Emergent Time as Phase Dynamics in the Logarithmic Superfluid Vacuum

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April 2026

Abstract

We show that time is not a fundamental dimension in the logarithmic superfluid vacuum framework but an emergent bookkeeping parameter generated by the phase dynamics of the condensate order parameter. The Madelung decomposition $\psi = \sqrt{\rho}\, e^{iS/\hbar_{\text{eff}}}$ defines time operationally as the phase accumulation rate: $dS/dt = \mu$, where the chemical potential $\mu(x) = m_{\text{eff}}\, c_s^2(x)/\hbar_{\text{eff}}$ is the local clock frequency. The condensate is a three-dimensional object; its state at any instant is fully specified by $\rho(\mathbf{x})$ and $S(\mathbf{x})$. The "time dimension" perceived by internal observers (phonons) is an artifact of writing the phonon equation of motion as a wave equation on a Lorentzian manifold. We demonstrate that all temporal phenomena in general relativity have condensate counterparts: gravitational time dilation is the spatial variation of $\mu(x)$, the twin paradox is path-dependent phase accumulation, the arrow of time is the irreversibility of phase advance in an open system, and the Hubble flow is the spatial phase winding rate. At the healing length $\xi \sim \ell_{\text{P}}$, the phase counter saturates, providing a minimum resolvable time interval $\Delta t_{\min} \sim t_{\text{P}}$. At acoustic horizons ($v = c_s$), the phase becomes locked and the emergent clock stops—reproducing infinite gravitational redshift without a metric singularity. The framework predicts that time did not exist before the condensate: the nucleation of the vacuum from the Bulk reservoir is simultaneously the origin of space, time, and the physical constants.

1 Introduction

The status of time in fundamental physics remains deeply problematic. In Newtonian mechanics, time is an absolute external parameter. In special relativity, it becomes a coordinate entangled with space. In general relativity, it is a dynamical variable—the metric determines the rate at which clocks tick. In canonical quantum gravity, the Wheeler-DeWitt equation [5] is timeless: the Hamiltonian constraint $\hat{H}\Psi = 0$ contains no time derivative, and the recovery of time evolution from the "frozen formalism" remains an open problem [6, 7].

The question "what is time?" has motivated diverse proposals: Barbour's timeless mechanics, where time is change [8]; the thermal time hypothesis of Connes and Rovelli, where time emerges from thermodynamic equilibrium [9]; and Volovik's observation that in superfluid helium, time is emergent from the condensate dynamics [10]. In all these approaches, time is not fundamental but derived.

In companion papers [11–15], we developed a superfluid vacuum model in which gravity, dark energy, dark matter, and the Planck scale all emerge from a logarithmic condensate. Throughout these papers, the time coordinate t appeared as a parameter in the wave equation and acoustic metric. In this paper, we examine the nature of this parameter and argue that it is not a fundamental dimension of reality but an emergent quantity generated by the phase dynamics of the order parameter.

2 The Phase Counter

2.1 Time from the Madelung decomposition

The vacuum condensate is described by a complex order parameter:

$$\psi(\mathbf{x}, t) = \sqrt{\rho(\mathbf{x}, t)}\, \exp\left(\frac{iS(\mathbf{x}, t)}{\hbar_{\text{eff}}}\right). \tag{1}$$

This decomposition, originally introduced by Madelung [2] and developed in the Bohmian formulation of quantum theory [3, 4], exposes the phase S as a dynamical scalar field distinct from the amplitude $\sqrt{\rho}$. The state of the condensate at any "instant" is fully specified by two three-dimensional fields: the density $\rho(\mathbf{x})$ and the phase action $S(\mathbf{x})$. The parameter t enters only through the Hamilton-Jacobi equation [11]:

$$\frac{\partial S}{\partial t} = -\mu(\mathbf{x}), \tag{2}$$

where $\mu(\mathbf{x})$ is the local chemical potential. In the rest frame of the condensate:

$$\mu(\mathbf{x}) = \frac{m_{\text{eff}}\, c_s^2(\mathbf{x})}{\hbar_{\text{eff}}}, \tag{3}$$

with c_s the local sound speed. The order parameter oscillates as $\psi \propto e^{-i\mu t}$, and t is the parameter counting these oscillations.

This is operationally identical to how a clock works: a clock is a physical system that oscillates at a known frequency, and "one second" is a fixed number of cycles. Here, the oscillator is the vacuum condensate itself, and the "frequency" is $\mu/\hbar_{\text{eff}}$. Time is not a dimension the condensate lives in; it is a label the condensate generates by oscillating.

