Mechanisms for dissipation and their consequences during inflation

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Overview

- Review warm inflation
- Review dissipative quantum field theory
- Dissipative mechanisms for warm inflation
- SUSY models
What is cosmic inflation

Short time interval when universe expands at accelerated rate

\[ a(t) \sim \exp(\text{H}t) \]

<table>
<thead>
<tr>
<th>Event</th>
<th>Time (seconds)</th>
<th>Temperature (GeV)</th>
</tr>
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<tbody>
<tr>
<td>BIG BANG</td>
<td>(10^{-42})</td>
<td>(10^{18})</td>
</tr>
<tr>
<td>INFLATION</td>
<td></td>
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<tr>
<td>BBN</td>
<td>(10^{-12})</td>
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<tr>
<td>Last scattering/recombination</td>
<td>(10^{3})</td>
<td>((10^{16}\text{K}))</td>
</tr>
<tr>
<td>Today</td>
<td>(10^{12})</td>
<td>(10^{18})</td>
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The puzzle of cosmological initial conditions:

\[
\frac{\Delta T}{T} < 10^{-5} \text{ in CMBR without causal contact}
\]

The inflation solution (1981+)

Accelerated expansion \( \ddot{a}(t) > 0 \) implies \( \rho + 3p < 0 \)

How to get from high energy physics?
Scalar field ("inflaton") dynamics

\[ \phi = \frac{\dot{\phi}}{2} + V(\phi) + \frac{(\nabla \phi)^2}{2R^2} \]

\[ p = \frac{\dot{\phi}}{2} - V(\phi) - \frac{(\nabla \phi)^2}{6R^2} \]

- Cold inflation: Just Choose \( V(\phi) \)

\[ \ddot{\phi} + 3H \dot{\phi} + V'(\phi) = 0 \]

Potential energy dominated \( 3H \dot{\phi} \gg \dot{\phi}, "\text{slow-roll}" \)

- Warm Inflation: \( \gamma \) dominates

\[ \ddot{\phi} + 3H \dot{\phi} + \gamma \dot{\phi} + V'(\phi) = 0 \]

Slow-roll now means \( \gamma \dot{\phi} \gg 3H \dot{\phi}, \ddot{\phi}, \text{overdamped} \)
Two basic inflation pictures

Cold Inflation

Inflation

Reheating

Warm Inflation

Inflation + continuous radiation production

\[ V(\phi) \]

\[ \rho \]

\[ \rho_v \]

\[ \rho_r \]

\[ t \]
**Nature of the fluctuations**

Thermal/quantum fluctuations leave “ripples” in early universe
- imprinted on CMBR at Last Scattering
- amplified by gravity to make structure

Cold inflation: Quantum
(Guth, Pi ‘82; Hawking ‘82;
Starobinsky ‘82;
Bardeen et. al. ‘83)

Warm Inflation: Thermal

\[ \delta \phi = \frac{k_{F}^{1/2}T^{1/2}}{2\pi} \]

\[ \gamma < 3H : k_{F} = H \]
(Moss ‘85, AB,Fang ‘95)

\[ \gamma > 3H : k_{F} = \sqrt{\gamma H} \]
(AB ‘99)

\[ \frac{\delta \rho}{\rho} = \frac{H \delta \phi}{\dot{\phi}} \]
Worked example - no $\eta$-problem

Model: $V = \frac{m^2}{2} \varphi^2$

$$\implies N_e \approx 2\sqrt{2} \frac{\varphi_0}{m} \frac{\gamma}{m_P}, \quad T \approx \frac{m^{3/4} m_P^{1/4} \varphi_0^{1/4}}{\gamma^{1/4}}, \quad \frac{\delta \rho}{\rho} \approx \left( \frac{\varphi_0}{m} \right)^{3/8} \left( \frac{\gamma}{m_P} \right)^{9/8}$$

For $N_e = 60$, $\frac{\delta \rho}{\rho} = 10^{-5}$ $\implies \frac{\varphi_0}{m} \approx 6 \times 10^8$, $\frac{\gamma}{m_P} \approx 4 \times 10^{-8}$

e.g., $m = 10^9 \text{GeV} \implies \frac{H}{m} \approx 0.17$, $\frac{\varphi_0}{m_P} \approx 6 \times 10^{-2}$, $T \approx 10^4 m$

