Can Thermal Masses constrain the Reheating Temperature?

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Inflation

- numerous hints that the universe underwent accelerated expansion
- at the end of the inflationary phase: particles produced in "reheating"
- underlying microphysics of both processes unknown
- if all relevant physics can be parameterised in one scalar dof ϕ
  - constraints on potential $V(\phi)$ during inflation...
  - ...but very little known about potential near minimum
- even in simple models it is a demanding task to model the details of the reheating process

Reheating

- early phase is a highly complicated far-from-equilibrium process that can yield interesting relics. . .
- . . .but temperature T_R at onset of radiation dominated era may be determined by late phase

Reheating

- early phase is a highly complicated far-from-equilibrium process that can yield interesting relics...
- ...but temperature T_R at onset of radiation dominated era may be determined by late phase
- several simplifications
  - decay products thermalise on time scales $\ll 1/\Gamma$
  - ϕ is the only far-from-equilibrium dof, it dissipates in a thermal bath with slowly ($\sim 1/\Gamma, 1/H$) changing temperature T
  - $V(\phi)$ during oscillatinos near minimum approximately harmonic
  - effective masses are dominated by "thermal masses"
  - dissipation via perturbative processes (e.g. decay)

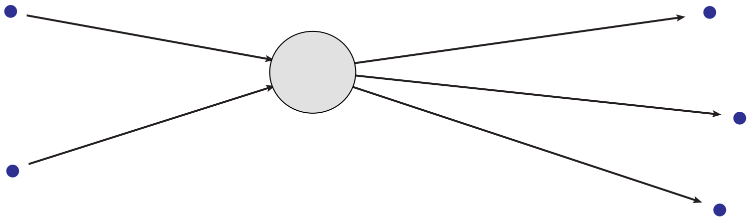
$\Rightarrow$ relaxation of a scalar that is (very) weakly coupled to a thermal bath

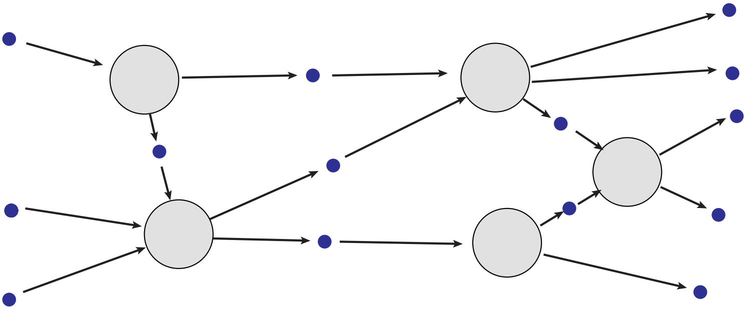
An upper Bound on T_R?

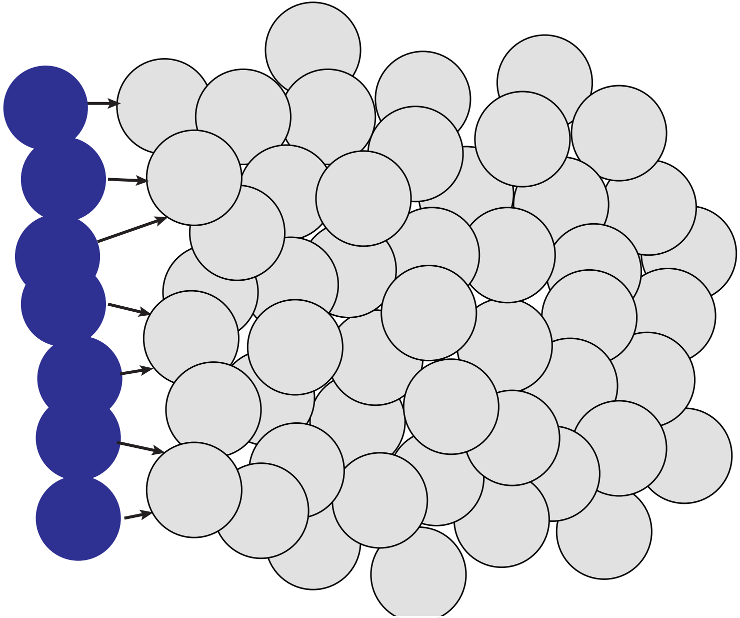
- dispersion relations of particles in a plasma are modified ("screening")
- simplest case: modifications can be parameterised by replacing intrinsic masses m by thermal masses $M(T)$
- it has been suggested that the decay $\phi \rightarrow \chi_1\chi_2$ (or similar $\phi \rightarrow \chi\chi\chi$ etc) is kinematically forbidden for $\sum_i M_i(T) > M_\phi(T)$ $\Rightarrow$ plasma cannot be heated to temperatures larger than T_c with $\sum_i M_i(T_c) = M_\phi(T_c)$! Kolb/Notari/Riotto 2003
- ϕ is very weakly coupled
  - $M_\phi(T) \approx m_\phi \gg m_i$
  - thermal masses $M_i(T)$ determined by stronger interactions in the bath

