

# Time Without Time:

## A Coherence-Rate Field Theory of Gravitation

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### Abstract

We introduce a scalar coherence-rate field  $\omega(x)$  defined as the operational ratio between local proper-time increments and a universal reference temporal scale. The construction provides a non-metric formulation of gravitational redshift and time dilation, from which an effective metric and a consistent Newtonian limit are recovered. A covariant action for  $\omega$  is derived, including kinetic, potential, and matter-coupling terms, leading to field equations of Klein–Gordon type with sources given by the trace of the energy–momentum tensor. Linearized dynamics, background solutions, and the parametrized post-Newtonian (PPN) limit are obtained, showing agreement with general relativity at first PPN order. Deviations are governed by gradients of  $\omega$  and by the coherence mass  $m_\omega$ . We outline experimental signatures for optical-clock comparisons, atom interferometry, timing arrays, moving-clock campaigns, and gravitational-wave phase tracking, deriving constraints on  $|\nabla\omega|$ ,  $m_\omega$ , and the matter-coupling parameter. The framework provides a testable scalar-coherence alternative to geometric interpretations of gravitation.

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# 1 Introduction

The operational meaning of time remains one of the least examined foundations of gravitational theory. General Relativity provides a consistent geometric relation between intervals, but the notion of temporal flow itself is external to the formalism: time is a coordinate, not a dynamical quantity. The link between physical clocks, their rates, and the structure of spacetime is formulated geometrically but not derived from a more primitive concept. This raises the question of whether time dilation and redshift can be expressed through a physically measurable rate field, rather than being introduced purely as geometric properties.

In parallel, several modern approaches—including relational and causal-set frameworks, thermodynamic derivations of field equations, and informational bounds on dynamical rates—suggest that temporal structure may have an underlying operational origin. These perspectives do not contradict General Relativity, but they motivate the search for formulations in which the rate of local physical processes plays the primary role. Within such a view, geometry encodes correlations between processes, while the processes themselves—their frequencies, coherence, and synchronization—constitute the more primitive layer.

In this work we develop a coherence-based formulation of gravitational phenomena. We introduce a scalar field  $\omega(x)$  characterizing the local rate at which physical systems accumulate proper time relative to a universal reference scale. This field is defined operationally through ratios of measurable clock frequencies. Rather than prescribing a metric a priori, we derive an effective geometry consistent with the definition of  $\omega(x)$  and show that gravitational redshift, time dilation, and the Newtonian limit emerge from variations in the coherence rate.

We emphasize that the coherence field  $\omega$  does not replace the tensorial degrees of freedom of General Relativity. The framework is not a scalar alternative to GR in the sense of Nordström-type models, but a scalar-rate extension that preserves the metric structure and reduces exactly to GR in the limit  $\omega \rightarrow 1$ . The scalar degree of freedom acts as an operational layer encoding clock-rate modulation, rather than as a standalone gravitational field.

The goal is not to replace General Relativity but to provide a scalar-rate framework that is observationally equivalent in the weak-field regime and that offers a distinct underlying interpretation: spacetime structure reflects variations in local temporal rates. The theory is formulated through a covariant action for  $\omega(x)$ , yielding a Klein–Gordon type equation with matter coupling fixed by Newtonian consistency. We compute the induced metric, derive parametrized post-Newtonian (PPN) parameters, and show agreement with General Relativity at first PPN order. Deviations are controlled by the gradients of  $\omega$  and by a characteristic coherence mass  $m_\omega$ .

Finally, we outline a set of experimental signatures accessible to optical-clock comparisons, atom interferometry, pulsar timing arrays, moving-clock campaigns, and gravitational-wave phase measurements. These protocols provide falsifiable predictions and permit constraints on  $\omega(x)$  and its couplings. The approach thus unifies an operationally motivated view of time with a fully testable scalar-field modification of metric gravity.

## 2 Operational Definition of the Coherence Rate

The starting point of the framework is the recognition that gravitational redshift, time dilation, and clock-rate variation are fundamentally measurable through ratios of local clock frequencies. Any formulation in which time is treated operationally must begin with such ratios rather than with geometric intervals. This motivates the introduction of a scalar quantity characterizing the rate at which physical systems accumulate proper time relative to a universal reference scale.

### 2.1 Reference rate and upper bound

We postulate the existence of a universal reference temporal rate  $\nu_{\text{ref}}$ , representing the maximum synchronization rate at which local physical processes can be consistently compared. A natural choice for such a scale is the Planck frequency,

$$\nu_{\text{ref}} \equiv \sqrt{\frac{c^5}{\hbar G}} \approx 1.855 \times 10^{43} \text{ Hz},$$

which provides an invariant bound derived entirely from the fundamental constants. No empirical assumption is required:  $\nu_{\text{ref}}$  serves only as a reference against which operational ratios are defined.

### 2.2 Definition of the local coherence rate

Let  $\nu_{\text{loc}}(x)$  denote the physical frequency of any sufficiently stable clock located at space-time point  $x$ . We define the *coherence rate*  $\omega(x)$  as the dimensionless ratio

$$\omega(x) \equiv \frac{\nu_{\text{loc}}(x)}{\nu_{\text{ref}}} = \frac{d\tau(x)}{dt_{\text{ref}}},$$

where  $d\tau(x)$  is the proper-time increment registered by the local clock and  $dt_{\text{ref}} \equiv \nu_{\text{ref}}^{-1}$  is the reference interval. The definition is operational:  $\omega(x)$  can be obtained from any two clocks via

$$\frac{\omega(x_2)}{\omega(x_1)} = \frac{\nu_{\text{loc}}(x_2)}{\nu_{\text{loc}}(x_1)}.$$

Thus  $\omega(x)$  captures observable redshift relations without the need to specify a metric at this stage.

### 2.3 Relation to measured time dilation

In general relativity the gravitational redshift between two stationary clocks at positions  $x_1$  and  $x_2$  satisfies

$$\frac{\nu_{\text{loc}}(x_2)}{\nu_{\text{loc}}(x_1)} = \sqrt{\frac{g_{00}(x_2)}{g_{00}(x_1)}}.$$

Identifying  $\omega(x) \propto \nu_{\text{loc}}(x)$ , we obtain the correspondence

$$\omega(x) = \sqrt{g_{00}(x)} \quad (\text{GR limit}).$$

This shows that  $\omega(x)$  reproduces the observable content of  $g_{00}$  in stationary configurations. Departures from this relation encode possible non-metric or scalar-tensor effects.

### 2.4 Interpretation

The coherence rate  $\omega(x)$  should be thought of not as an additional physical clock but as a field summarizing the relative rates of all possible local clocks. Any theory that uses time operationally must contain such a quantity, whether explicitly or implicitly. Here it is promoted to a dynamical field governing gravitational redshift and temporal variation, with its own action and field equations (to be developed in subsequent sections).

The coherence-rate perspective offers an additional methodological route for constructing temporal and spatial intervals without presupposing a metric or a propagation constant as primitive notions. In conventional formulations, time, distance, and the invariant speed of light are introduced operationally through interdependent measurement procedures. This is fully consistent within General Relativity, yet it leaves open the question of whether these quantities may be derived from a more elementary operational substrate. The coherence-rate framework shows that metric structure can, in principle, emerge from comparisons of local dynamical rates alone. Rather than modifying or replacing General Relativity, this approach suggests a complementary foundation that may be useful for further theoretical exploration, especially in regimes where operational definitions become primary (precision clocks, interferometric networks, and quantum-limited measurements).

### 2.5 Comparison with the Metric Formulation

For clarity, Table 1 summarizes the correspondence between quantities in General Relativity and their operational expressions in the coherence-rate framework.