- No $\eta$-problem: $m > H$
- No $\varphi$ amplitude problem: $\varphi < m_P$
- No graceful exit problem: inflation $\rightarrow$ RD automatic
- No quantum-to-classical trans. problem: $\delta \varphi$ classical
Energetics

- Consider GUT scale inflation: \( M \sim 10^{15}\text{GeV} \)

\[
\Rightarrow \quad \rho_v \sim M^4 \sim 10^{60}\text{GeV}^4 \quad \Rightarrow \quad H \sim 10^{10}\text{GeV}
\]

\( T > H \) requires > 1 part in \( \sim 10^{20} \) of \( \rho_v \rightarrow \rho_r \)

(influences structure formation)

\( T > 1\text{GeV} \) requires > 1 part in \( \sim 10^{60} \) of \( \rho_v \rightarrow \rho_r \)

(makes reheating unnecessary)

- Inflation pictures
  1. Cold inflation: basic assumption is no dissipation
  2. Warm inflation: radiation production inherent \((\text{AB, PRL 75, 3218 (1995)})\)

- Theoretical consideration

  Equipartition Hypothesis of Statistical Mechanics: *Scalar field should distribute its energy evenly amongst all degrees of freedom.*

  Dynamical Question: *Will relevant time scales during inflation prohibit the minute’ radiation production given above?*
Scalar Field ($\Phi$) Dynamics

\[ \mathcal{L}_\Phi = \frac{1}{2} (\partial_\mu \Phi)^2 - \frac{m_\phi^2}{2} \Phi^2 - \frac{\lambda}{4!} \Phi^4 \]

\[ \mathcal{L}_I = -\Phi \sum_{j=1}^{N_\psi} h_j \bar{\psi}_j \psi_j, \quad -\frac{1}{2} \sum_{j=1}^{N_\chi} g_j^2 \Phi^2 \chi_j^2 + \cdots \]

- Decompose into background $\varphi$ and fluctuations $\phi$: $\Phi = \varphi + \phi$

- Effective equation of motion (EOM) for $\varphi(t)$:

\[ \ddot{\varphi}(t) + 3H \dot{\varphi}(t) + \xi R \varphi(t) + m_\phi^2 \varphi(t) + \frac{\lambda}{6} \varphi^3(t) + \varphi(t) \sum_{j=1}^{N_\chi} g_j^2 \langle \chi_j^2 \rangle + \cdots = 0 \]

with $\langle \phi^2 \rangle$, $\langle \phi^3 \rangle$ and $\langle \chi_j^2 \rangle$ etc... evaluated perturbatively
Closed Time Path approach - Goal

Compute Observable
\[ \langle \hat{O}(t) \rangle \equiv \frac{\text{Tr}(\hat{\rho}(t)\hat{O})}{\text{Tr}(\hat{\rho}(t))} \]

Thermal initial state at \( T^< \):
\[ \rho(T^<) = \exp(-\beta H) = U(T^< - i\beta, T^<) \]

( \( U(t,t') \equiv \exp[-iH(t-t')] \), time evolution operator)

Thus
\[ \langle \hat{O}(t) \rangle = \frac{\text{Tr}[U(T^< - i\beta, T^<) U(T^<, t) \hat{O} U(t, T^<)]}{\text{Tr}[U(T^< - i\beta, T^<)]} \]

Also add large positive time \( T^> \)
\[ \langle \hat{O}(t) \rangle = \frac{\text{Tr}[U(T^< - i\beta, T^<) U(T^<, T^>) U(T^>, t) \hat{O} U(t, T^<)]}{\text{Tr}[U(T^< - i\beta, T^<)]} \]
Closed Time Path approach - Method

