Flavour in Resonant Leptogenesis

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- **WMAP Results and Matter–AntiMatter Asymmetry**

- **Flavoured Resonant Leptogenesis at the Electroweak Scale**

- **Phenomenological Implications**

- **Conclusions and Future Prospects**

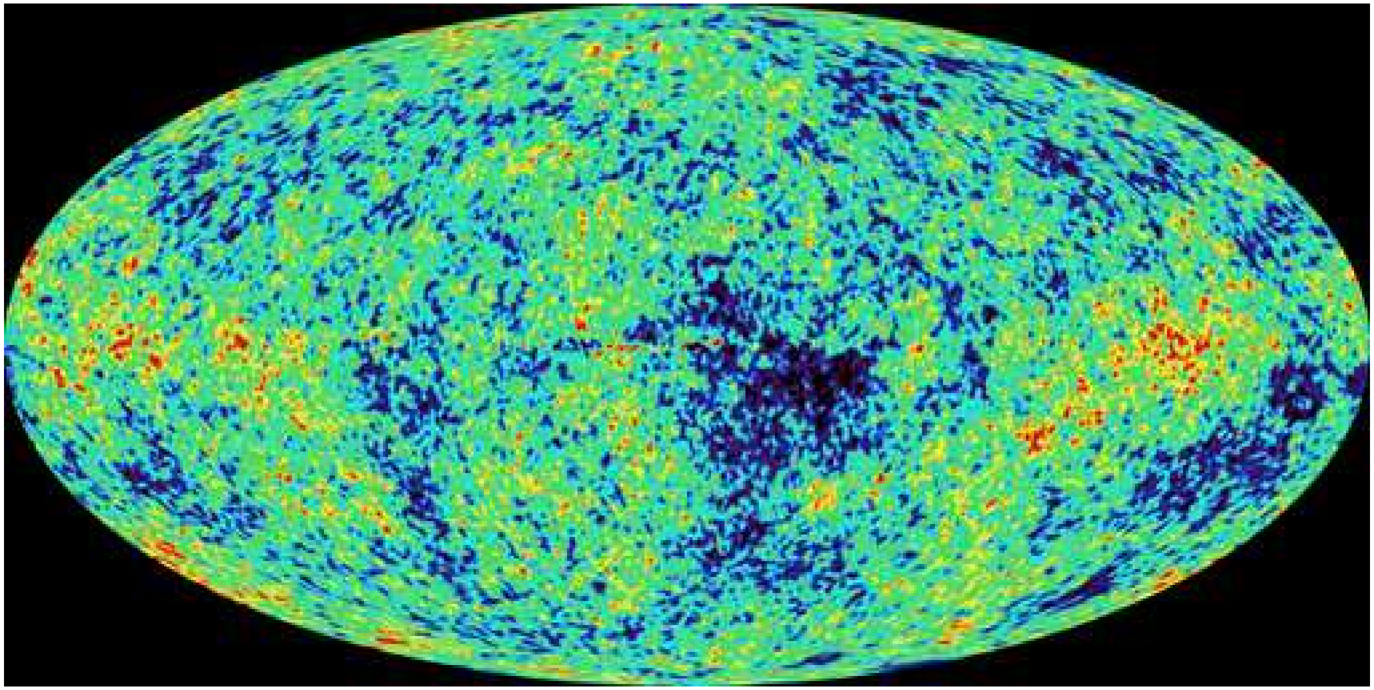
*Talk based on

A.P., PRL**95** (2005) 081602;

A.P. and T.E.J. Underwood, PRD**72** (2005) 113001.

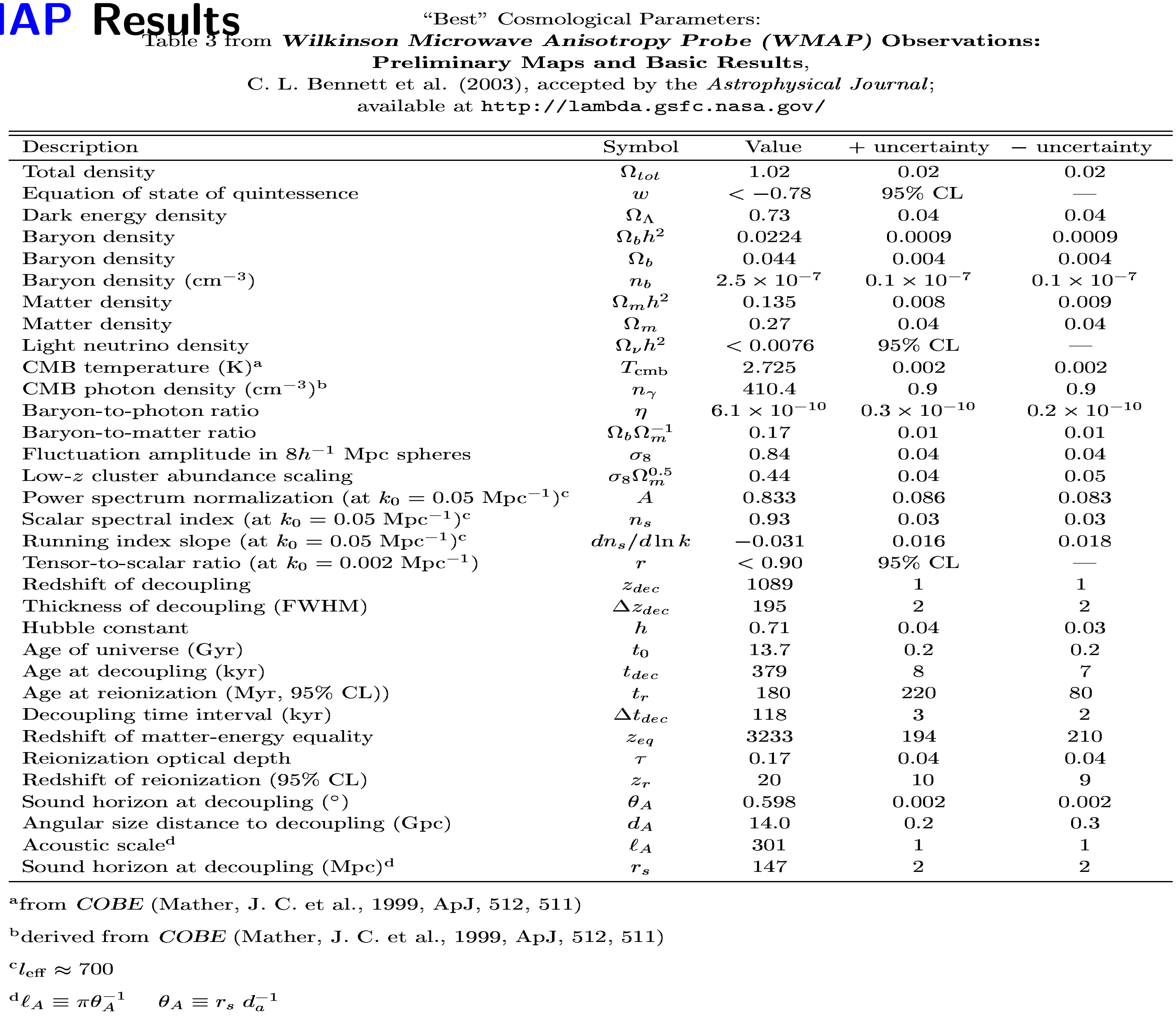
• WMAP Results and Matter–AntiMatter Asymmetry

Density perturbations as observed by WMAP



$$\frac{\delta T}{T} \sim \frac{\delta\rho}{\rho} \sim 10^{-5}$$

– WMAP Results



"Best" Cosmological Parameters:
Table 3 from ***Wilkinson Microwave Anisotropy Probe (WMAP) Observations:***
Preliminary Maps and Basic Results,
C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*;
available at `http://lambda.gsfc.nasa.gov/`

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$)[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$)[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$)[c]	$dn_s/d\ln k$	-0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002\ \mathrm{Mpc}^{-1}$)	r	< 0.90	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL))	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular size distance to decoupling (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2

[a] from *COBE* (Mather, J. C. et al., 1999, ApJ, 512, 511)

[b] derived from *COBE* (Mather, J. C. et al., 1999, ApJ, 512, 511)

[c] $l_{\mathrm{eff}} \approx 700$

[d] $\ell_A \equiv \pi \theta_A^{-1}$ $\theta_A \equiv r_s\, d_a^{-1}$

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

– Matter–AntiMatter Asymmetry

Sakharov's conditions for generating the BAU:

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

Scenarios for Baryogenesis:

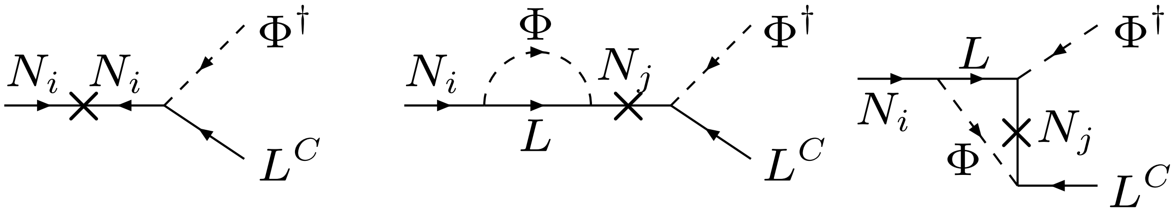
- **Baryogenesis through the decay of a heavy particle**
  Out-of-equilibrium, B-violating decay of a heavy GUT particle, e.g. in SO(10).
  [M. Yoshimura, PRL**41** (1978) 281; S. Dimopoulos and L. Susskind, PR**D18** (1978) 4500.]

