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What kind of science is cosmology?

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Abstract

In recent years, by theory and observation cosmology has advanced substantially. Parameters of the concordance or ΛCDM cosmological model are given with unprecedented precision ("precision cosmology"). On the other hand, 95% of the matter content of the universe are of an unknown nature. This awkward situation motivates the present attempt to find cosmology's place among the (exact) natural sciences. Due to its epistemic and methodical particularities, e.g., as a mathematized historical science, cosmology occupies a very special place. After going through some of the highlights of cosmological modeling, the conclusion is reached that knowledge provided by cosmological modeling cannot be as explicative and secure as knowledge gained by laboratory physics.

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1 Introduction

In the past two decades, cosmology has taken a promising course. Due to improved and new observational instruments and the observations made with them, a wealth of data has made possible the determination of cosmological parameters with higher precision than ever before ("precision cosmology"). On the theoretical side, the interaction of elementary particle physicists and astrophysicists has provided major contributions to the interpretation of observations. In spite of the progress made, the standard cosmological model, developed into the "concordance model", seems not to be in good shape. With 95% of the matter content of the universe presently being of an unknown nature, can any claim be made that today's cosmological model leads to a better understanding of the universe than the model of two decades ago?

In this situations it may not be contraproductive to inquire about the nature of the discipline. Here, we encounter a common endeavour of mathematics, theoretical physics, astronomy, astro-, nuclear and elementary particle physics with the aim of explaining more than the cosmogonic myths of our forefathers. Has cosmology become a natural science, even a branch of the exact sciences? It certainly is a field of research well established by all social criteria if we follow J. Ziman [1] and define natural science as an *empirical* science steered by public agreement among scientists. In this context, "empirical" means that conclusions are not merely drawn by rational thinking as in the humanities but that they are tested by help of reproducible *quantitative* experiments/observations. Data from these measurements are interpreted by consistent physical theories and receive a preliminary validation to be reconsidered in the light of new facts. Cosmology as a very young scientific discipline has not yet reached the same degree of differentiation as other subfields of physics.[1] Most of what follows will refer to *physical* cosmology on a solid empirical basis and to its subfield named here *originative* cosmology. In the latter, the speculative parts, **necessarily** implied by physical theorizing, are dominant;

[1]This is reflected by the PACS-classification which provides only 7 subclasses for cosmology, 20 for solar physics, and 178 for "solid earth physics".

they are just beginning to be linked to empirical testing or still await probing in the future.[2]

Three periods of extremely unequal duration in the time evolution of the expanding universe will be used for gaining an impression of cosmology. They are: The flashlike "very early universe" of $\Delta t \sim 10^{-12}s$ duration (before the assumed electroweak phase transition); it includes the inflationary era and **prior** Planck-scale modeling (quantum cosmology). Next, the "early universe" (until early structure formation) amounting to $\sim 4\%$ of the total age of the universe $[(13.27 \pm 0.12) \cdot 10^9\ y]$ and covering $\Delta t \sim 4.3 \cdot 10^8$ years; here, nucleosynthesis and the release of cosmic background radiation (CMB) can be found. Finally, the remaining period from structure formation (reionization) until today comprising $\sim 96\%$ of the time. Einstein's theory of gravitation will be the almost exclusive theoretical background adopted here because its implications for physical cosmology have been developed best. In the following, I shall use the words "cosmos" and "universe" as synonyms although they carry different rings; cosmos goes well with order and coherence, while universe implies uniqueness and entirety. Before going into details of cosmological modeling I will try to circumscribe cosmology as a field of research.

2 The content of cosmology

2.1 The universe: a well defined physical system?

Sciences or branches of science are classified by the subject investigated, or by the methods of investigation used. Thus, cosmology could be called "cosmophysics" in parallel with geophysics or solid state physics because its subject is the cosmos. In this spirit, in dictionaries, cosmology is defined as the general science of the universe [2], the science of the physical laws of the universe [3] or, as the Oxford Companion has it: "the study of the entire Universe" ([4], p. 61). A textbook tells us: "In cosmology we try to investigate *the world as a whole* and not to restrict our interest to closed subsystems (laboratory, Earth, solar system etc.)" [5]. The world *as a whole*, though, is not readily accessible, empirically. Whether bootstrap definitions like

[2] An endeavour purporting to belong to physics but without any connection to an empirical background will be called *make-believe* cosmology, cf. section 5.3. This is to function as a reminder that the universe exists not just "on paper" as the philosopher P. Valéry would have it.

the universe is "the largest set of objects (events) to which physical laws can be applied consistently and successfully" [6], or formulations as "the universe means all that exists in a physical sense" ([7], p. 1) are more helpful, is a matter of taste. Once in a while, even a religious flavour is added when the universe is "usually taken to mean the totatility of creation." ([8], p. XV).

In this situation, scientists provide qualifying attributes, and point to subfields of cosmology linked with them [7]): the *observable* universe, the *visible* universe, the *physical* universe, the *astronomical* universe [9], the *astrophysical* universe [10]. Although, at present the *biosphere* is not included in cosmology, by some of these attributes it is not strictly ruled out. In order to be able to do physics, an idealized subsystem of "all that exists" must be selected. A preliminary definition, i.e., "we understand the universe to be the largest presently observable gravitationally interacting system", would satisfy the needs of the practizing cosmologist.[3] From the point of view of epistemology, such a definition is hardly acceptable, though. The observable universe changes permanently, because the domain of nature observable to us depends on the power of the available measuring instruments. Consequently, a further definition of the "observable universe" reads as "what in principle we can observe" ([4], p. 314). Cautious authors have avoided the word "universe" altogether in favor of expressions like "the metagalaxy" [11], "distribution of matter on the largest scale" [12], or "structure on a large scale" (cf. [7]).

In spite of this situation, most cosmologists seem not to worry about the domain of application of their theories: in the wake of time they expect to find out. They take it for granted that the physical system "universe" is as meaningful as the *alterable* and *touchable* physical systems investigated in the laboratory.[4] Possibly, the cosmos is definable only in the sense of a mathematical limit process. Or, as an ontological construct: "the largest inextendible entity". Progress of research seems not to be hampered by this attitude.[5] In comparison, the concept of elementary particle is accepted in the sense of the smallest indivisible entity. At first, it should have been the atom, then the nucleus

[3]Gravitation is the dominant interaction on the largest scales. On smaller scales, all other interactions come into play.

[4]Untouchable physical systems as the Sun, a star, a galaxy exert direct sensorial reactions on us. The universe does not.

[5]In this spirit, in recent monographs the physical system "universe" remains undefined (cf. [13]).

and, presently, it is the quark - with no end of further subdivisions in sight. An approximative definition of the universe as a physical system may well be the only one allowed to physicists; however, there is the danger that the epistemological background gets out of sight. In fact, particularly in quantum cosmology and in approaches related to string theory, the universe is treated as an entity resembling more a particle among other particles than the totality of gravitationally interacting masses on the largest scale (Cf. also sections 2.1.1 and 5.3). In a way, methodologically, cosmophysics is *opposite* to phenomenological thermodynamics. There, valid laws are formulated without the need of knowing the detailed microscopical structure of matter. In cosmophysics, until recently (dark energy!) we were dealing with the detailed knowledge of structured parts of a system unknown in its totality.

If cosmology were just a branch of *applied mathematics* we could *define* it as the study of the global properties of "cosmological solutions" of certain field equations, notably Einstein's (cf. [14]). We would then include singularities (e.g., at the big bang) as boundary points of the Riemannian manifold representing the universe. However, the qualification of an exact solution as a model for the cosmos still would have to be made by borrowing ideas from physics; for example, by the kind of isometry group to be assumed. Possibly then, homogeneous and isotropic cosmological models with *compact* space sections of *negative* curvature would have to be discarded because they admit only a 3-parameter isometry group, globally [17].[6] The cosmological models of applied mathematics which, by careless use of language sometimes were called "cosmologies" ([22], [23], [24]) or "universes" ([25], [26]), need not have any relation to the world outside of our brains. This point is not a side issue: in the "multiverse scenario" no distinction is made between what is a mental construct and what, by its relation to empirical data, can be accepted as some kind of "reality" external to our mind, cf. section 5.3.

2.1.1 A mathematized historical science?

With astronomy, cosmological research shares the situation that its object, the universe, or parts of it of cosmic relevance, have to be observed at a space-time distance, measured on and inside the *past*

[6] Cf. also, cosmological models with multiply connected space sections ([18], [19], [20], [21]

lightcone from a tiny part of the Earth's (or the solar-system's) worldline. Experiments cannot be carried out for observing effects. Observational cosmology may be compared to geological, palaeontological or archeological field work: deeper and deeper strata of the past are excavated, with the difference to palaeontology and archeology being that the present state of the objects observed is unknown. Cosmological theory does not describe a museum of relics but a dynamical system. Also, for cosmology, better mathematical models exist.

This historical aspect is not the full story, but it shows up in many ways; one of them being the transformation of the concept "prediction". In cosmology, without exception, prediction is a conclusion from present observations to *past* times or, vice versa, after hypothetical input for past times, to consequences for the *present*. In slightly altering a statement of Friedrich Schlegel (who directed it toward historians): cosmologists are prophets for the past. In physics proper, prediction means the foretelling of a *future* state from conditions given *now*. The social usefulness of natural science (and technology) rests on this regular meaning of prediction. Certainly, cosmological models can be used to make exact *calculations* toward the future [27], [28]. For cosmological time scales these calculations are pointless, however, because they cannot be validated by observational tests: Will any of them be preserved for a test in $\sim 10^6$ years? Even if cosmological theory could provide us with a reliable description of the past, its validity for the future cannot be probed; it is a consequence of continuity assumptions for the mathematical equations of theoretical cosmology. If the precision of, say, spectroscopic measurements could be increased to the extent that the changes in redshift of distant objects can be monitored over a time-span within our lifetime, then extrapolations applicable to the motion of the objects, for the *near* future only, will become possible. In "make-believe cosmology", the "ultimate fate of the Universe" is broadly discussed with future events timed with little reservation (cf. 5.3).

A sober physical and philosophical assessment of a "lack of predictability in the real universe" is given by ([29], p. 61).

Nowadays, the word "prediction" is used by most physicists working in cosmology as meaning "a consequence of" without any implication of linking the present to the future. This can become rather quixotic as in: "[..], a fundamental discreteness of spacetime at the Planck scale of 10^{-33} cm seems to be a prediction of the theory [..]."

2.1.2 Other features peculiar to cosmology

A characteristic feature of the universe, once believed to be important, is its *uniqueness*: one and only one such physical system ("the world as a whole") can be thought of as given to us. Unfortunately, with the advent of quantum cosmology and superstring theory, a semantical erosion of the word "universe" has begun. Already two decades ago, we had been asked "How many universes are there?", when authors investigated "a dilute gas of universes" or a "single parent universe ... in a plasma of baby universes" [30]. We were approached to "suppose universes are emitted from $t = 0$ like photons from an antenna" [31]. At the time, it remained a miracle, though, what kind of tangible receptacle could house or receive multiple universes. By now, this problem seemingly has been fixed by the introduction of the concept "multiverse" (Cf. section 5.3).

