Nonequilibrium dynamics in the early universe

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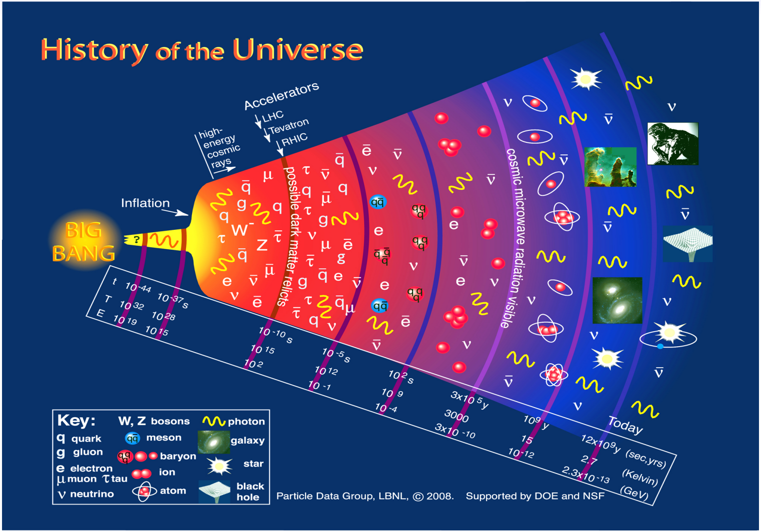
Outline

- Short introduction to thermal leptogenesis
- Non-equilibrium dynamics
  - Boltzmann equations
  - Kadanoff-Baym
- Solution to the Kadanoff-Baym
- Thermal leptogenesis
  - Boltzmann equations
  - Kadanoff-Baym
- Conclusions

History of the Universe



Matter-antimater asymmetry

BBN : $\frac{n_B}{n_\gamma} = (5.1 - 6.5) \times 10^{-10}$

WMAP: $\frac{n_B}{n_\gamma} = (6.19 \pm 0.15) \times 10^{-10}$

Sakharov's conditions

- Baryon number violation
- C, CP violation
- Departure from thermal equilibrium

The Standard Model satisfies the Sakharov conditions, but does not generate sufficient asymmetry!

An extension is required!

See-saw mechanism and Thermal Leptogenesis

Insertion of right-handed neutrinos ν_R

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{l}_L \tilde{\Phi} \lambda \nu_R - \frac{1}{2} \bar{\nu}_R^c M \nu_R + h.c.$$

- see-saw mechanism explains small neutrino masses
- mass term of $N \approx \nu_R + \nu_R^c$ violates lepton number
- mass and flavour eigenstates are not identical
- complex phases appear
- out-of-equilibrium decay of N generally violates CP and generates the asymmetry

See-saw mechanism and Thermal Leptogenesis

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⇒the study of the non-equilibrium dynamics of the Majorana particle is fundamental to understand leptogenesis

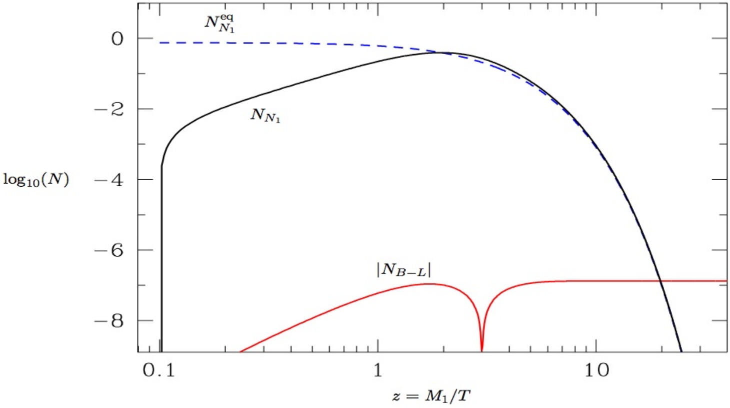
Kinetics of Thermal Leptogenesis

The dynamics of thermal leptogenesis is normally obtained with the calculation of abundances from the Boltzmann equations

$$\frac{dN_{N_1}}{dz} = -D\left(N_{N_1} - N_{N_1}^{\mathrm{eq}}\right),$$
$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\, D\left(N_{N_1} - N_{N_1}^{\mathrm{eq}}\right) - W_{ID}\, N_{B-L}$$

