Effective Field Theory Outside the Horizon 14rit184

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Our goal in getting together at BIRS was to complete our research program to identify the Effective Field Theory that describes the physics outside the Hubble horizon during inflation. Although we did not complete all of the work in the one week, we did clear up the majority of conceptual issues and cleared the way for completing a paper on the topic during the summer. It was posted to the ArXiV in late august (see http://arxiv.org/abs/1408.5002) [1].

1 Overview of the Field and Open Problems

It has long been known that Nature comes to us with an enormous variety of scales, and each can be understood largely on its own terms without needing to understand them all at once. One of the triumphs of 20th Century physics was the discovery that the mathematics with which we describe Nature — quantum field theory — shares this property. That is, in quantum field theory the details of short-distance physics tend to be largely irrelevant for the understanding of long-distance physics (a property called 'decoupling').

For example, not much need be known about the details of nuclei in order to understand the vast majority of the properties of atoms, and indeed this property was important for being able to unravel how atoms work. Ultimately this decoupling property — that states that each layer of structure can be understood on its own — is what allows progress in science.

Skillfully exploiting the decoupling property forces one to display the relevant scales in a problem and using the decoupling of one scale from another is often the difference between an untractable problem and a successful analysis. The tool for doing so is called an Effective Field Theory (EFT), which captures the long-distance dynamics together with the few ways it can depend on shorter-distance structure [2].

1.1 Implications for cosmology

This general observation has implications for cosmology which, as the science of the Universe as a whole, is the science of the longest scales of all. Cosmology is presently in a 'golden age' in which detailed measurements (such as of the Cosmic Microwave Background, or CMB) are for the first time allowing precision inferences about the overall contents and evolution of the Universe.

In particular, evidence has long been building that the Universe once passed through a very early epoch of accelerated Universal expansion, often called an inflationary phase [3]. Part of the evidence for this arises because correlations are observed in the sky (such as the temperature of the CMB as seen in different directions) that relate regions that have never been in causal contact (inasmuch as signals would have had to have

traveled faster than light to do so) throughout the history of the universe (if this history is extrapolated to the past without an epoch of accelerated expansion).

The regions between which correlations are difficult to understand lie outside the Hubble scale of the spacetime describing the cosmology and what happens during inflation to make understanding easier is that the Universe expands faster than does the Hubble length. This allows physical correlations to be established at small scales where causal processes can act, and then to be stretch out to become 'outside the horizon' or longer than the Hubble scale.

Since scales outside the horizon are the longest ones about which we have direct evidence, a long-standing question asks what the EFT is for physics outside the horizon.

2 Scientific Progress Made

We believed we knew what this EFT would be and used the workshop to try to decide if we were right. It turns out that we were, and so we were able to use our time to identify its features and check that it reproduces things people know about the extra-Hubble regime in inflationary cosmology.

Our proposal was that the EFT for extra-Hubble physics should be of the same form as the EFT that describes particles moving through a medium, like light or electrons through water or neutrinos through the Sun. These theories are a bit different from ordinary EFTs inasmuch as they allow information exchange between the degrees of freedom being followed (eg the particles) and those of their environment that are not being measured in detail (eg the fluid). As a result the appropriate description of these systems is a Lindblad equation [4], describing the evolution of the quantum density matrix of the system being measured.

In the inflationary application the system being followed (the 'particles') consists of all field modes that have wavelengths larger than the Hubble length, and those not being followed (the 'fluid') are those field modes with wavelengths shorter than the Hubble scale. By applying the Lindblad equation to this system we were able to show that the leading description turns out to agree with Starobinsky's Stochastic Theory of Inflation [5], which essentially treats the evolution of extra-Hubble modes as a random walk. We could show that the Lindblad equation reduces for the diagonal elements of the density matrix to the Fokker-Planck equation governing the probabilities of Starobinsky's random walk.

But we also found additional information. In principle we should be able to compute the systematic corrections to Starobinsky's formulation, in a way that has not yet been possible to do. We also found that all of the off-diagonal elements of the density matrix rapidly go to zero (in a field basis) and this has the physical interpretation of describing the de-coherence of initially quantum fluctuations (that are believed to give rise to primordial fluctuations in inflation) into classical fluctuations (as assumed in analyzing the implications of primordial fluctuations for observations on the CMB). We think this fills in an important conceptual missing step in the standard description of primordial fluctuations.

Our results were posted in the ArXiV listing given above, and will be submitted for publication to a journal soon. Our ideas have (so far) been well received at talks given at various meetings in North America and Europe over the summer.

References

[1] C.P. Burgess, R. Holman, G. Tasinato and M. Williams, EFT Beyond the Horizon: Stochastic Inflation and How Primordial Quantum Fluctuations Go Classical, arXiv:1408.5002.

[2] For some reviews aimed at gravity formulated as an EFT see:

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[3] A. D. Linde, "The Inflationary Universe," Rept. Prog. Phys. **47**, 925 (1984).

[4] C. Cohen-Tannoudji, J. Dupont-Roc and G. Grynberg, *Atom Photon Interactions*, Wiley, New York, 1992;

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[5] A. A. Starobinsky, Stochastic de Sitter (inflationary) stage in the early universe, *In *De Vega, H.j. (Ed.), Sanchez, N. (Ed.): Field Theory, Quantum Gravity and Strings*, 107-126*