If the uniqueness of the universe is accepted, why then is this system so special? Isn't the Earth unique, too? True, as far as its *individuality* is concerned. But the Earth is just one of the planets in the solar system and one of billions more conjectured around other stars (exoplanets).[7] It gets its individuality *by comparison* with other planets. In contradistinction, is there an empirical or a conceptual way of comparing "our" universe to "others"?[8] In speculations of past years, statistical methods were applied to a set of "universes" residing in the mind in order to get a handle on the values of fundamental constants of nature [32].

As a consequence of the uniqueness of the universe, *specific cosmic laws cannot obtain* [33]. It is not excluded that new physical laws will be discovered while we try to scientifically describe the cosmos. Such laws, however, will refer to properties of parts (subsystems) of the universe and to relations among them.

Can theories applying to a single object be falsified? The example of the *steady-state* cosmological model seems to show that falsification is possible for statements of cosmological theory, because observations made now are observations of past states of the universe. Yet, as the complex attempt at a revival of the steady-state model shows [34], some caution is in order. This, again, indicates that cosmology could

[7] The search for exoplanets with parameters close to those of the Earth may form a link to the biosphere.

[8] Of course, *cosmological models* can be compared with each other - on paper, though.

be interpreted as kind of a mathematized *historical* science: with falsification meaning nothing more than that our interpretation of the historical record has been mistaken and must be revised.

2.1.3 Initial conditions

The Einstein-field equations for the cosmological model being *hyperbolic* partial differential equations, a *Cauchy initial value problem* with given initial data must be solved in order that we may arrive at a unique solution. An additional chain of argumentation or even a theory must be developed by which the initial data actually in effect for the universe as we observe it are picked out from among the imagined set of all possible initial data. Thus *cosmogony*, the theory of what brought the cosmos into being, and cosmology are inseparable [9]. The rise of quantum cosmology indicates an attempt of bringing cosmogony into the reach of science (Cf. 5.2).

Already within classical theory, attempts had been made to understand homogeneity and isotropy near the big bang [37], [38]. R. Penrose suggested to assume homogeneity of space - corresponding to a low value of entropy - as an initial condition. He tentatively used the Weyl tensor as a measure of the entropy and required it to vanish at singularities in the past [39], [40], ([41], p. 344). Moreover, in this context, various *anthropic principles* ([42], [43] have been invoked since their first formulation, and are used even heavier, today.[10] In fact, within make-believe cosmology, the search for a rationale for the initial data required for the universe to be as it appears to be, seems to be a main motivation.

As an aside: a related question is whether observation of the physical system "universe" will permit, in principle, a reconstruction of its initial state. Even for as simple a system as the solar system such a task is rather difficult. From what can be learned from deterministic chaos and, in view of the possibility that the Einstein field equations need not be an ever-lasting foundation of cosmophysics, particularly

[9] The assumption of temporal closedness of the universe is one escape route in sight. With its painful consequences for causality and pre-(retro-) dictability, the idea has not yet been taken seriously. The idea of a cyclic universe with multiple beginnings and ends also has been proposed since antiquity. For recents proponents with very different suggestions, cf. [35], [36].

[10] The debate is still going on whether anthropic principles are useful as a selection principle with an exploratory value, or just express a demand for self-consistency of the cosmological model.

for what happened right after the big bang, we should remain reserved in this matter. Fortunately, for the standard cosmological model, initial data for the very beginning of the universe (at the big bang) are *not* needed. Nevertheless, initial data are required at the beginning of the inflationary phase. These may be guessed and validated in the sense of being consistent with what is derived theoretically and then observed (cf. 4.2).

The fact that we need initial, not final conditions reflects the open problem of the *arrow of time*: how to derive the unidirection of time when the basic equations are time-symmetric? Is it linked to the "collapse of the quantum wave function"? ([29], p. 76; cf. however [44].)

2.2 Cosmological questionaire

With the beginning of research in cosmology a list of general questions arose:
- Is *space* (defined by the distance range between gravitating bodies) of finite or infinite extension? [11]
- Is *time* (defined by the duration of certain systems as compared to others) of finite or infinite duration in the future, in the past?
- How does cosmic dynamics look (phases of accelerated and/or decelerated expansion, structure formation, etc.)?
- What is the matter content of the universe? In the form of baryons, of radiation (zero mass particles), of dark matter? What is dark matter made from?
- Is a non-vanishing cosmological constant needed?

If the system were finite in space and in past time, we might ask for the *total* mass (energy), angular momentum, electric charge, etc and the *age of the universe*. The last concept is reasonable only if all parts of the cosmos can be parametrized by one single time parameter. In case there is a dynamics, the initial state of the universe and its evolution in time are of interest. Numerous further questions will arise within the three pieces of cosmological modeling to be briefly discussed below. Some believe that, by the presently accepted cosmological model (ΛCDM), many of these questions have been brought nearer to an answer (Cf. section 3.3).

[11] The property of being infinite refers to the mathematical model. It has no observational meaning.

3 Cosmological modeling

3.1 General hypotheses

As far as the universe is traced by its large scale mass structures (galaxies, clusters of galaxies, superstructures), the questions asked in observational cosmology are concerned with the angular and in-depth distribution of such structures, their material content, the occurence of chemical elements, the origin of particular objects, as e.g., quasars, or galactic nuclei, the strength and time-evolution of magnetic and radiation fields, etc. In this respect, the highly isotropic microwave background (CMB), a Planck-distribution to temperature $\sim 2.7K$, interpreted to be of cosmological significance, is a very important characteristic. From the observations, properties will be ascribed to the universe serving as entries for cosmological model building.

As main result, a *compatibility* with observations of cosmological significance had been found: the *expansion of the universe* (redshift), the *isotropy of the slices of equal time* (CMB), and the "cosmic" abundance of light chemical elements. Isotropy does not refer to the position of the earth, the solar system or the Galaxy but to an imagined rest system defined by CMB itself. Nucleosynthesis calculations lead to a value for the average matter (baryon) density of the universe *consistent* with what is observed, directly, from luminous masses and, indirectly, through dynamical effects in galaxies and clusters of galaxies depending also on dark matter.

Before a *quantitative* description of the universe can be attempted, a particular cosmological model, i.e., a metric representing the gravitational potentials, and a description of its material sources, must be given. In order to reach a unique model, a number of simplifying assumptions usually is made. The historical and epistemological background is provided by what often is called the *Copernican Principle*: "The Earth does not occupy a prefered position in the universe." Expressed differently, some kind of *homogeneity* of space is demanded. Mathematically, this is expressed by requiring a transitive group of quasi-translations (isometries) to act on spacelike hypersurfaces. This still leaves a sizable number of cosmological models (cf. [45], particularly secs. 12.3, 12.4, and 15.3). Also, the Copernican principle is *untestable* as long as we cannot observe the universe, say, from another galaxy. It can be tested only along our past lightcone by the counting of sources as a function of redshift. By transforming redshifts (look-back times) into spatial distances, homogeneity of space then may be infered. However, the calculation already must involve a cosmological model.

In order to further reduce the number of cosmological models, the Copernican Principle is replaced by the *Cosmological Principle*: "The universe must be homogeneous and isotropic." Isotropy means that the rotation group acting on spacelike hypersurfaces is also a symmetry group. This principle leads to a unique class of cosmological models (FLRW, cf. section 3.2). It likewise is not testable from our vantage point in the universe.[12]

From the point of view of what is observed (large scale galaxy structure, cosmological background radiation (CMB)), the Cosmological Principle can lead merely to an approximate description of the universe. A large fraction of cosmologists starts with the Cosmological Principle and accounts for the inhomogeneities of the matter distribution and the minuscule anisotropies in CMB by superimposing them onto the model via perturbation calculations. Other cosmologists first apply an averaging over space volumes to the Einstein equations in order to take account of inhomogeneities. Time derivation and averaging over space do not commute. The procedure is called backreaction (of the inhomogenities) and leads to additional terms in the usual (Friedman-) equations for the homogeneous and isotropic model. For applications and a recent review cf. [48]), [49]. Still other researchers directly start from exact inhomogeneous and isotropic solutions of Einstein's equations (collected e.g., in [46]) and try to fit them to the observations. Suggestions also have been made for using the Cosmological Principle only as an initial condition for the development of the Universe [50], or for interpreting it in an average sense ("statistical cosmological principle" [51]).

In the following, we list a few assumptions necessarily leading to a homogeneous and isotropic cosmological model. These assumptions should be testable by their consequences. With better data, they could be relaxed as well.

- A_1 The physical laws, in the form in which they are valid here and now, are valid A) everywhere, and B) for all times for which the

[12] Homogeneity follows if the universe is isotropic around more than one point in a spacelike hypersurface, cf. [47]. It is surprising that authors think that "homogeneity on large scales *is* an extremely strong prediction of ΛCDM" ([69], p. 2) whereas this homogeneity is built into the ΛCDM-model as one of its fundamental assumptions.

cosmological model is expected to be valid. Otherwise, it would be impossible to uniquely interpret observations. In theory, it would make no sense to apply the standard model of elementary particles or Einstein's theory of gravitation to the early universe. A_1 can also express the hope that local and global physics (of the universe) are *not* inextricably interwoven: "physics on a small scale determines physics on large scale" [59]. The opposite view that "the physical laws, as we usually state them, already involve the universe as a whole" gets only a minority vote [60].

- A_2 The values ascribed to the fundamental constants here and now are the same everywhere and at all times.

When speaking about fundamental constants, we naively think of quantities like c (velocity of light), h (Planck's constant), k_B (Boltzmann constant), e (elementary charge), G (gravitational constant), or of dimensionless combinations of them. In order that the atomic spectra from distant objects can be interpreted, the fine structure constant must be assumed to be the same as in the laboratory. For a proper interpretation of gravitational lensing, the gravitational constant must be assumed to be the same as in the planetary system. Then, by observation, bounds for an eventual change in the fundamental constants can be obtained, in principle. Of course, it is the underlying theories which define these quantities to be constant or time-dependent: In scalar-tensor gravitational theory, the gravitational "constant" would be time-dependent by definition. For cosmological modeling in the framework of general relativity, A_2 is to apply for epochs since, and perhaps including, the inflationary phase. In elementary particle physics, for higher energies fundamental constants depend on the renormalization scale. This seems not yet to play a role for the present cosmological model. Nevertheless, effects of a running cosmological and gravitational constant on the evolution of the universe were studied in [52].

- A_3 The universe is connected (in the mathematical sense).

As we know from the occurence of horizons, A_3 cannot be sharpened to the demand that communication is possible between any two arbitrarily chosen events in the universe.