2.2 The 3+1 illusion

The acoustic metric experienced by phonons (photons) is [1, 11, 16]:

$$ds^2 = \frac{\rho}{c_s}\left[-(c_s^2 - v^2)\, dt^2 - 2\,\mathbf{v}\cdot d\mathbf{x}\, dt + d\mathbf{x}^2\right]. \tag{4}$$

This has four coordinates $(t, \mathbf{x})$ and a Lorentzian signature $(-, +, +, +)$. A phonon propagating on this metric experiences a 3+1 dimensional spacetime.

But the metric (4) is constructed entirely from three-dimensional quantities: $\rho(\mathbf{x})$, $c_s(\mathbf{x})$, and $\mathbf{v}(\mathbf{x})$. The "time dimension" is an artifact of writing the phonon equation of motion as a wave equation on a curved manifold. The underlying reality is a 3D condensate whose configuration evolves; t is the index labelling the sequence of configurations.

This is Volovik's insight applied to the vacuum: in superfluid helium, the phonon sees a 3+1 dimensional acoustic spacetime, but the helium itself is a 3D fluid in a laboratory with an external clock. For the vacuum condensate, there is no external clock—the phase oscillation is the only available timer, and the "time dimension" is entirely self-generated [10].

3 Gravitational Time Dilation as Chemical Potential Variation

3.1 The mechanism

The local clock rate is set by the chemical potential $\mu(\mathbf{x})$. Near a gravitating mass, the Painlevé-Gullstrand flow modifies the local vacuum density and sound speed. From the acoustic metric (4), the proper time interval is:

$$d\tau = \sqrt{-g_{00}}\, dt = \sqrt{\frac{\rho\, c_s}{1}}\, \sqrt{1 - v^2/c_s^2}\, dt\,. \tag{5}$$

In the weak-field limit ($v \ll c_s$):

$$\frac{d\tau}{dt} \approx 1 - \frac{v^2}{2c_s^2} = 1 - \frac{GM}{c^2 r}\,, \tag{6}$$

recovering the standard gravitational redshift. The physical content is: the condensate phase advances more slowly where the flow velocity is larger (i.e., deeper in the gravitational well), because the kinetic energy of the flow reduces the energy available for phase oscillation.

3.2 Numerical example: the solar surface

At the solar surface, $v^2/c^2 \sim GM_\odot/(c^2 R_\odot) \sim 2 \times 10^{-6}$. The chemical potential is reduced by one part in 5×10^5:

$$\frac{\delta\mu}{\mu} = -\frac{GM_\odot}{c^2 R_\odot} \approx -2.12 \times 10^{-6}\,. \tag{7}$$

A clock on the solar surface accumulates 2.12×10^{-6} fewer phase cycles per second than a clock at infinity. This is the Pound-Rebka effect [17], here derived from the condensate phase dynamics rather than from the metric tensor.

4 The Twin Paradox as Path-Dependent Phase Accumulation

The twin paradox has a transparent interpretation in the phase counter picture. Two observers A and B start at the same spacetime point with synchronized phases $S_A = S_B$. Observer B travels along a worldline γ_B through regions of varying $\mu(\mathbf{x})$ and flow velocity $\mathbf{v}(\mathbf{x})$, while A remains stationary.

The total phase accumulated by each observer is:

$$\Delta S_i = -\int_{\gamma_i} \mu\, d\tau_i\,, \qquad i = A, B\,. \tag{8}$$

When the observers reunite, the phase difference is:

$$\Delta S_A - \Delta S_B = -\int_{\gamma_A} \mu\, d\tau_A + \int_{\gamma_B} \mu\, d\tau_B\,. \tag{9}$$

The observer who accumulated fewer phase cycles has aged less. This is not a coordinate artifact: the phase difference is a scalar quantity, measurable by interfering the two condensate paths. Time dilation is the physical fact that different trajectories through the condensate accumulate different numbers of phase oscillations.

5 The Arrow of Time

5.1 Phase advance is irreversible

The condensate phase evolves as $S(t) = S_0 - \mu\, t$ with $\mu > 0$. The phase always decreases (the oscillation $e^{-i\mu t}$ always winds in the same direction). Time-reversal ($t \to -t$) would require $\psi \to \psi^*$, which reverses all momenta $\mathbf{v} = \nabla S/m_{\text{eff}} \to -\mathbf{v}$ and is not a symmetry of the boundary conditions.