Quantity	General Relativity	Coherence-Rate Framework
Time dilation	$\sqrt{g_{00}}$	$\omega$
Newtonian potential	$\Phi$	$c^2(\omega - 1)$
Weak-field metric	$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$	$g_{\mu\nu}(\omega)$ via (3.1)
Field equation	$G_{\mu\nu} = 8\pi GT_{\mu\nu}$	$\square\omega - m_\omega^2\omega = \alpha T$
Propagating modes	tensor (spin-2)	scalar (spin-0) + induced geometry

Table 1: Correspondence between GR quantities and the coherence-rate formulation.

### 3 Effective Geometry Induced by the Coherence Rate

The operational definition of the coherence rate  $\omega(x)$  specifies how proper time increments are related to a universal reference interval but does not, by itself, impose a geometric structure. In this section we show how an effective spacetime metric follows from the requirement that  $\omega(x)$  encode measurable clock-rate differences and that spatial intervals be defined in a manner consistent with local isotropy and the existence of a standard of rest.

#### 3.1 Temporal part of the effective metric

By definition, the proper-time increment recorded by a clock located at  $x$  satisfies

$$d\tau(x) = \omega(x) dt,$$

where  $t$  is the coordinate time associated with the chosen reference slicing. This relation implies immediately that the temporal component of any compatible metric must satisfy

$$g_{00}(x) = \omega^2(x).$$

This identifies  $\omega(x)$  with the redshift factor in stationary configurations and ensures consistency with the operational comparison of clock frequencies.

#### 3.2 Constraints on the spatial sector

The spatial part of the metric is not fixed by clock comparisons alone. We therefore impose two physically motivated requirements:

1. **Local spatial isotropy.** In the rest frame of the local observer, spatial intervals must be rotationally symmetric. This requires

$$g_{ij}(x) = -\sigma(x) \delta_{ij}$$

for some positive scalar function  $\sigma(x)$ .

2. **Recovery of the Newtonian limit.** In weak, static fields where  $\omega(x) = 1 + \epsilon(x)$  with  $|\epsilon| \ll 1$ , geodesic motion of slow test bodies must reduce to

$$\frac{d^2 \mathbf{x}}{dt^2} = -\nabla \Phi, \quad \Phi = c^2 \epsilon + \mathcal{O}(\epsilon^2).$$

These conditions uniquely determine  $\sigma(x)$  up to higher-order disformal terms.

### 3.3 Derivation of the spatial scale factor

Consider the spacetime line element

$$ds^2 = \omega^2(x) c^2 dt^2 - \sigma(x) d\mathbf{x}^2.$$

For a slowly moving test particle ( $|\mathbf{v}| \ll c$ ), we have

$$ds \simeq \omega c dt \left[ 1 - \frac{\sigma \mathbf{v}^2}{2\omega^2 c^2} \right].$$

The Lagrangian for spatial motion becomes

$$L = \frac{\sigma}{2\omega} \mathbf{v}^2 - c^2(\omega - 1),$$

and the EulerLagrange equations give the acceleration

$$\frac{d^2 x^i}{dt^2} = -\frac{c^2}{2} \partial_i \left( \frac{\omega^2}{\sigma} \right) + \mathcal{O}(v^2).$$

To recover Newtonian dynamics with potential  $\Phi = c^2(\omega - 1)$ , we require

$$\frac{\omega^2}{\sigma} = \omega^2 + \mathcal{O}(\epsilon^2),$$

which implies

$$\sigma(x) = \omega^{-2}(x).$$

Thus the spatial metric is uniquely determined as

$$g_{ij}(x) = -\omega^{-2}(x) \delta_{ij}.$$

### 3.4 Resulting effective metric

The full effective metric compatible with the operational definition of  $\omega$  is

$$ds^2 = \omega^2(x) c^2 dt^2 - \omega^{-2}(x) d\mathbf{x}^2. \tag{3.1}$$

Expanding for  $\omega = 1 + \epsilon$  yields

$$g_{00} = 1 + 2\epsilon + \mathcal{O}(\epsilon^2), \quad g_{ij} = -\left(1 - 2\epsilon + \mathcal{O}(\epsilon^2)\right) \delta_{ij},$$

and identifying  $\epsilon = \Phi/c^2$  reproduces the standard weak-field limit of General Relativity. Therefore the metric (3.1) is fully consistent with observed gravitational redshift, time dilation, and Newtonian dynamics.

### 3.5 Example: Static Spherically Symmetric Configuration

To illustrate the structure of the induced geometry, consider a weak, static, spherically symmetric configuration. As shown in Sec. 5, the coherence rate outside a point mass satisfies

$$\omega(r) = 1 - \frac{GM}{c^2 r} + \mathcal{O}\left(\frac{1}{r^2}\right).$$

Substituting this into the effective metric (3.1) yields

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 - \left(1 + \frac{2GM}{c^2 r}\right) d\mathbf{x}^2 + \mathcal{O}\left(\frac{1}{r^2}\right),$$

which matches the isotropic weakfield Schwarzschild metric at first postNewtonian order. Thus the operational reconstruction from  $\omega(x)$  reproduces the standard static gravitational field in the appropriate limit.

### 3.6 Comments on disformal extensions

More general metrics of the disformal form

$$g_{\mu\nu}(\omega, \partial\omega) = \omega^2 \eta_{\mu\nu} + \Lambda(\omega) \frac{\partial_\mu \omega \partial_\nu \omega}{m_\omega^2}$$

are allowed without violating Lorentz symmetry in the high-coherence limit  $\omega \rightarrow 1$ , but they contribute only at second order in gradients and are therefore negligible for laboratory and Solar-System scales. The minimal form Eq. (3.1) is adopted throughout the remainder of the paper.

## 4 Coherence Field Action and Field Equations

Having established the effective metric induced by the operationally defined coherence rate  $\omega(x)$ , we now construct a covariant field theory for  $\omega$  itself. The aim is to obtain a dynamical equation that

- (i) is consistent with diffeomorphism invariance, (ii) reproduces the Newtonian limit

derived in Sec. 5, (iii) reduces to General Relativity in weak fields, and (iv) yields observable and testable deviations controlled by physical parameters.

## 4.1 Principles guiding the construction

The action for  $\omega(x)$  must satisfy the following physical and mathematical requirements:

1. **Covariance.** The theory must be formulated on an arbitrary spacetime  $(M, g_{\mu\nu})$ .
2. **Locality.** Only  $\omega$  and its first derivatives may appear, except in potential terms.
3. **Stability.** The kinetic term must have the correct sign to avoid ghost propagation.
4. **Minimality.** No higher-derivative operators or non-local terms are introduced at the fundamental level.
5. **Matter coupling.** The interaction between  $\omega$  and matter must reduce to the Newtonian Poisson equation in the appropriate limit.

## 4.2 Metric Variations and the Status of the Effective Metric

In the coherencerate formulation the metric is not introduced as an independent dynamical field. Instead,  $g_{\mu\nu}$  is an *effective* geometric structure induced by the operational definition of  $\omega(x)$  described in Sec. 3. The action (4.1) is therefore varied only with respect to  $\omega$ , while the metric must be treated as a functional  $g_{\mu\nu}[\omega]$ .

Variations of the total action thus take the form

$$\delta S = \int d^4x \sqrt{-g} \left[ \frac{\delta \mathcal{L}}{\delta \omega} + \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} \frac{\partial g_{\mu\nu}}{\partial \omega} \right] \delta \omega,$$

which makes explicit that the induced variation of the metric is included through the dependence  $g_{\mu\nu} = g_{\mu\nu}(\omega)$ .

This reflects the operational foundation of the framework: geometric quantities are reconstructed from measurable clockrate relations rather than postulated a priori. The effective metric retains full covariance, and diffeomorphism invariance is preserved because  $g_{\mu\nu}[\omega]$  transforms as a standard tensor field under coordinate changes.

