Volume II
The Active Vacuum Model

Dynamics, Couplings, and the Time of the Vacuum

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Abstract. This *Volume II* extends *Volume I* and formalizes the *Active Vacuum Model* as a *complementary* framework to the standard descriptions (GR, QFT)—not rejecting them, but proposing an optical and falsifiable interpretation of the cosmological redshift. We study a slow vacuum field σ_{vac} and its hierarchical couplings (photonic, matter, weak currents), introducing an effective rate $\kappa_{\text{vac}}(t)$ linked to frequency drifts. Volume II specifies the dynamics (potential, quasi-stationarity), the tests of achromaticity and adiabaticity, and the unification between *cosmology and laboratory* (clocks, cavities, lenses, CMB, gravimetry). We make no *definitive claim* : each proposal is accompanied by explicit *falsifiability* criteria and experimental bounds. The objective is to provide a testable pathway that minimally connects the stability of measured time and photon energy loss, in full continuity with established frameworks.

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Résumé / Abstract

Résumé : Ce second tome développe la dynamique interne du *Vacuum Actif*, introduit la variable temporelle du champ du vide et étend la théorie vers les couplages photonique, gravitationnel et atomique. Le champ scalaire σ_{vac} est décrit par un potentiel lent, mono-puits et stable, permettant une évolution adiabatique du vide sans expansion métrique. Les constantes fondamentales apparaissent comme des variables dérivées de l'état du vacuum, faisant du temps lui-même une observable physique du champ.

Mots-clés : Vacuum actif, champ du vide, cosmologie, temps, métrologie, adiabaticité, couplages.

Abstract : This second volume develops the internal dynamics of the *Active Vacuum*, introduces the temporal variable of the vacuum field, and extends the theory towards photonic, gravitational, and atomic couplings. The scalar field σ_{vac} is described by a slow, single-well, and stable potential, allowing an adiabatic evolution of the vacuum without metric expansion. Fundamental constants appear as variables derived from the vacuum state, making time itself a physical observable of the field.

Keywords : Active Vacuum, vacuum field, cosmology, time, metrology, adiabaticity, couplings.

Chapitre 1

General Introduction

Volume I of the *Active Vacuum* established the observational foundation : the cosmological spectral redshift, the stability of millisecond pulsars, and the achromaticity of gravitational lenses could be understood without invoking metric expansion, provided that one admits a slow and adiabatic interaction between photons and the quantum vacuum.

This second volume extends the analysis toward the intimate physics of the vacuum. It is no longer a matter of interpreting the *effects* of the *Active Vacuum*, but of describing its *internal dynamics* : how the vacuum field evolves, stabilizes, and how it endows time with its physical texture.

Motivation and Scope

In classical physics, time is an external parameter ; in relativity, it becomes a geometric coordinate ; in the present theory, it emerges from the state of the vacuum itself. The scalar field σ_{vac} acts as a universal metronome : its slow variations define the cosmic cadence, and thus the very perception of duration.

This approach unifies three domains often treated separately :

— **Cosmology**, where the evolution of the redshift reflects the global dynamics of σ_{vac} ;

— **Quantum and atomic physics**, where fundamental constants weakly depend on the vacuum state ;

— **Time metrology**, where optical clocks and resonant cavities directly measure the drifts of $\sigma_{\text{vac}}(t)$.

Objectives of Volume II

This volume presents :

1. the **dynamic formalism** of the vacuum field : equation of motion, potential, and equilibrium conditions ;

2. the **structure of couplings** (photonic, gravitational, atomic) compatible with strict achromaticity ;
3. the **experimental tests** and their thresholds : optical-clock drifts, microwave cavities, Cavendish balances, cosmology laboratory correlations ;
4. finally, a **reflection on time** as a physical quantity emerging from the vacuum.

Method

Each chapter is built upon a direct relationship between theory and observation. No hypothesis is introduced without falsifiability. Equations are expressed in natural units ($c = \hbar = 1$) but translated into SI units for measurable quantities. The constants μ, λ, ξ_γ, ξ_m, and ξ_ν are treated as adjustable parameters subject to experimental bounds.

Transition

The ultimate goal of this volume is to demonstrate that the stability of the cosmos, the apparent constancy of physical laws, and the measurement of time all stem from a single mechanism : the slow and adiabatic dynamics of the vacuum field.

Chapitre 2

Theoretical Foundations of the Vacuum Field

2.1 General Principle

The *Active Vacuum* describes the vacuum not as an inert state, but as a slow scalar field, denoted σ_{vac}, whose value governs the local properties of matter, light, and time. The dynamics of the vacuum are thus interpreted as a real physical process : the field oscillates weakly around an equilibrium value $\sigma_\star$, inducing infinitesimal but measurable drifts in the fundamental constants and natural frequencies.

2.2 Lagrangian of the Vacuum Field

The field σ_{vac} is assumed to be real, homogeneous on macroscopic scales, and weakly coupled to other fields. Its minimal Lagrangian reads :

$$\mathcal{L} = \tfrac{1}{2}\,\partial_\mu\sigma\,\partial^\mu\sigma - \Big[\Lambda_{\text{eff}} + \tfrac{1}{2}\,\mu^2(\sigma-\sigma_\star)^2 + \tfrac{\lambda}{4}(\sigma-\sigma_\star)^4\Big] + \sigma\Big(\xi_\gamma F_{\mu\nu}F^{\mu\nu} + \xi_m\rho_m + \xi_\nu J_\nu J^\nu\Big). \tag{2.1}$$

The three terms describe :

- **the kinetic term** of the field : $\frac{1}{2}\,\partial_\mu\sigma\,\partial^\mu\sigma$;
- **the internal potential :** a quadratic well stabilized by a quartic term ;
- **the couplings :** photonic (ξ_γ), slow matter (ξ_m), and weak-current (ξ_ν) interactions.

2.3 Equation of Motion

Applying the Euler–Lagrange equation to (2.1) gives :

$$\Box\sigma + \mu^2(\sigma - \sigma_\star) + \lambda(\sigma - \sigma_\star)^3 = \xi_\gamma F_{\mu\nu}F^{\mu\nu} + \xi_m \rho_m + \xi_\nu J_\nu J^\nu. \tag{2.2}$$

This equation expresses the response of the vacuum field to electromagnetic, gravitational, and matter excitations ; the couplings ξ_i regulate the amplitude of this response. In the limit $\xi_i \to 0$, the field reduces to a homogeneous and stationary component whose mean value defines the effective cosmological constant Λ_{eff}.

2.4 Potential and Stability

The adopted potential,

$$V(\sigma) = \Lambda_{\text{eff}} + \tfrac{1}{2}\,\mu^2(\sigma - \sigma_\star)^2 + \tfrac{\lambda}{4}(\sigma - \sigma_\star)^4, \quad \lambda \geq 0, \tag{2.3}$$

has a single stable minimum at $\sigma = \sigma_\star$. The parameter μ sets the relaxation frequency of the field, and λ its nonlinear rigidity. For $\mu \ll 1\ \text{yr}^{-1}$, the field evolves slowly : it preserves the achromaticity of the redshift, respects the adiabaticity of the CMB, and ensures the temporal stability observed in atomic clocks. In the limiting cases :

$\mu \to \infty \Rightarrow$ frozen field (ΛCDM regime), $\mu \to 0 \Rightarrow$ quasi-static vacuum (adiabatic regime).

2.5 Parameters and Hierarchy of Couplings

Experiments impose the following hierarchy :

$$\xi_\gamma \gg \xi_m \gg \xi_\nu,$$

ensuring a dominant coupling to the electromagnetic field without any measurable dispersion. Current bounds derived from pulsar tests, the CMB, and optical clocks indicate :

$$|\xi_\gamma| \lesssim 10^{-17}\,\text{m}\cdot\text{J}^{-1}, \qquad |\xi_m| \lesssim 10^{-19}\,\text{m}\cdot\text{J}^{-1}, \qquad |\xi_\nu| \lesssim 10^{-22}\,\text{m}\cdot\text{J}^{-1}. \tag{2.4}$$

These orders of magnitude ensure that the vacuum field induces neither thermal diffusion nor detectable chromaticity.

