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Article

Universes Emerging from Nothing and Disappearing into Nothing as an Endless Cosmological Process

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Abstract: The equation of state of quantum fluctuations of the gravitational field of the universe depends on H^4, where H is the Hubble constant. This means that it is invariant with respect to the Wick rotation, i.e., the transition from Lorentzian space-time to Euclidean space-time and vice versa. It is shown that the quantum birth of universes from Euclidean space-time, i.e., from nothing, and their quantum disappearance to nothing (return to Euclidean space-time) by the time the density of the matter filling the universe becomes negligible could be a likely cosmological scenario. On an infinite time axis, this is an endless process of birth and death of universes appearing and disappearing and replacing each other. Within this scenario, our current universe is going to disappear into nothing at $z \leq -0.68$, i.e., after 18.37 billion years, and the lifetime of our universe and similar universes is about 32 billion years.

Keywords: universes; lifetime; birth; death; endless cosmological process

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1. Introduction

A cosmological scenario in which the universe appeared from nothing and finally disappeared into nothing was proposed in [1]. In this paper, we summarize all the known arguments in favor of this scenario, which are based on quantum fluctuations of the gravitational field of the universe (virtual gravitons) [2,3]. In Section 2, which can be considered a preamble to the main body of this paper, we show that, within the framework of general relativity (GR), classical stochastic gravitational waves (linear as well as nonlinear ones) are unable to produce an acceleration of the expansion of the universe if antigravity is not included in the scenario (although there are other points of view; see Section 2).

The main body of this paper (Sections 3–8) is dedicated to the quantum nature of cosmological acceleration and the cosmological scenario that follows. In Section 3, we show that, due to the expansion of the universe, the balance between the creation and annihilation of virtual gravitons is disrupted, in turn leading to the macroscopic quantum effect of cosmological acceleration with an equation of state, which is invariant with respect to the transition from Lorentzian to Euclidean space-time and vice versa. In Section 4, the same equation of state is obtained independently, directly from equations of one-loop quantum gravity. In Section 5, gravitational instantons are used to calculate the probabilities of transition from Lorentzian to Euclidean space-time and vice versa. In Sections 6 and 7, the recent appearance of dark energy and "Hubble tension" is briefly discussed as a consequence of the macroscopic quantum effect of virtual gravitons. Section 8 outlines the cosmological scenario.

2. Classical Gravitational Waves

As is known, without going beyond Einstein's theory, it is impossible to obtain an acceleration of the expansion of the universe. This is the reason why the dark energy (DE) effect (the contemporary exponential acceleration in the expansion of the universe detected observationally [4,5]) and the hypothetical exponential acceleration of the universe at the start of its evolution (inflation) [6] remain unsolved problems of cosmology. In [7], we used

Vereshkov's equations for classical stochastic nonlinear gravitational waves (SGW) to try to produce the acceleration of the expansion of the universe. The idea was that Vereshkov's theory (VT), as a bimetric theory (see [8–10]), could go beyond pure Einsteinian theory, with the hope being to derive acceleration from nonlinear gravitational waves. VT uses two metric tensors: standard g^i_k and stochastic $\widetilde{g^i_k}$ (ψ^k_i in the notation of [7]), where the average value of $\widetilde{g^i_k}$ across the statistical ensemble of SGWs is zero. It turns out that the de Sitter accelerating expansion is a solution to the VT equations, which are expressed as Equations (20)–(21) in [7]:

$$a(t) = exp(Ht) = exp(H_E\tau); \kappa\rho_{GW} = 3H^2; \kappa p_{GW} = -3H^2$$

where ρ_{GW}, p_{GW} are the energy density and the pressure of classical gravitational waves, $\kappa = 8\pi G$, and the speed of light, $c = 1, G$, is the gravitational constant. The scale factor is invariant with respect to the Wick rotation, where H and t are the Hubble constant and time in the Lorentzian space-time (LST), respectively, and $H_E = iH$ and $\tau = -it$ are the Hubble constant and time in Euclidean space-time (EST), respectively. According to Equation (8) in [7], this solution of the VT equations leads to $H^2 < 0$, which leads in turn to $\rho_{GW} < 0$. This means that this solution corresponds to an antigravity effect, which seems to have no physical meaning in the framework of classical general relativity.

