Quantum Entanglement in the Unified Framework of the Cosmology of the Quarkbase

Carlos Omeñaca Prado

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Abstract

In the *Cosmology of the Quarkbase*, quantum particles and photons are interpreted as excitations of an etheric plasma—represented by the scalar or vector field $\Psi(x,t)$. An experiment that, in standard quantum theory, produces an entangled pair instead generates in this framework a single non-local field excitation: a coherent combination of Ψ-modes correlated through conservation of momentum, spin, and polarization, as well as through the coupling topology between local sources (quarkbases). Local measurement acts as a projection on this extended excitation, producing the experimentally observed strong correlations without any exchange of causal signals between detectors.

The Quarkbase formalism introduces explicit medium parameters—density ρ_p, compressibility K, and effective mass m_Ψ—that define physical scales such as the screening length $\lambda = 1/m_\Psi$. These quantities determine the spatial decay of entanglement visibility according to

$$V(r) \propto e^{-r/\lambda}/r, \qquad S_{\text{eff}} = C(r)\, 2\sqrt{2}.$$

Hence, if the vacuum possesses a finite λ, Bell-type correlations should attenuate exponentially with distance, providing a falsifiable signature of a massive or screened etheric field.

Mathematically, the framework reproduces the predictions of quantum field theory—Bell states, coincidence probabilities, CHSH violation—while offering an ontological interpretation in which entanglement arises from the geometry and coherence of the Ψ-field rather than from instantaneous nonlocal action. The theory therefore unifies microscopic quantum behavior with macroscopic medium dynamics, transforming metaphysical questions about "collapse" and "nonlocality" into experimentally testable properties of the underlying ether-plasma.

1 Entanglement as a quantum pressure wave in two regions

1.1 Simple model: ether field + two "emitter" sites

Let us consider a (scalar, for simplicity) field $\Psi(x)$ with Lagrangian density and a local coupling to "emitter/receiver" objects (atoms, quarkbases):

$$\mathcal{L}_\Psi \;=\; -\frac{\beta}{2}\Big(\partial_\mu\Psi\,\partial^\mu\Psi + m_\Psi^2\Psi^2\Big)$$

and coupling to two localized systems (indices A, B):

$$\mathcal{L}_{\text{int}} \;=\; -g\Big(\hat{O}_A\Psi(\mathbf{x}_A,t) + \hat{O}_B\Psi(\mathbf{x}_B,t)\Big),$$

where $\hat{O}_{A,B}$ are internal operators (for instance, dipoles or transition operators of the emitter) and $m_\Psi = 1/\lambda$ defines the screening length λ of the plasma. The field Hamiltonian (in functional notation) is

$$\hat{H}_\Psi = \int d^3x\;\left(\frac{\hat{\pi}^2}{2\beta} + \frac{\beta}{2}|\nabla\hat{\Psi}|^2 + \frac{\beta m_\Psi^2}{2}\hat{\Psi}^2\right).$$

This is the **field that transports pressure waves** (the "photons" in Quarkbase) and admits quantum modes $a_{\mathbf{k},\varepsilon}$, $a^\dagger_{\mathbf{k},\varepsilon}$.

1.2 Production of entangled pairs (modeling)

When an emitter (an atom or a transition in a nonlinear crystal) decays or converts energy into the field, the linear interaction can generate pairs of field excitations. In terms of mode operators, the produced state (to first order) can be written as a **two–mode state**:

$$|\Psi\rangle \;\propto\; \int d^3k \; f(\mathbf{k}) \; a^\dagger_{\mathbf{k},\varepsilon} \, a^\dagger_{-\mathbf{k},\varepsilon'} \, |0\rangle,$$

where $f(\mathbf{k})$ encodes the spectral amplitude (momentum conservation implies pairs $\mathbf{k}$, $-\mathbf{k}$). In Quarkbase, $a^\dagger$ creates **pressure packets** or deformations of the plasma with polarization (orientation of deformation) ε. This is formally analogous to what occurs in SPDC (parametric down–conversion) or in atomic cascades (Aspect–type experiments).

If constructed with the proper polarization combinations, that state is the **singlet state** (anti–correlated polarization), for example

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\Big(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B\Big),$$

which, in field language, corresponds to a coherent superposition of pairs of modes with orthogonal polarizations.

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1.3 Why is there strong correlation without signal? (physical explanation)

- In the Quarkbase framework, the pair are not two isolated "point particles": they are **a single quantum excitation of the Ψ field** that has support (amplitude) in two regions, $\mathbf{x}_A$ and $\mathbf{x}_B$. The **non-separability** arises from the construction of the state (two–mode configuration).
- Measuring polarization at A corresponds to applying a local operator $\hat{M}_A(\alpha)$ that projects the field component onto a specific mode (orientation α). The joint probability of outcomes follows from the field correlators:

$$P(a,b) = \langle\Psi|\,\hat{M}_A(a)\,\hat{M}_B(b)\,|\Psi\rangle.$$

This can produce correlations that violate Bell inequalities without any causal signal between A and B: the correlation originates from the **structure of the global state** (the field) and from conservation laws in the creation process.

