The Impact-Triggered Flash Cascade (ITFC) Model: A Quantum-Interpreted Background Framework for Light Propagation

> Corresponding author: Koh, Hyun-Kyu

Co-author: Tendo Aris

Abstract

We propose the **Impact- Triggered Flash Cascade (ITFC)** model, which interprets visible light as a cascade of flashes emitted by an unobservable background of particles (U- particles) excited through contact with a high- speed driver (P- particle). In this framework the observable signal is not the P- particle itself but the propagation of the U**- cascade**. The speed constant c is not the speed of P; rather, it is the **critical rotational- transfer speed of** U. While a P- particle may satisfy $v_P \geq c$ (*a lower* bound), information transfer is limited by the cascade propagation speed $v_{eff} \leq c$, preserving local relativistic invariance. U- cascade propagation is governed by two phenomenological parameters—the effective transfer length λ and the local dwell/lag time τ_e—from which we obtain

$$v_{eff} = \frac{1}{c^{-1}+\tau_e/\lambda}, \qquad n = 1 + \frac{c\tau_e}{\lambda}$$

Rectilinear propagation, reflection/refraction (Fermat's principle and Snell's law), scattering/transparency (transport transition), and diffraction/interference (time- synchronization) follow consistently. We outline discriminative predictions including an ultra- high- vacuum gas- injection step test (Δn timing) and boundary- engineered scattering kernels via metasurfaces (non- integer refraction/polarization dependence). We also provide an agent- P/continuum- U hybrid simulation frame and diagrammatic guides. Contributions include: (i) a reinterpretation of c as a U- transfer invariant, (ii) redefinition of the photon as a U *−cascade** (observable), and (iii) a quantitative **medium- sensitivity law** $n = 1 + c\tau_e/\lambda$.

The present framework may also be viewed as a quantum-interpreted reformulation of a

background-medium picture. Rather than reviving a classical ether in its historical sense, we treat the unobservable background as a set of latent degrees of freedom whose localized excitations and transfer dynamics generate the observable optical signal.

1. Introduction

Scope notice. This paper focuses on phenomenology: we formalize optical consequences in terms of λ,, τ_e , κ without committing to a full microscopic model. A concrete definition of U- particles, their creation/interaction rules, a rotation- field- based dynamics, and a mapping to standard field theory will be presented **in subsequent papers**.

Historically, ether-like ideas failed in part because the background medium was assumed to possess classical mechanical properties that were difficult to reconcile with observed invariances. In the present work, the background is instead interpreted phenomenologically in quantum-like terms: not as a directly observable mechanical substance, but as an unobservable excitation-supporting substrate whose local transfer dynamics produce the effective propagation of light.

Baseline assumption (vacuum): If pair production is absent in vacuum, we adopt a massless- U baseline. No indirect- mass term is required; all ITFC observables are captured by the pair (λ, τ_e). Cosmology- level extensions may model Ω- driven modulation as slow changes in τ_e/λ rather than a rest mass.

Conventional optics treats light via Maxwell's equations and quantum electrodynamics [1, 5, 6, 9]. Here we examine whether a **contact- transfer mechanical micro- picture** can reproduce macroscopic optical laws while remaining compatible with relativistic constraints [2, 3, 6]. The central idea is: space is filled with unobservable background particles (U); impact by a high- speed driver (P) excites U into a transient, rapidly rotating state (**U***), which transfers rotation to neighboring U and emits a **flash**. The sequence of such flashes along the P track constitutes what we observe as **light**.

2. Rotation-Based Particle Motion — Linkage Summary

Earlier work postulated that superposed rotation fields modulate particle mobility and the distribution of momentum. In the present paper, these rotations are interpreted not as literal rigid-body motion, but as effective internal degrees of freedom of an unobservable background. In this sense, the ITFC framework may be read as a quantum-interpreted excitation-transfer model rather than a purely mechanical transport picture. An impact imparts linear impulse to P and a short-lived excitation to the background, whose transfer dynamics later appear as the observable optical signal.

3. Model Components

3.1 U- particles (unobservable background)

• **States**. Stable U_0 (non-emissive) and excited U^* (flash-emissive).

