The Little Review on Leptogenesis

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- **Matter–AntiMatter Asymmetry and Leptogenesis**
- **The Flavourdynamics of Leptogenesis**
- **Resonant Leptogenesis (RL)**
- **Phenomenology of RL Models**
- **Conclusions**

• Matter–AntiMatter Asymmetry and Leptogenesis

$$\eta_B^{\rm CMB} = \frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10} \qquad (\eta_B^{\rm BBN} = 3.4\text{–}6.9 \times 10^{-10}, \text{ at 95\% CL})$$

Sakharov's conditions for generating the BAU:

[A.D. Sakharov, JETP Lett. 5 (1967) 24.]

- B-violating interactions
- C and CP violation
- Out-of-equilibrium dynamics

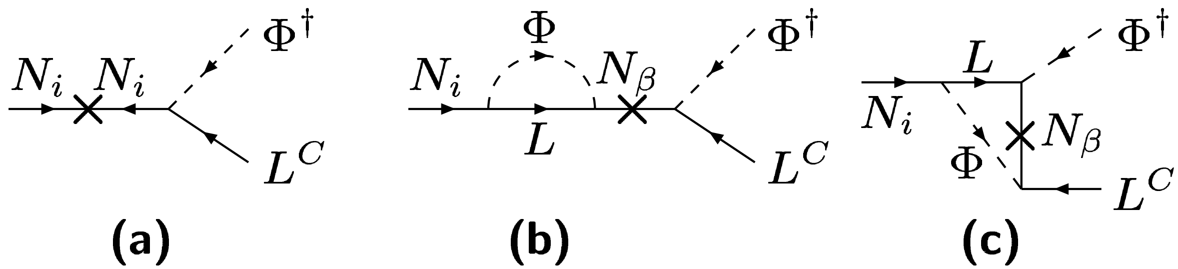
Typical Scenarios for Baryogenesis:

- **Baryogenesis through the decay of a heavy particle**
  Out-of-equilibrium, B-violating decay of a heavy GUT particle, e.g. in SO(10).
  [M. Yoshimura, PRL**41** (1978) 281; S. Dimopoulos and L. Susskind, PR**D18** (1978) 4500.]

- **Baryogenesis at the electroweak phase transition**
  BAU generated by $(B+L)$-violating sphaleron interactions at $T \sim T_c \approx 140$ GeV, through a 1st order phase transition.
  [V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, PLB155 (1985) 36;
  MSSM: M. Carena, M. Quirós, C. Wagner '96; K. Rummukainen, M. Laine '98 . . .]

- **Baryogenesis through Leptogenesis**
  Out-of-equilibrium L-violating decays of heavy Majorana neutrinos produce a net lepton asymmetry, converted into the BAU through $(B+L)$-violating sphaleron interactions.

  [M. Fukugita and T. Yanagida, PLB174 (1986) 45.]



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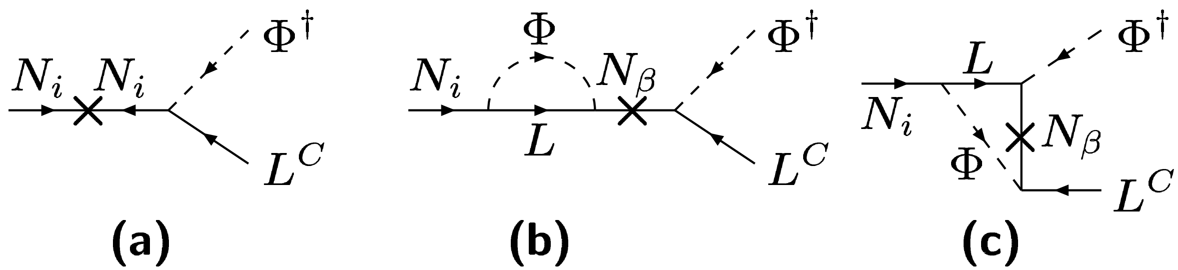

Models of Leptogenesis: [For a review, see, R.N. Mohapatra etal, RPP70 (2007) 1757]

- **Resonant Leptogenesis**

- **Dirac Leptogenesis** [K. Dick, M. Lindner, M. Ratz, D. Wright, PRL84 (2000) 4039.]

- **Other scenarios:** Non-thermal leptogenesis, Affleck–Dine, spontaneous leptogenesis, . . . [For a review, see, M. Dine and A. Kusenko, Rev. Mod. Phys. **76** (2004) 1.]

• The Flavourdynamics of Leptogenesis

BAU can be generated from and protected in a single lepton flavour:

$$\frac{1}{3}B - L_{e,\mu,\tau} \,.$$

[e.g. J.A. Harvey, M.S. Turner, PRD42 (1990) 3344;
H. Dreiner, G.G. Ross, NPB410 (1993) 188;
J.M. Cline, K. Kainulainen, K.A. Olive, PRD49 (1994) 6394.]

Two sources of flavour effects:

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Two sources of flavour effects:

- Charged-lepton Yukawa couplings $h_{e,\mu,\tau}$

[R. Barbieri, P. Creminelli, A. Strumia, N. Tetradis, NPB575 (2000) 61;
A. Pilaftsis, T.E.J. Underwood, PRD72 (2005) 113001;
E. Nardi, Y. Nir, J. Racker, E. Roulet, JHEP0601 (2006) 068;
A. Abada, S. Davidson, F. X. Josse-Michaux, M. Losada, A. Riotto, JCAP0604 (2006) 004.]

Modify BAU predictions by up to 1-order of magnitude.

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Modify BAU predictions by up to 1-order of magnitude.

- Heavy-neutrino Yukawa couplings $h^{\nu}_{l\alpha}$

[A. Pilaftsis, PRL95 (2005) 081602 [hep-ph/0408103];
T. Endoh, T. Morozumi and Z. h. Xiong, PTP111 (2004) 123;
A. Pilaftsis, T.E.J. Underwood, PRD72 (2005) 113001;
P. Di Bari, NPB727 (2005) 318; O. Vives, PRD73 (2006) 073006.]

Modify BAU predictions by many orders of magnitude, e.g. $> \; 10^6$!

Boltzmann Equations [A.P., T.E. Underwood, NPB692 (2004) 303; PRD72 (2005) 113001.]

$$\frac{d\eta_{N_\alpha}}{dz} = \frac{z}{H(z=1)} \Big[\Big(1 - \frac{\eta_{N_\alpha}}{\eta^{\rm eq}_{N_\alpha}}\Big) \sum_{k=e,\mu,\tau} \big(\Gamma^{D\,(\alpha k)} + \Gamma^{S\,(\alpha k)}_{\rm Yukawa} + \Gamma^{S\,(\alpha k)}_{\rm Gauge} \big)$$

$$- \frac{2}{3} \sum_{k=e,\mu,\tau} \eta_{\Delta L_k}\, \delta^k_{N_\alpha} \big(\widehat{\Gamma}^{D\,(\alpha k)} + \widehat{\Gamma}^{S\,(\alpha k)}_{\rm Yukawa} + \widehat{\Gamma}^{S\,(\alpha k)}_{\rm Gauge} \big) \Big] ,$$

$$\frac{d\eta_B}{dz} = - \frac{z}{H(z=1)} \Big[\eta_B + \frac{28}{51} \sum_{j=e,\mu,\tau} \eta_{L_j}$$

$$+ \frac{225}{561} \frac{v^2(T)}{T^2} \Big(\eta_B + \frac{108}{225} \sum_{j=e,\mu,\tau} \eta_{L_j} \Big) \Big] \, \Gamma_{\Delta(B+L)} ,$$

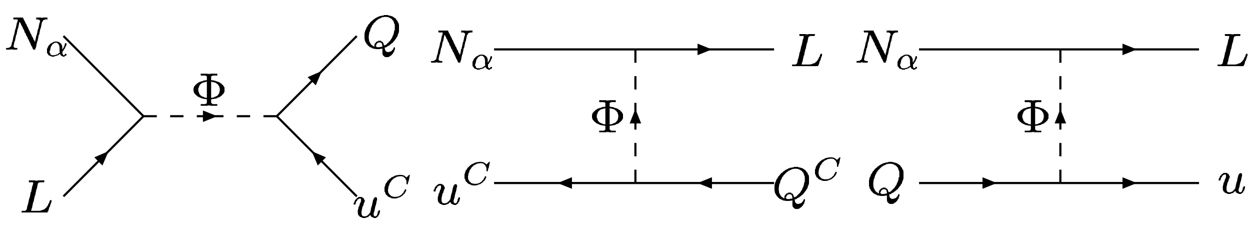
[S.Y. Khlebnikov, M.E. Shaposhnikov, NPB308 (1988) 885;
L. Carson, X. Li, L.D. McLerran, R.T. Wang, PRD42 (1990) 2127;
M. Laine, M.E. Shaposhnikov, PRD61 (2000) 117302.]

$$\frac{d\eta_{L_i}}{dz} = \frac{3}{2} \frac{d\eta_{\Delta L_i}}{dz} - \frac{2}{21} \frac{d\eta_{\Delta L}}{dz} + \frac{1}{3} \frac{d\eta_B}{dz} ,$$