The same finding applies to classical gravitational waves of small amplitude (linear waves) [11] because they are just a particular case of nonlinear waves. Here, there also exists a de Sitter expansion which is invariant with respect to the Wick rotation. And again, its energy density is negative. So, classical gravitational waves of small and/or finite amplitude cannot produce the acceleration of expansion if antigravity does not exist, although there are other points of view[1] (see [12–14] and the references therein). It can be said another way: classical stochastic gravitational waves are capable of providing the de Sitter accelerated expansion of the universe if they are of antigravity nature.

Of course, one can achieve an acceleration of expansion by making some arbitrary hypotheses, for example, assuming that the universe is filled with a hypothetical scalar field (see the quintessence [15–18]) or assuming that Einstein's equations are incomplete and require generalization (see [19]). In this work, we believe that Einstein's equations are valid. However, GR is a classical theory. If cosmological acceleration is a quantum effect, then GR is unable to describe it.

In the following two sections, using two independent approaches, we show that the equation of the state of virtual gravitons in the universe depends on H^4 so that it is invariant with respect to the Wick rotation $t = i\tau$.

3. Equation of State of Virtual Gravitons: Uncertainty Relation[2]

The creation and annihilation of virtual gravitons in the graviton vacuum is in a balance in standard conditions (as many as created as many are annihilated). However, the universe is rapidly expanding. During the lifetime of virtual particles, the universe manages to expand so quickly that virtual gravitons of the horizon wavelengths do not have time to annihilate back into the vacuum. This leads to a non-zero energy balance, which is spent on the acceleration of the expansion of the universe. That is, some of the gravitons that did not have time to annihilate are "stuck," and their energy is spent on accelerating the expansion of the universe. For the first time, this process was considered in [2], where it was shown that the probability of annihilation and creation processes are

$$w_{cr} = \frac{\alpha}{3\pi^2} H^3 (\overline{N}_{\mathbf{k}} + 1)(\overline{N}_{-\mathbf{k}} + 1), \; w_{ann} = \frac{\alpha}{3\pi^2} H^3 \overline{N}_{\mathbf{k}} \overline{N}_{-\mathbf{k}} \quad (1)$$

where $\alpha = O(1)$, $N_{\pm\mathbf{k}} \sim N_g/2$, and N_g is the average number of gravitons with wavelengths of the order of horizon H^{-1}. Thus, the balance equation reads [2]

$$\rho_g = \hbar\omega(w_{cr} - w_{ann}) = \frac{\alpha}{3\pi^2} \hbar H^4 (\overline{N}_{\mathbf{k}} + \overline{N}_{-\mathbf{k}} + 1) \simeq \frac{\alpha}{3\pi^2} \hbar N_g H^4 \quad (2)$$

where ρ_g is the energy density of gravitons and $\hbar\omega \sim \hbar H$. According to (2), the quantum spontaneous process of graviton creation leads to the non-zero effect. With an accuracy of the numerical factor α of the order of unity, this estimate coincides with the exact calculation of the energy density of virtual gravitons in the framework of one-loop quantum gravity (Section 4). The important fact is that the energy density of quantum gravitational waves (gravitons) depends on H^4: this is of crucial importance for our scenario (Section 8). The energy–momentum conservation law reads

$$\dot{\rho}_g + 3H(\rho_g + p_g) = 0 \tag{3}$$

where the superscript dot means the time derivative, and p_g is the pressure of the gravitons. According to (2), $\varrho_g = const$, so we obtain from (2) and (3)