Transitions: .

$$U_0 \xrightarrow{impact} U^* \xrightarrow{decay} U_0$$

U-particles are introduced phenomenologically as unobservable background degrees of freedom rather than directly observable mechanical constituents of a classical medium. Their excited state, denoted by $U*$, is interpreted as a localized excitation of the background. In this interpretation, the observable optical signal does not arise from the direct visibility of P itself, but from the transfer and decay of such localized background excitations.

• **Local dynamics**. Let ω denote transient angular speed.

$$\frac{d\omega}{dt} = -\frac{\omega}{\tau} + \sum_{j\in\aleph} \kappa\omega_j\, \Theta(r_c - \|r - r_j\|)$$

With decay time τ, coupling κ, interaction radius r_c . Emission intensity (phenomenology):

$$I_U(t) = \eta\left|\frac{d\omega}{dt}\right|^p, \quad p \geq 1, \eta > 0.$$

3.2 P- particles (high- speed drivers)

Properties. Effectively massless energy carriers, **not directly observable**. Average speed v_P with a **lower bound** C (i.e $v_P \geq C$). Here C is the **critical U- transfer speed** (the light constant).

Trajectory. Ballistic flight over an effective free length ℓ or transfer length λ , with direction changes upon contact according to a scattering kernel $p(\theta)$.

Contact rule. A single contact raises a local U angular speed by ω_0 and may deflect P by angle $\theta \sim p(\theta)$. **Observable propagation is governed by the U-cascade,** not by P directly.

3.3 Definition of the Cascade (Light)

Along a P track, the set $[U*]$ forms a time-ordered cascade of localized background excitations. The detector integrates the resulting flashes over a window Δt; the integrated signal is the observed intensity, and its stream defines an effective ray. In this interpretation, the ray is not the trajectory of a directly visible particle, but the macroscopic record of sequential excitation transfer through the background.

3.4 Observability (Afterimage Hypothesis)

P is inferred **only** via the spatio-temporal pattern of the U-cascade "afterimage". Identical P tracks may yield different apparent rays depending on λ, τ_e .

3.5 Chain Dynamics (Summary)

U-excitation dynamics and emission follow §3.1; cascade formation is determined by $\lambda, \tau_e, \kappa, r_c$.

3.6 Parameters

λ (effective transfer length), τ_e (local dwell/lag), c (U-transfer critical speed), $p(\theta)$ ($P \rightarrow U$ scattering kernel), etc.

3.7 Summary (Causal Direction)

Cause (P**)** moves with $v_P \geq c$ → **Medium (**U**)** undergoes transfer at c → **Observation (Light)** = cascade of flashes.

4. Effective Propagation Speed and Refractive Index

Although the present paper is focused primarily on light propagation, the same phase-based formalism suggests a possible quantum-interpreted extension to nuclear binding and beta decay. In this extension, phase symmetry within a bound system is treated as an effective equilibrium condition, while beta decay is interpreted as a phase-relaxation process that releases accumulated imbalance through an emitted lepton channel and the accompanying background response.

The observable signal is the U- cascade. For one step,

$$t_{step} = \lambda/c + \tau_e , \qquad v_{eff} = \frac{\lambda}{\lambda/c+\tau_e} = \frac{1}{c^{-1}+\tau_e/\lambda} .$$

Define the **effective refractive index**

$$n \equiv \frac{c}{v_{eff}} = 1 + \frac{c\tau_e}{\lambda} .$$

medium changes (density ρ_U, structure, coupling) modify λ and τ_e, thereby changing n [2, 3, 7].

5. Optical Laws — Consequences

5.1 Rectilinearity

If scattering is forward- peaked and $\lambda \gg r_c$, deflection is small and straight- ray propagation holds.

5.2 Reflection/Refraction (Variational Principle)

Light (the U- cascade) follows paths minimizing total time $T = \int \frac{ds}{v_{eff}(s)} = \int \frac{n(s)}{c} ds$. With

$$n(s) = 1 + \frac{c\tau_e(s)}{\lambda(s)},$$

Snell's law follows: $n_A \sin\theta_A = n_B \sin\theta_B$. Ray bending aligns with ∇n, i.e., with gradients of τ_e/λ [2, 7].

