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**LIFE AFTER INFLATION
AND THE COSMOLOGICAL CONSTANT PROBLEM**

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ABSTRACT

It is argued that if the present vacuum energy density ρ_v exceeds some extremely small critical value ρ_c ($\rho_c \sim 10^{-10^7} g.cm^{-3}$ for chaotic inflation in the theory $\frac{m^2}{2}\phi^2$), then the lifetime of mankind in the inflationary universe should be finite, even though the universe as a whole will exist without end. A possible way to justify the anthropic principle in the context of the baby universe theory and to apply it to the evaluation of masses of elementary particles, of their coupling constants and of the vacuum energy density is also discussed.

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The history of cosmology knows many doomsday predictions: The life in the universe will disappear after the stars stop shining, or after baryons will decay, or after the universe will collapse as a whole. However, after several milliard years, when the Sun will become dim, we will probably find some alternative sources of energy. 10^{30} (or 10^{40}) years later, when baryons will start decaying, there will be almost as many positrons as electrons. In principle, it is quite possible (and at that time it probably will not be technologically difficult) to convert positrons back to protons by making positron density three orders of magnitude bigger than the nuclear density and using monopoles as a catalyzer of baryon formation *via* the inverse Rubakov effect. Finally, it was discovered that in most versions of the inflationary universe scenario the universe as a whole never collapses, but rather enters a regime of eternal reproduction of new inflationary domains, which later give rise to an infinite number of exponentially large regions with new stars and baryons, where life appears again and again.

Let us consider for example chaotic inflation in the theory with the effective potential $V(\phi) = \frac{m^2}{2}\phi^2$. In this theory the classical scalar field $\phi > M_p$ decreases from its initial value ϕ_o very slowly [1],

$$\phi(t) = \phi_o - \frac{mM_p}{2(3\pi)^{1/2}}t, \quad (1)$$

where M_p is the Planck mass, whereas the size of the universe grows as

$$a(t) = a_o \exp\left(\frac{2\pi}{M_p^2}(\phi_o^2 - \phi^2(t))\right). \quad (2)$$

This expansion is quasiexponential, which means that during the time intervals few times bigger than the typical time $\tau = H^{-1} = (3/\pi)^{1/2} \frac{M_p}{2m\phi}$, where H is the Hubble parameter, the expansion of the universe can be described by the simple function $a(t) = a_o \exp(Ht)$. During the time H^{-1} the universe grows by e times, and its volume grows by $e^3 \sim 20$ times. At the same time the classical field $\phi(t)$ decreases by $\Delta\phi = M_p^2/2\pi\phi$, but simultaneously inhomogeneities $\delta\phi(x)$ are produced with a wavelength bigger than the size of the event horizon H^{-1} and with an average amplitude $|\delta\phi| \sim H/2\pi \sim \frac{m\phi}{(3\pi)^{1/2}M_p}$ [2]. Note, that $|\delta\phi| \gg \Delta\phi$ at $\phi > \phi^*$, where

$$\phi^* = M_p \left(\frac{M_p}{m}\right)^{1/2}. \quad (3)$$

This means that during the time interval $\tau = H^{-1}$ the total volume of inflationary domains containing the field $\phi \geq \phi^*$ grows by $O(\frac{e^3}{2}) \sim 10$ times, rather than decreases. Therefore inflationary domains with $\phi \geq \phi^*$ unceasingly reproduce themselves. This means that there is no end to the evolution of the universe in this scenario, and that in the course of time new and new exponentially large domains of the universe capable of supporting life will be produced [3]. Similar results are valid in the context of the new inflationary scenario as well [4].

