Void Coupling as Phase Coherence: A Resonance Foundation for Mass and Stability in the VERSF Framework

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General Reader Abstract

What gives matter its mass? In standard physics, particles acquire mass by interacting with the Higgs field. This paper proposes a different mechanism rooted in the Void Energy-Regulated Space Framework (VERSF), where reality emerges from a deeper information-processing layer called the void substrate.

The central idea is surprisingly intuitive. Imagine two oscillations — one belonging to a particle-like mode, the other belonging to the underlying substrate. When these oscillations are well synchronized (in phase with each other), opportunities arise for irreversible information changes called "bit-flips." But a single opportunity isn't enough — a particle must accumulate many successful opportunities before a bit-flip is fully committed, and the number required (called the anchoring depth) differs between particle types. Mass is proportional to the density of committed bit-flips per substrate tick — the more bit-flips completed per tick, the greater the mass. Good synchronization means frequent opportunities; shallow anchoring means fewer opportunities needed per commitment. Both contribute to higher mass.

We formalize this with a number called R that measures how well-synchronized the two oscillations are, ranging from 0 (completely out of sync) to 1 (perfectly locked together). From R we derive the probability that a bit-flip opportunity occurs at any given moment, and from that probability we derive mass. The key result is an equation — the "bridge formula" — that connects the abstract concept of synchronization quality to concrete, measurable mass.

This approach explains several features of the physical world. Stable particles are expected to correspond to modes in the high-coherence regime, where synchronization with the substrate is strong and resistant to disruption. Unstable particles correspond to modes at intermediate synchronization, where small fluctuations cause large changes in mass — leading to decay. The vast differences in mass between different particles (for example, the top quark is roughly 340,000 times heavier than the electron) emerge naturally from differences in synchronization quality and internal complexity.

The paper connects VERSF to the well-studied physics of synchronization — the same mathematics that describes fireflies flashing in unison, neurons firing together, and power grids

maintaining frequency — giving the framework concrete mathematical tools and a clear path toward testable predictions.

Technical Abstract

In the Void Energy-Regulated Space Framework (VERSF), mass emerges from irreversible bit-flipping dynamics on a zero-entropy substrate. Prior work defined void coupling as a statistical probability p_v without dynamical origin. This paper reinterprets void coupling as phase coherence between interface and substrate oscillations, introducing a coherence order parameter $R = |\langle \exp(i\Delta) \rangle|$ and deriving the micro-event probability p_ε as an explicit functional of R via an error-function bridge formula. The mass relation $m = (\eta \hbar p_\varepsilon)/(c^2 \Delta t K_c)$ remains structurally intact but acquires dynamical content grounded in synchronization physics. We derive fluctuation structure and decay widths from coherence drift, demonstrate robustness across Gaussian and von Mises phase distributions, present a noisy Adler phase-locking model as a minimal dynamical realization, and establish scaling relations yielding the primary prediction $m \propto g \cdot q^{N_{eff}(K_c)} / K_c$ as an exponential mass hierarchy governed by the effective number of independent alignment constraints. An explicit mapping of Standard Model Yukawa couplings to coherence–anchoring ratios is derived, with scale dependence arising naturally from the resolution-dependent character of phase averaging. The formalism connects VERSF anchoring to established synchronization theory and defines a concrete simulation protocol for mass prediction.

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1. Introduction

For general readers: This section explains the problem we're solving. Previous work in VERSF showed that mass comes from a process of irreversible information changes, but left unexplained why *some particles undergo these changes more readily than others. This paper answers that question: it's about how well-synchronized a particle is with the underlying fabric of reality.*

In the Void Energy-Regulated Space Framework (VERSF), mass emerges from irreversible bit-flipping dynamics on a zero-entropy substrate. Prior anchoring work established that rest mass scales as $m \propto p_v / K_c$, where p_v represented a void-coupling probability and K_c an anchoring commitment depth — the number of micro-events required to complete one irreversible state transition. This relation successfully connects mass to discrete information processing, but leaves p_v defined purely as the statistical occupancy of an anchorable subset, with no dynamical origin.

The absence of a dynamical grounding for p_v raises two problems. First, without a mechanism generating the coupling probability, the mass formula describes but does not explain the mass hierarchy. Second, without a dynamical variable underlying p_v, there is no natural route to time evolution, fluctuation spectra, or phase transitions — all of which a complete theory of mass emergence should accommodate.

This paper resolves both problems by reinterpreting void coupling as phase coherence between the interface mode and the substrate. We introduce a coherence order parameter R — the magnitude of the circular mean of the relative phase — and show that the micro-event probability p_ε is a derived functional of R. The mass relation remains structurally intact but acquires a dynamical interpretation: mass is regulated by the degree of phase synchronization between a mode and the void substrate, modulated by the anchoring depth required to commit each bit-flip.

This reformulation connects VERSF anchoring physics to the well-studied mathematics of synchronization theory, circular statistics, and phase-transition phenomena, opening a concrete pathway toward simulation, experimental prediction, and contact with established condensed-matter and quantum-coherence frameworks.

Contributions. This paper contributes six results to the VERSF program: (i) the separation of coherence R and micro-event probability p_ε as logically distinct quantities; (ii) a derived bridge formula connecting p_ε to R via the error function, with explicit derivation from the Gaussian phase distribution; (iii) a stability and decay interpretation via the coherence derivative dp_ε/dR; (iv) a scaling hypothesis linking internal mode complexity to the mass hierarchy through an exponential relation $m \propto g \cdot q^{N_{eff}} / K_c$, where N_{eff} is the effective number of independent alignment constraints; (v) a minimal dynamical model demonstrating how R emerges from phase-locking dynamics in the single-oscillator reduction of Kuramoto-type synchronization; and (vi) an explicit mapping of Standard Model Yukawa couplings to coherence–anchoring ratios, with a derived numerical prefactor and natural scale dependence.

2. Void Coupling and Void Anchoring: Distinct Roles in Mass Emergence

For general readers: Mass in VERSF comes from two separate processes working together. "Coupling" is how often a particle gets an opportunity to make an irreversible change — think of it as how often a key tries the lock. "Anchoring" is how many successful tries are needed before the change actually sticks — how many tumblers the key must turn. A particle's mass depends on both: how frequently opportunities arise and how many are needed. This section explains why keeping these concepts separate is essential to understanding why different particles have different masses.

Two distinct physical processes underlie mass emergence in VERSF: void coupling and void anchoring. They operate at different scales, answer different questions, and contribute different factors to the mass formula. Conflating them obscures the logic of mass emergence; separating them clarifies it.

Void coupling is the interaction between an interface mode and the void substrate. It determines whether, at any given tick, a micro-event — an opportunity for an irreversible bit-flip — can occur. Coupling is a per-tick, probabilistic, dynamical process. Its strength is governed by how well the interface mode's phase aligns with the substrate phase. High coupling means frequent micro-event opportunities; low coupling means the mode and substrate oscillate largely independently, and micro-events are rare. In this paper, we formalize void coupling as phase coherence R and derive the per-tick micro-event probability p_ε as a function of R.

Void anchoring is the accumulation process by which micro-events build toward an irreversible state commitment. A single micro-event does not complete a bit-flip. Rather, K_c successful micro-events must accumulate before the transition becomes irreversible — before the bit is "anchored." Anchoring is a counting process: it tracks how many successful coupling events have occurred and determines when the threshold for irreversibility is reached. The anchoring depth K_c characterizes the difficulty of commitment: shallow anchoring (small K_c) requires few micro-events and produces rapid, easily reversed transitions; deep anchoring (large K_c) demands many micro-events and produces robust, stable state commitments.

How they combine in the mass formula. Rest mass depends on both:

$$m = (\eta \hbar p_\varepsilon) / (c^2 \Delta t K_c)$$

The numerator contains p_ε — a coupling quantity — measuring how many micro-events occur per tick. The denominator contains K_c — an anchoring quantity — measuring how many micro-events are needed per committed transition. Mass is the ratio of coupling strength to anchoring depth: per-tick micro-event probability divided by the number required.

This separation has a direct physical analogy. Coupling is like how often a ratchet's pawl engages a tooth per attempted cycle. Anchoring is like the number of teeth per full revolution:

how many engagements are needed to complete one cycle? The density of completed revolutions per cycle — and therefore the emergent mass — depends on both.

Why the distinction matters. Without separating coupling from anchoring, one might attribute the entire mass hierarchy to a single parameter. The formalism developed here shows that the hierarchy arises from the interplay of three quantities: coherence R (how well-synchronized the mode is), alignment window ε (how precisely the phases must match), and anchoring depth K_c (how many successful alignments are needed). Two modes with identical coherence but different anchoring depths will have different masses. Two modes with identical anchoring depths but different coherence will also have different masses. The mass hierarchy is irreducibly two-dimensional in the coupling–anchoring plane when ε and g are treated as universal; if ε varies by channel or g varies by mode, it becomes higher-dimensional in (R, g, ε, K_c).