- A_4 In a continuum model, the material substrate of the universe

(including dark matter) is described by a mixture of *ideal* fluids - not *viscous* fluids.
- A_5 The material substrate of the universe evolves in time as a *laminar* flow - not a turbulent one.
The assumption of an ideal fluid without shear and rotation of the streamlines as expressed by A_4, A_5 uniquely leads to the FLWR-class of cosmological models. In A_4, an ideal fluid is characterized by the equation of state $p = w\ \rho$ with a constant $1 > w > 0$. [13] In fact, as an addition to the current standard cosmological model, effects of viscosity and turbulence in the course of the evolution of large-scale structures are being investigated (perturbation theory), e.g., in connection with dark matter, or dark energy, and magnetic fields of cosmological relevance, etc.

A_5 also expresses the possibility of a slicing of space-time into hypersurfaces of constant time. A fundamental hypothesis going into the standard model is the concept of a cosmic time *common* to all parts of the universe. In some cosmological models as, for example, in Gödel's, the local spaces of simultaneity are not integrable to one and only one 3-space of "simultaneous being". (Cf. section 3.5.)

3.1.1 Primordial Nucleosynthesis

Primordial nucleosynthesis is considered to form one of the pillars of the standard cosmological model. Nucleosynthesis for the light elements d, ^3He, ^7Li, except for ^4He, depends sensitively on a single parameter of cosmological relevance entering: the ratio $\eta = n_B/n_\gamma$ of the number of baryons to the number of photons in the universe. n_γ can be calculated from the microwave background. The decisive nuclear physics parameter is the neutron's lifetime. Because the production of ^4He depends on the number of existing neutrino families, it is possible to obtain an estimate consistent with what has been found with the largest particle acclerators [72]. Nevertheless, a recent measurement of the ^{4}He abundance "implies the existence of deviations from standart big bang nucleosynthesis" [53].

As to the comparison with observations, except for ^4He, for nine reliable determinations of ^3He from high redshift quasistellar sources,

[13] Here, p is the pressure and ρ the energy density of the ideal fluid. Both, the constancy of w and the range of values allowed will be relaxed.

and for seven reliable determinations of deuterium at high redshifts and low metallicity, the *observed* distribution of the light elements comes from measurements within the solar system and the Galaxy. The uncertainties are in the range of 0.2% for ^4He, $5-10\%$ for d, ^3He and 15% for ^7Li [56], [57]. There also remains an unexplained difference between the observed and the theoretically calculated values for the abundance of ^7Li. From these data a 5% determination of the baryon density is obtained [57]. There are also observations of the chemical abundance in very old stars [58], but their cosmological relevance is not yet clear. In addition to the restricted observation-volume, the empirical basis for the abundance of chemical elements thus is less secure than one might wish it to be. The comparison of calculated and observed abundances depends highly on astrophysical theory (models for the chemical evolution of galaxies and stars).

3.1.2 Empirical situation with regard to A_2

All we can safely claim today, with respect to A_1 and A_2, is that they are not in conflict with the empirical data. Reliable such data about a time dependence of the fundamental constants are still lacking, although much progress has been made. For the quantity looked at most often, i. e., $\dot{G}/G$, bounds between $|\dot{G}/G| \leq 10^{-10}\ y^{-1}$ and $|\dot{G}/G| \leq 10^{-13}\ y^{-1}$ have been derived from various investigations (solar system, radar and laser ranging to moon/satellites, astroseismology, binary pulsar, big bang nucleosynthesis, Ia supernovae). Cf. the review by García-Berro et al. ([54], p. 139-157). Most of the estimates are dependent on the cosmological model. Also, they suffer from short observation spans: measurements in the solar system cover the past 200 - 300 years [55]. At best, the observation time could be extended to $\sim 10^9$ y, i.e., the lifetime of the solar system. Only then would this be comparable to Hubble time $t_0 = \frac{1}{H_0} \simeq 9,77\frac{1}{h} \times 10^9 y$, with $H_0 = 100\ h\ kms^{-1}(Mpc)^{-1}$, the Hubble constant measuring present expansion.[14] The situation is not better for the estimates on $\dot{G}/G$ made from primordial nucleosynthesis (PN) giving a value for the ratio of $\frac{G_{PN}}{G_0} = 0.91 \pm 0.07$ taken at the time of big bang nucleosynthesis and at present. For CMB $\frac{G_{CMB}}{G_0} = 0.99 \pm 0.12$, i.e., since $\sim 3\ 10^5$

[14]The Hubble constant is the present value of the Hubble parameter $H(t) := \frac{\dot{a}}{a}$ where $a(t)$ is the scale function of the homogeneous and isotropic universe model. The dot means time derivation.

years. [57].

As to the determination of upper bounds for the fine structure constant α, constraints coming from terrestrial (Oklo natural reactor), high-redshift quasar absorption systems, big bang nucleosynthesis, and the angular spectrum of cosmic background radiation "do not provide any evidence for a variation of α" (cf. [54], p. 139). Typical results are $\frac{\Delta\alpha}{\alpha} = (-0.3 \pm 2.0) \times 10^{-15}\ y^{-1}$ (laboratory), $\frac{\Delta\alpha}{\alpha} = (0.05 \pm 0.24) \times 10^{-5}$ (quasars at $z = 1.508$)), and $\frac{\Delta\alpha}{\alpha} = (-0.054 \pm 0.09724)$ (CMB at $z \simeq 10^3$). Another interesting target has been the ratio of proton and electron mass $\mu = \frac{m_p}{m_e}$. A typical bound is $|\frac{\Delta\mu}{\mu}| = (-5.7 \pm 3.8) \times 10^{-5}$ for redshifts of $z = 2.377$ and $z = 3.0249$, respectively. (cf. [54], p. 159).

The time-independence of the fundamental constants which is particularly important in the inflationary phase, is not directly testable during this period.

3.1.3 Cosmological observation

In addition to fundamental suppositions for *theoretical* modeling, hypotheses for the gaining of data and the empirical testing of cosmological models are necessary. Such are, for example:
- B_1 The volume (spatial, angular) covered by present observation is a *typical* volume of the universe.
The application of B_1 may become problematic because of the occurence of *horizons* in many of the cosmological models used. There may be parts of the universe not yet observable (*particle* horizons) or parts which, in principle, cannot be oberserved from our position.
An example for observations n o t satisfying B_1 is formed by the sample used for gaining and calibrating spectra of Ia supernovae [61].

- B_2 Observation time is long enough in order to guarantee reliable data of cosmological relevance.

- B_3 Ambiguities in observation and theoretical interpretation (selection effects) are identified and taken into account by bias parameters.

An example for a bias parameter $b(z,k)$ is given by the expression for the observable galaxy overdensity δ_g as a measure of the underlying (average) matter density δ_m: $\delta_g = b(z,k)\ \delta_m$ ([62], eq. (3)). It is unclear whether these demands on observation are satisfied, at present. In particular, selection bias concerning luminous objects may be underestimated ([64], p. 321).

But it is in observation that tremendous progress has been made in the past two decades. 3-dimensional redshift surveys of galaxies[15] have been much extended. In particular, this was done by the 2dF galaxy redshift survey (combined with the 2QZ quasar redshift survey) (2003): patches of 2×2 degrees have been probed and 221414 galaxies (23424 quasars) measured out to $4 \cdot 10^9$ lightyears (up to $z = 0.22$) (2QZ: two 5×75 degree stripes both in the northern and southern sky) (http://www2.aao.gov.au/2dFGRS). Most impressive is the Sloan digital sky survey [65], [66]: it comprises $\sim 10^6$ galaxies, with the subsample of luminous red galaxies at a mean redshift $z = 0.35$ and 19 quasars at redshifts $z \geq 5.7$ up to $z = 6.42$ (http://www.sdss.org). Cf. also the "Union Sample" of Ia supernovae containing 57 objects with redshifts $0.015 < z < 0.15$, and 250 objects with high redshift [67]. In view of an assumed total of $\sim 10^{11}$ galaxies in the universe and the fact that angular position surveys extend only to depths of a fraction of the Hubble length, one cannot say that these surveys are exhaustive. Moreover, in view of the fact that estimates of the mass-luminosity ratio lead to $\Omega_{lum} \simeq 0.005$ for the relative density of luminous matter, the cosmological relevance of the galaxy surveys is questionable; they may amount only to a consistency check. The scale of homogeneity for which averaging of the observed large structures (superclusters, voids) is reasonable, has steadily increased in the past and could grow further, in the future. At present, the size of the Great Wall, i.e., $\simeq 400\ Mpc$ seems to point to a homogeneity scale of $\geq 100\ Mpc$ [68]. The surveys described have been used to test homogeneity, e.g., by counts of luminous sources in a redshift range of $0.2 < z < 0.36$, albeit with distance calculations within the homogeneous and isotropic ΛCDM-model [69].

Isotropy with respect to our observing position also has been put to a test; a statistically significant violation of isotropy for Ia supernovae at redshift $z < 0.2$ and refering to deviation in the Hubble diagram (Northern and Southern Hemispheres) has been found [70]. Problems related to observations were investigated carefully by G. F. R. Ellis [71], [7].

[15] redshift $z = \frac{\lambda' - \lambda}{\lambda}$ directly relates to distance D; for small distances, $z = H_0 D$.

3.2 More on the standard cosmological model

In the standard model, the gravitational field and space-time are described by a (pseudo-)Riemannian manifold with a homogeneous and isotropic Lorentz metric. It is an expression of the Cosmological Principle, which alternatively can be formulated as (cf. section 3.1): "No matter particle (of the averaged out ideal cosmic matter) has a prefered position or moves in a prefered direction in the universe". Consequently, the space sections of the spacetime manifold describing the universe are homogeneous and isotropic in the sense of an average (on the largest scales) over the observed matter distribution. The cosmological metric (gravitational potentials) is given by a Friedman-Lemaitre-Robertson-Walker solution (FLRW) of Einstein's field equations - with or without cosmological constant. The metric depends on a single free function $a(t)$ of cosmic time and allows for a choice among three space sections with *constant* 3-curvature ($k = 0, \ +1, \ -1$). The parameter k is related to the critical energy density $\rho_c = \frac{3c^4 \ H_0^2}{8\pi G}$ such that $k = 0$ for $\rho = \rho_c$; $k > 0$ for $\rho > \rho_c$ and $k < 0$ for $\rho < \rho_c$. This follows from the Friedman equations. When formulated with dimensionless (energy-) density parameters $\Omega_x := \frac{\rho_x}{\rho_c}$, where the index x stands for c (critical-), d (dark-), b (baryonic-), t (total matter), respectively, and $\rho_\Lambda = \frac{\Lambda c^4}{8\pi G}$, $\rho_k = \frac{kc^4}{8\pi G a(t)^2}$, one of the two Friedman equations reads (trivially, $\Omega_c = 1$):

$$1 = \Omega_t + \Omega_\Lambda + \Omega_k \tag{1}$$

with $\Omega_t = \Omega_b + \Omega_d + \Omega_{radiation}$. Due to its smallness, we mostly will neglect $\Omega_{radiation} = \Omega_\gamma(1 + 0.2271 N_{eff})$ with Ω_γ the photon density and N_{eff} the (effective) number of neutrino species ([84], p. 335).