5.2 The open-system origin

The irreversibility has a thermodynamic origin. In the open-system interpretation developed in Paper 3 [13], the vacuum condensate is not a closed system: it exchanges energy with the external reservoir (the Bulk). The phase advance $dS/dt = -\mu < 0$ corresponds to the condensate relaxing toward equilibrium with the Bulk. The forward direction of time is the direction in which the condensate's free energy decreases.

This connects three arrows of time:

- *Thermodynamic arrow*: entropy increases toward equilibrium with the Bulk.
- *Cosmological arrow*: the condensate evolves (expands) as it relaxes.
- *Quantum-mechanical arrow*: the phase accumulates monotonically.

All three are manifestations of the same underlying process: the condensate is not in its ground state with respect to the Bulk, and its evolution toward equilibrium defines the forward direction.

6 The Hubble Flow as Phase Winding

The Hubble parameter H_0 measures the rate at which the universe expands. In the superfluid vacuum framework, the expansion is the condensate's macroscopic flow.

In the Madelung formalism, the macroscopic flow velocity is the spatial gradient of the phase: $\mathbf{v} = \nabla S/m_{\text{eff}}$. A uniform Hubble expansion $\mathbf{v} = H_0\,\mathbf{r}$ therefore requires a spatial phase profile of the form:

$$S(\mathbf{x}) = \frac{1}{2}\, m_{\text{eff}}\, H_0\, |\mathbf{x}|^2 \,. \tag{10}$$

The Hubble parameter is physically realized as the curvature of the spatial phase field: $H_0 = \nabla^2 S/(3\, m_{\text{eff}})$. From the Friedmann equation derived in Paper 3 [13] with $w = -1$:

$$H_0^2 = \frac{8\pi G}{3}\, \rho_{\text{eff}} \,. \tag{11}$$

The expansion of the universe is not the stretching of a pre-existing spatial metric; it is the active, continuous winding of the condensate's spatial phase as the system evolves toward equilibrium with the Bulk reservoir. In the phase counter picture, H_0 is the rate at which new phase cycles are laid down per unit comoving distance.

7 Temporal Limits

7.1 The minimum time interval

The fastest possible phase oscillation of the condensate occurs at the maximum chemical potential, which is bounded by the healing-length regularization [15]:

$$\mu_{\max} = \frac{m_{\text{eff}}\, c^2}{\hbar_{\text{eff}}} \,, \tag{12}$$

giving a minimum resolvable time interval:

$$\boxed{\Delta t_{\min} = \frac{2\pi}{\mu_{\max}} = \frac{2\pi\, \hbar_{\text{eff}}}{m_{\text{eff}}\, c^2} \sim t_{\text{P}}} \tag{13}$$

Below this, the concept of "before and after" loses operational meaning: the condensate cannot support coherent phase evolution on shorter timescales. This is not a discretization of time but a resolution limit of the emergent clock.

7.2 Time at acoustic horizons

At the acoustic horizon of a black hole analogue, the inflow velocity reaches the sound speed: $v(r_H) = c_s$. The proper time factor becomes:

$$\frac{d\tau}{dt} = \sqrt{1 - v^2/c_s^2} \xrightarrow{r \to r_H} 0\,. \tag{14}$$

The phase counter stops. For external observers, the condensate at the horizon is phase-locked: no further oscillation cycles accumulate. This reproduces the infinite gravitational redshift at the Schwarzschild radius without requiring a metric singularity—the condensate remains well-defined and continuous; only the emergent clock ceases to function.

Inside the horizon ($v > c_s$), the phase accumulation resumes in a different mode: the "time" and "radial" coordinates exchange roles in the acoustic metric, just as in the Schwarzschild interior. The condensate continues to evolve, but the internal clock is no longer synchronized with external observers.

7.3 No time before the condensate

In the open-system interpretation [13], the vacuum condensate nucleated from the Bulk reservoir as a phase transition. Before this nucleation, there was no condensate, no phase oscillation, and therefore no emergent time. The question "what happened before the Big Bang?" is ill-posed: time is generated by the condensate, and asking about "before" the condensate is like asking what is north of the North Pole.

This resolves the initial singularity problem differently from other approaches. In loop quantum cosmology [18], the singularity is replaced by a bounce—time continues through the transition. In the superfluid vacuum, time itself begins at the nucleation event. There is no "before" because the clock did not exist.

8 Discussion

8.1 Relation to other approaches

The emergent time picture shares features with several existing proposals while differing in mechanism:

Barbour's timeless mechanics [8] treats time as emergent from the configuration space of the universe. Our approach is compatible: the condensate's configuration space is $\{\rho(\mathbf{x}), S(\mathbf{x})\}$, and t is a path parameter through this space. The difference is that we identify the specific physical mechanism (phase oscillation) that generates the parameter.

