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Effective Theories in Cosmology

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Summary

I take it as a great privilege that for four years and a half already I have been around in this "Big Bang business". On these pages I would like to clarify what this has been about for me: from a general introduction to cosmology to the research described in this thesis. Every now and then some corners are cut short, but then again I do not intend to keep the reader busy with this for four years and a half...

Man in an expanding universe

As we cannot simply step out of it for a second, the universe should be studied from within. In this first paragraph I want to explain briefly how man, despite its modest place in the universe, manages to extract quantitative information from the night sky.

First of all we need a method to determine distances in the cosmos. In everyday life we perceive depth when our brain compares the separate images caught by our left and right eye. The so-called "parallax method" applies this same principle in astronomy. Two measurements, with an interval of six months, are made of the angle that a star makes with the horizon. In these six months the earth changes its position: she completes half of her orbit around the sun. Just like we do not see exactly the same with our left and right eye, the two measurements of the position of the star yield two different results. From their difference follows the distance to the star.

A second method makes use of the brightest light source we know in the universe: type IA supernovas. These are enormous explosions that occur in some binary systems (two stars orbiting each other). They are perfect to be used as lighthouses in the cosmos as, to a very good approximation, they are all equally bright. That is to say: if they had all been equally distant. By comparing a supernova's brightness with those of another supernova whose distance to us we know, we find the distance to the first one.

Apart from the distance to a star we would also like to measure its velocity relative to us. This can for example be done by employing the Doppler effect. Anyone who has ever seen a fire truck passing knows this phenomenon. When the truck is approaching us the distance between two consecutive sound waves shrinks, and we hear the siren at a higher tone then the firemen do themselves. Once the fire truck has passed, its sound of waves reaching us are somewhat stretched out, and we perceive a lower tone.

This same effect also happens in the light waves that a star emits. When the star is moving towards us, its light waves seem to be closer to each other. When she is moving from us, we measure a larger distance between two consecutive wave fronts. By comparing a star's emitted pattern to what we would measure had she been at rest, we find its velocity.

In this same way Edwin Hubble measured the distances and relative velocities of many stars in the

’20s of the last century. He found not only that all stars are moving from us, but also that their velocities are proportional to their distances from us. A star that is three times further from us than another one, is moving three times as fast from us. How is that possible? Hubble thought and concluded “Because they all started in the same point!” The Big Bang theory had been born. Everything began at the same point in space and time. Had this one star not been moving three times faster, it would not have got three times further from us. We are observing the consequences of a cosmic explosion: after 13.8 billion years pieces are still flying around.

The background radiation

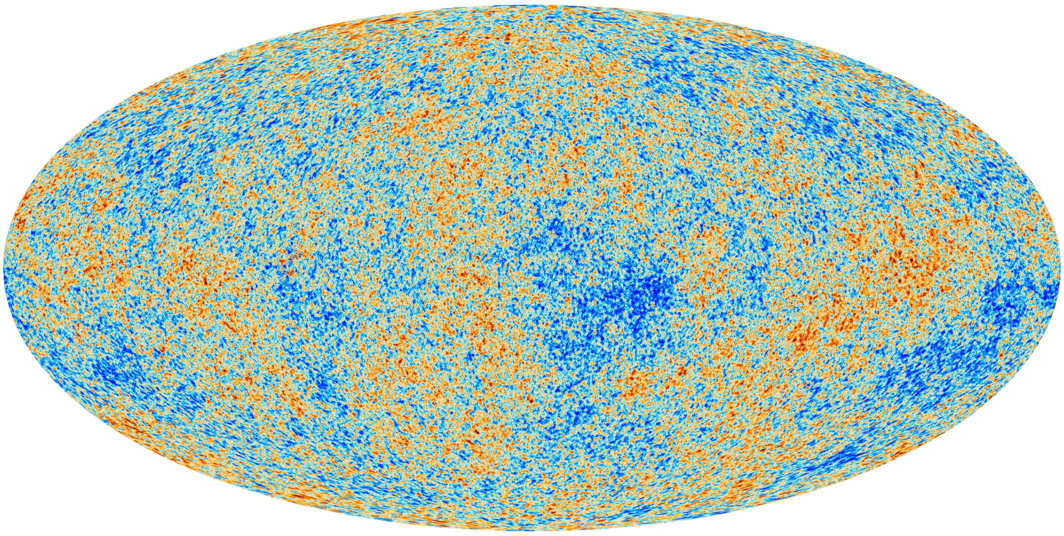
After Hubble the picture of the expanding, cooling universe has been refined much further. Increasingly precise measurements have yielded an ever more accurate model. This section is about one of the most important observations, indispensable for this thesis: the cosmic microwave background (CMB) radiation. When the universe was about 380,000 years old, the temperature decreased such that free electrons could no longer exist. Instead they got caught inside protons to form hydrogen. As a consequence, travelling light particles (photons) did no longer scatter off electrons, and their (straight) path through the cosmos was no longer disturbed. These photons are still travelling and produce a signal that we know as the CMB. It was discovered in the ’60s by Penzias and Wilson in the US. Looking for something totally different, they tried their very best to get rid of this “noise” signal. They even checked their telescope for pigeon droppings, but the signal persisted to be there. At this point they were made aware of the work by George Gamow, who was the first to speculate about the CMB. By chance Penzias and Wilson turned out to have made a Nobelprize-worthy discovery: a baby picture of the universe. As the photons in the CMB have travelled freely to us since 380,000 years after the Big Bang[4], they contain a lot of information about the early universe.

