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Creation of an inflationary universe out of a black hole

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ABSTRACT

We discuss a two-step mechanism to create a new inflationary domain beyond a wormhole throat which is created by a phase transition around an evaporating black hole. The first step is creation of a false vacuum bubble with a thin-wall boundary by the thermal effects of Hawking radiation. Then this wall induces a quantum tunneling to create a wormhole-like configuration. As the space beyond the wormhole throat can expand exponentially, being filled with false vacuum energy, this may be interpreted as creation of another inflationary universe in the final stage of the black hole evaporation.

Inflation in the early universe provides answers to a number of fundamental questions in cosmology such as why our Universe is big, old, full of structures, and devoid of unwanted relics predicted by particle physics models [1]. Furthermore, despite the great advancements in precision observations of cosmic microwave background (CMB) radiation, there is no observational result that is in contradiction with inflationary cosmology so far [2,3].

Inflationary cosmology has also revolutionized our view of the cosmos, namely, our Universe may not be the one and the only entity but there may be many universes. Indeed already in the context of the old inflation model [4,5], Sato and his collaborators found possible production of child (and grand child...) universes [6–8].

Furthermore, if the observed dark energy consists of a cosmological constant Λ, our Universe will asymptotically approach the de Sitter space which may up-tunnel to another de Sitter universe with a larger vacuum energy density [9–13] to induce inflation again to repeat the entire evolution of another inflationary universe. In such a recycling universe scenario, the Universe we live in may not be of first generation, and we may not need the real beginning of the cosmos from the initial singularity [12].

In this context, so far only a phase transition between two pure de Sitter space has been considered [14]. However, phase transitions which we encounter in daily life or laboratories are usually induced around some impurities which act as catalysts or boiling stones. In cosmological phase transitions, black holes may play such roles. In this manuscript we discuss a cosmological phase transition around an evaporating black hole to show that a wormhole-like configuration with an inflationary domain beyond the throat may be created after the transition.

The study of a phase transition around a black hole was pioneered by Hiscock [15]. More recently, Gregory, Moss and Withers revisited the problem [16]. They have observed that the black hole mass may change in the phase transition and calculated the Euclidean action taking conical deficits into account [16–18]. Moreover, a symmetry restoration activated by Hawking radiation [19,20] near a microscopic black hole has been investigated by Moss [21].

We consider a high energy field theory of a scalar field ϕ whose potential allows a thin-wall bubble solution of a metastable local minimum at $\phi = 0$ with the energy density ϵ^4 surrounded by the true vacuum with a field value ϕ_0 where the mass square is given by m^2. In such a theory Moss [21] argues that the symmetry is restored in the vicinity of the black hole horizon inside a thin wall bubble as the Hawking temperature, $T_H = M_{Pl}^2/(8\pi M_+)$, reaches the mass scale of the theory. Here M_+ and M_{Pl} are the black hole mass and the Planck mass, respectively. In the presence of plausible couplings of the relevant fields, he shows that the medium inside the bubble, where fields coupled to ϕ are massless, is thermalized with a temperature T which is substantially smaller than $m \sim T_H$. Then the free energy of the bubble configuration is given by

$$F(r,T) = \frac{4}{3}\pi r^3 \epsilon^4 + 4\pi r^2 \sigma - \frac{\pi}{18} q\tilde{m}^2 T^2 r^3 \quad (1)$$

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as a function of its radius r and T, where σ is the surface tension of the wall and $\tilde{m}^2$ denotes sum of the mass squared of species which receive a mass from ϕ outside the bubble. For simplicity we assume $\tilde{m}$ is of the same order of m and omit the tilde hereafter. Here q is related to the scattering parameter C defined by Moss [21] as $q \equiv (192\pi^2 C)^{-2/3}$, which can take a value of order of unity or even larger.

The relation between the thermalized temperature T and the bubble radius r_w is obtained by solving the Boltzmann equations for the radiated beam particles and thermalized medium with the boundary condition that only particles with energy larger than m would escape the bubble wall, which reads

$$\frac{1}{216} q^{-3/2} T^3 r^3 + 48 m T r^2 e^{-\beta m} = 1, \tag{2}$$

at $r = r_w$ with $\beta \equiv T^{-1}$.

The radius of the wall r_w is obtained by minimizing the free energy (1) under the condition (2). For example, when the inequality

$$m r_w \gg 10^4 q^{2/3} (\beta m)^2 e^{-\beta m} \tag{3}$$

is satisfied and the first term dominates the left hand side of (2), we find $T = 6\sqrt{q}/r_w$, so that the free energy is minimized at

$$r = r_w = \sqrt{\frac{3q}{2}\frac{m}{\epsilon^2}}. \tag{4}$$

For consistency of this solution with (3), ϵ and m must satisfy

$$\frac{m}{T} = \frac{1}{6\sqrt{2}}\frac{m^2}{\epsilon^2} \gtrsim 10, \tag{5}$$

which we assume hereafter. Then the thin wall condition $m r_w = \sqrt{\frac{q}{2}\frac{m^2}{\epsilon^2}} \gg 1$ is naturally satisfied.

Under the condition (5) thermal energy inside the bubble is subdominant compared with ϵ^4, so the geometry inside the bubble can be described by the Schwarzschild de Sitter metric. Furthermore, as the radiation temperature increases in association with the increase of the Hawking temperature, more high energy particles, which escape from the bubble and do not contribute to support the wall, are created to lower the effect of the radiation pressure. Thus, contrary to naive expectation, thermal effects on the created bubble become less important as the temperature increases, which can be also understood from the inequality $dr_w/dT < 0$ derived from (2).

