Particle Physics and Cosmology
37th Rencontres de Blois

Status of leptogenesis

Pasquale Di Bari
(University of Southampton)

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Status of leptogenesis

high scale leptogenesis

low scale leptogenesis

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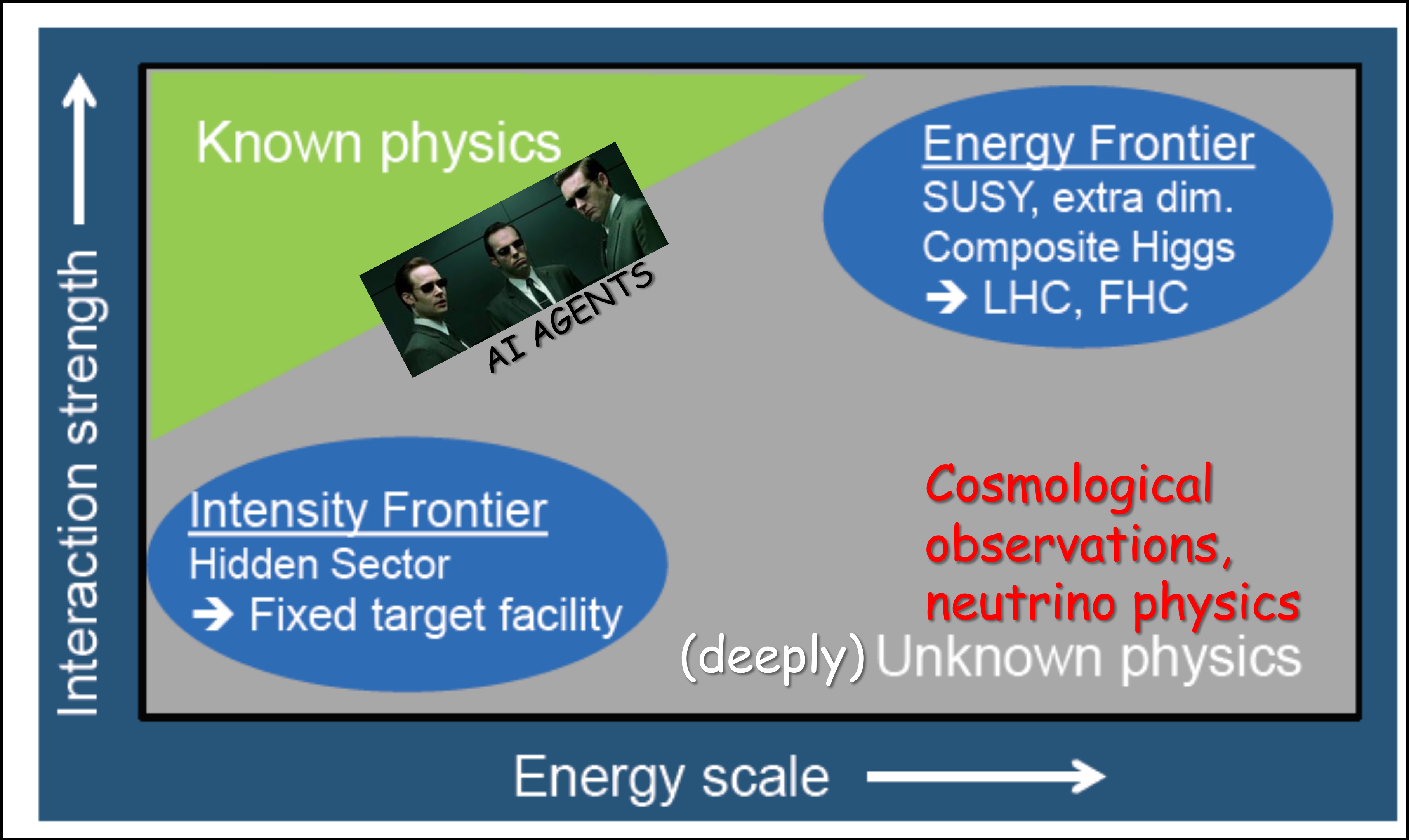
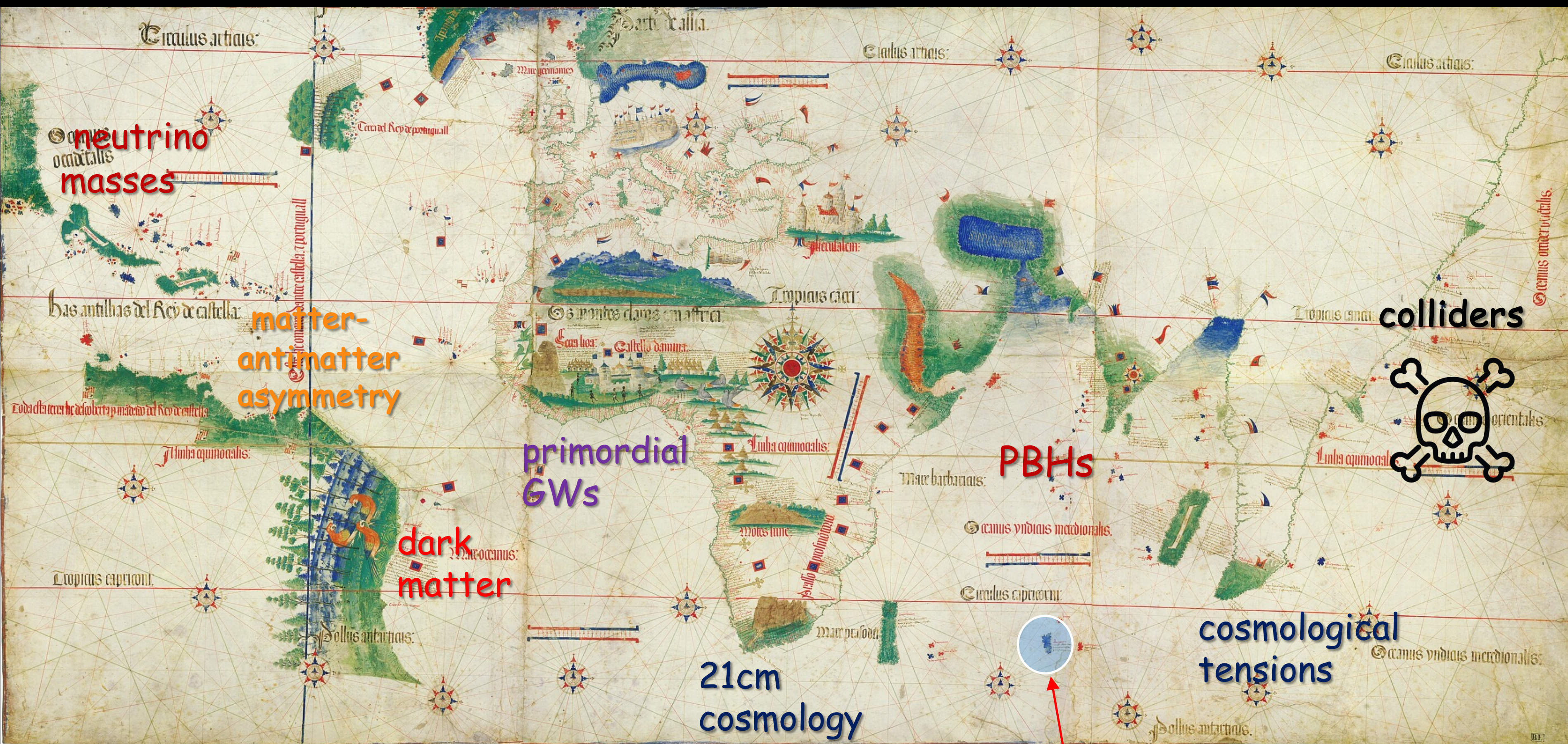
New frontiers

(SHIP proposal, 1504.04855)



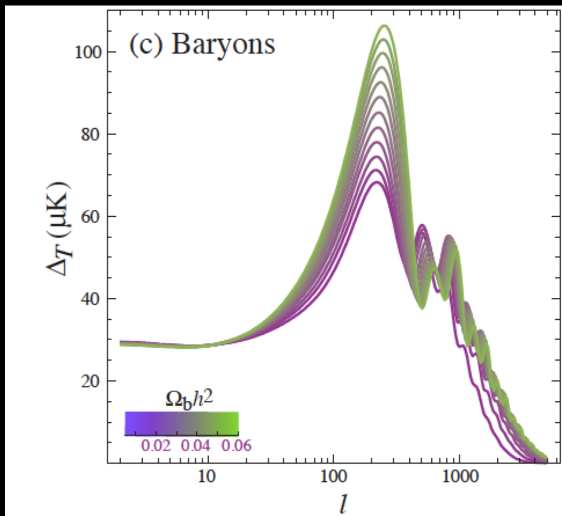
A map to navigate the deep unknown



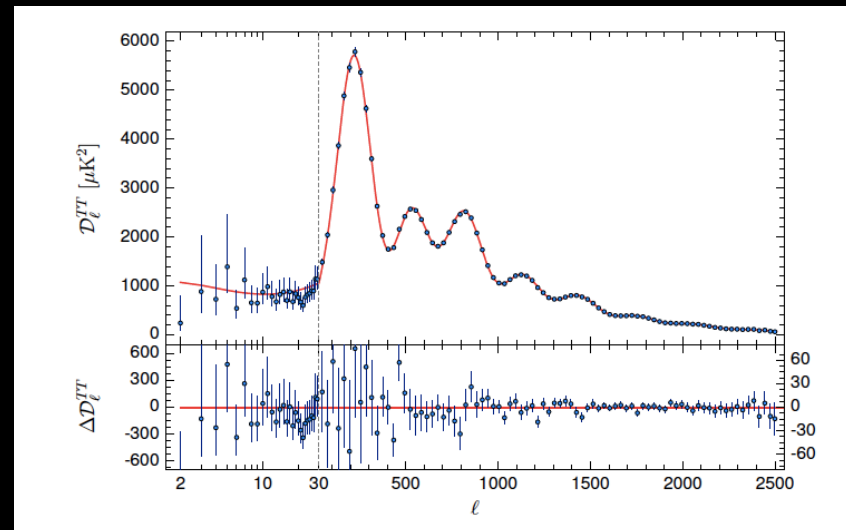
(Cantino planisphere, 1502, Biblioteca Estense Modena)

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 $\Longrightarrow$ it requires NEW PHYSICS!

