The Role of Quantum Mechanics in Modern Cosmology

Gabriele Veneziano

1 Introduction and Summary

A hundred years ago two radical paradigm changes in our understanding of the physical world had already been thoroughly established:

- **Quantum Mechanics (QM)** as the correct description of the atomic world and of the quanta of light, the photons, with which atoms interact. QM marked the end of classical determinism, as emblematically expressed by Heisenberg's uncertainty principle and by Planck's constant $\hbar$ quantifying that minimal unescapable uncertainty.
- **General Relativity (GR)** as Einstein's extension of Newtonian gravity to velocities comparable to the speed of light c. Its advent marked the end not only of absolute space and time[1] but also of an absolute geometry of space-time. It's successful tests (like the deflection of light by the sun or the precession of mercury's perihelion) had just been carried out dissipating any initial skepticism.

For many subsequent decades both QM and GR were developed and extended, scoring success after success. But the two disciplines hardly interacted with each other. They were considered to be applicable to two very distinct physical situations: the extremely microscopic and the extremely macroscopic worlds, respectively.

As atomic experiments further developed into subatomic ones, involving electrons, protons, neutrons and other elementary particles, the necessity of combining QM with Special Relativity (SR) became a necessity around the end World War II. This process went on for about 30 years, culminating in the formulation, in the early

[1]This was already the case for his previous theory, Special Relativity, which is unrelated to gravity.

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seventies, of the so-called Standard Model (SM) of elementary particles and of their mutual, non-gravitational interactions. The generic name for quantum-relativistic theories, such as the SM, is Quantum Field Theory (QFT). The limitation of QFT to non-gravitational interactions was felt unimportant for a long time, given the weakness of the gravitational force among elementary particles.

In parallel, GR pursued its own adventure with striking results, like predicting the existence of gravitational waves and black holes, both beautifully confirmed recently by the direct detection of gravitational waves originating from the coalescence of two black holes to form a third one [1]. Black holes are very massive compact objects, characterized by their mass and spin, and deforming the geometry of space to such an extent that nothing, not even light, can escape from a surface (the "horizon") surrounding them.

The other class of interesting GR solutions concerned the description of the Universe as a whole, as well as its evolution, under the simplifying assumption of an approximate isotropy and homogeneity (i.e. of being roughly the same in every region and direction). It culminated in the so-called hot big bang model of cosmology to be shortly described below.[2] In all these GR developments QM was happily ignored since quantum phenomena were insignificant for the physics of the macroscopic objects of interest to GR at the time.

This parallel development of QM and GR went on undisturbed till the late seventies, early eighties. But something changed, in this respect, during the last forty years or so: this is the topic to be discussed in this contribution.

2 Hot Big Bang Cosmology and Its Shortcomings

In order to understand why around the end of the seventies physicists working in GR and in QFT started to get closer and work together we have to recall some properties of Hot-Big-Bang cosmology.

Under the simplifying, but experimentally well supported, assumption of an approximately homogeneous and isotropic Universe, Einstein's equation can be solved once its matter content is given. An unexpected and startling feature of the solution is that, in general, a static Universe (one that is also the same, on average, at all times) is *not* allowed. The Universe must either expand or contract (or perhaps expand along some directions and contract along others). Physically, this result can be understood to be a consequence of the universal, attractive nature of gravity. An initial static Universe, left to itself, will tend to collapse. In the early twenties this looked like a serious blow for GR since people thought the Universe to be static.