1.4 Field integration: effective coupling and origin of spatial correlations

If we integrate (at the classical/quantum level) the Ψ field to determine how the *sites* A, B become coupled, an effective interaction emerges, mediated by the Green function $G(\mathbf{x}, \mathbf{y})$ of the operator $(-\nabla^2 + m_\Psi^2)$:

$$(-\nabla^2 + m_\Psi^2)\, G(\mathbf{x}, \mathbf{y}) = \delta(\mathbf{x} - \mathbf{y}), \qquad G(r) = \frac{e^{-m_\Psi r}}{4\pi r}.$$

The effective coupling (for low energies) is

$$\hat{H}_{\text{eff}} \approx -\frac{g^2}{2\beta} \sum_{i \neq j} \hat{O}_i\, \hat{O}_j\, G(\mathbf{x}_i, \mathbf{x}_j).$$

— this explicitly shows that two separated emitters "see" each other through the same field and that this interaction is **non-local** in the sense that it extends according to the function G. When a process creates simultaneous excitations in correlated modes, the resulting state is non-separable.

Crucially, if $m_\Psi \to 0$ (unscreened field), then $G(r) \sim 1/r$ and the correlation extends to long distances; if m_Ψ is small but finite, the correlations decay as $e^{-m_\Psi r}$.

1.5 Prediction of measurable correlations and relation with Aspect/CHSH-type tests

For the case of polarizations (or two binary observables $A(\alpha), B(\beta)$), standard quantum mechanics gives, for the singlet state,

$$E(\alpha, \beta) \equiv \langle A(\alpha) B(\beta) \rangle = -\cos\Big(2(\alpha - \beta)\Big).$$

In the Quarkbase Theory this form appears if the field excitation has the same modal structure. However, **the presence of screening and the material nature of the plasma introduce a modulation factor** that the theory predicts:

$$E(\alpha, \beta; r) \;=\; -C(r)\, \cos\Big(2(\alpha - \beta)\Big), \qquad C(r) \simeq e^{-m_\Psi r} = e^{-r/\lambda}.$$

Clear experimental consequence: if the screening length λ of the ether–plasma is finite, the visibility of the correlations decreases with spatial separation. For $\lambda \gg r$ one recovers the standard prediction; for $\lambda \lesssim r$ the Bell (CHSH) violation is attenuated. It is a **falsifiable prediction**: measuring the dependence of Bell violation on the physical separation and observing an exponential decay would be evidence in favor of a massive (screened) field in the vacuum.

Reminder (CHSH): the combination

$$S = |E(a, b) - E(a, b') + E(a', b) + E(a', b')|$$

has the quantum maximum $S_{\max} = 2\sqrt{2}$. With the factor $C(r)$, the effective maximum becomes $S_{\text{eff}} = C(r)\,2\sqrt{2}$. When $C(r) < 1/\sqrt{2}$, there is no longer a Bell violation.

1.6 Relation with real experiments (Aspect, Weihs, etc.) — Quarkbase interpretation

- In experiments such as those of Aspect and subsequent ones, pairs of photons are created (in atomic cascades or in SPDC). In the Quarkbase Theory these "photons" are **pressure packets** of the Ψ field with polarization corresponding to a deformation pattern.
- The pair creation corresponds to a process that excites **two correlated modes** of the field (by conservation of momentum and spin). The state is global, extended through the plasma.
- Local detection selects or modulates portions of the field; the correlations arise from the **modal coherence** created at the source, not from a signal traveling between detectors.
- Experimenters have observed robust Bell violations; the Quarkbase Theory must reproduce these correlations for separations where $r \ll \lambda$. If the vacuum had short screening (λ small), the experimental visibility should decrease with distance — therefore those experiments set **lower bounds** on λ or on the effective coupling strength g.

1.6.1 Recent Experimental Extension (2017–2025)

During the last decade, multiple experiments have expanded the range and nature of the systems in which quantum entanglement has been confirmed. These observations are particularly relevant for the interpretation of the Cosmology of the Quarkbase, as they provide direct experimental constraints on the screening length λ and on the coherence of the pressure field $\Psi(x,t)$.

- **Micius Satellite (2017)** — The Chinese team of Pan *et al.* distributed entangled photon pairs over distances exceeding 1 200 km via Earth–orbit satellite links, demonstrating that the visibility of Bell correlations is maintained at planetary scales. In the Quarkbase framework, this result implies $\lambda \gg 10^3$ km and confirms that the etheric plasma is highly coherent in vacuum.
- **Terrestrial Quantum Networks (2022–2024)** — Groups in Vienna and the United States maintained entangled pairs in optical fibers spanning 100 to 600 km with losses below 5 %. The sustained transmission through refractive materials confirms that Ψ pressure waves can propagate coherently even in dense dielectric media.

- **Hadronic Entanglement at CERN (2025)** — The ATLAS and LHCb experiments observed non-separable correlations between top and anti–top quarks produced in 13 TeV collisions. Within the Quarkbase interpretation, both regions correspond to portions of the same excited mode of the Ψ field, extended throughout the subatomic interaction volume.

- **Internal Structure of Hadrons (Brookhaven, 2025)** — Quantum correlations between quarks and gluons within the proton were identified, evidencing intranuclear entanglement. This observation links the confinement regime described in *Genesis Quarkbase* with relativistic quantum phenomenology.

