# A Quantum Universe Before the Big Bang(s)?

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**Abstract.** The predictions of general relativity have been verified by now in a variety of different situations, setting strong constraints on any alternative theory of gravity. Nonetheless, there are strong indications that general relativity has to be regarded as an approximation of a more complete theory. Indeed theorists have long been looking for ways to connect general relativity, which describes the cosmos and the infinitely large, to quantum physics, which has been remarkably successful in explaining the infinitely small world of elementary particles. These two worlds, however, come closer and closer to each other as we go back in time all the way up to the big bang. Actually, modern cosmology has changed completely the old big bang paradigm: we now have to talk about (at least) two (big?) bangs. If we know quite something about the one closer to us, at the end of inflation, we are much more ignorant about the one that may have preceded inflation and possibly marked the beginning of time. No one doubts that quantum mechanics plays an essential role in answering these questions: unfortunately a unified theory of gravity and quantum mechanics is still under construction. Finding such a synthesis and confirming it experimentally will no doubt be one of the biggest challenges of this century's physics.

## 1. Outline

- Three revolutions 100 years ago
- The cosmological model of the 21st century
- The importance of QM in (modern) cosmology
- Which Big Bang?
- Which quantum gravity?
- String theory (and cosmology)
- Conclusions

## 2. Three revolutions 100 years ago

Three crucial revolutions in physics took place at the dawn of last century:

- 1900: Max Planck, puzzled by an ultraviolet divergence in black-body radiation, introduces his famous constant $h$ and starts the *Quantum Revolution*, i.e. the *end of determinism*;
- 1905: Albert Einstein, building upon the finiteness and constancy of the speed of light $c$, introduces *Special Relativity*, i.e. the *end of absolute time*;

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- 1915-16: Albert Einstein again, starting from the observed universality of free-fall, introduces a geometric theory of gravity, *General Relativity*. It marks the *end of an absolute geometry*, which is deformed by matter in a way proportional to the gravitational constant $G$.

Since then a lot of progress has been made in combining in various ways those three revolutions. The most significant of these are:

## A. The Standard Model of Elementary Particles (SMEP)

## B. The Standard Model of Gravitation and Cosmology (SMGC)

Together, they form our present:

## Standard Model of Nature (SMN)

A. The SMEP is the result of combining the principles of the quantum and special relativity revolutions. We may say that it is the marriage between $h$ and $c$, the two constants of Nature characterizing those two revolutions. Its successes have been amazing, last but not least the discovery in 2012 at CERN of the Higgs boson implementing the Brout-Englert-Higgs mechanism. For lack of time I will not go any further into describing this pillar of the SMN. Rather, I would like to recall the present status of the Standard Model of Gravity before turning to its cosmological applications.

B. As already mentioned the Standard Model of Gravity is based on Einstein's General Relativity, a beautiful theory that can be regarded as a synthesis between special relativity and the Newtonian theory of gravity, a marriage between $c$ and $G$.

Its starting point is the so-called Equivalence Principle, deeply rooted in the observed universality of free fall. Tests of such universality are expected to reach soon incredible precision attaining the level of 1 part in $10^{15}$ in the coming few years from the already operative $\mu$scope experiment, with an even better precision foreseen from the future STEP experiment (if and when it will fly).

Besides, GR predicts well-verified corrections to Newtonian gravity (deflection of light, periastron precession, Lense-Thirring effect, . . . ). It also predicts qualitatively new phenomena, most notably:

- The existence and properties of black holes (BH)
- The existence of gravitational waves (GW)

Concerning BH, there has been for quite a while direct evidence for their existence, in particular for the presence, in the centre of most galaxies including our own, of huge black holes over a million times heavier than the sun.

Finally, as far as GW are concerned, the situation has changed dramatically this year when previous indirect evidence (through the observation of the slowing down of the revolution period of binary pulsars) was turned into direct observation in the LIGO interferometers by the LIGO/VIRGO collaboration. Amazingly, this confirmation of GR comes with further evidence for BH as well, this time as sources of GW when two of them (each one of tens of solar masses) merge.

