Shortcomings in the Understanding of Why Cosmological Perturbations Look Classical

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Abstract

There is a persistent state of confusion regarding the account of the quantum origin of the seeds of cosmological structure during inflation. In fact, a recent article [1] addresses the question “Why do the Cosmological Perturbations look Classical?” and offers an answer based on unitary quantum mechanics (i.e., without reference to the projection postulate) relying on the decoherence type of analysis. The argument is, thus, implicitly assuming that decoherence offers a satisfactory solution to the measurement problem in quantum mechanics. We will review here, why do we, together with various other researchers in the field, consider that this is not the case, in general, and particularly not at all in the situation at hand. In fact, as has been previously discussed [6, 7], we will argue that the cosmological situation is one where the measurement problem of quantum mechanics appears in a particular exacerbated form, and that, it is this, even sharper conundrum, the one that should be addressed when dealing with the inflationary account of the origin of the seeds of cosmic structure in the early universe.
I. INTRODUCTION

The coming of age of cosmological scientific inquiry with the recent outpurring of high precision empirical data, has been accompanied with the establishment of the inflationary paradigm as part of the standard model of cosmology. In fact, one of the major successes of inflationary cosmology is considered to be its ability to “account for” the spectrum of the temperature anisotropies in the cosmic microwave background, which is understood as the earliest observational data about the primordial density fluctuations that seed the growth of structure in our Universe.

The impact of the data obtained by the various missions: COBE, Boomerang, WMAP, and, hopefully in the near future, Planck, on our understanding of the universe reaches up to the very sources of the processes that made us possible: Galaxies, Stars Planets, life and human beings with all their scientific advances should be regarded as results of the evolution of those early inhomogeneities we are now studying.

However, when considering this account in more detail, one immediately notes that there is something truly remarkable about it, namely, that out of an initial situation, which is taken to be perfectly isotropic and homogeneous, and based on a dynamics that supposedly preserves those symmetries, one ends with a non-homogeneous and non isotropic situation. Most of our colleagues, who have been working in this field for a long time, would reassure us, that there is no problem at all by invoking a variety of arguments. It is noteworthy that these arguments would tend to differ, in general, from one inflationary cosmologist to another [27]. Other cosmologists do acknowledge that there seems to be something unclear at this point [31]. Actually, some recent books on the subject acknowledge that there is a problem. For instance, in [2], we find “... the field configurations must become locked into one of an ensemble of classical configurations with ensemble averages given by quantum expectation values... It is not apparent just how this happens....”, while [3] clearly acknowledges that the problem is not resolved simply by invoking decoherence: “.. However decoherence is not enough to explain the breakdown of translational invariance...”. Nevertheless several researchers in the field continue to hold the belief that the issues have been successfully resolved in that approach.

In a recent series of papers [6, 7], a critical analysis of such proposals has been carried out indicating that all the existing justifications fail to be fully satisfactory.

The aim of this manuscript is to present in general terms the issues surrounding the accounts of the quantum origin of cosmic structure, and, to illustrate the various traps, sources of confusion and inconsistencies one might encounter in this enterprise, through the discussion of a specific example which is paradigmatic of the position held by those colleagues who believe that the question has been settled. The article is organized as follows: In Section II we review the general setting, concentrating on the relation between the classical and quantum descriptions of a problem, and the difficulties in the transition between those two in the cosmological context. Section III will treat the applicability of quantum theory to cosmology, within the framework provided by the general views one can take about quantum mechanics. Section IV will focus on decoherence and refute the widespread notion that it, by itself, fully addresses the problem at hand. In Section V we will argue that the measurement problem becomes even more vexing in the cosmological context. Finally, in Section VI we discuss a specific article[1] which we consider as characterizing the predominant view regarding the issue, and show the extensive set of problems that are overlooked when taking such posture. We then end with a brief conclusion.
II. THE PROBLEM

For most of its existence, cosmology has been discussed in a classical language, as it is in fact done in many other disciplines closely tied to physics, such as hydrodynamics, bridge building and the study of trajectories of space probes, while everybody knows that our world is quantum mechanical. The justification is, of course, that we believe that the classical description is nothing but an approximation to the quantum description, and so, when we consider say the classical description of the trajectory of a satellite in space, we view it as indicating that the wave function of its constituting atoms (or even that of its more elementary constituents) is a sharply peaked wave packet where the uncertainties in the position and velocities are negligible compared with the precision of the description we are making. The classical description does not enter into a fundamental contradiction with the characteristics of our satellite trajectory. It would be very unsettling if we were forced to consider the classical elliptical trajectory around Earth while at the same time we were forced to admit that, at the more fundamental level, the satellite was described by a spherical wave function. We know this is not the case, because it is clear that the precise quantum description of the situation would call for a suitable superposition of energy and momentum eigen-functions leading to a wave packet corresponding to a sharply localized object. Needless to say that the precise way to accomplished this is filled with issues that, at this time, are technically insurmountable, but this is not the point here, the principle is clear. Moreover, we should recognize that in the case of the satellite, one is talking about an open system, and its interaction with the clearly identifiable environment is likely to play an important role in compatibilizing the quantum and classical descriptions.

In the cosmological setting, however, when we want to connect our classical descriptions of the cosmological late times with a quantum description of early cosmological times, we can not escape from the corresponding requirements. We know that our universe is quantum mechanical and, thus, the classical descriptions must be regarded as nothing but short-hand and imprecise characterizations of complicated quantum mechanical states involving peaked wave packets and complex correlations. The universe that we inhabit today is certainly very well described at the classical level by an in-homogeneous and anisotropic classical state, and such description, must, in accordance with the previous discussion, be nothing but a concise and imperfect description of an equally in-homogeneous and anisotropic quantum state, where the wave functions are peaked at those values of the variables corresponding to those indicated by the classical description (or values very close to those). This would, in principle, involve no essential differences from the case of the classical and quantum description of our satellite, except for the lack of a clearly identifiable environment, if we take the universe to include, by definition, all the degrees of freedom of our theory. But there is nothing that indicates that, even without the identification of an environment, we should not be able to make, in principle, such quantum semi-classical description through the use of the sharply peaked wave functions and taking into account all the interactions in the analysis of its dynamics. The situation changes dramatically, however, if we want to seriously consider a theory, in which the early quantum state of the universe was particularly simple in a very special and precise way. This is the case in the inflationary paradigm, and in particular as it refers to the predictions about the spectrum of perturbations that we believe constitute the seeds of cosmic structure.

Infation was initially devised as a mechanism to deal with the so called naturalness problems of standard Big Bang Cosmology: Namely, the Horizon problem, The Flatness
problem and the Primordial relics problem \[18\]. The essential idea is that if the Universe undergoes an early era of accelerated (almost exponential) expansion (lasting at least some 80 e-folds or so), it will come out of this period as an essentially flat and homogeneous space-time with an extreme dilution of all relics and, indeed, of all particle species. The states of all fields will be extremely well described by suitable vacua. The deviations from this state will be exponentially small. What is needed is something that behaves early on as a cosmological constant but that is later “turned off” as a result of its own dynamics, returning the universe to the standard Big Bang cosmological evolutionary path. This is generically thought to be the result of a scalar field with a potential of certain specific characteristics called the inflaton field. The remarkable fact is that this scheme also results in a spectrum of primordial quantum uncertainties of the inflaton field that matches the form of the famous Harrison-Z’eldovich spectrum of primordial perturbations and which has been observed in the various analysis of the extraordinary data on the CMB sky collected in the various recent experiments.

