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Dynamical mechanism of vacuum energy compensation

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Abstract The model of vacuum energy compensation due to interaction of a scalar field ϕ with curvature scalar of the form $\beta R\phi^2 f(\phi)$ is proposed. It is shown that with a simple power form of $f(\phi)$ the exponential expansion, induced by vacuum energy (or what is the same by cosmological constant), is transformed into canonical cosmological evolution of the universe dominated by relativistic matter.

1 Introduction

The problem of the cosmological term or, what is the same, of vacuum energy presents an outstanding challenge to both (quantum) field theory and cosmology. Lambda-term was introduced by Einstein at 1917 [1] in futile attempt to make stationary universe. According to Gamow recollection [2], Einstein considered this idea as "biggest blunder" of his life. The generalised by an addition of Λ-term the Hilbert–Einstein action of General Relativity (GR) takes the form:

$$S = -\frac{M_{Pl}^2}{16\pi}\int d^4x\sqrt{-g}(R+\Lambda) \equiv -\frac{M_{Pl}^2}{16\pi}\int d^4x\sqrt{-g}R - \varrho_{vac}\int d^4x\sqrt{-g}, \tag{1}$$

where $g_{\mu\nu}$ is the metric tensor, g is its determinant, $M_{Pl} = 1.22\times 10^{19}$ GeV is the Planck mass, related to the Newton gravitational coupling constant as $G_N = 1/M_{Pl}^2$. The cosmological constant Λ is equivalent to the energy density of vacuum:

$$\varrho_{vac} = \frac{M_{Pl}^2}{16\pi}\Lambda. \tag{2}$$

In absence of matter the GR equations has the so called De Sitter cosmological solution describing exponentially expanding universe.

To describe realistic universe one has to add into the above action the usual matter. The Einstein equations, with Lambda-term and matter included, have the form:

$$\frac{M_{Pl}^2}{8\pi}\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right) \equiv \frac{M_{Pl}^2}{8\pi}G_{\mu\nu} = T_{\mu\nu}^{(matt)} + T_{\mu\nu}^{(vac)}, \tag{3}$$

where $T_{\mu\nu}^{(matt)}$ is the energy–momentum tensor of matter. The energy–momentum tensor of vacuum has the form:

$$T_{\mu\nu}^{(vac)} = g_{\mu\nu}\varrho_{vac}. \tag{4}$$

The combination $G_{\mu\nu} = R_{\mu\nu} - g_{\mu\nu}R/2$ is called the Einstein tensor.

We assume that the space is homogeneous, isotropic, and 3D flat, so the 4D interval has the form:

$$ds^2 \equiv g_{\mu\nu}dx^\mu dx^\nu = dt^2 - a^2(t)d\mathbf{r}^2. \tag{5}$$

It is convenient to rewrite the Einstein equations in terms of the mixed, upper and lower, indices. In particular, using equation $G_0^0 = 3(\dot{a}/a)^2$, which is valid for metric (5), we come to the first Friedman equation:

$$\frac{3H^2M_{Pl}^2}{8\pi} = T_0^0 = \varrho_{matt} + \varrho_{vac}, \tag{6}$$

where $H = \dot{a}/a$ is the Hubble parameter and ϱ_{matt} is the energy density of matter. For example for relativistic matter in thermal equilibrium with temperature T the energy density of matter is equal to $\varrho_{matt} = \pi^2 g_* T^4/30$ where g_* is the number of relativistic species. Note that the trace of the energy–momentum tensor of relativistic matter vanishes: $T_\mu^{(rel)\mu} = 0$.

According to theoretical estimates, the magnitude of vacuum energy is by far larger than observational bounds on its possible value. It is tempting to identify vacuum energy with cosmological dark energy (DE), since they have the same equation of state: $P = -\varrho$, where P and ϱ are respectively

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the pressure and energy densities. As known, the dark energy makes about 70% of the total cosmological energy density and thus the cosmological density of DE is equal to:

$$\varrho_{DE} \sim 1\,\mathrm{keV/cm^3} \approx 10^{-47}\,\mathrm{GeV}^4. \tag{7}$$

On the other hand theoretical estimates give either infinitely large value or, in the case of cancellations of vacuum energies of bosonic and fermionic vacuum fluctuations [3,4], the result that could be of the order of the supersymmetry breaking scale:

$$\varrho^{\mathrm{vac}}_{\mathrm{SUSY}} \sim m^4_{\mathrm{SUSY}} \sim 10^{55}\varrho_{DE}, \tag{8}$$

where m_{SUSY} is supposed to be of order of 100 GeV. For more detail and extensive list of references see e.g. review [5].

