Vacuum Selection by Collapsing

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Abstract. In this talk, we discuss the possibility that the vacuum is dynamically determined in the history of the universe. The point is that some of the bubbles with a certain vacuum shrink by the evolution of the universe via gravity and may become black holes. It is interesting that in many cases false vacua are favored in the context of cosmology. By using this argument, supersymmetry (SUSY), if it exists, can be broken cosmologically. This talk is based on Ref. [1].

INTRODUCTION

Our motivation of this work is to understand the elementary particle physics, especially beyond the standard model. Usually elementary particle physicists expect to know the physics beyond the standard model by the experiments on particle physics (or for some people, by mathematical consistency). However, it may happen that the past of our universe gives some clues to explain some features of the rule of the nature (physics) as the past of human beings plays important roles in their behaviors. In this talk, we examine the possibility that the cosmology selects theories of elementary particle physics. Of course, it has been argued that the cosmology gives some constraints to the theory of the elementary particle physics in order not to break the success of the standard cosmology. For examples, the number of massless neutrinos must be around three in order to realize the Big Bang Nucleosynthesis. But such usual requirements are only constraints. Such an argument never explain why the number of neutrinos is three. We discuss the possibility that the cosmology explains something on the elementary particle physics. The point is following. The elementary particle theories determine the evolution of the universe. Some universes are expanding and other universes are shrinking. As the result, there are universes with various lifetimes. It is natural to expect that our universe has a tendency to have the features which the universes with longer life have.
But as you know the universe is only one. What does many universes mean? The answer in this talk is following. In the phase transition, generally there are several local or global minima. At that time, the many bubbles with different vacua can exist. Different vacua mean different physics, and different physics leads to different evolution of the universe. As the result, selection of the vacua occurs. Some bubbles may expand rapidly and dominate the universe, and other bubbles may shrink and disappear or become black holes.

There are lots of papers on the selection of the vacua [2–4] in the context of the inflation after the work on the chaotic inflation by Linde, but as long as I know, there are only a few papers on the selection of the vacua by recollapsing [4]. Banks et al discussed the selection only in the special case in the context of the string moduli problem.

Here we discuss the more general cases, in which the vacuum selection by recollapsing happens, because it is more important in the context of the selection of the theory. And we examine the features of the black holes which may appear as the Fossils. In the last of this talk we try to apply this argument to the elementary particle physics, especially to SUSY model.

VACUUM SELECTION

In this section we argue on the possibility that collapsing bubbles and expanding bubbles exist simultaneously, namely vacuum selection by recollapsing happens.

It is not easy to understand the evolution of the universe in phase transition, because the universe is essentially not homogeneous nor isotropic. Therefore we adopt the following simplifications.

The first assumption is that we use the Friedmann equation for the evolution of the bubble universes. We expect that the size of the bubbles is so large, maybe the Hubble scale, that the space in the bubble is almost homogeneous and isotropic.

The second assumption is that the phase transition does not change the energy density. This is only for the simplicity.

Under the first assumptions, we obtain the typical time scale of recollapsing for various cases in table 1.

| $\Lambda$ | $\Omega_I > 1$ | $\Omega_I = 1$ | $\Omega_I < 1$ |
|-----------|----------------|----------------|----------------|
| $\Lambda > 0$ | inflation | inflation | inflation |
| $\Lambda = 0$ (radiation dominated) | $O(t_I)(\Omega_I - 1)^{-3/2}$ | $\infty$ | $\infty$ |
| $\Lambda = 0$ (matter dominated) | $O(t_I)(\Omega_I - 1)^{-1}$ | $\infty$ | $\infty$ |
| $\Lambda < 0$ | $(O(t_I))$ | $(O(t_I))$ | $O(t_I)$ |

Table 1. The lifetime for recollapsing

Here $\Omega_I$ is the ratio of the density to the critical density at the initial time $t_I$. We can easily find several examples in which some of bubbles are recollapsing and others are expanding. For example, consider the following situation. The universe has the larger energy density than the critical density at the time $t_{\text{PPT}}$ when the
phase transition occurs. Before the phase transition, the potential has only one minimum, but after the phase transition, the potential has one global minimum with vanishing cosmological constant and the other minimum which is local. The bubble universe with the true vacuum recollapses because the energy density is larger than the critical density. The time scale for the recollapsing is $O(t_T)$ unless the energy density is tuned to the critical density. On the other hand, the bubble universe with the false vacuum inflates if the cosmological constant dominates the energy density before reaching the time when the bubble begins to shrink.

In order to regard the inflating universe as our universe, the inflation must stop some time because our universe does not inflate at present, namely cosmological constant must vanish till now. Here we expect that there is an unknown mechanism which realizes the vanishing cosmological constant. And such a mechanism automatically stop the inflation and the vacuum energy is released in the universe (reheating). Of course we have no reliable mechanism for the vanishing cosmological constant, so we do not discuss more on how to stop the inflation here.

