How generic is cosmic string formation in supersymmetric grand unified theories

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We study cosmic string formation within supersymmetric grand unified theories (GUTs). We consider gauge groups having a rank between 4 and 8. We examine all possible spontaneous symmetry breaking patterns from the GUT down to the standard model gauge group. Assuming standard hybrid inflation, we select all the models which can solve the GUT monopole problem leading to baryogenesis after inflation, and are consistent with proton lifetime measurements. We conclude that, in all acceptable spontaneous symmetry breaking schemes, cosmic string formation is unavoidable. The strings which form at the end of inflation have a mass which is proportional to the inflationary scale. Sometimes a second network of strings form at a lower scale. Models based on gauge groups which have a rank greater than 6 can lead to more than one inflationary era; they all end by cosmic string formation.

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I. INTRODUCTION

The interface between high energy physics and cosmology is very fruitful. Both high energy physics and cosmology enter the description of the evolution of the early Universe, at microscopic and macroscopic levels, respectively. However, cosmological models such as inflation must originate from the particle physics model describing interactions of the constituents of the early Universe plasma. Cosmology provides the ground to test fundamental theories at energies far beyond the ones accessible by any terrestrial accelerator.

The particle physics standard model (SM) has been tested to a very high precision. However, evidence of neutrino masses [1–3] proves that one must go beyond this model. The simplest explanation of the data is that neutrinos get mass via the see-saw mechanism [4] which results from the breaking of some left-right symmetry. This is the first hint suggesting an extension of the SM gauge group, although this is not strictly needed since right-handed neutrinos could be present without invoking any extra gauge symmetry. At present, supersymmetry (SUSY) is the only viable theory for solving the gauge hierarchy problem. In addition, in the supersymmetric standard model the gauge coupling constants of the strong, weak, and electromagnetic interactions, with SUSY broken at the TeV scale, meet in a single point at around $M_{\rm GUT}\simeq(2-3)\times10^{16}$ GeV. This strengthens the idea that there may be a gauge group G with a single gauge coupling constant, which describes the interactions between particles above the scale $M_{\rm GUT}$. These are the so-called supersymmetric grand unified theories (SUSY GUTs). From the point of view of cosmology, SUSY GUTs can provide the scalar field needed for inflation, they can explain the matter-antimatter asymmetry of the Universe, and they can provide a candidate for cold dark matter, namely, the lightest superparticle.

An acceptable SUSY GUT model should be in agreement with both the standard model and cosmology. The grand unified gauge group must be broken at the GUT scale down to the standard model gauge group. The GUT gauge group must therefore contain the SM gauge group $SU(3)_C\times SU(2)_L\times U(1)_Y$, and it must predict the phenomenology that has been observed at accelerators [5]. Constraining SUSY GUTs at accelerators is a challenge which will be undertaken in the future. On the other hand, even if accelerators can find SUSY particles and constrain the minimal supersymmetric standard model (MSSM), they will probably say only very little about GUTs and symmetry breaking patterns. Luckily, a number of new astrophysical data can be used to constrain the various schemes of spontaneously symmetry breaking (SSB) from a grand unified gauge group down to the standard model.

In building SUSY GUTs, one faces the appearance of undesirable stable topological defects, mainly monopoles, but also domain walls, according to the Kibble mechanism [6]. To get rid of the unwanted topological defects, one employs the mechanism of inflation. Inflation is also the most promising mechanism for generating density perturbations which lead to structure formation and cosmic microwave back-

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ground (CMB) temperature anisotropies, as confirmed by the recent Wilkinson microwave anisotropy probe measurements [7]. On the other hand, inflation usually requires fine-tuning of its parameters, leading to the naturalness issue. These fine tuning problems can be circumvented in SUSY models. In principle, we could build an inflationary scenario using a random scalar field with a given potential, which has nothing to do with either the SM or a gauge theory containing the SM. This could come, for example, from a hidden sector. An interesting possibility is that inflation comes from extensions of the SM, such as a GUT model, which is then self-consistent: monopoles form, inflation originates from the GUT itself and solves the monopole problem, and in addition it fits with CMB data, as well as other data such as the baryon asymmetry which is generated by oscillations of the inflaton field. Models along these lines have been constructed [8–10]. This scheme is the philosophy which we follow here.

Given an inflationary scenario, we investigate the topological defects which may be produced at subsequent phase transitions. We consider all possible symmetry breaking schemes and examine which kind of topological defects are left after inflation, if any. In all schemes, only local topological defects can arise, since we only consider gauge symmetries. If monopoles or domain walls are produced after inflation, then these SSB patterns are discarded, since these defects should have closed the Universe. The only acceptable SSB patterns are those which, after the inflationary stage, either lead to the formation of cosmic strings or to no defects at all. If cosmic strings (topological defects) are formed, we should examine their type (Nambu-Goto strings, superconducting strings) and then check their compatibility with the constraint coming from the recent measurements of the CMB temperature anisotropies [7,11]. If embedded strings are formed, then we should examine their stability. (They are in general unstable under small perturbations.) The symmetry breaking patterns leading to the formation of textures cannot be constrained, since local textures decay very fast [12] and therefore play no role in cosmology.

We organize the rest of the paper as follows: In Sec. II, we discuss the theoretical framework of our study. We discuss the various kinds of topological defects which may form, and the criterion for their formation. We briefly review the standard model for inflation in SUSY GUTs, and we comment on leptogenesis. In Sec. III, we discuss the choice of the gauge groups which we consider. In Sec. IV, we list all possible SSB patterns from the selected GUT gauge groups down to the standard model gauge group. We review the most common embeddings of the standard model in each GUT. Each embedding leads to specific SSB patterns. We list them all, giving the type of defect which is formed at each phase transition. We then discuss which of the SSB patterns are allowed from cosmology and we count for each group the number of schemes where strings are formed after inflation, as compared to the number of schemes with no defect. We round up with our conclusions in Sec. V. Finally, in the Appendix, we list the maximal subalgebras which we employ for the groups considered in our study.

II. THEORETICAL FRAMEWORK

A. Topological defects

The assumption of a GUT implies that our Universe has undergone a series of phase transitions associated with the spontaneous symmetry breaking of the GUT gauge group $G_{\rm GUT}$ down to the standard model gauge group $G_{\rm SM} = \mathrm{SU}(3)_{\rm C}\times \mathrm{SU}(2)_{\rm L}\times \mathrm{U}(1)_{\rm Y}$ at $M_{\rm GUT}\sim 3\times 10^{16}$ GeV. The last phase transition of the SSB pattern is the electroweak phase transition which takes place at $M_{\rm EW}\sim 10^2$ GeV as $G_{\rm SM}$ breaks down to $\mathrm{SU}(3)_{\rm C}\times \mathrm{U}(1)_{\rm Q}$. There might be one, more than one, or none intermediate symmetry group between $G_{\rm GUT}$ and $G_{\rm SM}$. The important cosmological consequence of these SSB schemes is the formation of topological defects via the Kibble mechanism [6].

If we have a system with a topologically nontrivial vacuum manifold, then fields in different spatial regions fall into different ground states, and thus SSB may be followed by the emergence of a network of topological defects during the associated phase transition. (For a review on topological defects the reader is referred to Refs. [13,14].) This leads to the GUT monopole problem: all GUTs based on simple gauge groups lead to the formation of topologically stable monopoles whose density is about 10^{18} times greater than the experimental limit. Homotopy theory tells us that topologically stable monopoles always form. Moreover, a wide variety of other defects may also form, leading to important astrophysical and cosmological implications.

In this paper, we study the formation of topological defects in realistic GUTs considering all possible SSB patterns of a given group. Allowing for standard hybrid inflation we can then throw away all schemes which lead to the formation of unwanted defects and check whether strings form at the end of inflation or after inflation has completed.

Let us consider the symmetry breaking of a group G down to a subgroup H of G. In order to see whether topological defects form during the phase transition associated with the breaking of G down to H, we can study the homotopy groups $\pi_{\rm k}(G/H)$ of the vacuum manifold $\mathcal{M}_n = G/H$. If $\pi_{\rm k}(G/H) \neq 0$, then topological defects are formed; if $k=0$ then domain walls form, if $k=1$ then cosmic strings form, if $k=2$ then monopoles form, and if $k=3$ then textures appear.

Spontaneous symmetry breaking patterns which lead to the formation of monopoles or domain walls are ruled out since they are incompatible with our Universe, except if an inflationary era took place after their formation. The reason why monopoles and domain walls are undesirable, is that in both cases they soon dominate the energy density of our Universe and close it. The textures are not studied in this work because in the local case, their relative contribution to the energy density of the Universe decreases rapidly with time [12]. Thus, we cannot constrain SSB patterns with textures because they cannot play a significant role in cosmology.

In addition to topological defects, a gauge field theory may have nontopological defects. It is possible to obtain a submanifold $\mathcal{M}_m (m<n)$, of the original vacuum manifold $\mathcal{M}_n$, by freezing out some combinations of the original fields. If the topology of $\mathcal{M}_m$ is such that the theory admits

topological defects, then one can create configurations of the unconstrained fields which correspond to topological defects. Provided these configurations satisfy the equations of motion of the unconstrained theory, then embedded defects appear [15,16]. More precisely, if we have a symmetry breaking $G \to H$ and $G_{\rm emb} \to H_{\rm emb}$, with $G_{\rm emb} \subset G$ and $H_{\rm emb} \subset H$, we examine whether $\pi_k(G_{\rm emb}/H_{\rm emb}) \neq 0$, which is the criterion for the appearance of embedded $(2-k)$-dimensional defects.

Embedded defects are not topologically stable and in general they are not dynamically stable either [17]. However, a number of mechanisms have been proposed in the literature, which may stabilize the embedded strings and therefore, they may play an important role in cosmology. For example, the pion string in the theory of strong interactions, and the electroweak Z string in the standard electroweak theory can be stabilized in the early Universe via finite-temperature plasma effects [18]. In addition, an electroweak Z string can be also stabilized by the presence of bound states of a complex scalar field [19]. Embedded gauge monopoles always suffer [20] from a long range instability (the Brandt-Neri-Coleman instability [21]), and therefore, we do not consider them.

B. Inflation in supersymmetric unified theories

Inflation is at present the most appealing theory which describes the early Universe. Inflation essentially consists of a phase of accelerated expansion which took place at a very high energy scale. Even though only special initial conditions eventually lead to successfully inflationary cosmologies, it has been argued [22] that these initial conditions are precisely the likely outcomes of quantum events occurred before the inflationary era. Thus, inflation is itself generic [22]. In addition, when the principles of quantum mechanics are taken into account, inflation provides a natural explanation for the origin of the large scale structures and the associated temperature anisotropies in the CMB radiation [23]. With the increasing data on the CMB, which seem to confirm an early inflationary era [7], one needs to find the most natural framework for inflation which can match the data. Inflation is most naturally realized in SUSY models. (For a review on inflation in SUSY models the reader in referred to Ref. [24].) The most natural scenario for inflation, up to date, is the so-called standard hybrid inflation. (The reader is referred to Refs. [25–27].)

