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 side, 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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Contents

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. Despite of the progress made, the standard cosmological model, reshaped 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 (Ziman 1968) 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.

In the following, it will be argued that, at present, two types of cosmological research go side by side: *physical* cosmology on a solid empirical basis, and what will be named *inventive* cosmology without the empirical background physics needs. Of course, physical cosmology also contains speculative parts as do other subdisciplines of physics; they are waiting to be linked to future empirical testing. (Cf. also 6.2). In the following, 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 Planck-scale models (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: an ill 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 (Funk &Wagnall 1974), the science of the physical laws of the universe (Petit Robert 1985) or, as the Oxford Companion has it: "the study of the entire Universe" (Liddle and Loveday 2008, p. 61). Another circumscription of the universe is: "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.)" (Sexl and Urbantke 1983). The world *as a whole*, though, is not readily accessible, empirically. Whether bootstrap definitions like the universe is "the largest set of objects (events) to which physical laws can be applied consistently and successfully" (Bondi 1961), or formulations as "the universe means all that exists in a physical sense" (Ellis 2006, 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.” (Carr 2007, p. XV).

In this situation, scientists provide qualifying attributes, and point to subfields of cosmology linked with them (Ellis 2006): the *observable* universe, the *visible* universe, the *physical* universe, the *astronomical* universe (Mc Vittie 1961), the *astrophysical* universe (Peebles 1993). Although the *biosphere* is excluded from 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.[1] 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” (Liddle & Loveday 2008, p. 314). Cautious authors have avoided the word “universe” altogether in favor of expressions like “the metagalaxy” (Alfven 1967), “distribution of matter on the largest scale” (Buchdahl 1981), or “structure on a large scale” (cf. Ellis 2006).

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 meaningful, although possibly defined 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.[2] 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 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

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

[2] In this spirit, in recent monographs the physical system “universe” remains undefined (cf. Mukhanov 2005).

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. Hawking and Ellis 1973). 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 (Ellis 1971)[3]. The cosmological models of applied mathematics which, by careless use of language sometimes were called "cosmologies" (Ellis 1991, Halliwell 1991, Ryan and Shepley 1975) or "universes" (Salvati 1986, Robertson and Noonan 1968), 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* lightcone from a tiny part of the Earth's (or the solar-system's) world-line. 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

[3] Cf. also, cosmological models with multiply connected space sections (Ellis and Schreiber 1986, Lachieze-Ray & Luminet 1995, Luminet et al. 2003, Aurich et al. 2008)

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.

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 (Dyson 1979, Discuss et al. 1985). These calculations are pointless, however, because they cannot be validated by observational tests after the relevant cosmological time scales: Will any of them be preserved at least for 10^6 years? Even if cosmological theory could provide us with a reliable description of the past, its validity for the future cannot be tested; it is a consequence of continuity assumptions for the mathematical equations of theoretical cosmology. Nevertheless, in "fanciful 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 (Ellis 2007a, p. 61).

Obviously, 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 [..]." By this, psychologically, the distance to the other parts of physics in which predictions for the *future* are made, can be minimized.

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" (Strominger 1991). We were approached to "suppose universes are emitted from $t = 0$ like photons from an antenna" (Susskind 1991). 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). 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"? [4] 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 (Linde 1990).

As a consequence of the uniqueness of the universe *specific cosmic laws cannot obtain* (Munitz 1963). 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 (Narlikar & Burbidge 2008), some caution is in order. This, again, indicates that cosmology could 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.

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

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 [5]. 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 (Collins and Hawking 1973, Misner 1968). 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 (Penrose 1979, 1986, 1989). Moreover, in this context, various *anthropic principles* (Carter 1974, Demaret & Lambert 1994) have been invoked since their first formulation, and are used even heavier, today.[6] In fact, within "inventive 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 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

[5] 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. Penrose (2005), Bojowald (2008).

[6] 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.

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"? (Ellis 2007a, p. 76; cf. however Zeh 1999.)

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? [7]
- 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).

