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Cosmic inflation / Inflation cosmique

Non-linear couplings, from the early to the late time universe

Couplages non linéaires, de l'univers primordial à l'univers récent

Francis Bernardeau [a,b,*]

[a] *CEA & CNRS, UMR 3681, Institut de physique théorique, 91191 Gif-sur-Yvette, France*
[b] *Sorbonne Universités, UPMC Université Paris-6 & CNRS, UMR 7095, Institut d'astrophysique de Paris, 98 bis bd Arago, 75014 Paris, France*

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ABSTRACT

Deciphering the mechanisms at play in the formation and evolution of the large-scale structure of the universe is part of the scientific goals of many projects of observational cosmology. In particular, large-scale structure observations can be used to infer mode-coupling effects, whether they come from the physics of the early universe or from its late time evolution. Specificities of such couplings are presented, noting that in principle they can be directly detected through bispectra of the cosmic microwave background temperature anisotropies or density in the local universe. The existence of such couplings have however more far-reaching consequences for the growth of the structure. Those are sketched as well as their possible observational impacts.

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RÉSUMÉ

La compréhension fine des mécanismes en jeu au cours de la formation des structures à grande échelle de l'univers est l'un des objectifs scientifiques communs à de nombreux projets de cosmologie observationnelle. Les observations des grandes structures permettent de révéler les effets des couplages de modes, qu'ils soient associés à des processus physiques dans l'univers primordial ou à l'évolution plus tardive de ces structures. Les propriétés de ces couplages sont décrites, en soulignant qu'en principe ils peuvent être directement détectés grâce au bispectre des anisotropies de température du fond diffus cosmologique ou du champ de densité dans l'univers local. L'existence de tels couplages a toutefois des conséquences plus profondes pour la croissance des structures. Celles-ci sont esquissées, ainsi que leurs possibles implications observationnelles.

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1. Introduction

The large-scale structure (LSS) of the universe and the cosmic microwave background (CMB) offer unique windows on the physics of the early Universe, in particular on inflationary models thought to be at the origin of the large-scale structure

* Correspondence to: Institut d'astrophysique de Paris, 98 bis bd Arago, 75014 Paris, France.
E-mail address: francis.bernardeau@iap.fr.

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of the universe. The statistical properties of the density and velocity perturbations for the former and of the temperature anisotropies and polarization for the latter depend both on the inflationary period during which they were created and on the physics at play after horizon crossing, during recombination time and during the subsequent stages of the evolution of the universe. The angular power spectrum of the CMB anisotropies has been extensively used to set constraints on the basic cosmological parameters and the shape of the inflationary potentials (see of course the Planck results in [1] and this volume).

At linear order in metric perturbations, physical processes at play affect the metric perturbations by a multiplicative transfer function. The characteristic features observed in the large-scale cosmological observations in general, such as spectra, originate therefore from the metric and fluid couplings that this transfer function encodes, whereas the overall amplitude of the initial (that is super-Hubble) metric perturbation and its scale dependences are determined by the inflationary phase. All these aspects, from the identification of modes in the early universe, to the late time growth of structure, are now fully understood (and detailed in standard reference textbooks, [2–7]) at least at the linear level. In such calculations, the metric perturbations are linearized so that the nonlinear couplings that are inherently present in the evolution equations are ignored. An important consequence in models that predict Gaussian initial metric fluctuations is that all cosmic fields will follow Gaussian statistical properties. This is a priori the case for generic models of inflation to be contrasted with models with active topological defects—such as textures or cosmic strings—that have soon been recognized as models that could produce large primordial non-Gaussianities (see the early works in [8–11]).

