Neutrino data creates holes in flavour space: an application to leptogenesis

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Neutrino masses and mixing: SM+ heavy RH neutrinos.

Seesaw

Matter anti matter asymmetry: Baryogenesis via leptogenesis

Planck 2019 Granada
3-7 June

Mainly based on: JHEP 1905 (2019) 011, RS, **Pasquale Di Bari, M. Fiorentin** and some upcoming studies (RS et al)

THE ROYAL SOCIETY

Things to note:

- ✍ **Neutrino oscillation** 👉 Neutrinos have masses.
- ✍ **Cosmology (PLANCK)** 👉 Neutrinos are light, even less than 1 eV.
- ✍ **Standard Model (SM) of particle physics** 👉 cannot explain neutrino masses and mixing.
- ✍ **Need extension of the SM** 👉 Minimal extension requires at least two heavy right handed (RH) neutrinos to explain small neutrino masses trough seesaw mechanism.
- ✍ **No conclusive evidence for antimatter** 👉 AMS experiment is searching for that.
- ✍ **CMB acoustic peak and light elements abundances after BBN** 👉 baryon to photon ratio $\simeq$ **6.2×10^{-10}**
- ✍ Seesaw is a simple and excellent mechanism to explain the baryon asymmetry

Neutrino oscillation data and other cosmological constraints:

Hint for CP violation (δ_{CP} = 215⁰) and normal mass ordering ($m_3 > m_2 > m_1$)

$\mathbf{Bf}^{+1\sigma}_{-1\sigma}$ **NuFiT, NoV, 2018**

$$\theta_{12}^{NEU} \simeq 33.82^{+0.78}_{1-0.762}$$
$$\theta_{13}^{NEU} \simeq 8.61^{+0.13}_{-0.13}$$
$$\theta_{23}^{NEU} \simeq 49.61^{+1.0}_{-1.2}$$

Angles

$$\Delta m^2_{12} \simeq 7.39^{+0.21}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$$
$$\Delta m^2_{23} \simeq 2.52^{+0.033}_{-0.0.032} \times 10^{-3}\ \mathrm{eV}^2$$

$\sum_i m_i < 0.17$ eV **PLANCK, 2017**

masses

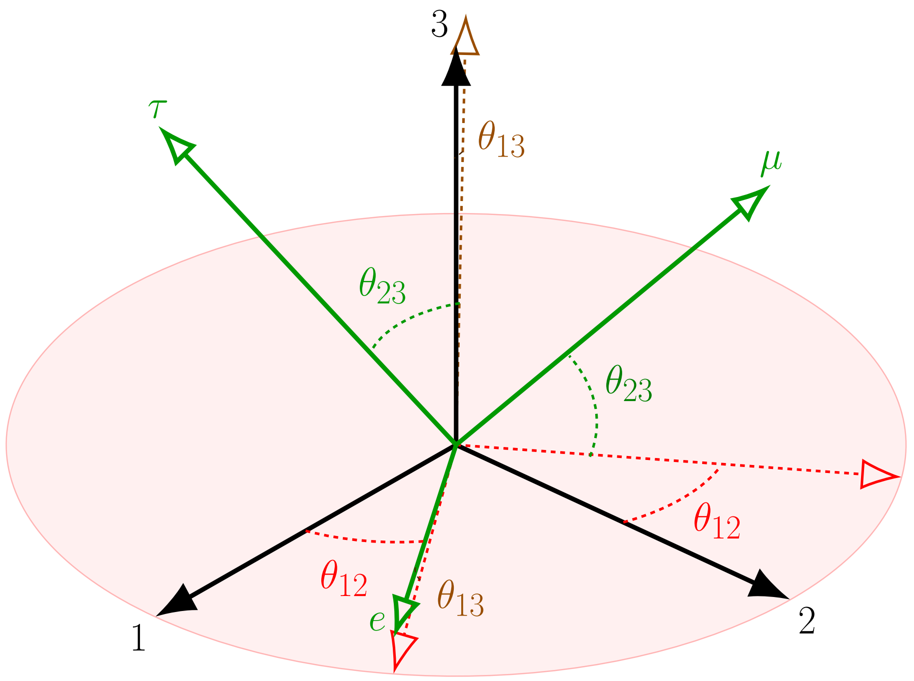


Figure: P. Di Bari, M. Fiorentin, RS JHEP 1905 (2019) 011

Basic idea to reconcile light neutrino masses and baryogenesis via leptogenesis

Minimal scenario: Introduce two RH neutrino field ν_{Ri}

$\overline{\nu_R}\, m_D\, \nu_L$

$\nu_R^T\, C\, M_R\, \nu_R$

Type -1 Seesaw : $m_\nu = m_D^T\, M_R^{-1} m_D$

$M_R \sim 10^{14}$ GeV $\Longrightarrow m_\nu \simeq 0.1$ eV

Light neutrinos are Majorana type

Heavy ν_R

Lepton+ Higgs

Anti Lepton+ anti Higgs

Mismatch: Lepton asymmetry; N_{B-L}

Sphaleron

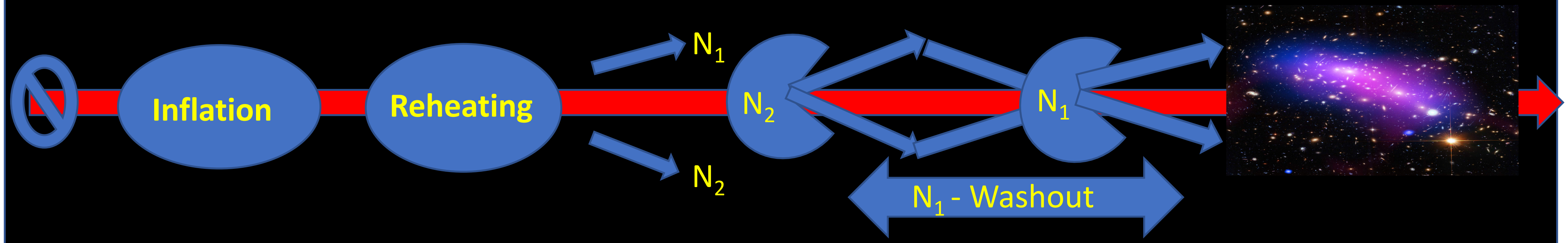
$\eta_B = 0.01 N_{B-L}$

C P VIOLATION

Types of leptogenesis:

Thermal Leptogenesis:

Compatible with non-SUSY scenario: Gravitino Problem



Non-thermal leptogenesis:

SUSY friendly

e.g., RH neutrinos could originate from non-thermal decays of inflaton, compatible with low T_{RH}