[7] 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 number of fundamental assumptions must be made for the modeling. We list a few, all of which seem to be dropped by the multiverse-compartment of "inventive cosmology":

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

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

Tacitely assumed is also a *principle of* simplicity demanding that the simpler cosmological model is the better one. The following requirements are reflections of this principle:

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

- 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.

Within a cosmological model, such hypotheses should be testable by their consequences. With better data, they could be relaxed as well. 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. Of course, it is the underlying theories which define these quantities to be constant or time-dependent. For cosmological modeling in the framework of general relativity, A_2 is to apply for epochs since and including the inflationary phase. 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. In A_4, an ideal fluid is characterized by the equation of state $p = w\ \rho$ with a constant $1 > w > 0$. [8] A_5 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".

3.1.1 Empirical situation

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 $|\dot{G}/G| \leq 10^{-10}$ and $|\dot{G}/G| \leq 10^{-13}$ have been given from various investigations (solar system, radar and laser ranging to moon/satellites, astro-seismology, binary pulsar, big bang nucleosynthesis, Ia supernovae) (cf. the review by García-Berro et al. 2007, 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 (Will 1981). At best, the observation time could be extended to $\sim 10^9$ y, i.e.,

[8] 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.

the lifetime of the solar system. This is short when compared 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.[9] The situation is not better for the estimates on $\dot{G}/G$ made from primordial nucleosynthesis (PN) giving a value for the ratio of $\frac{G_{PN}}{G_0} = 0.91 \pm 0.12$ taken at the time of big bang nucleosynthesis and at present (Steigmann 2009). As to PN as one of the pillars of the standard cosmological model, except for ^4H_e, and for nine reliable determinations of ^3He from high redshift quasistellar sources, the *observed* distribution of the light elements comes from measurements within the solar system and the Galaxy (Cf. also section 6.2). Of course, there are also observations of the chemical abundance in very old stars (Frebel 2008), but their cosmological relevance is not yet clear.

In addition to the restricted observation-volume, the empirical basis for the abundance of chemical elements perhaps is also 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). There remains also an unexplained difference between the observed and the theoretically calculated values for the abundance of ^7Li (Steigman 2009).

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. García-Berro et al. 2007, p. 139). Typical results are $\frac{\Delta\alpha}{\alpha} = (0.05 \pm 0.24) \times 10^{-5}$ (quasars) or $\frac{\Delta\alpha}{\alpha} = (-0.054 \pm 0.09724)$ (CMB). Another interesting target has been the ratio of proton and electron mass $\mu = \frac{m_p}{m_e}$. A typical bound is $|\frac{\Delta\mu}{\mu}| = (-5.7 \pm 3.8) \times 10^{-5}$ (cf. García-Berro et al. 2007, p. 159).

The time-independence of the fundamental constants which is particularly important in the inflationary phase, is not directly testable during this period. 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" (Ohanian 1976). The opposite view that "the physical laws, as we usually state them, already involve the universe as a whole" gets only a minority vote (Hoyle and Narlikar 1974).

[9] 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.

3.1.2 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.
- B_2 Observation time is long enough in order to guarantee reliable data of cosmological relevance.
- B_1 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: $\delta_g = b(z,k)\ \delta_m$ (Rassat et al 2009, eq. (3)). It is unclear whether these demands on observation are satisfied, at present. In particular, selection bias concerning luminous objects may be underestimated (Sandage 2008, p. 321).

But it is in observation that tremendous progress has been made in the past two decades. 3-dimensional redshift surveys of galaxies[10] 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 (Eisenstein et al. 2005, Percival et al. 2007): 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 (Kowalski et al 2008). 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, both A_3 and B_1 are questionable due to 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. The problems

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

related to observations were investigated carefully by G. Ellis (Ellis 1984, 2006). 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 (Walker et al. 1991).