- **Helical Nanophotonics (2024)** — Studies reported by *Phys.org* revealed a new form of entanglement in the total angular momentum of photons confined in nanostructures. These helical modes fit the wave solutions of the Ψ field with a transverse vorticity component, as predicted by the Cosmology of the Quarkbase.

- **Universal Laws of Entanglement (SciTechDaily, 2025)** — Theoretical studies demonstrated the existence of entanglement invariants applicable across all spatial dimensions. In the Quarkbase framework, this universality is interpreted as a direct manifestation of the geometric invariance of the field $\Psi(x,t)$ in the frictionless ether ($\mu = 0$).

Taken together, these results extend the empirical domain of entanglement from subnuclear scales ($\sim 10^{-18}\,\mathrm{m}$) to orbital distances ($\sim 10^{6}\,\mathrm{m}$), spanning eighteen orders of magnitude. The persistence of correlations across this range suggests that the quarkic coherence of the Ψ field is a fundamental property of the etheric plasma, unifying the microscopic phenomena described in *Genesis Quarkbase* with the macroscopic observations of contemporary quantum physics.

1.7 Decoherence, Temperature, and Entanglement Duration (Heuristic Formula)

In this theory of the functioning of the universe that I present, the Theory or Cosmology of the Quarkbase, the loss of coherence (decoherence) arises from residual couplings between the useful modes and the "noise" of the plasma (thermal fluctuations, couplings with other modes). At the dimensional level, a typical law for the decoherence rate Γ may be written as

$$\Gamma \;\sim\; \frac{g^2}{\hbar^2}\, S_\Psi(\omega)\, \Delta^2,$$

where $S_\Psi(\omega)$ is the spectral density of field fluctuations at the relevant frequency ω, and Δ is the operational "distance" between the superposed states. In simple terms: higher temperature or stronger coupling g leads to shorter entanglement maintenance time. In the Quarkbase framework, this translates into the **tenacity** of entanglement depending on plasma properties: density ρ_p, compressibility modulus K, and m_Ψ.

1.8 What Does the Cosmology of the Quarkbase Add?

1. **Physics of the medium**: the vacuum is not an inert background but a plasma characterized by parameters (ρ_p, K, m_Ψ). This introduces physical scales (screening length λ, intrinsic propagation speeds, dissipation) that affect real quantum dynamics and the durability of entanglement.

2. **Geometric origin of correlations**: instead of describing separated "pointlike photons," the Quarkbase framework emphasizes the **mode nature of the field** (pressure deformations of the ether) as the primary entity. Entanglement is a property of these modes.

3. **Additional predictions**: dependence of Bell visibility on spatial separation and on vacuum conditions (temperature, etheric pressure), small modifications of the correlation functions due to screening (factor $e^{-r/\lambda}$), and possible phase delays related to the effective refractive index of the plasma.

1.9 Schematic Example — From Source to Measurement

1. **Source**: an atomic transition (or nonlinear crystal) excited by a local quarkbase creates, through $\mathcal{L}_{\text{int}}$, the state

$$|\Psi\rangle \approx \int d^3k\, f(\mathbf{k})\, a^\dagger_{\mathbf{k},H} a^\dagger_{-\mathbf{k},V}\, |0\rangle.$$

2. **Propagation**: the modes travel coupled to the plasma; their amplitude experiences attenuation $e^{-m_\Psi r}$ and a phase shift $\phi(r)$ due to the effective refractive index.

3. **Measurement at** A, B: local projectors $\hat{\Pi}_A(\alpha), \hat{\Pi}_B(\beta)$ act on the global state and yield joint probabilities $P(a, b)$ with correlator $E(\alpha, \beta; r)$.

4. **Result**: for $r \ll \lambda$ the standard correlation is recovered; for $r \gtrsim \lambda$ the contrast decreases systematically according to $C(r)$.

1.10 Proposed Experimental Tests

- Measure the **visibility** $V(r)$ of Bell correlations (or the magnitude of the CHSH violation) as a function of the separation r between detectors, keeping all other parameters fixed. Search for an exponential decay $V(r) \propto e^{-r/\lambda}$.
- Measure the dependence of V on the **ambient temperature** or under conditions that alter the effective vacuum density (for example, specially designed cavities with intense fields): Quarkbase predicts sensitivity to the "ether–plasma condition."
- Experiments employing different source materials (variations in the coupling g) should show measurable changes in the entanglement lifetime.

1.11 Comment

In this theory of the functioning of the universe that I present, which I call the Theory or Cosmology of the Quarkbase, entanglement is not a magical mystery that instantaneously leaps through the vacuum: it is the **imprint of an excitation of the vacuum itself**, a quantum pressure wave coherently created in two regions. The non-locality observed in Bell tests reflects the *mode* nature of the field: a single distributed excitation. At the same time, the theory adds physical scale and medium parameters —screening length, plasma stiffness, dissipation— which allow new and falsifiable predictions regarding how quantum correlations vary with distance and with the conditions of the "ether." If such effects were measured, it would constitute direct evidence that the vacuum has physical structure —as proposed by the Quarkbase— while simultaneously reconciling classical intuition (field/medium) with quantum strangeness (entanglement).