The Bridging (B) matrix

Figures: P. Di Bari, M. Fiorentin, RS, JHEP 1905 (2019) 011

$$-\mathcal{L}^{\nu+\ell}_{Y+M} = \overline{L_\alpha}\, h^{\ell}_{\alpha\alpha}\, \ell_{R\alpha}\, \Phi + \overline{L_\alpha}\, h^{\nu}_{\alpha J}\, N_{RJ}\, \widetilde{\Phi} + \frac{1}{2}\, \overline{N^c_{RJ}}\, M_J\, N_{RJ} + \text{h.c.}$$

$$|L_J\rangle = \frac{m_{D\alpha J}}{\sqrt{(m_D^\dagger\, m_D)_{JJ}}}\, |L_\alpha\rangle$$

$$|L_J\rangle = \frac{m_{D\alpha J}\, U^\star_{\alpha i}}{\sqrt{(m_D^\dagger\, m_D)_{JJ}}}\, |L_i\rangle = \frac{(U^\dagger\, m_D)_{iJ}}{\sqrt{(m_D^\dagger\, m_D)_{JJ}}}\, |L_i\rangle$$

$$B_{iJ} \equiv \frac{(U^\dagger\, m_D)_{iJ}}{\sqrt{(m_D^\dagger\, m_D)_{JJ}}}$$

$$p^0_{IJ} \equiv |\langle L_J | L_I \rangle|^2 = \left| \sum_k B^\star_{kJ}\, B_{kI} \right|^2$$

$$B_{iJ} = \sqrt{\frac{m_i}{\widetilde{m}_J}}\, \Omega_{iJ}$$

Casas-Ibarra

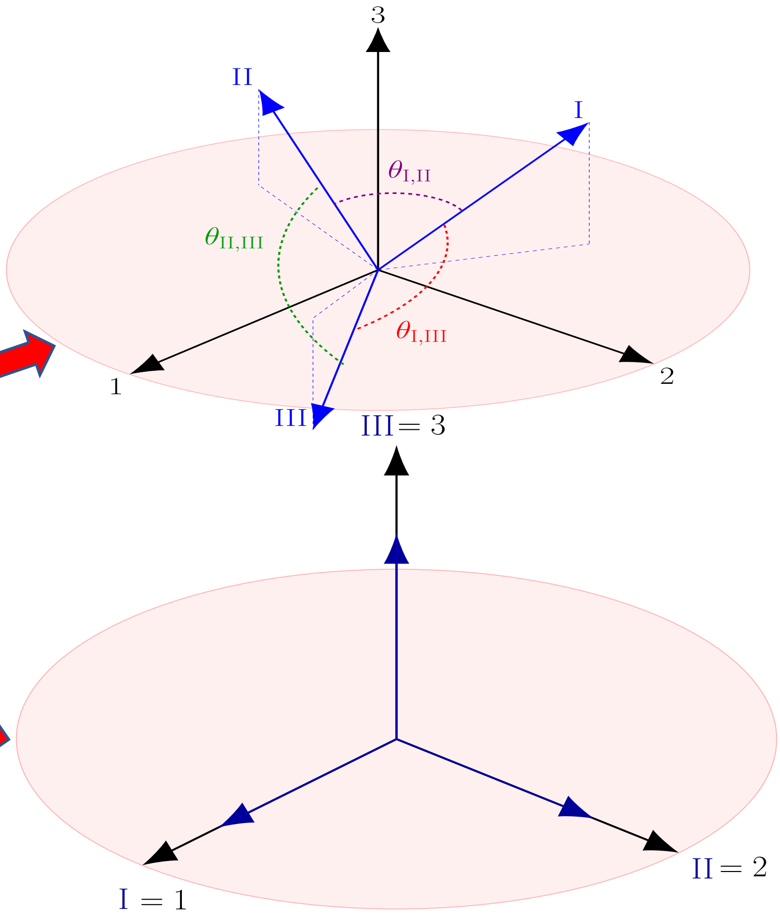
$$\widetilde{m}_J \equiv \frac{(m_D^\dagger\, m_D)_{JJ}}{M_J} = \sum_k m_k\, |\Omega_{kJ}|^2$$

$$m_D^\dagger\, m_D = \lambda_D^2\, P,$$

$$\Omega = P$$

$$m_i = \lambda_D^2 / M_J$$

JHEP 0906 (2009) 072
SF King, Mu Chun Chen



Form Dominance

Fine tuning in the seesaw and a new parametrization of the orthogonal matrix

$$m_i = m_{D\ell}^2 / M_J$$

$$m_i = \overline{m}_i \sum_J r_{iJ}\, e^{i\varphi_{iJ}} ,$$

$$r_{iJ} \equiv |\Omega_{iJ}^2| / \sum_J |\Omega_{iJ}^2| \propto 1/M_J$$

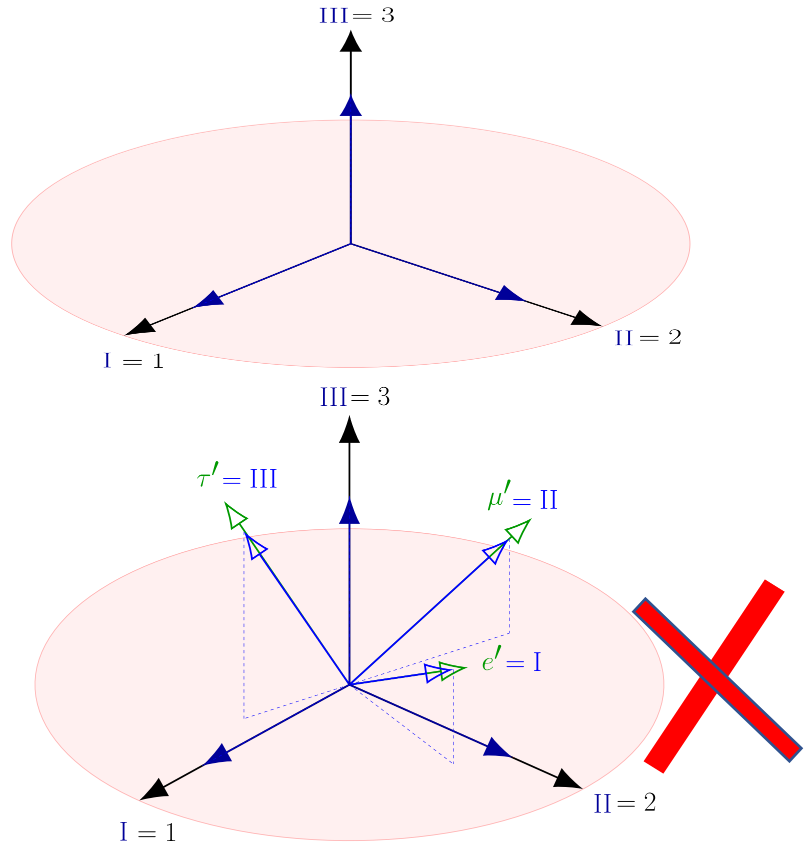
Fine tuning parameter:

$$\gamma_i \equiv \sum_J |\Omega_{iJ}^2| \geq 1$$

$$\Omega = \zeta \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos z_{23} & \sin z_{23} \\ 0 & -\sin z_{23} & \cos z_{23} \end{pmatrix} \begin{pmatrix} \cos z_{13} & 0 & \sin z_{13} \\ 0 & 1 & 0 \\ -\sin z_{13} & 0 & \cos z_{13} \end{pmatrix} \begin{pmatrix} \cos z_{12} & \sin z_{12} & 0 \\ -\sin z_{12} & \cos z_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\Omega(z_{12}, z_{13}, z_{23}) = R(\alpha_{12}, \alpha_{13}, \alpha_{23}) \cdot \Omega_{\rm boost}(\vec{\beta}) ,$$

