Supersymmetric cosmological particle production in time-dependent backgrounds

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1. Motivation

It is known that time-dependent vacuum expectation value of the background field in the presence of perturbative corrections to non-perturbative production causes the production of particles in

- non-adiabatic area (vacuum change, rotation of the basis, rescattering)
- adiabatic area (perturbation theory)

2. Fundamentals

Bogoliubov transformation:

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

Occupation number of produced particles:

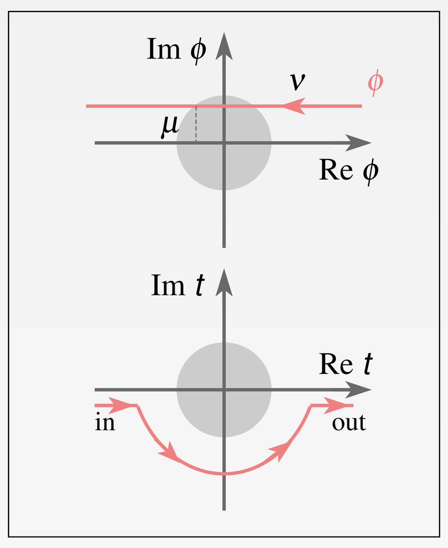
$$n_k \equiv \langle 0^{\text{in}}|N_k|0^{\text{in}}\rangle = \langle 0^{\text{in}}|a_{\vec{k}}^{\text{out}\,\dagger} a_{\vec{k}}^{\text{out}}|0^{\text{in}}\rangle = V|\beta_k|^2$$

Adiabaticity:

- adiabatic area: $\dot{\omega}_k/\omega_k^2 < 1$
  $$n_k(t) \approx \frac{\rho_k}{\omega_k} \approx \frac{1}{\omega_k}\left(\sqrt{\omega}e^{\pm i\int\omega}\right)^2 \approx \text{const}$$
- non-adiabatic area: $\dot{\omega}_k/\omega_k^2 > 1$
  $n_k(t) \neq$ const
  $\Rightarrow$ particle production

3. Change of the vacuum

- superpotential: $W = \frac{g}{2}\Phi X^2$
- asymptotically: $\langle\phi\rangle(t) = vt + i\mu$, $\langle\chi\rangle = \langle\psi_\chi\rangle = \langle\psi_\phi\rangle = 0$
- background field in **non-adiabatic region**: χ and ψ_χ particles are produced
- produced particles induce a new **linear potential** and an attractive force ("oscillations")
- occupation number: $n_k^\chi = V\cdot|e^{-i\int^t dt'\omega_k(t')}|^2 = V\cdot\exp\left(-\pi\frac{k^2+g^2\mu^2}{gv}\right)$
- each time the **number density** $\left(n = \int\frac{d^3k}{(2\pi)^3}\frac{n_k}{V}\right)$ of produced particles is:
  - $n_\phi \approx 0$ and $n_{\psi_\phi} \approx 0$
  - $n_{\psi_\chi} = \frac{(gv)^{3/2}}{(2\pi)^3}e^{-\pi g\mu^2/v}$
  - $n_\chi = \frac{(gv)^{3/2}}{(2\pi)^3}e^{-\frac{\pi(g^2\mu^2+m_S^2)}{gv}}$



4. Rescattering

Equation of motion for a scalar field Ψ with the **source term** $J(x)$:

$$\left(\partial^2 + M^2(x)\right)\Psi(x) + J(x) = 0$$

Yang-Feldman equation:

$$\Psi(x) = \sqrt{Z}\Psi^{\text{as}}(x) - iZ\int_{t_{\text{as}}}^{x^0} dy^0 \int d^3y[\Psi^{\text{as}}(x), \Psi^{\text{as}}(y)]J(y)$$

Generalized Bogoliubov transformation:

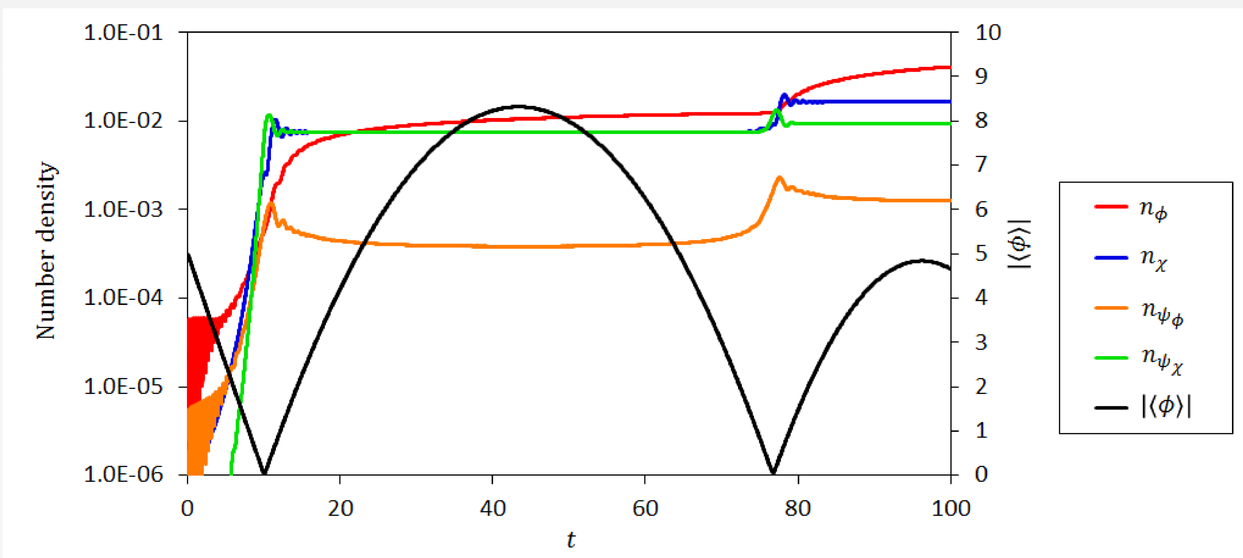
$$a_{\vec{k}}^{\text{out}} = \alpha_k a_{\vec{k}}^{\text{in}} + \beta_k a_{-\vec{k}}^{\text{in}\,\dagger} - i\sqrt{Z}\int d^4x e^{-i\vec{k}\cdot\vec{x}}\left(-\beta_k\Psi_k^{\text{in}}(x^0) + \alpha_k\Psi_k^{\text{in}\,*}(x^0)\right)J(x)$$

Occupation number:

$$n_k = \begin{cases} V|\beta_k|^2 + \ldots & (\beta_k \neq 0) \\ 0 + Z|\int d^4x e^{-i\vec{k}\cdot\vec{x}}\Psi_k^{\text{in}\,*}J|0^{\text{in}}\rangle|^2 & (\beta_k = 0)\end{cases}$$

g	n_χ	n_{ψ_χ}	n_ϕ	n_{ψ_ϕ}
0.1	45.85	50.66	1.83	1.66
0.5	47.33	47.74	4.26	0.66
0.8	45.26	45.36	8.72	0.66
1.5	36.8	37.04	25.03	1.13
1.6	35.67	35.94	27.16	1.24
1.8	32.85	33.14	32.59	1.41
2	43.45	43.61	12.27	0.67

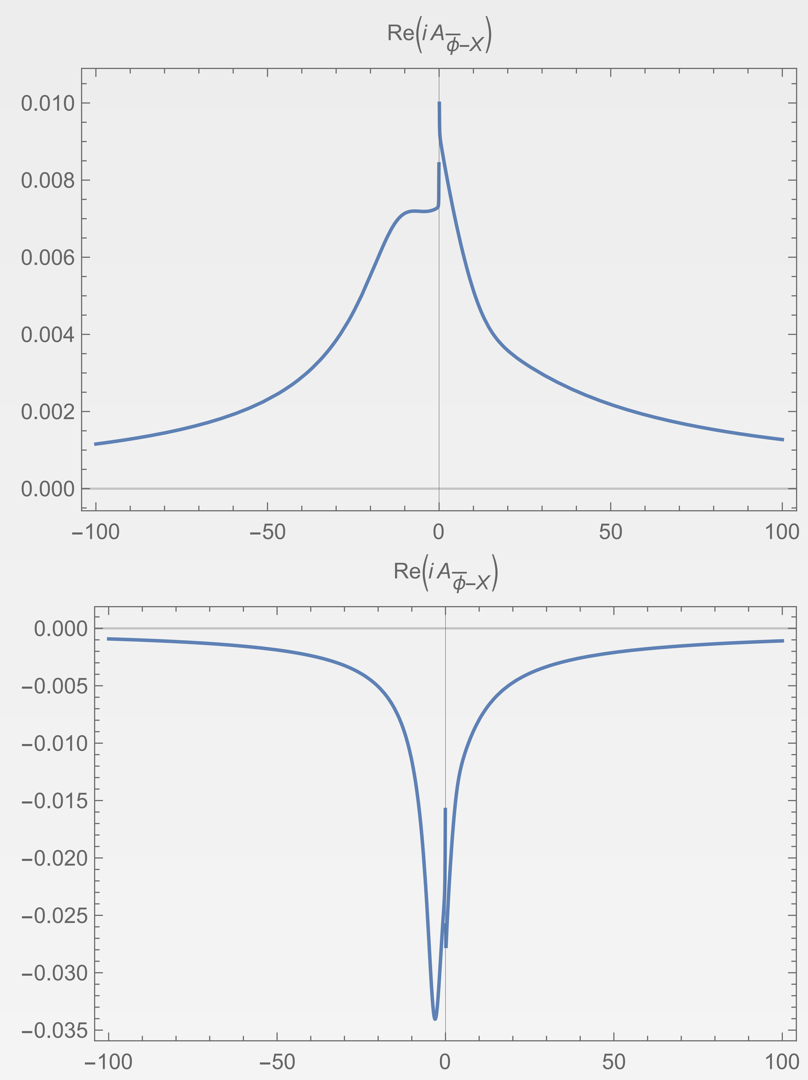
Number density of produced species as a part of the whole production (in %).