Resonant coupling vs. anchoring-effective coupling. The term "void coupling" requires a further distinction. In the original void anchoring framework (prior VERSF work), the probability parameter p_v was defined as the probability per tick that a micro-event contributes toward irreversible commitment. That is, p_v was an anchoring-effective coupling — not a generic measure of resonance strength.

In the present coherence reformulation, it is useful to distinguish two related but conceptually distinct quantities. *Resonant phase coupling*, measured by the coherence order parameter $R = |\langle \exp(i\Delta) \rangle|$, quantifies how well the interface mode tracks the substrate phase. *Anchoring-effective micro-event probability* determines how frequently irreversible commitments actually occur and therefore enters directly into the mass formula. Phase resonance does not automatically imply irreversible anchoring. A mode may track the substrate phase closely (high R) while only rarely entering the subset of aligned configurations that produce irreversible commitment.

We therefore define the anchoring-effective micro-event probability as:

$$p_v \equiv p_{eff} = g \cdot p_{align}$$

where $p_{align} = P(|\Delta| \leq \varepsilon)$ is the alignment probability derived from coherence via the bridge formula (Section 6), and $g \in [0, 1]$ is a gating factor — a structural selection factor determined by the geometry or topology of the anchorable subset, encoding the probability that an aligned configuration lies within the anchorable subset that produces irreversible commitment.

The mass relation therefore becomes:

$$m = (\eta \hbar) / (c^2 \Delta t) \cdot p_{eff} / K_c = (\eta \hbar) / (c^2 \Delta t) \cdot g \cdot p_{align} / K_c$$

This refinement preserves the structure of the original anchoring framework while supplying a dynamical origin for the probability parameter p_v. It also permits regimes in which a mode is strongly phase-coupled ($R \approx 1$) yet generates extremely small mass if anchoring is strongly gated ($g \ll 1$) — a structure potentially relevant for ultra-light species such as neutrinos.

Chirality and anchoring suppression. In addition to phase resonance, irreversible anchoring may require compatibility between the internal phase structure of the mode and the topology of the anchorable subset. For chiral modes — such as neutrino-like modes whose chirality structure restricts anchoring admissibility — only a restricted subset of aligned configurations may satisfy the necessary chirality constraints for irreversible commitment. This naturally introduces a suppression factor g, representing the fraction of aligned states that are anchorable. In such cases a mode may exhibit high phase coherence ($R \approx 1$) while remaining weakly anchoring-effective ($g \ll 1$), yielding ultra-light masses despite strong resonance with the substrate. This mechanism provides a structural route to neutrino mass suppression without abandoning the coherence–anchoring framework.

Chirality-class constraint on g. In this paper g is not treated as an independent continuous parameter per species. Rather, g is assumed to be determined primarily by discrete structural class (e.g., chiral vs. non-chiral anchoring admissibility) and is therefore expected to take values clustered by class — $g \in \{g_{chiral}, g_{nonchiral}, ...\}$ — with any residual mode dependence arising only from computable geometric overlap with the anchorable subset. This reduces the effective freedom from "one g per particle" to "one g per structural class," consistent with the interpretation of g as a topological selection factor. In the eigenmode program, g is computed as an overlap/selection measure on the same state space used to compute R and K_c, not tuned per species. The number of distinct structural classes is expected to be small (order 2–3), determined by the topology of the anchorable subset and the discrete admissibility of the mode (e.g., chiral vs. non-chiral anchoring). In particular, the class count is assumed to be much smaller than the number of particle species, so the class-level g constraint reduces parameter freedom rather than reintroducing it at a different level.

In Sections 3–6, p_ε denotes p_{align} — the alignment probability derived from coherence. From Section 7 onward, p_ε is redefined to denote $p_{eff} = g \cdot p_{align}$ — the anchoring-effective probability that enters the mass relation and counting process. Where the distinction matters, p_{align} is written explicitly.

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3. Definitions and Notation

For general readers: This section defines the key variables used throughout the paper. The most important are: the "relative phase" Δ (how far out of step two oscillations are), the "coherence" R (a single number from 0 to 1 measuring overall synchronization quality), and the "micro-event probability" p_ε (the chance per moment that a bit-flip opportunity occurs). If you follow only these three, the rest of the paper will make sense.

We define the following quantities used throughout the paper.

Interface phase φ_n — the phase of the interface mode at discrete tick n. This encodes the oscillatory state of a mode coupled to the void substrate.

Substrate phase θ_n — the phase of the local void substrate at tick n. The substrate provides the reference oscillation against which interface modes synchronize. Its physical origin is discussed in Section 4.

Relative phase:

$$\Delta_n = \varphi_n - \theta_n \pmod{2\pi} \quad (1)$$

Coherence order parameter (circular mean magnitude):

$$R = |\langle \exp(i\Delta) \rangle| \quad (2)$$

This is the standard Kuramoto-type order parameter measuring the degree of phase synchronization. $R = 1$ indicates perfect phase-locking; $R = 0$ indicates complete phase incoherence.

Alignment window ε — the maximum relative phase deviation within which a micro-event can occur. This is a structural parameter of the interface–substrate interaction, discussed further below.

Micro-event window probability:

$$p_\varepsilon = P(|\Delta| \leq \varepsilon) \quad (3)$$

The probability per tick that the relative phase falls within the alignment window, generating an anchorable micro-event.

Notation note. For readability we write $p_{align} := P(|\Delta| \leq \varepsilon)$ for the phase-alignment probability derived from coherence, and $p_{eff} := g \cdot p_{align}$ for the anchoring-effective probability entering the mass relation. This corresponds to the original anchoring paper's p_v, i.e., $p_v \equiv p_{eff}$. In Sections 3–6, p_ε denotes p_{align}; from Section 7 onward, p_ε denotes p_{eff} (see Section 2).

Anchoring depth K_c — the number of successful micro-events required to complete one irreversible bit-flip. Defined operationally as:

$$K_c = 2\pi / \langle \Delta\varphi_{event} \rangle \quad (4)$$

where $\langle \Delta\varphi_{event} \rangle$ is the mean phase advance per successful micro-event. The 2π in the numerator encodes a physical assumption: one completed anchoring event corresponds to one full phase cycle of the interface–substrate system. The 2π factor encodes the minimal closed cycle of the relative phase Δ required for self-consistent irreversible commitment — a bit-flip constitutes a complete state transition that must return the phase relationship to its starting configuration, and 2π is the minimal closed path in the U(1) phase space of Δ_n. In principle, modes with nontrivial winding structure could require integer multiples of 2π (captured by the action normalization η), but the single-cycle case is the minimal and generic requirement. Deeper anchoring (larger K_c) requires more micro-events per committed transition.

Emergent tick interval Δt — the fundamental discrete time step of the substrate clock. In VERSF, continuous time emerges from the accumulation of discrete ticks; Δt sets the temporal grain.

Action normalization η — the number of independent phase sectors per substrate cycle that contribute to anchoring. In the simplest single-sector models $\eta = 1$. For modes with internal rotational structure, η counts the distinct angular regions within one full 2π cycle where anchoring can independently occur. It is analogous to a topological winding number: a mode that completes η independent anchoring opportunities per substrate cycle contributes η times the action of a single-sector mode. The mass formula inherits this factor linearly, so η directly multiplies the effective per-tick micro-event probability.

On the nature of ε. The alignment window ε is not a free fitting parameter. It characterizes the angular width of the interface–substrate interaction potential — the range of relative phase over which the coupling is strong enough to trigger a micro-event. We treat ε as universal because it is set by the local curvature and threshold structure of the substrate coupling potential $U(\Delta)$ near its minimum. If micro-event registration occurs when $U(\Delta) \geq U^*$, then ε is determined by $U(\varepsilon) = U^*$ and is therefore substrate-defined rather than mode-defined. The potential $U(\Delta)$ is a property of the void substrate's response to phase misalignment; it does not depend on which mode is being coupled. Different modes experience the same substrate potential, just as different particles experience the same gravitational metric.

If ε varies with mode scale. If the universality assumption fails, ε becomes mode-dependent and the mass hierarchy acquires a genuinely three-dimensional structure in (R, ε, K_c). The bridge formula's exponential sensitivity to ε means that even mild variation can dominate the mass scaling. The formalism accommodates mode-dependent ε without structural modification; the implications are noted in Section 12.

Parameter classification. To prevent confusion about what is fixed versus what varies across modes, we state the status of each parameter explicitly:

- **Δt** — calibration constant, often identified with the Planck time t_P in VERSF; treated as universal and fixed throughout this paper.
- **η** — topological sector multiplicity (integer or $\mathcal{O}(1)$); in principle mode-dependent, reflecting the internal rotational structure of each mode. Set to unity for single-sector modes.
- **ε** — alignment window; treated as universal here, but could be channel-dependent in extensions involving distinct interaction potentials.
- **g** — anchoring gate factor (Section 2); a structural selection factor $\in [0, 1]$ determined by the geometry or topology of the anchorable subset. Encodes the fraction of phase-aligned configurations that produce irreversible commitment. From Section 7 onward, g is incorporated into p_ε via $p_\varepsilon := p_{eff} = g \cdot p_{align}$.
- **R, K_c** — mode-dependent observables; these are the quantities that vary across particle species and are the primary drivers of the mass hierarchy.
- **N_{eff}** — effective number of statistically independent phase sectors within a mode's internal structure, defined in Section 9. Determined by the mode's spatial extent ξ, the

internal correlation length ℓ_c, and the effective dimensionality d_eff via N_eff(ξ) ~ (ξ / ℓ_c)^d_eff. Controls the exponential suppression of micro-event probability for complex modes.

