Lepton Flavour Violation and θ_{13} in Minimal Resonant Leptogenesis

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Baryon Asymmetry

- **Baryon Asymmetry of the Universe (BAU)**

$$\eta_B = \frac{n_B}{n_\gamma} = (6.2 \pm 0.15) \cdot 10^{-10}$$

Cosmic Microwave Background

- **Necessary Conditions (Sakharov '67)**
  - Baryon Number B Violation
  - C and CP Violation
  - Out of Thermal Equilibrium Dynamics

- **Satisfied in Standard Model but generated Baryon Asymmetry too small**

Seesaw Type I

- **Standard Non-SUSY Seesaw with Singlet Right-handed Neutrinos**

$$-L_{Y,M} = \bar{L}\,\Phi\,Y^{l}\,l_R + \bar{L}\,\tilde{\Phi}\,Y^{\nu}\,\nu_R + \bar{\nu}_R^{C}\,M_R\,\nu_R + h.c.$$

- **Light Neutrino Masses**

$$m_\nu = \frac{-v^2}{2}\,Y_\nu^T\,M_R^{-1}\,Y_\nu$$

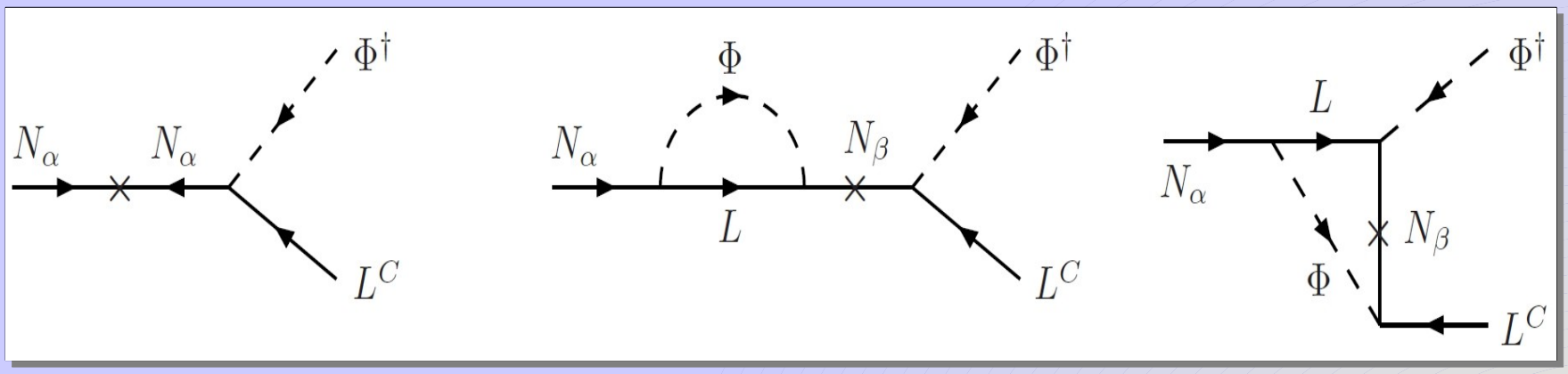
- **Parameter Regimes**
  - Super-heavy $\quad \nu_R \sim 10^{14}\ \mathrm{GeV} \quad \rightarrow Y_\nu \sim 1$
  - EW Scale $\quad \nu_R \sim 10^{2}\ \mathrm{GeV} \quad \rightarrow Y_\nu \sim 10^{-6}$
  - EW Scale + Cancellation $\quad \nu_R \sim 10^{2}\ \mathrm{GeV} \quad \rightarrow Y_\nu < 10^{-2}$

$$Y_\nu = \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha\, y_1 & \alpha\, y_2 & \alpha\, y_3 \\ \beta\, y_1 & \beta\, y_2 & \beta\, y_3 \end{pmatrix} \quad \text{and} \quad \frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0 \quad \Rightarrow m_\nu = 0$$

Buchmüller, Greub '91
Kersten, Smirnov '07

Thermal Leptogenesis

- **Baryogenesis through Leptogenesis**
  (Fukugita, Yanagida, '86)
  - Out-of-equilibrium decays of heavy Majorana neutrinos violating $L \rightarrow$ Lepton Asymmetry

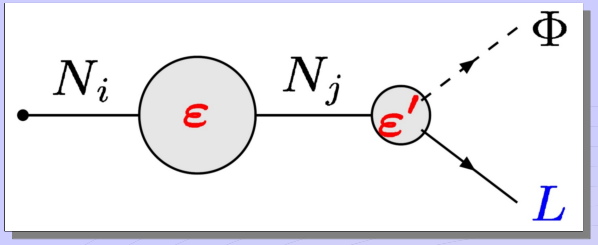


  - Conversion into baryon asymmetry through sphaleron processes violating $(B+L)$
  - Generally considered: Hierarchical heavy neutrinos with $M_1 > 10^9$ GeV

