LEPTOGENESIS IN LOW SCALE SEESAW MODELS

Marija Kekic

In collaboration with:
P. Hernandez, J. Racker, N. Rius, J. Lopez-Pavon

Nu@Fermilab, 21-25 July, Fermilab

MOTIVATION

Non-zero neutrino masses

Baryon asymmetry

MOTIVATION

Non-zero neutrino masses

Baryon asymmetry

Bariogenesis via leptogenesis

MOTIVATION

Non-zero neutrino masses

Baryon asymmetry

Bariogenesis via leptogenesis

Standard Leptogenesis scenario

Out of equilibrium decay of heavy states associated to neutrino masses (typically require large scale hard to test)

Fukugita, Yanagida, 1986;

...many works

MOTIVATION

Non-zero neutrino masses

Baryon asymmetry

Bariogenesis via leptogenesis

Standard Leptogenesis scenario

Out of equilibrium decay of heavy states associated to neutrino masses (typically require large scale hard to test)

Fukugita, Yanagida, 1986;
...many works

Leptogenesis via neutrino oscillations

Out of equilibrium in production of sterile neutrinos (natural at low-scale: testable?)

Akhmedov, Rubakov, Smirnov, 1998;
Asaka, Shaposhnikov, 2005; ...

THE MODEL

Minimal extension to SM- adding $N \geq 2$ right handed neutrinos

THE MODEL

Minimal extension to SM- adding $N = 3$ right handed neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{\alpha,i} \bar{L}^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{3} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$

THE MODEL

Minimal extension to SM- adding $N = 3$ right handed neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{\alpha,i} \bar{L}^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{3} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$

In Majorana mass basis

$$Y \equiv V^{\dagger} Diag(y_1, y_2, y_3) W$$

3x3 Majorana mass matrix

THE MODEL

Minimal extension to SM- adding $N = 3$ right handed neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{\alpha,i} \bar{L}^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{3} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$

In Majorana mass basis

3x3 Majorana mass matrix

$$Y \equiv V^\dagger Diag(y_1, y_2, y_3) W$$

6 CP phases, 2 of them Majorana phases

BARYOGENESIS

- Sakharov's conditions:

BARYOGENESIS

- Sakharov's conditions:

1. **Baryon number violation**

BARYOGENESIS

- Sakharov's conditions:

1. **Baryon number violation**

   SM - **sphalerons** transfer efficiently $\boldsymbol{\Delta_{\mathrm{L}}} \rightarrow \boldsymbol{\Delta_{\mathrm{B}}}$

   for $T > T_{EW}$

BARYOGENESIS

- Sakharov's conditions:

1. **Baryon number violation**
   SM - **sphalerons** transfer efficiently $\mathbf{\Delta_L} \rightarrow \mathbf{\Delta_B}$
   for $T > T_{EW}$

2. **Loss of thermal equilibrium**

BARYOGENESIS

- Sakharov's conditions:

1. **Baryon number violation**

   SM - **sphalerons** transfer efficiently $\mathbf{\Delta_L \to \Delta_B}$

   for $T > T_{EW}$

2. **Loss of thermal equilibrium**

   one of the states never gets to equilibrium before EW phase transition

   reservoir of lepton asymmetry

BARYOGENESIS

- Sakharov's conditions:

1. **Baryon number violation**

   SM - **sphalerons** transfer efficiently $\mathbf{\Delta_L \rightarrow \Delta_B}$

   for $T > T_{EW}$

2. **Loss of thermal equilibrium**

   one of the states never gets to equilibrium before EW phase transition

   reservoir of lepton asymmetry

3. **C and CP violation processes**

BARYOGENESIS

- Sakharov's conditions:

1. **Baryon number violation**

   SM - **sphalerons** transfer efficiently $\mathbf{\Delta_L \rightarrow \Delta_B}$

   for $T > T_{EW}$

2. **Loss of thermal equilibrium**

   one of the states never gets to equilibrium before EW phase transition

   reservoir of lepton asymmetry

3. **C and CP violation processes**

   CP- odd phases (W, V matrices) + CP- even phases (oscillations)

   CP asymmetries generated in the different flavours with

$$\mathbf{\Sigma_{\mathrm{active}}\Delta L_{\mathrm{active}} + \Sigma_{\mathrm{sterile}}\Delta N_{\mathrm{sterile}} = 0}$$

PREVIOUS WORK

- **Akhmedov-Rubakov-Smirnov (ARS)**
  - estimated the asymmetry only in the sterile sector (N=3 needed)
  - concluded that the right asymmetry could be generated without degeneracies

- **Shaposhnikov, Asaka and collaborators ($\nu\mathrm{MSM}$):**
  - included the transfer to the leptons
  - reduced to N=2 (different CP phases than ARS)
  - concluded that degeneracies were necessary

- **Drewes et al; and Shuve et al**
  - N=3 degeneracies can be lifted (proved for some points of phase space)

OUR GOAL

- Explore systematically the N=3 case (N=2 is a subclass):
  - identify the CP invariants that are relevant
  - clarify the connection ARS/Shaposhnikov and whether degeneracies are necessary generically

OUR GOAL

- Explore systematically the N=3 case (N=2 is a subclass):
  - identify the CP invariants that are relevant
  - clarify the connection ARS/Shaposhnikov and whether degeneracies are necessary generically

- For all this having precise **analytical predictions** is a **must**!

SETUP

- Mass range 0.1-100 GeV (decay before BBN) ***talk by J. Lopez-Pavon***
- The Majorana nature is irrelevant since $M/T \ll 1$
- The sterile neutrino production out of equilibrium
- The yukawa couplings are small and $y_3 \ll y_1, y_2$
- Other particles in kinetic equilibrium $\rho_x = e^{\mu_x/T} \rho_{eq}$
- Include only chemical potential of the lepton doublet
- Lepton asymmetry $\xrightarrow[T = T_{EW}]{\text{sphalerons}}$ Baryons

CP INVARIANTS

Asymmetry – CP odd → Proportional to weak basis rephasing invariants:

CP INVARIANTS

Asymmetry – CP odd $\longrightarrow$ Proportional to weak basis rephasing invariants:

$$J_W = -\mathrm{Im}[\mathrm{W}^\star_{23}\mathrm{W}^\star_{32}\mathrm{W}_{33}\mathrm{W}_{22}] \simeq \theta_{12}\theta_{13}\theta_{23}\sin\delta \qquad \text{Relevant for ASR}$$

$$\left.\begin{aligned} I_1^{(2)} &= -\mathrm{Im}[\mathrm{W}_{22}\mathrm{V}^\star_{21}\mathrm{V}_{11}\mathrm{W}^\star_{12}] \simeq \theta_{12}\bar{\theta}_{12}\sin\phi_1 \\ I_1^{(3)} &= -\mathrm{Im}[W_{11}V^*_{13}V_{23}W^*_{21}] \simeq \theta_{12}\bar{\theta}_{13}\bar{\theta}_{23}\sin(\bar{\delta}+\phi_1) \end{aligned}\right\} \text{Relevant for } \nu\mathrm{MSM}$$

$$I_2^{(3)} = \mathrm{Im}[\mathrm{W}_{23}\mathrm{V}^\star_{22}\mathrm{V}_{12}\mathrm{W}^\star_{13}] \simeq \bar{\theta}_{12}\theta_{13}\theta_{23}\sin(\delta-\phi_1)$$