Let us summarize how inflation arises naturally in SUSY GUTs based on gauge groups with rank greater or equal to 5. By naturally we mean that neither extra field nor any extra symmetry, is needed for inflation except those needed to build the GUT itself. In order to satisfy COBE data the inflationary scale has to be $\sim 10^{15.5}$ GeV [27] which is close to the GUT scale. Note that the problem of initial conditions is not completely solved, but the argument is that all the fields would come out from the quantum gravity period taking values which are of the order of the cutoff scale of the ultimate theory, which can be taken to be the Planck scale $M_{\rm Pl}$ or the string scale [28]. The horizon problem is solved for coupling constants of the order of 10^{-2}. The spectral index is predicted to be very close to one (we usually get $n \simeq 0.98$). Supergravity (SUGRA) corrections can be kept small [29].

The superpotential for hybrid inflation in SUSY GUTs is given by

$$W = \alpha S \bar{\Phi} \Phi - \mu^2 S, \tag{2.1}$$

where S is a GUT singlet, $\bar{\Phi}$ and Φ are GUT Higgs fields in complex conjugate representations which lower the rank of the group by one unit when acquiring nonzero vacuum expectation value (VEV), and α and μ are two constants (μ has dimensions of mass) which can both be taken to be positive with field redefinition. The superpotential given in Eq. (2.1) is the most general superpotential consistent with an R-symmetry under which $W \to e^{i\beta} W$, $\bar{\Phi} \to e^{-i\beta} \bar{\Phi}$, $\Phi \to e^{i\beta}\Phi$, and $S \to e^{i\beta}$.

The potential has two minima: one valley of local minima, for S greater than its critical value $S_c = \mu/\sqrt{\alpha}$, $\bar{\Phi} = \Phi$, and one global supersymmetric minimum ($V=0$) at $S=0$ and $\bar{\Phi} = \Phi = \mu/\sqrt{\alpha}$. Imposing chaotic initial conditions, i.e., $S \gg S_c$, the fields quickly settle down the valley of local minima. The potential $V = \mu^4 \neq 0$ and inflation can take place. SUSY is broken and the one-loop corrections to the effective scalar potential can be calculated [27]. This gives a little tilt to the scalar potential which helps the scalar field S to slowly roll down the valley of minima. The last 50 or so e-folds of inflation take place much below the Planck scale. When S falls below its critical value S_c, inflation stops by a waterfall regime, and the fields quickly settle down to the global minimum of the potential and supersymmetry is restored. SSB occurs at the end of inflation ($\bar{\Phi}$ and Φ acquire nonzero VEVs after inflation, or at most during the last e-fold; this is GUT model dependent). This is very important for cosmology because it implies that topological defects (if any) form at the end of inflation with a mass per unit length $\propto \mu/\sqrt{\alpha}$. Henceforth neither monopole nor domain walls should be associated with the SSB induced by the $\bar{\Phi}$ and Φ VEVs. They should not form at any subsequent phase transition either. We shall use this argument to constrain all SSB of a given $G_{\rm GUT}$. It was already done for supersymmetric SO(10) models [30]. It was found that among all the SSB patterns from SO(10) down to the standard model gauge group involving at most one intermediate symmetry breaking scale, only three are in agreement with observations. The proton is "stable" (R parity is conserved) and no unwanted defects form after inflation. In all these three SSB patterns, cosmic strings form at the end of inflation. They imply a mixed scenario with inflation and cosmic strings to account for the CMB temperature anisotropies. We shall generalize this to all GUTs predicting neutrinos masses via the see-saw mechanism.

Let us comment on CMB anisotropies from inflation and cosmic strings in SUSY GUTs models. In these scenarios, the multipole moments C_l add quadratically and they are proportional to the same scale $\Lambda_{\rm infl} = \mu/\sqrt{\alpha}$ with a proportionality constant which is model dependent [31]. This can be rewritten as $C_l^{\rm tot} = (1-x) C_l^{\rm infl} + x C_l^{\rm str}$, where $C_l^{\rm infl}, C_l^{\rm str} \propto (\Lambda_{\rm infl}/M_{\rm Pl})$. Here x depends on the CMB normalization for each scenario, on the coupling constant α of the trilinear term $\alpha S\bar{\Phi}\Phi$ in Eq. (2.1), on the dimension of Φ, and on the GUT itself. Local cosmic string predictions are unfortunately not very well established in detail and range from an almost flat spectrum [32] to a single wide bump at $\ell\sim500$ [33] with extremely rapidly decaying tail. Recent numerical simulations of local string networks [34] confirm the existence of a bump at around $\ell\sim600$. It seems that the microphysics of the string network plays a crucial role in the height and in the position of the bump [35,36]. Studies of mixed perturbation models (inflation + cosmic strings) impose strong constraints on the maximum contribution of the string network [33,11]. The initial condition is also not taken into account. (The distribution of strings forming at the end of inflation and their microstructure may be very different from those concerning strings formed at standard phase transitions.) What we can conclude is that the effect of cosmic strings on the CMB power is to lower the height of the first acoustic peak, and to displace it to smaller angular scales, as well as to wash out any secondary peaks [37]. In addition, topological defects induce non-Gaussian statistics, due to their nonlinear evolution [37].

So far, we have been discussing F-term inflation. D-term inflation [38] requires the existence (in addition to the GUT) of a U(1) factor with a nonvanishing Fayet-Iliopoulos term which can only appear if $\mathrm{Tr}Q\neq0$, where Q stands for the U(1) charge [39]. D-term inflation occurs in the following way: If one assumes an appropriate set of discrete and continuous symmetries, the linear term in Eq. (2.1) can be forbidden. The VEV of the fields $\bar{\Phi}$ and Φ can be then forced to equal the Fayet-Iliopoulos term which also sets the scale of inflation. This is the so-called D-term inflation [40]. The main advantage of D-term inflation is that it works for general Khäler potentials. However, if this extra U(1) is anomalous coming from string theory (this would be the best way to justify its presence), the F term is calculated using the Green-Schwarz mechanism and would be at the string scale which is far too high for inflation. At the end of D-term inflation cosmic strings always form. [This is easy to understand since we are breaking a U(1) gauge symmetry.] In this case they satisfy the Bogolomny bound and their contribution to C_l's is $x=0.75$ [31]. The string contribution is smaller in the F-term case [31] and as mentioned above, model dependent. We conclude that D-term inflation is not consistent with observations [11], but it does not concern us anyway, since we are interested in GUTs based on simple gauge groups.

Since topological defects always form at the end of standard hybrid inflation, it is easy to conclude that at least one intermediate symmetry breaking is needed between G_{GUT} and G_{SM}. One way to avoid the monopole problem in single step breaking GUTs is to consider the first nonrenormalizable term in Eq. (2.1) [8]. Its effect on the scalar potential is to ''shift'' the inflationary valley of local minima to a valley in which the GUT Higgs fields have already a nonvanishing VEV, implying that the GUT is already broken during inflation so that no topological defects form at the end of inflation [8,9]. Note that nonrenormalizable terms of all orders are in general present in the superpotential if no R symmetry is invoked to cancel them. However, their effect on the scalar potential is usually negligible. The way one can solve the monopole problem with SUSY GUTs hybrid inflation has been discussed in Ref. [10].

We thus assume standard hybrid inflation which can only occur when the rank of the group is lowered by (at least) one unit. We can then discuss how frequently cosmic strings form at the end of inflation with a mass proportional to the inflationary scale as discussed above, so that both inflation and cosmic strings contribute to the CMB temperature anisotropies. We point out that for GUTs based on gauge groups with rank strictly greater than 5, more than one stage of inflation can occur. This could lead to a multiple inflationary scenario with or without cosmic strings at each stage. If more than one stage of the SSB pattern lowers the rank of the group, there can be a succession of short bursts of inflation [41] which occur at different scales below the Planck scale and leave behind a distinctive signature in the spectrum of the generated scalar density perturbations [42]. In our scenarios, i.e., in the selected SSB which lead to various stages of inflation as well as to cosmic string formation at the end of each stage, multiple inflation combined with multiple string networks arises.

C. Leptogenesis

A cosmological scenario is incomplete if it does not discuss baryogenesis which has to occur after inflation has taken place. GUT baryogenesis is washed out by inflation and the window left for electroweak baryogenesis is very small. The most appealing scenario today for baryogenesis is that of leptogenesis [43] which requires nonzero neutrino masses. This scenario is strongly favored since the discovery of nonzero neutrino masses [1–3]. (For a review on baryogenesis scenarios and on the cosmological arguments which they render most of them unlikely, the reader is referred to Ref. [44].)

The most economical way for getting neutrino masses is the see-saw mechanism [4]. This requires the existence of SM gauge singlets (the right-handed neutrinos), which must get masses around $M_{\mathrm{R}}\sim10^{14}$ GeV from data on neutrino oscillations [1–3]. This means that there exist a superpotential mass term for the right-handed neutrinos of the form $M_{\mathrm{R}}N_iN_j$, where $i,j=1,2,3$ and M_{R} is a 3×3 mass matrix. The N_i's are SM singlets which couple with the MSSM lepton doublets L and electroweak up-type Higgs H_{u} via the superpotential term $h_{ij}l_iH_{\mathrm{u}}N_j$, where h_{ij} is a 3×3 complex Yukawa matrix. This gives rise to a nonzero mass matrix M_ν for the left-handed neutrinos. The basic idea of leptogenesis [43] is that when the Universe cools down and its temperature falls below $T\sim M_{\mathrm{R}}$, the right-handed (s)neutrinos stop being in thermal equilibrium with the surrounding plasma and decay into (s)leptons and electroweak Higgs (higgsinos); lepton number and CP are violated [45]. A net lepton asymmetry is produced which is then transformed into a baryon asymmetry via sphaleron transitions, which are effective between 10^{12} and 10^2 GeV [46]. The reheating temperature in supersymmetric models is bounded by above, i.e., $T_{\mathrm{RH}}<10^{10}$ GeV, to avoid an overproduction of gravitinos which would overclose the Universe.

The most effective way for leptogenesis is therefore nonthermal. This happens for example if the inflaton field decays into right-handed neutrinos and sneutrinos (see, for example, Ref. [47]). The resulting lepton asymmetry is then proportional to the reheating temperature, inversely proportional to the inflaton mass, and depends on neutrino mass parameters. Constraints from successful inflation, reheating, and neutrino masses can be satisfied. In these scenarios, the right-handed neutrino masses come from a superpotential term $\kappa_{ij}\Phi N_i N_j$, where the GUT Higgs field Φ is identified with the GUT Higgs field entering the inflationary superpotential given in Eq. (2.1). This is the same Higgs field which breaks $B-L$ (B and L are, respectively, baryon and lepton numbers) in GUTs, predicting right-handed neutrinos. Such GUTs contain a $U(1)_{B-L}$ gauge symmetry and the scale of neutrino masses is proportional to the $B-L$ breaking scale.

Another nonthermal process for leptogenesis is via decaying $B-L$ cosmic strings [48]. The Higgs field responsible for string formation is the same Higgs field which is used to break $B-L$. Since it gives mass to the right-handed neutrinos, there are right-handed neutrino zero modes trapped in $B-L$ cosmic string cores. These are released when cosmic string loops decay and leptogenesis takes place. If the superpotential given in Eq. (2.1) is used for inflation, as well as to break $B-L$, then $B-L$ cosmic strings form at the end of inflation. Such models were discussed in Ref. [49]. In this case both processes contribute to the lepton asymmetry of the Universe: the nonthermal process from reheating after inflation and the decay of cosmic strings.

In any case, the SSB patterns which can explain the baryon asymmetry of the Universe have the $B-L$ gauge symmetry broken at the end or after inflation. If inflation takes place at the $B-L$ breaking scale, both nonthermal scenarios will compete, somehow in the same way that both strings and inflation can contribute to CMB anisotropies. It would be very interesting to calculate in which proportion they contribute to the net baryon asymmetry of the Universe today.

