Scalar Field Damping in Thermal Plasma

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Motivation

- *This is part of an ongoing study on Inflation.*
- Hot big bang initial conditions of the radiation dominated universe were created during *reheating*.
- Reheating temperature is related to the dissipation rate

$$T_R \equiv \left(\frac{90}{8\pi^3 g_*}\right)^{1/4} \sqrt{\Gamma M_P}.$$

1305.0267

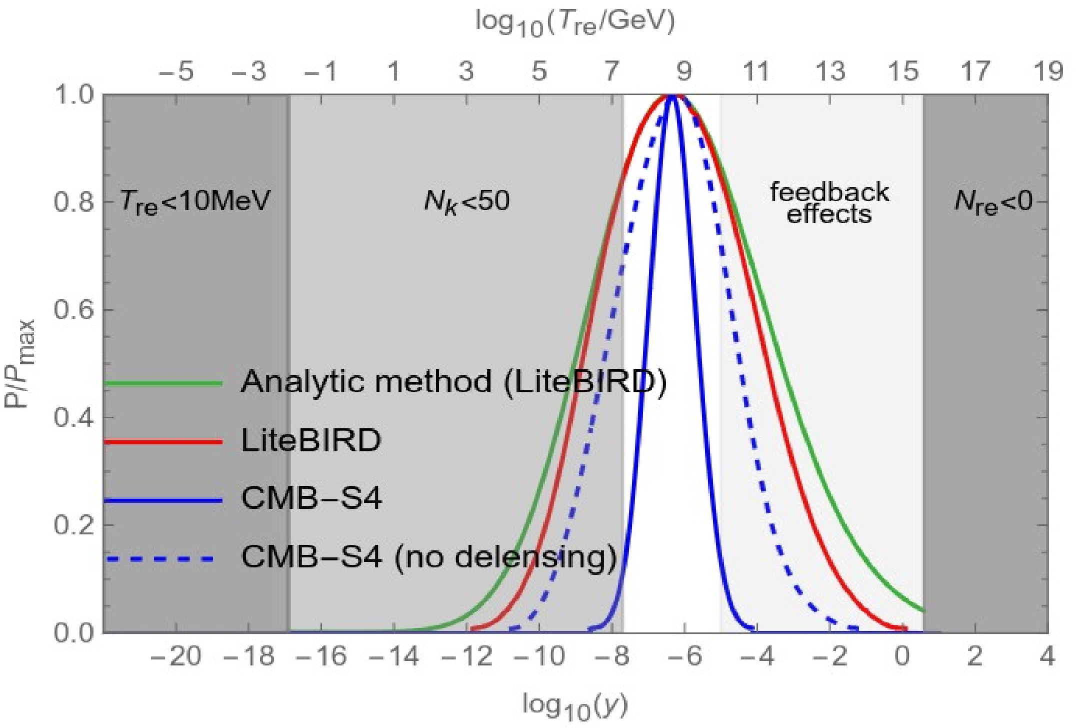
- Correction to M. Drewes, J. U. Kang, Nucl. Phys. B 875 (2013) 315–350, arXiv.1305.0267 [hep-ph]

Outline

- Importance of Reheating.
- Introduce the tools from thermal field theory.
- Apply it to a specific model & calculate the dissipation rate. Show how our results differ from *1305.0267.*
- Show possible thermal effects which arises.
- Summery and future steps.

Measuring the reheating temperature

- Reheating temperature T_{re} could be measured (constrained) by future experiments



Marco Drewes,Lei Ming,Isabel Oldengott, arXiv:2303.13503 [hep-ph]

Self-energy and decay rate

- For a general linear Inflation couplings $\phi\mathcal{O}[\mathcal{X}_i]$,

  We define the self-energies at leading order in the tiny Inflaton couplings as

$$\Pi^{>}(x_1,x_2) = \langle \mathcal{O}(x_1)\mathcal{O}(x_2)\rangle,\ \Pi^{<}(x_1,x_2) = \langle \mathcal{O}(x_2)\mathcal{O}(x_1)\rangle.$$

The **spectral selfe-nergy** $\Pi^{-}(x_1,x_2) = \Pi^{>}(x_1,x_2) - \Pi^{<}(x_1,x_2),$

Determines the **total relaxation rate** $\Gamma_{\boldsymbol{q}} \sim \Pi^{-}_{\boldsymbol{q}}(\Omega_{\boldsymbol{q}})$

Spectral Function

- Define the *spectral function* $\Delta^-(x_1, x_2)$

$$\Delta^-(x_1, x_2) = i\left(\langle\phi(x_1)\phi(x_2)\rangle - \langle\phi(x_2)\phi(x_1)\rangle\right).$$

- The Dyson-Schwinger equation

$$(\Box_1 + m^2)\Delta_{\mathcal{C}}(x_1, x_2) + \int_{\mathcal{C}} d^4x' \Pi_{\mathcal{C}}(x_1, x')\Delta_{\mathcal{C}}(x', x_2) = -i\delta_{\mathcal{C}}(x_1 - x_2)\ .$$

