N_1+N_2 Leptogenesis in $\Delta(27)$ with Universal Texture Zero

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Based on: ArXiv1904.10545

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Motivations

A Flavor problem:
How to account for massive neutrinos and lepton mixing?

$$\Delta m^2_{21} = (6.79 \div 8.01) \times 10^{-5}\text{eV}$$
$$\Delta m^2_{31} = (2.431 \div 2.622) \times 10^{-3}\text{eV}$$
$$\sin^2\theta_{12} = (2.75 \div 3.50) \times 10^{-1}$$
$$\sin^2\theta_{23} = (4.28 \div 6.23) \times 10^{-1}$$
$$\sin^2\theta_{23} = (2.044 \div 2.437) \times 10^{-2}$$

A Cosmological problem:
The Baryon Asymmetry of the Universe (BAU) obtained in the SM is too small by different orders of magnitude:

$$Y_B^{exp} = \frac{n_B - \bar{n}_B}{s} = (0.86 \div 0.88) \times 10^{-10}$$

Right Handed (RH) neutrinos

Seesaw:
RH neutrinos provide a natural answer to the smallness of LH neutrino masses:

$$m_i = -\frac{v_u^2 y_i^{\nu 2}}{M_i}$$

Leptogenesis (LpGn) :
Lepton number violating decays of RH neutrinos produce a Lepton asymmetry converted to a BAU by sphalerons.

Motivations

If seesaw is the origin of light neutrino masses then qualitative LpGn is **unavoidable**.

Quantitative? Matching the observed BAU constrains the unknown RH neutrino sector.

To be checked in the specific model! Note: original model for LpGn requires $M > 10^9$, close to “natural” seesaw scale.

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Outline

- **Model**
  - Universal Texture Zero
  - UTZ seesaw
- **Leptogenesis (LpGn)**
  - Boltzmann Equations
  - Leptogenesis parameters
- **Analysis**
  - Procedure
  - Results
  - Conclusions

Model: Universal Texture Zero

Model based on the Flasy $\mathcal{G}_f = \Delta(27) \times Z_N$

	L	e^c	N^c	$H_{u,d}$	Σ	S	ϕ_c	ϕ_b	ϕ_a	ϕ	ϕ_X
$\Delta(27)$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\mathbf{3}$
Z_N	0	0	0	0	2	-1	0	-1	2	0	X

Alignment:

$$\langle\phi_c\rangle = v_c \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \propto \langle\phi\rangle$$

$$\langle\phi_b\rangle = \frac{v_b}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}$$

$$\langle\phi_a\rangle = \frac{v_a}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ -1 \end{pmatrix}$$

Superpotential:

$$\mathcal{W}_Y = L_i e_j^c H_d \left[\frac{g_c^e}{\Lambda^2} \phi_c^i \phi_c^j + \frac{g_b^e}{\Lambda^3} \phi_b^i \phi_b^j \Sigma + \frac{g_a^e}{\Lambda^3} (\phi_a^i \phi_b^j + \phi_b^i \phi_a^j) S \right] +$$

$$+ L_i N_j^c H_u \left[\frac{g_c^\nu}{\Lambda^2} \phi_c^i \phi_c^j + \frac{g_b^\nu}{\Lambda^3} \phi_b^i \phi_b^j \Sigma + \frac{g_a^\nu}{\Lambda^3} (\phi_a^i \phi_b^j + \phi_b^i \phi_a^j) S \right]$$

$$\mathcal{W}_N = N_i^c N_j^c \left[\frac{g_c^N}{\Lambda} \phi^i \phi^j + \frac{g_b^N}{\Lambda^4} \phi_b^i \phi_b^j (\phi^k \phi^k \phi_a^k) + \frac{g_a^N}{\Lambda^4} (\phi_a^i \phi_b^j + \phi_b^i \phi_a^j)(\phi^k \phi^k \phi_b^k) \right]$$

$\square_c$ $\square_b$ $\square_{ab}$ $\square_{ba}$

$\square_{ij} = \phi_i \phi_j^T$ (rank-1 matrices)

Same Dirac and Majorana structures:

$$\begin{bmatrix} Y_{e,\nu} \\ M_N \end{bmatrix} = \begin{bmatrix} y_c^{e,\nu} \\ M_c \end{bmatrix} \square_c + \begin{bmatrix} y_b^{e,\nu} \\ M_b \end{bmatrix} \square_b + \begin{bmatrix} y_a^{e,\nu} \\ M_a \end{bmatrix} (\square_{ab} + \square_{ba})$$

(1,1)-Universal and symmetric Texture Zero (**UTZ**)

See: JHEP03(2018)007 Ivo de Medeiros Varzielas, Graham G. Ross and Jim Talbert

Model: UTZ see saw

As Dirac and Majorana matrices are in terms of rank-1 matrices, the UTZ is preserved after seesaw:

$$m_\nu \equiv - v_u^2 Y_\nu M_N^{-1} Y_\nu^T = m_c \square_c + m_b \square_b + m_a (\square_{ab} + \square_{ba})$$

$$m_a = -\frac{v_u^2 y_a^{\nu 2}}{M_a} \qquad m_b = m_a \left(2\frac{y_b^\nu}{y_a^\nu} - \frac{M_b}{M_a} \right) \qquad m_c = -\frac{v_u^2 y_c^{\nu 2}}{M_c}$$

$m_{a,b,c}$ entangle Dirac $y^\nu_{a,b,c}$ and Majorana $M_{a,b,c}$ neutrino couplings in a non-trivial way.

$$R_{TB}^T m_\nu R_{TB} = \begin{pmatrix} \frac{m_c}{6} & \frac{m_c}{3\sqrt{2}} & -\frac{m_c}{2\sqrt{3}} \\ \frac{m_c}{3\sqrt{2}} & \frac{m_c}{3} & \frac{6m_a - m_c}{\sqrt{6}} \\ \frac{m_c}{2\sqrt{3}} & \frac{6m_a - m_c}{\sqrt{6}} & \frac{4m_b - m_c}{2} \end{pmatrix} \xrightarrow{m_c < m_a, m_b} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sqrt{6}m_a \\ 0 & \sqrt{6}m_a & 2m_b \end{pmatrix} \quad \left(\boldsymbol{m_1 \simeq \frac{m_c}{6}}\right)$$

semi-diagonalized by a Tri-Bimaximal (TB) rotation

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sqrt{6}m_a \\ 0 & \sqrt{6}m_a & 2m_b \end{pmatrix} \xrightarrow{\sqrt{6}m_a < 2m_b} \boldsymbol{m_3 \simeq 2m_b \;,\; m_2 \simeq 3\frac{m_a^2}{m_b} \;,\; \sin\theta = \sqrt{\frac{m_2}{m_3}} \simeq \sqrt{\frac{3}{2}\frac{m_a}{m_b}}}$$

