Relativistic and Spectator Effects in Leptogenesis with heavy Sterile Neutrinos

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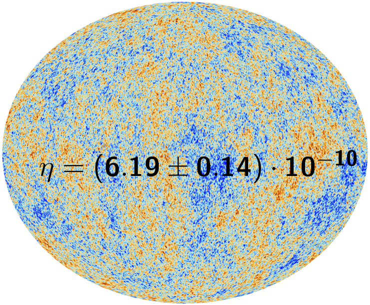
See also: arxiv:1904.09956,

written in Collaboration with Prof. Björn Garbrecht and Dr. Carlos Tamarit

Baryogenesis via Leptogenesis



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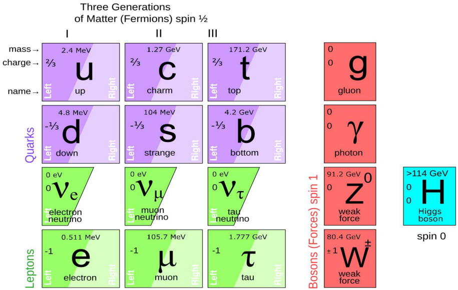

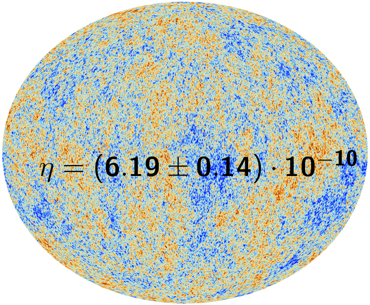

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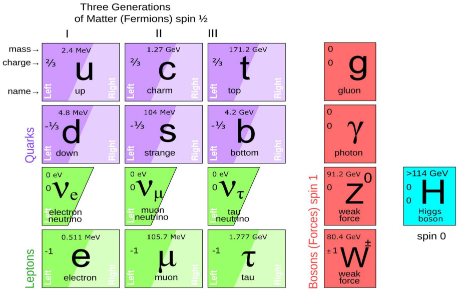

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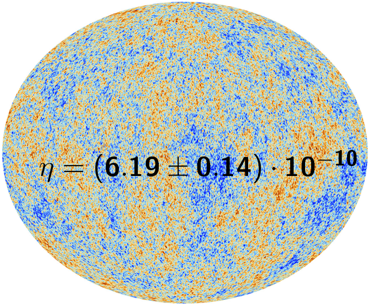

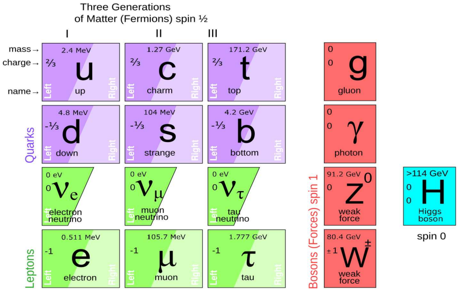

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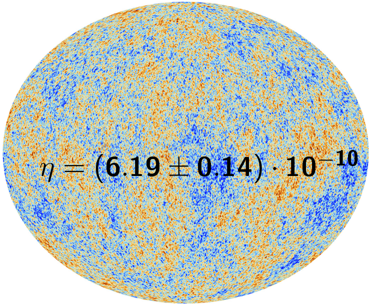

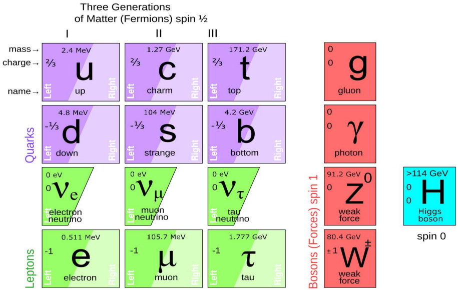

- Baryon Asymmetry ⇒ Standard Model needs more *CP*-violation
- One Solution: Add right-handed Majorana Neutrinos
- Standard Model transforms Lepton into Baryon asymmetry

High-Scale Leptogenesis from First Principles

Good: Nonrelativistic Semiclassical Boltzmann Equations

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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

