Focus week on: "New observational windows on the high scale origin of matter-anti-matter asymmetry"

KAVLI, IPMU, 10-14 January, 2022

SO(10)-inspired Leptogenesis

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Why going beyond the SM?

Even ignoring:

- ❑ (more or less) compelling theoretical motivations (quantum gravity theory, flavour problem, hierarchy and naturalness problems,…) and
- ❑ Experimental anomalies (e.g., $(g-2)_\mu$, R_K, R_K^*,…)

The SM cannot explain:

- ***Cosmological Puzzles*** :

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

- ***Neutrino masses and mixing***

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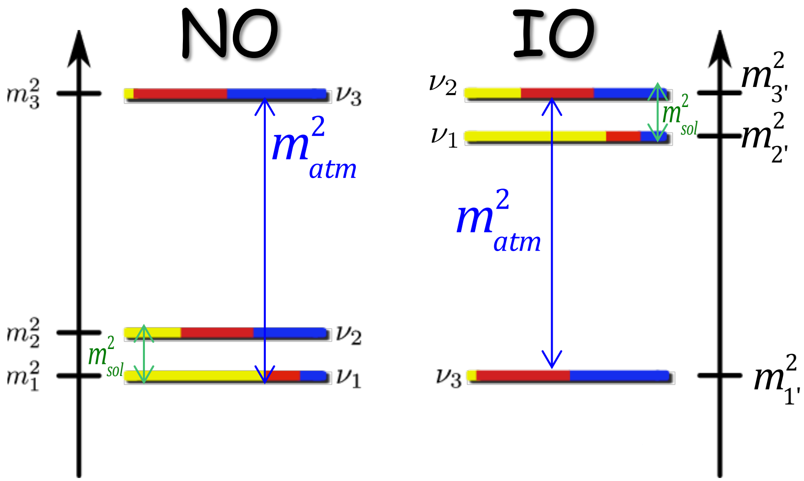
leptogenesis

Preamble

- A common statement in last years is that high scale leptogenesis is untestable.
- SO(10)-inspired leptogenesis provides a counter-example that clearly shows that, though challenging, it is possible, even just with standard low energy neutrino experiments, to have a high-scale leptogenesis scenario that is highly predictive, it is already tested now and has the potential for a high statistical significance support (or to be relatively quickly ruled out).
- Moreover new phenomenological avenues toward tests of high scale scenarios are now available and intensively explored, mainly GWs (talks by Domcke, Donsky, Turner,….)

Neutrino masses ($m_{1'}<m_{2'}<m_{3'}$)



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

$$IO: m_{2'} = \sqrt{m_{1'}^2 + m_{atm}^2 - m_{sol}^2}\,, \quad m_{3'} = \sqrt{m_{1'}^2 + m_{atm}^2}$$

m_{sol} = (8.6 ± 0.1) meV

m_{atm} = (50.0 ± 0.3) meV

(νfit 2021)

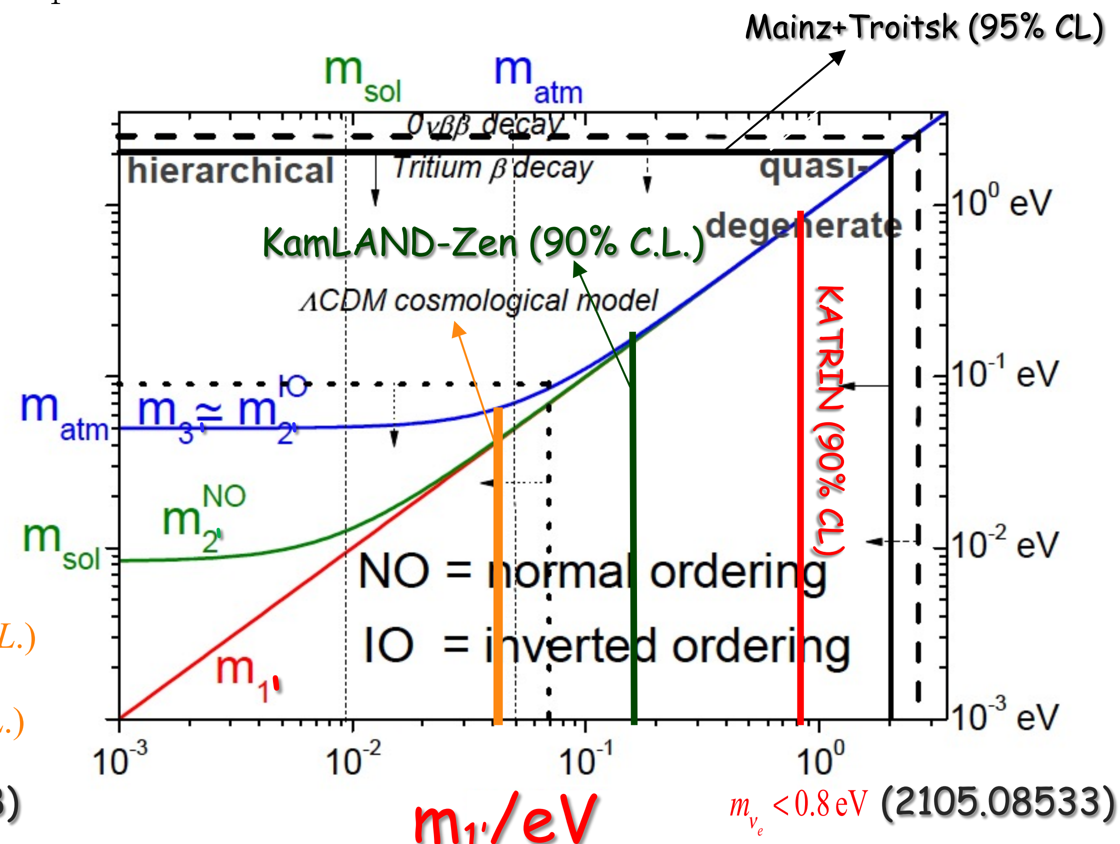
$$\sum_i m_i < 0.23\, eV \;\; (95\% C.L.)$$

$$\Rightarrow m_{1'} \leq 0.07\, eV$$ (Planck 2015)

$$\sum_i m_i < 0.146\, eV \;\Rightarrow\; m_{1'} \leq 0.041\,\text{eV} \quad (\text{NO}, 95\% C.L.)$$

$$\sum_i m_i < 0.172\, eV \;\Rightarrow\; m_{1'} \leq 0.042\,\text{eV} \quad (\text{IO}, 95\% C.L.)$$

(Choudury, Hannestad 1907.12598)



$m_{\nu_e} < 0.8\,\text{eV}$ (2105.08533)

Neutrino mixing parameters:

$$U_{\alpha i}=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}\begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma} \end{pmatrix}$$

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

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

Atmospheric, LB | Reactors, LB (CP violation) | Solar,Reactors | ββ0ν decay

$c_{ij}\equiv\cos\theta_{ij}\ ,\ s_{ij}\equiv\sin\theta_{ij}$

3σ ranges (NO)

$\theta_{12}=[31.27^\circ,35.86^\circ]$

$\theta_{13}=[8.20^\circ,8.97^\circ]$

$\theta_{23}=[39.5^\circ,52.0^\circ]$

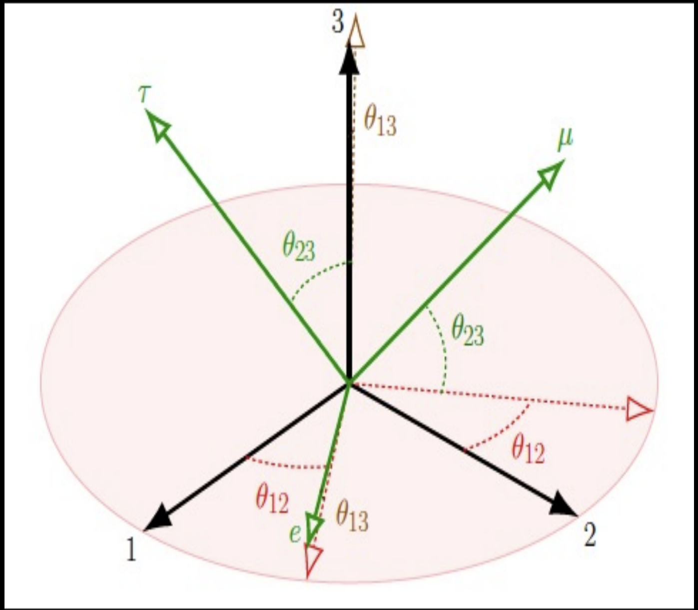
$\delta=[105^\circ,405^\circ]$

$\rho,\sigma=[0,360^\circ]$

(νfit October 2021, no SK atm. data)

NO just slightly favoured over IO:

$\Delta\chi^2$ (IO-NO)=2.6



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

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

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

$\Rightarrow$ neutrino masses: $m_i = m_{Di}$

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

<u>But many unanswered questions:</u>

- Why neutrinos are much lighter than all other fermions?
- Why large mixing angles (differently from CKM 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)

$$-\mathcal{L}^{\nu}_{\rm mass} = \overline{\nu_L}\, m_D\, \nu_R + \frac{1}{2}\overline{\nu_R^c}\, M\, \nu_R + \text{h.c.}$$

violates lepton number

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

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

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

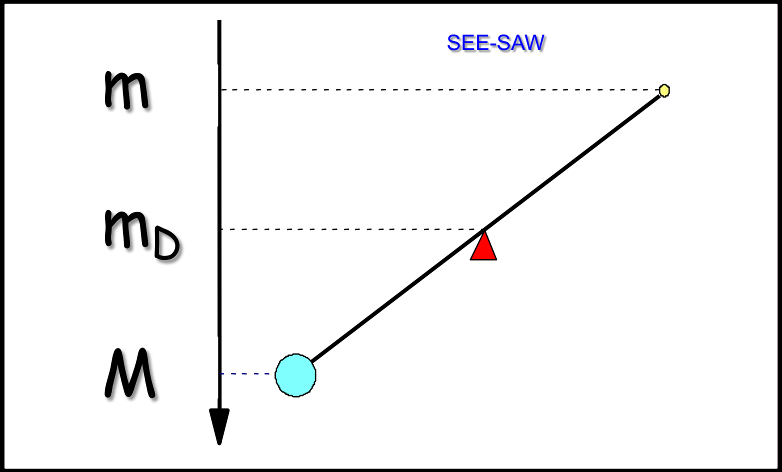
- 3(?) very heavy Majorana neutrinos N_I, N_{II}, N_{III} with $M_{III} > M_{II} > M_I \gg m_D$

1 generation toy model :

$m_D \sim m_{top}$,

$m \sim m_{atm} \sim 50$ meV

$\Rightarrow M \sim M_{GUT} \sim 10^{16}$ GeV



3 generation seesaw models: two limits

In the flavour basis (both charged lepton mass and Majorana mass matrices are diagonal):

$$-\mathcal{L}_{\rm mass}^{\nu+\ell} = \overline{\alpha_L}\, m_\alpha\, \alpha_R + \overline{\nu_{L\alpha}}\, m_{D\alpha I}\, \nu_{RI} + \frac{1}{2}\,\overline{\nu^c_{RI}}\, M_I\, \nu_{RI} + \text{h.c.}$$

$\alpha = e, \mu, \tau$

$I = 1,2,3$

bi-unitary parameterisation: $m_D = V_L^\dagger D_{m_D} U_R \qquad D_{m_D} \equiv diag(m_{D1}, m_{D2}, m_{D3})$

FIRST (EASY) LIMIT: ALL MIXING FROM THE LEFT-HANDED SECTOR

- $U_R = I \;\Rightarrow\;$ again $U = V_L^\dagger$ and neutrino masses: $m_i = \dfrac{m_{Di}^2}{M_I}$

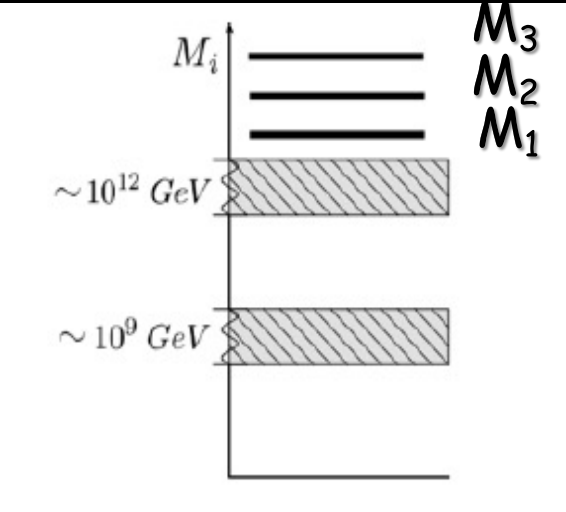
If also $m_{D1} = m_{D2} = m_{D3} = \lambda$ then simply: $M_I = \dfrac{\lambda^2}{m_i}$

Exercise: $\lambda \sim 100\, GeV$

$m_1 \sim 10^{-4}\, eV \qquad \Rightarrow M_3 \sim 10^{17}\, GeV$

$m_2 = m_{sol} \sim 10\, meV \Rightarrow M_2 \sim 10^{15}\, GeV$

$m_3 = m_{atm} \sim 50\, meV \Rightarrow M_1 \sim 10^{14}\, GeV$



Typically RH neutrino mass spectrum emerging in simple discrete flavour symmetry models

A SECOND LIMIT: ALL MIXING FROM THE RH SECTOR

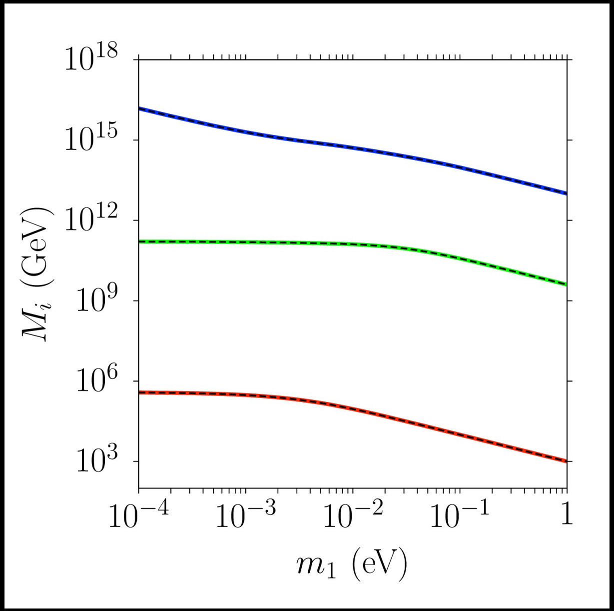
(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03; PDB, Riotto '08; PDB, Re Fiorentin '12)

- $V_L = I \Rightarrow M_1 = \frac{m_{D1}^2}{m_{\beta\beta}}; \quad M_2 = \frac{m_{D2}^2}{m_1 m_2 m_3} \frac{m_{\beta\beta}}{|(m_\nu^{-1})_{\tau\tau}|}; \quad M_3 = m_{D3}^2 |(m_\nu^{-1})_{\tau\tau}|$

If one also imposes (SO(10)-inspired models)

$$m_{D1} = \alpha_1 m_{up}; \quad m_{D2} = \alpha_2 m_{charm}; \quad m_{D3} = \alpha_3 m_{top}; \quad \alpha_i = O(1)$$

Barring very fine-tuned solutions, one obtains a very hierarchical RH neutrino mass spectrum



Combining discrete flavour + grand unified symmetries one can obtain basically all mass spectra between these two limits (we will be back on this)

WHAT CAN HELP TESTING THE EXISTENCE OF HEAVY RH NEUTRINOS AND THEIR MASS SPECTRUM?

