Impact of time-varying vev of the background field on particle production

Olga Fuksińska

University of Warsaw

Cargèse International School for Theoretical Particle Physics
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S.Enomoto, Z.Lalak

Motivation

Possible applications:

- baryogenesis
- leptogenesis
- inflation (preheating, reheating)
- ...

Adiabaticity

Equation of motion for some field α for a given k:

$$\ddot{\alpha}_k + \omega_k^2(t)\alpha_k = 0$$

where $\omega_k^2(t) := k^2 + m_k^2(t)$

Two regimes

- adiabatic region: $\dot{\omega}_k/\omega_k^2 < 1$ (WKB, $n_k^\alpha \approx$ const)
- non-adiabatic region: $\dot{\omega}_k/\omega_k^2 > 1$ (**particle production**)

It is known that varying background causes particle production - **time-dependent vev of the background field** is one of the possibilities.

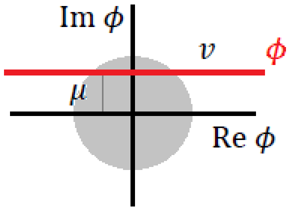
Models

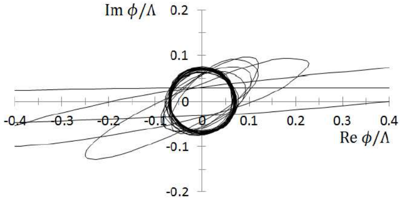
$$\mathcal{L} = -\frac{1}{2} g^2 |\phi|^2 \chi^2$$

(L.Kofman et al., arXiv:hep-th/0403001)

- asymptotically: $\langle \phi \rangle = vt + i\mu$
- background field in non-adiabatic region: χ particles are produced
- produced particles induce a new potential and an attractive force (″oscillations″)

- M1: $W = \frac{g}{2} \Phi X^2$
- M2: $W = \frac{g}{2} \Phi X^2 + h \Phi X \Psi$





(S.Enomoto et al., arXiv:hep-ph/1310.4751)

Back up slides

M1: asymptotic vacuum choice

$$V_{scalar} = \frac{g^2}{4}|\chi|^4 + g^2|\phi|^2|\chi|^2$$

$$\begin{cases} \left(\frac{\partial V}{\partial \phi^*}\right)_{vac} = g^2\langle\chi\rangle^2\langle\phi\rangle = 0 \\ \left(\frac{\partial V}{\partial \psi^*}\right)_{vac} = g^2\langle\chi\rangle\Big(\langle\phi\rangle + \frac{1}{2}\langle\chi\rangle\Big) = 0 \end{cases}$$

so our vacuum choices are:

- $\langle\phi\rangle = \langle\chi\rangle = 0$ (no production)
- $\langle\chi\rangle = 0$, $\langle\phi\rangle \neq 0$

E.o.m.:

$$\partial^2\langle\phi\rangle = 0$$

so

$$\langle\phi\rangle = vt + i\mu$$

M1: SUSY-breaking

We can include SUSY-breaking in our model in two ways:

- SUSY can be broken from the beginning, before the production occurs
- SUSY can be broken after the production and before rescattering

In both cases SUSY is broken during scattering and decays of produced particles after production.

We consider two possible soft SUSY-breaking terms:

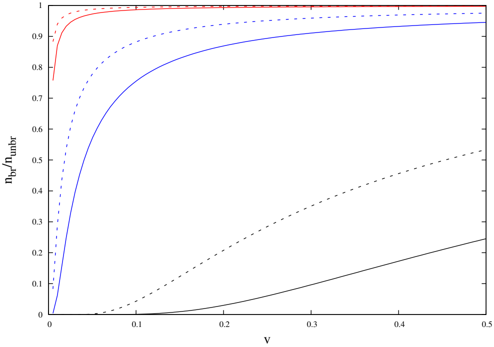
- $\delta\mathcal{L}_{soft} = m^2|\chi|^2$
- $\delta\mathcal{L}_{soft} = m^2|\chi|^2 + A\phi\chi^2 + h.c.$

Second possibility is crucial in gravity-mediation scenarios of SUSY-breaking, when $A \sim m$, in other scenarios it just come down to the first one ($A \ll m$).