Symmetry on large scales...

Then what do we see in the CMB? In two words: complete symmetry. The CMB’s temperature is 2.73 Kelvin ($\approx -270°$C), in all directions. This is a very surprising result. Two photons reaching a telescope on earth from opposite directions, were very distant from each other when they began their journey. In 13.8 billion years such a photon travels 13.8 billion light years (not even taking into account the expansion of the universe). At the start of their straight flight they were therefore more than 27 billion light years apart. Now, Einstein prescribes that information can not travel faster than the speed of light. When the CMB was emitted, the universe was about 380,000 years old. At that moment we expect that information (like a temperature) can have travelled over 380,000 light years at most. It is therefore very surprising that two photons that were more than ten thousand times further apart, still had managed apparently to adjust to the same temperature.

The uniform CMB temperature fits in well with our general picture of the universe on large scales. (Note that by “large” we here mean cosmologically large: length scales of 10^{24} meter and larger.) At such scales the visible universe looks the same everywhere and in all directions. Again the question rises: what caused all that homogeneity and isotropy?

[4]Note that the CMB was produced everywhere in the universe. Therefore there is no end to the CMB-bombardment. A CMB photon that arrives on earth today was simply produced a bit further away than one that was detected last year.



Projection of the temperature of the CMB. Red areas are a fraction warmer than the general background temperature of 2.73 Kelvin, blue areas are somewhat colder. The difference between the warmest and coldest spots is one thousandth of a degree. (esa.int/planck)

... perturbations on small scales

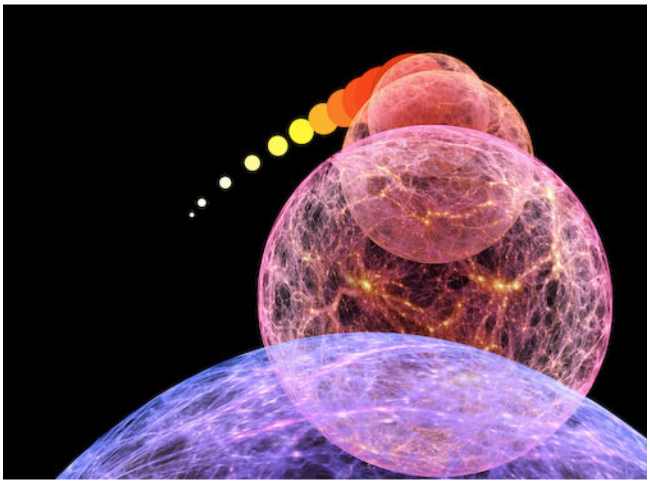
On smaller scales the universe is of course not at all that homogeneous. The closer we look, the more "perturbations" of the cosmological equilibrium situation manifest themselves: from star clusters to this booklet. This leads us to a second interesting question: what causes these perturbations? How do the first lumps come about in the originally perfectly symmetric primordial soup? The answer is partly in the background radiation. It turns out that on top of the universal background temperature of 2.73 Kelvin there exist tiny temperature fluctuations: a photon from the one area is just one thousandth part of a degree colder than a photon from another area. This indicates that when the CMB was emitted gravity in such an area was just a tiny bit stronger than the global average[5]. At such a place the soup gets pulled a bit more and a little clump is formed, which in turn pulls the rest a bit harder. With this principe the structures in the current universe can be explained quite easily.

