Lecture III

Leptogenesis:
Minimal scenario,
Flavour effects,
BSM models.

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 decays $N_i \xrightarrow{\Gamma} L_i + \phi^\dagger \qquad N_i \xrightarrow{\overline{\Gamma}} \overline{L}_i + \phi$

total CP asymmetries	$\varepsilon_i \equiv -\dfrac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$

$$\Rightarrow N_{B-L}^{fin} = \sum_{i=1,2,3} \varepsilon_i \times \kappa_i^{fin}$$

κ_i^{fin} → efficiency factors

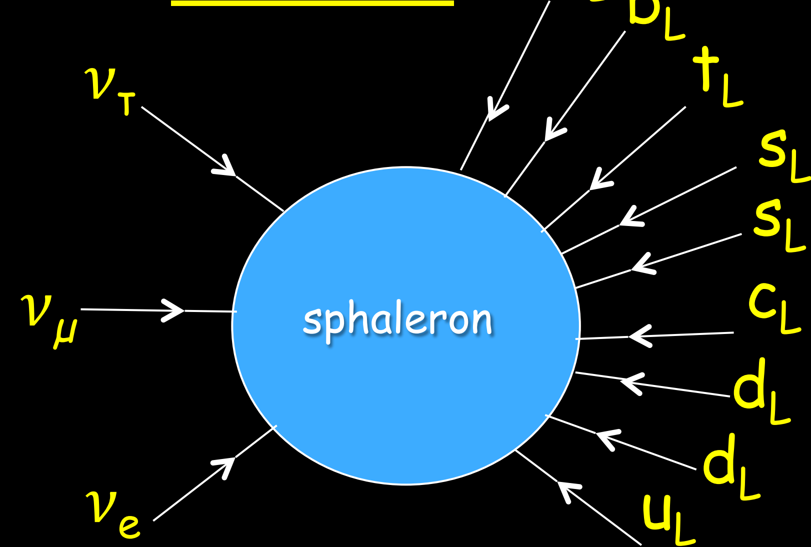
- Sphaleron processes in equilibrium

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

(Kuzmin, Rubakov, Shaposhnikov '85)

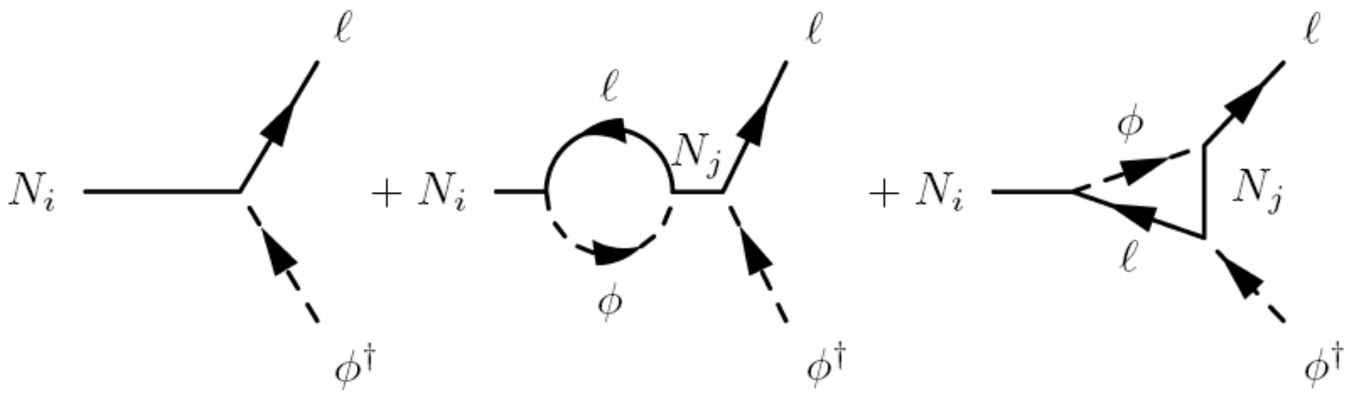
$$\Rightarrow \eta_{B0}^{lep} = \frac{a_{sph} N_{B-L}^{fin}}{N_\gamma^{rec}} \simeq 0.01 N_{B-L}^{fin}$$

ΔB=ΔL=3



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 !

N_1 dominated scenario (N_1 leptogenesis)

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

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

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

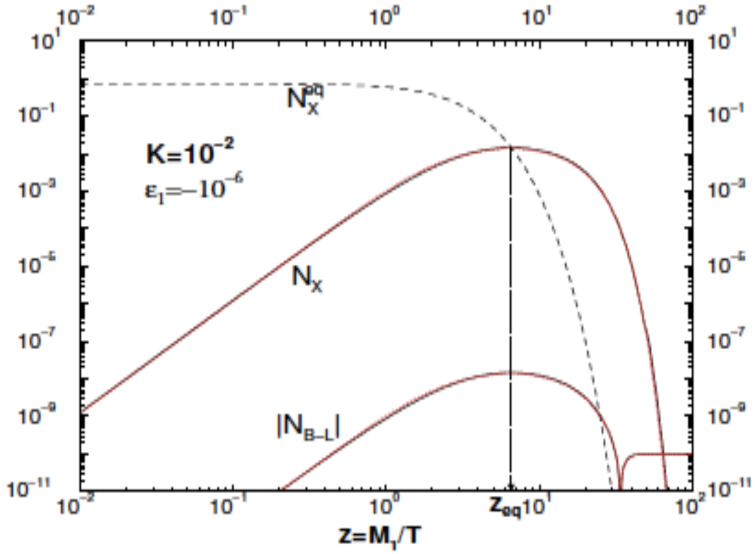
$$D_1 = \frac{\Gamma_{D,1}}{H\,z} = K_1\, z \left\langle \frac{1}{\gamma} \right\rangle , \quad W_{ID} \propto D_1 \propto K_1$$

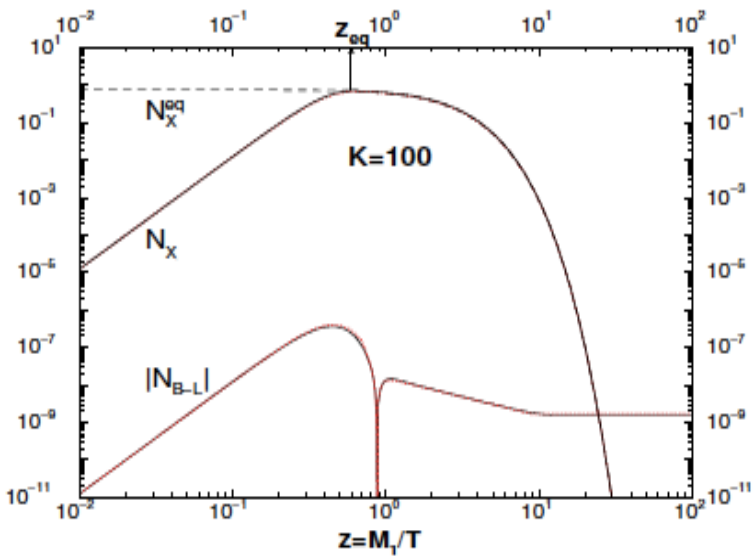
$$N_{B-L}(z; K_1, z_{\rm in}) = N_{B-L}^{\rm in}\, e^{-\int_{z_{\rm in}}^{z} dz'\, W_{ID}(z')} + \varepsilon_1\, \kappa_1(z)$$

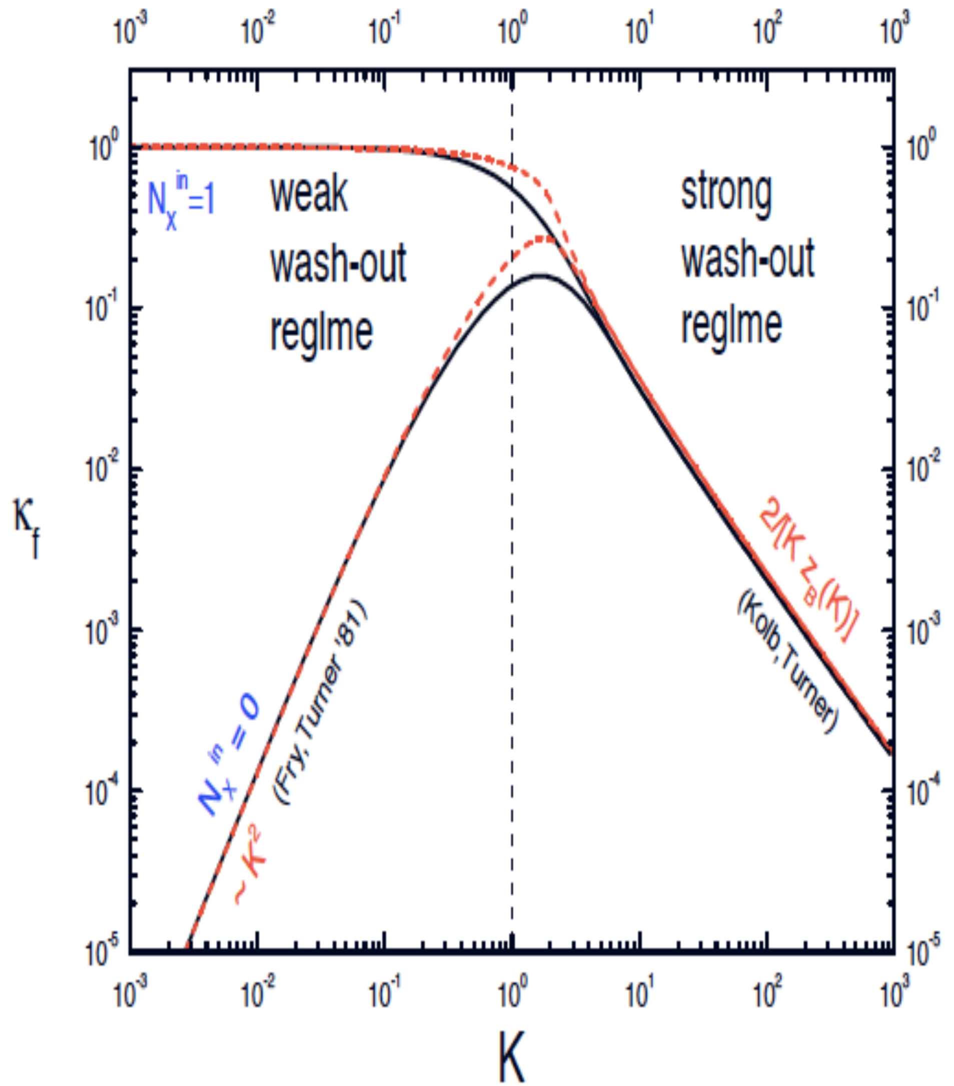
$$\kappa_1(z; K_1, z_{\rm in}) = -\int_{z_{\rm in}}^{z} dz' \left[\frac{dN_{N_1}}{dz'}\right] e^{-\int_{z'}^{z} dz''\, W_{ID}(z'')}$$

- Weak wash-out regime for $K_1 \lesssim 1$ (out-of-equilibrium picture recovered for $K_1 \rightarrow 0$)
- Strong wash-out regime for $K_1 \gtrsim 1$

Weak and strong wash-out: comparison







Seesaw parameter space

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

Problem: too many parameters

(Casas, Ibarra'01) $m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow$ $\Omega^T \Omega = I$ 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 but no signs so far of new physics at the TeV scale (or below) able to address the problem
- ❑ Insisting with high scale leptogenesis is challenging but there are a few strategies able to reduce the number of parameters

Vanilla leptogenesis ⇒ upper bound on ν masses

(Buchmüller, PDB, Plümacher '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: $K_1 \equiv \frac{\Gamma_{N_1}(T=0)}{H(T=M_1)}$

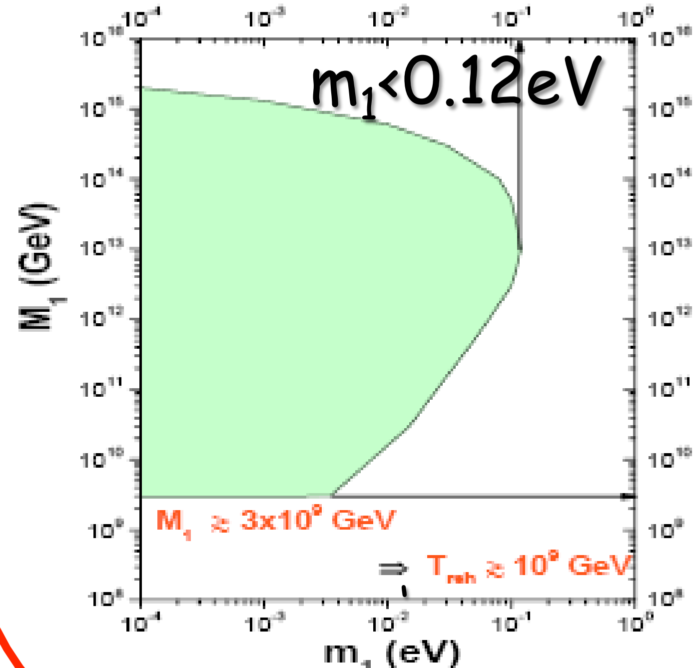
All the asymmetry is generated by the lightest RH neutrino

4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

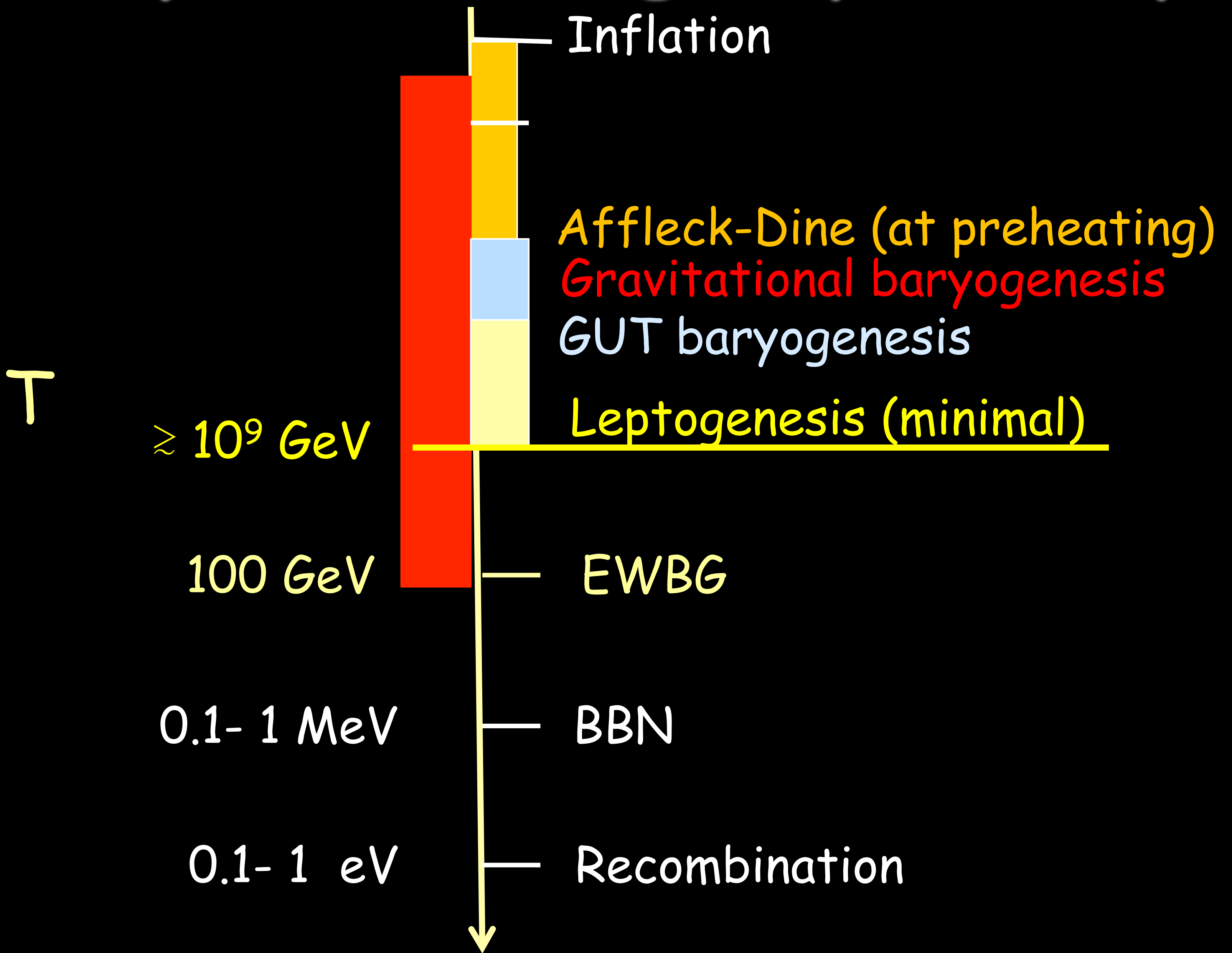
$$\varepsilon_1 \leq \varepsilon_1^{\max} \simeq 10^{-6} \left(\frac{M_1}{10^{10}\,\mathrm{GeV}}\right) \frac{m_{atm}}{m_1 + m_3}$$

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



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

A pre-existing asymmetry?

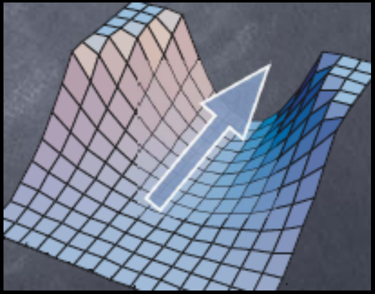


Affleck-Dine Baryogenesis

(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 !

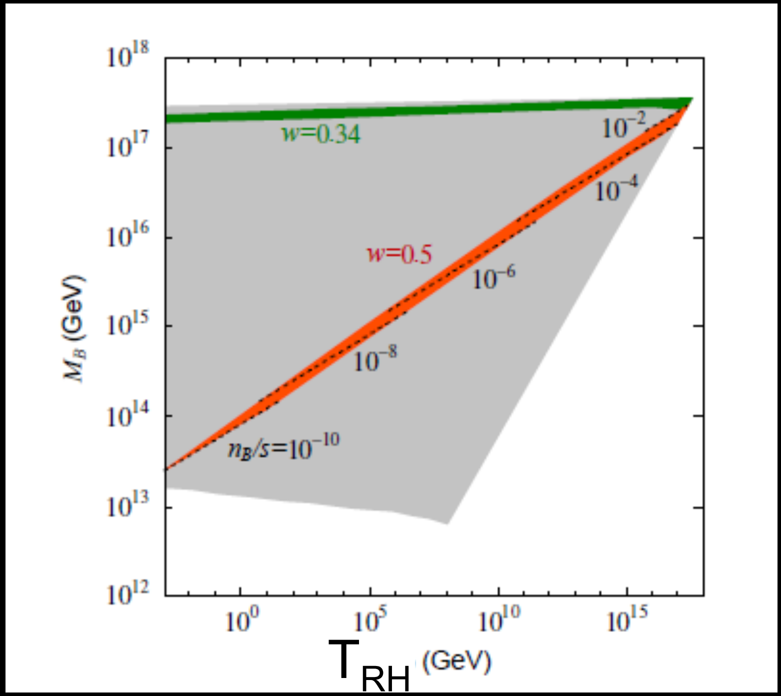
Gravitational Baryogenesis

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

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

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

Cutoff scale of the effective theory



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 $T_{RH} \gg 100$ GeV

Independence of the initial conditions (strong thermal leptogenesis)

(Buchmüller, PDB, Plümacher '04)

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

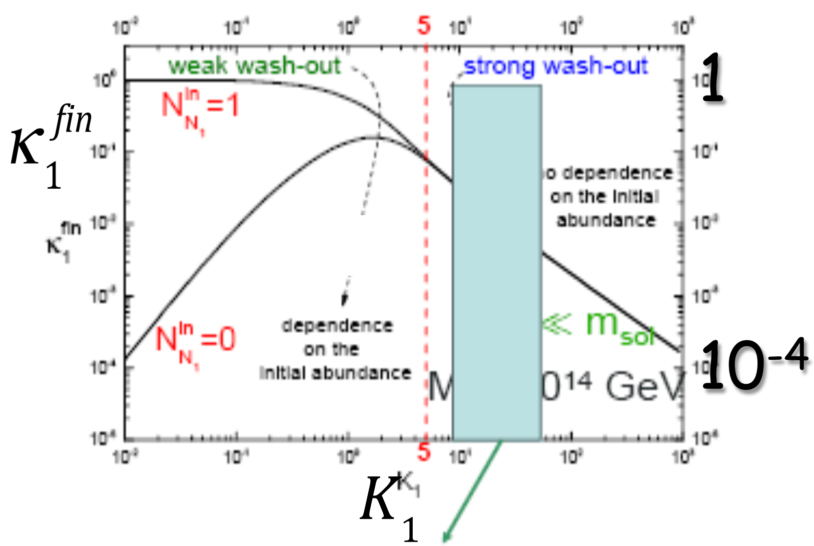
$$N_{B-L}^{\rm p,final} = N_{B-L}^{\rm p,initial}\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1}$$

Just a coincidence?