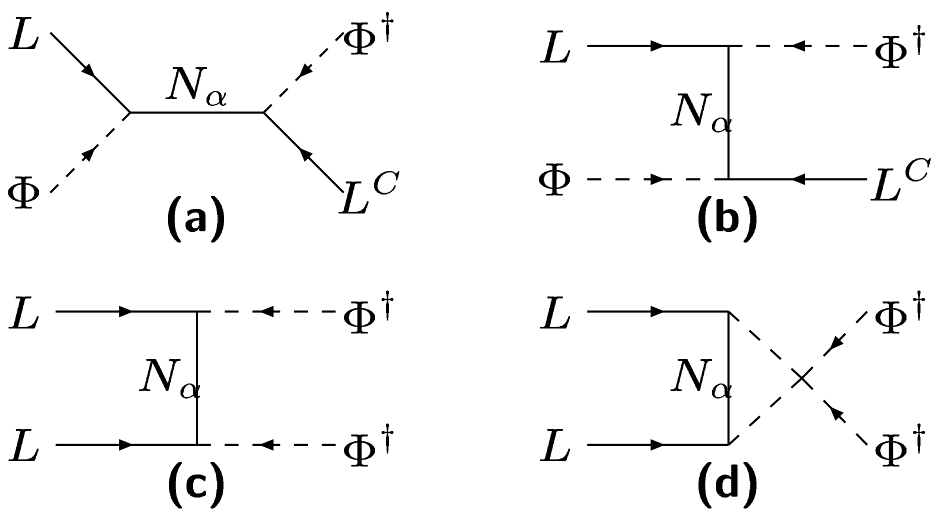
$$
\begin{aligned}
\frac{d\eta_{\Delta L_j}}{dz} = \; & \frac{z}{H(z=1)} \\
\times \Big\{ & \sum_{\alpha=1}^{3} \delta^{j}_{N_\alpha} \Big(\frac{\eta_{N_\alpha}}{\eta^{\rm eq}_{N_\alpha}} - 1\Big) \sum_{k=e,\mu,\tau} \Big(\Gamma^{D\,(\alpha k)} + \Gamma^{S\,(\alpha k)}_{\rm Yukawa} + \Gamma^{S\,(\alpha k)}_{\rm Gauge} \Big) \\
& - \frac{2}{3}\,\eta_{\Delta L_j} \Big[\sum_{\alpha=1}^{3} B^{j}_{N_\alpha} \Big(\widetilde{\Gamma}^{D\,(\alpha j)} + \widetilde{\Gamma}^{S\,(\alpha j)}_{\rm Yukawa} + \widetilde{\Gamma}^{S\,(\alpha j)}_{\rm Gauge} + \Gamma^{W\,(\alpha j)}_{\rm Yukawa} + \Gamma^{W\,(\alpha j)}_{\rm Gauge} \Big) \\
& \qquad + \sum_{k=e,\mu,\tau} \Big(\Gamma^{\Delta L=2\,(jk)}_{\rm Yukawa} + \Gamma^{\Delta L=0\,(jk)}_{\rm Yukawa} \Big) \Big] \\
& - \frac{2}{3} \sum_{k=e,\mu,\tau} \eta_{\Delta L_k} \Big[\sum_{\alpha=1}^{3} \delta^{j}_{N_\alpha}\,\delta^{k}_{N_\alpha} \Big(\Gamma^{W\,(\alpha k)}_{\rm Yukawa} + \Gamma^{W\,(\alpha k)}_{\rm Gauge} \Big) \\
& \qquad + \Gamma^{\Delta L=2\,(kj)}_{\rm Yukawa} - \Gamma^{\Delta L=0\,(kj)}_{\rm Yukawa} \Big] \Big\}
\end{aligned}
$$

Computational package: LeptoGen

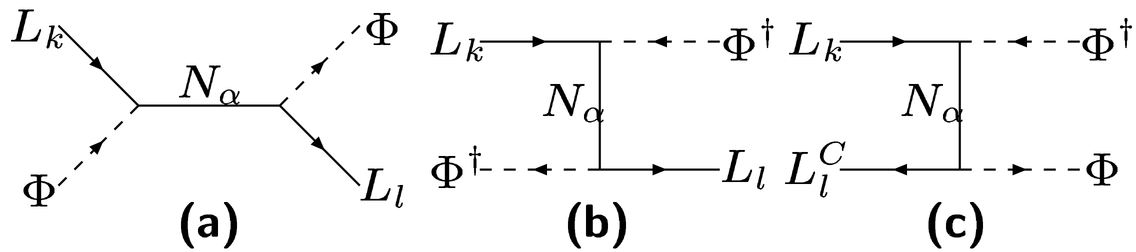
$\Delta L = 1$ scatterings involving L, N_i and quarks



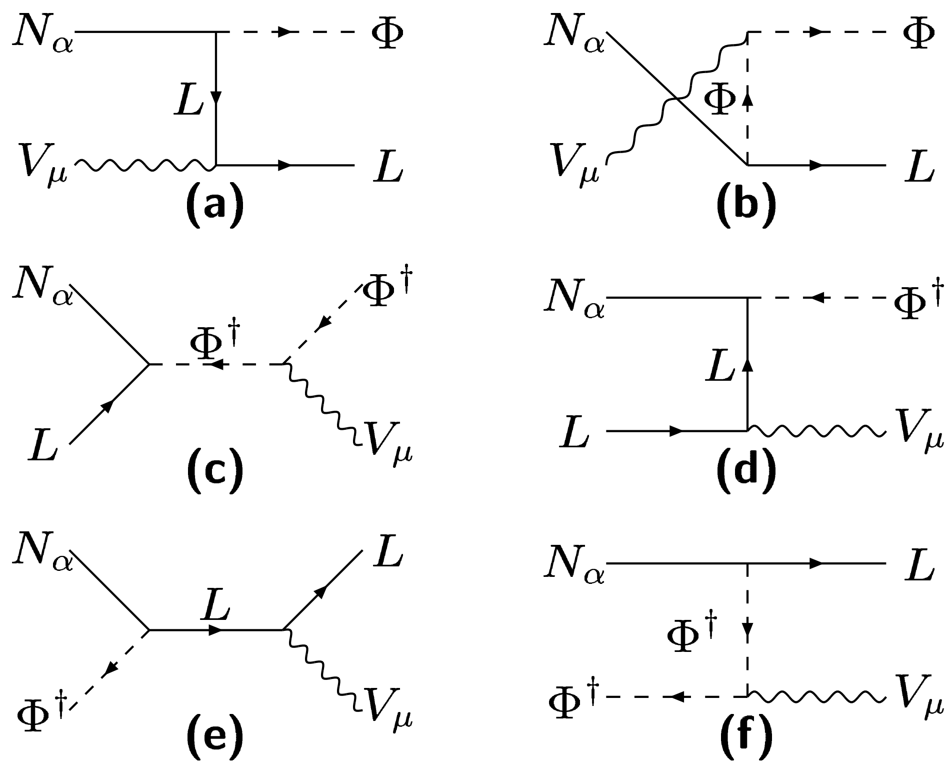
$\Delta L = 2$ scatterings involving L, Φ and N_α



$\Delta L = 0$ scatterings involving L, Φ and N_α

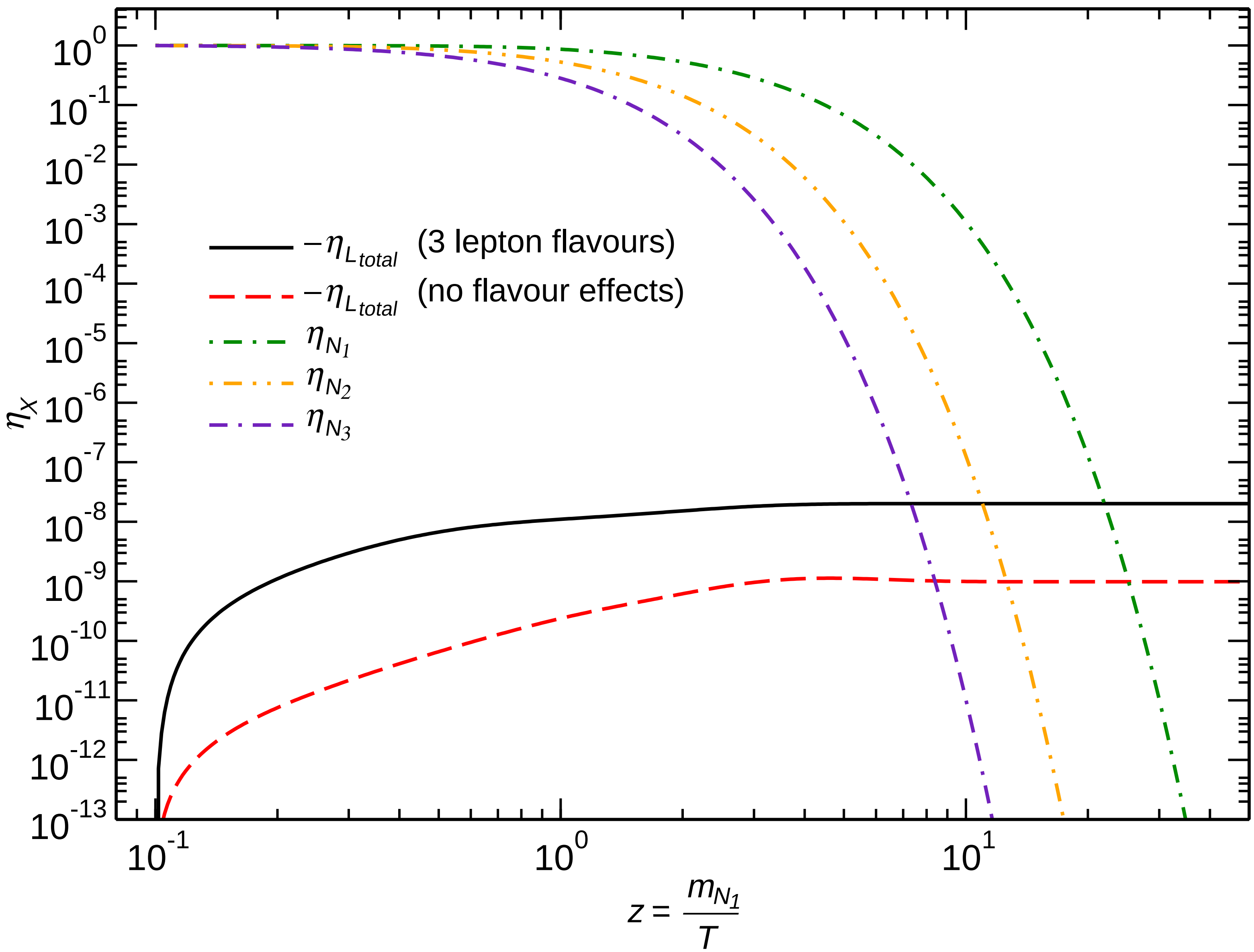


Gauge-mediated $\Delta L = 1$ scatterings



$m_{N_1} = 10^{10}$ GeV, $m_{N_2} = 2m_{N_1}$, $m_{N_3} = 3m_{N_1}$:

LeptoGen



• Resonant Leptogenesis

[A.P., PRD56 (1997) 5431; A.P. and T. Underwood, NPB692 (2004) 303;
inspired by the $K^0\bar{K}^0$ system: T.D. Lee, R. Oehme, C.N. Yang, PR106 (1957) 340.]