- **Baryogenesis at the electroweak phase transition**
  BAU is generated by means of $(B+L)$-violating sphaleron interactions at $T \sim T_c \approx 200$ GeV, during a 1st order phase transition.
  [V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, PL**B155** (1985) 36;
  MSSM: M. Carena, M. Quirós, C. Wagner; A. Riotto '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, PL**B174** (1986) 45.]

Other scenarios: Affleck–Dine, spontaneous baryogenesis, . . .

• Resonant Leptogenesis



(a) **(b)** **(c)**

Historic background:

T.D. Lee, R. Oehme, C.N. Yang, PR106 (1957) 340	($K^0\bar{K}^0$ formalism)
A.P., ZPC47 (1990) 95	(Resonant enhancement of CP asymmetries)
⋮	
J. Liu, G. Segré, PRD48 (1993) 4609	(off-resonant perturbative calculation)
M. Flanz, E. Paschos, U. Sarkar, PLB345 (1995) 248	(QM approach)
L. Covi, E. Roulet, F. Vissani, PLB384 (1996) 169	(finite-order calculation)
A.P., PRD56 (1997) 5431	(QFT approach to RL)
⋮	
A.P. and T. Underwood, hep-ph/0309342	(TeV- & EW- scale RL)

Recent related papers:

L. Boubekeur, hep-ph/0208003;

J. R. Ellis, M. Raidal and T. Yanagida, Phys. Lett. B **546** (2002) 228;

Y. Grossman, T. Kashti, Y. Nir and E. Roulet, Phys. Rev. Lett. **91** (2003) 251801;

G. D'Ambrosio, G. F. Giudice and M. Raidal, Phys. Lett. B **575** (2003) 75;

T. Hambye, J. March-Russell and S. M. West, JHEP **0407** (2004) 070;

E. J. Chun, Phys. Rev. D **69** (2004) 117303;

Y. Grossman, R. Kitano and H. Murayama, hep-ph/0504160;

S. Dar, S. Huber, V.N. Senoguz and Q. Shafi, Phys. Rev. D **69** (2004) 077701;

E. K. Akhmedov, M. Frigerio and A. Y. Smirnov, JHEP **0309** (2003) 021;

C.H. Albright and S.M. Barr, Phys. Rev. D **69** (2004) 073010;

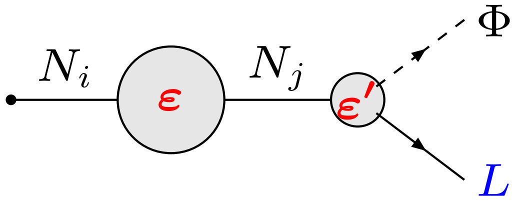
R. Gonzalez Felipe, F. R. Joaquim and B. M. Nobre, Phys. Rev. D **70** (2004) 085009;

G.C. Branco, R. González Felipe, F.R. Joaquim and B.M. Nobre, hep-ph/0507092.

$\vdots$

– Field-Theory Approach to Resonant Leptogenesis:

Formalism for incoherent mixing and decay of heavy Majorana neutrinos
[A.P., PR**D56** (1997) 5431; NP**B504** (1997) 61]:



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

where (2-gens only)

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

For 3-gen mixing, see A.P., T. Underwood, NP**B692** (2004) 303.

Resummed Effective Yukawa Couplings and Leptonic Asymmetries

Resummed decay amplitudes:

$$\mathcal{T}_{N_1} = (\bar{h}^\nu_+)_{l1}\, \bar{u}_l\, P_R u_{N_1}\,, \qquad \mathcal{T}^{\rm CP}_{N_1} = (\bar{h}^\nu_-)_{l1}\, \bar{u}_l\, P_R u_{N_1}\,,$$

$[(\bar{h}^\nu_+)_{l1} \overset{\rm CP}{\Longleftrightarrow} (\bar{h}^\nu_-)_{l1}]$, where

$$(\bar{h}^\nu_+)_{l1} = h^\nu_{l1} + iB_{l1} - \frac{i h^\nu_{l2}\, m_{N_1}\, (m_{N_1} A_{12} + m_{N_2} A^*_{12})}{m^2_{N_1} - m^2_{N_2} + 2i\, A_{22}\, m^2_{N_1}}\,,$$

$$(\bar{h}^\nu_-)_{l1} = h^{\nu\,*}_{l1} + iB^*_{l1} - \frac{i h^{\nu\,*}_{l2}\, m_{N_1}\, (m_{N_1} A^*_{12} + m_{N_2} A_{12})}{m^2_{N_1} - m^2_{N_2} + 2i\, A_{22}\, m^2_{N_1}}\,,$$

with

$$A_{12} = \frac{h^\nu_{l'i} h^{\nu\,*}_{l'j}}{16\pi}\,, \quad B_{l1} = \frac{h^{\nu *}_{l'1}\, h^\nu_{l'2}\, h^\nu_{l2}}{16\pi}\, f\left(\frac{m^2_{N_2}}{m^2_{N_1}}\right)\,,$$

are the resummed effective Yukawa couplings.

Leptonic Asymmetries:

$$
\begin{aligned}
\delta_{N_i} &= \frac{\Gamma(N_i \to L\Phi) \,-\, \Gamma(N_i \to L^C\Phi^\dagger)}{\Gamma(N_i \to L\Phi) \,+\, \Gamma(N_i \to L^C\Phi^\dagger)} \\
&= \frac{(\bar{h}^{\nu}_{+}{}^{\dagger}\bar{h}^{\nu}_{+})_{ii} \,-\, (\bar{h}^{\nu}_{-}{}^{\dagger}\bar{h}^{\nu}_{-})_{ii}}{(\bar{h}^{\nu}_{+}{}^{\dagger}\bar{h}^{\nu}_{+})_{ii} \,+\, (\bar{h}^{\nu}_{-}{}^{\dagger}\bar{h}^{\nu}_{-})_{ii}} \\
&\approx \varepsilon'_{N_i} \,+\, \varepsilon_{N_i} \,.
\end{aligned}
$$

ε'-type CP violation :

$$\varepsilon'_{N_i} \;=\; \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{ij}}{(h^{\nu\dagger}\,h^{\nu})_{ii}\,(h^{\nu\dagger}\,h^{\nu})_{jj}}\,\left(\frac{\Gamma^{(0)}_{N_j}}{m_{N_j}}\right)\; f\left(\frac{m^2_{N_j}}{m^2_{N_i}}\right)\,,$$

where

$$\Gamma^{(0)}_{N_j} \;=\; \frac{(h^{\nu\dagger}\,h^{\nu})_{jj}}{8\pi}\; m_{N_j}$$

is the tree-level decay width of N_j.

ε-type CP violation :

$$\varepsilon_{N_i} \;=\; \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{ij}}{(h^{\nu\dagger}\,h^{\nu})_{ii}\,(h^{\nu\dagger}\,h^{\nu})_{jj}}\;\frac{(m^2_{N_i}-m^2_{N_j})\,m_{N_i}\,\Gamma^{(0)}_{N_j}}{(m^2_{N_i}-m^2_{N_j})^2\;+\;m^2_{N_i}\Gamma^{(0)\,2}_{N_j}}$$

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

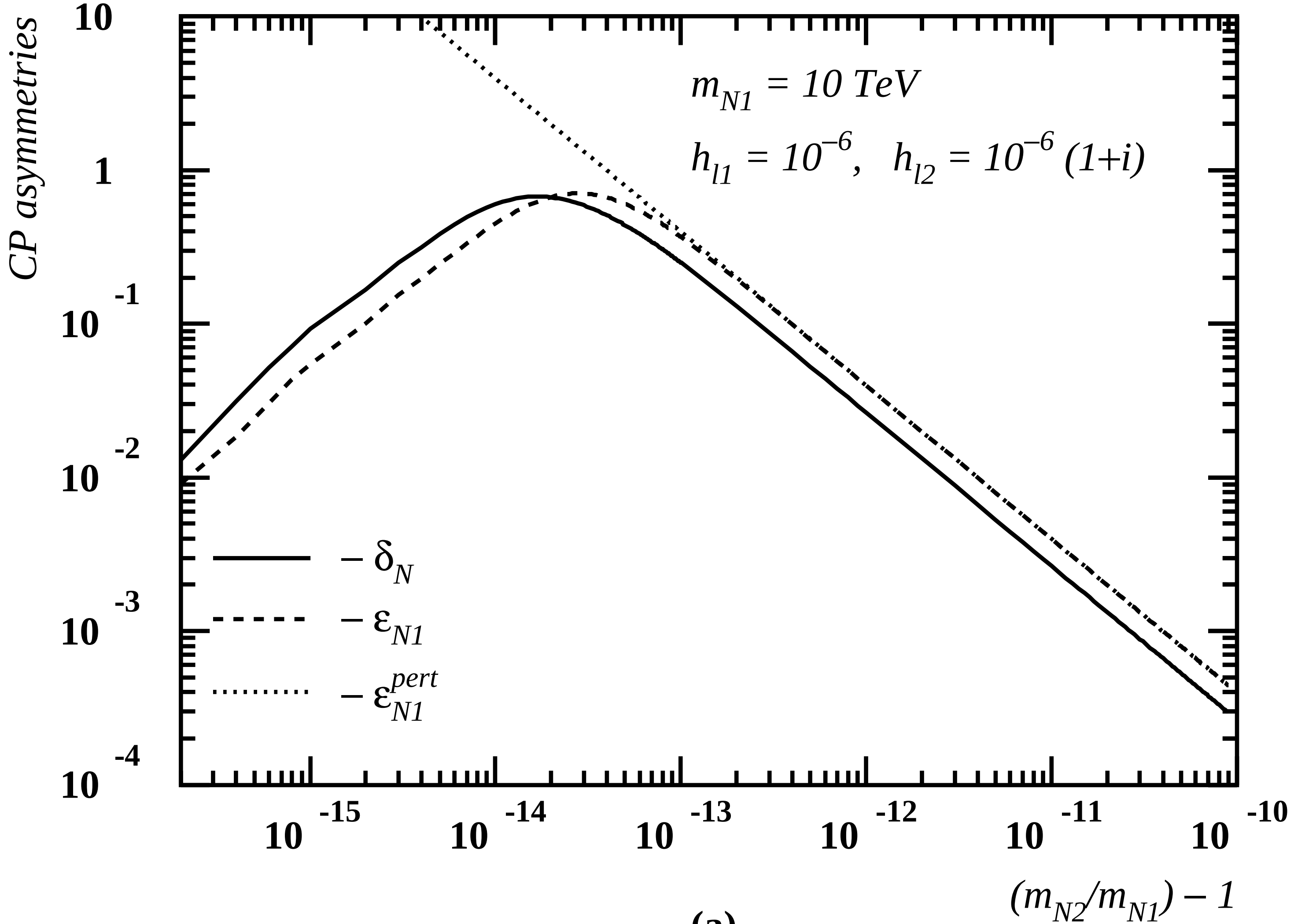
Resonant conditions for $O(1)$ leptonic asymmetries:

$\Rightarrow$ $$m_{N_2} - m_{N_1} \ \sim \ \tfrac{1}{2}\, \Gamma^{(0)}_{N_{1,2}}$$

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

[A.P., PRD**56** (1997) 5431.]

[A.P., PR**D56** (1997) 5431.]



(a)

• Flavoured Resonant Leptogenesis at the Electroweak Scale

Resonant τ-Leptogenesis (RτL) [A.P., PRL**95** (2005) 081602]

BAU generated by and protected in a single lepton flavour: $\frac{1}{3}B - L_\tau$.
3 gens of heavy Majorana neutrinos needed: $\nu_{1,2,3\,R}$.

· · ·

$$-\,\mathcal{L}_Y^{\rm lepton} \;=\; \frac{m_N}{2}\,(\bar{\nu}_{iR})^C\nu_{iR} \;+\; h^l_{ii}\,\bar{L}_i\Phi l_{iR} \;+\; h^{\nu_R}_{ij}\,\bar{L}_i\widetilde{\Phi}\nu_{jR} \;+\; {\rm H.c.}$$

3×3 **flavour structure**: SO(3)$_{\nu_R}\otimes$ U(1)$_{L_i+l_{iR}}$ $\Longrightarrow$ U(1)$_l$ $\simeq$ SO(2)$_l$.

U(1)$_l$ charges:

$$Q(L_i) \;=\; Q(l_{iR}) = 1\,, \quad Q\Big(\frac{\nu_{2R}+i\nu_{3R}}{\sqrt{2}}\Big) \;=\; -Q\Big(\frac{\nu_{2R}-i\nu_{3R}}{\sqrt{2}}\Big) \;=\; 1\,, \quad Q(\nu_{1R}) = 0$$

with

$$h^{\nu_R} \;=\; \left(\begin{array}{ccc} 0 & a\,e^{-i\pi/4} & a\,e^{i\pi/4} \\ 0 & b\,e^{-i\pi/4} & b\,e^{i\pi/4} \\ 0 & c\,e^{-i\pi/4} & c\,e^{i\pi/4} \end{array}\right)\,,$$

Explicit Breaking of $U(1)_l$

Yukawa sector:

$$h^{\nu_R} = \begin{pmatrix} \varepsilon_e & a\,e^{-i\pi/4} & a\,e^{i\pi/4} \\ \varepsilon_\mu & b\,e^{-i\pi/4} & b\,e^{i\pi/4} \\ \varepsilon_\tau & c\,e^{-i\pi/4} & c\,e^{i\pi/4} \end{pmatrix},$$

with $|\varepsilon_l| \sim 10^{-7}$, $|c| \sim 10^{-6}$, $|a| \sim |b| \sim 10^{-2}$.

Heavy Majorana neutrino sector:

[R. Gonzalez Felipe, F. R. Joaquim and B. M. Nobre, PRD**70** (2004) 085009]

$$\begin{aligned} M_S(m_N) &= M_S(M_X) - \frac{m_N}{8\pi^2}\,\mathrm{Re}\,[\,(h^{\nu_R})^\dagger h^{\nu_R}\,]\,\ln\frac{M_X}{m_N} \\ &= m_N\,\mathbf{1}_3 - \frac{|a|^2+|b|^2}{8\pi^2}\,m_N\,[\,\mathrm{diag}\,(0,1,1) + \mathcal{O}(\frac{|\varepsilon_{e,\mu,\tau}|}{(|a|^2+|b|^2)^{1/2}})\,]\,\ln\frac{M_X}{m_N} \\ &= m_N\,\mathbf{1}_3 + \Delta M_S\,, \end{aligned}$$

with $|(\Delta M_S)_{ij}| \ll m_N$, e.g. $|(\Delta M_S)_{ij}| \lesssim (10^{-5}\text{–}10^{-9}) \times m_N$.

Light neutrino-mass spectrum:

$$\mathbf{m}^{\nu} \;=\; \frac{v^2}{2m_N}\left(\begin{array}{ccc} \frac{\Delta m_N}{m_N}\,a^2-\varepsilon_e^2 & \frac{\Delta m_N}{m_N}\,ab-\varepsilon_e\varepsilon_\mu & \frac{\Delta m_N}{m_N}\,ac-\varepsilon_e\varepsilon_\tau \\ \frac{\Delta m_N}{m_N}\,ab-\varepsilon_e\varepsilon_\mu & \frac{\Delta m_N}{m_N}\,b^2-\varepsilon_\mu^2 & \frac{\Delta m_N}{m_N}\,bc-\varepsilon_\mu\varepsilon_\tau \\ \frac{\Delta m_N}{m_N}\,ac-\varepsilon_e\varepsilon_\tau & \frac{\Delta m_N}{m_N}\,bc-\varepsilon_\mu\varepsilon_\tau & \frac{\Delta m_N}{m_N}\,c^2-\varepsilon_\tau^2 \end{array}\right)\,,$$

where

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

and (in arbitrary complex units)

$$\frac{\Delta m_N}{m_N}\,a^2 \;=\; 4\,,\qquad \varepsilon_e \;=\; 2+\frac{21}{250}\,,\qquad \varepsilon_\mu \;=\; \frac{13}{50}\,,\qquad \varepsilon_\tau \;=\; -\frac{49}{128}\,,\qquad \frac{b}{a} \;=\; \frac{19}{50}\,.$$

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

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

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

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

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

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

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

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

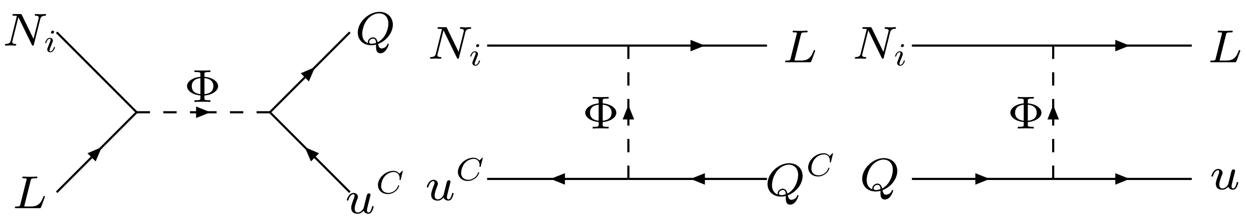
[S.Y. Khlebnikov, M.E. Shaposhnikov, NPB308 (1988) 885;
L. Carson, X. Li, L.D. McLerran, R.T. Wang, PRD42 (1990) 2127;
M. Laine, M.E. Shaposhnikov, PRD61 (2000) 117302.]