III. GRAND UNIFIED THEORIES

GUTs can solve many of the SM problems, such as the quantization of the electric charge, the quarks and leptons masses, and the origin of neutrino masses. On the other hand, SUSY solves the gauge hierarchy problem. In the MSSM with SUSY broken at around 10^3 GeV the strong, weak, and electromagnetic gauge coupling constants run with energy and reach the same value at $M_{\rm GUT}\sim 3\times 10^{16}$ GeV. Hence SUSY GUTs can describe particle interactions at energies above $M_{\rm GUT}$ and it must be broken down to the standard model gauge group. In this section, we select GUT gauge groups which lead to the correct SM phenomenology without fine tuning [50–52].

A single value for the three gauge coupling constants of the standard model can be obtained with a simple group or with a group which is the direct product of n identical simple groups with the addition of a discrete symmetry Z_n. Simple groups are divided into four infinite families, $SU(n+1)$, $SO(2n+1)$, $Sp(2n)$, and $SO(2n)$, where n denotes the rank of the group. In addition there are five simple exceptional groups, G_2, F_4, E_6, E_7, E_8, where the index corresponds to the rank of the group. The basic requirement for a GUT is that it must contain the standard model gauge group $G_{\rm SM} = SU(3)_C\times SU(2)_L\times U(1)_Y$ as a sub-group. Its rank must therefore be greater or equal to 4, which is the rank of $G_{\rm SM}$. Simple groups of rank 4 are $SU(5)$, $SO(9)$, $Sp(8)$, $SO(8)$, F_4 and we can add the semisimple group $SU(3)\times SU(3)$. Among these groups of rank 4, only $SU(5)$ and $SU(3)\times SU(3)$ have complex representations, which are needed in order to describe electroweak interactions. However, $SU(3)\times SU(3)$ cannot describe particles of integer and fractional charge and therefore it is also excluded. Thus, the only group of rank 4 which remains is $SU(5)$ [50].

In selecting GUT gauge groups, we have two additional constraints: the group must include a complex representation which is necessary to describe the standard model fermions, and it must be anomaly free. In principle, $SU(n)$ may not be anomaly free [53]; more precisely it depends on the chosen fermionic representation [50]. We assume that the $SU(n)$ groups which we use have indeed a fermionic representation that certifies that the model is anomaly free. With these constraints taken into account (we do not yet require see-saw mechanism for neutrino masses), only $SO(4n+2)$ with $n\geqslant 2$, $SU(n)$ with $n\geqslant 5$, and E_6 can be kept. We also point out that minimal SUSY SU(5) is ruled out by proton lifetime measurements.

The last constraint comes from neutrino masses. The fairly recent discovery of neutrino oscillations at Super-Kamiokande [1] implies that neutrino have a mass. The Sudbury Neutrino Observatory (SNO) [2] results and the KamLAND [3] direct measurement of neutrino mixing have confirmed the existence of nonzero neutrino masses. Since the standard model does not predict the existence of mass for the neutrino, we must go beyond. The simplest possibility is to add a singlet which plays the role of right-handed neutrino. One can also add a triplet of Higgs to the SM. But neutrino masses are predicted in GUTs which contain a $U(1)_{B-L}$ gauge symmetry [4]. The requirement of see-saw mechanism is our next constraint on the choice of the group. We point out that these models can also automatically lead to R-parity conservation [54] and baryogenesis via leptogenesis [43]. SUSY GUT models that we shall select at the end are self-consistent: they predict neutrino masses and R-parity conservation, they solve their own monopole problem with inflation, and at the end of inflation baryogenesis via leptogenesis can take place.

Regarding the upper bound on the rank, we limit our study to groups with rank r less than or equal to 8. Clearly, the choice of the maximum rank is in principle arbitrary. The choice of $r\leqslant 8$ could, in a sense, be motivated by the Horava-Witten [55] model, based on $E_8\times E_8$. Each factor E_8 (rank $r=8$) can be seen as confined in one brane. Thus, within a four-dimensional theory (no extra dimensions), the rank can be limited to $r=8$. To be more precise, within the framework of five consistent string theories in ten dimensions (i.e., type I open strings, type IIA and IIB closed strings, and the two closed heterotic strings), the rank of the gauge group is bounded to $r \leqslant 22$ [56]. However, it is at present believed that the five string theories are related by strong-weak coupling dualities, and they can be seen as different limits of one underlying theory, the M theory. In this context, one gets nonperturbative strings which have their own nonperturbative gauge group, thus enhancing, by a real lot, the maximum rank required in perturbation theory [56]. (A few years ago, the upper bound of the rank was found to be 10^5 [57].) Even though we limit our study to $r \leqslant 8$, we believe that we still capture the main results. Indeed, higher rank groups lead (as one can see in the following sections) to similar SSB patterns as the one considered for groups of smaller rank. At last, but not least, a fully exhaustive analysis is clearly impossible.

IV. SPONTANEOUS SYMMETRY BREAKING PATTERNS

In the previous section, we showed that a number of constraints restrict the choice of symmetry groups G_{GUT}. In this section, we study all possible spontaneous symmetry breaking patterns from G_{GUT} down to the standard model gauge group G_{SM} (or $G_{\mathrm{SM}} \times Z_2$) and we look for defect formation. Here Z_2 is a subgroup of the $\mathrm{U}(1)_{\mathrm{B-L}}$ gauge symmetry which is contained in various gauge groups such as SO(10), E(6), and SU(8). It plays the role of R parity. Recall that R parity in SUSY forbids all dimensions 3 and 4 (even dimension 5) baryon and lepton number violating operators, therefore forbidding fast proton decay. This discrete Z_2 symmetry can be left unbroken down to low energy when appropriate representations are used to implement the SSB pattern [54]. R parity is thus an automatic consequence of SUSY GUTs which contain $\mathrm{U}(1)_{\mathrm{B-L}}$. Only models with unbroken Z_2 at low energy are consistent with the proton lifetime measurements. Therefore when it appears in a SSB scheme, we keep it unbroken down to low energy.

We only consider maximal regular subgroups [52]; they are listed explicitly in the Appendix. We disregard special maximal subgroups because it is then really nontrivial to get G_{SM} with the correct phenomenology. We write down SSB schemes which are consistent with both group theory and particle physics phenomenology. Some of the SSB schemes may be extremely complicated for model building. For example, nontrivial Higgs representations may be needed. In fact, in model building with a minimal set of Higgs, we do not usually get many intermediate SSB scales. Also, in going beyond one or two intermediate SSB scales, the model loses its predictability. However, this is beyond the scope of the systematic search we are aiming to.

For each group, there may be different ways of embedding G_{SM} in a given maximal subgroup. We use different indices to refer to the embedding that we consider. The three indices C, L, and Y Stand for color, left, and hypercharge, respectively, but we use more generally the index C (L) when $\mathrm{SU}(n)_{\mathrm{C}} \supset \mathrm{SU}(3)_{\mathrm{C}}$ [$\mathrm{SU}(n)_{\mathrm{L}} \supset \mathrm{SU}(2)_{\mathrm{L}}$]. We use several other indices which correspond to different possible embeddings of G_{SM} in maximal subgroups of G_{GUT}. They are explained below when we list the various SSB patterns for each group. The definition of the weak hypercharge is given where needed. The microstructure of cosmic strings is very much dependent on these assignments, which can imply different cosmological and astrophysical effects such as superconductivity, nonthermal production of baryons, lepton asymmetry, or dark matter.

In order to simplify the notation, we write $4_{\mathrm{C}}2_{\mathrm{L}}2_{\mathrm{R}}$ which stands for $\mathrm{SU}(4)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}$, $3_{\mathrm{C}}2_{\mathrm{L}}2_{\mathrm{R}}1_{\mathrm{B-L}}$ for $\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}} \times \mathrm{U}(1)_{\mathrm{B-L}}$, etc. We also use the numbers $1,2,2',3$ over an arrow to distinguish the type of gauge defect which is formed during the corresponding phase transition: 1 stands for monopoles, 2 for topological cosmic strings, $2'$ for embedded strings, and 3 for domain walls; 0 indicates that no defect forms. If the number is given in brackets, it stands for the type of defect formed during the SSB of the same gauge group down to the same subgroup $\times Z_2$. As an example, $G \stackrel{1(1,2)}{\rightarrow} H(Z_2)$ means that monopoles form when G breaks down to H, while both monopoles and cosmic strings form when G breaks down to $H \times Z_2$. If (Z_2) appears but there is no number in brackets, it is because the Z_2 appeared during a previous transition and the type of defect which forms in the SSB with unbroken Z_2 is identical to the one without it. Finally, $G \rightarrow \cdots$ means that the SSB patterns of G down to G_{SM} have already been given.

A. Discrete symmetries

We briefly discuss various discrete symmetries which may appear during the SSB patterns. The Z_2 subgroup of $\mathrm{U}(1)_{\mathrm{B-L}}$ which plays the role of R parity is the only discrete symmetry that we shall consider in the SSB patterns. It must be there by naturalness for keeping the proton lifetime above the experimental limits, since we do not consider the existence of any other symmetry than G_{GUT} at the GUT scale.

Nevertheless, we point out that some discrete Z_n symmetries may be left unbroken when the rank of the group is lowered. This depends on the Higgs representation which is used to implement the SSB. However, only two discrete symmetries, the standard Z_2 parity and one Z_3 parity, are anomaly free and can remain unbroken at low energy [58]. (Note that by adding some gauge singlets and/or doublets two more Z_3 could be allowed.) Also, in order to get the Z_3 symmetry some very high Higgs-dimensional representations are needed [59]. For example, in order to get a residual Z_3 from E_6, one has to choose a 3003-dim Higgs representation. To simplify our work, we disregard these Z_n. They must be broken at some stage during the SSB pattern, so that they are broken today. From a cosmological point of view, when these discrete symmetries break, unwanted domain walls form. In a full model, they must therefore appear and be broken before inflation.

Another discrete symmetry Z_2^{C} can also be left unbroken when Pati-Salam or left-right symmetry groups appear. This leads to the formation of Z_2 strings which get connected via domain walls when Z_2^{C} breaks [60]. [This is not coming from the breaking of a gauge U(1) symmetry and hence does not enter in the comments above.] The Z_2^{C} symmetry is also known as D parity [61]. The scale of breaking of Z_2^{C} and $\mathrm{SU}(2)_{\mathrm{R}}$ may be, in principle, separated. We discuss all the

SSB patterns for SUSY SO(10) with and without unbroken D parity at high scale. Although the unbroken D parity may also appear in E_6 models, for reasons of simplification, we do not discuss it. The important issue is that it must be broken before inflation takes place.

B. SU(5)

The discussion of SU(5) GUT is very short, since SU(5) has a rank 4 and can only break directly down to the standard model gauge group. This SSB leads to the formation of topologically stable monopoles which are inconsistent with observations. One way to solve the monopole problem in SUSY SU(5) is to introduce an extra singlet and to give nontrivial initial conditions to the fields in the Higgs potential [62]. In the following section we discuss GUT gauge groups with rank greater or equal to 5.

C. SO(10)

SO(10) is a gauge group of rank 5, which contains as maximal subgroups $SU(5)\times U(1)$ and the Pati-Salam gauge group $G_{PS}=SU(4)_C\times SU(2)_R\times SU(2)_L$, where $SU(4)_C\supset SU(3)_C\times U(1)_{B-L}$.