$\Rightarrow$ T_c does not depend on the inflaton coupling!

- argument is based on single particle kinematics
- is this valid in a dense nonequilibrium plasma?







1. definition of asymptotic states in the omnipresent plasma?
2. when can modified dispersion relations be parameterised by thermal masses?
3. gauge theories: gauge independent results require inclusion of processes that naivlely are of higher order - how does that accord with use of single particle distribution functions?
4. inter particle distance $\sim$ Compton wavelength?
5. memory effects?
6. quantum coherence, interference?

Particles and Fields

- above problems arise if we *insist* to describe the system as a collection of individual (on-shell/classical) particles
- this is not always suitable (e.g. QCD near crossover, classical fields,. . .)
- it is also not necessary - we are interested in overall relaxation of the system

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Schwinger-Keldysh Formalism

Any quantum system can be described by correlation functions.

- no reference to asymptotic states and particles needed
- no trouble with “real intermediate state subtraction” etc
- allows to compute all observables at all times

Equations of Motion

- equations of motion form system of coulped 2nd order integro-differential equations of several variables that can only be solved numerically (Kadanoff-Baym equations)...
- ... but for the weak coupling to a thermal bath formal analytic solutions can be found for bosons and fermions!
  Anisimov/Buchmüller/MaD/Mendizabal 2008,2010; MaD 2010
- weak coupling of ϕ allows to obtain explicit analytic expression
  - no coherence effects on timescales $1/\Gamma$
  - no memory (ϕ: can be integrated, bath: erased by fast interactions)
  - but non-trivial kinematic effects
- allow to compute energy per mode as
  $\epsilon^{\phi}_{\mathbf{q}}(t) = \frac{1}{2}\left(\partial_{t_1}\partial_{t_2} + \omega^2_{\mathbf{q}}\right)\left(\Delta^+_{\mathbf{q}}(t_1,t_2) + \langle\phi_{\mathbf{q}}(t_1)\rangle\langle\phi_{\mathbf{q}}(t_2)\rangle\right)\Big|_{t_1=t_2=t}$

$$
\begin{aligned}
(\Box_1 + m^2)\Delta^-(x_1, x_2) &= -\int d^3\mathbf{x}' \int_{t_2}^{t_1} dt' \Pi^-(x_1, x')\Delta^-(x', x_2) \,, \\
(\Box_1 + m^2)\Delta^+(x_1, x_2) &= -\int d^3\mathbf{x}' \int_{t_i}^{t_1} dt' \Pi^-(x_1, x')\Delta^+(x', x_2) \\
&\quad + \int d^3\mathbf{x}' \int_{t_i}^{t_2} dt' \Pi^+(x_1, x')\Delta^-(x', x_2)
\end{aligned}
$$

$$\Delta^-_{\mathbf{q}}(t_1 - t_2) = i\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}e^{-i\omega(t_1-t_2)}\rho_{\mathbf{q}}(\omega)$$

$$\rho_{\mathbf{q}}(\omega) = \left(\frac{i}{\omega^2 - \omega^2_{\mathbf{q}} - \Pi^A_{\mathbf{q}}(\omega) - i\omega\epsilon} - \frac{i}{\omega^2 - \omega^2_{\mathbf{q}} - \Pi^R_{\mathbf{q}}(\omega) + i\omega\epsilon}\right)$$