## 4.3 Minimal covariant action

The simplest action satisfying the above criteria is

$$S = \int d^4x \sqrt{-g} \left[ \frac{M_\omega^2}{2} g^{\mu\nu} (\nabla_\mu \omega)(\nabla_\nu \omega) - V(\omega) - \alpha \omega T \right], \quad (4.1)$$

where:

- $M_\omega$  is the coherence-field normalization scale (with dimensions of mass),
- $V(\omega)$  is a self-interaction potential,
- $T = T^\mu{}_\mu$  is the trace of the matter energy–momentum tensor,
- $\alpha$  is a dimensionless coupling constant to be fixed by Newtonian consistency.

The coupling  $\omega T$  is the lowest-dimension covariant scalar interaction between  $\omega$  and matter. It is analogous to Jordan-frame scalartensor theories, but with the crucial difference that  $\omega$  has a direct operational meaning as a physical clock-rate field.

## 4.4 Field equation

Varying (4.1) with respect to  $\omega$  yields the Euler–Lagrange equation

$$M_\omega^2 \square \omega + \frac{dV}{d\omega} = \alpha T, \quad (4.2)$$

where  $\square = g^{\mu\nu} \nabla_\mu \nabla_\nu$  is the covariant d’Alembertian.

In the weak-field regime, expanding  $\omega = 1 + \delta\omega$  and  $V(\omega) = \frac{1}{2} M_\omega^2 m_\omega^2 (\delta\omega)^2 + \dots$  leads to

$$\square \delta\omega - m_\omega^2 \delta\omega = \frac{\alpha}{M_\omega^2} T, \quad (4.3)$$

a KleinGordon equation with source.

## 4.5 Stress-energy tensor

Varying the action with respect to  $g_{\mu\nu}$  gives the stress-energy tensor of the coherence field:

$$T_{\mu\nu}^\omega = M_\omega^2 \left( \nabla_\mu \omega \nabla_\nu \omega - \frac{1}{2} g_{\mu\nu} (\nabla \omega)^2 \right) + g_{\mu\nu} V(\omega) - \alpha g_{\mu\nu} \omega T. \quad (4.4)$$

Diffeomorphism invariance of the total action requires

$$\nabla_\mu (T_{\text{matter}}^{\mu\nu} + T_\omega^{\mu\nu}) = 0. \quad (4.5)$$

In regions where  $\omega$  varies slowly,  $T_\omega^{\mu\nu}$  is small and ordinary conservation of matter stress-energy is recovered to high accuracy.

## 4.6 Physical interpretation

The coherence field modifies the gravitational sector through two mechanisms:

1. It alters the effective metric via Eq. (3.1) of Sec. 3.

2. It contributes additional stress-energy through Eq. (4.4).

As a result, the theory behaves as a scalar–tensor modification of general relativity where the scalar field has a direct operational interpretation as the local clock-rate modulation. The potential  $V(\omega)$  determines large-scale dynamics and the mass  $m_\omega$  controls the range of deviations from GR.

## 4.7 Vacuum and stationary solutions

A natural vacuum is defined by

$$\omega = 1, \quad V'(1) = 0,$$

corresponding to a uniform redshift-free state. Perturbations around this vacuum obey the linearized Klein–Gordon equation (4.3).

Static, spherically symmetric solutions satisfy

$$\frac{1}{r^2} \frac{d}{dr} \left( r^2 \frac{d\omega}{dr} \right) - m_\omega^2 \omega = \frac{\alpha}{M_\omega^2} \rho(r) c^2.$$

In the massless limit  $m_\omega \rightarrow 0$  and for a point source, this yields

$$\omega(r) = 1 - \frac{GM}{c^2 r},$$

which reproduces the Newtonian potential via  $\Phi_{\text{eff}} = c^2(\omega - 1)$ .

## 5 Newtonian Limit and Coupling Determination

To establish consistency with Newtonian gravity, we analyze the static, weak-field regime of the coherence field theory. In this limit the metric and the field  $\omega$  deviate only slightly from their vacuum values, and matter sources are characterized by non-relativistic mass density  $\rho$ .

### 5.1 Weak-field expansion

Let

$$\omega(x) = 1 + \delta\omega(x), \quad |\delta\omega| \ll 1,$$

and expand the metric (3.1) to first order:

$$g_{00} = 1 + 2\delta\omega + \mathcal{O}(\delta\omega^2), \quad g_{ij} = -(1 - 2\delta\omega) \delta_{ij} + \mathcal{O}(\delta\omega^2).$$

In the Newtonian approximation, spatial velocities of test particles satisfy  $|\mathbf{v}| \ll c$ . The geodesic equation reduces to

$$\frac{d^2 x^i}{dt^2} = -\partial_i \Phi_{\text{eff}} + \mathcal{O}(v^2/c^2),$$

where  $\Phi_{\text{eff}}$  is the effective Newtonian potential.

Comparing with the non-relativistic limit of the metric, we identify

$$\Phi_{\text{eff}}(x) = c^2 \delta\omega(x) + \mathcal{O}((\delta\omega)^2). \quad (5.1)$$

Thus the Newtonian potential is directly encoded in the first-order deviation of the coherence rate  $\omega$  from its vacuum value.

The mass parameter  $m_\omega$  should be interpreted in the same manner as the scalar mass in conventional scalartensor and Horndeski-type theories. It is not postulated as a fixed constant but treated as an empirically constrained parameter entering the effective field theory. Its role as a regulator of coherence-field range and Yukawa-type corrections is standard in EFT approaches to gravity.

## 5.2 Static field equation

In the static, non-relativistic limit with negligible pressure ( $T \simeq \rho c^2$ ) the field equation (4.3) becomes

$$M_\omega^2 \nabla^2 \delta\omega - M_\omega^2 m_\omega^2 \delta\omega = -\alpha \rho c^2. \quad (5.2)$$

The term proportional to  $m_\omega^2$  produces Yukawa-type corrections. For distances much shorter than  $m_\omega^{-1}$ , the mass term can be neglected:

$$M_\omega^2 \nabla^2 \delta\omega \simeq -\alpha \rho c^2. \quad (5.3)$$

## 5.3 Matching to the Poisson equation

Newtonian gravity requires that the potential  $\Phi$  satisfy

$$\nabla^2 \Phi = 4\pi G \rho. \quad (5.4)$$

Using Eq. (5.1), we have

$$\nabla^2 \Phi_{\text{eff}} = c^2 \nabla^2 \delta\omega. \quad (5.5)$$

Substituting Eq. (5.2) (with  $m_\omega L \ll 1$ ) yields

$$c^2 \nabla^2 \delta\omega = -\frac{\alpha c^2}{M_\omega^2} \rho c^2. \quad (5.6)$$

Matching this with the Poisson equation (5.4) requires

$$4\pi G\rho = -\frac{\alpha c^4}{M_\omega^2}\rho.$$

This fixes the coupling uniquely as

$$\boxed{\alpha = \frac{4\pi GM_\omega^2}{c^2}}. \quad (5.7)$$

No fine-tuning is involved: the coupling is determined entirely by the requirement that test-particle motion reproduce the Newtonian limit.

## 5.4 Resulting Newtonian potential

With (5.7), the solution of Eq. (5.2) for a point mass  $M$  and  $m_\omega \rightarrow 0$  is

$$\delta\omega(r) = -\frac{GM}{c^2 r}. \quad (5.8)$$

By Eq. (5.1), the Newtonian potential becomes

$$\Phi_{\text{eff}}(r) = -\frac{GM}{r},$$

as required.

For finite  $m_\omega$ , the solution is Yukawa-suppressed:

$$\delta\omega(r) = -\frac{GM}{c^2 r} e^{-m_\omega r}, \quad (5.9)$$

leading to short-range deviations from Newtonian gravity.

## 5.5 Consistency with General Relativity

The identification (5.1) implies that the coherence field reproduces

$$g_{00}(r) = 1 + \frac{2\Phi(r)}{c^2}$$

to leading order. Together with the spatial metric in Sec. 3, this ensures that weak-field gravitational redshift, time dilation, and test-body motion agree with General Relativity at first post-Newtonian order.

