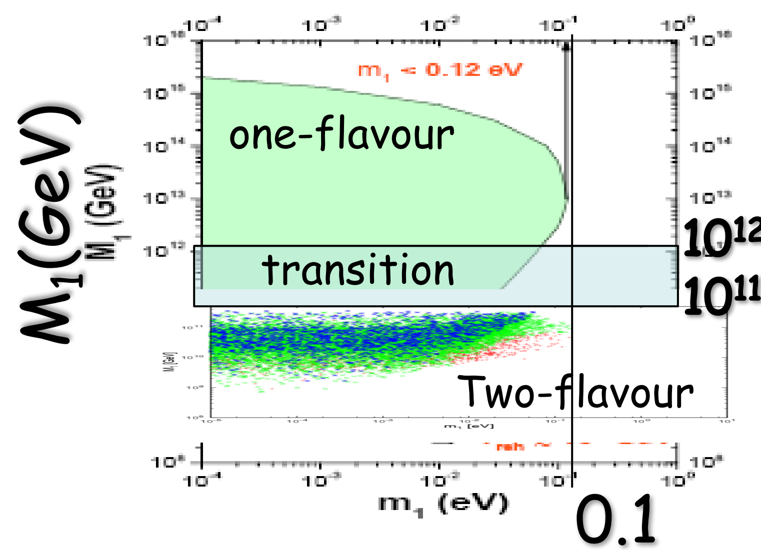


PMNS phases off



Imposing the validity of the Boltzmann equations



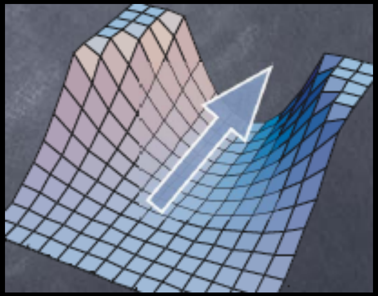


Affleck-Dine Baryogenesis

(Affleck, Dine '85)

