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## Higgs dynamics in the early universe

Vis, J.M. van de

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**Author:** Vis, J.M. van de

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# Summary

This is a thesis about particle physics and cosmology. Particle physics is the science of the smallest constituents of matter that we know, and the interactions between them. We describe particle physics in terms of the Standard Model. Over the last decades, a large range of experiments has established its validity by carefully studying the reaction products of collisions in particle accelerators. The Standard Model of particle physics is a very successful theory; all the particles that it predicts have been found experimentally and so far no significant deviations of their properties have been observed.

Cosmology is the study of the evolution of the universe as a whole. General Relativity, the theory of gravity, describes the expansion of the universe. Unlike particle physics, we can not test cosmology in experiments, but only through observations of the cosmos. Observational data, such as the distribution of galaxies and the properties of the Cosmic Microwave Background, are very important for reconstructing the history of the universe.

On the surface, it might seem like particle physics and cosmology do not have much to do with each other. After all, we don't need elementary particle physics to describe the motion of the planets in the solar system. Particle interactions take place on tiny length scales, so why would they become relevant when we study the evolution of the universe as a whole? There are three main answers to this question:

- **The evolution of the universe depends on the particle content.** There are various contributions to the total energy of the universe, e.g. radiation, massive particles and dark energy. The dominant contribution determines the expansion rate of the universe. Understanding the history of the universe requires knowledge of the properties of all particles that are present at different stages of the cosmological evolution.
- **The history of the universe determines the present day particle content.** The masses of the elementary particles, as well as their interaction rates depend on the temperature of the universe. Initially, all interaction rates are very large and particles get converted into each other incessantly. When the temperature decreases, certain interactions become slow compared to

the expansion rate of the universe. As a consequence, some particles stop interacting and their amount remains fixed from that moment on. This process is called ‘freeze-out’. The relic abundance of helium and the existence of a cosmic neutrino background are both results of freeze-out.

- **We can use cosmology to probe particle physics at very large energies.** There is strong evidence that the early universe goes through a period of cosmic ‘inflation’ during which it expands by at least a factor  $10^{78}$ . During this enormous expansion, the tiny length scales relevant for particle physics get blown up to cosmologically observable scales. We can thus use telescopes to study traces of particle physics in the very early universe. This is extremely interesting, because we can not assess the large energy scale of the early universe in any experiment in the laboratory.

There is fairly strong consensus amongst cosmologists about the history of the universe. The standard picture is that the universe initially goes through a period of inflation and then follows ‘Hot Big Bang’ evolution: the evolution from a hot and dense particle soup to the universe of stars and galaxies that we live in today. In this cosmological framework, which is summarized in figure 1, one can correctly predict the relative amounts of light chemical elements (hydrogen, helium and lithium) and also the temperature and properties of the temperature fluctuations of the Cosmic Microwave Background radiation.

There are however clear signs that our understanding of cosmology and particle physics is not complete. Examples are the strong experimental evidence for the existence of dark matter and dark energy, and the asymmetry between matter and antimatter, which is the topic of the second part of this thesis. These observations might be explained by the existence of new particles or a modification of the theory of gravity. Modifying our existing theories is a very subtle task, because the Standard Model and General of Relativity have survived many experimental tests. Modifications of the theories should not affect these successful predictions.

## The Higgs particle

The Higgs particle and the corresponding Higgs field play a very important role in this thesis. It is important to make a distinction between particles and fields. Fields are ubiquitous in physics. Examples are the gravitational field that determines how planets move around a star and the electric field that causes an electron to accelerate. We can associate a field to each particle of the Standard

