

**Vacuum Oscillator Φ -Field (VO Φ F):
a unified framework for spacetime, gravity, dark sectors, black holes and
quantum phenomena**

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Abstract

We propose the Vacuum Oscillator Φ -Field (VO Φ F) as an ontological and effective framework in which the observable Universe is described as a phase-locked oscillatory domain of a deeper vacuum field Φ . In this picture, cosmogenesis is interpreted as a lock-in transition of vacuum phase coherence that instantiates a physical notion of time, while spacetime geometry and gravitation emerge as effective descriptions of coarse-grained vacuum states rather than fundamental background structures.

The central organising quantity is the local vacuum oscillation frequency $\omega_\Phi(x)$, interpreted operationally as a physical vacuum clock. Its phase accumulation defines proper time along worldlines, and—when an appropriate weak-field identification between $\omega_\Phi(x)$ and the Newtonian potential $\Phi_N(x)$ is enforced—one recovers standard gravitational time dilation and the Newtonian limit of gravity to leading order. Spacetime geometry is treated as a functional $g_{\{\mu\nu\}}[\langle\Phi\rangle, \partial\langle\Phi\rangle]$ of coarse-grained vacuum state variables, with general relativity appearing as the effective dynamical description in empirically validated regimes.

Within this ontology, dark matter is identified with massive, weakly coupled excitations in hidden sectors $\Phi_{\{\text{dark},i\}}$, while dark energy corresponds to the coarse-grained background vacuum energy density encoded in an effective potential $V_{\{\text{eff}\}}(\langle\Phi\rangle)$. Black holes are interpreted as regions of Φ -collapse in which the operational vacuum clock degenerates ($\omega_\Phi \rightarrow 0$ in an effective description) and propagating excitations cease to be supported, while the tested exterior Kerr phenomenology is retained. Standard quantum phenomena—superposition, interference, measurement/decoherence, and entanglement—are embedded into a single-carrier picture as excitation patterns of Φ and their environment-induced decoherence, without modifying the Hilbert-space formalism of quantum field theory.

VO Φ F is designed to be falsifiable and motivates a three-axis empirical programme: (i) cosmological probes of vacuum and dark-sector dynamics through $H(z)$, H_0 , S_8 , and the matter power spectrum $P(k)$, subject to early-Universe constraints; (ii) strong-field astrophysical tests via black-hole imaging and gravitational-wave propagation/ringdown; and (iii) local precision searches for residual anomalies in vacuum timekeeping and phase accumulation using clock networks and interferometers, with electromagnetic channels (including ELF/ULF bands) treated conservatively via bounded effective operators.

Keywords:

Vacuum field, vacuum oscillator, emergent gravity, unified dark sector, dark matter and dark energy, quantum vacuum, black holes, wave function ontology, Λ CDM cosmology, ELF vacuum fluctuations, gravitational time dilation, quantum foundations

1. Introduction

The modern description of the Universe rests on three highly successful pillars: general relativity (GR) as the theory of gravitation, quantum field theory (QFT) as the framework for matter and radiation, and the Λ CDM cosmological model, in which a non-baryonic dark component and an effective cosmological constant dominate the present-day energy budget. Precision tests of GR in the Solar System and binary pulsars, the detection of gravitational waves, and the quantitative success of QED and the Standard Model collectively establish a remarkably accurate effective description of Nature across many scales.

At the same time, several central ingredients of this description have an unclear ontological status. Spacetime is treated as a smooth geometric object, yet its microscopic degrees of freedom remain unknown. The “vacuum” is simultaneously the ground state of quantum fields and a medium that exhibits fluctuations and boundary-dependent effects, yet it lacks an agreed-upon mechanical interpretation. Dark matter and dark energy constitute the majority of the cosmic energy budget in Λ CDM, yet their physical carriers remain unidentified. Finally, quantum states and measurement are formally well understood but conceptually contested, with ongoing debate over whether the wave function is ontic, epistemic, or purely instrumental.

This work is motivated by a single organising question: can GR, Λ CDM, and standard QFT be embedded into a more elementary carrier picture that preserves their empirically validated phenomenology while offering a unified ontology for timekeeping, gravity, the dark sector, black-hole boundary behaviour, and standard quantum phenomena?

1.1. Tensions, gaps, and ontological questions

On cosmological scales, Λ CDM provides an excellent fit to a broad range of datasets, but its dominant components are defined primarily by their gravitational roles. In current concordance fits, non-baryonic dark matter accounts for roughly $\approx 27\%$ of the cosmic energy density, while dark energy accounts for roughly $\approx 68\%$ (with the remainder in baryonic matter and radiation; the precise values are model- and dataset-dependent). Despite this success, two persistent issues motivate exploration of deeper structure.

First, the cosmological-constant problem highlights a tension between naive vacuum-energy expectations in QFT and the observed small effective vacuum energy density. Whatever the

resolution, it appears to require a mechanism that connects the gravitational role of vacuum energy to the microphysics of the vacuum state. Second, mild parameter tensions (notably in H_0 and S_8) may or may not be systematics, but they motivate the question of whether the effective dark sector could possess subtle dynamics beyond a strictly constant Λ and a strictly cold, collisionless dark matter component.

On the gravity and information side, black holes are described geometrically in GR by the Kerr family, with well-defined horizons, shadows, and photon rings, yet the classical theory is silent on the physical content of the interior regime where curvature invariants diverge. The black-hole information problem further suggests that a purely geometric account is incomplete at the level where quantum degrees of freedom and gravity interact.

On the quantum-phenomena side, QFT provides a precise formalism for superposition, interference, and entanglement, but the ontology of the wave function and the measurement process remains debated. The quantum vacuum is a particularly striking example: it is a state of minimal energy and simultaneously a structured entity with fluctuations and observable consequences, inviting a more concrete “mechanics of the vacuum” viewpoint.

The common thread across these domains is the vacuum and its dynamics. This motivates treating the vacuum not merely as a formal ground state, but as a candidate physical carrier whose regimes organise timekeeping, gravity, dark components, and quantum phenomena.

1.2. Inspirations: emergent gravity, vacuum as a medium, and unified dark-sector ideas

Several research programmes motivate the idea that spacetime structure may be emergent and that the vacuum may behave as a non-trivial medium. Emergent- and analogue-gravity approaches demonstrate that effective metrics and horizon-like behaviour can arise from collective degrees of freedom in condensed-matter systems, strengthening the intuition that geometry may be an effective description rather than a primitive. Superfluid-vacuum scenarios similarly treat the vacuum as a structured medium whose collective dynamics can mimic relativistic behaviour. In cosmology, unified dark-sector models attempt to describe dark matter and dark energy as different regimes of a single effective component.

Most existing approaches, however, address only part of the overall conceptual landscape—geometry, or dark components, or quantum interpretation—without offering an explicit single-carrier ontology that simultaneously connects (i) timekeeping, (ii) gravity, (iii) dark-

sector phenomenology, (iv) black-hole boundary behaviour, and (v) standard quantum phenomenology, while remaining explicitly test-driven.

The present work is an attempt to formulate such an integrative framework, not as a UV-complete theory of quantum gravity, but as a coherent vacuum-oscillator ontology designed to reduce to GR, Λ CDM, and QFT in validated regimes and to define falsifiable axes where controlled deviations could be sought.

1.3. Guiding idea: a vacuum oscillator Φ and a vacuum-clock variable $\omega_\Phi(x)$

We postulate a global vacuum field $\Phi(x)$ as a candidate physical carrier underlying the effective structures described by GR, Λ CDM, and QFT. The central organising quantity is the local vacuum oscillation frequency $\omega_\Phi(x)$, interpreted operationally as a vacuum clock. In this picture:

- proper time corresponds to accumulated phase of the vacuum oscillator along a worldline;
- gravitational time dilation arises from spatial variability of $\omega_\Phi(x)$ in the weak-field regime, once an appropriate mapping to the Newtonian potential $\Phi_N(x)$ is enforced;
- visible matter corresponds to excitations supported by a “visible” sector $\Phi_{\{vis\}}$;
- dark matter corresponds to massive, weakly coupled excitations in hidden sectors $\Phi_{\{dark,i\}}$;
- dark energy corresponds to the coarse-grained background vacuum energy density encoded in an effective potential $V_{\{eff\}}(\langle\Phi\rangle)$;
- black holes correspond to regions where the effective vacuum-clock description degenerates ($\omega_\Phi \rightarrow 0$ in an effective description), while the tested exterior Kerr phenomenology is preserved;
- standard quantum phenomena correspond to excitation patterns of Φ and their decoherence through coupling to macroscopic environments, without altering the Hilbert-space formalism.

A recurring conceptual point is the separation between phase coherence associated with the vacuum-clock role and energetic, propagating degrees of freedom. In VOOF, vacuum-clock phase structure organises timekeeping and coherence, while energy transport and

electromagnetic activity remain properties of the effective visible-sector dynamics. This separation is essential for maintaining compatibility with the empirical success of standard electromagnetism and for framing precision tests conservatively.

1.4. Scope of this work: from ontology to falsifiable tests

The goal of this preprint is not to provide a UV-complete microphysical model of Φ or to derive Standard Model parameters. Instead, the paper aims to:

- (i) state a coherent vacuum-oscillator ontology with a minimal effective formal layer;
- (ii) show how GR, Λ CDM, and QFT can be recovered as effective descriptions of appropriate Φ -regimes;
- (iii) organise falsifiability along three complementary axes—cosmological, strong-field astrophysical, and local precision experiments—without assuming a signal and without committing to a unique potential $V_{\text{eff}}(\Phi)$.

Accordingly, the weak-field identification between $\omega_\Phi(x)$ and $\Phi_N(x)$ is used as an enforced consistency condition rather than as a new prediction: agreement with high-precision gravitational clock tests fixes the corresponding mapping parameters in the infrared regime where GR is well validated.

1.5. Positioning: between interpretation and effective theory

VO Φ F sits between a purely interpretational stance and a fully specified quantitative alternative to Λ CDM/GR. On one hand, it provides an ontological reading of time, vacuum structure, and quantum states within a single-carrier picture. On the other hand, it is formulated to be empirically accountable: deviations from standard phenomenology are parameterised conservatively and are pushed into regimes where they can be progressively bounded or detected by dedicated observations and precision experiments.

The framework is therefore intended to be constrained: it is scientifically meaningful only insofar as it identifies a disciplined route from ontology to falsifiable signatures.

1.6. Relation to existing approaches

To clarify the conceptual scope of the present work and avoid confusion with earlier proposals, this section briefly positions the Vacuum Oscillator Φ -Field (VO Φ F) framework relative to several established lines of research. A recurring theme across modern theoretical physics is

that time and spacetime structure may be emergent, and that the physical vacuum may possess nontrivial dynamical degrees of freedom. VOΦF does not seek to replace these approaches within their domains of validity. Rather, it is proposed as an integrative ontological layer that (i) remains compatible with empirically validated regimes of general relativity (GR), quantum field theory (QFT), and Λ CDM, and (ii) organizes gravity, the dark sector, black-hole boundary behaviour, and standard quantum phenomenology around a single vacuum carrier Φ .