SO(3,C) isomorphic to the proper Lorentz group

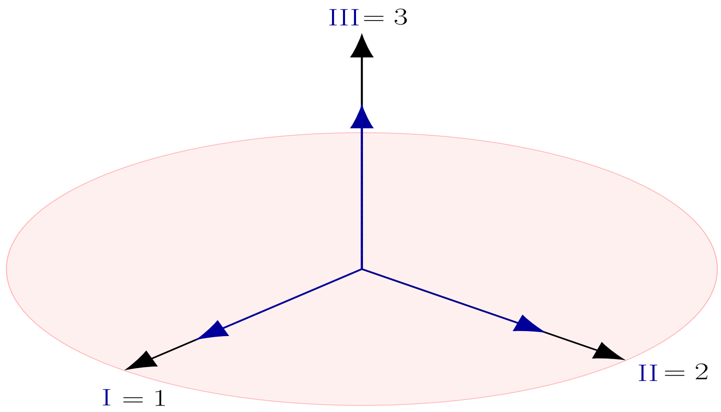


A new parametrization for the orthogonal matrix: Lorentz boost in the flavour space

$$\Omega(z_{12}, z_{13}, z_{23}) = R(\alpha_{12}, \alpha_{13}, \alpha_{23}) \cdot \Omega_{\text{boost}}(\vec{\beta}) \,,$$

R is the usual SO(3) rotation matrix

$$\Omega^{\text{Boost}}(\xi, \hat{n}) = \begin{pmatrix} \cosh\xi + n_1^2(1-\cosh\xi) & n_1 n_2(1-\cosh\xi) - i n_3 \sinh\xi & n_1 n_3(1-\cosh\xi) + i n_2 \sinh\xi \\ n_1 n_2(1-\cosh\xi) + i n_3 \sinh\xi & \cosh\xi + n_2^2(1-\cosh\xi) & n_2 n_3(1-\cosh\xi) - i n_1 \sinh\xi \\ n_1 n_3(1-\cosh\xi) - i n_2 \sinh\xi & n_2 n_3(1-\cosh\xi) + i n_1 \sinh\xi & \cosh\xi + n_3^2(1-\cosh\xi) \end{pmatrix}$$

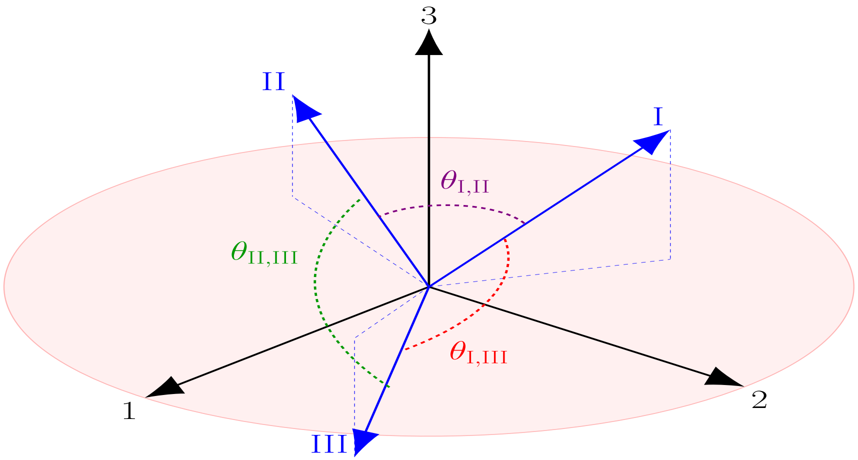


$$\Omega_{\text{boost}}(0,0,\beta) = \begin{pmatrix} \cosh\psi & -i\sinh\psi & 0 \\ i\sinh\psi & \cosh\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

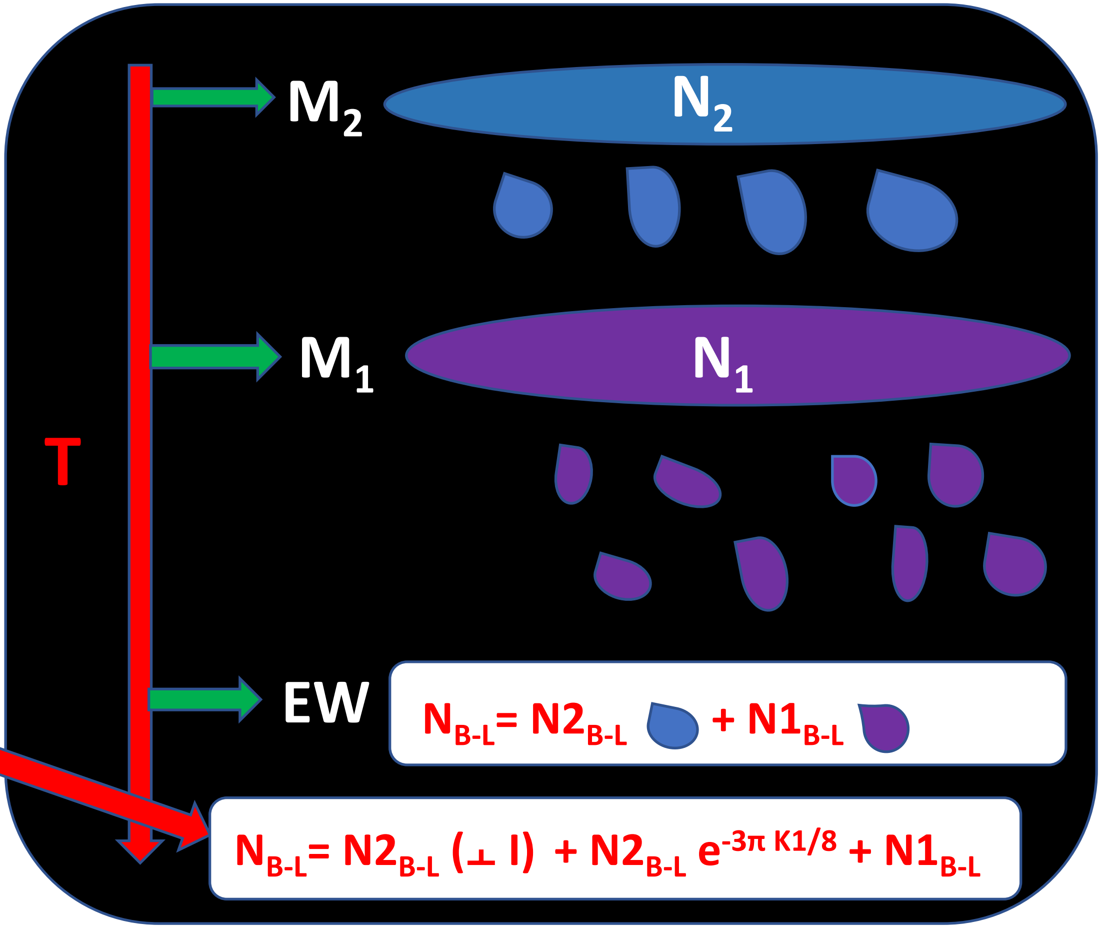
$$\gamma_i \equiv \sum_J |\Omega_{iJ}^2| \geq 1$$

