

Relativistic and Spectator Effects in Leptogenesis with heavy Sterile Neutrinos

Philipp Klose

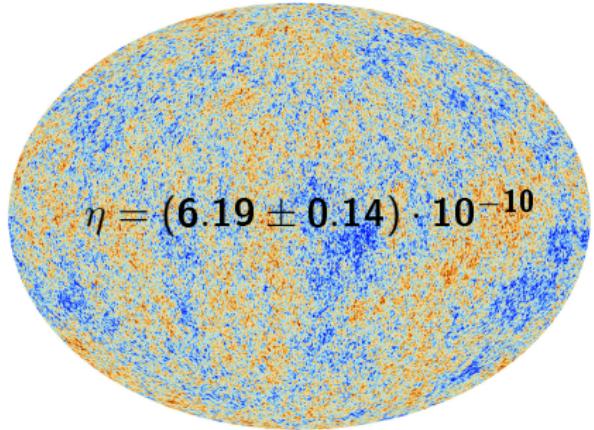
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DESY Theory Workshop 2019

See also: arxiv:1904.09956,

written in Collaboration with Prof. Björn Garbrecht and Dr. Carlos Tamarit based at the
Technical University of Munich

Baryogenesis via Leptogenesis



Three Generations of Matter (Fermions) spin $\frac{1}{2}$			
	I	II	
mass →	2.4 MeV	1.27 GeV	171.2 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
name →	u up left	c charm left	t top left
Quarks	Left	Right	Right
	d down left	s strange left	b bottom left
	Left	Right	Right
Leptons			
	0 eV $0\nu_e$ electron neutrino	0 eV $0\nu_\mu$ muon neutrino	0 eV $0\nu_\tau$ tau neutrino
	Left	Right	Right
	e electron -1	μ muon -1	τ tau -1
	Left	Right	Right
Bosons (Forces) spin 1			
	g gluon	γ photon	Z^0 weak force
	Left	Right	Right
Bosons (Forces) spin 0			
	H Higgs boson	W^\pm weak force	W^\pm weak force
	Left	Right	Right

- Baryon Asymmetry \Rightarrow Standard Model needs more CP -violation
- One Solution: Add sterile, CP -violating Majorana Neutrinos

High-Scale Leptogenesis from First Principles

Good: Nonrelativistic Semiclassical Boltzmann Equations

Better: Generalized Relativistic Boltzmann Equations from first principles of Non-equilibrium QFT

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“New” Physics we add:

- Thermal corrections for intermediate temperatures
- Helicity dependence of N_1 interactions
- Interplay of relativistic and spectator effects

See also:

- Phys. Lett. B 174 (1986), p. 45-47 for initial leptogenesis paper
- arXiv:1404.2915 for partially equilibrated spectators
- arXiv:1002.0022 and arXiv:1012.3784 for thermal corrections
- arXiv:1002.1326 and arXiv:1007.4783 for leptogenesis from first principles

Minimal Model for Leptogenesis

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \overline{N_i} (\mathrm{i} \not{\partial} - M_i) N_i - (F_i \overline{N_i} \widetilde{\phi} \mathbf{P}_L I_{\parallel} + \text{h.c.})$$

- 2 sterile, hierarchical Neutrinos N_1, N_2 with $10^{10} \text{ GeV} \lesssim M_1 \ll M_2$
- N_i couple to single lepton flavour combination I_{\parallel}

Integrate out heavier $N_2 \Rightarrow$ effective theory with only N_1

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Free Parameters

- 1 Washout Strength:

$$K \equiv \frac{\Gamma(N_1 \rightarrow l\phi)}{H(M_1 = T)}$$

- 2 N_1 Decay Asymmetry:

$$\epsilon \equiv \frac{\Gamma(N_1 \rightarrow l\phi) - \Gamma(N_1 \rightarrow \bar{l}\phi)}{\Gamma(N_1 \rightarrow l\phi) + \Gamma(N_1 \rightarrow \bar{l}\phi)}$$

Generalized Relativistic Boltzmann Equations

$$\frac{d}{dx} Y_{N_1\text{even}} = -\Gamma (Y_{N_1\text{even}} - Y_{N_1\text{eq}})$$

$$\frac{d}{dx} Y_{N_1\text{odd}} = -\Gamma Y_{N_1\text{odd}} + \eta_{N_1} \tilde{\Gamma} \left(Y_{I_{\parallel}} + \frac{1}{2} Y_{\phi} \right)$$

$$\frac{d}{dx} Y_{B-L} = +\tilde{\Gamma} Y_{N_1\text{odd}} - \epsilon_{\text{eff}} \Gamma (Y_{N_1\text{even}} - Y_{N_1\text{eq}}) + \eta_{N_1} \Gamma \left(Y_{I_{\parallel}} + \frac{1}{2} Y_{\phi} \right)$$

