IN2P3 Prospectives 2020

GT05 Physique de l'inflation et énergie noire

Cosmic Inflation - Theory

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Inflation [1, 2] is a high-energy phase of accelerated expansion that was first introduced 40 years ago as a possible solution to the hot Big Bang model problems. During inflation, vacuum quantum fluctuations are stretched to astrophysical scales and parametrically amplified. This gives rise to primordial cosmological perturbations, leading to Cosmic Microwave Background (CMB) fluctuations and large-scale structures in the universe. Inflation predicts that these perturbations should be almost Gaussian, close to scale invariance and phase coherent, predictions that have been remarkably well confirmed. Further, their detailed statistics allow one to constrain the microphysics of inflation and its dynamics. Inflation has thus become a very active field of research, since the energy scales involved during this early epoch are many orders of magnitude larger than those accessible in particle physics experiments.

Below we review open issues in inflationary cosmology, that we think will be at the heart of research in early universe cosmology in the next decade. This proposal has been prepared in close collaboration with other efforts, which led other proposals, where observational prospects that would allow us to address these open issues in the future are detailed:

- Cosmic inflation from ground based CMB polarization experiments (led by Josquin Errard)
- Fundamental physics from ground based CMB experiments (lead by Thibaut Louis)
- Cosmic inflation and fundamental physics from space: LiteBIRD (led by Matthieu Tristram)

These proposals are therefore tightly connected, and strongly support each other.

1 Embedding inflation in high-energy physics

Inflation can proceed at energy scales as high as 10^{16} GeV, where particle physics remains elusive. Various implementations of inflation have been proposed, embedded in different extensions of the standard model of particle physics. However, many theoretical issues remain open to understand inflation in the context of fundamental physics.

An important open problem is how to embed inflation in string theory (the most promising candidate theory for the quantum description of gravitation and its unification with the other interactions). A lively discussion is underway about whether this is even possible in principle. Several proposals for a string-theoretical realization of *de Sitter space-time* (which for many practical purposes is a close approximation to an inflationary universe geometry) exist, among which the KKLT model [3] is the best studied. However it is an ongoing debate whether these constructions are reliable or not, and some have argued they are based on uncontrolled approximations. Other models which may be under better control are string theory monodromy models [4], which are based on the existence of fields enjoying an approximate symmetry. Beside the analysis of specific models, a vivid discussion on more general terms is underway about the possibility, even in principle, of realizing de Sitter space-time and/or inflation in a consistent quantum gravity theory. Indeed, a set of conjectures have recently been put forward, referred to as *swampland conjectures*, which posit the existence of strong constraints on de Sitter/inflationary solutions in a consistent fundamental theory (see [5] for an example concerning specifically inflation).

Beyond specific details, string theory models of inflation display some general features. These are typically multi-field models, and this may give rise to possible observable effects (non Gaussianities, entropic perturbations, etc.). Furthermore, string theory models tend to predict a very small amplitude for primordial tensor perturbations, much below the sensitivity of current or near-future experiments. Therefore, a detection of primordial tensor modes would put string theory models of inflation under a strong pressure.

A general question concerning embedding inflation in any fundamental framework is its relation with the cosmological constant problem: why is it that the vacuum energy, estimated from quantum effects in particle physics, does not seem to contribute to the observed curvature of space-time? Ideally, a satisfying scenario of inflation/reheating should be coupled with a mechanism to make the effective cosmological constant after reheating very near zero (many orders of magnitude below the scale of inflation itself and all other scales of high energy physics) and at the same time leaving a tiny amount of dark energy (in the form of a residual cosmological constant or a set of dynamical degrees of freedom) to drive the observed late-time acceleration of the universe. These questions mix the classical and the quantum regime, and physics on the very short and the very large scales. This makes it very hard to address these problems within the well-understood frameworks of effective field theory and classical general relativity. While none of the string theory models discussed above addresses these questions, a proposal [6] was recently put forward by APC theorists for a mechanism of *self-tuning* of the cosmological constant, based on the *gauge/gravity duality* (a string theory byproduct). These models also offer an alternative way of realising de Sitter/inflation [7, 8] with respect to standard string theory constructions, which may evade the *swampland* arguments.