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\overline{N_i}\big(\mathrm{i}\,\partial\!\!\!/ - M_i\big)N_i - \big(F_i\,\overline{N_i}\widetilde{\phi}\,\mathrm{P}_L\,l_\parallel + \mathrm{h.c.}\big)$$

- 2 sterile Neutrinos N_1, N_2
- Hierarchical Masses $10^{10}\,\mathrm{GeV} \lesssim M_1 \ll M_2$
- N_i couple to single lepton flavour combination $l_\parallel$

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Free Parameters

1. Washout Strength:

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

2. N_1 Decay Asymmetry:

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

Generalized Relativistic Boltzmann Equations

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

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

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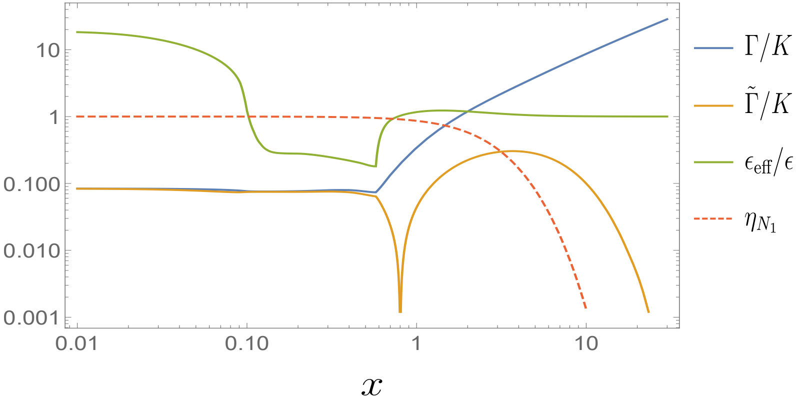
$\Rightarrow$ Encode thermal bath via efficiency κ_f:

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

Numerics for the Transport Coefficients



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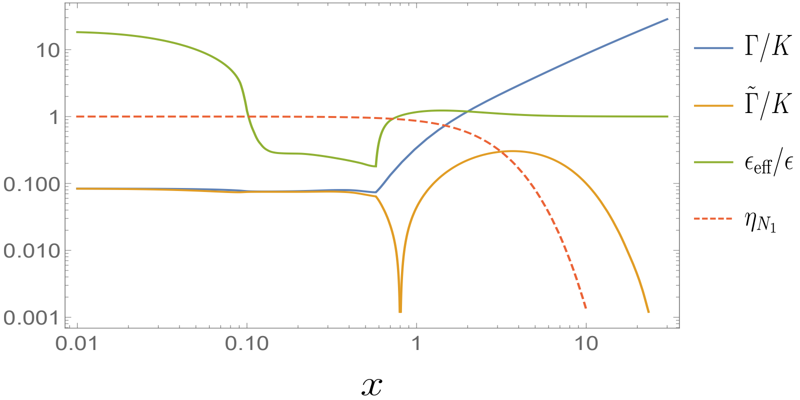