Models of Baryogenesis

- From phase transitions:

  - ELECTROWEAK BARYOGENESIS (EWBG)

    * in the SM
    * in the MSSM
    * in the nMSSM
    * in the NMSSM
    * in the 2 Higgs model
    * …………………

- Affleck-Dine:

  - at preheating
    - Q-balls
  - ……….

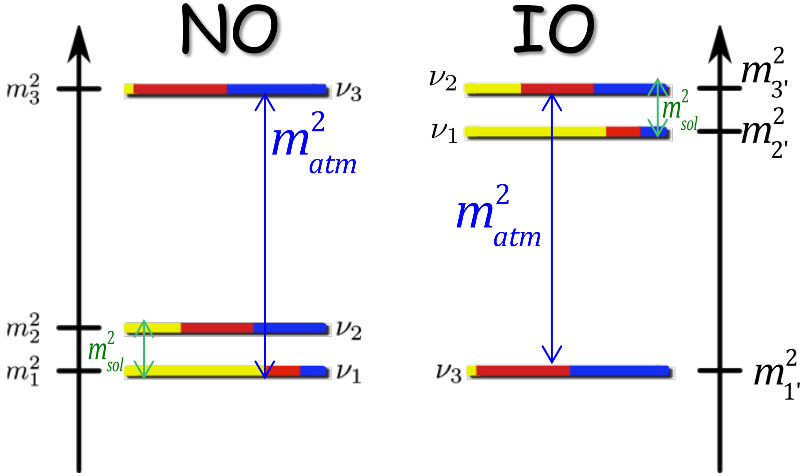
- From Black Hole evaporation
- Spontaneous Baryogenesis
- ……………………………………
- From heavy particle decays:

  - GUT Baryogenesis
  - **LEPTOGENESIS**

There is a clear reason why it is currently the most attractive model

(also Peter Matak's talk yesterday in neutrino parallel session)

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



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

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

$m_{sol} = (8.6 \pm 0.1)\ meV$

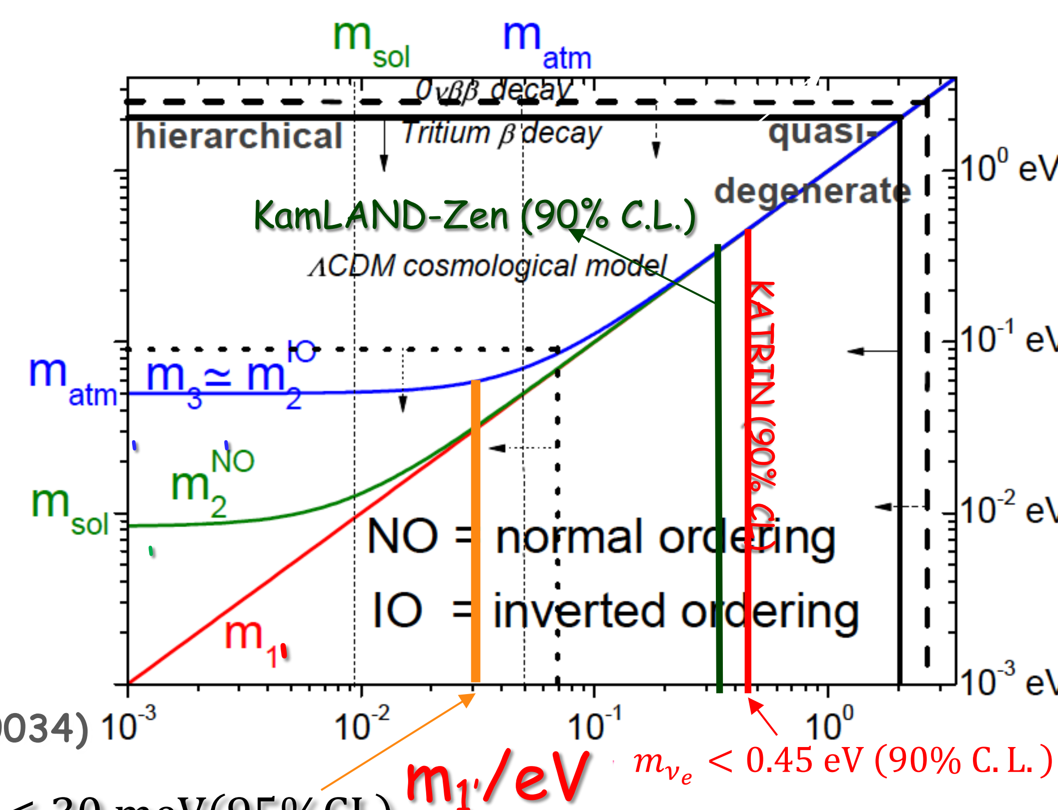
$m_{atm} = (50.0 \pm 0.3)\ meV$

Lower bound on neutrino masses (NO)

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

For IO it would be much more stringent:

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



Cosmological upper bound (Planck 2023, 2309.10034)

$$\sum m_i \lesssim 0.11\text{ eV (95\%CL)} \Rightarrow \text{for NO: } m_1 < 30\text{ meV(95\%CL)}$$

Neutrino mixing parameters:

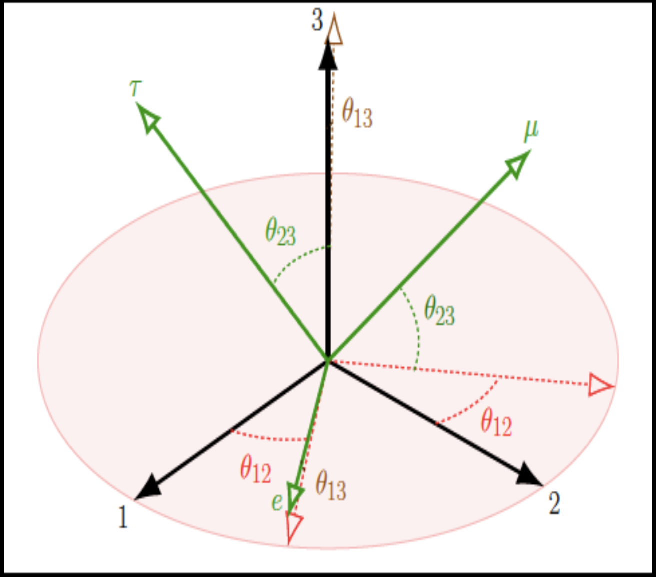
$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}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

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

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, including new JUNO results)

$\theta_{12} = [31.63°, 35.95°]$

$\theta_{13} = [8.19°, 8.89°]$

$\theta_{23} = [41.3°, 49.9°]$

$\delta = [-236°, 4°]$

$\rho, \sigma = [0°, 360°]$

NO favoured over IO:

$\Delta\chi^2$ (IO-NO)=9.41

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)

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

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):

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

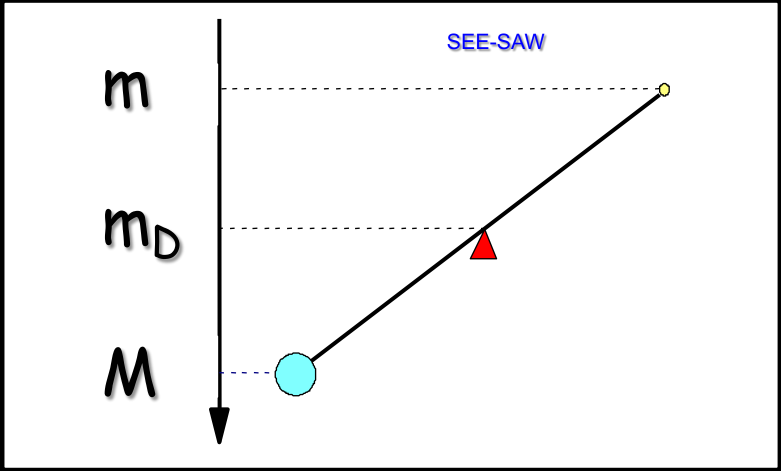
- 3(?) very heavy Majorana neutrinos N_I, N_{II}, N_{III} with $M_{III} > M_{II} > M_I \gg m_D$

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

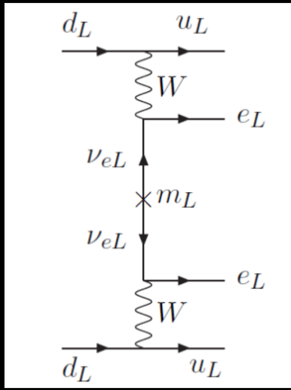


Neutrinos are predicted to be Majorana particles

Both light and heavy neutrinos are Majorana neutrinos:

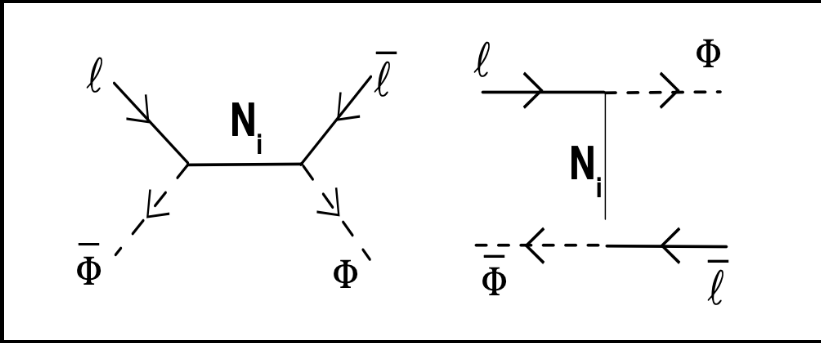
$$\nu_i \equiv \nu_{iL} + \nu_{iL}^c \qquad N_I \equiv N_{IR} + N_{IR}^c$$

- For light neutrinos:



$0\nu\beta\beta$ decay

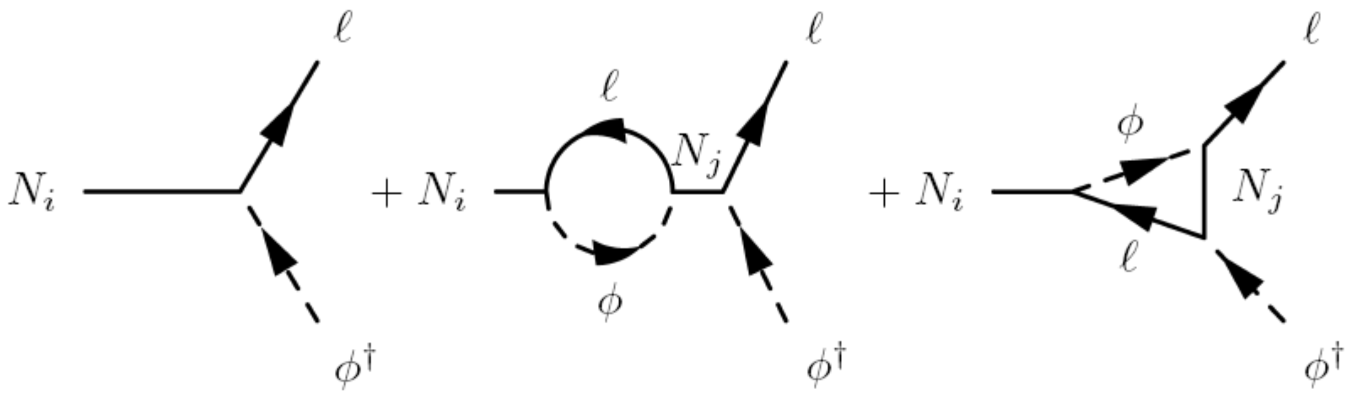
- For heavy neutrinos:



They are both $\Delta L = 2$ processes

Total CP asymmetries

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



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

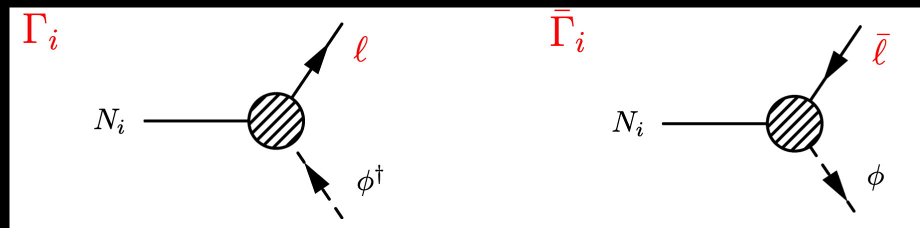
It does not depend on U !

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 neutrino decays



$$\varepsilon_I \equiv -\frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

total CP asymmetries $\varepsilon_I \equiv \frac{\Gamma_I - \bar{\Gamma}_I}{\Gamma_I + \bar{\Gamma}_I}$

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

efficiency factors

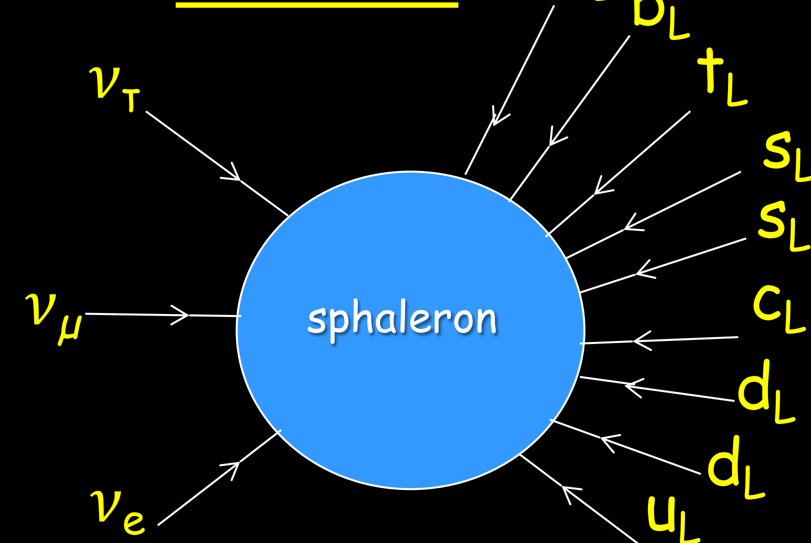
- Sphaleron processes in equilibrium

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

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

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

ΔB=ΔL=3



Seesaw parameter space

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

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

Orthogonal parameterisation

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

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

light neutrino parameters

heavy neutrino parameters escaping experimental information

- ❑ Popular solution in the LHC era: *low-scale* leptogenesis, potential direct discovery of RH neutrinos in lab neutrino experiments such as FASER (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,Garbrecht et al 2025)

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

1) Lepton flavor composition is neglected

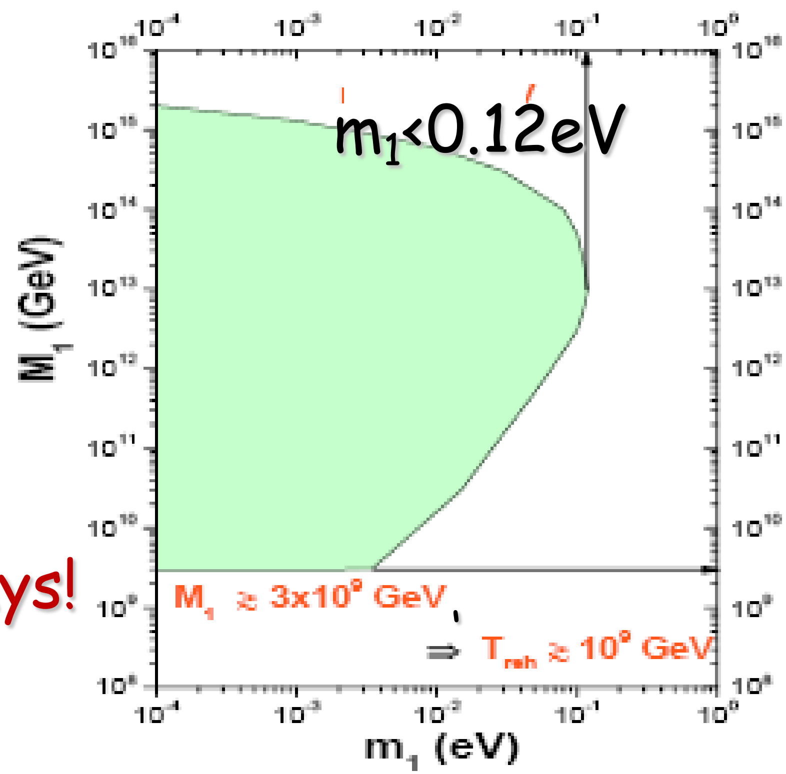
2) Hierarchical spectrum ($M_2 \gtrsim 2M_1$)

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

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



4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

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

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

Independence of the initial conditions (strong thermal leptogenesis)

(Buchmüller,PDB,Plümacher '04)

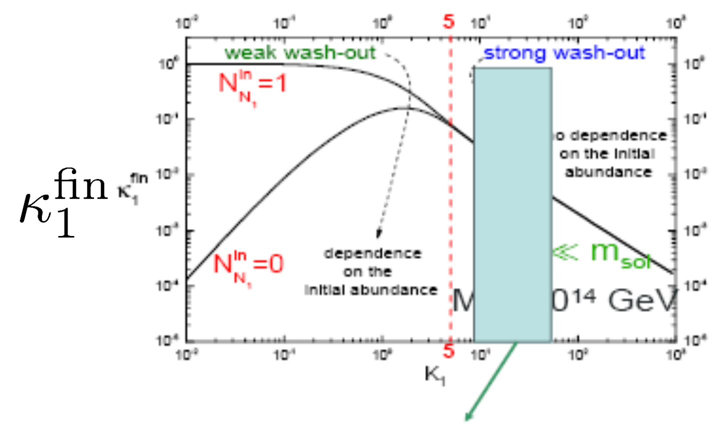
wash-out of a pre-existing asymmetry N^{p}_{B-L}

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

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

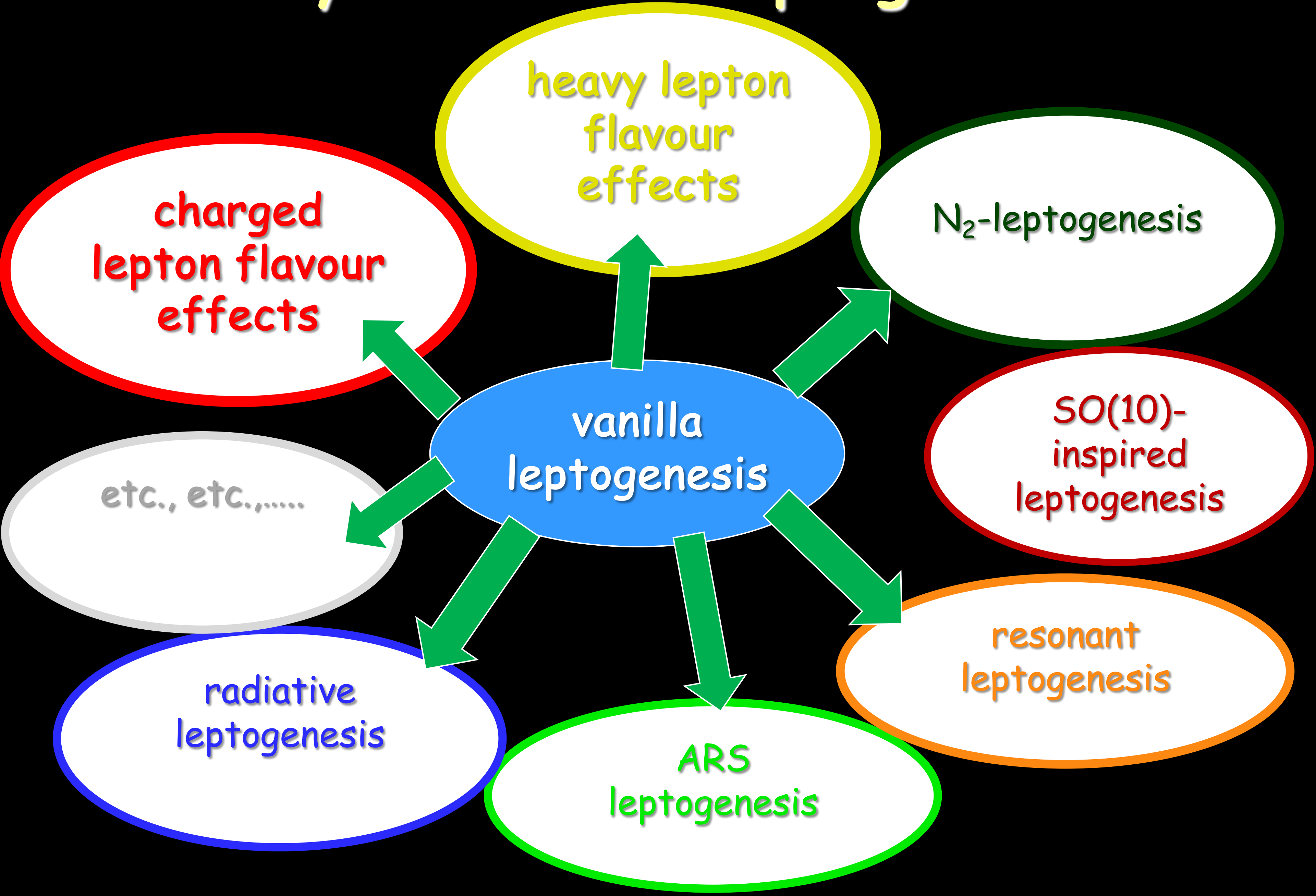
equilibrium neutrino mass: $$m_* = \frac{16\pi^{5/2}\sqrt{g_*}}{3\sqrt{5}}\,\frac{v^2}{M_{\rm Pl}} \simeq 1.08\times 10^{-3}\ {\rm eV}.$$