Preferred-time structures in gravity.

A number of effective gravitational theories introduce a distinguished temporal structure. Hořava–Lifshitz gravity employs a preferred foliation with anisotropic scaling between space and time in the ultraviolet as a route toward improved high-energy behaviour (Hořava, 2009). Einstein–æther models introduce a dynamical unit timelike vector field that locally breaks Lorentz invariance and encodes a preferred frame (Jacobson and Mattingly, 2001; Jacobson, 2008). These theories demonstrate that treating temporal structure as dynamical can be mathematically consistent with relativistic gravity and can be strongly constrained in the infrared by observations. VOΦF is conceptually adjacent insofar as it assigns timekeeping a physical substrate; however, it differs in the identification of that substrate. The operational flow of proper time is identified not with a fundamental foliation or preferred vector field, but with a local oscillatory phase and frequency of a vacuum field Φ . In this sense, time is realised as a vacuum clock whose local rate is given by the phase evolution of Φ , while the empirically tested relativistic symmetries are required to be recovered effectively in the appropriate regimes.

Time as emergent from correlations or statistical structure.

In quantum foundations, the Page–Wootters mechanism and related “timeless” approaches interpret time as a relational quantity emerging from correlations between subsystems of a globally stationary quantum state (Page and Wootters, 1983; Moreva et al., 2014). In a different but complementary direction, the thermal time hypothesis links the flow of time to the modular structure of states in algebraic quantum theory, suggesting that time can be state-dependent and emergent from the statistical structure of the system (Connes and Rovelli, 1994). VOΦF is compatible with the general lesson of these frameworks—that time need not be a fundamental external parameter—but adds a concrete unifying carrier: the vacuum

oscillator Φ provides a physical phase variable whose coherence and local frequency define an effective time standard. Unlike approaches that remain primarily relational or informational, VOΦF places this emergent temporality in a dynamical vacuum medium that also interfaces with gravity, cosmology, and coherence-sensitive measurements.

Emergent geometry and the vacuum as a medium.

The analogue-gravity programme has shown that effective metrics, horizons, and relativistic phenomena can emerge in condensed-matter systems, strengthening the intuition that spacetime geometry may be an effective description of deeper microscopic degrees of freedom (Unruh, 1981; Barceló et al., 2011). Related condensed-matter-inspired views treat the vacuum as a structured medium whose collective dynamics can mimic gravitational and relativistic behaviour (Volovik, 2003). VOΦF aligns with this emergent-geometry perspective but centres the organisation on a specific variable: the local oscillation frequency $\omega_\Phi(x)$ and phase coherence of the vacuum field Φ . In this picture, gravitational redshift and time dilation arise as effective manifestations of spatial and dynamical variability of the vacuum clock, rather than as fundamental geometric primitives.

Unified dark-sector phenomenology.

A separate class of models seeks to describe dark matter and dark energy within a single effective component, such as unified dark fluids or generalised Chaplygin-gas models (Kamenshchik et al., 2001; Bento et al., 2002). These approaches aim to reduce the number of independent cosmological ingredients while reproducing Λ CDM phenomenology in appropriate limits. VOΦF shares the goal of ontological economy but proposes a different mechanism: dark matter corresponds to massive, weakly coupled excitations or structured modes in hidden sectors of a common vacuum carrier Φ , whereas dark energy corresponds to the coarse-grained background energy density of the vacuum oscillator encoded in an effective potential $V_{\text{eff}}(\langle \Phi \rangle)$. Λ CDM is recovered as an effective statistical description in the coarse-grained regime, while controlled deviations—if required by data—remain testable via cosmological observations and precision experiments.

2. Ontology of the vacuum field Φ

2.1 Amplitude–phase structure of the vacuum oscillator

At the level of an effective description, the vacuum field Φ admits a natural decomposition into an amplitude and a phase,

$$\Phi(x) \sim A(x) e^{i\theta_\Phi(x)}.$$

The local vacuum oscillation frequency

$$\omega_\Phi(x) \equiv \frac{\partial \theta_\Phi}{\partial \tau}$$

defines the physical flow of proper time along a worldline.

Importantly, phase coherence of the vacuum oscillator need not be associated with local energy transport or electromagnetic activity. Amplitude variations contribute to stress–energy and gravitating effects, while phase structure primarily organises temporal ordering, interference phenomena, and synchronisation across spacetime.

As a consequence, phase dynamics may remain largely decoupled from direct electromagnetic observables, including ELF-band measurements, except through indirect effects on precision clocks, interferometers, or other coherence-sensitive probes.

This amplitude–phase distinction underlies all subsequent interpretations of time, gravity, quantum phenomena, and observational constraints within the VO Φ F framework.

2.2 Basic assumptions

Throughout this work, x may be read operationally: in the coherent regime it coincides with effective spacetime coordinates, while in the pre-temporal regime it should be regarded as a label on a pre-geometric substrate. The metric $g_{\mu\nu}$ is then a self-consistent functional of coarse-grained Φ -state variables in the coherent phase.

The framework proposed in this work rests on the following ontological assumptions:

Existence of a global vacuum field $\Phi(x)$. There exists a vacuum field $\Phi(x)$, defined on a four-dimensional spacetime manifold (or its suitable generalisation), which acts as the physical carrier of both spacetime geometry and all matter fields.

Space, time, matter and radiation as different regimes of Φ . What we conventionally describe as “space”, “time”, “matter” and “radiation” corresponds to different regimes of the state of Φ :

- coarse-grained properties of Φ define an effective spacetime metric,
- stable excitations in the “visible” sector reproduce the fields of the Standard Model,
- excitations in weakly coupled sectors behave as dark-matter-like or otherwise hidden degrees of freedom.

Quantum vacuum as a non-trivial state of Φ .

The quantum vacuum is a non-zero, structured state of Φ with characteristic fluctuations; the associated vacuum energy behaves effectively like dark energy on cosmological scales.

Gravity from spatial variations of the oscillation frequency of Φ .

The local vacuum oscillation frequency $\omega_\Phi(x)$ of the field Φ defines the effective flow of proper time, while spatial gradients of $\omega_\Phi(x)$ correspond to what is classically described as the gravitational potential. In the weak-field limit one can write

$$\mathbf{g}(x) \propto -\nabla\omega_\Phi(x),$$

where $\mathbf{g}(x)$ is the classical gravitational acceleration.

Black holes as regions of Φ -collapse.

Black holes are interpreted as regions in which Φ loses its ability to support propagating excitations (collapse of Φ , $\omega_\Phi \rightarrow 0$), which macroscopically leads to the appearance of horizons, black-hole shadows and photon rings.

In this sense, the “core mechanics” is effectively one-parameter: all observable degrees of freedom—time, gravity, matter fields, dark sectors, black holes and quantum phenomena—are treated as different dynamical regimes of a single quantity: the local vacuum oscillation frequency $\omega_\Phi(x)$ and its modes.

Taken together, these postulates define what I will call the vacuum-oscillator Φ framework (VO Φ F). All concrete realizations with different choices of $V_{\text{eff}}(\Phi)$ and interaction terms that respect these assumptions will be referred to as VO Φ F-type models.

2.3 Sectoral structure of the vacuum field

At the effective level, I model the vacuum as a multi-component scalar field

$$\Phi(x) = (\Phi_{\text{vis}}(x), \Phi_{\text{dark},1}(x), \Phi_{\text{dark},2}(x), \dots),$$

where

- Φ_{vis} denotes the component responsible for visible matter and gauge fields,
- $\Phi_{\text{dark},i}$ denote components corresponding to different classes of dark modes (e.g. dark-matter-like excitations or other hidden sectors).

All sectors jointly contribute to the total vacuum energy density, whereas only the visible sector and, potentially, certain subsets of the dark sectors are directly accessible to our detectors.

2.4 Minimal effective dynamics

A minimal effective description can be written schematically as

$$\mathcal{L} = \mathcal{L}_{\text{GR}}[g_{\mu\nu}] + \mathcal{L}_{\text{SM}}[\psi, A_\mu, g_{\mu\nu}] + \mathcal{L}_\Phi[\Phi_{\text{vis}}, g_{\mu\nu}] + \mathcal{L}_{\text{dark}}[\Phi_{\text{dark},i}, g_{\mu\nu}] + \mathcal{L}_{\text{int}}[\Phi, \psi, A_\mu].$$

Here:

- $\mathcal{L}_{\text{GR}} = \frac{1}{16\pi G} R$ is the usual Einstein–Hilbert term.
- \mathcal{L}_{SM} is the Standard Model Lagrangian on the background metric $g_{\mu\nu}$.

In the visible sector we take

$$\mathcal{L}_\Phi = \frac{1}{2} \partial_\mu \Phi_{\text{vis}} \partial^\mu \Phi_{\text{vis}} - V_{\text{vis}}(\Phi_{\text{vis}}),$$

where V_{vis} is an effective potential.

In the dark sector,

$$\mathcal{L}_{\text{dark}} \supset \sum_i [\frac{1}{2} \partial_\mu \Phi_{\text{dark},i} \partial^\mu \Phi_{\text{dark},i} - V_i(\Phi_{\text{dark},i})].$$

The coupling to visible matter has the schematic form

$$\mathcal{L}_{\text{int}} \supset g_\Phi \Phi_{\text{vis}} T_\mu^\mu,$$

where T_μ^μ is the trace of the energy–momentum tensor of visible matter.

At a coarse level one can write a schematic equation of motion

$$\square\Phi(x) + \frac{dV_{\text{eff}}(\Phi)}{d\Phi} = \alpha T_\mu^\mu(x) + \dots,$$

where \square is the d'Alembertian operator built from the emergent metric $g_{\mu\nu}$, and the ellipsis denotes self-interactions in the dark sectors and higher-order corrections.

2.5 Time and space as effective descriptions of the state of Φ

In standard GR the metric $g_{\mu\nu}(x)$ is the primary geometric object. In the Φ framework, the metric is interpreted as a functional of the coarse-grained state of the vacuum field:

$$g_{\mu\nu}(x) = F_{\mu\nu}(\langle\Phi(x)\rangle, \partial\langle\Phi(x)\rangle).$$

The local vacuum oscillation frequency $\omega_\Phi(x)$ plays the role of a “vacuum clock”:

- proper time along a worldline parametrises the sequence of changes of the state of Φ ,
- the local rate of these changes is proportional to $\omega_\Phi(x)$.

In regions with smaller $\omega_\Phi(x)$ proper time flows more slowly; in regions with larger $\omega_\Phi(x)$ it flows faster. Mass–energy deforms the state of Φ in such a way that it locally reduces $\omega_\Phi(x)$, thereby reproducing gravitational time dilation.

