Author: Torrado Cacho, Jesús
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Summary

Part I

When the electro-magnetic radiation coming from the sky is observed at microwave wavelengths, one finds a mild background of radiation which is practically constant in all directions (once one removes the biggest foreground contributions, such as the radiation coming from our own galaxy). What is the origin of that radiation? When was it originated? When attempting to describe the current cosmological data with General Relativity, scientists of the early decades of the XX century found that the Universe must have been (and is) expanding for all of its life. As a gas that gets hotter when compressed, the Universe must have been much hotter in the past. So much that at some point electrons had so much energy that they preferred being detached from the atomic nuclei, streaming and scattering freely together with photons, forming what we call a *plasma*. Once the the Universe's growth diluted some of this energy, the electrons fell to the nuclei to form atoms, and the photons were free to travel through space and reach us. They form the background radiation we can see today, and that we call Cosmic Microwave Background, or simply CMB.

When one carefully observes the CMB, the first feature that shows up is how strikingly constant it is across all the sky. This is certainly not what we would expect. On the one hand, two regions of the universe emitting a practically equal signal is an indication that they are in *equilibrium* – the hotter and colder regions have been exchanging energy until they were at the same temperature. On the other hand, according to the speed our Universe expands in our cosmological model, regions that are separated by more than a few degrees in the sky are so very far apart that they never had time, since the beginning of the Universe to the emission of the CMB, to exchange any energy at all. So how can they be in equilibrium?

This contradiction was resolved in the 80's with a crucial modification of the cosmological model: we assume that in the early instant of the Universe it underwent an explosively accelerated (near-exponential) expansion. Such an expansion would stretch a small patch with almost constant temperature to a region bigger than the amount of the Universe that we can see today. Therefore, what is far apart in the Universe today, was so close in the past that there was almost no difference in temperature between these points. This explosive expansion stage was called *inflation*.

As the most stringent supporting evidence for inflation, the CMB also contains most of the information about inflation that we possess today. This information is found in some very small fluctuations in the CMB, ten thousand times smaller than the almost constant temperature of the CMB background. Those fluctuations originated when the explosive expansion turned small quantum random fluctuations on very small scales into differences of density of matter across big distances in the cosmos. If the fluctuations that we observe today were generated at very small scales, they must be well related to each other, or *correlated*. We characterise their correlation by averaging the difference in temperature over pairs of points in the sky separated by a certain angle. We call this average as a function of scale the *2-point correlation function* or *power spectrum*. If instead of having been generated very close to each other, the fluctuations were completely random and unrelated, those averages would be very close to zero. Instead, they are quite sizeable, and their precise properties can tell us much about the quantum origin of the fluctuations.

At the time of writing this thesis the Planck mission of the European Space Agency has made available its first batch of data, and we are waiting for the next and final release. Those data provide us with a very accurate measurement of the 2-point correlations of the CMB fluctuations, which is in agreement with that of previous experiments. In addition to that, the next data release is expected to contain a measurement of the 3-point correlation function or *bispectrum*, which is an average of the correlation between the fluctuations over three different points in the sky, instead of two. The 3-point correlation function, never measured before with sufficient precision, is of crucial importance for the study of inflation, since there is a specific prediction for it: if inflation occurred in the simplest way possible, we expect the 3-point correlations to be very close to zero, which corresponds to the initial fluctuations being Gaussian. Different, more complicated settings of inflation predict diverse and characteristic 3-point correlations. The moment is ripe, therefore, to test extensions of the simplest framework.

In the simplest model of inflation, the explosive expansion is caused by the presence of a single kind of *matter* in the universe, the *inflaton*, which possesses a negative pressure. In this thesis, we work under the assumption that the inflation, though dominant, was not alone – there were more species present, which appear to the inflation as a stiff background. When the inflation interacts with its background, the correlation functions of the CMB fluctuations at 2 and 3 points would possess small but distinctive features. By searching for those features in the CMB data, we can find out if the inflation evolved in such a non-trivial background, and even resolve the particular shape of it.