Minimal scenario of leptogenesis

(Fukugita,Yanagida '86)

- Type I seesaw mechanism
- Thermal production of RH neutrinos: $T_{RH} \gtrsim T_{lep} \simeq M_i / (2 \div 10)$

heavy neutrinos decay $N_I \xrightarrow{\Gamma_I} L_I + \phi^\dagger \qquad N_I \xrightarrow{\overline{\Gamma}} \overline{L}_I + \phi$

total CP asymmetries $\varepsilon_I \equiv -\frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$ $\Rightarrow N_{B-L}^{fin} = \sum_{I=1,2,3} \varepsilon_I \times \kappa_I^{fin}$

efficiency factors

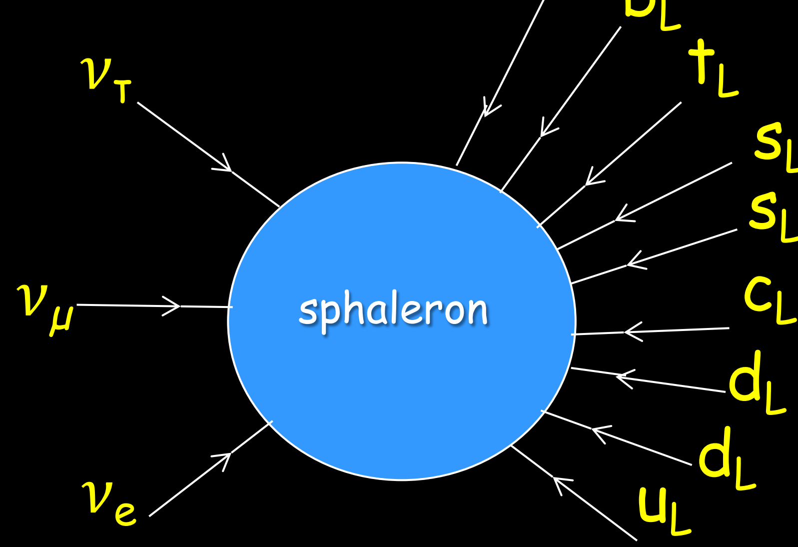
- Sphaleron processes in equilibrium

$\Rightarrow \; T_{lep} \gtrsim T^{off}_{sphalerons} \simeq 132$ GeV

(Kuzmin,Rubakov,Shaposhnikov '85
D'Onofrio, Rummukainen, Tranberg 1404.3565)

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

$\Delta B = \Delta L = 3$



Seesaw parameter space

Combining $\eta_{B0}^{lep} \simeq \eta_{B0}^{CMB} \simeq 6\times 10^{-10}$ with low energy neutrino data can we test seesaw and leptogenesis?

(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: *low-scale* leptogenesis, potential direct discovery of RH neutrinos in lab neutrino experiments (but no signs so far).
- *High-scale* leptogenesis is challenging to test but there are a few strategies able to reduce the number of parameters in order to obtain testable predictions on low energy neutrino parameters

Vanilla leptogenesis ⇒ upper bound on ν masses

(Buchmüller,PDB,Plümacher '04; Blanchet, PDB '07)

1) Lepton flavor composition is neglected

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

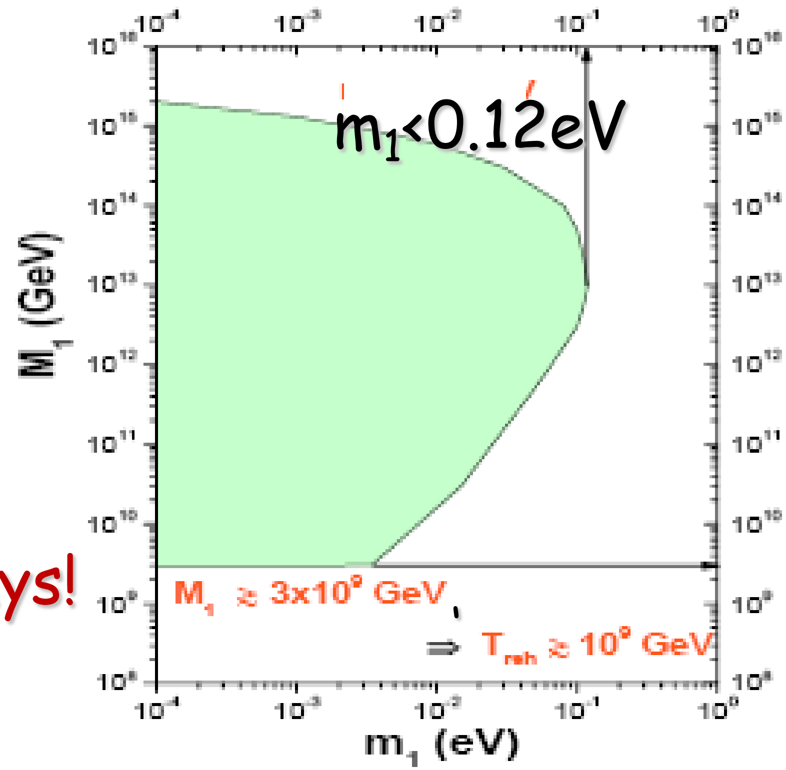
All the asymmetry is generated by the lightest RH neutrino decays!

4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

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

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



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

IS SO(10)-INSPIRED LEPTOGENESIS RULED OUT ?

Independence of the initial conditions

(Buchmüller,PDB,Plümacher '04)

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

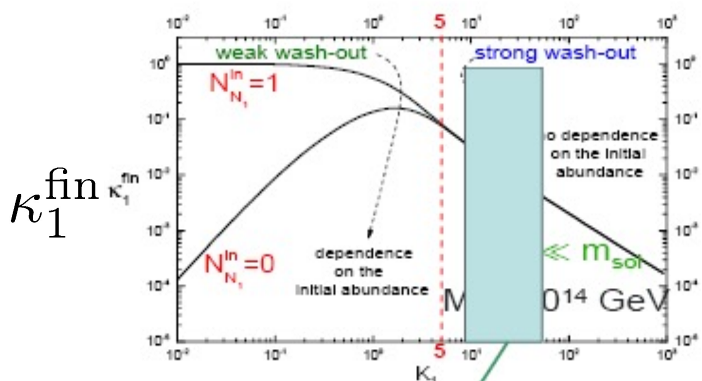
$$N_{B-L}^{\rm p,final} = N_{B-L}^{\rm p,initial}\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1}$$

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

Just a coincidence?

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

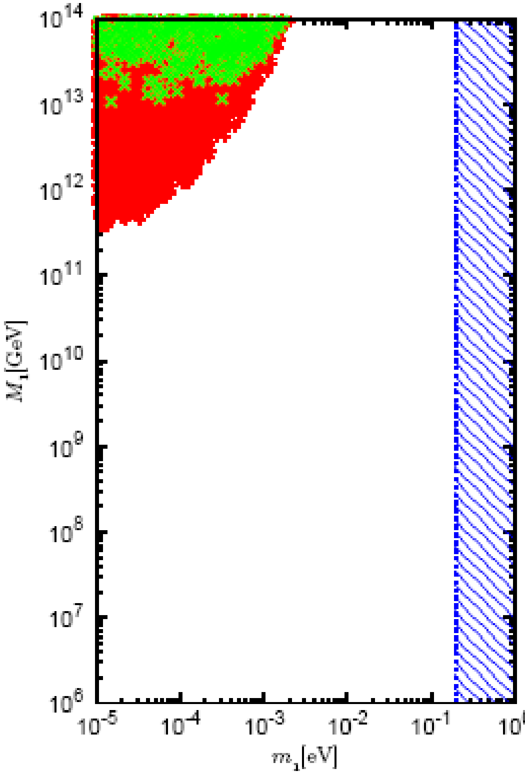
Independence of the initial N_1 abundance



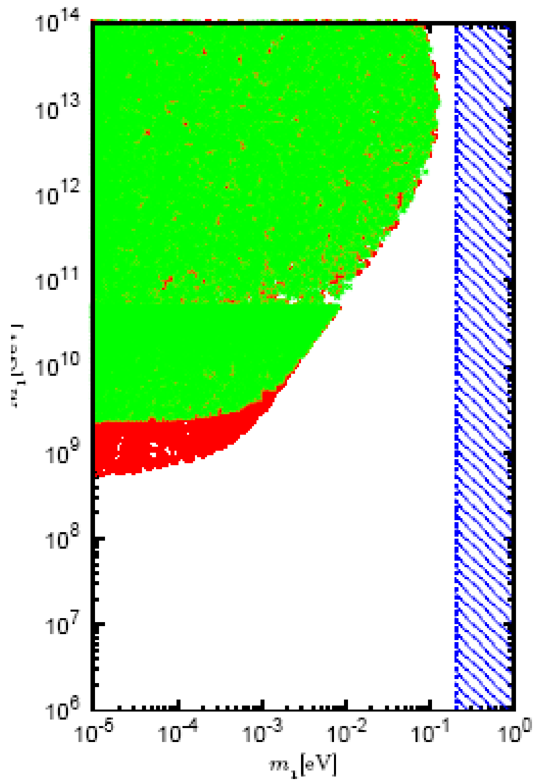
$K_{\rm sol} \simeq 9 \lesssim K_1 \lesssim 50 \simeq K_{\rm atm}$

Leptogenesis "conspiracy"

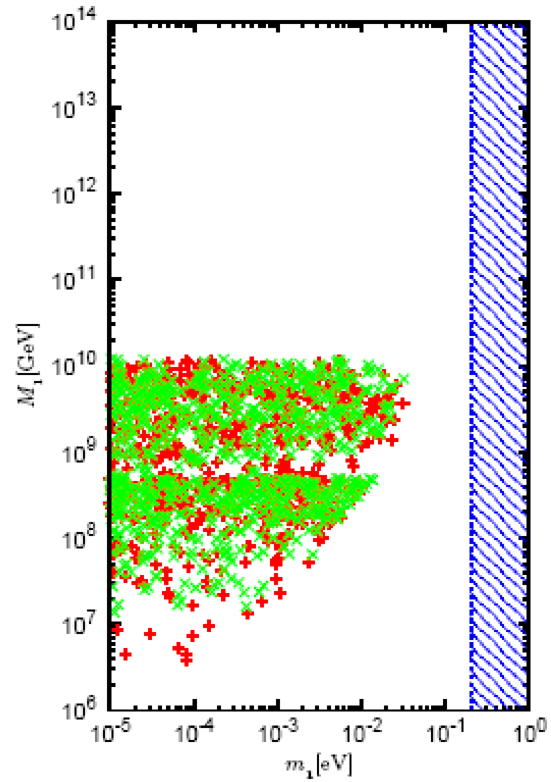
$m_{atm} = 10^{-5}\ eV$



$m_{atm} = 0.05\ eV$



$m_{atm} = 10\ eV$



Green points: Unflavored

Red points: Flavored

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!

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

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

- ❑ **$T \ll 10^{12}$ 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

- ❑ $T \ll 10^9$ GeV then also μ-Yukawas in equilibrium ⇒ **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) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1e+\mu}\kappa_1^{fin}(K_{1e+\mu})$

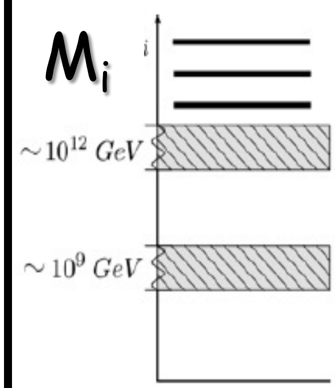
~ 10^{9} GeV — TRANSITION REGIME: DENSITY MATRIX APPROACH NEEDED

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

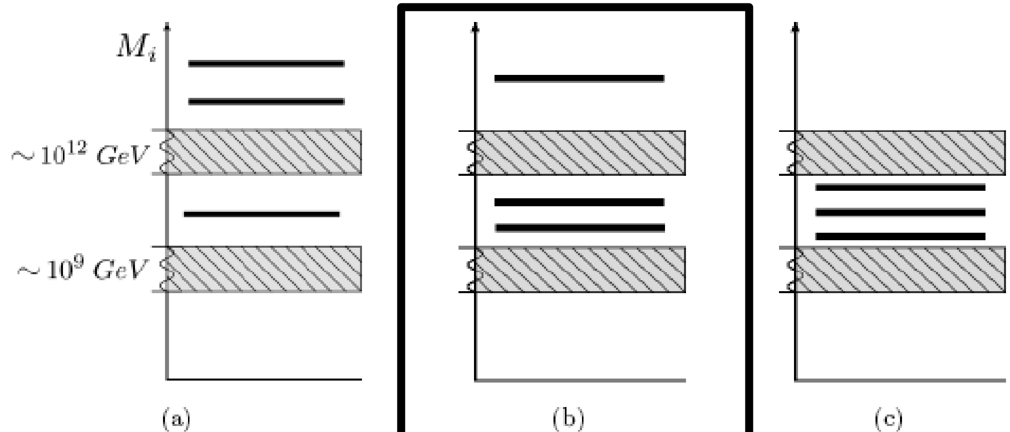
Heavy neutrino lepton flavour effects: 10 scenarios