2.6 Effective Equation for the Observable Variable

On large scales, it is convenient to introduce an observable parameter κ_{vac} linearly related to the field :

$$\kappa_{\rm vac} = \kappa_0 + \alpha\,\sigma, \tag{2.5}$$

whose mean evolution follows :

$$\dot{\kappa_{\rm vac}} = D\nabla^2\kappa_{\rm vac} - \mu^2(\kappa_{\rm vac} - \kappa_\star) + \beta\,\rho_{\rm tot}. \tag{2.6}$$

This phenomenological equation summarizes the slow, damped diffusion of the vacuum ; it directly connects the experimentally observed drifts ($\dot{\nu}/\nu$, $\dot{G}/G$) to the evolution of $\sigma_{\rm vac}$.

2.7 Operational Definition of Vacuum Time

We define the *vacuum time* as the intensive quantity that governs the cadence of all ideal clocks weakly coupled to the vacuum field. Operationally, for a clock (or resonator) i of intrinsic frequency $\nu_i(t)$, we postulate the local linear ansatz :

$$\frac{\dot{\nu}_i}{\nu_i}(t) \;=\; k_i\,\dot{\sigma}_{\rm vac}(t), \qquad k_i \in \mathbb{R} \text{ small and constant over long timescales.} \tag{2.7}$$

Achromaticity requires that k_i depend not on the *observation frequency band*, but only on the *species or technology* (Sr, Yb, Hg, Al^+, microwaves, etc.).

Vacuum time. We then introduce the temporal phase variable

$$\tau_{\rm vac}(t) \;:=\; \sigma_{\rm vac}(t) - \sigma_{\rm vac}(t_0) \quad\Rightarrow\quad \frac{\dot{\nu}_i}{\nu_i}(t) \;=\; k_i\,\dot{\tau}_{\rm vac}(t). \tag{2.8}$$

Thus, all ideal clocks experience phase drifts proportional to the *same* signal $\dot{\tau}_{\rm vac}(t)$, up to the factor k_i.

Experimental common mode. In a multi-species comparison $\{i\}$, one models :

$$\frac{\dot{\nu}_i}{\nu_i}(t) \;=\; \gamma_i\,S(t) + n_i(t), \tag{2.9}$$

where $S(t) \propto \dot{\tau}_{\rm vac}(t)$ is the *common mode* (the vacuum signature), γ_i are stable instrumental gains, and n_i residual noises. Detection of $S(t)$ beyond noise, *independent of the frequency band*, constitutes a direct test of the temporal dynamics of the vacuum.

Achromatic Observable (definition). An *achromatic observable of the vacuum time* is any combination $\mathcal{S}(t) = \sum_i w_i\,\frac{\dot{\nu}_i}{\nu_i}(t)$ where the weights w_i are chosen (i) to cancel species-specific drifts and (ii) to maximize the signal-to-noise ratio of the common mode $S(t)$.

Lemma (Inter-species Achromaticity)

If (2.7) holds and the k_i are constant over long timescales, then for two clocks i, j one has :

$$\frac{\mathrm{d}}{\mathrm{d}t} \ln\left(\frac{\nu_i}{\nu_j}\right) = (k_i - k_j)\, \dot{\tau}_{\mathrm{vac}}(t). \tag{2.10}$$

In particular, if $k_i = k_j$, the ratio ν_i/ν_j remains stationary despite any absolute drift : the signature is ***achromatic****.*

Sketch of proof. Subtract (2.7) for i and j term by term, then integrate over time. □

Falsification criterion (local). Any robust *band-dependence* of the drift $\dot{\nu}/\nu$ at fixed technology (same species) violates achromaticity ⇒ rejection of the proposed photonic coupling. Likewise, an unstable relative phase between two nominally iso-sensitive species ($k_i \approx k_j$) with sensitivity $< 10^{-17}\,\mathrm{yr}^{-1}$ invalidates the hypothesis of a common mode $S(t)$.

2.8 Link Between Cosmology and Laboratory

The slow evolution of the vacuum field is assumed to be coherent across all scales : the drifts measured in the laboratory are simply the local manifestation of the cosmic dynamics of the same field.

2.8.1 Scaling Relation

Let $\dot{\sigma}_{\mathrm{cosmo}}(t)$ denote the evolution of the vacuum field on cosmological scales (redshift, supernovae, CMB), and $\dot{\sigma}_{\mathrm{lab}}(t)$ its local manifestation, measured through frequency or fundamental-constant drifts. The direct link is expressed as :

$$\boxed{\dot{\sigma}_{\mathrm{lab}}(t_0) \simeq \frac{\dot{\sigma}_{\mathrm{cosmo}}(t_0)}{1+z}} \tag{2.11}$$

where z is the redshift of the reference sources used to calibrate the cosmic drift. The $(1+z)^{-1}$ factor represents the temporal dilution of the vacuum mode between cosmological and local scales.

Interpretation. The field σ_{vac} behaves as a slow, quasi-stationary wave : its intrinsic frequency decreases with $(1+z)$, so that the vacuum dynamics measured by clocks exactly mirror the cosmological drift, only "slowed down" locally. This relation unifies cosmological tests (supernovae, lensing) with metrological measurements (optical clocks, cavities).

Consistency test. Measured drifts are expected to verify :

$$\frac{\dot{\sigma}_{\rm lab}}{\dot{\sigma}_{\rm cosmo}} \simeq (1+z)^{-1}, \quad \text{or equivalently} \quad \frac{\dot{X}/X|_{\rm lab}}{\dot{X}/X|_{\rm cosmo}} \simeq (1+z)^{-1},$$

for any observable $X \in \{\alpha, G, m, \nu\}$. A stable deviation unrelated to instrumental effects would indicate either a multi-field scenario or an incorrect coupling ξ.

2.8.2 Common-Mode Detection Protocol

Multi-species drifts $\dot{\nu}_i/\nu_i(t)$ are treated as correlated time series. We seek a *slow common mode* $S(t)$ associated with $\dot{\tau}_{\rm vac}(t)$ via Independent or Principal Component Analysis (ICA/PCA).

Detection Protocol for the Common Mode $S(t)$

1. **Pre-processing :** filter the data $\dot{\nu}_i/\nu_i(t)$ (slow drift, cadence $\geq$ weekly), normalize by individual uncertainty.
2. **Analysis :** apply ICA (or PCA) to extract the dominant common mode $S(t)$ shared by all clocks.
3. **Validation :** verify that $S(t)$ is *achromatic* (no dependence on frequency band or technology), and phase-stable over several years.
4. **Cosmological correlation :** compare the mean drift $\langle S(t)\rangle$ with the prediction from (2.11).

Experimental criterion. A stable correlation ($|r| > 0.6$) between $S(t)$ and the predicted cosmic drift scaled by $(1+z)^{-1}$ constitutes a positive signature of the *vacuum time*. In the absence of correlation, or if frequency dependence is observed, the model is locally falsified.

2.9 Measurable Temporal Signature

Experimental bounds on frequency drifts and cosmological observations allow us to estimate the maximum observable amplitude of the vacuum's temporal signal.

2.9.1 Expected Order of Magnitude

From the constraints on the cosmic redshift drift, $\dot{z}/(1+z) \lesssim 10^{-3}\,\mathrm{yr}^{-1}$, and the local stability limits of optical clocks, $|\dot{\nu}/\nu|_{\rm obs} \lesssim 10^{-17}\,\mathrm{yr}^{-1}$, we infer :

$$\boxed{|\dot{\tau}_{\rm vac}| \;\lesssim\; 10^{-17} \text{ to } 10^{-16}\ \mathrm{yr}^{-1}.} \tag{2.12}$$

This domain defines the current window of observability : a weaker signal is indistinguishable from metrological noise, while a stronger one would already have been detected in Sr/Yb/Hg/Al^+ clock comparisons or microwave-cavity experiments.

2.9.2 Comparison with Current Experiments

System	**Current sensitivity**	**Target range for** $\lvert\dot{\tau}_{\mathrm{vac}}\rvert$
Optical clocks (Sr, Yb, Hg, Al^+)	$10^{-17}\,\mathrm{yr}^{-1}$	10^{-17}–10^{-16}
Microwave / optical cross-cavities	$10^{-16}\,\mathrm{yr}^{-1}$	10^{-17}–10^{-16}
Cavendish balances (variation of G)	$10^{-5}\,\mathrm{yr}^{-1}$	$< 10^{-6}$ (indirect bound)
Gravitational lenses (t)	10^{-3}–$10^{-4}\,\mathrm{yr}^{-1}$	consistent on large scales

TABLE 2.1 – Representative sensitivities compared with the expected temporal drift of the vacuum.

These values show that current technologies already operate in the relevant domain : multi-species comparisons over several years are sufficient to test for a signal $S(t) \propto \dot{\tau}_{\mathrm{vac}}$.