The space sections for $k = +1$ are compact; those for $k = 0, -1$ usally are called "open" as if they could have only infinite volume. This misconception is perpetuated in otherwise excellent presentations of cosmology; in contradistinction, a sizeable number of space forms of negative curvature with finite volume were known to mathematicians since many years (cf. [20], [73], p. 405). This is important because different topologies can be consistent with the WMAP-data [74].

The lumpiness of matter in the form of galaxies, clusters of galaxies, and superstructures is played down in favour of a continuum model of smeared out freely falling matter like in an ideal gas. Its particles follow timelike (or lightlike) geodesics of the FLRW-metric. Inhomogeneity then is reintroduced through linear perturbation theory on this idealized background. In two stages in the history of the universe, both with power-law expansion, the equation of state considered above refer to pressureless matter (baryon dominated universe) and to radiation where $p = 1/3\ \rho$ (radiation dominated universe).[16] At present, a general equation of state $p = w\rho$, with w being allowed to be negative, is deemed necessary because the cosmological constant may be simulated by $p = -\rho$.

Moreover, from observations alone, it seems unclear whether it is possible to discriminate, in our neighborhood, between a Friedman model and spatially inhomogeneous models centered around our position and resembling a Friedman model (Lemaître-Tolman-Bondi- or Stephani exact solutions). For a review cf. section 2.3 of [76]. Also, a metric combining the FLRW-model and "a perturbed Newtonian setting" has been used to approximately describe features of both the local universe and its large-scale structure [77].

The FLRW-metric describing the cosmological model does not care whether its primordial states are warm or cold. Only when the vanishing of the divergence of the energy-momentum tensor of matter is interpreted as describing the first law of non-relativistic thermodynamics, the expansion of the universe can be seen as an *adiabatic* process, with the ensuing decline of temperature following the expansion of space. In consequence, it is possible to interpret the microwave background as a relic of an early, hot state of the universe. On the other hand, adiabaticity is violated at the end of the inflationary period where particles and heat are generated. From local physical processes we expect the entropy of the universe to grow with the expansion (deviation from homogeneity). In principle, statistical mechanics (kinetic theory) is the only way for defining properly the concepts of temperature and entropy of the universe: no "external" heat bath is available. Whether they make sense depends on the existence of an unambiguous procedure for coarse graining in phase space. For the entropy concept, cf. the point of view of a strong supporter ([35], section 27).

Mathematically, the most important consequence of the FLRW-models is that they show the occurence of infinite density - as well as a metrical *singularity* appearing in the *finite* past: the famous big bang. By mathematical theorems of Penrose and Hawking [14], singularities receive

[16] At redshift $z \sim 3600$, the period of matter domination follows the radiation-dominated one; decoupling of photons is set at $z \sim 1100$. For a detailed discussion of the standard model and the early universe cf. [75] or [13].

a *generic* geometric significance within cosmological model building. Their physical aspects were studied by Belinskii & Khalatnikov ([15], [16]). From the point of view of observational cosmology, the infinities connected with the big bang cannot and need not be taken seriously.

We have seen in section 2.1.1 that the "predictive" power of the standard cosmological model is nothing more than an expression of self-consistency. By use of the cosmological model, from the temperature at one *past* time, e.g., at the decoupling of radiation and matter T_{dec}, the present background photon temperature would be calculated to be $T_{phot}(0) = \frac{T_{dec}}{1+z}$ and the baryon temperature $T_{bary}(0) = \frac{T_{dec}}{(1+z)^2}$. The temperature of the neutrino background then is fixed. The consistency problem comes up because T_{dec} can be calculated via the Saha equation which includes $\eta = n_B/n_\gamma$, a number which can be read off from the CMB. Of course, this single chain of arguments is supported consistently by others; e.g., the fluctuations in mass density at decoupling must be such that their growth (gravitational instability) until now is consistent with the observed relative anisotropies of 10^{-5} in the otherwise isotropic CMB etc. As in other parts of physics, there is a net of theoretical conclusions relating empirical data and theory.

The standard cosmological model faced the task of getting away from the homogeneity and isotropy of the averaged out large scale matter content in order to arrive at an explanation of the large scale structures consistent with the required time periods. The hypothesis of primordial adiabatic Gaußian density fluctuations with a nearly scale-invariant spectrum together with various competing scenarios as *cold* or *hot dark matter* (in the form of weakly interacting particles), *cold baryon matter*, cosmic string perturbations, local explosions etc, for some years had not been consistent with the full range of extragalactic phenomena [78], [79], [80]. By now, this debate seems to be ended: the cold dark matter scenario is accepted.

3.3 The concordance model of the universe (ΛCDM)

Due to the observations pointing to an *accelerated* expansion[17] of the universe in the present era, and due to much progress in astrophysical structure formation theory, the standard cosmological model of the early 90s took the following turn: (1) In structure formation,

[17] The so-called *deceleration* parameter is defined by $q = -\frac{a\ddot{a}}{\dot{a}^2}$. Negative q means acceleration.

cold dark matter, i.e., non-relativistic particles subject to gravity, and able to contribute to the growth of matter inhomogeneities (against radiation drag) better than and before baryons can do so, came to play a decisive role; (2) the space sections of the FLRW cosmological model were assumed to be flat ($k = 0$); (3) the cosmological constant $\Lambda \neq 0$ mimicking a constant energy density became re-installed. A consequence was that due to $\Omega_k = 0$ in the Friedman equation (1): $\Omega_t + \Omega_\Lambda = 1$. Because Ω_t contains both, baryonic and dark matter, and due to $\Omega_m = \Omega_b + \Omega_d \simeq 0.25$, a missing mass $\Omega_\Lambda \simeq 0.75$ resulted, named "dark energy" [81]. This naming occured due to the original interpretation of the cosmological constant as a representation of "vaccum energy" in the sense of the energy of fluctuations of quantum fields (cf. the end of 3.5).

Observation of the luminous-galaxy large-scale-structure also showing baryonic acoustic oscillations (BAO), of the temperature anisotropies of the cosmic backgound radiation (CMB) as well as the determination of the value of the Hubble constant, and the age of the universe, all have been used to support the ΛCDM model. In particular, CMB measurements by the WMAP (Wilkinson Microwave Anisotropy Probe)-satellite as reflected in the acoustic peaks from baryonic and dark matter give information on ([82], table 7, p. 45):

- the geometry of space sections ($\rightarrow$ k small, $-0.0179 < \Omega_k < 0.0081$);
- matter energy density $\Omega_m = \Omega_b + \Omega_d \sim 0.258 \pm 0.03$;
- vacuum energy density $\Omega_\Lambda \sim 0.726 \pm 0.015$;
- baryon density $\Omega_b \sim 0.0456 \pm 0.0015$;

as well as about further cosmological parameters:

- cold dark matter density $\Omega_d = 0.228 \pm 0.013$;
- tilt $n = 0.960 \pm 0.013$ of the initial power spectrum $P_{initial} \sim \bar{k}^n$ where $\bar{k}$ is the wave number of the initial fluctuations, [18]
- the Hubble constant $H_0 = 70.5 \pm 1.3\ kms^{-1}(Mpc)^{-1}$.

All these results are based on the CDM model for structure formation. Two further numbers w_0, w_z parametrize a generalized equation of state $p = w(z)\rho$, with $w(z) = w_0 + \frac{z}{1+z} w_z$ being allowed to become redshift-dependent [83]. A "minimal" parameter base of the ΛCDM model is given by $\Omega_m, \Omega_c, \Omega_\Lambda, \tau, \Delta^2_{\mathcal{R}}, n$ where $\tau = 0.084 \pm 0.016$ is the optical depth due to reionization (electron scattering) [84]. A

[18] In fact, the amplitude of curvature fluctuations is defined by $\Delta_{\mathcal{R}}(\bar{k})^2 := \Delta_{\mathcal{R}}(\bar{k_0})^2 (\frac{\bar{k}}{\bar{k_0}})^{n(\bar{k_0}) - 1 + \frac{1}{2} \frac{dn}{dln(k)}}$ if n is allowed to vary. $\bar{k}_0 = 0.002\ Mpc^{-1}$.

7-parameter model with $\Omega_m, \Omega_b, \Omega_d, w_0, w_a, h, n$ is considered in [62]. The errors in Ω_d, Ω_b, and the Hubble constant are claimed to be 3% ([82], p. 2-3). From WMAP, the baryon accoustic peaks and supernovae, a bound on the summed neutrino masses m_ν (of the standard model of elementary particles) has been deduced: $\Sigma m_\nu \leq 0.62\ eV$ [63]. Eventually, this will be confronted with precise measurements of the neutrino masses on Earth.

3.4 Matter content of unknown origin

3.4.1 Dark matter

From observation of the bulk motion of galaxies and clusters of galaxies in the past 65 years, it is known that more mass than that of the luminous objects must be present. This is needed for an understanding of the dynamics of such objects, for galaxy formation, and for the interpretation of the results of weak gravitational lensing from clusters of galaxies. The mass is missing in and around galaxies (halos). For a review cf. [86]. As we know from section 3.3, baryons, mostly in the form of gas, contribute to only ca. 4%-5% of the relative critical density $\Omega_c = 1$ ([4], p. 90). Besides being required to provide an enhancement of gravity, dark matter is assumed to be "non-interacting", i.e., pressureless, otherwise. Computer simulations like the Aquarius Project [87] or MS-II have excellently taken into account and reproduced dark matter: "from halos similar to those hosting Local Group dwarf spheroidal galaxies to halos corresponding to the richest galaxy clusters" ([88], abstract).

For a tentative explanation of dark matter either new cold (i. e., non-relativistic) particles (WIMPs,[19] axions, neutralinos or other light supersymmetric particles, primordial black holes), as well as Q-balls, and other unobserved exotic objects were suggested. The composition of dark matter particles is closely bound to baryogenesis [89]. Eventually, dark matter particles must be found in accelerator-experiments, and their masses measured, in order that their existence be more than speculative. Alternatively, new theories of gravitation have been suggested removing the need for dark matter, as are Modified Newtonian Dynamics (MOND) (cf. [92], Scalar-vector-tensor-gravity (STVG) [93], translational gauge theory [94], [95], etc. Up to now, none of the particles invoked were seen, and none of the alternative theories were

[19]Weakly interacting particles.

able to replace Newtonian theory in all aspects. From the modeling of galaxy formation, hot dark matter in the form of neutrinos seems to be excluded.

