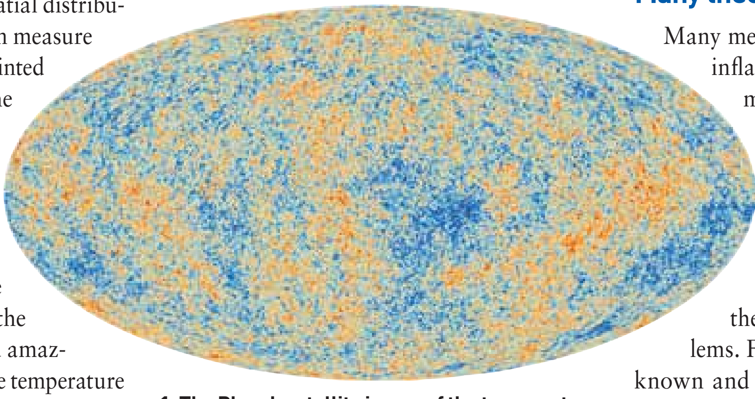
# Inflation and the Higgs particle

**George Ellis and Jean-Philippe Uzan consider inflationary universe possibilities in the light of the Planck satellite observations.**

A huge step forward in theoretical cosmology was the proposal by Alan Guth in 1981 of *inflation*: an epoch of rapidly accelerating expansion in the very early universe driven by a scalar field called the inflaton that caused the universe to expand through at least 60 e-folds in a tiny fraction of a second. This was originally argued to solve the problem of why the universe is so smooth on very large scales but, crucially, it turned out to provide the first basis for a coherent theory of astronomical structure formation. In this view, structures such as galaxies started with quantum fluctuations in the very early universe, amplified and stretched to large scales by the inflationary expansion (Mukhanov and Chibisov 1981). This leads to curvature and density fluctuations, imprinted on the surface of last scattering that occurred 380 000 years after the inflationary epoch when the universe has cooled down enough to allow matter and radiation to decouple from each other. These were then the seeds for astronomical structure formation occurring because of gravitational attraction at much later times.

But as well as affecting the distribution of matter, resulting in a characteristic spatial distribution of the inhomogeneities we can measure today, these fluctuations were imprinted in temperature fluctuations on the last scattering surface. These fluctuations lead to anisotropy patterns characterized by peaks in the angular power spectrum of the cosmic background radiation that has propagated freely since the time of last scattering. In 2013, the Planck satellite produced new and amazingly precise measurements of these temperature fluctuations (figure 1). These detailed observations (Planck collaboration 2013a) provide a huge data set that allows theorists to better constrain models of inflation, and so improve understanding of the origins of astronomical structures in the universe.



1: The Planck satellite image of the temperature fluctuations on the last scattering surface. An angular power spectrum analysis of this data reveals the preferred physical scales that determine structure formation outcomes at later times. (ESA/Planck Collaboration)

## The importance of data

The issue here is that while the broad mechanism of inflation is well understood, the specifics are not. Indeed, it is not a unique theory: there exist over a hundred options for what the inflaton might be. It is a generic mechanism, but not a precise physical theory linked to a definite particle or field. That is why any new data that constrain such models are important. The way the Planck measurements constrain these many options was discussed by the Plank team (Plank collaboration 2013b,c) and has been catalogued in a comprehensive way in *Encyclopaedia Inflationaris* by Martin *et al.* (2013).

Now a key issue is: What criteria for good inflationary theories were used in these important analyses? Although not explicitly stated, there were essentially two:

- Criterion 1: Internal coherence/consistency of the dynamical theory proposed; i.e. the theory makes scientific sense.
- Criterion 2: Observational tests confirming the outcome of the theory; i.e. the theory can be tested, and observations are compatible with its predictions.

It is these criteria that underlie the deliberations in the papers by the Planck collaboration (2013a,b,c). However, there are two further important criteria lurking in the wings, not specifically mentioned by authors of either of these papers. They are:

- Criterion 3: High probability: the model should not depend on fine-tuned initial conditions. This was one of the original main drivers for the introduction of the theory of inflation.
- Criterion 4: Links to other physics. This is based on the fact that one of the major driving forces of physics for the past several hundred years has been to unify apparently distinct physical phenomena by giving a single explanation for both.

