Non-decoupling of heavy scalars in cosmology
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Summary

If a system heats up, more degrees of freedom become available. In ice certain vibrations of the water molecule are not available, yet in liquid water they are. This can be made visible by putting both ice and water in a microwave oven. The microwave emits radiation exactly at the wavelength of one of these vibrations and is therefore very efficient in heating water. On the other hand, heating ice with a microwave oven takes much longer.

In our universe there are many degrees of freedom that can be made visible only at very high temperatures. Some of those we know, or at least we think we know. The Higgs particle, the particle the LHC in Geneva is looking for, is a well known example of a degree of freedom that is observable only at very high temperatures. We think we know the Higgs particle exists because it betrays its existence at lower temperatures due to certain corrections to specific processes. Some of these processes have been measured very accurately and the measurements can be explained only by assuming the existence of a Higgs particle.

There are likely many more degrees of freedom at very high temperatures that we do not yet know. We currently do not know which theory explains the physics at the highest temperatures. What we do know is that all proposed candidates predict many new degrees of freedom. In order to understand such theories, it is important to know the degrees of freedom associated to it. These degrees of freedom are visible only under very special circumstances. Such circumstances are not available on earth, but our universe offers possibilities. This thesis is about what we can learn from these degrees of freedom by studying the properties of our universe. Why it is that our universe is such an exquisite measuring instrument for these degrees of freedom, what we have learned and can still learn about them is the subject of this summary.

Our universe

According to the latest measurements, our universe is 13.7 ± 0.4 billion (10^9) years old. Furthermore, our universe is at large scales spatially flat, homogeneous and isotropic. Spatially flat means that parallel lines will stay parallel forever. On a curved surface parallel lines will not stay parallel. For example, on a positively curved surface, such as the surface of the earth, parallel lines shall always cross (figure 6). Homogeneous means that the universe is the same everywhere. This is of course not meant to be true at small scales: a cubic metre in the middle of a star is clearly different from a cubic metre in the emptiness of outer space. Yet, if we compare the properties of a randomly chosen cube with sides of approximately 100 million light years[9] such cubes turn out to be very similar to any other randomly chosen cube. Isotropy means that the universe is the same in all directions, which of course must be understood also to be valid only at scales of about 100 million light years.

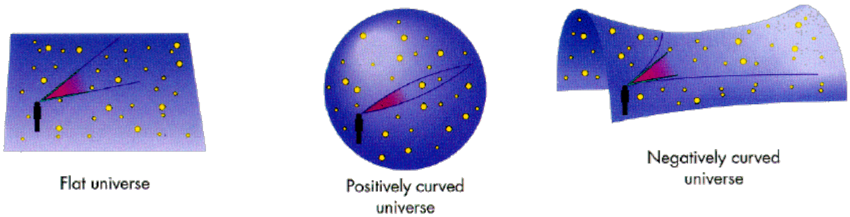

Figure 6: *In a flat universe parallel lines stay parallel. In a curved space this is different: in a positively curved space parallel lines will close up on each other, in a negatively curved universe the distance between parallel lines will keep increasing (edited version of an image from James Schombert).*

A flat, homogeneous and isotropic universe is very special. An apt illustration is provided by the first radiation that could travel freely through our universe, the microwave background radiation (figure 7). This radiation is emitted when the universe cooled down below the point where hydrogen was ionised, which happened approximately 380,000 years after the big bang. In the early universe all hydrogen was ionised, its positive nucleus and negative electron were not bound together but formed a charged plasma in which they could move freely. The free electrons in that plasma are very efficient in scattering light. Therefore, all particles of light were constantly scattered and thus could not travel freely. Then, 380,000 years after the big

[9] A light year is the distance light travels in one year, which is approximately 9.5 trillion (10^{12}) kilometres.

bang, the universe cooled down enough, to about 3000°C, to allow the electrons to bind to the hydrogen nuclei and form atomic hydrogen. Atomic hydrogen is much less efficient in scattering light, thereby allowing the particles of light to travel mostly unscattered to our telescopes. This radiation thus provides us with a picture of the universe as it was 380,000 years after the big bang. Due to the expansion of the universe this radiation has cooled down by about a factor 1100, to a temperature of 2.73 Kelvin (−270.4°C) today.