Einstein was upset by this failure and ingeniously found a (we would say today "natural") solution by adding a new term to his equations, the so-called cosmological constant, Λ. Choosing properly its sign it produces a repulsive force that compensates

[2] For some history and more details see Ugo Moschella's and Kai Schmitz's nice contributions to this volume.

the gravitational pull. When, in 1927, Hubble discovered, via the famous red-shift, that the Universe is actually expanding, Einstein retracted his proposal calling it his *biggest blunder* and went back to his original equations.[3]

Once we accept the expanding-Universe solution of Einstein's equations we can retrace its implications for our past history. Here we encounter another surprise: in our past the Universe was obviously smaller than today, and therefore denser. Furthermore, since Einstein's equations relate the density of matter to the curvature of spacetime (meaning a deviation from our usual Euclidean geometry) the Universe was also more and more curved. The problem is that there is no mechanism, within GR, to stop and limit that growth of density, curvature (and temperature). Instead, one finds that all these quantities reach simultaneously an infinite (hence unphysical) value at a finite time in our past, the Big-Bang, an event that would have occurred some 13.8 billion years ago. In jargon one calls such an event a "singularity". Finally, since the solution does not make sense before that instant, one is forced to accept that time did have a beginning, precisely at the Big Bang. This has been the standard cosmological dogma till the early eighties. And, I am afraid, it is the picture that (most) scientists are conveying to the general public even today.

Hot big bang cosmology had some indisputable successes. First of all it predicted, before its accidental discovery by Penzias and Wilson in 1965, the existence of a thermal bath of electromagnetic radiation, the so-called cosmic microwave background (CMB), throughout the Universe. A hot early Universe also explains how light elements, like helium and lithium, were synthesized out of hydrogen and predicts successfully their present abundance. It is therefore undeniable that the Universe, long ago, has been extremely (though not necessarily infinitely) hot. We can also locate the time of the big bang quite accurately: whether it was infinitely—or simply very—hot will not change appreciably the number I mentioned since all those early processes occurred in a tiny fraction of a second! As we shall see, what is not necessarily justified is to call that number the *age of the Universe*.

Actually, here is a first signal that QM can play a role in cosmology. As pointed out first by Max Planck at the beginning of last century any quantum theory of gravity will be characterized by a length or time scale given by the appropriate combinations of c, $\hbar$ and Newton's constant G. These are called Planck length and Planck time and their values in meters and seconds are:

$$l_P = \sqrt{\frac{\hbar G}{c^3}} \sim 1.6210^{-35}\text{m} \; ; \; t_P = \sqrt{\frac{\hbar G}{c^5}} \sim 5.3910^{-44}\text{s} \; ; \; M_P = \sqrt{\frac{\hbar c}{G}} \sim 2.1810^{-5}\text{g} \, , \tag{1}$$

where, for later convenience, we have also introduced the Planck mass in grams.

Precisely because the Universe was so dense and curved at its birth, we can ask whether one can reliably calculate its early evolution while neglecting quantum effects i.e. by using GR as it is. Even in the absence of a satisfactory theory of

[3] In hindsight Einstein's blunder was not so much in introducing Λ, but in having to fix it at precisely the value that leads to a static Universe. Any tiny deviation from that value would either lead to an expansion or to a contraction: in modern terminology Einstein's Λ had to be fine-tuned to an extremely high accuracy.

quantum gravity one can argue that this is only justified from a few Planck times after the Big Bang on. In other words, statements based on GR about the Universe at times of order t_P from the Big-Bang, or earlier, and at fortiori the Big-Bang itself, cannot be taken seriously.

But, we may ask, what's wrong with Hot Big Bang cosmology if we decide to start our history of the Universe a few Planck times after the Big Bang and use GR from then on? This has been the pragmatic attitude of cosmologists till the seventies. Identifying what's wrong with that cosmological scenario led to the development of inflationary cosmology in the eighties.

The shortcomings of the Hot Big Beng scenario can be all ascribed to a general property of ordinary matter: the fact that gravity is an attractive force. That implies that the expansion of a Universe containing ordinary matter tends to decelerate since the gravitational attraction resists the expansion.[4] I will only mention two serious shortcoming of Hot-Big-Bang cosmology, both related to the above-mentioned property of the hot big bang scenario.