- *D*: decays and inverse decays processes
- ε_1: CP violating parameter
- *W*: wash-out terms, which compete with the generation of the asymmetry

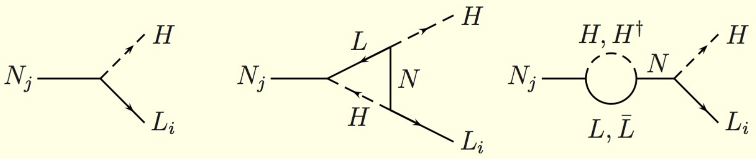
Asymmetry from Boltzmann equations



(Buchmuller, Peccei, Yanagida, 2005)

CP asymmetry

Leptogenesis is a pure quantum phenomena. The CP violation is the result of interference between tree-level and 1-loop diagrams



In vacuum

- $$\epsilon = \frac{3}{16\pi} \sum_{i=2,3} \frac{\mathrm{Im}[(\lambda\lambda^\dagger)^2_{i1}]}{(\lambda\lambda^\dagger)_{11}} \frac{M_1}{M_i}$$

Methods

- Boltzmann equations (BE)
- (full) quantum Boltzmann equations (QBE)
- Kadanoff-Baym equations (KBE)

Is a Quantum Treatment possible? YES

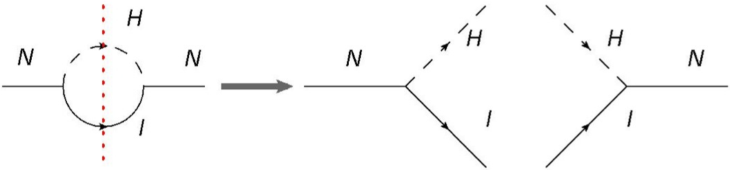
- spacial homogeneity
- weak coupling $\Rightarrow$ perturbative
- background plasma is in equilibrium
- backreaction can be neglected

'Weak coupling to a thermal bath'

Boltzmann vs Kadanoff-Baym Equations

- initial value problem for density matrix $\rho(t)\dots$
- $\dots$or for correlation functions $\langle\dots\rangle = \mathrm{tr}(\rho\dots)$
- KBE contain full quantum mechanics

$$\text{particle numbers} \Leftrightarrow \text{correlation functions}$$
$$\text{collision term} \Leftrightarrow \text{self energies}$$



Π, Π encode information about all decay and scattering processes

Before we continue, we must remember the following...

- we want to describe the dynamics of an out-of-equilibrium Majorana neutrino
- we will study the evolution of correlators or Green's functions through the Kadanoff-Baym equations
- these new propagators will have all the out-of-equilibrium information required to generate the lepton asymmetry

KBE Formalism

Statistical and Spectral Propagators

Scalars

$$\begin{aligned}\Delta^{+}(x_1,x_2) &= \frac{1}{2}\langle\{\Phi(x_1),\Phi(x_2)\}\rangle_c\\ \Delta^{-}(x_1,x_2) &= i\langle[\Phi(x_1),\Phi(x_2)]\rangle_c\end{aligned}$$

Fermions

$$\begin{aligned}S^{+}_{\alpha\beta}(x_1,x_2) &= \frac{1}{2}\langle[\Psi(x_1)_\alpha,\bar{\Psi}_\beta(x_2)]\rangle_c\\ S^{-}_{\alpha\beta}(x_1,x_2) &= i\langle\{\Psi(x_1)_\alpha,\bar{\Psi}_\beta(x_2)\}\rangle_c\end{aligned}$$