Can express as a path integral

\[
U(t, t') \equiv \int \mathcal{D}\Phi \exp \left( i \int_{t'}^t d^4x \mathcal{L}[\Phi] \right)
\]

\[
Z[J^+, J^-, J^\beta] = \text{Tr}[U(T^- - i\beta, T^-; J^\beta) U(T^-, T^+; J^-) U(T^+, T^-; J^+)]
\]

\[
= \int \mathcal{D}\Phi^+ \mathcal{D}\Phi^- \mathcal{D}\Phi^\beta \exp \left( i \int_{T^-}^{T^+} d^4x [\mathcal{L}^{J^+}[\Phi^+] - \mathcal{L}^{J^-}[\Phi^-]] + i \int_{T^-}^{T^- - i\beta} d^4x \mathcal{L}^{J^\beta}[\Phi^\beta] \right)
\]

e.g. scalar field theory:

\[
\mathcal{L}^J[\Phi] = \frac{1}{2} [\partial_\mu \Phi \partial^\mu \Phi - m^2 \Phi^2] - \frac{\lambda}{4!} \Phi^4 + J\Phi
\]
How to obtain the $\varphi$-effective EOM

**Tadpole Method**: demand $\langle \phi \rangle = 0$ and compute

Example: $S = \int d^4 x \left[ \frac{1}{2} \partial_\mu \Phi \partial^\mu \Phi - \frac{m^2}{2} \Phi^2 - \frac{\lambda}{4!} \Phi^4 \right]$, \quad $\Phi = \varphi + \phi \implies$

$$S = \int d^4 x \left[ -\frac{\varphi}{2} \square + m^2 \right] \varphi - \phi \left[ \frac{1}{2} \square + m^2 \right] \phi - \phi \left[ \square + m^2 \right] \varphi - \frac{\lambda}{4!} (\varphi^4 + 4 \varphi^3 \phi + 6 \varphi^2 \phi^2 + 4 \varphi \phi^3 + \cdots)$$

$\langle \phi \rangle = 0$ at lowest nontrivial order $\implies$

$$(\frac{\varphi + m^2}{x} + \lambda \varphi^3 + \frac{1}{2} \lambda \varphi + \frac{1}{4} \lambda \varphi - \frac{1}{4} \lambda \varphi) + \left( \frac{1}{3!} \lambda \varphi^2 + \frac{3}{16} \lambda \varphi \right) + \left( \frac{1}{6} \lambda \varphi - \frac{1}{6} \lambda \varphi \right) \equiv G_{ij}^\phi(x, x') \quad \text{where} \quad i, j = \pm$$

$$(\frac{\varphi + m^2}{x} + \lambda \varphi^3 + \frac{1}{2} \lambda \varphi + \frac{1}{4} \lambda \varphi - \frac{1}{4} \lambda \varphi) = 0$$
Tadpole Method (cont.) - Explicit EOM

\[ ( ) = 0 \implies \]

\[ 0 = \int d^4x' G_{\phi}^{++}(x, x') \left[ \times + * + \begin{array}{c} \includegraphics[width=1cm]{circle.png} \\ + \end{array} + \begin{array}{c} \includegraphics[width=1cm]{circle.png} \\ \end{array} - \begin{array}{c} \includegraphics[width=1cm]{circle.png} \\ \end{array} + \begin{array}{c} \includegraphics[width=1cm]{circle.png} \\ \end{array} - \begin{array}{c} \includegraphics[width=1cm]{circle.png} \\ \end{array} + \begin{array}{c} \includegraphics[width=1cm]{circle.png} \\ \end{array} \right] \]

\[ \implies [ ] = 0, \text{ now convert to analytic expression} \]

e.g. \[ \begin{array}{c} \includegraphics[width=1cm]{circle.png} \\ \end{array} \begin{array}{c} \includegraphics[width=1cm]{circle.png} \\ \end{array} = \frac{3}{16} \lambda^2 \varphi(t') \int d^4y \left[ G_{\phi}^{++}(x', y) G_{\phi}^{++}(x', y) - G_{\phi}^{+-}(x', y) G_{\phi}^{+-}(x', y) \right] \varphi^2(t_y) \]

\[ = \frac{3}{8} \lambda^2 \varphi(t') \int d^4y \text{Im} \left[ G_{\phi}^{++}(x', y) G_{\phi}^{++}(x', y) \right] \varphi^2(t_y), \text{ etc ...} \]