Note that, so far, we have only discussed tests of classical General Relativity ($\hbar = 0$). As we will see in a moment, things change considerably once we extend the applications of GR to cosmology.

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## 3. 21st century's cosmology

Let us start by recalling the cosmological model that prevailed in last century till the eighties. It was based on GR and was characterized by what we may call a *classical dogma* known under the resounding name of Hot Big Bang (HBB) cosmology. According to it:

> The Universe was born about 13.5 billion years ago
> in state of extremely high temperature and density.
> A singularity[1] prevents us from going beyond that moment
> in our past, therefore identified with the beginning of time.

Since then, an adiabatic expansion, very rapid initially, then slower and slower, cooled down the Universe. Today we see relics of that catastrophic event in the cosmic microwave background (CMB), a thermal spectrum of photons with a temperature of about $2.7K$.

The HBB scenario had several important successes. There is very little doubt that an event *like* a hot big bang must have taken place in our past. Unfortunately, its necessarily precise form poses some puzzling questions. For lack of time I will only mention a few of them.

### 1. The homogeneity problem

The universe is very homogeneous and isotropic on large scales: the CMB temperature varies by only one part in a hundred thousand (i.e. by tens of $\mu K$) depending of the direction it is coming from. Now, this property is put by hand (as initial condition) in the HBB scenario!

If, instead, we start from generic initial conditions and the expansion has always been a decelerating one, the Universe has always been too big (for its age!) for being able to become homogeneous in the short time elapsed since $t = 0$.

The problem can be visualized in Fig. 1, where the blue ellipses, representing the size of our observable Universe at a given time in our past, are compared to the red ones, representing the distance traveled by light from the Big Bang till that generic time. Clearly, throughout our past history the blue ellipses were larger than the red ones, showing that thermalization by causal processes (that cannot travel faster than light) is impossible.

### 2. The flatness problem

We can measure (e.g. by CMB experiments) how far the present geometry of space is from being exactly Euclidean. The result is that it can only have a very small spatial curvature (this is often stated by saying that $\Omega \sim 1$, or that the energy density is nearly critical). However, during a decelerating expansion spatial curvature increases meaning that, in order not to be larger than measured today, it had to be extremely small right after the HBB. Again an initial condition that one has to put in by hand.

### 3. Generating the large-scale structure of the Universe

The HBB model either predicts too much structure or none at all (i.e. no galaxies, clusters, stars). To get the right amount of structure one needs again a very fine-tuned initial state. All three problems can be ascribed to two basic features of HBB cosmology:

- The existence of a beginning of time;
- An always decelerating expansion (usually implied by the fact that ordinary matter resists the expansion).

[1] A moment at which several physical quantities, like, density and temperature become infinitely large.

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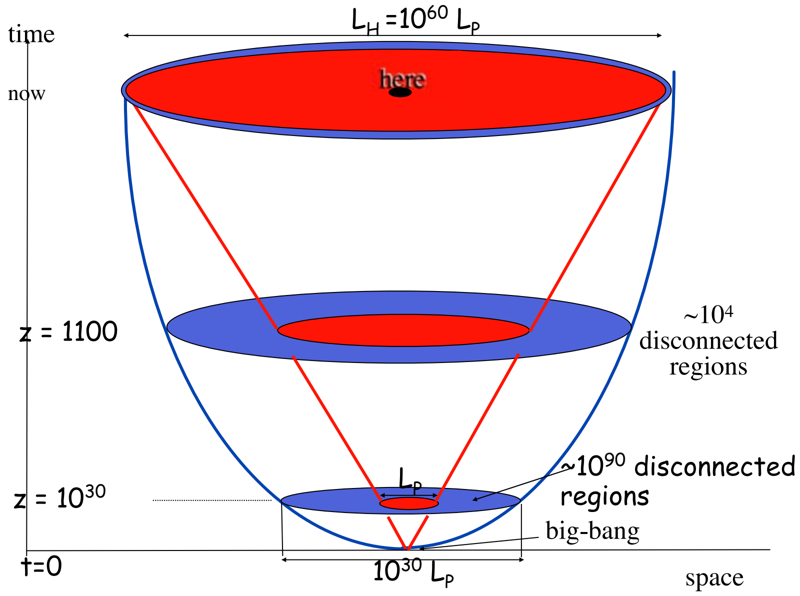



**Figure 1.** Time evolution (from bottom up) of the size of our presently observable Universe (blue ellipses) and of the distance traveled by light since the Big Bang (red ellipses) in the old HBB scenario. In our past the red ellipses were always smaller than the blue ones.