Yields: $B - L$ Asymmetry $\Leftrightarrow Y_{B-L} = \frac{1}{s}(n_B - n_L)$

N_1 number densities $\Leftrightarrow Y_{N_1\text{even/odd}} = \frac{1}{s}(n_{N_1,+} \pm n_{N_1,-})$

Time Var.: $x \equiv M_1/T \propto a(t)$

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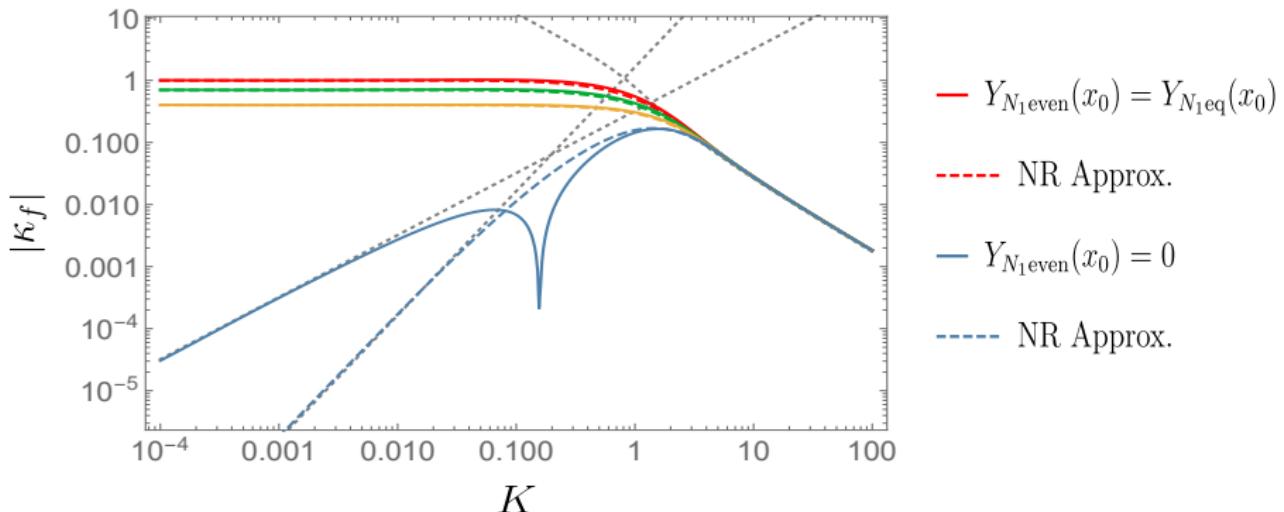
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\Rightarrow Encode thermal bath via efficiency κ_f :

$$Y_{B-L}(x \rightarrow \infty) = \epsilon_0 Y_{N_1,\text{eq}}(x_0) \cdot \kappa_f$$

Corrected Weak Washout Efficiency Scaling

- Leptogenesis without Spectators:



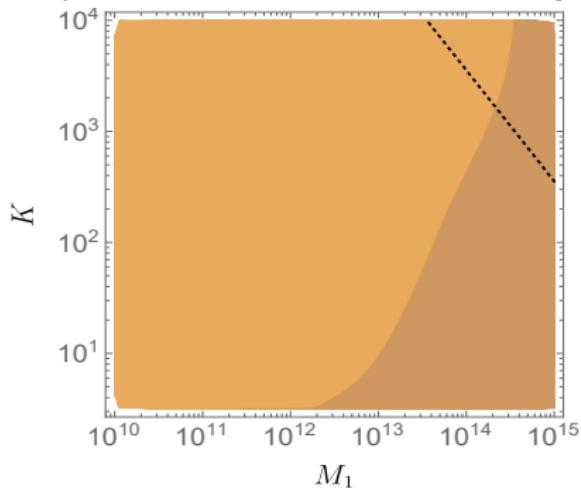
⇒ Corrected Efficiency Scaling for $K \ll 1$ & $Y_{N_1\text{eq}}(x_0) = 0$:

$$\kappa_f \approx -0.32 K + O(K^2) \quad \text{vs.} \quad \kappa_f^{\text{NR}} \approx 1.65 K^2$$