5.3 Scattering and Turbidity

Stronger transport scattering shortens λ (e.g $,\lambda \approx 1/(\rho_U, \sigma_{tr})$) and typically increases τ_e by multiple contacts; hence $n = 1 + c\tau_e/\lambda$ rises and v_{eff} falls, transitioning to a transport regime characterized by an effective transport mean free path ℓ^* and diffusion coefficient $D \sim v_{eff}\ell^*/3$. Measurables: increased turbidity and delayed pulse tails [3, 12].

5.4 Diffraction/Interference as Time Synchronization

Two cascades arriving within a threshold **sync time** τ_c produce fringes within the detector's integration window Δt_{int}. The **coherence length** is $L_c = v_{eff}$, τ_c = $\frac{c,\tau_c}{1+c,\tau_e/\lambda}$ Vacuum-like conditions (small τ_e/λ) yield $v_{eff} \rightarrow c$ and longer L_c , enhancing visibility; media with larger τ_e/λ reduce L_c and modulate fringe patterns [2, 7].

6. Relativistic Constraints and Local Invariance

Treat c as the invariant **U-transfer critical speed**. Although $v_P \geq c$ may hold, observable information propagates with $v_{eff} \leq c$. Michelson–Morley-type nulls are recovered by **covariant scaling** of U-parameters (e.g., an invariant τ_e/λ in a local inertial frame), which removes first-order anisotropy [4, 6].

A weak dependence of the transfer parameters on large-scale background structure may be considered as a possible extension of the present formalism. Such an extension is not essential to the core ITFC model developed here, which is restricted to local propagation phenomenology.

7. Numerical Simulation Frame

Microscopic (agent-based): Monte-Carlo P-jumps plus U-lattice reaction-transfer

$U_0 \leftrightarrow U^*$.

Continuum (PDE):

$$\partial_t u^*(r,t) = D\nabla^2 u^* - \frac{u^*}{\tau} + S_P(r,t),$$

where S_p is a source tied to P tracks [3, 12].

Table 1. Model Parameters (Baseline & Sweep)

name	meaning	unit	baseline_A (vac- like)	baseline_B (dense/boundary)	sweep
ρ_U	U- particle number density	arb.	1e- 3	1.0	1e- 4 – 3.0
σ_{tr}	transport cross section	arb. area	1e- 3	1e- 1	1e- 4 – 1
$\lambda \approx 1/(\rho_U \sigma_{tr})$	effective transfer length	arb. length	derived	derived	derived
τ_e	dwell / lag per step	time	0.01 (λ/c)	0.3 (λ/c)	0 – 1 (λ/c)
τ	decay time of excited U	time	$5\tau_e$	$2\tau_e$	1-10τ_e
κ	transfer coupling strength	1/time	$0.05/\tau_e$	$0.2/\tau_e$	$0.01 - 0.5/\tau_e$
r_c	transfer radius	length	0.5λ	0.8λ	$0.1 - 1.0\lambda$
$p(\theta)$	scattering kernel (P→U)	—	forward- peaked	broadened (near- Lambertian)	HG g: $0.9 \rightarrow 0.0$
c	U- transfer critical speed	speed	1.0 (nondim)	1.0	fixed
v_p	P speed (unobserved)	speed	$1.5c$	$1.2c$	$\geq c$
$v_{eff} = 1/(1/c + \tau_e/\lambda)$	effective propagation speed	speed	computed	computed	computed
	effective refractive	—	≈ 1.01	≈ 1.3	$1.0 - 2.0$

$n = 1 + c\tau_e/\lambda$	index				
τ_c	sync time for interference	time	$100\tau_e$	$50\tau_e$	**10** $- 200\tau_e$
$L_c = v_{eff}\tau_c$	coherence length	length	computed	computed	computed
Δt_{int}	detector integration window	time	$50\tau_e$	$50\tau_e$	$10 - 200\tau_e$
observables	$\Delta T, V, n_{eff}$	—	measure	measure	record vs sweep

Note. Start with dimensionless units and map to physical units in later experimental design. Baseline_A is vacuum- like; Baseline_B represents strong boundary/scattering conditions [3, 12].

