Non-relativistic leptogenesis

Dietrich Bödeker, Bielefeld U.

Work with Mirco Wörmann

JCAP 1402 (2014) 016 arXiv:1311.2593

Meudon, June 2014

Outline

baryogenesis through leptogenesis

non-relativistic approximation

relativistic corrections

radiative corrections

Baryogenesis

baryon asymmetry of the Universe

$$\eta_B \equiv \frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$$

measured from cosmic microwave background, big bang nucleosynthesis

Sakharov: asymmetry can be dynamically generated if there is

- baryon number violation
- C and CP violation
- non-equilbrium

Baryon number violation

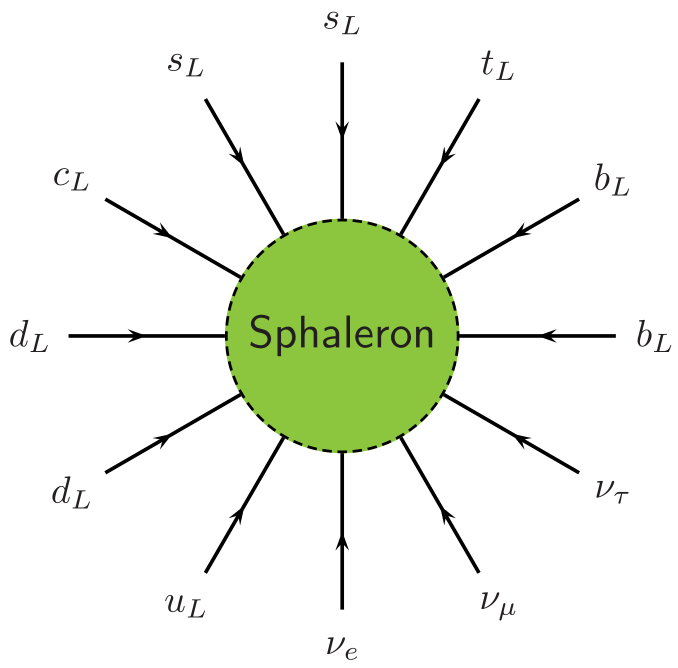
Standard Model : $B - L$ is conserved

chiral anomaly $\Rightarrow$ $B + L$ is not conserved in the Standard Model [t'Hooft]

$B + L$ violation unsuppressed for $T \gtrsim 100$ GeV

'sphaleron' processes

[pic. from Buchmüller, DiBari, Plümacher]



Lepton asymmetry $\leftrightarrow$ Baryon asymmetry

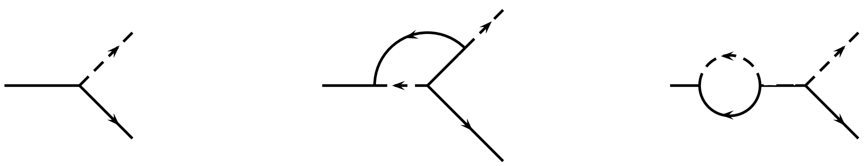
Baryogenesis through leptogenesis [Fukugita, Yanagida]

SM + sterile (right-handed) neutrinos N_i

$$\mathscr{L}_N = \frac{i}{2}\overline{N}_i \partial\!\!\!/ N_i - \frac{1}{2} M_{ij} \overline{N_i^c} N_j + h_{ij} \overline{N}_i \tilde{\varphi}^\dagger \ell_j + \text{ h.c.}$$

Majorana mass M_{ij} $\rightarrow$ lepton number violation

complex Yukawa couplings h_{ij} $\rightarrow$ CP-violation



$$\Gamma(N \rightarrow \ell\varphi) \neq \Gamma(N \rightarrow \bar{\ell}\bar{\varphi})$$

expansion of the Universe $\rightsquigarrow$ non-equilibrium

out of equilibrium decay of N $\rightsquigarrow$ asymmetry

Equilibrium and non-equilibrium

interaction rates Γ_i :

