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Pablo Ortiz

On the front cover: illustration by *Pablo Ortiz*.

Effects of Heavy Fields on Inflationary Cosmology

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Pablo Ortiz

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To my parents,
my sister, and Helena.

Las matemáticas son como una corriente de agua.
Existen diversas teorías complicadas, es cierto,
pero la lógica básica es muy sencilla.
De igual modo que el agua fluye
desde un lugar elevado hacia otro más bajo
tomando la distancia más corta,
sólo hay una corriente matemática.
Al observar con atención,
el curso se hace visible por sí solo.
Basta con que mires fijamente.
No tienes que hacer nada más.
Si te concentras y aguzas la vista, todo se aclara.
En este mundo no hay nada, salvo las matemáticas,
que me trate con tanta amabilidad.

Math is like water.
It has a lot of difficult theories, of course,
but its basic logic is very simple.
Just as the water flows from high to low
over the shortest possible distance,
figures can only flow in one direction.
You just have to keep your eye on them
for the route to reveal itself. That's all it takes.
You don't have to do a thing.
Just concentrate your attention
and keep your eyes open,
and the figures make everything clear to you.
In this whole, wide world,
the only thing that treats me so kindly is math.

Haruki Murakami, *1Q84*

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Preface

The very early universe is a tremendously exciting scenario which has always raised many fundamental and philosophical questions. Before the 1960's we have always assumed that the universe was very homogeneous and isotropic on large scales, which is a corollary of the Copernican principle, that roughly states that we are not located in any particular instant in time or point in space. This was an assumption about the universe called 'cosmological principle'. But in 1965, Penzias and Wilson measured the temperature of the cosmic microwave background (CMB) radiation and found out that it was extremely homogeneous and isotropic, which basically proved what had been assumed until then. The discovery of the CMB gave them the Nobel prize in Physics in 1978.

The physics of the CMB radiation is very well understood and is determined by the hydrodynamical behaviour of the cosmic fluids present before and after the time when the CMB was emitted, approximately 380000 years after the Big Bang. Before that time, the cosmic fluid formed by baryons, photons, and dark matter, was extremely hot and the hydrogen was ionised. Because of that, the electrons of the hydrogen atoms were free and continuously scattering with the photons, which did not let the photons travel freely through the cosmic fluid, and therefore the universe was opaque. It was not until the universe cooled down sufficiently and reached a temperature of about 0.3 eV that the hydrogen atoms were formed, binding the free electrons. This moment is called *recombination*. Right after this happens, the photons' mean free path rapidly increases and they become practically free to travel through the cosmic fluid, eventually reaching us today. This epoch is known as *decoupling* and the burst of photons released at that time constitutes the CMB radiation. This explains why the CMB is so important for cosmologists: it provides the oldest ‘picture’ of the universe, or at least the oldest picture that our ‘cameras’ are able to capture.

The most important property of the CMB is its strikingly homogeneous distribution, with temperature anisotropies of the level of only one part in a hundred thousand, which later on grow to form the large scale structure observed nowadays. These observations gave rise to the Big Bang puzzles, since a universe where gravity was always attractive would undergo a decelerated expansion, unable to explain such a degree of homogeneity. In short, if the evolution was tracked down backwards in time, regions separated by more than two degrees in the CMB sky were *never* in causal contact, and the homogeneity puzzle becomes a problem of very unlikely initial conditions. It was then realised in the 1980’s that an early epoch of accelerated expansion could explain how the whole CMB sky arose from one single causal patch of the universe, hence solving the homogeneity puzzle.

The stage of accelerated expansion of space is called inflation. The natural candidate to describe a perfect fluid with negative pressure that can lead to accelerated expansion is a scalar field whose kinetic energy is much smaller than its potential energy. This scalar field is called *the inflaton*. It turns out that the generic predictions of a single scalar field slowly rolling down on a scalar potential are in remarkable agreement with the observations, and therefore inflation driven by a scalar field had a tremendous success. More importantly, in the quantum mechanical picture of inflation, the quantum fluctuations of this scalar field will cause the universe to inflate slightly different in different parts, and these same quantum fluctuations can explain the temperature fluctuations observed in the CMB radiation. The dynamics of the inflaton fluctuations interplays with the energy density of photons, baryons, and dark matter, altogether originating the pattern observed when the CMB is emitted. Remarkably, the CMB contains primordial information about the inflaton fluctuations that we are able to decipher in order to access more detailed information about the inflationary era.