Final Expression:

\[ \ddot{\varphi} + 3H \varphi + m^2 \varphi + \frac{\lambda}{6} \varphi^3 + \text{local 1-loop terms} \quad V_{\text{eff}} + \frac{3}{8} \lambda^2 \varphi(t') \int d^4y \text{Im} \left[ G_{\phi}^{++}(x', y) G_{\phi}^{++}(x', y) \right] \varphi^2(t_y) \]

\[ + \frac{1}{3} \lambda^2 \int d^4y \text{Im} \left[ G_{\phi}^{++}(x', y) G_{\phi}^{++}(x', y) G_{\phi}^{++}(x', y) \right] \varphi(t_y) = 0 \]
Green’s function $G_{\phi}^{ij}(x, x')$ - Basic Properties

$$G_{\phi}(x, x') = \begin{pmatrix} G_{\phi}^{++}(x, x') & G_{\phi}^{+-}(x, x') \\ G_{\phi}^{-+}(x, x') & G_{\phi}^{--}(x, x') \end{pmatrix} = \begin{pmatrix} i\langle T_{+}\phi(x)\phi(x')\rangle & i\langle \phi(x')\phi(x)\rangle \\ i\langle \phi(x)\phi(x')\rangle & i\langle T_{-}\phi(x)\phi(x')\rangle \end{pmatrix}$$

Fourier space: $G_{\phi}(x, x') = i\int \frac{d^3q}{(2\pi)^3} e^{i\mathbf{q}.(x-x')} \tilde{G}_{\phi}(\mathbf{q}, t - t')$

$$\tilde{G}_{\phi}^{++}(\mathbf{q}, t - t') = \tilde{G}_{\phi}^{>}(\mathbf{q}, t - t')\theta(t - t') + \tilde{G}_{\phi}^{<}(\mathbf{q}, t - t')\theta(t' - t),$$
$$\tilde{G}_{\phi}^{-+}(\mathbf{q}, t - t') = \tilde{G}_{\phi}^{>}(\mathbf{q}, t - t')\theta(t' - t) + \tilde{G}_{\phi}^{<}(\mathbf{q}, t - t')\theta(t - t'),$$
$$\tilde{G}_{\phi}^{+-}(\mathbf{q}, t - t') = \tilde{G}_{\phi}^{<}(\mathbf{q}, t - t'),$$
$$\tilde{G}_{\phi}^{--}(\mathbf{q}, t - t') = \tilde{G}_{\phi}^{>}(\mathbf{q}, t - t').$$

Hermiticity: $\tilde{G}_{\phi}^{>}(\mathbf{q}, t - t') = \tilde{G}_{\phi}^{>}(\mathbf{q}, t' - t)$

Continuity: $\frac{d}{dt} \left[ \tilde{G}_{\phi}^{>}(\mathbf{q}, t - t') - \tilde{G}_{\phi}^{>}(\mathbf{q}, t' - t) \right]_{t=t'} = i\delta(t-t')$
Two stage dissipative mechanism

(I. G. Moss and C. Xiong, hep-ph/0603266)

Basic Lagrangian - inflaton field coupled to heavy field (> T)
which in turn coupled to light fields (< T)

Examples:

\[ \phi \to \chi \to \psi \text{ with } m_\chi > 2m_\psi > m_\phi \]

\[ \mathcal{L}_I = -\frac{1}{2}g^2\phi^2\chi^2 - g'\phi\overline{\psi}_\chi\psi_\chi - h\chi\overline{\psi}_\psi\psi, \]

\[ \phi \to \chi \to y \text{ with } m_\chi > 2m_y > m_\phi \]

\[ \mathcal{L}_I = -\frac{1}{2}g^2\phi^2\chi^2 - g'\phi\overline{\psi}_\chi\psi_\chi - hg\phi\chi y^2, \]

\[ \phi \to \psi_\chi \to \psi_d, y \text{ with } m_\chi > m_{\psi_y} + m_y > m_\phi \]

\[ \mathcal{L}_I = -\frac{1}{2}g^2\phi^2\chi^2 - g'\phi\overline{\psi}_\chi\psi_\chi - h\overline{\psi}_\chi\psi_y y + c.c., \]
Interaction generic in inflation models