- **The flatness problem**
  Present observations of the CMB show that today the geometry of space (on large scales) is very close to being Euclidean. However, it is easy to show that, for a *decelerating expansion*, deviation from (the flat) Euclidean geometry tends to increase with time. Inserting the appropriate numbers one finds that, unless the Universe was already Euclidean to one part in 10^{30} a few Planck times after the big bang, it would be impossible to understand why it is now observed to be Euclidean up to, at most, one part in a hundred.
- **The isotropy/homogeneity problem**
  The CMB has a frequency spectrum typical of a thermal distribution at a temperature of about $2.7K$ (meaning 2.7°C above the absolute zero). As I already mentioned, predicting the existence of the CMB, including a fairly good estimate of its temperature, was one of the successes of HBB cosmology. So what's the problem? The problem is that this temperature, when measured along different directions in the sky, looks exactly the same.[5] For a *decelerating expansion*, however, one finds that the CMB radiation coming from, say, opposite directions in the sky, originated from regions of space that were *all the time* so far separated from each other that there was no way they could have ever interacted, exchanged energy, and thermalized. In other words, in order to explain the isotropy of the CMB, the newly born Universe had to be already extremely isotropic.

Both shortcomings can be best regarded as *extreme fine tuning* problems, meaning that they can only be solved if one chooses initial condition (say a few Planck times after the big bang) corresponding to: i. an extremely small spatial curvature, and ii. an extremely homogeneous/isotropic Universe.

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[4] Conversely, gravitational attraction would accelerate a contracting phase and this is why one gets an infinite contraction rate at the big bang itself.

[5] The first experiment to reveal that this was only true up to variations of tens of microKelvins (i.e. differences of about one part in a hundred thousand) was the celebrated COBE satellite experiment in 1992 [2].

3 A Simple Solution: Inflation!

It will not have escaped the attentive reader that the source of the above difficulties is closely related to the one confronted by Einstein when he was trying to get a static Universe from his equations: the attractive Nature of gravity! In order to get an *accelerated expansion* one has to find some repulsive contribution like the cosmological constant Λ introduced—and then rejected—by Einstein.

Indeed introducing a large-enough positive Λ one does achieve, instead of a static Universe, one that has an accelerating expansion. This is, incidentally, one of the favorite explanations for the recent acceleration of the expansion as measured e.g. by the Supernovae experiments [3, 4]. Why then not play that same game in the early Universe?

The problem is that a cosmological constant, as its name says, corresponds to an energy density that remains constant in time, in spite of the expansion. Since, instead, other forms of energy density (matter, radiation) decrease with time, an initial largish cosmological constant would have dominated every other form of energy since the early days after the Big Bang. And this is incompatible with what we know about the history of the Universe.

Fortunately however, field theories, even at the classical level, offer better alternatives. A very simple and popular one is to invoke the potential energy stored in a scalar field when the value of the field is not the one corresponding to the minimum of the potential. QFT abounds of such fields, a famous example being the Higgs field. Today the Higgs field has a non-vanishing value corresponding to where its potential energy is as small as possible. Its non-zero value generates masses for most of the elementary particles we know. But one can argue that, when the temperature of the Universe was very high, the Higgs field was actually zero. At the same time its potential energy was larger than it is today. Well, that positive potential energy behaves precisely like a cosmological constant and can produce an accelerating expansion. With an important difference: unlike a cosmological constant put in by hand, the Higgs field can evolve (e.g. as the Universe expands and cools down) and its potential energy can eventually disappear in favor of other more conventional forms of energy (e.g. radiation).

The Higgs field was just an example (yet taken as a serious possibility by some authors) to illustrate how a scalar field can play the role of a "dynamical" Λ, doing its job when it's needed, and then kindly disappearing when it's no longer necessary. This accelerated (quasi exponential) expansion of the Universe has been dubbed inflation, and the hypothetical scalar field responsible for it is called the inflaton.

A long enough inflationary epoch completely solves the problems we mentioned: if there were some initial deviations from Euclidean geometry (called spatial curvature in GR terminology) it is wiped out almost completely so that, even after a long decelerating expansion, it is still small (but perhaps non zero and measurable) today. By the same token, inflation can wipe out any initial inhomogeneity or anisotropy by stretching space so much that any initial ripples are now far beyond our cosmological horizon. It looks as if all problems have been cured, but that's were QM makes its entry on the scene, as we will now discuss.