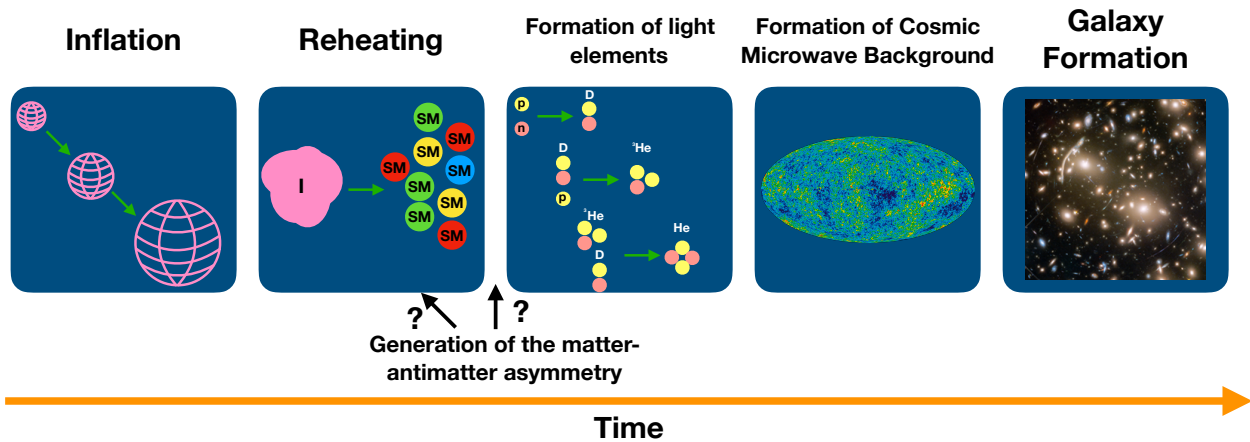


FIGURE 1: Timeline of the early universe. The picture merely shows the chronological order of the events, but time intervals are not to scale. The moment in which the asymmetry between matter and antimatter was formed is unknown. We know that this should have happened between inflation and the formation of light chemical elements.

Model. The particles, that can be detected in particle colliders, are excitations or ‘ripples’ of these fields. An example is the photon, which is an excitation of the electromagnetic field. Particles are localized in a small part of space, but the corresponding fields fill the entire space (although their values can be zero).

The values of the fields are determined by the corresponding potential energy function. We are all familiar with this concept through our experience with gravitational potential energy. This is the amount of energy that you need to climb a mountain, for example. Our experience also tells us that nature tends to minimize potential energy, this happens for example when a rock rolls down the slope of a mountain. The potential energy of all Standard Model fields is smallest when the fields are zero, except for the Higgs field. The potential of the Higgs field is shown in the left panel of figure 2. The black line displays the value of the potential energy as a function of the value of the field. The minimum is located at some non-zero value. The other particles of the Standard Model interact with the Higgs particle but also with the background value of the field. The interaction with the background value makes these particles massive.

The left panel of figure 2 shows the potential at low temperature. This picture is applicable today. In the early universe however, the large energy density during inflation and the high temperature after inflation modify the shape of the potential. In the research described in this thesis, the Higgs field is never at the low-temperature minimum. We will see that a displacement from this minimum leads to very interesting dynamics.

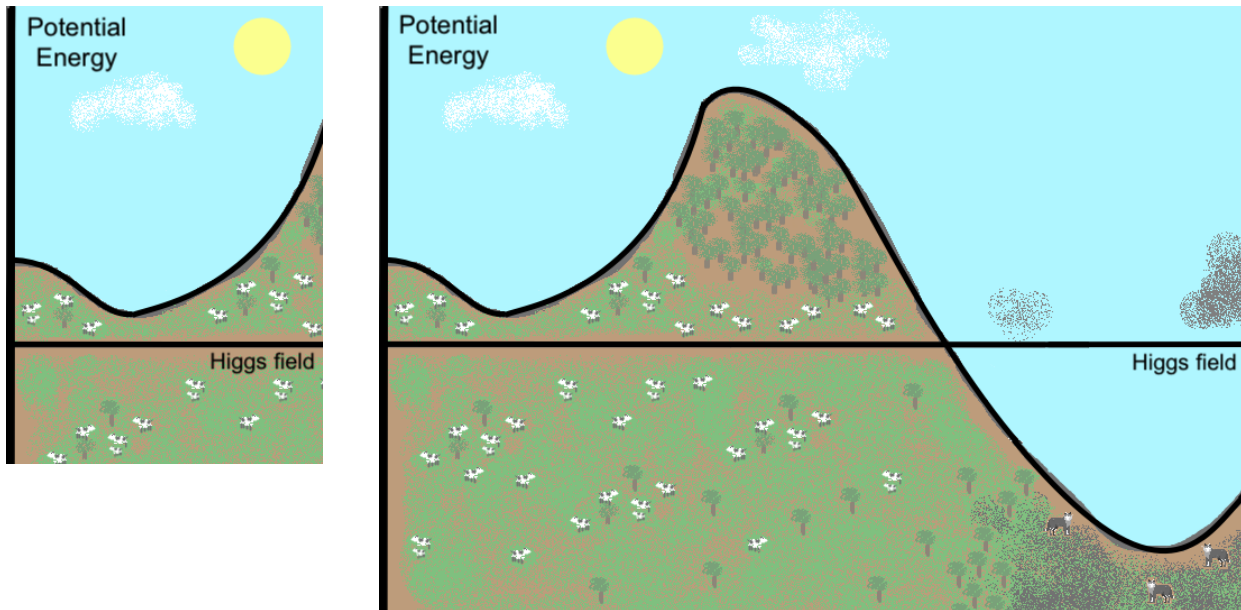


FIGURE 2:

Left: The Standard Model Higgs potential at low temperature. The Higgs field sits at the valley to minimize the potential energy.

Right: Measurements suggest that the Higgs potential might actually have a second minimum at a much larger field value.

