Mathematical Formulation of Mass-Dependent Temporal Behavior and Emergent Transient Wormhole Geometry

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1. Scope and intent of the formulation

This formulation provides a *phenomenological, comparative description across particle populations ordered by rest-mass scale.*

It does **not** describe the dynamical evolution of individual particles, does not modify quantum state evolution, and does **not** derive from first-principles general relativity or quantum field theory.

All relations below are *effective, scale-dependent, and interpretive.* They are intended to clarify the conceptual structure of the associated descriptive framework rather than to introduce new physical laws.

2. Relation to curvature and wormhole influence

Within this framework:

- *Particle-associated spacetime curvature* is taken to scale with rest mass.
- *Wormhole influence* is taken to increase as effective curvature influence weakens.

Phenomenologically:

$$\text{Wormhole influence} \propto \frac{1}{\text{effective curvature}}$$

Since effective curvature decreases with decreasing rest-mass scale, wormhole influence becomes significant below the crossover region.

3. Emergence of the crossover mass scale

The crossover region is defined phenomenologically as the range of particle rest masses for which the influences of particle-bound wormhole and particle-associated spacetime curvature become comparable.

No sharp boundary or unique crossover mass value is implied. Instead, the crossover represents a gradual transition on the rest-mass scale separating curvature-dominated behavior from wormhole-influenced behavior.

Formally, the crossover region may be characterized by the qualitative condition:

$$\text{curvature influence} \sim \text{wormhole influence}$$

Interpretation

- *For masses well above the crossover region:* Classical curvature influence dominates; effective locality holds.
- *Within the crossover region:* Curvature influence and wormhole influence are comparable; classical locality begins to lose descriptive adequacy.
- *For masses below the crossover region:* Wormhole influence becomes increasingly significant; effective nonlocal behavior emerges.

The effective temporal ordering scale $T_{\text{eff}}(m)$ varies smoothly across the crossover region but does not reach its fundamental lower bound within this region.

4. Domain of applicability

The effective temporal ordering parameter $T_{\text{eff}}(m)$ is not defined in the massless case $m = 0$. In the absence of a rest frame, no intrinsic temporal ordering can be assigned.

5. Effective temporal ordering scale

We introduce an **effective temporal ordering scale** $T_{\text{eff}}(m)$ associated with particles of rest mass m.

T_{eff} characterizes the **effective resolution at which successive particle states may be meaningfully distinguished** relative to an external reference. It is **not** a physical clock time, not a proper time, and does not modify quantum time evolution; a conceptual distinction between *clock-based time* and T_{eff} is discussed in Section 8.

Within this phenomenological framework, $T_{\text{eff}}(m)$ is assumed to vary monotonically with rest mass below the crossover region: particles of smaller rest mass correspond to larger values of Teff(m), while larger rest masses correspond to smaller values.

No functional dependence of $T_{\text{eff}}(m)$ on mass is assumed or derived.

6. Fundamental lower bound on effective temporal resolution

A lower bound on effective temporal ordering is imposed:

$$T_{\text{eff}} \geq t_{\text{min}}$$

where $t_{\text{min}} \sim t_{\text{P}}$ denotes a **minimal temporal resolution** associated with Planck time.

7. Illustrative Ordering Across Mass Scales in the Nonlocal Regime

7.1 Define the regime

Let:

m_A: lower-mass endpoint of applicability (smallest nonzero rest mass considered, above massless limit)
m_B: upper-mass endpoint below the crossover region

with:

$$0 < m_A < m < m_B < m_{\text{crossover}}$$

Thus, we consider a domain of applicability consisting of particles with nonzero rest mass whose masses lie below the crossover scale at which classical curvature effects dominate. Let this mass interval be denoted by:

$$m \in (m_A, m_B)$$

where:

- $m_A > 0$ denotes the lower endpoint of the regime (excluding strictly massless particles such as photons),
- $m_B < m_{\text{crossover}}$ denotes the upper endpoint of the regime, lying below the crossover mass scale.

All particles within this interval are described as exhibiting effective nonlocal behavior within the phenomenological framework.

Within this interval, we assume only a monotonic ordering of the effective temporal ordering scale $T_{\text{eff}}(m)$, such that:

$$\forall m_1, m_2 \in (m_A, m_B), m_1 < m_2 \Longrightarrow T_{\text{eff}}(m_1) > T_{\text{eff}}(m_2)$$

The symbol "∀" denotes “for all”, indicating that the relation holds for every particle mass within the specified interval.

That is, particles closer to the lower mass endpoint exhibit larger effective temporal ordering parameters, while particles closer to the crossover boundary exhibit smaller values.