This is the basis of the claim that inflation “accounts for the seeds of the cosmic structure”, which continue to evolve after inflation has ended, and after leaving their mark on the CMB, result in the emergence of the structure of our universe characterized by galaxy clusters, galaxies, stars planets and, later on, of the conditions permitting our own existence.

The predictive power is, thus, remarkable, but it would be completely lost if we needed to rely on the imperfections of the state that resulted from inflation. That is, if the whole picture depended, in a critical way, on the minute deviations from the very simple state that we indicated is thought to describe the universe as it emerges from the inflationary regime, we would not be able to make any predictions. It could well be that the structure of our universe today (and the markings on the CMB) depended in that way on the minute inhomogeneities that remained after the inflationary epoch, but in that event, the matching of the spectra of the quantum uncertainties and that of the CMB spectra would be nothing but a miraculous coincidence. We do not believe in such coincidences; however, that does not mean that we should avoid taking a critical look at the “successful account”. In particular we must carefully inquire into the identification of these quantum uncertainties and the spectrum of the seeds of structure that characterize our universe. In so doing, one must be careful in taking the simple state that inflation provides as if that was the complete description of the starting point of the whole account, because we have no way of justify saying anything about the remaining imperfections, except to assume that they are exponentially small.

Therefore, in turning back to the main subject, the issue we want to discuss is: does the standard inflationary scenario, which starts off by arguing that the universe entered, as the result of inflation, into a simple state characterized as the vacuum of all fields and the flat FRW space-time, when put together with decoherence arguments, really account for the transition from that H.&I. early state of the universe, to the anisotropic and inhomogeneous universe we inhabit?\[1\]

\[1\] This point is sometimes characterized as the “transition from the quantum regime to the classical regime”, but we find this a bit misleading: most people would agree that there are no classical or quantum regimes. The fundamental description ought to be a quantum description, always, but there are regimes in which certain quantities can be described to a sufficient accuracy by their classical counterparts representing the corresponding expectation values. This depends, of course, on the physical state, the underlying dynamics, the quantity of interest, and the context in which we might want to use it. But as we have argued, it should be clear that whenever a classical description of a situation is appropriate, it is nothing
This article will be devoted, to a large extent, to deal with the conceptual issues above, and will not include the developments that are possible when taking a stricter ontological view of the essence of quantum physics, and consequently adding new elements to deal with the shortcomings we encounter in the present context, and would refer the interested readers to other articles the dwell on those topics.[6, 7].

We now proceed to consider the views one can take regarding quantum theory, and how they impact its application to problems in cosmology.

III. COSMOLOGY AND VIEWS ON QUANTUM PHYSICS

In analyzing the present topic, we have to consider the views that one might take regarding cosmology and quantum physics, first to enhance the sharpness of the discussion, in order to avoid possible misunderstandings, and to clarify to the reader the reasons for our posture regarding the matter at hand.

The issue we are facing is related to the so called “measurement problem in quantum mechanics” a subject that has puzzled physicists and philosophers of physics from the time of the inception of the theory [10]. These issues continue to attract the attention of several thinkers in our field, and we are, for the most part, merely recounting the status of the general problem, touching, when appropriate, on the particular instance of the problem: the cosmological setting, a subject that has received much less attention from the physics community. There are, of course, notable exceptions to the assessment above, represented by thinkers like R. Penrose [17], J. Hartle [20], and others.

Any reasonably complete discussion of the interpretation of Quantum Mechanics is well beyond the scope of this manuscript, and needless is to say that much more exhaustive discussions on the subject exist in the literature [21], but we must include a very brief account of what seems to be the most common postures, in order to contextualize our discussion. Let us thus briefly consider some of the views that can be taken on the subject of Quantum Theory vis a vie the “measurement problem” that are relevant to our situation:

a) Quantum physics as a complicated theory of statistical physics. It is a position that holds that quantum mechanics acquires meaning only as it is applied to an ensemble of identically prepared systems. In this view, one must accept that a single atom, in isolation, is not described by quantum mechanics. Let us not get confused by the correct, but simply distracting, argument that atoms in isolation do not exist. The point is whether, to the extent to which we do neglect its interactions with distant atoms, and specially with the electromagnetic field which, even in its vacuum state is known to interact with the atom, quantum mechanics is applicable to the description of a single atom. Again, what can we mean by that, if we know that in order to be able to say anything about the atom, we must make it interact with a measuring device? Well, the question is simply whether applying the formalism of quantum mechanics to treat the isolated atom can be expected to yield correct results as it pertains the subsequent measurements? One might think that this is a nonsensical question, as these results are always statistical in nature. The point is that this statement is not really accurate: for instance, if the atom (say, of hydrogen) was known

but a shortened and approximated version of an underlying quantum description where the correspondence would be between quantum states with relatively peaked wave-funtions for the relevant quantity around the corresponding classical value of that quantity.
to having been prepared in its ground state, the probability of measuring any energy, other
than the one in the ground state, is zero. In fact, for any observable commuting with the
hamiltonian the predictions are not statistical at all, but 100% deterministic and precise!
If so, there must be something to the description of that single atom by its usual quantum
mechanical state. It is thus blatantly false the notion that quantum mechanics can not
be applied to single system[12]. What is true, of course, is that, in applying the theory
to a single system, the predictions we can make with certainty are very limited, with the
extent of such limitations being determined, both by the nature of the system’s dynamics,
and by the way the system was initially prepared. Moreover, in relation with the issue
that concerns us in this article, taking a posture like this about quantum physics, would be
admitting from the beginning that we have no right to employ such theory in addressing
questions concerning the unique universe to which we have access, even if we were to accept
that somehow there exists an ensemble of universes to which we have no access. Note,
moreover, that we should beware from confusing statistics of universes and statistics within
one universe. Furthermore, if a quantum state serves only to represent an ensemble, how
is each element of the ensemble to be described? Perhaps, it can not be described at all?
What do we do in that case with our universe?

b) Quantum physics as a theory of human knowledge. Within this view of quantum
theory, the state of a quantum system does not reflect something about the system, but just
what we know about the system. Such view, naturally rises the question: what is there
to be known about the system if not something that pertains to the system? The answer
comes in the form of: correlations between the system and the measuring devices, but then,
what is the meaning of these correlations? The usual meaning of the word “correlation”
implies some sort of coincidence of certain conditions pertaining to one object with some
other conditions pertaining to the second object. However, if a quantum state describes
such correlation, there must be some meaning to the conditions pertaining to each one of
the objects. Are not these, then, the aspects that are described by the quantum mechanical
state for the object? If we answer in the negative, it must mean that there are further
descriptions of the object that can not be casted in the quantum mechanical state vector.
On the other hand, if we answer in the positive we are again taking a view whereby the state
vector says something about the object in itself. Perhaps we are just going in circles. For
those who read these considerations as philosophical nonsense, let us just say that if we follow
this view, we have no right to consider questions about the evolution of the universe in the
absence of sapient beings, and much less to consider the emergence, in that universe, of the
conditions that are necessary for the eventual evolution of humans, while using a quantum
theory. We could take it even further: what would be the justification for considering states
in any model of quantum gravity, if we took such view of quantum physics?