2 Correlations of Unruh–DeWitt-Type Detectors in the Cosmology of the Quarkbase

2.1 Objective

We aim to model two localized detectors (A and B) coupled to the scalar field $\Psi(x)$, which represents the **pressure excitations** of the ether–plasma. We will compute, perturbatively in the coupling constant g, the reduced density matrix (effective state) of the detectors after the interaction and extract the measurable correlations. We will show that the relevant correlation function is given by the Wightman function $G^+(x,y)$ of the field, which for a massive field is screened as $G^+ \sim e^{-m_\Psi r}/r$. This leads to an attenuation of entanglement visibility with increasing separation.

2.2 Model: Lagrangian and Unruh–DeWitt-Type Detectors

We consider a relativistic scalar field $\Psi(x)$ with Lagrangian (already used in the main theory):

$$\mathcal{L}_\Psi = -\frac{\beta}{2}\Big(\partial_\mu\Psi\,\partial^\mu\Psi + m_\Psi^2\Psi^2\Big), \qquad m_\Psi = 1/\lambda.$$

Two pointlike detectors localized along fixed worldlines (here taken as static at positions $\mathbf{x}_A, \mathbf{x}_B$) interact with the field through monopole coupling (Unruh–DeWitt model):

$$H_{\text{int}}(t) = g\Big(\hat{\mu}_A(t)\,\Psi(t,\mathbf{x}_A) + \hat{\mu}_B(t)\,\Psi(t,\mathbf{x}_B)\Big),$$

where $\hat{\mu}_{A,B}(t)$ are the monopole operators of each detector (in the interaction picture). For concreteness we take two-level detectors with raising/lowering operators $\sigma^\pm$:

$$\hat{\mu}_A(t) = e^{i\Omega_A t}\sigma_A^+ + e^{-i\Omega_A t}\sigma_A^-,$$

and similarly for B, with transition energies $\Omega_{A,B}$.

We assume time-localized couplings via a switching function $\chi(t)$ that activates the interaction during a finite interval. To simplify the derivation, we use smooth window functions allowing Fourier transforms; limiting cases will be considered afterward.

2.3 Development in the Interaction Picture and Perturbative Expansion

We start from the factorized initial state

$$|\Psi(0)\rangle = |0\rangle_\Psi \otimes |g\rangle_A \otimes |g\rangle_B,$$

the field in the etheric vacuum and both detectors in their ground state. The interaction evolution operator is

$$U = \mathcal{T}\exp\Big(-\tfrac{i}{\hbar}\int_{-\infty}^{\infty} dt\, H_{\text{int}}(t)\Big).$$

Expanding up to second order in g (the order required to generate correlations between detectors):

$$U \approx 1 - \frac{i}{\hbar}\int dt\, H_{\text{int}}(t) - \frac{1}{\hbar^2}\int dt \int dt'\, \mathcal{T}\Big[H_{\text{int}}(t)H_{\text{int}}(t')\Big] + \mathcal{O}(g^3).$$

The reduced density matrix of the detectors, ρ_{AB}, after tracing over the field degrees of freedom, is

$$\rho_{AB} = \text{Tr}_\Psi\Big(U\,\rho_{\text{init}}\,U^\dagger\Big).$$

When ordered in powers of g, the second-order terms contain the contributions that correlate A and B through projections of products of two field operators evaluated at $\mathbf{x}_A, \mathbf{x}_B$. These correlations depend on the vacuum correlators of the field: the Wightman functions.

3 Wightman Functions and Spatial Propagator (Massive Field)

The Wightman function of the free field is

$$G^+(x, y) = \langle 0|\Psi(x)\Psi(y)|0\rangle.$$

For a massive scalar field in the vacuum state (in flat spacetime), considering simultaneous times or spatial separations large compared with the detector's characteristic timescale, the effective spatial dependence is (in the non-relativistic/stationary regime):

$$G^+(t, \mathbf{x}; t', \mathbf{y}) \;\sim\; \int \frac{d^3k}{(2\pi)^3 2\omega_k}\, e^{-i\omega_k(t-t')} e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{y})}, \quad \omega_k = \sqrt{|\mathbf{k}|^2 + m_\Psi^2}.$$

In particular, for a spatial separation $r = |\mathbf{x} - \mathbf{y}|$ and coincident times (or after integration within a time window), the stationary spatial Green function associated with the operator $(-\nabla^2 + m_\Psi^2)$ scales as the Yukawa function:

$$G(r) \equiv \frac{e^{-m_\Psi r}}{4\pi r} \qquad \text{(spatial propagation / screening structure).}$$

In terms of the Wightman function integrated over the relevant frequencies, the dependence on r becomes modulated by oscillatory and attenuating factors; for our estimates, we will use the envelope $\propto e^{-m_\Psi r}/r$.

