Preheating with backreaction effects in theories with light fields

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in collaboration with
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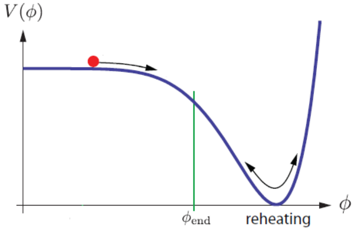
Post-inflationary particle production



Example of an inflaton potential,
D.Baumann "TASI Lectures on Inflation".

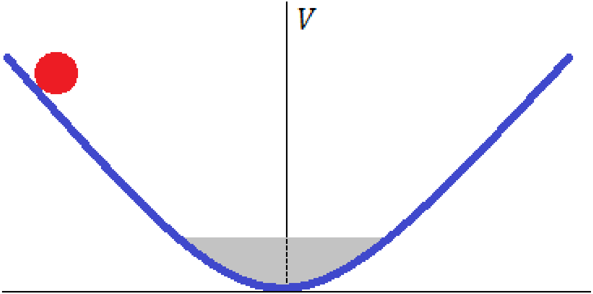
- accelerated expansion (**inflation**), when $V(\phi) \gg \frac{1}{2}\dot{\phi}^2$
- the end of inflation, when $V(\phi) \sim \frac{1}{2}\dot{\phi}^2$
- **reheating**, when the energy density of the inflaton is converted into radiation - highly non-thermal and cold Universe gets defrosted and thermalised

Preheating - non-adiabatic and non-perturbative stage of coherent oscillations right after the end of inflation

- non-adiabaticity: the occupation number of the homogeneous part of the inflaton is very large at the end of inflation - it behaves as a classical field, an external force acting on the quantum fields coupled to inflaton and their masses change very rapidly in time
- non-perturbativity: particles with masses larger than the inflaton mass can be produced

Backreaction

Backreaction: produced states can change the effective mass term of inflaton



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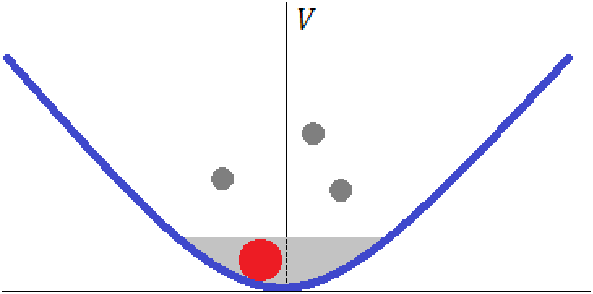

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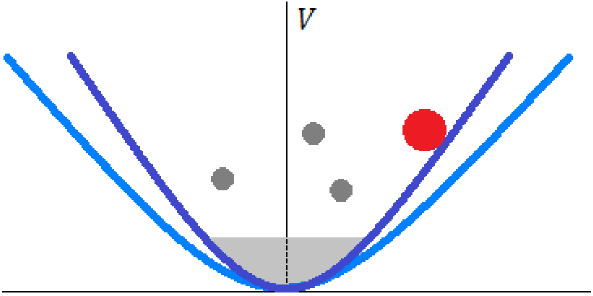

Backreaction

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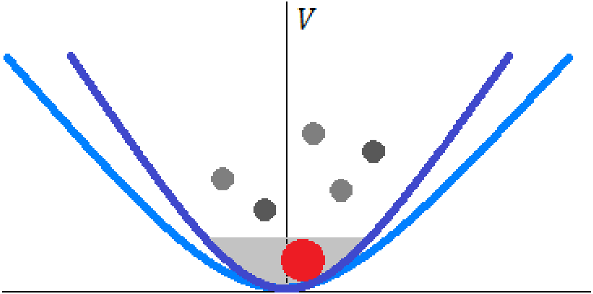

Backreaction

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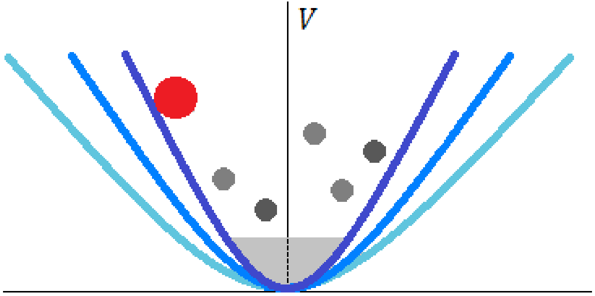


Models with light fields

Our goal

to investigate the particle production in the models with light fields indirectly coupled to inflaton including backreaction:

...
L. R. W. Abramo, R. H. Brandenberger, V. F. Mukhanov: 9704037
L. Kofman, A. Linde, A. Starobinsky: 9704452
L. Kofman et al.: 0403001
R. Brandenberger, R. Costa, G. Franzmann: 1504.00867
D. Roest, M. Scalisi, P. Werkman: 1607.08231
...