c) Quantum physics as an non-completable description of the world. Here we refer to
any posture that effectively, if not explicitly, states: “The theory is incomplete, and no
complete theory containing it exists or will ever do”. This view will be considered as being
held by the many physicists that, while not openly advocating such posture, will direct
us to use quantum mechanics “as we all know how” while reminding us that no violation

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2 One can find statements in this sense in well known books, for instance “Quantum Theory is not a theory
about reality, it is a prescription for making the best possible predictions about the future, if we have
certain information about the past” [13]. See also [14]
of quantum mechanics has ever been observed. While this is, with not doubt, a literally correct statement, we must remind our colleagues that by this, they refer, of course, to the rules as found in any quantum mechanics textbook, that essentially rely on the Copenhagen interpretation, which, as we all know, raises severe interpretational issues that become insurmountable once we leave the laboratory and consider applying quantum theory to something like the universe itself. According to this view, we should content ourselves using its tools, and making, in the situation at hand, “non-rigorous predictions”. We must acknowledge, however, that in situations where one can not point to the classical-quantum dividing line, where we can not identify the system and the apparatus, nor the observables that are to be measured, the entity carrying out those measurements and the time at which the measurements are to be thought as taking place, we have no clearly defined scheme specifying how to make the desired predictions. That is, in dealing with the questions pertaining to the early universe in terms of quantum theory, we have no clear and specific rules for making predictions. However, according to the colleagues arguing for such practical posture, we should be content with the fact that the predictions have, in fact, been made, and that they do seem to agree with observations. The issue is, of course, that in the absence of a well defined set of rules, rules that are explicit to the point where a computer could, in principle, arrive to the predictions using only the explicit algorithm and the explicitly stated inputs, we have no way to ascertain whether or not, such “predictions” do or do not, follow from the theory. We can not be sure whether or not, some unjustified choices, manipulations and arguments have been used as part of the process by which the predictions have been obtained. Correct quantitative predictions are not enough. They must first be actual predictions. This should be quite clear, particularly, when thinking about cases where the argumentative connections used in arriving to the “predictions” are so loose that never-ending debates can arise which can not be translated into arguments about precise mathematical statements. Specially suspect are, of course, those “predictions” that are, in fact, retrodictions, and on this point we should be aware that long before inflation was invented, Harrison and Z’eldovich had already concluded the form of the primordial spectrum, based on rather broad observations about the nature of the large scale structure of our universe.

d) Quantum physics as part of a more complete description of the world. Here we are not referring to an extension of the theory into some sort of hidden variable type, as the problem we want to face here about the theory is not its indeterminism, but the so called “measurement problem” (see [13] for more extensive discussions on the problem). Completing the theory would require something that removes the need for an external measurement apparatus, an external observer, etc. There are, for instance, ideas like generalization of quantum physics using a scheme based on sums over decoherent histories proposed by J. Hartle [20], others invoking something like the dynamical reduction models proposed by Ghirardi, Rimini & Weber [23], and the ideas of R. Penrose about the role of gravitation in modifying quantum mechanics in the merging of the two aspects of physical reality [17] (See also [16]). In the particular context of inflationary cosmology, our own work [6, 7, 44] offers an example of an analysis in which the issues are faced directly and which leads to the possibility of confrontation with observations. In this sense this is the position we advocate,

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3 In practice this view is essentially indistinguishable from the so called FAPP (For all Practical purposes) approach to the matter [19]
inspired in part by the arguments made in [17, 23], and by the problem at hand 4.

e) Quantum physics as a complete description of the world. The view that quantum mechanics faces no open issues and that, in particular, the measurement problem has been solved.

Among the holders of these views one can further identify two main currents: those that subscribe to ideas along the so called "many world interpretation of quantum mechanics" and consider this to be a solution to the measurement problem, and those that hold a view that the measurement problem in quantum mechanics has been solved by the consideration of "decoherence". Let us first note that the many world interpretation does very little to ameliorate the measurement problem, as there is a mapping between what in that approach would be called the splittings of worlds, and what would be called "measurements" in the Copenhagen interpretation. Thus every question that can be made in the latter interpretation has a corresponding one in the many worlds interpretation. For the case of the measurement problem the issues would be: When does a world splitting occur? Why, and under what circumstances does it occur? What constitutes a trigger?

Concerning the decoherence mechanism as a solution to the measurement problem, we would like to start by quoting the postures that in these regards are held by several people that have considered the issue at length, in order to dispel the widespread notion that such is the consensus view:

Take for instance the conclusion: “Many physicist nowadays think that decoherence provides a fully satisfying answer to the measurement problem. But this is an illusion.” Arnold Neumaier [24].

Or the warning against misinterpretations:

“...note that the formal identification of the reduced density matrix with a mixed state density matrix is easily misinterpreted as implying that the state of the system can be viewed as mixed too... the total composite system is still described by a superposition, it follows from the rules of quantum mechanics that no individual definite state can be attributed to one of (the parts) of the system ...”, M. Schlosshauer [25].

Or the explicit refutation:

“Does decoherence solve the measurement problem? Clearly not. What decoherence tells us is that certain objects appear classical when observed, But what is an observation? At some stage we still have to apply the usual probability rules of Quantum Theory.” E. Joos [26].

We will, of course, not reproduce the complete discussion by these authors here and would turn the interested reader to the corresponding references.

However, we will see that, when dealing with cosmology, the problem becomes even more vexing and acute. Nonetheless, most researchers in the field seem to take some version of decoherence as the paradigm where the direct application of the standard forms of quantum mechanics to the problem at hand finds its justification. Significantly, the diversity of precise approaches indicates some degree of in-satisfaction of some researchers with the views of others [27].

Before engaging on the specific discussion of the cosmological case, let us review briefly what decoherence is, and what it can and cannot do.

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4 We will however not discuss this issue further in this manuscript, whose objective is to argue that the problem exists, rather than to advocate a particular approach towards its solution.
IV. DECOHERENCE

Decoherence is the process by which a system that is not isolated, but in interaction with an environment (as are all physical systems, except the universe itself) “looses” or “transfers” coherence into the degrees of freedom of such environment. It is a well studied effect that follows rather than supersedes the laws of quantum physics. It is, therefore, clear that, in principle, it can not be thought to offer explanations that go beyond what can be directly inferred from the application of the principles of quantum physics. Its main achievement is to allow for the studying the conditions in which the quantum interferences expected from the idealized consideration of a system as isolated, become observationally suppressed as the result of the system’s interaction with the environment.

The basic recipe for an analysis of decoherence in a given situation follows the following steps:

1) Divide D.O.F.: system + environment (identify inaccessible or irrelevant D.O.F.).
2) Compute Reduced Density matrix (trace over environment D.O.F.).
3) Perform suitable time average so that the off-diagonal matrix elements vanish.
4) Regard the diagonal density matrix as describing a statistical ensemble.