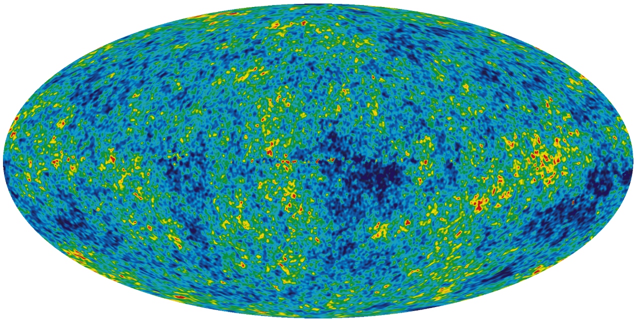

Figure 7: *The microwave background radiation as observed by the Wilkinson Microwave Anisotropy Probe (WMAP). The temperature of the radiation is on average* 2.73 *K, about* −270.4°C*. When emitted, this radiation had a temperature of about* 3000°C *but has cooled down to the current temperature due to the expansion of the universe. The temperature difference is displayed in false colors and represents temperature differences in the order of a hundred thousandth of a degree.*

From figure 7 it is evident that the temperature of this radiation is approximately equal everywhere. This is very nonsensical: the radiation that is received at say the north pole took 13.7 billion years to travel to us, the same holds for the radiation that is received at the south pole. Therefore, the distance between the points observed at both poles is 27.4 billion light years. These points can currently not see each other, and yet the temperatures are equal. Looking at it more closely, it is actually a lot stranger. As this radiation was emitted 380.000 years after the big bang at that time light could not have travelled more than 380,000 light years. Therefore, we would not expect areas larger than 380,000 light years at the time of the emission of the microwave background radiation to share the same temperature. Such an area turns out to cover about one degree of our current sky. This means there are about 40,000 independent areas with a surface area of one square degree that all have the same temperature, despite the fact that they have never been in causal contact at the time they emitted their temperature signal.

When we look closer at this signal, it turns out that there are correlated ripples, as can be seen in figure 1.3 in the introduction. The first peak is related to the distance sound has travelled since the big bang, a sound wave at the size of the horizon would have been at its maximum. The other peaks are the higher harmonics. Yet, at distances larger than the sound horizon, up to the size of our current visible universe, the signal is found to be correlated. This appears to violate the idea that, since the big bang, no signal can have covered more distance than light.

Also a flat universe is uncommon. Gravity has the tendency to amplify existing concentrations of matter, which increases the curvature. That means that a universe that is flat now must have been very flat in the past. A flat universe means that the kinetic energy of matter is equal to the gravitational energy that keeps that matter together. In order to have a universe that is as flat as observed today the balance between kinetic- and gravitational energy must have been very finely tuned. For example, when the background was created, the allowed imbalance is of the order of four millionth of a percent. 10^{-35} seconds after the big bang (in the next paragraph the meaning of this number will become clear) the energies needed to be balanced by less than one part in 10^{27}. To illustrate, if a rocket is sent with a similar precision to the most nearby star,[10] the rocket will still be aimed with the precision of the radius of an atom, one ten-billionth of a metre.

Summarising, we can say that our universe is very sensitive to the initial parameters. To get a universe that is as our universe today requires a very precise tuning of these parameters, which is called finetuning. When much finetuning is needed, it is usually considered to be unnatural and problematic. Our universe requires a lot of finetuning, unless a physical mechanism can be found that automatically tunes the parameters to the required values. This mechanism has been found: inflation.

