Quenching preheating by light fields

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in collaboration with
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Motivation

Preheating - exponentially and non-perturbatively produced states typically correspond to the fields directly interacting with the inflaton, they do affect the mass term of the inflaton through backreaction effects

...
L. Kofman, A. Linde, A. Starobinsky: 9405187
L. Kofman, A. Linde, A. Starobinsky: 9704452
J. H. Traschen, R. H. Brandenberger: PRD42 (1990)
A. D. Dolgov, D. P. Kirilova, Sov. J. Nucl. Phys. 51 (1990)
R. Allahverdi et al.: 1001.2600
M. A. Amin et al.: 1410.3808
...

In our previous study S. Enomoto, O. Fuksińska, Z. Lalak: 1412.7442 we showed that light fields which are not coupled directly to the background can be produced due to quantum corrections and their abundance can be sizeable, even for the massless case.

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
...

Models

I) Two scalar system:

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

ϕ - inflaton, $\langle 0^{\rm in}|\,\phi\,|0^{\rm in}\rangle = \langle\phi(t)\rangle$

χ - another scalar field coupled directly to ϕ, $m_\phi \gg m_\chi$, $\langle\chi\rangle = 0$

II) System with the additional light sector:

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

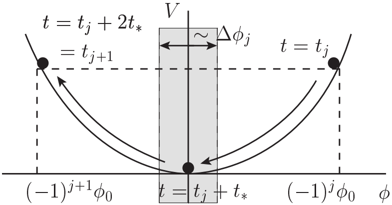
ξ_n - N light or massless fields not coupled to ϕ, $m_\phi \gg m_\xi$, $\langle\xi_n\rangle = 0$

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

Particle production

$$V = \frac{1}{2} g^2 \phi^2 \chi^2 + \frac{1}{2} m_\phi^2 \phi^2$$

- asymptotically:
  $\langle\phi\rangle(t) = \phi_0 \cos[m_\phi(t - t_0)]$, $\langle\chi\rangle = 0$
- non-adiabatic region: $|\phi| \lesssim \sqrt{m_\phi |\phi_0| / g}$
- background field in **non-adiabatic region**:
  χ particles are produced during
  $\Delta t_j \sim (g v_j)^{-1/2}$



$$t_* = \frac{\pi}{2m_\phi}$$

- produced particles induce a new **linear potential** L. v Kofman et al.: 0403001

$$\rho_\chi = \int \frac{d^3k}{(2\pi)^3} n_k \sqrt{k^2 + g^2 |\phi(t)|^2} \approx g|\phi(t)| n_\chi$$

that affects the dynamics of the inflaton

Numerical results for multi-scalar systems

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

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

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

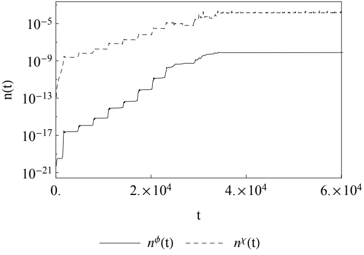
- solve eoms for all the species for t_{ini} and calculate their number density
- do the same for $t_{ini} + \Delta t$ taking into account the backreaction of previously produced states on the evolution of the background (given by the induced potential coming from non-zero energy density)
- repeat it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

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

we are in agreement!

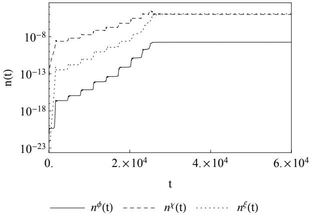


$g = 0.1$, $m_{\phi} = 0.001M$
($M \sim 0.04 M_{PL}$, $M_{PL} \sim 1.22 \cdot 10^{19}$ GeV)

In general it is difficult to obtain the analytical results for indirect production products, like $\tilde{\phi}$. In this system it is a safe approximation to neglect its production but it depends on the target precision.

System with the additional light sector

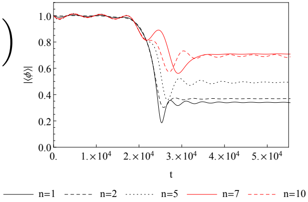
- all the states are produced abundantly
- for $n_\xi \sim n_\chi$: quenching of the preheating (due to enhancement of the backreaction effects: $n_\xi \uparrow$)
- expectation: most of the energy would be transferred to ξ_n fields as they are very light but: $N \uparrow \Leftrightarrow |\langle\phi\rangle|^{final}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



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

The physical mass of χ

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



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

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

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

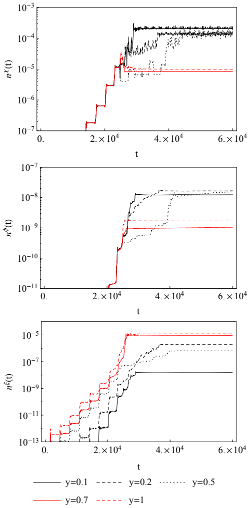
	our work	instant preheating
inflaton's behaviour	oscillations	no oscillations
mechanism of production	the quantum corrections	decay
origin of the quenching	backreaction	rapid decay

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:
	$y\uparrow \;\Leftrightarrow\; n_\chi^{final}\downarrow, n_\phi^{final}\downarrow$
ξ_n	both initial and final stages are strongly influenced
	$y\uparrow \;\Leftrightarrow\; n_\xi^{final}\uparrow$
	$y\downarrow \Leftrightarrow$ energy transfer to $\langle\phi\rangle\uparrow$

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



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

Varying y with fixed g

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

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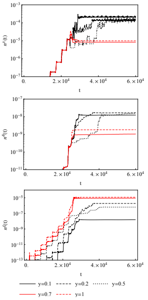
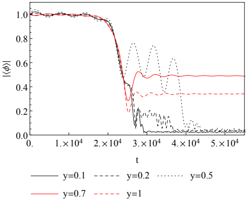
ξ_n	both initial and final stages are strongly influenced
	$y \uparrow \quad \Leftrightarrow \quad n_\xi^{final} \uparrow$
	$y \downarrow \Leftrightarrow$ energy transfer to $\langle\phi\rangle \uparrow$

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





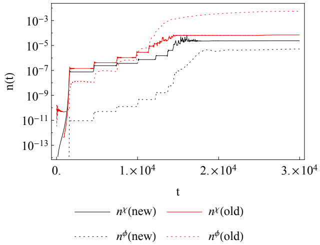
$g = 0.1, N = 1, m_\phi = 0.001M$

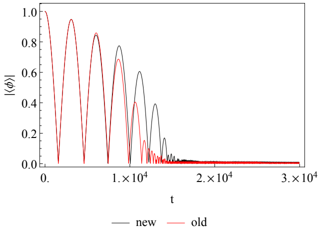
Thank you for your attention.

Back-up slides

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

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

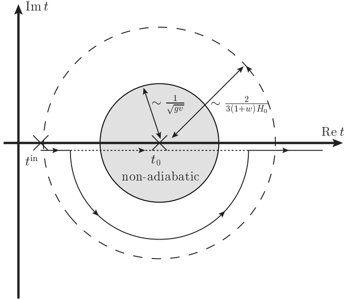
Following K. Enqvist, M. Sloth: 0109214 the number density of produced particles in the expanding universe is

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

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.