This answer to the question how structure formation begins instantly points to a new one: what causes the temperature fluctuations in the CMB? How come that already when the universe was only 380,000 years old, gravity was not totally homogeneous anymore?

Cosmological inflation

The paradigm of cosmological inflation, proposed by Alan Guth in 1980 and further developed by (among many others) Slava Mukhanov and Andrei Linde, solves both of the problems sketched above in one go.

[5] A stronger gravitational force at some place attracts more particles and therefore leads to a higher temperature. However, it takes more energy now for a photon to escape. This is a stronger effect. The net result therefore is that we measure a somewhat lower temperature.



Cosmological inflation: an explosion of space itself. This artist's impression shows what an "observer outside the universe" would see. (scienceblogs.com)

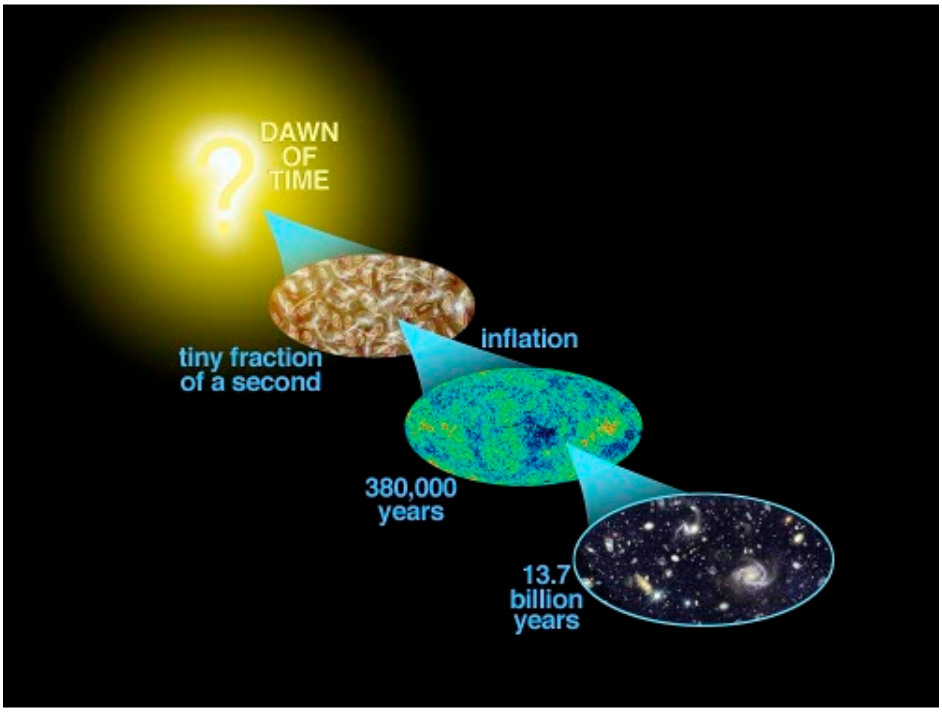
Or better: in one explosion. The hypothesis is that when the universe was (much) younger than one second, it has undergone an enormous expansion. This adds to the "standard" expansion measured by Hubble. Guth demonstrated that if in a fraction of the first second the universe increases its size by a factor of 10^{26} at least[6], we can explain why it looks so homogeneous. According to Guth initially the universe does not have to be that homogeneous. The consequence of the enormous expansion (inflation) of the universe is that everything that we can see today, was confined to a very small space before inflation took place. At such small scales it is not difficult to imagine homogeneity.

To understand how inflation solves the problem of structure formation as well, a bit more background knowledge is needed. Einstein has shown by his famous formula $E = mc^2$ that to create a particle with mass m out of nothing, one needs an amount of energy of mc^2. At the other hand there is quantum mechanics stating that on the smallest length scales (the order of the size of an atom, about 10^{-10} meter) there is always some uncertainty in the amount of energy. Even in the vacuum there can be some energy for some short time. And where there is energy, there can be particles! Merging Einstein's (special) relativity with quantum mechanics shows that even in the vacuum two particles can be created out of nothing, which after a short time collide and disappear in thin air again. The vacuum therefore is not really empty. It is more like a boiling pot, with bubbles of the size of an atom.