The Problems: once one has understood why certain interferences can not be observed in practice, it is tempting to conclude that one has understood the “emergence of classicality”, and that therefore there is nothing left of the so called “measurement problem” in quantum mechanics. This turns out to be a simplistic and misguided conclusion, as indicated by the quotations listed above. There are, actually, at least two very serious problems with considering decoherence in this light:

I) The basis problem: it is clear that the diagonal nature of the reduced density matrix obtained in the step 3) of the program above, will be lost, in general, upon a change of basis for the Hilbert space of the system at hand. This is taken to mean that the nature of the system-environment interaction selects a so called pointer basis, which underscores the aspects that have become classical as a result of decoherence. The point, of course, is that this leaves one with the usual situation whereby, if the selected basis is, say, the position basis, the momentum of the system remains undetermined and thus one can not argue that classicality has really emerged.

II) The definite outcomes problem: here the problem is the absence of sufficient justification for the interpretation of the mixed state described by the density matrix as describing a statistical ensemble and in regarding a single system as being in definite, yet unknown, state among the ones represented in the diagonal elements of the density matrix. The result that emerges from the decoherence calculations rather indicates that the system must be regarded as coexisting in the various alternatives, but with the interferences in the appropriate observables, being suppressed. Selecting among these alternatives can be viewed as deciding between the “choice vs. coexistence” interpretations. In order to argue that decoherence really leads to the emergence of classicality, one would have to advocate the “choice” interpretation; i.e., that somehow only one of the decoherent possibilities represent reality, but well known, and experimentally confirmed aspects of quantum mechanics such as the violation of Bell’s inequalities, force us to opt for the “coexistence” interpretation [29].

5 In an EPR setup, for instance, the experimentalist who is dealing with one of the particles of the EPR pair, might invoke decoherence by arguing that the D.O.F. of the second particle are, at that time, inaccessible
The next example, from ordinary non-relativistic quantum mechanics, serves as a clear analogy of the situation we face: consider a single particle in a state corresponding to a minimal wave packet centered at $\vec{X} = (D, 0, 0)$ (the vectors in 3-D space are given in cartesian coordinates $(x, y, z)$). Let the particle have its spin pointing in the $+y$ direction. Take this state and rotate it by an angle $\pi$ about the $z$ axis. Now consider the superposition of the initial and the rotated states. The resulting state is clearly symmetric under rotations by $\pi$ around $z$. Now consider taking the trace over the spin D.O.F. The resulting density matrix is diagonal. Can we say that the situation has become classical? Of course not. Is the state still invariant under rotations of magnitude $\pi$ about the $z$ axis? Obviously, the answer is yes. Can a mathematical manipulation with no physical process counterpart ever change the state of the system? Answering yes would take you to the view discussed in b) of section III.

Therefore, we must conclude that, neither decoherence, nor the many worlds interpretation do offer satisfactory solutions to the measurement problem. But, is it perhaps the case that when both are put together they do offer one?

### A. On the shortcomings of decoherence plus many world interpretation as solution to the measurement problem

Consider the traditional problem of Shroedinger’s cat: The traditional paradigmatic problem that brings to the forefront the interpretational problems of Quantum Mechanics. A cat is placed in a box with an undecayed atom whose decay is arranged to trigger the release of certain poisonous gas that would kill the cat. The unitary evolution of Quantum Mechanics then leads, after some appropriate time, to a state of the system which is a superposition of Undecayed-atom/Live-cat with Decayed-atom/Dead-cat. The issue is how to make sense of this situation. The proponents of decoherence or decoherence plus multiple world interpretation offer the following solutions to the problem:

Concretely:

1) Let us say, we have prepared the system in an initial setup of the box with the cat and with the un-decayed atom, and that

2) after a short time this has evolved into a state typical Dead -Alive cat that is represented by the would be wave function $\psi = c_1 \psi_1 + c_1 \psi_1$.

3) Then, we invoke de-coherence (of any kind) and end up with a diagonal density matrix (operator).

4) Then one argues that the problem is solved.

This is the decoherence solution.

But upon closer inspection, it seems rather unclear in what sense does this mean that the problem is solved. If we take the view that the quantum state represents the reality “out to him. But taking this as support for the “choice” view would lead to the “conclusion” that the individual particles have (even if unknown to him) a well defined spin. This conclusion is incorrect, as it is known to lead to contradictions (See [35]).
there”, as would be necessary in any realistic interpretation of Quantum theory (rather than, say, the view b) of section III), we would still face a serious interpretative issue because the equation in 3 above, continues to represent a situation in which the two alternatives Dead and Alive coexist (even if they do not interfere).

At this point, we need to rely on an interpretational instruction, for which must be, one of the following two OPTIONS:

5a) “One of the two ALTERNATIVES becomes reality, and the other disappears”. This is, of course, analogous to the collapse (or Bohr’s reduction postulate). So we are almost back to square one.

or we could consider the view offered by the decoherence plus many world interpretation:

5b) “The two alternatives coexist in a reality only a branch of which corresponds to what we perceive, (presumably because we or our mind is entangled with the system). This seems to be the point of view adopted, in general, by the school of de-coherence solutions to the measurement problem and it seems closely connected with the ”many worlds” interpretation.

There is a serious problem with such “solution” (i.e the interpretation 5b). It has to do with the issue of how do we treat the “things that happen”?.

The problem in this particular case is the following:

The posture 5b) indicates that we only perceive one branch of reality, and that there are many other branches “out there” of which we can not know anything about, and that, moreover, (unless re-coherence forbidden in principle within some modified version of the theory) might re-cohere with our branch leading to completely unpredictable, and yet observable effects. We can not justifiably argue that re-coherence is impossible, or even unlikely because we do not know what is going in in those branches that we do not perceive. In fact, this posture seems to eliminate any justification we might have in stating that the initial (would be) wave function in the previous example, corresponds to that of 2). This is so simply because we could not, at step 1) argue that we had described the totality of the existing reality, any more than we could, in step 5b) argue that the (say) Dead Cat alternative, represents the totality of existing reality.  

Thus, decoherence together with the many worlds interpretation fails to offer a satisfactory resolution of the matter.

V. THE EXACERBATED PROBLEM: APPLYING QUANTUM PHYSICS TO THE EARLY UNIVERSE

We should point out that some researchers in the field, such as [31], have acknowledged that there is something mysterious in the standard account of the emergence of structure, and people like J. Hartle [20] have pointed out the need to generalize quantum mechanics to deal with cosmology, and, of course, R. Penrose, who in his last book [32] has stressed the relevance of the general measurement problem in quantum mechanics to the problem of breakdown of the H.&I. during inflation, comparing it with the problem of the breakdown of spherical symmetry in a particle decay. In our view, this analogy does not emphasize the point that, in the cosmological context, the problem is even more severe than in ordinary situations, because, in that case, we can not even rely on the strict Copenhagen interpretation as a source of “ safe and practical rules”.

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As an example that exhibits quite clearly the deepening of the problem in this context, let’s consider the following quotation from a well known thinker on these sort of issues in quantum theory: "As long as we remain within the realm of mere predictions concerning what we shall observe (i.e. what will appear to us) and refrain from stating anything concerning “things as they must be before we observe them ” no break in the linearity of quantum dynamics is necessary. ” D’Espagnat [33].

However, in the cosmological setting, we need to deal, precisely, with this situation: we need to think about the state of affairs of the universe before the emergence of the conditions that make us possible, before we existed and before we ever carried out an observation or measurement.