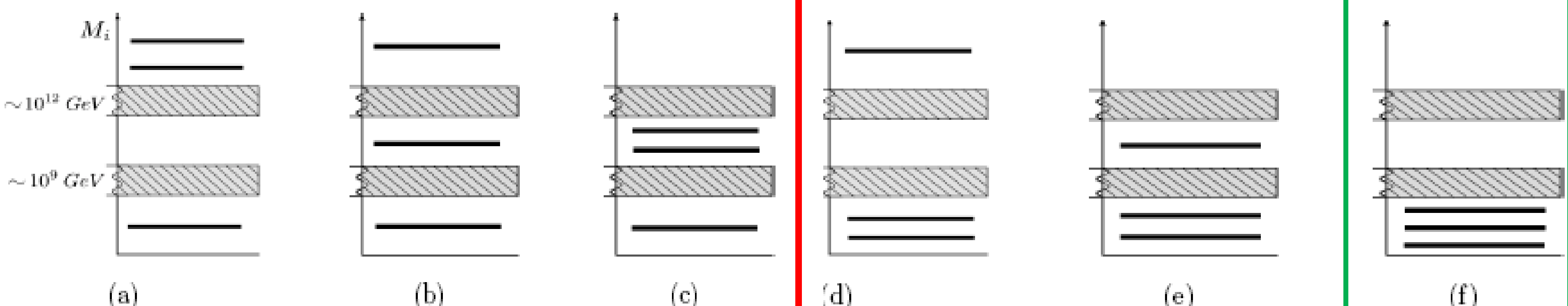
Typically rising in discrete flavour symmetry models

Heavy neutrino flavored scenario



2 RH neutrino scenario





N_2-dominated scenario:

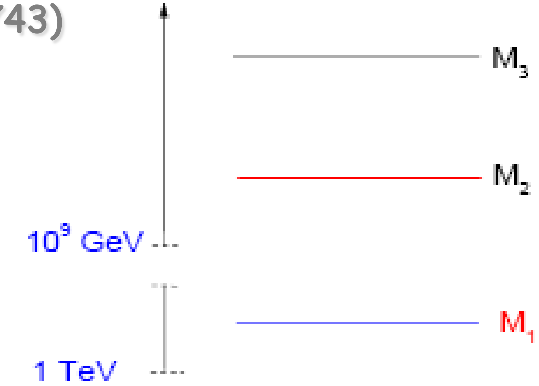
☛ N_1 produces negligible asymmetry;

Low scale leptogenesis

Examples: Resonant+ ARS leptogenesis

N_2-leptogenesis

(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

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

- With flavor effects the domain of successful N_2 dominated leptogenesis greatly enlarges: the probability that $K_1 < 1$ is less than 0.1% but the probability that either K_{1e} or $K_{1\mu}$ or $K_{1\tau}$is less than 1 is ~23%

  (PDB, Michele Re Fiorentin, Rome Samanta)

- Existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$'s not to be negligible

- It is the only hierarchical scenario that can realise strong thermal leptogenesis (independence of the initial conditions) if the asymmetry is tauon-dominated and if $m_1 \gtrsim 10$ meV (corresponding to $\Sigma_i m_i \gtrsim 80$meV)

  (PDB, Michele Re Fiorentin, Sophie King arXiv 1401.6185)

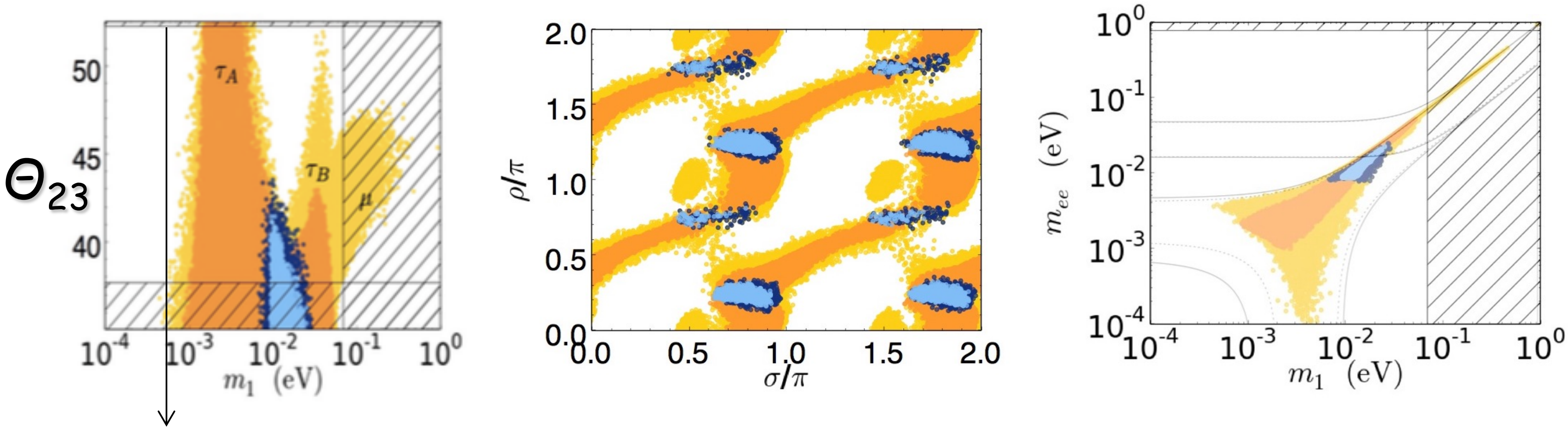
- N_2-leptogenesis rescues SO(10)-inspired models!

N_2-leptogenesis rescues SO(10)-inspired leptogenesis

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

- dependence on α_1 and α_3 cancels out $\Rightarrow$ the asymmetry depends only on $\alpha_2 \equiv m_{D2}/m_{charm}$: $\eta_B \propto \alpha_2^2$

$\alpha_2=5$ NORMAL ORDERING $I \leq V_L \leq V_{CKM}$ $V_L = I$



- ➤ Lower bound $m_1 \gtrsim 10^{-3}$ eV
- ➤ θ_{23} upper bound

- ➤ Majorana phases constrained about specific regions

- ➤ Effective $0\nu\beta\beta$ mass can still vanish but bulk of points above meV

- ➤ INVERTED ORDERING IS NOW EXCLUDED
- ➤ Strong thermal leptogenesis is realised for a subset (blue regions)
- ➤ Muon-dominated solution appear for $V_L \neq I$

Imposing SO(10)-inspired conditions

Seesaw formula

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

Leptonic mixing matrix

$$U^\dagger \, m_\nu \, U^\star = -D_m$$

Bi-unitary parameterisation

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

SO(10)-inspired conditions

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

Majorana mass matrix
(in the Yukawa basis)

$$U_R^\star \, D_M \, U_R^\dagger \; = M = D_{m_D} \, V_L^\star \, U^\star \, D_m^{-1} \, U^\dagger \, V_L^\dagger \, D_{m_D} \simeq -D_{m_D} \, m_\nu^{-1} \, D_{m_D}$$

RH neutrino mass spectrum (V_L=I)

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

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

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

0νββ neutrino mass

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

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

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

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

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

Decrypting SO(10)-inspired leptogenesis (V_L=I)

(PDB, Re Fiorentin, Marzola,1411.5478)

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

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

$K_{1\tau}$

SO(10)-inspired leptogenesis phase

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

successful leptogenesis condition

$$\eta_B^{SO10\,lep}(m_1,m_{sol},m_{atm},\theta_{12},\theta_{23},\theta_{13},\delta,\rho,\sigma;\alpha_2)=\eta_B^{\rm obs}$$

This condition identifies an hypersurface in the space of low energy neutrino parameters

All numerical results are accurately reproduced for V_L=I

In particular, one has a strong tau-dominance:

$$\varepsilon_{2\tau}:\varepsilon_{2\mu}:\varepsilon_{2e} = \alpha_3^2\,m_t^2 : \alpha_2^2\,m_c^2 : \alpha_1^2\,m_u^2\,\frac{\alpha_3 m_t}{a_2\,m_c}\,\frac{\alpha_1^2\,m_u^2}{\alpha_2^2\,m_c^2}\,.$$

Some insight into τ solutions

They split into two (bordering) regions. Both of course realise the crucial condition $K_{1\tau} \lesssim 1$ but in a different way:

τ_A solutions:

- 1 meV $\lesssim m_1 \lesssim$ 30 meV
- $K_{2\tau} \gtrsim 20$ (strong washout at the production)
- $2\sigma - \delta \simeq 2n\pi$ (n integer) for $m_1 \ll m_{sol}$
- They can realise strong thermal leptogenesis for $m_1 \gtrsim 10$ meV

τ_B solutions:

- 30 meV $\lesssim m_1 \lesssim$ 70 meV
- $1 \leq K_{2\tau} \lesssim 10$ (mild washout at the production)
- $\rho \simeq 2n\pi$ (n integer)
- They cannot realise strong thermal leptogenesis since $K_{1\mu} \lesssim 4$ (they cannot wash-out efficiently a large pre-existing muonic asymmetry)

Turning on a mismatch between neutrino Yukawa and weak basis ($V_L \neq 1$)

$$V_L = \begin{pmatrix} c_{12}^L c_{13}^L & s_{12}^L c_{13}^L & s_{13}^L e^{-i\delta_L} \\ -s_{12}^L c_{23}^L - c_{12}^L s_{23}^L s_{13}^L e^{i\delta_L} & c_{12}^L c_{23}^L - s_{12}^L s_{23}^L s_{13}^L e^{i\delta_L} & s_{23}^L c_{13}^L \\ s_{12}^L s_{23}^L - c_{12}^L c_{23}^L s_{13}^L e^{i\delta_L} & -c_{12}^L s_{23}^L - s_{12}^L c_{23}^L s_{13}^L e^{i\delta_L} & c_{23}^L c_{13}^L \end{pmatrix} \begin{pmatrix} e^{i\rho_L} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma_L} \end{pmatrix}$$

$$s_{ij}^L \equiv \sin\theta_{ij}^L \,, \;\; c_{ij}^L \equiv \cos\theta_{ij}^L$$

By definition in SO(10)-inspired leptogenesis: $0 \leq \theta^L_{ij} \lesssim \theta^{CKM}_{ij}$ ($\Leftrightarrow I \leq V_L \lesssim V_{CKM}$)

The upper bounds are not strictly determined, as far as the RH neutrino mass spectrum is such that one can assume N_2-dominated leptogenesis.

Full analytical solution (relaxing V_L=I): RH neutrino mass spectrum and mixing matrix

light neutrino mass matrix in the Yukawa basis

$$m_\nu \to \tilde{m}_\nu = V_L m_\nu V_L^T$$

RH neutrino masses

$$M_1 \simeq \frac{\alpha_1^2 m_u^2}{|(\tilde{m}_\nu)_{11}|}, \quad M_2 \simeq \frac{\alpha_2^2 m_c^2}{m_1 m_2 m_3} \frac{|(\tilde{m}_\nu)_{11}|}{|(\tilde{m}_\nu^{-1})_{33}|}, \quad M_3 \simeq \alpha_3^2 m_t^2 \, |(\tilde{m}_\nu^{-1})_{33}|$$

RH neutrino phases

$$\Phi_1 \simeq -\mathrm{Arg}[-(\tilde{m}_\nu)^*_{11}], \; \Phi_2 \simeq \mathrm{Arg}\left[\frac{(\tilde{m}_\nu)_{11}}{(\tilde{m}_\nu^{-1})_{33}}\right] - 2(\rho+\sigma) - 2(\rho_L + \sigma_L), \; \Phi_3 \simeq \mathrm{Arg}[(\tilde{m}_\nu^{-1})_{33}]$$

RH neutrino mixing matrix

$$U_R \simeq \begin{pmatrix} 1 & -\frac{m_{D1}}{m_{D2}} \frac{(\tilde{m}_\nu)^*_{12}}{(\tilde{m}_\nu)^*_{11}} & \frac{m_{D1}}{m_{D3}} \frac{(\tilde{m}_\nu^{-1})^*_{13}}{(\tilde{m}_\nu^{-1})^*_{33}} \\ \frac{m_{D1}}{m_{D2}} \frac{(\tilde{m}_\nu)_{12}}{(\tilde{m}_\nu)_{11}} & 1 & \frac{m_{D2}}{m_{D3}} \frac{(\tilde{m}_\nu^{-1})^*_{23}}{(\tilde{m}_\nu^{-1})^*_{33}} \\ \frac{m_{D1}}{m_{D3}} \frac{(\tilde{m}_\nu^{-1})_{13}}{(\tilde{m}_\nu^{-1})_{33}} & -\frac{m_{D2}}{m_{D3}} \frac{(\tilde{m}_\nu^{-1})_{23}}{(\tilde{m}_\nu^{-1})_{33}} & 1 \end{pmatrix} D_\Phi \;, \quad D_\Phi \equiv \left(e^{-i\frac{\Phi_1}{2}}, e^{-i\frac{\Phi_2}{2}}, e^{-i\frac{\Phi_3}{2}}\right)$$

Full analytical solution for the asymmetry ($I \le V_L \lesssim V_{CKM}$)

Flavoured decay parameters

$$K_{I\alpha} = \frac{\sum_{k,l} m_{Dk} m_{Dl} V_{Lk\alpha} V^*_{Ll\alpha} U^*_{RkI} U_{Rli}}{M_I m_*}$$

Flavoured CP asymmetries

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

Final B-L asymmetry

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

This time one has: $\eta_B^{SO10\,lep}(m_1, m_{sol}, m_{atm}, \theta_{12}, \theta_{23}, \theta_{13}, \delta, \rho, \sigma; \alpha_2, V_L) = \eta_B^{\mathrm{obs}}$

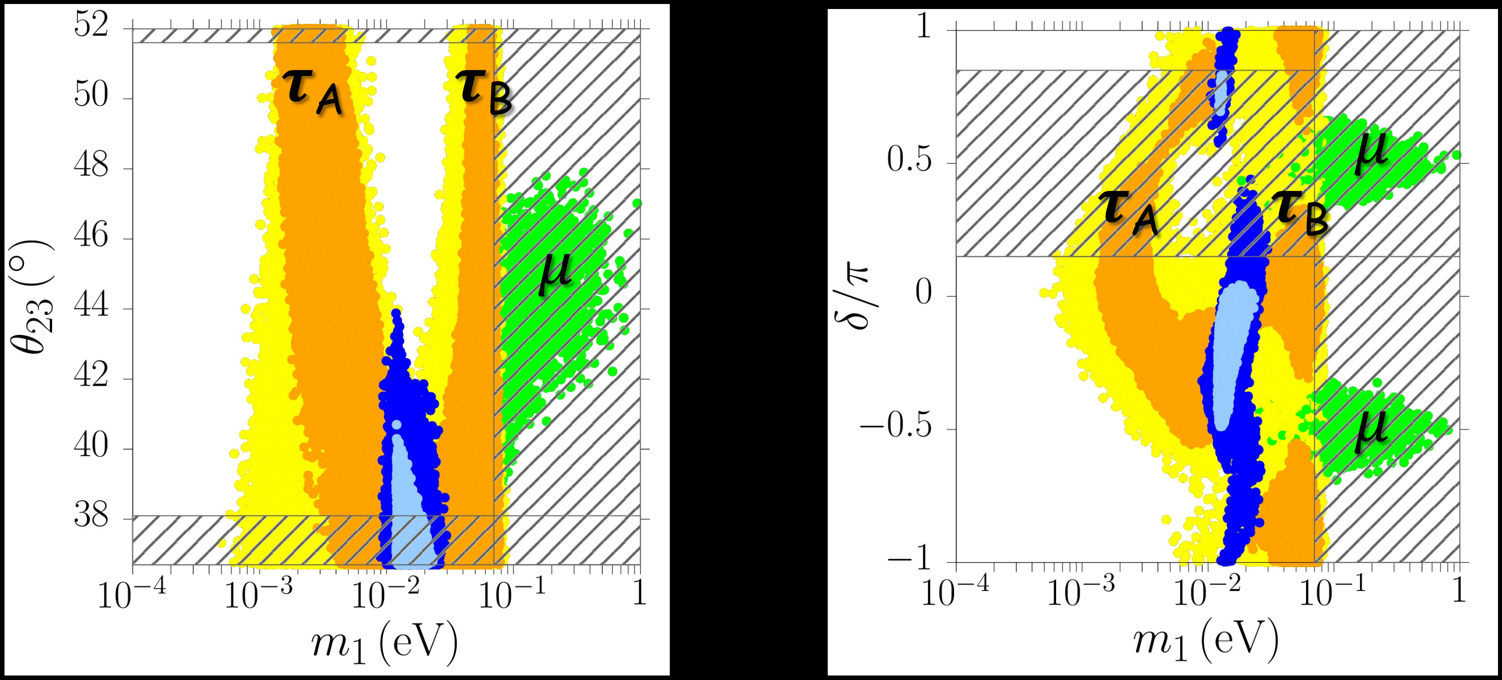
The dependence on the 6 parameters in V_L give some thickness to the hypersurface that becomes a layer but the smallness of the θ^L_{ij} however still make in a way that constraints do relax but in general do not evaporate.

