Finite Temperature Effects in Warm Hybrid Inflation

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Inflationary Cosmology - Two Dynamical Realizations

There are different dynamical realizations of Inflation.

- Cold Inflation
    - The inflaton is treated as an isolated system.
    - Other initial components of energy density are redshifted away.
    - A separate reheating phase after inflation brings the universe to a radiation dominated regime.
- Warm Inflation
    - Interactions leading to dissipation of inflaton energy to other degrees of freedom.
    - Inflationary expansion occurs concurrently with particle production.
    - Radiation can eventually dominate the energy density without a separate reheating phase.

"The Inflationary Universe: A possible soultion to the Horizon and Flatness Problems", AH Guth, Phys.Rev. D23 (1981) 347-356
"Warm Inflation", A Berera, Phys.Rev.Lett.75:3218-3221,1995

Warm Inflation

- Warm inflation is realised when a dissipative term, Υ, is included as a friction term in the evolution equation for the inflaton

$$\begin{array}{ccc} \text{Cold Inflation} & & \text{Warm Inflation} \\ \ddot{\phi}(t) + 3H\dot{\phi}(t) + V_\phi = 0 & \rightarrow & \ddot{\phi}(t) + (3H + \Upsilon)\dot{\phi}(t) + V_\phi = 0 \end{array}$$

- Energy lost by the inflaton field is gained by some other fluid ρ_α
- If $\rho_\alpha = \rho_R$ then the evolution equation for the radiation energy density becomes

$$\begin{array}{ccc} \text{Cold Inflation} & & \text{Warm Inflation} \\ \dot{\rho_R} + 4H\rho_R = 0 & \rightarrow & \dot{\rho_R} + 4H\rho_R = \Upsilon\dot{\phi}^2 \end{array}$$

- Radiation is not necessarily redshifted.

"Warm Inflation", A Berera, Phys.Rev.Lett.75:3218-3221,1995

Warm Inflation Model Building - SUSY model

- Supersymmetry protects the potential from large radiative corrections
- Inflaton potential is protected from large thermal corrections*
  - Fields coupled to the inflaton, denoted χ, are heavy because of the coupling to the inflaton
  - Heavy χ fields are in turn coupled to light y fields
- This can be realised with the superpotential

$$W = W(\Phi) + g\Phi X^2 + hXY^2$$

- The scalar component of the superfield Φ describes the inflaton field ϕ
- X is the superfield for the heavy catalyst fields χ
- The last term allows the heavy catalyst field to decay into light degrees of freedom in the supermultiplet Y

* "Dissipation coefficients from scalar and fermion quantum field interactions", M Bastero-Gil,A Berera, R Ramos, JCAP 1109:033,2011

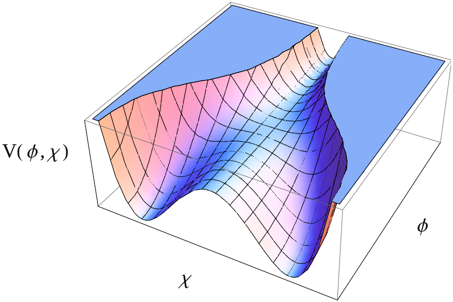
Hybrid Inflation

- This decay mechanism for the inflaton can be readily realised with a hybrid model of inflation
- Inflaton field is responsible for slow-roll inflation
- Waterfall field triggers the end of inflation

- The hybrid inflation potential is

$$V(\phi,\chi) = \frac{1}{4\lambda}(M^2 - \lambda\chi^2)^2 + \frac{1}{2}\phi^2 + \frac{1}{2}g^2\phi^2\chi^2$$

- Effective mass squared of the χ field is $-M^2 + g^2\phi^2$
- When $\phi > \phi_c = M/g$ the minimum of V is at $\chi = 0$
- When $\phi < \phi_c = M/g$ the tachyonic instability drives the system to a global minimum at $\phi = 0$ and $\chi^2 = M^2/\lambda$