Inflation

In 1980 Alan Guth proposed the idea that just after the big bang our universe went through a period of exponential expansion, inflation. This very rapid expansion can solve the issues with finetuning, as described in the previous paragraph. Inflation is caused by a positive vacuum energy in our universe. Solving Einstein's equations in the presence of a positive vacuum energy, one finds as a solution an exponential

[10] The most nearby star is of course our sun. Yet here I am referring to Proxima Centauri, at a distance of 4.2 light years.

accelerated expansion.[11] This has many consequences.

A first consequence of inflation is that the distance between two points can grow faster than the distance light can travel. This is illustrated in figure 1.2(a) in the introduction. This allows the possibility that the current observable universe before inflation covered such a small area that light at that point in time was able to cross the entire visible universe. This allowed the universe to attain thermal equilibrium before inflation, explaining why the microwave background radiation has the same temperature everywhere as the whole observable universe has been in thermal contact.

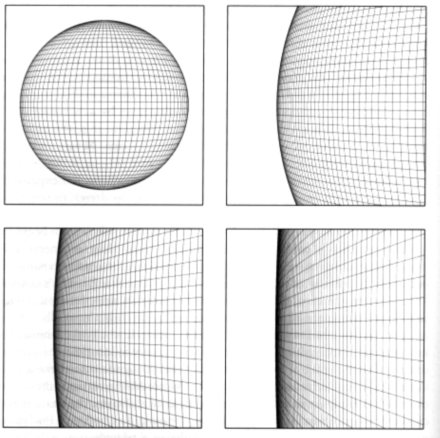

Figure 8: *In an exponential accelerated expanding universe the curvature decreases (image from Margaret Hanson).*

A second consequence of inflation is that the universe becomes increasingly flat, that kinetic and gravitational energy become increasingly balanced. The equations of general relativity normally yield a curvature that increases with time, in an exponentially expanding universe the curvature instead decreases with time (figure 8). Given enough inflation, the universe will be very flat and the kinetic and gravitational energy will be very balanced, up to the required one part in 10^{27}.

[11] Einstein had used this observation to add a cosmological constant to his equations, such that the acceleration term exactly cancels the deceleration caused by gravity. This would allow a static universe. He later called this idea his "biggest blunder of my career", as it was found by Willem de Sitter to be incapable of explaining a static universe. Several years later, in 1929, Edward Hubble discovered that the universe is not static but expanding. Yet, while Einstein's proposed term does not allow a static solution of our universe, it does allow an exponential accelerated expanding one.

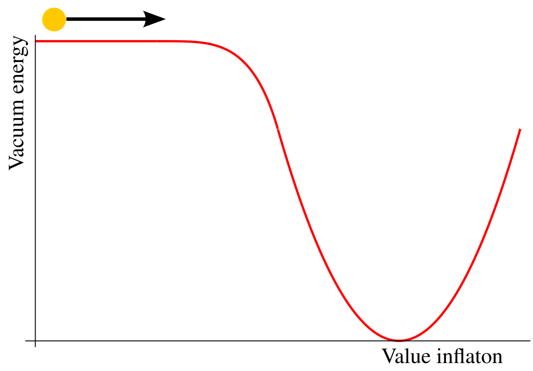

Figure 9: *Inflation is caused by a field that during some period in time generates a large vacuum energy. Inflation ends when this field stops generating this vacuum energy and eventually dumps all its energy into the matter that currently fills the universe.*

A third consequence of inflation, the consequence this thesis is partially built upon, is that inflation predicts ripples. After inflation, these ripples will travel as sound waves through the universe to generate the observed correlated ripples in the microwave background radiation (figure 7 and 1.3). In order to understand the generation of these ripples, it is first needed to study the mechanism that drives inflation.

As stated, a vacuum energy leads to an exponentially accelerated expansion of the universe. We now turn to the mechanism that can generate such a vacuum energy for a period of time. When this mechanism stops working inflation will end and the vacuum energy will turn into the particles that we are made of. In order to achieve this, we need a field that generates a vacuum energy when it is not in its state of minimal energy. Furthermore, a slow development towards the state of minimum energy is required. This can be achieved by a field that can spend long periods of time outside its state of minimum energy, as is depicted in figure 9. During inflation, the field will sit on the flat elevated stretch, in order to fall down the abyss at the end of inflation.