Gatto-Sartori-Tonin structure

The correct neutrino mixing is obtained if $\boldsymbol{m_c < m_a < m_b}$

m_ν is compatible with a Normal Ordered neutrino spectrum

See: JHEP03(2018)007 Ivo de Medeiros Varzielas, Graham G. Ross and Jim Talbert

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$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sqrt{6}m_a \\ 0 & \sqrt{6}m_a & 2m_b \end{pmatrix} \xrightarrow{\sqrt{6}m_a < 2m_b} \boldsymbol{m_3 \simeq 2m_b \;,\; m_2 \simeq 3\frac{m_a^2}{m_b} \;,\; \sin\theta = \sqrt{\frac{m_2}{m_3}} \simeq \sqrt{\frac{3}{2}\frac{m_a}{m_b}}}$$

Fit of the model:

$$m_b = \sqrt{\Delta m_{31}^2/2} \simeq 25\,\text{meV}$$

$$m_a = m_b\sqrt{\Delta m_{21}^2/3} \simeq 9.5\,\text{meV}$$

Neutrinos		Charged leptons	
m_a/meV	8.95	y_a^e	3.01×10^{-4}
m_b/meV	24.6	y_b^e	3.90×10^{-3}
m_c/meV	2.26	y_c^e	7.16×10^{-2}
γ_m	2.51	γ_e	0.13
δ_m	1.26	δ_e	-1.31

See: JHEP03(2018)007 Ivo de Medeiros Varzielas, Graham G. Ross and Jim Talbert

Model: Majorana Masses

Structure of Dirac matrices: $y_a^{e,\nu} : y_b^{e,\nu} : y_c^{e,\nu} \sim \epsilon_{e,\nu}^3 : \epsilon_{e,\nu}^2 : 1$

$$Y_{e,\nu} \simeq y_c^{e,\nu} \begin{pmatrix} 0 & \epsilon_{e,\nu}^3 & \epsilon_{e,\nu}^3 \\ \epsilon_{e,\nu}^3 & \epsilon_{e,\nu}^2 & \epsilon_{e,\nu}^2 \\ \epsilon_{e,\nu}^3 & \epsilon_{e,\nu}^2 & 1 \end{pmatrix}$$

$\epsilon_e \equiv y_a^e / y_b^e = 0.15$

$\epsilon_\nu \equiv y_a^\nu / y_b^\nu$ not fixed by phenomenology

$$m_{a,c} = -\frac{v_u^2 {y_{a,c}^{\nu}}^2}{M_{a,c}}$$

$$m_b = m_a \left(2\frac{y_b^\nu}{y_a^\nu} - \frac{M_b}{M_a} \right)$$

For the correct neutrino mixing $m_c < m_a < m_b$:

$$\frac{m_a}{m_b} = \left(2\frac{y_b^\nu}{y_a^\nu} - \frac{M_b}{M_a} \right) \sim \left(\frac{2}{\epsilon_\nu} - \frac{M_b}{M_a} \right) \xrightarrow{m_a < m_b} \frac{M_a}{M_b} < \epsilon_\nu$$

$$\frac{m_a}{m_c} = \frac{y_c^{\nu 2}}{y_a^{\nu 2}} \frac{M_a}{M_c} \sim \frac{1}{\epsilon_\nu^6} \frac{M_a}{M_c} \xrightarrow{m_c < m_a} \frac{M_a}{M_c} < \epsilon_\nu^6$$

N_3 with $M_3 \sim M_c$ effectively decouples after seesaw

We expect a hierarchical spectrum for the RH masses: $\boldsymbol{M_1 < M_2 \ll M_3}$

See: JHEP03(2018)007 Ivo de Medeiros Varzielas, Graham G. Ross and Jim Talbert

LpGn: Boltzmann Equations

Generation of the BAU through N_i-leptogenesis is a non equilibrium process treated by means of **Boltzmann equations (BEs)**.

We can use simplified BEs, in MSSM, 3-flavoured regime:

$$\frac{dY_{N_i}}{dz} = -2D(Y_{N_i} - Y^{eq}_{N_i}) \ , \quad \frac{dY_{\tilde{N}_i}}{dz} = -2D(Y_{\tilde{N}_i} - Y^{eq}_{\tilde{N}_i}) \qquad Y_B = \frac{10}{31}\sum_{\alpha} Y_{\Delta_\alpha}(z \gg 1)$$

$$\frac{dY_{\Delta_\alpha}}{dz} = 2\varepsilon^{\alpha}_{N_i} D(Y_{N_i} - Y^{eq}_{N_i}) + 2\varepsilon^{\alpha}_{\tilde{N}_i} D(Y_{\tilde{N}_i} - Y^{eq}_{\tilde{N}_i}) + \frac{K^{\alpha}_{N_i}}{K_{N_i}} W \sum_{\alpha'} A_{\alpha\alpha'} Y_{\Delta'_\alpha}$$

$(\alpha = e, \mu, \tau \ , \ i = 1,2,3)$

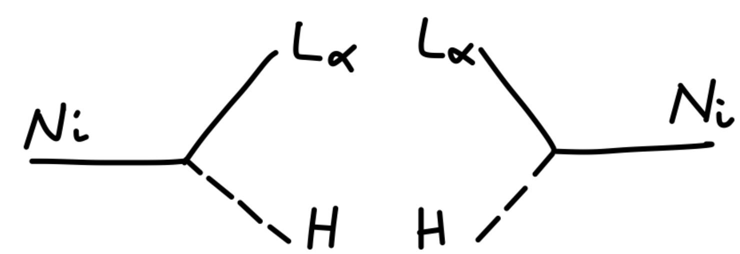
$Y_{N_i}, Y_{\tilde{N}_i}$: number densities of RH (s)neutrinos.