Resonant Leptogenesis

- **Lepton asymmetry dominated by self-energy contribution ε for**

$$|m_{N_1} - m_{N_2}| \ll m_{N_{1,2}}$$



$$\delta_{il} = \frac{\Gamma_{il} - \Gamma_{il}^C}{\Gamma_{N_i}} = \sum_j \frac{\mathrm{Im}\left[\left(Y_\nu^+ Y_\nu\right)_{ij}\left(Y_\nu^+\right)_{il}\left(Y_\nu\right)_{jl}\right]}{\left(Y_\nu^+ Y_\nu\right)_{ii}\left(Y_\nu^+ Y_\nu\right)_{jj}} \frac{\Gamma_{N_j}}{m_{N_j}} \frac{\left(m_{N_i}^2 - m_{N_j}^2\right) m_{N_i} \Gamma_{N_j}}{\left(m_{N_i}^2 - m_{N_j}^2\right)^2 + m_{N_i}^2 \Gamma_{N_j}^2}$$

$$\Gamma_{N_i} = \frac{\left(Y_\nu^+ Y_\nu\right)_{ii}}{8\pi} m_{N_i}$$

- ***O*(1) Lepton asymmetry in resonance** (Pilaftsis '97)

$$|m_{N_1} - m_{N_2}| \approx 1/2\,\Gamma_{N_{1,2}}$$

$$\frac{\mathrm{Im}\left(Y_\nu^+ Y_\nu\right)_{ij}^2}{\left(Y_\nu^+ Y_\nu\right)_{ii}\left(Y_\nu^+ Y_\nu\right)_{jj}} \approx 1$$

Resonant Leptogenesis

- **Number Densities, Boltzmann Equations**

$$\frac{d\,\delta\eta_{N_i}}{dz} = -\frac{z}{n_\gamma H}\left(\frac{\eta_{N_i}}{\eta_N^{\mathrm{eq}}} - 1\right)\gamma_{L\Phi}^{N_i} \qquad z = \frac{M_N}{T}$$

$$\frac{d\,\eta_{L_l}}{dz} = \frac{z}{n_\gamma H}\left[\sum_{i=1}^{3}\left(\frac{\eta_{N_i}}{\eta_N^{\mathrm{eq}}} - 1\right)\delta_{il}\gamma_{L\Phi}^{N_i} - \frac{2}{3}\eta_{L_l}\sum_{k=e,\mu,\tau}\left(\gamma_{L_k^C\Phi^+}^{L_l\Phi} + \gamma_{L_k\Phi}^{L_l\Phi}\right) - \frac{2}{3}\sum_{k=e,\mu,\tau}\eta_{L_k}\left(\gamma_{L_l^C\Phi^+}^{L_k\Phi} - \gamma_{L_l\Phi}^{L_k\Phi}\right)\right]$$

  - Dominant contribution from real intermediate ν_R states

Resonant Leptogenesis

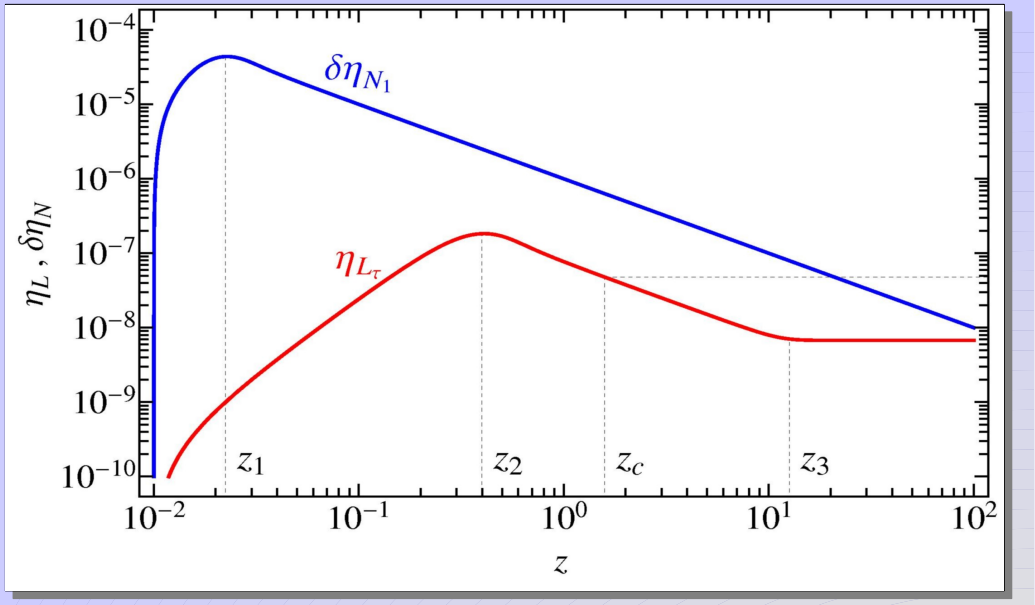
- **Number Densities, Boltzmann Equations**

$$\frac{d\,\delta\eta_{N_i}}{dz} = \frac{K_1(z)}{K_2(z)}\left(1+\left(1-\frac{\Gamma_{N_i}}{H}z\right)\delta\eta_{N_i}\right)$$

$$\frac{d\,\eta_{L_l}}{dz} = z^3 K_1(z)\sum_{\alpha=1}^{3}\left(\delta_{il}\,\delta\eta_{N_i} - \frac{2}{3}B_{il}\,\eta_{L_l}\right)$$

$$\delta\eta_{N_i} = \eta_{N_i}/\eta_N^{\mathrm{eq}} - 1$$

$$B_{il} = (\Gamma_{il} + \Gamma_{il}^C)/\Gamma_{N_i}$$



- **Strong Washout**

$$z_c > z_2 = 2\max\left(B_{il}K_{N_i}\right)^{-1/3}, \quad K_{N_i} = \frac{\Gamma_{N_i}}{H}$$