2.6 Reduction to known effective theories

Schematically:

- **GR (gravity).** On scales much larger than the microscopic structure of Φ , and neglecting exotic degrees of freedom in the dark sectors, the equations of motion for $\langle\Phi\rangle$ and $g_{\mu\nu}$ reduce to Einstein's equations with an effective cosmological constant Λ_{eff} arising from the background energy of Φ .
- **QFT on curved spacetime.** For a given background geometry $g_{\mu\nu}$ and small excitations around a vacuum configuration of Φ , one recovers the standard description of particles as excitations of fields propagating on curved spacetime.
- **Λ CDM cosmology.** On cosmological scales:
 - the vacuum energy density of Φ yields an effective cosmological constant,
 - an appropriate subset of modes $\Phi_{\text{dark},i}$ behaves as cold, non-baryonic dark matter.

Λ CDM thus appears as an effective, statistical description of the full dynamics of Φ .

In the following sections this ontology is used to interpret gravity (Section 3), the dark sector (Section 4), black holes (Section 5) and quantum phenomena (Section 6).

2.7 Cosmogenesis as a Φ phase transition (lock-in of the vacuum clock)

A recurrent ambiguity in standard “Big Bang” language is that it suggests an explosion of matter into a pre-existing space. Within the Φ ontology adopted here, the opposite reading is taken: the time-domain in which spacetime geometry, dynamics and causal structure exist is itself an emergent phase of the vacuum oscillator. Cosmogenesis is therefore interpreted not as an event occurring *in* time, but as a phase transition of the vacuum field Φ from a pre-temporal regime into a coherent oscillatory regime in which time becomes physically instantiated.

2.7.1 Pre-temporal vacuum state

I assume that the vacuum field Φ admits regimes in which a globally coherent oscillation frequency is not defined. In such regimes the vacuum may be described as *pre-temporal* in the following operational sense: there exists no globally meaningful phase variable that can parametrise ordered sequences of events. Importantly, this does not correspond to “nothingness”, but rather to a state in which time, understood as a physical ordering parameter tied to a vacuum clock, is not yet realised.

Local fluctuations of Φ may occur in this pre-temporal regime, but in the absence of phase coherence they do not define a stable notion of duration, causality or geometry. Consequently, standard spacetime concepts are not applicable at this level of description.

2.7.2 Instability threshold and lock-in of the vacuum clock

Cosmogenesis is modelled as a transition from an incoherent (or weakly coherent) regime of the vacuum field to a coherent oscillatory regime characterised by a nonzero local vacuum frequency ω_{Φ} and a well-defined phase field θ_{Φ} . The central mechanism of this transition is *lock-in*: above an instability threshold, local oscillatory patches of Φ do not decay back to noise, but instead self-amplify and synchronise.

Qualitatively, one may introduce a coherence (or order) parameter Q_{Φ} and formulate the transition criterion as follows:

- **below threshold:** fluctuations of Φ remain incoherent and decay, and no stable ω_Φ can be defined;
- **above threshold:** oscillations grow, phase coherence emerges, and a stable vacuum clock ω_Φ becomes well defined.

In this view, the “Big Bang” corresponds to the onset of a globally connected time-domain in which the vacuum clock locks in across an extended region. The establishment of a coherent phase field allows ω_Φ to serve as the physical substrate of proper time, thereby instantiating causal structure. In this ontology, spacetime is not the stage on which Φ evolves; rather, a coherent oscillatory regime of Φ is what makes an effective spacetime description meaningful in the first place.

2.7.3 Emergent spacetime and early-domain growth

Once a coherent oscillatory regime is established, an effective geometric description becomes applicable. In the Φ framework, the metric $g_{\mu\nu}$ is treated as a functional of coarse-grained vacuum state variables, including ω_Φ and its gradients. Accordingly, the earliest stage of the Universe may be re-interpreted not primarily as an expansion of matter into emptiness, but as the rapid growth and homogenisation of a coherent time-domain: a swift increase of the region over which ω_Φ and θ_Φ are well defined and mutually compatible.

This perspective provides a natural ontological slot for inflation-like behaviour. The rapid establishment of global phase coherence offers an interpretation of horizon-type intuitions—namely, why distant regions of the observable Universe share consistent physical laws—without, at this stage, committing to a specific inflaton field or potential. Quantitative cosmological predictions within this framework still require an explicit choice of the effective potential $V_{\text{eff}}(\Phi)$ and of the relevant couplings governing the post-lock-in dynamics.

During the transient lock-in regime, phase dynamics dominate: the stabilisation of temporal ordering precedes the emergence of familiar gravitational behaviour. Only after phase coherence is established does amplitude structure acquire its standard role as stress–energy, allowing a classical geometric description to emerge.

2.7.4 Remnant coherence defects as observational handles

If cosmogenesis involves a phase transition followed by rapid coherence growth, it is natural to consider the possibility of residual, extremely weak non-idealities of the vacuum state. Such

remnants may take the form of mild spatial variations, incomplete homogenisation, or long-lived memory of the early lock-in process.

In conservative terms, these effects could manifest observationally as small departures from perfect isotropy or homogeneity, or as subtle tensions among independently inferred cosmological parameters. No specific anomaly is claimed here as evidence for Φ dynamics. Rather, the point is conceptual: a phase-transition origin of the time-domain renders such signatures natural targets for falsifiable empirical tests, to be discussed in Section 7.

2.8 Multiple time-domains and a non-geometric multiverse

The phase-transition reading of cosmogenesis suggests a minimal notion of a “multiverse” within the Φ ontology: distinct, dynamically stable time-domains corresponding to different coherent solutions (or phases) of the vacuum field. Crucially, these domains need not be embedded as “bubbles in a common space”; rather, they are best regarded as distinct solutions in the configuration space of Φ , each instantiating its own effective time and geometry.

In this interpretation:

1. Multiplicity means multiple stable oscillatory regimes of Φ , potentially with different effective parameters (e.g., background ω_Φ scales, sectoral couplings, or symmetry-breaking patterns).
2. No traversable contacts are expected in the naive geometric sense, because “adjacency” requires a shared metric/time-domain structure. Where two solutions are dynamically incompatible, their overlap corresponds to loss of coherence rather than a stable “portal”.
3. The empirically relevant question is therefore not travel between domains, but whether our domain’s early lock-in dynamics can leave testable residual signatures (Section 7).

2.9 Scales, dimensional analysis, and a minimal parameter set

A recurring difficulty of vacuum-substrate ontologies is that they may appear underconstrained unless a clear separation is made between

- (i) the ontological layer and

(ii) a minimal phenomenological parameterisation that is directly testable.

In this section, a compact VOOF parameter set is introduced whose sole purpose is to organise empirical constraints, without committing to a unique microscopic model of the vacuum field Φ .

The core identification of the framework is the mapping between the local vacuum oscillation frequency $\omega_\Phi(x)$ and the weak-field gravitational potential $\Phi_N(x)$,

$$\frac{\omega_\Phi(x) - \omega_\infty}{\omega_\infty} = \gamma \frac{\Phi_N(x)}{c^2}, \frac{d\tau}{dt} = \chi(\omega_\Phi) \simeq 1 + \beta \frac{\omega_\Phi - \omega_\infty}{\omega_\infty},$$

so that the product $\beta\gamma$ controls the leading gravitational time-dilation law. Agreement with standard gravitational clock tests in the Solar System and terrestrial laboratories requires $\beta\gamma \simeq 1$ within current experimental precision. This illustrates a general principle of the VOOF framework: wherever it is constructed to reproduce GR and QFT as effective theories, the corresponding parameters are not free predictions but are fixed, or tightly constrained, by existing high-precision data.

Beyond the purely gravitational sector, possible non-standard low-energy imprints of Φ can be encoded in a small set of gauge-invariant effective operators. A conservative example is a weak coupling between the vacuum oscillator and electromagnetism,

$$\delta\mathcal{L}_{\Phi\text{-EM}} \sim \epsilon_1 \Phi F_{\mu\nu}F^{\mu\nu} + \epsilon_2 \Phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \epsilon_3 \partial_\mu\Phi J^\mu + \dots,$$

where J^μ denotes an effective visible-sector current and the ellipsis represents higher-order and/or derivative operators. The role of the coefficients ϵ_i is not to assert the existence of a new macroscopic force, but to provide a systematic bookkeeping device: shielded magnetometry, resonant detectors, clock networks, and related precision experiments can be used to place upper bounds on ϵ_i as functions of frequency band, environmental conditions, and shielding geometry.

At cosmological scales, an analogous minimal parameterisation treats the background vacuum energy density

$$\rho_{\Phi\text{-vac}}(t) \equiv V_{\text{eff}}(\langle\Phi\rangle(t))$$

and the dark-sector excitation content $\rho_{\Phi\text{-dark}}(t)$ as effective components whose time dependence is constrained by the observed expansion history $H(z)$, the cosmic microwave background, baryon acoustic oscillations, and the growth of large-scale structure. The

emphasis here is not on specifying a particular microphysical origin for these functions, but on identifying which broad classes of effective potentials $V_{\text{eff}}(\Phi)$ and dark-mode properties allow the framework to remain simultaneously compatible with

- (i) Λ CDM-like background evolution where it is strongly supported by data, and
- (ii) controlled deviations in regimes where current observational tensions motivate them.

This explicit separation between ontology and minimal phenomenological parameterisation serves two purposes. First, it renders the framework strictly falsifiable: sufficiently tight bounds on the parameter set

$$(\beta\gamma, \epsilon_i, \rho_{\Phi\text{-vac}}(z), \rho_{\Phi\text{-dark}}(z))$$

can either confine VOΦF to practical irrelevance or identify a motivated region of parameter space. Second, it clarifies what would constitute genuine explanatory gain: not the proliferation of free parameters, but the identification of a simple and stable class of effective models in which a single Φ -dynamics consistently organises gravitational timekeeping, dark-sector phenomenology, black-hole boundary behaviour, and low-energy probe channels within one coherent framework.

3. Time and gravity from the vacuum oscillator Φ

3.1. Local oscillation frequency and proper time

The basic quantity controlling the flow of time is the local vacuum oscillation frequency $\omega_\Phi(x)$.

Along a timelike worldline γ ,

- the field Φ executes a sequence of oscillations, and
- the accumulated phase of these oscillations defines proper time.

I postulate the relation

$$d\tau(x) = \chi(\omega_\Phi(x)) dt,$$

where t is a global coordinate time, and $\chi(\omega_\Phi)$ is a monotonic function with $\chi(\omega_\infty) = 1$ in an asymptotically homogeneous region. In the linear regime,

$$\chi(\omega_\Phi(x)) \simeq 1 + \beta \frac{\omega_\Phi(x) - \omega_\infty}{\omega_\infty},$$

with a dimensionless constant $\beta = \mathcal{O}(1)$.