Y_{Δ_α} : total (particle+sparticle) number densities of $\Delta_\alpha = B/3 - L_\alpha$ *(conserved by sphalerons)*

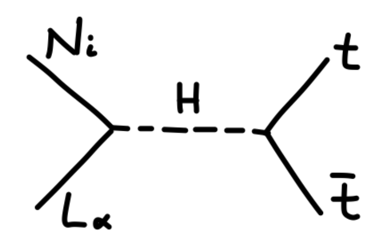
$D, W = \Gamma_{D(W)}/\mathrm{H}z$: *decay and washout terms*

$\varepsilon^{\alpha}_{N_i}, K^{\alpha}_{N_i}$: *decay factors and CP asymmetries (geometrical model factors)*

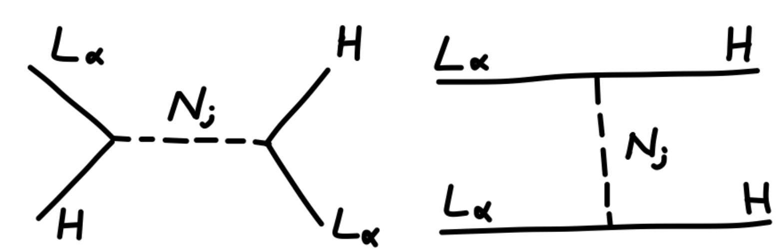
Decays (Inverse)



$\Delta L = 1$ Scatterings



~~$\Delta L = 2$ Scatterings~~



See: arXiv:hep-ph/0609038v4, S. Antusch, S. F. King, A. Riotto

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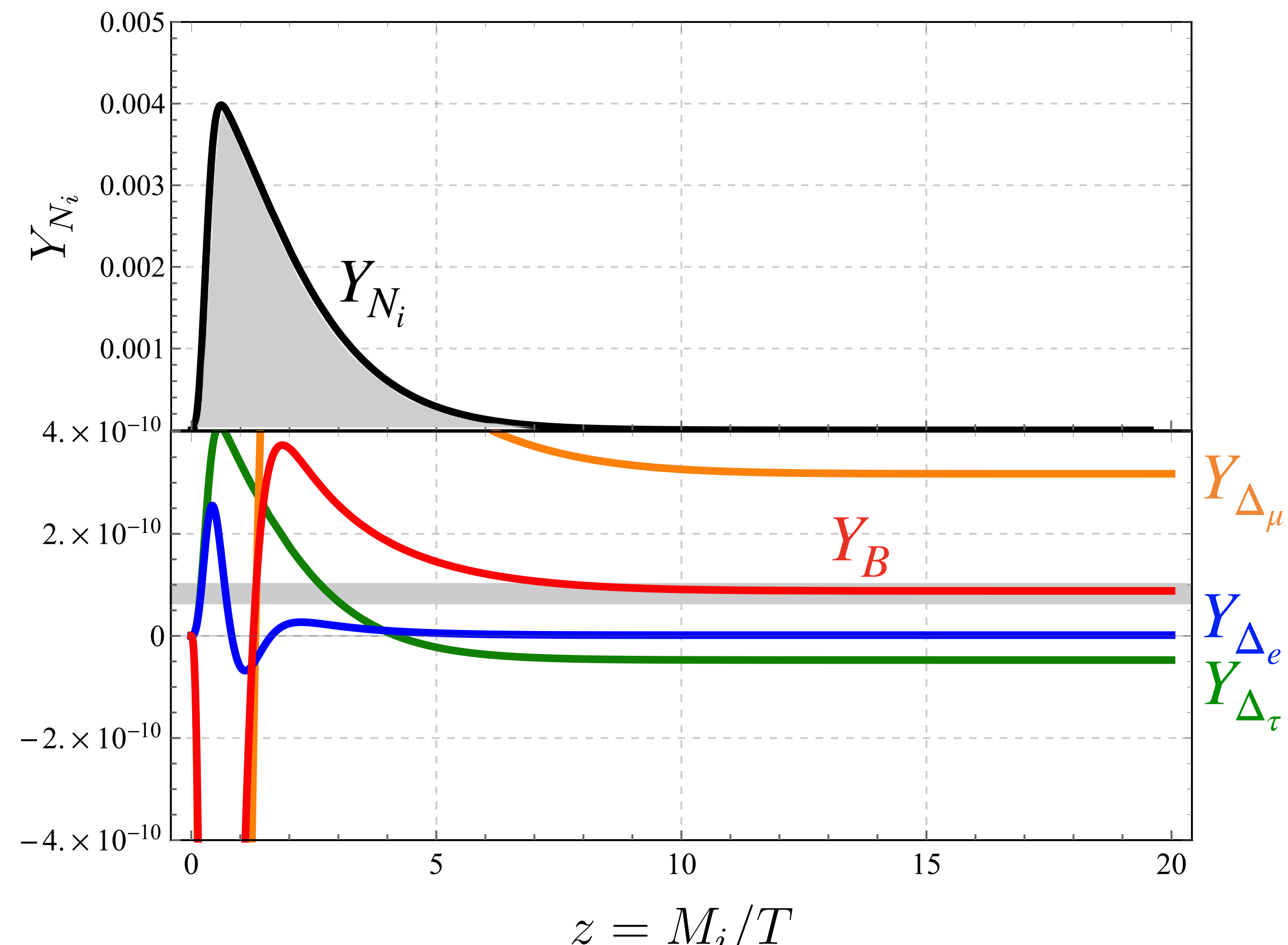

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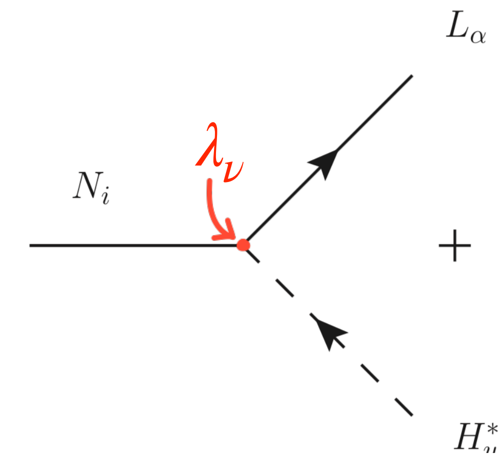
LpGn: Decay Factors & CP asymmetries

The nature of RH neutrino masses imply the decays $N_i \to L_\alpha H_u$ and $N_i \to \overline{L}_\alpha H_u^*$

Decay factors dominated by tree level diagram

$$K^\alpha_{N_i} \equiv \frac{\Gamma(N_i \to L_\alpha H_u) + \Gamma(N_i \to \overline{L}_\alpha H_u^*)}{\mathrm{H}(M_i)}$$

