DISCRETE 2026

13 - 17 November 2026

Comenius University Bratislava



Extended SO(10)-inspired leptogenesis

(based on: Pasquale Di Bari and Xubin Hu, 2507.06144 and 2611.16604)

Pasquale Di Bari

(University of Southampton)

Plan of the talk

SO(10)-inspired leptogenesis

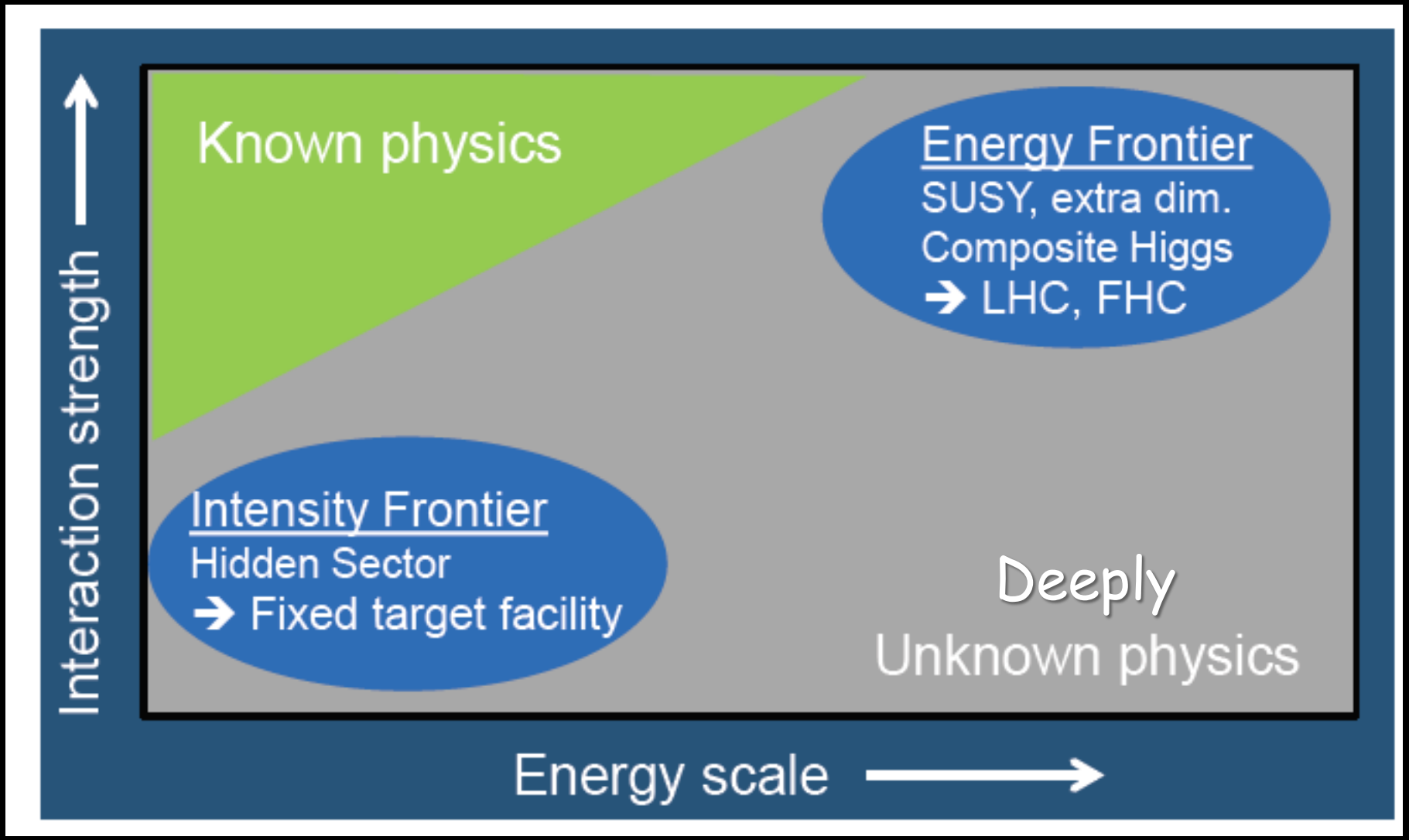


extended SO(10)-inspired leptogenesis

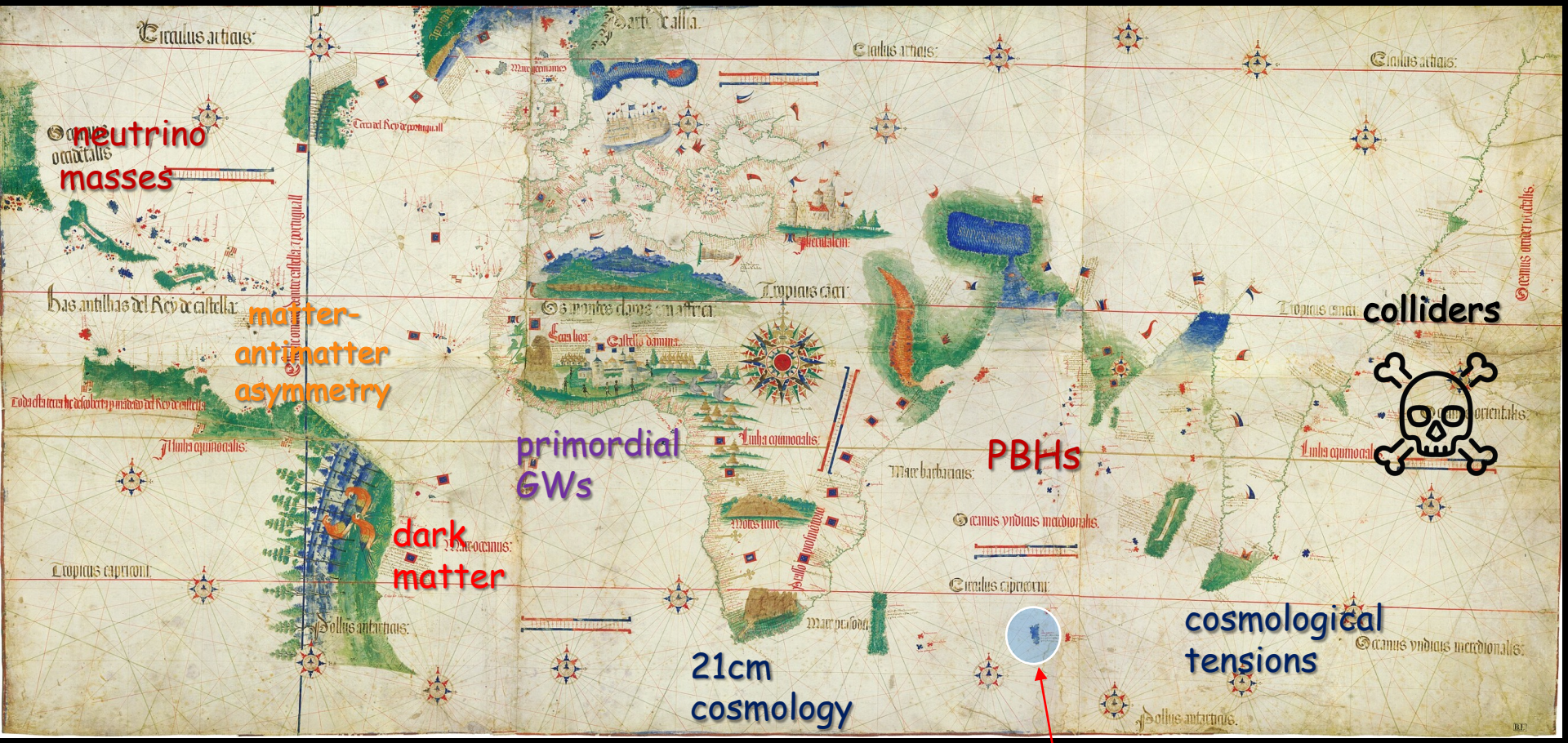


New frontiers

(SHIP proposal, 1504.04855)

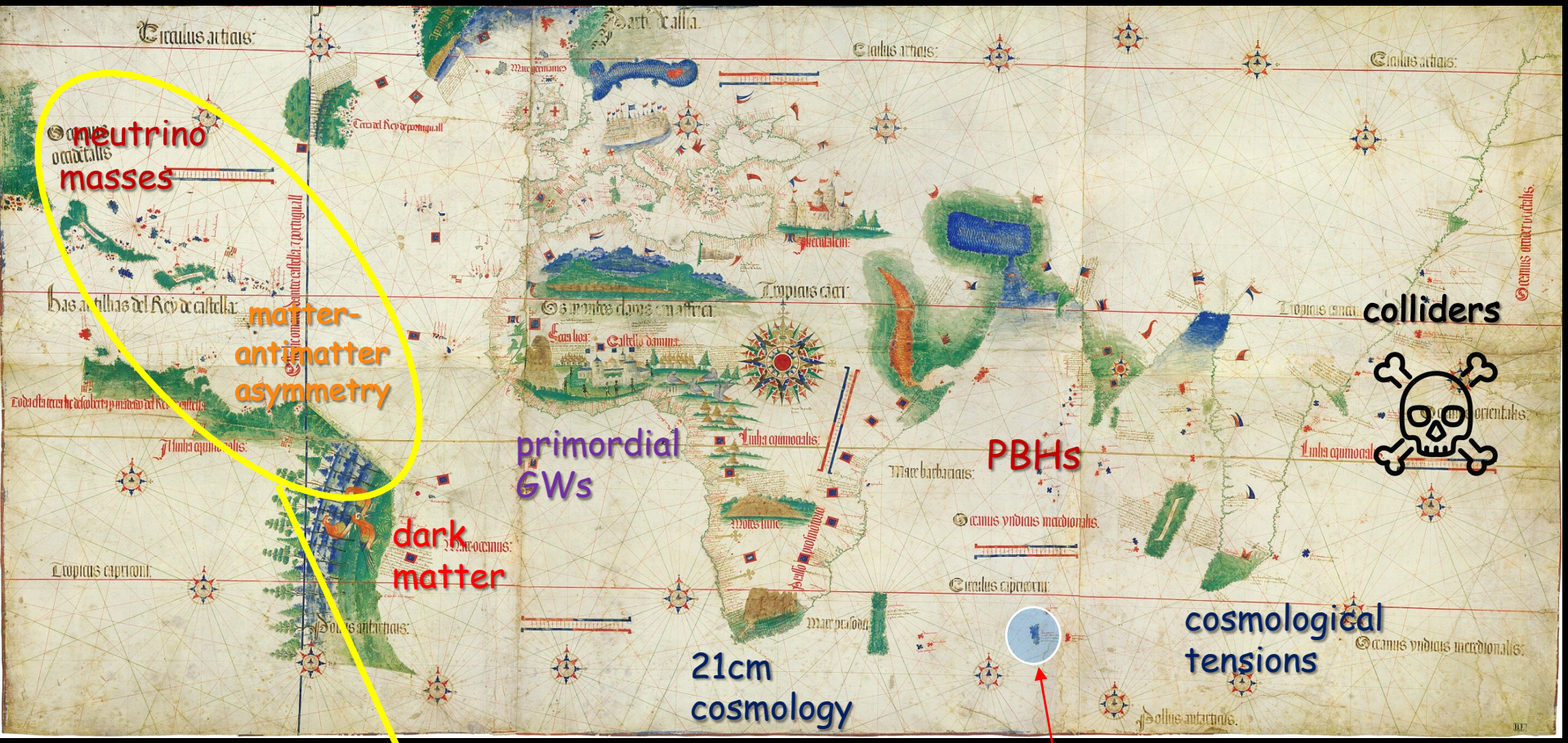


Navigating the deep unknown with neutrinos and cosmology



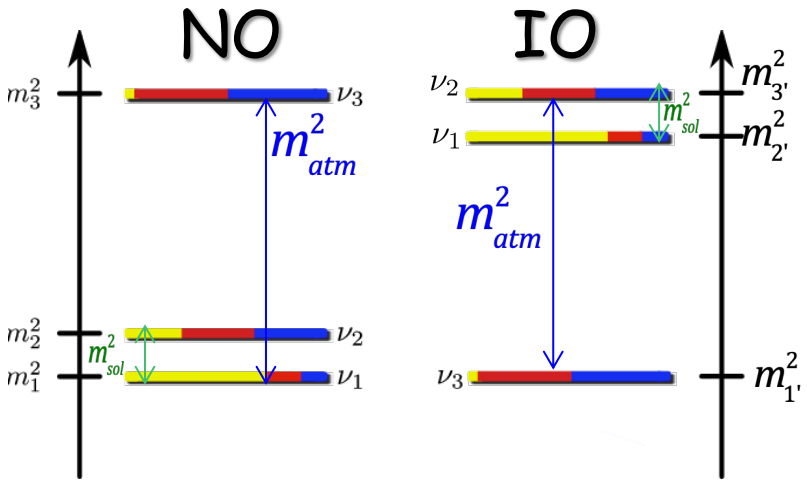
(Cantino planisphere, 1502, Biblioteca Estense Modena)

Navigating the deep unknown



(Cantino planisphere, 1502, Biblioteca Estense Modena)

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



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

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

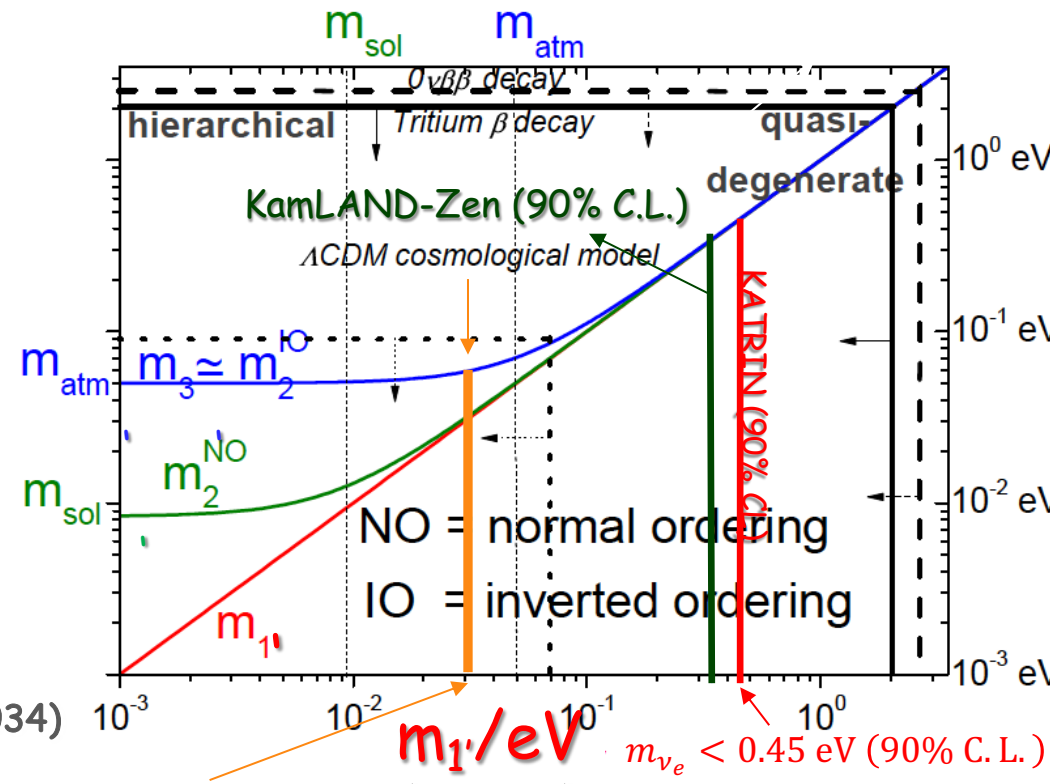
$$m_{sol} = (8.7 \pm 0.1)\ \text{meV}$$
$$m_{atm} = (50.0 \pm 0.2)\ \text{meV}$$