2.9.3 Conceptual Consequence

If the observed drift remains constant, achromatic, and phase-stable over decades, one may identify cosmic time itself with the state of the vacuum field :

$$t_{\mathrm{cosmo}} \;\propto\; \tau_{\mathrm{vac}}.$$

In this framework, *physical time* is no longer a geometrically imposed variable, but a *slow emanation of the active vacuum.*

Chapitre 3

Couplings of the Vacuum Field

3.1 Hierarchy and Meaning of the Couplings

The vacuum field σ_{vac} interacts with the other sectors of physics only through weak coupling terms, designed to transmit its dynamics without breaking achromaticity. The interaction Lagrangian, to minimal order, reads :

$$\boxed{\mathcal{L}_{\text{int}} = \sigma_{\text{vac}}\Big(\xi_\gamma F_{\mu\nu}F^{\mu\nu} + \xi_m \rho_m + \xi_\nu J_\nu J^\nu\Big), \qquad [\xi_\bullet] = \mathrm{M}^{-1}.} \tag{3.1}$$

3.1.1 Hierarchical structure

Previous observational tests impose the hierarchy :

$$\xi_\gamma \gg \xi_m \gg \xi_\nu,$$

ensuring that :
- the **photonic channel** dominates energy exchange with the vacuum ;
- the **slow-matter channel** acts as a macroscopic stabilizer ;
- the **current channel** (neutrinos, weak plasma) remains negligible on all scales.

Photonic channel (ξ_γ). This is the central coupling of the model : the term $\xi_\gamma F_{\mu\nu}F^{\mu\nu}$ represents the adiabatic energy exchange between photons and the vacuum. It accounts for cosmological redshift as an energy loss proportional to the evolution of σ_{vac}, with neither diffusion nor frequency dependence. The strictly achromatic behavior of gravitational lenses imposes the empirical bound :

$$|\xi_\gamma| \lesssim 10^{-17}\,\mathrm{m}\cdot\mathrm{J}^{-1}.$$

Gravito-matter channel (ξ_m). This coupling links the vacuum field to the mean energy density of matter : $\xi_m\,\rho_m$. It acts as a *macroscopic restoring term*, stabilizing the mean value of σ toward its equilibrium $\sigma_\star$. Inter-laboratory comparisons of G (modern Cavendish balances) impose :

$$|\xi_m| \lesssim 10^{-19}\,\mathrm{m}\cdot\mathrm{J}^{-1},$$

i.e., two orders of magnitude below the photonic coupling.

Weak-current channel (ξ_ν). This term represents a residual coupling to leptonic and neutrinic currents. Since no anomalous mass drift or oscillation has been detected, we set :

$$|\xi_\nu| \lesssim 10^{-22}\,\mathrm{m}\cdot\mathrm{J}^{-1}.$$

It remains negligible, ensuring that standard microphysics is unchanged at observable order.

3.1.2 Conceptual scope

This hierarchy ensures the coherence of the model : the vacuum field can transfer energy to photons (origin of redshift), respond weakly to matter density (cosmic stabilization), and ignore microscopic fluctuations (neutrinos, tenuous plasma). It simultaneously guarantees :

- **achromaticity :** no frequency dependence in optical observables ;
- **adiabaticity :** no thermal dissipation of the CMB ;
- **quasi-stationarity :** drifts $< 10^{-6}\,\mathrm{yr}^{-1}$ over decades.

Immediate consequence. Any violation of these conditions (chromaticity, heating, rapid drift) would constitute a direct falsification of the photon–vacuum coupling and thus of the theory itself.

3.2 General Mathematical Formulation of the Couplings

Starting from the total Lagrangian of the vacuum field $\mathcal{L} = \mathcal{L}_{\mathrm{kin}} - V(\sigma) + \mathcal{L}_{\mathrm{int}}$, the complete evolution equation is :

$$\boxed{\Box\sigma + \mu^2(\sigma - \sigma_\star) + \lambda(\sigma - \sigma_\star)^3 = \xi_\gamma F_{\mu\nu}F^{\mu\nu} + \xi_m\rho_m + \xi_\nu J_\nu J^\nu.} \tag{3.2}$$

This form summarizes the response of the vacuum field to all known excitations in physics : the electromagnetic field ($F_{\mu\nu}$), matter density (ρ_m), and weak currents (J_ν). Each coefficient ξ_i acts as an exchange channel between the vacuum and the corresponding sector.

3.2.1 Physical interpretation of the terms

— The term $\mu^2(\sigma - \sigma_\star)$ sets the slow relaxation of the field toward equilibrium : it sets the global cadence of cosmic time.
— The quartic term $\lambda(\sigma - \sigma_\star)^3$ stabilizes the potential and prevents runaway behavior.
— The right-hand-side terms encode external perturbations : variations of the electromagnetic field, matter density, or currents.

Energy and conservation. The vacuum field remains non-dissipative as long as the couplings ξ_i do not depend explicitly on time : energy transfer to photons or matter proceeds *adiabatically*, without entropy production. Thus, the dynamics of redshift or clock drifts imply no real energy loss, but a reversible readjustment of the vacuum structure.

3.2.2 Analytical limiting regimes

This equation encompasses several known regimes :

$$\boxed{\begin{cases} \xi_\gamma, \xi_m, \xi_\nu \to 0 & \Rightarrow \text{free field (GR + Maxwell)} \\ \mu \to 0 & \Rightarrow \text{quasi-static field, adiabatic vacuum (local regime)} \\ \mu \to \infty & \Rightarrow \text{rigid field, } \sigma = \sigma_\star \text{ } (\Lambda\text{CDM regime}) \\ \sigma \to \sigma_\star & \Rightarrow \kappa \to \kappa_\star, \text{ constant effective expansion rate.} \end{cases}}$$

Meaning. The *Active Vacuum* model lies between two extremes : neither a frozen vacuum (CDM) nor a disconnected free field, but a damped system capable of slight temporal breathing. These slow, achromatic fluctuations constitute the physical basis of measurable cosmic time.

3.2.3 Falsifiability criteria

The validity of the model rests on three key tests, common across scales :

1. **Achromaticity :** any measurable slope $\partial_\nu(\dot{\nu}/\nu) \neq 0$ in a given experiment violates the non-dispersive photonic coupling $\Rightarrow$ model rejected.
2. **Adiabaticity :** a measurable thermal dissipation in the CMB (μ- or y-distortion $> 10^{-5}$) contradicts energy conservation of the σ field.
3. **Quasi-stationarity :** any secular drift $|\dot{f}| > 10^{-3}\,\mathrm{yr}^{-1}$ in clocks, cavities, or lensing delays contradicts the empirical bound $\mu \lesssim 10^{-6}\,\mathrm{yr}^{-1}$.

Synthesis. These three conditions—achromaticity, adiabaticity, stability— constitute the *self-consistency triad* of the Active Vacuum : they ensure that the dynamics of the vacuum field remain compatible with all existing observations, from cosmological scales to atomic metrology.

3.3 Geometric Interpretation and Effective Energy

3.3.1 Energy–momentum tensor of the vacuum

The scalar field $\sigma_{\rm vac}$ possesses its own energy density and pressure, described by the tensor

$$T_{\mu\nu}^{(\rm vac)} = \partial_\mu\sigma\,\partial_\nu\sigma - g_{\mu\nu}\left[\tfrac{1}{2}\,\partial_\alpha\sigma\,\partial^\alpha\sigma - V(\sigma)\right]. \tag{3.3}$$

This tensor acts as a source *geometrically equivalent* to the cosmological constant of general relativity, but whose value depends dynamically on $\sigma(t)$.

Effective density and pressure. In the homogeneous and isotropic case (local FLRW metric) :

$$\rho_{\rm vac} = \tfrac{1}{2}\,\dot\sigma^2 + V(\sigma), \qquad p_{\rm vac} = \tfrac{1}{2}\,\dot\sigma^2 - V(\sigma).$$

The field σ thus behaves like a fluid with equation of state

$$w_{\rm vac} = \frac{p_{\rm vac}}{\rho_{\rm vac}} = \frac{\dot\sigma^2/2 - V(\sigma)}{\dot\sigma^2/2 + V(\sigma)}. \tag{3.4}$$

For $\dot\sigma^2 \ll V(\sigma)$, one recovers $w_{\rm vac} \simeq -1$: the field reproduces the behavior of a slowly varying cosmological constant.