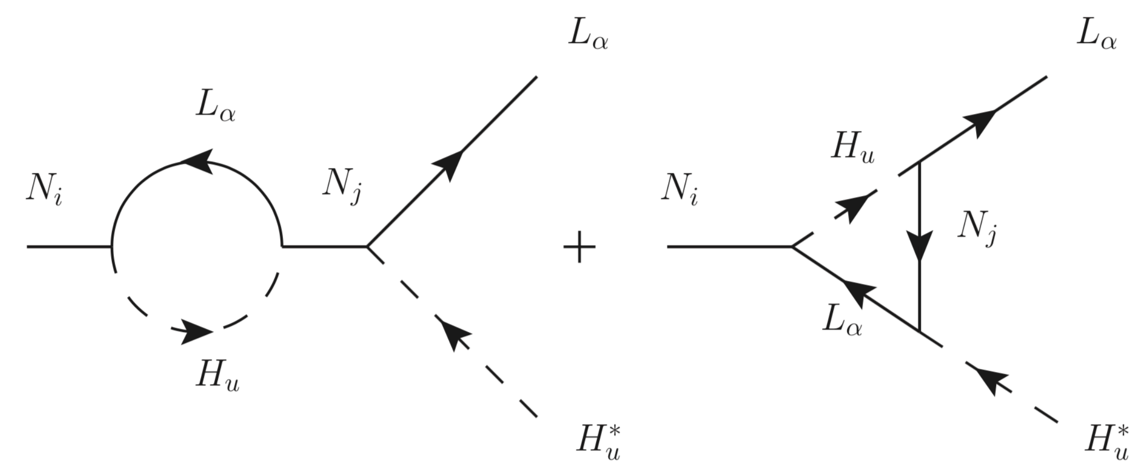
$$K^\alpha_{N_i} = \frac{v_u^2}{m_* \boldsymbol{M_i}} (\lambda_\nu)^\dagger_{i\alpha} (\lambda_\nu)_{\alpha i}$$



CP asymmetries arise only at loop level

$$\varepsilon^\alpha_{N_i} \equiv \frac{\Gamma(N_i \to L_\alpha H_u) - \Gamma(N_i \to \overline{L}_\alpha H_u^*)}{\Gamma(N_i \to L_\alpha H_u) + \Gamma(N_i \to \overline{L}_\alpha H_u^*)}$$

$$\varepsilon^\alpha_{N_i} = \frac{1}{8\pi} \sum_{j \neq i} \frac{\mathrm{Im}[(\lambda_\nu)^\dagger_{i\alpha} (\lambda_\nu{}^\dagger \lambda_\nu)_{ij} (\lambda_\nu)_{\alpha j}]}{(\lambda_\nu{}^\dagger \lambda_\nu)_{ii}} \times \begin{cases} -3\boldsymbol{M_i}/\boldsymbol{M_j} & \text{if} \quad M_i \\ 2\boldsymbol{M_j}/\boldsymbol{M_i} & \text{if} \quad M_i < M_j \end{cases}$$



They are **fully geometrical factors** that depend only on the specific model!

$$\lambda_\nu^* = V_{eL} \boldsymbol{Y_\nu} V_N^T$$

$(Y_e^{diag} = V_{eL} Y_e V_{eR}^\dagger)$ $\quad$ $(M_N^{diag} = V_N Y_e V_N^T)$

See: arXiv:hep-ph/0609038v4, S. Antusch, S. F. King, A. Riotto

LpGn: Decay Factors & CP asymmetries

At LO we can consider $\lambda_\nu \sim Y_\nu \simeq y_c^\nu \begin{pmatrix} 0 & \epsilon_\nu^3 & \epsilon_\nu^3 \\ \epsilon_\nu^3 & \epsilon_\nu^2 & \epsilon_\nu^2 \\ \epsilon_\nu^3 & \epsilon_\nu^2 & 1 \end{pmatrix}$

Washout weaker in the electron

$$K_{N_1}^{\alpha} \sim \left|\frac{M_3}{M_1}\right| \epsilon_\nu^6 \begin{pmatrix} \epsilon_\nu^2 \\ 1 \\ 1 \end{pmatrix}$$

$$K_{N_2}^{\alpha} \sim \left|\frac{M_3}{M_2}\right| \epsilon_\nu^4 \begin{pmatrix} \epsilon_\nu^2 \\ 1 \\ 1 \end{pmatrix}$$

Aligned

$$\varepsilon_{N_1}^{\alpha} \sim \frac{3}{8\pi}\left|\frac{M_1}{M_2}\right| \epsilon_\nu^4 \begin{pmatrix} \epsilon_\nu^2 \\ 1 \\ 1 \end{pmatrix}$$

Always subdominant compared with $\varepsilon_{N_1}^{\mu,\tau}$

$\varepsilon_{N_1}^{\mu,\tau}$ are the dominant contributions to $Y_{\Delta_\alpha}^{i=1}$

$$\varepsilon_{N_2}^{\alpha} \sim \frac{3}{8\pi}\left|\frac{M_2}{M_3}\right| \begin{pmatrix} \epsilon_\nu^4 \\ \epsilon_\nu^2 \\ 1 \end{pmatrix} + \frac{1}{4\pi}\left|\frac{M_1}{M_2}\right| \epsilon_\nu^6 \begin{pmatrix} \epsilon_\nu^2 \\ 1 \\ 1 \end{pmatrix}$$

This gives an important contribution when $M_2 \sim M_3$

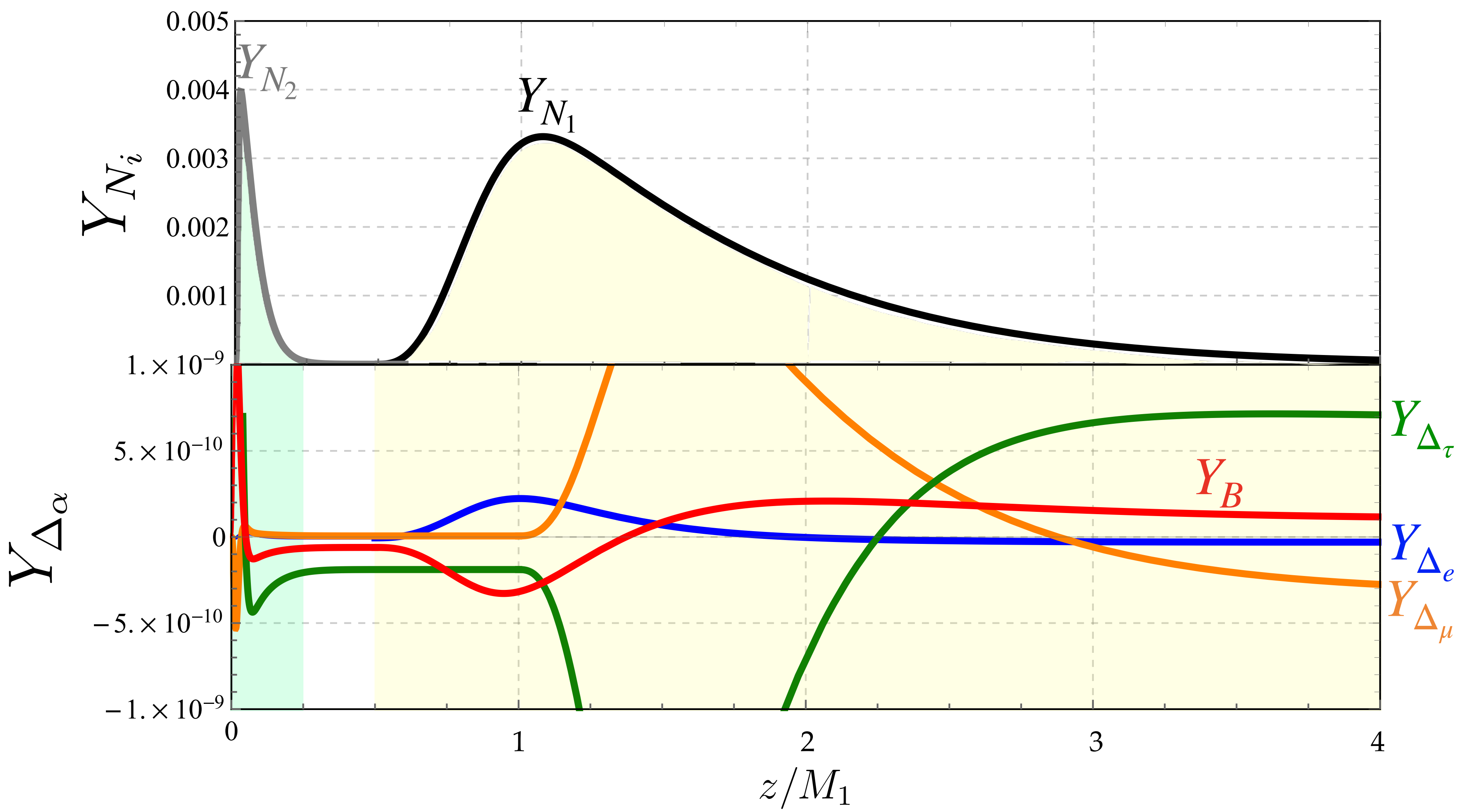
Always subdominant compared with $\varepsilon_{N_1}^{\alpha}$