Lower bound on neutrino masses (NO)

$$\Rightarrow \sum m_i \gtrsim 58\text{meV}\ (95\%\text{CL})$$

For IO it would be much more stringent:

$$\sum m_i \gtrsim 98\text{meV}\ (95\%\text{CL})$$



Cosmological upper bound (*Planck* 2023, 2309.10034)

$$\sum m_i \lesssim 0.11\ \text{eV}\ (95\%\text{CL}) \Rightarrow \text{for NO (IO):}\ \ m_{1'} < 26\ (9)\text{meV}(95\%\text{CL})$$

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)

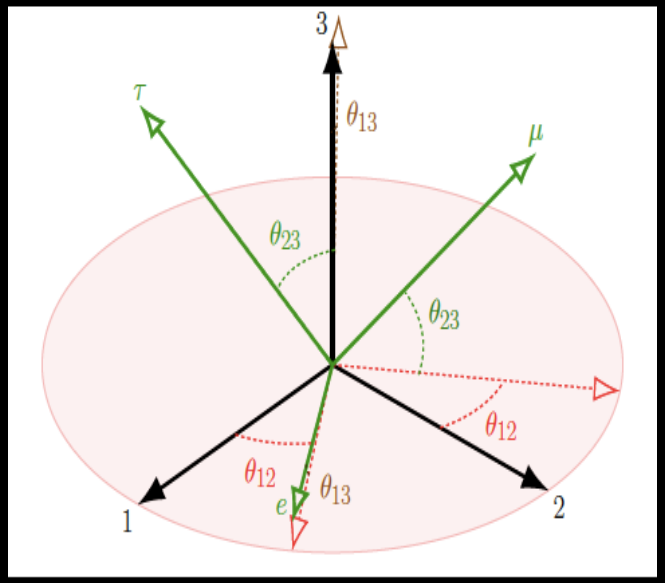
(νfit v6.1 November 2025, with SK atm. data)

$\theta_{12} = [31.63°, 35.95°]$
$\theta_{13} = [8.19°, 8.89°]$
$\theta_{23} = [41.3°, 49.9°]$
$\delta = [-236°, 4°]$
$\rho, \sigma = [0°, 360°]$

NO favoured over IO:

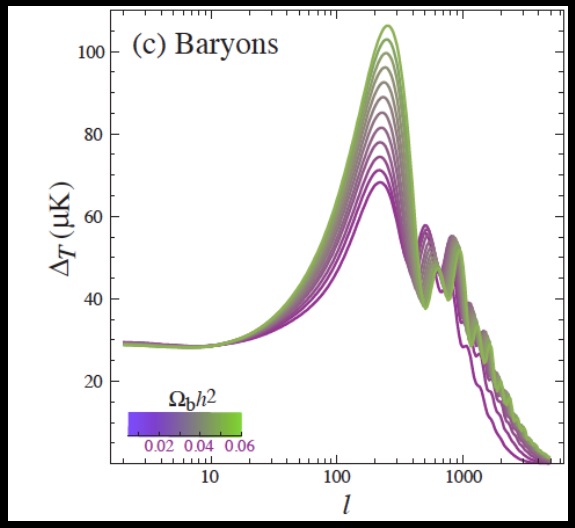
$\Delta\chi^2$ (IO-NO)=5.9 (not including JUNO)

(νfit 7.0: talk by Gonzalez-Garcia
$\Delta\chi^2$ (IO-NO) ≃ 9.6 prelim.)

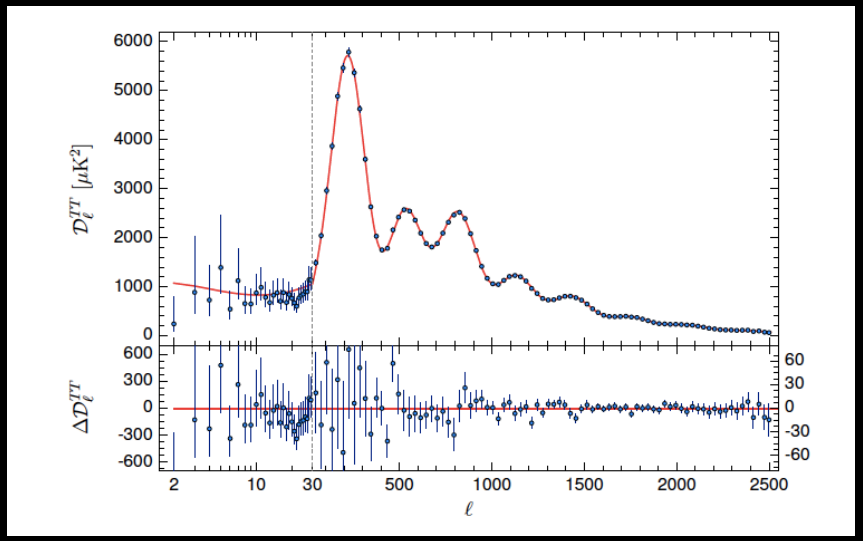


Baryon asymmetry of the universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2018, 1807.06209)



(CMB+BAO)

$$\Omega_{B0} h^2 = 0.02242 \pm 0.00014$$

$$\eta_{B0} \equiv \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \simeq \frac{n_{B0}}{n_{\gamma 0}} \simeq 273.5\, \Omega_{B0} h^2 \times 10^{-10} = (6.12 \pm 0.04) \times 10^{-10} = \eta_{B0}^{CMB}$$

- Consistent with (older) BBN determination but more precise and accurate
- today the asymmetry coincides with the matter abundance since there is no evidence of primordial antimatter
- Even though all 3 Sakharov conditions are satisfied in the SM, any attempt to reproduce the observed value fails by many orders of magnitude ⟹ it requires NEW PHYSICS!

Minimally extended SM

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

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

Dirac Mass

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

diagonalising m_D : $m_D = V_L^\dagger D_{m_D} U_R$

$$D_{m_D} \equiv \begin{pmatrix} m_{D1} & 0 & 0 \\ 0 & m_{D2} & 0 \\ 0 & 0 & m_{D3} \end{pmatrix}$$

$\Rightarrow$ 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)

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

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):

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

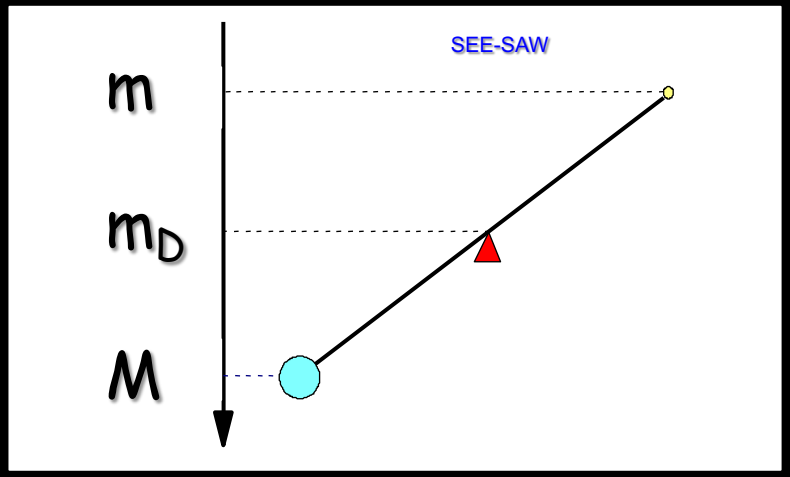
- 3(?) very heavy Majorana neutrinos N_I, N_{II}, N_{III} with $M_{III} > M_{II} > M_I \gg m_{Di}$

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):

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

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

$I = 1,2,3$

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: $m_i = \dfrac{m_{Di}^2}{M_I}$

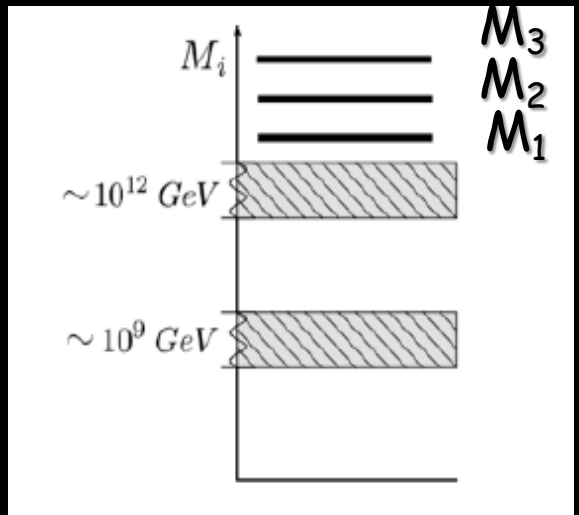
  If also $m_{D1} = m_{D2} = m_{D3} = \lambda$ then simply: $M_I = \dfrac{\lambda^2}{m_i}$

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 (...;Bertuzzo, PDB, Feruglio, Nardi 0908.0161; Hagedorn, Molinaro, Petcov 0908.0240; .....)

SO(10)-inspired conditions

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

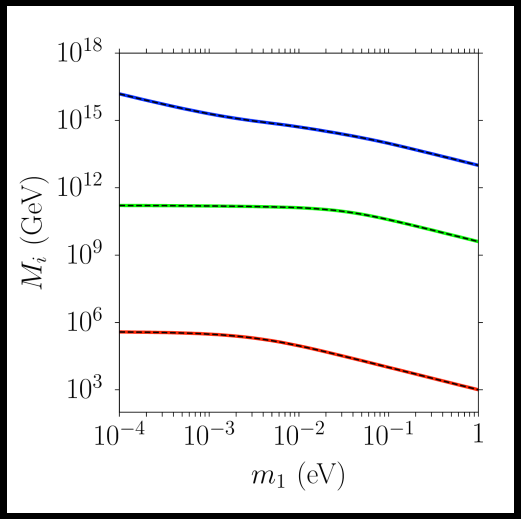
bi-unitary parameterisation: $m_D = V_L^\dagger D_{m_D} U_R \qquad D_{m_D} \equiv diag(m_{D1}, m_{D2}, m_{D3})$

Inspired by SO(10)-models:

- $V_L \simeq V_{CKM} \simeq I$
- $m_{D1} = \alpha_1 m_{\rm up}\,; m_{D2} = \alpha_2 m_{\rm charm}; m_{D3} = \alpha_3 m_{\rm top};\ \alpha_i = \mathcal{O}(1)$

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

Barring fine-tuned solutions (for $m_{ee} \simeq 0$ and/or $(m_\nu^{-1})_{\tau\tau} \simeq 0$), one obtains a very hierarchical seesaw neutrino mass spectrum with $M_1 \ll 10^9$ GeV



Neutrinos are predicted to be Majorana particles

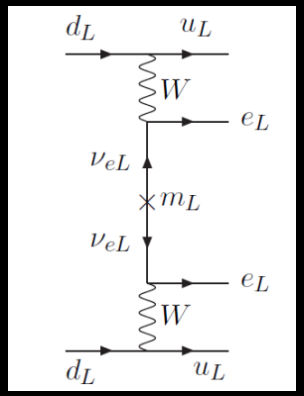
Both light and heavy neutrinos are Majorana neutrinos:

$$\nu_i \equiv \nu_{iL} + \nu_{iL}^c = \left[U_{i\alpha}^\dagger \nu_{L\alpha} + (U_{i\alpha}^\dagger \nu_{L\alpha})^c\right] - \left[V_{Lij'}^\nu \, \xi_{j'I'}^\star \, \nu_{RI'} + (V_{Lij'}^\nu \, \xi_{j'I'}^\star \, \nu_{RI'})^c\right] ,$$

$$N_I \equiv N_{IR} + N_{IR}^c = \left[U_{RII'} \, \nu_{RI'} + (U_{RII'} \, \nu_{RI'})^c\right] + \left[U_{RII'} \, \xi_{I'j'}^T \, \nu_{Lj'} + (U_{RII'} \, \xi_{I'j'}^T \, \nu_{Lj'})^c\right]$$

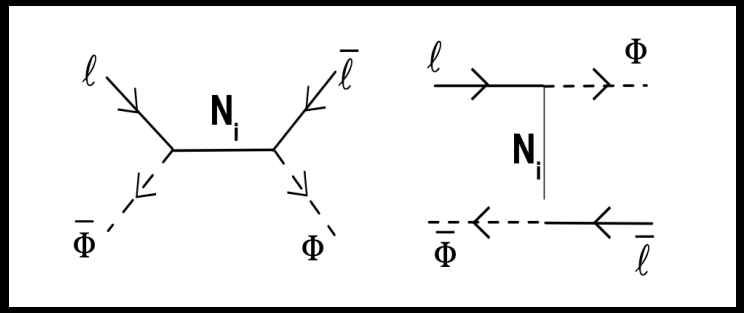
$$\xi \equiv m_D \, M^{-1}$$

- For light neutrinos:



$0\nu\beta\beta$ decay

- For heavy neutrinos:



They are both $\Delta L = 2$ processes

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 $N_I \xrightarrow{\Gamma_I} L_I + \phi^\dagger \qquad N_I \xrightarrow{\bar{\Gamma}} \bar{L}_I + \phi$

total CP asymmetries $\varepsilon_I \equiv -\dfrac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$

$$\Rightarrow N_{B-L}^{fin} = \sum_{I=1,2,3} \varepsilon_I \times \kappa_I^{fin}$$

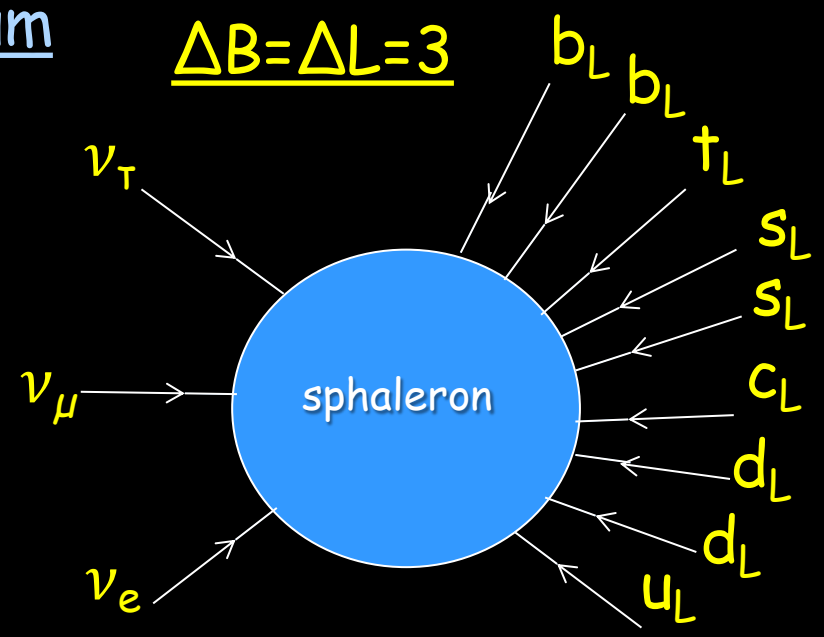
efficiency factors

- Sphaleron processes in equilibrium

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

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

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



Seesaw parameter space

Combining $\eta_{B0}^{lep} \simeq \eta_{B0}^{CMB} \simeq 6\times10^{-10}$ with low energy neutrino data can we test seesaw and leptogenesis?

