PROCEEDINGS OF SCIENCE

The uncertain Universe and the first measurement

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Working within the framework of the superfluid vacuum approach to quantum gravity, we reflect on the era preceding the inflationary epoch. We conjecture that the newly formed background was a many-body system in a quantum superposition of its states, which created the primordial multiverse with statistically uncertain spacetime geometry. Then, at some stage, measurement occurred, probably the first one ever, which broke the superposition, akin to the Schrödinger's cat thought experiment, and reduced this multiverse to one state, the Universe. We demonstrate that this measurement can be viewed as the transfer of quantum information of a Shannon type, which leads to the occurrence of logarithmic nonlinearity in evolution equations. The background condensate thus became the logarithmic liquid and superfluid; it formed what we call now the physical vacuum. After that, the Universe entered the dilaton-driven inflationary epoch followed by the contemporary 'dark energy' period driven by a combination of the quintessence and phantom fields non-minimally coupled to each other. These three scalar fields are shown to be projections of superfluid vacuum density and its fluctuations.

High Energy Astrophysics in Southern Africa 2025 (HEASA 2025)
September 16 - 20, 2025
Johannesburg, South Africa

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PoS(HEASA2025)016

The current standard model of cosmology is mostly dealing with the following two periods of the Universe evolution: the contemporary acceleration period, commonly referred to as the 'dark energy' era (DE), preceded by the epoch of exponential expansion of space - the inflation - driven by a repulsive force which is somewhat similar to the one during the DE era but at a significantly higher energy density. Majority of observational data to date, coming from cosmic microwave background, redshift surveys and supernovae, are related to footprints left by these two periods [1].

The pre-inflationary period largely remains a mystery, both in empirical and theoretical ways. Before inflation, even the macroscopic world and large-scale structures of spacetime we currently perceive had not yet come to existence. There exists however one easily observable natural phenomenon, whose origin is directly related to that epoch. This is our Universe itself, its diverse yet quite orderly and mathematically predictable structure, which allows us to exist, rationalize surrounding reality and be able to draw the laws of nature. This mathematical predictability of our Universe and experimental reproducibility of its properties are not to be taken for granted - because the pre-inflationary continuum was likely evolving in a strong quantum regime characterized by high levels of statistical uncertainty in dynamics and structure. How did our Universe evolve from that proverbial Schrödinger's cat box, the primordial multiverse, remains an open question nowadays, probably the biggest of them all.

Superfluid vacuum theory. Let us assume that physical vacuum is quantum liquid described by state vector $|\Psi\rangle$ and wavefunction $\Psi(\mathbf{x}, t) = \langle \mathbf{x}|\Psi\rangle$. The latter obeys the standard quantum-mechanical normalization condition $\int_{\mathbf{V}} |\Psi|^2 d\mathbf{V} = \int_{\mathbf{V}} \rho d\mathbf{V} = \mathcal{M} = m\mathcal{N} > 0$, where $\mathcal{M}$ and $\mathbf{V}$ are the total mass and volume of the liquid, m and $\mathcal{N}$ are mass and number of constituent particles. For reasons to be justified later, we assume that the time evolution of $|\Psi\rangle$ is governed by the logarithmic Schrödinger equation (LogSE)

$$i\hbar\partial_t \Psi = \left[\hat{H} - \hbar b \ln(|\Psi|^2/\rho_0)\right] \Psi, \tag{1}$$

where $\hat{H} = -(\hbar^2/2m)\nabla^2 + V_{\text{ext}}(\mathbf{x}, t)$ is Hamiltonian operator, $V_{\text{ext}}(\mathbf{x}, t)$ is external potential, and b and ρ_0 are real-valued parameters. Logarithmic nonlinearity of this type happens to be instrumental in a theory of physical vacuum known as the theory of superfluid vacuum (SV), or simply SVT, some landmark works being [2–5], whereas the monograph [6] can be recommended for a general introduction. (There are also extensive studies of the logarithmically nonlinear models and around [7] and latest reviews of applications [8, 9]).

According to the superfluid vacuum paradigm, physical vacuum is a quantum liquid with suppressed dissipative fluctuations, the superfluid (SF), which is formally defined in 3D Euclidean space but makes the latter unobservable for observers operating only with the small-amplitude low-momentum fluctuations of this fluid. Instead, such observers would perceive 4D curved spacetime by measuring trajectories of small excitations of background superfluid viewed as relativistic probe particles [6]. The mapping which relates these two pictures, quantum 3D Euclidean and classical 4D relativistic, is called the superfluid-spacetime correspondence (SF/ST), see [4] for details.

