PROCEEDINGS OF SCIENCE

Cosmological defects

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Topological defects can play an important role in cosmology. In this short contribution I will discuss a less explored effect that arises in the context of first order phase transitions, by which defects can act as impurities catalysing the decay of the false vacuum. This dynamics actually takes place in one of the simplest extensions of the Standard Model, the xSM, where domain wall configurations associated to the new singlet scalar are shown to enhance the tunneling rate. This dramatically changes the way the electroweak phase transition proceeds, with implications for the corresponding spectrum of gravitational waves.

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1. Introduction

Topological defects may have formed throughout the history of the Universe [1–3] with important consequences for cosmology. Notable examples are the monopole problem in Grand Unified Theories [4], the possibility of mediating baryon number violation [5, 6], and non–thermal production of dark matter [7]. In this contribution, I will discuss another intriguing effect in the context of first order phase transitions, where topological defects can play the role of impurities, or seeds, catalysing the decay of the false vacuum [8–12]. In this case the probability of bubble nucleation is no longer homogenous in space, but can be strongly enhanced in the vicinity of the seeds.

Catalysis is in fact a very general mechanism, and the nature of the impurities can be vastly different depending on the relevant energy scales. In cloud chambers for example, charged particles streaming in a closed environment filled with supersaturated vapor act as seeds for condensation. In high–energy physics, black holes can similarly favor bubble nucleation [13, 14] thus shortening the lifetime of the metastable electroweak vacuum in the Standard Model (SM) [15].

Studies of this kind allow to exclude the presence of the seeds as they would lead to catastrophic contradictions with observations. In what follows, I will take a different approach and discuss the effect of seeded tunneling during thermal phase transitions in the early Universe, where impurities can lead to observable consequences in agreement with standard cosmology, e.g., in the stochastic background of gravitational waves (GWs). The following material is based on Refs. [16–18].

2. Electroweak phase transition via domain wall seeds

As a particularly motivated example, I will consider the electroweak phase transition (EWPT) by which the Higgs field acquires its vacuum expectation value at temperatures $T \sim 100$ GeV. While this process is predicted to be a smooth crossover in the SM [19], new physics at the electroweak scale can make the EWPT strongly first order, possibly allowing for baryogenesis as well as for the generation of an observable GW background [20].

The simplest new physics model that can turn the electroweak crossover into a first order transition is arguably the extended SM (xSM), where only a singlet scalar field, S, is added to the theory. As the new scalar is relatively light, it can be detected at colliders primarily through its mixing with the Higgs boson. Therefore, a Z_2 symmetry under which only S is odd is usually imposed to naturally suppress such a mixing, making this setup a "nightmare scenario" that can easily evade collider constraints [21].

The thermal history of the xSM is well established, see e.g. [22], and in a significant part of the parameter space the phase transition proceeds in two steps:

$$(h, S) = (0, 0) \to (0, \pm v_s) \to (v, 0), \tag{1}$$

so that the Z_2 symmetry is broken at the first step by the singlet S developing a non–zero vacuum expectation value, but is eventually restored when the system falls in the electroweak vacuum with $h = v$. This final step is actually the one of interest as it can be strongly first order.

The temporary breakdown of the Z_2 comes however with an additional implication, namely the formation of domain walls where the S field interpolates between the two possible disconnected vacua, $S = \pm v_s$ [2]. The crucial observation we are going to make is that the nucleation of bubbles

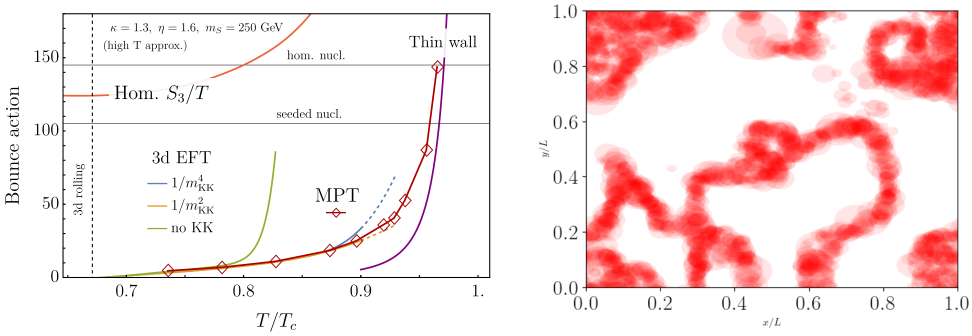

Figure 1: Left. Homogenous bounce $B_{\rm hom} = S_3/T$, and seeded bounce $B_{\rm s}$ evaluated with different methods, as a function of T normalized to the critical temperature, T_c. See text for more details. **Right.** 2D slice of seeded bubbles nucleated on the domain wall surface. Courtesy of Henrique Rubira.