3.2. Weak-field limit and Newtonian gravity

In the weak-field limit the metric can be written as

$$ds^2 \simeq -(1 + \frac{2\Phi_N}{c^2}) c^2 dt^2 + (1 - \frac{2\Phi_N}{c^2}) d\vec{x}^2,$$

with the Newtonian potential $\Phi_N(x)$ satisfying

$$\vec{g}(x) = -\nabla \Phi_N(x).$$

I assume the relation

$$\frac{\omega_\Phi(x) - \omega_\infty}{\omega_\infty} = \gamma \frac{\Phi_N(x)}{c^2},$$

which gives

$$d\tau(x) \simeq [1 + (\beta\gamma) \frac{\Phi_N(x)}{c^2}] dt.$$

Choosing $\beta\gamma = 1$ reproduces the standard expression for gravitational time dilation. In particular,

$$\vec{g}(x) \propto -\nabla \omega_\Phi(x),$$

so the classical gravitational field corresponds to the gradient of the vacuum oscillation frequency.

3.3. Relation to the metric and GR

The weak-field relations can be embedded in the full description by interpreting

$$g_{\mu\nu}(x) = F_{\mu\nu}(\langle \Phi(x) \rangle, \partial \langle \Phi(x) \rangle).$$

In a quasi-static regime one may write

$$g_{00}(x) \simeq -[1 + 2 \varepsilon(\omega_\Phi(x))],$$

with $\varepsilon(\omega_\Phi) \propto (\omega_\Phi - \omega_\infty)/\omega_\infty$ chosen such that

$$\varepsilon(\omega_\Phi(x)) \simeq \frac{\Phi_N(x)}{c^2}.$$

Einstein's equations

$$G_{\mu\nu}[g] = 8\pi G T_{\mu\nu}^{(\text{tot})} + \Lambda_{\text{eff}} g_{\mu\nu}$$

can then be viewed as effective equations for the functional $F_{\mu\nu}$, driven by the dynamics of Φ and its coupling to matter.

3.4. Equivalence principle and free fall

The universality of free fall is realised via:

Universal low-energy coupling.

The dominant low-energy coupling between Φ and matter is proportional to the trace of the energy-momentum tensor:

$$\mathcal{L}_{\text{int}} \supset g_\Phi \Phi_{\text{vis}} T^\mu_\mu.$$

All forms of visible energy-momentum deform the vacuum in the same way.

Free motion as extremum of vacuum phase.

Free trajectories extremise the integrated phase of the vacuum:

$$S \sim \int \omega_\Phi(x(\lambda)) d\lambda,$$

which, to leading order, coincides with the action of a particle in GR and leads to the geodesic equation.

Under these assumptions, standard tests of the equivalence principle constrain only small deviations in how ω_Φ couples to different sectors.

3.5. Example: time dilation in the Earth–GPS system

To check the consistency of the ansatz

$$\frac{\omega_\Phi(x) - \omega_\infty}{\omega_\infty} = \gamma \frac{\Phi_N(x)}{c^2}, \quad \frac{d\tau(x)}{dt} \simeq 1 + \beta \frac{\omega_\Phi(x) - \omega_\infty}{\omega_\infty},$$

with the choice $\beta\gamma = 1$, consider the classic example of clock-rate differences between the Earth's surface and a GPS satellite orbit.

In the weak-field limit GR gives

$$\frac{d\tau}{dt} \simeq 1 + \frac{\Phi_N(x)}{c^2},$$

where $\Phi_N(x) = -GM_\oplus/r$ is the Newtonian potential and M_\oplus is the mass of the Earth. For two radii r_1, r_2 , the fractional difference in clock rate is

$$\Delta \square(\frac{d\tau}{dt}) \simeq \frac{\Phi_N(r_2) - \Phi_N(r_1)}{c^2} = -\frac{GM_\oplus}{c^2} \left(\frac{1}{r_2} - \frac{1}{r_1} \right).$$

Take:

- Earth mass $M_\oplus \approx 5.97 \times 10^{24}$ kg,
- Earth radius $R_\oplus \approx 6.37 \times 10^6$ m,
- GPS orbital altitude $h \approx 2.02 \times 10^7$ m, so $r_1 = R_\oplus$, $r_2 = R_\oplus + h \approx 2.66 \times 10^7$ m,
- gravitational constant $G \approx 6.67 \times 10^{-11}$ SI,
- speed of light $c \approx 3.0 \times 10^8$ m/s.

Inserting these numbers one obtains

$$\Delta \square(\frac{d\tau}{dt}) \simeq +5.3 \times 10^{-10}.$$

In other words, an atomic clock in a GPS orbit ticks by about 5×10^{-10} faster per second than an identical clock on the Earth's surface (ignoring, for the moment, the special-relativistic effect due to the satellite's velocity). This is precisely the order of magnitude that must be taken into account in practical GPS corrections.

Within the present Φ ontology:

- the gradient of $\omega_\Phi(x)$ around the Earth is related to $\Phi_N(x)$ by $(\omega_\Phi - \omega_\infty)/\omega_\infty = \gamma \Phi_N/c^2$;
- the identification $\beta\gamma = 1$ ensures that the fractional clock-rate difference $\Delta(d\tau/dt)$ matches the GR result;
- the above example can therefore be treated as a simple “sanity check” of the mapping $\omega_\Phi \leftrightarrow \Phi_N$: with an appropriate choice of ansatz parameters we obtain a numerically correct reconstruction of a well-measured effect.

This simple calculation is not a new prediction—we enforce agreement with GR via $\beta\gamma = 1$ —but it shows that interpreting gravitational time dilation as a consequence of the spatial gradient of $\omega_\Phi(x)$ is numerically fully compatible with existing clock measurements in a gravitational field.

4. Dark matter and dark energy as modes of the vacuum oscillator Φ

In the standard Λ CDM cosmology, the dominant components of the cosmic energy budget are dark matter ($\approx 25\text{--}30\%$) and dark energy ($\approx 65\text{--}70\%$). Within the VOOF ontology, both components are realised as different dynamical regimes of a single vacuum field Φ , rather than as fundamentally distinct substances.

4.1 Dark matter as hidden excitations of Φ

The vacuum field is decomposed into a visible sector and a set of dark sectors,

$$\Phi(x) = (\Phi_{\text{vis}}(x), \Phi_{\text{dark},1}(x), \Phi_{\text{dark},2}(x), \dots).$$

Dark matter is identified with stable, massive excitations in the sectors $\Phi_{\text{dark},i}$. The dark-sector dynamics is described at the effective level by

$$\mathcal{L}_{\text{dark}} \supset \sum_i \left[\frac{1}{2} \partial_\mu \Phi_{\text{dark},i} \partial^\mu \Phi_{\text{dark},i} - V_i(\Phi_{\text{dark},i}) \right],$$

where the curvature of V_i around its minimum sets the effective mass and self-interactions of a given mode.

For a broad class of such modes, the coarse-grained cosmological behaviour is indistinguishable from that of cold dark matter: the excitations are non-relativistic, stable on cosmological timescales, and weakly coupled to the visible sector. Their local energy density,

$$\rho_{\text{dark}}(x) = \sum_i \rho_i(x; \Phi_{\text{dark},i}),$$

contributes to the total energy-momentum tensor, deforms the local vacuum frequency $\omega_\Phi(x)$, and thereby sources the gravitational field,

$$\mathbf{g}(x) \propto -\nabla \omega_\Phi(x).$$

The absence (or extreme weakness) of couplings to electromagnetism ensures that these modes neither emit nor absorb light.

4.2 Galactic haloes and rotation curves

In Λ CDM, the approximately flat rotation curves of spiral galaxies are explained by dark-matter haloes. In the VOOF framework, an equivalent description emerges naturally: the stellar and gaseous components correspond to ordered excitations of Φ_{vis} , while the galactic halo is a

quasi-stationary configuration of dark-sector modes $\Phi_{\text{dark},i}$ surrounding the visible galaxy. The energy stored in these modes deforms $\omega_\Phi(x)$ such that its spatial gradients sustain approximately flat rotation curves.

In the weak-field regime this reproduces the Poisson equation,

$$\nabla^2 \Phi_N(x) \propto \rho_{\text{vis}}(x) + \rho_{\text{dark}}(x),$$

with ρ_{dark} interpreted as energy stored in dark vacuum excitations.

4.3 Dark energy as the background of the vacuum oscillator

Dark energy is interpreted as the background energy of the vacuum field,

$$\rho_{\Phi\text{-vac}}(t) \equiv V_{\text{eff}}(\langle\Phi\rangle(t)),$$

where V_{eff} includes contributions from all sectors of Φ . In a homogeneous FRW background the total energy density can be written as

$$\rho_{\text{tot}}(t) = \rho_{\text{vis}}(t) + \rho_{\text{dark}}(t) + \rho_{\Phi\text{-vac}}(t).$$

If the background value $\langle\Phi\rangle$ evolves sufficiently slowly, $\rho_{\Phi\text{-vac}}$ behaves effectively as a cosmological constant with equation of state $w \simeq -1$.

From this perspective, the cosmological-constant problem is reformulated as a problem of vacuum dynamics: either different sectoral contributions partially compensate, or only a specific coarse-grained projection of the full vacuum energy of Φ gravitates through the effective metric.

Observationally, the present-day dark-energy density is of order

$$\rho_\Lambda \sim 5 \times 10^{-10} \text{ J m}^{-3} \sim 6 \times 10^{-27} \text{ kg m}^{-3},$$

corresponding to an energy scale $E_\Lambda \equiv \rho_\Lambda^{1/4} \sim \text{meV}$. Dimensional estimates of this scale can be used to illustrate the extreme smallness of the effective vacuum stiffness, but their detailed interpretation requires a concrete microscopic model of Φ and is not pursued here.

4.4 Λ CDM as an effective description and possible tensions

In this framework, Λ CDM emerges as an effective statistical description of a broad class of Φ -configurations in which dark-sector excitations behave as cold matter and the vacuum background is approximately constant. Slow evolution of $\langle\Phi\rangle(t)$ or transient excitation of specific $\Phi_{\text{dark},i}$ modes could, in principle, introduce mild redshift dependence in $\rho_{\Phi\text{-vac}}(z)$ or

$\rho_{\text{dark}}(z)$. Such effects provide a natural conceptual slot for small deviations from pure Λ CDM behaviour, should future data require them, without committing to a specific form of $V_{\text{eff}}(\Phi)$.

4.5 Section summary

Within the VOOF ontology, dark matter consists of hidden, massive excitations in dark sectors of the vacuum field, while dark energy corresponds to the background energy of the vacuum oscillator encoded in $V_{\text{eff}}(\langle \Phi \rangle)$. Both components arise from a single carrier Φ and feed into the same quantity $\omega_\Phi(x)$, whose gradients generate gravity. Λ CDM is recovered as an effective description in the appropriate coarse-grained regime.

5. Black holes as regions of vanishing vacuum oscillations (Φ -collapse)

5.1. Black holes in general relativity

In classical general relativity, a black hole is characterised by a set of geometric and observational features: an event horizon that causally disconnects the interior from future null infinity; a shadow observed against a luminous background, corresponding to photon capture and strong lensing; and a photon ring associated with unstable circular null geodesics. At the level of the classical field equations, these structures are well described by the Kerr (or Schwarzschild) metric.