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

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

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)

$$m_D = V_L^\dagger \, D_{m_D} \, U_R$$

$$D_{m_D} = \mathrm{diag}\{m_{D1}, m_{D2}, m_{D3}\}$$

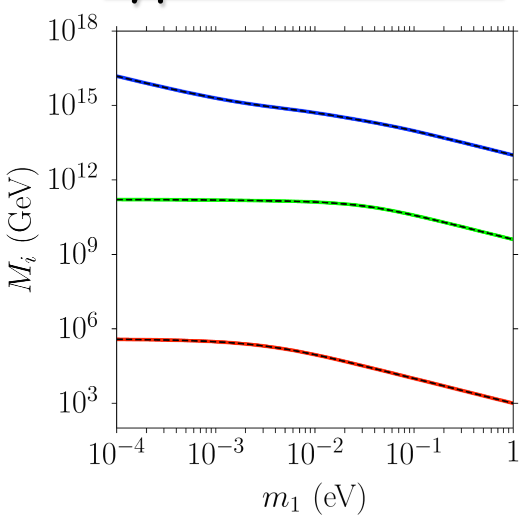
SO(10)-inspired conditions:

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



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

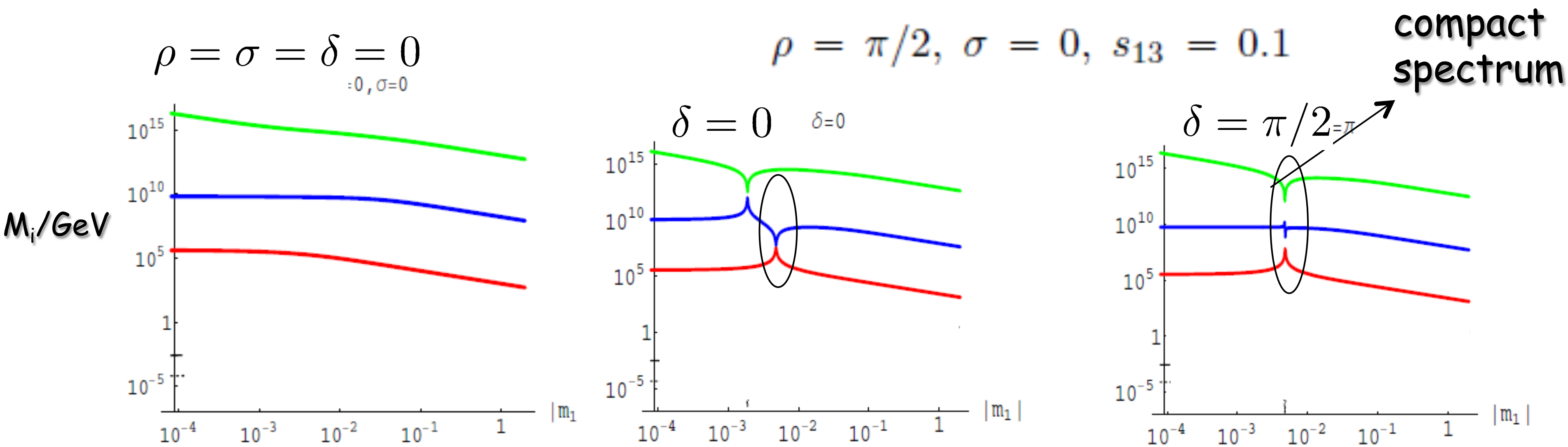
RULED OUT ?

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

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

Crossing level solutions

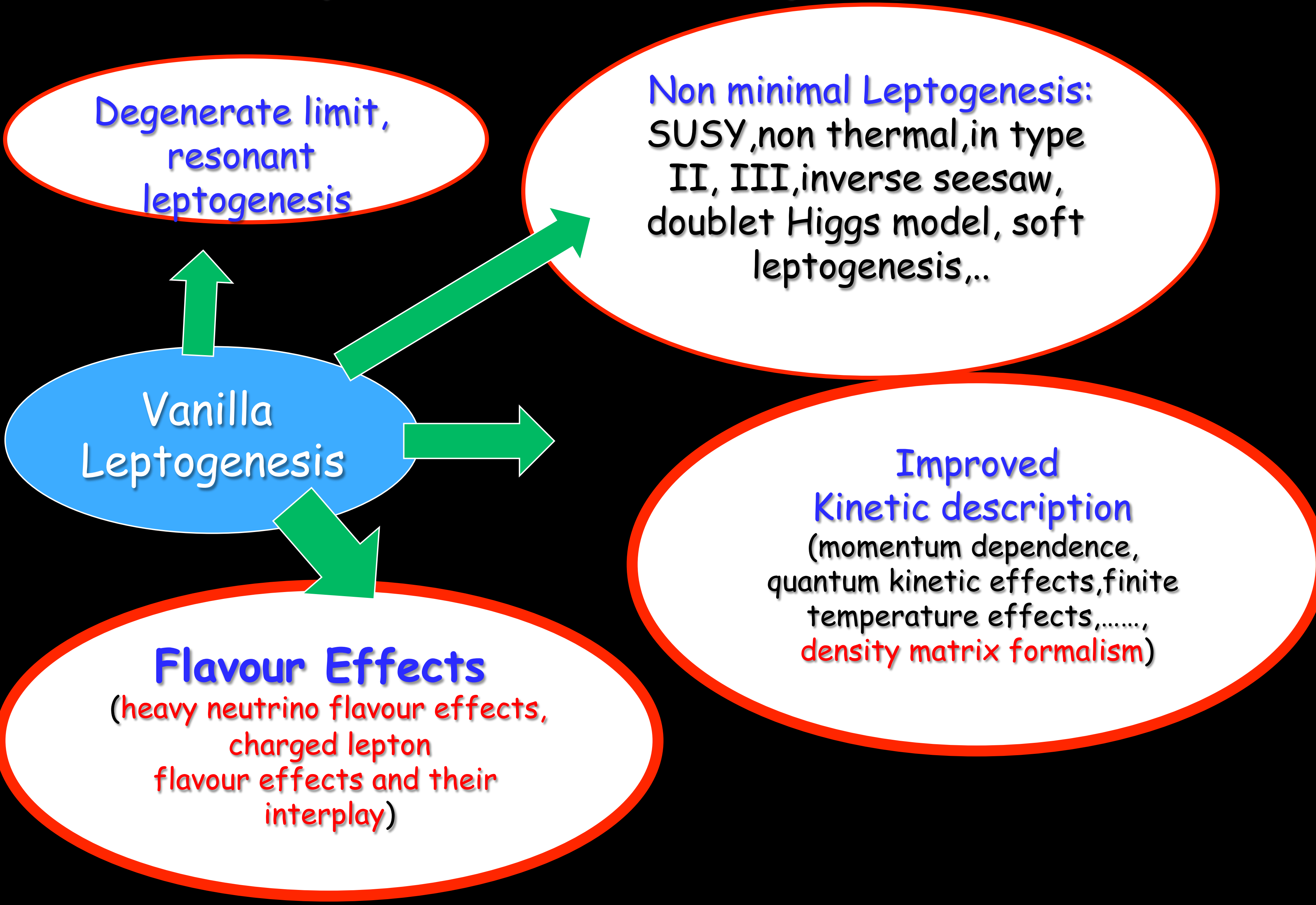
(Akhmedov, Frigerio, Smirnov hep-ph/0305322)



- About the crossing levels the N_1 CP asymmetry is enhanced
- The correct BAU can be attained for a fine tuned choice of parameters but even more importantly these solutions imply huge fine-tuned cancellations in the seesaw formula. 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)

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 << 10^{12} GeV ⇒ τ-Yukawa interactions are fast enough break the coherent evolution of $|l_1\rangle$ and $|\bar{l}'_1\rangle$

⇒ incoherent mixture of a τ and of a μ+e components ⇒ 2-flavour regime

- T << 10^9 GeV then also μ-Yukawas in equilibrium ⇒ 3-flavour regime

M_1

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

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

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

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

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

Two fully flavoured regime

- Classic Kinetic Equations (in their simplest form)

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

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

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

(α = τ, e+μ)

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

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

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

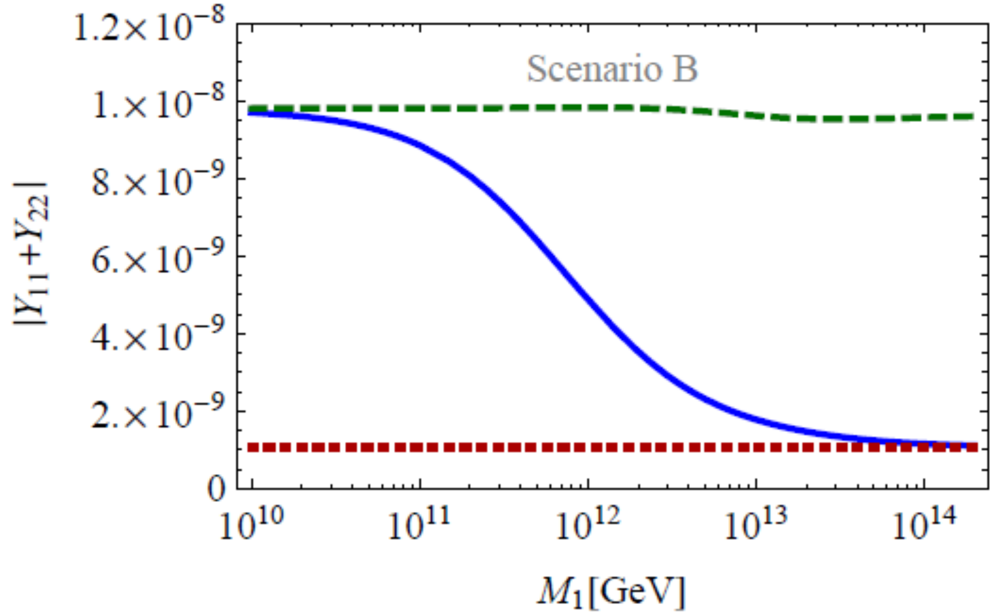
$$\Rightarrow N_{B-L}^{\rm fin} = \sum_\alpha \varepsilon_{1\alpha}\,\kappa_{1\alpha}^{\rm fin} \simeq 2\,\varepsilon_1\,\kappa_1^{\rm fin} + \frac{\Delta P_{1\alpha}}{2}\left[\kappa^{\rm f}(K_{1\alpha}) - \kappa^{\rm fin}(K_{1\beta})\right]$$

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

Density matrix formalism to describe the transition regimes

(De Simone, Riotto '06; Beneke, Gabrecht, Fidler, Herranen, Schwaller '10, Blanchet,PDB,Jones,Marzola '11)

$$\frac{dN^{B-L}_{\alpha\beta}}{dz} = \varepsilon^{(1)}_{\alpha\beta}\, D_1\,(N_{N_1} - N^{\rm eq}_{N_1}) - \frac{1}{2}\, W_1\, \{\mathcal{P}^{0(1)}, N^{B-L}\}_{\alpha\beta} - \frac{{\rm Im}(\Lambda_\tau)}{H\, z}(\sigma_1)_{\alpha\beta}\, N^{B-L}_{\alpha\beta}\ ,$$



Fully two-flavoured regime limit

Unflavoured regime limit

Three main implications of flavour effects

- Lower bound on M_1 (an therefore on T_{RH}) is <u>not</u> relaxed
  upper bound on m_1 is slightly relaxed to ~0.2eV

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

- 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 would vanish!
  So one needs quite a special Ω

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

General considerations:

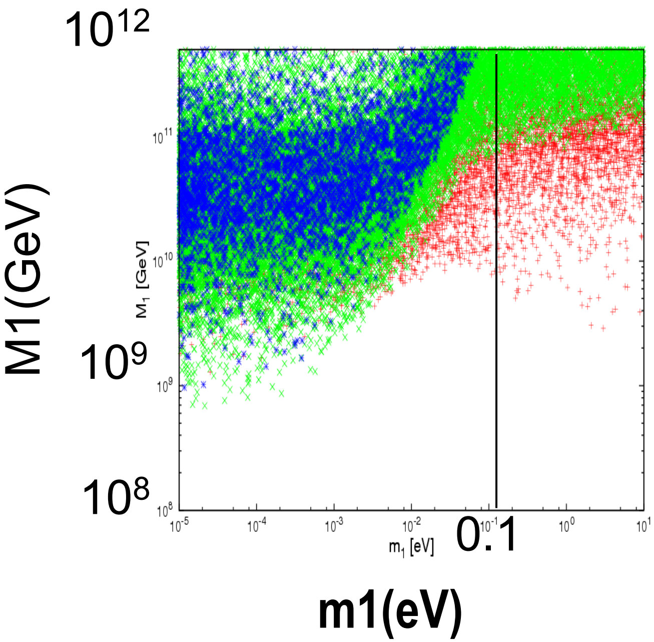
- CP violating value of δ is strictly speaking neither necessary nor sufficient condition for successful leptogenesis and no specific value is favoured model independently but….

- ….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!):

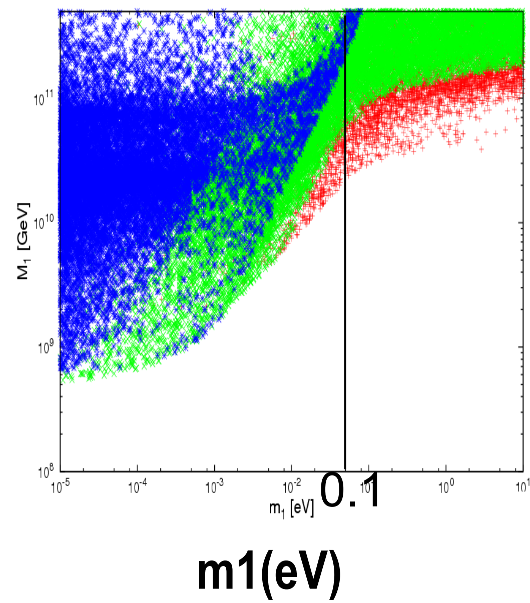
  discovering CP violating value of δ would support a complex m_D

Neutrino mass bounds and role of PMNS phases

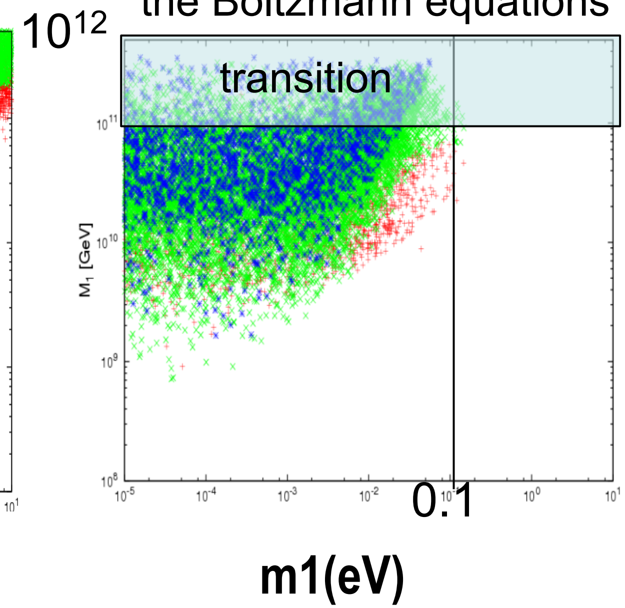
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)

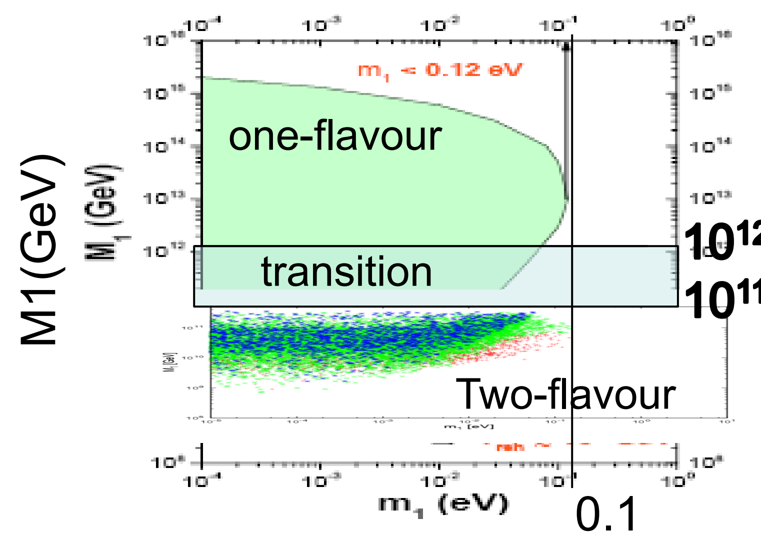


PMNS phases off



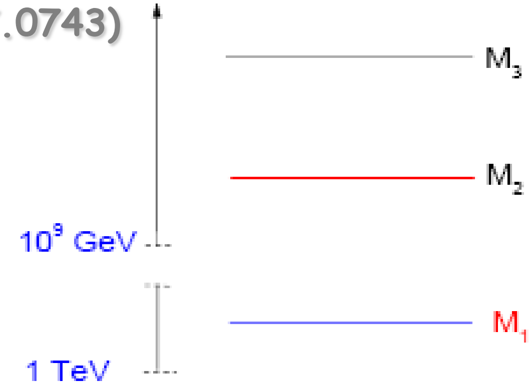
Imposing the validity of the Boltzmann equations





The N_2-dominated scenario

(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

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

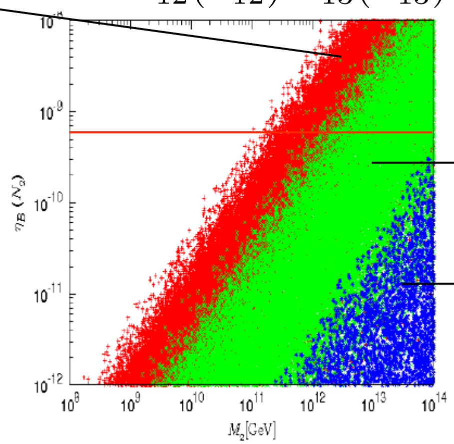
- Adding flavour effects: lighest RH neutrino wash-out acts on individual flavour ⇒ much weaker

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

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

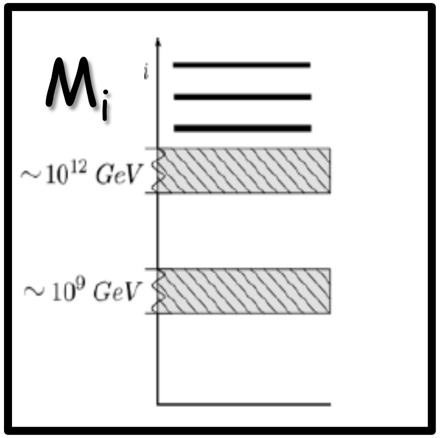
- With flavor effects the domain of successful N_2 dominated leptogenesis greatly enlarges
- Existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$'s not to be negligible

Heavy neutrino lepton flavour effects: 10 hierarchical scenarios

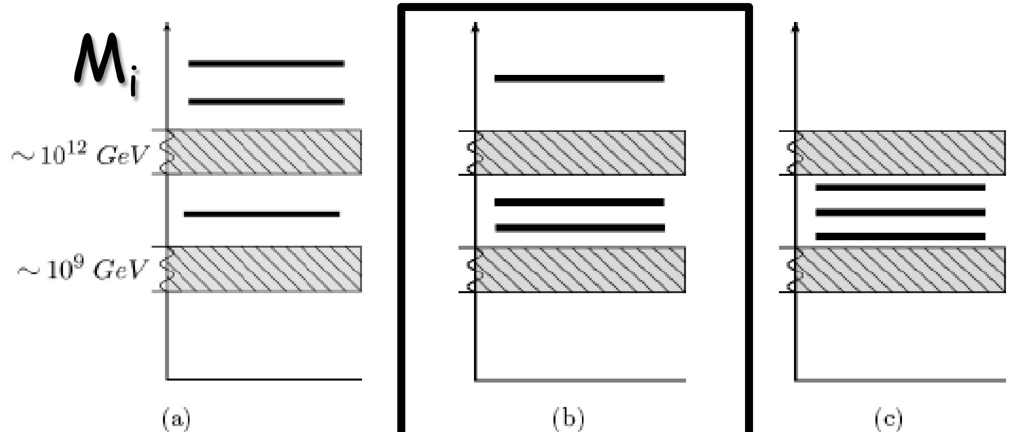
(Bertuzzo, PDB, Marzola, 1007.1641)