Independence of the initial N_1 abundance



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

Beyond vanilla Leptogenesis



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!

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

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

- 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 τ-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) $\quad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1\mu}\kappa_1^{fin}(K_{1\mu}) + \varepsilon_{1e}\kappa_1^{fin}(K_{1e})$

The lower bounds on M_1 and on T_{reh} get relaxed:

(Blanchet,PDB '08)

In the two flavour regime:

$$N_{B-L}^{\rm f} \simeq 2\,\varepsilon_1\,\kappa(K_1) + \frac{\Delta p_{1\tau}}{2}\,\left[\kappa(K_{1\tau_1^\perp}) - \kappa(K_{1\tau})\right]$$

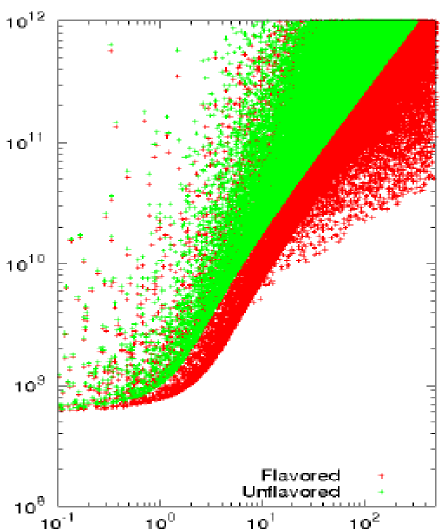
$$\frac{\Delta P_{i\alpha}}{2} \simeq \frac{1}{8\,\pi\,(h^\dagger\,h)_{ii}}\sum_{j\neq i}\left\{{\rm Im}\left[h^\star_{\alpha i}\,h_{\alpha j}\left(\frac{3}{2\,\sqrt{x_j}}(h^\dagger h)_{ij} + \frac{1}{x_j}(h^\dagger h)_{ji}\right)\right]\right\}$$

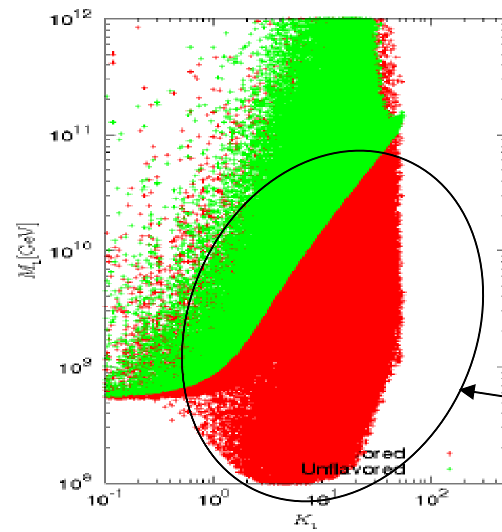
$$x_j = \frac{M_j^2}{M_1^2}$$

It dominates for $|\Omega_{ij}|\lesssim 1$ but is upper bounded because of Ω orthogonality:

$$\left|\frac{\Delta P_{1\alpha}}{2}\right| < \overline{\varepsilon}(M_1)\,\sqrt{P^0_{1\alpha}}$$

It is usually neglected but since it is not upper bounded by orthogonality, for $|\Omega_{ij}|>>1$ it can be important





$|\Omega^2_{ij}| \lesssim 10$

The lower bound gets relaxed

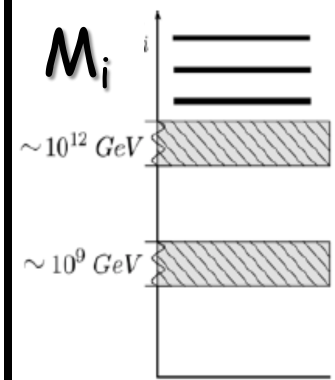
Heavy neutrino lepton flavour effects: 10 scenarios

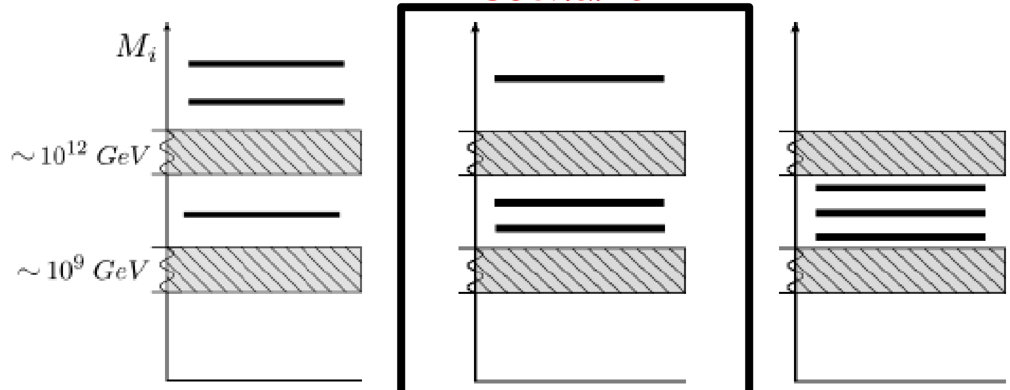
(PDB hep-ph/0502082; Bertuzzo, PDB, Feruglio, Nardi 2009; Bertuzzo, PDB, Marzola 2009)

Heavy neutrino flavored scenario

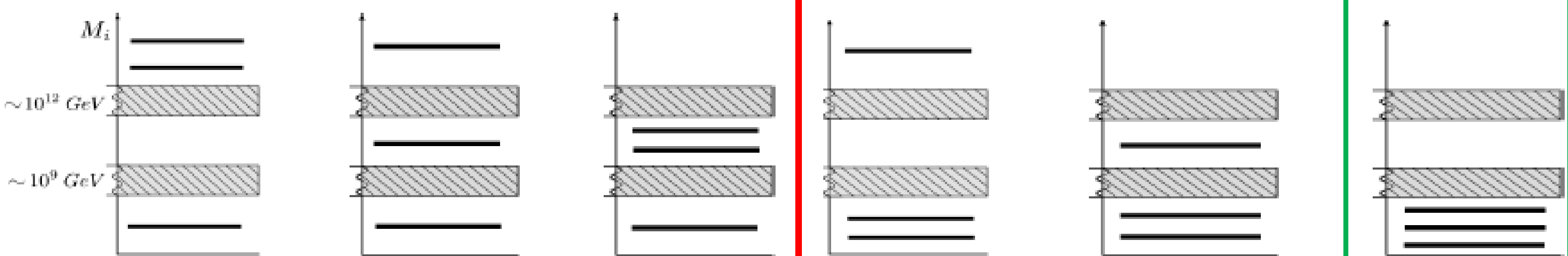
2 RH neutrino scenario

Typically rising in discrete flavour symmetry Models: if $T_{RH}<M_2$ then vanilla leptog, is recovered





(a) (b) (c)



(a) (b) (c) (d) (e) (f)

N_2-dominated scenario:

- N_1 produces negligible asymmetry;
- (b) is the only that can realise strong thermal leptogenesis…
- …and emerges within SO(10)-inspired models.

Low scale leptogenesis

Examples: resonant, ARS, radiative leptogenesis

N_2-leptogenesis

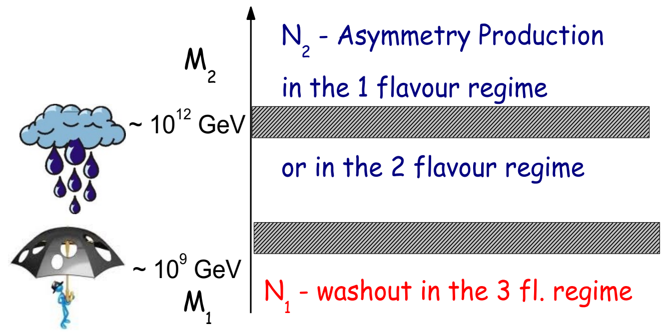
(PDB hep-ph/0502082, Vives hep-ph/0512160; Blanchet,PDB 0807.0743)

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

A two stage process:



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

- 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 ~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)
  This is an important motivation for $0\nu\beta\beta$ experiments

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

SO(10)-inspired models

(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03; PDB, Riotto '08; PDB, Re Fiorentin, Marzola 1411.5478; PDB, Re Fiorentin 1705.01935)

If one imposes SO(10)-inspired conditions:

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

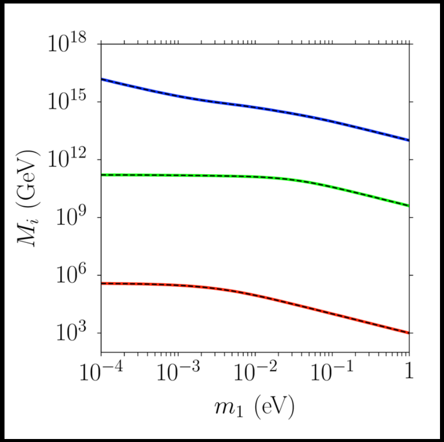
Barring very fine-tuned solutions, one obtains a very hierarchical RH neutrino mass spectrum

light neutrino mass matrix in the Yukawa basis: $m_\nu \to \tilde{m}_\nu = V_L m_\nu V_L^T$

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

typical RH neutrino mass spectrum

the lightest RH neutrino is lighter than 10^9 GeV



This very hierarchical RH neutrino mass spectrum is obtained for any choice of V_L barring very fine-tuned crossing level solutions (PDB, Xubin Hu 2507.06144 and in preparation)

Full analytical solution (V_L arbitrary): RH neutrino mass spectrum and mixing 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

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

RH neutrino phases

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

RH neutrino mixing matrix

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

General analytical solution for the asymmetry

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

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

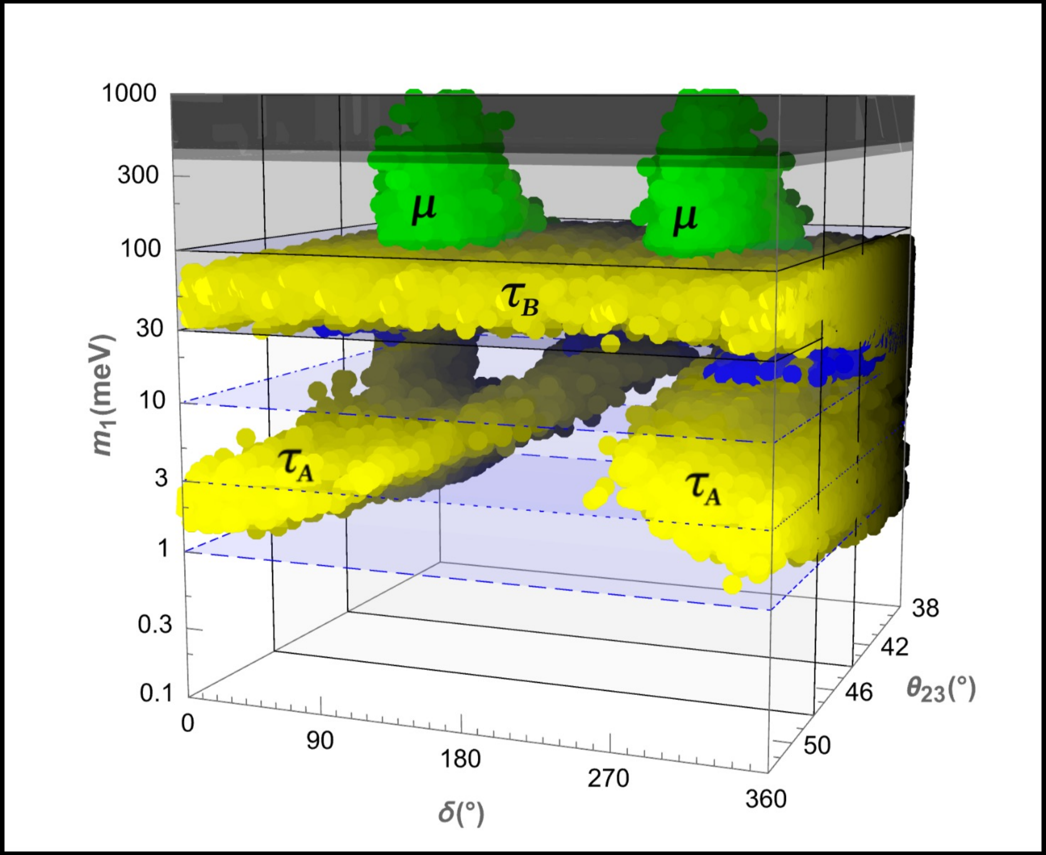
Successful SO(10)-inspired leptogenesis condition:

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

- There is no dependence on α_1 and α_3 determining M_1 and M_3
- 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)

$\alpha 2=5$ <u>NORMAL ORDERING</u> $I \leq V_L \leq V_{CKM}$



~2x10^6 points out of ~2x10^9 trials (success rate is ~0.1%)

(PDB, R. Samanta 2005.03057; PDB, Xubin Hu 2507.06144)

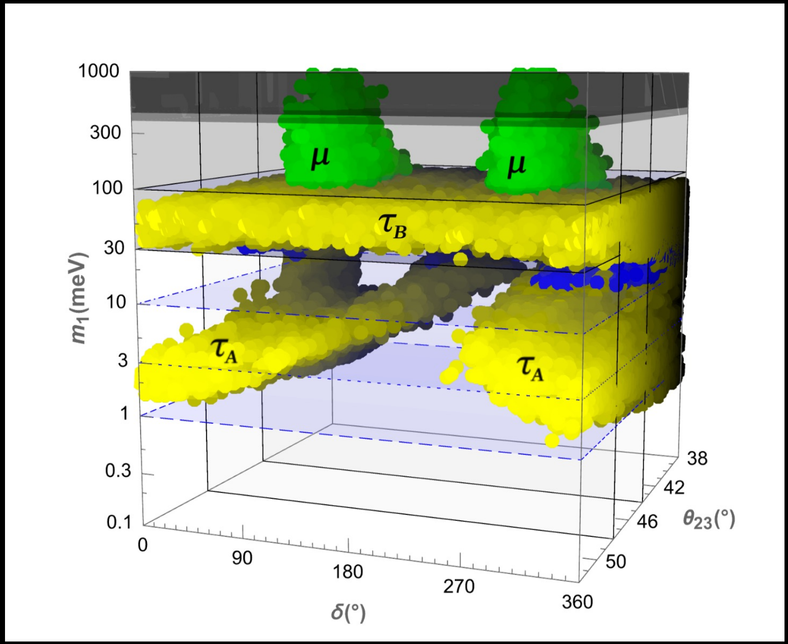
➢ N_2-leptogenesis (with flavour effects) does rescue SO(10)-inspired models! It works only for NO

(PDB, Riotto 0809.2285 and 1012.2343;0810.1104)

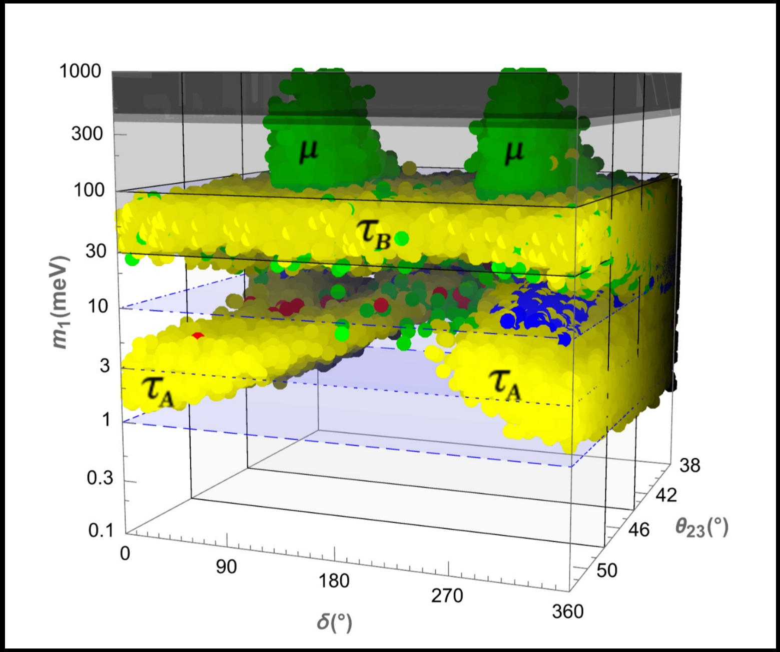
3-dim projection of the allowed region (NO)

α_2=5 <u>NORMAL ORDERING</u> $I \leq V_L \leq V_{CKM}$

without flavour coupling



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



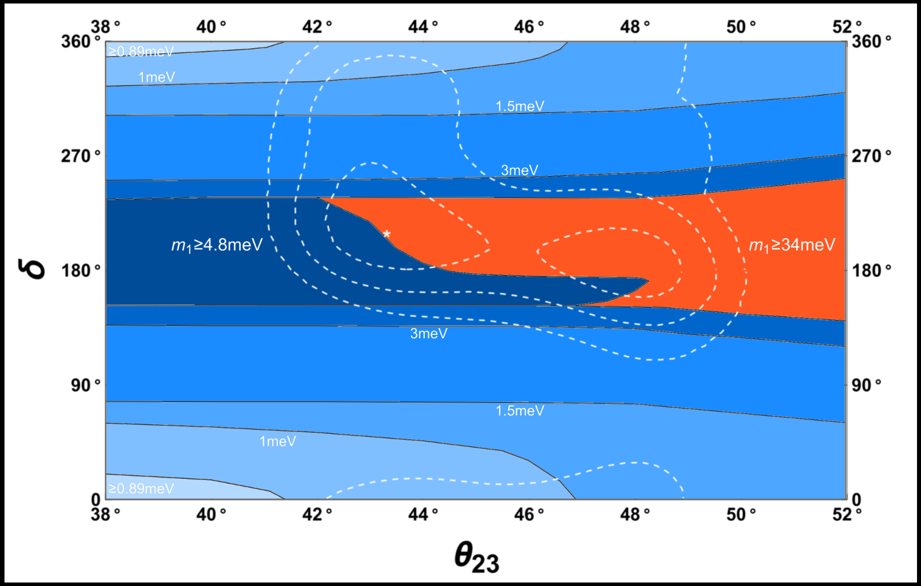
(PDB, Xubin Hu 2507.06144)