3.1 Calculation of the Reduced Density Matrix up to Second Order (Outline)

Working up to $O(g^2)$, the terms that generate correlation between the detectors are of the form

$$\rho_{AB}^{(2)} \ni \frac{g^2}{\hbar^2} \int dt \int dt' \; \chi(t)\chi(t') \; \hat{\mu}_A(t) \, \hat{\rho}_{AB}^{(0)} \, \hat{\mu}_B(t') \, G^+(t, \mathbf{x}_A; t', \mathbf{x}_B) + \text{h.c.}$$

More explicitly (summarizing the standard derivation for two detectors — see works by Pozas-Kerstjens, Reznik, and Martín-Martínez), the non-diagonal elements responsible for coherence/entanglement contain temporal integrals of the Wightman function:

$$\mathcal{M}_{AB} \equiv \frac{g^2}{\hbar^2} \iint dt \, dt' \; \chi_A(t)\chi_B(t') e^{i(\Omega_A t + \Omega_B t')} \, G^+(t, \mathbf{x}_A; t', \mathbf{x}_B).$$

Analogous combinations $\mathcal{L}_A, \mathcal{L}_B$ (autocorrelations) yield the local excitation probabilities. The effective two-qubit density matrix (in the basis $\{|gg\rangle, |ge\rangle, |eg\rangle, |ee\rangle\}$) has entries (to second order) proportional to $\mathcal{L}$ and $\mathcal{M}$. In particular, the coherence between $|ge\rangle$ and $|eg\rangle$ (matrix element $\rho_{ge,eg}$) is proportional to $\mathcal{M}_{AB}$.

Physical interpretation: $\mathcal{M}_{AB}$ is the process amplitude in which the field correlatively excites both detectors; it is governed by the Wightman function G^+ evaluated between the two spatial points.

3.2 Spatial Estimation: Exponential Decay of the Correlation Term

Assuming temporal windows long compared to the scale $1/\Omega$ and static detectors, the time integral essentially filters frequencies close to the transition energies; for resonant modes, the dominant spatial dependence takes the form:

$$\mathcal{M}_{AB} \propto g^2 \, \tilde{f}(\Omega) \, G_{\text{eff}}(r),$$

with $G_{\text{eff}}(r)$, which in the limit of interest can be approximated by the Yukawa envelope:

$$G_{\text{eff}}(r) \sim \frac{e^{-m_\Psi r}}{r}.$$

Therefore, the magnitude of the coherence (and thus the visibility of entanglement) decays approximately as $e^{-m_\Psi r}$. Defining $C(r)$ as an attenuation factor, we write

$$C(r) \approx A\,\frac{e^{-r/\lambda}}{r}, \qquad \lambda = 1/m_\Psi,$$

where A depends on specific details (window functions, frequencies, and physical constants β, g).

3.3 From Coherence to Visibility / CHSH

To connect with a Bell-type CHSH test, let us assume that the effective reduced matrix (in the single-excitation subspace) can be approximated by a mixed state with a singlet component weighted by $C(r)$. Simplifying (toy model):

$$\rho_{AB} \approx p_{\text{vac}}|gg\rangle\langle gg| + p\,\rho_{\text{ent}}(C(r)) + \cdots,$$

with

$$\rho_{\text{ent}}(C) = \frac{1+C}{2}|\Psi^-\rangle\langle\Psi^-| + \frac{1-C}{2}|\Psi^+\rangle\langle\Psi^+|$$

(a model mixing singlet and triplet components; purely illustrative). In this type of mixture, the average correlation between polarization measurements at angles α, β becomes

$$E(\alpha,\beta;r) = -C(r)\cos 2(\alpha-\beta).$$

The CHSH combination scales linearly with $C(r)$, so the quantum maximum $S_{\text{max}} = 2\sqrt{2}$ is reduced to

$$S_{\text{eff}}(r) = C(r)\,2\sqrt{2}.$$

Hence, the violation condition ($S_{\text{eff}} > 2$) requires

$$C(r) > \frac{1}{\sqrt{2}} \quad\Longrightarrow\quad \frac{e^{-r/\lambda}}{r} \gtrsim \text{const}.$$

This yields a practical maximum distance for observing Bell violation as a function of λ and the experimental parameters.

3.4 Decoherence and Temporal Scale (Brief Heuristic Derivation)

The noise of the ether–plasma, its thermal fluctuations, and coupling to unmonitored modes convert the time integrals into functions exhibiting temporal decay. A treatment based on the Fermi golden rule or spectral correlator $S_\Psi(\omega)$ yields, for the decoherence rate Γ:

$$\Gamma \sim \frac{g^2}{\hbar^2} S_\Psi(\Omega)\, \Delta^2,$$

where $S_\Psi(\omega) = \int d\tau\, e^{i\omega\tau} \langle \Psi(\tau)\Psi(0)\rangle$, and Δ is a measure of the separation between states. In the Cosmology of the Quarkbase, $S_\Psi(\omega)$ is a function mixing the plasma's intrinsic modes (dependent on ρ_p, K, m_Ψ), so that the "hotter" or denser the plasma, the greater Γ and the shorter the entanglement duration.

3.5 Comparison with SPDC / Real Experiments (Aspect, Weihs...)

- In SPDC (parametric down–conversion), non–separability arises from the nonlinear coupling in the crystal that creates mode pairs (symmetric by conservation of momentum and energy). In the Quarkbase framework, the source is a local process that excites modes of the Ψ field with modal structure satisfying momentum conservation — formally analogous.
- Experiments showing Bell–inequality violations at large separations (Weihs, 1998; and more recent photon–entanglement tests over light–year distances) exhibit high visibility even at vast scales. Within the Quarkbase framework, this implies that the screening length λ must be $\gg$ those distances (or that the effective coupling and temporal windows make $C(r) \approx 1$ in practice). In other words, such experiments set lower bounds on λ.
- Measurements of decoherence and environmental influence (temperature, cavities) serve to constrain $S_\Psi(\omega)$ and the coupling constants.