- **Baryon Asymmetry** (independent of initial conditions)

$$\eta_B \approx -\frac{28}{51}\frac{1}{27}\frac{3}{2}\sum_{l=e,\mu,\tau}\frac{\delta_l}{K_l \min\left(z_c, z_3^l\right)}$$

$$\delta_l = \sum_{i=1}^{3}\delta_{il}, \quad K_l = \sum_{i=1}^{3} B_{il}K_{N_i}$$

Flavoured Resonant Leptogenesis

- **Anti-Seesaw Mechanism** (Mohapatra, Valle '86; Pilaftsis '05)
  → electroweak scale heavy neutrinos
  → generate light neutrino masses ≈ 0.1 eV through breaking of flavour symmetry

$$SO(3) \to U(1)_{L_e+L_\mu} \times U(1)_{L_\tau}$$

$$M_R = M_N (1_3 + \Delta m_N)$$
$$M_N \approx 100 - 500\,\mathrm{GeV}$$

$$Y_\nu = \begin{pmatrix} \epsilon_e & a_e e^{-i\pi/4} & a_e e^{i\pi/4} \\ \epsilon_\mu & a_\mu e^{-i\pi/4} & a_\mu e^{i\pi/4} \\ \epsilon_\tau & \kappa_1 e^{-i\gamma_1} & \kappa_2 e^{i\gamma_2} \end{pmatrix}$$

- SO(3) breaking parameters

$$a_{e,\mu} \approx 10^{-2}, \quad \kappa_i \approx 10^{-4}, \quad \epsilon_{e,\mu,\tau} \approx 10^{-7}, \quad \Delta m_N \approx 10^{-10}$$

→ **Resonant τ Leptogenesis**
large e, μ Yukawa couplings, τ lepton number approx. protected

Minimal Resonant Leptogenesis

- **Radiative generation of heavy neutrino mass splitting**
  Radiative Resonant Leptogenesis (Gonzalez Felipe et al., Turzynski, '04)
- **Universality at GUT scale**

$$M_R = \mathrm{diag}(M_N, M_N, M_N)$$

- **RG Evolution**

$$\Delta M_N \approx -\frac{M_N}{8\pi^2} \ln\left(\frac{M_{\mathrm{GUT}}}{M_N}\right) \mathrm{Re}\left(Y_\nu^+ Y_\nu\right)$$

Generation of correct heavy neutrino mass differences $\approx 10^{-10}$ in **RτL**

Neutrino Mass Spectrum

- **Three quasi-degenerate heavy Majorana neutrinos**

$$M_{N_1} \approx M_{N_2} \approx M_{N_3} \approx 100-500 \text{ GeV}, \quad \Delta M_N \approx \Gamma_{N_i} \approx 10^{-8} \text{ GeV}$$

- **Three hierarchical light Majorana neutrinos**

$$m_\nu = \frac{-v^2}{2} Y_\nu^T M_R^{-1} Y_\nu = \frac{v^2}{2 M_N} \begin{pmatrix} \delta m_N a_e^2 - \epsilon_e^2 & \delta m_N a_e a_\mu - \epsilon_e \epsilon_\mu & -\epsilon_e \epsilon_\tau \\ \delta m_N a_e a_\mu - \epsilon_e \epsilon_\mu & \delta m_N a_\mu^2 - \epsilon_\mu^2 & -\epsilon_\mu \epsilon_\tau \\ -\epsilon_e \epsilon_\tau & -\epsilon_\mu \epsilon_\tau & -\epsilon_\tau^2 \end{pmatrix}$$