These results imply that life in the inflationary universe will never disappear. Unfortunately, this conclusion does not automatically mean that one can be very optimistic about the future of mankind. Even though new domains of our type are permanently produced during inflation, later on each particular domain either will become practically empty and unsuitable for life or it will evolve into a huge black hole and collapse [5]. The only possible strategy of survival which we see at the moment is to travel from old domains to the new ones, which are displaced near the self-reproducing inflationary domains and always have large enough density of baryons. In the worst case, if we will be unable to travel to such distant places ourselves, we can try to send some information about us, our life and our knowledge, and maybe even stimulate development of such kinds of life there, which would be able to receive and use this information. In such a case one would have a comforting thought that even though life in our part of the universe will disappear, we will have some inheritors, and in this sense our existence is not entirely meaningless. (At least it would be not worse than what we have here now.)

In order to check whether such a possibility does actually exist, it would be necessary to perform a detailed investigation of the global structure of the universe, and especially of its causal structure, which becomes very nontrivial in the context of inflationary cosmology [6]. One should answer the question whether it is actually possible to travel or to send a signal from our part of the universe to a vicinity of a nearby self-reproducing inflationary domain, and to do it in such a way that after a long time which is necessary for the signal to arrive the density of matter near this domain will be sufficiently large for the existence of life there. At present we do not know any no-go theorems which would imply that it is generally impossible and that one cannot elaborate any successful strategy of survival of life in our part of the universe. One of the main aims of this paper is to show that the answer to this question may depend crucially on the value of the vacuum energy density, i.e. on the absence or presence of a tiny cosmological constant in the Einstein equations.

Namely, according to [3], the self-reproducing domains appear in the inflationary universe independently of the existence or nonexistence of a small energy density ρ_v of the vacuum state in which we live now (if it is not negative and as big as $-10^{-6} M_p^4$). However, the causal structure of the universe, the possibility of communication between its different domains and the possibility of the existence of life there depend crucially on the value of ρ_v . For example, if ρ_v is negative and its absolute value is much bigger than the present energy density of matter $\rho_o \sim 10^{-29} g.cm^{-3}$, each domain of the universe after inflation and a sufficiently long subsequent period of expansion behaves as an anti de Sitter space and collapses at a time $t \sim M_p \rho_v^{-1/2} \ll M_p \rho_o^{-1/2} \sim 10^{10}$ years, i.e. much earlier than the time necessary for the development of life of our type. Note, that this process occurs locally, at different times in different places of a self-reproducing universe. Therefore one may escape the local collapse by travelling towards the self-reproducing domains. However, since the

typical distance between our place and a nearby self-reproducing domain is extremely large, such a journey is possible only if the lifetime of the anti de Sitter domain $t \sim M_p \rho_v^{-1/2}$ is also extremely large and, consequently, the absolute value of ρ_v is extremely small (see below).

If the vacuum energy density is positive and bigger than $10^{-27} g.cm^{-3}$, formation of galaxies of our type becomes impossible [7]. Smaller values of ρ_v do not affect galaxy formation, but do affect the causal structure of the universe. For example, the universe with $\rho_v > \rho_0$ at the time $t > 10^{10}$ years behaves as de Sitter space with the event horizon of the size $H^{-1} \sim 10^{28} cm$ (i.e. smaller than the particle horizon $\sim t$ now). In such a universe the distance between the galaxies grows as e^{Ht} , and after a time of the order $H^{-1} < 10^{10}$ years there would remain only one (our own) galaxy inside our event horizon. (The galaxy itself is not stretched by the universe expansion since it is a gravitationally bounded system with the energy density much bigger than ρ_0 .) It is well known that in the exponentially expanding universe one can travel or send any information only to those regions which were inside the event horizon at the moment when the information was sent. This means that soon after the beginning of the exponential expansion of the universe with $\rho_v > \rho_0$ there will be no possibility to travel or send information to other galaxies, and it is certainly impossible to send a signal to any self-reproducing inflationary domain, since a typical distance from our place to any such domain is much bigger than H^{-1} .