M1: Number density of produced particles

After one transition through the non-adiabatic region:

- $n_\phi \approx 0$ and $n_{\psi_\phi} \approx 0$
- $n_{\psi_\chi} = \frac{(gv)^{3/2}}{(2\pi)^3} e^{-\pi g \mu^2 / v}$
- n_χ depends on chosen pattern of SUSY-breaking:
  - from the beginning:
    $n_\chi = \frac{(gv)^{3/2}}{(2\pi)^3} e^{-\frac{\pi(g^2\mu^2+m^2)}{gv}}$
  - before rescattering:
    $n_\chi = \frac{(gv)^{3/2}}{(2\pi)^3} e^{-\pi g \mu^2 / v}$



solid line: $g^2 = 20$
dashed line: $g^2 = 100$

red: $m = 0.002$
blue: $m = 0.04$
black: $m = 1$

M1: Scattering during production

Scattering can affect number density of created particles during production when:

$$\frac{1}{\Gamma} \ll \Delta t = \frac{v}{g n_\chi}$$

Possible processes:

- in both SUSY-breaking scenarios: $\psi_\chi\psi_\chi \to \psi_\phi\psi_\phi$, $\chi\chi \to \psi_\phi\psi_\phi$, $\psi_\chi\psi_\chi \to \phi\phi$, $\chi\chi \to \phi\phi$
- additional in gravity-mediation scenario: $\chi\chi \to \psi_\chi\psi_\chi$

In M1 model (renormalization of wave-function is taken into account):

$$\Gamma^{-1}_{\psi_\chi\psi_\chi\to\psi_\phi\psi_\phi} \propto \frac{v^4}{n_\chi^3} \gg \frac{v}{g n_\chi}$$

$$\Gamma^{-1}_{\chi\chi\to\psi_\phi\psi_\phi} \propto \frac{v^4}{n_\chi^3} \gg \frac{v}{g n_\chi}$$

$$\Gamma^{-1}_{\psi_\chi\psi_\chi\to\phi\phi} \propto \frac{v^4}{n_\chi^3} \gg \frac{v}{g n_\chi}$$

$$\Gamma^{-1}_{\chi\chi\to\phi\phi} \propto \frac{v^4}{g^4 n_\chi^3} \gg \frac{v}{g n_\chi}$$

$$\Gamma^{-1}_{\chi\chi\to\psi_\chi\psi_\chi} \propto \frac{v^8}{g^4 n_\chi^5} \gg \frac{v}{g n_\chi}$$

All these relations hold because of the exponential character of n_χ: no effect.

M2: asymptotic vacuum choice

$$V_{scalar} = |g\chi + h\psi|^2|\phi|^2 + |\frac{g}{2}\chi + h\psi||\chi|^2 + h^2|\phi|^2|\chi|^2$$

$$\begin{cases} \left(\frac{\partial V}{\partial \phi^*}\right)_{vac} = \left((g^2+h^2)|\chi|^2 + h^2|\psi|^2 + gh(\chi\psi^* + \chi^*\psi)\right)_{vac}\langle\phi\rangle = 0 \\ \left(\frac{\partial V}{\partial \psi^*}\right)_{vac} = \langle\chi\rangle\left((g^2+h^2)|\phi|^2 + h^2|\psi|^2 + \frac{1}{2}g^2|\chi|^2\right)_{vac} + gh\langle\psi\rangle\left(|\phi|^2 + |\chi|^2\right)_{vac} + \\ + \frac{1}{2}gh\langle\chi\rangle^2\langle\psi^*\rangle = 0 \\ \left(\frac{\partial V}{\partial \chi^*}\right)_{vac} = h^2\psi\left(|\psi|^2 + |\chi|^2\right) + gh\chi\left(|\phi|^2 + \frac{1}{2}|\chi|^2\right) = 0 \end{cases}$$

so our vacuum choices are:

- $\langle\phi\rangle = \langle\chi\rangle = 0$
- $\langle\phi\rangle = 0$, $\langle\psi\rangle = -\frac{g}{2h}\langle\chi\rangle$
- $\langle\chi\rangle = \langle\psi\rangle = 0$

Once again: $\langle\phi\rangle = vt + i\mu$.