3.4.2 Dark energy

Since about a decade, observation of the luminosity-redshift relation of type Ia supernovae has been interpreted as pointing to an *accelerated* expansion of the cosmos [96], [97]. The simplest explanation is provided by a non-vanishing cosmological constant Λ within the standard cosmological model. In this case, dark energy would be distributed evenly everywhere in the cosmos. It apparently has not played a significant role at early times although reliable knowledge beyond $z = 1$ is not available ([102], p. 8).

Besides the cosmological constant, tentative dynamical explanations have been given for cosmic acceleration. There, the main divide is between those keeping Einstein gravity or proposing alternative theories. In the first group, we find, on the matter side,

- a new scalar field Φ, named *quintessence*. Strictly speaking, "quintessence" stands for a number of model theories for the scalar field like cosmic inflation stands for a large number of different models.[20] Quintessence models work with an equation of state $w = \frac{p}{\rho}$ with $-1 < w < -\frac{1}{3}$. The kinetic energy term is the usual $\nabla_i\Phi\nabla^i\Phi$ while for an extended set of models, i.e., k-essence theories, the kinetic term may read as $f(\nabla_i\Phi\nabla^i\Phi)\ g(\Phi)$ with arbitrary functions f, g. In both sets of theories, the scalar field can interact with baryonic and/or dark matter. There are even more speculative approaches taking the kinetic energy terms to be *negative* (phantom fields) [100]. For further alternative theories of gravitation, cf. the reviews about the understanding and consequences of cosmic acceleration by [76], [101] and [102]. Within Einstein gravity, another road has also been taken:

- By a suitable averaging procedure. It is argued that the differences in gravity between observers in bound systems (e.g., galaxies), and volume-averaged comoving locations within voids (underdense regions) in expanding space can be so large as to significantly affect the

[20] In a specific model, the scalar field has been named "cosmon" [98]. Another suggestion leads to a pseudo-Nambu-Goldstome boson [99].

parameters of the effective homogeneous and isotropic cosmological model [103]. A great deal of research is available [104], [49], and has lead to testable consequences [105]. The observations seem not yet conclusive with regard to whether we are located in such an underdense void of an extension $200 - 300\ Mpc$ [106].

If we refrain from accepting proposed ad-hoc-changes of the Friedman equations, among the theories suggested as replacements of Einstein gravity there are theories with higher-order field equations.[21] In one class, the curvature scalar R is replaced by an arbitrary function $f(R)$. For a general review cf. [107]; for a critical status report [108]. Again, scalar-vector-tensor theories of gravitation and vector-tensor theories [109] were put forward. In "make-believe cosmology" models with a higher number of spacelike dimensions are considered, e.g., five-dimensional braneworld models and also string related theories. Cf. section 5.3.

In comparison with dark matter, the observational status of dark energy remains less secure. Observed is a dimming of the luminosities of type Ia supernovae from the luminosity-distance relationship. Together with the homogeneity assumption this leads to acceleration ([76], p. 17, [85]). With further assumptions added, e.g., of flat space sections, dark energy then is reached. At present, the only promising method for its future empirical grounding seems to be (statistical) weak lensing. In contrast, for dark matter the case is very strong, cf. [110], [86].

3.5 Further conceptual pecularities of the standard model

As discussed in section 2, the standard model of cosmology is not free from epistemological and methodological problems. To list one more: Newton's absolute space appears in disguise in the form of an *absolute reference system*. In particular, (absolute) *cosmic time* or era is without *operational* background: the only clock measuring it is the universe itself. *By definition*, cosmic time is identified with atomic time. By what sequence of clocks the measured time intervals of which must be overlapping, can precise time keeping be realized for the full age of the universe? In particular, which "clocks" to use before structure formation, before nucleosynthesis, before baryogene-

[21] That is, with Lagrangians of higher-order in the curvature tensor.

sis, during the inflationary phase? From the radiocarbon method we know that "radiocarbon years" must be recalibrated to correspond to "calendar years". Such a re-calibration (in terms of radioactivity- and astronomical clocks etc) is necessary also for cosmological time. In the very early universe described by quantum cosmology, only some sort of "internal" time seems to be possible.

Also, there is *no operational* way of introducing simultaneity. The local method of signaling with light cannot be carried out, in practice, if distances of millions of light years are involved and the geometry in between the large masses is uncertain. It cannot be used, *in principle*, for the full volume of space if event horizons are present. The cosmological models containing the concept of "simultaneous being of part of the universe" (technically, the space sections or 3-spaces of equal times) are catering to past pre-relativistic needs. For the relativistic space-time concept, access to the universe is gained through the totality of events on and within our past light cone. Hence, "simultaneous being" must be replaced by "what may be experienced at an instant at one place" (a stacking of light cones). Some of the objects at the sky, the radiation of which we observe today, may not exist anymore.

A special case of the *hierarchy problem*, i.e., the so-called *cosmological constant problem*, arises if the cosmological constant Λ is not seen as just an additional parameter of classical gravity, but interpreted as the contribution by vacuum fluctuations of quantum field theory. In this case, its value should be immensely larger than the value derived from observations by a factor of $\sim 10^{60}$ (in theories with supersymmetry), or $\sim 10^{120}$ (no supersymmetry). In [111] a solution to this problem within quantum gravity has been suggested.

4 The inflationary flash

4.1 Particle cosmology

As we are going back in cosmological time, a remark concerning particle cosmology seems in order. While the temperature of the universe heats up toward the big bang, it is assumed that matter undergoes a number of phase transitions. All those happening before the so-called electroweak phase transition at $\sim (100 - 200)\ GeV$, occur at energies not yet attainable in the laboratory (accelerator particle physics). All are speculative, as e.g., the grand unification phase transition at which the strong interaction unifies with the weak and electromagnetic forces. The confinement-deconfinement (QCD)-phase transition at $10^{-5}s$ after the big bang seems to be the only one in future reach of accelerator physics. Cosmic inflation preceeds all the mentioned events; whether it is ending in a phase transition or not, is debated. After the end of inflation, copious particle creation and then thermalization is asumed to occur followed by baryogenesis. Cosmological modeling after inflation is characterized by a change of paradigm when compared to later eras: while, in principle, the description of matter by a continuous distribution is retained, in practice matter is differentiated into elementary units: elementary particles, nuclei, atoms and their reactions; they interact, can be produced or anihilated. The interplay of elementary particle reaction rates and the expansion rate of the universe requires different equations of state for different particle species at the same epoch. Nuclear physics comes in much later: the end of primordial nucleosynthesis is assumed to have happened at $\simeq 10^2 s$ after the big bang. Particle physicists are interested in the very early universe as a testbed for their theories concerning high energies. While by the later evolution of the cosmos limits are set on such theories (from CBM), the direct contributions of elementary particle physics to the early universe are speculative.

Again, cosmological modeling of the early states of the universe is based on a number of hypotheses, simplifying the modeling. A selection would be:

- C_1 Baryogenesis occurs after the end of inflation.

As to C_1, the end of inflation (reheating) is not well understood; it is difficult to reconcile the slow-roll conditions with the known couplings of particle physics candidates for the inflaton. The origin of the matter-antimatter asymmetry in the cosmos must and can be explained (cf. [89]). A number of theories have been suggested, some of them using leptogenesis (sphaleron-interaction) [90].

- C_2 Both, the reactions and reaction rates of individual particles, and collective phenomena are important in the early universe.

The assumed occurence of phase transitions cannot be understood without taking into account collective interactions. For a review of such phase transitions in the early universe cf. [91].

- C_3 Elementary particles do not interact gravitationally; gravitation acts merely as an external field.

This assumption expresses the subordinate role gravitation plays in the modeling of the early universe despite the assumption that then matter was extremely condensed. The gravitational field is assumed to show up only in the expansion of the universe or, perhaps, in pair production of elementary particles, if quantum field theory in curved space as we understand it is applicable (there exists not yet a fully worked out model for strong curvature). For special aspects cf. [112], [113], [114]. [22]

- C_4 Temperature and entropy of the universe are well defined after (local) thermodynamic equilibrium is reached.

- C_5 While, in epochs after inflation, matter is in thermodynamical equilibrium, different particle species can and will decouple from the equilibrium distribution.

As to the application of thermodynamics and kinetic theory to the early universe (C_4, C_5), it is known that, in the FLRW cosmological models, an exact equilibrium distribution is permitted only in two limiting cases: the ideal radiative model (rest mass of particles is zero) and the "heavy mass"-model (infinite rest mass) [115]. Thermodynamically, the expanding universe is treated as a *quasi-static* system with a relaxation time small with regard to the expansion (Hubble) time.[23] This is called *local thermodynamical equilibrium.* Whether such a concept can be valid for *infinite* volume (open space-sections with $k = 0, -1$) seems questionable. From this perspective, a "small" universe would be preferable. The time dependence of cosmic temperature implied by the cosmological model (adiabatic cooling), could be interpreted as a characteristic sign for the universe being a *non-equilibrium* system.

[22] Of course, in the very early universe, the gravitational field might not exist on its own but be united with the other fundamental interactions in a Super Grand Unified Field.

[23] Relaxation time, for massive particles, is related to mass diffusion or heat transport etc. For massless particles it may be approximated by the collision time and does not depend on volume.

4.2 The inflationary model

If the validity of the FLRW-cosmological models is extrapolated to very early epochs, an inflationary period between $\simeq 10^{-36}s$ and $\simeq 10^{-34}s$ after the big bang is assumed to have happened. During it, all distance scales in the universe must increase by at least 75 e-folds ([13], p. 239). In connection with the cosmological standard model, a number of questions then could be answered:
- What makes the universe as isotropic and homogeneous as it is (horizon problem)? - Why does the overall density parameter Ω differ from $\Omega_{\mathrm{C}} = 1$ by only by very little (flatness problem)? - How can the ratio $\eta = \frac{\eta_B}{\eta_\gamma} \simeq (4-7) \cdot 10^{-10}$ be explained (entropy problem)?

In order to answer these questions, the idea of the *inflationary scenario* was invented [116], [117], [32], [118]. Its characteristic feature is a scalar field ϕ, the "inflaton"[24], which is supposed to dominate the matter content at very early epochs. This scalar field must be very weakly coupled to all other matter fields. Usually, although not necessarily, ϕ is taken to be the order parameter of a phase transition from a symmetric phase with high energy corresponding to $\phi = 0$ (false vacuum) to a phase with *broken symmetry* and $\phi =$ const $\neq 0$ (true vacuum). An analogue would be the delayed transition from the gaseous to the fluid state with undercooling. The phase transition is made to start at $\simeq 10^{-35}$ seconds after the big bang. Dynamically, it is tripartite: after the tunneling of a potential barrier between the false and the true vacuum, a slow descent ("role-down") toward the true vacuum (supercooling) to a period of field oscillations, (reheating) must occur. In this last interval, the inflaton decays into the matter particles/fields we see today, and by producing heat. The reheating process is non-adiabatic and claimed to bring an increase in the entropy (of the universe) by a factor of 10^{130}. [25] The equation of state of the inflaton field is unusual if compared with materials in the laboratory: its pressure is negative with $p = -\rho$ ($w = -1$). Gravitational attraction is overwhelmed by repulsion responsible for the rapid expansion of the universe during the inflationary period.