This result can be considerably strengthened in all realistic models of inflation. To do it one should first make an estimate of a typical distance l^* from our place to a nearby inflationary self-reproducing domain. This can be easily done, since there should be many such domains in each region of initial size $H^{-1}(\phi)$ containing field $\phi > \phi^*$, and there should be no such domains inside the regions of initial size H^{-1} containing field $\phi < \phi^*$. For the theory $m^2 \phi^2/2$ this gives, according to (2), (3),

$$l^* \sim H^{-1}(\phi^*) \exp\left(\frac{2\pi\phi^{*2}}{M_p^2}\right) \left(\frac{T_R}{T_o}\right). \quad (4)$$

Here $H^{-1}(\phi^*) = M_p \left(\frac{8\pi}{3V(\phi^*)}\right)^{1/2}$, T_R is the reheating temperature of the universe after inflation, T_o is the present temperature of the blackbody radiation in the universe. The last factor appears due to the additional stretching of the universe when the temperature falls down from T_R to T_o . Typically this factor is of the order of 10^{30} and $H^{-1}(\phi^*)$ is of the order of 10^{-30} cm. Therefore from (3), (4) it follows that

$$l^* \sim \exp(2\pi M_p/m) \text{ cm} \sim \exp((2\pi)10^6) \text{ cm}. \quad (5)$$

The numerical estimate in (5) follows from the well-known result that density perturbations generated during inflation in this scenario have an amplitude necessary for the subsequent

process of galaxy formation if $m \sim 10^{-6} M_p$. The universe becomes exponentially expanding and acquires an event horizon $H^{-1}(\rho_v) = M_p (\frac{8\pi}{3\rho_v})^{-1/2}$ at the late stages of its evolution, when the energy density of matter, which decreases as t^{-2} , becomes smaller than the vacuum energy density ρ_v . It occurs at the time which is bigger than the present age of the universe $t_o \sim 10^{10}$ years by the factor $(\frac{\rho_o}{\rho_v})^{1/2}$. At that time the distance l^* from us to the nearby inflationary self-reproducing domain grows by a factor $(\frac{\rho_o}{\rho_v})^{1/3}$, since the scale factor of a cold matter dominated universe grows as $t^{2/3}$. The causal connection between us and this region will be possible only if this distance will remain smaller than $H^{-1}(\rho_v)$,

$$M_p (\frac{8\pi}{3\rho_v})^{-1/2} > M_p (\frac{8\pi}{3V(\phi^*)})^{-1/2} \exp(\frac{2\pi\phi^{*2}}{M_p^2}) (\frac{T_R}{T_o}) (\frac{\rho_o}{\rho_v})^{1/3}, \quad (6)$$

which implies that the causal connection is possible only if ρ_v is smaller than some critical value ρ_c , where

$$\rho_c = \frac{V^3(\phi^*)}{\rho_o^2} (\frac{T_R}{T_o})^6 \exp(-\frac{12\pi M_p}{m}) \sim 10^{-10^7} g.cm^{-3}. \quad (7)$$

Here $V(\phi^*) \sim m M_p^3 \sim 10^{-6} M_p^4$, $\rho_o \sim 10^{-29} g.cm^{-3} \sim 10^{-125} M_p^4$, $T_R \sim 10^{10} GeV$. One can easily see that the constraint (7) on the value of the vacuum energy density ρ_v is very stringent and practically does not depend on the particular values of $V(\phi^*)$, ρ_o and T_R .

Returning to the case of a negative vacuum energy, it can be shown by methods similar to those used above that in this case as well a causal contact between our part of the universe and a nearby self-reproducing inflationary domain is impossible if $|\rho_v| > \rho_c$, since in this case the time which is necessary for the contact is bigger than the time before the local collapse of our part of the universe.

These results are rather unexpected. It was clear *a priori* that the existence of a non-vanishing vacuum energy may slightly change the conditions of our life, but it was difficult to imagine that the development of life in our part of the universe may depend crucially on the existence or nonexistence of a tiny vacuum energy density $|\rho_v| \geq 10^{-10^7} g.cm^{-3}$.