Superfluid vacuum theory thus turns out to be a framework for quantum gravity models: it generalizes GR, places it on quantum-mechanical foundations and makes the theory of gravitational interaction a subset of quantum fluid mechanics and condensed matter physics, cf. figure 1. Superfluidity itself is responsible for the inviscid flow of the physical vacuum thus explaining

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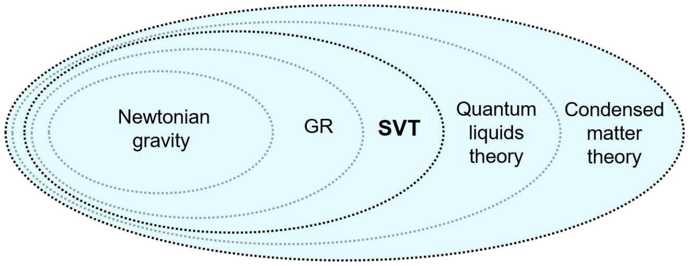

Figure 1: Embedding of various theories of gravity into condensed matter physics.

negative results of Earth's dragging in the Michelson–Morley-type experiments, which, along with the SF/ST correspondence, makes an important difference of SVT from classical ether models abandoned in favour of theory of relativity more than a century ago.

The SVT approach differentiates observers into two types: F(ull)-observers who observe the vacuum as 3D quantum fluid, and the above-mentioned observers who can only operate with small fluctuations, the R(elativistic)-observers. The workflow is to quantize the underlying Euclidean fluid; then use the SF/ST correspondence to obtain the relativistic gravity as the "infrared" limit:

$$\underbrace{SV\ \ dynamics \xRightarrow{\text{LogSE}} \Psi \xRightarrow{\text{SF/ST}}}_{\text{quantum Euclidean}} \underbrace{g_{\mu\nu} \xRightarrow{\text{'EFE'}} T_{\mu\nu}}_{\text{relativistic gravity}} ,$$

where by 'EFE' we mean Einstein field equations in a general sense, i.e., any field-theoretical equations which relate the geometry of spacetime to the distribution of matter within it, described by the stress-energy tensor $T_{\mu\nu}$ observed by R-observers. For example, in the most natural case, this tensor can be defined using the covariant conservation argument akin to the canonical theory of general relativity (GR): $\nabla_\mu T^{\mu\nu} = 0 \ \Rightarrow\ T_{\mu\nu} \sim G_{\mu\nu}$, where $G_{\mu\nu}$ being the Einstein tensor [3]. In practice, however, it is the stress-energy tensor which is known, but not the background superfluid's dynamics or wavefunction; therefore, one needs to follow the reversed workflow, or make certain assumptions about the 3D flow or wavefunction and check if they yield spacetime geometry and dynamics agreeing with experiments.

Inflationary and 'dark energy' epochs. Let us consider now a special case when superflow is laminar with constant velocity, if viewed by F-observers. The R-observers, according to the SF/ST correspondence [4], discover themselves in one of conformally flat 4D spacetimes. In the leading-order approximation with respect to $\hbar/m$, the analogous metric can be written as $g_{\mu\nu} \sim \rho\,\eta_{\mu\nu} \sim |\Psi|^2\,\eta_{\mu\nu}$, where $\eta_{\mu\nu}$ is the Minkowski metric. This is a rather large class of spacetimes which includes de Sitter and others with exponential-type expansion.

From this metric, one can reverse-engineer the basic Lorentz-covariant action functional describing the gravitational interaction experienced by R-observers [3, 5]:

$$S_{\mathrm{I}} = \frac{1}{2}\int d^4x\sqrt{-g}\,\mathrm{e}^{2\Phi}\left[R + 3!(\partial\Phi)^2\right] - \int d^4x\sqrt{-g}V_0\,, \tag{2}$$

where $(\partial f)^2 \equiv g^{\mu\nu}\partial_\mu f\,\partial_\nu f$, and $\Phi = \ln(\rho/\rho_0)$ is a function of SV density $\rho = |\Psi|^2$; here and till the end of this section, we work in Planck units. The topological term with the reference value

$V_0 = \text{const}$ for energy counting can always be added to a field action. One can see that, in the R-observer's picture, background superfluid generates not only the spacetime but also the scalar field which can drive exponential expansion. Therefore, model (2) can be applied to the inflationary epoch in the early universe, because it can describe ; it also explains the origin of the dilaton field from superfluid vacuum density.