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

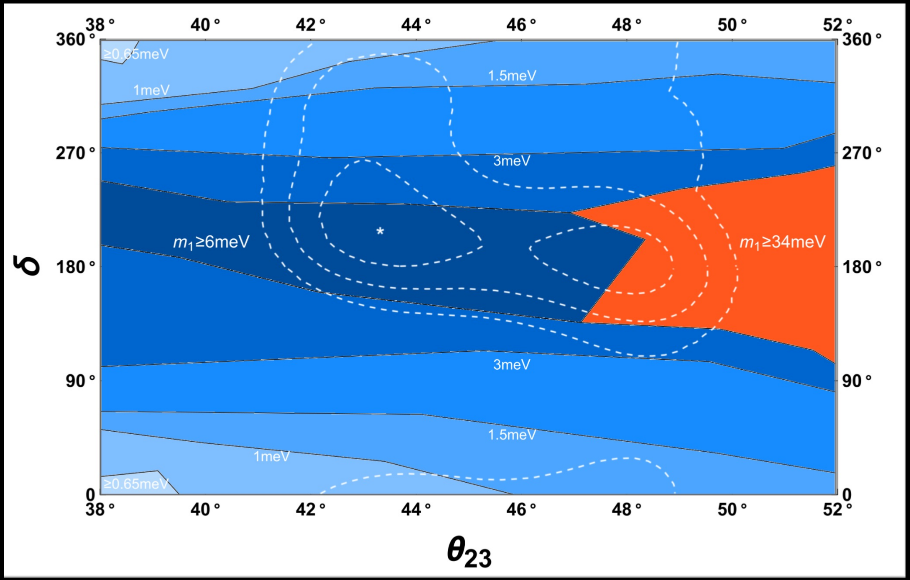
Including flavour coupling, new muonic solutions appear and even some very marginal electronic solutions (red points)

Lower bound on the absolute neutrino mass scale

Without flavour coupling

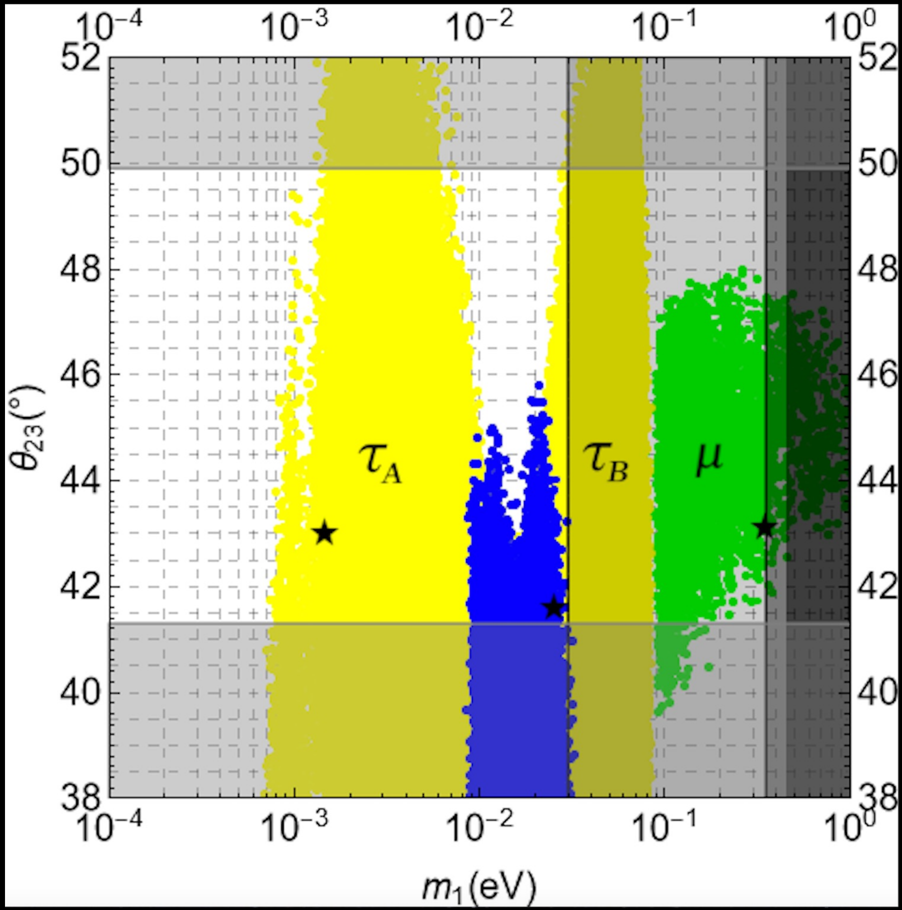


With flavour coupling



(PDB, Xubin Hu 2507.06144)

Upper bound on the atmospheric mixing angle



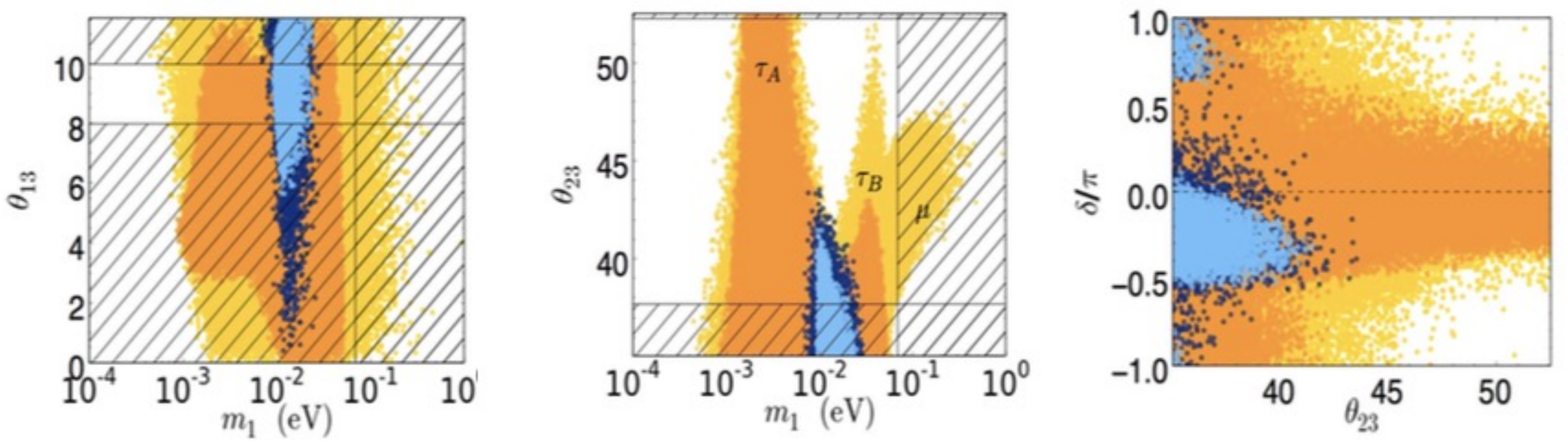
For 10 meV$\lesssim m_1 \lesssim$ 30 meV the atmospheric mixing angle has to be in the first octant

Strong thermal SO(10)-inspired leptogenesis

(PDB, Marzola 09/2011, DESY workshop and 1308.1107; PDB, Re Fiorentin, Marzola 1411.547

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

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



- 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)

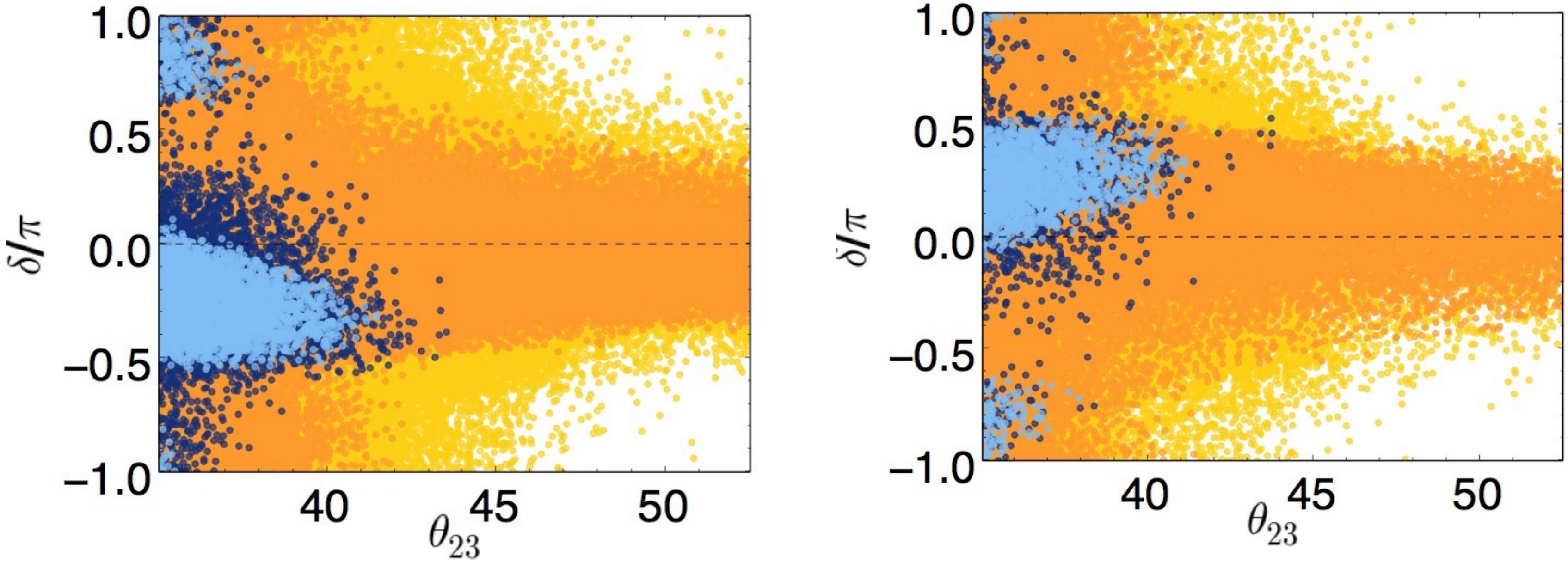
- Θ_{23} preferably in the first octant;