"Hybrid Inflation", A Linde, Phys.Rev.D49:748-754,1994

Supersymmetric Hybrid Inflation

- Supersymmetric hybrid inflation can be realised with the superpotential

$$W = W(\Phi) + g\Phi(X^2 - M^2) + hXY^2$$

- The scalar and fermionic components of the X superfields, $\chi = (\chi_R + i\chi_i)/\sqrt{2}$ and ψ_χ, acquire non-vanishing masses during inflation

$$\begin{gathered} m^2_{\chi I} = 2g^2(\phi^2 + M^2) \\ m^2_{\chi R} = 2g^2(\phi^2 - M^2) \\ m^2_{\tilde{\chi}} = 2g^2\phi^2 \end{gathered}$$

- The hybrid transition will happen when $\phi = \phi_c = M$

* "Warm Inflation Model Building", M Bastero-Gil, A Berera, Int.J.Mod.Phys.A24:2207-2240,2009

Dissipation in Warm Inflation

- In warm inflation the coupling between the inflaton, waterfall fields and light fields leads to the dissipation of inflaton energy during inflation.

$$\begin{array}{ccccc} \text{Inflaton} & & \text{Waterfall fields} & & \text{Light fields} \\ \phi & \rightarrow & \chi & \rightarrow & \text{y} \end{array}$$

- The waterfall fields are unstable against decay into the Y sector

$$\chi \rightarrow yy, \psi_y \psi_y \qquad \psi_\chi \rightarrow y \psi_y$$

- Allows inflaton energy to be transferred to Y sector
- Dissipation acts as a friction term $\Upsilon\dot{\phi}$ in the equation of motion of the inflaton field ϕ

Dissipative Coefficient

The dissipative coefficient Υ receives leading contributions from

- Low-momentum contribution Υ_{lm}
    - Υ_{lm} corresponds to off-shell production
    - Υ_{lm} dominates for $m_i >> T$
- Pole contribution Υ_{pole}
    - Υ_{pole} corresponds to on-shell production
    - Υ_{pole} dominates for $m_i << T$

The expression for the Dissipative coefficient Υ is*

$$\begin{aligned}\Upsilon &= \Upsilon_{lm} + \Upsilon_{pole} \\ &= \sum_{i=\chi_{R,I}} \left[0.64 h^2 g^8 N_x N_y \frac{T^3\phi^6}{m_i^8} + \frac{16}{\sqrt{2\pi}} \frac{g^2 N_x}{h^2 N_y} \left(\frac{2g^2\phi^2}{2g^2\phi^2 + m_i^2}\right) \sqrt{T m_i} e^{-m_i/T}\right]\end{aligned}$$

* "General Dissipation coefficient in low-temperature warm inflation", M Bastero-Gil, A Berera, R Ramos, J Rosa, JCAP 01, 016 (2013)

The Scalar Potential at One Loop

- Interactions between the inflaton ϕ and the waterfall field χ lead to radiative corrections to the scalar potential

- The scalar potential during inflation is given by the tree-level potential, $V_0 + f(\phi)$, and radiative corrections given by the Coleman-Weinberg potential*

- At one loop this gives

$$V(\phi) = V_0 + f(\phi) + \frac{1}{32\pi^2} \sum_{\chi_{R,I},\psi_\chi} m_i^4(\phi) \left[log \left(\frac{m_i^2(\phi)}{\mu^2} \right) - \frac{3}{2} \right]$$

- where $V_0 = g^2 M^4$, $f(\phi) = |W'(\phi)|^2$, μ is the renormalization scale, and we sum over the χ mass multiplets

$$\begin{gathered} m_{\chi I}^2(\phi) = 2g^2(\phi^2 + M^2) \\ m_{\chi R}^2(\phi) = 2g^2(\phi^2 - M^2) \\ m_{\tilde{\chi}}^2(\phi) = 2g^2\phi^2 \end{gathered}$$

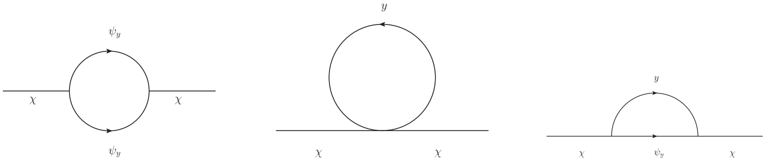
* “Radiative Corrections as the origin of Spontaneous Symmetry Breaking”, S Coleman, E Weinberg, Phys.Rev. D7 (1973) 1888-1910