RL is based on the observation that selfenergies dominate the lepton asymmetries if $|m_{N_1} - m_{N_2}| \ll m_{N_{1,2}}$.

[J. Liu, G. Segré, PRD48 (1993) 4609;
M. Flanz, E. Paschos, U. Sarkar, PLB345 (1995) 248;
L. Covi, E. Roulet, F. Vissani, PLB384 (1996) 169.]

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L. Covi, E. Roulet, F. Vissani, PLB384 (1996) 169.]

Several variants:

- **Soft RL**

[L. Boubekeur, hep-ph/0208003 (unpublished);
Y. Grossman, T. Kashti, Y. Nir, E. Roulet, PRL91 (2003) 251801;
G. D'Ambrosio, G. F. Giudice, M. Raidal, PLB575 (2003) 75.]

- **Radiative RL**

[R. Gonzalez Felipe, F. R. Joaquim and B. M. Nobre, PRD70 (2004) 085009;
G. C. Branco, A. J. Buras, S. Jager, S. Uhlig, A. Weiler, JHEP0709 (2007) 004.]

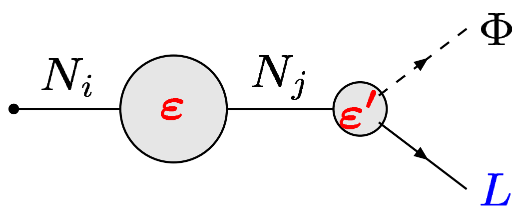
- **Coherent RL** (via sterile neutrino oscillations)

[E. K. Akhmedov, V. A. Rubakov, A. Y. Smirnov, PRL81 (1998) 1359;
T. Asaka, M. Shaposhnikov, PLB620 (2005) 17;
M. E. Shaposhnikov, arXiv:0804.4542]

The Field-Theory of Resonant Leptogenesis:

LSZ-type formalism for mixing and decay of heavy Majorana neutrinos

[A.P., PRD56 (1997) 5431; NPB504 (1997) 61.]



$$\times\ [S_{ii}(\not{p})]^{-1}\, u_{N_i}(p) \ = \ \mathcal{T}_{N_i}$$

2-N Model:

$$S_{ij}(\not{p}) \ = \ \begin{pmatrix} \not{p} - m_{N_1} + \Sigma_{11}(\not{p}) & \Sigma_{12}(\not{p}) \\ \Sigma_{21}(\not{p}) & \not{p} - m_{N_2} + \Sigma_{22}(\not{p}) \end{pmatrix}^{-1}$$

[For 3-N mixing, see, A.P., T. Underwood, NPB692 (2004) 303.]

ε'-type CP violation :

$$\varepsilon'_{N_i} = \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{ij}}{(h^{\nu\dagger}\,h^{\nu})_{ii}\,(h^{\nu\dagger}\,h^{\nu})_{jj}} \left(\frac{\Gamma_{N_j}}{m_{N_j}}\right) f\left(\frac{m^2_{N_j}}{m^2_{N_i}}\right),$$

where

$$\Gamma_{N_j} = \frac{(h^{\nu\dagger}\,h^{\nu})_{jj}}{8\pi}\,m_{N_j}$$

ε-type CP violation :

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Note that $\varepsilon_{N_{1,2}}$ are of the same sign!

Resonant conditions for $O(1)$ leptonic asymmetries:

[A.P., PRD56 (1997) 5431.]

$\Rightarrow$ $$m_{N_2} - m_{N_1} \sim \frac{1}{2}\, \Gamma_{N_{1,2}}$$

$\Rightarrow$ $$\frac{\mathrm{Im}\,(h^{\nu\dagger}\, h^{\nu})^2_{ij}}{(h^{\nu\dagger}\, h^{\nu})_{ii}\,(h^{\nu\dagger}\, h^{\nu})_{jj}} \sim 1$$

Resonant conditions for $O(1)$ leptonic asymmetries:

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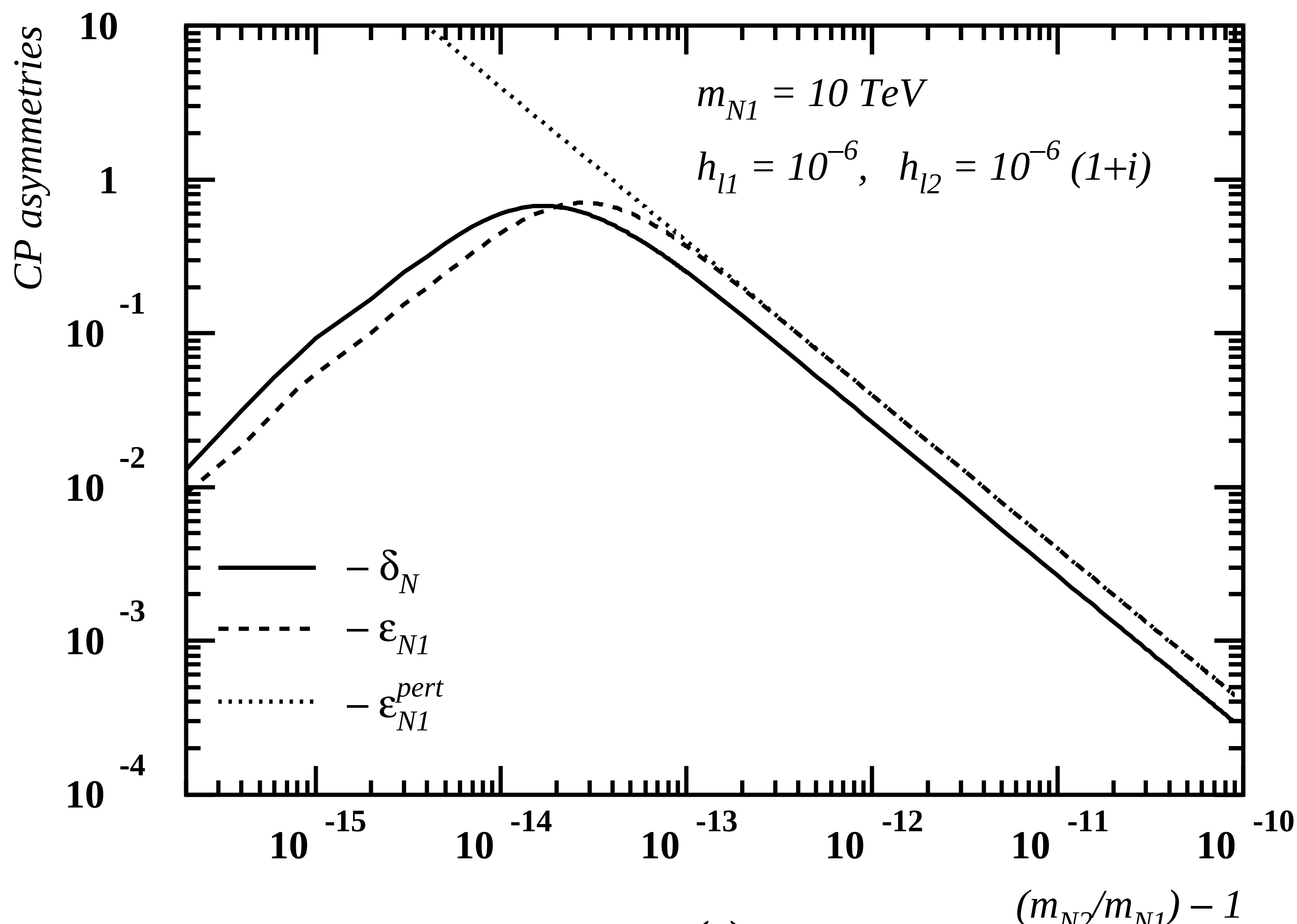


(a)

Flavour Effects in Resonant Leptogenesis

– The Non-Seesaw Paradigm

[A.P., PRL95 (2005) 081602 [hep-ph/0408103];
based on A.P., ZPC55 (1992) 275;
R.N. Mohapatra, J.W.F. Valle, PRD34 (1986) 1642.]

Break SO(3) and $U(1)_l$ flavour symmetries:

$$\mathrm{SO(3)} \ \xrightarrow{\sim h_\tau} \ \mathrm{SO(2)} \simeq \mathrm{U(1)}_l \ \xrightarrow{\sim h_e} \ \mathrm{I}$$

$U_l(1)$-broken Yukawa sector:

$$m_D \ = \ \frac{v}{\sqrt{2}} \begin{pmatrix} \varepsilon_e & a\,e^{-i\pi/4} & a\,e^{i\pi/4} \\ \varepsilon_\mu & b\,e^{-i\pi/4} & b\,e^{i\pi/4} \\ \varepsilon_\tau & c\,e^{-i\pi/4} & c\,e^{i\pi/4} \end{pmatrix} ,$$

with $a \sim b \sim 10^{-2} \sim h_\tau$, $\quad c \lesssim 10^{-4} \quad$ & $\quad |\varepsilon_l| \sim 10^{-7} \sim h_e$.

$$\Longrightarrow \quad m_\nu^{\rm light} \ \sim \ \frac{m_e^2}{m_N} \ \sim \ 0.1 \text{ eV} \quad \Longrightarrow \quad m_N \ \sim \ 100 - 500 \text{ GeV}$$

$\Longrightarrow$ 3 nearly degenerate heavy Majorana neutrinos.