Thus the system can be approximated by a spherically symmetric thin wall with tension σ separating outside Schwarzschild geometry with mass parameter M_+ and inside Schwarzschild de Sitter geometry with vacuum energy density $\epsilon^4 \equiv 3M_{Pl}^2 H^2/(8\pi)$ whose mass parameter we denote by M_-.

We use the equation of motion of the wall obtained by Israel's junction condition to discuss quantum tunneling of the bubble to show that the final state is a wormhole-like configuration. Beyond the throat is a false vacuum state which inflates to create another big universe. Then one may regard that the final fate of an evaporating black hole is actually another universe. We do not take thermal effects to tunneling into account, as they would only enhance the tunneling rate.

We label the inner Schwarzschild de Sitter geometry with a suffix $-$ and outer Schwarzschild geometry with a suffix $+$. Then the outer and inner metrices are given by

$$ds^2 = -f_\pm(r)dt^2 + \frac{dr^2}{f_\pm(r)} + r^2 d\Omega^2, \tag{6}$$

$$f_+(r) \equiv 1 - \frac{2GM_+}{r}, \quad f_-(r) \equiv 1 - \frac{2GM_-}{r} - H^2 r^2.$$

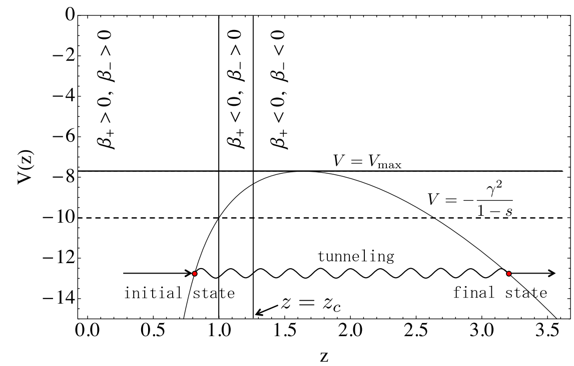

Fig. 1. Shape of the potential $V(z)$ as a function of z with $s = 0.9$. We have taken $\gamma = 1$ for illustrative purpose, although we actually expect $\gamma \ll 1$ for $\phi_0 \ll M_{\rm Pl}$. β_+ changes its sign at $z = 1$, and β_- at $z = (1 - \gamma^2/2)^{-1/2} \equiv z_c$.

We describe the wall trajectory in terms of the local coordinates $(t_\pm(\tau), r_\pm(\tau), \theta, \varphi)$ on each side depending on the proper time τ of an observer on the wall. They satisfy

$$f_\pm(r_\pm)\dot{t}_\pm^2(\tau) - \frac{\dot{r}_\pm^2(\tau)}{f_\pm(r_\pm)} = 1, \tag{7}$$

where a dot denotes derivative with respect to τ. We take the radial coordinates so that the radius of the bubble is given by $R = r_+ = r_-$ in both outer and inner coordinates. The evolution of the bubble wall is described by the following equation [16,22,23] based on Israel's junction condition [24]

$$\beta_- - \beta_+ = 4\pi G\sigma R \equiv \Sigma R, \tag{8}$$

where $\beta_+ \equiv f_+ \dot{t}_+ = \pm\sqrt{f_+ + \dot{R}^2}$ and $\beta_- \equiv f_- \dot{t}_- = \pm\sqrt{f_- + \dot{R}^2}$. From (8) we find the wall radius satisfies the following equation similar to an energy conservation equation of a particle in a potential $V(z)$.

$$\left(\frac{dz}{d\tau'}\right)^2 + V(z) = E, \ V(z) \equiv -\frac{1}{1-s}\frac{\gamma^2}{z} - \left(\frac{1-z^3}{z^2}\right)^2, \tag{9}$$

$$E \equiv -\frac{\gamma^2}{[2GM_+\chi(1-s)]^{\frac{2}{3}}}, \ \chi \equiv (H^2 + \Sigma^2)^{\frac{1}{2}}, \gamma \equiv \frac{2\Sigma}{\chi}. \tag{10}$$

Here dimensionless coordinate variables are defined by

$$\tau' \equiv \frac{\chi^2 \tau}{2\Sigma}, \ z^3 \equiv \frac{\chi^2 R^3}{2GM_+(1-s)}, \ \text{with } s \equiv \frac{M_-}{M_+}. \tag{11}$$

As is seen in Fig. 1, the potential $V(z)$ has a concave shape with the maximum $V(z_m) \equiv V_{\rm max}$ given by

$$V_{\rm max} = -3\frac{z_m^6 - 1}{z_m^4}, \tag{12}$$

with

$$z_m^3 = \left[2 + \left(\frac{1}{2} - \frac{\gamma^2}{4(1-s)}\right)^2\right]^{\frac{1}{2}} - \left(\frac{1}{2} - \frac{\gamma^2}{4(1-s)}\right), \tag{13}$$

for $s < 1$. From (8) we also find

$$M_+ = M_- + \frac{4\pi}{3}R^3\epsilon^4 + 4\pi R^2 \sigma \frac{\beta_+ + \beta_-}{2}. \tag{14}$$

We may consider the evolution of the system taking the initial condition that the bubble is at rest at $R = r_w$ as the Hawking temperature has increased to above m so that thermal support on the