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

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

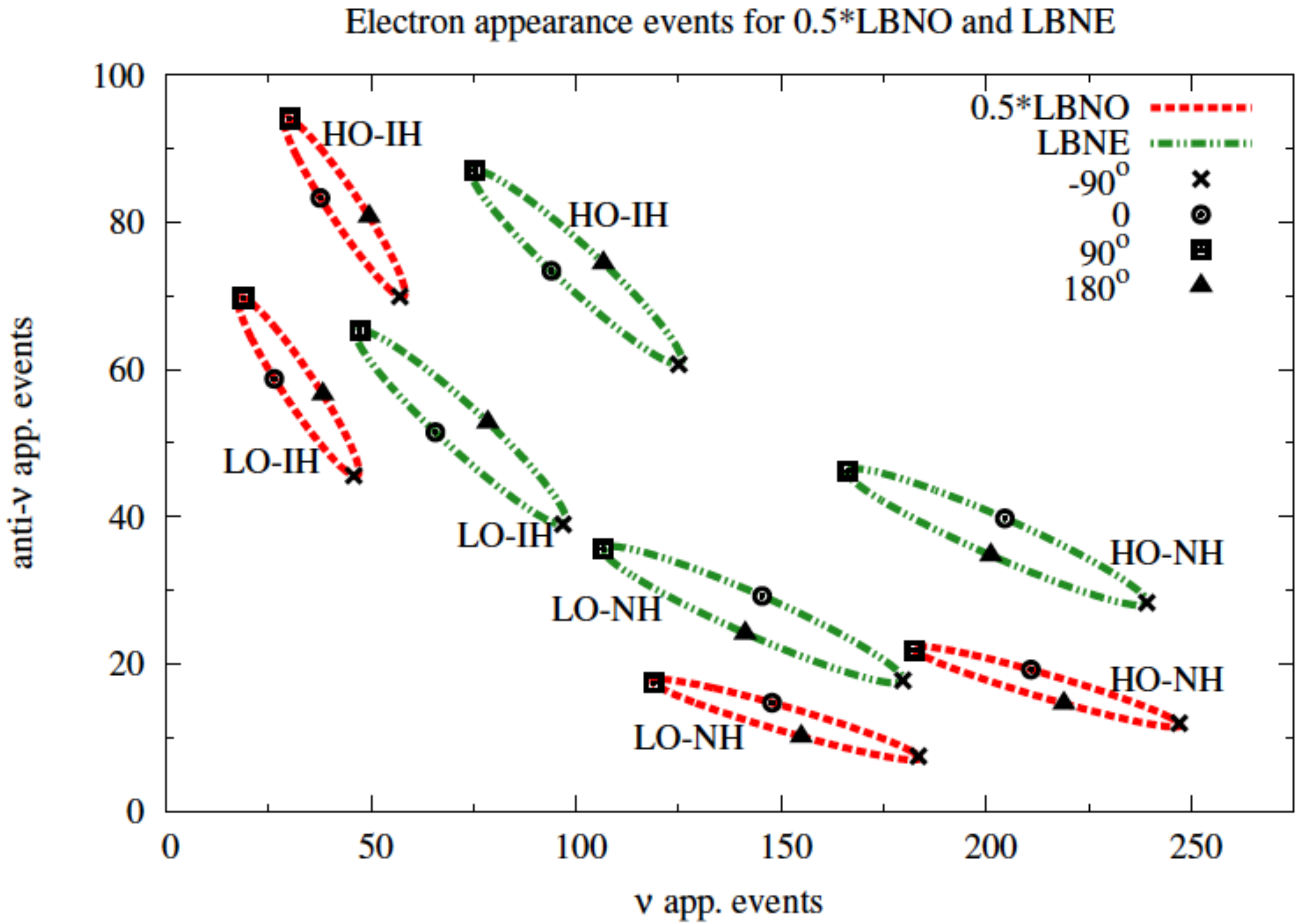


F term D term

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

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

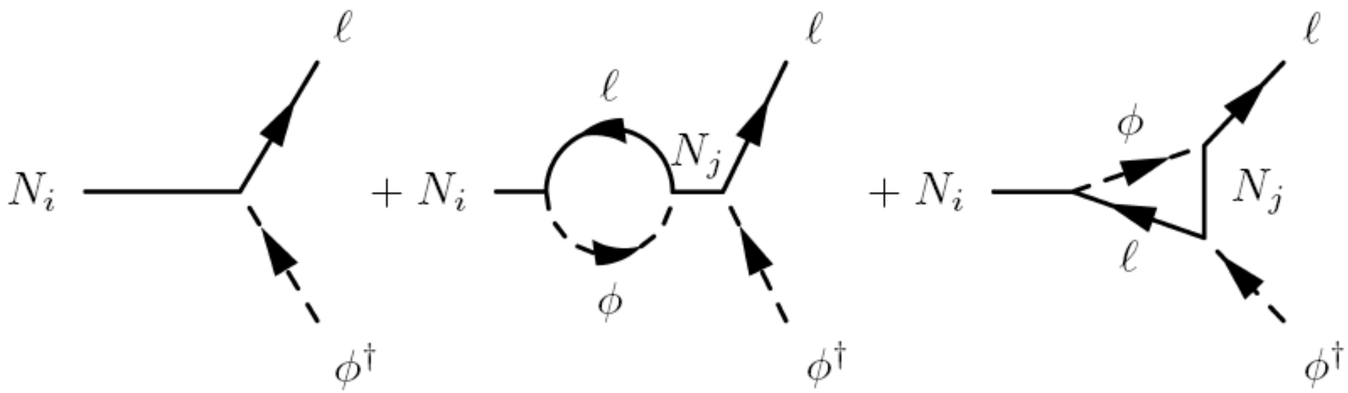
The final asymmetry is 📷 T_{RH} and the observed one can be reproduced for low values T_{RH} ⌿ 10 GeV !



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

Total CP asymmetries

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



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

It does not depend on U !