1. $\Gamma_i \gg H$ 'spectator processes' $\rightsquigarrow$ thermal equilibrium

2. $\Gamma_i \ll H$ $\rightsquigarrow$ quasi-conserved charge

3. $\Gamma_i \sim H$ slow, non-trivial non-equilibrium dynamics

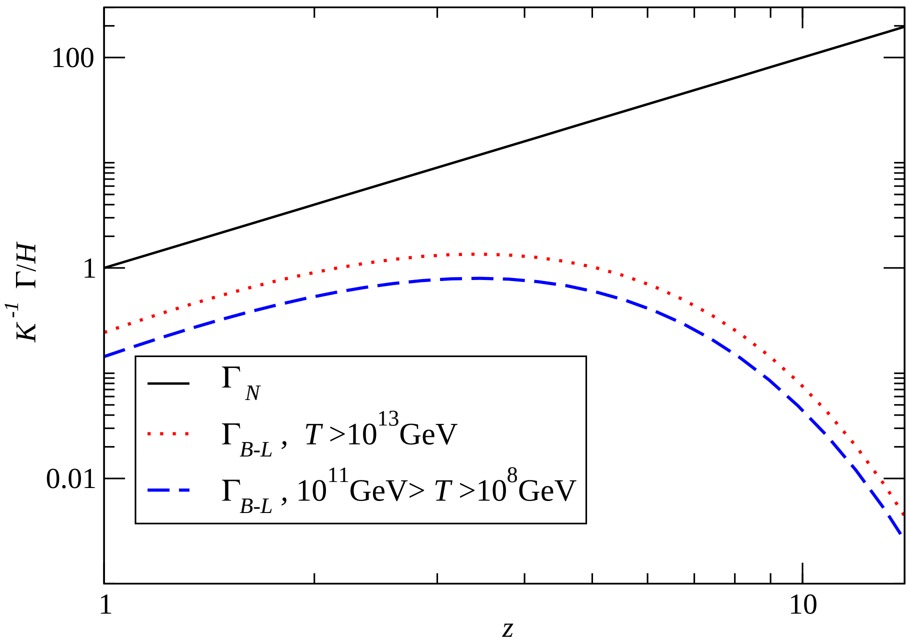
usually only few quantities i have $\Gamma_i \sim H$.

among them:

- number density n_N

- asymmetry n_{L-B}

Rates vs $z \equiv M/T$



n_N gets closer to equilibrium

exponentially small for $T \ll M$

l'genesis must happen before

$B - L$ washout rate

$\Gamma_{B-L} \to 0$ for $z \to \infty$

asymmetry freezes in

Γ_{B-L} maximal for $z \sim 4$

$$K \equiv \left.\frac{\Gamma_0}{H}\right|_{T=M}$$ 'washout factor'

for $K \gtrsim 1$ leptogenesis happens

- close to equilibrium
- at $T \lesssim M$: non-relativistic regime

See-saw mechanism

Higgs mechanism $\rightsquigarrow$ Dirac mass $m_D \sim hv$

with $v = 246$GeV Higgs vacuum expectation value

neutrino mass matrix (1 family) $\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$

assume $M \gg m_D$

eigenvalues:

$$M_N \simeq M, \qquad m_\nu \simeq \frac{m_D^2}{M} \sim \frac{h^2 v^2}{M}$$

'explains' hierarchy between m_ν and m_e

Washout factor

$$K = \frac{\Gamma_0}{H}\bigg|_{T=M} \sim \frac{h^2 M}{M^2/m_{\rm Pl}} \sim \frac{M m_\nu}{v^2}\frac{m_{\rm Pl}}{M} \sim \frac{m_\nu m_{\rm Pl}}{v^2}$$

determined by known scales

Washout factor (cont'd)

more precisely: $$K = \frac{\widetilde{m}_1}{m_*}$$

$$\widetilde{m}_1 = \frac{(m_D m_D^\dagger)_{11}}{M} \qquad m_* \simeq 10^{-3}\text{ eV}$$

$\widetilde{m}_1 >$ smallest light neutrino mass [Fujii, Hamaguchi, Yanagida]

$$(\Delta m^2_{\text{solar}})^{1/2} < \widetilde{m}_1 < (\Delta m^2_{\text{atmospheric}})^{1/2} \quad \Leftrightarrow \quad 7.4 < K < 46$$

$\rightsquigarrow$ non-relativistic regime

Which quantities are out of equilibrium?

in general not only n_N, but also the N-momentum spectrum

standard assumption: kinetic equilibrium

problem: $\Gamma_{\text{kinetic equilibration}} \sim \Gamma_{\text{chemical equilibration}}$

full Boltzmann equation?