- $g^2 \phi^2 \chi^2$ generic to inflation models (for reheating)

- for $g \gtrsim 10^{-3}$ require SUSY for flat potential

- Minimal SUSY model with this interaction

$$W = \sqrt{\lambda} \Phi^3 + \frac{g}{\sqrt{2}} \Phi X^2 + \frac{h}{\sqrt{2}} XY^2$$

($\Phi = \phi + \theta \psi + \theta^2 F$, $X = \chi + \theta \psi \chi + \theta^2 F \chi$, $Y = y + \theta \psi y + \theta^2 F y$)

$$\Longrightarrow \mathcal{L}_{int} \sim \frac{1}{4} g^2 |\phi|^2 |\chi|^2 + \frac{1}{4} g \phi \psi \chi \psi + \frac{g}{2} \phi \bar{\psi} \chi \psi + \frac{1}{\sqrt{2}} h \chi \bar{\psi} y \psi y + \ldots$$

- For $\langle \phi \rangle \equiv \varphi \neq 0$ SUSY is broken with $m_{\chi_1} \gg m_{\psi \chi} \gg m_{\chi_2}$

($V_{1-loop} \sim g \lambda \varphi^4 < V_{tree} \sim \lambda \varphi^4$, so flatness preserved)

- $\Longrightarrow$ dissipative mechanism through $\phi \rightarrow \chi \rightarrow \bar{\psi} y + \psi y, 2y, \ldots,$

  just like our toy model, so all results follow
Green’s Function - equilibrium approximation

Gives lower bound estimate of dissipative effects

(Moss and Xiong, hep-ph/0603266)

Low temperature regime ($m_\chi < T$):

$$G_{\text{equil}}(\mathbf{k}, t) = \frac{i}{2(\omega_k - i\Gamma_\chi)} \exp[-i(\omega_k - i\Gamma_\chi)t] + f(\omega_k - i\Gamma_\chi, t) - f(\omega_k + i\Gamma_\chi, t)$$

where

$$\omega_k = \sqrt{k^2 + m_\chi^2},$$

$$f(\omega, |\mathbf{k}|, t) = \frac{\exp(i\omega t)}{4\pi\omega} E_1(i(|\mathbf{k}| + \omega)t) - \frac{\exp(-i\omega t)}{4\pi\omega} E_1(i(|\mathbf{k}| - \omega)t)$$

At small time, i.e. $t \sim \tau_\chi = \Gamma_\chi^{-1} \log \frac{m_\chi^2}{\Gamma_\chi^2}$, the behavior same as the exponential decay approximation.

At larger time, power-law decay behavior.

Leads to dissipative coefficient:

$$\gamma_{\text{equil}}(\varphi, T) = 4 \times 10^{-2} g^2 h^4 \left( \frac{g\varphi}{m_\chi} \right)^4 \frac{T^3}{m_\chi^2}$$
Realistic models - equilibrium approx. I
(Bastero-Gil and AB, hep-ph/0610343)

Monomial potentials:

\[ V = V_0 \left( \frac{\phi}{m_P} \right)^n + \frac{g^2}{2} \phi^2 \chi^2 + \frac{h}{\sqrt{2}} \chi \bar{\psi} y \psi + \frac{h}{\sqrt{2}} g \phi (\chi^+ y^2 + h.c.) + \ldots \]

Solves "eta" - problem, \( m_\phi > H \)

Solves large \( \phi \) amplitude problem - \( \phi < m_P \)

For monomial potentials in the standard inflation picture ("chaotic inflation"), both the above are problems

Problem - Order 100's of fields are needed

Main point: These results are based on well established dissipative calculations which thus demonstrate radiation production during inflation is very possible. Model building details will improve as (less understood) nonequilibrium effects treated.
Realistic models - equilibrium approx. II
(Bastero-Gil and AB, hep-ph/0610343)