Also notice that now: $\varepsilon^{\max}_{2e} : \varepsilon^{\max}_{2\mu} : \varepsilon^{\max}_{2\tau} \simeq 1 : |V_{L23}| : |V_{L21} V_{L31}|$

This explains why tauon solutions are still favoured but this time also muon solutions appear and in the supersymmetric case even very marginal electron solutions

SO(10)-inspired leptogenesis confronting long baseline and absolute neutrino mass experiments

α_2=5

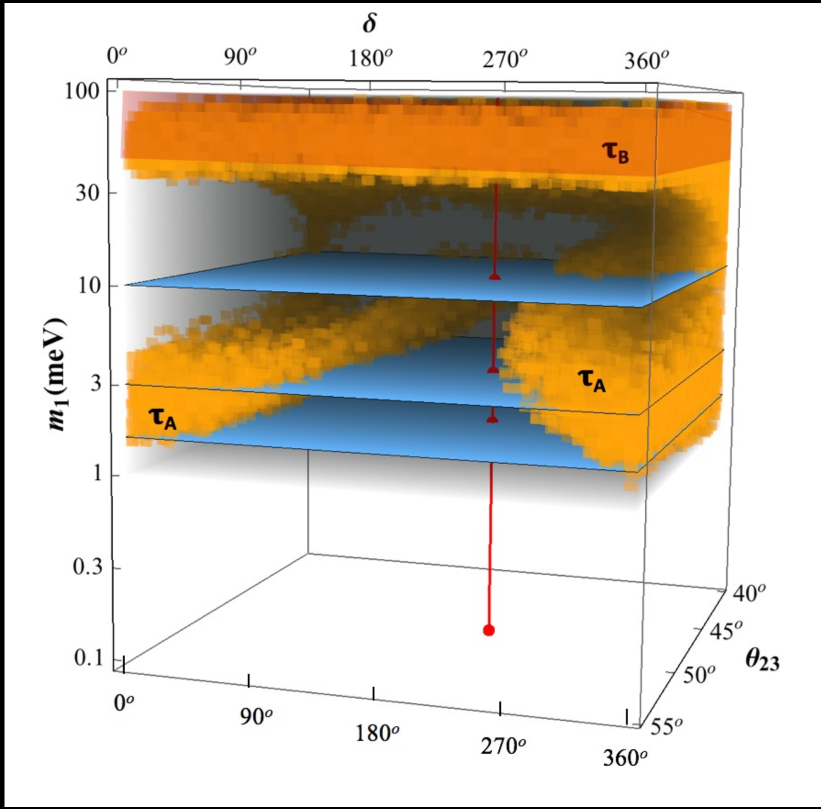


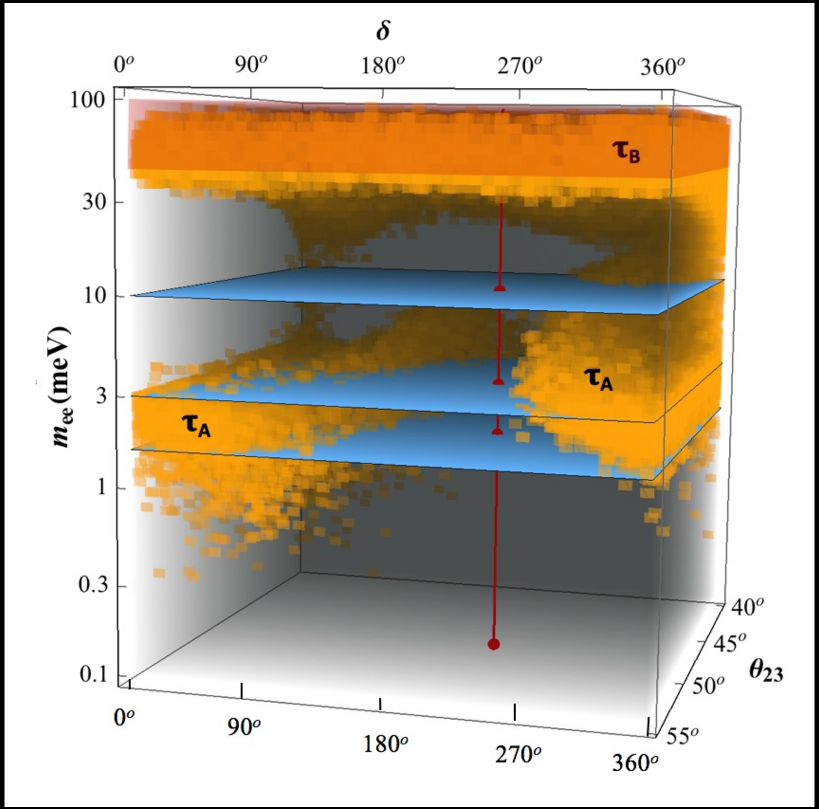
Projecting the allowed region (an hypersurface in the space of neutrino parameters) on planes can hide a more complex structure corresponding potentially to stronger predictions.

SO(10)-inspired leptogenesis confronting long baseline and absolute neutrino mass experiments.....in 3D

(PDB, R. Samanta 2005.03057)

α_2=5



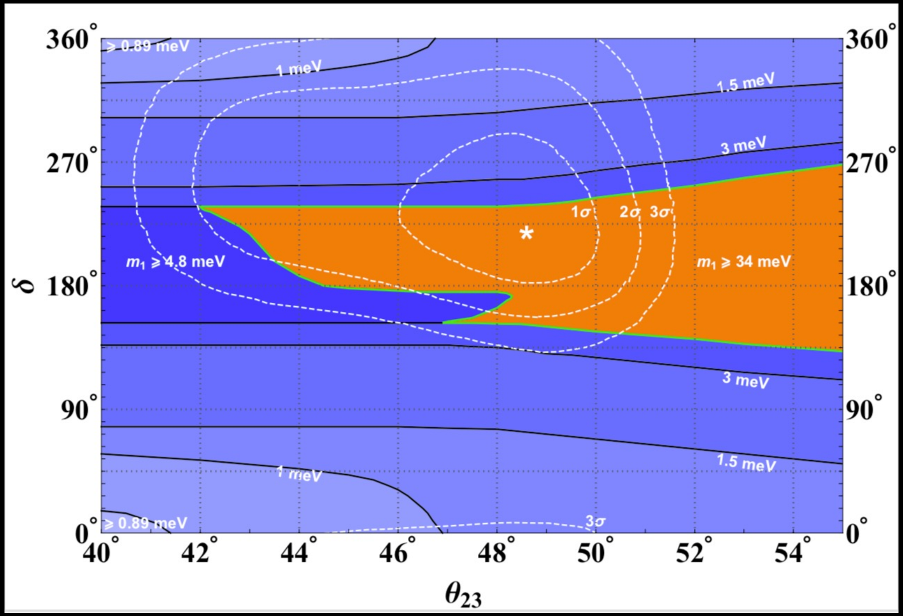


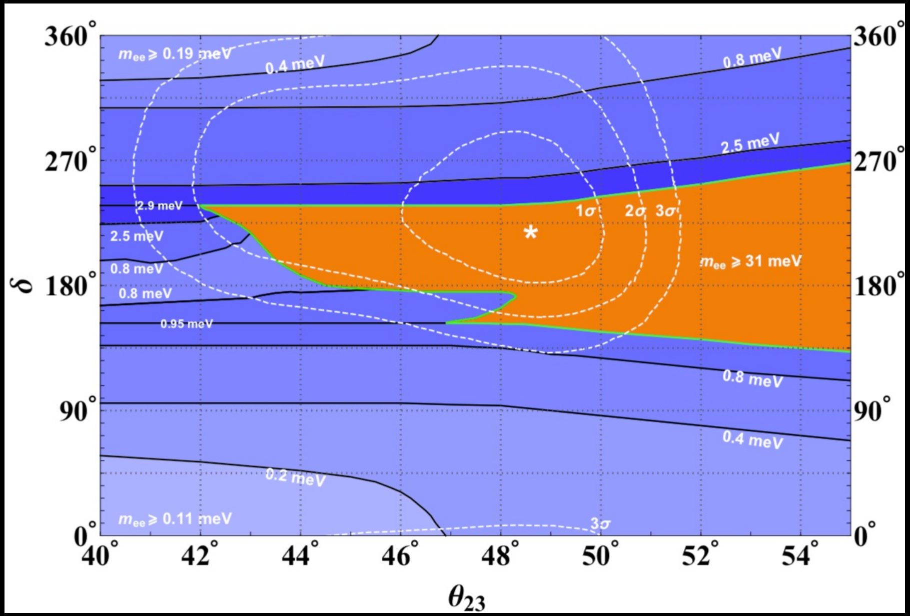
For certain values of δ and θ_{23} the lower bound on the absolute neutrino mass scale is much more stringent: $m_1, m_{ee} \gtrsim 30$ meV

SO(10)-inspired leptogenesis: lower bound on the absolute neutrino mass scale as a function of δ and θ_{23}

(PDB, R. Samanta 2005.03057)

$\alpha_2=5$





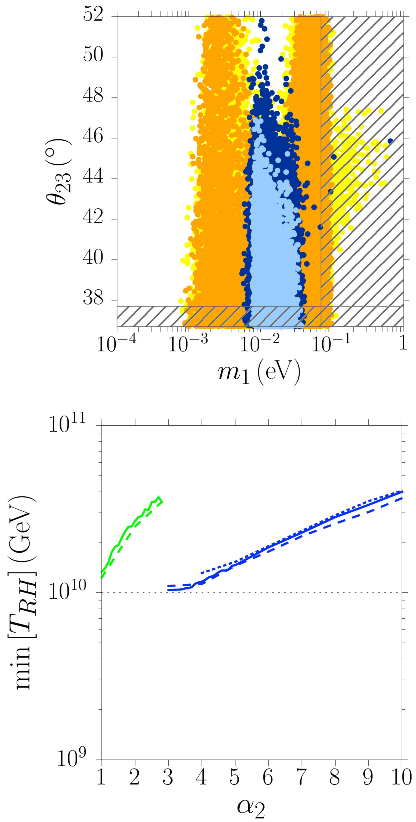
Future precise measurements of δ and θ_{23} will have an important impact on SO(10)-inspired leptogenesis, in particular a precise determination of δ might be crucial. Ultimately if measured neutrino mixing parameters will lie on the hypersurface (implying $0\nu\beta\beta$ discovery) a strong case for discovery can be made (this has to take into account also θ_{13}, θ_{12}, m_{sol}, m_{atm})

Notice that CP conserving values of δ are possible since CP violation comes from high energy phases (they can be identified with those in the orthogonal matrix)

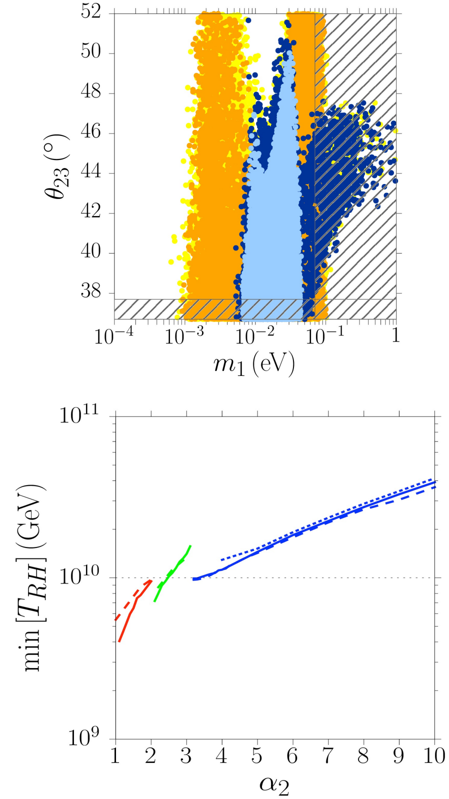
SUSY SO(10)-inspired leptogenesis

(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

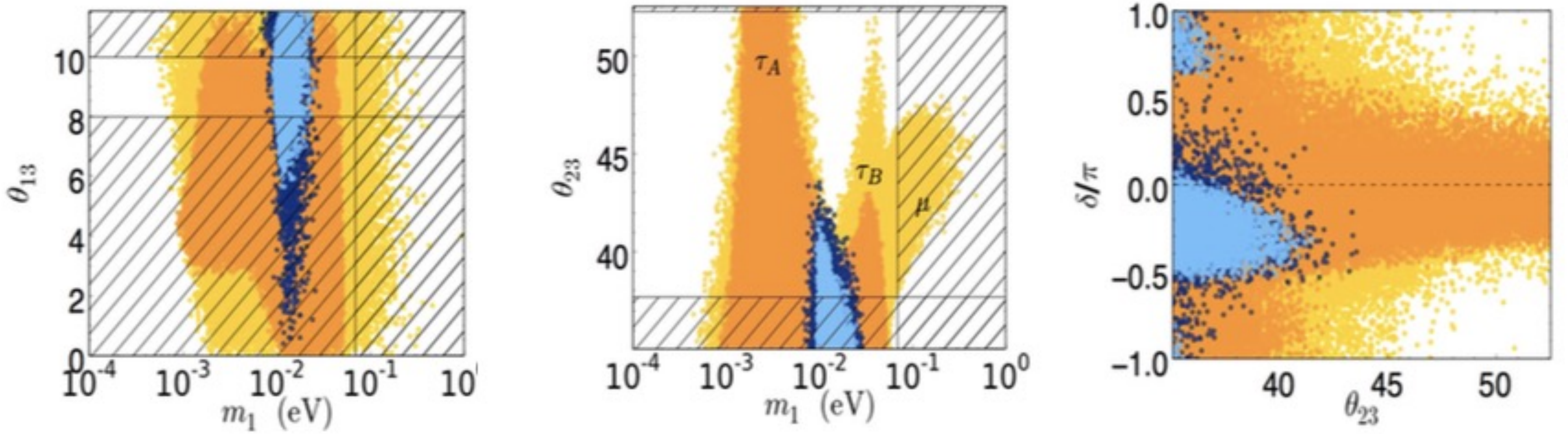
(Blanchet,Marfatia 1006.2857)