Since, as we stated, the 3-point correlation function of the Planck mission has not been released at the time of writing this thesis, we searched in the Planck data for features in the 2-point correlation function. After we found the best candidates, we computed the associated 3-point correlations that we expect to see in the new data release of Planck, and left them as test for our simple extension of the simplest model of inflation. In addition, we enlarged our search to include Large Scale Structure (LSS) data, which also contains some information on inflation, since galaxies and clusters are the final outcome of primordial fluctuations. The LSS data confirmed the best candidates that we found in Planck's CMB sky.

Part II

With the recent discovery of the Higgs particle in the ATLAS and CMS experiments of the Large Hadron Collider (LHC), all of the main predictions of the Standard Model of Particle Physics have been fulfilled, and it can be considered *complete*. Nevertheless, there is a number of experimental and theoretical reasons that encourage us to attempt to extend it.

On the experimental side, one phenomenon has already been clearly observed that finds no explanation within the Standard Model: *neutrino oscillations*, i.e. how streaming neutrinos spontaneously change their *flavour* between the three possible ones. This phenomenon has been measured beyond doubt in different sources, from the stream of neutrinos coming from the Sun, to those generated at particle accelerators. This kind of behaviour is only possible for particles possessing a non-zero mass, while Standard Model neutrinos are necessarily massless particles. Any explanation for neutrino masses implies physics beyond the Standard Model.

The nature of Dark Matter also lacks an explanation within the Standard Model. The presence of Dark Matter is necessary to explain the cosmological and galactic dynamics of the Universe as we observe it (same for Dark Energy, which is not discussed here). Despite that fact, Dark Matter has never been directly observed in accelerators or astrophysical particle physics experiments. Therefore, little is known about the *Dark Matter particle* and its possible fitting in an extension of the Standard Model.

On the theoretical side, there exist several arguments. For starters, the mass of the Higgs particle, though not predicted by the Standard Model, is surprisingly low. The surprise comes from the fact that particles are made heavier through loop interactions with the particles they are coupled to. Since the Higgs field is coupled to all the fermions of the Standard Model, we would expect that they have driven its mass much higher. This suggests the existence of a symmetry that cancels such contributions. One possibility is introducing counterparts of the Standard Model particles with different spin but approximately equal mass. The difference in spin would automatically cancel the contributions to the Higgs mass, and, due to the mass of the new particles been approximately equal to those known, the new particles could possibly be observed at the LHC within the next years. We call that symmetry *Super-Symmetry* (SUSY), and we abbreviate it as MSSM, the *minimal possible SUSY extension to the Standard Model.*

SUSY has an additional consequence: it hints towards the unification of all fundamental forces operating at subatomic scale, i.e. electro-magnetic, *strong* and *weak* forces. We call this speculative phenomenon *Grand Unification*, and any theory that describes it in detail is called *Grand Unification Theory* (GUT). GUT's would explain why the *hyper-charge*, one of the quantum numbers of the Standard Model particles, is in fact quantised. SUSY, combined with GUT, would also provide us with several candidate particles to constitute the Dark Matter that we observe (indirectly) in the Universe.

The MSSM possesses all the desired features mentioned above, but at the cost of introducing many new free parameters in the model. This makes it less predictive, which is never desirable for a physical model. In addition, it does not address the quantum nature of the remaining fundamental interaction: gravity. Those issues can be addressed assuming that the MSSM is embedded in String Theory. String Theory provides us with a well-defined description of quantum gravity, and, once the geometry and some properties of the theory have been chosen, all the phenomenology at all energy scales, including those that we can observe today, can be computed.

This is the case in particular of the setting considered in this thesis, Heterotic Strings compactified in Symmetric Toroidal Orbifolds, *compactification* meaning the assumption that the extra dimensions are finite and very small compared to the scales of Standard Model physics. In this theory, one only needs to specify the geometry of 6 extra dimensions, together with the effect of that geometry in the messengers of the fundamental interactions (in that case, a *rank-16* GUT): given that, the content and possible interactions of all fundamental particles are determined.

In this thesis, we perform a classification of all possible symmetric toroidal orbifolds in which heterotic strings can be compactified. In order to achieve that, we make use of their correspondence to crystallographic space groups, which are already known up to dimension 6, and whose number is fortunately finite. We establish which of those crystallographic groups possess the desired properties to describe the MSSM at low energies, and compute some of the relevant properties that allow for the description of the particle content and their interactions. We also relate our classification to previous, incomplete ones in the literature.