It is noteworthy that during cosmological evolution, vacuum energy underwent colossal jumps during phase transitions from a symmetrical phase to a phase with broken symmetry. The problem of vacuum energy becomes especially serious if we consider the structure of the vacuum of quantum chromodynamics. As is known, a proton consists of three light quarks: $p = uud$, where the mass of each quark is, roughly speaking, 5 MeV. Therefore, one should expect that the proton mass should be very small, $m_p \approx (15\,\mathrm{MeV} - E_{bind})$, where E_{bind} is the binding energy of quarks in a proton. The result obtained is slightly more than 0.01 fraction of the proton mass. The missing contribution to the mass comes from the nontrivial properties of the QCD vacuum. Contrary to intuitive expectations, this vacuum turns out to be not empty, but filled with a condensate of quarks, q [6] and gluon fields [7]:

$$\langle \bar{q}q \rangle \neq 0, \ \langle G_{\mu\nu}G^{\mu\nu} \rangle \neq 0, \tag{9}$$

where $G_{\mu\nu}$ is the field strength tensor of the gluon fields, which are analogous to the Maxwell field strength field $F_{\mu\nu}$, with an account of self-interactions inherent to non-abelian gauge theories.

Energy densities of these condensates are about $\varrho^{(cond)}_{vac} \approx 1\ \mathrm{GeV}^4$. However, it is argued that quarks inside a proton destroy the condensates and the proton mass would be equal to:

$$m_p = 2m_u + m_d - \varrho^{(cond)}_{vac} l_p^3 \sim 1\ \mathrm{GeV}, \tag{10}$$

where $l_p \sim 1/(\mathrm{GeV})$ is the proton size. The energy density of the condensate must be negative and by 47 orders of magnitude larger than the observed value (7). Thus there is experimentally known contribution to vacuum energy and one has to conclude that something else, except for quarks and gluons, "lives" in vacuum and this "something," perhaps some new field, compensates ϱ_{vac} by 47 orders of magnitude.

There are several suggestions in the literature, where the problem of vacuum energy is discussed. Probably incomplete list of recent works includes [8–12]. Somewhat similar approach to that in the presented paper was studied in earlier papers [13–15], where the singular interaction between a kinetic term of a scalar field and curvature scalar was considered:

$$L_{int} = \frac{\partial_\mu\phi\partial^\mu\phi}{2R^2}. \tag{11}$$

In subsequent work [16] several different types of the interaction potential between the curvature scalar and a scalar field have been considered. However, in each case, the transition to the canonical cosmology dominated by usual matter was not realised.

The first model of dynamical reduction of vacuum energy via interaction of R with a scalar field, proposed in [17], involved a massless scalar field with the action:

$$\begin{aligned} S_\phi &= \int d^4x\sqrt{-g}\mathcal{L} \\ &= \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - U(\phi, R)\right]. \end{aligned} \tag{12}$$

Homogeneous field $\phi = \phi(t)$ in FLRW metric (5) satisfies the equation of motion:

$$\ddot{\phi} + 3H\dot{\phi} + \partial U/\partial\phi = 0. \tag{13}$$

It is assumed that ϕ is non-minimally coupled to gravity with the potential $U(\phi, R)$ chosen in the simplest form:

$$U = \frac{1}{2}\left(\beta R + m^2\right)\phi^2. \tag{14}$$

The coupling of scalar field to curvature scalar of such a form was stimulated by the suggestion to construct conformally invariant description of scalar field in curved space time, see e.g. [18,19] and a comment below Eq. (22).

It is easy to see that when $\beta R < 0$ and $|\beta R| > |m^2|$ the equation of motion (13) in de Sitter space-time has unstable solutions, exponentially rising with time, since at constant curvature R the square of the effective mass of the field ϕ is negative. A similar situation occurs in the Higgs model, when long-wave states with $\phi = 0$ turn out to be unstable.

With rising ϕ its influence on cosmological evolution can no longer be neglected and, as can be easily verified, the initial exponential expansion, $a(t) \sim \exp(H_{vac}t)$, will asymptotically transform into a power-law one: $\phi \sim t$ and $a(t) \sim t^\kappa$, where κ is a certain constant expressed through the model parameters. Thus, the reverse reaction of ϕ to the cosmological expansion leads to the transformation of the exponential expansion law into the Friedman law, despite the presence of nonzero vacuum energy.