Strong thermal SO(10)-inspired leptogenesis

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

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

$\alpha_2=5$ ❑ blue regions: $N_{B-L}^{pre-ex}=10^{-3}$ ($I \leq V_L \leq V_{CKM}$; $V_L=I$)



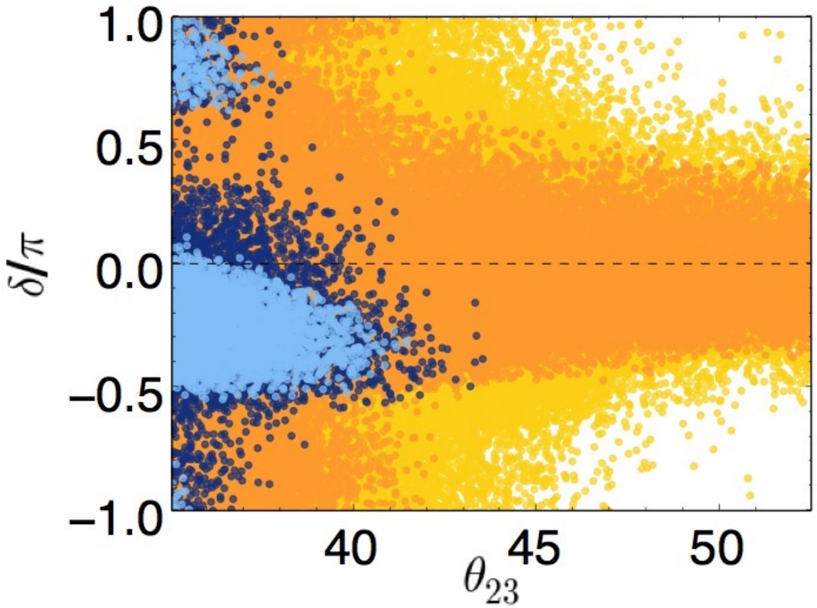
- Absolute neutrino mass scale: $8 \lesssim m_1/\text{meV} \lesssim 30 \Leftrightarrow 70 \lesssim \sum_i m_i/\text{meV} \lesssim 120$
- Non-vanishing Θ_{13} (first results presented before Daya Bay discovery)
- Θ_{23} preferably in the first octant;

Why do we live in a matter (and not antimatter) dominated universe?

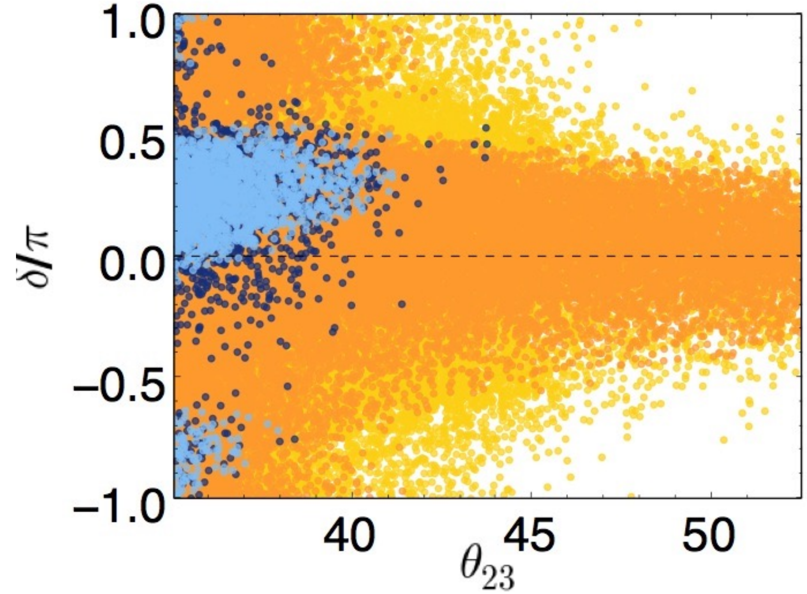
(PDB, Marzola, Re Fiorentin, 1411.5478)

$\alpha_2=5$ ❑ blue regions: $N_{B-L}^{pre-ex}=10^{-3}$ ($I \leq V_L \leq V_{CKM}$; $V_L=I$)

Matter dominated universe ($\eta_B \sim +\, 6\times10^{-10}$)



Antimatter dominated universe ($\eta_B \sim -\, 6\times10^{-10}$)



For sufficiently large θ_{23} one has sign(η_B)=-sign(sin δ)

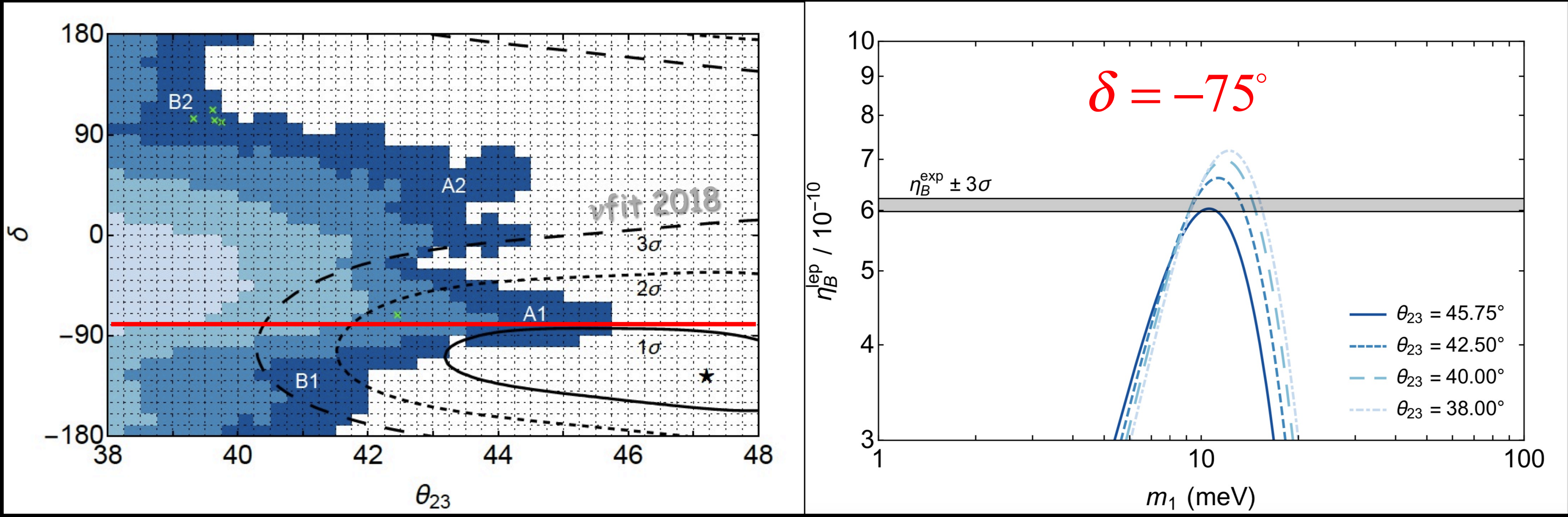
⇒ We would live in a matter dominated universe because sin δ < 0

Strong SO(10)-inspired leptogenesis confronting long baseline experiments

(PDB, Marco Chianese 1802.07690)

Pre-existing initial asymmetry: $N_{B-L}^{p,i} = 10^{-3}$

$$\alpha_2 = m_{D2} / m_{charm} = 5$$



"The more stringent experimental lower bound on atmospheric mixing angle starts to corner STSO10-leptogenesis"

Strong SO(10)-inspired leptogenesis confronting long baseline experiments

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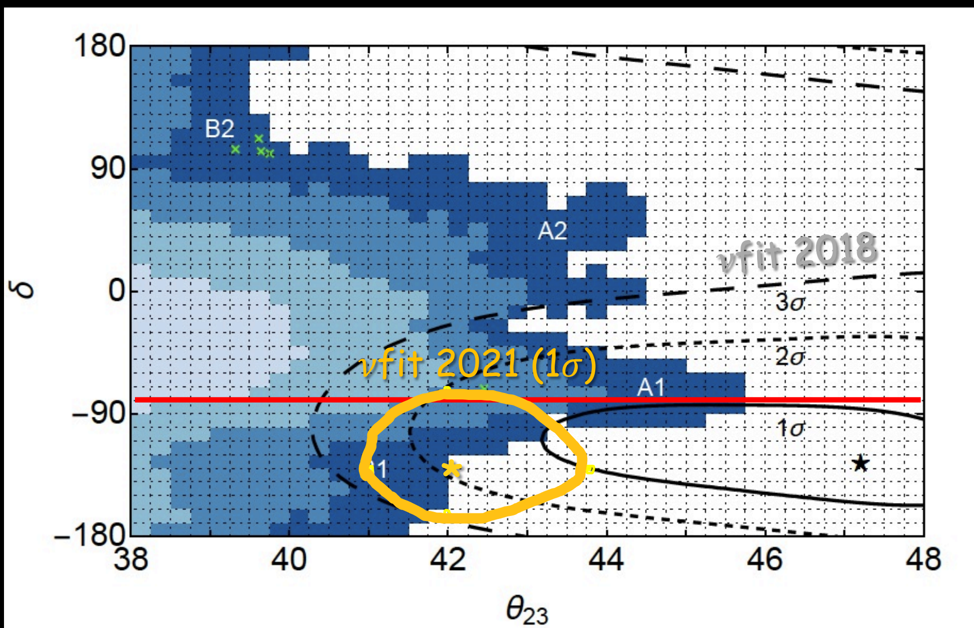
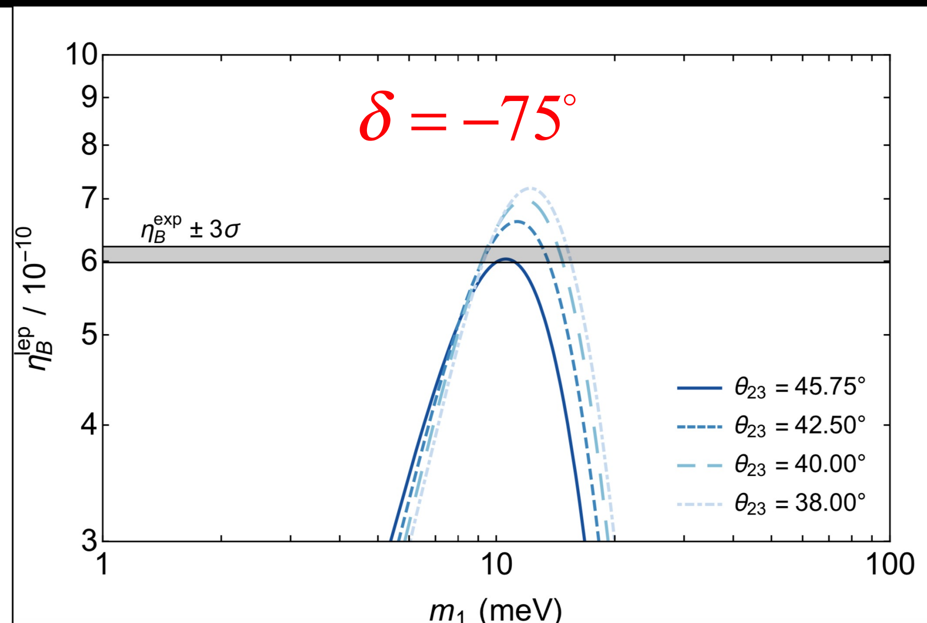




"The more stringent experimental lower bound on atmospheric mixing angle starts to corner STSO10-leptogenesis"

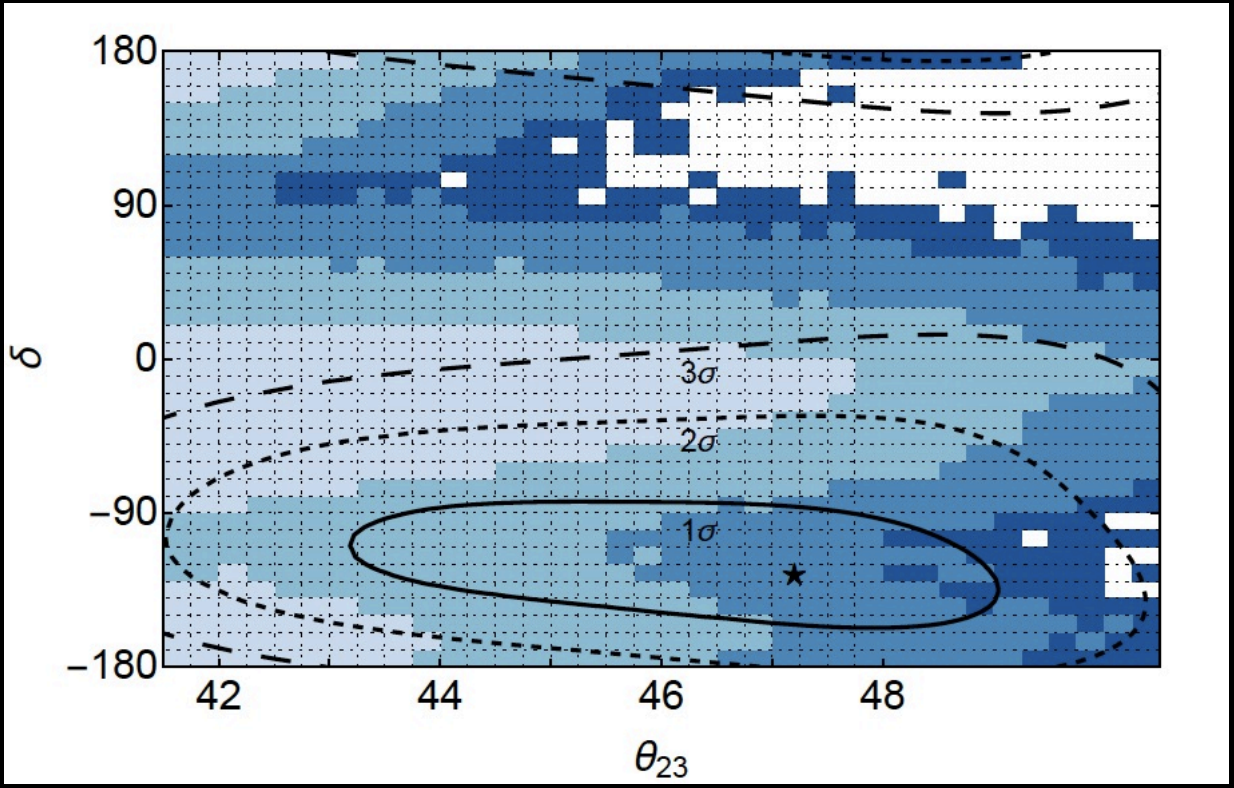
However new SK atmospheric data seem to favour first octant if combined in global analysis (νfit October 2021) and moreover