$$\gamma_1 = \gamma_2 = \gamma^2\,(1+\beta^2)$$

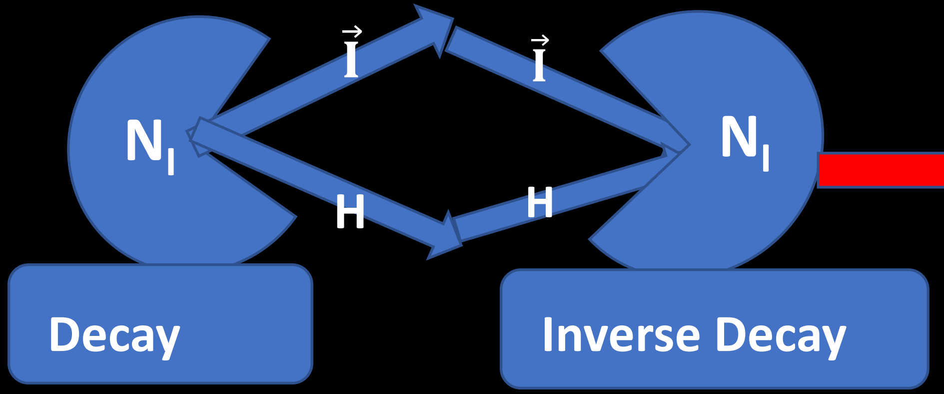
One flavour leptogenesis : Computation of the lepton asymmetry

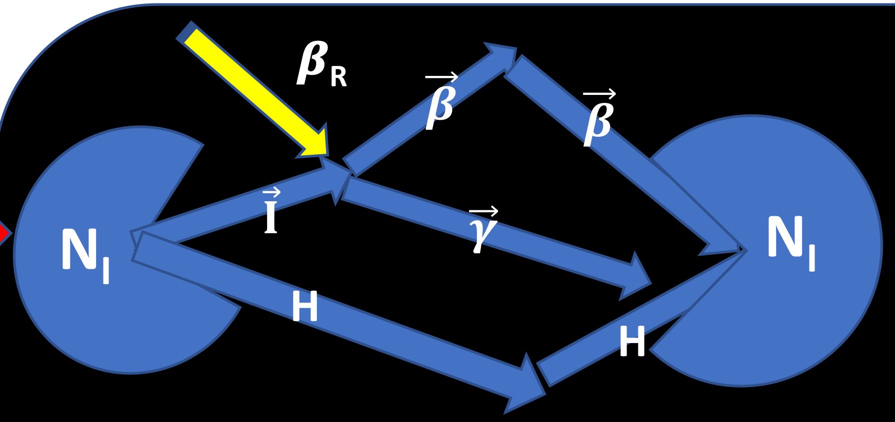


N_1 can only washout the asymmetry generated by N_2 in the direction of $\vec{I}$. Component orthogonal to $\vec{I}$ will always survive. Hence there will always be a survival asymmetry generated by N_2 except in a special case where $\Theta_{I,II} = 0$.



Importance of flavor effects:





$\vec{I} = P_{I\alpha}\vec{\alpha}$, $\alpha = e, \mu, \tau$, $P_{I\alpha} = K_{i\alpha} / \Sigma_\alpha K_{i\alpha}$

$K_{i\alpha} = P_{I\alpha} K_i$ ← Magnitude of the Decay parameter has been reduced

If 10^9 GeV < M_I < 10^{12} GeV: $\vec{\beta} = \vec{\tau}$, $\vec{\gamma} = \vec{e} + \vec{\mu}$

M_I < 10^9 GeV : All the three flavors act individually

One flavor leptogenesis : Computation of the lepton asymmetry
(sorry for showing so many equations!)

Boltzmann Equations:

$$\frac{dN_i}{dz} = -D_i(N_{N_i} - N_{N_i}^{\rm eq}), \text{ with } i = 1,2$$

$$\frac{dN_{B-L}}{dz} = -\sum_{i=1}^{2} \varepsilon_i D_i (N_{N_i} - N_{N_i}^{\rm eq}) - \sum_{i=1}^{2} W_i N_{B-L},$$

Inverse Decay: $W_i^{\rm ID} = \frac{1}{4} K_i \sqrt{x_{1i}} \mathcal{K}_1(z_i) z_i^3.$

$Z_i = M_i/T$, $x_{1i} = (M_i/ M_1)^2$

$$\kappa_i(z) = -\int_{z_{\rm in}}^{\infty} \frac{dN_{N_i}}{dz'} e^{-\sum_i \int_{z'}^{z} W_i^{\rm ID}(z'')dz''} dz'.$$

$$\kappa_1^\infty = \frac{2}{K_1 z_B(K_1)}\left(1 - e^{-\frac{K_1 z_B(K_1)}{2}}\right),$$

$$\kappa_2^\infty = \frac{2}{K_2 z_B(K_2)}\left(1 - e^{-\frac{K_2 z_B(K_2)}{2}}\right) e^{-\int_0^\infty W_1^{\rm ID}(z)dz}$$

$$\equiv \frac{2}{K_2 z_B(K_2)}\left(1 - e^{-\frac{K_2 z_B(K_2)}{2}}\right) e^{-3\pi K_1/8},$$

where

$$z_B(K_i) = 2 + 4K_i^{0.13} e^{-\frac{2.5}{K_i}}$$

and one uses

$$\int_0^\infty z^{\alpha-1} \mathcal{K}_n(z) dz = 2^{\alpha-2}\Gamma\left(\frac{\alpha-n}{2}\right)\Gamma\left(\frac{\alpha+n}{2}\right)$$

P. Di Bari and A. Riotto : P LB 671, 462 (2009)

Importance of the new parametrization on N2 leptogenesis

Old parametrization:

$$\Omega = \zeta \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos z_{23} & \sin z_{23} \\ 0 & -\sin z_{23} & \cos z_{23} \end{pmatrix} \begin{pmatrix} \cos z_{13} & 0 & \sin z_{13} \\ 0 & 1 & 0 \\ -\sin z_{13} & 0 & \cos z_{13} \end{pmatrix} \begin{pmatrix} \cos z_{12} & \sin z_{12} & 0 \\ -\sin z_{12} & \cos z_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