CP INVARIANTS

- A generic expectation for the CP-asymmetry relevant for leptogenesis is

$$\Delta_{CP} = \sum_{\alpha,k} |Y_{\alpha k}|^2 \sum_{i,j} \mathrm{Im}[Y_{\alpha i} Y^*_{\alpha j} (Y^\dagger Y)_{ij}] f(M_i, M_j)$$

- In the limit of vanishing y_3

$$\begin{aligned}\Delta_{CP} = {} & y_1^2 y_2^2 (y_2^2 - y_1^2) \sum_{i,j} \mathrm{Im}[W^*_{1i} W_{1j} W^*_{2j} W_{2i}] f(M_i, M_j) \\ & + y_1 y_2 (y_2^2 - y_1^2) \left\{ \left[(y_1^2 - y_2^2) I_1^{(2)} + y_2^2 I_1^{(3)} \right] [f(M_1, M_2) - f(M_2, M_1)] \right. \\ & \left. - I_2^{(3)} [g(M_3) - g(M_2)] \right\}\end{aligned}$$

KINETIC EQUATIONS

- Starting from Raffelt-Sigl formalism

$$\dot{\rho}_+ = -i[H_{re}, \rho_+] + [H_{im}, \rho_-] - \frac{\gamma_N^a + \gamma_N^b}{2}\{Y^\dagger Y, \rho_+ - \rho_{\mathrm{FD}}\}$$
$$+ i\gamma_N^b \mathrm{Im}[\mathrm{Y}^\dagger \mu \mathrm{Y}]\rho_{\mathrm{FD}} + \mathrm{i}\frac{\gamma_{\mathrm{N}}^{\mathrm{a}}}{2}\{\mathrm{Im}[\mathrm{Y}^\dagger \mu \mathrm{Y}], \rho_+\},$$
$$\dot{\rho}_- = -i[H_{re}, \rho_-] + [H_{im}, \rho_+] - \frac{\gamma_N^a + \gamma_N^b}{2}\{Y^\dagger Y, \rho_-\}$$
$$+ \gamma_N^b \mathrm{Re}[\mathrm{Y}^\dagger \mu \mathrm{Y}]\rho_{\mathrm{FD}} + \frac{\gamma_{\mathrm{N}}^{\mathrm{a}}}{2}\{\mathrm{Re}[\mathrm{Y}^\dagger \mu \mathrm{Y}], \rho_-\},$$
$$\dot{\mu_\alpha} = -\mu_\alpha(\gamma_\nu^b \mathrm{Tr}[\mathrm{Y}\mathrm{Y}^\dagger \mathrm{I}_\alpha] + \frac{\gamma_\nu^{\mathrm{a}}}{\rho_{\mathrm{FD}}}\mathrm{Tr}[\mathrm{Re}[\mathrm{Y}^\dagger \mathrm{I}_\alpha \mathrm{Y}], \rho_+])$$
$$+ \frac{\gamma_\nu^a + \gamma_\nu^b}{\rho_{FD}}\mathrm{Tr}[\mathrm{Re}[\mathrm{Y}\mathrm{I}_\alpha \mathrm{Y}]\rho_- + \mathrm{i}\,\mathrm{Im}[\mathrm{Y}^\dagger \mathrm{I}_\alpha \mathrm{Y}]\rho_+]$$

KINETIC EQUATIONS

- Starting from Raffelt-Sigl formalism

$$\dot{\rho}_+ = -i[H_{re}, \;\ldots\; \frac{\gamma_N^b}{\ldots}\{Y^\dagger Y, \rho_+ - \rho_{\mathrm{FD}}\}$$

$$+i\gamma_N^b \mathrm{Im} \;\ldots\; {}^\dagger \mu \mathrm{Y}], \rho_+\},$$

$$\dot{\rho}_- = -i[H_{re}, \;\ldots\; \frac{\gamma_N^b}{\ldots}\{Y^\dagger Y, \rho_-\}$$

$$+\gamma_N^b \mathrm{Re}[\mathrm{Y}^\dagger \mu \mathrm{Y}]\rho_{\mathrm{FD}} + \frac{\gamma_N^a}{2}\{\mathrm{Re}[\mathrm{Y}^\dagger \mu \mathrm{Y}], \rho_-\},$$

$$\rho_\pm = \frac{\rho_N \pm \bar{\rho}_N}{2}$$

$$\dot{\mu}_\alpha = -\mu_\alpha(\gamma_\nu^b \mathrm{Tr}[\mathrm{Y}\mathrm{Y}^\dagger \mathrm{I}_\alpha] + \frac{\gamma_\nu^{\mathrm{a}}}{\rho_{\mathrm{FD}}}\mathrm{Tr}[\mathrm{Re}[\mathrm{Y}^\dagger \mathrm{I}_\alpha \mathrm{Y}], \rho_+])$$

$$+\frac{\gamma_\nu^a + \gamma_\nu^b}{\rho_{FD}}\mathrm{Tr}[\mathrm{Re}[\mathrm{Y}\mathrm{I}_\alpha \mathrm{Y}]\rho_- + \mathrm{i}\,\mathrm{Im}[\mathrm{Y}^\dagger \mathrm{I}_\alpha \mathrm{Y}]\rho_+]$$

KINETIC EQUATIONS

- Starting from Raffelt-Sigl formalism

$$\dot{\rho}_+ = -i[H_{re}, \rho_+] + [H_{im}, \rho_-] - \frac{\gamma_N^a + \gamma_N^b}{2}\{Y^\dagger Y, \rho_+ - \rho_{\mathrm{FD}}\}$$
$$+ i\gamma_N^b \mathrm{Im}[\mathrm{Y}^\dagger \mu \mathrm{Y}]\rho_{\mathrm{FD}} + \mathrm{i}\frac{\gamma_\mathrm{N}^\mathrm{a}}{2}\{\mathrm{Im}[\mathrm{Y}^\dagger \mu \mathrm{Y}], \rho_+\},$$

$$\dot{\rho}_- = -i[H_{re}, \rho_-] + [H_{im}, \rho_+] - \frac{\gamma_N^a + \gamma_N^b}{2}\{Y^\dagger Y, \rho_-\}$$
$$+\gamma_N^b \mathrm{Re} \ldots \rho_-\},$$

$$\dot{\mu}_\alpha = -\mu_\alpha(\gamma_\nu^b \ldots \mathrm{Y}], \rho_+])$$
$$+ \frac{\gamma_\nu^a + \ldots}{\rho_{FD}} \ldots \mathrm{Y}]\rho_+]$$

