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# WAS COSMIC INFLATION DRIVEN BY QUANTUM FIELD OR ITS PRODUCT ?

B. P. GONG[1]
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## ABSTRACT

Inflationary model provides a conceptual explanation of the horizon problem, the flatness problem and may also suppress the over abundant magnetic monopoles predicted by Grand Unified Theories. Although various inflationary models have been proposed since 1981, difficulties like fine tuning is not only unsolved but also becomes severer in confrontation with data of Planck Satellite. This paper proposes an alternative model of inflation: the spontaneous symmetry breaking phase transition at early universe is only responsible for the production of magnetic monopoles expected by Grand Unified Theories; it is the subsequent energy release of monopole annihilation that drives the inflation. As a result, the early universe underwent a free expansion with a heat source originating in the annihilation, which expects a smooth, plateau-like potential consistent with the observational data. Beside interpreting a number of long standing inflationary problems, the new scenario predicts a significant increase of entropy during the inflation, and tends to produce large scale structures exceed scale of 300 million light-years correlated with a CMB smoothen and flatten by a simple dynamical mechanism.

*Subject headings:* annihilation, monopole, inflation, phase transition

## 1. INTRODUCTION

The first inflationary model, so called old inflation(Guth 1981), proposed an inflation based on a scalar field theory undergoing a first order phase transition. The scalar field was initially trapped in a local minimum of some potential, and then leaked through the potential barrier and rolled towards a true minimum of the potential, which produces finite sized fluctuation containing stable phase, bubbles.

The flat potential at the “false vacuum" phase results in an exponential expansion. Such a non-thermal process cannot be simultaneous everywhere, so that bubbles would be carried apart by the expanding phase so quickly for them to coalesce and produce a large bubble. The resultant universe would be highly inhomogeneous and anisotropic, opposite to what is observed in the cosmic microwave background.

The successor to the old inflation was new inflation(Linde 1982; Albrecht et al. 1982), with a scalar field undergoing second order phase transition free of potential barrier. It requires a very flat potential in order to produce inflation suffering from severe fine-tuning problem (Steinhardt 2011).

One of the most popular inflationary models is the chaotic inflation(Linde 1983), which is based on a scalar field, but it does not require any phase transition. In such a model a patch of the universe with a large and uniform scalar field can invoke inflation solving the flatness and horizon problem.

It ends up with a chaotic inflation which is locally flat and homogeneous in our patch of universe, while it can be curved and inhomogeneous in other patches. In such a case, the scalar field describing inflation at the Planck time is completely decoupled from all other physics(Coles & Lucchin 2002).

These models appear different, whereas, they share common features. The exponential expansion of the universe is achieved by the Friedman equation,

$$H^2 = (\frac{\dot{a}}{a})^2 = \frac{8\pi G}{3}\rho = \frac{8\pi G}{3}T^4_{GUT} = t^{-2}_{exp} \,, \qquad (1)$$

where, $\rho$ is the sum of the energy density of the radiation, the matter and vacuum field, etc. Inflationary models assume that as temperature drops below, $T_{GUT}$, the critical temperature of phase transition, the energy density of the universe is dominated by $\rho \approx T^4_{GUT}$ (Albrecht et al. 1982), the difference of energy density between the initial “false vacuum" phase and the lower energy “true vacuum" phase. The exponential expansion is ensured by a constant $T_{GUT}$ during the inflation.

The exponential increase of scale factor, $a$, results in supercooling, an exponential decrease of the universe temperature, $T$, under the adiabatic expansion $Ta = const$. After reaching the bottom temperature of only $\sim 10^{1-2}$K, the universe is required to be reheated to temperature of e.g., $\sim 10^{27}$K, until the dominance of energy density $\sim T^4$. However, detailed physics of switching dominances is unknown, so is the consequence of supercooling and “super" reheating to the subsequent evolution of the universe.

This paper suggests a simple and easy model of inflation. Firstly, the scalar field is only responsible for the production of MMs predicted by GUTs('t Hooft 1974; Carrigan & Trower 1983) during the Spontaneous Symmetry Breaking (SSB) phase transition from “false vacuum" phase to the “true vacuum" phase. Secondly, it is the subsequent magnetic monopole (MM) annihilation that gives rise to bubble collisions which results in a stable energy density and drives the inflation.