A Heat Bath during Inflation

- In warm inflation radiation is not necessarily red-shifted during inflation

$$W = W(\Phi) + g\Phi(X^2 - M^2) + hXY^2$$

- The last term in W allows the waterfall field to decay to light degrees of freedom in the Y supermultiplet
- This allows for particle creation in the Y sector and the formation of a thermal bath
- Presence of a thermal bath induces thermal corrections to the masses of the waterfall field χ and ψ_χ through the following interactions with the light scalars and fermions in the Y sector, y and ψ_y



* "General dissipation coefficient in low-temperature warm inflation", M Bastero-Gil, A Berera, R Ramos, J Rosa, JCAP 01, 016 (2013)

Thermal Corrections to the Waterfall field

- Allowing for the existence of g_* light degrees of freedom in the thermal bath coupling to fields in the X sector, the waterfall field masses are shifted by a positive factor denoted $\alpha^2 T^2$

$$\begin{aligned} m_{\chi I}^2(\phi, T) &= 2g^2(\phi^2 + M^2) + \alpha^2 T^2 \\ m_{\chi R}^2(\phi, T) &= 2g^2(\phi^2 - M^2) + \alpha^2 T^2 \\ m_{\bar{\chi}}^2(\phi, T) &= 2g^2\phi^2 + \alpha^2 T^2 \end{aligned}$$

- If only fields in the Y sector are present in the thermal bath then $g_* = (15/4)N_y$ and $\alpha = h\sqrt{N_y/2}$
- Inserting into the Coleman-Weinberg expression for radiative corrections at one loop the potential becomes

$$V(\phi, T) = V_0 + f(\phi) + \frac{1}{32\pi^2} \sum_{\chi_{R,I}, \psi_\chi} m_i^4(\phi, T) \left[log\left(\frac{m_i^2(\phi, T)}{\mu^2} \right) - \frac{3}{2} \right]$$

“Thermal Effects on Pure and Hybrid Inflation”, L Hall, I Moss, Phys.Rev.D71:023514,2005

Hybrid Transition at Finite Temperature

- Inflation ends when the mass squared of the real scalar component $m^2_{\chi_R}$ becomes negative

- Without thermal corrections $m^2_{\chi_R}(\phi) = 2g^2(\phi^2 - M^2)$
- Critical value of ϕ for the end of inflation, ϕ_c, is constant

$$\phi_c = M$$

- Thermal corrections mean $m^2_{\chi_R}$ becomes temperature dependent
- The critical value of ϕ now evolves as

$$\phi_c = \left(M - \frac{\alpha^2}{2g^2}T^2\right)^{1/2}$$

Numerical Results

Evolution of ϕ/M_p for initial conditions that give spectral index $n_s = 0.962$ and $r = 0.019$. Solid lines show evolution with thermal corrections included.

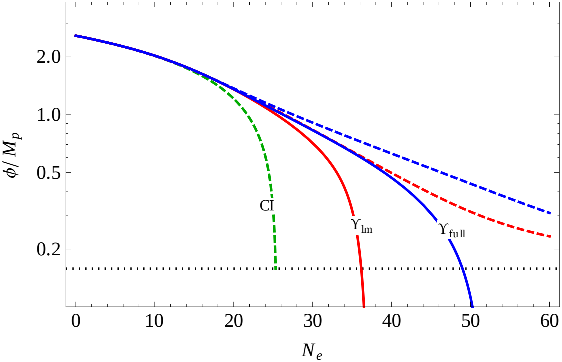


Figure: Evolution of ϕ/m_p for standard cold inflation, warm inflation with $\Upsilon = \Upsilon_{lm}$ and $\alpha^2 = 0$, warm inflation with $\Upsilon = \Upsilon_{lm} + \Upsilon_{pole}$ and $\alpha^2 = 0$, $\Upsilon = \Upsilon_{lm}$ and $\alpha^2 = h^2 N_y/2$, and warm inflation with $\Upsilon = \Upsilon_{lm} + \Upsilon_{pole}$ and $\alpha^2 = h^2 N_y/2$. $h = 0.34$, $M = 0.158 m_p$, $N_x = 5 \times 10^6$, $g = 10^{-3}$, $N_y = 50$, and initial value of $\Phi(0) = 2.58 m_p$.