At the same time, GR provides no physical description of the inner singularity. The divergence of curvature invariants signals the breakdown of the classical geometric description, but does not specify what physical degrees of freedom cease to exist, nor how time, information, or matter should be understood in this regime.

This motivates the search for an interpretation in which the exterior phenomenology of black holes is preserved, while the interior is re-expressed in terms of more fundamental degrees of freedom.

5.2. Decay of vacuum oscillations and Φ -collapse

Within the VO Φ F framework, the vacuum field Φ normally oscillates with a nonzero local frequency $\omega\Phi(x)$. These oscillations support:

- propagating excitations identified with particles and radiation,
- a well-defined local flow of proper time,
- an effective spacetime geometry through coarse-grained variations of $\omega\Phi(x)$.

In regions of increasing compactness, the energy density stored in excitations of Φ deforms the local vacuum state. As compactness increases, the local oscillation frequency $\omega\Phi(x)$ is progressively reduced. Beyond a critical threshold, the oscillatory regime of the vacuum can no longer sustain stable propagating modes or a meaningful notion of local time.

We define a **Φ -collapse region**, denoted $\mathcal{C}\Phi$, as the set of points for which the effective vacuum oscillation frequency tends to zero,

$$\omega_\Phi(x) \rightarrow 0,$$

and no stable oscillatory modes of Φ exist. Inside $\mathcal{C}\Phi$:

- propagating visible-sector excitations (photons, particles) are absent,
- no local vacuum clock operates,
- the effective spacetime description in terms of a smooth metric loses its operational meaning.

For an external observer, the Φ -collapse region corresponds to the interior of a black hole. Importantly, this interpretation does not modify the exterior Kerr geometry, which remains valid wherever $\omega\Phi(x)$ is nonzero.

5.3. Event horizon, photon ring, and shadow in the Φ -language

The radial profile of the vacuum oscillation frequency $\omega\Phi(r)$ around a compact object naturally distinguishes three regimes:

1. Outer oscillatory region. Far from the compact object, $\omega\Phi(r) \approx \omega\infty$ and the vacuum supports free propagation of matter and radiation.
2. Strong-field oscillatory shell. In the vicinity of the photon ring, spatial gradients $|\nabla\omega\Phi|$ are large but $\omega\Phi(r)$ remains nonzero. The vacuum still supports electromagnetic modes, although their trajectories are strongly bent. In this regime, unstable photon orbits arise.
3. Φ -collapse interior. At smaller radii, $\omega\Phi(r)$ effectively vanishes and the vacuum no longer supports propagating modes. This defines the Φ -collapse region $\mathcal{C}\Phi$.

In this picture:

- the event horizon corresponds to the boundary between the oscillatory regime of Φ and Φ -collapse,
- the photon ring is interpreted as the outermost shell in which vacuum oscillations remain sufficiently coherent to support quasi-bound electromagnetic trajectories,
- the shadow is the projection of the Φ -collapse region onto the observer's sky.

This reinterpretation preserves the standard geometric predictions of GR while assigning them a vacuum-dynamical meaning.

5.4. Interior scenarios and sectoral structure

At the effective level, several qualitatively distinct scenarios for the interior Φ -dynamics can be considered:

(A) Terminal Φ -collapse.

The Φ -collapse region represents a local endpoint of the vacuum description: $\omega\Phi \rightarrow 0$, no oscillatory degrees of freedom persist, and no further spacetime region is physically instantiated.

(B) Sector-selective collapse.

The visible component Φ_{vis} collapses, while some dark-sector modes $\Phi_{\text{dark},i}$ remain dynamically active. In this case, the black-hole interior may act as an interface that redistributes energy and information between sectors without supporting ordinary spacetime structure.

(C) Transient topological configurations.

Extreme deformations of Φ may resemble bridge-like configurations in field-configuration space. In the absence of exotic stabilising mechanisms, such configurations are expected to be unstable and to terminate in Φ -collapse rather than forming traversable wormholes.

Discriminating between these scenarios requires a microscopic theory of Φ and lies beyond the scope of the present work.

5.5. Hawking radiation and information flow

In semiclassical gravity, Hawking radiation arises from quantum fluctuations near the event horizon. In the Φ -framework, this process is associated with the strong gradients of $\omega\Phi(x)$ at the boundary between oscillatory vacuum and Φ -collapse.

Because this boundary cannot be perfectly static at the quantum level, vacuum fluctuations of Φ generate correlated excitations in the visible and dark sectors. The outgoing component is observed as Hawking radiation, while the ingoing component contributes to the growth or maintenance of the Φ -collapse region.

The approximate thermality of Hawking radiation reflects the statistics of vacuum fluctuations in a strongly deformed oscillatory background. Questions of exact unitarity and information

recovery depend on the full multi-sector dynamics of Φ and are not resolved at the effective level considered here.

5.6. Section summary

Within the VO Φ F ontology, black holes are interpreted as boundary configurations of the vacuum oscillator Φ , characterised by a transition from an oscillatory regime with nonzero $\omega\Phi(x)$ to a Φ -collapse region where $\omega\Phi\rightarrow 0$. In this transition:

- the vacuum loses the ability to support propagating excitations and local time,
- the effective spacetime description reaches the limits of its applicability,
- the observed horizon, photon ring, and shadow acquire a vacuum-dynamical interpretation.

This framework preserves all tested exterior predictions of GR while providing a coherent physical meaning to the interior regime in which classical geometry ceases to be adequate.

6. Quantum phenomena within the vacuum oscillator Φ

6.1. Particles and waves as excitations of Φ

In standard quantum field theory (QFT), particle species are understood as quantised excitations of underlying fields: photons are excitations of the electromagnetic field, electrons are excitations of the electron field, and so on. The familiar “wave–particle duality” reflects the fact that a single field admits extended wave-like configurations while also exchanging energy with detectors in quantised events.

Within the VO Φ F ontology, this successful formal picture is not modified. Rather, it is assigned a unified carrier: the effective fields of QFT are treated as sectoral, coarse-grained modes of the vacuum field Φ . In this reading, a “particle” corresponds to a stable excitation pattern supported by an appropriate mode of Φ , while the associated “wave” corresponds to the spatial distribution and phase structure of that excitation in configuration space.

No ontological split between wave and particle is required: a single underlying carrier supports extended propagation and discrete absorption. Quantisation is retained as a property of the effective field theory description of excitations, while VO Φ F provides a common substrate in which these excitations are embedded.

6.2. The wave function as an effective description of a Φ -excitation

Let $|\Psi_\Phi\rangle$ denote the quantum state of the full vacuum field, and let $\hat{\Phi}_{\text{exc}}$ denote (schematically) an operator that creates or selects a particular excitation sector corresponding to a given effective field mode. The one-particle amplitude in the position basis may be written as

$$\psi(x) \equiv \langle x | \hat{\Phi}_{\text{exc}} | \Psi_\Phi \rangle.$$

This expression is intended as a schematic identification of the familiar one-particle wave function with a projection of the global field state onto a specific excitation sector; it is not a proposal to alter the standard formalism.

In this ontology:

- $|\psi(x)|^2$ quantifies the spatial intensity distribution associated with the relevant excitation sector;

- it determines, together with the detector coupling, the propensity for a localised detection event;
- the full physical state remains an element of the usual Hilbert/Fock space, while $\psi(x)$ is a reduced description appropriate for one-particle phenomenology.

Superposition has a direct reading: it corresponds to the coexistence of multiple compatible excitation patterns within the global state of Φ (or, equivalently, within the effective field description that emerges from Φ).

6.3. Interference in the double-slit experiment

Consider the double-slit experiment with a source preparing a single excitation of a given effective mode. In the standard description, the corresponding wave function propagates through both slits, and the two components interfere behind the barrier, producing an interference pattern in $|\psi(x)|^2$.

In VO Φ F, the interpretation is direct: the excitation pattern supported by the relevant Φ -mode propagates as an extended oscillatory configuration. The screen couples locally and irreversibly to this excitation sector, responding in discrete events (a pixel fires, a grain blackens). Individual outcomes are localised, yet their statistical distribution reproduces the interference structure encoded in the excitation pattern.

Thus, interference is not a paradoxical coexistence of “particle” and “wave”; it is the standard interference of an excitation configuration, combined with quantised absorption by macroscopic matter.

6.4. Measurement, decoherence, and effective “collapse”

Prior to measurement, the relevant excitation sector can be in a coherent superposition of spatial or internal configurations. During measurement:

- the excitation sector couples to many degrees of freedom of the detector and environment;
- different branches of the superposition correlate with different (effectively orthogonal) macroscopic detector microstates;
- environmental entanglement rapidly suppresses observable interference between macroscopically distinct branches.

Formally, one may retain unitary evolution of the combined system (excitation sector + detector + environment). “Collapse” is then an effective description: it summarises the practical loss of phase coherence between branches in the reduced state of the subsystem accessible to observation.

VOΦF adds an ontological emphasis: the branching structure corresponds to distinct global excitation patterns supported by the common carrier Φ , while the appearance of definite outcomes is understood as the emergence of robust, decohered records in macroscopic degrees of freedom.

6.5. Entanglement and nonlocal correlations

Entanglement is retained in its standard quantum meaning: a global state $|\Psi_\Phi\rangle$ that cannot be factorised into independent local states of subsystems. In VOΦF language, the correlations are encoded in the global structure of the excitation pattern supported by Φ (equivalently, in the global state in Hilbert space).

A measurement on one subsystem:

- locally correlates the detector with one branch of the global state,
- updates conditional probabilities for outcomes on the distant subsystem,
- does not require superluminal signalling.

Bell-inequality violations exclude local hidden-variable models, but they are consistent with nonlocal correlations in a single global quantum state. VOΦF does not introduce additional hidden variables; it preserves the standard Hilbert-space structure and reads nonlocality as a property of the global excitation state supported by a common carrier.

6.6. Section summary

Within VOΦF, standard quantum phenomena acquire a unified carrier interpretation without altering QFT:

- wave–particle duality arises because Φ -supported excitations propagate as extended patterns but exchange energy with detectors in quantised events;
- interference and superposition reflect coherent phase structure of excitation patterns;

- measurement corresponds to decoherence and the formation of robust macroscopic records;
- entanglement corresponds to global structure of the Φ -state, yielding nonlocal correlations without signalling.

The same carrier Φ that supports quantum excitations also underlies timekeeping and gravity through the vacuum-clock variable $\omega_\Phi(x)$. Potential probe channels for ultra-weak vacuum dynamics—particularly via clocks, interferometers, and other coherence-sensitive systems—are organised in the empirical programme of Section 7.