Table 2. Numerical Settings (Recommended)

item	symbol	value	note
domain length	L_{dom}	200λ	periodic or absorbing BC
grid spacing	Δx	$\lambda/20$	resolve transfer front
Time step	Δt_{num}	0.5•min($\lambda/c, \tau_e$)	stability / CFL- like guard
Total steps	N_{step}	1e5	cover many transfers
Particles per cell (P)	N_p	10-100	Monte- Carlo variance control
Recording cadence	—	every 50 steps	for $\Delta T, V, n_{eff}$
sources	S_p	scripted tracks	single/dual tracks for interference

Output metrics. ΔT: time delay across length L ($\int ds/v_{eff}$); V: fringe visibility $(I_{max} - I_{min})/(I_{max} + I_{min})$; n_{eff} : path- averaged refractive index $(1/L) \int n(s)ds$.

8. Experimental Predictions and Discriminators

1. Pressure/density- dependent index. Control residual gas (affecting λ, τ_e) and measure $\Delta T \sim L\Delta(\tau_e/\lambda)$ **[2, 3, 12].**

2. Boundary dynamics. Design interfaces (metasurfaces) to tailor $p(\theta)$, inducing non- integer refraction and polarization- dependent n [3, 11].

3. Time- synchronization interferometry. Scan pulse delay and locate the threshold τ_c for fringe onset [2, 7].

4. UHV gas- injection step test. Micro- step $\lambda,\ \tau_e$ by controlled injections and read out femto–picosecond timing shifts via interferometry: $\Delta n \approx c\Delta(\tau_e/\lambda)$ [2 ,3, 4].

5. Kernel engineering at boundaries. Actively vary $p(\theta)$ and compare with ITFC predictions (cascade- transfer delays) [3, 11].

6. Annual/azimuthal modulation interferometry. Earth's orbit and rotation modulate the relative angle to Ω. Measure annual/diurnal components of $\Delta(\tau_{swap}/\lambda)$ as femto–picosecond delays. Scan latitude/longitude/azimuth to reject systematics and set an upper bound on $\Delta n(\Omega)$ [4].

9. Mapping to Topological Terminology (Optional)

U- background corresponds to a near- zero phase- feedback exterior of a quasi- isolated system; contact transitions are phenomenologically analogous to entropy- direction inversions. This gives a dictionary between rotation- based/phase- based language without altering predictions.

9.1 Phase Symmetry in Nuclear Binding and Phase Relaxation (Beta Decay)

We interpret nuclear binding as a tendency to maintain **phase symmetry (or equilibrium)** within a bound system.

Let Φ_i and Φ_j denote the phases of nucleons i and j, and introduce a short-range envelope $U(R_{ij}) \sim -J_0 exp(-R_{ij}/\lambda_N)$. A phenomenological binding energy can be written as:

$$E_{bond} = -\sum_{<i,j>} J_{ij}(R_{ij})cos(\phi_i - s_{ij}\phi_j - \pi p_{ij}) + \sum_{<i,j>} U(R_{ij})$$

where $s_{ij} \in \{\pm 1\}$ represents the coupling sign (in-phase or anti-phase), and

$p_{ij} \in \{0,1\}$ encodes a π-junction (e.g., neutron-mediated anti-phase coupling).
Energy minimization enforces local phase equilibrium, naturally producing short-range strong attraction and saturation behavior [8, 9, 10].

In this framework, beta decay is interpreted as a **phase relaxation (phase-slip) process** that occurs when accumulated phase imbalance exceeds a critical barrier.
Introducing an isospin angle α with an effective potential:

$$U_{iso}(\alpha) = -J_{pn}\, cos\, \alpha + \frac{K}{2}\alpha^2$$

a phase-slip transition $\alpha \rightarrow \alpha \pm \pi$ occurs when the phase energy exceeds a threshold E_b.
The released energy is partitioned as:

$$Q = \Delta E_{phase} - E_b = T_e + T_\nu + E_{U-cascade} \geq 0$$

where T_e and T_ν denote the kinetic energies of the emitted electron and (anti)neutrino, and the remaining energy is carried by the U-cascade (flash chain) [8, 9, 10].

Charge conservation is ensured via the label-charge continuity relation

(Appendix D.5′):

$$\partial_t \rho_q + \nabla \cdot J_q = S_{slip}$$

which reduces to standard conservation ($S_{slip} \to 0$) in the rapid recombination limit. Thus, beta decay is interpreted as a dynamical process restoring phase equilibrium within the bound system.