That is, we can not rely on ourselves and our measuring apparatuses, as part of the explanation, precisely because both are the result of the emergence of the conditions we want to explain.

Next we turn to consider a particular account that which we consider representative of the views held by the large class of colleagues in the filed who believe that there is no problem with the inflationary account of the quantum origin of cosmic structure. The objective is to illustrate in that concrete example the serious problems that, often ignored, lie behind those views.

VI. KIEFER-POLARSKI

With all of our general discussion in mind, let us look carefully at the account recently given in [1] of the question “Why do the Cosmological Perturbations Look Classical to us?”. We think this work can be used to illustrate the problematic aspects affecting most of the accounts used by over-enthusiastic inflationary cosmologists. We should stress that most of what lies ahead has been discussed in [6], with some points having been made indirectly in [16].

Before considering in detail the discussion of that article, the first thing that should be clear from the title is that the authors start by taking an exceedingly narrow view of the issue: Underlying the whole work it is clear that, in their view, all that needs to be understood is “why do we see the perturbations as classical”, taking as a given that we are here with our machines and their limitations, to act as observers of the cosmological perturbations, and ignoring the fact that we are one of the outcomes of these perturbations. This very narrow view of the problem seem to ignore that the issue is set within the more general problem of cosmology. The point, as we have already noted, is that cosmology is the quest for the understanding of how the universe evolved, including the emergence of galaxies, stars, planets and eventually life, with the much later appearance of human beings capable of looking at the sky and of studying the traces of the perturbations in question. Therefore, by limiting the question to an issue of observation, the authors are implicitly putting into the formulation of the problem what should indeed be part of the answer: That the universe eventually develops the structure that makes feasible the emergence of human beings capable of viewing the CMB sky. Once that fundamental aspect of the problem is overlooked, the question becomes simply why the spectrum has certain detailed features, and a big part of the main problem is bypassed. This approach is, in a sense, the application to quantum problems in cosmology, of the generic approach to the measurement problem in quantum mechanics that starts off by assuming that one of the parts of the subsystem is a classical apparatus, or that one has a classical observer. This is clearly not a way to
address the issue from within a quantum theory of reality, unless, of course one takes the
view that quantum theory is not such a thing, but rather one of the rather unpalatable
possibilities enumerated in section III. Any such approach seems to call into question the
whole justification for applying quantum theory to cosmology.

Moreover when we consider the question posed as “why do we see the per-
turbations as classical” one can not but wonder what would we have in mind
when considering the alternatives that such question seems to evoke. In other
words, what would it mean for us not to see the perturbations as classical? What
would they look like if we saw them as quantum mechanical?. Clearly bringing
our own selves into the center of the question in this way, transforms the issue
into something that can not be addressed in the simple terms the authors have
in mind.

Furthermore, apart from the issues above, we will see that the arguments found in [1],
rely on several misinterpretations and on incorrect arguments. In order to see the extent of
the problems we must look at the proposal in more detail.

The setting is that of a background Robertson Walker space-time undergoing exponential
inflation and described with the metric:

$$ds^2 = a(\eta)^2 \left[-d\eta^2 + \delta_{ij} dx^i dx^j\right],$$

(1)

where the scale factor is given by $a(\eta) = -\frac{1}{H_I \eta}$, with $H_I^2 \simeq (8\pi/3)GV$ with the scalar
potential, $\phi_0$ in slow-roll regime. The conformal time $\eta$ running from $-\infty$ to 0. The
quantum aspect of the scalar field $\phi$ is described in terms of a rescaled field $y \equiv a\delta\phi$. The
field is written in terms of creation and anihilation operators and written in terms of its
(spatial) Fourier transform:

$$y(\eta, k) = f_k(\eta) \hat{a}_k + f_k^+(\eta) \hat{a}_k^*$$

(2)

with $f_k = \frac{-i}{\sqrt{2k}} e^{-ik\eta}(1 - \frac{i}{k\eta})$ and where the conjugate momentum

$$p(\eta, k) = g_k(\eta) \hat{a}_k + g_k^+(\eta) \hat{a}_k^*$$

(3)

with $g_k = -i\frac{\sqrt{2}}{k} e^{-ik\eta}$. (Note that we have suppresed the distinction of the vector $\vec{k}$ and its
magnitude $k$ for simplicity of notation.)

The authors note that they can write these operators as combinations of the time inde-
pendent operators

$$\hat{Y}(k) = \frac{1}{\sqrt{k}}(\hat{a}_k + \hat{a}_k^*), \quad \& \quad \hat{P}(k) = \sqrt{\frac{2}{k}}(\hat{a}_k - \hat{a}_k^*).$$

(4)

With coefficients

$$f_{k1} = \Re(f_k) = \frac{-1}{\sqrt{2k}} [\sin(\eta k) + \frac{1}{\eta k} \cos((\eta k)]$$

$$f_{k2} = \Im(f_k) = \frac{-1}{\sqrt{2k}} [\cos(\eta k) - \frac{1}{\eta k} \sin((\eta k)]$$

(5)

$$g_{k1} = \Re(g_k) = \frac{-1}{\sqrt{2k}} \sin(\eta k), \text{and} \quad g_{k2} = \Im(g_k) = \frac{-1}{\sqrt{2k}} \cos(\eta k)$$

(6)

respectively.
The first set of considerations offered in that work under the name "Quantum to Classical Transition: the pragmatic view", are based on the properties of these functions. The point is that in the limit \( k\eta \to 0 \) (corresponding, for a given \( k \), to the infinity future of a never-ending inflationary era) the coefficients \( f_{k2} \) and \( g_{k1} \) vanish. This is next used to argue that the non-commutativity of the operators \( Y(k) \) and \( P(k) \) becomes irrelevant and can be ignored as it concerns the quantum field and its momentum conjugate.

The first thing we note is that this discussion so far, applies to the quantum field operator itself and thus nothing of what has been said up to this point is limited to the vacuum state alone. Thus, in principle should apply to all states. The quantum field has become equivalent in all generality to a classical field. But why should this be limited to the inflaton field? All fields present during inflation should be subject to the same analysis, thus, we would conclude that all fields in nature are equivalent to their classical counterpart. After all, every field that exists should be present in its corresponding vacuum state during the inflationary epoch. The fields are not simply turned on when we need them. This is required by the working hypothesis behind all of physics regarding the Invariance of the laws of physics in “time”. The conclusion is, of course, incorrect for other fields, why should it be correct for the inflaton? It seems that the only possible posture here is that the modes of all quantum fields have become classical if they correspond to wavelengths that are “large enough”. But then we must ask ourselves: large enough in comparison to what? the human scale? perhaps the current horizon scale? Anyway, it seems clear that in order to justify this approach, one would need to introduce several other ad hoc rules into the theory. Moreover, as it has been recently discussed in\(^{[33]}\), the position that one could consider the quantum field simply as a collection of independent modes, as would be needed in order to subject the different modes to very different treatments (such as considering some to be classical, while others are considered fully quantum mechanical), is untenable in light of the locality of the field theory and the need for composite operator renormalization.