7. Predictions and empirical tests of the Φ framework

The vacuum-oscillator Φ framework is physical only insofar as it can be confronted with data. The purpose of this section is therefore not to “announce” a detection channel, but to specify what would count as support, what would count as failure, and which observations constrain the admissible space of VO Φ F-type effective models. I organise the empirical programme into three complementary regimes: (i) cosmology, (ii) strong-field astrophysics, and (iii) local precision experiments (including, but not limited to, ELF/ULF bands).

7.1 General falsifiability criteria

The Φ framework would be strongly constrained if one finds that:

- For no reasonable class of effective potentials $V_{\text{eff}}(\Phi)$ and couplings can the framework reproduce core cosmological observables (CMB, BAO, SN Ia, $H(z)$, $P(k)$) without pathologies (instabilities, superluminal modes, or gross conflicts with early-Universe constraints such as BBN).
- High-precision data remain fully consistent with pure Λ CDM and Kerr–GR in regimes where typical VO Φ F realisations generically predict nonzero deviations, forcing those deviations to be so small that the framework becomes empirically indistinguishable from the standard effective description.
- Local precision experiments place upper bounds on any non-standard Φ –matter or Φ –EM couplings that are sufficiently tight to make additional vacuum dynamics practically irrelevant at accessible scales.

The framework would be supported if one finds that:

- A simple, stable class of $V_{\text{eff}}(\Phi)$ and/or dark-sector mode properties improves the global fit to cosmological data relative to Λ CDM (e.g., reducing the H_0 and/or S_8 tensions) without degrading agreement with CMB, BAO, SN Ia, and structure growth.
- Strong-field observations (EHT imaging, gravitational-wave ringdown) reveal repeatable, model-consistent anomalies that cannot be absorbed into astrophysical systematics and that map onto controlled deviations predicted by a VO Φ F-type effective model.

- Local precision channels (clocks, interferometers, magnetometry) reveal reproducible residual signals that survive stringent instrumental and environmental null tests and can be parameterised as Φ -induced modulations within a conservative effective-operator framework.

7.2 Cosmological tests

Within the Φ ontology:

- $\rho_{\Phi\text{-vac}}(t) = V_{\text{eff}}(\langle\Phi\rangle(t))$ plays the role of dark energy (approximately constant in the Λ CDM-like regime),
- massive weakly coupled modes $\Phi_{\text{dark},i}$ behave as dark matter.

Key test classes:

Expansion history $H(z)$ and early-time constraints.

Any time dependence in $\rho_{\Phi\text{-vac}}(z)$ modifies $H(z)$ and therefore affects CMB, BAO, SN Ia, and (in principle) 21-cm probes. Importantly, the early Universe severely constrains additional energy density or non-standard evolution: successful BBN and CMB physics restrict the allowed deviations in the MeV–eV era. VOΦF-type models must therefore reproduce standard early-time behaviour to high precision unless they provide a quantitatively consistent alternative.

H_0 and S_8 tensions.

Mild vacuum/dark-sector dynamics can shift the inferred values of H_0 and S_8 by modifying distance ladders, early-time sound horizon calibration, or growth history. A particularly strong form of support would be the existence of a minimal, stable class of VOΦF-type models that reduces both tensions while preserving consistency across the full dataset suite.

Matter power spectrum $P(k)$ and small-scale structure.

Masses and self-interactions of $\Phi_{\text{dark},i}$ modes can change the shape of $P(k)$, halo profiles, and small-scale suppression/enhancement. Upcoming surveys constrain these properties in the same spirit as standard dark-matter microphysics constraints, but with the additional VOΦF interpretation that these are mode properties of Φ -sectors.

7.3 Astrophysical tests: black holes and gravitational waves

The interpretation of black holes as regions of Φ -collapse and gravity as variability of the vacuum clock suggests two observational families of constraints.

(i) Shadows and photon rings.

If the near-horizon effective behaviour differs slightly from Kerr (due to nontrivial Φ -sector structure near the collapse boundary), one may obtain small changes in ring thickness, substructure, or brightness profiles relative to Kerr-GRMHD predictions. Because astrophysical systematics are significant (accretion flow, plasma emissivity, viewing geometry), the appropriate target is not “any difference,” but repeatable residuals that track controlled deviations in the near-horizon effective description.

(ii) Gravitational-wave propagation and ringdown.

Additional vacuum modes may lead to (model-dependent) effects such as weak dispersion, extra polarisations, or small corrections to quasi-normal mode spectra. Current detectors already constrain large deviations; future measurements (especially precision ringdown and space-based bands) progressively tighten allowed departures from standard propagation and Kerr ringdown templates.

7.4 Local precision tests: vacuum timekeeping and ultra-weak couplings (including ELF/ULF)

The most direct local probes of a “vacuum clock” framework are **precision timekeeping and phase-sensitive experiments**, because VO Φ F ties proper time to accumulated phase of Φ .

A conservative phenomenological parameterisation is to allow a small residual modulation beyond GR,

$$d\tau/dt = 1 + \Phi_N/c^2 + \delta_\Phi(x, t),$$

where δ_Φ is required by existing data to be extremely small in ordinary environments. The experimental goal is not to assume a signal, but to bound (or detect) classes of δ_Φ : static, transient, or oscillatory.

Clocks and clock networks.

Clock comparisons (terrestrial and satellite links) directly constrain anomalous components of proper-time flow. Long baselines and network correlations are particularly powerful because they discriminate local systematics from spatially coherent effects.

Interferometers and phase-accumulation probes.

Atom interferometers and optical interferometers measure accumulated phase differences with extreme sensitivity. Any Φ -induced contribution to phase transport can be constrained even if it does not present as an electromagnetic field.

ELF/ULF as one practical band, not the definition of the test.

If Φ admits macroscopic coherent excitations at very low frequencies, then dedicated ELF/ULF searches can be performed. The professional framing here is: “we search for residual narrow-band or structured modulations after controlling for known environmental couplings,” rather than “signals that penetrate shielding in non-EM ways” (because every real instrument has leakage paths and cross-couplings that must be modelled).

A conservative effective-operator bookkeeping for ultra-weak EM couplings is:

$$\delta\mathcal{L}_{\Phi\text{-EM}} \sim \epsilon_1 \Phi F_{\mu\nu} F^{\mu\nu} + \epsilon_2 \Phi F_{\mu\nu} \tilde{F}^{\mu\nu} + \dots$$

Null results then translate into bounds on ϵ_i (as functions of frequency band and experimental configuration).

Methodologically, any credible local search should prioritise:

- diversified sensors and independent readouts,
- strict environmental monitoring,
- cross-correlation across independent instruments and sites,
- preregistered analysis pipelines where feasible,
- replication as the decisive criterion.

7.5 Existing ELF/ULF channels: MEG, satellites, magnetometer networks

Existing infrastructures provide complementary constraints:

- MEG systems can be analysed for persistent, instrument-independent residual structure, but must contend with physiological and facility-specific backgrounds.
- Satellite magnetometers probe ionospheric/magnetospheric dynamics; extracting “new physics” requires careful separation of known geophysical drivers.

- Global magnetometer networks enable synchronous correlation tests across large baselines. Any candidate anomaly must survive geomagnetic-storm screening, power-grid contamination checks, and instrument cross-validation.

Schumann resonances (≈ 7.83 Hz and harmonics) provide a natural baseline in ELF studies, but they are also strongly influenced by atmospheric and ionospheric conditions. For VOOF purposes, the key is not “finding structure,” but demonstrating statistically robust residuals that cannot be reduced to known geophysical variability and instrumental artefacts.

7.6 Black-hole formation as a sharp strong-field consistency requirement

In VOOF, a black hole corresponds to a Φ -collapse region where the vacuum oscillator ceases to support propagating excitations and a well-defined local vacuum clock. Operationally, this implies the existence of a collapse surface Σ_Φ separating an exterior domain (effective spacetime + propagation valid) from an interior domain where the effective propagation/clock description degenerates.

A crucial consistency point is that in Kerr spacetime $g_{tt} = 0$ defines the ergosurface, not the event horizon. The event horizon is a Killing horizon generated by

$$\chi^\mu = t^\mu + \Omega_H \phi^\mu,$$

defined by the condition $\chi^\mu \chi_\mu|_{\Sigma_H} = 0$. In Boyer–Lindquist form this corresponds to $\Delta(r) = 0$, giving the outer horizon radius.

Define the dimensionless spin parameter $a_* = cJ/(GM^2)$ and $r_g = GM/c^2$. The Kerr outer horizon radius is

$$r_+(M, a_*) = r_g \left(1 + \sqrt{1 - a_*^2}\right).$$

The VOOF collapse surface must coincide with the Kerr outer horizon within observational accuracy in regimes where the framework is required to reproduce GR:

$$r_\Phi(M, a_*) = r_+(M, a_*) [1 + \mathcal{O}(\varepsilon)],$$

with ε constrained by strong-field imaging and ringdown data.

This requirement is intentionally hard and largely model-independent: it does not depend on the detailed choice of V_{eff} , the number of dark sectors, or cosmological parameter fitting. It is a local strong-field consistency condition of the ontology.

7.7 “Information-like” modulations: a cautious hypothesis

The Φ framework logically allows the possibility that some vacuum-sector dynamics could generate structured, non-Gaussian, or low-complexity residuals in certain channels. However, claims of “information carriers” require an exceptionally high evidential bar and must be formulated conservatively.

A professionally safe statement is:

If persistent modulations with strong statistical structure were detected across independent instruments and/or sites, and if known terrestrial, instrumental, atmospheric, and geophysical sources were convincingly excluded, such signals would motivate modelling as non-standard dynamics in the vacuum sector Φ .

Even in that situation, the minimal scientific conclusion would be “previously unmodelled structured residuals,” not a claim of intent, agency, or communication. Any stronger interpretation would require separate work, with replication and multidisciplinary background elimination as prerequisites.

7.8 Section summary

By construction, VO Φ F is testable:

- cosmology constrains $\rho_{\Phi\text{-vac}}(z)$ and dark-mode phenomenology relative to Λ CDM,
- strong-field observations constrain the near-horizon consistency of Φ -collapse with Kerr–GR and any additional propagation effects,
- local precision experiments constrain (or could detect) residual anomalies in timekeeping and phase accumulation, with ELF/ULF searches as one practical subset of that broader class.

As data accumulate, admissible VO Φ F-type model space can be progressively narrowed, potentially supported in specific regimes, or pushed toward empirical irrelevance.

7.9 Precision laboratory probes beyond ELF: clocks, interferometers, and equivalence-principle tests

While ELF/ULF searches provide a practical low-frequency window, the broader and more direct class of local probes is precision timekeeping and phase-sensitive metrology.

- Clock networks directly test the vacuum-clock postulate by constraining anomalous components of $d\tau/dt$ beyond GR redshift predictions.
- Interferometers (optical and matter-wave) constrain additional phase-accumulation terms that would arise if Φ dynamics weakly modulate phase transport.
- Equivalence-principle tests strictly bound any non-universal coupling of Φ to matter. The conservative VO Φ F stance is that leading low-energy couplings are universal (e.g., trace-type couplings), with composition dependence either absent or suppressed below current bounds.