Parameter counting and non-fittability. Although the mass relation can be written as m ∝ g · p_ε(R, ε) / K_c, the quantities (R, g, K_c) are not treated as freely adjustable per particle species. In the VERSF program they are mode observables determined by the same underlying interface dynamics: R is computed from the phase statistics of the mode, K_c is computed from its cycle-closure/winding structure, and g encodes structural selection (e.g., chirality/topological admissibility) that is fixed once the mode class is specified. The alignment window ε is treated as substrate-defined and universal in the present work. Under this interpretation, the apparent "four-parameter freedom" collapses to a small set of universal substrate parameters plus a discrete set of mode-specific outputs from the eigenmode map. The Standard Model treats y_f as an independent parameter per fermion; the VERSF program aims to reduce this to a small number of universal substrate parameters plus computed mode observables. The framework becomes predictive once the eigenmode computation program is executed: (R_j, K_{c,j}, g_j) are computed, not fitted, and the mass spectrum is the image of the dynamics rather than an arbitrary assignment.

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4. Nature of the Substrate Phase

For general readers: If we claim particles synchronize with the void substrate, we need to explain what the substrate's "oscillation" actually is — otherwise we've just invented a hidden clock and smuggled it into the theory. This section argues that the substrate's phase isn't imposed from outside but emerges naturally from the void's own structure, much like how a magnet spontaneously "chooses" a direction to point even though no external force picks the direction. Only the difference *between the particle's phase and the substrate's phase matters — the absolute values are meaningless, like the difference between two clocks mattering even though neither has the "right" time.*

The substrate phase θ_n requires careful interpretation. It is not an externally imposed oscillator, not a background field inserted by hand, and not a hidden degree of freedom smuggled into the formalism. It is an emergent consequence of the void substrate's discrete clock structure and its associated phase degeneracy.

Phase degeneracy of the substrate clock. A discrete tick substrate generically admits a phase-origin degeneracy: shifting the tick index $n \mapsto n + n_0$ leaves the physics invariant but changes the phase origin. This is a U(1) symmetry of the substrate dynamics — the void clock has no preferred "starting tick." The substrate phase θ_n can be understood as a local choice of this phase origin, spontaneously selected by boundary conditions and coarse-graining, analogous to how a ferromagnet spontaneously selects a magnetization direction from a rotationally invariant Hamiltonian. The void possesses a phase not as an external oscillator but as a spontaneously selected phase reference of a periodic substrate update rule.

Only relative phases are physical. This framing has an important consequence: θ_n functions as a local phase reference — a gauge-like degree of freedom — and only the relative phase $\Delta_n = \varphi_n - \theta_n$ carries physical content. This is consistent with the formalism developed in this paper, which depends entirely on Δ_n and never on φ_n or θ_n individually. A global shift $\theta_n \to \theta_n + \delta$, $\varphi_n \to \varphi_n + \delta$ leaves all observables (R, p_ε, m) unchanged. The coherence order parameter R measures how well the interface mode tracks the substrate's locally chosen phase convention — not the absolute phase of either oscillation.

Relation to void entropy structure. In VERSF, the void is a zero-entropy state — the ground state of the information-theoretic substrate. A zero-entropy state is maximally ordered, and the discrete tick structure of this ordered state defines a natural periodicity. The substrate phase θ_n is the local expression of this periodicity. Phase fluctuations in θ_n, if they exist, would represent departures from perfect void order and would themselves carry entropy cost — they correspond to local disorder in the substrate clock.

What the interface mode does is oscillate *relative to* this locally selected phase reference. Void coupling measures how well the interface mode tracks it. When tracking is good (small Δ_n), micro-events are frequent and mass is efficiently generated. When tracking is poor (large, random Δ_n), the mode is effectively decoupled and no mass emerges.

Operational definition. Operationally, θ_n is defined as the phase of the local substrate clock mode obtained by coarse-graining the void state over the minimal correlation cell — the smallest spatial region within which the void maintains definite phase coherence. This definition makes θ_n computable in any discrete simulation: given a lattice of void states, one identifies the correlation cell, extracts the dominant oscillatory mode within it, and reads off its phase at tick n.

A complete derivation of the substrate clock dynamics — including whether the U(1) degeneracy is exact or softly broken — remains an open problem (see Section 12), but the operational definition given here is sufficient for the coherence formalism and does not require importing any external oscillatory mechanism.

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5. Phase Coherence Formalism

For general readers: This section develops the mathematics of synchronization quality. The key quantity R ranges from 0 (no synchronization — like two clocks running at random relative to each other) to 1 (perfect lock-step). We show that R drops off rapidly as the "wobble" in the phase difference increases, and that this behavior is robust — it doesn't depend on the specific mathematical assumptions we make about how the wobble is distributed.

The coherence order parameter R inherits its mathematical structure from circular statistics. Its key properties follow directly from the definition.

Bounds:

$0 \leq R \leq 1$ (5)

These bounds are exact. The lower bound is saturated when phase differences are uniformly distributed; the upper bound is saturated under perfect phase-locking ($\Delta_n = \text{const}$ for all n).

Uniform random phase (incoherent limit):

$\Delta \sim \text{Uniform}(0, 2\pi) \Rightarrow R = 0$ (6)

In this limit, the circular mean of $\exp(i\Delta)$ vanishes by symmetry. No net phase alignment exists, and the mode is fully decoupled from the substrate.

Gaussian phase fluctuations (partially coherent regime):

$\Delta \sim \mathcal{N}(0, \sigma^2) \Rightarrow R = \exp(-\sigma^2/2)$ (7)

This result follows from the characteristic function of the Gaussian distribution evaluated at unit frequency. Coherence depends only on the phase variance σ^2 and contains no dependence on the alignment window ε. It is an intrinsic property of the phase-locking dynamics, not of the measurement apparatus.

The exponential sensitivity to phase variance has an important physical consequence: coherence degrades rapidly as fluctuations grow. A mode with $\sigma = 1$ rad retains only $R \approx 0.61$; at $\sigma = 2$ rad, coherence has collapsed to $R \approx 0.14$. Maintaining high coherence requires active suppression of phase fluctuations — a constraint that becomes increasingly difficult to satisfy as the internal complexity of the mode grows.

Robustness: von Mises distribution. The Gaussian phase model is appropriate for small to moderate fluctuations but is not periodic on $[0, 2\pi)$. The natural periodic generalization is the von Mises distribution:

$f(\Delta) = \exp(\kappa \cos \Delta) / (2\pi I_0(\kappa))$ (8)

where $\kappa > 0$ is the concentration parameter and I_0 is the modified Bessel function of the first kind of order zero. The coherence order parameter for the von Mises distribution is:

$R = I_1(\kappa) / I_0(\kappa)$ (9)

where I_1 is the modified Bessel function of order one. In the high-concentration limit ($\kappa \gg 1$), the von Mises distribution approaches the wrapped Gaussian and $R \to 1 - 1/(2\kappa)$. In the low-concentration limit ($\kappa \to 0$), $R \to 0$. The monotonic relationship between concentration and coherence is preserved. The corresponding micro-event probability is:

$p_\varepsilon(\kappa, \varepsilon) = \int_{-\varepsilon}^{\varepsilon} \exp(\kappa \cos \Delta) / (2\pi I_0(\kappa)) \, d\Delta$

and since $R(\kappa) = I_1(\kappa)/I_0(\kappa)$, this defines p_ε as an implicit function $p_\varepsilon(R, \varepsilon)$. No closed-form analog of the Gaussian bridge formula Eq. (14) exists, but the relationship is computable for any R and ε by numerical inversion and integration. Crucially, in the high-concentration regime ($\kappa \gg 1$) where the von Mises approaches the wrapped Gaussian, the quantitative mapping from R to p_ε converges to the Gaussian bridge formula: both distributions yield the same $p_\varepsilon(R, \varepsilon)$ to leading order when $\sigma \ll \pi$. The two predictions diverge only for low coherence ($R \lesssim 0.3$), where the wrap-around structure of the von Mises becomes significant. Since the physically most important regime for stable particles is high coherence (R near 1), the Gaussian bridge formula is quantitatively reliable precisely where it matters most. The Gaussian treatment used throughout this paper therefore reflects a generic feature of peaked, symmetric phase distributions, not an artifact of a special distributional choice.