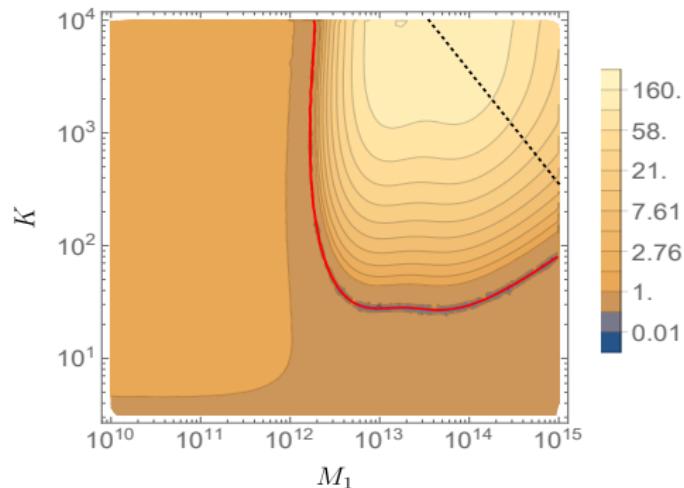
Strong Washout Initial Condition Dependence

- Realistic Model for $M_1 \sim 10^{13}$ GeV
⇒ Dynamic b-Yukawa & weak Sphaleron interactions

κ_f enhancement for $Y_{N_1\text{even}}(x_0) = Y_{N_1\text{eq}}(x_0)$



κ_f enhancement for $Y_{N_1\text{even}}(x_0) = 0$



- Equal Baseline Efficiency
- $\sim 10^2$ Enhancement and Initial condition dependence !

Take Home Messages

Summary:

- We derived Generalized Relativistic Boltzmann Equations from First Principles
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- Interplay Relativistic Effects & Spectators \Rightarrow Strong Washout Initial Condition Dependence

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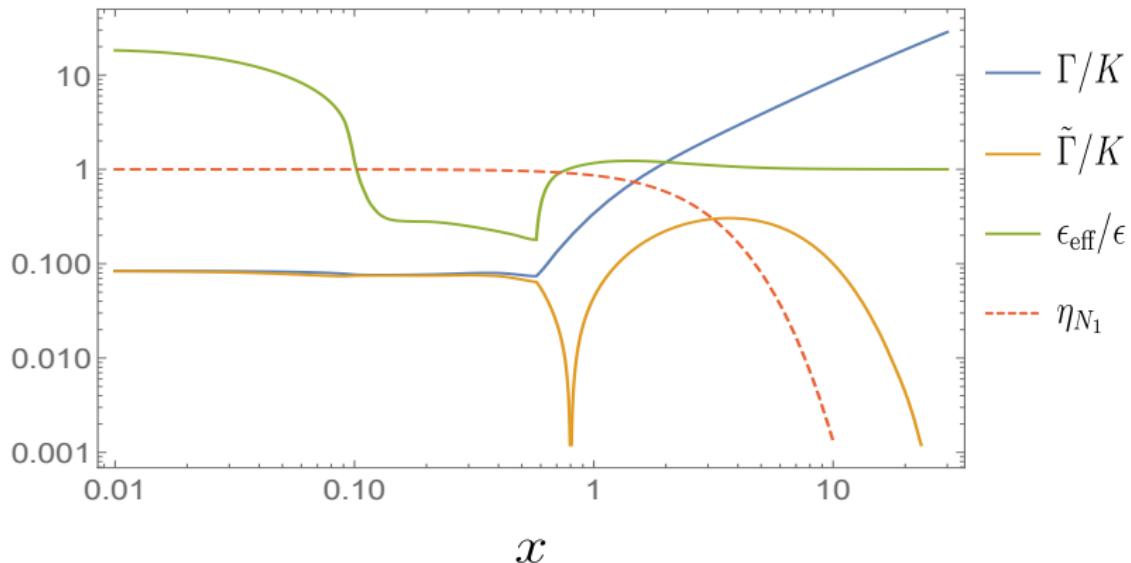
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- Interplay Relativistic Effects & Spectators \Rightarrow Strong Washout Initial Condition Dependence

$\sim 10^2$ Enhancement for vanishing initial N_1 abundance!