The field required to generate inflation is called the inflaton. This field develops slowly and has to obey the laws of quantum mechanics. One of the most important properties of quantum mechanics is that everything is somewhat uncertain. This means that the value of the field will also be somewhat uncertain and can thus differ from place to place. This generates quantum ripples, that due to the rapid expansion of the universe will be blown up to the size of our visible universe and thereby form the ripples in the microwave background radiation.

For this mechanism to work it is needed that the universe in a very, very short time expands by a very, very huge amount. In numbers, in about 10^{-34} seconds the universe must expand by a factor 10^{24}. Expanding this thesis by a similar amount, it would end up filling the current visible universe. Such an extremely rapid expansion places strong requirements on the field that drives inflation. The vacuum energy must, despite the rapid expansion of the universe, remain very constant in order to create ripples that match the observed ripples in the microwave background radiation. The needed requirement is called the “slow-roll” condition. It turns out to be very simple to write down a single field equation that satisfies this condition. The problem is that our universe contains more than one field.

High energy physics and inflation

The physics of the particles that we are made from, electrons and quarks,[12] as well as the forces that influence these particles[13] is described by particles and fields. At low temperatures there are already many fields. Increasing the temperature, the situation all but improves, as at higher energy more instead of fewer degrees of freedom become available.

At this moment we do not know a theory that can simultaneously describe the physics at the smallest scales, the scales of electrons and quarks, and the largest scales, the scale of galaxies and our universe. At the smallest scales the quantum theories for electrodynamics, the weak and the strong force are very accurately described by the standard model. At the largest scales the only relevant force is gravity, which is accurately described by Einstein’s theory of general relativity, but does not have a quantum version. Because it is currently not known how to combine general relativity with quantum mechanics there is to date no description of gravity at the scales of the standard model.

Yet, we do have candidates for a quantum theory that should describe both the standard model and general relativity. The main candidate is string theory. In this theory, the fundamental building block is not a point particle but a tiny string. This allows to overcome the issues with gravity at the smallest scales. However, it turns out that string theory does not work properly in three dimensions. The problems can be

[12]Quarks are the particles that protons and neutrons are made of. In turn, protons and neutrons are the building blocks of atomic nuclei that together with electrons make atoms.

[13]Electromagnetism, the strong force that keeps atomic nuclei together and the weak force that causes radioactivity.

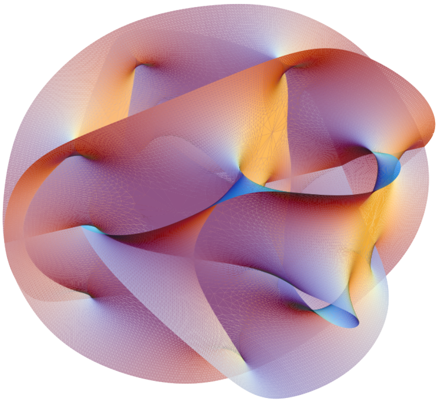

Figure 10: *A projection of a six dimensional space of the kind that is used for compactification. The many sizes and shapes of both the overall volume and the "holes" are degrees of freedom (image from Andrew Hanson).*

solved in a space with nine dimensions.[14] This of course contradicts our observations of our obviously three dimensional world. Yet, our observations are limited to the scales we can actually measure. We know the universe has three large dimensions, but it might just be that there are also a number of small dimensions. Compare this to a long rope: at close the rope clearly is three dimensional, with a length along the rope and a thickness along the two dimensional cross section. Yet, if looked upon from afar, the thickness is no longer visible. Also for the physics of the rope the "small dimensions" can become irrelevant. If you make a wave in the rope the thickness usually does not matter much. Together with the material the thickness will determine the stiffness, but for describing the wave the only relevant degree of freedom is a coordinate along the length of the rope. Only at very short wavelengths it will be possible to have thickness distortions which will make the "small dimensions" visible.

