Reheating After Swampland Conjecture

Vahid Kamali

BASU and IPM

January, 2019
1 Introduction

2 Old Inflation
   ▪ Tunneling

3 New Inflation
   ▪ Slow-roll
   ▪ Energy Density Evolution
   ▪ Reheating

4 Swampland Conjecture

5 Warm Inflation
   ▪ Evolution of warm inflation
   ▪ Condition of Warm inflation

6 Results

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6 Results
Old inflation

First order phase transition
Old inflation

First order phase transition

- Tunneling effect
Old inflation

First order phase transition

- Tunneling effect
- Graceful exit problem
First order phase transition
First order phase transition

- Slow-roll
First order phase transition

- Slow-roll
- Thermalization
Swampland

- Field excursion
Swampland

- Field excursion
- Distance conjecture
The idea of old inflation was introduced in term of scalar field theory which experiences the first order phase transition.
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new Inflation

Condition

We know from G.R in order to realize inflation, it requires an equation of state $P < -\rho/3$, thus a substance with negative pressure that scalar fields can provide such an equation of state.

\[
\rho(\phi) = \frac{1}{2} \dot{\phi}^2 + V(\phi) \quad P(\phi) = \frac{1}{2} \dot{\phi}^2 - V(\phi)
\] (1)

Evolution of the Inflaton
new Inflation

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**Evolution of the Inflaton**

**Evolution of Energy Density**
Evolution of the Scalar Field

Related Equations

Energy Density Conservation

\[ \dot{\rho} + 3H(\rho + P) = 0, \]  

(2)

Equations Describing the Evolution of Scalar Field

\[ \ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0, \quad \epsilon = \frac{1}{2}M_p^2(V')^2, \]
Related Equations

- Energy Density Conservation

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\[ \ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0, \quad \epsilon = \frac{1}{2}M_p^2\left(\frac{V'}{V}\right)^2, \]

where $H$ is Hubble parameter.

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Reheating Interacting Potential

$$V(\phi, \chi) = \lambda_4 (\phi^2 - \phi_0^2)^2 + \frac{1}{2} g_2 \phi^2 \chi^2$$

$$V(\phi, \chi) = \lambda_4 \phi^4 + \alpha_4 (\chi^2 - M_2)^2 + \frac{1}{2} g_2 \phi^2 \chi^2$$

$$V(\phi, \chi) = \frac{1}{2} m_2^2 \phi_\phi^2 + \frac{1}{2} m_2^2 \chi_\chi^2 + \sigma \phi \chi^2 + h_2 \phi^2 \chi^2 + k \chi^4$$

where $\sigma$, $h$, $k$ are coupling constants

Thermalization
Interacting Potential

- Non-thermal phase

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- Particle Creation

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V(\phi, \chi) = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} m_\chi^2 \chi^2 + \sigma \phi \chi^2 + h^2 \phi^2 \chi^2 + k \chi^4
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where \( \sigma, h, k \) are coupling constants
Reheating

Interacting Potential

- **Non-thermal phase**

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where \(\sigma, h, k\) are coupling constants

- **Thermalization**
The theory of string suggests a vast landscape of vacua which are surrounded by maybe bigger swampland low-energy-looking-consistent semi-classical effective field theories (EFT) coupled to gravity, which are physically consistent with quantum theory of gravity if:

1. Field conjecture
   \[ \Delta \phi < c_1 \]  
   (5)

2. Distance conjecture
   \[ |\nabla V(\phi)| V > c_2 M_p \]  
   (6)
or
   \[ \text{min}(\nabla_i \nabla_j V(\phi)) V \leq -c_3 M_p^2 \]
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2. Distance conjecture
   
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   or
   
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Swampland

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\frac{\Delta \phi}{M_p} < c_1
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1. Field conjecture

\[ \frac{\Delta \phi}{M_p} < c_1 \]  \hfill (5)

2. Distance conjecture

\[ \left| \nabla V(\phi) \right| > \frac{c_2}{M_p} \]  \hfill (6)

or

\[ \min \left( \nabla_i \nabla_j V(\phi) \right) \leq -\frac{c_3}{M_p^2}, \]
Warm inflation

The other dynamical realization of inflation is warm inflation. In this picture, similar to cold inflation, the scalar inflaton field must be potential energy dominated to realize inflation. The difference between warm and cold inflation is: In this picture the inflaton is not assumed to be an isolated, non-interacting field during the inflation period.
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Condition of Warm inflation

\[ \dot{\rho} + 3H(\rho + P) = -\Gamma \dot{\phi}^2 \]

\[ \dot{\rho} + 4H\rho = \Gamma \dot{\phi}^2 \]