Furthermore, from working with laboratory fluids, we know that the laminar flow cannot stay so for long, due to fluctuations which inevitably occur and cause turbulence. By perturbing superfluid density in eq. (2) and changing to the Einstein frame, $g^{(\mathrm{I})}_{\mu\nu} = (\bar{\rho}/\rho_0)^{-2} g^{(\mathrm{DE})}_{\mu\nu} = \mathrm{e}^{-\sqrt{2/3}\,\phi} g^{(\mathrm{DE})}_{\mu\nu}$, one derives the model [5]:

$$S_{\mathrm{DE}} = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}\mathrm{e}^{-\lambda\phi}(\partial\sigma)^2 - V_0\mathrm{e}^{-2\lambda\phi} - \Delta V(\phi,\sigma)\right] + S^{(M)}, \tag{3}$$

where $\phi = \sqrt{3!}\,\ln(\bar{\rho}/\rho_0)$ and $\sigma = \sqrt{3!}\,\rho/\rho_0 = \sqrt{3!}\,(\bar{\rho} + \delta\rho)/\rho_0$ are the quintom, a combination of, respectively, quintessence and phantom fields, λ is the quintessence scale parameter, $\Delta V(\phi,\sigma)$ is the scalar potential's perturbation, and $\bar{\rho}$ and $\delta\rho$ are, respectively, average density and perturbation. The term $S^{(M)} = \int d^4x\sqrt{-g}\mathcal{L}_M$ is added to account for the other matter and radiation content of the universe, which was generated during and after the inflaton-quintom transition.

Model (3) is a non-minimally-coupled generalization of models which are popular in the quintessence and phantom cosmology [10]. Field-theoretical actions (2) and (3) thus form the *quinton* system, which comprises the dilaton field, which drives the inflation and subsequently transforms into the quintom, a combination of the quintessence and tachyonic phantom fields, which plays as a role of dark energy. From F-observer's viewpoint, these three fields are projections of the dynamical evolution of superfluid vacuum density and its fluctuations onto the measuring apparatus of a relativistic observer.

Pre-inflationary period. Let us now reflect on the times preceding the inflationary epoch. What kind of reality existed before the inflationary epoch's spacetime occurred? Why did the superfluid vacuum occur? Why logarithmic?

It is natural to begin by assuming that the original medium was consisting of $\mathcal{N}$ indistinguishable particles each described by state vectors $|\aleph_k\rangle$, $k = 1, 2, \ldots\mathcal{N}$ defined in a single-particle Hilbert space. According to the SF/ST correspondence, those particles were evolving in 3D Euclidean space because fluid, whose fluctuations would create relativistic observers in 4D spacetime, has not been formed yet. The dynamics of those particles is thus governed by a set of $\mathcal{N}$ conventional (linear) Schrödinger equations for $|\aleph_k\rangle$'s. The total system is then described by the product of state vectors $|\aleph_1\rangle \otimes |\aleph_2\rangle \otimes \ldots \otimes |\aleph_{\mathcal{N}}\rangle$ defined, in general, in a Fock space.

As an asymptotic limit of their evolution, those indistinguishable particles appear to be in one state, $|\aleph_k\rangle \to |\aleph\rangle$. This results in the occurrence of a collective system of exact copies, the Bose-Einstein condensate, which can be described by a vector $|\Psi\rangle$ defined in a single-particle Hilbert space: $|\aleph\rangle \otimes |\aleph\rangle \otimes \ldots \otimes |\aleph\rangle \mapsto |\Psi\rangle$. This state vector's evolution is governed by a linear Schrödinger equation, which obeys the superposition principle meaning that any linear combination of its solutions is also a solution. As a result, the formed condensate had a non-zero probability of being in any and all of the states forming that superposition. Because each of those wavefunction solutions generates its own spacetime (according to the general fluid-spacetime correspondence), the primordial background was the multiverse, i.e., the statistical ensemble of different spacetimes. If a relativistic observer were existing at that time then a repeated measurement would produce, apart from standard measurement errors, different results, with their probability weights assigned by different multiverse's states.