7.2 Introduction of an Ordering Parameter

To represent this ordering without introducing dynamics, we define a dimensionless phenomenological ordering parameter:

$$\lambda: (m_A, m_B) \to [0,1]$$

with the following interpretation:

- $\lambda(m_A) = 1,$
- $\lambda(m_B) = 0,$
- $\lambda(m)$ decreases monotonically with increasing mass.

In other words, this implies that for a particle of mass m lying in the mass scale between A and B, we have:

$$\lambda(m) \in [0,1]$$

Here, the symbol "∈" denotes *set membership,* indicating that $\lambda(m)$ takes values within the closed interval [0,1].

7.3 Phenomenological Ordering Relation

The effective temporal ordering scale for any particle within the interval (m_A, m_B) is then written as:

$$\forall m \in (m_A, m_B): \qquad T_{\text{eff}}(m) = \big(1 - \lambda(m)\big) T_{\text{eff}}(m_B) + \lambda(m) T_{\text{eff}}(m_A)$$

This expression is a convex ordering relation that places strictly between its endpoint values:

$$T_{\text{eff}}(m_A) > T_{\text{eff}}(m) > T_{\text{eff}}(m_B) \qquad \forall m \in (m_A, m_B)$$

We assume only that effective temporal ordering varies monotonically with rest mass below the crossover region. Given two reference points in this regime, any particle must lie between them in ordering. The convex combination is the most general ordering-preserving parametrization consistent with these assumptions, without introducing dynamics or linearity.

7.4 Reference Masses and Illustrative Examples

Specific particle masses, such as the neutrino mass m_ν and the electron mass m_e, may be chosen as convenient reference points within the interval (m_A, m_B). These do not define the boundaries of the regime but serve as empirically meaningful anchors.

For example, if a particle's mass is chosen illustratively to lie midway in the ordering between two reference masses, one may assign equal weighting:

$$\lambda_{\text{mid}} = \frac{1}{2}$$

yielding:

$$T_{\text{eff}}(m_{\text{mid}}) = \frac{1}{2} [T_{\text{eff}}(m_A) + T_{\text{eff}}(m_B)]$$

Such midpoint assignments are not predictive and do not imply linear dependence; they serve only to demonstrate internal consistency of the ordering framework.

Interpretive Clarification

The relation is introduced as a phenomenological parametrization expressing monotonic ordering across mass scales. It does not assert linear dependence, nor does it encode dynamics. The parameter λ serves only to locate a particle within the nonlocal regime relative to chosen reference masses. Any future microscopic theory may replace this relation with a derived form.

7.5 Neutrinos: The three flavors on the mass scale

The symbol m_ν denotes a phenomenological neutrino mass scale within the low-mass, nonlocal regime. Neutrinos are observed through three weak-interaction channels—electron neutrino (ν_e), muon neutrino (ν_μ), tau neutrino, (ν_τ)—commonly referred to as neutrino flavors.

These flavor states do not possess definite rest masses. Each is a quantum superposition of distinct neutrino mass eigenstates with different masses. Consequently, it is **not meaningful** to assign a unique T_{eff} to a specific neutrino flavor or to rank neutrino flavors by mass.

Accordingly, m_ν should be understood as a phenomenological neutrino mass scale rather than the mass of any particular flavor. Any neutrino flavor may serve as a valid low-mass reference point without altering the qualitative ordering relations.

By contrast, the electron is a mass eigenstate with a well-defined rest mass and does not exhibit flavor mixing or mass superposition.

8. Time vs. Temporal Ordering Scale $T_{\text{eff}}(m)$

Time can be understood as a paradoxical indicator defined by an observer's clock used to describe the progressive change of a system, thereby serving as an external reference that orders events and assigns durations.

By contrast, the effective temporal ordering scale $T_{\text{eff}}(m)$ introduced here is not a clock-based notion of time. It does not measure duration or govern dynamics. Instead, it characterizes how finely successive particle states can be meaningfully distinguished relative to an external time reference, and varies phenomenologically across particle mass scales.

9. Summary of mathematical structure

Quantity	Meaning
m	Particle rest mass (nonzero)
$T_{\text{eff}}(m)$	Effective temporal ordering scale
$t_{\min}$	Fundamental lower bound (Planck-scale)
Wormhole influence	Inversely related to effective curvature

10. Final consistency statement

This mathematical formulation:

- preserves standard quantum evolution,
- introduces no new dynamics or equations of motion, and respects relativistic causality.
- treats mass as **a scale-ordering parameter,** not a variable, remains strictly phenomenological.