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

Orthogonal parameterisation

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

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

light neutrino parameters

heavy neutrino parameters escaping experimental information

- *Low-scale* seesaw models, potential direct discovery of RH neutrinos in lab neutrino experiments (ξ not too small).

- *High-scale* seesaw models are challenging to test (ξ is tiny) 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,Garbrecht et al 2025)

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

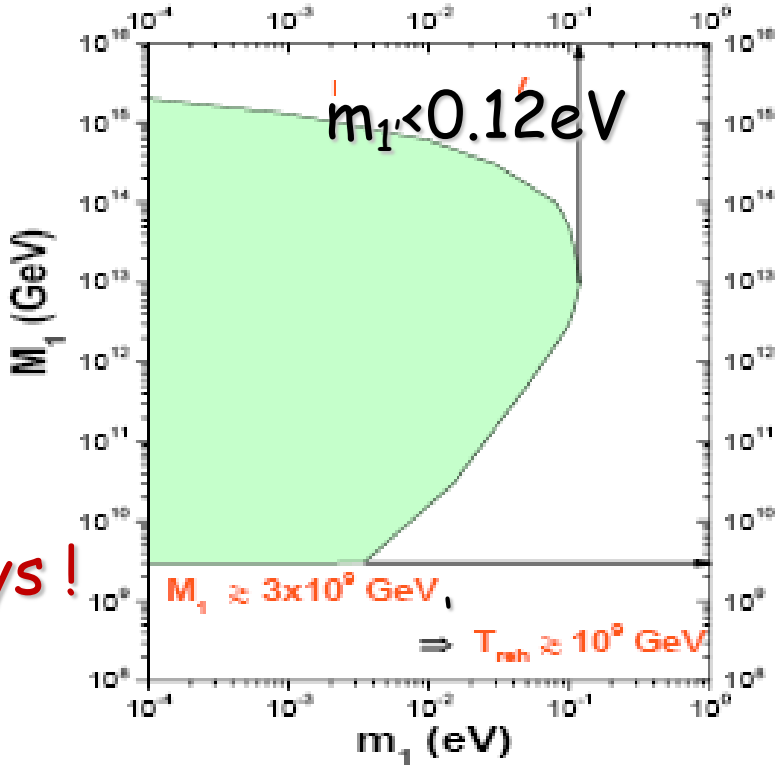
All the asymmetry is generated by the lightest RH neutrino decays !

4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

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

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



No dependence on the leptonic mixing matrix U: it cancels out in ε_1⇒ no sensitivity to mixing parameters.

SO(10)-inspired conditions

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

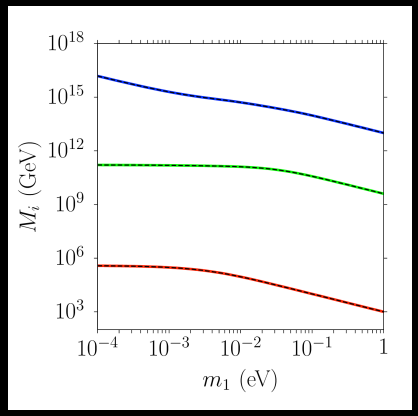
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Inspired by SO(10)-models:

- $V_L \simeq V_{CKM} \simeq I$
- $m_{D1} = \alpha_1 m_{\rm up}\,; m_{D2} = \alpha_2 m_{\rm charm}; m_{D3} = \alpha_3 m_{\rm top};\ \alpha_i = \mathcal{O}(1)$

$$\Rightarrow\ M_1 \simeq \frac{m_{D1}^2}{m_{ee}}\ ;\ M_2 \simeq \frac{m_{D2}^2}{m_1 m_2 m_3}\frac{m_{ee}}{|(m_\nu^{-1})_{\tau\tau}|};\ \ M_3 \simeq m_{D3}^2 |(m_\nu^{-1})_{\tau\tau}$$

Barring very fine-tuned solutions, one obtains a very hierarchical RH neutrino mass spectrum with $M_1 \ll 10^9$ GeV



Since $M_1 \ll 10^9$ GeV, one would conclude, within vanilla leptogenesis, that the observed asymmetry cannot be reproduced

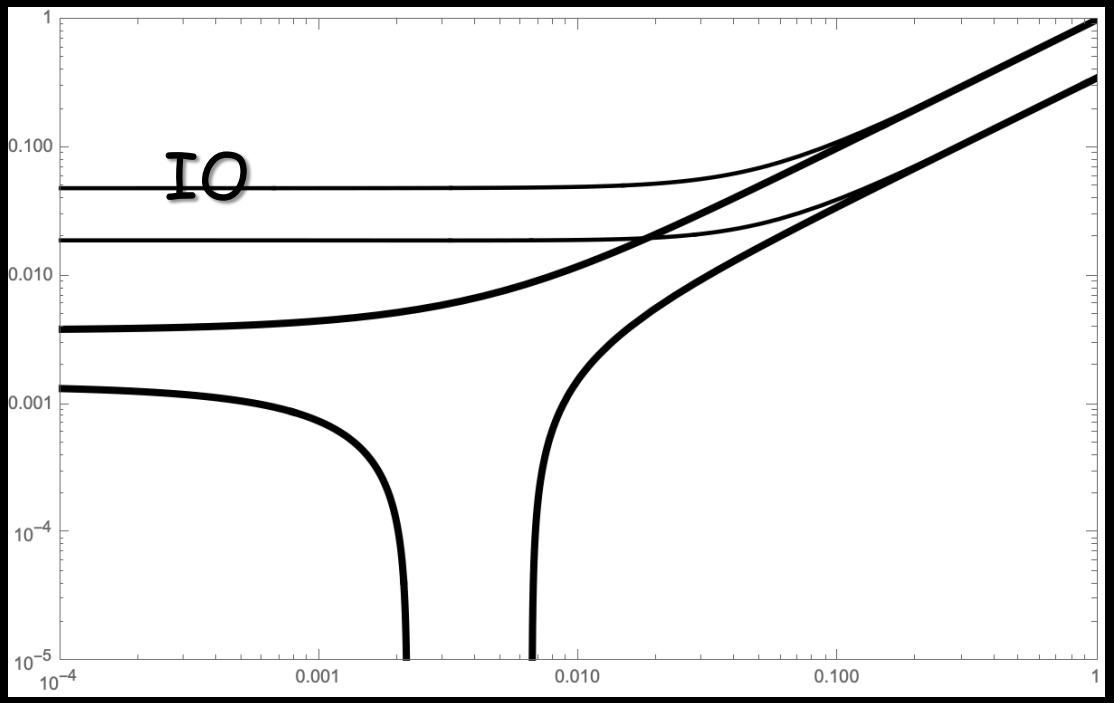
Important interplay with neutrino oscillation data

(Branco, Gonzalez-Felipe, Joaquim, Rebelo hep-ph 0202030)

$$M_1 \simeq \frac{m_{D1}^2}{m_{ee}} \xrightarrow{m_1 << m_{sol}} \frac{(\alpha_1 m_{up})^2}{m_{sol} s_{12}^2} \sim 10^5 \text{GeV}$$

With current data $s_{12}^2 \sim 0.3$ and $M_1 << 10^9$ GeV but with the old (pre-SNO) small mixing angle solution $s_{12}^2 << 1$ and one could have $M_1 > 10^9$ GeV.

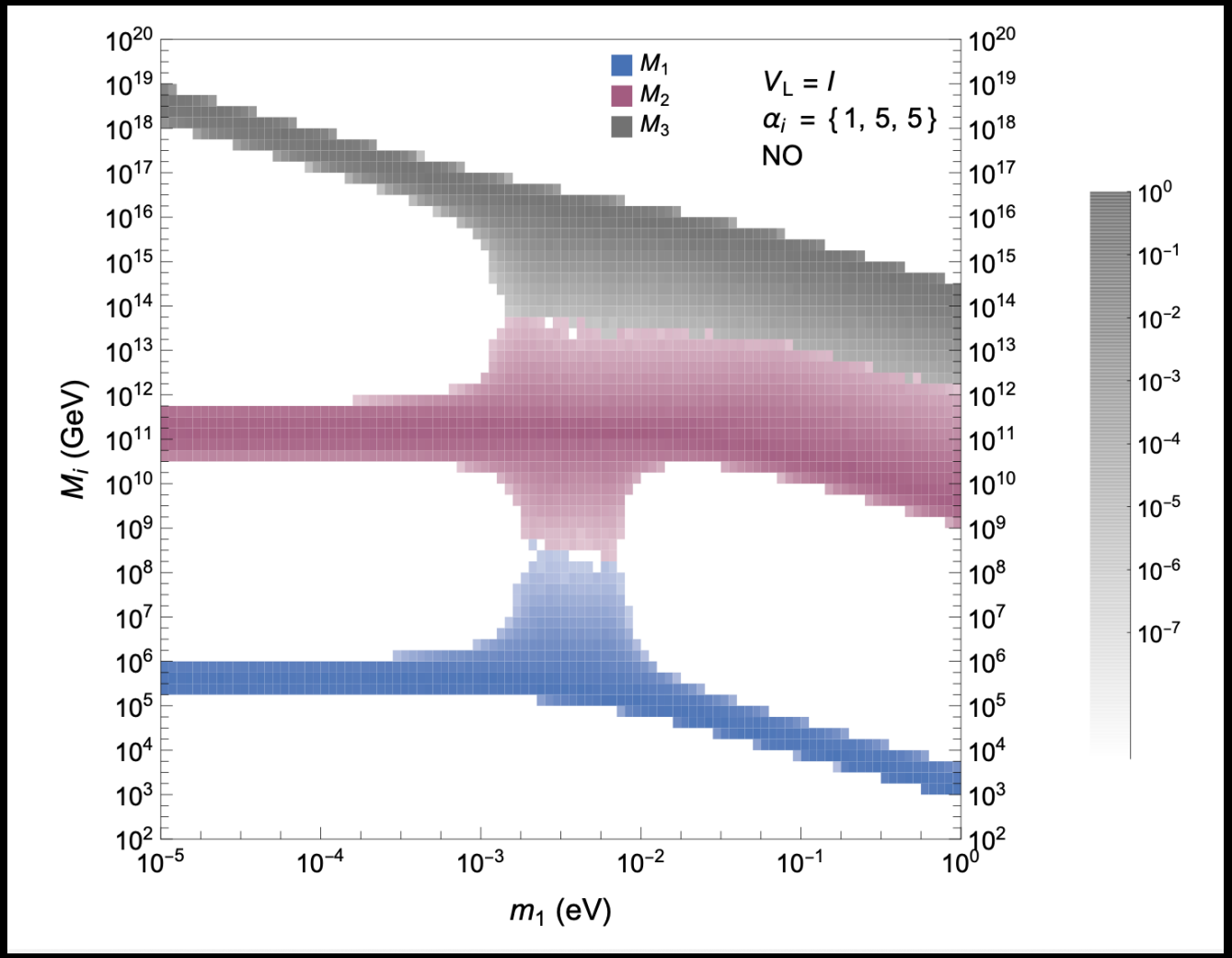
Important interplay with Ovββ effective mass



Can't we just be in the region where m_{ee} can be made arbitrarily small allowing for some phase cancellation? This would also rise M_1 above 10^9 GeV

A random scan for V_L=I confirms that $M_1 \ll 10^9$ GeV

(PDB, Xubin Hu 2611.16604)



Orthogonal matrix within SO(10)-inspired models (V_L=I)

(PDB, Marzola, Re Fiorentin 1411.5478)

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

For small m_{ee} one gets large entries ($|\Omega|_{iJ}$>>1) in the orthogonal matrix that signal strong fine-tuning in the seesaw relation: light neutrino masses are not the result of the seesaw but of the strong cancellations.

Full analytical solution (valid for arbitrary V_L) for RH neutrino masses and orthogonal matrix