Among the shortcomings of this simple model is that the energy–momentum tensor of this field is not proportional to the metric tensor, $T_{\mu\nu} \neq \Lambda g_{\mu\nu}$, and therefore the vacuum energy does not vanish, even asymptotically. The change in the expansion regime is achieved due to the weakening of the gravitational interaction. The gravitational coupling constant

decreases with time, first exponentially, and then as the square of time: $G_N \sim 1/t^2$. If such a change in G_N took place in the early universe and later somehow stabilised, then this mechanism could explain the hierarchy of the gravitational and electroweak scales. The suggestion is quite far fetched and speculative. It is based on the assumption of unification of gravitational and all other forces at some high energies. The evolution to low energies might explain a much weaker gravitational coupling due to decrease of G_N.

Let us mention in this connection a recent paper [20], where exactly the same statement as in Ref. [17] was repeated, namely that the effective vanishing of vacuum energy is forced by the time variation of the gravitational coupling constant.

2 Generalisation of the model

In the future we plan to eliminate the shortcomings of the simplest original model with the interaction (14) studying instead a more general coupling between scalar field ϕ and the curvature scalar in the form:

$$\mathcal{L}_F = \frac{1}{2}\phi^2\left[\beta R F(R,\phi) + m^2\right]. \tag{15}$$

Our purpose is to find any model which is free of the problems mentioned above and allows to effectively eliminate vacuum energy.

In this work we study as a toy model a simple modification of interaction (15) that can effectively do the job of transformation of exponential cosmological expansion into the observed power law one. To this end we assume the following coupling of curvature to scalar field ϕ and adjust the form of such interaction that this task is fulfilled:

$$\begin{aligned}\mathcal{L}_f &= \frac{1}{2}\phi^2\left[\beta R f(\phi) + m^2\right] \\ &\equiv \frac{1}{2}\left[\phi^2 m^2 + \beta R Q(\phi)\right],\end{aligned} \tag{16}$$

where we introduced the notation $Q(\phi) = \phi^2 f(\phi)$.

Equation of motion for homogeneous field ϕ takes the form:

$$\begin{aligned}&g^{\mu\nu} D_\mu D_\nu \phi + m^2\phi + \frac{1}{2}\beta R \partial_\phi Q \\ &\quad = \ddot{\phi} + 3H\dot{\phi} + m^2\phi + \frac{1}{2}\beta R\, \partial_\phi Q = 0,\end{aligned} \tag{17}$$

where D_μ is the covariant derivative in metric (5) and $\partial_\phi Q = \partial Q/\partial\phi$.

The energy–momentum tensor of ϕ is defined as the variation of the action over the metric tensor:

$$T_{\mu\nu} = \frac{2}{\sqrt{-g}}\frac{\delta S}{\delta g^{\mu\nu}}, \tag{18}$$

and correspondingly:

$$\begin{aligned}T_{\mu\nu} &= (\partial_\mu\phi)(\partial_\nu\phi) - (1/2)g_{\mu\nu}\left[g^{\alpha\beta}(\partial_\alpha\phi)(\partial_\beta\phi) - m^2\phi^2\right] \\ &\quad -\beta Q(\phi)\left(R_{\mu\nu} - g_{\mu\nu}R/2\right) + \beta\left(D_\mu D_\nu - g_{\mu\nu}D^2\right)Q(\phi).\end{aligned} \tag{19}$$

The covariant derivatives of Q are equal to:

$$D_\mu Q = (\partial_\phi Q)\partial_\mu\phi, \quad D^2 Q = \partial_\phi^2 Q \partial_\mu\phi\partial^\mu\phi + \partial_\phi Q D^2\phi. \tag{20}$$

Using equation of motion (17) we find the trace of the energy–momentum tensor:

$$\begin{aligned}T^\nu_\nu &= -(\partial\phi)^2(3\beta\partial_\phi^2 Q + 1) + 2m^2\phi^2 + \beta Q R + 3\beta \\ &\quad \times\left[(\partial_\phi Q)m^2\phi + \beta R(\partial_\phi Q)^2/2\right].\end{aligned} \tag{21}$$

For a special case $Q = \phi^2$ the trace is

$$\begin{aligned}T^\nu_\nu &= -(6\beta+1)(\partial_\mu\phi)(\partial^\mu\phi) \\ &\quad +\beta(6\beta+1)R\phi^2 + 2(1+3\beta)m^2\phi^2.\end{aligned} \tag{22}$$

This is the well known result [18,19]. Note that for $\beta = -1/6$ and $m = 0$ the trace vanishes.