$$\delta m_N = 2(\Delta m_N)_{23} + i[(\Delta m_N)_{33} - (\Delta m_N)_{22}]$$

→ massless lightest neutrino
→ **normal** or **inverted** mass hierarchy

$$\Delta m_{31}^2 \approx \pm 2 \cdot 10^{-3} \text{ eV}^2$$

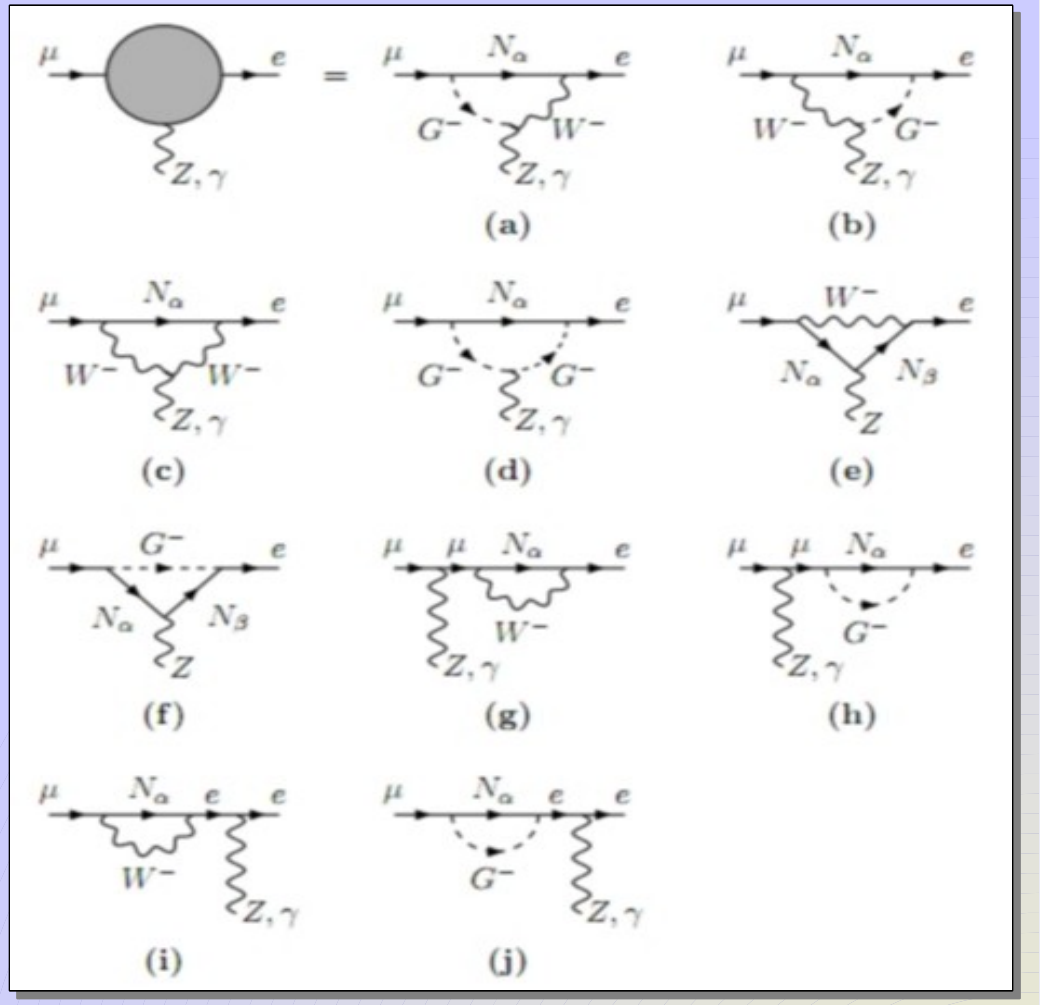
- **Invert seesaw formula to determine Yukawa parameters** e.g. $(m_\nu)_{ee} = \frac{v^2}{2 M_N}\left(\delta m_N a_e^2 - \epsilon_e^2\right)$ (0ν2β mass)

Lepton Flavor Violating Processes

- $\mu \to e\gamma$

$$\mathrm{Br}(\mu \to e\gamma) \approx \frac{\alpha_w^3 s_w^3}{1024\pi^2} \frac{m_\mu^4}{m_W^2} \frac{m_\mu}{\Gamma_\mu} \left(\frac{v^2 (Y_\nu Y_\nu^+)_{\mu e}}{M_N^2} \right)^2$$
$$\approx 9 \cdot 10^{-4} \frac{|a_e|^2 |a_\mu|^2 v^4}{M_N^4}$$

Observable rates for consistent values of τ–Yukawa couplings κ_i



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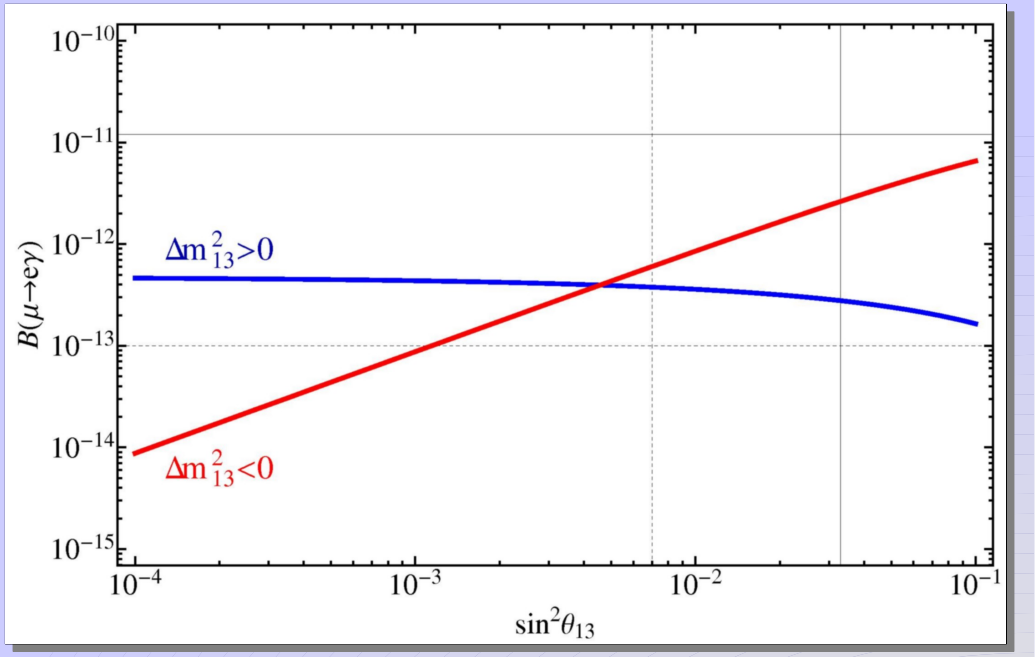