$$\rho_g = -p_g = \frac{\alpha}{3\pi^2}\hbar N_g H^4 \tag{4}$$

From the Friedmann equation, we obtain

$$3H^2 = 8\pi G\rho \tag{5}$$

Combining (2) and (5), we obtain

$$H^2 = \frac{\pi}{G\hbar N_g} \tag{6}$$

(As we show in Section 4, in the framework of one-loop quantum gravity, $\alpha = \frac{9}{8}$). According to (6), there is no passage to the classical limit $\hbar \to 0$. This means that we meet a situation typical for macroscopic quantum effects such as superfluidity and superconductivity. This conclusion was confirmed by exact calculations [3] in the framework of one-loop quantum gravity, which is finite in the absence of matter and the presence of a ghost sector [20]. In the second loop, it is non-renormalizable [21]. There is a huge number of measurements of the Hubble constant obtained by different methods (see, e.g., Wikipedia's paper, "Hubble Law") that range from $H_{0,z\sim1100}$ = 67.4 ± 0.5 km s^{-1} Mpc^{-1} [22] to H_0 = 73.30 ± 1.04 km s^{-1} Mpc^{-1} [23]. For this range of Hubble constants, (6) demonstrates that the number of virtual gravitons under the horizon is $N_g \sim 10^{122}$. This is a familiar number, of course. The main self-contradiction of the ΛCDM model is the unexplainable ratio of a vacuum energy Λ to its observational value, which is of the order of 10^{122}. In quantum theory, this is the number of virtual gravitons under the universe's horizon. Note that the latest (at the present time) observational data show that the cosmological constant is not perhaps a constant at all[3] [24]. This is not yet a proven fact (the accuracy is only 2 sigma). However, the other contradictions already noted above (an order of 122 of magnitude contradiction between the observational and theoretical value of the cosmological constant, plus the inability to answer the long-standing question "Why Now?"[4]) testify not in favor of an ΛCDM model where Lambda = const by definition. Despite the contradictions noted above, a seemingly strong argument in favor of the Lambda CDM model is its seeming consistency with the available observational data. In reality, however, the GCDM model (where G stands for gravitons) is consistent with the SNe Ia observational data and has the same accuracy as the ΛCDM model [25]. Note also that all observational data (with no exceptions) are based on measurements of the equation of state parameter $w = p/\rho$, where p and ρ are the pressure and energy density of matter filling the universe. For a cosmological constant $w_\Lambda = -1$, all observational data show that w = −1. This fact is widely considered as a confirmation of the validity of the ΛCDM model; it is necessary, however, to note that virtual gravitons also produce a de Sitter expansion with $w_G = -1$. It is possible that there are also other models with w = −1. So, observational data tell us only that w = −1, and nothing more. Thus, the difference between the models can be found only by measuring w(z).

4. Equation of State of Virtual Gravitons from One-Loop Quantum Gravity

The equation of state of virtual gravitons in the framework of one-loop quantum gravity was considered in [2,3,26]. Taking this opportunity in the present paper to correct an inaccuracy in [1][5], we will present in this section a calculation of the equation of state of virtual gravitons from one-loop quantum gravity. For the convenience of the reader, we present here the general scheme of reasoning set out in detail in [3,26]. One-loop quantum gravity cosmology can be represented as a theory of gravitons in a macroscopic space-time with self-consistent geometry if one is dealing with a curvature that is much less than the Planck curvature. The interaction of gravitons with the macroscopic field determines the quantum state of gravitons, and the macroscopic geometry depends on the graviton state. The graviton operator and the background metric are taken from the unified gravitational field, which is described by exact equations of quantum gravity. The classical component of the unified field is a function of coordinates and time, but the quantum component of the same unified field is a tensor operator function, which also depends on coordinates and time. Thus, the original exact equations should be the operator equations of the quantum theory of gravity in the Heisenberg representation. In [3,26], the rigorous mathematical derivation of these equations can be found. It is important to note the unavoidable appearance of the auxiliary ghost fields introduced by Feynman [27] and known as Faddeev–Popov ghosts [28][6]. Namely, ghosts ensure the one-loop finiteness of quantum gravity, making the theory mathematically consistent [2,3]. In the self-consistent theory of gravitons, the background metric is described by regular vacuum Einstein equations [2]

$$R_i^k - \frac{1}{2}\delta_i^k R = \kappa\left(\left\langle \Psi_g \middle| \hat{T}^k_{i(grav)} \middle| \Psi_g \right\rangle + \left\langle \Psi_{gh} \middle| \hat{T}^k_{i(ghost)} \middle| \Psi_{gh} \right\rangle\right) \tag{7}$$