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6. Derivation of the Bridge Formula

For general readers: This is the paper's central mathematical result. We derive an equation — the "bridge formula" — that converts synchronization quality (R) into the concrete probability that a bit-flip opportunity occurs at any given moment. Think of it this way: if you know how well-synchronized two oscillations are, this formula tells you how often the synchronization is close enough for something to happen. The derivation is four steps of standard calculus; the result is a single equation that connects the abstract to the measurable.

The bridge formula connecting micro-event probability p_ε to coherence R is derived here from first principles rather than stated as a result.

Step 1: Gaussian phase distribution. Assume the relative phase is drawn from a Gaussian with zero mean and variance σ^2:

$$f(\Delta) = (1 / \sqrt{(2\pi\sigma^2)}) \exp(-\Delta^2 / (2\sigma^2)) \quad (10)$$

Validity note. Although Δ is defined modulo 2π, Eq. (10) is used as a small-fluctuation approximation valid when $\sigma \ll \pi$, so wrap-around probability is negligible. For fully periodic treatments, the von Mises model (Section 5) provides the natural replacement.

Step 2: Integration over the alignment window. The micro-event probability is the integral of the phase density over the window $[-\varepsilon, \varepsilon]$:

$$p_\varepsilon = \int_{-\varepsilon}^{\varepsilon} f(\Delta)\, d\Delta \quad (11)$$

Substituting the Gaussian density and evaluating:

$$p_\varepsilon = \int_{-\varepsilon}^{\varepsilon} (1/\sqrt{(2\pi\sigma^2)}) \exp(-\Delta^2/(2\sigma^2))\, d\Delta$$

Applying the standard substitution $u = \Delta/(\sigma\sqrt{2})$:

$p_\varepsilon = (2/\sqrt{\pi}) \int_0^{\{\varepsilon/(\sigma\sqrt{2})\}} \exp(-u^2)\, du$

$p_\varepsilon = \mathrm{erf}(\varepsilon / (\sigma\sqrt{2}))$ (12)

Step 3: Express σ^2 in terms of R. From the Gaussian coherence result Eq. (7):

$R = \exp(-\sigma^2/2) \Longrightarrow \sigma^2 = -2 \ln R$ (13)

Step 4: Substitute into Eq. (12).

$p_\varepsilon = \mathrm{erf}(\varepsilon / \sqrt{(-4 \ln R)})$ (14)

This is the bridge formula. It establishes that the micro-event probability is a derived function of two quantities: the coherence order parameter R (a dynamical variable) and the alignment window ε (a structural parameter of the interface–substrate interaction).

Properties of the bridge formula. The formula is well-defined for $0 < R \leq 1$. In the high-coherence limit ($R \to 1$), $\ln R \to 0$ and the argument of the error function diverges, giving $p_\varepsilon \to 1$: nearly every tick produces a micro-event. In the low-coherence regime ($R \to 0$), $|\ln R| \to \infty$ and the argument approaches zero, giving $p_\varepsilon \to 0$: micro-events become vanishingly rare. Between these limits, p_ε increases monotonically with R for fixed ε, confirming that better phase synchronization reliably produces more frequent micro-events.

High-coherence expansion. Near $R \approx 1$, write $R = 1 - \delta$ with $\delta \ll 1$. Then $\ln R \approx -\delta$, so $\sigma^2 \approx 2\delta$ and:

$p_\varepsilon \approx \mathrm{erf}(\varepsilon / (2\sqrt{\delta}))$ (15)

For $\varepsilon^2/(4\delta) \gg 1$ (tight coherence relative to window width), $p_\varepsilon \approx 1 - (2\sqrt{\delta})/(\varepsilon\sqrt{\pi}) \cdot \exp(-\varepsilon^2/(4\delta))$. The departure from unity is exponentially small, confirming that high-coherence modes generate micro-events at nearly every tick.

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7. Mass Relation

For general readers: This section connects synchronization to actual mass. The logic is: synchronization quality → per-tick bit-flip probability → committed bit-flips per tick → mass. The formula says mass equals the density of committed information changes per substrate tick times a fundamental constant of nature (ħ, Planck's reduced constant) divided by the speed of light squared — echoing Einstein's $E = mc^2$. More synchronization means more bit-flips per tick means more mass. More anchoring depth (more bit-flips required per committed change) means less mass. Crucially, continuous time itself emerges from the accumulation of these ticks — so mass is not a "rate" in the ordinary sense but a per-tick information-processing density.

The mass formula carries forward from prior VERSF anchoring work, now with p_ε explicitly grounded in phase coherence.

Notation reminder. The bridge formula (Section 6) derives p_{align}; the mass relation uses $p_{eff} = g \cdot p_{align}$. From this point onward we write $p_\varepsilon := p_{eff} = g \cdot p_{align}$ for the anchoring-effective micro-event probability that enters the counting process and mass relation; the alignment probability derived from coherence is denoted explicitly as p_{align}.

Rest mass:

$$m = (\eta \hbar\, p_\varepsilon) / (c^2 \Delta t\, K_c) \quad (16)$$

The quantity p_ε sets the per-tick micro-event probability and, together with K_c, determines the expected number of ticks per committed bit-flip. Under the VERSF action postulate — developed and motivated in prior VERSF anchoring work, where it is derived from the requirement that each irreversible bit-flip constitute a minimal quantum of action — each completed cycle contributes $\eta \hbar$ of action, yielding Eq. (16). The denominator $c^2 \Delta t\, K_c$ converts from micro-event counting to rest mass via the tick interval, anchoring depth, and mass-energy equivalence.

Flip period — the mean time between completed bit-flips:

$$T_{bit} = (\Delta t\, K_c) / p_\varepsilon \quad (17)$$

This is the product of the tick interval, the number of required micro-events (K_c), and the inverse of the per-tick success probability ($1/p_\varepsilon$). T_{bit} sets the characteristic emergent timescale of mass generation for a given mode — it counts the expected number of ticks per committed bit-flip and converts to duration via Δt.

Rest energy:

$$E = \eta \hbar / T_{bit} \quad (18)$$

Combining with the flip period yields the expected $E = mc^2$ identity, confirming dimensional and structural consistency.

Mass scaling (explicit dependence chain):

$$m \propto p_{eff} / K_c = g \cdot p_{align}(R, \varepsilon) / K_c \quad (19)$$

Here $p_{align}(R, \varepsilon)$ is given by the bridge formula (Eq. 14), and g encodes anchoring admissibility (Section 2). Mass is ultimately determined by four quantities: the phase coherence R (dynamical), the alignment window ε (structural), the anchoring gate g (topological/chirality-class), and the anchoring depth K_c (topological). The mass hierarchy across particle species arises from different combinations of these parameters.

8. Stability and Fluctuation Structure

For general readers: Why are protons stable for billions of years while other particles decay in fractions of a second? This section shows the answer lies in synchronization quality. Highly synchronized modes produce bit-flip opportunities so reliably that the process is almost clock-like — the particle is rock-solid. Moderately synchronized modes are vulnerable: small wobbles in synchronization quality cause big swings in the per-tick bit-flip probability, leading to decay. The mathematics predicts that stability is exponentially strong for well-synchronized particles — explaining why certain particles are essentially immortal while others vanish almost instantly.

The stochastic character of micro-event generation produces intrinsic fluctuations in the anchoring process. These fluctuations determine particle stability, decay widths, and spectral line structure. In this section p_ε denotes the anchoring-effective probability p_{eff}, since it is the probability of registering commitment-contributing micro-events in the counting process.

Waiting-time distribution. The total number of ticks N required to accumulate K_c successful micro-events follows a negative binomial distribution $NB(K_c, p_\varepsilon)$.

Mean waiting time:

$$E[N] = K_c / p_\varepsilon \quad (20)$$

Variance:

$$\mathrm{Var}(N) = K_c(1 - p_\varepsilon) / p_\varepsilon^2 \quad (21)$$

Coefficient of variation of the waiting time:

$$CV = \sqrt{((1 - p_\varepsilon) / K_c)} \quad (22)$$

The CV characterizes the fractional fluctuation in the number of ticks required to complete one bit-flip cycle. Two limiting behaviors are physically significant. When $p_\varepsilon \to 1$ (high coherence, near-deterministic micro-events), $CV \to 0$ regardless of K_c: the anchoring process becomes clock-like and the particle is maximally stable. When K_c is large with p_ε moderate, $CV \propto 1/\sqrt{K_c}$: deeper anchoring suppresses fluctuations statistically, producing greater stability through redundancy.