If, instead, a phase of accelerated expansion took place in the primordial Universe, then:
The homogeneity and flatness problems (see below for the 3rd one) are easily solved, since the Universe was so tiny during the inflationary phase that it could have easily become homogeneous by causal processes. This (a posteriori) very simple observation gave rise to an alternative to the HBB called the inflationary scenario (in which fig. 1 is replaced by fig. 2).

Eventually, in the nineties, cosmologists arrived to what is now considered the new standard model of cosmology, often dubbed as the "Concordance Model", a model which combines the inflationary paradigm with that of a dark sector in the energy budget of the Universe. The dark sector consists of two components:

- Dark Matter, whose existence is called for by the otherwise mysterious rotation curves of galaxies;
- Dark Energy, which is needed to explain the recent acceleration in the expansion.

So far, we are still talking classical physics/GR and everything looks fine. So why bother with the quantum?

## 4. The importance of QM in (modern) cosmology

There are, at least, two reasons why inflation without quantum mechanics does not solve the cosmological problems posed by HBB cosmology.

- The origin of large-scale structure

  Without QM inflation produces a perfectly homogeneous Universe. That's because any initial *classical* inhomogeneity (which, by definition, has to be on length scales larger than the Planck length) is stretched far beyond our present horizon during the 60 or more e-folds of expansion and thus effectively erased. In other words, without QM the structures we see today in the sky could not have formed.

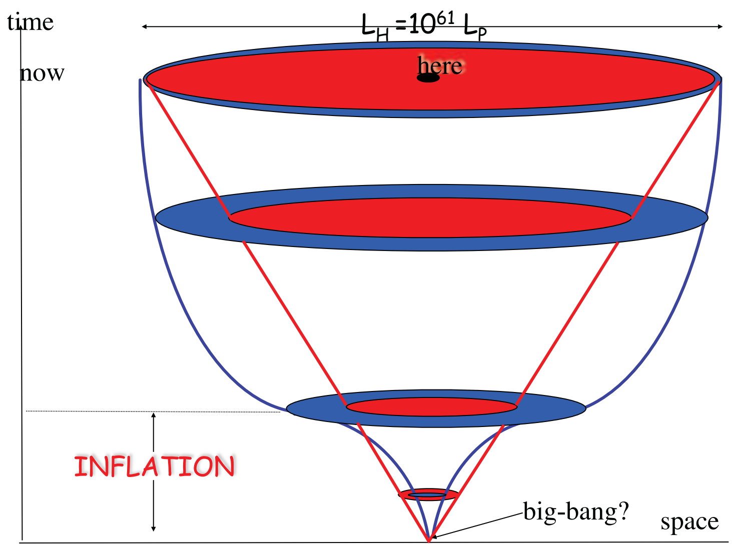



**Figure 2.** Time evolution (from bottom up) of the size of our presently observable Universe (blue ellipses) and of the distance traveled by light since the Big Bang (red ellipses) in the inflationary scenario. In our far past the red ellipses were larger than the blue ones.

Instead, with QM, classical initial inhomogeneities are erased, but they replaced by calculable quantum fluctuations produced, amplified and stretched throughout the inflationary epoch (see [1] for a recent review). Those created during the last 60 e-folds are still within our horizon today. And indeed the CMB fluctuations we observe today (e.g. via the Planck satellite) carry an imprint of those primordial quantum fluctuations.
Although, so far, we have only observed the so called density/curvature perturbations these, as the name indicates, can be either seen as matter or as geometry perturbations, the distinction between the two being coordinate(gauge)-dependent. Thus, I maintain that CMB observations are already[2] a clear indication that gravity needs to be quantized like we already know to be the case for the other fundamental interactions.