Here, Ψ_g and Ψ_{gh} are the quantum state vectors of gravitons and ghosts, respectively. The explicit form of the energy–momentum tensors (EMT) of gravitons $\hat{T}^k_{i(grav)}$ and ghosts $\hat{T}^k_{i(ghost)}$ is presented in [3].

From [3], we obtain the following system equations for the background (where we use the conformal time $\eta = \int dt/a$):

$$\begin{aligned} 3\frac{a'^2}{a^4} = \kappa\rho_g = \frac{1}{16\pi^2}\int_0^\infty \frac{k^2}{a^2} dk \Big(\sum_\sigma \langle \Psi_g | \hat{\psi}'^{+}_{\mathbf{k}\sigma}\hat{\psi}'_{\mathbf{k}\sigma} + k^2 \hat{\psi}^{+}_{\mathbf{k}\sigma}\hat{\psi}_{\mathbf{k}\sigma} | \Psi_g \rangle \\ -2\left\langle \Psi_{gh} \middle| \bar{\theta}'_{\mathbf{k}}\theta'_{\mathbf{k}} + k^2 \bar{\theta}_{\mathbf{k}}\theta_{\mathbf{k}} \middle| \Psi_{gh} \right\rangle \Big) \end{aligned} \tag{8}$$

$$\begin{aligned} 2\frac{a''}{a^3} - \frac{a'^2}{a^4} = -\kappa p_g = -\frac{1}{16\pi^2}\int_0^\infty \frac{k^2}{a^2} dk \Big(\sum_\sigma \Big\langle \Psi_g \Big| \hat{\psi}'^{+}_{\mathbf{k}\sigma}\hat{\psi}'_{\mathbf{k}\sigma} \\ -\frac{k^2}{3}\hat{\psi}^{+}_{\mathbf{k}\sigma}\hat{\psi}_{\mathbf{k}\sigma} \Big| \Psi_g \Big\rangle - 2\Big\langle \Psi_{gh} \Big| \bar{\theta}'_{\mathbf{k}}\theta'_{\mathbf{k}} - \frac{k^2}{3}\bar{\theta}_{\mathbf{k}}\theta_{\mathbf{k}} \Big| \Psi_{gh} \Big\rangle \Big) \end{aligned} \tag{9}$$

And for fluctuations, we obtain

$$\hat{\phi}''_{k,\sigma} + (k^2 - \frac{a''}{a})\hat{\phi}_{k,\sigma} = 0 \tag{10}$$

$$\hat{\vartheta}''_{k} + (k^2 - \frac{a''}{a})\hat{\vartheta}_{k} = 0 \tag{11}$$

where $\hat{\psi}_{k\sigma} = \frac{1}{a}\hat{\phi}_{k\sigma}$ and $\hat{\theta}_k = \frac{1}{a}\hat{\vartheta}_k$; σ is the polarization index; $a(\eta)$ is the FLRW scale factor; and superscript "+" denotes a complex conjugation. Primes denote derivatives over conformal time η. The de Sitter expansion in terms of conformal time is

$$a_S = -(H\eta)^{-1}, -\infty < \eta \le 0 \tag{12}$$

The exact solutions to (10) and (11) over the de Sitter background (12) read [2]

$$\hat{\psi}_{\mathrm{k}\sigma} = \frac{1}{a_S}\sqrt{\frac{2\kappa\hbar}{k}}[\hat{c}_{\mathrm{k}\sigma}f(x) + \hat{c}^{+}_{-\mathrm{k}-\sigma}f^{+}(x)],$$
$$\hat{\theta}_{\mathrm{k}} = \frac{1}{a_s}\sqrt{\frac{2\kappa\hbar}{k}}[\hat{\alpha}_{\mathrm{k}}f(x) + \hat{\bar{\beta}}_{-\mathrm{k}}f^{+}(x)], \tag{13}$$

$$f(x) = (1 - \frac{i}{x})e^{-ix} \tag{14}$$

where $x = k\eta$.