Supercooling and “super" reheating are unnecessary in the new scenario. Because the annihilation of over abundant MMs would invoke enormous energy release, which results in a free expansion of the universe, rather than adiabatic one widely assumed.

## 2. MM ANNIHILATION

The breaking of Grand Unified Theories (GUTs) could be a many stage process with several different scale $M_x$, from grant unified, e.g., $SO(10)$ to grand unified $SU(5)$ or other ones, as long as the transition leaves unbroken a symmetry group containing a U(1) factor.

The mass of a MM is of order $M_m \approx M_x/\alpha \approx 10^{16}$GeV, where $M_x \approx 10^{14-15}$GeV is the mass of the superheavy vector

[1] Department of Physics, Huazhong University of Science and Technology, Wuhan, 430074, People's republic of China; bpgong@mail.hust.edu.cn

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meson, and $\alpha \approx 1/50$ the fine structure constant. Detailed mechanism by which MMs were produced depends on the nature of phase transition; in particular, on whether it was a second-order (or weakly first-order) or a strongly first-order transition(Preskill 1984).

Unlike the other superheavy particles in GUTs, MMs are absolutely stable, their density per comoving volume can be reduced only by annihilation of MM pairs. However, such an annihilation becomes difficult with rapid expansion of the universe, since $M\bar{M}$ pairs had an increasingly more difficult time finding each other. As a result, the annihilation has not been considered an efficient mechanism to reduce density of MMs per comoving volume(Preskill 1984).

Preskill investigated the suppress of over abundant MMs through annihilation(Preskill 1979). The $M\bar{M}$ pairs can be annihilated by capturing each other in magnetic Coulomb bound states, and then cascading down(Preskill 1979). As long as the mean free path of a MM is shorter than the capture distance the annihilation rate can be given by the flux of M's diffusing through the dense plasma of charged particles toward an $\bar{M}$, which corresponds to a cross section of(Preskill 1979),

$$D = \langle\sigma v\rangle \approx \beta T^{-2}, \quad (2)$$

where $\beta \approx 94$. The process of capturing $M\bar{M}$ pairs has been thought relatively inefficient because the monopoles are so heavy; which fails to keep pace with the expansion of the universe(Preskill 1984). A dimensionless ratio has been used as a criteria of efficiency of the annihilation,

$$r \equiv \frac{n}{T^3}, \quad (3)$$

which can be treated as a normalized number density of MMs counting out the effect of the universe expansion. Once the smallest possible initial MM abundance, $r \sim 10^{-10}$ is established in the phase transition, then the dimensionless ratio $r$ becomes unchanged under adiabatic expansion with $Ta = const$. In such a case, the MM abundance is not further reduced by annihilation at all.

On the other hand, even if $r \ll 10^{-10}$ can be reached, such a normalized number density is too low for $M\bar{M}$ to catch each other, which prevents the annihilation from happening in a comoving volume.

The only way to further reduce the normalized number density of MMs is through nonadiabatic effect(Preskill 1984). In fact, the energy release of annihilation naturally corresponds to a heat source to a comoving volume, which could result in a nonadiabatic process provided that the annihilation is stable during the inflation. Following analysis shows that a stable annihilation can be achieved.

Differing from the inflation driven by scalar field, in the new scenario as shown in Fig1 the phase transition is only responsible for generation of MMs as $T < T_{GUT}$. Then the universe gets reheated by latent heat from e.g., $10^{14-15}$GeV to $\sim 10^{16}$GeV, the energy gap of which is much less than that of the reheat after supercooling predicted by scalar field driven inflation. The annihilation of $M\bar{M}$ pairs thus initiates at $\sim 10^{16}$GeV.

Is the energy release of annihilation sufficient to drive the inflation ? With Eq (2), the cross section of annihilation of MM pairs at temperature $T \approx 10^{28}$K can be estimated,

$$\langle\sigma v\rangle \sim \beta \frac{ck_b^2}{\hbar\sigma}(\frac{10^{28}K}{T})^2 \approx 10^{-48} m^3 s^{-1}, \quad (4)$$

where $k_b$ is the Boltzmann constant, $\hbar$ is the Planck constant, $c$ is the speed of light, and $\sigma$ is the Stefan-Boltzmann constant.

