Exploring

Hidden Regimes during Preheating

with Effective Field Theory Methods

Inflation

Radiation

time

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1) How can the inflaton, ϕ, transfer its energy to other fields at the end of inflation?

The first thing that comes to mind is for the inflaton to perturbatively decay into lighter fields.
Being light, such decay products will act like radiation.
When the decay rate wins over the rate of expansion, such decays will lead to radiation domination at the end of inflation.

However, at the end of inflation, it is reasonable to assume that the energy momentum density of the universe continues to be dominated by the inflaton. In this case, for times $m_\emptyset \geq H$, the background evolves as

$$H_p = H_m - \frac{3H_m^2}{4m_\emptyset}\sin(2m_\emptyset t + \Delta) \qquad \text{where} \qquad \dot{H} \cong -H_m^2 \qquad \ddot{H} \cong m_\emptyset H^2$$

which is similar to matter domination. Couplings of the inflaton to other fields can be introduced at the level of perturbations. Assuming a second species of scalar perturbations $\delta\chi$, such a background can set these perturbations into parametric resonance and allow for the exponential growth of certain modes at certain times. The era during which these processes take place on this background is called *"Preheating"*, and it prepares the initial conditions to increase the efficiency of perturbative decays and reheating which will follow [1].

In addition to interactions that lead to particle production, the Effective Field Theory (EFT) methods [2] during Preheating [4] involves three different types of derivative couplings among the inflationary and reheating perturbations [6]. The focus of this poster are these derivative interactions.

3) In Conclusion

- The regimes where one of the species affects the dispersion relation of the other while not appearing as an effective mode itself, are named as **"Hidden Regimes"** during preheating.
- Previous preheating literature involves examples of only the class of β_1 couplings, which so far has been noted to be not very efficient for resonant production of small wavelength modes [5]. Looking at the dispersion relations, here it is noted that
  - At scales below the scale of derivative coupling R_1, the reheating modes appear to effect the canonical momenta of the **inflaton perturbations**, which are the low energy species with a sound speed.
  - β_3 interactions accommodate the **reheating modes** as the light degrees of freedom with a modified dispersion relation. Indicating that these later type of interactions may be more promising for resonant production in the reheating sector through derivative couplings.
  - Derivative couplings of β_2 and β_3 imply a sound speed and modified dispersion relations for both of the species even at energies where both modes appear to propagate freely. This suggests that these EFT coefficients address models with additional heavy degrees of freedom.

Denoting $F = \{\tilde{\pi}_{ck}, \tilde{\chi}_{ck}\}$, while WKB like solutions to hold: $F \sim e^{-i\int \omega(t')dt'}$, $\dot{F} \sim \omega F$

- In the regime $R_1 \gg \omega \gg m_\phi \gg H_p$

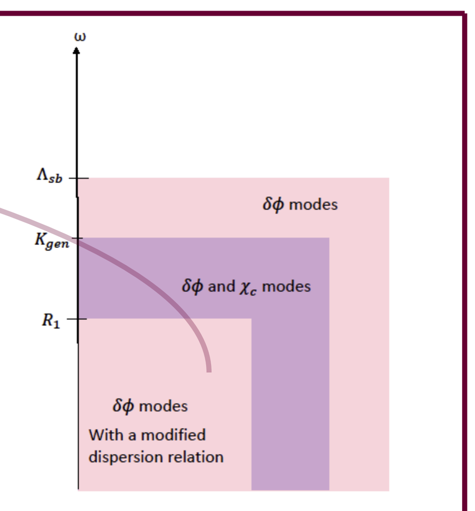
$$L^{(2)}_{\beta_1} \simeq \int d^3x\Big[-2R_1\dot{\tilde{\pi}}_c\tilde{\chi}_c - \frac{1}{2a^2}(\partial_i\tilde{\chi}_c)^2 - \frac{1}{2a^2}(\partial_i\tilde{\pi}_c)^2 - \frac{1}{2}\tilde{m}_\chi^2\tilde{\chi}_c^2 - \frac{1}{2}\tilde{m}_\pi^2\tilde{\pi}_c^2 + 3HR_1\tilde{\pi}_c\tilde{\chi}_c - \frac{\ddot{H}}{\dot{H}}R_1\tilde{\pi}_c\tilde{\chi}_c\Big]$$

$$p_\pi \equiv \frac{\partial L}{\partial\dot{\tilde{\pi}}_c} = -2R_1\tilde{\chi}_c,$$

$$p_\chi \equiv \frac{\partial L}{\partial\dot{\tilde{\chi}}_c} = 0$$

The effective dof : $\tilde{\pi}_{\mathbf{ck}}$

$\tilde{\chi}_{\mathbf{ck}}$ acts as the conjugate momenta



$$R_1 \equiv \frac{\beta_1}{\sqrt{-2m_{pl}^2\dot{H}}} = \mathcal{O}\left(\frac{m_{pl}H}{m_\phi}\right) = \mathcal{O}\left(\frac{\Lambda_{sb}^2}{m_\phi}\right)$$

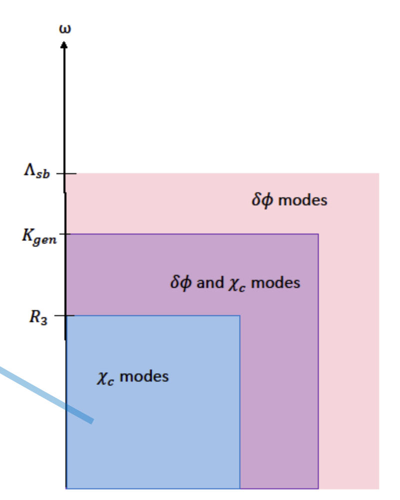
Dispersion relations:

Set $m_i = 0,\ \alpha_1 = 1,\ \alpha_{2,4} = 0, R_1, R_3 \sim \text{const},\ \tilde{m}_\chi, \tilde{m}_\pi \sim \text{const} \ll R_1$

- for $k \gg R_1 \longrightarrow \omega \sim k$
- for $R_1 \gg k \longrightarrow \omega_+ \sim \text{const}$ & $\omega_- \simeq \dfrac{k^2}{2R_1}$

- In the regime $R_3 \gg \omega \gg m_\phi,\ R_2 \gg H_p,\ \rho_3 \ll 1$

$$L^{(2)}_{\beta_3} \simeq \int d^3x\left[-R_3\dot{\tilde{\chi}}_c\tilde{\pi}_c - \frac{1}{2a^2}(\partial_i\tilde{\chi}_c)^2 - \frac{1}{2a^2}(\partial_i\tilde{\pi}_c)^2 - \frac{1}{2}\tilde{m}_\chi^2(t)\tilde{\chi}_c^2 - \frac{1}{2}\tilde{m}_\pi^2(t)\tilde{\pi}_c^2\right]$$



$$K_{bck} = (m_{pl}H)^{1/3}R_3^{1/3} \sim R_3^{1/3}.$$

The effective dof : $\tilde{\chi}_{\mathbf{ck}}$

$\tilde{\pi}_{\mathbf{ck}}$ acts as the conjugate momenta

$$p_\pi \equiv \frac{\partial L}{\partial\dot{\tilde{\pi}}_c} = 0,$$

$$p_\chi \equiv \frac{\partial L}{\partial\dot{\tilde{\chi}}_c} = -R_3\tilde{\pi}_c$$

Dispersion relations:

- for $k \gg R_3 \longrightarrow \omega \sim c_\rho k$ where $c_\rho^2 = \frac{1\pm\rho_3^2}{1-\rho_3^2}$
- for $R_3 \gg k \longrightarrow \omega_+ \sim \text{const}$ & $\omega_- \simeq \dfrac{k^2}{R_3}$

Assuming: $\alpha_1 \sim \frac{1}{m_\phi^4}m_{pl}^2\dot{H}$, $\alpha_3 \sim \frac{1}{m_\phi^2}m_{pl}^2\dot{H}$. and $\beta_1 = b_1\frac{m_{pl}^2\dot{H}}{m_\phi}$, $\beta_2 = b_2\frac{m_{pl}^2\dot{H}}{m_\phi^2}$, $\beta_3(t) = b_3\frac{m_{pl}^2\dot{H}}{m_\phi^2}$.

2) EFT Interactions [3,4] in the unitary gauge: $S = S_g + S_\chi + S_{g\chi}$

$$S_g = \int d^4x\sqrt{-g}\left[\frac{m_{Pl}^2}{2}R - m_{Pl}^2\left(3H^2(t) + \dot{H}(t)\right) + m_{Pl}^2\dot{H}(t)g^{00} + \frac{m_2^4(t)}{2}(\delta g^{00})^2 - \frac{\bar{M}_2^2(t)}{2}(\delta K^\mu{}_\mu)^2 + \ldots\right]$$

$$S_\chi = \int d^4x\sqrt{-g}\left[-\frac{\alpha_1(t)}{2}\partial^\mu\chi\partial_\mu\chi + \frac{\alpha_2(t)}{2}\left(\partial^0\chi\right)^2 - \frac{\alpha_3(t)}{2}\chi^2 + \alpha_4(t)\chi\partial^0\chi\right]$$

$$S_{g\chi} = \int d^4x\sqrt{-g}\left[\beta_1(t)\delta g^{00}\chi + \beta_2(t)\delta g^{00}\partial^0\chi + \beta_3(t)\partial^0\chi - (\dot{\beta}_3(t) + 3H(t)\beta_3(t))\chi\right]$$

Performing a time diffeomorphism:

$$\left.\begin{aligned} t &\to \tilde{t} = t + \xi^0 \\ \pi &\to \tilde{\pi} = \pi - \xi^0 \end{aligned}\right\} \qquad \begin{aligned} &\beta(t) \to \beta(t+\pi) \\ &g^{00} \to g^{00} + 2g^{0\mu}\partial_\mu\pi + g^{\mu\nu}\partial_\mu\pi\partial_\nu\pi \\ &\partial^0\chi \to \partial^0\chi + g^{\mu\nu}\partial_\mu\chi\partial_\nu\pi \end{aligned}$$

The diffeomorphism that takes one out of the unitary gauge corresponds to

$$\xi^0 = -\pi$$

where

$$\boxed{\delta\phi = \pi_c = \frac{\pi}{c_\pi}\sqrt{-2m_{pl}^2\dot{H}} = \frac{\pi}{c_\pi}\dot{\phi}_0}$$

Further conventions: $\tilde{\chi}_c \equiv \sqrt{\alpha_1 + \alpha_2}\chi a^{3/2}$

$$c_\pi^{-2} = 1 - \frac{M_2^4}{m_{pl}^2\dot{H}}$$

$$\rho_3 \equiv \frac{\beta_3}{\sqrt{-2m_{pl}^2\dot{H}}}, \quad R_2 \equiv \frac{\ddot{\beta}_3}{\sqrt{-2m_{pl}^2\dot{H}}}, \quad R_3 \equiv \frac{\dot{\beta}_3}{\sqrt{-2m_{pl}^2\dot{H}}}.$$

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