Light neutrino-mass spectrum: [A.P., T. Underwood, PRD72 (2005) 113001.]

$$m_\nu^{\rm light} \;=\; \frac{v^2}{2m_N}\begin{pmatrix} \frac{\Delta m_N}{m_N}a^2-\varepsilon_e^2 & \frac{\Delta m_N}{m_N}ab-\varepsilon_e\varepsilon_\mu & \frac{\Delta m_N}{m_N}ac-\varepsilon_e\varepsilon_\tau \\ \frac{\Delta m_N}{m_N}ab-\varepsilon_e\varepsilon_\mu & \frac{\Delta m_N}{m_N}b^2-\varepsilon_\mu^2 & \frac{\Delta m_N}{m_N}bc-\varepsilon_\mu\varepsilon_\tau \\ \frac{\Delta m_N}{m_N}ac-\varepsilon_e\varepsilon_\tau & \frac{\Delta m_N}{m_N}bc-\varepsilon_\mu\varepsilon_\tau & \frac{\Delta m_N}{m_N}c^2-\varepsilon_\tau^2 \end{pmatrix},$$

where

$$\Delta m_N \;=\; 2(\Delta m_M)_{23}+i[(\Delta m_M)_{33}-(\Delta m_M)_{22}],\qquad \frac{b}{a}\;=\;\frac{19}{50}\,,$$

and (in $\sim 10^{-7}$ units)

$$\sqrt{\frac{\Delta m_N}{m_N}}\,a \;=\; 2\,,\quad \varepsilon_e \;=\; 2+\frac{21}{250}\,,\quad \varepsilon_\mu \;=\; \frac{13}{50}\,,\quad \varepsilon_\tau \;=\; -\frac{49}{128}\,.$$

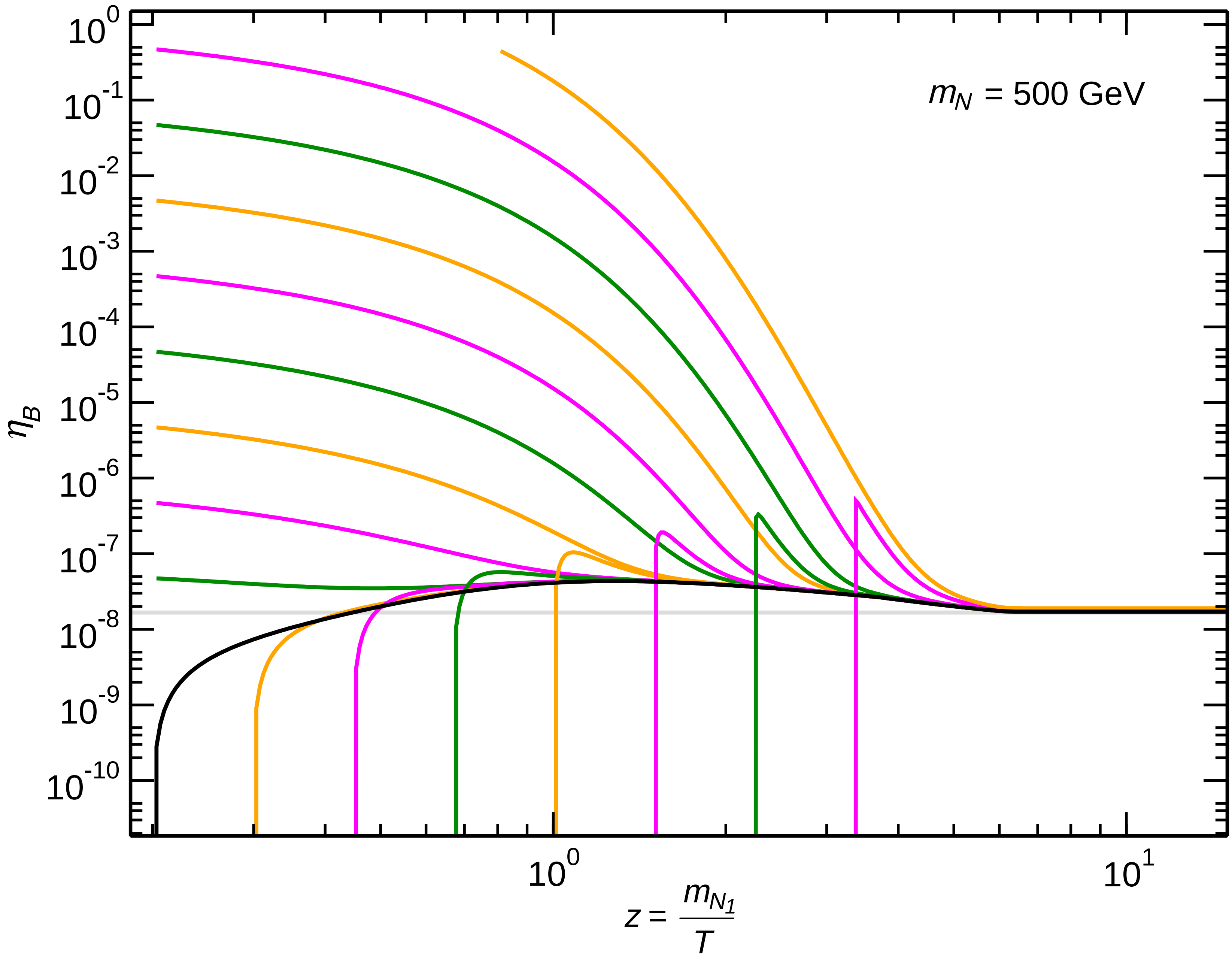
Prediction: inverted mass hierarchy, $m_{\nu_3} < m_{\nu_1} < m_{\nu_2}$, with

$$m^2_{\nu_2}-m^2_{\nu_1} \;=\; 7.54\times 10^{-5}\ {\rm eV}^2\,,\qquad m^2_{\nu_1}-m^2_{\nu_3} \;=\; 2.45\times 10^{-3}\ {\rm eV}^2\,,$$

$$\sin^2\theta_{12} \;=\; 0.362\,,\qquad \sin^2\theta_{23} \;=\; 0.341\,,\qquad \sin^2\theta_{13} \;=\; 0.047\,.$$

Resonant Leptogenesis

[A.P. and T. Underwood, PRD72 (2005) 113001.]



Qualification of Models for Baryogenesis

Q-Factor (a measure of the dependence of the BAU on initial conditions):

$$Q \;=\; \ln \left| \frac{\delta\eta_B{}^{\rm in}}{\delta\eta_B{}^{\rm fin}} \right| \ .$$

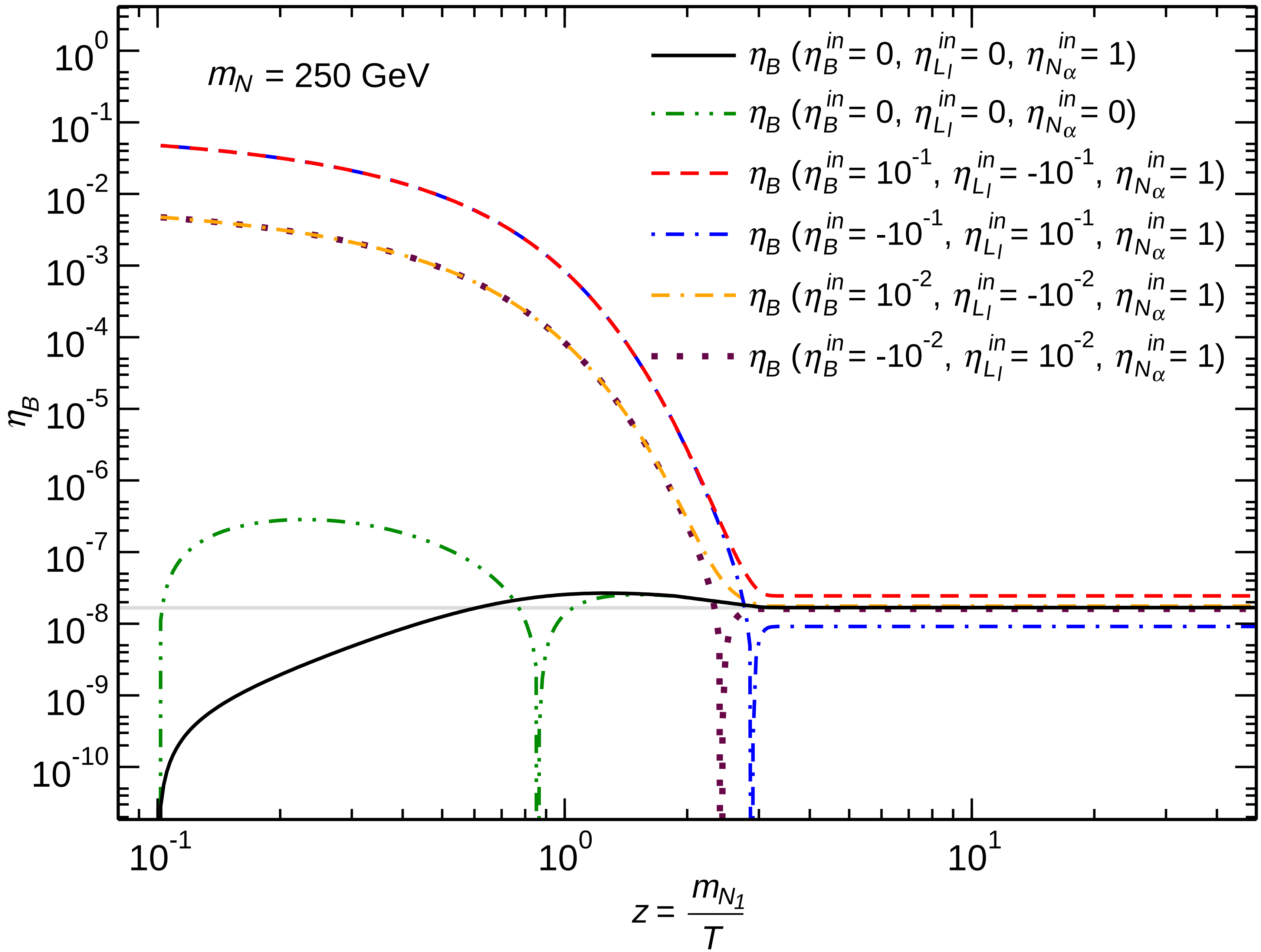
$T_{\rm in}$ is a typical initial temperature of the baryogenesis mechanism, e.g. $T_{\rm in} \sim m_N$ or $T_{\rm in} \sim T_c^{\rm EW}$.