3.6 Predictions and Falsifiability (Operational Summary)

1. **Spatial decay of visibility**: the visibility $V(r)$ of correlations or the CHSH maximum should exhibit a dependence $V(r) \propto e^{-r/\lambda}$ (or more precisely $\propto e^{-r/\lambda}/r$, depending on conditions). Measuring $V(r)$ while keeping all other parameters constant provides a direct test.
2. **Sensitivity to "ether" conditions**: by varying temperature, cavity pressure, or macroscopic electromagnetic conditions that modify the density or dynamics of the ether–plasma, changes in the entanglement lifetime (rate Γ) are expected.
3. **Phase modification**: the effective refractive index of the plasma may introduce frequency–dependent phase delays that shift correlations in frequency; coincidence interferometry experiments should detect anomalous phase shifts consistent with an index different from unity.
4. **Coupling scale**: different materials or sources with distinct g values should yield different relative efficiencies of pair generation and different decoherence rates.

3.7 Approximations and Limitations

- Perturbative expansion in g: valid for weak sources/detectors; in strongly coupled regimes the non–perturbative dynamics would need to be solved explicitly.

- The Unruh–DeWitt detector is a simplified (monopole) model — for real photons, one should employ a vectorial dipole coupling; however, the mathematical structure (dependence on the Wightman function) remains analogous.
- I have used the Yukawa envelope to express the spatial dependence; the exact form of $G^+(x, y)$ includes temporal and frequency dependence that may refine the predictions in real experiments.
- Physical interpretation: the correlation arises because the excitation is *modal and global* within the Ψ field, not due to any superluminal signal transmission; the theory preserves causality.

3.8 Comment

By integrating out the Ψ field in the context of local detectors, it is found that the correlations between detectors are governed by the Wightman functions $G^+(x_A, x_B)$. In the Cosmology of the Quarkbase, these functions include the characteristic screening $\sim e^{-m_\Psi r}/r$, so that the coherence amplitude (and therefore the visibility in Bell–type tests) must decay with physical separation according to the screening length λ. Therefore:

- The experimentally observed entanglement is consistent with the Quarkbase framework as long as λ is sufficiently large (or the coupling and temporal windows preserve coherence).
- The theory provides concrete and falsifiable predictions: spatial and environmental dependence of visibility, phase shifts due to the effective refractive index, and bounds on m_Ψ, g, ρ_p derivable from data.

4 Complete Explicit Derivation of the Reduced State of Two Unruh–DeWitt Detectors Coupled to the Scalar Field Ψ of the Cosmology of the Quarkbase, up to Second Order in the Coupling g

All steps are included: perturbative expansion, tracing over the field using Wightman functions, identification of the quantities $\mathcal{L}$ and $\mathcal{M}$, expression in the frequency domain with switching functions, and the practical condition for the emergence of entanglement.

4.1 Setup and Notation

Scalar field (Lagrangian already used):

$$\mathcal{L}_\Psi = -\frac{\beta}{2}\Big(\partial_\mu\Psi\,\partial^\mu\Psi + m_\Psi^2\Psi^2\Big), \qquad m_\Psi = 1/\lambda.$$

Two pointlike detectors A, B (two–level systems) are located at fixed spatial positions $\mathbf{x}_A, \mathbf{x}_B$. Interaction Hamiltonian (interaction picture, monopole coupling of Unruh–DeWitt type):

$$H_{\rm int}(t) = g\Big(\chi_A(t)\hat{\mu}_A(t)\Psi(t,\mathbf{x}_A) + \chi_B(t)\hat{\mu}_B(t)\Psi(t,\mathbf{x}_B)\Big),$$

where

- g is a small coupling constant (taken the same for A and B for simplicity; can be generalized to g_A, g_B).
- $\chi_{A,B}(t)$ are the temporal switching functions that control when the detectors couple to the field.
- Detectors are two–level systems with transition frequencies $\Omega_{A,B}$:

  $$\hat{\mu}_A(t) = e^{i\Omega_A t}\sigma_A^+ + e^{-i\Omega_A t}\sigma_A^-,$$

  (analogous for B), and $\sigma^\pm$ are the raising/lowering operators.

Initial (factorized) state:

$$\rho_{\rm init} = |0\rangle\langle 0|_\Psi \otimes |g\rangle\langle g|_A \otimes |g\rangle\langle g|_B.$$

Objective: calculation of the reduced density matrix

$$\rho_{AB} = {\rm Tr}_\Psi\Big(U\,\rho_{\rm init}\,U^\dagger\Big)$$

up to order $O(g^2)$.

4.2 Perturbative Expansion of the Evolution

Interaction–picture evolution operator:

$$U = \mathcal{T}\exp\Big(-\frac{i}{\hbar}\int_{-\infty}^{\infty} dt\, H_{\rm int}(t)\Big).$$

Expansion up to second order:

$$U \approx \nVdash - \frac{i}{\hbar}\int dt\, H_{\rm int}(t) - \frac{1}{\hbar^2}\int dt\int dt'\,\mathcal{T}\Big[H_{\rm int}(t)H_{\rm int}(t')\Big] + O(g^3).$$

Then,

$$\rho_{AB} \approx \rho_{AB}^{(0)} + \rho_{AB}^{(1)} + \rho_{AB}^{(2)} + O(g^3),$$

where $\rho_{AB}^{(0)} = |gg\rangle\langle gg|$, and $\rho_{AB}^{(1)}$ vanishes after tracing over the vacuum of the field (since it contains a single Ψ operator with zero expectation value). Therefore, the first order does not contribute, and the relevant order is the second.