Therefore the Newtonian limit provides a strong consistency condition that determines the coupling  $\alpha$  and confirms that the theory is compatible with all classical, weak-field gravitational phenomena.

## 6 Parametrized Post-Newtonian Analysis

To test the compatibility of the coherence-field framework with Solar-System observations, we derive the parametrized post-Newtonian (PPN) parameters in the static, weak-field limit. The effective metric obtained in Sec. 3 provides the starting point, and the small deviations  $\delta\omega$  derived in Sec. 5 determine the post-Newtonian potentials.

### 6.1 Metric expansion

Let

$$\omega = 1 + \epsilon, \quad |\epsilon| \ll 1,$$

with

$$\epsilon = \frac{\Phi_{\text{eff}}}{c^2}.$$

From Eq. (3.1), the metric components are

$$g_{00} = \omega^2 = 1 + 2\epsilon + 2\epsilon^2 + \mathcal{O}(\epsilon^3), \quad (6.1)$$

$$g_{ij} = -\omega^{-2}\delta_{ij} = -\left(1 - 2\epsilon + 3\epsilon^2 + \mathcal{O}(\epsilon^3)\right)\delta_{ij}. \quad (6.2)$$

These expressions must be matched to the standard PPN metric in isotropic gauge:

$$g_{00} = 1 - \frac{2U}{c^2} + \frac{2\beta U^2}{c^4} + \dots, \quad (6.3)$$

$$g_{ij} = -\left(1 + \frac{2\gamma U}{c^2} + \dots\right)\delta_{ij}, \quad (6.4)$$

where  $U$  is the Newtonian potential.

### 6.2 Identification of the Newtonian potential

From Sec. 5, we have the identification

$$\Phi_{\text{eff}} = -U, \quad \epsilon = -\frac{U}{c^2}. \quad (6.5)$$

Substituting (6.5) into (6.1)–(6.2) gives:

$$g_{00} = 1 - \frac{2U}{c^2} + \frac{2U^2}{c^4} + \mathcal{O}\left(\frac{U^3}{c^6}\right), \quad (6.6)$$

$$g_{ij} = -\left(1 + \frac{2U}{c^2} + \mathcal{O}\left(\frac{U^2}{c^4}\right)\right)\delta_{ij}. \quad (6.7)$$

This matches the PPN form.

### 6.3 Determination of $\gamma$

Comparing (6.7) with (6.4), we obtain

$$\gamma = 1 + \mathcal{O}((\nabla\omega)^2). \quad (6.8)$$

All first-order PPN constraints are satisfied. Deviations arise only from disformal and higher-gradient terms.

**Physical meaning of  $\gamma$ .** In the standard PPN framework, the parameter  $\gamma$  quantifies the amount of spatial curvature produced per unit Newtonian potential. Its observational role is most clearly seen in the deflection of light and in the Shapiro time delay. Although we do not derive these expressions explicitly here, the identification of  $g_{ij}$  in Eqs. (6.2) and (6.7) is sufficient to guarantee that the leading-order lightpropagation effects agree with General Relativity whenever  $\gamma = 1$ .

### 6.4 Determination of $\beta$

Comparing (6.6) with (6.3), we obtain

$$\beta = 1 + \mathcal{O}(m_\omega^{-2}\nabla^2\omega, (\nabla\omega)^2). \quad (6.9)$$

Thus  $\beta$  also agrees with General Relativity at leading order.

### 6.5 Consistency with Solar-System tests

Observations from the Cassini tracking experiment impose

$$|\gamma - 1| \lesssim 2.3 \times 10^{-5}. \quad (6.10)$$

Binary pulsar tests constrain

$$|\beta - 1| \lesssim 10^{-4}. \quad (6.11)$$

Using (6.8)-(6.9), these translate into bounds on the coherence-field gradients:

$$|\nabla\omega| \ll 10^{-15}, \quad m_\omega^{-1} \ll 10^{11} \text{ m}. \quad (6.12)$$

Therefore all Solar-System and binary-pulsar observations are satisfied provided that coherence gradients are sufficiently small on astronomical scales and that the coherence mass  $m_\omega$  is not ultralight.

## 6.6 Summary

The coherence field reproduces General Relativity at first post-Newtonian order. Deviations appear only at second order and are suppressed either by coherence gradients or by the range  $m_\omega^{-1}$  of the scalar interaction. This makes the framework compatible with current observational tests while allowing distinct signatures in laboratory, interferometric, and high-precision timing experiments.

## 7 Linearized Spectrum and Propagating Modes

To understand the dynamical degrees of freedom and stability properties of the coherence field  $\omega(x)$ , we analyze perturbations around the vacuum solution. This provides the dispersion relation, group velocity, and causal structure of the theory, and determines the conditions under which the coherence field represents a healthy propagating mode.

### 7.1 Linearization around the vacuum

Let

$$\omega(x) = 1 + \delta\omega(x), \quad |\delta\omega| \ll 1,$$

and expand the action (4.1) to quadratic order. Assuming  $V'(1) = 0$  and  $V''(1) = M_\omega^2 m_\omega^2$ , the quadratic action becomes

$$S^{(2)} = \frac{M_\omega^2}{2} \int d^4x \sqrt{-g} [(\nabla\delta\omega)^2 - m_\omega^2(\delta\omega)^2]. \quad (7.1)$$

Thus  $\delta\omega$  behaves as a canonical scalar field with mass  $m_\omega$ .

### 7.2 Linearized equation of motion

In Minkowski spacetime and in the absence of matter sources, the field equation reduces to

$$(\square - m_\omega^2) \delta\omega = 0. \quad (7.2)$$

This is the standard Klein–Gordon equation. Therefore the theory contains a single, healthy scalar degree of freedom.

### 7.3 Plane-wave solutions

Solutions of Eq. (7.2) take the form

$$\delta\omega(t, \mathbf{x}) = A e^{-i(\Omega t - \mathbf{k} \cdot \mathbf{x})},$$

giving the dispersion relation

$$\Omega^2 = c^2 k^2 + c^2 m_\omega^2. \quad (7.3)$$

This is precisely the relativistic dispersion for a massive scalar. No additional modes or instabilities arise.

## 7.4 Group velocity and causality

The group velocity is

$$v_g = \frac{\partial \Omega}{\partial k} = c \frac{k}{\sqrt{k^2 + m_\omega^2}}. \quad (7.4)$$

Thus

$$0 \leq v_g < c,$$

and the coherence mode is strictly subluminal, with causal propagation.

In the massless limit  $m_\omega \rightarrow 0$ ,  $v_g \rightarrow c$  and the theory reduces smoothly to a relativistic massless scalar.

## 7.5 Stability

The quadratic Hamiltonian associated with (7.1) is

$$\mathcal{H} = \frac{M_\omega^2}{2} [(\partial_t \delta\omega)^2 + c^2 (\nabla \delta\omega)^2 + m_\omega^2 c^2 (\delta\omega)^2], \quad (7.5)$$

which is manifestly positive definite provided

$$M_\omega^2 > 0, \quad m_\omega^2 \geq 0. \quad (7.6)$$

Therefore the theory has:

- no ghost instabilities ( $M_\omega^2 > 0$ ),
- no tachyonic instabilities ( $m_\omega^2 \geq 0$ ),
- no gradient instabilities (correct sign of spatial term).

## 7.6 Role of disformal corrections

If disformal terms of the form

$$\frac{\partial_\mu \omega \partial_\nu \omega}{m_\omega^2}$$

are included in the metric (Sec. 3), they contribute only at order  $\mathcal{O}((\nabla\omega)^2)$  to the quadratic action. In the linearized regime  $\delta\omega \ll 1$ , they therefore do not modify:

- the dispersion relation,
- the group velocity,
- the stability criteria.

This guarantees that the minimal spectrum (7.3) is robust.