I) two scalar system:

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}m_\chi^2\chi^2 - \frac{1}{4}g^2\phi^2\chi^2$$

II) system with the additional light sector:

$$\mathcal{L} = \tfrac{1}{2}(\partial\phi)^2 + \tfrac{1}{2}(\partial\chi)^2 - \tfrac{1}{2}m_\phi^2\phi^2 - \tfrac{1}{2}m_\chi^2\chi^2 - \tfrac{1}{4}g^2\phi^2\chi^2$$
$$\underline{+\sum_n \tfrac{1}{2}(\partial\xi_n)^2 - \sum_n \tfrac{1}{2}m_\xi^2\xi_n^2 - \sum_n \tfrac{1}{4}y^2\chi^2\xi_n^2}$$

ϕ - inflaton, $\langle 0^{\rm in}|\,\phi\,|0^{\rm in}\rangle = \langle\phi(t)\rangle$
χ - another scalar field coupled directly to ϕ, $m_\phi \gg m_\chi$, $\langle\chi\rangle = 0$
ξ_n - N light or massless fields not coupled to ϕ, $m_\phi \gg m_\xi$, $\langle\xi_n\rangle = 0$

χ particles are produced resonantly and ξ_n through the interactions with χ.

Numerical results for multi-scalar systems

We are interested in time-evolution of particle number density for each species:

$$n(t) = \int \frac{d^3k}{(2\pi)^3} \frac{\langle N_{\mathbf{k}} \rangle}{V}$$

$$N_k(t) = \frac{1}{2\omega_k} \left(\dot{\hat{\phi}}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} + \omega_k^2 \hat{\phi}^\dagger_{\mathbf{k}} \hat{\phi}_{\mathbf{k}} \right) + \frac{i}{2} \left(\hat{\phi}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} + \dot{\hat{\phi}}^\dagger_{\mathbf{k}} \hat{\phi}_{\mathbf{k}} \right)$$

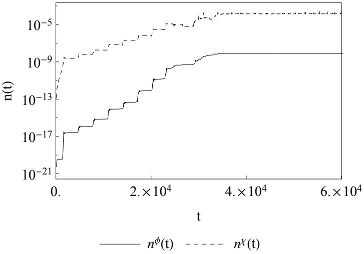
- solve eoms for all the species for t_{ini} and calculate their number density
- do the same for $t_{ini} + \Delta t$ taking into account the backreaction of previously produced states on the evolution of the background (given by the induced potential coming from non-zero energy density)
- repeat it till you reach t_{fin}

Two scalar system

According to L. Kofman et al.: 0403001 the first production of χ particles results in the number density

$$n_\chi^{(1)} \sim \frac{\left[g m_\phi \langle \phi(0) \rangle\right]^{3/2}}{(2\pi)^3} \sim 4 \cdot 10^{-9}$$

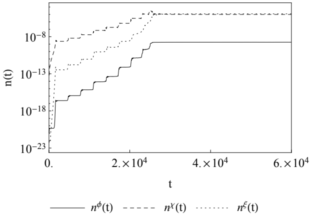
we are in agreement!



$g = 0.1$, $m_\phi = 0.001M$
($M \sim 0.04 M_{PL}$, $M_{PL} \sim 1.22 \cdot 10^{19}$ GeV)

System with the additional light sector

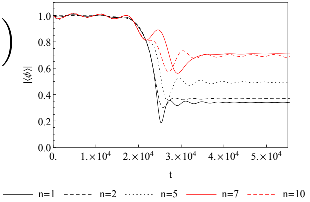
- all the states are produced abundantly
- for $n_\xi \sim n_\chi$: quenching of the preheating (due to enhancement of the backreaction effects: $n_\xi \uparrow$)
- expectation: most of the energy would be transferred to ξ_n fields as they are very light but: $N \uparrow \Leftrightarrow |\langle\phi\rangle|^{final} \uparrow$, energy transfer to $\xi \downarrow$



$g = 0.1, y = 1, N = 1, m_\phi = 0.001M$

The physical mass of χ

$$M_\chi^2 = m_\chi^2 + \frac{1}{2}g^2\langle\phi\rangle^2 + \frac{1}{2}g^2\int\frac{d^3p}{(2\pi)^3}\left(\frac{1}{V}\langle\hat{\phi}_{\mathbf{p}}^\dagger\hat{\phi}_{\mathbf{p}}\rangle - \frac{1}{2\omega_{\phi p}}\right)$$
$$+\frac{1}{2}y^2\sum_n\left(\frac{1}{V}\langle\hat{\xi}_{n\mathbf{p}}^\dagger\hat{\xi}_{n\mathbf{p}}\rangle - \frac{1}{2\omega_{\xi p}}\right) + \mathcal{O}(y^4, y^2g^2, g^4)$$



Once ϕ or ξ_n are produced they also generate χ's effective mass which results in particle production area becoming narrower: $n_\chi \downarrow$.