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

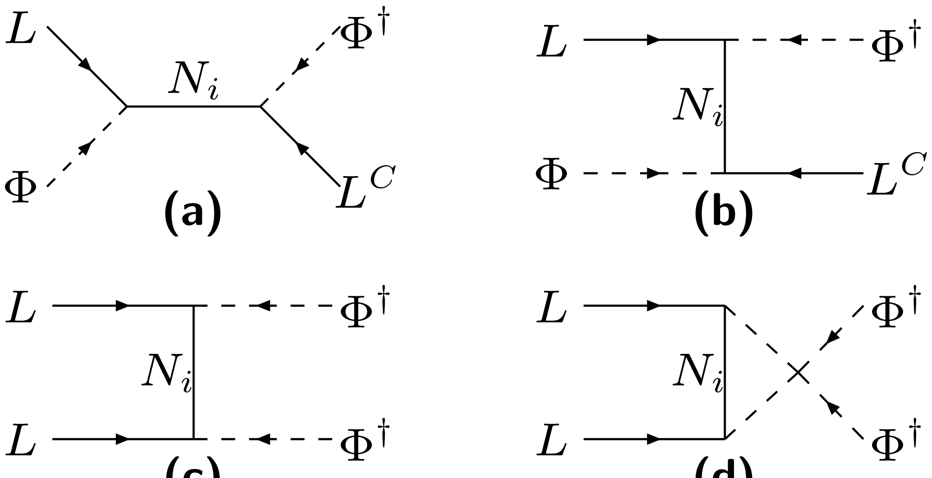
$$
\begin{aligned}
\frac{d\eta_{\Delta L_j}}{dz} &= \frac{z}{H(z=1)} \\
&\times \Big\{ \sum_{\alpha=1}^{3} \delta^{j}_{N_\alpha} \Big(\frac{\eta_{N_\alpha}}{\eta^{\rm eq}_{N_\alpha}} - 1\Big) \sum_{k=e,\mu,\tau} \Big(\Gamma^{D\,(\alpha k)} + \Gamma^{S\,(\alpha k)}_{\rm Yukawa} + \Gamma^{S\,(\alpha k)}_{\rm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