The next thing we should note is that, when speaking about an operator, the issue of what is small and what is not can only make sense once one has identified the way one wants to extract a number from the operator at hand. In general, one will need to consider the matrix element of the operator in a certain class of states, including the states constructed through the application of other relevant operators on certain collection of relevant states (in our case, that would involve the states constructed out of the vacuum by suitable application of field operators, i.e., the Fock space). Moreover, it is not at all clear why one should not consider one of the most direct, the c-numbers that can be extracted from the operators at hand: the field conjugate momentum commutators. Taking this more rigorous mathematical stand, one sees that it is rather unclear how can one convincingly argue that the operator in question vanishes. In fact, the decoherence arguments presented in\(^{[1]}\) up to this point rely on the behaviour of the field and momentum conjugate as operators, and not just on particulars of the state. So, if we were to accept them, we would conclude it is not just the vacuum state that becomes classical, but the full quantum mechanical system, as a physical entity!.

Next, we should recall that inflation is not supposed to continue indefinitely, but must stop at some point (even if something like 80 e-folds of expansion are accomplished in its while) the quantity that is being discarded in the arguments of\(^{[1]}\) is not, strictly speaking, zero (in any of the senses that can be given to this statement, as discussed above). One can argue that is extremely small, and thus negligible, but in order to do that one would have to face other issues: 1) In comparison to what is it to be taken as small? certainly not as
its contribution to the commutator of field and momentum conjugate is concerned. 2) Why should we trace over it? presumably because the quantities are too small to be measured, but this, of course, can only mean, “to be measured by us with current technology” as there is no possibility of arguing about the un-measurability of those quantities by other conceivable beings, or even by future generations of humans.

This reliance on what is experimentally accessible to us with our current technology (or that which the author envisions as being attainable in the relatively near future) is prevalent throughout the analysis in [1]: We find it in the separation of the field \( y \) and momentum conjugate \( P \) in their equations 24, and 25 of their work, and the reliance on the existence of modes characterized by the functions \( f_k \) and \( g_k \) that “become vanishingly small” as a result of inflation. These are thus considered as unobservable, negligible, etc.

But let us consider the concrete argument in more detail: The first point is that such functions only serve to connect the operators \( \hat{y}(k, \eta) \) and momentum conjugate \( \hat{p}(k, \eta) \) with the operators \( \hat{Y}_k \) and \( \hat{P}_k \). The point is that even if we identify an operator \( \hat{O} \) which is written in terms of other operators with coefficients that vanish in a certain limit, we must concern ourselves with how is this connected with the quantities we measure. In the inflationary setting, we can always construct the operator \( a(\eta)^n \hat{O}(\eta) \) and note that, for an appropriate choice of \( n \), it does not decrease at all. Actually, in the case at hand we can even look at the commutator as an observable that does not tend to zero even if \( a \to \infty \). In fact, it is worthwhile mentioning that if we consider instead of the rescaled field \( \hat{y}(\eta, k) = a\hat{\phi}(\eta, k) \) and its conjugate momentum \( \hat{p}(\eta, k) \), the original un-scaled inflaton field \( \hat{\phi}(\eta, k) \) and its conjugate momentum \( \hat{\pi} = a\hat{\phi}(\eta, k) \), we end up replacing the functions \( f_k \) and \( g_k \) of section II of [1] by \( f'_k = f_k/a \) and \( g'_k = g_k/a \) and when resorting to a similar analysis, as done in that paper, we would see that the mode \( g_{k1} \) no longer vanishes in the \( a \to \infty \) limit. The ratio of the different modes, is of course, unaltered but in order to argue for the un-observability of such mode, the authors would have to argue that the big value of the other mode somehow makes this mode unobservable, and in order to justify that, they would have to get into the issues regarding the possible precision of instruments, thus bringing more clearly into the focus their reliance on our own limitations as experimentalists.

Further down, one finds several, unjustified identifications that often rely on mixing up classical and quantum arguments: We can see this, explicitly at several points in this paper:

i) For instance below equation 26 of [1]:

\[
p(k, \eta) = p_{cl}(k, \eta) = \frac{g_{k2}}{f_{k1}} y(k, \eta)
\]  

(7)

where presumably here the authors have in mind something like the value corresponding to the maximum of the Wigner functional, with the given the value of \( y \) held fixed, we read: “For a given realization of the perturbation \( y(k, \eta) \), the corresponding momentum \( p_{cl}(k, \eta) \) is fixed and equal to the the classical momentum corresponding to this value of \( y(k, \eta) \). Then the quantum system is effectively equivalent to the classical random system, which is an ensemble of classical trajectories with certain probability associated with each of them”.

Let us consider the above statement: First, what justifies talking about a given realization? What are these realizations? Where, in the standard quantum theory, is there any reference to “a realization”? In fact, one must wonder if the authors are thinking that each one of them is characterized by a definite value of field and momentum conjugate, as characterized by equation 26 (reproduced above) of [1]? Perhaps this is only the mean values of the corresponding quantities in some quantum states? If so, which ones? Then we are told
that “the quantum system is equivalent to classical random system”, indicating that, according to the authors, there is associated to our quantum system a given “probability assigned to each of the element” of a certain classical ensemble. What is this classical ensemble supposed to be representing? Should we view our universe as an element of an ensemble of classical universe? In that case, our particular universe would be classical! Perhaps what the authors have in mind is to associate with a classical ensemble the collection of possible outcomes of certain measurements. That is to say that quantum state is not characterizing the objective physical conditions of the system under description, but it is just a codification of the results of subsequent measurements. This does not seem to have any justification, unless one is taking the view a) of section III, which, as we have seen, does not allow us to apply quantum theory to cosmology.

Regarding the state of the field, the situation at hand, is just that in terms of the original creation and annihilation operators, the state we identified as a vacuum is now a squeezed state. But having a squeezed state has no effect on the quantum field and momentum operators which do, of course, continue to satisfy the Heisenberg uncertainties. The authors seem to ascribe a fundamental value to the squeezing of the state ignoring that one can always find a new set of operators in terms of which, the evolved vacuum will look as a “standard vacuum”.

One can see in a very transparent way what lies behind such arguments by considering a simple harmonic oscillator in Quantum Mechanics. The Hamiltonian $H = \frac{p^2}{2m} + \frac{m\omega^2 x^2}{2}$, (with $\omega^2 = k/m$) and standard commutation relations $[p, x] = -i$. We can write the usual creation and annihilation operators as

$$a = \frac{e^{s_0}}{\sqrt{2}} x + i \frac{e^{-s_0}}{\sqrt{2}} p, \quad a^\dagger = \frac{e^{s_0}}{\sqrt{2}} x - i \frac{e^{-s_0}}{\sqrt{2}} p$$

with $e^{s_0} = \sqrt{m\omega}$. These operators satisfy the usual commutation relations $[a, a^\dagger] = 1$. We can now define (without changing the system or its hamiltonian), for arbitrary values of $s$, new operators:

$$a_s = \frac{e^s}{\sqrt{2}} x + i \frac{e^{-s}}{\sqrt{2}} p, \quad a_s^\dagger = \frac{e^s}{\sqrt{2}} x - i \frac{e^{-s}}{\sqrt{2}} p$$

