Reheating After Swampland Conjecture

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Swampland conjecture is in contrast with effective thermal field theory of reheating epoch. The effective potential of the scalar field, which is firstly responsible for the accelerated expansion of the universe, at the reheating epoch with temperature \( T < T_c \) has a non-zero minimum which violates the de Sitter conjecture. This concern can be resolved in the context of warm inflation.

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

\[
\frac{\Delta \phi}{M_p} < c_1
\]

where \( \Delta \phi \) is excursions of the scalar fields in the field space, and:

\[
\frac{|\nabla V(\phi)|}{V} > \frac{c_2}{M_p} \quad \text{or}
\]

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

where \( V(\phi) \) is the potential of low-energy EFT, \( c_i \sim \mathcal{O}(1) \) are universal constants and \( \min(\nabla_i \nabla_j V(\phi)) \) is defined in an orthonormal frame as Hessian eigenvalue minimum [1,2]. The second case in Eq.(2) is refined distance swampland conjecture [3]. In this note we will examine EFT of reheating epoch, after inflation, in the context of string swampland conjecture.

Thermal field theory and phase transitions: Known or hypothetical early universe theories of cosmology have been discussed by quantum field theories coupled to gravity which are the low-energy limit of string theory. In a cosmological thermal systems with temperature \( T \), which is comparable with the energy scales of the cosmological system or Hubble parameter \( (T \sim H) \), the thermodynamic potential instead of scalar field potential \( V(\phi) \) is important:

\[
V(\varphi, T) = V(\varphi) + \frac{1}{24} m^2(\varphi) T^2 - \frac{\pi^2}{90} T^4 + Q.C, \quad (3)
\]

where \( T > m, m^2(\varphi) = \frac{\partial^2 V}{\partial \varphi^2} \), Q.C is quantum corrections and \( \varphi = \langle \phi \rangle \) is the expectation value of the scalar field in a thermal equilibrium as thermodynamic variable. Using a toy but important symmetry breaking scalar field model with potential:

\[
V(\varphi) = V_0 - \frac{1}{2} \mu^2 \varphi^2 + \frac{1}{4} \lambda \varphi^4, \quad (4)
\]

we can study phase transition which has a crucial role at early time cosmology. This potential without thermal corrections has two minima at \( \varphi_{\text{min}} = \pm \frac{\mu}{\lambda} \), where the thermodynamic system settles into one of them as broken phase and a maximum at \( \varphi_{\text{max}} = 0 \). When the thermal corrections become important the shape of the potential as a function of \( \varphi \) is modified. At temperature \( T_{\text{up}} \) which is higher than critical temperature \( T_c \), the thermodynamic system settles into a new symmetric phase with the new minimum \( \phi = 0 \) (Fig.1). This procedure is a phase transition between broken and symmetric phases which can be first or second order. \( T_c \) is the critical temperature of thermal system at phase transition point.

In the first-order phase transition when the temperature changes between \( T_{\text{low}} \) and \( T_{\text{up}} \) (where \( T_{\text{low}} < T_c < T_{\text{up}} \)) there are two local minima, with a barrier between them, in the shape of modified potential[see Fig.2]. If our system is firstly in temperature \( T_{\text{up}} \) and the temperature falls below critical temperature \( T_c \), the system has to return some time in metastable state \( \varphi = 0 \) because of the potential barrier which separates false vacuum \( \varphi = 0 \) and true vacuum \( \varphi = \frac{\mu}{\sqrt{\lambda}} \). At critical temperature \( T = T_c \) the values of potential are similar for two local minima Fig.[2]. The phase transition between \( T_{\text{up}} \) and \( T_{\text{low}} \) case can be done by quantum tunneling of the potential barrier which lead to bubble nucleation in the broken phase.

In second-order phase transition case when the system has temperature \( T_{\text{up}} \) the shape of modified potential has just a minimum and after phase transition to broken phase with temperature, \( T_{\text{low}} \) the shape of the potential has a local minimum and a local maximum Fig.[3]. Therefore there is no barrier and also no metastable state.

The idea of old inflation [4,5] was introduced in term of scalar field theory which experiences the first-order phase transition. This idea has a "graceful exit" problem. Transition to the thermal universe is the main problem of this model. During first-order phase transition, the bubbles are nucleated and expanded after tunneling of the scalar field from false to true vacuum. After crossing of these bubbles the gradient of the scalar field at the boundary of crossing bubbles produces the energy density of reheating epoch of the universe evolution. But the problem is that the bubbles could not cross each other because of the expansion of the universe. The idea of old inflation in term of first-order phase transition could not explain the thermal epoch after inflation and the temperature of nucleosynthesis epoch.