Computational package: LeptoGen

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

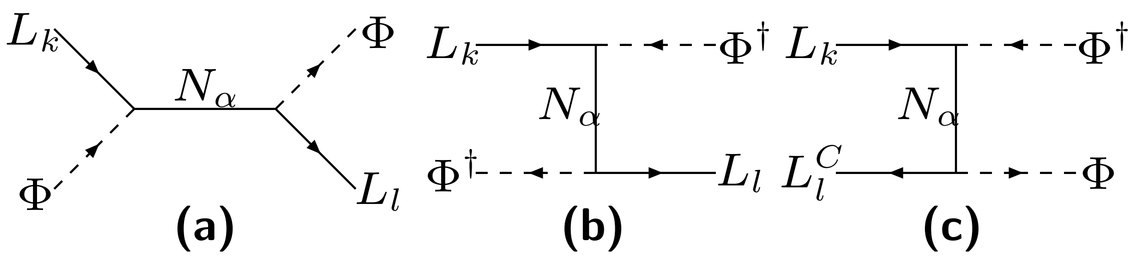


$\Delta L = 2$ scatterings involving L, Φ and N_i

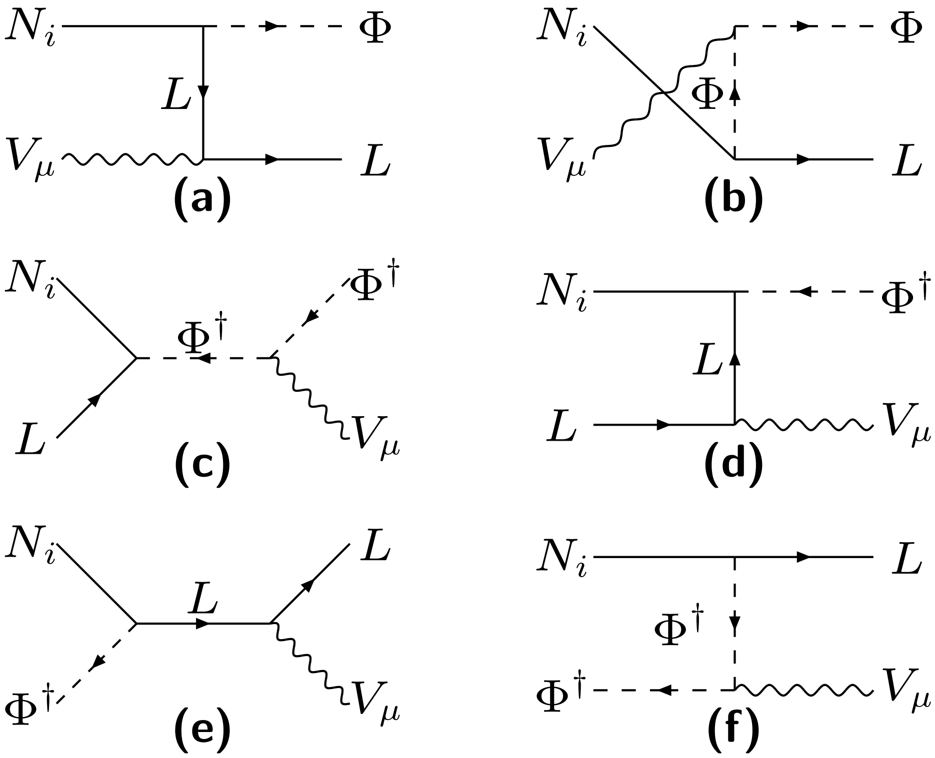


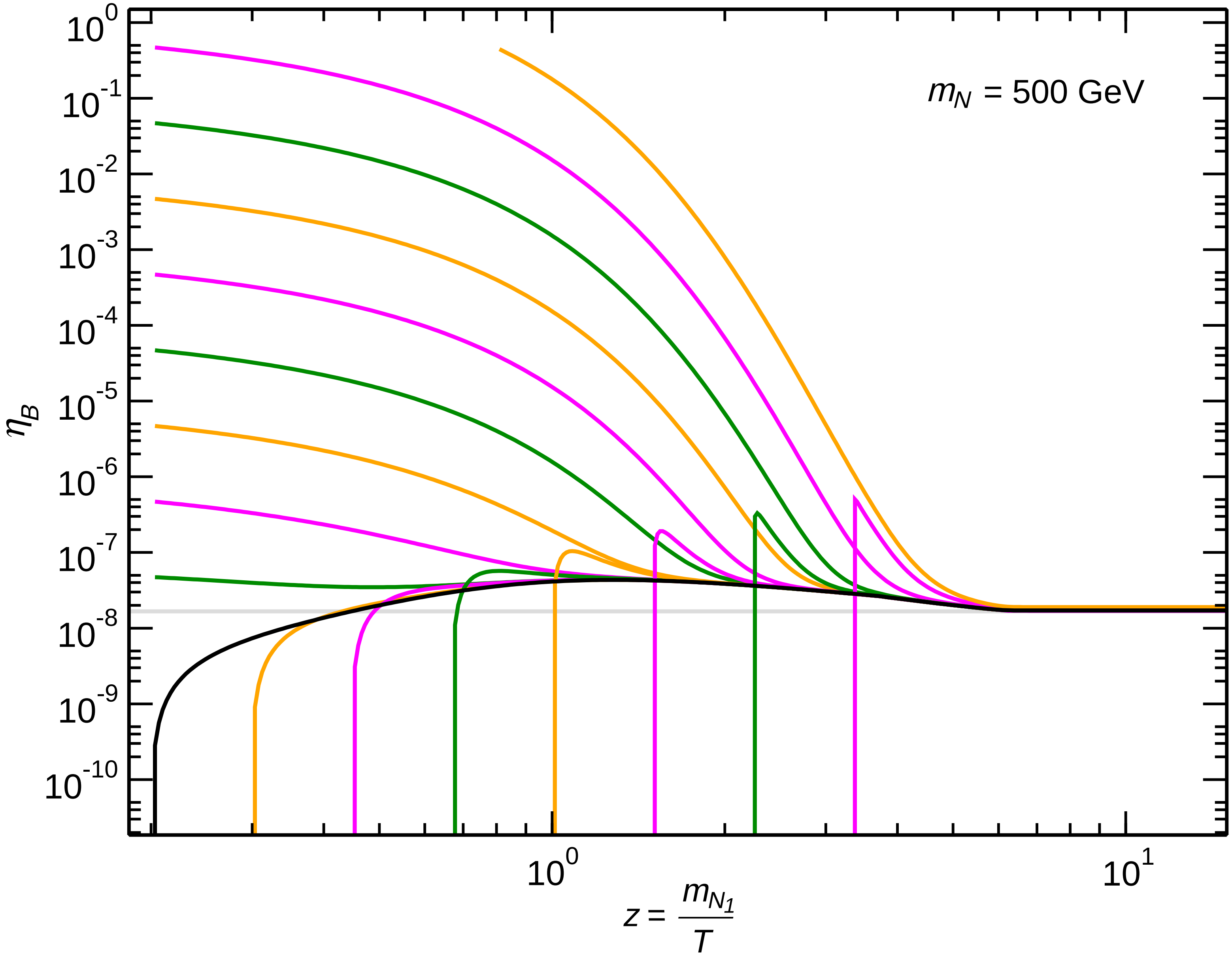
(a) **(b)** **(c)** **(d)**

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

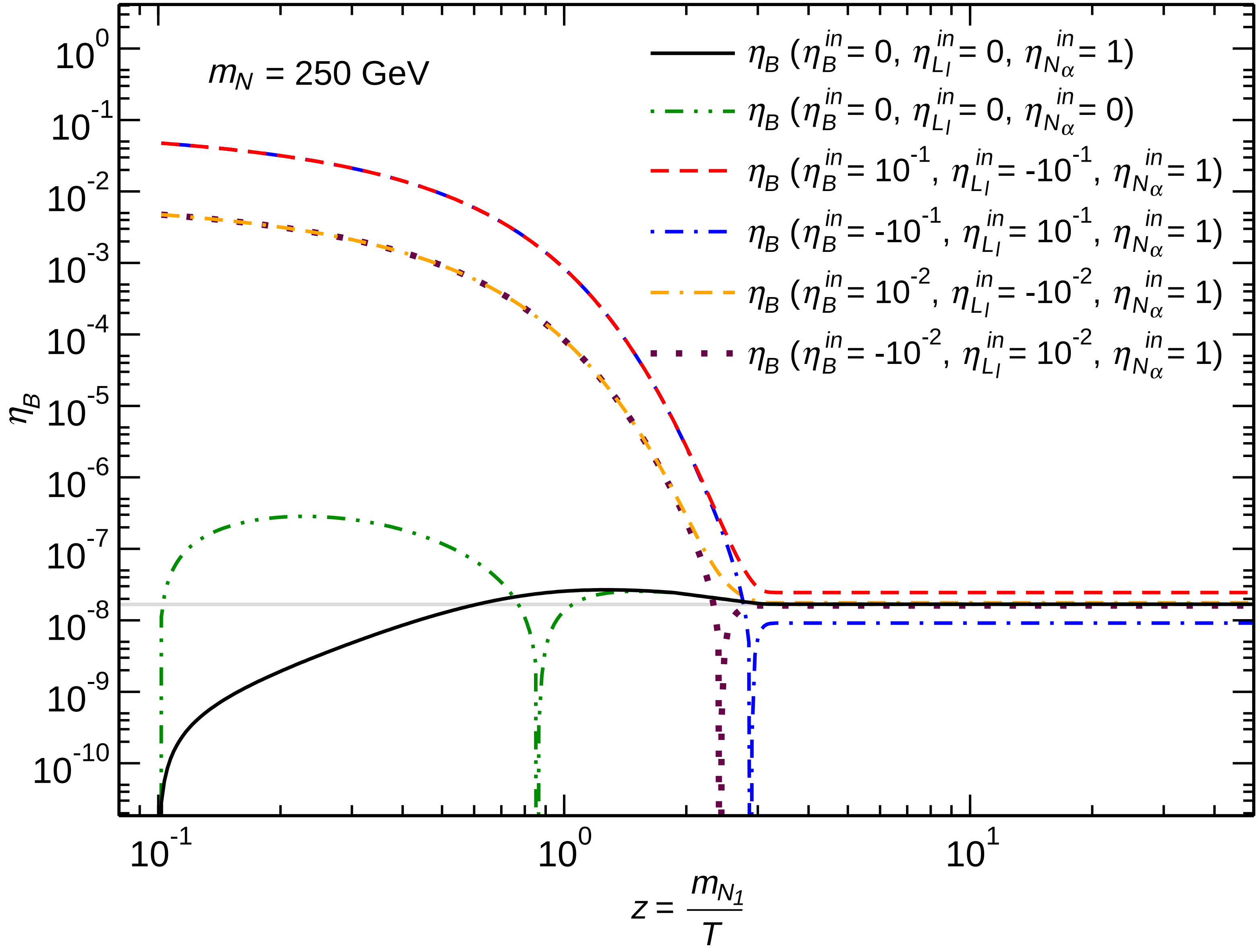


Gauge-mediated $\Delta L = 1$ scatterings

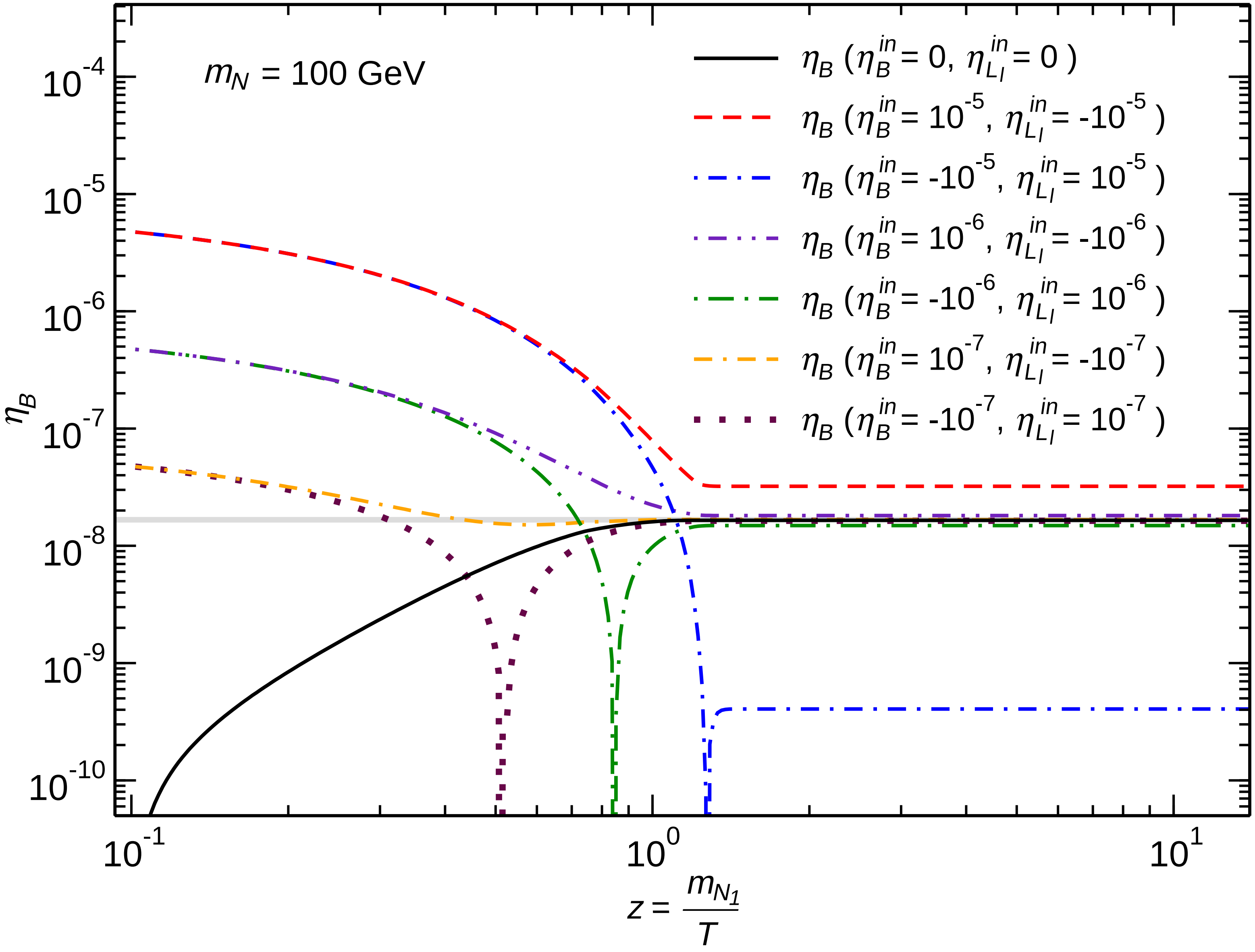



m_N = 500 GeV
η_B
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{0}
10^{1}
$z = \frac{m_{N_1}}{T}$

LeptoGen


m_N = 250 GeV
η_B (η_B^{in}= 0, $\eta_{L_l}^{in}$= 0, $\eta_{N_\alpha}^{in}$= 1)
η_B (η_B^{in}= 0, $\eta_{L_l}^{in}$= 0, $\eta_{N_\alpha}^{in}$= 0)
η_B (η_B^{in}= 10^{-1}, $\eta_{L_l}^{in}$= -10^{-1}, $\eta_{N_\alpha}^{in}$= 1)
η_B (η_B^{in}= -10^{-1}, $\eta_{L_l}^{in}$= 10^{-1}, $\eta_{N_\alpha}^{in}$= 1)
η_B (η_B^{in}= 10^{-2}, $\eta_{L_l}^{in}$= -10^{-2}, $\eta_{N_\alpha}^{in}$= 1)
η_B (η_B^{in}= -10^{-2}, $\eta_{L_l}^{in}$= 10^{-2}, $\eta_{N_\alpha}^{in}$= 1)
η_B
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-1}
10^{0}
10^{1}
$z = \frac{m_{N_1}}{T}$