See: ArXiv1904.10545, Fredrik Björkeroth, Ivo de Medeiros Varzielas, M.L. López-Ibáñez, AM, Oscar Vives

Analysis: Procedure

Assumption of hierarchical RH neutrino masses: $M_1 < M_2 \ll M_3$. Within this framework:

- Any N_3 generated asymmetry is assumed negligible.
- The two lightest RH neutrinos do not interfere with each other: the generation of the asymmetry from N_1 decays and from N_2 decays proceed independently.



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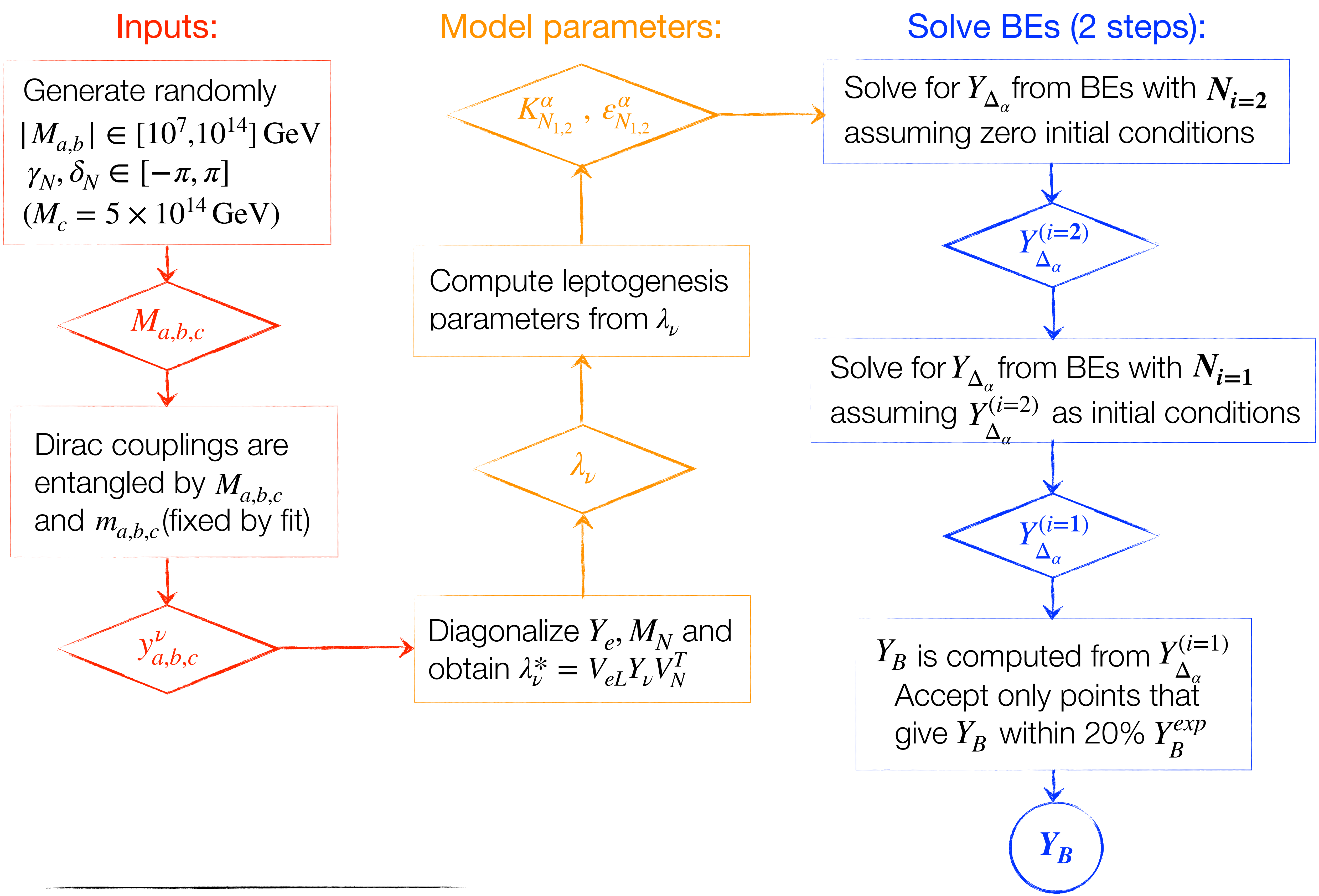