Majorana

$$\begin{aligned}G^{+}_{\alpha\beta}(x_1,x_2) &= \frac{1}{2}\langle[N_\alpha(x_1),N_\beta(x_2)]\rangle_c\\ G^{-}_{\alpha\beta}(x_1,x_2) &= i\langle\{N_\alpha(x_1),N_\beta(x_2)\}\rangle_c\end{aligned}$$

Kadanoff-Baym Equations

$$
\begin{aligned}
(\partial_1^2 + m^2)\Delta^-(x_1, x_2) &= -\int d^3\mathbf{x}' \int_{t_2}^{t_1} dt' \Pi^-(x_1, x')\Delta^-(x', x_2) \\
(\partial_1^2 + m^2)\Delta^+(x_1, x_2) &= -\int d^3\mathbf{x}' \int_{t_i}^{t_1} dt' \Pi^-(x_1, x')\Delta^+(x', x_2) \\
&\quad + \int d^3\mathbf{x}' \int_{t_i}^{t_2} dt' \Pi^+(x_1, x')\Delta^-(x', x_2)
\end{aligned}
$$

- Thermal quantum equations for the evolution of propagators
- convolution with the self-energy
- can be solved numerically and in a certain regime analytically

How? 'weakly coupled particle'

Weak Coupling to a thermal Bath

- consider fields that are weakly coupled to a large bath in equilibrium
- assume interaction mainly with bath fields $\mathcal{X}$
  - then self energies are computed with equilibrium propagators
  - in practice realised by using couplings that are linear in the field of interest, e.g. $g\phi\mathcal{O}[\mathcal{X}]$, $g\Psi\mathcal{O}[\mathcal{X}]$, at leading order in g

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For such systems

- spectral propagators Δ^-, S^-, G^- are time translation invariant
- KBE are equivalent to a stochastic Langevin equation
- KBE can be solved analytically up to a *memory integral*

Kadanoff-Baym Equations

$$(\partial_{t_1}^2 + \omega_{\mathbf{q}}^2)\Delta_{\mathbf{q}}^-(t_1 - t_2) = -\int_{t_2}^{t_1} dt' \Pi_{\mathbf{q}}^-(t_1 - t')\Delta_{\mathbf{q}}^-(t' - t_2)$$

$$(\partial_{t_1}^2 + \omega_{\mathbf{q}}^2)\Delta_{\mathbf{q}}^+(t_1, t_2) = -\int_{t_i}^{t_1} dt' \Pi_{\mathbf{q}}^-(t_1 - t')\Delta_{\mathbf{q}}^+(t', t_2) + \int_{t_i}^{t_2} dt' \Pi_{\mathbf{q}}^+(t_1 - t')\Delta_{\mathbf{q}}^-(t' - t_2)$$

- Convolution only in time coordinates
- spectral function is time translational invariant
- statistical propagator will depend also on the center of mass coordinate

Solutions

Properties of the Solutions

- retarded self-energy $\Pi^R = \Pi^R|_{T=0} + \delta\Pi^R(T)$ is the decisive quantity
- $\mathrm{Re}\Pi^R$ gives thermal mass
- $\mathrm{Im}\Pi^R$ decay width Γ to resonance

Three regimes

1. $|\mathrm{Re}\Pi|, |\mathrm{Im}\Pi| \ll \omega_{\mathbf{q}}^2$
2. $|\mathrm{Re}\Pi| \approx \omega_{\mathbf{q}}^2, |\mathrm{Im}\Pi| \ll \omega_{\mathbf{q}}^2$
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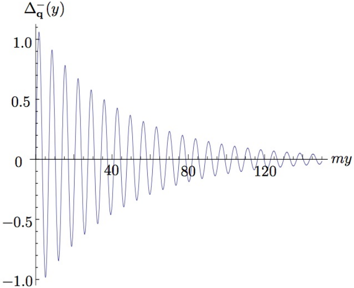
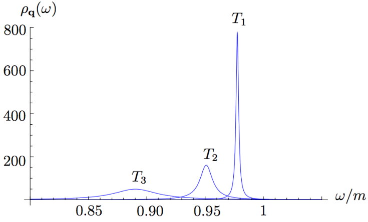
   single resonance kinematically behaves like quasiparticle
   but total energy receives vacuum contribution
3. $|\mathrm{Re}\Pi|, |\mathrm{Im}\Pi| \approx \omega_{\mathbf{q}}^2$
   particle interpretation and Boltzmann equations break down,
   at large T possibly even in a weakly coupled theory