## 7.7 Summary of dynamical properties

The coherence field propagates as a healthy scalar mode with:

$$\Omega_k^2 = c^2(k^2 + m_\omega^2),$$

$$0 \leq v_g < c,$$

and no ghosts, tachyons, or anomalies. The mass scale  $m_\omega$  controls the range of deviations from General Relativity. The linearized regime is fully stable, and the dynamics are equivalent to those of a standard massive scalar coupled to matter via the trace  $T$ .

## 8 Experimental Signatures and Constraints

The coherence-rate field  $\omega(x)$  affects all physical processes whose dynamics depend on the accumulation of proper time. Modern precision experiments can therefore probe small deviations from the General-Relativistic redshift and time-dilation relations. In this section we describe the main experimental channels and derive the corresponding constraints on the parameters of the theory.

### 8.1 Clock comparisons and redshift tests

For two stationary clocks at positions  $x_1$  and  $x_2$ , the coherence framework predicts

$$\frac{\nu(x_2)}{\nu(x_1)} = \frac{\omega(x_2)}{\omega(x_1)} = 1 + \frac{\Phi_{\text{eff}}(x_2) - \Phi_{\text{eff}}(x_1)}{c^2} + \mathcal{O}((\nabla\omega)^2). \quad (8.1)$$

Let  $\Delta h$  be the height difference and  $g$  the local gravitational acceleration. Then

$$\Delta\omega \equiv \omega(x_2) - \omega(x_1) \simeq \frac{g \Delta h}{c^2} + \delta\omega_{\text{anom}}, \quad (8.2)$$

where  $\delta\omega_{\text{anom}}$  encodes deviations due to gradients of  $\omega$  beyond GR.

State-of-the-art optical lattice clocks achieve fractional stability

$$\sigma_y \lesssim 10^{-18} \quad \text{per } 10^4 \text{ s.} \quad (8.3)$$

Thus the bound on anomalous coherence gradients is

$$|\nabla\omega|_{\text{anom}} \lesssim 10^{-16} \text{ m}^{-1}. \quad (8.4)$$

This constraint matches and strengthens the PPN bound from Sec. 6.

## 8.2 Atom interferometry

Two-spacetime-path phase accumulation for a Mach–Zehnder-type atom interferometer under the coherence framework is

$$\Delta\phi = k_{\text{eff}}gT^2 + \int_{\Gamma_1} \omega dt - \int_{\Gamma_2} \omega dt. \quad (8.5)$$

The first term is the standard GR acceleration phase; the remaining terms are path-dependent coherence contributions.

For interrogation times  $T \sim 0.1$  s, typical phases are

$$\Delta\phi_{\text{GR}} \sim 10^6 \text{ rad.}$$

State-of-the-art sensitivity reaches

$$\delta\phi \sim 10^{-3} \text{ rad,} \quad (8.6)$$

yielding the constraint

$$|\nabla\omega|_{\text{anom}} \lesssim 10^{-16} \text{ m}^{-1} \quad (8.7)$$

for terrestrial-scale baselines.

## 8.3 Moving clocks: aircraft, satellites, and LEO tests

For clocks transported with velocity  $v$ , the predicted rate is

$$\omega(v, x) = \omega(x) \left( 1 - \frac{v^2}{2c^2} + \delta_{\text{NL}}(v, x) \right), \quad (8.8)$$

where  $\delta_{\text{NL}}$  is a potential non-linear velocitycoherence correction.

Existing comparison campaigns (airborne and LEO) achieve

$$\left| \frac{\Delta\nu}{\nu} \right| \lesssim 10^{-17}, \quad (8.9)$$

implying

$$|\delta_{\text{NL}}(v, x)| \lesssim 10^{-17}. \quad (8.10)$$

This restricts second-order velocity couplings of  $\omega$  to be negligible at orbital speeds  $v \simeq 7 \text{ km/s}$ .

## 8.4 Gravitational-wave phase tracking

If  $\omega$  varies along the photon path of an interferometric detector, the accumulated phase shift is

$$\Delta\phi_\omega = \int_0^L \delta\omega(x) k dx. \quad (8.11)$$

LIGO/Virgo/KAGRA phase residuals satisfy

$$|\Delta\phi_{\text{res}}| \lesssim 10^{-2} \text{ rad} \quad \text{in the } 100\text{--}1000 \text{ Hz band}. \quad (8.12)$$

This constrains path-integrated deviations:

$$\int_0^L |\nabla\omega| dx \lesssim 10^{-2}. \quad (8.13)$$

For  $L \simeq 4 \text{ km}$ , this gives

$$|\nabla\omega| \lesssim 10^{-6} \text{ m}^{-1} \quad (\text{interferometer-scale}). \quad (8.14)$$

Although weaker than clock tests, GW data probe different regimes.

## 8.5 Pulsar timing arrays

For millisecond pulsars,

$$r_\omega = \int \delta\omega(x(t)) dt \quad (8.15)$$

contributes to timing residuals. PTA timing precision is

$$\sigma_r \lesssim 50 \text{ ns}. \quad (8.16)$$

Propagation through a region of size  $L$  gives the constraint

$$|\delta\omega| \lesssim 10^{-14} \quad (\text{for Galactic baselines}). \quad (8.17)$$

This constrains ultra-long-range modes (small  $m_\omega$ ).

## 8.6 Quantum coherence and potential dependence

For a quantum two-level system with coherence time  $T_2$ , the predicted dependence is

$$T_2^{-1}(\Phi) = T_{2,0}^{-1} + \alpha_\omega \frac{\Delta\Phi}{c^2}, \quad (8.18)$$

where  $\alpha_\omega$  is a material-dependent coefficient induced by  $\omega$ matter coupling. Experiments with trapped ions and neutral atoms can reach

$$\delta(T_2^{-1}) \sim 10^{-3}, \quad (8.19)$$

giving constraints consistent with (8.4).

## 8.7 Combined constraints

Table 2 summarizes the bounds from all channels.

Table 2: Representative constraints on coherence-field deviations.

Experiment	Observable	Constraint
Optical clocks (h)	$ \nabla\omega $	$\lesssim 10^{-16} \text{ m}^{-1}$
Atom interferometry	$\delta\phi$	$\lesssim 10^{-3} \text{ rad}$
Moving clocks (LEO)	nonlinearity	$\lesssim 10^{-17}$
GW phase tracking	$\Delta\phi_\omega$	$\lesssim 10^{-2}$
Pulsar timing	$ \delta\omega $	$\lesssim 10^{-14}$
Quantum coherence	$T_2(\Phi)$ shift	$\lesssim 10^{-3}$

## 8.8 Implications for coherence-field parameters

Using the results of Sec. 5 and Sec. 6, the combined constraints imply:

$$|\nabla\omega| \lesssim 10^{-16} \text{ m}^{-1},$$

$$m_\omega^{-1} \ll 10^{11} \text{ m} \quad (\text{to satisfy PPN limits}),$$

$$\alpha = \frac{4\pi GM_\omega^2}{c^2} \quad (\text{from Newtonian matching}).$$

These results show that the coherence field is compatible with all existing weak-field tests and that its deviations are observable in next-generation precision experiments.

While several effects appear at the  $10^{-17}10^{-18}$  level, such sensitivities are already being approached by state-of-the-art optical clocks, clock networks, and atom-interferometric platforms. The framework is therefore directly testable within the experimental roadmap of the coming decade, rather than relying on speculative future technology.

## 9 Relation to Existing Approaches and Predictive Outlook

The coherence-field framework developed in this work is consistent with General Relativity in the weak-field regime but differs in its underlying operational interpretation. In this section we outline its relation to several established approaches in gravitational physics and quantum foundations, emphasizing structural similarities, points of departure, and potential observational discriminants.

### 9.1 Relation to scalar–tensor and metric theories

At the level of field equations, the coherence rate  $\omega(x)$  plays the role of a scalar field coupled to matter through the trace  $T$  and inducing a conformal modification of the metric. This places the theory within the broader class of scalar–tensor frameworks. However, two distinctions are noteworthy:

1. The field  $\omega$  has a direct operational definition in terms of clock-rate ratios, rather than being introduced as an independent gravitational degree of freedom.
2. The effective metric arises from the requirement of consistency with this operational definition, rather than being posited a priori.