Numerics for the Transport Coefficients



- We computed leading log thermal corrections
- Higgs decays important for ϵ_{eff} at high temperatures

Details on Γ , $\tilde{\Gamma}$

Decay Rates:

$$\Gamma = K \frac{1}{2} (\gamma_{\text{LNC}} + \gamma_{\text{LNV}}) , \quad \tilde{\Gamma} \equiv K \frac{1}{2} (\gamma_{\text{LNC}} - \gamma_{\text{LNV}})$$

where

$$\begin{aligned}\gamma_{\text{LNC}} &\equiv \left\langle \frac{32\pi}{T_{\text{com}}} \frac{(k_\mu + \tilde{k}_\mu) \hat{\Sigma}_{N_1}^{\mathcal{A}\mu}(k)}{k_0} \right\rangle \\ \gamma_{\text{LNV}} &\equiv \left\langle \frac{32\pi}{T_{\text{com}}} \frac{(k_\mu - \tilde{k}_\mu) \hat{\Sigma}_{N_1}^{\mathcal{A}\mu}(k)}{k_0} \right\rangle\end{aligned}$$

Sterile Neutrino Momenta:

$$\tilde{k}^\mu \equiv \frac{1}{2} h \text{tr} [\mathsf{P}_h \gamma^5 \gamma^\mu \not{k}] = (|\mathbf{k}|, k_0 \hat{\mathbf{k}}) , \quad k^2 = M_1^2 a^2(t)$$

Thermal Average:

$$\langle X(\mathbf{k}) \rangle = \frac{2}{n_{N_1, \text{eq}}} \int \frac{d^3 \mathbf{k}}{(2\pi)^3} X(k) \frac{1}{e^{\beta k_0} + 1}$$

Details on ϵ_{eff}

Source Term:

$$\epsilon_{\text{eff}} \Gamma = \epsilon_0 K \left\langle \frac{(32\pi)^2}{T} \frac{\hat{\Sigma}_{N_1\mu} \hat{\Sigma}_{N_1\mu}}{k_0} \right\rangle$$

Reduced Selfenergy Decomposition:

$$\hat{\Sigma}_{N_1}^\mu = \frac{1}{k^2} [k^\mu (\hat{\Sigma}_{N_1}^\alpha k_\alpha) - \tilde{k}^\mu (\hat{\Sigma}_{N_1}^\alpha \tilde{k}_\alpha)]$$

\Rightarrow

$$\begin{aligned}\epsilon_{\text{eff}} \Gamma &= \epsilon_0 K \left\langle \frac{k_0}{T} \frac{T^2}{M_1^2 a^2(t)} \frac{(32\pi)^2}{T^2} \frac{\hat{\Sigma}_{N_1\mu}(k^\mu + \tilde{k}^\mu)}{k_0} \frac{\hat{\Sigma}_{N_1\mu}(k^\mu - \tilde{k}^\mu)}{k_0} \right\rangle \\ &\approx \epsilon_0 K \frac{T^2}{M_1^2 a^2(t)} \left\langle \frac{k_0}{T} \right\rangle \left\langle \frac{32\pi}{T} \frac{\hat{\Sigma}_{N_1\mu}(k^\mu + \tilde{k}^\mu)}{k_0} \right\rangle \left\langle \frac{32\pi}{T} \frac{\hat{\Sigma}_{N_1\mu}(k^\mu - \tilde{k}^\mu)}{k_0} \right\rangle \\ &= \epsilon_0 K \frac{T^2}{M_1^2 a^2(t)} \left\langle \frac{k_0}{T} \right\rangle \gamma_{\text{LNC}} \gamma_{\text{LNV}}\end{aligned}$$

Reduced Sterile Neutrino Selfenergy

$$\hat{\Sigma}_{N_1}^{\mu}(k) = f_F^{-1}(k_0) \int \frac{d^4 p}{(2\pi)^4} f_F(p_0) f_B(k_0 - p_0) \Delta_{\phi}^A(k - p) \text{tr} [\gamma^{\mu} S_I^A(p)]$$

Spectral Functions:

$$S_I^A(p) = P_L \left[(\not{p} - \Sigma_I^H(p)) \cdot \frac{\Gamma_I}{\Omega_I^2 + \Gamma_I^2} - \Sigma_I^A(p) \frac{\Omega_I}{\Omega_I^2 + \Gamma_I^2} \right] P_R ,$$

$$\Delta_{\phi}^A(q) = \frac{\Gamma_{\phi}}{\Omega_{\phi}^2 + \Gamma_{\phi}^2}$$

$$\Gamma_{\phi}(q) = \Pi_{\phi}^A , \quad \Gamma_I(p) = 2(p_{\mu} - \Sigma_{I,\mu}^H) \cdot \Sigma_I^{A,\mu} ,$$