- The need to reheat after inflation

Inflation cools down the Universe (in case it was hot before inflation) to practically zero temperature. How can we generate a hot Universe *after* inflation? If we do not, there is no way to generate the CMB or to have the primordial nucleosynthesis of light elements such as Helium!
Note that, in inflationary cosmology, the Universe is still expanding after inflation. How can it keep expanding and yet reheat? This is where a second intervention of QM takes place by providing a dissipative, non adiabatic conversion of potential energy into a hot thermal soup of elementary particles. Indeed, one of the challenges for any inflationary model is to be able to generate sufficient reheating (or entropy production). It is hard, although perhaps not impossible, to find a classical mechanism achieving that goal but QM does it in a very natural way.

[2] The observation of cosmological tensor perturbation through the B-mode CMB polarization would be, of course, the ultimate smoking gun for the need to quantize gravity.

## 5. Which Big Bang?

An important consequence of our previous discussion is that the phase of reheating after inflation plays the role of the big bang of the old HBB cosmology, modulo some important differences:

1. It has no singularity (such as an infinite temperature) associated with it (if any it's non trivial to make it hot enough);
2. It has nothing to do with the beginning of time!

During many decades we have taught the general public the simple equation:

$$\text{Big Bang} = \text{Beginning of Time}$$

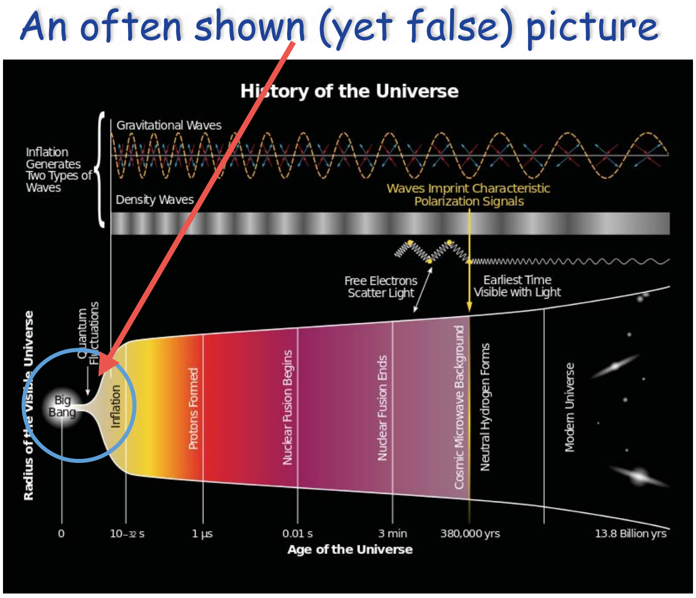
But, as just discussed, according to modern inflationary cosmology, we have to distinguish:

The *physical* non singular BB, at the end of inflation, the one that left measurable relics (the CMB, light nuclei) and:

A *theoretical* singular BB that could have preceded inflation whose relics have been washed out by inflation. In any case:

The BB we know something about has nothing to do with the beginning of time.

Thus the often shown picture depicted below is very misleading.




In conclusion, we are led to accept, on the basis of our discussion, a necessarily quantum cosmology taking place before and during the (true/physical) Big Bang!!

But what about the beginning of time? What preceded inflation? We do not know the answer to this question and standard inflationary cosmology is pretty agnostic about it. We only know that the answer lies in the answer to another question:

Which is the correct quantum theory[3] of gravity?

## 6. Which quantum gravity?

Quantizing General Relativity is a notoriously difficult task. Unlike in the SMEP, in the case of gravity the ultraviolet infinities that are present in any local quantum field theory (in four

[3] We are referring here to a full-fledged consistent quantum theory of gravity: cosmological perturbations can be treated semi-classically without such a complete quantum gravity formulation.

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dimensions) cannot be lumped into a finite number of renormalization constants.

