On multifield inflation, adiabaticity, and the speed of sound of the curvature perturbations

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Summary

Early Time Cosmology

Not even the most optimistic scientists and philosophers of the past could have guessed the impressive descriptive power of our current cosmological model. While it is certain that outstanding achievements have been made in every branch of the natural sciences, it is particularly remarkable that a substantial development has also been reached in our understanding of the Cosmos. Indeed, it is not at all clear from first principles that any kind of knowledge can be reached in the understanding of a system of which we are just a tiny, tiny part. In fact, the Universe is at least, 10^{26} times larger and 10^{8} times older than ourselves[7].

According to the theory of General Relativity, the geometry of space and time is affected by the energy density of the different components that make up part of the Universe, and *vice versa*. This interconnection is what determines the history of the Universe and the evolution of its internal constituents. The interplay between this theoretical framework and observations suggests that the Universe started expanding from a spacetime singularity 13.8×10^{9} years ago. The history of the establishment of this model is of course long and complex, but it is fair to say that it can be traced back to the works of Lemaître and Hubble, where the recession of distant galaxies was first established. The natural reticence to the logical consequences of such model - implying a dynamical cosmos and the apparent presence of a spacetime singularity in the past- could only be overcome after the accumulation of overwhelming observational evidence sustained by elegant mathematics.factor to many of the new developments in physics: to astonish the human[8].

Our current cosmological model further suggests that most of the present day energy in the cosmos comes from two unknowns constituents: the so-called dark matter and dark energy. The reader, amazed by the fact that we were able to describe such an old and vast Universe, might feel betrayed, as we have really little idea of what is the microscopic nature of the most important components of the present Universe. The reason for this "knowledge within ignorance" to be possible is that only a few numbers are enough to describe the influence of such

[7]If, as Protagoras said, man is the measure of all things, then we might metaphorically declare: man is of the size of the Universe!

[8]Of course, physics is just one example in which this feeling can be proven. Any deep interrogation, experience or contemplation of any phenomena, however simple, will certainly create such state of mind.

constituents on large cosmological scales, such as their equation of state parameter (relating pressure to density) and their present energy density. This simplification is common in everyday life: we only need to know a few functional characteristics of the objects that surround us in order to make use of them. While a superficial knowledge of dark energy and dark matter might be good enough for explaining some cosmological observations, a deeper understanding of the microscopic nature of these elements (or whatever they might be) is by all means necessary in order to provide a complete and fully satisfactory model of nature.

The presence of dark energy and dark matter are not the only mysterious phenomena for which we have no satisfactory full explanation. An additional conundrum of our standard cosmological model is the overall homogeneity of the Universe. This refers to the observation that *at sufficiently large scales* galaxies are evenly distributed through space[9]. Moreover, even the present highly inhomogeneous small scale regions (dense clusters of galaxies versus voids depleted of any trace of matter) are the result of very tiny initial perturbations of a highly homogeneous initial state.

Furthermore, the initial state of homogeneity is not only deduced from our present state but it is actually measured by looking at the so-called Cosmic Microwave Background. This is a relic radiation of our Universe emitted about 380.000 years after the spacetime 'singularity'. This corresponds to a 0.001% of its present age, so it can be considered as a photograph of its primeval state. The Cosmic Microwave Background, commonly known as the CMB, is indeed a highly homogeneous sea of radiation (described by one single temperature), whose small temperature inhomogeneities are only of the order of one part in 10^5.

The homogeneity of the observable Universe, combined with its finite age, is a problem for cosmologists because it challenges one of the most basic principles in physics, causality. Light rays, which define the maximum speed at which information can travel, have only traveled a finite distance since the beginning of time. Therefore, any observer in the Universe is only causally connected to a finite portion of their surroundings. Now, if the CMB temperature of the different portions of our observable Universe is the same, we would expect all of these different portions to be causally connected. Then comes the problem: in our present cosmological model, only very small regions of space were causally connected at the

[9]These *sufficiently large scales* are the scales we need to consider in cosmology, since they are not affected by the 'environmental' local forces (as the gravitational attraction of galaxies and cluster of galaxies) and follow instead the macroscopic flow of spacetime.

time when the CMB was created[10]. Therefore, how did all these causally disconnected regions manage to reach the very same temperature, if they never shared any information?

This thesis studies some aspects of the favourite solution to this conundrum, the idea of cosmic inflation. In very simple words, this theory states that the Universe, in a very primitive stage of evolution, expanded almost exponentially. This first burst of exponential expansion causes our Universe to emerge from a very tiny primeval volume which was indeed in causal contact before the inflationary expansion. This solves the homogeneity problem. Quite impressively, an inflationary era not only homogenizes the primordial Universe but also creates small density and tensor fluctuations[11]. As the density fluctuations are needed in order to seed the present inhomogeneities, the theory of inflation is then basically providing a mechanism for the emergence of all the structures that we can see around us.

