SURFACE REHEATING AS A NEW PARADIGM

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In this talk we briefly review the standard idea of reheating and then present a new paradigm of reheating the Universe through surface evaporation.

1. Introduction

Finite temperature effects are important to be considered in the early Universe. Given the fact that there is no direct evidence for the particle content in the early Universe beyond the Standard Model (SM) of electroweak scale $\sim 100$ GeV, and in cosmology there is no direct evidence of thermal history beyond the era of Big Bang Nucleosynthesis (BBN) $\sim 1$ MeV, it becomes a challenging problem understanding the physics of the very early Universe. In spite of this there are numerous observational hints which suggests the extension of the physics beyond the SM. It is also paramount to keep in mind that in an expanding Universe the local thermodynamical equilibrium can be achieved only if the particle interactions, or at much higher energy scales string interactions, or interactions between non-perturbative objects such as D-branes are first of all well known, and then their respective interaction rates follow: $\Gamma_i(T) \geq H(T)$. A simple example will illustrate our point. For $2 \rightarrow 2$ particle interactions the scattering rate is given by $\Gamma \sim \alpha^2 T$ ($\alpha$ is a coupling constant), which becomes smaller than $H \sim T^2/M_P$ (we use reduced Planck scale $M_P = 2.436 \times 10^{18}$ GeV) at sufficiently high temperatures. It was noticed that elastic $2 \rightarrow 2$ processes maintain thermal equilibrium typically only up to $T_{max} \sim 10^{14}$ GeV, while chemical equilibrium is lost already at $T \sim 10^{12}$ GeV \textsuperscript{1}. In $N = 1$ su-
pergravity the situation is completely different where the temperature of thermal bath must not exceed $10^{10}$ GeV, which we shall discuss below.

In this talk we describe a new paradigm of reheating the Universe, which is known as surface reheating. We will highlight why this mechanism is interesting and may occur in a wide class of field theories.

1.1. Standard lore of reheating and constraints

Here we quickly review the standard lore of reheating the Universe. It is commonly believed that inflation is one of the most promising early Universe paradigm, which besides explaining homogeneous, flat and isotropic Universe, also explains the seed mechanism for galaxy and large scale structure formation. The inflaton might be a gauge or non-gauge singlet, and could also provide a non-vanishing dominating energy density which leads to quasi-de-Sitter expansion of the Universe. The inflaton decays after the end of inflation when it starts oscillating about its minimum. The decaying inflaton into a pair of fermions can reheat the Universe with a relativistic thermal bath of temperature

$$T_{rh} = \left( \frac{90}{\pi^2 g_*} \right)^{1/4} \sqrt{\Gamma_\phi M_P} = 0.3 \left( \frac{200}{g_*} \right)^{1/4} \sqrt{\Gamma_\phi M_P} .$$

In the above $g_*$ is the number of relativistic degrees of freedom at $T_{rh}$ and $\Gamma_\phi = \alpha m_\phi \sim \alpha H_{inf}$ is the inflaton decay rate where $m_\phi$ denotes mass of the inflaton, and $H_{inf}$ denotes the scale of inflation in many inflationary models. The process of thermalization is quite complicated and it may not happen instantly.

The reheat temperature must be above MeV in order to keep the success of the BBN. In particularly supersymmetric theories there is also an upper bound on reheat temperature. The relativistic thermal bath generates gravitinos thermally, and non-thermally during inflaton oscillations. The gravitino interactions with matter are Planck mass suppressed, e.g. the helicity $\pm 3/2$ mode decays into gauge bosons and gauginos through dimension 5-operator with a life time $\tau_{3/2\rightarrow A_{\mu\lambda}} \sim M_P^2/m_{3/2}^3$. Gravitino in a gravity mediated supersymmetry breaking scenario gets a mass of order $\sim 100$ GeV. This means that they decay after BBN era. The over produced gravitinos inject enough entropy to ruin the success of the BBN. The bound on reheat temperature comes out to be

$$T_{rh} \leq 10^9 \left( \frac{m_{3/2}}{100 \text{ GeV}} \right)^{-1} \text{ GeV} .$$

It turns out that in high scale inflation models it is hard to satisfy this bound on reheat temperature unless the coupling $\alpha$ is small. In particular
the string motivated inflation models where the string scale is close to the grand unification scale $\sim 10^{17}$ GeV, and the inflaton sector couples to the matter sector via string coupling, the problem gets severe, see e.g. 7. In general this problem is dubbed as *gravitino problem*, and only late thermal inflation 8, or low scale inflation can be the solution, i.e. 9. Similar problem arises with moduli fields appearing from string theory.