(PDB, Marzola, Re Fiorentin 1411.5478; PDB, Re Fiorentin 1705.01935)

light neutrino mass matrix in the Yukawa basis

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

RH neutrino masses

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

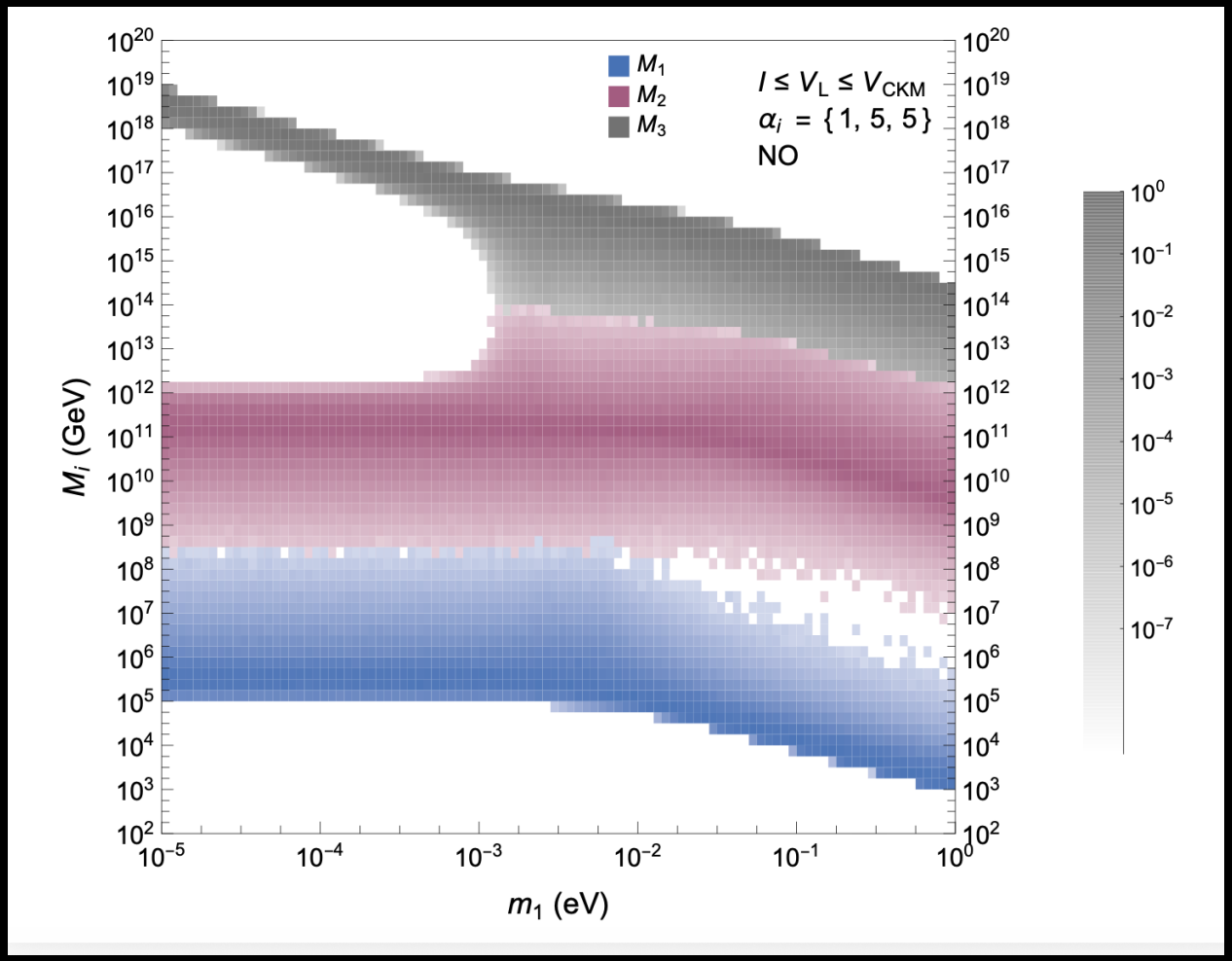
Orthogonal matrix

$$\Omega \simeq \begin{pmatrix} \frac{(\tilde{m}_\nu W^\star)_{11}}{\sqrt{-m_1 \tilde{m}_{\nu 11}}} & \sqrt{\frac{m_2 m_3 (\tilde{m}_\nu^{-1})_{33}}{\tilde{m}_{\nu 11}}} \left(W_{21}^\star - W_{31}^\star \frac{(\tilde{m}_\nu^{-1})_{23}}{(\tilde{m}_\nu^{-1})_{33}} \right) e^{i(\rho+\sigma+\rho_L+\sigma_L)} & \frac{W_{31}^\star}{\sqrt{m_1 (\tilde{m}_\nu^{-1})_{33}}} \\ \frac{(\tilde{m}_\nu W^\star)_{12}}{\sqrt{-m_2 \tilde{m}_{\nu 11}}} & \sqrt{\frac{m_1 m_3 (\tilde{m}_\nu^{-1})_{33}}{\tilde{m}_{\nu 11}}} \left(W_{22}^\star - W_{32}^\star \frac{(\tilde{m}_\nu^{-1})_{23}}{(\tilde{m}_\nu^{-1})_{33}} \right) e^{i(\rho+\sigma+\rho_L+\sigma_L)} & \frac{W_{32}^\star}{\sqrt{m_2 (\tilde{m}_\nu^{-1})_{33}}} \\ \frac{(\tilde{m}_\nu W^\star)_{13}}{\sqrt{-m_3 \tilde{m}_{\nu 11}}} & \sqrt{\frac{m_1 m_2 (\tilde{m}_\nu^{-1})_{33}}{\tilde{m}_{\nu 11}}} \left(W_{23}^\star - W_{33}^\star \frac{(\tilde{m}_\nu^{-1})_{23}}{(\tilde{m}_\nu^{-1})_{33}} \right) e^{i(\rho+\sigma+\rho_L+\sigma_L)} & \frac{W_{33}^\star}{\sqrt{m_3 (\tilde{m}_\nu^{-1})_{33}}} \end{pmatrix}, \quad (17)$$

where we defined $W \equiv V_L U$.

For small mixing angles in V_L it is clear that the same considerations apply as in the case V_L=I and why the result $M_1 \ll 10^9$ GeV still holds

A random scan for $I<V_L<V_{CKM}$ still confirms $M_1 \ll 10^9$ GeV



One could think to get successful leptogenesis in the vicinity of crossing level solutions (Akmedov, Frigerio, Smirnov 0305322) ….but there is another more attractive solution

N_2-leptogenesis

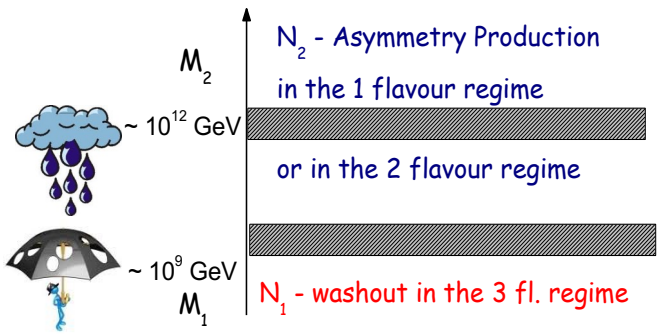
(PDB hep-ph/0502082, Vives hep-ph/0512160; Blanchet,PDB 0807.0743)

- 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: $K_{1e}+K_{1\mu}+K_{1\tau}=K_1$

A two stage process:



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

- 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 ~50% (taking into account experimental data)

  (PDB, Michele Re Fiorentin, Rome Samanta 1812.07720)

- 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 $m_{ee} \gtrsim 10$ meV ⇒ $m_1 \gtrsim 10$ meV (corresponding to $\Sigma_i m_i \gtrsim 80$meV).

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

  ⇒ important motivation for $0\nu\beta\beta$ experiments

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

General analytical solution for the asymmetry

Final B-L asymmetry

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

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

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

- The RH neutrino mixing matrix can also be expressed in terms of low energy neutrino parameters and V_L: $U_R = U_R(m_\nu, V_L, \alpha_i)$. The dependence on α_1 and α_3 cancels out in $N_{B-L}^{\rm lep,f}$

⇒ Successful SO(10)-inspired leptogenesis condition:

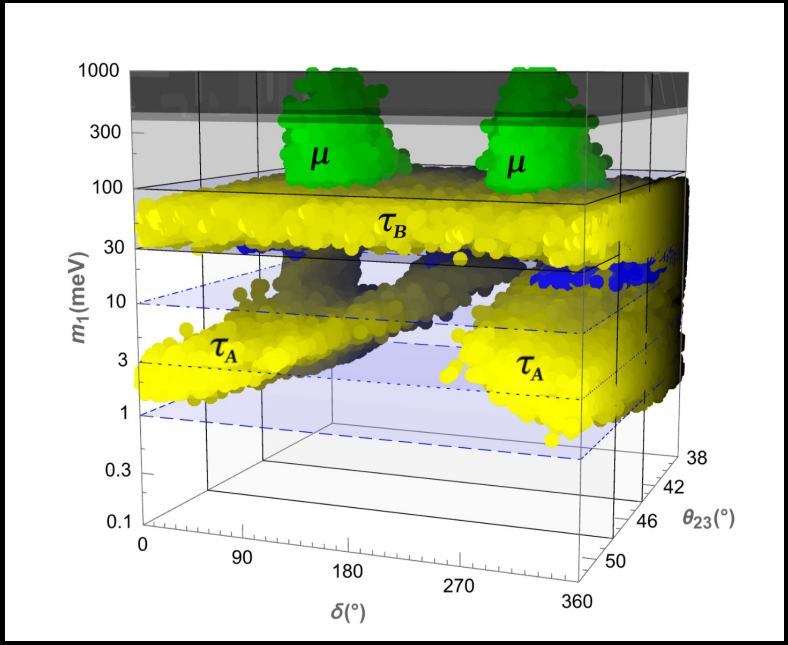
$$\eta_B^{SO10lep}(m_1, m_{sol}, m_{atm}, \theta_{12}, \theta_{23}, \theta_{13}, \delta, \rho, \sigma; \alpha_2, V_L) = \eta_B^{\rm obs}$$

- SO(10) inspired conditions also impose $V_L \sim V_{CKM}$
- In the approximation $V_L = I$ this would identify a hypersurface in the space of low energy neutrino parameters yielding interesting constraints and predictions.
- Turning small angles in V_L at the level of the angles in V_{CKM} gives some thickness to the hypersurface but the constraints remain.

3-dim projection of the allowed region (NO)

(PDB, Xubin Hu 2507.06144)

α_2=5 NORMAL ORDERING $I \lesssim V_L \lesssim V_{CKM}$



~ 10^6 solutions out of
~ 10^{10} trials

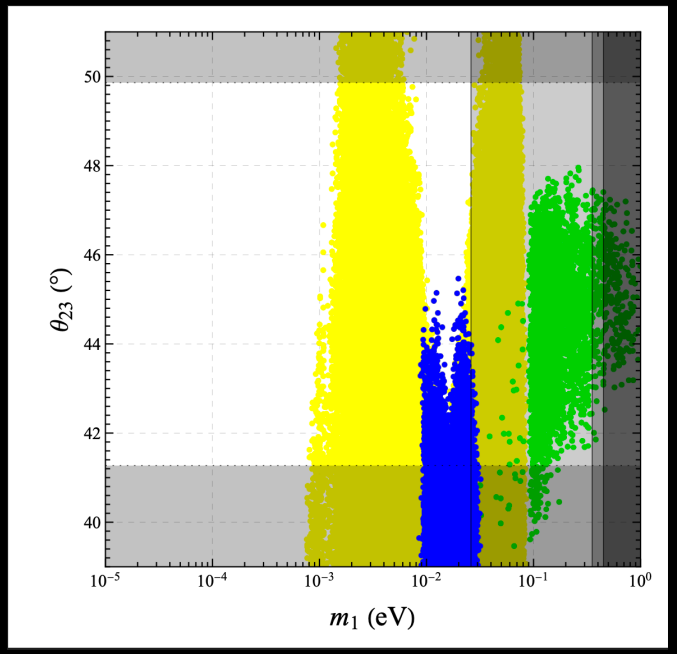
tauonic muonic electronic Strong-thermal leptogenesis (subset of tauonic)

- Inverted ordering is not viable
- Lower bound $m_1 \gtrsim 1$ meV
- There is a subset of solutions realizing STRONG THERMAL CONDITION

2-dim projection in the plane m_1 - θ_{23}

(PDB, Xubin Hu 2507.06144, 2611.16604)

α_2=5 NORMAL ORDERING $I \leq V_L \leq V_{CKM}$



tauonic muonic electronic Strong-thermal leptogenesis (subset of tauonic)

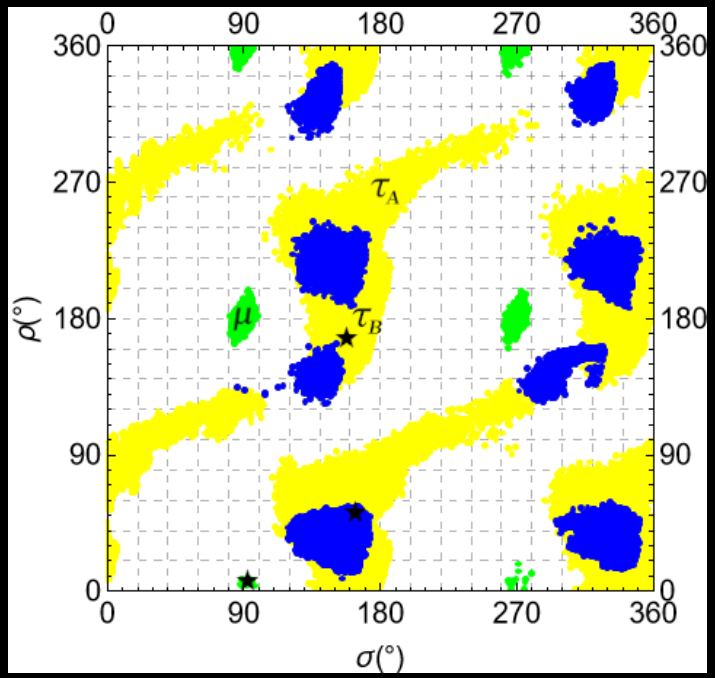
In the range 10 meV $\lesssim m_1 \lesssim$ 30 meV the atmospheric mixing angle needs to be in the first octant

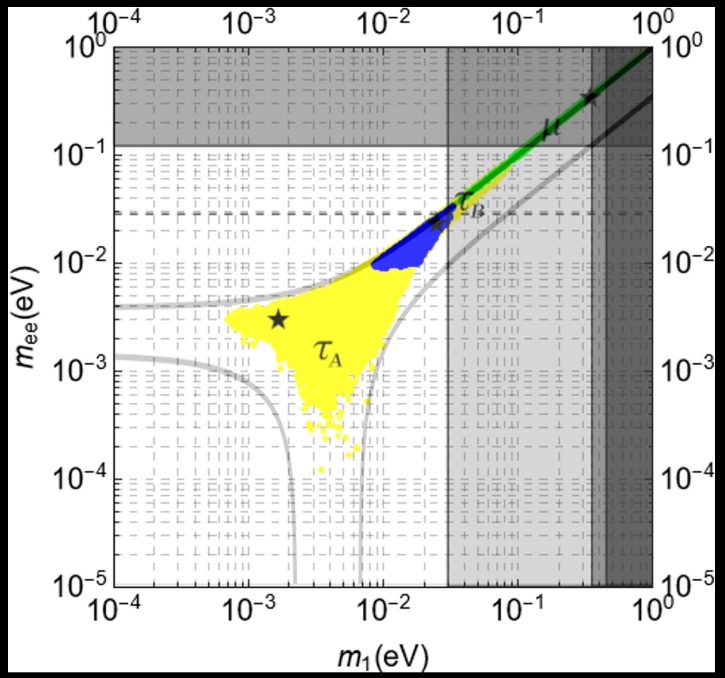
This is the same range where strong thermal solutions exist

Majorana phases and $0\nu\beta\beta$ effective mass

(PDB, Xubin Hu 2507.06144)

α_2=5 NORMAL ORDERING $I \leq V_L \leq V_{CKM}$





tauonic muonic electronic Strong-thermal leptogenesis (subset of tauonic)

