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Testing quantum gravity with cosmology / Tester les théories de la gravitation quantique à l'aide de la cosmologie

Do we *really* understand the cosmos?

Comprenons-nous vraiment *le cosmos ?*

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A R T I C L E   I N F O

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A B S T R A C T

Our *knowledge* about the universe has increased tremendously in the last three decades or so — thanks to the progress in observations — but our *understanding* has improved very little. There are several fundamental questions about our universe for which we have no answers within the current, operationally very successful, approach to cosmology. Worse still, we do not even know how to address some of these issues within the conventional approach to cosmology. This fact suggests that we are missing some important theoretical ingredients in the overall description of the cosmos. I will argue that these issues — some of which are not fully appreciated or emphasized in the literature — demand a paradigm shift: We should not think of the universe as described by a specific solution to the gravitational field equations; instead, it should be treated as a special physical system governed by a different mathematical description, rooted in the quantum description of spacetime. I will outline how this can possibly be done.

R É S U M É

Notre *connaissance* de l'univers s'est drastiquement accrue au cours de ces trois dernières décennies – grâce au progrès accomplis en matière d'observation – mais notre *compréhension* de celui-ci ne s'est que très peu améliorée. Il est plusieurs questions fondamentales touchant notre univers pour lesquelles nous n'avons pas de réponses avec l'approche actuelle de la cosmologie, au demeurant couronnée d'un grand succès d'un point de vue opérationnel. Pire encore, nous ne savons même pas comment appréhender certains problèmes dans le cadre de l'approche conventionnelle de la cosmologie. Ceci suggère que des ingrédients théoriques importants d'une description complète du cosmos nous font encore défaut. J'affirmerai ici que ces questions – dont la littérature n'a pas encore pleinement pris la mesure ou suffisamment insisté dessus – exigent un changement de paradigme : nous ne devrions pas penser à l'univers comme étant décrit par une solution spécifique aux équations du champ gravitationnel, mais plutôt comme devant être considéré comme un système physique spécifique gouverné par une description mathématique différente, pre-

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nant ses racines dans une description quantique de l'espace-temps. Je soulignerai comment ceci peut être fait.

1. Motivation

Spectacular progress in cosmological observations in the last four decades has helped us to develop a standard model of the universe which is very successful. In this model, the smooth universe is described by a *specific* solution to the field equations of gravity, say, Einstein's equations, and can be parameterized by a small set of numbers ($H_0, \Omega_B, \Omega_{\rm DM}, \Omega_{\rm DE}, \Omega_R$ ...with their usual meanings). In addition, the formation of structures in the universe is described quite adequately in terms of the growth of perturbations around this smooth universe. These perturbations, generated during an inflationary phase,[1] can be characterized by a power spectrum $P(k) = Ak^n$ with two more parameters, A and n. Both theory and observations are mature enough today to test not only the lowest order predictions (for, e.g., scale invariance of the perturbations, corresponding to $n = 1$), but also higher order effects (like, for, e.g., the deviation $(n - 1)$, in specific models). Thus, on the whole, the description of the universe can be based on a set of well defined parameters which are directly observable.

At the next level of probing, such a description encounters three kinds of difficulties, of which the first two are well-known in the literature and the third one will be the core topic of discussion in this article.

The first kind of difficulty is related to technical issues and details in the model. The following questions, for example, belong to this set: Can we correctly describe the properties and statistics of dwarf galaxies? Do we understand the detailed mechanism which caused the reionization in the universe? Most cosmologists (including me) believe that it is just a question of time before we have satisfactory and consistent answers to such issues within the standard description.

The second kind of difficulty which arises in cosmology is related to the description of the matter sector. Examples are questions like: What is the nature and abundance of the dark matter[2] particle? How can we explain the baryon-to-photon ratio in our universe? These issues are more fundamental than the first kind of problems but most of us believe that we do have an algorithmic procedure available to attack these problems, *within the framework of conventional cosmology*. For example, a successful extension of the standard model in high energy physics might allow us to compute such numbers from first principles. The current difficulty is then only due to our inadequate understanding of particle physics at high enough energies.

The third kind of problems — which, as I said, we will be concerned with — are those which we have no clue as to how to address. The most important example in this category is the extremely tiny — but non-zero — value of the cosmological constant.[3] As regards this set, I am not so much concerned about the lack of a viable solution as with the fact that we do not even know how to properly attack these problems within the framework of conventional cosmology. In some cases, which I will discuss, it is not even clear how to precisely state these problems within the context of the standard model of cosmology.

After some clarifications on the notion of expansion of the universe (Sec. 2) I will describe, in Sections 3 to 6, these foundational conundrums in cosmology. Based on this discussion, I will argue (see Sec. 7) that it is fundamentally incorrect to describe the universe as a specific solution to the gravitational field equations. Instead we should think of the universe a special system and look for a different paradigm to describe its evolution. I will suggest, towards the end of the article, some possible ingredients of such a paradigm and explain (see Sec. 8) how it can solve the cosmological constant problem. I will use the mostly positive signature and set $c = 1$, $\hbar = 1$ and (occasionally) $G = 1$. The Greek indices range over 1, 2, 3 while the Latin indices range over 0–3.

2. Expansion of the universe is in the eye of the beholder

The standard cosmological model is based on a specific solution to gravitational field equations. It is generally believed that one key feature of this solution is the 'expansion' of the smooth background universe which is supposed to distinguish the Friedmann solution from, say, the spacetime describing the region around the Sun. What is not adequately emphasized

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[1] I would love to have a viable alternative to the inflationary generation of perturbations, but there is none which can be considered a worthy challenger. So, in this article I will accept the inflationary paradigm as a working hypothesis.

[2] Verification of Einstein's equations at cosmological scales require testing the hypothesis $G^a_b - \kappa T^a_b = 0$ where $\kappa = 8\pi G$. When the directly observed values of these two tensors $G^a_b(\text{obs})$ and $T^a_b(\text{obs})$ lead to $G^a_b(\text{obs}) - \kappa T^a_b(\text{obs}) \equiv \kappa Q^a_b \neq 0$, as it happens in our universe, Einstein's theory appears to flunk the test. We can then either postulate a modified matter tensor $T^a_b = T^a_b(\text{obs}) + Q^a_b$, (as done in the case of dark matter) or a modification of theory by $G^a_b = G^a_b(\text{obs}) - \kappa Q^a_b$, (as done in the case of dark energy which I take to be the cosmological constant). I will accept both these modifications, viz, the postulates of dark matter and the cosmological constant, in this article. One can question these assumptions, but again I find that all alternatives are much worse theoretically.

[3] In this article, I will assume that dark energy *is* cosmological constant. Other explanations for dark energy are more ad hoc, not demanded by observations, do not explain why cosmological constant is zero and leaves the fine tuning problem unanswered. I do not think these models are better alternatives to the postulate of a cosmological constant.

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