Of course, the events we are discussing here will occur in a very distant future (at $t \sim 10^{5.10^6}$ years), but it is very difficult not to be curious about our common fate as it can be understood at the present level of the development of science. Another possible application of these results would be to use them in order to obtain a strong anthropic bound $|\rho_v| < \rho_c \sim 10^{-10^7} g.cm^{-3}$, which would help us to solve the cosmological constant problem. At the first glance, such an idea certainly cannot work, since the existence of the vacuum energy $-10^{-29} g.cm^{-3} < \rho_v < 10^{-27} g.cm^{-3}$ does not prevent formation of galaxies and can hardly have any effect on the appearance of life in the universe [7]. Moreover, until very recently the general attitude of physicists to the Anthropic Principle was rather sceptical,

to say the least. It was believed that the weak, strong and electromagnetic interactions are the same in all parts of our universe, that the fundamental constants of Nature are universal and it is meaningless to discuss the possibility to live in a universe of a different type. This attitude was somewhat changed first when it was understood that in accordance with the chaotic inflationary universe scenario the universe should contain an exponentially large (or maybe even infinitely large) number of exponentially large domains (mini-universes), in which all kinds of symmetry breaking and all kinds of compactification which are possible in a theory of a given type are actually realized [1]. In other words, the universe becomes divided into many exponentially large domains with different types of low-energy physics and maybe even with different dimensionality [8] inside each of them. This made it possible to get a justification of a kind of Weak Anthropic Principle : If many exponentially large domains with the low-energy physics of our type do exist in the universe described by a given theory, then it is quite natural that we live in one of such domains rather than in a domain where life of our type is impossible [9]. With the invention of the theory of many universes interacting with each other only globally [10], and especially with the development of the baby universe theory [11-13] the situation changed even more. As it will be argued below, in the context of the baby universe theory it is possible to justify the Strong Anthropic Principle as well.

According to the baby universe theory [11-13], we may live in different quantum states of the universe $|\alpha_i\rangle$, corresponding to different choices of the “fundamental constants”, such as the vacuum energy ρ_v (cosmological constant $\Lambda = 8\pi\rho_v/M_p^2$), gravitational constant $G = M_p^{-2}$, fine structure constant α , etc. By measuring the coupling constants we actually determine in which quantum state $|\alpha_i\rangle$ we live now, and after that we cannot “jump” to another quantum state with other constants. That is why we are used to believe that we live in a classical universe with well-determined and unchanging laws of physics.

It would be very desirable to understand why do we live in a universe in a quantum state $|\alpha_i\rangle$ with an extremely small (or even vanishing) cosmological constant, with $M_p \sim 10^{19}$ GeV, $\alpha = 1/137$, etc. A possible idea is to compute the wave function of the universe and then to prove that it is entirely concentrated near some particular values of the coupling constants [13, 14]. However, the validity of the euclidean approach to quantum cosmology used in most of the papers on this problem is far from being clear [9], and it is quite possible also that the wave function of the universe actually does not have any sharp peak at $\Lambda = 0$ [15, 16]. Moreover, it is not quite clear whether it is the wave function of the whole universe that is to be computed. It is known that in quantum mechanics only those statements can make sense that can be formulated in a concrete operational way. For example, at the classical level one can speak of the age of the universe t . However, the essence of the Wheeler-DeWitt equation for the wave function of the universe is that this wave function *does not depend on time*, since the total Hamiltonian of the universe, including the Hamiltonian of

the gravitational field, vanishes identically [17, 18]. Therefore if one would wish to describe the evolution of the universe with the help of its wave function, one would be in trouble. The resolution of this paradox is rather instructive [18]. The notion of evolution is not applicable to the universe as a whole since there is no external observer with respect to the universe, and there is no external clock as well which would not belong to the universe. However, we do not actually ask why the universe *as a whole* is evolving in the way we see it. We are just trying to understand our own experimental data. Thus, a more precisely formulated question is why *we see* the universe evolving in time in a given way. In order to answer this question one should first divide the universe into two main pieces: i) an observer with his clock and other measuring devices and ii) the rest of the universe. Then it can be shown that the wave function of the rest of the universe does depend on the state of the clock of the observer, i.e. on his “time” [18]. This time dependence in some sense is “objective”, which means that the results obtained by different (macroscopic) observers living in the same quantum state of the universe and using sufficiently good (macroscopic) measuring apparatus agree with each other [19].