Hybrid potential:

\[ V = V_0 \left( 1 + \left( \frac{\phi}{M} \right)^n \right) + \frac{g^2}{2} \phi^2 \chi^2 + \frac{h}{\sqrt{2}} \chi \bar{\psi} y \psi + \frac{h}{\sqrt{2}} g \phi (\chi^\dagger y^2 + h.c.) + \ldots \]

Solves "eta" and large \( \phi \) amplitude problems

Similar to the monomial potential cases

Many fields but less than monomial case. Could realize in SO(10) and \( E_6 \) GUT models with \( \chi \)-fields in \( 210 \) - large but within periphery of interesting

Treating nonequilibrium effects and relaxing strict low-temperature constraints will improve results
Green’s Function - exponential decay form

Common ansatz for slightly out-of-equilibrium system

(M. Morikawa and M. Sasaki, Prog. Theor. Phys. 72, 782 (1984))

Low temperature regime ($m_\chi < T$):

$$G_{\text{exp}}(k, t) \approx \frac{1}{2(\omega_k - i\Gamma_\chi)} \exp[-i(\omega_k - i\Gamma_\chi)t]$$

Idea - At low $T$ it becomes harder to maintain thermal equilibrium

Also studied by: Morikawa (‘86), Ringwald (‘87), Lawrie (‘89),
Gleiser + Ramos (‘94), Berera + Ramos (‘01), Yokoyama (‘05) etc...

Numerical evidence in support of this approximation:
Aarts and Berges (2001)

Leads to dissipative coefficient:

$$\gamma_{\text{exp}}(\varphi) = \frac{g^4 \varphi^2(t)\Gamma_\chi}{32\pi \sqrt{m_\chi^2 + \Gamma_\chi^2} \sqrt{2m_\chi \sqrt{m_\chi^2 + \Gamma_\chi^2} + 2m_\chi^2}}.$$
Green’s Function - exponential decay form
(M. Morikawa and M. Sasaki, Prog. Theor. Phys. 72, 782 (1984))

Schwinger-Dyson equations

\[
\left[\Box + m_\phi^2 + \frac{\lambda}{2} \varphi^2\right] G_\phi(x, x') + \int d^4 z \Sigma_\phi(x, z) G_\phi(z, x') = i\delta(x, x')
\]

Ansatz Solution, \( G_\phi^> (q, t - t') = \)

\[
\frac{1}{2\omega_\phi} \left\{ [1 + n_\phi(\omega_\phi - i\Gamma_\phi)] e^{-i(\omega_\phi - i\Gamma_\phi)(t-t')} + n_\phi(\omega_\phi + i\Gamma_\phi) e^{i(\omega_\phi + i\Gamma_\phi)(t-t')} \right\} \theta(t - t') + \\
\frac{1}{2\omega_\phi} \left\{ [1 + n_\phi(\omega_\phi + i\Gamma_\phi)] e^{-i(\omega_\phi + i\Gamma_\phi)(t-t')} + n_\phi(\omega_\phi - i\Gamma_\phi) e^{i(\omega_\phi - i\Gamma_\phi)(t-t')} \right\} \theta(t' - t)
\]

\( G_\phi^< (q, t - t') = G_\phi^> (q, t' - t) \)

\( n_\phi - \) Bose distribution function, \( \omega_\phi \equiv \omega_\phi(q) \) and \( \Gamma_\phi(q) = \frac{\text{Im}\Sigma_\phi(q, \omega_\phi)}{2\omega_\phi} \)
\( \varphi \)-effective equation of motion

\[
\ddot{\varphi}(t) + 3H(t)\dot{\varphi}(t) + \xi R(t)\varphi(t) + \frac{dV_{\text{eff}}(\varphi(t))}{d\varphi(t)} + g^4 \varphi(t) \int_{t_0}^{t} dt' \varphi(t') \dot{\varphi}(t') K(t, t') = 0,
\]

where

\[
K(t, t') = \int_{-\infty}^{t} dt'' \int \frac{d^3 q}{(2\pi)^3} \sin \left[ 2 \int_{t''}^{t} d\tau \omega_\chi(\tau) \right] \times \frac{\exp \left[ -2m_\chi \Gamma_\chi \int_{t''}^{t} d\tau / \omega_\chi(\tau) \right]}{4\omega_\chi(t) \omega_\chi(t'')},
\]