$\Delta\chi^2$ (IO-NO)=7.0

Strong SO(10)-inspired leptogenesis confronting long baseline experiments
(PDB, Marco Chianese 1802.07690)

Pre-existing initial asymmetry: $N_{B-L}^{p,i} = 10^{-3}$

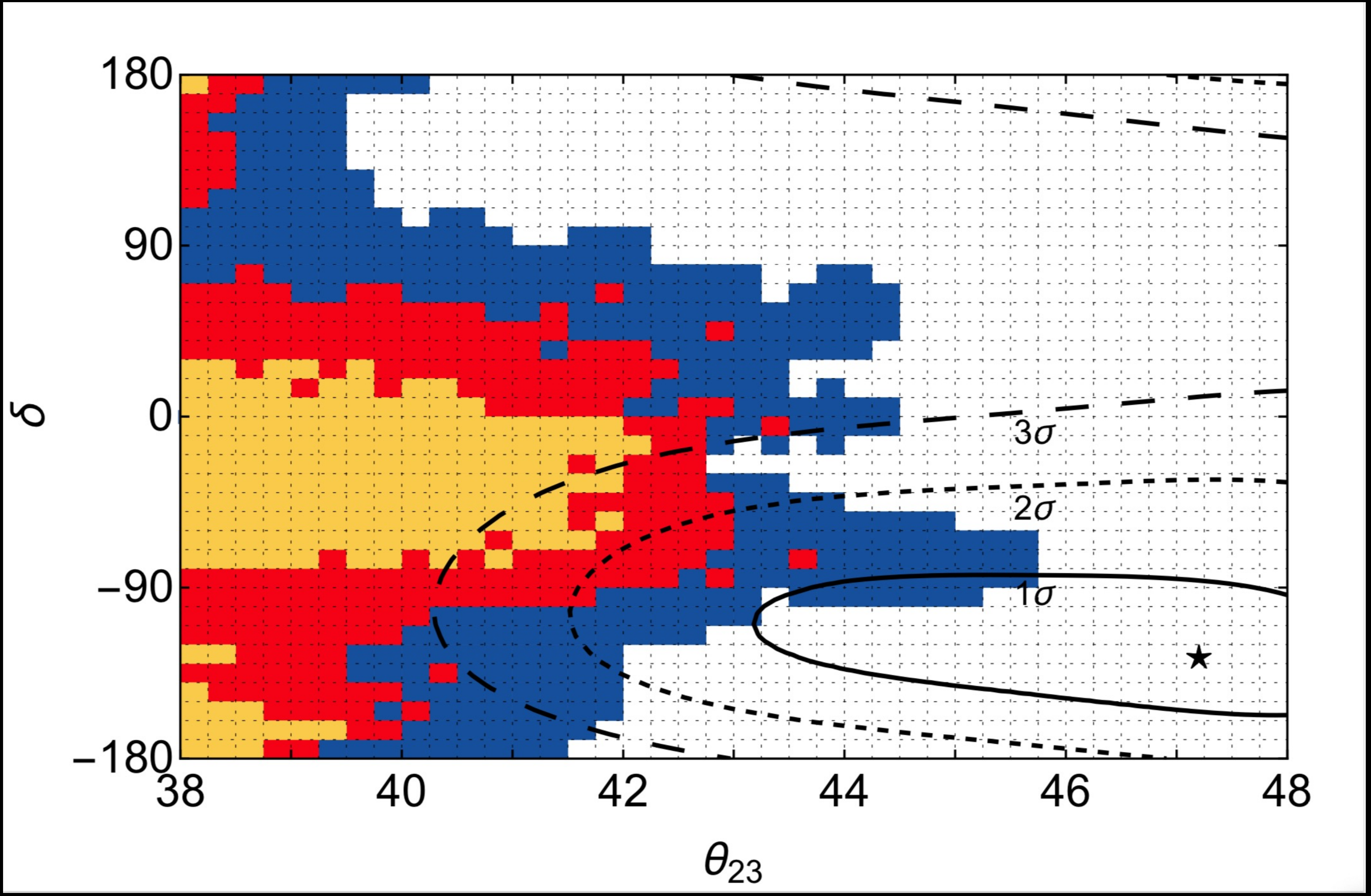
$$\alpha_2 = m_{D2} / m_{charm} = 6$$



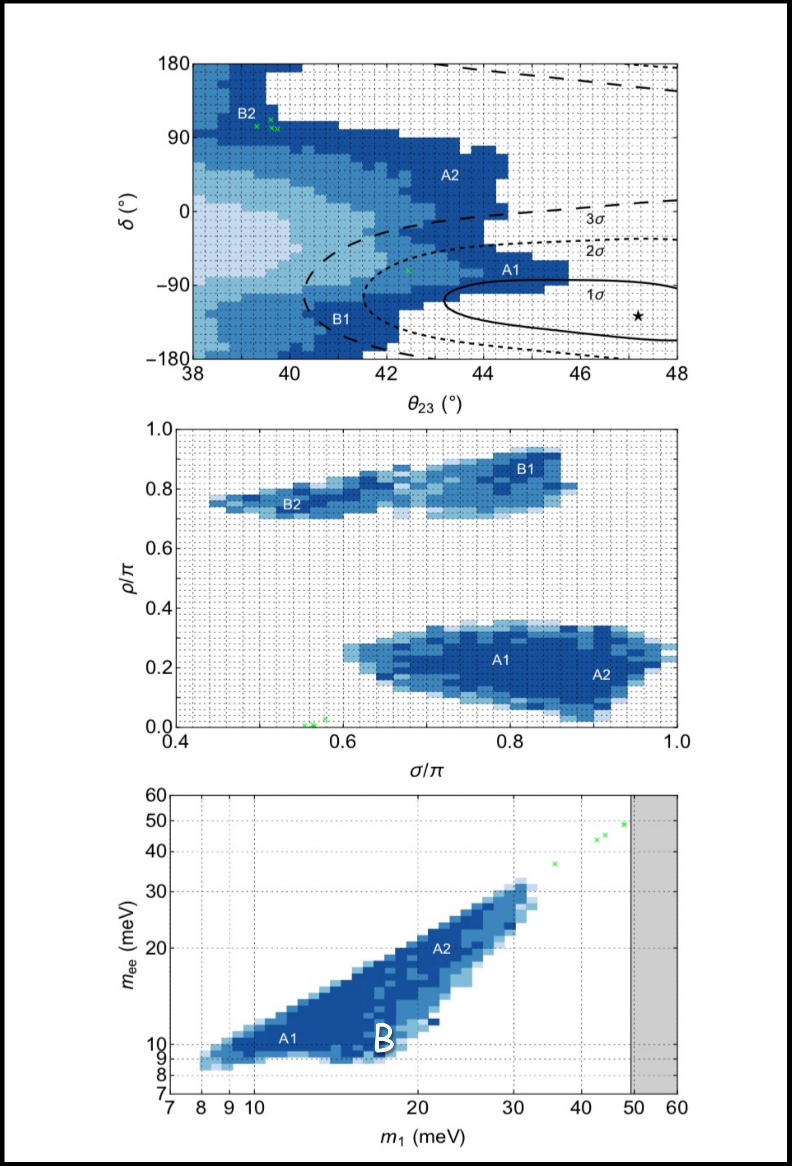
The asymmetry is proportional to α_2^2 ⇒one can place a lower bound from data but there is also an upper bound from theory since $M_2 \propto \alpha_2$ and the asymmetry calculation is valid only for $M_2 \lesssim 10^{12}$GeV ⇒a second octant measurement would indeed corner the scenario

Strong SO(10)-inspired leptogenesis confronting long baseline experiments
(PDB, Marco Chianese 1802.07690)

Pre-existing initial asymmetry: 10^{-3}, 10^{-2}, 10^{-1}



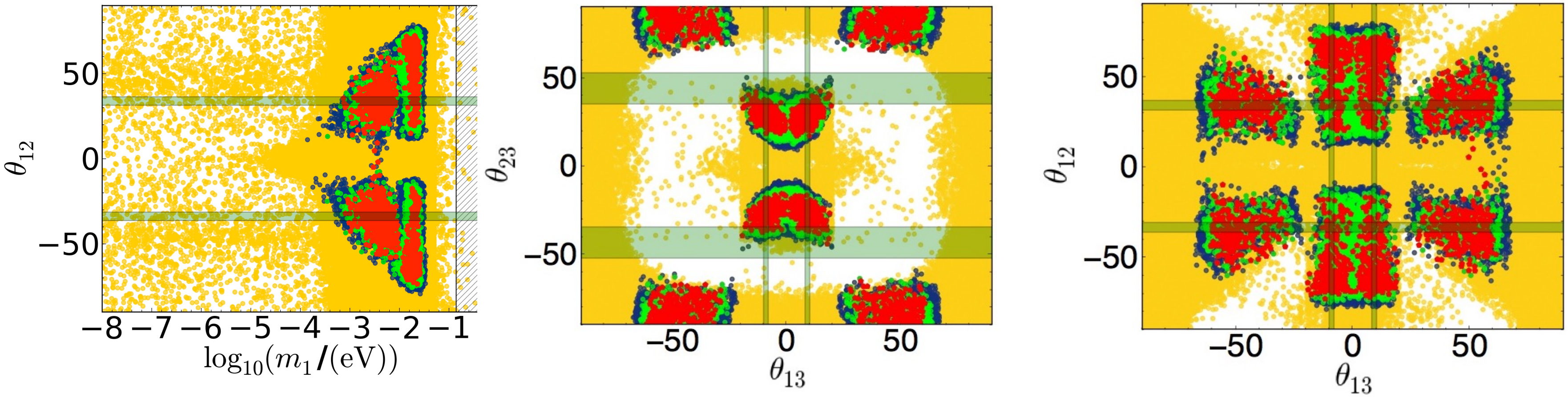
Strong SO(10)-inspired leptogenesis, Majorana phases and $0\nu\beta\beta$ decay
(PDB, Marco Chianese 1802.07690)



How significantly can the STSO10 solution be supported by data?

(PDB, Marzola '13)

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



If θ_{23} is found in the first octant then p≲10%
If NO is confirmed then p≲5%
If $\sin\delta < 0$ is confirmed then p≲2%
If $\cos\delta < 0$ is found then p≲1%

This would sum up to the coincidence $m_{sol}, m_{atm} \sim 10\, m_*$
If also absolute neutrino mass scales (m_1 and m_{ee}) will fall within the expected range (implying $0\nu\beta\beta$ signal) then strong case for discovery (notice also that Majorana phases impose non arbitrary m_{ee}/m_1)

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 $M_{GUT}=2\times10^{16}$ GeV one obtains the masses:

up-quark mass matrix $\quad M_u = v_{10}^u Y_{10} + v_{126}^u Y_{126} + v_{120}^u Y_{120}\,,$

down-quark mass matrix $\quad M_d = v_{10}^d Y_{10} + v_{126}^d Y_{126} + v_{120}^d Y_{120}\,,$

neutrino mass matrix $\quad M_D = v_{10}^u Y_{10} - 3 v_{126}^u Y_{126} + v_{120}^D Y_{120}\,,$

charged lepton mass matrix $\quad M_l = v_{10}^d Y_{10} - 3 v_{126}^d Y_{126} + v_{120}^l Y_{120}\,,$

RH neutrino mass matrix $\quad M_R = v_{126}^R Y_{126}\,,$

LH neutrino mass matrix $\quad M_L = v_{126}^L Y_{126}\,,$

→ 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

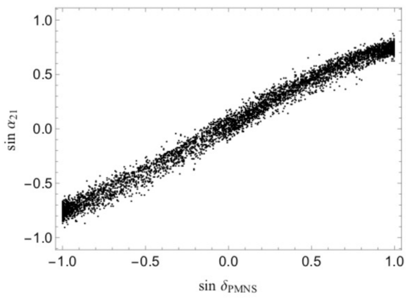
NOTE: these models do respect SO(10)-inspired conditions

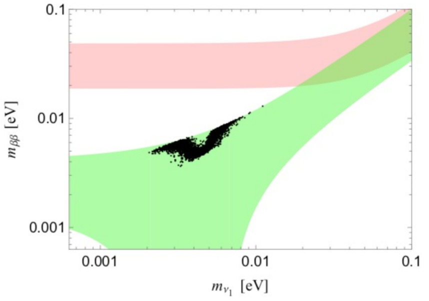
A recent realistic fit

(Mummidi and Patel, 2109.04050)

Observable	$O_i^{\rm th}$	$O_i^{\rm exp}$	$P_i = (O_i^{\rm th} - O_i^{\rm exp})/\sigma$
y_u	2.91×10^{-6}	2.91×10^{-6}	0.0
y_c	1.49×10^{-3}	1.47×10^{-3}	0.1
y_t	0.437	0.443	-0.1
y_d	3.46×10^{-6}	5.04×10^{-6}	-1.0
y_s	0.87×10^{-4}	1.01×10^{-4}	-0.4
y_b	5.30×10^{-3}	5.40×10^{-3}	-0.2
y_e	2.18×10^{-6}	2.16×10^{-6}	0.1
y_μ	4.68×10^{-4}	4.51×10^{-4}	0.4
y_τ	7.75×10^{-3}	7.63×10^{-3}	0.2
$\Delta m^2_{\rm sol}$ [eV^2]	7.48×10^{-5}	7.42×10^{-5}	0.1
$\Delta m^2_{\rm atm}$ [eV^2]	2.517×10^{-3}	2.517×10^{-3}	0.0
$\|V_{us}\|$	0.2352	0.2321	0.1
$\|V_{cb}\|$	0.0393	0.0399	-0.2
$\|V_{ub}\|$	0.0036	0.0036	0.0
$\sin\delta_{\rm CKM}$	0.924	0.931	-0.1
$\sin^2\theta_{12}$ (θ_{12})	0.311 (33.90°)	0.304 (33.44°)	0.2
$\sin^2\theta_{23}$ (θ_{23})	0.554 (48.1°)	0.573 (49.2°)	-0.3
$\sin^2\theta_{13}$ (θ_{13})	0.02229 (8.59°)	0.02219 (8.57°)	0.0
η_B	6.10×10^{-10}	6.12×10^{-10}	-0.1
	Predictions		
$\delta_{\rm PMNS}$[°]	354.6	M_{N_1} [GeV]	4.36×10^9
α_{21} [°]	181.8	M_{N_2} [GeV]	1.97×10^{11}
α_{31} [°]	123.7	M_{N_3} [GeV]	8.86×10^{11}
m_{ν_1} [eV]	0.0060		
m_β [eV]	0.0108		
$m_{\beta\beta}$ [eV]	0.0082		

TABLE I. Results and predictions obtained for the best fit solution corresponding to $\chi^2 = 1.7$ at the minimum.