The resultant energy density owing to the annihilation with small drop in temperature and large expansion of scale factor, can be estimated,

$$\rho_m \sim (\frac{M_m}{10^6 J})(\frac{\langle\sigma v\rangle}{10^{-48} m^3 s^{-1}})(\frac{N_m}{10^{88}})^2(\frac{t}{10^{-34} s}) \approx 10^{100} Jm^{-3}. \quad (5)$$

Notice that the energy density of annihilation of Eq (5) is sufficient to solve the flatness problem (Weinberg 2008), which can drive an exponential expansion by Eq (1) with $\chi = (8\pi G\rho_m/3)^{1/2}$.

The exponential expansion of scale factor of $a_f/a_0 \sim 10^{26}$ at a temperature drop of $T_f/T_0 \sim 10^{-1}$ corresponds to a change of the dimensionless ratio, $r$ of Eq (3),

$$\frac{r_f}{r_0} \sim \frac{(a_0 T_0)^3}{(a_f T_f)^3} \sim 10^{-75}, \quad (6)$$

which is far beyond the criteria of annihilation of Eq (3). In such a case, the rapidly decrease of number density of MMs by the exponential expansion would prevents the capture of M$\bar{M}$ pairs from possible, such that the annihilation would have terminated at the very beginning of inflation, $t/t_0 \ll t_f/t_0$. In other words, the exponential expansion is too fast for further annihilation to proceed, which is analogy to the inhomogeneous problem of the old inflation(Guth 1981).

The annihilation of MMs can drive a non-exponential expansion like the free expansion of the universe which relates temperature, $T$, scale factor, $a$, and time, $t$, by

$$T^{-\omega} \propto a \propto t^{\omega} . \quad (7)$$

With an index $\omega \approx 26$, such a free expansion can gives rise to an inflation with an expansion of scale factor from $a_0 \sim 10^{-26} cm$ to $a_f \sim 1 cm$, at a temperature change from $T_0 \sim 10^{28} K$ to $T_f \sim 10^{27} K$. Then the question becomes: can such a free expansion satisfy the criteria of Eq (3), and keep a stable annihilation during the inflation?

The first law of thermodynamics, $dU + pdV = dQ$ (where $U$ is the total energy of the volume, $pdV$ denotes work done to the surrounding, and $dQ = TdS$ represents energy supply to the volume as heat). In the case of adiabatic expansion, $dQ = 0$, the universe expands at the expense of the reduction of total energy, $dU < 0$, which can leads to supercooling of the universe. In contrast, if there is a stable source of energy supply, the universe can expand as $pdV = TdS$, with a constant total energy, $dU = 0$. In other words, the universe undergoes free expansion, equivalent to an isothermal process.

With pressure and energy density relation of $p = \kappa\rho$ and entropy density $s = Sn$, we have,

$$\frac{pdV}{TdS} = \frac{\kappa\rho dV}{TdS} = 1 , \quad (8)$$

thus $\rho/s = nT/\kappa$ (where $\rho = nM_m$) can be obtained, from which the dimensionless ratio of Eq (3) becomes,

$$r = \frac{n}{s} = \frac{nT}{\kappa M_m} = \frac{1}{\kappa k_b}\frac{T}{T_0} n. \quad (9)$$

It is worth mention that in the case of free expansion, the dimensionless ratio of Eq (9) obtained by the first law of thermodynamics is of no difference from that of the Boltzmann equation.

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How the number density of MMs vary under the free expansion ? It differs radically from that of scalar field driven inflation. In case of strongly first-order transition, as the universe temperature drops below $T_{GUT}$, bubbles of the stable broken-symmetry phase begin to nucleate. These bubbles expand, collide and coalesce filling the universe with the stable phase. Inside each bubble, the scalar field $\phi$ is quite homogeneous, so that each bubble contains a negligible number of MMs. But when the expanding bubbles collide more MMs can be produced (Preskill 1984).

Suppose an initial bubble collision resulted in a condensation triggering the production and annihilation of more MMs. Then it leads to a Gamma-Ray-Burst like fireball, giving rise to a rapidly expanding shell which further collides with bubbles or other condensations and resulting in a number of new fireballs, etc. Consequently, cascading processes occur in the annihilation process which generates numerous fireballs releasing enormous energy dominating the inflation.