10. Limitations and Open Problems

• Establish a precise **effective field theory** mapping to Maxwell/QED [1, 5, 6, 9].

• Quantitatively confront **high- precision null experiments** [4].

• Integrate a **nonlinear detector model** for biological perception.

11. Conclusion

ITFC redefines light as a **cascade of U- particle flashes** and interprets the light constant as a **U- transfer critical speed**. Thus, while a driver P may satisfy $v_P \geq c$, information transfer remains bounded by $v_{eff} \leq c$. Medium sensitivity is quantified by $n = 1 + c\tau_e/\lambda$. The frame unifies rectilinearity, reflection/refraction, scattering/turbidity, and diffraction/interference through the single spatial field τ_e/λ. We propose UHV step tests and boundary- kernel engineering as near- term discriminators.

In addition to its optical interpretation, the ITFC framework may be read as a phenomenological background-excitation model. In this view, observable propagation is determined by the transfer of localized excitations through unobservable background degrees of freedom. Possible large-scale background modulation may be explored in future work, but it is not essential to the present formulation, which is primarily concerned with the local phenomenology of light propagation.

Future work. (1) Construct a rotation- field micro- model and an EFT correspondence; (2) infer τ_e, λ from metasurface/nanointerferometry datasets; (3) precision comparisons of

$\Delta T, V, n_{eff}$; (4) investigate possible large-scale extensions of the background-transfer formalism.

Appendix A. Covariant Parameter-Scaling Hypothesis (Sketch)

In local inertial frames, let $\lambda \propto f(\Phi)$ and $\tau_e \propto f(\Phi)$ scale homogeneously with a local scalar Φ, keeping . Then $v_{eff}^{-1} = c^{-1} + const$ is locally invariant and first-order anisotropy cancels.

Appendix B. Notation

ρ_U: U-particle number density; σ: (transport) cross section; ℓ: transport mean free path; λ: effective transfer length; τ, τ_e: decay/dwell constants; κ: transfer coupling; r_c: transfer radius; c: U-transfer critical speed; n: effective refractive index; u^*: excited U concentration; v_p: P speed; v_{eff}: effective cascade speed.

Appendix C. Diagrams (v1)

Display note. If Mermaid is unavailable, use the ASCII alternates. Variables appear in plain text (tau_e, lambda, r_c).

[Fig. 1] U-cascade propagation (P track and excitations)

```
flowchart LR
   P0((P)) --> U1((U*))
   U1 --> U2((U*))
   U2 --> U3((U*))
   P0 -. dotted path .-> P1((P))
   P1 --> U4((U*))
   U4 --> U5((U*))
   classDef glow fill:#fffbd6,stroke:#555;
```

```
    class U1,U2,U3,U4,U5 glow;
```

ASCII alt:

```
P path:    . . . . . . . . .
                      o* -> o* -> o*            (U* : excited U; flash)
                                  \
                                    -> o* -> o*
```

r_c : local transfer radius

lambda : effective transfer length between successive U*

[Fig. 2] Trajectory change at a boundary (refraction/reflection)

```
flowchart LR
    subgraph A[region A: n_A = 1 + c*tau_eA/lambda_A]
    IA[/incident ray θ_A/]
    end
    subgraph B[region B: n_B = 1 + c*tau_eB/lambda_B]
    RB[/refracted ray θ_B/]
    end
    IA -->|boundary| RB
```

ASCII alt:

```
region A (n_A) | region B (n_B)
   \
     \    θ_A               |    / θ_B
       \____boundary|_/________
```

Snell: n_A * sin(θ_A) = n_B * sin(θ_B)

with n = 1 + c * tau_e / lambda

[Fig. 3] Time- synchronization interference (coherence length L_c)

```
P-chain #1: |*    *    *    *    *|
P-chain #2:        |*    *    *    *    *|
                        <---- Δt ---->
```

Detector window Δt_int: [===========]

Sync time τ_c: threshold for fringe formation

L_c = v_eff * τ_c = c * τ_c / (1 + c * tau_e / lambda)