It is interesting that the evolution of the universe prefers local minima in many cases, in contrast with the common sense that the physics prefers less energy state like the global minimum. Actually the local minimum is unstable in the context of the ordinary field theory. The lifetime of the unstable vacuum is estimated by using instanton calculation which was discussed by Coleman [5]. The condition for longer lifetime than the age of our universe ($\sim 10^{20}$ seconds) gives $10^{200} \Lambda^4 / (\text{GeV})^4 \leq e^{S(\bar{\phi})}$, where $S(\bar{\phi})$ and $\Lambda$ are the action of the scalar $\phi$ and the typical scale of the potential, respectively. Here $\bar{\phi}$ is an instanton solution. When the difference of the potential energy between the two minima $\Delta V$ is much smaller than the typical scale $\Lambda^4$, then we get $S(\bar{\phi}) \sim 2\pi^2 O(1)/\epsilon^3$, where $\Delta V \sim \epsilon \Lambda^4$. Therefore $\epsilon \sim 1/10$ is small enough to satisfy the above condition. This situation seems not to require strong fine tuning, or rather it is not natural that a scalar potential has no local minimum with the above feature. Therefore we think that it is not unnatural that we are living in a false vacuum.

### PRIMORDIAL BLACK HOLES

If the recollapsing bubbles exist in our present horizon, these may become black holes. Here we make a simple argument for the bubbles with horizon size radius at the phase transition, because this is a typical scale in the context of cosmology.

The total mass of the bubble can be estimated from the size of the bubbles and the energy density. We have already taken the horizon length as the size of the bubbles. Since the bubble is recollapsing soon after the phase transition, the density is simply estimated by the phase transition temperature. Therefore in such case, the mass of the bubble becomes horizon mass at the phase transition; $M_{\text{Bubble}} \sim \rho H^3 \sim m_P^3/T_{PT}^2$. The Schwarzschild radius for the mass can be estimated as $R_S \sim 1/H$. It is surprising that the Schwarzschild radius is the same order of the magnitude of the horizon length. Therefore we can expect that the bubbles will
become black holes. Notice that the density outside the bubbles becomes smaller than the inside density in contrast with the usual situation in which the density of the universe is totally homogeneous and there is no special region like black holes.

The black holes evaporate by the Hawking radiation. The lifetime is estimated as \( \tau_{BH} \sim 2560 \pi G^2 M_{BH}^4 / g^* \sim 2560 \pi M_{BH}^5 / (g^* T_{PT}^6) \). Here \( g^* \) is the number of freedom at the temperature. As the summary, see table 2.

| \( T_{PT} \) (GeV) | \( 1 \) | 100 | 10\(^9\) | 10\(^{12}\) | 10\(^{19}\) |
|---------------------|--------|------|--------|--------|--------|
| \( M_{BH} \) (g)   | \( O(10^{34}) \sim O(M_{Solar}) \) | \( O(10^{29}) \) | \( O(10^{15}) \) | \( O(10^9) \) | \( O(10^{-5}) \) |
| \( T_H \) (GeV)    | \( O(10^{-21}) \) | \( O(10^{-17}) \) | \( O(10^{-5}) \) | \( O(10^6) \) | \( O(10^{14}) \) |
| \( \tau_{BH} \) (s) | \( O(10^{74}) \) | \( O(10^{62}) \) | \( O(10^{20}) \sim \tau_0 \) | \( O(1) \) | \( O(10^{-42}) \) |

Table 2. Here \( M_{Solar} \) is the solar mass and \( \tau_0 \) is the age of our universe.

When the temperature of the phase transition is smaller than \( 10^9 \) GeV, we may find the small black holes in our universe. Actually Massive Astrophysical Compact Halo Object (MACHO)s with the solar mass were discovered by gravity lensing effect [6]. It is interesting that the mass scale is related with the QCD phase transition. When the temperature of the phase transition is larger than \( 10^9 \) GeV, the black holes evaporate until now. Global minima disappear in the history and only the universe with the local minima is realized.

**COSMOLOGICAL SUSY BREAKING**

If SUSY exists, the scalar potential also exists. Generally the scalar potential has local minima with longer life than the age of our universe. Since the cosmology prefers the local minima, it seems to be natural that the SUSY is spontaneously broken cosmologically even if the scalar potential has SUSY vacua. We call this phenomenon cosmological SUSY breaking.

The natural scale will be the scale of the typical scale of the potential. If SUSY exists at the Planck scale, the Planck scale is the natural scale for the SUSY breaking. Of course our argument is strongly dependent on the initial conditions, so we can consider the case of lower SUSY breaking scale. By using cosmological SUSY breaking, we can make a simpler model [1] in which SUSY is cosmologically broken and the SUSY breaking is mediated by the standard gauge interactions. The point is that these models are allowed to have SUSY vacua.

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