4 The Crucial Role of Quantum Mechanics

As we have just explained inflation is very efficient for smoothing out any inhomogeneity already present at its onset. However, without the help of quantum mechanics, inflation, if it lasts long enough to solve the fine-tuning problems of hot BB cosmology, does this too efficiently: it produces an exactly homogeneous Universe.

On the other hand, in order to generate the large-scale structures we see in the sky, one has to start with a small, but finite, amount of inhomogeneities. The level of inhomogeneities we have measured in the CMB is roughly of the right order of magnitude to be able to do the job as the Universe keeps expanding and cooling down. This is again due to the attractive nature of gravity making it easy for over-dense regions to grow by accretion of surrounding matter. But what can then produce those small initial fluctuations in the CMB temperature? The mere assumption of a long inflationary phase cannot.

Quantum mechanics, instead, does just that. Although *initial* fluctuations are very effectively wiped out, quantum mechanics keeps creating small-scale fluctuations *all the time* during inflation. Like any other distance, the wavelengths of these fluctuations are stretched during the inflationary era. They are also amplified as soon as their wavelength exceeds a certain length scale (inversely) related to the energy density during inflation (which is roughly constant). This is one important free parameter: it can be called the scale of inflation l_i.

In Fig. 1 we show, in a cartoon-like style, how the initial classical perturbations (wiggles in green), as well as some quantum fluctuation (wiggles in red) produced in the earlier stages of inflation, are stretched beyond our present horizon and how, instead, quantum perturbations generated at sufficiently late times during inflation (also in red), are still within our visible Universe.

Given a specific model of inflation, the amount of fluctuations generated at different wavelength can be computed. Their magnitude is fixed by quantum mechanics in terms of the ratio of Planck's length (which, as indicated in (1), contains Planck's constant) and the above-mentioned scale of inflation l_i which, instead, has a completely classical meaning. Hence, roughly, in order to get perturbations at the level of one part in 10,000, we need a scale of inflation of about $10^5 l_P \sim 10^{-30}$m., still a very short length scale! In turn this will fix the value of the inflaton's potential energy during inflation (which is also sometimes referred to as the scale of inflation).

Another parameter that has to be fixed is the slope of the inflaton potential: it has to be sufficiently small for inflation to last for a long time and for the scale l_i to increase very slowly during inflation (as indicated in Fig. 1). This produces an almost scale-invariant spectrum with a slight "red tilt" (a slight preference for longer wavelengths over smaller ones). In conclusion, up to adjusting a few parameters,

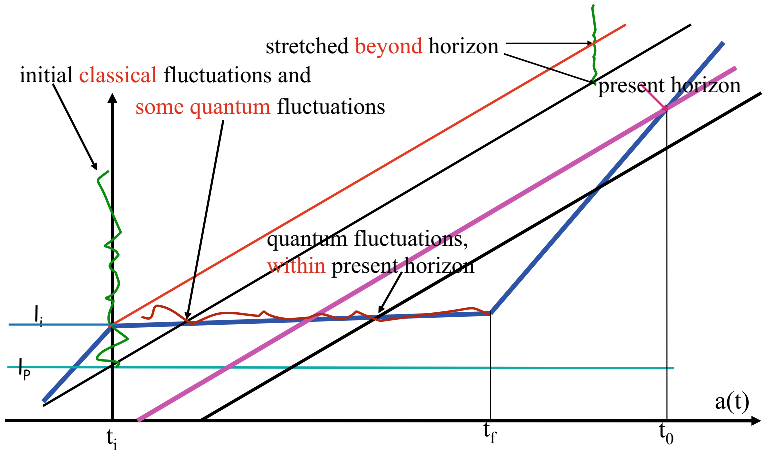

Fig. 1 Kinematics of inflation and of perturbations therein. The horizontal axis represents time in terms of the so-called scale factor $a(t)$, that tells us how physical distances are stretched by the expansion. This is why different wavelengths evolve according to straight, parallel lines. t_i, t_f, t_0 represent the beginning of the inflationary epoch, its end (to be associated with the Big Bang), and the present time, respectively. On the vertical axis we have other relevant length scales: the Planck length l_P and the "inflation scale" l_i. The thick blue line represents the horizon size (how far in space one can communicate) at different times. Its value at t_0 (our present horizon) limits the range of present observations

inflation, together with a crucial help of quantum mechanics, can explain in an amazingly precise way the temperature fluctuations of the CMB as measured very accurately by the PLANCK satellite experiment (see Fig. 2) [5].