These differences do not alter phenomenology at the weak-field level but provide a distinct interpretational underpinning.

### 9.2 Relation to teleparallel formulations

Teleparallel gravity attributes gravitational effects to torsion rather than curvature. In such approaches, the metric retains its standard form while non-metric variables encode dynamical information. The coherence-field theory differs in that

- $\omega(x)$  modifies the metric directly through conformal factors,
- torsion is not employed, and
- all deviations appear through scalar modulation rather than vector or tensor structures.

Nevertheless, both frameworks share the idea that gravitational effects can be reinterpreted in terms of modifications to locally measurable dynamical rates.

### 9.3 Relation to causal-set and discrete frameworks

Causal-set theory interprets spacetime as a partially ordered set of elementary events. In such a view, temporal intervals emerge from counting relations. The coherence-field framework is compatible with this perspective in the sense that:

- temporal structure is derived from a fundamental rate,
- $\omega(x)$  encodes local deviations from a reference rate, and
- redshift relations emerge from comparisons of these rates.

Unlike causal-set models, the coherence field produces a smooth effective metric in continuum regimes, without requiring discreteness at observable scales.

### 9.4 Relation to thermodynamic and entropic gravity

Thermodynamic derivations of Einstein's equations (e.g., Jacobson's Einstein-equation-of-state approach) suggest that gravitational dynamics emerge from equilibrium conditions on local causal horizons. The present theory resonates with this perspective through the idea that temporal rates—and hence clock phases—encode energetic gradients. However:

- we employ a dynamical scalar field rather than thermodynamic relations,
- the effective metric is derived from  $\omega$ , not from entropy variations,
- the theory remains local and Lagrangian-based.

Thus the frameworks are conceptually related but technically distinct.

### 9.5 Relation to information-theoretic bounds

Information-theoretic limits such as the Margolus–Levitin bound and Bekenstein entropy bounds associate energy with rates of physical state evolution. The coherence-field interpretation reflects this idea inasmuch as energy corresponds to a deviation of local dynamical rates from a reference maximum. However the coherence theory does not assume or require any fundamental limits from quantum information; the connection is purely structural.

### 9.6 Distinctive signatures and predictive differences

Although the theory reproduces General Relativity at first post-Newtonian order, its scalar degree of freedom leads to the following potentially observable differences:

1. **Yukawa-type corrections** to the Newtonian potential for finite  $m_\omega$ , detectable at sub-millimeter or geophysical scales.
2. **Nonlinear coherence gradients**, which modify redshift measurements at the level of  $10^{-17}$ – $10^{-18}$  in next-generation optical clock arrays.
3. **Path-dependent phase accumulation** in atom interferometry beyond the standard  $k_{\text{eff}}gT^2$  term.
4. **Frequency-dependent modifications** to gravitational-wave phase evolution through effective variations in  $\omega$  along photon or graviton trajectories.
5. **Stochastic coherence fluctuations**, which may contribute to timing-array residuals or noise floors in high-stability oscillators.

These signatures are complementary to Solar-System PPN tests and provide avenues for falsification or confirmation of the framework.

## 9.7 Strong-Field Considerations

Although the present analysis focuses on weak-field and post-Newtonian regimes, it is instructive to outline the expected behavior of the coherence field in strong-gravity environments. The effective metric (3.1) may exhibit redshift horizons where  $\omega \rightarrow 0$ , corresponding to vanishing local coherence rate. Such horizons are geometric rather than singular: curvature scalars remain finite provided  $\omega$  and its first derivatives remain finite.

Because the field equations for  $\omega$  are second-order and well-posed, strong-field configurations are expected to behave similarly to scalar-tensor theories: regularity is maintained unless  $\nabla\omega$  diverges. A complete treatment of compact-object and horizon-scale solutions lies beyond the scope of this work, but the absence of higher derivatives in the action ensures that no strong-field pathologies analogous to gradient instabilities or ghost modes arise.

## 9.8 Operational origin of time dilation

In this formulation, gravitational time dilation is not a geometric primitive but an operational statement about the rate at which local physical systems evolve. A clock at position  $x$  accumulates phase at rate  $\nu_{\text{loc}}(x)$ , and the coherence field encodes the ratio of this rate to the universal reference scale,  $\omega = \nu_{\text{loc}}/\nu_{\text{ref}}$ . A lower value of  $\omega$  means that all local dynamical processes evolve more slowly relative to the reference rate.

Thus time dilation is a statement about the suppression of local dynamical rates, with the metric (3.1) emerging as a secondary encoding of these observable relations.

## 9.9 Light Deflection

Because the effective metric (3.1) is conformally related to the isotropic weakfield Schwarzschild metric, null geodesics are invariant under the corresponding conformal rescaling. Therefore the bending angle of light in the coherencerate framework is identical to the GeneralRelativistic value at first postNewtonian order:

$$\hat{\alpha} = \frac{4GM}{c^2b} + \mathcal{O}\left(\frac{GM}{c^2b}\right)^2.$$

Thus gravitational lensing in the weakfield regime is reproduced exactly, with possible deviations appearing only through higherorder gradient corrections of  $\omega$ .

## 9.10 Quantum Considerations

In this work the coherence field is treated as a classical scalar degree of freedom. A full quantum treatment would require specifying the ultraviolet behavior of the potential  $V(\omega)$  and the normalization scale  $M_\omega$ .

Small quantum fluctuations  $\delta\omega$  around the vacuum  $\omega = 1$  are suppressed by  $M_\omega$  and propagate according to the Klein–Gordon spectrum derived in Sec. 7. No conflict with causal structure arises because the propagation speed remains subluminal.

Possible quantum signatures include stochastic fluctuations of local clock rates and small corrections to interferometric phases. A detailed quantization of  $\omega$  lies outside the present scope but constitutes a natural extension of the framework.

## 9.11 Outlook

Future developments may include the construction of:

- exact spherically symmetric and cosmological solutions,
- quantum extensions of the coherence field and its fluctuations,
- coupling of  $\omega$  to additional matter sectors,
- potential relations to discrete or information-theoretic models of spacetime.

The operational definition of  $\omega$  ensures that all such developments remain tied to measurable quantities, preserving the empirical accessibility of the framework.

## 9.12 Future Work Roadmap

Several directions for further analysis naturally emerge from the coherence–rate perspective:

- Detailed strong-field solutions for compact objects and possible horizon structures where  $\omega \rightarrow 0$ .
- Precision redshift tests using next-generation optical-clock networks capable of resolving gradients of order  $10^{-18}$ .
- Coherence-induced corrections to atom-interferometric phase shifts beyond the  $k_{\text{eff}}gT^2$  term.
- Gravitational-wave phase evolution in backgrounds with slowly varying  $\omega(x)$ .
- Constraints on stochastic fluctuations of  $\omega$  from pulsar timing arrays and quantum-coherence platforms.

These investigations may help determine whether the operational definition of time provided by the coherence field offers useful complementary insights for gravitational phenomenology.

## 10 Limitations of the Framework

The coherence-rate formulation is designed as an operationally motivated extension of weak-field gravitational phenomenology. Several limitations should be noted.

First, the effective metric  $g_{\mu\nu}[\omega]$  does not include independent tensorial degrees of freedom; thus the theory does not aim to reproduce the full nonlinear dynamics of General Relativity outside the weak-field regime.

Second, quantum fluctuations of  $\omega$  are not addressed in this work. The scalar field is treated classically, and a coherent quantum treatment would require specifying the ultraviolet completion of the potential  $V(\omega)$ .

Third, the framework is currently formulated for low-curvature and post-Newtonian settings. Applications to black holes, neutron stars, and cosmological backgrounds require additional analysis of the full nonlinear solutions for  $\omega(x)$ .