New parametrization

$$\Omega(z_{12}, z_{13}, z_{23}) = R(\alpha_{12}, \alpha_{13}, \alpha_{23}) \cdot \Omega_{\rm boost}(\vec{\beta}),$$

Asymmetry from N_2 will survive if $K_{i\alpha} < 1$

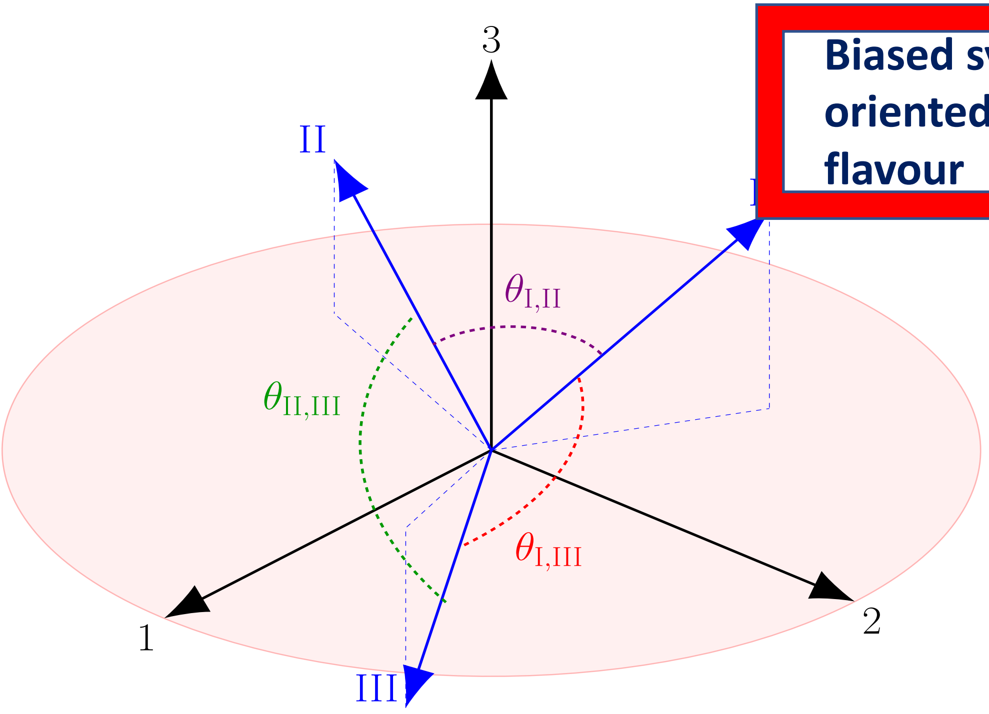
Randomly generate all the parameters

Generate random matrices in a group theoretic way

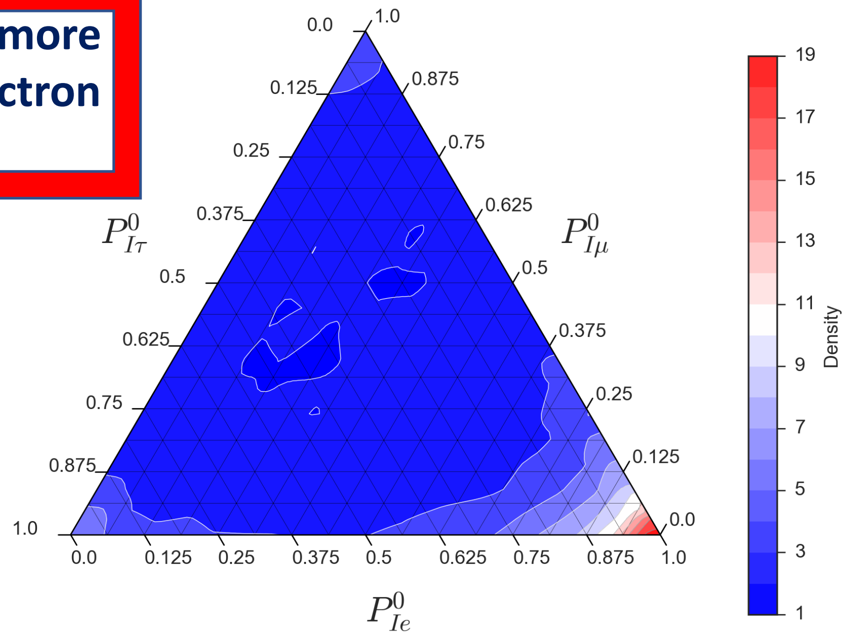
$$K_{I\alpha} = \frac{1}{m^*} \left| \sum_i U_{\alpha i} \sqrt{m_i} \Omega_{iI} \right|^2,$$

$$m_{D\alpha J} = U_{\alpha i} \sqrt{m_i}\, \Omega_{iJ} \sqrt{M_J}\,.$$

Generating the decay parameters randomly with no experimental information: all the angles and phases are generated randomly [0, 360^0].



Biased system: I is more oriented to the electron flavour



Generating the decay parameters randomly with no experimental information: Using Haar Measure: `Representing seesaw neutrino models and their motions in lepton flavor space', Rome Samanta, Pasquale Di Bari and Michele Re Fiorentin. JHEP 1905 (2019) 011

The leptonic mixing matrix is an element of U(3). Haar Measure corresponding to U(3)

$$dV \equiv d(\sin^2\theta_{12})d(\sin^2\theta_{23})d(\cos^4\theta_{13})\prod_j d\alpha_j,$$

$$K_{I\alpha} = \frac{1}{m^*}\left|\sum_i U_{\alpha i}\sqrt{m_i}\Omega_{iI}\right|^2$$