Energy fluctuations from coherence drift. If the coherence R undergoes slow stochastic drift δR, the resulting fluctuation in rest energy is:

$$\delta E \propto (dp_\varepsilon/dR) \cdot \delta R \quad (23)$$

The derivative dp_ε/dR follows from the bridge formula Eq. (14) by the chain rule. Writing $p_\varepsilon = \mathrm{erf}(x)$ with $x(R) = \varepsilon / \sqrt{(-4 \ln R)}$, we have $dp_\varepsilon/dR = (2/\sqrt{\pi}) \exp(-x^2) \cdot dx/dR$. Computing

dx/dR by differentiating $x = \varepsilon(-4 \ln R)^{-1/2}$ with respect to R gives $dx/dR = 2\varepsilon / (R(-4 \ln R)^{3/2})$. Combining:

$$dp_\varepsilon/dR = (4\varepsilon) / (\sqrt{\pi} \cdot R \cdot (-4 \ln R)^{3/2}) \cdot \exp(-\varepsilon^2 / (-4 \ln R)) \quad (24)$$

This closed-form expression has the following limiting behavior. As $R \to 1$, $\ln R \to 0$ and $(-4 \ln R)^{3/2} \to 0$ in the denominator, but the exponential term $\exp(-\varepsilon^2/(-4 \ln R)) \to 0$ faster, dominating the algebraic prefactor and ensuring $dp_\varepsilon/dR \to 0$. As $R \to 0$, $(-4 \ln R)^{3/2} \to \infty$ in the denominator, so $dp_\varepsilon/dR \to 0$. The derivative therefore peaks at intermediate coherence and vanishes in both limits, implying that marginally coherent modes are most susceptible to energy fluctuations.

This provides a natural mechanism for decay widths:

$$\Gamma \propto |dp_\varepsilon/dR| \cdot \sigma_R \quad (25)$$

where σ_R is the standard deviation of coherence fluctuations. Stable particles correspond to modes deep in the high-coherence regime where dp_ε/dR is small; unstable resonances occupy intermediate coherence where the derivative is large.

Near-unity expansion of decay width. For $R = 1 - \delta$ with $\delta \ll 1$, we have $-4 \ln R \approx 4\delta$, so Eq. (24) gives $dp_\varepsilon/dR \propto \exp(-\varepsilon^2/(4\delta)) / \delta^{3/2}$. The decay width becomes:

$$\Gamma \propto \exp(-\varepsilon^2/(4\delta)) \cdot \sigma_R / \delta^{3/2} \quad (26)$$

The exponential suppression dominates: decay width is exponentially small for tightly coherent modes. This provides a concrete mechanism for the observed stability of fundamental particles — they occupy the extreme high-coherence regime where the decay width is suppressed beyond any power law.

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9. Scaling Relations and the Mass Hierarchy

For general readers: Why is the top quark 340,000 times heavier than the electron? This section proposes an answer: more internally complex particles have to keep more "pieces" synchronized simultaneously, and the difficulty of doing so grows exponentially with complexity. Imagine trying to get a room of people to clap in unison — easy with 3 people, nearly impossible with 300. The same principle applies here: larger, more complex modes find it exponentially harder to maintain the phase synchronization needed for frequent bit-flips, so they end up with exponentially less mass. This single mechanism — exponential decay of synchronization with internal complexity — naturally produces the enormous range of masses we observe in nature.

The formalism developed above determines the mass of a single mode given its coherence R, alignment window ε, and anchoring depth K_c. To address the mass hierarchy — why different

particle species have the masses they do — we require scaling relations connecting these parameters to the internal structure of each mode.

9.1 Coherence Decay with Internal Complexity

Consider a mode whose internal phase field extends over a characteristic scale ξ, measured in units of the substrate correlation length. Maintaining coherence requires phase alignment across all internal degrees of freedom. If phase fluctuations accumulate independently across the internal structure, the total phase variance grows as:

$$\langle(\Delta\varphi)^2\rangle \sim C \cdot \xi^{\alpha} \quad (27)$$

where C is a coupling constant and $\alpha > 0$ is a fluctuation growth exponent determined by the dimensionality and statistics of the internal phase field ($\alpha = 1$ for diffusive accumulation, $\alpha = 2$ for ballistic).

Substituting into the Gaussian coherence result Eq. (7):

$$R(\xi) \sim \exp(-(C/2)\, \xi^{\alpha}) \quad (28)$$

Coherence decays exponentially with internal complexity. Modes with larger internal structure are exponentially harder to keep phase-locked to the substrate.

9.2 Micro-Event Probability Scaling

Anchoring-effective probability. In the hierarchy analysis we model the anchoring-effective micro-event probability p_{ε} (= p_{eff}). Under the gating decomposition $p_{eff} = g \cdot p_{align}$ (Section 2), the multiplicative alignment hypothesis below is applied to p_{align}, while g is treated as a class-level structural factor.

A mode of internal scale ξ embedded in a d-dimensional interface must maintain simultaneous phase alignment across its internal structure for a micro-event to register. We make the following independence assumption explicit:

Assumption (multiplicative alignment). The internal phase field of the mode can be decomposed into N_{eff} statistically independent phase sectors, each of which must independently satisfy the alignment condition $|\Delta| \leq \varepsilon$ for a global micro-event to occur.

Justification. Why multiplicative rather than additive? An additive model $p_{align} \sim N_{eff} \cdot q$ would imply that increasing internal complexity increases the chance of global alignment — the wrong qualitative direction. A linear suppression model $p_{align} \sim 1/N_{eff}$ cannot generate observed hierarchies spanning 10^5–10^{17} without extreme fine-tuning of other parameters. Multiplicative suppression is the minimal structure that (i) decreases with complexity, (ii) is stable under coarse-graining, and (iii) naturally produces large hierarchies from modest changes in N_{eff}. Partial correlations are handled by replacing N_{eff} with an effective independent count based on the correlation length ℓ_c (below); this softens the exponent rather than eliminating

exponential structure. In simulation, the hypothesis is directly falsifiable: measure p_align as a function of estimated N_eff and test whether ln p_align scales linearly with N_eff.

The number of effectively independent sectors is not simply ξ^d, because partial correlations within the internal phase field reduce the number of independent alignment constraints. If ℓ_c is the internal correlation length — the scale over which phase fluctuations are correlated — then:

$$N_{eff}(\xi) \sim (\xi / \ell_c)^{d_{eff}} \quad (29)$$

where d_eff is the effective dimensionality of the independent sector decomposition. In the fully uncorrelated limit $\ell_c \to 1$, $N_{eff} \to \xi^d$ and $d_{eff} = d$. In the strongly correlated limit $\ell_c \to \xi$, $N_{eff} \to 1$ and the mode aligns as a single unit. Physical systems occupy the intermediate regime where d_eff encodes the correlation structure: it is a correlation-controlled exponent, not a handwavy fit, and need not equal the geometric dimension d.

In this analysis, ℓ_c is treated as mode-independent — a property of the substrate's intrinsic correlation structure rather than of the mode itself. However, in many physical systems correlation lengths grow with system size near criticality. If $\ell_c = \ell_c(\xi)$ (or equivalently $\ell_c = \ell_c(K_c)$), the effective sector count N_eff and the resulting mass hierarchy would be modified. In particular, if ℓ_c grows with ξ, the effective number of independent sectors grows more slowly than $(\xi)^{d_{eff}}$, softening the exponential decay. This possibility is noted as an open question; the present treatment assumes constant ℓ_c as the simplest case.

Under the multiplicative assumption, if each independent sector has an alignment probability $q \in (0, 1)$ — defined as $q \equiv P(|\Delta| \leq \varepsilon)$ evaluated on a single effectively independent sector, i.e., the per-sector analog of the global p_align — then the global alignment probability is:

$$p_{align} = q^{N_{eff}(\xi)} \quad (30)$$

Thus $p_{eff} = g \cdot q^{N_{eff}}$ under class-level gating (Section 2).

In the simplest case, q is substrate-defined and approximately universal for a given ε; mode dependence then enters primarily through N_eff. Since q is determined by the same alignment window ε and per-sector phase statistics, it is approximately universal under the same assumptions that justify ε universality (Section 3). If q varies across modes (for example, due to mode-dependent local coupling geometry), it introduces an additional degree of freedom beyond N_eff. The present treatment assumes universal q as the minimal case.

Taking logarithms:

$$\ln p_{align} = N_{eff}(\xi) \cdot \ln q \quad (31)$$

Since $\ln q < 0$, this gives exponential decay of p_align with N_eff. This exponential form is the fundamental scaling prediction of the multiplicative alignment assumption.

Over restricted ranges of ξ relevant to observed particle species, this exponential decay may be parametrized as an effective power law p_align(ξ) ∝ ξ^{−d_eff} for convenience, but the power-law form is not derived from the multiplicative assumption. It is a phenomenological approximation whose validity range must be established by simulation.

9.3 Anchoring Depth Scaling

Anchoring depth scales linearly with the coherent domain size:

K_c ~ ξ (32)

The physical content is that a mode with a larger coherent structure requires proportionally more micro-events to commit a single irreversible transition, because the bit-flip must propagate across the full coherent domain.

9.4 Mass Scaling Along the Hierarchy

Eliminating ξ via K_c ~ ξ, the effective independent sector count becomes N_eff(K_c) ~ (K_c / ℓ_c)^d_eff. Substituting into Eq. (30):

p_align(K_c) = q^{N_eff(K_c)} (33)

The mass relation m ∝ p_eff / K_c = g · p_align / K_c then gives the primary structural prediction:

m ∝ g · q^{N_eff(K_c)} / K_c (34)

This is an exponential hierarchy: mass decreases exponentially with the effective number of independent alignment constraints, modulated by the linear anchoring depth. This is substantially more falsifiable than a power law — it predicts a specific functional form (exponential times inverse-linear) that can be tested directly once N_eff is measured in simulation.