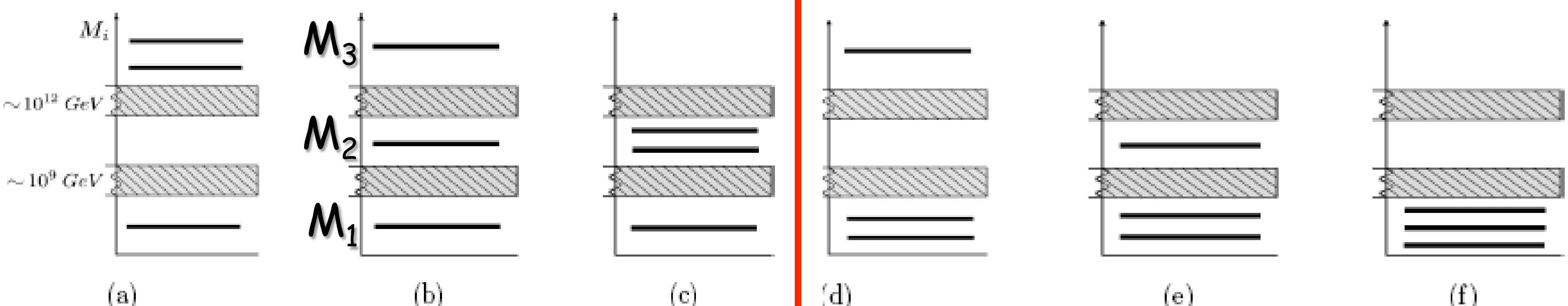
Typically rising in discrete symmetries flavour Models

Heavy neutrino flavored scenario



2 RH neutrino scenario





N_2 -dominated scenario:

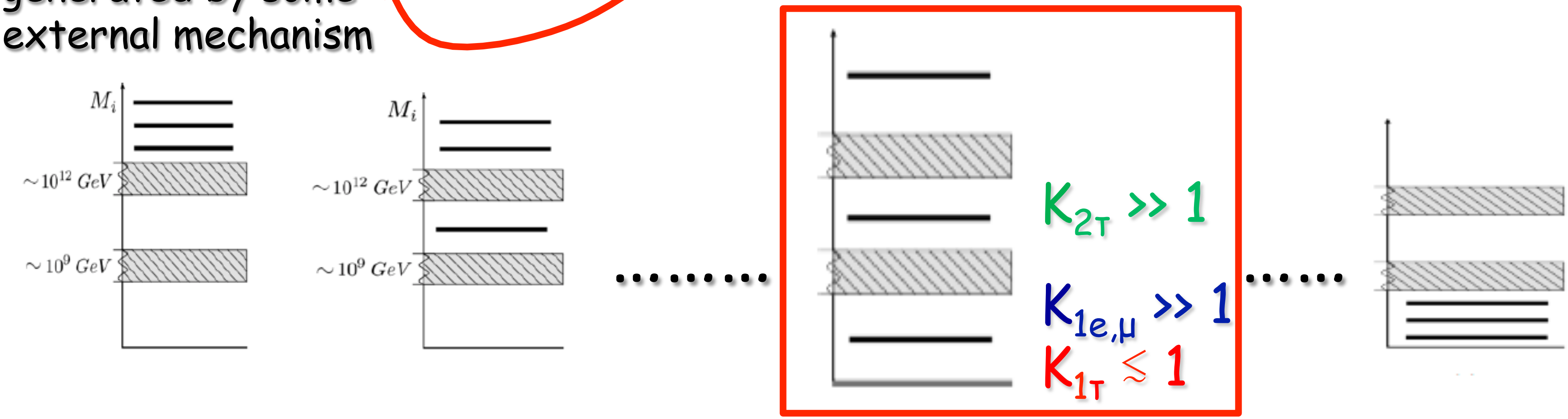
- N_1 produces negligible asymmetry;
- It emerges naturally in SO(10)-inspired models;
- It is the only one that can realise STRONG THERMAL LEPTOGENESIS

The problem of the initial conditions in flavoured leptogenesis

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

Residual "pre-existing" asymmetry possibly generated by some external mechanism ($N^{\rm p,f}_{B-L}$)

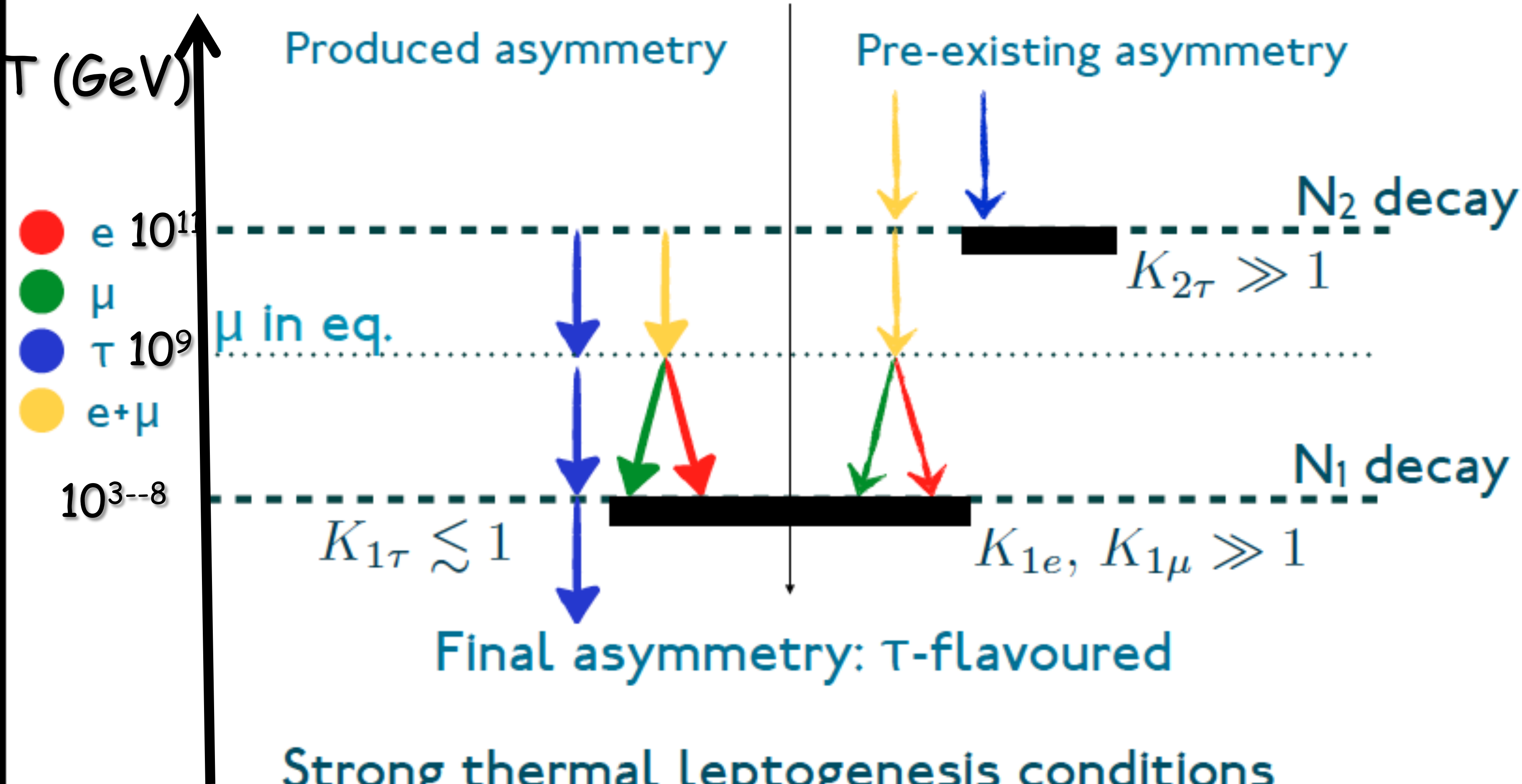
Asymmetry generated from leptogenesis ($N^{\rm lep,f}_{B-L}$)



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

(Bertuzzo,PDB,Marzola '10)

How is STL realised? - A cartoon



Strong thermal leptogenesis conditions

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

Courtesy of Michele Re Fiorentin

A lower bound on neutrino masses (NO)

(PDB, Sophie King, Michele Re Fiorentin 2014)

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

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

Starting from the flavoured decay parameters:

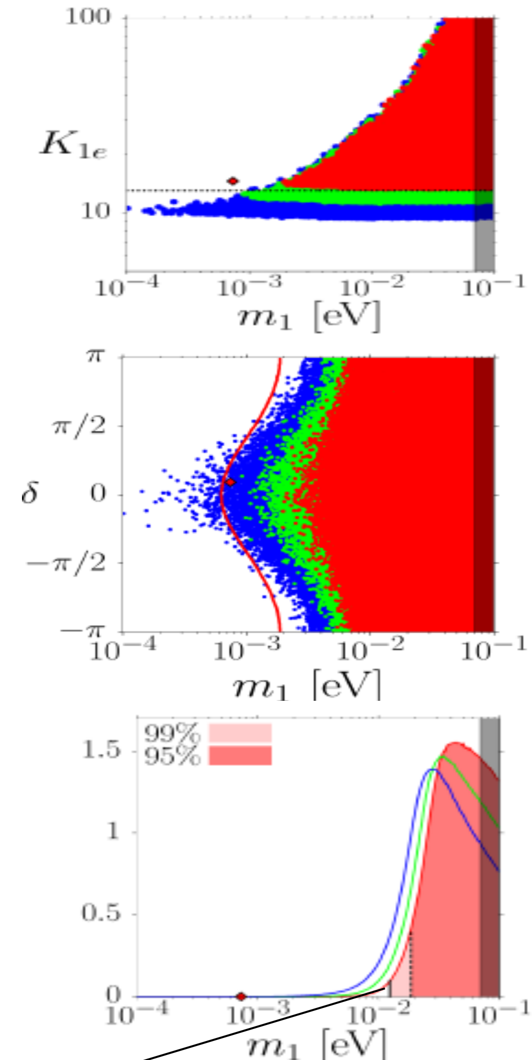
$$K_{i\beta} \equiv p^0_{i\beta}\, K_i = \left|\sum_k \sqrt{\frac{m_k}{m_\star}}\, U_{\beta k}\, \Omega_{ki}\right|^2$$

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

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

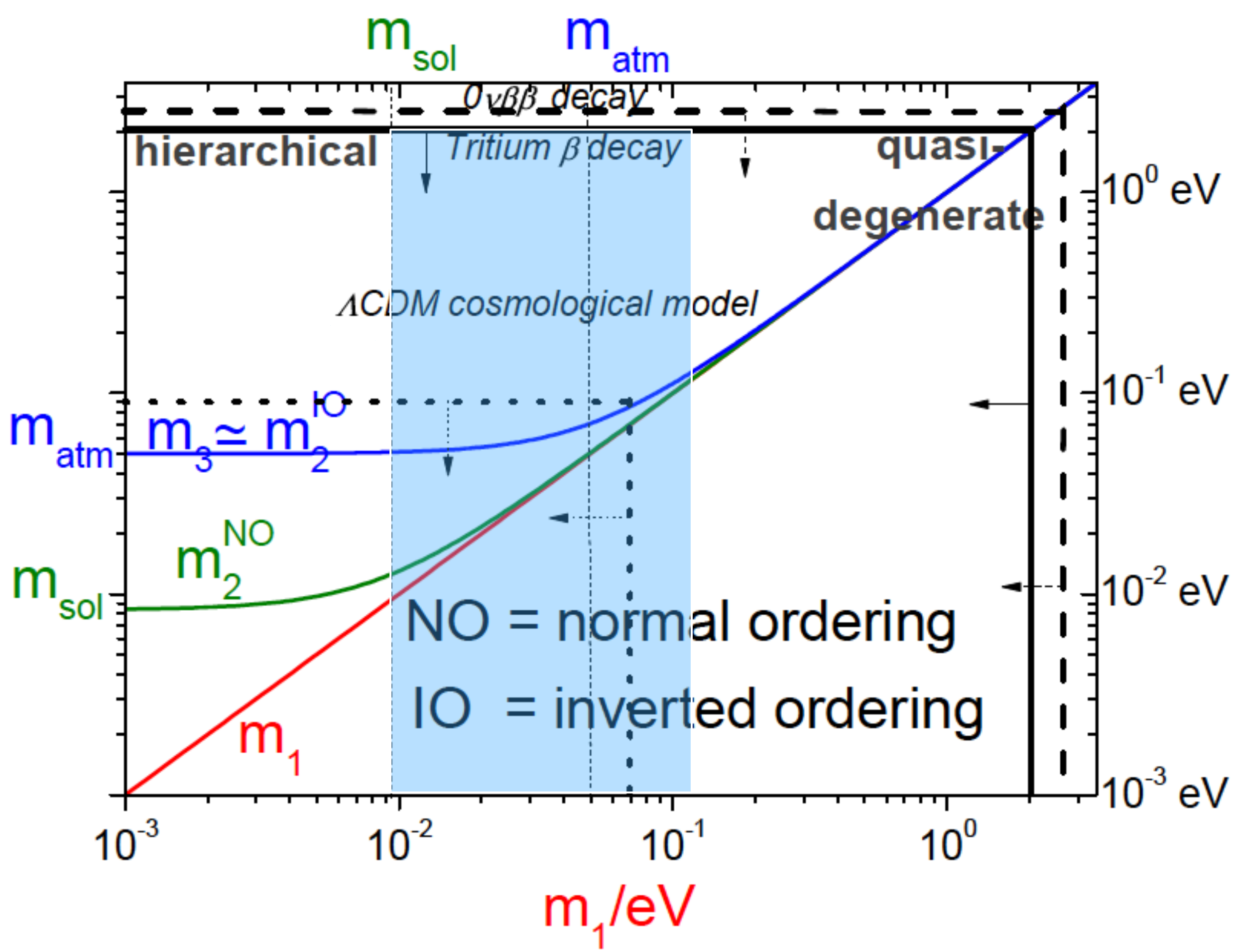
$$K^{0,\max}_{1\alpha} \equiv \left(\max[|\Omega_{21}|]\,\sqrt{\frac{m_{\rm sol}}{m_\star}}\,\left|U_{\alpha 2} - \frac{U_{\tau 2}}{U_{\tau 3}}\,U_{\alpha 3}\right| + \left|\frac{U_{\alpha 3}}{U_{\tau 3}}\right|\,\sqrt{K^{\max}_{1\tau}}\right)^2$$

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



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

A new neutrino mass window for leptogenesis



$0.01\ \mathrm{eV} \lesssim m_1 \lesssim 0.1\ \mathrm{eV}$ (NO)

SO(10)-inspired leptogenesis

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

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

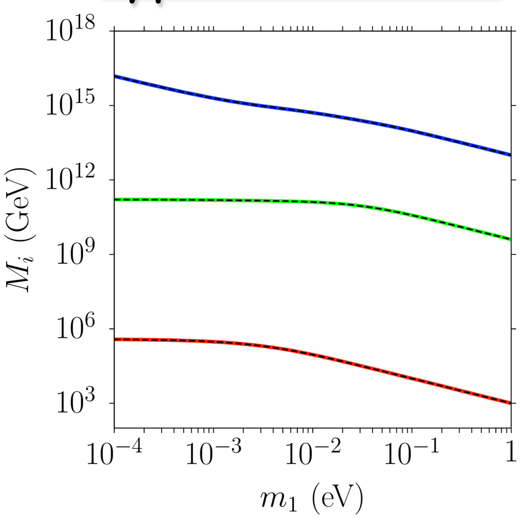
SO(10)-inspired conditions:

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



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

RULED OUT ?

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

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

Imposing SO(10)-inspired conditions

Seesaw formula $m_\nu = -m_D \frac{1}{D_M} m_D^T \, .$

light neutrino mass matrix (flavour basis) $m_\nu = -U D_m U^T$

Biunitary parameterisation $m_D = V_L^\dagger \, D_{m_D} \, U_R$

SO(10)-inspired conditions: $m_D \sim m_{\text{up quarks}}$

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

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

Majorana mass matrix (in the Yukawa basis)

A diagonalization problem:

$$U_R^\star \, D_M \, U_R^\dagger = M = D_{m_D} \, V_L^\star \, U^\star \, D_m^{-1} \, U^\dagger \, V_L^\dagger \, D_{m_D} = -D_{m_D} \tilde{m}_\nu^{-1} D_{m_D}$$

The predicted baryon asymmetry of the Universe from SO(10)-inspired leptogenesis

Right-handed neutrino masses

$$
\begin{aligned}
M_1 &\simeq \frac{\alpha_1^2\, m_{\rm u}^2}{|(\widetilde{m}_\nu)_{11}|}\,, \\
M_2 &\simeq \frac{\alpha_2^2\, m_{\rm c}^2}{m_1\, m_2\, m_3}\, \frac{|(\widetilde{m}_\nu)_{11}|}{|(\widetilde{m}_\nu^{-1})_{33}|}\,, \\
M_3 &\simeq \alpha_3^2\, m_{\rm t}^2\, |(\widetilde{m}_\nu^{-1})_{33}|\,,
\end{aligned}
$$

$$
V_L = \begin{pmatrix}
c^L_{12}\, c^L_{13} & s^L_{12}\, c^L_{13} & s^L_{13}\, e^{-{\rm i}\,\delta_L} \\
-s^L_{12}\, c^L_{23} - c^L_{12}\, s^L_{23}\, s^L_{13}\, e^{{\rm i}\,\delta_L} & c^L_{12}\, c^L_{23} - s^L_{12}\, s^L_{23}\, s^L_{13}\, e^{{\rm i}\,\delta_L} & s^L_{23}\, c^L_{13} \\
s^L_{12}\, s^L_{23} - c^L_{12}\, c^L_{23}\, s^L_{13}\, e^{{\rm i}\,\delta_L} & -c^L_{12}\, s^L_{23} - s^L_{12}\, c^L_{23}\, s^L_{13}\, e^{{\rm i}\,\delta_L} & c^L_{23}\, c^L_{13}
\end{pmatrix} {\rm diag}\left(e^{i\,\rho_L}, 1, e^{i\,\sigma_L}\right)
$$

Right-handed neutrino phases and mixing matrix

$$
\begin{aligned}
\Phi_1 &= {\rm Arg}[-\widetilde{m}^\star_{\nu 11}]\,, \\
\Phi_2 &= {\rm Arg}\left[\frac{\widetilde{m}_{\nu 11}}{(\widetilde{m}_\nu^{-1})_{33}}\right] - 2\,(\rho+\sigma) - 2\,(\rho_L+\sigma_L)\,, \\
\Phi_3 &= {\rm Arg}[-(\widetilde{m}_\nu^{-1})_{33}]\,,
\end{aligned}
$$

$$
D_\phi \equiv {\rm diag}(e^{-i\,\frac{\Phi_1}{2}}, e^{-i\,\frac{\Phi_2}{2}}, e^{-i\,\frac{\Phi_3}{2}})\,,
$$

$$
U_R \simeq \begin{pmatrix}
1 & -\frac{m_{D1}}{m_{D2}}\,\frac{\widetilde{m}^\star_{\nu 12}}{\widetilde{m}^\star_{\nu 11}} & \frac{m_{D1}}{m_{D3}}\,\frac{(\widetilde{m}_\nu^{-1})^\star_{13}}{(\widetilde{m}_\nu^{-1})^\star_{33}} \\
\frac{m_{D1}}{m_{D2}}\,\frac{\widetilde{m}_{\nu 12}}{\widetilde{m}_{\nu 11}} & 1 & \frac{m_{D2}}{m_{D3}}\,\frac{(\widetilde{m}_\nu^{-1})^\star_{23}}{(\widetilde{m}_\nu^{-1})^\star_{33}} \\
\frac{m_{D1}}{m_{D3}}\,\frac{\widetilde{m}_{\nu 13}}{\widetilde{m}_{\nu 11}} & -\frac{m_{D2}}{m_{D3}}\,\frac{(\widetilde{m}_\nu^{-1})_{23}}{(\widetilde{m}_\nu^{-1})_{33}} & 1
\end{pmatrix} D_\Phi\,,
$$

The predicted baryon asymmetry of the Universe from SO(10)-inspired leptogenesis

Flavoured decay parameters and CP asymmetries

$$K_{i\alpha} = \frac{\sum_{k,l} m_{Dk}\, m_{Dl}\, V_{Lk\alpha}\, V^{\star}_{Ll\alpha}\, U^{\star}_{Rki}\, U_{Rli}}{M_i\, m_{\star}}$$

Efficiency factors At the production

$$\kappa(K_{i\alpha}) \simeq \frac{2}{K_{i\alpha}\, z_{\rm B}(K_{i\alpha})}\left[1 - \exp\left(-\frac{1}{2}K_{i\alpha}\, z_{\rm B}(K_{i\alpha})\right)\right]$$

Final flavoured (B/3 – Lα) asymmetries

$$\begin{aligned}
N_{\Delta_e}^{\rm lep,f} &\simeq \varepsilon_{2e}\,\kappa(K_{2e}+K_{2\mu})\, e^{-\frac{3\pi}{8}K_{1e}}\,,\\
N_{\Delta_\mu}^{\rm lep,f} &\simeq \varepsilon_{2\mu}\,\kappa(K_{2e}+K_{2\mu})\, e^{-\frac{3\pi}{8}K_{1\mu}}\,,\\
N_{\Delta_\tau}^{\rm lep,f} &\simeq \varepsilon_{2\tau}\,\kappa(K_{2\tau})\, e^{-\frac{3\pi}{8}K_{1\tau}}\,,
\end{aligned}$$