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. By help of this geometry, an important hypothesis underlying the model, i.e., the *cosmological principle*, is expressed:

A_6 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.[11] The cosmological metric (gravitational potential) 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, $\Omega_c = 1$):

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

[11] It is possible to theoretically derive homogeneity from isotropy plus other plausible assumptions (Ehlers et al. 1968)

with $\Omega_t = \Omega_b + \Omega_d + \Omega_{radiation}$. Due to its smallness, we mostly will neglect $\Omega_{radiation}$.

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. Steiner 2008, Ellis 2007b, p. 405).

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 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).[12] 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 $p = -\rho$.

From the observational point of view, homogeneity of the space sections is a fiction. 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. Moreover, from observations alone, it seems impossible to discriminate, in our neighborhood, between a Friedman model and a spatially inhomogeneous, *static* model resembling a Friedman model (Ellis et al. 1978). Friedman's model wins out, because the observed redshifts from luminous matter are interpreted as marks for the expansion of the universe leading, among others, to CBM.

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

[12]The period of matter domination follows the radiation-dominated one. For a detailed discussion of the standard model and the early universe cf. Boerner 2003 or Mukhanov 2005.

space. In consequence, it is possible to interpret the microwave background as a relic of an early, hot phase 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 whether there is an unambiguous procedure for coarse graining in phase space. For the entropy concept, cf. the point of view of a strong supporter (Penrose 2005, 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 theorems of Penrose and Hawking (Hawking and Ellis 1973), singularities receive a *generic* significance within cosmological model building. 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: if the temperature at one *past* time, e.g., at the decoupling of radiation and matter, was such and such, then today we should measure microwave *and* neutrino backgrounds of temperatures 2.7 and 1.9 K, respectively. If the backgrounds observed would be at other temperatures, the initial data at some prior epoch would have to be changed. If they were not observed at all, some part of the modeling (e.g., the application of non-relativistic thermodynamics) ought to be replaced by a better idea. Of course, this single chain of argument 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 (Silk 1987, Peebles and Silk 1990, Bothun 1998). 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[13] 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, 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 $\Omega_t \simeq \Omega_m \simeq 0.25$, a missing mass $\Omega_\Lambda \simeq 0.75$ resulted, named "dark energy" (Turner 1998). 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. 3.5).

Observation of the luminous galaxy large scale structure also showing baryonic acoustic oscillations (BAO) and 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, have all 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 (WMAP 2008, table 7, p. 45):

- the geometry of space sections ($\rightarrow$ k small, $-0.0179 < \Omega_k < 0.0081$);
- matter energy density $\Omega_m = \Omega_b + \Omega_d \sim 0.258 \pm 0.03$;

[13] The so-called *deceleration* parameter is defined by $q = -\frac{a\ddot{a}}{\dot{a}}$.

- 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, [14]
- 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 (Linder 2003). 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) (Komatsu et al 2009). A 7-parameter model with $\Omega_m, \Omega_b, \Omega_d, w_0, w_a, h, n$ is considered by (Rassat et al. 2009).

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 gravitational lensing from clusters of galaxies. The mass is missing in and around galaxies (halos). From primordial nucleosynthesis of light elements and the anisotropies in the cosmic background radiation (CMB), it is estimated that baryons, mostly in the form of gas, contribute to only ca. 4%-5% of the relative critical density $\Omega_c = \frac{\rho}{\rho_c}$ (Liddle & Loveday 2008, p. 90). Besides being required to provide an enhancement of gravity, dark matter is assumed to be "non-interacting", otherwise. A computer simulation (MS-II) has 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" (Springel, White et al. 2009).

For a tentative explanation of dark matter either new cold (i. e.,

[14] 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 alloed to vary. $\bar{k}_0 = 0.002\ Mpc^{-1}$)

non-relativistic) particles (WIMPs,[15] 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 (Buchmüller 2007). Alternatively, new theories of gravitation have been suggested removing the need for dark matter, as are Modified Newtonian Dynamics (MOND) (cf. Sanders & McGaugh 2002), Scalar-vector-tensor-gravity (STVG) (Brownstein & Moffat 2006), translational gauge theory (Hehl & Mashoon 2009a,b), etc. Up to now, none of the particles invoked were seen, and none of the alternative theories were 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 (Ries 1998, Perlmutter 1999). 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. Usually, it is assumed to play no role in the Early Universe.

