Why Superluminal Motion Exists Without Violating Causality: A κ-Observability Interpretation of Wave Propagation

Abstract

In standard physics, the existence of a universal speed limit is postulated through Lorentz symmetry, while superluminal phenomena such as phase velocities are dismissed as non-physical. This leaves unresolved why faster-than-light motion appears mathematically natural yet operationally forbidden.

We present a resolution based on the UNNS (Unbounded Nested Number Sequences) framework, in which propagation is classified by κ-observability rather than by speed alone. We show that phase, group, and signal velocities correspond to distinct κ-levels, and that the relativistic speed limit emerges as a constraint on κ_3-admissible causal tokens rather than on substrate dynamics. This explains why superluminal patterns exist without enabling causal paradox, and reinterprets Lorentz symmetry as an observability-preserving gauge.

1 The Puzzle of Superluminal Motion

Wave mechanics routinely admits velocities exceeding the speed of light. Phase velocities $v_{\text{phase}} = \omega/k$ may exceed c, and group velocities may transiently do so in dispersive media. Yet no experiment has ever demonstrated faster-than-light causal signaling.

Standard treatments resolve this by declaring phase velocity "non-physical" and elevating signal velocity as the only meaningful notion of propagation. This distinction, while correct, is descriptive rather than explanatory: it does not clarify *why* some velocities are excluded from observability while others are not, a limitation noted in foundational critiques of postulate-based relativistic explanations [2].

We argue that this hierarchy arises from observability constraints rather than kinematics.

2 κ-Observability: A Hierarchy of Constraints

In the UNNS framework, a process is not characterized solely by its dynamics but by the level of observability it attains. We distinguish four κ-levels:

- κ_0 (definability): the process exists at the substrate level.
- κ_1 (local registrability): the process admits a locally trackable carrier.
- κ_2 (cross-observer consistency): different observers agree on the registered carrier.
- κ_3 (re-entry persistence): the carrier survives reuse as a causal record.

Only processes that reach κ_3 can function as reusable causal signals.

3 Wave Velocities as κ-Separated Phenomena

We now map standard wave-mechanical velocities onto this hierarchy, building on the classical distinction between phase, group, and signal velocities established in dispersive wave theory [1].

3.1 Phase Velocity (κ_0)

Phase velocity corresponds to global oscillatory structure. It is well-defined mathematically and may exceed c, but it lacks localization and continuity.

- κ_0: definable
- κ_1: fails (no registrable carrier)

Thus phase velocity is real but unobservable.

3.2 Group Velocity (κ_1)

Group velocity describes the motion of an envelope and can support energy transport.

- κ_1: typically passes
- κ_2: conditional on dispersion and stability

Crucially, subluminal group velocity is *necessary but not sufficient* for observability.

3.3 Signal Velocity (κ_3)

Information transfer requires persistence and observer agreement.

- κ_1: carrier exists
- κ_2: observer-consistent
- κ_3: persistent causal token

Only κ_3-admissible processes constitute causal signaling.

4 Historical Context: From Sommerfeld–Brillouin to κ-Observability

The tension between superluminal wave phenomena and relativistic causality is not new, and has been extensively analyzed in classical dispersion theory following the work of Sommerfeld and Brillouin [1].

It was already recognized in the early development of wave mechanics and electrodynamics, most notably in the work of Sommerfeld and Brillouin on signal propagation in dispersive media.

4.1 Sommerfeld and Brillouin: Front Velocity and Causality

Sommerfeld and Brillouin showed that while phase and group velocities may exceed the speed of light in dispersive materials, the *front velocity*—the speed at which a genuinely new disturbance appears—is bounded by c [1]. This result preserved relativistic causality without forbidding superluminal wave behavior at the level of mathematical solutions.

Crucially, their analysis already implied a hierarchy:

- Phase velocity is mathematically meaningful but causally irrelevant.
- Group velocity governs energy transport but may be distorted by dispersion.
- Signal or front velocity alone constrains causal influence.

However, the Sommerfeld–Brillouin framework stopped at this descriptive distinction. It established *that* causality is preserved, but not *why* only certain modes of propagation qualify as physically meaningful signals.