which are related to the original creation annihilation operators are obtained through a “Lorentzian rotation”. In fact, these operators satisfy the same commutation relations $[a_s, a_s^\dagger] = 1$. However, following the logic of [1], we would have to say, by looking at equation 9 that in the limit when $s$ is very large (i.e. $s \rightarrow \infty$) the fact that $x$ and $p$ do not commute becomes irrelevant and that, therefore, we are in an essentially classical situation, where for each value of $a_s$ there is a corresponding value of $a_s^\dagger$ (which, in this case, would be the same value). This argument would imply that through the simple act of choosing to express things in terms of suitable variables we can change the nature of a purely quantum mechanical system into something which is essentially classical?. The analogy with the situation being examined in [1] can be further strengthened by noting that, as a matter of fact, the above construction is just what is used to define squeezed states, namely, the states annihilated by the operator $a_s$ are squeezed states when seen from the point of view of the usual basis of the harmonic oscillator Hilbert space: $\{|n>^{osc}\}$. Analogously, the usual ground state of the harmonic oscillator would appear as a squeezed state when viewed in the basis of generated by repeated application of $a_s^\dagger$ on the “displaced vacuum” $|0, s>$. (the state defined by $a_s|0, s> = 0$). Therefore, the claim made just below equation 26 of [1], that such equation “is true for the quantum system (in the operator
"sense)" is incorrect. If we try to give to these lines of argument “the benefit of the doubt”, we would have to assume that the authors have in mind some sort of notion of a “preferential role” for the particular operators that represent variables that are “more natural”, and that there is some particular aspect of the state of the field one is dealing with that bypasses the counter-arguments we have exposed above (some sort of argument that would say, for instance that the relevant parameter is $s_0$ rather than the “unnatural” parameter $s$). That seems to be the tenor of part of the discussion in section V of [1], but we will get to that shortly and see that it also fails to pass further scrutiny. However, before doing so we must lastly point out that a related situation where $s$ is very large can be indeed achieved by forcing the “natural” parameter $s_0$ to be very large, corresponding, for instance, to the situation where $m$ is very large for fixed value $k$. Actually, we can choose both to be very large while keeping the value of $\omega$ fixed at any desired value. But it should be clear that, in that case the ground state of an harmonic oscillator is not a classical state. For instance, the uncertainty of the momentum is much larger than the corresponding expectation value, and the energy levels of the system are separated by the usual $\Delta E = \hbar \omega$.

Finally, we must note that these squeezed states of the electromagnetic field are well studied in the field of quantum optics, and, in fact, rather than being “almost classical” as indicated in [1], they are known to exhibit extremely quantum behavior [40]. For example, we note that when a system consisting of two harmonic oscillators, is in a state where both degrees of freedom are in squeezed states, the appearance of highly nonclassical EPR correlations is inescapable[41]. Thus in the case of an infinite set of harmonic oscillators in squeezed states, such as the vacuum of quantum field we are interested on, the situation can not be said to be anything but of a highly quantum-mechanical nature.

On further examination, we find explicitly other problematic statements in this section of [1], such as:

ii) Further below equation 26 of [1], we find: “an analogous situation happens for a free non-relativistic particle possessing an initial Gaussian minimal uncertainty wave function…. At very late times the position of the particle does not longer depend on its initial wave position $x(t) \sim (p_0/m)t$. We get an equivalence with an ensemble of classical particles obeying this where $p_0$ is a random variable with probability $P(p_0) = |\Psi|^2(p_0)$”.

Thus according to such statement, if we wait enough, a free quantum particle becomes classical? It is hard to see what possibly could the authors have in mind here.

Next we consider the arguments on section V of [1] entitled Quantum To Classical Transition: Decoherence we see the authors recast their arguments (requiring, in turn, some recasting of our own counter-arguments) relying now, explicitly, on the standard decoherence argument that misinterprets the fact that the reduced density matrix has the form used in describing a statistical ensemble, to argue that the system has become one of the latter. Thus, the whole argument in this section is based on the assumption that decoherence does offer a solution to the measurement problem in QM, an assumption that, as we discussed in the previous sections, is incorrect.

We will now look exactly how and where do the problems arise in this specific case.

The first issue that is addressed is that of the identification of the environment: Here the authors note that “in any fundamental theory.. there is an abundance of different fields with different interactions. Among them there will not be difficult to find appropriate candidates for environmental fields generating decoherence for primordial fluctuations”.

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6 Defined with respect to the usual construction of Quantum Field theory in Minkowski space-time
The problem with this is that, in the same way that inflation is supposed to drive the inflaton perturbations into the vacuum state, it will drive all other fields into their corresponding vacuum state. In fact, if there are interactions among the various fields, inflation is going to drive the whole quantum system of fields into the appropriate vacuum of the combined system. The equivalence principle indicates that all fields will be affected by the expansion associated with the gravitational sector, in the same fashion, and thus it would be quite difficult to generate any mechanism by which the inflaton ends up in its vacuum and other fields do not.

The authors then argue that even if appropriate environmental fields do not exist, the fact that the theory is nonlinear indicates that there will be interactions among the different modes. But again, the authors seem to ignore the fact, that if they want to take into account such interactions, they must recognized that the vacuum to which inflation drives the fields is the full non-perturbative vacuum. One can not claim that the initial state of the inflaton is the free vacuum, and then argue that the interaction plays an important role in generating the desired classicality. Nature does not rely on perturbation theory, only our description of it does. Moreover, if we want to take into account the self interaction, the fact that the Lagrangian that describes it is translationally and rotationally invariant, ensures that the resulting state will be homogeneous and isotropic, (as well as pure). This situation brakes the analogy with the case of a quantum particle interacting with a bath of photons.

Then the authors argue that the entanglement of the state, when considering the individual modes is analogous to the Hawking and Unruh effects. But this is highly misleading because in both of these latter situations one is interested in looking at the state, as it is perceived by observers limited to specific regions of space time and who do not have - by definition- access to certain degrees of freedom. In the cosmological case, the authors seem to be implicitly assuming, that one is again interested in the observations made by observers that do not have access to certain degrees of freedom, but as we have argued before, that is not the case: In cosmology, we want to understand the conditions that lead to the emergence of such observers (i.e., Us).

Otherwise, cosmology should no longer be regarded as the search for an explanation of the evolution of the universe in terms of the laws physics, but rather as the mere attempt to retrodiction of information, given the fact that we are here with our particular specificities, including those that limit our ability to monitor certain degrees of freedom. Why should one contemplate inflation at all if that were the case?

The authors then acknowledge that the coincidence of certain classical and quantum expectation values in a pure quantum state is not the same as an ensemble of stochastically distributed classical values, but reiterate a quantum to classical to transition occurs thanks to decoherence and squeezing.

They argue that the cosmological fluctuations represent the system to be de-cohered, and the other fields (or the inaccessible parts of the the fluctuations) represent the environment. As we have already pointed out, the argument on which the authors rely to justify the treatment of some degrees of freedom as environment is the inability of creatures like ourselves to observe them. Therefore, this posture, leads us to a a circular explanation: We are the result of the evolution of the initial cosmic fluctuations, and the emergence of them is understood in terms of some of our characteristics as sapient beings.

The point is, of course, that in taking this point of view one is using the technological limitations of humans of the XXI century as part of the explanation of the emergence of cosmic structure which eventually would make those human possible. Hardly a satisfying
view of the explanatory powers of cosmology as a science.