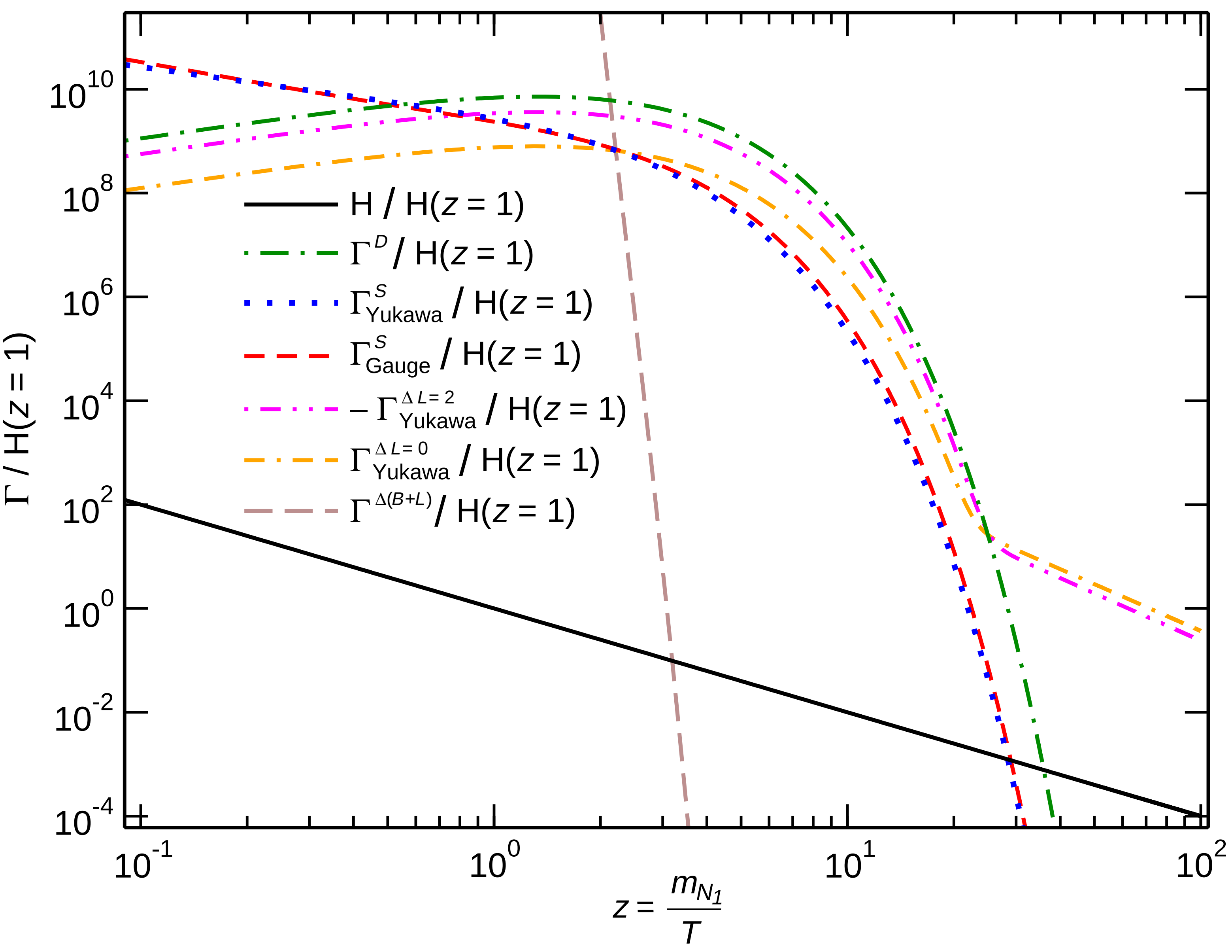
LeptoGen



m_N = 100 GeV
η_B (η_B^{in}= 0, $\eta_{L_l}^{in}$= 0)
η_B (η_B^{in}= 10^{-5}, $\eta_{L_l}^{in}$= -10^{-5})
η_B (η_B^{in}= -10^{-5}, $\eta_{L_l}^{in}$= 10^{-5})
η_B (η_B^{in}= 10^{-6}, $\eta_{L_l}^{in}$= -10^{-6})
η_B (η_B^{in}= -10^{-6}, $\eta_{L_l}^{in}$= 10^{-6})
η_B (η_B^{in}= 10^{-7}, $\eta_{L_l}^{in}$= -10^{-7})
η_B (η_B^{in}= -10^{-7}, $\eta_{L_l}^{in}$= 10^{-7})
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
η_B
10^{-1}
10^{0}
10^{1}
$z = \frac{m_{N_1}}{T}$

$m_N = 250$ GeV:

LeptoGen



– **Order-of-magnitude estimate of the BAU in a RτL model**

Define single lepton-flavour wash-out K-factors:

$$K^l_{N_\alpha} \;=\; \frac{\Gamma(N_\alpha \to L_l \Phi) \;+\; \Gamma(N_\alpha \to L_l^C \Phi^\dagger)}{H(T = m_N)}\;.$$

$\boldsymbol{m_N = 250}$ GeV:

$K^l_{N_\alpha}$		α 1	2	3
	e	1.0×10^{10}	1.0×10^{10}	25
l	μ	1.4×10^{9}	1.4×10^{9}	20
	τ	2.5	2.5	5.0

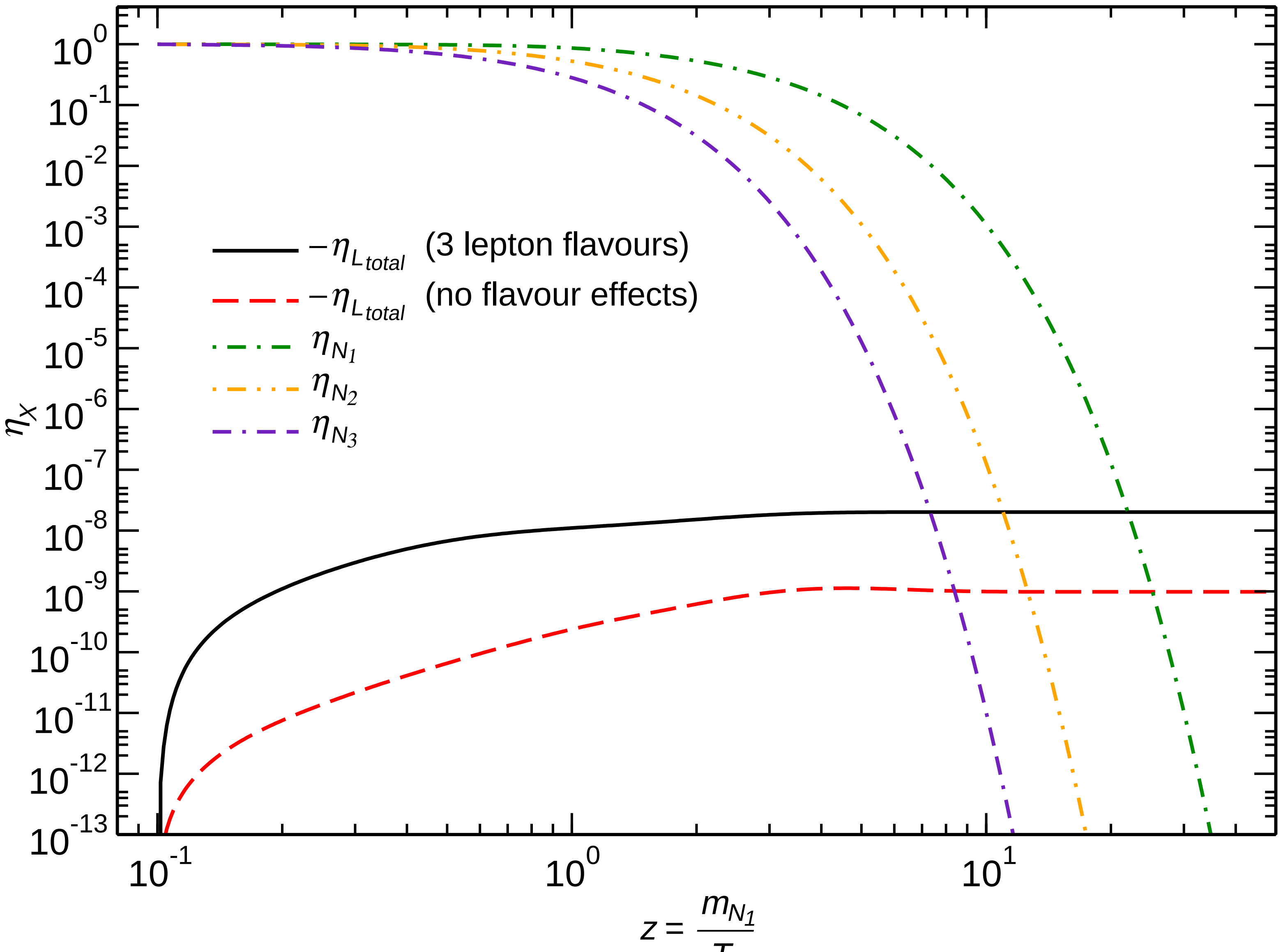
Naive order-of-magnitude estimate:

$$\eta_B \;\sim\; -\,10^{-2} \times \sum_{l,\alpha} \delta^l_{N_\alpha}\, \frac{K^l_{N_\alpha}}{K_l\, K_{N_\alpha}} \;\sim\; 6 \times 10^{-10}\;,$$

where $\delta^\tau_{N_3} \;\sim\; -\,10^{-6}$, $K_l = \sum_\alpha K^l_{N_\alpha}$ and $K_{N_\alpha} = \sum_l K^l_{N_\alpha}$.

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

LeptoGen



Recent related papers:

A. Abada, S. Davidson, F.-X. Josse-Michaux, M. Losada, A. Riotto, hep-ph/0601083;

E. Nardi, Y. Nir, E. Roulet, J. Racker, hep-ph/0601084.

• Phenomenology of RτL Models

• $0\nu\beta\beta$ Decay

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

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

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

RτL models generically realize an inverted light-neutrino hierarchy, with an effective Majorana mass given by

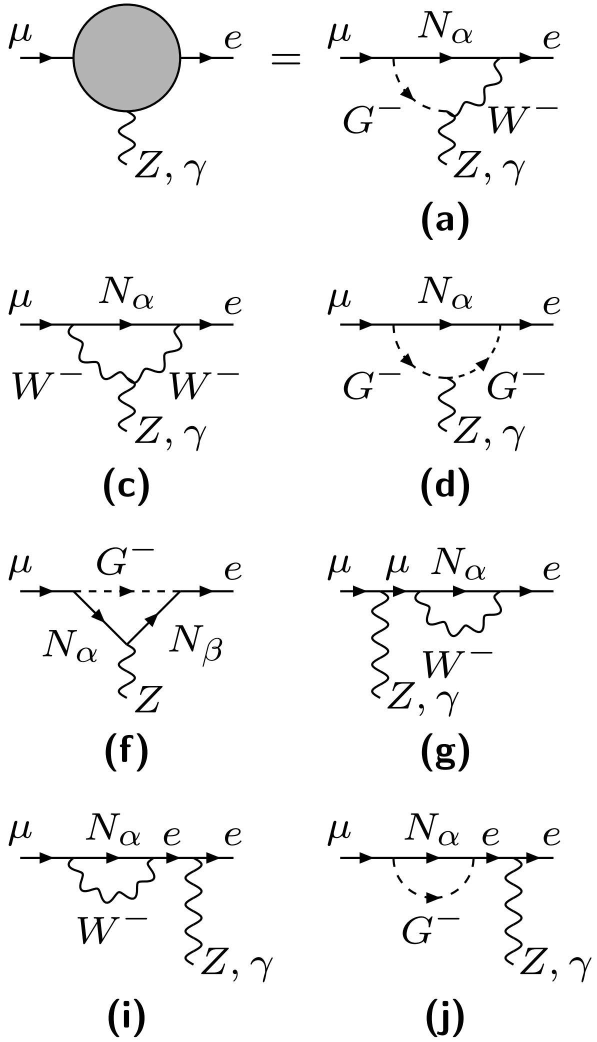
$$ |\langle m\rangle| \ = \ |(\mathbf{m}^\nu)_{ee}| \ = \ \frac{v^2}{2m_N}\,\Big|\,\frac{\Delta m_N}{m_N}\,a^2 \ - \ \varepsilon_e^2\,\Big| \ \approx \ 0.013\ \mathrm{eV}\ , $$

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

Future proposals for $0\nu\beta\beta$ experiments sensitive to $|\langle m\rangle| \sim 0.01$–$0.05$ eV, such as SuperNEMO . . .