Together, these precision-lab probes complement cosmological and strong-field constraints by testing the framework's central object (vacuum timekeeping) in controlled terrestrial and near-Earth conditions, without assuming any particular frequency band or speculative signal class.

8. Synthesis, discussion, and conclusions

8.1. What the VOΦF framework claims (and what it does not)

This work proposed the Vacuum Oscillator Φ-Field (VOΦF) as an ontological and effective framework in which a single vacuum carrier $\Phi(x)$ underlies timekeeping, gravity, the dark sector, black-hole boundary behaviour, and standard quantum phenomena. The central organising variable is the local vacuum oscillation frequency $\omega_\Phi(x)$, interpreted operationally as a physical “vacuum clock”: its phase accumulation defines proper time, while spatial variability of $\omega_\Phi(x)$ reproduces gravitational redshift and the weak-field Newtonian limit when the mapping to Φ_N/c^2 is enforced.

It is essential to separate two layers:

- **Effective-compatibility layer (conservative core).** VOΦF is constructed to reduce to GR, Λ CDM, and standard QFT in the regimes where they are strongly validated. In this layer, the framework primarily reorganises known physics into a single carrier ontology and introduces a minimal, test-driven parameterisation for possible deviations.
- **Model-completion layer (open microphysics).** The present work does not select a specific microscopic form of $V_{\text{eff}}(\Phi)$, does not derive Standard Model gauge structure, and does not present global numerical fits to cosmological data. Those steps are intentionally deferred: the goal here is to define the ontology, clarify the mapping to known effective theories, and specify falsifiable axes of tests.

8.2. Main synthesis across Sections 2–7

The framework can be summarised as follows.

Ontology and effective description (Section 2). The vacuum is treated as a physical carrier $\Phi(x)$ with visible and dark components ($\Phi_{\text{vis}}, \Phi_{\text{dark},i}$). Spacetime geometry $g_{\mu\nu}$ is interpreted as an effective coarse-grained functional of the vacuum state rather than a fundamental background. At the effective level, Φ admits an amplitude–phase decomposition, with the important conceptual separation that amplitude fluctuations are naturally associated with energetic and gravitating content, whereas phase structure organises coherence, interference and synchronisation. In particular, vacuum-clock phase coherence need not present as electromagnetic activity.

Time and gravity from the vacuum clock (Section 3). Proper time is interpreted as phase accumulation of the vacuum oscillator along a worldline, and a simple weak-field identification $(\omega_\Phi - \omega_\infty)/\omega_\infty \propto \Phi_N/c^2$ reproduces standard gravitational time dilation when parameters are fixed to match GR clock tests. This is not advertised as a new prediction; rather, it establishes internal consistency with precision timekeeping constraints and clarifies what “vacuum time” would mean operationally.

Dark matter and dark energy as Φ -regimes (Section 4). Dark matter is interpreted as stable, massive excitations in weakly coupled sectors $\Phi_{\text{dark},i}$, while dark energy corresponds to the background vacuum energy density $V_{\text{eff}}(\langle\Phi\rangle)$. Λ CDM appears as an effective statistical description of a certain class of Φ -configurations. Any allowed departures must remain consistent with early-Universe constraints and late-time structure growth.

Black holes as Φ -collapse (Section 5). Black holes are interpreted as boundary configurations of the vacuum oscillator where an effective collapse region occurs and the operational notion of a local vacuum clock degenerates ($\omega_\Phi \rightarrow 0$ in an effective description). The exterior Kerr phenomenology is preserved where it is empirically tested. The interior is not “solved” here; instead, a structured set of scenarios is identified (terminal collapse vs sector-selective dynamics vs transient configuration-space bridges), explicitly flagged as requiring microphysical completion.

Quantum phenomena in a single-carrier ontology (Section 6). Standard quantum phenomenology—superposition, interference, decoherence/measurement, and entanglement—is embedded into a vacuum-carrier picture without altering the Hilbert-space formalism. In this reading, quantum states describe oscillatory patterns of Φ and their coupling to macroscopic environments; “collapse” is an effective description of decoherence and branching, not a modification of unitary dynamics.

Empirical programme (Section 7). VO Φ F is defined to be falsifiable through three test axes: cosmological (expansion history and growth), strong-field astrophysical (near-horizon structure and gravitational-wave propagation/ringdown), and local precision experiments (clocks, interferometers, and—optionally as a practical subset—ELF/ULF searches parameterised by conservative effective operators). The framework is constrained if it cannot realise a class of stable effective models compatible with the combined dataset suite.

8.3. Limitations and open questions

Several limitations are intrinsic to the present paper and are stated as such.

1. **No unique microphysical model is fixed.** The form of $V_{\text{eff}}(\Phi)$, the sector content, and the detailed couplings are not specified uniquely. This is a deliberate choice: the paper defines the ontology and the falsifiable parameterisation rather than a single “final theory”.
2. **No global cosmological fit is performed.** Whether a simple VOOF-type model improves upon Λ CDM (e.g., in H_0/S_8 tensions) remains an empirical question requiring dedicated model selection and statistical inference.
3. **Black-hole interiors are not derived.** The Φ -collapse interpretation provides a physical reading for “where classical geometry fails”, but interior dynamics (and any unitarity resolution) require microphysical completion.
4. **Local channels must be treated conservatively.** Precision timekeeping and interferometry are the cleanest direct probes of the “vacuum clock” postulate. Any magnetometry/ELF-related claims must be formulated as bounded effective couplings with strict null-test logic, not as assumptions of exotic penetrations or “information carriers”.

These limitations sharpen the research programme: the value of VOOF is in providing a coherent organising structure and a disciplined route to constraints, not in asserting premature numerical predictions.

8.4. Interpretational addendum (non-derivational extensions)

This subsection records optional interpretational embeddings that are compatible with standard formalism but are **not** claims of new derivations. They are included to show how VOOF can maintain conceptual unity across scales without contradicting earlier assumptions.

8.4.1. Electromagnetism and magnetism as phase-transport bookkeeping in Φ_{vis} (interpretational)

VOOF does not modify electromagnetism. The empirically validated description of the electromagnetic field as a $U(1)$ gauge theory with potential $A_\mu(x)$ and field strength

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

is retained.

The purpose of this addendum is narrower: to provide an ontological reading compatible with the standard formalism while avoiding conflict with the earlier distinction between (i) vacuum-clock phase coherence and (ii) energetic propagating degrees of freedom.

A useful conceptual separation is:

- The **vacuum-clock phase** (encoded in θ_Φ and $\omega_\Phi = \partial\theta_\Phi / \partial\tau$) organises proper time and gravitational redshift in the effective description. Its coherence need not couple directly to electromagnetic observables.
- **Electromagnetism** is an energetic, propagating sector of the effective theory. It carries stress-energy and mediates local interactions.

An interpretational bridge can nonetheless be stated: in many contexts, charged matter can be represented by an order-parameter-like decomposition with amplitude and phase. Schematically, for an appropriate phase-bearing component of the visible sector one may write

$$\Phi_{\text{vis}}(x) \sim \rho(x) e^{i\theta(x)},$$

where $\theta(x)$ is **not** the global vacuum-clock phase θ_Φ , but a phase variable associated with charged degrees of freedom in the effective theory.

In gauge theory, comparing such phases across spacetime requires a compensating structure. This motivates an ontological reading in which the gauge potential acts as a bookkeeping variable for phase transport under local symmetry: it encodes how phase comparisons remain consistent. Nontrivial field strength corresponds to nontrivial curvature of this phase-transport structure, as in standard gauge theory.

Two points preserve technical consistency:

- This is not a claim that A_μ is a pure gradient of a single-valued phase (which would imply $F_{\mu\nu} = 0$). Nonzero $F_{\mu\nu}$ corresponds to curvature of the effective connection.
- This is not a derivation of QED or of the Standard Model gauge group; it is an interpretation compatible with the established formalism.

Within this view, magnetism corresponds to the rotational component of the gauge potential in the nonrelativistic limit,

$$\mathbf{B} = \nabla \times \mathbf{A},$$

and magnetic phenomena in matter correspond to collective organisation of charged excitations and their internal degrees of freedom, accurately described by quantum many-body theory. VOOF merely supplies a unified carrier reading: the relevant charged excitations are Φ_{vis} -supported modes, and macroscopic magnetic order corresponds to low-entropy collective organisation within the visible sector.

Finally, this interfaces naturally with the local precision axis (Section 7). Any ultra-weak vacuum imprints in electromagnetic channels can be parameterised conservatively by gauge-invariant effective operators (as couplings to be bounded, not asserted new forces), e.g.

$$\delta\mathcal{L}_{\Phi\text{-EM}} \sim \epsilon_1 \Phi F_{\mu\nu} F^{\mu\nu} + \epsilon_2 \Phi F_{\mu\nu} \tilde{F}^{\mu\nu} + \dots,$$

so that null results translate into upper bounds on ϵ_i .

8.4.2. Chemistry, nuclei, and nucleosynthesis as stable Φ_{vis} -patterns across scales (interpretational)

VOOF does not propose modifications to quantum chemistry or nuclear reaction networks. Instead, it offers a unifying ontological statement: atoms, molecules, and nuclei can be regarded as stable excitation patterns (or metastable minima) in the configuration space of the visible sector Φ_{vis} , described effectively by standard quantum theory in the relevant regimes.

Chemistry.

Molecular binding is quantitatively described by quantum mechanics and quantum chemistry (Coulomb interactions, Pauli principle, exchange, Born–Oppenheimer separation). In VOOF language, molecular orbitals correspond to stable, low-energy Φ_{vis} -supported patterns in multi-centre environments; bond formation corresponds to relaxation into a configuration that minimises an effective energy functional under particle-number and nuclear constraints. This adds no new chemical force; it provides a carrier-level interpretation consistent with the fact that chemistry probes a constrained low-energy regime where the effective description reduces to QED plus nonrelativistic many-body theory on an approximately fixed background.

Nuclei and element formation.

The origin of elements is quantitatively described by nuclear physics and astrophysical nucleosynthesis: BBN sets light-element abundances, stellar burning builds heavier nuclei up to the iron group, and neutron-capture processes (e.g., r-process) populate the heaviest nuclei. VOOF does not alter these mechanisms. It re-reads them as transitions between allowed Φ_{vis} -configurations under extreme thermodynamic and density conditions: at sufficiently high temperatures bound nuclear configurations are not supported; as systems cool or decompress, the configuration space admits metastable minima corresponding to bound nuclei.

This perspective also clarifies falsifiability constraints. Any framework that modifies the effective expansion history $H(t)$ or introduces additional energy-density components in the MeV era is tightly constrained by successful BBN. In VOOF terms, admissible early-Universe dynamics of $\rho_{\Phi\text{-vac}}(z)$ or dark-mode energy density $\rho_{\Phi\text{-dark}}(z)$ must remain within the narrow band compatible with observed light-element yields. Thus, the “pattern” ontology does not grant arbitrary freedom; it inherits stringent consistency requirements from standard cosmological and nuclear data.