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

(S.F. King 2014)

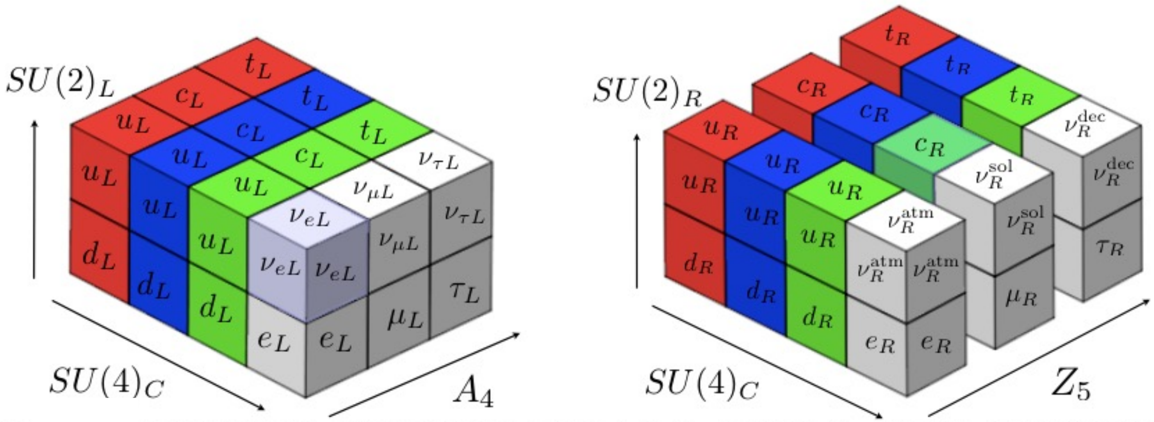


Figure 1: A to Z of flavour with Pati-Salam, where $A \equiv A_4$ and $Z \equiv Z_5$. The left-handed families form a triplet of A_4 and are doublets of $SU(2)_L$. The right-handed families are distinguished by Z_5 and are doublets of $SU(2)_R$. The $SU(4)_C$ unifies the quarks and leptons with leptons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

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

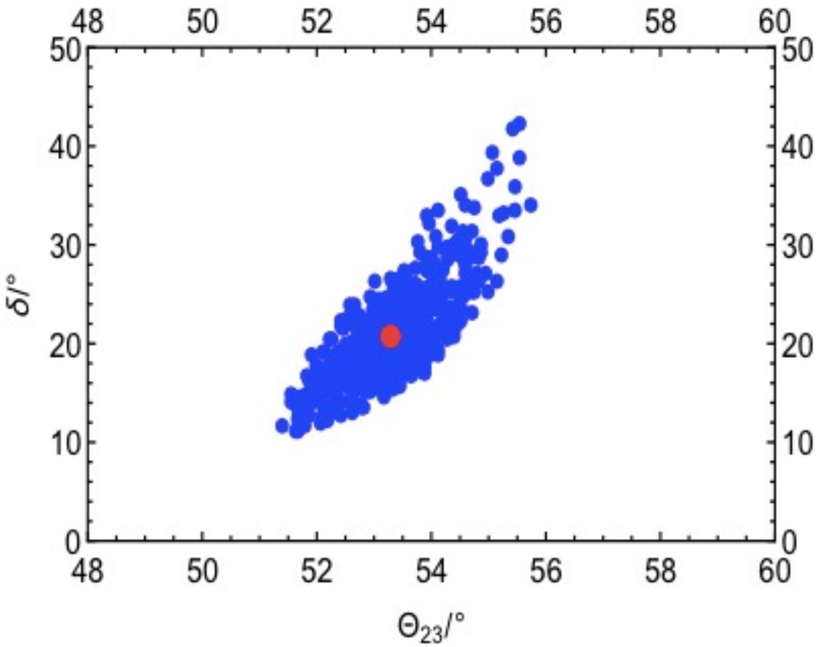
CASE B:

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

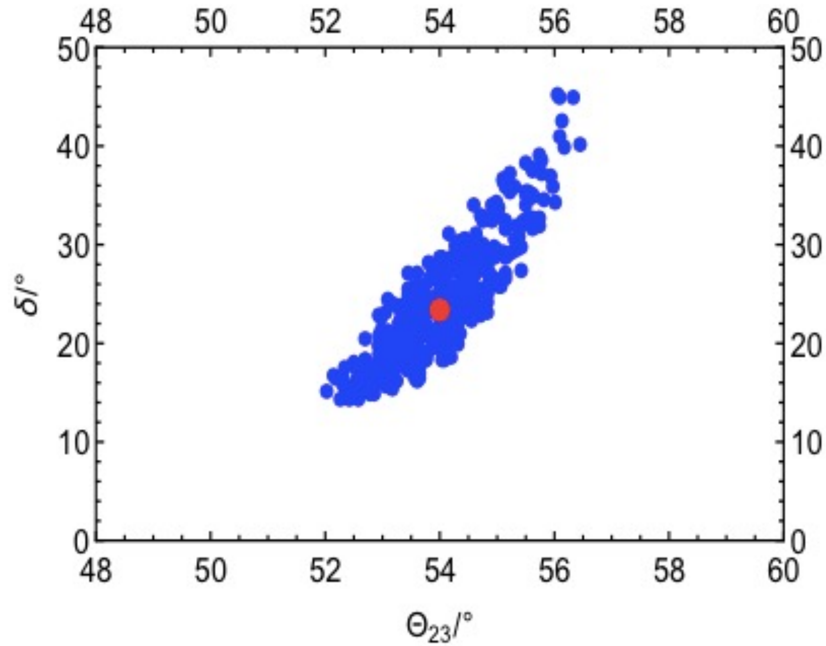
There are 2 solutions (only for NO)

(PDB, S.F. King 1507.06431)

CASE A



CASE B



This region will be tested relatively quickly

Gravitational waves

from

neutrino mass genesis

PDB, Danny Marfatia, Ye-Ling Zhou 2001.07637

PDB, Danny Marfatia, Ye-Ling Zhou 2106.00025

First order phase transition associated to Majorana mass generation in the Majoron model

$$-\mathcal{L}_{N_I+\sigma} = \overline{L_\alpha}\, h_{\alpha I}\, N_I\, \widetilde{\Phi} + \frac{\lambda_I}{2}\sigma\, \overline{N_I^c}\, N_I + V_0(\sigma) + h.c. \quad (respecting\ U_L(1)\ symmetry)$$

$$\sigma = \frac{1}{\sqrt{2}}(\sigma_1 + i\sigma_2)\,, \qquad <\sigma> = \frac{v_T}{\sqrt{2}}$$

At the end of the σ-phase transition, after SB, L is violated and

$$\sigma = \frac{e^{i\theta}}{\sqrt{2}}(v_0 + S + iJ) \qquad M_I = \lambda_I \frac{v_0}{\sqrt{2}} \sim M \ (seesaw\ scale)$$

Dirac neutrino mass matrix $m_D = v_{ew}\, h/\sqrt{2}$ generated after EWSB

At the moment let us assume $T_* > v_{ew}$ (high scale scenarios)

After both symmetry breakings: $m_\nu = -\frac{v_{ew}^2}{2}\frac{h_{\alpha I} h_{\beta I}}{M_I}$

Given the measured values of the neutrino oscillation mass scales, RH neutrinos thermalise prior to the phase transition and contribute to the thermal potential

DARK SECTOR ≡ N_I 's + J + S   VISIBLE SECTOR ≡ SM particles

The minimal model

$$V_0(\sigma) = -\mu^2 |\sigma|^2 + \lambda |\sigma|^4 \quad (\lambda, \mu^2 > 0)$$

$$\Longrightarrow \quad v_0 = \sqrt{\mu^2/\lambda}$$

In the broken phase

$$\sigma = \frac{e^{i\theta}}{\sqrt{2}} \left(v_0 + S + i J \right)$$

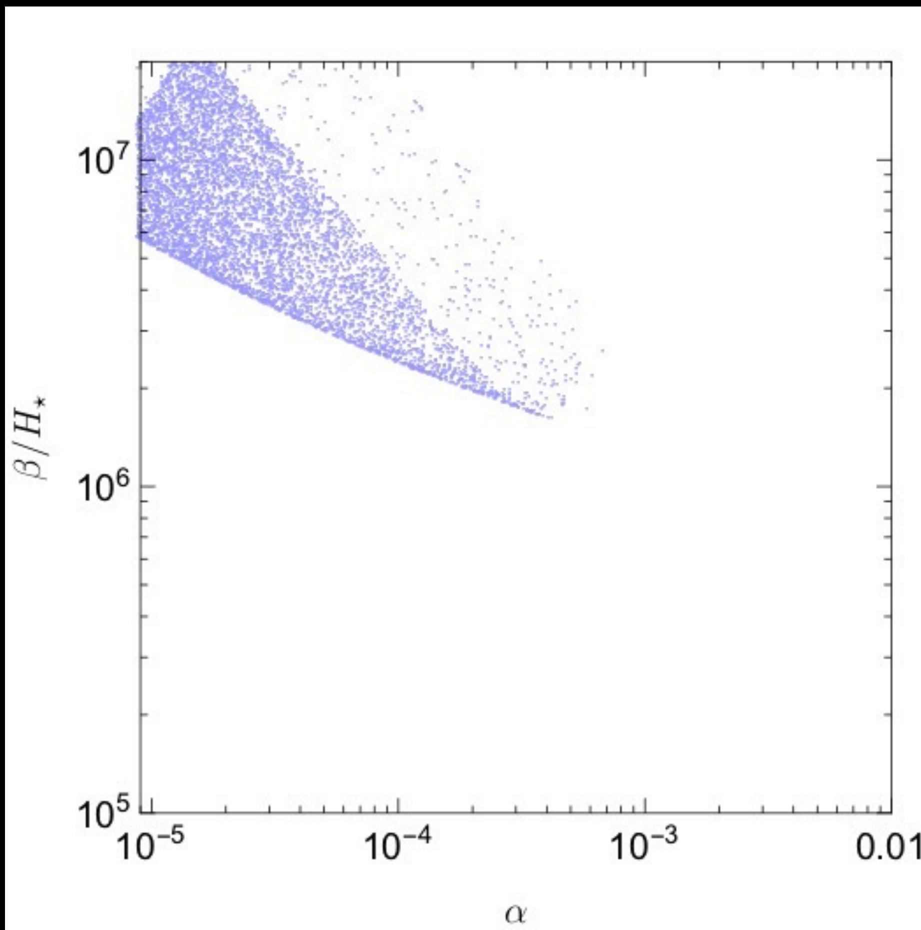
massless Majoron

$\hookrightarrow m_S^2 = 2 \lambda v_0^2$!!

For the one-loop finite temperature effective potential one finds a polynomial:

$$V_{\rm eff}^T(\sigma_1) \simeq D\,(T^2 - T_0^2)\sigma_1^2 - A\,T\,\sigma_1^3 + \frac{1}{4}\lambda_T\,\sigma_1^4\,,$$

The minimal model



⇒ No detectable signal! (by many orders of magnitude)

(Espinosa, Quirós '07)
(Kehayias, Profumo '09)

Adding an auxiliary scalar

very heavy real scalar

$$V_0(\sigma,\eta) = V_0(\sigma) + \underbrace{V_{\eta\sigma}(\sigma,\eta) + V_\eta(\eta)}_{\text{new terms}}$$

the most important term is contained in $V_{\eta\sigma}$:

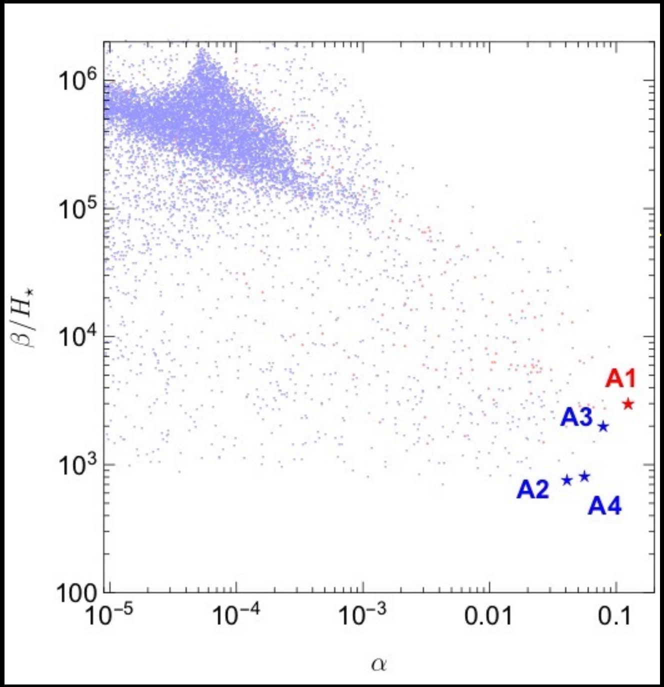
$$V_{\eta\sigma}(\eta,\sigma) = \frac{\delta_1}{2}|\sigma|^2\eta + \frac{\delta_2}{2}|\sigma|^2\eta^2$$