Equation of motion of warm inflation

\[ \ddot{\phi} + (3H + \Gamma) \dot{\phi} + \frac{dV}{d\phi} = 0 \]

\[ \epsilon = \frac{M_p^2}{\rho} \left( 1 + Q \right) \left( \frac{V'}{V} \right)^2 \]

\[ \delta \phi_{\text{warm}} \sim \sqrt{HT} \delta \phi_{\text{cold}} \sim H \]

In warm inflation model we have \( T > H \).
Condition of Warm inflation

Conservation equation

\[ \dot{\rho}_{\phi} + 3H(\rho_{\phi} + P_{\phi}) = -\Gamma \dot{\phi}^2 \]
\[ \dot{\rho}_{\gamma} + 4H\rho_{\gamma} = \Gamma \dot{\phi}^2; \]
Condition of Warm inflation

- Conservation equation

\[
\dot{\rho}_\phi + 3H(\rho_\phi + P_\phi) = -\Gamma \dot{\phi}^2
\]
\[
\dot{\rho}_\gamma + 4H \rho_\gamma = \Gamma \dot{\phi}^2;
\] (7)

- Equation of motion of warm inflation

\[
\ddot{\phi} + (3H + \Gamma) \dot{\phi} + \frac{dV}{d\phi} = 0
\] (8)

\[
\epsilon = \frac{M_p^2}{2(1 + Q)} \left( \frac{V'}{V} \right)^2
\]

\[
Q = \frac{\Gamma}{3H}
\]
Condition of Warm inflation

- Conservation equation

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- Perturbation of the scalar field

\[
\delta\phi_{\text{warm}}^2 \sim \sqrt{HT} \quad \delta\phi_{\text{cold}} \sim H;
\]
Condition of Warm inflation

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\dot{\rho}_\phi + 3H(\rho_\phi + P_\phi) = -\Gamma \dot{\phi}^2 \\
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\delta \phi_{\text{warm}}^2 \sim \sqrt{HT} \\
\delta \phi_{\text{cold}} \sim H;
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(9)
Perturbation

Perturbation of warm inflation, first approximation

Power-spectrum

\[ P_R \sim H^2 \dot{\phi}^2 \delta \phi^2; \]  

Tensor-scalar ratio

\[ r = \left( \frac{H_T}{16} \right) \epsilon; \]  

Spectral Index

\[ n_s = 1 + d \ln P_R / d \ln k; \]
Perturbation of warm inflation, first approximation

- Power-spectrum

\[ P_R \sim \frac{H^2}{\dot{\phi}^2} \delta \phi^2; \]  

(10)

Tensor-scalar ratio

\[ r = \left( \frac{H_T}{16} \right)^2 \epsilon; \]  

(11)

Spectral Index

\[ n_s = 1 + \frac{d \ln P_R}{d \ln k}; \]  

(12)
Perturbation

Perturbation of warm inflation, first approximation

- Power-spectrum

\[ \mathcal{P}_R \sim \frac{H^2}{\phi^2} \delta \phi^2; \]  \hspace{1cm} (10)

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## Perturbation

### Perturbation of warm inflation, first approximation

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  \[ (12) \]

- We can present these parameters for our model
Data Set

- Important perturbation parameters in low dissipative regime can be compared with observational data.
Data Set

- Important perturbation parameters in low dissipative regime can be compared with observational data

![Graph showing r vs. ns]

- $1\sigma$ and $2\sigma$ confidence regions which borrowed from Planck [?], $r - n_s$ trajectories of the present model in high dissipative regime. The solid red, dashed orange and dot-ashed green lines correspond to $\Gamma_0$ values: $3.14 \times 10^{-3}$, $6.28 \times 10^{-3}$ and $1.25 \times 10^{-2}$. 
### Data Set

- \( n_s - n_{\text{run}} \)

<table>
<thead>
<tr>
<th>ns</th>
<th>run</th>
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<tr>
<td>0.02</td>
<td>0.04</td>
</tr>
</tbody>
</table>

The area corresponds to Planck data and \( n_s - n_{\text{run}} \) trajectories relate to our model. The solid red, dashed orange and dot-ashed green lines correspond to \( \Gamma_0 \) values: 

- \( 3.14 \times 10^{-3} \)
- \( 6.28 \times 10^{-3} \)
- \( 1.25 \times 10^{-2} \)
The area corresponds to Planck data and $n_s - n_{\text{run}}$ trajectories relate to our model. The solid red, dashed orange and dot-ashed green lines correspond to $\Gamma_0$ values: $3.14 \times 10^{-3}$, $6.28 \times 10^{-3}$ and $1.25 \times 10^{-2}$. 
Thanks for your attention