A reason behind the many inflationary models is the ambiguity in potential energy of the inflaton field: it may be taylored at will. In some of the models investigated by now, the phase transition is pictured as

[24] More precisely, the inflaton is the field quantum of the inflaton field.

[25] During the inflationary phase, entropy grows linearly with cosmic time t, afterwards only with $ln\ t$ ([119], p. 319).

a nucleation of bubbles of the broken-symmetry phase within a matrix of the symmetric phase. During supercooling such a bubble can grow exponentially by 40 - 50 orders of magnitude (of 10) and more within a time of the order of a (few hundred) $\cdot 10^{-35}$ seconds. The gravitational field during the exponential growth is described by de Sitter's solution of the field equations (with constant Hubble parameter), the space sections of which are *flat* ($k = 0$). By construction, the inflationary model can solve both the entropy and the horizon problems: the presently observable part of the universe lies within a single inflating bubble. This means that, at the epoch of decoupling of photons and baryons, the various regions of the universe from which the cosmic microwave background originated have been causally connected. The model is said to also remove the flatness problem: inflation drives the density prameter Ω toward one [22]. Whether $\Omega = 1$ is desirable or not, seems to be entirely up to one's private beliefs, though.[26] There are also inflationary models with negative and positive 3-curvature k [120], [121]. Hence, it seems questionable whether "the flatness of the universe" is an unavoidable consequence of inflation ([13], p. 354).[27] We note that the inflaton field might be inhomogeneous and yet not violating the homogeneity and isotropy of the energy-momentum tensor of the cosmological model; the overall homogeneity would then be lost, however.

Although debates about the inflationary model have not ended (cf. [122], [112], [123], [124], by the following result its acceptance became overwhelming: through quantum fluctuations of the inflaton field, the model was able to provide the nearly scale invariant spectrum in the growing mode of (adiabatic) density perturbations which had been required from observations.[28] To make the amplitudes fit the density fluctuations reflected by the anisotropy of CMB, fine-tuning is required, though. In this context, it has been shown that large-angle (low-l) correlations of the CMB (from the 3-year WMAP-data) exhibit statistically significant anomalies. This is weakening "the agreement of the observations with the predictions of generic inflation" ([127], p.

[26] $\Omega = 1$ is an unstable fixpoint in the phase diagram of the time evolution of the Friedman models.

[27] Also, as noted by R. Penrose, if theory implies flat space sections, no observation, as small as its error bar can be made, will be able to exlude nonzero curvature ([35], p. 772).

[28] An admixture of isocurvature (non-adiabatic) perturbations below 10% (3%) seems to be permitted [125], [126].

16).

4.3 ΛCDM-questionaire (implying inflation)

While the inflationary model needed for the ΛCDM model has solved a number of problems, it created others:

- By what physics are the initial conditions for inflation generated?
- What is the inflaton field?
- What is tested by present observations: the nearly scale-invariant spectrum of density perturbations, or the inflationary scenario, in toto?
- What is dark energy?
- Why dark energy has become dominant only "recently" in the evolution of the universe (coincidence problem)?
- Did dark energy play a role in the formation of large scale structure, or not?
- Is an interaction of dark matter and dark energy excluded?

At present, there seems to be no consent on a fundamental theory for the very early universe in which the inflationary model is embedded and its initial conditions fixed. Cf. critical remarks by [128]. [29] The inflaton is not the Higgs particle (both are not observed). Is it connected to a model of hybrid inflation (2 scalar fields!) with the s-neutrino as the inflaton? [130] Is there a link to the scalar field introduced in a later epoch and named "quintessence" (Cf. section 3.4.2). Will there be a *technically accomplished* model for inflation still lacking? [30] What determines the high energy of the false vacuum? What kind of traces of the inflationary period can we *observe*? One such effect following from inflationary models is a stochastic background of primordial gravitational waves: metric tensor modes could be seen in the polarization measurements of CMB. So far, they have not (yet) been detected. If observed, certain inflationary models with respect to others could be ruled out. If not found, this also can be reproduced by some models. Gravitational waves from inflation are not to be mixed up with "gravitons" eventually generated during the Planck era, nor with the still different "gravitons" claimed by string theory.

[29] Cf. however [129] with a worked out suggestion that quantum geometry lead to inflation.

[30] For different inflationary models including chaotic, double, hybrid, new and eternal inflation cf. [131], [132].

The coincidence problem is alleviated if cosmic acceleration is modeled by space- and time-dependent fields replacing the cosmological constant; a fine-tuning of their contribution to the energy density needed can always be made such that it is largest late in the evolution of the universe. In view of the merely indirect empirical tests through consistency of the full cosmological model, the inflationary scenario is still rather speculative.

5 Originative cosmology

5.1 Quantum gravity

In a third stage of cosmological modeling, the epoch around and before the Planck time (10^{-44} s) is briefly dealt with. At such extremely early epochs, quantum mechanics and quantum field theory are applied. At present, a consistent and mathematically rigorous quantum field theory of gravitation, i.e., *quantum gravity*, is under construction but still not completed.[31] Nevertheless, within general relativity, intriguing schemes like *canonical quantization* in the geometrodynamics approach [133], [134], [135], its gauge theoretical variant *loop quantization* [137],[136], [138], [139], *covariant quantization*, e.g., in the form of Feynman path integral quantization [140], and the (numerically implemented) models of causal dynamical triangulation [141], [142] are pursued with impressive success.[32] Some general hypotheses are made:

- The gravitational field must be quantized around and before the Planck epoch.
- Unlike in the procedure for other fields, quantization of gravity must be done in a background independent manner (in canonical quantization).
- All local and global degrees of freedom of the gravitational field must be taken into account.
- Einstein's field equations hold right up to the big bang singularity.

That gravity ought to be be quantized is the majority vote. Some think that quantization must be performed within a theory in which

[31] This is no surprise, when we think that even quantum field theory in Minkowski space has not yet been made mathematically rigorous in all aspects.

[32] It is an open question whether these different approaches will lead to equivalent quantum theories of gravitation.

all fundamental interactions are united, e.g., a claim made by string theory. At present, string theory does not yet noticeably contribute to a solution of the most pressing questions in quantum gravity; it still is in "a rather preliminary stage" ([143], p. 753). Few believe in gravity as a *classical* field generated, perhaps, as an *effective* field by the other fundamental interactions.[33] Looked at from usual field quantization, at the root of the difficulties with quantization of gravity is its (perturbative) non-renormalizability. From a more technical point of view, quantization with (Hamiltonian and diffeomorphism) constraints, as in the case of the Hamiltonian formulation of general relativity, is a hurdle. Moreover, it is not entirely clear whether it suffices to quantize the gravitational field on a continuous space-time or, whether the very concept of a manifold ought to be replaced by discrete sets (causal set theory), combinatorily defined discrete structures like graphs, or spin networks (cf. [144], [145]). In loop gravity, while continuous 3-geometries still are investigated, area- and volume operators with a discrete spectrum do appear. Whether they are observables in the usual sense, i.e., commuting with the diffeomorphism constraints, is not entirely clear.[34] Background independence means that quantization should not rely on a metrical structure but, at most, on a differentiable manifold (cf.[146] [147]. Consequently, a lot of advanced mathematics is required. As no empirical input is available at present, "mathematical consistency is the only guiding principle to construct the theory" ([138], p. XX). The recent endeavour to derive rigorous results belongs into mathematical physics. For a critical discussion cf. [148], [149]. Quantum gravity is said to apply to two main systems: the very early universe (quantum cosmology) and to evaporating black holes.

5.2 Quantum cosmology

5.2.1 Law of initial conditions?

On the one hand, application of quantum mechanics to the universe is seen as an *intermediate* step in between the big bang and the inflationary epoch with the aim of providing initial conditions for inflation. But

[33] This is not to be mixed up with gravity dealt with as an effective quantum field theory with a high-energy cut-off.

[34] For a detailed discussion of the volume operator cf. [138], Secs. 13.1-13.6, pp. 432-457.

quantum cosmology also has been taken as a program for a *cosmogonic* theory: an attempt to construct a theory *determining uniquely* the initial conditions of the universe [150], [151], [152]. Turned around: as a program for a theory avoiding the big bang singularity.[35] Such an endeavor makes sense only if the universe itself carries the rationale for its initial data. If transferred to human life, this would mean that the reason for us coming to life does not lie in our parents but in ourselves. Strange as this thought may be (above the level of protozoans): a human being and the universe are quite different systems. It seems plausible, philosophically, that the cosmos cannot be thought of without the inclusion of a reason for its coming into being. In classical theory, the very idea of *prescribing uniquely* the initial data of a system by help of its *dynamics* is violating the spirit of physics. Perhaps, quantum theory could make the difference. For a positive suggestion in this direction within quantum cosmology, cf. [154], [155].

5.2.2 The Wheeler-DeWitt equation

In the Hamiltonian formulation, space-time is foliated into space sections, and the Einstein field equations are decomposed into time-evolution equations and constraint equations on the 3-geometries ${}^3g$. Canonical quantization leads to the Wheeler-DeWitt equation (WDW) for the *wave function* of the universe ψ, a formal analogue of the stationary Schrödinger equation [36]. It is a functional $\psi[{}^3g, \phi]$ of the geometry of space sections and the matter fields ϕ and hence defined on an infinite-dimensional space called *superspace*. The spacetime geometry can be pictured as a trajectory in superspace. The wave function of the universe represents the superposition of all possible space-time geometries correlated with matter functions [156]. It is assumed to be a pure state. Mathematically, the WDW-equation is not well defined (factor ordering and regularization problems). Nevertheless, one of the successes of the canonical approach is that its semiclassical approximation bridges the gap to quantum field theory on a fixed background [153].

In model calculations, isotropy and homogeneity of the space geometry is assumed and leads to a wave function ψ depending on just one

[35] From quantum cosmology, we may expect more than forming a "toy model for full quantum gravity in which the mathematical difficulties disappear", cf. ([153], p. 894).

[36] In reality, WDW comprises an infinite number of equations.

geometric variable: the scale factor a of the Friedman models. Usually, only a single scalar matter field ϕ is taken into account such that $\psi = \psi[a, \phi]$. In this case, the infinite dimensional superspace is reduced to a finite number of degrees of freedom, i.e. to *minisuperspace*.