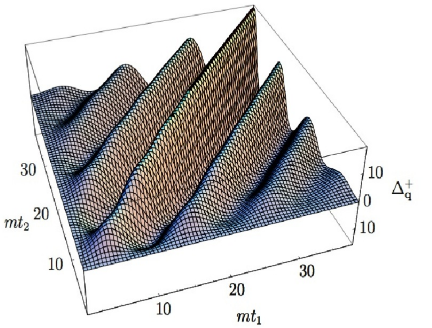
The Spectral Function

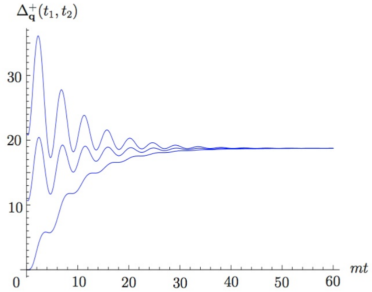




- Damped oscillatory behaviour
- Breit-Wigner breaks down at high temperatures

The Statistical Propagator





- depends on two time arguments
- equilibrates independent of initial conditions after characteristic time $\tau \sim {}^1/_\Gamma$
- oscillates with plasma frequency

Non-equilibrium Majorana

The width

$$\Sigma_{\mathbf{p}}(\omega) = (a_{\mathbf{p}}(\omega)\not{p} + b_{\mathbf{p}}(\omega)\not{u})C^{-1}$$

$$\Gamma = -2\mathrm{Im}\left(b(\omega_{\mathbf{p}}) + \frac{a(\omega_{\mathbf{p}})M^2}{\omega_{\mathbf{p}}}\right)$$

Small width solution

$$G^{-}_{\mathbf{p}}(y) = \left(i\gamma_0 \cos[\omega_{\mathbf{p}} y] + \frac{M - \mathbf{p}\gamma}{\omega_{\mathbf{p}}}\sin[\omega_{\mathbf{p}} y]\right) e^{-\frac{\Gamma|y|}{2}} C^{-1}$$

$$G^{+}_{\mathbf{p}}(t,y) = -\left(i\gamma_0 \sin[\omega_{\mathbf{p}} y] - \frac{M - \mathbf{p}\gamma}{\omega_{\mathbf{p}}}\cos[\omega_{\mathbf{p}} y]\right)$$
$$\times \left[\frac{\tanh\left(\frac{\beta\omega}{2}\right)}{2} e^{-\frac{\Gamma|y|}{2}} + f_N^{eq}(\omega) e^{-\Gamma t}\right] C^{-1}$$

Out-of-equilibrium particle

- non-equilibrium propagators can be found using the KBE
- solutions to the KBE can be found analytically using the time-translation invariance of the self-energy
- emphasis on the initial conditions
- the Majorana particle will be used to generate the asymmetry

Application to Leptogenesis

Hierarchical Majorana model

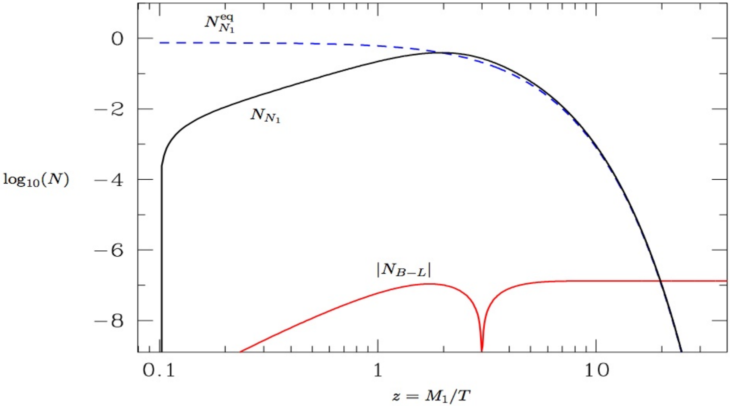
- two heavy Majoranas are integrated out, leaving an effective Lagrangian