Flavoured CP asymmetries

$$\varepsilon_{2\alpha} \simeq \frac{3}{16\,\pi\, v^2}\,\frac{|(\widetilde{m}_\nu)_{11}|}{m_1\, m_2\, m_3}\,\frac{\sum_{k,l} m_{Dk}\, m_{Dl}\, {\rm Im}[V_{Lk\alpha}\, V^{\star}_{Ll\alpha}\, U^{\star}_{Rk2}\, U_{Rl3}\, U^{\star}_{R32}\, U_{R33}]}{|(\widetilde{m}_\nu^{-1})_{33}|^2 + |(\widetilde{m}_\nu^{-1})_{23}|^2},$$

Final total asymmetry and baryon-to-photon ratio

$$N_{B-L}^{\rm p,f} = \sum_\alpha N_{\Delta_\alpha}^{\rm p,f}\,,$$

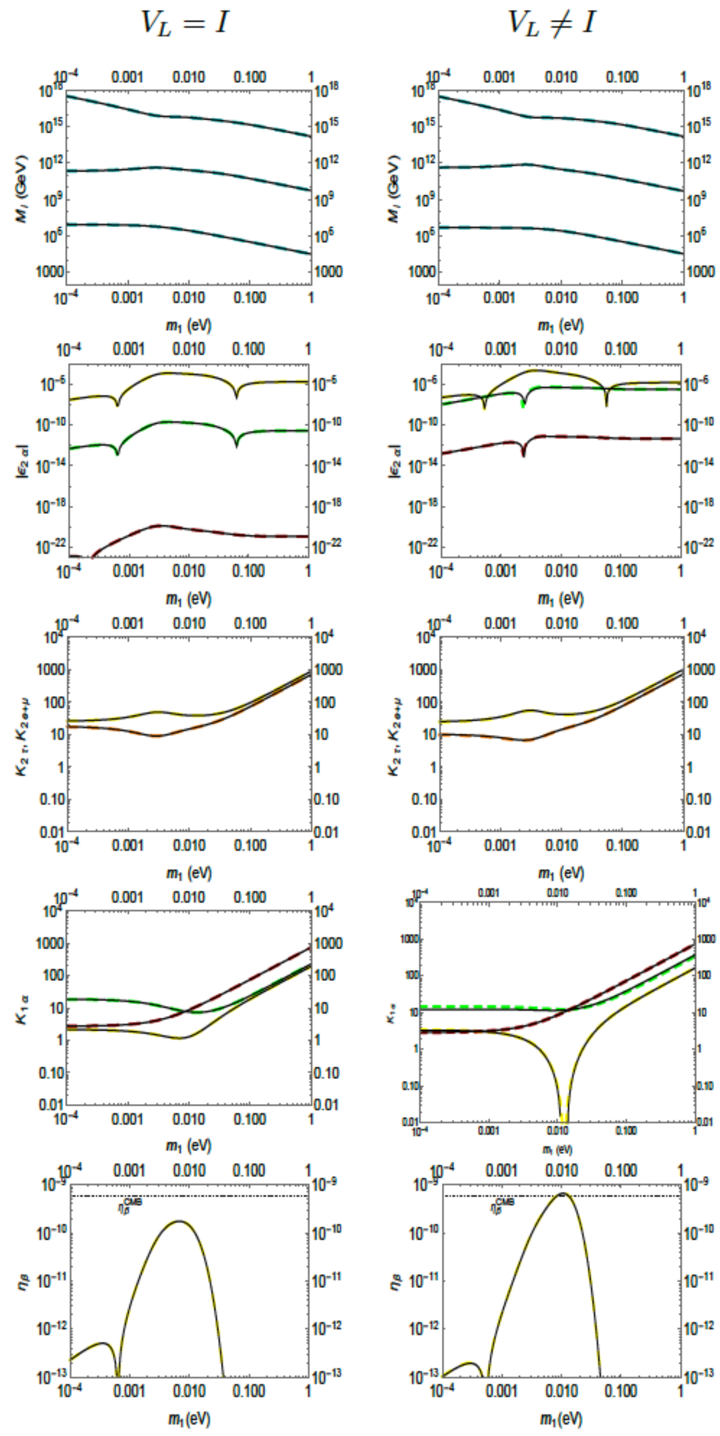
$$\eta_B^{\rm lep} = a_{\rm sph}\,\frac{N_{B-L}^{\rm lep,f}}{N_\gamma^{\rm rec}} \simeq 0.96\times 10^{-2}\, N_{B-L}^{\rm lep,f}\,.$$

An example

$$(\alpha_1, \alpha_2, \alpha_3) = (5, 5, 5),$$

$$(\theta_{13}, \theta_{12}, \theta_{23}) = (8.4°, 33°, 42°)$$

$$(\delta, \rho, \sigma) = (-0.6\pi, 0.23\pi, 0.78\,\pi);$$



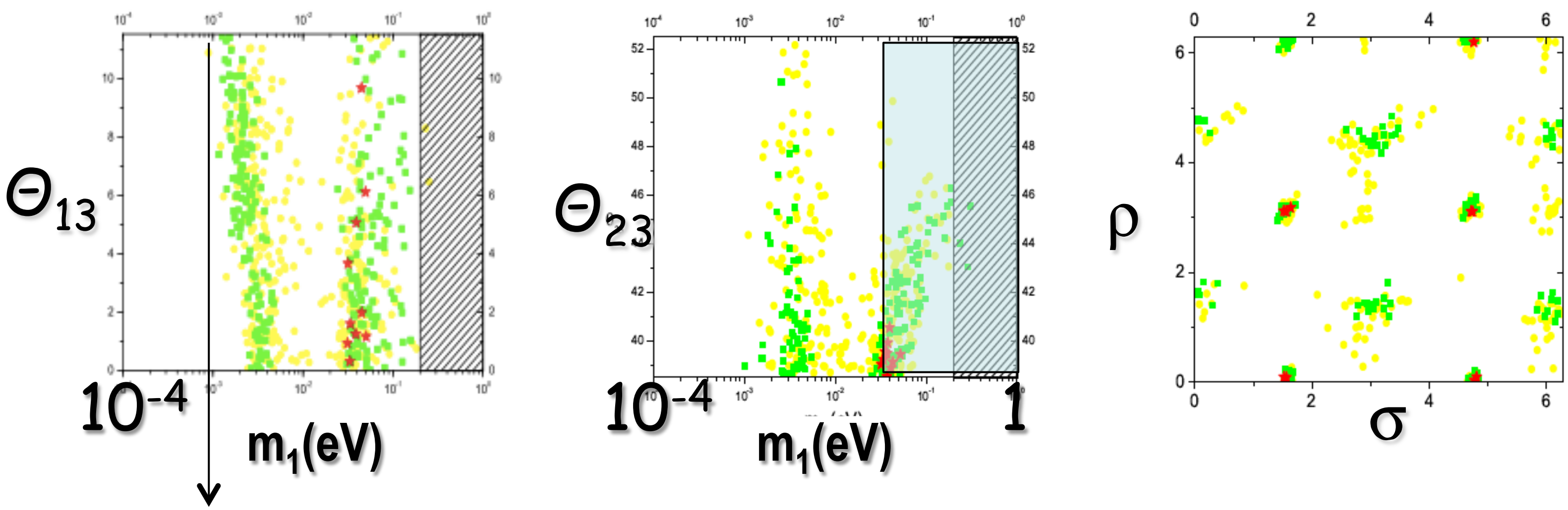
Rescuing SO(10)-inspired leptogenesis

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

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

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

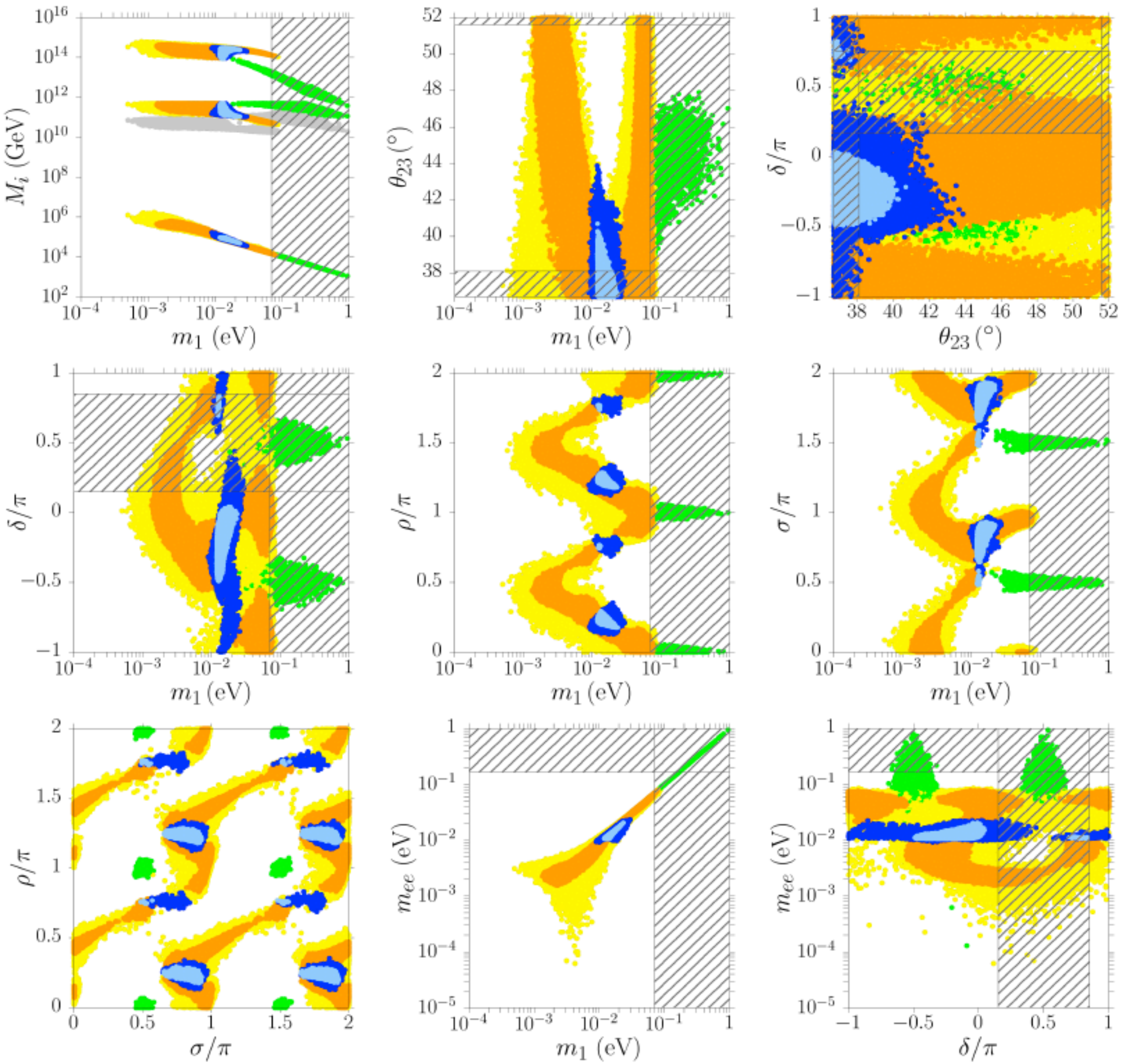
NORMAL ORDERING



- ➢ 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

* Type II seesaw contribution provides an alternative way (Abada et al. 080.2058)



M_i (GeV)
m_1 (eV)
θ_{23} (°)
δ/π
ρ/π
σ/π
m_{ee} (eV)

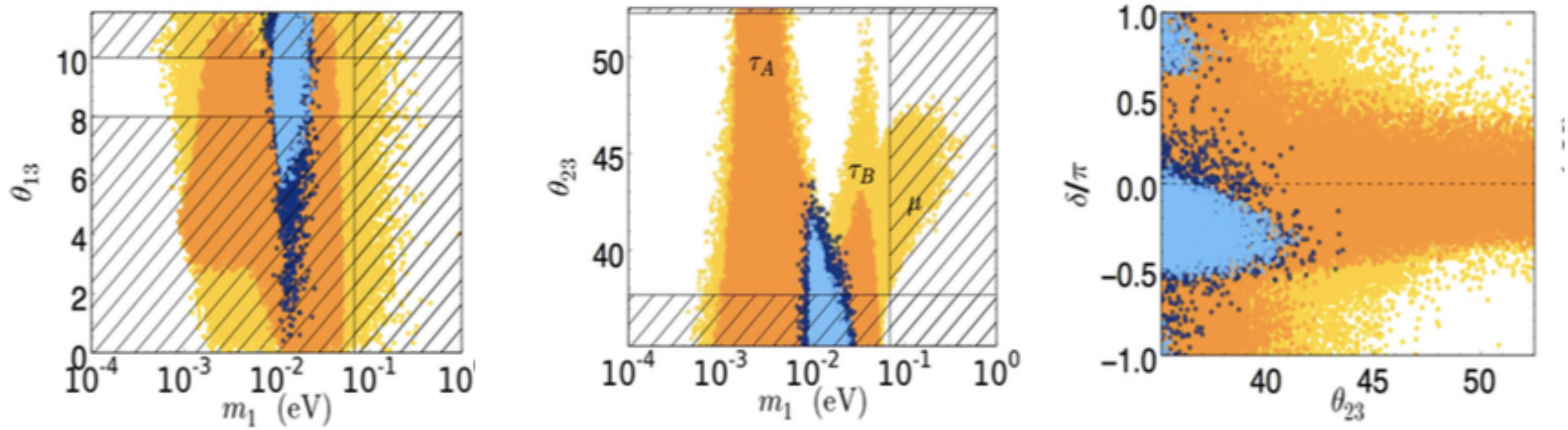
Strong thermal SO(10)-inspired (STSO10) solution

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



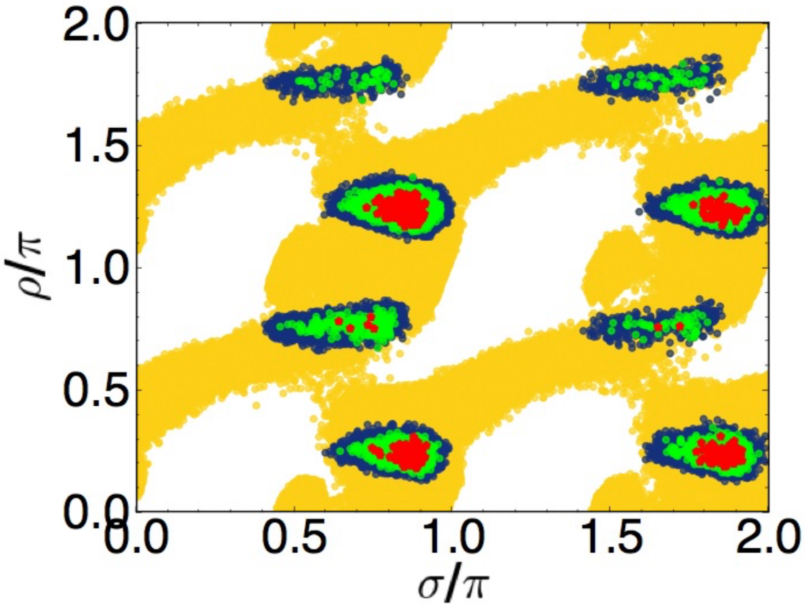
- Absolute neutrino mass scale: $8 \lesssim m_1/\text{meV} \lesssim 30 \Leftrightarrow 70 \lesssim \sum_i m_i/\text{meV} \lesssim 120$
- Non-vanishing Θ_{13};
- Θ_{23} strictly in the first octant;

STSO10: Majorana phases and neutrinoless double beta decay

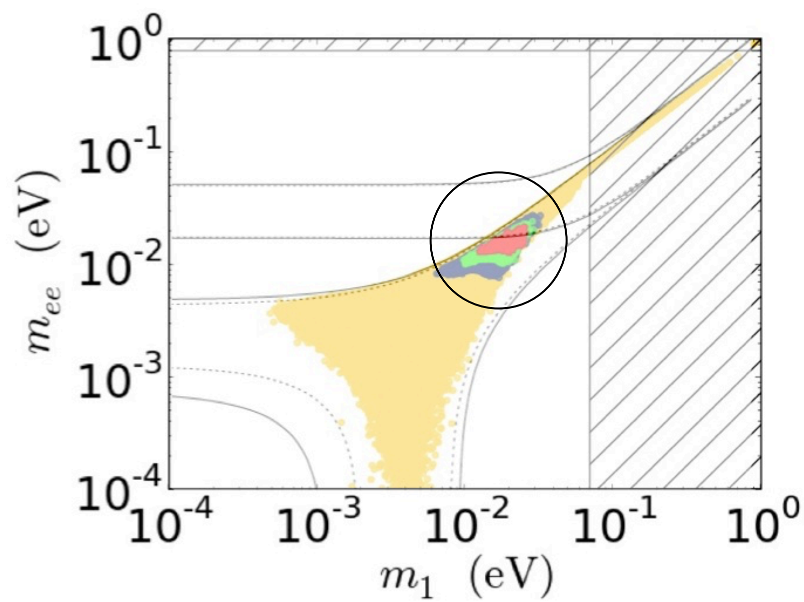
(PDB,Marzola1308.1107;PDB,Re Fiorentin,Marzola 1411.5478)

α_2=5 ➢ NORMAL ORDERING (N^p_{B-L}= 0, 0.001, 0.01, 0.1)

Majorana phases



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



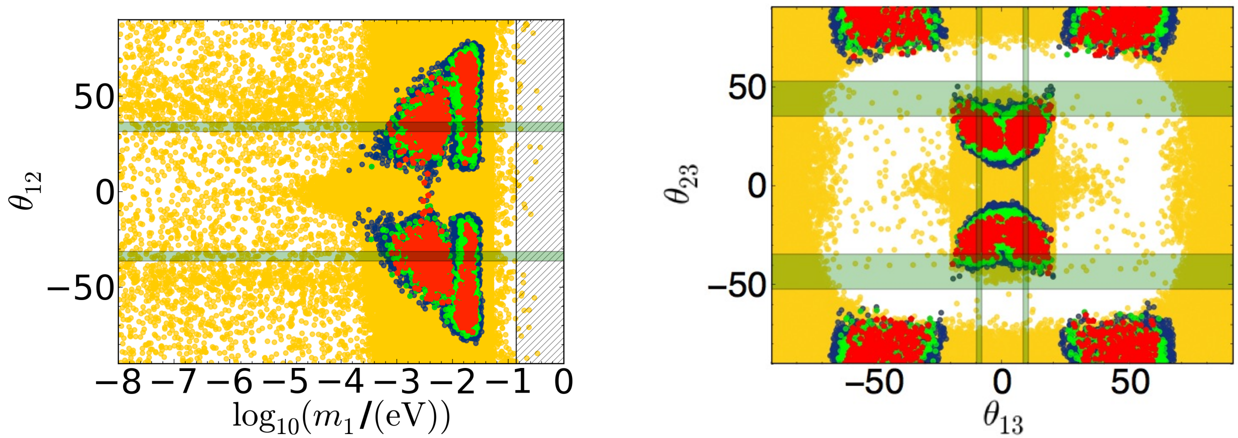
- ❑ Majorana phases are constrained around definite values
- ❑ Sharp prediction on the absolute neutrino mass scale: both on m_1 and m_{ee}
- ❑ Despite one has normal ordering, m_{ee} value might be within exp. Reach
- ❑ Cosmology should also at some point detect deviation from the Hier.Limit
- ❑ If also these predictions are satisfied exp, then $p \lesssim 0.01\%$

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≲10%

If NO is found then p≲5%

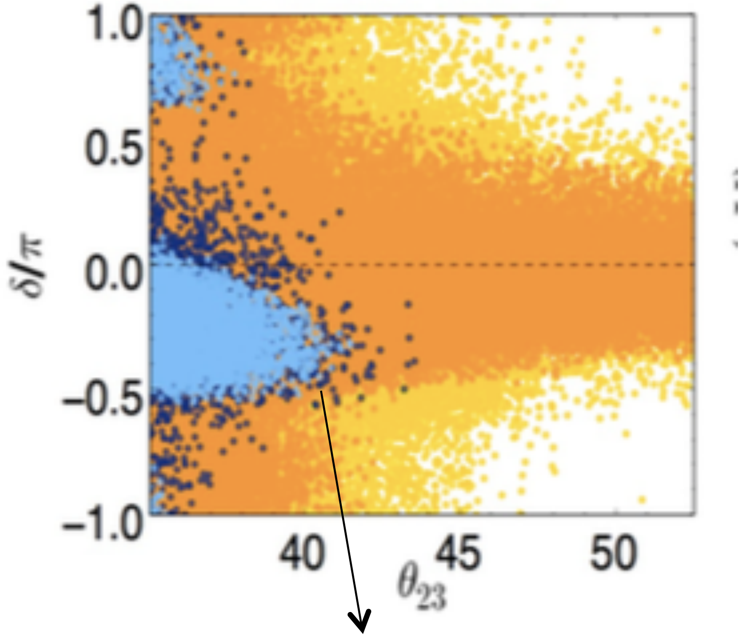
If sin δ < 0 is confirmed then p≲2%

If cos δ < 0 is found then p≲1%?