The quantum metric fluctuations (13) are unable to form a self-consistent de Sitter solution in real time because of the non-computability of the integrals

$$\int\limits_0^\infty x^n e^{\pm 2ix} dx$$

arising in the right-hand side of Equations (8) and (9). However, they can do this if these incomputable integrals are re-defined in the following way [2]:

$$\int\limits_0^\infty x^n e^{\pm 2ix} dx = \lim_{\delta\to 0}\int\limits_0^\infty x^n e^{\pm 2ix - \delta x} dx$$

In accordance with [2], we finally obtain the following energy density of virtual gravitons:

$$\rho_g = \frac{3\hbar N}{8\pi^2}H^4,\ p_g = -\rho_g \tag{15}$$

where N is a generalized parameter of the graviton vacuum state. By order of magnitude, it is N_g. Note that the energy density of the virtual gravitons depends again on H^4. Another way to calculate the incomputable integrals mentioned above is a passage to EST (Euclidean space-time), where divergences can be removed by a choice of integration constants [1] and then reverting to LST. If one repeats the above calculations in imaginary time $\tau = -it$, i.e., in EST, we obtain [1]

$$\rho_g = \frac{\hbar H_E^4}{2\pi^2}\int_{-\infty}^{0} N_k[\zeta^2 - (1-\zeta)^2]exp(2\zeta)\zeta d\zeta \tag{16}$$

$$N_k = \sum_\sigma \langle \Psi_g | \hat{Q}^{+}_{\mathrm{k}\sigma}\hat{Q}_{\mathrm{k}\sigma} | \Psi_g \rangle - 2\left\langle \Psi_{gh} \middle| \hat{q}^{+}_{\mathrm{k}}\hat{q}_{\mathrm{k}} \middle| \Psi_{gh} \right\rangle \tag{17}$$

where $\hat{Q}_{\mathbf{k}\sigma}$ and $\hat{q}_k$ are the operator constants of the integration of Equations (10) and (11) for gravitons and ghosts, respectively, in imaginary time. Note that we have to have a flat spectrum $N_k = const$ to obtain a constant in the LHS of (16). In accordance with [1], under reasonable assumptions about the occupation numbers of gravitons and ghosts, we obtain

$$N_k = (\langle n_g \rangle - \left\langle n_{gh} \right\rangle) \tag{18}$$

In the RHS of (18), we have a difference between the average numbers of gravitons and ghosts under the horizon of the universe. So, from Equations (3) and (16)–(18), we obtain the following for EST:

$$\rho_g = \frac{3\hbar H_E^4}{2\pi^2}(\left\langle n_{gh} \right\rangle - \langle n_g \rangle),\ p_g = -\rho_g \tag{19}$$

In accordance with (19), for LST, we obtain the same form with the only change of $H_E^4 = H^4$.

$$\rho_g = \frac{3\hbar H^4}{2\pi^2}(\left\langle n_{gh} \right\rangle - \langle n_g \rangle),\ p_g = -\rho_g \tag{20}$$

Here,

$$\left| \langle n_g \rangle - \left\langle n_{gh} \right\rangle \right| \approx N_g \tag{21}$$

Considering (20) and (21), we see that the α parameter in (4) is in fact

$$\alpha = 9/8 \tag{22}$$

One can see that ghosts must prevail over gravitons to make the energy density positive. Figuratively speaking, ghosts must be "materialized" to produce acceleration.

This is an expected result because the ghost system is an antigravitating one[7]. As was shown in [3], the physical nature of this solution is a macroscopic quantum condensate. All the equations of state listed above in Equations (4), (15), (19), and (20) have a common feature: the energy density depends on H^4, which means that it is invariant with respect to the transfer from Lorentzian to Euclidean space-times and vice versa.

