Inflaton Decay: The Role of thermal Masses

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DESY Theory Workshop 2008 | 1. 10. 2008, Hamburg

Motivation

- temperature T is a very important parameter in the early universe
- T determines the rates for thermal particle production
- in different models several bounds exist (e.g. leptogenesis, gravitino problem...)

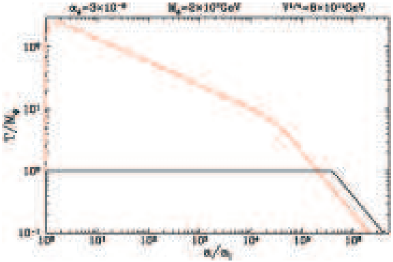
Reheating

In inflationary cosmology the universe is heated by the decay of the inflaton ϕ at the end of inflation

- initially all energy is in the zero mode of ϕ
- zero mode decays in oscillations around potential minimum
- most of the decay process happens in a background plasma of decay products

In a plasma the fundamental excitations of quantum fields are different from the particles in vacuum.

- resonances in plasma obtain effective mass and width
- effective masses of decay products may become larger than m_ϕ
- does this kinematically forbid further decay?
- claim: this puts a bound on the reheating temperature [Kolb,Notari,Riotto 2003]
- has been challenged [Yokoyama 2004]



does the effect exist?

is it cosmologically relevant?

QFT of nonequilibrium (NEQ) systems

- full quantum mechanics of NEQ system can be described by Kadanoff Baym equations
- define spectral and statistical propagator
  $\Delta^-(x_1.x_2) = i\langle[\phi(x_1), \phi(x_2)]\rangle \quad \Delta^+(x_1, x_2) = \frac{1}{2}\langle\{\phi(x_1), \phi(x_2)\}\rangle$

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

This neglects Hubble expansion, but generalisation is straightforward e.g.[Hohenegger,Kartavtsev,Lindner 2008]

Weak coupling to a thermalized bath

Consider Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + g\phi\mathcal{O}[\mathcal{X}] + \mathcal{L}_\mathcal{X}$$

$[\mathcal{X}]$ denotes all (bosonic or fermionic) fields that couple to ϕ

- $[\mathcal{X}]$ can have arbitrary interactions (gauge, Yukawa, scalar...) amongst each other
- assumption: bath fields are coupled stronger than coupling to ϕ so that bath thermalizes fast compared to the timescale of ϕ evolution
- then only backreaction of ϕ on the bath is a slow change in temperature, can be ignored when computing decay rate in a particular moment
- this allows to find general solution for the KB equations

Solution to KB equations

$$\Delta^{-}_{\mathbf{q}}(y) = \frac{i}{2\pi}\int_{-\infty}^{\infty} d\omega e^{-i\omega y}\rho_{\mathbf{q}}(\omega),$$

$$\rho_{\phi}(q) = \frac{-2\mathrm{Im}\Pi^{R}_{\phi}(q) - \omega\epsilon}{\left(q^2 - m_P^2 - \mathrm{Re}\Pi^{R}_{\phi}(\omega,\mathbf{q})\right)^2 + \left(\mathrm{Im}\Pi^{R}_{\phi}(q) + \omega\epsilon\right)^2},$$

$$\begin{aligned}
\Delta^{+}_{\mathbf{q}}(t_1,t_2) &= \Delta^{+}_{in;\mathbf{q}}\dot{\Delta}^{-}_{\mathbf{q}}(t_1)\dot{\Delta}^{-}_{\mathbf{q}}(t_2) \\
&+ \dot{\Delta}^{+}_{in;\mathbf{q}}\left(\dot{\Delta}^{-}_{\mathbf{q}}(t_1)\Delta^{-}_{\mathbf{q}}(t_2) + \Delta^{-}_{\mathbf{q}}(t_1)\dot{\Delta}^{-}_{\mathbf{q}}(t_2)\right) \\
&+ \ddot{\Delta}^{+}_{in;\mathbf{q}}\Delta^{-}_{\mathbf{q}}(t_1)\Delta^{-}_{\mathbf{q}}(t_2) \\
&+ \int_0^{t_1} dt' \int_0^{t_2} dt'' \Delta^{-}_{\mathbf{q}}(t_1 - t')\Delta^{-}_{\mathbf{q}}(t'' - t_2)\Pi^{+}_{\mathbf{q}}(t' - t'').
\end{aligned}$$