Equations for non-relativistic leptogenesis

idea: for non-relativistic N, one can neglect their motion

$\rightsquigarrow$ only n_N and n_{B-L} need to be considered

$$\left(\frac{d}{dt} + 3H\right) n_{_N} = -\Gamma_{_N} \left(n_{_N} - n_{_{N,eq}}\right) + \Gamma_{_{N,B-L}}\, n_{_{B-L}}$$

$$\left(\frac{d}{dt} + 3H\right) n_{_{B-L}} = \Gamma_{_{B-L,N}} \left(n_{_N} - n_{_{N,eq}}\right) - \Gamma_{_{B-L}}\, n_{_{B-L}}$$

coefficients Γ_i only depend on temperature

equations are valid to all orders in the SM couplings

radiative corrections can be included in Γ_i

Leading order coefficients

use Boltzmann equation for $f_N(t,\mathbf{p})$

$$\left(\partial_t - Hp\partial_p\right) f_N = \frac{M\Gamma_0}{E_N}\left(e^{-E_N/T} - f_N\right)$$

tree level decay rate

$$\Gamma_0 = \frac{|h_{11}|^2 M}{8\pi}$$

integrate over $\mathbf{p}$ $\rightsquigarrow$ no closed equation for n_N

here: non-relativistic approximation $1/E_N \simeq 1/M$ $\rightsquigarrow$

$$\left(\frac{d}{dt} + 3H\right) n_N = -\Gamma_N \left(n_N - n_{N,eq}\right) \qquad \text{with} \qquad \Gamma_N = \Gamma_0$$

Leading order coefficients (cont'd)

CP-asymmetry in N-decays

$$\epsilon \equiv \frac{\Gamma(N \to \varphi\ell) - \Gamma(N \to \overline{\varphi}\overline{\ell})}{\Gamma(N \to \varphi\ell) + \Gamma(N \to \overline{\varphi}\overline{\ell})}$$

$\rightsquigarrow$ source for $B-L$ asymmetry

$$\left(\frac{d}{dt} + 3H\right) n_{B-L} = \Gamma_{B-L,N} \left(n_N - n_{N,eq}\right)$$

$$\Gamma_{B-L,N} = \epsilon \, \Gamma_0$$

$$\epsilon \sim h^2 \sim \frac{m_\nu M}{v^2} \quad \rightsquigarrow \quad \text{lower bound } M \gtrsim 10^8 \text{GeV}$$

Leading order coefficients (cont'd)

washout term: inverse decays

initial state particles are

- relativistic

- in kinetic equilibrium

no non-relativistic approximation

$$\left(\frac{d}{dt} + 3H\right) n_{B-L} = \Gamma_{B-L,N}\left(n_N - n_{N,eq}\right) - \Gamma_{B-L}\, n_{B-L}$$

with

$$\Gamma_{B-L} = \frac{3}{\pi^2}\left(c_\ell + \frac{c_\varphi}{2}\right) z^2 K_1(z) \Gamma_0$$

Relativistic corrections

now $$\frac{1}{E_N} = \frac{1}{\sqrt{\mathbf{p}^2 + M^2}} \simeq \frac{1}{M}\left(1 - \frac{\mathbf{p}^2}{2M^2}\right) \qquad \rightsquigarrow$$

$$\left(\frac{d}{dt} + 3H\right) n_N = -\Gamma_N \left(n_N - n_{N,eq}\right) + \Gamma_{N,u}\left(u - u_{eq}\right)$$