The cascading results in rapid increase of number of MMs participating annihilation, which can roughly compensate the decrease of number density owing to the expansion, $a^{-3}$. It ends up with an approximately constant number density of MMs participating annihilation during inflation. Therefore, a stable rate of annihilation can be maintained during the inflation.

The free expansion as shown in Eq (7), corresponds to a relation of scale factor to temperature by $a^{-3} \propto T^{3\omega}$, which can keep an approximately constant number density of $n = Na^{-3} \sim const$, if a number of MMs of $N \propto T^{-3\omega}$ are produced and annihilated through the cascading collision of bubbles.

At temperature, $T \geq 1\times 10^{28}$K, an initiating number of MMs of $N_0 \sim 10^{11}$ can give rise to the number of MMs participating annihilation up to $N_f \sim 10^{11}(T_0/T_f)^{3\omega} \sim 10^{88}$, with an index of $\omega \approx 26$.

Immediately after the maximum annihilation, the index becomes $\omega < 26$, so that the number of MMs participating annihilation reduces rapidly, $N_f \sim N_0(T_0/T_f)^{3\omega} \ll 10^{88}$, when the annihilation driven inflation essentially ends at temperature $T < 1\times 10^{28}$. The ratio of number density of MMs at the initial and final inflation is read,

$$\frac{n}{n_o} = \frac{Na^{-3}}{N_0 a_0^{-3}} \sim \frac{T_0^{3\omega}}{T_0^{3\omega_0}} \tag{10}$$

At temperature, $T \geq 1\times 10^{28}$K during the inflation, one has nearly constant number density of MMs participating annihilation, $n/n_o \sim 1$, with $\omega = \omega_0 \approx 26$.

In contrast, at the end of inflation of temperature, $T < 1\times 10^{28}$K, we have $\omega < \omega_0$, which corresponds to a rapidly decease of number density $n$, so that the ratio becomes $n/n_o \ll 1$.

Under the free expansion, the criteria of annihilation as shown in Eq (9) becomes,

$$\frac{r}{r_0} = \frac{T}{T_0}\frac{n}{n_0} \tag{11}$$

An increasing number of MMs are annihilated in the case of ratio of $r/r_0 \sim 10^{-1}$ when $M\bar{M}$ pairs can find each other easily, which leads to a stable annihilation during the inflation.

The stable annihilation corresponds a Hubble constant, $H = \dot{a}/a$ of

$$H = \frac{\dot{a}}{a} = -\omega\frac{\dot{T}}{T} \propto T^2 \tag{12}$$

The annihilation rate can be estimated through Eq (2),

$$\Gamma \sim n\langle\sigma v\rangle \sim n\frac{\beta}{T^2} \tag{13}$$

A ratio of $R = \Gamma/H$ can be obtained by Eq (12) and Eq (13),

$$\frac{R}{R_0} \sim \frac{n}{n_0}(\frac{T}{T_0})^{-4} \tag{14}$$

Eq (14) indicates $R/R_0 > 1$ during the inflation, so that the inflation occurs in thermal equilibrium. Therefore, the validity of annihilation induced free expansion in the whole inflation is guaranteed by Eq (10), Eq (11) and Eq (14).

The expansion in thermal equilibrium can increase the entropy of the universe,

$$\frac{S}{S_0} = \frac{sa^3}{s_0 a_0^3} \sim (\frac{T_0}{T})^{3\omega-3} \sim 10^{75} \tag{15}$$

Such a significant increase of entropy during inflation as shown in Eq (15) may account for how the high entropy found in our universe could have been generated.

At the end of inflation, the annihilation induced heat comes to a halt, $TdS \approx 0$, so that universe cools down through radiation. By the rapidly cooling and other processes, the temperature, scale factor and time of the universe can come back to normal values expected by standard model of cosmology around the desert era of the universe.

The role of energy release of MM annihilation in the free expansion of the universe needs to be revisited. In fact, the expansion of the universe owing to energy transfer from the decay of a massive particle species to radiation has been discussed decades ago(Kolb & Turner 1990b), which predicts an evolution of radiation energy density, $\rho_R$, in the form of the first law of thermal dynamics,

$$d(a^3\rho_R) + p_R d(a^3) = -d(a^3\rho_\psi) = (a^3\rho_\psi)dt/\tau$$
$$\dot{\rho}_R + 4H\rho_R = \rho_\psi/\tau \tag{16}$$

The sign change at right hand side of Eq (16), is due to the number reduction of massive particles, $\psi$, in a comoving volume by their decay(Kolb & Turner 1990b).