$$\mathcal{L} = \bar{l}_{Li}\tilde{\phi}\lambda^*_{i1}N + N^T\lambda_{i1}Cl_{Li}\phi - \frac{1}{2}MN^TCN$$
$$+ \frac{1}{2}\eta_{ij}l^T_{Li}\phi\, Cl_{Lj}\phi + \frac{1}{2}\eta^*_{ij}\bar{l}_{Li}\tilde{\phi}\, C\bar{l}^T_{Lj}\tilde{\phi}\ ;$$

- effective vertex:

$$\eta_{ij} = \sum_{k>1}\lambda_{ik}\frac{1}{M_k}\lambda^T_{kj}$$

Boltzmann approach for asymmetry



(Buchmuller, Peccei, Yanagida, 2005)

Boltzmann approach for asymmetry

The coupled differential equations in a static universe are given by

$$\frac{\partial f_N}{\partial t} = \mathcal{C}[f_N] \qquad \text{for Majorana}$$
$$\frac{\partial f_{l-\bar{l}}}{\partial t} = \mathcal{C}[f_{l-\bar{l}}, f_N] \qquad \text{for lepton asymmetry}$$

$\mathcal{C}[f]$: collision term
Inserting the solution for the Majoranas to the asymmetry equation, and without wash-out terms

$$f_{l-\bar{l}} = -\epsilon_{CP}\frac{1}{k}\int_{\mathbf{q},\mathbf{p}}(2\pi)^4\delta^4(k+q-p)p\cdot k$$
$$\times f_{l\phi}f_N^{eq}\frac{1}{\Gamma}(1-e^{-\Gamma t})$$

KBE approach for the Asymmetry

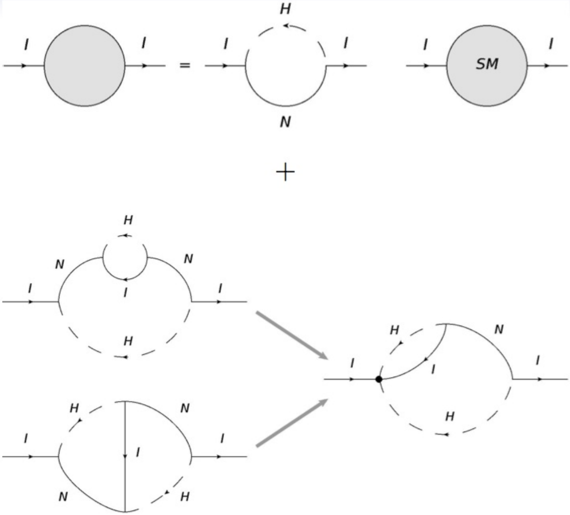
How to calculate the asymmetry without reference to particle number or distribution function?

- define *lepton number matrix*

$$L_{\mathbf{k}ij}(t_1, t_2) = -\mathrm{tr}[\gamma^0 S^{+}_{\mathbf{k}ij}(t_1, t_2)].$$

- $L_{\mathbf{k}ii}(t, t)$ gives leptonic charge in flavour i at time t
- CP-violation comes from interference between LO and NLO terms (tree level and 1-loop level)
- Considering an stationary universe and neglecting wash-out terms

Lepton Self-Energy



Kadanoff-Baym Equations for the asymmetry

$$
\begin{aligned}
(i\gamma_0\partial_{t_1} - \mathbf{q}\gamma - m)S^{-}_{\mathbf{q}}(t_1, t_2) &= -\int_{t_1}^{t_2} dt' \Pi^{-}_{\mathbf{q}}(t_1, t')S^{-}_{\mathbf{q}}(t', t_2) \\
(i\gamma_0\partial_{t_1} - \mathbf{q}\gamma - m)S^{+}_{\mathbf{q}}(t_1, t_2) &= -\int_{t_i}^{t_1} dt' \Pi^{-}_{\mathbf{q}}(t_1, t')S^{+}_{\mathbf{q}}(t', t_2) \\
&\quad + \int_{t_i}^{t_2} dt' \Pi^{+}_{\mathbf{q}}(t_1, t')S^{-}_{\mathbf{q}}(t', t_2)
\end{aligned}
$$