These equations of state are similar to what comes from conformal anomalies, as was shown by Starobinsky [29] and Zeldovich [30].

It is worth noting that all known attempts to consider quantum corrections to Einstein's theory have led to a dependence of energy density on H^4, i.e., to its invariance with respect to a transition from LST to EST and vice versa. It is this fact that underlies the idea of the cosmological scenario proposed in [1,7] and here.

5. Transition from Euclidean Space-Time to Lorentzian Space-Time and Vice Versa: Gravitational Instantons

As a matter of fact, the idea of the appearance of the universe from EST, i.e., from "nothing", has a long history (see, e.g., [31–39] and the references therein). To calculate the probability of a transition from EST to LST, one needs to consider a gravitational instanton which (if it exists) can provide the tunneling of a de Sitter expansion regime from EST to LST. The detailed consideration of this problem is given in [3], Section 7.3. In general, instantons are intermediaries between two vacua. In this particular case, it is about a transition from EST to LST. The probability of such a transition is $\exp(-S)$, where S represents action in EST, i.e., in imaginary time. A full theory of gravitational instantons applicable to the graviton-ghost system was presented in [3] (Section 7). As was shown in [3], in the framework of one-loop quantum gravity, S = 0 in imaginary time; thus, the equation of the state and energy density of gravitons (19) obtained in EST can be tunneled into LST with the probability being equal to 1, which is almost obvious because of the invariance of (19, 20) with respect to Wick's rotation. This type of tunneling could explain the origin of inflation, and this was a reason why an avalanche of publications on gravitational instantons appeared in the 80s (see, e.g., [39] and the references therein).

As was mentioned in [7], the existing inflation theories applicable to the existing universe usually start with approximately $10^8 t_p$ and last about $(10^{11} - 10^{12})t_p$, where the Planck time is $t_p \approx 5.4 \cdot 10^{-44}$ sec. Therefore, a one-loop approximation of quantum gravity is probably applicable to such a case. Recall that the one-loop approximation of quantum gravity is applicable only to empty space (with no matter in it) and the presence of a ghost sector [20]. Obviously, there was no matter at $10^8 t_p$.

To calculate the tunneling probability from LST to EST, i.e., a possible end of our universe, we have to calculate the probability of tunneling from our Lorentzian space-time to Euclidean space-time, i.e., to nothing. In distinction on the previous case, we have to use action in LST, i.e., in real time. This was obtained by [3] (Section 3), and it reads

$$\begin{aligned} S &= \int dt\left(-\frac{3\dot{a}^2 a}{N} + L_{\text{grav}} + L_{\text{ghost}}\right), \\ L_{\text{grav}} + L_{\text{ghost}} &= \frac{1}{8}\sum_{\mathbf{k}\sigma}\left(\frac{a^3}{N}\dot{\hat{\psi}}^{+}_{\mathbf{k}\sigma}\dot{\hat{\psi}}_{\mathbf{k}\sigma} - Nak^2\hat{\psi}^{+}_{\mathbf{k}\sigma}\hat{\psi}_{\mathbf{k}\sigma}\right) - \frac{1}{4}\sum_{\mathbf{k}}\left(\frac{a^3}{N}\dot{\bar{\theta}}_{\mathbf{k}}\dot{\theta}_{\mathbf{k}} - Nak^2\bar{\theta}_{\mathbf{k}}\theta_{\mathbf{k}}\right). \end{aligned} \tag{23}$$

where L_{grav}, L_{ghost} are graviton and ghost Lagrangians, respectively. N is the Lagrange multiplier, which is a variation variable (the choice of N can be made after a variation of action, e.g., $N = 1$).