Despite this technical simplification, the main problem cannot be circumnavigated: a *unique* solution of the Wheeler-DeWitt equation is obtained only if a *boundary* condition for ψ is chosen. Several suggestions to this end have been made. In the path integral formulation [150], [157] ψ is determined by a summing over all paths describing *compact euclidean* 4-geometries with regular matter fields. All 4-geometries must have a given 3-geometry as their boundary (no-boundary-condition)[37]. An alternative condition is Vilenkin's quantum tunneling from nothing (where "nothing" corresponds to the vanishing of the scale factor a): the universe is nucleating spontaneously as a DeSitter space [159], [160]. This boundary condition has been criticized on the ground that it equally well describe tunneling *into* nothing. For a detailed discussion cf. ([119], section 8.3, [153], section 4.2). In loop quantum cosmology, the WDW-equation is replaced by a discrete evolution equation.

Because the dynamical equations follow from the constraints on the spatial hypersurfaces, the wave function of the universe cannot depend on an *external* time parameter as is cosmic time. In minisuperspace, the Wheeler-DeWitt equation is a *hyperbolic* differential equation the dynamics of which is depending on two variables, a and ϕ, both of which can play the rôle of an *internal* time. The ambiguity in the selection of an internal time parameter permits reinterpretation of the WDW-equation as a Klein-Gordon equation. In particular (cosmological) models, the (bounded) volume of the space sections are used as a measure of time. At the big bang, in loop quantum gravity, the (degenerated) eigenvalue of the volume operator is zero.

5.2.3 Puzzles of quantum cosmology

An acceptable quantum cosmology will have to solve three internal problems:
- to give a definition of time,
- to determine the role of "observers",

[37]Cf. C.J. Isham [158]: "the universe is created ex nihilo since the 4-manifold has only the connected 3-space as its boundary".

- to describe the "emergence" of a classical universe from the quantum one,
plus one external:
- to link quantum cosmology with empirical data.

The striking inequality in the treatment of time and space is an inheritance from non-relativistic quantum mechanics. Presently, at best, time appears as a notion in a semiclassical approximation scheme ([119], section 5.2). For a detailed discussion of the "quantum problem of time" cf. ([138], section 2.4).[38]

A straightforward application of the Copenhagen-interpretation of quantum mechanics to the wave function of the universe does not make sense. Who is the classical observer carrying out preparation- and other measurements? A way out is to assume that the (quantum) universe is divided into one part as "the system to be looked at" and the remainder as "the measuring apparatus" [162]. A continuous shift of the borderline between observing and observed parts of the universe would then be necessary. In fact, if quantum gravity is to lead to the existence of a classical limit, i.e., how classical space-time can emerge including Einstein's field equation, another part might have to be defined, the "environment". Its wave function is entangled with the measuring part of the universe ("the apparatus"). The interaction with the environment will lead to "decoherence" and provide classical properties by a continuous measurement process [163], [164]. Possibly, measuring apparatus and environment can be made to coincide in the universe. For the interpretation of the wave function of the universe, it may be unavoidable to employ some version of Everett's interpretation of quantum mechanics; in it the splitting of the wave function by a measurement is equivalent to splitting the universe into many copies. In each of these copies one of the allowed measurement results occurs [165].[39] Another proposal replaces the "many worlds" of Everett by a "many histories" interpretation in which observers making measurements are within "decohering" histories of the same universe [152].

Originative cosmology is taking place in our *minds* - as pure mathematics does. By it, awareness of what could be *potentially* real is produced. Passage from the potentially to the *actually* real requires

[38] It has also been argued that time can be eliminated altogether [161].
[39] Cf. also [166].

a linking to an *empirical basis*. In the example of Bose condensation, the time span between the suggestion of the idea and its experimental validation was relatively short: it took about 60 years. The agreement among scientists in the case of quantum cosmology may take a very much longer time.

5.3 Make-believe cosmology: the multiverse

The conceptually well founded development of quantum cosmology and quantum gravity is very removed from the multiverse scenario to be briefly sketched now. A multiverse is an ensemble of universes. At best, the elements ("universes") of the set are generated from some underlying theory, e.g., from the "string landscape" (see below). At worst, the ensemble is just assumed to exist. A multiverse can be represented by a higher-dimensional space-time with four or more *space* dimensions. Often, this is done within the framework of "braneworld", in which a 3-dimensional space resides in a higher dimensional space, called "the bulk" to which time is added. Gravitation can play in the bulk, all other interactions are restricted to the brane. The additional spatial dimensions may be compactified or not. The multiverse can also consist of an infinite number of replica of one and the same universe as the many-worlds interpretation of quantum mechanics would imply. Another case is the multi-domain multiverse with its "universe-bubbles" bifurcating away from another in particular inflationary schemes (eternal inflation). For a discussion of different brands of multiverses cf. [167].

5.3.1 Multiverse models

The multiverse-concept is introduced in order to help solving philosophical problems inherent in, or superimposed on cosmology. With the first, avoidance of the singularity at the big bang is meant, with the second an attempt at bringing the biosphere back into the realm of the universe (anthropic principles).

In a special approach in brane cosmology, the *ekpyrotic model*, the universe is embedded as a 3-(mem)brane in a higher-dimensional space plus time along with other universes ("parallel branes"). All expand independently according to general relativity. The ekpyrotic model hypothesizes that the origin of the observable universe occurred when two parallel branes collided [168]. It is the precurser to cyclic universe models [169]. In them, a periodical big crunch is followed by a big bang with up to trillions of years ($\sim 10^{12}$) in between each bang and crunch. Density and temperature remain finite. The cyclic universes are said to be an alternative to inflation; they produce the right density fluctuation spectrum [170]. A further example for a multiverse scenario is the so-called "string landscape". It is the energy-"manifold" formed by all degenerated string vacuum solutions (their number is given as of the order of $\sim 10^{500}$). From each vacuum state a universe is assumed to "nucleate" with a certain probability. Relying on an estimate ascribed to R. Penrose ([35], p. 728-730), the nucleation of "our" universe (at energies $\sim 10^{16}\ GeV$) would have had only a probability of $10^{-10^{123}}$.

5.3.2 Philosophical issues

If all this is not solely forming a mental construct, not just philosophers might have difficulties in relating the multiverse with the notion of "all that exists in a physical sense". M. Rees is reducing the problem to a semantical one: what we now call "universe" could be named "metagalaxy"; the "multiverse" would be re-named "universe" ([171], p. 57). This stand hides a change in ontology: the multiverse is taken to exist in the same sense as the solar system does. In a correspondence about whether Everett's "many-worlds" interpretation of quantum mechanics should be taken as describing infinitely many "really existing" universes, or only logical mental possibilities, B. DeWitt sided with the first claim and asked: "Is there any difference" between things "physically real" and "abstractions such as numbers and triangles"? ([172], p. 10). In this spirit, it has been claimed recently that the introduction of the concept multiverse is leading to "an extension of the Copernican Principle": "The universe is not at the center of the world (the multiverse)" [173], p. 13). We cannot but conclude that, in the mind of the author, the multiverse now is "all that exists in a physical sense". A little less daring was, two decades ago, Tipler's definition of the Universe (with a capital U) to consist of all logically possible universes where "Universe" was the totality of everything in existence and "universe" a single Everett-branch [174], [175]. Enthusiasm and playfulness may have seduced some theorists to act on a quip, heard occasionally,: "All that can be thought of and expressed by a mathematical scheme must be realized in nature, somewhere". The "realistic" view of the multiverse leads to the uneasy task of finding a link between this system and empirical data upon which physics as we know it is based. A task which may well be impossible to fulfill (Cf. [73] p. 406). It is not made easier by the fact that in many of the multiverse definitions, their universe-elements are causally disjoint: they cannot be observed from our place. Apparently, on the assumption that quantum mechanics is valid also in the multiverse and that the wavefunctions of the universe-elements can form an entangled state, we are offered imprints of the multiverse on CMB in the form of two underdense regions (voids) one of which is connected with the cold spot ([173], p. 8-9).

A regress ad infinitum is not excluded, with its first step being the introduction of the concept "multi-multiverse" as the set of all multiverses.[40]

5.3.3 Multiverse questionaire

The questions asked within the multiverse scenario are quite different from those of "quantum cosmology" (section 4.3), or "physical cosmology" (section 2.2). We list some of them:
- How large is the multiverse (finite, infinite)?
- What is its precise structure?
- Do all members have the same (or similar) properties (dimension, geometry, physical laws)?
- How can the members be compared (i.e., empirically, not just by a mathematical classification)?
- Is the multiverse (as an ensemble) a dynamical system (with a history), or not?
- Why is there a need for a selection principle leading to a particular universe?
- How can the values for the (dimensionless) physical constants be derived from the multiverse?
- Can the multiverse provide the initial conditions for a universe like "ours"?

While, previously, cosmologists were satisfied with trying to find out whether the fundamental physical constants are depending on cosmic time, or not, now the demand is to explain why they have the particular values observed [177]. Cosmological modeling is transformed into a bird's eye view of the universe: scientists working in multiverse

[40] The plural "multiverses" has already been amply used, albeit only as a logical possibility, not as "reality". Cf. several articles in [8] with ([176], p. 368) as an example.

theory seemingly put themselves "outside" of "their" universe (mentally, that is). The necessary fine-tuning of some of the parameters required for life to exist seems to be a strong motivation for the concept of multiverse. It appears to me that many of the above questions are meaningless within physics; at this time, they seem to belong into philosophical thinking about the cosmos.

6 The science of cosmology

We have seen that cosmology shows features of descriptive astronomy, explicatory astrophysics, palaeontology, history, mathematics, physics, and natural philosophy. As long as it is handled as *cosmophysics*, i.e., as an extension of physics from the galactic through the extragalactic realm to ever larger massive gravitating structures, it is part and parcel of physics proper. Questions relating to parts of the cosmic picture are debated like those in other branches of physics; an example would be given by the three methods for determining baryonic acoustic oscillations [62]. The evolution in (past) time is more problematic. As soon as a description of the universe ("the world as a whole") by a cosmological model is attempted, knowledge gained is of a "softer" character than knowledge from astrophysics and planetary science research. Synge's statement of the mid 60s, i.e., that "of all branches of modern science, cosmological theory is the least disciplined by observation" [178]), must be shifted nowadays to the inflationary model, quantum cosmology and to string theory, though. To what degree can we trust in cosmological modeling, to its more than merely descriptive imaging of the universe? In view of the necessary correction of the distance scale which occured in the 1960s, and of the sudden change from $\Lambda = 0$ to a non-vanishing contribution of the cosmological constant in the 1990s, it should come not as a surprise when scientists from other quarters will keep reserved, a little. This applies especially to the concept of dark energy.