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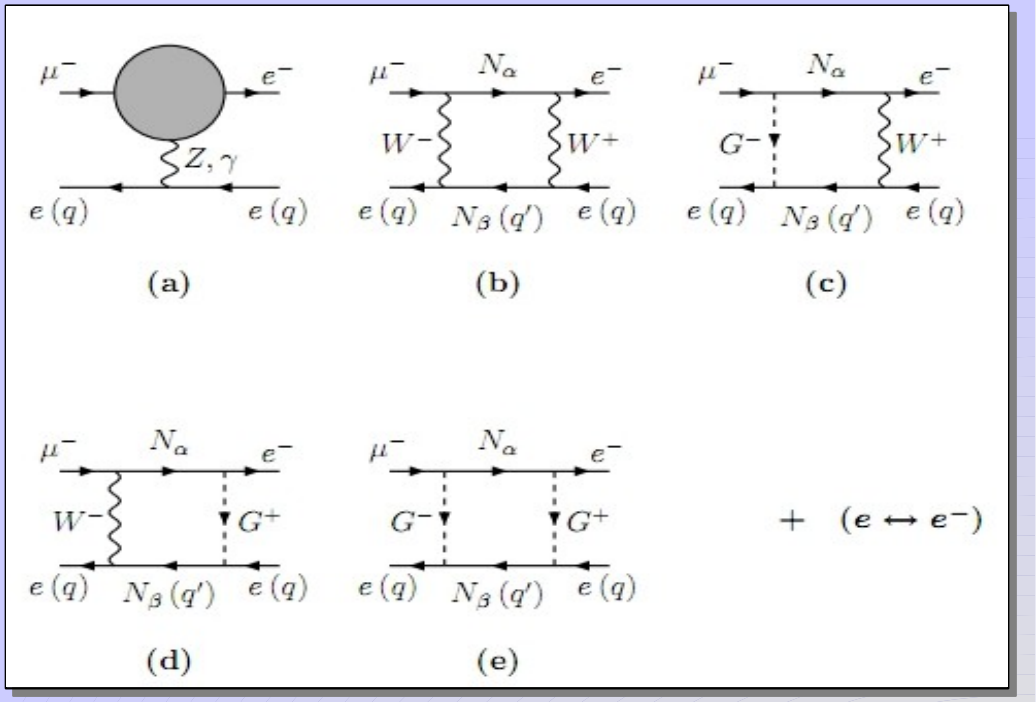


- **Coherent μ–e conversion in nuclei**

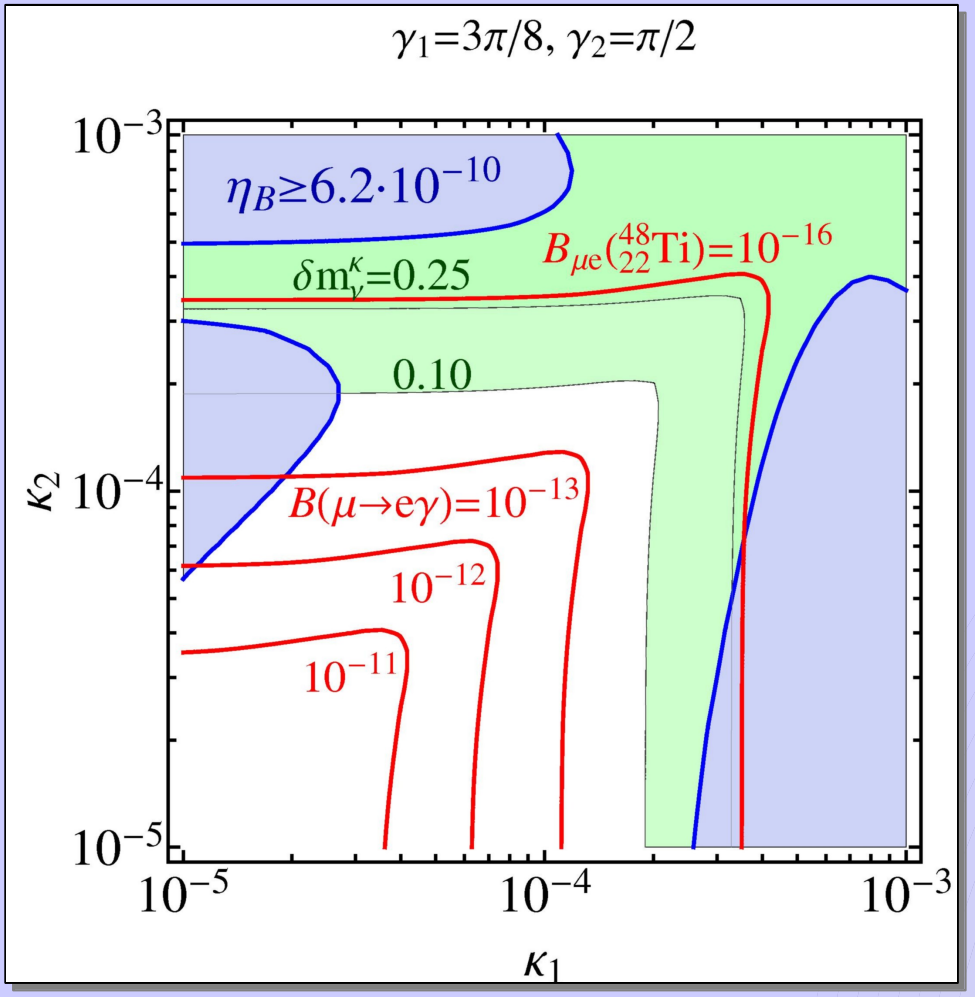
$$\mathrm{R}(\mu \to e, {}^N_Z\mathrm{X}) = \frac{\Gamma(\mu + {}^N_Z\mathrm{X} \to e + {}^N_Z\mathrm{X})}{\Gamma(\mu + {}^N_Z\mathrm{X} \to \mathrm{capture})} \approx 0.1 \times \mathrm{Br}(\mu \to e\gamma) \quad \text{for} \quad m_N \approx 100 \ \mathrm{GeV}$$