$T_{\rm fin}$ is the freeze-out temperature of the baryogenesis mechanism.

If $Q \gg 1 \quad \Longrightarrow \quad$ no-strong dependence of the BAU on the initial conditions.

If $Q < 0 \quad \Longrightarrow \quad$ BAU does strongly depend on the initial conditions.

Resonant Leptogenesis [A.P. and T. Underwood, PRD72 (2005) 113001.]



Resonant Leptogenesis

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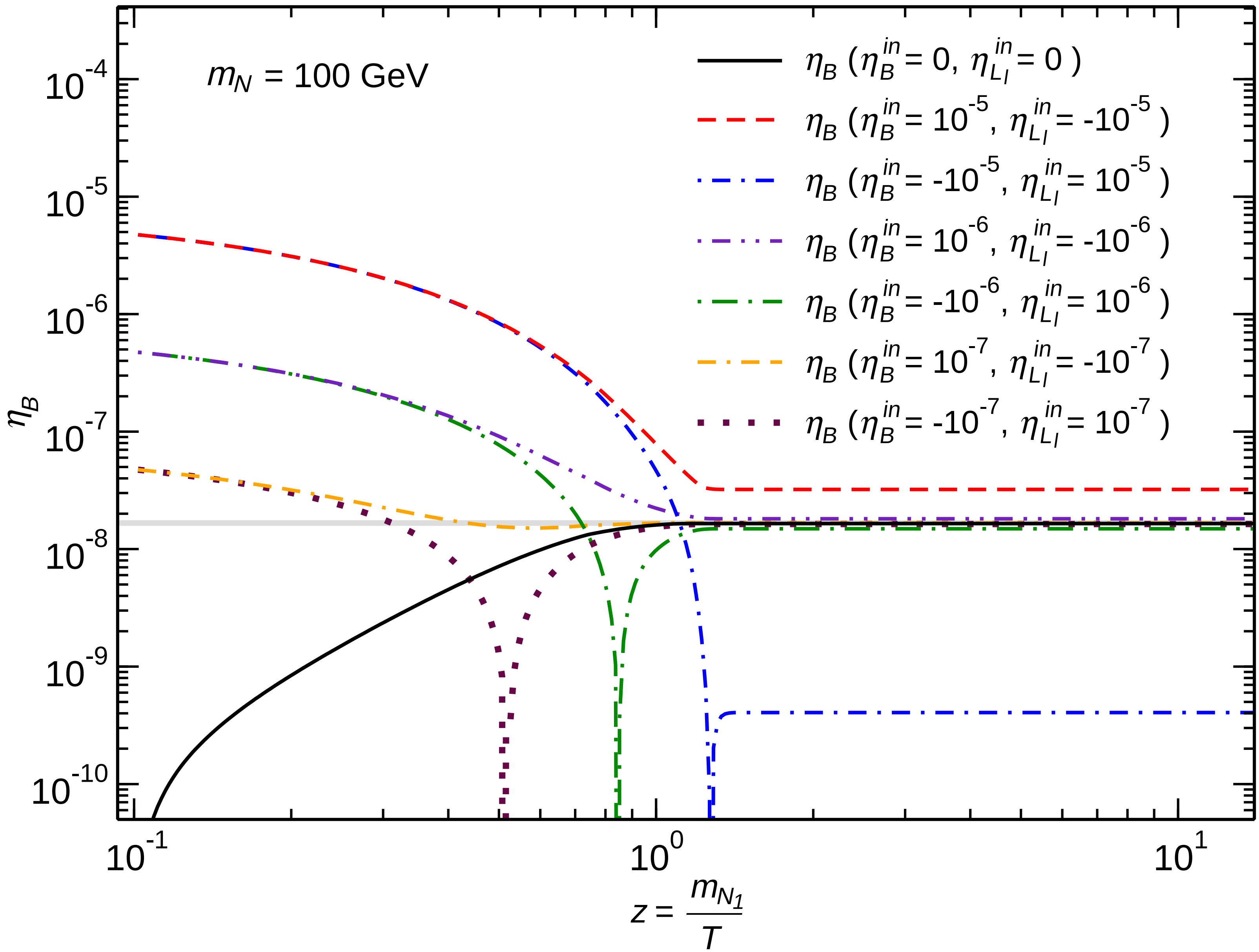


Calculation must be done in the broken phase

[A.P., PRD**78** (2008) 013008]

• Phenomenology of RL Models

• $0\nu\beta\beta$ Decay

$$ {}^{A}_{Z}X \;\to\; {}^{A}_{Z+2}X \;+\; 2e^- \; . $$

Half-life for $0\nu\beta\beta$ decay:

$$ [T_{1/2}^{0\nu\beta\beta}]^{-1} \;=\; \frac{|\langle m\rangle|^2}{m_e^2}\, |\mathcal{M}_{0\nu\beta\beta}|^2\, G_{01} \; . $$

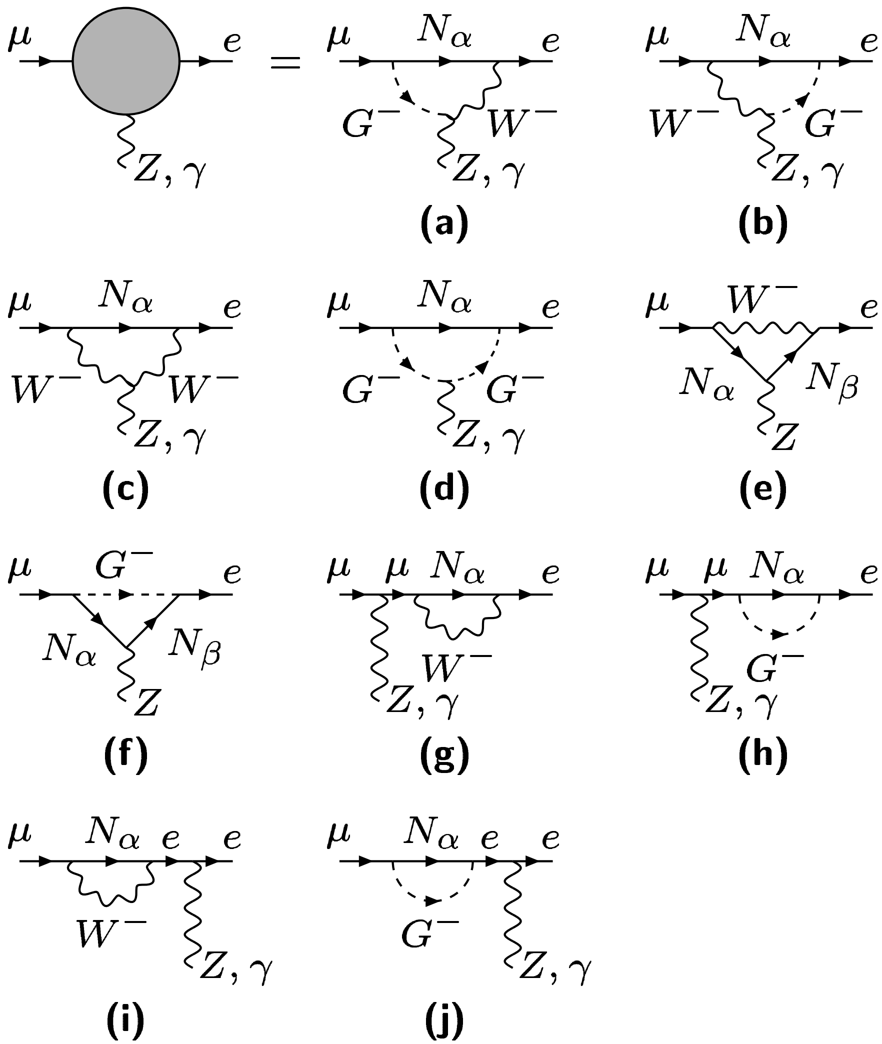
RτL realizes inverted light-neutrino hierarchy, with:

$$ |\langle m_{0\nu\beta\beta}\rangle| \;=\; |(\mathbf{m}^{\nu})_{ee}| \;=\; \frac{v^2}{2m_N}\, \Big|\, \frac{\Delta m_N}{m_N}\, a^2 \;-\; \varepsilon_e^2 \,\Big| \;\approx\; 0.013\ \mathrm{eV} \; . $$

Future $0\nu\beta\beta$ experiments will be sensitive to $|\langle m\rangle| \sim 0.01$–$0.05$ eV.

• $\mu \to e\gamma$

[T.P. Cheng, L.F. Li, PRL45 (1980) 1908.]