Because of this problem the old model of inflation was
FIG. 1. The phase transition happens between symmetric case (red graph) and symmetry broken case (blue graph) during early time evolution of the universe.

FIG. 2. Old inflation as a first order phase transition is in term of tunneling between false vacuum (local minimum at $\phi = 0$) and true vacuum (global minimum at $\phi > 0$). In this figure we can compare the symmetric phase with $T > T_c$ and broken phase with $T < T_c$.

not expected as a workable model in cosmology. The idea of new inflation was introduced soon after the old one in term of second-order phase transition \[6, 7\].

In this scenario the universe expands during short time slow-roll epoch, when the kinetic energy density is smaller than potential energy density $V(\phi)$, and perturbation modes of scalar field cross the horizon and freeze out. These perturbations lead to curvature perturbations in the context of general relativity. The early perturbations are initial seeds of large scale structure and temperature fluctuations of cosmic microwave background (CMB). Observational data analysis results of perturbation of CMB temperature can be used to constrain models of inflation \[8\]. After accelerated expansion or slow-roll epoch of the universe evolution where the inflaton field, as a quanta of inflation, rolls slowly the nearly flat part of the potential it goes to the minimum of the potential Fig. 3. Oscillation of inflaton around the minimum of the potential with the energy exchange to another mainly light fields during nearly matter-like era $\rho \propto a^{-3}$. Reheating has three steps \[9–13\], most of the inflaton energy density transfer to bosonic particles during non-perturbative broad parametric resonance or preheating epoch at first step. The decay of bosonic particles to standard particles is the second step and finally, thermalization is the third step. The particle creations during reheating epoch are usually studied with interacting two fields potential:

$$V(\phi, \chi) = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} m^2 \chi^2 + \sigma \phi \chi^2 + h^2 \phi^2 \chi^2 + k \chi^4 \tag{5}$$

where the inflaton field interacts with other fields in the model which is generally presented by $\chi$. Non-thermal phase transitions idea before standard particle creation with the symmetry breaking potentials

$$V(\phi, \chi) = \frac{\lambda}{4} (\phi^2 - \phi_0^2)^2 + \frac{1}{2} g^2 \phi^2 \chi^2, \tag{6}$$

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

can be used to explain topological defects and cosmic strings problem before thermalized era \[14\]. Potentials \[5\] and \[6\] are explicitly in contrast with the second part of second swampland conjecture (distance conjecture) which is about the condition of potential form of the EFT.

Discussion and Conclusions: The contradiction between potentials \[5\] and the second part of distance conjecture may not be the case if the potential provides the first condition of this conjecture. The main problem between reheating and distance conjecture is thermalization part. At the thermalization step, for all models of inflation, the form of potential near the minimum is approximately quadratic, on the other hand, there is a thermal bath with temperature $T$. Considering thermal
part of reheating we need a thermal effective field theory with the potential (see blue long-dashed curve in Fig.3):

$$V(\varphi, T) \approx \frac{1}{2} m_\varphi^2 \varphi^2 + \frac{1}{24} m^2(\varphi) T^2 - \frac{\pi^2}{90} T^4 + QC,$$

(7)

This potential is obviously in contrast with the first part of distance conjecture at the minimum of the potential (see long-dashed blue curve in Fig.3). The potential also could not cover the second part of the conjecture near the minimum of the potential. These mean that thermal EFT of reheating is suffered from swampland string theory conjecture. The solution may be a warm inflation model [15–18]. In the context of warm inflation, inflaton field interacts with the light fields during slow-roll epoch and the inflation era connects to radiation dominated era smoothly (see Fig.4). The universe heats up during the slow-roll epoch of warm inflation and there is no need to the separated reheating epoch. On the other hand, there were some discussions about slow-roll part of warm inflation which cover the swampland conjecture [13–22]. All solutions of the contradictions between string theory and (cold)inflation theory that have been proposed in the literature [22, 49] may solve the slow-roll part but are unable to explain the contradiction between reheating epoch and string swampland, as we have discussed in this note. Main conclusion of our work is introducing warm inflation as a solution of swampland conjecture, slow-roll and reheating problems.

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