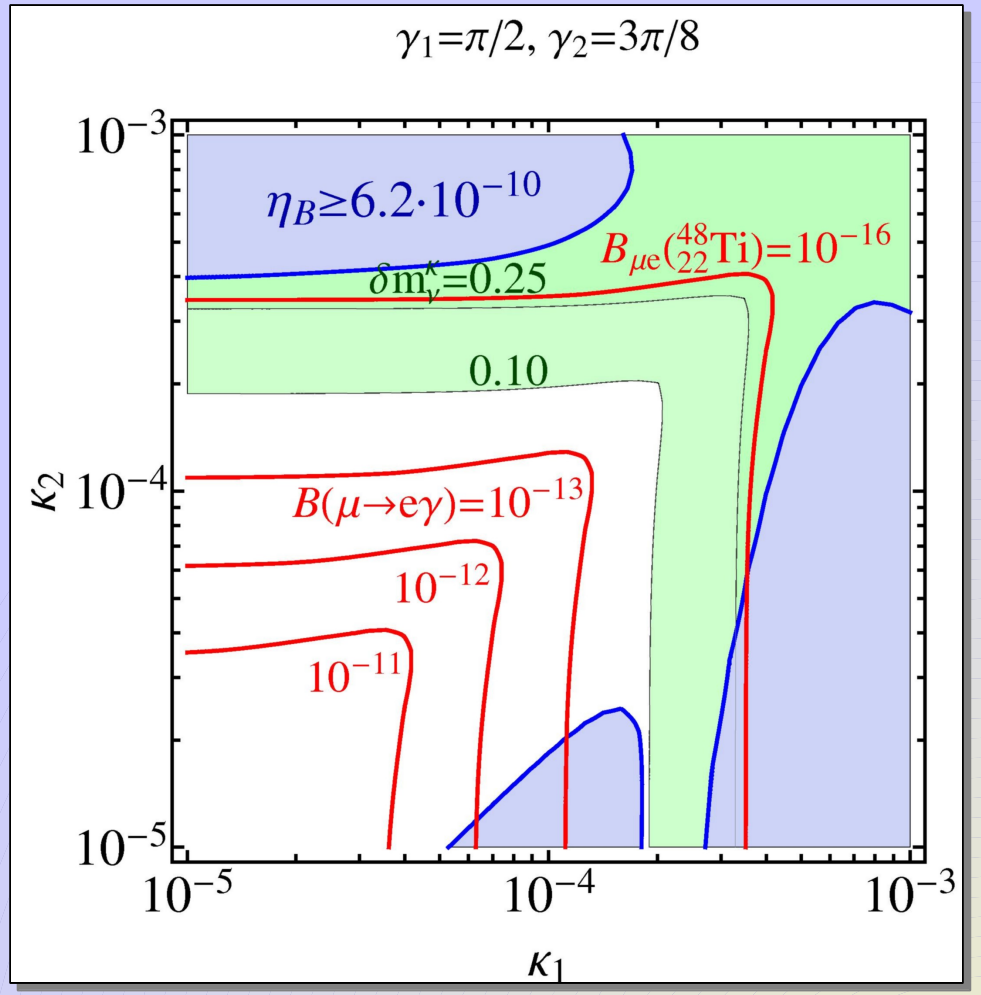
- ***τ–e and τ–μ* flavor changing processes**