Nowadays, thanks to the overwhelming experimental effort, we cosmologists are extremely lucky to count on many data sets that allow us to penetrate into the finest details of the inflationary stage. In particular, precise measurements of the two- and three-point correlation functions allow us to perform model selection, since the three-point function is very sensitive to the dynamical details of the inflationary model in question. More specifically, the simplest standard inflationary models whose two-point function agrees with the observations, also predict a very suppressed three-point function. Thus, a detection of a large enough three-point function is a smoking gun for non-canonical models of inflation. Despite the success of these simplest models, it has been recently detected a series of hints of anomalies in both the two- and the three-point function, which make us think that there might be a mechanism during inflation generating scale-dependent features in the correlation functions.

Over the last decades, many different extensions of the simplest inflationary models have been proposed, in particular the possibility of having more degrees of freedom present during inflation, which would interact with the inflaton producing a rich phenomenology. This is motivated not only from the observational point of view, but also from the theoretical point of view, since the high energies at which inflation occurs suggest a theoretical framework based on high energy theories such as supergravity or string theory, where the presence of additional fields is ubiquitous.

I was lucky enough to start my research in cosmology when the experiments have reached the level of accuracy where these additional degrees of freedom might be detected. In particular, the Planck mission was able to measure the three-point function of the CMB, although the data has not been made public yet. Therefore, I was motivated to study in which situations the theory is robust in the presence of additional fields, under which conditions inflation can succeed including these interactions, and which situations would yield detectable features in the observations of the CMB. In particular, in the papers (chapters 2 and 3)

- '*Localized correlated features in the CMB power spectrum and primordial bispectrum from a transient reduction in the speed of sound.*'
  Ana Achúcarro, Vicente Atal, Pablo Ortiz and Jesús Torrado. *Phys.Rev.* **D89** (2014) 103006, `arXiv:1311.2552[astro-ph.CO]`,

- '*Inflation with moderately sharp features in the speed of sound: GSR and in-in formalism for power spectrum and bispectrum.*' Ana Achúcarro, Vicente Atal, Bin Hu, Pablo Ortiz and Jesús Torrado. *Phys.Rev.* **D90** (2014) 023511, `arXiv:1404.7522[astro-ph.CO]`,

we studied the theoretical regime in which interactions of the inflaton with heavy fields can lead to detectable imprints in the two- and three-point correlation functions of the CMB. We then searched for signatures coming from these interactions in the CMB data and we found reasonable fits to the power spectrum. In addition, these features have a correlated signature in the bispectrum that is also in reasonable agreement with the analyses of the Planck collaboration. More importantly, we restrict ourselves to the regime where the fits to data can be consistently interpreted by a well motivated and consistent theoretical framework, and we provided new techniques that allow us to explore wider regions of the theoretical landscape in a simpler manner.

In this same spirit, I explored the restrictions imposed by additional sectors of fields in supergravity scenarios, where there might be hundreds of additional degrees of freedom. Therefore, it is of extreme importance to keep under theoretical control the interactions with the inflaton field, which also lead to restrictions on the parent supergravity and on the different inflationary regimes that might be realised. In the paper (chapter4)

- '*Sgoldstino Inflation.*' Ana Achúcarro, Sander Mooij, Pablo Ortiz and Marieke Postma. *JCAP* **1208** (2012) 013, `arXiv:1203.1907[hep-th]`.

we propose a setup in which all the additional fields preserve supersymmetry and the type of couplings permit a consistent truncation and decoupling from the inflaton field. This allows us to give a consistent description of inflation in terms of two real scalar fields, in which the truncated sector of fields must satisfy certain conditions in order to not spoil inflation.

Last, we extended the work in supergravity by including more general couplings between the inflaton and the additional fields. Moreover, we used the tools of random matrix theory to account for the statistics of a large number of additional fields. Apart from inflation, we also explored the possibility of achieving stable vacua able to describe the stage of present expansion of the universe (or else a hypothetical vacuum before inflation). This imposes other restrictions on the sector of additional fields. Thus, with the paper (chapter 5)

- '*Perturbative stability along the supersymmetric directions of the landscape.*' Kepa Sousa and Pablo Ortiz. `arXiv:1408.6521[hep-th]`.

we are cornering the landscape of supergravity theories that can lead to successful inflation and/or description of the present vacuum, or alternatively, a hypothetical pre-inflationary vacuum state. In order to do this, we are characterising the truncated sector by its statistical and geometrical properties. We are also incorporating a new element, utilising not only the supersymmetry breaking direction to derive constraints, but also the supersymmetric directions in field space, which are to be described by their statistics.

All together, the research done with my collaborators has helped in analysing the possibility that additional fields are present during inflation, where we have studied many different aspects of it: from the theoretical consistency to the detectability. We have taken care of providing consistent descriptions and taking into account the (sometimes forgotten) presence of additional heavy degrees of freedom during inflation. We have provided novel methods to calculate their impact on the CMB observations, and we have studied the regimes in which supergravity theories can consistently describe inflation with multiple sectors.