An idealized history of the expansion of the Universe is just a first step towards the establishment of a viable cosmological model. We also have to provide an explanation for why the Universe evolved in this particular way. As we said previously, the dynamics of the Universe, i.e., whether it expands, contracts or stays static, depends on its energy content. It follows that in order to have an initial era of inflation, some unknown "matter" field must be the cause. This hypothetical field is called the inflaton.

In physics, it is useful to classify fields according to their symmetries. One possibility is to classify them according to the way they change as we perform a rotation of the spacetime coordinates. This classification is very important, since the symmetry properties of a given field determine the structure of their equations of motion. The simplest fields which could cause inflation are *scalar* fields, which are fields that are invariant under spacetime rotations[12]. Still, the supposition that the inflaton might be a scalar field is not yet enough for making this a satisfactory model, since this field might not exist in nature! Whether the inflaton field is present in nature or not, we do not know, since we have no idea of what is the correct description of the fundamental particles at the energy scale at which inflation might have happened. Let us note that the Standard Model of Particles has been tested up to the TeV scale (at the LHC experiment), but that inflation might have happened at energies which are of the order of 10^{13} times higher. Any

[10]The causally connected regions correspond to regions in the sky of the angular size of the moon.
[11]Tensor fluctuations correspond to gravitational waves.
[12]For example, a fundamental scalar field is the recently discovered Higgs field.

theory about how particle physics is like at those energies is then highly speculative. In physics we like, however, to speculate. Ideally we do it following ideas which have proven to be good guiding principles for the explanation of physical phenomena. As we already mentioned, one of this principles is symmetry. In particular, we like to think about particles and forces as the representations of certain symmetries. Following this abstract principle physicists have been able to predict the existence of new particles, that were later discovered in the laboratory. Moreover, apparently disjoint phenomena have proven to be part of the same symmetry group.

This opens the possibility that all particle interactions might be fundamentally described by only one single symmetry group. This might be relevant for the theory of inflation, since one of the features of all the known 'unification' routes is that they predict the existence of many particles at high energies. This is exactly what inflation needs, since the inflaton should presumably be an unknown new particle living at higher energies[13]. However, a closer look shows that this may not be an 'easy marriage'.

On the one hand, the statistical properties of the CMB tell us that if inflation happened it should have been dominated by one *single* field. On the other hand, high energy theories (predicting particles from symmetries) generically predict the existence of many fields. Both pictures are consistent with each other if the spectrum of the multifield theory obeys some very specific properties. If one and only one of these particles is light and all the rest are heavy[14], then the many-particle theory is *effectively* reduced to the theory of a single light particle.

The reason for the possibility of constructing an effective theory, is that nature can be described at different levels. At different length scales (or, equivalently, energy scales) the degrees of freedom needed to describe a system might be different. For example, a stream of water might be understood macroscopically as a liquid with certain properties as density and viscosity. However when we look at the stream of water at a microscopic scale, we need molecules interacting through electrical

[13] A possible unification of the fundamental forces is only *one* of the possible motivations for considering the presence of additional fields at higher energies. Indeed, one might be much more agnostic as inflation doesn't need all the ingredients of the theories of unification to be feasible. For example, even the Higgs field could play the role of the inflaton (needing an additional coupling between the Higgs field and gravity to be feasible). Whether physicists are more attracted by the minimality of adding just one new interaction to the Standard Model of Particles (as in Higgs inflation), or are inspired by (much) more complicated theories of unification (that have the additional advantage of explaining some other 'conundrums' present in our models), we consider it to be a matter of taste.

[14] By light/heavy we mean particles with masses much smaller/larger than the energy scale of inflation (that is related to the rate of expansion at that time). We can do this comparison between mass and energy since they are related through the famous Einstein formula $E = mc^2$.

forces to describe the system. Both are descriptions of the same system, but at different scales.

Importantly, we do not need to know the microscopic description in order to study the system at the macroscopic scale. Indeed, the macroscopic properties of the system can simply be measured at the macroscopic scale. In physics this phenomenon is known as *decoupling*, and the systematic understanding on how it operates provides a framework for addressing many problems in modern physics. This principle is, to some extent, a big relief: we don't need to understand the physics of the fundamental particles in order to study the mechanical properties of water!

From another point of view, this is exactly what has been preventing us from succeeding in finding an ultimate model for all the fundamental interactions. Indeed, we are constrained to build accelerators to directly probe very high energy (small scale) particles. Today these accelerators reach only 0.00000000001 % of all the energy scales we would like to probe. We might then say to have rediscovered what Heraclitus said more than 2000 years ago: "Nature loves to hide".