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

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

➢ NORMAL ORDERING

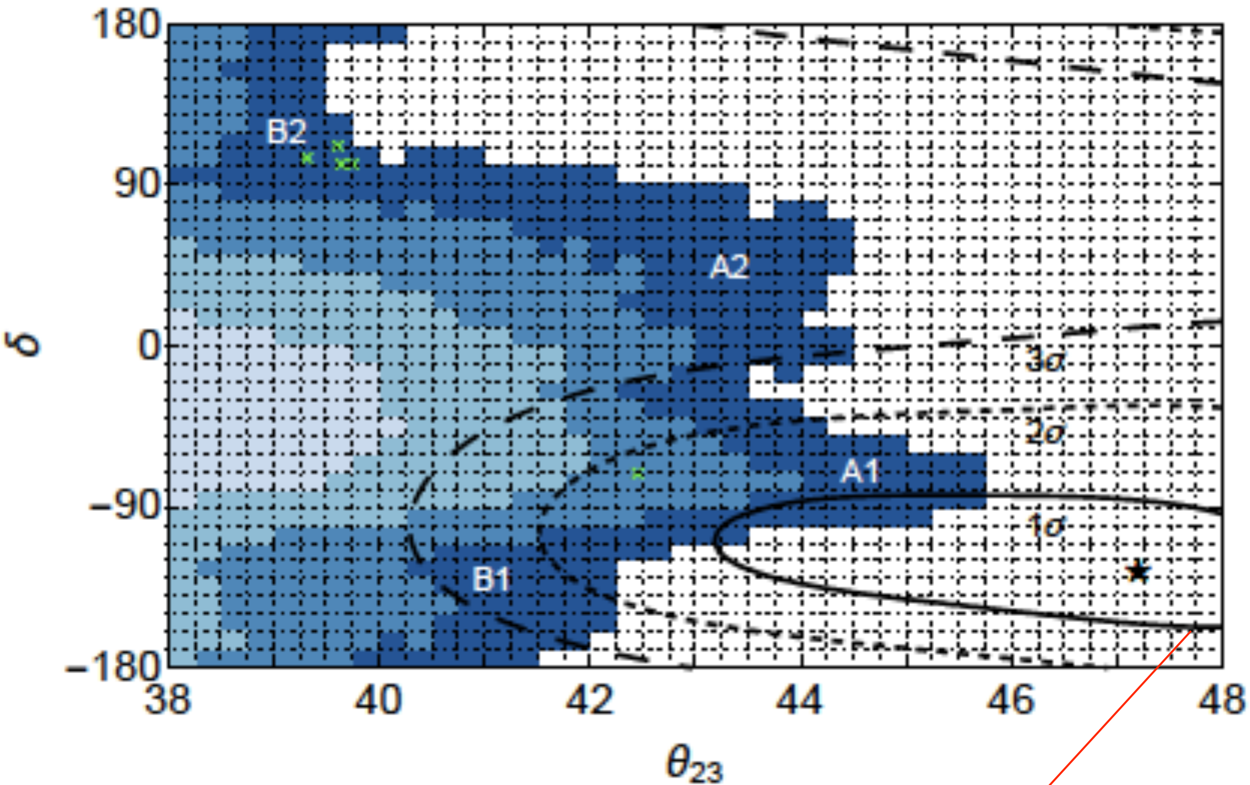


- For values of $\Theta_{23} \gtrsim 38^0$ the Dirac phase is predicted to be $\delta \sim -60^0$: the exact range depends on Θ_{23} but in any case $\cos\delta > 0$
- The new experimental results seem to support this solution: a precise determination of Θ_{23} and δ can further test this solution.
- The current data also slightly favour NO compared to IO (at ~2σ)

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

(PDB, Marco Chianese 2018)

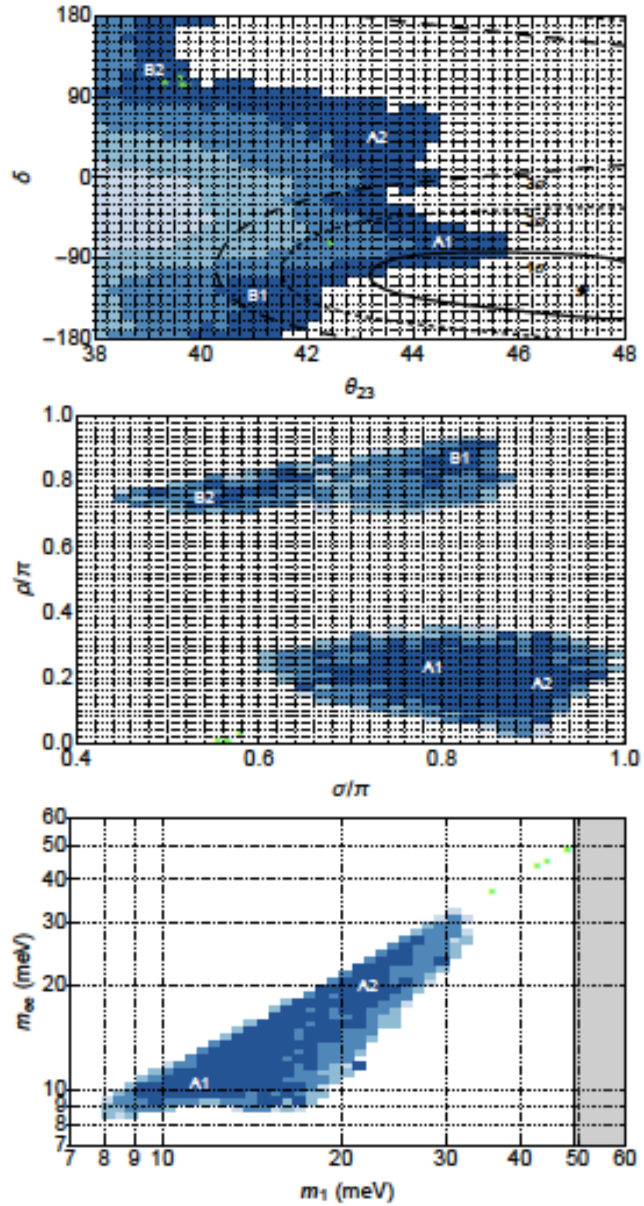
$$\alpha_2 = 5 \qquad N_{B-L}^{p,i} = 10^{-3}$$



Latest νfit collaboration experimental constraints
(see http://www.nu-fit.org)

Strong thermal SO(10)-inspired solution

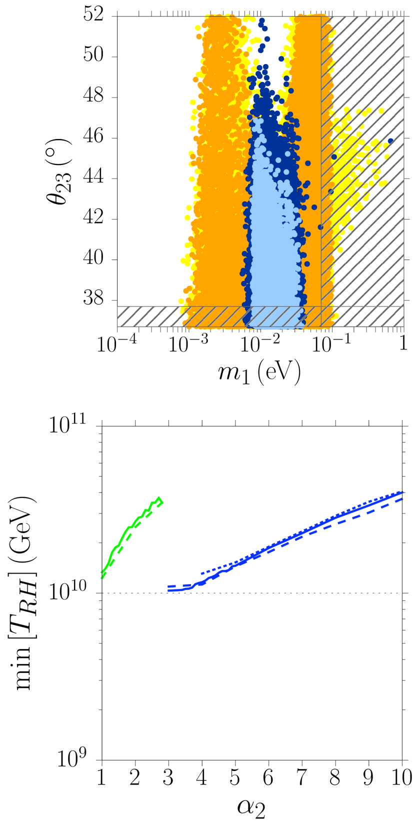
(PDB, Marco Chianese 2018)



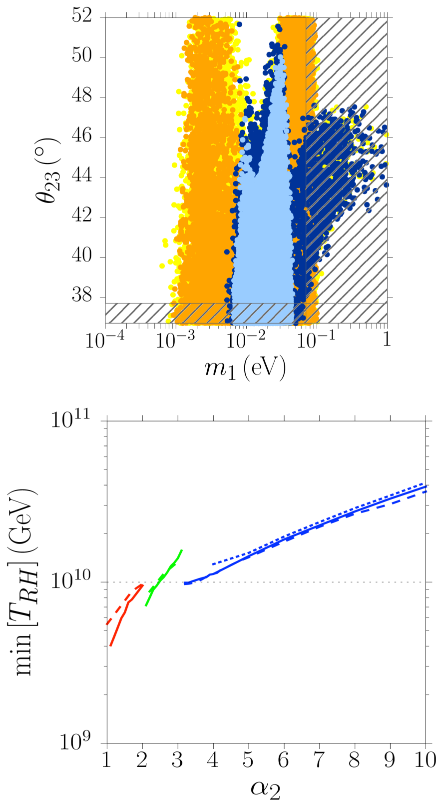
SUSY SO(10)-inspired leptogenesis

(PDB, Re Fiorentin, Marzola, 1512.06739)

tan β=5



tan β=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)

An example of realistic model:
SO(10)-inspired leptogenesis in the "A2Z model"

(S.F. King 2014)

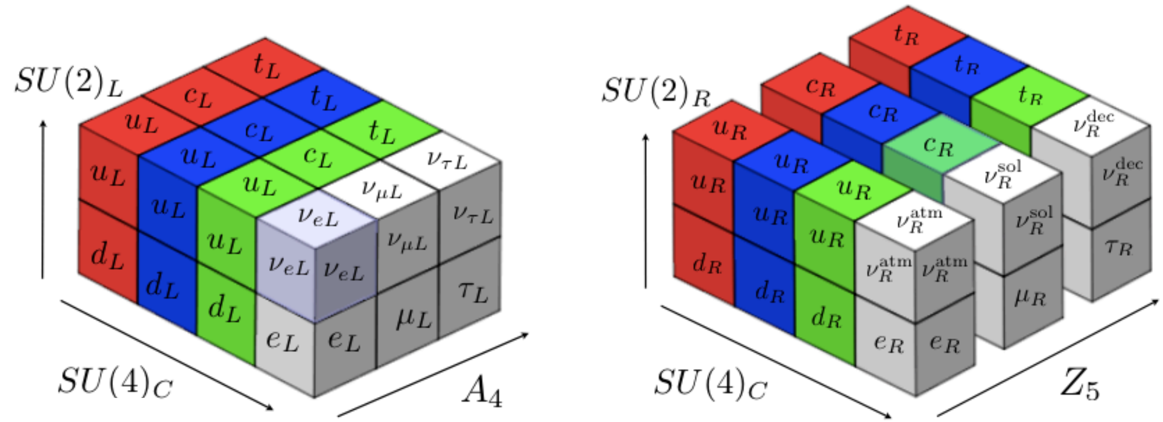


Figure 1: A to Z of flavour with Pati-Salam, where $A \equiv A_4$ and $Z \equiv Z_5$. The left-handed families form a triplet of A_4 and are doublets of $SU(2)_L$. The right-handed families are distinguished by Z_5 and are doublets of $SU(2)_R$. The $SU(4)_C$ unifies the quarks and leptons with leptons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

Neutrino sector:

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

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:

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

Leptogenesis in the "A2Z model"

(PDB, S.King 2015)

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

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

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

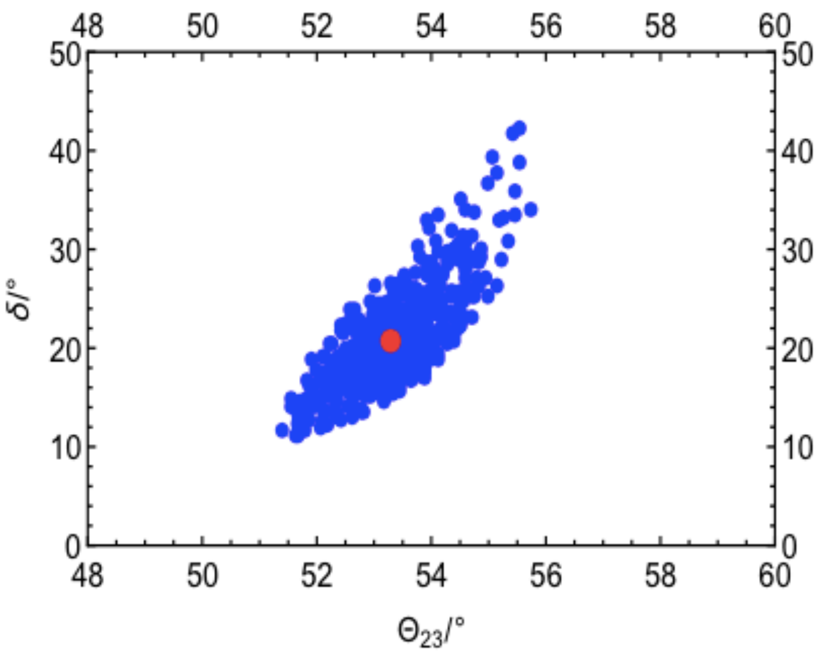
$$\eta_B^{(e)} \simeq -0.01\, \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, \frac{K_{2e}}{K_{2e}+K_{2\mu}}\, C^{(2)}_{\tau^\perp\tau}\, e^{-\frac{3\pi}{8}\, K_{1e}}$$

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

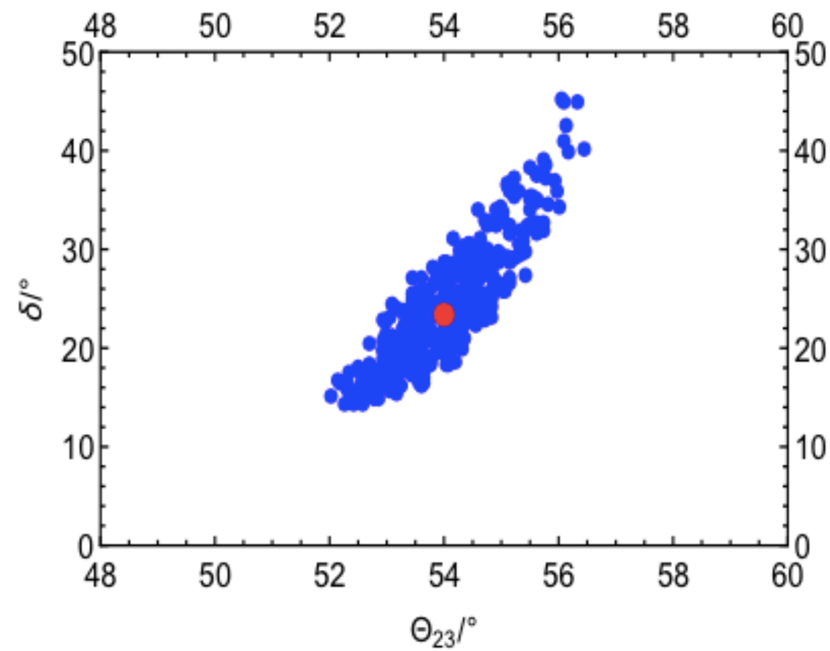
There are 2 solutions (only for NO)

(PDB, S.F. King 1507.06431)

CASE A



CASE B



This region will be tested relatively quickly: it is now quite disfavoured by the new data

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:

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

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 $M_{GUT}=2\times10^{16}$ 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 : the obtained quite good fits especially including supersymmetry but no leptogenesis and usually compact Spectrum solutions very fine tuned**

- Babu, Bajc, Saad 1612.04329: they find a good fit with NO, hierarchical RH neutrino spectrum but no leptogenesis

- de Anda, King, Perdomo 1710.03229: $SO(10) \times S_4 \times Z_4^R \times Z_4^3$ model: it fits fermion parameters and also find successful leptogenesis respecting the constraints we showed: interesting prediction on neutrinoless double beta decay effective neutrino mass m_{ee} ~11 meV.

Recent fits within SO(10) models: an example

(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)

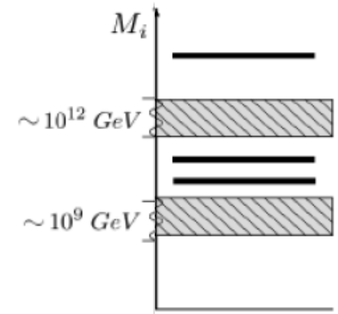
"full" Higgs Content $10_H + \overline{126}_H + 120_H$ (FN, FS)

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

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.

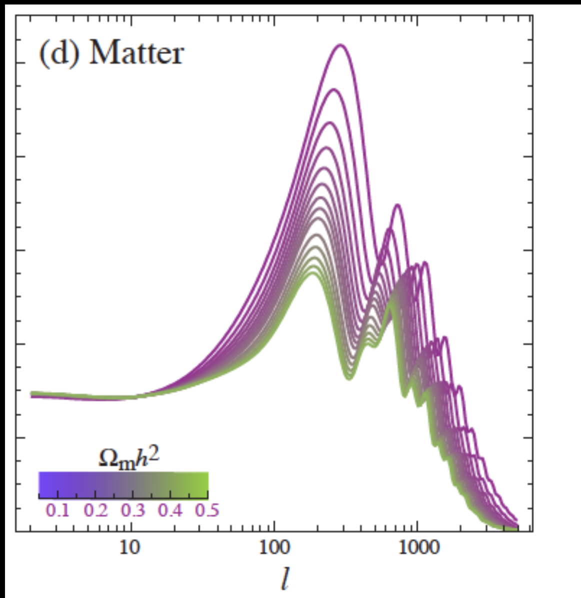
$$M_1 \gtrsim 2\times 10^{10}\,\text{GeV} \Rightarrow T_{RH} \gtrsim 6\times 10^{9}\,\text{GeV}$$

- 2 RH neutrino model can be also obtained from 3 RH neutrino models with 1 vanishing Yukawa eigenvalue ⇒ potential DM candidate

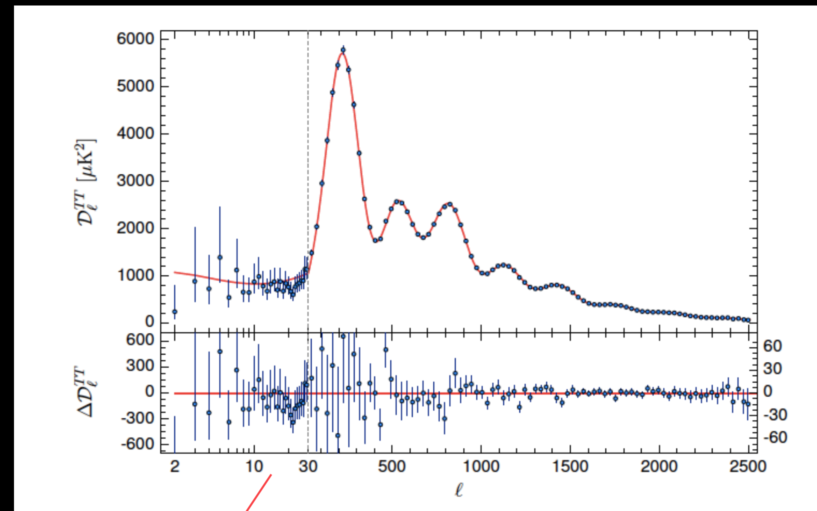
(A.Anisimov, PDB hep-ph/0812.5085)

The Dark Matter of the Universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2015, 1502.10589)