M2: Number density of produced particles, bosons

E.o.m. for bosons:

$$\partial^2\chi + (g^2 + h^2)|\phi|^2\chi + gh|\phi|^2\psi = 0$$
$$\partial^2\psi + gh|\phi|^2\chi + h^2|\phi|^2\psi = 0$$

fields χ and ψ are mixed $\rightarrow$ mass eigenstates are not the interacting ones

After diagonalization of the mass matrix, e.o.m. for mass eigenstates:

$$\partial^2\chi'_k + \left(m^2_{\chi'} + k^2\right)\chi'_k = 0$$
$$\partial^2\psi'_k + \left(m^2_{\psi'} + k^2\right)\psi'_k = 0$$

where

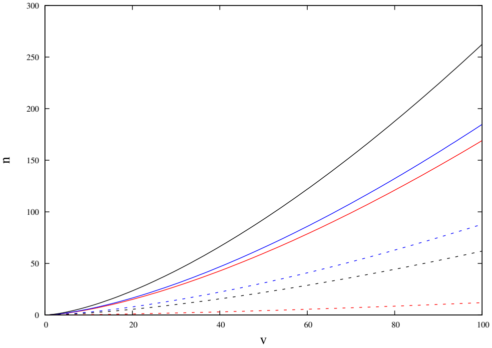
$$m^2_{\chi'} = |\phi|^2\left(\tfrac{g^2+2h^2}{2} + \tfrac{g}{2}\sqrt{g^2+4h^2}\right) = |\phi|^2\tilde{g}^2$$
$$m^2_{\psi'} = |\phi|^2\left(\tfrac{g^2+2h^2}{2} - \tfrac{g}{2}\sqrt{g^2+4h^2}\right) = |\phi|^2\tilde{h}^2$$

Mass eigenstates are free: there are no interaction terms coming from the derivative of diagonalizing matrix which is constant.

M2: Number density of produced particles, bosons

Number density of produced bosons:

- $n_{\chi'} = \frac{(\tilde{g}v_\phi)^{3/2}}{(2\pi)^3} e^{-\pi\tilde{g}\frac{\mu_\phi^2}{v_\phi}}$
- $n_{\psi'} = \frac{(\tilde{h}v_\phi)^{3/2}}{(2\pi)^3} e^{-\pi\tilde{h}\frac{\mu_\phi^2}{v_\phi}}$



blue: $g = 5, h = 10$
red: $g = 10, h = 5$
black: $g = h = 10$

solid line: heavier
dashed line: lighter

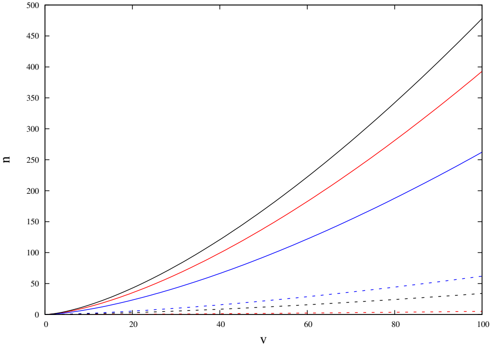
M2: Number density of produced particles, fermions

Masses of fermionic mass-eigenstates:

- $m_{\tilde{\chi}'} = \frac{1}{2}\langle\phi\rangle\left(g + \sqrt{g^2 + h^2}\right)$
- $m_{\tilde{\psi}'} = \frac{1}{2}\langle\phi\rangle\left(g - \sqrt{g^2 + h^2}\right)$

Number density of produced fermions:

- $n_{\tilde{\chi}'} \approx \frac{(v(\sqrt{g^2+h^2}+g))^{3/2}}{(2\pi)^3}$
- $n_{\tilde{\psi}'} \approx \frac{(v(\sqrt{g^2+h^2}-g))^{3/2}}{(2\pi)^3}$



blue: $g = 5, h = 10$
red: $g = 10, h = 5$
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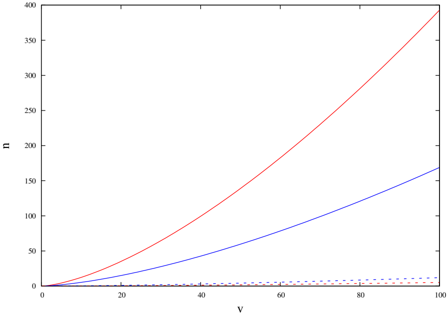

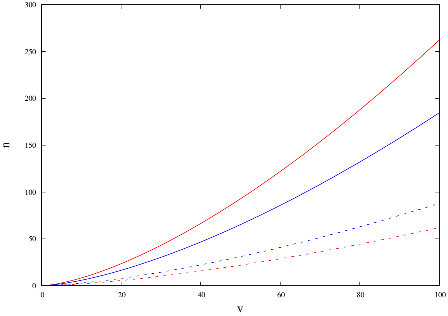

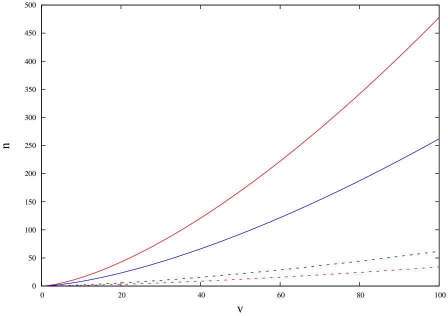

top left: $g = 10, h = 5$
bottom left: $g = 5, h = 10$
above: $g = h = 10$

blue: bosons
red: fermions

solid line: heavier
dashed line: lighter

Gauge theory

In case of gauge theory we have additional terms in the scalar potential that can change the choice of vacuum and can provide us with flat directions:

$$V_{scalar} = W_i^* W^i + \frac{1}{2}\Big(\sum_{a,i} e_a^2 \phi_i^* T^a \phi_i\Big)^2$$

a: generators of the gauge group
e: gauge coupling

U(1) symmetry:

- M1
  - $\langle\phi\rangle = \langle\chi\rangle = 0$ (no production)
  - $\langle\chi\rangle = 0$ and $e^2 = 0$
  - $\langle\phi\rangle = 0$ and $e^2 = -2g^2$
- M2
  - $\langle\phi\rangle = \langle\chi\rangle = \langle\psi\rangle = 0$ (no production)
  - $\langle\phi\rangle = \langle\chi\rangle = 0$ or $\langle\psi\rangle = \langle\chi\rangle = 0$ and $e^2 = 0$
  - $\langle\phi\rangle = \langle\psi\rangle = 0$ and $\Big(gh = 0$ (back to M1 or $W = h\Phi X\Psi$) or $e^2 = -2g^2\Big)$

Gauge theory

SU(2) symmetry:

- M1
  - $\langle\chi\rangle = \langle\phi\rangle = 0$ (no production)
  - $\langle\chi\rangle = 0$ and $e^2 = 0$
  - $\langle\phi\rangle = 0$ and $e^2 = -\frac{2}{3}g^2$
- M2
  - $\langle\chi\rangle = \langle\phi\rangle = \langle\psi\rangle = 0$ (no production)
  - $\langle\chi\rangle = \langle\phi\rangle = 0$ and $h = 0$ (back to M1) and $e^2 = 0$
  - $\langle\chi\rangle = \langle\psi\rangle = 0$ and $gh = 0$ (back to M1 or $W = h\Phi X\Psi$) and $e^2 = -\frac{2}{3}g^2$
  - $\langle\phi\rangle = \langle\psi\rangle = 0$ and $e^2 = 0$

D-flat directions for both U(1) and SU(2):

- M1: $\langle\phi\rangle^2 = \frac{1}{2}\langle\chi\rangle^2$
- M2: $\langle\phi\rangle^2 = \frac{1}{2}\langle\chi\rangle^2 + \frac{1}{2}\langle\psi\rangle^2$

Fayet-Illiopoulos term

In case of U(1) symmetry we can add a new term:

$$V_{FI} = \kappa D$$

then scalar potential takes form

$$V_{scalar} = \sum_i |m_i|^2 |\phi_i|^2 + \frac{1}{2}\left(\kappa - e\sum_i q_i |\phi_i|^2\right)^2$$

Our vacuum possibilities changes to:

- M1
  - $\langle\phi\rangle = \langle\chi\rangle = 0$ (no production)
  - $\langle\phi\rangle = 0$ and $e = 0$ or $\kappa = -\frac{1}{2}e\langle\chi\rangle^2$
  - $\langle\chi\rangle = 0$ and $e = 0$ or $\kappa = e\langle\phi\rangle^2$
- M2
  - $\langle\phi\rangle = \langle\chi\rangle = \langle\psi\rangle = 0$ (no production)
  - $\langle\phi\rangle = \langle\psi\rangle = 0$ and $gh = 0$ (back to M1 or $W = h\Phi X\Psi$)
  - $\langle\phi\rangle = \langle\chi\rangle = 0$ and $e = 0$ or $\kappa = -\frac{1}{2}e\langle\psi\rangle^2$
  - $\langle\psi\rangle = \langle\chi\rangle = 0$ and $e = 0$ or $\kappa = e\langle\phi\rangle^2$

Conclusions

- time-varying mass terms are the source of particle production, can be used in various cosmological scenarios (also SUSY)
- asymptotic vacua choices and couplings between supermultiplets (fields) are crucial for quantitative description of produced particles
- U(1) gauge symmetry does not change the structure of produced particles, F-I and SU(2) term does (next step: how?)
- next step: U(1) x SU(2), applications