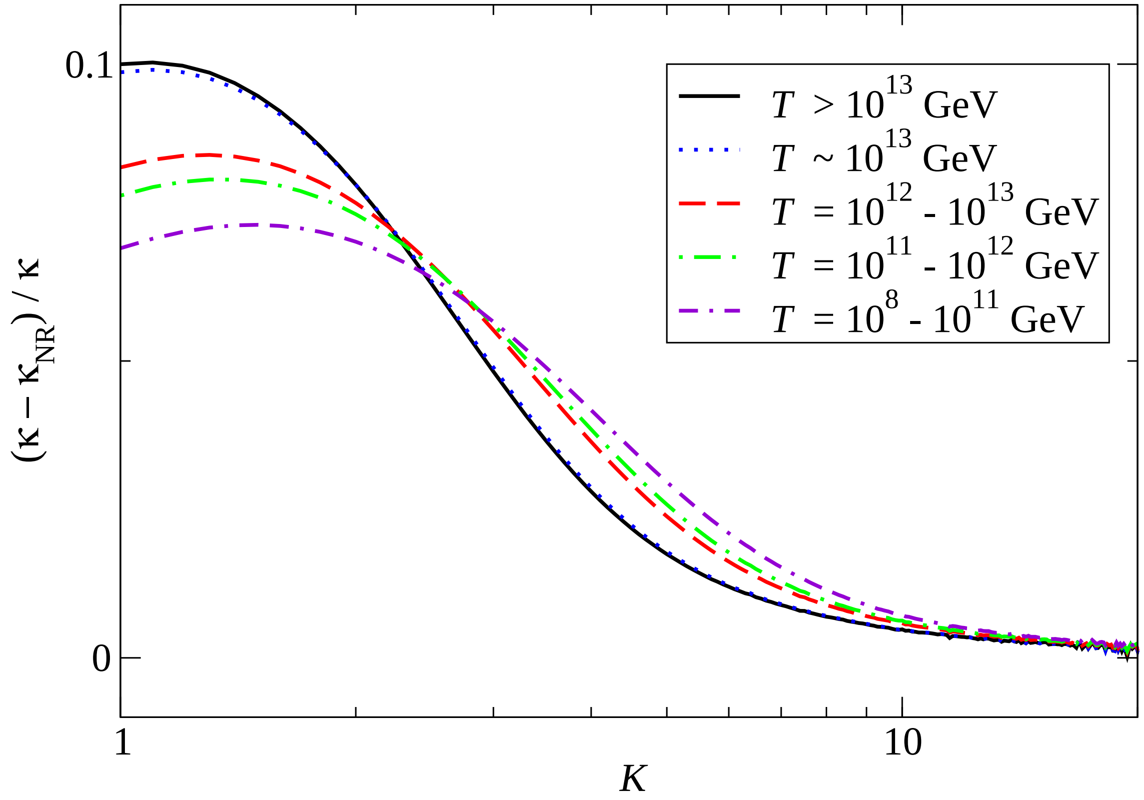
$$u \equiv \frac{\text{kinetic energy density}}{M}$$

similar correction in equation for asymmetry

additional equation

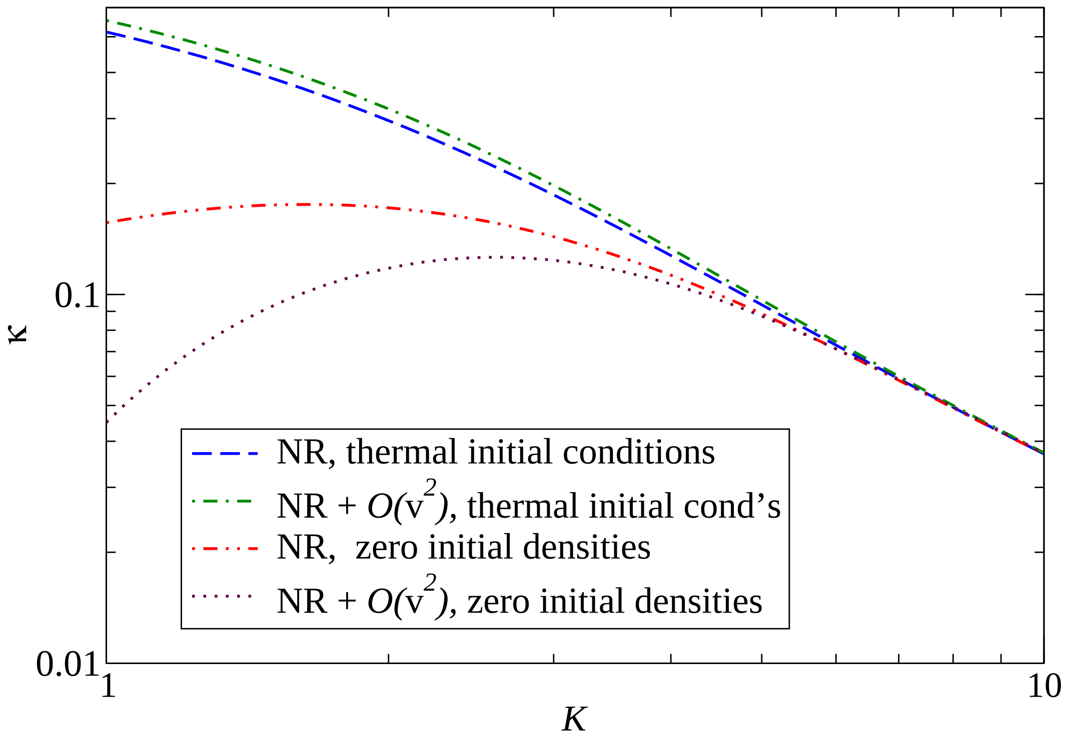
$$\left(\frac{d}{dt} + 5H\right) n_u = -\Gamma_u \left(u - u_{eq}\right)$$