In (23), the background metric is taken to be in the form

$$ds^2 = dt^2 - a\left(t\right)^2\gamma_{\alpha\beta}dx^\alpha dx^\beta = dt^2 - a\left(t\right)^2\left(dx^2 + dy^2 + dz^2\right)$$

A variation of action (23) over N leads to (24)

$$\delta S = \delta N\int a^3 dt\left\{\left(\frac{3\dot{a}^2}{N^2a^2}\right) + \frac{1}{8}\sum_{k,\sigma}\left(-\frac{1}{N^2}\dot{\hat{\psi}}_{k\sigma}\widehat{\psi_{k\sigma}}^{+}_{k\sigma} - \frac{k^2}{a^2}\hat{\psi}_{k\sigma}\widehat{\psi_{k\sigma}}^{+}\right) - \frac{1}{4}\sum_{k}\left(-\frac{1}{N^2}\dot{\theta}^{+}_{k}\dot{\theta}_{k} - \frac{k^2}{a^2}\theta_k\theta_k^{+}\right)\right\} \tag{24}$$

If we choose $N = 1$ in (24), average over 3-volume and come back from conformal time η to real time t in (8), we can see that the integrand in curly brackets is the left-hand side minus the right-hand side of (8), i.e., $\delta S = 0$. In accordance with the Principle of Least Action $S = const = 0$, exp(−S) = 1. So, the probability of a transition back to EST is again unity, which is also almost obvious for the same reason, namely due to the invariance of (19, 20) with respect to the transfer from LST to EST and vice versa.

6. Why Now?

One-loop quantum gravity also provides an answer to the question: "Why Now?", i.e., why did cosmological acceleration come into play now, i.e., very recently? The reason is a conformal non-invariance of the gravitational field, which manifests itself as the third term in Equations (9) and (10). Note that over the de Sitter background (12), Equation (10) reads

$$\ddot{\hat{\phi}}_{\mathbf{k},\sigma} + (k^2 - \frac{2}{\eta^2})\hat{\phi}_{\mathbf{k},\sigma} = 0 \tag{25}$$

Note also that (25) does not change its form when gravitons are propagating inside matter with the equation of state $p = 0$ [25][8]. Thus, when the equation of state of the matter filling the universe changes from $p = \rho/3$ to $\rho = 0$, i.e., around z = 1100–1200 [25,40], gravitons feel as though they are in a vacuum and can produce the acceleration considered above, i.e., start the dark energy effect any time after the matter changes its equation of state (for more details see [25]).

7. "Hubble Tension" and Early Dark Energy

Obviously, the initiation of DE after a change in the equation of state of the universe matter from $p = \rho/3$ to $\rho = 0$ would resemble the initial DE (so-called early dark energy—EDE), which may be needed, possibly, for the explanation of the origin of "Hubble tension" [41]. In the frame of the GCDM model, EDE is simply a choice of initial conditions [25]. However, this topic is beyond the scope of this paper.

8. Conclusion: The Cosmological Scenario

In conclusion, we have arrived at the following cosmological scenario ([1,7] and the present paper). A flat inflationary Universe could have been formed by tunneling from EST to LST, i.e., from "nothing". After that it should evolve in accordance with inflation scenarios that are beyond the scope of this paper (see, e.g., [6,42–44]). Then the standard Big

Bang cosmology starts and lasts until the matter of the universe changes its equation of state from $\rho = \rho/3$ to $\rho = 0$. After that quanta of the gravitational field (virtual gravitons) start to form the DE effect. After that, to the extent that space continues to empty as $\rho_M \sim a^{-3}$, the universe gets the opportunity again to form a gravitational instanton (as in the beginning) but to tunnel back from LST to EST, i.e., disappear to nothing. After that, the entire scenario can be repeated indefinitely[9]. In accordance with the "Planck Collaboration" [45], the energy density of ordinary and dark matter today is about $\Omega_m(0) = 0.315 \pm 0.007$. After the Universe expands, e.g., 3.16 times, i.e.,

$$a_{end}/a_{today} = 3.16 = 1/1 + z_{end}$$

the matter content will be close to 1%, i.e., negligible. So, in this scenario, our current universe can disappear into nothing at $z_{end} \leq -0.68$. To recalculate this result in terms of time, one can use the Friedmann equation, which leads to the following:

$$\int_{t_{today}}^{t_{end}} dt = -\frac{1}{H_0} \int_0^{-0.68} \frac{dz}{(1+z)((\Omega_m(0) \cdot (1+z)^3) + (1 - \Omega_m(0)))^{\frac{1}{2}}} \tag{26}$$