Then we see the explicit reliance on decoherence as a solution to the measurement problem, a reliance that we have shown in the previous sections to be, in general, unjustified. Nonetheless it is used profusely. In fact, just below equation 47 of [1] we read: “it (the matrix density) assumes the form of an approximate ensemble for the various states which occur with probability...”

This is precisely the generic misinterpretation that M. Schlosshauer has warned us about, and which should cite here once again: “...note that the formal identification of the reduced density matrix with a mixed state density matrix is easily misinterpreted as implying that the state of the system can be viewed as mixed too... the total composite system is still described by a superposition, it follows from the rules of quantum mechanics that no individual definite state can be attributed to one of (the parts) of the system ...”.

Again, some of the most conspicuous and clear contradictions that arise when we give ourselves the right to use unjustified interpretational extrapolations such as this, can be seen by considering the standard Bohm-EPR[34] setup while entertaining the notion that the two particles might have a particular spin orientation in the absence (or before) a measurement is carried out [35]. We could, for instance, decide to trace over the spin D.O.F. of one of the particles of the EPR pair and obtain, for the spin D.O.F. of the other particle, a diagonal density matrix, and be tempted to interpret this as indicating that the particle has one of the two spins orientations. But we know this leads to contradictions: It allows one to deduce that the Bell’s inequalities should hold, but these are not only contrary to Quantum Mechanics, but have been shown to be violated experimentally [30]. Such position is thus untenable.

Besides these problems, we encounter in the account of [1] various additional questionable aspects

The most simple of them is the argument on which they base selection of the so called “pointer basis”:

After equation 48 [1] we find: “fields coupling to cosmological fluctuations are expected to couple to field amplitudes and not canonically conjugate momenta of field amplitudes” Why is this so? Should we understand that, if this were not the case, the whole scheme would crumble?” If so, it would be imperative to know, for instance, why can’t there be vector fields $A^\mu$ similar to gauge fields that couple precisely to the combinations of the form $\psi \nabla_\mu \psi$? Doesn’t the reheating process require a coupling (even if indirect) of the inflaton with all ordinary fields, including the electromagnetic one?

Why can’t the inflaton field be a part of a multiplet coupling to a non-abelian gauge fields? One might say that this is a requirement of the model and with out it the whole scheme doesn’t work. Fine, let us say we follow the authors in this proposal. But then, what about couplings to gravitation which should be universal and then include all forms of energy momentum including that associated with the conjugate momenta to the field amplitudes? Perhaps the argument is that the coupling to gravitation is too small and thus the correlations with the metric variables is negligible, but then, how do we make sense of the fact that it is precisely through the imprint on the metric and the corresponding gravitational red-shift that the Newtonian potential induces in the photons, that we do observe the CMB anisotropies?

One should also note that the posture in [1] goes against the usual understanding of when a situation is classical: Following their point of view, all squeezed states people are so excited to be able to construct in quantum optics would have to be regarded as classical. But we all
know that situation can be described as essentially classical when the quantum uncertainties are very small in comparison with the expectation values of the quantity of interest or in comparison with the precision of our analysis. Nonetheless, in section IV of [1], after having argued that the situation after inflation is essentially classical, the authors instruct us that we should rely, for the relevant predictions, on the quantity \( \langle 0| \delta \phi^2 |0 \rangle \) (eq. (42) of [1] ) which is nothing but the uncertainty associated with the quantity \( \delta \phi \) whose expectation value is ZERO. The fact is that in this section the authors warn us that in computing the power spectrum, what we must compute is the “quantum average”. That is, we should not rely too much on all the arguments indicating the situation was classical. So what is it?, the situation is essentially classical or is it not? Why should we compute the quantities we see using a quantum object, if the situation looks classical? In fact, one must wonder, why should we base our calculations on the vacuum state rather than on one of the states |n > in the ensemble of states corresponding to:

\[
\rho_s \approx \sum_n |c_n|^2 |n \rangle \langle n|
\]

which according to equation (47) of [1], is supposed to emerge from the decoherence analysis? Aren’t these, according to [1], precisely those states that look classical and which we are supposed to observe?

It thus seems, that in order to make some sense of the posture adopted in that work, one must take it to mean something like “The cosmological fluctuations look classical to us but in reality the state of our universe is the result of the unitary quantum mechanical evolution of the vacuum, and it is thus still homogeneous and isotropic. It just does not look like that to us”. This, in turn, takes us to the posture discussed in 5b) which as we argued, would make it impossible to use quantum mechanics at all.

Therefore we must conclude that the position taken in [1] is self contradictory: We are supposed to observe the universe in one of the states – one of those schematically shown in equation 47 of [1] (the equation above)– that make up the superposition in which the system actually is, but on the other hand, in order to compare with observations we must make use of the full superposition, i.e. the vacuum state. Is it not the view advocated by these authors that we live in one branch and thus only see the corresponding state |n >? If so, why should the comparisons with observations be made using the full fledged superposition associated with the vacuum state? As they say: “one can not have the cake, an eat it too”.

VII. CONCLUSIONS

In the cosmological setting, we seek a historical; that is a development in time, describing the cosmic evolution, that follows the laws of physics. Such description should explain how did WE arise, in a path covering the emergence of the primordial density fluctuations, of

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7 In fact, we could now turn around and ask for instance: what exactly are these states |n >? What are, for instance, the uncertainties in the field and momentum variables for each of these states? How would we even proceed in attempting to answer such questions?

8 It is worthwhile mentioning that one would need to take into account the evolution of the expectation values of field operators in the corresponding state, if in the analysis of the problem one chooses to follow such posture to its full conclusion. This would, in turn, lead to the uncovering of the type of unconventional effects analyzed in [6, 44].
galaxies, stars, and planets, and eventually living organisms, humans, cultures, etc.. Such an account should not rely on the measurement (in) abilities of the late evolved creatures to explain the emergence of conditions that make them possible. From this perspective, one can not justify identifying some D.O.F as irrelevant environment, based on the current, or even permanent, limitations of humans, in the analysis of the emergence of the primordial density fluctuations, for doing so leads to a circular argument with no explanatory value. Alternative postures such as that in 5b) would make the use of quantum mechanics, unjustified in general, as discussed there.

One can not take one position regarding quantum mechanics (or any theory) in one instance and a different one in another.

It is still a remarkable fact that the HZ spectrum coincides with the calculations of the uncertainties in the evolved quantum state of the inflaton field. But we need to understand why is that.

There are, of course, alternatives, but those require the introduction of some novel aspect in physics, such as a “dynamical collapse of the wave function”, along the proposals by Penrose [17], Diosi [42], GRW [23], and [43]. We have shown one simple implementation of these ideas in the exploratory work [6] with further analysis in [44].

So we see, that we as a scientific community face a dilemma: We either content ourselves with the fact that calculations lead to results that match the observations but which can not be fully justified within the context of the interpretations provided by our current physical theories, or we admit the shortcomings and start to work to clarify the issues, and hopefully gain some new insights in our quest to understand the functioning of our world. There is no doubt that in taking the second approach we will be led to consider erroneous proposals and explore paths that turn out to be dead ends, (as could be the case with our own works mentioned above) but rather than see this as a deterrent, we should take heed from Francis Bacon’s profound observation9 about scientific methodology: “truth emerges more readily from error that from confusion”.

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