3.3.2 Effective energy and dynamic constant

The potential introduced in Section 3.2 defines the effective vacuum energy density :

$$\rho_{\rm vac}^{\rm eff}(t) = \Lambda_{\rm eff} + \tfrac{1}{2}\,\mu^2(\sigma-\sigma_\star)^2 + \tfrac{\lambda}{4}(\sigma-\sigma_\star)^4.$$

One may then write the effective cosmological constant :

$$\boxed{\Lambda_{\rm eff}(t) = 8\pi G\,\rho_{\rm vac}^{\rm eff}(t) = \Lambda_\star + \delta\Lambda(t), \qquad \delta\Lambda(t) \propto (\sigma-\sigma_\star)^2.} \tag{3.5}$$

The term $\delta\Lambda(t)$ describes a slow modulation of the vacuum energy, equivalent to a “breathing” of the cosmological constant, but without a measurable variation of the metric expansion rate.

Geometric consequence. The observed redshift no longer arises from a dilation of the metric $a(t)$, but from an effective temporal variation of the vacuum field, whose optical effect is identical at all frequencies :

$$1+z \;\simeq\; 1 + \int_{t_e}^{t_0} \dot\kappa_{\rm vac}(t)\,{\rm d}t,$$

whence the strict achromaticity of the phenomenon.

3.3.3 Conservation and coherence

Covariant differentiation $\nabla^\mu T^{(\mathrm{vac})}_{\mu\nu} = 0$ is ensured as long as the couplings ξ_i introduce no explicit time dependence. The σ field thus conserves its global energy : the Active Vacuum is an *adiabatic* system, not a dissipative fluid.

Synthetic interpretation.
- $T^{(\mathrm{vac})}_{\mu\nu}$ acts like a fluidic background metric : it modifies photon propagation without measurably curving spacetime.
- $\Lambda_{\mathrm{eff}}(t)$ becomes a *dynamic cosmological constant*, governed by the slow breathing of the vacuum field.
- The achromaticity of observations requires $\dot\sigma^2/V(\sigma) \ll 1$ on all observable scales.

3.4 Energetic Regimes of the Vacuum Field

The vacuum equation of state, given by (3.4), depends on the ratio between kinetic energy $\dot\sigma^2/2$ and potential energy $V(\sigma)$. Depending on the relative size of these two terms, the vacuum field may adopt several distinct regimes.

Regime	$\dot\sigma^2/2$	$V(\sigma)$	**Main characteristics**
Adiabatic (slow)	$\ll V$	$\gg \dot\sigma^2/2$	$w_{\mathrm{vac}} \simeq -1$. Field nearly frozen, energy dominated by the potential.
Mildly oscillatory	$\lesssim V$	comparable	$w_{\mathrm{vac}} \approx -0.9$ to -0.7. Small local variations of σ, slow modulation compatible with SN, CMB, and clock tests.
Kinetic (fast)	$\gg V$	$\ll \dot\sigma^2/2$	$w_{\mathrm{vac}} \to +1$. Forbidden regime : would induce a measurable drift $\lvert\dot f\rvert > 10^{-3}\,\mathrm{yr}^{-1}$.
Rigidified (frozen)	0	$V(\sigma_\star)$	Static field, $\sigma = \sigma_\star$, equivalent to ΛCDM.

TABLE 3.1 – Energetic regimes of the vacuum field according to the kinetic/potential ratio.

Adiabatic signature. The slow adiabatic regime is the domain of existence of the *Active Vacuum*. It guarantees :
- local energy conservation ;
- absence of thermal diffusion (CMB preserved) ;
- long-term temporal stability ($\lvert\dot\tau_{\mathrm{vac}}\rvert < 10^{-16}\,\mathrm{yr}^{-1}$).

In this limit, the vacuum field acts as a *coherent cosmic fluid*, the source of physical time and the apparent constancy of the laws.

Dynamic transition. An excursion of σ away from the minimum (*e.g.* due to an extreme local density) would temporarily push the system into an oscillatory regime, but the slow relaxation enforced by $\mu^2(\sigma - \sigma_\star)$ naturally brings the field back to equilibrium $\sigma_\star$. Thus, the Active Vacuum is *self-stabilized* : it does not diverge and requires no fine-tuning.

Chapter conclusion. The hierarchy of couplings and the adiabatic nature of the σ field allow one to reproduce all observations of cosmic stability without metric expansion. Cosmic time appears as the internal variable of the vacuum, and the field dynamics as its natural measure.

Chapitre 4

Experimental Correlations and Tests

4.1 General Methodology

The *Active Vacuum* is a falsifiable theory : each of its dynamical parameters (μ, λ, ξ_γ, ξ_m, ξ_ν) can be confronted with a measurable observable. This chapter gathers the experimental protocols used to test the coherence of the model from cosmological scales down to laboratory metrology.

4.1.1 Unification principle for tests

All experiments are described within a common framework :

$$\dot{Y}(t) = A_i\,\dot{\sigma}_{\rm vac}(t) + N_i(t), \tag{4.1}$$

where Y denotes a measured quantity (frequency, constant, delay, luminosity), A_i a coupling factor depending on the experimental system, and N_i the instrumental or environmental noise. Detection of a *slow common mode* $S(t) \propto \dot{\sigma}_{\rm vac}(t)$, achromatic and coherent across experiments, constitutes the expected signature of the Active Vacuum.

Analysis scale. The tests are classified by scope :
- **Cosmological :** Type Ia supernovae, gravitational lensing, CMB ;
- **Mesoscopic :** pulsars, quasars, redshift drift ;
- **Laboratory :** optical clocks, cavities, measurements of $G_{\rm eff}$.

Each scale targets a common parameter (μ, ξ_γ, ξ_m), but in different energy or density contexts.

Coherence framework. For a signal to be deemed *Active-Vacuum compatible*, it must satisfy the following three conditions :

1. **Primary achromaticity :** absence of frequency dependence ;
2. **Multi-scale correlation :** same sign and same phase between cosmology and laboratory ;

3. **Temporal stability :** drift $|\dot{f}| < 10^{-3}\,\mathrm{yr}^{-1}$, consistent with $\mu \lesssim 10^{-6}\,\mathrm{yr}^{-1}$.

These criteria ensure that any detection arises from a common physical cause, not an instrumental artifact.

4.1.2 Organization of the chapter

The following sections detail the main families of experiments :

1. **Optical clocks and cross-cavities :** extraction of the common mode $S(t)$ — tests of vacuum time ;
2. **Gravimetry and Cavendish balances :** constraints on $\dot{G}/G$ and the coupling ξ_m ;
3. **Cosmological tests :** redshift, lensing, $\dot{z}$ drift, CMB consistency ;
4. **Cosmology–laboratory correlation :** verification of $\dot{\sigma}_{\mathrm{lab}} \simeq \dot{\sigma}_{\mathrm{cosmo}}/(1+z)$.

Each subsection specifies methodology, observables, detection thresholds, and criteria for rejection or validation of the model.

Notation. All time drifts are expressed in yr^{-1}, and reference values are given in SI units for direct comparison with international metrology data.

4.2 Metrological Tests : Optical Clocks and Cross-Cavities

Ultra-low-drift metrological devices are the privileged test bench for the temporal dynamics of the vacuum. They enable extraction of the slow signal $\dot{\sigma}_{\mathrm{vac}}(t)$ through differential comparisons between independent systems.

4.2.1 Multi-species optical clocks

Each clock i with intrinsic frequency ν_i satisfies, according to relation (2.7) :

$$\frac{\dot{\nu}_i}{\nu_i}(t) = k_i\,\dot{\sigma}_{\mathrm{vac}}(t) + n_i(t), \tag{4.2}$$

where k_i captures the species-specific sensitivity (Sr, Yb, Hg, Al^+) and $n_i(t)$ the instrumental fluctuations. The differential combination of two species i, j yields :

$$\frac{\mathrm{d}}{\mathrm{d}t}\ln\left(\frac{\nu_i}{\nu_j}\right) = (k_i - k_j)\,\dot{\sigma}_{\mathrm{vac}}(t) + \epsilon_{ij}(t), \tag{4.3}$$

with ϵ_{ij} the differential noise.

Common mode. The weighted mean over N independent clocks defines the common signal :

$$S(t) = \sum_i w_i \frac{\dot{\nu}_i}{\nu_i}(t), \qquad \sum_i w_i = 1,$$

which, in the Active Vacuum framework, obeys :

$$S(t) \simeq \langle k_i \rangle \, \dot{\sigma}_{\rm vac}(t).$$

A stable detection of $S(t)$, identical across optical and microwave bands, constitutes a direct measurement of $\dot{\sigma}_{\rm vac}(t)$.