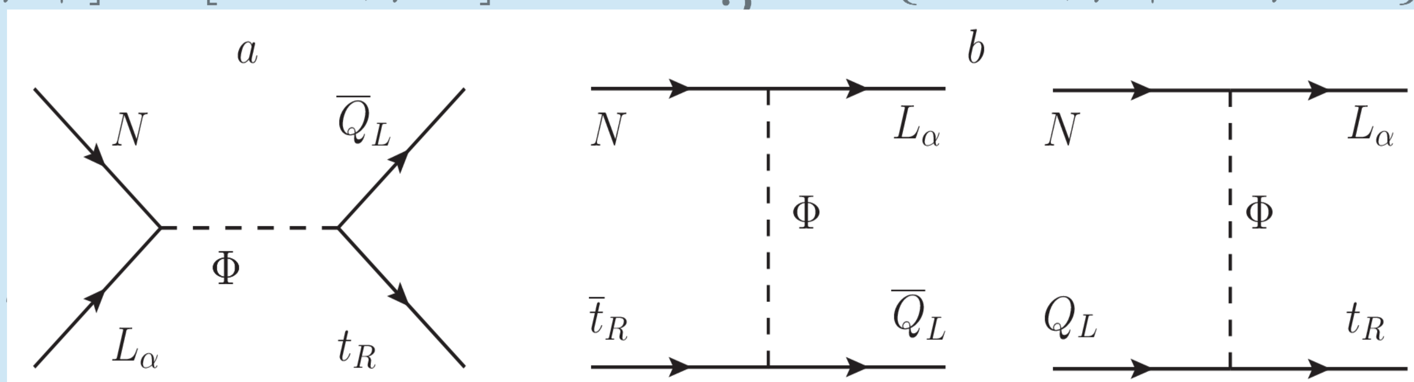
Chemical potential,
diagonal in the charged leptons basis

KINETIC EQUATIONS

- Starting from Raffelt-Sigl formalism

$$\dot{\rho}_+ = -i[H_{re}, \rho_+] + [H_{im}, \rho_-] - \frac{\gamma_N^a + \gamma_N^b}{2}\{Y^\dagger Y, \rho_+ - \rho_{\rm FD}\}$$

$$+i\gamma_N^b \mathrm{Im}$$



$$\dot{\rho}_- = -i[H_{re},$$

$$+\gamma_N^b \mathrm{Re}$$

$$\dot{\mu}_\alpha = -\mu_\alpha(\gamma$$

$$+\frac{\gamma_\nu^a +}{\rho_{FD}}\mathrm{Tr}[\mathrm{Re}[Y I_\alpha Y]\rho_- + \mathrm{i}\,\mathrm{Im}[Y^\dagger I_\alpha Y]\rho_+]$$

$$\gamma^b_{N,Q} = 2\gamma^a_{N,Q} = 2\gamma^b_{\nu,Q} = 4\gamma^a_{\nu,Q} = \frac{3}{16\pi^3}\frac{y_t^2 T^2}{k_0}$$

KINETIC EQUATIONS

- There is no analytical solution
- We try to solve equations perturbing in the mixing of V and W matrices

- Usual assumptions:
  - Neglecting non-linear effects
  - Average momentum approximation

KINETIC EQUATIONS

- There is no analytical solution
- We try to solve equations perturbing in the mixing of V and W matrices

- Usual assumptions:
  - Neglecting non-linear effects
  - Average momentum approximation

$$Tr[\mu](t) = \Sigma_{I_{CP}} I_{CP} A_{I_{CP}}(t)$$

$$I_{CP} = I_1^{(2)}, I_1^{(3)}, I_2^{(3)}, J_W$$

ANALYTICAL SOLUTION

$$A_{I_1^{(2)}}(t) = y_1 y_2 (y_2^2 - y_1^2)\left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right)\gamma_N^2 G_1(t),$$

$$A_{I_1^{(3)}}(t) = -y_1 y_2 (y_2^2 - y_1^2)\left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right)\gamma_N^2 G_2(t),$$

$$A_{I_2^{(3)}}(t) = y_1 y_2 \left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right)\gamma_N G_3(t),$$

$$A_{J_W}(t) = \gamma_1 \gamma_2 \left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right) G_{41}(t) - \frac{\gamma_N}{2\bar{\gamma}_N} G_{42}(t).$$

ANALYTICAL SOLUTION

$$A_{I_1^{(2)}}(t) = y_1 y_2 (y_2^2 - y_1^2) \left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right) \gamma_N^2 G_1(t),$$

$$A_{I_1^{(3)}}(t) = -y_1 y_2 (y_2^2 - y_1^2) \left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right) \gamma_N^2 G_2(t),$$

$$A_{I_2^{(3)}}(t) = y_1 y_2 \left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right) \gamma_N G_3(t),$$

$$A_{J_W}(t) = \gamma_1 \gamma_2 \left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right) G_{41}(t) - \frac{\gamma_N}{2\bar{\gamma}_N} G_{42}(t).$$

- the right yukawa dependence!
- **valid in the fast collision regime** $\mathbf{t} > \gamma_{\mathbf{i}}^{-\mathbf{1}}$

  provided that $\mathbf{t} < \gamma_{\mathbf{i}}^{-\mathbf{1}} \theta_{\mathbf{i3}}^{\mathbf{2}}$

ANALYTICAL SOLUTION

$$A_{I_1^{(2)}}(t) = y_1 y_2 (y_2^2 - y_1^2) \left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right) \gamma_N^2 G_1(t),$$

$$G_1(t) \equiv \left(e^{-\bar{\gamma}_2 t} - e^{-\bar{\gamma}_1 t}\right) \mathrm{Re}\left[i J_{20}(\Delta_{12}, -\Delta_{12}, t) + 2\Delta_v J_{201}(\Delta_{12}, -\Delta_{12}, t) \right.$$
$$\left. + \frac{1}{2} \sum_{k=1}^{2} (-1)^k e^{-\bar{\gamma}_k t} \mathrm{Re}\left[J_{210}(\Delta_{12}, -\Delta_{12}, t) \left(-2\Delta_v + i(2\bar{\gamma}_k - \gamma_1 - \gamma_2)\right)\right] \right.$$

$$J_{20}(\alpha_1, \alpha_2, t) \equiv \int_0^t dx_1 \; e^{i\frac{\alpha_1 x_1^3}{3}} \int_0^{x_1} dx_2 x_2 \; e^{i\frac{\alpha_2 x_2^3}{3}}$$

$$J_{210}(\alpha_1, \alpha_2, t) \equiv \int_0^t dx_1 \; e^{i\frac{\alpha_1 x_1^3}{3}} \int_0^{x_1} dx_2 x_2 \; e^{i\frac{\alpha_2 x_2^3}{3}}$$