To this date, the most interesting attempts to quantum GR are those of Loop Quantum Gravity and of Asymptotic Safety. Both assume that one can make sense of quantum gravity by modifying the way to quantize GR, not GR itself. Their viability as theoretically consistent quantum theories is still to be demonstrated. The cosmological applications of LQG apparently reach conclusions similar to those of string theory. It is hard (at least for me) to assess the reliability of those claims.

By contrast, a drastically new approach to quantum gravity (and quantum field theory in general) is offered by (super)string theory thanks to a consistent non-local modification of fundamental interactions below a certain length scale. In order to introduce the basic concepts underlying string theory it is good to recall:

A lesson from particle physics

According to our present understanding, at the most microscopic quantum level, all fundamental interactions are transmitted by massless particles of spin 1 or 2. The first (e.g. the photon) give rise to non-gravitational interactions, while the latter (the graviton) is responsible for gravity.

Once the existence of such particles is assumed the basic theoretical structure of both gauge theories and general relativity (gauge invariance, general covariance) follows from consistency.

As we shall see in a moment, in string theory the existence of massless spinning particles is a consequence of Quantum Mechanics. Therefore Quantum String Theory (QST) represents a kind of Copernican Revolution in which quanta come first, quantum field theory comes next, and classical field theory (Maxwell, General Relativity,... ) comes last. Let us see how.

## 7. String theory (and cosmology)

String theory: what's that? We do not quite have a definite answer to this question but, at least at a superficial level, the best reply seems to be:

String Theory is the theory of strings

Jokes apart, what that means is that one replaces the grand principles of gauge invariance and general covariance, which are at the basis of our SMN, by *just* the assumption that everything is made of:

Relativistic Quantum Strings

In other words, when the particles that are usually considered elementary and point-like are looked at with sufficient resolution they actually appear as little one-dimensional objects, open or closed strings (depending on whether or not they have ends). String theory thus combines two of the fundamental revolutions of a century ago (and two fundamental constants, $\hbar$ and $c$) but, rather than adding from the very beginning the third (General Relativity and $G$), simply adds the string postulate. As we shall argue below this will be enough thanks to some quantum magic. In one symbolic equation we can write:

$$\text{SR} + \text{QM} + \text{Strings} = \text{Magic Cocktail}$$

Let us start with two crucial quantum miracles:

### *7.1. Quantum magic I: emergence of a fundamental length*

Classical relativistic strings have no characteristic length scale. Their tension $T$ is simply a conversion factor associating a string size $L$ with a string mass $M \sim TL$. Note the analogy with GR, where, through $G$ and $c$ we also associate a length (a Schwarzschild radius $R$) to a given mass $R = 2GMc^{-2}$.

By contrast, quantum strings have a minimal (optimal) size $L_s$ given by $L_s^2 = \hbar/T$. This a truly fundamental scale analogous to the Bohr radius of an atom in non-relativistic QM. There is, again, an analogy with GR, which, at the quantum level, does have a length scale, the Planck length $L_P^2 = G\hbar c^{-3}$.

The string length scale $L_s$ plays many different crucial roles in QST. In particular, all interactions are smeared over regions of order $L_s$ and thus softened at distances shorter than $L_s$. This basic property of quantum strings cures the ultraviolet problems of conventional quantum gravity.

### *7.2. Quantum magic II: massless spinning particles*

Classical string cannot have angular momentum without also having a finite size, and thus, through the string tension, a finite mass. Indeed one can prove a classical lower bound on the mass of a bosonic string with (orbital) angular momentum $J$:

$$M^2 \geq 2\pi T J \tag{1}$$

This classical inequality is slightly violated at the quantum level and becomes (after a consistent regularization of the divergent sum):

$$M^2 \geq 2\pi T(J - a\hbar) \quad , \quad a = 0, \frac{1}{2}, 1, \frac{3}{2}, 2. \tag{2}$$

with the half-integer values of $a$ occurring in the case of the superstring. This quantum miracle is obviously what leads to the already anticipated Copernican Revolution:

$M = 0, J = 1$ provides the photons and the other gauge bosons mediating non-gravitational forces

$M = 0, J = 2$ provides a graviton, mediating the gravitational force.

