Matter Formation as the Breakdown of Linear Propagation: Response Saturation and the Emergence of Stable Excitations

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In standard quantum field theory, matter creation is treated as an allowed transition between field states, governed by conservation laws but lacking a dynamical account of why stable, localized excitations emerge from freely propagating modes. In this work, we propose a response-based interpretation in which matter formation occurs when linear propagation ceases to be the lowest-cost response of an underlying medium. We introduce a minimal, scale-agnostic framework in which radiation corresponds to coherent linear excitations, while matter emerges through saturation of linear response, localization, and dynamical stabilization of excitation modes. This picture reproduces known particle-production thresholds and conservation laws without modifying standard quantitative predictions, while providing a physical mechanism for the radiation–matter distinction. The approach clarifies the functional role of matter formation, identifies proto-matter as a transient nonlinear regime, and outlines constraints and falsifiable limits for response-based cosmologies.

I. INTRODUCTION

Modern physics successfully predicts when and how particle creation occurs, yet remains largely silent on *why* matter exists as stable, localized excitations rather than dispersing radiation. In quantum field theory (QFT), particles are excitations of fields, and "creation" corresponds to changes in occupation number governed by interaction terms and conservation laws [1, 2]. While operationally precise, this description does not supply a physical mechanism explaining why the vacuum supports persistent excitations or why linear propagation fails in extreme regimes.

In gravitational contexts, matter is introduced as an external source through the stress–energy tensor, and spacetime geometry responds accordingly. General relativity (GR) does not describe the origin or stabilization of matter, nor does it define a notion of matter creation intrinsic to spacetime dynamics [3]. Even in curved-spacetime QFT, particle production is observer-dependent and kinematic, rather than mechanistic [4].

This paper addresses this conceptual gap by proposing a minimal response-based interpretation of matter formation. We argue that matter emerges when freely propagating excitations cease to be a viable linear response of the medium, forcing reorganization into stable, localized excitation patterns. The goal is not to replace standard calculations, but to clarify the physical role and function of matter creation within a broader dynamical framework.

II. RADIATION AS LINEAR, COHERENT PROPAGATION

In the standard description, radiation corresponds to massless or weakly coupled field excitations propagating freely through spacetime. These excitations are well described by linear equations of motion, obey superposition, and maintain phase coherence over long distances. In this regime, energy transport is delocalized, and no persistent rest-frame structure is formed.

From a response-theoretic perspective, this regime corresponds to linear response of the underlying medium. Let Φ denote a generic excitation variable and S a source term. In the linear regime,

$$\delta\Phi(x) = \int d^4x'\,\chi(x,x')\,S(x'), \tag{1}$$

where χ is a linear response kernel. As long as this approximation holds, excitations propagate without inducing lasting structural change in the medium.

Radiation, in this view, is not defined by the absence of substance, but by the absence of sustained nonlinear back-reaction. This characterization is fully consistent with quantum electrodynamics and relativistic field theory, and does not modify their predictions in the regimes where they are validated.

III. SATURATION AND BREAKDOWN OF LINEAR RESPONSE

Linear propagation cannot persist arbitrarily. As energy density, field gradients, or boundary constraints increase, higher-order response terms become relevant. Expanding the response schematically,

$$\delta\Phi = \chi S + \chi_2 S^2 + \chi_3 S^3 + \cdots, \tag{2}$$

the linear approximation fails when

$$\left|\frac{\chi_2 S^2}{\chi S}\right| \gtrsim 1, \tag{3}$$

or when analogous higher-order terms dominate.

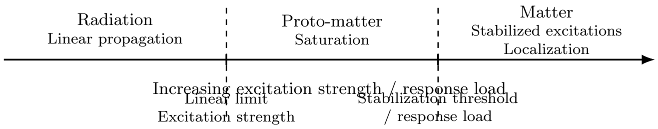

FIG. 1. Schematic response-regime diagram illustrating the transition from linear propagation (radiation) to nonlinear saturation (proto-matter) and response-stabilized localized excitations (matter). The horizontal axis represents increasing excitation strength or response load; no specific scale is implied.