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

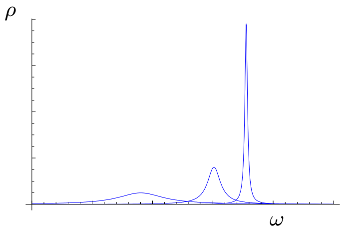
$$\Delta^-_{\mathbf{q}}(y) \simeq \frac{\sin(\Omega_{\mathbf{q}} y)}{\Omega_{\mathbf{q}}} e^{-\Gamma_{\mathbf{q}}|y|/2}; \qquad y = t_1 - t_2, \qquad t = (t_1 + t_2)/2$$

$$\begin{aligned}
\Delta^+(y;t) \;\simeq\;& \frac{\Delta^+_{\mathbf{q},\mathrm{in}}}{2}\big(\cos(2\Omega_{\mathbf{q}} t) + \cos(\Omega_{\mathbf{q}} y)\big)e^{-\Gamma_{\mathbf{q}} t} \\
&+ \frac{\dot{\Delta}^+_{\mathbf{q};\mathrm{in}}}{\Omega_{\mathbf{q}}} \sin(2\Omega_{\mathbf{q}} t) e^{-\Gamma_{\mathbf{q}} t} \\
&- \frac{\ddot{\Delta}^+_{\mathbf{q},\mathrm{in}}}{2\Omega^2_{\mathbf{q}}}\big(\cos(2\Omega_{\mathbf{q}} t) - \cos(\Omega_{\mathbf{q}} y)\big)e^{-\Gamma_{\mathbf{q}} t} \\
&+ \frac{\coth(\frac{\beta\Omega_{\mathbf{q}}}{2})}{2\Omega_{\mathbf{q}}} \cos(\Omega_{\mathbf{q}} y)\left(e^{-\Gamma_{\mathbf{q}}|y|/2} - e^{-\Gamma_{\mathbf{q}} t}\right)
\end{aligned}$$

$$\langle \phi_{\mathbf{q}}(t)\rangle \simeq \dot{\phi}_{\mathbf{q},\mathrm{in}} \frac{\sin(\Omega_{\mathbf{q}} t)}{\Omega_{\mathbf{q}}} e^{-\Gamma_{\mathbf{q}} t/2} + \phi_{\mathbf{q},\mathrm{in}} \cos(\Omega_{\mathbf{q}} t) e^{-\Gamma_{\mathbf{q}} t/2}$$

Spectrum of Excitations

important quantity: spectral densities ρ_i of bath constituents



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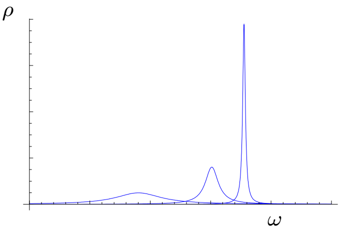
- if ρ_i features narrow peaks:
  - can be interpreted as quasiparticle with dispersion relation $\omega = \Omega_i$ and width Γ_i given by *Re* and *Im* of poles
  - energy transfer between field modes happens via approximately energy conserving decays and scatterings of quasiparticles



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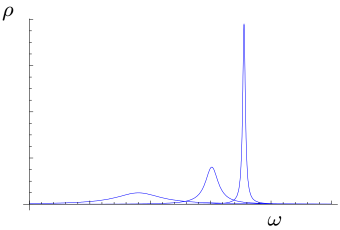

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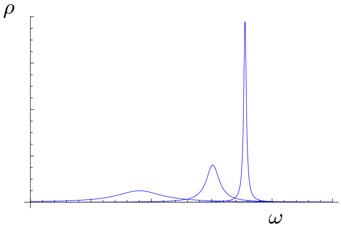
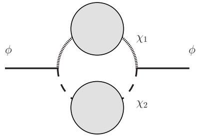
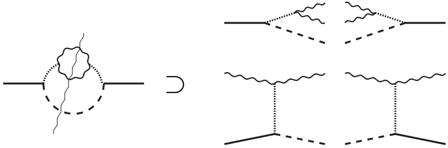
$\Rightarrow$ need fully dressed spectral densities in the medium



consider diagrams of the type
in ϕ-self-energy (=collision term)