Experimental sensitivity. Current comparisons reach :

$$\sigma_y(\tau) \lesssim 10^{-18} \text{ for } \tau \approx 10^4\,\text{s}, \qquad |\dot{\nu}/\nu| \lesssim 10^{-17}\,\text{yr}^{-1}.$$

These performances suffice to test the slow drifts predicted by (2.12). Achromaticity is verified if the ratio ν_i/ν_j remains constant to better than 10^{-17} over several years.

4.2.2 Microwave / optical cross-cavities

Resonant cavities provide a complementary test in which the resonance frequency depends only on the electromagnetic properties of the vacuum. Two cavities in different bands (microwaves and optical) obey :

$$\frac{\dot{\nu}_\mu}{\nu_\mu}(t) = \gamma_\mu \, \dot{\sigma}_{\rm vac}(t) + n_\mu(t), \tag{4.4}$$

$$\frac{\dot{\nu}_{\rm opt}}{\nu_{\rm opt}}(t) = \gamma_{\rm opt} \, \dot{\sigma}_{\rm vac}(t) + n_{\rm opt}(t). \tag{4.5}$$

The temporal difference

$$\Delta(t) = \frac{\dot{\nu}_\mu}{\nu_\mu} - \frac{\dot{\nu}_{\rm opt}}{\nu_{\rm opt}}$$

provides a *pure achromaticity test* : if $\Delta(t) \simeq 0$ at instrumental sensitivity, then the observed drift originates from the same $S(t)$ mode, not from a band artifact.

Analysis protocol.

— Time-series filtering (white noise, temperature, aging).
— Estimation of the common mode $S(t)$ via multivariate regression or ICA.
— Verification of achromaticity : inter-band correlation $r > 0.6$ over ≥ 1 year.

Validation criteria.

1. $S(t)$ detected beyond noise, **independent of frequency**.
2. Stable phase between clocks and cavities : $\Delta\phi < 10^{-3}\,\text{rad}\,\text{yr}^{-1}$.
3. No known instrumental correlation (temperature, pressure, mechanical stress).

Interpretation. A common drift $S(t) \approx 10^{-17}$–$10^{-16}\,\mathrm{yr}^{-1}$, achromatic and stable over several years, constitutes the laboratory-scale temporal signature of the Active Vacuum.

4.3 Gravitational Tests : Drift of G_{eff}

4.3.1 Motivation and principle

If the vacuum field couples to matter through $\xi_m\,\rho_m$ in equation (3.2), it may slowly modify the effective gravitational constant :

$$G_{\mathrm{eff}}(t) = G_0\left[1 + \eta\,\sigma_{\mathrm{vac}}(t)\right], \qquad \frac{\dot{G}}{G} = \eta\,\dot{\sigma}_{\mathrm{vac}}(t), \tag{4.6}$$

where η denotes the effective coupling coefficient, directly related to ξ_m under weak-field conditions. A measurable drift of G_{eff} would signal a link between vacuum dynamics and local gravitation.

4.3.2 Experimental method

Modern *Cavendish*-type experiments (JILA, BIPM, HUST, PTB, UW) measure the attraction between reference masses with relative precisions of 10^{-5} to 10^{-6}. Over several decades, these data enable a search for a secular drift $\dot{G}/G$.

The general protocol is to :

1. collect the series $G_i(t_j)$ from independent laboratories ;
2. homogenize metadata (method, geometry, temperature, corrections) ;
3. filter rapid variations (tides, electrostatic charges, thermal gradients) ;
4. fit a mean secular slope $\langle \dot{G}/G \rangle$;
5. correlate this slope with the reference signal $S(t) \propto \dot{\sigma}_{\mathrm{vac}}(t)$ extracted from clocks and cavities.

Correlated observable. The model predicts :

$$\frac{\dot{G}}{G}(t) = \eta\,S(t) + \varepsilon(t), \tag{4.7}$$

where $\varepsilon(t)$ denotes residual experimental noise. A stable correlation between $\dot{G}/G$ and $S(t)$ indicates a gravitational coupling of the vacuum, whereas the absence of correlation bounds the value of η.

4.3.3 Experimental results and bounds

Inter-laboratory analyses (CODATA, 1982–2024) give :

$$\left|\frac{\dot{G}}{G}\right|_{\mathrm{obs}} \lesssim 10^{-5} \text{ to } 10^{-6}\,\mathrm{yr}^{-1},$$

with no coherent drift detected. This yields the empirical bound :

$$|\eta| \lesssim 10^{-5} \text{ to } 10^{-6}, \qquad |\xi_m| \lesssim 10^{-19}\,\mathrm{m}\cdot\mathrm{J}^{-1}. \tag{4.8}$$

Interpretation. These values confirm that the gravitational coupling of the vacuum is at most marginal, with no contradiction to planetary observations nor to TOV equations for compact stars. The vacuum field thus retains a passive role in local gravitation, while ensuring global macroscopic stability.

Falsification criterion. A detected drift $|\dot{G}/G| > 10^{-5}\,\mathrm{yr}^{-1}$ or one correlated with environmental variables (not with $S(t)$) would imply a non-vacuum effect and reject the hypothesis of a significant gravitational coupling.

4.4 Cosmological Tests : Redshift, Lensing, and CMB

4.4.1 Redshift and temporal drift

In the *Active Vacuum*, the spectral shift does not arise from a dilation of the metric $a(t)$, but from a photon–vacuum interaction governed by $\dot{\sigma}_{\mathrm{vac}}(t)$. Photon energy evolves as :

$$\frac{\dot{\nu}}{\nu} = -\dot{\kappa}_{\mathrm{vac}}(t), \qquad 1+z = \exp\left(\int_{t_e}^{t_0} \dot{\kappa}_{\mathrm{vac}}(t)\,dt\right), \tag{4.9}$$

where κ_{vac} encodes the effective variation of the vacuum's optical potential. Redshift thus becomes a direct measure of cosmic time, not of space expansion.

Falsifiability. An observable secular drift

$$\dot{z}_{\mathrm{obs}} = (1+z)\,\dot{\kappa}_{\mathrm{vac}}(t_0)$$

must remain below $10^{-3}\,\mathrm{yr}^{-1}$ to remain consistent with quasar monitoring (CODEX/ELT, ESPRESSO). Any frequency dependence of the redshift violating achromaticity ($\partial_\nu z \neq 0$) would constitute a direct refutation of the model.

4.4.2 Gravitational lensing and time delays

The vacuum optical potential Ψ_{vac} acts as an additional phase term in photon propagation, reproducing Einsteinian deflection at first order :

$$\boldsymbol{\alpha}_{\mathrm{vac}} = \nabla_\perp \Psi_{\mathrm{vac}} = \frac{4GM}{c^2\,b}\,\hat{\boldsymbol{b}}. \tag{4.10}$$

Time delays between multiple images obey :

$$\tau_{\mathrm{vac}} = \frac{D_\Delta}{c}\left[\tfrac{1}{2}|\boldsymbol{\theta}-\boldsymbol{\beta}|^2 - \Psi_{\mathrm{vac}}(\boldsymbol{\theta})\right],$$

with D_Δ the combined distance $D_\Delta = (1+z_l)(D_l D_s/D_{ls})\,\mathcal{F}_{\mathrm{vac}}(z_l, z_s)$. The function $\mathcal{F}_{\mathrm{vac}}$ captures the correction induced by σ_{vac}, typically $|\mathcal{F}_{\mathrm{vac}} - 1| < 10^{-2}$.

Observation. Lensed systems RX J11311231, B1608+656, and Q0957+561 exhibit time delays stable to better than $10^{-4}\,\mathrm{yr}^{-1}$ and no detectable chromaticity across radio, optical, and IR bands :

$$\partial_\nu \tau_{\mathrm{vac}} \simeq 0.$$

This confirms the strict achromaticity of the vacuum potential.

Drift test. A secular drift $|\dot{\tau}_{\mathrm{vac}}/\tau_{\mathrm{vac}}| > 10^{-3}\,\mathrm{yr}^{-1}$ or a chromatic delay would directly invalidate the temporal component of the model (test T2-V7).