Solution to KB equations

$$\rho_\phi(q) = \frac{-2\mathrm{Im}\Pi_\phi^R(q) - \omega\epsilon}{\left(q^2 - m_P^2 - \mathrm{Re}\Pi_\phi^R(\omega, \mathbf{q})\right)^2 + \left(\mathrm{Im}\Pi_\phi^R(q) + \omega\epsilon\right)^2},$$

ρ determines spectrum of the theory
$\mathrm{Re}\Pi_\phi^R$ gives effective mass to ϕ
$\mathrm{Im}\Pi_\phi^R$ determines width of ϕ resonance $\Rightarrow$ determines lifetime

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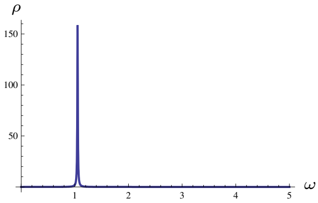
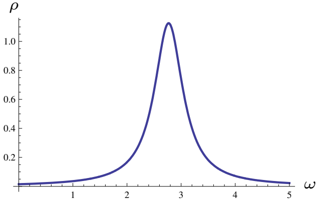
- without self energy: $\rho \propto \delta(p^2 - m^2)$
- interaction gives effective mass by $\mathrm{Re}\Pi^R$ and finite width by $\mathrm{Im}\Pi^R$
- typically mass and width increase with T
- if $\mathrm{Im}\Pi^R \ll m^2$resonanes have (quasi)particle like character
- inverse lifetime $\tau^{-1} = \Gamma = \frac{\mathrm{Im}\Pi^R(\omega)}{\omega}$



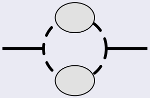


Computation of Π^R I

$$\mathcal{L}_\chi = \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - \frac{1}{2} m_\chi^2 \chi^2 + \frac{\lambda}{4!}\chi^4 + g\phi\chi^2$$

self energy to lowest order given by loop diagram:

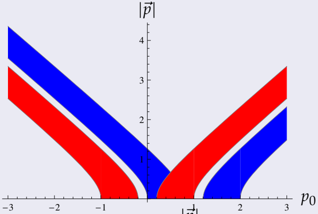
higher order corrections can be estimated by resummation

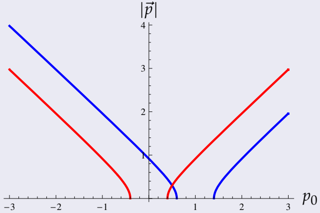


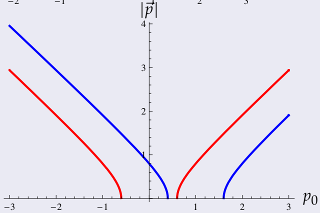
we use the real time formalism to compute the diagrams

Computation of Π^R II

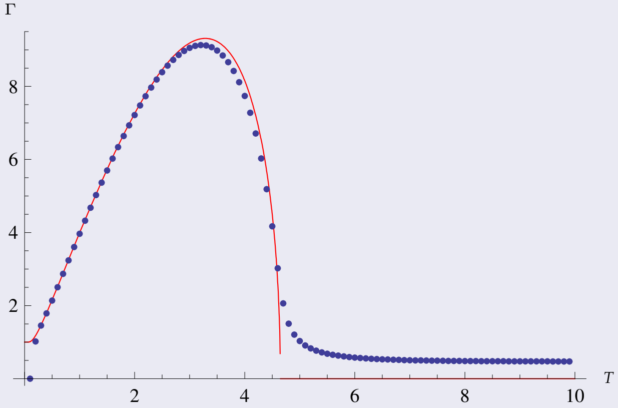
$$\mathrm{Im}\Pi_\phi^R(k) \propto \int \frac{d^4p}{(2\pi)^4}\rho_\chi(p)\rho_\chi(k-p)$$







Result



What can we learn from this?

- if χ-masses become large before χ becomes broad decay becomes strongly suppressed above some critical temperature T_c
- if χs are sufficiently broad below T_c offshell decays will further heat the plasma beyond T_c

$\Rightarrow$ whether bound on T_R exists depends on masses and couplings

Scattering

- this only takes into account the decay $\phi \rightarrow \chi\chi$
- if one includes additional couplings and fields energy transfer can happen through scatterings , e.g.
  - $\phi\chi \rightarrow \chi\chi$
  - $\chi_1\phi \rightarrow \chi_2$
  - ...
- in reality the inflaton can be coupled to many other fields in different ways
- these channels allow energy transfer and heating through on-shell processes even if $m_\phi < m_\chi$

Conclusions

Does the effect exist?

- depends on couplings and masses
- in particular: does χ become heavy or broad first?

Is it cosmologically relevant?

- depends on particular model
- in general not