But we are not done yet …We need to produce the CMB itself if we want to explain its temperature fluctuations! As we have already discussed the CMB is a left-over of a hot Big Bang. Where is the hot big bang in the inflationary scenario? If it preceded inflation its consequences got wiped out by inflation. Indeed, inflation is an adiabatic expansion that cools the Universe down to essentially zero temperature. The only way out is to reheat (or just heat if it was always cold) it *at the end* of inflation so that it gets gently cooled by the later expansion.

This is the well-known reheating issue in inflationary cosmology. It is solved by dissipating the inflaton's potential energy through some quantum irreversible process, such as quantum particle creation in an external field. I like an analogy with a waterfall in which there is a lot of potential energy stored upstream of the fall, which gets converted into heat (or electricity if we are so smart to use it) as it goes down the fall. Achieving a large enough reheating temperature is one important constraint on models of inflation.

This is the second, equally important intervention of QM in inflationary cosmology. Together they produce, out of a fairly generic initial state, a hot big bang with a sufficiently high (but finite!) temperature and the right amount of fluctuations to seed the large scale structures within our observable Universe!

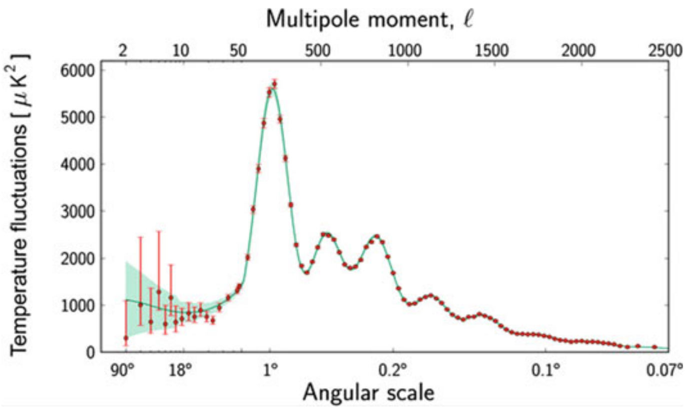

Fig. 2 The PLANCK satellite spectrum of CMB temperature fluctuations as a function of the angular difference between two directions in the sky (shown on the horizontal axis). With a few adjustable parameters, inflation accurately explains the very non trivial structure of these fluctuations including its famous "acoustic peaks". At large angular scales statistical fluctuations prevent any reliable test [5]

This line of reasoning led, around the turn of the millennium, to the formulation of what can be called the Standard Model of Gravitation and Cosmology. It is based on General Relativity, a crucial input from quantum mechanics, and the addition of two *dark sectors*. One dark sector we have already mentioned: it is the invisible (hence dark) energy responsible for the recent acceleration in the expansion of the Universe. The second, instead, is a form of massive matter that interacts with ordinary atomic matter only gravitationally. As explained in great detail in Kai Schmitz's contribution, dark matter is necessary for explaining many features of our Universe, in particular the formation of large scale structures from the seeds we see in the CMB.

The cosmological component of the Standard Model of Gravitation and Cosmology is modestly called "The Concordance Model of Cosmology". A very appealing paradigm indeed, although we still do not know the real nature of its dark sector and we are still far from fully placing it into a grander picture of all known particles and interactions.