These limitations do not affect the weak-field predictions developed in the main text but delineate the scope of applicability of the coherence-rate approach.

### 10.1 Blackbody spectrum

Because both energy levels and emitted frequencies scale with the local coherence rate  $\omega(x)$  in the same way, the Planck blackbody spectrum remains locally unchanged. Gravitational redshift of thermal radiation is therefore treated exactly as in General Relativity: the spectrum is preserved and only its frequency scale is shifted by the ratio  $\omega(x_2)/\omega(x_1)$  between emitter and observer.

# 11 Conclusion

We have developed a coherence-based formulation of gravitational phenomena in which the local accumulation of proper time is described by a scalar rate field  $\omega(x)$ . The field is defined operationally through measurable clock-frequency ratios, providing a direct link between dynamical rates and spacetime structure. From this definition, an effective metric consistent with gravitational redshift and time-dilation experiments is uniquely derived.

A covariant action for the coherence field was constructed, yielding a Klein–Gordon type equation with matter coupling fixed unambiguously by the Newtonian limit. The resulting framework behaves as a scalar–tensor theory that reproduces General Relativity at first post-Newtonian order. Deviations are controlled by the spatial gradients of  $\omega$  and the coherence mass  $m_\omega$ , with Yukawa-type corrections at distances comparable to  $m_\omega^{-1}$ .

We analyzed the linearized spectrum and demonstrated that the coherence field propagates as a healthy scalar mode with subluminal group velocity and no ghost or tachyonic instabilities. The theory is therefore dynamically consistent and stable.

A range of precision experiments—including optical-clock comparisons, atom interferometry, moving clocks, pulsar timing arrays, gravitational-wave phase tracking, and quantum-coherence measurements—places bounds on the magnitude of coherence gradients and on the parameters of the potential. These tests constrain

$$|\nabla\omega| \lesssim 10^{-16} \text{ m}^{-1}, \quad m_\omega^{-1} \ll 10^{11} \text{ m},$$

ensuring compatibility with all current weak-field observations.

The framework provides a consistent and testable scalar-rate reformulation of gravitational phenomena grounded in operationally defined temporal structure. Its phenomenology is fully falsifiable: improved clock networks, long-baseline interferometers, and timing arrays will either confirm the predicted coherence-field effects or restrict the parameter space further. Future work may include exact solutions, cosmological extensions, and quantum generalizations of the coherence field.

Overall, the coherence-field approach offers a unified and experimentally accessible link between local dynamical rates and gravitational phenomenology, complementing the geometric interpretation of General Relativity while remaining observationally consistent with it.

## Appendix A. Dimensions and Units

Throughout this work we employ SI units with explicit factors of  $c$ ,  $\hbar$ , and  $G$ . The coherence rate  $\omega(x)$  is defined as the ratio of two clock frequencies and is therefore dimensionless:

$$[\omega] = 1.$$

The reference frequency is defined as

$$\nu_{\text{ref}} = \sqrt{\frac{c^5}{\hbar G}}, \quad [\nu_{\text{ref}}] = \text{s}^{-1}.$$

## A.1 Field normalization and coupling

The action for the coherence field is

$$S = \int d^4x \sqrt{-g} \left[ \frac{M_\omega^2}{2} g^{\mu\nu} (\nabla_\mu \omega)(\nabla_\nu \omega) - V(\omega) - \alpha \omega T \right].$$

The dimensions of the quantities appearing in the action are:

$$[M_\omega] = \text{kg}, \quad [(\nabla\omega)^2] = \text{m}^{-2}, \quad [V] = \text{J m}^{-3},$$

and since  $T = T^\mu{}_\mu$  is a trace of the stress-energy tensor,

$$[T] = \text{J m}^{-3}.$$

Because  $\omega$  is dimensionless, the coupling  $\alpha$  must also be dimensionless:

$$[\alpha] = 1.$$

## A.2 Potential and mass parameter

The potential is expanded around the vacuum value  $\omega = 1$  as

$$V(\omega) = \frac{1}{2} M_\omega^2 m_\omega^2 (\omega - 1)^2 + \dots.$$

The parameter  $m_\omega$  has units of inverse length:

$$[m_\omega] = \text{m}^{-1}.$$

This identifies  $m_\omega^{-1}$  as the characteristic range of coherence-field modifications. Higher-order coefficients in  $V(\omega)$  scale as powers of  $M_\omega^2 m_\omega^2$ .

## A.3 Effective Newtonian potential

To leading order, the effective Newtonian potential is defined as

$$\Phi_{\text{eff}} = c^2(\omega - 1), \quad [\Phi_{\text{eff}}] = \text{m}^2 \text{s}^{-2},$$

consistent with standard gravitational units.

The matching condition derived in Sec. 5 fixes the coupling,

$$\alpha = \frac{4\pi G M_\omega^2}{c^2},$$

which is dimensionless because

$$[G] = \text{m}^3 \text{kg}^{-1} \text{s}^{-2}, \quad [M_\omega^2] = \text{kg}^2.$$

Thus the dimensional factors cancel.

## A.4 Summary of key dimensions

$$[\omega] = 1,$$

$$[M_\omega] = \text{kg},$$

$$[m_\omega] = \text{m}^{-1},$$

$$[V] = \text{J m}^{-3},$$

$$[T] = \text{J m}^{-3},$$

$$[\alpha] = 1,$$

$$[\Phi_{\text{eff}}] = \text{m}^2 \text{s}^{-2}.$$

All quantities in the coherence-field action and its derived equations are therefore dimensionally consistent.

# Appendix B. Linearized Spectrum and Stability

This appendix provides a detailed derivation of the linearized spectrum, dispersion relation, Hamiltonian structure, and stability properties of the coherence field introduced in Sec. 4. We expand the full action to quadratic order around the vacuum solution and analyze the resulting dynamical modes.

## B.1 Expansion of the action

Let the coherence field be decomposed as

$$\omega(x) = 1 + \delta\omega(x), \quad |\delta\omega| \ll 1.$$

Assuming that the potential satisfies

$$V(1) = 0, \quad V'(1) = 0, \quad V''(1) = M_\omega^2 m_\omega^2,$$

the action (4.1) becomes, to quadratic order,

$$S^{(2)} = \frac{M_\omega^2}{2} \int d^4x \sqrt{-g} [g^{\mu\nu} \partial_\mu \delta\omega \partial_\nu \delta\omega - m_\omega^2 (\delta\omega)^2]. \quad (\text{B.1})$$

Thus  $\delta\omega$  is a canonical scalar field with mass  $m_\omega$ .

## B.2 Linearized field equation

Varying (B.1) yields

$$(\square - m_\omega^2) \delta\omega = 0. \quad (\text{B.2})$$

In a locally inertial frame,  $\square = \eta^{\mu\nu} \partial_\mu \partial_\nu$ , and the equation reduces to the standard Klein–Gordon equation.

## B.3 Plane-wave modes

Looking for solutions of the form

$$\delta\omega(t, \mathbf{x}) = A e^{-i(\Omega t - \mathbf{k} \cdot \mathbf{x})},$$

we obtain the dispersion relation

$$\Omega^2 = c^2 k^2 + c^2 m_\omega^2. \quad (\text{B.3})$$

This corresponds to a single relativistic massive scalar mode, with no extra degrees of freedom.

## B.4 Group velocity and causal propagation

The group velocity is

$$v_g = \frac{\partial \Omega}{\partial k} = c \frac{k}{\sqrt{k^2 + m_\omega^2}}. \quad (\text{B.4})$$

Thus,

$$0 \leq v_g < c.$$

Propagation is therefore strictly causal, with luminal speed recovered as  $m_\omega \rightarrow 0$ .

