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Comment: Cosmology, 2001

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The progress made in cosmology recently is truly impressive on both the physical and the observational front, as is evidenced by the talks presented at this meeting. However, from the viewpoint of relativists there are some issues that still need attention, in addition to those commonly recognized as needing completion.

The basic task all agree on is

(a) tidying up the analysis of structure formation theory and detailed matter and CBR observations in relation to CBR nonlinearities [1] and inflationary models [2, 3], and hence determining the major late-time cosmological parameters [4][1].

With the rest of the community we wish to see some further major physical issues sorted out, specifically:

(b) physical identification of the inflaton and associated initial vacuum state, thus changing the inflationary paradigm to a specific and perhaps even testable physical theory;
(c) identification and physical explanation of both non-baryonic dark matter and the late-time cosmological constant (or quintessence);
(d) clarification on the role of non-perturbative trans-Planckian physics in terms of affecting post-inflationary conditions;
(e) attaining a full understanding of the ending of inflation in both chaotic and non-chaotic models; and
(f) understanding the problem of the central concentrations of galaxies and their substructure.

However, we would also like to see some more geometric themes pursued because they would considerably clarify and solidify the emerging model. The most important of these are the following.

1. Studies of anisotropic and inhomogeneous cosmological models [5], making clear what fraction of these models (a) inflate and then (b) are isotropized by inflation both in terms of geometry and matter motion.
2. Embedding studies of these models, and of the subspace of isotropic models, in a space-of-spacetimes framework that will allow adequate assessment of generality and stability of claimed results [6]; this means determining the associated dynamical systems properties [7] and attempting yet again to solve the issue of a good measure on this space.

[1] I give just one or two representative references in each case; the vast literature may be accessed via the lanl.arXiv.org e-Print archives at http://xxx.lanl.gov.

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3. Observational analyses that include determining limits both on present-day and past large-scale anisotropies and inhomogeneities (see, e.g., [8, 9]) as well as being open minded about global topology, and including vector modes in observational analyses even if inflation says they are not there—indeed particularly because this is so.
4. Including in these studies inflationary Friedmann models with $k = -1$ as well as $k = +1$, in which cases the scale-free assumption breaks down [10]; this should be done particularly because the $k = 0$ models are of measure zero in the space of Friedmann models, and—contrary to claims made from time to time—are *not* indicated by inflationary theory (the dynamics of inflation is unable to affect the value of k). Also, in particular, carrying out theoretical and observational analyses that test the assumption of almost-flat spatial sections, rather than assuming it.
5. Studies of dynamical nonlinearities of inhomogeneous evolution, including mode mixing (mixing both of scalar, vector and tensor modes, as well as of the different comoving wavelengths within each mode), the back reaction issue [11] (and hence the averaging and fitting problem, see, e.g., [12, 13]), and consistency analyses of the equations and gauges used, preferably as far as possible carried out in a gauge invariant and covariant manner.
6. Perusal of the full spectrum of possibilities for trans-Planckian physics, including non-commutative geometry [14] and loop quantum gravity [15] as well as models motivated by string theory [16].
7. Clarification of the multiverse concept that is increasingly being suggested [17]. How well is it defined? To what degree can it be observationally tested? How are ambiguities due to infinities handled? How unique is it?

The key issue here is that one needs to examine inhomogeneous and anisotropic models in order to adequately model the real universe and to examine stability and probability of cosmological solutions, in particular, determining generic behaviour through phase planes and exact theorems, and observational properties through examining null geodesics in these models. One cannot examine these concepts adequately by exclusively using Friedmann–Lemaître models based on the evolving Robertson–Walker geometries, let alone models with even higher symmetry (such as de Sitter spacetimes)—but that is what is sometimes attempted. These models are of measure zero in the space of all models and there is no reason to believe they demonstrate generic behaviour—indeed, through a variety of counter-examples, we know that they do not do so. Hence use of these models alone to understand cosmology could be misleading because almost all universes—and in particular realistic universe models representing the inhomogeneity of the real universe—would not necessarily behave in this way.

Whatever dynamics precedes the hot-big-bang era, whether or not inflation took place, one eventually runs into the problem of establishing initial conditions for those dynamics. The usual aim is to demonstrate either that these dynamics are probable, or that their probability is irrelevant. High probability is difficult to establish without the proper setting of a well-determined probability measure on the space of generic cosmological models, which is needed to establish stability and fragility of results obtained. For example, the often used idea of 'fine tuning' implies showing that a model is improbable, which implies consideration of the family of all plausible cosmological models, including all geometrical possibilities. However we have no well-established measure of probability on the family of cosmological models. Showing the irrelevance of probability is the aim of a varied family of models, including inflation. It is claimed [2] that no matter how small the probability of inflation starting in this generic geometric setting is, once it has started it will come to dominate because of the explosive nature of inflationary expansion. However, one would like to see how this turned from a reasonably plausible idea into a precise provable statement. The challenge is to devise and prove some theorems that show this idea is in fact correct. A key further point here is the problem of verifying the required dynamics: we do not know that the postulated physics, which is required to make this work, is in fact correct, and it will be very difficult to test it independently. Indeed, it is not even established that general relativity is valid as a theory of gravitational interactions over cosmological distance scales at recent times.

The overall theme of this comment is an advocacy for looking at the full space of possibilities compatible with present-day observations, instead of some pre-chosen subset. This exercise may well just serve to confirm the present standard model but insofar as it does so, the result will be based on much more solid grounds than if we do not carry out those investigations.

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