Secondary phenomenology. Over restricted ranges of K_c where N_eff varies modestly, the exponential decay may be approximated as an effective power law:

m ∝ K_c^{−(d_eff + 1)} (effective, finite-range) (35)

The power-law form is not the fundamental prediction of the formalism. It is a phenomenological parametrization that may prove useful for fitting observed mass ratios over a limited range, but the exponential form Eq. (34) is the structural prediction that simulations should test.

For d_eff ≈ 3 and moderate K_c, both forms produce a steep mass hierarchy spanning many orders of magnitude for modest variation in K_c — the correct qualitative feature.

Status. The multiplicative alignment assumption (Eq. 30) is the central physical postulate of this section. The introduction of N_eff via the correlation length ℓ_c ensures the assumption is not artificially strong: correlations within the internal phase field reduce the effective sector count and soften the exponential decay relative to the fully uncorrelated limit. The exponential hierarchy Eq. (34) is the primary prediction; the power-law Eq. (35) is a secondary convenience. Both require validation by explicit simulation of phase-field dynamics on discrete substrates.

Worked numerical example (toy demonstration). The following illustrates how exponential suppression generates large mass hierarchies from modest structural differences. It is illustrative rather than a claim of calibrated parameter values.

Assume Planck-tick calibration $\Delta t = t_P$, single-sector $\eta = 1$ (prefactor cancels in ratios), and equal class-level g for both species. Choose per-sector alignment probability $q = 0.8$ and assume $N_{eff}(K_c) = A \cdot K_c$ with $A = 1$ for simplicity. The mass ratio between a top-like mode and an electron-like mode reduces to:

$$m_t / m_e = (q^{N_t} / K_{c,t}) / (q^{N_e} / K_{c,e}) = q^{\Delta N} \cdot (K_{c,e} / K_{c,t})$$

To reproduce the observed order-of-magnitude hierarchy $m_t/m_e \approx 3.4 \times 10^5$, one needs $q^{\Delta N} \cdot (K_{c,e}/K_{c,t}) \approx 3.4 \times 10^5$. If (for illustration) $K_{c,e}/K_{c,t} \approx 10^6$ — i.e., the electron-like mode has anchoring depth one million times deeper than the top-like mode — then the remaining factor required is $q^{\Delta N} \approx 0.34$. With $q = 0.8$, this corresponds to $\Delta N \approx 5$ constraints (since $0.8^5 \approx 0.33$). This ratio is illustrative; the eigenmode program (Section 12) treats K_c as a computed output rather than a fitted parameter.

This demonstrates the key point: exponential dependence makes large hierarchies possible with modest differences in effective constraint count ΔN_{eff}, while anchoring depth ratios account for the bulk scaling. The real predictive program is to compute (K_c, N_{eff}, q, g) from mode geometry; this example only illustrates that the mechanism is numerically plausible without extreme fine-tuning.

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10. Minimal Dynamical Model

For general readers: So far we've described what *synchronization does (produces mass) and* how *to measure it (the R parameter), but we haven't shown* where *synchronization comes from. This section provides a simple example — not the final answer, but a proof that the mechanism works. We take a well-understood equation from synchronization science (used to describe things like electronic oscillators locking to a reference signal) and show that it naturally produces a coherence value R, which feeds through our bridge formula to produce mass. The model also reveals a threshold effect: below a critical coupling strength, synchronization fails entirely and no mass emerges — a kind of "mass switch" built into the physics.*

The following model is not proposed as the fundamental dynamics of void-substrate coupling but as proof of concept that the $R \to p_\varepsilon \to m$ chain is realizable in a concrete, analytically tractable

dynamical system. Its purpose is to demonstrate that coherence R emerges naturally from the competition between coupling and noise, and that the formalism of Sections 5–7 applies without modification once R is given a dynamical origin.

Model. Consider a single interface oscillator with phase φ coupled to a substrate oscillator with fixed frequency ω_0:

$$d\varphi/dt = \omega + \kappa \sin(\theta - \varphi) + \sigma_\eta \cdot \xi(t) \quad (36)$$

where ω is the natural frequency of the interface mode, κ is the coupling strength, σ_η is the noise amplitude, and ξ(t) is unit white noise. The substrate phase advances deterministically: $\theta(t) = \omega_0 t$. This is the noisy Adler equation [6], the single-oscillator reduction of Kuramoto-type population synchronization [1], and the simplest model exhibiting a synchronization transition.

Steady-state coherence. In the synchronized regime ($|\omega - \omega_0| < \kappa$), the relative phase $\Delta = \varphi - \theta$ fluctuates around a fixed point. The steady-state distribution of Δ is approximately von Mises with concentration parameter:

$$\kappa_{eff} = 2\kappa / \sigma_\eta^2 \quad (37)$$

The coherence order parameter is then:

$$R = I_1(\kappa_{eff}) / I_0(\kappa_{eff}) \quad (38)$$

Micro-event probability. Evaluating p_ε from the steady-state distribution:

$$p_\varepsilon \approx \mathrm{erf}(\varepsilon / \sqrt{(-4 \ln R)}) \quad (39)$$

where R is given by Eq. (38).

Physical content. This toy model demonstrates three essential features. First, R emerges dynamically from the competition between coupling strength κ and noise σ_η, without being inserted by hand. Second, there exists a synchronization threshold: when noise dominates coupling ($\kappa_{eff} \ll 1$), $R \to 0$ and $p_\varepsilon \to 0$, producing no mass. Mass emergence requires sufficient coupling to overcome noise — a phase transition in the synchronization sense. Third, the dependence of p_ε on coupling strength κ is monotonic and saturating: increasing κ beyond the threshold produces diminishing returns in mass, consistent with the physical expectation that there is a maximum mass achievable for a given anchoring depth.

This model is illustrative, not a claim that actual void-substrate coupling follows Adler dynamics. Its purpose is to demonstrate that the $R \to p_\varepsilon \to m$ chain is realizable in concrete dynamical systems, that R emerges from the competition between deterministic coupling and stochastic noise without being imposed, and to motivate the phase-transition structure discussed in Section 11.1.

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11. Relation to Standard Model Mass Structure

For general readers: The Standard Model of particle physics explains mass through the Higgs mechanism — particles acquire mass by interacting with the Higgs field. This paper doesn't claim to replace that explanation. Instead, it asks: what determines the strength *of each particle's interaction with the Higgs? The Standard Model treats these strengths (called Yukawa couplings) as unexplained numbers that must be measured experimentally. This section shows that the synchronization framework provides a possible microphysical origin for those numbers: each particle's Yukawa coupling is determined by its synchronization quality and anchoring depth. We also show that the formalism is compatible with the way these couplings change at different energy scales (a phenomenon called "running"), and that the synchronization threshold has a structural parallel to the phase transition that gives the Higgs its mass-generating power.*

11.1 Higgs–VERSF Bridge: Yukawa Couplings as Coherence–Anchoring Ratios

In the Standard Model, fermion masses arise from Yukawa couplings to the Higgs field. In the electroweak broken phase:

$$m_f = y_f v / \sqrt{2} \quad (40)$$

where y_f is the dimensionless Yukawa coupling and $v \approx 246$ GeV is the Higgs vacuum expectation value. The Standard Model does not predict the numerical values of y_f; they are empirical inputs.

In the VERSF coherence–anchoring formalism, the rest mass of a mode is:

$$m_f = (\eta \hbar\, p_{\varepsilon,f}) / (c^2 \Delta t\, K_{c,f}) \quad (41)$$

with micro-event probability $p_{\varepsilon,f}$ derived from coherence R_f via the bridge formula Eq. (14) and anchoring depth $K_{c,f}$ defined by Eq. (4). In the original void anchoring formulation (prior VERSF work), the void coupling probability p_v was defined as the per-tick probability that a micro-event contributes toward irreversible commitment. In the present notation this corresponds to the anchoring-effective probability $p_{eff} = g \cdot p_{align}$, so $p_v \equiv p_{eff}$. The present coherence formalism supplies dynamical substructure by deriving $p_{align} = P(|\Delta| \le \varepsilon)$ from coherence R (Section 6), while retaining the original mass scaling $m \propto p_v / K_c$ unchanged. Equating Eqs. (40) and (41) yields the explicit bridge between Yukawa couplings and coherence–anchoring structure:

$$y_f = (\sqrt{2}\, \eta\, \hbar) / (v\, c^2\, \Delta t) \cdot p_{\varepsilon,f} / K_{c,f} \quad (42)$$

This relation is dimensionally consistent: $\hbar/(c^2\Delta t)$ has units of mass, v has units of mass, and $p_{\varepsilon,f}/K_{c,f}$ is dimensionless, so y_f is dimensionless as required.