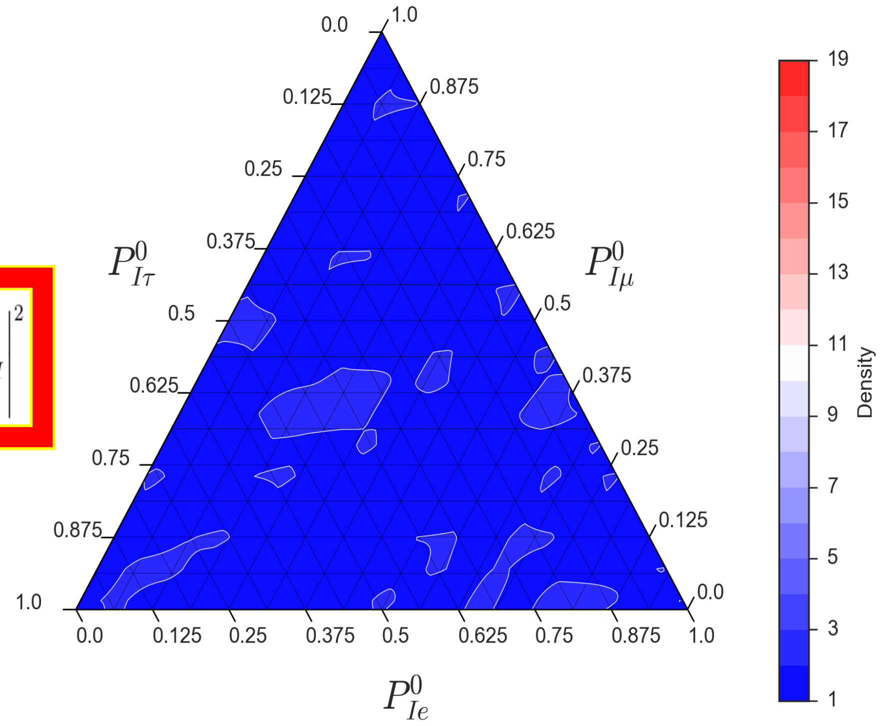
The orthogonal matrix is an element of $SO(3)_C$ which is isomorphic to the Lorentz group $O(3,1)^{+}$.

$$\Omega = \Omega^{\text{Rotation}}\Omega^{\text{Boost}},$$

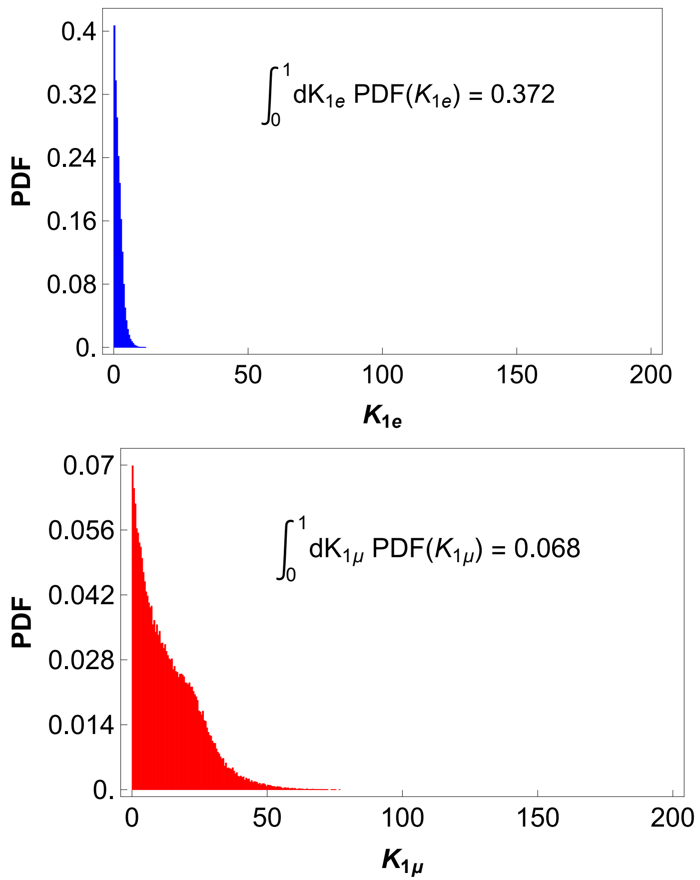
$$\Omega^{\text{Rotation}} \in SO(3)_{\mathbb{R}}$$