Besides the cosmological constant, tentative dynamical explanation 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.[16] 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 function f. In both sets of theories, the scalar field can interact with baryonic and/or dark matter. For further alternative theories of gravitation, cf. the reviews about

[15] Weakly interacting particles.

[16] In a specific model, the scalar field has been named "cosmon" (Wetterich 2002). Another suggestion leads to a pseudo-Nambu-Goldstome boson (Frieman et al. 1995).

the understanding and consequences of cosmic acceleration by (Silvestri &Trodden 2009) and (Caldwell & Kamionkowski 2009). Within Einstein gravity, another road has also been taken:
- A different 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 parameters of the effective homogeneous and isotropic cosmological model (Wiltshire 2007).

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.[17] In one class, the curvature scalar R is replaced by an arbitrary function $f(R)$. For a general review cf. Sotiriou & Faraoni 2008; for a critical status report Straumann 2008. Again, scalar-vector-tensor theories of gravitation were put forward. In "inventive 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 status of dark energy remains less secure, observationally (McGaugh 2007). It seemingly has not played a significant role at early times although reliable knowledge beyond $z = 1$ is not available (Caldwell & Kamionkowski 2009, p. 8).

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 baryogenesis, 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

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

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).

4 The inflationary flash

4.1 Particle cosmology

As we are going back in cosmological time, a remark concerning particle cosmology seem 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. Cosmic inflation preceeds all the mentioned events; whether it is ending in a phase transition or not, is debated. Toward the end of inflation, baryogenesis is assumed to have occured. Cosmological modeling after baryogenesis is characterized by a change of paradigm if 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: atoms, nuclei, elementary particles 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 the later evolution of the cosmos sets limits on such theories, the contributions of elementary particle physics to the early universe are speculative.

Again, cosmological modeling of the early universe is based on a number of hypotheses, a selection of which is:
- C_1 Baryogenesis occurs at the end of inflation.
- C_2 Individual particles, their reactions and reaction rates are important in the early universe, not collective phenomena.
- C_3 Elementary particles do not interact gravitationally; gravitation acts merely as an external field.
- C_4 Temperature and entropy of the universe are well defined.
- C_5 While, in each epoch, matter is in thermodynamical equilibrium, different particle species can and will decouple from the equilibrium distribution.

Such assumptions simplify the modeling of the early states of the universe. 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. Buchmüller 2007). As to C_2, we just might not yet know all the physical laws needed, and all the particles present in the early universe. C_3 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.

(Hollands & Wald 2002; Buchholz & Schlemmer 2007).[18]

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) (Bernstein 1988). Thermodynamically, the expanding universe is treated as a *quasistatic* system with a relaxation time small with regard to the expansion (Hubble) time.[19] Whether more than *local* equilibrium still is 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, must be interpreted as a characteristic sign for the universe being a *non-equilibrium* system.

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 (Mukhanov 2005, 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 $\Omega_C = 1$ 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 (Guth 1981, Albrecht and Steinhardt 1982, Linde 1990, Kolb and Turner 1990). Its characteristic feature is a scalar field ϕ, the "inflaton"[20], 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 sym-

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

[19]Relaxation time usually is equated with collision time which does not depend on volume.

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

metric 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}. [21] 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 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 (Ellis 1991). Whether $\Omega = 1$ is desirable or not, seems to be entirely up to one's private beliefs, though.[22] There are also inflationary models with negative and positive 3-curvature k (Bucher, M.

[21] During the inflationary phase, entropy grows linearly with cosmic time t, afterwards only with $ln\ t$ (Kiefer 2007, p. 319).