This example teaches us an important lesson. By an investigation of the wave function of the universe *as a whole* one sometimes gets information which has no direct relevance to the observational data, e.g. that the universe does not evolve in time. (Moreover, it is rather difficult to give any probabilistic interpretation to the wave function of the universe as a whole, since typically it is not normalizable.) In order to describe the universe *as we see it* one should divide the universe into several macroscopic pieces and calculate a conditional probability to observe it in a given state under an obvious condition that the observer and his measuring apparatus do exist. (A similar approach was used e.g. in [20].) This simple condition, however, is very restrictive. In order to understand its meaning one should remember the famous Einstein-Podolsky-Rosen experiment, where two fermions (or photons) are produced by a decay of a spin zero particle. By a measurement of a spin of one of the particles an observer instantaneously determines the spin of another particle even if this particle and the observer are not in a causal contact at the moment of the measurement. This apparent paradox is resolved if one takes into account that prior to the measurement one should describe both particles by the wave function of the pair of particles rather than by separate wave functions of each of them. The knowledge of this wave function (the fact that it corresponds to a state with zero angular momentum) and the knowledge of the spin of one of these particles makes it possible to determine the spin of another particle without making any causal contact with it, just for the reason that there is a strong correlations between spins of particles in a system with a vanishing total angular momentum. For example, the conditional probability to find the second particle in a state with spin $s = -1/2$ is equal to unity under the condition that the first particle has a spin $s = +1/2$.

Similarly, any scientific exploration of the properties of the universe starts from the division of the universe into two subsystems (the observer with his measuring devices and the rest of the universe). Due to a strong correlation between the properties of these two subsystems, an investigation of our own properties, the properties of our environment and our measuring devices makes it possible to say a lot about the properties of the rest of the universe such as the vacuum energy, the values of some coupling constants etc.

It is important also, that in the EPR experiment one can choose different apparatus, e.g. the one which measures a linear polarization of the first photon, or the one which measures its circular polarization. After the measurement the second photon will be either linearly or circularly polarized, depending on our choice of measuring device. Similarly, many kinds of life and many types of measuring devices may exist, but what we are studying is the correlation of *our* kind of life, environment and measuring devices with the properties of the rest of the universe. But this means that in the context of the baby universe theory one can actually make sense of the Strong Anthropic Principle and try to explain why the electromagnetic coupling constant, the gravitational coupling constant and some other parameters of the theory have those particular values which we know: With other values of the coupling constants the existence of life *of our type* and of the measuring devices we use would be impossible. (Note, however, that in this interpretation the Strong Anthropic Principle has nothing in common with designing the universe for the benefit of human beings or with changing the whole universe by our own will, just as the determination of the properties of the second particle in the EPR experiment and the dependence of these properties on our choice of measuring device has nothing to do with the acausal action at a distance.)

If this idea is correct, then there is no need to compute the most probable values of the cosmological constant and of the gravitational constant by the investigation of the wave function of the universe as a whole, and it is not surprising that some of the results of the corresponding investigation look as counterintuitive as the statement that the universe as a whole does not depend on time. Rather one should investigate the probability to measure some particular eigenvalues of the operators corresponding to the "constants" Λ, e, m_e, G in the quantum state of the universe in which we live now under the obvious condition that we can live and perform our measurements here. In some cases (e.g. in the case of the constants e, m_e, G) the corresponding investigation is rather simple and straightforward. For example, according to [21], an increase of m_e by more than 2.5 times would make impossible the existence of atoms. An increase of e by more than 30 % would lead to an instability of proton and nuclei. A change of the strong interaction constant by more than 10 % would lead to the absence of heavy nuclei and of hydrogen in the universe. An increase or decrease of the weak interaction constant by an order of magnitude would lead to absence of complex elements or of hydrogen respectively. An increase of the gravitational

constant G by an order of magnitude would make the lifetime of the Sun so small that no biological molecules would appear on the Earth. An even bigger increase of G would lead to an extremely efficient nucleosynthesis and to the absence of hydrogen in the universe [21, 22]. A smaller value of G would make expansion of the universe more slow. In such a universe the departure from thermal equilibrium during the process of baryosynthesis would be small, this process would be inefficient and the universe now would be practically empty.