Now we introduce a more complicated function instead of $f(\phi)$, or better to say instead of $Q(\phi)$, to cure the problems of a simpler model described above:

$$\bar{Q}(\phi, M_0, k) = \phi^2(1 + \sigma\phi^2/M_0^2)^k, \tag{23}$$

where M_0, k, and σ are some constant parameters to be fixed below. We take $\sigma = \pm 1$.

The derivatives of $\bar{Q}$ over ϕ are given by:

$$\partial_\phi\bar{Q} = \frac{2k\sigma\phi^3(1+\sigma\phi^2/M_0^2)^{k-1}}{M_0^2} + 2\phi(1+\sigma\phi^2/M_0^2)^k, \tag{24}$$

$$\begin{aligned}\partial_\phi^2\bar{Q} &= \frac{4(k-1)k\sigma^2\phi^4(1+\sigma\phi^2/M_0^2)^{k-2}}{M_0^4} \\ &\quad +\frac{10k\sigma\phi^2(1+\sigma\phi^2/M_0^2)^{k-1}}{M_0^2} + 2(1+\sigma\phi^2/M_0^2)^k.\end{aligned} \tag{25}$$

Taking trace of Einstein equations (3) we find the relation:

$$\begin{aligned}&R\left(\beta\bar{Q} + \frac{3\beta^2(\partial_\phi\bar{Q})^2}{2} + \frac{M_{Pl}^2}{8\pi}\right) \\ &= (\partial\phi)^2(3\beta\partial_\phi^2\bar{Q} + 1) - 2m^2\phi^2 - 3\beta m^2\phi(\partial_\phi\bar{Q}) \\ &\quad -4\varrho_{vac} - \tilde{T}^\nu_\nu,\end{aligned} \tag{26}$$

where $(\partial\phi)^2 = g^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi)$ and $\tilde{T}^\nu_\nu$ is the trace of the energy–momentum tensor of the other kinds of matter. This equation allows to express R through ϕ and its first derivative.

3 Numerical calculations

There are the following two differential equations that govern cosmological evolution:

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi + \frac{1}{2}\beta R\,\partial_\phi Q = 0, \tag{27}$$

$$\dot{H} + 2H^2 = -R/6, \tag{28}$$

where R is a known function of ϕ and its first derivative given by Eq. (26).

To proceed further it is convenient to introduce dimensionless variables:

$$\tau = tH_0,\ \varphi = \phi/H_0,\ h = H/H_0,\ \frac{d}{dt} = H_0\frac{d}{d\tau},$$
$$R = rH_0^2,\ \varrho_{vac} = H_0^4\lambda,\ \bar{Q} = H_0^2 q,\ M_0 = H_0\mu. \tag{29}$$

Here H_0 is a normalisation constant, fixed by the condition $H_0^2 = 8\pi\,\varrho_{vac}^{(in)}/(3M_{Pl}^2)$, where $\varrho_{vac}^{(in)}$ is the original large vacuum energy. In what follows we denote derivative over τ by prime: $df/d\tau \equiv f'$.

The dimensionless function $q = \bar{Q}/H_0^2$ is expressed through dimensionless field φ as:

$$q = \frac{\bar{Q}}{H_0^2} = \varphi^2\left(1 + \sigma\varphi^2/\mu^2\right)^k. \tag{30}$$

The derivatives of $\bar{Q}$ (24), (25) turn into:

$$\frac{\partial_\phi \bar{Q}}{H_0} \equiv q_1 = \frac{2k\sigma\varphi^3(1+\sigma\varphi^2/\mu^2)^{k-1}}{\mu^2} + 2\varphi^2\left(1+\sigma\varphi^2/\mu^2\right)^k, \tag{31}$$

$$\partial_\phi^2\bar{Q} \equiv q_2 = \frac{4(k-1)k\sigma^2\varphi^4(1+\sigma\varphi^2/\mu^2)^{k-2}}{\mu^4} + \frac{10k\sigma\varphi^2(1+\sigma\varphi^2/\mu^2)^{k-1}}{\mu^2} + 2\left(1+\sigma\varphi^2/\mu^2\right)^k. \tag{32}$$