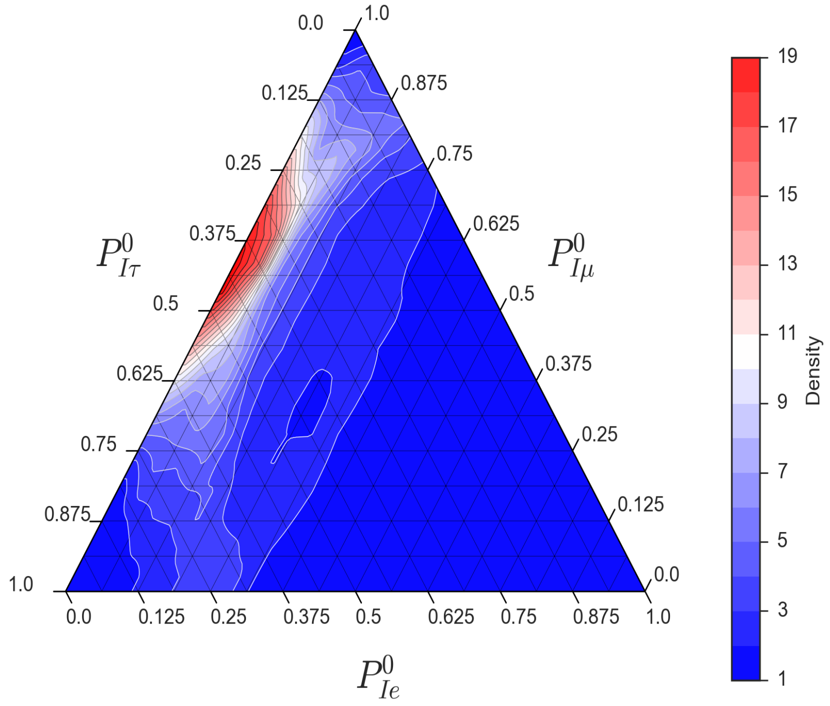
HM

$$dV \equiv d(\sin\phi_2)d\phi_1 d\phi_3.$$

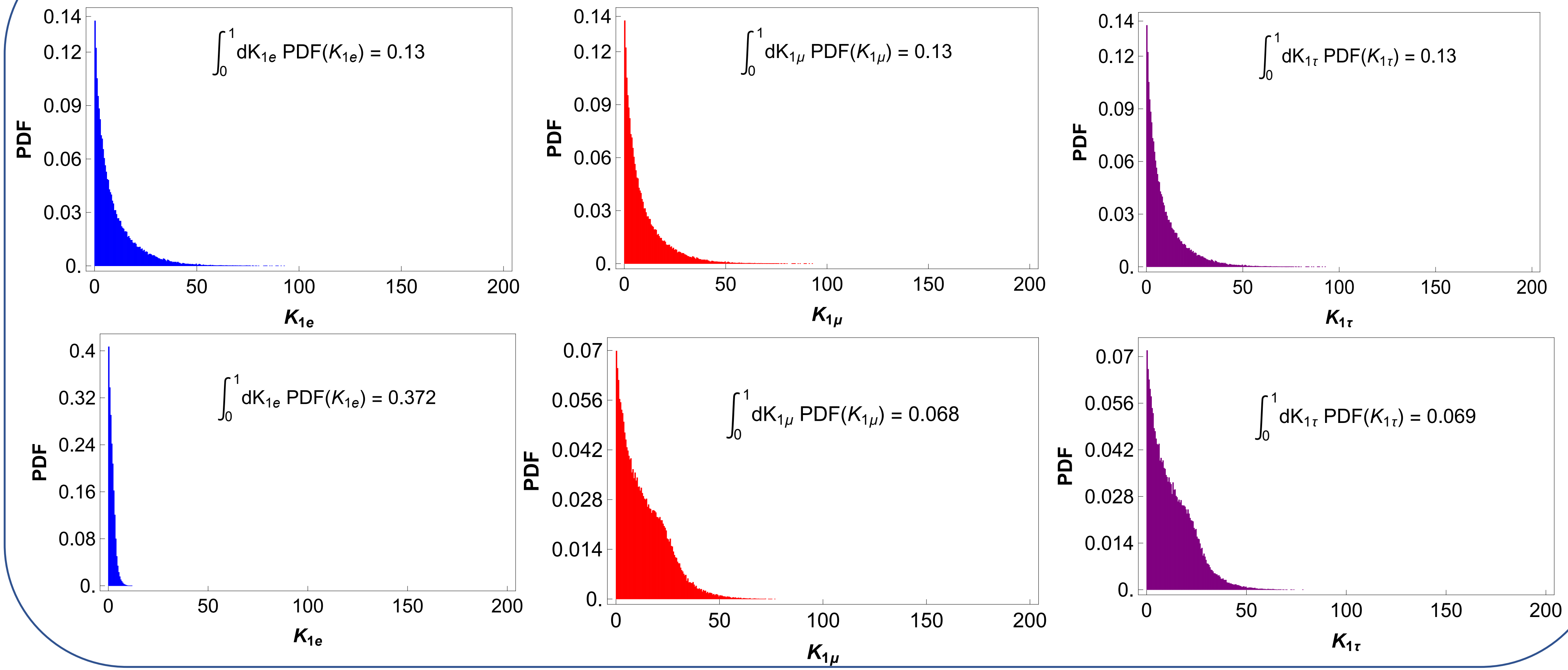


Putting experimental information: NuFiT lateset, 2018

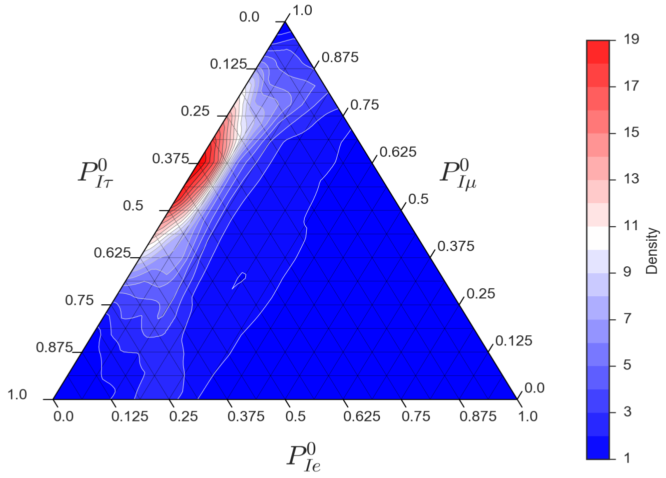


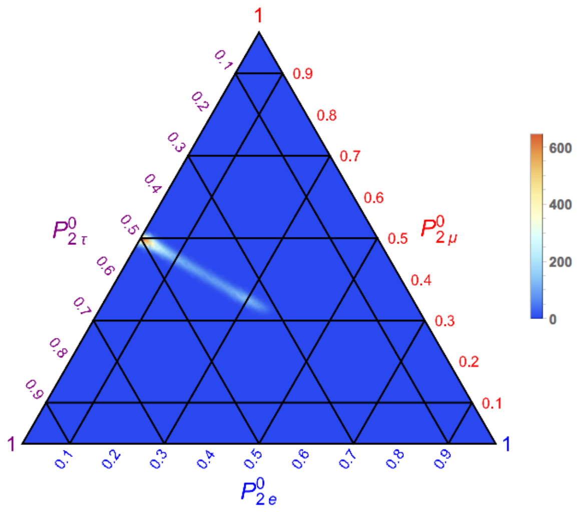


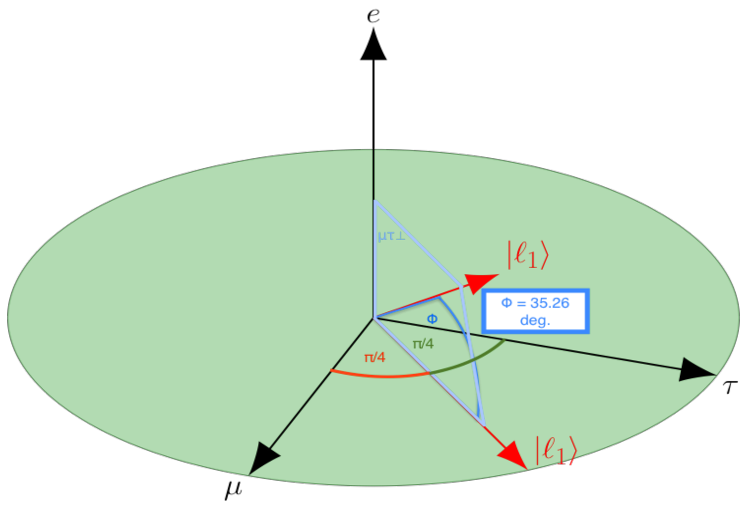
Neutrino oscillation data enhances the probability of the decay parameter being smaller



Example 1: A model with $CP^{\mu\tau}$ flavour symmetry: $P_{1\mu}= P_{1\tau}$, $\theta_{23}= 45^0$, Cos $\delta = 90^0$ or 270^0