Given $H_0 = 67.4 \frac{km}{s \cdot Mpc}$ [45], (26) indicates that $t_{end} - t_{today} = 18.37$ billion years. Considering today's age of the universe, $t_{today} = 13.78$ billion years [45], one can say that the lifetime of a universe similar to ours is about $T_{lifetime} = 32.15$ billion years.

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Notes

1 Although negative energy density of gravitational waves can arise in quantum theories (see, e.g., [46] or antigravitation subsystem of Faddeev-Popov ghosts in Section 4), for classical gravitational waves such a solution, apparently, makes no physical sense, despite the fact that static gravitational energy is negative. We did not mention the antigravity nature of these solutions in our works [7,11] and we are doing it now.

2 An anonymous referee raised the question of how virtual gravitons might be detectable. This question is beyond the scope of this paper, but readers might consult Dyson Freeman (8 October 2013). "Is a Graviton Detectable?". International Journal of Modern Physics A. 28 (25): 1330041–1." See also Jiehui Liang, Ziyu Liu, Zihao Yang et al., 2024, Nature, 628, 78–83.

3 Let me remind you of the well-known fact that George Gamow remarked upon in his book [47]: "Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder of his life".

4 Why does dark energy appear exactly in our epoch of cosmic evolution, i.e., why now?

5 In [1], instead of (14), we used a complex conjugated solution with $[0, \infty]$ integration limits in (16). It does not change the final result (19, 20), but it was decided to fix this error here. The correct argumentation follows in the main text.

6 For completeness, note the following quotation from Cécile DeWitt-Morette about Bryce De Witt on "Faddeev-Popov ghosts". "And so it happened that Bryce was one of the first few mavericks ready to tackle the problem. There were just a few others, such as Richard Feynman and Ludwig Faddeev. Was his genius undervalued? Bryce once complained about the name "Faddeev Popov ghosts" for the fictitious particles that appear in the Feynman rules for gauge- and gravity theories. His paper contained the same expressions and had been published earlier. But the difference was only two weeks, and, characteristically, Bryce had buried his result in three extremely lengthy and technical papers, where Faddeev and Popov only needed two pages, which was all that was really needed. If you want completeness, Feynman's name should also have been added; he was the first to notice these ghosts, although he could only handle the one-loop case and had not done it quite correctly" [48]. Thus, the correct name of these ghosts must be "Feynman-de Witt-Faddeev-Popov ghosts".

[7] At first glance, "ghost materialization" seems unusual because ghosts are not physical particles. A detailed discussion of this fact can be found in footnotes #1 and #2 in [3]. In short, the universe as a whole is a region of interaction for gravitons, so all the gravitons are virtual in the universe. There are no asymptotic states in the universe where ghosts must disappear as happens in the canonical S-matrix theory, which is inapplicable to the universe as whole. So, the question of the fate of ghosts in the universe will be open until a full (not one-loop) quantum gravity theory appears.

[8] For matter with the equation of state $p = 0$, the expansion low is $a(t) = const \cdot t^{\frac{2}{3}}$. In conformal time, it is $a(\eta) = const \cdot \eta^2$, so that $\frac{a''}{a} = \frac{2}{\eta^2}$. There are two only regimes in which conformal non-invariance of the gravitational field produces $\frac{a''}{a} = \frac{2}{\eta^2}$. They are de Sitter expansions (12) and matter with the equation of state $p = 0$.

[9] At first sight, this scenario looks similar to the "Cycles of Time" scenario of R. Penrose [49]. The main difference (leaving out the details) is that the lifetime of universes is finite in our scenario, which is distinct from [45], where it is infinite, which leads to the conception of cycles of time.

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