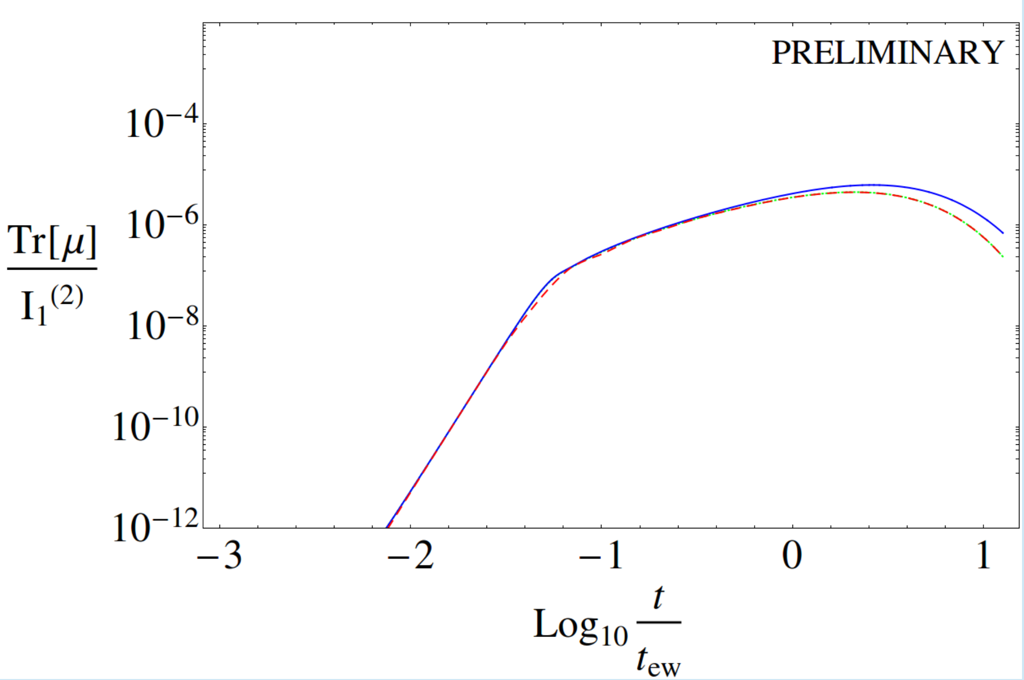
$$J_{201}(\alpha_1, \alpha_2, t) \equiv \int_0^t dx_1 x_1 \; e^{i\frac{\alpha_1 x_1^3}{3}} \int_0^{x_1} dx_2 \; e^{i\frac{\alpha_2 x_2^3}{3}}$$

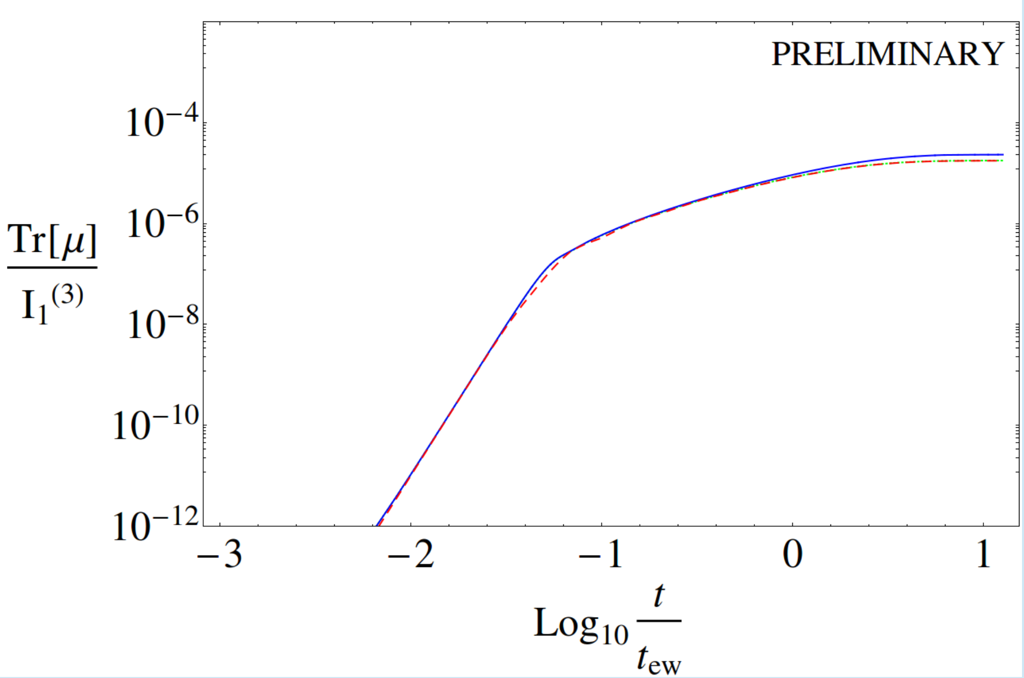
NUMERICAL CHECK

- We solve equations numerically and compare with our analytic solution

NUMERICAL CHECK

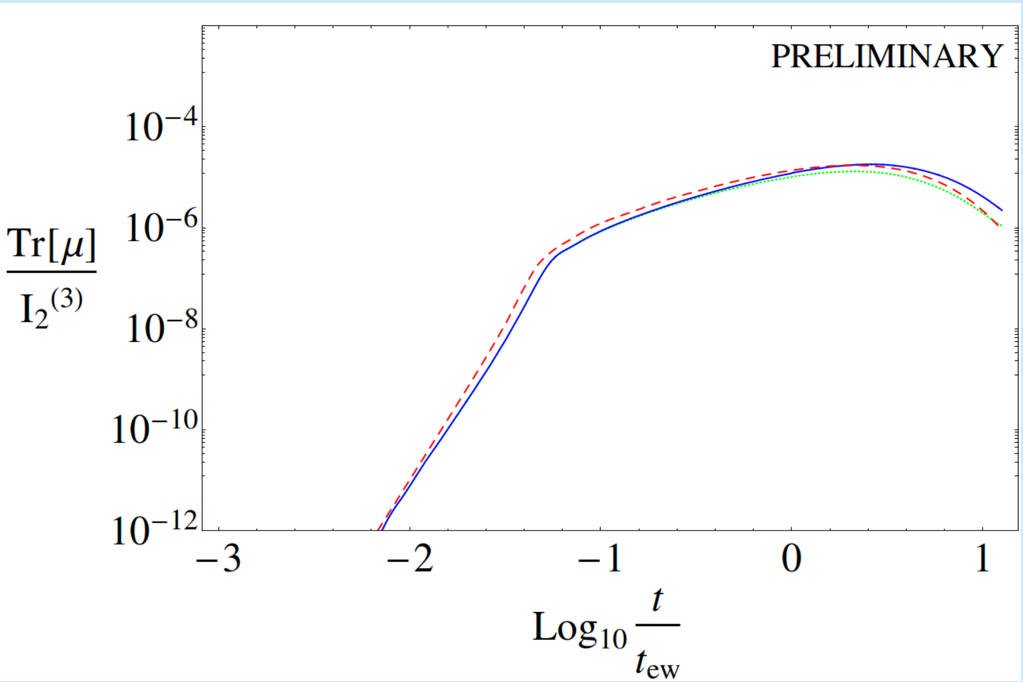
- $A_{I_1^{(2)}}(t)$
- $A_{I_1^{(3)}}(t)$