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

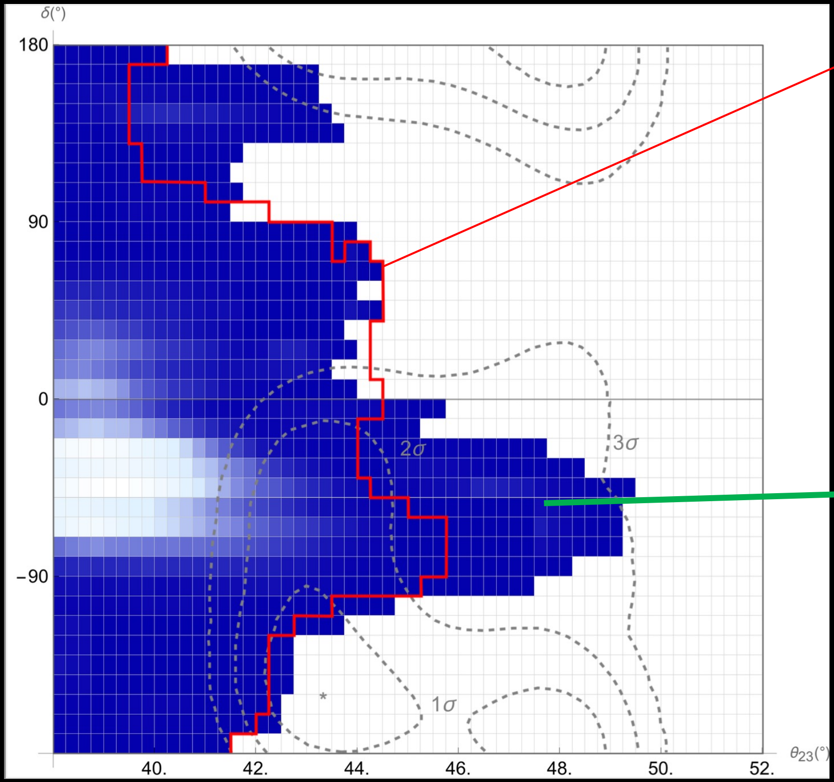
New atmospheric neutrino remove the tension

(PDB, Xubin Hu, 2507.06144)

The new SK atmospheric data seem to favour first octant when combined in global analysis (νfit September 2024) and moreover $\Delta\chi^2$ (IO-NO)=6.1: there is a potential interesting overlap now

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

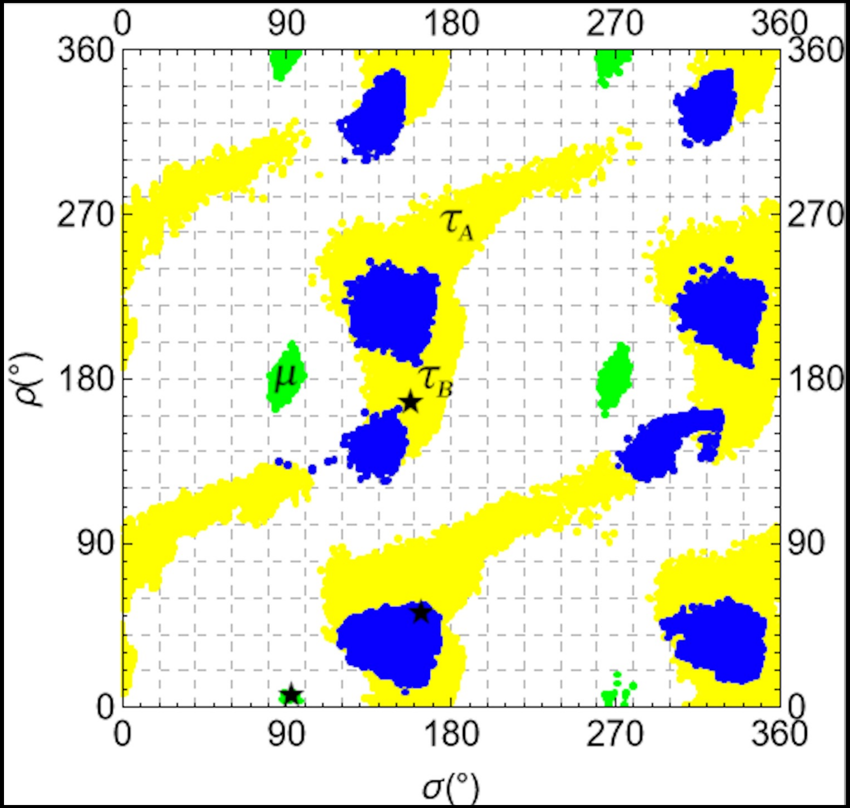
$$\alpha_2 = m_{D2} / m_{charm} = 5$$

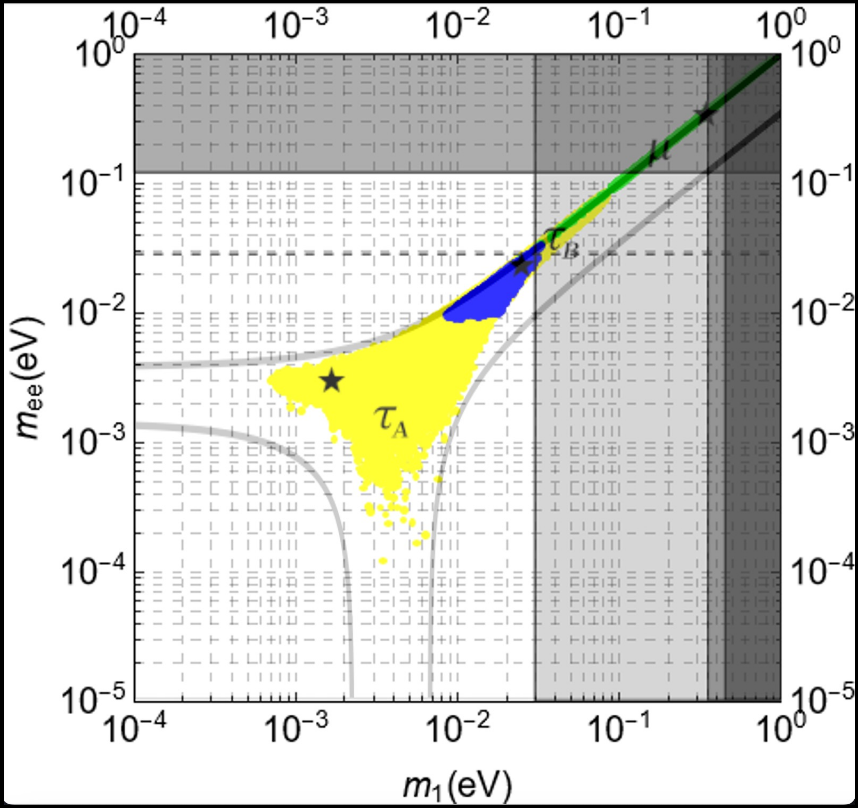


"old" solutions confirmed (no flavour coupling effects)

new solutions found including flavour coupling

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





There are strong constraints on the Majorana phases and this yields a lower bound on m_{ee}

KamLAND2-Zen, LEGEND1000, CUPID aims at improving the upper bound to m_{ee} < 20 meV in ne
years (talks by Shimizu at Neutrino 2024 and by BORRA and IMBERT at this workshop)

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:

$$16 \otimes 16 = 10_S \oplus \overline{126}_S \oplus 120_A$$

⇒ The Higgs fields of <u>renormalizable</u> 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	$M_R = v_{126}^R Y_{126}\,,$

→ 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
$\theta_{12}^{CKM}/10^{-2}$	22.735 ± 0.072	22.729 ($\theta_{12}^{CKM}=13.023°$)	22.730 ($\theta_{12}^{CKM}=13.023°$)
$\theta_{23}^{CKM}/10^{-2}$	4.208 ± 0.064	4.206 ($\theta_{23}^{CKM}=2.401°$)	4.204 ($\theta_{23}^{CKM}=2.408°$)
$\theta_{13}^{CKM}/10^{-3}$	3.64 ± 0.13	3.64 ($\theta_{13}^{CKM}=0.208°$)	3.64 ($\theta_{13}^{CKM}=0.208°$)
δ_{CKM}	1.208 ± 0.054	1.209 ($\delta_{CKM}=69.322°$)	1.212 ($\delta_{CKM}=69.457°$)
$\Delta m^2_{21}/10^{-5}$	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 ($\theta_{13}=8.60°$)
δ_{CP}° (NO)	207.5 ± 38.5	240.49	-
δ_{CP}° (IO)	284.5 ± 29.5	-	263.49
$\eta_B/10^{-10}$	$6.12\pm0.04^\ddagger$	7.6 (7.6)	9.6 (51)
χ^2	-	1.45	$5.76^\dagger$

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

$M_1=6.6\times10^4$ GeV

$M_2=2.1\times10^{12}$ GeV

$M_3=8.1\times10^{14}$ GeV

Why is the lower bound on m_1 violated? Because $\theta_{23}^L\simeq45^\circ\Rightarrow$ extended SO(10)-insp. lep

Resonant leptogenesis

- leptogenesis with a degenerate heavy neutrino spectrum:

$$\frac{M_2-M_1}{M_1} \ll 1 \Rightarrow \text{(under some conditions)} \quad \varepsilon_1 \to \xi_\varepsilon\, \varepsilon_1, \quad \xi_\varepsilon \gg 1$$