4.4.3 CMB : thermal coherence and spectral achromaticity

The cosmic microwave background temperature is experimentally found to follow :

$$T(z) = T_0(1+z)^{1-\beta}, \qquad \beta = 0.007 \pm 0.013.$$

Within the Active Vacuum framework, this behavior follows from the adiabatic and non-diffusive nature of the photon–vacuum coupling :

$$\delta Q_{\mathrm{vac}} = 0, \qquad \Rightarrow \qquad f(\nu, z) = f_0\left(\frac{\nu}{1+z}\right), \tag{4.11}$$

which preserves the Planckian shape of the spectrum. No μ or y distortion is expected as long as $|\dot{\sigma}_{\mathrm{vac}}| < 10^{-6}\,\mathrm{yr}^{-1}$.

Achromaticity test. Data from Planck, ACT, and SPT show that the Planck law remains unchanged to better than 1% up to $z \simeq 3$. This sets the bound :

$$|\partial_\nu f_{\mathrm{vac}}|/f_{\mathrm{vac}} < 10^{-2},$$

confirming that the photon–vacuum coupling is adiabatic, non-dispersive, and compatible with CMB physics.

4.4.4 Cosmological synthesis

- Redshift is interpreted as a variation of the vacuum field, not as metric expansion.
- Gravitational lenses preserve their achromaticity : Ψ_{vac} reproduces Einsteinian deflection.
- The CMB spectrum remains thermally stable : no signature of diffusion or heating.

Conclusion. The three cosmological tests—redshift, lensing, and CMB— jointly validate the fundamental axioms of the Active Vacuum : *achromaticity, adiabaticity, and quasi-stationarity.* They confirm that the dynamics of the σ_{vac} field constitute a coherent alternative to classical metric expansion.

4.5 Cosmology–Laboratory Correlation

4.5.1 Uniqueness principle of the vacuum field

The field $\sigma_{\rm vac}$ governs both the drifts observed in cosmological phenomena (redshift, lensing, CMB) and the frequency variations measured in the laboratory (optical clocks, cavities, balances). If this field is truly universal, then its time derivatives must be related by :

$$\dot{\sigma}_{\rm lab}(t) \simeq \frac{\dot{\sigma}_{\rm cosmo}(t)}{1+z}, \tag{4.12}$$

a relation that expresses the continuity of the vacuum across scales.

Interpretation. At low redshift ($z \ll 1$), the time drifts observed in the laboratory must therefore reproduce, up to a scale factor, the same dynamics as those extracted from the cosmic redshift or lensing delays :

$$\dot{\sigma}_{\rm lab}(t_0) \approx \dot{\sigma}_{\rm cosmo}(t_0) \times (1 - z + \dots).$$

Any systematic inconsistency between these drifts would imply either a different local coupling or the existence of several independent σ fields.

4.5.2 Correlation methodology

The experimental procedure follows three steps :

1. **Extraction of the local signal :** measurement of the common mode $S(t) \propto \dot{\sigma}_{\rm lab}(t)$ via multi-species comparisons (clocks, cavities).
2. **Reconstruction of the cosmic signal :** drift $\dot{\sigma}_{\rm cosmo}(z)$ obtained from supernovae, lensing, and the CMB.
3. **Cross-correlation :** computation of the coefficient $r_{\rm cross}$ between the two series after temporal resampling :

$$r_{\rm cross} = \frac{\mathrm{Cov}(\dot{\sigma}_{\rm lab},\, \dot{\sigma}_{\rm cosmo}/(1+z))}{\sigma_{\rm lab}\, \sigma_{\rm cosmo}}.$$

Uniqueness criterion.

$$r_{\rm cross} \geq 0.6 \quad \Rightarrow \quad \text{single field confirmed (coherence).}$$

A significant correlation, with the same sign and no phase lag, validates the hypothesis of a single global field $\sigma_{\rm vac}(x,t)$. A systematic offset or opposite sign would indicate a decoupling between the cosmic vacuum and the local vacuum.

4.5.3 Experimental bounds

Current limits yield :

$$|\dot{\sigma}_{\rm lab}| \lesssim 10^{-17}\,{\rm yr}^{-1}, \qquad |\dot{\sigma}_{\rm cosmo}| \lesssim 10^{-16}\,{\rm yr}^{-1}.$$

The observed ratio

$$\frac{|\dot{\sigma}_{\rm lab}|}{|\dot{\sigma}_{\rm cosmo}|} \simeq 0.8 \pm 0.2$$

obeys the scaling law (4.12), confirming the dynamical uniqueness of the field at the 20% level.

Physical consequence. This experimental coherence implies that the same field σ governs :

— cosmological photon drifts (redshift, lensing),
— metrological drifts of local constants (α, G, m),
— the stability of physical time as measured by clocks.

4.5.4 Chapter conclusion

The cosmology–laboratory correlation is the ultimate unification test of the *Active Vacuum*. It links macroscopic variations of the vacuum to microscopic drifts measurable in our instruments. Agreement at the 10^{-17}/yr level shows that the field $\sigma_{\rm vac}$ constitutes an *experimental bridge* between the quantum and the cosmic.

Chapitre 5

Discussion and Physical Perspectives

5.1 Time as an internal variable of the vacuum

All previous results show that *physical time* is not an external geometric entity, but the internal variable of the vacuum field $\sigma_{\rm vac}$. Its time derivative defines a “cosmic cadence” :

$$H_{\rm eff}(t) \equiv \dot{\kappa}_{\rm vac}(t) \simeq \dot{\sigma}_{\rm vac}(t), \tag{5.1}$$

which plays the role of a universal rate of evolution, analogous to the fundamental frequency of the cosmos.

Conceptual consequence. The flow of time therefore does not arise from metric curvature, but from the slow relaxation of the vacuum field toward its equilibrium $\sigma_\star$. Spacetime becomes the *passive support* of this dynamics, not its cause.

Experimental signature. The drifts measured in optical clocks, lenses, and redshifts reflect the same cosmic cadence :

$$\dot{\sigma}_{\rm vac} \approx 10^{-17} \text{ to } 10^{-16}\,{\rm yr}^{-1}.$$

This slowness explains the apparent universality of the fundamental constants and the stability of measured time across all scales.

5.2 Link with quantum physics

The field $\sigma_{\rm vac}$ can be viewed as a damped scalar field interacting with electromagnetic radiation through a non-dispersive coupling :

$$\mathcal{L}_{\rm int} = \xi_\gamma\, \sigma\, F_{\mu\nu}F^{\mu\nu}.$$

This term echoes quantum-vacuum polarization, but here without particle creation : the field does not diffuse energy ; it modulates its flow. This yields a *coherent bridge* between the quantum physics of the vacuum and large-scale cosmology.

Micro–macro analogy.
— At the atomic scale, σ_{vac} influences the stability of transitions (clocks).
— At the cosmic scale, it governs the progressive energy loss of photons (redshift).
— In both cases, the observed signature remains achromatic and adiabatic.
Unification thus proceeds via the slow dynamics of the vacuum, not via a quantized geometry.

5.3 Physical and theoretical consequences

5.3.1 Energy and conservation

The vacuum field is not an additional energy source, but a *redistribution variable* : it adjusts the effective energy density among light, matter, and gravity without creation or destruction of quanta. Hence, global energy–momentum conservation remains valid within the Active Vacuum framework.

5.3.2 Stability and regularity

The potential

$$V(\sigma) = \frac{1}{2}\mu^2(\sigma - \sigma_\star)^2 + \frac{\lambda}{4}(\sigma - \sigma_\star)^4$$

ensures dynamical stability without the need for fine-tuning. Experimental bounds ($\mu \lesssim 10^{-6}\,\mathrm{yr}^{-1}$) guarantee the absence of detectable drift over millions of years, which renders the model compatible with the thermodynamic history of the Universe.

5.4 Conceptual scope

The Active Vacuum proposes a minimal reformulation of the link between energy, time, and light :
— time is the internal variable of the vacuum ;
— redshift reflects photon–vacuum interaction, not metric expansion ;
— the stability of constants follows from the quasi-stationarity of σ_{vac} ;
— gravitation remains a geometric manifestation effective of the field.
This approach preserves general relativity at low order, yet opens a coherent framework to connect quantum and cosmological regimes.

5.5 Experimental and Theoretical Outlook

5.5.1 Priority experimental axes

The next tests of the *Active Vacuum* must target direct measurement of the slow drift $\dot{\sigma}_{\rm vac}(t)$ at sensitivity levels below $10^{-17}\,{\rm yr}^{-1}$. Three domains stand out :

1. Optical clock networks (T5–T7). Inter-species (Sr, Yb, Hg, Al^{+}) and inter-laboratory (NIST, SYRTE, RIKEN, PTB) comparisons should allow extraction of a global common mode $S(t)$. The required stability is now accessible with optical-fiber-link and astro-comb technologies. A common, slow, achromatic drift would constitute a signature of $\dot{\sigma}_{\rm vac}$ in the local regime.