Additional contribution to CP violation:

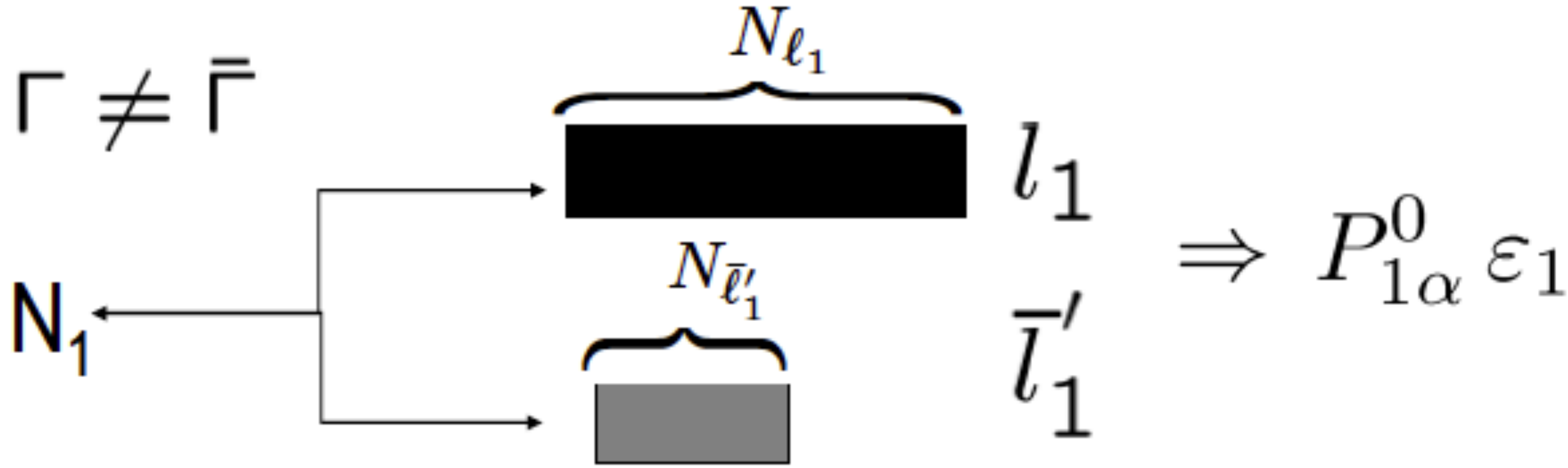
(Nardi, Racker, Roulet '06)

($\alpha = \tau$, e+μ)

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

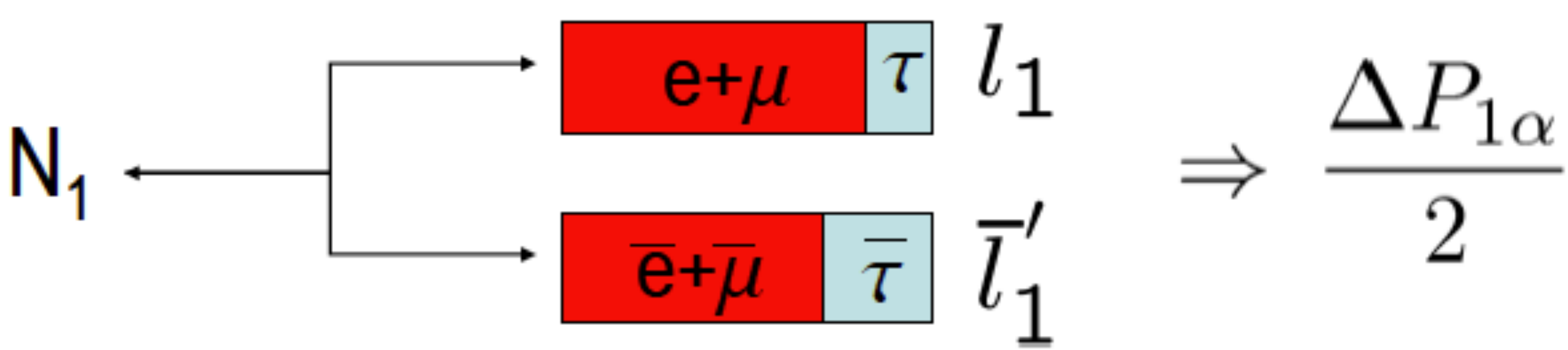
depends on U !