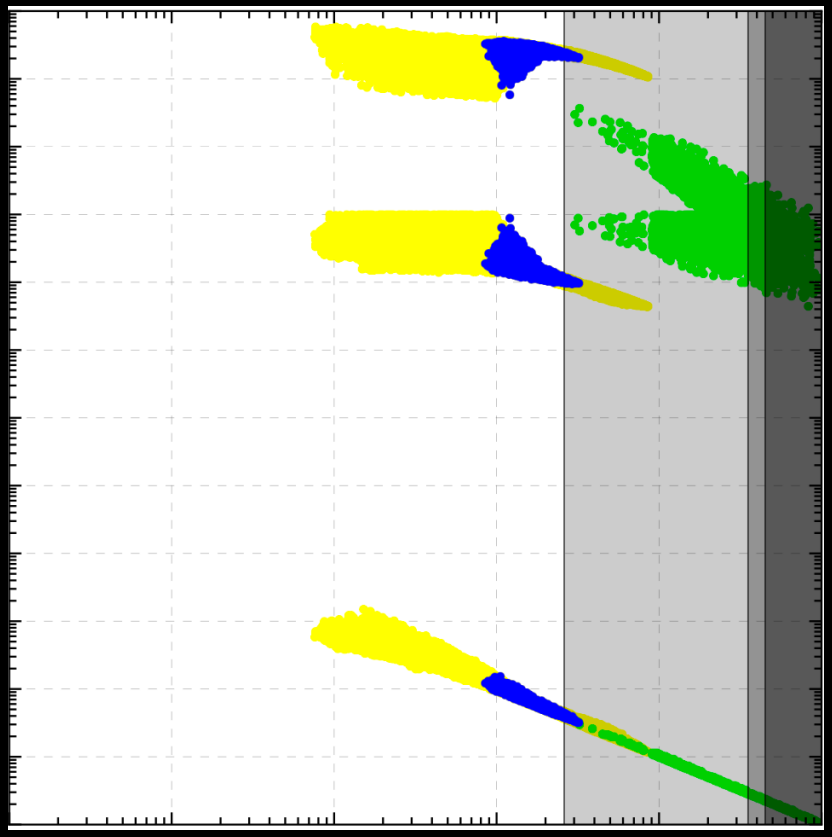
Solutions cluster around particular values of Majorana phases

Strong thermal solutions will be fully tested by next generation **$0\nu\beta\beta$ experiments (KamLAND2-ZEN, LEGEND 1000, CUPID,…)**

RH neutrino mass spectrum

(PDB, Xubin Hu 2507.06144)

α_2=5 NORMAL ORDERING $I \lesssim V_L \lesssim V_{CKM}$

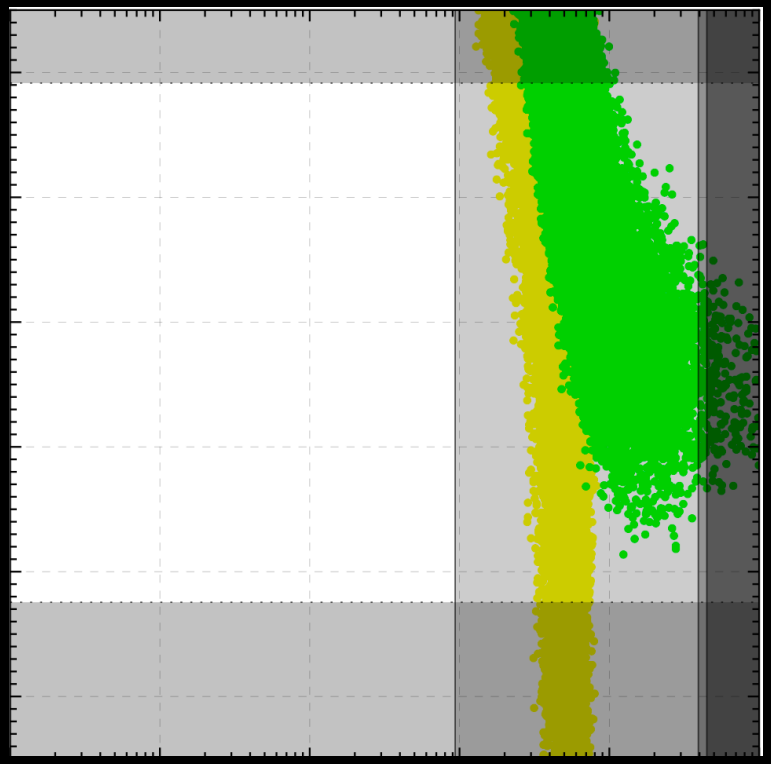


tauonic muonic electronic Strong-thermal leptogenesis (subset of tauonic)

2-dim projection in the plane m_1 - θ_{23}

(PDB, Xubin Hu 2611.16604)

α_2=5 INVERTED ORDERING $I \leq V_L \leq V_{CKM}$



tauonic muonic

Leptogenesis in SO(10) with a minimal Yukawa sector

(Babu, Bajc, Saad, 1612.04329; K Babu, PDB, C.S. Fong, S. Saad 2409.03840)

- The most attractive models realizing SO(10)-inspired leptogenesis are…….. …..SO(10) models !
- SO(10) unifies all fermions of a generation into a single spinorial 16-dimensional representation that, in addition to SM fermions, contains 1 RH neutrino: it naturally predicts 3 RH neutrino species
- 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 SO(10) SSB at $M_{GUT}=2\times10^{16}$ GeV one obtains the masses:

up-quark mass matrix

down-quark mass matrix

neutrino mass matrix

charged lepton mass matrix

RH neutrino mass matrix

$$\begin{aligned}
M_u &= v^u_{10}Y_{10} + v^u_{126}Y_{126} + v^u_{120}Y_{120}\,,\\
M_d &= v^d_{10}Y_{10} + v^d_{126}Y_{126} + v^d_{120}Y_{120}\,,\\
M_D &= v^u_{10}Y_{10} - 3v^u_{126}Y_{126} + v^D_{120}Y_{120}\,,\\
M_l &= v^d_{10}Y_{10} - 3v^d_{126}Y_{126} + v^l_{120}Y_{120}\,,\\
M_R &= v^R_{126}Y_{126}\,,
\end{aligned}$$

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

A recent realistic fit

(K Babu, PDB, C.S. Fong, S. Saad 2409.03840)

Observables (Δm^2_{ij} in eV^2)	Values at M_Z scale		
	Input	Benchmark Fit: NO	Benchmark Fit: IO
$y_u/10^{-6}$	6.65±2.25	7.30	10.0
$y_c/10^{-3}$	3.60±0.11	3.59	3.57
y_t	0.986±0.0086	0.986	0.986
$y_d/10^{-5}$	1.645±0.165	1.636	1.635
$y_s/10^{-4}$	3.125±0.165	3.122	3.148
$y_b/10^{-2}$	1.639±0.015	1.639	1.637
$y_e/10^{-6}$	2.7947±0.02794	2.7945	2.7906
$y_\mu/10^{-4}$	5.8998±0.05899	5.9011	5.9080
$y_\tau/10^{-2}$	1.0029±0.01002	1.0022	1.0023
$\theta_{12}^{\rm CKM}/10^{-2}$	22.735±0.072	22.729 ($\theta_{12}^{\rm CKM}$ =13.023°)	22.730 ($\theta_{12}^{\rm CKM}$ =13.023°)
$\theta_{23}^{\rm CKM}/10^{-2}$	4.208±0.064	4.206 ($\theta_{23}^{\rm CKM}$ =2.401°)	4.204 ($\theta_{23}^{\rm CKM}$ =2.408°)
$\theta_{13}^{\rm CKM}/10^{-3}$	3.64±0.13	3.64 ($\theta_{13}^{\rm CKM}$ =0.208°)	3.64 ($\theta_{13}^{\rm CKM}$ =0.208°)
$\delta_{\rm CKM}$	1.208±0.054	1.209 ($\delta_{\rm CKM}$ =69.322°)	1.212 ($\delta_{\rm CKM}$ =69.457°)
$\Delta m^2_{21}/10^{-5}$	7.425±0.205	7.413	7.506
$\Delta m^2_{31}/10^{-3}$ (NO)	2.515±0.028	2.514	-
$\Delta m^2_{32}/10^{-3}$ (IO)	-2.498±0.028	-	-2.499
$\sin^2\theta_{12}$	0.3045±0.0125	0.3041 ($\theta_{12}=33.46°$)	0.3067 ($\theta_{12}=33.63°$)
$\sin^2\theta_{23}$ (NO)*	0.5705±0.0205	0.4473 ($\theta_{23}=41.98°$)	-
$\sin^2\theta_{23}$ (IO)*	0.576±0.019	-	0.5784 ($\theta_{23}=49.51°$)
$\sin^2\theta_{13}$ (NO)	0.02223±0.00065	0.02223 ($\theta_{13}=8.57°$)	-
$\sin^2\theta_{13}$ (IO)	0.02239±0.00063	-	0.02238 ($\theta_{13}=8.60°$)
$\delta^\circ_{\rm CP}$ (NO)	207.5±38.5	240.49	-
$\delta^\circ_{\rm CP}$ (IO)	284.5±29.5	-	263.49
$\eta_B/10^{-10}$	6.12±0.04‡	7.6 (7.6)	9.6 (51)
χ^2	-	1.45	5.76†

For NO:

light neutrino masses

m_1= 0.038 meV
m_2= 8.6 meV
m_3= 50.1 meV
m_{ee}=3.7 meV

heavy neutrino masses

M_1=6.6x10^4 GeV

M_2=2.1x10^{12} GeV

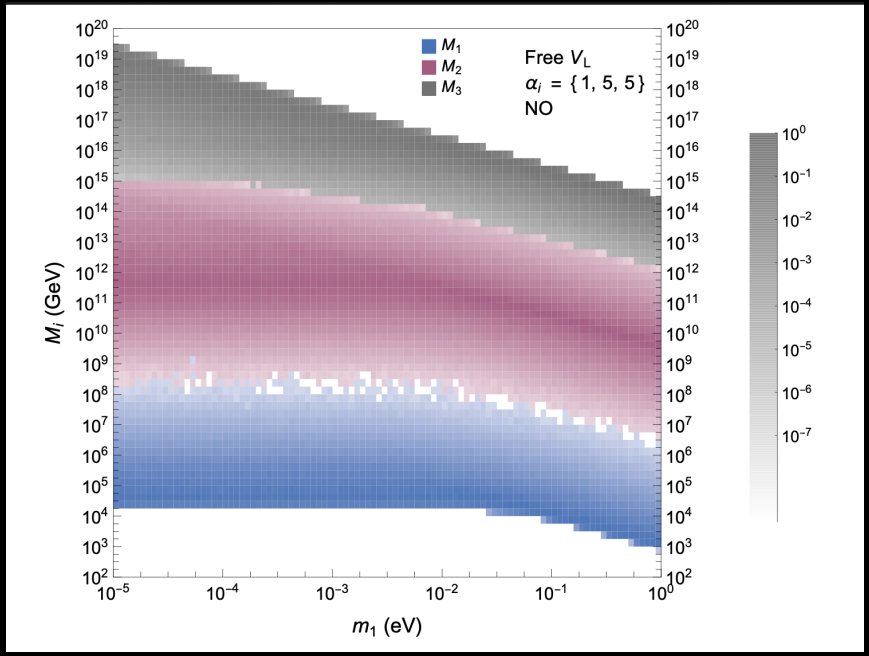
M_3=8.1x10^{14} GeV

Why is the lower bound on m_1 violated? Because $\theta_{23}{}^{L} \simeq 45^\circ \Rightarrow$ extended SO(10)-insp. lep

Extended SO(10)-inspired conditions

What happenes for an arbitrary V_L? This extends SO(10)-inspired leptogenesis to a very broad class of models simply characterized by:

- ~~$V_L \simeq V_{CKM} \simeq I$~~
- $m_{D1} = \alpha_1 m_{\rm up}\,; m_{D2} = \alpha_2 m_{\rm charm}; m_{D3} = \alpha_3 m_{\rm top};\ \alpha_i = \mathcal{O}(1)$



Even for arbitrary V_L the heavy neutrino mass spectrum necessarily requires N_2 -leptogenesis as the scenario to reproduce the observed asymmetry: it is very general

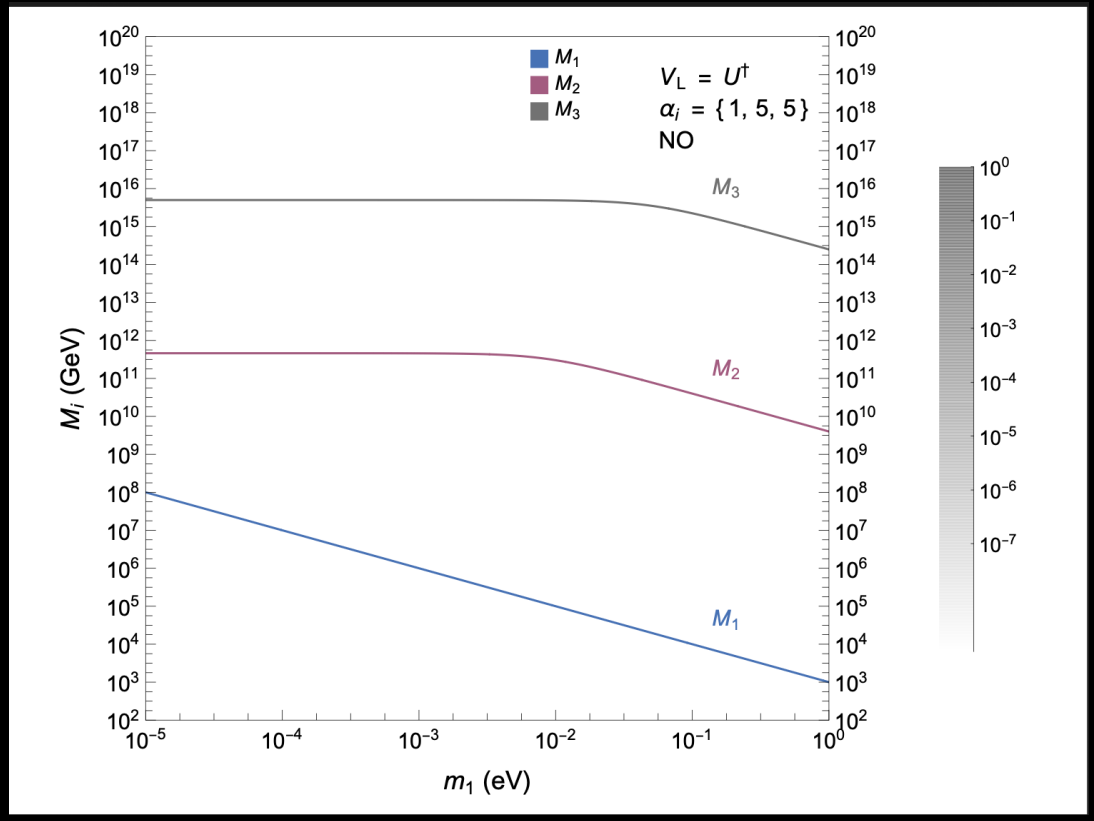
A cross check

(PDB, Xubin Hu **2611.16604**)