In order to give explicit definition for the hypercharge, we consider the following decomposition [63]:

$$SO(10)\supset SU(5)\times U(1)_V \supset SU(3)_C\times SU(2)_L\times U(1)_Z\times U(1)_V. \tag{4.1}$$

There are two possible assignments for the hypercharge Y that reproduce the SM and they depend on whether it is only included in $SU(5)$ or also in SO(10). In the first case

$$\frac{Y}{2}=Z. \tag{4.2}$$

It is used for SSB via the Georgi-Glashow model [64]; we add no subscript to $SU(5)$. In the second case

$$\frac{Y}{2}=-\frac{1}{5}(Z+V), \tag{4.3}$$

and it is used for the breakings via the flipped $SU(5)$ model [65], in which case we add the subscript F, i.e., we write 5_F. In $SO(10)$, all the standard model fermions of each family plus a right-handed neutrino belong to the 16-dimensional representation. The decomposition of the 16 under SU(5) and $SU(5)_F$ is given in Refs. [64,65].

Thus, there are two ways of embedding SU(5) $\times U(1)_V\supset SU(3)_C\times SU(2)_L\times U(1)_Z$ in minimal SO(10) GUT, but there is only one way for $SU(2)_R$ [63]. Here V is related to the third component I_R^3 of $SU(2)_R$ and to $B-L$, which is contained in SO(10) by

$$V=-4I_R^3-3(B-L), \tag{4.4}$$

and related to Z by

$$Z=-I_R^3+\tfrac{1}{2}(B-L). \tag{4.5}$$

Thus, in the first case,

$$\frac{Y}{2}=-I_R^3+\frac{1}{2}(B-L), \tag{4.6}$$

while in the second case

$$\frac{Y}{2}=I_R^3+\frac{1}{2}(B-L). \tag{4.7}$$

We list below the SSB schemes of SO(10) via SU(5) subgroups. We indicate the type of defect(s) formed at each phase transition

$$SO(10)\begin{cases} \xrightarrow{1} 5\ 1_V \begin{cases} \xrightarrow{2(2)} 5\ (Z_2) \xrightarrow{1} G_{SM}\ (Z_2) \\ \xrightarrow{1} 3_C\ 2_L\ 1_Z\ 1_V \xrightarrow{2(2)} G_{SM}\ (Z_2) \\ \xrightarrow{1,2(1,2)} G_{SM}\ (Z_2) \end{cases} \\ \xrightarrow{1} 5_F\ 1_V \xrightarrow{2'(2)} G_{SM}\ (Z_2) \\ \xrightarrow{0(2)} 5\ (Z_2) \xrightarrow{1} G_{SM}\ (Z_2). \end{cases} \tag{4.8}$$

In Ref. [66] it has already been shown that if a 126-dimensional Higgs field is used, SO(10) is broken down to $SU(5)\times Z_2$ and stable cosmic strings arise. However, since the next SSB leads to monopole formation, this model is incompatible with cosmology.

SO(10) can also break via the left-right symmetric groups $G_{PS}\supset SU(3)_C\times SU(2)_R\times SU(2)_L\times U(1)_{B-L}$, in which case the assignment of the hypercharge is given by Eq. (4.7). As explained in the previous section, a discrete symmetry known as D parity (noted as Z_2^{C}) can appear, leading to the formation of walls bounded by strings; such configurations are not problematic for cosmology. However, if inflation takes place before the formation of domain walls, then these would become cosmologically catastrophic; this situation is forbidden. Another Z_2 appears when SO(10) is breaking via G_{PS} [60]; indeed, it is not SO(10) but its universal covering group Spin(10) which is really broken to ([Spin(6) $\times$Spin(4)]/Z_2)($\times Z_2^{\mathrm{C}}$). [We remind the reader that SU(4) $\times$SU(2)$\times$SU(2)$\sim$Spin(6)$\times$Spin(4).] The quotient Z_2 results from the nontrivial intersection of Spin(6) and Spin(4) and implies the formation of monopoles.

The SSB patterns of G_{PS} and G_{PS} with D parity down to G_{SM} (Z_2) are, respectively, given by

$$4_{\mathrm{C}}\;2_{\mathrm{L}}\;2_{\mathrm{R}} \begin{cases} \xrightarrow{1}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;2_{\mathrm{R}}\;1_{\mathrm{B-L}} \begin{cases} \xrightarrow{1}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}}\;1_{\mathrm{B-L}} \xrightarrow{2\;(2)} G_{\mathrm{SM}}\;(Z_2) \\ \xrightarrow{2'(2)}\; G_{\mathrm{SM}}\;(Z_2) \end{cases} \\ \xrightarrow{1}\; 4_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}} \begin{cases} \xrightarrow{1}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}}\;1_{\mathrm{B-L}} \xrightarrow{2(2)} G_{\mathrm{SM}}\;(Z_2) \\ \xrightarrow{2'(2)}\; G_{\mathrm{SM}}\;(Z_2) \end{cases} \\ \xrightarrow{1}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}}\;1_{\mathrm{B-L}} \xrightarrow{2(2)} G_{\mathrm{SM}}\;(Z_2) \\ \xrightarrow{1(1,2)}\; G_{\mathrm{SM}}\;(Z_2) \end{cases} \tag{4.9}$$

and

$$4_{\mathrm{C}}\;2_{\mathrm{L}}\;2_{\mathrm{R}}\;Z_2^{\mathrm{C}} \begin{cases} \xrightarrow{1}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;2_{\mathrm{R}}\;1_{\mathrm{B-L}}\;Z_2^{\mathrm{C}} \begin{cases} \xrightarrow{3}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;2_{\mathrm{R}}\;1_{\mathrm{B-L}} \rightarrow \cdots \\ \xrightarrow{1,3}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}}\;1_{\mathrm{B-L}} \xrightarrow{2\;(2)} G_{\mathrm{SM}}\;(Z_2) \\ \xrightarrow{2',3\;(2,3)}\; G_{\mathrm{SM}}\;(Z_2) \end{cases} \\ \xrightarrow{1}\; 4_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}}\;Z_2^{\mathrm{C}} \begin{cases} \xrightarrow{3}\; 4_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}} \rightarrow \cdots \\ \xrightarrow{1,3}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}}\;1_{\mathrm{B-L}} \xrightarrow{2(2)} G_{\mathrm{SM}}\;(Z_2) \\ \xrightarrow{3\;(2,3)}\; G_{\mathrm{SM}}\;(Z_2) \end{cases} \\ \xrightarrow{3}\; 4_{\mathrm{C}}\;2_{\mathrm{L}}\;2_{\mathrm{R}} \rightarrow \text{Eq. (4.9)} \\ \xrightarrow{1}\; 4_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}} \rightarrow \cdots \\ \xrightarrow{1,3}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;2_{\mathrm{R}}\;1_{\mathrm{B-L}} \rightarrow \cdots \\ \xrightarrow{1,3}\; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{R}}\;1_{\mathrm{B-L}} \xrightarrow{2(2)} G_{\mathrm{SM}}\;(Z_2) \\ \xrightarrow{1,3(1,2,3)}\; G_{\mathrm{SM}}\;(Z_2). \end{cases} \tag{4.10}$$

The SSB schemes of SO(10) via the left-right groups with associated defect formation are

$$
\mathrm{SO}(10)\left\{\begin{array}{lll}
\stackrel{1}{\rightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}} & \rightarrow\ \text{Eq. (4.9)}\\
\stackrel{1,2}{\rightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}}\ Z_2^{\mathrm{C}} & \rightarrow\ \text{Eq. (4.10)}\\
\stackrel{1,2}{\rightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ Z_2^{\mathrm{C}} & \rightarrow\ \cdots\\
\stackrel{1}{\rightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}} & \rightarrow\ \cdots\\
\stackrel{1,2}{\rightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}}\ 1_{B-L}\ Z_2^{\mathrm{C}} & \rightarrow\ \cdots\\
\stackrel{1}{\rightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}}\ 1_{B-L} & \rightarrow\ \cdots\\
\stackrel{1}{\rightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{B-L} & \stackrel{2(2)}{\rightarrow}\ G_{\mathrm{SM}}\ (Z_2)\\
\stackrel{1(1,2)}{\rightarrow} & G_{\mathrm{SM}}\ (Z_2). &
\end{array}\right.
\tag{4.11}
$$

The SSB patterns listed above and the type of defect indicated above the arrows, contain all the information one needs to address the question of whether cosmic strings (topological or embedded) are expected to exist in models which are compatible with both particle physics and cosmology. The acceptable models must be consistent with proton lifetime measurements, solve the GUT monopole problem with inflation, and explain the baryon asymmetry of the Universe. Inflation takes place when the rank of the group is lowered and nonthermal leptogenesis (i.e., $B-L$ breaks at the end of inflation) is efficient. For GUTs based on gauge groups which have a rank less than or equal to 5 such as SO(10) or SU(6), in each SSB pattern, there is one single choice for the phase transition where hybrid inflation can take place. In SO(10), nonthermal leptogenesis always takes place at the end of inflation. On the other hand, for GUTs based on gauge groups which have a rank greater than 5, there may be more than one choice for the phase transition which leads to inflation. In these GUTs where inflation can take place at different stages in the SSB patterns, $B-L$ is not necessarily broken at the end of inflation. Models satisfying all constraints must lead to efficient leptogenesis; $B-L$ must be broken at the end of inflation.

Since in standard hybrid inflation SSB takes place at the end of inflation, in the schemes which are consistent with cosmology from a defect point of view, inflation can only take place during a given phase transition, with no monopoles or domain walls at this or at a subsequent phase transition.

For SO(10), we find that there are 68 SSB patterns which do not lead to formation of unwanted defects after inflation and all these models lead to the formation of topological strings or embedded ones, at the end of inflation. More precisely, we find that there are 34 SSB patterns with topological strings and unbroken matter parity, i.e., $G_{\mathrm{SM}}\times Z_2$. There are 21 SSB patterns leading to the formation of topological strings, but with broken R parity. Finally, there are 13 SSB schemes with embedded strings. In SO(10), when embedded strings are formed, R parity is always broken. In all these models, $B-L$ is broken at the end of inflation and leptogenesis is efficient. As discussed earlier, the proton lifetime measurements require unbroken R parity. There are therefore only 34 SSB patterns which satisfy all the constraints and they all lead to the formation of topological cosmic strings at the end of inflation.

