GTCF Notes: Emergent Quantum Layer from the Coherence Field Framework

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These notes derive the *linear, quantizable fluctuation sector* that can emerge from the quartic GTCF local structure when combined with (i) a coherence pixel (covariant smoothing) and (ii) a cosmological (FRW) background fixed by the global coherence dynamics. We do *not* claim an axiomatic derivation of all interpretational postulates of quantum mechanics (e.g. Born rule as a theorem) unless explicitly stated.

1 Starting point: local GTCF and coherence pixel

We take the local coherence Lagrangian density

$$\mathcal{L}_{\mathrm{loc}} = \frac{(\bar{X} - X_{\mathrm{ref}})^2}{\Lambda^4}, \qquad X \equiv \frac{1}{2}\left(\dot{\phi}^2 - \frac{(\nabla\phi)^2}{a^2}\right), \tag{1}$$

where ϕ is dimensionless, $\Lambda \equiv \Lambda_{\mathrm{coh}}$, and $\bar{X}$ is the pixel-smeared kinetic invariant.

Explicit covariant kernel (pixel)

We implement the coherence pixel as a covariant smoothing operator

$$\bar{X} \equiv A_\ell[X], \qquad (1 - \ell^2 \Box)\, \bar{X} = X, \tag{2}$$

with $\ell \equiv \ell_{\mathrm{coh}}$ and $\Box$ the covariant d'Alembertian. Causality is ensured by choosing the *retarded* Green's function of $(1 - \ell^2 \Box)$.

For homogeneous FRW backgrounds, $\bar{X} = X$.

2 Hubbard–Stratonovich (exact rewriting)

The quartic structure in $(\bar{X} - X_{\rm ref})^2$ can be linearized by introducing an auxiliary field σ:

$$\mathcal{L}_{\rm HS} = \sigma(\bar{X} - X_{\rm ref}) - \frac{\Lambda^4}{4}\sigma^2, \tag{3}$$

which is equivalent to (1) upon eliminating σ via its algebraic equation of motion.

Varying (3) with respect to σ gives

$$\bar{X} - X_{\rm ref} - \frac{\Lambda^4}{2}\sigma = 0 \quad \Rightarrow \quad \sigma = \frac{2}{\Lambda^4}(\bar{X} - X_{\rm ref}). \tag{4}$$

3 FRW background from global coherence branch

On an FRW background $\phi = \phi_0(t)$,

$$X_0(t) = \frac{1}{2}\dot{\phi}_0^2(t), \qquad \bar{X}_0 = X_0. \tag{5}$$

From the horizon-limited global coherence branch (as in the v3 development), the homogeneous field satisfies

$$\ddot{\phi}_0 + 3H\dot{\phi}_0 = 0 \quad \Rightarrow \quad \dot{\phi}_0(t) = \frac{C}{a^3(t)}, \qquad X_0(t) = \frac{C^2}{2a^6(t)}. \tag{6}$$

Therefore the homogeneous auxiliary background is

$$\sigma_0(t) = \frac{2}{\Lambda^4}\Big(X_0(t) - X_{\rm ref}\Big) = \frac{C^2}{\Lambda^4 a^6(t)} - \frac{2X_{\rm ref}}{\Lambda^4}. \tag{7}$$

A nonzero $\sigma_0(t)$ is the mechanism by which a quadratic (wave-like) fluctuation sector can *emerge* from the underlying quartic structure.

4 Fluctuations: quadratic action and emergence of wave dynamics

Write fluctuations as

$$\phi(t, \mathbf{x}) = \phi_0(t) + \pi(t, \mathbf{x}), \qquad \sigma(t, \mathbf{x}) = \sigma_0(t) + s(t, \mathbf{x}). \tag{8}$$

Expand X to second order in π:

$$X = X_0 + \delta X^{(1)} + \delta X^{(2)} + \cdots , \tag{9}$$

$$\delta X^{(1)} = \dot{\phi}_0 \, \dot{\pi}, \tag{10}$$

$$\delta X^{(2)} = \frac{1}{2}\left(\dot{\pi}^2 - \frac{(\nabla\pi)^2}{a^2}\right). \tag{11}$$

By linearity of A_ℓ,

$$\delta \bar{X}^{(1)} = A_\ell[\delta X^{(1)}], \qquad \delta \bar{X}^{(2)} = A_\ell[\delta X^{(2)}]. \tag{12}$$

Keeping terms quadratic in (π, s) in (3) yields

$$\mathcal{L}^{(2)} = \sigma_0 \, \delta \bar{X}^{(2)} + s \, \delta \bar{X}^{(1)} - \frac{\Lambda^4}{4} s^2. \tag{13}$$

Since s is algebraic at this order, integrate it out:

$$\frac{\partial \mathcal{L}^{(2)}}{\partial s} = 0 \Rightarrow s = \frac{2}{\Lambda^4} \delta \bar{X}^{(1)}. \tag{14}$$

Substituting back gives the effective quadratic Lagrangian for π:

$$\boxed{\mathcal{L}^{(2)}_{\text{eff}}[\pi] = \frac{\sigma_0}{2} A_\ell \left[\dot{\pi}^2 - \frac{(\nabla\pi)^2}{a^2}\right] + \frac{\dot{\phi}_0^2}{\Lambda^4} \left(A_\ell[\dot{\pi}]\right)^2} \tag{15}$$

and the quadratic action

$$\boxed{S^{(2)}[\pi] = \int dt \, d^3x \, a^3(t) \, \mathcal{L}^{(2)}_{\text{eff}}[\pi].} \tag{16}$$

