The universe on edge: Limits of the effective field theory approach in the very early universe
Oberreuter, J.M.

Citation for published version (APA):
Oberreuter, J. M. (2013). The universe on edge: Limits of the effective field theory approach in the very early universe
SUMMARY

In a way, physics is still recovering from the 1896 revolution started by Max Planck in Berlin, then being fostered in Göttingen and from there finally conquering the world: the conception of quantum mechanics. The fact that objects on a very small scale such as atoms, atomic nuclei and photons behave qualitatively very different from our every day experience is not only puzzling the layman, but still ignites a lot of discussions in physics. A very important one is, how this theory tallies with the other big theory developed around the beginning of the previous century, namely the theory of relativity.

QUANTUM MECHANICS AND RELATIVITY

The two big theories, which we have in physics are in a way antagonists. To see this, it is important to realize that every theory in physics comes with a domain of applicability. For a specific question in mind, there is a suitable theory to answer it, and if not, it can be developed. The beauty is, that mostly, a theory does not only apply to one question but to a whole class of them. We even know, which questions belong to the same class and all of them thus need to be treated with the same theory, otherwise leaving us with a puzzling contradiction. The different classes are characterized by the value of some parameter e.g. some energy scale.

In the case of quantum mechanics, the parameter which occurs in all the expressions is Planck’s constant $\hbar$, which is negligibly small compared to all the other quantities, that enter in the physics of everyday questions. However, it is of the same order of magnitude as quantities on the atomic scale. All questions for which $\hbar$ is a considerable number should be treated quantum mechanically. In the case of the theory of special relativity the distinguishing parameter ist the speed of light. The intriguing effects of special relativity are all supressed and invisible, if the velocities involved in the problem are small as compared to the speed of light, as in everyday situations, but they do becomes visible for situations involving cosmic rays, ultra-fast trains or warp-driven space-flight. There is one new insight, though, which is very substantial to special relativity and has changed the way we are thinking about physics very fundamentally since the Newtonian paradigm. This is the observation, that time and space are not independent coordinates, which provide labels for when and where a specific event has happened, they
Summary

Figure 3.1: The standard model of particle physics contains and describes all the elementary particles we know of today. Source: Fermilab

are rather intricately related and cannot be considered or even exist separate from each other. Special relativity has uncovered that the notion of space must be extended, called space-time.

It is very informative to understand the motivation, which led Einstein to the discovery of special relativity. What puzzled him was that the laws of classical mechanics according to Newton were incompatible with the laws of electrodynamics as uncovered by Maxwell. The motivation for developing special relativity was to unify two theories, which were completely correct in their own realm but led to a contradiction in a regime, which brought their characteristics to an overlap.

Many years later, the same problem arose with the theory of special relativity and the theory of quantum mechanics. Combining the symmetry of space-time with quantum physics it turned out that the “whole is more than the sum of its parts”. This new thing took the shape as quantum field theory. It is the theory, which describes the creation, annihilation, the behaviour and interaction of elementary particles. The standard model of particle physics, in which all matter and forces are fundamentally described by such particles, is formulated in the language of quantum field theory with specific symmetries, which relate the couplings and masses of particles. Thanks to the symmetries those particles can be grouped in families and generations, as is depicted in figure 3.1.

The next revolution in relativity was the discovery of general relativity, which is our still valid theory of gravity. We use it to calculate the planetary motions, correct the signals of GPS-satellites and explain the development of the cosmos. At the basis of this extension of his earlier theory of special relativity was Einsteins insight, that acceleration, which you feel for instance in a rollercoaster, has the same effect, namely being pushed into the seat, as gravity, which accelerates freely falling objects or gives them a weight, if they are held fixed. Thinking this idea through, it turns out that the four dimensional continuum of space and time is not flat and static but rather bent, curved and not fixed at all. The motion of a body is perceived as its motion on the shortest path through space and time. Every mass in the continuum will cause
some deformation, some bending, like a heavy sphere would do on a rubber sheet. A smaller object, a planet, say, passing a heavier object, the sun, say, feels this distortion and will alter its path to keep it being the shortest. Projected into the three dimensional space, this will then have the effect that it orbits the heavier object due to the gravitational force exerted by it.