Unfortunately, the $M = J = 0$ case provides dangerous extra massless particles (and corresponding long-range forces, but this matter is beyond the scope of this lecture).

### *7.3. A Theory of everything?*

In QST all elementary particles correspond to different vibrations of the same basic objects: open and closed strings! Thus, combining the two miracles we just described, provides:

**A unified and finite theory of elementary particles, and of their gauge and gravitational interactions, not just compatible with, but based upon, Quantum Mechanics!**

Quantizing strings gives rise, directly, to quantum versions of gauge and gravitational interactions whose classical limits are the conventional field theories traditionally seen as the starting point of QFTs. Furthermore, the first quantization of strings also provides short-distance corrections without which QFTs are plagued by UV divergences!

### *7.4. String Cosmology*

We are now finally ready to ask the question: What does string theory tell us about the beginning of time [4]?

We have already stressed that QST implies short-distance modifications of GR. Not surprisingly these intervene as soon as the curvature-radius of the geometry (e.g. $H^{-1}$) becomes comparable to $L_s$, the minimal size of a quantized string.

Intuitively, this minimal size implies an upper limit to density, temperature, and curvature, all the quantities that supposedly blow-up at the putative beginning of time. Apparently, there

[4] See also a non-specialized article of mine in Scientific American [2].

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is no place for the singular Big Bang of the old BB cosmology. But what is there to replace it? The answer is not known, but two possibilities emerge as most likely:

- A cosmology without a classical beginning.
  A very quantum "stringy" phase replaces the old big bang. The concepts of a classical space and time spring out of that phase as emerging concepts. This possibility is sketched in Fig. 3.
- A cosmology without a beginning.
  Here the "stringy" phase plays the role of a "quantum bridge" between our epoch and another classical one, seen as a sort of gravitational collapse from which the Universe bounced when the curvature radius became of order $L_s$ (a Big Bounce). This possibility is sketched in Fig. 4.

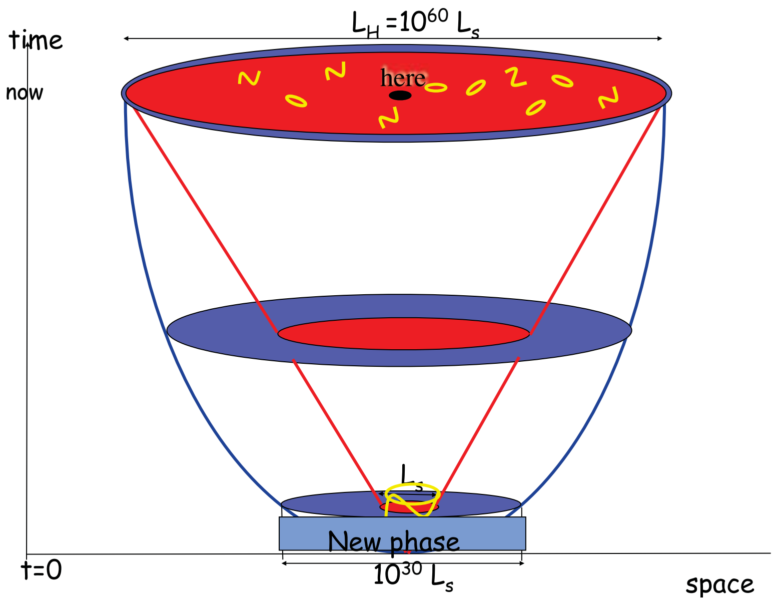


**Figure 3.** A cosmology without a classical beginning.

The pre-bounce phase could either prepare or just replace the inflationary one. In the latter case we may very well expect some:

## Observable Cosmological Relics of a pre-big bang phase

The following ones are particularly noteworthy (see [3] and references therein):

- A stochastic background of gravitational waves, possibly observable in the next decade by advanced LIGO and/or VIRGO. A possible spectrum is illustrated in Fig. 5.
- A new source of adiabatic density/curvature fluctuations, with distinctive properties w.r.t. those of conventional inflation (e.g. with no primordial $B$-polarization in the CMB!)
- A new mechanism to generate seeds for the cosmic magnetic fields which are known to exist on galactic and inter-galactic scales and whose origin is mysterious in the absence of a mechanism producing appropriate seeds for them.