Local (IR) limit and stability conditions

On wavelengths $\gg \ell$ we may approximate $A_\ell \simeq 1$. Then

$$S^{(2)} \approx \int dt \, d^3x \, a^3 \left[A(t)\dot{\pi}^2 - B(t)\frac{(\nabla\pi)^2}{a^2}\right], \qquad A(t) = \frac{\sigma_0}{2} + \frac{\dot{\phi}_0^2}{\Lambda^4}, \quad B(t) = \frac{\sigma_0}{2}. \tag{17}$$

The effective propagation speed is

$$c_s^2(t) = \frac{B(t)}{A(t)} = \frac{\sigma_0}{\sigma_0 + 2\dot{\phi}_0^2/\Lambda^4}. \tag{18}$$

Ghost-free requires $A(t) > 0$. Gradient stability requires $B(t) > 0$, i.e. $\sigma_0(t) > 0 \Leftrightarrow X_0(t) > X_{\text{ref}}$.

Pixel effects (UV behaviour)

With explicit $A_\ell = (1-\ell^2\Box)^{-1}$, Fourier modes acquire a transfer function that modifies UV behaviour and effectively introduces a physical scale ℓ; in WKB (locally Minkowski) one has schematically

$$A_\ell(\omega, k) \sim \frac{1}{1+\ell^2\omega^2-\ell^2k^2/a^2}, \tag{19}$$

so high-frequency/high-k contributions are regulated at the level of the action.

5 Canonical quantization of the emergent linear sector

From (17) (or directly from (15) when treated carefully as a nonlocal theory), define the canonical momentum in the IR-local limit:

$$\Pi_\pi \equiv \frac{\partial(a^3\mathcal{L}^{(2)}_{\rm IR})}{\partial\dot{\pi}} = 2a^3A(t)\dot{\pi}. \tag{20}$$

Canonical quantization postulates the equal-time commutator

$$[\hat{\pi}(t,\mathbf{x}), \hat{\Pi}_\pi(t,\mathbf{y})] = i\hbar\,\delta^3(\mathbf{x}-\mathbf{y}). \tag{21}$$

Introduce the Mukhanov-type variable

$$v \equiv z(t)\,\pi, \qquad z^2(t) \equiv 2a^3(t)A(t), \tag{22}$$

and conformal time $d\eta = dt/a$. Then the IR action becomes

$$S^{(2)} = \frac{1}{2}\int d\eta\, d^3x \left[(v')^2 - c_s^2(\nabla v)^2 + \frac{z''}{z}v^2\right], \tag{23}$$

leading to the mode equation

$$v_k'' + \left(c_s^2k^2 - \frac{z''}{z}\right)v_k = 0, \tag{24}$$

with the standard Wronskian normalization fixed by (21):

$$v_k v_k'^* - v_k^* v_k' = i\hbar. \tag{25}$$

This is the explicit sense in which a *quantizable linear wave sector* emerges from the quartic GTCF structure:

- the background (global coherence) fixes $\dot{\phi}_0(t)$ and thus $X_0(t)$,
- $X_0(t) - X_{\rm ref}$ fixes $\sigma_0(t)$,

- $\sigma_0(t)$ generates the quadratic kinetic/gradient structure for π,
- which admits canonical quantization in the usual QFT-in-FRW sense.

6 Nonrelativistic limit and Schrödinger form (effective)

For a regime where the emergent sector admits approximately constant $A(t) \to A_* > 0$, $c_s^2 \to c_*^2$ on relevant timescales, one has an effective linear wave equation. A standard route to a Schrödinger-like limit is to separate fast oscillations and define a slowly varying complex envelope (e.g. via a Madelung/WKB ansatz), but this requires specifying the relevant dispersion regime and coupling to matter; it is therefore model-dependent and not asserted as universal here.

7 What is achieved vs what remains

Achieved (derived)

1. From quartic GTCF local structure with a pixel kernel and FRW background, we derived a *closed quadratic action* for fluctuations (16)–(15).
2. In the IR-local limit, we obtained explicit kinetic and gradient coefficients $A(t), B(t)$ and sound speed $c_s^2(t)$ (17)–(18).
3. We gave the canonical quantization procedure and mode equation (24) with normalization (25).

Remains open (not claimed as derived here)

1. A theorem-level derivation of the Born rule from the dynamics alone (requires additional structure/assumptions).
2. A complete treatment of the nonlocal operator A_ℓ at the quantum level beyond the IR limit (renormalization/UV completion issues).
3. Explicit predictions for laboratory quantum phenomena require identifying how matter degrees of freedom couple to ϕ and how the emergent sector maps to standard QM observables.

Summary (minimal)

Within GTCF, the quartic coherence structure $(\bar{X} - X_{\rm ref})^2$ can be rewritten exactly via an auxiliary field σ. On an FRW background fixed by the global coherence branch,

$\sigma_0(t) \propto (X_0(t) - X_{\rm ref})$ can become nonzero. A nonzero σ_0 generates an emergent quadratic action for fluctuations π, which admits standard canonical quantization and yields the linear mode dynamics (24). This provides a concrete, testable mathematical bridge from the coherence framework to an emergent quantum fluctuation sector.