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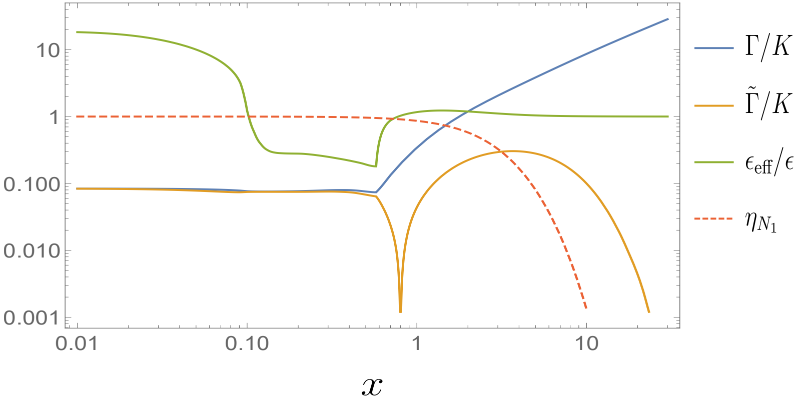
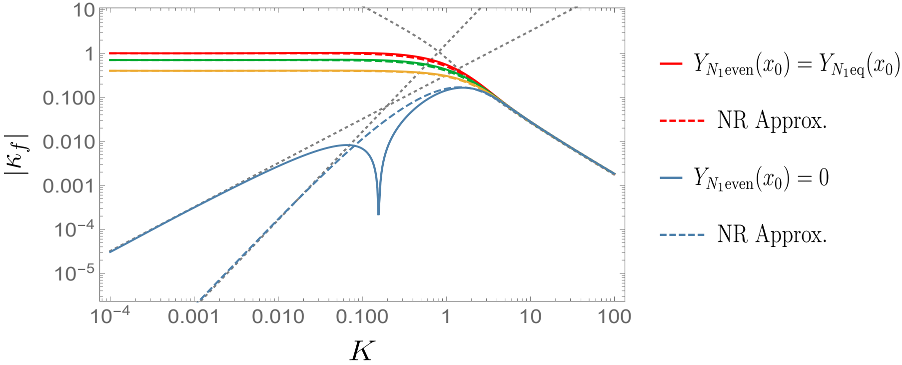


- We computed leading log thermal corrections
- Higgs decays important for ϵ_{eff} at high temperatures

Corrected Weak Washout Efficiency Scaling

- Leptogenesis without Spectators:



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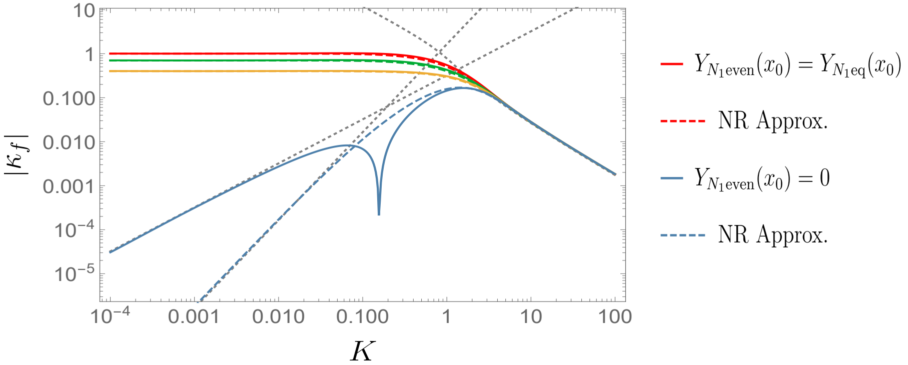


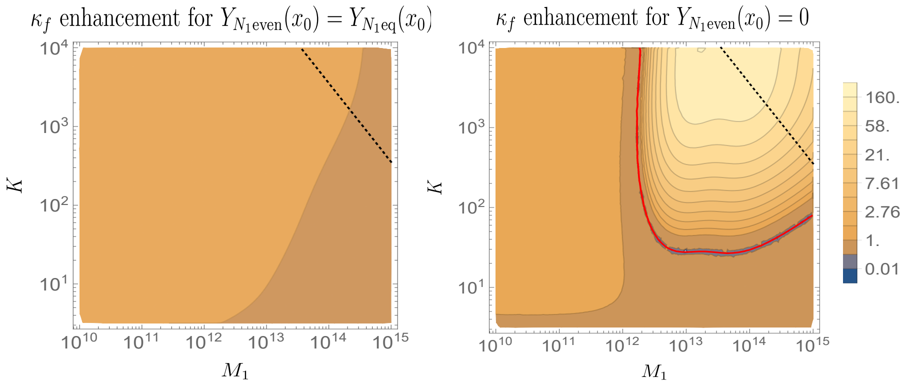
$\Rightarrow$ Corrected Efficiency Scaling for $K \ll 1$ & $Y_{N_1\text{eq}}(x_0) = 0$:

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

Strong Washout Initial Condition Dependence

- Realistic Model for $M_1 \sim 10^{13}\,\mathrm{GeV}$

  $\Rightarrow$ Dynamic b-Yukawa & weak Sphaleron interactions



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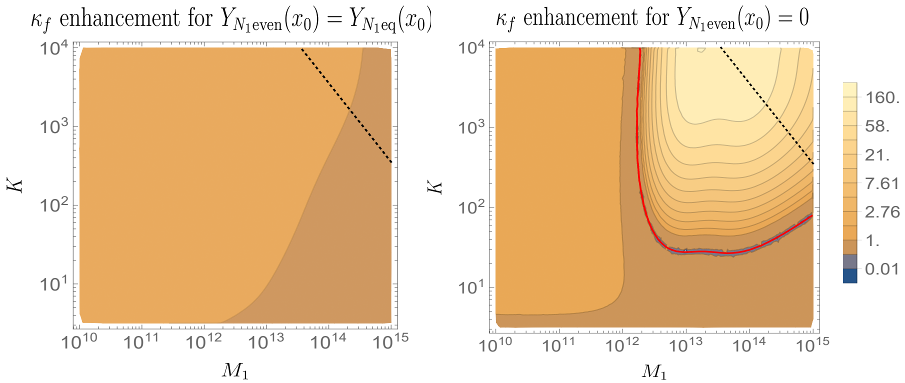

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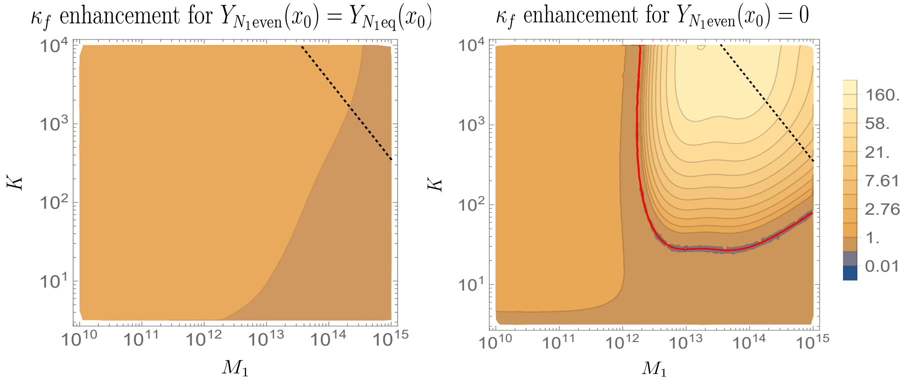

- Equal Baseline Efficiency
- $\sim 10^2$ **Enhancement and Initial condition dependence !**

Take Home Messages

Summary:

- We derived Generalized Relativsitc Boltzman Equations from First Principles

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

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- Interplay Relativistic Effects & Spectators ⇒ Strong Washout Initial Condition Dependence

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

Details on Γ, $\tilde{\Gamma}$

Decay Rates:

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

where

$$\gamma_{\mathsf{LNC}} \equiv \left\langle \frac{32\pi}{T_{\mathrm{com}}} \frac{(k_\mu + \tilde{k}_\mu)\hat{\Sigma}^{\mathcal{A}\mu}_{N_1}(k)}{k_0} \right\rangle$$

$$\gamma_{\mathsf{LNV}} \equiv \left\langle \frac{32\pi}{T_{\mathrm{com}}} \frac{(k_\mu - \tilde{k}_\mu)\hat{\Sigma}^{\mathcal{A}\mu}_{N_1}(k)}{k_0} \right\rangle$$

Sterile Neutrino Momenta:

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

Thermal Average:

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

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:

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

$\Rightarrow$

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

Reduced Sterile Neutrino Selfenergy

$$\hat{\Sigma}^{\mu}_{N_1}(k) = f_F^{-1}(k_0) \int \frac{d^4p}{(2\pi)^4} f_F(p_0) f_B(k_0 - p_0) \Delta^{\mathcal{A}}_{\phi}(k-p) \, \mathrm{tr}\left[\gamma^{\mu} S^{\mathcal{A}}_{l}(p)\right]$$