As a cross check set we set $V_L = U^\dagger$

$\Longrightarrow$ heavy neutrino mass spectrum reduces to the special limit we saw:

$$m_i = \frac{m_{Di}^2}{M_I}$$

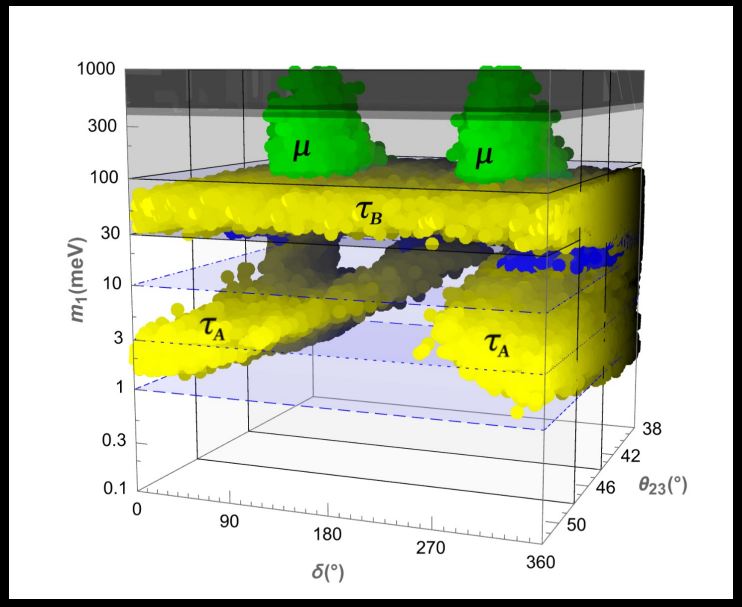


Extended SO(10)-inspired leptogenesis

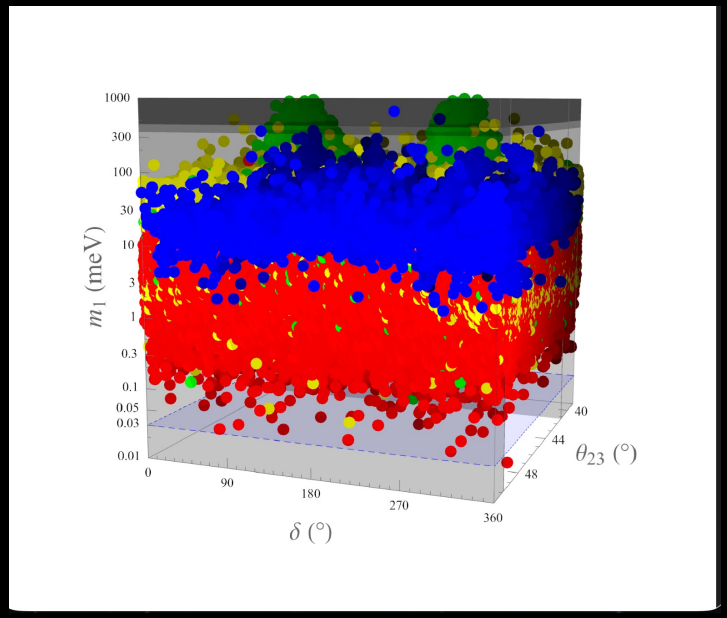
(PDB, Xubin Hu 2611.16604)

NORMAL ORDERING

SO(10)-inspired leptogenesis



extended SO(10)-inspired leptogenesis



~ 10^6 solutions
~ 10^9 trials

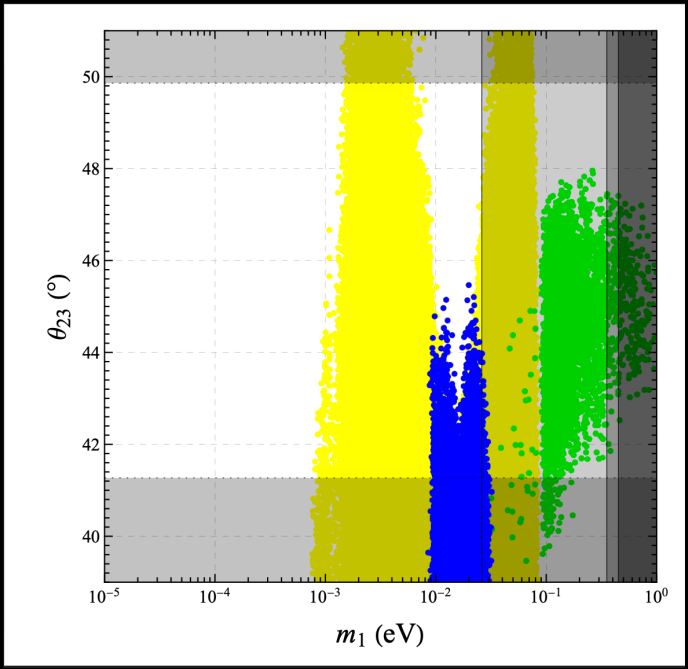
- Solutions are found for any value of θ_{23} and δ for $m_1 \gtrsim 10^{-5}$ eV

Extended SO(10)-inspired leptogenesis

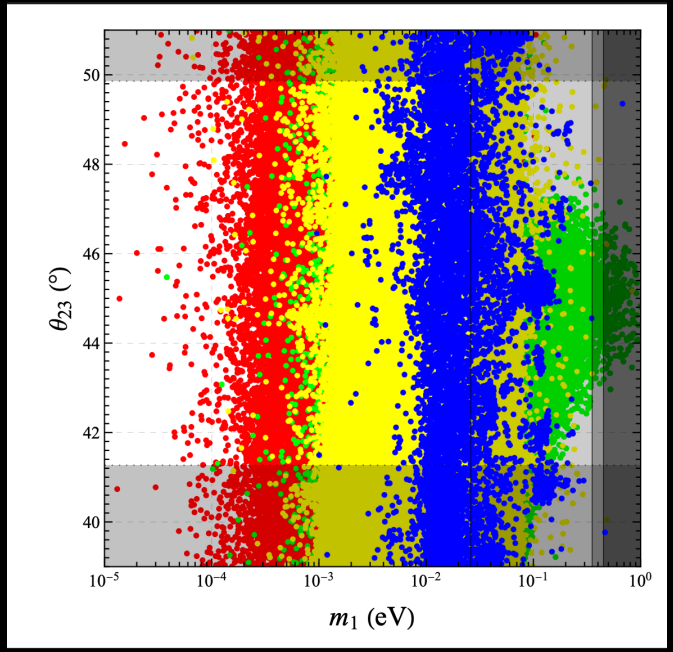
(PDB, Xubin Hu 2611.16604)

NORMAL ORDERING

SO(10)-inspired leptogenesis



extended SO(10)-inspired leptogenesis

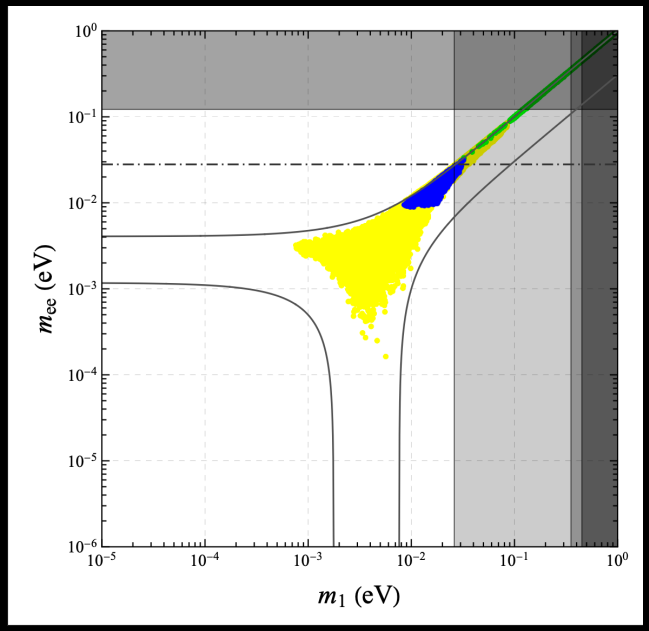


Extended SO(10)-inspired leptogenesis

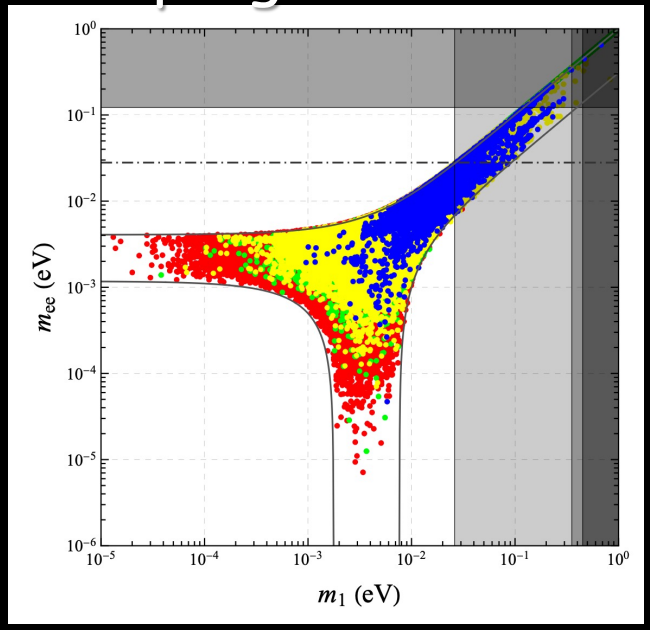
(PDB, Xubin Hu 2611.16604)

NORMAL ORDERING

SO(10)-inspired leptogenesis



extended SO(10)-inspired leptogenesis



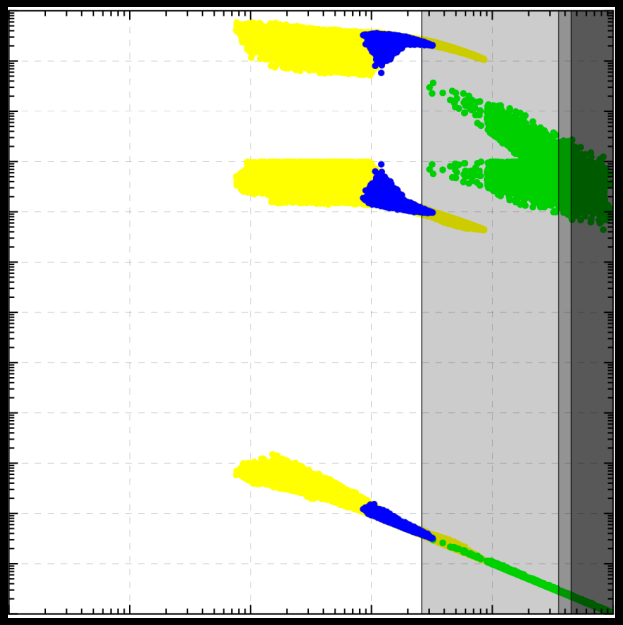
- Even for arbitrary V_L there is still a lower bound both on m_1 and m_{ee} (though relaxed by about 1 order of magnitude

Extended SO(10)-inspired leptogenesis

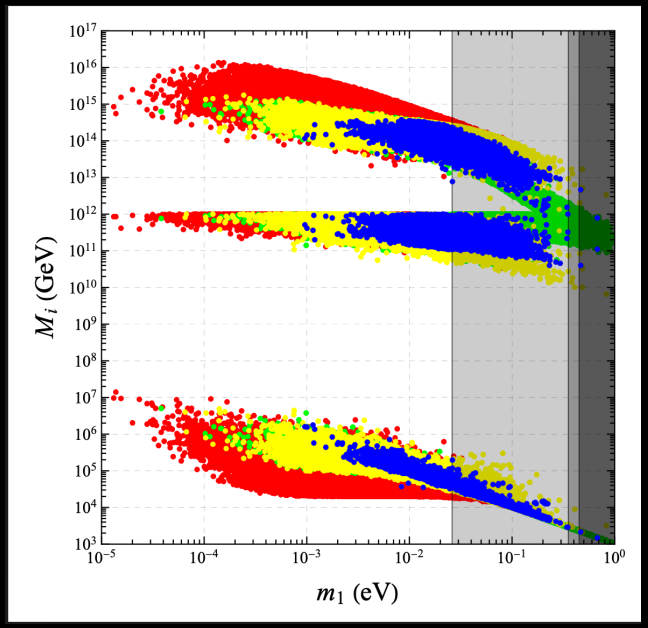
(PDB, Xubin Hu 2611.16604)

NORMAL ORDERING

SO(10)-inspired leptogenesis



extended SO(10)-inspired leptogenesis

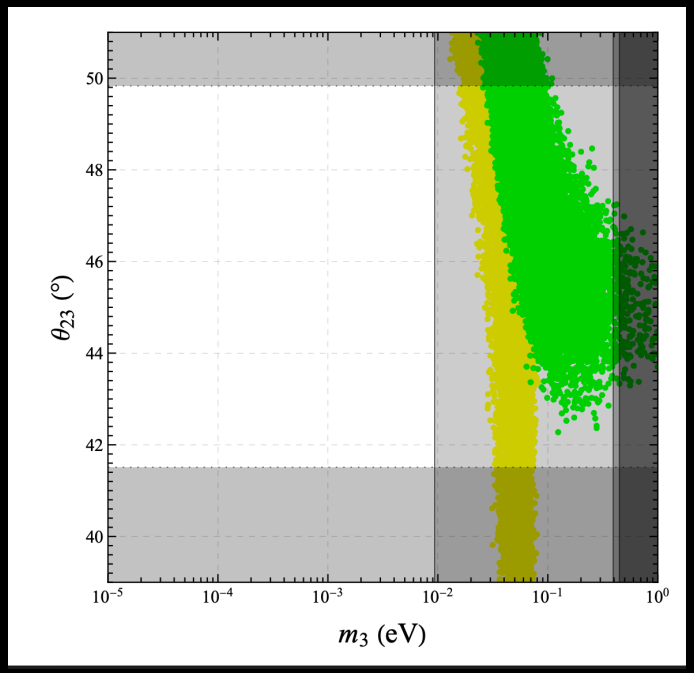


Extended SO(10)-inspired leptogenesis

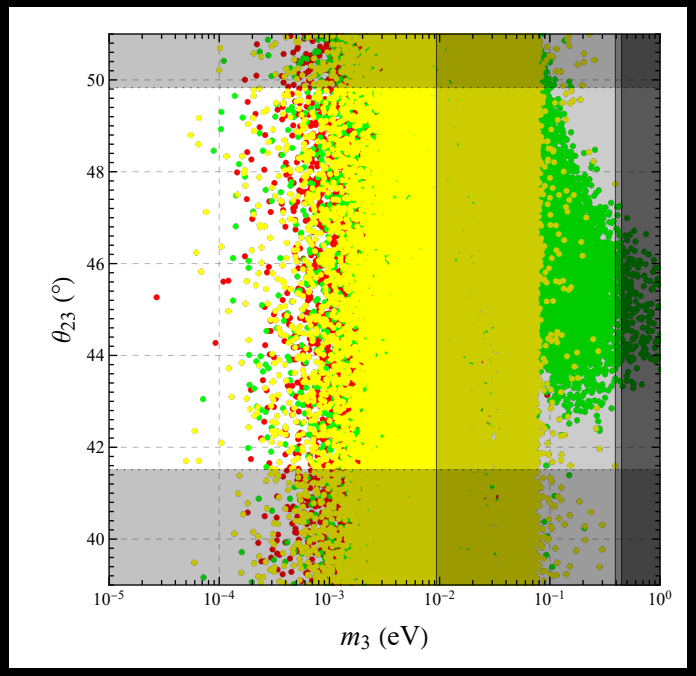
(PDB, Xubin Hu 2611.16604)