• $\mu \to e\gamma$

[T.P. Cheng, L.F. Li, PRL**45** (1980) 1908;
SUSY: F. Borzumati, A. Masiero, PRL**57** (1986) 961;
A. Ilakovac, A.P., NPB**437** (1995) 491.]



(a) **(b)** **(c)** **(d)** **(e)** **(f)** **(g)** **(h)** **(i)** **(j)**

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

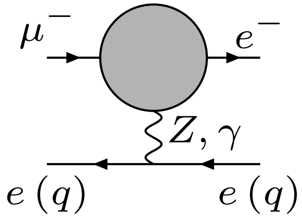
$$B(\mu \to e\gamma)$$

$$\sim\ 7 \cdot 10^{-4} \times \frac{(h^\nu_{eN} h^\nu_{\mu N})^2 v^4}{m_N^4}$$

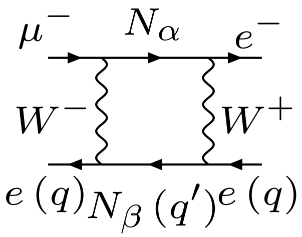
$$\sim 10^{-12}\ .$$

Proposed experimental sensitivity to $B(\mu \to e\gamma)$ is $\sim 10^{-14}$, according to the MEG collaboration at the PSI.

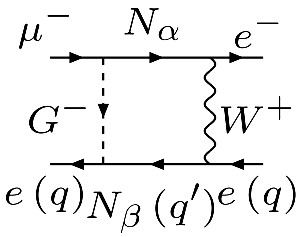
• Coherent $\mu \to e$ Conversion in Nuclei ($^{48}_{22}$Ti)



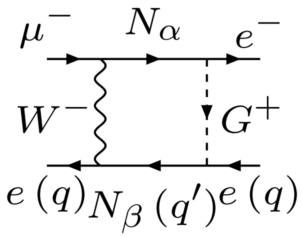
(a)



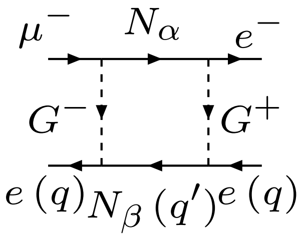
(b)



(c)



(d)



(e)

$+ \quad (\boldsymbol{e} \leftrightarrow \boldsymbol{e}^-)$

$\boldsymbol{m_N = 250}$ GeV:

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

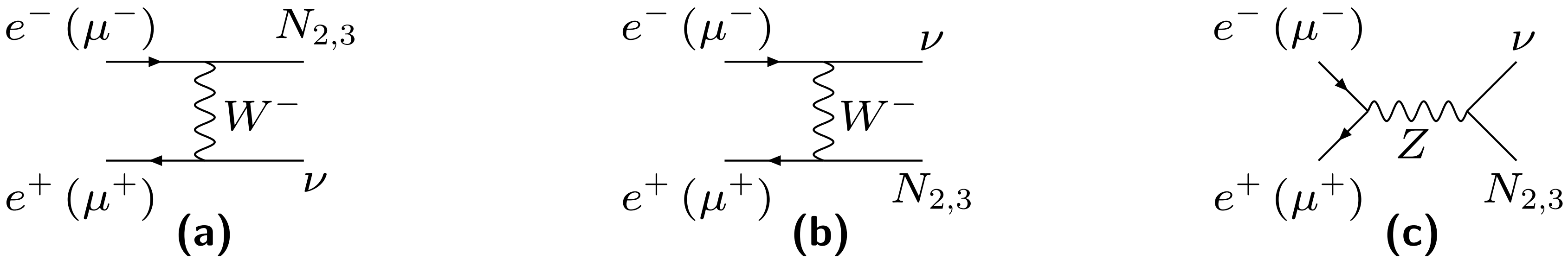
MECO collaboration at BNL will be sensitive to effects at the 10^{-16} level.

• $\boldsymbol{\mu \to eee}$

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

• Collider Heavy Majorana Neutrino Production

[For a recent study, see F. del Aguila and J.A. Aguilar–Saavedra, JHEP **0505** (2005) 026]



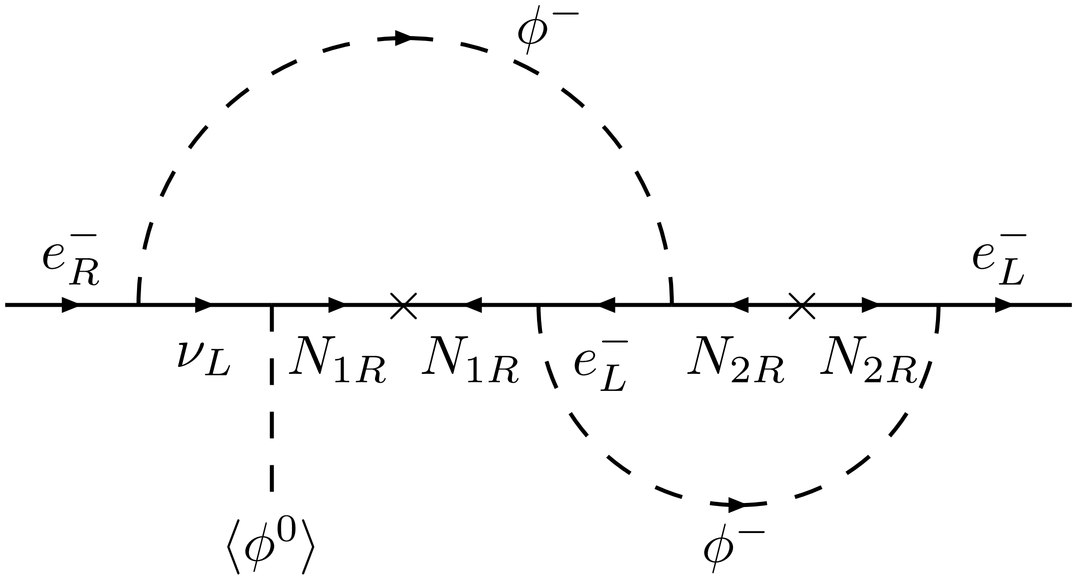
Production cross section for $\sqrt{s} = 1$ TeV ($m_N = 200$–500 GeV):

$$\sigma(e^- e^+ \to N\nu) \;\sim\; 10^5 \times \frac{|h^{\nu}_{eN}|^2 v^2}{m_N^2} \;\; \mathrm{fb}$$

With total integrated luminosity 100 fb^{-1}, we get for $|h^{\nu}_{eN}| \sim 10^{-2}$ and $m_N \sim v \sim 200$ GeV, about 1000 events!

• Electric Dipole Moment (EDM) Predictions

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



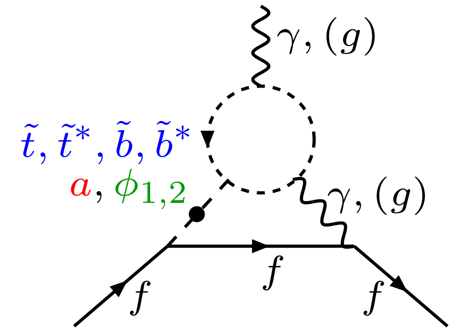
$$\frac{d_e}{e} \sim \frac{1}{(16\pi^2)^2}\,\frac{m_e}{m_{N_1}^2}\,\frac{\mathrm{Im}\,(h^{\nu\,\dagger}\,h^\nu)_{12}^2\,m_{N_1}\,m_{N_2}\,(m_{N_2}^2 - m_{N_1}^2)}{(m_{N_1}^2 + m_{N_2}^2)^2}\;\ln\frac{m_{N_1}}{M_W}$$

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

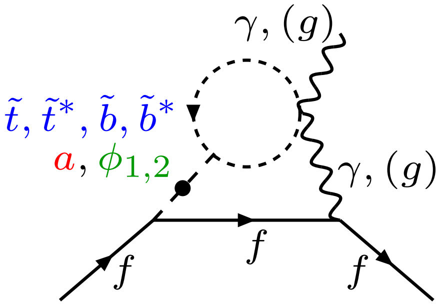
$\therefore$ Observation of an electron EDM $d_e \gtrsim 10^{-32}\ e\cdot\mathrm{cm}$ will rule out leptogenesis in the SM with singlet neutrinos.