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

et al. 1995; Gott, J. R. 1986). Hence, it seems questionable whether "the flatness of the universe" is an unavoidable consequence of inflation (Muhkanov 2005, p. 354).[23]

Although debates about the inflationary model have not ended (cf. Albrecht & Sorbo 2002; Hollands & Wald 2002; Kofman et al. 2002; Turok 2004), 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. To make the amplitudes fit the density fluctuations reflected by the anisotropy of CMB, fine-tuning is required, though.

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. however (Bojowald 2002) with a worked out suggestion that quantum geometry leads to inflation. 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 (Antusch et al. 2005)? 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

[23] 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 (Penrose 2005, p. 772).

inflation still lacking? [24] What determines the high energy of the false vacuum? Can we *observe* traces of the inflationary period? 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.

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, inflation forms a borderline case of *inventive cosmology*.

5 Inventive 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.[25] Nevertheless, within general relativity, intriguing schemes like *canonical quantization* in the geometrodynamics approach (DeWitt 1967, Wheeler 1968, Kucha$\hat{r}$ 1973), its gauge theoretical variant *loop quantization* (Ashtekar 1986, 2007; Thiemann 2007), *covariant quantization*, e.g., in the form of Feynman path integral quantization (Hamber 2009), and the (numerically implemented) models of causal dynamical triangulation (Loll 1998; Ambjorn et al. 2005) are pursued with impressive success. Some general hypotheses are made:

- The gravitational field must be quantized around and before the

[24] For different inflationary models including chaotic, double, hybrid, new and eternal inflation cf. (Guth 1997, Liddle & Lyth 2000).

[25] 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.

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 all fundamental interactions are united, e.g., a claim made by string theory. Few believe in gravity as a *classical* field generated, perhaps, as an *effective* field by the other fundamental interactions.[26] 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 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. Smolin 2005; Sorkin 2005). In loop gravity, while continuous 3-geometries still are investigated, area- and volume operators with a discrete spectrum do appear. Wether they are observables in the usual sense is not entirely clear.[27] Background independence means that quantization should not rely on a metrical structure but, at most, on a differentiable manifold (cf. Giulini 2007). 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" (Thiemann 2007, p. XX). The recent endeavor, to derive rigorous results belongs into mathematical physics. Quantum gravity is said to apply to two main systems: the very early universe (quantum cosmology) and to evaporating black holes.

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

[27]For a detailed discussion of the volume operator cf. Thiemann 2007, Secs. 13.1-13.6, pp. 432-457.

5.2 Quantum cosmology

5.2.1 Law of inertial 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 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 (Hartle and Hawking 1983, Vilenkin 1988, Gell-Mann and Hartle 1990). Turned around: as a program for a theory avoiding the big bang singularity! 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. (Bojowald 2001, 2003).

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, an analogue of the stationary Schrödinger equation [28]. 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 (Zeh 1986). In model calculations, isotropy and homogeneity of the space geometry is assumed and leads to a wave function ψ depending on just one geometric variable: the

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

scale factor a of the Friedman models. Moreover, 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 (Hartle and Hawking 1983, Hawking 1984) 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)[29]. 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 (Vilenkin 1982, 1984, 1988). This boundary condition has been criticized on the ground that it equally well describe tunneling *into* nothing. For a detailed discussion cf. (Kiefer 2007, section 8.3). In loop quantum cosmology, the WDW-equation is replaced by a discrete evolution equation.

Obviously, the wave function of the universe does not 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. A different suggestion uses the (bounded) volume of the space sections 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,
- to describe the "emergence" of a classical universe from the quantum

[29]Cf. C.J. Isham (Isham 1987): "the universe is created ex nihilo since the 4-manifold has only the connected 3-space as its boundary".

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 (Kiefer 2007, section 5.2). For a detailed discussion of the "quantum problem of time" cf. (Thiemann 2007, section 2.4).[30]

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" (Finkelstein and Rodriguez 1986). 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 (Zeh 1971, Joos and Zeh 1985, Kiefer 1988). 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 (Everett 1957). 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 (Gell-Mann and Hartle 1990).

Inventive 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 a linking to an *empirical basis*. In the example of Bose condensation,

[30] It has also been argued that time can be eliminated altogether (Barbour 1993).