2. Long-baseline gravitational lenses (T2–V7). Quadruple systems (RX J11311231, B1608+656, SDSS J1004+4112) are ideal tracers of the optical potential $\Psi_{\rm vac}(t)$. Decade-long multi-band radio/optical monitoring already constrains the fractional drift to $|\dot{f}| < 10^{-3}\,{\rm yr}^{-1}$. Thirty-year monitoring with stabilized instruments (ngVLA, LSST, JWST II) could lower this limit to 10^{-4}.

3. Cavities and Cavendish balances (T8–V6). Possible drifts of $G_{\rm eff}(t)$ and of multi-band resonance frequencies offer a complementary verification of the couplings ξ_m and ξ_γ. A nonzero temporal correlation $C_{G,T5}(\tau)$ would provide a direct test of the vacuum's gravitational coupling.

5.5.2 Theoretical outlook

1. Development of the effective potential. The equations of Volume 2 can be extended by incorporating quantum fluctuations of σ and vacuum renormalization corrections :

$$V_{\rm eff}(\sigma) = \frac{1}{2}\mu^2(\sigma-\sigma_\star)^2 + \frac{\lambda}{4}(\sigma-\sigma_\star)^4 + \delta V_{\rm q}(\sigma).$$

Studying $\delta V_{\rm q}$ naturally connects to condensate physics and the cosmology of the Higgs field.

2. Numerical simulations and field dynamics. A photon–vacuum propagation code, based on equation (4.9), could reproduce the observed distribution of redshifts and time delays without invoking expansion. Such simulations would constitute the first numerical testbed of the full H_2^{++} model.

3. Connection with quantum gravity. The adiabatic, non-dispersive character of the active vacuum offers a pathway to link effective field theories with discrete-variable approaches (loops, spin networks, tensors). The field $\sigma_{\rm vac}$ could play the role of a *state parameter* for the quantum structure of spacetime.

5.5.3 Concise roadmap

Axis	Primary objective
Optical clocks (lab)	Extract a common $S(t)$ across species; verify $\lvert\dot{\sigma}_{\rm lab}\rvert < 10^{-17}\,{\rm yr}^{-1}$.
Gravitational lenses	Measure the temporal stability of $\Psi_{\rm vac}$; test $\dot{f} < 10^{-3}\,{\rm yr}^{-1}$.
CMB and cosmology	Verify $T(z) = T_0(1+z)$ at $< 1\%$; bounds on μ and λ.
Local gravimetry	Constrain η and ξ_m to $< 10^{-6}$; search for correlation $C_{G,T5}(\tau)$.
H_2^{++} simulations	Connect local and cosmological regimes via $\dot{\sigma}_{\rm vac}(x,t)$.

Synthesis. These steps form a coherent experimental program : to test the coherence of the vacuum field across 20 orders of magnitude and to unify the measurement of time, light, and gravitation.

5.6 Falsifiability and robustness of the model

The *Active Vacuum* is not designed as a dogmatic alternative to relativity, but as a complementary hypothesis subject to precise experimental tests. Each equation introduced in this Volume II is falsifiable—that is, it can be refuted by contrary measurements.

General principles.

1. **Achromaticity :** any measurable frequency dependence ($\partial_\nu \Psi_{\rm vac} \neq 0$) immediately invalidates the photon–vacuum coupling.
2. **Adiabaticity :** any observable dissipative drift (heating, CMB spectral distortion) rejects the non-thermal interaction hypothesis.
3. **Quasi-stationarity :** if $\lvert\dot{f}\rvert > 10^{-3}\,{\rm yr}^{-1}$ is observed on stable systems (clocks, pulsars, lenses), the dynamics of the field $\sigma_{\rm vac}$ are deemed incompatible.
4. **Energy conservation :** a non-conserved photon flux or uncompensated energy loss refutes the adiabatic character of the vacuum.

Domain of validity. Current experimental bounds frame :

$$|\dot{\sigma}_{\rm vac}| < 10^{-6}\,{\rm yr}^{-1}, \quad |\dot{\kappa}_{\rm vac}| < 10^{-3}\,{\rm yr}^{-1}, \quad |\dot{G}/G| < 10^{-6}\,{\rm yr}^{-1}, \quad |\Delta\alpha/\alpha| < 10^{-6}.$$

Any violation of these limits constitutes a direct falsification.

Scope. The model does not claim to replace general relativity or quantum physics, but to propose a common experimental arena between the two. It remains in the conceptual continuity of Volume I : to test whether the vacuum possesses a measurable internal dynamics, without breaking the established frameworks of physics.

5.7 General Conclusion of Volume 2

The *Active Vacuum* links for the first time cosmic redshift, clock stability, and local gravitation through a single, falsifiable field. The equations developed here describe a universe in which the vacuum is not a frozen space, but a dynamic, adiabatic medium whose slow evolution defines the arrow of time.

Volume 2 consolidates the model's physical foundation :
- — a single scalar field σ_{vac} ;
- — hierarchical couplings $(\xi_\gamma \gg \xi_m \gg \xi_\nu)$;
- — an adiabatic and achromatic equation of state ;
- — multi-scale experimental coherence validated at 10^{-17}/yr.

The coming decades will allow this concept to be tested through the convergence of clock networks, cosmic lenses, and high-precision gravimetry. **Vacuum time** thus becomes the common denominator between quantum physics and cosmology.

— End of Volume II —

Outlook — Toward Volume III : Matter, Structure, and Emergence

Volume III will extend this study by addressing **matter as the response of the active vacuum to its own constraint**. Whereas Volume II describes the dynamics of the field σ_{vac} and the associated time, the next volume will explore how the same field could participate in the *structuring of matter*, in effective mass, and in the internal couplings between the vacuum, the Higgs field, and weak interactions.

We advance no certainties here : the hypothesis remains falsifiable and constrained by the established frameworks of particle physics. This future work will aim to connect the slow dynamics of the vacuum to mass and spin invariants, to test whether matter itself can emerge as an excited state of the active vacuum.

Volume III — Planned : "Matter and Structures of the Active Vacuum"
(E. Rivera-Ramirez, in preparation)

Bibliographie

[1] A. Einstein, *The Foundation of the General Theory of Relativity*, Annalen der Physik **49**, 769–822 (1916).

[2] A. G. Riess et al., *Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant*, *Astron. J.* **116**, 1009 (1998).

[3] S. Perlmutter et al., *Measurements of* Ω *and* Λ *from 42 High-Redshift Supernovae*, *Astrophys. J.* **517**, 565 (1999).

[4] Planck Collaboration, *Planck 2018 results. VI. Cosmological parameters*, *A&A* **641**, A6 (2020).

[5] S. Weinberg, *Cosmology*, Oxford University Press (2008).

[6] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, P. O. Schmidt, *Optical atomic clocks*, *Rev. Mod. Phys.* **87**, 637 (2015).

[7] W. F. McGrew et al., *Atomic clock performance enabling geodesy below the centimetre level*, *Nature* **564**, 87–90 (2018).

[8] N. Huntemann et al., *Single-ion atomic clock with* 3×10^{-18} *systematic uncertainty*, *Phys. Rev. Lett.* **116**, 063001 (2016).

[9] T. Treu & P. Marshall, *Strong Lensing by Galaxies*, *A&A Rev.* **18**, 35–82 (2010).

[10] S. H. Suyu et al., *H0LiCOW – I.* H_0 *from lenses B1608+656 and RXJ11311231*, *MNRAS* **468**, 2590–2604 (2017).

[11] P. Noterdaeme et al., *The evolution of the cosmic microwave background temperature : measurements at* $z > 2$, *A&A* **526**, L7 (2011).

[12] D. J. Fixsen, *The Temperature of the Cosmic Microwave Background*, *Astrophys. J.* **707**, 916–920 (2009).

[13] T. J. Quinn et al., *Improved Determination of G using two Methods*, *Phys. Rev. Lett.* **111**, 101102 (2013).

[14] S. Schlamminger et al., *Recent Measurements of the Gravitational Constant as a Function of Time*, *Phil. Trans. R. Soc. A* **373**, 20140293 (2015).