Since the statistical uncertainty of large-scale spacetime geometry is not reported in the literature, to the best of our knowledge, it is natural to expect that the linear superposition was broken at some point so that the primordial statistical ensemble was reduced to one state. What could possibly cause the breakdown of this superposition thus reducing the multiverse to the Universe we experience nowadays?

Let us assume that, some kind of measurement was applied to primordial condensate. In its simplest form, it can be viewed as extracting or exchanging the Shannon-type information [11, 12], which in our case is proportional to the logarithm of the probability that the measurement results in the outcome $|\Psi\rangle$: $I_\Psi = -\log_2(|\Psi|^2/|\overline{\Psi}|^2)$ bits where $|\overline{\Psi}|^2$ is a reference value of the probability density. The change of system's total energy during such information transfer can be written in the form (assuming the units $k_B = 1$ in what follows):

$$E_{\text{tot}} = E + \mathcal{E}_\Psi \langle\Psi|I_\Psi|\Psi\rangle = E \pm T_\Psi \mathcal{S}_\Psi, \tag{4}$$

where $\mathcal{E}_\Psi$ is the energy cost per transferred bit, $E = \langle\Psi|\hat{H}|\Psi\rangle$ is the averaged dynamical energy of the system, $\mathcal{S}_\Psi = -\langle\Psi|\ln(|\Psi|^2/|\overline{\Psi}|^2)|\Psi\rangle$ is the quantum-informational entropy, and $T_\Psi = |\mathcal{E}_\Psi|/\ln 2$ is the quantum-mechanical temperature forming a thermodynamic conjugate pair with $\mathcal{S}_\Psi$. Formula (4) suggests that the Hamiltonian operator $\hat{H}$ must be generalized to the time evolution operator:

$$\hat{H}_{\text{tot}}|\Psi\rangle = \left[\hat{H} - \mathcal{E}_\Psi \log_2(|\Psi|^2/|\overline{\Psi}|^2)\right]|\Psi\rangle, \tag{5}$$

which means that the corresponding evolution equation acquires nonlinearity of a type (1) exactly. As a result, our condensate's evolution equation is no longer linear, quantum superposition is broken, the multiverse is reduced, and background matter becomes the logarithmic superfluid.

To conclude the report, it was shown that in pre-inflationary world, measurement based on a transfer of quantum Shannon information occurred. It broke the quantum superposition, reduced primordial multiverse to the Universe, and formed the quantum background of a logarithmic superfluid type. After that, in the R-observer picture, the Universe entered the inflationary epoch, described by the dilaton gravity (2), followed by the contemporary 'dark energy' period where evolution is driven by a combination of quintessence and phantom fields non-minimally coupled to each other (3). These fields however are projections of SV density and its fluctuations Thus, SVT offers the golden mean in the dispute between corpuscular and geometrical explanations of DE/DM-attributed phenomena: the nature of the fundamental background superfluid is ultimately corpuscular, if viewed by Euclidean F-observers, but its particles are unobservable by relativistic observers who perceive the Lorentzian curved spacetime instead [13].

Apart from predictions of the phenomena occurred during the inflationary and DE epochs, which could be derived, respectively, from the models (2) and (3), SVT cosmology draws a number predictions from its idea of the pre-inflationary epoch. The main set of predictions is based on a possibility of the "infrared" (small-fluctuation) regime breakdown in some domain of space, under some extreme conditions. As a result of such transition, the four-dimensional Lorentzian description must be replaced with the quantum Euclidean one. This makes possible various post-relativistic phenomena such as luminal boom, superluminal propagation and vacuum Cherenkov radiation, which are a very powerful and fast way of releasing energy [14]. For instance, such phenomena can significantly contribute to the generation and release of energy in blazars/quasars, fast radio bursts and ultra-relativistic radio objects with continuous optical spectra. Superluminal propagation of astrophysical jets and objects should also cause specific optical phenomena which can be deduced by analogy with acoustic effects during sonic booms in atmosphere.

Another set of predicted phenomena, though a rather speculative one, can be made on an assumption that the primordial multiverse somehow survived somewhere in a large-scale spatial domain. As a result, such domain would have a geometry which is a statistical ensemble of multiple spacetimes. Observational data coming from such domain would have an additional statistical uncertainty depending on a probabilistic weight of the spacetimes members of the ensemble. Although, such uncertainty has not been reported elsewhere, to the best of our knowledge.

Acknowledgments

This research is supported by Department of Higher Education and Training of South Africa and in part by National Research Foundation of South Africa (Grants Nos. 95965 and 132202).

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