5 The True Place of the Big Bang in Modern Cosmology

It clearly emerges from our discussion that the place of the Big Bang in the history of the Universe has moved from its original place and that its very meaning has changed. To put it simply: the Big Bang is no longer the singular beginning of time. It is nothing but the moment (or the process) at which the Universe, after its extreme cooling due to inflation, reheats up as a result of quantum dissipative processes. Thus,

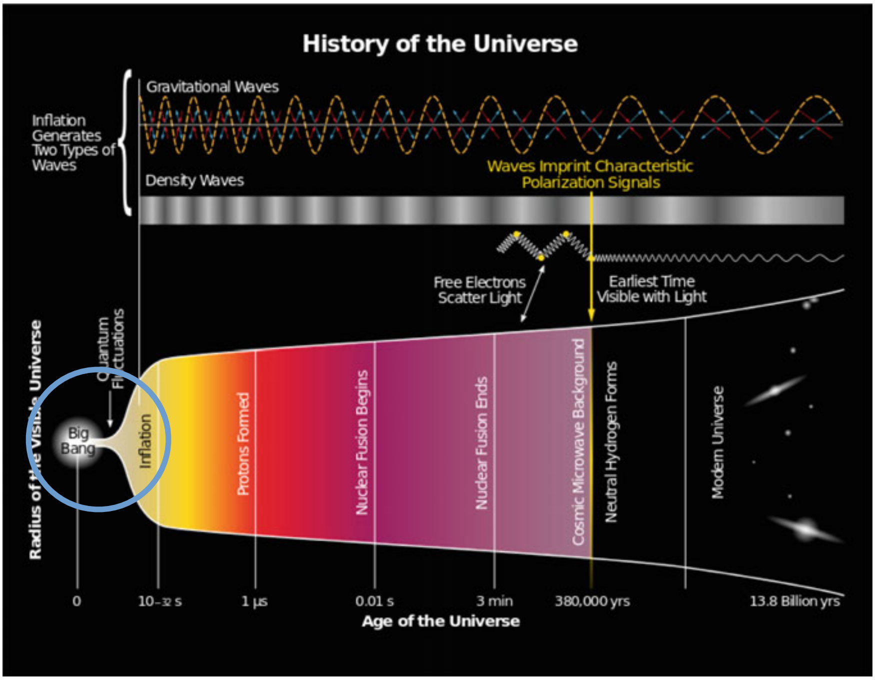

Fig. 3 A popular conventional way of depicting the history of the Universe in which the Big Bang is (mis)placed before inflation (Credit BICEP2 Collaboration)

standard cartoons that illustrate the history of the Universe, such as the one shown in Fig. 3, need to be revised.

Furthermore it is now legitimate, and even physically relevant, to ask: what happened before the Big Bang? And we even know part of the answer, at least for a certain lapse of time before the new Big Bang: there was an inflationary phase and we can study it through the imprint it left (by the quantum fluctuations produced during inflation) on the CMB and on the large-scale structure of the Universe. Studying what happened before the Big Bang has become a physical, *no longer* a metaphysical, question.

An even more direct look at what went on before the Big Bang will hopefully come in the not-too-distant future, from the detection and study of gravitational waves produced during inflation. Gravitational waves, unlike the electromagnetic ones of the CMB, travelled undisturbed even when the Universe was very hot and charged particles were not yet combined to form neutral atoms (this is why it it is impossible to look at the CMB beyond the time of recombination).

The inflationary scenario (or the concordance model of modern cosmology) does not represent, however, a fully self-contained history of the Universe. In particular, they leave open the question of how, when and where inflation started.

We understand pretty well what are the conditions to be satisfied—in a certain region of space and for a certain interval of time—in order for that region to undergo a long inflationary phase and to become, today, as large as our visible Universe. We understand much less the global structure of the Universe. It could have inflationary patches of different kinds with non-inflating regions separating them. Also, each distinct inflationary patch could have different physical properties (the so-called "Multiverse").