Spectral Functions:

$$S^{\mathcal{A}}_{l}(p) = \mathrm{P}_L \left[\left(\not{p} - \Sigma^{\mathcal{H}}_{l}(p)\right) \cdot \frac{\Gamma_l}{\Omega_l^2 + \Gamma_l^2} - \Sigma^{\mathcal{A}}_{l}(p) \frac{\Omega_l}{\Omega_l^2 + \Gamma_l^2} \right] \mathrm{P}_R \ ,$$

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

$$\Gamma_\phi(q) = \Pi^{\mathcal{A}}_{\phi} \ , \qquad \Gamma_l(p) = 2\left(p_\mu - \Sigma^{\mathcal{H}}_{l,\mu}\right) \cdot \Sigma^{\mathcal{A},\mu}_{l} \ ,$$

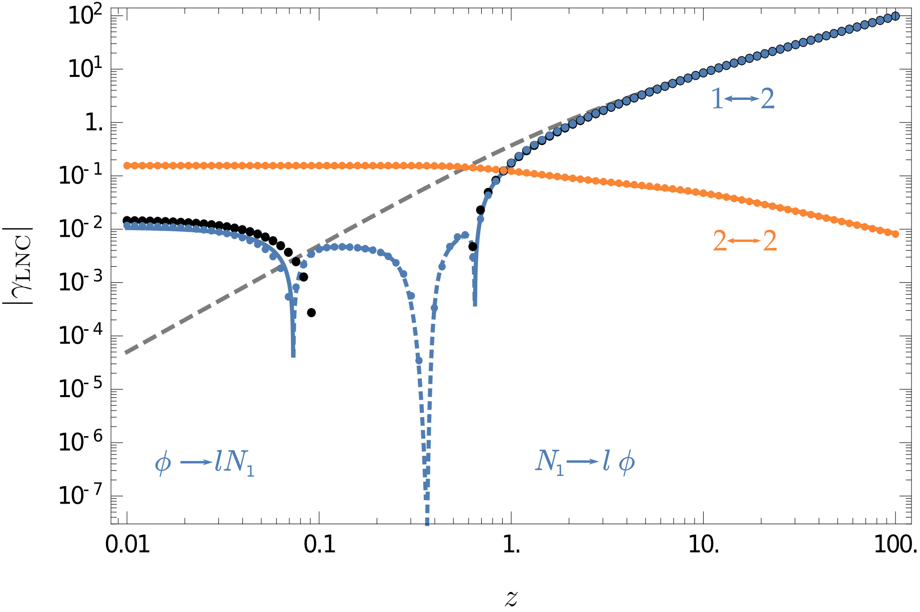
$$\Omega_\phi(q) = q^2 - \Pi^{\mathcal{H}}_{\phi} \ , \quad \Omega_l(p) = \left(p_\mu - \Sigma^{\mathcal{H}}_{l,\mu}\right)^2 - \left(\Sigma^{\mathcal{A}}_{l,\mu}\right)^2$$

Standard Model HTL Selfenergies:

$$\Pi^{\mathcal{H},\mathrm{HTL}} = m_\phi^2 \ , \quad \Sigma^{\mathcal{H},\mathrm{HTL}}_{l}(p) = \frac{m_l^2}{4} \frac{\tilde{\not{p}}}{|\mathbf{p}|^2} \ln\left|\frac{p_0 + |\mathbf{p}|}{p_0 - |\mathbf{p}|}\right| - \frac{m_l^2}{2} \frac{\hat{\not{p}}}{|\mathbf{p}|^2} \ ,$$

$$\Pi^{\mathcal{A},\mathrm{HTL}} = 0 \ , \qquad \Sigma^{\mathcal{A},\mathrm{HTL}}_{l}(p) = \frac{m_l^2}{4} \frac{\tilde{\not{p}}}{|\mathbf{p}|^2} 2\pi\, \theta(-p^2) \ .$$

Individual Contributions to γ_{LNC}



Individual Contributions to γ_{LNV}