$\phi(t=0) = 5 + 0.05i$, $\dot{\phi}(t=0) = -0.5$, $g = 2$

5. Rotation of the basis

When $\langle\chi\rangle \neq 0$ we get additional production due to rotation of the basis for fermionic mass eigenstates.



$\langle\chi\rangle = v_\chi t + i\mu_\chi$
above: $v_\chi = 0.5, v_\phi = 0.3, \mu_\chi = 0.01, \mu_\phi = 0.02$,
below: $v_\chi = -0.5, v_\phi = 0.3, \mu_\chi = 0.01, \mu_\phi = 0.02$

Overall effect is a few orders of magnitude smaller than the production connected with the change of the vacuum.

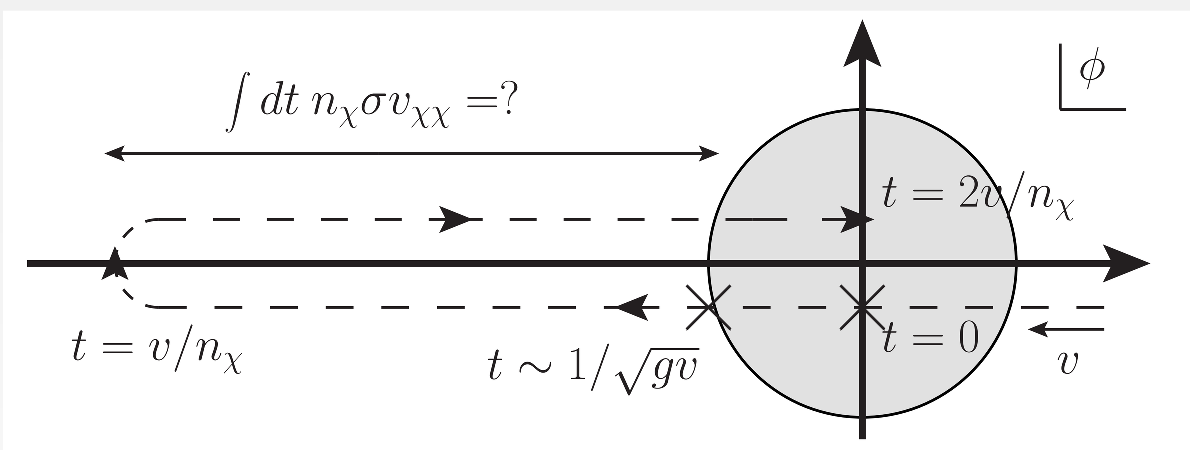
6. Perturbative production

Perturbative production in the adiabatic region can be described by **Boltzmann equation**:

$$\dot{n}_k - Hk\frac{\partial n_k}{\partial k} = \frac{1}{E}\int\frac{d^3p_2d^3p_3}{4(2\pi)^5E_2E_3}\delta^{(4)}(K-p_2-p_3)\left(\sum_m(-n_{\vec{k}}+n_2n_3)|\mathcal{M}_m|^2\right) + $$
$$+\frac{1}{E}\int\frac{d^3p_4d^3p_5d^3p_6}{8(2\pi)^2E_4E_5E_6}\delta^{(4)}(K+p_4-p_5-p_6)\left(\sum_m(-n_{\vec{k}}n_4+n_5n_6)|\mathcal{M}_m|^2\right),$$

where $K = (E,\vec{k})$ and $k = |\vec{k}|$.

Preliminary conclusion:
perturbative production is comparable to non-perturbative one



7. Literature

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- S.Enomoto, S.Iida, N.Maekawa, T.Matsuda, arXiv:1310.4751 [hep-ph]
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