- optical theorem relates resummed self energies to multiparticle amplitudes Weldon 1983; Landshoff 1996; Bedaque/Das/Naik 1997
- in medium additional amplitudes involving bath quanta contribute
- widths Γ_i parameterise the effect of multi-particle scatterings, including off-shell contributions and interferences



$\Rightarrow$ resummed perturbation theory can be employed

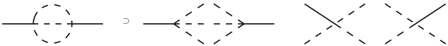
The Physical Picture

- in a dense medium (multiple) scatterings contribute to the dissipation rate (“Landau damping”)
- Schwinger-Keldysh formalism and resummed perturbation theory allow a consistent first principles computation, including interferences and without reference to asymptotic states
- processes involving many quanta may contribute at same order as naively leading terms because
  - additional vertex suppression compensated by large occupation numbers
  - quanta in soft, collinear “bremsstrahlung” are almost on-shell
  - amplification due to induced transitions
- their contribution may be parameterised by widths of resonances in the plasma
- for broad resonances: no simple arguments in terms of single particle kinematics hold

Quasiparticle Regime

- narrow resonances: energy exchange between field modes can be viewed as approximately energy conserving decays and scatterings of quasiparticles
- leading order:
  - 3-vertices:

  - 4-vertices:



$\Rightarrow$ even at leading order decay is not the only process!

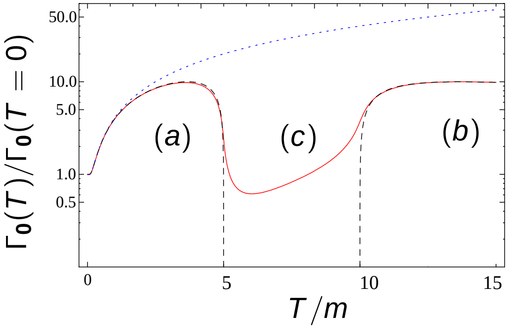
- small apparent violation of energy conservation is due to multiple scatterings encoded in quasiparticle widths, it may have considerable effects

3-Vertex $\phi\chi_1\chi_2$, $\Gamma_i/M_i \sim 10^{-2}$

(a) on-shell decay $\phi \leftrightarrow \chi_1\chi_2$ + higher order

(b) on-shell absorbtion $\phi\chi_1 \leftrightarrow \chi_2$ + higher order

(c) off-shell only



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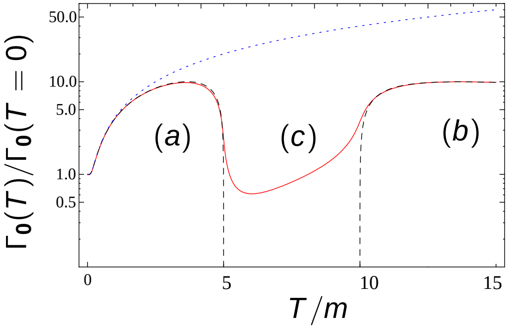
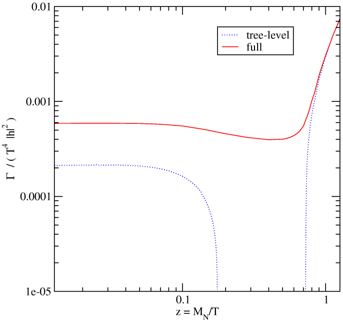
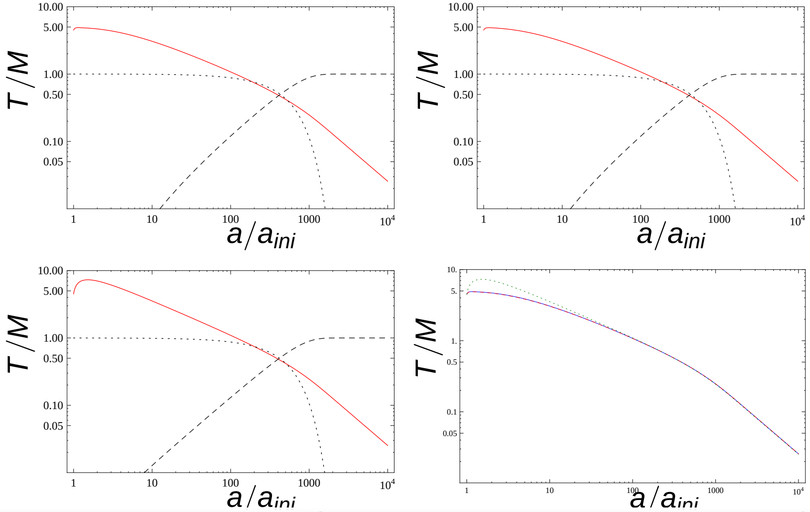