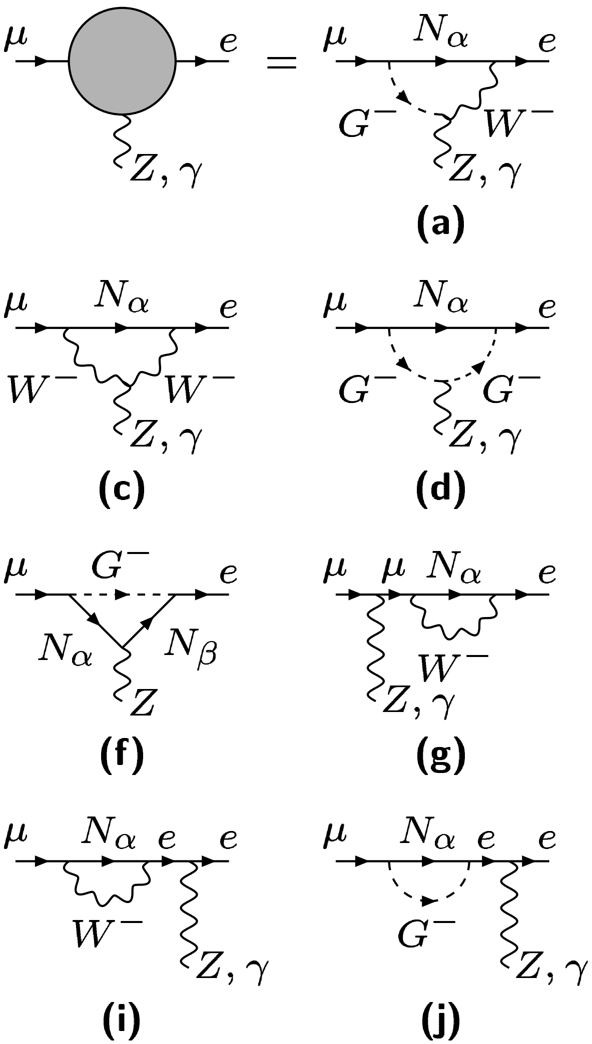
For $h^\nu_{eN_{2,3}} = h^\nu_{\mu N_{2,3}} = 8 \times 10^{-3}$ and $m_N = 250$ GeV:

$$B(\mu \to e\gamma) \sim 7 \cdot 10^{-4} \times \frac{(h^\nu_{eN} h^\nu_{\mu N})^2 v^4}{m_N^4} \sim 10^{-12} \,.$$

MEG sensitivity:
$B(\mu \to e\gamma) \sim 10^{-13}$–$10^{-14}$.

• $\mu \to e\gamma$

[T.P. Cheng, L.F. Li, PRL45 (1980) 1908.]



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$$\sim 10^{-12}\ .$$

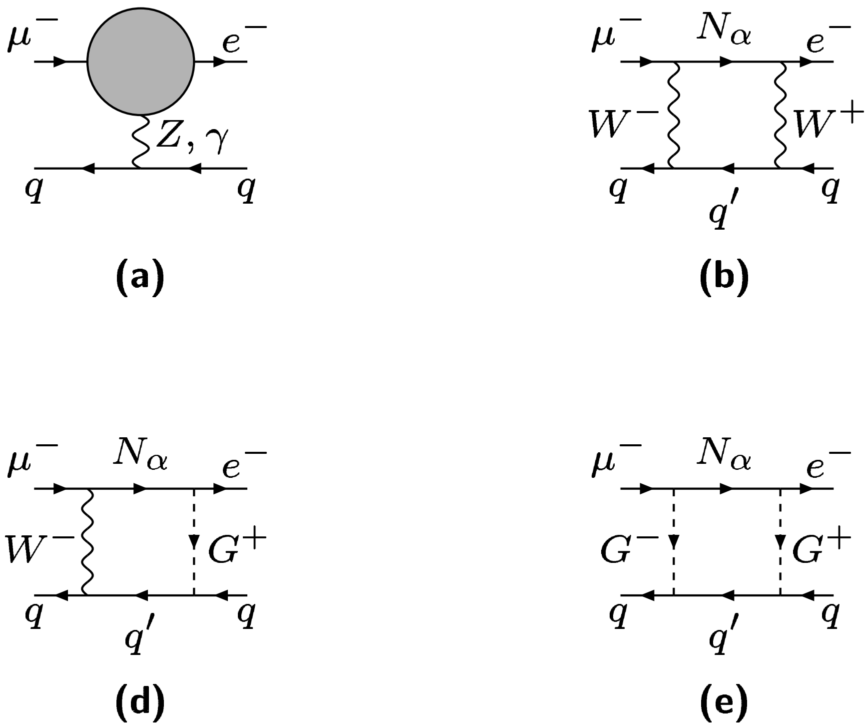
MEG sensitivity:
$B(\mu \to e\gamma) \sim 10^{-13}$–$10^{-14}$.

Other effects at the Z-boson pole, such as breaking of lepton universality are small.

[J. Bernabéu, J.G. Körner, A.P., K. Schilcher, PRL71 (1993) 2695;
J. Bernabéu, A. Santamaria, J. Vidal, A. Mendez, J.W.F. Valle, PLB187 (1987) 303;
J.G. Körner, A.P., K. Schilcher, PLB300 (1993) 381.]

• Coherent $\mu \to e$ Conversion in Nuclei ($^{48}_{22}$Ti)

[A.P., T. Underwood, PRD72 (2005) 113001;
hadronic part from R. Pla, J. Bernabéu, An. Fís. 67 (1971) 455.]

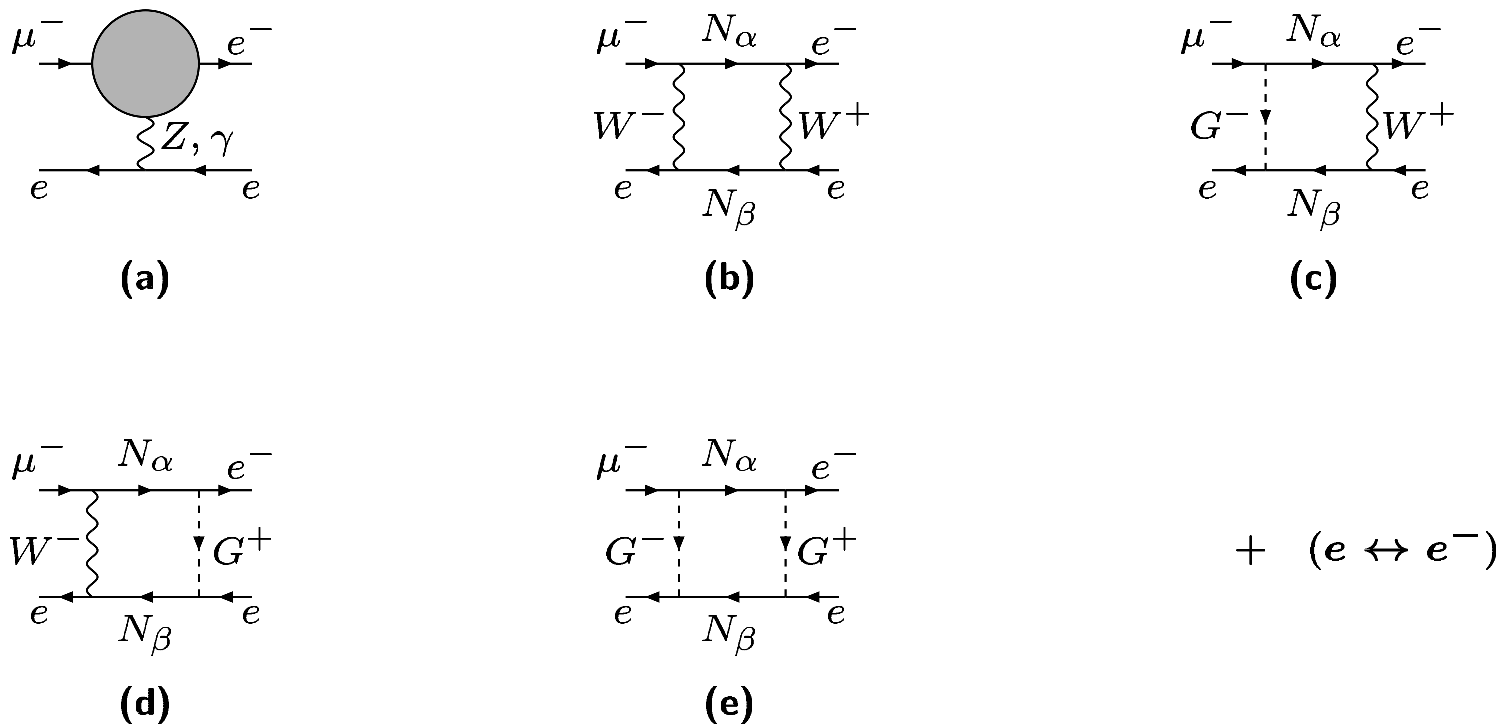


$\boldsymbol{m_N = 250}$ GeV:

$$B(\mu \to e) \ \approx \ 0.5 \times B(\mu \to e\gamma) \ \sim \ 5 \times 10^{-13} \ .$$

PRISM/PRIME . . . will be sensitive to $B(\mu \to e) \ \sim \ 10^{-13}$–$10^{-18}$.

• $\mu \to eee$ [A. Ilakovac, A.P., NPB437 (1995) 491.]



$m_N = 250$ GeV:

$$B(\mu \to eee) \ \approx \ 1.4 \cdot 10^{-2} \times B(\mu \to e\gamma) \ \sim \ 1.4 \times 10^{-14} \ .$$

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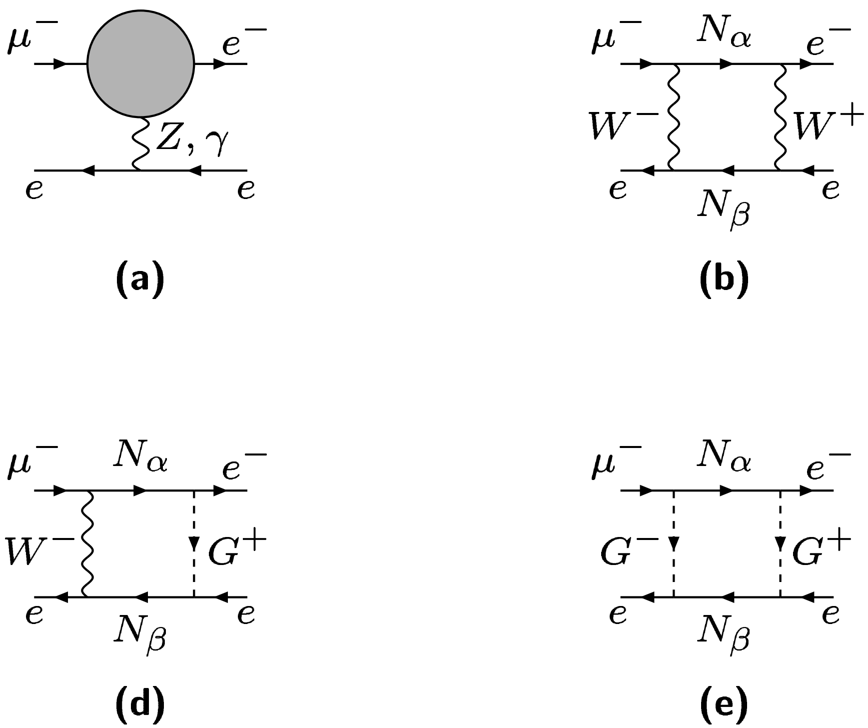
[A. Ilakovac, A.P., NPB437 (1995) 491.]