The work done by Mukhanov has shown that during inflation this process of particle creation and annihilation is hampered. Because of the very rapid expansion of the universe, both particles do not get back to each other anymore. The bubbles in the vacuum do not disappear anymore, but are blown up to sizes that exceed quantummechanical scales and that can influence the "big" world. In his famous calculation, partly sketched in chapter 1, Mukhanov showed that blown up quantum bubbles precisely form the seeds that (over the next 380,000 years) grow into the tiny temperature fluctuations in the CMB. Ultimately all structure that we know originates from a pot of primordial soup that is boiling over!

In the last 30 years hundreds of models of inflation have been proposed. The most influential model builder is probably Andrei Linde, who is also co-author of article [5] on which this thesis is based. Every

[6]This expansion is faster than the speed of light, but there is no violation of special relativity. It is space itself that is expanding, there is no information travelling faster than light through space.



The history of the universe. Before (and during) the Big Bang we know nothing. Inflation blows up a small, causally connected part of space thereby generating the homogeneous universe that we observe. Quantum bubbles (of the inflaton field) are stretched out and lead to the temperature fluctuations in the background radiation. These evolve further to all structures we observe in the universe today. (scienceblogs.com)

model is characterized by the properties of the "inflaton" (the particle that causes inflation to happen) and the forces that act on it. This leads to precise predictions of the statistical properties of the CMB fluctuations that can be tested experimentally.

Inflation with the Higgs field

Recently there has been much attention for models that make the Higgs particle (discovered at CERN in Geneva last year) responsible for inflation. This has the advantage that there is no need to postulate a new particle (all other known particles are fundamentally incapable). Therefore the number of new parameters to be determined experimentally is minimal. Even better: by combining the results of the LHC (like the mass of the Higgs particle) with cosmological measurements of the CMB, the theory can really be tested. At the moment the Higgs mass seems a tiny bit too small for the model to work. However there are still too many issues not well understood, theoretical as well as experimental, to be able to draw a definitive conclusion.

The chapters 3 and 4 of this thesis describe our research of one of these not well understood elements of Higgs inflation. When the Higgs particle is used in the early universe as an inflaton, it has more freedom of movement than when it is measured at CERN. The vibrations of the quantum field associated to the Higgs particle follow a pattern that is more dynamical. That is why the usual Higgs theory needs to be generalized. In a simplified model we have precisely shown what are the consequences of these extra dynamics, and shown how the theory is still "gauge invariant" (invariant under modification of certain parameters).

Superinflation

Since the early '70s there has been a lot of interest for supersymmetry, supergravitation and superstringtheory. These "supertheories" have in common that, by proposing (many) new particles, some theoretical shortcomings of the current standard theorem can be overcome. The ultimate goal: a theory that describes gravity on quantum scales, has still not been found. However, the validity of standard theorems can be stretched out to higher energy scales. Experimentally, however, no postulated new "superparticle" has been found. Another problem is that the huge number of unknown parameters in these new theorems drastically reduces their predictability.

The chapters 5 and 7 of this thesis describe how inflation can work in such a "super context". Chapter 5 tries to decouple the dynamics of inflation as much as possible from the model's other dynamics. In this way inflation's predictability can be maintained, even if there is so little quantitative information available about the other (super)particles in the model. Chapter 7 shows how an existing model of inflation can be made compatible with superstringtheory. This last theory requires the existence of extra spatial dimensions, which are only observable on extremely high (experimentally unaccessible) energy scales. Still these extra dimensions have some indirect influence on the physics on lower energy scales, and we have shown under which conditions these new effects do not spoil inflation.

Particle production during inflation

Chapter 6 looks at a model in which during inflation extra particles are produced. It follows from adding one new particle and one new coupling (between that particle and the inflaton) to the most standard model of inflation. The question is now: which observable quantity is most sensitive to this new coupling, and can therefore be used to constrain it? We have pointed out that, contrary to what was claimed in literature, for once this observable was not to be found in the CMB. It turns out that the very limited presence of a certain type of black holes in the universe puts the most stringent pressure on this proposed coupling. We show as well how these same models can still work in an "superenvironment" (embedded in a model of supergravitation).

Future research

So what is next now? I know more than four years and a half ago, but I have more questions as well. At this point my first goal is to work out the model of Higgs inflation in much further detail. Different research groups have different opinions on the theory's precise predictions, and I first of all want to work out how the effects studied by us further influence this debate. But there is so much more to do, also because the new measurements of the PLANCK satellite constrain the existing models ever further. Less than a hundred years after Hubble's discovery cosmology has become a precision science. I am happy that I will have three more years at least to work on that, at a place where the sun shines in daytime and the stars light up at night...