In the case of single-field standard slow-roll inflation, it has been unambiguously shown in [12] that it can produce only very weak non-Gaussian signals. It has however been realized that some models of inflation might produce significant deviation from Gaussianity, whether in the context of non-standard single-field inflation (such as DBI inflation,[1] see [14]), in the context of the curvaton model [15,16] or in the context of multiple-field inflation [17–19]. The question of the observation of primordial non-Gaussianities is then largely open. In general, however, primordial deviations from Gaussianity are in competition with the couplings induced during the non-linear evolution of the cosmic fields. This is the issue we would like to present in this short review paper, whether it is at the level of the CMB observations—in the observation of the CMB bispectrum in particular—or at the level of the LSS observations. The second section will be devoted to the general formalism; the third and fourth ones explore respectively the consequences of such couplings for CMB and LSS observations. In the last section, a general scheme that one may want to employ in order to extract cosmological information out of LSS observations is sketched.

2. The gravity-induced mode coupling structure

Hereafter, for the sake of our presentation, we assume that on super-Hubble scales, the only significant scalar perturbations are *adiabatic*—they correspond to only one scalar degree of freedom—and that they obey a nearly Gaussian statistics (observations anyhow exclude strongly non-Gaussian initial metric perturbations). To be more precise, they can be described in the Fourier space by a single scalar field[2] $\zeta(\mathbf{k})$ defined in such a way that it is constant at super-Hubble scales (see [20] and also [12]), $\mathbf{k}$ being a comoving wave-number, that satisfies

$$\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\rangle_h = P_\zeta(k_1) \tag{1}$$

and

$$\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle_h = 2\, f_{\rm NL}^{\zeta}(\mathbf{k}_1,\mathbf{k}_2)P_\zeta(k_1)P_\zeta(k_2) + \text{sym.} \tag{2}$$

where $\langle\ldots\rangle_h$ stands for the ensemble average of product of Fourier modes after the $\delta_{\rm D}(\sum\mathbf{k}_i)$ factor that always appear in such ensemble averages (due to statistical homogeneity) has been dropped and where "sym." stands for the two other terms obtained by permutation of the wave-numbers. This defines the primordial power spectrum $P_\zeta(k)$ and the primordial mode coupling amplitude[3] $f_{\rm NL}^{\zeta}$. Considering an observable quantity θ related to the perturbation variables, the effect of evolution can generically be recapped[4] as

$$\theta(\mathbf{k}) = \mathcal{T}_\theta^{(1)}(k)\,\zeta_0(\mathbf{k}) + \int_{\mathbf{k}_1\ldots\mathbf{k}_p} \mathcal{T}_\theta^{(2)}(\mathbf{k}_1,\mathbf{k}_2)\,\zeta_0(\mathbf{k}_1)\zeta_0(\mathbf{k}_2) + \ldots \tag{3}$$

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1 These models of inflation can be captured with an effective theory model as shown initially in [13].

2 Note that the choice of ζ as the primordial field is not unique and one could have chosen the Bardeen potential. With such a choice, however, the $f_{\rm NL}^{\zeta}$ incorporates only the inflation-dependent couplings—$f_{\rm NL}^{\zeta}$ is proportional to the slow-roll parameter in single-field inflation, for instance. The other coupling terms induce by the change of variable can be incorporated into $\mathcal{T}^{(2)}$; see Eq. (5) below.

3 This is the expression for the bispectrum obtained assuming ζ could be expanded as $\zeta = \zeta_G + f_{\rm NL}^{\zeta}\zeta_G\zeta_G$, where ζ_G is assumed to obey Gaussian statistics. This is not however a valid description when the bispectrum originates from multiple-field couplings or from quantum calculation. The formal expression (2) is always valid though; see Refs. [21,22].

4 Things are actually slightly more complicated since usually observables cannot be decomposed into 3D Fourier modes. The functions $\mathcal{T}_\theta^{(1)}(k)$ and $\mathcal{T}_\theta^{(2)}(\mathbf{k}_1,\mathbf{k}_2)$ should then be thought as projection operators. This is in particular the case for temperature anisotropies and polarizations. This does not affect, however, the general point we want to make in this introductory section.

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