## B.5 Hamiltonian structure

The canonical Hamiltonian density derived from (B.1) is

$$\mathcal{H} = \frac{M_\omega^2}{2} [(\partial_t \delta\omega)^2 + c^2 (\nabla \delta\omega)^2 + c^2 m_\omega^2 (\delta\omega)^2]. \quad (\text{B.5})$$

This is positive definite provided

$$M_\omega^2 > 0, \quad m_\omega^2 \geq 0. \quad (\text{B.6})$$

Hence:

- No ghost instabilities (positive kinetic energy).
- No tachyonic instabilities (real mass parameter).
- No gradient instabilities (correct sign for spatial derivatives).

The coherence field is dynamically stable in all regimes where the quadratic expansion is valid.

## B.6 Role of background curvature

In a curved background  $(M, g_{\mu\nu})$ , the linearized equation becomes

$$(\square_g - m_\omega^2) \delta\omega = 0. \quad (\text{B.7})$$

Curvature corrections enter through  $\square_g$  but do not alter the sign of the kinetic, gradient, or mass terms. Therefore, local stability properties are unchanged.

## B.7 Influence of matter sources

In the presence of matter, the full equation is

$$(\square - m_\omega^2) \delta\omega = \frac{\alpha}{M_\omega^2} T, \quad (\text{B.8})$$

as described in Sec. 5. The source term does not modify the propagating spectrum unless  $T$  varies rapidly on coherence-field length scales. In quasi-static or slowly varying matter configurations, the perturbations remain governed by (B.3).

## B.8 Summary

The linearized coherence field satisfies a Klein–Gordon equation with mass  $m_\omega$  and has a standard relativistic dispersion relation. The Hamiltonian is positive definite for  $M_\omega^2 > 0$  and  $m_\omega^2 \geq 0$ , ensuring dynamical stability. Propagation is subluminal, and no additional propagating degrees of freedom arise. The linearized limit is therefore consistent and robust across all physically relevant regimes.

# Appendix C. Cosmological Background Solutions

We analyze homogeneous and isotropic cosmological solutions of the coherence-field equations derived in Sec. 4. The goal is to determine the behavior of  $\omega$  in an FLRW background and identify the conditions under which the coherence field contributes effectively to cosmic expansion.

The purpose of this appendix is not to propose an alternative cosmological model to  $\Lambda$ CDM, but to show that the coherence field admits consistent homogeneous solutions and remains compatible with the standard expansion history. A detailed cosmological model lies beyond the scope of the present work; crucially, for any  $m_\omega > 0$  the field dynamically relaxes to  $\omega \rightarrow 1$ , reproducing the GR limit at late times.

## C.1 Background metric and symmetry reduction

Consider a spatially flat FLRW metric,

$$ds^2 = c^2 dt^2 - a^2(t) d\mathbf{x}^2, \quad (\text{C.1})$$

where  $a(t)$  is the scale factor. Spatial homogeneity and isotropy require that the coherence rate depend only on cosmic time,

$$\omega = \omega(t). \quad (\text{C.2})$$

The matter sector is described by a perfect fluid with energy density  $\rho(t)$  and pressure  $p(t)$ , giving stress-energy trace

$$T = \rho c^2 - 3p. \quad (\text{C.3})$$

## C.2 Reduced action and field equation

Substituting (C.1)(C.2) into the action (4.1) and using  $\sqrt{-g} = a^3(t)$  gives the reduced Lagrangian

$$L_{\text{eff}} = \frac{M_\omega^2 a^3}{2} [\dot{\omega}^2 - m_\omega^2 c^2 (\omega - 1)^2] - a^3 \alpha \omega T. \quad (\text{C.4})$$

Variation yields the background equation of motion,

$$M_\omega^2 (\ddot{\omega} + 3H\dot{\omega}) + M_\omega^2 m_\omega^2 c^2 (\omega - 1) = \alpha T, \quad (\text{C.5})$$

where

$$H \equiv \dot{a}/a. \quad (\text{C.6})$$

### C.3 Interpretation

Equation (C.5) is a damped, driven oscillator with Hubble friction, mass term, and matter-source term. The source-to-friction ratio determines whether  $\omega$  tracks the matter density or evolves independently.

### C.4 Static and quasi-static solutions

In the regime where  $\dot{\omega} \approx 0$  and  $\ddot{\omega} \approx 0$ , Eq. (C.5) reduces to

$$m_\omega^2 c^2 (\omega - 1) = \frac{\alpha}{M_\omega^2} T. \quad (\text{C.7})$$

For pressureless matter ( $p \approx 0$ ),

$$\omega - 1 \simeq \frac{\alpha}{M_\omega^2 m_\omega^2 c^2} \rho c^2 = \frac{4\pi G \rho}{m_\omega^2 c^2}, \quad (\text{C.8})$$

using the coupling  $\alpha = 4\pi G M_\omega^2 / c^2$  from Sec. 5.

Thus:

- \*\*If  $m_\omega$  is large\*\*, deviations decay as  $1/m_\omega^2$  and

$$\omega \rightarrow 1,$$

meaning the coherence field \*does not participate\* in cosmological dynamics.

- \*\*If  $m_\omega$  is small\*\*,  $\omega$  acquires a slow, density-dependent shift.

### C.5 Dynamical solutions

Neglecting the source term during radiation domination ( $T \approx 0$ ), the equation reduces to

$$\ddot{\omega} + 3H\dot{\omega} + m_\omega^2 c^2 (\omega - 1) = 0. \quad (\text{C.9})$$

Solutions:

1. \*\*Massive coherence field ( $m_\omega \gg H/c$ )\*\*

$$\omega(t) - 1 \propto a^{-3/2}(t) \cos(m_\omega c t + \phi_0), \quad (\text{C.10})$$

exponentially damped by Hubble friction.

2. \*\*Light coherence field ( $m_\omega \ll H/c$ )\*\*

$$\omega(t) = \omega_0 + \omega_1 t^{-1} + \dots, \quad (\text{C.11})$$

drifting slowly toward a constant determined by initial conditions.

## C.6 Effective energy density and equation of state

The energy density and pressure of  $\omega$  follow from

$$\rho_\omega c^2 = \frac{M_\omega^2}{2} \dot{\omega}^2 + \frac{M_\omega^2 m_\omega^2 c^2}{2} (\omega - 1)^2 + V_{\text{higher}}(\omega), \quad (\text{C.12})$$

$$p_\omega = \frac{M_\omega^2}{2} \dot{\omega}^2 - \frac{M_\omega^2 m_\omega^2 c^2}{2} (\omega - 1)^2 - V_{\text{higher}}(\omega). \quad (\text{C.13})$$

Thus:

- **\*\*For kinetic domination\*\***:  $p_\omega \simeq \rho_\omega c^2$  (stiff fluid). - **\*\*For potential domination\*\*** (massive field near minimum):  $p_\omega \simeq -\rho_\omega c^2$ . - **\*\*For slow roll of light fields\*\***: intermediate equation of state.

These results mirror standard scalar-field cosmology.

## C.7 Late-time attractor

If  $m_\omega$  is nonzero, cosmic expansion drives  $\omega$  to the minimum of its potential:

$$\omega(t) \rightarrow 1 \quad (t \rightarrow \infty). \quad (\text{C.14})$$

Thus the coherence field naturally restores the GR limit at late times.

## C.8 Summary

Homogeneous cosmological dynamics of  $\omega(t)$  reduce to a damped, driven scalar-field equation. The behavior depends on the mass scale  $m_\omega$ :

- **Massive coherence field** ( $m_\omega \gg H/c$ ): rapid decay to  $\omega = 1$ , negligible cosmological impact.
- **Light coherence field** ( $m_\omega \ll H/c$ ): slow evolution, potentially contributing to effective dark-energy-like behavior.
- **Matter-dominated epoch**:  $\omega - 1 \propto \rho/m_\omega^2$ , suppressed unless  $m_\omega$  is ultralight.

In all cases, the system remains dynamically stable and approaches the GR limit whenever the potential has a quadratic minimum.

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