The Spectral Density

- The spectral density is given as

$$\rho_{\mathbf{q}}(\omega) = \frac{-2\mathrm{Im}\Pi^R_{\mathbf{q}}(\omega) + 2\omega\epsilon}{(\omega^2 - m^2 - \mathbf{q}^2 - \mathrm{Re}\Pi^R_{\mathbf{q}}(\omega))^2 + (\mathrm{Im}\Pi^R_{\mathbf{q}}(\omega) + \omega\epsilon)^2}.$$

- The quasi-particle dispersion relation, for weakly coupled theories

$$\omega^2 - \mathbf{q}^2 - m^2 - \mathrm{Re}\Pi^R_{\mathbf{q}}(\omega) = 0,$$

- In the Zero width approximation

$$\rho^0_{i\mathbf{p}}(p_0) = 2\pi Z_{i\mathbf{p}}\mathrm{sign}(p_0)\delta(p_0^2 - \Omega^2_{i\mathbf{p}}) + \rho^{\mathrm{cont}}_{i\mathbf{p}}(p_0).$$

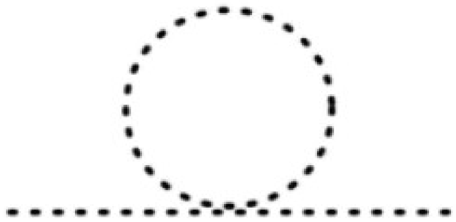
The Model

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 + \sum_{i=1}^{2}\left(\frac{1}{2}\partial_\mu\chi_i\partial^\mu\chi_i - \frac{1}{2}m_i^2\chi_i^2 - \frac{\lambda_i}{4!}\chi_i^4\right) - g\phi\chi_1\chi_2 + \mathcal{L}_{\text{bath}}.$$

1305.0267

- The χ_i fields receive thermal masses

$$M_i^2 = m_i^2 + \lambda_i \int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{f_B(\omega_i)}{2\omega_i} \approx m_i^2 + \frac{\lambda_i}{24}T^2.$$



Leading order contribution

- Leading order contribution to the relaxation rate

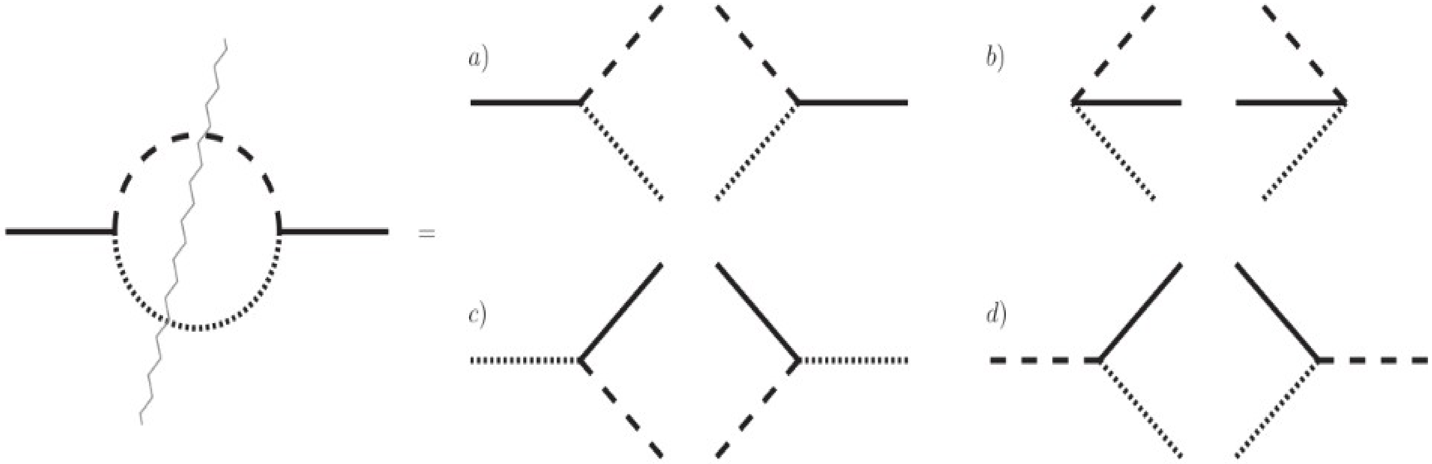
$$\Gamma_{\mathbf{q}} = -ig^2 \int \frac{d^4p}{(2\pi)^4} \left(1 + f_B(p_0) + f_B(\omega - p_0)\right) \rho_{1\mathbf{p}}(p_0)\rho_{2\mathbf{q}-\mathbf{p}}(\omega - p_0).$$

Diagrammatic Interpretation of the decay rate

- In the Zero width approximation for quasi-particles

$$
\begin{aligned}
\Gamma_{\mathbf{q}} &= -ig^2 \int \frac{d^3\mathbf{p}}{(2\pi)^2} \frac{1}{4\Omega_2\Omega_1} \\
\times & \Bigg[\Big((f_1+1)(f_2+1) - f_1 f_2 \Big) \Big(\delta(\omega - \Omega_1 - \Omega_2) - \delta(\omega + \Omega_1 + \Omega_2) \Big) \\
+ & \Big((f_1+1) f_2 - (f_2+1) f_1 \Big) \Big(\delta(\omega - \Omega_1 + \Omega_2) - \delta(\omega + \Omega_1 - \Omega_2) \Big) \Bigg]
\end{aligned}
$$