In order to go from the nine spatial dimensions of string theory to the three spatial dimensions of our world, we need a method to make six dimensions very small, "compactification". To achieve this, it is assumed that the nine dimensional space is made of our three dimensional space with at each point a very small six dimensional

[14]Often, string theory is said to live in a ten dimensional space. These are nine spatial dimensions and time.

space (figure 10). The size and shape of this six dimensional space are not fixed, but can vary from point to point. This gives additional degrees of freedom that in our three dimensional world will be visible as so-called scalar fields. So far, these fields have not been found, which means that the sizes and shapes of this six dimensional space must be very stable. This is not the natural state, a problem that has only been partially solved at the beginning of this century. It has been discovered that this six dimensional space can be kept small by adding equivalents of electromagnetic fields and charges, because changing the shape or size of a space with an electromagnetic field requires energy.

One of the best known mechanisms to achieve this is the mechanism proposed in 2003 by Kachru, Kallosh, Linde and Trivedi (KKLT). An issue with this mechanism is that it uses a stepped approach to reach the solution, where each step is assumed to be independent from the previous steps. In chapter 2 we have shown that this is in general not the case and that large corrections to this mechanism can be expected. Another mechanism to fix the sizes and shapes of the six dimensional space is the so-called large volume scenario.[15] This scenario uses a similar stepwise approach as the KKLT mechanism to stabilize the sizes and shapes. Yet, in this model the corrections turn out to be much smaller because these corrections are getting smaller when the volume gets larger.

In chapter 3 we look at a model in the supergravity-theory and study how in supergravity a vacuum energy can be added. Supergravity can be used as a low energy description of string theory. A problem of both string theory and supergravity is that they describe spaces with a negative vacuum energy. Inflation requires a positive vacuum energy, in our current universe the vacuum energy is almost identically zero.[16] In order to achieve this, an "uplifting"-term has to be added. The problem with such an "uplifting"-term is that often the theory will become unstable after adding such a term. We have shown that the mechanism that turns stable theories unstable also allows the opposite, and turn a specific class of unstable theories stable after "uplifting".

In the last two chapters, chapters 4 and 5, we look at the possible means to find out the nature of the extra small dimensions. We do this in the specific context of inflation, because during inflation the correction terms play the most important role.

[15] Large volume here means large with respect to the size of individual strings which are about 10^{-33} meter in size. From our point of view this large volume is still very small, in the order of 10^{-23} meter, which is too small to be detectable by the LHC in Geneva.

[16] Recent observations have shown that also in our current universe there is a positive vacuum energy, because the expansion of our universe is currently accelerating. However, the required energy term is much, much smaller than the vacuum energy during inflation.

Intuitively, this makes sense: if three dimensions get 10^{24} times larger, why do the other six dimensions not participate? As argued in chapter 2 it is not easy to keep the small dimensions small. Mechanisms that do keep these dimensions small generally require extra corrections. Such corrections can play a big role during inflation, to the extent that inflation is not described by only one field but by many. If these fields are approximately equally massive and thus can easily contribute to inflation we are in the domain of multi-field inflation. This kind of inflation is studied by many people and results in interesting means to test the theory with observations of our universe.

We have shown that even when the fields that influence the inflaton field are much more massive they also have consequences. The common assumption is that contributions from such very massive degrees of freedom are strongly suppressed. Yet, during inflation these degrees of freedom can determine up to a very large degree what is the trajectory along which the inflaton field develops. This can cause the inflaton field to experience turns (cover image and figure 4.1). Such turns turn out to generate potentially observable signals in the microwave background radiation. This offers the opportunity to study the physics of these very massive degrees of freedom by studying the microwave background radiation. This is one of the main conclusions of this thesis.