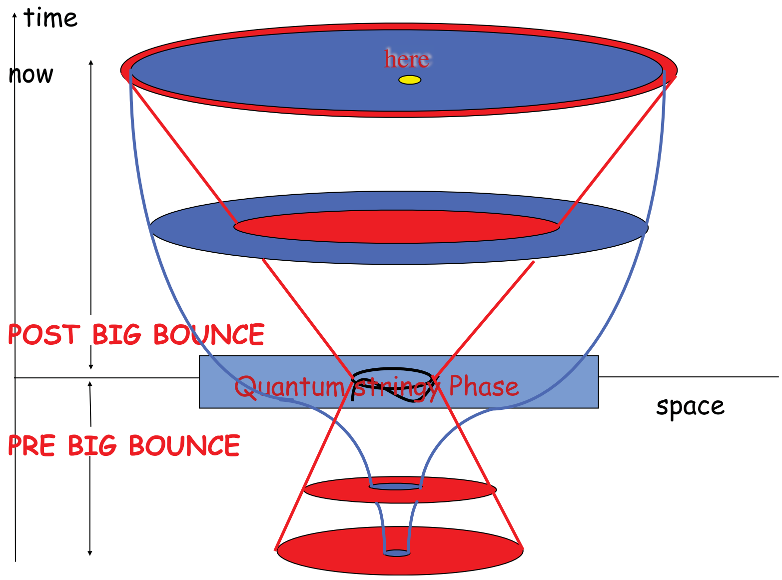


**Figure 4.** A cosmology without a beginning.

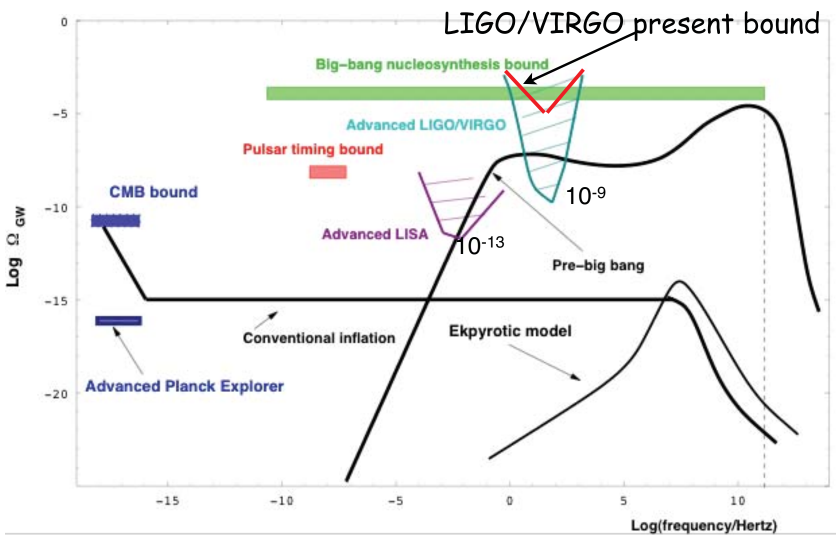


**Figure 5.** Different possible sources of a stochastic background of GW and the expected sensitivities for their detection.

## 8. Conclusions

Classical GR ($h = 0$) works very well in a large number of situations . . . but:

- For its cosmological applications, and in particular in the inflationary scenario, GR needs QM.
- QM is at the origin of large scale structures in the Universe. It is also necessary to reheat it at the end of inflation.
- That moment of reheating plays the role of the traditional big bang but has nothing to do with the beginning of time.
- We don't know what preceded/started inflation. Answering such a question requires knowing the correct theory of quantum gravity and there are not so many options for it.
- In a string-theory context quantum gravity itself, as well as other QFTs, follows from QM, the classical BB singularity is (almost certainly) avoided, and the question of the beginning of time is well posed ...

...but not yet solved!

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