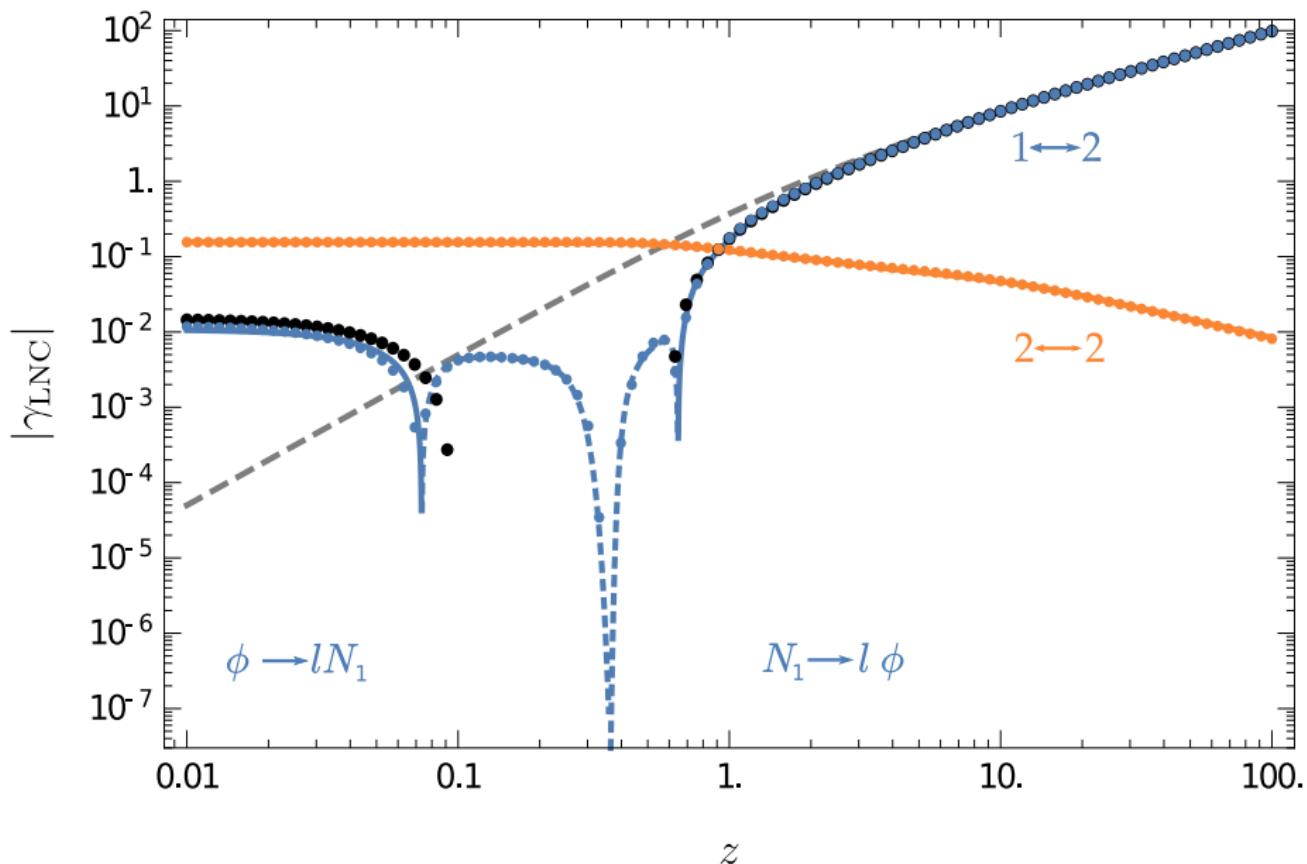
$$\Omega_{\phi}(q) = q^2 - \Pi_{\phi}^H , \quad \Omega_I(p) = (p_{\mu} - \Sigma_{I,\mu}^H)^2 - (\Sigma_{I,\mu}^A)^2$$

Standard Model HTL Selfenergies:

$$\Pi^{\mathcal{H},\text{HTL}} = m_{\phi}^2 , \quad \Sigma_I^{\mathcal{H},\text{HTL}}(p) = \frac{m_I^2}{4} \frac{\not{p}}{|\mathbf{p}|^2} \ln \left| \frac{p_0 + |\mathbf{p}|}{p_0 - |\mathbf{p}|} \right| - \frac{m_I^2}{2} \frac{\not{p}}{|\mathbf{p}|^2} ,$$

$$\Pi^{\mathcal{A},\text{HTL}} = 0 , \quad \Sigma_I^{\mathcal{A},\text{HTL}}(p) = \frac{m_I^2}{4} \frac{\not{p}}{|\mathbf{p}|^2} 2\pi \theta(-p^2) .$$

Individual Contributions to γ_{LNC}



Individual Contributions to γ_{LNV}