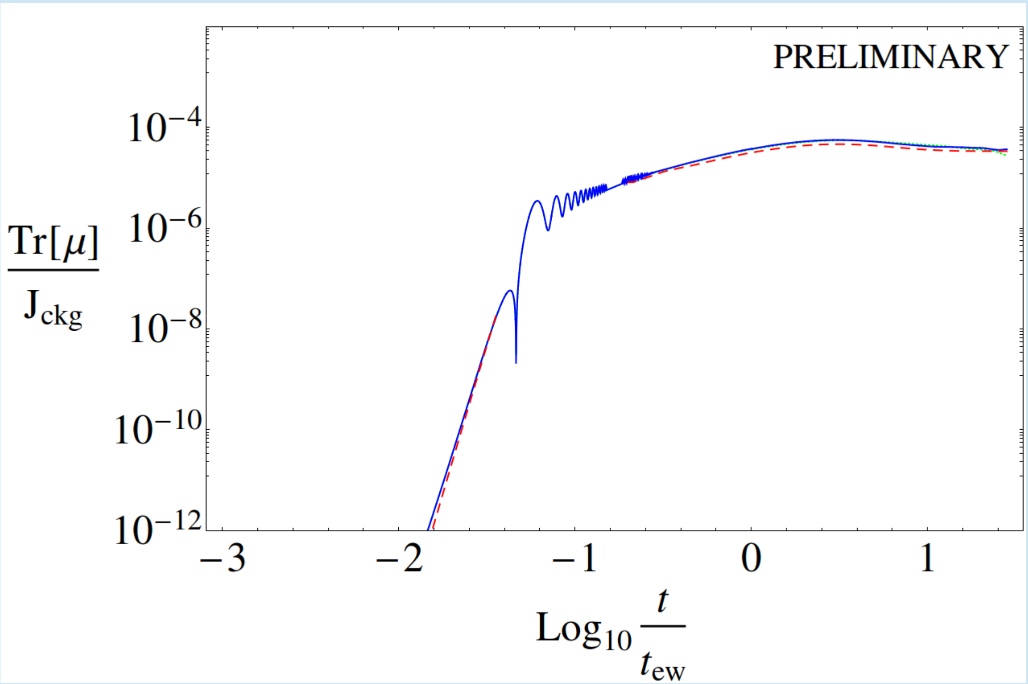




NUMERICAL CHECK

- $A_{I_3^{(2)}}(t)$
- $A_{J_W}(t)$





BARYON ASYMMETRY

- Measured baryon asymmetry

$$Y_B^{exp} = \frac{n_B - \overline{n}_B}{s} \simeq 8.6(1) \times 10^{-11}$$

- Transfer of lepton asymmetry

$$Y_B = -\frac{28}{79} Y_L; \quad Y_L = \frac{90}{\pi^4 g_\star} Tr[\mu]; \quad g_* = 106.75$$

$$\Rightarrow \quad Y_B \simeq 3 \times 10^{-3} Tr[\mu(t_{\mathrm{EW}})]$$

BARYON ASYMMETRY

- Measured baryon asymmetry

$$Y_B^{exp} = \frac{n_B - \overline{n}_B}{s} \simeq 8.6(1) \times 10^{-11}$$

- Transfer of lepton asymmetry

$$Y_B = -\frac{28}{79} Y_L; \quad Y_L = \frac{90}{\pi^4 g_\star} Tr[\mu]; \quad g_* = 106.75$$

$$\Rightarrow \quad Y_B \simeq 3 \times 10^{-3} Tr[\mu(t_{\mathrm{EW}})]$$

- Simple exercise:
  Naive seesaw scaling in $\nu\mathrm{MSM}$ model:

$$\mathrm{y}_1^2 = 2\frac{\sqrt{\Delta_{sol}} M_1}{v^2}, \quad y_2^2 = 2\frac{\sqrt{\Delta_{atm}} M_2}{v^2}$$

$$\mathrm{Tr}[\mu](t_{EW}) \simeq 7 \times 10^{-10} \frac{I_1^{(2)} - 2 I_1^{(3)}}{|\Delta M_{12}^2(\mathrm{GeV}^2)|^{2/3}}$$

PARAMETER SCAN

- We have used Casas-Ibarra parameters

$$Y = -iU^{\star}_{PMNS}\sqrt{m_{light}}R(z_{ij})^T\sqrt{M}\frac{\sqrt{2}}{v}$$

- We allow order 10 theoretical uncertainty

PARAMETER SCAN
$\nu\mathrm{MSM}$

- First we consider the case of $\nu\mathrm{MSM}$;where M_3 is effectively decoupled

$$m_{3(1)} = 0, \quad z_{i3} = 0, \quad R \to R(z_{ij})(P)$$

$$P \quad \text{is} \;\; 123 \to 312 \quad \text{permutation} \quad \text{matrix}$$