Solution of the Asymmetry

$$L_{\mathbf{k}ij}(t,t) = -\epsilon_{ij}\,\frac{16\pi}{|\mathbf{k}|}\int_{\mathbf{q},\mathbf{q}'}\frac{k\cdot k'}{|\mathbf{k}'|\omega} f_{l\phi}(k,q) f_N^{eq}(\omega) f_{l\phi}(k',q')$$

$$\times \frac{\frac{1}{4}\Gamma}{((\omega-|\mathbf{k}|-|\mathbf{q}|)^2+\frac{\Gamma^2}{4})((\omega-|\mathbf{k}'|-|\mathbf{q}'|)^2+\frac{\Gamma^2}{4})}$$

$$\times \Big(\cos[(|\mathbf{k}|+|\mathbf{q}|-|\mathbf{k}'|-|\mathbf{q}'|)t] + e^{-\Gamma t}$$

$$-(\cos[(\omega-|\mathbf{k}|-|\mathbf{q}|)t] + \cos[(\omega-|\mathbf{k}'|-|\mathbf{q}'|)t])e^{-\frac{\Gamma t}{2}}\Big)\,,$$

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$$-(\cos[(\omega-|\mathbf{k}|-|\mathbf{q}|)t] + \cos[(\omega-|\mathbf{k}'|-|\mathbf{q}'|)t])e^{-\frac{\Gamma t}{2}}\Big)\,,$$

$$f_{Li}(t,k) = -\epsilon_{ii}\frac{16\pi}{|\mathbf{k}|}\int_{\mathbf{q},\mathbf{p},\mathbf{q}',\mathbf{k}'} k\cdot k' f_{l\phi}(k,q) f_N^{eq}(\omega)$$

$$\times \frac{1}{\Gamma}(2\pi)^4\delta^4(k+q-p)(2\pi)^4\delta^4(k'+q'-p)$$

$$\times \left(1-e^{-\Gamma t}\right)$$

On-Shell Approximation (unjustified!)

$$L^{os}_{\mathbf{k}ij}(t,t) = -\epsilon_{ij}\frac{16\pi}{k}\int_{\mathbf{q},\mathbf{q}',\mathbf{p},\mathbf{k}'} k\cdot k' f_{l\phi}(k,q) f_N^{eq}(\omega) f_{l\phi}(k',q')$$
$$\times \frac{1}{\Gamma}(2\pi)^4\delta^4(k+q-p)(2\pi)^4\delta^4(k'+q'-p)$$
$$\times \left(1-e^{-\frac{\Gamma t}{2}}\right)^2$$

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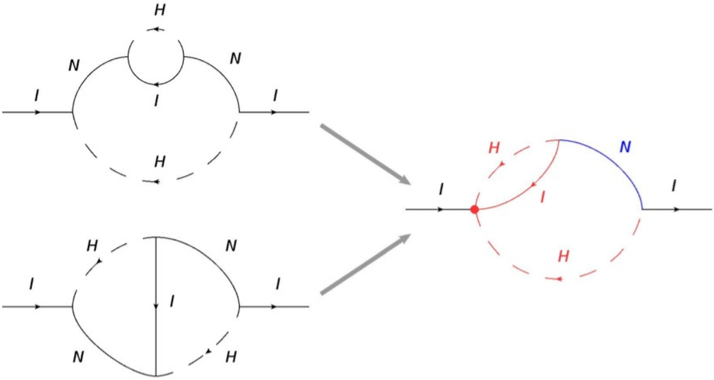
$$\times \left(1-e^{-\Gamma t}\right)$$