This list can be easily continued, but we hope that the results discussed above clearly demonstrate that the correlation between the properties of observers and the properties of the quantum state of the rest of the universe is very strong indeed. Moreover, most of the results discussed above are not so much *anthropic*, they just show that a small deviation from the present values of coupling constants would make impossible the existence of all measuring devices we use. In the context of the baby universe theory this means that the distribution of the conditional probability to make measurements in a quantum state with given values of weak, strong, gravitational and some other “fundamental constants” proves to be sharply peaked near the actual values of these constants we have measured in the quantum state of the universe in which we live now. This peak in the probability distribution should be especially narrow in unified theories of all fundamental interactions where the values of different coupling constants are strongly correlated due to the underlying symmetry of the theory. This indicates that if one wishes to get an order-of-magnitude estimate of the coupling constants, in some cases one can do it without a computation of these constants in the context of the “big fix” paradigm [14], and if one still wishes to make a computation (which, of course, is a good idea), then one should compute the amplitudes corresponding to the actual experimental environment rather than the amplitudes corresponding to the metaphysical “universe in itself” investigated by an imaginary external observer. (The discussion of the time-independence of the wave function of the universe shows that in the context of quantum cosmology the subtle difference between the amplitudes of these two types can be crucially important.)

Now let us return to the discussion of the cosmological constant problem. The possibility to explain the small value of the vacuum energy density $|\rho_v| < 10^{-29} g.cm^{-3}$ with the help of the Anthropic Principle is much less clear, but is not hopeless. From the results of ref. [7] it follows that formation of galaxies and appearance of life of our type is possible only if $-10^{-29} g.cm^{-3} < \rho_v < 10^{-27} g.cm^{-3}$. In the context of the baby universe theory this means that the conditional probability to measure the vacuum energy density ρ_v is concentrated in the interval between $-10^{-29} g.cm^{-3}$ and $10^{-27} g.cm^{-3}$ under the condition that the measurement is made by an observer of our type. This result could be strengthened up to the desirable constraint $|\rho_v| < 10^{-29} g.cm^{-3}$ if it would be possible to prove that life on the Earth has an extragalactic origin. (Any communication between galaxies would be

hampered by the exponential expansion of the universe with $\rho_v > 10^{-29} g.cm^{-3}$.) Unfortunately, at the moment we have no evidence in favour of this extravagant hypothesis. (Of course, one can turn this argument upside down and say that the vanishing of the cosmological constant can be considered as an argument in favour of the extragalactic origin of life. However, this will be true only if no other solution of the cosmological constant problem will be found.)

Another possibility is related to the results obtained in the first part of this paper. It may be not unreasonable to assume that the conditional probability to be born in the universe in a quantum state with a given value of ρ_v is proportional to the total volume of those parts of the universe with this value of ρ_v where life of our type can appear. From the investigation performed in the beginning of this paper it follows that in the quantum states with $|\rho_v| < 10^{-29} g.cm^{-3}$ the total volume of the parts of the universe where life can exist is much bigger than in the states with $|\rho_v| > 10^{-29} g.cm^{-3}$, and it may be especially big in the states with $|\rho_v| < 10^{-10^7} g.cm^{-3}$. If there is some relation between the total volume of the parts of the universe where life can exist and the volume where life of our type can appear, then one can argue that the probability that we measure the vacuum energy density ρ_v in our quantum state of the universe $|\alpha_i\rangle$ is peaked in the region $|\rho_v| < 10^{-10^7} g.cm^{-3}$. This would be more than enough to solve the cosmological constant problem.