**GENESIS**

Since space and time are not fixed but evolve and change according to the laws of general relativity, this theory gives us the fascinating prospect of studying the genesis of the universe itself. Depending on the initial conditions, on the amount and kind of matter in the universe, its evolution can be calculated and looks distinctly different. Ideally, those theoretical results can be compared with experimental findings and thus teach us about the real nature of nature.

A classic and very important such observation is that the light coming from other galaxies is red-shifted. This means its frequency is lower than we would naturally expect. This can be attributed to the same effect, which makes the siren of an approaching ambulance sound higher than when it recedes, the Doppler effect. The light from distant galaxies shows, that they are receding from us and we can conclude that the universe is expanding. The theory, indeed, has a solution, which describes an expanding universe, characterized by the Hubble parameter, the rate at which distances in the universe become larger.

If this observation is extrapolated backwards in time the cosmos shrinks and all galaxies get closer and closer together. At some point, they all merge and the density of mass increases continuously. Thereby, the universe gets hotter and hotter. At some point, matter will change its shape and state, first atoms disintegrate, then nuclei until all the matter is transformed into a hot and dense plasma, which is even unpenetrable by light. If this extrapolation is done even further, at some point, we hit a singularity and the theory breaks down. That means, the concentration of matter curves space-time infinitely strong. General relativity cannot deal with that. This is also the point, where our ability to go even further back in time within the established paradigm stops. We perceive this point as the beginning of the universe and we picture this beginning as a big bang, a spontaneous, very energetic explosion, which provided enough energy to drive the cosmic evolution ever since.

**SOME KEY COSMOLOGICAL PROBLEMS**

We don’t like singularities. Rather than having any physical meaning, they signal that we have not understood the physics of the problem we are looking at. Also, our natural curiosity does not want to be forbidden to ask questions like what was before the big bang. In other words, we want to resolve the big bang singularity, we want to have a theory, which is well under control and which allows to describe the dynamics not only some time after, but also during and maybe even before the big bang.
But even in the time after the big bang, where the theory of general relativity is applicable and does make predictions, those do not tally very well with observations. There are three classic problems of big bang cosmology, which make it necessary to adjust the cosmological scenario at early times in some crucial ways. Those problems are the so-called flatness problem, the horizon problem and the monopole problem.

Measurements indicate that the universe is very smooth and flat. Large parts of it are empty and the deformations of space-time caused by the matter scarcely distributed throughout it are very small as compared to the scale of the universe. But this is a very unlikely situation according to the standard cosmology as derived from general relativity. This lack of plausibility is perceived as the flatness problem.

Furthermore, when we look at the very eldest photons which can be observed, the cosmic microwave background radiation, a very striking fact ist that their temperature is very uniform. We can assign the same temperature to it, no matter which direction in the sky the radiation is coming from. In general, physical systems need some time to attain a uniform temperature, to equilibriate. If you pour a cup of coffee, its temperature is higher than the temperature of the room, in which you are going to sit down and drink it. You can only enjoy it hot because it takes some time until the room temperature and the temperature of the coffee have equilibriated and you better make sure to finish it before that happens. The cup of coffee will only equilibriate with its surrounding. It will not equilibriate with the air in the room of your neighbour’s house. The regions from which the background radiation coming from different directions emenates, however, never were in touch. This could only happen, to remain in the picture, if you and your neighbours have made an agreement to keep your houses at exactly the same temperature. It seems very unlikely that this sort of conspiracy has happened in the early universe, which is referred to as the horizon problem.

Finally, monopoles are something like electrons, however, they do not carry electric but magnetic charge. Usually, magnets always come with a north- and a south pole. If you split those, you do not get two particles with either a north- and a south “charge”, corresponding to an electron and a positron, but you get two magnets with both north- and south poles. This asymmetry between electric and magnetic force is supposed to disappear at energies much higher than attainable at particle accelerators but much lower than those, which occured in the early universe. This means, that magnetic monopoles should have been just as abundant as electrons back then. Up to date, we have not found a single such monopole. The question, where they have gone is known as the monopole problem.