## Part I: Reheating the universe after inflation

In the standard picture of cosmology, the evolution of the universe starts with a period of inflation. During this period, the universe expands by an enormous factor. Inflation is driven by the inflaton field, which has a large amount of potential energy that dominates the entire universe. After a while, inflation ends. The inflaton then transfers its energy to the production of Standard Model particles. These particles form the hot and dense particle soup that evolves according to the standard Hot Big Bang model. The energy transfer from the inflaton to the Standard Model particles is called ‘reheating’.

### Higgs stability during reheating

The exact shape of the Higgs potential depends on the interactions of the Higgs field with other fields. Assuming that there are no new particles beyond the Standard Model, results from collider experiments indicate that the Higgs potential might look like the right panel of figure 2 instead of the left panel. There is a second, much deeper, minimum at a larger value of the Higgs field. We know that the Higgs field can not be situated in the deep minimum nowadays, since that would lead to a collapsing universe. In the present day universe, the bump that separates the minima prevents

a transition from the shallow minimum to the deep minimum. In the early universe, however, the Higgs field was displaced from the present day minimum, so we must try to understand why the Higgs field ended up in the shallow, safe minimum instead of the deep, dangerous minimum.

At first glance it seems that, during inflation, the energy in the universe is much larger than the energy required for the Higgs field to go over the bump; the Higgs field would thus end up in the deep minimum. Fortunately, an interaction between the Higgs field and gravity prevents this transition. This interaction raises the height of the barrier, such that the Higgs field can not pass it during inflation.

But unfortunately, the interaction between the Higgs field and gravity leads to problems during reheating, when the inflaton oscillates at the bottom of its potential causing the barrier to periodically appear and disappear. This leads to very efficient production of Higgs particles. In chapter 3 we show that the fate of the universe depends on the strength of the Higgs-gravity interaction. If the interaction is very strong, the efficient production of Higgs particles allows the Higgs field to transition to the dangerous deep vacuum. For a weaker Higgs-gravity interaction, we can not draw a conclusion, as our computational tools are not suitable to demonstrate that the Higgs stays in the safe area left from the barrier. The reason is that it is very difficult to correctly describe non-static processes.

So what should we conclude from this? Our mere presence proves that the universe did not collapse during reheating. Does this imply that the Higgs-gravity interaction is not so strong that the Higgs transitioned to the deep minimum during reheating? It might. It might also mean that the potential looks like the left panel of figure 2 after all, which could be the result of the presence of yet unknown particles.

### **Reheating after Higgs inflation**

There are many different models for inflation. Typically, inflation is driven by a so-called scalar field. The Higgs field is the only scalar field that has been observed experimentally. It is therefore an interesting candidate for inflation. The Higgs field can only drive inflation if its potential becomes very flat (and positive) for very large field values. To satisfy this condition, we again need a Higgs-gravity interaction, which must be larger than the one of chapter 3.

Since the interactions between the Higgs field and the other Standard Model fields are known, we can predict how reheating proceeds in the Higgs inflation scenario. In chapter 4 we find that the

reheating process depends on the strength of the Higgs-gravity interaction. When the interaction is very strong, reheating is extremely fast, and the energy density in the Higgs field gets almost instantly transferred to the gauge bosons of the electroweak interaction. These gauge bosons will in turn decay into all the other particles of the Standard Model. When the Higgs-gravity interaction is weaker, reheating takes longer, and happens mostly through the production of Higgs particles. The Higgs particles will then also decay into other Standard Model particles.

## Part II: Generating the matter-antimatter symmetry

According to the Standard Model, each particle has a corresponding antiparticle, that has the same mass, but opposite charge. If a particle and an antiparticle collide, they annihilate each other. All the matter that we see around us, on earth and in the universe, is actual matter, not antimatter. If particle physics were described by the Standard Model throughout the entire history of the universe, there would be no asymmetry between matter and antimatter. Apparently some unknown particle-physics process generated an excess of matter at some moment in the history of the universe. This process is referred to as ‘baryogenesis’.

The Standard Model can not provide a process for baryogenesis for two reasons: it does not distinguish strongly enough between particles and antiparticles, and it does not give rise to any useful out-of-equilibrium process. Being out-of-equilibrium simply implies that the rate at which matter is created is not equal to the rate at which it is destroyed. If these rates always remain equal, an excess of matter can not be formed. Examples of out-of-equilibrium processes are the freeze-out of interaction rates and first-order phase transitions. To explain the excess of matter over antimatter, the Standard Model thus needs to be extended, for example by the addition of new particles that interact differently with matter and antimatter.