Size of relativistic corrections



efficiency factor $$\lim_{z\to\infty} \frac{n_{B-L}}{n_\gamma^{\rm eq}} \equiv \frac{3}{4}\,\epsilon\,\kappa$$

Dependence on initial conditions



corrections small in strong washout regime

deviations from kinetic equilibrium small

previous work using full Boltzmann equation:

larger discrepancy between full and approximate treatment

caused by using Boltzmann-statistics in washout term

Radiative corrections

so far: LO, decays and inverse decays $1 \leftrightarrow 2$

include radiative corrections: $2 \leftrightarrow 2$, $1 \leftrightarrow 3$, $1 \leftrightarrow 2$ virtual corrections

radiative corrections known for Γ in [Laine, Schröder] [Saldo, Lodone, Strumia]

$$\frac{\partial f_N}{\partial t}\bigg|_{f_N=0} = \frac{M_N}{E_N} f_{N,\mathrm{eq}} \Gamma$$

if we assume

$$\frac{\partial f_N}{\partial t}\bigg|_{f_N=0} = \frac{M}{E_N} \left(f_{N,\mathrm{eq}} - f_N\right) \Gamma$$

at leading order in h^2, all orders in Standard Model interactions [Weldon]

$\rightsquigarrow$ radiative corrections to Γ_N

Radiative corrections to Γ

$$\Gamma_N = \Gamma_u = a\Gamma_0, \qquad \Gamma_{N,u} = (a - 2b)\Gamma_0$$

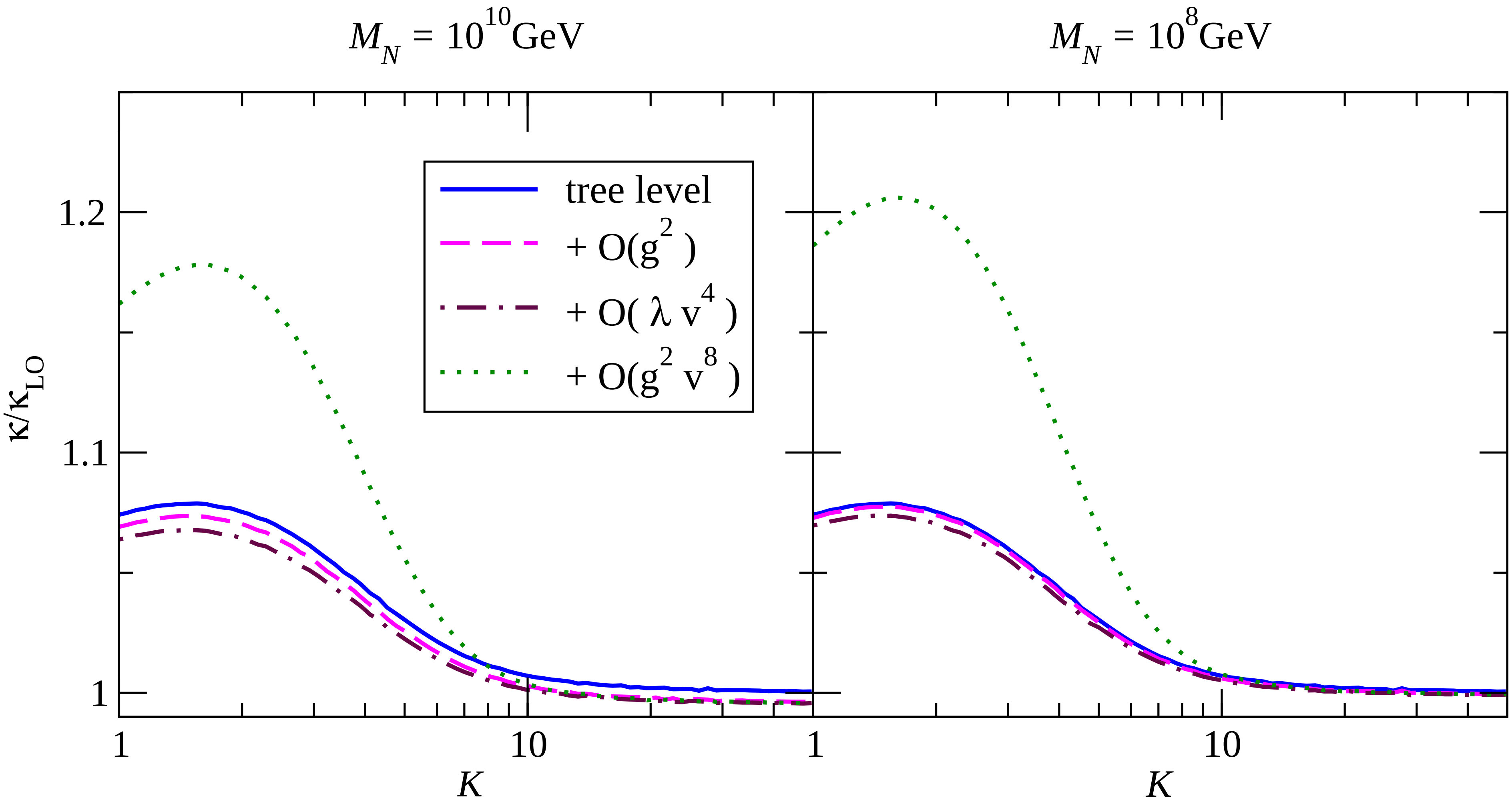
[DB, Wörmann]

$$a = 1 - \frac{\lambda T^2}{M_N^2} - |h_t|^2 \left[\frac{21}{2(4\pi)^2} + \frac{7\pi^2}{60} \frac{T^4}{M_N^4} \right] + (g_1^2 + 3g_2^2) \left[\frac{29}{8(4\pi)^2} - \frac{\pi^2}{80} \frac{T^4}{M_N^4} \right] + O\left(g^2 \frac{T^6}{M_N^6}, g^3 \frac{T^2}{M_N^2} \right)$$