for NH only

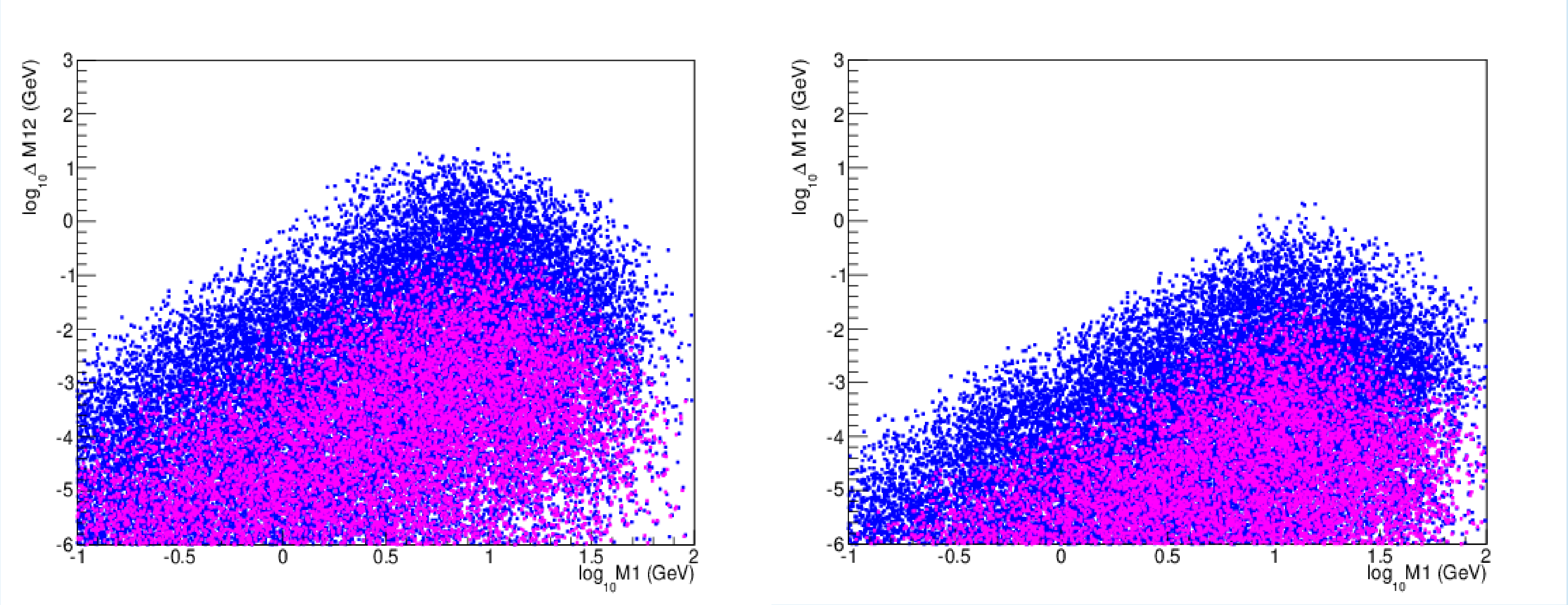
7 free parameters:
3 heavy masses, one complex angle and 3 phases from PMNS matrix