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 Fanciful 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, it 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. (Tegmark 2004).

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 (Khoury et al. 2001). It is the precurser to cyclic universe models (Khoury et al. 2004). 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 (Khoury et al. 2002) 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 (Penrose 2005, 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

As long as all this is a mental construct, eventually only philosophers might have difficulties to relate 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 called "meta-galaxy"; the "multiverse" would be re-named "universe" (Rees 2007, 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"? (Gardner 2003, 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)" (Mersini-Houghton 2008, 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 (Tipler 1986, Tipler and Barrow 1987). 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. Ellis 2007b 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 CBM in the form of two underdense regions (voids) one of which is connected with the cold spot (Mersini-Houghton 2008, 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.[31]

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

[31] The plural "multiverses" has already been amply used, albeit only as a logical possibility, not as "reality" (cf. several articles in (Carr 2007) with (Aguirre 2007, p. 368) as an example.

time, or not, now the demand is to explain why they have the particular values observed (Tegmark et. al 2006). Cosmological modeling is transformed into a bird's eye view of the universe: scientists working in multiverse 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 part 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 (Rassat et al. 2009). However, 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 that "of all branches of modern science, cosmological theory is the least disciplined by observation" (Synge 1966), must be shifted nowadays to the inflationary model and to quantum cosmology, though.

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 see 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 no empirical foundation whatsoever. 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 reaching 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? 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 much. 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 (Straumann 2006), 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). [32]

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.[33] There still is a discrepancy between the value of the Hubble constant H_0 claimed by the ΛCDM-model (cf. section 3.3) and the much lower value $H_0 = 62.3 \pm 1.3$ (± 4.0) based on the high-accuracy distance indicators of the astronomers (Tammann et al. 2008). Similar problems arise for the large angle scale in CMB, or temperature and noise fluctuations (Li et al. 2009).

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 mean-

[32] 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 (Sapone & Kunz 2009).

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

ingful 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 (Jephcoat & Refson 2001). Explanations are still debated (existence of layers etc) but, unlike the anisotropies of CBM, it seems unlikely that those in the inner core can be explained by small perturbations to an isotropic Earth (Anderson 2002). 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 with its many-body interactions, collective phenomena, phenomenological interactions, complicated phase transitions. But, is it exluded that this apparent simplicity of the universe is due to the assumptions underlying the cosmological model and not an intrinsic feature of the cosmos? A second 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” (Anderson 2002).

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. The discovery of an iridium-rich layer at the Cretaceous-Tertiary boundary (Alvarez & Alvarez et al. 1980) and the ensuing suggestion of an asteroid impact as its cause, are 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. 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? Do we know more about them than about the fossils of palaeontology?

6.2.2 Error bars

The error bars of a few percent given by "precision cosmology" are amazing. These numbers are reliably calculated by the best methods available (after filtering and averaging of the primary data). How significant 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 (Dalrymple 2001) or, for the material from which it was formed (Amelin et al. 2002). Should't the absolute dating become more and more precise, the *less* we go back in time? Yet, absolute dating in palaeo-anthropology tends to be no better than dating in cosmology. E.g., the first appearance of hominids is set to be $(7.0 \; \pm 0.2) \; 10^6 \; y$ by help of $^{10}Be/\,^{9}Be$-dating of the surrounding sediments (Lebatard, A. E. et al. 2008).

There is a discrepancy between the precision given for cosmological parameters 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. WMAP 2008, 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 (Madau et al. 2009). 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. (Springel, White et al. 2005). 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. Opher 1997, Mukhanov 2005, 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 the ΛCDM-model are very relevant if changes of the cosmological model will be attempted; they are as irrelevant 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. Kragh 2003). 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 cultural endeavor. In view of the haziness of the universe's extension in time and space, and due to its methodological and epistemic problems, knowledge coming from cosmological models cannot be as secure and explicative as knowledge from laboratory physics. Silk called cosmology a *falsifiable myth* (Silk 1987). Certainly, a tremendous number 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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