How do these criteria work out for inflationary theories, in the light of the Planck satellite observations?

Although it has often been claimed that inflation solves the issue of probability – criterion 3 – this claim has come under sustained criticism *inter alia* by Roger Penrose. Now Ijjas *et al.* (2013) have revisited the issue in the light of the Planck data and conclude that none of the inflationary theories is probable. If correct, it means that the dream of proving the universe is probable has not come true: it is indeed a special place. This claim will undoubtedly be contested, in part because it is technically complex: it depends on the unresolved issue of determining a unique measure for inflationary models, which is highly disputed territory. We will not comment on it further here, but will turn to criterion 4, which we believe is a key issue that needs greater consideration than it has been given.

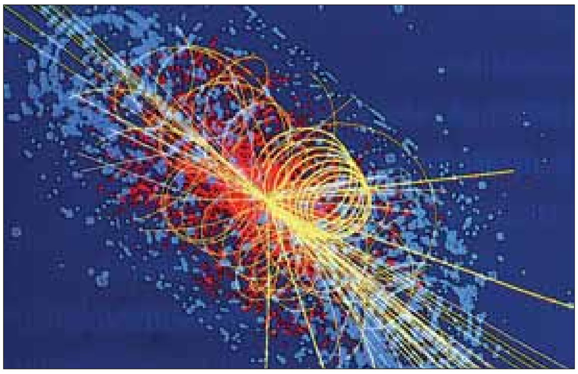
## Many theories

Many mechanisms have been proposed for inflation, involving *inter alia* supposed multiple fields with unconstrained potential functions that can be chosen at will; effects devolving down from higher dimensions; effects of alternative gravitational theories; echoes of quantum gravity, and so on. But these theories have two related problems. First, they are usually not based in known and tested physical interactions, but rather either in theories such as supersymmetry that have been hypothesized for good reasons, but remain unproven – they may or may not be true; or in terms of interactions proposed purely in order to explain inflation. Thus they do not unite different aspects of physics. Related to this is the fact that if you propose some mechanism as the inflaton and it does nothing else testable in any other branch of physics, it is a form of saving the phenomenon, not a general mechanism with varied applications. It may make specific predictions in the inflationary context such as the existence of specific kinds of gravitational waves, but that does not unite this inflation mechanism to laboratory measurements outside this context. What we really want is a proposed mechanism that is not just used to explain one phenomenon (inflation), but also unites several phenomena in different contexts.

Now the further major experimental physics result in 2013 was the confirmation on 14 March that the CMS and ATLAS experiments at the Large Hadron Collider have, through analyses of collision fragments at the LHC (figure 2), detected an elementary particle that is probably (with more than 99% certainty) the long sought-after Higgs boson (ATLAS Collaboration 2012, CMS Collaboration 2012). This particle plays a key role by providing the mass of what would otherwise be massless particles.

So a key question to ask is if there could possibly be a link between these two results: could the Higgs particle, confirmed at the LHC, be the inflaton? And the remarkable result is that the Planck data show this is indeed possible: the Higgs as inflaton produces predictions that are compatible with the observations made by the Planck satellite, provided it is non-minimally coupled to gravity (Planck collaboration 2013a,b).

This result has not been particularly emphasized either by the Planck team or by the authors of the *Encyclopaedia Inflationaris*. But in our view this is the single most important result to come out of Planck, as far as the primordial universe is concerned. If it were the case that the Higgs was indeed the inflaton, it would link the most important physics experiment of recent years with the most dramatic recent astronomical observations in a way that fulfils our dreams of unifications in physics in an extraordinarily satisfying way. And that seems theoretically possible (Martin *et al.* 2013, Bezrukov and Shaposhnikov 2008, Bezrukov *et al.* 2013).