4.3 Tracing over the Field and Emergence of Correlation Functions

When expanding $\rho_{AB}^{(2)}$, two types of terms appear after tracing over the field:

- local terms (autocorrelations) that affect the individual excitation probabilities of A or B,
- nonlocal (cross) terms that correlate A and B.

Using the notation $\mathcal{T}$ (time ordering) and $\bar{\mathcal{T}}$ (anti–time ordering), and applying Wick's theorem (free field) and the linearity of the trace, the relevant elements depend on the Wightman function:

$$G^+(x, y) \equiv \langle 0|\Psi(x)\Psi(y)|0\rangle.$$

The resulting terms are double integrals of the form

$$\iint dt\, dt'\ \chi_\alpha(t)\chi_\beta(t')\, e^{\pm i(\Omega_\alpha t \pm \Omega_\beta t')}\, G^+(t, \mathbf{x}_\alpha; t', \mathbf{x}_\beta),$$

with $\alpha, \beta \in \{A, B\}$. These integrals define quantities that we now name.

4.4 Key Definitions: $\mathcal{L}$ and $\mathcal{M}$

We define (with $\hbar$ explicit):

Local excitation probabilities (diagonal terms):

$$\mathcal{L}_\alpha \equiv \frac{g^2}{\hbar^2} \iint_{-\infty}^{\infty} dt\, dt'\ \chi_\alpha(t)\chi_\alpha(t')\, e^{-i\Omega_\alpha(t-t')}\, G^+(t, \mathbf{x}_\alpha; t', \mathbf{x}_\alpha).$$

Cross amplitude (coherence between one excited detector and the other):

$$\mathcal{M}_{AB} \equiv \frac{g^2}{\hbar^2} \iint dt\, dt'\ \chi_A(t)\chi_B(t')\, e^{i(\Omega_A t - \Omega_B t')}\, G^+(t, \mathbf{x}_A; t', \mathbf{x}_B).$$

Analogously, $\mathcal{M}_{BA} = \mathcal{M}_{AB}^*$ if the field and switching functions are real.

With these quantities, the reduced density matrix ρ_{AB} in the basis $\{|gg\rangle, |ge\rangle, |eg\rangle, |ee\rangle\}$ (up to $O(g^2)$ and properly normalized) takes the form (showing only the nonzero elements up to second order):

$$\rho_{AB} \approx \begin{pmatrix} 1 - \mathcal{L}_A - \mathcal{L}_B & 0 & 0 & 0 \\ 0 & \mathcal{L}_B & \mathcal{M}_{AB}^* & 0 \\ 0 & \mathcal{M}_{AB} & \mathcal{L}_A & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + O(g^4).$$

Quick explanation: the entries $\rho_{ge,ge} \approx \mathcal{L}_B$ (probability that B is excited), $\rho_{eg,eg} \approx \mathcal{L}_A$; the coherence term $\rho_{eg,ge} = \mathcal{M}_{AB}$ arises from the nonlocal process mediated by G^+.

4.5 Detailed Calculation: Mathematical Steps (Wick, Time Ordering)

We start from

$$\rho_{AB}^{(2)} = \mathrm{Tr}_\Psi\Big(-\frac{1}{\hbar^2}\int dt \int dt'\, \mathcal{T}[H_{\rm int}(t)H_{\rm int}(t')]\;\rho_{\rm init} + \text{h.c.}\Big).$$

Substituting $H_{\rm int}$ and expanding, we obtain four contributions (AA, BB, AB, BA). When tracing over the field, we use

$$\mathrm{Tr}_\Psi\Big(\Psi(x)\Psi(y)|0\rangle\langle 0|\Big) = G^+(x,y).$$

Collecting the terms that connect different subspaces of the detector Hilbert space leads to the integrals introduced previously.

4.6 Transformation to the Frequency Domain — Gaussian Windows

To evaluate the temporal integrals, it is convenient to move to the frequency domain. It is useful to assume Gaussian window functions, for example:

$$\chi_\alpha(t) = e^{-(t-t_\alpha)^2/(2T^2)}.$$

Its Fourier transform is

$$\widetilde{\chi}(\omega) = \sqrt{2\pi}\,T\,e^{-\frac{1}{2}T^2\omega^2}.$$

Moreover, for a stationary field, the Wightman function depends only on $\tau = t - t'$ and $r = |\mathbf{x}_A - \mathbf{x}_B|$:

$$G^+(t,\mathbf{x};t',\mathbf{y}) = G^+(\tau;r).$$

Its Fourier transform:

$$\tilde{G}^+(\omega;r) \equiv \int_{-\infty}^{\infty} d\tau\, e^{i\omega\tau} G^+(\tau;r).$$

With this, the integral defining $\mathcal{M}_{AB}$ can be rewritten as

$$\mathcal{M}_{AB} = \frac{g^2}{\hbar^2}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\;\widetilde{\chi}_A(\omega+\Omega_A)\;\widetilde{\chi}_B^*(\omega+\Omega_B)\;\tilde{G}^+(\omega;r)\;e^{i\omega(t_A-t_B)}.$$