While nature loves to hide, it leaves some traces. Indeed, all the properties of the macroscopic system, e.g. viscosity for water, emerge from the details of the microscopic theory. Making the connection between the small and large scales might be very difficult, but if we are able to do it, we can gain knowledge about the microphysics by looking at the system macroscopically. This has tremendous consequences, since it tells us that we can gain knowledge about very high energy physics without the need of large accelerators to directly probe those energies.

This Thesis

In this thesis we have studied the situation in which the extra and very heavy fields can leave an imprint in the 'speed of propagation' of the inflaton density waves (known as the speed of sound). This is an example in which we can relate a macroscopic variable (e.g. the speed of sound of the inflaton's perturbations) with the microscopic details of the theory (e.g. the presence of very massive fields).

As the inflaton's perturbations seed the perturbations seen in the CMB, the speed of sound of the inflaton can have important consequences in the statistics of the CMB. Depending on the time dependence of the speed of sound, these effects are different in nature. In this thesis we have studied the case in which the speed of sound is allowed to vary very smoothly and very rapidly.

The former situation, in which the speed of sound varies smoothly, is quite simple to analyse. Indeed, no new mathematical or statistical tools are needed in order to compute predictions and compare them with observations. Let us note that the question whether the high energy degrees of freedom leave a trace in the low energy theory or not is totally circumstantial, as it depends on how these different fields are coupled, for which there is no a priori preference. In this thesis, we have shown how a particular class of interactions leading to "spiral" trajectories in field space, can lead to measurable effects. These models are the inspiration for the cover of this thesis.

The second part of this thesis concerns the study of a rapidly varying speed of sound. This situation demands the use of more sophisticated techniques for calculating the predictions of such models since we are no longer allowed to use approximations based on smooth and slow evolution of the variables. Moreover, in order to know whether such models are good for fitting the data we need to perform a direct and sophisticated comparison with the CMB maps. We perform an analysis based on the fact that, in models with a reduced speed of sound, there is a very specific correlation between the two- and the three-point function[15]. While we find some hints that such correlation could be present in the 2013 Planck satellite data of the CMB, the most recent data from 2015 seems not to favour its presence. An extended analysis with the new data is needed, which we plan to carry out in the future.

The last chapter of this thesis deals with the predictions of the so-called natural model of inflation. As we said previously, for inflation to be successful we need the presence of one very light field. However, we cannot simply say that a field is light and then forget about it. One of the most important lessons in modern physics is that the masses and charges of particles are not simple constants, but receive corrections from quantum effects involving all the remaining particles present in the theory (including also self-corrections). In the case of inflation, these effects might dominate the inflaton mass to the point where it is not light enough to support inflation. This is indeed the case for one interesting class of inflationary models, the so-called large-field models[16]. Large-field models are very appealing since they produce a relatively high amount of gravitational waves, whose detection could be very important for understanding the details of inflation, or even, to put

[15] These are measures of the correlation of the inflaton perturbations between two or three points in space. These quantities are very useful for statistically describing any map.

[16] Large-field models are those in which the inflaton field traverses a large 'distance' in field space. It more precisely means that the difference between the field values at the beginning and at the end of inflation is of the order of the Planck mass.

the inflationary paradigm under stress. It is then very unsatisfactory that we do not know how to consistently describe, in generality, this class of models.

One of the few models of large-field inflation in which this is not a problem is the case of natural inflation, in which there is symmetry 'protecting' the mass of the inflaton. It refers to the generic situation in which a model for inflation respects more symmetries when we consider a massless version of the same model. Then, one can show that quantum corrections will not increase the mass to dangerous levels. This scenario might sound very appealing from a fundamental level, but the prediction of its simplest version are in tension with the observed properties of the CMB. Indeed, this theory predicts a ratio of temperature to tensor perturbations which is too high, and/or a spectrum of the temperature perturbations which is too 'red' (meaning that the amplitude of the two-point correlation function at large scales is too big when compared with the small scales). In the last chapter we reconsider the predictions for natural inflation. While in the original model only one field is driving the dynamics, we show that in the case in which there is an additional field the predictions for such a model are indeed consistent with the observations.

Conclusions

In this thesis we present various aspects of early time cosmology. Our motivation is not only to acquire an understanding of the overall dynamics of the Universe but also to understand what might be the spectrum of particles and forces at energy scales which are today impossible to probe directly. In particular, we show how observations of the cosmos might reveal the presence of some heavy unknown particles. Discovering such particles would open the gate to a present day hidden sector of Particle Physics, and its implications might be enormous for solving many of the long-standing open questions in modern physics.