D. SU(6)

SU(6) is the second group of rank 5. The maximal subgroups of SU(6) are given in Table I. Recall that SU(6) does not contain $B-L$ and, therefore it cannot accommodate the data on neutrino oscillations. There are only few possibilities for the spontaneous symmetry breaking patterns from SU(6) down to the G_{SM}. We list them below, indicating also the type of defects, if any, formed at each phase transition.

$$
\mathrm{SU}(6)\left\{\begin{array}{lll}
\stackrel{1}{\rightarrow} & 5\ 1_6 & \left\{\begin{array}{ll}\stackrel{2}{\rightarrow}\ 5 & \stackrel{1}{\rightarrow}\ G_{\mathrm{SM}}\\ \stackrel{1}{\rightarrow}\ 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1\ 1 & \stackrel{2}{\rightarrow}\ G_{\mathrm{SM}}\\ \stackrel{1,2}{\rightarrow}\ G_{\mathrm{SM}} & \end{array}\right.\\
\stackrel{1}{\rightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1 & \left\{\begin{array}{ll}\stackrel{1}{\rightarrow}\ 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1\ 1 & \stackrel{2}{\rightarrow}\ G_{\mathrm{SM}}\\ \stackrel{2'}{\rightarrow}\ G_{\mathrm{SM}} & \end{array}\right.\\
\stackrel{1}{\rightarrow} & 3_{\mathrm{C}}\ 3_{\mathrm{L}}\ 1 & \left\{\begin{array}{ll}\stackrel{1}{\rightarrow}\ 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1\ 1 & \stackrel{2}{\rightarrow}\ G_{\mathrm{SM}}\\ \stackrel{2'}{\rightarrow}\ G_{\mathrm{SM}} & \end{array}\right.\\
\stackrel{1}{\rightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1\ 1 & \stackrel{2}{\rightarrow}\ G_{\mathrm{SM}}\\
\stackrel{0}{\rightarrow} & 5 & \stackrel{1}{\rightarrow}\ G_{\mathrm{SM}}\\
\stackrel{1}{\rightarrow} & G_{\mathrm{SM}}. &
\end{array}\right.
\tag{4.12}
$$

TABLE I. Maximal regular subgroups of grand unification gauge groups with rank not greater than 8.

Rank	Group	Maximal subalgebras
4	SU(5)	$SU(3)_C \times SU(2)_L \times U(1)_Y$ $SU(4) \times U(1)$
5	SO(10)	$SU(5) \times U(1)_V$ $SU(5)_F \times U(1)_V$ $SU(4)_C \times SU(2)_L \times SU(2)_R = G_{PS}$
	SU(6)	$SU(5) \times U(1)_6$ $SU(4)_C \times SU(2)_L \times U(1)$ $SU(3)_C \times SU(3)_L \times U(1)$
6	E_6	$SO(10) \times U(1)_{V'}$ $SU(6) \times SU(2)_R$ $SU(6) \times SU(2)_L$ $SU(3)_C \times SU(3)_L \times SU(3)_{(R)}$
	SU(7)	$SU(6)_{SM} \times U(1)$ $SU(5)_C \times SU(2)_L \times U(1)$ $SU(5)_{SM} \times SU(2) \times U(1)$ $SU(4)_C \times SU(3)_L \times U(1)$
7	SO(14)	$SU(7) \times U(1)$ $SO(10) \times SU(2) \times SU(2)$
	SU(8)	$SU(7) \times U(1)$ $SU(6) \times SU(2) \times U(1)$ $SU(5) \times SU(3) \times U(1)$ $SU(4) \times SU(4) \times U(1)$
8	SU(9)	$SU(8) \times U(1)$ $SU(7) \times SU(2) \times U(1)$ $SU(6) \times SU(3) \times U(1)$ $SU(5) \times SU(4) \times U(1)$

Following the same approach as in the case of SO(10), one finds that there are six cosmologically allowed SSB schemes (from a defect point of view). They all lead to the formation of topological strings or embedded ones, at the end of inflation. There are four schemes with topological strings and two with embedded ones. However, SU(6) does not contain $U(1)_{B-L}$, data on neutrino oscillations cannot be accommodated without extension of the minimal version and R parity is not there. Thus, minimal SU(6) is not an acceptable group for particle physics.

E. E_6

E_6 is a group of rank 6 and it has three regular maximal subgroups which can accommodate the standard model

$$SO(10) \times U(1)'_V,$$

$$SU(3)_C \times SU(3)_L \times SU(3)_{(R)},$$

$$SU(6) \times SU(2).$$

We study the SSB patterns of E_6 via each of them in the following sections. (We follow the notation of Ref. [63].)

1. Breaking E_6 via SO(10)×U(1)

Let us start with $E_6 \supset SO(10) \times U(1)_{V'}$ and $SO(10) \supset SU(5) \times U(1)_V$. There are three possible assignments for the hypercharge Y which reproduce the SM depending on whether $U(1)_Y \subset SU(5)$, or $U(1)_Y \subset SO(10)$, or $U(1)_Y \subset E_6$. They are, respectively, given by [63]

$$\frac{Y}{2} = Z, \tag{4.13}$$

$$\frac{Y}{2} = -\frac{1}{5}(Z+V), \tag{4.14}$$

$$\frac{Y}{2} = -\frac{1}{20}(4Z - V - 5V'). \tag{4.15}$$

So the $U(1)_Y$ with hypercharge given in Eq. (4.13) is only contained in SU(5) and is valid for the breakings through the Georgi-Glashow model. The hypercharge in Eq. (4.14) is contained in SO(10) and is the one appearing in the breakings through flipped SU(5). Finally the last assignment of Y in Eq. (4.15) correspond to $U(1)_Y \subset E_6$. This is the subgroup which appears in the breaking of E_6 through the E-twisted SU(5) model, for example. We distinguish the SU(5) of each of these three cases by writing it as 5, 5_F, or 5_E, respectively. The SSB patterns for 5 $1_V 1_{V'}$ and $5_F 1_V 1_{V'}$ are, respectively, given by

$$
5\ 1_V\ 1_{V'}\left\{\begin{array}{lll}
\overset{2\ (2)}{\to} & 5\ 1_{V'}\ (Z_2) & \left\{\begin{array}{llll}\overset{2}{\to} & 5\ (Z_2) & \overset{1}{\to} & G_{SM}\ (Z_2)\\ \overset{1}{\to} & G_{SM}\ 1_{V'}\ (Z_2) & \overset{2}{\to} & G_{SM}\ (Z_2)\\ \overset{1,2}{\to} & G_{SM}\ (Z_2) & & \end{array}\right.\\
\overset{1}{\to} & G_{SM}\ 1_V\ 1_{V'} & \left\{\begin{array}{llll}\overset{2}{\to} & G_{SM}\ 1_V & \overset{2(2)}{\to} & G_{SM}\ (Z_2)\\ \overset{2(2)}{\to} & G_{SM}\ 1_{V'}\ (Z_2) & \overset{2}{\to} & G_{SM}\ (Z_2)\end{array}\right.\\
\overset{2}{\to} & 5\ 1_V & \to\ \cdots\\
\overset{1,2(1,2)}{\to} & G_{SM}\ (Z_2), &
\end{array}\right. \tag{4.16}
$$

where the hypercharge is given by Eq. (4.13), and

$$
5_F\ 1_V\ 1_{V'}\left\{\begin{array}{llll}
\overset{2}{\to} & 5_F\ 1_V & \overset{2'(2)}{\to} & G_{SM}\ (Z_2)\\
\overset{2,2'(2)}{\to} & G_{SM}\ (Z_2), & &
\end{array}\right. \tag{4.17}
$$

where the hypercharge is given by Eq. (4.14). In the E-twisted case the hypercharge is given by Eq. (4.15) and $5_E 1_V 1_{V'}$ can only breakdown to $G_{SM}\ (Z_2)$.

The SSB patterns with $E_6 \supset SO(10)\times U(1)_{V'} \supset SU(5) \times U(1)_V \times U(1)_{V'}$ are therefore given by

$$
E_6 \overset{1}{\to} 10\ 1_{V'}\left\{\begin{array}{llll}
\overset{2}{\to} & 10 & \to & \cdots\\
\overset{1}{\to} & 5\ 1_V\ 1_{V'} & \to & \text{Eq. (4.16)}\\
\overset{1}{\to} & 5_F\ 1_V\ 1_{V'} & \to & \text{Eq. (4.17)}\\
\overset{1}{\to} & 5_E\ 1_V\ 1_{V'} & \overset{2'(2)}{\to} & G_{SM}\ (Z_2)\\
\overset{0(2)}{\to} & 5\ 1_{V'}\ (Z_2) & \to & \cdots\\
\overset{1,2}{\to} & 5\ 1_V & \to & \cdots\\
\overset{2(2)}{\to} & 5\ (Z_2) & \overset{1}{\to} & G_{SM}\ (Z_2)\\
\overset{1}{\to} & 5_F\ 1_V & \overset{2'(2)}{\to} & G_{SM}\ (Z_2)\\
\overset{1}{\to} & G_{SM}\ 1_V & \overset{2(2)}{\to} & G_{SM}\ (Z_2)\\
\overset{1(1,2)}{\to} & G_{SM}\ 1_{V'}\ (Z_2) & \overset{2}{\to} & G_{SM}\ (Z_2)\\
\overset{1}{\to} & G_{SM}\ (Z_2). & &
\end{array}\right. \tag{4.18}
$$

SO(10) in $E_6 \supset SO(10)\times U(1)_{V'}$ can also break via $SU(4)\times SU(2)\times SU(2)$ which can be the Pati-Salam group G_{PS} or $SU(4)_{C'}\times SU(2)_L \times SU(2)_G$ [67]. In the first case, $U(1)_{V'}$ is orthogonal to G_{SM}, and the hypercharge assignment is exactly the same as in the SO(10) case [Eq. (4.7)]. In the second case, the hypercharge is given by

$$
Y = \frac{1}{4}V' - \frac{1}{12}C', \tag{4.19}
$$

where C' is the fifteenth generator of $SU(4)_{C'}$.

The SSB patterns with $E_6 \supset SO(10)\times U(1)_{V'} \supset SU(4) \times SU(2)\times SU(2)\times U(1)_{V'}$ with associated defects are

$$
E_6 \overset{1}{\to} 10\ 1_{V'}\left\{\begin{array}{lll}
\overset{1,2}{\to} & 4_C\ 2_L\ 2_R\ 1_{V'} & \to\ \text{Eq. (4.21)}\\
\overset{0}{\to} & 4_{C'}\ 2_L\ 2_G\ 1_{V'} & \to\ \text{Eq. (4.22)}\\
\overset{1}{\to} & 4_C\ 2_L\ 2_R & \to\ \text{Eq. (4.9)}\\
\overset{1}{\to} & 3_C\ 2_L\ 2_R\ 1_{B-L}\ 1_{V'} & \to\ \cdots\\
\overset{1}{\to} & 3_C\ 2_L 1_R\ 1_{B-L}\ 1_{V'} & \to\ \cdots,
\end{array}\right. \tag{4.20}
$$