Appendix D. Effective Action (Lagrangian) — Sketch

This appendix presents a refined **effective action** sketch for ITFC while preserving the phenomenological parameters $\lambda,\ \tau_e,\ \tau_{swap},\ \kappa$. The purpose is twofold: (i) encode **memory effects** and **finite transfer range** directly in the action, and (ii) to recover, in the long- wavelength and low- frequency limit, the ITFC propagation law

$$t_{step} = \frac{\lambda}{c} + \tau_{eff},$$

$$v_{eff} = \frac{1}{c^{-1} + \tau_{eff}/\lambda},$$

$$n = 1 + \frac{c\tau_{eff}}{\lambda}$$

Where

$$\tau_{eff} = \begin{cases} \tau_e \ , dilute \ \ background, \\ \tau_{swap}, dense \ \ swap - dominated \ \ background. \end{cases}$$

The effective action introduced in Appendix D is not presented as a complete microscopic quantum theory, but as a coarse-grained phenomenological model compatible with a quantum-interpreted background picture.

D.1 Fields and External Source

Let $\psi(x) \equiv \psi(\mathrm{t}, \mathbf{r})$ denote an effective scalar field representing the i**ntensity/state of U-transfer**, I.e. the observable carrier of the U-cascade. The P-track enters only through an external source

$$J_p(x) = g \int d\tau \ \delta^{(4)}(x - X(\tau)),$$

where $X(\tau)$ is the worldline of the P-particle. Thus, P itself is not directly observable; only the induced field ψ is.

D.2 Effective Action (Sketch)

The refined effective action is written as

$$S_{eff} = \int d^4x \ \left[\frac{1}{2}(\partial_t\psi)^2 - \frac{c^2}{2}|\nabla\psi|^2 - V(\psi) + J_P\psi\right] + \frac{1}{2}\int d^4x d^4x' \psi(x) K(x - x') \psi(x').$$

Here $K(x - x')$ is a **causal nonlocal kernel** satisfying

$$K(t - t' < 0, r - r') = 0,$$

so that temporal ordering and observable causality are preserved.

A separable illustrative form is

$$K(x - x') = K_t(t - t')\ K_r(r - r'),$$

with

$$K_t(\Delta t) = \frac{\alpha}{\tau_{eff}} exp\left(-\frac{\Delta t}{\tau_{eff}}\right) \Theta(\Delta t),$$

$$K_r(\Delta r) = -\beta\ \frac{c}{\lambda}\ \frac{exp(-|\Delta r|/\lambda)}{N_\lambda},$$

where N_λ is a normalization factor and α, β are matching coefficients.

If a cosmic reversible rotation field $\Omega = \Omega(R)$ is included, the kernel may be parameterized as

$$K(x - x'; \Omega) = K_t(t - t'; \Omega) K_r(r - r'; \Omega),$$

with Fourier transform

$$\widetilde{K}(\omega, k; \Omega) \simeq A(\Omega)(i\omega) + B(\Omega)k^2 + \cdots .$$

The matching conditions are then imposed as

$$\left(\frac{\partial \widetilde{K}}{\partial (i\omega)}\right)_{\omega=0,k=0} = \frac{1}{\tau_{swap}(\Omega)}, \qquad \left(\frac{\partial \widetilde{K}}{\partial k^2}\right)_{\omega=0,k=0} = -\frac{c}{\lambda(\Omega)}$$

These ensure the long-wavelength relations

$$v_{eff}(\Omega) = \frac{1}{c^{-1} + \tau_{swap}(\Omega)/\lambda(\Omega)}, \quad n(\Omega) = 1 + \frac{c\tau_{swap}(\Omega)}{\lambda(\Omega)}$$

D.3 Equations of Motion and Dispersion (Linearized)

Near a local steady state, take

$$V(\psi) \backsimeq \frac{m^2}{2}\psi^2.$$

Then the Euler–Lagrange equation becomes

$$\begin{aligned} \partial_t^2\psi - c^2\nabla^2\psi + m^2\psi \\ + \int d^4x' \; K(x - x')\psi(x') \\ = -J_P(x). \end{aligned}$$

For a plane-wave ansatz

$$\psi(x) \sim e^{i(k\cdot r - \omega t)},$$

one obtains the dispersion relation

$$-\omega^2 + c^2k^2 + m^2 + \widetilde{K}(\omega, k) = 0.$$

In the long- wavelength/low- frequency regime,

$$\widetilde{K}(\omega, k) \approx A(i\omega) + Bk^2 + \cdots ,$$

And the coefficients A and B are fixed by the ITFC matching rules below.