$$b = - \left[|h_t|^2 \frac{7\pi^2}{45} + (g_1^2 + 3g_2^2) \frac{\pi^2}{60} \right] \frac{T^4}{M_N^4} + O\left(g^2 \frac{T^6}{M_N^6}, g^3 \frac{T^2}{M_N^2} \right)$$

[Laine, Schröder]

thermal corrections are formally higher order than our relativistic corrections



radiative corrections to efficiency factor

Recent progress

next-to-leading order corrections to washout rate Γ_{B-L} [DB, Laine, arXiv:1403.2755]

schematically:

$$\Gamma \sim h^2 \mathcal{W} \, \Xi^{-1}$$

$\mathcal{W}$ = spectral function, dynamical, similar to Γ

NLO corrections to $\mathcal{W} = O(g^2)$

Ξ = susceptibility matrix

surprise: NLO corrections to $\Xi = O(g)$

Summary

- for phenomenologically interesting parameters the baryon asymmetry of the Universe is created by non-relativistic sterile neutrinos

- equations for non-relatistic leptogenesis simple, valid to all orders in Standard Model couplings

- relativistic corrections can be systematically included,

- are small in strong washout regime

- radiative corrections were included

- recently: radiative corrections to washout

- leading correction $= O(g)$

Outlook

- radiative corrections to source of asymmetry not yet known

- hopefully non-relativistic approximation is helpful

- bounds on light neutrino mass from successful leptogenesis