where

$$
4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}}\ 1_{\mathrm{V}'} \left\{ \begin{array}{lll}
\stackrel{2}{\longrightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}} & \longrightarrow\ \text{Eq. (4.9)} \\
\stackrel{1}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{B-L}}\ 1_{\mathrm{V}'} & \left\{ \begin{array}{llll}
\stackrel{2}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{B-L}} & \stackrel{2\ (2)}{\longrightarrow} & G_{\mathrm{SM}}\ (Z_2) \\
\stackrel{2\ (2)}{\longrightarrow} & G_{\mathrm{SM}}\ 1_{\mathrm{V}'}\ (Z_2) & \stackrel{2}{\longrightarrow} & G_{\mathrm{SM}}\ (Z_2) \\
\stackrel{2\ (2)}{\longrightarrow} & G_{\mathrm{SM}}\ (Z_2) & &
\end{array} \right. \\
\stackrel{1}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}}\ 1_{\mathrm{B-L}}\ 1_{\mathrm{V}'} & \left\{ \begin{array}{llll}
\stackrel{1}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{B-L}}\ 1_{\mathrm{V}'} & \longrightarrow & \cdots \\
\stackrel{2}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}}\ 1_{\mathrm{B-L}} & \longrightarrow & \cdots \\
\stackrel{2'\ (2)}{\longrightarrow} & G_{\mathrm{SM}}\ 1_{\mathrm{V}'}\ (Z_2) & \stackrel{2}{\longrightarrow} & G_{\mathrm{SM}}\ (Z_2) \\
\stackrel{1,2}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{B-L}} & \stackrel{2\ (2)}{\longrightarrow} & G_{\mathrm{SM}}\ (Z_2)
\end{array} \right. \\
\stackrel{1}{\longrightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{V}'} & \left\{ \begin{array}{llll}
\stackrel{2}{\longrightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}} & \longrightarrow & \cdots \\
\stackrel{1}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{B-L}}\ 1_{\mathrm{V}'} & \longrightarrow & \cdots \\
\stackrel{2'\ (2)}{\longrightarrow} & G_{\mathrm{SM}} 1_{\mathrm{V}'}\ (Z_2) & \stackrel{2}{\longrightarrow} & G_{\mathrm{SM}}\ (Z_2) \\
\stackrel{1,2}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{B-L}} & \stackrel{2\ (2)}{\longrightarrow} & G_{\mathrm{SM}}\ (Z_2) \\
\stackrel{2\ (2)}{\longrightarrow} & G_{\mathrm{SM}}\ (Z_2) & &
\end{array} \right. \\
\stackrel{1\ (1,2)}{\longrightarrow} & G_{\mathrm{SM}} 1_{\mathrm{V}'}\ (Z_2) & \stackrel{2}{\longrightarrow}\ G_{\mathrm{SM}}\ (Z_2) \\
\stackrel{1,2}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}}\ 1_{\mathrm{B-L}} & \longrightarrow\ \cdots \\
\stackrel{1}{\longrightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{B-L}} & \stackrel{2\ (2)}{\longrightarrow}\ G_{\mathrm{SM}}\ (Z_2) \\
\stackrel{1,2\ (1,2)}{\longrightarrow} & G_{\mathrm{SM}}\ (Z_2) &
\end{array} \right. \tag{4.21}
$$

and

$$
4_{\mathrm{C}'}\ 2_{\mathrm{L}}\ 2_{\mathrm{G}}\ 1_{\mathrm{V}'} \left\{ \begin{array}{lll}
\stackrel{1}{\longrightarrow} & 4_{\mathrm{C}'}\ 2_{\mathrm{L}}\ 1_{\mathrm{G}}\ 1_{\mathrm{V}'} & \left\{ \begin{array}{llll}
\stackrel{2}{\longrightarrow} & 4_{\mathrm{C}'}\ 2_{\mathrm{L}}\ 1_{\mathrm{V}'} & \stackrel{2'}{\longrightarrow} & G_{\mathrm{SM}} \\
\stackrel{2'}{\longrightarrow} & G_{\mathrm{SM}} & &
\end{array} \right. \\
\stackrel{0}{\longrightarrow} & 4_{\mathrm{C}'}\ 2_{\mathrm{L}}\ 1_{\mathrm{V}'} & \stackrel{2'}{\longrightarrow}\ G_{\mathrm{SM}} \\
\stackrel{2'}{\longrightarrow} & G_{\mathrm{SM}}. &
\end{array} \right. \tag{4.22}
$$

There are also more direct schemes with these embeddings:

$$E_6 \left\{ \begin{array}{llll} \overset{1}{\rightarrow} & 5\ 1_{\mathrm{V}}\ 1_{\mathrm{V}'} & \rightarrow & \text{Eq. (4.16)} \\ \overset{1}{\rightarrow} & 5_{\mathrm{F}}\ 1_{\mathrm{V}}\ 1_{\mathrm{V}'} & \rightarrow & \text{Eq. (4.17)} \\ \overset{1}{\rightarrow} & 5_{\mathrm{E}}\ 1_{\mathrm{V}}\ 1_{\mathrm{V}'} & \overset{2'\ (2)}{\rightarrow} & G_{\mathrm{SM}}\ (Z_2) \\ \overset{1}{\rightarrow} & 5\ 1_{\mathrm{V}} & \rightarrow & \cdots \\ \overset{1}{\rightarrow} & 5\ 1_{\mathrm{V}'} & \rightarrow & \cdots \\ \overset{0}{\rightarrow} & 5 & \overset{1}{\rightarrow} & G_{\mathrm{SM}} \\ \overset{1}{\rightarrow} & 5_{\mathrm{F}}\ 1_{\mathrm{V}} & \overset{2'\ (2)}{\rightarrow} & G_{\mathrm{SM}}\ (Z_2) \\ \overset{1}{\rightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}}\ 1_{\mathrm{V}'} & \rightarrow & \text{Eq. (4.21)} \\ \overset{1}{\rightarrow} & 4_{\mathrm{C}'}\ 2_{\mathrm{L}}\ 2_{\mathrm{G}}\ 1_{\mathrm{V}'} & \rightarrow & \text{Eq. (4.22)} \\ \overset{1}{\rightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}} & \rightarrow & \text{Eq. (4.9)} \\ \overset{1}{\rightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}} & \rightarrow & \cdots \\ \overset{1}{\rightarrow} & 4_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{V}'} & \rightarrow & \cdots \\ \overset{1}{\rightarrow} & 4_{\mathrm{C}'}\ 2_{\mathrm{L}}\ 1_{\mathrm{V}'} & \overset{2'}{\rightarrow} & G_{\mathrm{SM}} \\ \overset{1}{\rightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 2_{\mathrm{R}}\ 1_{\mathrm{B-L}}\ 1_{\mathrm{V}'} & \rightarrow & \cdots \\ \overset{1}{\rightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{B-L}}\ 1_{\mathrm{V}'} & \rightarrow & \cdots \\ \overset{1}{\rightarrow} & 3_{\mathrm{C}}\ 2_{\mathrm{L}}\ 1_{\mathrm{R}}\ 1_{\mathrm{B-L}} & \overset{2\ (2)}{\rightarrow} & G_{\mathrm{SM}}\ (Z_2) \\ \overset{1}{\rightarrow} & G_{\mathrm{SM}}\ 1_{\mathrm{V}} & \overset{2\ (2)}{\rightarrow} & G_{\mathrm{SM}}\ (Z_2) \\ \overset{1\ (1,2)}{\rightarrow} & G_{\mathrm{SM}}\ 1_{\mathrm{V}'}\ (Z_2) & \overset{2}{\rightarrow} & G_{\mathrm{SM}}\ (Z_2) \\ \overset{1\ (1,2)}{\rightarrow} & G_{\mathrm{SM}}\ (Z_2). & & \end{array} \right. \tag{4.23}$$

$E(6)$ is a group of rank 6, and therefore there are *a priori* two possible choices for the onset of inflation in each SSB pattern. We consider first the SSB schemes which are compatible with observations from a defect point of view and then we add the constraint coming from leptogenesis. We recall that for nonthermal leptogenesis, $B-L$ must break at the end of inflation. Our results are the following: we find that there are in total 382 SSB patterns which are consistent from a defect point of view, 184 leading to topological strings and conserved R parity, 146 with topological strings and broken R parity, and 51 with embedded strings. There is one SSB scheme with no defect formation after the inflationary era; however R parity is broken. Once nonthermal leptogenesis constraint is included, there remain 146 schemes with topological strings and conserved R parity, 101 with topological strings and broken R parity, and 51 with embedded strings. The total number of SSB patterns which satisfy all constraints is 146. All of them lead to the formation of topologically stable cosmic strings whose mass per unit length can be computed and is proportional to the inflationary scale.

2. Breaking E_6 via $SU(3)_C \times SU(3)_L \times SU(3)_R$

We proceed with $E_6 \supset \mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R} \supset \mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_{\mathrm{Y}_\mathrm{L}} \times \mathrm{SU}(3)_\mathrm{R}$. There exist three different SU(2) subgroups of $\mathrm{SU}(3)_\mathrm{R}$, namely, $\mathrm{SU}(3)_\mathrm{R} \supset \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_{\mathrm{Y}_\mathrm{R}}$, $\mathrm{SU}(3)_\mathrm{R} \supset \mathrm{SU}(2)'_\mathrm{R} \times \mathrm{U}(1)_{\mathrm{Y}'_\mathrm{R}}$, and $\mathrm{SU}(3)_\mathrm{R} \supset \mathrm{SU}(2)_\mathrm{E} \times \mathrm{U}(1)_{\mathrm{Y}_\mathrm{E}}$. Following Ref. [63], we use the notation $\mathrm{SU}(2)_{(\mathrm{R})}$ which can stand for any of the three groups $\mathrm{SU}(2)_\mathrm{R}$, $\mathrm{SU}(2)'_\mathrm{R}$, or $\mathrm{SU}(2)_\mathrm{E}$. Identically, $\mathrm{U}(1)_{\mathrm{Y}_{(\mathrm{R})}}$ can stand for $\mathrm{U}(1)_{\mathrm{Y}_\mathrm{R}}$, or $\mathrm{U}(1)_{\mathrm{Y}'_\mathrm{R}}$ or $\mathrm{U}(1)_{\mathrm{Y}_\mathrm{R}}$.

There are again three possible assignments for the hypercharge which are given in Eqs. (4.13), (4.14) and (4.15). They can also be expressed in terms of $I^3_{(\mathrm{R})}$, the third component of $\mathrm{SU}(2)_{(\mathrm{R})}$, and Y_L and $Y_{(\mathrm{R})}$, the quantum numbers of $\mathrm{U}(1)_{\mathrm{Y}_\mathrm{L}}$ and $\mathrm{U}(1)_{\mathrm{Y}_{(\mathrm{R})}}$. (We refer the reader to Ref. [63] for details.)

If $\mathrm{U}(1)_{\mathrm{B-L}} \subset E_6$ is imposed, there are also three possible assignments of $B-L$ [63]:

$$B-L=-\tfrac{1}{5}(V-4Z)=\tfrac{2}{3}Y_\mathrm{L}+\tfrac{2}{3}Y_\mathrm{R}, \tag{4.24}$$

or

$$B-L=\tfrac{1}{20}(16Z+V+5V')=\tfrac{2}{3}Y_\mathrm{L}+\tfrac{2}{3}Y'_\mathrm{R}, \tag{4.25}$$

or

$$B-L=-\tfrac{1}{20}(8Z+3V-5V')=\tfrac{2}{3}Y_L+\tfrac{2}{3}Y_\mathrm{E}. \tag{4.26}$$

It was shown in Ref. [63] that among these $3\times 3=9$ possible assignments for the hypercharge Y and $B-L$ only six are consistent with the standard model because $\mathrm{U}(1)_{\mathrm{B-L}}$ and $\mathrm{U}(1)_\mathrm{Y}$ cannot be orthogonal to the same $\mathrm{SU}(2)_{(\mathrm{R})}$ subgroup of $\mathrm{SU}(3)_\mathrm{R}$. The possible relations between Y and $B-L$ can be expressed in terms of $I^3_{(\mathrm{R})}$. We have the following 6 possibilities:

$$\frac{Y}{2}=-I^3_\mathrm{R}+\frac{1}{2}(B-L)=-I^{3\prime}_\mathrm{R}+\frac{1}{2}(B-L), \tag{4.27}$$

where $B-L$ is given by Eqs. (4.24), (4.25),

$$\frac{Y}{2}=I^3_\mathrm{R}+\frac{1}{2}(B-L)=-I^3_\mathrm{E}+\frac{1}{2}(B-L), \tag{4.28}$$

where $B-L$ is given by Eqs. (4.24), (4.26), and

$$\frac{Y}{2}=-I^{3\prime}_\mathrm{R}+\frac{1}{2}(B-L)=I^3_\mathrm{E}+\frac{1}{2}(B-L), \tag{4.29}$$

where $B-L$ is given by Eqs. (4.25), (4.26).