### 1.2. Surface Reheating

A novel way to avoid the gravitino and other moduli problems is reheating via the surface evaporation of an inflatonic soliton. Compared with the volume driven inflaton decay, the surface evaporation naturally suppresses the decay rate by a factor: \( \text{area/volume} \propto L^{-1} \) where \( L \) is the effective size of an object whose surface is evaporating. The larger the size, the smaller is the evaporation rate, and therefore the smaller is the reheat temperature.

Reheating as a surface phenomenon has been considered \(^2\) in a class of chaotic inflation models where the inflaton field is not real but complex. As the inflaton should have coupling to other fields, the inflaton mass obtains radiative corrections resulting in a running inflaton mass with a potential

\[
V = m^2 |\Phi|^2 \left[ 1 + K \log \left( \frac{|\Phi|^2}{M^2} \right) \right],
\]

where the coefficient \( K \) could be negative or positive, and \( m \) is the bare mass of the inflaton. The logarithmic correction to the mass of the inflaton is something one would expect because of the possible Yukawa and/or gauge couplings to other fields. Though it is not pertinent, we note that the potential Eq. (3) can be generated in a supersymmetric theory if the inflaton has a gauge coupling \(^{10}\) where \( K \sim -\left( \frac{\alpha}{8\pi} \right) (m^2_{1/2}/\tilde{m}_\ell^2) \), where \( m^2_{1/2} \) is the gaugino mass and \( \tilde{m}_\ell \) denotes the slepton mass and \( \alpha \) is a gauge coupling constant. It is also possible to obtain the potential in a non-supersymmetric (or in a broken supersymmetry) theory, provided the fermions live in a larger representation than the bosons. In this latter situation the value of \( K \) is determined by the Yukawa coupling \( h \) with \( K = -C(h^2/16\pi^2) \), where \( C \) is some number.

As long as \(|K| \ll 1\), during inflation the dominant contribution to the potential comes from \( m^2 |\Phi|^2 \) term, and inflationary slow roll conditions are satisfied as in the case of the standard chaotic model. COBE normalization then implies \( m \sim 10^{13} \) GeV. If \( K < 0 \), the inflaton condensate feels a negative pressure and it is bound to fragment into lumps of inflatonic matter \(^2\). Moreover, since the inflation potential Eq. (3) respects a global \( U(1) \) symmetry and since for a negative \( K \) it is shallower than \( m^2 |\Phi|^2 \), it admits
a $Q$-ball solution, see\textsuperscript{10}. The main idea behind this mechanism is that the fermions coupled to the inflaton $h\phi \bar{\psi} \psi$ decays only through the surface of the inflatonic $Q$-ball. The fermion production is blocked by Pauli blocking inside the $Q$-ball\textsuperscript{11}.

The inflatonic $Q$-balls can be created with a size $R \sim |K|^{-1/2} m^{-1}$ when the inflaton oscillates around its minimum. The quantum fluctuations in the inflaton grow non-linear because of the self-coupling by virtue of the Logarithmic correction. The evaporation rate of the fermions can be given by\textsuperscript{2}

$$\Gamma_Q = \frac{1}{Q} \frac{dQ}{dt} \simeq \frac{1}{1.8 |K|^{3/2}} \left( \frac{m}{M_P} \right)^2 m. \tag{4}$$

Note that the decay rate is determined by the ratio $m/M_P \simeq 10^{-6}$, which is fixed by the anisotropies seen in the cosmic microwave background radiation. Even though we are in a relatively large coupling limit $h \sim 1$, the decay rate mimics that of a Planck suppressed interaction of the inflatonic $Q$-ball. The reheat temperature turns out to be $T_{rh} \sim 10^8 |K|^{-3/4}$. The value of $K$ depends on the nature of the inflaton coupling, but for relatively small value $|K| \sim 0.1$, we note that we obtain a reheat temperature which can avoid gravitino and moduli problems.

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