Matter as a Generator of Space-Time: A Reading of Causal Fermion Systems

olivier Croissant

Abstract

We propose an interpretation of recent work on *causal fermion systems* (CFS) according to which the structure of space-time emerges from the interactions of matter with itself. By combining two major results — discretization and finite propagation speed (Finster, 2018) and the emergence of Fock dynamics via *holographic mixing* (Dappiaggi, Finster, Kamran, Reintjes, 2025) — we argue that space and fields do not pre-exist but appear as phenomena derived from fermionic dynamics. We then discuss the limits of this emergence, particularly during the big bang and inside black holes, where the usual notions of dimension and time lose their absolute character.

1 Introduction

The CFS paradigm is based on the causal action principle, a variational principle defined on a measure of fermionic correlation operators. This framework does not presuppose a continuous space-time, but rather causes causal and metric structures to emerge as consequences of action minimizations. Our objective is to show how recent results reinforce the idea that **matter generates space-time through self-interaction**.

2 Discretization and Finite Propagation Speed Results (2018)

2.1 Space-Time Discretization

Finster (2018) demonstrates that any minimizer of the causal action leads to a discrete structure of space-time, composed of spectral points defined by the correlation operators. Thus, space-time is not a given continuum, but the support of the fermionic measure.

2.2 Finite Propagation Speed

On macroscopic scales, the dynamics of linearized fields obey a finite propagation speed, analogous to the speed of light. Physical causality thus appears as an emergent property of the underlying fermionic structure.

3 Holographic Mixing and Fock Dynamics (2025)

3.1 Linearized Equations and Non-Local Potentials

CFS in Minkowski space lead to a Dirac equation with non-local potentials, arising from a multitude of stochastic vector contributions.

3.2 *Holographic Mixing* Mechanism

The introduction of holographic phases and phase shift effects between the fermionic components allows for the generation of bosonic field operators. Their commutation relations naturally realize the canonical commutation relations (CCR).

3.3 Emergence of QED

In an appropriate limit, the dynamics reformulates as a unitary evolution in fermionic and bosonic Fock spaces, reproducing standard QED with an ultraviolet cutoff. Thus, bosonic fields (like the photon) appear as *effective excitations of fermionic matter*.

4 Synthesis: Matter as the Creator of Space-Time

By bringing together the two results:

- **Discretization and causality** (2018) show that the structure of space-time is an emergent effect of the causal action principle applied to fermions.
- **Holographic mixing** (2025) shows that fields and QFT dynamics also emerge from this same fermionic structure.

A Unifying Principle. In this framework, the distinction between matter and space-time loses its fundamental meaning. Space-time emerges from the energy distribution in fermionic form, while matter itself is described by these correlations. Thus, geometry and matter are two manifestations of a single principle, formalizable by CFS and their correlations. Given the parametric richness of CFS (Hilbert dimension, spin-dimension, choice of measure, variational constraints), we have sufficient freedom to model the complex phenomenology of the energy-spatio-temporal continuum.

5 Beyond the Lorentzian Continuum

5.1 Variable Signature and Dimension

The space-time continuum of signature $(1, 3)$ appears only as an approximation valid in asymptotic and local regimes. Under extreme conditions (big bang, black holes), the effective dimension of space-time can vary, or even become undefinable at pre-Planckian scales. This flexibility is consistent with "running dimension" scenarios observed in other quantum gravity approaches.

5.2 The Relativity of Time

The energy-spatio-temporal continuum gives rise to a notion of time that is only local. When a system crosses the horizon of a black hole, it leaves the observable universe of an external observer, and the notion of time ceases to be unambiguous. This indeterminacy is in agreement with the Wheeler–DeWitt equation, which does not involve a unique time parameter: the global dynamics is richer than a simple evolution according to a real variable, and translates into internal correlations of the system. Furthermore, effects like the Unruh effect remind us that the presence of energy is itself relative to the choice of gauge and observer.

6 Perspectives

This framework opens the way to a computational reinterpretation: the finite propagation speed and the Fock space structure can be understood as constraints of complexity and computational resources, related to the internal dynamics of CFS. Such an approach would allow building a bridge between complexity theory, gravitation, and quantum fields.

7 Analogy Between Interaction Networks and CFS

A striking parallel can be drawn between recent results on finite propagation in networks of local interactions (e.g., neural networks trained with IS loss under NTK) and those obtained for causal fermion systems (CFS). In both cases, the fundamental structure imposes a finite speed limit for the propagation of influence, correlations, or information.

Networks (NTK + IS-loss)	**Causal Fermion Systems (Finster, 2018)**
Nodes V connected by edges E, metric distance $d(x, y)$	Space-time points defined as support of the measure ρ on $F \subset L(H)$
Local updates (range-R), Lipschitz-bounded	Local interaction via the causal action principle, variation bounded by constraints
Propagation theorem: $\lvert\langle O_x(t), O_y(0)\rangle\rvert \le C \exp\left(-\frac{d(x,y)-vt}{\xi}\right)$ with $v = R$ (discrete light cone)	Finite propagation result: state perturbations propagate with bounded speed (analogous to c), defining an emergent causal cone
No instantaneous influence: existence of a limit v determined by the graph architecture	No instantaneous action at a distance: existence of a limit c determined by the discrete fermionic structure
Effect of IS loss: improves the spectral condition and robustness *inside* the cone, but does not increase v	Effects of holographic phases: modify the effective dynamics, but do not remove the speed limit

Common Principle. In both frameworks, the propagation speed is not a constant imposed *a priori*, but the structural consequence of the architecture of local interactions. In other words, the propagation limit (speed of light in physics, speed v in a learning graph) is a *universal emergence* of locality and correlations.

References

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