In part II of this thesis we study the possibility of generating the matter-antimatter asymmetry during the ‘electroweak phase transition’. This process is sketched in figure 3. The existence of the electroweak phase transition is a consequence of the temperature dependence of the Higgs potential. At large temperature, the potential only has a minimum at zero field value. As the temperature lowers, the potential changes shape and the minimum at non-zero field, that we see in figure 2, appears. The electroweak phase transition is the moment when the Higgs field transitions from zero to the non-zero value. From that moment on, the other particles become massive. In the Standard Model, this is not a first-order phase transition, but a smooth, continuous process. Since the nature

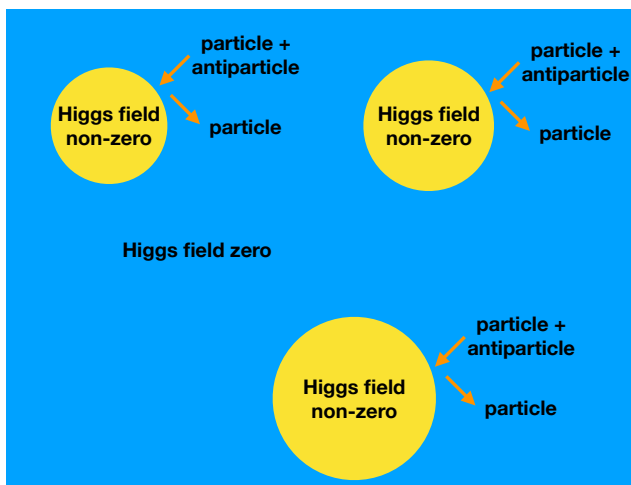


FIGURE 3: Sketch of electroweak baryogenesis. The first-order phase transition proceeds by the formation of bubbles in which the Higgs field has a non-zero value. The surrounding particles and antiparticles interact with the bubbles. In these interactions, an excess of matter is created. While swallowing the excess of matter, the bubbles expand until they fill the entire universe.

of the phase transition depends on the shape of the Higgs potential, we need to modify the potential by adding some new particle.

### Model-independent description of baryogenesis during the electroweak phase transition

There are many different particles that one could add to fulfil the conditions for successful baryogenesis. Of course, the addition of these particles should be consistent with results from particle-physics experiments. In principle, for each different model of new physics, one should make a comparison to experimental results and compute the value of the matter-antimatter asymmetry.

In chapter 6 we attempt to study baryogenesis in a way that does not depend on the chosen model of new physics. As long as the newly added particles are sufficiently heavy, all models of new physics can be parameterized in a unified way: the Standard Model is extended by a set of so-called ‘effective operators’, which are new interactions between Standard Model particles. The conditions for the generation of the matter-antimatter asymmetry can now be fulfilled. One can compare the different effective operators to their experimental constraints and compute the value of the baryon asymmetry including these operators. In this way, all models with new heavy particles can be studied in one go.

In chapter 6 we focus on two effective operators in particular: a new interaction for the Higgs field and an interaction that distinguishes between top quarks and anti-top quarks. Unfortunately, we find that the method with effective operators is not completely feasible. The new particles that

need to be added to get a first-order phase transition need to be relatively light, which prohibits a parameterization in terms of effective operators. Our wish to study electroweak baryogenesis in a completely model-independent way can thus not be fulfilled.

## The importance of leptons

The outcome of chapter 6 is not only disappointing because the approach with effective operators is not completely feasible, but also because the value of the matter-antimatter asymmetry is too small to explain the observed value. The strength of the interaction that distinguishes between particles and antiparticles is proportional to the mass of the particle. Since the top is the heaviest matter particle, the effects of other matter particles are often neglected in computations of the matter-antimatter asymmetry.

In chapter 7 we have shown that the tau lepton, a particle that is much lighter than the top quark, can play an important role during electroweak baryogenesis. Even if the new interaction that distinguishes between particles and antiparticles is only effective in the top-quark sector, including the tau leptons in the computation still enhances the asymmetry. The asymmetry becomes even larger when the distinction between particles and antiparticles is in the tau-lepton sector. The reason for this is the weaker experimental constraint on the new interaction involving the tau, but also the fact that the tau lepton can move more easily through the medium surrounding the bubbles, allowing more time for the matter excess to be formed. In this model, the observed value of the matter-antimatter asymmetry can be explained.

## Outlook

The research described in this thesis does of course not end here. A possible direction of further research would be to reconcile the topics of chapters 3 and 4. It could be possible that the Higgs potential has a second, deep minimum but also supports inflation. What would happen during reheating in this case? To make really accurate predictions about reheating, one should use so-called lattice computations. Comparing lattice results to our results using the framework of chapter 4 is work in progress. Accurate predictions for reheating are essential for using the data from the Cosmic Microwave Background to determine the feasibility of different inflationary models.

On the electroweak baryogenesis side, the computational accuracy should be improved. There are different methods for computing the matter-antimatter asymmetry and the relation between these

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methods should be better understood. Future collider and gravitational-wave experiments might shed light on the electroweak phase transition and, hopefully, help to understand how the matter-antimatter asymmetry was generated.