Inclusion of SM widths



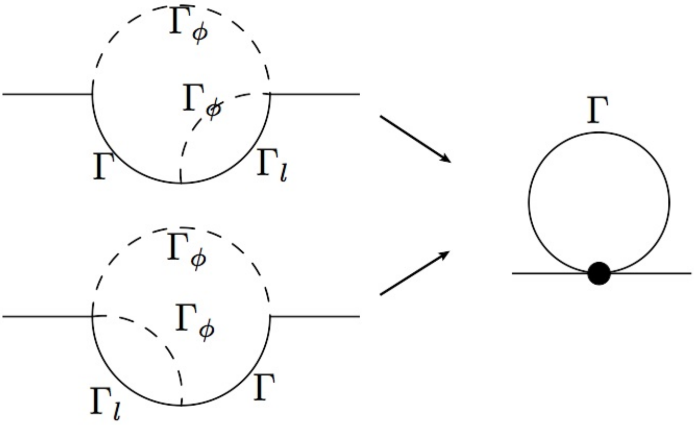
Inclusion of SM widths

$$\tilde{L}_{\mathbf{k}ij}(t,t) = -\epsilon_{ij}\,\frac{16\pi}{|\mathbf{k}|}\int_{\mathbf{q},\mathbf{q}'}\frac{k\cdot k'}{|\mathbf{k}'|\omega}f_{l\phi}(k,q)f_N^{eq}(\omega)f_{l\phi}(k',q')$$
$$\times\frac{1}{\Gamma}\frac{\frac{1}{4}\Gamma_{l\phi}\Gamma'_{l\phi}}{((\omega-k-q)^2+\frac{1}{4}\Gamma_{l\phi}^2)((\omega-k'-q')^2+\frac{1}{4}\Gamma'^2_{l\phi})}$$
$$\left(1-e^{-\Gamma t}\right) + \text{oscillatory terms}$$

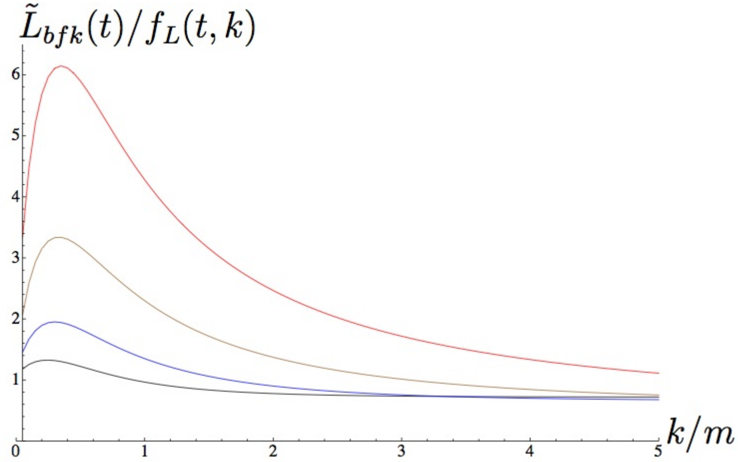
$$f_{Li}(t,k) = -\epsilon_{ii}\frac{16\pi}{|\mathbf{k}|}\int_{\mathbf{q},\mathbf{p},\mathbf{q}',\mathbf{k}'}k\cdot k' f_{l\phi}(k,q)f_N^{eq}(\omega)$$
$$\times\frac{1}{\Gamma}(2\pi)^4\delta^4(k+q-p)(2\pi)^4\delta^4(k'+q'-p)$$
$$\times\left(1-e^{-\Gamma t}\right)$$

BUT: This is not yet a consistent treatment of gauge interactions!!!

Inclusion of decay widths



Comprison between Boltzmann and KBE



Conclusions

- We computed the generated lepton asymmetry for hierarchical heavy neutrino masses and a constant (or very slowly changing) temperature without semi-classical approximations.
- Quantum and non-Markovian effects can be crucial for leptogenesis.
- We find significant deviations from Boltzmann equations due to off-shell effects, memory effects and temperature dependent corrections.
- The consistent inclusion of all SM corrections remains an issue.