\[
\omega_\chi(\tau) = \left[ q^2 \frac{a(t)}{a(\tau)} + m_\chi^2(\tau) + 2(6\xi - 1)H \right]^{1/2},
\]

\[
m_\chi = g\varphi \quad \Gamma_\chi \approx \frac{h^2 m_\chi}{8\pi} \quad H = \sqrt{\frac{8\pi V_{\text{eff}}}{3m_P^2}} \quad a(t) \approx \exp(Ht)
\]
Adiabatic-Markovian Approximation

For $\frac{\dot{\varphi}}{\varphi} < H, \Gamma_\chi$; \quad $H < \Gamma_\chi, m_\chi$; \quad $\varphi$-effective EOM becomes:

$$\ddot{\varphi} + [3H + \gamma(\varphi)]\dot{\varphi} + \xi \varphi R\varphi + \frac{dV_{\text{eff}}(\varphi)}{d\varphi} = 0,$$

where

$$\gamma_{\text{exp}}(\varphi) = \frac{g^4 \varphi^2(t) \Gamma_\chi}{32\pi \sqrt{m_\chi^2 + \Gamma_\chi^2} \sqrt{2m_\chi \sqrt{m_\chi^2 + \Gamma_\chi^2} + 2m_\chi^2}}.$$
Results - comparing approximations

Evolution of \( \varphi(t) \) for \( V = \frac{\lambda}{4} \varphi^4 \), \( \lambda = 10^{-13} \),
\( g = h = 0.37 \), \( \xi = 0 \), \( \varphi(0) = m_P \), \( \dot{\varphi}(0) = 0 \).

\( T > H \) during inflation (so affects \( \delta \varphi \)) for
- e.g., \( g = h > 10^{-2} \) or \( h = 0.1, g > 10^{-3} \)
Realistic models - exp. decay approx.

**SUSY hybrid warm inflation**

(AB and Bastero-Gil, PRD72, 103526 (2005)):

\[ W = \kappa \Phi (X_1 X_2 - \mu^2) + g X_1 N N \]

\[ N = \frac{1}{\sqrt{2}} (\nu + i \psi_{\nu}) \]

**Sneutrino MSSM warm inflation**

(AB+Bastero-Gil, PRD72, 0507124 (2005)):

\[ W = M_i N_i N_i + (h_N)_{ij} H_u L_i N_j + h_t H_u Q_3 U_3 + \cdots \]

Dissipative channel:

\( N_i \) couple \( H_u \) which decay to tops
Warm inflation on a computer

[AB, G. Lacagnina (lattice gauge), C. Verdozzi (condensed matter)]

Purpose:
- Study of overdamped motion and its universal features
- Study of how equipartition is achieved

Feasible goals:
- Numerical simulations of classical/quantum models from condensed matter:
  - Fermi-Paste-Ulam
  - Caldeira-Leggett
- Simulations of lattice quantum field theory models:
  - Caldeira-Leggett, $\phi^4$ ...

Example of overdamping in the classical regime
Relevance of warm inflation

- Correct treatment of dynamics in generic inflation models

- Model Building
  - Can have inflation models with $m_\phi > H$
  - Particle physics during inflation phase, eg. magnetic fields baryogenesis...

- Observational implications
  - Running spectral index in simple models
  - Blue and red spectra are possible
  - Oscillating power spectra
Conclusion

- Generic interactions in all inflation models \((g^2\phi^2\chi^2, g\phi\bar{\psi}\psi)\) yield dissipative effects DURING inflation (warm inflation)
  - Result firmly established using well understood equilibrium approximation, leaves no doubt warm inflation occurs
  - Accounting for nonequilibrium effects not so well understood but expect will make warm inflation much more robust, work in progress

- For strong dissipation \(\gamma > 3H\) important model building prospects
  - NO eta-problem \(m_\phi > H\)
  - NO \(\phi\) amplitude problem \(\phi < m_{Planck}\)