Similarly, in the case of annihilation drive expansion, the total number of MMs shall decrease for at least 23 order of magnitude during the inflation (as shown in next section), which reduces rapidly at the end of inflation as discussed under Eq (10). As a result, the energy release of annihilation also corresponds to a positive term of energy input at right hand side of Eq (16).

If one adopts the adiabatic expansion, $d(\rho a^3) = -pd(a^3)$, the energy-momentum tensor of a perfect fluid in cosmology, $T_{ij}$, becomes,

$$\dot{\rho} + 3(\rho + p)H = 0. \tag{17}$$

It appears that MMs and their energy release through annihilation can be represented by $\rho$ in Eq (17), which is equivalent to ultra-relativistic particles (also gas of photons) in thermal equilibrium of equation of state, $p = \rho/3$, corresponding to a positive pressure. However, such a suggestion would cause a problem as follows. The original term $\rho$ in Eq (17) can represent both nonrelativistic and relativistic matter, which expands at the expense of the decrease of the total energy of the volume. In other words, the term $\rho$ absorbs energy of the volume, which would correspond to a positive pressure $p$ in Eq (17).

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On the contrary, the energy release of the annihilation is analogous to the heat source in isothermal process, which inputs energy into the volume to power the expansion, rather than consumes energy, so that the volume actually expands at the expense of the energy release of annihilation. Therefore, the time derivative of the energy release of annihilation is same as that of the total energy in Eq (17), which are both decrease with time.

Even if one put the effect of annihilation into the term $\rho$ in the adiabatic expansion of Eq (17), it corresponds to, $\rho = \dot{\rho}_m \tau < 0$, a negative term, differing from the positive assumption under Eq (17).

## 3. DISCUSSION

The free expansion driven by the annihilation induced bubble collisions corresponds to an efficient rate of MM annihilation differing from that of low efficiency under adiabatic expansion. In such a scenario, the energy density and pressure of the universe are dominated by the energy release of MM annihilation during the inflation.

The new scenario: first interprets a number of longstanding problems on inflation; second consists with the features of cosmic microwave background (CMB) exhibited by the Planck satellite; third allows large scale structures exceeding the 'End of Greatness' hypothesis.

Furthermore, the free expansion predicts an early universe in thermal equilibrium which avoids the inhomogeneity problem of the old inflation with bubbles driven apart by vacuum field exponentially. The annihilation of over abundant MMs of, $N \sim 10^{88}$, is welcome, because their annihilation provides sufficient energy to account for the e-folds required in solving the flatness problem. This automatically and efficiently solves the problem of over abundant MMs predicted by GUTs, as Guth's old inflation can reduce the number density of MMs rather than the total number of MMs. The number of MMs at the end of inflation should be reduced over 20 order of magnitude, so that the remnant number below $N \leq 10^{65}$ is not contradictory to the limit of Dark Matter of current universe.

The high precision data of Planck satellite data(Planck Collaboration & Ade 2014) calls the simplest, single-field, plateau-like models. However, such a single-field is difficult to survive the inflationary paradigm.

Since the simplest power law models require only one parameter and absolutely no tuning of parameters to obtain 60 or more e-folds of inflation, while the plateau-like models require three or more parameters and must be fine-tuned to obtain even a minimal amount of inflation

Yet the Planck data(Planck Collaboration & Ade 2014) forbids the power-law inflation and only allows the unlikely plateau-like inflation. This is the so called the inflationary unlikeliness problem(Ijjas et al. 2013).

In the new scenario, the plateau like potential is achieved by annihilation induced energy density $\rho(T) \approx T^4$ which mimics the scalar field, $V(\phi) \approx \phi^4$. In other words, the form of power-law energy density exhibits a plateau-like potential as the free expansion corresponds to a negligible change of universe temperature, $T$, comparing with over 60 e-folds increase of the scale factor. This not only makes the overall scenario of inflation much simpler and easier to achieve, but also prevents the fine tuning problem in scalar field driven inflationary models from happening,

Beginning from roughly equal energy density at Planck time and evolve forward in time as kinetic ($a^{-6}$) , gradient energy ($a^{-2}$) and the scalar field ($a^{-4}$), gradients and inhomogeneities quickly dominate which prevents the inflation from happening(Ijjas et al. 2013).