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



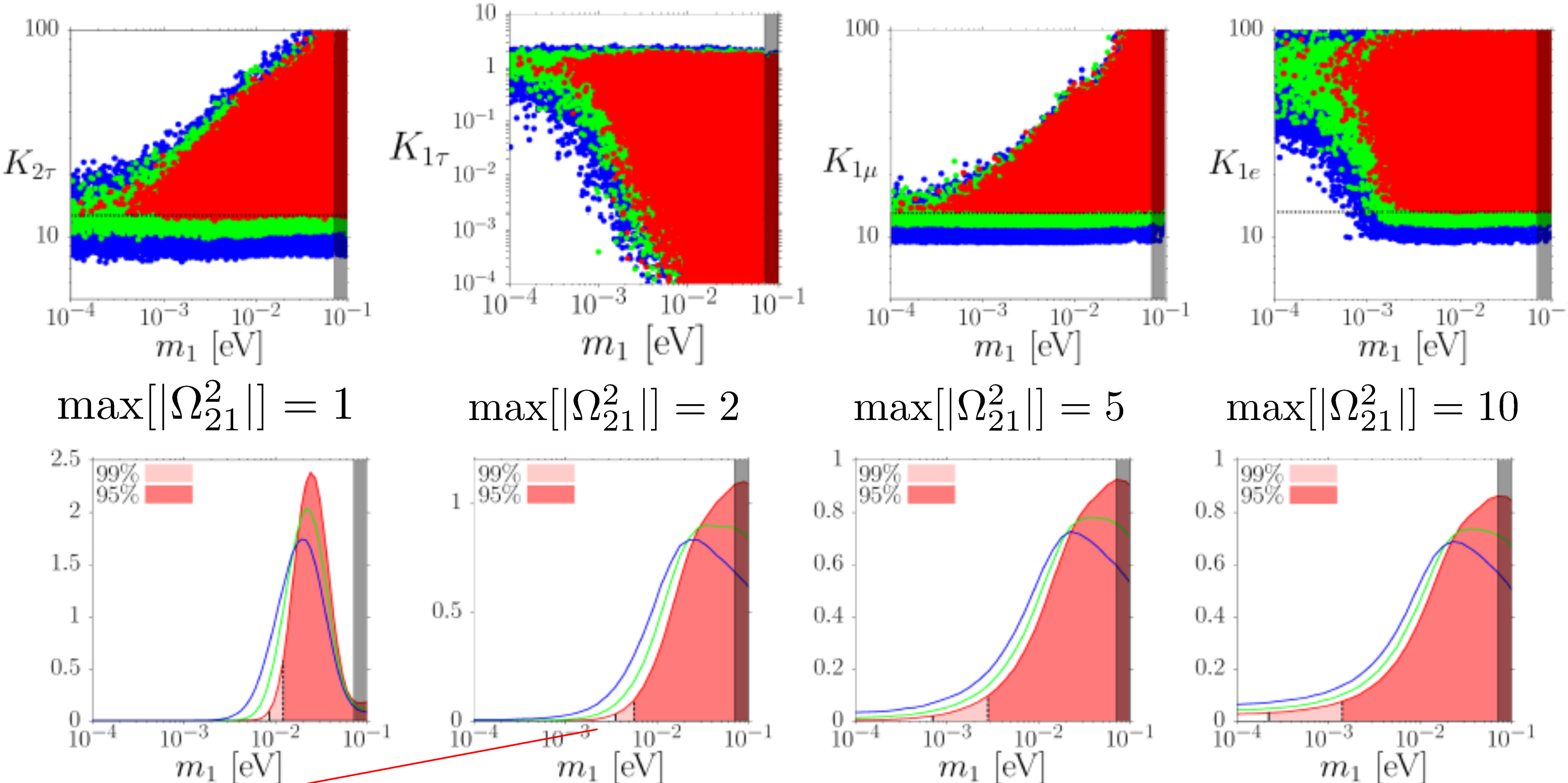
2) $|\bar{l}'_1\rangle \neq CP|l_1\rangle$

+



A lower bound on neutrino masses (IO)

