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Z_2 massive axions, domain walls and inflation

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ABSTRACT

We have analyzed a $U(1)$ model which is broken explicitly to a Z_2 model. The proposal results in generating two types of stable domain walls, in contrast with the more common $N_{DW} = 1$ version which is already used to explain axion invisibility for the $U_{PQ}(1)$ model. We have tried to take into account any possible relation with previous studies. We have studied some of the domain properties, proposing an approximate solution which satisfies boundary conditions and the static virial theorem, simultaneously. Invoking the mentioned approximation, we have been able to obtain an analytical insight about the effect of parameters on the domain wall features, particularly on their surface energy density which is of great importance in cosmological studies when one tries to avoid domain wall energy domination problem. Next, we have mainly focused on the likely inflationary scenarios resulting from the model, including saddle point inflation, again insisting on analytical discussions to be able to follow the role of parameters. We have tried to relate inflationary scenarios to the known categories to take advantage of the previous detailed studies under the inflationary topic over the decades. We have concluded that any successful inflationary scenario requires large fields within the present model. Calculations are mainly done analytically, although numerical results are also obtained to reinforce the analytical results.

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1. Introduction

Recent observations have reached an unprecedented accuracy that has to be taken into account in any cosmological modeling [1–4]. Nowadays, we have enough discriminating data to investigate the practicability of a proposed inflationary scenario precisely [5,6]. It is widely believed that the recent Planck data favors the simplest inflationary models consisting of a single field slow-roll [6]. Although alternative inflationary models always remain in the valid domain [7], many of them have been ruled out due to incorrect predictions particularly in the density perturbation spectral index on the CMB as well as the power of primordial gravitational waves [2]. This decisive information is at our disposal now, thanks to several experiments and decades of rehearsing on the issue. Simultaneously, we are witnessing remarkable experiments in particle physics and quantum field theory. No one can doubt that cosmology and quantum field theory are tightly bound and any achievement in one of them must be considered as a clue for the other. There are many attempts to find a QFT motivation as a decisive sign of an acceptable inflationary scenario [8–10] and conversely, the capability of a QFT paradigm to include the inflation, is supposed as a supportive sign for the paradigm [11,12]. On the other hand, after experimental confirmation of the Higgs boson existence, the last predicted particle of the standard model [13,14], there are more attention on the inflationary capability of symmetry breaking scenario [13,15–18]. The measured Higgs mass in the LHC also raised another problem: the Higgs mass and the top quark mass together increase the chance of a metastable vacuum for the electroweak theory [19–21].

Topologically, a discrete vacuum means domain wall production if the symmetry breaking is **perfect** [22–24]. We have known after Zeldovich's 1975 paper [25] that domain walls are drastically in contradiction with the observed cosmic mean energy density unless the domain wall energy density is low enough. Such low energy scales never provide appropriate outline for a successful inflation although the CMB residual dipole anisotropy might be explained using them [26]. The domain wall problem also appears when one tries to solve the strong CP problem by means of introducing a new axion field [27]. Indeed, to explain invisibility of axions due to their weak coupling to matter one could hypothesize more quark species than the usual standard model quarks, or assume two Higgs doublets. The latter case is more appealing in quantum field theory since it offers the modest possible extension to the standard model. Moreover, the need of explaining the mass of dark matter put the multi-Higgs theories under the spotlight. Assuming a two doublet Higgs scenario, one inevitably encounters even number of domain walls separated by strings. The number of appearing domain walls are two times the number of the generators. If the energy scale of domain walls is high enough such that domain wall production precedes the inflation, then one has an explanation for not observing such walls, like what happens for magnetic monopoles. Domain walls also could leave no significant remnant in the later stages if they disappear soon enough. There are some known mechanisms for destructing a domain wall which could operate alone or in combination with each other [28]. The most famous one is assuming a metastable domain wall which automatically tends to ruin it [28,29]. Of course, the decay time could be very long, for example the decay time of electroweak metastable vacuum, in the case of existence, is of the order of the age of the universe [21]. Potentially, unstable domain walls are also among the best candidates for justification of baryogenesis. Amid the other options one can mention destabilizing a domain wall by another defect collision or embarking the symmetron mechanism [30]. There is a very interesting idea that mini black holes could trigger the electroweak vacuum decay in a similar way. On the other hand, one can generalize the natural inflation to include a dynamical modulus in addition to the proposed angular field dynamics. This generalization promotes $U_{PQ}(1)$ to the double field potential in which the $U(1)$ symmetry is broken to Z_n discrete symmetry [31]. In this regard, it is worth having an exhaustive analysis of the potential with explicit $U(R) \longrightarrow Z_n$ symmetry breaking, to know both the inflationary behavior and possible domain wall properties.

Here, we try a double field potential [32] with two discrete vacua as a model for domain wall formation and inflation, trying to avoid rendering numerical results before having an analytical picture. We therefore keep the track of the model parameters employing appropriate approximations. The assumed potential is very close to the original Higgs potential [33,34] except that the continuous $U(1)$ symmetry is now broken to a Z_2 symmetry with two discrete vacuua which produce domain walls [35]. To get more familiar with the domain wall properties which potentially could be produced

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