PARAMETER SCAN

νMSM

IH

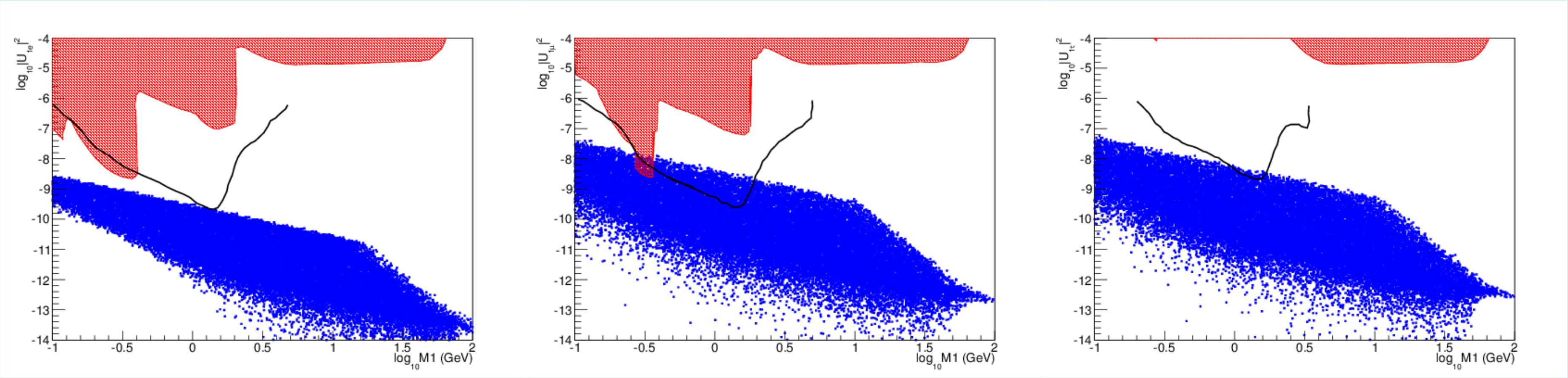
NH



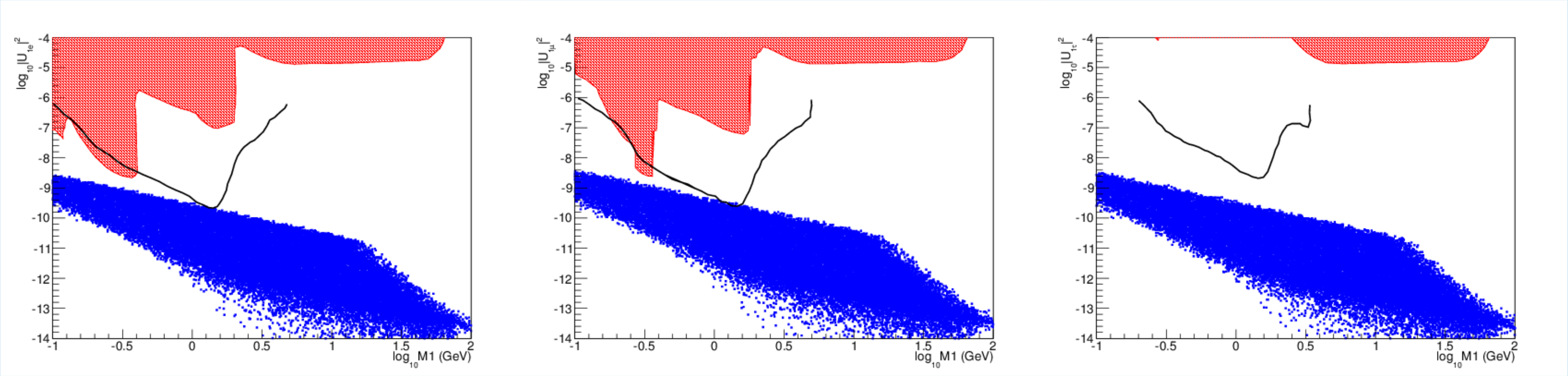
PARAMETER SCAN

νMSM

IH



NH



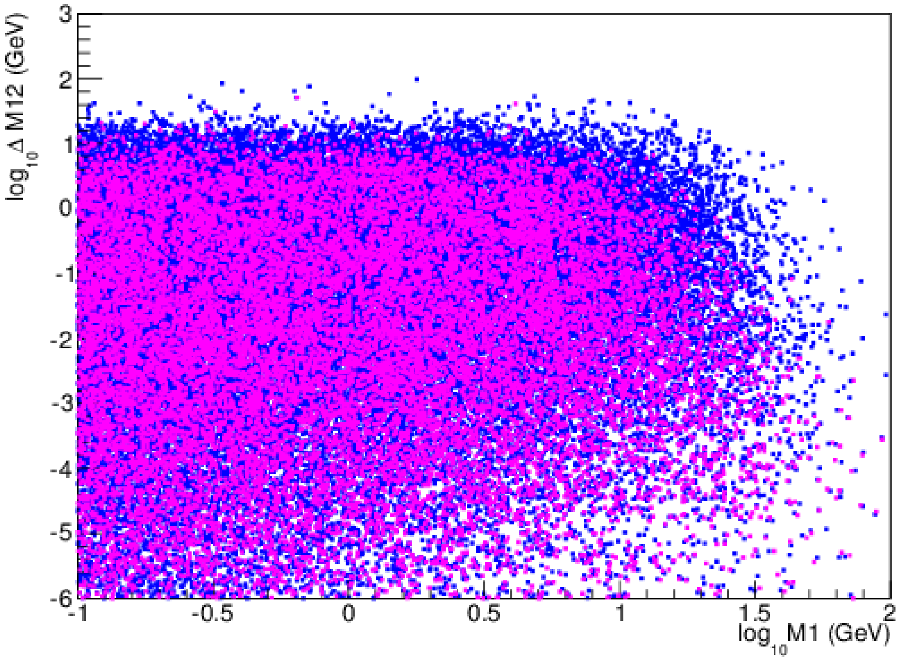
PARAMETER SCAN
FULL PARAMETER SPACE

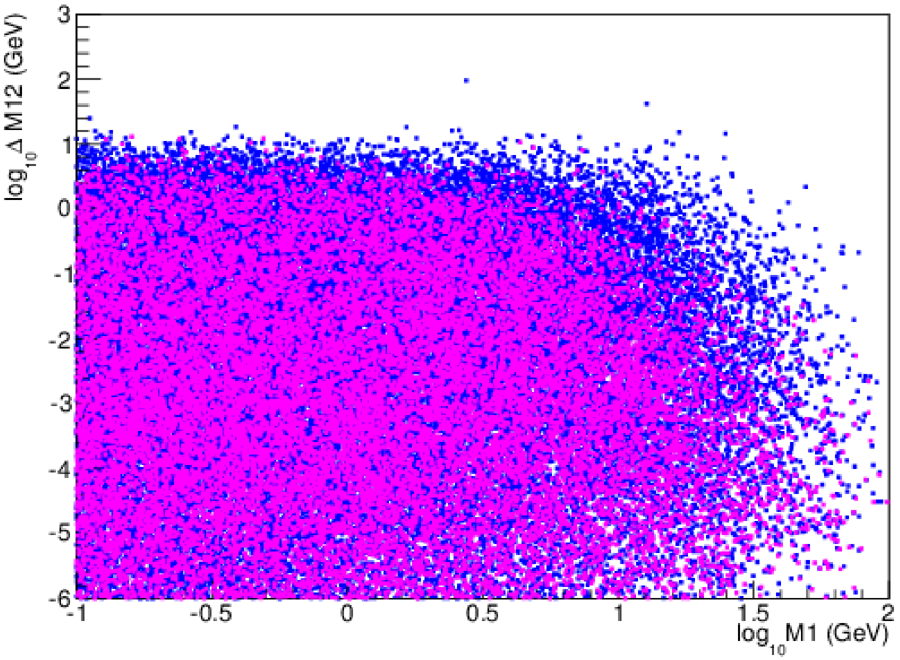
- In the 3 sterile neutrino case there are 5 more free parameters: the lightest neutrino mass and 2 complex angles.

PARAMETER SCAN
FULL PARAMETER SPACE

IH

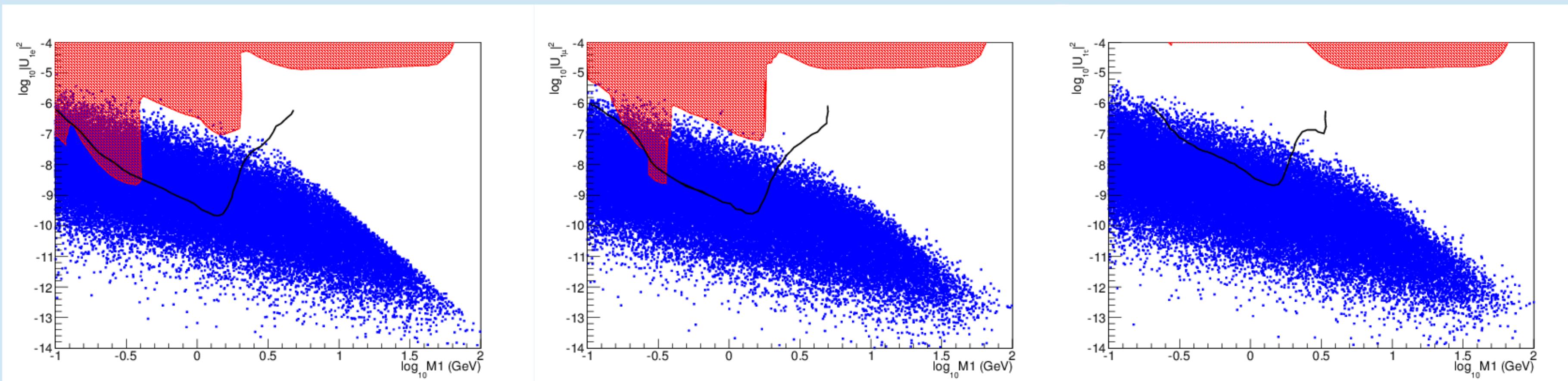
NH



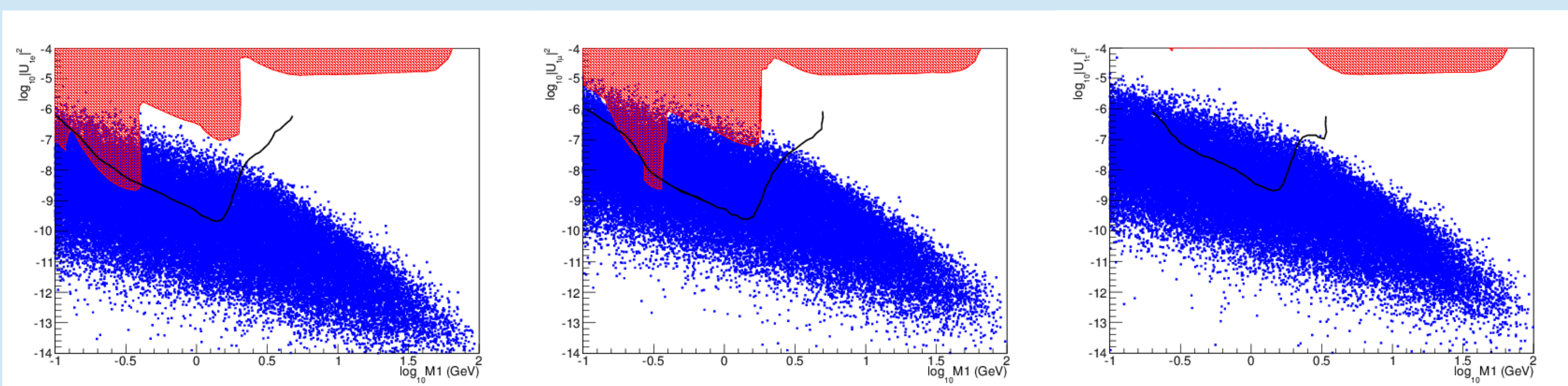


PARAMETER SCAN
FULL PARAMETER SPACE

IH



NH



PARAMETER SCAN

- We do not find direct correlations between baryon asymmetry with delta, neutrinoless double beta decay amplitude, or, in the case of ASR, with the lightest neutrino mass.