While in the scenario of the annihilation induced inflation, the energy release of annihilation of MMs is equivalent to a potential of $V(T) \propto a^{-4/\omega} \approx a^{-0.15}$, which is much larger than that of gradient energy of $\sim a^{-2}$. This automatically solves the problem that inflation could be prohibited by gradient energy(Ijjas et al. 2013). Moreover, the new scenario can also be consistent with a number of results from Planck(Planck Collaboration & Ade 2014).

(1) The measured spatial curvature is small—- since the energy density of annihilation is sufficient to invoke a flat universe.

(2) The spectrum of fluctuations is nearly scale-invariant. (3) There is a small spectral tilt, consistent with the existence of a simple dynamical mechanism. (4) And the fluctuations are nearly Gaussian, eliminating exotic and complicated dynamical possibilities.

Question (2-4) can be understood as results of scalar perturbations, like the density and the pressure perturbations originating in annihilation driven bubble collision. With equivalent energy density $\rho_m \approx T^4$ and relation of free expansion $a \propto T^{-\omega}$, such a process mimics a dynamic mechanism smoothing and flattening the early universe.

Once the cascading process occurs in the annihilation induced bubble collision, the inflation shall terminate at the maximum number of MMs annihilation. In such a case it tends to produce huge bubbles by the energy release from the largest condensations of MMs at the end of inflation. The large scale structures left over could exceed the 'End of Greatness' hypothesis, a scale of 300 million light-years. As the annihilation induced bubble collision is dominant during inflation, it not only leaves imprints on the large-scale structure, but also on cosmic CMB.

Moreover, it also affects the ratio of E and B modes CMB polarization which is a signature of the effects of the scalar vs the tensor perturbations on the CMB anisotropies.

Combined analysis on the CMB polarization, large scale structures and CMB data like the Planck satellite may further test the validity of the annihilation induced inflation, and shed new light on the extension of the Standard Model.

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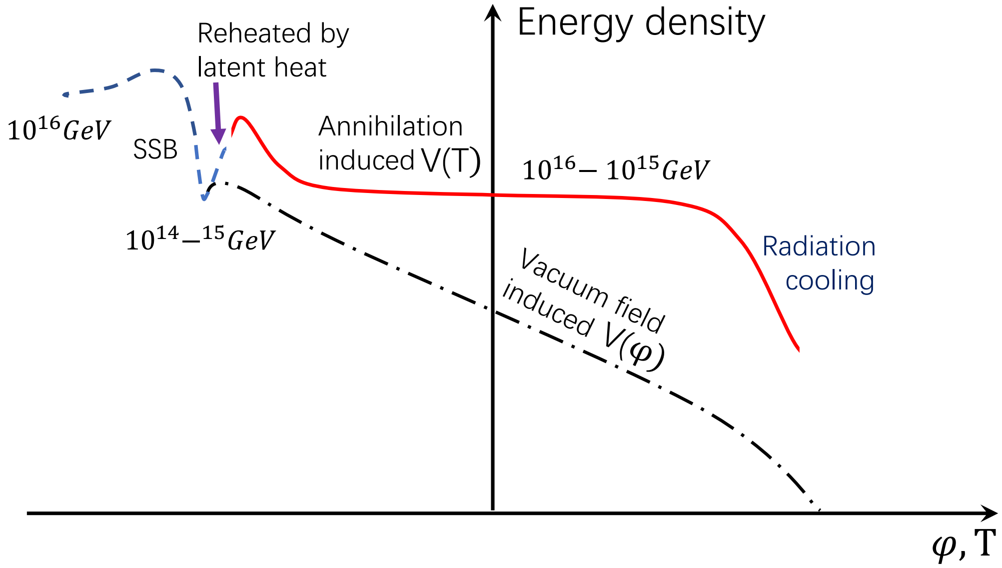


FIG. 1.— Schematic illustration of annihilation induced inflation free of supercooling. Step 1 phase transition responsible for production of initial MMs (dashed); step 2 a free expansion driven by annihilation of MMs (red).