In the SSB patterns of E_6 via $\mathrm{SU}(3)^3$ there will therefore often appear the intermediate symmetry group $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_{(\mathrm{R})} \times \mathrm{U}(1)_{\mathrm{Y}_\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}_{(\mathrm{R})}}$. This intermediate group can breakdown to $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_{(\mathrm{R})} \times \mathrm{U}(1)_{\mathrm{B-L}}$ and the SSB patterns which follow just a generalization of those written previously for $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_{\mathrm{B-L}}$.

The SSB of $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_{(\mathrm{R})} \times \mathrm{U}(1)_{\mathrm{Y}_\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}_{(\mathrm{R})}}$ down to G_SM with associated defects formation are given by

$$3_\mathrm{C}\ 2_\mathrm{L}\ 2_{(\mathrm{R})}\ 1_{\mathrm{Y}_\mathrm{L}}\ 1_{\mathrm{Y}_{(\mathrm{R})}} \left\{ \begin{array}{l} \xrightarrow{1}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 2_{(\mathrm{R})}\ 1_{\mathrm{B-L}} \left\{ \begin{array}{l} \xrightarrow{1}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_{(\mathrm{R})}\ 1_{\mathrm{B-L}} \xrightarrow{2\ (2)} G_\mathrm{SM}\ (Z_2) \\ \xrightarrow{2'\ (2)} G_\mathrm{SM}\ (Z_2) \end{array} \right. \\ \xrightarrow{1}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_{(\mathrm{R})}\ 1_{\mathrm{Y}_{(\mathrm{R})}}\ 1_{\mathrm{Y}_\mathrm{L}} \left\{ \begin{array}{l} \xrightarrow{2}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_{(\mathrm{R})}\ 1_{\mathrm{B-L}} \xrightarrow{2\ (2)} G_\mathrm{SM}\ (Z_2) \\ \xrightarrow{2\ (2)} G_\mathrm{SM}\ (Z_2) \end{array} \right. \\ \xrightarrow{1,2}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_{(\mathrm{R})}\ 1_{\mathrm{B-L}} \xrightarrow{2\ (2)} G_\mathrm{SM}\ (Z_2) \\ \xrightarrow{2'\ (2)} G_\mathrm{SM}\ (Z_2). \end{array} \right. \tag{4.30}$$

We must count six times each SSB when we evaluate the number of allowed schemes.

We also have

$$3_C\ 3_L\ 2_{(R)}\ 1_{(Y_R)} \left\{ \begin{array}{llll} \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 2_{(R)}\ 1_{Y_{(R)}}\ 1_{Y_L} & \rightarrow & \text{Eq. (4.30)} \\ \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 1_{(R)}\ 1_{Y_{(R)}}\ 1_{Y_L} & \rightarrow & \cdots \\ \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 2_{(R)}\ 1_{B-L} & \rightarrow & \cdots \\ \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 1_{(R)}\ 1_{B-L} & \stackrel{2\ (2)}{\rightarrow} & G_{SM}\ (Z_2) \\ \stackrel{2'\ (2)}{\rightarrow} & G_{SM}\ (Z_2) & & \end{array} \right. \tag{4.31}$$

and

$$3_C\ 2_L\ 3_R\ 1_{Y_L} \left\{ \begin{array}{llll} \stackrel{1}{\rightarrow} & 3_C\ 2_{(R)}\ 2_L\ 1_{Y_L}\ 1_{Y_{(R)}} & \rightarrow & \text{Eq. (4.30)} \\ \stackrel{2'}{\rightarrow} & 3_C\ 2_{(R)}\ 2_L\ 1_{B-L} & \rightarrow & \cdots \\ \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 1_{(R)}\ 1_{Y_L}\ 1_{Y_{(R)}} & \rightarrow & \cdots \\ \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 1_{(R)}\ 1_{B-L} & \stackrel{2\ (2)}{\rightarrow} & G_{SM}\ (Z_2) \\ \stackrel{2'\ (2)}{\rightarrow} & G_{SM}\ (Z_2), & & \end{array} \right. \tag{4.32}$$

also

$$3_C\ 3_L\ 1_{(R)}\ 1_{Y_{(R)}} \left\{ \begin{array}{llll} \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 1_{Y_L}\ 1_{(R)}\ 1_{Y_{(R)}} & \rightarrow & \cdots \\ \stackrel{2'}{\rightarrow} & 3_C\ 2_L\ 1_{(R)}\ 1_{B-L} & \stackrel{2\ (2)}{\rightarrow} & G_{SM}\ (Z_2) \\ \stackrel{2'\ (2)}{\rightarrow} & G_{SM}\ (Z_2). & & \end{array} \right. \tag{4.33}$$

The SSB patterns of E_6 via $SU(3)_C \times SU(3)_L \times SU(3)_R$ with associated defects formation are given by

$$E_6 \stackrel{0}{\rightarrow} 3_C\ 3_L\ 3_R \left\{ \begin{array}{llll} \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 2_{(R)}\ 1_{Y_{(R)}}\ 1_{Y_L} & \rightarrow & \text{Eq. (4.30)} \\ \stackrel{1}{\rightarrow} & 3_C\ 3_L\ 2_{(R)}\ 1_{(Y_R)} & \rightarrow & \text{Eq. (4.31)} \\ \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 3_R\ 1_{Y_L} & \rightarrow & \text{Eq. (4.32)} \\ \stackrel{1}{\rightarrow} & 3_C\ 3_L\ 1_{(R)}\ 1_{Y_{(R)}} & \rightarrow & \text{Eq. (4.33)} \\ \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 1_{(R)}\ 1_{Y_{(R)}}\ 1_{Y_L} & \rightarrow & \cdots \\ \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 2_{(R)}\ 1_{B-L} & \rightarrow & \cdots \\ \stackrel{1}{\rightarrow} & 3_C\ 2_L\ 1_{(R)}\ 1_{B-L} & \stackrel{2\ (2)}{\rightarrow} & G_{SM}\ (Z_2) \\ \stackrel{1\ (1,2)}{\rightarrow} & G_{SM}\ (Z_2). & & \end{array} \right. \tag{4.34}$$

There are more direct breakings which are given by

$$E_6 \begin{cases} \xrightarrow{1} & 3_C\ 2_L\ 2_{(R)}\ 1_{Y_L}\ 1_{Y_{(R)}} & \rightarrow & \text{Eq. (4.30)} \\ \xrightarrow{1} & 3_C\ 3_L\ 2_{(R)}\ 1_{Y_{(R)}} & \rightarrow & \text{Eq. (4.31)} \\ \xrightarrow{1} & 3_C\ 2_L\ 3_R\ 1_{Y_L} & \rightarrow & \text{Eq. (4.32)} \\ \xrightarrow{1} & 3_C\ 2_L\ 1_{(R)}\ 1_{Y_L}\ 1_{Y_{(R)}} & \rightarrow & \cdots \\ \xrightarrow{1} & 3_C\ 2_L\ 2_{(R)}\ 1_{B-L} & \rightarrow & \cdots \\ \xrightarrow{1} & 3_C\ 2_L\ 1_{(R)}\ 1_{B-L} & \xrightarrow{2\ (2)} & G_{SM}\ (Z_2). \end{cases} \tag{4.35}$$

There is now the possibility of having inflation and embedded strings forming at the end of inflation together with R parity conservation. The total number of schemes satisfying cosmological constraints for defects is 1086, with 522 schemes leading to the formation of topological strings at the end of inflation with conserved R parity, 384 with topological strings and broken R parity, 162 models with embedded strings and broken R parity, and 18 schemes with embedded strings and conserved R parity. When the constraint of leptogenesis is added, we find 444 schemes leading to the formation of topological strings at the end of inflation with conserved R parity, 312 with topological strings and broken R parity, and 138 models with embedded strings and broken R parity. There is not any model with embedded strings and R parity. In conclusion, there are 444 models satisfying all constraints, and they all lead to the formation of topological cosmic strings at the end of inflation.

3. Breaking E_6 via SU(6)×SU(2)

We end with $E_6 \supset \mathrm{SU}(6)\times\mathrm{SU}(2)$. There are two possibilities, namely, $\mathrm{SU}(6)\times\mathrm{SU}(2)_L$ or $\mathrm{SU}(6)\times\mathrm{SU}(2)_R$. A third possibility would be $\mathrm{SU}(6)\times\mathrm{SU}(2)_I$, where $\mathrm{SU}(2)_I$ is called *inert* [68] because it is orthogonal to G_{SM} which is embedded completely inside SU(6). However, since in SUSY models this embedding is not compatible with the proton lifetime, we do not study it.

We first study $E_6 \supset \mathrm{SU}(6)\times\mathrm{SU}(2)_L$. We consider the following SSB patterns of E_6 via $\mathrm{SU}(6)\times\mathrm{SU}(2)_L$ which we write together with the more direct breakings:

$$\begin{matrix} E_6 \xrightarrow{0} 6\ 2_L \\ \text{or}\quad E_6 \end{matrix} \begin{cases} \xrightarrow{1} & 3_C\ 3_R\ 2_L\ 1_{Y_L} & \rightarrow & \text{Eq. (4.32)} \\ \xrightarrow{1} & 4_C\ 2_L\ 2_R\ 1_{V'} & \rightarrow & \text{Eq. (4.21)} \\ \xrightarrow{1} & 4_{C'}\ 2_L\ 2_G\ 1_{V'} & \rightarrow & \text{Eq. (4.22)} \\ \xrightarrow{0} & 4_C\ 2_L\ 2_R & \rightarrow & \cdots \\ \xrightarrow{1} & 4_C\ 2_L\ 1_R\ 1_{V'} & \rightarrow & \cdots \\ \xrightarrow{1} & 4_C\ 2_L\ 1_R & \rightarrow & \cdots \\ \xrightarrow{1} & 3_C\ 2_L\ 2_{(R)}\ 1_{Y_L}\ 1_{Y_{(R)}} & \rightarrow & \text{Eq. (4.22)} \\ \xrightarrow{1} & 3_C\ 2_L\ 2_{(R)}\ 1_{B-L} & \rightarrow & \cdots \\ \xrightarrow{1} & 3_C\ 2_L\ 1_{(R)}\ 1_{Y_L}\ 1_{Y_{(R)}} & \rightarrow & \cdots \\ \xrightarrow{1} & 3_C\ 2_L\ 1_{(R)}\ 1_{B-L} & \xrightarrow{2\ (2)} & G_{SM}\ (Z_2) \\ \xrightarrow{1\ (1,2)} & G_{SM}\ (Z_2). \end{cases} \tag{4.36}$$