4.2 The Unresolved Gap in Classical Wave Theory

In classical and quantum wave theory, the exclusion of superluminal signaling is typically handled by a combination of:

- analyticity assumptions on response functions,
- boundary conditions on initial disturbances,
- and appeals to relativistic postulates.

While mathematically rigorous, these arguments treat the speed limit as an external constraint. They do not explain why the physical world privileges front velocity over other velocities, nor why certain mathematically well-defined solutions fail to become observable signals.

As a result, textbooks often adopt pragmatic language, labeling phase velocity as "not physical" without providing a structural criterion for physicality itself.

4.3 UNNS as a Completion Rather Than a Revision

The UNNS framework may be understood as a conceptual completion of the Sommerfeld–Brillouin program rather than a replacement.

Where Sommerfeld and Brillouin distinguished velocities by their causal roles, UNNS distinguishes them by their *level of observability*:

- Phase velocity corresponds to κ_0-definable structure: mathematically real but not locally registrable.
- Group velocity corresponds to κ_1-registrable carriers, whose physical relevance depends on stability and dispersion.
- Signal or front velocity corresponds to κ_3-persistent causal tokens.

In this reading, the Sommerfeld–Brillouin front velocity is not an independent postulate but the operational manifestation of κ_3-admissibility.

4.4 Why UNNS Goes Beyond Classical Results

The key advance provided by UNNS is the explicit identification of failure modes. Rather than declaring certain velocities "unphysical," UNNS classifies them as

- non-registrable (κ_1 collapse),
- observer-inconsistent (κ_2 collapse),
- or non-persistent (κ_3 collapse).

This makes it possible to state precisely why superluminal patterns exist without enabling causal signaling, and why attempts to promote such patterns to signal carriers necessarily fail.

In this sense, the κ-Limited Propagation Principle generalizes the Sommerfeld–Brillouin front-velocity result from a property of wave equations to a structural constraint on observability itself.

4.5 From Descriptive Boundaries to Structural Explanation

Historically, Sommerfeld and Brillouin demonstrated that relativistic causality is preserved despite the existence of superluminal wave phenomena. UNNS explains this preservation by locating the speed limit at the level of admissible records rather than at the level of substrate dynamics, addressing a gap left open by traditional postulate-based formulations [2].

Thus, the transition from Sommerfeld–Brillouin theory to UNNS is not a rejection of classical wave mechanics, but its conceptual closure: the point where the distinction between phase, group, and signal velocity is grounded in a general theory of observability.

5 The κ-Limited Propagation Principle (KLP)

We formalize the above as the κ-Limited Propagation Principle:

> There exists a finite constant c such that propagation processes exceeding this rate fail to instantiate κ_3-admissible causal tokens. This ceiling is invariant across observers.

Importantly, KLP does not forbid faster-than-light dynamics; it forbids faster-than-light *observability.*

6 Why γ Becomes Imaginary

In special relativity,

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

diverges and becomes imaginary for $v > c$.

In the κ-interpretation, this is not a mathematical pathology but a diagnostic: beyond the ceiling, observer-consistent registrable records cease to exist. The imaginary regime marks κ_2 collapse rather than illegal motion.

7 FTL Without Paradox

Causal paradox requires a reusable message-token. Such a token must satisfy κ_3.

For any faster-than-light process, at least one of the following occurs:

- κ_1 collapse: no carrier
- κ_2 collapse: observer inconsistency
- κ_3 collapse: no persistent record

Therefore, faster-than-light patterns cannot generate causal loops. FTL does not imply paradox; it implies observability failure, consistent with established analyses of non-signaling superluminal wave phenomena [1].

This sharply distinguishes UNNS from tachyonic models, which assume κ_3-admissible superluminal particles and thereby generate paradox.

8 Relation to Physical Relativity

From this perspective, Lorentz symmetry is not fundamental geometry but the unique transformation family preserving κ_2 consistency below the observability ceiling. Spacetime geometry emerges as a compressed encoding of observability constraints.

The speed of light is not the maximum speed of motion, but the maximum speed of causal registrability.

9 Conclusion

Superluminal motion exists ubiquitously at the substrate level. What is constrained is not motion itself, but the ability of motion to instantiate observer-consistent causal records. The relativistic speed limit emerges as a κ-admissibility bound, resolving long-standing conceptual tensions in wave mechanics and relativity without introducing ad hoc prohibitions.

References

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