Numerical Results

Evolution of $m_{\chi R}/T$ for both low-momentum contribution on its own and the full dissipative coefficient for initial conditions that give spectral index $n_s = 0.962$ and $r = 0.019$. Solid lines show evolution with thermal corrections included.

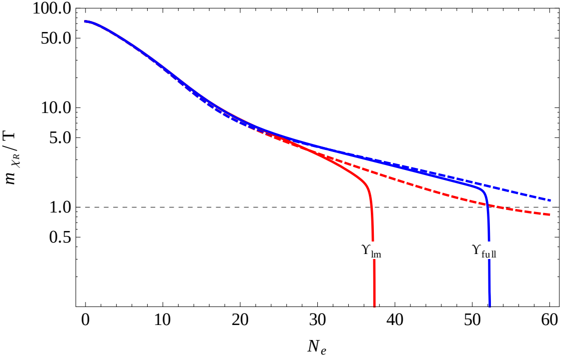


Figure: Evolution of $m_{\chi R}/T$ for standard cold inflation, warm inflation with $\Upsilon = \Upsilon_{lm}$ and $\alpha^2 = 0$, warm inflation with $\Upsilon = \Upsilon_{lm} + \Upsilon_{pole}$ and $\alpha^2 = 0$, $\Upsilon = \Upsilon_{lm}$ and $\alpha^2 = h^2 N_y/2$, and warm inflation with $\Upsilon = \Upsilon_{lm} + \Upsilon_{pole}$ and $\alpha^2 = h^2 N_y/2$. $h = 0.34$, $M = 0.158 m_p$, $N_x = 5 \times 10^6$, $g = 10^{-3}$, $N_y = 50$, and initial value of $\Phi(0) = 2.58 m_p$.

Conclusion

- Dissipation in warm inflation causes a friction term Υ in the inflaton's equation of motion, leading to particle production occuring concurrently with inflationary expansion.
- The dissipative coefficient receives a contribution from low-momentum "off-shell" modes and from the pole "on-shell" modes of the waterfall field.
- Thermal corrections increase the mass of the waterfall field lowering the critical value of ϕ, but also suppresses dissipation so the critical value is reached faster.
- With thermal corrections included in the example shown the low-momentum contribution alone increases the number of e-folds by ~ 10 e-folds
- With thermal corrections included in the example shown the pole contribution adds a further ~ 15 e-folds taking the total to ~ 52 e-folds with spectral index $n_s = 0.962$ and $r = 0.019$

THANK YOU FOR LISTENING

Extra slide

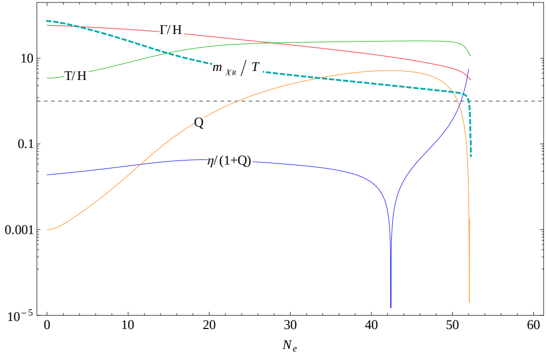


Figure: Evolution of $\eta/(1+Q)$, Q, T/H, Γ/H and m_{χ_R}/T for warm inflation with $\Upsilon = \Upsilon_{lm} + \Upsilon_{pole}$ and $\alpha^2 = h^2 N_y/2$. $h = 0.34$, $M = 0.158 m_p$, $N_x = 5 \times 10^6$, $g = 10^{-3}$, $N_y = 50$, and initial value of $\Phi(0) = 2.58 m_p$. Spectral index $n_s = 0.962$