In connection with these deeper questions too, QM is bound to play a crucial role: presumably, a full fledged quantum theory of gravity and of the other forces will be needed in order to make progress. So far, an approximate semiclassical approximation was sufficient provided the scale of curvature during inflation was sufficiently small in Planck units. And we know that this was the case during the last phase of inflation because of the smallness of the quantum fluctuations we measure in the CMB. But, if we want to go back even further, a full quantum theory of gravity is very likely needed.

At present, the leading candidate for such a consistent theory is (super)string theory. It is not possible, within the space at my disposal, to even try to describe in any detail what string theory is. It suffices to say that it is a candidate unified quantum theory of all forces and elementary particles based on three basic ingredients (the first two of which we have already discussed and used):

- Quantum mechanics
- Special Relativity
- The postulate that *all* elementary particles are one-dimensional objects, strings. These come in two kinds, open and closed. They are characterized by a single dimensionful parameter, the string tension T (its energy per unit length).

Note that we have *not* included GR in the above assumptions. In the same way that one can define a Planck length, a Planck time, and a Planck mass via Eq. (1), one can define a string length, a string time, and a string mass by:

$$l_s = \sqrt{\frac{c\hbar}{T}} \;\; ; \;\; t_s = \sqrt{\frac{\hbar}{cT}} \;\; ; \;\; M_s = \sqrt{\frac{\hbar T}{c^3}} \tag{2}$$

Notice that these "string quantities" go to the corresponding Planckian ones if we identify the string tension T with $\frac{c^4}{G}$. Is this the way string theory represents gravity? Not quite. In string theory the quantities appearing in (2) are the most basic ones, as we shall see in a moment.

By contrast, Newton's constant G (and thus Planck's time, length and mass) are not as fundamental. They are related to the string quantities through the so-called string coupling g_s a dimensionless number that controls the strength of *all* interactions. It is roughly related to the famous fine structure constant $\alpha \sim 1/137$ of QED. Because of this value of g_s the string length is not expected to be more than a couple of orders larger than the Planck length[6] but this is sufficient for it to have a huge impact on quantum gravity. At the string mass/energy scale all four forces unify and have a strength given in terms of g_s^2. At low energy string theory is well described by its "massless modes" hopefully to be identifiable with the particles of the standard model or of some extension of it, while at high-energy and short distances it will differ from an ordinary quantum field theory in essential ways.

The existence of these massless modes is of course phenomenologically crucial. It is actually a consequence of QM since, classically, the only massless strings would be point-like. Instead quantum mechanically a string can have a finite size and yet be massless and even carry non zero angular momentum. These latter strings of spin up to 2 would represent the carriers of all known long range interactions (including gravity mediated by the spin-2 graviton this is why GR comes out of string theory!) and possibly more …

The finite size of strings, on the other hand, manifests itself through modifications of the predictions of QFT when scales of order l_s or shorter are probed. This is precisely what happens when the Universe, as described by GR, has an age of the order of t_s. Since $t_s > t_P$ this means that string modifications intervene *before* one enters a Planckian regime.

Several gedanken experiments have been considered in order to study this *Stringy* regime and have confirmed the softening of GR expectations at short distances. They are sometimes described by an effective Generalized Uncertainly Principle (GUP) reading [6]

$$\Delta x \geq \frac{\hbar}{\Delta p} + \frac{c\Delta p}{T} \geq 2l_s \,, \tag{3}$$

in which the first term is the usual Heisenberg's uncertainty, the second its "stringy" extension, and the last inequality is easily proven. Here we see l_s emerging as a minimal measurable length. Armed with these rough notions about strings, let's go back to the question we asked earlier.

6 Before Inflation …

General theorems proven by by S. Hawking and R. Penrose in the seventies state that, within General Relativity, an initial singularity is unavoidable. However, "before" (as we go backward in time) reaching the singularity we necessarily encounter a situation in which certain physical quantities (density, temperature, curvature of spacetime) reach values of $\mathcal{O}(1)$ when measured in the string units of (2). Because of the (small but sufficient) hierarchy between string and Planck units, string effects intervene *before* one reaches the regime in which quantum gravity corrections go out of control.