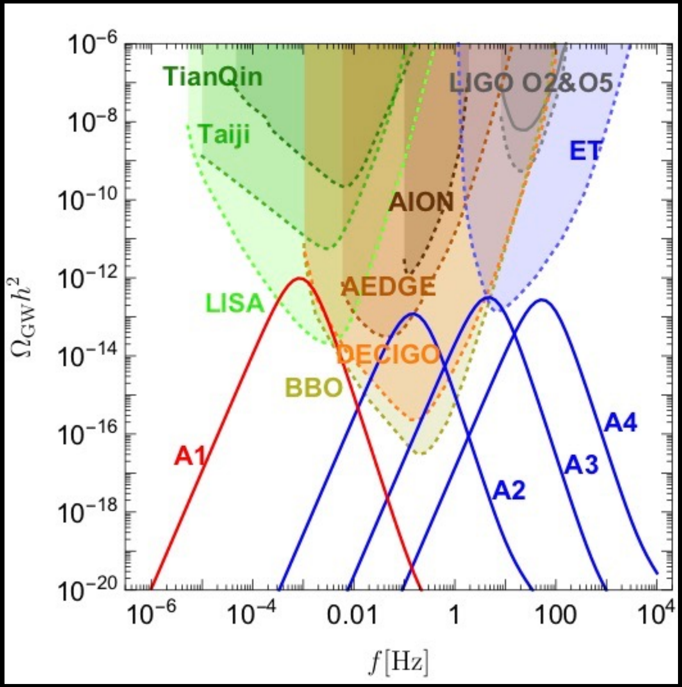
η undergoes a PT settling to its true vacuum prior to the σ-PT

$$\Rightarrow V_{eff}^T(\sigma_1,\tilde{\mu}) = \frac{1}{2}\tilde{M}_T^2\sigma_1^2 - (AT+\tilde{\mu})\sigma_1^3 + \frac{1}{4}\lambda_T\sigma_1^4$$

$\tilde{\mu} \propto \delta_2$

Adding an auxiliary scalar: GW spectrum





	Inputs				Predictions			
	$m_S/{\rm GeV}$	$\tilde{\mu}/{\rm GeV}$	$M/{\rm GeV}$	$v_0/{\rm GeV}$	$T_\star/{\rm GeV}$	α	$\beta/H_\star$	a_0
A1	0.06190	0.0005857	0.5361	3.5873	0.6504	0.1248	2966	0.05951
A2	156.2	13.15	465.6	1014	721	0.04139	754.8	0.3886
A3	1036	13.72	7977	44424	9180	0.08012	1975	0.06268
A4	43874	1856	181099	567378	247807	0.05611	809.7	0.1944

GW signals and Hubble tension

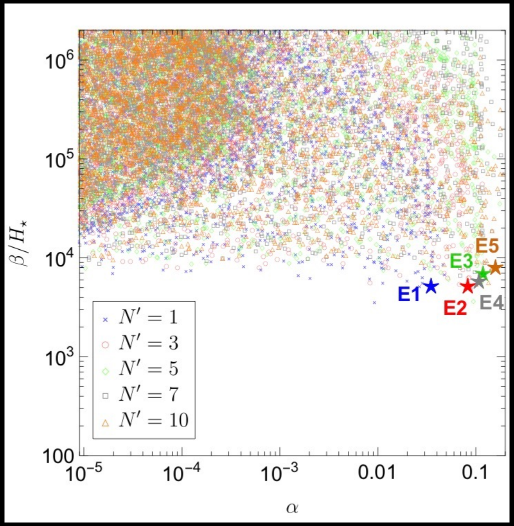
Astrophysical measurements find a value of the Hubble constant higher than the value inferred within the LCDM model from CMB anisotropies:

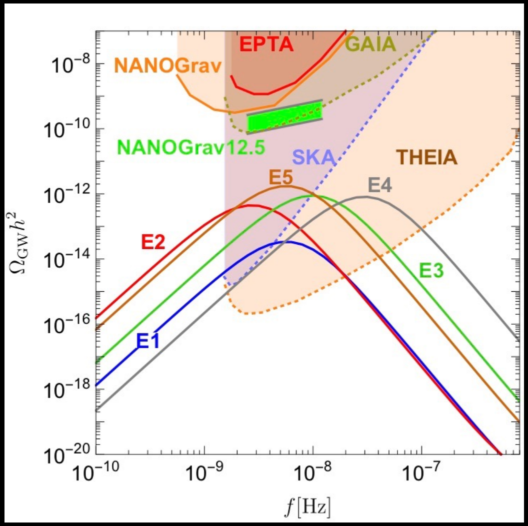
$$H_0 = 67.66 \pm 0.42 \text{ km s}^{-1}\text{Mpc}^{-1} \quad \leftarrow 4.2\sigma \text{ tension} \rightarrow \quad H_0 = 73.2 \pm 1.3 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Just an injection of dark radiation reconciles H_0 measurements but worsens the fit compared to the LCDM model. One needs to reduce the sound horizon at recombination without altering the well fitted CMB observables. An interaction between the Majoron background and ordinary neutrinos (see also Chacko et al '04)

$$-\mathcal{L}_{\nu-\text{dark}} = \frac{i}{2}\sum_{i=2,3}\lambda_i\,\overline{\nu_i}\,\gamma^5\,\nu_i\,\eta + \frac{i}{2}\lambda_1\overline{\nu_1}\,\gamma^5\,\nu_1\,J + \text{h.c.}\,,$$

does exactly that improving the fit (Escudero, Witte 1909.04044). Dark sector and ordinary neutrinos equilibrate AFTER the sigma-PT so that $T'=T_\nu \simeq 0.6T$ and $\Delta N_\nu \sim 0.5$ at recombination but $\Delta N_\nu \sim 0.1$ at BBN and the GW signal can be further enhanced increasing N' (but there is an upper limit from stability)





SUMMARY

- Seesaw neutrino mass models are an attractive explanation of neutrino masses and mixing easily embaddable in realistic grandunified models (with or without flavour symmetries)

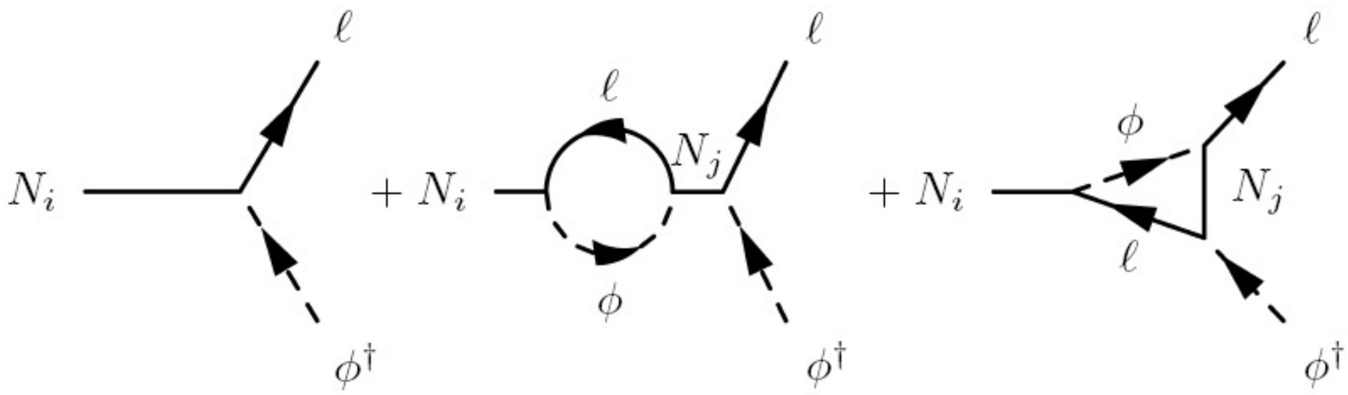
- Absolute neutrino mass scale experiments combined with neutrino mixing will in the next year test SO(10)-inspired leptogenesis predicting some deviation from the hierarchical limit

- Imposing strong thermal condition selects a subset of solutions leading to quite stringent predictions with the potential of a highly statistic significance support from low energy neutrino data.

- GWs introduce new opportunities to test high scale leptogenesis models…..we likely need however very high frequency experiments to probe the most interesting energy scales one expects.

Total CP asymmetries

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

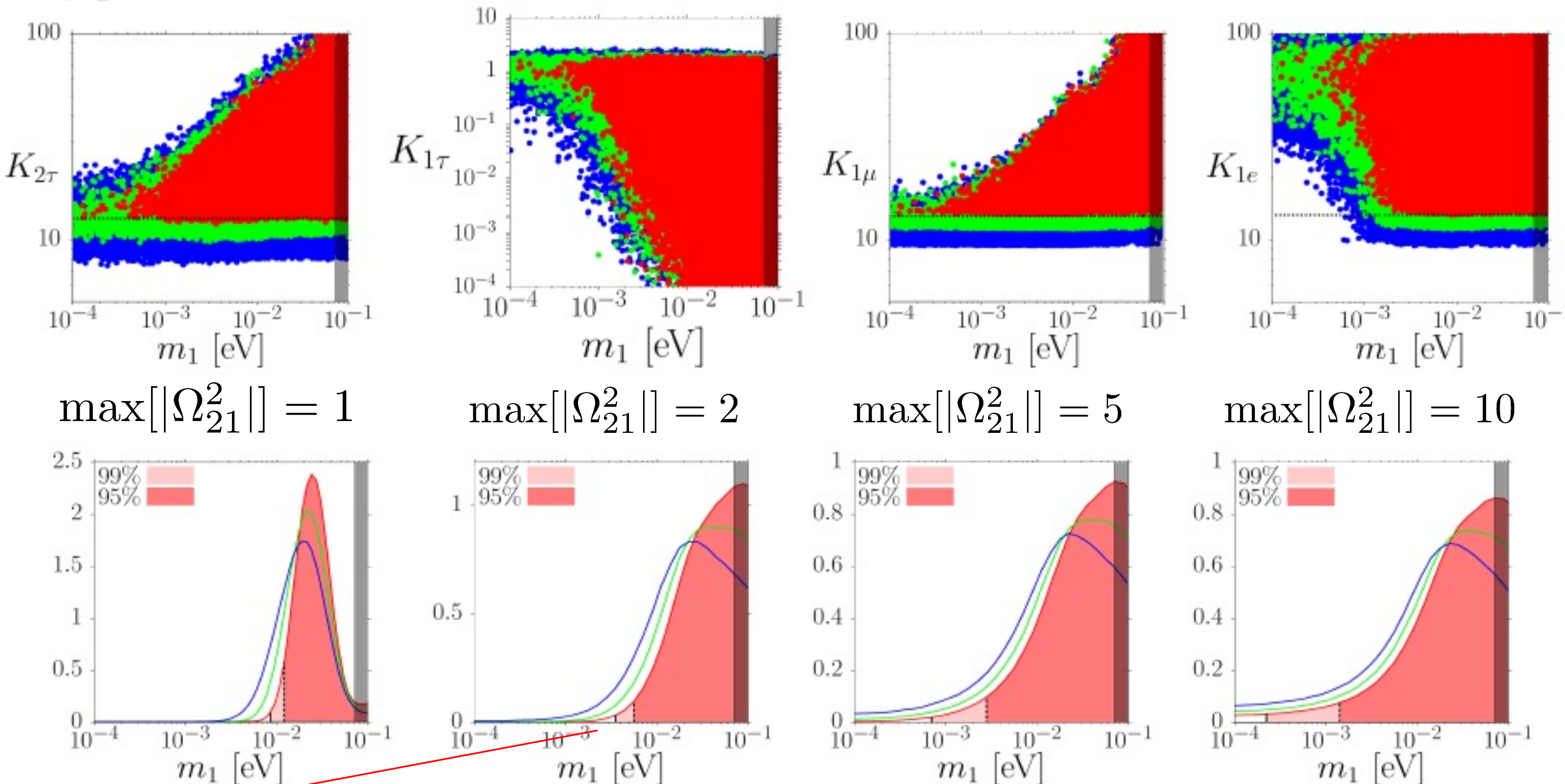


$$\varepsilon_i \simeq \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(m_D^\dagger\, m_D)^2_{ij}\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

It does not depend on U !

A lower bound on neutrino masses (IO)

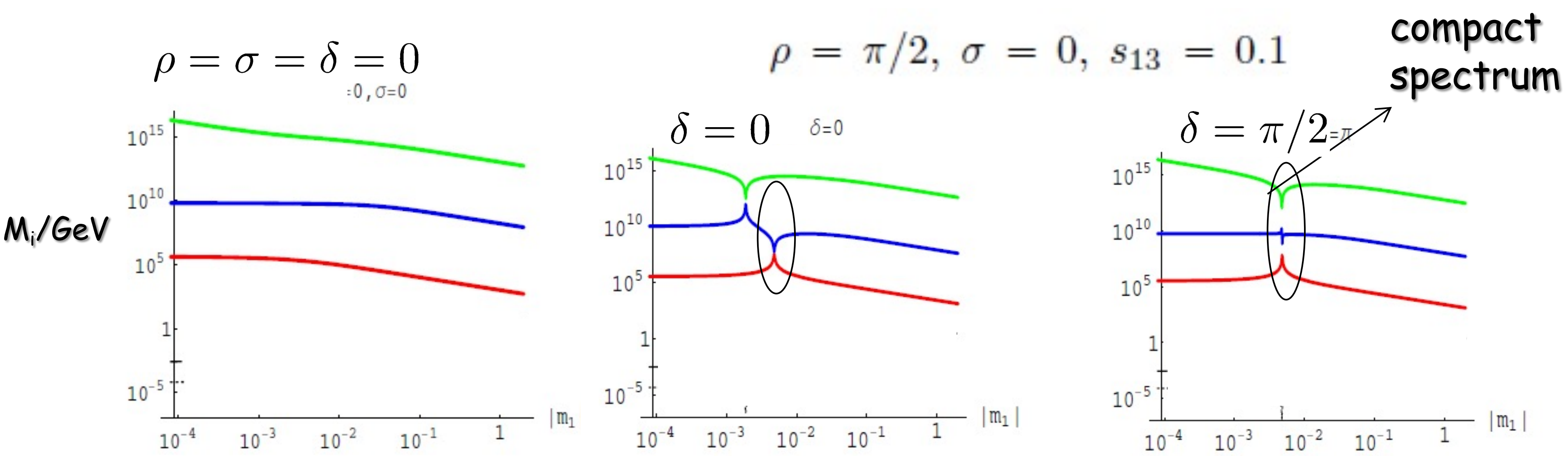
$N_{B-L}^{P,i}$ = 0.001, 0.01, 0.1 $\max[|\Omega^2_{21}|] = 2$ INVERTED ORDERING



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

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)