$g = 0.1, y = 1, m_\phi = 0.001M$

Thank you for your attention.

Back-up slides

Instant preheating

"We describe a new efficient mechanism of reheating. Immediately after rolling down the rapidly moving inflaton field ϕ produces particles χ, which may be either bosons or fermions. This is a nonperturbative process which occurs almost instantly; no oscillations or parametric resonance is required. (...) When the particles χ become sufficiently heavy, they rapidly decay to other, lighter particles. (...)"

G. Felder, L. Kofman, A. Linde: 9812289

- three fields - background ϕ, χ interacting with ϕ and some other field ψ not coupled to ϕ
- χ particles produced within one-time oscillation of ϕ decay immediately to ψ before the next oscillation of ϕ
- ψ states can be also produced even though there is no direct interaction between ϕ and ψ

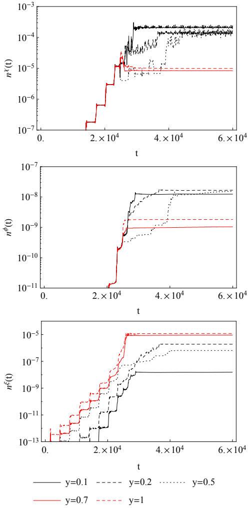
	our work	instant preheating
inflaton's behaviour	oscillations	no oscillations
mechanism of production	the quantum corrections	decay
origin of the quenching	backreaction	rapid decay

Varying y with fixed g

$$\frac{1}{4}g^2\phi^2\chi^2 \quad \sum_n \frac{1}{4}y^2\chi^2\xi_n^2$$

produced states	effect of varied y
χ, ϕ	does not influence the initial stage of preheating influences the final n_χ and n_ϕ: $y\uparrow \quad \Leftrightarrow \quad n_\chi^{final}\downarrow, n_\phi^{final}\downarrow$
ξ_n	both initial and final stages are strongly influenced $y\uparrow \quad \Leftrightarrow \quad n_\xi^{final}\uparrow$ $y\downarrow\Leftrightarrow$ energy transfer to $\langle\phi\rangle\uparrow$

For $n_\xi^{final} \sim n_\chi^{final}$: quenching of the preheating
($y = 0.7$ and $y = 1$)



$g = 0.1, N = 1, m_\phi = 0.001M$

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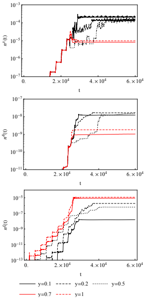
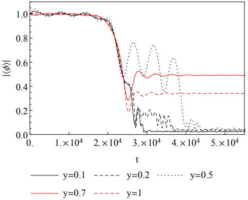


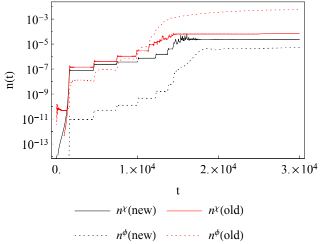


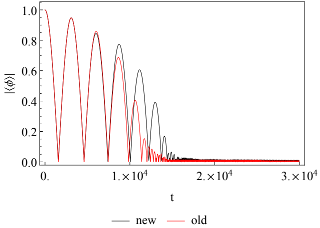
$g = 0.1, N = 1, m_\phi = 0.001M$

The new method vs the old one

old	new
S. Enomoto, O. Fuksińska, Z. Lalak: 1412.7442	O. Czerwińska, S. Enomoto, Z. Lalak: 1701.00015
massless background	massive background
asymptotic approximation	interacting field theory
artificial infinite growth for massless states (secularity)	no secularity

However:
the old results with secularity are still applicable
at the early stages of particle production process.