6.1 The epistemic value of cosmology

The most characteristic feature of research in the natural sciences is the collection of precise empirical data and their connection by self-consistent theories. In consequence, technical applications, possible derivation of novel relations among the empirical data ("new effects") obtain as well as models of explanation and understanding for the systems investigated. It is essential that such explicatory models map, with a minimum of hypotheses, a larger piece of the network of relationships found in the external world into percepts of our mind. It is particularly important that we are lead, by such understanding, to new possibilities of qualitative or, better, quantitative experimentation/observation. In view of such demands, is cosmological theory represented by the ΛCDM-model simple, empirically well based and conceptually clear? It may be too simple as we will discuss in section 6.2.2. Parts of it, among them the large scale structure and cosmic background radiation, are empirically extremely well supported. Other parts are only very indirectly, e.g., the inflationary scenario. The part concerned with the era right after the big bang (quantum cosmology) has not yet come near an empirical foundation. Although the range of their validity is unknown, Einstein's equations, their homogeneous and isotropic solutions, the methods to deviate from them (perturbation theory), and the quest for initial conditions are conceptually very clear. This cannot be said of the big bang concept (origin of space and time?) or, rather, of the whole Planck era which is neither conceptually nor methodically under control. The concept of inflation is very clear, in principle, but hazy in its technical details, e.g., during reheating. An application of cosmology, beneficial for society, is the development of technology for the improvement of observational tools. Another very important one is the emergence of an understanding of the world ("Weltbild") independent of a particular society and its cultural background; it is owed to the disciplining force of the laws of nature.

6.2 The explanatory value of cosmology

Nevertheless, one might still worry about the significance of knowledge produced by cosmological theory, in particular, about the "explanatory power" of the standard model. The concept is used here in the sense of a convincing reduction to, or a link with simpler *established* facts. Have we now understood, beyond a mere *description*, why, in the modeled evolution of the cosmos, first an extreme *global* thinning of matter *against* gravitational attraction had to occur while, subsequently, massive superstructures arose from *local* condensations against *global* expansion? Is it clear why the expansion of the universe after an explosive phase with deceleration parameter $q = -1$ slowed down to $q \simeq \frac{1}{2}$ and then steped up again to today's $q = -0.7 \pm 0.1$ from type Ia supernovae? Playing it all back to stochastic perturbations of a quantized scalar field of unknown origin and uncertain dynamics compensating gravitational attraction by its negative pressure does not explain enough. The more so as the initial values have to be put in by hand as long as no convincing theory for the era before inflation is available.

It is difficult, from the theoretical point of view, to make transparent the web of assumptions, logical deductions, and empirical input spun by cosmologists if the explanatory value of the cosmological model is to be evaluated. Hypotheses of differing weight are intermingled as, for example, the classical, *relativistic, nonlinear* theory of gravitation, *nonrelativistic* thermodynamics and kinetic theory for massive particles in perturbation theory, the relativistic Einstein-Boltzmann equation for the *fluctuations* of photon and neutrino fields, the *linear* theory of density fluctuations with non-linear complements, quantum field theory in curved space (during inflation), quantization of gravitation, nuclear physics (primordial nucleosynthesis) and high energy physics (baryogenesis). Approximations are made whenever they are needed for a calculation with the aim of connecting theory and data.

Special case studies could bring more light. A presentation from which one might try to get an impression of the explanatory value of cosmological modeling are lecture notes by N. Straumann [179], although not written under this aspect. In them, all calculational steps from primordial quantum fluctuations until how they show up in the acoustic peaks of oscillating matter describing the anisotropy of CMB are taken. An 8-parameter description for density-, velocity- and metric perturbations is used within two different 2-fluid-models *before* (electrons, baryons, photons plus dark matter) and *after* recombination (electrons, baryons, dark matter plus photons). [41]

The reliability of the empirical data also has to placed under scrutiny. There are ambiguities in the interpretation of observations of the large scale structure (redshift surveys) due to selection effects and the evolution of objects.[42] There still is a discrepancy between the value of the Hubble constant H_0 claimed by the ΛCDM-model (cf. section 3.3)

[41] In this work, it is assumed that dark energy does not contribute to the formation of large scale structures. Other authors wish to include dark energy perturbations during the matter dominated era [180].

[42] It is notoriously difficult to get reliable distance measurements beyond redshift $z = 1$.

and the much lower value $H_0 = 62.3 \pm 1.3$ (± 4.0) based on the high-accuracy distance indicators of the astronomers [64]. Similar problems arise for the large angle scale in CMB, or temperature and noise fluctuations [181].

6.2.1 Comparison with other natural sciences

A juxtaposition of cosmology with other branches of natural science with the aim to compare their relative explicative strengths is meaningful only in part. Of special interest are disciplines with historical aspects like geology, geophysics and paleontology. There, the evolution of systems is also modeled, if only on shorter time scales than the cosmological ones. One could become inclined to believe that knowlegde about the Earth must be easier to obtain and be more secure than knowledge about past eras of the universe. Yet, this seems not to be the case. An example is the enigmatic solid inner core of the Earth, thought to be formed from small nickel-iron crystals. Apparently, it is not homogeneous as one might assume, but shows large scale structures and anisotropy found through seismic waves [182]. Explanations are still debated (existence of layers etc) but, unlike the anisotropies of CMB, it seems unlikely that those in the inner core can be explained by small perturbations to an isotropic Earth [183]. Scenarios about the making of an inner planetary core seemingly have not yet converged to an accepted standard one as the inflationary scenario has in cosmological theory.

Why is it that the physics of the Earth‘s innermost core cannot be described as precisely (in terms of error bars) as the physics of the universe reflected by the concordance model? A tentative answer would be that the physics of the universe gets simpler the further we look back into the past. Simpler than solid state physics applied to the Earth with its many-body interactions, collective phenomena, phenomenological interactions, complicated phase transitions. This view is supported by the fact that the inner core of the *gaseous* Sun apparently is known much better. But, is it exluded that the apparent simplicity of the universe is due to the simplifying assumptions underlying the cosmological model and not an intrinsic feature of the cosmos? In fact, the ΛCDM-model including inflation is built in such a way that the imprints of inflation may be seen in CMB, but that the microwave background cannot show traces of the ensuing eras before the last scattering surface. A weaker argument might be that the rate of change in the cosmos, after the formation of large structure, is smaller than in geology. In the inner core of the Earth "one might expect to see changes on a human scale" [183].

A similar situation prevails in palaeontology, in which, as in cosmology, many disciplines like physics, geology, anatomy, technical mechanics, and biology work together. Here, the evolutionary history of the Earth including its biosphere is studied. As an example, fossils, say of feathered dinosaurs of various periods (in the range of million years duration), are compared. Phylogenetic trees are constructed with the help of mathematics. The discovery of an iridium-rich layer at the Cretaceous-Tertiary boundary [184] and the ensuing suggestion of an asteroid impact as its cause, were tentatively combined to unravel the mystery of the observed event of mass extinction (of the dinosaurs), ca. $65 \cdot 10^6\ y$ before the present.[43] Does this idea have an assimilable explicatory power as the idea of an inflationary period of the universe, even if it cannot be expressed within a mathematical model? Aren't the "standard candles" used in observational cosmology comparable to fossils? Perhaps, the success with solar nucleosynthesis led us to believe that we know more of the physics of supernovae millions of light years away than what is known about the touchable fossils of palaeontology.

6.2.2 Error bars

The statistical errors of a few percent given by "precision cosmology" are amazing (Cf. 3.3). These numbers are reliably calculated by the best methods available (after filtering and averaging of the primary data). Thus, on the one hand, they stand for the progress made in assessing the data. In this context, the increased use of methods of Bayesian statistics is notable [185]. On the other hand, how significant then is the uncertainty of $\sim 1\%$ for the age of the universe? It is roughly the same uncertainty as presented for the age of the Earth [186] or, for the material from which it was formed [187]. Should't the absolute dating become more and more precise, the *less* we go back in time? Yet, absolute (chronometric) dating in palaeo-anthropology tends to be no better than dating in cosmology: the first appearance of hominids is claimed to be $(7.0 \pm 0.2)\ 10^6\ y$ by help of $^{10}Be/\ ^{9}Be$-dating of the surrounding sediments [188]. An answer could be that the limits

[43] This dating remains virtually unchanged since the 1960s.

in accuracy are set by nuclear physics (radiometric dating), i.e., by a precise knowledge of half-lives and decay constants. The errors vary from $0.1\% - 1\%$ (uranium) to $\leq 10\%$ (potassium-argon). In addition, uncertainties from geochemistry (distribution of isotopes) and from isotope-chronostratography (changes in the environment needed for the calibration of radioactivity data) must be added. Dating errors in palaeo-anthropology thus cannot be much better than dating in primordial or stellar nucleosynthesis. For uncertainties in big bang nucleosynthesis cf. 3.1.1.

There is a discrepancy between the precision presently ascribed to cosmological parameters (errors of 1% to 10%) and the lack of *qualitative* knowledge. Quantitatively, the time of (photon) decoupling (via CMB) is set at $380081^{+5843}_{-5841}\ y$ after the big bang (cf. [82], Hinshaw, G, Weiland, J.L. et al., p. 45, table 7). Can this compensate the fact that we know less about the much later formation-details of luminous galaxies *near* to us? Although it is widely believed that their nuclei house massive black holes, neither by theory nor by simulations, an understanding of black hole galaxy seeds has been reached [189]. The same holds for spiral galaxies with thin disks. The ΛCDM-model can give only a relatively crude picture of structure formation and evolution. But perhaps, this is the domain of astrophysics, not of cosmology. Simulations of galaxy formation and evolution have met with great success, cf. [190]. Similarly, the age at reionization is given to be $432^{+90}_{-67} \times 10^6\ y$. The hope is that plasma physics at that time has been understood well enough and that its consequences for CMB have been taken into account (cf. [191], [13], p. 407-409). For the *cognitive* value of a physical model numerical precision does not play the decisive role. However, numerical precision has to be taken dead serious for predictions into the future. The precise numbers produced by CMB within the ΛCDM-model are very relevant if alterations of the cosmological model will be attempted. However, they are as irrelevant to society with regard to the future as are the ages related to palaeontology. Progress of precision cosmology reflected by the narrowing of error bars may be of an *intra-theoretical* value, only.

7 Conclusion

Throughout history mankind has tried to picture the world and to understand its origin and its features (Cf. [192]). In cosmology as a very young scientific discipline, ideas of different scientific quality are encountered. In this situation, opinions seem to play a prominenter role than in some other parts of physics. Nevertheless, today, through the ΛCDM-model, physical cosmology provides an image of the universe not in conflict with the wealth of data gained by painstaking observation and intelligent theoretical interpretation. The achieved scientific description of "the world as a whole" is a remarkable asset independent of a particular cultural background. Nevertheless, the question asked in the title can receive only a guarded answer: As described in this paper, in view of the haziness of the universe's extension in time and space, and because of the methodological and epistemic problems of cosmological modeling, knowledge gained about the "world as a whole" cannot be as secure and explicative as knowledge from laboratory or planetary physics. Silk called cosmology a *falsifiable myth* [78]. Certainly, a tremendous amount of additional empirical data concerning the large scale structure obtained since has been used to strengthen the cosmological model. Yet, with almost all of the universe's matter content unexplained, the situation still is the same: We modestly conclude that mathematical modeling, in particular when dealing with the early and earliest epochs of the universe, cannot produce but the cosmological myths adequate for our time.

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