**2: Computer simulation of particle traces from an LHC collision in which a Higgs boson is produced. (CERN/L Taylor)**

## Cosmology as philosophy

Why do we emphasize criterion 4 so much? It is because the most important progress in scientific cosmology in the past century was the development of links between cosmology and other branches of physics. Initially, cosmology was linked only to gravitation, through the use of Einstein's general theory of relativity to predict the evolution of the universe. That was a huge unification, linking falling apples, the motion of the Moon round the Earth and the Earth round the Sun, and the evolution of the universe itself. But this did not succeed in convincing physicists that cosmology was a serious science, even though observational links to galaxy number counts and redshifts were successfully developed and used to constrain cosmological models. Until the 1960s, most physicists thought cosmology was just philosophy, hardly worth taking seriously.

That changed first when atomic physics became relevant to the early universe through Gamow's realization that a hot Big Bang early phase must have occurred, with decoupling of matter and radiation at about 4000 K leading to the existence of cosmic blackbody background radiation that would be observable today, as confirmed by observations. The exquisite accuracy of the blackbody spectrum of this radiation measured by the COBE satellite confirmed the application of standard atomic physics to the early universe at the time of decoupling, about 13.8 billion years ago. The second highlight was the development of the theory of primordial nucleosynthesis, linking nuclear physics to the evolution of the universe between a fraction of seconds to 20 minutes after it started, and confirmed by astronomical observations of light element abundances (despite the open issue of lithium-7). It is this that made cosmology a respectable physical science, now included in the annual Review of Particle Physics published by the Particle Physics Data Group in the *Physical Review*. It was on the basis of primordial nucleosynthesis that the first hints of the existence of three families of neutrinos was obtained (Steigman *et al.* 1977, Yang *et al.* 1979), before accelerator physics confirmed this result. It is important to keep in mind that the temperature of the universe later than 1 second after the Big Bang is smaller than 1 MeV, so that the non-gravitational physics (nuclear physics, atomic physics, electromagnetism) required to interpret all existing observations then is under control from an experimental point of view, and non speculative.

The dream of linking particle physics to the very early universe was a high hope when inflation was proposed. So far it has not been realized, because the majority of proposals for the inflationary mechanisms are highly speculative: they are not linked to well established physics, despite the existence of many inflationary models derived from the phenomenology of supersymmetry or string theory, which remain speculative theoretical frameworks (Lyth and Riotto (1999). But the proposal of the Higgs as the inflaton can make this potential connection a reality, linking inflation to a fundamental particle that has experimentally determinable properties. Note that the Higgs of the standard model of particle physics is too heavy to be the inflaton if general relativity is the correct theory of gravitation: in order to be successful, this model requires a modification involving universal coupling of the Higgs boson, which can be argued to be generated from quantum fluctuations. This means that the theory of gravity will not strictly be described by general relativity but rather by a scalar-tensor theory. However, with a Higgs mass of 125 GeV, one expects modification of general relativity to become important roughly below $10^{-17}$ m in the laboratory today, far beyond what can be tested at present.

The idea needs to be tested. In particular, at the end of inflation the universe is cold and empty, in a Bose condensate state with the inflaton oscillating coherently in its potential. The production of the particles we observe today is thought to occur in a process called reheating, during which the inflaton decays into other particles. In this scenario, the Higgs needs first to decay to W and Z gauge bosons which then decay into fermions (Garcia-Bellido *et al.* 2009), and it is still an open question to determine whether this leads to a successful model of the universe. In Higgs inflation, one can play with only one parameter, the coupling of the Higgs to the curvature, so the model is tightly constrained.

## Summary

This may or may not work out. But *a priori*, this is by far the best proposal for the inflaton we can hope for: it relates inflation to a particle that we know exists, in contrast to all the other proposals. Thus it genuinely links particle physics to cosmology. If it works, it will be one of the greatest unifications in physics. The bottom line then would be that the Higgs not only gives mass to particles, but also gives rise to the seeds of galaxies! It beats all the other inflationary theory proposals hands down in terms of the crucial criterion 4 – and links two of the most important experiments of the last couple of years. And it would point to the need for gravitation beyond general relativity, about which many have speculated on other grounds. ●

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