

Leptogenesis — Towards a Complete Quantum Mechanical Calculation in a Thermal Bath

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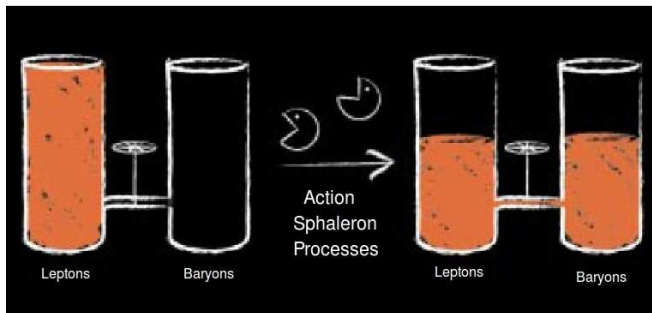
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- 1 Motivation
- 2 Quantum Mechanical Ansatz
 - Boltzmann Equations
 - Kadanoff-Baym-Equations
- 3 Lepton Asymmetry
 - Thermal Bath
 - Gauge Interactions
- 4 Summary and Outlook

Baryogenesis via Leptogenesis

Think of initial lepton asymmetry instead of baryon asymmetry:
⇒ sphalerons convert imbalance to baryons (B-L conserved)



J. M. Cline



baryon asymmetry

- Standard Model: Khlebnikov, Shaposhnikov

$$B = \left(\frac{8n_f + 4n_H}{22n_f + 13n_H} \right) (B - L)$$

- $(B - L)$ conserved \Rightarrow no asymmetry!
- add right-handed Majorana neutrinos N_R that break $B - L$ (seesaw partners of the ordinary neutrinos)
- out-of-equilibrium decays of N_R generate lepton asymmetry
- interaction of lightest Majorana neutrino $N_1 = \nu_{R1} + \nu_{R1}^c \equiv N$ with Higgs and lepton doublets Fukugita, Yanagida

$$\mathcal{L} = \lambda^* \bar{l}_L \tilde{\phi} \nu_R - \frac{1}{2} \bar{\nu}_R^c M \nu_R + h.c.$$

(use hierarchical Majorana neutrino masses $M \equiv M_1 \ll M_2, M_3$)

- generation of baryon asymmetry: $T \sim M$
- derive an effective lagrangian with the two heavier neutrinos being integrated out
- generation of lepton asymmetry: process close to equilibrium \Rightarrow linearize Boltzmann equations
- example: BE for Majorana neutrino

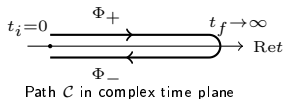
$$g_N \frac{\partial}{\partial t} \delta f_N(t, p) = -g_N \frac{\partial}{\partial t} f_N(p) - \frac{1}{2E} \int d\Phi_{\bar{1}\bar{2}}(p) \delta(f_N(t, p)) (|\mathcal{M}(N \rightarrow l\phi)|^2 + |\mathcal{M}(N \rightarrow \bar{l}\bar{\phi})|^2)$$

- analogue for lepton doublets \Rightarrow decay of N leads to lepton asymmetry

Kadanoff-Baym Equations & Schwinger-Keldysh Formalism

- BE first order diff. eq. for number densities, local in time; valuable approximation for nonequilibrium processes in dilute, weakly coupled gas
- interactions in thermal plasma strong (non-Abelian gauge symmetries) \Rightarrow validity questionable
- need full quantum mechanical description
- use Green's functions \Rightarrow Kadanoff-Baym equations

- field Φ coupled to thermal bath with self-energy Π



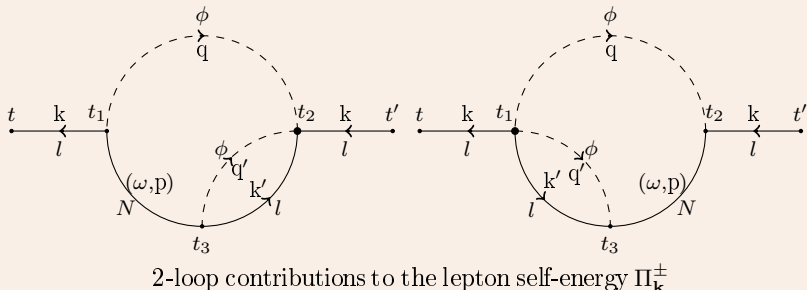
- Kadanoff-Baym equations for correlation functions Δ^{\cong}

$$(\square_1 + m^2)\Delta^{\cong}(x_1, x_2) = - \int d^4x' \left(\Pi^{\cong}(x_1, x')\Delta^A(x', x_2) + \Pi^R(x_1, x')\Delta^{\cong}(x', x_2) \right)$$

Majorana Neutrino in Bath of Higgs and Leptons

- 1 integrate out heavy Neutrinos $M_2, M_3 \ll M_1 \equiv M$
- 2 compute lepton asymmetry, that is generated during approach of right-handed N to equilibrium

Contributions



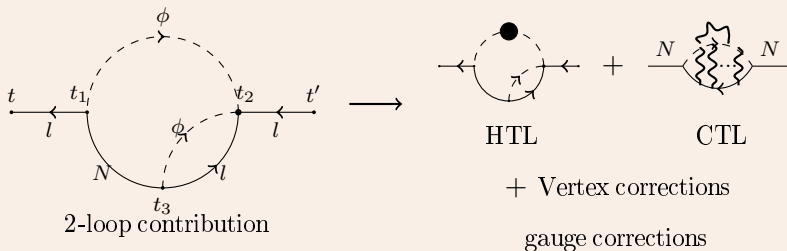
- lepton asymmetries based on BE were compared with those from KBE Anisimov, Buchmüller, Drewes, Mendizabal: 1012.5821 [hep-ph]
- Hubble expansion, wash out effects neglected
- current leptogenesis calculations have uncertainty of at least one order of magnitude

To Do

Need the systematic inclusion of gauge interactions with the thermal bath in a full quantum mechanical calculation based on KBE.

Hard and Collinear Thermal Loops (HTL/CTL)

Diagrams



HTL-resummed Propagator:

$$\text{---} \bullet \text{---} = \text{---} \star \text{---} + \text{---} \bigcirc \text{---} + \text{---} \text{wavy} \text{---} + \text{---} \star \text{---} + \dots$$

CTL scales:

- momenta at lightcone scale $P \sim T$, $P^2 \sim g^2 T^2$
- loop momentum K hard & collinear with P

Anisimov, Besak, Bödeker

- leptogenesis was introduced and discussed via BE and KBE
- good alignment between BE and KBE
- but: calculations have uncertainties of at least one order of magnitude
- include systematically gauge interactions with thermal bath in full quantum mechanical calculation (\rightarrow CTL)

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