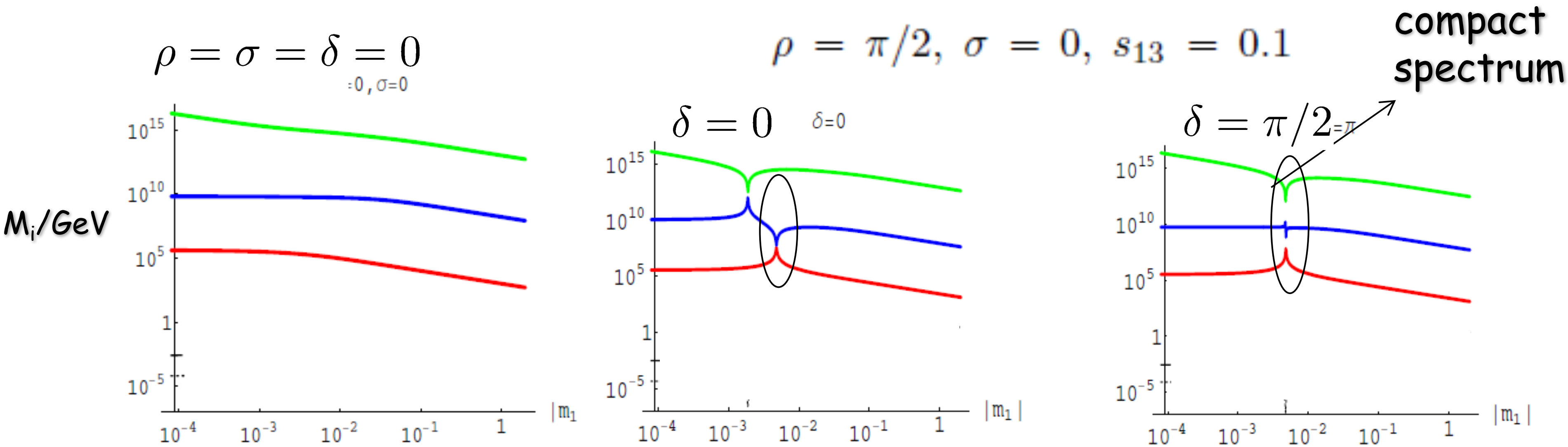
$N^{P,i}_{B-L}$ = 0.001, 0.01, 0.1 $\max[|\Omega^2_{21}|] = 2$ INVERTED ORDERING



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

Crossing level solutions

(Akhmedov, Frigerio, Smirnov hep-ph/0305322)

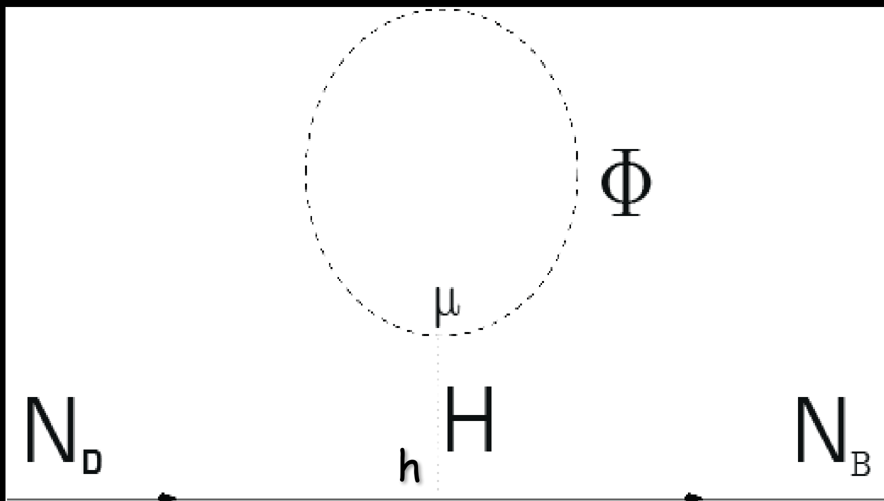


- About the crossing levels the N_1 CP asymmetry is enhanced
- The correct BAU can be attained for a fine tuned choice of parameters: many realistic models have made use of these solutions

(e.g. Ji, Mohapatra,Nasri '10; Buccella, Falcone, Nardi, '12; Altarelli, Meloni '14, Feng, Meloni, Meroni, Nardi '15; Addazi, Bianchi, Ricciardi 1510.00243)

A possible GUT origin

(Anisimov,PDB, 2010, unpublished)



$$\frac{1}{\Lambda_{\text{eff}}} = \frac{h\mu}{M_{\text{GUT}}^2}$$

$$\Lambda_{\text{eff}} >> M_{\text{GUT}}!$$