Unfortunately, this line of reasoning, which may lead to a justification of the so-called Final Anthropic Principle [22] in its strongest form, is still far from being well elaborated. There are many obvious and less obvious objections which can be raised against the arguments suggested above. It is quite possible that the cosmological constant problem eventually will be solved in quite a different way, e.g. by some modification of ideas proposed in [10, 13, 14]. However, the efficiency of the Anthropic Principle for the determination of many other coupling constants in the context of the baby universe theory and the existence of a strong correlation between the value of the cosmological constant and the lifetime of mankind makes it very tempting to continue an investigation of the possibilities discussed above. At the very least, what we have obtained already is a surprising result that the existence of the vacuum energy density as small as $10^{-10^7} g.cm^{-3}$ would be fatal for the future evolution of life in our part of the universe. This is the first indication of the potential practical importance of recent attempts to investigate the cosmological constant problem. Unfortunately (or, may be, fortunately), it may take as much as $10^{5.10^6}$ years until the significance of the current work on this problem will be fully appreciated.

REFERENCES

- [1] A. D. Linde, Phys.Lett. B 175 (1983) 177.
- [2] A. Vilenkin and L. H. Ford, Phys. Rev. D 25 (1982) 1231; A. D. Linde, Phys. Lett. B 116 (1982) 335; A. A. Starobinsky, Phys.Lett. B 117 (1982) 175.
- [3] A. D. Linde, Phys.Lett. B 175 (1986) 395; A. S. Goncharov and A. D. Linde, JETP 65 (1987) 635.
- [4] P. Steinhardt, in: The Very Early Universe, eds. S. W. Hawking, G. Gibbons and S. Siklos (Cambridge U.P., Cambridge, 1983); A. D. Linde, Non-singular Regenerating Inflationary Universe, Cambridge university preprint (1982); A. Vilenkin, Phys. Rev. D 27 (1983) 2848.
- [5] A. D. Linde, Phys.Lett. B 211 (1988) 29.
- [6] A. S. Goncharov, A. D. Linde and V. F. Mukhanov, Intern. J. Mod. Phys. A 2 (1987) 561.
- [7] S. Weinberg, Phys. Rev. Lett. 59 (1987) 2607; Rev. Mod. Phys. 61 (1989) 1.
- [8] A. D. Linde and M. I. Zelnikov, Phys. Lett. B 215 (1988) 59.
- [9] A. D. Linde, Phys. Lett. B 200 (1988) 272.
- [10] A. D. Linde, Particle Physics and Inflationary Cosmology (Gordon and Breach, to be published).
- [11] S. Coleman, Nucl. Phys. B 307 (1988) 864.
- [12] S. Giddings and A. Strominger, Nucl. Phys. B 307 (1988) 854.
- [13] T. Banks, Nucl. Phys. B 309 (1988) 493.
- [14] S. Coleman, Nucl. Phys. B 310 (1989) 643.
- [15] J. Polchinski, Phys. Lett., to be published.
- [16] W. Fischler, I. Klebanov, J. Polchinski and L. Susskind, Stanford University preprint, (1989).
- [17] J. A. Wheeler, in Batelleis Recontres, eds. C. DeWitt and J. A. Wheeler (Benjamin, New York, 1968).
- [18] B. S. DeWitt, Phys. Rev. 160 (1967) 113.

- [19] H. Everett, *Rev. Mod. Phys.*, 29 (1957) 454; B. S. DeWitt and N. Graham, *The Many-Worlds Interpretation of Quantum Mechanics* (Princeton University Press, Princeton, 1973).
- [20] S. W. Hawking and D. N. Page, *Nucl. Phys. B* 264 (1986) 185.
- [21] I. L. Rosental, *Big Bang, Big Bounce: How Particles and Fields Drive Cosmic Evolution* (Springer, Berlin, 1988).
- [22] J. Barrow and F. Tipler, *The Cosmological Anthropic Principle* (Oxford University Press, Oxford, 1986).