When confronted with observations, among the various models of inflation that have been proposed, a substantial fraction has been ruled out by recent CMB measurements [9, 10]. Yet a large number of candidates remain. This can be explained by the fact that the CMB gives access to a limited range of scales only. The time frame during which these scales are generated during inflation is therefore limited as well, and cannot encompass more than ~ 7 e-folds (over the ~ 60 e-folds elapsed between the generation of these scales and the end of inflation). This means that the constraints on the inflationary potential that the CMB can place are restricted to a small region. Measurements of the spectral distortions of the CMB by PIXIE-like experiments will probe the primordial power spectrum on smaller scales, extending the part of the inflationary potential being probed to ~ 17 e-folds [11]. But ultimately, to constrain a wider range of the inflationary potential and further constrain the microphysics, one may need to combine the CMB with other data sets that probe different scales.

Another theoretical framework in which inflation can be embedded is Supersymmetry which allows to link the physics at the high energy scale of inflation and beyond to the TeV scale, describing both the inflation era (as it naturally encompasses flat directions that provide a way for inflation to occur), and the physics at the LHC. Such a theory can predict multiple observables (from cosmology, high-energy physics, direct dark matter searches ...) that can then be compared to measurements to further assess the favoured/disfavoured area in the parameters space within a coherent description of our universe. The study of such models from a theoretical, phenomenological and experimental point of view is described in another proposal to the GT5, "*SUSY Cosmic Inflation*", that we fully support as it complements this proposal.

2 Primordial gravitational waves

An important prediction of inflation, untested so far, is that primordial gravitational waves should be produced in the early universe, leaving an imprint in the B-mode polarisation of the CMB anisotropies. Their detection would be a key experimental advance, as they would lead to a determination of the energy scale of inflation and of the inflaton field excursion (at least in the simplest models). It would also allow us to test the consistency relation that relates the amplitude of the tensor power spectrum with its tilt.

3 Reheating the universe

After inflation, the energy contained in the fields driving inflation needs to decay into the other degrees of freedom of the standard model of particle physics, and the universe needs to thermalise. This epoch is known as reheating and is driven by the interactions between the inflaton and the other fundamental fields. By constraining reheating, one can thus learn about these couplings, and probe the inflationary potential in a field regime that is different from where inflation takes place.

The physics of reheating is however poorly known, since a direct observational access to the reheating epoch would require to probe scales that exit the Hubble radius around the end of inflation, with a wavelength today that can be as small as one meter (if inflation proceeds at $\rho_{\mathrm{inf}} = 10^{16}\mathrm{GeV}$, it otherwise scales with $\rho_{\mathrm{inf}}^{-1/4}$). Contrary to the scales accessed in the CMB (of the order of 10^6 parsecs), such distances fall far into the non-linear regime and cannot be directly studied with cosmological surveys.

Within a given model of inflation, reheating can however be constrained from the fact that the expansion history during this epoch determines the location of the observational window along the inflationary potential, *i.e.* it allows one to relate physical scales with the time frame during inflation when they are produced. It can therefore be indirectly constrained by CMB observations [12].

In many relevant inflationary scenarios, reheating proceeds through a first rapid period of explosive particle creation (called preheating). This results in a highly occupied, far-from-equilibrium state which undergoes a strongly nonlinear evolution which often results in a very slow turbulent regime, which delays thermalisation for a long time. Dynamical calculation of the reheating dynamics involve advanced non-equilibrium (quantum) field theory techniques are of notorious difficulty because of the large time scales involved [13]. It is, to date, not clear whether (and if yes on what time scale) such simulations are able to produce a thermalised universe.