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[6] For the learned reader: there is here an amusing analogy with the theory of weak interactions where there is a fundamental mass scale given by the $W - Z$ masses and another, more phenomenological one, associated with Fermi's constant G_F. Also there the ratio of the two scales is given by a coupling whose value is not very far from 1.

String effects, on the other hand, are well known to tame the bad behavior of quantum gravity at short distances (solving e.g. its "non-renormalizability" problem). It is also known, for instance, that string theory sets un upper limit (of course of $O(1)$ in string units) to temperature (the so-called Hagedorn temperature). And even measuring distances (and time intervals) smaller than l_s (or t_s) don't make sense in view of (3).

We may thus reasonably guess that, within string theory, there is no place for a singularity taking place before inflation. Rather, the singularity and what follows it for a time $O(t_s)$ should be replaced by a *stringy phase* during which a conventional classical description of space time is no longer valid. String theory allows for solutions that do not correspond to any smooth classical geometry and yet are perfectly well defined. One such solution could represent the true beginning and evolve at later times into a more conventional inflationary epoch.

There is, however, an interesting alternative to this possibility within string theory, going under the name of Pre Big Bang (PBB) scenario. Born in the early nineties it has been the prototype of a whole class of cosmologies now known as *bouncing* cosmologies. In this class of scenari, the usual cosmological expansion (with or without an inflationary epoch) is preceded by a contracting phase which, through a bounce, turns into an expansion. Such a behavior is forbidden in Einstein's gravity but quantum/string effects could possibly induce such a bounce.

Many scenarios of this sort have been proposed, but I'll limit myself to describe the original one since it is deeply rooted in some novel symmetries characteristic of string theory. These symmetries, known as T-dualities, involve in an essential way a scalar field which is ubiquitous in string theory as an inevitable partner of the gravitational field: it is called the dilaton and plays a very important role in string theory. The above mentioned string coupling g_s is not a God-given number but is itself a field, the dilaton. Even if we know, through its connection with the fine structure constant, that the value of this fields cannot have changed appreciably since many billions years, it is all but excluded that it may have evolved in primordial cosmology and, a fortiori, before the hot Big Bang.

Actually the symmetries of string cosmology associate with the usual decelerated expanding solution one of accelerated expansion (i.e. of inflation), the acceleration being driven by the evolution of the dilaton from the regime of extremely weak coupling to the one corresponding to its present value. This pre-bounce phase has been dubbed dilaton-driven inflation (DDI). While the coupling grows so does the ratio l_P/l_s so that, while the size of the Universe keeps growing all the time in units of l_s, it undergoes a contraction before the bounce if sizes are measured in units of l_P. What remains true, independently of the units adopted, is that the curvature of spacetime grows before the bounce and decreases afterwards: the curvature undergoes a bounce! Details of the bounce itself will only be describable in a full quantum string theory context to be still fully developed.

A very ambitious possibility is that the DDI phase plays the role of ordinary inflation so that, after the bounce, one goes over directly to a standard hot big bang cosmology (explaining the name given to this scenario). Quantum particle production during the pre-bounce phase has been shown to be able to heat-up the initially cold Universe. A detailed scenario has been constructed (see [7] and references therein), invoking other fields present in string theory, which is compatible with CMB observations and predicts a vanishingly small B-mode in the CMB polarization. It may also be able to generate seeds for the observed cosmic (intergalactic) magnetic fields whose origin is still very mysterious.

On the negative side, the PBB scenario can (but does not and does not automatically) generate a quasi-scale invariant spectrum of perturbations and may also have difficulties in washing away certain kinds of initial anisotropy. Therefore, a more modest possibility would be that the pre-bounce phase is followed by the above-mentioned string phase and, finally, by a long enough conventional inflationary epoch.

Of course all of this is highly speculative. The good side of the story is that it is no longer a tabu to ask experimentally questions like: What happened before the Big Bang? What happened before inflation? One day we may even find out, scientifically, the answer to a philosophical question that goes back to Augustin, Aristotele, and probably much farther in the history of mankind: *Did time have a beginning*?

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