Finally we come to following two differential equations:

$$h' + 2h^2 = -\frac{r}{6}, \tag{33}$$

$$\varphi'' + 3h\varphi' + \beta r q_1/2 = 0, \tag{34}$$

where dimensionless curvature r is determined by Eq. (26) and equals to:

$$r = \frac{(3\beta q_2+1)(\varphi')^2 - 2(m/H_0)^2\varphi^2 - 3\beta(m/H_0)^2\varphi q_1 - 4\lambda - \tilde{T}/H_0^4}{3\beta^2 q_1^2/2 + M_{Pl}^2/(8\pi H_0^2) + \beta q}. \tag{35}$$

In what follows we assume that the mass of field ϕ is zero, $m = 0$, and that the trace of energy–momentum of other kinds of matter also vanishes, since it is supposed to be relativistic, $\tilde{T}_\nu^\nu = 0$, so r turns into

$$r_0 = \frac{(3\beta q_2+1)(\varphi')^2 - 4\lambda}{3\beta^2 q_1^2/2 + M_{Pl}^2/(8\pi H_0^2) + \beta q}. \tag{36}$$

Equations (33), (34) with r_0 given by Eq. (36) are solved numerically taken $\sigma = 1$. In Fig. 1 the evolution of dimensionless functions $h(\tau)$, $\varphi(\tau)$ and r_0 are presented at small values of dimensionless time τ, left panel (a) and large τ, right panel (b) and for the initial value of dimensionless vacuum energy $\lambda^{(in)} = 10^4$. Figure 2 is the same for $\lambda^{(in)} = 10^2$. For convenience we multiply all presented quantities by different numerical factors, indicated in figure captions, to make them of similar magnitude to be depicted in the same figures.

Numerical calculations demonstrate that even huge by absolute magnitude initial values of r_0 quickly tends down to zero, thus demonstrating that vacuum energy is compensated. Indeed, a constant value of curvature corresponds to a constant value of the Hubble parameter and therefore to exponentially expanding de Sitter universe. The impact of field ϕ results in asymptotical vanishing of R. Correspondingly, the de Sitter expansion turns into power law expansion. In other words, vacuum energy is completely compensated and we arrive to cosmology dominated by relativistic matter.

The Eqs. (33), (34) with $r_0 = 0$ are trivially solved analytically leading to the asymptotic results:

$$h(\tau) \to [2(\tau+\tau_0)]^{-1},\quad \varphi' \to C\tau^{-3/2},$$
$$\varphi \to const, \tag{37}$$

which pretty well agree with the numerical calculations. Evidently, $H \sim 1/2t$ corresponds to the canonical radiation dominated cosmology.

Let us note that numerical calculations are valid till $\tau \approx 30{-}40$. At larger τ instability of the numerical procedure leads unreasonable results, but at high τ we fortunately have accurate analytic solutions.

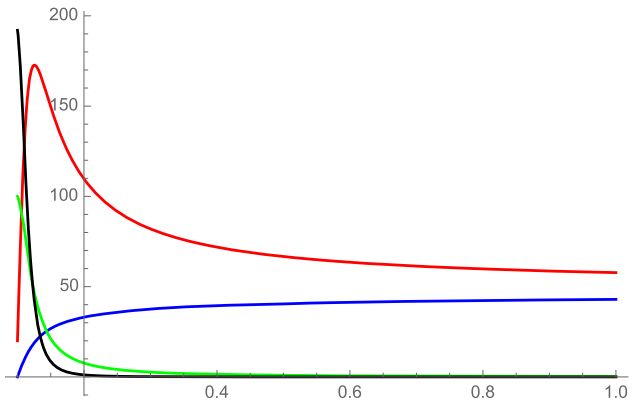
4 Conclusion

The model suggested in this paper efficiently does the job of elimination any original vacuum energy down to zero and leads to resulting realistic cosmology governed by relativistic matter. According to the relation:

$$R = -6(\dot{H} + 2H^2), \tag{38}$$

that is valid in arbitrary homogeneous and isotropic metric, the vanishing of R leads to the Hubble parameter satisfying equation:

$$\dot{H} + 2H^2 = 0. \tag{39}$$



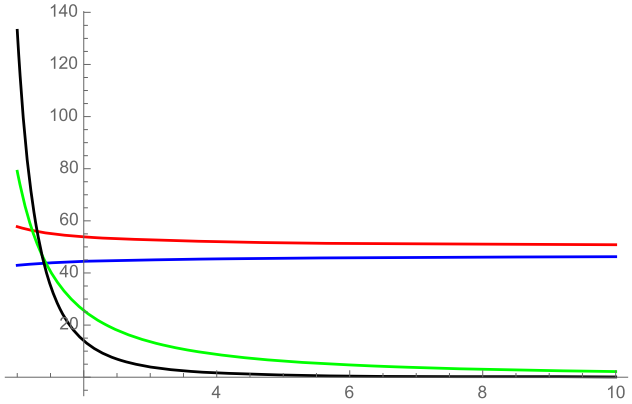
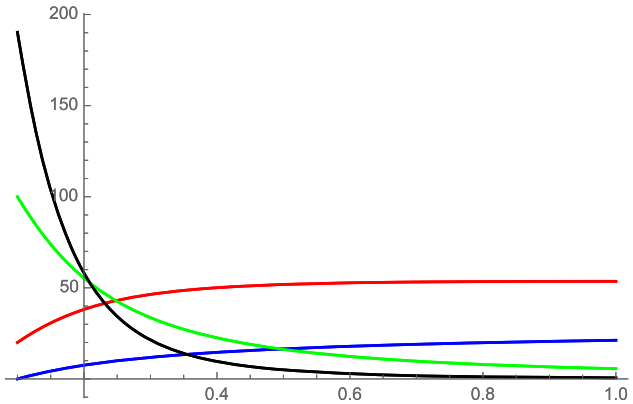


Fig. 1 Left panel: Small τ. Evolution of $10^2\tau h$ (red), $10^3\varphi$ (blue), $10^2\varphi'$ (green) and $(-r_0)$ (black) as functions of time τ. Right panel: Large τ. Evolution of $10^2\tau h$ (red), $10^3\varphi$ (blue), $3\cdot 10^4\varphi'$ (green) and $(-10^5 r_0)$ (black) as functions of time τ. The value of the initial vacuum energy is $\lambda^{(in)} = 10^4$, and $h_{in} = 2$, $\varphi_{in} = 0$, and $\varphi'_{in} = 1$ and $k = 3$



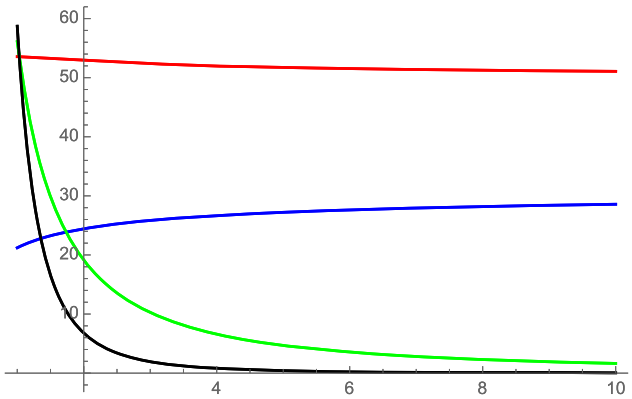


Fig. 2 Left panel: Small τ. Evolution of $10^2\tau h$ (red), $10^2\varphi$ (blue), $10^2\varphi'$ (green) and $(-10^2 r_0)$ (black) as functions of time τ. Right panel: Large τ. Evolution of $10^2\tau h$ (red), $10^2\varphi$ (blue), $10^3\varphi'$ (green) and $(-10^4 r_0)$ (black) as functions of time τ. The value of the initial vacuum energy is $\lambda^{(in)} = 10^2$, and $h_{in} = 2$, $\varphi_{in} = 0$, and $\varphi'_{in} = 1$ and $k = 3$

This equation has the evident solution

$$H \equiv \frac{\dot{a}}{a} = \frac{1}{2(t+t_0)}, \tag{40}$$

where a is the cosmological scale factor.

Correspondingly to the scale factor behaves as $a(t) \sim (t+t_0)^{1/2}$, which is typical for the cosmological model dominated by relativistic matter. In other words, we started with the universe with non-zero (and large) vacuum energy. Initially the expansion was the exponential one. Later, and quite quickly, the expansion turned into a power law form that is typical for cosmology dominated by relativistic matter. However, the pre-existing usual matter could be strongly diluted via initial exponential expansion and practically washed out. On the other hand, in the process of expansion gravitational particle production would be quite efficient, see e.g. book [19], that could create enough matter for our normal universe.

As the next steps we need to include into the model non-relativistic matter and check if the transition to matter dominated cosmology could be successfully achieved. Another related problem is a possibility of description of cosmological dark energy in the proposed framework. Presumably it can be realised by introduction of more complicated dependence on curvature scalar, analogously to the known description of dark energy by modified gravity through $F(R)$ generalisation of General Relativity. This is supposed to be a matter of future studies.

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