The $\mathrm{SU}(2)_L$ of G_{SM} can also be contained in SU(6), so that E_6 breaks down to $\mathrm{SU}(6)\times\mathrm{SU}(2)_R$. We consider the following SSB schemes of E_6 via $\mathrm{SU}(6)\times\mathrm{SU}(2)_R$ which we write together with the more direct breakings:

$$\begin{array}{c} E_6 \overset{0}{\rightarrow} 6\ 2_{\rm R} \\ \text{or}\quad E_6 \end{array} \left\{ \begin{array}{lll} \overset{1}{\rightarrow} & 4_{\rm C}\ 2_{\rm L}\ 2_{\rm R}\ 1_{V'} & \rightarrow \quad \text{Eq. (4.21)} \\ \overset{1}{\rightarrow} & 4_{\rm C}\ 2_{\rm L}\ 1_{\rm R}\ 1_{\rm V'} & \rightarrow \quad \cdots \\ \overset{0}{\rightarrow} & 4_{\rm C}\ 2_{\rm L}\ 2_{\rm R} & \rightarrow \quad \cdots \\ \overset{1}{\rightarrow} & 4_{\rm C}\ 2_{\rm L}\ 1_{\rm R} & \rightarrow \quad \cdots \\ \overset{1}{\rightarrow} & 3_{\rm C}\ 2_{\rm L}\ 2_{\rm R}\ 1_{\rm B-L}\ 1_{\rm V'} & \rightarrow \quad \cdots \\ \overset{1}{\rightarrow} & 3_{\rm C}\ 2_{\rm L}\ 2_{\rm R}\ 1_{\rm B-L} & \rightarrow \quad \cdots \\ \overset{1}{\rightarrow} & 3_{\rm C}\ 2_{\rm L}\ 1_{\rm R}\ 1_{\rm B-L} & \overset{2\ (2)}{\rightarrow} \quad G_{\rm SM}\ (Z_2) \\ \overset{1\ (1,2)}{\rightarrow} & G_{\rm SM}\ (Z_2). & \end{array} \right. \tag{4.37}$$

The total number of schemes satisfying cosmological constraints for defects is 1270, with 664 schemes leading to the formation of topological strings at the end of inflation with conserved R parity, 422 with topological strings and broken R parity, 170 models with embedded strings and broken R parity, and 12 schemes with embedded strings and conserved R parity. When the constraint of leptogenesis is added, we find 534 models satisfying all constraints, and they all lead to the formation of topological cosmic strings at the end of inflation.

F. SU(7)

SU(7) is the second group of rank 6. The embeddings which one can choose are

$$\mathrm{SU}(7) \supset \mathrm{SU}(6)_{\rm SM} \times \mathrm{U}(1) \quad \text{with} \quad \mathrm{SU}(6)_{\rm SM} \supset G_{\rm SM},$$

$$\mathrm{SU}(7) \supset \mathrm{SU}(6) \times \mathrm{U}(1) \quad \text{with} \quad \mathrm{SU}(6) \times \mathrm{U}(1) \supset G_{\rm SM},$$

$$\mathrm{SU}(7) \supset \mathrm{SU}(4)_{\rm C} \times \mathrm{SU}(3)_{\rm L} \times \mathrm{U}(1),$$

$$\mathrm{SU}(7) \supset \mathrm{SU}(5)_{\rm C} \times \mathrm{SU}(2)_{\rm L} \times \mathrm{U}(1) \quad \text{with}$$

$$\mathrm{SU}(5)_{\rm C} \times \mathrm{SU}(2)_{\rm L} \times \mathrm{U}(1) \supset G_{\rm SM},$$

$$\mathrm{SU}(7) \supset \mathrm{SU}(5)_{\rm SM} \times \mathrm{SU}(2) \times \mathrm{U}(1) \quad \text{with}$$

$$\mathrm{SU}(5)_{\rm SM} \supset G_{\rm SM}.$$

In the first and later cases $G_{\rm SM}$ is completely embedded in the SU(6) (SU(5)) factor.

The only possibility for getting inflation without defect formation at the end or after, is if we have the later scheme, where the SU(2) factor is orthogonal to $G_{\rm SM}$. The SSB patterns which could accommodate an epoch of inflation with no defect (of any kind) formation at a later stage are

$$\mathrm{SU}(7) \overset{1}{\rightarrow} 5_{\rm SM}\ 2\ 1 \left\{ \begin{array}{lll} \overset{2}{\rightarrow} \ 5_{\rm SM}\ 2 & \overset{1}{\rightarrow}\ \mathrm{G}_{\rm SM}\ 2 & \overset{0}{\rightarrow}\ \mathrm{G}_{\rm SM} \\ \overset{1}{\rightarrow} \ \mathrm{G}_{\rm SM}\ 2\ 1 & \overset{2}{\rightarrow}\ \mathrm{G}_{\rm SM}\ 2 & \overset{0}{\rightarrow}\ \mathrm{G}_{\rm SM} \\ \overset{1,\ 2}{\rightarrow} \ \mathrm{G}_{\rm SM}\ 2 & \overset{0}{\rightarrow}\ \mathrm{G}_{\rm SM}. & \end{array} \right. \tag{4.38}$$

However, these models are inconsistent with proton lifetime measurements and minimal SU(7) does not predict neutrino masses. These models are therefore incompatible with high energy physics phenomenology.

G. Higher rank groups

There are two groups of rank 7, namely, SO(14) and SU(8). These groups are particularly interesting since they both contain $\mathrm{U}(1)_{\rm B-L}$. In what follows, we discuss the embeddings of the $G_{\rm SM}$ in these groups and we then comment on the SSB patterns, without writing down explicitely all of them. We just aim to extract those scenarios which can lead to inflation without cosmic string formation at the end of inflation or afterwards.

SO(14) has only two maximal subalgebras,

$$\mathrm{SU}(7) \times \mathrm{U}(1),$$

$$\mathrm{SO}(10) \times \mathrm{SU}(2) \times \mathrm{SU}(2).$$

The only possibility for getting inflation without strings in the first case is to embed the standard model in $\mathrm{SU}(5)_{\rm SM} \subset \mathrm{SU}(7)$ and in $\mathrm{SU}(5)_{\rm SM} \times \mathrm{SU}(2) \times \mathrm{U}(1) \subset \mathrm{SU}(7)$ so that the SU(2) and the two U(1)s in $\mathrm{SU}(5)_{\rm SM} \times \mathrm{SU}(2) \times \mathrm{U}(1) \times \mathrm{U}(1) \subset \mathrm{SO}(14)$ are orthogonal to $G_{\rm SM}$. These models are also inconsistent with observations from both particle physics and cosmological point of view.

If we consider the maximal sub-algebra SO(10)$\times$SU(2) $\times$SU(2), then the only way would be to embed $G_{\rm SM}$ in SO(10) so that the two SU(2) factors are inert, and break SU(2) down to identity after the breaking of SO(10). These models are also inconsistent with observations.

SU(8) maximal subgroups are SU(7)$\times$U(1) and SU(m) $\times$SU(n)$\times$U(1), where $m+n=8$. One may have SU(m)$\supset$SU(3)$_{\rm C}$ and SU(n)$\supset$SU(2)$_{\rm L}$ or for $m(n)\geqslant 5$ embed $G_{\rm SM}$ in SU(m) so that SU(n)$\times$U(1) is orthogonal to it. The only way to get inflation without strings in the first case is to embed $G_{\rm SM}$ entirely in SU(7), break U(1) before inflation and we are left with the SU(7) cases mentioned above. These models are inconsistent from both the cosmological and particle physics requirements that we have. One can easily show that in the second case where SU(m,n)$\supset$SU(3)$_{\rm C}$ and SU(n,m)$\supset$SU(2)$_{\rm L}$ all SSB patterns with inflation and leptogenesis lead to the formation of cosmic strings at the end of inflation (topological or embedded ones) and if unbroken R-parity is required, the strings are topological and topologically stable down to low energies. The only possibility for having inflation without strings might be the last case where m or $n>5$ and to embed $G_{\rm SM}$ in SU(m,n). But here again, it seems impossible to fit leptogenesis after inflation. Therefore all SU(8) models with standard hybrid inflation and baryogenesis lead to the formation of cosmic strings at the end of inflation.

Finally, there is one group of rank 8, SU(9). Following the same procedure as for the SU(8) case, we conclude that none of the SSB schemes lead to inflation without strings after the end of the inflationary era.

V. CONCLUSION AND DISCUSSION

Current data from the realm of cosmology strongly support an early inflationary era. In addition, current CMB temperature anisotropies data minimize a possible contribution from cosmic strings. On the other hand, many GUTs naturally lead to cosmic string formation. We are thus faced with a crucial quest, namely, how often GUTs lead to cosmic string formation? Or, in other words, which is a natural inflationary scenario? Answering these questions is the motivation of our study.

In the context of SUSY GUTs, we have studied the cosmological implications of SSB patterns from grand unified gauge groups $G_{\rm GUT}$ down to the standard model gauge group $G_{\rm SM}$. The aim is to select all the schemes which can satisfy both cosmological and particle physics constraints, among them lead to inflation and solve the GUT monopole problem, explain the baryon asymmetry of the Universe, predict neutrino masses, and lead to automatic R parity conservation. To perform this analysis, we limit ourselves to simple gauge groups which contain $G_{\rm SM}$, have a complex representation, are anomaly free, and have a rank not greater than 8. Such gauge groups are SU(5), SO(10), SU(6), E_6, SU(7), SO(14), SU(8), and SU(9). We take a large number of possible embeddings of $G_{\rm SM}$ in $G_{\rm GUT}$ and we list in detail all possible SSB patterns of $G_{\rm GUT}$ down to $G_{\rm SM}$. We also investigate whether defects are formed during the SSB schemes and of which kind they are. We assume standard hybrid inflation which emerges naturally in SUSY GUTs, the inflaton field being a linear combination of a singlet field and one component of the complex GUT Higgs fields which are used to lower the rank of the group by one unit. We then examine whether monopoles or domain walls are formed after the end of inflation. We disregard such SSB patterns. We also disregard SSB schemes with broken R parity. To be consistent with leptogenesis, we require that the gauged $B-L$ symmetry, which is contained in GUTs which predict neutrino masses via the see-saw mechanism and unbroken R parity, is broken at the end inflation. This, for example, implies that we throw away SU(6) or SU(7). We then compare the SSB patterns where topological cosmic strings or embedded strings are formed after inflation with respect to the SSB patterns where there are no defects at all after the end of the inflationary era.

Among the SSB schemes which are compatible with high energy physics and cosmology, we did not find any without strings after inflation. One should thus only consider mixed models, where inflation coexists with cosmic strings. On the other hand, various cosmological issues, and, in particular, the CMB temperature anisotropies, set bounds to the cosmic string contribution. This can help constraining or ruling out realistic GUT models where the string contribution can always be computed. One may also have to reconsider the validity of the whole theoretical framework.

We also find the existence of SSB patterns, for GUTs based on gauge groups which have a rank greater than 6, which predict the formation of secondary string networks at lower energies. Finally, in all models with strings and inflation, the strings forming at the end of inflation are the so-called $B-L$ cosmic strings [48]. Their contribution to the baryon assymmetry of the Universe is nonnegligible and may compete with the non-thermal process of leptogenesis from reheating.

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APPENDIX: MAXIMAL SUBGROUPS

We list the maximal subgroups of each GUT which is studied in this paper. They are necessary for finding the SSB patterns. Most of the information given here is taken from Ref. [52]. We only consider maximal regular subgroups because it is very difficult and unnatural to get $G_{\rm SM}$ via maximal special subgroups. As discussed in Sec. IV A some discrete symmetries may also appear during the SSB patterns, they do not appear here. Sometimes, there is more than one possibilities to embed a maximal regular subgroup in the GUT, and we add indices to make this explicit to the reader. In general, a subscript C means that this groups contains $SU(3)_C$ as a subgroup and subscript L means that this groups contains $SU(2)_L$ as a subgroup. Definitions of indices for each maximal subgroup will be obvious to the reader in each section dedicated to a given GUT.

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