$+ \quad (e \leftrightarrow e^-)$

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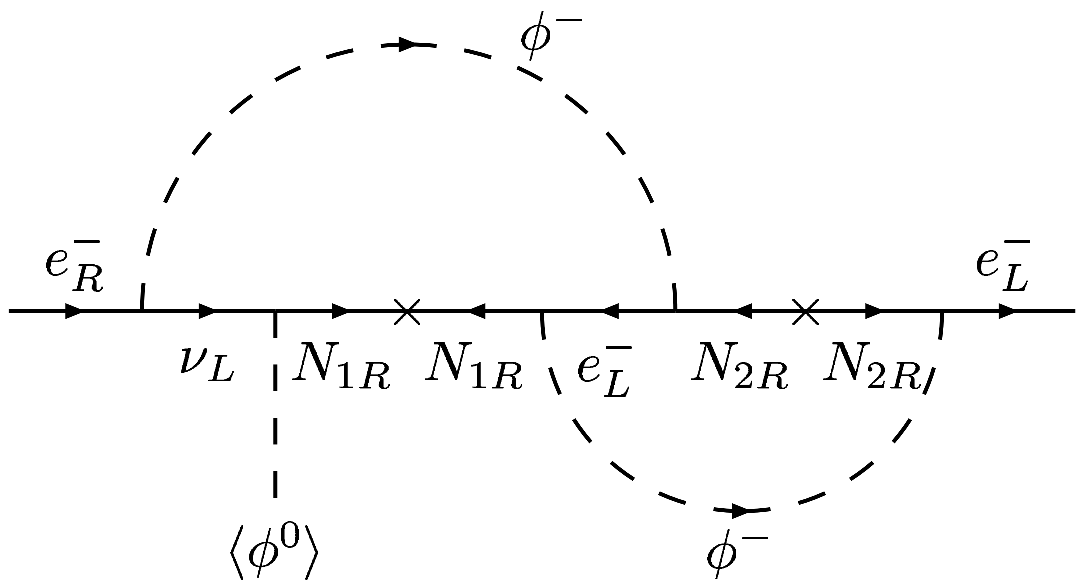
No new experiment proposed yet!

• **Electric Dipole Moment (EDM) Predictions**

[A.P., IJMPA**14** (1999) 1811; J.P. Archaumbault, A. Czarnecki, M. Pospelov, PRD**70** (2004) 073006.]



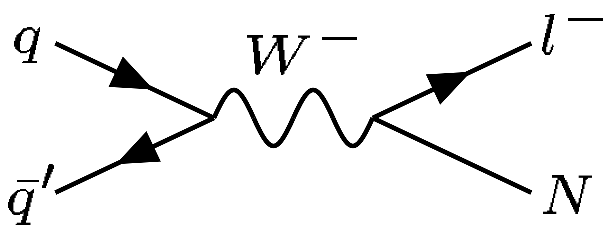
$$\frac{d_e}{e} \sim \frac{1}{(16\pi^2)^2}\,\frac{m_e}{m_{N_1}^2}\,\frac{\mathrm{Im}\,(h^{\nu\,\dagger}\,h^\nu)_{12}^2\; m_{N_1}\,m_{N_2}\,(m_{N_2}^2 - m_{N_1}^2)}{(m_{N_1}^2 + m_{N_2}^2)^2}\;\ln\frac{m_{N_1}}{M_W}$$

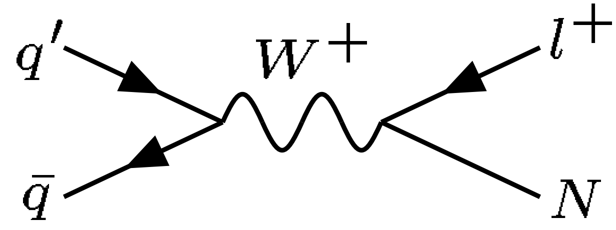
$$\sim (10^{-25}\ \mathrm{cm}) \times \frac{M_W^2}{m_{N_1}m_{N_2}}\,\mathrm{Im}\,(h^{\nu\,\dagger}\,h^\nu)_{12}^2 \;\lesssim\; 10^{-32}\ \mathrm{cm}$$

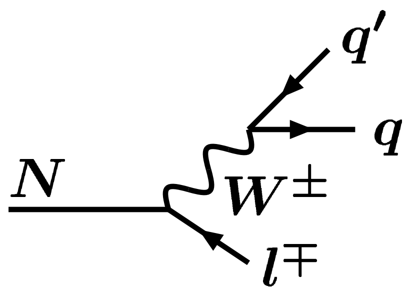
$\therefore$ Observation of an electron EDM $d_e \gtrsim 10^{-32}\ e\cdot\mathrm{cm}$ will rule out leptogenesis in the SM with singlet neutrinos.

• Heavy Majorana Neutrino Production at the LHC

[A.P., ZPC55 (1992) 275; A. Datta, M. Guchait, A.P., PRD50 (1994) 3195;
T. Han, B. Zhang, PRL97 (2006) 171804;
F. del Aguila, J. A. Aguilar-Saavedra, R. Pittau, JHEP0710 (2007) 047.]





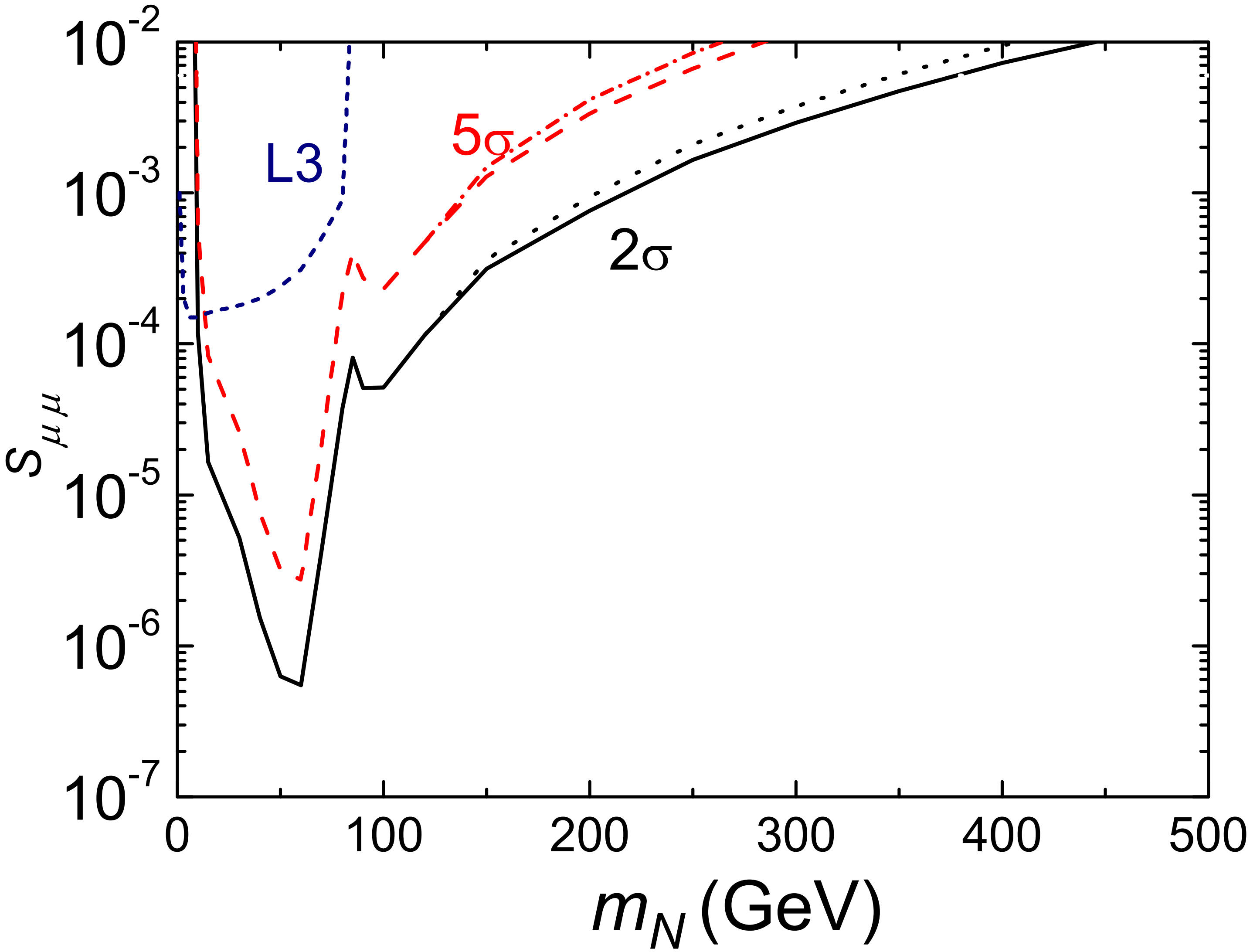


Signal: 2 leptons + 2 jets + no $\not{p}_T$

- **LNV signatures:** $pp \to e^+e^+,\ e^+\mu^+,\ e^-e^-,\ e^-\mu^-,\ e^-\tau^- \ldots$
- **LFV signatures:** $pp \to e^+\mu^-,\ e^-\mu^+,\ e^-\tau^+ \ldots$
- **CP Asymmetries**

[S. Bray, J.S. Lee, A.P., NPB786 (2007) 95.]