$g = 1, m_\phi = 0.001M$

EOMs

$$\begin{aligned}
\langle \hat{\phi}^\dagger_{\mathbf{k}} \hat{\phi}_{\mathbf{k}} \rangle^\cdot &= \langle \dot{\hat{\phi}}^\dagger_{\mathbf{k}} \hat{\phi}_{\mathbf{k}} \rangle + \langle \hat{\phi}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} \rangle \\
\langle \hat{\phi}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} \rangle^\cdot &= \langle \dot{\hat{\phi}}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} \rangle + \langle \hat{\phi}^\dagger_{\mathbf{k}} \ddot{\hat{\phi}}_{\mathbf{k}} \rangle \\
&= \langle \dot{\hat{\phi}}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} \rangle - \omega_k^2 \langle \hat{\phi}^\dagger_{\mathbf{k}} \hat{\phi}_{\mathbf{k}} \rangle - \langle \hat{\phi}^\dagger_{\mathbf{k}} \hat{J}_{\mathbf{k}} \rangle \\
\langle \dot{\hat{\phi}}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} \rangle^\cdot &= \langle \ddot{\hat{\phi}}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} \rangle + \langle \dot{\hat{\phi}}^\dagger_{\mathbf{k}} \ddot{\hat{\phi}}_{\mathbf{k}} \rangle \\
&= -\omega_k^2 (\langle \dot{\hat{\phi}}^\dagger_{\mathbf{k}} \hat{\phi}_{\mathbf{k}} \rangle + \langle \hat{\phi}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} \rangle) - \langle \dot{\hat{\phi}}^\dagger_{\mathbf{k}} \hat{J}_{\mathbf{k}} \rangle - \langle \hat{J}^\dagger_{\mathbf{k}} \dot{\hat{\phi}}_{\mathbf{k}} \rangle
\end{aligned}$$

where

$$\hat{J}_{\mathbf{k}} \equiv \int d^3x e^{-\mathbf{k}\cdot\mathbf{x}} J(t, \mathbf{x}).$$

Physical mass of ϕ is determined by the relation:

$$\begin{gathered}
0 = \langle \hat{\phi}^\dagger_{\mathbf{k}} \hat{J}_{\mathbf{k}} \rangle = (m^2 - M^2) \langle \hat{\phi}^\dagger_{\mathbf{k}} \hat{\phi}_{\mathbf{k}} \rangle \\
+ \int d^3x e^{-i\mathbf{k}\cdot\mathbf{x}} \left\langle \hat{\phi}^\dagger_{\mathbf{k}} \frac{dV(x)}{d\phi} \right\rangle
\end{gathered}$$

to remove the infinite part of the mass correction.

Expansion of the universe

we neglect the expansion of the universe $\Leftrightarrow$ we assume that the mean time the trajectory spends in the non-adiabatic region is smaller than the Hubble time

$$\frac{1}{\sqrt{gv}} < \frac{2}{3H(w+1)}$$

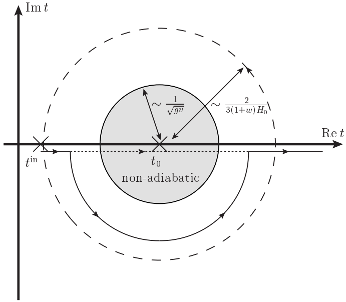
Following K. Enqvist, M. Sloth: 0109214 the number density of produced particles in the expanding universe is

$$n_\chi^{(j)} \sim n_\chi^{(1)} \cdot 3^{j-1} \left(\frac{5}{2}\right)^{3/2} \frac{1}{j^{5/2}}$$

j - the number of oscillations.

For $j \sim 10$ and $n_\chi^{(10)} \sim 1 \times 10^{-6}$, the oscillation phase finishes when $\frac{1}{2} m_\phi^2 \langle\phi_j\rangle^2 \sim \rho_\chi^{(j)} \sim g\langle\phi_j\rangle n_\chi^{(j)}$:

we are in agreement!



Bogoliubov transformation (L.E. Parker & D.J. Toms, N. D. Birrell & P. C. W. Davies, ...)

These two sets of operators act in the same Hilbert space so we can express one using another

$$a_k^{\text{out}} = \alpha_k a_k^{\text{in}} + \beta_k a_k^{\text{in}\,\dagger}$$
$$a_k^{\text{out}\,\dagger} = \alpha_k^* a_k^{\text{in}\,\dagger} + \beta_k^* a_k^{\text{in}}$$

and calculate commutation relation in the new basis

$$[a_k^{\text{out}}, a_k^{\text{out}\,\dagger}] = [\alpha_k a_k^{\text{in}} + \beta_k a_k^{\text{in}\,\dagger}, \alpha_k^* a_k^{\text{in}\,\dagger} + \beta_k^* a_k^{\text{in}}] = \ldots = \left(|\alpha_k|^2 - |\beta_k|^2\right)[a_k^{\text{in}}, a_k^{\text{in}\,\dagger}]$$

Commutation relation is fixed so we obtain the **normalization condition** for **Bogoliubov coefficients** in case of the scalar field

$$|\alpha_k|^2 - |\beta_k|^2 = 1.$$

For fermions: $|\alpha_k|^2 + |\beta_k|^2 = 1$ because of the different form of commutation relation.

Occupation number of produced particles

$$n_k \equiv \langle 0^{\text{in}}|N_k|0^{\text{in}}\rangle = \langle 0^{\text{in}}|a_{\vec{k}}^{\text{out}\,\dagger} a_{\vec{k}}^{\text{out}}|0^{\text{in}}\rangle = V|\beta_k|^2.$$

It seems that if $\beta_k = 0$ particles are not produced.