Finally, one may note (without replacing nuclear theory) that shell closures, magic numbers, and enhanced stability regions can be viewed as especially robust Φ_{vis} -configurations in the carrier’s configuration space. This is presented as a conceptual backdrop rather than a derivation, and any quantitative programme in this direction is left for future work.

8.5. Concluding perspective

In summary, VOOF is best viewed as an ontological superstructure built above GR, QFT, and Λ CDM rather than as a competing replacement of their validated regimes. Its central claim is organisational: a single vacuum carrier Φ , via its local clock variable $\omega_\Phi(x)$ and its sectoral modes, can place timekeeping, gravity, dark components, black-hole boundary behaviour, and standard quantum phenomenology into one coherent picture while remaining empirically accountable.

The framework’s scientific fate is therefore clear. If there exists a simple class of VOOF-type effective models that (i) matches or improves cosmological fits relative to Λ CDM, (ii) remains consistent with strong-field constraints from black-hole imaging and gravitational waves, and (iii) survives increasingly tight local precision bounds, then the vacuum oscillator Φ becomes a plausible candidate for the right “ontological level” of description of the vacuum. If not,

empirical constraints will progressively compress the admissible parameter space and push VOFF toward a purely interpretational role.

Either outcome is informative: the framework is designed to be constrained.

9. Limitations and outlook

9.1. Ontological status and scope of the Φ framework

In this work the vacuum field Φ is introduced as an ontological hypothesis, not as an established ingredient of the Standard Model of particle physics or of the standard cosmological model. I do not claim that current data demonstrate the existence of a global vacuum oscillator. The claim is conditional: if such a field exists, then (i) general relativity, Λ CDM, and standard quantum field theory can be understood as effective descriptions of its dynamics in different regimes; (ii) timekeeping, gravity, the dark sector, black holes, and standard quantum phenomena acquire a common physical substrate; and (iii) one obtains a concrete set of cosmological, astrophysical, and laboratory tests that can in principle falsify or support the framework.

Accordingly, the Φ framework should be read as a proposal for a *mechanics of the vacuum*, not as a final fundamental theory. In its present form it is explicitly an effective framework, intended to be compatible with the empirically validated infrared regimes of GR, Λ CDM, and QFT. I do not derive the Standard Model gauge structure or a complete theory of quantum gravity. Instead, I show that a relatively simple ontological layer organised around Φ and its local vacuum-clock variable $\omega_\Phi(x)$ can coherently connect several domains of modern physics while remaining test-driven and falsifiable.

At a deeper microscopic level, Φ itself may be an effective description of more fundamental degrees of freedom (e.g. discrete, condensed, or emergent structures). Here I remain agnostic and treat Φ as a coarse-grained vacuum field whose local oscillation frequency $\omega_\Phi(x)$ provides an operational notion of time. In this sense the organising core is economical: time, gravity, visible and dark sectors, black holes, and quantum phenomena are treated as different dynamical regimes of the local vacuum frequency $\omega_\Phi(x)$ and its modes.

9.2. Relation to earlier approaches and novelty

The general intuition that the vacuum may be a non-trivial medium, and that time or geometry may be emergent, appears across several research programmes, including emergent-gravity and analogue-gravity constructions, superfluid-vacuum scenarios, unified dark-sector models, and relational or state-dependent notions of time in quantum foundations.

VOFF is positioned as an integrative ontology that packages a specific set of organising identifications into one framework. To the best of my knowledge, the distinctive combination of the following elements within a single effective ontology is not standard in the existing literature:

- (i) a single vacuum field $\Phi(x)$ whose local oscillation frequency $\omega_\Phi(x)$ operationally defines proper time and whose weak-field gradients reproduce the Newtonian potential (via an enforced mapping);
- (ii) a sectoral realisation of dark matter and dark energy as modes of Φ (hidden massive excitations and a background vacuum energy density $V_{\text{eff}}(\langle \Phi \rangle)$), with Λ CDM recovered as the coarse-grained limit;
- (iii) an interpretation of black holes as Φ -collapse regions in which the operational vacuum clock degenerates ($\omega_\Phi \rightarrow 0$ at the effective level), while preserving the tested exterior Kerr phenomenology;
- (iv) an embedding of standard quantum phenomenology (superposition, interference, decoherence, entanglement) into the same single-carrier ontology, without modifying the formal structure of QFT.

The contribution of this preprint is therefore twofold. First, it articulates a coherent vacuum-oscillator ontology that ties together timekeeping, gravity, dark components, black-hole boundary behaviour, and quantum phenomenology. Second, it provides minimal working relations and a disciplined, multi-axis falsifiability programme that connects the ontology to observations and precision experiments. The proposed relations are to be read as effective, “working” links: they demonstrate feasibility and guide tests, and may be refined without abandoning the core ontological identification.

9.3. Main simplifications and limitations

The present framework involves several deliberate simplifications.

No explicit choice of $V_{\text{eff}}(\Phi)$ and no full nonlinear dynamics.

I do not specify a concrete effective potential $V_{\text{eff}}(\Phi)$, nor do I present a complete nonlinear dynamical system for Φ that would uniquely determine cosmological evolution, stability, or strong-field behaviour. Many conclusions are therefore qualitative: the framework identifies where dark matter, dark energy, quantum vacuum effects, and black-hole boundary behaviour

can naturally live within one carrier ontology, but it does not yet provide a fully specified dynamical model.

No global cosmological fits and no full stability analysis.

I do not perform quantitative fits to CMB, BAO, SN Ia, $P(k)$, or to the H_0/S_8 tensions, nor do I provide a systematic perturbative stability analysis of candidate Φ_{dark} sectors. Mapping the viable region in the space of potentials and couplings that is simultaneously compatible with all current datasets and free of instabilities is left for future work.

No derivation of Standard Model gauge structure or ultraviolet completion.

Particle masses, gauge couplings, and the gauge group are treated as effective inputs rather than derived from Φ . The framework is intentionally infrared: it targets a consistent ontology below the Planck scale. Ultraviolet completion and the microstructure underlying Φ are deferred.

No detailed claims about local exotic regimes.

Repulsive behaviour appears naturally in cosmology through vacuum energy and effective equation-of-state behaviour. I do not analyse speculative local “antigravity” regimes or technological implications; such questions become meaningful only after the framework is constrained by the basic cosmological and strong-field tests.

9.4. Testability along complementary axes

The empirical content of VOΦF is organised along three complementary axes.

Cosmological axis.

Measurements of $H(z)$, H_0 , growth of structure and $P(k)$, together with SN Ia, BAO, and CMB data, constrain the admissible forms of $V_{\text{eff}}(\Phi)$, the composition and dynamics of Φ_{dark} modes, and the allowed evolution of $\rho_{\Phi\text{-vac}}(z)$. Any viable realisation must reduce effectively to Λ CDM where it is tightly supported while allowing controlled deviations only where the data motivate them.

Astrophysical axis.

Black-hole imaging (shadows and photon rings), gravitational-wave propagation and ringdown, and nonlinear dark-matter phenomenology (haloes, lensing) probe the strong-field and nonlinear regimes relevant to Φ -collapse and to the dynamics of Φ_{dark} modes.

Local precision axis.

Because VO Φ F identifies proper time with a vacuum-clock variable, precision timekeeping (clock networks), interferometers, and equivalence-principle tests are direct probes of the core postulate: any residual dynamics beyond GR would manifest as anomalous components in phase accumulation or clock comparisons. Optional electromagnetic channels (including ELF/ULF searches) can be included conservatively via gauge-invariant effective operators and treated as null-test constraints on ultra-weak couplings rather than as assumptions of anomalous penetrations.

If a simple class of potentials and couplings provides a coherent description across these axes, this would motivate Φ as a useful physical level of description. If not, the framework will be constrained or falsified accordingly.

9.5. Open questions and directions for future work

The limitations above define a concrete agenda.

(i) Explicit effective models and global fits. Identify simple families $V_{\text{eff}}(\Phi; \vartheta)$ and interaction structures $\mathcal{L}_{\text{int}}(\Phi; \vartheta)$ enabling computation of $H(z; \vartheta)$, growth observables, and dark-sector phenomenology, and confront them with combined cosmological datasets.

(ii) Dynamics and stability of Φ_{dark} in structure formation. Analyse halo phenomenology (density profiles, velocity distributions, lensing), including perturbative stability and any self-interactions, and identify parameter regions consistent with observed small-scale structure.

(iii) Φ -collapse and black-hole thermodynamics. Develop the Φ -collapse picture in the language of QFT on curved spacetime, including Hawking-type processes, entropy, and information flow in a multi-sector setting, with explicit attention to observational constraints from imaging and ringdown.

(iv) Precision-laboratory forecasts. Translate the vacuum-clock postulate into detector-level signals for clocks and interferometers, and (where relevant) set up a conservative effective-operator programme for bounding any ultra-weak couplings in electromagnetic channels.

(v) Microstructure and ultraviolet completion. Explore candidate microscopic realisations (e.g. condensate-like models, discrete networks, or other emergent structures) and clarify how an effectively one-parameter description in terms of $\omega_\Phi(x)$ could emerge in the infrared.

In this sense, the present work is intended as a starting point: a coherent vacuum ontology and a map of falsifiable tests, rather than a final solution to unification.

9.6. Coherence, metastability, and phase organisation across scales (heuristic perspective)

This final subsection is offered strictly as a heuristic perspective, not as a claim of mechanistic identity between cosmological and biological systems. Many nonlinear oscillator ensembles—across physics—share a common dynamical vocabulary: phase coherence, metastability, susceptibility near critical thresholds, and amplification through feedback. VOΦF centres on the emergence of coherent time-domains and on the organisation of effective dynamics by a vacuum-clock variable $\omega_\Phi(x)$. Independently, other complex systems (including biological ones) are often modelled using related concepts such as synchronisation and metastable state transitions.

The only intended message is methodological: when a framework is built around coherence and phase organisation, a conservative way forward is to (i) characterise stability and susceptibility regimes, (ii) specify how small perturbations could or could not be amplified within the model’s own dynamics, and (iii) demand reproducible, falsifiable signatures rather than relying on qualitative analogies. No cross-domain causal claims are implied.

Author Contributions (CRediT taxonomy)

Patryk Rosa: Conceptualization; Methodology; Software; Formal analysis; Data curation; Visualization; Writing – original draft; Writing – review & editing; Funding acquisition.

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Clinical-Trial Registration

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Clinical and regulatory disclaimer

All references to pharmacological agents and stimulation protocols are included solely as mechanistic parameters within the computational framework. No dosing regimens are proposed, and nothing herein should be construed as medical advice. Experimental doses cited are reported verbatim from the original studies and are not intended as clinical recommendations.

Ethics Statement

This study reports secondary analyses and computational modelling only; no new human or animal experiments were conducted.

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