LHC sensitivity with 100 fb^{-1}



[T. Han, B. Zhang, PRL97 (2006) 171804.]

CP Asymmetries

[S. Bray, J.S. Lee, A.P., NPB786 (2007) 95.]

- **Lepton Number Violation:**

$$A_{\rm CP}({\rm LNV1}) \;=\; \frac{\sigma(pp\to e^+e^+W^-X) - K\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^+e^+W^-X) + K\sigma(pp\to e^-e^-W^+X)}\,,$$

$$A_{\rm CP}({\rm LNV2}) \;=\; \frac{\sigma(pp\to e^+\mu^+W^-X) - K\sigma(pp\to e^-\mu^-W^+X)}{\sigma(pp\to e^+\mu^+W^-X) + K\sigma(pp\to e^-\mu^-W^+X)}\,,$$

$$R_{\rm CP}({\rm LNV}) \;=\; \frac{\frac{\sigma(pp\to e^+e^+W^-X)}{\sigma(pp\to e^+\mu^+W^-X)} - \frac{\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^-\mu^-W^+X)}}{\frac{\sigma(pp\to e^+e^+W^-X)}{\sigma(pp\to e^+\mu^+W^-X)} + \frac{\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^-\mu^-W^+X)}}\,.$$

- **Lepton Flavour Violation:**

$$A_{\rm CP}({\rm LNC}) \;=\; \frac{\sigma(pp\to e^+\mu^-W^\pm X) - \sigma(pp\to e^-\mu^+W^\pm X)}{\sigma(pp\to e^+\mu^-W^\pm X) + \sigma(pp\to e^-\mu^+W^\pm X)}\,,$$

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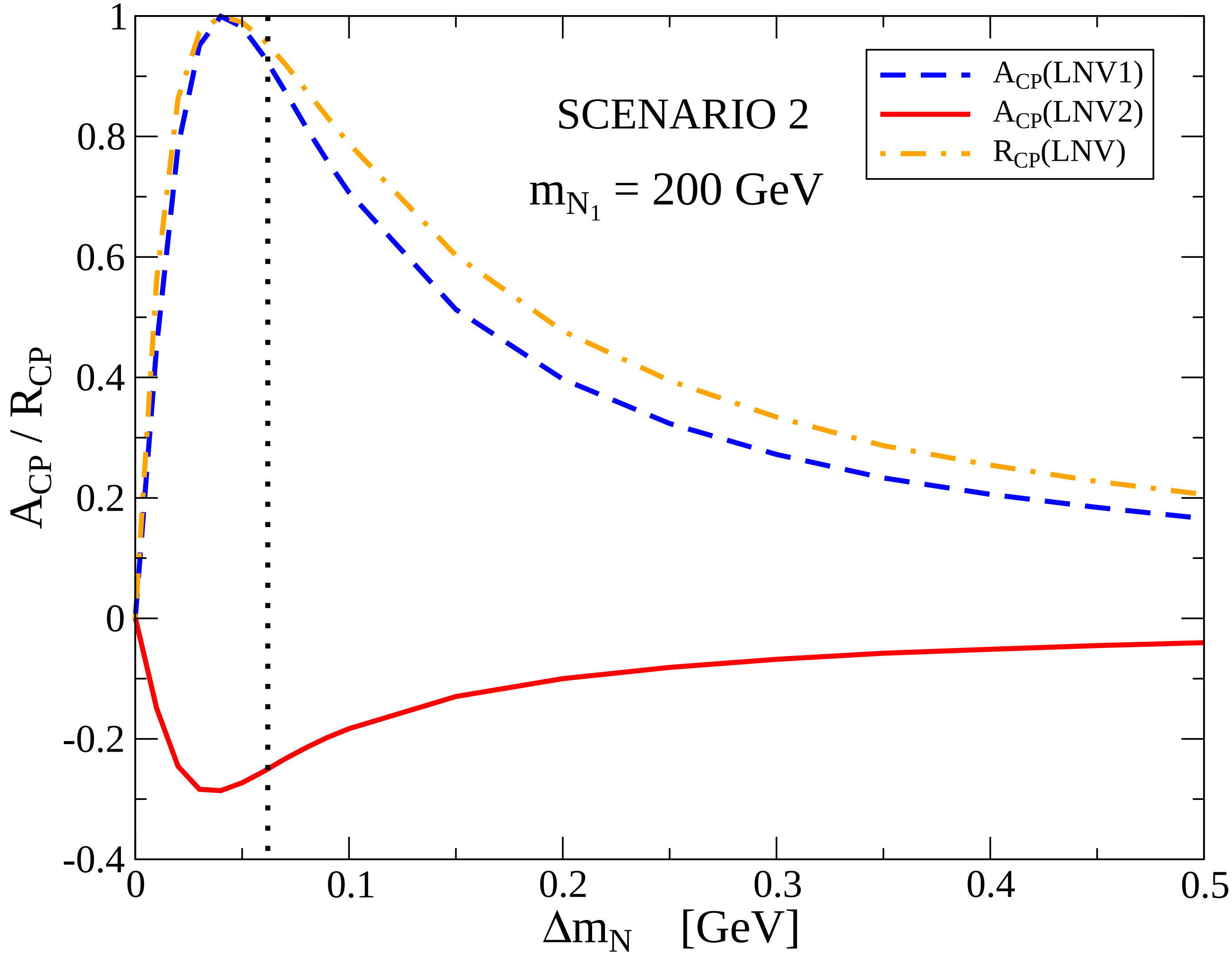
Resonant CP Violation through Mixing of Heavy Majorana Neutrinos

[S. Bray, J.S. Lee, A.P., NPB786 (2007) 95.]



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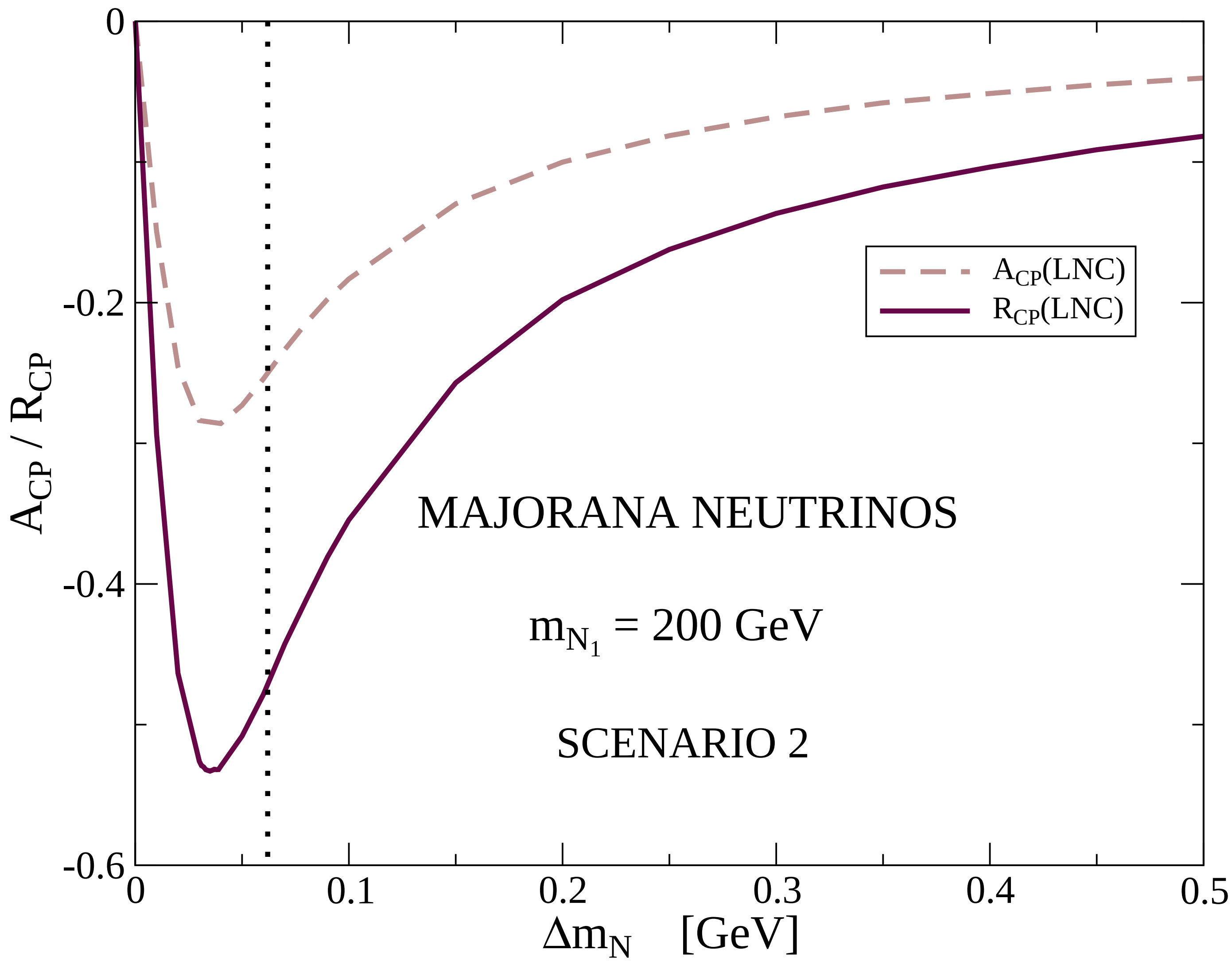

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- Strong correlations among the predictions for LFV and LNV at the observable level ($m_N = 250$ GeV):

$$\begin{aligned} B(\mu \to e\gamma) &\sim 10^{-13}, \\ B(\mu \to e) &\approx 0.5 \times B(\mu \to e\gamma), \\ B(\mu \to eee) &\approx 1.4 \cdot 10^{-2} \times B(\mu \to e\gamma), \\ |\langle m_{0\nu\beta\beta} \rangle| &\approx 0.01 \text{ eV}. \end{aligned}$$