An equivalent criterion may be expressed in terms of phase coherence. Let ℓ_c and τ_c denote characteristic coherence length and time scales for the propagating mode. A radiation description is valid when

$$\lambda \gg \ell_c, \qquad T \gg \tau_c, \tag{4}$$

where λ and T are the wavelength and period of the excitation. Saturation occurs when these inequalities fail locally, preventing maintenance of coherent traveling-wave solutions.

At this point, "radiation" ceases to be a meaningful description. The system is not converting energy into matter by choice; it is forced out of the linear regime by response limitations.

IV. PROTO-MATTER: LOCALIZED NONLINEAR EXCITATIONS

Beyond saturation, energy becomes localized into transient, strongly coupled configurations. We refer to this regime as *proto-matter*. Proto-matter consists of localized excitations that are neither freely propagating radiation nor yet stable matter.

These configurations:

- exhibit strong coupling to the medium,
- lack long-term stability,
- possess incomplete phase coherence,
- typically decay back into radiation unless stabilized.

Proto-matter is not an additional particle species; it is a dynamical regime. Its existence is implied by the breakdown of linear response and does not require new degrees of freedom beyond those already present in the excitation spectrum.

This regime is analogous to transient structures in nonlinear optics, fluid dynamics, and condensed matter systems, where localization precedes either decay or stabilization.

V. STABILIZATION AND EMERGENCE OF MATTER

Only a restricted subset of proto-matter configurations reduce the total response cost of the medium. These configurations minimize stress, maintain internal phase coherence, and resist dispersion. Dynamical selection favors these modes, while all others decay.

We identify such dynamically selected configurations with *fundamental particles*. Their defining features include:

- persistence in a rest frame,
- resistance to acceleration (inertia),
- discrete internal quantum numbers.

In this framework, rest mass corresponds to the energy required to maintain a localized excitation against dispersion, while inertia reflects the cost of reconfiguring the surrounding medium during acceleration. Matter is therefore a response-stabilized excitation, not a primitive constituent.

Importantly, this interpretation preserves all conservation laws and threshold conditions predicted by QFT. For example, in photon–photon pair production $\gamma\gamma \to e^+e^-$, the standard energy threshold reflects the minimum stress required to force stabilization into localized excitation modes, rather than an arbitrary permission granted by the vacuum [1].

VI. COMPOSITE MATTER AND BINDING

Once stable fundamental excitations exist, composite structures form through shared response fields. Overlapping deformations of the medium lower total response energy, producing bound states.

In this view:

- binding energy corresponds to reduced medium stress,
- composite inertia reflects the combined response footprint,
- chemical and nuclear stability arise from response minimization.

No additional postulates are required to explain the emergence of atoms, molecules, or condensed phases. Composite matter formation follows naturally from the same response principles governing fundamental stabilization.

VII. CONSISTENCY WITH STANDARD PHYSICS

The response-based interpretation advanced here does not modify the quantitative predictions of quantum field theory, general relativity, or particle physics in their tested regimes. Linear propagation, perturbative interactions, and geometric gravity are recovered as effective descriptions when response is weak and coherence is maintained.

Matter formation, in this framework, does not introduce new forces or violate symmetries. It provides a physical interpretation of processes already encoded in standard theory, including pair production, vacuum polarization, and threshold phenomena [5].

VIII. CONSTRAINTS AND FALSIFIABILITY

This framework is constrained by several non-negotiable requirements:

- Recovery of Lorentz invariance in the coherent regime,
- Exact conservation of energy–momentum,
- Agreement with observed particle-production thresholds,
- Absence of observable deviations in tested domains.

Observable deviations are confined to regimes involving extreme energy density, strong gradients, or long coherence breakdown lengths. Failure to identify any such deviations places upper bounds on response parameters and coherence scales, providing a clear route to falsification.

IX. CONCLUSIONS

Matter formation need not be treated as an inexplicable allowance of the vacuum. A response-based interpretation identifies matter as the dynamically selected outcome when linear propagation fails, yielding stable, localized excitations that minimize medium stress. This framework clarifies the functional role of matter creation, introduces proto-matter as a transient nonlinear regime, and reconciles radiation and matter as distinct response phases of the same underlying system.

While not yet a complete microphysical theory, this approach restores causal mechanism to a domain traditionally handled kinematically, and it defines clear constraints and pathways for further development.

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