Diagrammatic Interpretation



Result

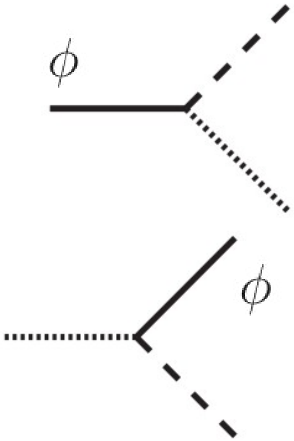
$$\Pi_0^-(\omega) = 2i\left(\mathcal{D}_0^{[g]}(\omega) + \mathcal{S}_0^{[g]}(\omega)\right)$$

$$\mathcal{D}_0^{[g]}(\omega) = \frac{A}{\bar{\omega}_1 + \bar{\omega}_2}\Theta(\omega - M_1 - M_2)$$

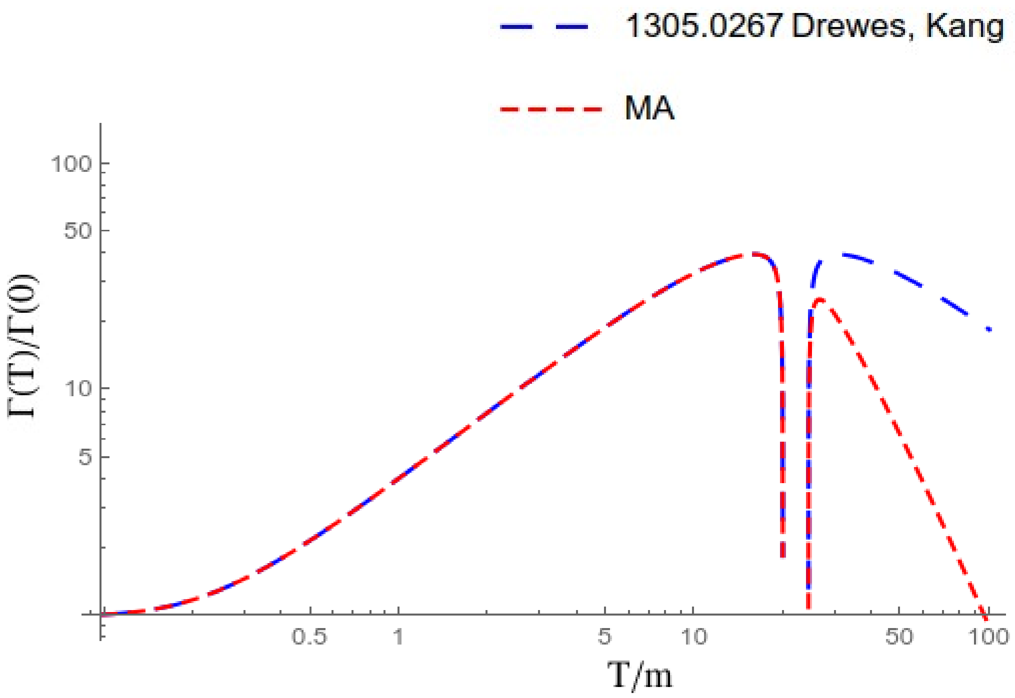
$$\mathcal{S}_0^{[g]}(\omega) = \frac{A}{\bar{\omega}_1 - \bar{\omega}_2}\Big(\Theta(M_1 - \omega - M_2) - \Theta(M_2 - \omega - M_1)\Big)$$

$$A = -\frac{g^2}{8\pi}\sqrt{\bar{\omega}_1^2 - M_1^2}\Big(1 + f(\bar{\omega}_1) + f(\bar{\omega}_2)\Big)$$

$$\bar{\omega}_1 = \frac{\omega^2 + M_1^2 - M_2^2}{2\omega} \qquad \bar{\omega}_2 = \frac{\omega^2 - M_1^2 + M_2^2}{2\omega}$$



Behavior of the decay rate



- The rate Γ as a function of T, normalized to its zero temperature value.
- Allowed regimes as a function of temperature

$$M \geqslant M_1 + M_2 \qquad \phi \leftrightarrow \chi_1\chi_2$$
$$|M_1 - M_2| \gtrsim M. \qquad \chi_i\phi \leftrightarrow \chi_j$$

- For this choice of parameters λ1 = 0.01, λ2 = 1, m1 = m2 = 0.001m.

Summary

- On-shell contribution to the relaxation rate gives rise to processes such as decays $\phi \leftrightarrow \chi_1\chi_2$, and inverse decays $\chi_i\phi \leftrightarrow \chi_j$
- These processes are relevant to the reheating process.
- The damping rate can be used to estimate the dissipation rate during inflation itself (interesting for *warm inflation*).
- These kinematic effects can be relevant for Baryogenesis, dark matter production.
- Next step is to include higher order and study landau damping effects.

Murakoze Cyane