D.4 Long- Wavelength Matching (Design Rules)

The refined design rules are:

$$(M1) \qquad t_{step} = \frac{\lambda}{c} + \tau_{eff} \Longrightarrow v_{front} = \frac{1}{c^{-1} + \tau_{eff}/\lambda} \equiv v_{eff} \ ,$$

$$(M2) \qquad n = \frac{c}{v_{eff}} = 1 + \frac{c \ \tau_{eff}}{\lambda} \ ,$$

$$(C1) \quad \left(\frac{\partial \widetilde{K}}{\partial(i\omega)}\right)_0 = \frac{1}{\tau_{eff}},$$

$$(C2) \quad \left(\frac{\partial \widetilde{K}}{\partial k^2}\right)_0 = -\frac{c}{\lambda} \ .$$

Choosing $\alpha, \beta,$ and N_λ so that $(C1) - (C2)$ hold ensures that the **front velocity** of the causal U-cascade response reproduces the ITFC law.

> **Remark.** In a generic nonlocal medium, phase velocity and group velocity need not coincide with the signal front velocity. In ITFC, the physically relevant quantity is the propagation of the **U-cascade front.**

D.5 Minimal Potential and Stability

A stable minimal potential may be chosen as

$$V(\psi) = \frac{m^2}{2}\psi^2 + \frac{\lambda_4}{4!}\psi^4 + \cdots, \qquad m^2 \geq 0, \quad \lambda_4 \geq 0.$$

If one prefers a phase interpretation, a periodic form such as

$$V(\phi) = \Lambda_\phi(1 - cos\,\phi)$$

may be used instead.

D.5′ Label-Charge Continuity (Noether Sketch)

Assume a global $U(1)$-like symmetry associated with a label charge q. Then the effective current obeys

$$\partial_t \rho_q + \nabla \cdot J_q = 0.$$

D.6 Summary

The refined effective action preserves:

$$\begin{array}{ll} (1)\ casuality, & (2)\ finite\ \ memory \\ /\ range\ \ (\tau_{eff}, \lambda), & (3)\ invariant\ \ c. \end{array}$$

in the long-wave-length limit. In laboratory vacuum without pair production, any effective-mass construct may be set to zero, and the pair (λ, τ_e) alone suffices. A full microscopic derivation and EFT correspondence remain future work.

References

[1] Maxwell, J. C., *A Treatise on Electricity and Magnetism*, Vols. I–II, Clarendon Press, Oxford (1873).

[2] Born, M. and Wolf, E., *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*, 7th expanded ed., Cambridge University Press (1999).

[3] Landau, L. D., Lifshitz, E. M., and Pitaevskii, L. P., *Electrodynamics of Continuous Media*, 2nd ed., Butterworth-Heinemann / Elsevier, Vol. 8 of Course of Theoretical Physics (1984).

[4] Michelson, A. A. and Morley, E. W., “On the Relative Motion of the Earth and the Luminiferous Ether,” *American Journal of Science* **34**(203), 333–345 (1887).

[5] Feynman, R. P., *QED: The Strange Theory of Light and Matter*, Princeton University Press (1985).

[6] Jackson, J. D., *Classical Electrodynamics*, 3rd ed., Wiley (1998).

[7] Hecht, E., *Optics*, 5th ed., Pearson (2016).

[8] Sakurai, J. J. and Napolitano, J., *Modern Quantum Mechanics*, 2nd ed., Cambridge University Press (2017).

[9] Peskin, M. E. and Schroeder, D. V., *An Introduction to Quantum Field Theory*, CRC Press / Westview Press (1995).

[10] Weinberg, S., *The Quantum Theory of Fields*, Vol. I, Cambridge University Press (1995).

[11] Joannopoulos, J. D., Johnson, S. G., Winn, J. N., and Meade, R. D., *Photonic Crystals: Molding the Flow of Light*, 2nd ed., Princeton University Press (2008).

[12] Ishimaru, A., *Wave Propagation and Scattering in Random Media*, Vols. I–II, Academic Press (1978).