of true vacuum in the final step of the transition happens with different probability depending on whether the bubble is close or far from the S domain walls. This can be quantified by defining a nucleation rate per domain wall surface [23], γ_S, as

$$\gamma_S = \sigma_{\rm DW} \exp(-B_{\rm s}(T)/T), \tag{2}$$

where $\sigma_{\rm DW}$ is the domain wall tension. The rate γ_S is controlled by the seeded bounce action $B_{\rm s}(T)$, and it is now a quantitative question to determine whether nucleation will first occur around the walls or deep inside the homogenous domains where $|S| = v_S$.

In answering this question, one has to take into account that seeded bubbles can only form on the domain wall surface rather than everywhere in space, and the corresponding nucleation condition is actually stricter. For the EWPT one finds $B_{\rm s} \lesssim 100$, whereas for the homogenous bounce around the same temperature one has $B_{\rm hom} = S_3/T \lesssim 145$. Despite this, seeded nucleation still dominates over the homogeneous one, as $B_{\rm s}$ can be largely reduced compared to $B_{\rm hom}$, as shown in Fig. 1 left for a representative benchmark. Here, the seeded bounce action $B_{\rm s}$ has been evaluated according to three different methods: within a 2+1 effective field theory living on the domain wall (solid lines from green to blue with increasing level of accuracy) [16], by the thin wall approximation in purple, and by directly solving the equations of motion with reduced symmetry (red diamonds) [18] with the help of the Mountain Pass Theorem (MPT) [24]. In fact, as the presence of the walls breaks rotational invariance, the seeded critical bubble will not be spherical but rather of ellipsoidal shape, complicating the computation of the corresponding action.

As we can see, these methods agree in their overlapping region of validity, providing a robust prediction for seeded nucleation happening at higher temperatures than the homogeneous one (identified as the point where the bounce action crosses the corresponding nucleation condition, $T^{\rm n}_{\rm seed}/T_c \sim 0.95$ vs $T^{\rm n}_{\rm hom}/T_c \sim 0.80$), thus determining the way the phase transition completes. Similarly, one can show that points in parameter space where homogeneous bubbles fail to nucleate can become phenomenologically viable once seeded tunneling is taken into account.

Let me now discuss the implications of this scenario for the GW spectrum generated in this last step of the transition. In addition to the seeded nucleation rate, $\beta_{\rm s} = \frac{{\rm d}B_{\rm s}}{{\rm d}t}|_{T=T^{\rm s}_{\rm n}}$, the DW network introduces a second scale in the problem given by the average distance between walls, $(\xi H)^{-1}$, where ξ is the average number of walls per Hubble volume. In the case of sparse networks where $\xi H/\beta \ll 1$, this second time scale controls the completion of the transition. Thus, many small bubbles will first merge on the surface of the walls, as shown in Fig. 1 right, and eventually expand as large planar bubbles until collision with the neighbor walls. The effective bubble size is therefore increased, and the corresponding GW signal is enhanced and shifted to lower frequencies [17].

3. Conclusion

I have discussed seeded nucleation in one of the simplest extensions of the SM where the electroweak phase transition is first order, the xSM with Z_2 symmetry. The role of catalysing seeds is played by the singlet domain walls formed in the first step of the transition. In fact, the tunneling rate around these walls turns out to be strongly enhanced compared to standard homogeneous nucleation, and eventually dictates how the transition completes. Differently from previous applications of catalysis, seeded nucleation can leave observable imprints in the gravitational wave spectrum, by shifting the peak to lower frequencies and enhancing the overall amplitude. The mechanism presented here is not limited to Z_2 domain walls, but applies more generally to multi–step phase transitions entailing the formation of transient defects, e.g. strings or monopoles, with still largely unexplored phenomenological implications.

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