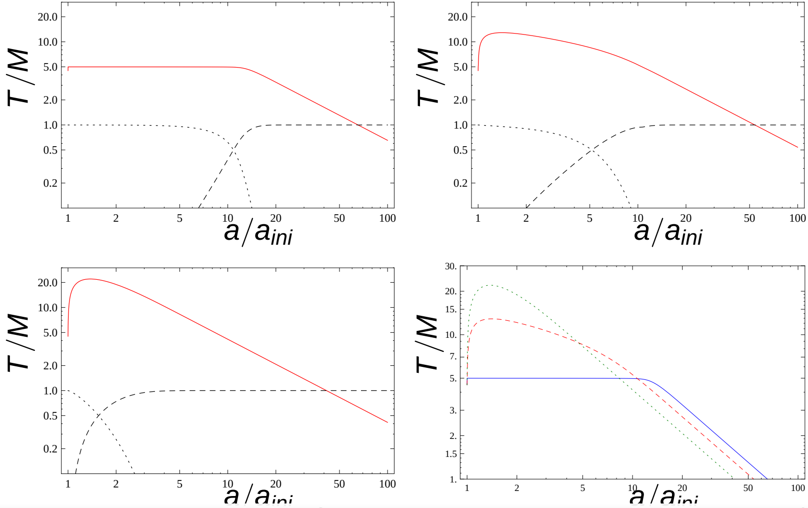


Anisimov/Besak/Bödeker 2010

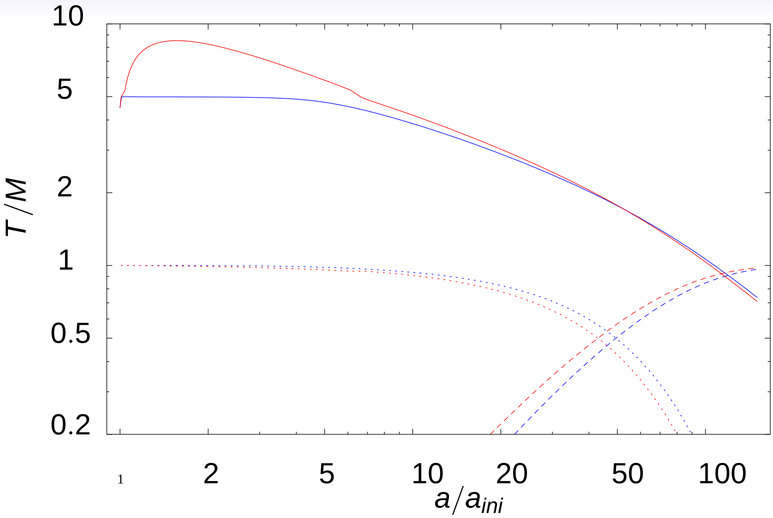
Example I: Upper Bound T_c by Thermal Masses



Example II: Heating for $T > T_c$ by Off-Shell Processes



Example III: Heating for $T > T_c$ by Scatterings



Conclusions

- Medium related modifications of the dispersion relations in the primordial plasma can affect the thermal history during reheating. . .
- . . . but only in special cases thermal masses allow to impose an upper bound on the temberature if
  - effective masses are dominated by thermal masses (not coupling to $\langle\phi\rangle$)
  - resonances in the plasma have a sufficiently narrow width to suppress off-shell dissipation (quasiparticle description)
  - there are no other channels of dissipation (scatterings, Laundau damping. . .)