Planck-tick calibration and numerical prefactor. Under the VERSF calibration $\Delta t = t_P$ (Planck time), one has the identity:

$\hbar / (c^2 t_P) = m_P$ (43)

so Eq. (42) becomes:

$y_f = \sqrt{2}\, \eta\, (m_P / v) \cdot p_{\varepsilon,f} / K_{c,f}$ (44)

Using $m_P \approx 1.22 \times 10^{19}$ GeV and $v \approx 246$ GeV:

$m_P / v \approx 4.96 \times 10^{16}$, $\sqrt{2}\, m_P / v \approx 7.02 \times 10^{16}$ (45)

so the bridge may be written numerically as:

$y_f \approx (7.0 \times 10^{16})\, \eta \cdot p_{\varepsilon,f} / K_{c,f}$ (46)

This makes explicit that the observed Yukawa couplings correspond to extremely small coherence–anchoring ratios. For the top quark ($y_t \approx 1$), we require $\eta\, p_\varepsilon / K_c \approx 1.4 \times 10^{-17}$. For the electron ($y_e \approx 2.9 \times 10^{-6}$), we require $\eta\, p_\varepsilon / K_c \approx 4 \times 10^{-23}$. The smallness of these ratios is not a flaw of the mapping: it is precisely the regime expected if micro-event probability is exponentially suppressed by the effective number of independent alignment constraints (Section 9), yielding an exponential hierarchy of the form $m \propto g \cdot q^{N_{eff}(K_c)} / K_c$. The six-order-of-magnitude separation between top and electron Yukawas corresponds, in the exponential picture, to a comparatively small shift in the effective alignment sector count N_{eff} for reasonable per-sector alignment probabilities $q < 1$, illustrating the efficiency of exponential suppression mechanisms.

Structural relation to electroweak symmetry breaking. This bridge does not claim to replace the Higgs mechanism at the effective-field-theory level. Rather, it proposes a microphysical interpretation of the Yukawa parameters. In the Standard Model, masses vanish above the electroweak transition because the Higgs condensate disappears ($v \to 0$), even though Yukawa couplings y_f remain nonzero. In the coherence–anchoring picture, mass vanishes when the effective committed bit-flip density p_ε / K_c tends to zero — whether due to loss of coherence ($R \to 0 \Rightarrow p_\varepsilon \to 0$) or divergence of anchoring depth ($K_c \to \infty$) — even though structural parameters such as ε, η, and the anchoring rule remain defined. The parallel is therefore not an identification $v \leftrightarrow R$, but the existence of a threshold phenomenon that switches on mass generation when a coherent/condensed phase forms.

Scope. Equation (42) provides a clean correspondence: Yukawa couplings map to coherence–anchoring ratios multiplied by a universal prefactor set by $(v, \Delta t, \eta)$. Whether this interpretation can reproduce the detailed mass spectrum of quarks and leptons — including generation mixing, CKM/PMNS matrix structure, and radiative corrections — remains an open question requiring explicit computation of coherence and anchoring parameters for each particle species. The role of this bridge is interpretive: it situates the coherence mechanism as a candidate microscopic origin for Yukawa hierarchies, while leaving the Standard Model as the correct low-energy effective description.

This mapping therefore applies to anchoring-effective probabilities rather than to generic resonance strength.

When the Yukawa bridge becomes predictive. Equations (42)–(46) are a correspondence relation: they translate Standard Model Yukawa parameters into coherence–anchoring quantities. The mapping becomes predictive only when combined with the structural hierarchy result of Section 9. Under the exponential hierarchy $m \propto g \cdot q^{N_{eff}(K_c)} / K_c$ (with universal q and substrate correlation structure), Yukawa ratios between species satisfy:

$$y_i / y_j = (g_i / g_j) \cdot q^{\Delta N_{eff}} \cdot (K_{c,j} / K_{c,i})$$

For species within the same structural class $g_i = g_j$, the ratio reduces to $q^{\Delta N_{eff}} \cdot (K_{c,j} / K_{c,i})$, where $\Delta N_{eff} := N_{eff}(K_{c,i}) - N_{eff}(K_{c,j})$, and the approximation assumes universal q (Section 9.2) and class-level g (Section 2). In this way the framework replaces "one free Yukawa per species" with a small set of universal substrate parameters (q, ℓ_c, and effective dimensionality d_{eff}) plus mode outputs $K_{c,i}$ from the eigenmode map. This is the sense in which the coherence–anchoring program aims to supply a microphysical origin for Yukawa hierarchies rather than merely restating them.

11.2 Scale Dependence of Coherence

The Standard Model treats Yukawa couplings as scale-dependent quantities that run under renormalization group (RG) flow. If the coherence formalism is to provide a microphysical foundation for effective Yukawa parameters, it must be compatible with this scale dependence.

The coherence order parameter $R = |\langle \exp(i\Delta) \rangle|$ is defined via an averaging operation that implicitly depends on the resolution at which phase fluctuations are probed. Let μ denote a UV momentum scale in the renormalization-group sense. Increasing μ corresponds to resolving shorter-distance fluctuations, which increases the phase variance accessible to the averaging procedure.

If phase variance grows with scale according to:

$$\sigma^2(\mu) = \langle \Delta^2 \rangle_\mu \quad (47)$$

then coherence becomes scale-dependent via the Gaussian result Eq. (7):

$$R(\mu) = \exp(-\sigma^2(\mu)/2) \quad (48)$$

Higher μ (UV, finer resolution) resolves more fluctuations, increasing σ^2 and decreasing R. Lower μ (IR, coarser resolution) averages over short-distance noise, reducing effective σ^2 and increasing R. The generic sign of the coherence flow is therefore:

$$dR/d \ln \mu < 0 \quad (49)$$

Coherence increases toward the infrared. This is physically natural within VERSF: the macroscopic world exhibits well-defined, stable particle masses precisely because long-distance effective behavior reflects coherence that has been enhanced by averaging over short-distance phase noise.

11.3 Running of Effective Yukawa Couplings

Since p_ε is a derived functional of R via the bridge formula Eq. (14), it inherits scale dependence:

$$p_\varepsilon(\mu) = p_\varepsilon(R(\mu)) \quad (50)$$

Differentiating with respect to scale:

$$dp_\varepsilon/d\ln\mu = (dp_\varepsilon/dR) \cdot (dR/d\ln\mu) \quad (51)$$

The closed-form derivative Eq. (24) ensures that this flow vanishes in both extreme coherence limits ($R \to 0$ and $R \to 1$) and peaks at intermediate coherence. Effective coupling strengths are therefore most sensitive to scale where coherence is neither maximal nor minimal.

The Yukawa mapping Eq. (42) then gives:

$$dy_f/d\ln\mu = (\sqrt{2}\,\eta\, m_P / v) \cdot [\, (1/K_c)\, dp_\varepsilon/d\ln\mu - (p_\varepsilon/K_c^2)\, dK_c/d\ln\mu \,] \quad (52)$$

This expression has the same structural form as a renormalization group equation: effective couplings flow under scale transformations according to competing contributions from interaction strength ($dp_\varepsilon/d\ln\mu$) and internal structure ($dK_c/d\ln\mu$). The coherence formalism is therefore compatible with scale-dependent effective couplings, since both phase coherence and anchoring observables depend on resolution; deriving the Standard Model's specific beta-function structure would require incorporating gauge and Higgs-sector dynamics into the substrate framework.

However, the present framework does not reproduce the detailed one-loop structure of Standard Model Yukawa beta functions, which have the form $\beta_y = y(ay^2 - bg^2 + \cdots)$ involving Yukawa self-enhancement, gauge-coupling suppression, and Higgs coupling terms. The coherence flow Eq. (52) has no gauge sector and no Higgs self-coupling contribution. Incorporating gauge structure into the coherence formalism and deriving the specific form of the Standard Model beta functions from coherence dynamics remains an open problem.

On fixed points. Mass parameters evolve under the scale dependence of coherence and anchoring. Non-trivial fixed points — where $dR/d\ln\mu$ and $dK_c/d\ln\mu$ simultaneously vanish — would correspond to scale-stable masses. However, if $\sigma^2(\mu)$ grows monotonically with resolution (the generic case for accumulated fluctuations), then $R(\mu)$ decreases monotonically and no fixed points exist without a feedback mechanism. Such stabilization could in principle arise if the anchoring process itself suppresses phase variance growth at specific scales, but whether this occurs in full VERSF dynamics remains an open question.

12. Limitations and Open Questions

For general readers: Every honest scientific paper should be clear about what it hasn't solved. This section lists the open problems: we haven't derived the substrate's clock from deeper principles, we haven't proven our scaling assumptions, and we haven't yet run the simulations needed to test the predictions. We also include a speculative conjecture — that the synchronization framework might explain why particles come in families — which is suggestive but unproven.

Several aspects of the formalism remain incomplete and are noted here for transparency.