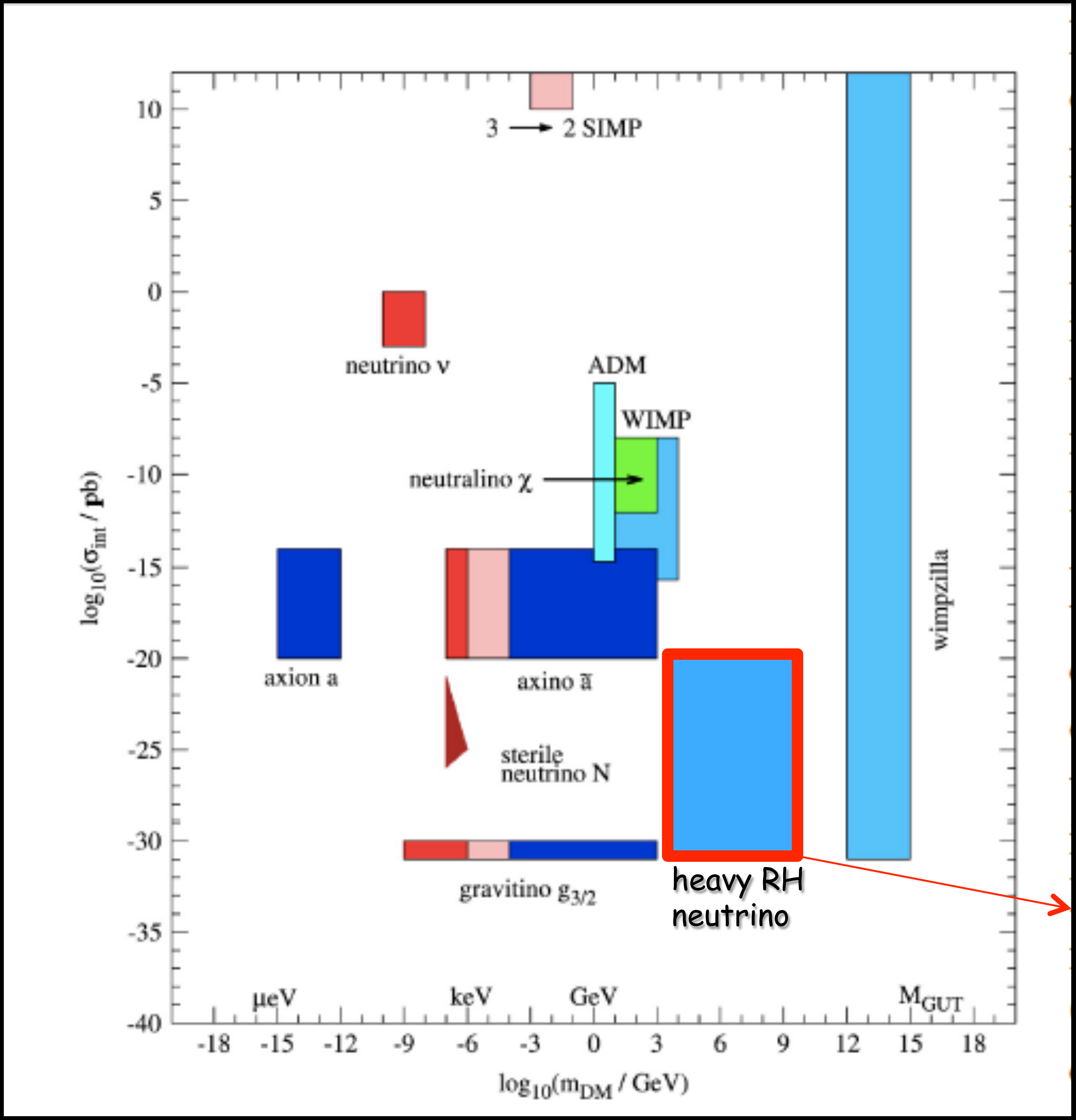


CMB +"ext"

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

Beyond the WIMP paradigm

(from Baer et al.1407.0017)



(PDB, Anisimov '08)

An alternative solution: decoupling 1 RH neutrino ⇒ 2 RH neutrino seesaw

(Babu, Eichler, Mohapatra '89; Anisimov, PDB '08)

1 RH neutrino has vanishing Yukawa couplings (enforced by some symmetry such as Z_2):

$$m_D \simeq \begin{pmatrix} 0 & m_{De2} & m_{De3} \\ 0 & m_{D\mu2} & m_{D\mu3} \\ 0 & m_{D\tau2} & m_{D\tau3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & 0 & m_{De3} \\ m_{D\mu1} & 0 & m_{D\mu3} \\ m_{D\tau1} & 0 & m_{D\tau3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & m_{De2} & 0 \\ m_{D\mu1} & m_{D\mu2} & 0 \\ m_{D\tau1} & m_{D\tau2} & 0 \end{pmatrix},$$

What production mechanism? Turning on tiny Yukawa couplings?

Yukawa basis:

$$m_D = V_L^\dagger \, D_{m_D} \, U_R \, .$$

$$D_{m_D} \equiv v \, \mathrm{diag}(h_A, h_B, h_C), \text{ with } h_A \leq h_B \leq h_C .$$

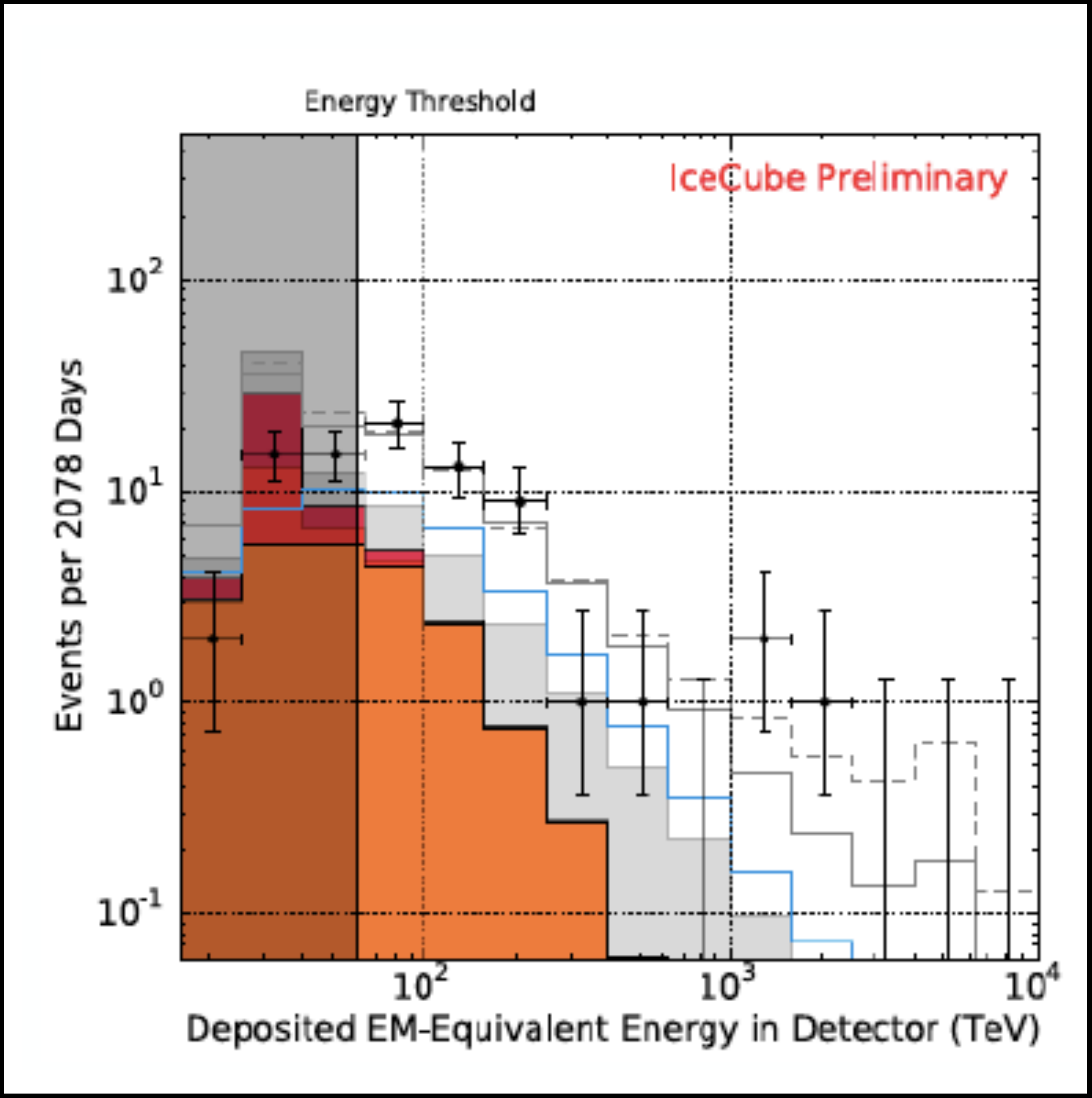
$$\tau_{\rm DM} = \frac{4\pi}{h_A^2 \, M_{\rm DM}} \simeq 0.87 \, h_A^{-2} \, 10^{-23} \left(\frac{\rm GeV}{M_{\rm DM}}\right) \, {\rm s} \quad \Rightarrow \quad \tau_{DM} > \tau_{DM}^{\min} \simeq 10^{28}\, s \Rightarrow h_A < 3\times 10^{-26} \sqrt{\frac{GeV}{M_{DM}} \times \frac{10^{28}\, s}{\tau_{DM}^{\min}}}$$

One could think of an abundance induced by RH neutrino mixing, considering that:

$$N_{DM} \simeq 10^{-9} (\Omega_{DM,0} h^2) N_\gamma^{prod} \frac{TeV}{M_{DM}}$$

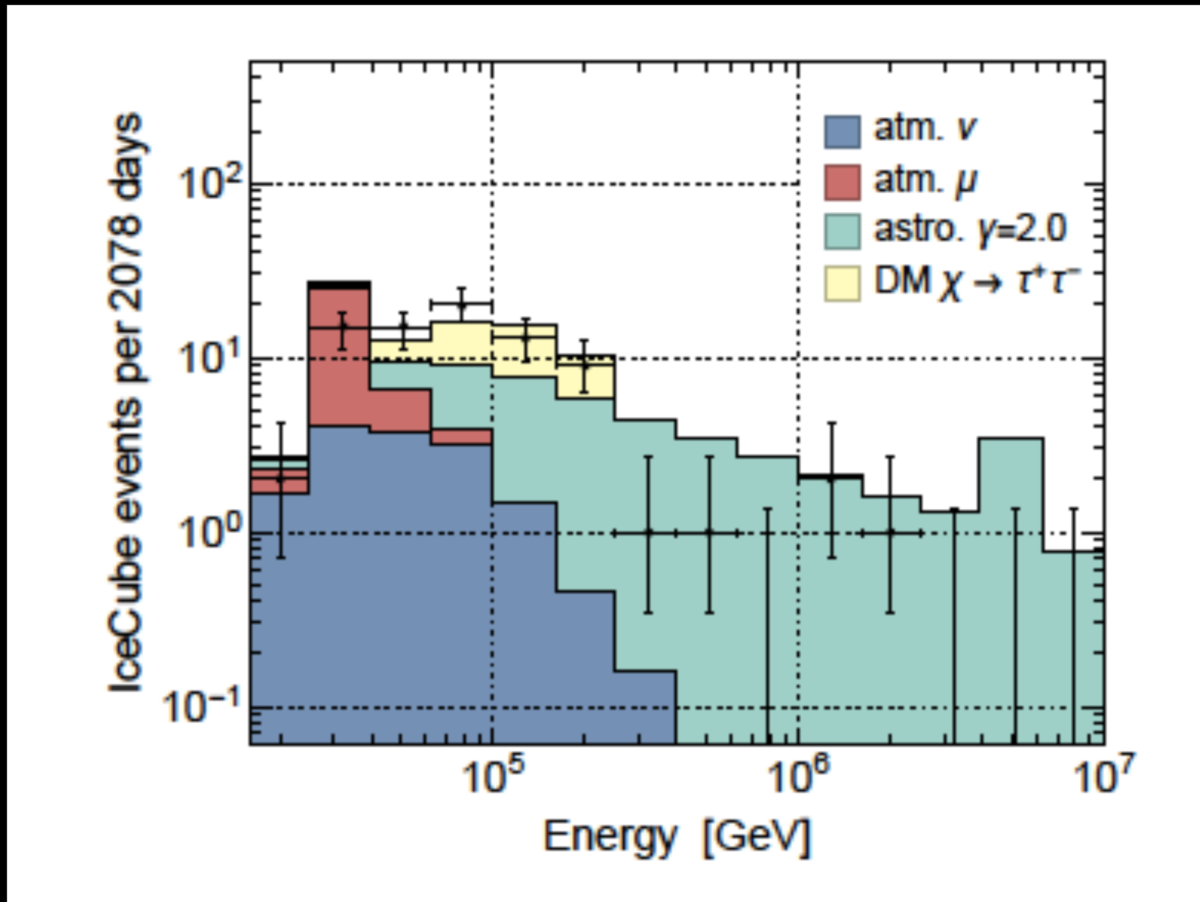
It would be enough to convert just a tiny fraction of ("source") thermalised RH neutrinos but it still does not work with standard Yukawa couplings

IceCube detection of very high energy neutrinos



(Talk by Halzen at PAHEN17, 25-26 September, Naples)

An excess at E~100 TeV?



(Chianese, Morisi, Miele 1707.05241)

Proposed production mechanisms

Starting from a 2 RH neutrino seesaw model

$$m_D \simeq \begin{pmatrix} 0 & m_{De2} & m_{De3} \\ 0 & m_{D\mu 2} & m_{D\mu 3} \\ 0 & m_{D\tau 2} & m_{D\tau 3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & 0 & m_{De3} \\ m_{D\mu 1} & 0 & m_{D\mu 3} \\ m_{D\tau 1} & 0 & m_{D\tau 3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & m_{De2} & 0 \\ m_{D\mu 1} & m_{D\mu 2} & 0 \\ m_{D\tau 1} & m_{D\tau 2} & 0 \end{pmatrix},$$

many production mechanisms have been proposed:

- from $SU(2)_R$ extra-gauge interactions (LRSM) (Fornengo,Niro, Fiorentin);
- from inflaton decays (Anisimov,PDB'08; Higaki, Kitano, Sato '14);
- from resonant annihilations through SU(2)' extra-gauge interactions (Dev, Kazanas,Mohapatra,Teplitz, Zhang '16);
- From new $U(1)_Y$ interactions connecting DM to SM (Dev, Mohapatra,Zhang '16);
- From $U(1)_{B-L}$ interactions (Okada, Orikasa '12);
- …………………

In all these models IceCube data are fitted through fine tuning of parameters responsible for decays (they are post-dictive)

RH neutrino mixing from Higgs portal

(Anisimov,PDB '08)

Assume new interactions with the standard Higgs:

$$\mathcal{L} = \frac{\lambda_{IJ}}{\Lambda}\,\phi^\dagger\,\phi\,\overline{N_I^c}\,N_J$$ (I,J=A,B,C)

In general they are non-diagonal in the Yukawa basis: this generates a RH neutrino mixing.
Consider a 2 RH neutrino mixing for simplicity and consider medium effects:

From the Yukawa interactions: $V_J^Y = \frac{T^2}{8\,E_J}\,h_J^2$

From the new interactions: $V_{JK}^\Lambda \simeq \frac{T^2}{12\,\Lambda}\,\lambda_{JK}$

effective mixing Hamiltonian (in monocromatic approximation)

$$\Delta H \simeq \begin{pmatrix} -\frac{\Delta M^2}{4p} - \frac{T^2}{16p}\,h_S^2 & \frac{T^2}{12\Lambda} \\ \frac{T^2}{12\Lambda} & \frac{\Delta M^2}{4p} + \frac{T^2}{16p}\,h_S^2 \end{pmatrix} \Rightarrow \sin 2\theta_\Lambda^{\rm m} = \frac{\sin 2\theta_\Lambda}{\sqrt{\left(1+v_S^Y\right)^2 + \sin^2 2\theta_\Lambda}}$$

$\Delta M^2 \equiv M_S^2 - M_{\rm DM}^2$.

$v_S^Y \equiv T^2\,h_S^2/(4\,\Delta M^2)$

If $\Delta m^2 < 0$ ($M_{DM} > M_S$) there is a resonance for $v_S^Y=-1$ at:

$$z_{\rm res} \equiv \frac{M_{\rm DM}}{T_{\rm res}} = \frac{h_S\,M_{\rm DM}}{2\sqrt{M_{\rm DM}^2 - M_S^2}}$$

Non-adiabatic conversion

(Anisimov,PDB '08; P.Ludl.PDB,S.Palomarez-Ruiz '16)

Adiabaticity parameter at the resonance

$$\gamma_{\rm res} \equiv \frac{|E^{\rm m}_{\rm DM} - E^{\rm m}_{\rm S}|}{2\,|\dot{\theta}_m|}\Bigg|_{\rm res} = \sin^2 2\theta_\Lambda(T_{\rm res})\,\frac{|\Delta M^2|}{12\,T_{\rm res}\,H_{\rm res}}\,,$$

Landau-Zener formula

$$\frac{N_{N_{\rm DM}}}{N_{N_{\rm S}}}\Bigg|_{\rm res} \simeq \frac{\pi}{2}\,\gamma_{\rm res}$$

(remember that we need only a small fraction to be converted so necessarily γ_{res}<<<1)

$$\Rightarrow \quad \Omega_{\rm DM}\,h^2 \simeq \frac{0.15}{\alpha_{\rm S}\,z_{\rm res}}\left(\frac{M_{\rm DM}}{M_{\rm S}}\right)\left(\frac{10^{20}\,{\rm GeV}}{\widetilde{\Lambda}}\right)^2\left(\frac{M_{\rm DM}}{\rm GeV}\right)$$

For successful dark-matter genesis

$$\Rightarrow \quad \widetilde{\Lambda}_{\rm DM} \simeq 10^{20}\sqrt{\frac{1.5}{\alpha_{\rm S}\,z_{\rm res}}\,\frac{M_{\rm DM}}{M_{\rm S}}\,\frac{M_{\rm DM}}{\rm GeV}}\;{\rm GeV}$$

2 options: either $\Lambda < M_{Pl}$ and λ_{AS}<<< 1 or $\lambda_{AS}\sim 1$ and $\Lambda >>> M_{Pl}$:

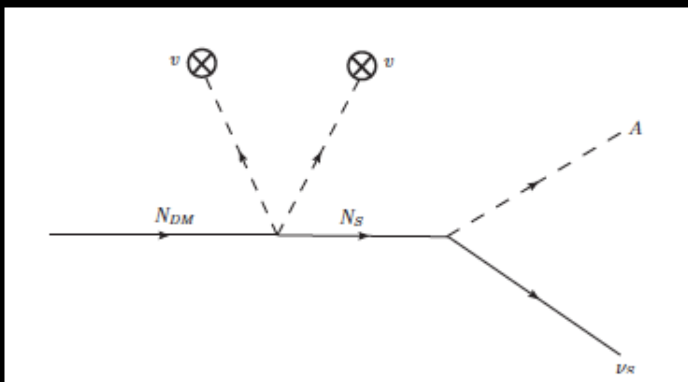
it is possible to think of models in both cases.

Constraints from decays

(Anisimov,PDB '08; Anisimov,PDB'10; P.Ludl.PDB,S.Palomarez-Ruiz'16)

2 body decays

DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe



$$\theta^0_\Lambda = \left(\frac{v^2}{\widetilde{\Lambda}}\right)^2 \frac{1}{\Gamma_S^2/4 + M_S^2\,\delta_{DM}^2}$$

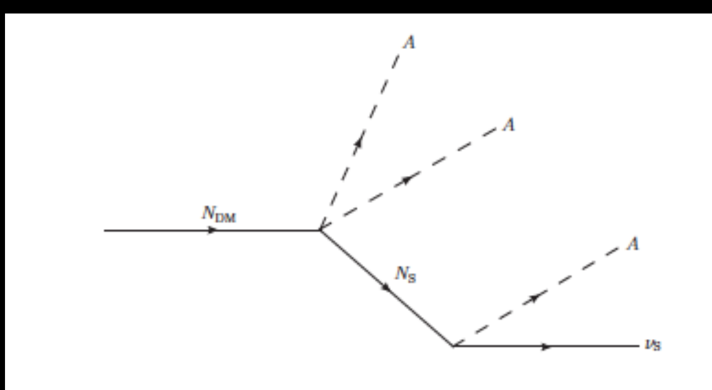
mixing angle today

Lower bound on M_{DM} ($\tau_{28} \equiv \tau_{DM}^{min}/10^{28}$s)

$$M_{DM} \geq M_{DM}^{min} \simeq 2.5 \times 10^{12}\, z_{res}^{5/3}\, \tau_{28}^{1/3} \left[\frac{(1 + M_S/M_{DM})^2}{4\, M_{DM}/M_S}\right]^{1/3} \mathrm{GeV}$$

4 body decays

$$N_{DM} \to 2\,A + N_S \to 3\,A + \nu_S \;\; (A = W^\pm, Z, H).$$

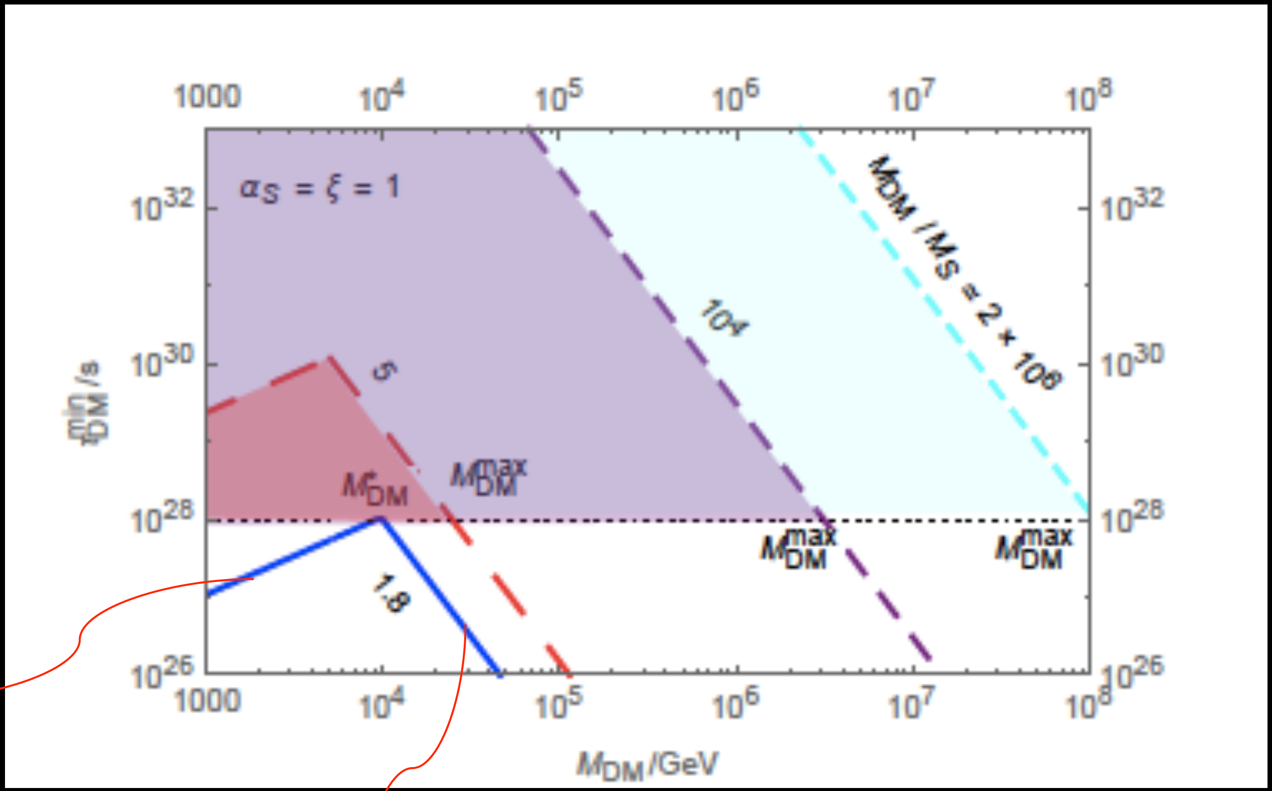


Upper bound on M_{DM} ($\tau_{28} \equiv \tau_{DM}^{min}/10^{28}$s)

$$M_{DM} \lesssim M_{DM}^{max(A)} \simeq \frac{5 \times 10^3\,\mathrm{GeV}}{\alpha_S^{2/3}\, z_{res}^{1/3}\, \tau_{28}^{1/3}} \left(\frac{M_{DM}}{M_S}\right)^{2/3}$$

3 body decays and annihilations also can occur but yield weaker constraints

Decays: a natural allowed window on M_{DM}



Lower bound from 2 body decays

Upper bound from 4 body decays

Increasing M_{DM}/M_S relaxes the constraints since it allows higher T_{res} (⇒more efficient production) keeping small N_S Yukawa coupling (helping stability)! But there Is an upper limit to T_{res} from usual upper limit on reheat temperature.

