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Hot big bang or slow freeze?

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ABSTRACT

We confront the big bang for the beginning of the universe with an equivalent picture of a slow freeze — a very cold and slowly evolving universe. In the freeze picture the masses of elementary particles increase and the gravitational constant decreases with cosmic time, while the Newtonian attraction remains unchanged. The freeze and big bang pictures both describe the same observations or physical reality. We present a simple "crossover model" without a big bang singularity. In the infinite past space–time is flat. Our model is compatible with present observations, describing the generation of primordial density fluctuations during inflation as well as the present transition to a dark energy-dominated universe.

The early stages in the evolution of our universe are generally depicted as a big bang. The temperature of an early plasma of radiation and particles was much higher than the temperature of 2.7 K measured in the cosmic microwave background (CMB), exceeding in early stages by far the temperature of the sun or any other object in the present universe. This fireball resulted from a type of extremely fast primordial explosion — the big bang. Characteristic time scales of the early stages of the explosion were 10^{-30} seconds or shorter, extremely tiny as compared to the present time scale of the cosmic expansion of around 10^{10} years.

In this note we contrast the big bang picture with a very different alternative picture of a slow freeze. We present a specific "crossover model" which is described both in the freeze and big bang pictures. In the freeze picture the characteristic mass scale is set by a parameter

$$\mu = 2 \cdot 10^{-33}\ \text{eV}. \tag{1}$$

This parameter is about the value that the present Hubble parameter takes in the big bang picture. In contrast to the big bang picture, however, the time scale $\mu^{-1} = 10^{10}$ yr ($\hbar = c = k_B = 1$) characterizes the evolution of the universe during the radiation- and matter-dominated epochs as well. For the inflationary epoch in primordial cosmology, the characteristic time scale increases to even larger values, tending to infinity in the infinite past. The evolution of the universe has always been very slow. The cosmological solution can be continued to the infinite past. No big bang singularity is present.

In the freeze picture, the universe is shrinking rather than expanding during the radiation- and matter-dominated epochs [1]. Correspondingly, the temperature decreases if we look back in time — the early universe was an extremely cold place. At the time when the CMB was emitted, the temperature of the plasma was only 82 mK. And the universe was even much colder further in the past. Looking backwards in time, we may associate the early stages of the universe with a state of "freeze" from which the universe is very slowly thawing.

Despite the striking differences to the big bang picture for the evolution of geometry and temperature, this freeze picture is compatible with all present cosmological and experimental observations. The crucial ingredient is the increase of all particle masses as well as the Planck mass, induced by a scalar field χ whose value increases monotonically. In the infinite past, χ goes to zero, while its present value has reached the reduced Planck mass $\chi(t_0) = M = 2.44 \cdot 10^{18}$ GeV. In our normalization, χ can be associated directly with the variable Planck mass. The mass of the electron m_e or the proton m_p is proportional to χ. The strict observational bounds on a time variation of the ratio between nucleon mass and Planck mass, or the ratio m_e/m_p, are obeyed. The electromagnetic fine structure constant does not depend on χ, such that atomic binding energies scale $\sim m_e \sim \chi$.

Looking towards the past, the electron mass decreases even faster than the temperature. At the time of the CMB emission one has $m_e \approx 14.2$ eV, such that $T/m_e = 5 \cdot 10^{-7}$, with the binding energy of hydrogen around 50 times the temperature. The size of the hydrogen atom at this moment is 1.9 μm, a factor 36000 larger than the present Bohr radius. The scale factor at least scattering was larger than today, $a_{ls}/a_0 \approx 33$. However, the ratio of the scale factor divided by the size of the hydrogen atom was a factor 1091 smaller than at present, the same as in the big bang picture. Physical observables are dimensionless and can therefore depend only on dimensionless ratios of masses or lengths. Thus the big bang and freeze pictures can describe the same physical reality.

The potential and kinetic energy of the homogeneous scalar field $\chi(t)$ can be associated with dynamical dark energy [2,3].

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The scalar field χ plays the role of the cosmon. Our model contains no fixed parameter for the gravitational constant. The Planck mass increases with time and is huge at present due to a long exponential increase of $\chi(t)$. The tiny ratio of the present dark energy density divided by the fourth power of the Planck mass, $\rho_h(t_0)/\chi^4(t_0) = \rho_h(t_0)/M^4$, is explained dynamically and does not require any tuning of parameters. In the early stages of cosmology the same scalar field χ acts as the inflaton. Our model realizes "cosmon inflation" [4].

The proposed crossover model can be described equivalently in a big bang picture. This is achieved by a Weyl scaling [5,6] of the metric. In the resulting "Einstein frame" the Planck mass or m_e and m_p do no longer depend on time. In this frame our model becomes a standard quintessence model with an exponential potential. Also inflation takes a familiar form. Physical observables do not depend on the choice of frame [7–11] ("field relativity" [1]). They are often computed most easily in the Einstein frame. The naturalness of our model is, however, better understood in the freeze frame.

We emphasize that the ratio between temperature and the electron mass was higher in the past than today in both pictures. In this relative sense the "hot plasma" inferred from nucleosynthesis or the CMB is realized in nature, independently of the picture. When we compare the temperature of the plasma to the present temperature of the CMB the possible time evolution of the electron mass enters, however. This leads in the freeze picture to a plasma temperature much smaller than the present CMB-temperature.

In this note we investigate a very simple model which involves only three dimensionless parameters besides the masses and couplings of the particles of the standard model of particle physics. It is compatible with all present cosmological observations, ranging from primordial density fluctuations to the present properties of dark energy. Involving no more free parameters than the ΛCDM model of a cosmological constant, our model is subject to many observational tests and possible falsification.