$\to$ suppressed due to small τ neutrino Yukawa coupling κ_i

Viable Parameter Space

- **Normal light neutrino mass hierarchy**

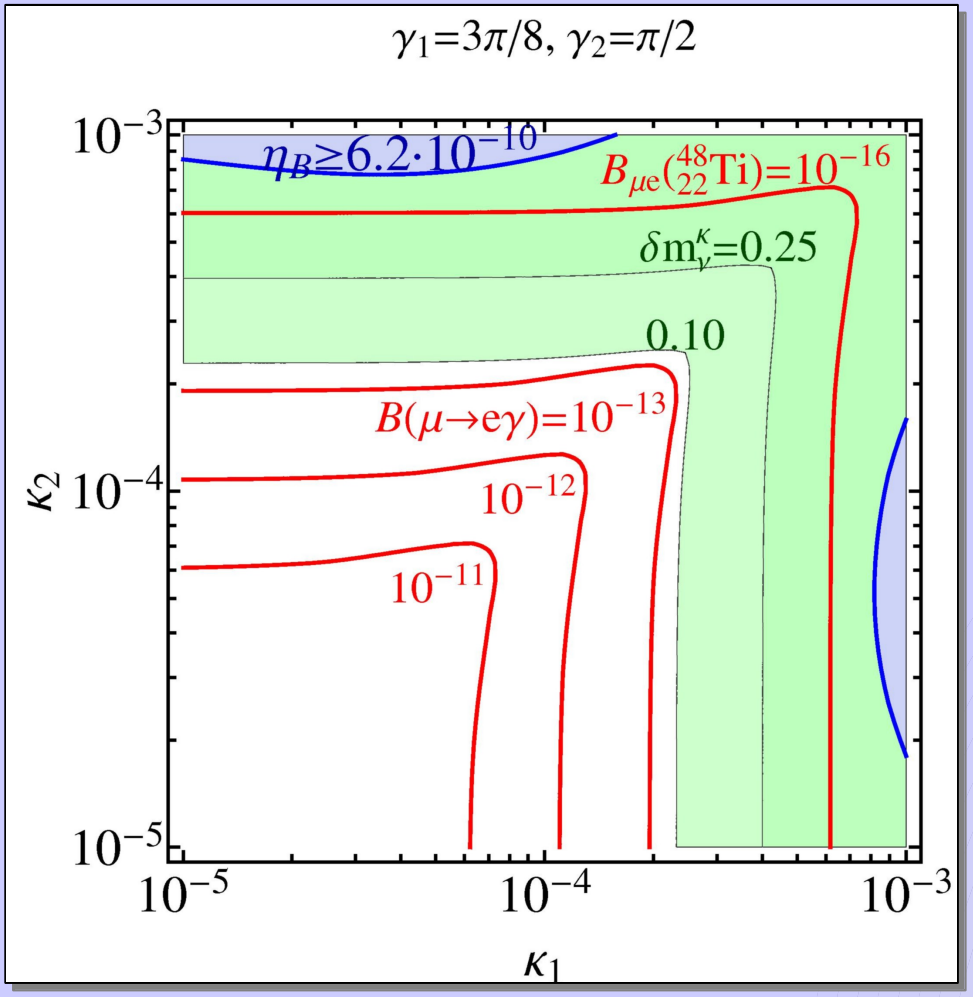


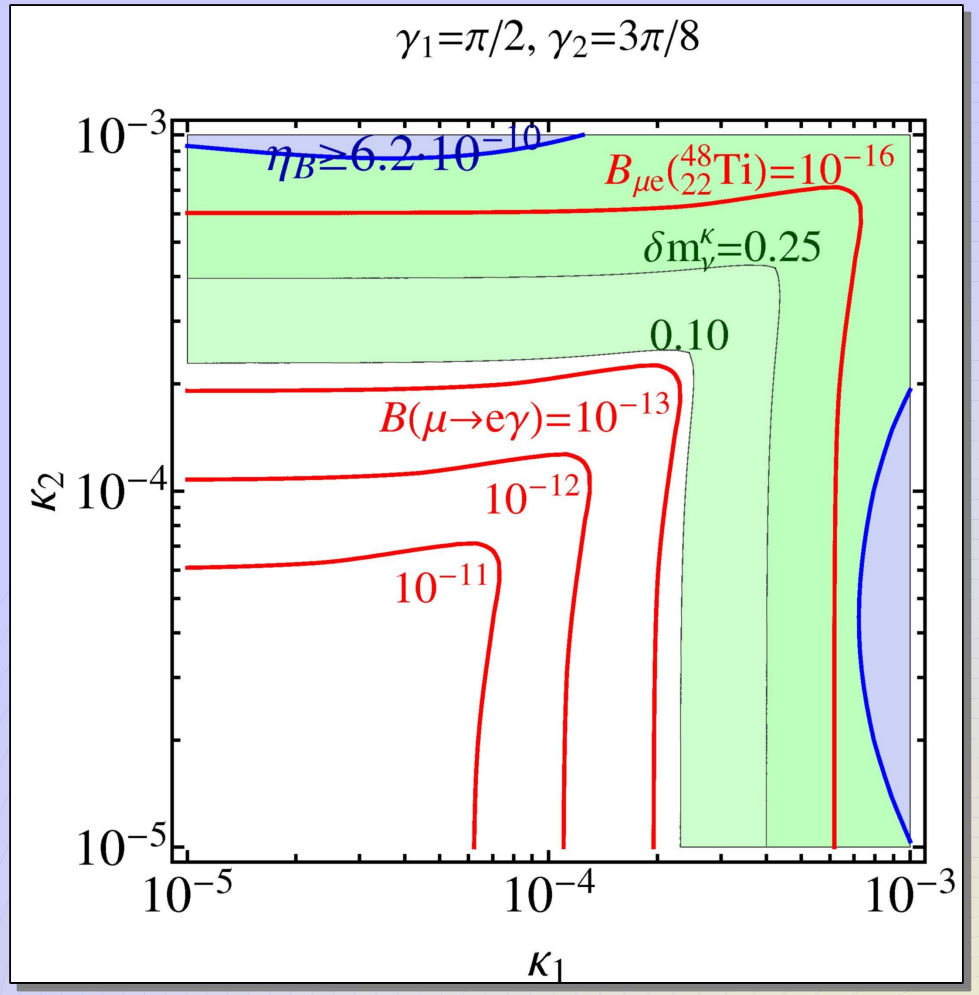


- **Successful leptogenesis and testable LFV processes**

Viable Parameter Space

- **Inverse light neutrino mass hierarchy**





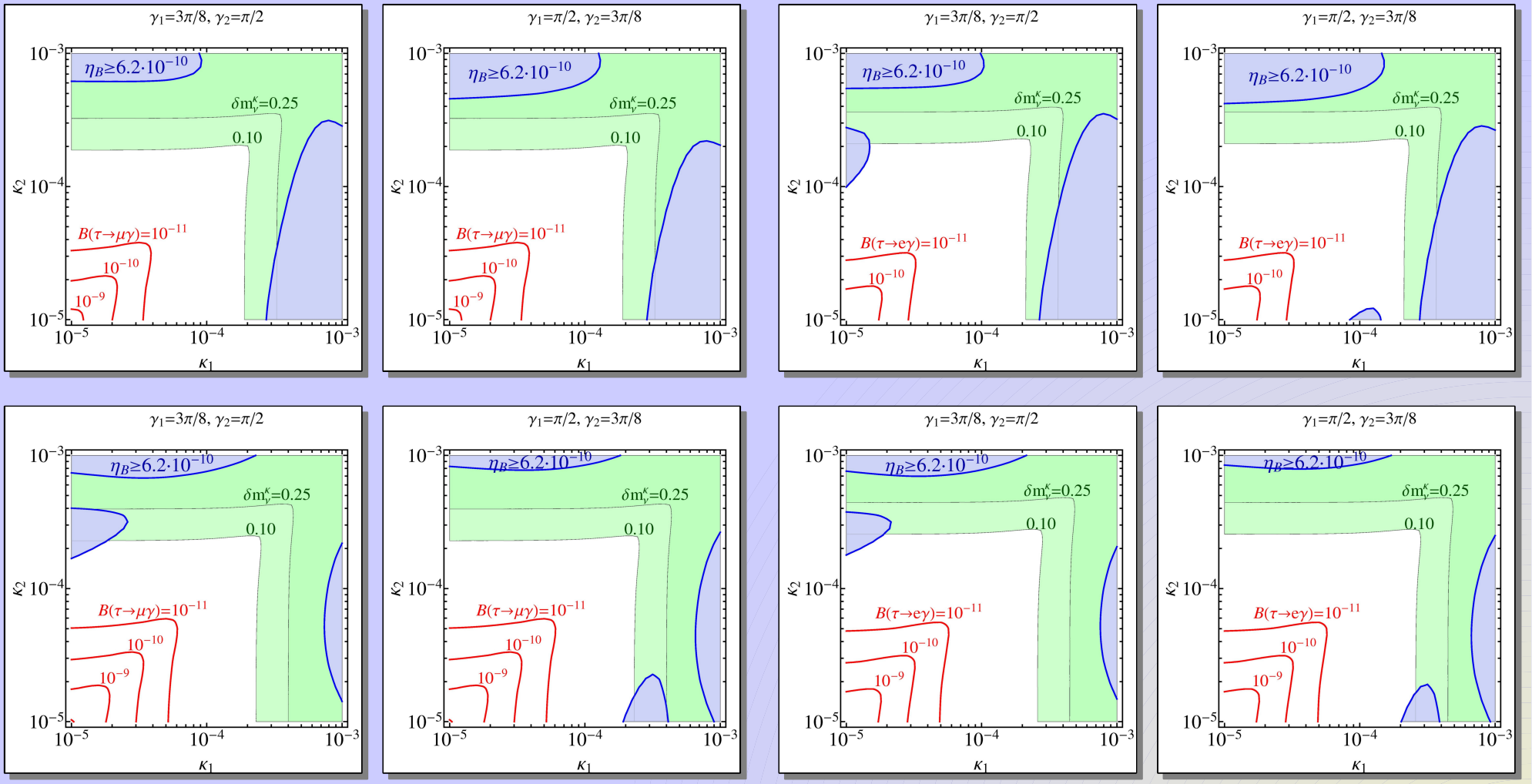
- **Difficult to achieve large LFV rates and successful leptogenesis**

Resonant e and μ Leptogenesis

ReL **RμL**

norm ν

inv ν



- **Analogous results to RτL, but leptogenesis difficult to test with LFV processes due to experimental sensitivity**

Conclusion

- **Baryogenesis through Resonant Leptogenesis**
- **EW Scale Heavy Neutrinos $M_N \approx 100$ GeV**
- **Flavour Model**
  - Resonant τ Leptogenesis
  - Alternatives: Resonant e, μ Leptogenesis
  - Radiative generation of heavy neutrino mass splitting
- **Predictive Framework with Rich Phenomenology**
  - Neutrino physics
  - Observable LFV rates
  - CP violation
  - Heavy neutrino production at the LHC