INVERTED ORDERING

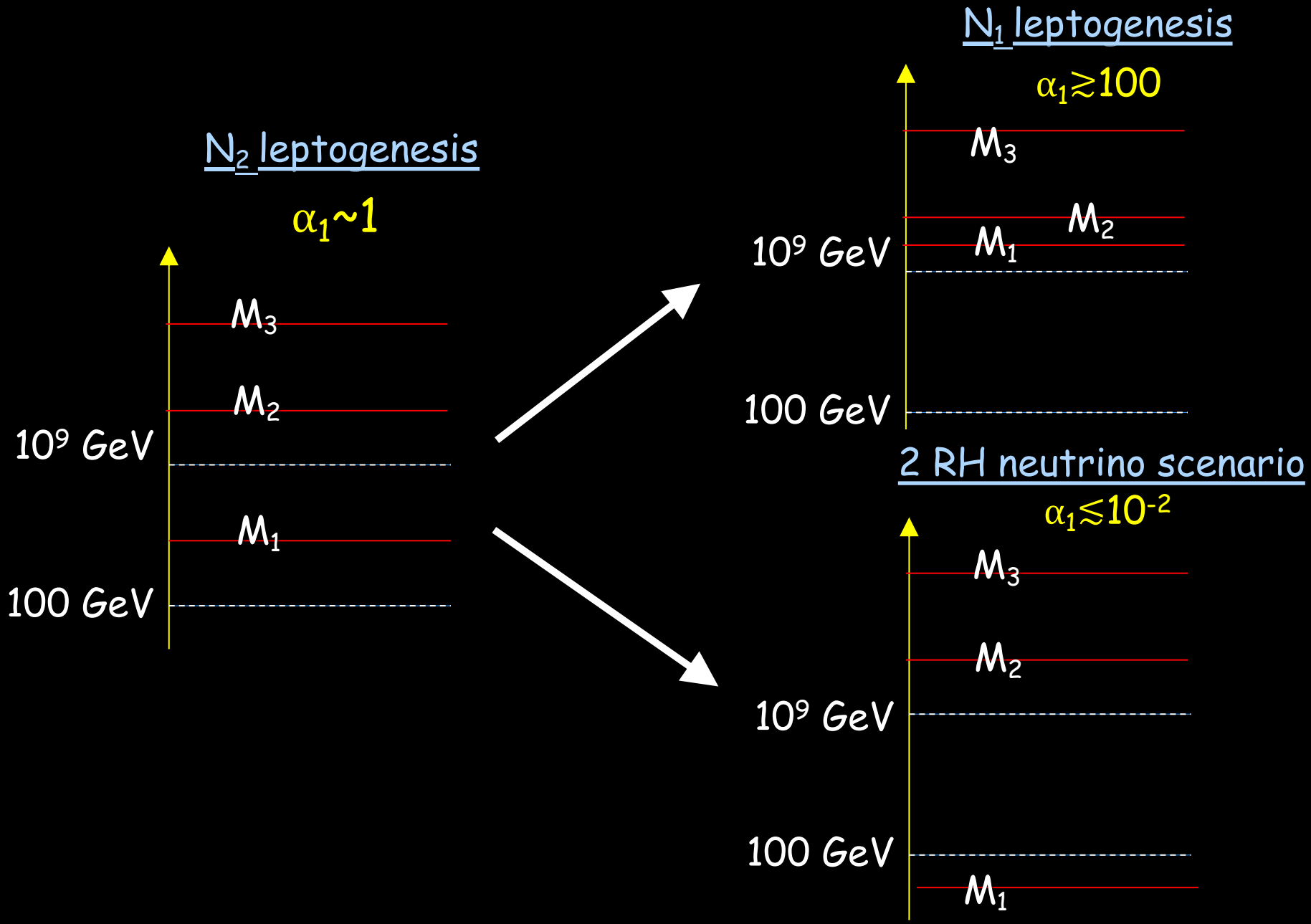
SO(10)-inspired leptogenesis



extended SO(10)-inspired leptogenesis



How to depart from N_2 leptogenesis?



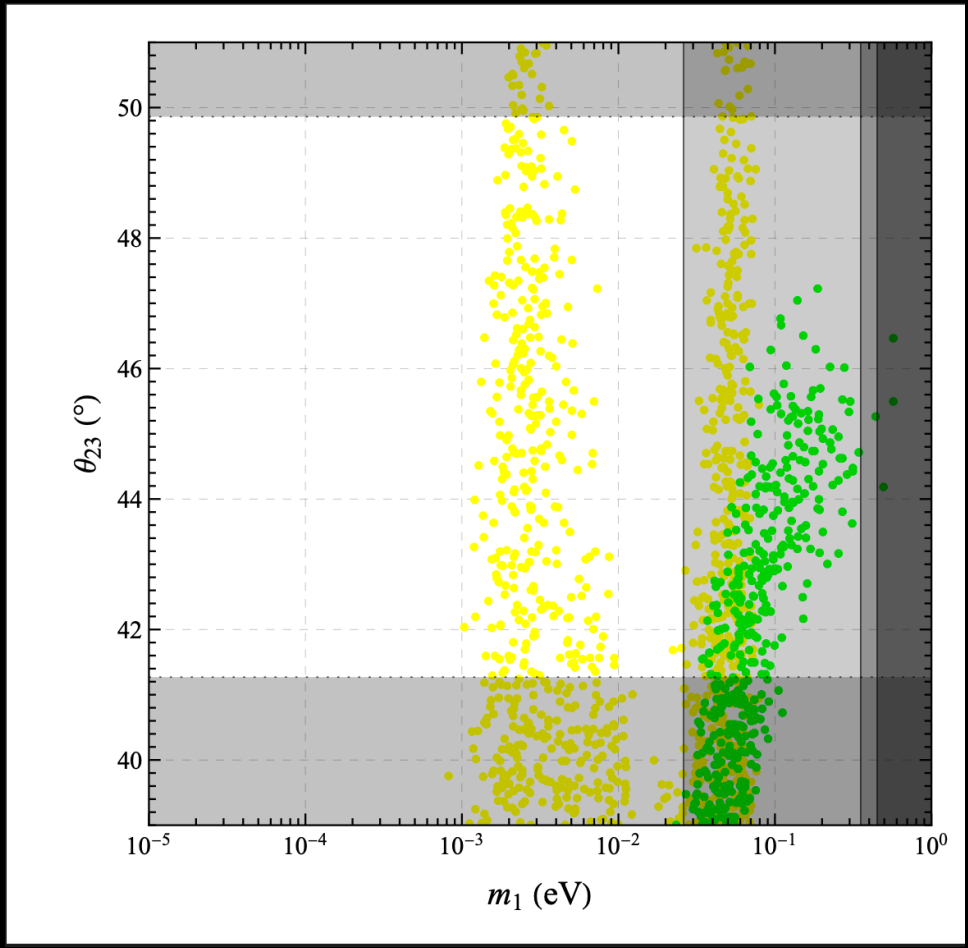
Conclusions

- Even extending SO(10)-inspired conditions allowing for arbitrary V_L the conclusion $M_1 << 10^9$ GeV still holds, requiring N_2-leptogenesis scenario to reproduce the observed asymmetry
- The lower bounds on m_1 and m_{ee} are still there, though relaxed
- IO solutions appear
- If new data should support SO(10)-inspired leptogenesis with $V_L \sim$ I, this can be regarded as a sign in favour of GUTs. In particular NO should be confirmed.
- Exciting times!

Turning on just 1 angle in V_L: θ^L_{23}

(PDB, Xubin Hu 2611.16604)

NORMAL ORDERING

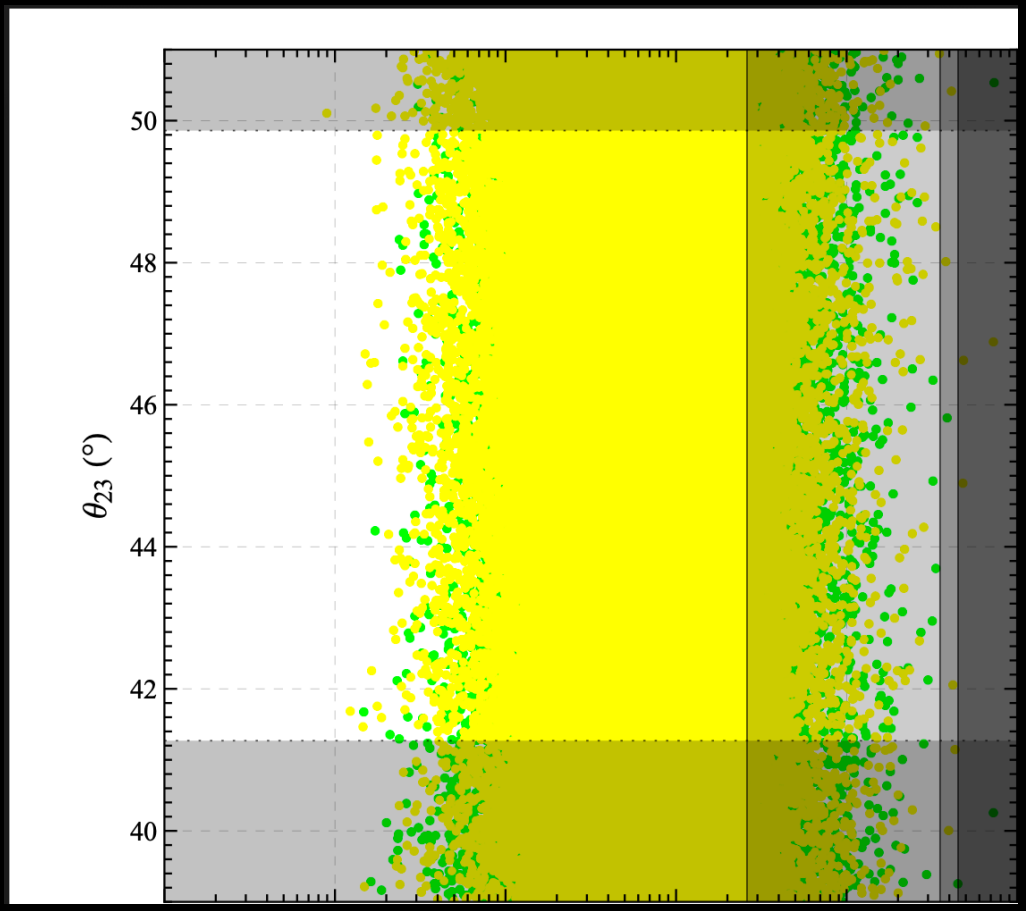


$0 < \theta^L_{23} < 1°$

Turning on just 1 angle in V_L: θ^L_{23}

(PDB, Xubin Hu 2611.16604)

NORMAL ORDERING

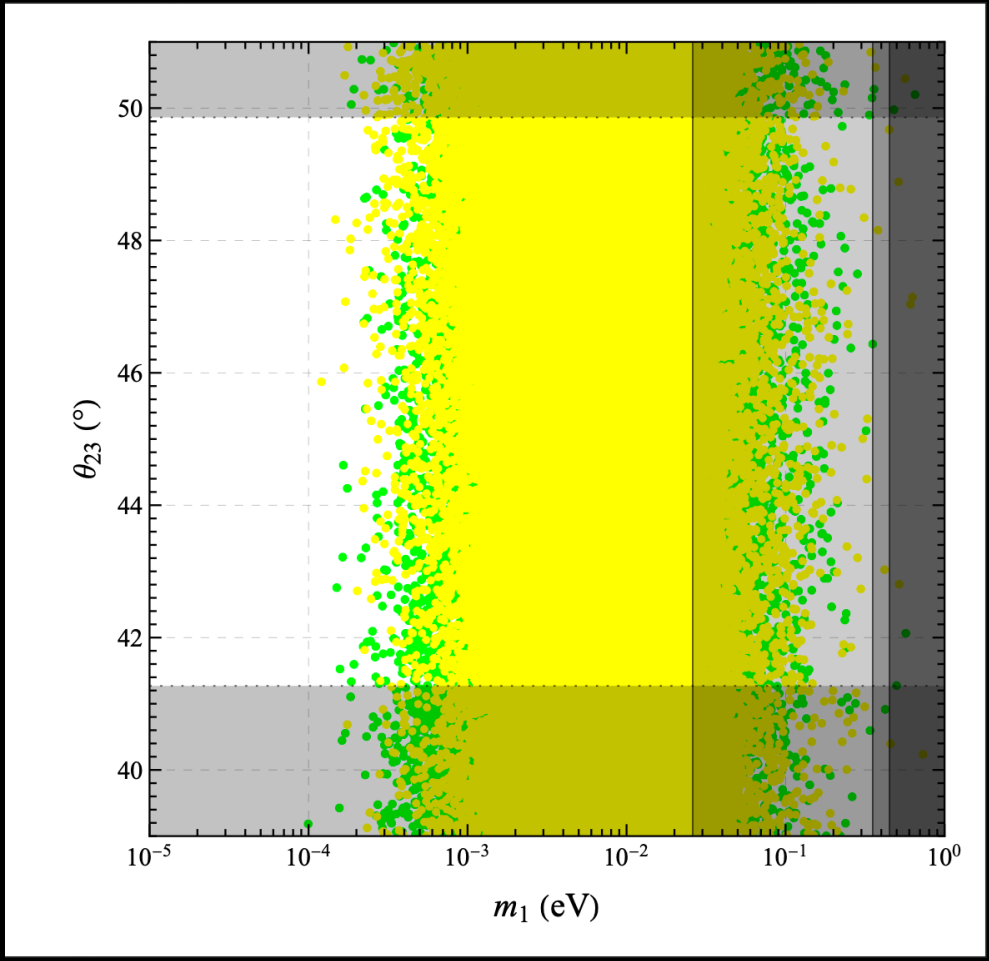


$30° < \theta^L_{23} < 40°$

Turning on just 1 angle in V_L: θ^L_{23}

(PDB, Xubin Hu 2611.16604)

NORMAL ORDERING



$40° < \theta^L_{23} < 50°$

Majorana mass from new physics: effective theory approach

(Weinberg 1979)

Allowing for lepton number violation:

$$\mathcal{L}_{\text{Weinberg}} = (\overline{L^c_\alpha}\,\tilde{\phi}^*)\frac{g_{\alpha\beta}}{\Lambda}(\tilde{\phi}^\dagger L_\beta) + h.c.$$

After EWSSB this generates a left-left neutrino Majorana mass term:

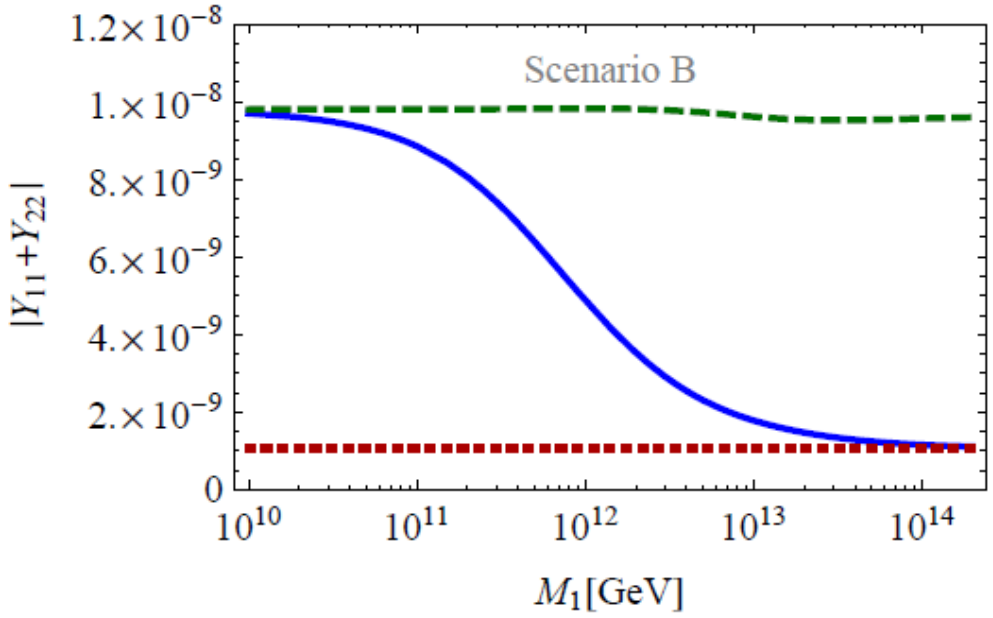
$$\Rightarrow -\mathcal{L}^{\nu}_{\text{Mayorana}} = \overline{\nu^c_{L\alpha}}\, m_{\nu\alpha\beta}\, \nu_{L\beta} \quad \text{with} \quad m_{\nu\alpha\beta} = \frac{g_{\alpha\beta} v^2}{\Lambda} \propto \frac{m_D^2}{\Lambda}$$

(seesaw formula)

Density matrix and CTP formalism to describe the transition regimes

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

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



Fully two-flavoured regime limit

Unflavoured regime limit

Charged lepton flavour effects

(Barbieri et al '98; Abada et al '06; Nardi et al. '06; Blanchet, PDB, Raffelt '06; Riotto, De Simone '06)

Flavor composition of lepton quantum states matters!