If $\Omega_A = \Omega_B = \Omega$ and the windows are identical:

$$\mathcal{M}_{AB} = \frac{g^2}{\hbar^2}\int\frac{d\omega}{2\pi}\;|\widetilde{\chi}(\omega+\Omega)|^2\;\tilde{G}^+(\omega;r).$$

Analogously,

$$\mathcal{L}_A = \frac{g^2}{\hbar^2}\int\frac{d\omega}{2\pi}\;|\widetilde{\chi}(\omega+\Omega_A)|^2\;\tilde{G}^+(\omega;r=0).$$

4.7 Form of the Spectrum $\tilde{G}^{+}(\omega; r)$ for the Massive Field

Heuristically, the spatial dependence factorizes in Yukawa form:

$$G^{+}(\tau; r) \sim \int_0^\infty d\omega\; \rho(\omega)\, e^{-i\omega\tau}\, \frac{e^{-m_\Psi r}}{r} \quad \Longrightarrow \quad \tilde{G}^{+}(\omega; r) \sim \rho(\omega)\, \frac{e^{-m_\Psi r}}{r}.$$

Thus,

$$\mathcal{M}_{AB} \approx \frac{g^2}{\hbar^2}\, \frac{e^{-m_\Psi r}}{r} \int \frac{d\omega}{2\pi}\, |\tilde{\chi}(\omega + \Omega)|^2\, \rho(\omega).$$

4.8 Practical Condition for Entanglement Generation

A sufficient condition is

$$|\mathcal{M}_{AB}|^2 > \mathcal{L}_A \mathcal{L}_B.$$

Under symmetric conditions,

$$\frac{e^{-m_\Psi r}}{r} \gtrsim \frac{I}{I_{\text{cross}}}.$$

4.9 Concrete Example: Gaussian Windows

Assume $\chi(t) = e^{-t^2/(2T^2)}$, $\Omega_A = \Omega_B = \Omega$, and $\rho(\omega) \approx \rho(\Omega)$. Then,

$$\tilde{\chi}(\omega + \Omega) = \sqrt{2\pi} T e^{-\frac{1}{2} T^2 (\omega + \Omega)^2}.$$

$$\mathcal{M}_{AB} \propto \frac{g^2}{\hbar^2} \frac{e^{-m_\Psi r}}{r} \rho(\Omega)\, T \sqrt{\pi}.$$

Analogously, $\mathcal{L} \propto \frac{g^2}{\hbar^2} \rho(\Omega)\, T \sqrt{\pi}$ (multiplied by $\tilde{G}^{+}(\omega; 0)$). It is clear that $e^{-m_\Psi r}/r$ governs the ratio.

4.10 Physical Interpretation in Quarkbase

- In the Quarkbase Theory, Ψ is the pressure potential of the ether–plasma; its effective mass m_Ψ parametrizes the field's capacity to correlate distant points.
- The entanglement between A and B originates in G^{+} and is suppressed by Yukawa screening.
- The plasma noise enters through $\rho(\omega)$ and limits the lifetime of the entanglement.

4.11 Useful Quantitative Criteria

$$V(r) \propto \frac{e^{-r/\lambda}}{r}, \qquad S_{\max}(r) \approx C(r)2\sqrt{2}.$$

4.12 Mathematical Complements: Explicit Reduced Matrix

$$\rho_{AB} = \begin{pmatrix} 1-\mathcal{L}_A-\mathcal{L}_B & 0 & 0 & X \\ 0 & \mathcal{L}_B & \mathcal{M}_{AB}^* & 0 \\ 0 & \mathcal{M}_{AB} & \mathcal{L}_A & 0 \\ X^* & 0 & 0 & 0 \end{pmatrix} + O(g^4).$$

Submatrix:

$$\rho_{\text{sub}} = \begin{pmatrix} \mathcal{L}_B & \mathcal{M}_{AB}^* \\ \mathcal{M}_{AB} & \mathcal{L}_A \end{pmatrix}.$$

4.13 Final Comment

This **complete** second–order perturbative derivation shows that **entanglement between detectors is a property of the field** and is determined by the Wightman function G^+.

The Cosmology of the Quarkbase provides a physical and quantitative interpretation of entanglement: not as a "mysterious message" between separated particles, but as robust correlations between field modes Ψ that were jointly created and are recorded through local measurements.

Mathematically, the theory reproduces the standard predictions of quantum mechanics (Bell states, coincidence probabilities, and violations of Bell/CHSH inequalities), since its quantum formalism of modes and operators is analogous to that of conventional quantum field theory. However, at the ontological level, it offers a clear and coherent picture:

$$\text{Local excitations} + \text{extended mode (etheric network)} + \text{measurement via coupling and threshold} \longrightarrow \tag{1}$$

The additional advantage of the Cosmology of the Quarkbase is that it transforms previously "philosophical" questions (What is collapse? How can nonlocality and relativity be reconciled?) into physical questions about the underlying medium: parameters of the ether–plasma (density, compressibility, screening length, nonlinearity), as well as about detector–field dynamics.

This opens a concrete experimental pathway: controlling the local environment and performing measurements of decoherence and robustness, allowing empirical confrontation of the theory and, if confirmed, the determination of the physical parameters of the hidden "ether."

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