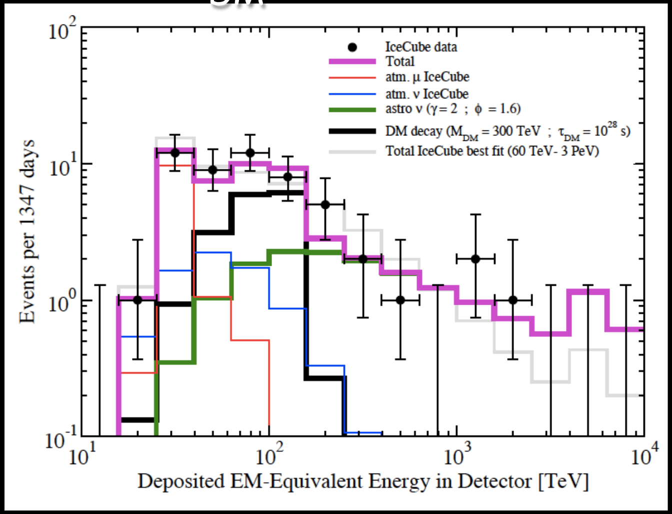
Decays:very high energy neutrinos at IceCube

(P.Ludl.PDB,S.Palomarez-Ruiz'16)

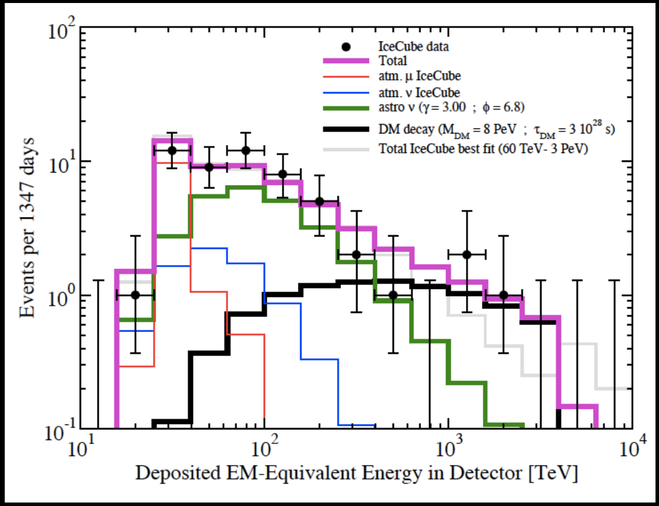
- Since the same interactions responsible for production also unavoidably induce decays ⇒ the model predicts high energy neutrino flux component at some level ⇒ testable at neutrino telescopes (Anisimov,PDB '08)

Neutrino events at IceCube: 2 examples of fits where a DM component in addition to an astrophysical component helps fitting HESE data:

M_{DM}=300TeV



M_{DM}=8 PeV



- Some authors claim there is an excess at (60-100) TeV taking into account also MESE data (Chianese,Miele,Morisi '16)

- But where are the γ 's in FERMI? Multimessenger analysis is crucial.

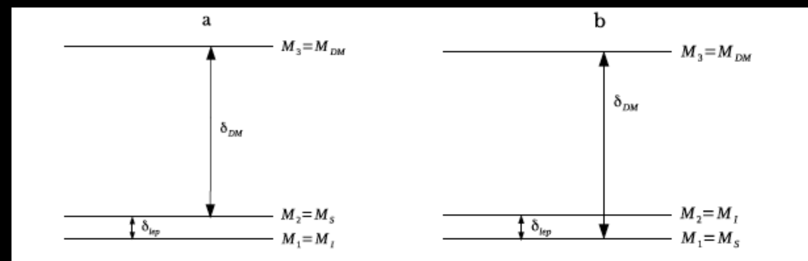
Unifying Leptogenesis and Dark Matter

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

- Interference between N_A and N_B can give sizeable CP decaying asymmetries able to produce a matter-antimatter asymmetry but since $M_{DM} > M_S$ necessarily $N_{DM} = N_3$ and $M_1 \simeq M_2$ ⇒ leptogenesis with quasi-degenerate neutrino masses

$$\delta_{DM} \equiv (M_3 - M_S)/M_S$$

$$\delta_{lep} \equiv (M_2 - M_1)/M_1$$



$$\varepsilon_{i\alpha} \simeq \frac{\overline{\varepsilon}(M_i)}{K_i} \left\{ \mathcal{I}_{ij}^{\alpha}\, \xi(M_j^2/M_i^2) + \mathcal{J}_{ij}^{\alpha}\, \frac{2}{3(1 - M_i^2/M_j^2)} \right\}$$

(Covi, Roulet, Visssani '96)

$$\overline{\varepsilon}(M_i) \equiv \frac{3}{16\,\pi} \left(\frac{M_i\, m_{\rm atm}}{v^2} \right) \simeq 1.0 \times 10^{-6} \left(\frac{M_i}{10^{10}\,{\rm GeV}} \right),$$

$$\xi(x) = \frac{2}{3} x \left[(1+x) \ln \left(\frac{1+x}{x} \right) - \frac{2-x}{1-x} \right],$$

Analytical expression for the asymmetry:

$$\eta_B \simeq 0.01\, \frac{\overline{\varepsilon}(M_1)}{\delta_{\rm lep}}\, f(m_\nu, \Omega)\,,$$

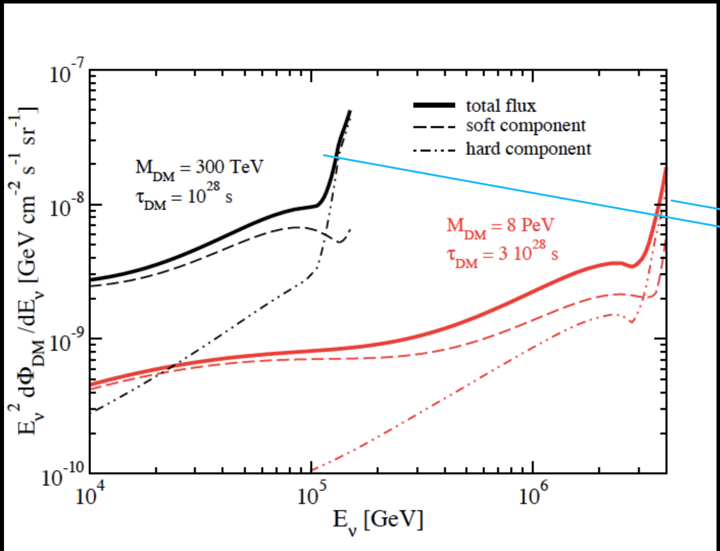
Efficiency factor

$$f(m_\nu, \Omega) \equiv \frac{1}{3} \left(\frac{1}{K_1} + \frac{1}{K_2} \right) \sum_\alpha \kappa(K_{1\alpha} + K_{2\alpha})\, [\mathcal{I}_{12}^{\alpha} + \mathcal{J}_{12}^{\alpha}]\,,$$

- $M_S \gtrsim 2\, T_{sph} \simeq 300$ GeV ⇒ $10\ \text{TeV} \lesssim M_{DM} \lesssim 10\ \text{PeV}$
- $M_S \lesssim 10$ TeV
- $\delta_{lep} \sim 10^{-5}$ ⇒ leptogenesis is not fully resonant

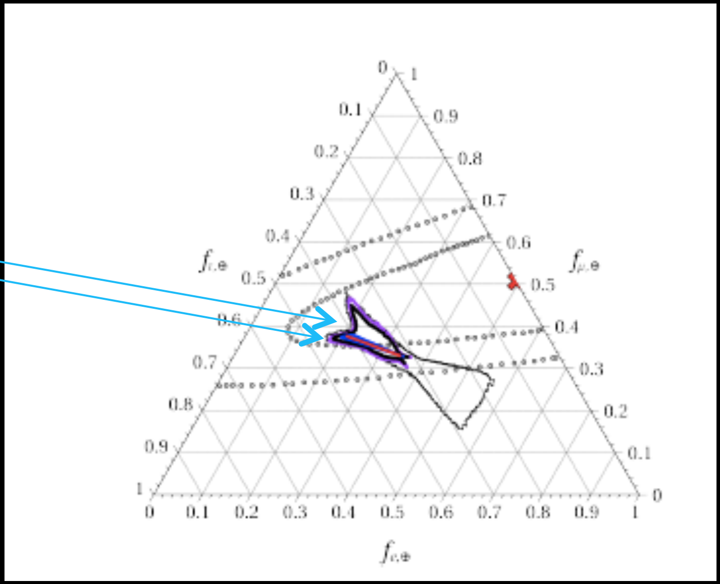
Decays: a distinct flavour composition

Energy neutrino flux



Hard component

Flavour composition at the detector (Normal Hierarchy)



For Normal Hierarchy it is interesting that the electron neutrino hard component is strongly suppressed (it can be even vanishing).

At the detector this is smeared out by mixing but it might be still testable in future.

Summary

- Neutrinos in Cosmology is not just a topic with important historical results but it is still one of the best motivated routes to understand the cosmological puzzles

- High energy scale leptogenesis is the most attractive scenario of baryogenesis in the absence of new physics at TeV scale or below

- N_2-dominated scenario 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 encouraging.
  Deviation of neutrino masses from the hierarchical limits is expected;
  Despite NO neutrinoless double beta decay signal still detectable (when?)

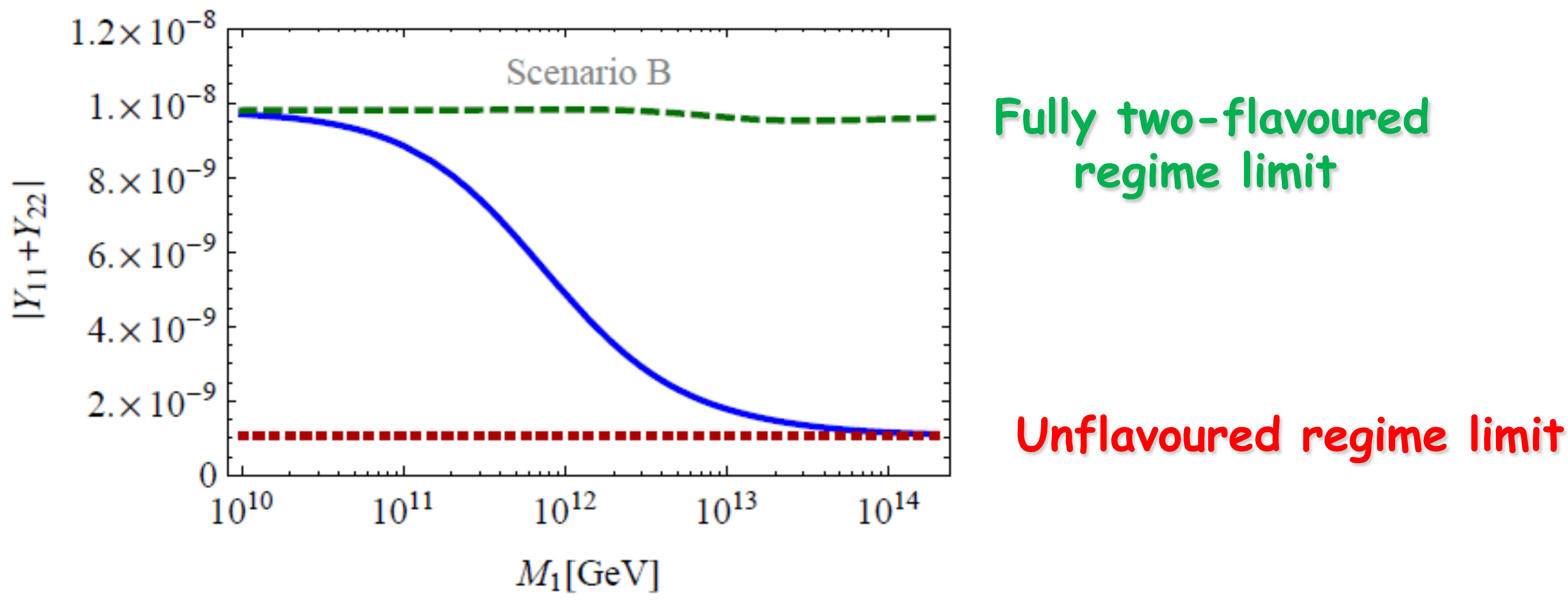
- Study of realistic models

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

Density matrix and CTP formalism to describe the transition regimes

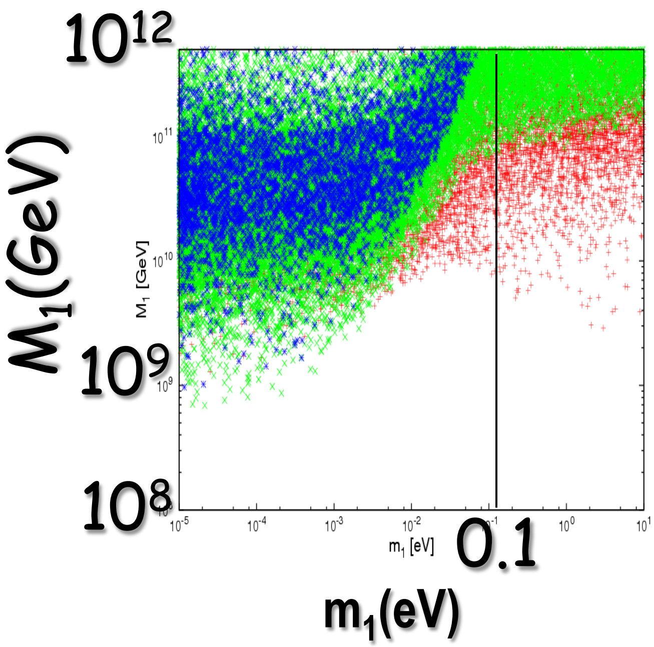
(De Simone, Riotto '06; Beneke, Gabrecht, Fidler, Herranen, Schwaller '10)

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

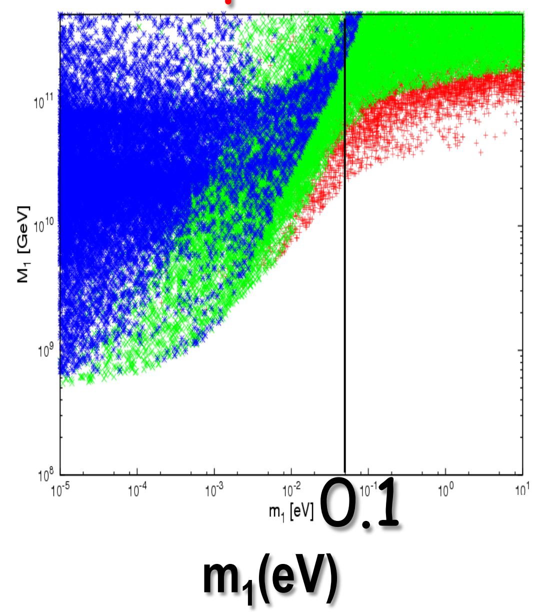


Neutrino mass bounds and role of PMNS phases

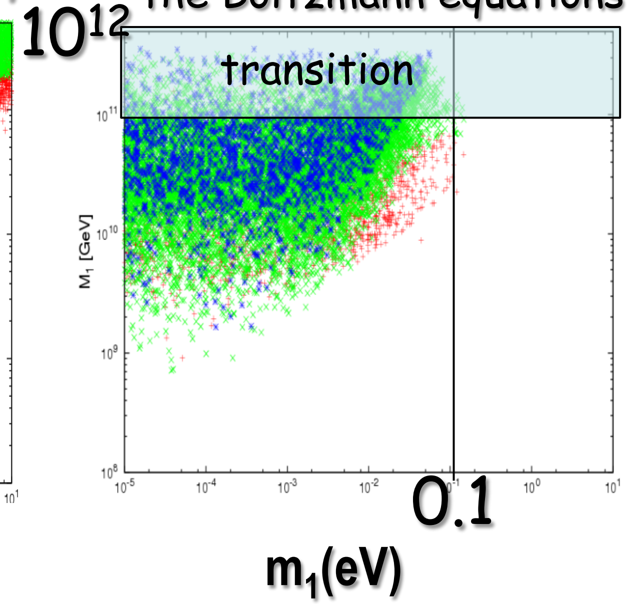
(Abada et al.' 07; Blanchet,PDB,Raffelt;Blanchet,PDB '08)

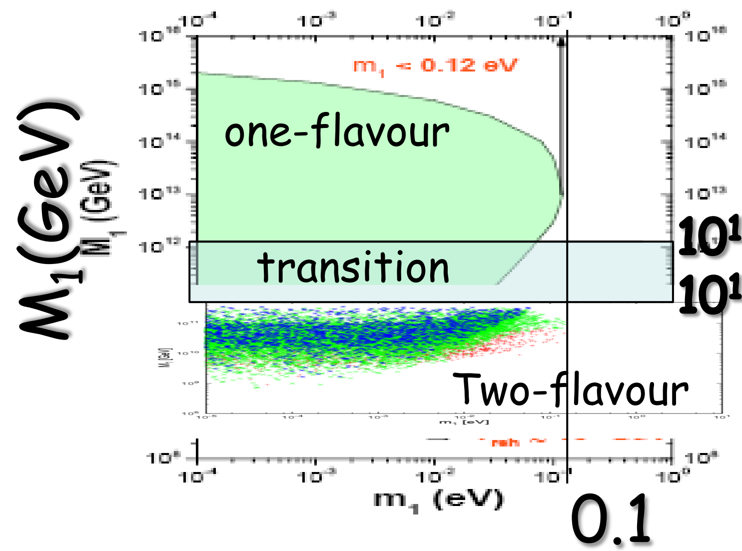


PMNS phases off



Imposing the validity of the Boltzmann equations



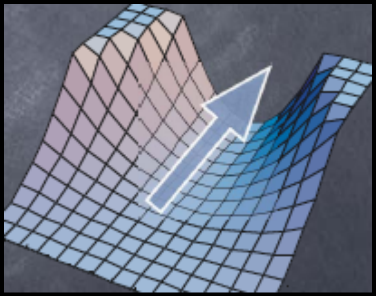


Affleck-Dine Baryogenesis

(Affleck, Dine '85)