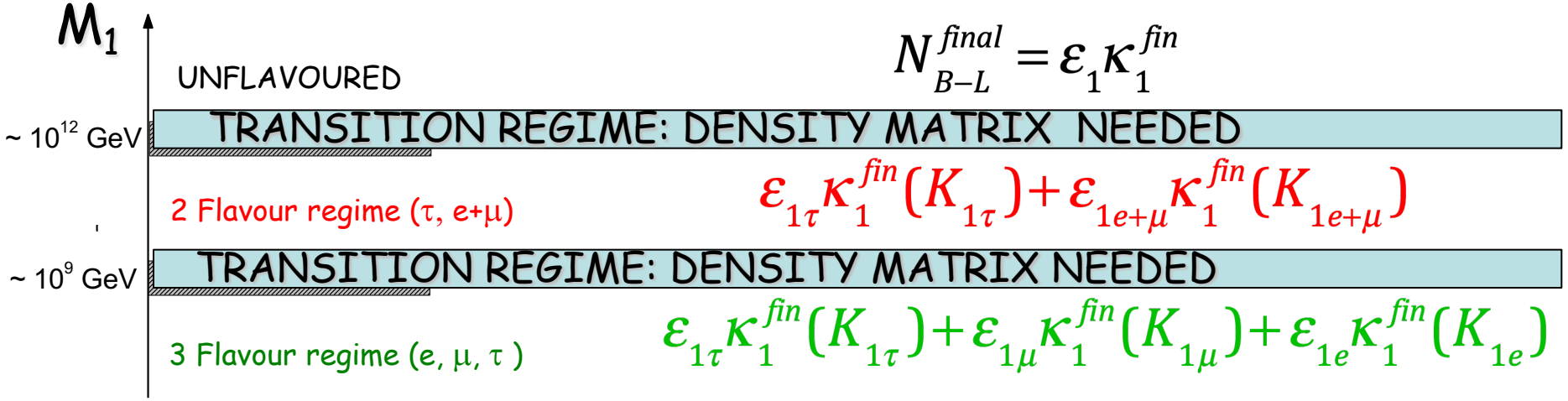
$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1\rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau)$$

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

- $M_1 \ll 10^{12}$ GeV ⇒ τ-Yukawa interactions are fast enough break the coherent evolution of $|l_1\rangle$ and $|\overline{l}'_1\rangle$

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

- $M_1 \ll 10^{9}$ GeV then also τ-Yukawas in equilibrium ⇒ 3-flavour regime

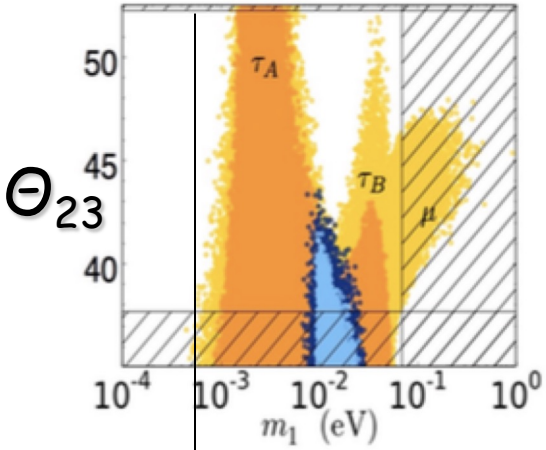


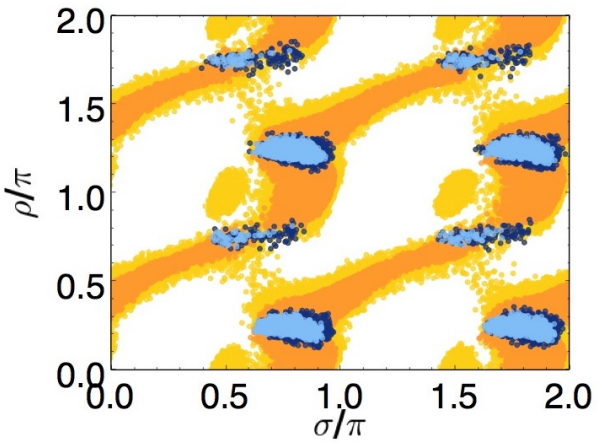
N_2-leptogenesis rescues SO(10)-inspired leptogenesis

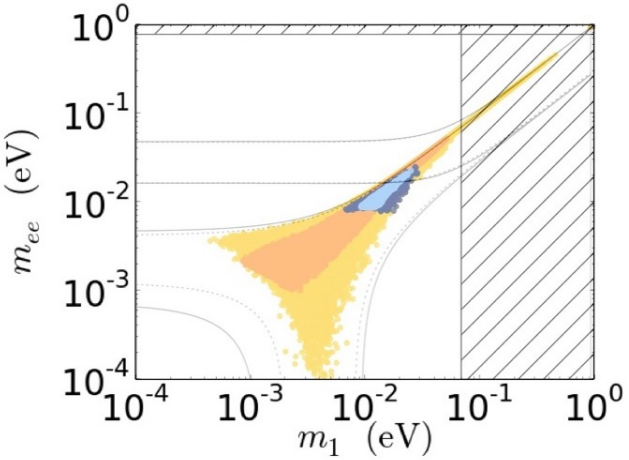
(PDB, Riotto 0809.2285;1012.2343)

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

α_2=5 NORMAL ORDERING $V_L = I$ $I \leq V_L \leq V_{CKM}$







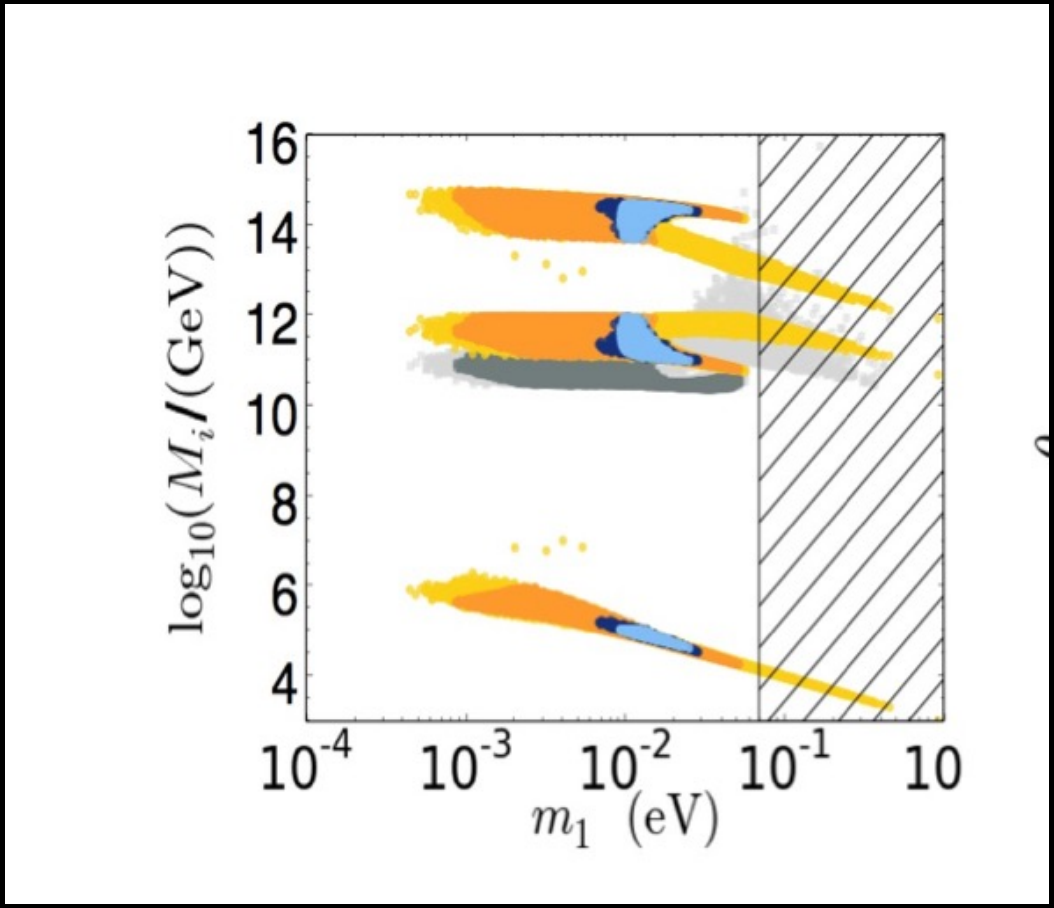
- Lower bound $m_1 \gtrsim 10^{-3}$ eV
- Θ_{23} upper bound

- 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 INCOMPATIBLE
- Strong thermal leptogenesis is realised for a subset (blue regions)
- Muon-dominated solution appear for $V_L \neq I$

α_2=5 NORMAL ORDERING $V_L = I$ $I \leq V_L \leq V_{CKM}$



Even turning of small mixing angles in V_L does not change the result that in SO(10)-inspired models $M_1 \ll 10^9$ GeV

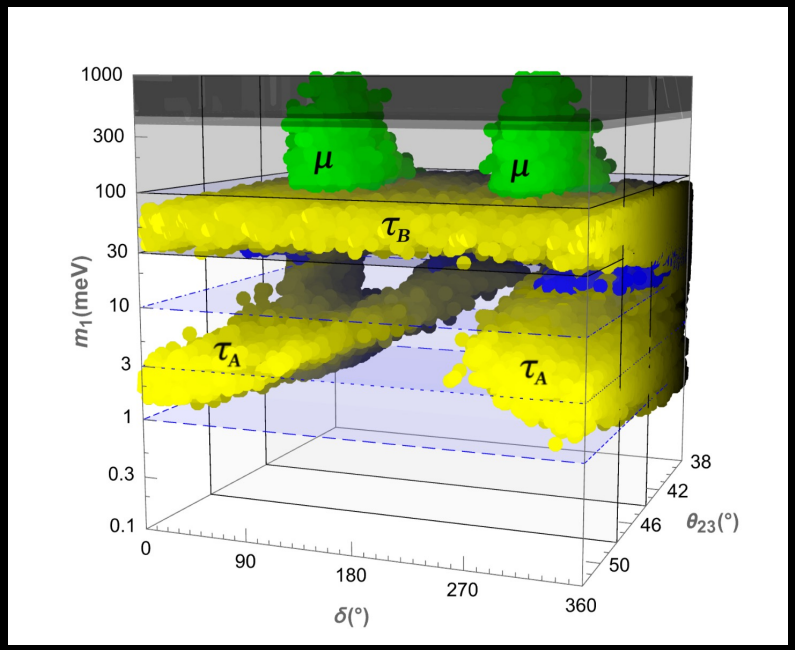
$\Rightarrow$ N_2 leptogenesis is still unavoidable

3-dim projection of the allowed region (NO)

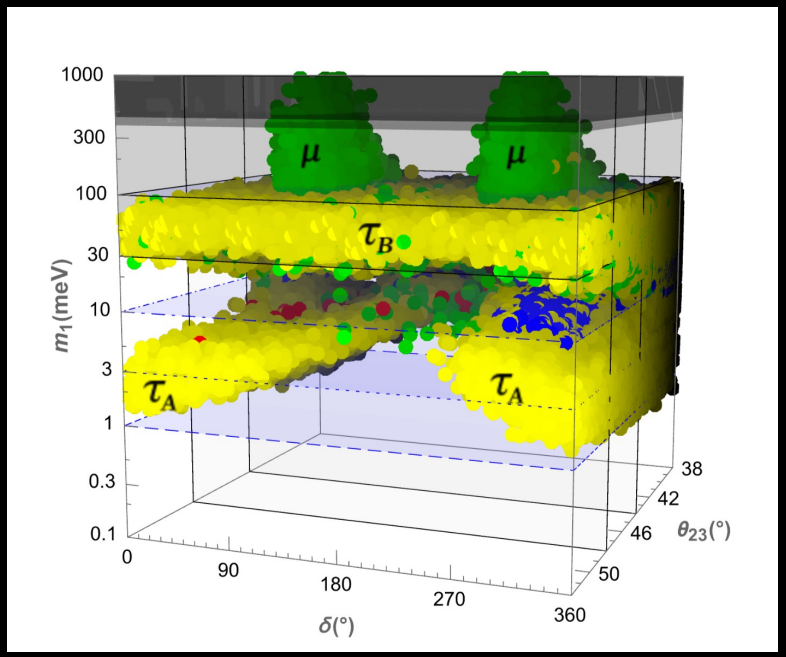
(PDB, Xubin Hu 2507.06144)

α_2=5 **NORMAL ORDERING** $I \leq V_L \leq V_{CKM}$

without flavour coupling



with flavour coupling (originating from spectator processes, mainly Higgs asymmetry)



tauonic muonic electronic Strong-thermal leptogenesis (subset of tauonic)

Including flavour coupling, new muonic solutions appear and even some very marginal electronic solutions (red points)

Including radiative corrections or using density matrix equation have even smaller impact on these constraints (coming soon),