4 Quantum field theory on inflating backgrounds

The inflationary paradigm relates the large-scale structures to primordial fluctuations of quantum origin. Its theoretical foundations therefore rely on understanding the deep aspects of quantum field theories (QFT) in curved space-times and, in particular, in inflating backgrounds (*e.g.*, de Sitter space). Specific phenomena, with no analog in flat Minkowski space-time, such as gravitational particle creation, have important consequences, *e.g.*, for the treatment of loop corrections to inflationary observables. These are interesting not only for observational prospects but also because they play a key role for fundamental questions like the very justification of the inflationary predictions (based on a linear description), or the quantum-to-classical transition (quantum decoherence). Finally, such quantum effects may reveal interesting unforeseen phenomena and open new paths for model building.

One of the most debated theoretical aspects is whether the backreaction of quantum fields may be strong enough to significantly change the classical geometry, e.g. to make de Sitter space-time spontaneously decay. The indication from perturbative quantum field theory so far has been inconclusive, and it is likely that this question may be settled only using non-perturbative methods. This is an active field of research in the APC theory group, where different approaches are being used, such as the exact renormalisation group [14, 15] and gauge/gravity duality for quantum field theories on curved space-times [16, 17].

5 Can inflation produce primordial black holes?

Primordial Black Holes (PBHs) [18] are expected to form from rare large density perturbations produced during inflation, when they re-enter the cosmological horizon and collapse into black holes (BHs). For the scales probed in the CMB, the amplitude of the fluctuations is too small to yield a substantial abundance of PBHs. At smaller scales however, where the amplitude of the fluctuations is less constrained, inhomogeneities produced during inflation could be large enough, and PBHs thus open up a new observational window into the physics of the last e-folds of inflation, and reheating.

There has been renewed interest in PBHs since the LIGO/VIRGO collaboration reported the first detection of gravitational waves associated to black-hole mergers in 2015 [19]. They may indeed explain the existence of progenitors for these events. PBHs may also solve a number of problems currently encountered in astrophysics and cosmology, such as explaining part of all of the dark matter (two mass windows are left open for PBHs to constitute an appreciable fraction, and possibly all, of dark matter, around $M \sim 10^{-12} M_\odot$ and $M \sim 10 - 100 M_\odot$), explaining the seeding of the super-massive black holes in galactic nuclei [20], the generation of the large-scale structure [21, 22] (either individually through the "seed" effect or collectively through the "Poisson" effect), the minimum radius and the large mass-to-light ratios of ultra-faint dwarf galaxies [23], and the generation of correlations between the soft X-ray and infrared backgrounds [24].

6 How did inflation start?

The potentials favoured by the latest CMB measurements are such that no fine tuning is required in homogeneous field configuration space to start inflation [25]. However, how likely it is that inflation starts in an inhomogeneous universe is still an open question. Recent progress in numerical relativity techniques now allow us to address this issue. The first works conducted [26–28] seem to suggest that inflation is rather likely to start, especially in large-field models. These studies are however limited to specific setups and have all technical limitations, and more needs to be done. Setting initial conditions for inflation, in the light of potential pre-inflationary phases (possibly contracting phases followed by a bounce), remains an important task.

7 Can we prove that cosmological perturbations are of quantum mechanical origin?

While it has been shown [29] that some CMB observables can be reproduced by classical states, it is still not clear whether a genuinely quantum signal can be seen in the CMB, that would confirm the quantum origin of cosmological perturbations. Indeed, although a large quantum signal is in principle present at CMB scales [30–32] (yielding for instance maximal Bell inequality violations that could be tested experimentally), it is difficult to detect in practice since it is hidden in tiny quantities (often referred to as the "decaying modes") that are beyond the scope of any realistic experiment at present. Theoretical developments in Quantum Information Theory may however provide new tools to reveal the signal.

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