CONCLUSION

- We have studied the mechanism of leptogenesis in a low-scale seesaw model.
- We have developed an analytical approximation to the quantum kinetic equations which works both in the weak and strong washout regimes (provided mixings are small).
- We have used this analytical solution to scan the full parameter space.
- No direct correlations are found between Y_B and delta or the neutrinoless double beta decay rate, nor the lightest neutrino mass.
- We are still trying to clarify the degeneracy requirement.

CONCLUSION

- We have studied the mechanism of leptogenesis in a low-scale seesaw model.
- We have developed an analytical approximation to the quantum kinetic equations which works both in the weak and strong washout regimes (provided mixings are small).
- We have used this analytical solution to scan the full parameter space.
- No direct correlations are found between Y_B and delta or the neutrinoless double beta decay rate, nor the lightest neutrino mass.
- We are still trying to clarify the degeneracy requirement.

THANK YOU

BACKUP SLIDES

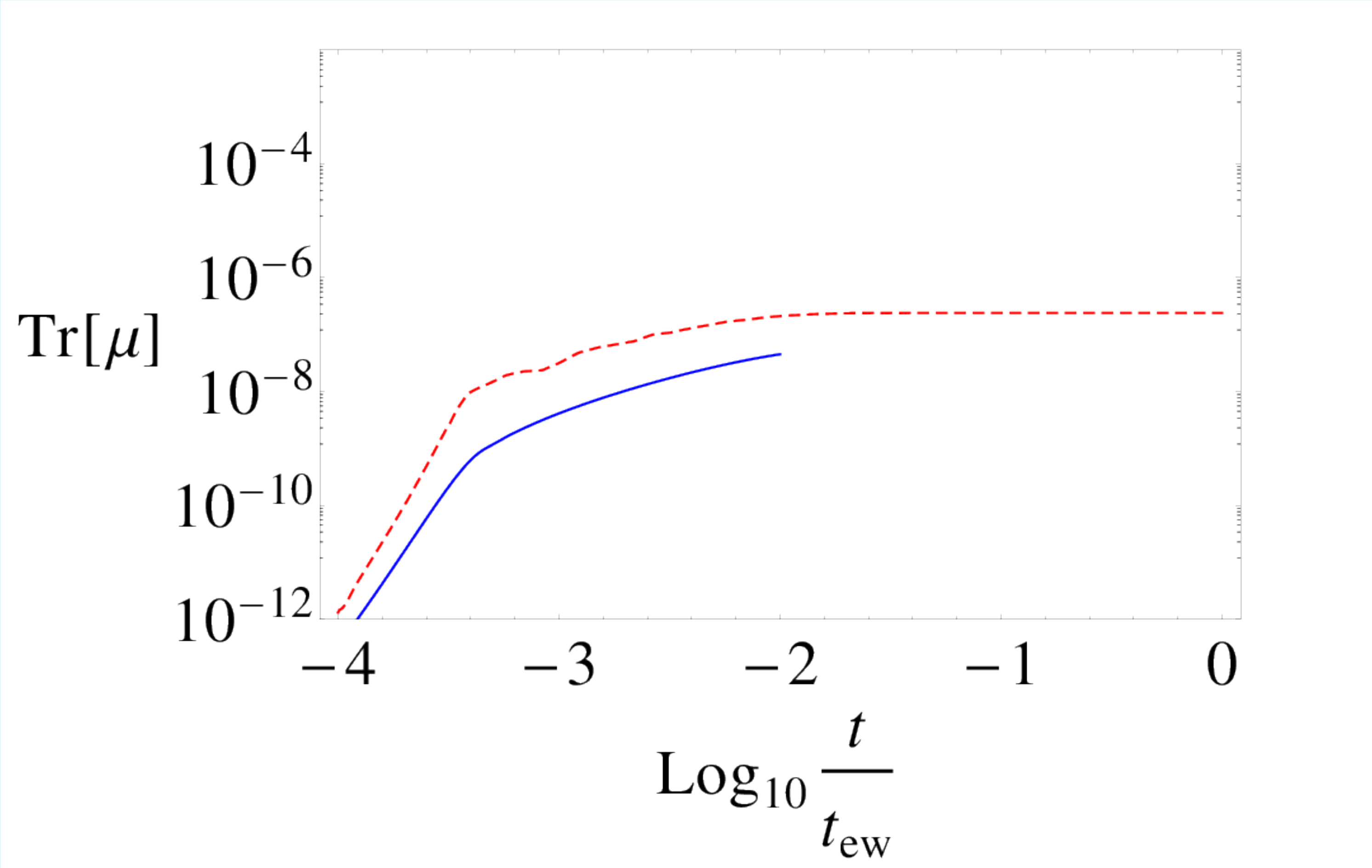
$$\rho_{\pm} = \frac{\rho_N \pm \bar{\rho}_N}{2}$$

$$\gamma_N^{a,b} = \frac{1}{2k_0} \sum_i \int_{\mathbf{p_1},\mathbf{p_2},\mathbf{p_3}} \rho_{eq} |M_{N(\nu),i}|^2 (2\pi)^4 \delta(k + p_1 - p_2 - p_3)|$$

$$r_{\pm} = \frac{\sum_i \int_{\mathbf{p_1},\mathbf{p_2},\mathbf{p_3}} \rho_{\pm}(\mathbf{p_1}) |M_i^{(a)}|^2 (2\pi)^4 \delta(k + p_1 - p_2 - p_3)|}{\sum_i \int_{\mathbf{p_1},\mathbf{p_2},\mathbf{p_3}} \rho_{eq}(\mathbf{p_1}) |M_i^{(a)}|^2 (2\pi)^4 \delta(k + p_1 - p_2 - p_3)|}$$

In the case of dominant top quark scattering:

$$\gamma_{N,Q}^b = 2\gamma_{N,Q}^a = 2\gamma_{\nu,Q}^b = 4\gamma_{\nu,Q}^a = \frac{3}{16\pi^3} \frac{y_t^2 T^2}{k_0}$$



10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$\mathrm{Tr}[\mu]$
-4
-3
-2
-1
0
$\mathrm{Log}_{10}\frac{t}{t_{\mathrm{ew}}}$