General Case

P. Di Bari and Michele Re Fiorentin and RS JHEP 1905 (2019) 011

$CP^{\mu\tau}$ symmetric case

E.g., Walter Grimus et al Phys.Lett. B579 (2004)
RS et al JHEP 1806 (2018) 085

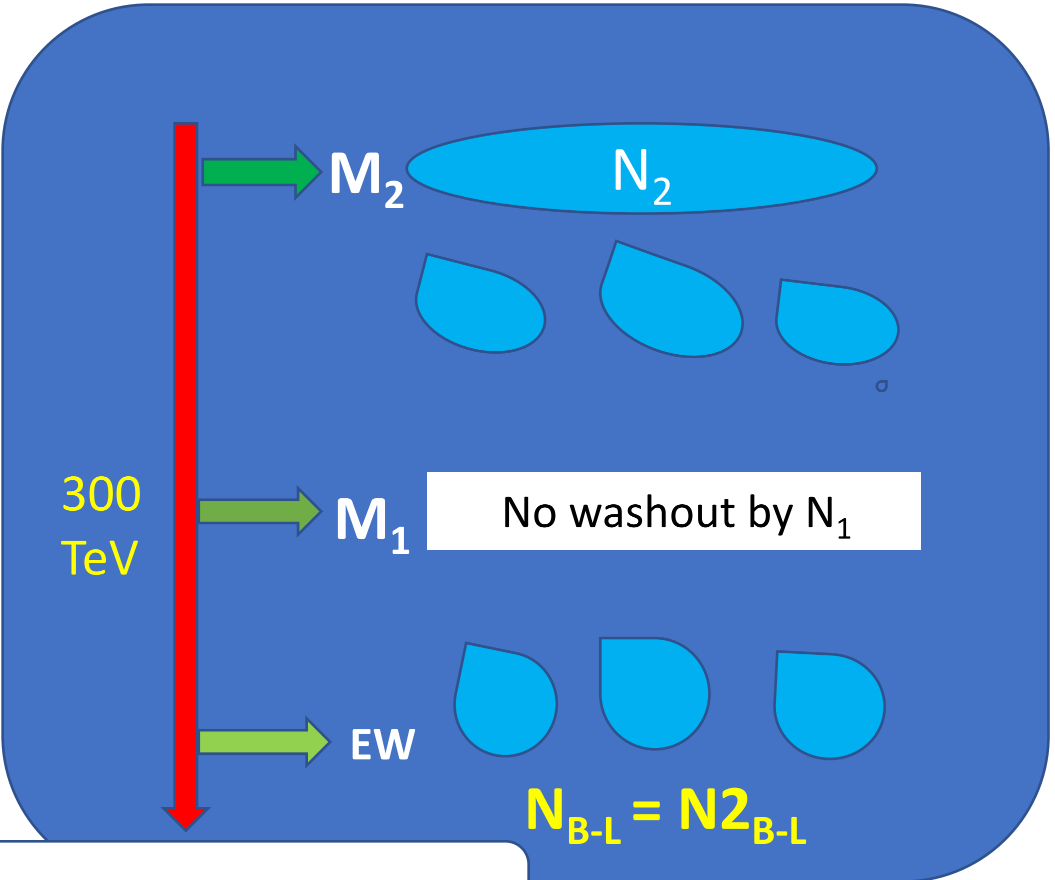
Example 2: Standard Type-I seesaw with Higgs portal (dim 5) interaction, 3 RH neutrinos, the lightest one is a decaying Dark Matter → IceCube Signal

DM Production due to matter effect:

Higgs portal interaction: $1/\Lambda\ N_I N_J \Phi\Phi$ induces matter of diagonal matter potential (Majorana self-energy)

$V_{IJ}(T) \approx T^2/12\Lambda$ (I,J= DM, Source)
(Density matrix computation)

→ N1 (Dark matter) is produced non-adiabatically and non-resonantly due to the mixing with N2).



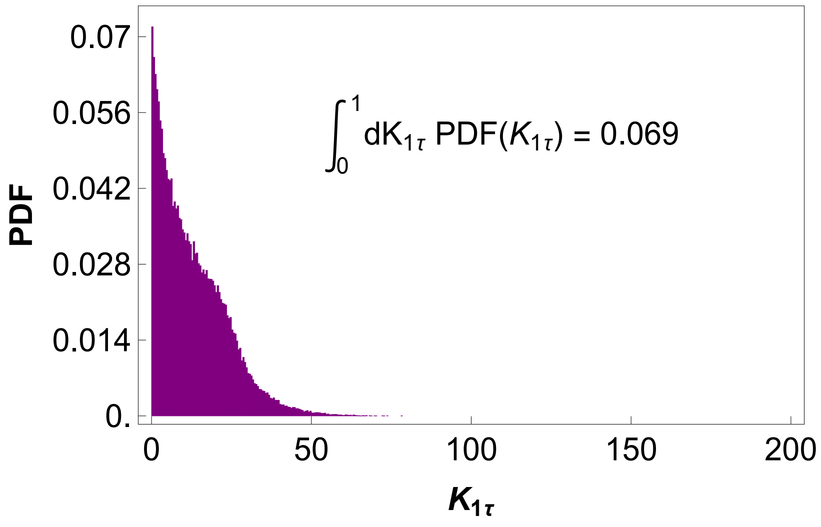
RS, PD Bari, YL Zhou, K.Farrag, T. Katori (to appear)

SO(10) inspired models:

e.g., Akhmedov, Frigerio, Smirnov, 2003
Di Bari, Riotto, 2009

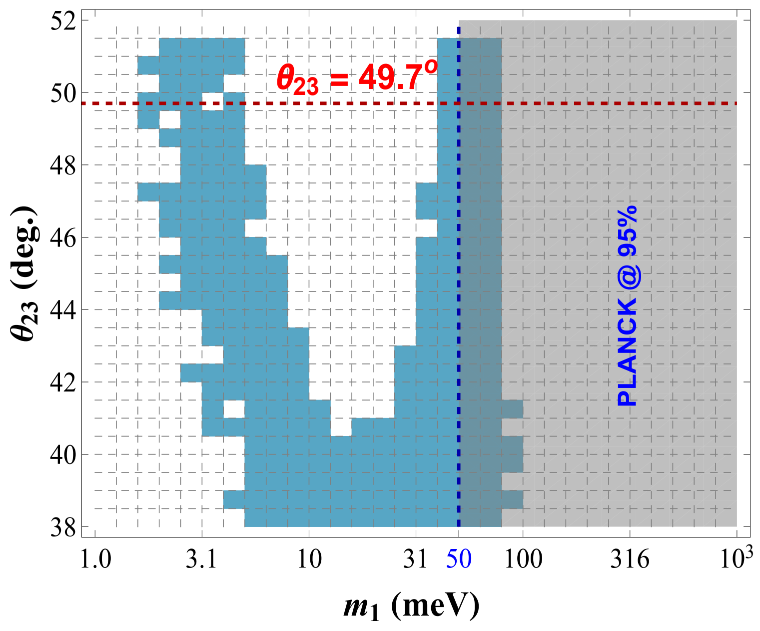
- The Dirac masses are not too different from the quark masses.
- $m_{D3} \approx$ top, $m_{D2} \approx$ **α** charm, $m_{D1} \approx$ up → $M3 \approx 10^{14}$ GeV, $M2 \approx 10^{10}$ GeV, $M1 \approx 10^{5}$ GeV (natural spectrum)

Only $K_{1\tau} < 1$ is relevant, since **not enough CP violation** in electron and muon flavour :



SO(10)-leptogenesis predictive

RS, PD Bari, Feorentin (2019)



Conclusion

1. We have shown how neutrino seesaw model could be visualized graphically

3. We introduce the idea of Lorentz boost in flavour space and show, how this is related to fine tuning in seesaw models.

4. We introduce a new parametrization of the orthogonal matrix and show how this leads to flavour unbiased theory.

5. Neutrino oscillation data creates 'electronic hole' with a higher probability (37%), thus the asymmetry generated by N_2 would more likely to pass through.

6. Discussed some intersesting models eg. SO(10), Decaying DM and model with flavor symmetries.

One flavor leptogenesis : Computation of the lepton asymmetry

Caution: We are only discussing the hierarchical scenario