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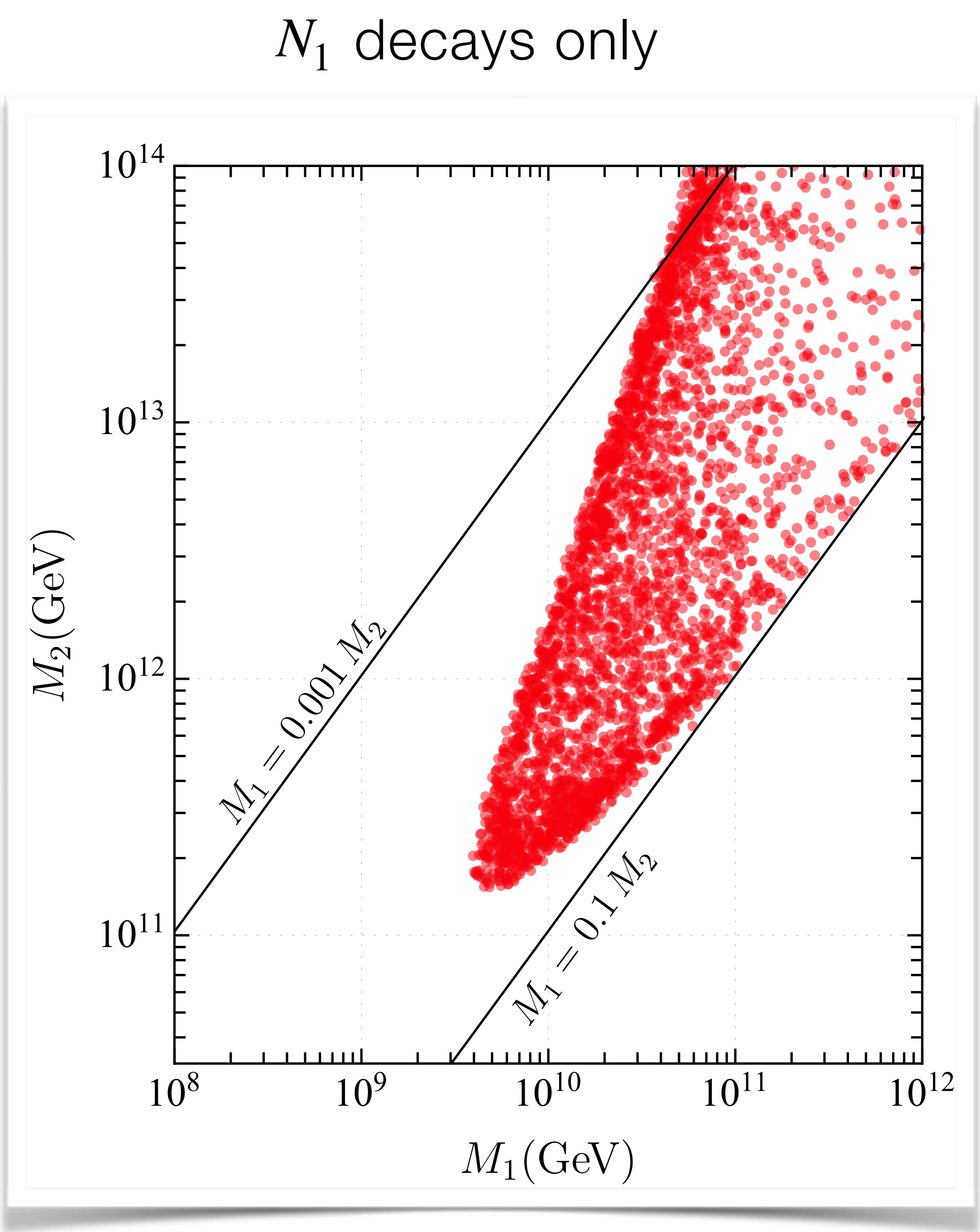
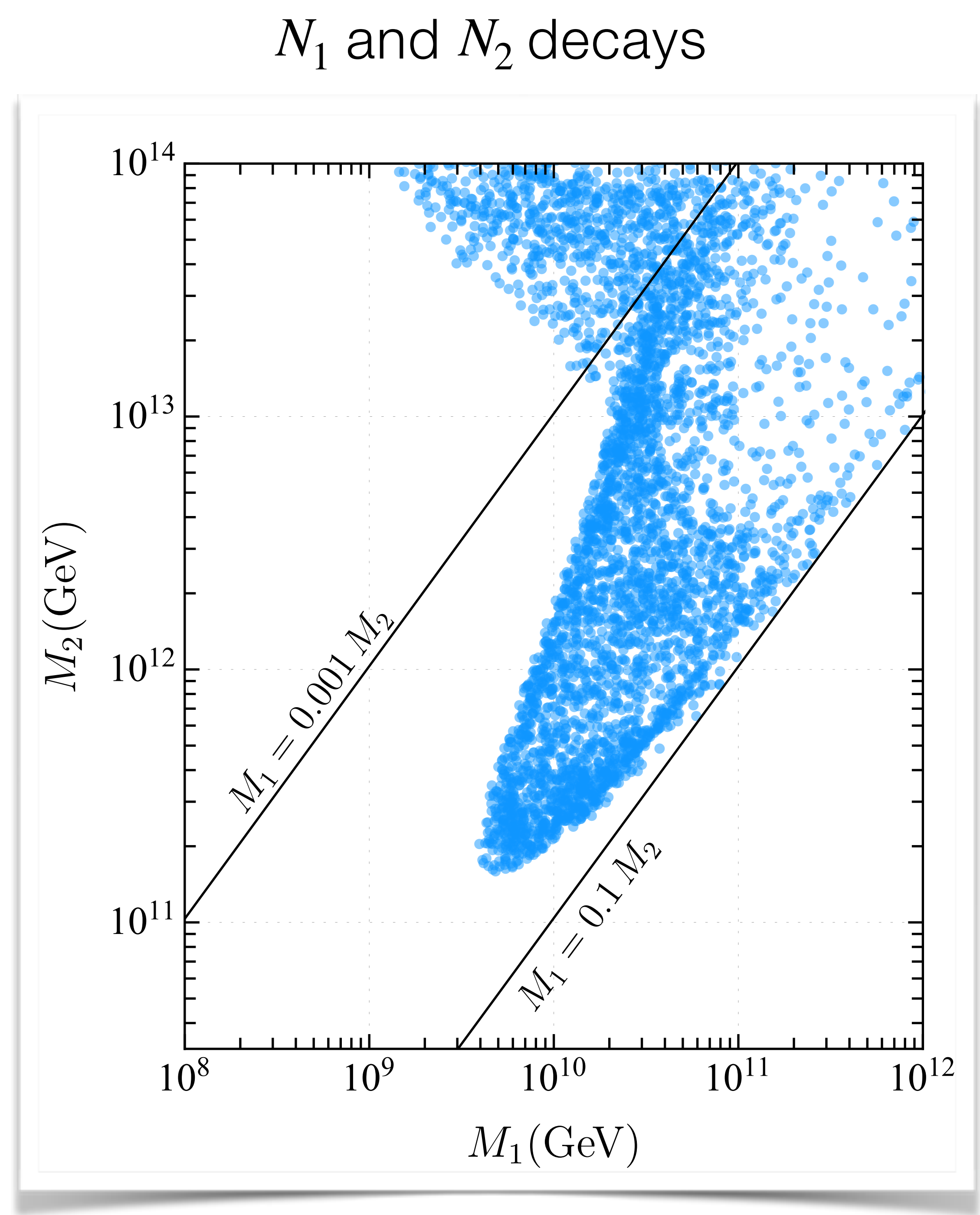
Analysis: Results