The thermal time hypothesis [9] defines time flow from the modular automorphism of a thermal state. In our framework, the condensate's thermal equilibrium with the Bulk provides the thermal state, and the phase advance is the modular flow. The approaches may be equivalent at a formal level.

Volovik's emergent time [10] in superfluid helium is the closest analogue. Our contribution is to connect this explicitly to the PPN-constrained acoustic metric, gravitational time dilation, and the arrow of time through the open-system boundary condition.

The Wheeler-DeWitt equation [5] describes a "frozen" universe with no time evolution. In the condensate picture, the resolution is that the universe IS frozen from the Bulk perspective: the condensate's 3D configuration exists timelessly. Time is an internal label generated by the phase dynamics, not an external parameter imposed on the system.

8.2 What is and is not claimed

We do not claim that time is an illusion or that change does not occur. The condensate genuinely evolves: $\rho(\mathbf{x})$ and $S(\mathbf{x})$ change. What we claim is that the "time dimension" perceived by internal observers is constructed from this evolution, not prior to it. The 3+1 Lorentzian signature of the acoustic metric is a derived structure, not a fundamental one.

We also do not claim to resolve the measurement problem in quantum mechanics. The phase of the condensate is a classical field; the transition to quantum mechanics for its excitations involves additional structure (the quantum potential Q) that is beyond the scope of this paper.

8.3 Testable consequences

The emergent time picture makes three predictions distinct from fundamental 3+1 spacetime:

(i) *Minimum time resolution* $\Delta t_{\min} \sim t_{\mathrm{P}}$: this is the same prediction as Paper 5 [15], derived here from the phase counter picture rather than the Bohm potential. The two derivations agree, providing a consistency check.

(ii) *Quadratic dispersion modification at the Planck scale*: if time is phase accumulation at rate μ, then at energies approaching $m_{\mathrm{eff}}c^2$ the effective time evolution becomes nonlinear, producing a quadratic-in-energy dispersion modification $\Delta v/c \sim (E/E_{\mathrm{P}})^2$. The current experimental bound from gamma-ray burst observations constrains linear-in-energy dispersion at $E_{QG} \gtrsim 1.2\, E_{\mathrm{P}}$ [20]; the framework's quadratic prediction is below this bound by many orders of magnitude and remains consistent with current data while predicting a specific functional form testable by future observations.

(iii) *No pre-Big-Bang signatures*: if time began with the condensate, there should be no cosmological signatures of a pre-existing epoch (no bounce imprint in the CMB). This contrasts with loop quantum cosmology, which predicts observable signatures of the bounce in the CMB power spectrum at low multipoles [19].

9 Conclusion

We have shown that time in the logarithmic superfluid vacuum framework is not a fundamental dimension but an emergent parameter generated by the phase dynamics of the condensate order parameter.

The chemical potential $\mu(\mathbf{x}) = m_{\mathrm{eff}}\, c_s^2/\hbar_{\mathrm{eff}}$ sets the local clock rate. Gravitational time dilation is the spatial variation of μ; the twin paradox is path-dependent phase accumulation; the arrow of time is the irreversibility of phase advance in an open system exchanging energy with the Bulk; and the Hubble flow is the spatial phase winding rate.

The condensate is a three-dimensional object. Its state is fully specified by two spatial fields: $\rho(\mathbf{x})$ and $S(\mathbf{x})$. The "time dimension" perceived by phonons (photons) is an artifact of the acoustic metric's Lorentzian signature, constructed entirely from these 3D fields.

At the healing length $\xi \sim \ell_{\mathrm{P}}$, the phase counter saturates, providing a minimum time resolution $\Delta t_{\min} \sim t_{\mathrm{P}}$. At acoustic horizons, the phase locks and the emergent clock stops. Before the condensate nucleated, there was no phase oscillation and therefore no time.

The framework unifies the thermodynamic, cosmological, and quantum-mechanical arrows of time as manifestations of a single process: the condensate's relaxation toward equilibrium with the Bulk reservoir.

Acknowledgments

The author thanks C. Barceló, S. Liberati, and M. Visser for the acoustic metric framework. The methodological stance of this paper—treating the condensate phase as a real classical field whose oscillation rate underlies emergent temporal phenomena—is indebted to the Madelung-de Broglie-Bohm tradition, particularly as developed in P. R. Holland's exposition of the quantum theory of motion. Claude (Anthropic) and Gemini (Google) were used as editorial and computational tools during manuscript preparation. All scientific content, equations, and interpretations are the author's own.

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