Crossover model. The coupled cosmon-gravity system of our model is specified by the quantum effective action

$$\Gamma = \int d^4x \sqrt{g}\left\{-\frac{\chi^2}{2}R + \left(\frac{2}{\alpha^2} - 3\right)\partial^\mu\chi\,\partial_\mu\chi + V(\chi)\right\}, \qquad (2)$$

from which the field equations for the metric and the cosmon follow by variation. The metric $g_{\mu\nu}$ appears in the curvature scalar R, $\partial^\mu = g^{\mu\nu}\partial_\nu$ and $g = -\det(g_{\mu\nu})$. For the cosmon potential we assume $V = \mu^2\chi^2$ for large χ and $V = \lambda\chi^4$ for small χ, as implemented by

$$V = \frac{\mu^2\chi^4}{m^2 + \chi^2}, \qquad \lambda = \frac{\mu^2}{m^2}. \qquad (3)$$

Stability requires $\alpha^2 > 0$, with $\alpha \to \infty$ corresponding to the "conformal value". The action (2) involves two dimensionless parameters α and λ. It specifies our model combined with an assumption on the χ-dependence of particle masses that we discuss next. For this simple model we will find solutions of the homogeneous and isotropic field equations which have no singularity and can account for all present observations in cosmology.

Our model is based on the assumption of the existence of two fixed points for quantum gravity. For the first one, relevant for $\chi = 0$, scale symmetry is exact and not spontaneously broken. All particles are massless. The second fixed point corresponds to $\chi \to \infty$ where scale symmetry is again exact. For $\chi \neq 0$ scale symmetry is spontaneously broken, however, resulting in massive particles. For $\chi \to \infty$, spontaneous scale symmetry breaking induces a Goldstone boson, the dilaton. Cosmology describes the transition between the two fixed points, with $\chi \to 0$ in the infinite past and $\chi \to \infty$ in the infinite future. Intermediate values of χ are associated to a crossover between the two fixed points. In this region scale symmetry is violated by the appearance of parameters with dimension mass or length. In the scalar-gravity sector this concerns the potential (3).

Scale symmetry (or dilatation symmetry) plays a central role for the deeper particle physics understanding of our model and the judgment of its naturalness. (This symmetry is no longer easily visible in the Einstein frame.) Dilatation symmetry states the invariance of physics under a multiplicative scaling of all mass and associated length scales. It is realized as an exact symmetry if the quantum effective action contains no parameter with dimension of mass or length. The parameters μ or m in the potential (3) have dimension mass and reflect a violation of scale symmetry (dilatation anomaly). Nevertheless, scale symmetry of the effective action (2) and the associated field equations is realized for the limits $\chi \to 0$ and $\chi \to \infty$. Besides the "explicit scale symmetry breaking" by the mass scales μ and m any cosmological solution with a non-vanishing χ amounts to "spontaneous scale symmetry breaking". For present cosmology this spontaneous symmetry breaking is the dominant ingredient for the observed particle masses and the gravitational constant [2].

In general, quantum effects violate scale symmetry. This is reflected in the χ-dependence of dimensionless couplings as gauge couplings g or Yukawa couplings. For "running couplings" or non-vanishing β-functions, as $\tilde{\beta}_g = \chi\,\partial g(\chi)/\partial\chi$, the solution $g(\chi)$ can only depend on a dimensionless quantity as χ/m and therefore necessarily involves a mass scale m (dimensional transmutation). By the same argument, any χ-dependence of dimensionless ratios, as $m_e(\chi)/m_p(\chi), m_p(\chi)/\chi$ or $V(\chi)/\chi^4$, reflects a violation of scale symmetry.

Since a dimensionless quantity as $v = V/\chi^4$ can only depend on m/χ, its flow equations in dependence on the "renormalization scale" m is directly related to the flow equation in dependence on the field χ

$$m\frac{\partial v}{\partial m} = -\chi\frac{\partial v}{\partial\chi} = -\tilde{\beta}_v. \qquad (4)$$

We will assume the existence of two fixed points for $m = 0$ and $m \to \infty$, or correspondingly for $\chi \to \infty$ and $\chi = 0$, $\tilde{\beta}_v(\chi = 0) = 0$, $\tilde{\beta}_v(\chi \to \infty) = 0$, with fixed point values $v(\chi = 0) = \lambda$, $v(\chi \to \infty) = 0$. For a fixed point in the flow of all dimensionless couplings and ratios scale symmetry becomes exact. (This is well known from critical phenomena in statistical physics.) At a fixed point all β-functions for appropriately renormalized dimensionless quantities vanish. Since the β-functions and therefore their zeros are connected to quantum effects, we may call the scale symmetry associated to a fixed point "quantum scale symmetry".

For $\chi \to 0$ we approximate in Eq. (3) $m^2 + \chi^2$ by m^2. The potential involves then only the dimensionless parameter λ and becomes indeed scale invariant. (Scale symmetry breaking terms are suppressed by χ^2/m^2.) In the asymptotic past $t \to -\infty$ the field χ approaches zero and our model realizes dilatation symmetry. On the other hand, for $\chi \to \infty$ the potential divided by the fourth power of the effective Planck mass goes to zero, $V/\chi^4 \to \mu^2/\chi^2 \to 0$. Up to small corrections $\sim \mu^2/\chi^2$ the limit $\chi \to \infty$ describes again the approach to a situation with effective quantum scale symmetry. A fixed point $\lim_{\chi\to\infty}(V/\chi^4) = 0$ solves the cosmological constant problem if the cosmological solution implies that χ diverges for asymptotic time $t \to \infty$. This is realized for our model and explains why no fine tuning of parameters is needed in order to realize the tiny present dark energy density in units of the Planck mass.