Higgs-mediated EDMs and Electroweak Baryogenesis in the MSSM

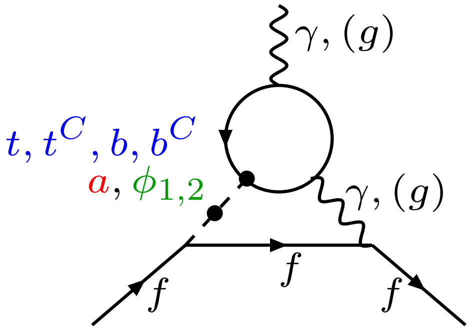
[D. Chang, W.-Y. Keung, A.P., PRL**82** (1999) 900; A.P., NP**B644** (2002) 263.]



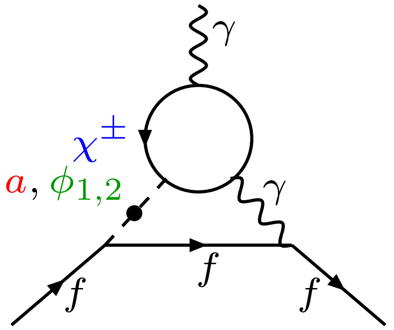
(a)



(b)

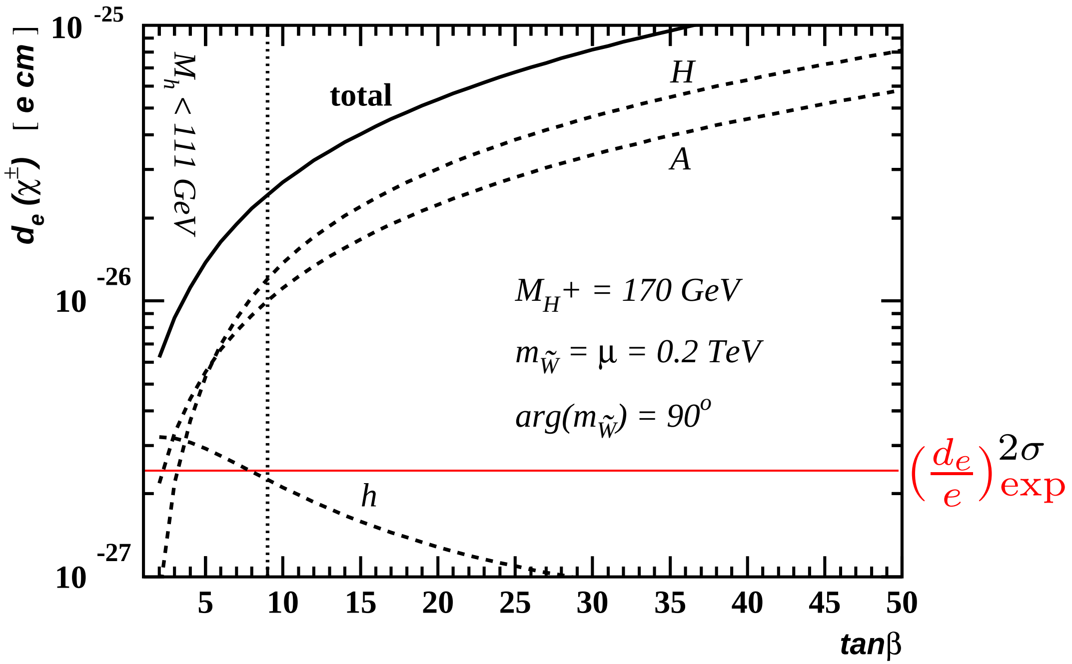


(c)



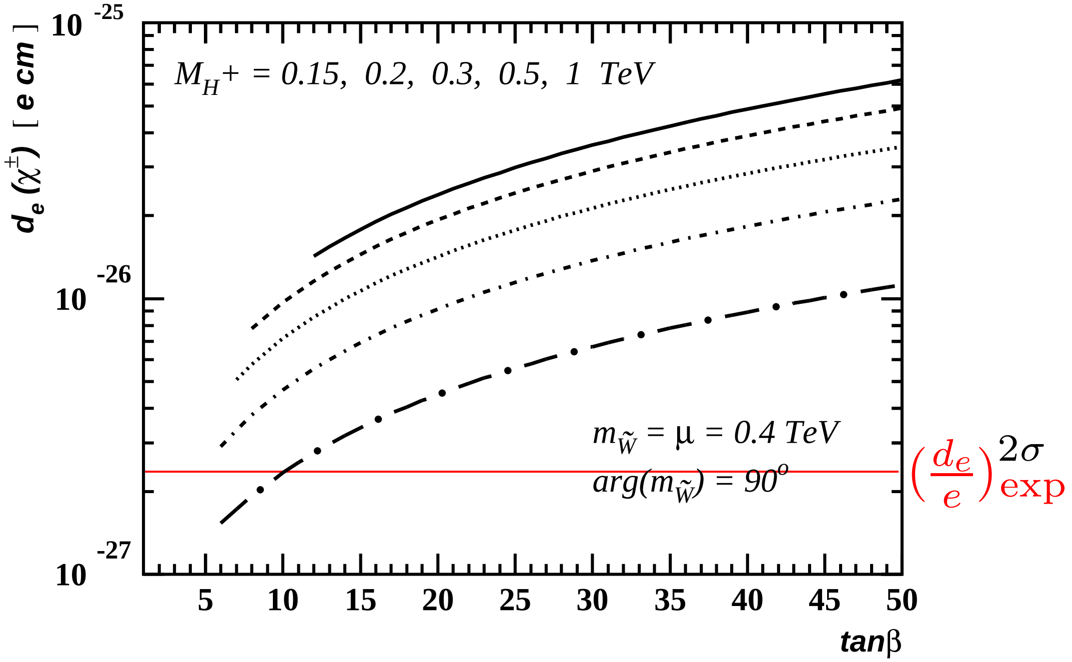
(d)

$$d_f \;\propto\; \arg(\mu A_t,\ \mu m_{\tilde g},\ \mu m_{\widetilde W})\,,\ \tan\beta\,,\ \frac{1}{M_a}$$



$d_e(\chi^\pm)$ [e cm]
10^{-25}
10^{-26}
10^{-27}
$M_h < 111$ GeV
total
H
A
h
M_{H^+} = 170 GeV
$m_{\tilde{W}} = \mu$ = 0.2 TeV
$arg(m_{\tilde{W}}) = 90^o$
$\left(\frac{d_e}{e}\right)^{2\sigma}_{\rm exp}$
5
10
15
20
25
30
35
40
45
50
tanβ

(a)



$d_e(\chi^\pm)$ [e cm]
10^{-25}
10^{-26}
10^{-27}
M_{H^+} = 0.15, 0.2, 0.3, 0.5, 1 TeV
$m_{\tilde{W}} = \mu$ = 0.4 TeV
$arg(m_{\tilde{W}}) = 90^o$
$\left(\frac{d_e}{e}\right)^{2\sigma}_{\rm exp}$
5
10
15
20
25
30
35
40
45
50
tanβ

(b)

• Conclusions

- **Resonant Leptogenesis provides an interesting mechanism for explaining our observable matter–antimatter asymmetric Universe.**

- **Final Baryon Asymmetry is almost independent of any pre-existing lepton- or baryon-number abundance.**
  This is due to quasi-in-equilibrium dynamics and the resonant lepton-to-antilepton conversion.

- **Improved BEs derived with single lepton-flavour effects included.**
  - Scale of leptogenesis can be as low as $T_c \approx 130$ GeV, in complete agreement with the current neutrino data.
  - Models with signatures at the observable level: $B(\mu \to e\gamma) \sim 10^{-13}$, $B(\mu \to eee) \sim 10^{-14}$, $B(\mu \to e) \sim 10^{-13}$, LNV/LFV at the ILC.
  - Observation of an electron EDM $d_e \gtrsim 10^{-32}\ e \cdot \mathrm{cm}$ will rule out leptogenesis in the SM with singlet neutrinos.

- **Resonant τ-Leptogenesis could, *in principle*, provide a laboratory testable solution to the Baryon Asymmetry in the Universe.**

• Future Prospects

- **Further improvements on calculable theoretical uncertainties, currently at the ∼ 30% level.**
  Thermal effects beyond HTL, Bose–Fermi statistics effects, higher-order corrections, $1 \leftrightarrow 3$ processes, . . .

- **Connections between neutrino-mass parameters, leptogenesis and laboratory observables in constrained minimal versions of RL models.**

- **Any links of EW-scale RL models with inflation?**

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- **Connections between neutrino-mass parameters, leptogenesis and laboratory observables in constrained minimal versions of RL models.** [A.P. and T. Underwood, work in progress]

- **Any links of EW-scale RL models with inflation?**

  F_D-Term Hybrid Model: [B. Garbrecht and A.P., hep-ph/0601080]

$$\begin{aligned} W \ &= \ \kappa \widehat{S}\,(\widehat{X}_1\widehat{X}_2 \ - \ M^2) \ + \ \lambda \widehat{S}\widehat{H}_u\widehat{H}_d \ + \ \frac{\rho}{2}\widehat{S}\,\widehat{N}_i\widehat{N}_i \\ &\quad + \ h^{\nu}_{ij}\widehat{L}_i\widehat{H}_u\widehat{N}_j \ + \ W^{(\mu=0)}_{\rm MSSM} \ + \ \text{FI } D\text{-term of U(1)}_X \end{aligned}$$