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

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



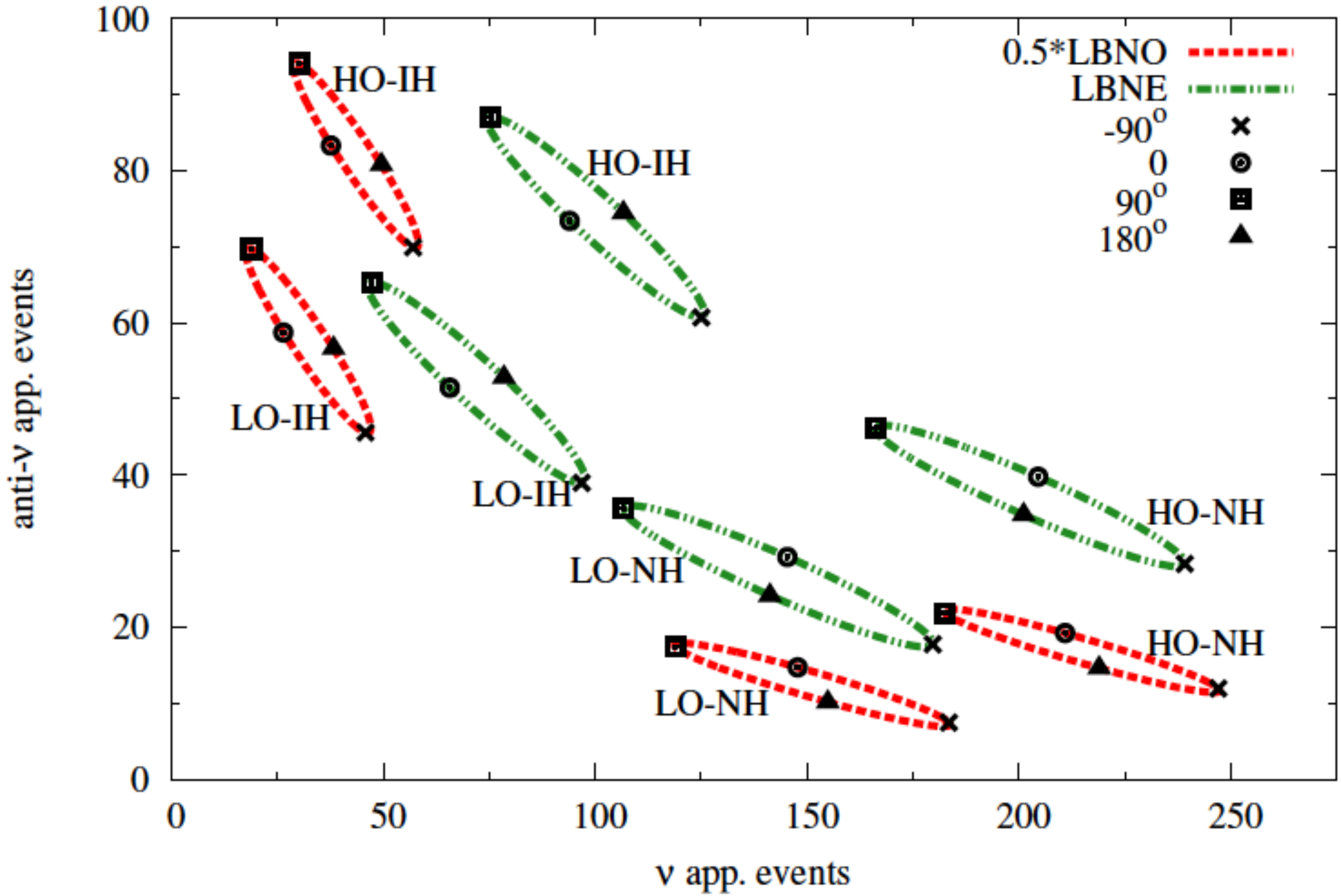
F term D term

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

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

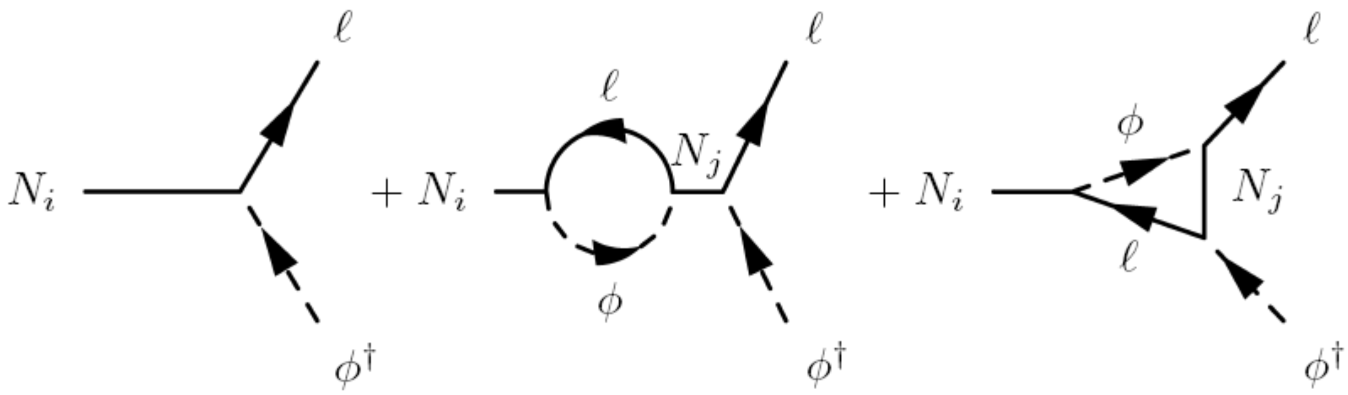
The final asymmetry is ? T_{RH} and the observed one can be reproduced for low values T_{RH} ? 10 GeV !

Electron appearance events for 0.5*LBNO and LBNE



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:

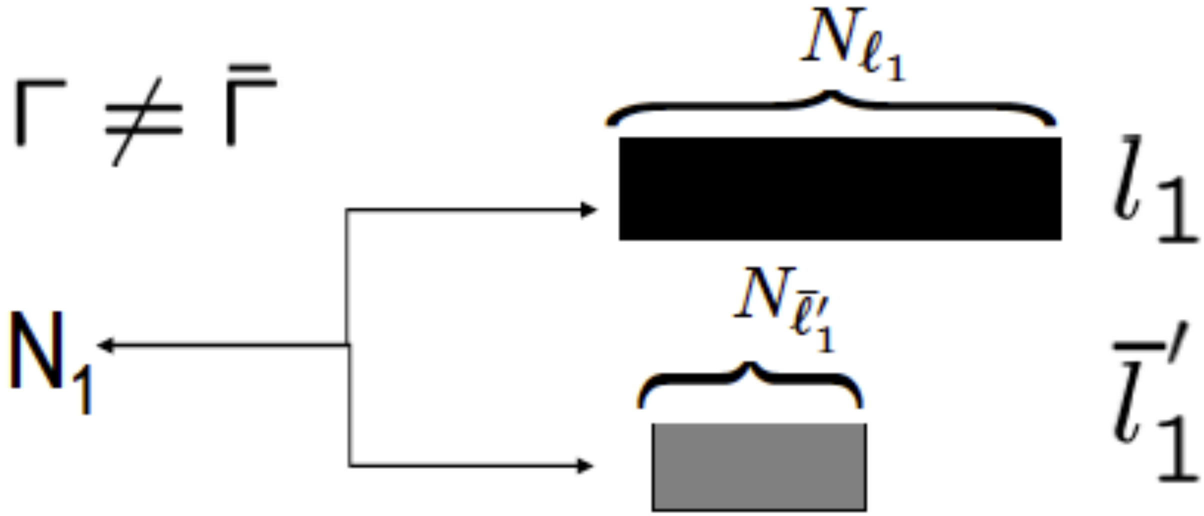
(Nardi, Racker, Roulet '06)

(α = τ, e+μ)

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

depends on U !

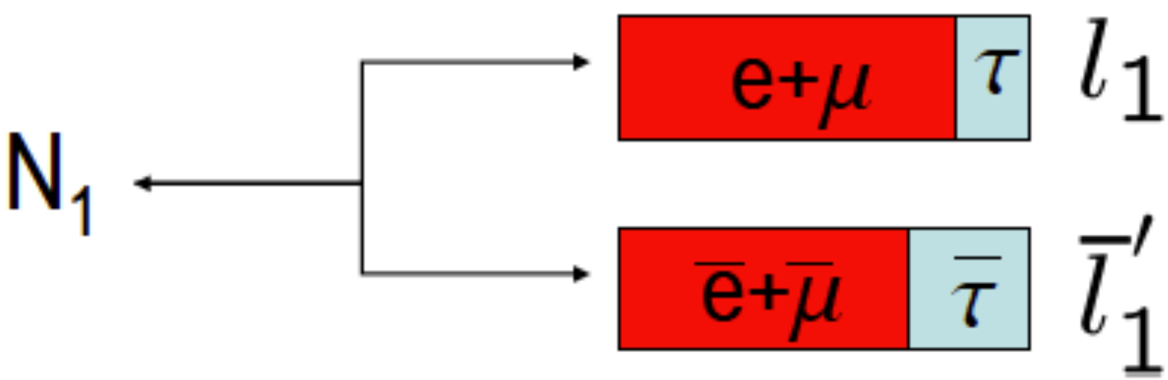
1) $\Gamma \neq \bar{\Gamma}$



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

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

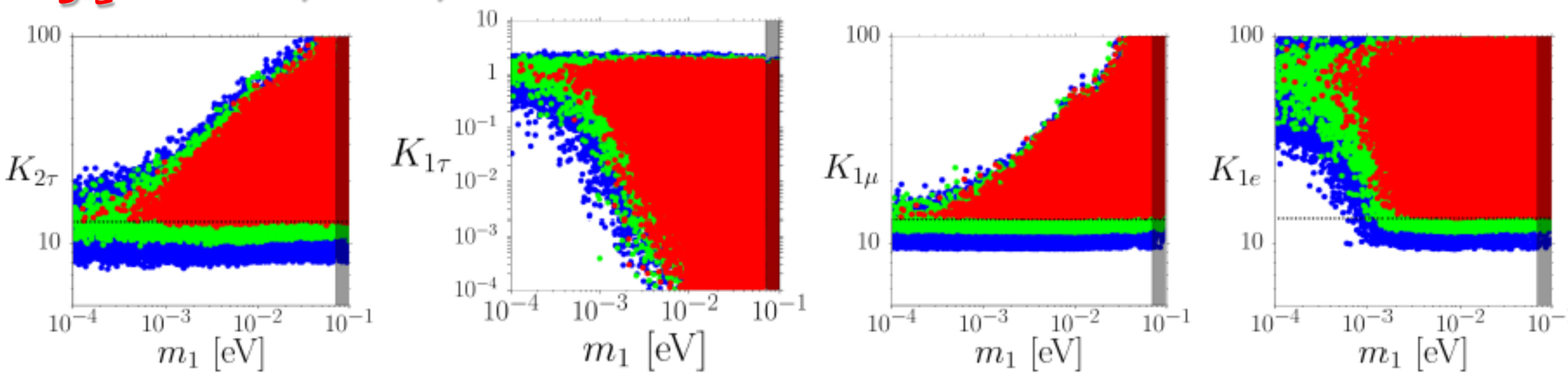
+



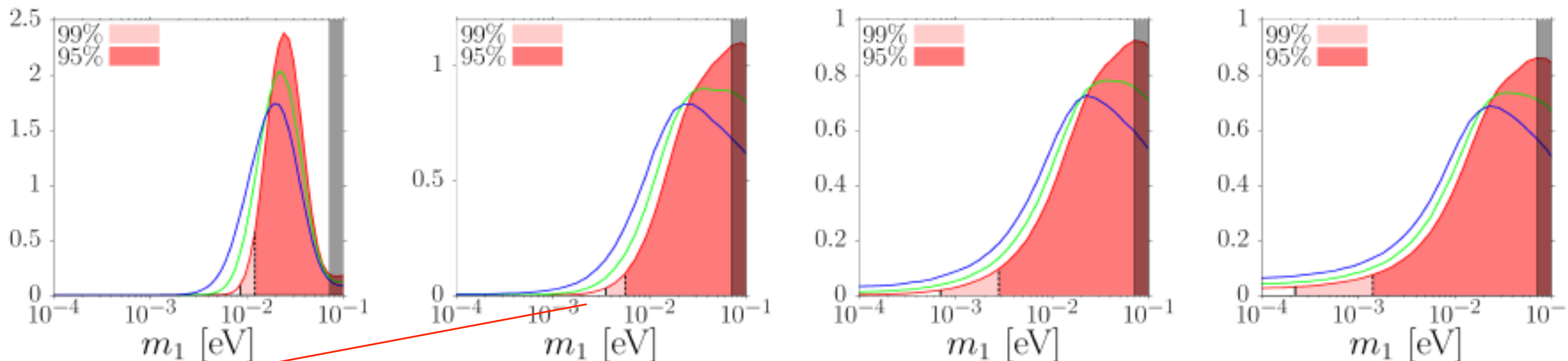
$\Rightarrow \; \frac{\Delta P_{1\alpha}}{2}$

A lower bound on neutrino masses (IO)

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



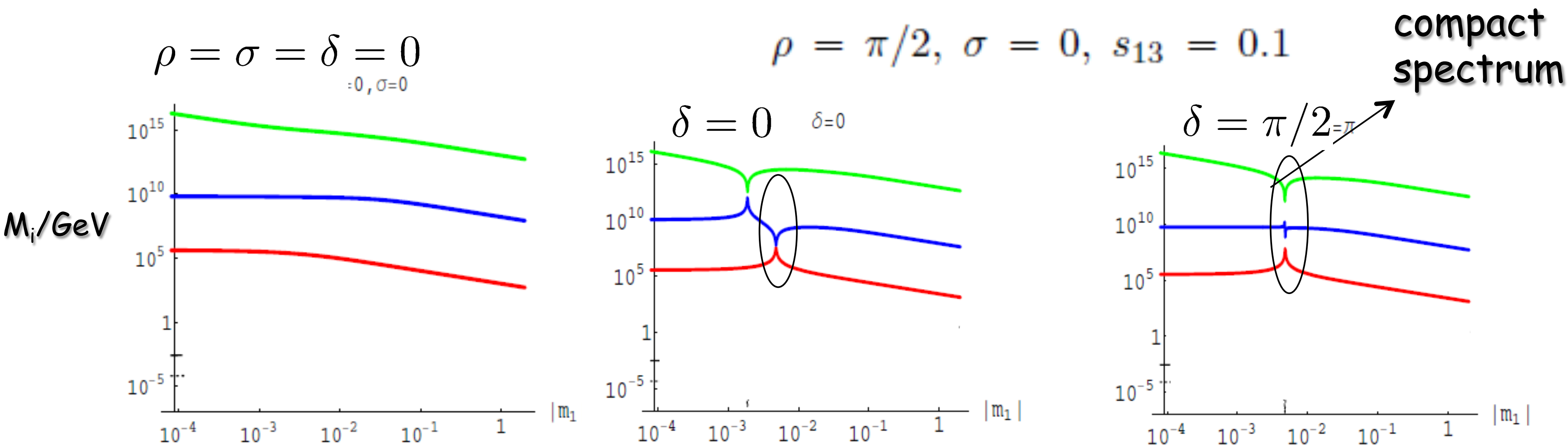
$\max[|\Omega^2_{21}|] = 1$ $\max[|\Omega^2_{21}|] = 2$ $\max[|\Omega^2_{21}|] = 5$ $\max[|\Omega^2_{21}|] = 10$



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

Crossing level solutions

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

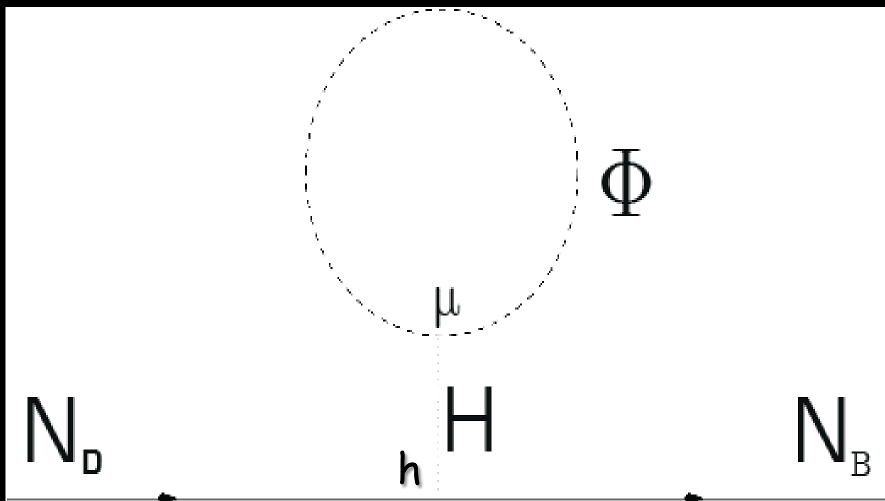


- About the crossing levels the N_1 CP asymmetry is enhanced
- The correct BAU can be attained for a fine tuned choice of parameters: many realistic models have made use of these solutions

(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

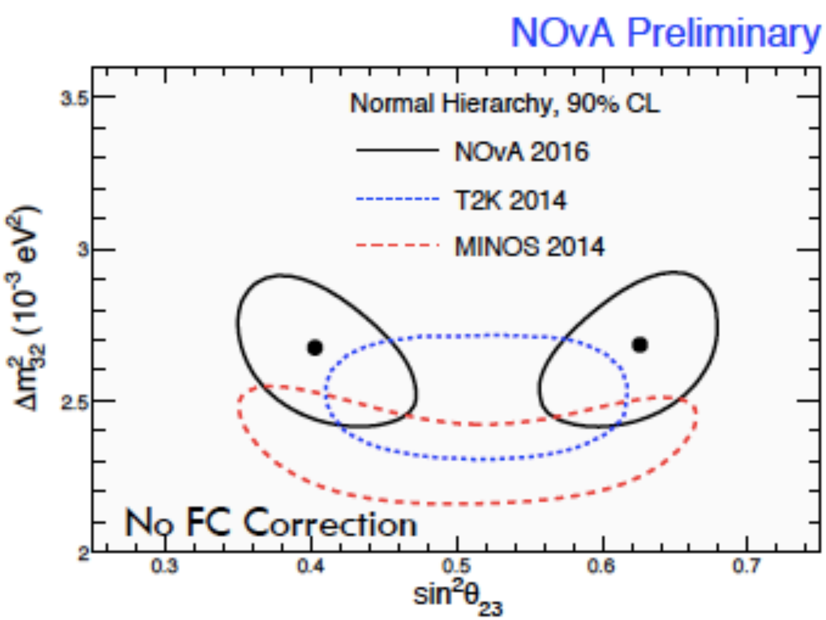
(Anisimov,PDB, 2010, unpublished)

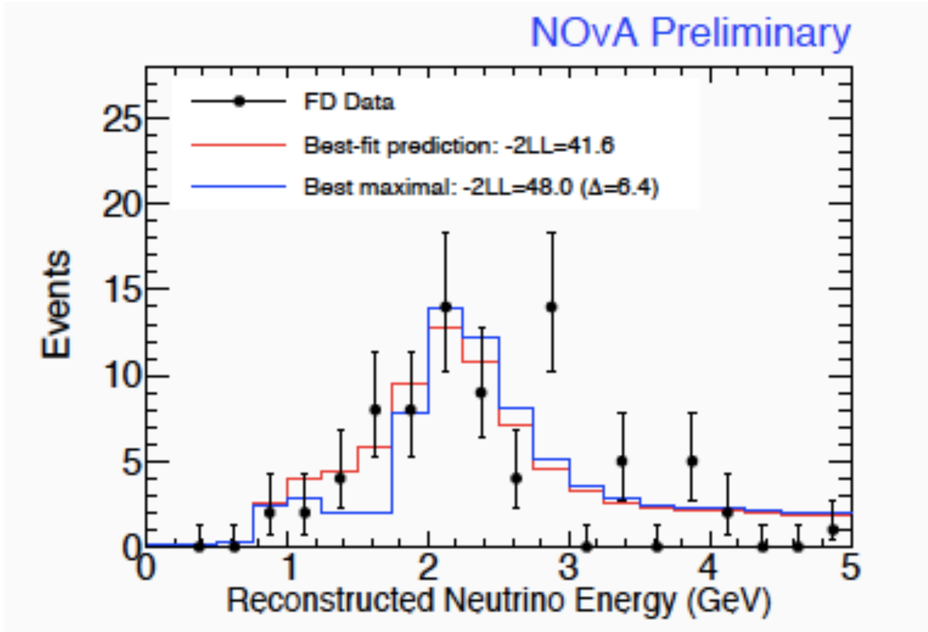


$$\frac{1}{\Lambda_{\mathrm{eff}}} = \frac{h\mu}{M_{\mathrm{GUT}}^2}$$

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

NOvA results (Neutrino 2016)





Best Fit (in NH):

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

Maximal mixing excluded at 2.5σ

Some tension with T2K results not detecting any deviation from maximal mixing