It is essential to understand the nature of these problems. They do not prove anything or render the theory of general relativity invalid. They are problems with how “natural”, how likely it is, that the universe has come into the shape it is today under the assumption of the theory. The naturalness of the observed world within a model is perceived as a measure of the amount of understanding which a certain model comprises.
Cosmic inflation is supposed to have blown up the cosmos in a very short time to a multitude of its original size. The curvature of the universe is only visible, if its radius is not too big as compared to the scale of our experiment. Thus, the universe looks flat after inflation. Source: Griffith Observatory, Caltech.

A cartoon of the expansion of the cosmos from the big bang until today. This thesis is concerned with the part on the very left until the formation of the cosmic microwave background. Source: LAMBDA archives WMAP.

Figure 3.2: Cosmic inflation

Inflation as the New Cosmological Paradigm

The most popular mechanism to resolve these problems, which has been proposed to date, is cosmic inflation. The idea behind it is that if only the universe had expanded very rapidly at the beginning, the above problems would be solved or rather eliminated. During such a rapid expansion, the universe would have been blown up to $10^{28}$ times its size within an instant. This would be large enough, that all the observable cosmos originated from the same piece of the primordial soup (or coffee). Then, it is not surprising, that it has the same temperature everywhere and the horizon problem is solved. It would also have reduced every initial curvature of the universe to being unperceivable, just as the curvature of the earth is unperceivable on an everyday scale, because the radius of our planet is too big (see figure 3.2(a)). In this picture, there is no flatness problem. Also, magnetic monopoles which might well have been there at the beginning of the evolution are being homeopathically diluted during this expansion and it is no surprise that we do not observe them, which finally removes the monopole problem.

It turns out that the equations of general relativity admit the possibility of such a rapid expansion. Such a cosmic inflation would be caused by a particle, the inflaton, which has a very high potential energy at the very beginning of the universe. It would blow up the universe until at some point, it converts its energy to kinetic energy and leaves the universe alone.

Let us carefully note again, what kind of a solution this is. Several fine-tuning problems of tweaking the initial conditions of our universe have been replaced by the dynamics of one physical field, the inflaton. The period of inflation makes the cosmic evolution independent of
the precise form of the initial conditions and increases the naturalness of our universe. Rather than tweaking some parameters into convenient shape, the task of the cosmologist is now to study the physical dynamics of a newly postulated field and come up with some idea to prove its existence.

I should mention, that inflation has nothing to say about how to deal with the big bang singularity. The inflationary period will definitely remove the big bang from our observability. Since the evolution does not depend crucially on the initial conditions any longer, which would have to be imposed at the time of the big bang, it seems less crucial from an observational point of view to understand the big bang. It remains, though, an inconsistency of the theory, which should be dealt with.

**THE EARLY UNIVERSE AS A LABORATORY FOR QUANTUM GRAVITY**

Traditionally, cosmological models use only general relativity as their underlying theory. This is a good theory to study the late evolution of the universe. When examining the very early universe, however, the typical length scales are small such that the effects of quantum mechanics are important and gravity cannot be applied without taking them into account. The early universe is an era, where gravity was strong and length scales were small. The laws of quantum mechanics should then be applied to gravity.

This is a big challenge. The difference between gravity and the other forces is that gravity couples to everything, to every energy, to every mass, even to itself. Where for the other forces, we only have to measure a small number of coupling constants, for gravity, there are infinitely many. Thus, it is difficult to quantize gravity. The approach for doing it nevertheless, which is considered in this thesis is *string theory*. The idea behind it is to replace elementary, point-like particles by extended objects as it is suggested in figure 3.3. These objects can vibrate just as the strings of a violin. Different particles are just an interpretation of different harmonics of the vibration of these strings, just like different tunes. Those strings have a very high tension, so that they look very much like point particles at everyday energies, where they are completely