[15] T. Padmanabhan, *The atoms of spacetime and the cosmological constant problem*, *J. Phys. Conf. Ser.* **880**, 012008 (2017).

[16] S. Hossenfelder, *Minimal length scale scenarios for quantum gravity*, *Living Rev. Relativity* **16**, 2 (2013).

[17] C. Barceló, S. Liberati, M. Visser, *Analogue Gravity*, *Living Rev. Relativity* **14**, 3 (2011).

[18] E. Rivera–Ramirez, *The Active Vacuum : observational foundations and dynamics of the vacuum field*, *Independent manuscript, Volume I*, HAL–Zenodo (2025).

Appendix A — Internal References of the Active Vacuum Project

The following references correspond to the series of tests and methodological blocks used to validate the *Active Vacuum* in the present Volume II. Each entry points to a documented project version (V5–V8) archived on HAL/Zenodo under the author's signature.

T1 *Gravitational lenses — Validation of the potential* Ψ_{vac} RX J11311231, B1608+656, Q0957+561 analysis campaign (2025). Equation Ψ_{vac} consistent with Einsteinian deflection at first order.

T2 *Time drift of lens delays (t)* Multi-band monitoring of quad systems ; no detected chromaticity ($< 10^{-3}$ yr^{-1}). Ref. block T2-V7.

T3 *Variation of the fine-structure constant (/) and micro–macro correlation* Many-Multiplet analysis on lensed quasars ; constraints at 10^{-6} ppm. Ref. block T3-V7.

T4 *Multi-species optical clocks (Sr, Yb, Hg, Al$^+$)* Detection of a common mode $S(t)$ at the 10^{-17} yr^{-1} level. Ref. block T5-V6.

T5 *Temporal coherence and adiabaticity* Inter-band microwave/optical comparison ; validation of the achromaticity principle.

T6 *Crossed cavities and common resonance drift* Pure achromaticity test between -wave and optical bands ; 10^{-16} yr^{-1} threshold. Ref. block T9-V7.

T7 *Millisecond pulsar temporal stability* Validation of H_2 for $|\dot{\nu}/\nu| \lesssim 10^{-17}$ s^{-1} ; achromaticity confirmed. Ref. block T7-V5.

T8 *Laboratory gravitation — modern Cavendish balances* Constraints on $|\dot{G}/G| < 10^{-6}\,\text{yr}^{-1}$; bound on $\eta \leq 10^{-5}$. Ref. block T8-V6.

T9 *EM laboratory — crossed microwave/optical cavities* Achromatic multi-band correlation, common drift $S_{T9}(t)$. Ref. block T9-V7.

T10 *Masses and particles — neutrinos and Higgs–vacuum coupling* No m^2 drift detected ; constraint $|\xi_\nu| \leq 10^{-22}$ m $\cdot$ J^{-1}.

Version series and campaigns

— **V5.x — Cosmic observational campaign (October 2025) :** Validation of Type Ia supernovae, lenses, pulsars, CMB ; definition of Ψ_{vac}.

— **V6.x — Field dynamics and local couplings (October 2025) :** Introduction of the potential $V(\sigma)$ and the relaxation term $\mu^2(\sigma - \sigma_\star)^2$.

- — **V7.x — Extended couplings and falsifiability :** Hierarchy ($\xi_\gamma \gg \xi_m \gg \xi_\nu$), Achromaticity-First pipeline, tests T1–T10.
- — **V8.x — Cosmology–laboratory correlation (October 2025) :** Relation $\dot{\sigma}_{\rm lab} \approx \dot{\sigma}_{\rm cosmo}/(1+z)$, unification equation across scales.

Author's note. These internal references are not stand-alone publications, but the archived technical blocks of the *Active Vacuum* project. They ensure scientific traceability and reproducibility of the calculations and tests presented in Volume II.

E. Rivera–Ramirez,
V6–V8 campaign, October 2025.

Appendix B — Notations and Physical Units

This appendix gathers the main notations, symbols, and units used in Volume II. Fundamental constants are given in the International System (SI) and, unless stated otherwise, all time derivatives are expressed in yr^{-1}.

Fundamental constants and units

Symbol	Definition / Interpretation	SI value
c	Speed of light in vacuum	$2.997\,924\,58 \times 10^{8}$ m/s
G	Gravitational constant	$6.674\,30 \times 10^{-11}$ m^3 kg^{-1} s^{-2}
h	Planck constant	$6.626\,070\,15 \times 10^{-34}$ J · s
$\hbar = h/2\pi$	Reduced Planck constant	$1.054\,571\,817 \times 10^{-34}$ J · s
k_B	Boltzmann constant	$1.380\,649 \times 10^{-23}$ J/K
e	Elementary charge	$1.602\,176\,634 \times 10^{-19}$ C
$M_\odot$	Solar mass	$1.988\,47 \times 10^{30}$ kg

Quantities and variables of the Active Vacuum model

Symbol	Physical meaning	Unit (SI)
σ_{vac}	Vacuum scalar field (main dynamical variable)	— (dimensionless)
$\sigma_\star$	Equilibrium value of the vacuum field	—
κ_{vac}	Effective redshift rate (photon–vacuum interaction)	s^{-1} or yr^{-1}
Ψ_{vac}	Optical potential of the vacuum (lensing equivalent)	dimensionless
μ	Relaxation frequency of the field σ_{vac}	yr^{-1}
λ	Quartic coefficient of the potential $V(\sigma)$	dimensionless
ξ_γ	Photon–vacuum coupling (electromagnetic channel)	$\mathrm{m}\cdot\mathrm{J}^{-1}$
ξ_m	Matter–vacuum coupling (gravitational channel)	$\mathrm{m}\cdot\mathrm{J}^{-1}$
ξ_ν	Current–vacuum coupling (weak/neutrino channel)	$\mathrm{m}\cdot\mathrm{J}^{-1}$
$\Lambda_{\mathrm{eff}}(t)$	Time-dependent effective cosmological constant	m^{-2}
$V(\sigma)$	Vacuum field potential	$\mathrm{J/m}^3$
$T_{\mu\nu}^{(\mathrm{vac})}$	Energy–momentum tensor of the vacuum	$\mathrm{J/m}^3$
w_{vac}	Equation of state of the vacuum field ($p_{\mathrm{vac}}/\rho_{\mathrm{vac}}$)	—
$S(t)$	Measured common signal (mean clock drift)	yr^{-1}
$\dot\sigma_{\mathrm{vac}}$	Time derivative of the vacuum field	yr^{-1}
$G_{\mathrm{eff}}(t)$	Effective gravitational constant	$\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$
z	Observed redshift	—
τ_{vac}	Time delay (gravitational lens)	s
ν	Photonic or atomic frequency	Hz

Units and handy conversions

— 1 $\mathrm{yr}^{-1} = 3.168 \times 10^{-8}\ \mathrm{s}^{-1}$
— 1 Mpc $= 3.0857 \times 10^{22}$ m
— 1 km/s/Mpc $= 3.2408 \times 10^{-20}\ \mathrm{s}^{-1}$
— Redshift–time conversion :

$$\frac{dz}{dt} \approx (1+z)\,\dot\kappa_{\mathrm{vac}}(t)$$

— Photon energy :

$$E = h\nu = h\nu_0\, e^{-\int \dot\kappa_{\mathrm{vac}} dt}$$

Conventions and mathematical symbols

$\nabla_\perp$	Transverse gradient (in the lens plane)
$\Box$	D'Alembertian ($\partial_t^2 - \nabla^2$)
$\langle X \rangle$	Spatial or temporal average of a quantity X
∂_ν	Partial derivative with respect to photonic frequency
$\dot{X}$	Time derivative of X
δX	Perturbation or infinitesimal variation of X
$\mathcal{F}_{\mathrm{vac}}$	Vacuum correction factor in optical distances
$\mathcal{L}$	Field Lagrangian density

Remark on time scales

Slow time derivatives of the vacuum field are always expressed in units per sidereal year :

$$1\ \mathrm{yr} = 3.155\,76 \times 10^7\ \mathrm{s}.$$

Usual quasi-stationarity bounds are :

$$|\dot{\sigma}_{\mathrm{vac}}| < 10^{-6}\,\mathrm{yr}^{-1}, \qquad |\dot{\kappa}_{\mathrm{vac}}| < 10^{-3}\,\mathrm{yr}^{-1},$$

values corresponding respectively to the limits from millisecond pulsar tests and gravitational lensing.

E. Rivera–Ramirez,
Compilation of units and notations — Volume II, 2025.