The substrate phase θ_n is given a physical interpretation in Section 4 as a spontaneously selected phase reference arising from the U(1) degeneracy of the substrate clock, but the dynamics of this spontaneous selection are not yet derived from deeper VERSF axioms. A complete treatment should derive the substrate clock dynamics from the entropy-gradient structure of the void and determine whether the U(1) phase degeneracy is exact or softly broken.

The Gaussian assumption for the phase distribution, while analytically tractable and shown to be robust against generalization to the von Mises distribution (Section 5), may break down in strongly coupled or topologically nontrivial regimes. A full treatment should characterize the phase distribution from the microscopic dynamics.

The scaling exponents α and d_{eff} in Section 9 are physically motivated by the multiplicative alignment assumption with correlation-controlled effective sector count, but not derived from first principles within VERSF. The internal correlation length ℓ_c and its dependence on mode structure remain to be determined. These values may depend on the specific anchoring topology and could differ across particle families.

Composite particle treatment — where multiple anchoring channels interact — requires a multi-channel extension of the coherence formalism. The framework is naturally suited to this (each channel carries its own R_i and $K_{c,i}$), but the interaction terms between channels have not yet been specified.

The alignment window ε is treated as a universal constant (Section 3). A deeper theory should derive ε from the curvature of the interface–substrate interaction potential and determine whether it varies across modes. If ε is mode-dependent, the mass hierarchy becomes genuinely three-dimensional in (R, ε, K_c). In the high-coherence regime, the bridge formula gives $1 - p_\varepsilon \sim (\sqrt{(-4 \ln R)} / (\varepsilon\sqrt{\pi})) \exp(-\varepsilon^2/(-4 \ln R))$, showing exponential sensitivity to ε: if $\varepsilon(\xi)$ decreases with internal complexity, it steepens the hierarchy beyond the R-only effect; if it increases, it softens it. The general mass scaling becomes $m(\xi) \propto p_\varepsilon(R(\xi), \varepsilon(\xi)) / K_c(\xi)$.

The toy model of Section 10 demonstrates that R emerges in noisy Adler dynamics but does not constitute a derivation of the actual void-substrate coupling law. Identifying the correct dynamical equation governing φ_n remains an open problem.

Eigenmode computation program. The quantities (R, K_c, g) are not introduced as tunable parameters per particle species. They are intended to be derived from a single underlying interface dynamics via an eigenmode analysis. The minimal program is as follows. (1) Define a discrete interface state variable c(x, n) (e.g., contrast pair or admissibility vector) evolving on the substrate tick n. (2) Specify the local update operator U acting on c, including the substrate phase reference θ and mode phase φ = arg(c). (3) Compute eigenmodes ψ_j of the linearised (or Floquet) operator describing phase evolution around a stable cycle. (4) For each mode ψ_j, compute coherence R_j = |⟨exp(iΔ_j)⟩| from the induced Δ_j distribution. (5) Compute alignment probability p_{align,j} = P(|Δ_j| ≤ ε) via the bridge formula or via numerical integration. (6) Compute anchoring depth K_{c,j} from phase-winding closure: K_{c,j} = 2π / ⟨Δφ_event⟩*j. (7) Compute gating factor g_j as a structural overlap/selection measure: the fraction of aligned configurations that lie in the anchorable subset (e.g., chirality/topology admissibility filter). (8) Predict mass via m_j ∝ (g_j · p*{align,j}) / K_{c,j}, and compare ratios across modes without fitting per species. This program makes the framework predictive: once the update operator U (and substrate parameters ε, Δt, etc.) is fixed, the spectrum {m_j} is an output. The present paper establishes the mapping from these outputs to mass and stability; the eigenmode analysis is the next technical deliverable.

The scale dependence of coherence (Section 11.2–11.3) is compatible with running effective couplings, but the resulting flow equations do not reproduce the detailed one-loop structure of Standard Model Yukawa beta functions. The SM beta functions involve gauge-coupling suppression, Yukawa self-enhancement, and Higgs coupling terms — none of which are present in the current coherence flow. Deriving the SM beta function structure from coherence dynamics, or identifying the additional ingredients needed, is an open problem that would significantly strengthen the connection to established particle physics.

Conjecture: coherence collapse and symmetry breaking. The synchronization transition in the toy model — the threshold below which R = 0 and no mass emerges — has a suggestive parallel to symmetry breaking. Above the critical coupling, the relative phase locks to a definite value, breaking the rotational symmetry Δ → Δ + const. Mass emergence is coincident with this symmetry breaking. If this parallel extends to the full VERSF framework, particle families might correspond to distinct synchronization phases — different stable configurations of the phase-locking dynamics, each with its own characteristic R, ε, and K_c. Phase transitions between configurations could correspond to particle transmutations or the restoration of symmetry at high energy (where high noise destroys coherence and mass). The Kuramoto model on complex networks is known to exhibit multiple synchronization transitions and coexisting synchronized clusters, which could in principle map onto family structure. This conjecture is structurally motivated by the formalism but entirely untested; it is recorded here as a direction for future investigation, not as a claim of the present paper.

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13. Conclusion

For general readers: The paper's central message is that mass emerges from the interplay of synchronization and anchoring commitment. A particle's mass is determined by two things

working together: how well its internal oscillation locks onto the underlying substrate's rhythm (synchronization — which controls how often bit-flip opportunities arise), and how many successful alignments are needed to commit an irreversible change (anchoring depth — which controls how many opportunities it takes to complete one bit-flip). A third parameter, the alignment precision required, modulates both. This gives us a concrete recipe: simulate the synchronization, measure the anchoring depth, predict the mass. The mathematics connects to a well-established branch of science (synchronization theory), which means decades of existing tools and results become immediately applicable to fundamental physics.

Void coupling, previously an abstract statistical parameter in the VERSF anchoring formalism, is identified here as phase coherence between interface and substrate oscillations. The coherence order parameter $R = |\langle \exp(i\Delta) \rangle|$ measures the quality of phase synchronization; the micro-event probability p_ε is derived from R through an explicit bridge formula Eq. (14) involving the error function. The mass relation $m = (\eta \hbar p_\varepsilon)/(c^2 \Delta t K_c)$ remains structurally intact but now possesses a dynamical interpretation grounded in synchronization physics.

What the coherence reformulation buys VERSF. Prior to this paper, the mass relation $m \propto p_v / K_c$ was a structural result that did not explain what set p_v for any given mode. The coherence formalism transforms p_v from an input parameter into a derived quantity determined by synchronization dynamics. The mass formula is now falsifiable at a deeper level: one can simulate the phase dynamics, extract R and K_c, and predict mass. The formalism provides a natural mechanism for particle decay — unstable particles occupy intermediate coherence where dp_ε/dR is large, while stable particles occupy the high-coherence regime where decay width is exponentially suppressed. The connection to Kuramoto synchronization theory opens VERSF to the full toolkit of synchronization analysis: bifurcation diagrams, frequency-locking regions, chimera states, and multi-oscillator dynamics. And the Yukawa mapping $y_f = \sqrt{2}\, \eta\, (m_P/v) \cdot p_{\varepsilon,f}/K_{c,f}$ derived in Section 11 situates the formalism within Standard Model mass structure rather than in opposition to it.

The key results are: the separation of coherence R from micro-event probability p_ε as logically distinct quantities connected by a derived relation; the identification of mass as ultimately regulated by four parameters — phase coherence, alignment window, anchoring gate, and anchoring depth; the derivation of fluctuation structure and decay widths from coherence drift with exponential suppression at high coherence; a scaling argument yielding the exponential hierarchy $m \propto g \cdot q^{N_{eff}(K_c)} / K_c$ as the primary structural prediction of the mass hierarchy; an explicit mapping of Yukawa couplings to coherence–anchoring ratios with a computed numerical prefactor; and a minimal dynamical model demonstrating the emergence of R from phase-locking dynamics with an associated mass-generating phase transition.

Predictive protocol. The formalism yields a three-step computational procedure for mass prediction:

Step 1: Simulate phase dynamics, extract $R = |\langle \exp(i(\varphi - \theta)) \rangle|$

Step 2: Measure anchoring depth $K_c = 2\pi / \langle \Delta\varphi_{event} \rangle$

Step 3: Compute $p_\varepsilon = \mathrm{erf}(\varepsilon / \sqrt{(-4 \ln R)})$, then $m = (\eta \hbar p_\varepsilon)/(c^2 \Delta t K_c)$

Each step involves quantities measurable within a discrete phase-field simulation. The formalism connects VERSF anchoring physics to the established mathematics of Kuramoto synchronization, circular statistics, and phase-transition theory, and opens a concrete pathway from theoretical framework to quantitative prediction.

Falsifiability. The mechanism makes a specific structural prediction: simulations of a discrete phase-field interface must produce a stable high-coherence regime with measured N_eff(K_c) yielding an exponential mass hierarchy $m \propto g \cdot q^{N_{eff}} / K_c$. If no such regime exists — if coherence cannot be sustained, or if the measured mass scaling deviates qualitatively from exponential-times-inverse-linear — the mechanism is falsified.

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14. References

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