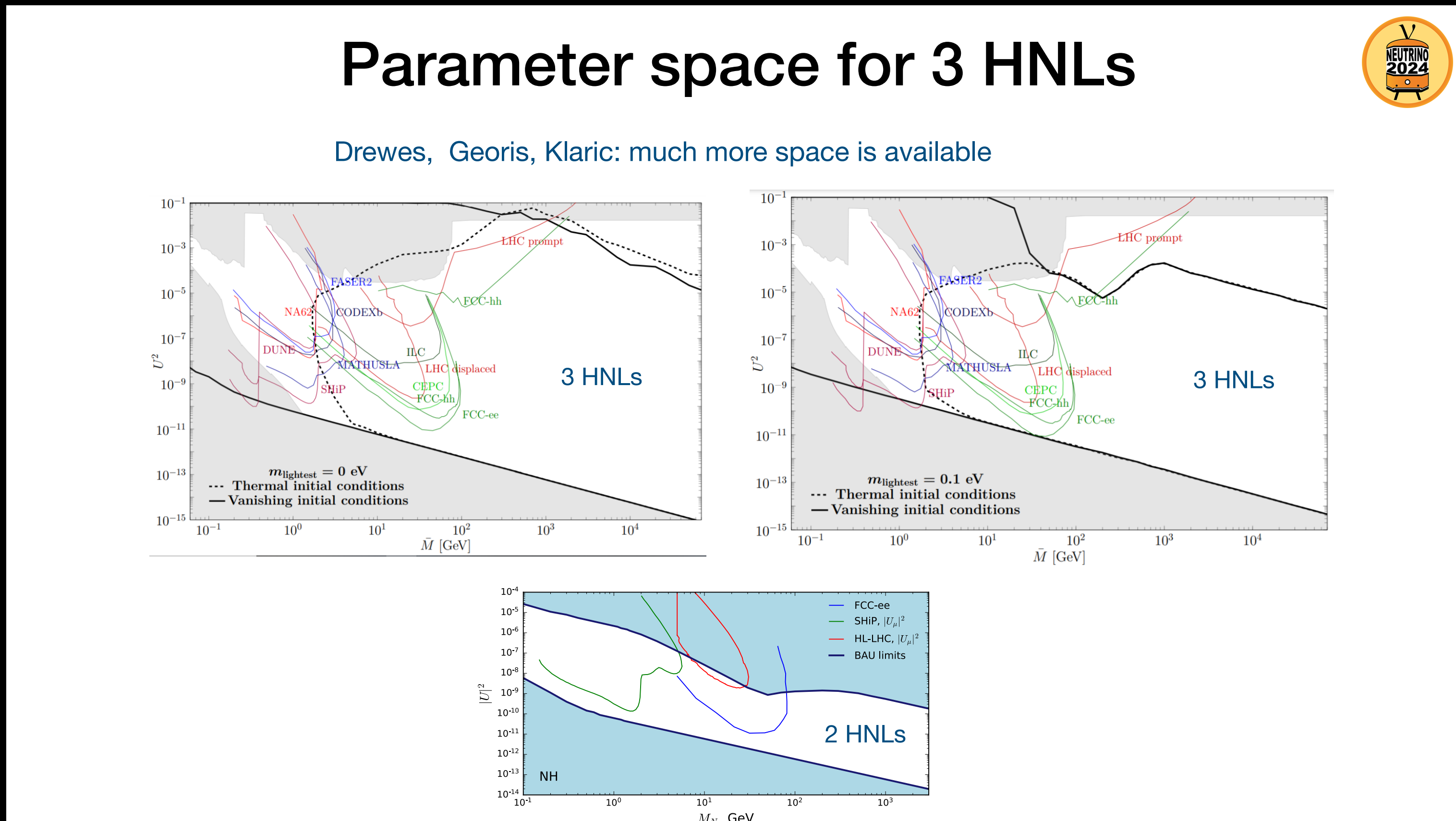
$$\Rightarrow M_1^{\rm min} \to \frac{M_1^{\rm min}}{\xi_\varepsilon}$$

the bounds can be evaded but one has to justify such small degeneracies

- Resonant leptogenesis can be realized with RH neutrino masses as low as 1 TeV: testable at colliders? (Pilaftsis, Underwood 0309342)
- In a minimal picture (just type I seesaw extension) it is highly fine-tuned (strong compensation between asymmetry produced and washed-out)
- Introducing a $U_{B-L}(1)$ gauge symmetry one can produce the RH neutrinos from Z' decays (Blanchet Chakco Granor Mohapatra 0904.2174)
- Recently, a novel mechanism accounting for two-loop thermal effects is claimed to produce the asymmetry at low scale without requiring strong mass degeneracies (Li, Pilaftsis 2604.06493)

Leptogenesis via RH neutrino mixing (ARS leptogenesis)

(Akhmedov, Rubakov, Smirnov 1999)



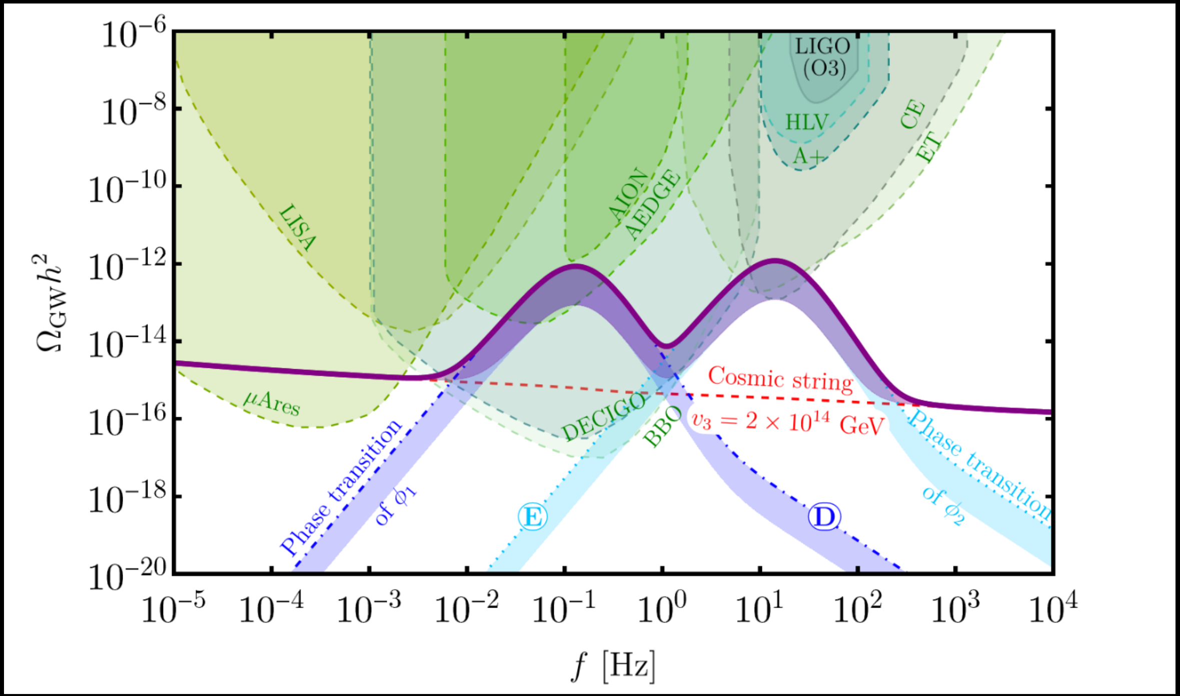
(M. Shaposhnikov at Neutrino 2024)

- The asymmetry is generated when seesaw neutrinos are ultrarelativistic and it is never washed-out (freeze-out leptogenesis)
- For this reason there is a strong dependence on the initial conditions and the observed value is not predicted but fitted.
- However, it can be tested in LLP searches experiments and it complies `naturalness' idea
- (no destabilizing scale of new physics above the EW scale)

Can we test leptogenesis with gravitational waves?

There is a flourish of activities:

- From FOPTs associated to Majorana mass generation (PDB, D.Marfatia, Y.Zhou 2106.00025)
- From cosmic strings produced during symmetry breakings of GUTs
  (J.A.Dror, T. Hiramatsu, K.Kohri, H. Murayama, G.White 1908.03227
  B.Fu, S.F. King, Marsili,Pascoli,Turner,Zhou2209.00021)
- ……………..
- Combination of cosmic string and FOPTs production:



M_1~100 GeV

M_2~10^4GeV

(PDB, S.F. King, M. Rahat 2306.04680)

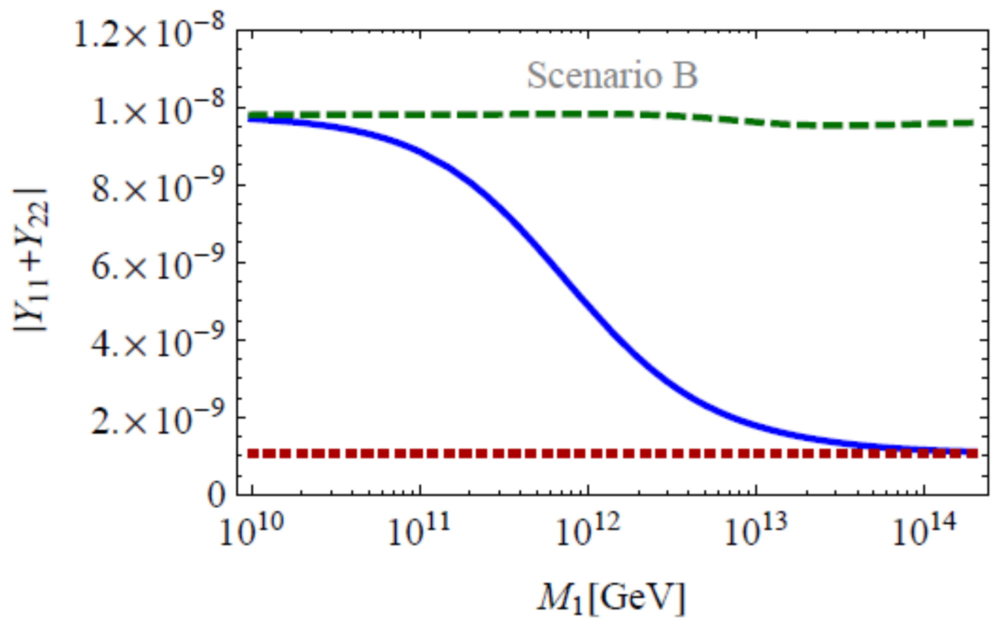
Conclusions

- The matter-antimatter asymmetry puzzle might be related to an explanation of neutrino masses and this seems today the most attractive scenario.
- Discovery of $0\nu\beta\beta$ would be the crucial experimental test since it would probe lepton number violation.
- SO(10)-inspired leptogenesis provides a well motivated class of scenarios relying on N_2-leptogenesis. The observed value of the asymmetry emerges naturally. It leads to interesting predictions, in particular there is a lower bound on the absolute neutrino mass scale and we are now starting to probe the bulk of the solutions with absolute neutrino mass scale experiments. NO is strongly favoured (IO requires an extended V_L): JUNO results might support soon this expectation.
- A subset of the solutions realizes strong thermal leptogenesis: highly non-trivial. In this case the atmospheric neutrino mixing angle should be strictly in the first octant and CP Dirac phase in the 4th quadrant. $0\nu\beta\beta$ signal should be within reach of next generation experiments.
- Low scale leptogenesis scenarios have the advantage to be testable in lab but at the expense of introducing new parameters (e.g. mass degeneracy) and the observed value of the asymmetry is fit
- Gravitational waves provide new ways to test leptogenesis.
- Exciting times!

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