---

1 As a note added in proof let me point out that very recently the spectacular results of the PLANCK satellite mission have confirmed the inflationary paradigm to very high and unprecedented accuracy.
contracted, but they look extended at the high energies of the early universe. This theory has a very rich structure and contains a graviton, the quantum particle of the gravitational force. However, the idea also has some problems. Mathematical consistency requires the theory to be formulated in ten dimensions rather than the four dimensions, to which our cosmos has evolved. To comply with the world around us, we need to get rid of the extra six dimensions. The way to do this is to curl them up to a very small size, much smaller than the accuracy of our experiments. At high energies, though, these extra dimensions would be visible. Research over the past decennia have shown that there is an enormous number of ways to go from ten to four dimensions and a lot of research in both physics and mathematics has been examining the structures that can arise. We are not concerned with such questions here. For us, the important observation is that by compactifying extra dimensions, a lot of new parameters are introduced into the theory. In principle, the size, the shape and the exact form of the compactification is not specified. These parameters are new objects in the theory, so-called moduli fields. This means both good and bad luck for cosmology. On the one hand, these fields might be the inflaton, which we have conjectured above. On the other hand, it is rather unclear how these extra fields influence the dynamics of the cosmos.

**Singularity Resolution and Inflation in This Thesis**

Is string theory going to help us tame the big bang singularity? This is the first question which I am investigating in my thesis.

String theory has blessed us with a surprising insight: the physics of string theory in a certain space-time can be described by a quantum field theory on its boundary. This novel technique goes under the name of AdS/CFT-correspondence or gauge/gravity duality. The information about what is happening within a space-time, like our cosmos, can be recovered by studying a well understood theory on its boundary. Even better, the stronger gravity, the better behaved and understood is the corresponding field theory. Remember that the biggest problem with the big bang is that gravity becomes infinitely strong.

I use a very specific realisation, a toy model of a big bang singularity and examine, how it looks in the field theory, which belongs to it. It turns out that the field theory replicates the singularity of gravity. The big bang desguises itself as an instability in the field theory. However, this is only true in the limit, where the strings shrink to point particles. I have performed a calculation, in which the coupling between strings, which is supposed to give an important contribution to the physics in the early universe, is taken into account. It turns out, that including these string theory effects regularizes the field theory and makes the big bang a reasonable concept. It even makes sense now to ask what happened before the big bang, albeit we are very far from answering such questions.

In the second part of the thesis, I turn my attention to cosmic inflation. Its effectiveness very much depends on the specific form of the potential of the inflaton field. For it to support
Summary

inflation long enough to solve the cosmological problems, it needs to be very flat. To have a really natural explanation of this phase of cosmology, this potential should be derived from a fundamental theory like string theory. Only then, Inflation would really solve the fine-tuning problem, because only then is the phenomenon explained in a natural way from a deeper understanding.

The proliferation of fields, which we have in string theory upon compactification, makes it very difficult to examine a model in all detail. Therefore, the usual procedure is to truncate ones model to only a few interesting fields and keep the rest nicely tugged away under the assumption that this can be done without invalidating ones model.

The question which I have investigated together with my colleagues is if those fields take revenge. We show that the effect these degrees of freedom have on the model are usually greatly underestimated. Only under very specific circumstances is it admissible to neglect these fields. In the physically relevant cases, these conditions amount to choose conditions – again – in a very specific manner. Thus, fine-tuning, which inflation was supposed to remove, seems to have just been swept under some rug, which our more thorough analysis has lifted.

CONCLUSION

Examining the cosmology of the very early universe within a fundamental theory like string theory is necessary and exciting but dangerous. On the one hand, string theory has new features and techniques, which allow us to study the cosmological problems in a qualitatively different fashion. My results indicate that some of the gravest problems might be solved by string theory. On the other hand, string theory is beyon human control. One must be careful that one has really taken all the effects into account, which might well silently been reintroduce the problems one has set out to solve.

Meanwhile, advances in cosmology such as the ones reported in this thesis are well capable of satisfying the human curiosity and the frontier of exploration is yet again pushed ahead a bit.