Allowed values of RH neutrino masses $M_{1,2}$ giving Y_B within 20% ($M_3 \simeq 5 \times 10^{14}\,\mathrm{GeV}$)

See: ArXiv1904.10545, Fredrik Björkeroth, Ivo de Medeiros Varzielas, M.L. López-Ibáñez, AM, Oscar Vives

Analysis: Results

Correct BAU above

$M_1 \simeq 4 \times 10^9\,\text{GeV}\,, \text{M}_2 \simeq 2 \times 10^{11}\,\text{GeV}$

Two regions:

$\mathbf{M_1/M_2 \in [0.002, 0.1]}$

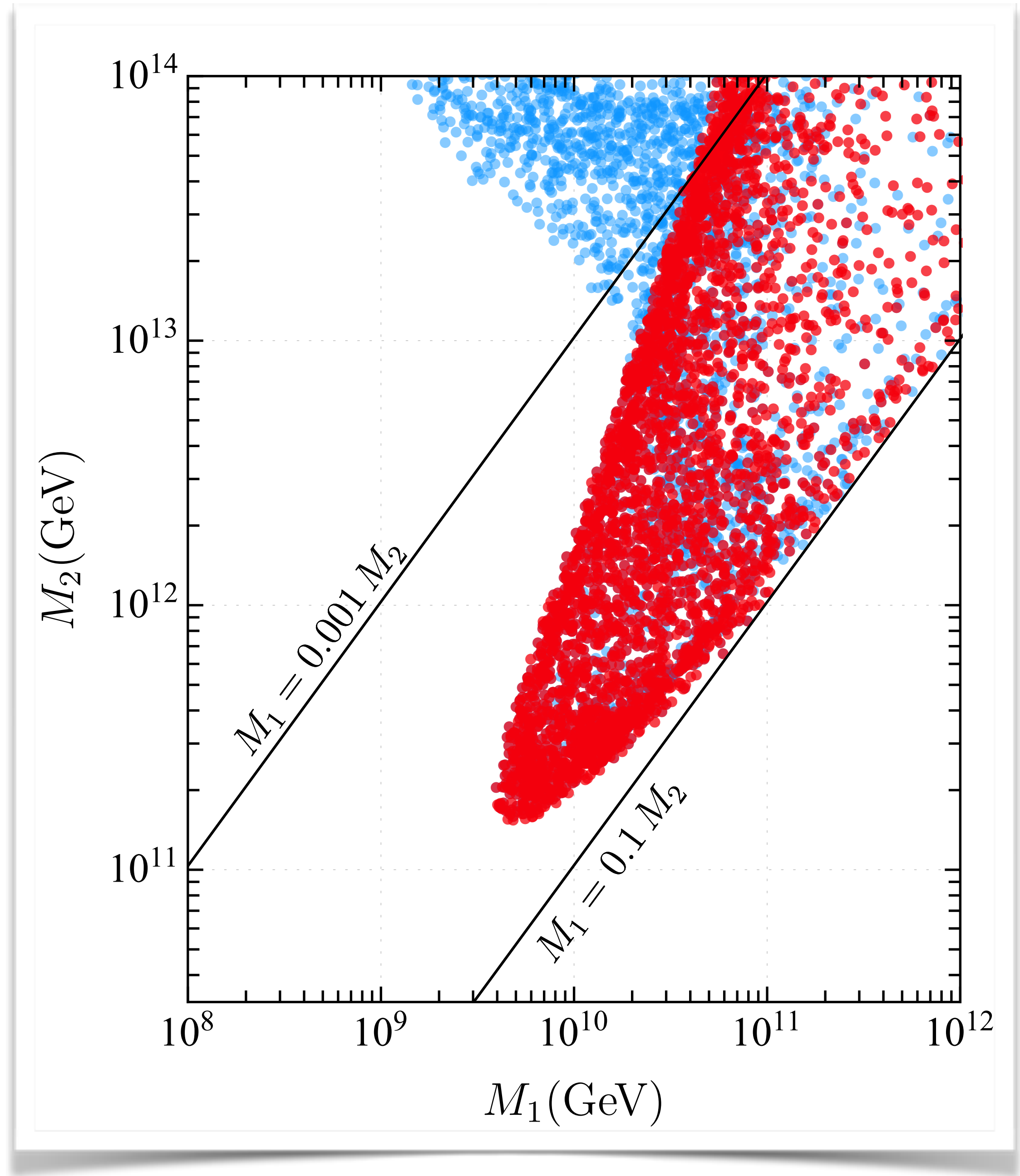
$\mathbf{M_2 \ll M_3}$

$\mathbf{M_1 \ll M_2}$

$\mathbf{M_2/M_3 > 0.1}$

BAU consistent with leptogenesis from N_1

N_1 and N_2 decays



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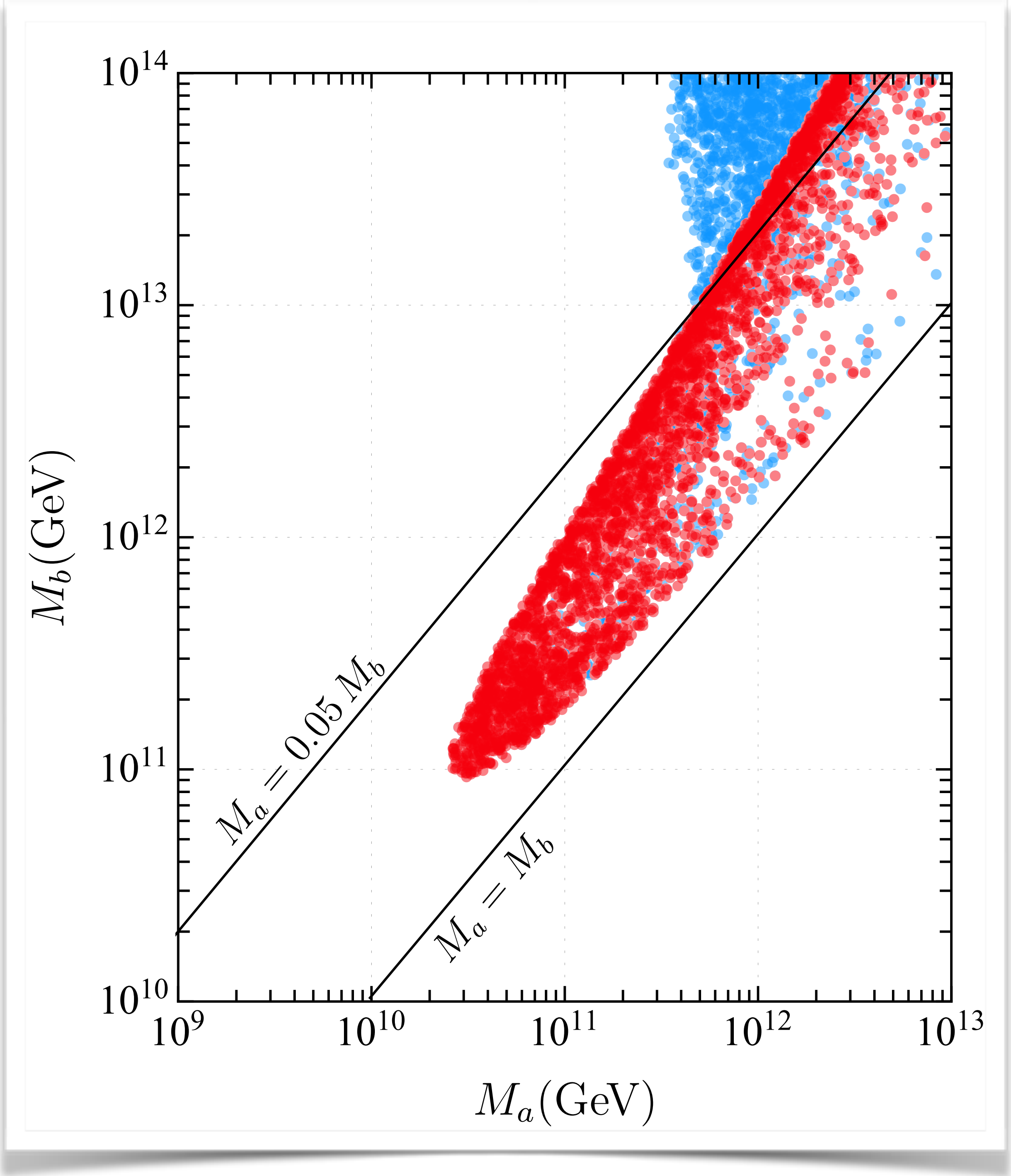
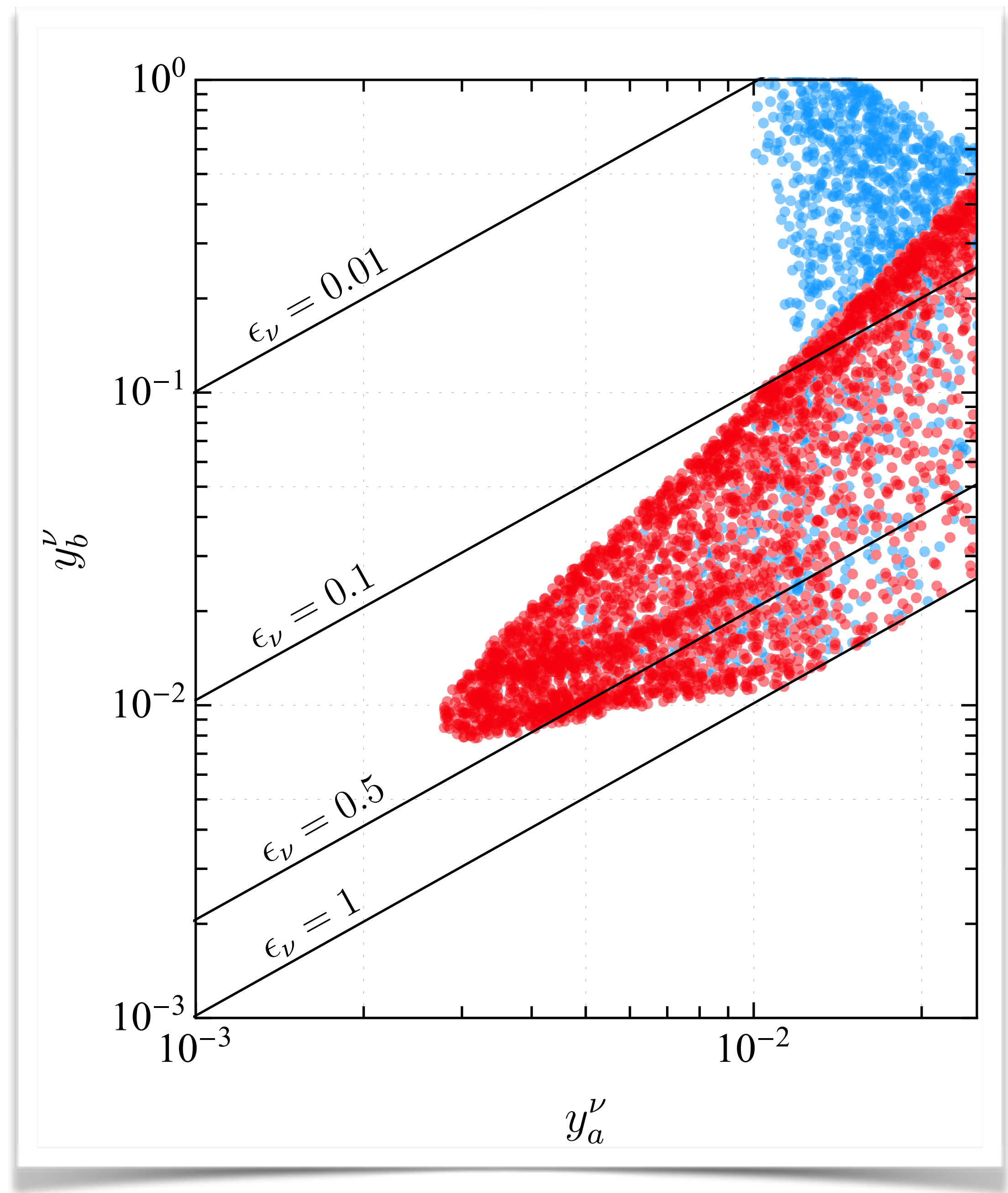


Allowed values of
RH input mass parameters ($M_{a,b}$)

Allowed values of
Dirac neutrino couplings ($y^{\nu}_{a,b}$)



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Conclusions

- We have studied the generation of the BAU through N_1+N_2-leptogenesis in the UTZ $SO(10)\times\Delta(27)\times Z_N$ flavoured GUT model

  - Leptogenesis yields the observed BAU for a considerable region of the parameter space.

    - The preferred mechanism is N_1 leptogenesis: $M_1 > 4\times10^9$ GeV, with $M_2 > 2\times10^{11}$ GeV, while $0.002 < M_1/M_2 < 0.1$.
      N_2 leptogenesis possible but not compatible with the model!

      - We can constrain the neutrino Yukawa couplings, which are bounded from below: $y_a^{\nu} > 0.003,\ y_b^{\nu} > 0.008$

Thank you

谢谢